The X-Files: the BSM ILC Case

Jürgen R. Reuter, DESY

The Virtue of Lepton Colliders

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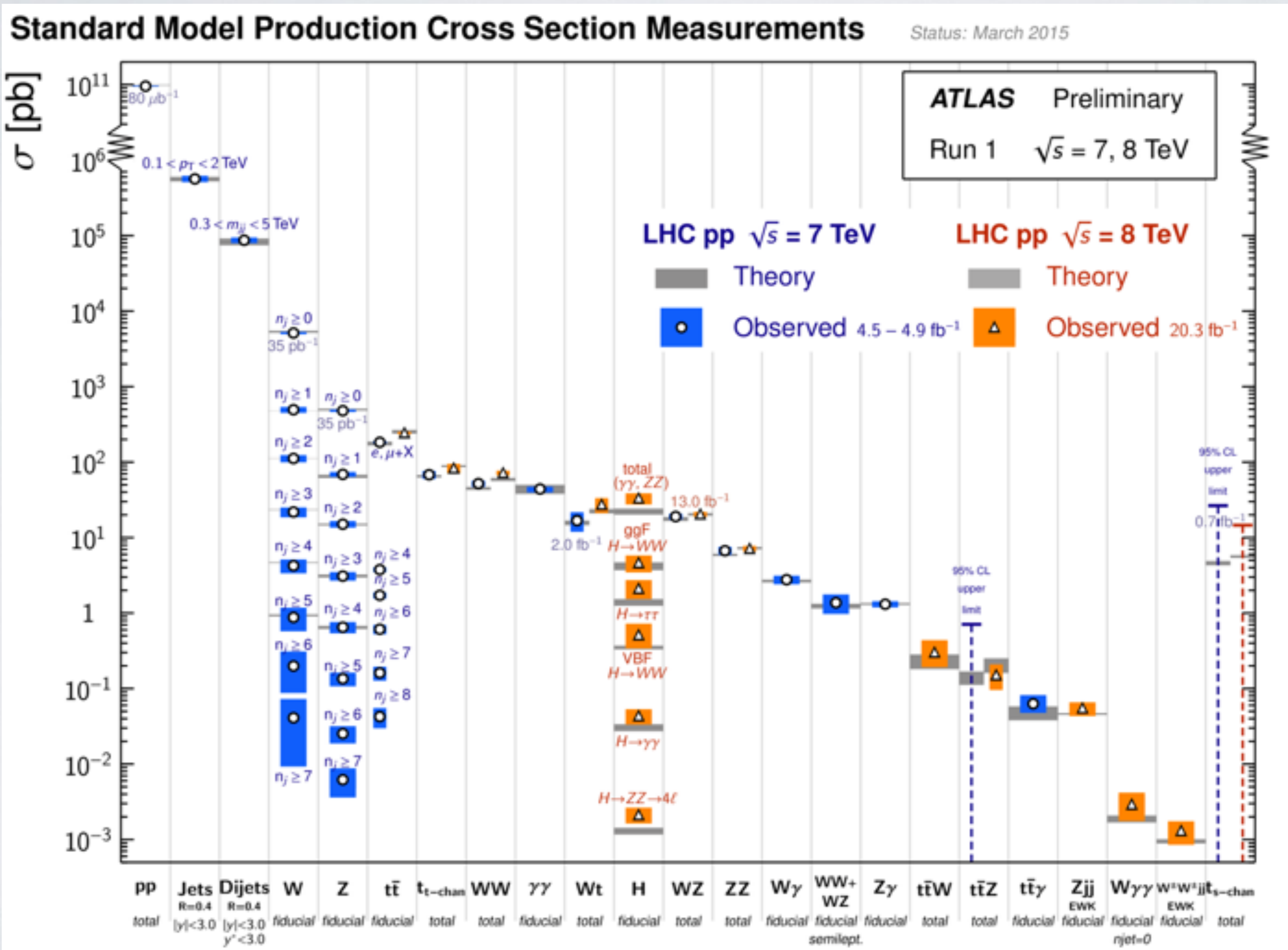

precision hadron collider physics

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

Not only unexpected…also predicted/partially unpredicted

D) First jet physics in e+e-: 1978, PETRA, DESY: **Gluon discovery** (e^-e^+ beams)

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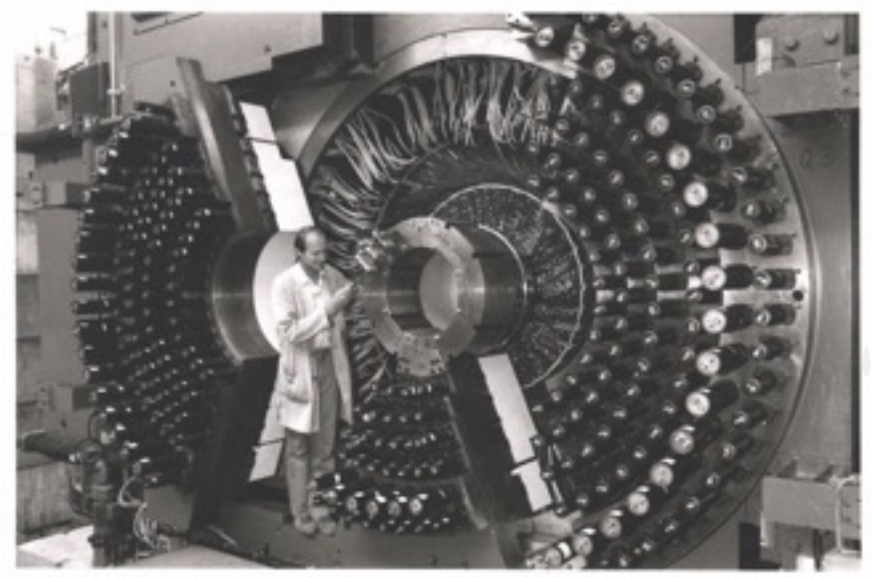

E) B meson oscillations: 1987, ARGUS, DESY: **Top mass > 100 GeV** ($e^- e^+$ beams)

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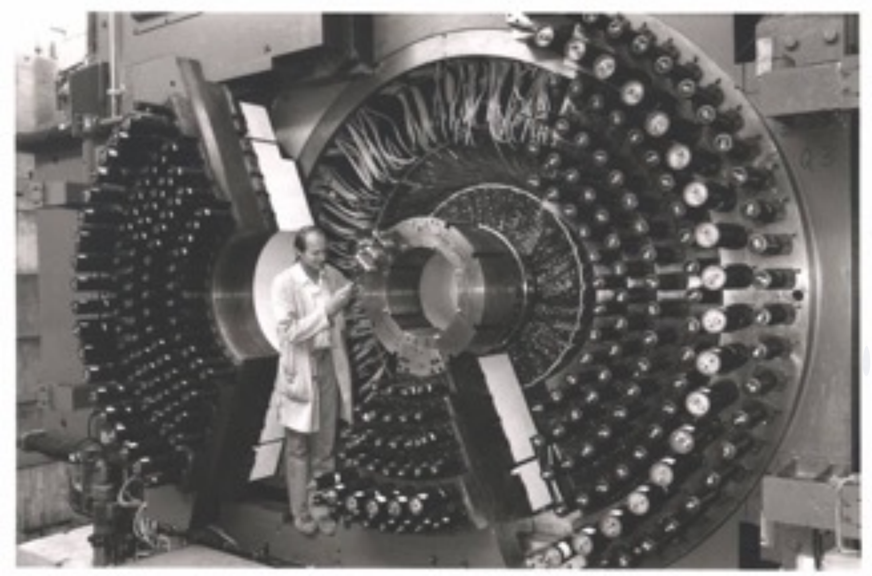

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F) Electroweak Precision: 1989-96, LEP, CERN: **Higgs mass < 200 GeV** ($e^- e^+$ beams)

The Discovery Conundrum

Sp($\bar{p}$)S p$\bar{p}$ @ 0.54 TeV		
Tevatron p$\bar{p}$ @ 1.8,1.96 TeV		
LHC pp @ 7,8,13,14 TeV		
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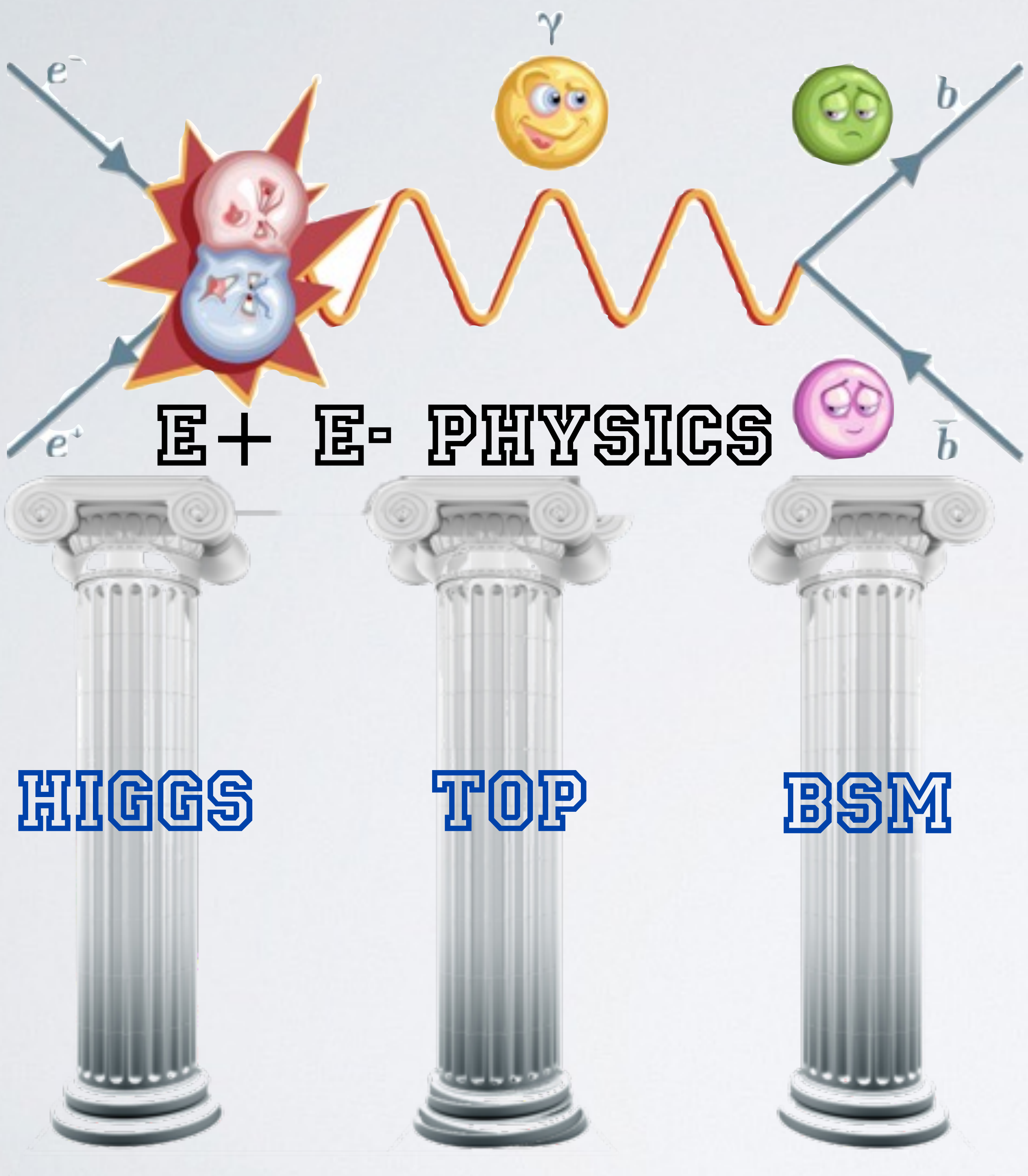
"FCC-hh" pp @ 60,80,100 TeV (?)	no guarantee ??	prepared by ILC e+e- @ 0.35,0.5 TeV ??

Conditions for (lepton) collider discoveries

- **New particle in kinematic reach of your collider**
  - Example: Charm discovery, electroweakino
  - Difficult to predict: might need symmetry, coupling strength, indirect evidence [DM]
- **New physics in (rare) decays of known particles**
  - Example: anomalies in rare *B* decays, anomalies in Higgs decays
  - Difficult to predict: needs tremendous technical knowledge of known physics
- **Deviations within existing interactions**
  - Example: e+e- → hadrons below charm threshold, *Z'* in contact interactions
  - Difficult to predict: needs theoretical hint, experimental hint from somewhere else
- **Decipher structure of new but known interactions**
  - Example: gluon discovery (massless carrier of confining theory), Higgs self-interaction
  - Has guidance from existing experimental data; correct theory needs to be known
- **Discovery of new strong interactions**
  - Example: quark substructure, composite Higgs
  - Mostly for non-perturbative physics;

The Pillars of Lepton Physics



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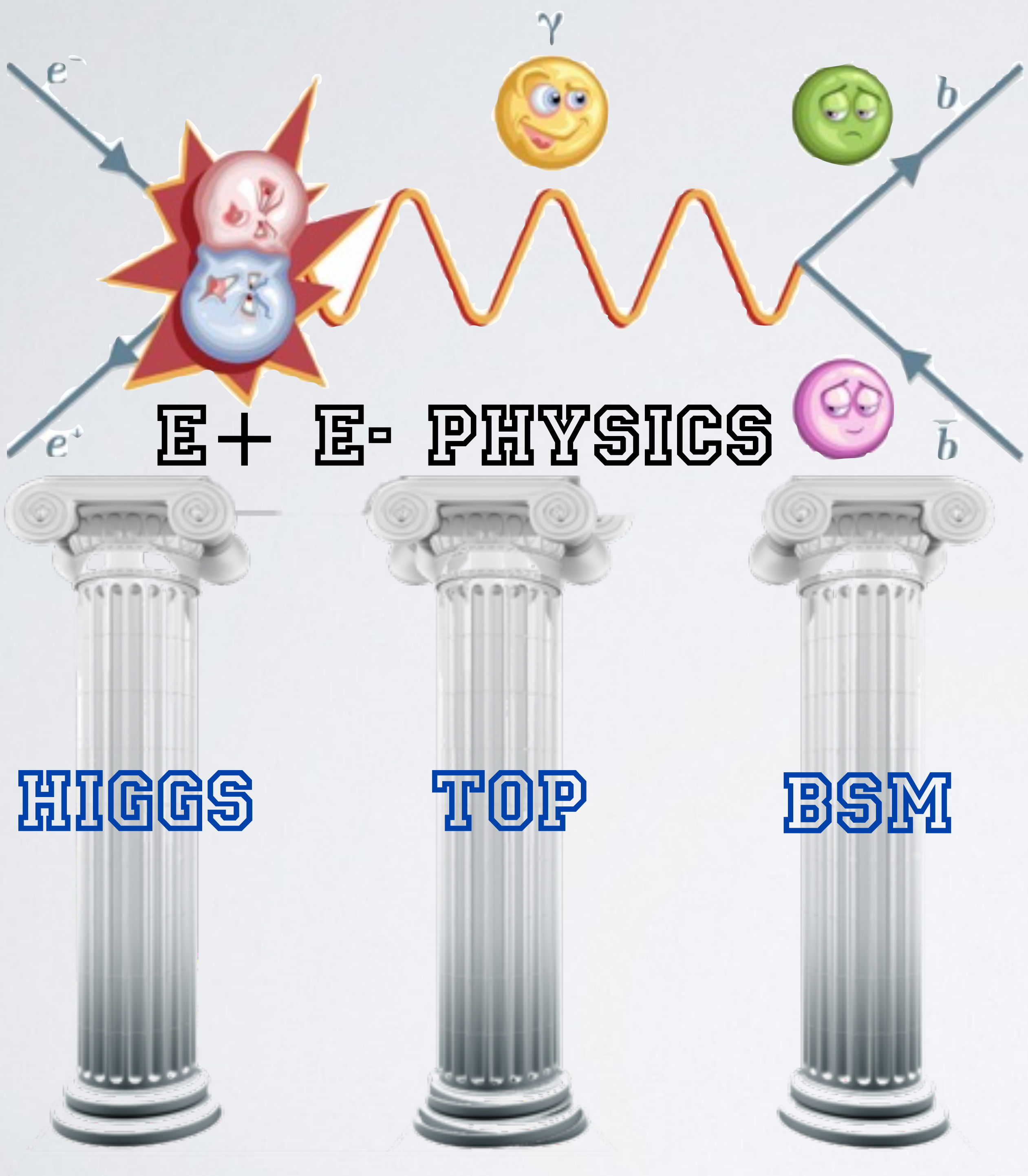
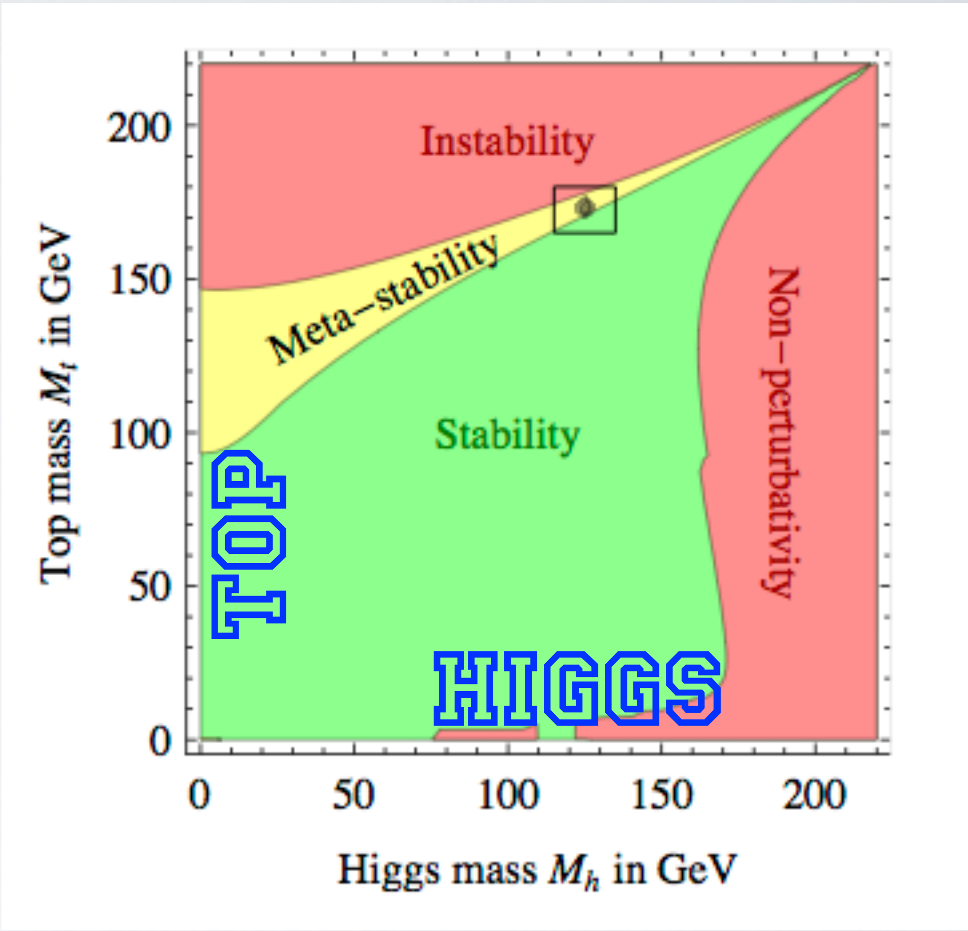


Electroweak vacuum & excitations:



(note: plot under assumptions of NO additional BSM)

Paradigmatic Standard Candle Telescopes

Standard (Model) candles can be used as Telescopes for [indirect] BSM searches

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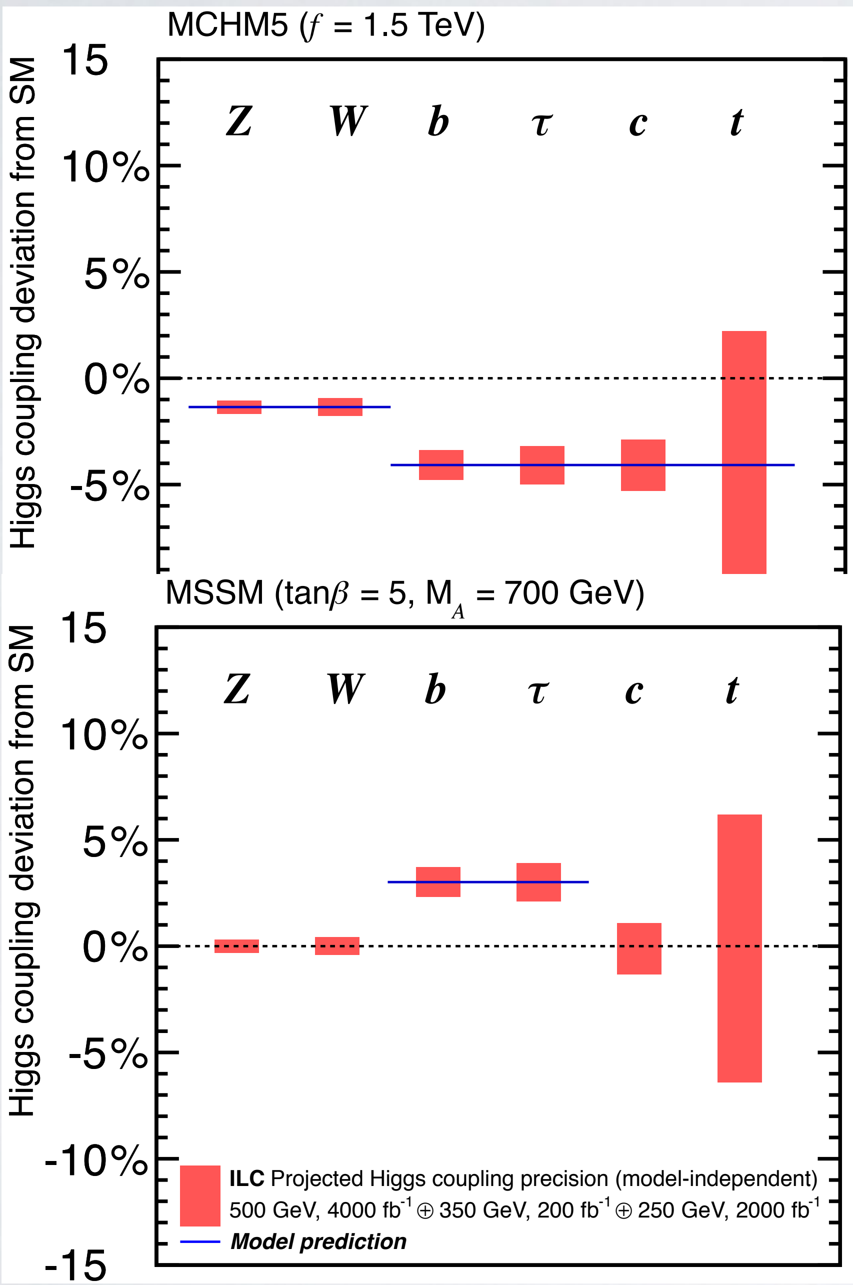
Search for anomalous Higgs couplings



Talks by S. Gori / M. Peskin

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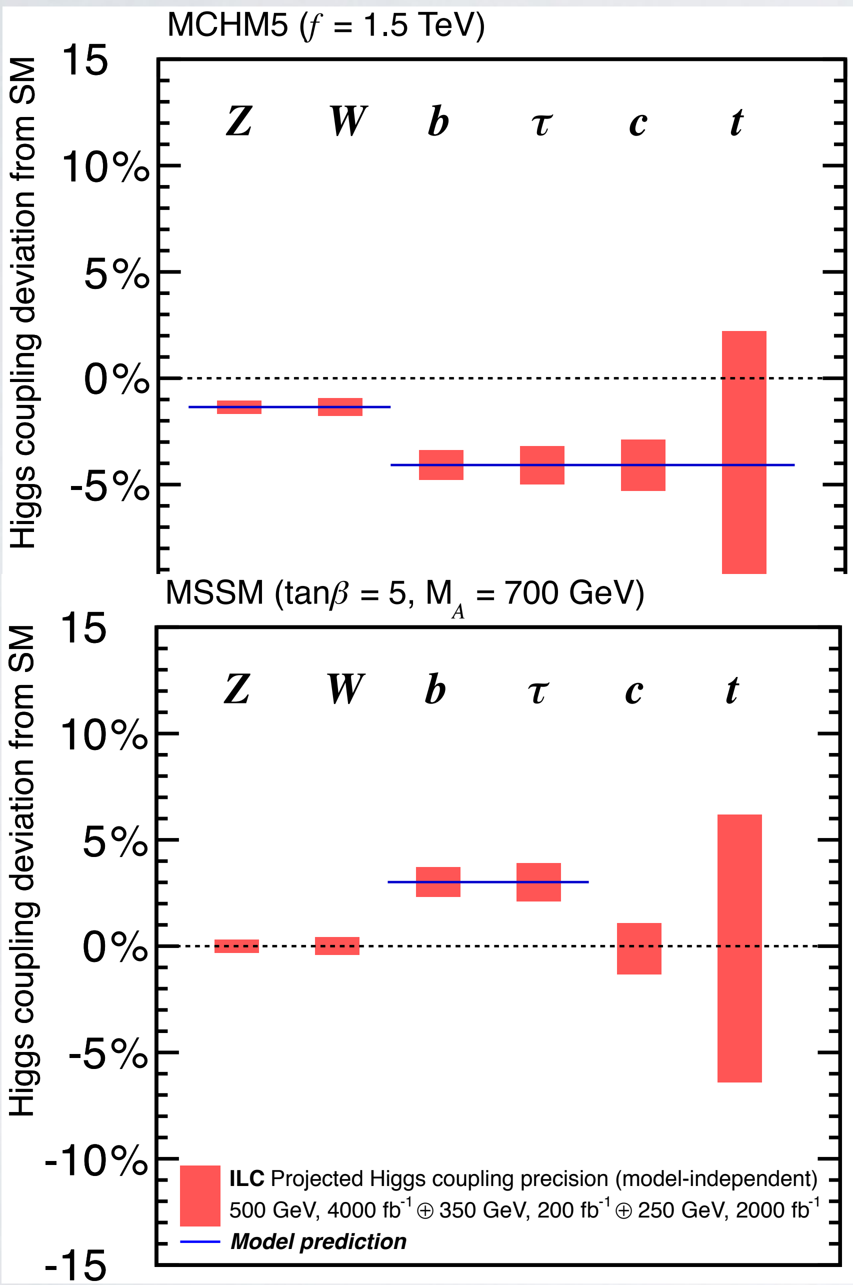
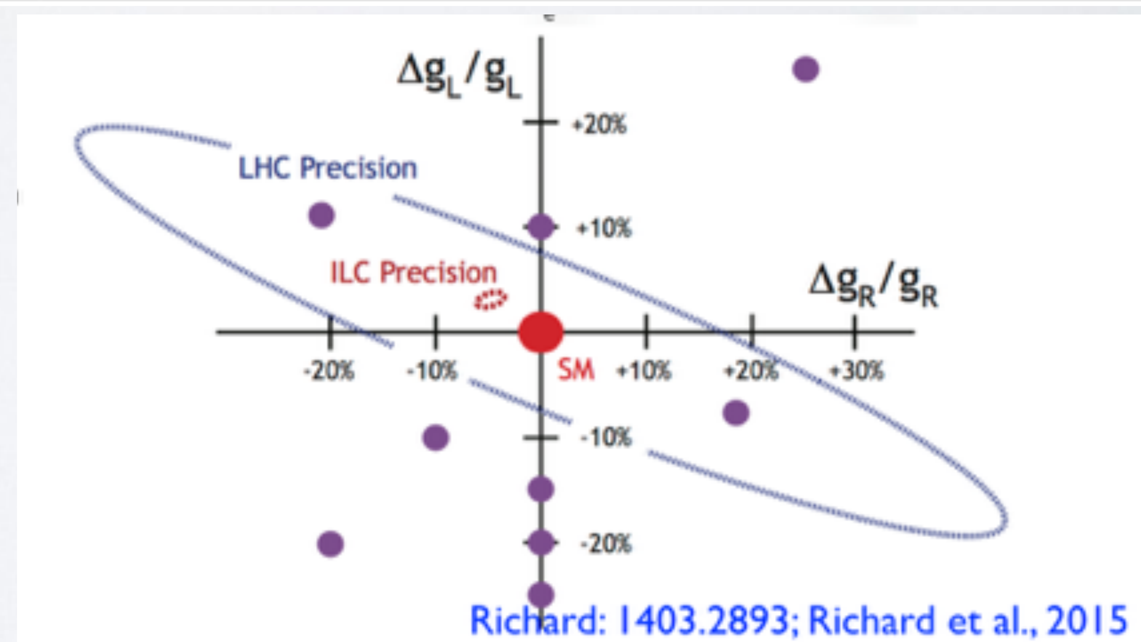


Anomalous Top couplings as BSM probes

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\tilde{F}_{1V}^X(k^2)+\gamma_5\tilde{F}_{1A}^X(k^2)\right)+\frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X(k^2)+\gamma_5\tilde{F}_{2A}^X(k^2)\right)\right\}$$



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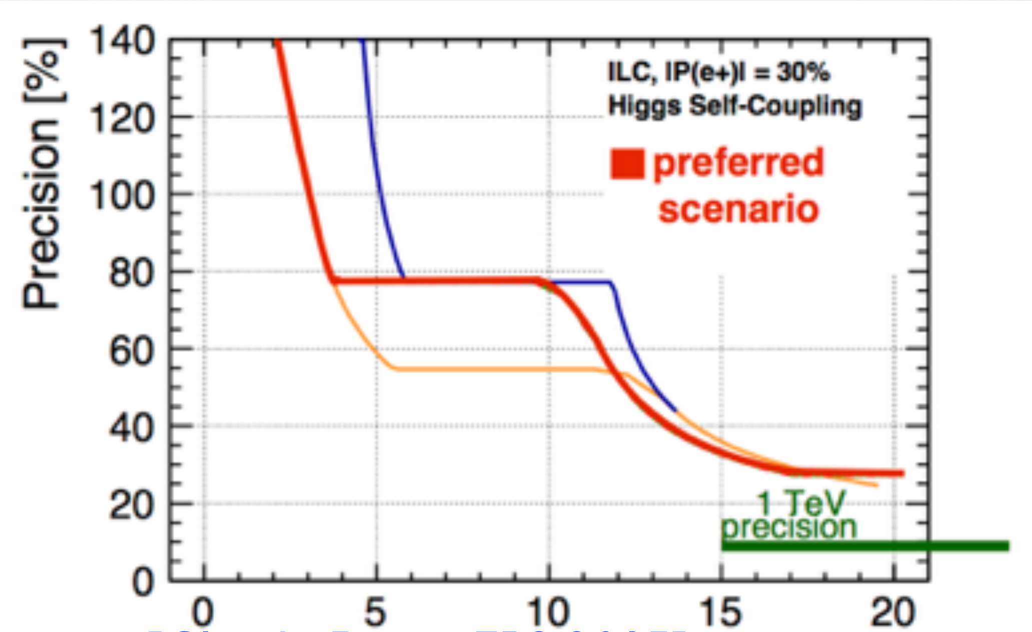
Handle to electroweak symmetry breaking

hhh: Mapping out Higgs potential
(only direct access to EWSB using only Higgs)

- most promising: $HH \to bbbb$ *and* $HH \to WW^{*}bb$ [Junping Tian, 2013]
- 500 GeV, 4/ab: $\Delta\lambda / \lambda = 28$ %



[Claude Dürig, EPS 2015]

tth: Resolving eminent source of Higgs dynamics
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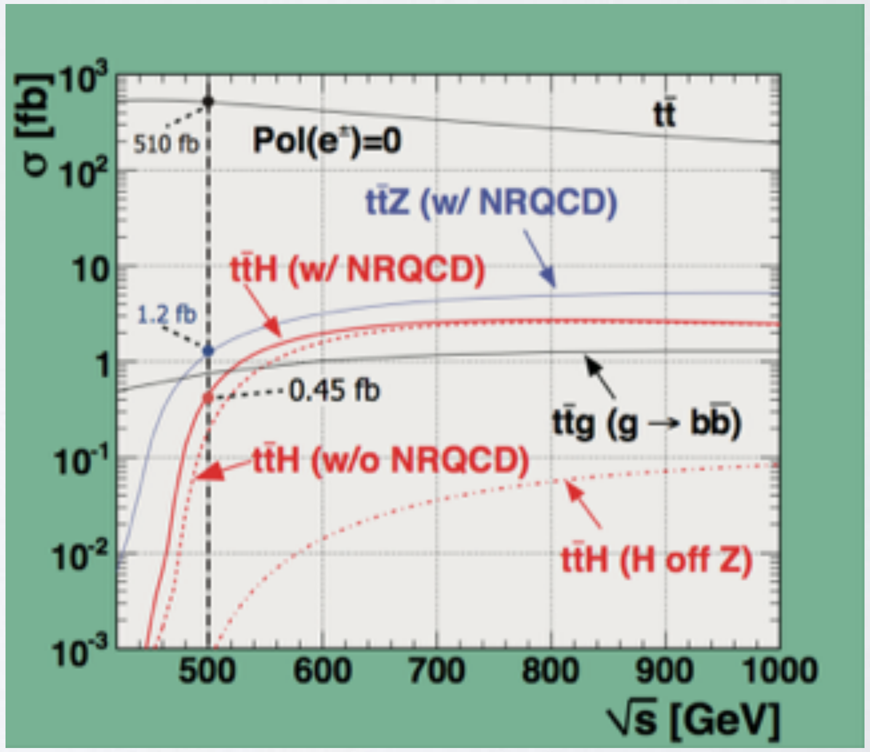
- if dynamics behind top/Higgs system: *tth* is the access key



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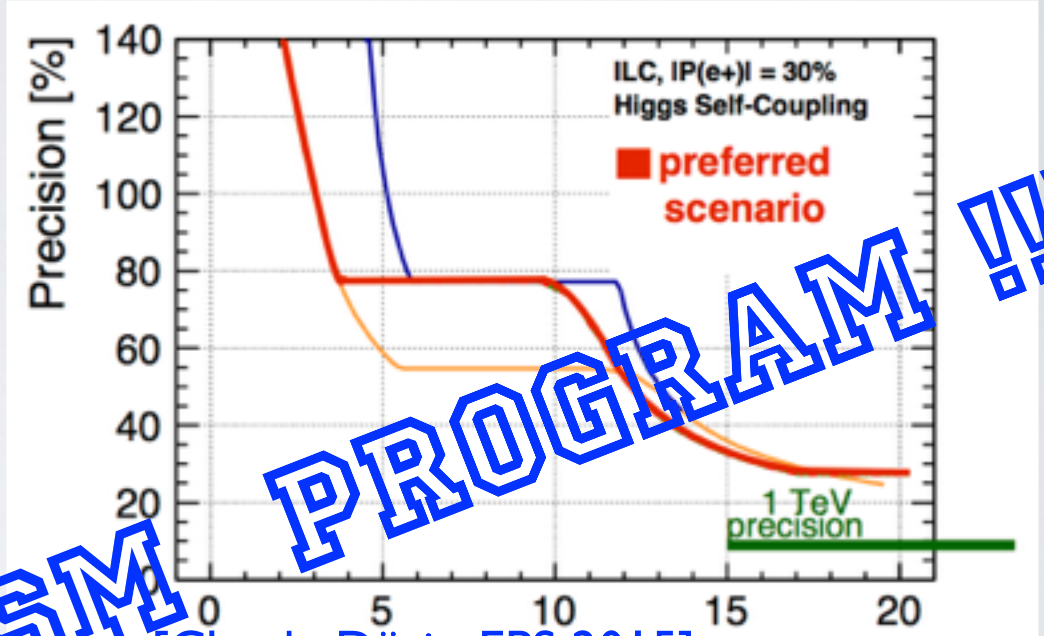

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THIS IS PART OF BSM PROGRAM !!!

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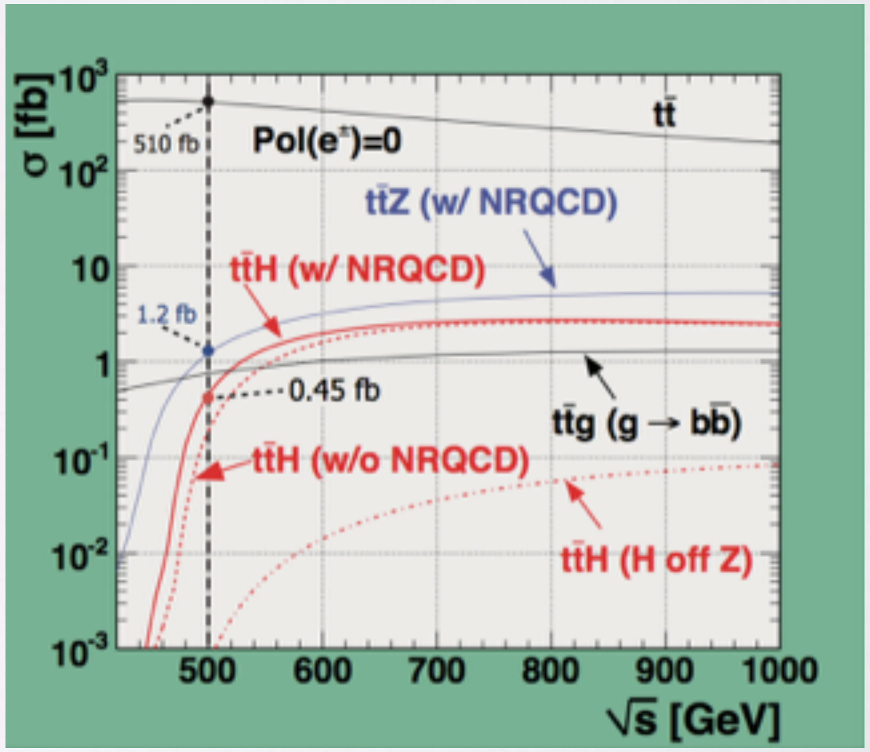
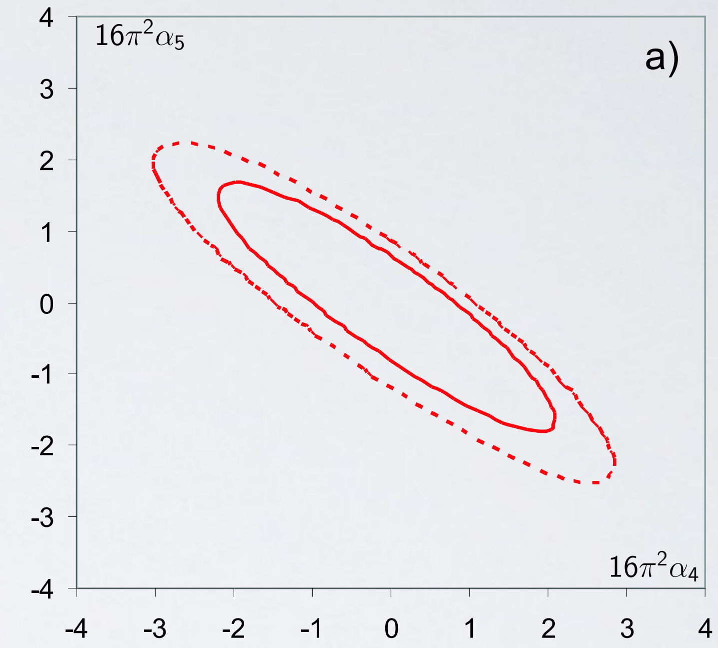


High-Energy Electroweak Sector

- 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: $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$, $ZZ \to ZZ$

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



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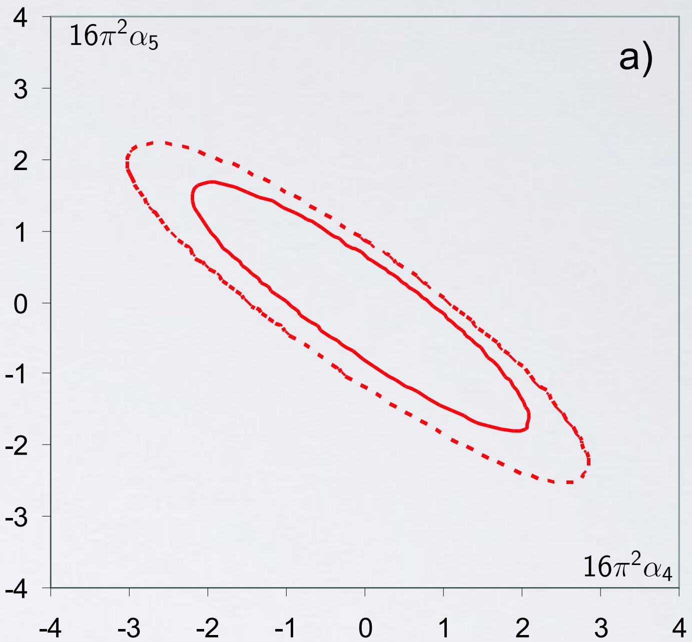

✴ Interpretation as limits on Electroweak Resonances:

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; 1511.00022; in prep. for ILC1000+CLIC

✴ Probably LC with 1-3 TeV and polarization outweighs 14-30 TeV pp [longitudinal/transversal!!]

Dark Matter Searches

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

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

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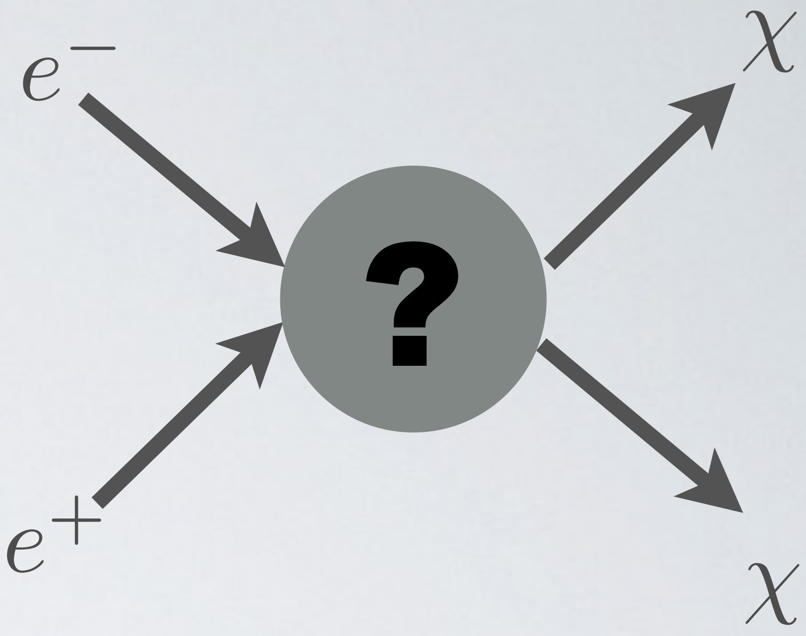
- Polarisation to suppress backgrounds: *W* exchange killed a lot by P(e+,e-)

Bartels/Berggren/List: arXiv: 1206.6639



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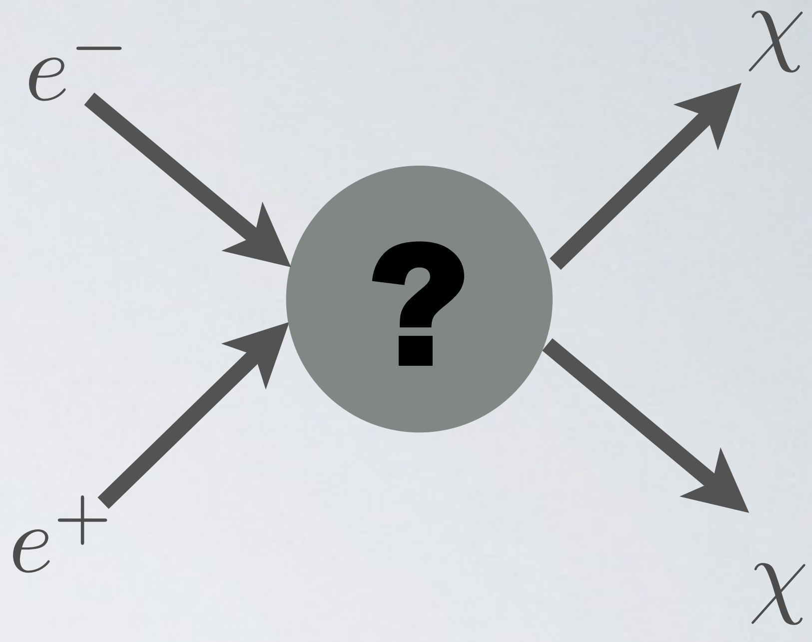

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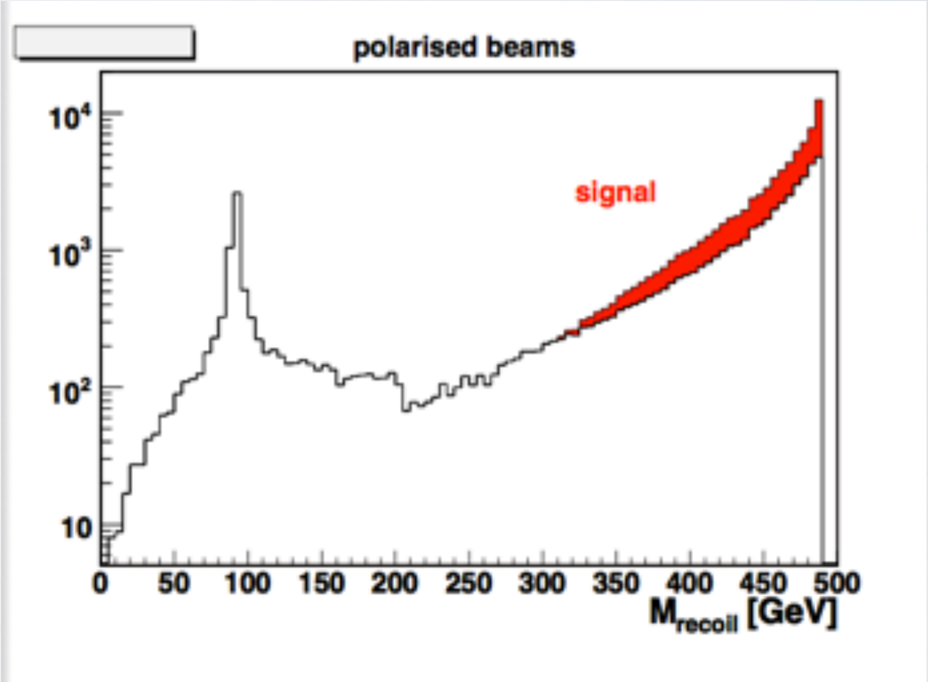

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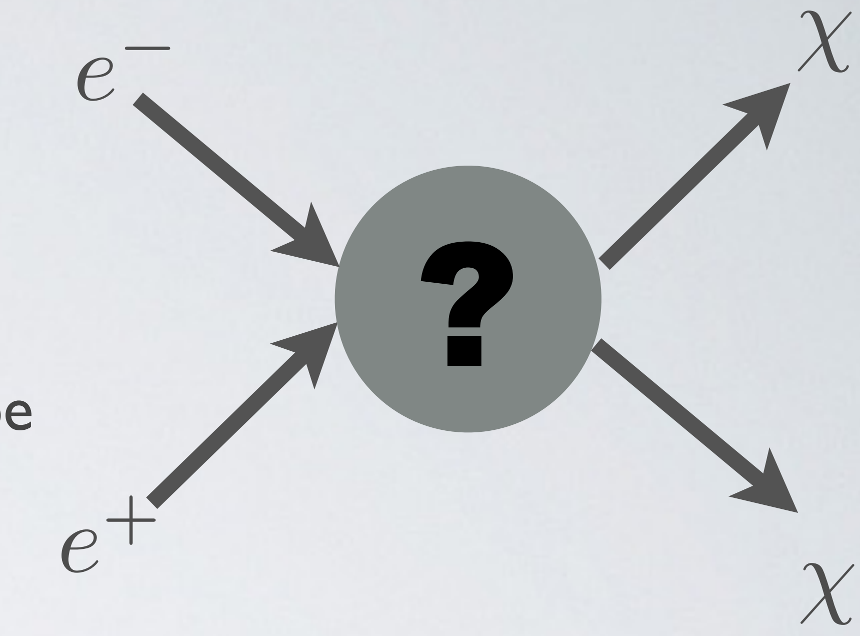

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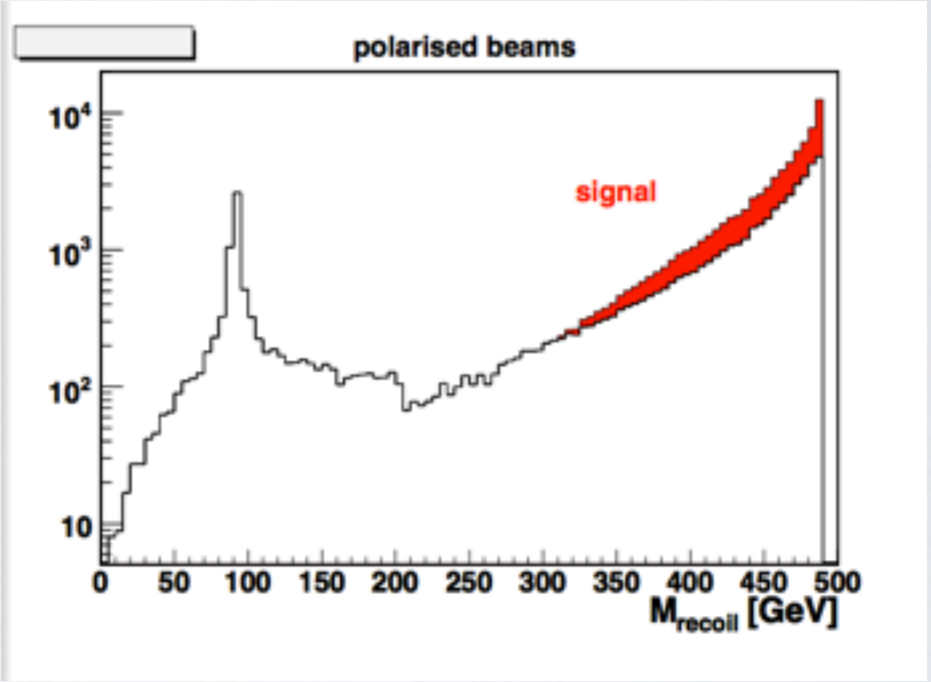

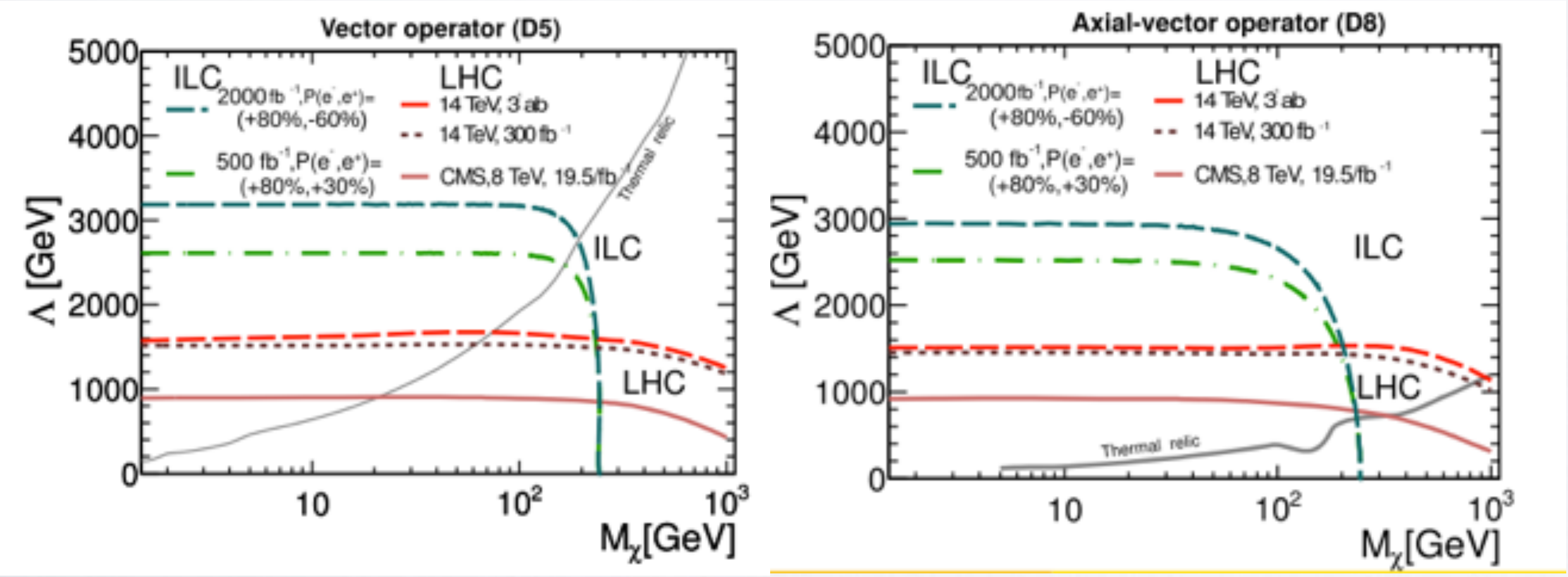

⋆ Vector operator: “spin-independent”
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LHC accesses higher masses, ILC lower cross sections (few caveats)

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

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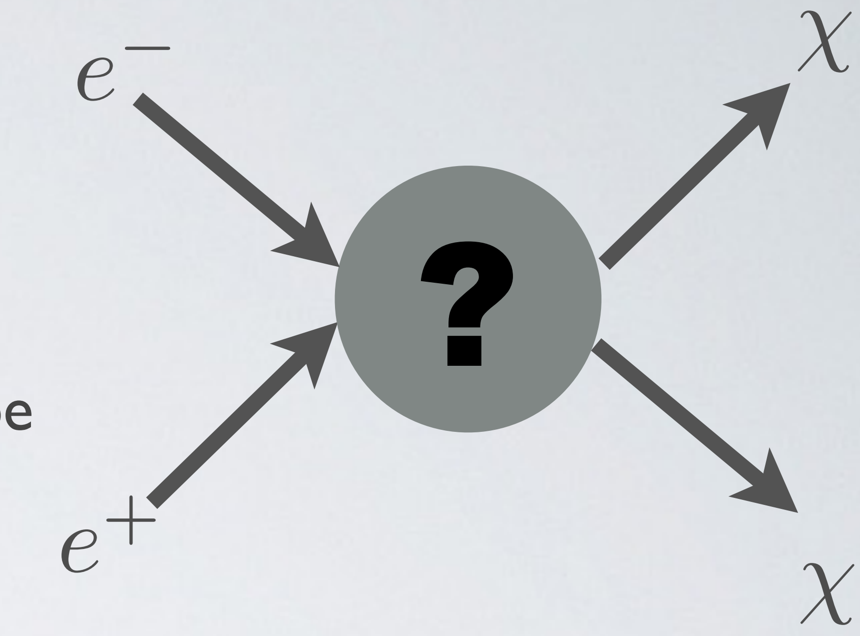

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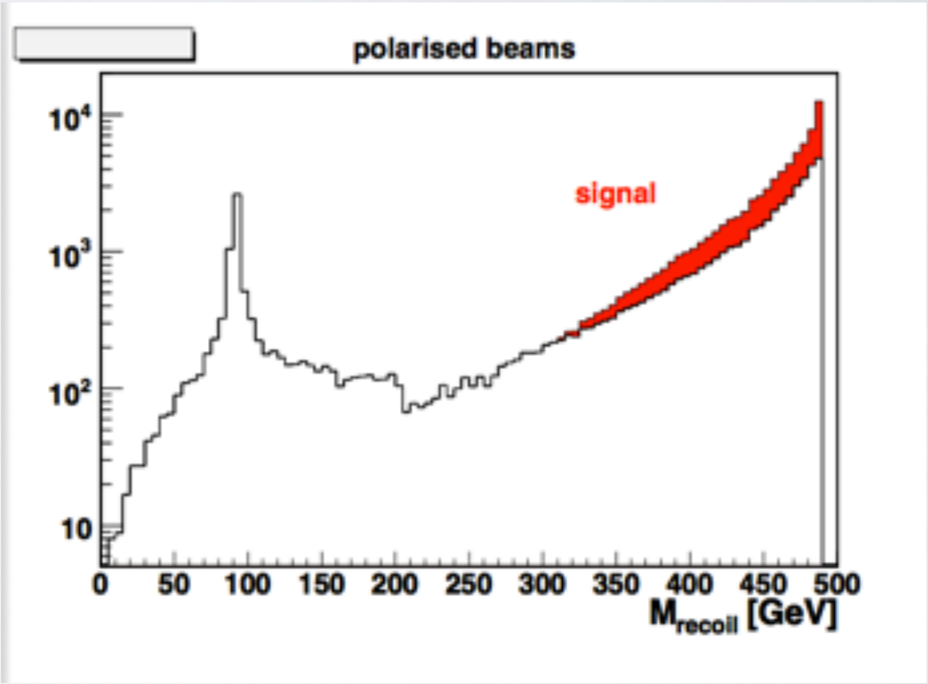

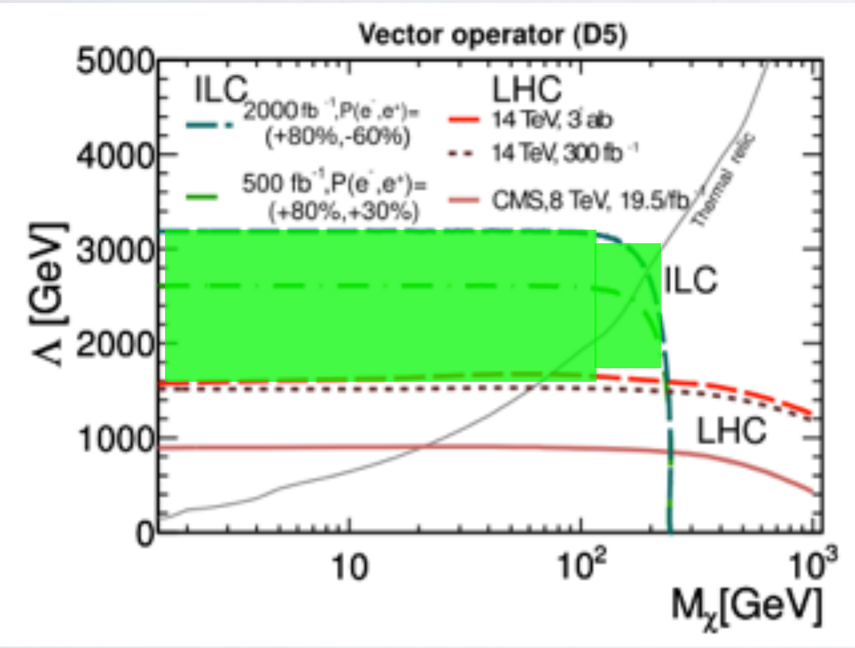

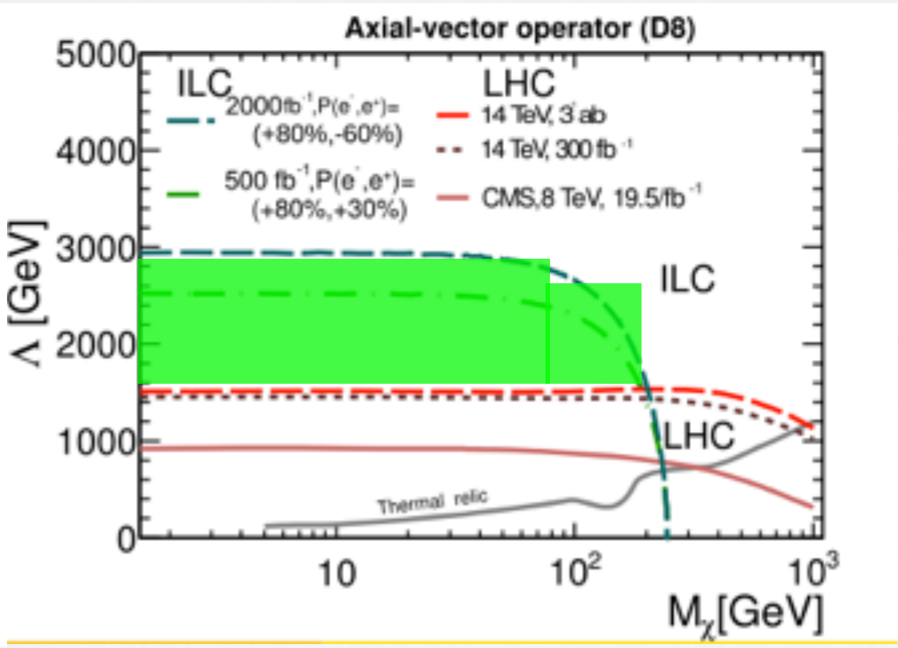

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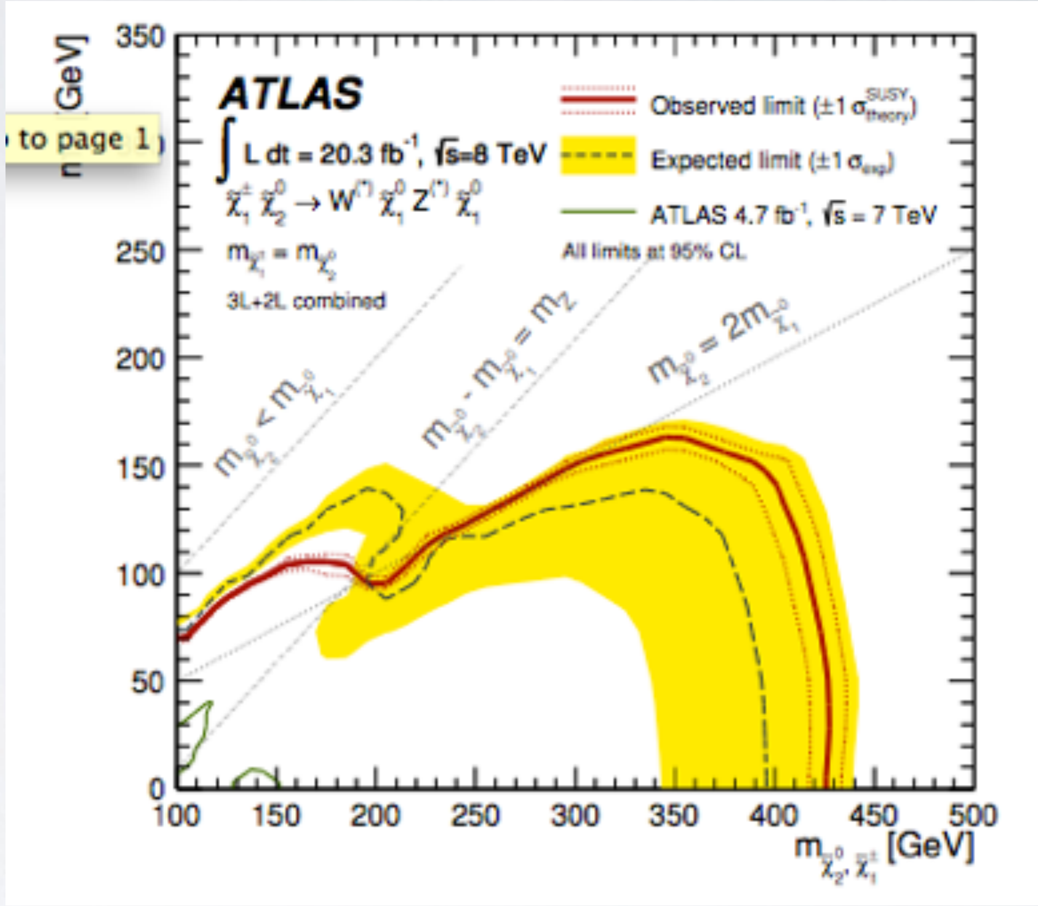
- e+e-: electroweak production ⇒ allows (more) model-independent searches for EW particles
- Example: SUSY searches for partners of electroweak particles (EW gauginos / Higgsinos)
- LHC searches: assumptions $M_{\tilde\chi_1^0} = M_{\tilde\chi_1^\pm}$ $\quad \mathrm{BR}(\tilde\chi_1^\pm \to W^\pm \tilde\chi_1^0)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



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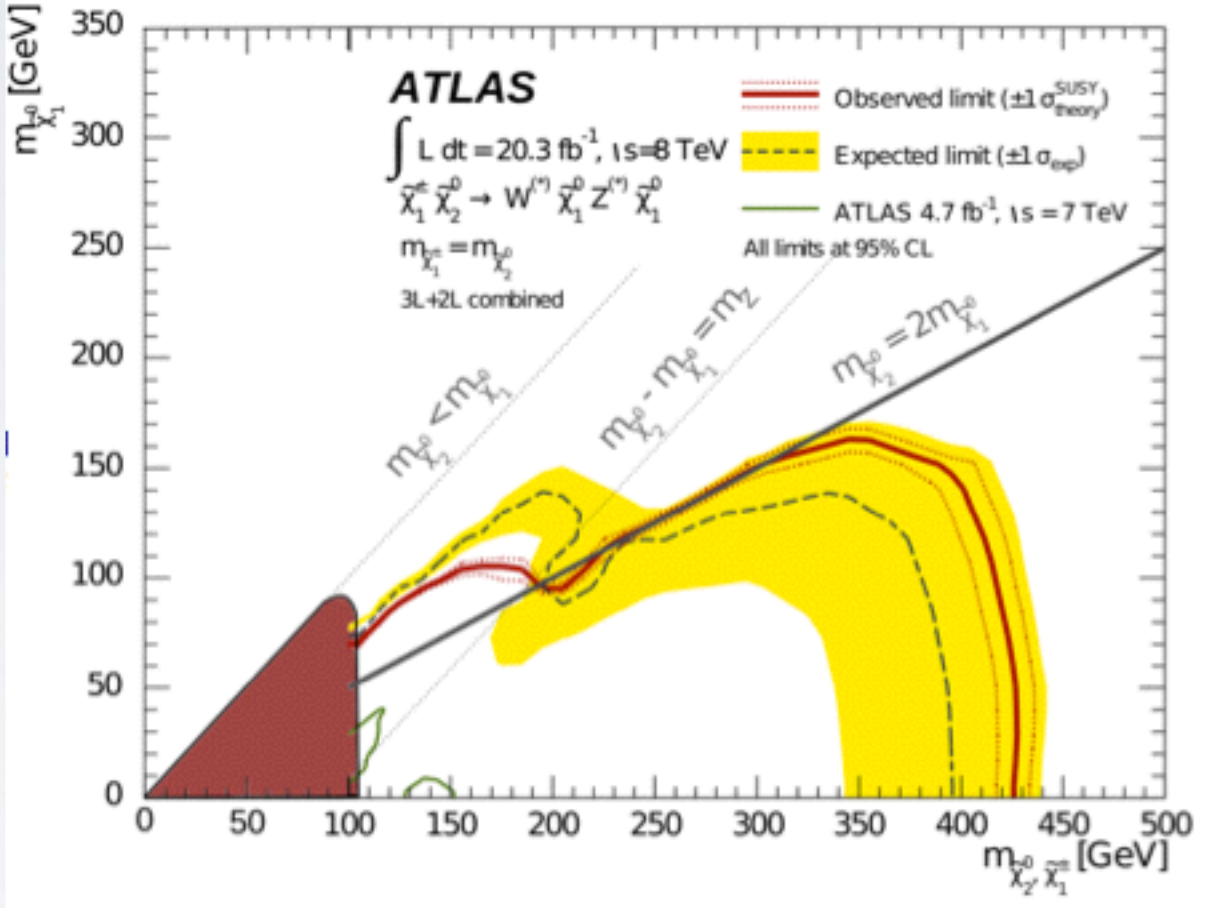
- LEP chargino search (all decay modes)
- No gaugino-mass GUT relation below line



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- e+e-: electroweak production ⇒ allows (more) model-independent searches for EW particles
- Example: SUSY searches for partners of electroweak particles (EW gauginos / Higgsinos)
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★ LHC projections to 14 TeV (arXiv: 1307.7292)
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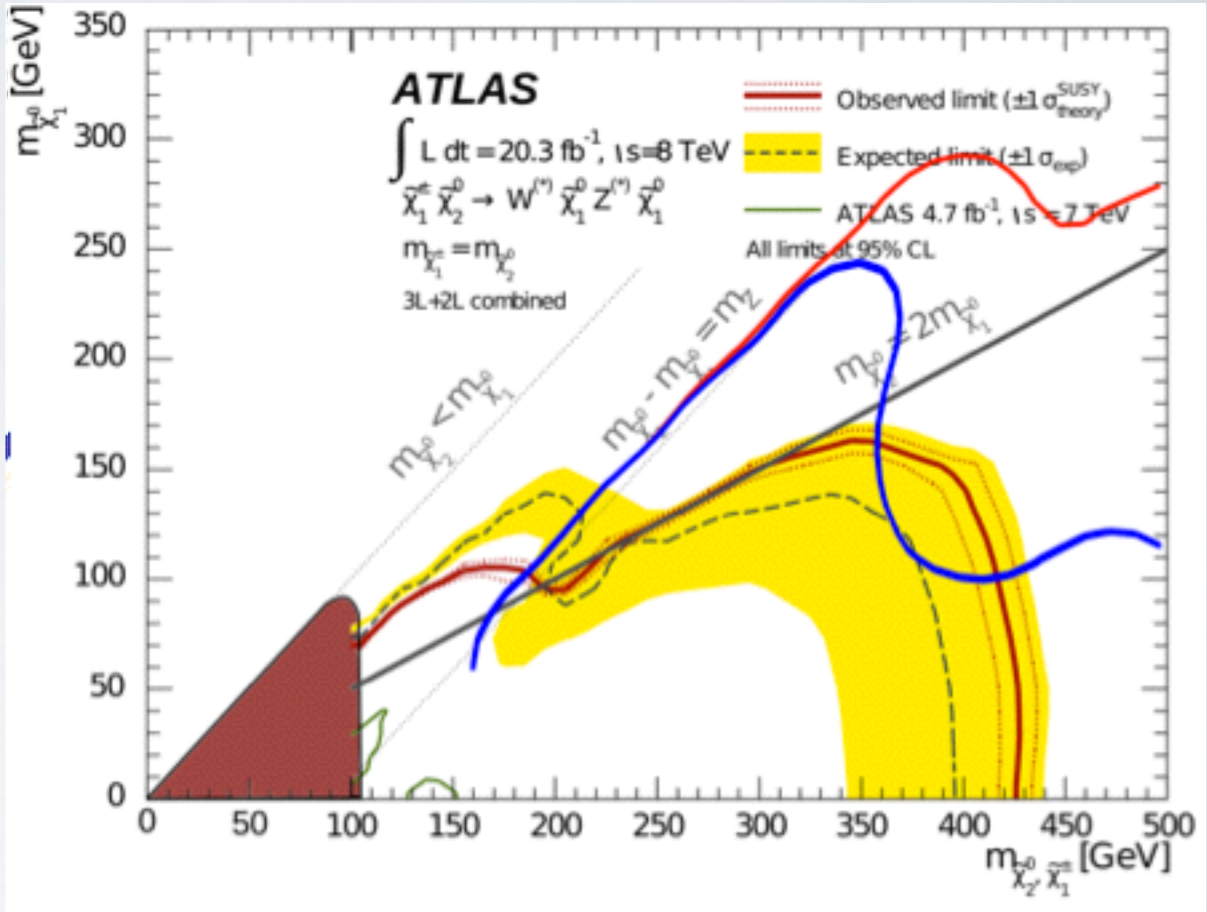

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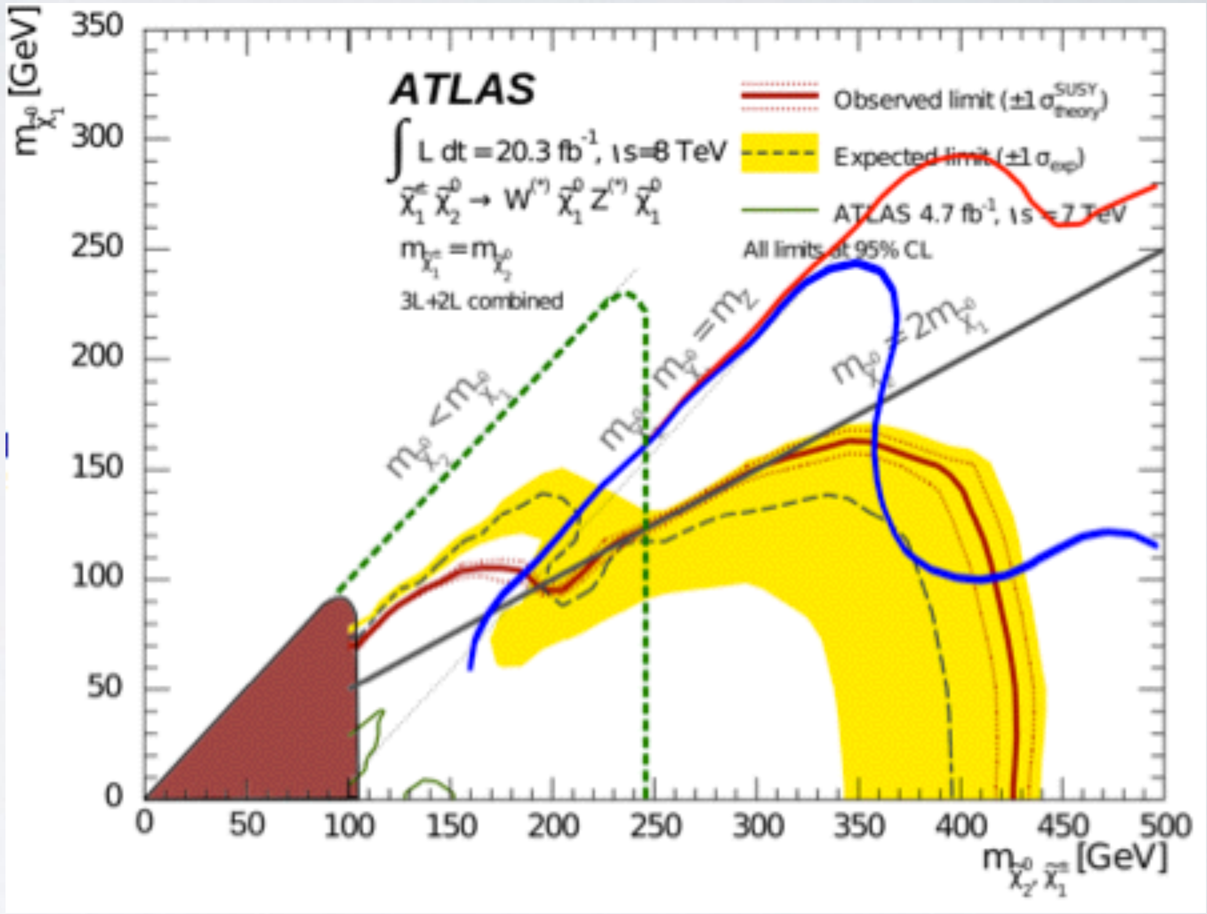

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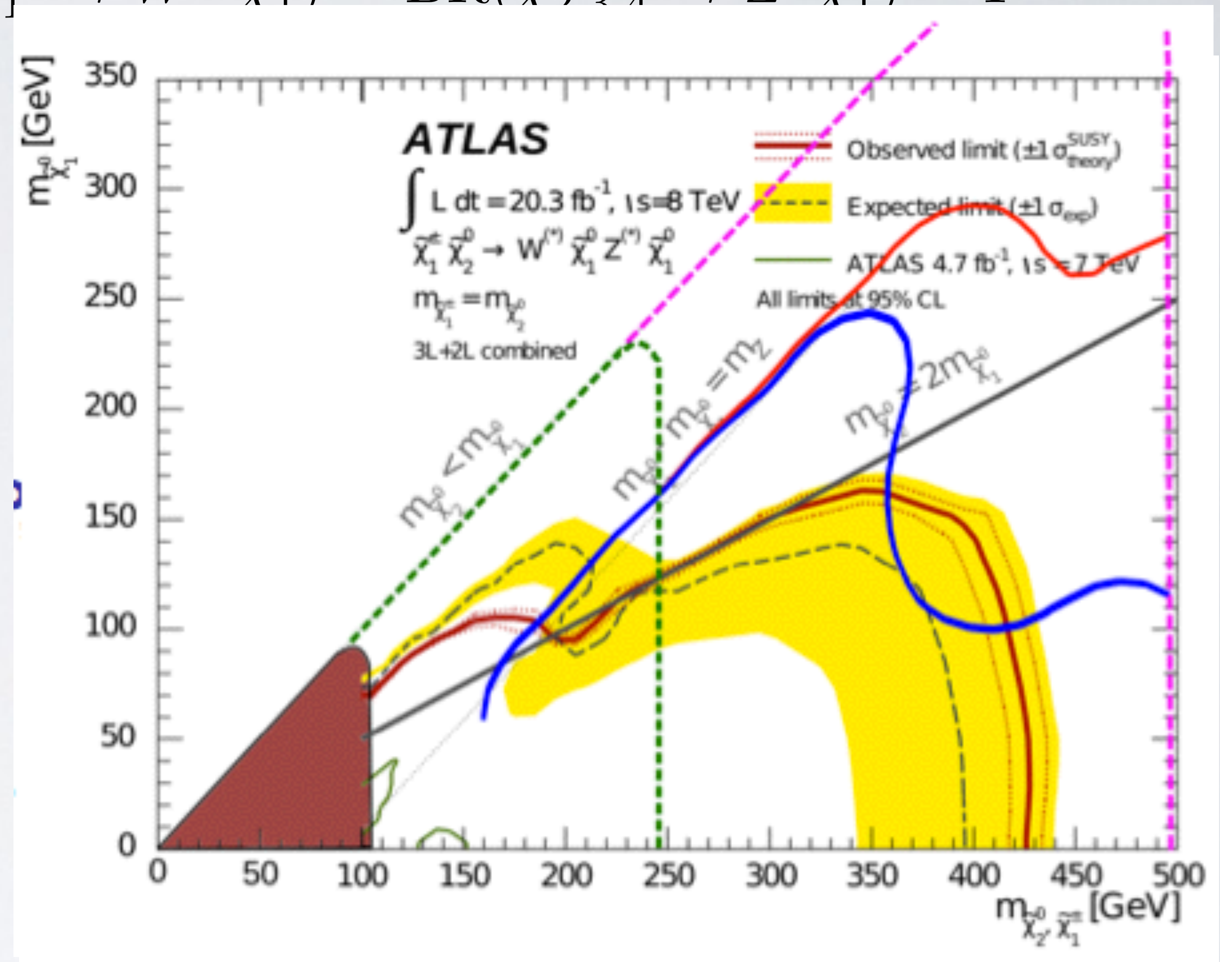

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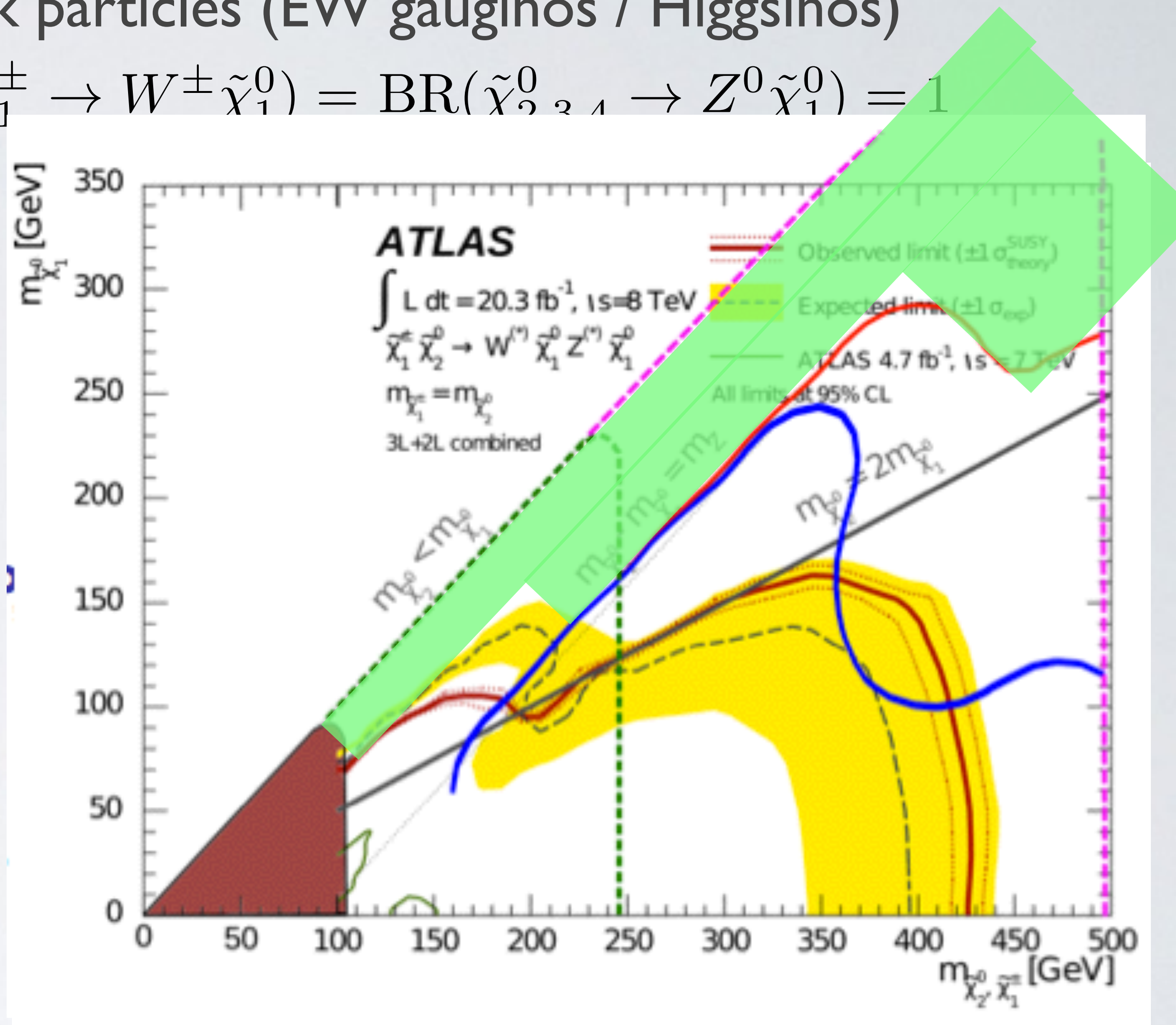

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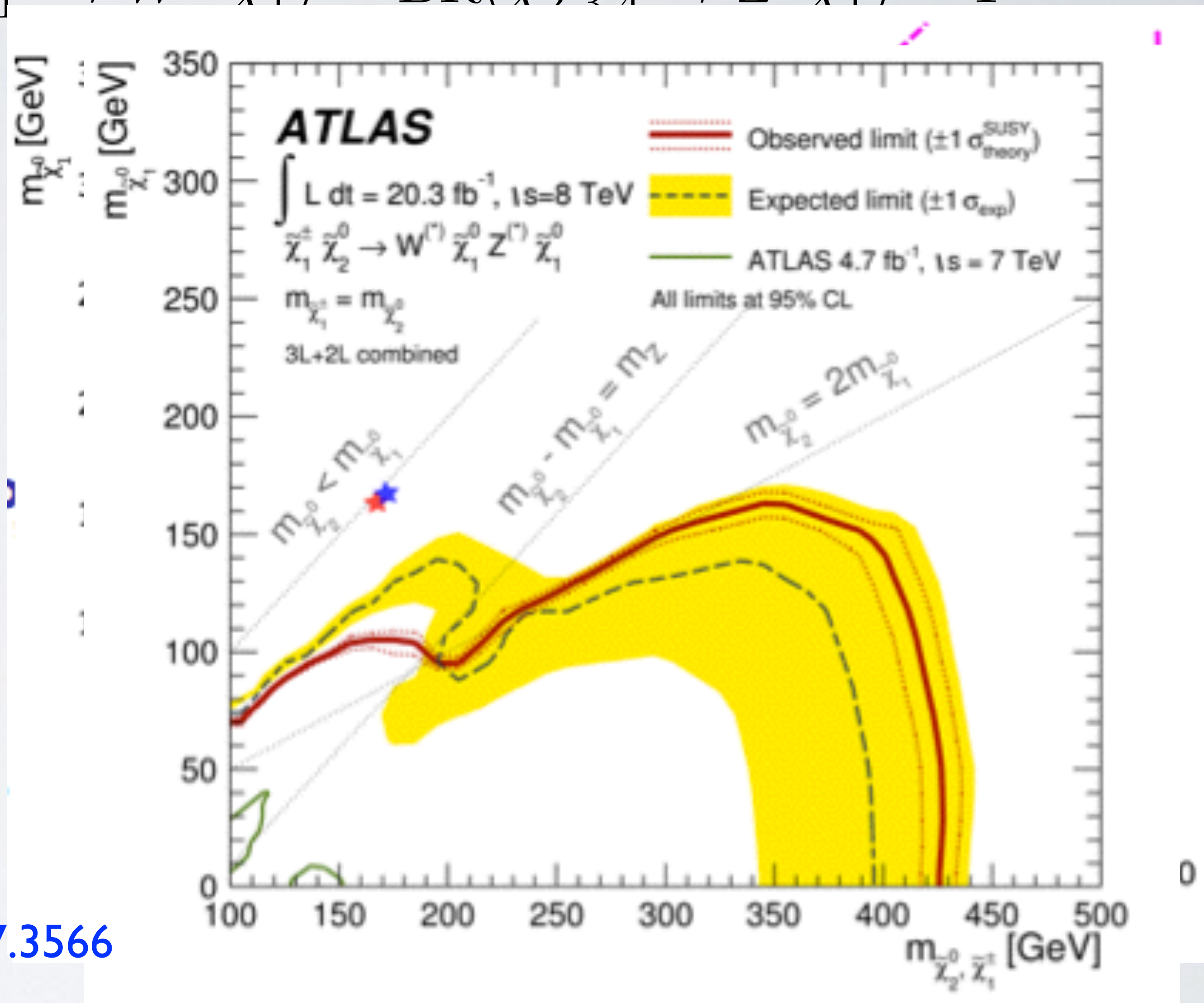
- Benchmark searches for degenerate EW-inos

$\Delta(M) = 1600 \text{ MeV}, M_{\tilde{\chi}_1^0} = 164.2 \text{ GeV}$

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

Sert et al.: arXiv:1307.3566



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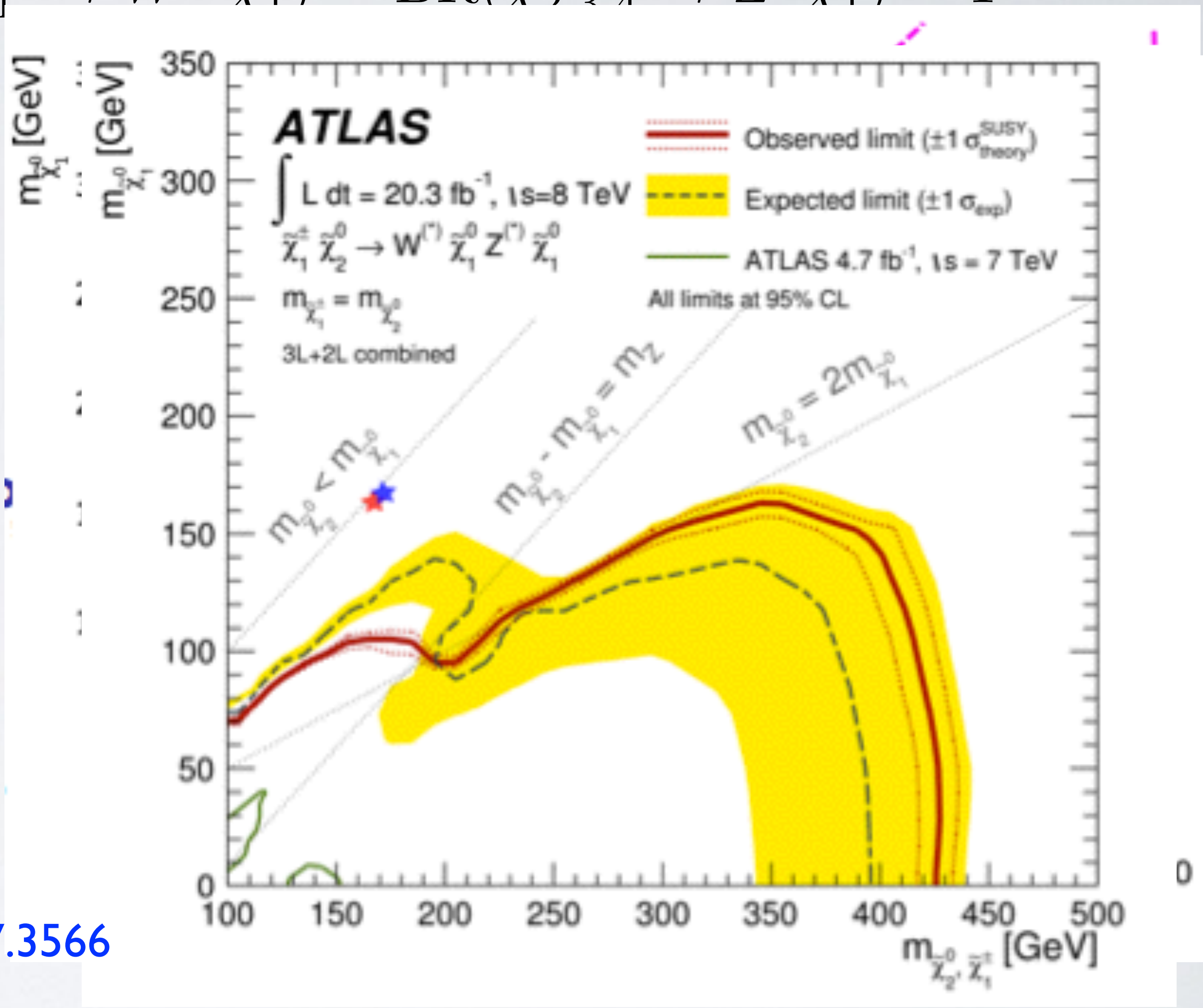

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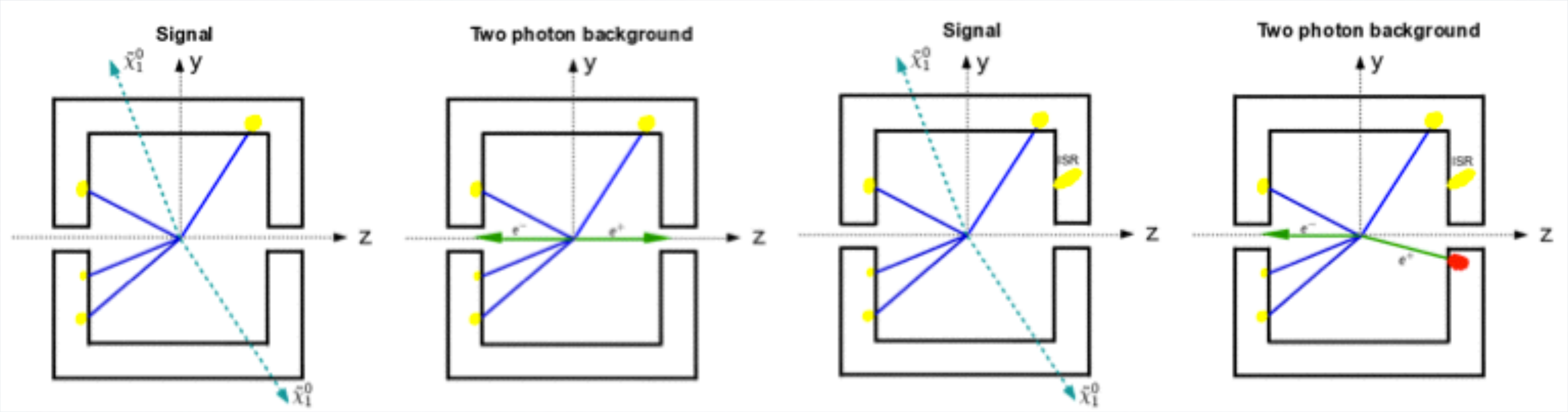
SUSY signals: $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$, $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ (all *s*-channel, no *t*-channel [Higgsino])

Search for New Weakly Interacting Particles (I)

- Dig out of γγ background: tag ISR photon (only moderate 'kick' for signal / accesses bkgd.)



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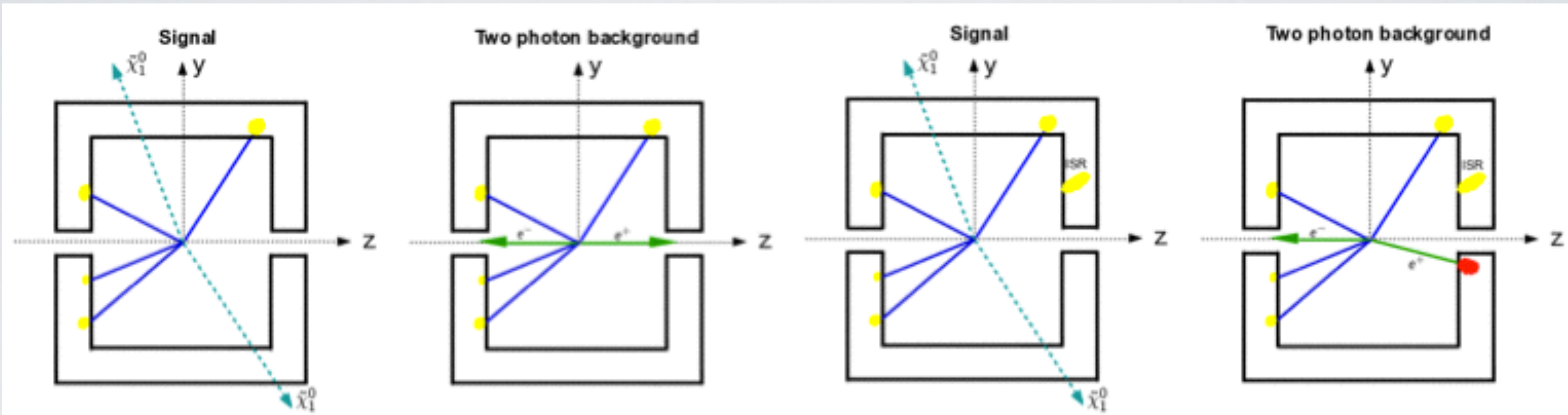

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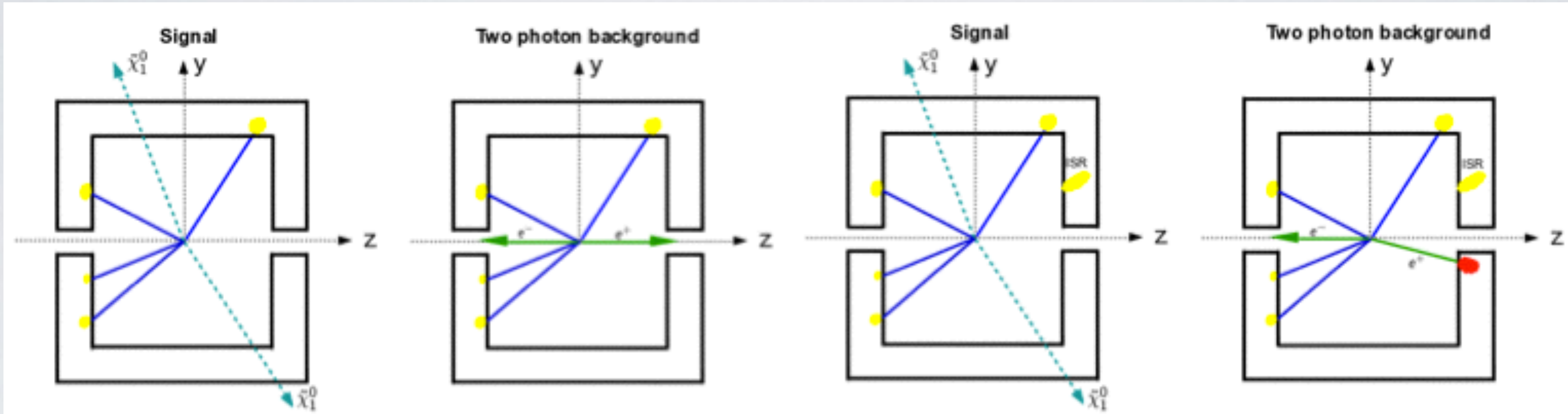

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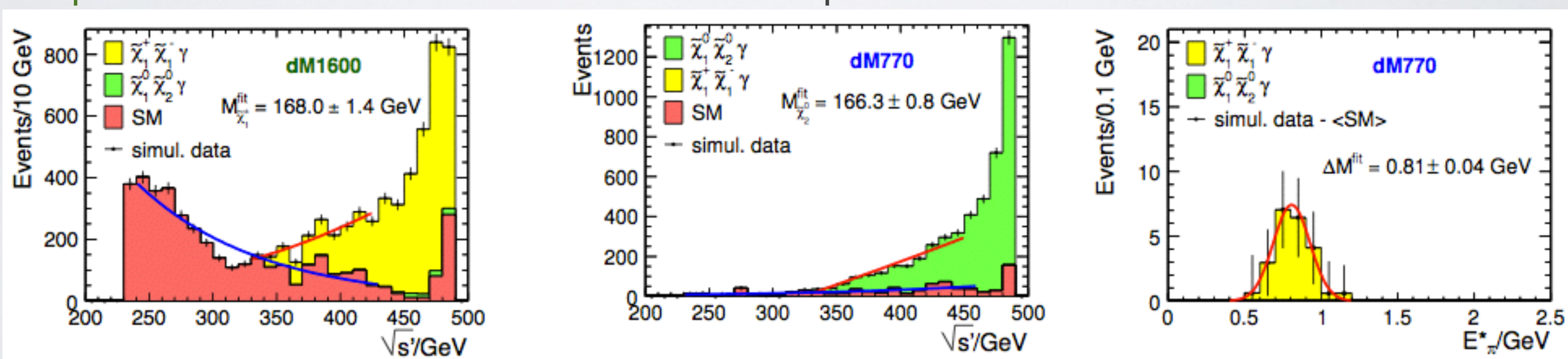

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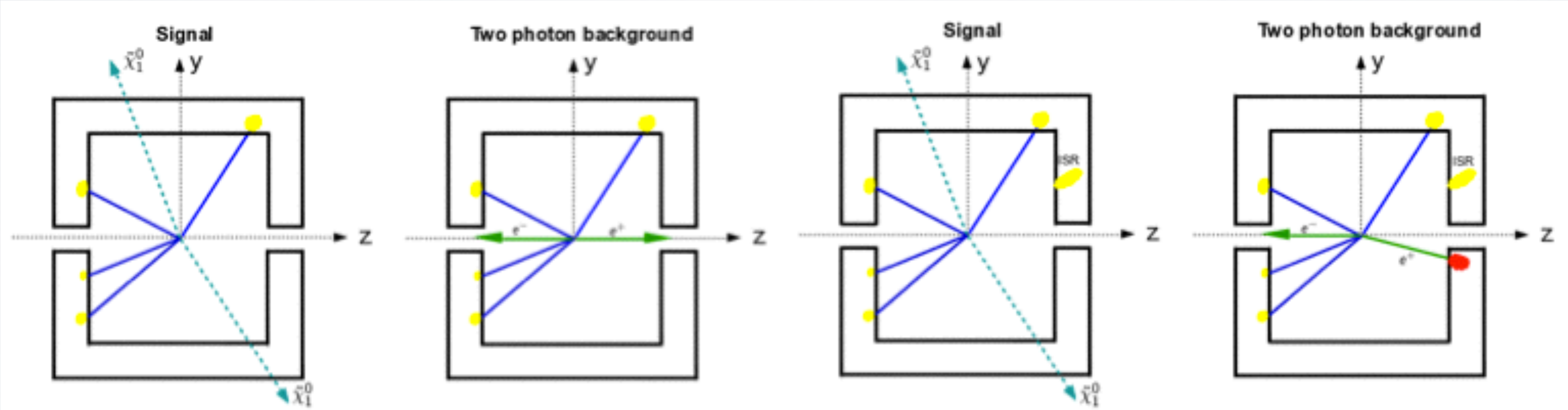

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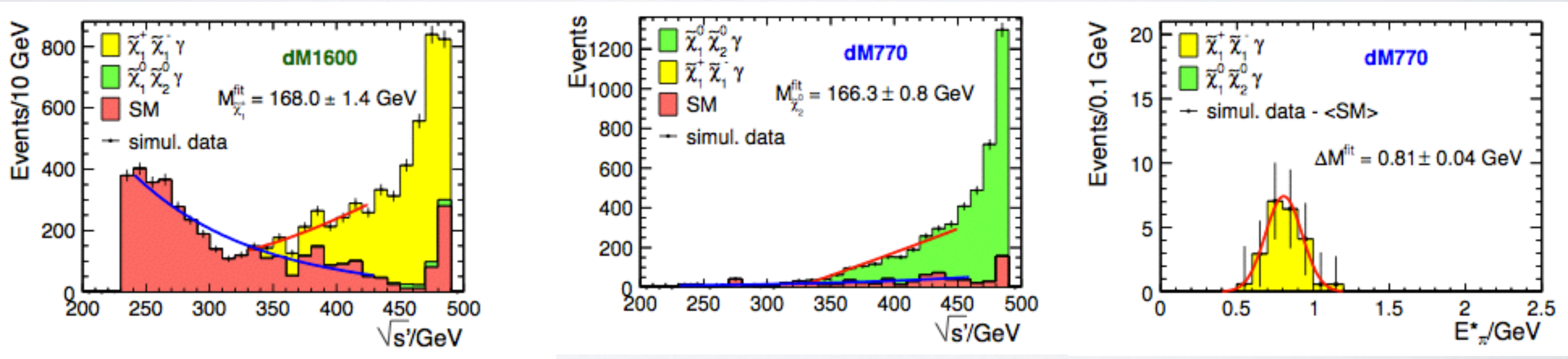

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- Parameter extraction: from E_π : $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 100$ MeV and $\mu \sim 4\%$

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

  $M_{\mathrm{NLSP}} - M_{\mathrm{LSP}}$ plane
- Examples: $\tilde{\mu}_R$ NLSP

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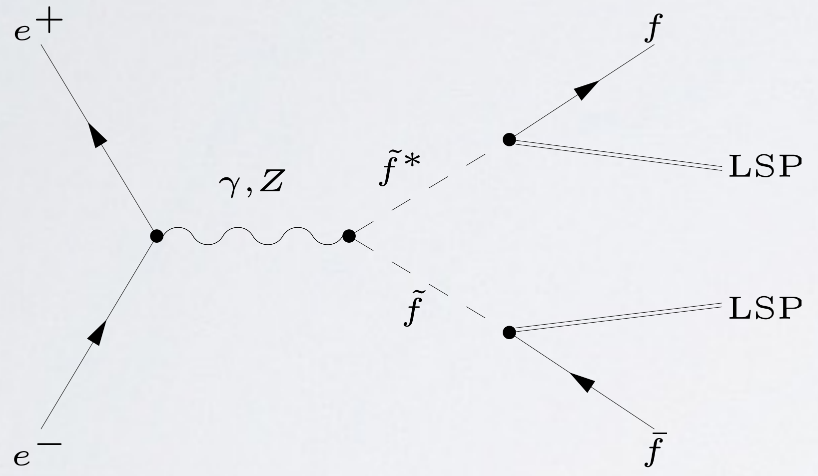
Berggren, arXiv:1308.1461



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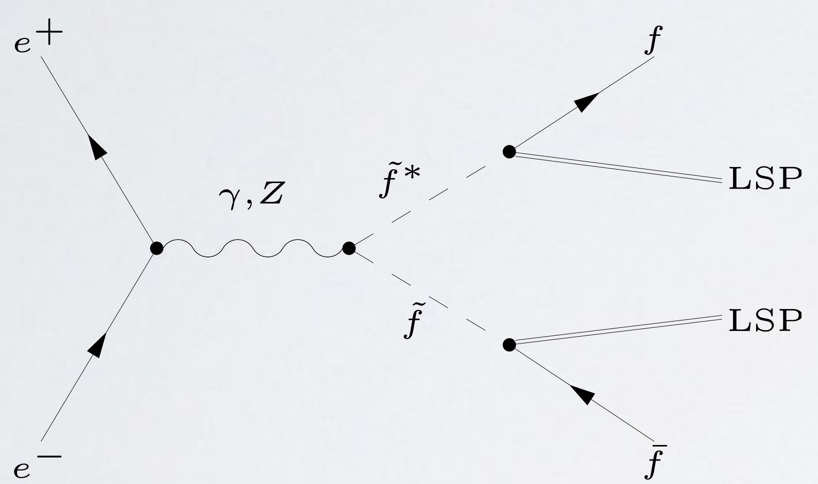
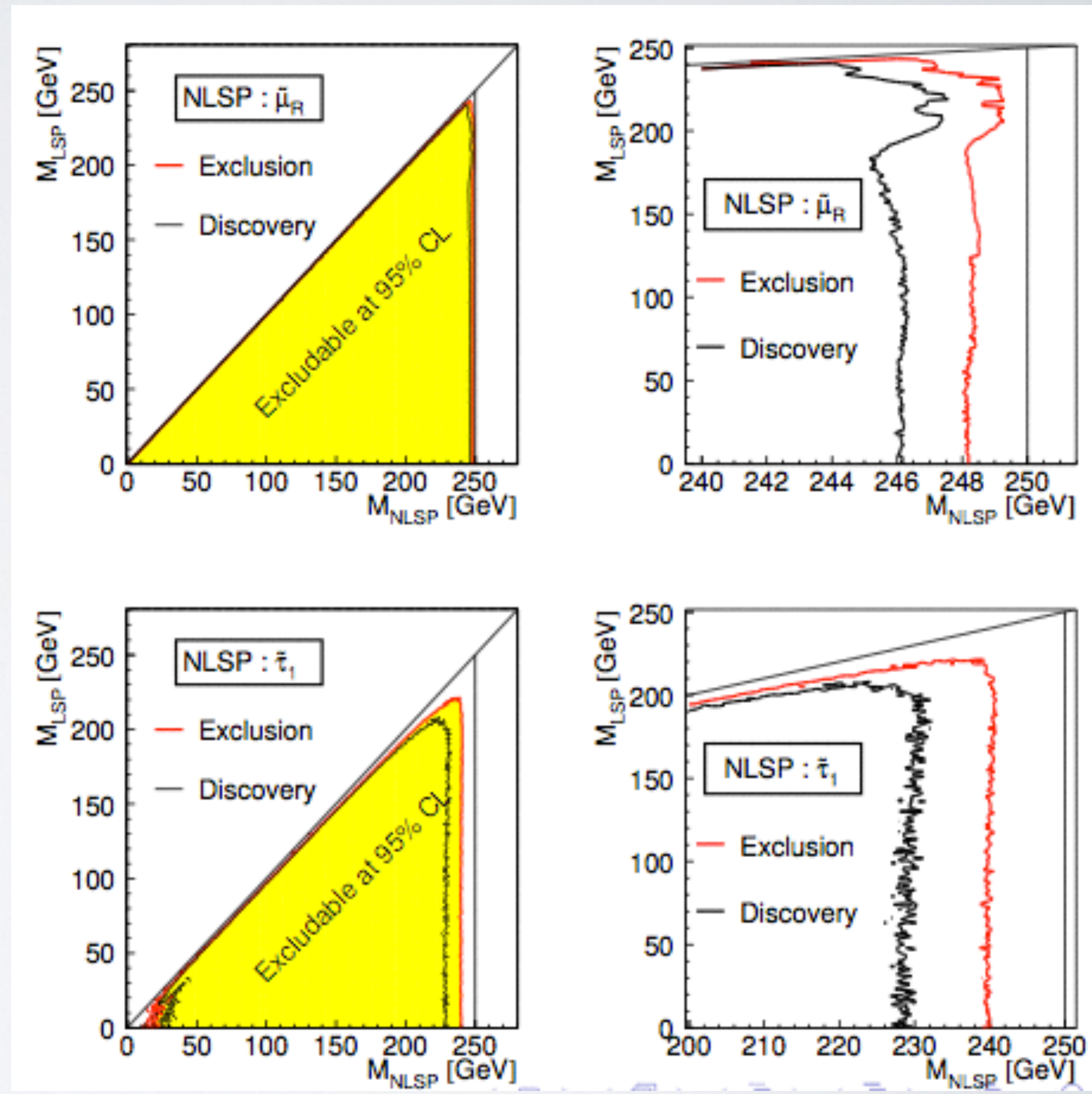


Discover/exclude close to kinematical limit



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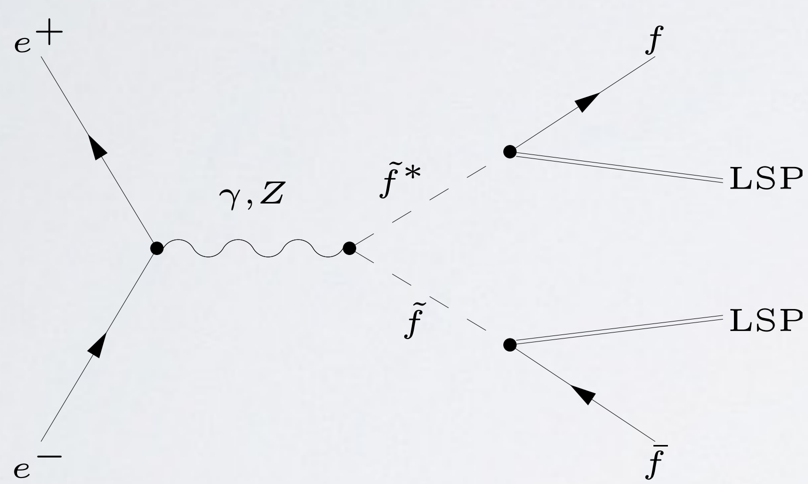

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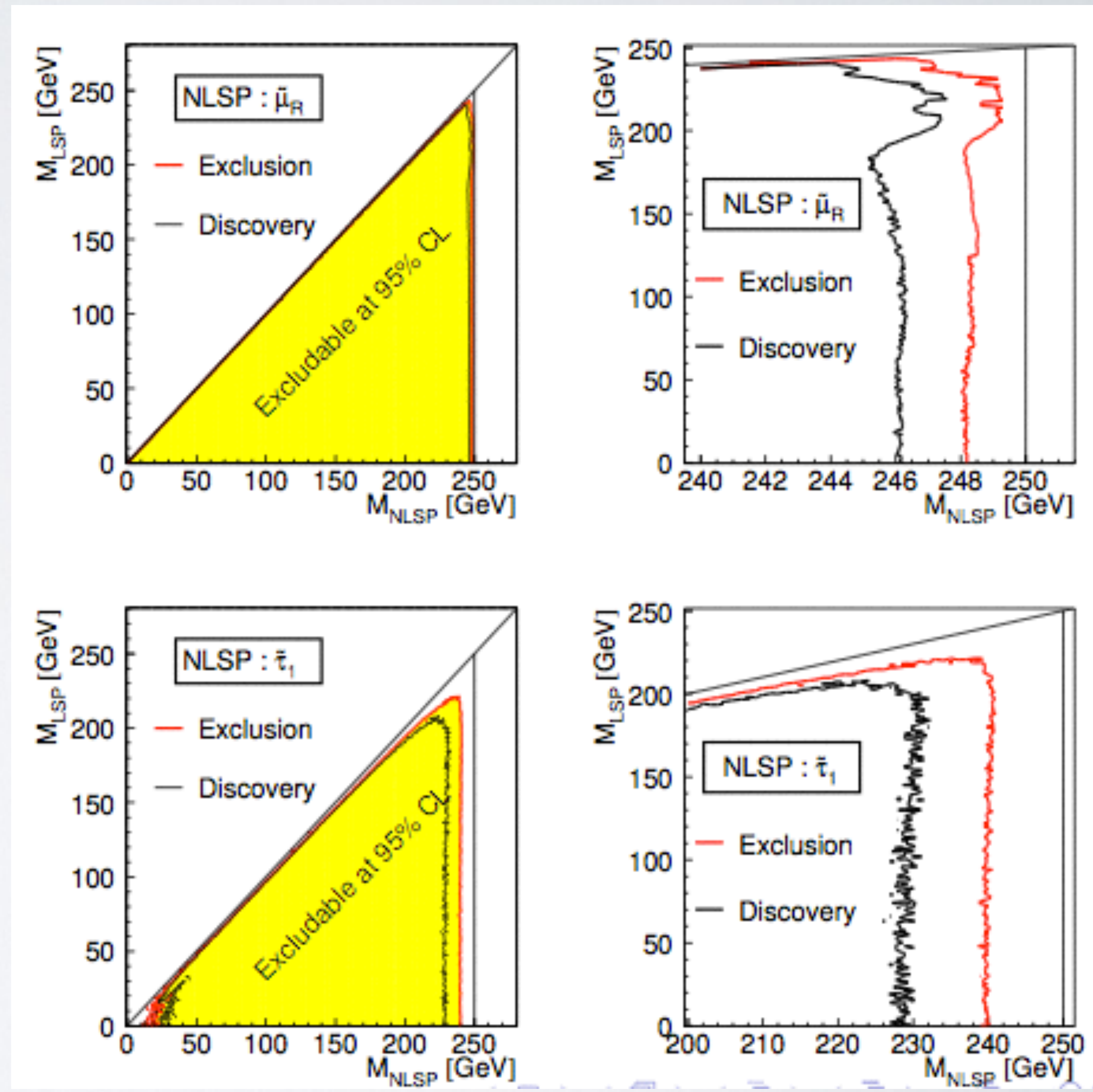

Even for sneutrino NLSP

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

Search for New Weakly Interacting Particles (II)

- ⋆ Other candidates: axion-like particles in strongly-interacting models
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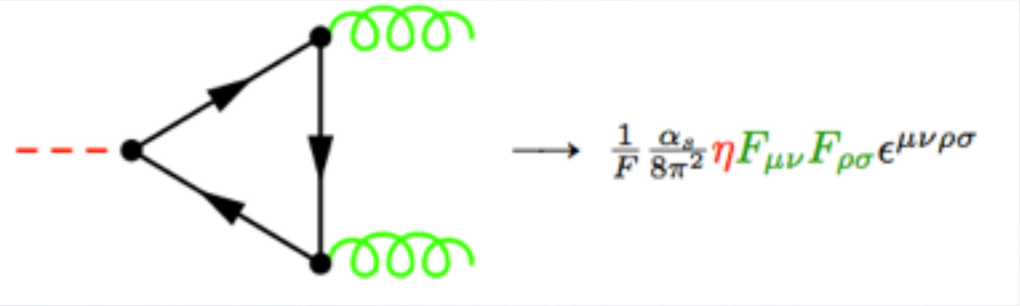

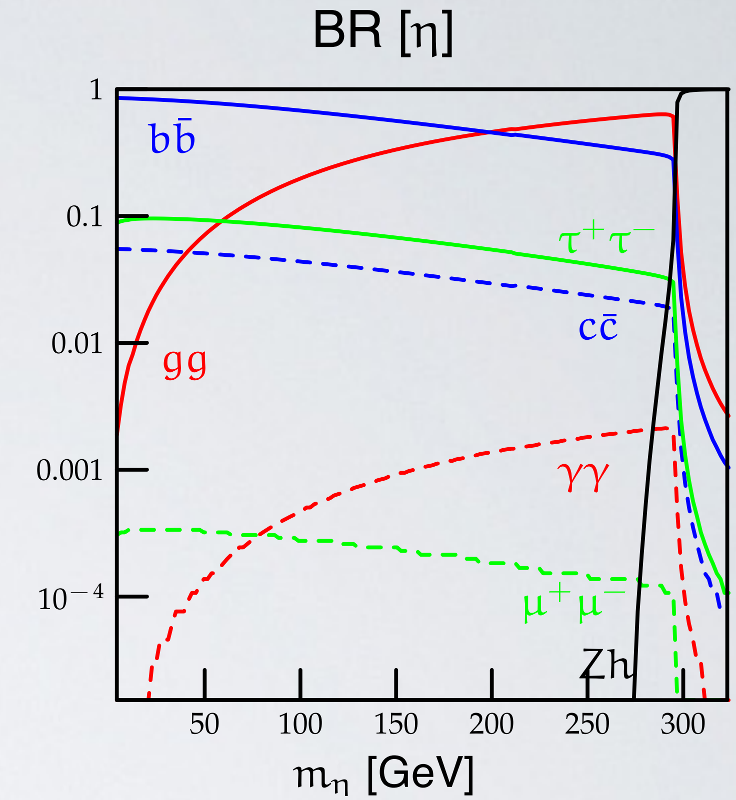

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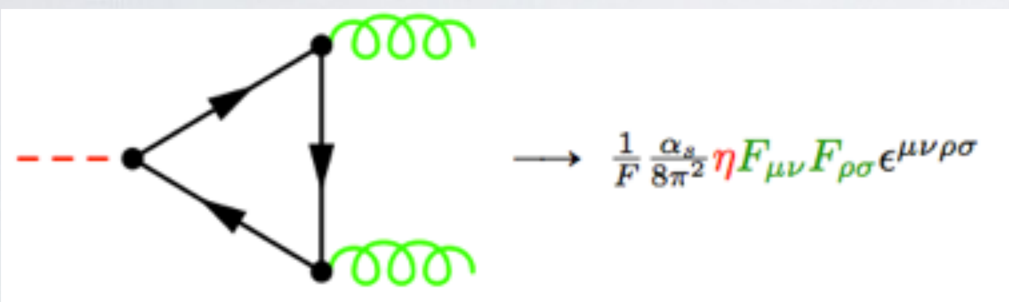
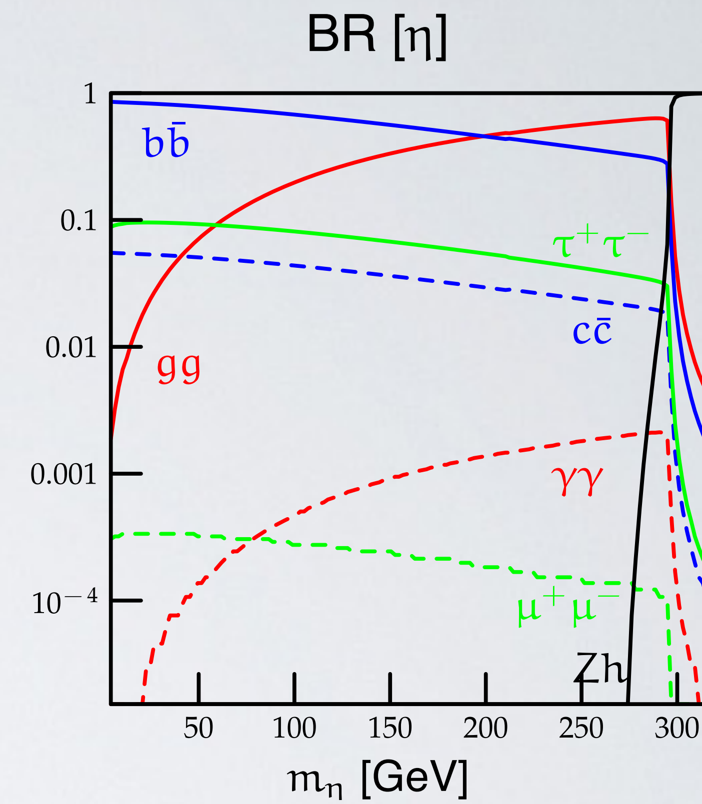
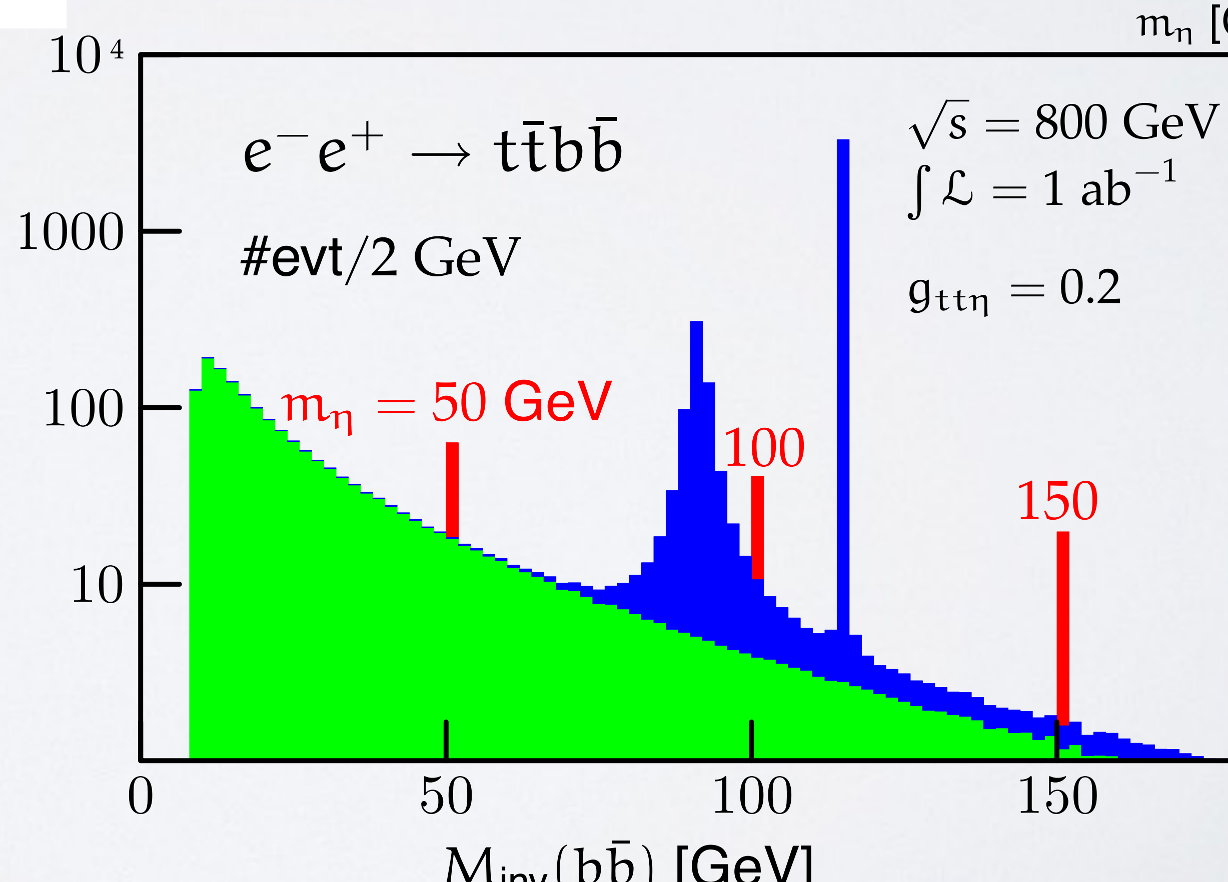




★ e+e- colliders allow detection in the low-mass regime:

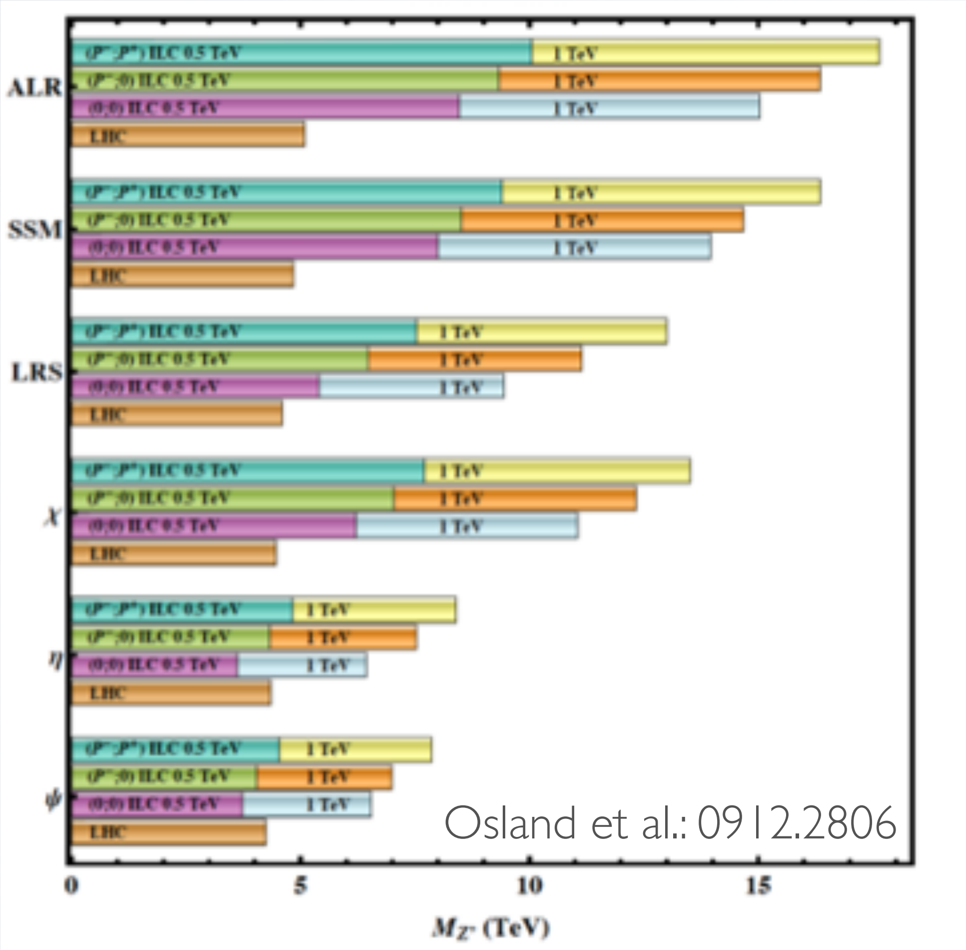
$$e^+e^- \to t\bar{t}\eta$$

"tt Recoil spectrum search"



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 allow discoveries and model discrimination
- ⋆ Access to scales up to tens of TeV!!



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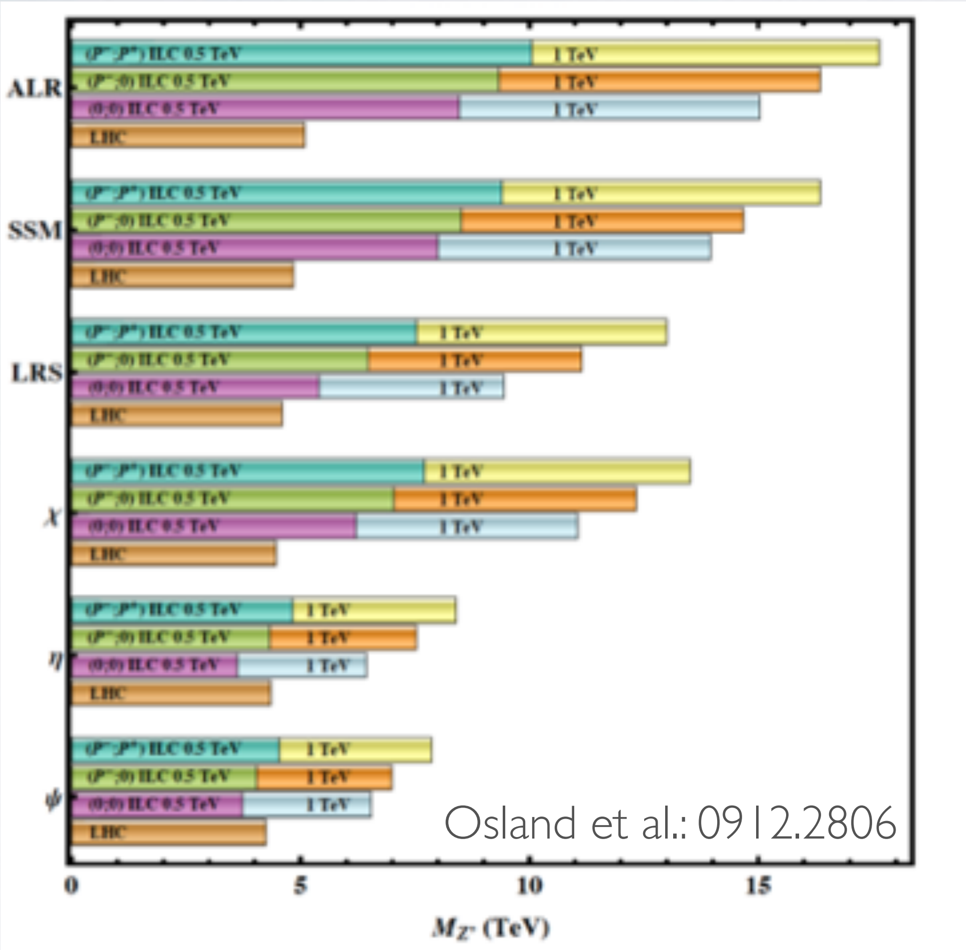
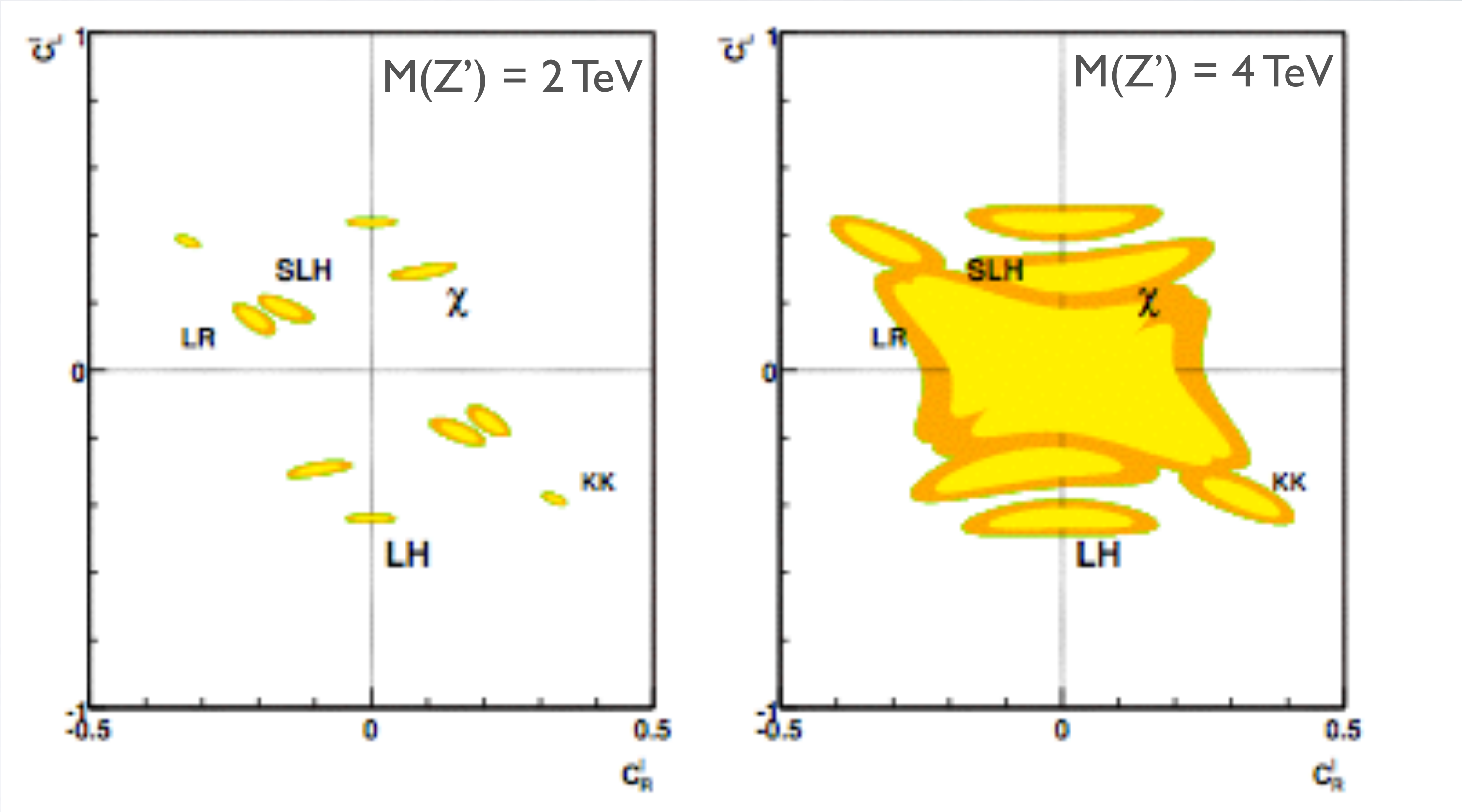


Osland et al.: 0912.2806



Godfrey/Kalyniak/Tomkins: 0511335

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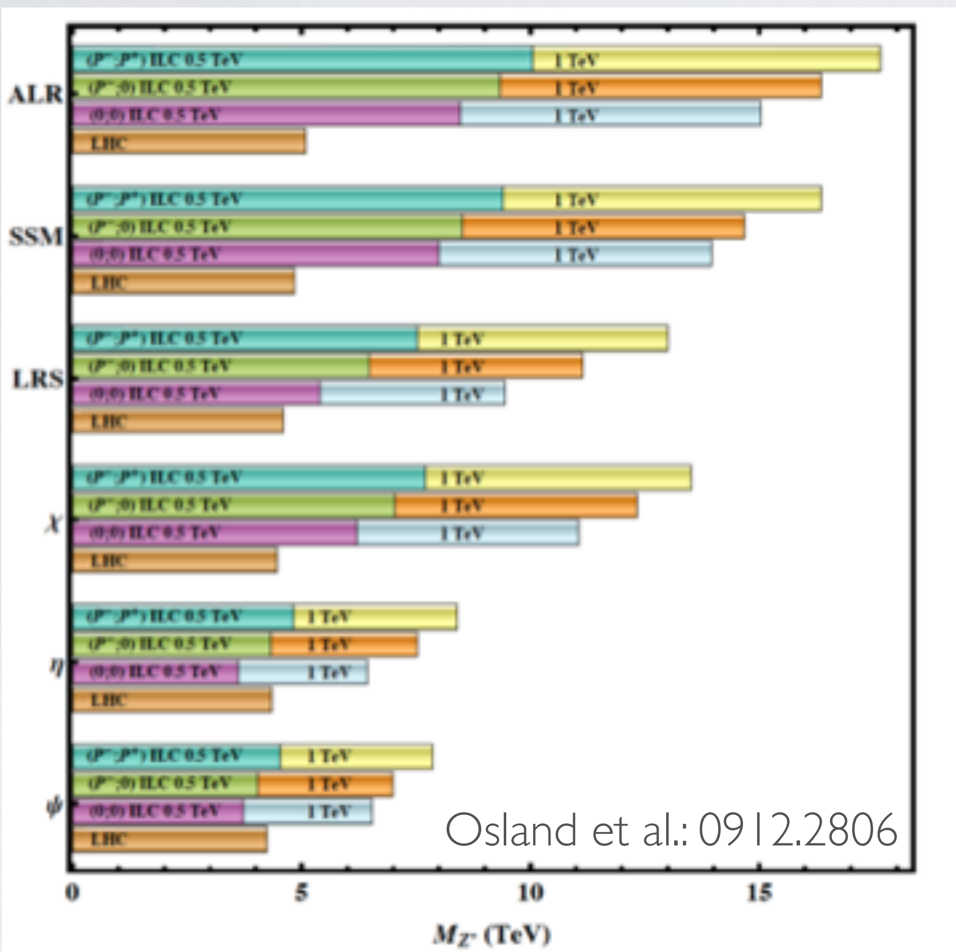

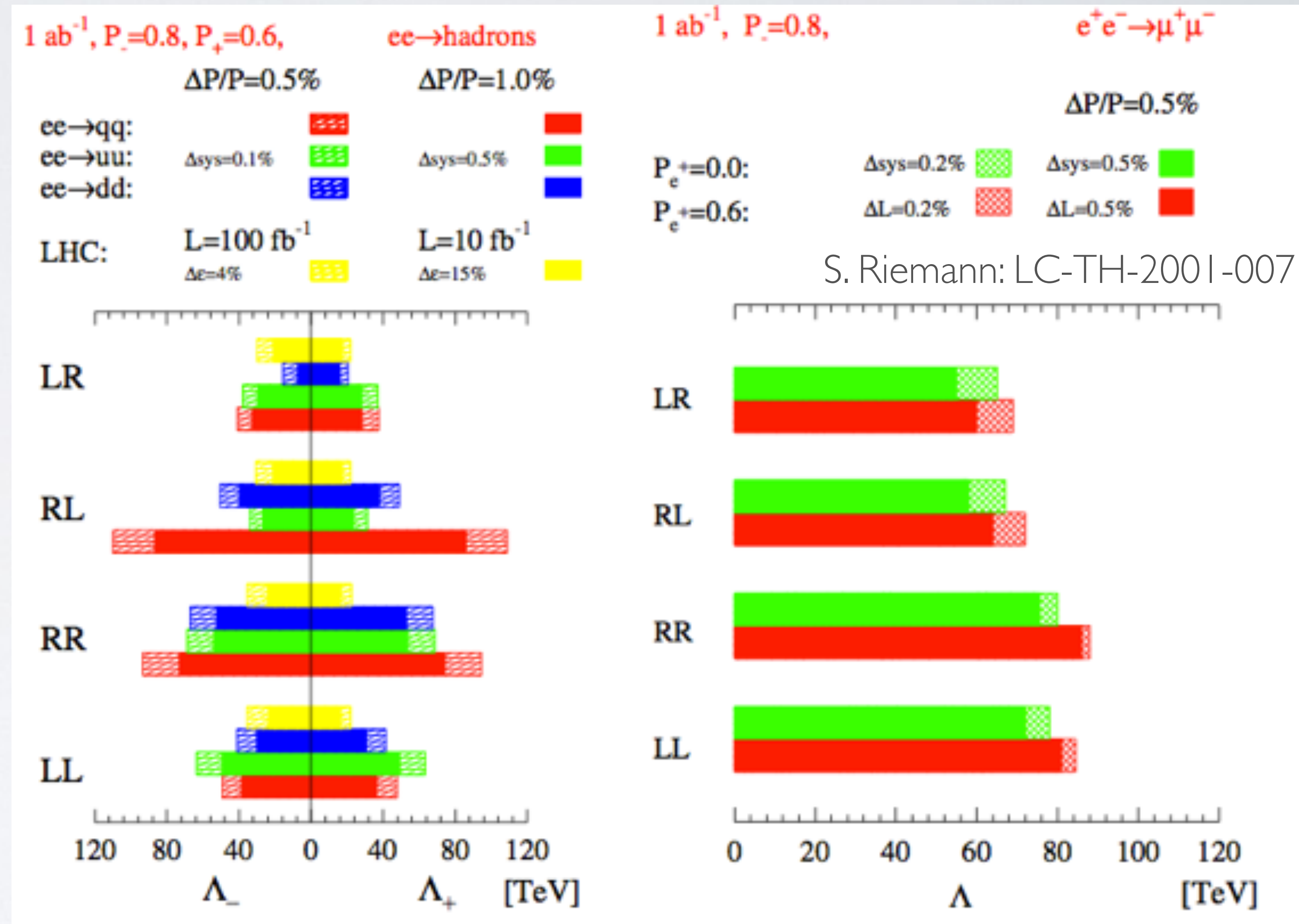

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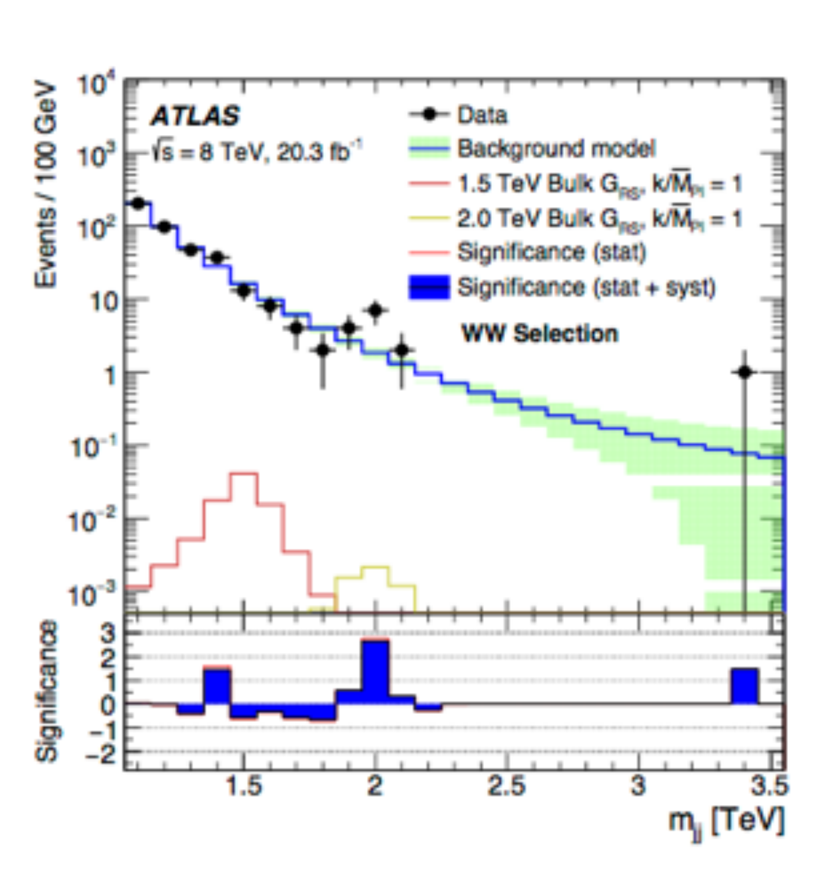
- ★ Contact interactions are sensitive to scales close to 100 TeV

What if: … possible final words from LHC



Consider LHC signal with 4+ σ at the end of Run II or HL-Run ….

Before a 40-100 TeV pp machine, ILC is the *only* option to confirm this signal and discriminate it

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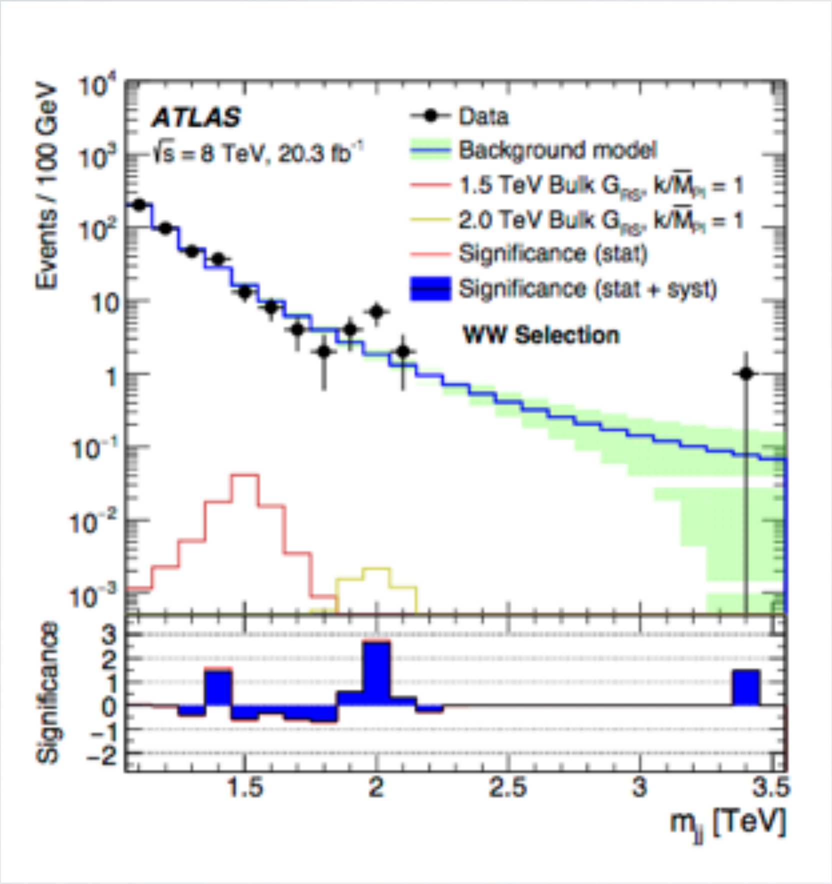

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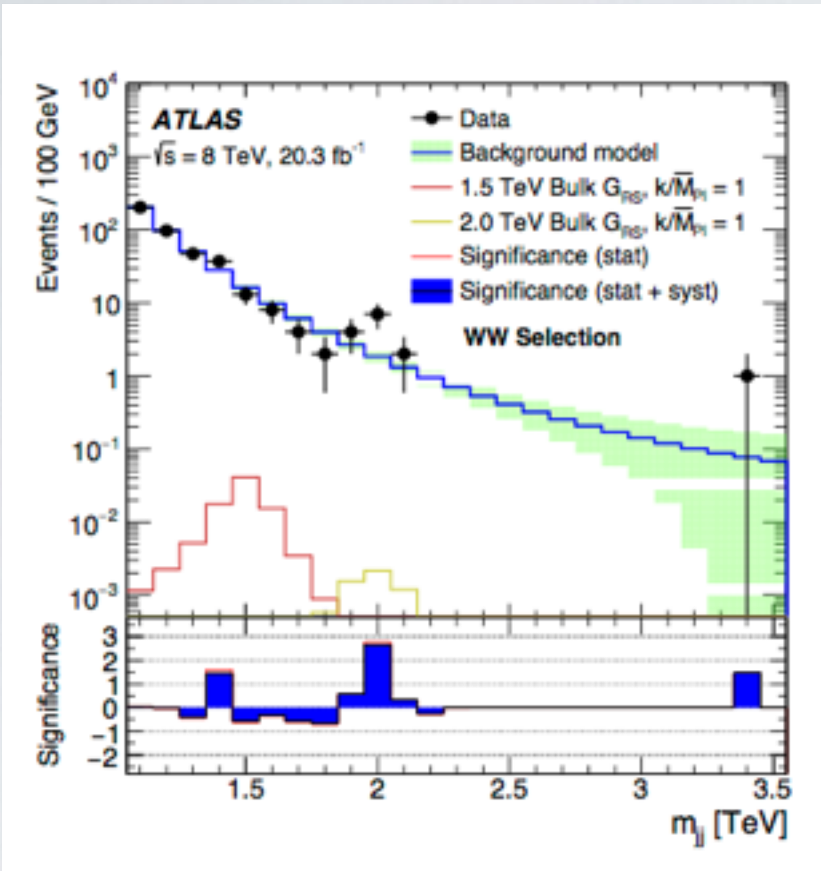

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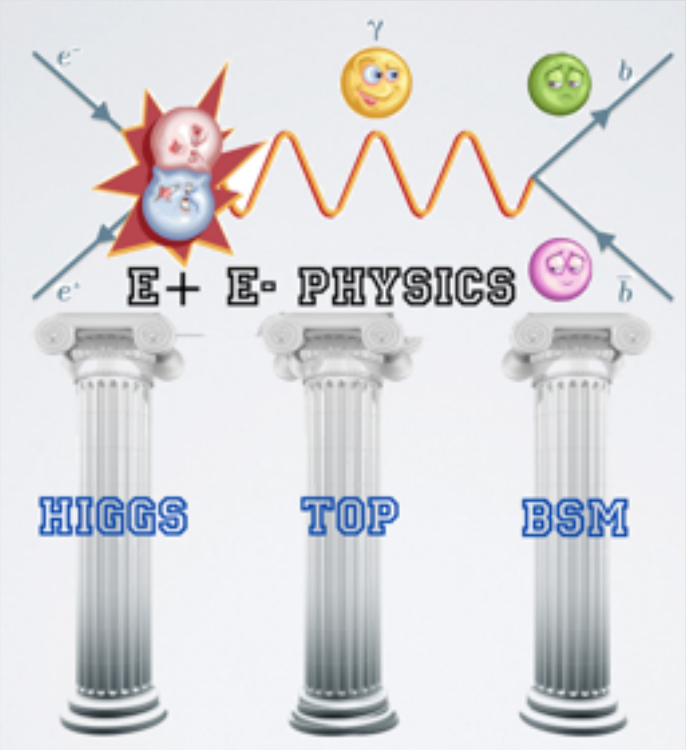
Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1] the LEP Electroweak Working Group,[2] the SLD Electroweak and Heavy Flavour Groups

data are also used to predict the mass of the top quark, $m_t = 173^{+13}_{-10}$ GeV, and the mass of the W boson, $m_W = 80.363 \pm 0.032$ GeV. These indirect constraints are compared to the direct measurements, providing a stringent test of the Standard Model. Using in addition the direct measurements of m_t and m_W, the mass of the as yet unobserved Standard Model Higgs boson is predicted with a relative uncertainty of about 50% and found to be less than 285 GeV at 95% confidence level.

Lessons and Homework



- e+ e- machines offers indispensable physics program e.g. 1506.05992
- Model-independent Higgs/top program: part of BSM program!
- Model-independent electroweak searches (no-lose theorem!)
- Dark Matter direct searches (lepton-hadron complementarity)
- e+e- ≳ 1 TeV surpass LHC for EW/NC searches
- Search for light electroweak particles not covered by LHC (e.g. tt recoil)
- e+e- resolves many LHC search constraints
- Mandatory for confirming/discriminating possibly unclear LHC discovery

FINAL HOMEWORK: put all this in a concise framework/document

let there be leptons
at the end of the tunnel ....