Top Quark Phenomenology:

ADD model and the Minimal Length Scenario

K. Mimasu, S. Moretti

Overview

- ➡ ADD Model
  - Background
  - Particles and coupling to SM
  - Virtual gravitons
- ➡ Minimal Length Scenario: natural regulator
- ➡ t-tbar channel at collider experiments
  - precision LHC discovery channel
- ➡ ADD+MLS in the t-tbar channel: LHC reach to set bounds
- ➡ Outlook & Summary

The ADD Model

Motivation

- Alternative viewpoint on the gauge hierarchy problem proposed by Arkani-Hamed, Dimopoulos and Dvali *(arXiv:hep-ph/9803315)*
    - δ compact extra dimensions
    - Fundamental Planck scale is very low ~ O(TeV)
    - SM degrees of freedom localised on a 3-brane embedded in the bulk
- 'Large' extra dimensional volume allows the fundamental Planck scale to be as low as the electroweak scale

$$M_4^2 = M_D^{2+\delta} V_\delta$$

- Simplest realisation of a model with transverse extra dimensions
- Toroidal compactification: $\mathcal{M}_4 \times T_\delta$
- Common radius R

The ADD Model

Particles and Coupling

- Linearised gravity in D dimensions – degrees of freedom described by fluctuations of the metric about flatness:

$$g_{MN} = \eta_{MN} + \kappa h_{MN}; \quad \kappa^2 = \frac{1}{M_D^{2+\delta}} \qquad h_{MN} = \left(\begin{array}{c|c} G_{\mu\nu} & A_{\mu j} \\ \hline A_{i\nu} & \phi_{ij} \end{array}\right)$$

- Kaluza Klein reduction leads to a 4D effective action for the Lorentz group reps into which the D dimensional tensor decomposes

$$h_{MN}(x^\mu, y^i) = \sum_{\vec{n}} h_{MN}(x^\mu) \exp(i\frac{2\pi n\cdot y}{R})$$

- Massless zero modes

- Each (non zero) KK level consists of:
  - 1 tensor field (graviton)
  - δ-1 vector fields (graviphotons)
  - (δ^2-δ-2)/2 + 1 scalars (graviscalars + radion)

$$m_n = \frac{2\pi|\vec{n}|}{R}$$

The ADD Model

KK Gravitons

- Each KK level has universal coupling to matter via the energy-momentum tensor

$$S_{int} = \int d^4x \sqrt{g} \mathcal{L}_{SM} \Rightarrow \sum_{\vec{n}} \int d^4x \, G^{\vec{n}}_{\mu\nu} T^{\mu\nu} + \phi^{\vec{n}} T^{\mu}_{\mu}$$

- Scalars and vectors decouple apart from the radion
- Although each mode couples with strength ~$1/M_4$, the sum of contributions from all modes increase the effective coupling up to $1/M_D$
- Collider signals could arise from
  - real production (X + missing E_T)
  - virtual production (excesses in σ or differential distributions)
- Large extra dimensions = many closely spaced KK levels – approximate the sum of propagators as an integral *(Han et al. arXiv:hep-ph/0508097)*

$$D(p^2) = \sum_{\vec{n}} \frac{1}{p^2 - m_n^2 + i\epsilon} \Rightarrow \int^{\Lambda^2} \frac{\rho(m_n) dm_n{}^2}{p^2 - m_n^2 + i\epsilon}$$

- Ad hoc cutoff...

Minimal Length Scenario

Natural Regulator

- Perturbative string theory brings about the possibility of having a minimal length scale – strings cannot probe distances smaller than the string scale: $l_S \sim 1/M_{pl}$

- Generalised uncertainty principle, modified relation between p and k

$$[\hat{x}, \hat{p}] = i \frac{\partial p}{\partial k}$$

- Interesting from a phenomenological point of view in the framework of large extra dimensions because of the lowered fundamental Planck scale, M_D

- Modification of the momentum measure to account for the squeezing of high momentum modes – tool for regularising UV divergences

$$d^4p \rightarrow d^4p \prod_{\mu} \frac{\partial k_{\mu}}{\partial p_{\mu}}$$

- Use MLS to incorporate a smooth UV cutoff for the sum over KK mode amplitudes

Minimal Length Scenario

Phenomenological Approach

- Many issues which aren't addressed – our approach is to parametrise the effects of MLS at $l_S \sim 1/M_{D/S}$ and apply them to the ADD
- How this extension affects bounds on the parameters of the model in the light of early LHC data in the t-tbar channel
  - Regularisation of the KK graviton sum
  - Modification of the phase space integration *(Hossenfelder et al. arXiv:hep-th/0305262)*

$$\tilde{\rho}(m_n) = \rho(m_n)\frac{\partial \omega}{\partial E}; \qquad d\tilde{\sigma} = d\sigma \prod_i \frac{E_i}{\omega_i} \prod_\mu \frac{\partial k_\mu}{\partial p_\mu}$$

- Unruh relations: $k_M = \frac{1}{l_S}\tanh\left(\frac{p_M}{M_S}\right)$

$$D(s) = \frac{R^d s^{d/2-1}}{(4\pi)^{d/2}\Gamma(d/2)}\left[\pi sech^2\left(\frac{\sqrt{s}}{M_S}\right) + 2iI'\right]; \qquad I' = P\left[\int_0^\infty \frac{y^{d-1}}{1-y^2} sech^2\left(\frac{\sqrt{s}}{M_S}y\right) dy\right]$$

- Finite! Numerically integrable

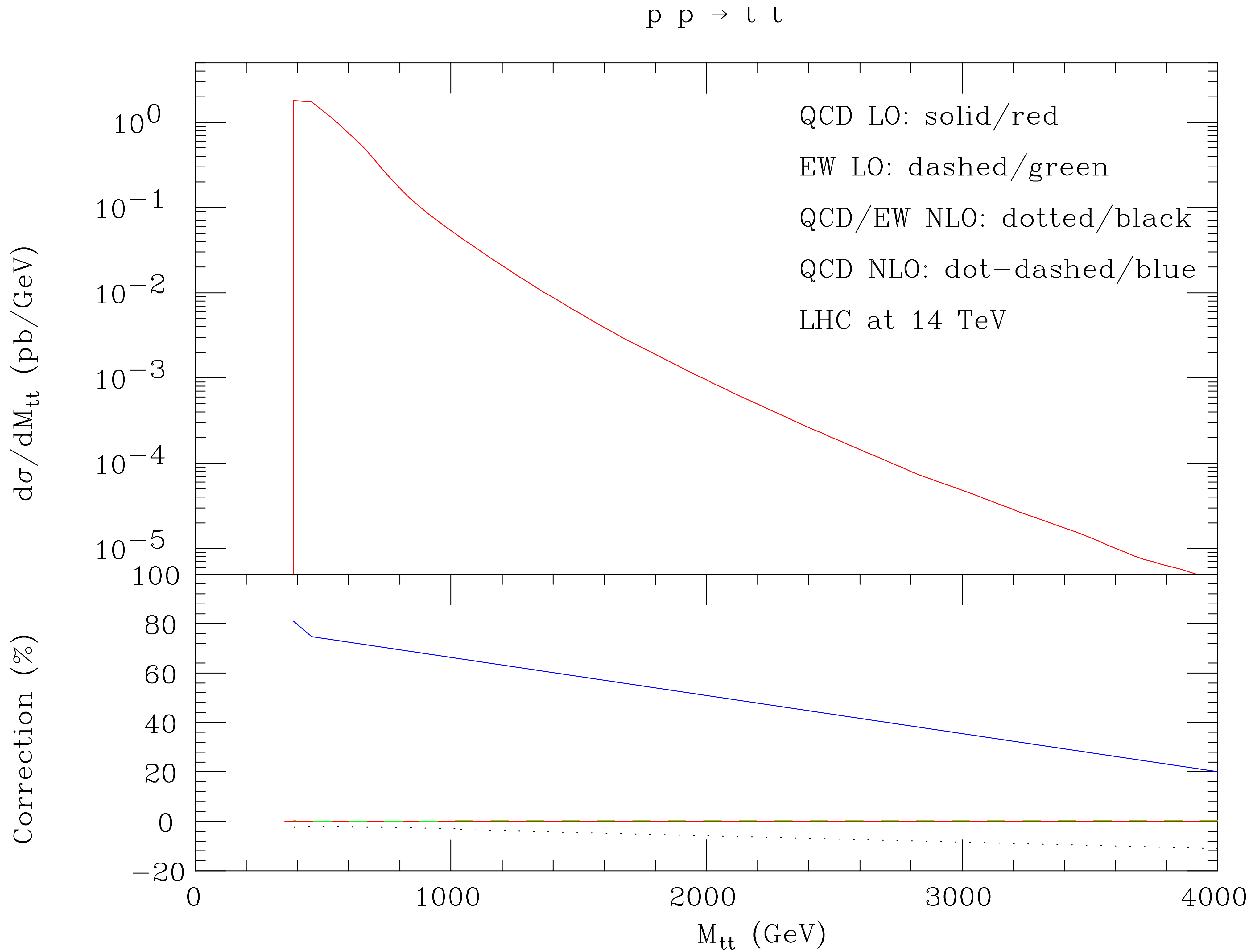
The t-tbar Channel

Why we love it...

- One of the main LHC discovery channels – NLO σ ~ 830 pb at 14 TeV
  - Low statistical uncertainty
- Dominated (~90%) by gluon fusion
  - PDF's are important – always improving
- NLO fully known, NNLO on the way (NLL,NNLL)
  - Theoretical errors under control
  - Normalisation of SM background known
- Experimental uncertainty predominantly due to b-tagging and jet energy scale
- Possible to define asymmetries ($\Gamma_{top} > \Lambda_{QCD}$) spin information transferred to decay products – A_{FB}, spin asymmetries
- 'Precision' channel, m_t = 173.3±1.1 GeV/c^2 (CDF)

The t-tbar Channel

NLO SM Corrections to t-tbar cross-section



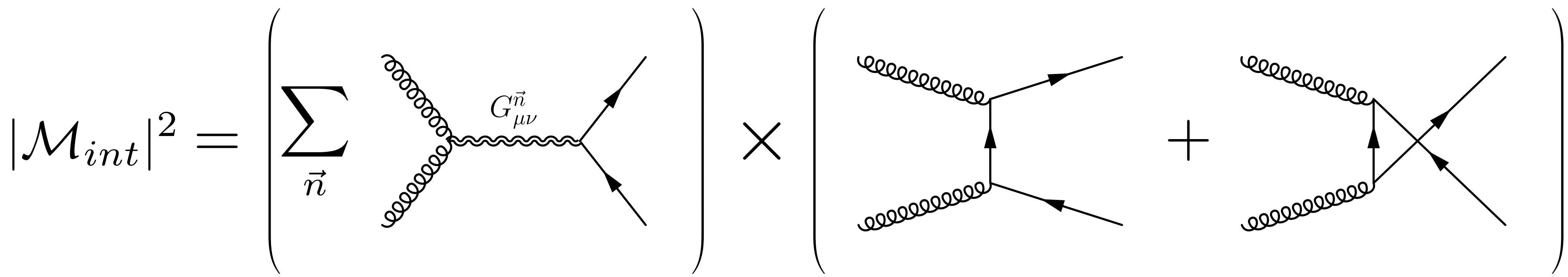
The t-tbar Channel

ADD Interference Terms

- In general, KK graviton interactions are suppressed by powers of M_S
- Interference terms with the SM (QCD) will dominate if they exist

$$\sigma_T \sim \sigma_{SM} + (M_S)^{-4}\sigma_{int} + (M_S)^{-8}\sigma_{grav}$$

- For a hadron collider, the di-quark initial state is mediated by a gluon – colour structure prevents an interference term with ADD
- gg initial state in the t and u channels are colour singlets and will therefore contribute an interference term



- Promising way to search for evidence of large extra dimensions – excess in the t-tbar cross-section, invariant mass distribution

The t-tbar Channel

Our Study

- ➡ Look at the effect of the ADD model and MLS on the t-tbar cross section as a function of the fundamental scale, M_S, determine the reach of the LHC to set bounds on it
- ➡ Consider other observables such as differential distributions that could yield deviations from the SM
- ➡ Based on work done on the Drell-Yan channel *(Bhattacharya et al. arXiv:hep-ph/0408295)*
  - MLS: $M_S > 1.5$ TeV @ Tevatron, $M_S > 6$ TeV @ LHC (14 TeV)
  - Improve on LHC bounds, look at 7 TeV and look to compare with early data
- ➡ For consistency, compute tree-level ADD/MLS contribution and compare it to tree-level SM predictions
- ➡ Included q-qbar initial state as well as pure graviton contribution from gg diagram *(Mathews et al. arXiv:hep-ph/9811501v4)*

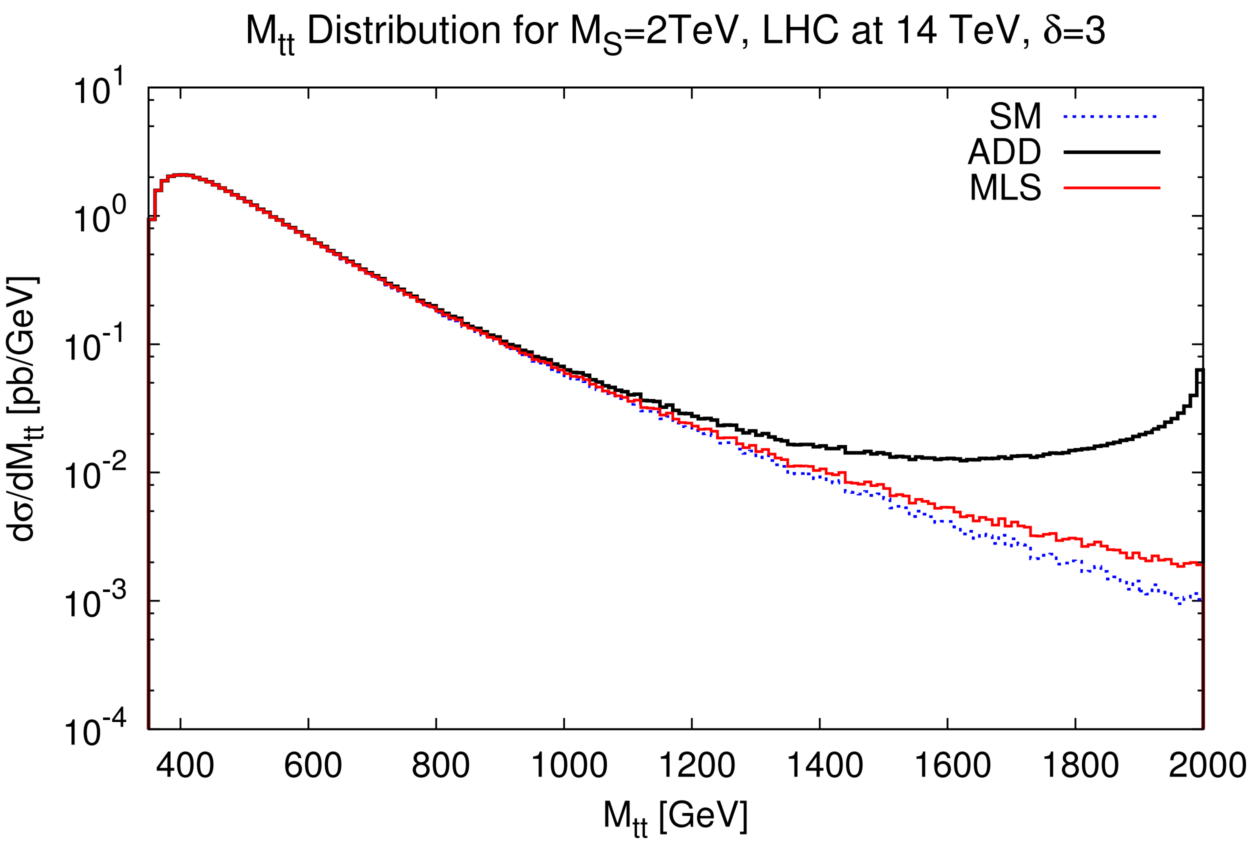
The t-tbar Channel

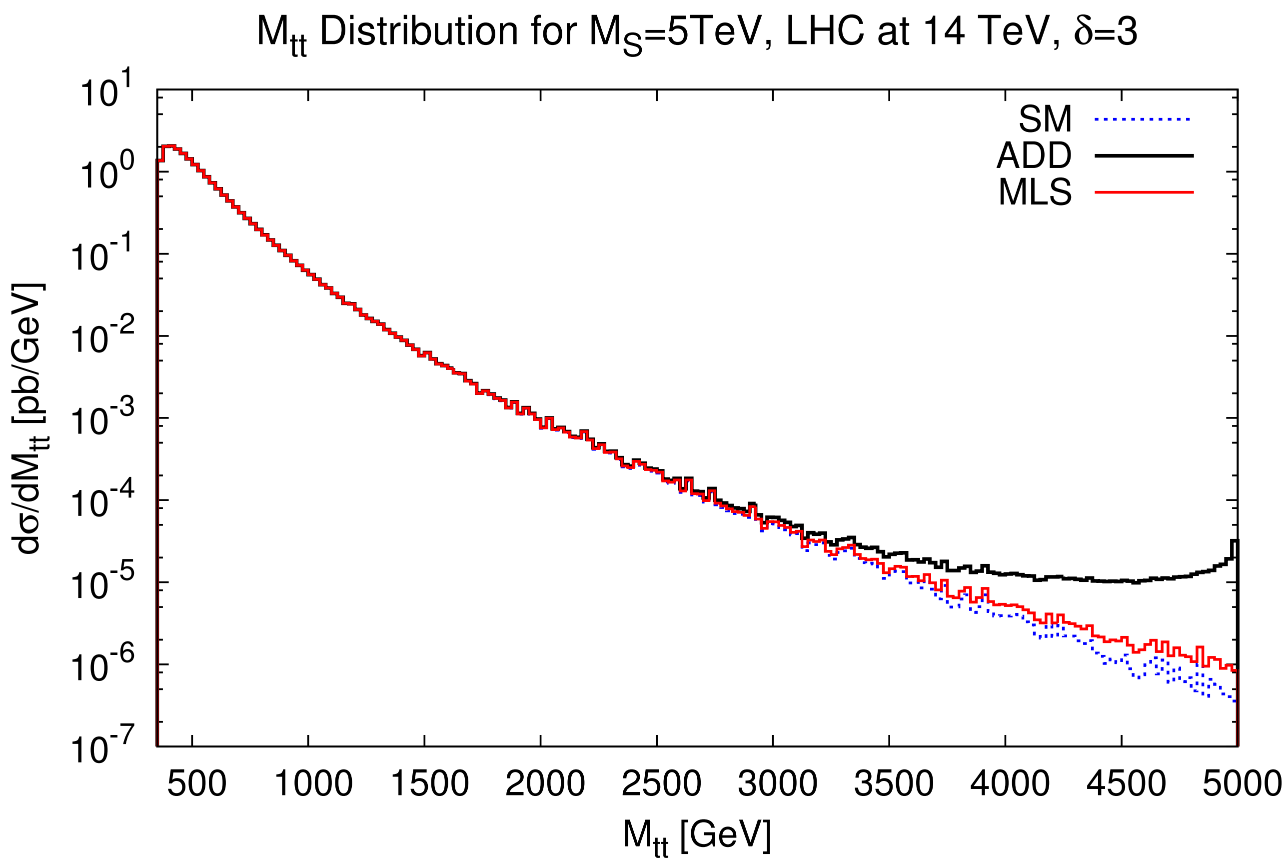
Our Study

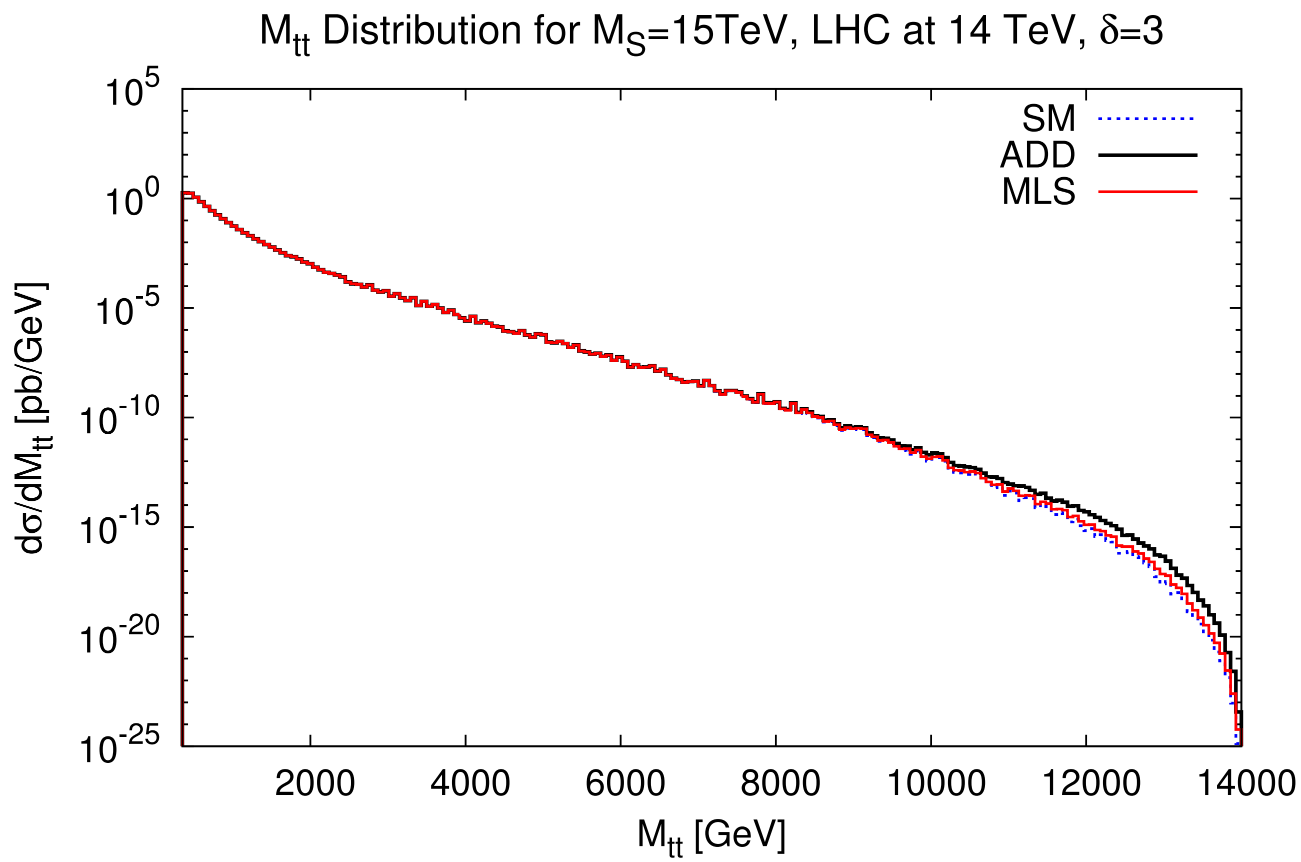
- ➡ Calculate the contribution to the t-tbar cross section of ADD with and without MLS over a region of parameter space
  - Vary fundamental Planck scale, M_S
  - Vary number of extra dimensions, δ=3-6
  - Compare ADD+MLS to pure ADD in terms of reach on M_S bounds, divergent behaviour
- ➡ Experimental setup: LHC at 14TeV (100 fb^{-1}) and Tevatron (4 fb^{-1}), adding LHC at 7 TeV (5 fb^{-1}) for possible data comparison.
  - CTEQ6 PDF sets
  - Madgraph for LO SM matrix elements: QCD + EW (v. small)
  - Make kinematical cuts (invariant mass) to minimise SM background and focus on regions where NLO corrections are not as important compared to ADD
- ➡ When determining reach to set bounds on M_S, fold in the t-tbar reconstruction efficiencies for various decay channels: ~4%(3%) at the LHC(Tevatron)

Differential Distributions

- Use differential cross-section wrt invariant mass to guide kinematic cuts and look at behaviour as one approaches the cutoff M_S (M_D)
- Divergence of the ADD cross-section as one approaches the cutoff
- MLS tames this behaviour – prevents over-estimation of cross-section

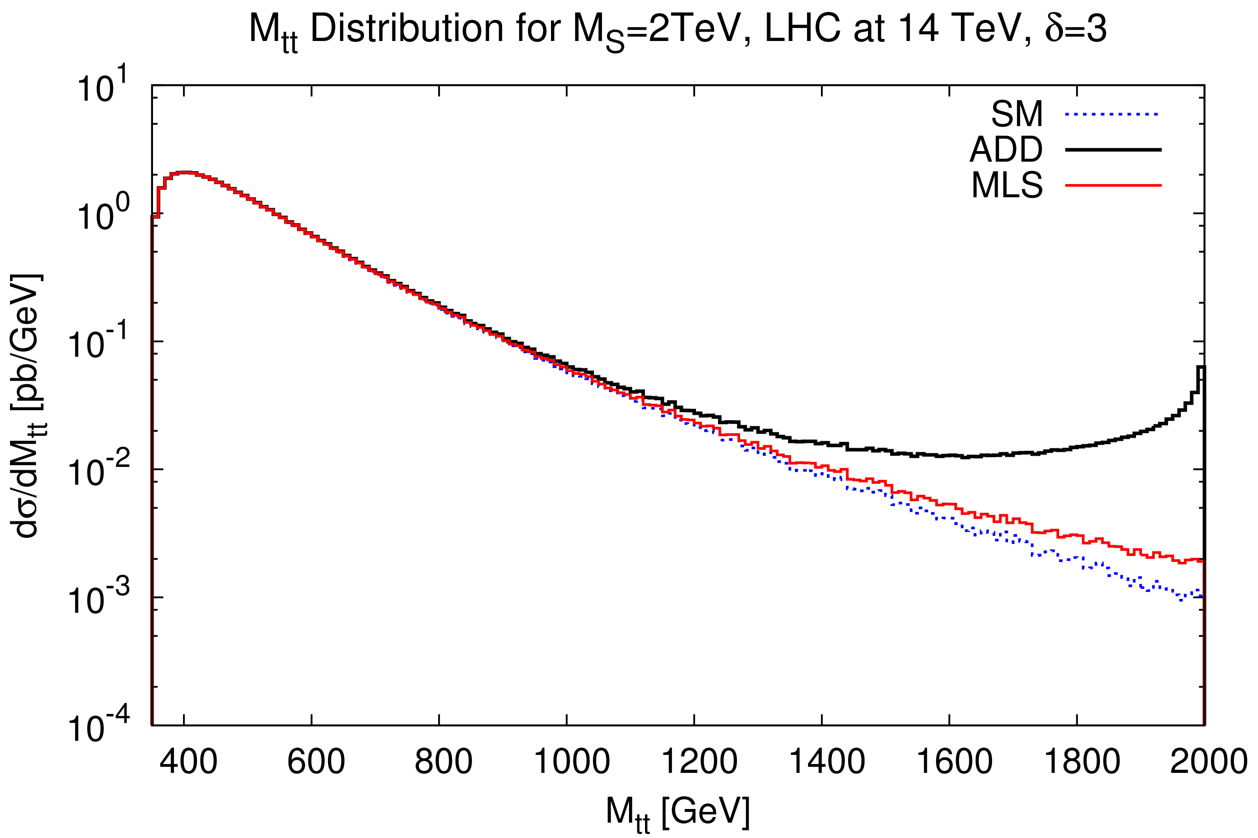


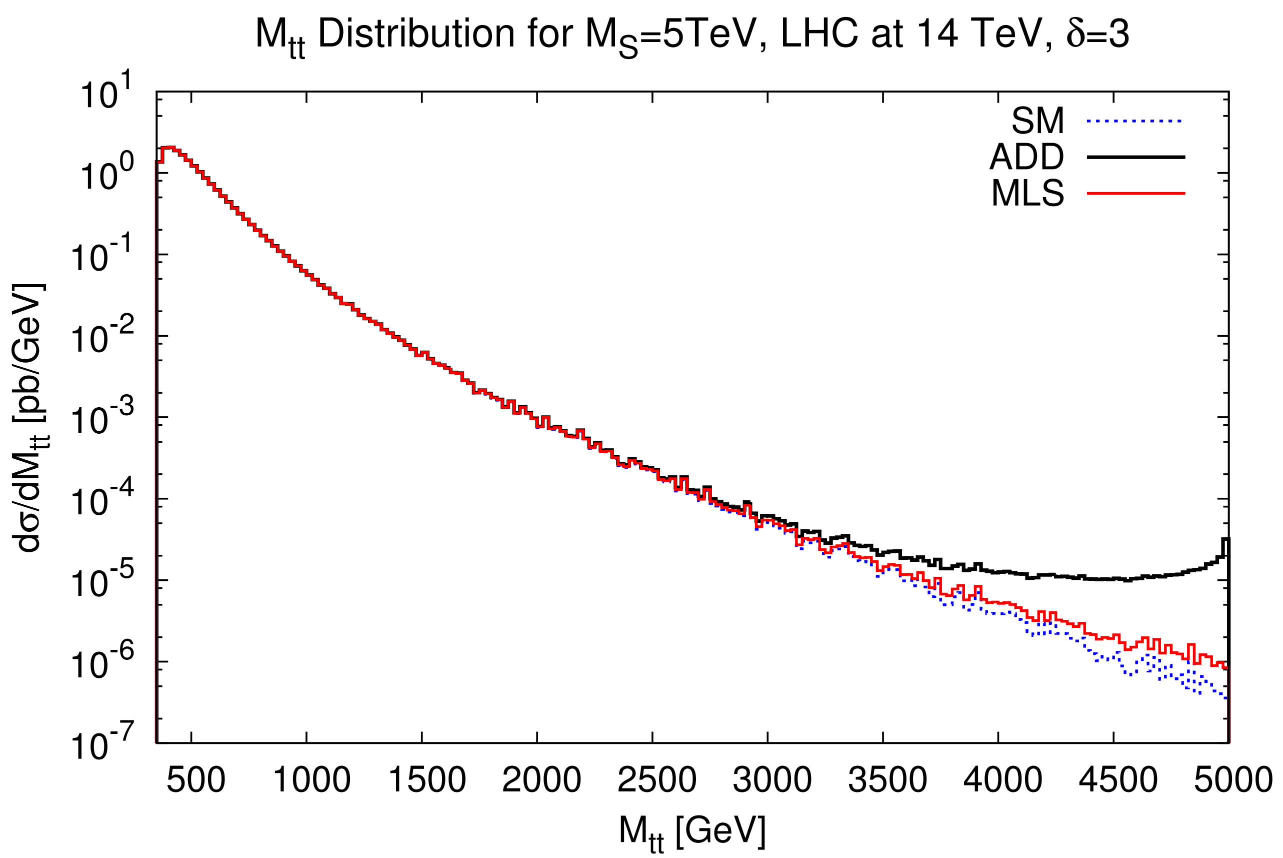


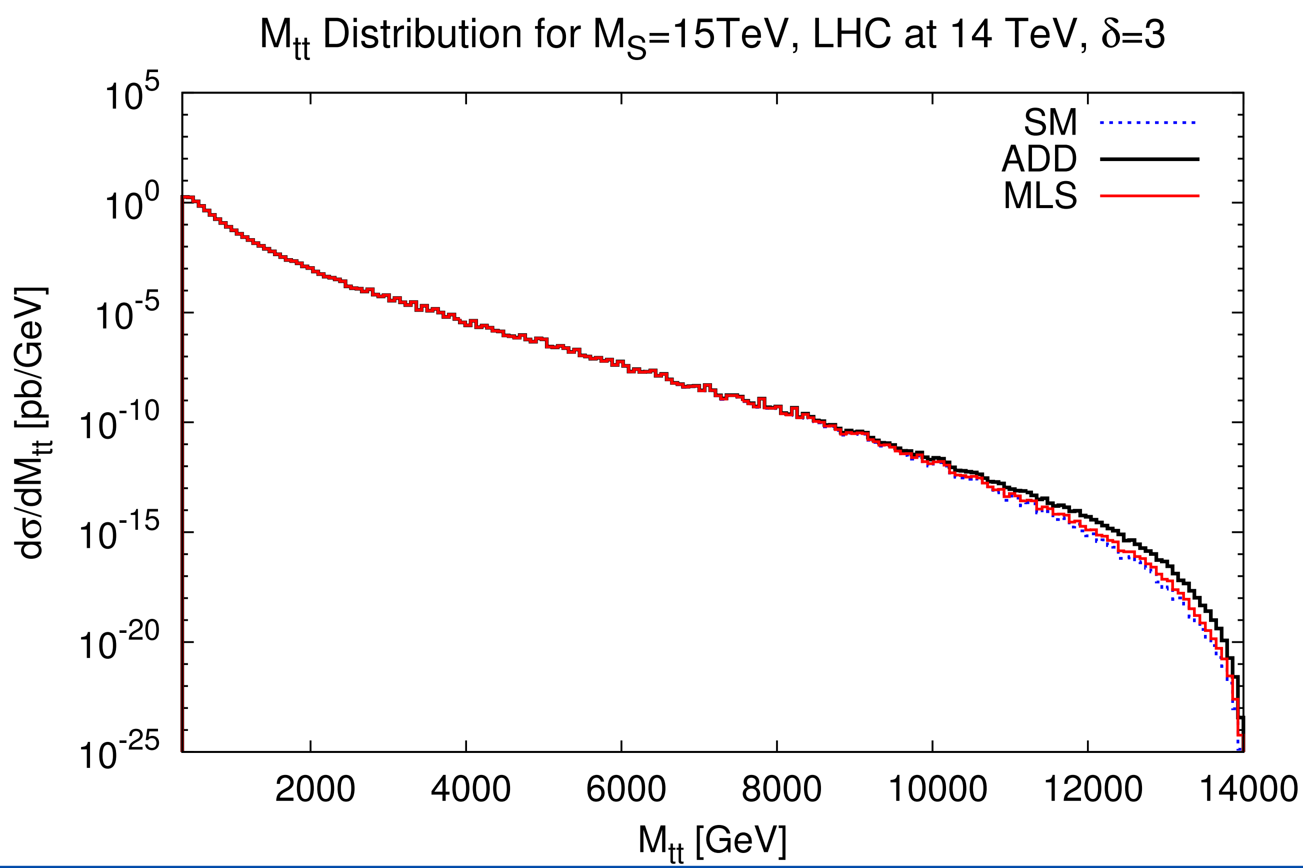


Differential Distributions

- MLS competes better with ADD for larger δ
- Invariant mass cut of 1 TeV
- Integrate invariant mass up to $0.8M_S$
- Within this range - can expect some excesses of order 100% depending on parameters

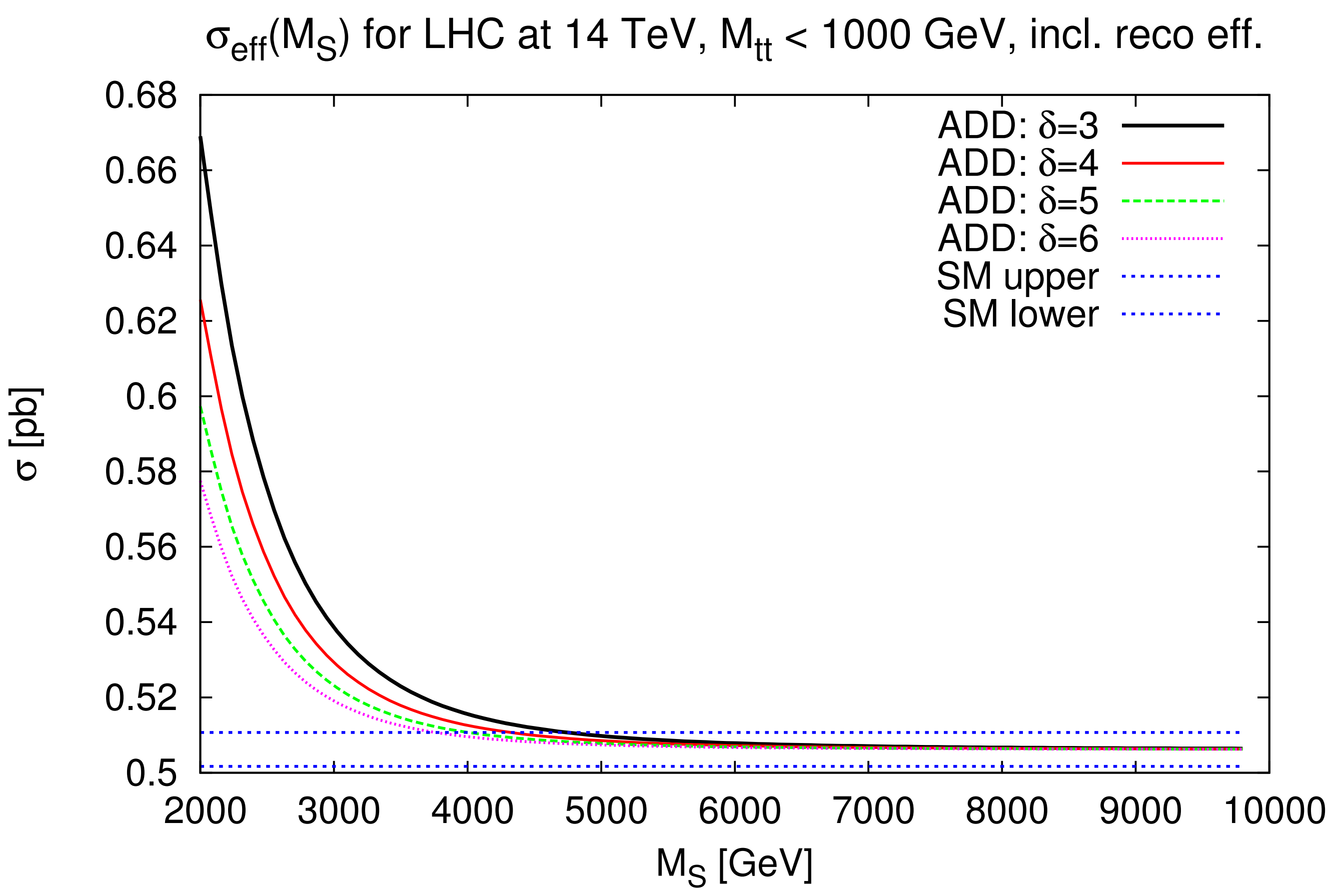


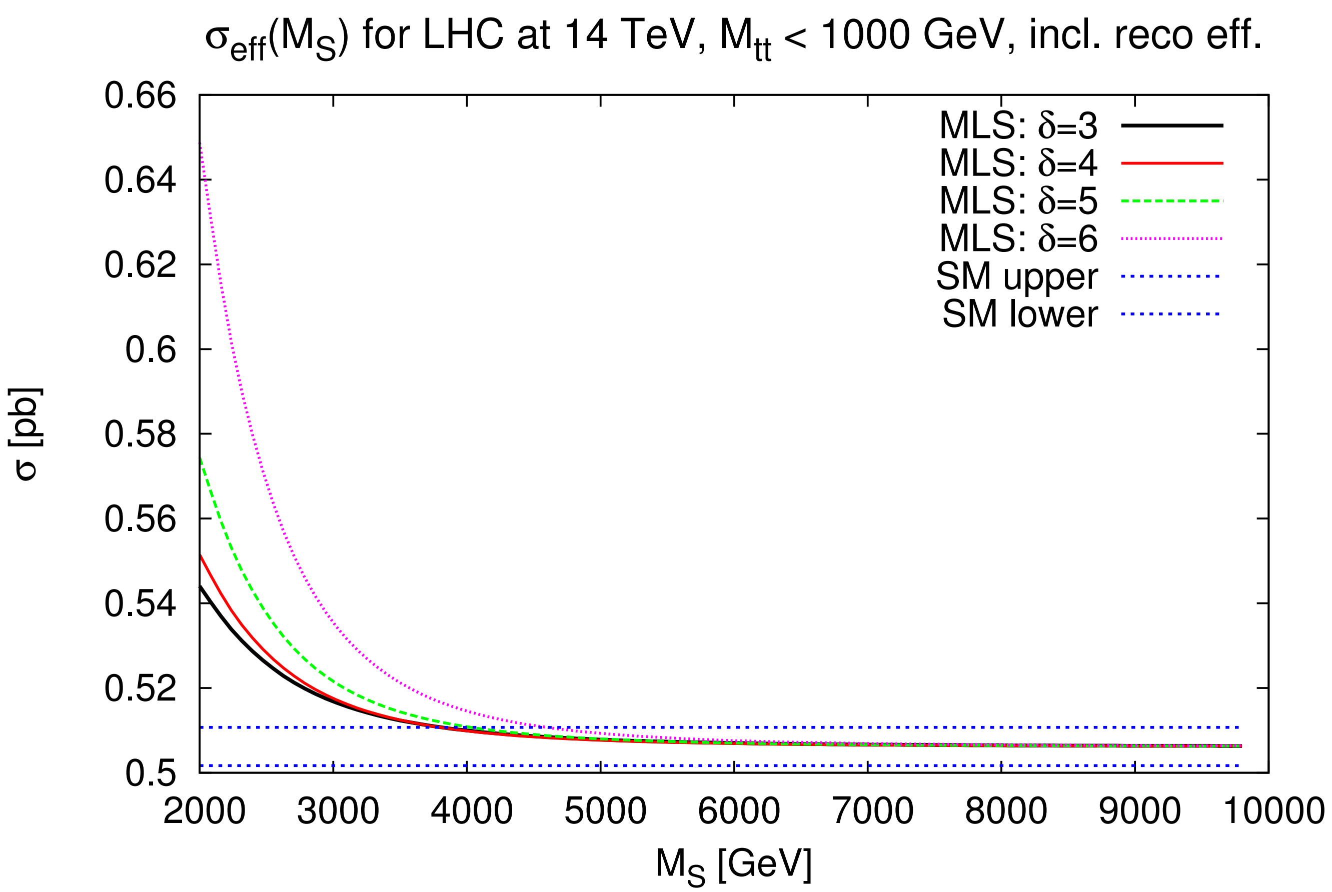




Total Cross-section: LHC at 14 TeV

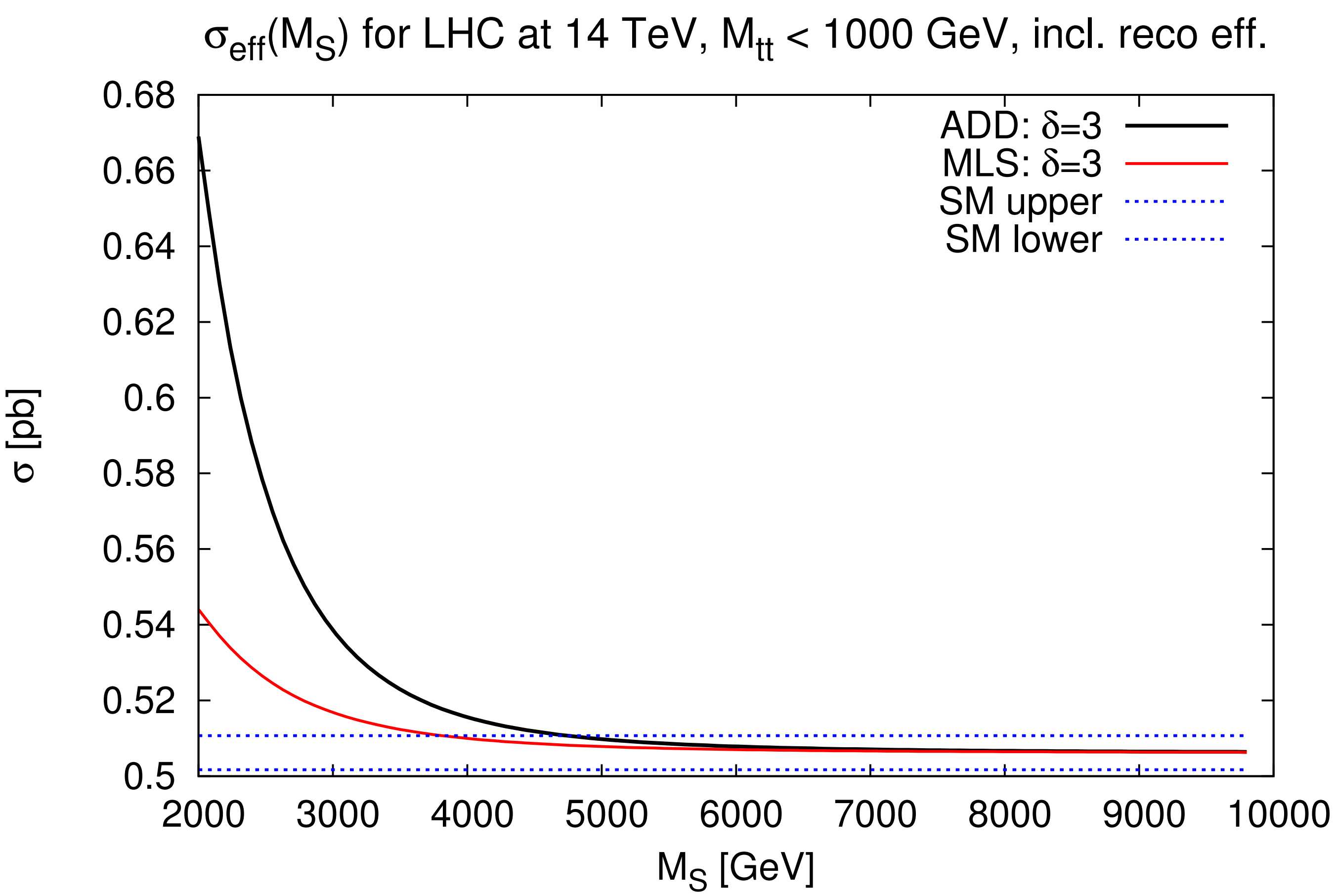
- Determined appropriate invariant mass ranges for 3 experimental setups
- Plot total production cross-section as a function of M_S and compare against 95% CL upper and lower bounds for LO SM cross-section
- LHC at 14 TeV – assumed 100 fb^{-1}
- Reconstruction efficiencies had a significant effect on attainable bounds – need more integrated luminosity

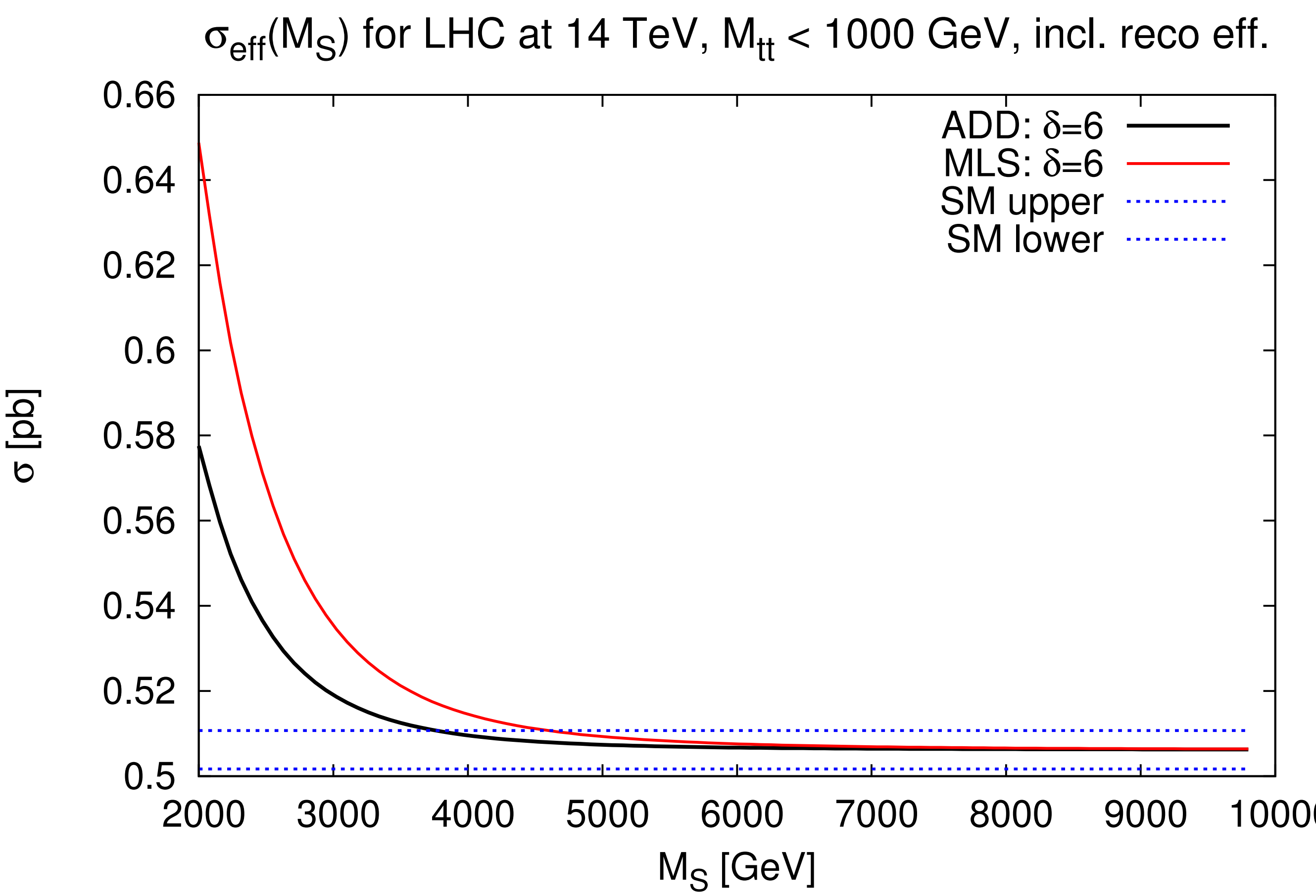




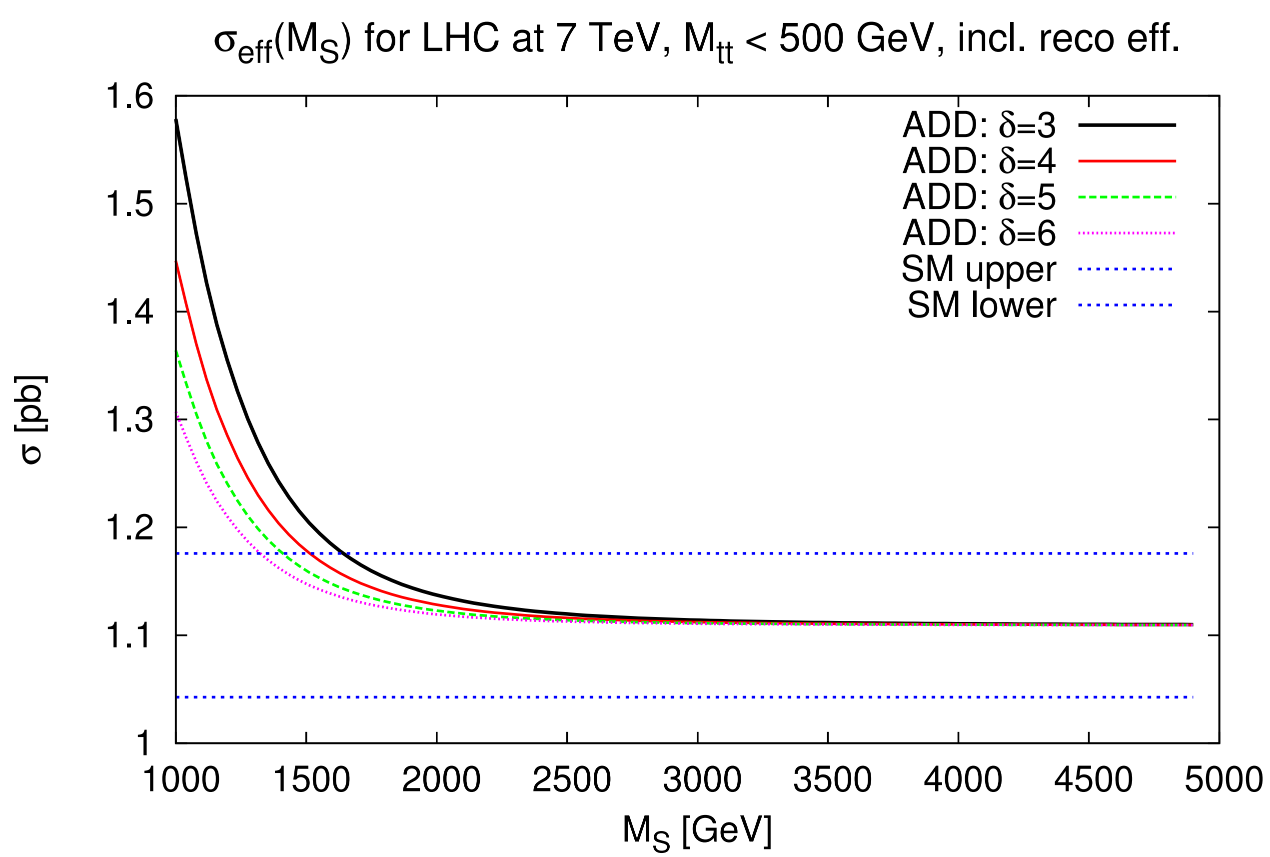
Total Cross-section: LHC at 14 TeV

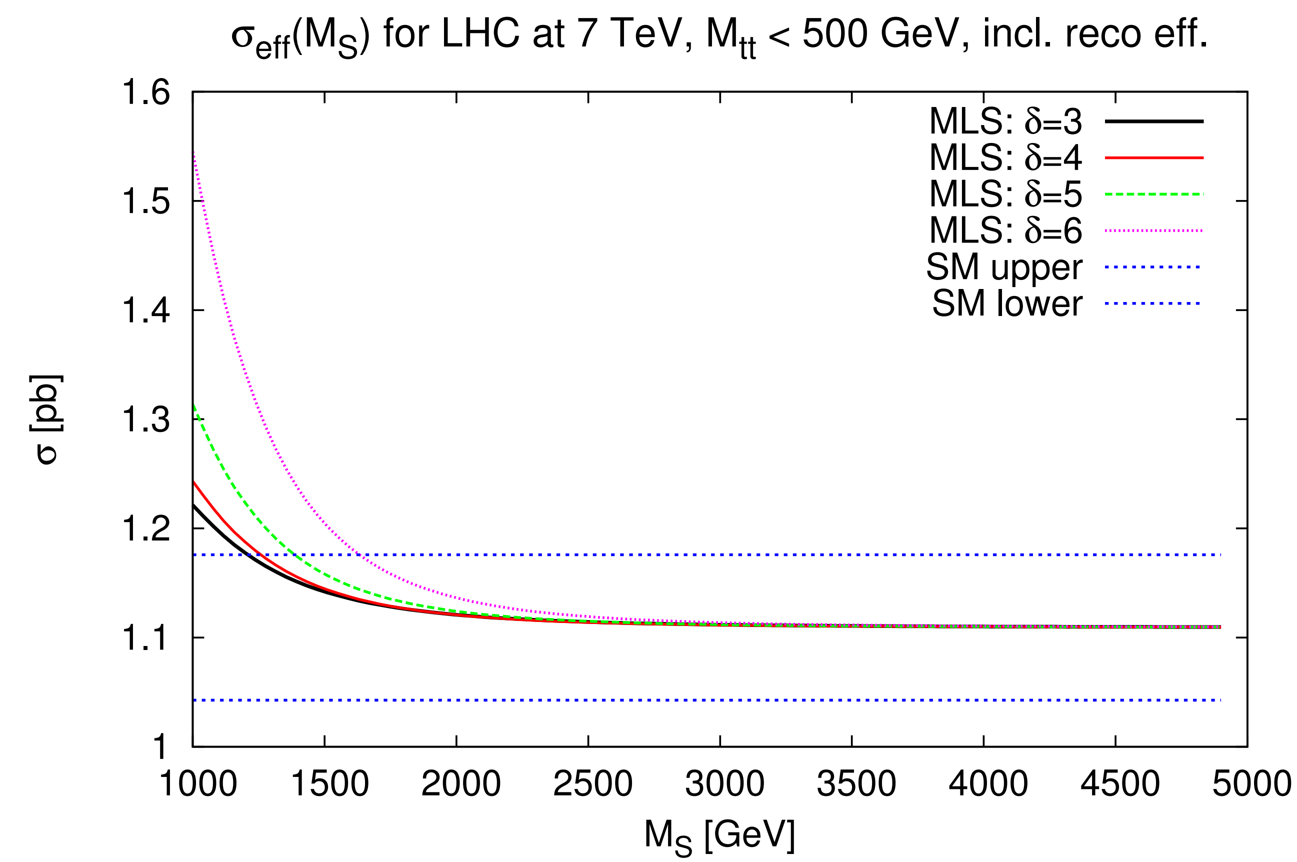
- Show that the LHC at 14 TeV has the potential to reach fundamental scales of up to ~4.2 TeV – lowered to 4 TeV in the MLS
- Relies on a large amount of data
- Drell-Yan study did not include acceptance or reconstruction efficiencies
- Tevatron does not improve bounds because of dominance of q-qbar initial state
- LHC at 7 TeV shows some promise of determining bounds assuming 5 fb^{-1}

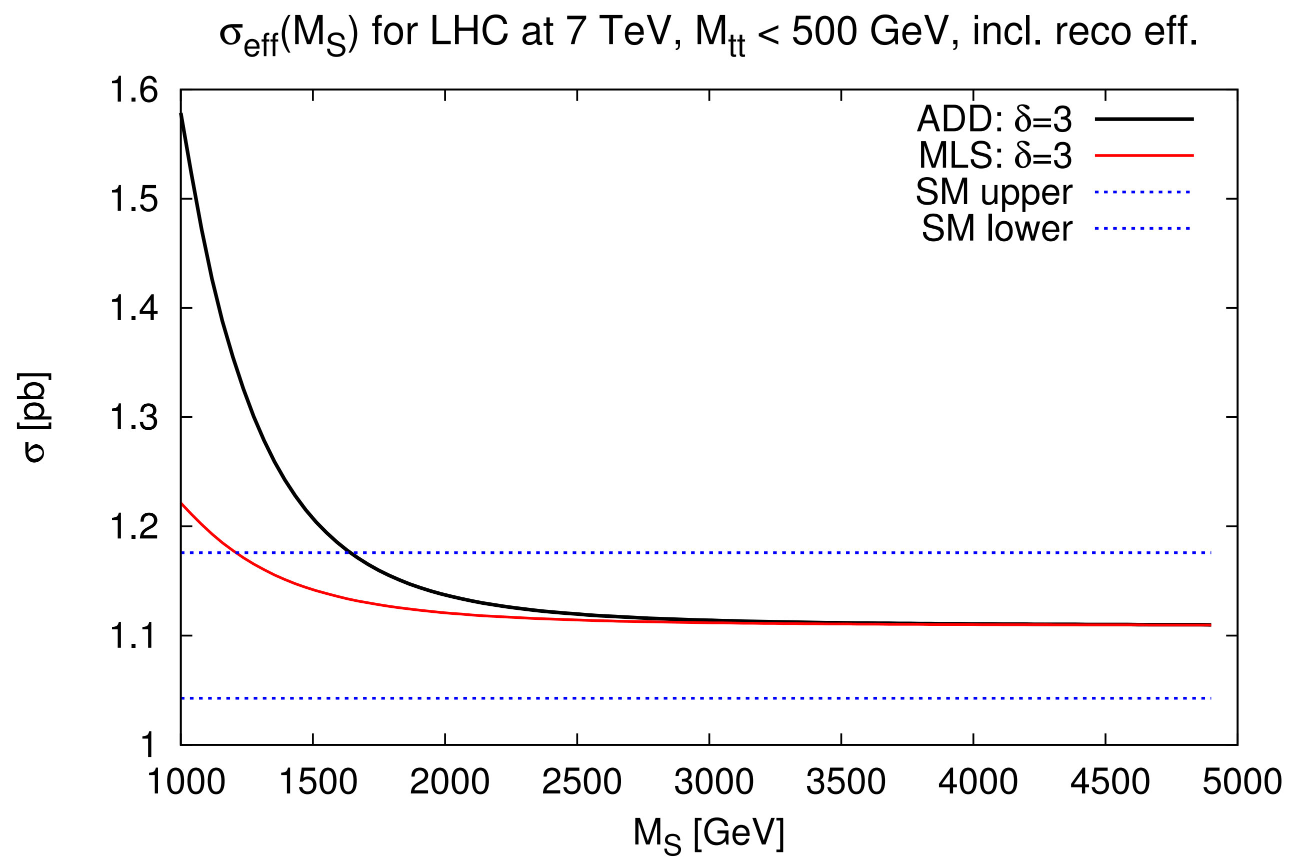


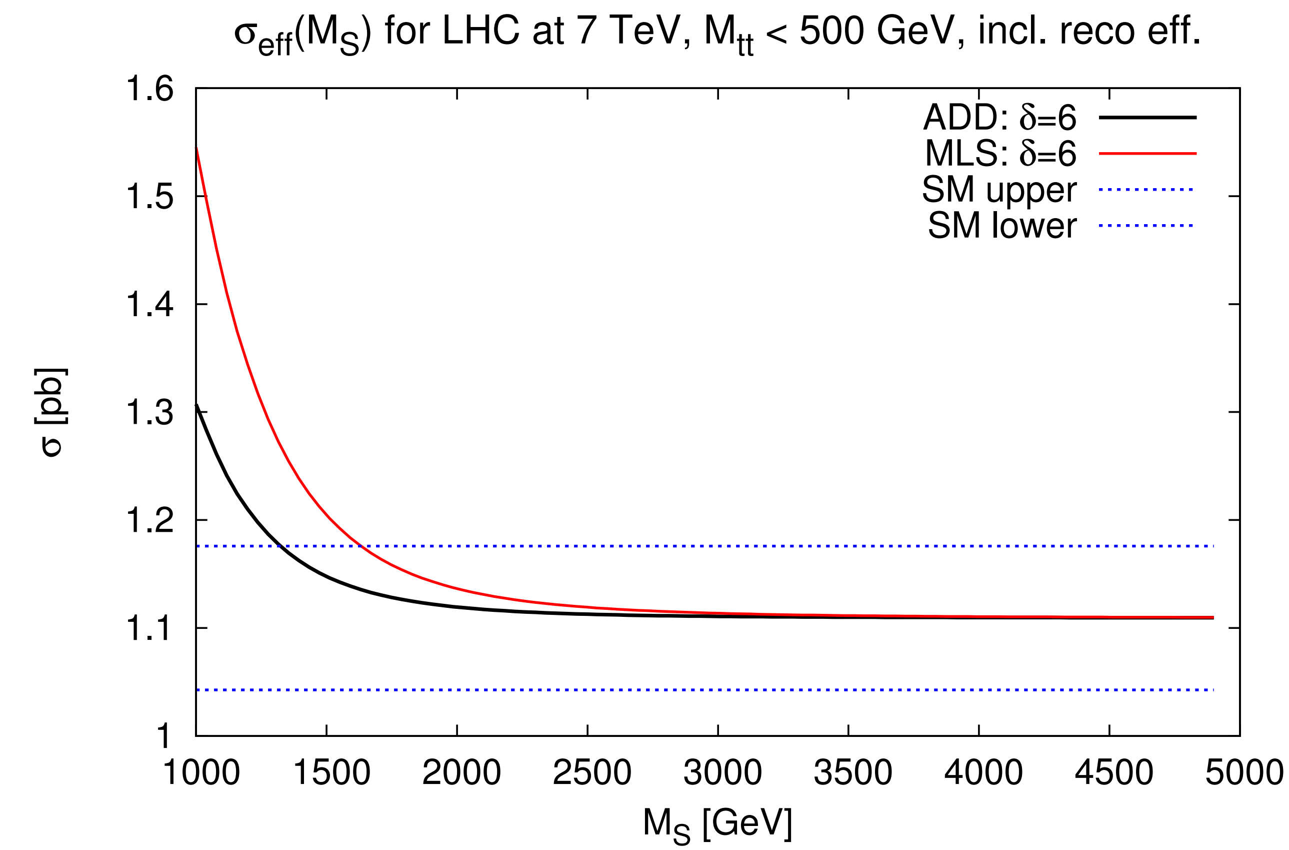


Total Cross-sections: LHC at 7 TeV









Results

Bounds on M_S

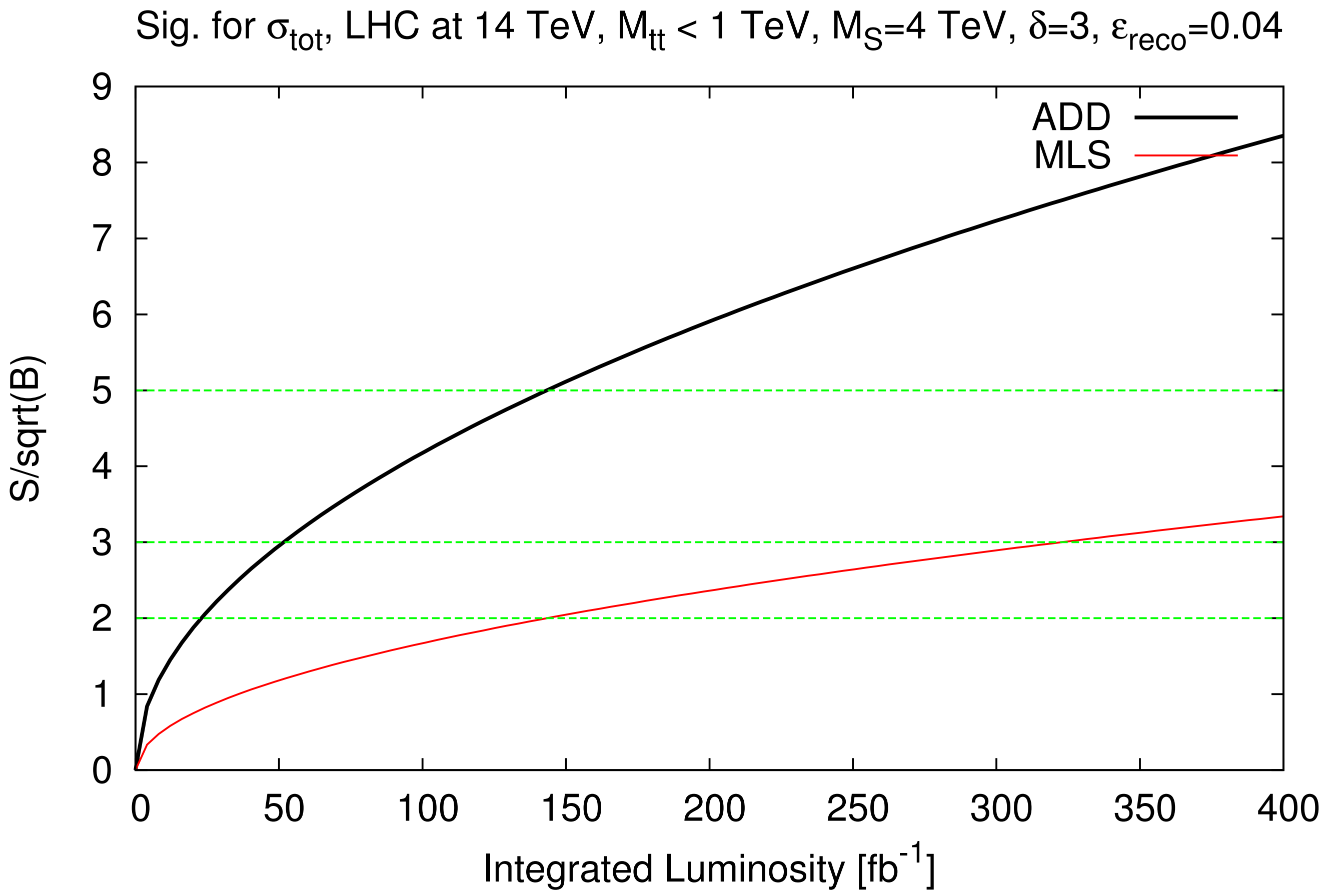
M_S Bounds	t-tbar (incl. $\varepsilon_{reco.}$)		Drell-Yan		L_{int}
	ADD	MLS	ADD	MLS	fb^{-1}
LHC @ 14 TeV	4.2 TeV	4 TeV	7 TeV	6 TeV	100
LHC @ 7 TeV	1.5 TeV	1.3 TeV			5

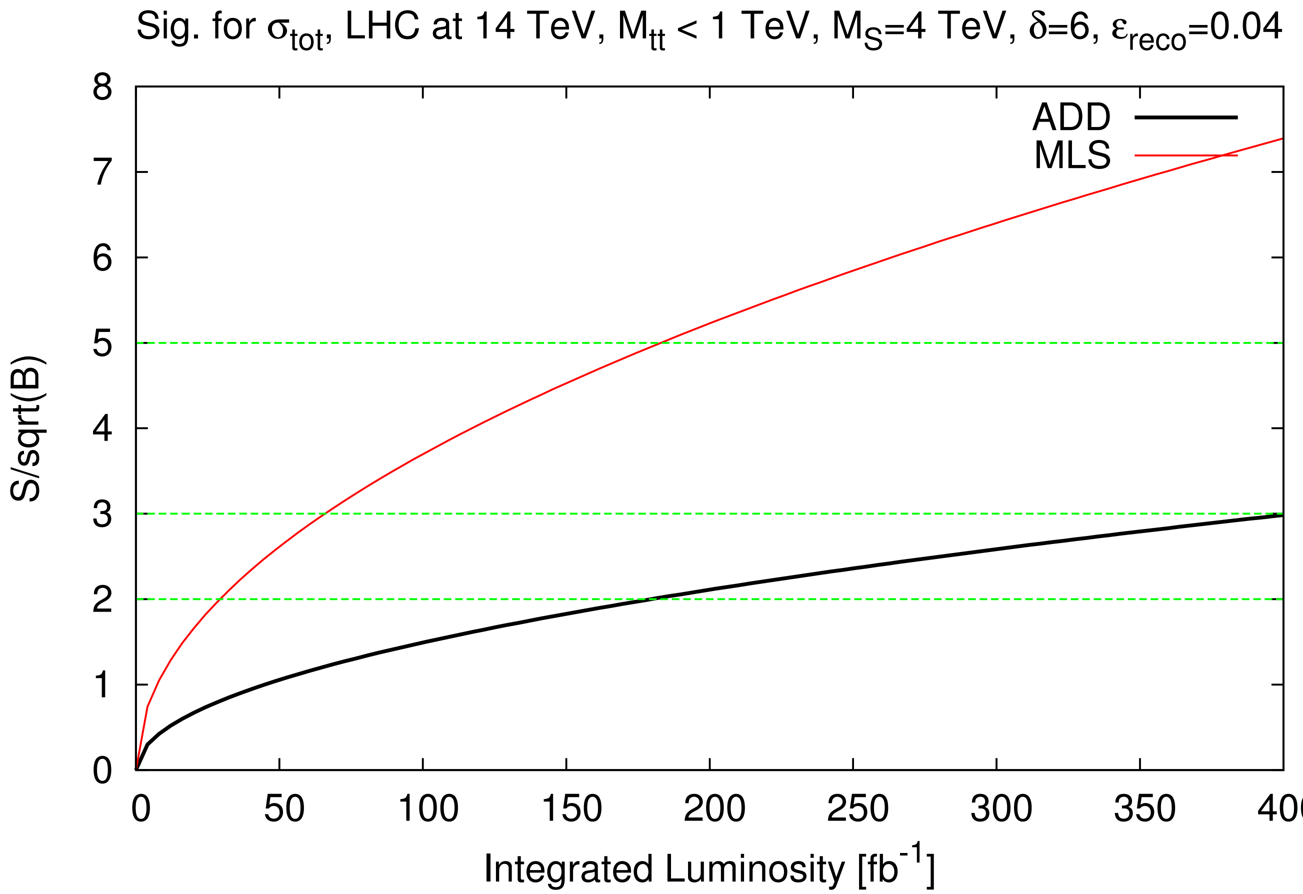
- Overall, in taming the divergent nature of the cross-sections, MLS lowers the reach of experiments to set bounds on M_S
- More focused cuts could improve signal to background ratio, help make up for the losses due to poor reconstruction efficiencies
- In principle t-tbar channel at the LHC could improve on the reach of Drell-Yan because of the gg initial state and ADD interfering with QCD rather than EW at the Tevatron

Results

Significance plots: LHC @ 14 TeV

- ➡ As an example: significance of ADD/MLS signal in deviation from SM t-tbar cross section as a function of luminosity for M_S = 4 TeV
- ➡ LHC at design luminosity certainly has potential to probe the existence of large extra dimensions with fundamental scales of several TeV
- ➡ More focused event selection will certainly improve ability to set bounds





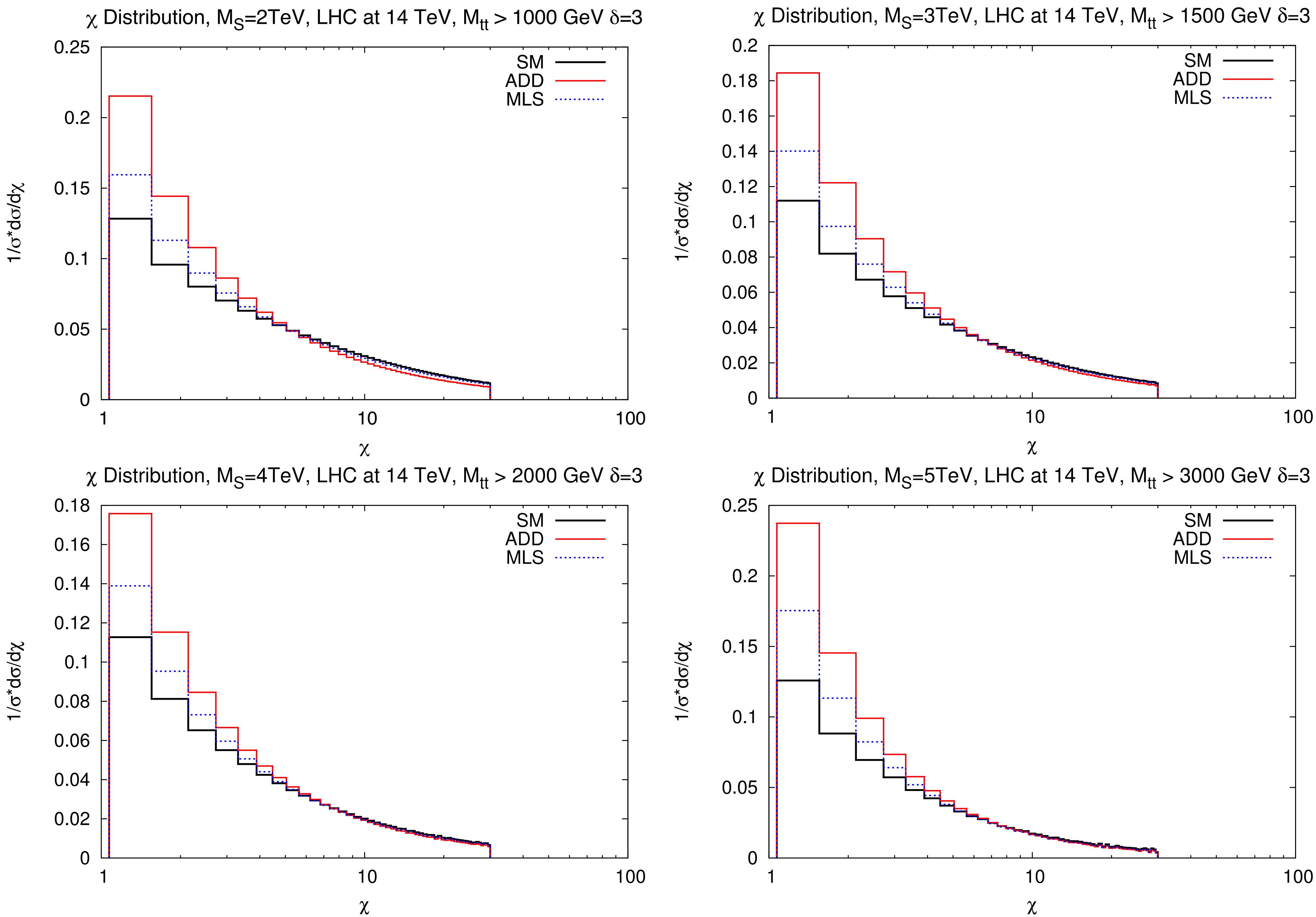
Outlook

Further Investigations and Paper

- These are rough numbers: what we really want is to compare with early data and get some real bounds perhaps combining the Drell-Yan and t-tbar channels
- Started by looking at simple quantities like total cross-section and invariant mass distributions but there are many more variables that one could look at
- Could exploit the potential of asymmetries at the LHC via interference with SM
  - EW or NLO QCD for t-tbar
  - Drell-Yan
- Recent paper has looked at centrality ratio $\chi = \exp(y_1 - y_2)$ as a discerning variable: measure of angular distribution *(Franceschini et al. arXiv:1101.4919v2 [hep-ph])*
- A kinematical variable being measured at ATLAS and CMS to quantify angular distribution of dijet final state
- Expected to be flatter for QCD than for the exchange of a spin 2 particle

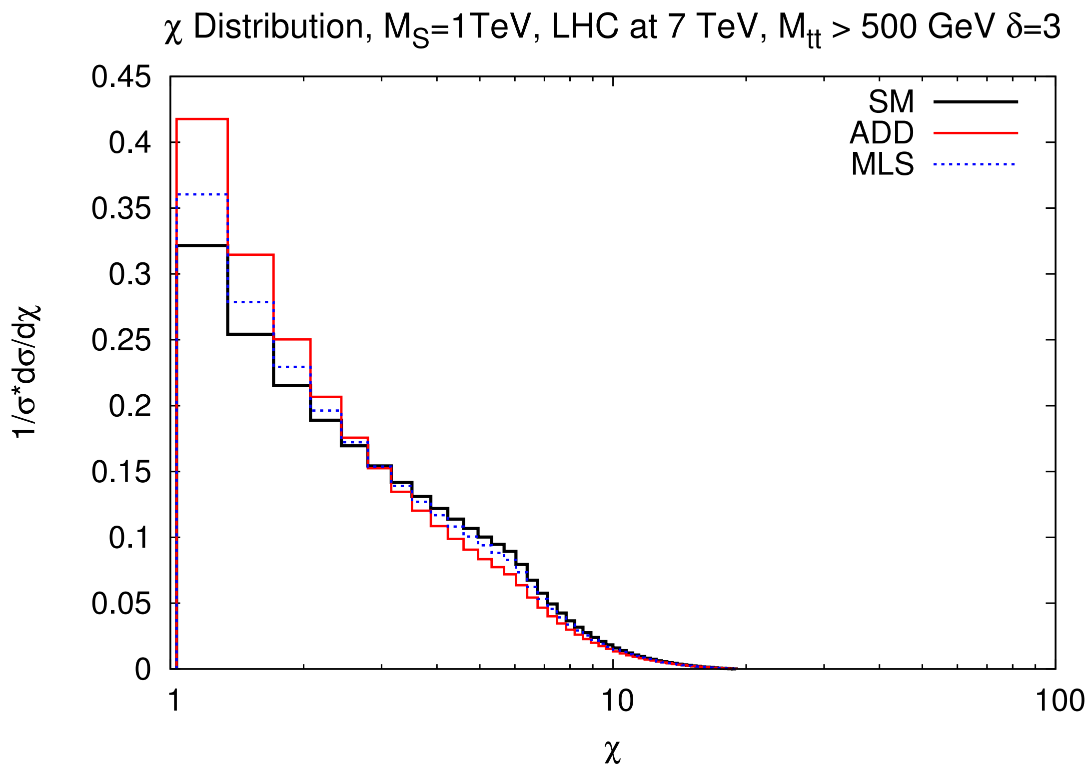
Outlook

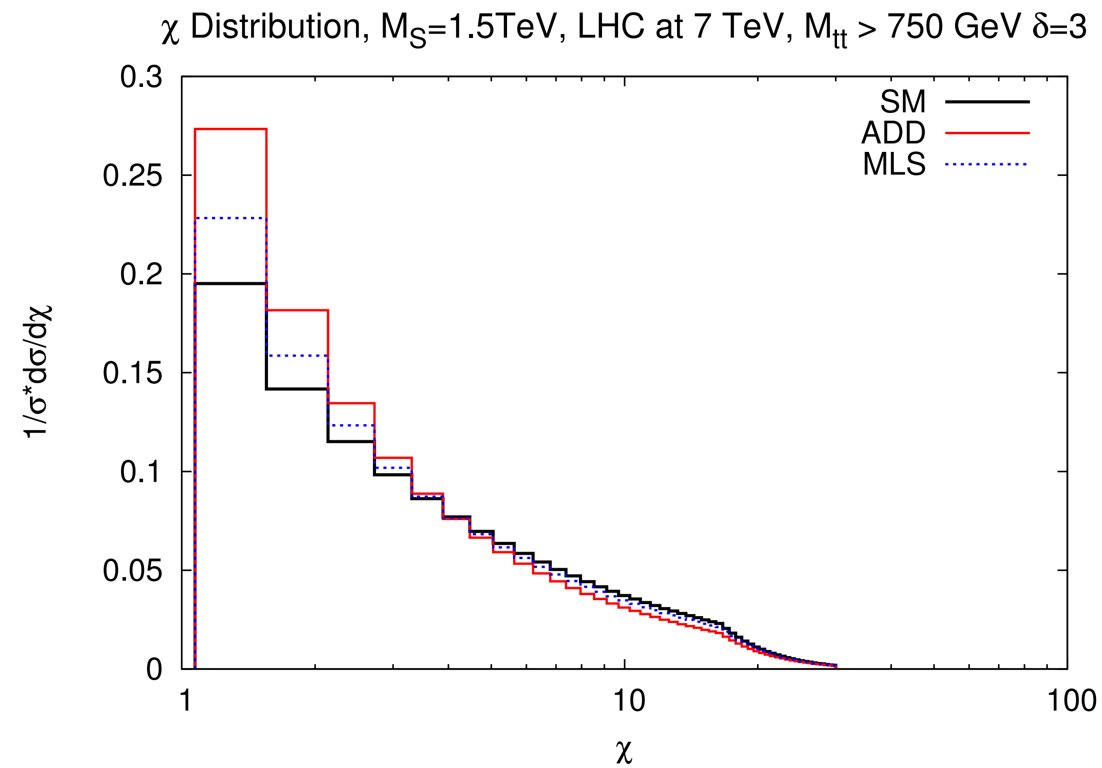
Centrality Ratio

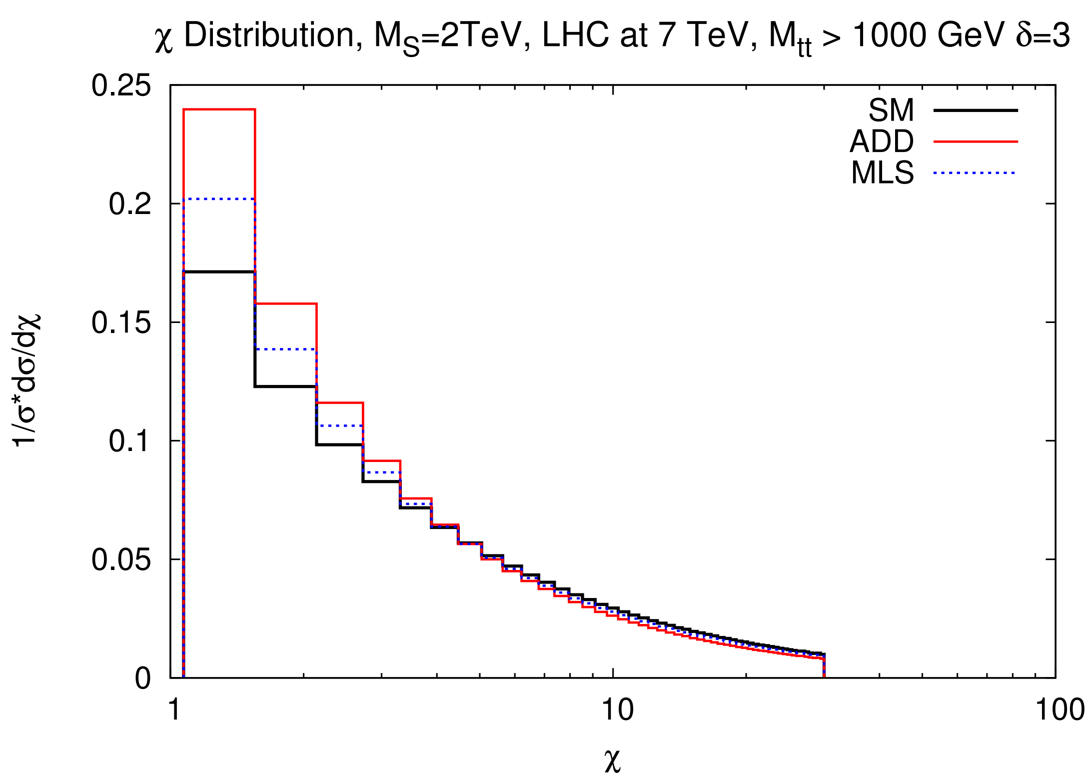


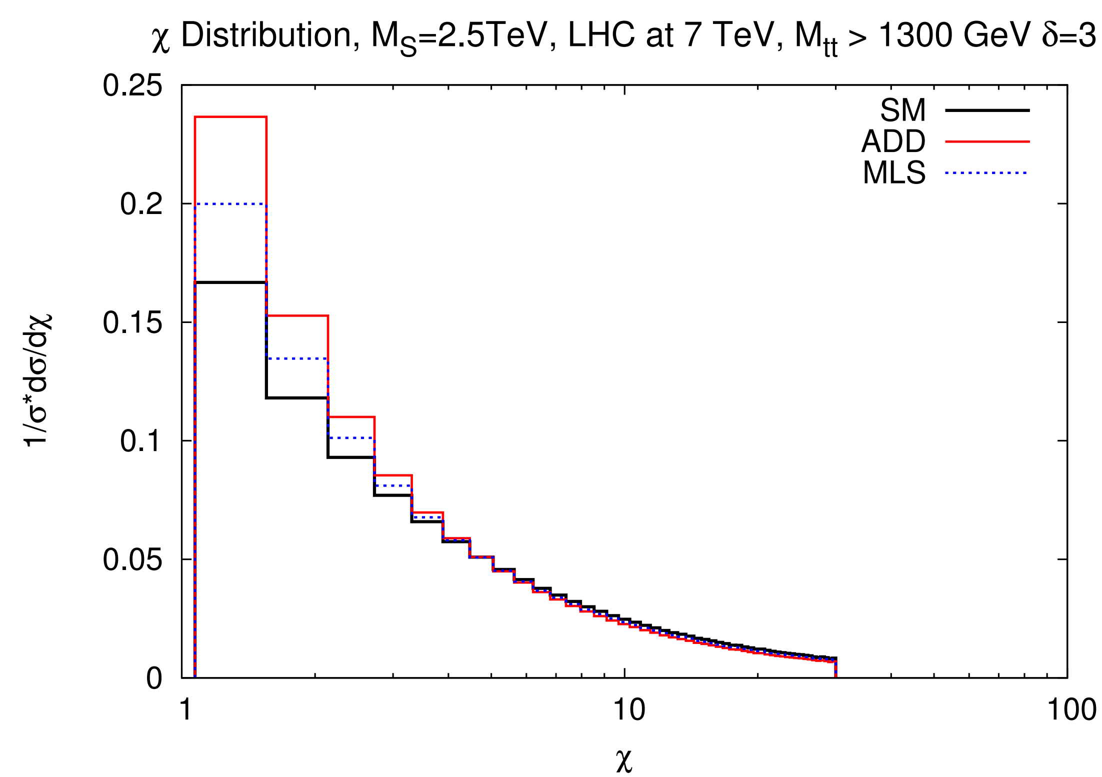
Outlook

Centrality Ratio









Summary

- Considered a simple extension of the ADD model whereby a minimal length is assumed applied to the t-tbar channel
- This scenario, as expected, regulates some of the divergent behaviour of the ADD model by suppressing high mass virtual KK modes
- Looking at the total cross-section and invariant mass distributions, investigated the reach of collider experiments to set bounds on the fundamental Planck scale of the model, M_D
- Considered LHC at design energy, Tevatron and also ‘early LHC data’ scenario with the aim of using data and obtaining bounds
- Reconstruction efficiency of the t-tbar final state limits the ability to set bounds on M_S without large amounts of data
- Potential to look at other quantities such as χ and asymmetries