Spissitudinal Explorations

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Fernando Pessoa

Today I'm divided between the loyalty I owe

The Tobacco Shop across the street, as a real thing outside,

And the feeling that everything's a dream, as a real thing inside.

From Pessoa to More

Henry More

- Neo-platonist philosopher from Cambridge.
- First to conceive of a fourth spatial dimension.
- This dimension was the domain of consciousness/psyche.
- Coined the word spissitude to describe this dimension.

Johann Zöllner

- Johann Zöllner – 19th-century astronomer from Leipzig.
- Took the idea of spissitude forward by performing "psychical experiments".
- Zöllner's idea was to use the explanatory power of the fourth dimension so that psychic phenomena can be reduced to physics.

Kaluza

- With Kaluza, the fourth dimension re-appeared in the early 20th century, stripped of its mystical baggage.
- Encouragement from Einstein's theory of gravity.
- Kaluza worked with a 5-d space-time and showed a way to unify gravity and electromagnetism.
- Nordström's work on 5-d unification preceded Kaluza's by a few years.

Klein

- If this extra dimension is physical, why don't we observe it?
- Klein suggested that the extra dimension is compactified into a small circle.
- The radius of compactification needs to be very tiny.

Back to 4 dimensions

- Think of a scalar field in 5 dimensions, $\phi(x, y)$. where y is compactified to a circle of radius R.
- Fourier expand this field in terms of infinite number of $\phi_n(x)$ which are 4-dimensional fields.
- So a single 5-d field appears as a tower of states in 4 dimensions, with a mass $|n|/R$ for every mode n.
- Moreover, a 5-d particle of a given spin appears as states of different spins in 4-d.
- Bad news: All particles, except the zero-mode, of the order of Planck scale.

The Standard Model

- Loss of interest in Kaluza-Klein theory with discovery of nuclear forces.
- The Standard Model:
  $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge theory.
- Fermions: Quarks and leptons; Bosons: Gauge particles.
- Consistent with all known data – LEP and Tevatron.

Symmetry Breakdown

- Masses of gauge bosons and fermions in contradiction with gauge symmetry.
- Spontaneous symmetry breaking $\longrightarrow$ Higgs scalar.
- Only particle of the SM yet to be discovered.
- With the Higgs, SM is renormalizable and unitary.
- Is it possible that the SM is valid upto very high energies?

Large Hadron Collider (LHC)

- One of the major physics goals of the LHC is the Higgs discovery.
- The LHC is a pp collider with $\sqrt{s} = 14$ TeV.
- Collisions of quarks and gluons at TeV energies allow new particles to be produced.
- ATLAS and CMS are the two detectors which the two experimental groups at LHC will use.

Hierarchy Problem

- The Higgs mass is not protected by any symmetry.
- Radiative corrections to Higgs mass quadratically divergent.
- With no cut-off, except the Planck scale the problem of fine-tuning becomes severe.
- Solution 1: Impose a symmetry that will protect the Higgs mass – Supersymmetry.
- Solution 2: Lower the cut-off by having new physics switch on at the TeV scale.

Branes

- In the strong coupling limit of string theories, solitonic modes appear $\longrightarrow$ Dp-branes.
- A Dp-brane is a $p+1$ dimensional dynamical object.
- End points of open strings (associated to gauge particles) are localised on the D-branes. Closed strings (corresponding to gravitons) are free to propagate in the bulk.

The ADD Model

- Imagine our 4-d universe to be a 3-brane in a higher-d spacetime.
- SM localised on the brane and gravitons free to move around over the entire space-time.
- If the compactification radius of n extra dimensions is R, then

$$M_{\mathrm{P}}^2 = M_S^{n+2} R^n \ , \tag{1}$$

where M_S is the low-energy effective string scale.

Large Extra Dimensions

- If R is large, M_S can be of the order of a TeV. For such a value of M_S, $R = 10^{32/n-19}$ m.

n	R (in m)
1	10^{13}
2	10^{-3}
3	4.5×10^{-9}
4	10^{-12}
5	2.5×10^{-13}
6	2.1×10^{-14}

Graviton in 4-d

- The extra dimensions are compactified on a torus.
- What does the higher-d graviton manifest as?
- K-K excitations of the graviton corresponding to a tower of spin-2, spin-1 and spin-0 excitations.
- The spin-2 K-K states $\Longrightarrow$ infinite tower of massive gravitons, spin-0 state $\Longrightarrow$ dilaton, spin-1 state $\Longrightarrow$ negligible couplings.

Graviton couplings

- The 4-d graviton couples, as usual, to the energy-momentum tensor of SM particles.
- Coupling suppressed by $1/M_P$. But summing over the tower makes it of TeV strength $\Longrightarrow$ Experimental consequences!

Collider signatures: Direct

- The tower of gravitons can be produced in collider experiments.
- These gravitons escape detection so give rise to missing energy signatures.
- Existing experimental information yield bounds on M_S. 500 GeV – 1.2 TeV at LEP2 and around 600 GeV to 1.1 TeV at Tevatron (for n between 2 and 6).

Constraints from Supernovae

- Gravitons can also be produced in the core of supernovae in nucleon-nucleon processes and can carry away energy from the core.
- Data on SN1987A (Kamiokande and IMB experiments) imply bounds on M_S of the order of 70 TeV for n=2 and about 2 TeV for n=3.
- For $n > 2$, LHC will be able to probe the range that existing experiments cannot.

Collider signatures: Indirect

- Exchange of gravitons as intermediate states can modify the cross-section for the production of SM particles.
- A host of such processes have been analysed and bounds in the vicinity of a TeV have been obtained.
- Again, LHC will be able to uncover more of the paramater range.

Small Extra Dimensions

- A model with a large compactification radius is not stable – the hierarchy problem returns in a different garb.
- An attempt to solve the hierarchy problem without introducing a large compactification radius – the model of Randall and Sundrum.
- In this 5-d model, the fifth dimension y of a small radius R_c is compactified on a $\mathbf{S}^1/\mathbf{Z}^2$ orbifold in an AdS spacetime.

Warped Model

- Two branes are at the orbifold fixed points: a Planck brane at $y = 0$ and a TeV brane at $y = \pi$.
- The model uses a warped metric

$$ds^2 = e^{-KR_c y}\eta_{\mu\nu}dx^\mu dx^\nu + R_c^2 dy^2. \tag{2}$$

where K is a mass scale related to the curvature.

From Plancks to Logs

- The warp factor acts as a conformal factor for fields on the brane.
- The term $\exp(-KR_c y)$ for the TeV brane at $y = \pi$ generates a factor of 10^{15} by an exponent of order 30 and solves the hierarchy problem.
- Problem: Mass scales that suppress higher dimensional operators inducing proton decay or neutrino masses also get rescaled.

AdS/CFT

- AdS/CFT: Type IIB String Theory on $\text{AdS}_5 \times S^5$ is dual to an $\mathcal{N}=4$ SU(N) 4D gauge theory.

(3) $$\frac{R_{AdS}^4}{l_s^4} = 4\pi g_{YM}^2 N$$

with $R_{AdS} \equiv 1/k$, l_s is the string length and g_{YM} is the gauge theory coupling.

- Description of purely bulk gravity with stringy corrections are neglected, valid only for $R_{AdS} \gg l_s \Longrightarrow g_{YM}^2 N \gg 1$.

More on AdS/CFT

- Upshot: The RS model is dual to a 4-d theory which is strongly coupled.
- The dual theory is conformally invariant down to the TeV scale and the invariance is broken by the TeV brane.
- The K-K excitations as well as the fields localised on the TeV brane are TeV-scale composites of the strong sector.
- Since all the SM fields are localised on the TeV brane, the RS theory is dual to a theory of TeV-scale compositeness.

Exploring the Bulk

- The way out is to localise only the Higgs on the brane – composite Higgs.
- RS solutions for the zero-modes suggest they can be localised anywhere in the bulk but the KK modes are localised close to the TeV brane.
- Localise zero modes paying attention to flavour hierarchy, EW precision tests and avoidance of FCNCs.

On Localising Scalars

- Start with the bulk scalar field equation.
- Obtain the zero-mode solution using separation of variables.
- Usual Dirichlet or Neumann boundary conditions do not yield any non-trivial solutions.
- One needs to include boundary mass terms – a boundary mass parameter gets introduced.
- This parameter can be tuned to localise the zero-mode scalar anywhere in the bulk.

Locating the fermions

- To get a large Yukawa coupling i.e. overlap with the Higgs one needs to localise the fermion close to the TeV brane and far away from the brane to get a small Yukawa.
- The top sector: the doublet needs to be as far away from the TeV brane as allowed by R_b whereas the t_R needs to be close to the TeV brane to get the large Yukawa of the top.
- FCNCs and precision electroweak tests $\Longrightarrow$ KK gauge bosons masses $\sim$ 2-3 TeV.

KK gluons

- Interesting signal – KK gluon production.
- The KK gluon coupling to t_R is enhanced by a factor ξ compared to α_s where $\xi \equiv \sqrt{\log(M_{pl}/\mathrm{TeV})} \sim 5$.
- Consequently, it decays predominantly to tops if produced.
- To the $(t, b)_L$ doublet its coupling is α_s.
- To the light quarks its couplings are suppressed by a factor $1/\xi$.

KK Gluon Production

- However, the ggg_{KK} vanishes because of the the orthogonality of the profiles of these particles.
- So gg initial state does not contribute, only $q\bar{q}$ does. The has been studied in the context of the LHC and Tevatron.
- At the LHC, KK gluon masses of the order of 2-3 TeV can be probed.
- The measured top cross-section from Tevatron Run II yields a bound of about 800 GeV results at the 95% confidence level.

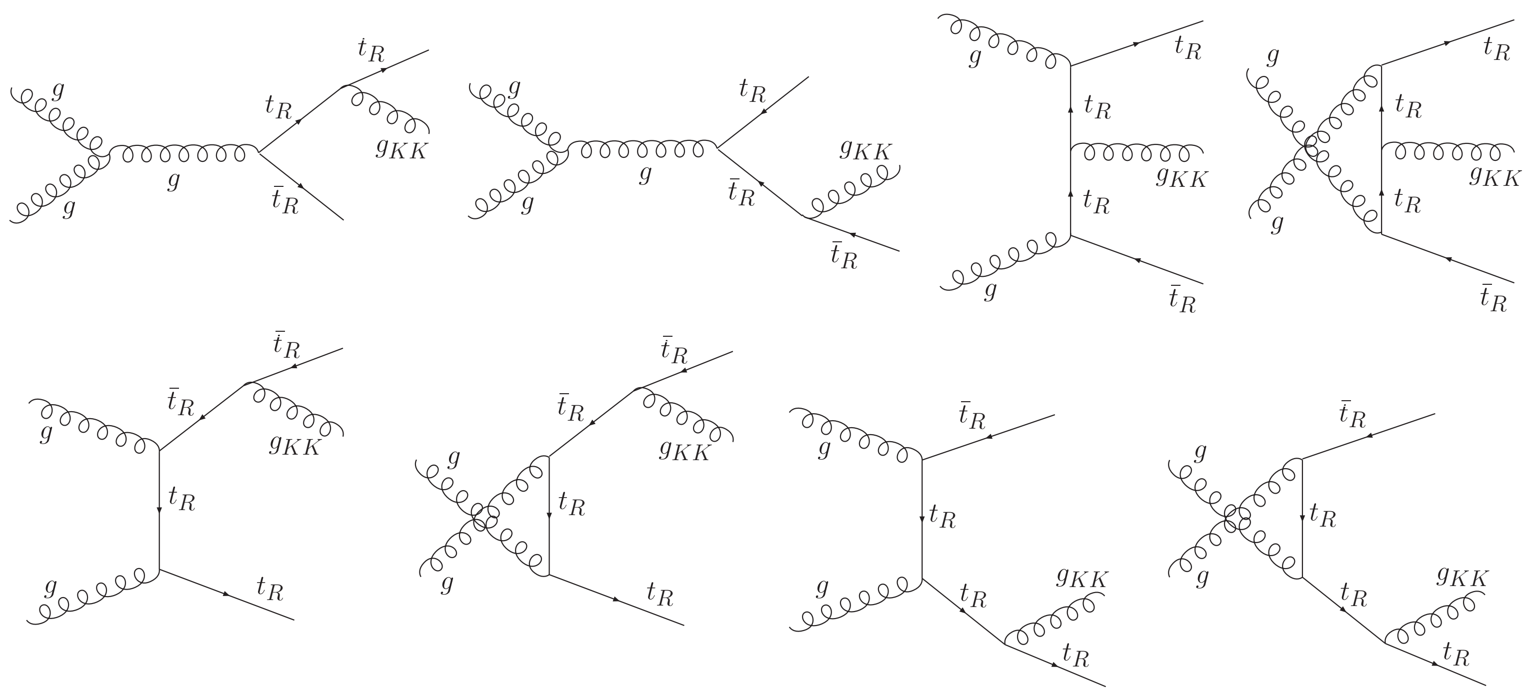
Associated Production

- It is useful to consider other production mechanisms so that the gg initial state also contributes.
- The production of a KK gluon in association with a $t\bar{t}$ pair has been studied.
- Spectacular 4 top final state signals.
- LHC can use this process to reach up to 3 TeV in KK gluon masses.

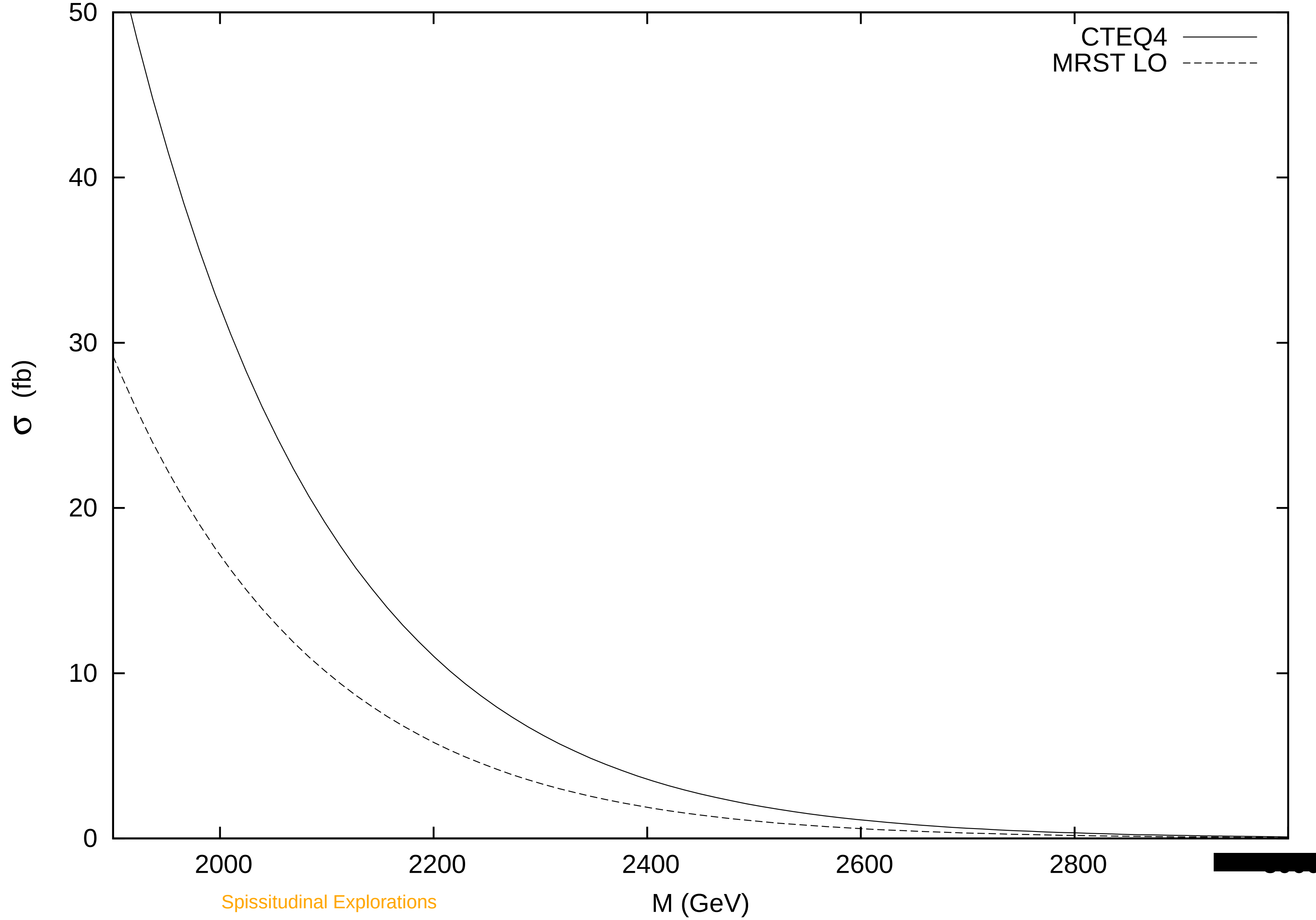
Feynman Diagrams

(a)

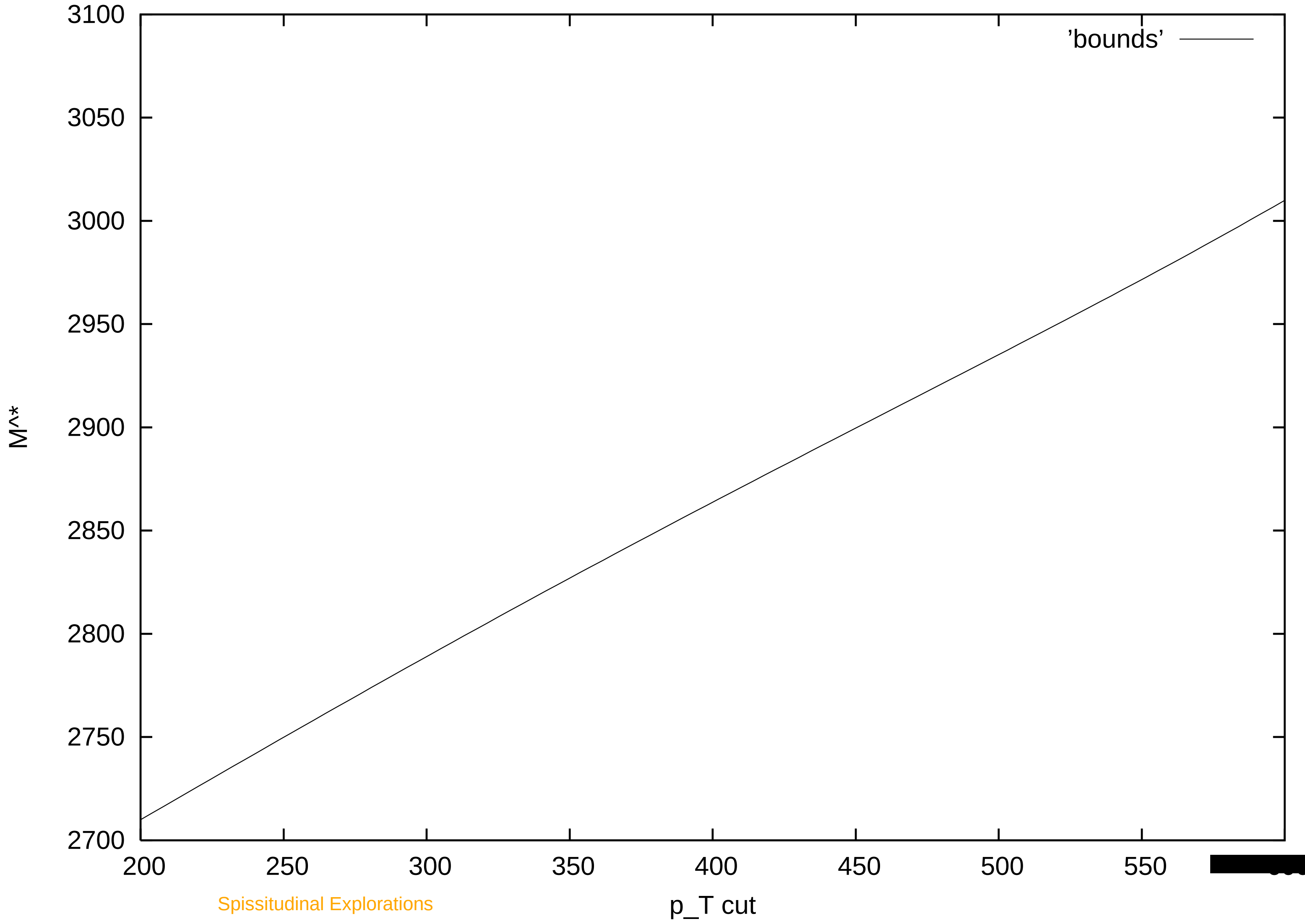
(b)



Cross-Section



M vs p_T-cut



3100
3050
3000
2950
2900
2850
2800
2750
2700
M^*
'bounds'
200
250
300
350
400
450
500
550
p_T cut

Signal vs. Background

p_T-cut (GeV)	M^* (GeV)	Signal Events	Background Events
200	2710	49.2	97
300	2790	28.7	33
400	2870	16.5	11
500	2930	10.0	4
600	3010	6.5	1.7

Table 1: *The numbers of signal and background events for an integrated luminosity of 100 fb*$^{-1}$ *for different values of* p_T*-cut and the corresponding values of* M^*.