Missing Energy Signals in $t\bar{t}$ Production as a Probe of Large Extra Dimensions at an e^+e^- Collider

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Outline

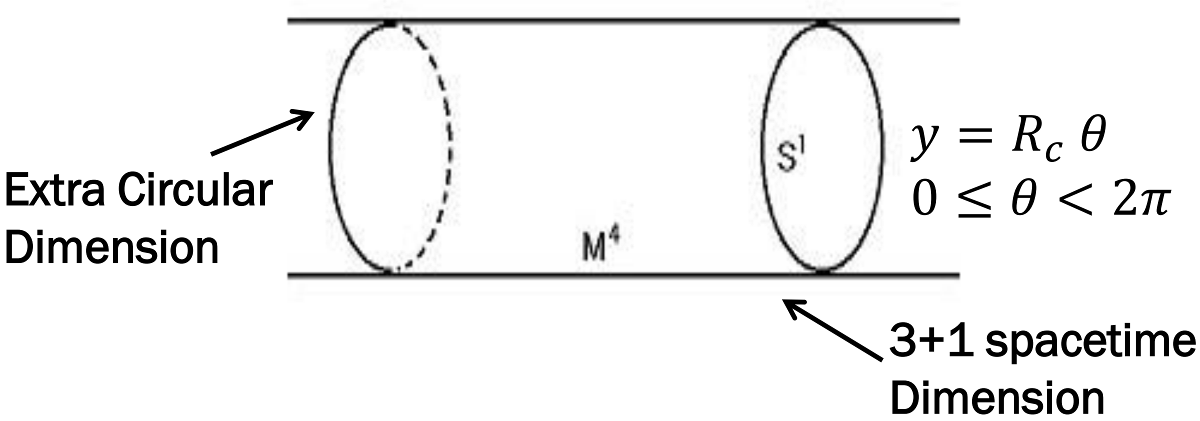
- Motivation
- ADD Model
- Process
- Signals for the ADD Model
- Summary

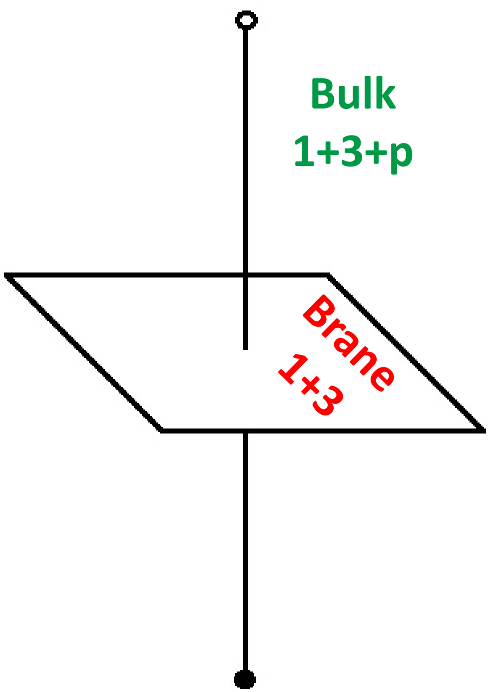
Motivation

- BSM physics is needed to address Hierarchy Problem
- New e^+e^- colliders (ILC, CLIC) has been proposed with high luminosity
- Expected energy: 1 TeV (ILC) and 3 TeV (CLIC)
- Higher energy scale may be probed at these machines
- MET in the final state $t\bar{t}G_{\vec{n}}$ can be used to search Large Extra Dimension

'ADD' Model

- Extra p periodic spatial dimension
- $ds^2 = dt^2 - d\vec{x}^2 - dy_1^2 - dy_2^2 - \cdots - dy_p^2$
- Each y_i is like a circle (with radius R_c)



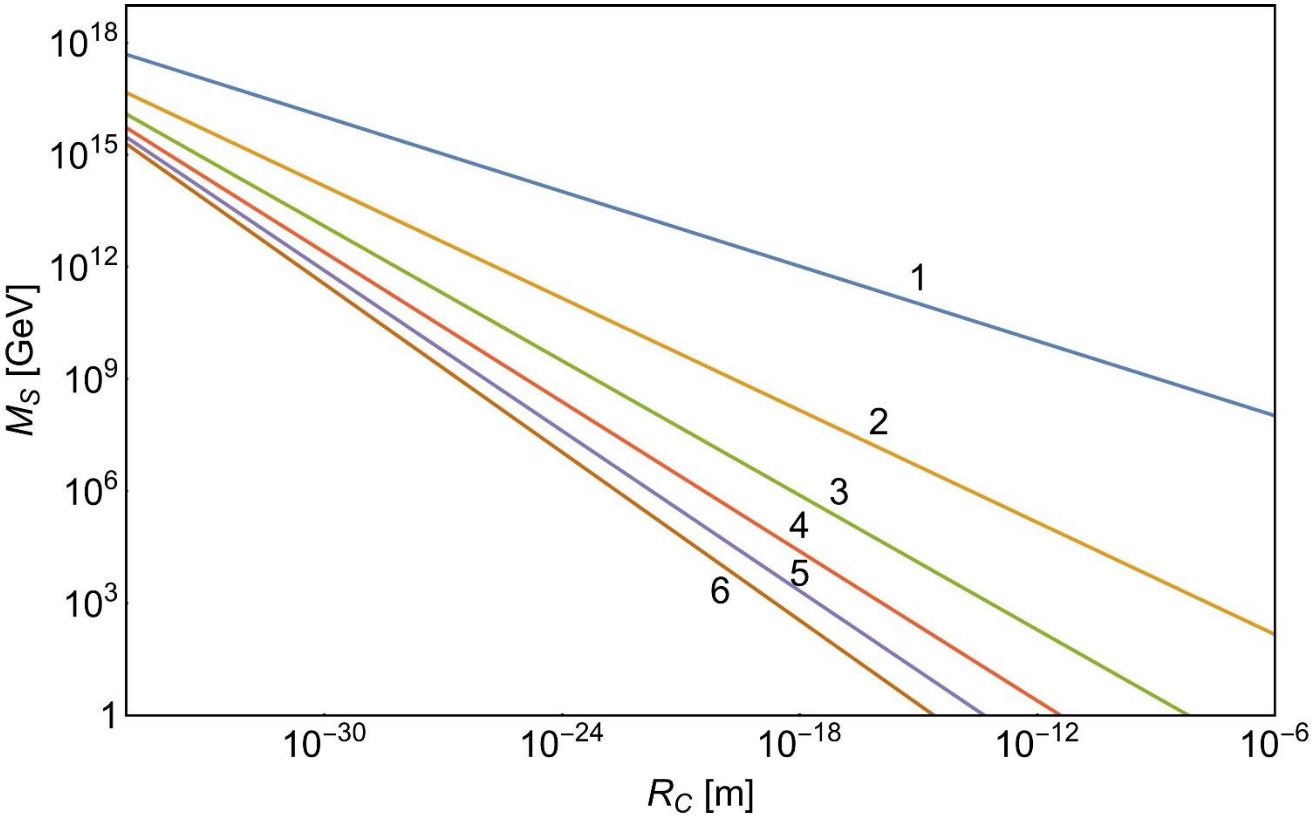


- Gravitational field is free to propagate through ***bulk***
- SM fields are confined to ***brane***

ADD Model

- Definition of Planck mass M_P is changed to M_S

$$M_S^{2+p}\, R_c^p = 2\pi(4\pi)^{\frac{p}{2}}\Gamma(p/2)M_P^2$$



Gravitational Field

- Bulk gravitational field

$$h_{\mu\nu}(x^\lambda,\vec{y}) = \sum_{\vec{n}} h_{\mu\nu}^{(\vec{n})}(x^\lambda)\, e^{i\vec{n}\cdot\vec{y}}$$

- Mass of each mode: $M_{\vec{n}}^2 = \frac{|\vec{n}|^2}{R_c^2}$
- Quasi-continuum states

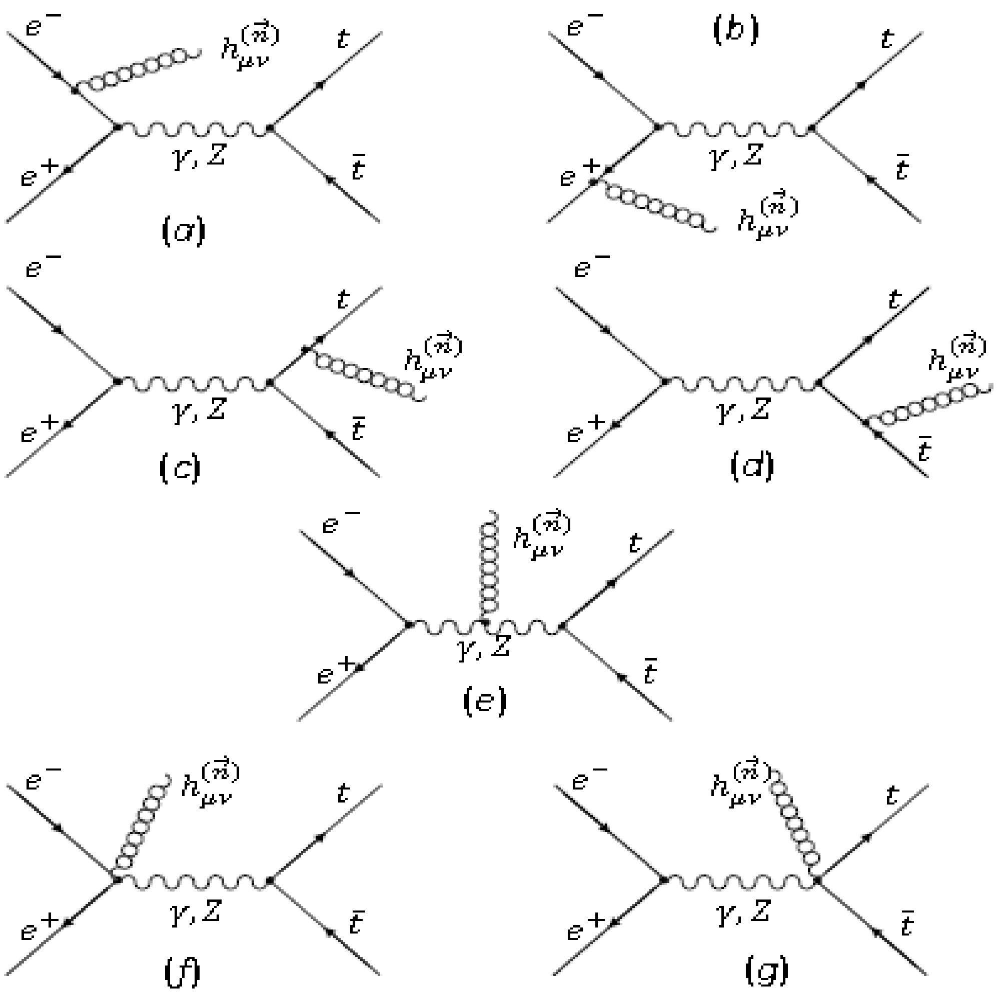
$$\rho(M_{\vec{n}}) = \frac{R_c^p\, M_{\vec{n}}^{p-2}}{(4\pi)^{\frac{p}{2}}\Gamma(\frac{p}{2})}$$

Cross-section

- Process:
  - $e^+e^- \to t\bar{t}G_{\vec{n}}$ (2b + MET + leptons)

$$\sigma = \int^{\sqrt{s}-2m_t} dM^2 \rho(M^2) \times \frac{1}{2s}\int \overline{\left|M_{e^+e^-\to t\bar{t}G_{\vec{n}}}\right|^2}\, d\Phi_3$$

- Background:
  - $e^+e^- \to t\bar{t}$
  - $e^+e^- \to t\bar{t}Z(Z \to \nu\bar{\nu})$

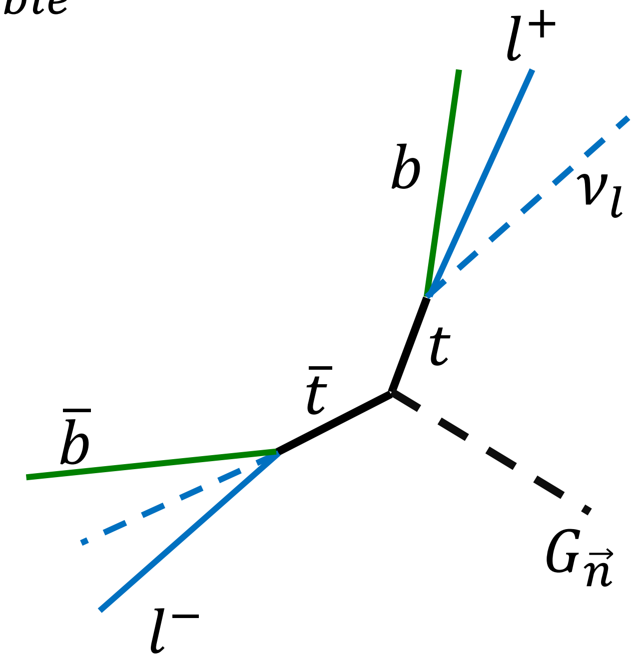


Decay of top

- top further decays: $t \to b + W^+$ and $W^+ \to l^+ + \nu_l$
  $\to q + \overline{q}'$
- Neutrinos are not detected & leaves missing $\vec{P}_T$

$$\vec{P}_T^{missing} = -\sum \vec{P}_T^{visible}$$

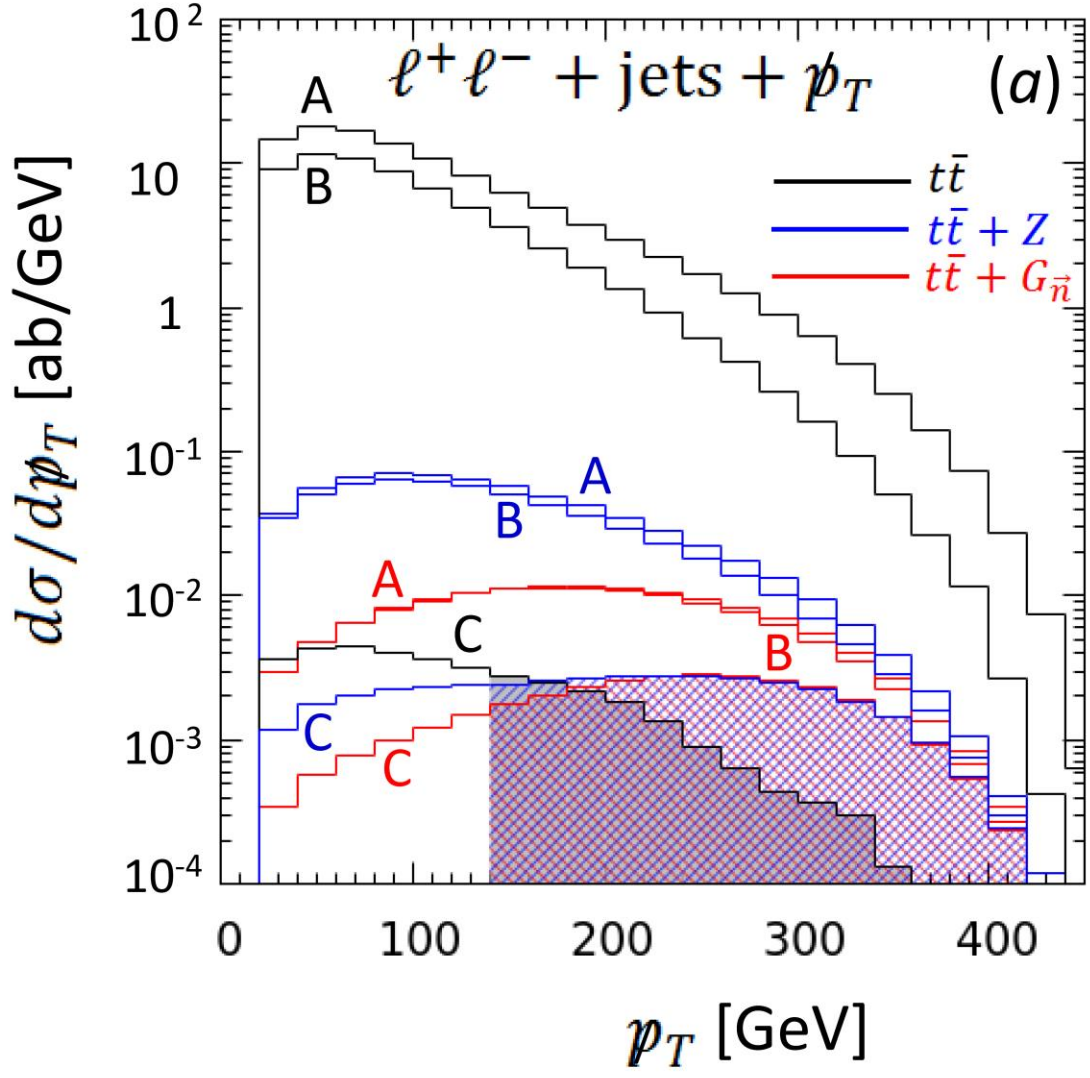
- 3 kinds of final states:
  - Di-lepton event – $2b + 2l + \text{MET}$
  - Single-lepton event – $2b + l + \text{MET}$
  - Hadronic events – $2b + \text{MET}$



Kinematic cuts: Two-lepton

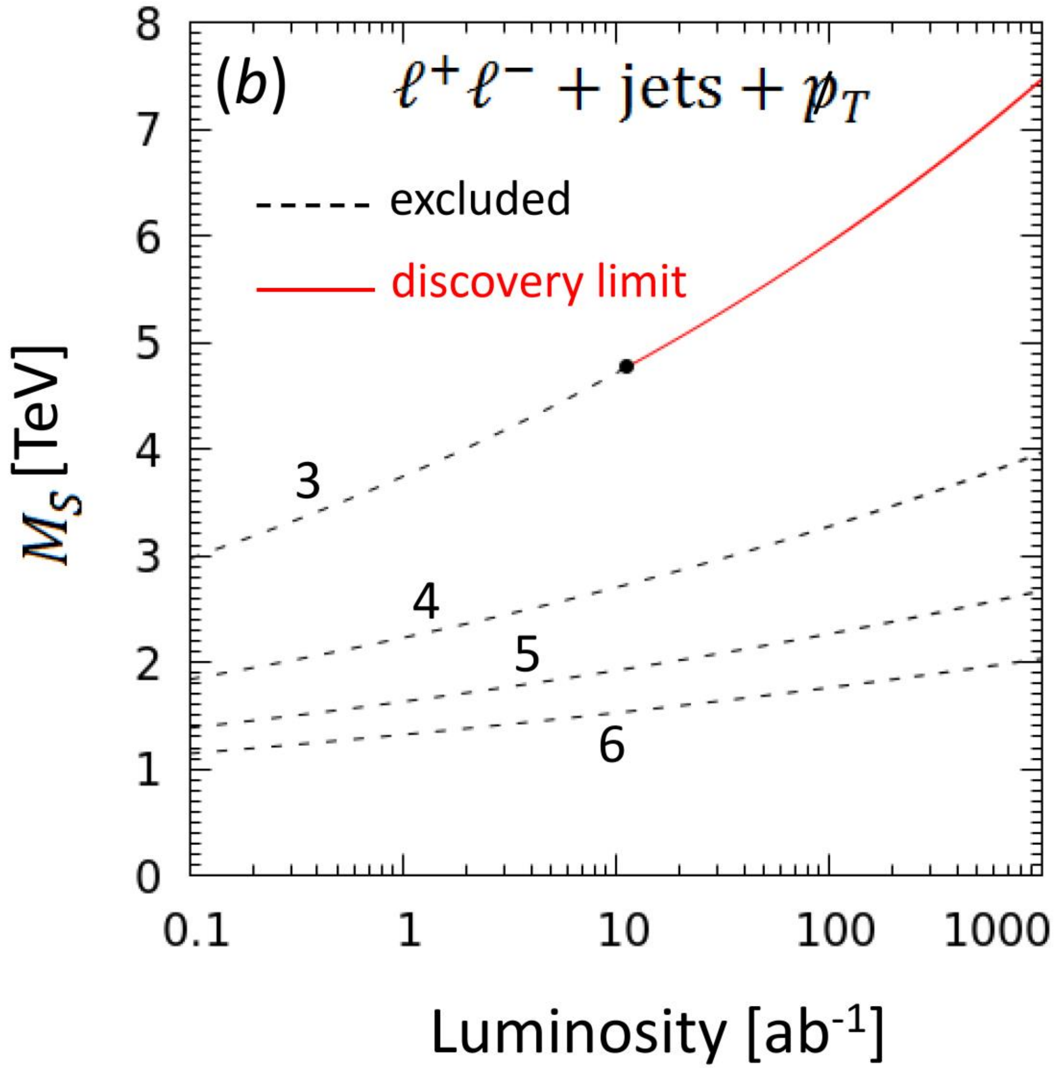
Variables	Set A	Set B	Set C	Set F	Unit
$p_{T_{l_1}}$	> 20.0 $-$	> 30.0 < 250.0	> 30.0 < 250.0	> 30.0 < 250.0	GeV
$p_{T_{l_2}}$	> 20.0 $-$	> 20.0 < 200.0	> 20.0 < 200.0	> 20.0 < 200.0	GeV
$p_{T_{j_1}}$	$-$	< 250.0	< 250.0	< 250.0	GeV
$p_{T_{j_2}}$	$-$	< 200.0	< 200.0	< 200.0	GeV
$\Delta R_{l_1 l_2}$	$-$	$-$	< 2.2	< 2.2	
$\Delta R_{j_1 j_2}$	$-$	$-$	< 2.0	< 2.0	
$\not{p}_T$				< 150.0	GeV
σ_{tt} σ_{ttZ} $\sigma_{ttG_{\vec{n}}}$	4462.0 27.4 6.2	2320.5 20.6 5.0	0.6 1.6 1.4	0.2 1.1 1.2	ab

ILC: Two-lepton



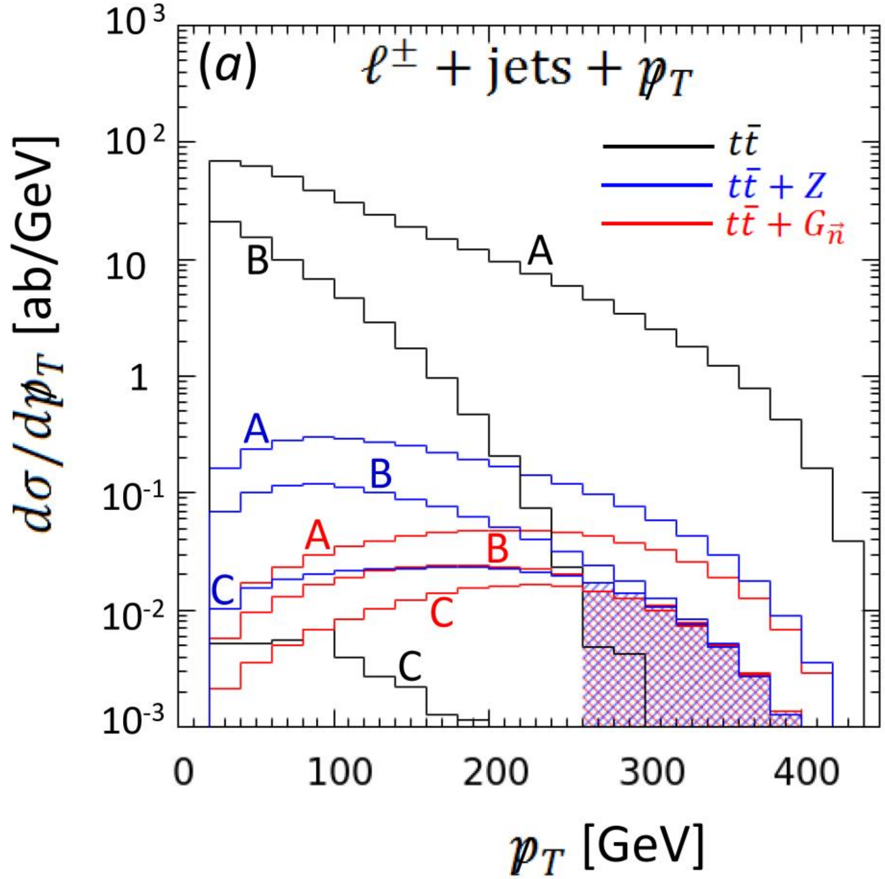
$M_S = 4.77$ TeV
$p = 3$

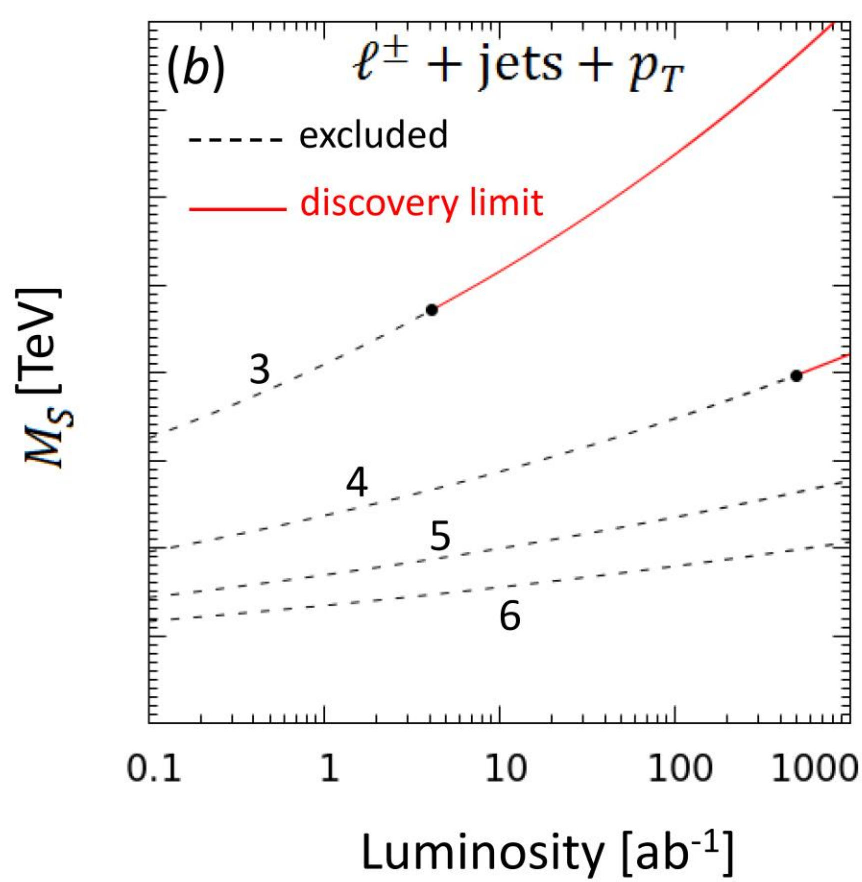
ILC: Two-lepton



ILC: One-lepton

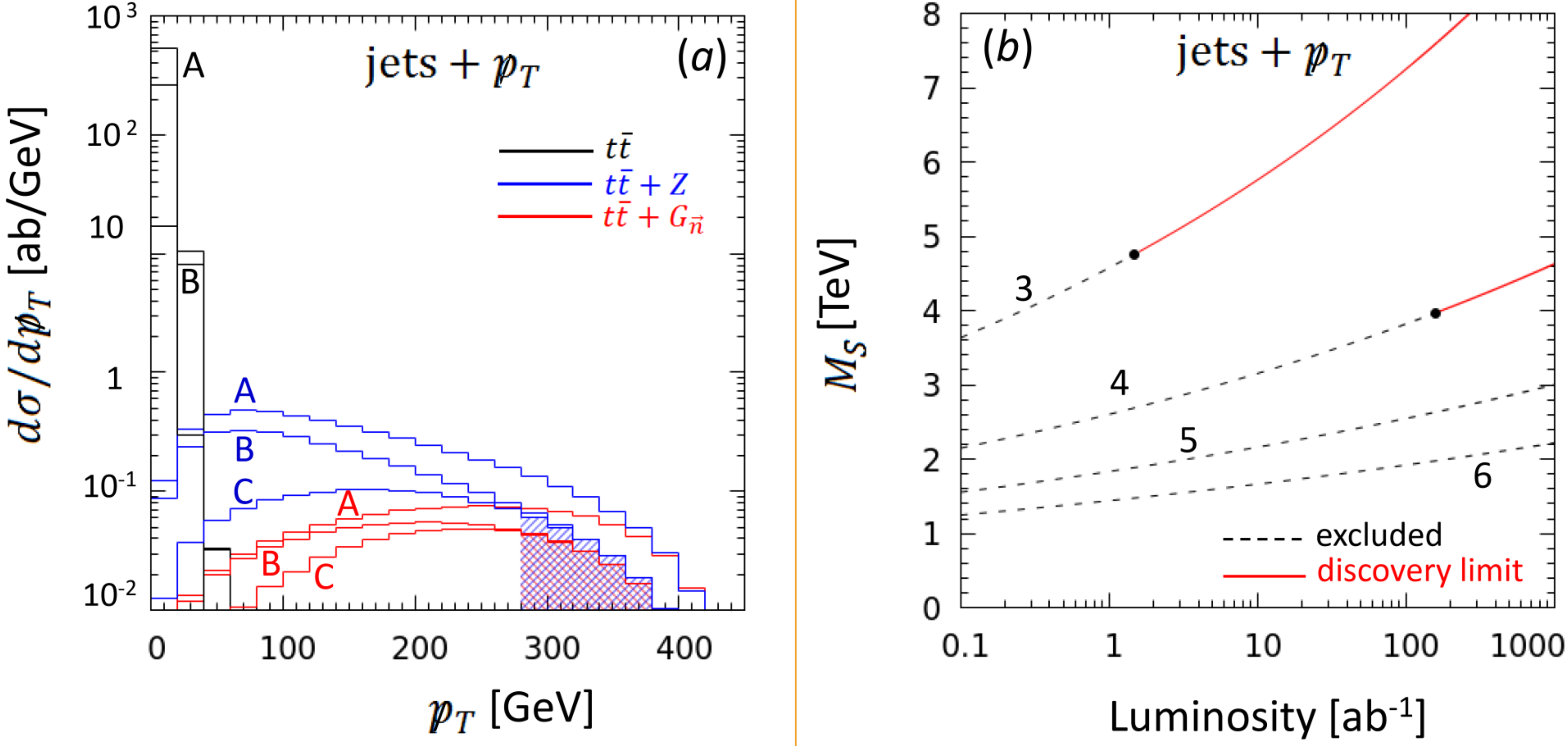
$M_S = 4.77$ TeV, $p = 3$





ILC: Hadronic

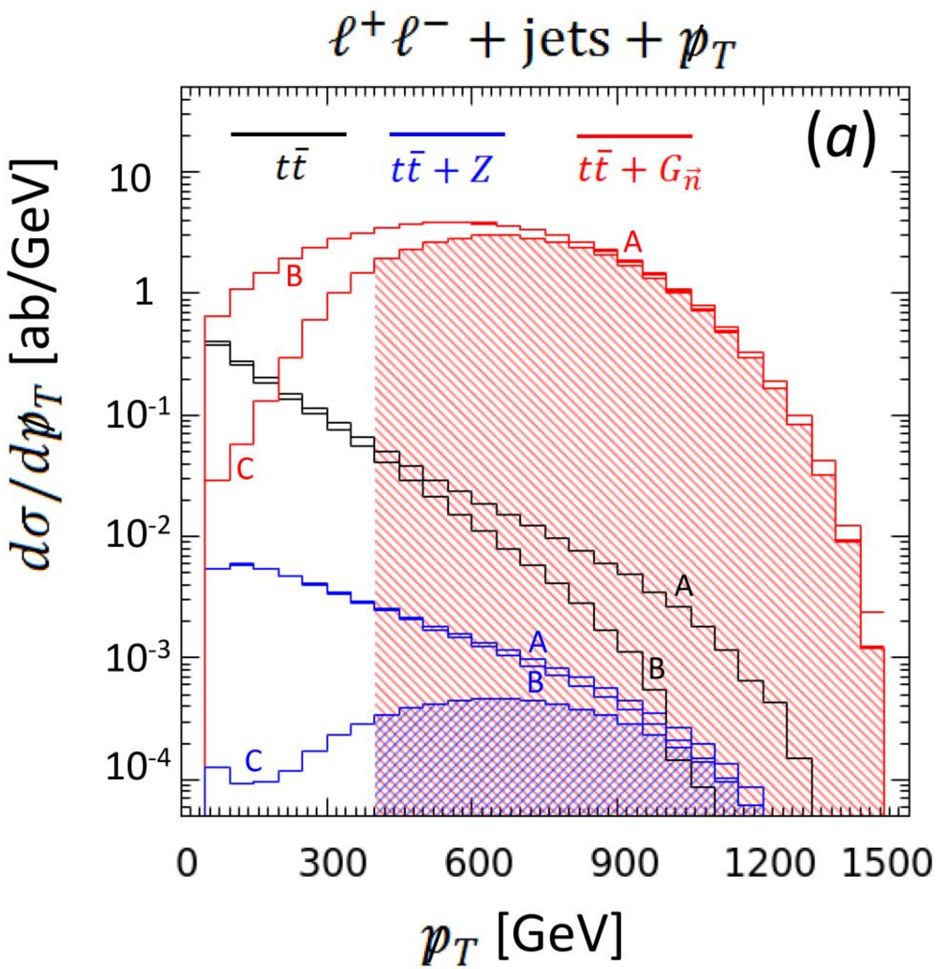
$M_S = 4.77$ TeV, $p = 3$

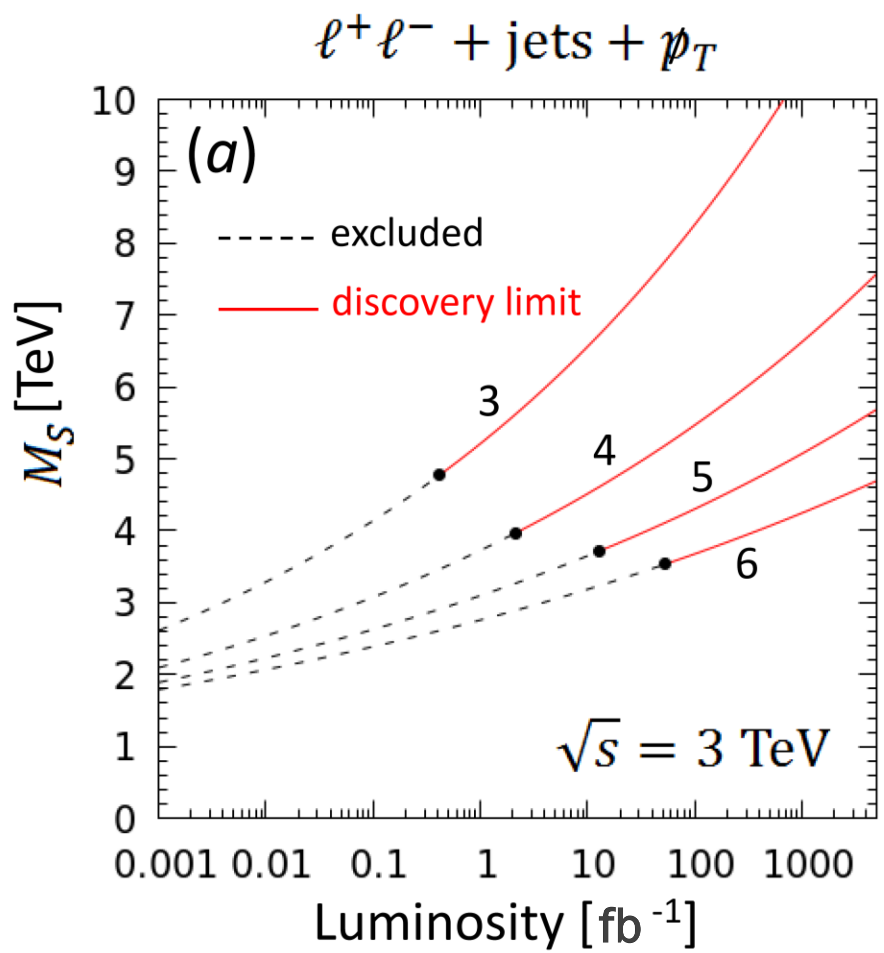


CLIC: Two-lepton

Variables	Set A	Set B	Set C	Set F	Unit
$p_{T_{l_1}}$	> 50.0 $-$	> 50.0 < 1000.0	> 50.0 < 1000.0	> 50.0 < 1000.0	GeV
$p_{T_{l_2}}$	> 50.0 $-$	> 50.0 < 800.0	> 50.0 < 800.0	> 50.0 < 800.0	GeV
$p_{T_{j_1}}$	$-$	< 800.0	< 800.0	< 800.0	GeV
$p_{T_{j_2}}$	$-$	< 800.0	< 800.0	< 800.0	GeV
$\Delta R_{l_1 l_2}$	$-$	$-$	< 2.5	< 2.5	
$\Delta R_{j_1 j_2}$	$-$	$-$	< 2.5	< 2.5	
$\not{p}_T$				< 400.0	GeV
σ_{tt} σ_{ttZ} $\sigma_{ttG_{\vec{n}}}$	76.3 2.4 2687.8	66.4 2.3 2658.0	0.0 0.3 1767.3	0.0 0.2 1586.5	ab

CLIC: Two-lepton





Summary and Outlook

- We studied $e^+e^- \to t\bar{t}G_{\vec{n}}$ process at ILC and at CLIC.
- Signals for extra dimensions 3 can be observable with $\sim 1\ \mathrm{ab}^{-1}$ luminosity.
- At 3 TeV in e^+e^- collider, signals for extra dimensions can be observed with $\sim 1\ \mathrm{fb}^{-1}$ luminosity.
- We will extend this work in the context of LHC.

THANK YOU

Kaluza-Klein Modes

- Translation along y:

$$x^\mu \to x'^\mu = x^\mu$$

$$y \to y' = y + \kappa\xi(x^\mu)$$

- Each KK mode transforms as:

$$\phi_n(x^\mu) \to \phi'_n(x^\mu) = \phi_n(x^\mu)\boxed{e^{iny\xi(x^\mu)/R_c}}$$

Gauge Transformation

$$Q_n = n(\frac{\kappa}{R_c})$$

- $\frac{1}{R_c} \sim 10^{19}\text{GeV}$

Kaluza-Klein Modes

- Scalar field $\phi(x^\mu, y)$ with mass M_0
- Fourier series

$$\phi(x^\mu, y) = \sum_n \phi_n(x^\mu) e^{iny/R_c}$$

- Klein-Gordon equation

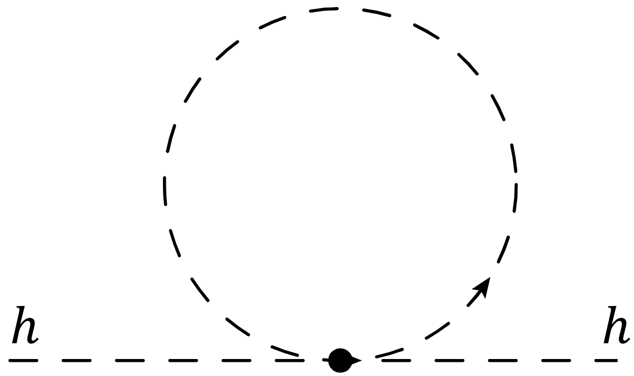
$$\left(\Box - \frac{\partial^2}{\partial y^2} + M_0^2\right) \phi(x^\mu, y) = 0$$

$$\Rightarrow \left(\Box + M_0^2 + \frac{n^2}{R_c^2}\right) \boxed{\phi_n(x^\mu)} = 0$$

KK mode

- Mass of each mode: $M_n = \sqrt{M_0^2 + \frac{n^2}{R_c^2}}$

Hierarchy Problem

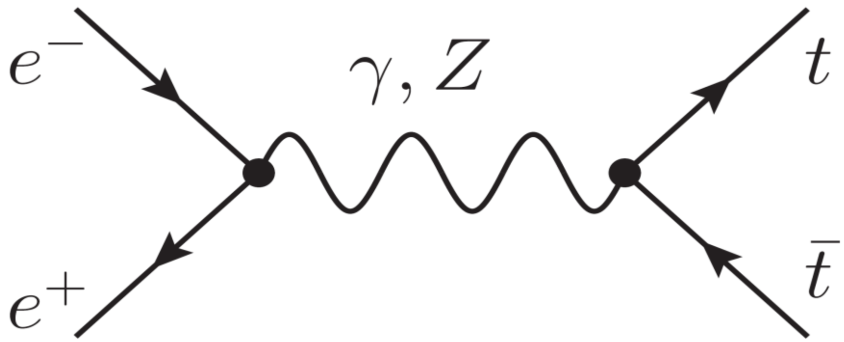


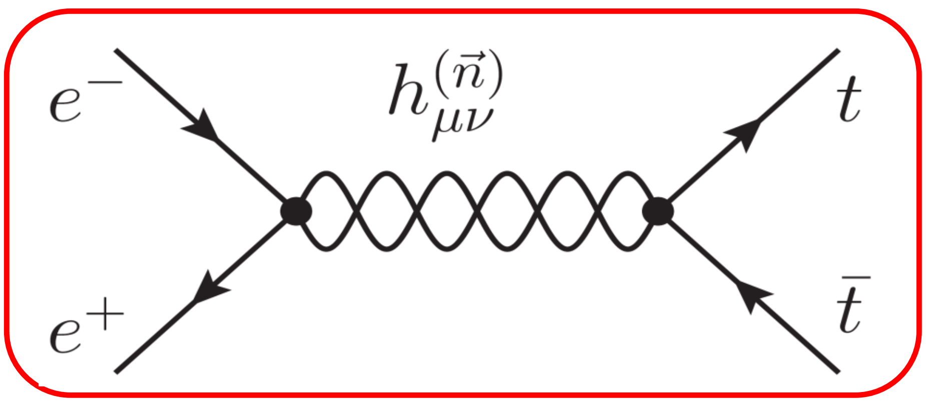
$$\boxed{\delta M_h^2} = \boxed{\lambda\,\Lambda^2} + \lambda M_h^2 \log\frac{\Lambda^2}{M_h^2} + \text{ finite terms}$$

$$\Lambda \sim M_S \sim 10^3 \text{ GeV}$$

$e^+ + e^- \rightarrow t + \bar{t}$

- Lowest order Feynman diagrams





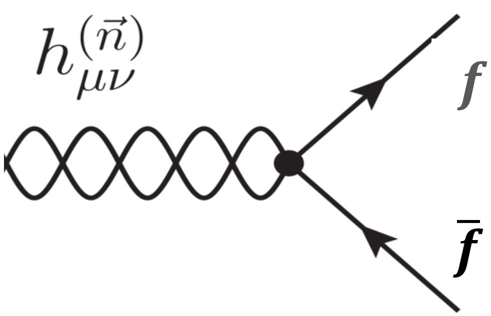
Contribution $\propto \frac{s^2}{M_S^4} \sim 0.08$

$E_{CM} = 3\ TeV, M_S = 4\ TeV$

Graviton Interaction

- Gravity-matter interaction term

$$S_{int} = \sum_{\vec{n}} \frac{\kappa}{2} \int d^4x \, h_{\mu\nu}^{(\vec{n})}(x^\lambda) \, T^{\mu\nu}(x^\lambda)$$



$$A \propto \kappa = M_P^{-1}$$

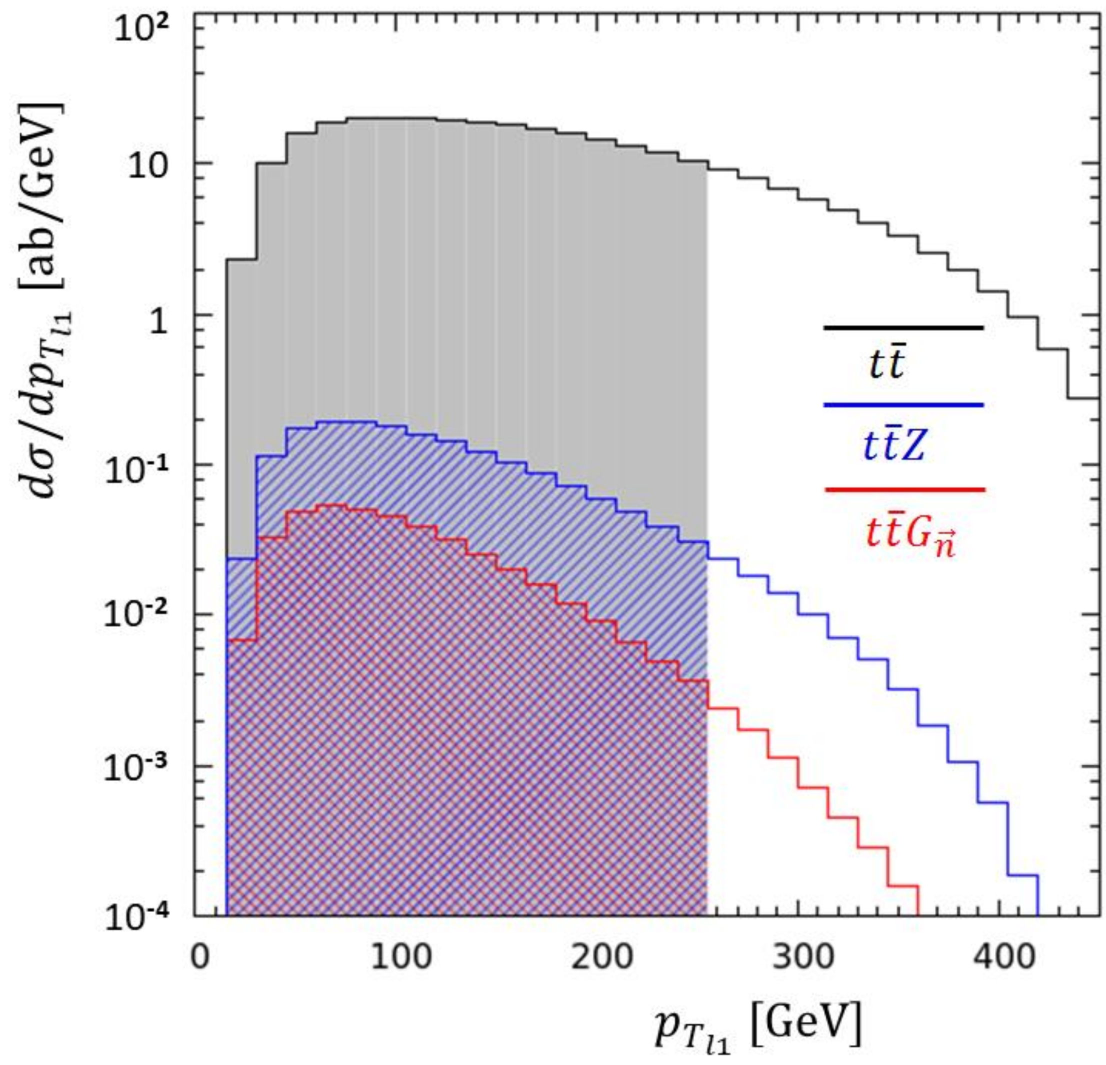
$$\overline{\mathcal{M}^2} \propto \kappa^2$$

$$dM\rho(M)\overline{\mathcal{M}^2} \propto \kappa^2 R_c^p$$

$$\propto M_S^{-(2+p)}$$

- Though coupling $\kappa \propto M_P^{-1}$, it collectively gives observable strength

CUT SELECTION



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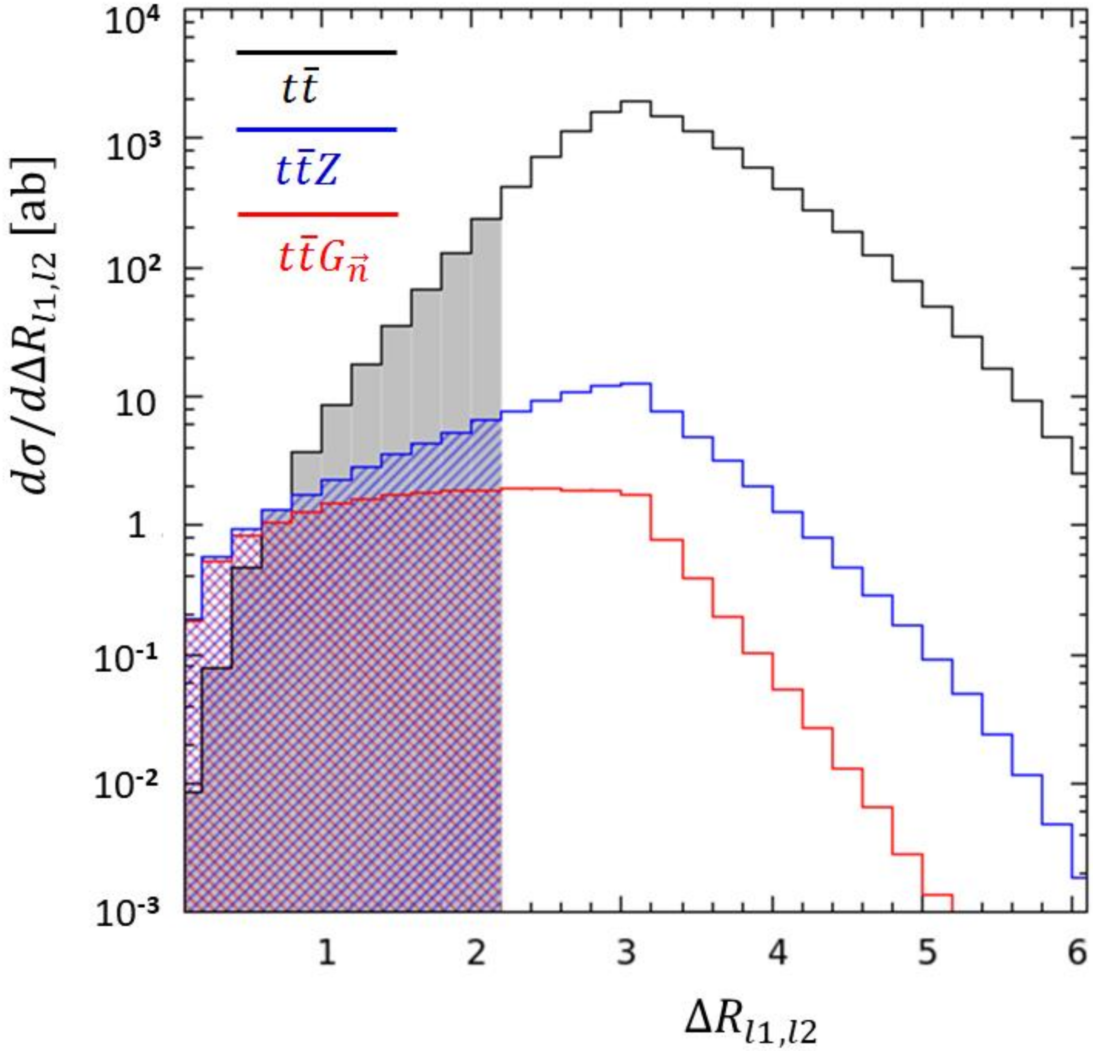
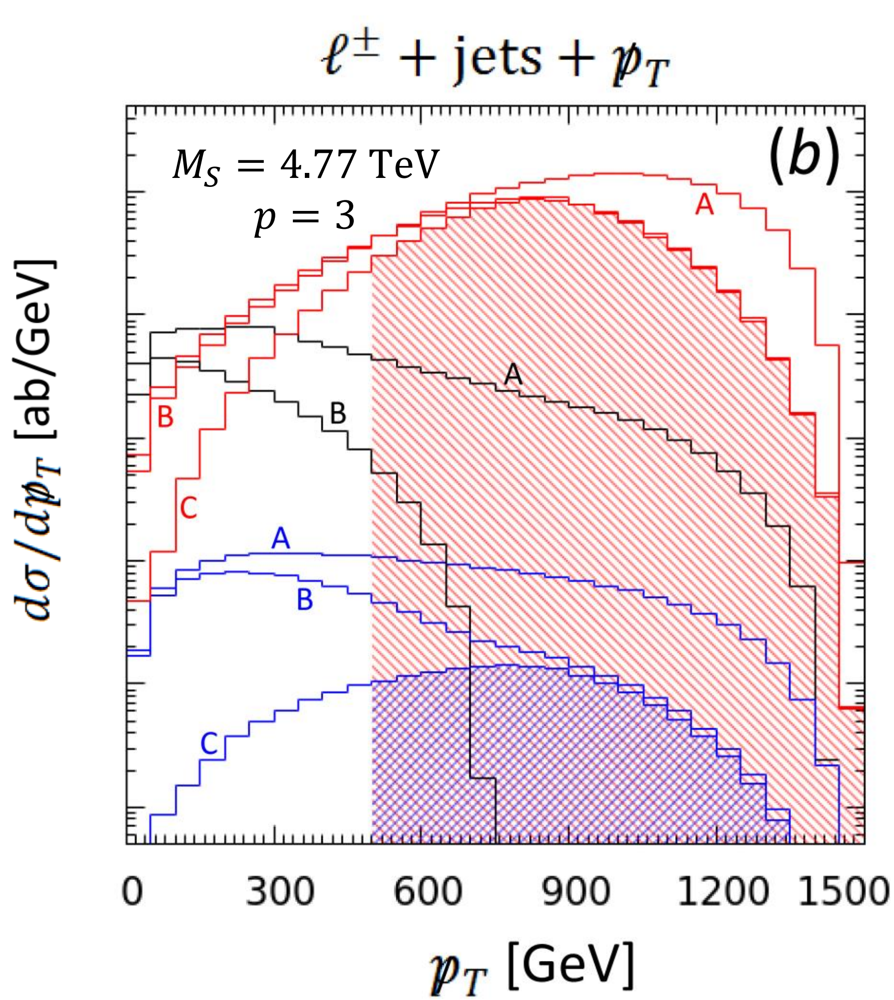
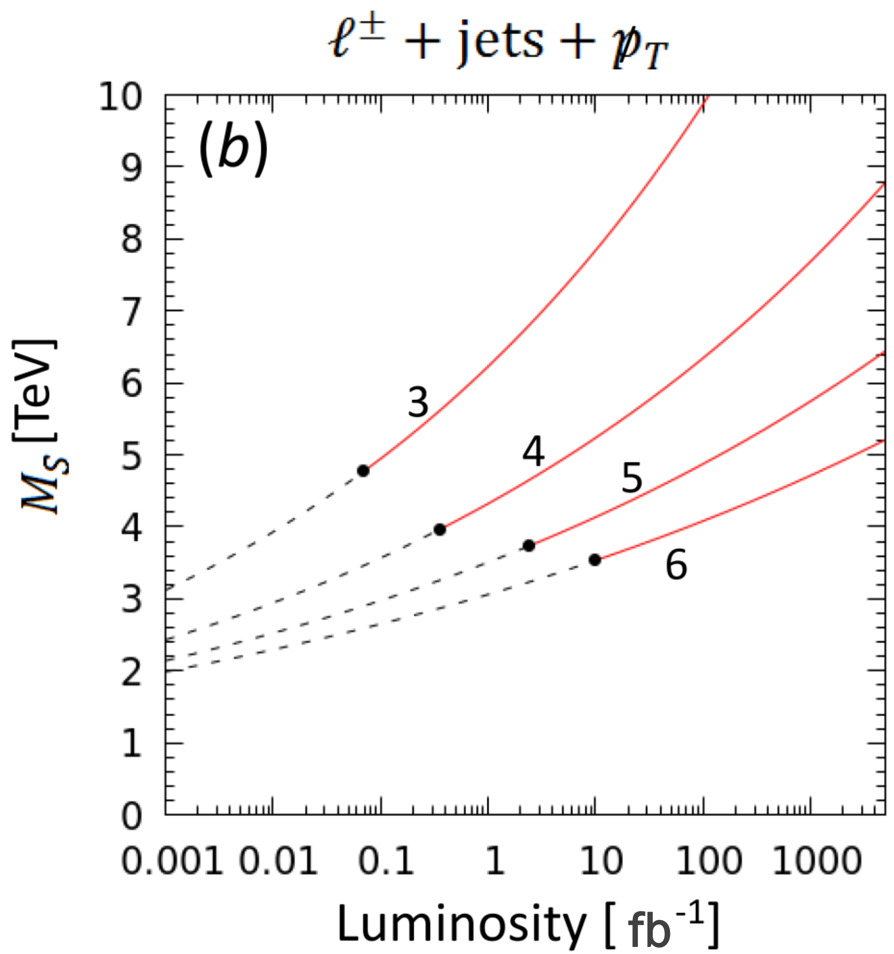


CLIC: One-lepton





CLIC: Hadronic