Top quark as a gate to new physics
Z' production in top events at an e^+e^- collider

Ambroise Espargilière

LAPP, Annecy, France

ICPP II Istanbul

Outline

Physics context

A broad landscape

On the road to Grand Unification

- Many possible paths ...
  - Super Symmetry (SUSY) (+ String Theory, M-Theory)
  - Kaluza-Klein (KK) theories ... (Randall-Sundrum (RS), Pati-Salam, ...)
  - ...
- No experimental hint so far ...

The Dark Matter puzzle

- A well known problem
  - Dynamics of galaxies $\longrightarrow$ DM
  - Gravitational lensing $\longrightarrow$ DM
  - $\approx 25\%$ of Universe energy budget = Dark Matter (DM)
  - Unknown nature ...

A broad landscape

DM Candidates

in GUTs: proton stability $\longrightarrow$ stability of a DM candidate

- SUSY: R-parity $\longrightarrow$ Neutralino $\tilde{\chi}_0$ (LSP)
- RS: Z^3 symmetry $\longrightarrow$ LZP

A broad landscape

DM Candidates

in GUTs: proton stability $\longrightarrow$ stability of a DM candidate

- SUSY: R-parity $\longrightarrow$ Neutralino $\tilde{\chi}_0$ (LSP)
- RS: Z^3 symmetry $\longrightarrow$ LZP

Randall-Sundrum Dark Matter

- Left-Right Analogy $\longrightarrow$ $SU(2)_{\mathrm{R}}$
- Right handed neutrinos (ν')
- Z' = neutral gauge boson of $SU(2)_{\mathrm{R}}$ coupling to RH states of matter

see [1] for details.

Randall-Sundrum Dark Matter

Expected properties:

(chosen among a wide range of possibilities, details in [2] and [3])

- Small coupling to SM through Z^0/Z' mixing ($O(1\%)$, *direct detection constraints*)
- Z' couples to the SM only *via* RH top quark t_{R}
- $m_{Z'}$ in the TeV range but as light as possible
- $m_{\nu'}$ a bit below $m_{Z'}/2$ (*relic density constraint*)

Randall-Sundrum Dark Matter

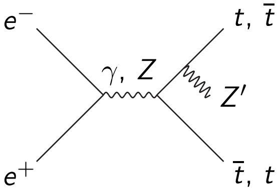
Expected properties:

(chosen among a wide range of possibilities, details in [2] and [3])

- Small coupling to SM through Z^0/Z' mixing ($O(1\%)$, *direct detection constraints*)
- Z' couples to the SM only *via* RH top quark t_{R}
- $m_{Z'}$ in the TeV range but as light as possible
- $m_{\nu'}$ a bit below $m_{Z'}/2$ (*relic density constraint*)

Z' production in top events

- Channel of interest $e^+e^- \rightarrow t\bar{t}Z'$:

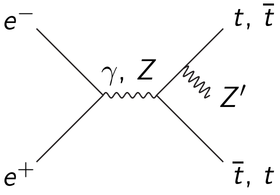


Decay modes

- $Z' \rightarrow t\bar{t}$
- $Z' \rightarrow \nu'\bar{\nu}'$

Z' production in top events

- Channel of interest $e^+e^- \to t\bar{t}Z'$:

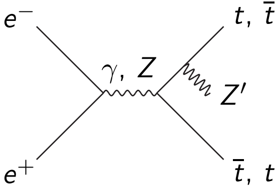


Decay modes

- $Z' \to t\bar{t}$
- $Z' \to \nu'\bar{\nu}'$

Z' production in top events

- Channel of interest $e^+e^- \to t\bar{t}Z'$:



Decay modes

- $Z' \to t\bar{t}$
- $Z' \to \nu'\bar{\nu}'$

The study will focus on $Z' \to \nu'\bar{\nu}'$ in $3\,\mathrm{TeV}$ e^+e^- collisions.

Z' production in top events

- cross sections of $e^+e^- \to t\bar{t}Z'$ @3 TeV:

$m_{Z'}$	Cross sect.	$\sigma_{Z'\to\mathrm{inv.}}$	$\sigma_{Z'\to t\bar{t}}$
200 GeV/c^2	14.9 fb	14.9 fb	0
300 GeV/c^2	8.7 fb	8.7 fb	0
400 GeV/c^2	5.6 fb	2.4 fb	3.2 fb
500 GeV/c^2	3.7 fb	1.2 fb	2.5 fb
600 GeV/c^2	2.6 fb	0.8 fb	1.8 fb
700 GeV/c^2	1.8 fb	0.5 fb	1.3 fb

ISR included

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z',\ Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Z' Event selection

Characteristics of the signal ($e^+e^- \rightarrow t\bar{t}Z'$, $Z' \rightarrow \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z',\ Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events ($25\,\mathrm{fb}$)

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z'$, $Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events (25 fb)
- Non $t\bar{t}$ SM processes (hadronic decay modes)

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z'$, $Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events (25 fb)
- Non $t\bar{t}$ SM processes (hadronic decay modes)
  - $e^+e^- \to W^+W^-$ (263 fb) Very reducible

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z', \; Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events (25 fb)
- Non $t\bar{t}$ SM processes (hadronic decay modes)
  - $e^+e^- \to W^+W^-$ (263 fb) Very reducible
  - $e^+e^- \to Z^0Z^0$ (16 fb)

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z',\ Z' \to \text{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events ($25\,\text{fb}$)
- Non $t\bar{t}$ SM processes (hadronic decay modes)
  - $e^+e^- \to W^+W^-$ ($263\,\text{fb}$) Very reducible
  - $e^+e^- \to Z^0Z^0$ ($16\,\text{fb}$)
  - $e^+e^- \to W^+W^-Z^0$ ($11\,\text{fb}$)

Z' Event selection

Characteristics of the signal ($e^+e^- \to t\bar{t}Z'$, $Z' \to \mathrm{inv.}$)

- Large number of final state particles
- Large number of jets (≈ 6)
- Missing energy

Background (@3 TeV)

- SM $t\bar{t}$ events (25 fb)
- Non $t\bar{t}$ SM processes (hadronic decay modes)
  - $e^+e^- \to W^+W^-$ (263 fb) Very reducible
  - $e^+e^- \to Z^0Z^0$ (16 fb)
  - $e^+e^- \to W^+W^-Z^0$ (11 fb)
  - $e^+e^- \to Z^0Z^0Z^0$ (< 1 fb)

Z' Event selection

Analysis framework

- Analysis done at generator level

Z' Event selection

Analysis framework

- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity

Z' Event selection
Analysis framework

- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity
    - Neglect all non $t\bar{t}$ SM backgrounds

Z' Event selection

Analysis framework

- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity
  - Neglect all non $t\bar{t}$ SM backgrounds
  - Results must be scaled according to real top tagging performance

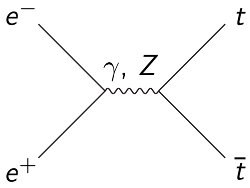
- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity
  - Neglect all non $t\bar{t}$ SM backgrounds
  - Results must be scaled according to real top tagging performance
- Background for this study:

Z' Event selection

Analysis framework

- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity
  - Neglect all non $t\bar{t}$ SM backgrounds
  - Results must be scaled according to real top tagging performance
- Background for this study:

background 1: $e^+e^- \rightarrow t\bar{t}$



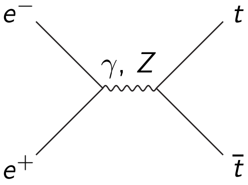
Z' Event selection

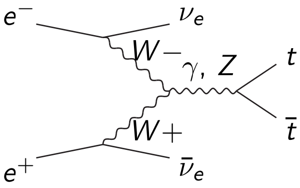
Analysis framework

- Analysis done at generator level
- Assume $t\bar{t}$ event tagging with full efficiency + full purity
  - Neglect all non $t\bar{t}$ SM backgrounds
  - Results must be scaled according to real top tagging performance
- Background for this study:

background 1: $e^+e^- \to t\bar{t}$

background 2: $e^+e^- \to t\bar{t} + \nu\bar{\nu}$





Z' Event selection

Discriminative variables

- Event dynamics (jet/hemisphere energies, momenta, ...)
- Event shape (sphericity, aplanarity, ...)
- Missing Energy & Co.

Boosted Decision Tree (BDT) results

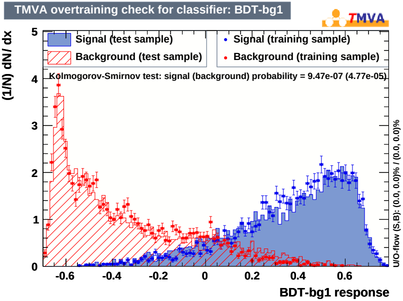
	Sig. *vs* Bg1	Sig. *vs* Bg2	$\not{P}_{\mathrm{T}}$ cut
$\int \mathrm{ROC}$	0.955	0.971	N/A
$S_{\max}$	99.6	113.8	88.6
$\epsilon@S_{\max}$	90.8%	97.4%	85%
$B@S_{\max}$	18.0%	14.6%	40.3%
$S_{\max}$ cut	-0.0378	-0.3391	$175\,\mathrm{GeV}$

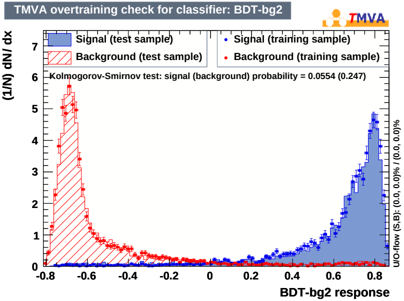
Z' Event selection

Discriminative variables

- Event dynamics (jet/hemisphere energies, momenta, ...)
- Event shape (sphericity, aplanarity, ...)
- Missing Energy & Co.

Boosted Decision Tree (BDT) results





Measurement of Z' mass

Method

The key spectrum

Total event invariant mass (M_{event})

- No missing energy $\Rightarrow M_{\mathrm{event}}$ = Centre of mass energy / c^2
- Heavy invisible particle $\Rightarrow M_{\mathrm{event}} = E_{\mathrm{cm}} - M_{\mathrm{inv}}$
- M_{inv} directly readable ?

Measurement of Z' mass

Method

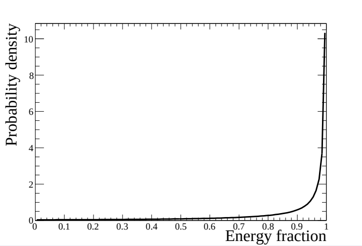
The key spectrum

Total event invariant mass (M_{event})

- No missing energy $\Rightarrow$ M_{event} = Centre of mass energy / c^2
- Heavy invisible particle $\Rightarrow$ $M_{\mathrm{event}} = E_{\mathrm{cm}} - M_{\mathrm{inv}}$
- M_{inv} directly readable ?

ISR Smearing

- E_{cm} not nominal
- low energy tail
- $E_{\mathrm{cm}} - M_{\mathrm{inv}}$ smeared into a smooth fading



Measurement of Z' mass

Method

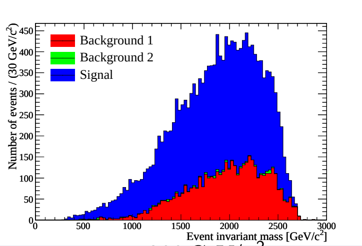
The key spectrum

Total event invariant mass (M_{event})

- No missing energy $\Rightarrow$ M_{event} $=$ Centre of mass energy / c^2
- Heavy invisible particle $\Rightarrow$ $M_{\mathrm{event}} = E_{\mathrm{cm}} - M_{\mathrm{inv}}$
- M_{inv} directly readable ?

ISR Smearing

- E_{cm} not nominal
- low energy tail
- $E_{\mathrm{cm}} - M_{\mathrm{inv}}$ smeared into a smooth fading



$m_{Z'} = 200\,\mathrm{GeV}/c^2$

Measurement of Z' mass

Method

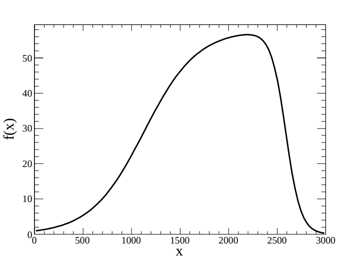
The key spectrum

Total event invariant mass (M_{event})

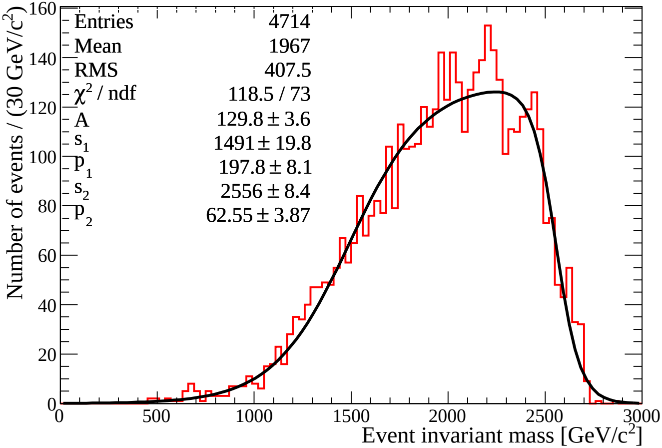
- No missing energy $\Rightarrow M_{\text{event}}$ = Centre of mass energy / c^2
- Heavy invisible particle $\Rightarrow M_{\text{event}} = E_{\text{cm}} - M_{\text{inv}}$
- M_{inv} directly readable ?

ISR Smearing

$$f(x) = \frac{A}{(e^{\frac{s_1 - x}{p_1}} + 1)(e^{\frac{x - s_2}{p_2}} + 1)}$$



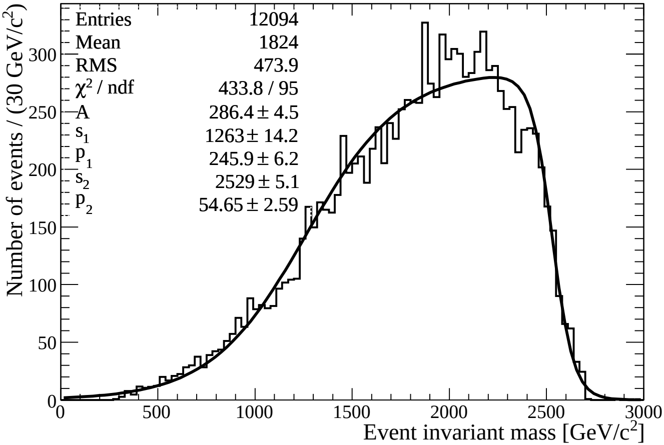
Background only



Measurement of Z' mass

Method

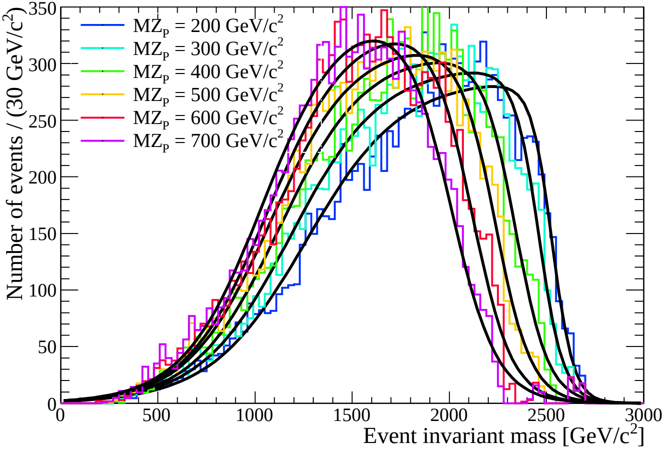
Background subtracted



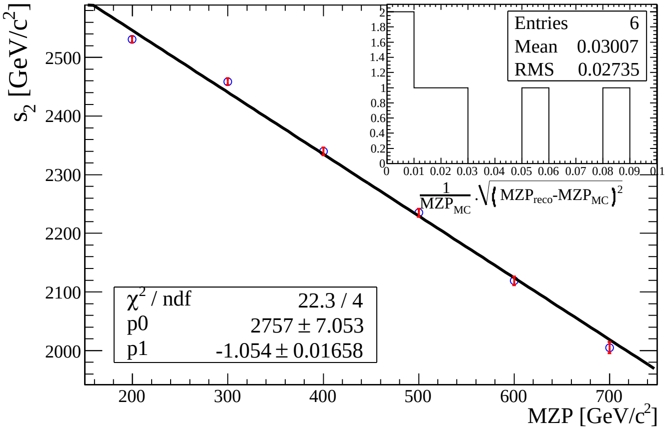
Measurement of Z' mass

Method

For various Z' masses (identical statistics)



A clear relation: $m_{Z'} = \frac{(2757 \pm 8) - s_2}{1.05 \pm 0.02}$



Roadmap

- Use statistics corresponding to predicted cross sections
- Apply selection cuts
- Measure cross section
- Apply $m_{Z'}$ measurement method
- Determine resolution on $m_{Z'}$

Cross section measurement

- Int. luminosity $= 1\,\mathrm{ab}^{-1}$ (≈3 years at CLIC)
- Event Selection efficiency = 0.884±0.005

$m_{Z'}$	events yield	True cross sect.	Measured cross sect.
200	12094	14.9 fb	(13.7 ± 0.2) fb
300	7411	8.7 fb	(8.4 ± 0.1) fb
400	2150	2.4 fb	(2.4 ± 0.04) fb
500	1192	1.2 fb	(1.3 ± 0.02) fb
600	815	0.8 fb	(0.9 ± 0.02) fb
700	642	0.5 fb	(0.7 ± 0.02) fb

The s_2 parameter

$m_{Z'}$	events yield	significance	s_2	measured $m_{Z'}$
200	12094	92.7	2529 ± 5.1	$217\,\mathrm{GeV}/c^2$
300	7411	66.6	2448 ± 7.7	$294\,\mathrm{GeV}/c^2$
400	2150	24.6	2342 ± 19.7	$395\,\mathrm{GeV}/c^2$
500	1192	13.5	2282 ± 39.5	$454\,\mathrm{GeV}/c^2$
600	815	8.4	913 ± 82	$1756\,\mathrm{GeV}/c^2$
700	642	5.6	962 ± 78	$1710\,\mathrm{GeV}/c^2$

- Below 1000 events, the fit fails
- $m_{Z'}$ measurement possible from 200 to 500 GeV/c^2 ($@\int\mathcal{L} = 1\,\mathrm{ab}^{-1}$)

Measurement of process cross section and Z' mass

Results

Resolution on $m_{Z'}$

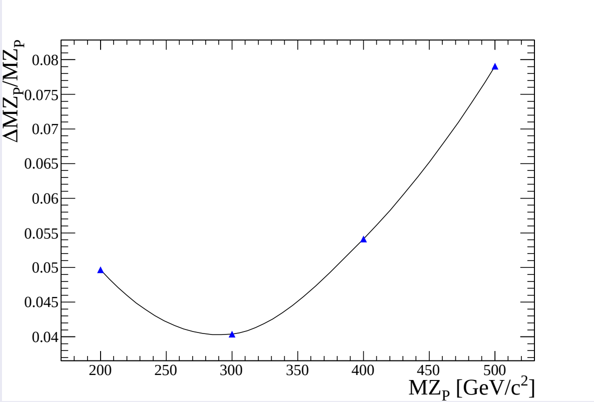
- $m_{Z'}(s_2) = \frac{k - s_2}{\alpha}$
- Error on $m_{Z'}$:

$$\Delta m_{Z'} = \underbrace{\frac{\Delta k}{\alpha}}_{\text{constant term}} \oplus \underbrace{\frac{m_{Z'} \Delta\alpha}{\alpha}}_{\text{linear term}} \oplus \underbrace{\frac{\Delta s_2}{\alpha}}_{\text{fit term}}$$

$$= 7.8\,\mathrm{GeV}/c^2 \oplus 0.95 \Delta s_2 \oplus 1.9\% m_{Z'}$$

Resolution on $m_{Z'}$

- $m_{Z'}(s_2) = \frac{k - s_2}{\alpha}$
- Error on $m_{Z'}$:



Input from full simulation

Full simulation

- ILD-like detector for CLIC

Input from full simulation

Full simulation

- ILD-like detector for CLIC
- CLIC 3 TeV beamstrahlung

Input from full simulation

Full simulation

- ILD-like detector for CLIC
- CLIC 3 TeV beamstrahlung
- $\gamma\gamma \rightarrow$ *hadrons* background ($\approx 3/BX$)

Input from full simulation

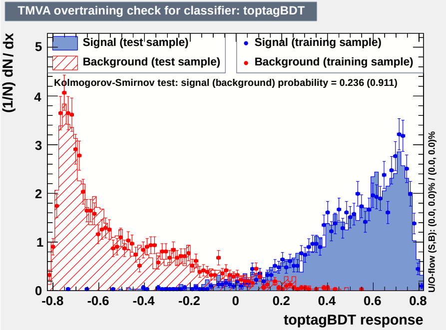
Full simulation

- ILD-like detector for CLIC
- CLIC 3 TeV beamstrahlung
- $\gamma\gamma \rightarrow$ *hadrons* background ($\approx 3/BX$)
- Pandora PFA reconstruction

Input from full simulation

Full simulation

- ILD-like detector for CLIC
- CLIC 3 TeV beamstrahlung
- $\gamma\gamma \rightarrow$ *hadrons* background ($\approx 3/BX$)
- Pandora PFA reconstruction

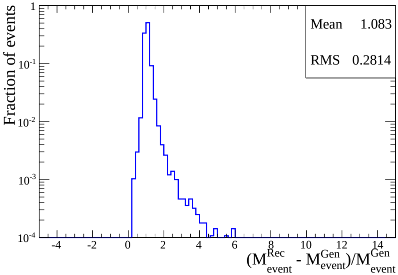


Input from full simulation

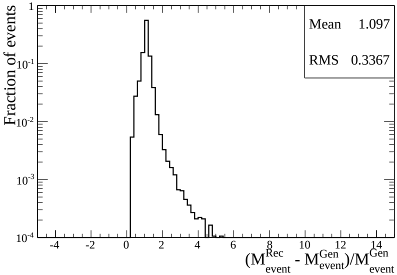
Full simulation

- ILD-like detector for CLIC
- CLIC 3 TeV beamstrahlung
- $\gamma\gamma \rightarrow$ *hadrons* background ($\approx 3/BX$)
- Pandora PFA reconstruction

Without $\gamma\gamma \rightarrow$ *hadrons*



with $\gamma\gamma \rightarrow$ *hadrons*



Conclusion

- RS DM candidate = RH neutrino ν'

Conclusion

- RS DM candidate $=$ RH neutrino ν'
- Z' $=$ neutral gauge boson for interaction with ν'

Conclusion

- RS DM candidate = RH neutrino ν'
- Z' = neutral gauge boson for interaction with ν'
- Z' produced in the channel $e^+e^- \to t\bar{t}Z'$

Conclusion

- RS DM candidate = RH neutrino ν'
- Z' = neutral gauge boson for interaction with ν'
- Z' produced in the channel $e^+e^- \to t\bar{t}Z'$

- $Z' \to \mathrm{inv.}$ detectable for mass $\in [0.2, 0.8]\,\mathrm{TeV}/c^2$ ($\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$)

Conclusion

- RS DM candidate = RH neutrino ν'
- Z' = neutral gauge boson for interaction with ν'
- Z' produced in the channel $e^+e^- \to t\bar{t}Z'$

- $Z' \to \mathrm{inv.}$ detectable for mass $\in [0.2, 0.8]\,\mathrm{TeV}/c^2$ ($\int\mathcal{L} = 1\,\mathrm{ab}^{-1}$)
- $m_{Z'}$ precision better than 10% if $m_{Z'} \in [0.2, 0.5]\,\mathrm{TeV}/c^2$

Conclusion

- RS DM candidate = RH neutrino ν'
- Z' = neutral gauge boson for interaction with ν'
- Z' produced in the channel $e^+e^- \to t\bar{t}Z'$

- $Z' \to \mathrm{inv.}$ detectable for mass $\in [0.2, 0.8]\,\mathrm{TeV}/c^2$ ($\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$)
- $m_{Z'}$ precision better than 10% if $m_{Z'} \in [0.2, 0.5]\,\mathrm{TeV}/c^2$
- Measurement maybe harder with finite detector resolution + machine background

A note about the work related here can be found *here*

Bibliography

Kaustubh Agashe and Géraldine Servant.
Warped unification, proton stability, and dark matter.
Phys. Rev. Lett., 93(23):231805, Dec 2004.

Geneviève Bélanger, Alexander Pukhov, and Géraldine Servant.
Dirac neutrino dark matter.
Journal of Cosmology and Astroparticle Physics, january 2008.
doi: 10.1088/1475-7516/2008/01/009.

C.B. Jackson, Géraldine Servant, Gabe Shaughnessy, Tim M.P. Tait, and Marco Taoso.
Higgs in space!
Journal of Cosmology and Astroparticle Physics, 2010(04):004, 2010.

Acknowledgement

Geneviève Bélanger

Jean-Jacques Blaising

Marco Battaglia

Géraldine Servant

Alexander Pukov

Peter Skands

Catherine Adloff
Yannis Karyotakis
Jan Blaha
Maximilien Chefdeville