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Identifying Large Extra Dimensions in dilepton production at the Large Hadron Collider

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Introduction

It is generally expected that New Physics (NP) will manifest itself at colliders such as the LHC and the ILC (International e^+e^- Linear Collider).

The NP effects will be observed either **directly**, as in the case of new particle production, e.g., ***Z'*** and vector ***W'*** bosons, SUSY or Kaluza-Klein (KK) resonances, or **indirectly** through deviations of observables (cross sections and asymmetries) from SM predictions.

In the case of **indirect** discovery many different NP Scenarios may lead to the **same** or **very similar** experimental signatures.

There are many different NP scenarios predicting new particle exchanges which can lead to Contact Interaction (**CI**) below direct production threshold.

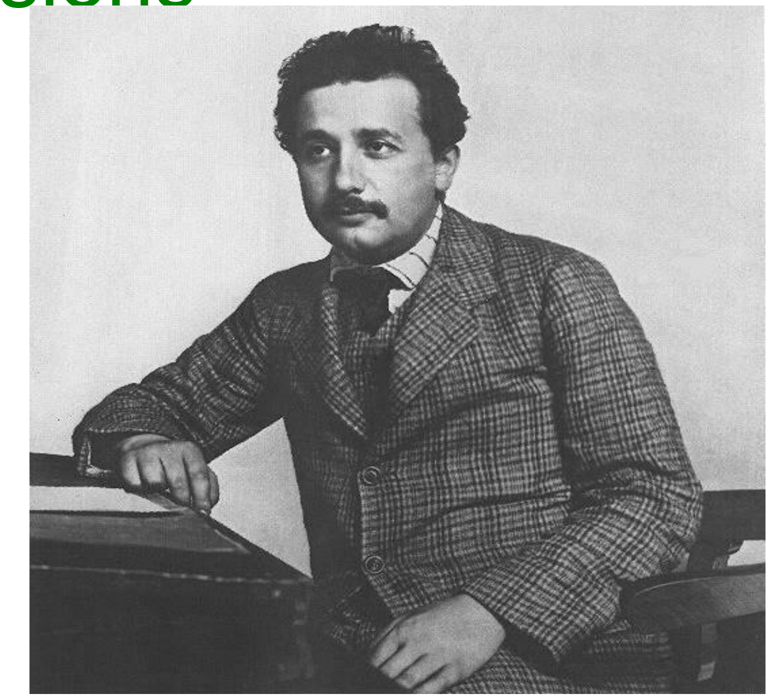
Here we **develop a technique** based on the center-edge asymmetry which offers a way to identify tensor (graviton) exchange both in ADD scenario in $pp \to l^+ l^- + X$ at the LHC.

A fifth dimension? Some History:

Gunnar Nordstrom
1881-1923

- Finnish physicist Nordstrom showed in 1914 that gravity and electromagnetism could be unified in a single theory with 5 dimensions

- However, this theory incorporated Nordstrom's theory of gravity – in competition with Einstein's at the time – and was largely ignored



A fifth dimension?

Theodor Kaluza
1885-1954

- Polish mathematician Kaluza showed in 1919 that gravity and electromagnetism could be unified in a single theory with 5 dimensions – using Einstein's theory of gravity

“The idea of achieving a unified theory by means of five-dimensional world would never have dawned on me…At first glance I like your idea tremendously”

The fifth dimension

Oskar Klein
1894-1977

- Swedish physicist Klein proposed in 1926 that the fifth dimension was real, but too tiny to be observed
- Computed it had a size of

0.0000000000000000000000000000001 centimeters

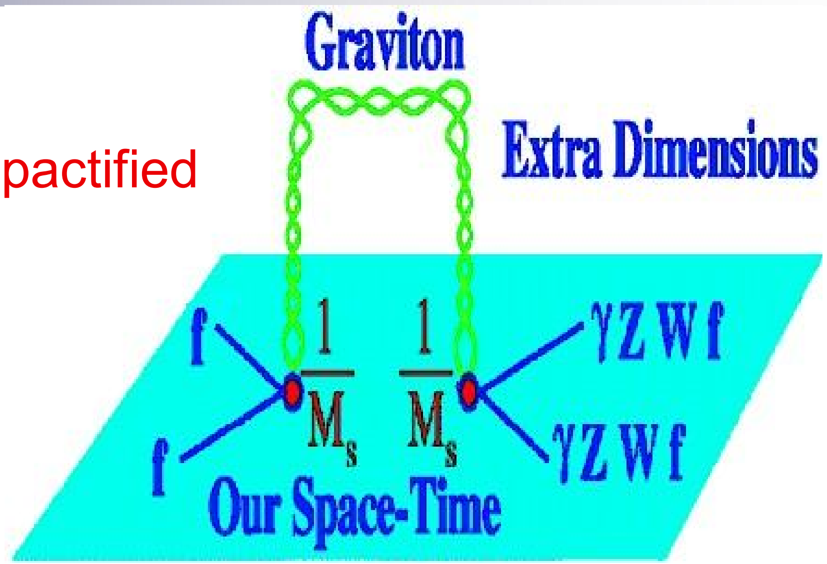
to unify gravity with electromagnetism

"Klein's paper is beautiful and impressive"

(Arkani-Hamed-Dimopoulos-Dvali:1998)

ADD scenario: Gravity in "large“ compactified extra dimensions (gauge hierarchy)

- Gravity only can propagate in the full 4+N space



- Virtual exchange of the graviton KK excitation states is governed by the effective Lagrangian (similar to dim-8 CI):

$$L^{ADD} = i\frac{4\lambda}{M_H^4}T^{\mu\nu}T_{\mu\nu}$$

where $\mathbf{M}_H$ is the cut-off scale (convention of *Hewett*), λ = ± 1.

- Introduce UV cut-off when summing over KK states:

$$\mathcal{M} \sim \sum_{\vec{n}=1}^{\infty} \frac{G_{\mathrm{N}}}{M^2 - m_{\vec{n}}^2} \to \frac{2}{d-2} \cdot \frac{1}{M_H^4(\mathrm{HLZ})},$$

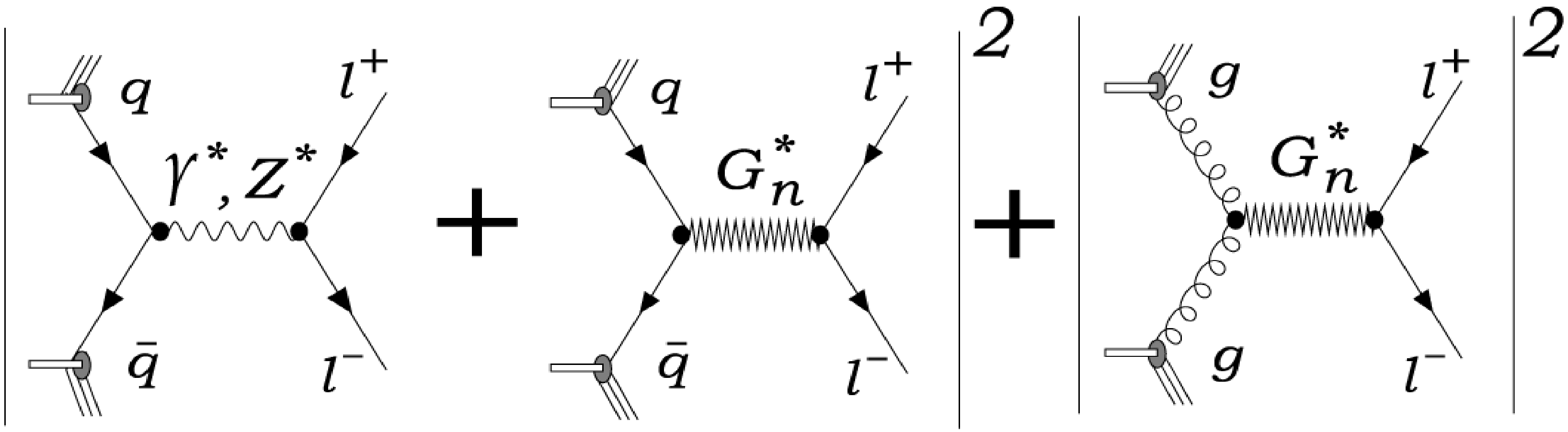
A different approach was given in ADD model which proposes the size of the extra dimensions could be roughly at millimeter and at the TeV scale that leads to possible observation at the LHC

$$pp \rightarrow l^+l^- + X$$

SM: $q\bar{q} \rightarrow \gamma, Z \rightarrow l^+l^-$

Graviton exchange signatures in ADD scenario:

$$q\bar{q} \rightarrow G \rightarrow l^+l^-, \quad gg \rightarrow G \rightarrow l^+l^-$$



Feynman diagrams for dilepton production at leading order in the ADD model

ATLAS search summary

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

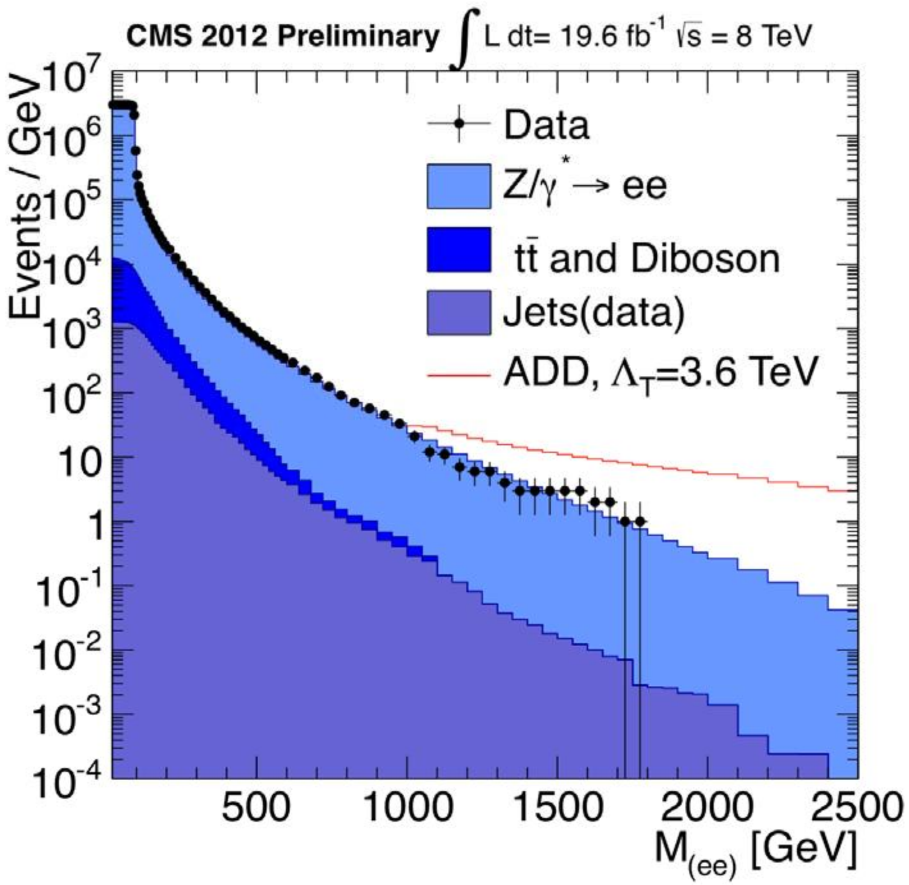
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Mass limit	√s (TeV)		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	7	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	8	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	8	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	8	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	8	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	8	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	8	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	7	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	8	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	8	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	8	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV	7		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV	7		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV	8		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV	8		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.28 TeV	8		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV	8		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV	8		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV	8		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV	8		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	7	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	8	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	8	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	M_* 731 GeV	8	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	8	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	7	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	7	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	7	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	8	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	8	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	8	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	8	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	8	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	8	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	8	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	8	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	8	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV	8		to be submitted to PLB
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	7	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	5.8	$N^\pm$ mass 245 GeV	8	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	7	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	7	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	7	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

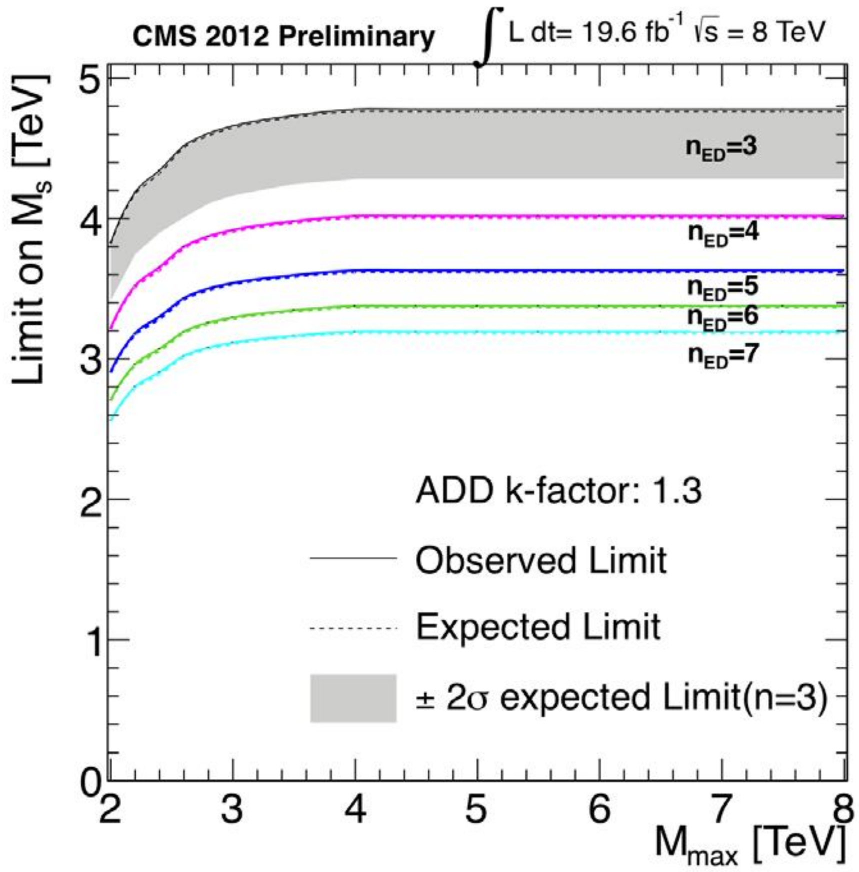
$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

10^{-1} 1 10 **Mass scale [TeV]**

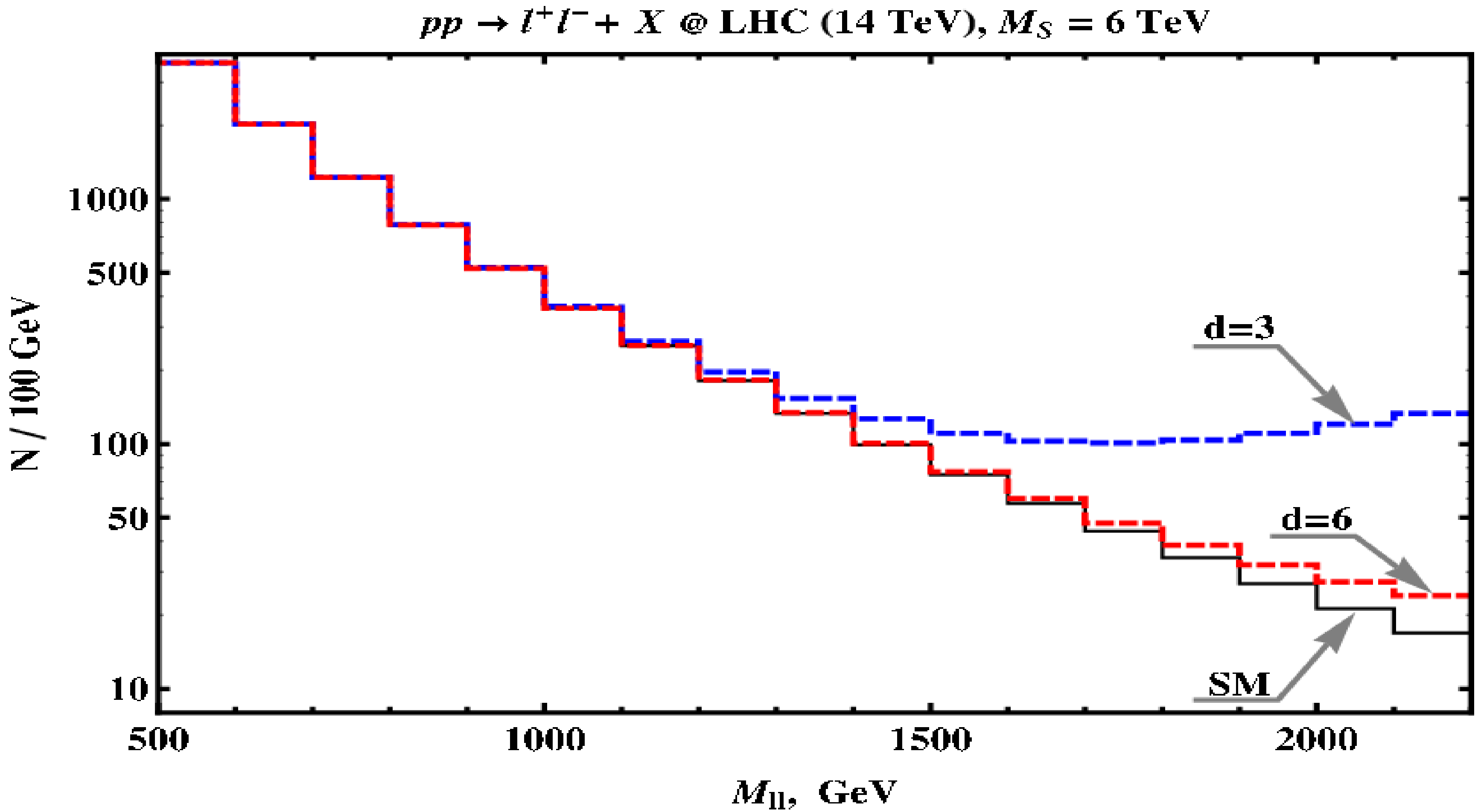
*Only a selection of the available mass limits on new states or phenomena is shown.

Limits on the ADD model





To estimate the discovery reach of graviton towers in the ADD model one can use the invariant mass distributions of lepton pairs that have significantly different behavior in the SM and the ADD model

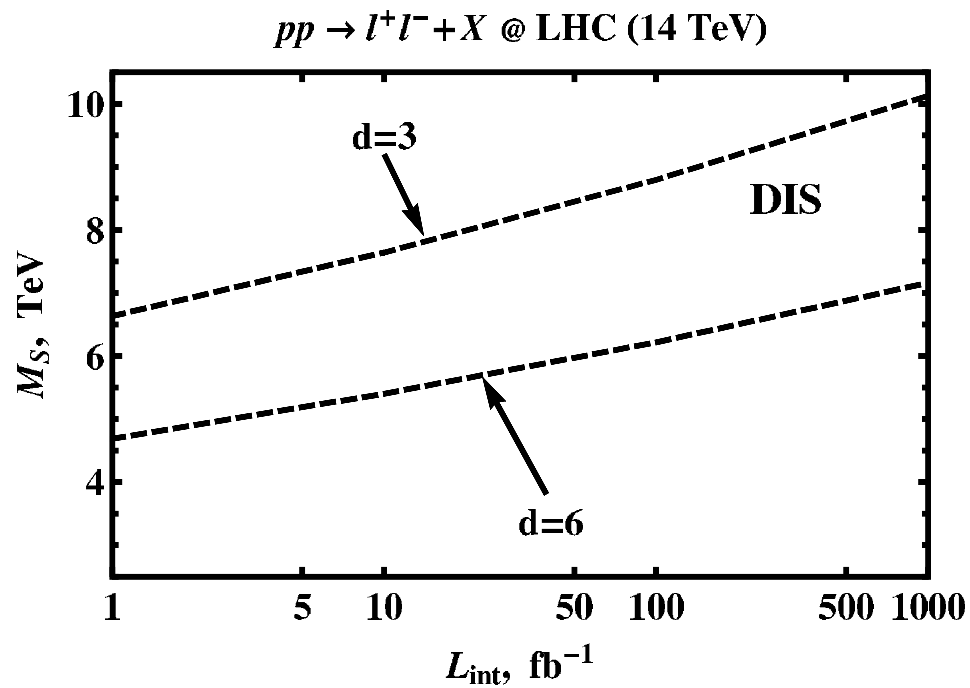


Effects of extra dimensions on the dilepton mass spectrum at the LHC. Histograms shows the spectrum in the SM model as well as in the ADD scenario with cutoff Ms=6 TeV and different number of extra dimensions (d=3,6) at the LHC.

Discovery reach

$$\chi^2 = \sum_{bin} \left(\frac{\Delta N_{bin}}{\delta N_{bin}} \right)^2 \qquad \boxed{\chi^2 = 3{,}84,}$$

$$N_{bin} = \varepsilon_e \mathcal{L}_{\rm int} \sigma_{bin},\ \varepsilon_e = 90\%, \qquad \Delta N_{bin} = N_{bin}^{\rm ADD} - N_{bin}^{\rm CM},\ \delta N_{bin} = \sqrt{N_{bin}}.$$



The results of the analysis are demonstrated in Fig. 2 In particular, Fig. 2 shows discovery reach on cutoff scale Ms at 95 % C.L. for d=3 and d=6 as a function of integrated luminosity at the LHC

Various New Physics possibilities

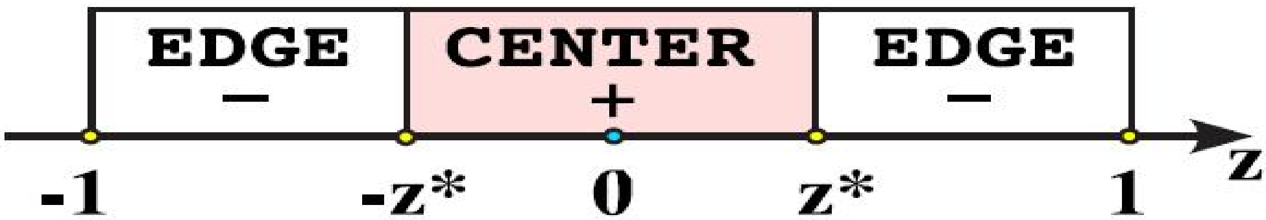
- Composite models
- Heavy Z' exchanges
- Scalar and vector leptoquarks
- Sneutrino exchange
- Anomalous Gauge Couplings (AGC)
- Exchange of gauge boson KK towers
- Virtual KK graviton exchange (ADD)
- etc.

Of course, there may be many other sources of CI from NP models as yet undiscovered, as was the low-scale gravity scenario only several years ago.

Centre-Edge Asymmetry A_{CE} (parton level)

$$A_{CE} = \frac{\hat{\sigma}_{CE}}{\hat{\sigma}},$$

$$\hat{\sigma}_{CE} = \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right]\frac{d\hat{\sigma}}{dz}\,dz,$$



$$z \equiv z_{CM} = \cos\theta_{CM}\,; \quad \theta_{CM} = \angle\left(q, e^-\right)$$

ACE in CI and Ext. Dim. scenarios

$$\frac{d\sigma_{q\bar{q}}^{\mathrm{CM}}}{dz} = \frac{3}{8}(1+z^2)\cdot\sigma_{q\bar{q}}^{\mathrm{CM}}$$

NP=CI

$$\frac{d\sigma_{q\bar{q}}^{\mathrm{NP}}}{dz} = \frac{3}{8}(1+z^2)\cdot\sigma_{q\bar{q}}^{\mathrm{NP}}$$

$$A_{\mathrm{CE}}^{\mathrm{CM}} = \frac{\sigma_{q\bar{q}}^{\mathrm{CM}}[\frac{1}{2}z^*(z^{*2}+3)-1]}{\sigma_{q\bar{q}}^{\mathrm{CM}}} = \frac{1}{2}z^*(z^{*2}+3)-1$$

$$A_{\mathrm{CE}}^{\mathrm{NP}} = \frac{\sigma_{q\bar{q}}^{\mathrm{NP}}[\frac{1}{2}z^*(z^{*2}+3)-1]}{\sigma_{q\bar{q}}^{\mathrm{NP}}} = \frac{1}{2}z^*(z^{*2}+3)-1.$$

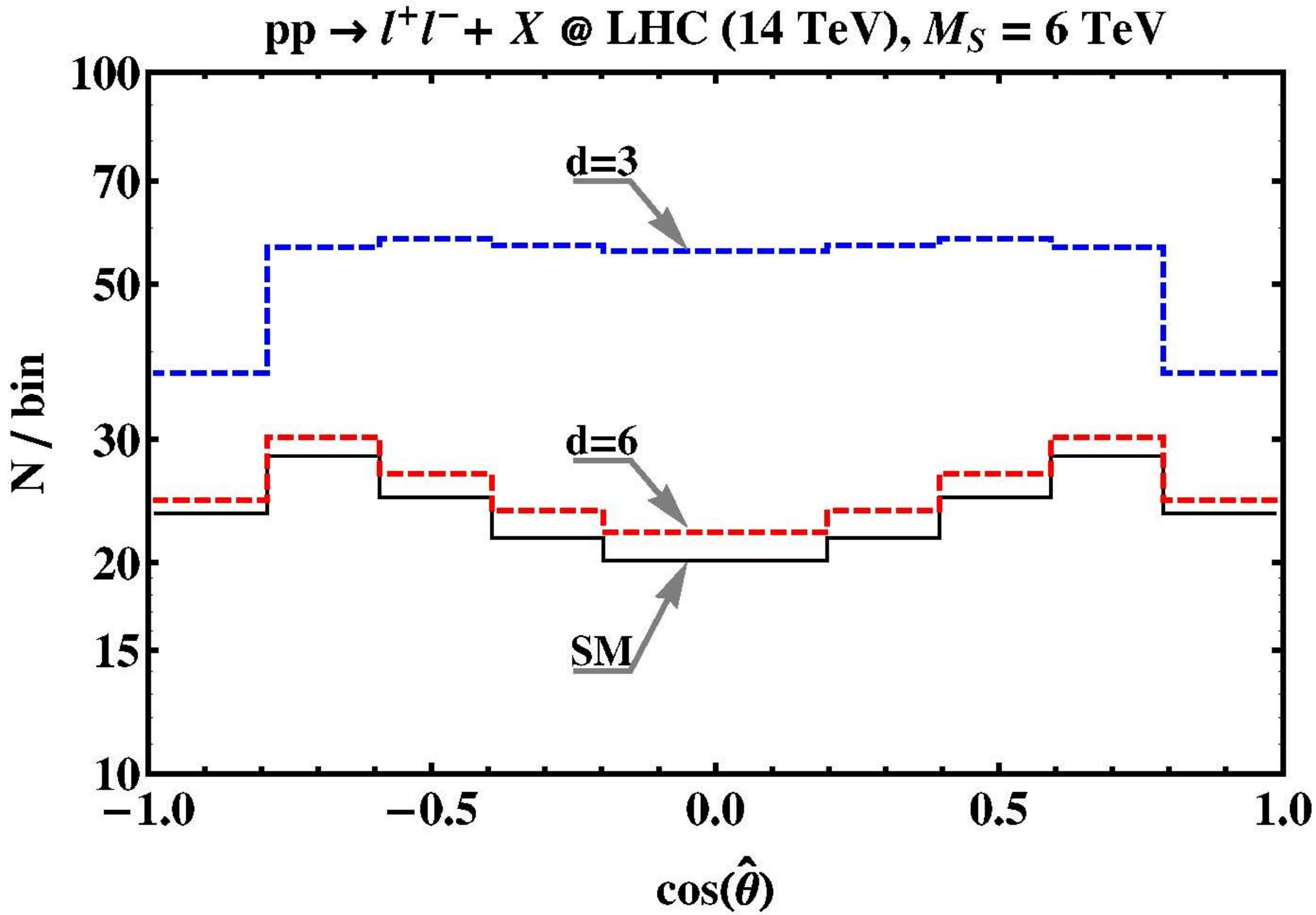
$$A_{\mathrm{CE}}^{\mathrm{CM}} = A_{\mathrm{CE}}^{\mathrm{NP}} = \frac{1}{2}z^*(z^{*2}+3)-1$$

$$\frac{d\sigma^{\mathrm{ADD}}}{dz} = \frac{3}{8}(1+z^2)\sigma_{q\bar{q}}^{\mathrm{CM}} + \frac{5}{8}(1-3z^2+4z^4)\sigma_{q\bar{q}}^{G} + \frac{5}{8}(1-z^4)\sigma_{gg}^{G} + \frac{1}{4}(1-3z^2)\sigma^{GZ}(2$$

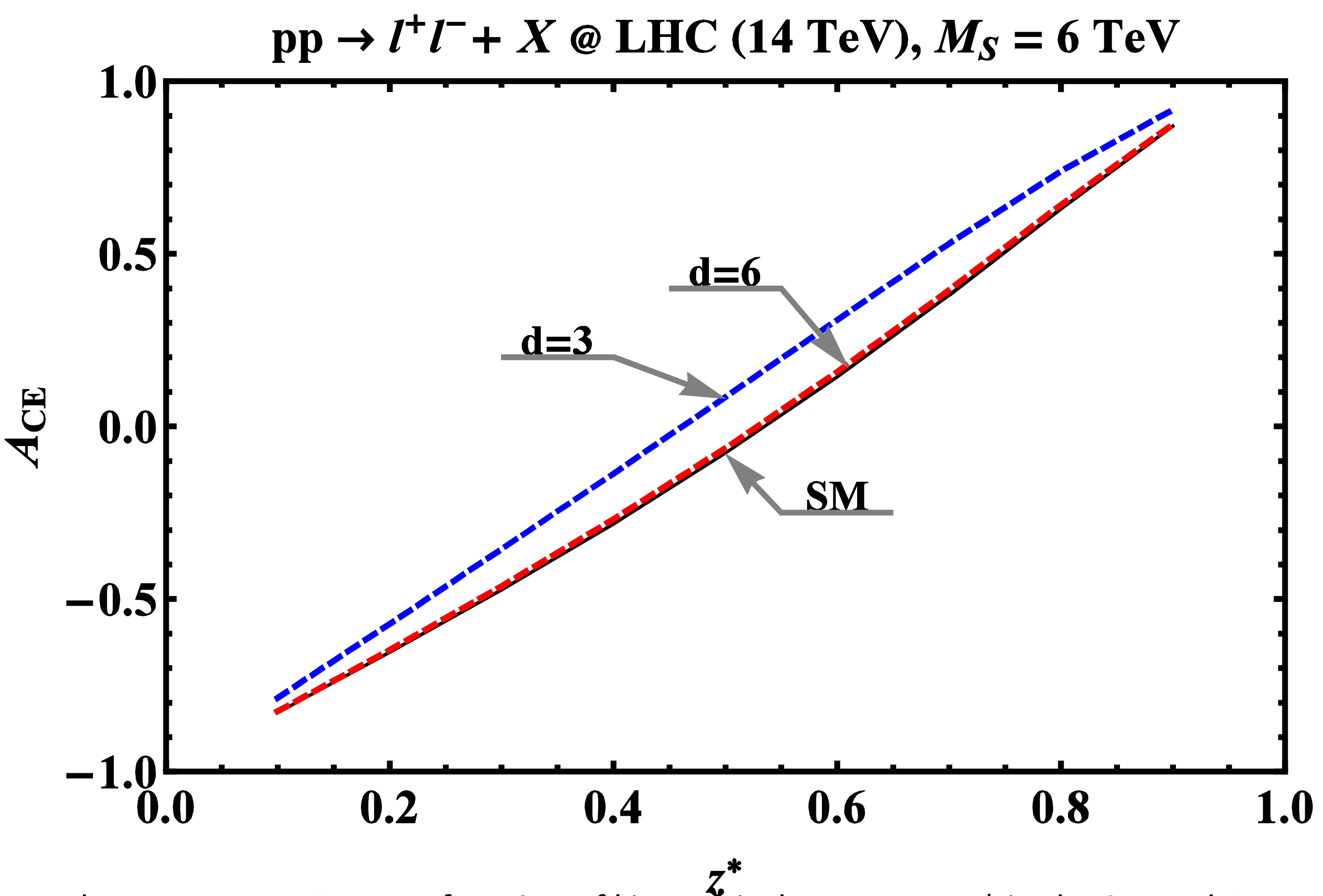
$$A_{\mathrm{CE}}^{\mathrm{ADD}} = \frac{\sigma_{\mathrm{CE}}^{\mathrm{ADD}}}{\sigma^{\mathrm{ADD}}}$$

$$ADD: A_{CE}^{ADD} \neq A_{CE}^{NP}$$

Angular distributions



Center-edge asymmetry ACE

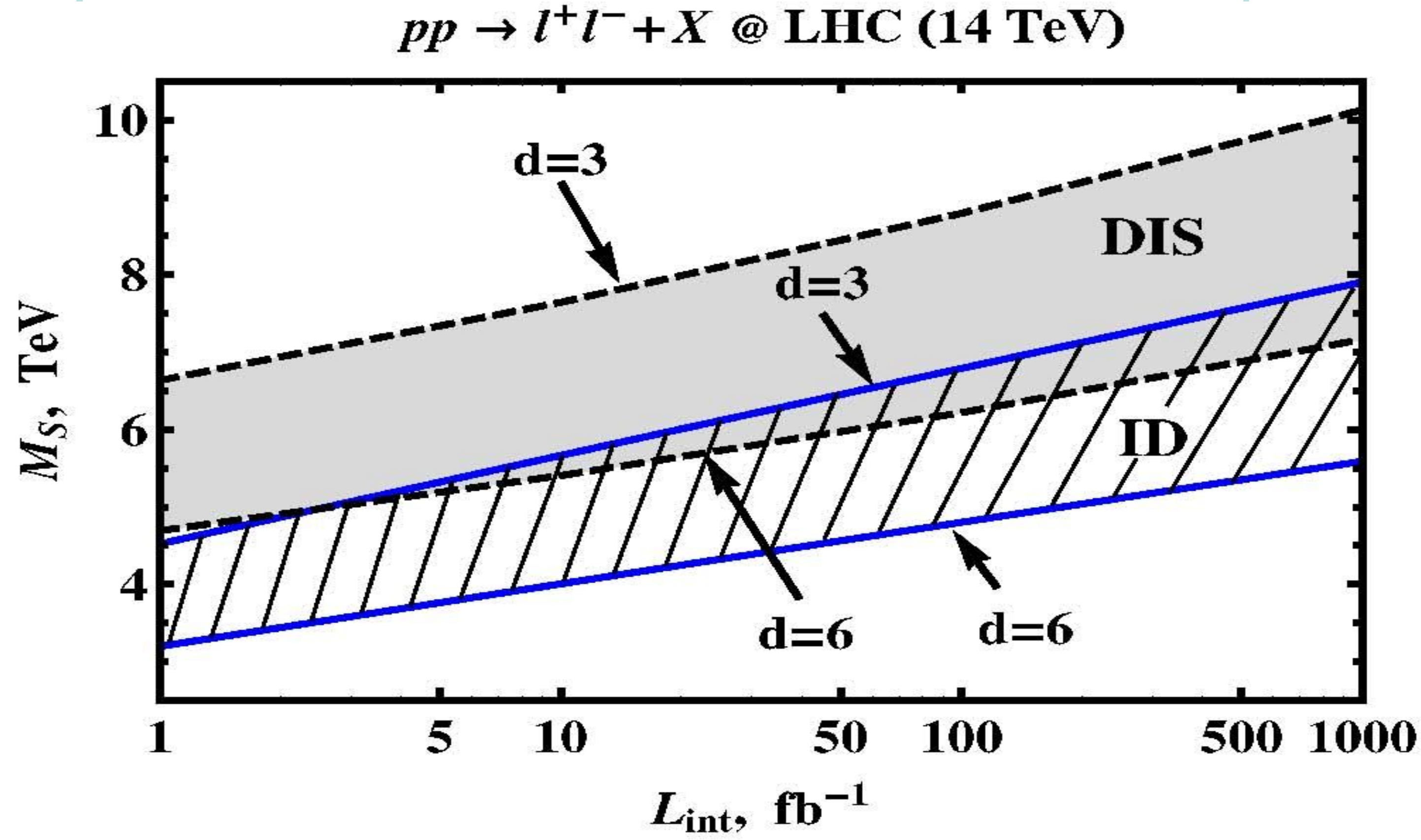


Center-edge asymmetry Ace as a function of kinematical parameter Z* in the SM and ADD scenario

CI: $\Delta A_{CE} = A_{CE}^{CI} - A_{CE}^{SM} = 0$

ADD: $\Delta A_{CE} = A_{CE}^{ADD} - A_{CE}^{SM} \neq 0$

Identification reach



Discovery (gray band) and identification (hatched) reaches on Ms (in TeV) at 95% as a function of integrated luminosity for different number of extra dimensions (d=3-6) at the LHC with 14 TeV

Conclusions

- By considering the present and future LHC energy regimes, we reanalyse the potential of the LHC to discover the effects of large extra dimensions and to discriminate between various theoretical models.

- Specifically, in latter case we explore the capability of the LHC to distinguish spin-2 Kaluza-Klein towers of gravitons exchange from other new physics effects which might be conveniently parametrized by the four-fermion contact interactions. Centre-edge asymmetry provides unique graviton exchange signature in lepton pair production at the LHC energies

- We find that the LHC with planned energy 14 TeV and luminosity 100 fb^{-1} will be capable of discovering (and identifying) graviton exchange effects in the large extra dimensions with the cutoff parameter of order M_S = 6.2 TeV (4.8 TeV) for d = 6 and M_S = 8.8 TeV (6.8 TeV) for d = 3.


Thanks for your attention!