Summer school and workshop on high energy physics at the LHC

Phenomenology and experimental aspects of SUSY and searches for extradimensions at the LHC

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Natal, Brazil

21-31 October

Tentative outline

LECTURE 1

- Motivations and short introduction to supersymmetry (SUSY)

LECTURE 2

**- minimal SUSY extensions of the standard model (SM) phenomenology
Higgs sector, sfermions and gauginos**

- direct search examples at the LHC + some indirect constraints

LECTURE 3

- dark matter

LECTURE 4

- extra dimensions searches at the LHC

Extra dimensions phenomenology

tentative outline

- motivations, models
- ADD approach (and black holes)
- TeV^{-1} extra dimension(s)
- Universal Extra Dimensions (UED)
- Randall Sundrum approach (RS) and bulk RS
- string states (intersecting branes (at angles))
- extra-dimensions, GUT, supersymmetry

Motivations for extra dimensions

top-down

unification

superstring theories (branes, duality, M-theory)

bottom-up

address hierarchy problem of SM

can address :

- symmetry breaking (EW, SUSY) → boundary conditions

- SM fermions masses and mixing

EW observables precision measurements
K and B physics (CP violation), rare decays, ...

model building is challenging !

Models for extra dimensions

many possible approaches

with different impact on phenomenology depending on

how many extra dimensions ? 1 or more ?

which geometry ? which type of compactification ?

how large and which consequences?

which fields where ?

How many and which “geometry” ?

- factorizable or 'flat' (3 space + 1 time + D - 4 extra space dimensions)

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \qquad \mu, \nu = 0, 1, 2, 3, \ldots D$$

- non factorizable or warped (3 space + 1 time + 1 extra space dimension **y**)

$$ds^2 = a(y)(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2 \qquad \mu, \nu = 0, 1, 2, 3$$

warp factor

6D multiple warping ? arXiv:1001.2666

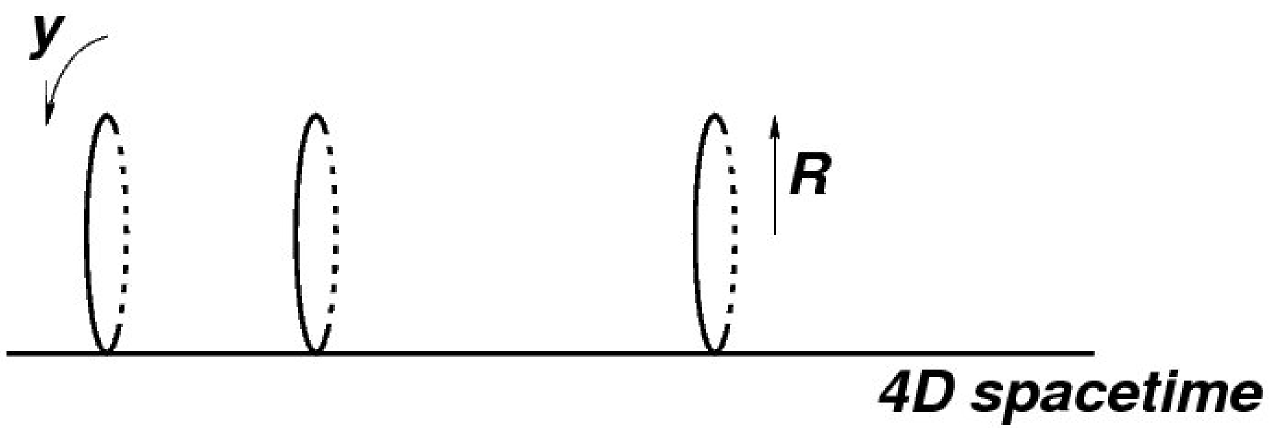
$$ds^2 = b(z)[a(y)\eta_{\mu\nu} dx^\mu dx^\nu + r_y^2 dy^2] + r_z^2 dz^2$$

see also Davoudiasl, Rizzo JHEP11(2008)013

which type of compactifications ?

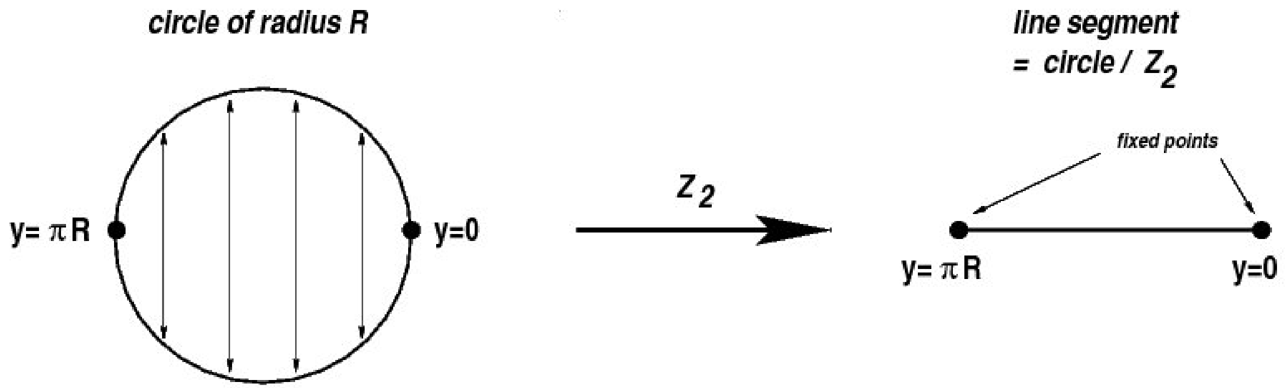
extra dimensions not (yet) seen → must be small and 'compact'

- on circle(s) or torus



- on orbifolds (coset space M/H where H is a group of discrete symmetries of a manifold M,

→ space singular at some fixed points) **e.g. one of the simplest case S^1/Z_2 :**



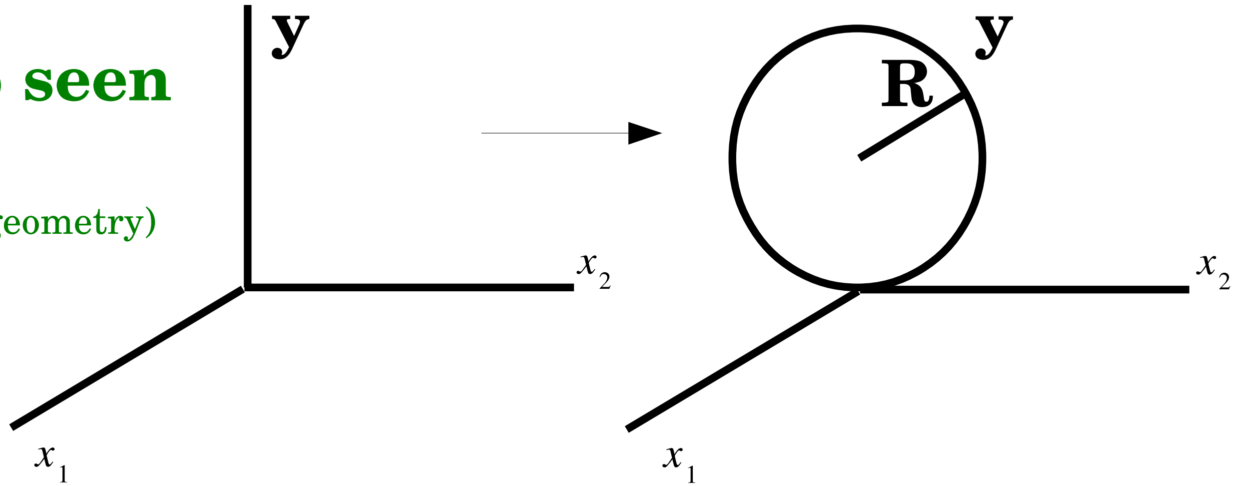
'fixed points ' with respect to the Z_2 discrete symmetry $\Gamma : y \to -y$

How Large and which consequence?

Extra dimensions not (yet) seen

→ must be 'small' (for 'flat' geometry)

→ **compact**



compactified dimensions leads to periodicity conditions

Fourier mode expansion of fields

$$\Phi(x,y)=\sum_k \phi^{(k)}(x)e^{\frac{iky}{R}}$$

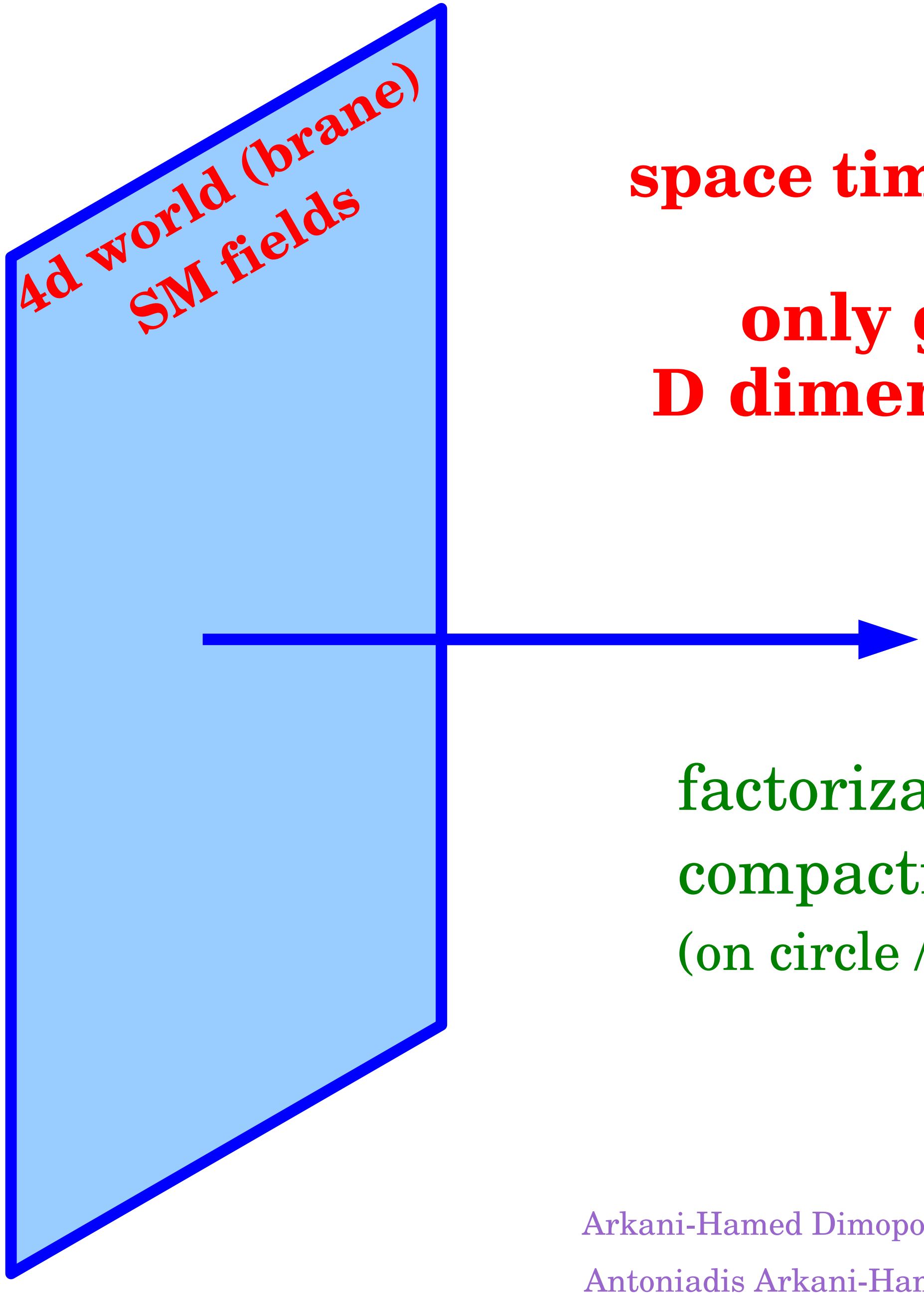
infinite number of **Kaluza-Klein (KK)** modes/states/excitations

k^{th} mode mass

$$m_k^2=m_0^2+\frac{k^2}{R^2}$$

→ **tower of KK states**

which fields/particles and where ?



space time of D = 4 + n dimensions

only gravity propagates in
D dimensional *(bulk)* full space

factorizable geometry

compactified **n** extra-dimensions

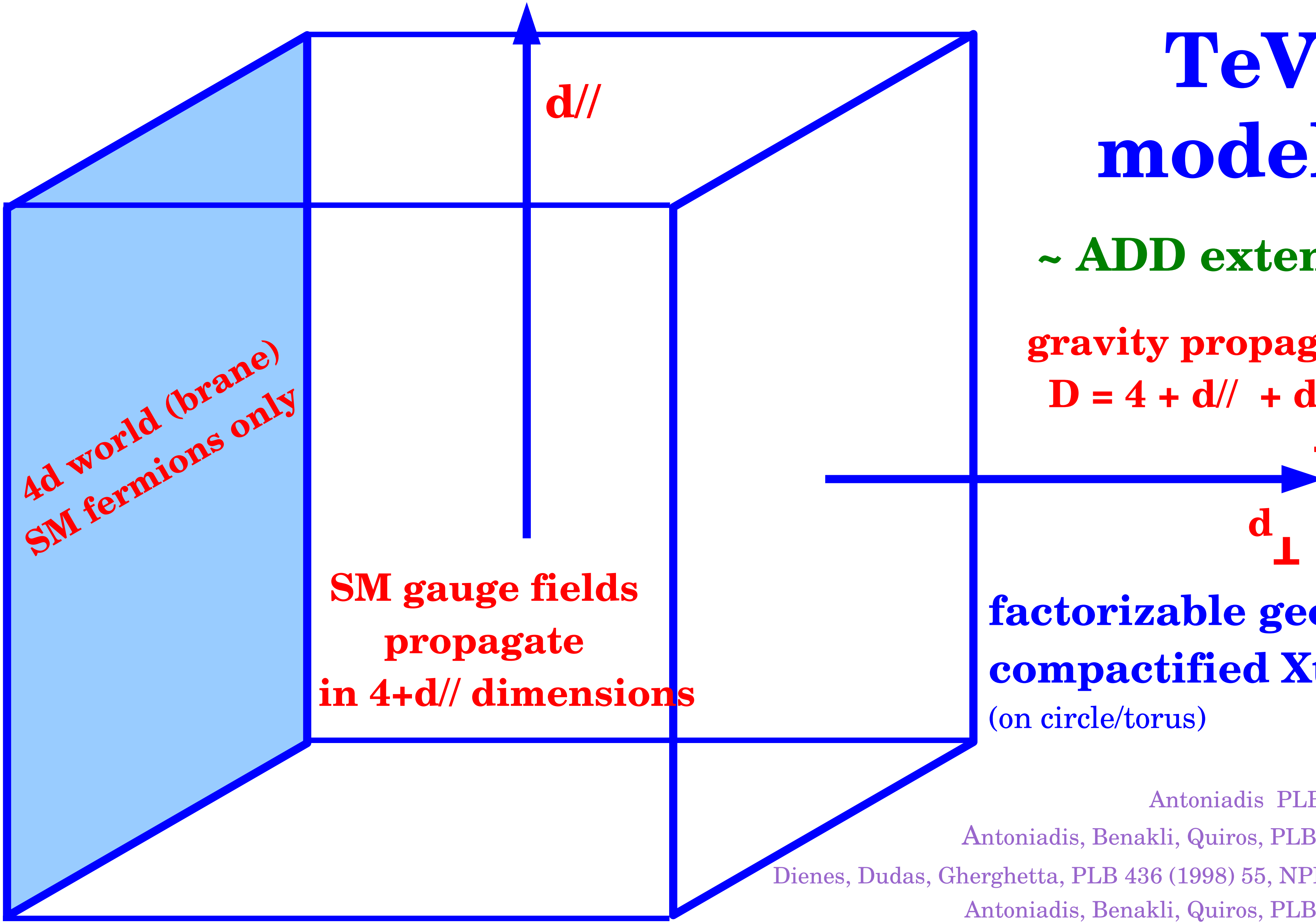
(on circle / torus) as small as ~ mm ?

ADD model

Arkani-Hamed Dimopoulos Dvali, PLB 429 (1998) 263, PRD59 (1999) 086004

Antoniadis Arkani-Hamed Dimopoulos Dvali, PLB 436 (1998) 257

which fields/particles and where ?



$\mathbf{TeV^{-1}}$ models

~ ADD extension

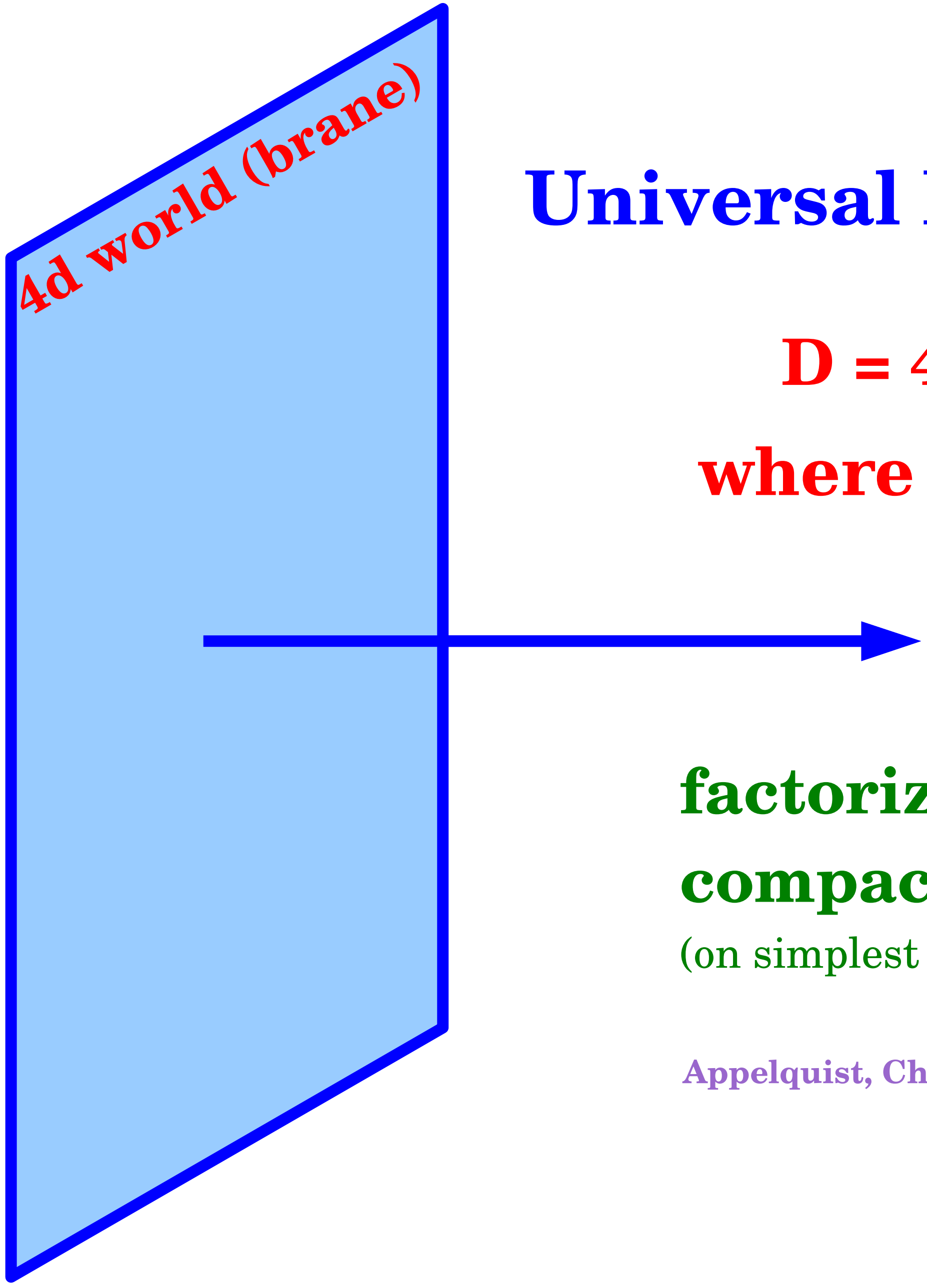
gravity propagates in
$D = 4 + d_{//} + d_{\perp}$ bulk

factorizable geometry
compactified Xtradim
(on circle/torus)

Antoniadis PLB246 (1990) 377
Antoniadis, Benakli, Quiros, PLB 331 (1994) 313
Dienes, Dudas, Gherghetta, PLB 436 (1998) 55, NPB 537 (1999) 47
Antoniadis, Benakli, Quiros, PLB 460 (1999) 176
Rizzo, Wells, PRD61, 016007
Cheung, Landsberg, PRD65, 076003

d// size: $R^{-1} \approx TeV \approx 10^{-19}\,m$

which fields/particles and where ?



Universal Extra-Dimensions (UED)

D = 4 + n bulk (n=1 mostly)

where SM gauge AND fermion fields propagate

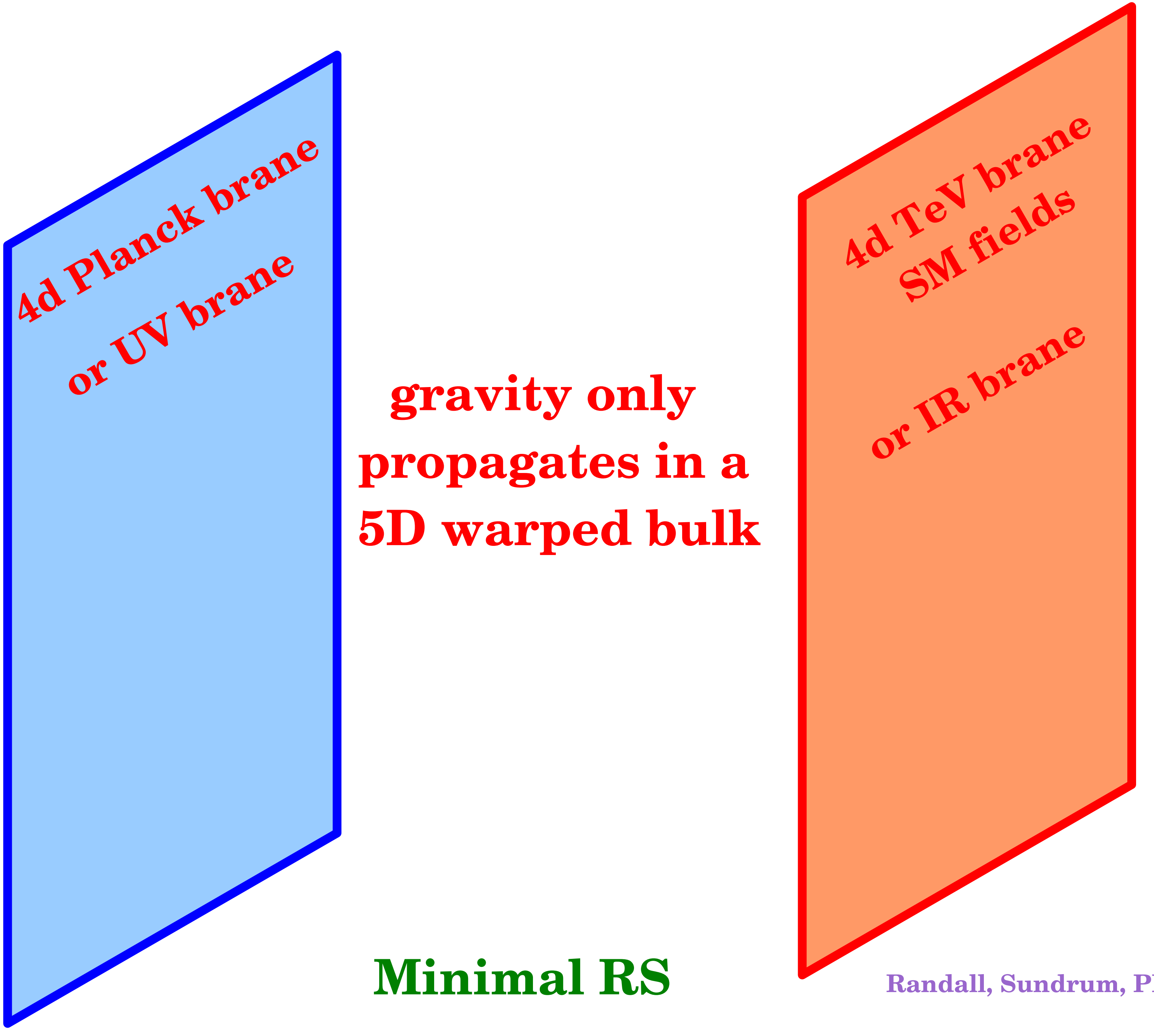
factorizable geometry

compactified extra-dimensions

(on simplest orbifold)

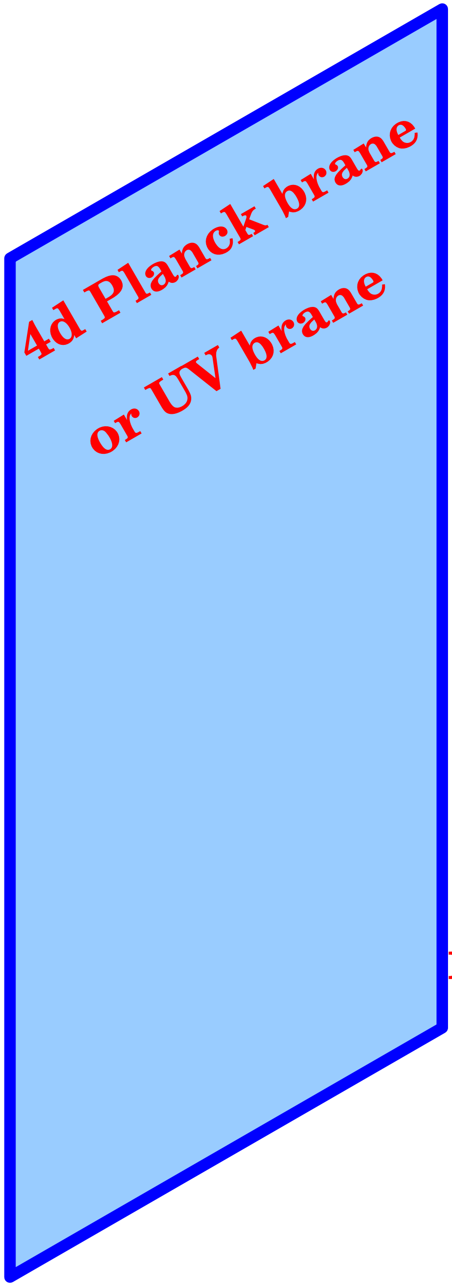
Appelquist, Cheng, Dobrescu, PRD64, 035002

which fields/particles and where ?



Randall, Sundrum, PRL 83 (1999) 3370

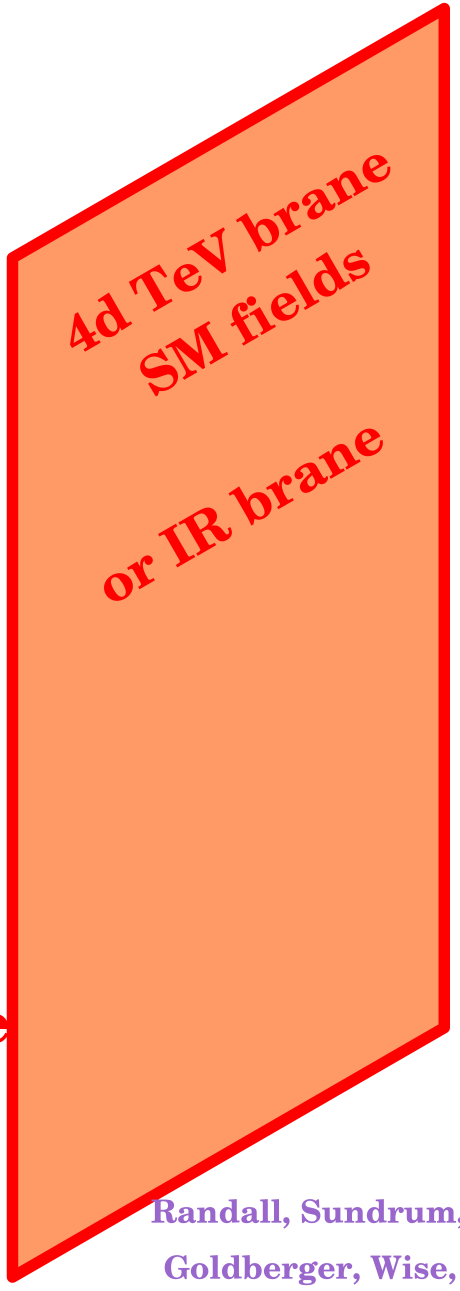
which fields/particles and where ?



gravity
propagates in a
5D warped bulk

+

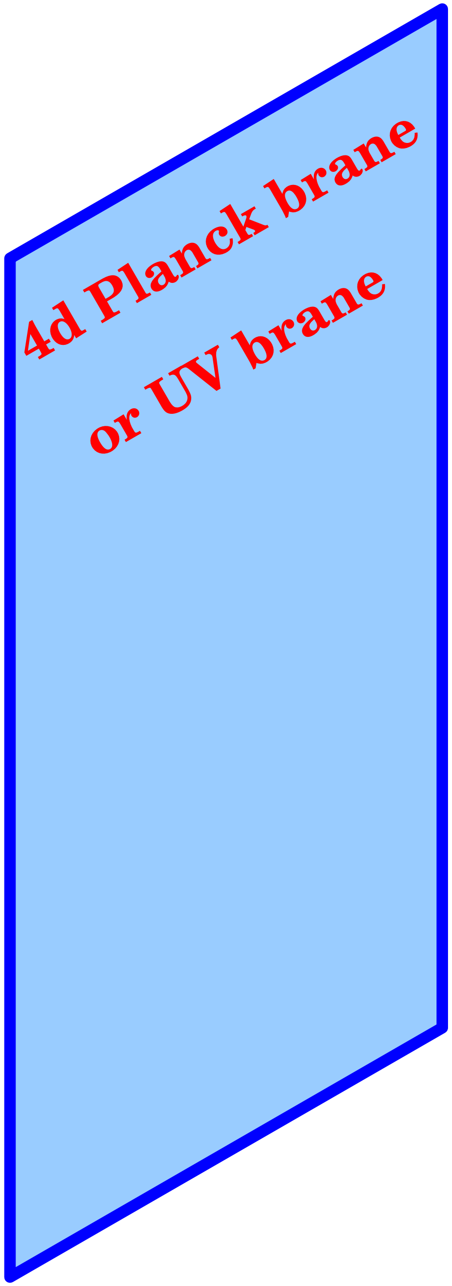
scalar for
interbrane distance
stabilization



stabilized RS

Randall, Sundrum, PRL 83 (1999) 3370
Goldberger, Wise, PRL 83 (1999) 4922,
PRD 60, 107505,
PBL 474 (2000) 275

which fields/particles and where ?

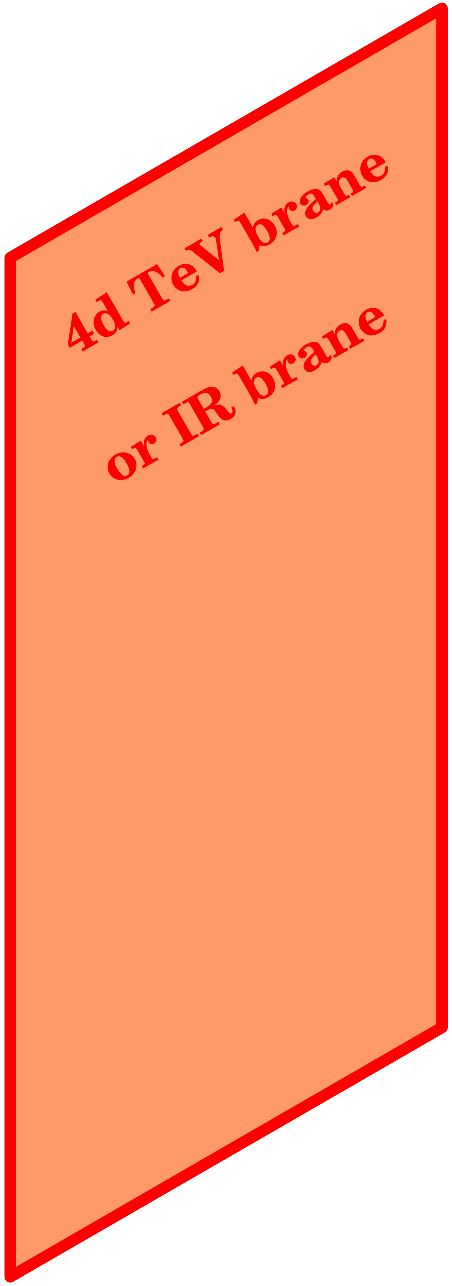


not only gravity
propagates in a
5D warped bulk

but also
fermion and
gauge fields

Higgs localized
close to TeV brane

Bulk RS



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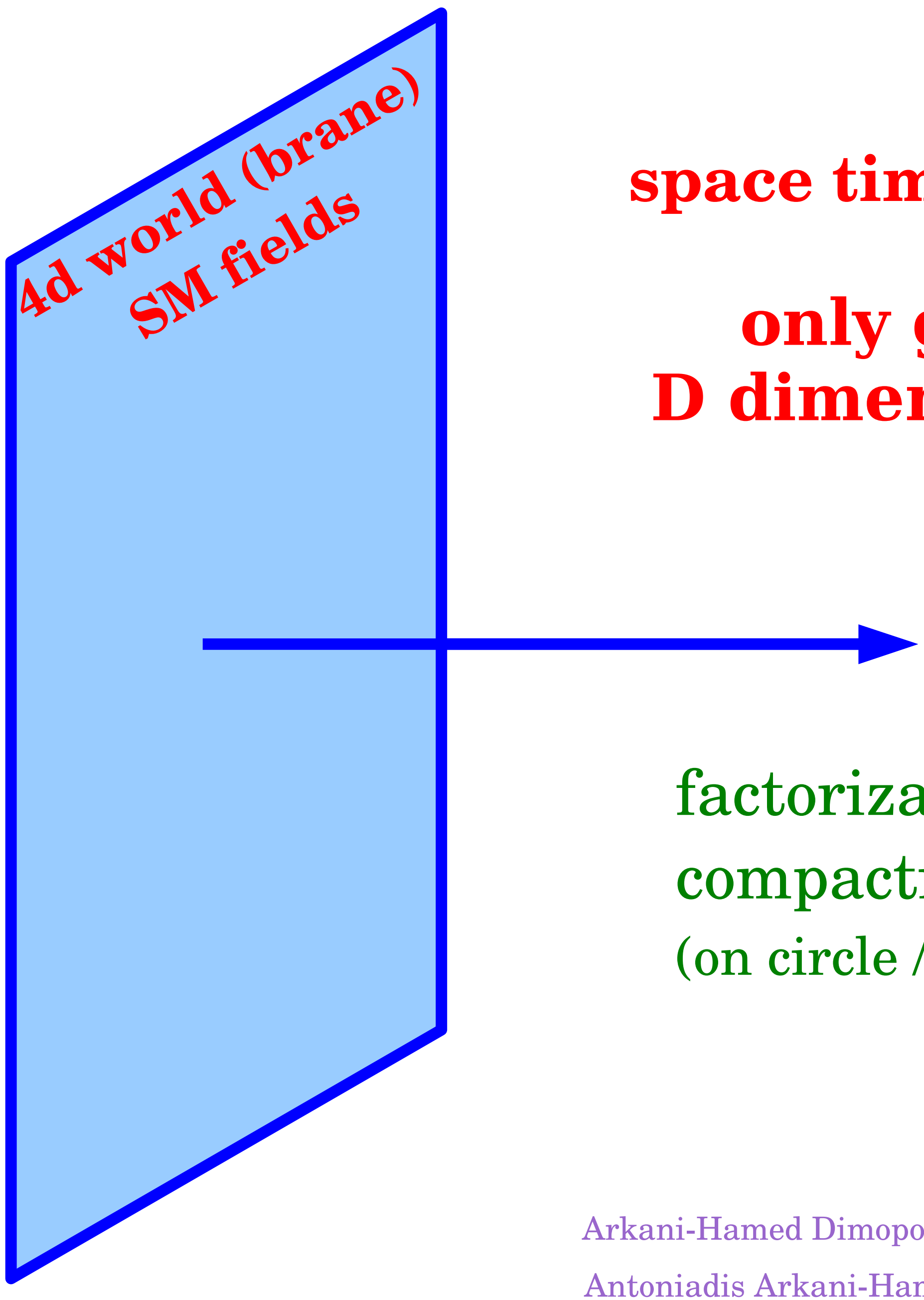

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Antoniadis Arkani-Hamed Dimopoulos Dvali, PLB 436 (1998) 257

ADD approach

Arkani-Hamed Dimopoulos Dvali,
PLB 429 (1998) 263, PRD59 (1999) 086004
Antoniadis Arkani-Hamed Dimopoulos Dvali,
PLB 436 (1998) 257

gravity at TeV scale in a bulk of 4 + n compactified dimensions

SM fields confined in 4D brane

one of 1[st] approach of the KK idea renewal after the string duality and brane revolution

address the hierarchy problem $$M^2_{Pl(4)} \sim M^{n+2}_{Pl(4+n)} R^n$$

$$for\ M_D \equiv M_{Pl(4+n)} = 1\ TeV$$

N	1	2	3 ...
R	10^{10} km	1 mm	1 nm

O(solar system) — for 10^{10} km

'large' ED — for 1 mm and 1 nm

phenomenology and constraints from various areas:

- short distance gravity measurement (backup)
- astrophysics and cosmology (backup)
- **collider physics**

Han, Lykken, Zhang, PRD5 9, 105006
Hewett, PRL 82 (1999) 4760
Giudice, Rattazzi, Wells, NPB 544 (1999) 3
Mirabelli, Perelstein, Peskin, PRL 82 (1999) 2236

ADD approach

the graviton Kaluza-Klein modes have masses equal to $|k|/R$ and therefore the different excitations have mass splittings

$$\Delta m \sim \frac{1}{R} = M_D \left(\frac{M_D}{\bar{M}_{Pl}}\right)^{\frac{2}{n}} = \left(\frac{M_D}{\text{TeV}}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}$$

using $\bar{M}_{Pl} \equiv \sqrt{V_n}\, \bar{M}_D^{\frac{n}{2}+1} = (2\pi R)^{\frac{n}{2}}\, \bar{M}_D^{\frac{n}{2}+1} \equiv R^{\frac{n}{2}}\, M^{\frac{n}{2}+1}$

for $M_D \equiv \sqrt{V_n}\, \bar{M}_D^{\frac{n}{2}+1} = (2\pi R)^{\frac{n}{2}}\, \bar{M}_D^{\frac{n}{2}+1} \equiv R^{\frac{n}{2}}\, M^{\frac{n}{2}+1}$

n	4	6	8
Δm	20 keV	7 MeV	0.1 GeV

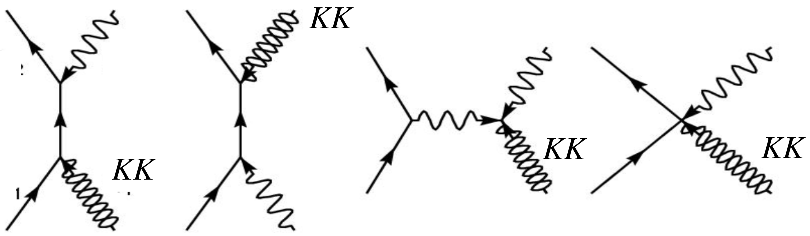
ADD signatures at colliders in a nutshell

- direct searches → KK graviton in final states

states close to each other in mass O(fraction of eV) quasi-continuum

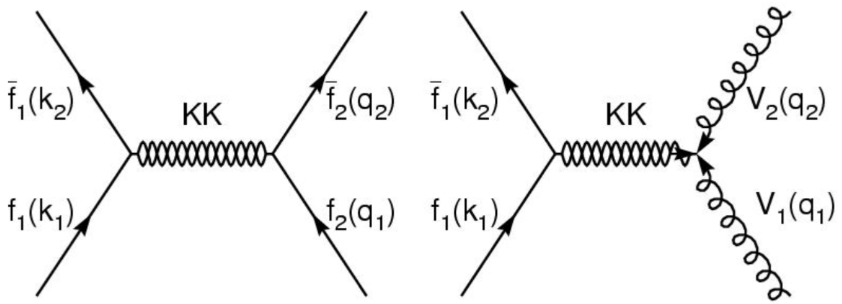
compensating ~O(1/Mpl) coupling of each KK state to SM fields

look for jet + missing energy
photon + missing energy
Z + missing energy



sizeable Xsection directly related to n and scale M_D $\sigma \approx E^n / M_D^{n+2}$

- indirect searches → no KK states in final states



look for deviation in fermion or boson pairs production (diff.) Xsections measurements

Xsection divergent for n > 1 → need a cutoff

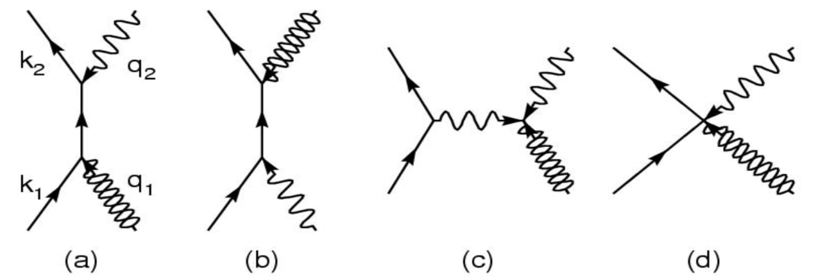
cut-off M_S not related to scale M_D → assume $M_S \approx M_D$

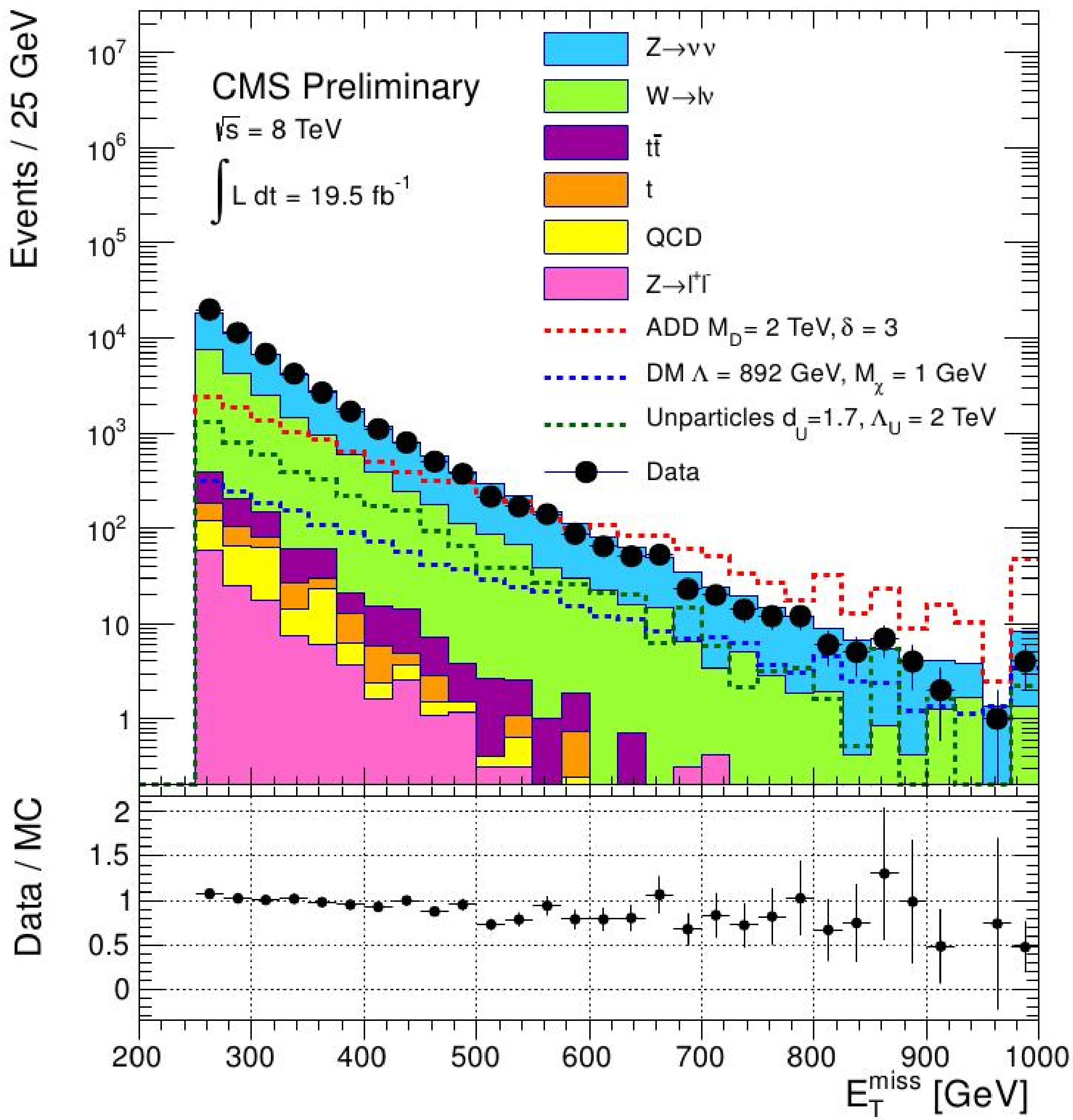
(possible regularization in string theories context)

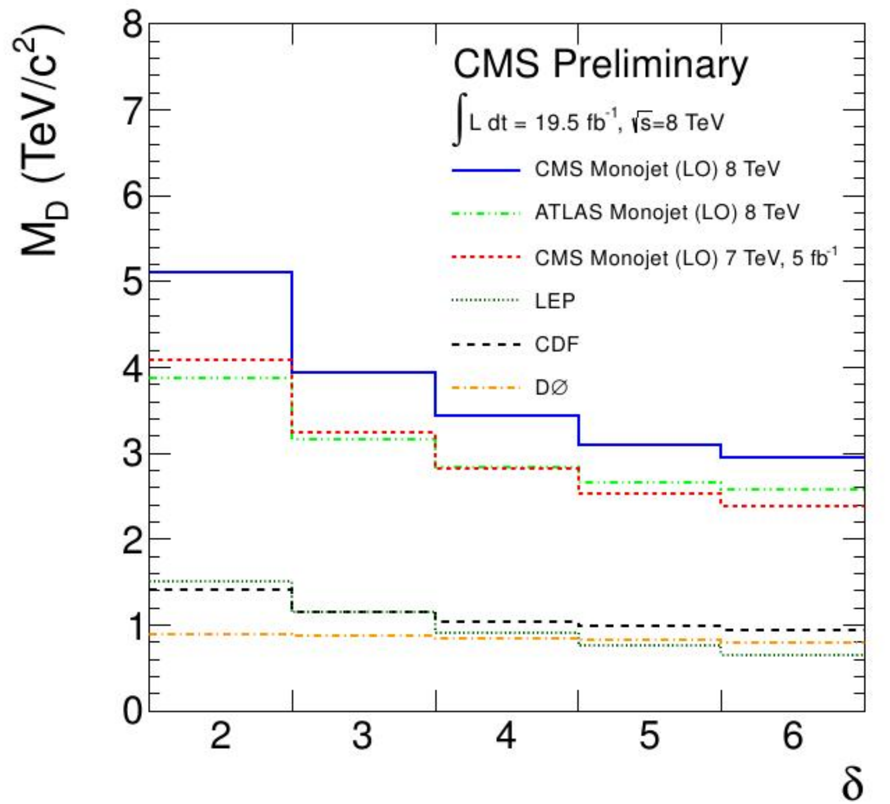
PreLHC collider constraints on scales ~O(1.6 – 2.1 TeV) for n = 2

mono-jet (“direct” ADD)

CMS-EXO-12-048



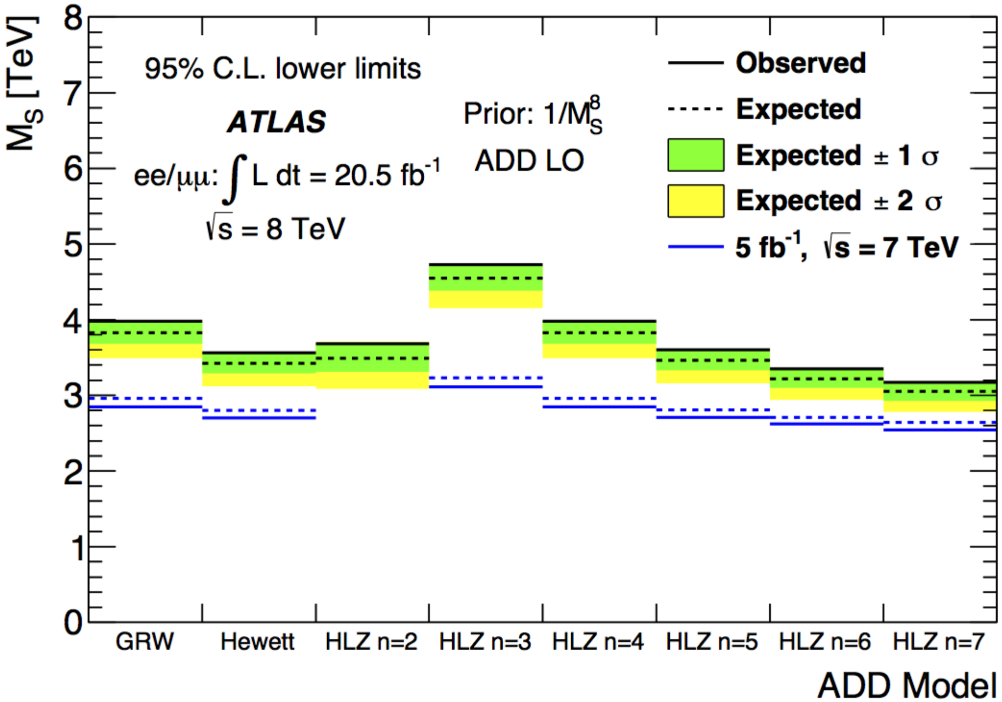


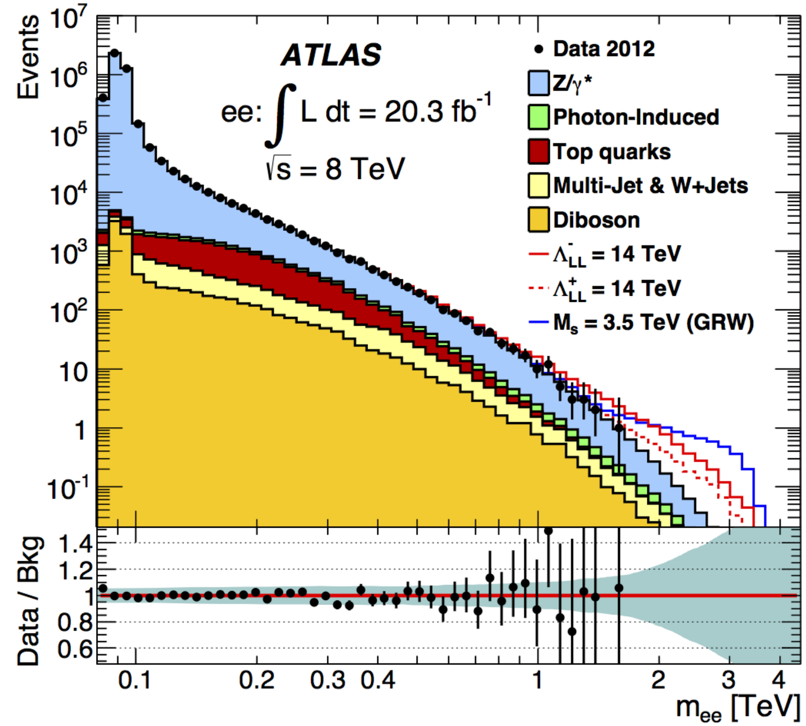


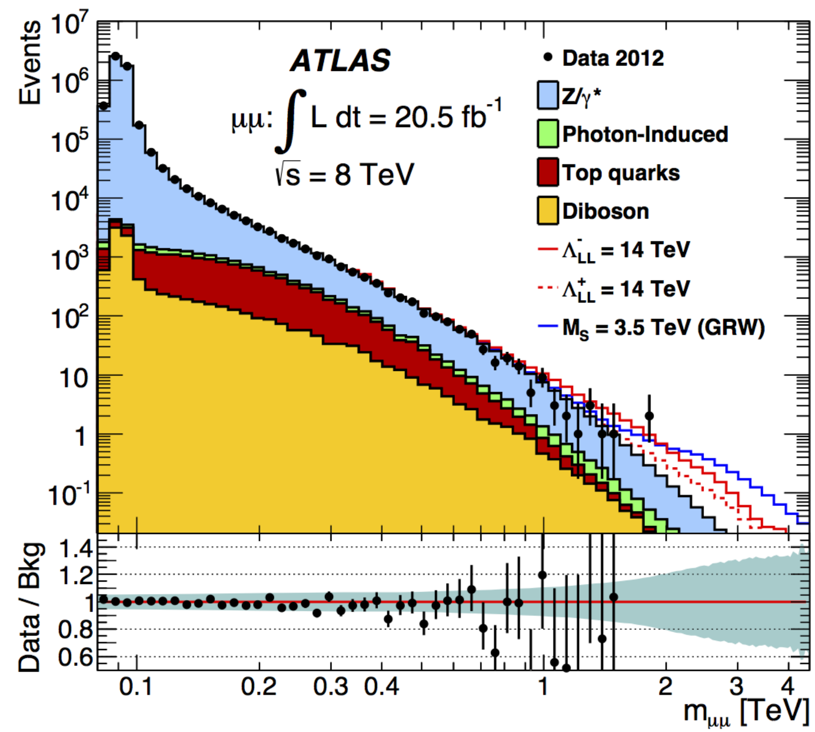
non resonant dilepton

ATLAS arXiv:1407.2410

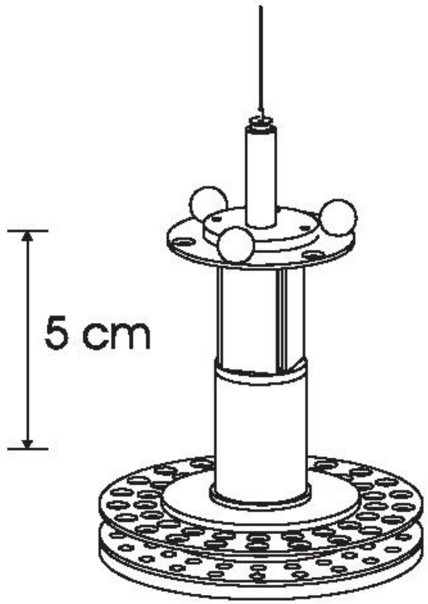
("indirect" ADD)

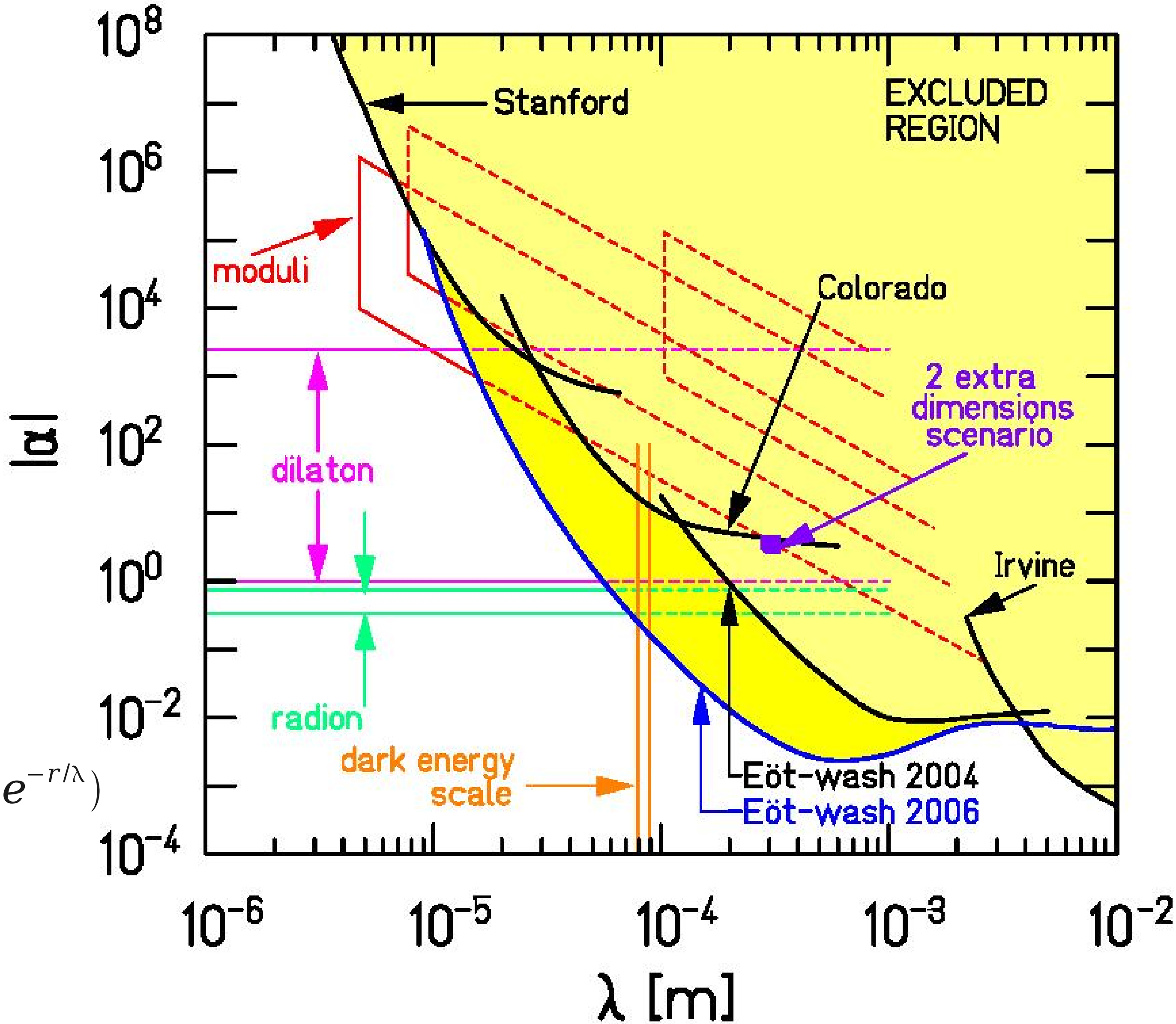






From torsion balance test of gravitational Inverse square law





$$V(r) = -G_{Newton} \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

R $\lesssim$ 50 microns

Kapner, Cook, Adelberger, Gundlach, Heckel, Hoyle, Swanson, PRL 98 (2007) 021101

Black Holes

Myers, Perry, Annals, Phys. 172 (1986) 304
Argyres, Dimopoulos, March-Russel, PLB 441 (1998) 96
Banks, Fischler, hep-th/9906038
Emparan, Horowitz, PRL 85 (2000) 499
Giddings, Thomas, PRD65, 056010
Dimopoulos, Landsberg, PRL 87 (2001) 161602
Anchordoqui, Goldberg, Shapere, PRD 66, 024033
Dimopoulos, Emparan, PLB 526 (2002) 393
Kanti, Int.J.Mod.Phys. A19 (2004) 4899
Lect.Notes.Phys.769(2009)387

Schwarzschild radius ('flat' ED ~ ADD)

4D $R_s \approx \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$ $R_s \ll 10^{-35}\ m$

(4+n)D $R_s \approx \frac{1}{M_d} \left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$ $R_s \approx 10^{-19}\ m$

if **colliding parton impact parameter $< R_S$**
and **$E_{CM} \sim M_{BH} > M_D$**

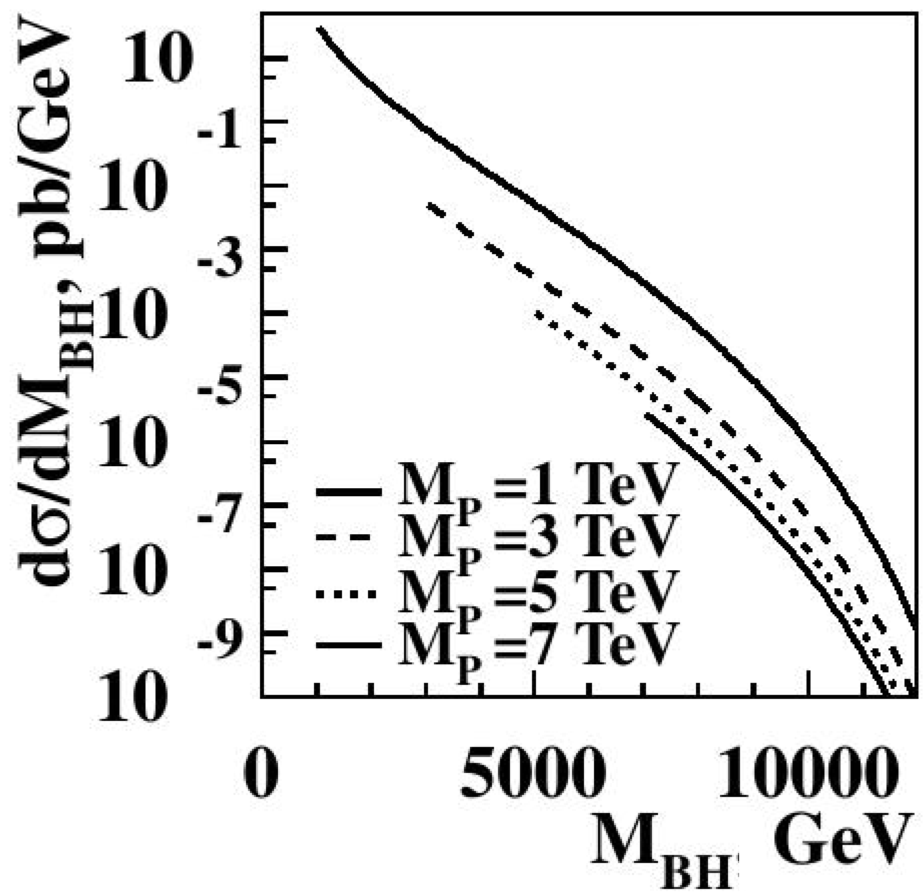
a black hole can form

Cross sections are large

$$\sigma(parton_i\ parton_j \rightarrow BH) \approx \pi R_S^2$$

semi-classical approach

$$\sigma(pp \rightarrow BH) \approx 1\text{nb} - 1\,fb$$



Dimopoulos, Landsberg, PRL 87 (2001) 161602

Black Holes decay

a highly asymetric rotating created Black Hole goes through

Balding phase

shedding of quantum numbers except a few i.e. M, Q ...

invisible energy (15% of total energy ?)

Spin-down phase

loss of angular momentum by Hawking radiation

visible energy (25% of total energy ?)

Schwarzschild phase $M_{BH} >> M_D$

Hawking radiation at $T_H \approx M_D \left(\frac{M_D}{M_{BH}}\right)^{\frac{1}{n+1}} (n+1)$

thermal evaporation black body spectrum + grey-body factors from strong. Grav. field)

visible energy (60% of total energy ?) → **mostly in SM particles on our brane**

Planck phase $M_{BH} \approx M_D$ **(regime of quantum gravity)**

quanta emission ?

string ball formation and evaporation at Hagedorn temperature ?

Black Holes

BH evaporate/decay democratically into SM particles (or SM+SUSY)

mainly on the brane through Hawking radiation

decay is fast $\sim 10^{-26}$ s ⟶ Black Holes do not escape the detector

spectacular signatures with large jet/lepton multiplicities and small MET

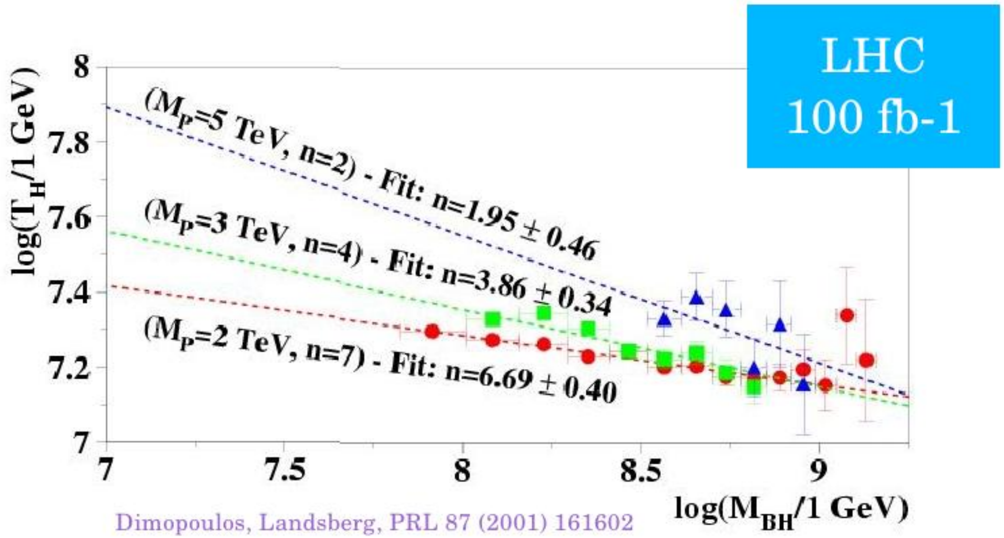
possible to carry dedicated studies → dimensionality of space-time

measure Hawking temperature of black hole T_{BH}

(e.g. from energy spectrum of some decay product)

as a function of its mass M_{BH}

(e.g. from total energy of all of its decay product)



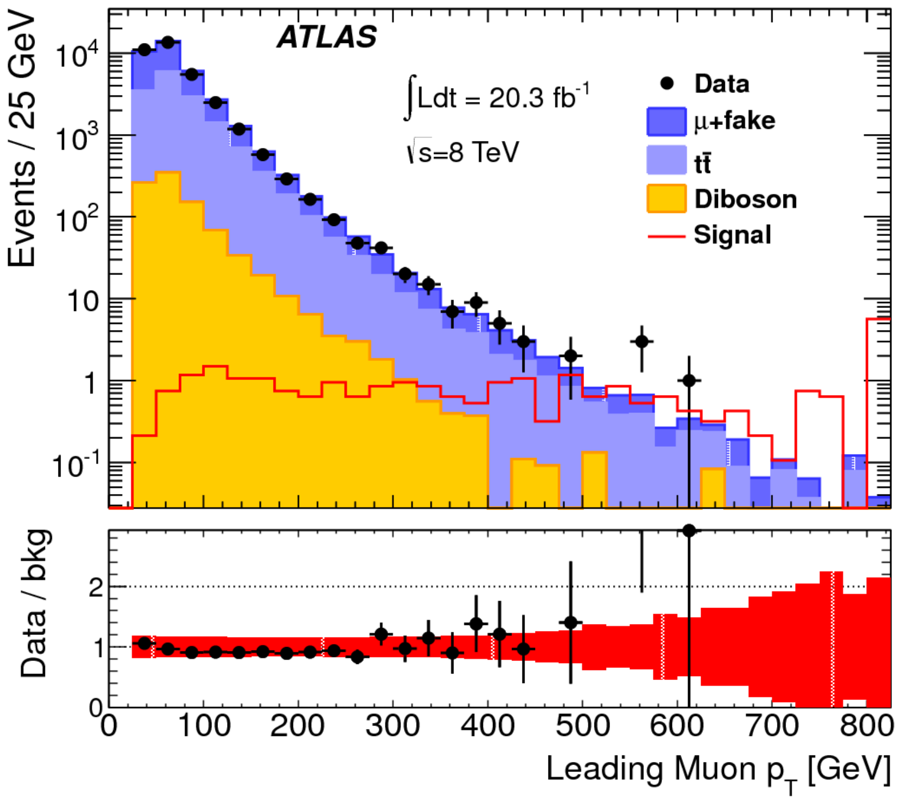
Dimopoulos, Landsberg, PRL 87 (2001) 161602

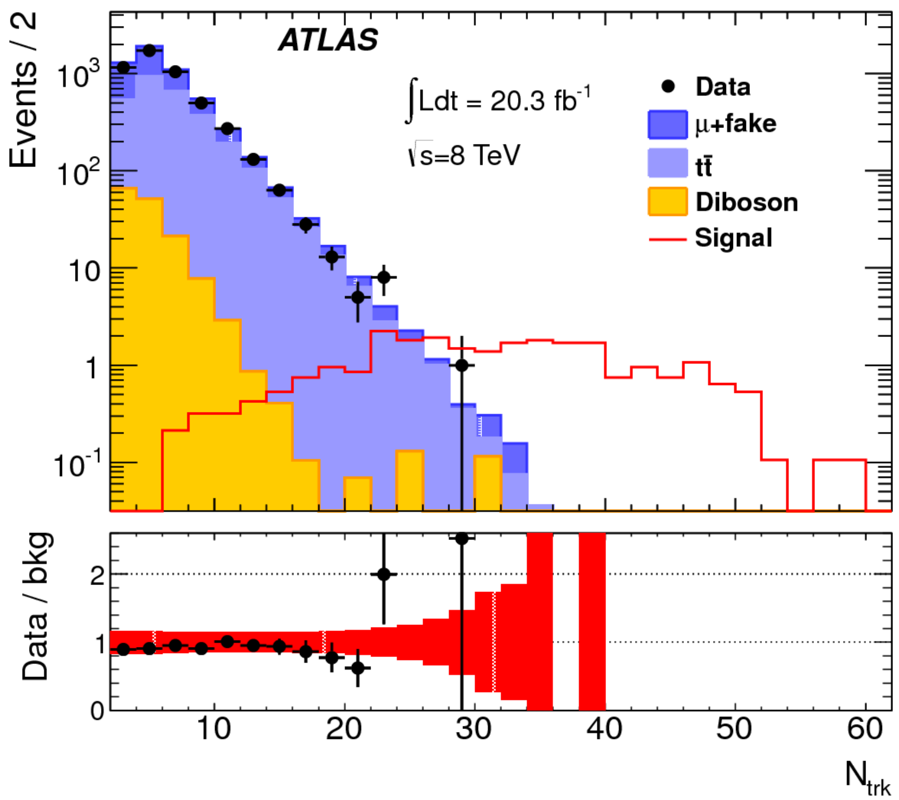
and check that $\log(T_{BH}) = -\frac{1}{n+1}\log(M_{BH}) + \text{const}$ (extra-dimension equivalent of the Wien law)

black holes

ATLAS PRD 88 (2013) 072001

dimuon final state and large track multiplicity





black holes

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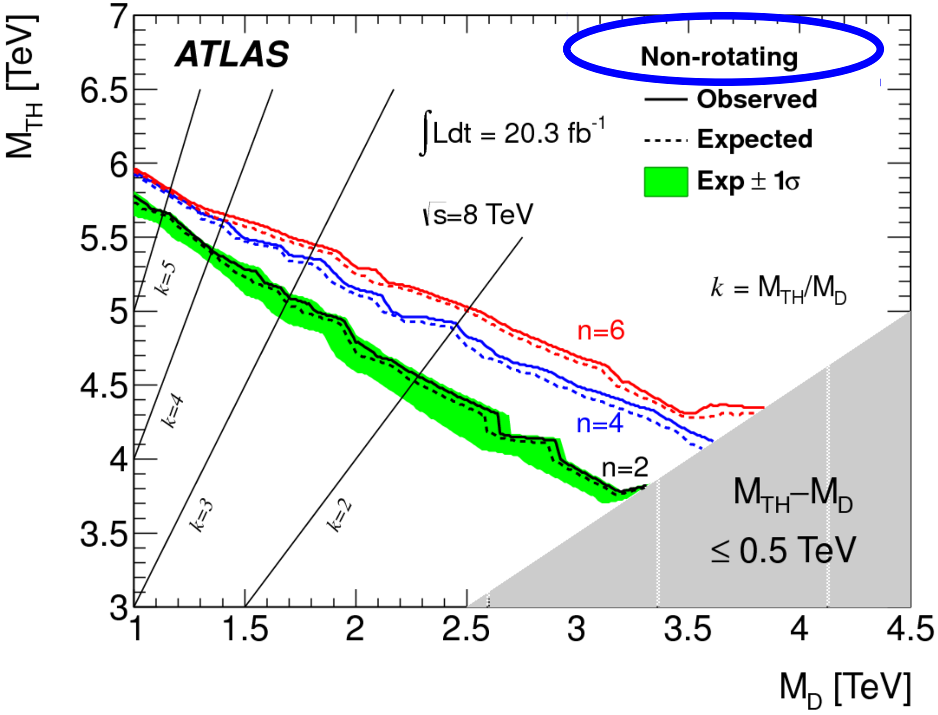

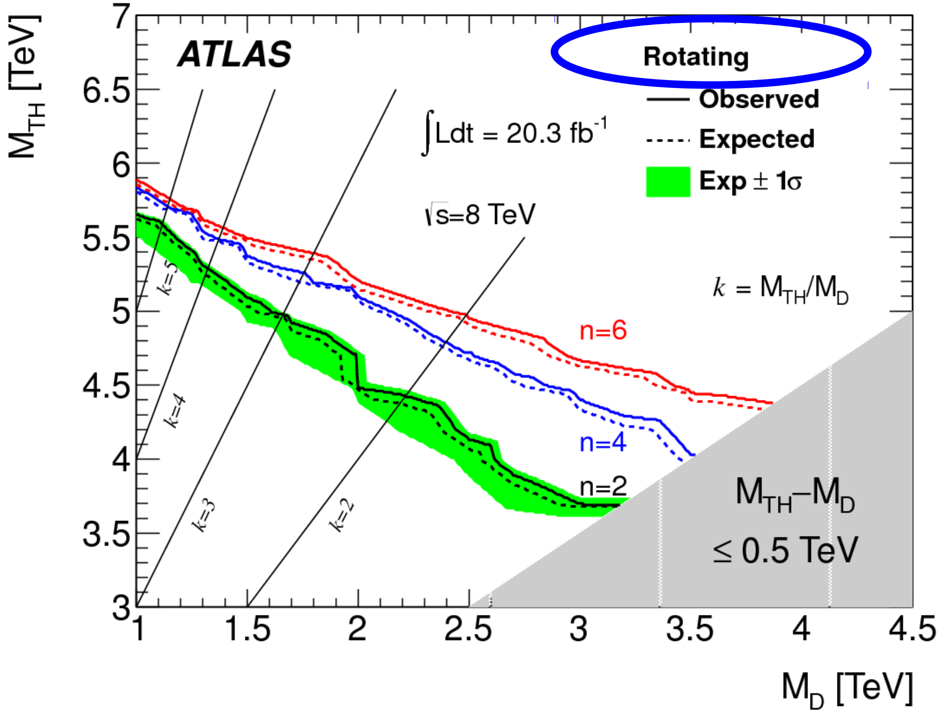

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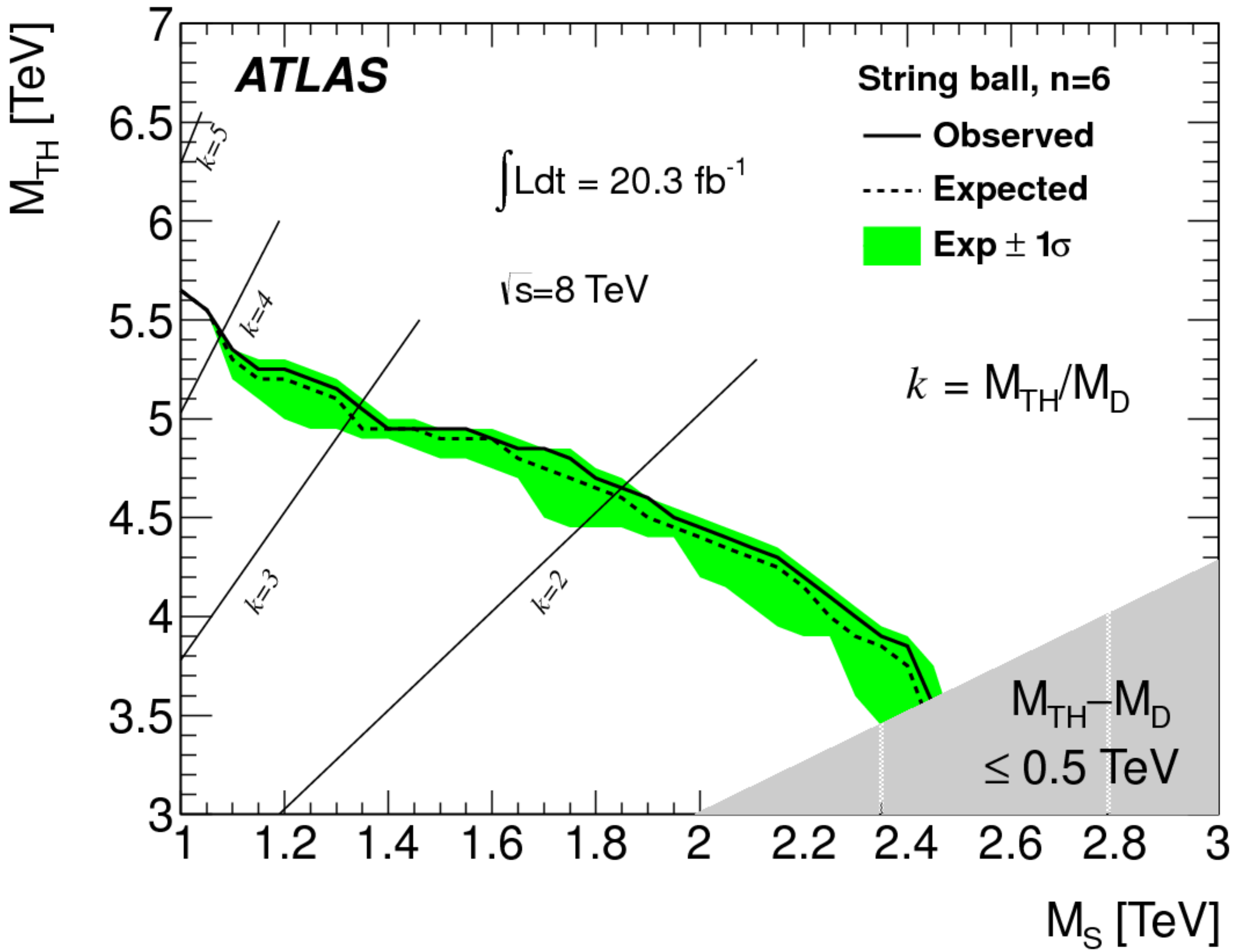
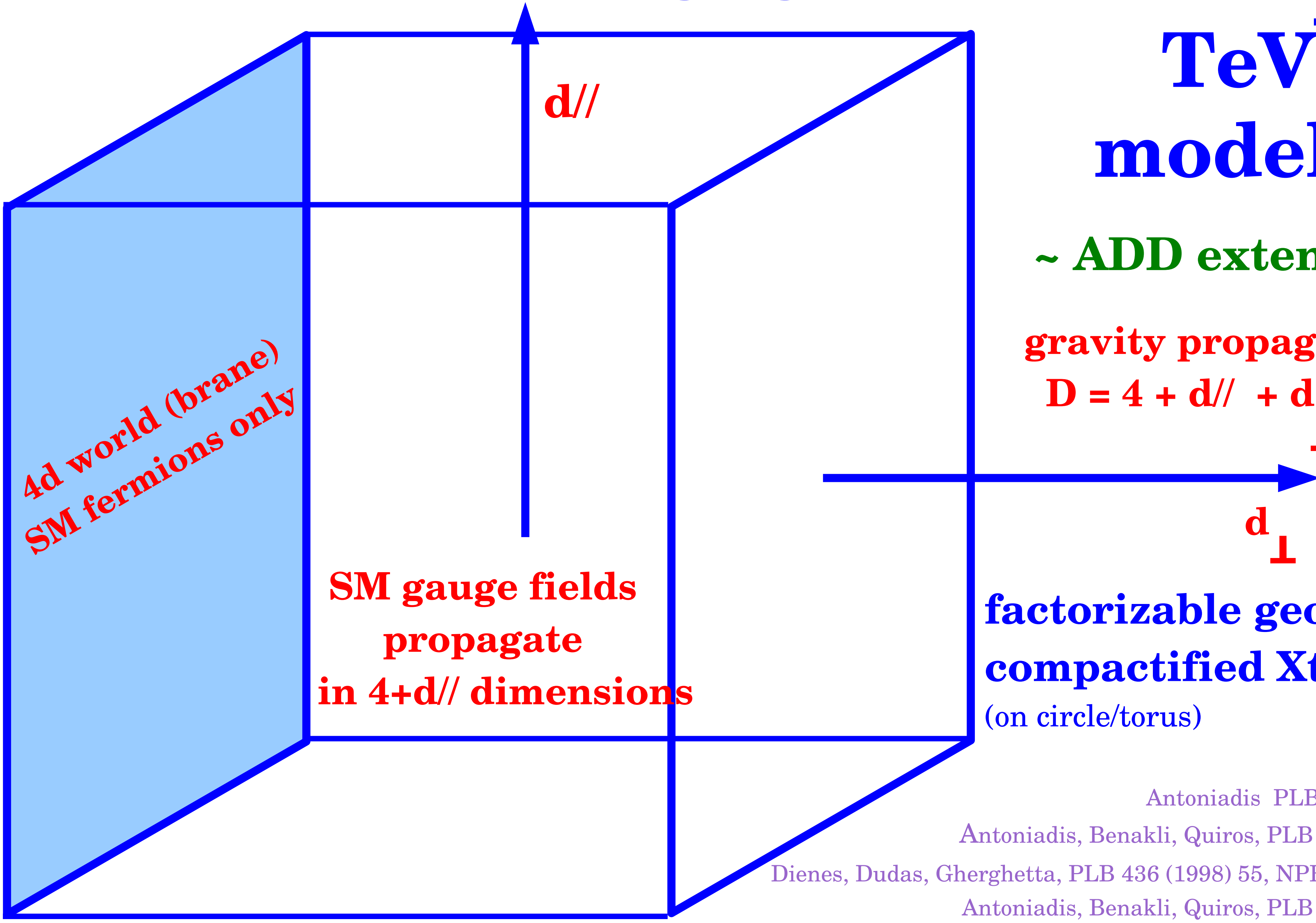


TEV^{-1} (KK gauge bosons)

TeV^{-1} models

~ ADD extension

gravity propagates in
D = 4 + d// + d$_\perp$ bulk



factorizable geometry
compactified Xtradim
(on circle/torus)

d// size: $R^{-1} \approx TeV \approx 10^{-19}\,m$

Antoniadis PLB246 (1990) 377
Antoniadis, Benakli, Quiros, PLB 331 (1994) 313
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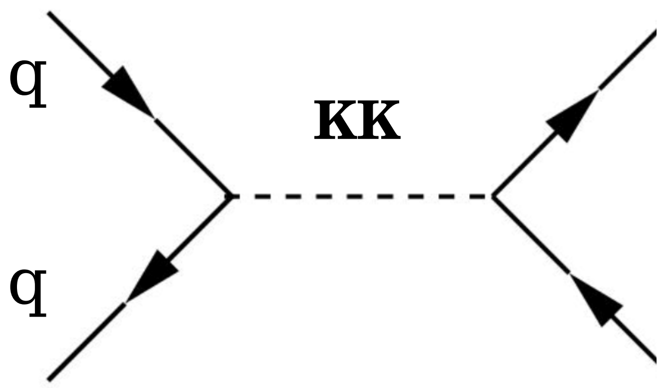
- gauge bosons in 'flat' 5D bulk with R = O (TEV^{-1}) extra dimension

- KK 0th mode identified with SM gauge bosons (can mix with non-zero modes)

- combined constraints from LEP, HERA, TEVATRON: $\mathbf{M_{KK} = R^{-1} > 6.8\ TeV}$
Cheung, Landsberg, PRD65, 076003

direct searches (before LHC): $\mathbf{M_{KK} > O\ (1\ TeV)}$

- **resonant production if** $M_{KK} < E_{CM}$
search for dilepton or dijet invariant mass peak
(or transverse mass jacobian peak from single lepton)
to look for the 1st mode at least
2nd, 3rd modes for KK pattern would be desirable



Coupling: finite at 5D, divergent for > 5D
but can regularized in specific approaches

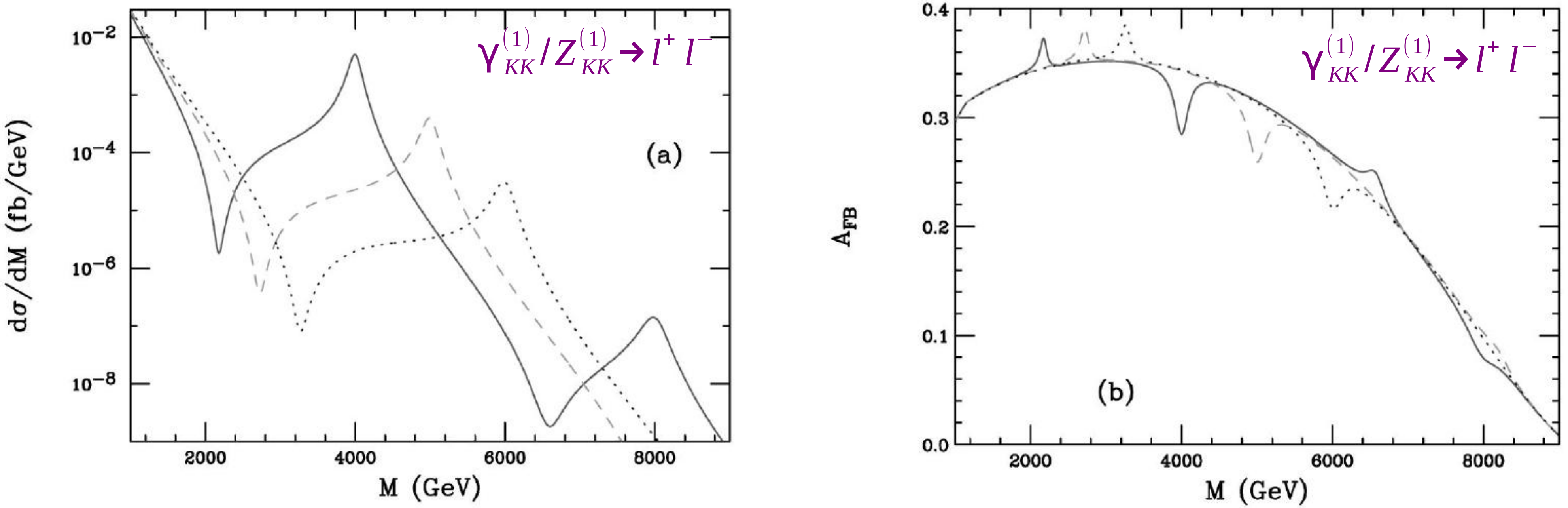
- **virtual effects (?) if** $M_{KK} > E_{CM}$

Xsection deviations, asymmetries

TEV^{-1} (KK gauge bosons)

naively, from normalization of gauge fields kinetic energy term → KK gauge bosons couple to SM fermions with a strength larger than the 0-mode by a universal factor of $\sqrt{2}$

example of 4, 5 and 6 TeV $\gamma_{KK}^{(1)}$ and $Z_{KK}^{(1)}$ (which are nearly degenerate in mass as well as with $W_{KK}^{(1)}$) production at the 14 TeV LHC (fermions in one 4D brane)



Rizzo,PRD61 (2000) 055005

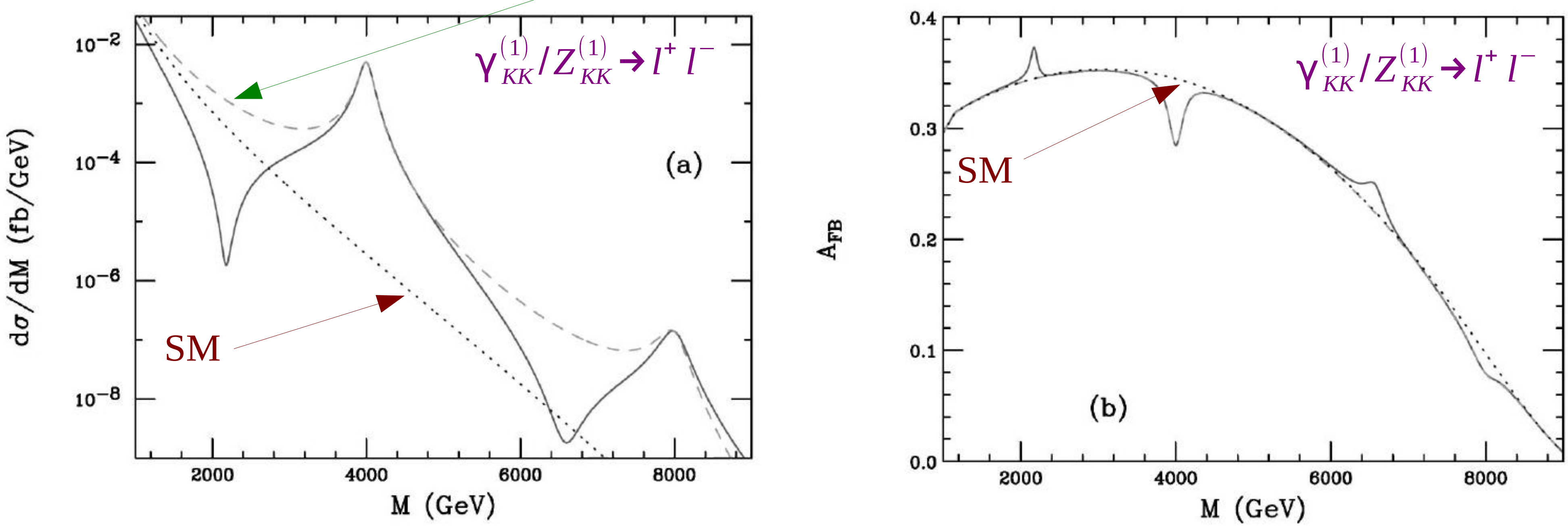
angular distributions to demonstrate that states are spin-1 (if enough statistics)

dips in the distributions → signal for KK scenarios ?

TEV^{-1} (KK gauge bosons)

dips in the distributions → signal for KK scenarios ?

may depend on fermion location → dips can disappear with different fermions assignments



Rizzo,PRD61 (2000) 055005

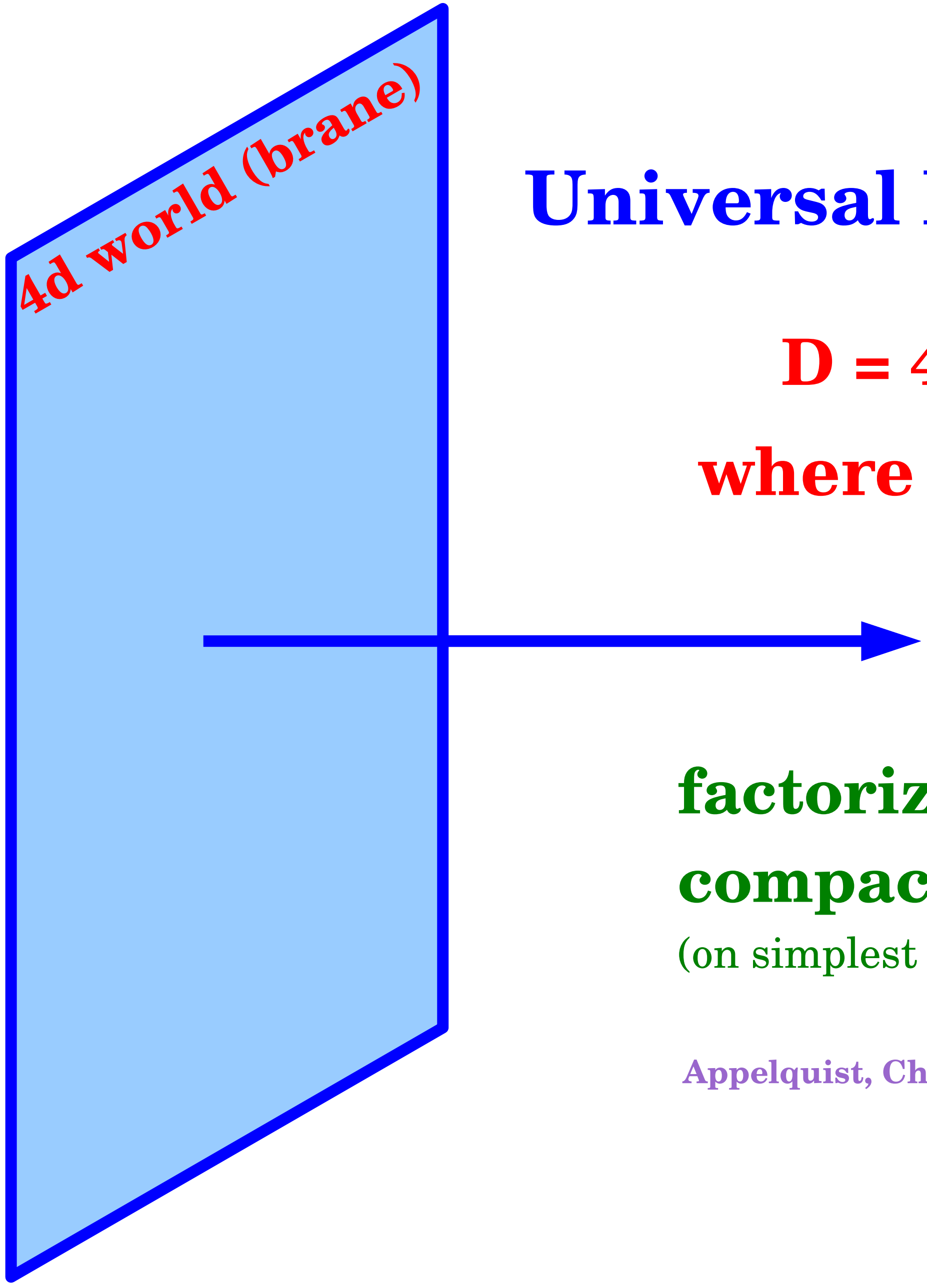
if access to second KK level kinematically difficult at LHC →

difficult to distinguish an ordinary Z' and degenerate $\gamma_{KK}^{()1}/Z_{KK}^{(1)}$

difficult to demonstrate the KK nature of the resonance at the LHC ?

way out with lepton collider even below the resonance (see later on) ?

which fields/particles and where ?



Universal Extra-Dimensions (UED)

D = 4 + n bulk (n=1 mostly)

where SM gauge AND fermion fields propagate

factorizable geometry

compactified extra-dimensions

(on simplest orbifold)

Appelquist, Cheng, Dobrescu, PRD64, 035002

Minimal Universal Extra Dimensions (mUED)

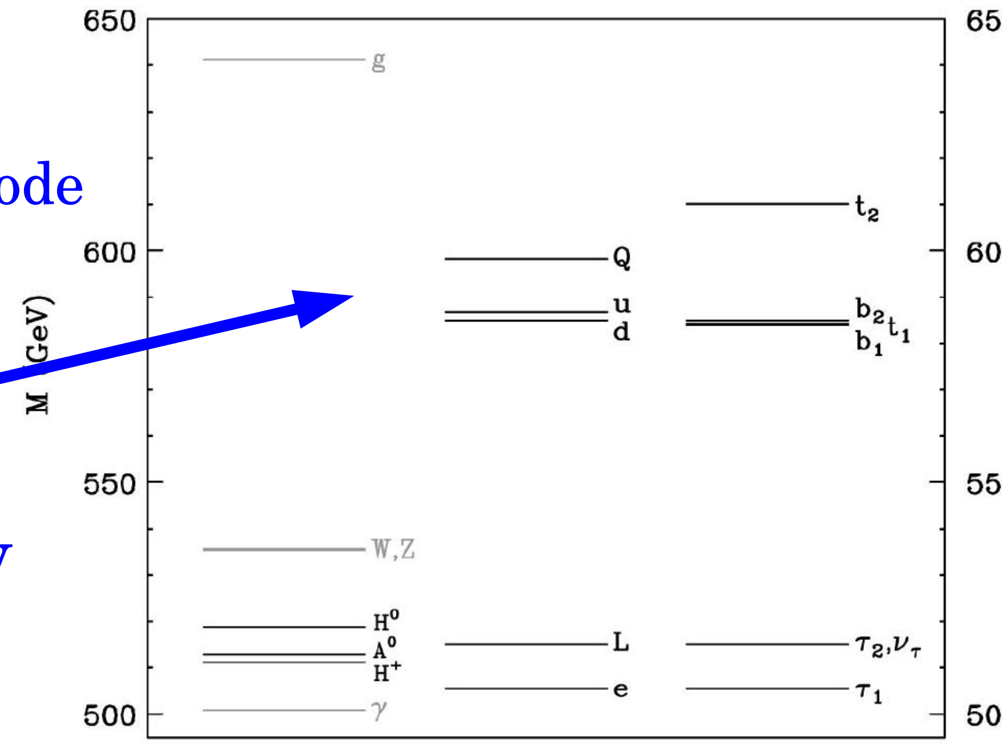
- all SM fields in a 5D bulk
  further extension of TeV^{-1}

- 4D SM particles identified to 0th KK mode

- 1^{st} (and beyond) KK modes are massive
  loop corrections involving bulk fields
  lead to non degenerate mass spectrum

- EW constraints ➜ M > 300 – 600 GeV

- momentum conservation in bulk
  ➜ KK-parity conservation
  ➜ pheno. similar to SUSY with conserved R-parity



Cheng, Matchev, Schmaltz PRD66, 056006

- **KK states produced in pairs**
- **1 KK + 1 SM in a KK state decay**
  possible cascade decays
- **stable LKP (DM candidate)**
  source of MET

Minimal UED

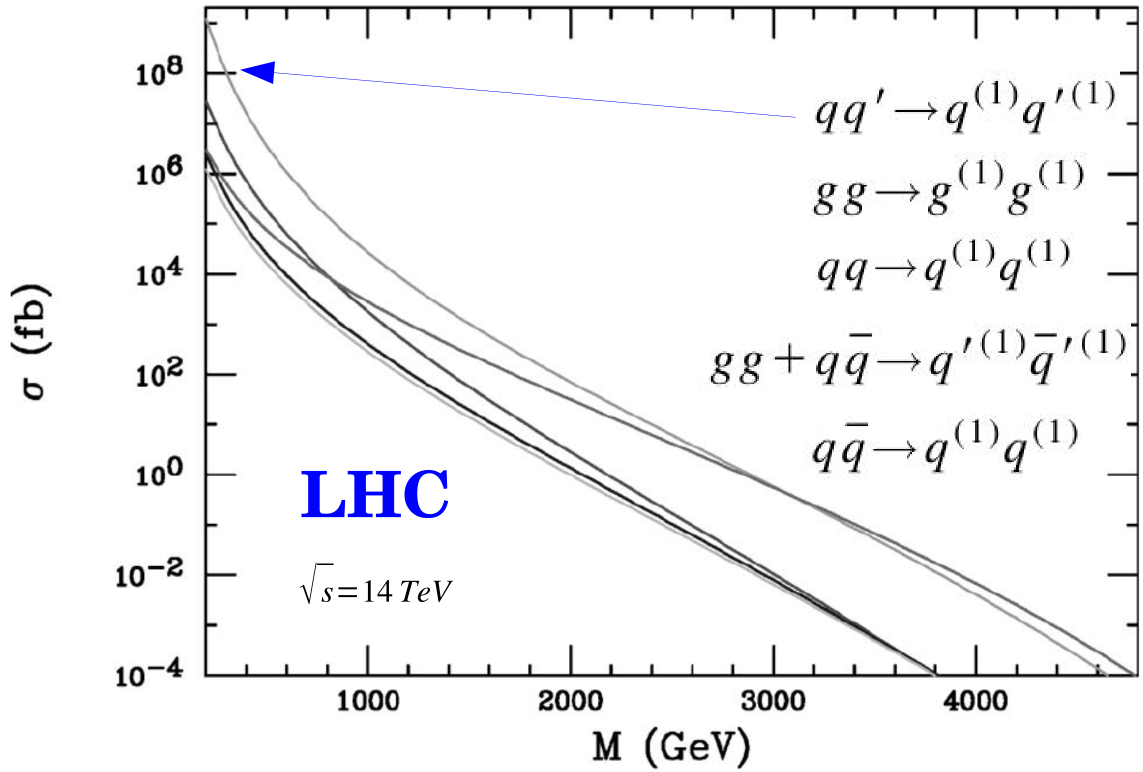
- pair production of lightest coloured KK states $\rightarrow$ largest Xsection

- possible signatures:

4 leptons + MET

3 (or 2 leptons ...) + jets + MET

2 (or more) jets + MET



Rizzo, PRD 64, 095010

Minimal UED

example of decay flow

$Br(g_1 \to Q_1 Q) \approx 0.5$

$Br(g_1 \to q_1 q) \approx 0.5$

$Br(q_1 \to q \gamma_1) \approx 1$

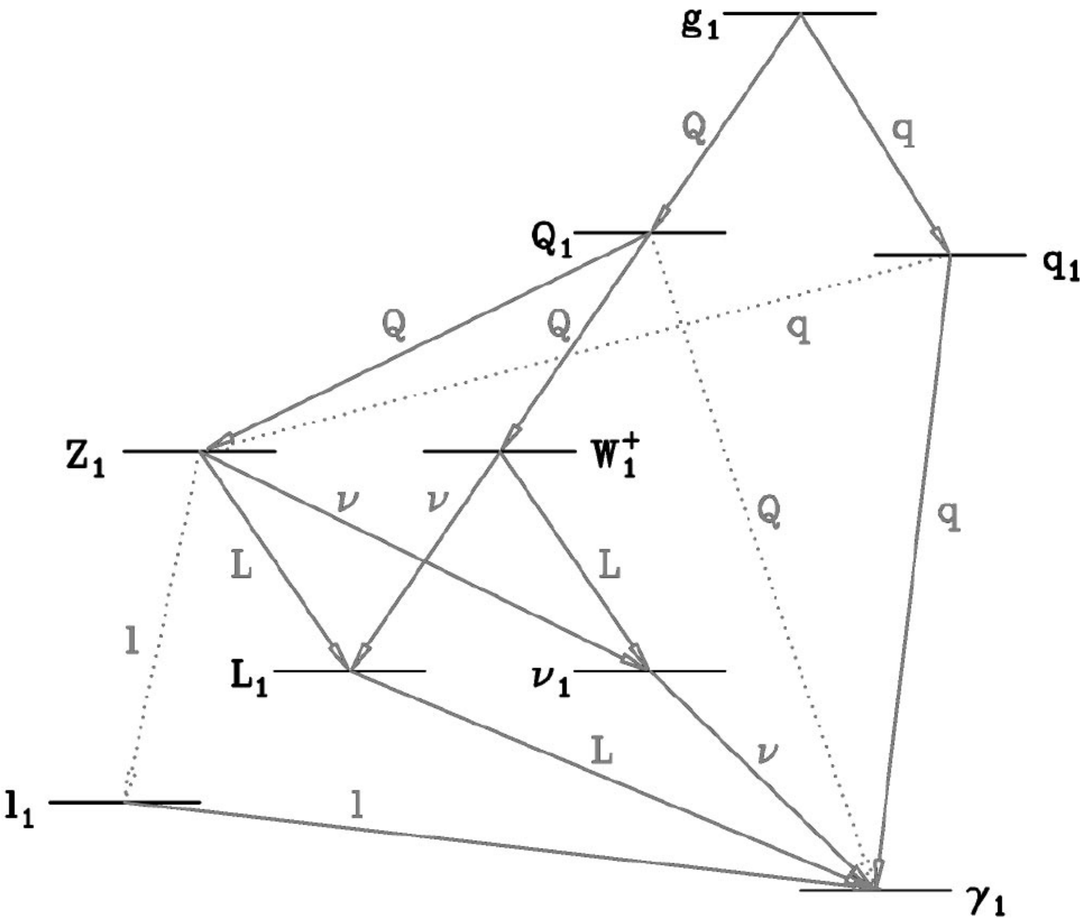
$Br(Q_1 \to Q Z_1 : W_1 : \gamma_1) \approx 0.33 : 0.65 : 0.02$

$Br(W_1 \to \nu L_1 : \nu_1 L) \approx 1/6 : 1/6$

$Br(Z_1 \to \nu \nu_1 : L L_1) \approx 1/6 : 1/6$

$Br(L_1 \to \gamma_1 L) \approx 1$

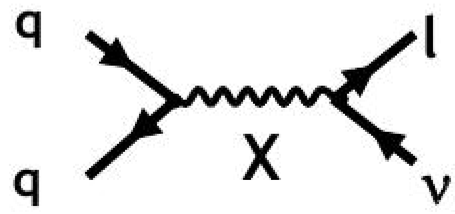
$Br(\nu_1 \to \gamma_1 \nu) \approx 1$



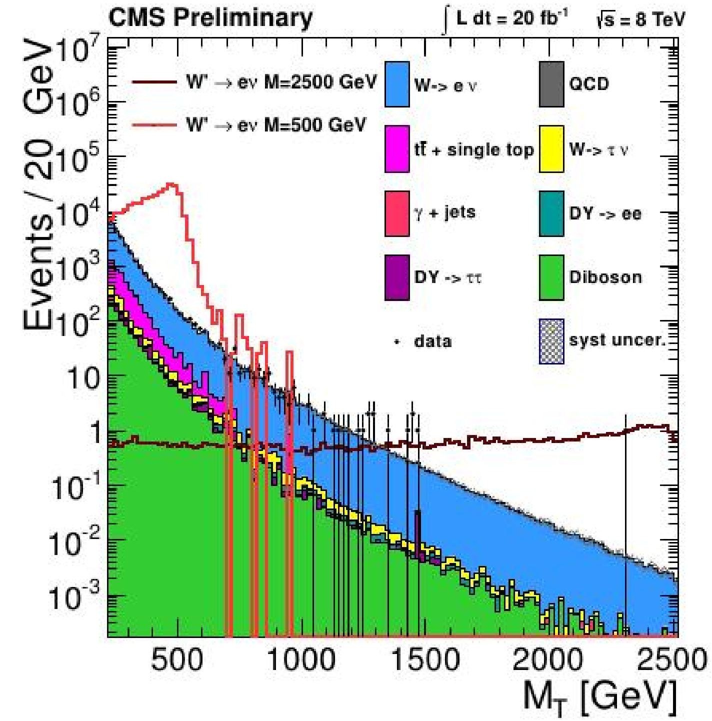
Cheng Matchev Schmaltz PRD66, 056006

Lepton + MET

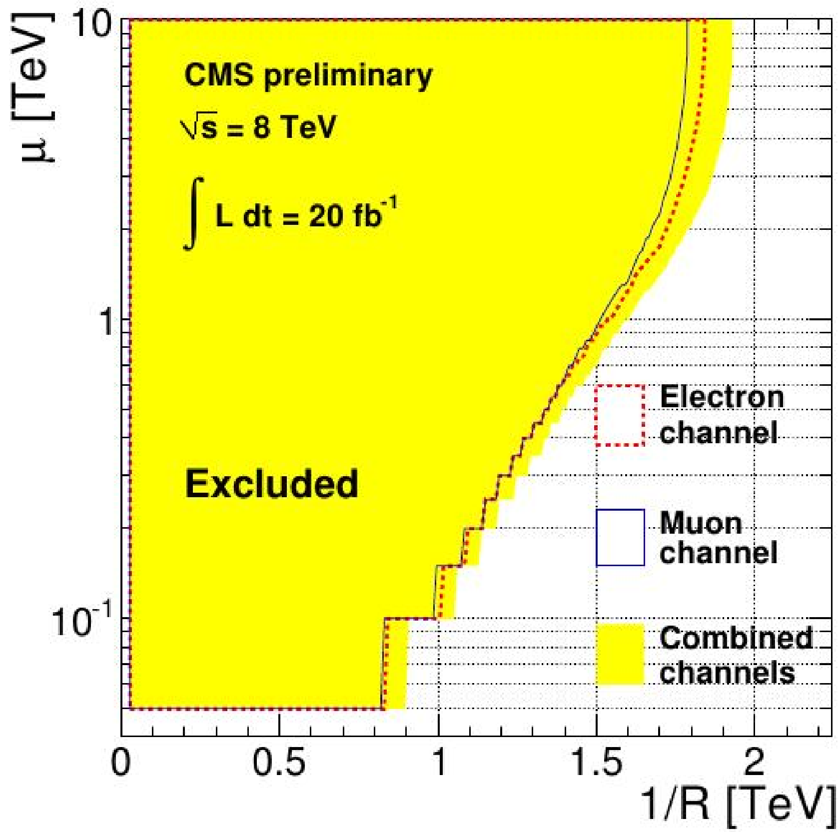
CMS-EXO-12-060

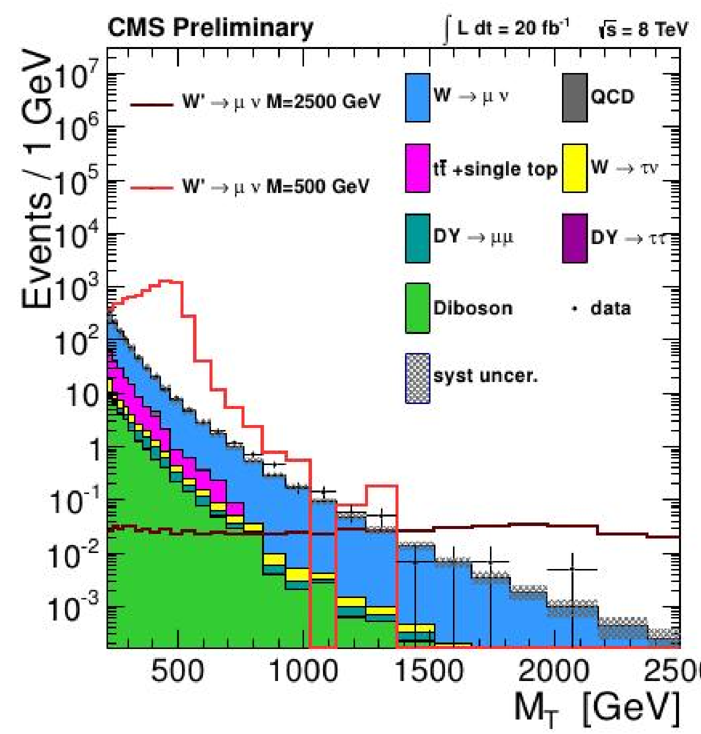


$$m_T = \sqrt{2\, p_T\, E_T^{miss}\left(1-\cos\theta_{l\nu}\right)}$$



(TeV-1, UED, Bulk RS)

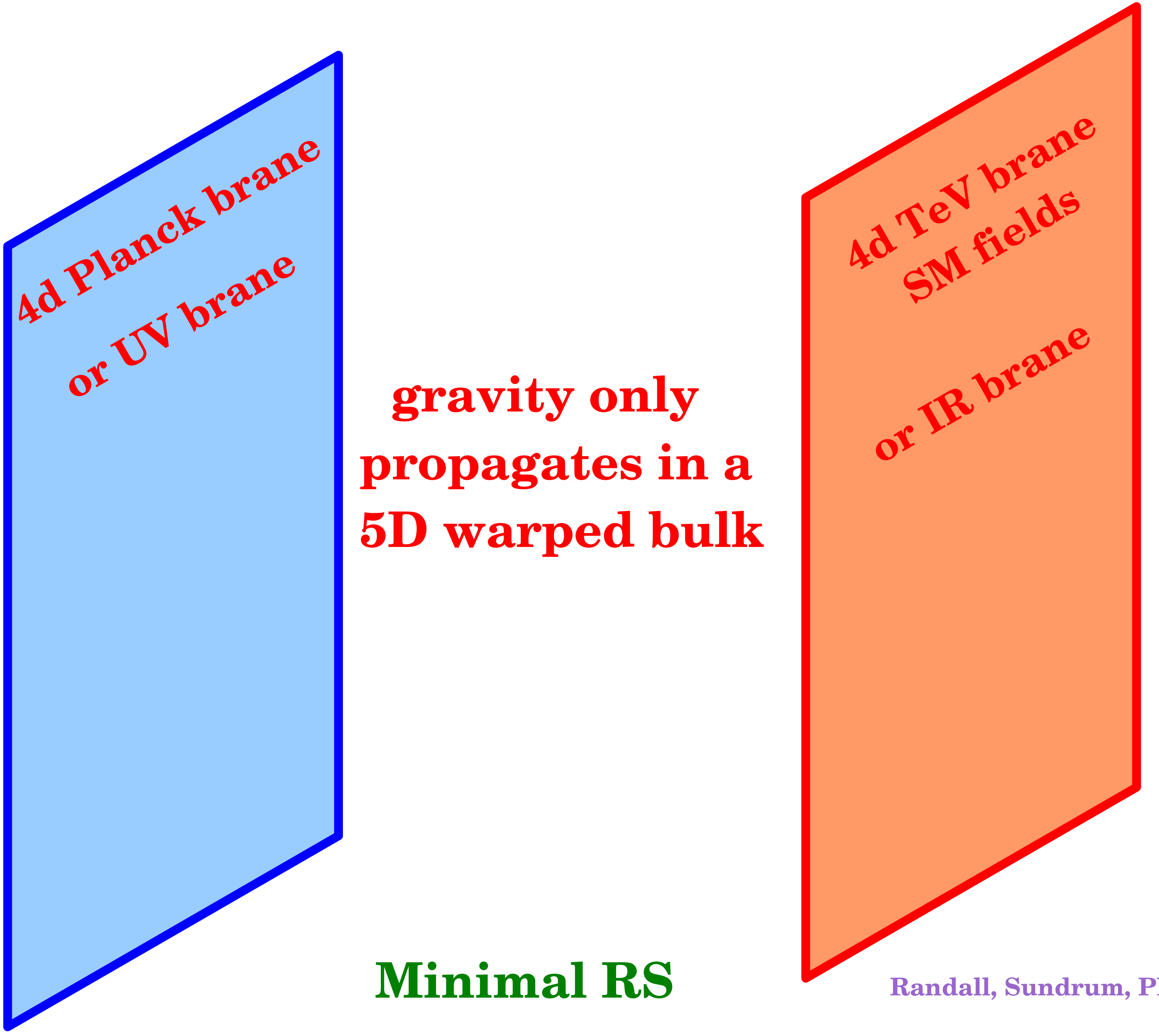




$m_{W_{KK}^{(1)}} >$ **1.7 TeV** ($\mu = 0.05$ TeV)

$m_{W_{KK}^{(1)}} >$ **3.7 TeV** ($\mu = 10$ TeV)

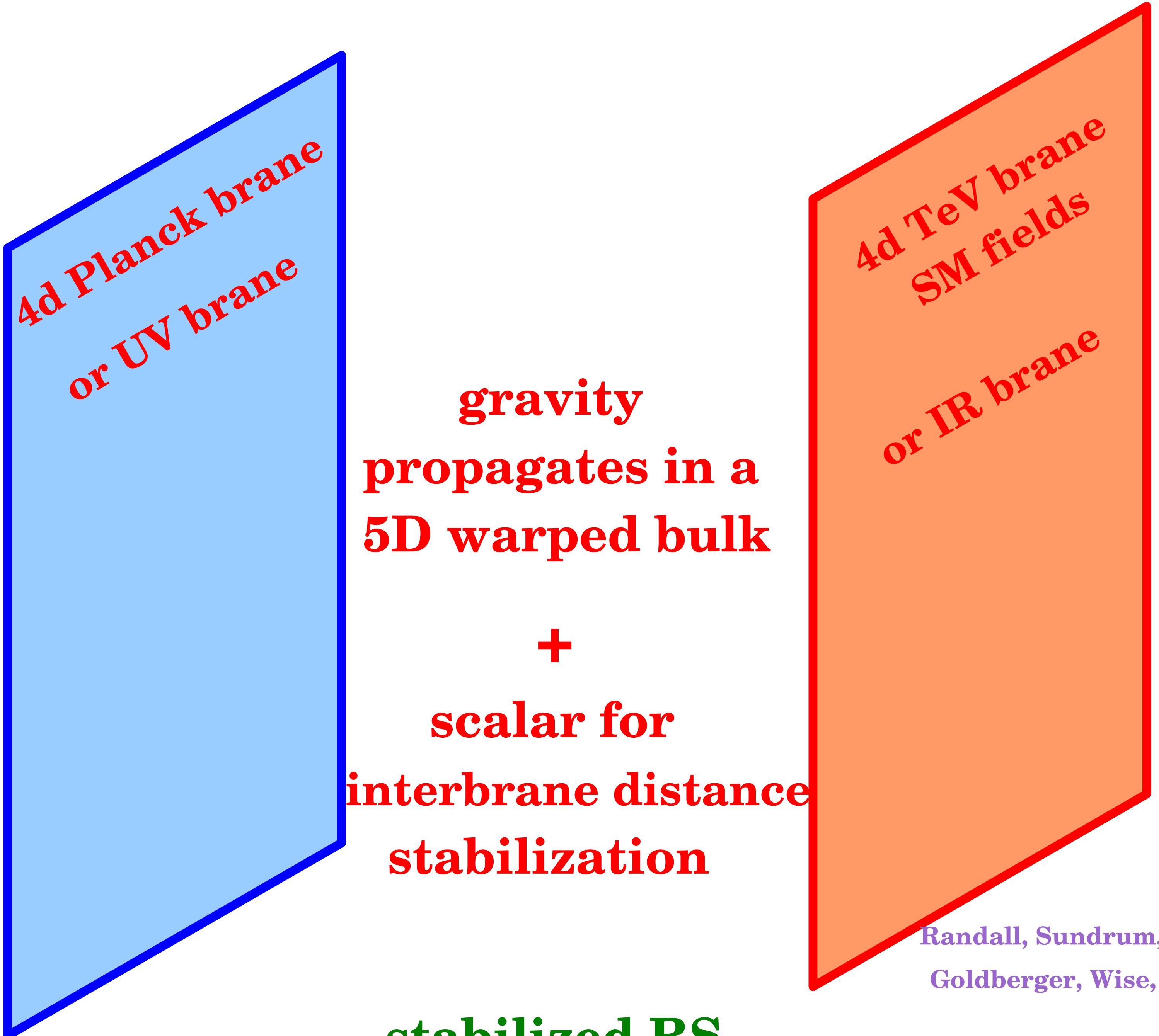
which fields/particles and where ?



Minimal RS

Randall, Sundrum, PRL 83 (1999) 3370

which fields/particles and where ?



stabilized RS

Randall, Sundrum, PRL 83 (1999) 3370

Goldberger, Wise, PRL 83 (1999) 4922,

PRD 60, 107505,

PBL 474 (2000) 275

Minimal RS

Randall, Sundrum, PRL 83 (1999) 3370

- **gravity only** in a 5D warped bulk (with 1 compact ED) and 2 4D branes

$$ds^2 = e^{-2kr_c\phi}(\eta_{\mu\nu}dx^\mu dx^\nu) + r_c d\phi^2 \qquad \phi \in [0,\pi] \qquad k \sim M_{Pl(4)}$$

- **warp factor** allows to generate TeV scale on one brane **(TeV Brane)** from Planck scale on the other brane **(Planck Brane)**

$$\Lambda_\pi = M_{Pl(4)} e^{-\pi k r_c} \rightarrow \Lambda_\pi \sim 1 \text{ TeV} \quad \text{for} \quad k r_c \sim 12 \quad r_c = 10^{-32} \text{ cm}$$

- **KK graviton** with O(TeV) spacing $m_n = k\, x_n e^{-k r_c \pi}$ x_n roots of Bessel function J_1

- **SM fields on TeV brane coupling to massive KK graviton** $\sim 1/\Lambda_\pi$

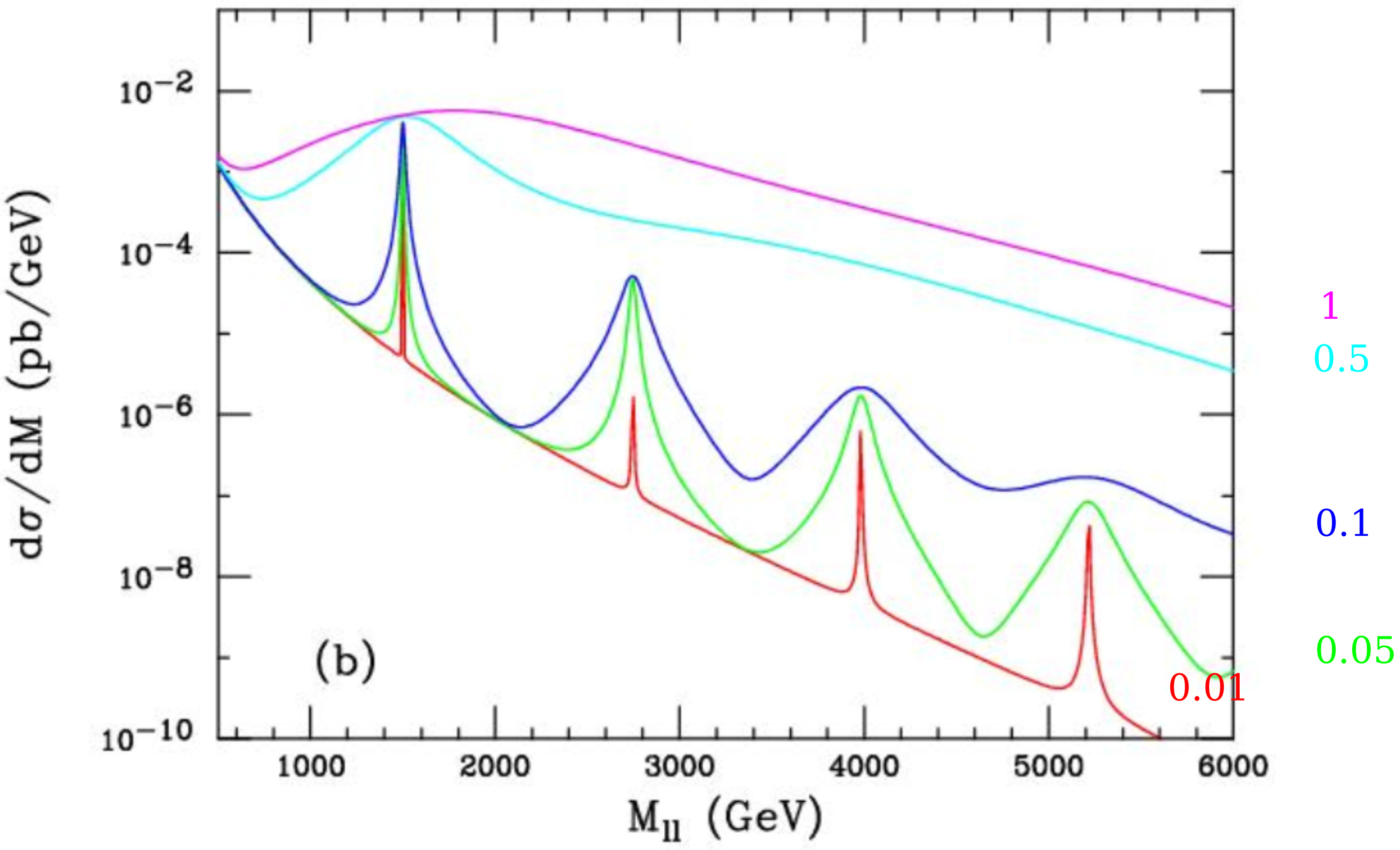
- phenomenology described by 2 parameters

m_1 mass of 1st mode, and $c = \dfrac{m_1}{x_1 \Lambda_\pi}$ $\qquad 0.01 < c < 0.1$ theoretically reasonable range

search for narrow resonances $pp \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, ZZ$

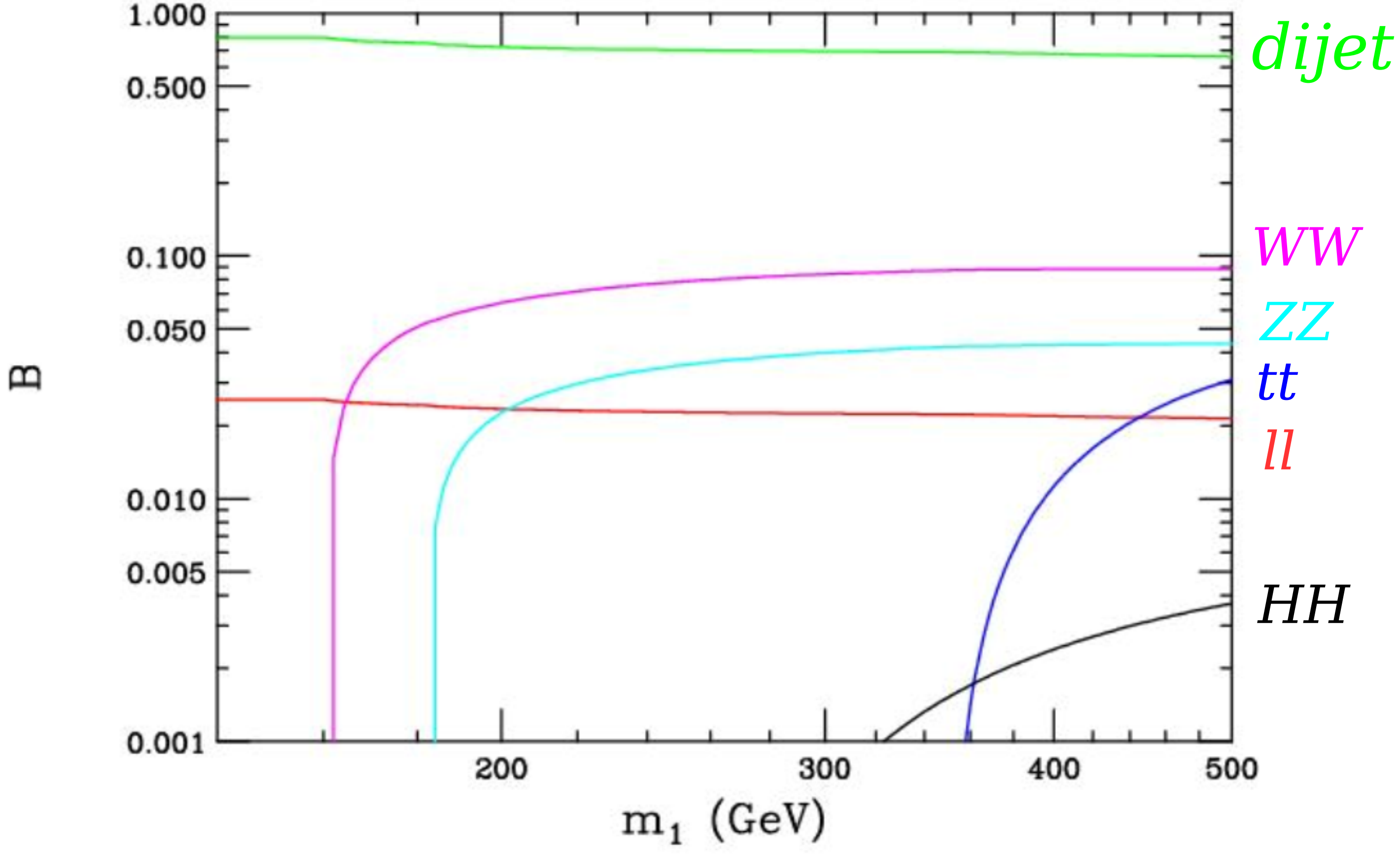
minimal RS

G_{KK} production at LHC for various c parameter



Davoudiasl, Hewett, Rizzo, PRD 63, 075004

Minimal RS: G_{KK} decays

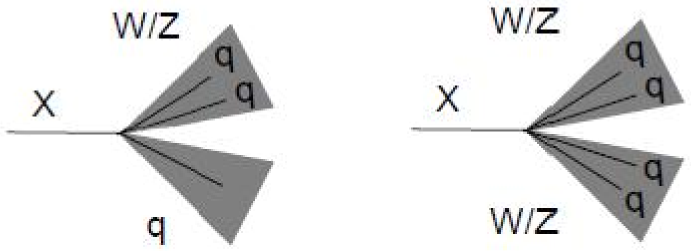


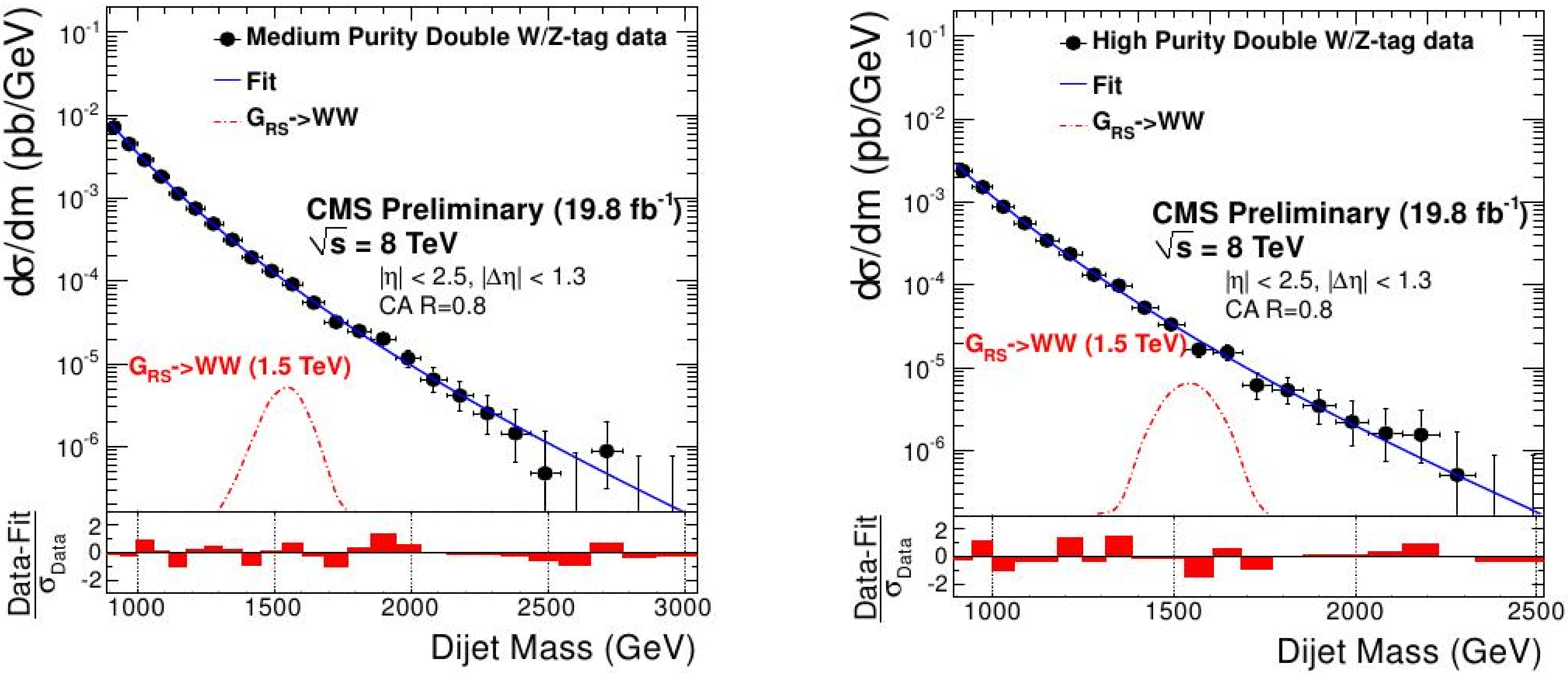
Davoudiasl, Hewett, Rizzo, PRD 63, 075004

resonant diboson (jets channel)

CMS-EXO-12-024, arXiv:1405.1994

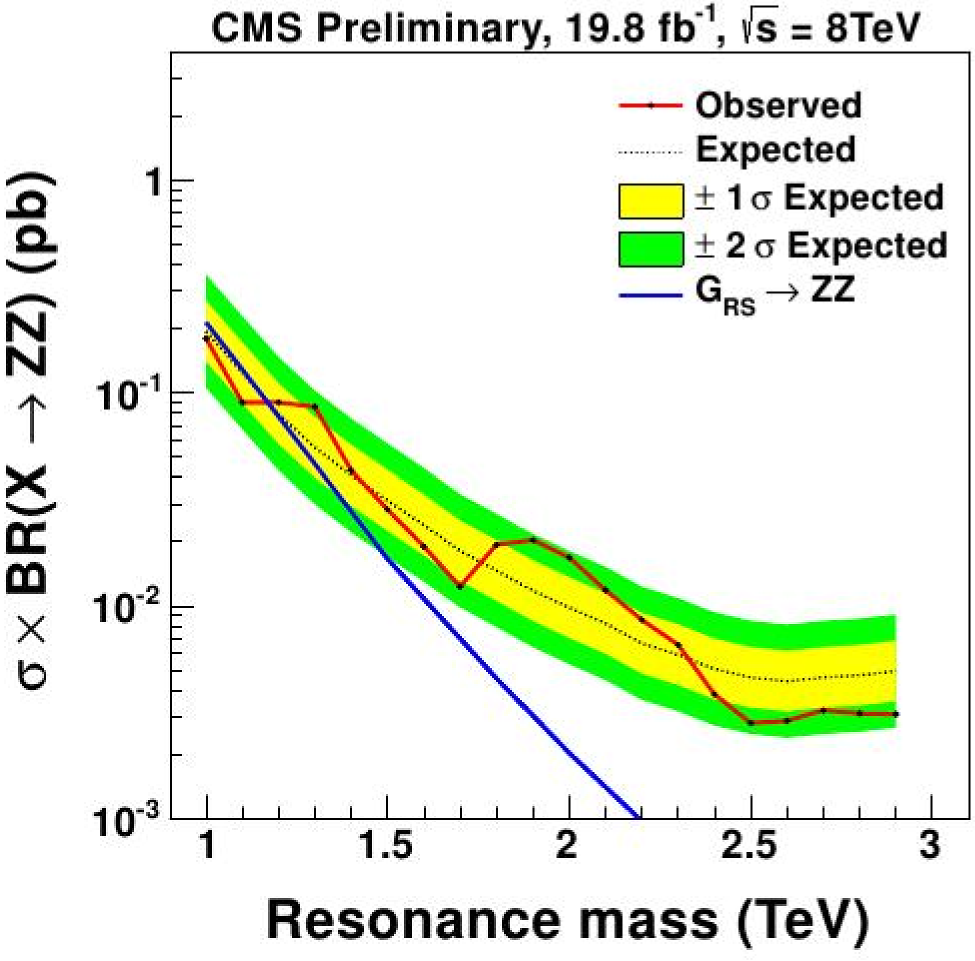
- 1 or 2 leading jet, **W/Z tagged**

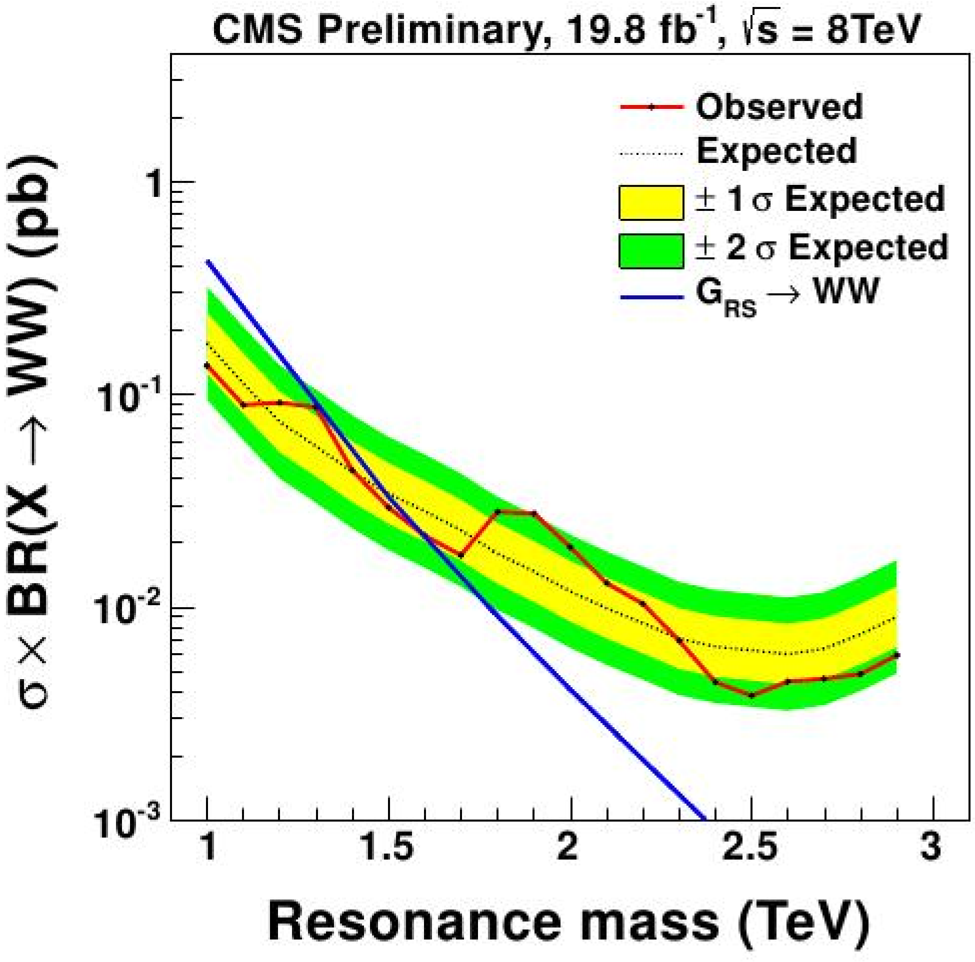




resonant diboson (jets channel)

CMS-EXO-12-024, arXiv:1405.1994





$m_{G_{KK}^{(1)}}$ **> 1.17 TeV** $(\tilde{k}=0.5)$

$m_{G_{KK}^{(1)}}$ **> 1.59 TeV** $(\tilde{k}=0.5)$

Stabilized RS

gravitational fluctuations around RS metric $ds^2 = e^{-2kr_c\phi}(\eta_{\mu\nu} dx^\mu dx^\nu) + r_c d\phi^2$

→ contain massless scalar mode (modulus) $r_c \to T(x)$: **the radion**

→ v.e.v stabilizing the interbrane distance $\langle T(x) \rangle = r_c$

(Goldberger Wise mechanism)
bulk scalar generating potential
can stabilize the modulus
at minimum of potential

radion must be massive to recover ordinary 4D Einstein gravity

in order to have $k r_c \approx 12$ **radion should be lighter than O(TeV) KK graviton**

radion likely the lightest state from RS models
radion couples directly to gluon and photon

possible Higgs-radion mixing (also in type I string)

parameterized by ξ with $|\xi| \approx O(1)$

Goldberger, Wise, PRL 83 (1999) 4922
Goldberger, Wise, PRD 60, 107505
Goldberger, Wise, PBL 474 (2000) 275
Csaki, Graesser, Randall, Terning, PRD 62 (2000) 045015
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stabilized RS

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Mahanta, Datta, PLB 483 (2000) 196
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Cheung, PRD 63, 056007
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Chaichian, Datta, Huitu, Yu, PLB 524 (2002) 161
Das, Mahanta, PLB 529 (2002) 253
Azuelos, Cavalli, Przysiezniak, Vacavant, Eur. Phys. J. Direct C4 (2002) 16
Csaki, Graesser, Kribs, PRD63, 065002
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Antoniadis, Sturani, NPB 631 (2002) 66
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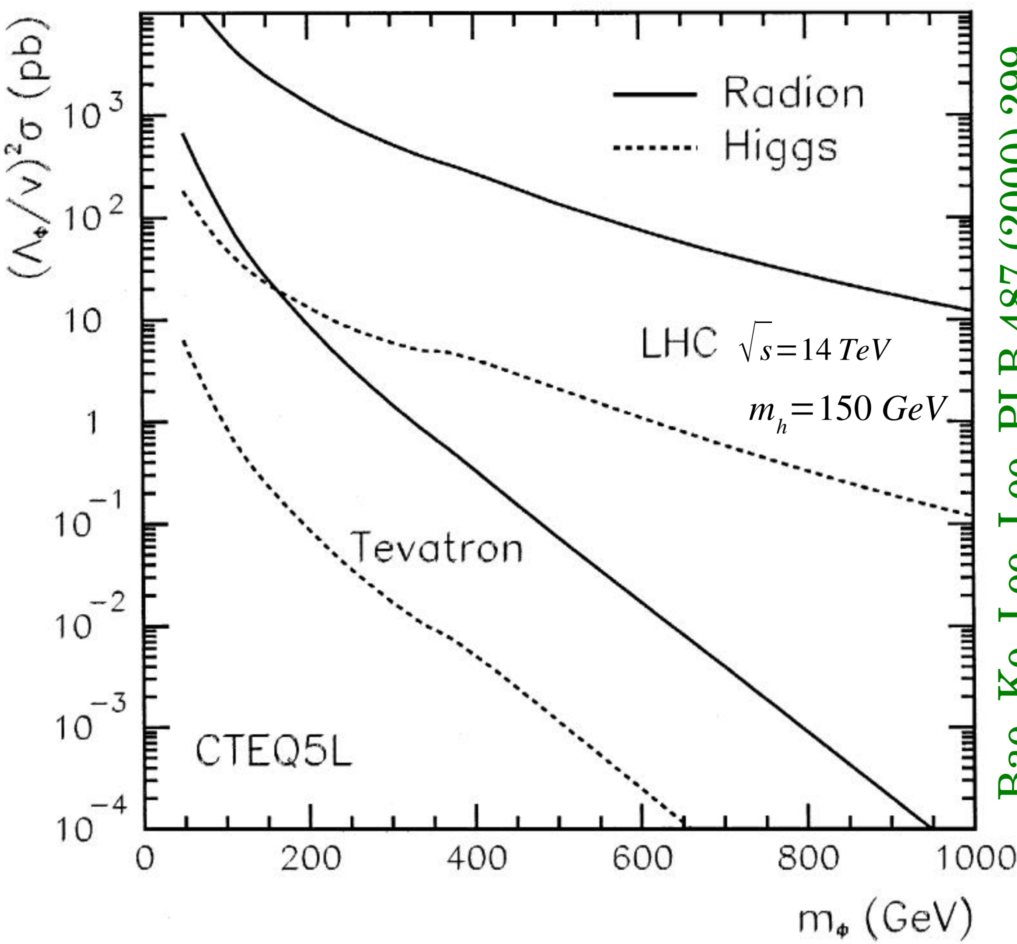
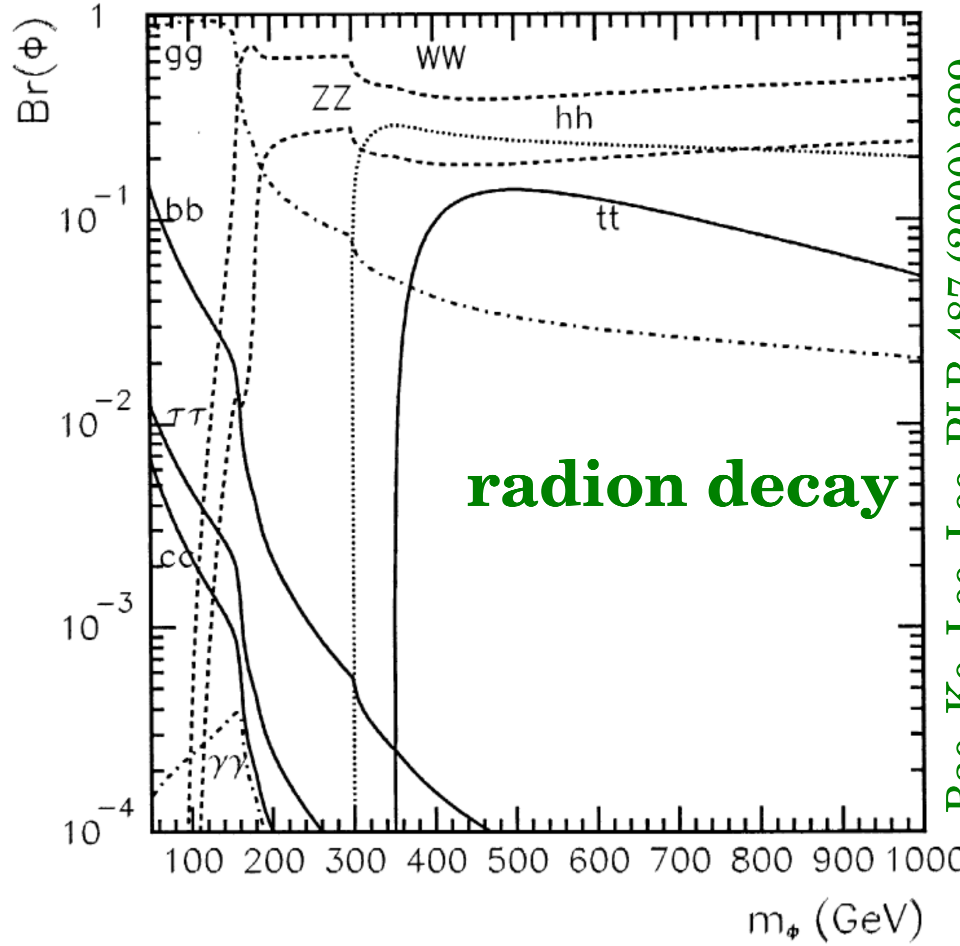
Hewett, Rizzo, JHEP, 08 (2003) 028
Battaglia, De Curtis, De Roeck, Dominici, Gunion, PLB 568 (2003), 92
Das, Mahanta, Mod. Phys. Lett. A19 (2004) 1855
Gunion, Toharia, Wells, PLB 585 (2004) 295
Cheung, Kim, Song, PRD69, 075011
Das, PRD 72,055009
Csaki, Hubisz, Lee, PRD 76,125005

radion production



Bae, Ko, Lee, Lee, PLB 487 (2000) 299

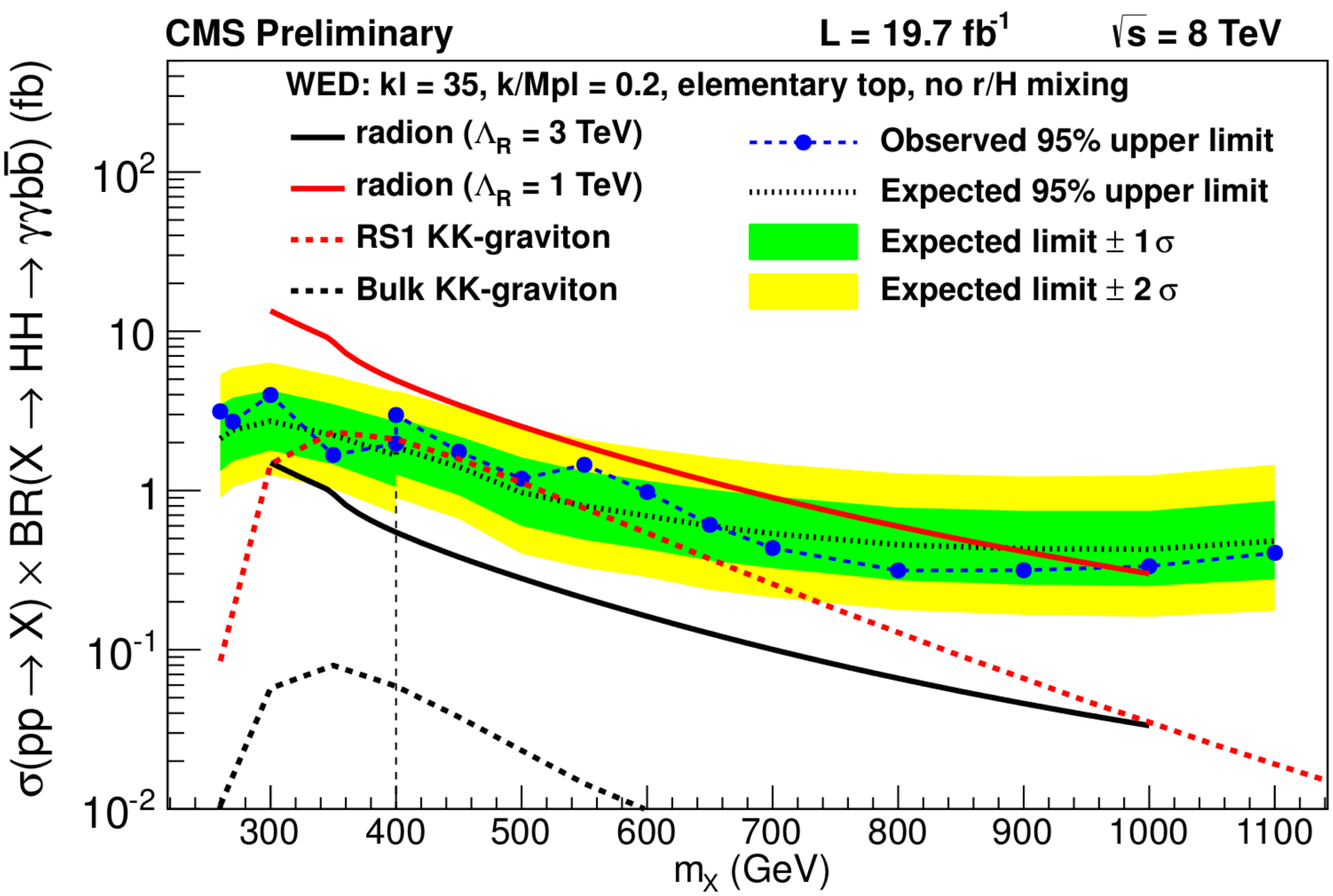
radion decay



Bae, Ko, Lee, Lee, PLB 487 (2000) 299

stabilized RS

CMS-PAS-HIG-13-032



radion with $\Lambda_R = 1$ TeV is observed (expected) to be excluded

with masses below 0.97 (0.88) TeV

Bulk RS models

- to solve hierarchy problem

→ only SM Higgs has to be localized on/near TeV Brane

- fermion and gauge fields allowed to propagate in the Xtra dim

- SM particles correspond to KK zero modes of 5D fields

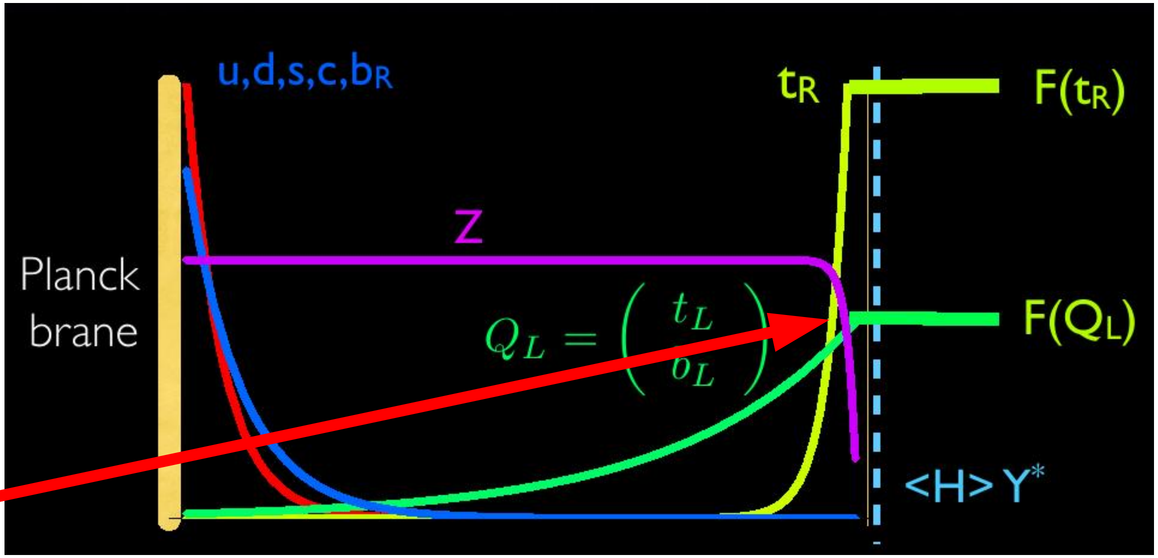
bulk profile of SM fermion depends on its 5D mass parameter

- choose to localize 1st and 2nd generation fermions near Planck brane

→ FCNC from higher dim operator suppressed by scales >> TeV

→ SM Yukawa coupling hierarchies

1st and 2nd generation small Yuk. coup. with Higgs localized near TeV brane



top quark can be localized near TeV brane to account for its large Yukawa coupling

from Weiler's talk at GDR Terascale(http://terascale.in2p3.fr)
http://indico.in2p3.fr/conferenceDisplay.py?confId=1617

constraints on Bulk RS models

from:

- **EW precision data** via Oblique parameters S T U
- **FCNC (K physics, CPV, B physics, rare decays)**
- $Z \rightarrow b_L b_L$ i.e. (t_L, b_L) not too close to TeV brane

and with various symmetries in the bulk

- larger bulk gauge symmetry i.e. $SU(2)_L \times SU(2)_R \times U(1)_X$, $SO(5) \times U(1)$, ...
- flavor symmetries

→ **KK gauge mass > 3 TeV**

→ **KK graviton mass > 2 - 4 TeV** dependent on specific models

w/o fermions in bulk and bulk symmetry > 23 TeV

→ **Fermionic excitations > 1 – 2 TeV**

Additional SU(2) doublet **states with exotic charge** (5/3) **0.5 – 0.8 TeV**

constraints on Bulk RS models

from:

- **EW precision data** via Oblique parameters S T U
- **FCN** ... **cays)**

- $(=\sqrt{6}$

and w

- large
- flavo

Delgado, Pomarol, Quiros, JHEP (2000) 030
Huber, NPB 666 (2003) 269
Burdman, PLB 590 (2004) 86
Agashe, Perez, Soni PRL 93 (2004) 201804, PRD71, 016002
Moreau, Silva-Marcos, JHEP 03 (2006) 090
Agashe, Contino, NPB 742 (2006) 59
Cacciapaglia,Csaki, Galloway, Marandella, Terning, Weiler, JHEP 04 (2008) 006
Casagrande, Goertz, Haisch, Neubert, Pfoh, JHEP 10 (2008) 094
Santiago, JHEP 12 (2008) 046
Csaki, Falkowski, Weiler, JHEP 09 (2008)008
Fitzpatrick, Perez, Randall, PRL 100 (2008) 171604
Bouchart, Moreau, NPB 810 (2009) 66
Blanke, Buras, Duling, Gori, Weiler, JHEP03 (2009) 001
Blanke, Buras, Duling, Gemmler, Gori, JHEP 03 (2009) 108
Csaki, Perez, Surujon, Weiler, arXiv:0907.0474
Bauer, Casagrande, Grunder, Haisch, Neubert, PRD79, 076001
Csaki, Falkowski, Weiler, PRD 80, 016001
....

Flavour physics constraints striking hard →
huge activity in RS flavor models development

→

→ pendent on specific models

→

Additional SU(2) doublet **states with exotic charge** (5/3) **0.5 – 0.8 TeV**

Bulk RS models signatures

- KK graviton

$$g\,g \rightarrow G \rightarrow t\,\bar{t}$$

$$g\,g \rightarrow G \rightarrow W_L W_L \rightarrow l\,\nu\,j\,j$$

$$g\,g \rightarrow G \rightarrow W_L W_L \rightarrow e^{\pm}\,\mu^{\mp}\,2\nu$$

$$g\,g \rightarrow G \rightarrow Z_L Z_L \rightarrow 4\,l$$

- KK Gluon

$$pp \rightarrow g^{(1)} \rightarrow t\,\bar{t}$$

- KK EW neutral gauge boson

$$p\,p \rightarrow Z' \rightarrow W\,W \rightarrow 2\,l\,2\,\nu$$
$$\rightarrow l\,\nu\,j\,j$$

- KK EW charged gauge boson

$$pp \rightarrow W' \rightarrow t\,\bar{b} \rightarrow W\,\bar{b}\,b \rightarrow l\,\nu\,\bar{b}\,b$$

$$pp \rightarrow W'^{+} \rightarrow W^{+}\,h$$

- KK fermions (e.g.)

$$pp \rightarrow g + g^{(1)} \rightarrow t^{(1)}\bar{t}^{(1)} \rightarrow W^{+}\,b\,W^{-}\,\bar{b} \rightarrow l^{-}\,\nu\,b\,\bar{b}\,jj\,(l=e,\mu)$$

Davoudiasl, Hewett, Rizzo, PLB 473 (2000) 43
Grossman, Neubert, PLB474 (2000) 361
Pomarol, PLB 486 (2000) 153
Chang, Hisano, Okada, Yamaguchi, PRD62, 084025
Randall, Schwartz, JHEP 11 (2001) 003
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Csaki, Erlich, Terning, PRD66 (2002) 064021
Hewett, Petriello, Rizzo, JHEP 09 (2002) 030
Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050
Carena, Delgado, Ponton, Tait, Wagner, PRD68, 035010, PRD71, 015010
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006
Skiba, Tucker-Smith, PRD75, 115010
Aguilar-Saavedra, PLB 625 (2005) 234, PLB 633 (2006) 792
Agashe, Contino, Darold, Pomarol, PLB 641 (2006) 62
Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006
Holdom, JHEP 03 (2007) 063
Antipin, Atwood, Soni, PLB 666 (2008) 155
Antipin, Soni, JHEP10 (2008) 018
Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350
Baur, Orr, PRD 77, 114001
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, PRD76, 115015
Djouadi, Moreau, Singh, NPB 797 (2008) 1
Contino Servant, JHEP 06 (2008) 026
Antipin, Tuominen, PRD 79, 075011
Aguilar, Aguilar-Saavedra, Moretti, Piccinini, Pittau, Treccani, arXiv:0912.3799

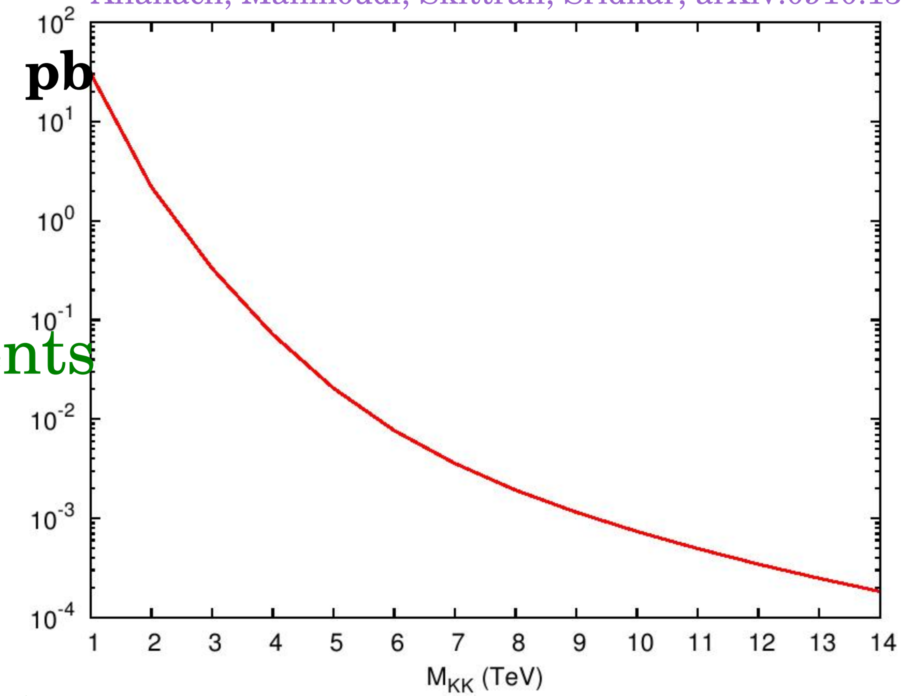
Bulk RS models

KK gluon

Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Baur, Orr, PRD 77, 114001
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

$g^{(1)}$ production suppressed

→ small coupling to proton constituents

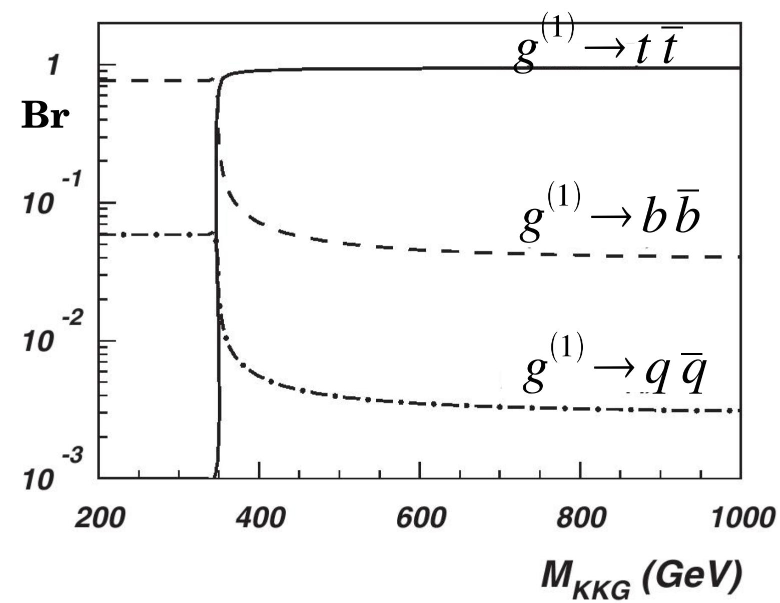


fermionic decay dominated by top quark

bias towards RH top

a heavy KK gluon is broad

above 1 TeV   width ~ M_{KK} / 6

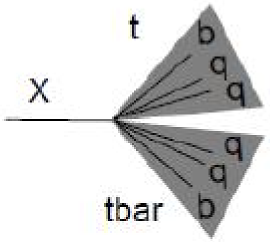


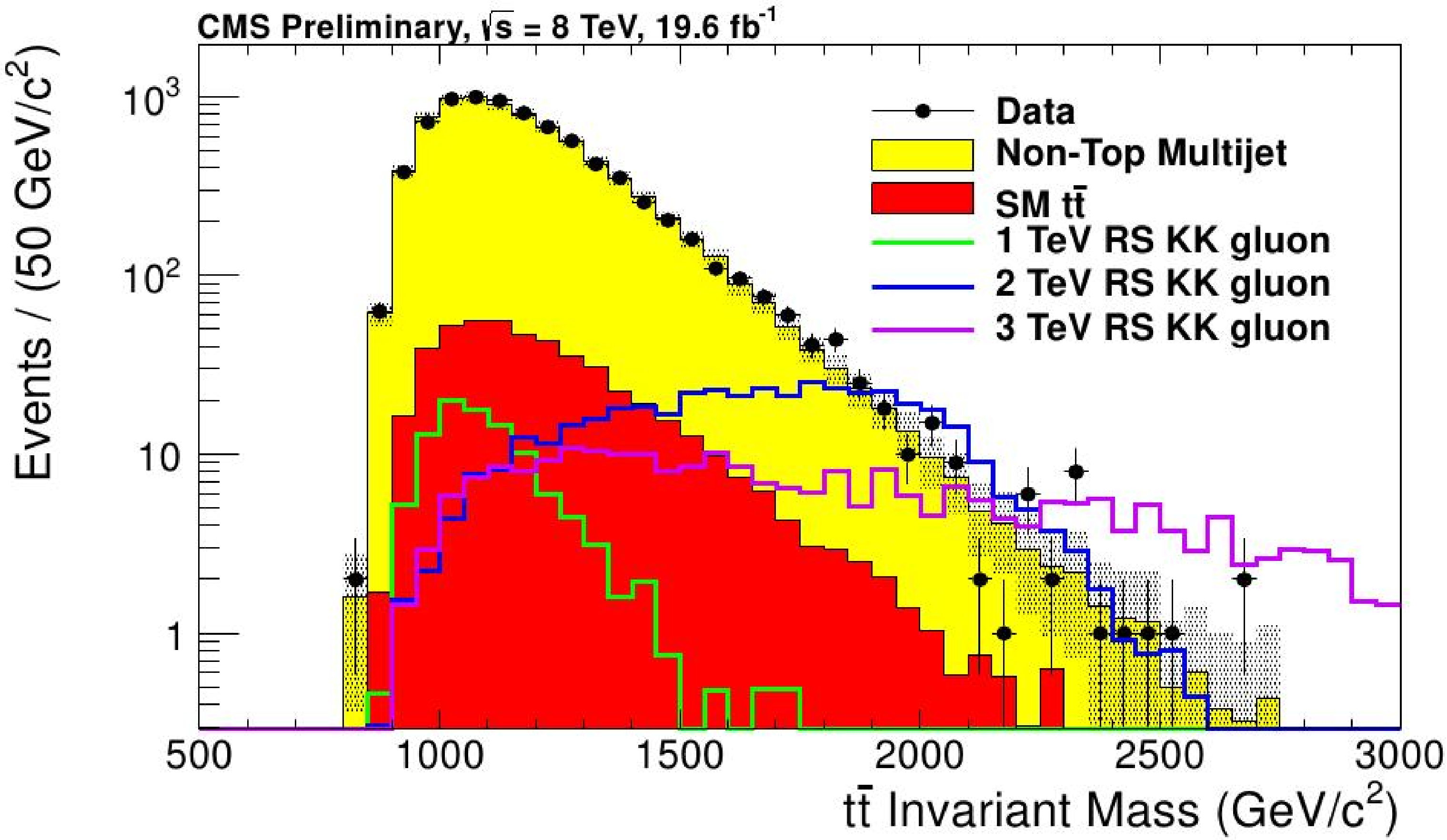
hadronic $t\bar{t}$

CMS-B2G-12-005

- look at hadronically decaying boosted top quarks

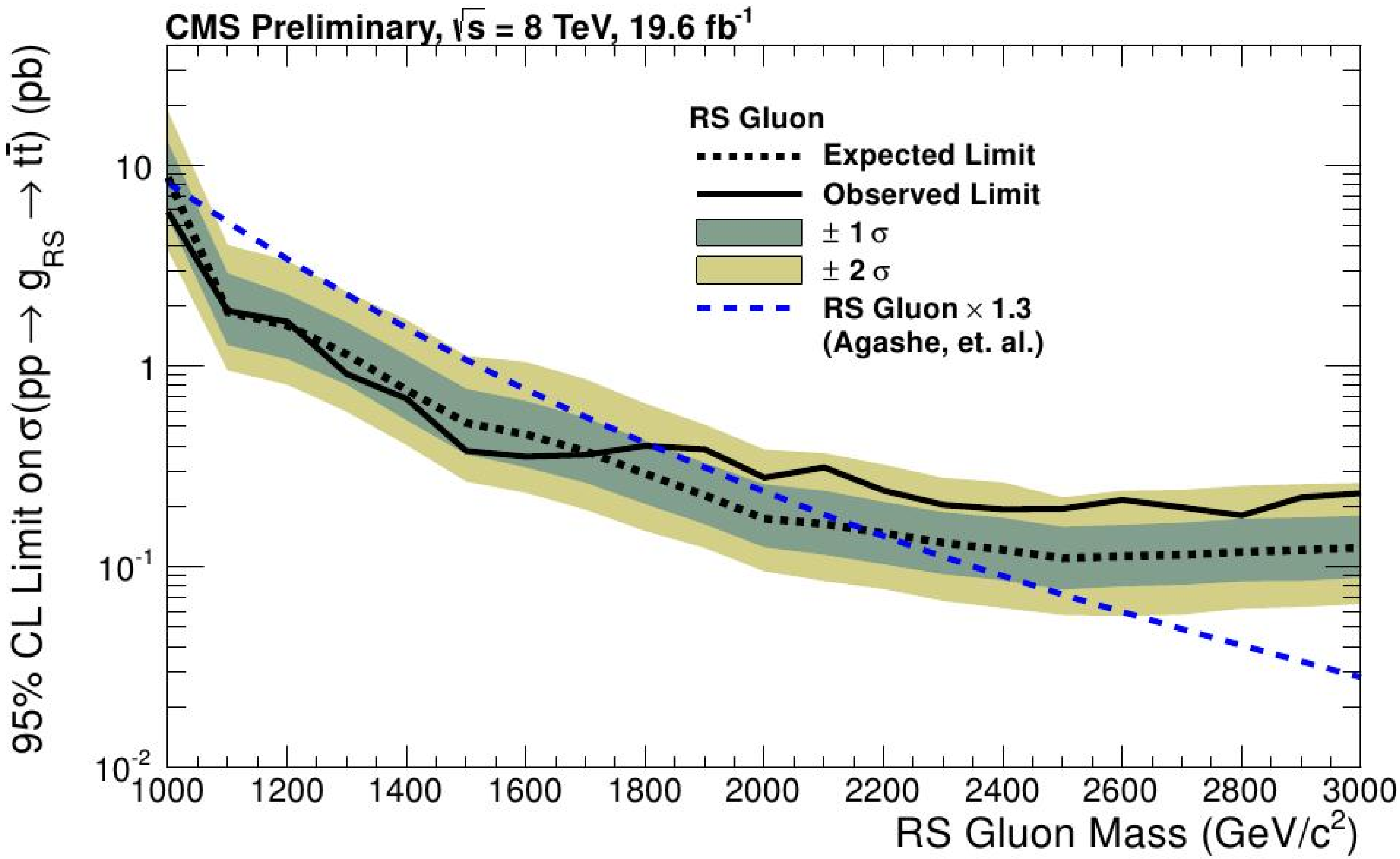
- use a (boosted) top tagging algorithm





hadronic $t\bar{t}$

CMS-B2G-12-005



obtain constraint on KK gluon mass $m_{g_{KK}^{(1)}} > 1.8$ **TeV**

BACKUP

ADD Formalism issues

- Hewett

interference (sign and n dependence undetermined)

$$\pm\lambda / M_S^4 \quad \text{with} \quad \lambda \text{ conventionally} \quad \lambda = \pm 1$$

- Giudice Rattazzi Wells

interference (sign fixed and n dependence undetermined) $\sim 1/\Lambda_T^4$

- Han Lykken Zhang

interference (sign fixed) F / M_{HLZ}^4

$$F = \log \frac{M_{HLZ}^2}{s} \qquad n=2$$

$$F = \frac{2}{n-2} \qquad n>2$$

- conversion rules

$$M_s[Hewett\ \lambda=+1] = [\frac{2}{\pi}]^{\frac{1}{4}} \Lambda_T(GRW)$$

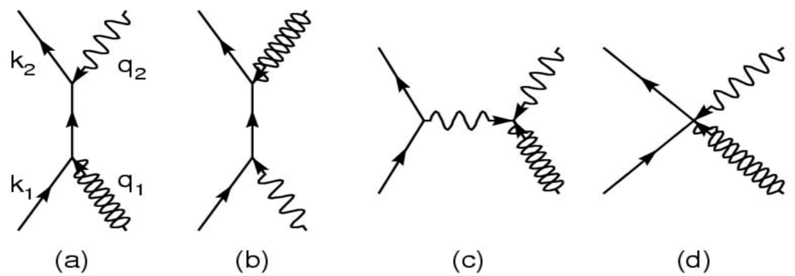
$$\frac{\lambda}{M_S^4(Hewett)} = \frac{\pi}{2} \frac{F}{M_{HLZ}^4}$$

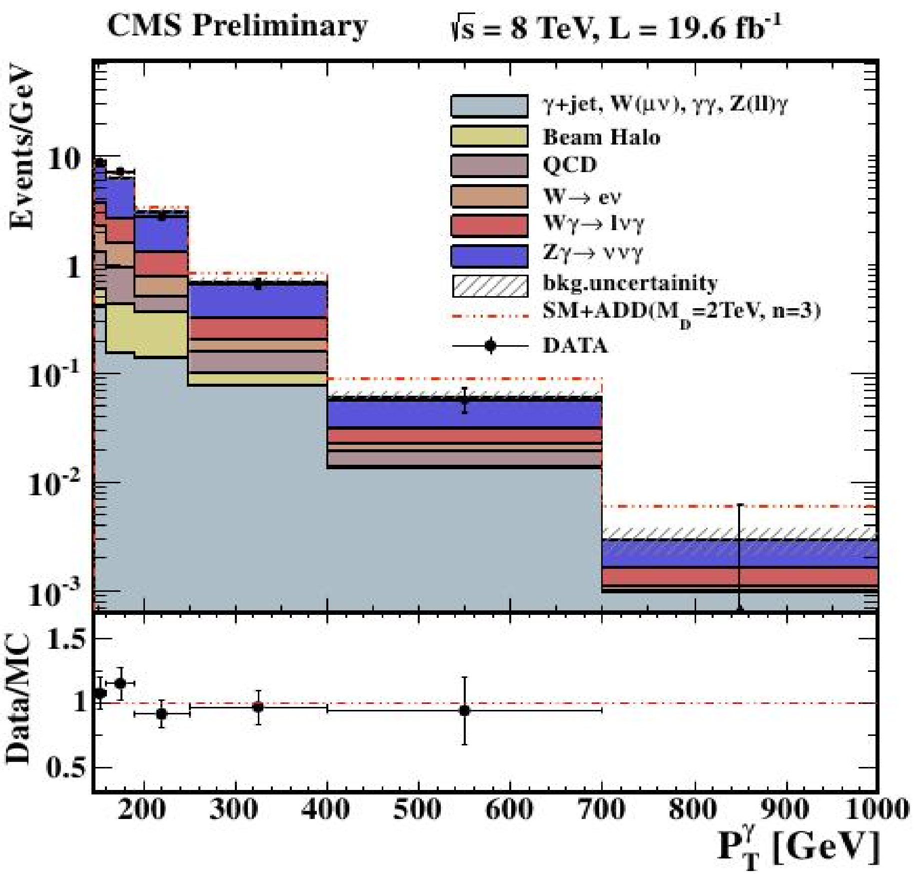
$$\frac{1}{\Lambda^4(GRW)} = \frac{F}{M_{HLZ}^4}$$

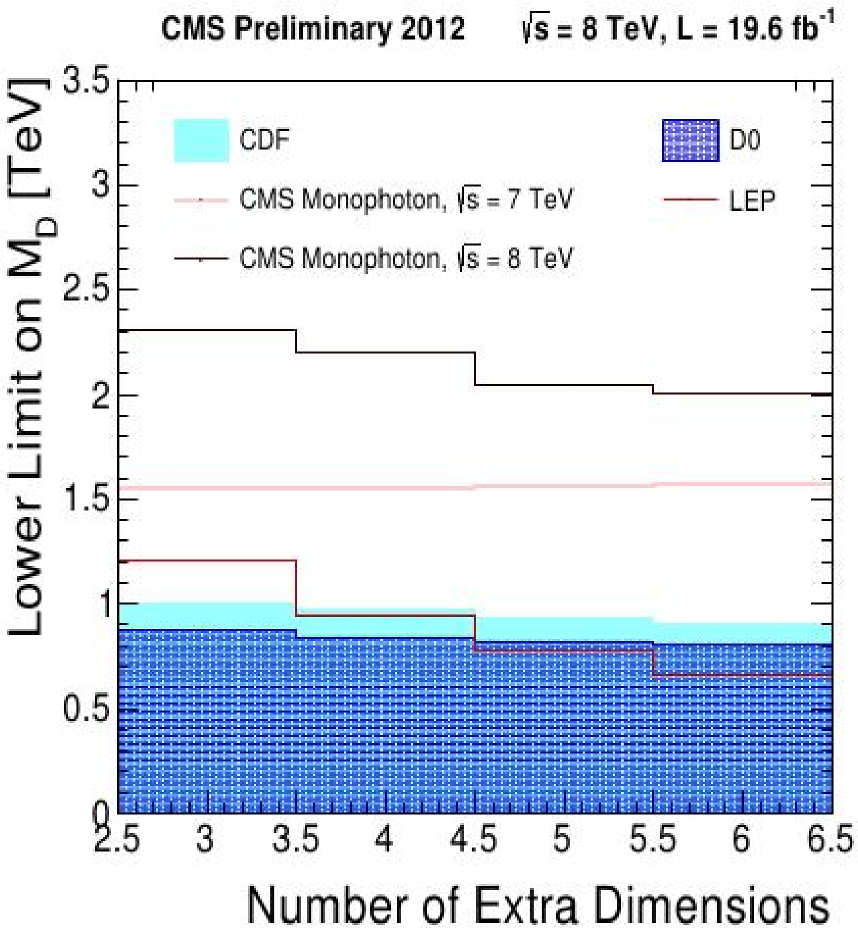
Han, Lykken, Zhang, PRD5 9, 105006
Hewett, PRL 82 (1999) 4760
Giudice, Rattazzi, Wells, NPB 544 (1999) 3

mono-photon ("direct" ADD)

CMS-EXO-12-047

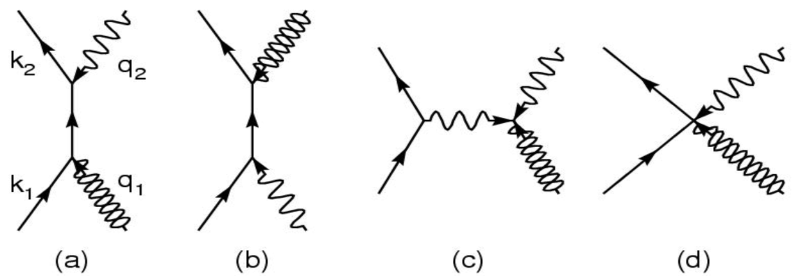


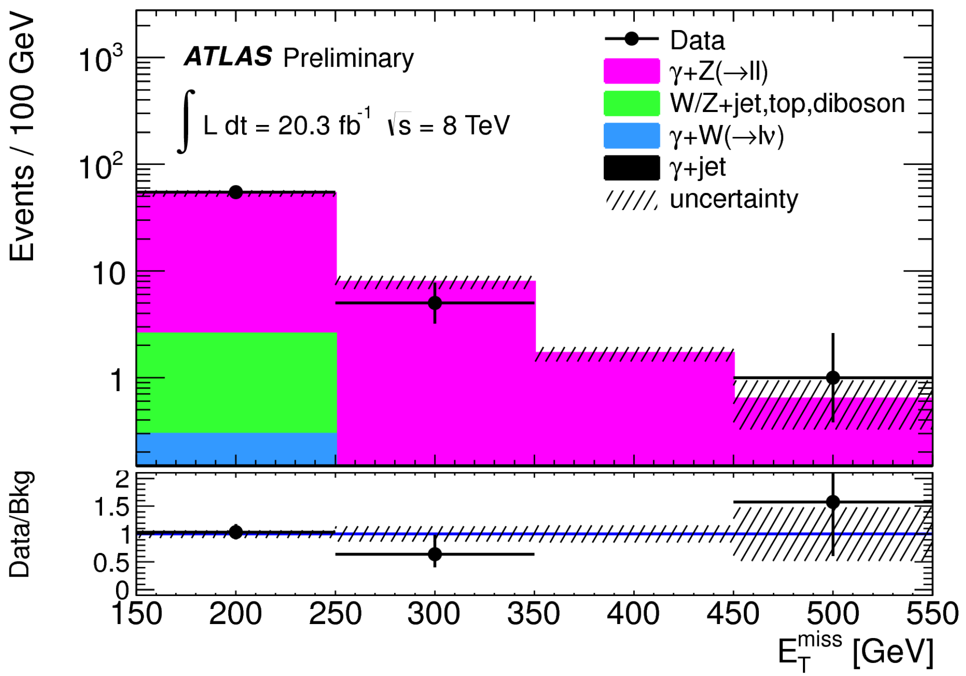


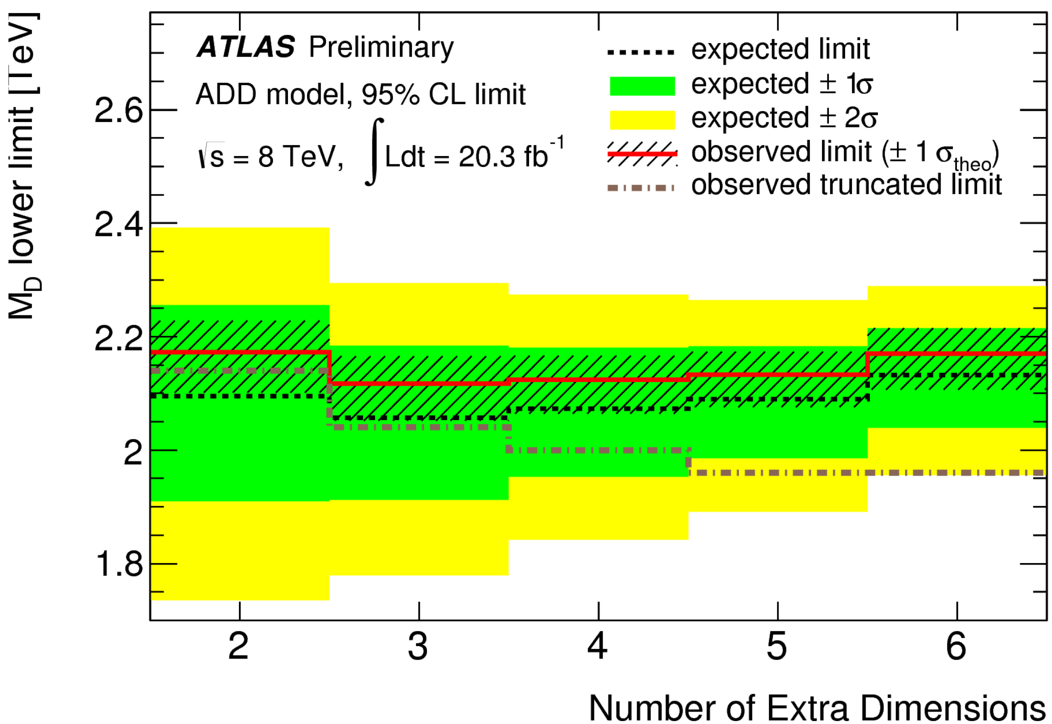


mono-photon ("direct" ADD)

ATLAS-CONF-2014-051



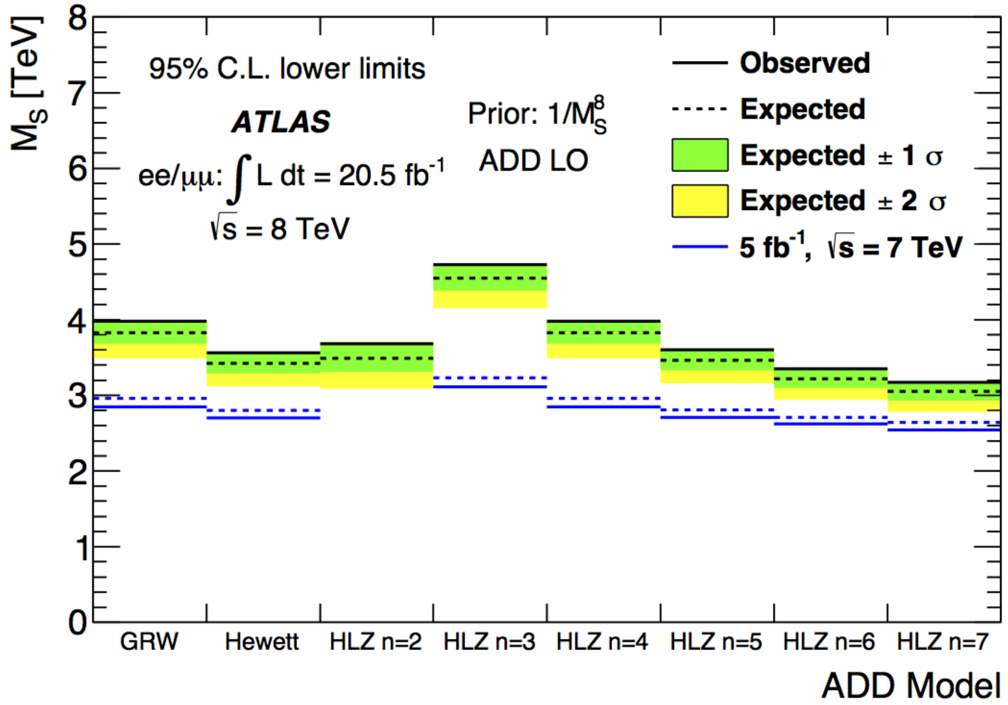


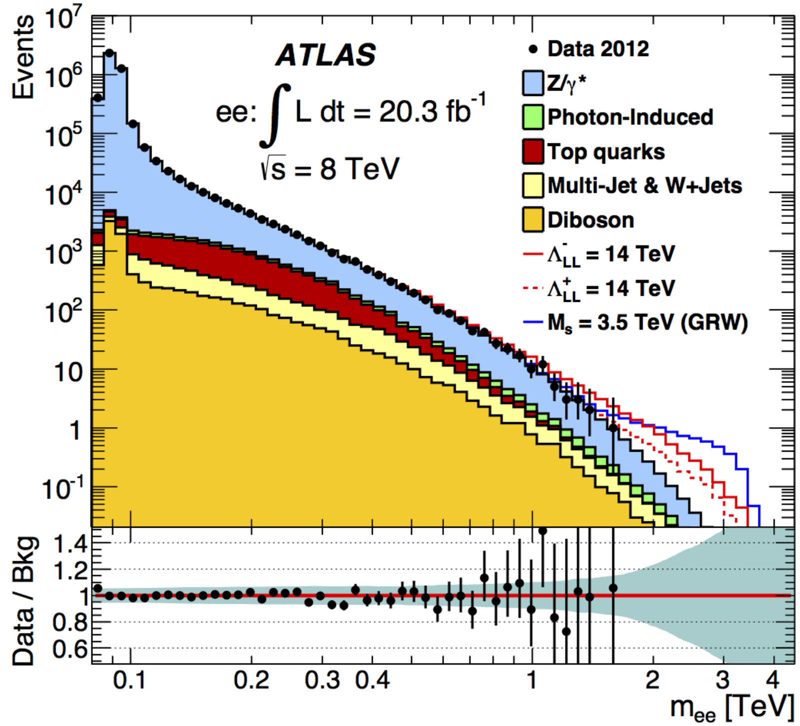


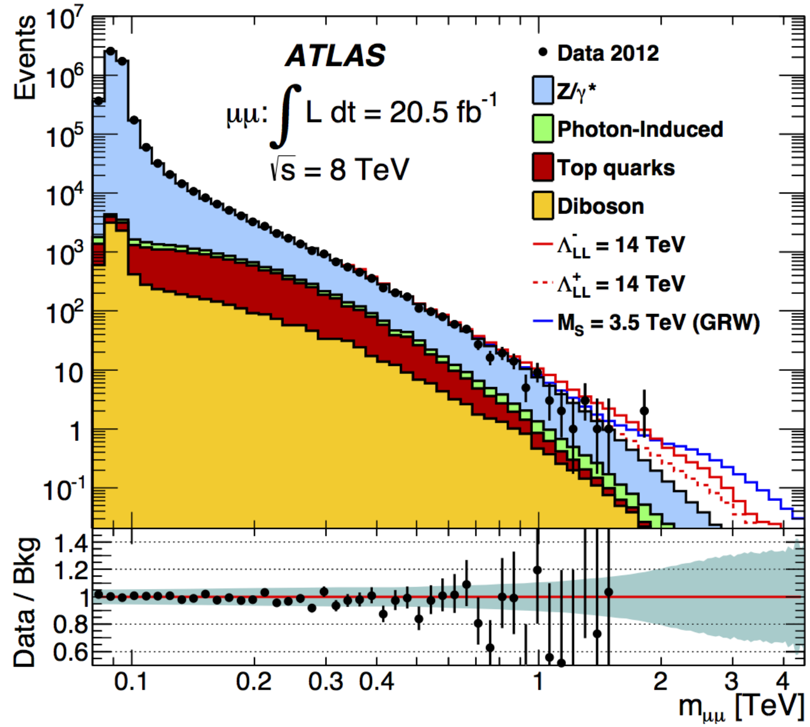
non resonant dilepton

ATLAS arXiv:1407.2410

("indirect" ADD)







non resonant dilepton

CMS-EXO-12-027

CMS-EXO-12-031

("indirect" ADD)

ADD k-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
$\mu\mu$, $\sigma_{s,\mu\mu} < 0.25$ fb (0.25 fb expected) at 95% CL							
1.0 (observed)	3.64	3.48	4.33	3.64	3.29	3.06	2.89
1.0 (expected)	3.65	3.50	4.34	3.65	3.30	3.07	2.90
1.3 (observed)	3.77	3.69	4.49	3.77	3.41	3.17	3.00
1.3 (expected)	3.78	3.70	4.50	3.78	3.42	3.18	3.01
ee, $\sigma_{s,ee} < 0.19$ fb (0.19 fb expected) at 95% CL							
1.0 (observed)	3.90	3.72	4.64	3.90	3.52	3.28	3.10
1.0 (expected)	3.89	3.70	4.62	3.89	3.51	3.27	3.09
1.3 (observed)	4.01	3.99	4.77	4.01	3.63	3.37	3.19
1.3 (expected)	4.00	3.95	4.76	4.00	3.61	3.36	3.18
$\mu\mu$ and ee, per channel $\sigma_s < 0.12$ fb (0.12 fb expected) at 95% CL							
1.0 (observed)	4.01	4.14	4.77	4.01	3.63	3.37	3.19
1.0 (expected)	4.00	4.13	4.76	4.00	3.62	3.37	3.18
1.3 (observed)	4.15	4.35	4.94	4.15	3.75	3.49	3.30
1.3 (expected)	4.14	4.37	4.93	4.14	3.74	3.48	3.30

Astrophysical Constraints

	M_D	M_D
γ ray from galactic bulge (from EGRET)	450 TeV (n=2) $3.8\ 10^{-10}$ m	1.9 TeV (n=3) $4.2\ 10^{-12}$ m
neutron star halo (KK decay) (from EGRET)	454 TeV (n=2)	27 TeV (n=3)
neutron star excess heat (from HST)	1680 TeV (n=2)	60 TeV (n=3)

Branon

- in ('flat') extra-dimensions models with low brane tension f (lower than M_D) fluctuations of the brane position along the extra-dimensions are the only relevant low energy modes

- the particles associated to the fluctuations of the brane in the extra dimensions are scalar particles called branons π^α

- branons can be massive (with mass M)

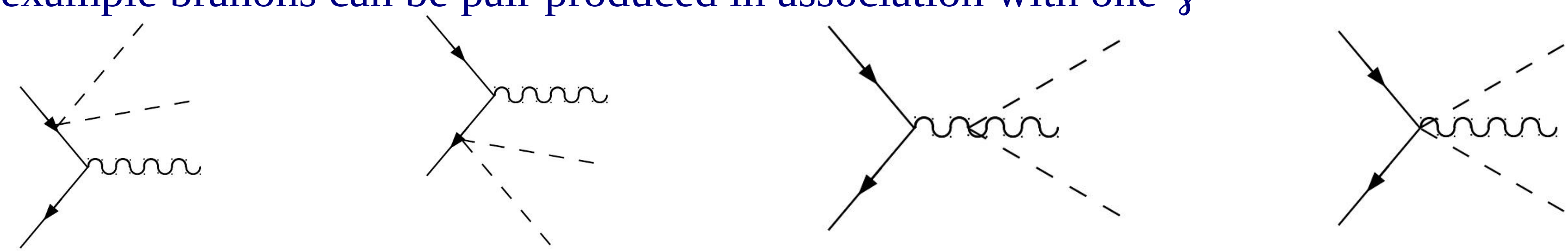
- branons interact by pairs with the SM energy momentum tensor via a mass term and derivative term with f^4 suppressed couplings

$$L_{\text{branon}} = \frac{1}{2} g^{\mu\nu} \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - \frac{1}{2} M^2 \pi^\alpha \pi^\alpha + \frac{1}{8 f^4} \left(4 \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - M^2 \pi^\alpha \pi^\alpha g_{\mu\nu} \right) T^{\mu\nu}$$

- branons are stable, weakly interacting and invisible $\rightarrow$ DM candidate

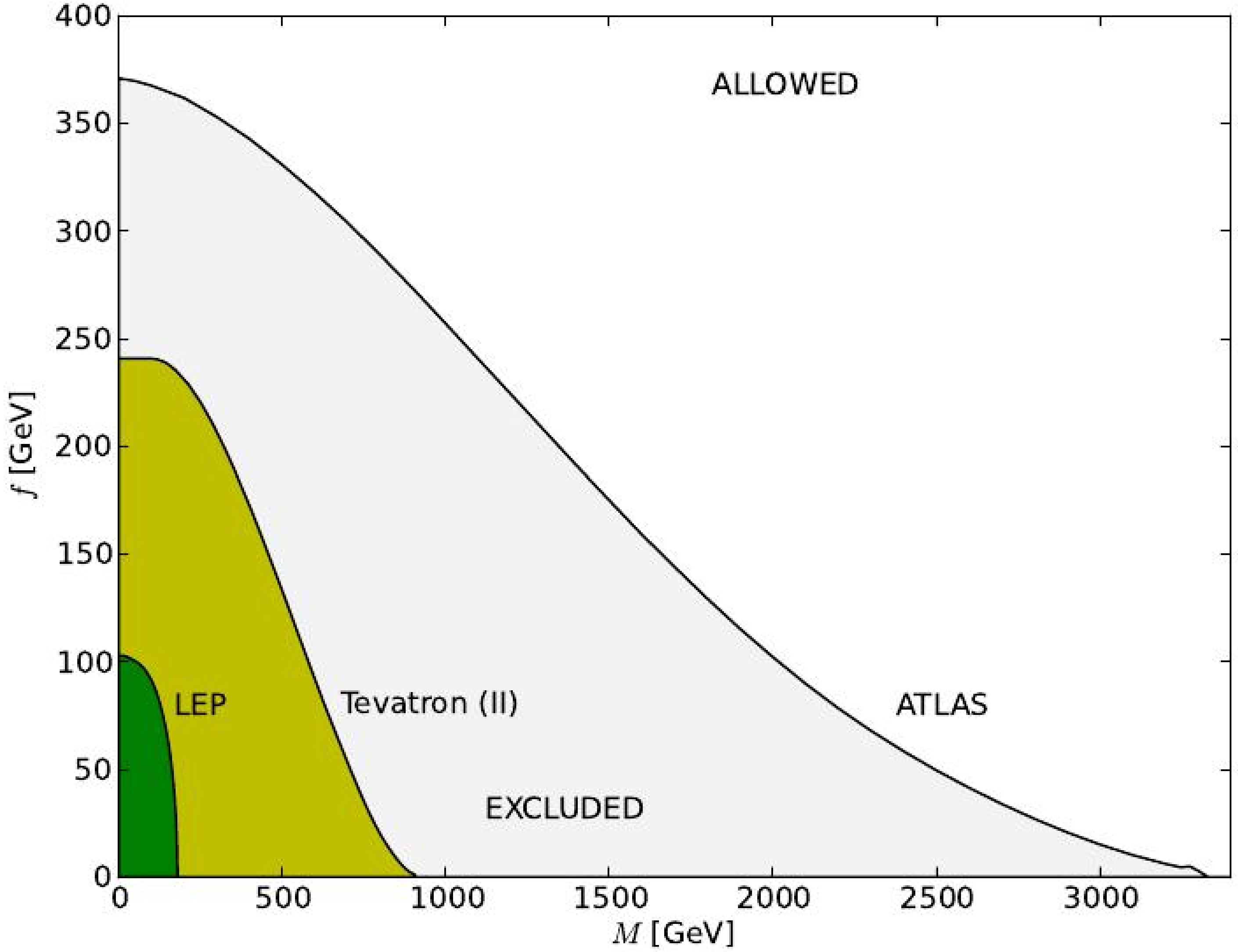
- despite their coupling suppression, branons can be abundantly pair produced in association SM particles at the LHC (and to some extent also at ILC and CLIC, ...)

- for example branons can be pair produced in association with one γ



e.g. J.A.R. Cembranos, A. Dobado, A.L. Maroto PRD 70 (2004) 096001

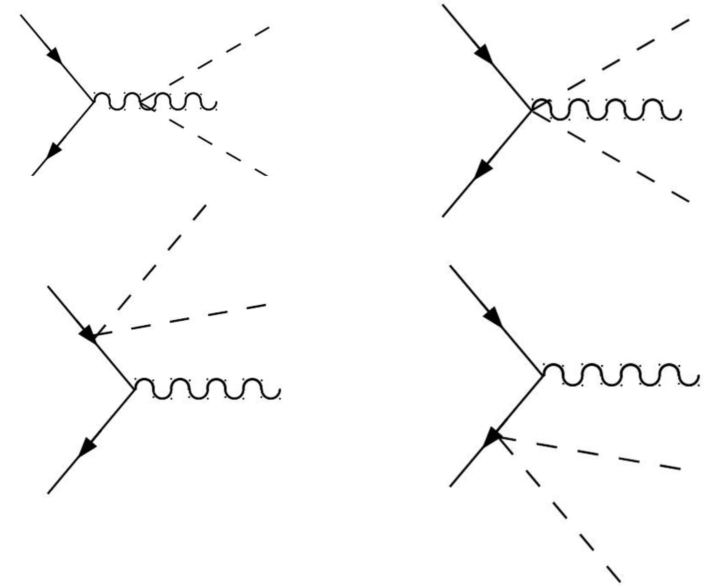
Branons

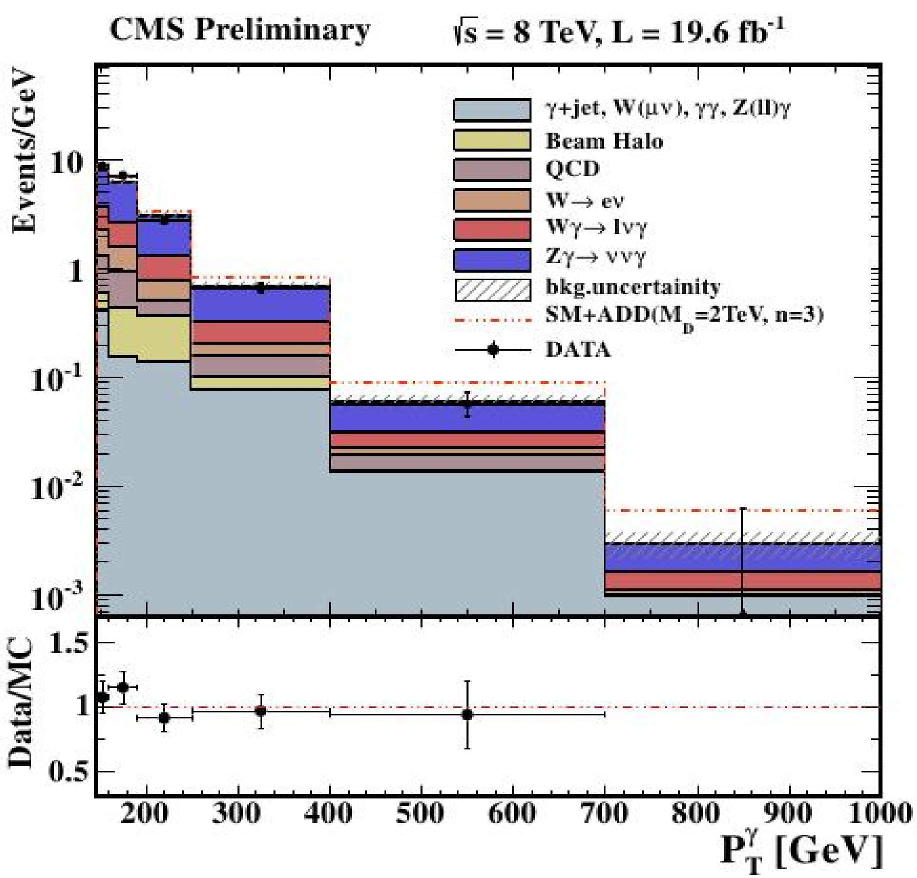


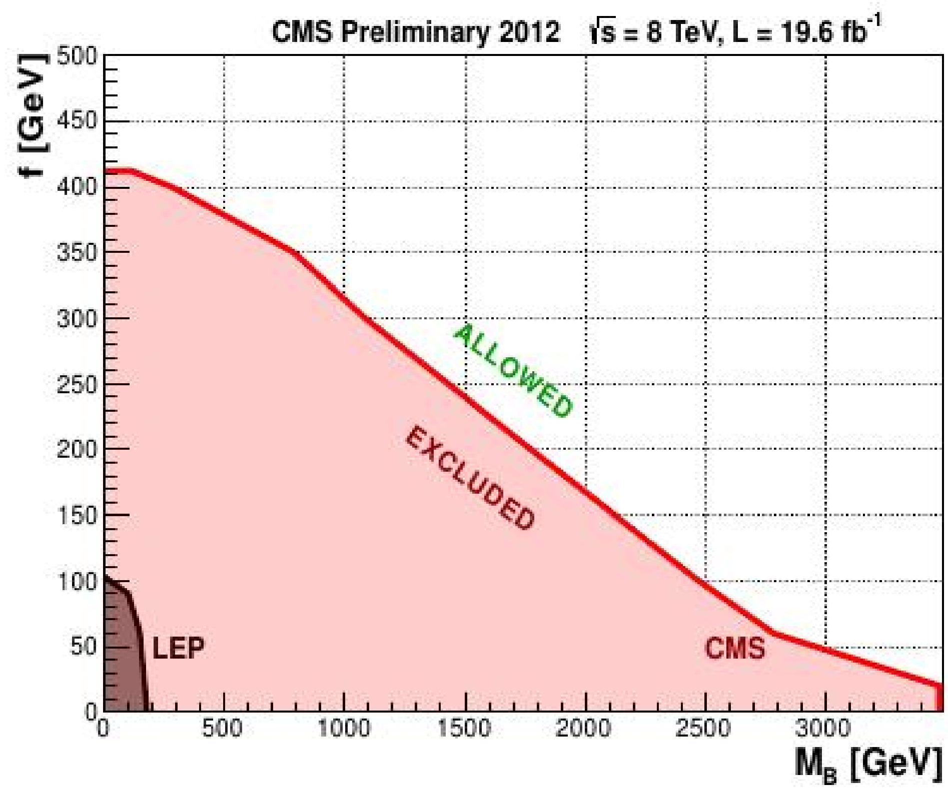
e.g. J.A.R. Cembranos, A. Dobado, A.L. Maroto PRD 88 (2013) 075021

mono-photon (branons)

CMS-EXO-12-047

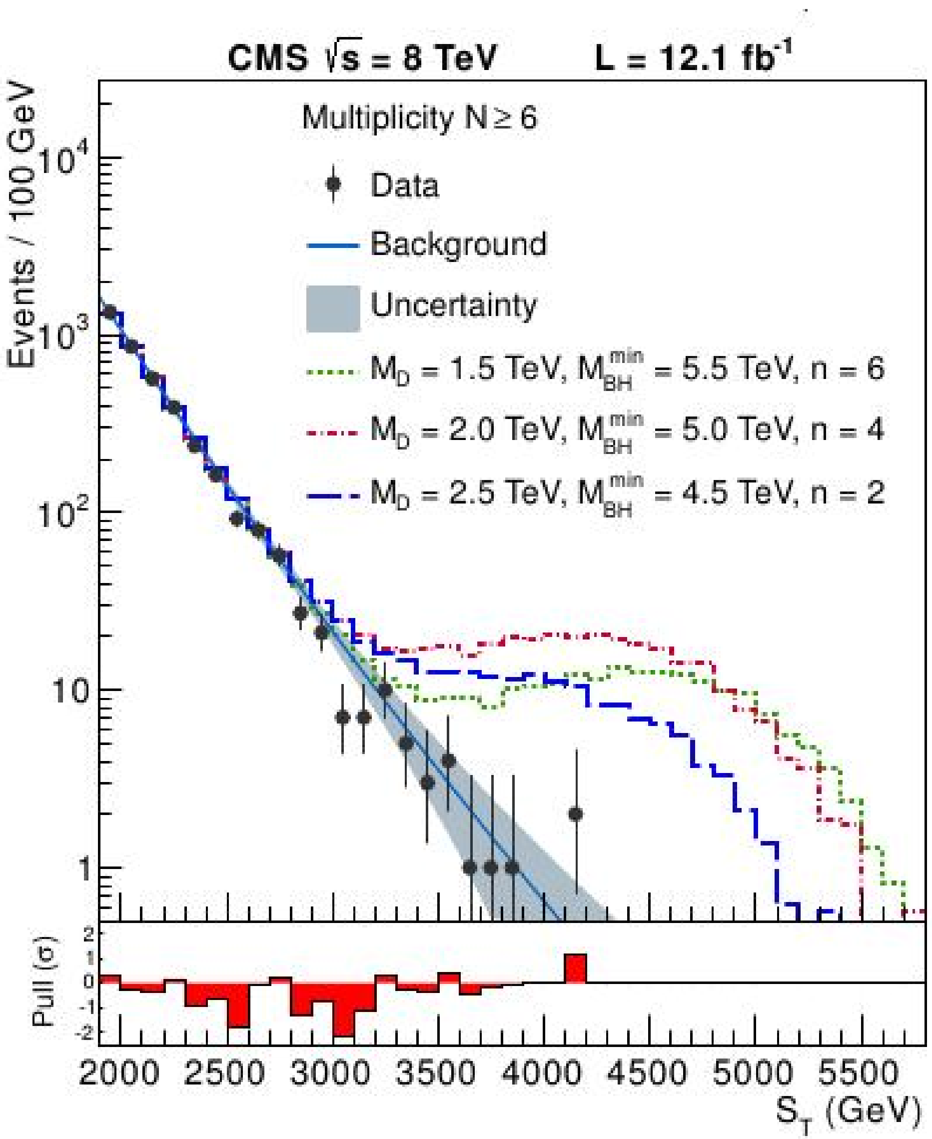


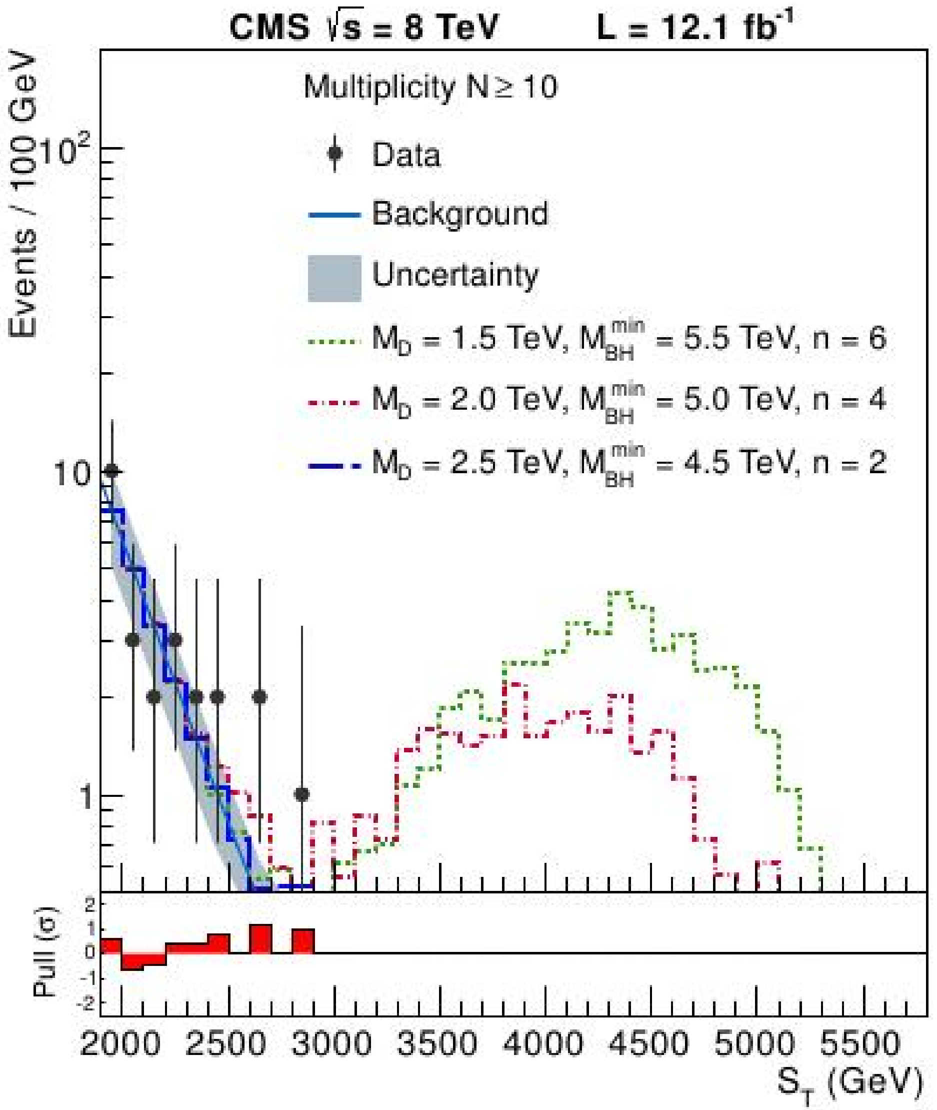




black holes

CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158

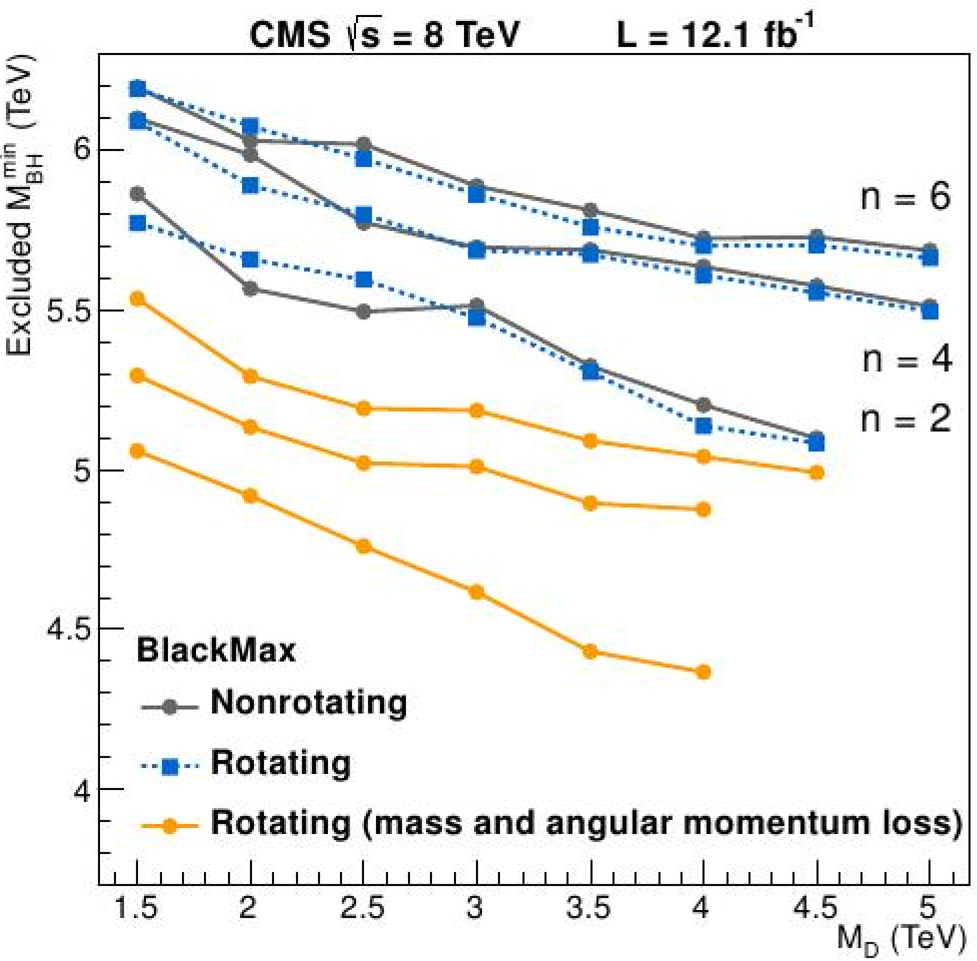


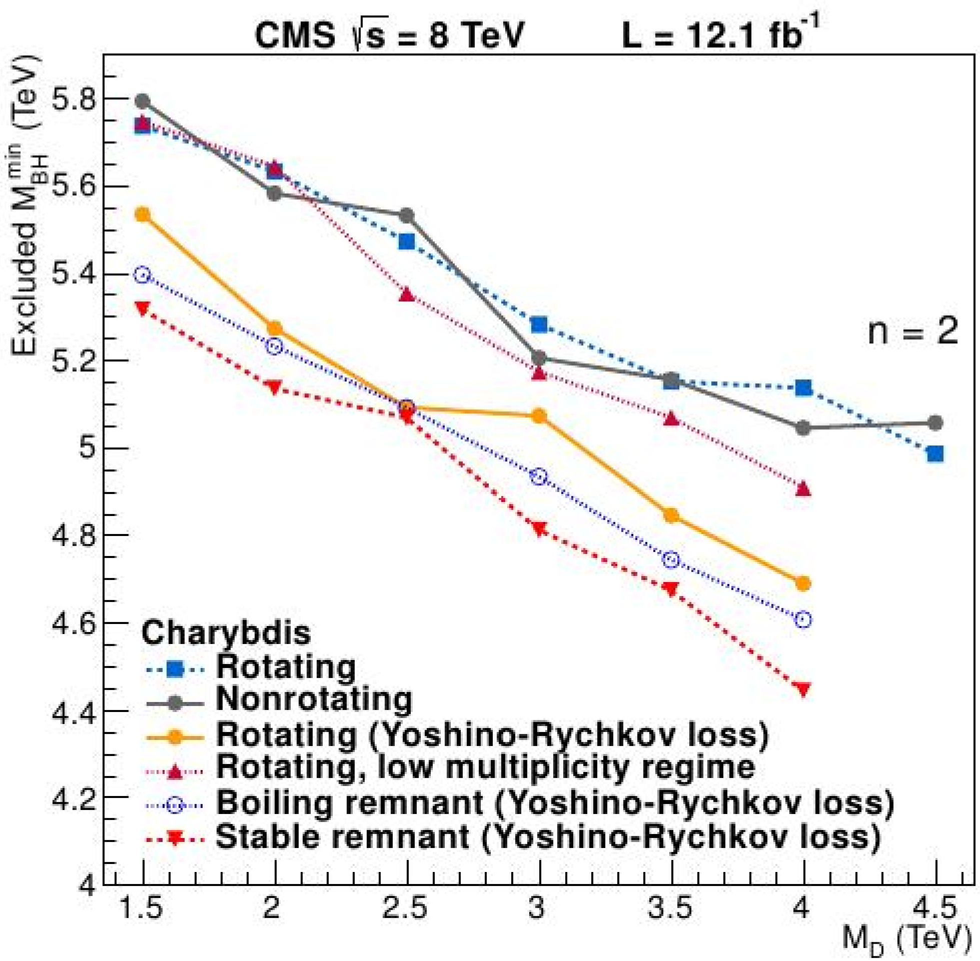


S_T = scalar sum of transverse energies of all final-state objects in the event (i.e. jets, leptons and photons)

black holes

CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158



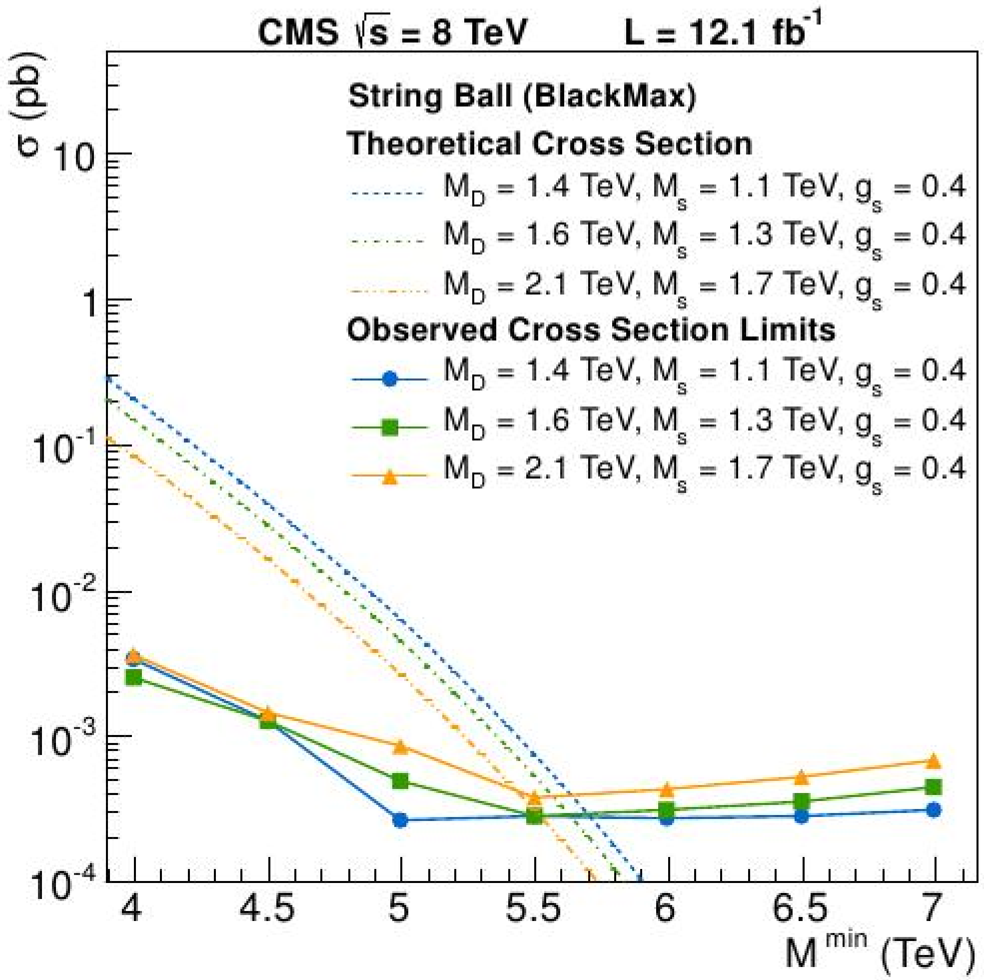


95 % CL lower limits on BH mass as a function of M_D

area below the curves are excluded

black holes

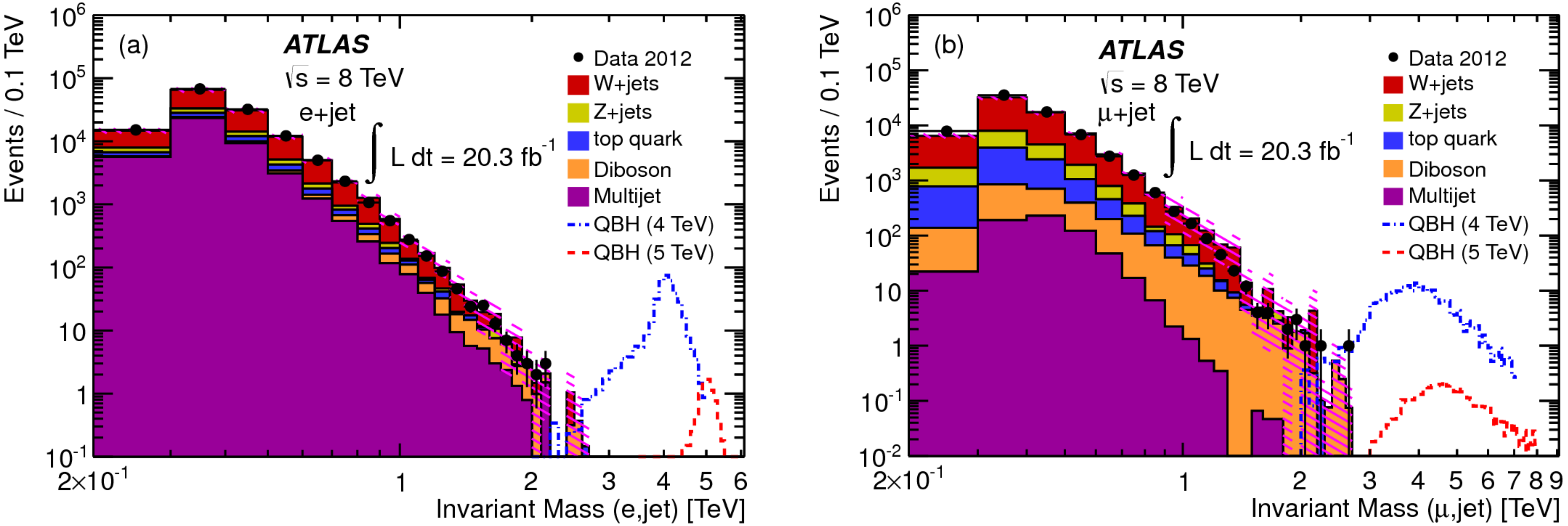
CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158



black holes

ATLAS PRL 112 (2014) 091804

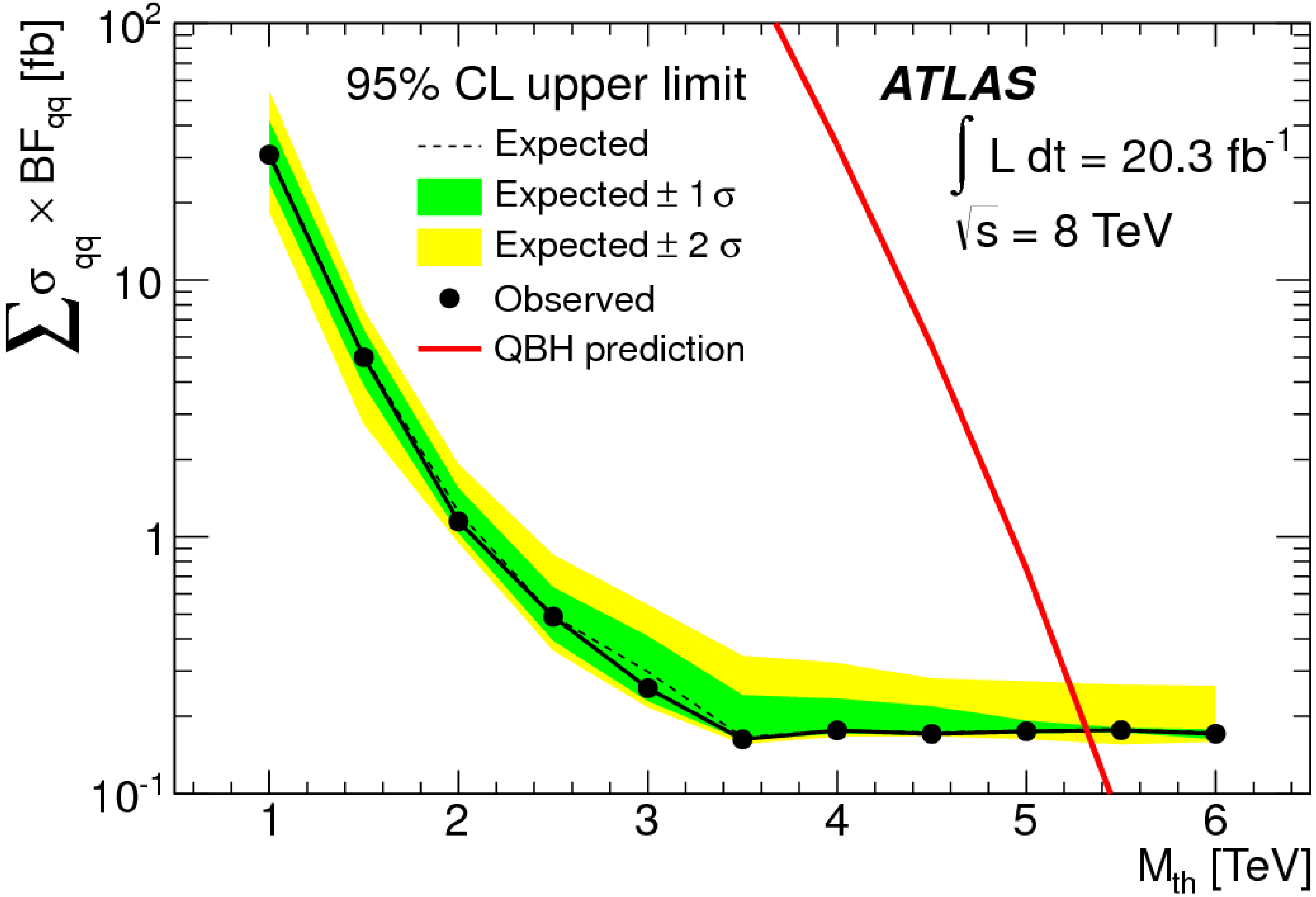
High mass lepton+jets final states



black holes

ATLAS PRL 112 (2014) 091804

High mass lepton+jets final states



TEV^{-1} (KK gauge bosons)

what if more than one TeV^{-1} extra dimension ?

⇒ details of compactifying manifold may become important

- KK excitation spacings more intricate
- many levels degenerate in mass
- strength of couplings to fermions may become level dependent

⇒ constraints from precision measurement more tricky to derive

- assume that the couplings of at least the first few levels to fermions are not vastly different than the naive one (see few slides above)
- in the limit where the effects KK states exchanges viewed as a set as a set of contact interaction (effective approach)

➜ new dimension-6 operators with coefficient proportional to a dimensionless quantity V

$$V = (M_W R) \sum_{\boldsymbol{n}=1}^{\infty} \frac{g_{\boldsymbol{n}}^2}{g_0^2} \frac{1}{\boldsymbol{n}\cdot\boldsymbol{n}}$$

$g_{\boldsymbol{n}}$ is the coupling of the $\boldsymbol{n}$th level and assuming a simple compactification where 1st KK excitation(s) have mass $\propto \frac{1}{R}$

the sum in V does not converge with more than one extra dimension

Rizzo, PRD61 (2000) 055005

TEV^{-1} (KK gauge bosons)

1st way out : truncation (T)

⇒ sum over a finite number of terms $n_{\max}$ i.e only those states whose mass is below M_s which now acts simply as cutoff

2nd way out : exponential (E)

⇒ exponential damping of contribution from higher terms in the sum (from considerations of the flexibility of the brane or in string context)

$$V = (M_W R) \sum_{\boldsymbol{n}=1}^{\infty} \frac{g_{\boldsymbol{n}}^2}{g_0^2} \frac{1}{\boldsymbol{n}\cdot\boldsymbol{n}} e^{-\frac{\boldsymbol{n}\cdot\boldsymbol{n}}{n_{\max}}}$$

Rizzo,PRD61 (2000) 055005

lower bound on the mass of the 1st KK state (TeV) for different compactifications i.e. $Z_2 \times Z_2$, $Z_{3,6}$ and $Z_2 \times Z_2 \times Z$

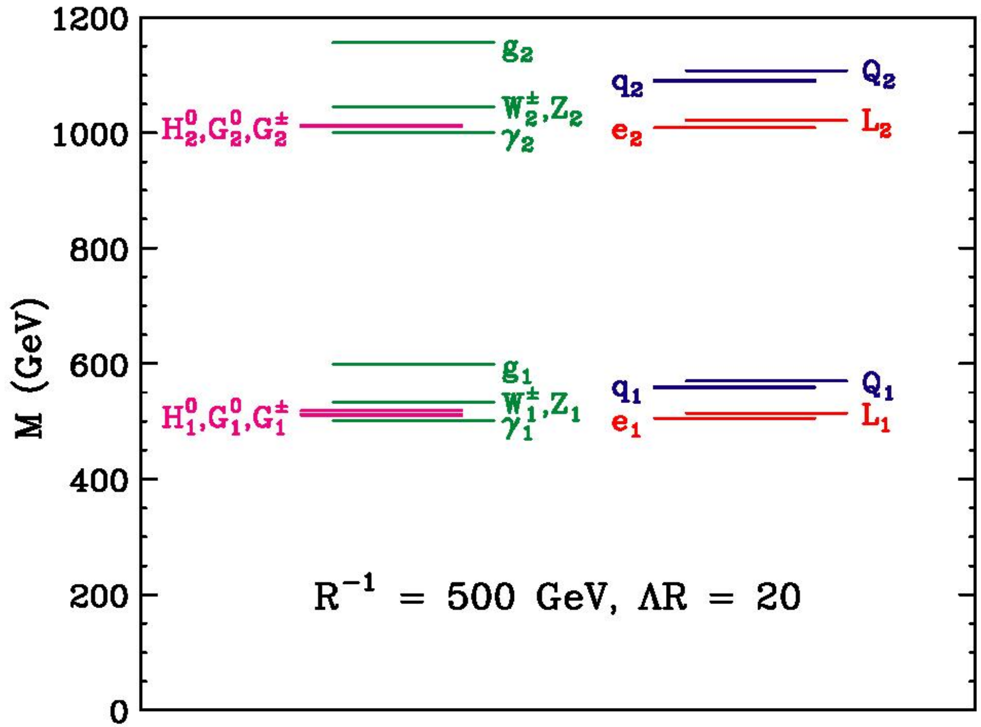
n_{max}	$Z_2 \times Z_2$ T	$Z_2 \times Z_2$ E	$Z_{3,6}$ T	$Z_{3,6}$ E	$Z_2 \times Z_2 \times Z_2$ T	$Z_2 \times Z_2 \times Z_2$ E
2	5.69*	4.23*	6.63*	4.77*	8.65	8.01
3	6.64	4.87*	7.41	5.43*	11.7	10.8
4	7.20	5.28*	7.95	5.85*	13.7	13.0
5	7.69	5.58*	8.36	6.17*	15.7	14.9
10	8.89	6.42	9.61	7.05	23.2	22.0
20	9.95	7.16	10.2	7.83	33.5	31.8
50	11.2	8.04	12.1	8.75	53.5	50.9

discriminating mUED w.r.t SUSY ?

Datta, Kong, Matchev, PRD75 (2005) 096006

search for level 2 KK modes

i.e. search for KK tower structure



at similar masses

Xsection(UED) > Xsection(SUSY)

e.g. for s-channel production :

- both L and R handed SU(2) doublet KK fermions in UED (in susy only L handed SU(2) doublet squarks)
- integrating different angular distributions for fermions $(1+\cos^2\theta)$ vs scalars $(1-\cos^2\theta)$
- for production close to threshold (heavy particles) different Xsection threshold suppression for fermions (β) vs scalars (β^3)

Level 2 KK-quarks (pairs or associated with KK gluons) can be produced directly

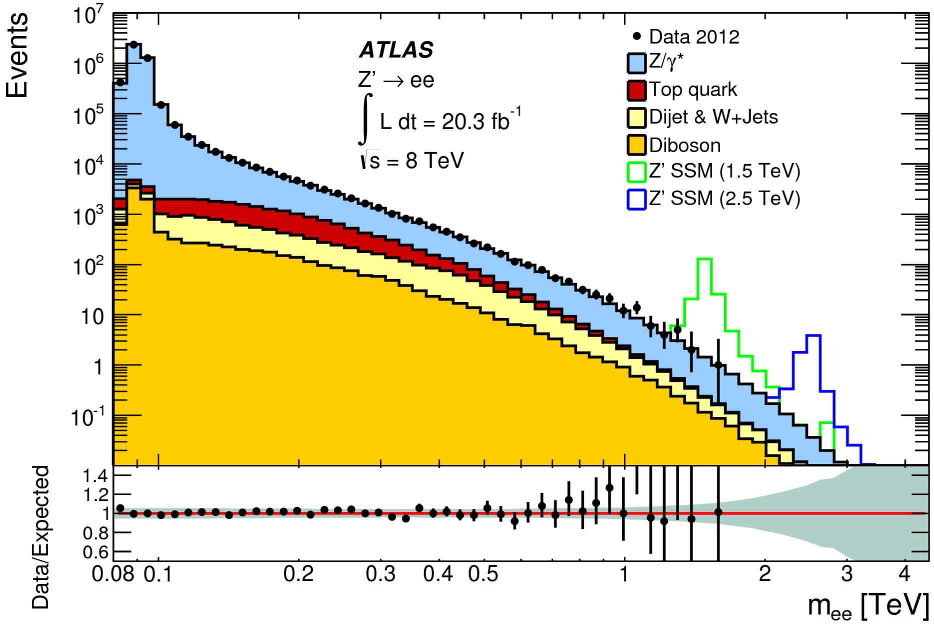
BUT

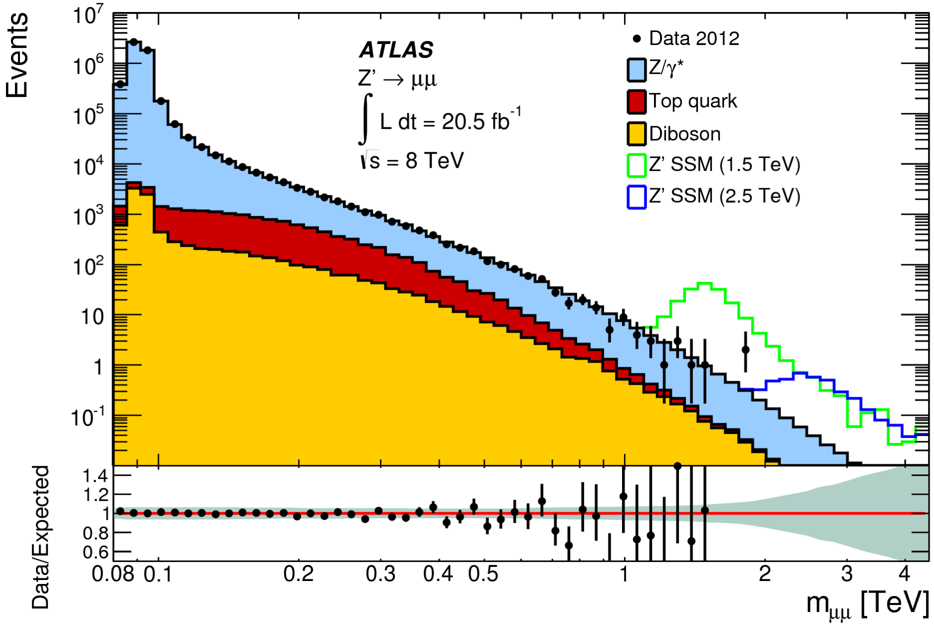
Br (Nleptons + MET) • Xsection still challengingly small

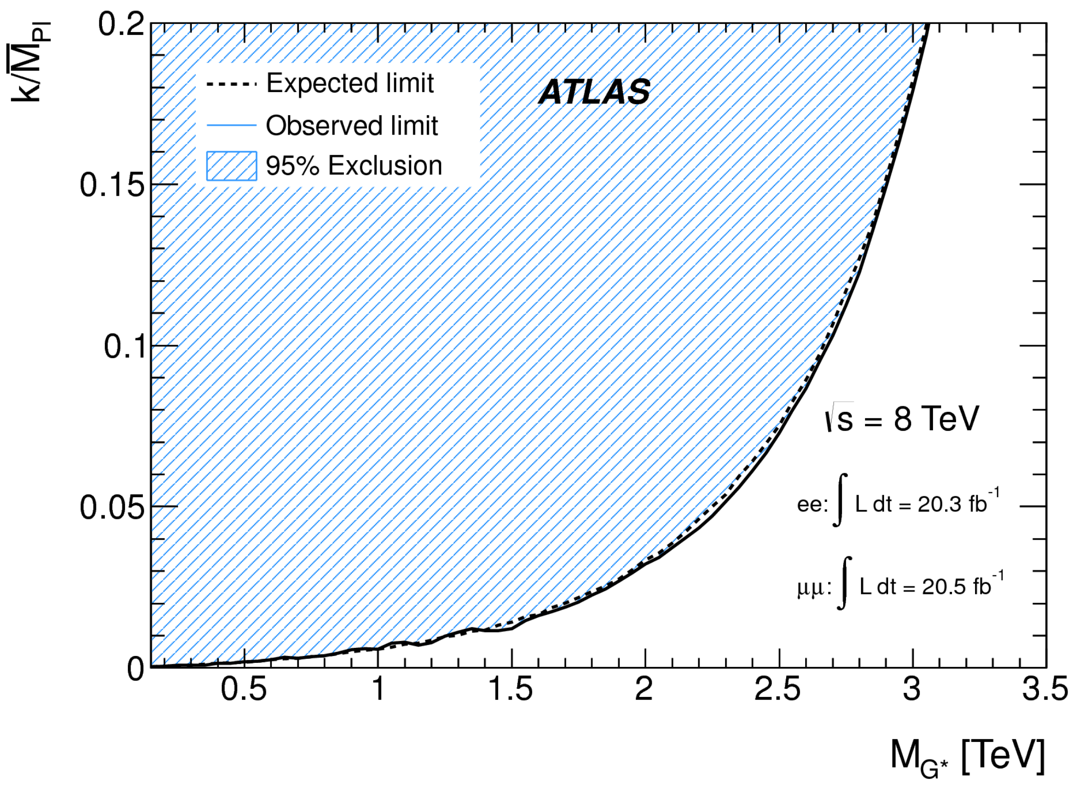
& challenging small statistics to distinguish from level 1 modes

resonant dilepton

PRD 90 (2014) 052005







Bulk RS models

- to solve hierarchy problem

→ only SM Higgs has to be localized on/near TeV Brane

- fermion and gauge fields allowed to propagate in the Xtra dim

- SM particles correspond to KK zero modes of 5D fields

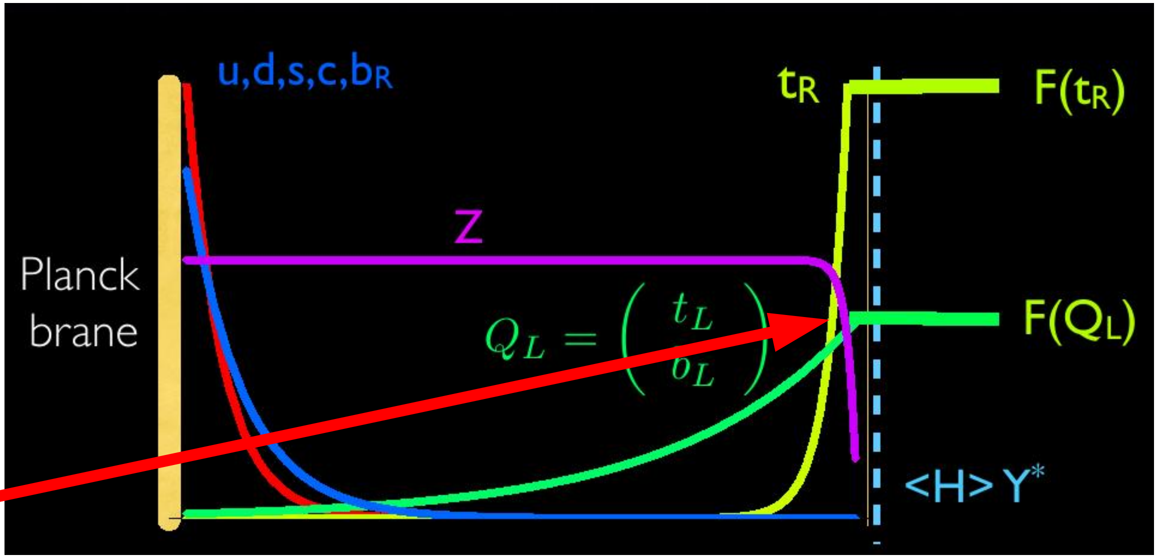
bulk profile of SM fermion depends on its 5D mass parameter

- choose to localize 1st and 2nd generation fermions near Planck brane

→ FCNC from higher dim operator suppressed by scales >> TeV

→ SM Yukawa coupling hierarchies

1st and 2nd generation small Yuk. coup. with Higgs localized near TeV brane



top quark can be localized near TeV brane to account for its large Yukawa coupling

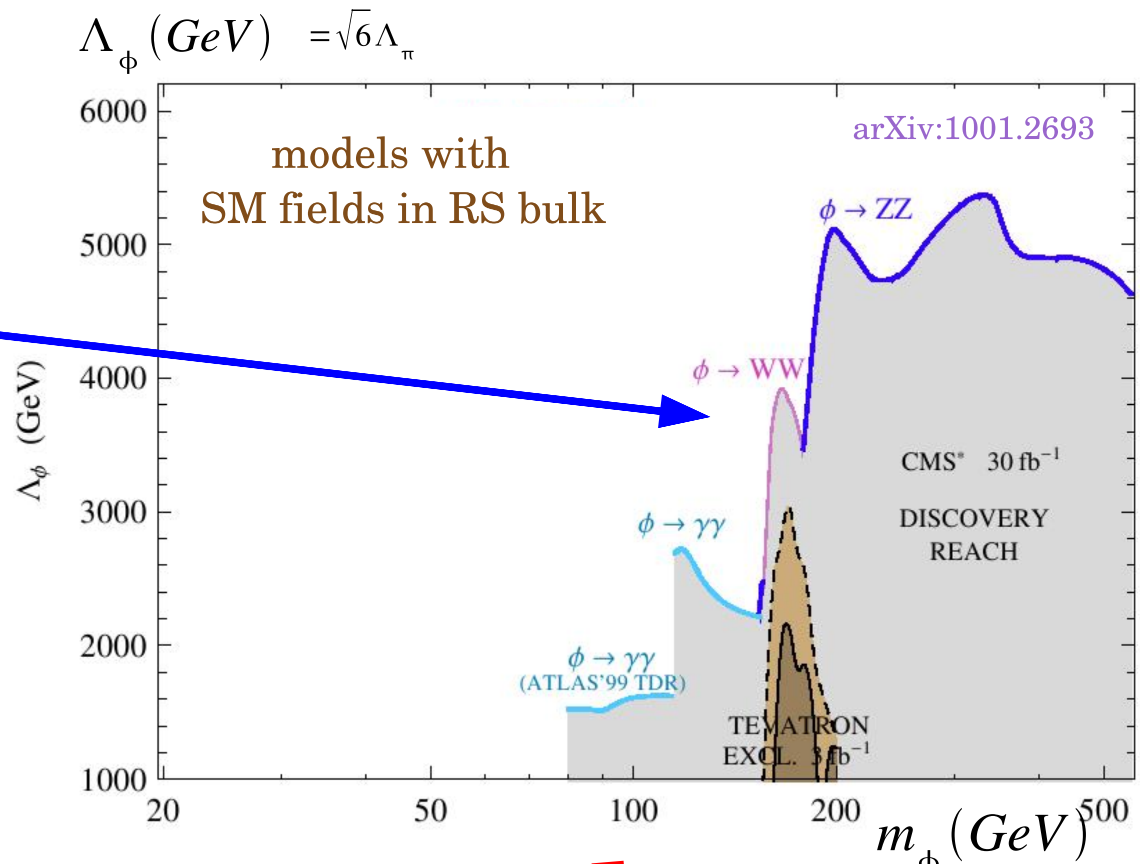
from Weiler's talk at GDR Terascale(http://terascale.in2p3.fr)
http://indico.in2p3.fr/conferenceDisplay.py?confId=1617

stabilized RS

- pure radion effects on precision EW data are small

Gunion, Toharia, Wells, PLB 585 (2004) 295

- radion searches using SM Higgs searches



$\phi \to h\,h$ also possible

key difference w.r.t SM Higgs
→ direct couplings to gluons

Radion and bulk RS

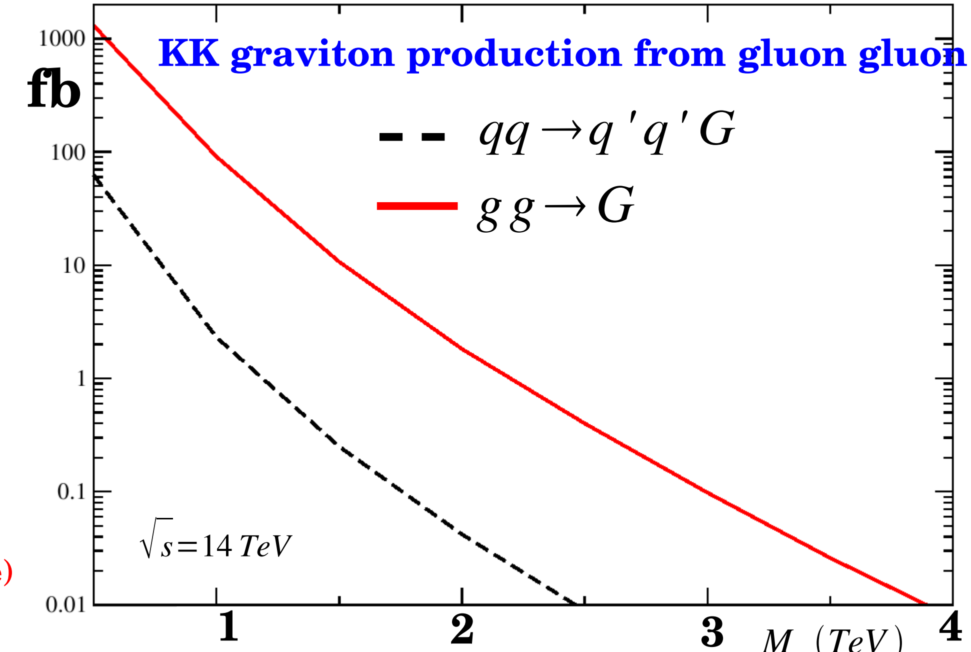
Rizzo, JHEP 06 (2002) 056
Csaki, Hubisz, Lee, PRD76, 125015
Azatov, Toharia, Zhu, PRD80, 031701

Bulk RS models

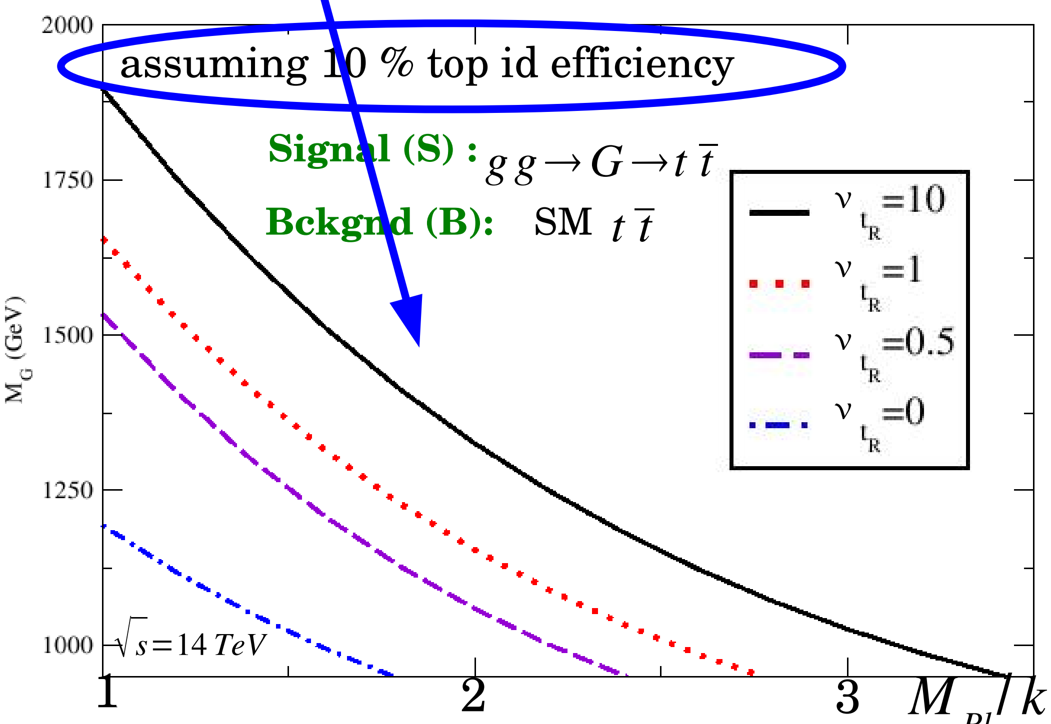
KK Graviton search

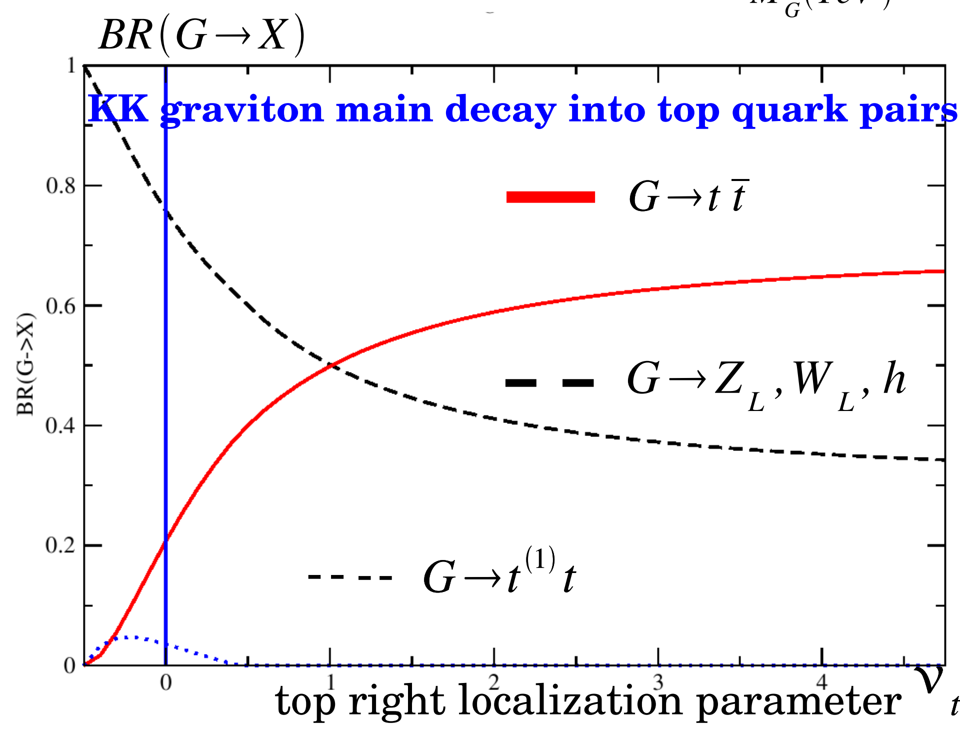
Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006
Antipin, Atwood, Soni, PLB 666 (2008) 155
Antipin, Soni, JHEP10 (2008) 018

- **KK Graviton close to TeV Brane**
- 1st (and 2nd) generation fermion near Planck brane
  i.e. small coupling with 1st and 2nd quark generation
- **gluon profile is flat**
- **t and b quark close to TeV brane**



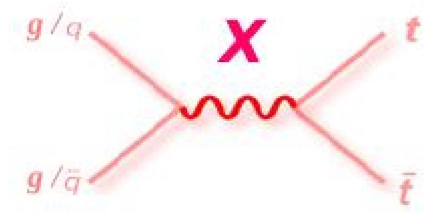
$\frac{S}{\sqrt{B}}=5$ **reach for various t quark IR localization** ν_{tR} (the bigger the closer to IR brane)





semileptonic $t\bar{t}$

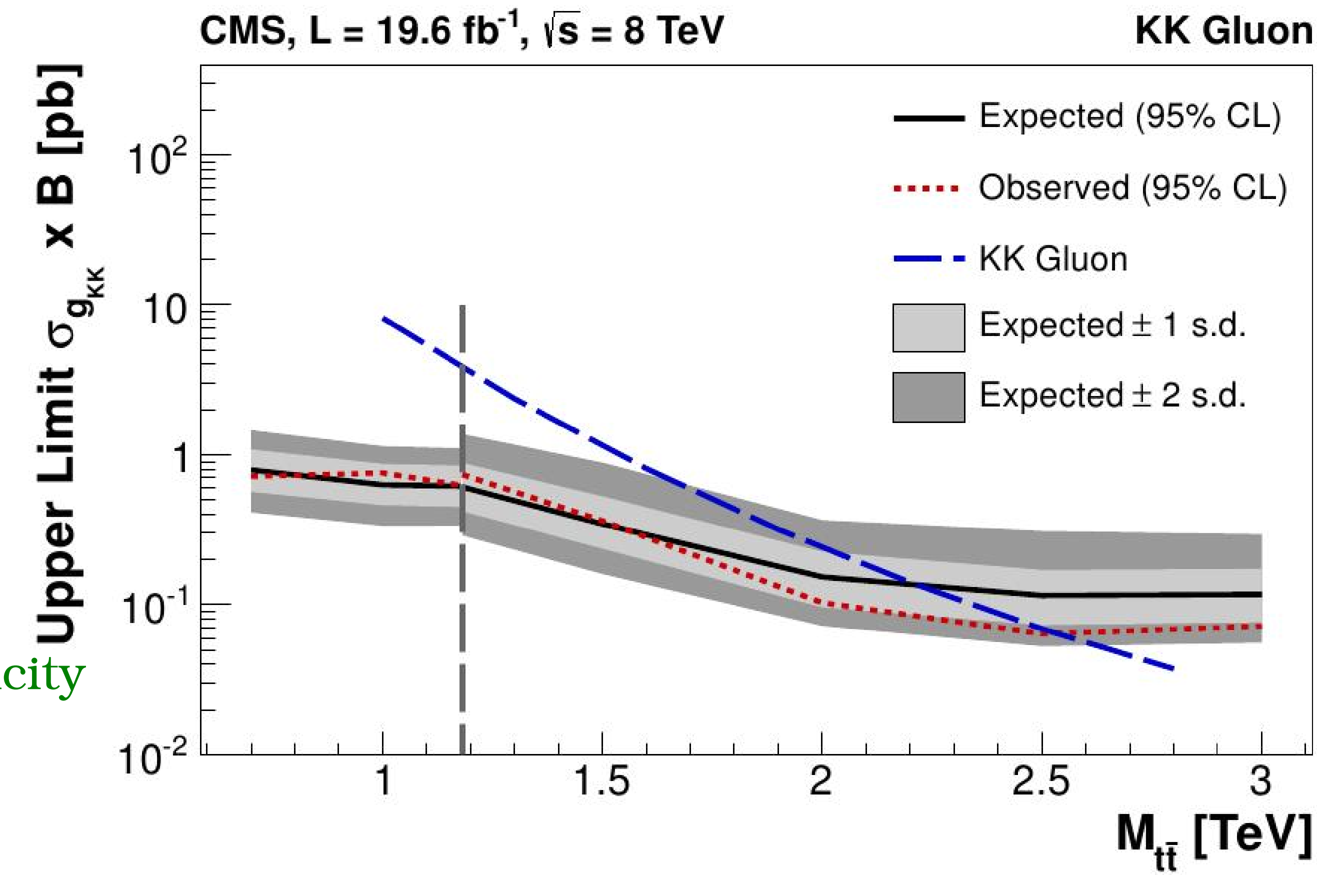
CMS-B2G-12-006



- 2 analyses
  low/high mass coverage
  i.e. threshold/boosted

  transition at ~ 1 TeV

- for boosted analysis
  less isolation
  smaller b-tagged jet multiplicity
  higher 'wide' jet multiplicity
  jet substructure



- limits from the
  combination of the
  2 analyses

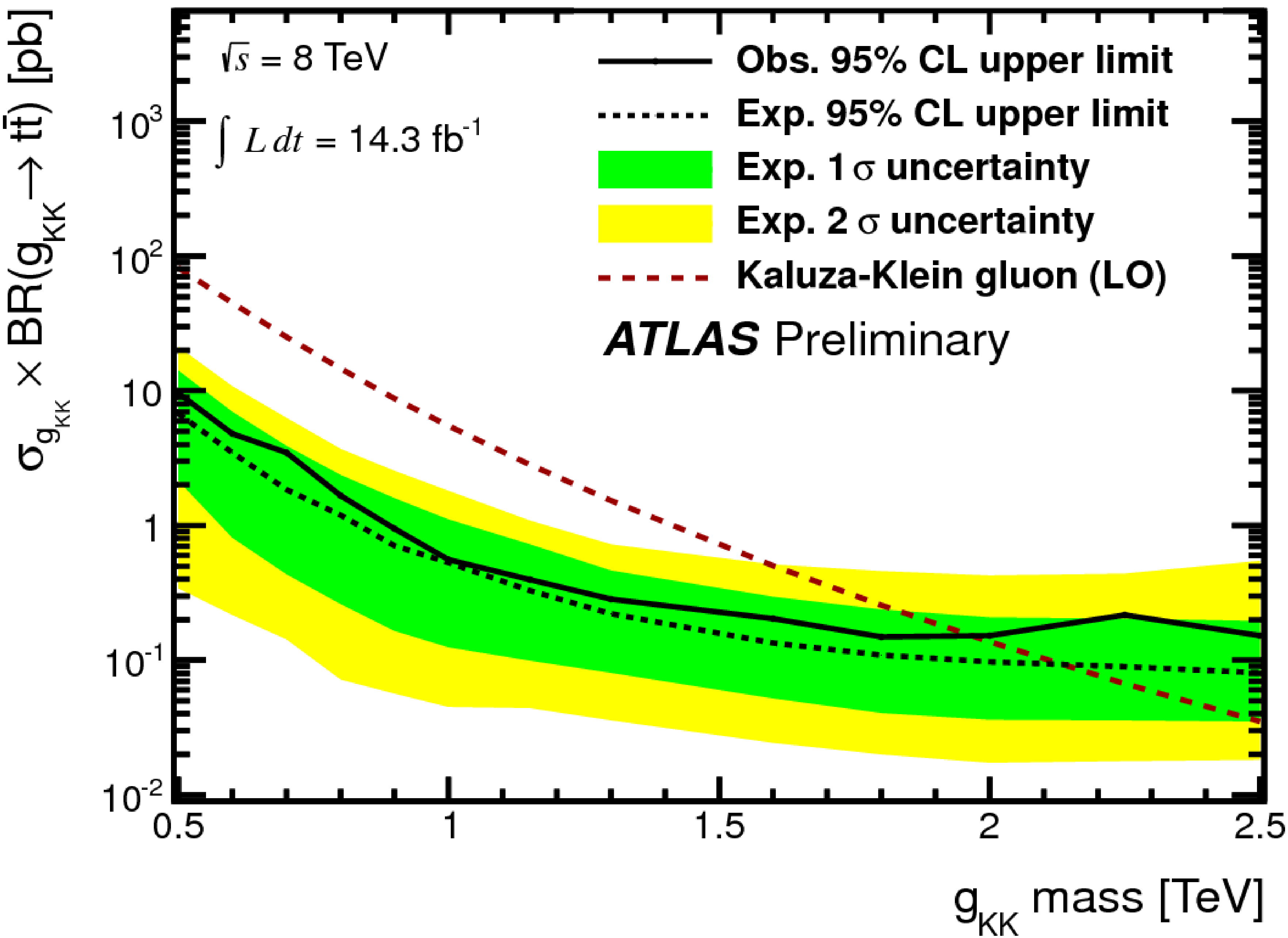
$m_{g_{KK}^{(1)}} > 2.54$ TeV

$\sigma . Br(pp \to g_{KK}^{(1)} \to t\bar{t}) < 0.101$ pb $(0.150^{+0.072}_{-0.055}$ pb expected$)$

for $m_{g_{KK}^{(1)}} = 2$ TeV

semileptonic $t\bar{t}$

ATLAS-CONF -2013-052



States with exotic charge (bulk RS)

$MCHM_5$ example : $SO(5) \times U(1)_X \times SU(3)_C$ **as gauge symmetry in the RS bulk**

$SO(5) \times U(1)_X \times SU(3)_C$ broken down to $SO(4) \times U(1)_X \times SU(3)_C$ near IR brane with 4 pseudo Goldstone bosons identified with the Higgs doublet

$SO(4) \approx SU(2)_L \times SU(2)_R$ enlarged to $O(4)$ seen as the custodial symmetry

$G_{SM} = SU(2)_L \times U(1)_Y \times SU(3)_C$ near UV brane and with $Y = X + T_3^R$

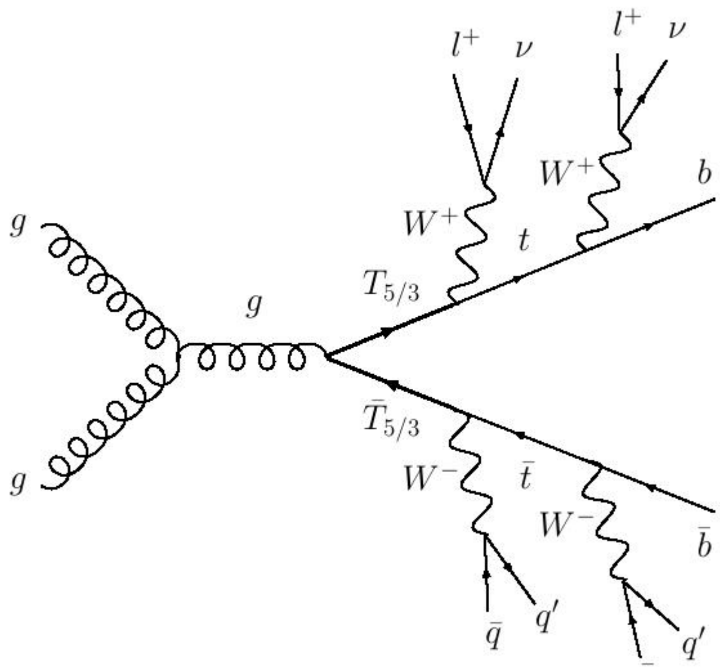
heaviness of top quark $\Rightarrow$ lowest t_{KK} and lightest O(4) custodial partners (i.e. custodians) are significantly lighter than the other KK resonances

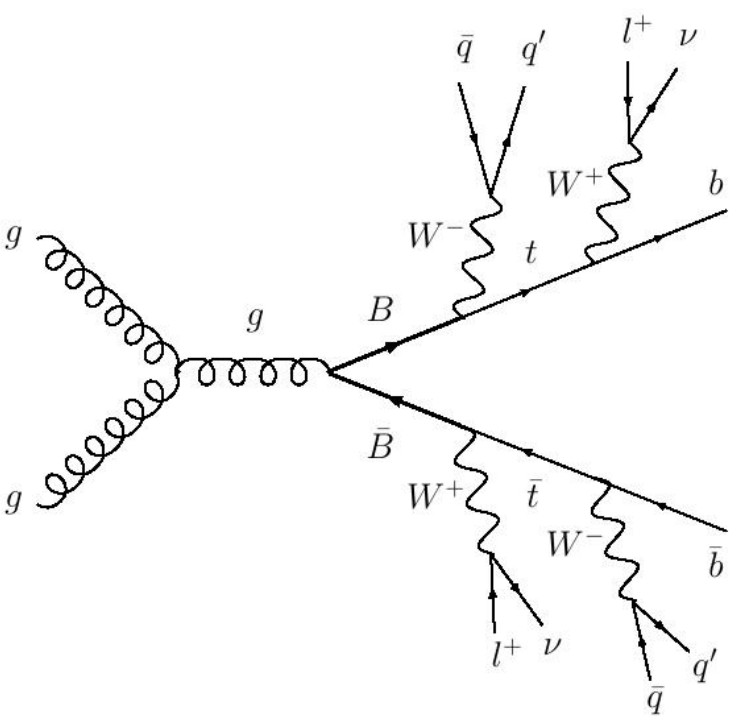
light custodians have e.m charges $5/3$, $2/3$, $-1/3$

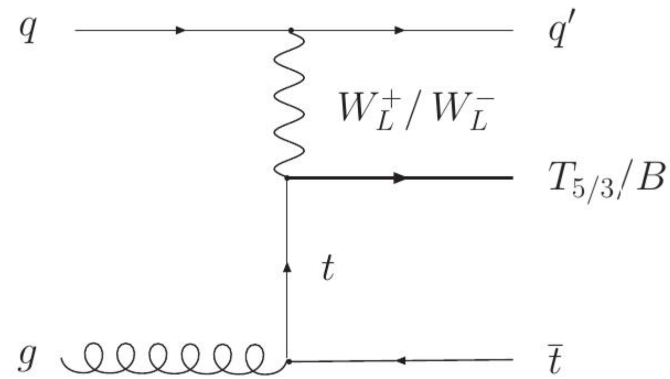
they have mass roughly in the $500 - 1500$ GeV range

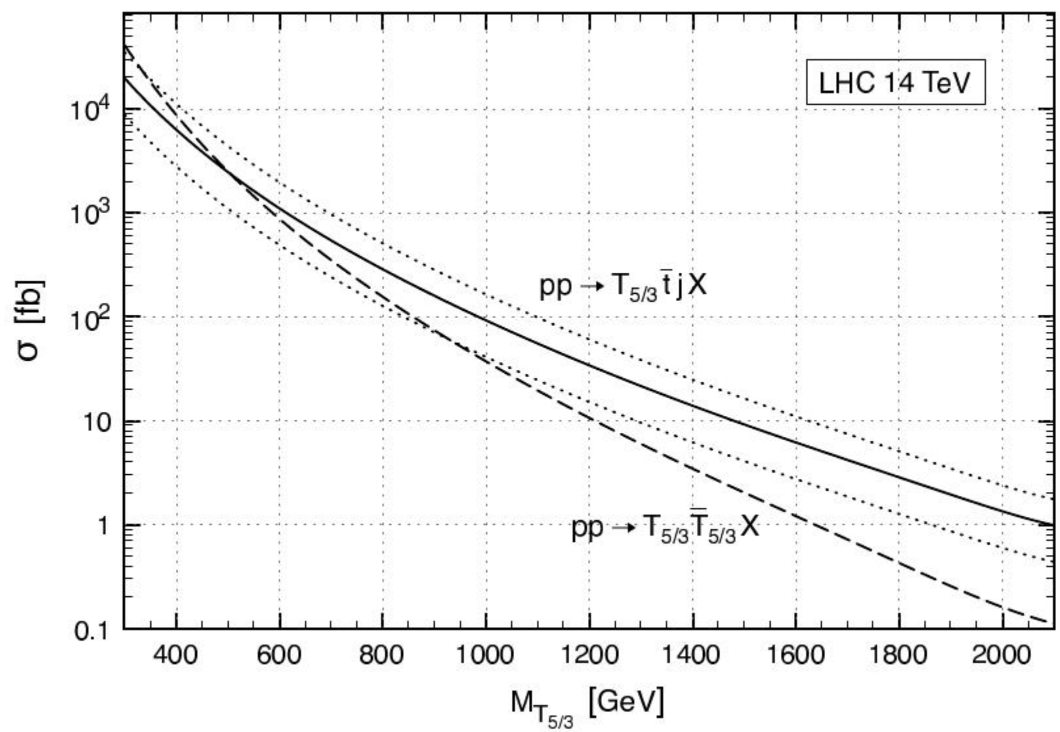
Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050
Agashe, Contino, Pomarol,, NPB 719 2005 165
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006
Contino, Darold, Pomarol,, PRD 75 2007 055014
Contino, Servant, JHEP 06 2008 026

States with exotic charge (bulk RS)







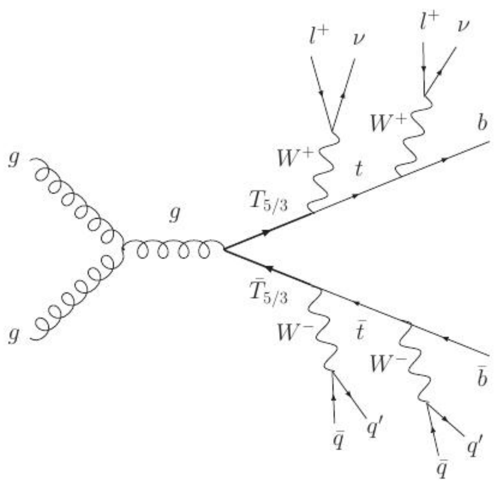


Contino, Servant, JHEP 06 2008 026

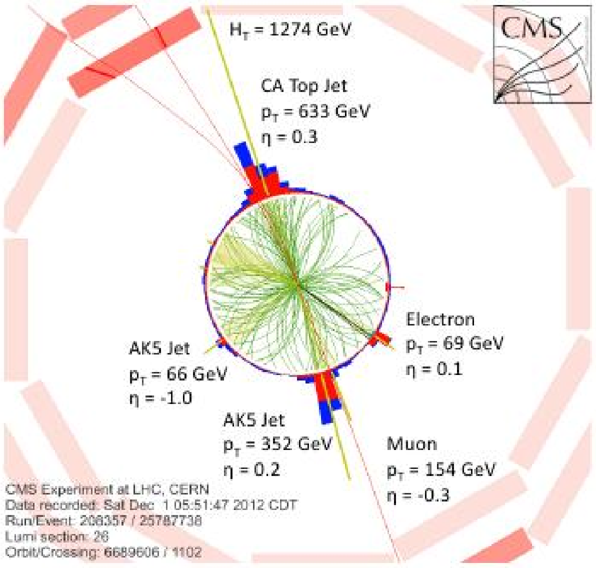
Exotic fermions (5 e/3)

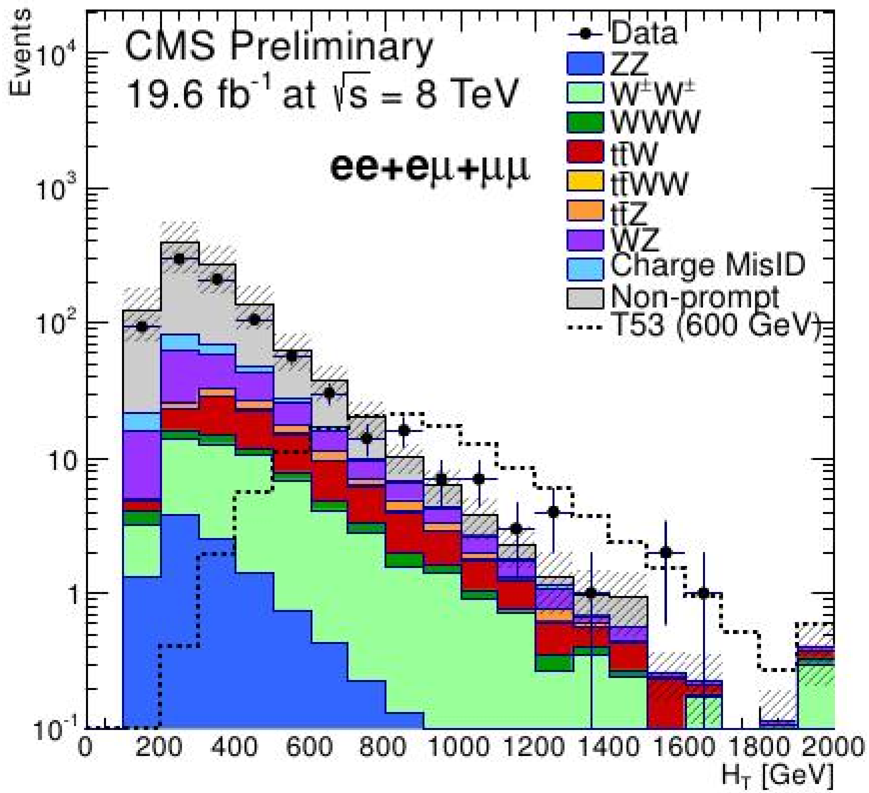
CMS-B2G-12-012

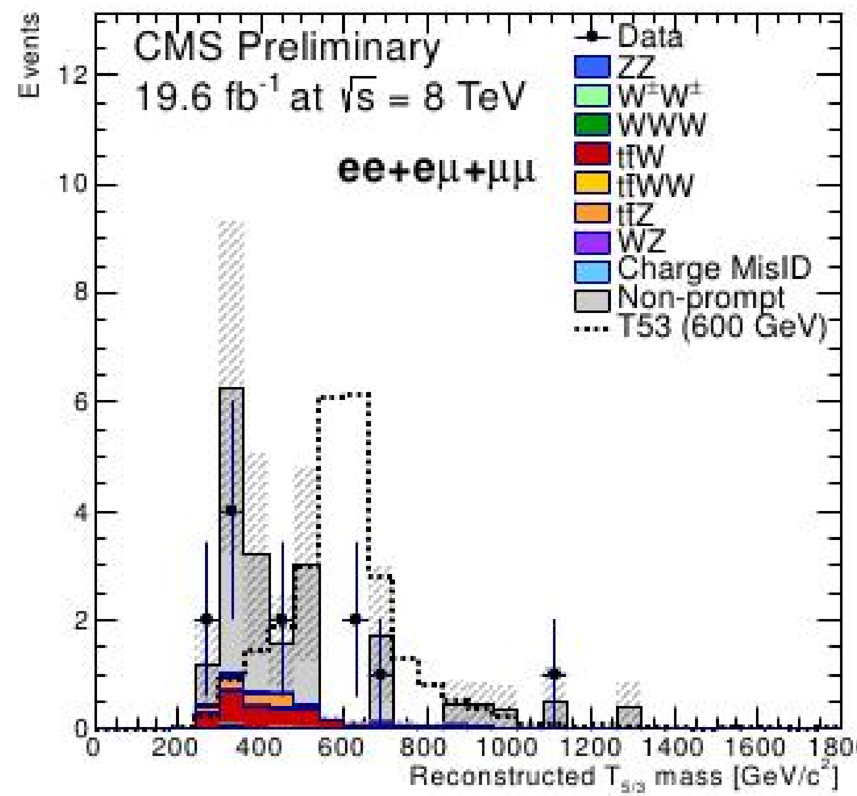
(suited for bulk RS)



same sign dilepton





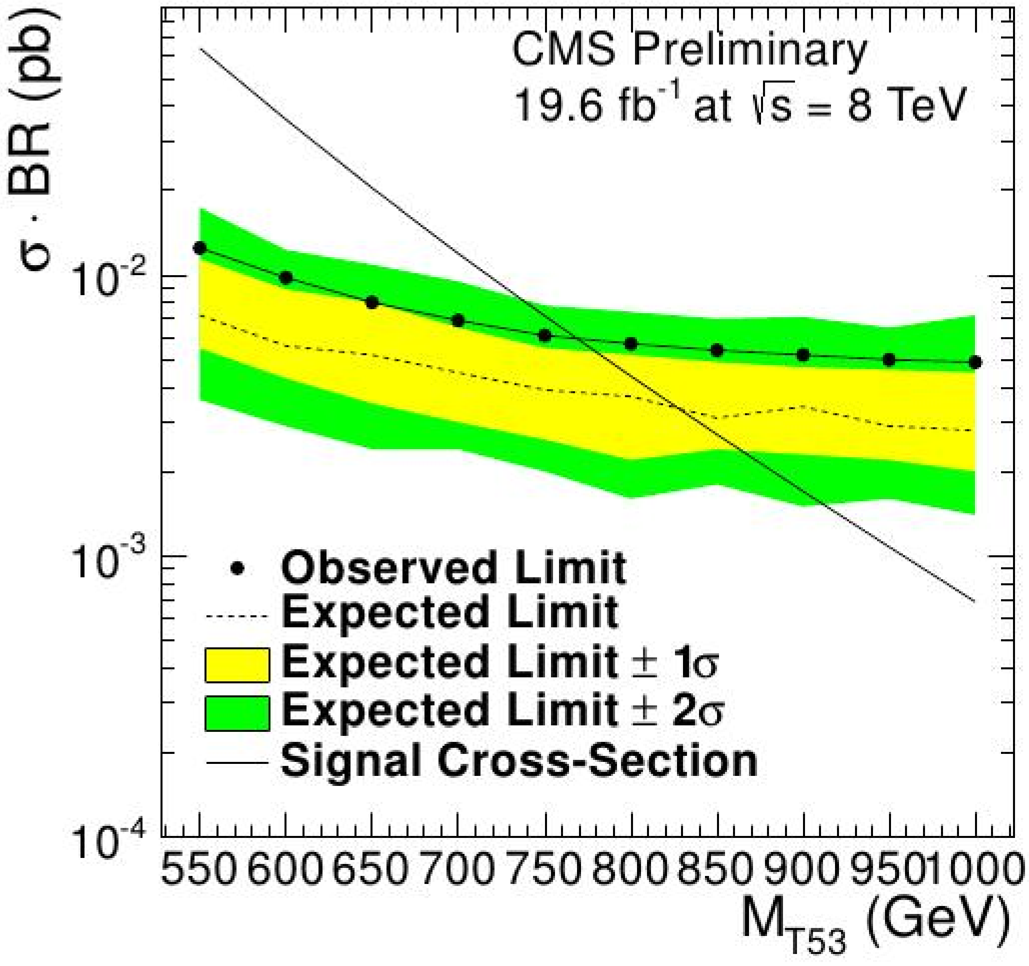


***H_T* = scalar sum of all jets and all leptons**

Exotic fermions (5 e/3)

CMS-B2G-12-012

(bulk RS)



$M_{T_{5/3}} > 770$ GeV

String states

assume fundamental scale is low (TeV) and fundamental theory is string theories

→ strings scale Ms is low (TeV)

spectrum of string states made of 'zero' mass states and massive states

'zero' mass states → graviton, anti-sym tensor field, dilaton (scalar)

+ others identified with SM fields

massive states → (infinite number of) massive Regge excitations of various spin

with masses of order of string scale → then here low (TeV) !

'correction' from Regge excitations : $\dfrac{s^2}{M_s^4}, \quad \dfrac{t^2}{M_s^4}, \quad \dfrac{u^2}{M_s^4}$ (back to pointlike particle limit when $s^2/M_s^4 \to 0$)

4-point amplitudes with Regge excitation : $O(g_s) \sim \dfrac{1}{25}$ i.e. bigger than the one from QFT with KK graviton exchange which is $O(g_s^2)$

also present in spectrum : KK AND winding excitations of the SM fields

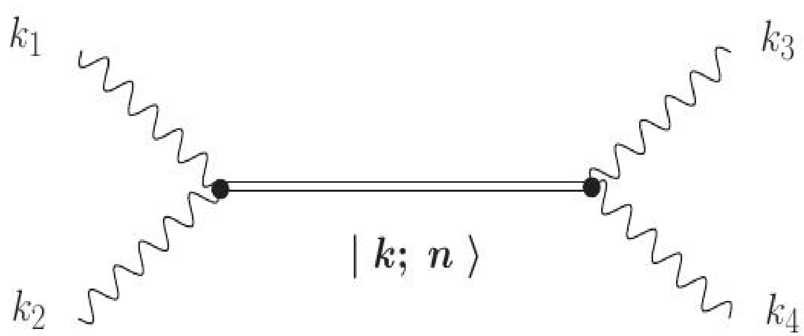
with masses near string scale, AND moduli

String states

Cullen, Perelstein, Peskin , PRD 62 (2000) 055012
Dudas, Mourad, NPB 575 (2000) 3
Anchordoqui, Goldberg, Nawata, Taylor, PRL 100 (2008) 171603
Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0804.2013
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, PRL 101 (2008) 241803
Lust, Stieberger, Taylor, NPB 808 (2009) 1
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, NPB 821 (2009) 181
Lust, Schlotterer Stieberger, Taylor, NPB 828 (2010) 139
Lust Int. J. Mod. Phys A26 (2011) 4686

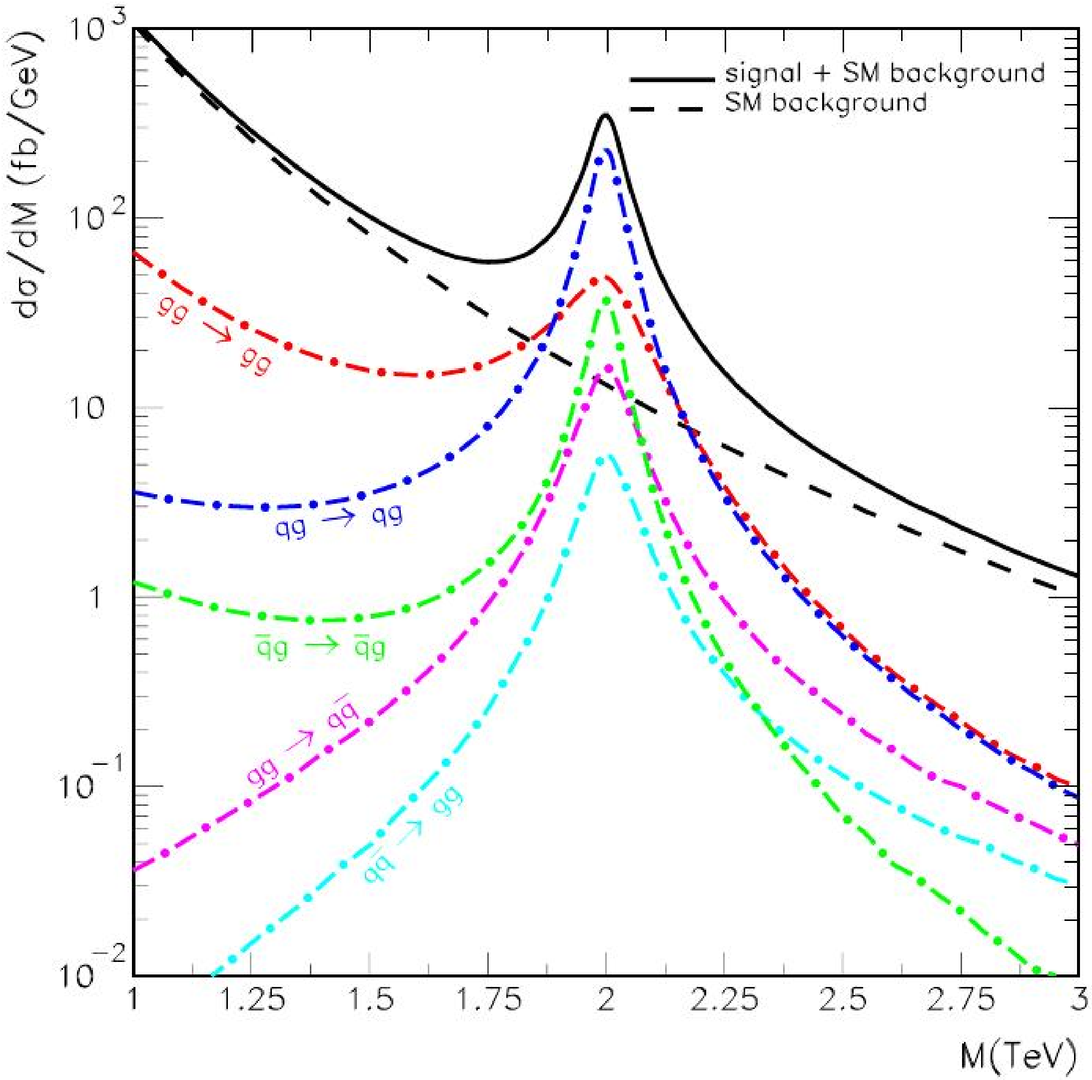
dijets production via Regge excitations

$$M_n^2 = n M_{\text{string}}^2 = \frac{n}{\alpha'}$$



many possible combinations

$g\ g \rightarrow g\ g$
$q\ g \rightarrow q\ g$
$\bar{q}\ g \rightarrow \bar{q}\ g$
$g\ g \rightarrow q\ \bar{q}$
$q\ \bar{q} \rightarrow g\ g$

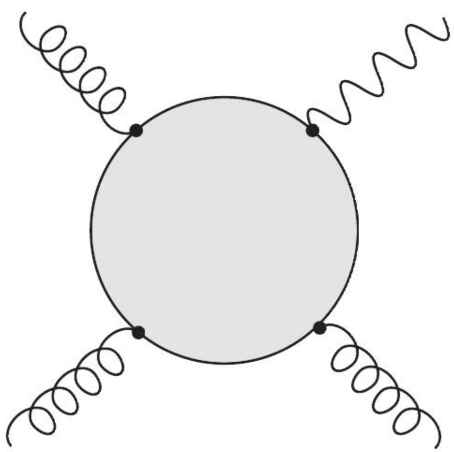


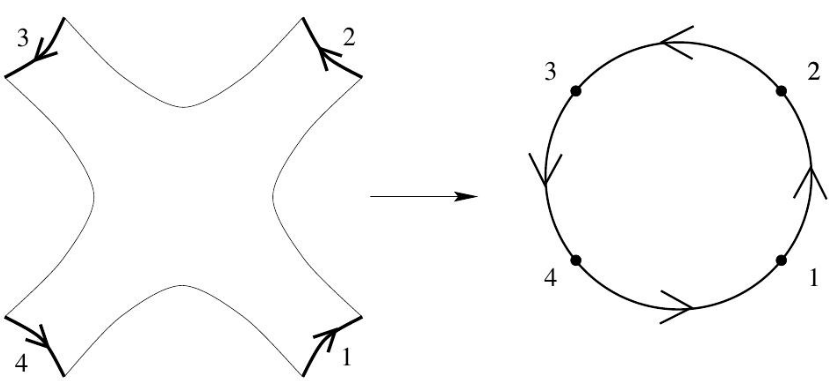
tri-jets production or more via Regge excitations also possible

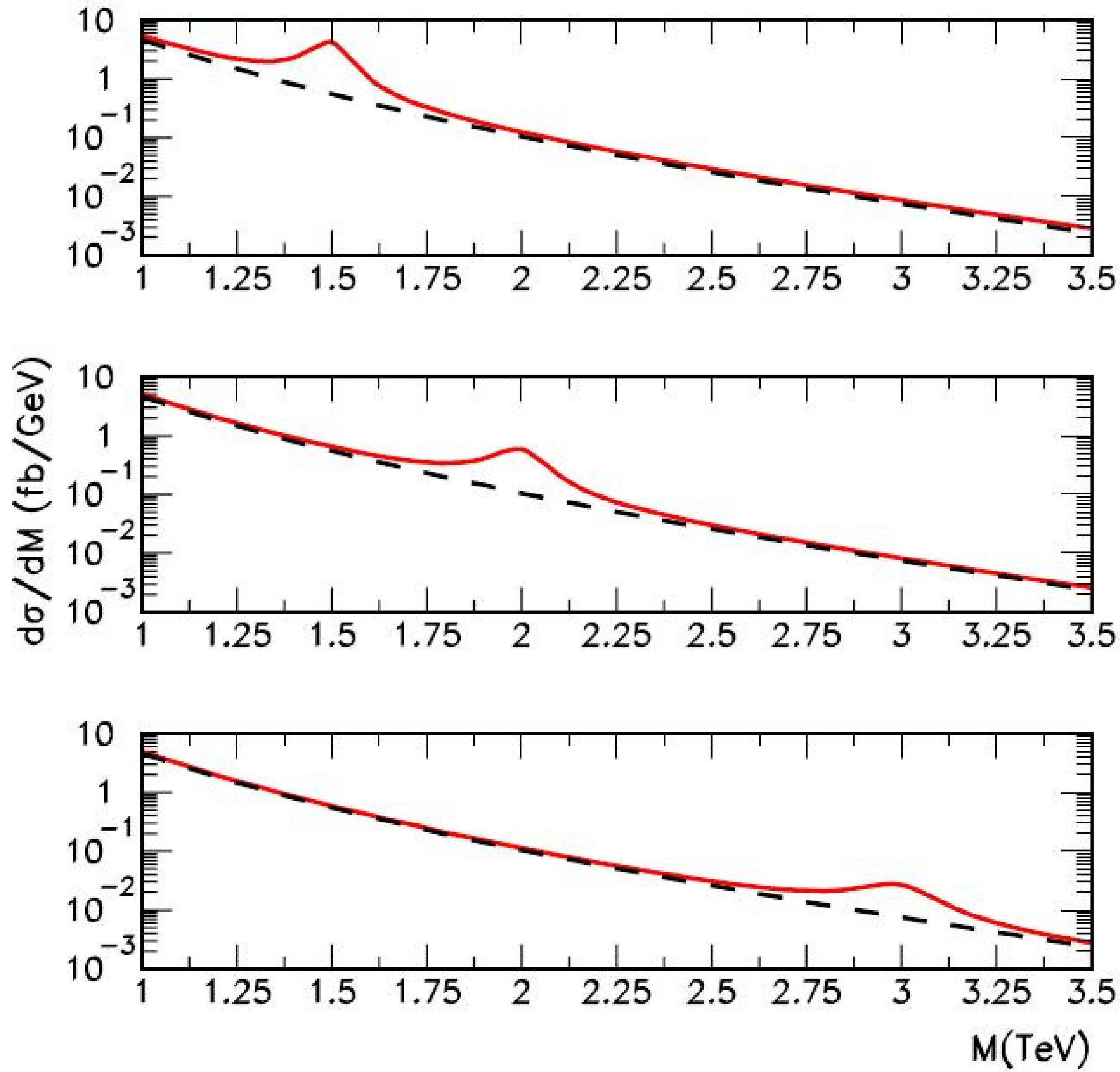
String states

direct photon via string states

$$g\ g \rightarrow \gamma + g$$



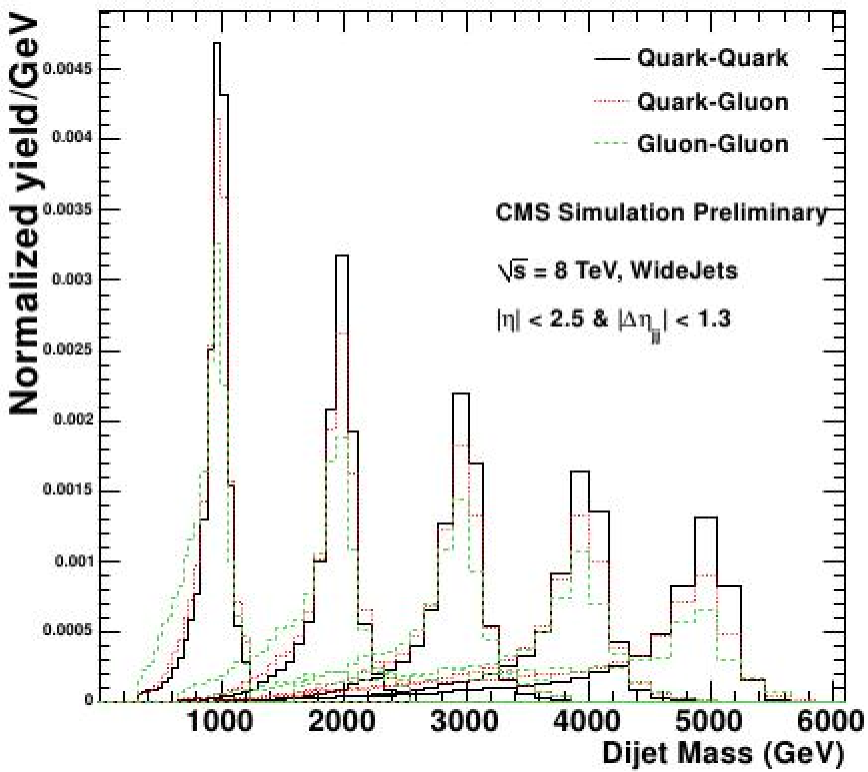


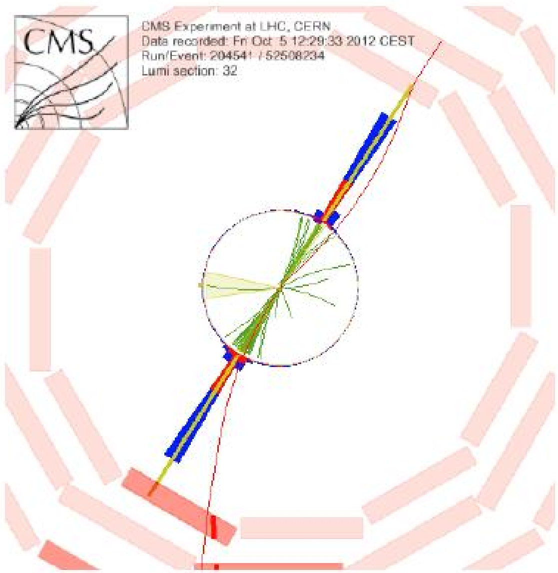


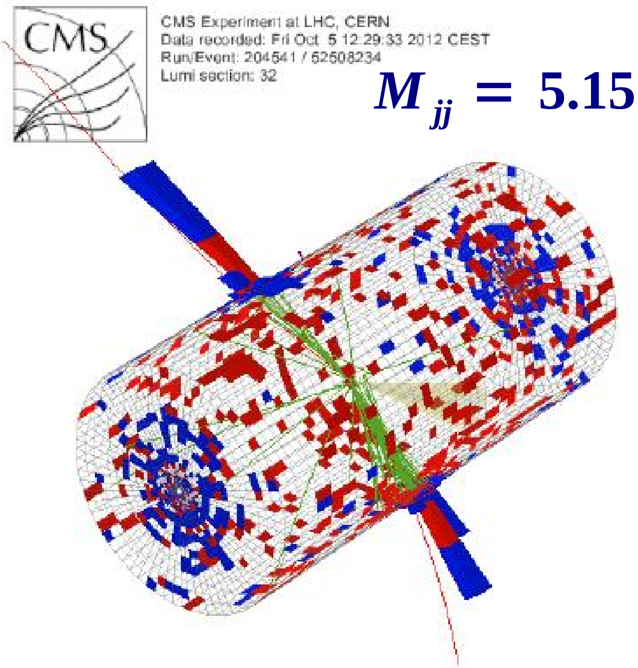
resonant dijets

CMS-EXO-12-059

(**RS**, **string states,** final state also suited for search for TeV-1, Bulk RS)







M_{jj} = 5.15 TeV

$q\bar{q} \rightarrow G_{KK} \rightarrow q\bar{q}$

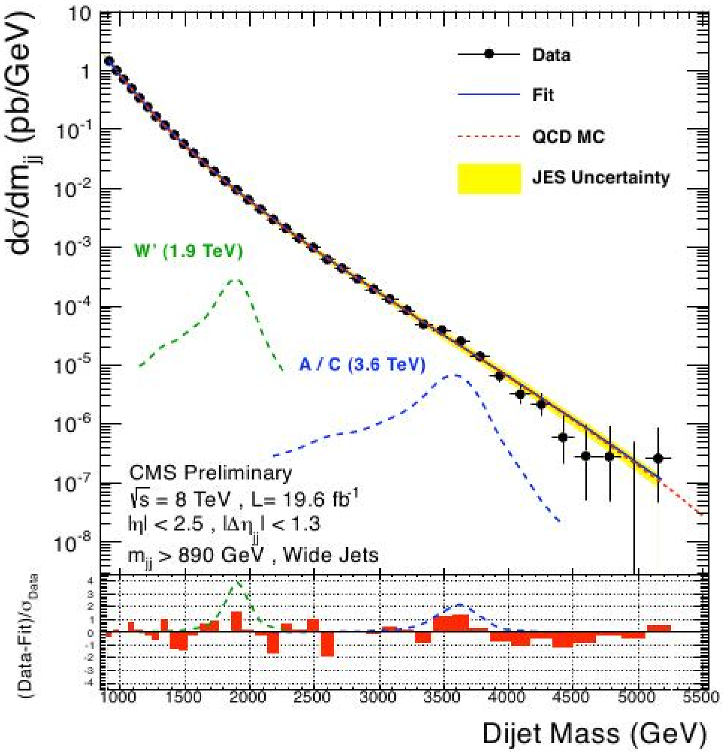
$q\,g \rightarrow q^{*} \rightarrow q\,g$

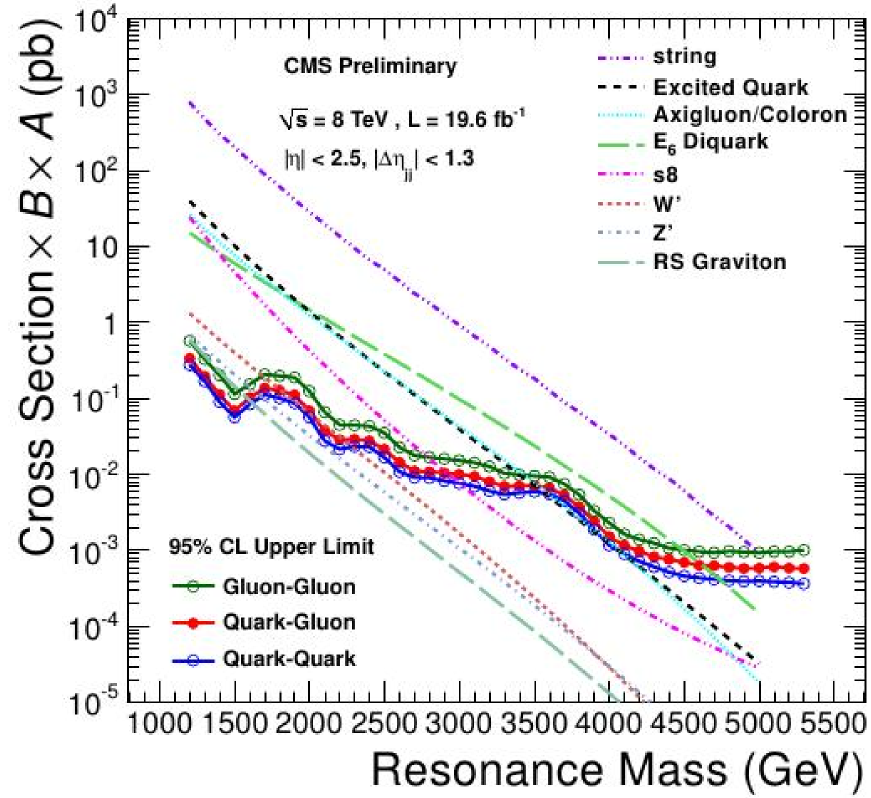
$g\,g \rightarrow G_{KK} \rightarrow g\,g$

resonant dijets

CMS-EXO-12-059

(RS, string states, final state also suited for search for TeV-1, Bulk RS)





Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
→ String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
→ RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

stabilized RS

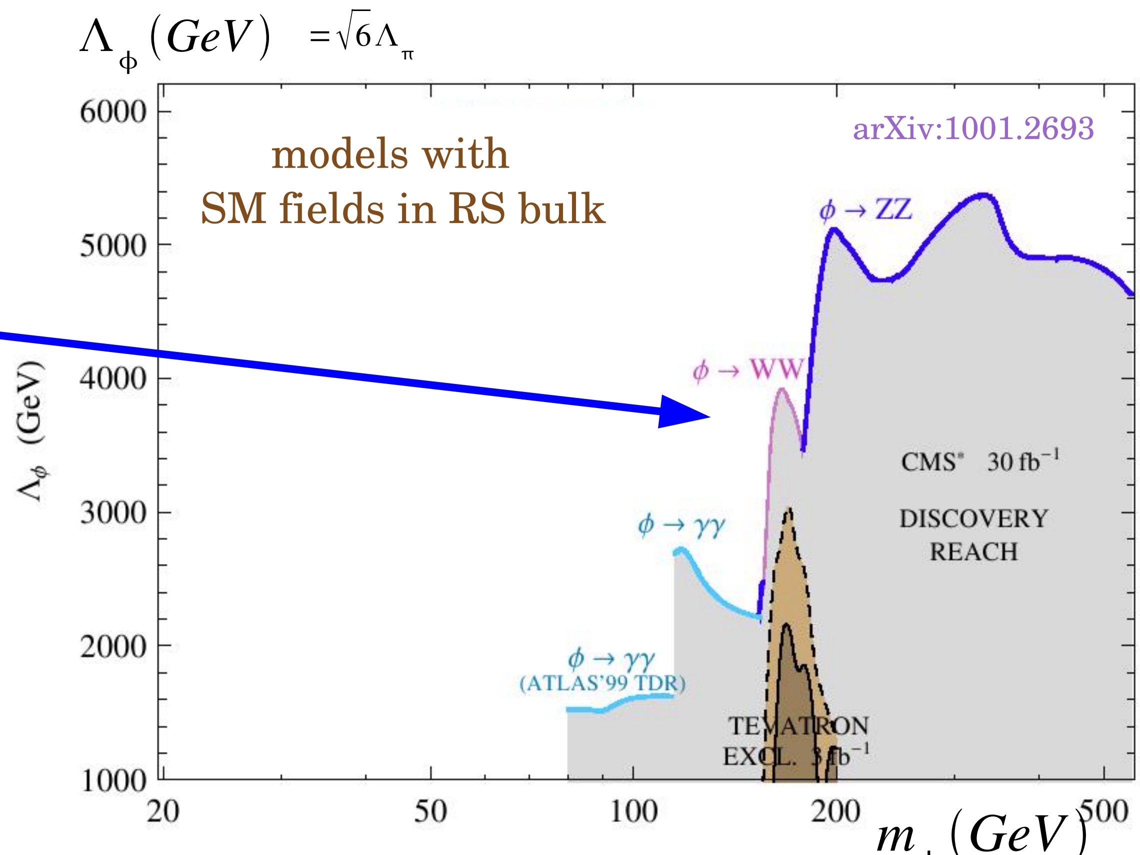
- pure radion effects on precision EW data are small

Gunion, Toharia, Wells, PLB 585 (2004) 295

- radion searches using SM Higgs searches

$\phi \rightarrow h\,h$ also possible

key difference w.r.t SM Higgs
→ direct couplings to gluons



Radion and bulk RS
Rizzo, JHEP 06 (2002) 056
Csaki, Hubisz, Lee, PRD76, 125015
Azatov, Toharia, Zhu, PRD80, 031701

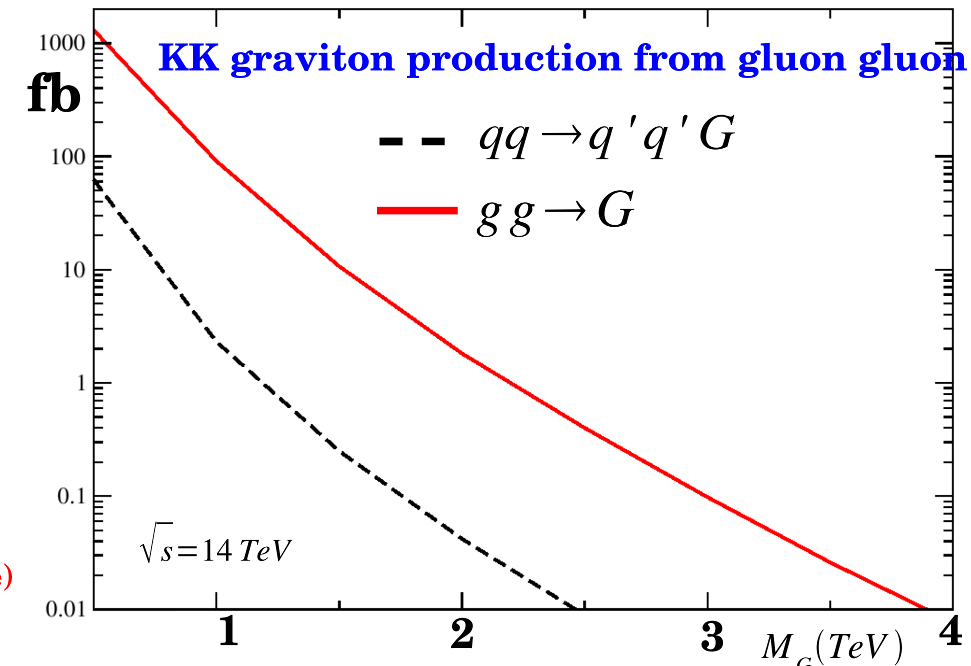
Bulk RS models

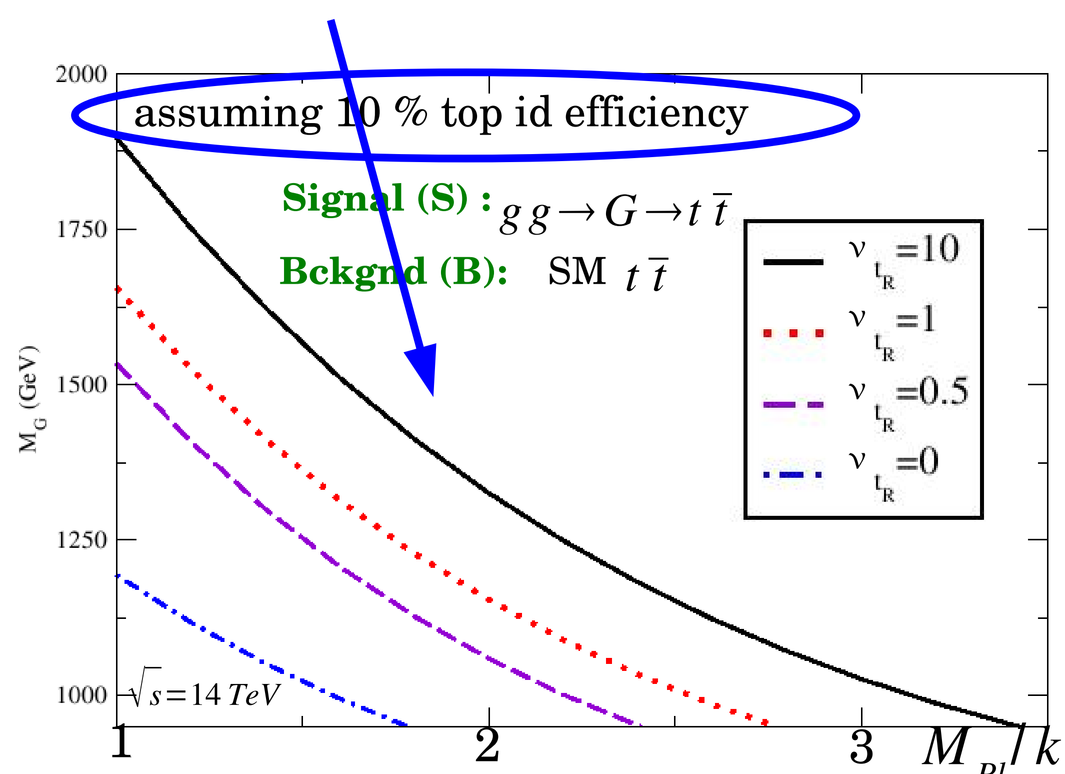
KK Graviton search

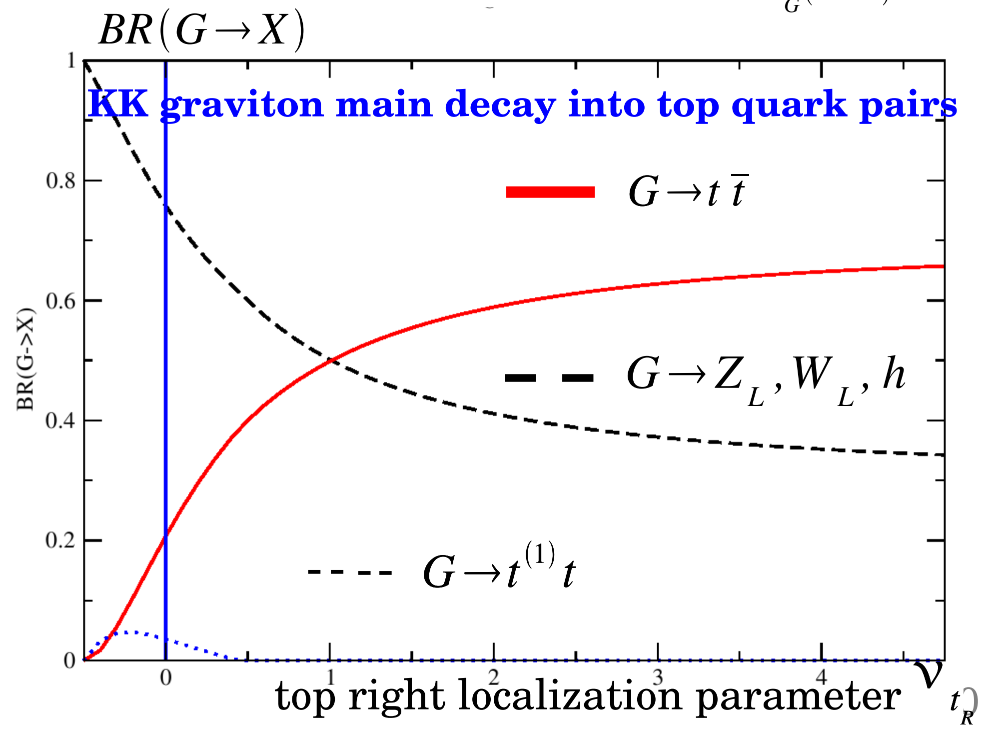
Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006
Antipin, Atwood, Soni, PLB 666 (2008) 155
Antipin, Soni, JHEP10 (2008) 018

- **KK Graviton close to TeV Brane**
- 1st (and 2nd) generation fermion near Planck brane
  i.e. small coupling with 1st and 2nd quark generation
- **gluon profile is flat**
- **t and b quark close to TeV brane**

$\frac{S}{\sqrt{B}}=5$ **reach for various t quark IR localization** ν_{tR} (the bigger the closer to IR brane)

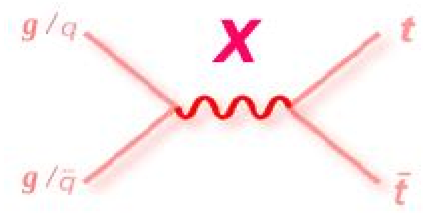






semileptonic $t\bar{t}$

CMS-B2G-12-006



- 2 analyses

  low/high mass coverage

  i.e. threshold/boosted

  transition at ~ 1 TeV

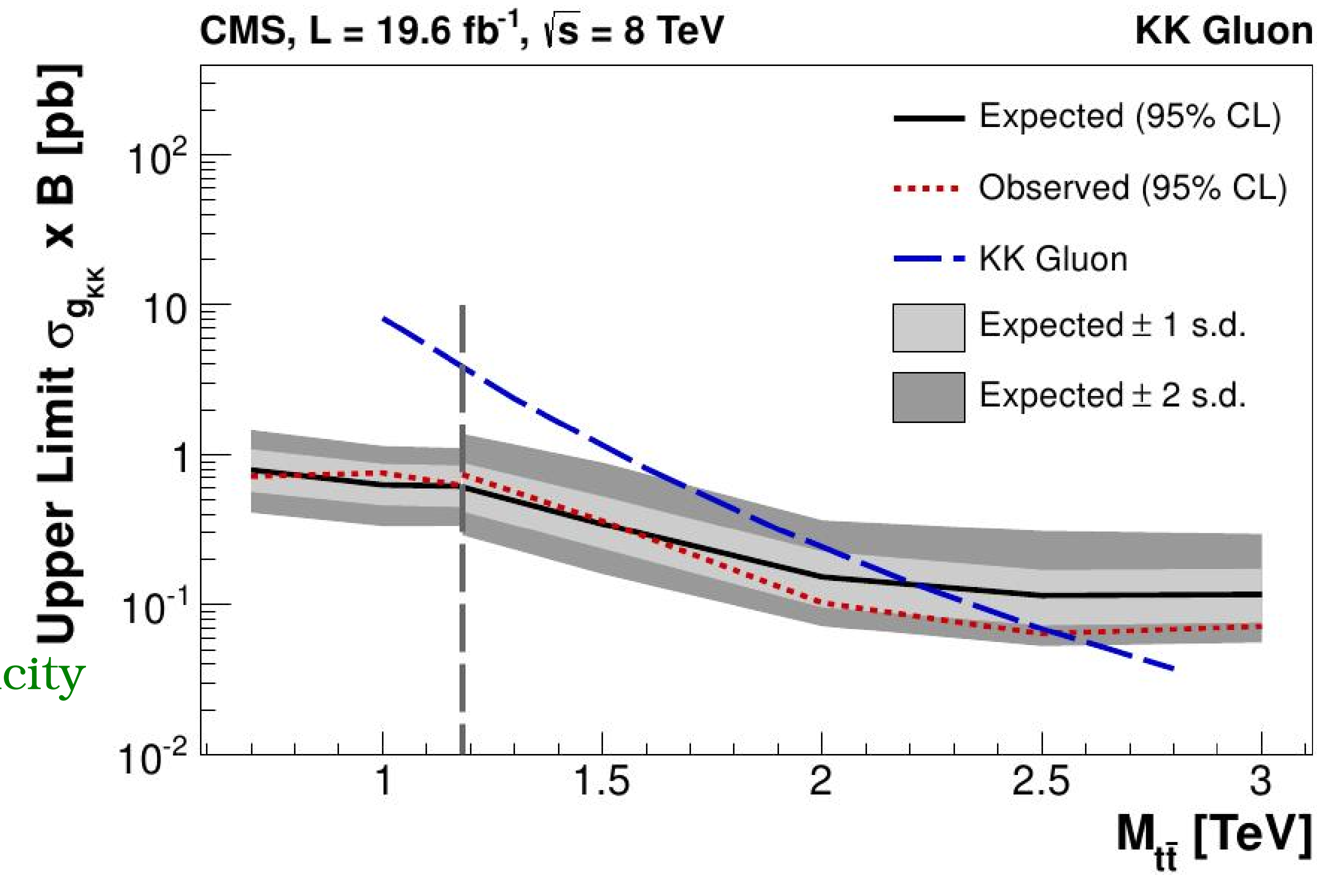
- for boosted analysis

  less isolation

  smaller b-tagged jet multiplicity

  higher 'wide' jet multiplicity

  jet substructure



- limits from the combination of the 2 analyses

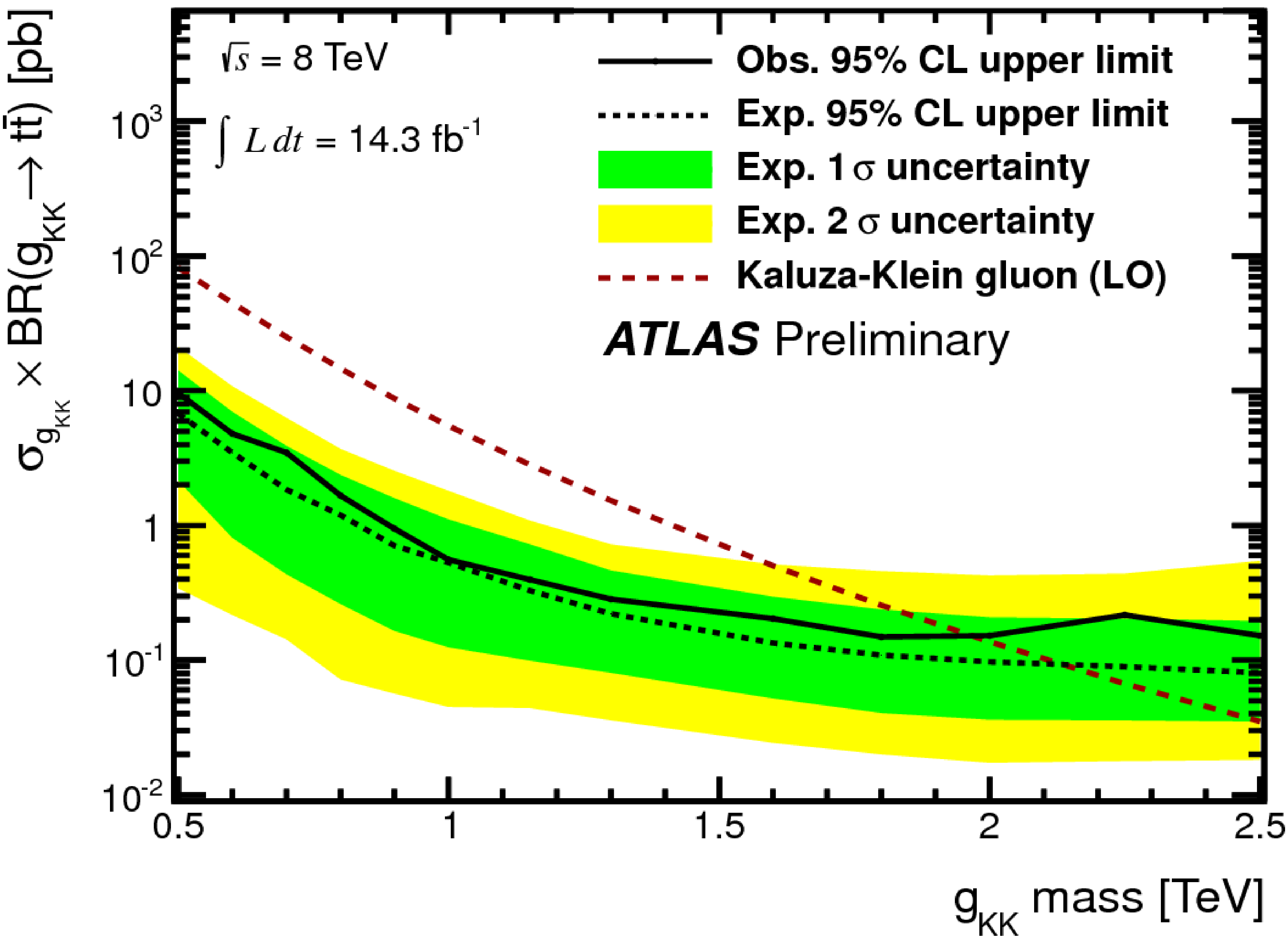
$m_{g_{KK}^{(1)}} > 2.54$ TeV

$\sigma . Br(pp \rightarrow g_{KK}^{(1)} \rightarrow t\bar{t}) < 0.101$ pb $(0.150^{+0.072}_{-0.055}$ pb expected$)$

for $m_{g_{KK}^{(1)}} = 2$ TeV

semileptonic $t\bar{t}$

ATLAS-CONF -2013-052



States with exotic charge (bulk RS)

MCHM$_5$ example : $SO(5)\times U(1)_X \times SU(3)_C$ **as gauge symmetry in the RS bulk**

$SO(5)\times U(1)_X \times SU(3)_C$ broken down to $SO(4)\times U(1)_X \times SU(3)_C$ near IR brane with 4 pseudo Goldstone bosons identified with the Higgs doublet

$SO(4) \approx SU(2)_L \times SU(2)_R$ enlarged to $O(4)$ seen as the custodial symmetry

$G_{SM} = SU(2)_L \times U(1)_Y \times SU(3)_C$ near UV brane and with $Y = X + T_3^R$

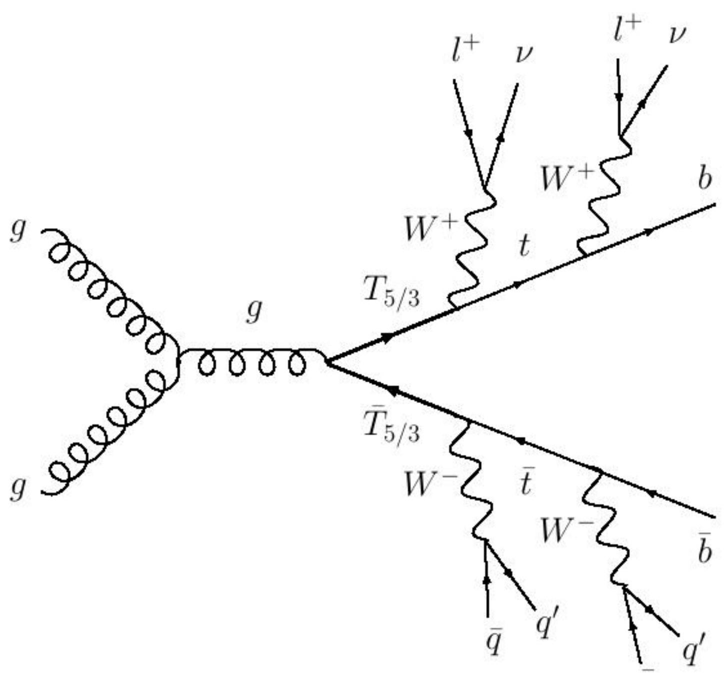
heaviness of top quark $\Rightarrow$ lowest t_{KK} and lightest O(4) custodial partners (i.e. custodians) are significantly lighter than the other KK resonances

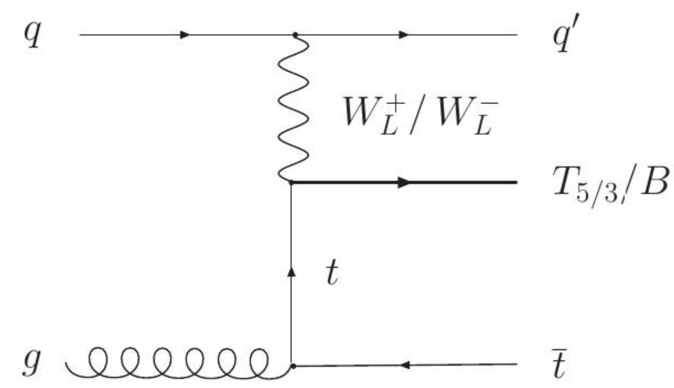
light custodians have e.m charges $5/3,\ \ 2/3,\ \ -1/3$

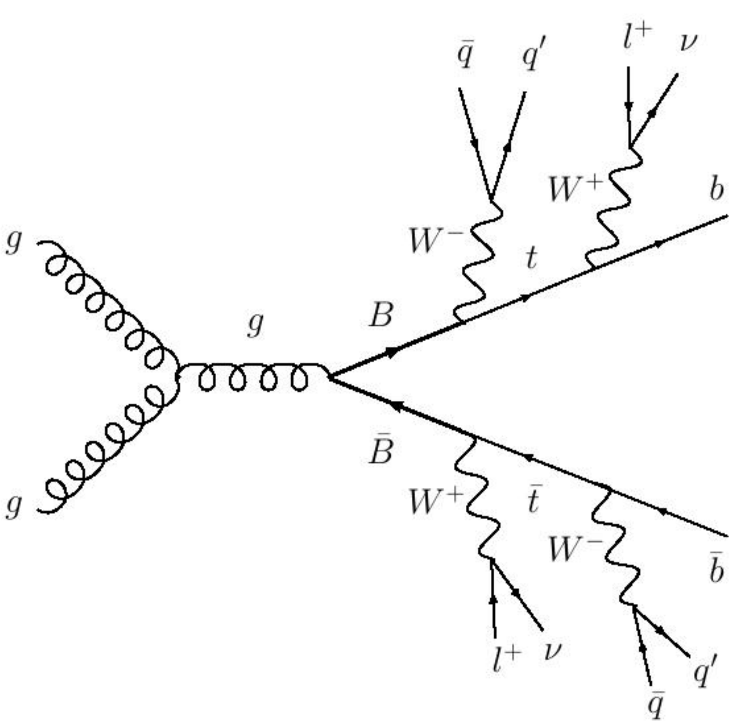
they have mass roughly in the $500-1500$ **GeV range**

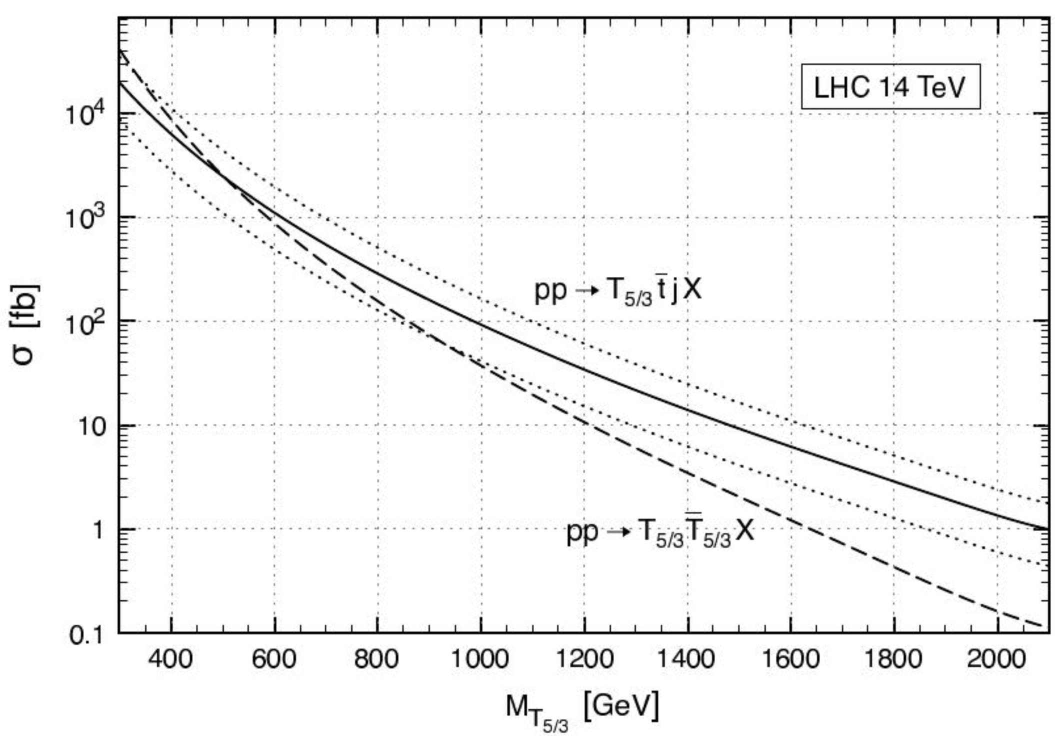
Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050
Agashe, Contino, Pomarol,, NPB 719 2005 165
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006
Contino, Darold, Pomarol,, PRD 75 2007 055014
Contino, Servant, JHEP 06 2008 026

States with exotic charge (bulk RS)







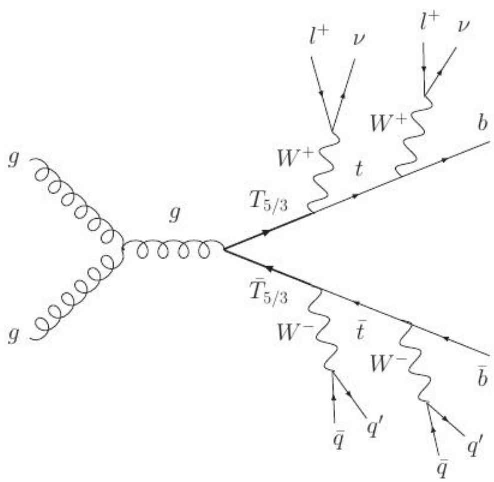


Contino, Servant, JHEP 06 2008 026

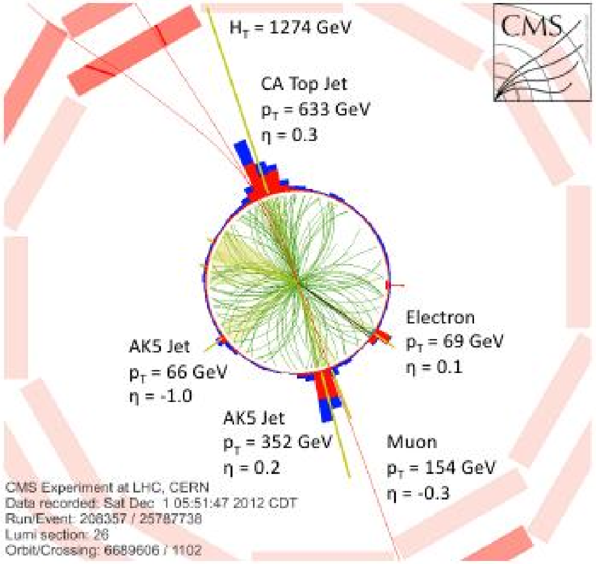
Exotic fermions (5 e/3)

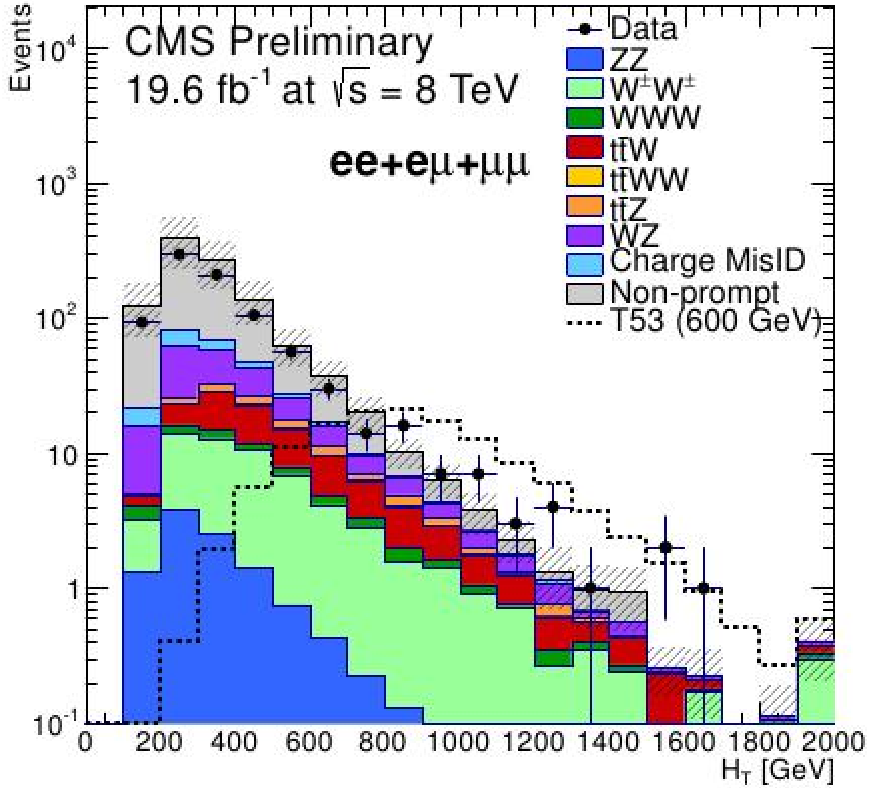
CMS-B2G-12-012

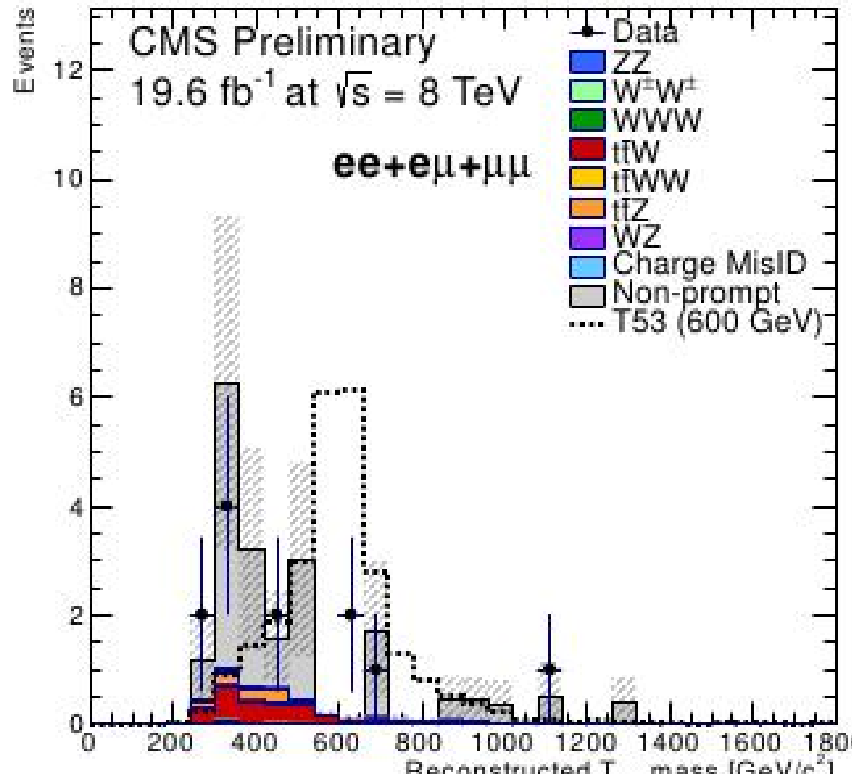
(suited for bulk RS)



same sign dilepton





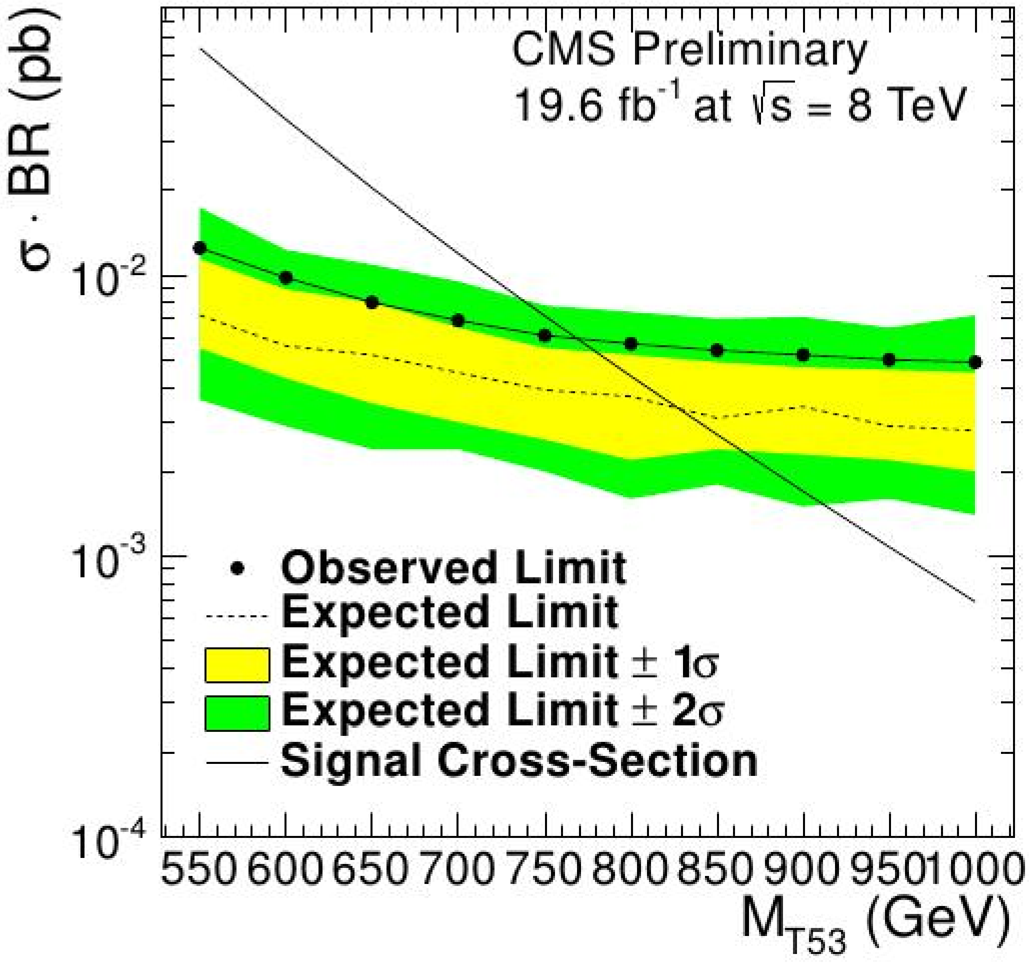


***H_T* = scalar sum of all jets and all leptons**

Exotic fermions (5 e/3)

CMS-B2G-12-012

(bulk RS)



$M_{T_{5/3}} > 770$ GeV

String states

assume fundamental scale is low (TeV) and fundamental theory is string theories

→ strings scale Ms is low (TeV)

spectrum of string states made of 'zero' mass states and massive states

'zero' mass states → graviton, anti-sym tensor field, dilaton (scalar)

+ others identified with SM fields

massive states → (infinite number of) massive Regge excitations of various spin

with masses of order of string scale → then here low (TeV) !

'correction' from Regge excitations : $\frac{s^2}{M_s^4}, \quad \frac{t^2}{M_s^4}, \quad \frac{u^2}{M_s^4}$ (back to pointlike particle limit when $s^2/M_s^4 \to 0$)

4-point amplitudes with Regge excitation : $O(g_s) \sim \frac{1}{25}$ i.e. bigger than the one from QFT with KK graviton exchange which is $O(g_s^2)$

also present in spectrum : KK AND winding excitations of the SM fields

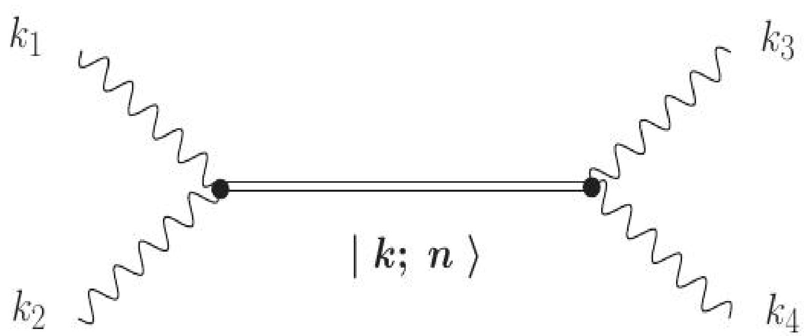
with masses near string scale, AND moduli

String states

Cullen, Perelstein, Peskin , PRD 62 (2000) 055012
Dudas, Mourad, NPB 575 (2000) 3
Anchordoqui, Goldberg, Nawata, Taylor, PRL 100 (2008) 171603
Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0804.2013
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, PRL 101 (2008) 241803
Lust, Stieberger, Taylor, NPB 808 (2009) 1
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, NPB 821 (2009) 181
Lust, Schlotterer Stieberger, Taylor, NPB 828 (2010) 139
Lust Int. J. Mod. Phys A26 (2011) 4686

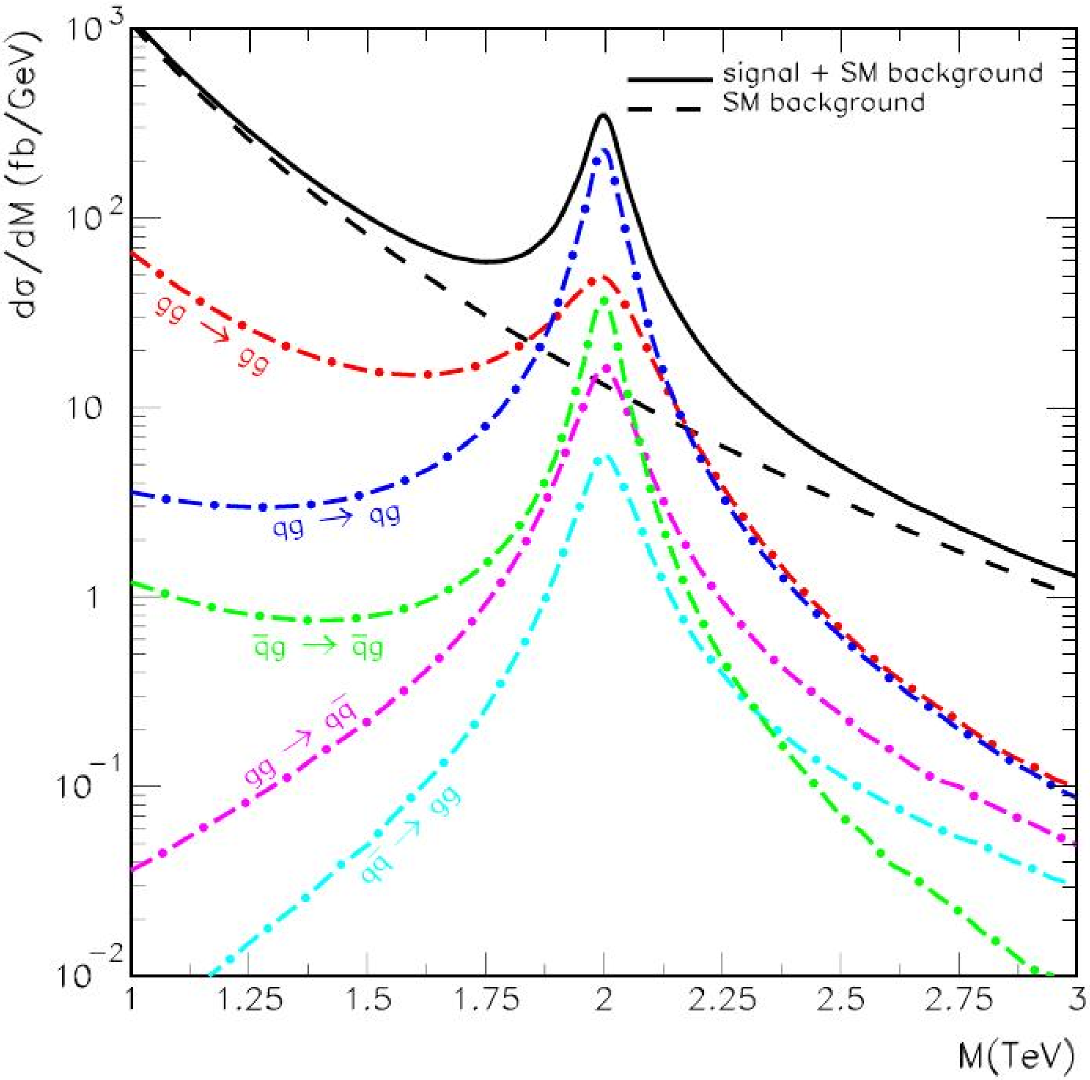
dijets production via Regge excitations

$$M_n^2 = n M_{\text{string}}^2 = \frac{n}{\alpha'}$$



many possible combinations

$g\ g \rightarrow g\ g$
$q\ g \rightarrow q\ g$
$\bar{q}\ g \rightarrow \bar{q}\ g$
$g\ g \rightarrow q\ \bar{q}$
$q\ \bar{q} \rightarrow g\ g$

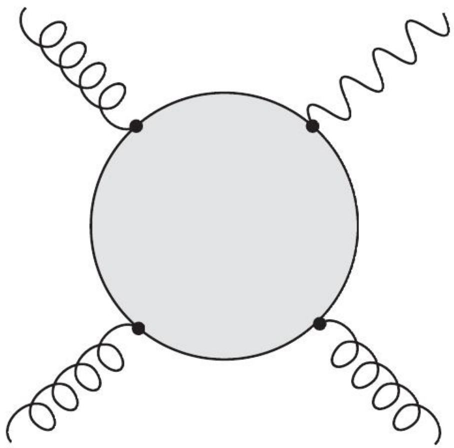


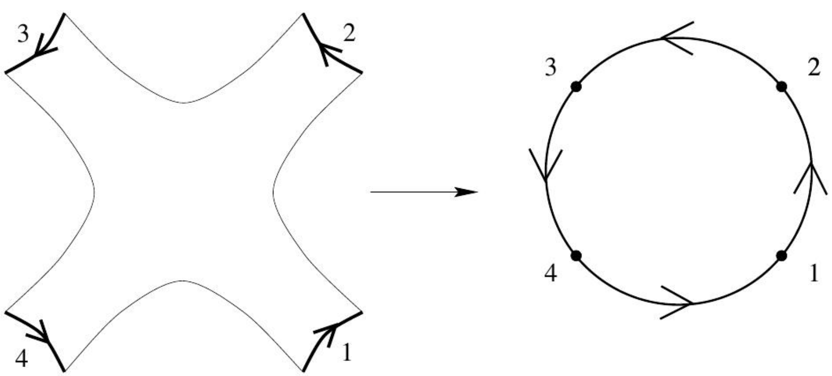
tri-jets production or more via Regge excitations also possible

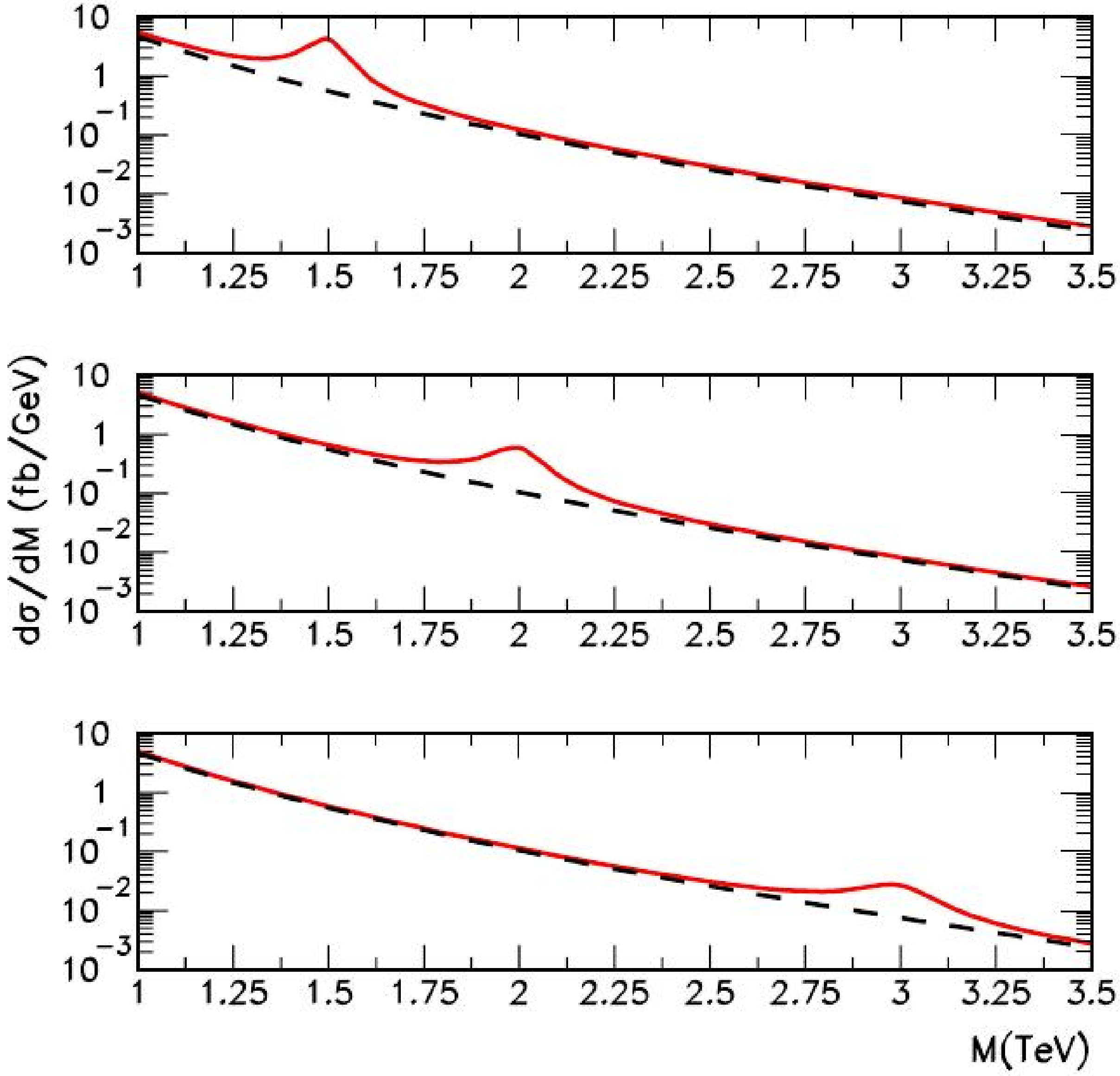
String states

direct photon via string states

$g\ g \rightarrow \gamma + g$



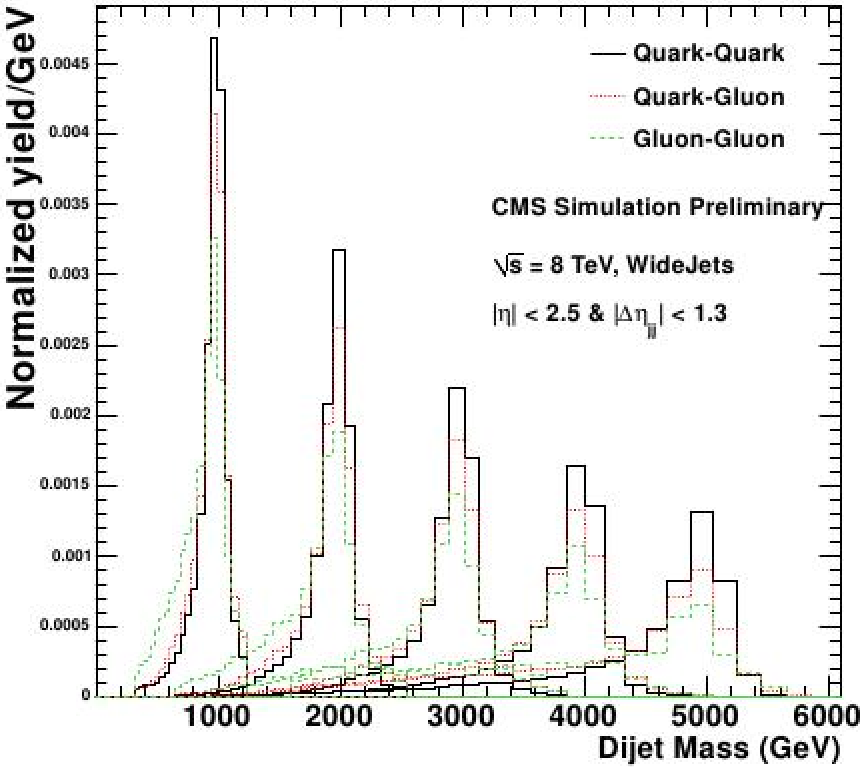




resonant dijets

CMS-EXO-12-059

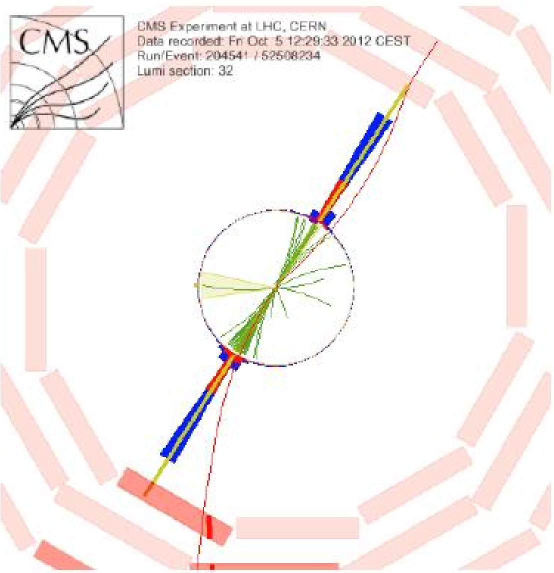
(**RS**, **string states,** final state also suited for search for TeV-1, Bulk RS)

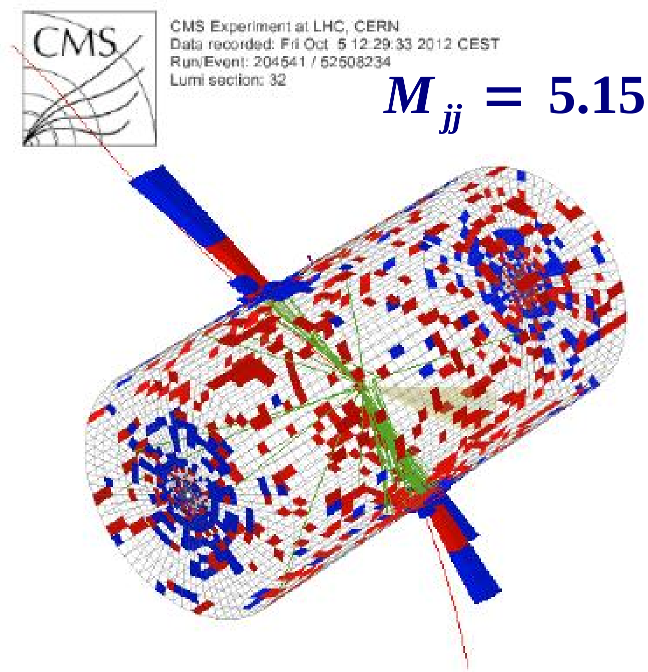


$$q\,\bar{q} \rightarrow G_{KK} \rightarrow q\,\bar{q}$$

$$q\,g \rightarrow q^{*} \rightarrow q\,g$$

$$g\,g \rightarrow G_{KK} \rightarrow g\,g$$





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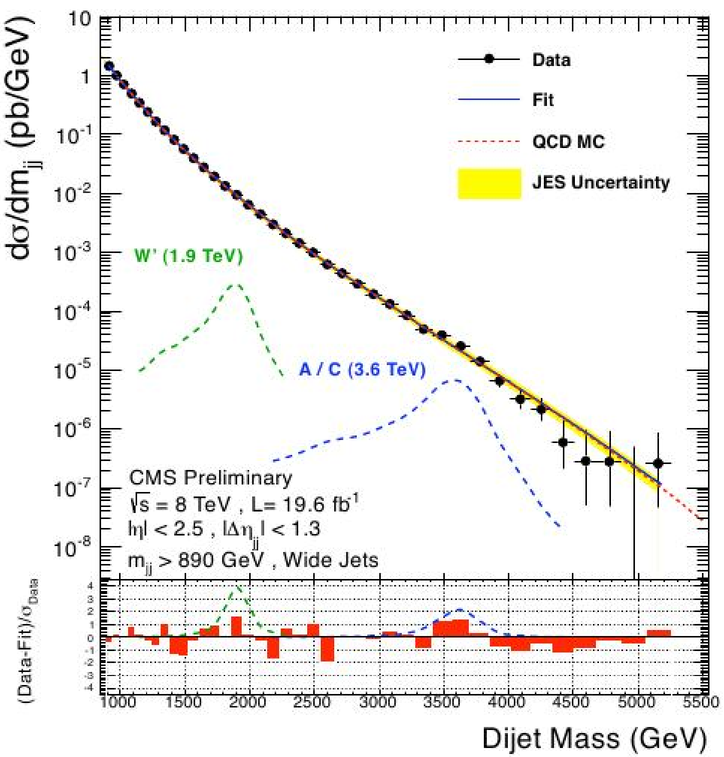

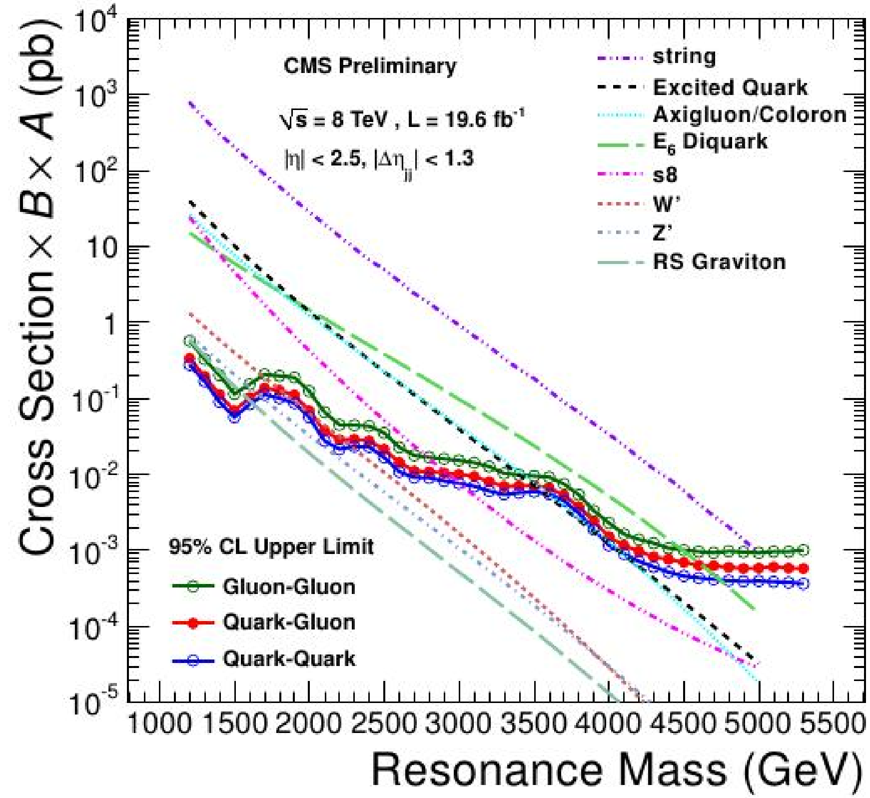

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