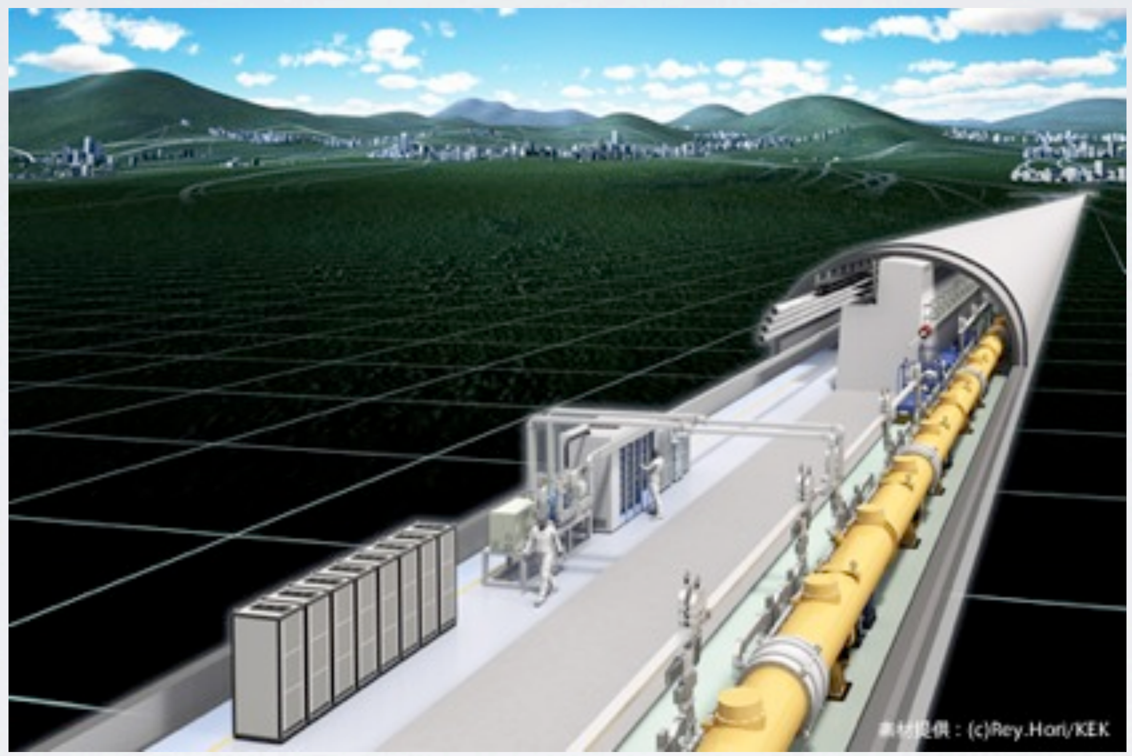
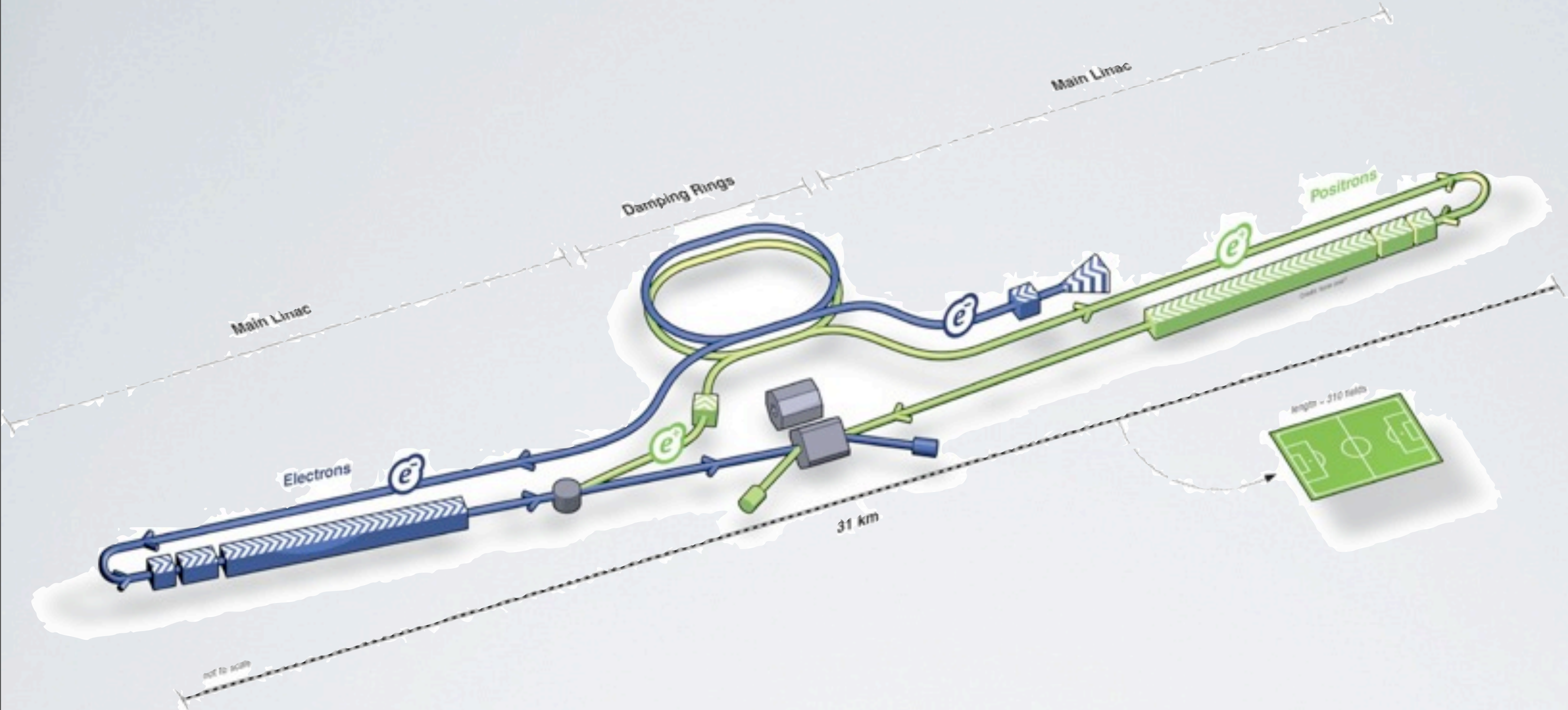
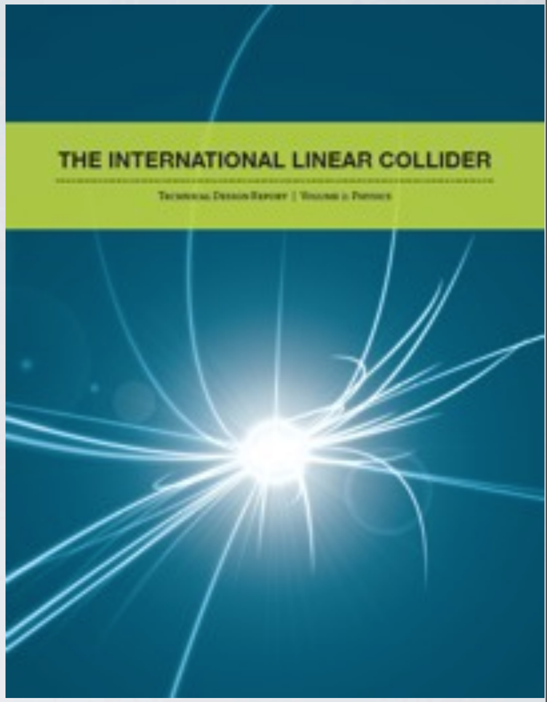
Beyond the Standard Model at the International Linear Collider



Jürgen R. Reuter, DESY

ILC — 500 GeV e+ e- Collider





- e+ e- collider, 31 km length, c.m. energy: 500 GeV (tunable, 200-x) [Upgrade: 1 TeV]
- Polarisation: 80% e- and at least 30% e+
- Integrated Luminosity: 250/fb/yr
- Two detectors/experiments (shared interaction point)
- Experimental setup:
  - ✴ Well-defined initial state
  - ✴ Pure electroweak production (small theory errors)
  - ✴ Triggerless operation
- Concurrent running with LHC high-luminosity phase

Proposal from Japan:　北上市 (Kitakami-Shi Site)

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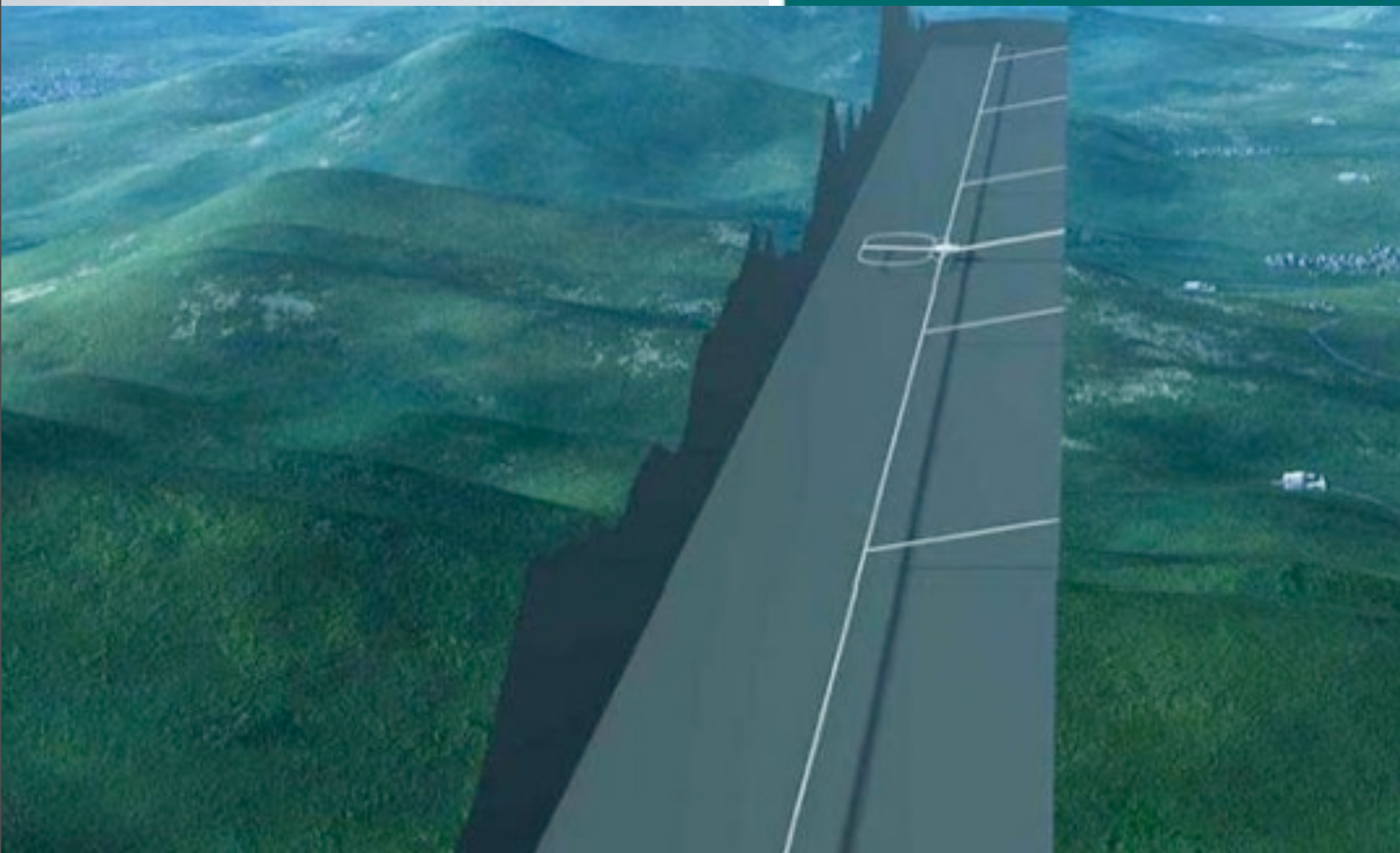

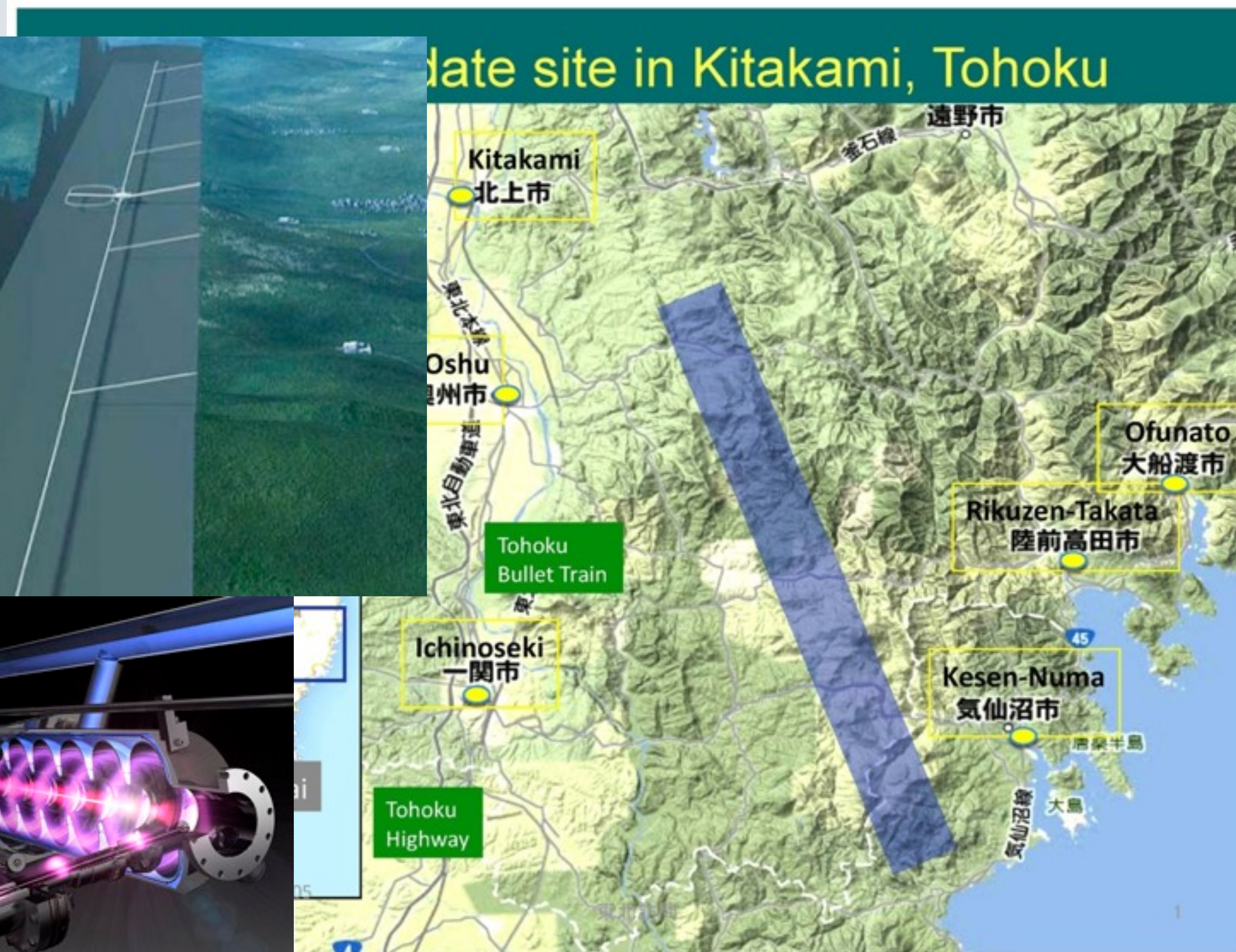

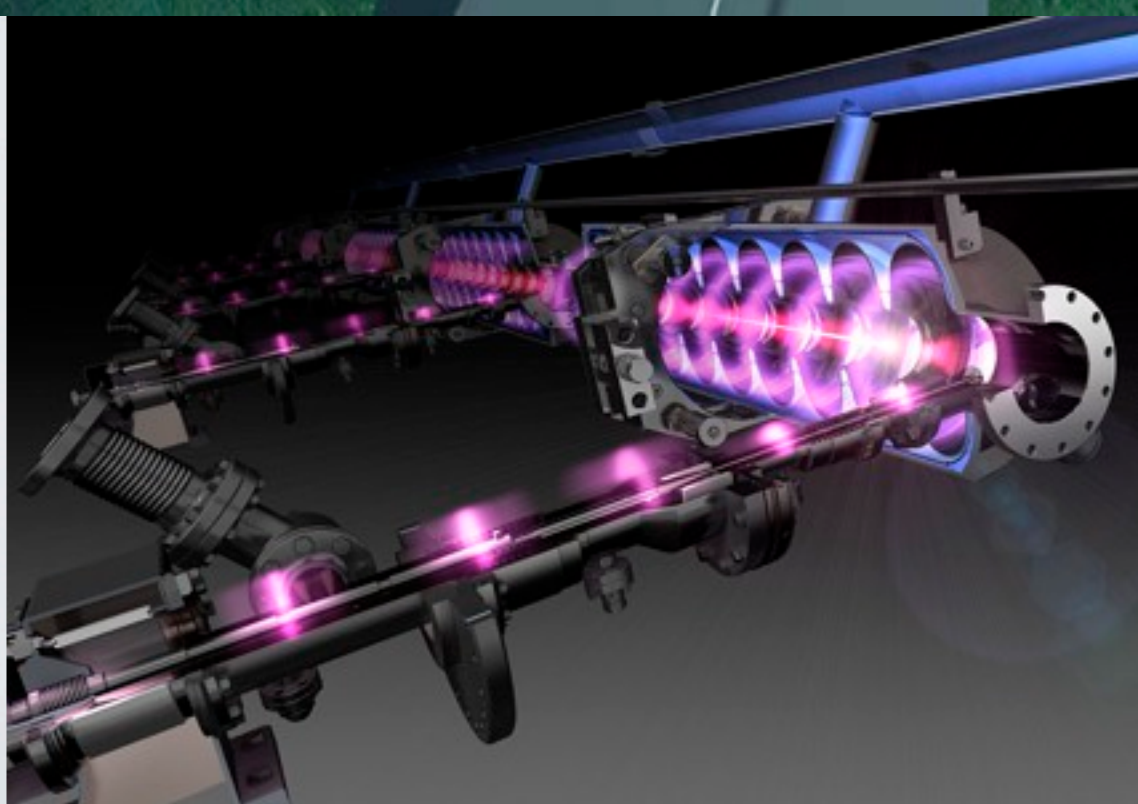

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C) Charm/tau discovery: 1974/76
SLAC: **SM flavor structure**
($e^- e^+$ beams)

Dark Matter Searches

- Assumption: weakly interacting particle χ
- $ee \to \chi\chi$ invisible, use bremsstrahlung:

  $ee \to \chi\chi\gamma$ (analogous to LHC: $pp \to \chi\chi j$)
- Irreducible backgrounds: $ee \to \nu\nu\gamma$,

  $ee \to ee\gamma$ with ee lost in the beampipe
- Polarisation to suppress backgrounds: *W* exchange killed

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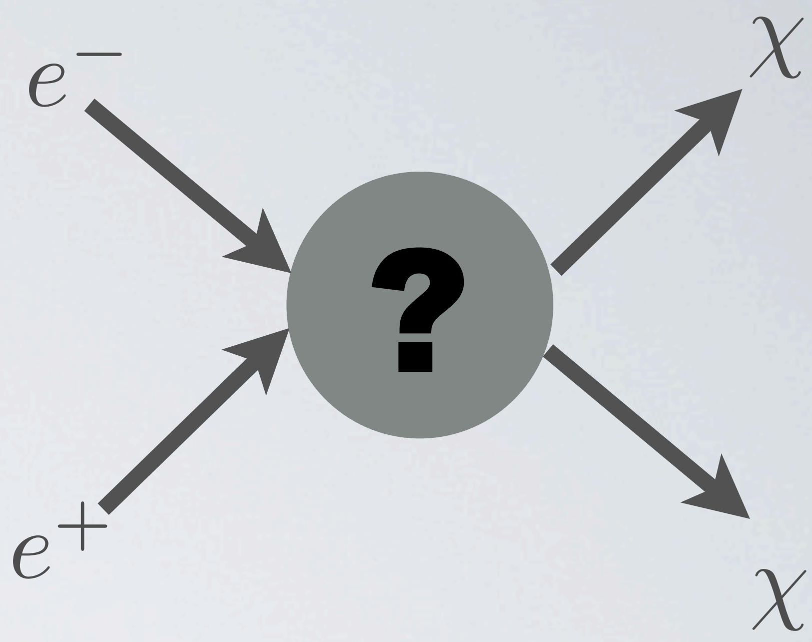
Bartels/Berggren/List: arXiv: 1206.6639



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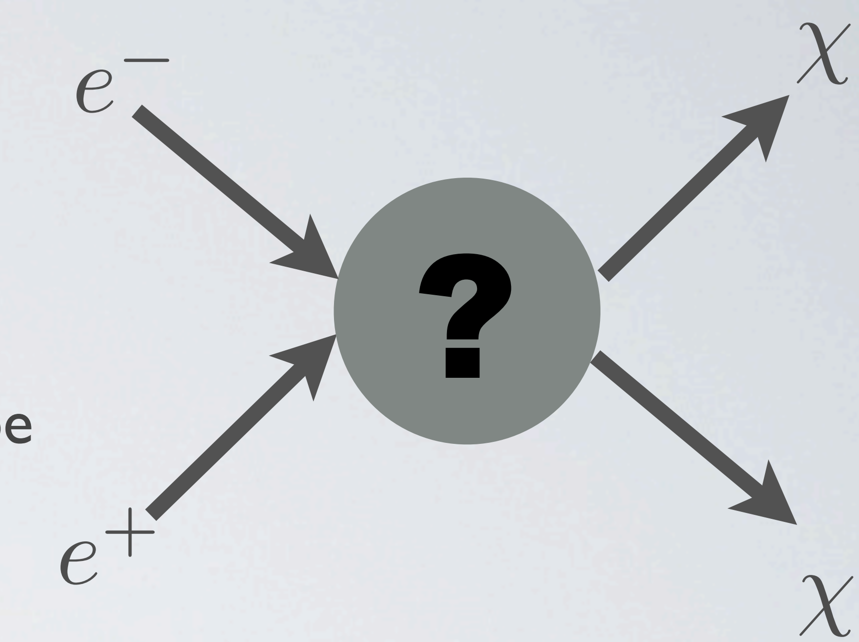

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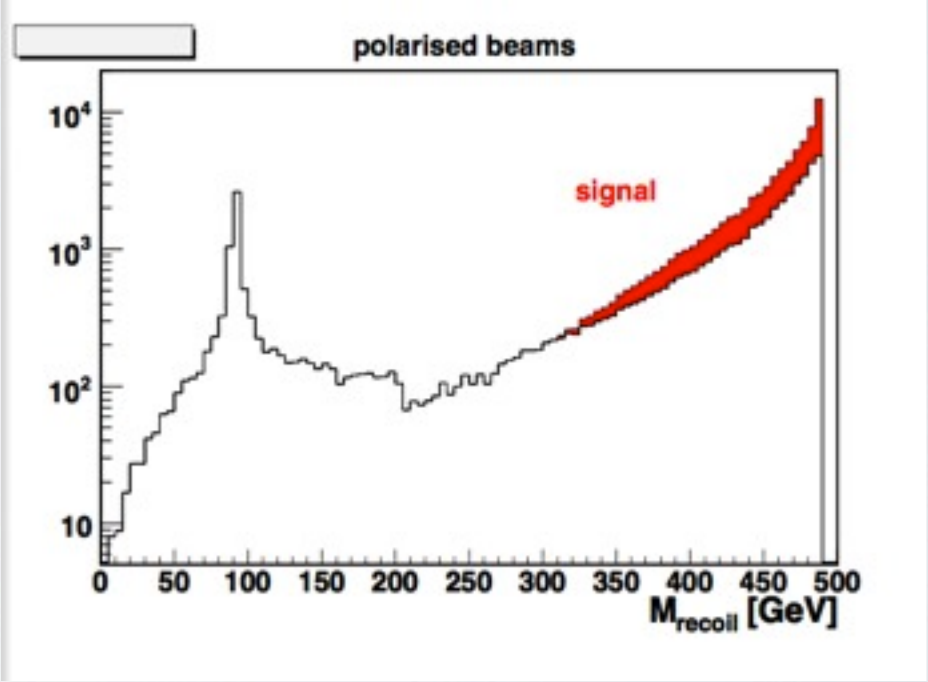
- **Search for signals in the photon recoil spectrum**



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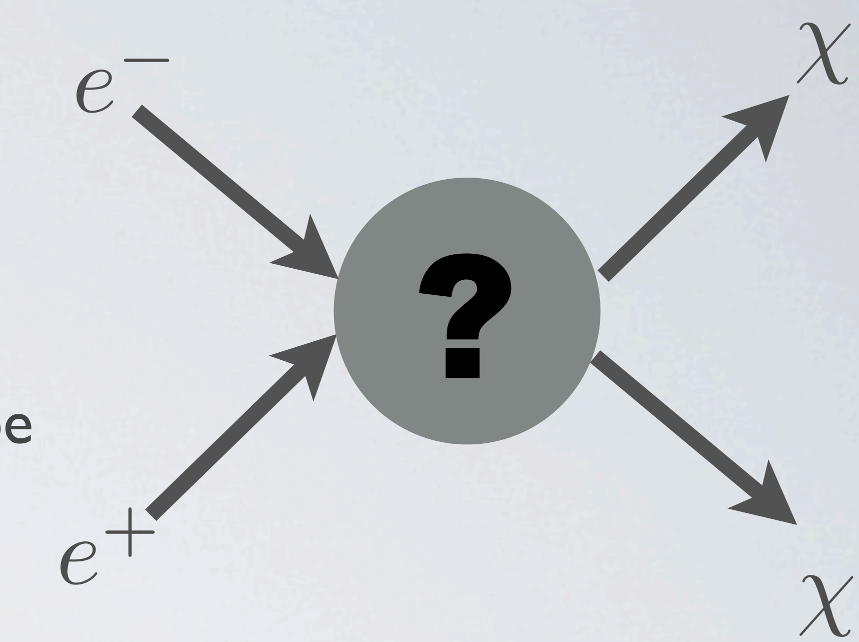

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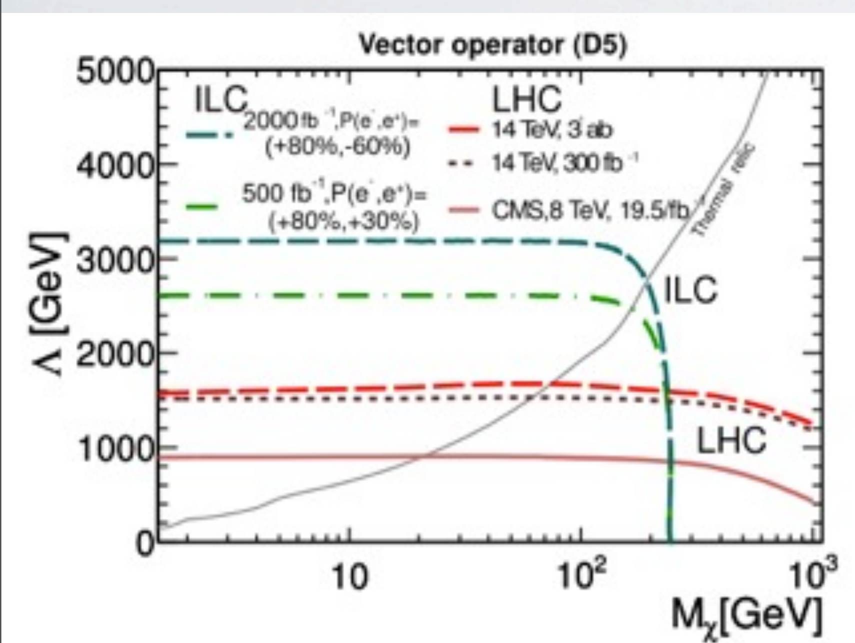

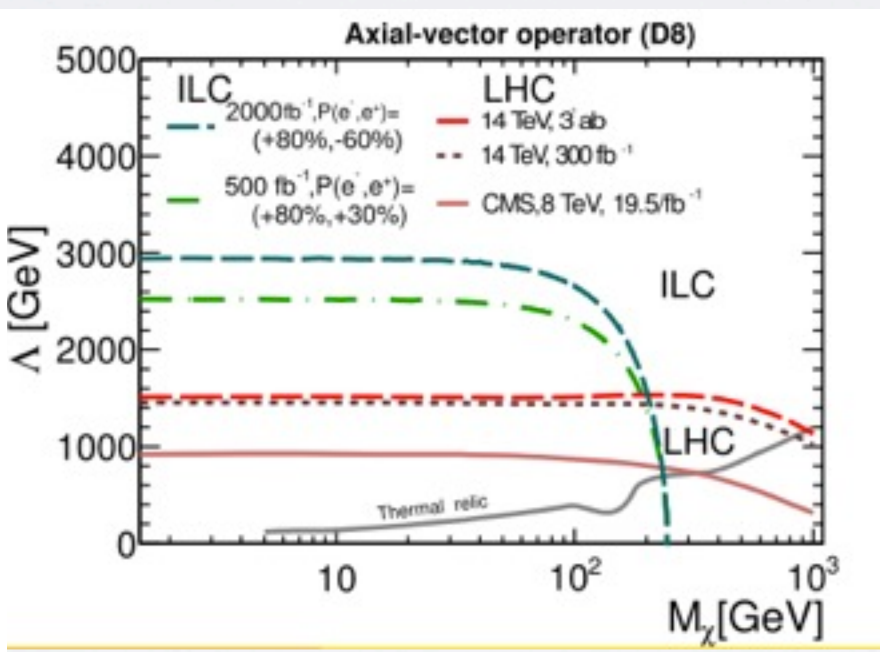

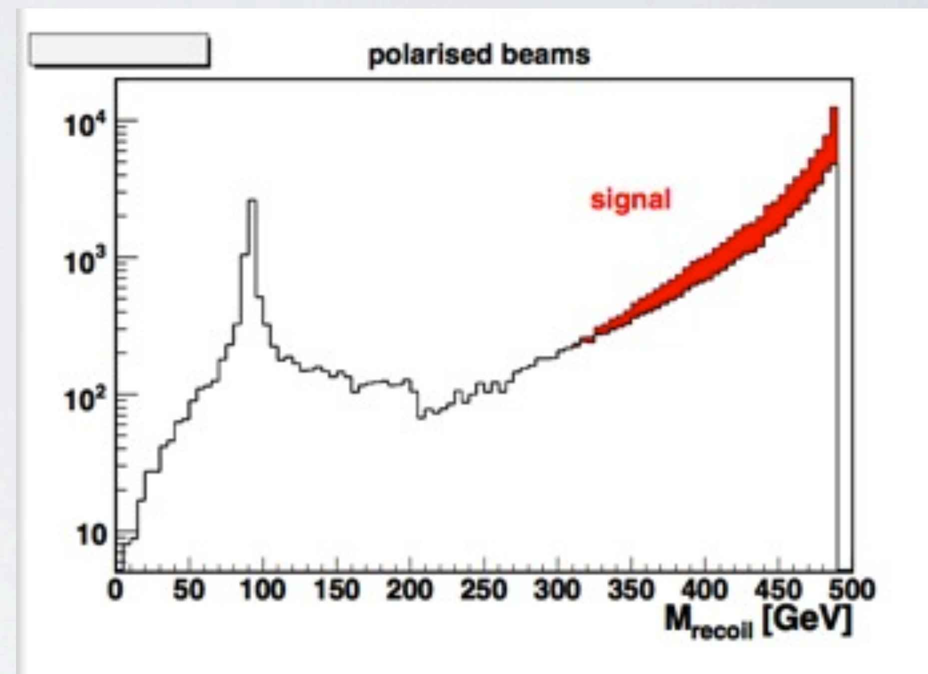

★ Vector operator: "spin-independent"
★ Axial-vector operator: "spin-dependent"

LHC accesses higher masses, ILC lower cross sections (few caveats)

CMS-PAS EXO-12-048; arXiv:1307.5327

Model-Independent Electroweak Searches

- Main advantage of ee machine: perfectly defined initial state, elementary particle collision
- Testbed SUSY: Scan over all NLSP candidates
- Model-independent exclusion/discovery reach in

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- Examples: $\tilde{\mu}_R$ NLSP

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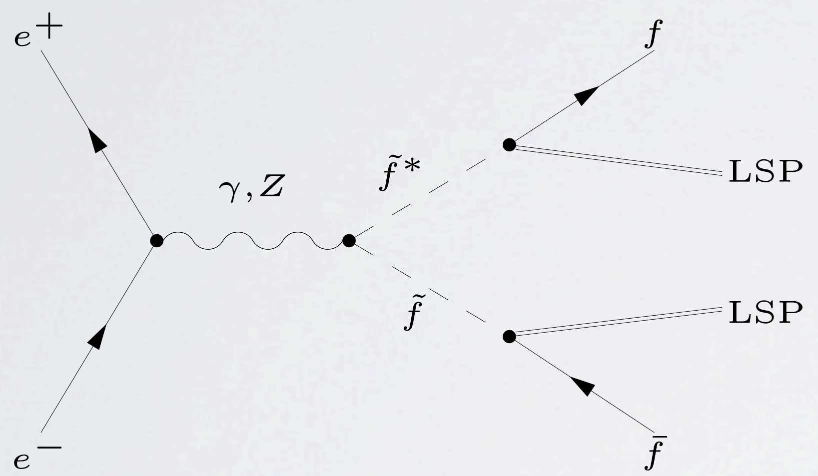

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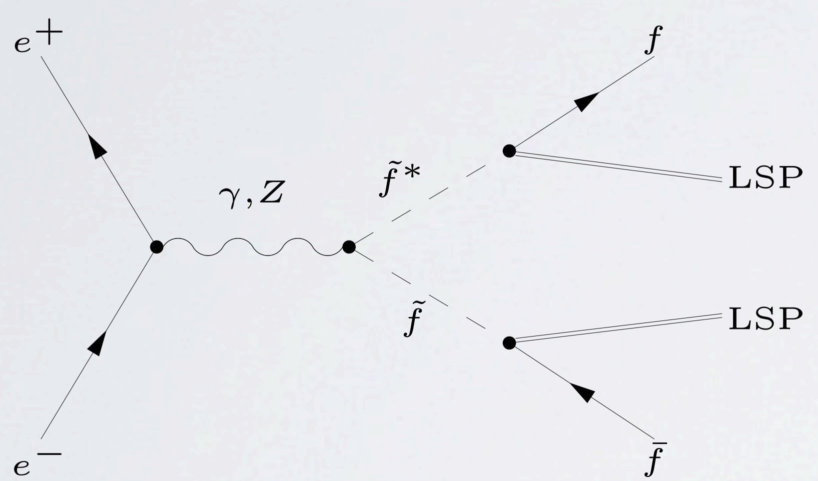
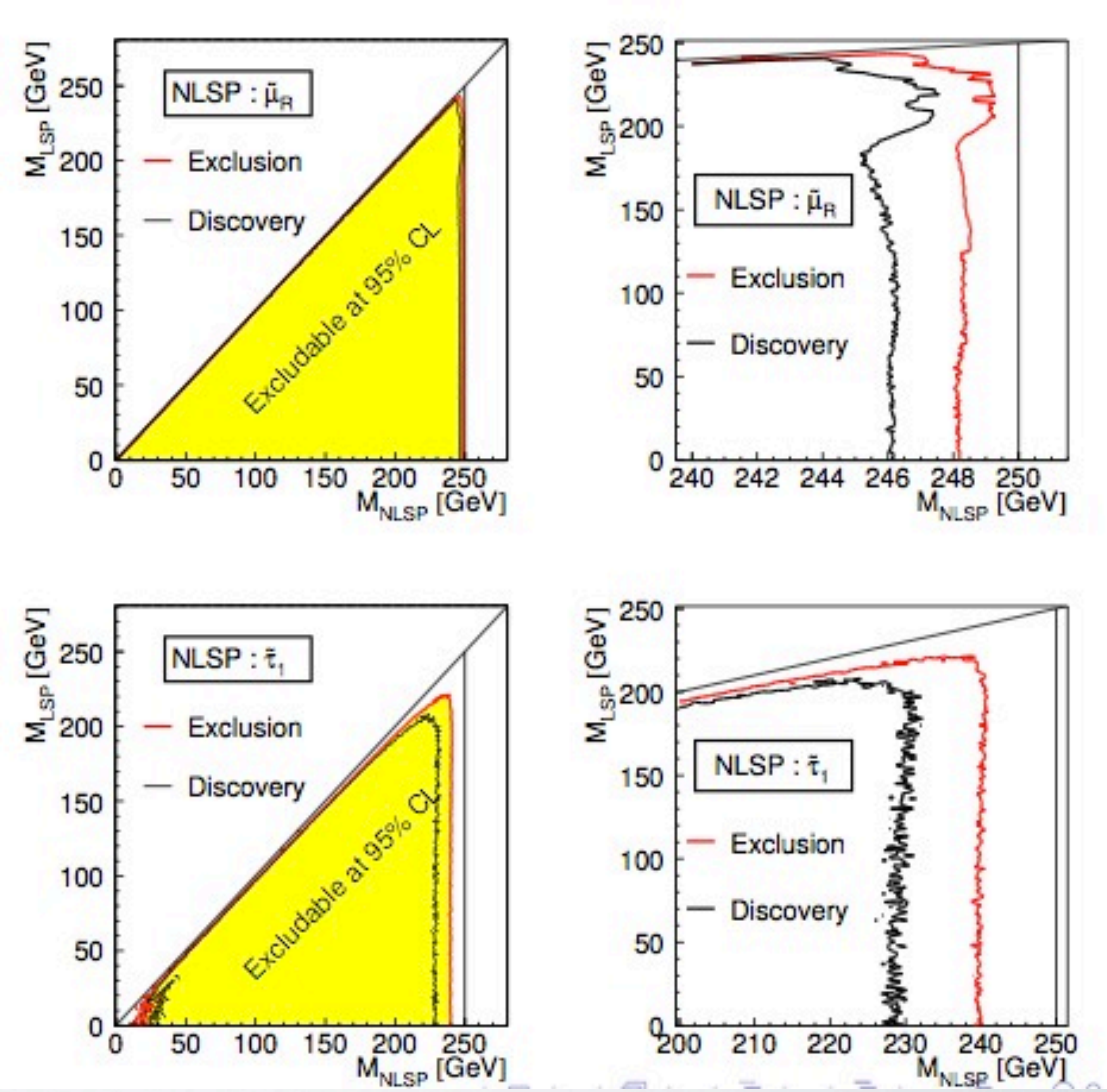


Discover/exclude close to kinematical limit



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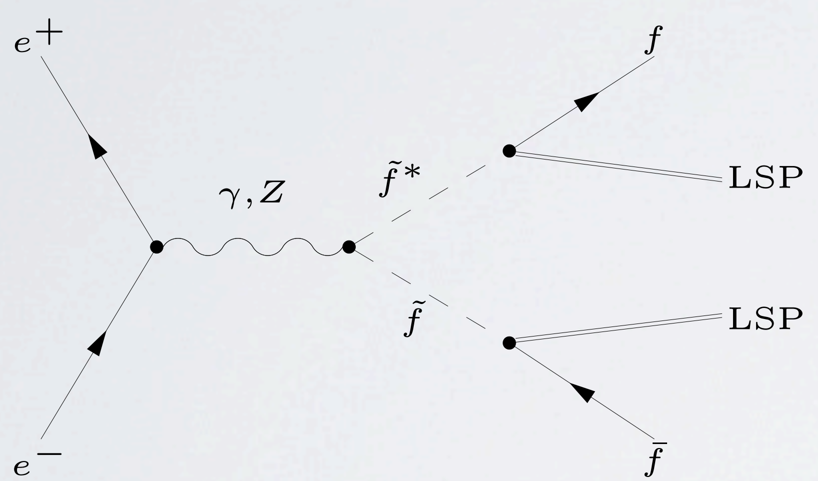

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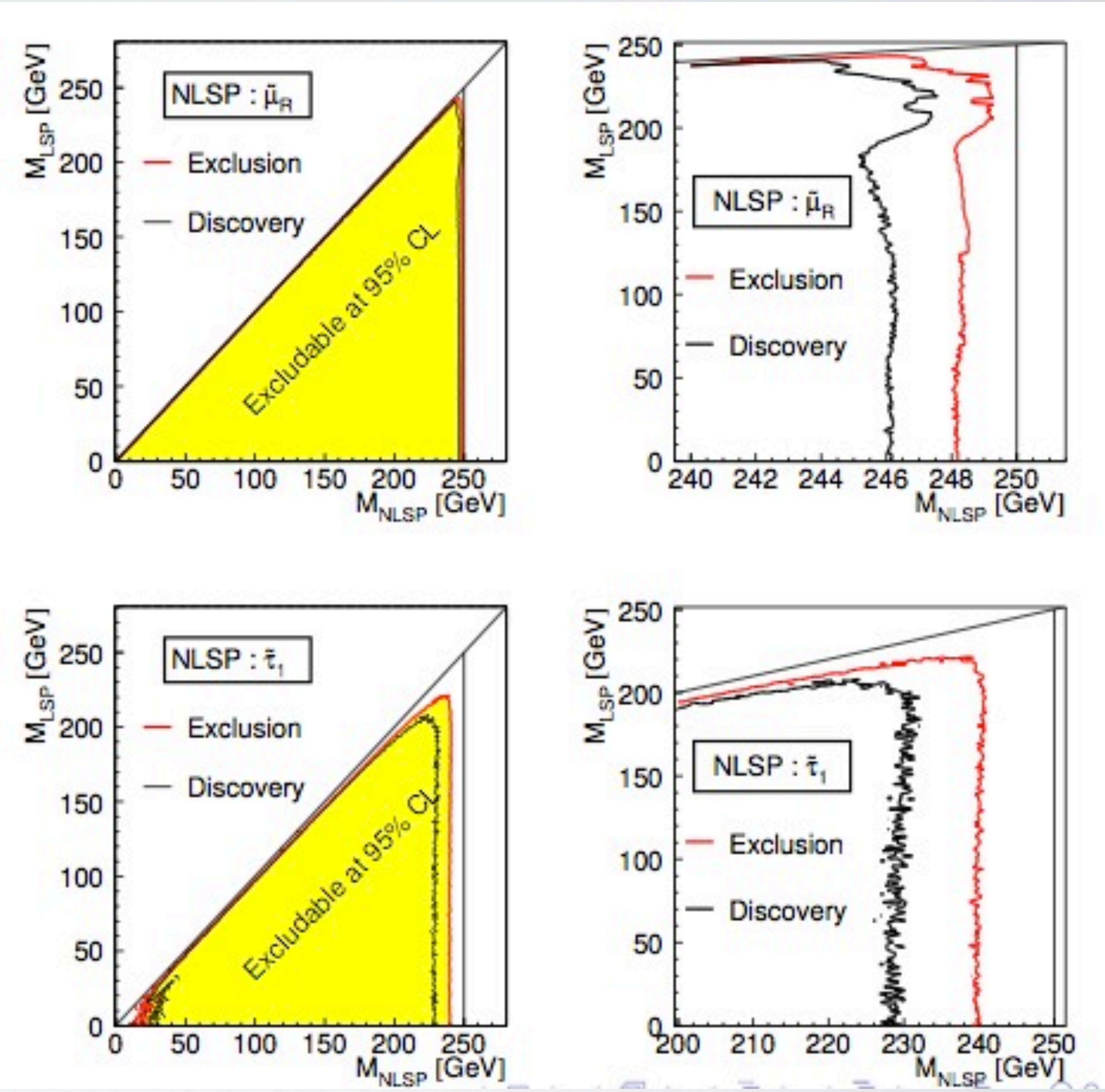
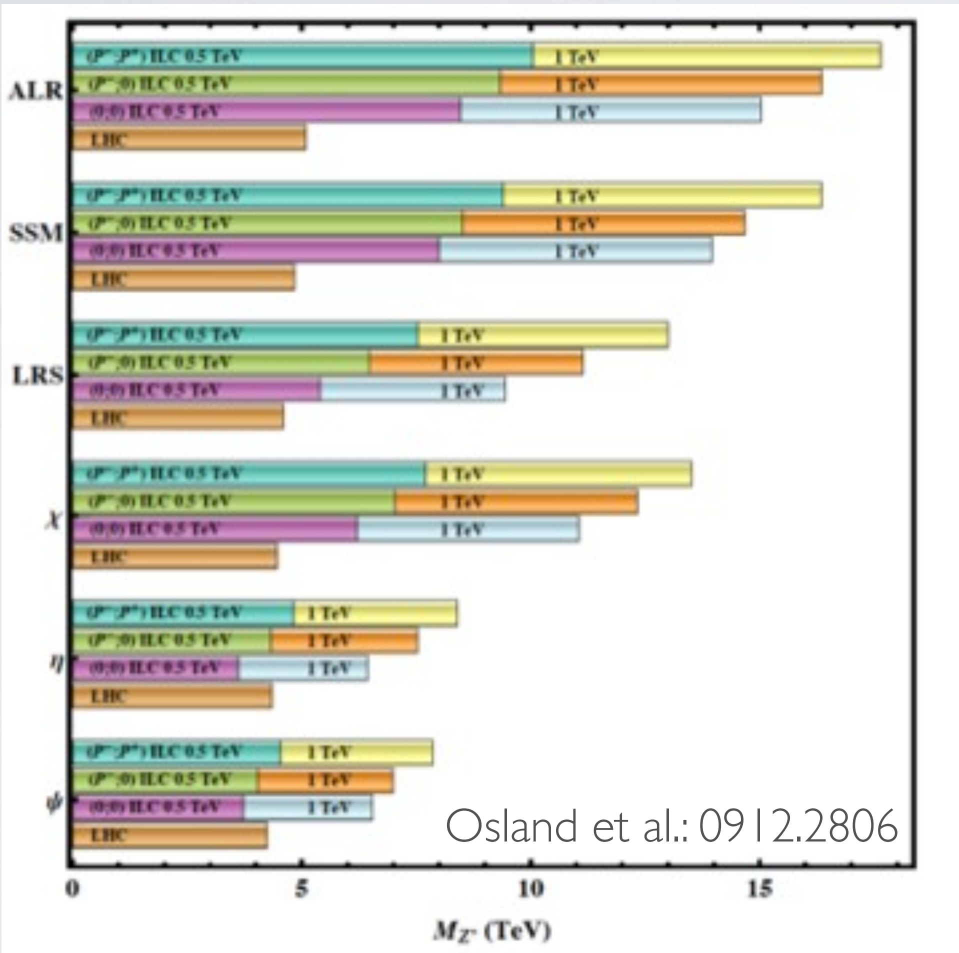


Even for sneutrino NLSP

Kalinowski/Kilian/JRR/Robens/Rolbiecki, arXiv: 0809.997

New Neutral Currents: *Z'* searches

- ★ Neutral current paved path to understanding gauge structure of the SM
- ★ Promising way to go beyond: many GUT models predict additional neutral currents (Z')
- ★ High-precision ILC measurements allows model discrimination
- ★ Access to scales up to tens of TeV!!



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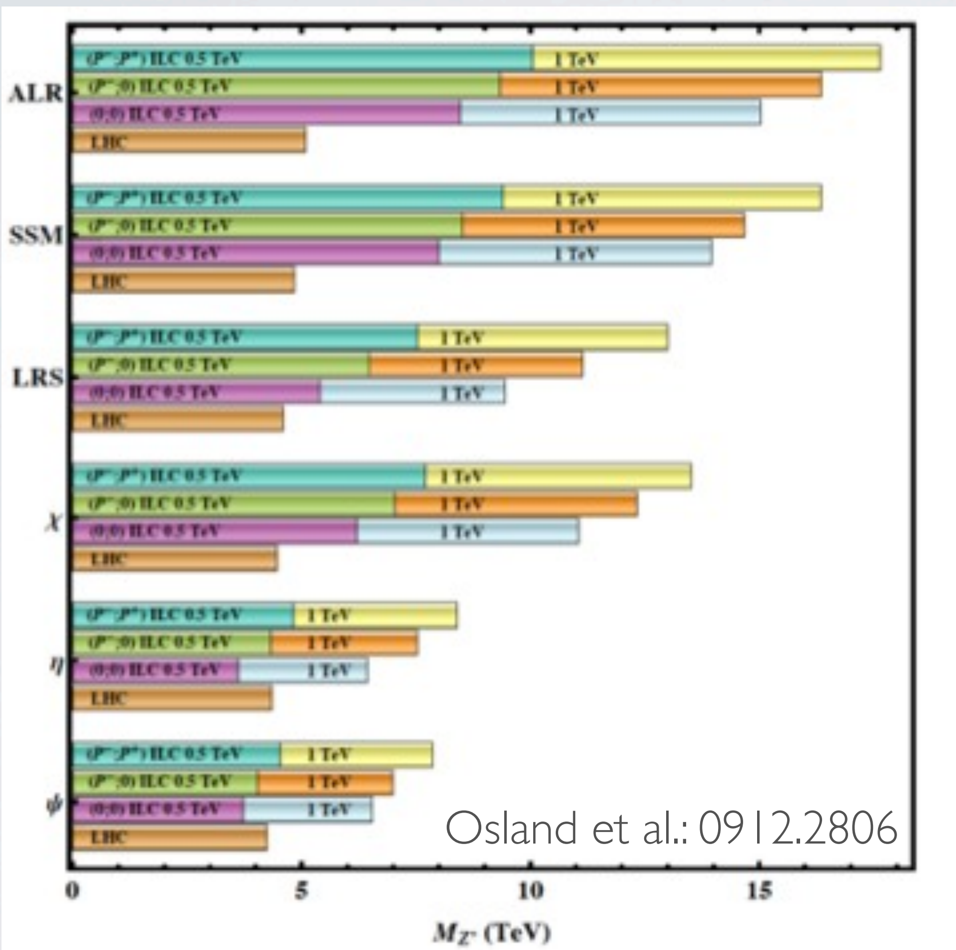

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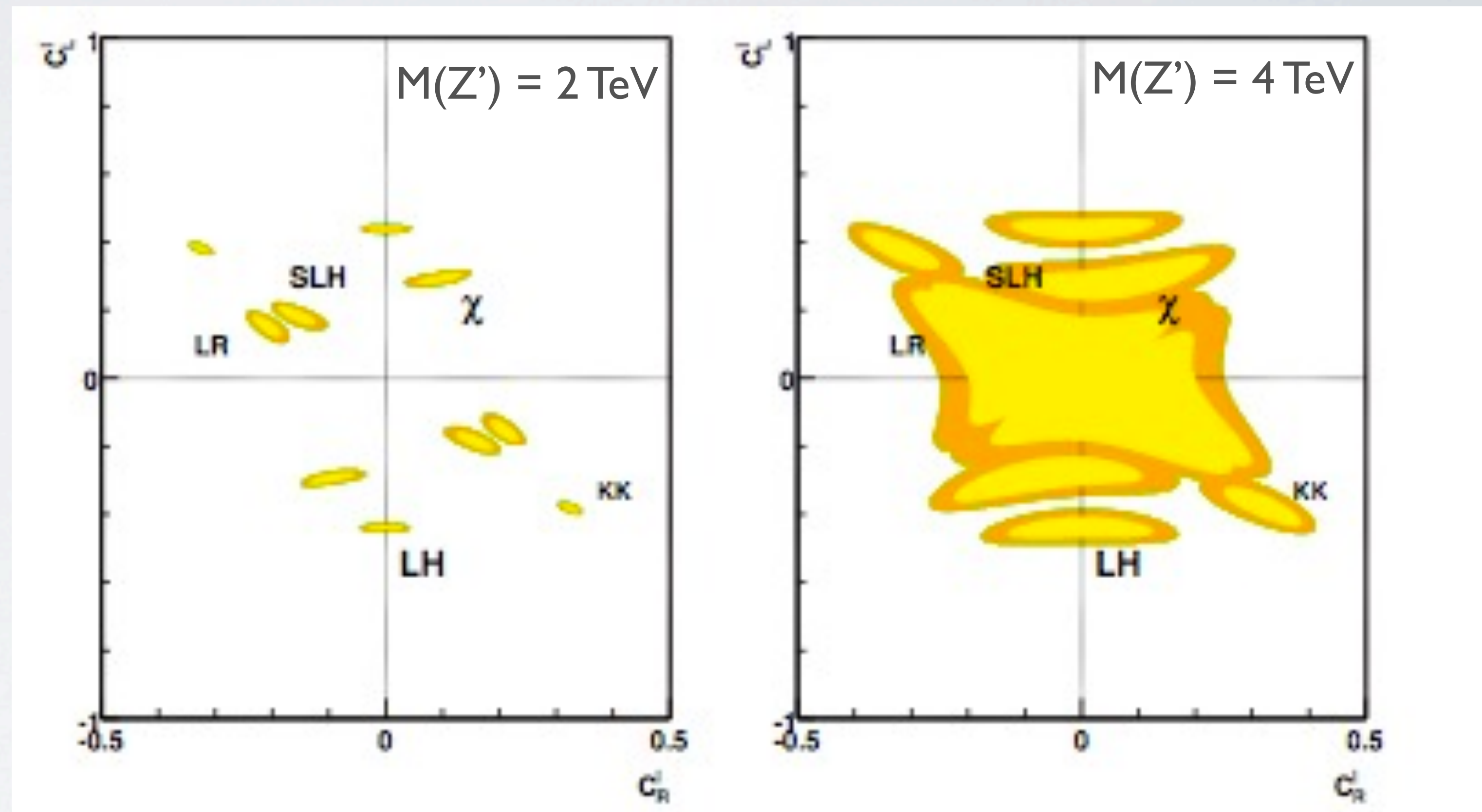

Godfrey/Kalyniak/Tomkins: 0511335

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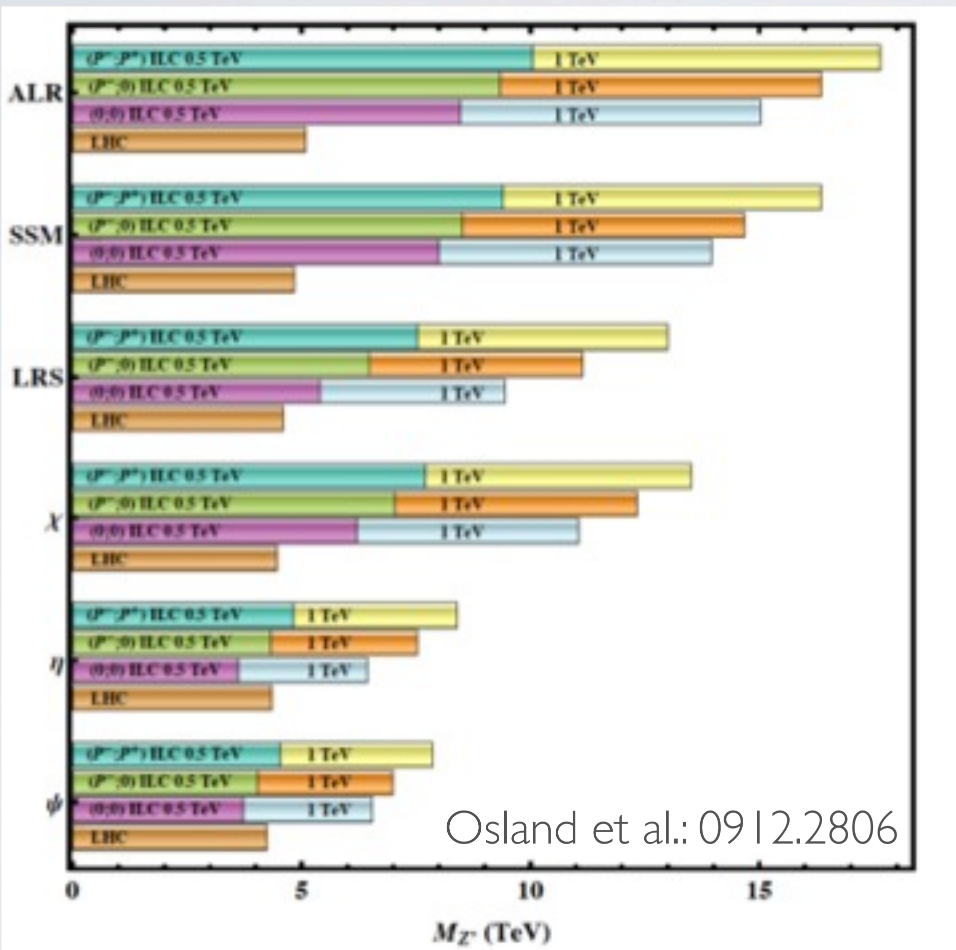

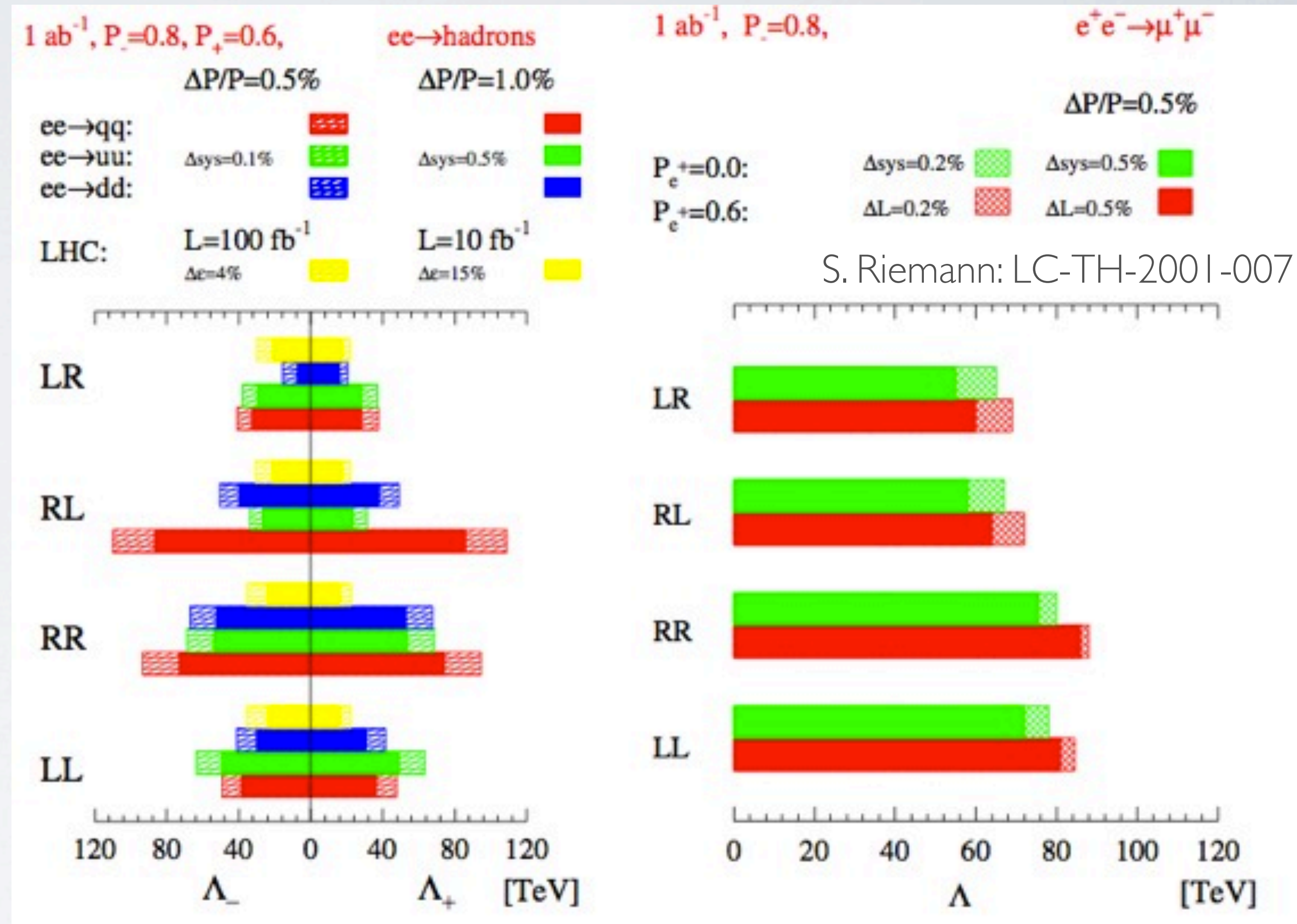

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- ★ Contact interactions are sensitive to scales close to 100 TeV

High-Energy Electroweak Sector

- Vector Boson Scattering: access to New Physics in W, Z selfcoupl. Beyer/JRR/Mönig ...., arXiv:hep-ph/0604048
- 1 TeV, 1/ ab , full 6-fermion states, P(80% e-, 60% e+), binned likelihood
- Contributing channels: WW→WW, WW→ZZ, WZ→WZ, ZZ→ZZ

Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

$SU(2)_c$ conserved case, all channels

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-1.41	1.38
$16\pi^2\alpha_5$	-1.16	1.09

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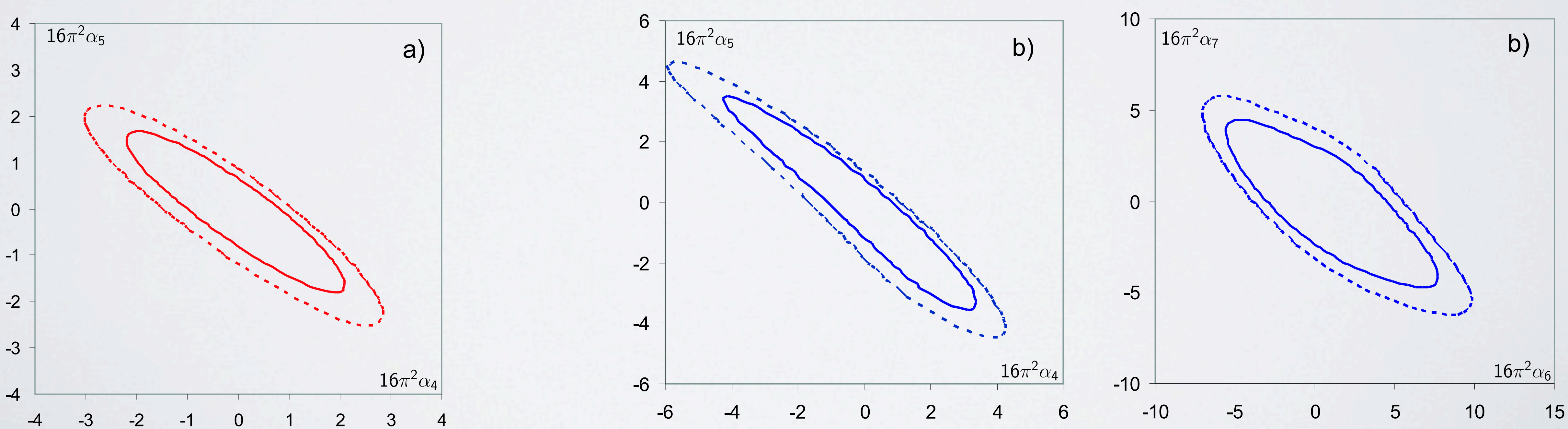

High-Energy Electroweak Sector

- Access also via Triboson Production: $e^+e^- \to WWZ/ZZZ$
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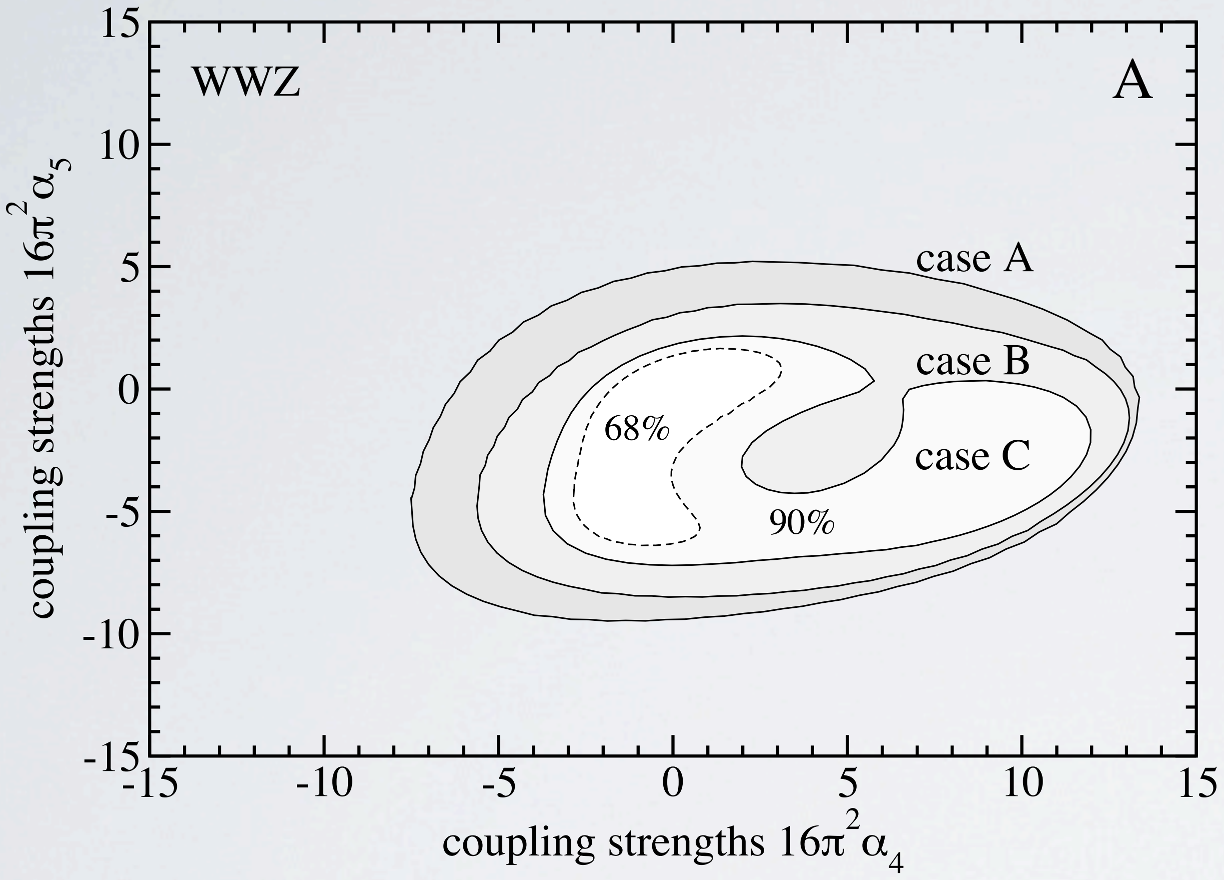

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- Fast detector simulation
- 1 TeV, 1 / ab , full 6-fermion final states
- Use of 32% full-hadronic decays
- Durham jet algorithm
- Main background: *tt* → 6 jets
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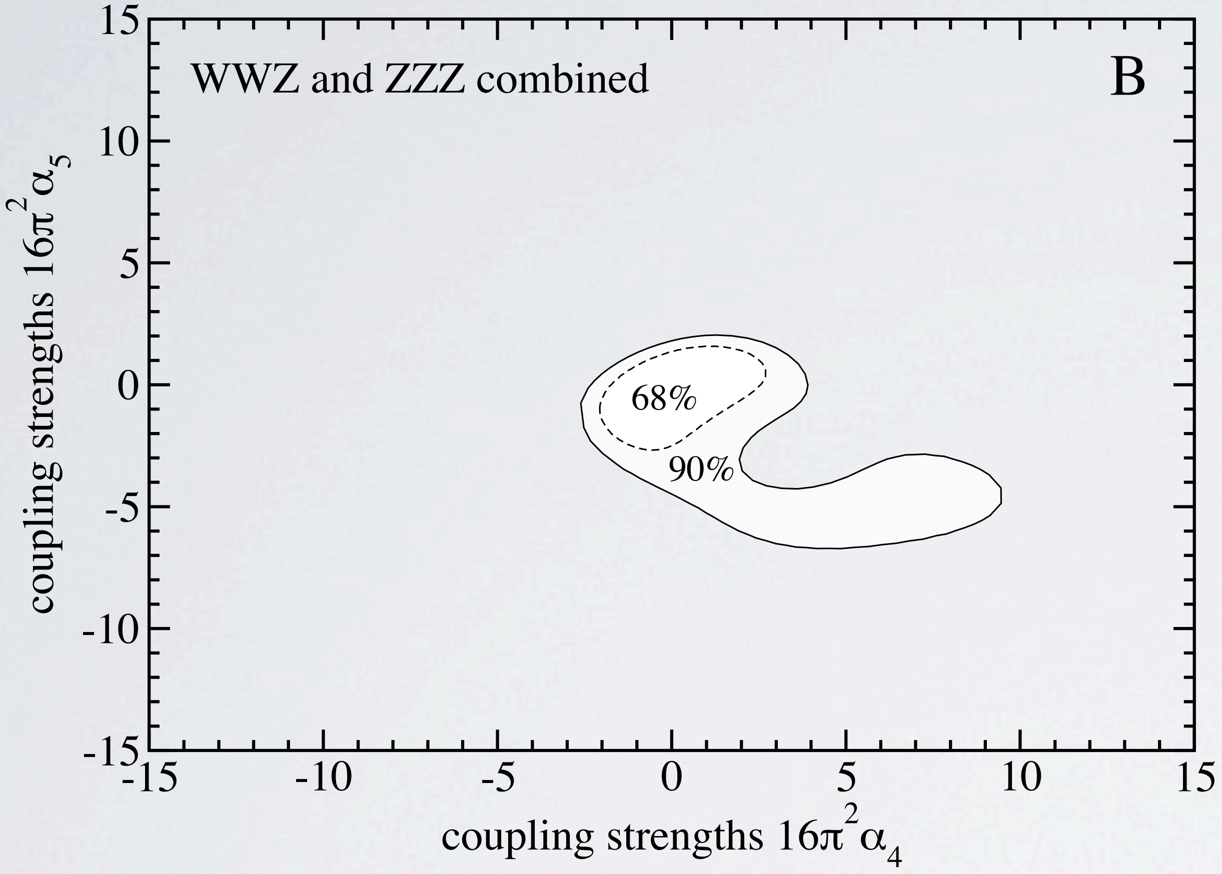

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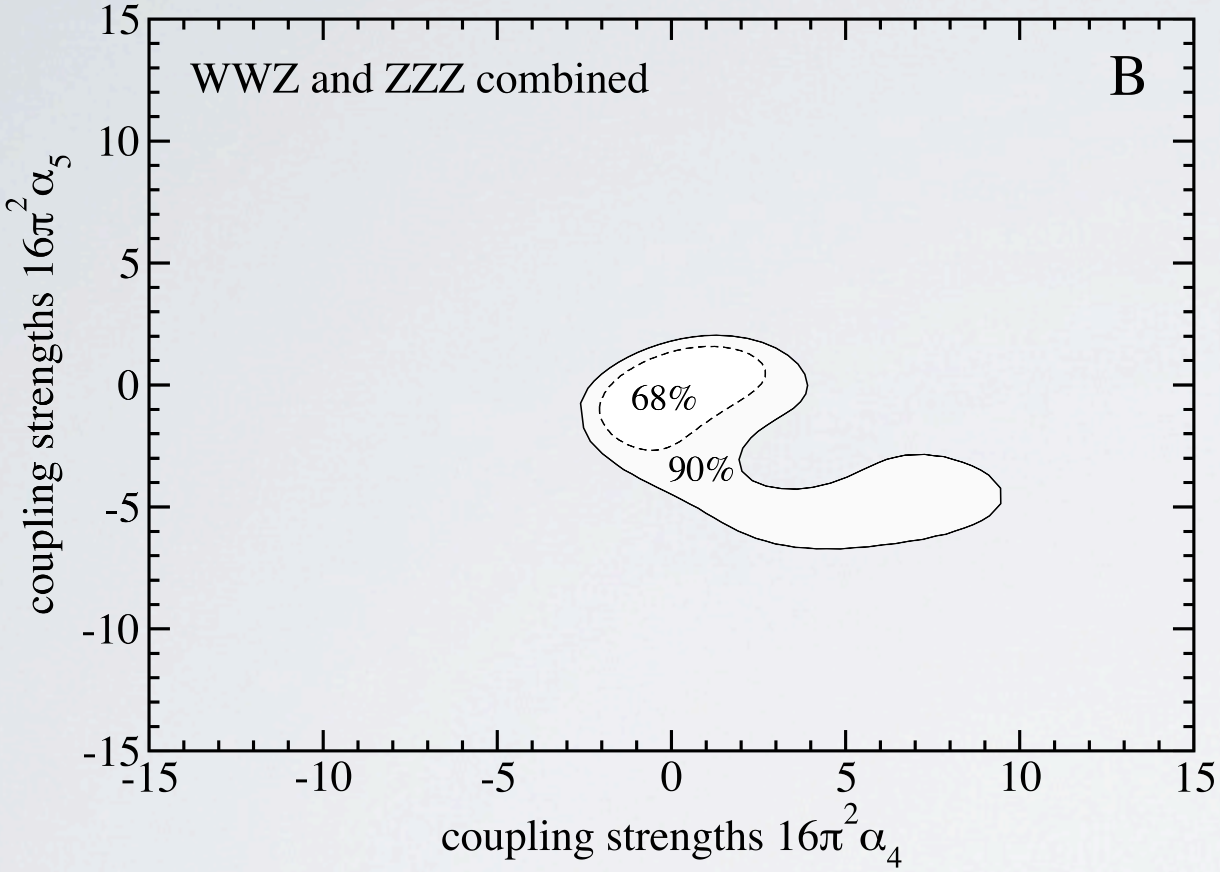

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✳ Interpretation as limits on Electroweak Resonances:

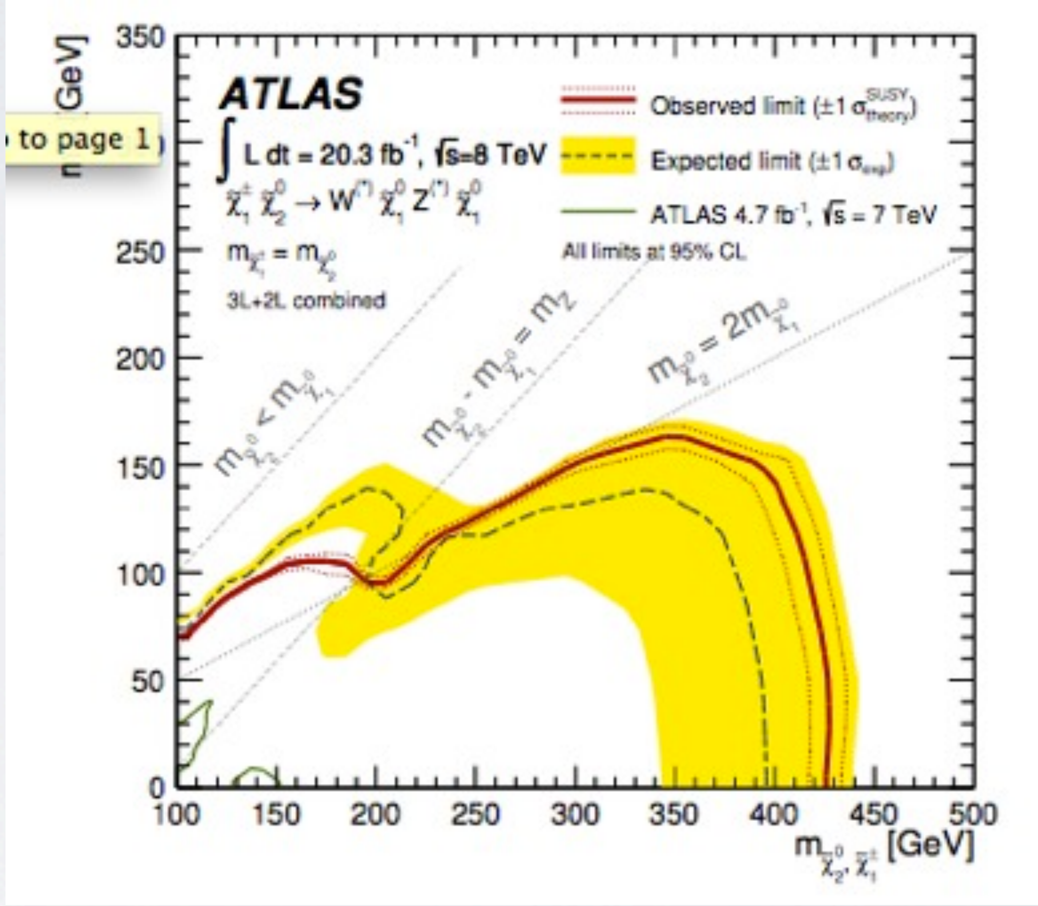
Spin	$I=0$	$I=1$	$I=2$
0	1.55	–	1.95
1	–	2.49	–
2	3.29	–	4.30

Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

- ✳ Results for 1 TeV, but very good discovery potential already at 500 GeV
- ✳ No final conclusion on LHC reach yet: Alboteanu/Kilian/JRR, 0806.4145; Kilian/Ohl/JRR/Sekulla, 1408.6207

Search for New Weakly Interacting Particles (I)

- ILC: electroweak production ⇒ allows (more) model-independent searches for EW particles
- Example: SUSY searches for partners of electroweak particles (EW gauginos / Higgsinos)
- LHC searches: assumptions $M_{\tilde\chi_1^0} = M_{\tilde\chi_1^\pm}$ $\quad \mathrm{BR}(\tilde\chi_1^\pm \to W^\pm \tilde\chi_1^0) = \mathrm{BR}(\tilde\chi_{2,3,4}^0 \to Z^0 \tilde\chi_1^0) = 1$



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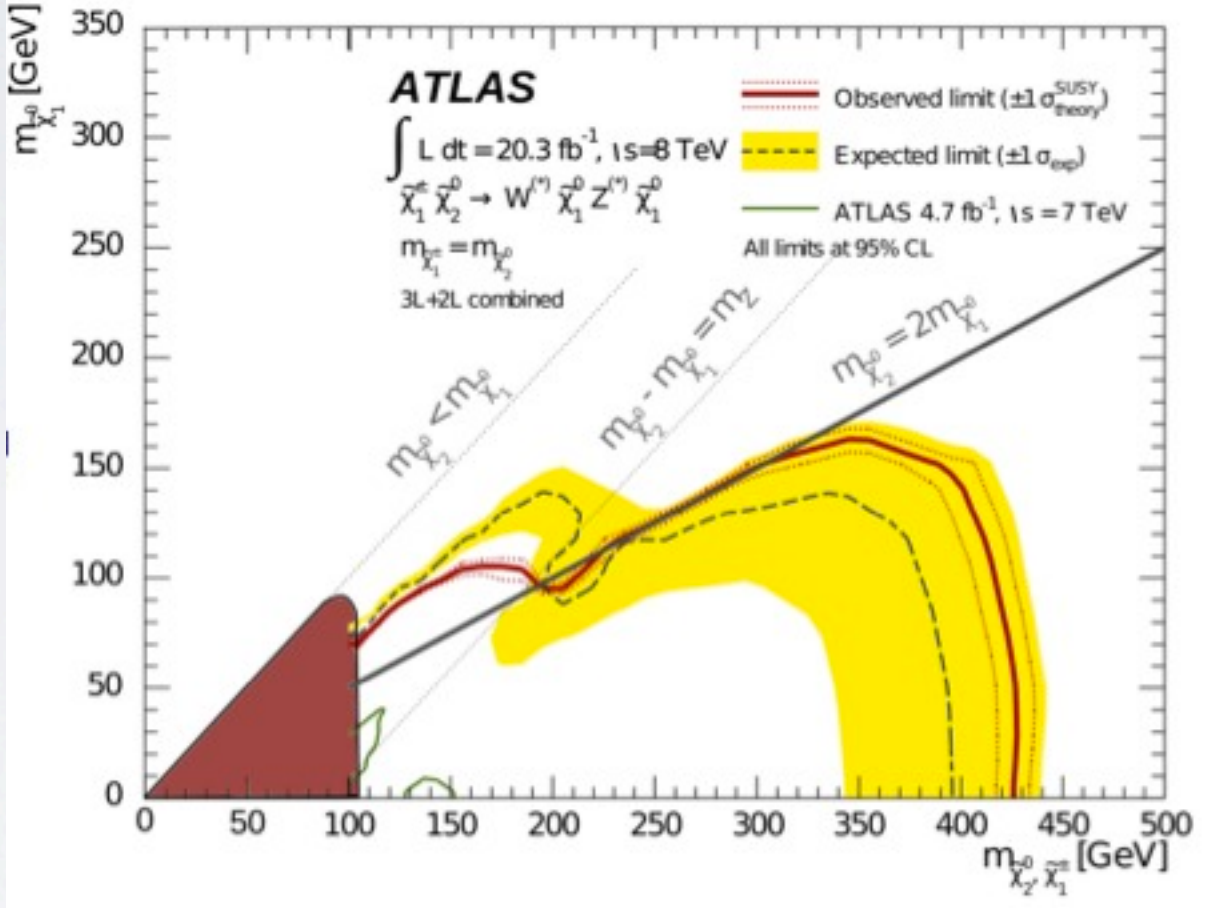
- No gaugino-mass GUT relation below line



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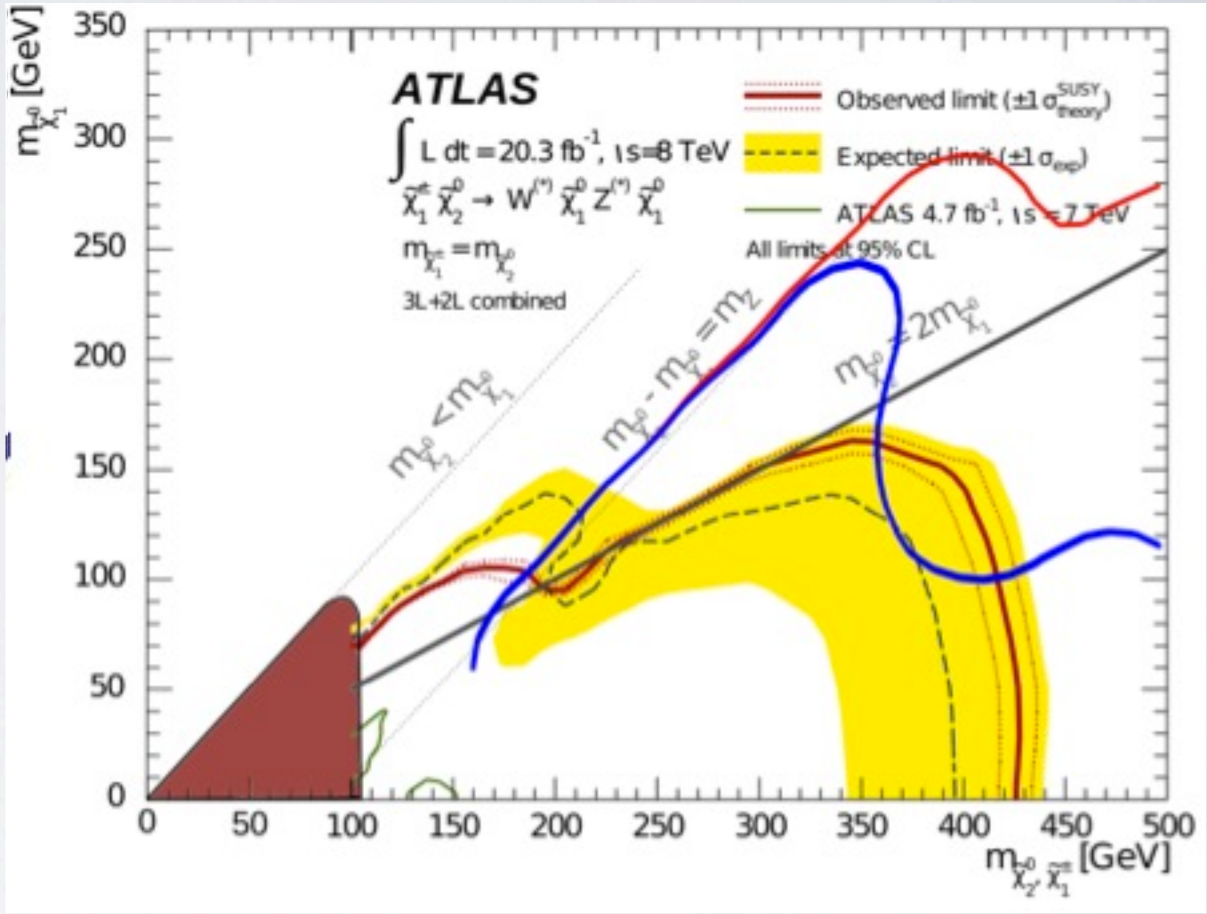
★ LHC projections to 14 TeV (arXiv: 1307.7292)
300 / fb and 3000 / fb



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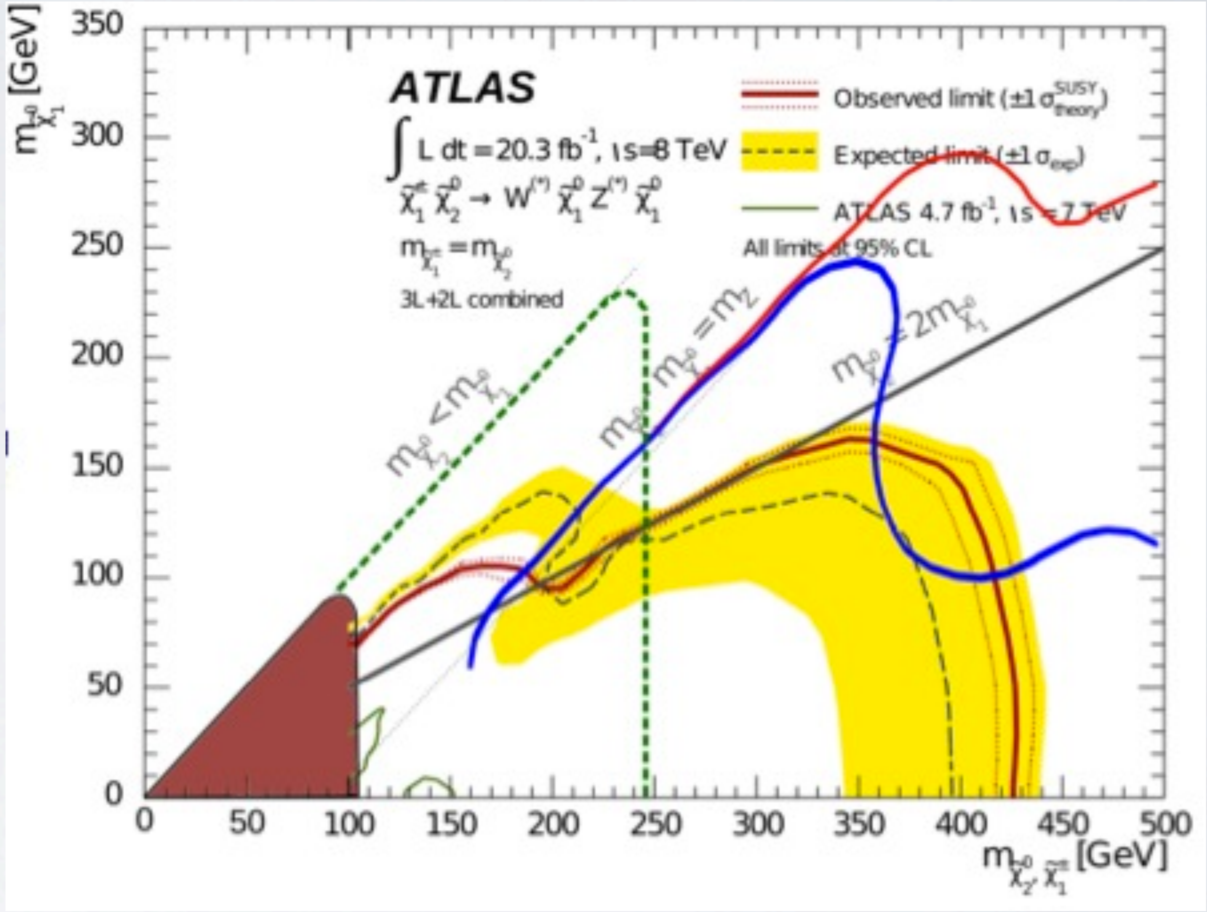
500 GeV ILC generic searches



Search for New Weakly Interacting Particles (I)

✳ ILC: electroweak production ⇒ allows (more) model-independent searches for EW particles

✳ Example: SUSY searches for partners of electroweak particles (EW gauginos / Higgsinos)

✳ LHC searches: assumptions $M_{\tilde{\chi}_1^0} = M_{\tilde{\chi}_1^\pm}$ $\mathrm{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_{2,3,4}^0 \to Z^0 \tilde{\chi}_1^0) = 1$

- LEP chargino search (all decay modes)
- No gaugino-mass GUT relation below line

★ LHC projections to 14 TeV (arXiv: 1307.7292)
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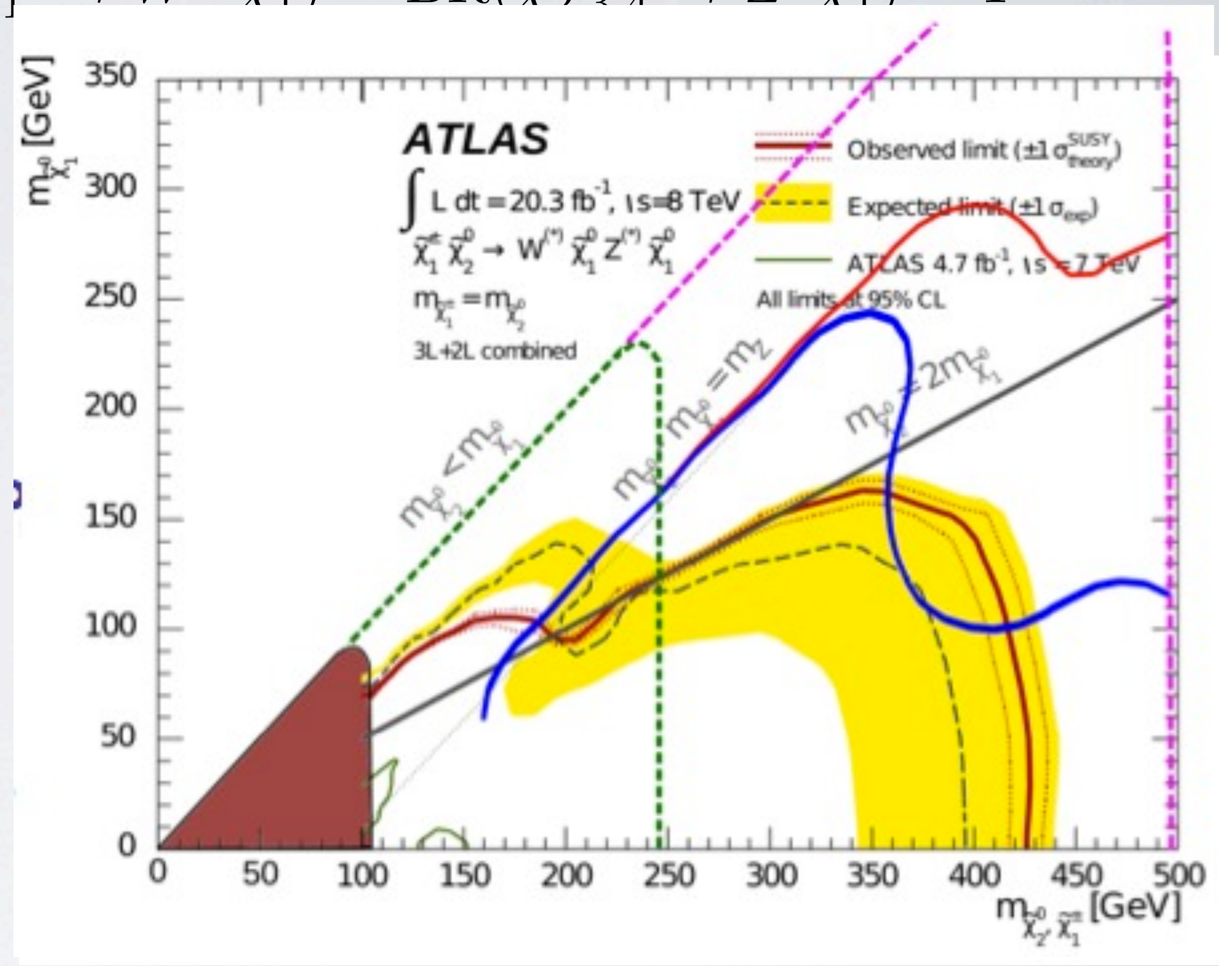
Upgrade to 1 TeV covers parameter space



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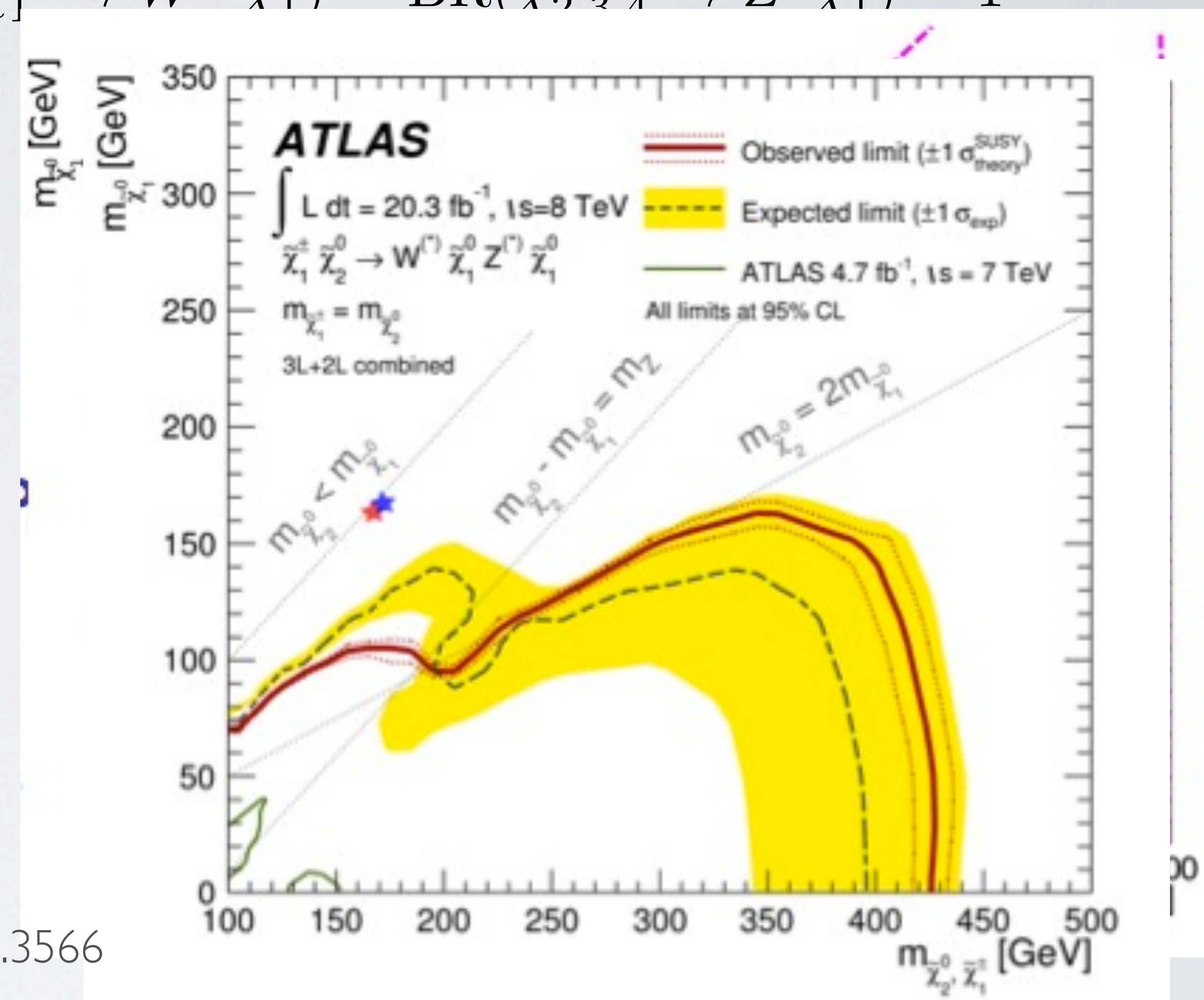

- Benchmark searches for degenerate EW-inos

$\Delta(M) = 1600 \text{ MeV}, M_{\tilde{\chi}_1^0} = 164.2 \text{ GeV}$ Sert et al.: arXiv:1307.3566

$\Delta(M) = 770 \text{ MeV}, M_{\tilde{\chi}_1^0} = 166.6 \text{ GeV}$

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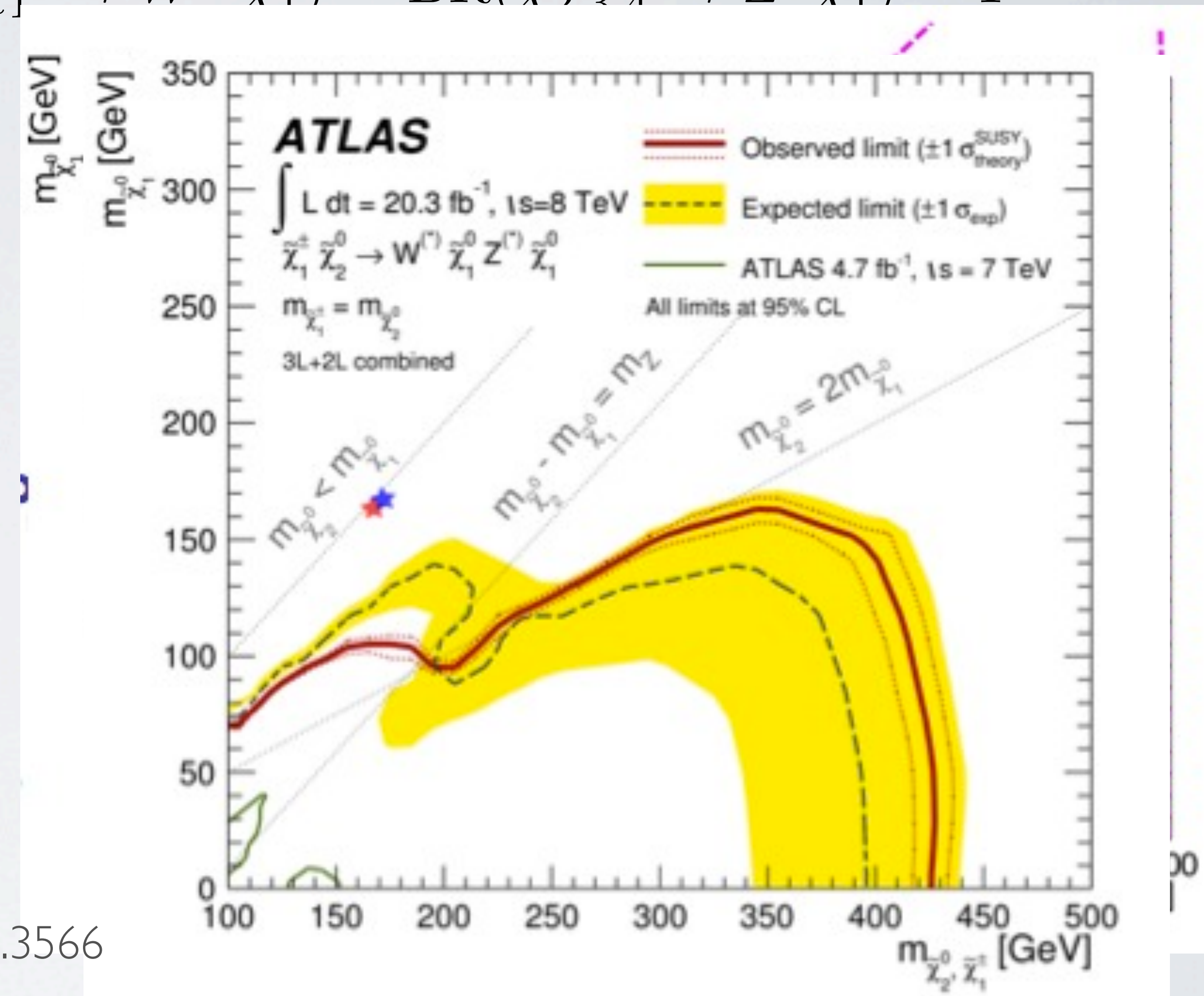
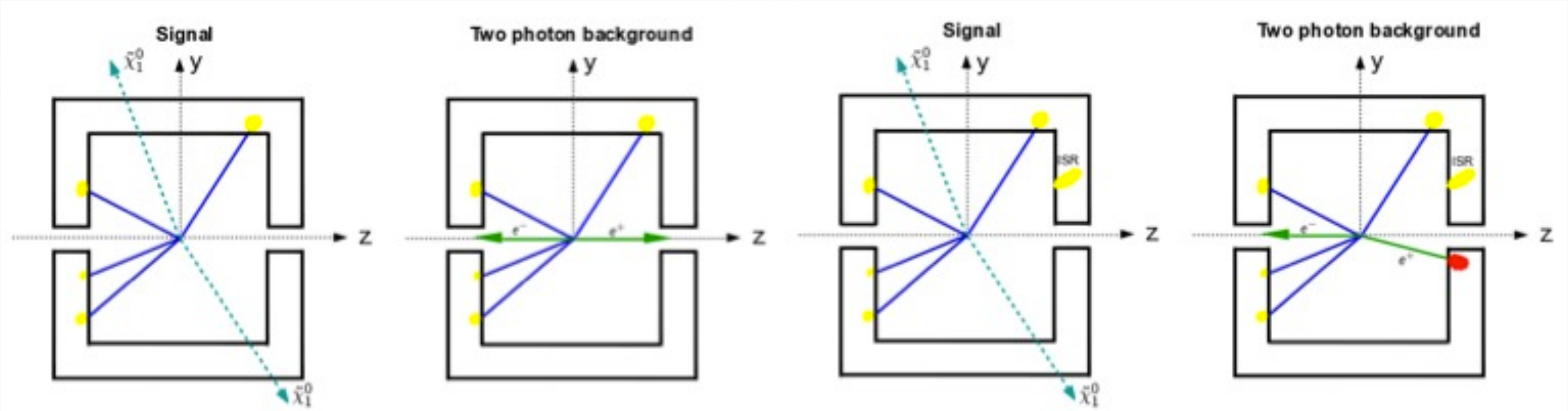


SUSY signals: $e^+e^- \to \tilde\chi_1^+ \tilde\chi_1^-, \quad e^+e^- \to \tilde\chi_1^0 \tilde\chi_2^0$ (all *s*-channel, no *t*-channel [Higgsino])

Search for New Weakly Interacting Particles (I)

✦ Dig out of $\gamma\gamma$ background: tag ISR photon (only moderate 'kick' for signal / accesses bkgd.)



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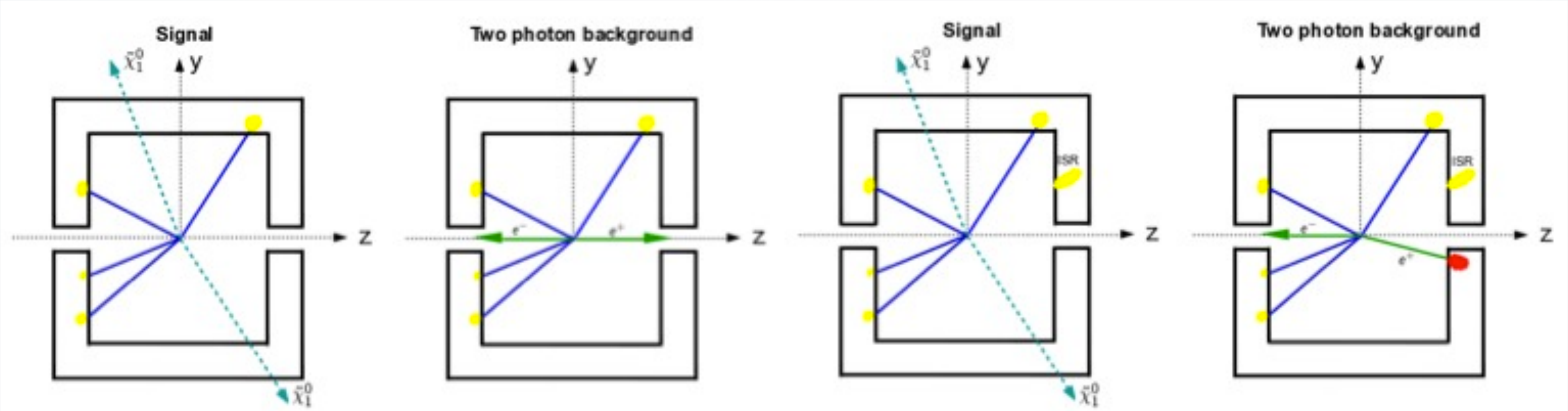

- Select chargino (semi-leptonic mode) vs. neutralino (radiative decay)

$$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 jj, \tilde{\chi}_0^1 \ell^\pm \nu$$
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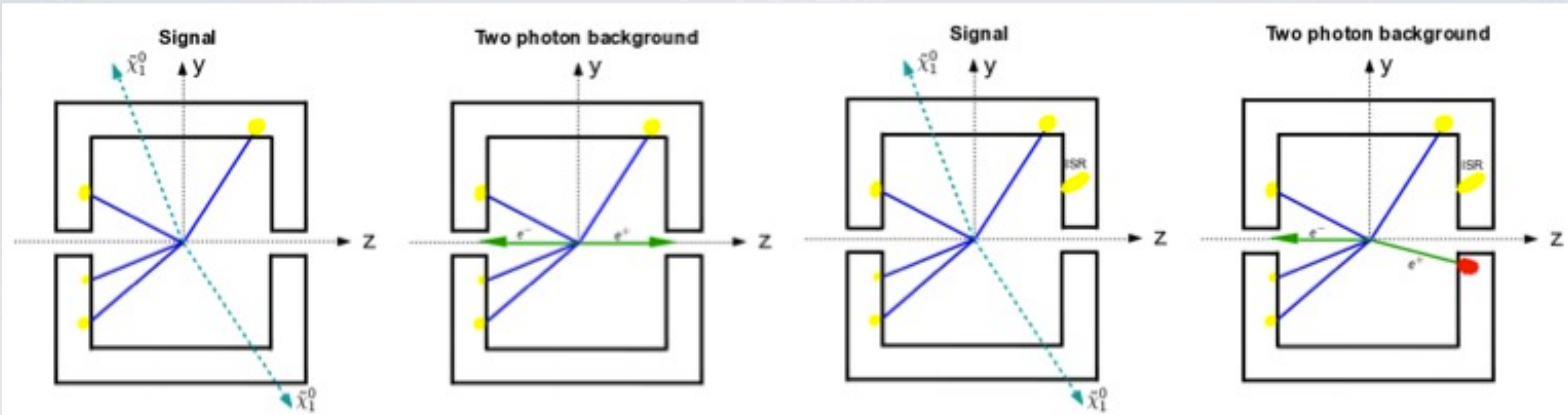

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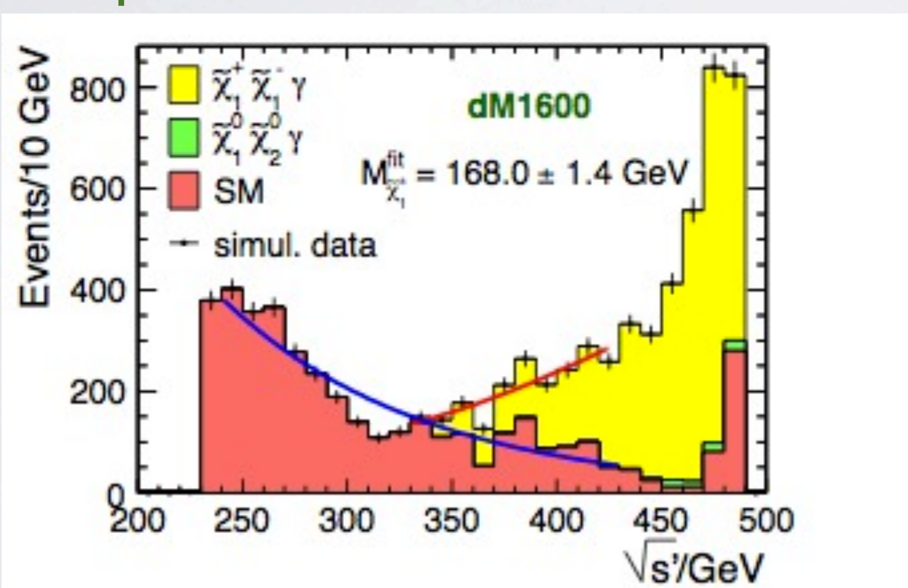

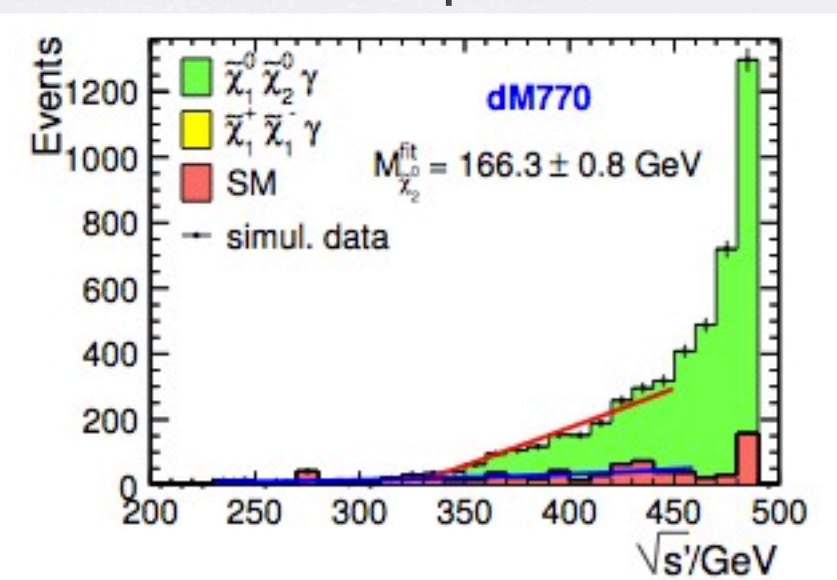

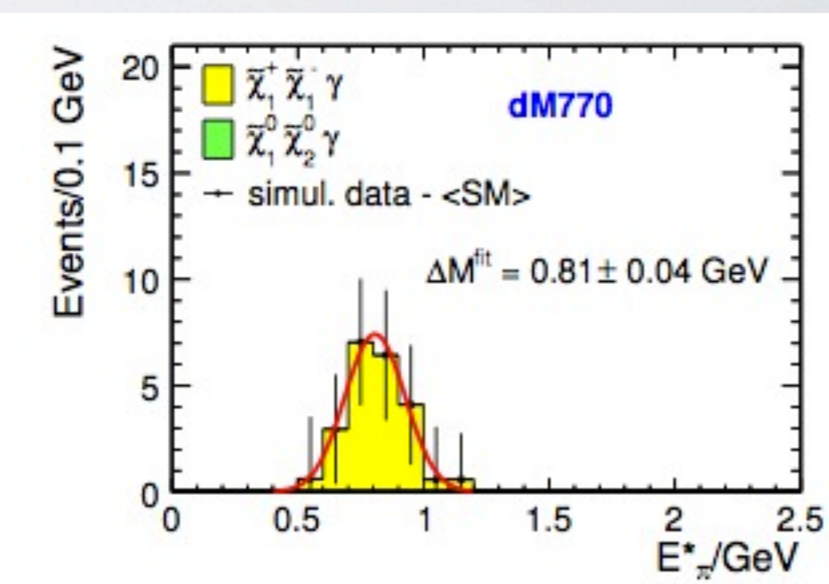

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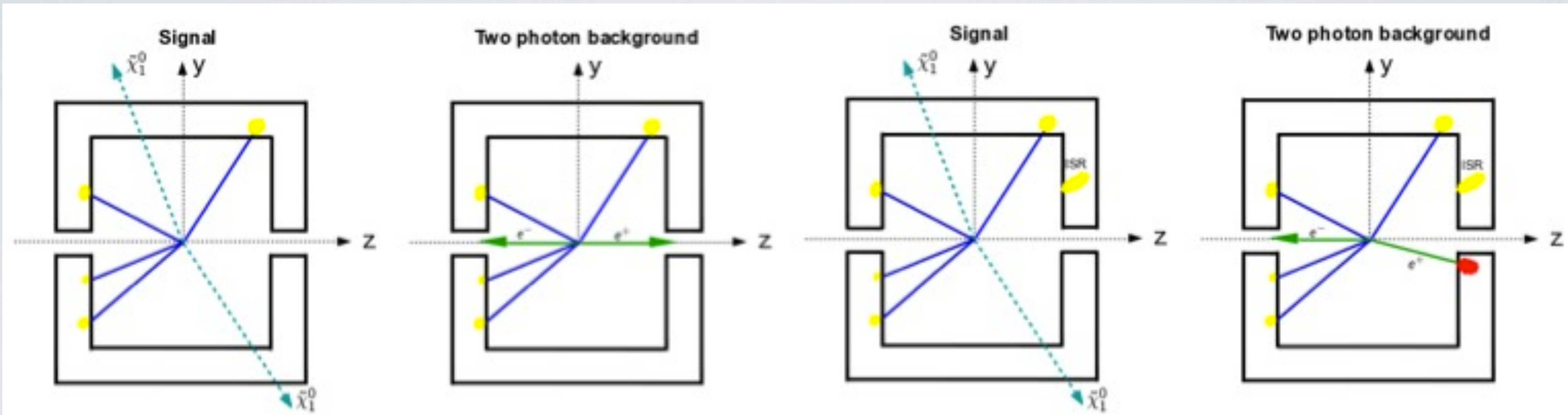

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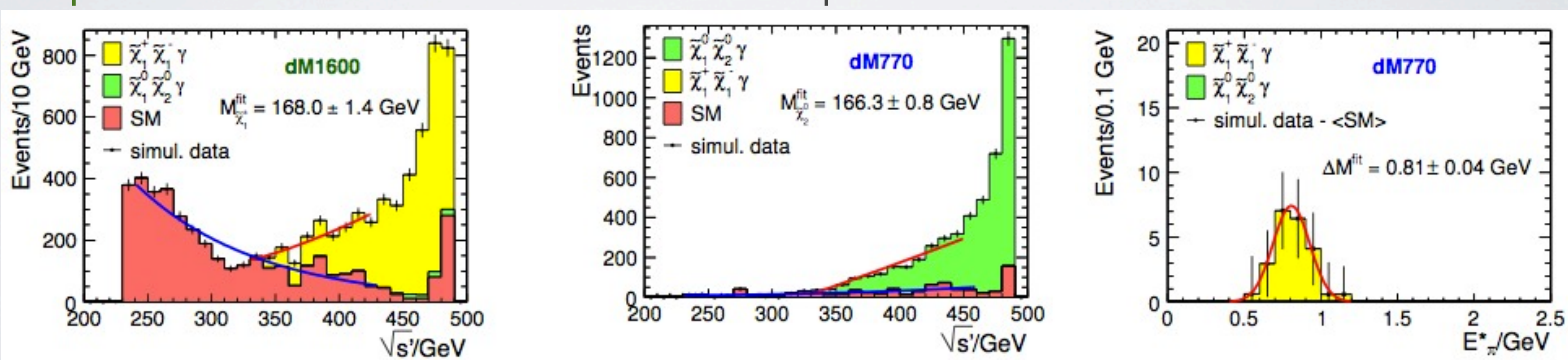

- Parameter extraction: from E_π : $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 100$ MeV and $\mu \sim 4\%$

Search for New Weakly Interacting Particles (II)

- Other candidates: axion-like particles in strongly-interacting models
- Prime example: Little Higgs Models — Kilian/Rainwater/JRR, arXiv: hep-ph/0411213, hep-ph/0609119
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  - Gauged *U(1)* group: *Z'* ⟷ Ungauged *U(1)* group: η
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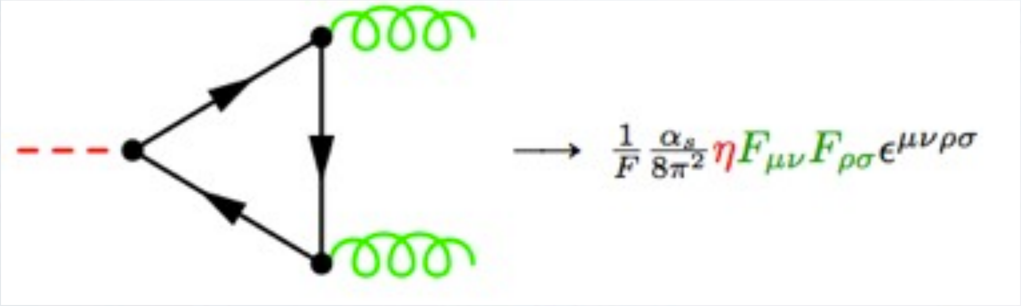
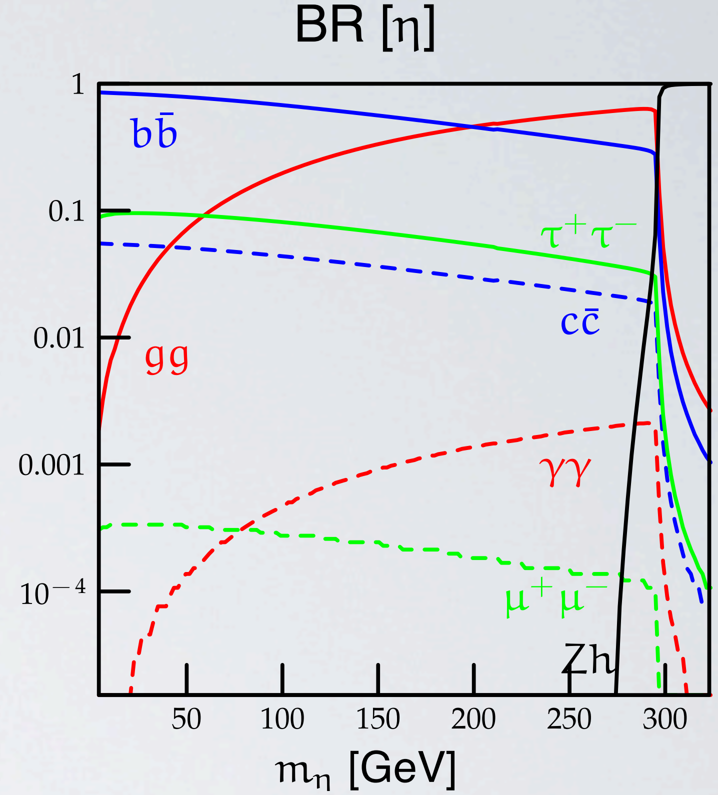
  - *m*[η] ≲ 400 GeV (at LHC only accessible for ≳ 200 GeV)
  - SM singlet, couplings to SM fermion suppressed *v / F*





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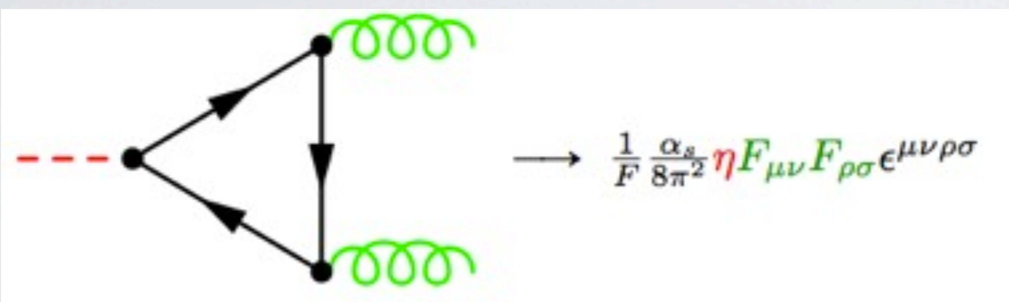
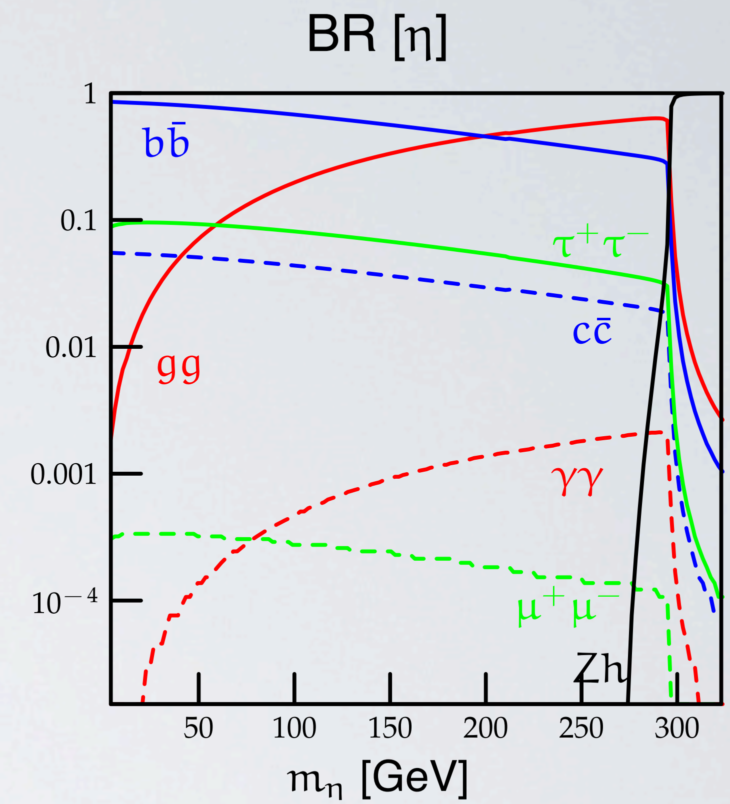
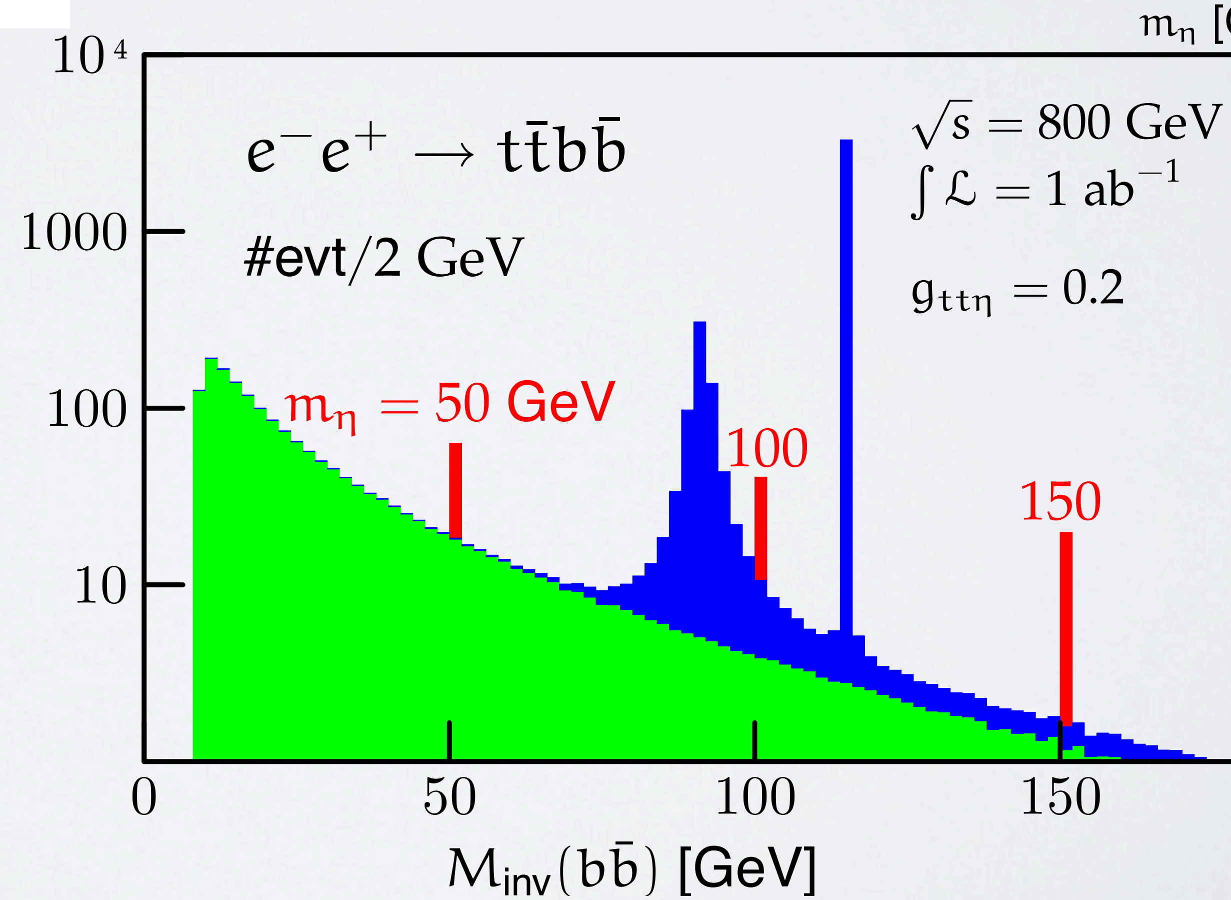




⋆ ILC allows detection in the low-mass regime:

$$e^+e^- \to t\bar{t}\eta$$



Paradigmatic Standard Candle Telescopes

3 main pillars of ILC physics:

1. Higgs Physics
   ↪ Felix Sefkow's Talk
2. Top Physics
   ↪ Frank Simon's Talk
3. BSM Physics
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Standard (Model) candles can be used as Telescopes for [indirect] BSM searches

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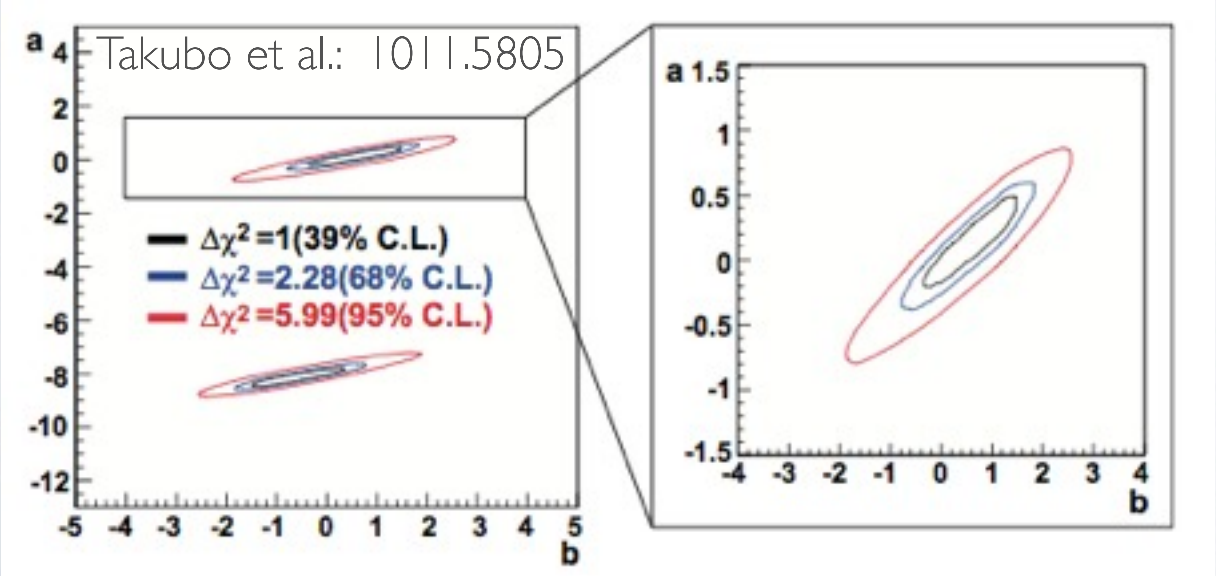

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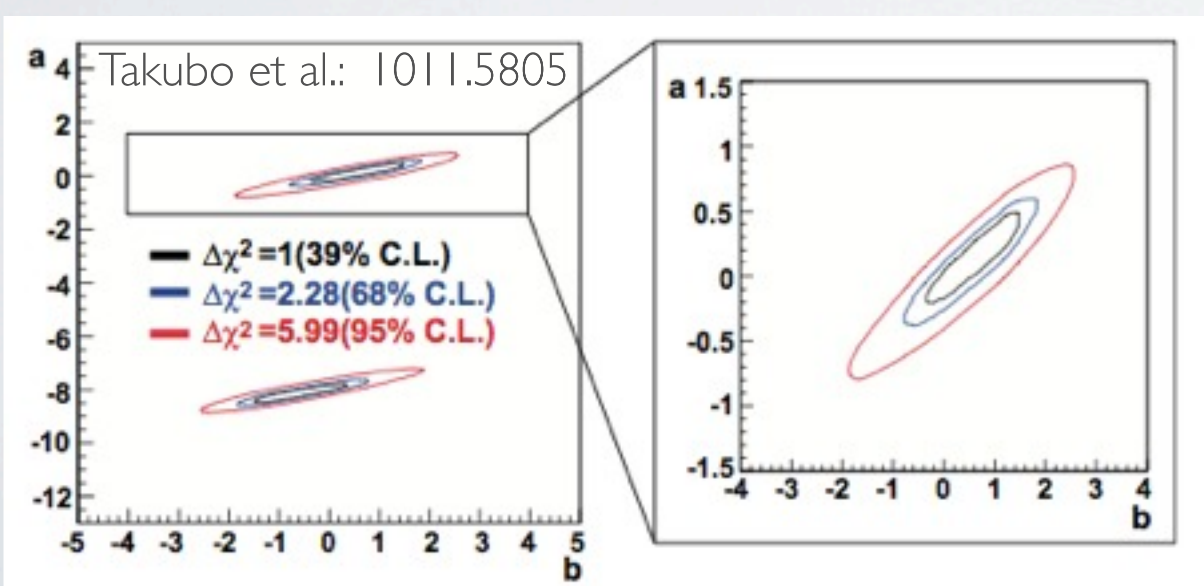
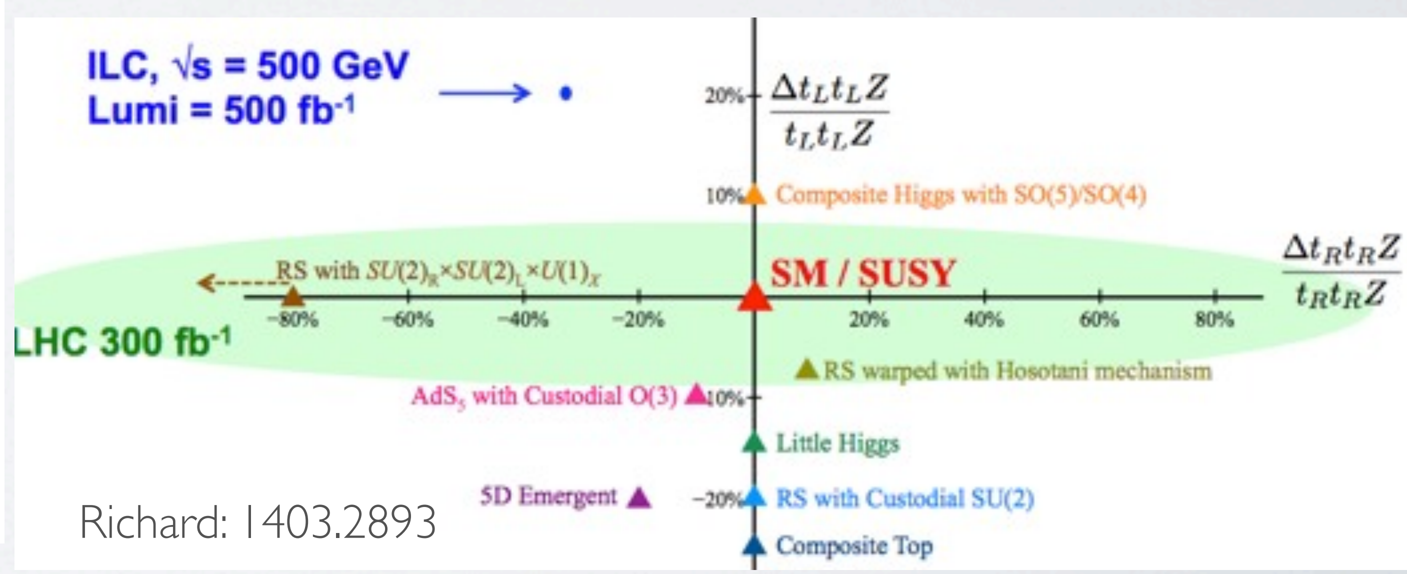


Anomalous Top couplings as BSM probes



Conclusions and Outlook

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- Model-independent electroweak searches
- Dark Matter direct searches
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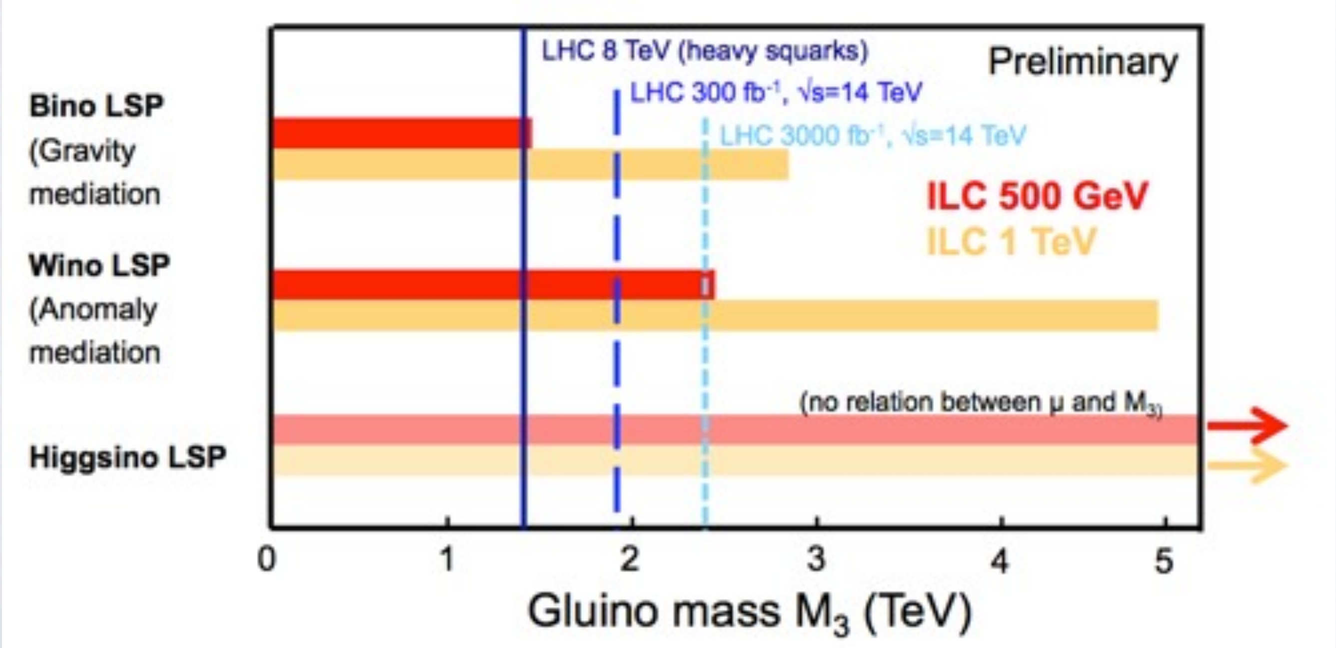

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3 km tunnel for e- now

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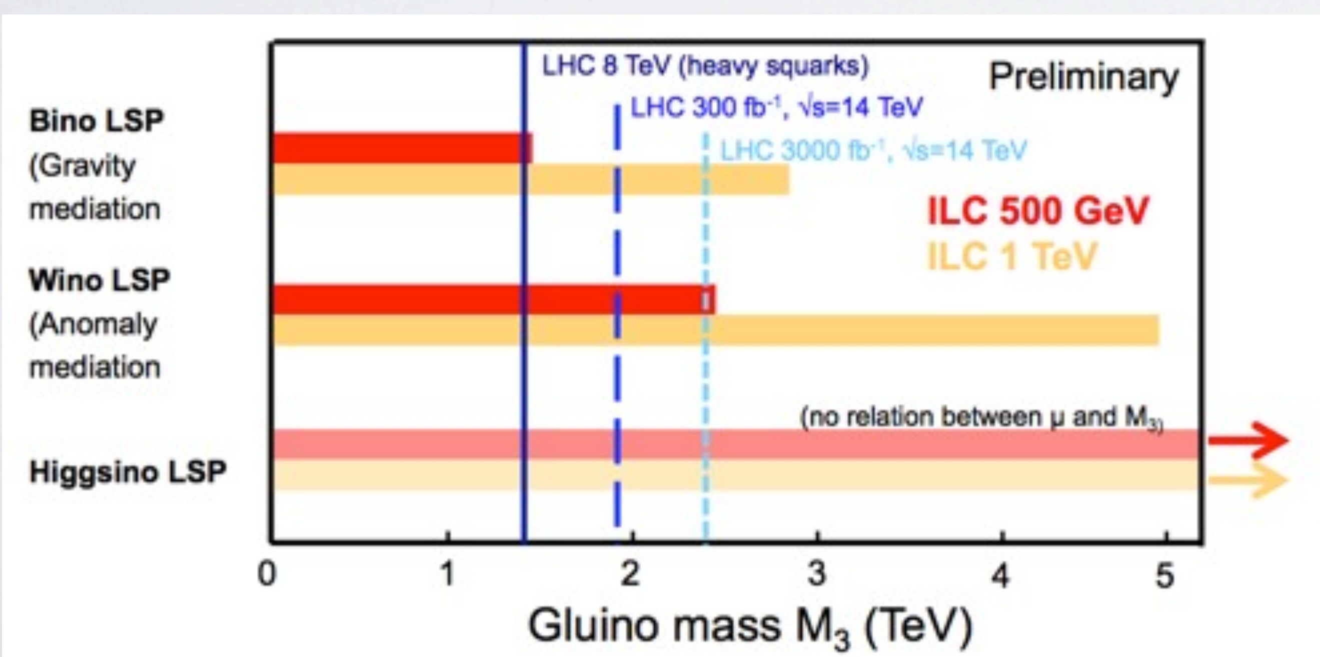

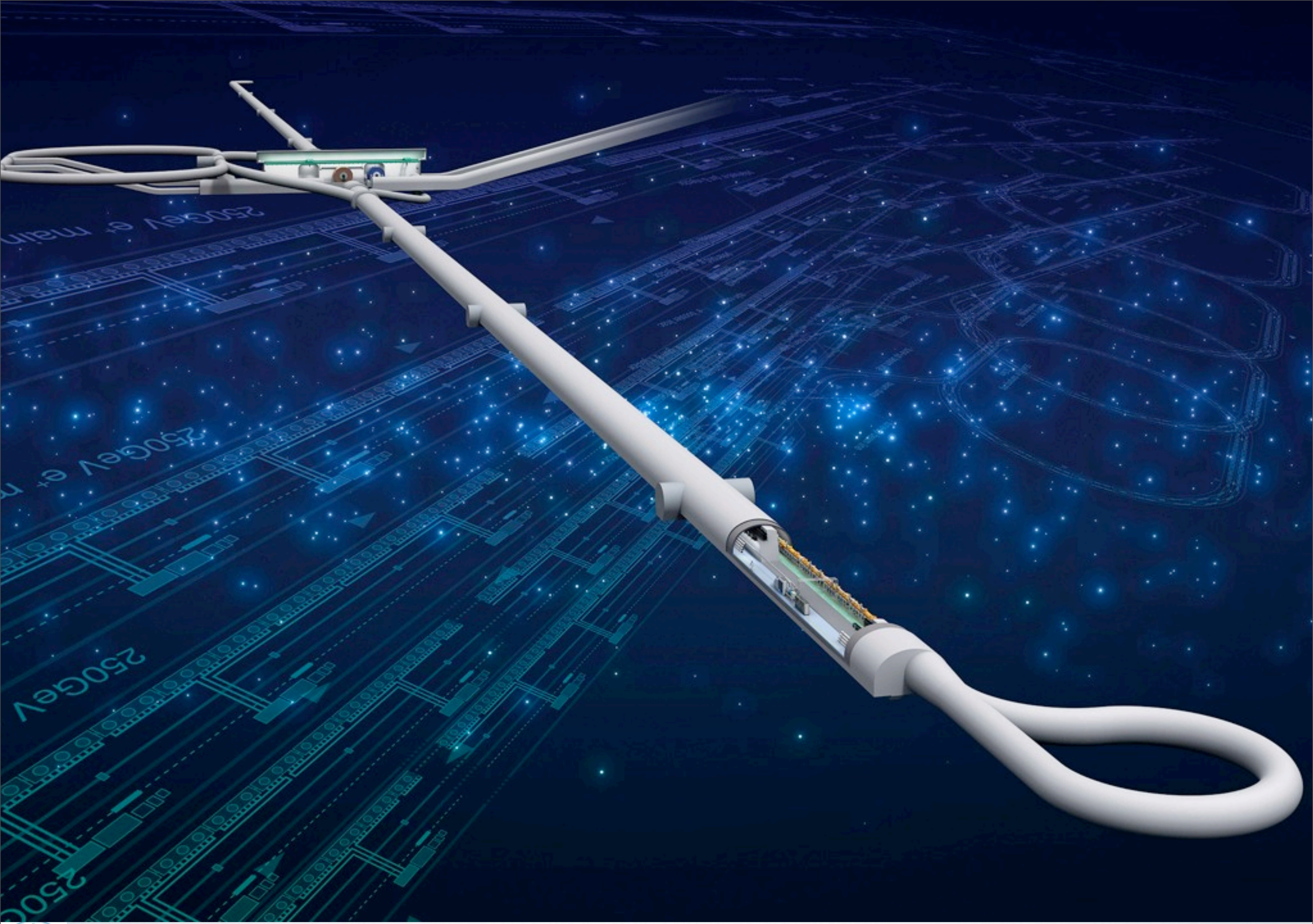

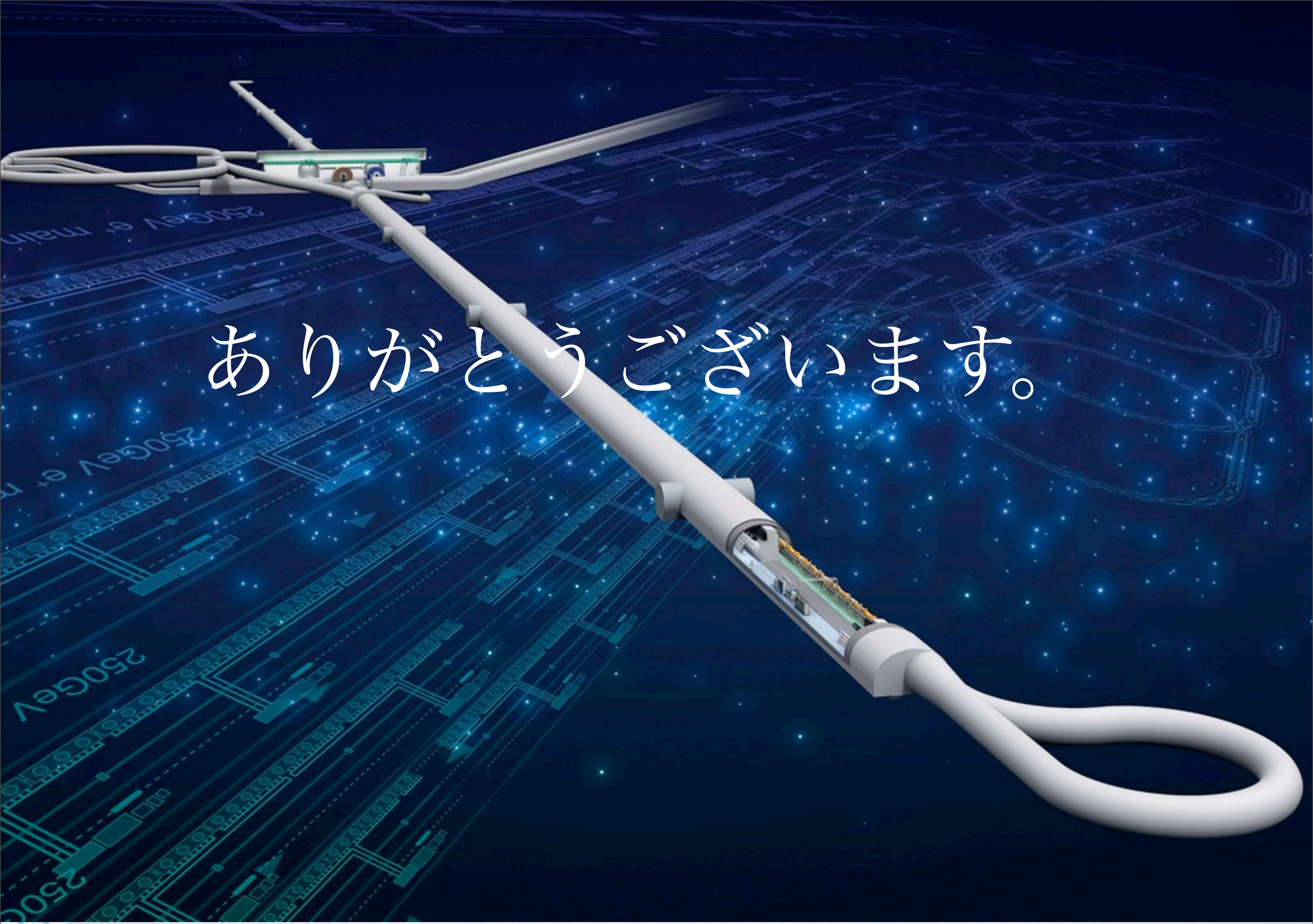

ありがとうございます。