Exotic leptons at future linear colliders

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in collaboration with O. Panella (Phys. Rev. D 92, 015023 (2015))

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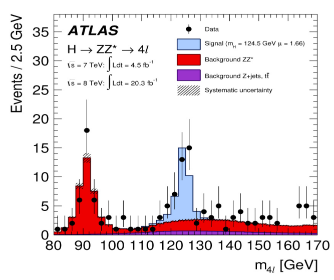
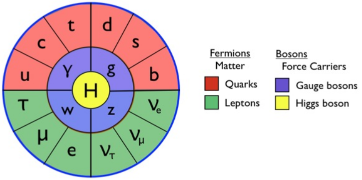
Outline

The Standard Model today...

- Discovery of the Higgs boson:
  ⇒ last great success
- The picture might appear complete
- Quite a few fundamental particles
  ⇒ explain a lot of phenomena

G. Aad et al. (ATLAS coll.), Phys. Rev. D 90 052004 (2014)





Particles of the Standard Model

However...

- m_h is UV sensitive
- neutrino masses

...

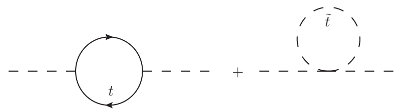
- dark matter
- baryon asymmetry in the universe

SUSY et al

- SUSY provides an elegant solution for the *hierarchy problem*

  H.P. Nilles, Phys. Rep. 110 (1984), H.E. Haber and L. Kane, Phys. Rep. 117 (1985)

  $\Rightarrow$ the Higgs mass is protected by a new symmetry (fermion-boson)



- Composite Higgs

  D.B. Kaplan and H. Georgi, Phys. Lett. 136 B (1984)

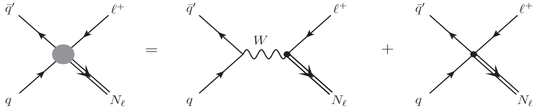
  $\Rightarrow$ emerge as a bound state of some unknown constituents

What if SM particles are not elementary objects?

- Compositeness and partial compositeness: E. Eichten, K.D. Lane and M.E. Peskin Phys. Rev. Lett. 50 811 (1983); N. Cabibbo, L. Maiani and Y. Srivastava, Phys. Lett. 139 B 459 (1984); U. Baur, M. Spira and P. Zerwas, Phys. Rev. D 42 815 (1990)
- Effective Lagrangian approach: operators suppressed by Λ, no explicit UV completion is needed

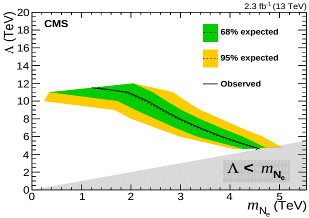
Excited fermions at colliders

- excited leptons and quarks $e^*, \mu^*, u^*, d^*, ...$ with mass m^*
- contact interactions (CI) and gauge interactions (GI), parameters (Λ, m^*)



Standard charged for leptons ($Q = 0$ and $Q = -1$)

- LHC at 7-8 TeV: $m^* > 2.45$ TeV for $\Lambda = m^*$; $\Lambda > 10$ TeV for $m^* = 0.6$ TeV



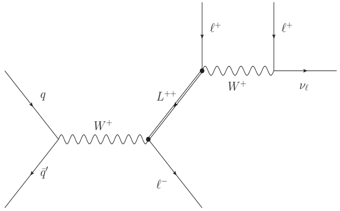
G. Aad et al. (ATLAS coll.) New. J. Phys. 15, 093011 (2013), V. Khachatryan et al. (CMS coll.), JHEP 1603 (2016) 125

- recent CMS analysis excludes composite neutrinos with masses $m^* < 4.35(4.70)$ for a di-jet $e^- e^-$ (di-jet $\mu^- \mu^-$) final state, when $m^* = \Lambda$ A. M. Sirunyan et al. (CMS coll.), arXiv:1706.08578

What about exotic charged fermions?

- exotic fermion states by weak isospin symmetry (exotic charges $Q = -2, 4/3, 5/3$)
- probe composite models with an expected lower SM background

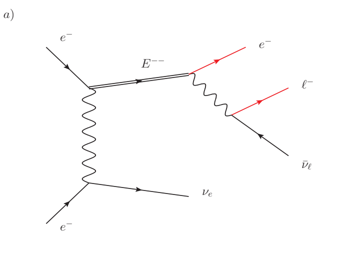
At LHC



S. B. et al, Phys. Rev. D 85 095018 (2012);

R. Leonardi, O. Panella and L. Fanó, Phys. Rev. D 90 055001 (2014)

At Linear Colliders ??



- excited fermions at linear colliders were searched already long ago

  K. Hagiwara, D Zeppenfeld and S. Komamiya, Z. Phys. C 29 115 (1985); O. Cakir and A. Ozansoy, Phys. Rev. D 77, 035002 (2008)
- investigate the prospects for searches at the next generation linear colliders

Extended Isospin Model

- compositeness of fermions studied within Weak Isospin Invariance

G. Pancheri and Y. Srivastava, Phys. Lett. 146 B 87 (1984)

- analogy with Strong Isospin → learning about strong bound states long before discovering quarks and gluons

Strong sector

- strong isospin multiplets: hadronic resonances
- typical energy scale $\simeq \mathcal{O}(1\text{GeV})$

Electroweak sector

- electroweak isospin multiplets: excited fermions (exotic charges)
- the typical energy scale $\simeq \mathcal{O}(1-10\text{TeV})$ (?)

Construction of the multiplets:

1) Standard Model $q, \ell \in I_W = 0, \frac{1}{2}$ and $W^{\pm}, Z^0, \gamma \in I_W = 0, 1$

2) $\Rightarrow$ excited fermions $\in I_W \leq \frac{3}{2}$

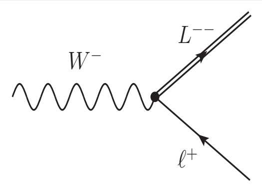
Doubly charged leptons and GI

Isospin multiplets: $Q = I_{3W} + \frac{Y}{2}$, $L \equiv$ excited lepton

$$\begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad I_W = 1, Y = -2 \qquad\qquad \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix}, \quad I_W = \frac{3}{2}, Y = -1$$

Gauge Interactions (GI):

- Difference between multiplets: chiral projectors (P_R, P_L) and the unknown couplings ($f, \tilde{f}$)



$$\mathcal{L}_{\text{GI}}^{(1)} = i\frac{g\,f}{\Lambda}\left(\bar{\psi}_E\,\sigma_{\mu\nu}\,\partial^\nu\,W^\mu\,P_R\,\psi_e\right) + h.c.$$

$$\mathcal{L}_{\text{GI}}^{(3/2)} = i\frac{g\,\tilde{f}}{\Lambda}\left(\bar{\psi}_E\sigma_{\mu\nu}\,\partial^\nu\,W^\mu\,P_L\,\psi_e\right) + h.c.$$

Doubly charged leptons and CI

- Contact Interactions (CI) widely used to describe four-fermion interactions between excited and SM fermions

$$\mathcal{L}_{CI} = \left(\frac{g_*^2}{2\Lambda^2}\right) j^\mu j_\mu$$

with

$$j_\mu = \left(\eta \bar{f}_L \gamma_\mu f_L + \eta' \bar{f}_L \gamma_\mu f_L^* + \eta'' \bar{f^*}_L \gamma_\mu f_L^* + h.c.\right) + (L \to R)$$

- just pick the fermion fields necessary for the L^{--} interaction

$$j_\mu = \left[\bar{\psi}_\nu(x)\gamma_\mu P_L \psi_e(x) + \bar{\psi}_E(x)\gamma_\mu P_L \psi_e(x) + h.c.\right]$$

$$\Rightarrow \mathcal{L}_{CI} = \frac{g_*^2}{\Lambda^2}\left[\bar{\psi}_\nu(x)\gamma^\mu P_L \psi_e(x)\, \bar{\psi}_E(x)\gamma_\mu P_L \psi_e(x) + h.c.\right]$$

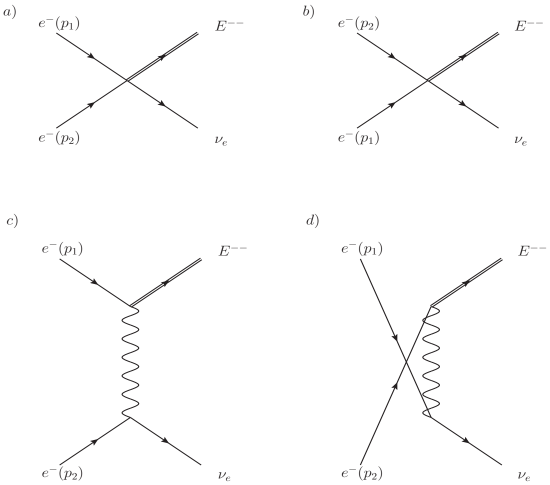
- GI implemented in CalcHEP S. B. et al, Phys. Rev. D 85 095018 (2012);

  A. Pukhov et al. hep-ph 9908288; A. Belyaev, N. D. Christensen and A. Pukhov Comput. Phys. Commun. 184, 1729 (2013) (CalcHEP refs.)

- CI implemented in CalcHEP R. Leonardi, O. Panella and L. Fanó, Phys. Rev. D 90 055001 (2014)

$e^- e^- \to E^{--}\nu_e$: PRODUCTION PROCESS

- $e^- e^-$ beam option: allows for single production of E^{--}



Production cross section: GI

Different isospin multiplets and GI:

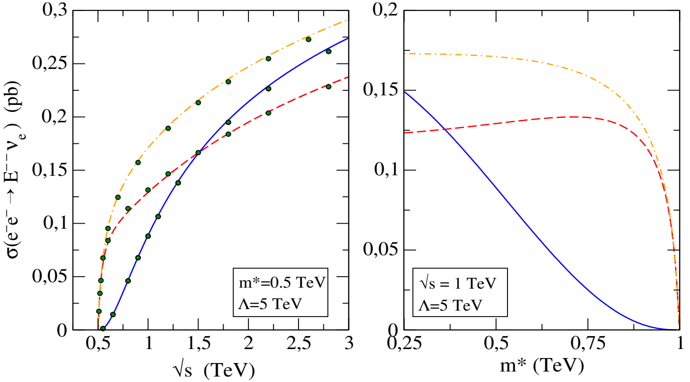
- sensitivity to angular distributions and interference of kinematic channels

Results for E^{--} within different multiplets

$$\left(\frac{d\sigma}{dt}\right)_{I_W=1} = \frac{1}{4s^2\Lambda^2}\frac{g^4 f^2}{16\pi}\frac{t}{(t-M_W^2)^2}\left[m^{*2}(t-m^{*2})+2su+m^{*2}(s-u)\right] + \frac{1}{4s^2\Lambda^2}\frac{g^4 f^2}{16\pi}\frac{u}{(u-M_W^2)^2}\left[m^{*2}(u-m^{*2})+2st+m^{*2}(s-t)\right],$$

$$\left(\frac{d\sigma}{dt}\right)_{I_W=3/2} = \frac{1}{4s^2\Lambda^2}\frac{g^4 \tilde{f}^2}{16\pi}\frac{t}{(t-M_W^2)^2}\left[m^{*2}(t-m^{*2})+2su-m^{*2}(s-u)\right] + \frac{1}{4s^2\Lambda^2}\frac{g^4 \tilde{f}^2}{16\pi}\frac{u}{(u-M_W^2)^2}\left[m^{*2}(u-m^{*2})+2st-m^{*2}(s-t)\right] + \frac{1}{8s^2\Lambda^2}\frac{g^4 \tilde{f}^2}{16\pi}\frac{1}{(u-M_W^2)}\frac{1}{(t-M_W^2)}\left(2stu+\frac{3}{4}utm^{*2}\right).$$

Production cross section: GI



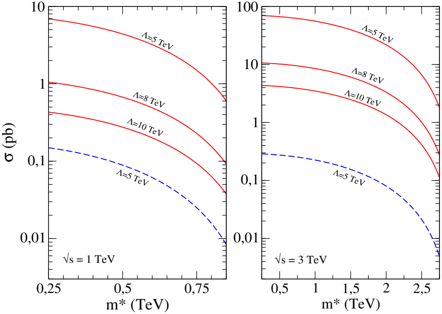
- the interference shows up for $E^{--} \in I_W = 3/2$, zero for $E^{--} \in I_W = 1$
- it pushes down $\sigma_{I_W=3/2}$, e.g. a factor $1/3$ at energies of $\sqrt{s} = 1$ TeV

Production cross section: CI

Results for the σ_{CI}:

$$\sigma_{CI} = \left(\frac{g_*^2}{\Lambda^2}\right)^2 \frac{s}{4\pi}\left(1-\frac{m^{*2}}{s}\right)^2 = \left(\frac{s}{\Lambda^2}\right)^2 \frac{4\pi}{s}\left(1-\frac{m^{*2}}{s}\right)^2 ,$$

- $g_*^2 = 4\pi$, some affinities with $g_\rho^2 \simeq 4\pi \times 2.1$,



$e^- e^- \to E^{--} \nu_e$

- standard adopted normalization $\Rightarrow \sigma_{CI}$ is dominant over σ_{GI}
- we use CI+GI for both production and decays of E^{--}

Final state signature

- we consider the following decays

$$E^{--}(\to W^- e^-) \to e^- \ell^- \nu_\ell$$

- the signature we investigate is

$$e^- e^- \to e^- e^- \nu_e \bar{\nu}_e \, (\mathrm{LSD} + \not{E}_T)$$

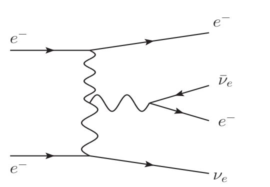
Analysis structure:

- Signal (CI + GI): 8 diagrams (CalcHEP),
- Standard Model Background:
  - irreducible: 28 + 301 (CalcHEP and MadGraph)
  - reducible (CalcHEP and MadGraph)
- Study the kinematic variables ⇒ kinematic cuts
- Detector effects: cuts on p_T and geometrical acceptance
- Beam effects: ISR and Beamstrahlung
- Statistical significance $S(\Lambda, m^*)$ and exclusion plots

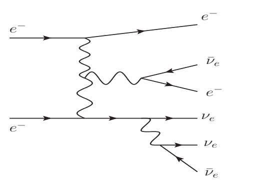
SM background preliminaries: base cuts

$p_T^{min}(e^-) > 15$ GeV	$p_T^{max}(e^-) > 50$ GeV	$p_T(\nu) > 15$ GeV	$\lvert\eta(e^-)\rvert < 2.5$

G. Aarons et al. (ILC coll.) 0709.1893; L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts 1202.5940, E. Accomando et al (CLIC coll.) hep-ph/0412251

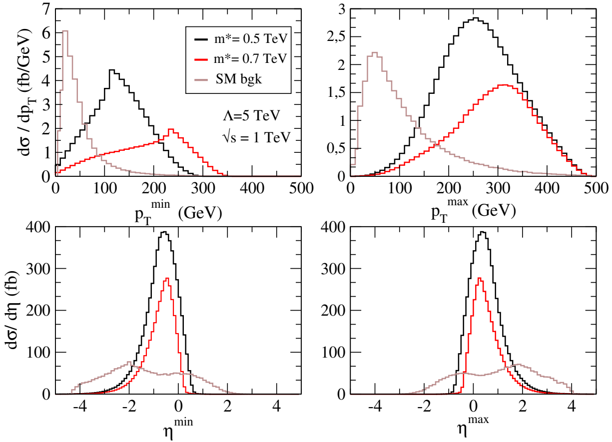


- Set 1): $e^- e^- \to e^- e^- \nu_e \bar{\nu}_e$
- 28 diagrams (exchange of identical particles)
- $\sigma = 188.2$ fb at $\sqrt{s} = 1$ TeV
- $\sigma = 209.3$ fb at $\sqrt{s} = 3$ TeV



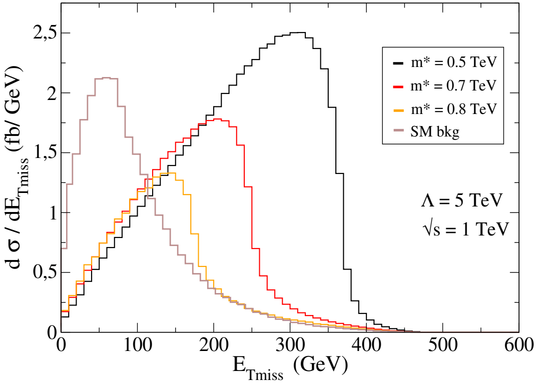
- Set 2): $e^- e^- \to e^- e^- \nu_e \nu_e \bar{\nu}_e \bar{\nu}_e$
- 301 diagrams (exchange of identical particles)
- $\sigma = 0.306$ fb at $\sqrt{s} = 1$ TeV
- $\sigma = 1.356$ fb at $\sqrt{s} = 3$ TeV

Kinematics distributions sample



- Adopted improved cuts: $p_T^{max}(e^-) > 200$ GeV, $-1 < \eta^{max}(e^-) < 2.5$

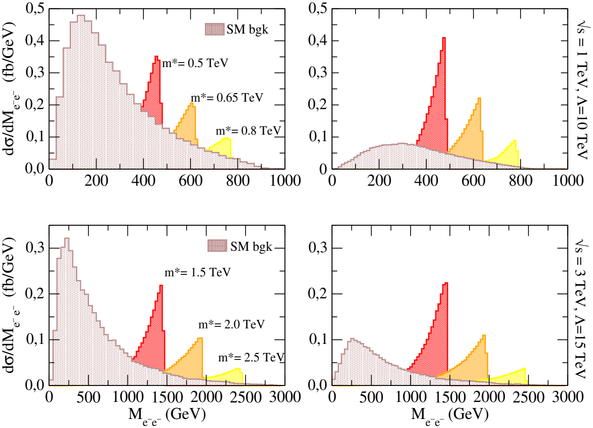
Kinematics distributions sample



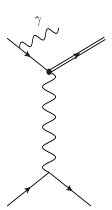
- Adopted improved cuts: $p_T^{max}(e^-) > 200$ GeV, $-1 < \eta^{max}(e^-) < 2.5$ and $\not{E}_T > 100$ GeV

Cuts and LSD invariant mass distribution

- a useful distribution to look at is $M_{e^- e^-}$ (invariant LSD mass)
- comparison of the base (left panels) and improved cuts (right panels)



ISR and beamstrahlung



Initial state radiation (ISR):

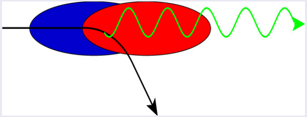
- incoming electrons radiate a photon
- already implemented in CalcHEP

M. Skrzypek and S. Jadach, Z. Phys. C 49 577-584 (1991)

Beamstrahlung:

- electrons radiate photons due to EM field of the other bunch
- already implemented in CalcHEP

P. Chen, Phys. Rev. D 46 (1992)



- Both processes induce energy loss and beam degradation
- Cross sections are affected: we consider **this effect** in the simulation

ISR and beamstrahlung

Parameters

	σ_x^* (nm)	σ_y^* (nm)	σ_z^* (μm)	N
ILC	481	2.8	250	1.74×10^{10}
CLIC	45	1	44	3.72×10^{9}

G. Aarons et al. (ILC coll.) arXiv:0709.1893; L. Lissen, A. Miyamoto, M. Stanitzki and H. Weerts arXiv 1202.5940;

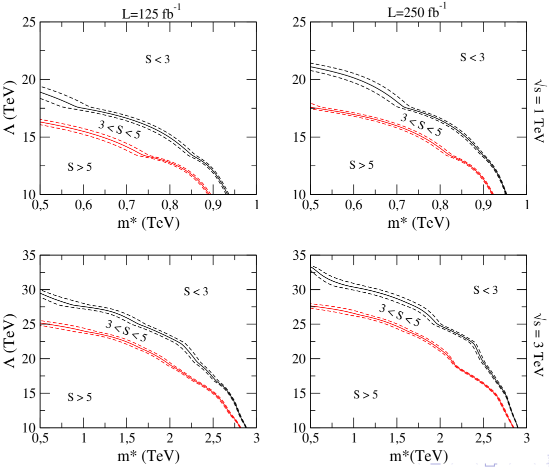
E. Accomando (CLIC Physics Working Group) hep-ph/0412251.

ILC - $\sqrt{s} = 1$ TeV			
Model	σ (fb)	σ_{ISR} (fb)	σ_{ISR} / σ
SM ($e^-e^- \to e^-e^-\nu_e\bar{\nu}_e$)	35.2	29.6	≈ 0.84
$\Lambda = 10,\ m^* = 0.5$ (TeV)	25.67	19.93	≈ 0.78
$\Lambda = 10,\ m^* = 0.65$ (TeV)	17.36	12.32	≈ 0.71
$\Lambda = 10,\ m^* = 0.8$ (TeV)	8.16	4.86	≈ 0.60

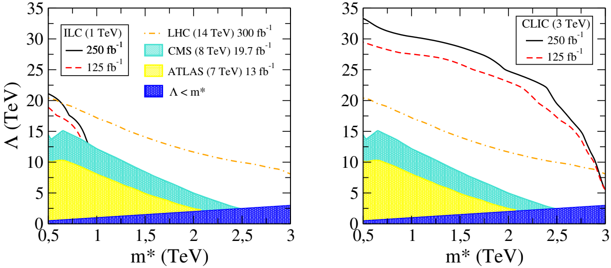
- For $m^* > 0.5$ TeV the effect is larger for the signal
- The larger m^* the more important the effect (degradation of the high energy peak)

Statistical significance for e^-e^- collisions

- $S = \frac{N_s}{\sqrt{N_s+N_b}}$, given $N_s = L\sigma_s$ and $N_b = L\sigma_b$ as function of m^* and Λ
- Reduced luminosity: $L_{e^-e^-} = \frac{1}{4} L_{e^+e^-}$ D. Shulte, Int. J. Mod. Phys. A 18 2851 (2003)



Accessible (Λ, m^*) phase space: LHC and LC



Comments:

G. Aad ae al. (ATLAS coll.) New J. Phys. 15 093011 (2013); CMS coll. CMS-PAX-EXO-14015 (2014)

- comparison of excited leptons within different multiplets:
  1. $m^* = 0.6$ TeV: $\Lambda > 15$ TeV at LHC (run I)
     $\Lambda > 18$ TeV ($\Lambda > 28$) at ILC (CLIC),
  2. $m^* = 2$ TeV: $\Lambda > 5$ TeV at LHC (run I)
     $\Lambda > 22$ TeV ($\Lambda > 25$) at CLIC for $L = 125$ fb^{-1} ($L = 250$ fb^{-1}),
- CLIC fares well for $m^* = 2$ TeV with LHC run II at $L = 300$ fb^{-1} (**same particle**)

Conclusions

- Production of E^{--} at Linear Colliders
- We focus on the e^-e^- beam setting ($L_{e^-e^-} = \frac{1}{4} L_{e^+e^-}$)

- For gauge interactions: interference between u and t kinematic channels
- For production within gauge interactions: the interference plays a role

- Shape the detection strategy: SM irreducible background + kinematic cuts
- Set of kinematic cuts for ideally reconstructed particles, however ISR and Beamstrahlung are considered

- At ILC and CLIC: (Λ, m^*) **can be rather extended**
- High mass region ($m^* = 2$ TeV): $\Lambda >$ 22-25 TeV at **CLIC**, whereas $\Lambda > 5$ TeV (run I) and $\Lambda > 11.6$ TeV (run II) at LHC

Outlook

More realistic benchmarks for the parameters excluded regions

- Provide the simulation of reconstructed particles

  $\rightarrow$ detector efficiencies beyond the geometrical acceptance

- Consider polarized beams and see the effect on cross sections

Neutral excited leptons at linear colliders

- The neutral excited leptons, L^0, are suitable for implementing baryogenesis via leptogenesis D. Zhuridov, Phys. Rev. D 94 (2016) no.3; S. B. and O. Panella Eur. Phys. J. C **77** (2017) no.9, 644
- E_6 string-inspired models also provide neutral fermions

  M. Dhuria, C. Hati, R. Rangarajan and U. Sarkar, Phys. Rev. D 91 5 (2015)

Back 1

Parameters

CLIC - $\sqrt{s} = 3$ TeV			
Model	σ (fb)	σ_{ISR} (fb)	σ_{ISR} / σ
SM ($e^- e^- \to e^- e^- \nu_e \bar{\nu}_e$)	78.8	40.6	≈ 0.51
$\Lambda = 15,\ m^* = 1.5$ (TeV)	48.35	8.28	≈ 0.17
$\Lambda = 15,\ m^* = 2.0$ (TeV)	31.64	4.42	≈ 0.14
$\Lambda = 15,\ m^* = 2.5$ (TeV)	13.98	1.52	≈ 0.11

G. Aarons et al. (ILC coll.) arXiv:0709.1893; L. Lissen, A. Miyamoto, M. Stanitzki and H. Weerts arXiv 1202.5940;

E. Accomando (CLIC Physics Working Group) hep-ph/0412251.

Back 2

Reducible backgrounds: $e^- e^- \rightarrow jet\, jet\, e^- \nu_e \rightarrow \sigma \sim \mathcal{O}(100) fb$

- Jets or Photons misidentified with leptons

  $\Rightarrow$ it helps jet rejection factors $\mathcal{O}(10^{-5})$

  G. Aad et al (ATLAS coll.) arXiv:0901.0512

- Non-prompt leptons from heavy flavour hadrons $\Rightarrow$ Again coming from jets
- The other jet has to be lost or not reconstructed or understood as missing energy...