Top quark spin correlations in the Randal-Sundrum scenario at the LHC

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- Spin properties of the top quark (polarization, spin correlation)
- Top production in theories with extra dimensions
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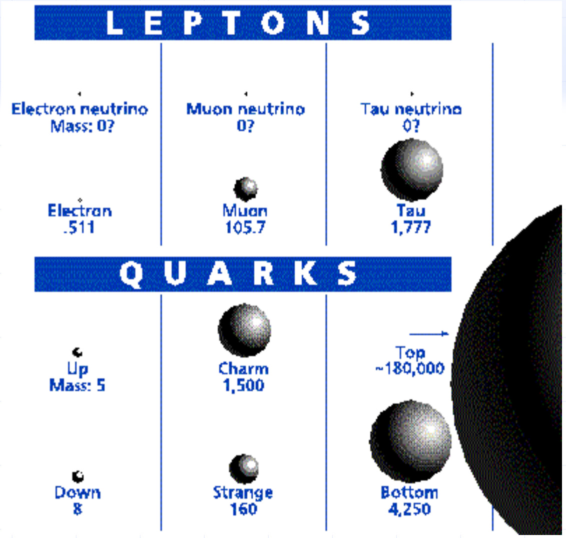
- Conclusion

Top quark

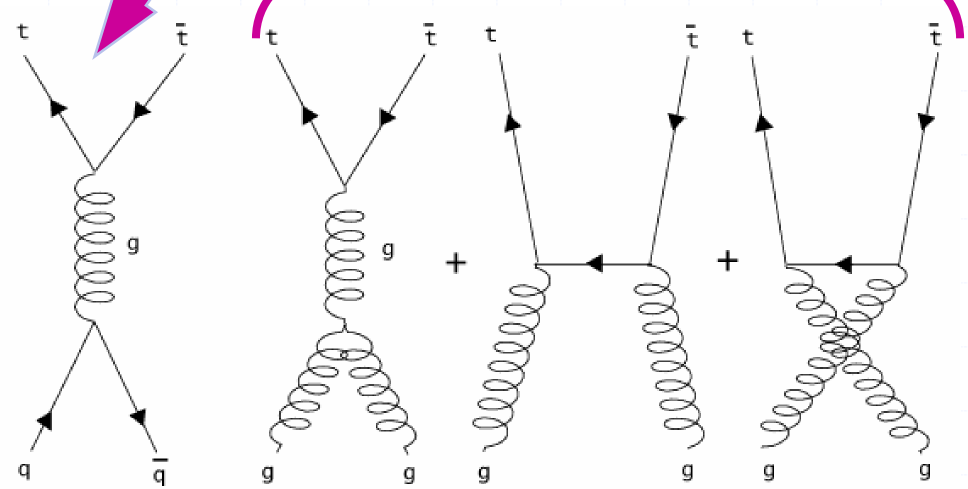
- The heaviest quark of the Standard Model.
- High mass: 175 GeV (as the atom of gold).



LHC: Proton-proton interactions with CMS energy 14 TeV
The most of the top quarks produced in top-antitop pairs

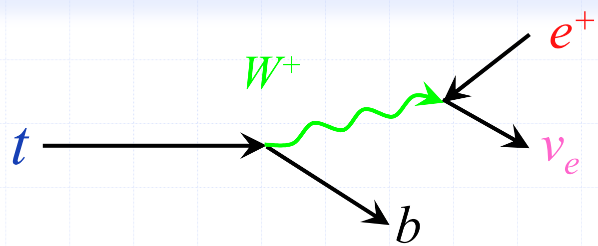
- gluon-gluon fusion (87 %)
- quark-antiquark annihilation (13 %)

} $\sim 10 \cdot 10^6$ pairs/year



- Observed in 1995 in Fermilab (produced ~200 pairs).
- Lifetime: 10^{-24} *s* -> does not hadronise, the angular distribution of decay products is influenced by the spin properties of *t* quark.
- The only one quark, where we can study its spin properties.
- Spin properties of *t* quarks sensitive to some effects beyond the Standard Model.

Decay of top quark



$t \to b + W^+$ – 98.8 %

$W^+ \to \bar{d} + u$, $\bar{s} + c$, ... } 67.6 %

$e^+ + \nu_e$, $\mu^+ + \nu_\mu$ } 21.6 %

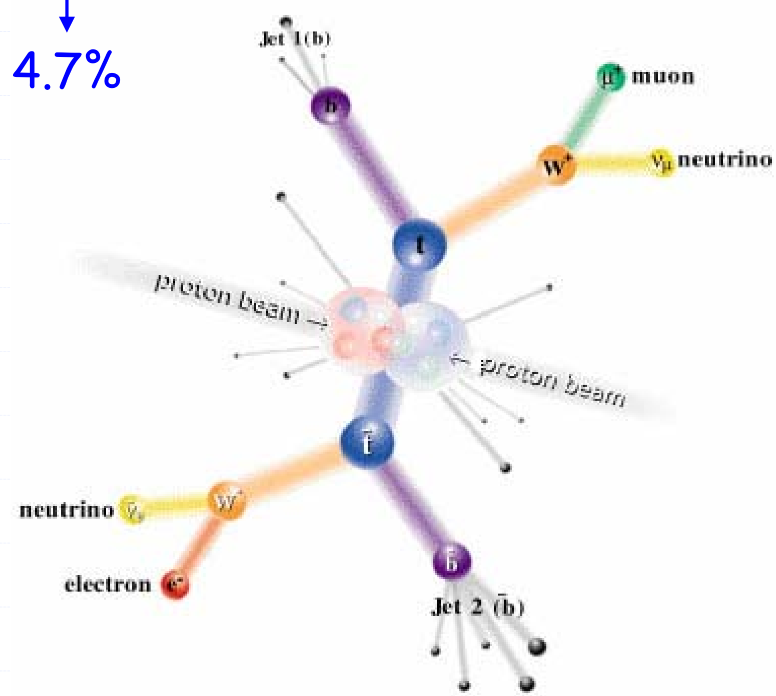
$\tau^+ + \nu_\tau$ – 10.8 %

$\tau^+ \to e^+ + \nu_e + \nu_\tau$, $\mu^+ + \nu_\mu + \nu_\tau$, ... } 35.2 %

$$t \to b + W^+ \to b + \begin{matrix} e^+ \\ \mu^+ \end{matrix} + \nu$$

$$\bar{t} \to \bar{b} + W^- \to \bar{b} + \begin{matrix} e^- \\ \mu^- \end{matrix} + \bar{\nu}$$

4.7%



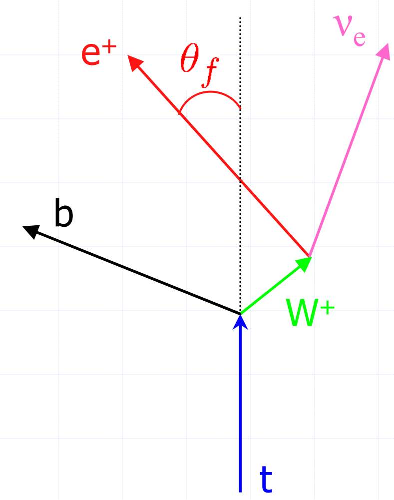
Polarization of the top quark

It is possible to study the polarization of the top quark using the decay products:

$$\frac{1}{N}\frac{dN}{d\cos\theta_f} = \frac{1}{2}(1 + \alpha_f \cos\theta_f)$$

The angle between the direction of movement of particle *f* in the top rest frame and the direction of top quark spin.

-0.41 for b
0.41 for W^+
0.35 for jet
1.0 for e^+, μ^+



- At LHC, the top (antitop) quarks are produced (in a good approximation) as the helicity eigen-states.
- The top and antitop quarks are produced as unpolarized – the same number of left- and right-handed top quarks.

Spin correlation of top-antitop pairs

The number of top-antitop pairs with the same and opposite helicity is not the same.

$$
\begin{aligned}
A &= 4\,\langle(\hat{\mathbf{p}}_t \cdot \mathbf{S}_t)(\hat{\mathbf{p}}_{\bar{t}} \cdot \mathbf{S}_{\bar{t}})\rangle \\
&= \frac{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) - \sigma(t_\uparrow \bar{t}_\downarrow) - \sigma(t_\downarrow \bar{t}_\uparrow)}{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) + \sigma(t_\uparrow \bar{t}_\downarrow) + \sigma(t_\downarrow \bar{t}_\uparrow)} \\
&= 1 - 2\underbrace{\frac{\sigma(t_\uparrow \bar{t}_\downarrow) + \sigma(t_\downarrow \bar{t}_\uparrow)}{\sigma(t_\uparrow \bar{t}_\uparrow) + \sigma(t_\downarrow \bar{t}_\downarrow) + \sigma(t_\uparrow \bar{t}_\downarrow) + \sigma(t_\downarrow \bar{t}_\uparrow)}} \neq 0
\end{aligned}
$$

Fraction of top-antitop pairs with the opposite helicities

SM prediction:

$$A = 0.319$$

- If the top quark is coupled to a new physics beyond the SM, the top-antitop spin correlation could be altered.

How to measure spin correlation

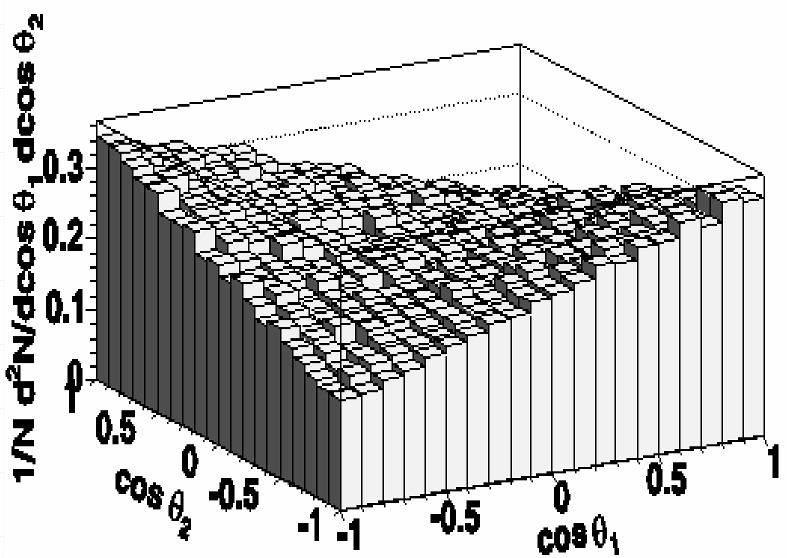
The double differential angular distribution of top and anti-top decay products:

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_f \, d\cos\theta_{\bar{f}}} = \frac{1}{4}(1 - A\,\underbrace{|\alpha_f\alpha_{\bar{f}}|}_{=1 \text{ for double-lepton channel}}\cos\theta_f\cos\theta_{\bar{f}})$$

=1 for double-lepton channel

The best statistical unbiased estimator:

$$A = -9 < \cos\theta_f \cos\theta_{\bar{f}} >$$



$A = 0.319$

Measurement of top spin correlation

In the ATLAS experiment:

- F. Hubaut, E. Monnier, P. Pralavorio, K. Smolek, V. Šimák: *ATLAS sensitivity to top quark and W boson polarization in ttbar events*, Eur.Phys.J. C44 (2005) 13-33.
- Semileptonic and dileptonic top-antitop channel.

- At the LHC, it is possible to increase the assymetry by applying an upper cut on the top-antitop invariant mass:

$$M_{t\bar{t}} < 550\ GeV/c^2$$

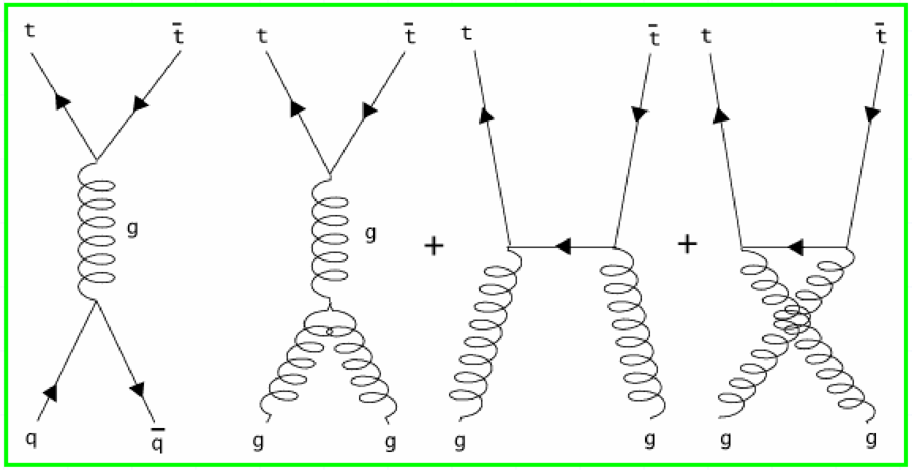
$$\Downarrow$$

$$A = 0.422$$

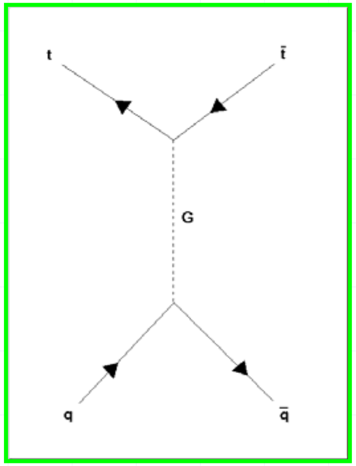
- Combining the results of both channels allow to measure the SM spin correlation *A* with a 3% precision for 10 fb^{-1}.

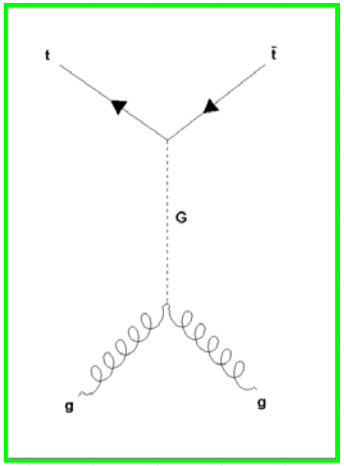
Top quarks in theories with extra dimensions

- We studied two brane world scenarios:
  - ✓ ADD (Arkani-Hamed, Dimopoulos, Dvali)
  - ✓ RS I (Randal, Sundrum)
- Kaluza-Klein states of gravitons can contribute to the top-antitop production.



SM contribution





KK states contribution

- KK gravitons can give rise to characteristic angular distributions and spin configurations of outgoing particles, which reflect the spin-2 nature of KK gravitons.

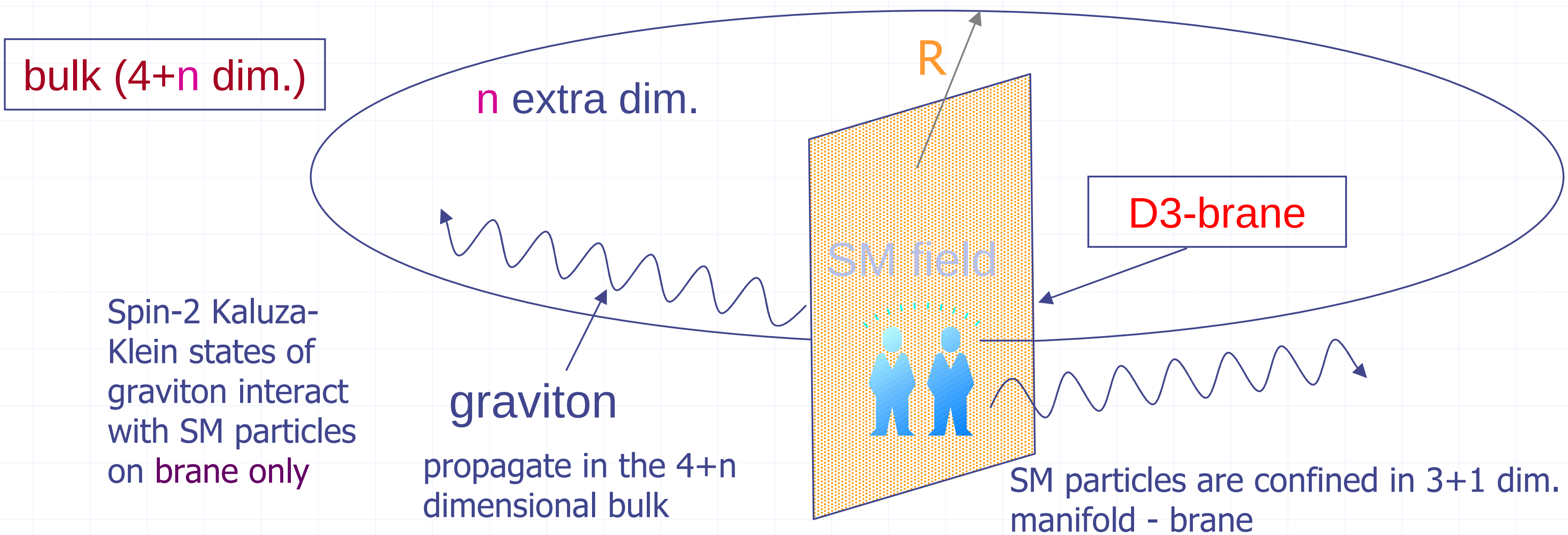
ADD model with large extra dimensions

- Theory with n extra-dimensions compactified with large radii.

N. Arkani-Hamed, et al, PLB429 (1998) 263, hep-ph/9803315
I. Antoniadis, et al, PLB436 (1998) 257, hep-ph/9804398

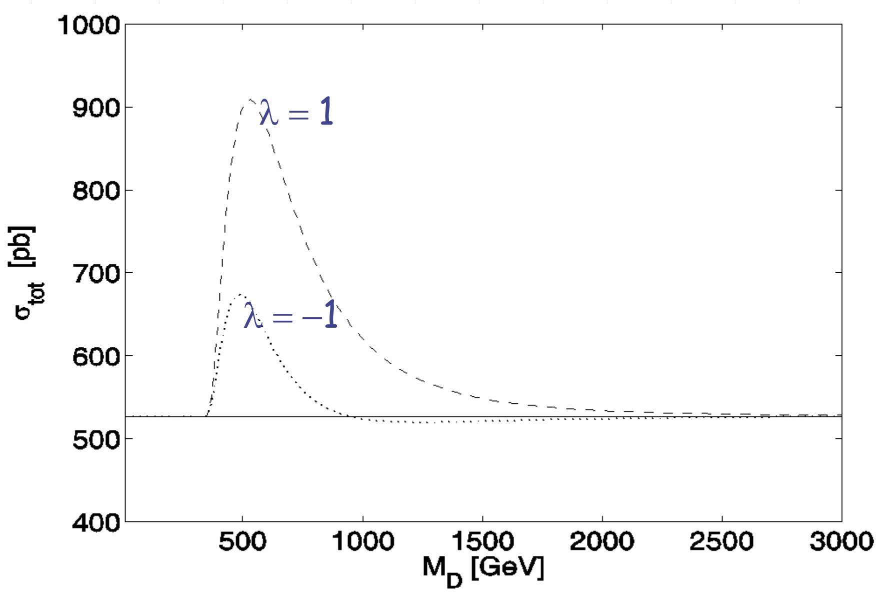
- n-extra dimensions are compactified on n-torus with common radius R
- D3-brane is embedded in 4+n dimensional bulk

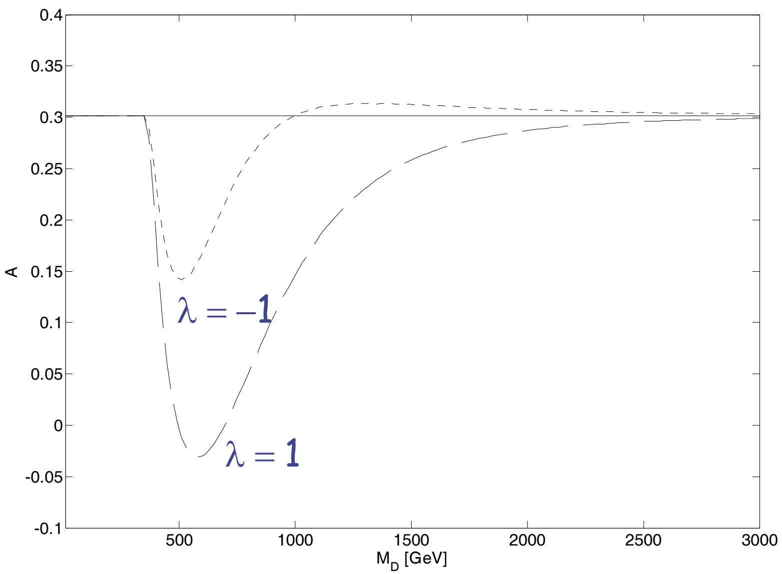
$M_{PL}{}^2 = M_D{}^{n+2} R^n$
M_D= low-energy effective string scale (~ 1 TeV for R ~ 1 mm, n = 2)



Top production in ADD model

- We computed full density matrix for top-antitop production.
- We studied spin correlation of top-antitop in ADD model.
- M. Arai, N. Okada, K. Smolek, V. Šimák: Phys.Rev. D70 (2004) 115015





- $\lambda = \pm 1$ – connected to the regularization procedure for the contributions from the infinite number of KK gravitons. λ represents the sign of the interference term between SM and ADD contribution in the $gg \to t\bar{t}$ process.

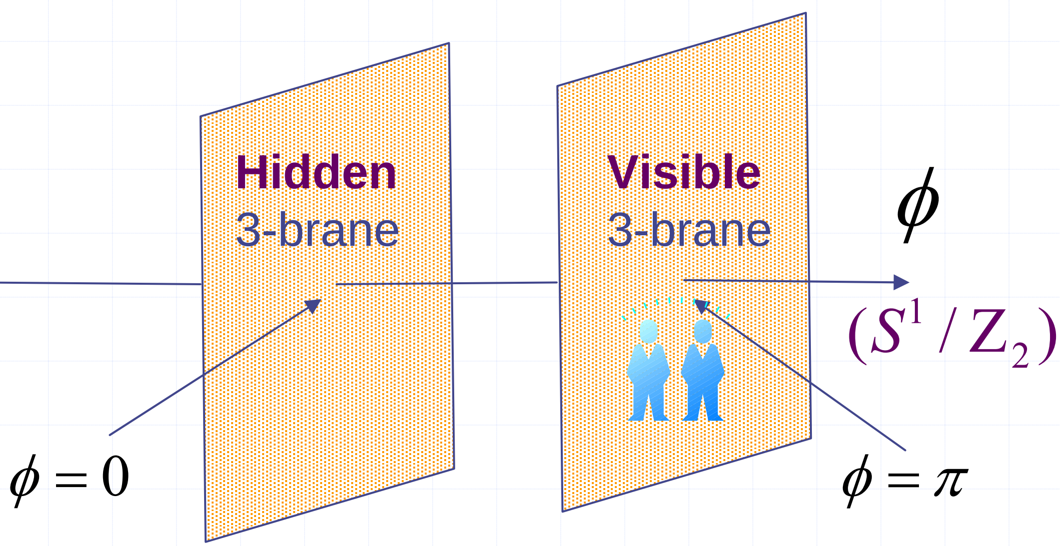
- A sizable deviation of the top spin correlations from the SM one can be visible for the scale M_D below 2 TeV.

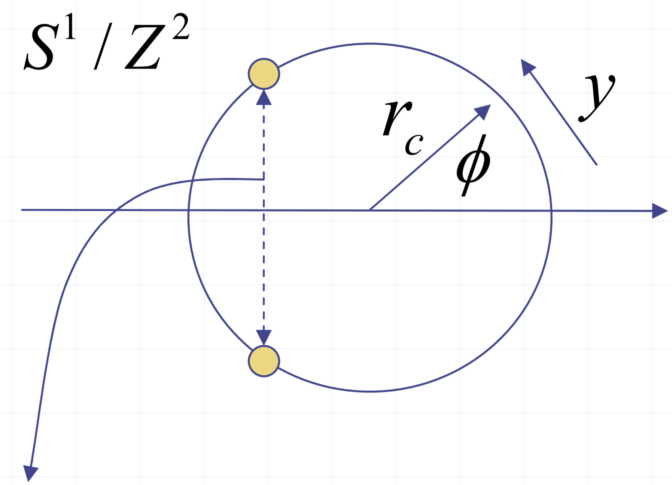
Randal-Sundrum scenario

- In ADD scenario, the energy density of brane (gravitational field that brane produces) is ignored.

<u>RS scenario:</u>

- 5 dimensional theory.
- Warped extra dimension. 5th dimension is compactified with orbifold symmetry.
- Randall, Sundrum, PRL83 (1999) 3370; 4690





Two points are identified.

$$y \leftrightarrow -y$$

$$y \rightarrow y + 2\pi r_c$$

r_c - compactification radius

Randal-Sundrum scenario

- The effective interaction Lagrangian:

$$\mathcal{L}_{\text{int}} = -\frac{1}{\bar{M}_{\text{pl}}} T^{\mu\nu}(x) h^{(0)}_{\mu\nu}(x) - \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x) \, ,$$

$h^{(n)}_{\mu\nu}$ - n-th graviton KK mode

$\bar{M}_{\text{pl}}$ - reduced Plack mass

$T^{\mu\nu}$ - energy-momentum tensor of SM fields on the visible brane

- Sum of all intermediate KK gravitons gives a finite value.
- The graviton zero mode couples with the usual strengts -> negligible effect.

- Each KK graviton strongly couples to SM fields with Λ_π suppressed couplings.

$$\Lambda_\pi = e^{-\kappa r_c \pi} \bar{M}_{\text{pl}} = \frac{m_1}{x_1} \left(\frac{\bar{M}_{\text{pl}}}{\kappa} \right) \sim \text{TeV}$$

κ - 5-dimensional curvature

- For $\kappa r_c \simeq 12, \ \Lambda_\pi = \mathcal{O}(1 \ \text{TeV})$ and give a natural solution to the gauge hierarchy problem.

Randal-Sundrum scenario

- Mass spectrum of gravitons

$$m_n = \kappa x_n e^{\kappa r_c \pi} = m_1 \frac{x_n}{x_1}$$

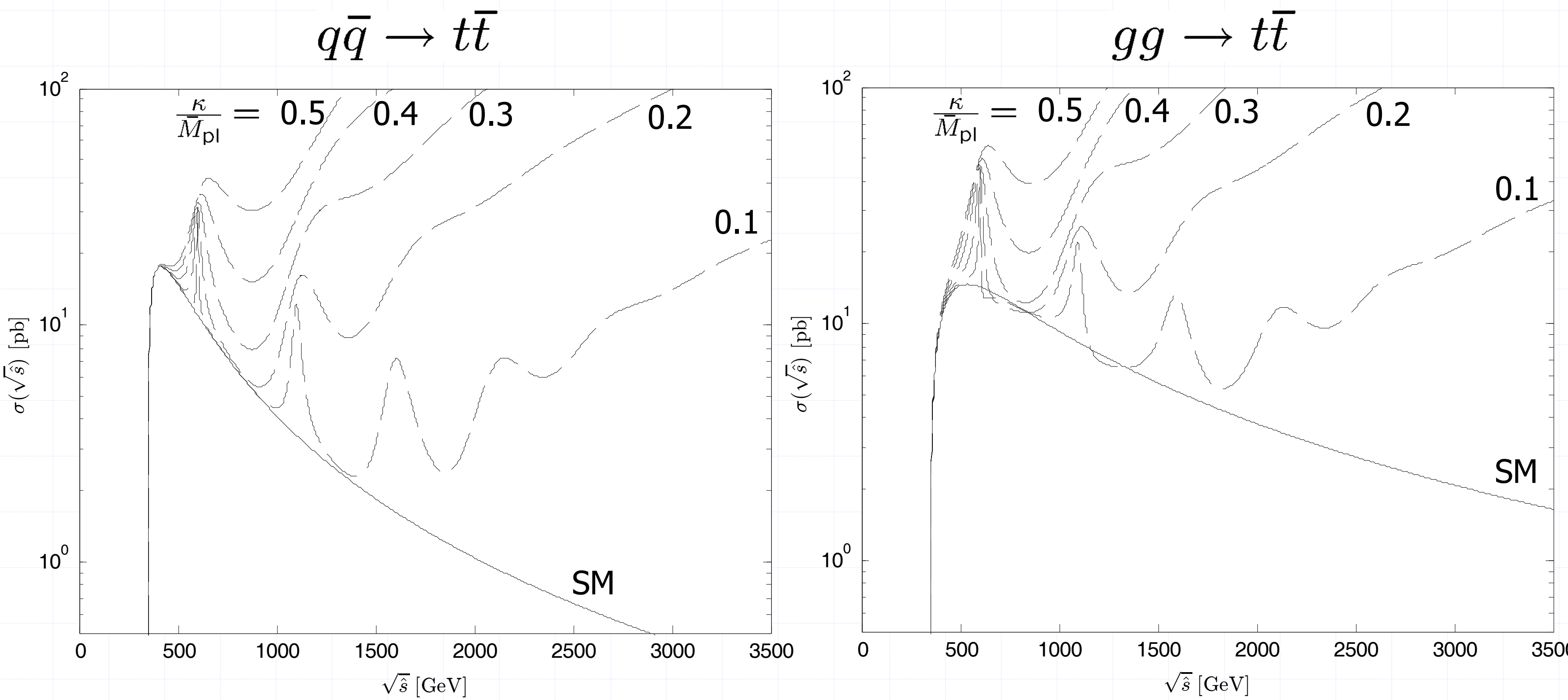
x_n - roots of the Bessel function of the first order (x_1 = 3.83, x_2 = 7.02,...)

- We can expect a resonant production of KK gravitons at colliders.
- The resonance gives rise to an enhancement of production of the top-antitop pairs and provide a big statistical advantage for studying the top spin correlations around the resonance pole.

- In our analysis we used:
  - ✓ m_1 = 600 GeV/c² - $m_1 \geq$ 600 GeV/c² from D0 experiment
  - ✓ $\frac{\kappa}{\bar{M}_{\mathrm{pl}}} = 0.1\ (0.2,\ 0.3,\ 0.4,\ 0.5)$ - guarantees the perturbation of the graviton
  - ✓ m_t = 175 GeV/c²
  - ✓ PDF CTEQ5M1

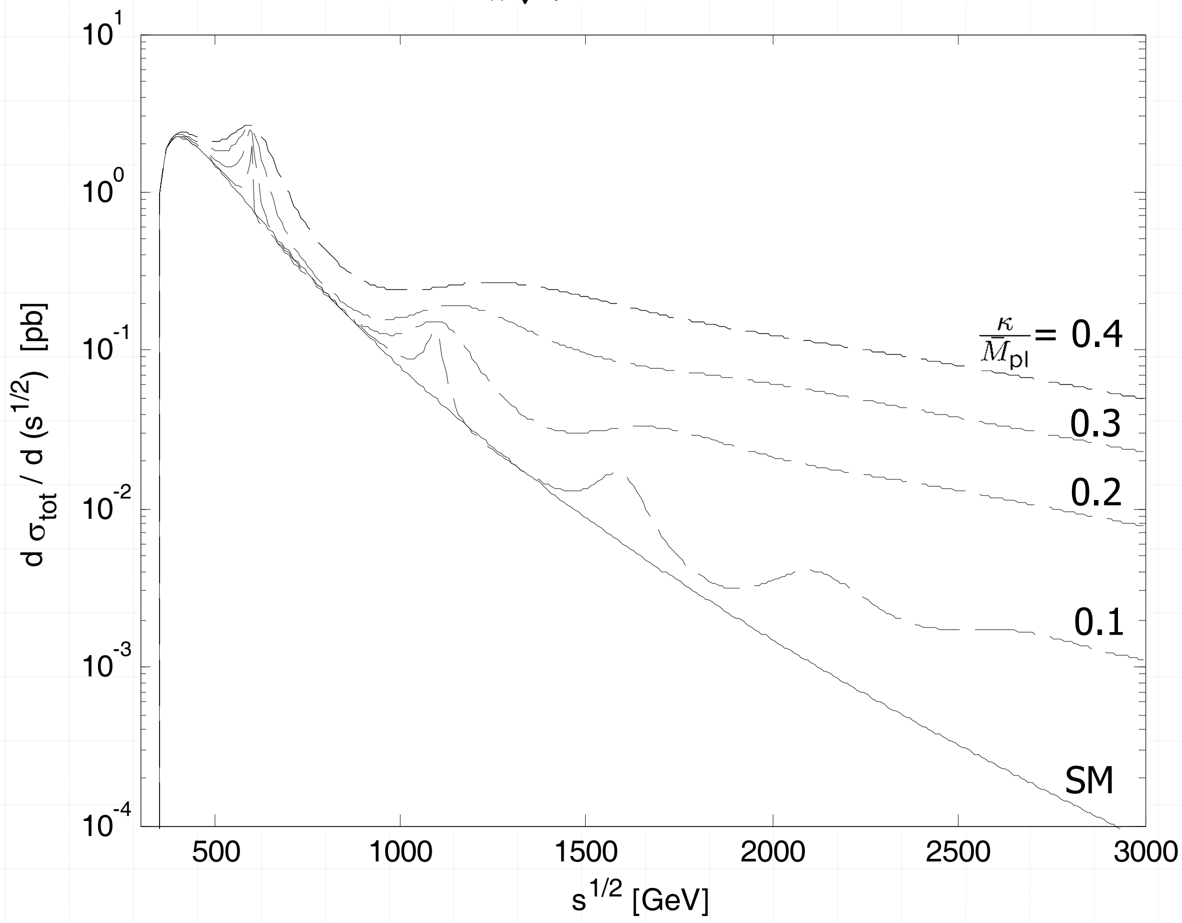
Top quark in Randal-Sundrum scenario - results

The dependance of the cross section of the top-antitop quark pair production by quark annihilation and gluon fusion on the CMS energy of colliding partons.



Top quark in Randal-Sundrum scenario - results

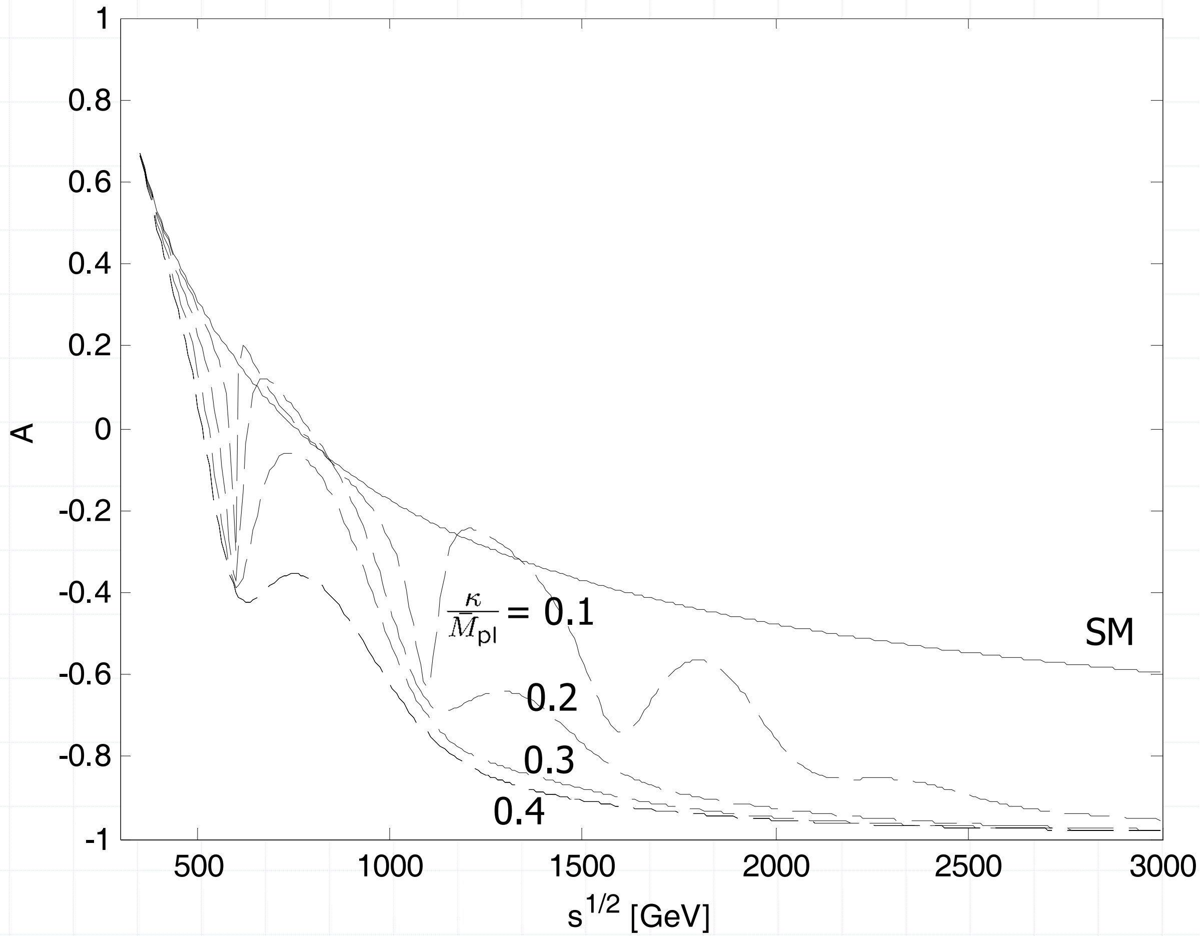
Total differential cross section $\frac{d\sigma_{tot}(pp\to t\bar{t})}{d\sqrt{\hat{s}}}$ as a function of the CMS energy of colliding partons.



• Resonant production of the KK gravitons give rise to an enhancement of the deviations from the SM.

Top quark in Randal-Sundrum scenario - results

Spin asymmetry *A* as a function of the CMS energy of colliding partons.



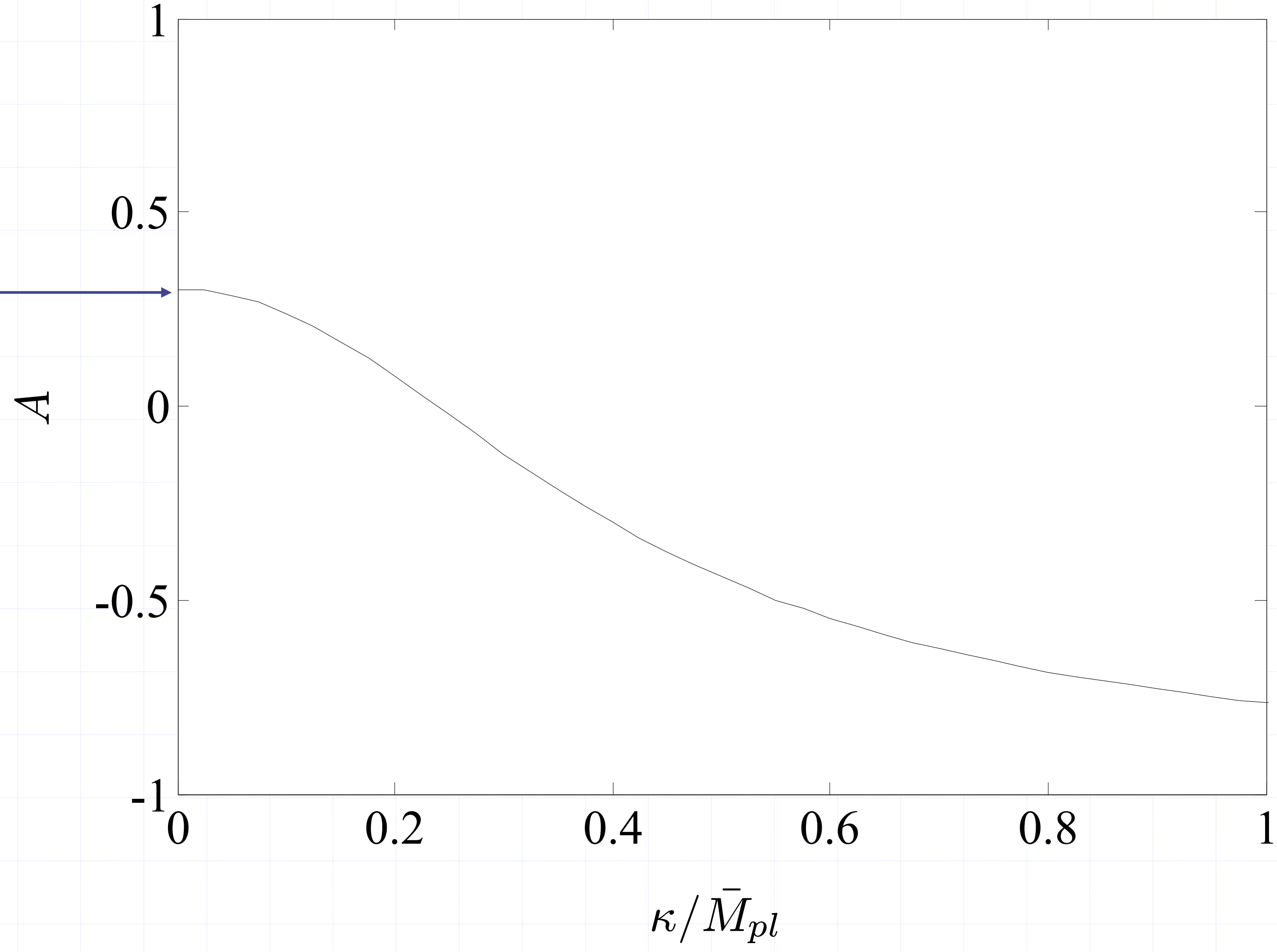
- Resonant production of the KK gravitons give rise to an enhancement of the deviations from the SM.

Top quark in Randal-Sundrum scenario - results

Spin asymmetry A as a function of $\frac{\kappa}{\bar{M}_{\mathrm{pl}}}$.

m_1 = 600 GeV/c^2

SM value



Conclusions

- Because of its high mass, the top quark is an ideal place to search for physics beyond the SM.
- The ADD model with large extra dimensions or RS model is an example of such physics.
- In addition to cross section and various kinematical distributions, the spin correlation is sensitive to the existence extra dimensions.
- We studied in detail the production of top-antitop quarks at LHC for the RS scenario.
- The influence of gravitons in the RS model on the spin correlation of top-antitop quarks could be visible at the LHC.
- Resonant production of the KK gravitons give rise to a remarkable enhancement of the deviations from the SM. This is a crucial difference from the case in the ADD model.