Рождение пары мюонов на БАК в процессе, индуцированном фотонами, в модели с дополнительной размерностью и малой кривизной пространства-времени

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Семинар ОТФ, 9 октября 2018 года

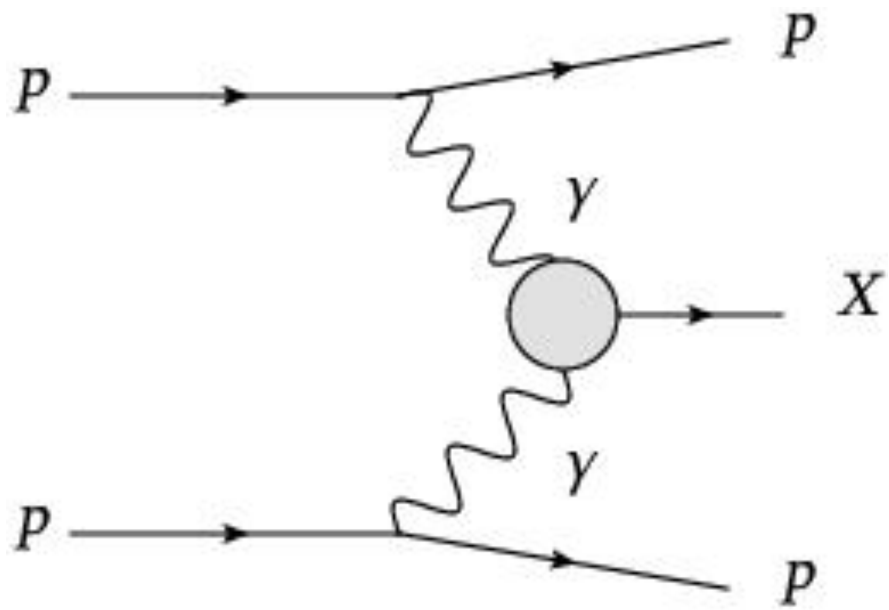
…всего натуральнее было бы постановить, что только те науки распространяют свет, кои способствуют выполнению начальственных предписаний.

М.Е. Салтыков –Щедрин,
«Дневник провинциала в Петербурге»

План доклада

- Эксклюзивное рождение в столкновении фотонов и его экспериментальное изучение.
- Модель Рандалл-Сундрума (РС) с одной дополнительной размерностью и ее обобщение.
- Процесс на БАК, индуцированный фотонами. Приближение эквивалентных фотонов.
- Дифференциальное и полное сечения для процесса $pp \to p\gamma\gamma p \to p\mu^+\mu^- p$ при энергии 14 ТэВ в РС модели с малой кривизной пространства-времени.
- Заключение.

Photon-induced exclusive production



Schematic diagram for the reaction pp → pγγp → pXp
(X =$\mu^+\mu^-$, e^+e^-, γγ, WW, ZZ, H, *etc.*)

Forward detectors at the LHC can detect intact outgoing protons in interval:

$$\xi_{\min} < \xi < \xi_{\max}$$

where ξ is momentum fraction loss of the proton

Acceptance ranges:

ATLAS Forward Physics Collaboration (AFP)	$0.0015 < \xi < 0.15$ $0.015 < \xi < 0.15$
CMS-TOTEM Precision Proton Spectrometer (CT-PPS)	$0.0015 < \xi < 0.5$ $0.1 < \xi < 0.5$

Experimental studies of photon-induced reactions

Tevatron, CDF Collaboration, 2009:

$pp \to p\gamma\gamma p \to pl^+l^-p$ ($l = e, \mu$)

LHC (7 TeV), CMS Collaboration, 2012:

$pp \to p\gamma\gamma p \to pl^+l^-p$ ($l = e, \mu$)

LHC (7 TeV), ATLAS Collaboration, 2014:

$pp \to p\gamma\gamma p \to pl^+l^-p$ ($l = e, \mu$)

LHC (8 TeV), ATLAS Collaboration, 2016:

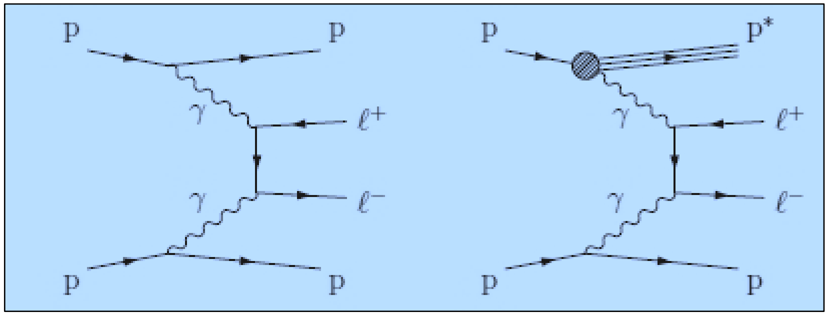
$pp \to p\gamma\gamma p \to pl^+l^-p$ ($l = e, \mu$)

First observation of proton-tagging $\gamma\gamma$ collision:
LHC (13 TeV), CMS-TOTEM Collaboration, 2018

$pp \to p\gamma\gamma p^* \to pl^+l^-p^*$

$m(l^+l) > 110$ GeV

12 $\mu^+\mu^-$, 8 e^+e^-



Randall-Sundrum scenario

Background metric (y is extra coordinate)

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^{\mu}dx^{\nu} - dy^2$$

warp factor

Periodicity: $(x, y \pm 2\pi r_c) = (x, y)$

Z_2-symmetry: $(x, y) = (x, -y)$

→ orbifold S^1/Z_2 $0 \le y \le \pi r_c$

Two fixed points: $y=0$ and $y=\pi r_c$

→ two (1+3)-dimensional branes

5-dimensional action $S = S_g + S_1 + S_2$

$$S_g = \int d^4x \int dy \sqrt{G} \left(2M_5^3 R^{(5)} - \Lambda\right)$$ (gravity term)

$$S_{1(2)} = \int d^4x \sqrt{g_{1(2)}} \left(L_{1(2)} - \Lambda_{1(2)}\right)$$ (brane terms)

Einstein-Hilbert's equations:

$$\sigma'^2(y) = -\frac{\Lambda}{24M_5^3}$$

$$\sigma''(y) = \frac{1}{12M_5^3}[\Lambda_1\delta(y) + \Lambda_2\delta(\pi r_c - y)]$$

Original Randall-Sundrum solution

(Randall & Sundrum, 1999)

$$\sigma_{\rm RS}(y) = \kappa\,|\,y\,|$$

$$\Lambda_{\rm RS} = -24M_5^3\kappa^2, \quad (\Lambda_1)_{\rm RS} = -(\Lambda_2)_{\rm RS} = 24M_5^3\kappa$$

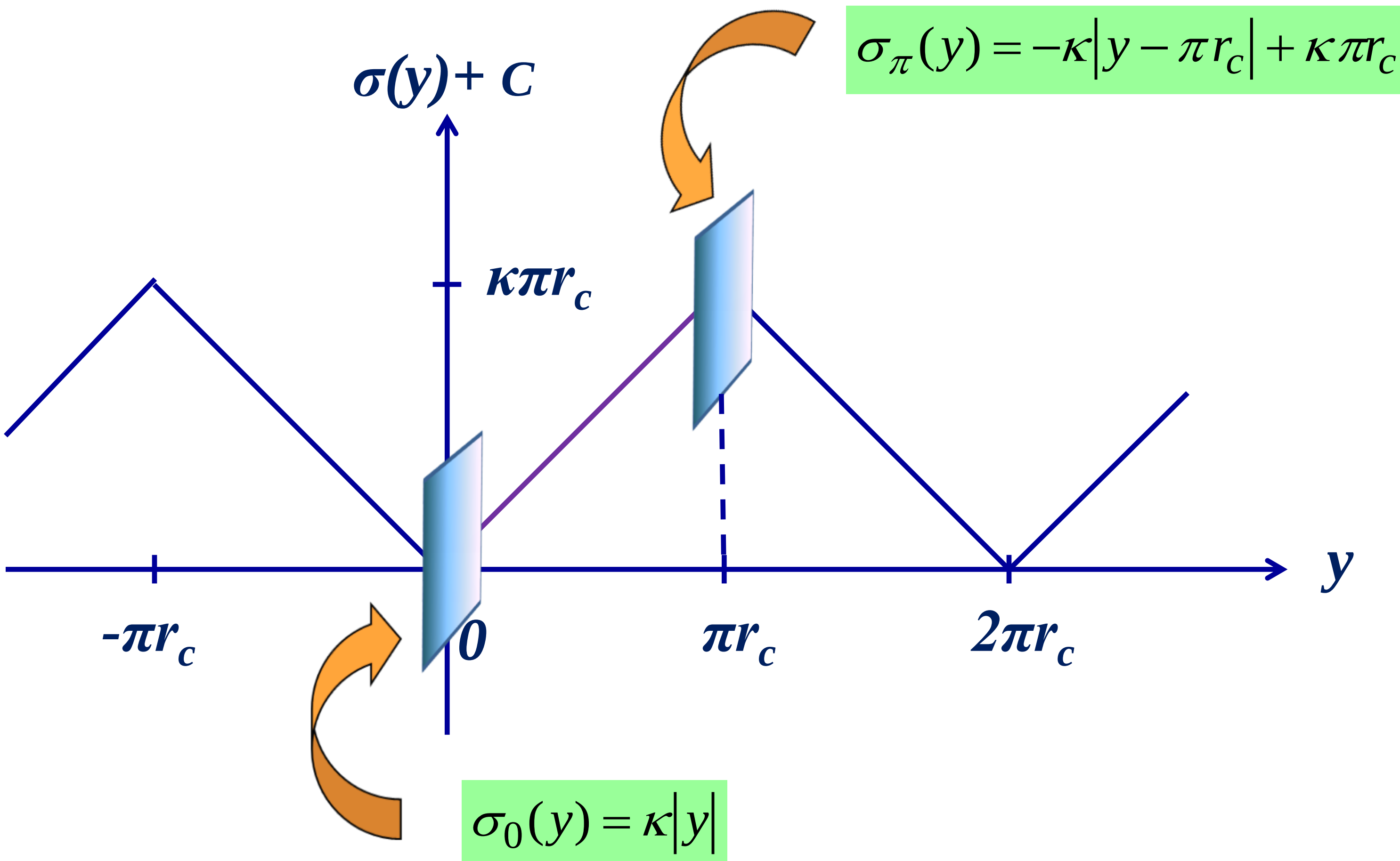
$$\sigma'_{\rm RS}(y) = \kappa\varepsilon(y) \qquad \sigma''_{\rm RS}(y) = 2\kappa\delta(y)$$

The RS solution:

- does not **explicitly** reproduce the jump on TeV brane (at $y=\pi r_c$)
- is **not symmetric** with respect to both branes (located at $y=0$ and $y=\pi r_c$)
- does not include a **constant** term

Generalization of RS solution

Two equivalent solutions related to different branes



Generalized solution $(0 \leq C \leq \kappa\pi r_c)$

$$\sigma(y) = \frac{1}{2}\left[\sigma_0(y) + \sigma_\pi(y)\right] - C = \frac{\kappa}{2}\left(|y| - |y - \pi r_c|\right) + \frac{\kappa\pi r_c}{2} - C$$

with fine tuning

$$\Lambda = -24 M_5^3 \kappa^2, \quad \Lambda_1 = -\Lambda_2 = 12 M_5^3 \kappa$$

factor of 2 different than that of RS

1-st derivative of σ(y)

$$\sigma'(y) = \frac{\kappa}{2}\left[\varepsilon(y) - \varepsilon(y - \pi r_c)\right]$$

2-nd derivative of σ(y) $\sigma''(y) = \kappa\left[\delta(y) - \delta(y - \pi r_c)\right]$

Hierarchy relation

$$M_{\mathrm{Pl}}^2 = \frac{M_5^3}{\kappa} \exp(2\mathbf{C})$$

Interaction Lagrangian
(*massive gravitons only*)

$$L(x) = -\frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x) T_{\alpha\beta}(x) \eta^{\mu\alpha} \eta^{\nu\beta}$$

Masses of KK gravitons
(x_n are zeros of $J_1(x)$)

$$m_n = x_n \frac{M_{\mathrm{Pl}}}{\sqrt{\exp(2\pi\kappa r_c) - 1}} \left(\frac{\kappa}{M_5}\right)^{3/2}$$

Masses of KK gravitons m_n and coupling Λ_π depend on C via M_5 and κ

→ **Different values of C result in quite diverse physical models**

Two interesting physical scenarios

I. C = 0 $\sigma(0) = 0, \quad \sigma(\pi r_c) = \kappa \pi r_c$

→ $M_{\rm Pl}^2 \simeq \dfrac{M_5^3}{\kappa}$ **that requires** $M_5 \sim \kappa \sim M_{\rm Pl}$

Masses of KK resonances $m_n \simeq x_n \kappa \exp(-\kappa \pi r_c)$

→ **RS1 model** *(Randall & Sundrum, 1999)*

Graviton spectrum - heavy resonances, with the lightest one above 1 TeV

II. C = κπr$_c$

$$\sigma(0) = -\kappa\pi r_c, \quad \sigma(\pi r) = 0$$

→ $$M_{\rm Pl}^2 \cong \frac{M_5^3}{\kappa} \exp(2\pi\kappa r_c)$$

$\kappa \ll M_5$ $\kappa r_c \approx 9.5$ for $M_5 = 1\,\text{TeV}, \kappa = 100\,\text{MeV}$

Masses of KK resonances $m_n \cong x_n \kappa$

→ **RSSC model: scenario with small curvature of 5-dimensional space-time**

For small κ, graviton spectrum is similar to that of the ADD model

(Giudice, 2005 Petrov & A.K., 2005)

RSSC model vs. ADD model

RSSC model is **not** equivalent to the ADD model with one **flat** ED of size $R=(\pi\kappa)^{-1}$ up to $\kappa \approx 10^{-18}$ eV

Hierarchy relation for small κ

$$M_{\mathrm{Pl}}^2 \cong \frac{M_5^3}{\kappa}\left[\exp(2\pi\kappa r_c)-1\right] \xrightarrow{2\pi\kappa r_c \ll 1} M_5^3(2\pi r_c)$$

But the inequality $2\pi\kappa r_c \ll 1$ means that

$$\kappa \ll \frac{M_5^3}{M_{\mathrm{Pl}}^2} \approx 0.17\cdot 10^{-18}\left(\frac{M_5}{1\mathrm{TeV}}\right)^3 \mathrm{eV}$$

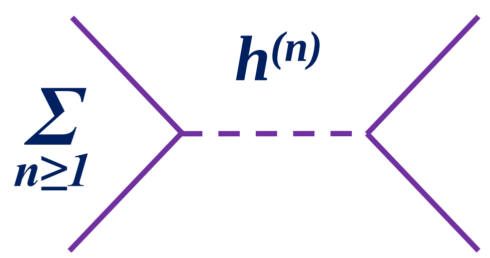
Virtual Gravitons at the LHC

pp-collisions at LHC mediated by KK graviton exchange in *s*-channel

Processes: $pp \to l^+l^-\,(\gamma\gamma,\, 2\,jets) + X$

Sub-processes: $q\bar{q},\; gg \to h^{(n)} \to f\bar{f},\, \gamma\gamma$

KK gravitons



Matrix element of sub-process

$$M = A \times S$$

Tensor part of graviton propagator

where $$A = T^{in}_{\mu\nu} P^{\mu\nu\alpha\beta} T^{f}_{\alpha\beta}$$

Energy-momentum tensors

$$S(s) = \frac{1}{\Lambda_\pi^2} \sum_{n=1}^{\infty} \frac{1}{s - m_n^2 + i m_n \Gamma_n}$$

*(process **independent**)*

Graviton widths $$\Gamma_n = \eta\, m_n^3 / \Lambda_\pi^2, \ \ \eta \cong 0.1$$

Recall that $m_n \cong z_n \kappa$

$$\sum_{n=1}^{\infty} \frac{1}{z_n^2 - z^2} = \frac{1}{2z} \frac{J_{\nu+1}(z)}{J_\nu(z)}, \quad J_\nu(z_n) = 0$$

$$S(s) \approx -\frac{1}{4\bar{M}_5^3 \sqrt{s}} \frac{\sin 2A + i \sinh 2\varepsilon}{\cos^2 A + \sinh^2 \varepsilon}$$ *(A.K, 2006)*

where $A = \frac{\sqrt{s}}{\kappa}, \ \varepsilon = \frac{\eta}{2} \left(\frac{\sqrt{s}}{\bar{M}_5} \right)^3$

Equivalent Photon Approximation (EPA)

Field of fast charged particle is similar to electromagnetic radiation

(Fermi, 1924; Weizsäcker, 1934; Williams, 1935)

Spectrum of photon emitted by proton

(Q^2 is photon virtuality, $E_\gamma = \xi E$ its energy)

$$\frac{dN}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1-\frac{E_\gamma}{E}\right)\left(1-\frac{Q^2_{\min}}{Q^2}\right)F_E + \frac{E_\gamma^2}{2E^2}F_M\right]$$

(Budnev et al.,1975)

$$Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E(E-E_\gamma)} \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2} \qquad F_M = G_M^2$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1+\frac{Q^2}{Q_0^2}\right)^{-4} \qquad Q_0^2 = 0.71\,\mathrm{GeV}^2$$

$$\mu_p^2 = 7.78$$

square of proton magnetic moment

Effective γγ-luminosity

$$\frac{dL_{\gamma\gamma}}{dW} = \int\limits_{Q^2_{\min}}^{Q^2_{\max}} dQ_1^2 \int\limits_{Q^2_{\min}}^{Q^2_{\max}} dQ_2^2 \int\limits_{y_{\min}}^{y_{\max}} dy \frac{W}{2y} f_1\left(\frac{W^2}{4y}, Q_1^2\right) f_2\left(y, Q_2^2\right)$$

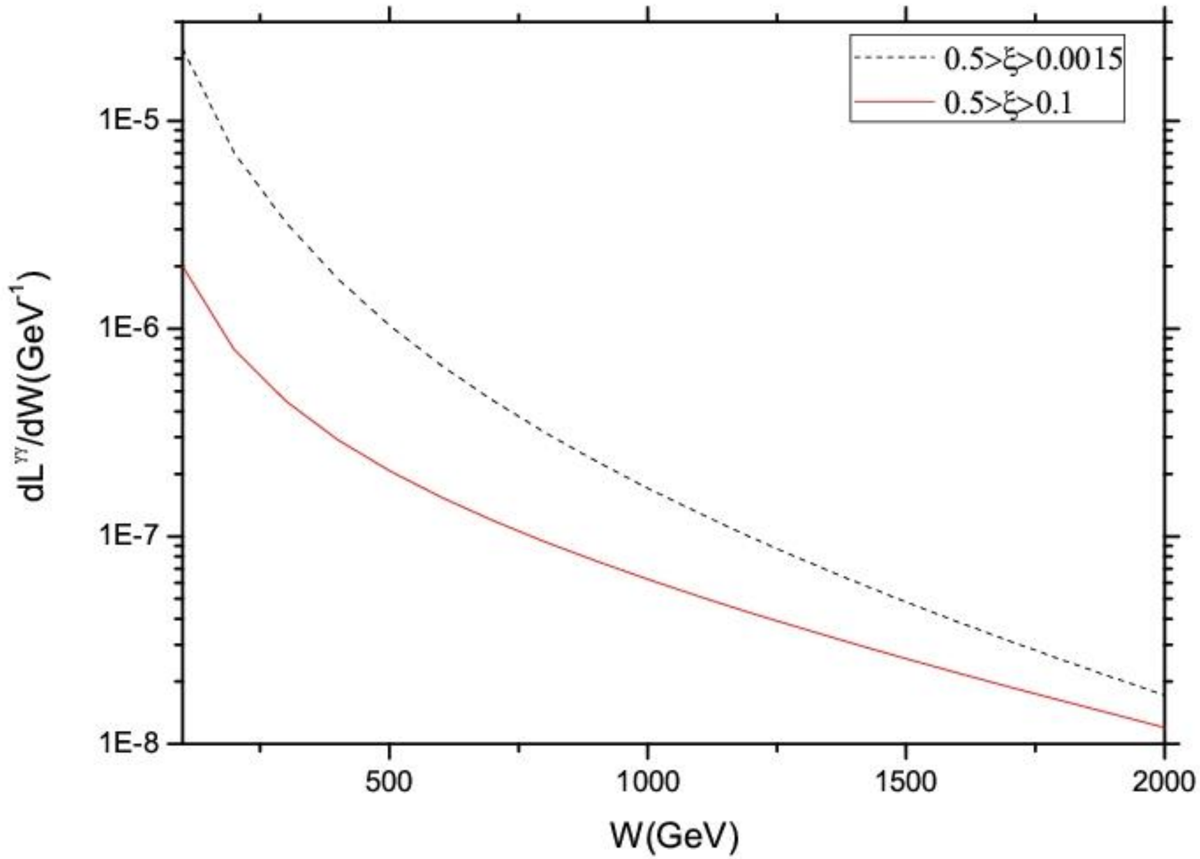
$Q^2_{max} = 2$ GeV^2

PDFs

Cross section for the process pp → pγγp → pXp

$$d\sigma = \int \frac{dL_{\gamma\gamma}}{dW} d\sigma_{\gamma\gamma\to X}(W) dW$$

W = invariant energy of two photons

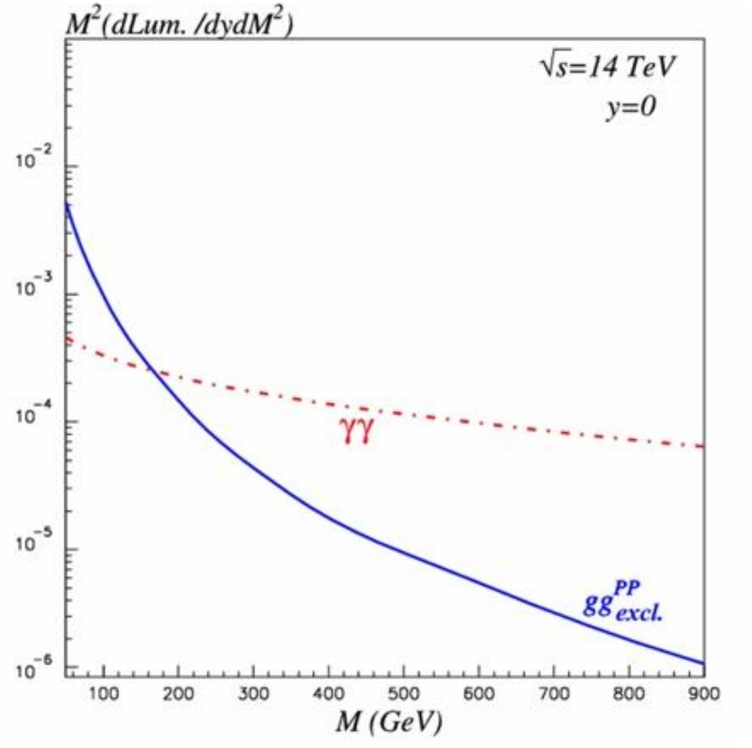


Effective γγ luminosity (in GeV^{-1}) as a function of invariant mass of two photons (forward detector acceptance: 0.0015 (0.1) < ξ < 0.5)

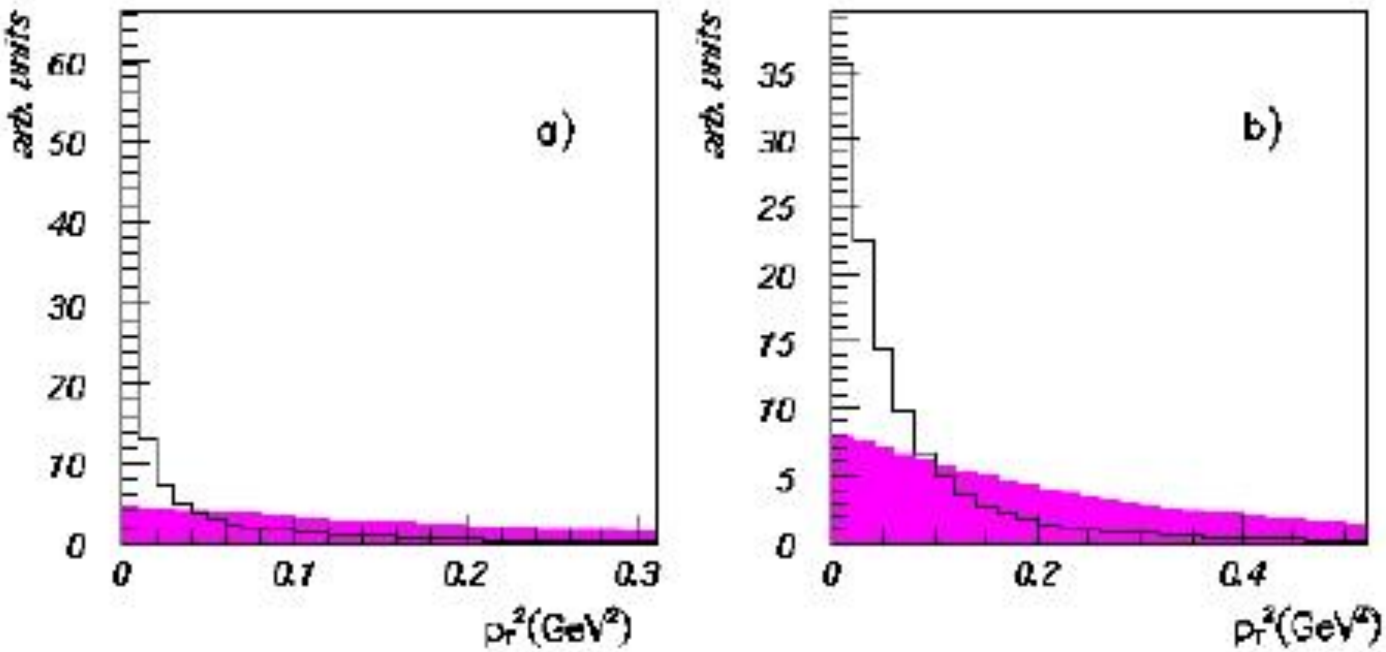
γγ process vs. *gluon induced process*

Exclusive event requires no extra gluon radiation into final state

Sudakov suppression in QCD cross section leads to enhancement in γγ for M_X > 150-200 GeV



γγ process vs. *double-Pomeron exchange*



True (a) and observed (b) p_t^2 distribution of scattered protons in photo-production (line) and diffraction (filled hystogram) (in arbitrary units)

$p_t^2 < 0.005\ GeV^2$ → ***Diffractive contribution is significantly reduced***

Matrix element squared consists of electromagnetic, KK and interference terms

$$|M|^2 = |M_{\rm em}|^2 + |M_{KK}|^2 + |M_{\rm int}|^2$$

$$|M_{\rm em}|^2 = -2e^4\left[\frac{\hat{s}+\hat{t}}{\hat{t}} + \frac{\hat{t}}{\hat{s}+\hat{t}}\right]$$

$$|M_{KK}|^2 = \frac{1}{4}|S(\hat{s})|^2\left[-\frac{\hat{t}}{8}\left(\hat{s}^3 + 2\hat{t}^3 + 3\hat{t}\hat{s}^2 + 4\hat{t}^2\hat{s}\right)\right]$$

$$|M_{\rm int}|^2 = -\frac{1}{4}e^2\,\mathbf{Re}\,S(\hat{s})(\hat{s}^2 + 2\hat{t}^2 + 2\hat{s}\hat{t})$$

$\hat{s}, \hat{t}$ are Mandelstam variables of sub-process $\gamma\gamma \to \mu^+\mu^-$

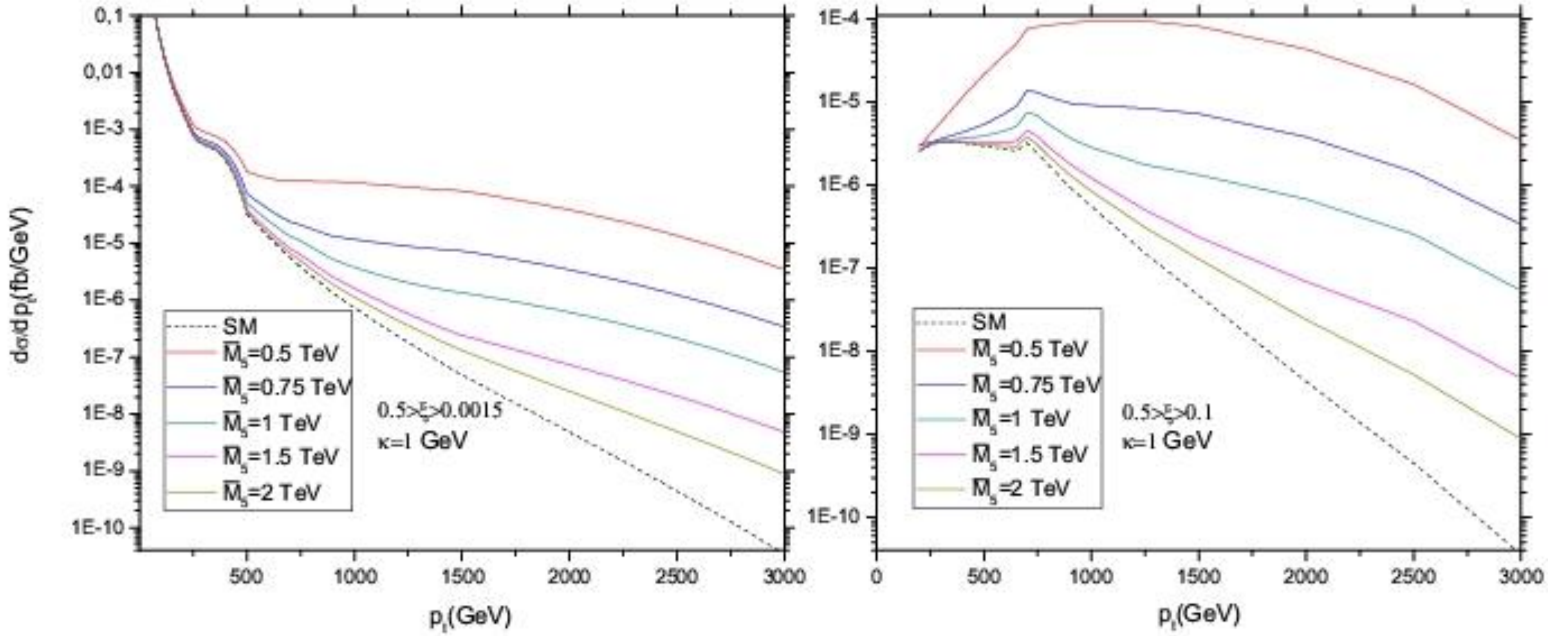
Differential and total cross sections

Cuts on transverse momenta of final muons and their rapidities:

$p_t > 30$ GeV, $|\eta| < 2.4$

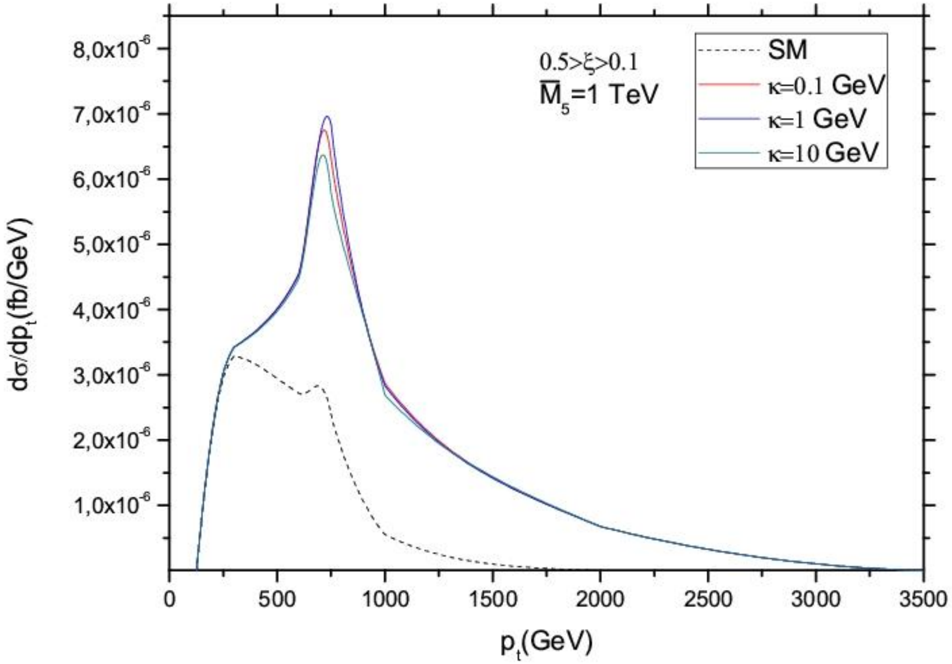
κ = 1 GeV

0.0015 < ξ < 0.5 **0.1 < ξ < 0.5**



Differential cross section (in fb/GeV) for the process $pp \to p\gamma\gamma p \to p\mu^+\mu^- p$ as a function of transverse momenta of final muons p_t

$0.1 < \xi < 0.5$ $M_5 = 1$ GeV

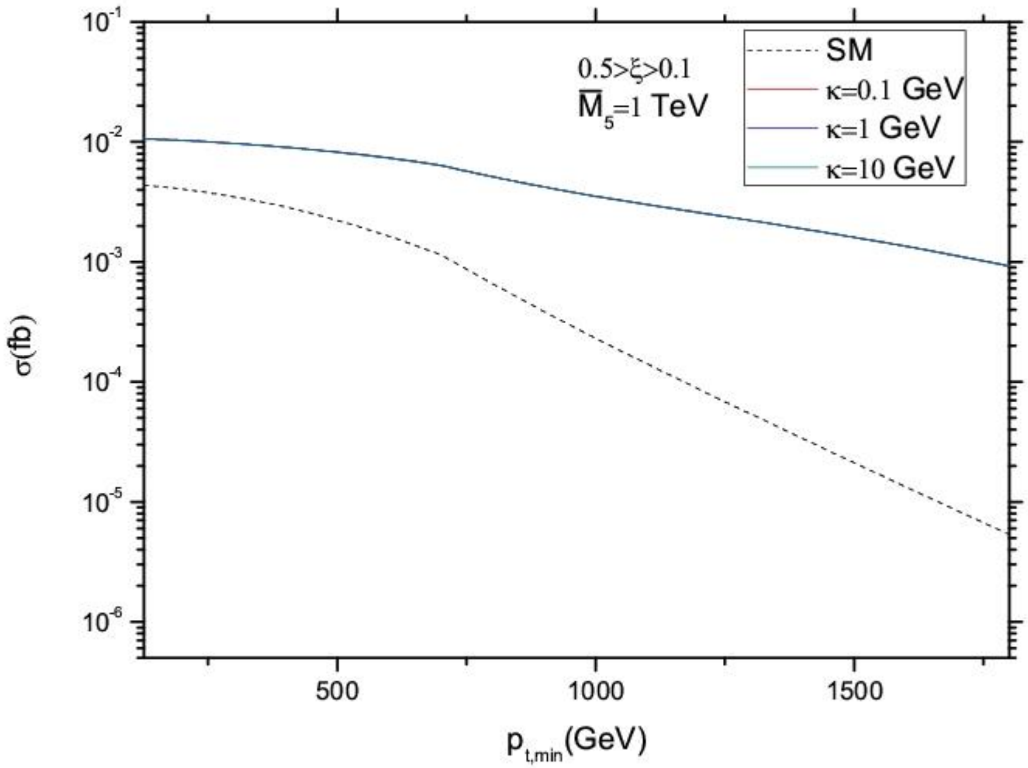


Differential cross section for the process $pp \to p\gamma\gamma p \to p\mu^+\mu^- p$ for different values of the curvature parameter κ

No noticeable dependence on parameter κ

Total cross section as a function of minimal transverse momentum of final muons $p_{t,min}$

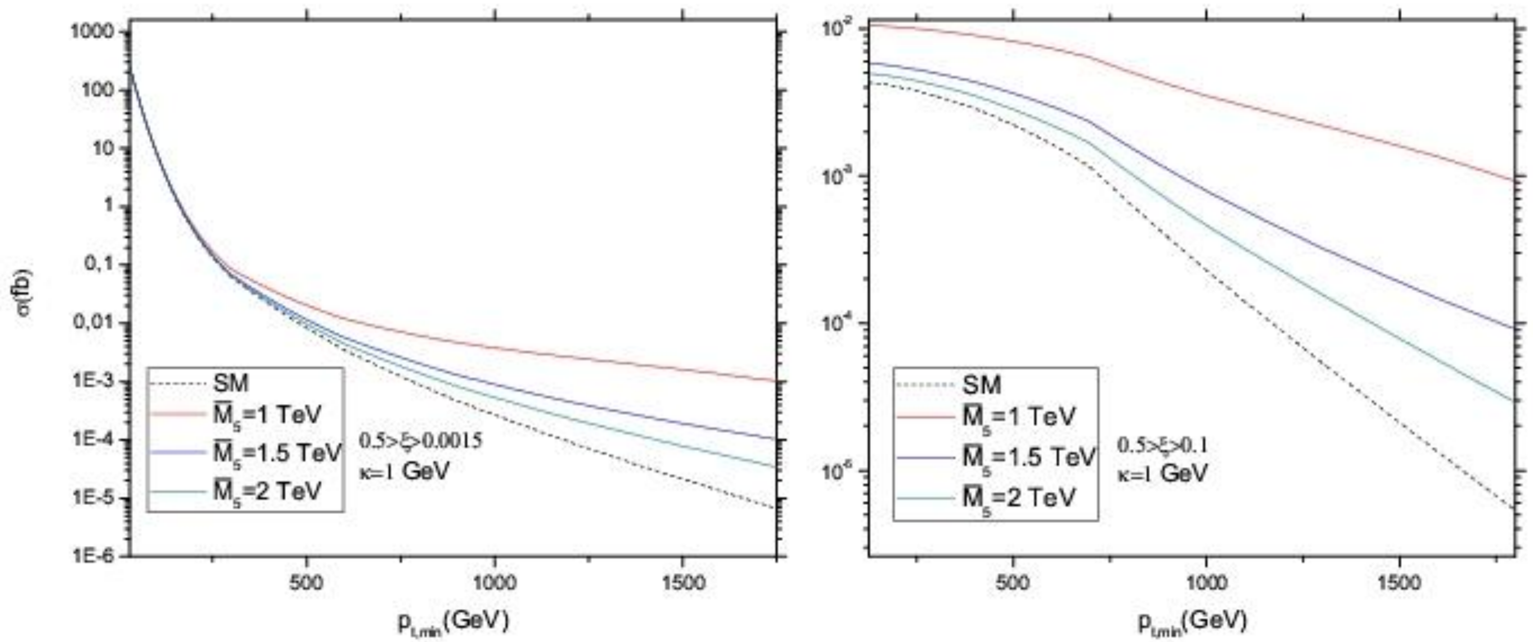
$$\sigma(p_t > p_{t,\min}) = \int\limits_{p_{t,\min}} \frac{d\sigma}{dp_t} dp_t$$



Total cross section (in fb) for the process $pp \to p\gamma\gamma p \to p\mu^+\mu^-p$ as a function of minimal transverse momentum of final muons $p_{t,min}$ for different values of κ

κ = 1 GeV

$0.0015 < \xi < 0.5$ $0.1 < \xi < 0.5$



Total cross section for the process $pp \to p\gamma\gamma p \to p\mu^+\mu^- p$ as a function of minimal transverse momentum of final muons $p_{t,min}$ for different values of M_5

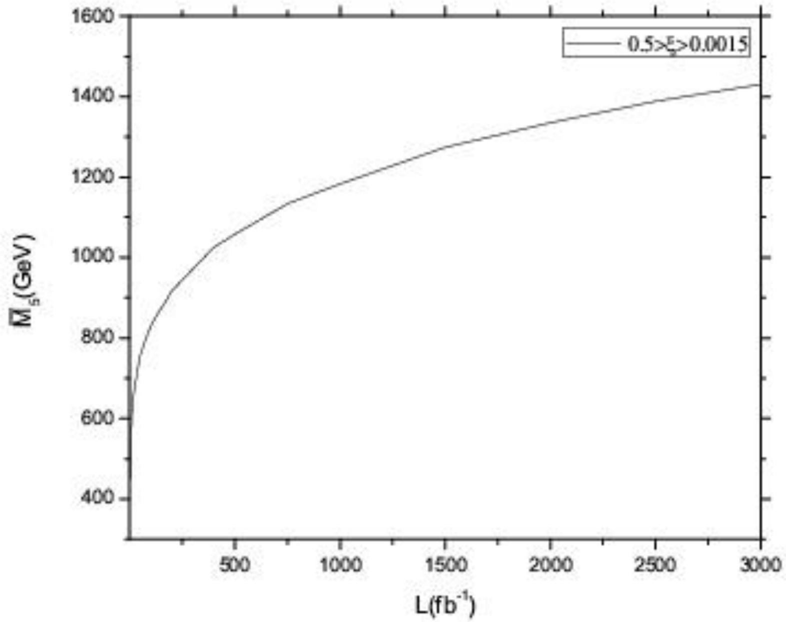
Statistical significance

$$S = \sqrt{2\left[\left(N_S + N_B\right)\ln\left(1 + N_S / N_B\right) - N_S\right]}$$

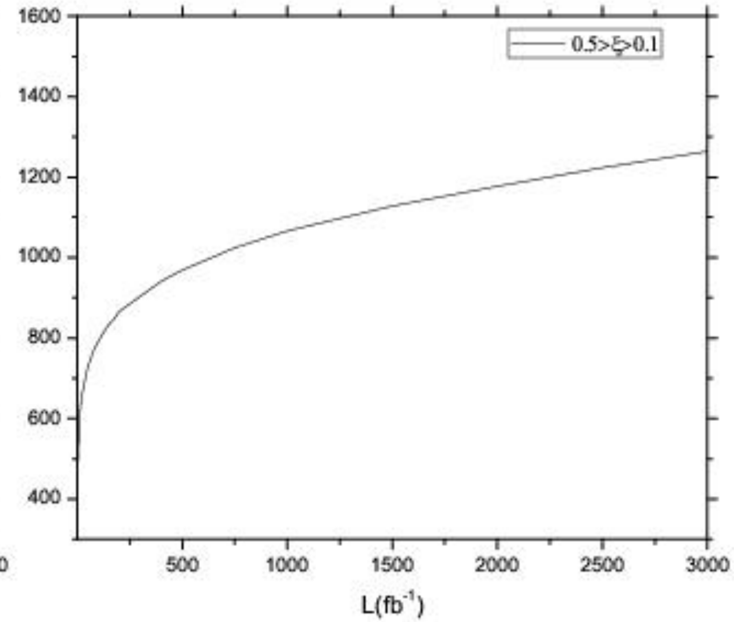
N_S (N_B) - number of signal (background) events

$$S \approx \frac{N_S}{\sqrt{N_B}}, \quad N_S << N_B$$

$0.0015 < \xi < 0.5$
$p_t > 500$ GeV



$0.1 < \xi < 0.5$
$p_t > 30$ GeV



95% C.L. search limit for 5-dimensional Planck scale M_5 as a function of integrated LHC luminosity with cuts p_t > 500 GeV (30 GeV), $|\eta|< 2.4$ imposed

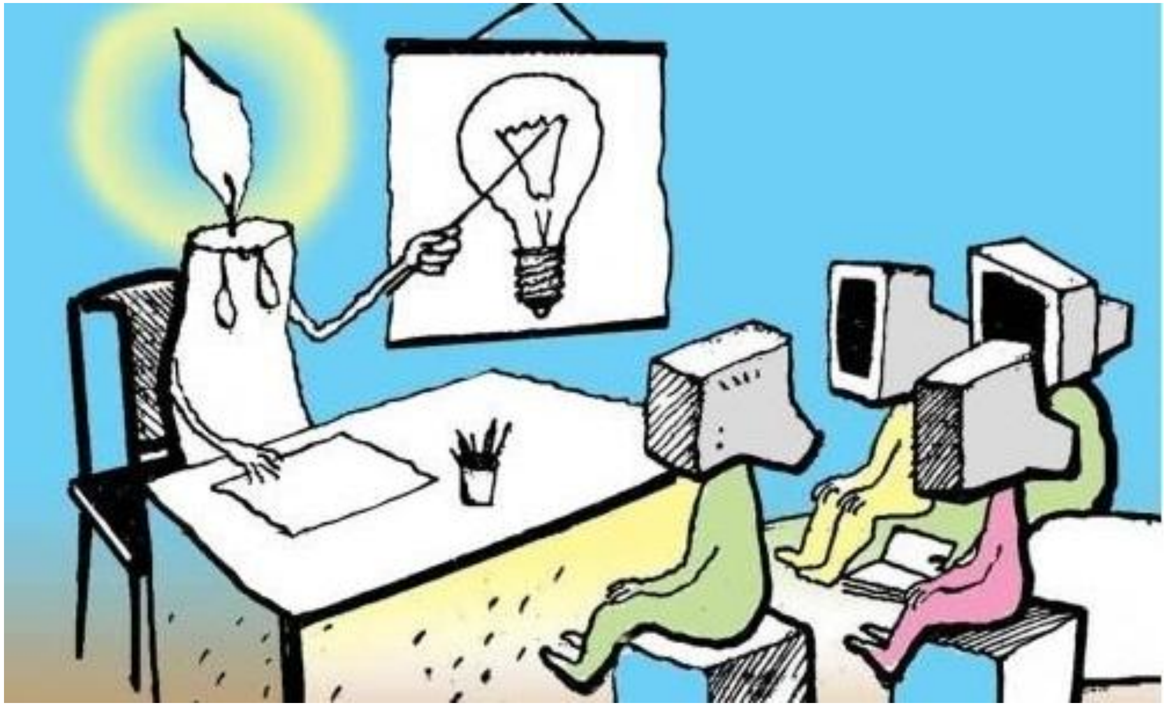
Заключение

- В рамках модели с одной дополнительной размерностью и малой кривизной пространства-времени изучено рождение пары мюонов на БАК в процессе, индуцированном фотонами.
- Обобщенное решение для метрики в рассмотренной модели:
  - симметрично относительно обеих бран;
  - имеет на них правильные скачки;
  - совместимо с симметриями орбифолда;
  - зависит от константы.

Заключение (продолжение)

- Начальные $\gamma\gamma$-состояния естественно приводят к эксклюзивному рождению с «неповреждёнными» протонами на БАК.
- Нами вычислены дифференциальное и полное сечения процесса $pp \to p\gamma\gamma p \to p\mu^+\mu^- p$ при энергии 14 ТэВ.
- С достоверностью 95% оценены значения 5-ти мерной массы Планка M_5, доступные для обнаружения на БАК в данном процессе (например, M_5 =1-1.2 ТэВ для L=1000 фб$^{-1}$).
- Результат не зависит от другого параметра модели κ, определяющего кривизну пространства-времени, при условии $\kappa \ll M_5$.

Спасибо за внимание!



Back-up slides

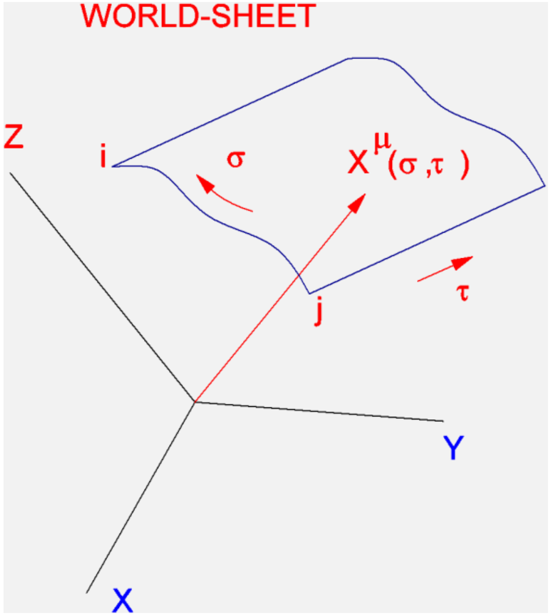
n	Obs. limit [TeV]	Exp. limit [TeV]
3	2.85	3.32
4	2.86	3.29
5	2.88	3.28
6	2.90	3.28

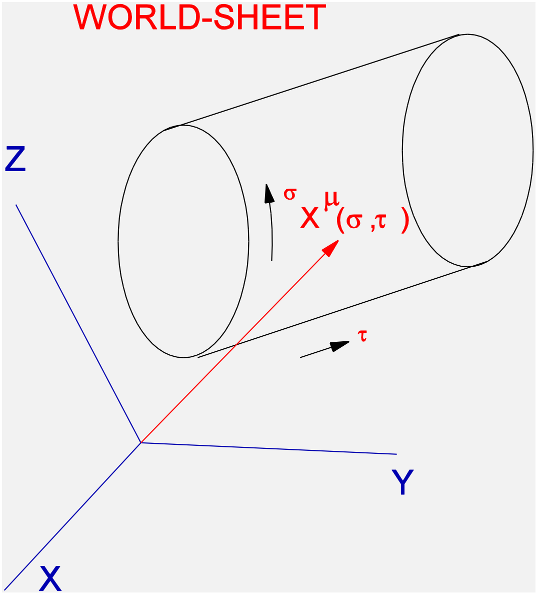
95% C.L. expected and observed lower limits on D-dimensional Planck scale M_D (D=4+n) as a function of number of extra dimensions n in the ADD model (CMS, 13 TeV, 35.9 fb^{-1})

(CMS Collaboration, arXiv:1810.00196)

Strings needs extra dimensions (EDs)

Superstrings: D= 10
(6 EDs must be compactified)

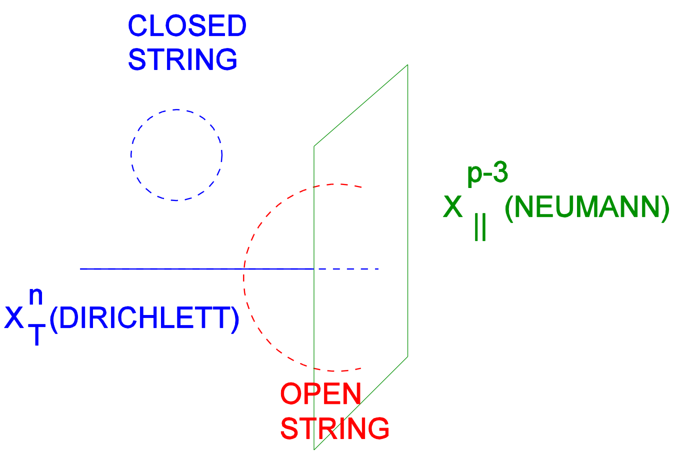




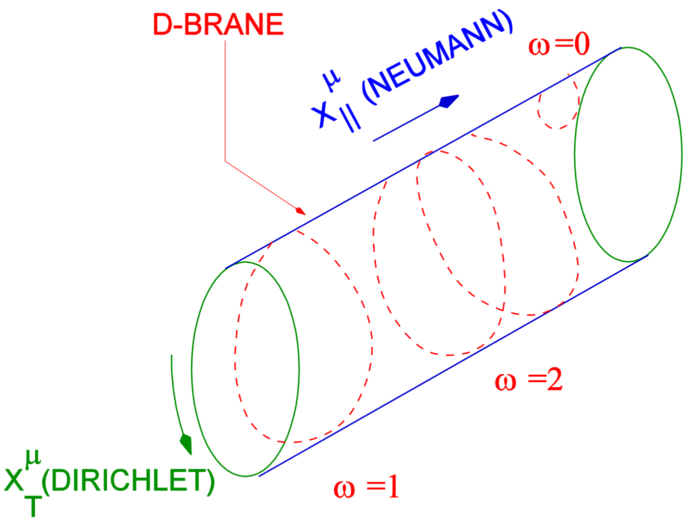
World sheets of open (left) and closed (right) strings propagating in the space-time

Propagation of strings in extra dimensions

Six internal compact dimensions:
(p-3) longitudinal , n = (9-p) transverse



COMPACT DIMENSIONS



Closed strings propagate in the bulk

Open strings propagate with ends at x_T = const for different windings

- string scale $M_S = l_S^{-1}$
- string coupling λ_S
- Planck scale $M_{\rm Pl} = l_{\rm Pl}^{-1}$
- gauge coupling g

string tension $\alpha' = M_S^{-2}$

6 internal compact dimensions:
(p-3) longitudinal ,
n = (9-p) transverse

Ten-dimensional action

$$S = \int_{bulk} d^{10}x \frac{1}{\lambda_S^2} l_S^{-8} \mathrm{R} + \int_{brane} d^{p+1}x \frac{1}{\lambda_S} l_S^{3-p} \mathrm{F}^2$$

Upon compactification of EDs:

$$\frac{1}{l_{\rm Pl}^2} = \frac{V_L V_T}{\lambda_S^2 l_S^8} \qquad \frac{1}{g^2} = \frac{V_L}{\lambda_S l_S^{p-3}}$$

D-dimensional
Planck scale (D=4+n)

$$M_D^{2+n} = M_S^{2+4} / (g^4 V_L l_s^{3-p})$$

→

Hierarchy relation

$$M_{\rm Pl}^2 = M_D^{2+n} R_T^n$$

Explicit account of periodicity and Z_2-symmetry

Solution for the warp function in variable $x = y/r_c$ *(A.K., 2015)*

$$\sigma(y) = \frac{\kappa r_c}{2}\left[\left|\mathrm{Arccos}(\cos x)\right| - \left|\mathrm{Arccos}(\cos x) - \pi\right|\right] + \frac{\pi\kappa r_c}{2} - C$$

Arccos(z) is principal value of inverse cosine

$$0 \le \mathrm{Arccos}(z) \le \pi, \quad -1 \le z \le 1$$

$$\mathrm{Arccos}(\cos x) = \begin{cases} x - 2n\pi, & 2n\pi \le x \le (2n+1)\pi \\ -x + 2(n+1)\pi, & (2n+1)\pi \le x \le 2(n+1)\pi \end{cases}$$

(see, for instance, Gradshteyn &Ryzhik)

In particular, $\sigma(y) = \kappa y$ for $0 \le y \le \pi r_c$

Orbifold symmetries:

$\sigma(y + 2\pi r_c) = \sigma(y)$ **(periodicity)**

$\sigma(-y) = \sigma(y)$ **(Z_2 symmetry)**

1-st derivative of σ(y): $(y \neq \pi n r_c\,,\ n = 0, \pm 1, \pm 2, \ldots)$

$\sigma'(y) = \kappa\,\mathrm{sign}(\sin(x))$ $\sigma'(-y) = -\sigma'(y)$

2-nd derivative of σ(y):

$$\sigma''(y) = \frac{\kappa}{r_c} \sum_{n=-\infty}^{\infty} \left[\delta(x + 2\pi n) - \delta(x - \pi + 2\pi n)\right]$$

Orbifold symmetries:

$$\sigma(y+2\pi r_c)=\sigma(y)$$ (periodicity)

$$\sigma(-y)=\sigma(y)$$ (Z_2 symmetry)

1-st derivative of σ(y): $(y \neq \pi n r_c,\ n = 0, \pm 1, \pm 2, \dots)$

$$\sigma'(y)=\kappa\,\mathrm{sign}\left[\sin(y/r_c)\right]$$

$$\sigma'(-y)=-\sigma'(y)$$

2-nd derivative of σ(y):

$$\sigma''(y)=\kappa\sum_{n=-\infty}^{\infty}\left[\delta\left(y+2\pi n r_c\right)-\delta\left(y-\pi r_c+2\pi n r_c\right)\right]$$

$$\sigma''(-y)=\sigma''(y)$$

III. C = κπr$_c$ /2

$$\sigma(0) = -\sigma(\pi r_c) = \kappa\pi r_c / 2$$

"symmetric" scheme

→ $$M_{\rm Pl}^2 \cong \frac{2M_5^3}{\kappa}\sinh(2\pi\kappa r_c)$$

Masses of gravitons $m_n \cong x_n \kappa \exp(-\kappa\pi r_c / 2)$

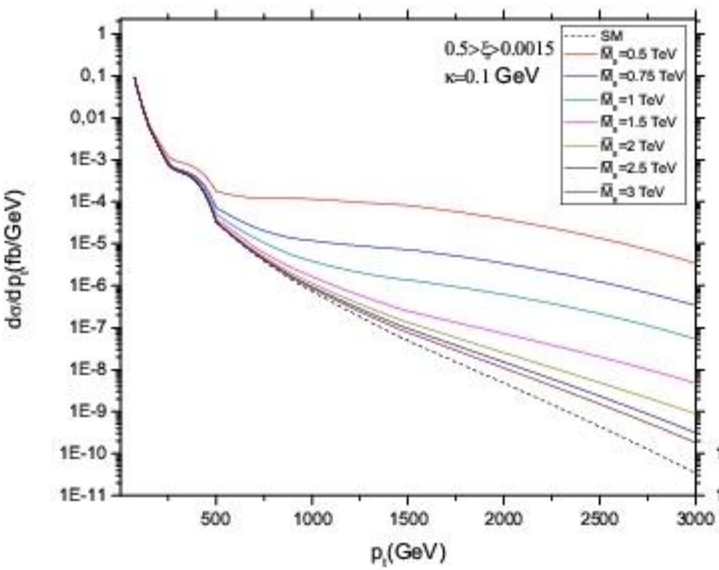
Let $M_5 = 2\cdot 10^9\,\text{GeV},\ \kappa = 10^4\ \text{GeV}$

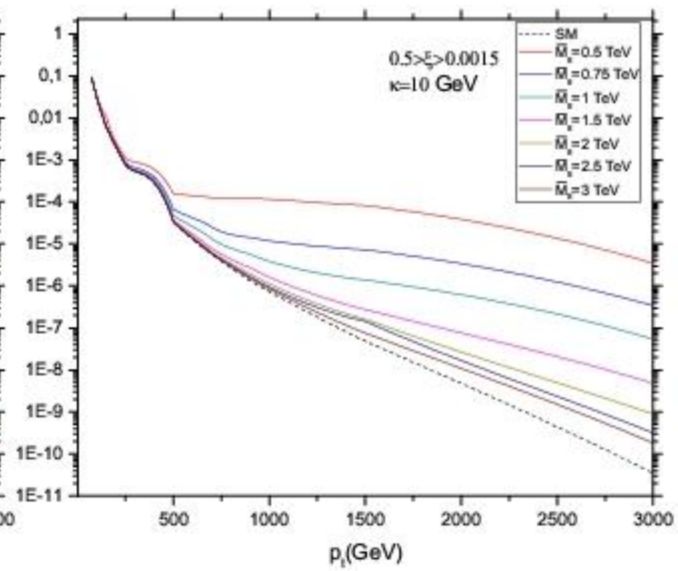
→ $$m_n \cong 3.7\, x_n\, (\text{MeV})$$ ***(A.K., 2015)***

Almost continuous spectrum of KK gravitons

0.0015 < ξ< 0.5

κ = 0.1 GeV   κ = 1 GeV





Dependence of differential cross section for the process pp → pγγp → pμ⁺μ⁻p on curvature parameter κ