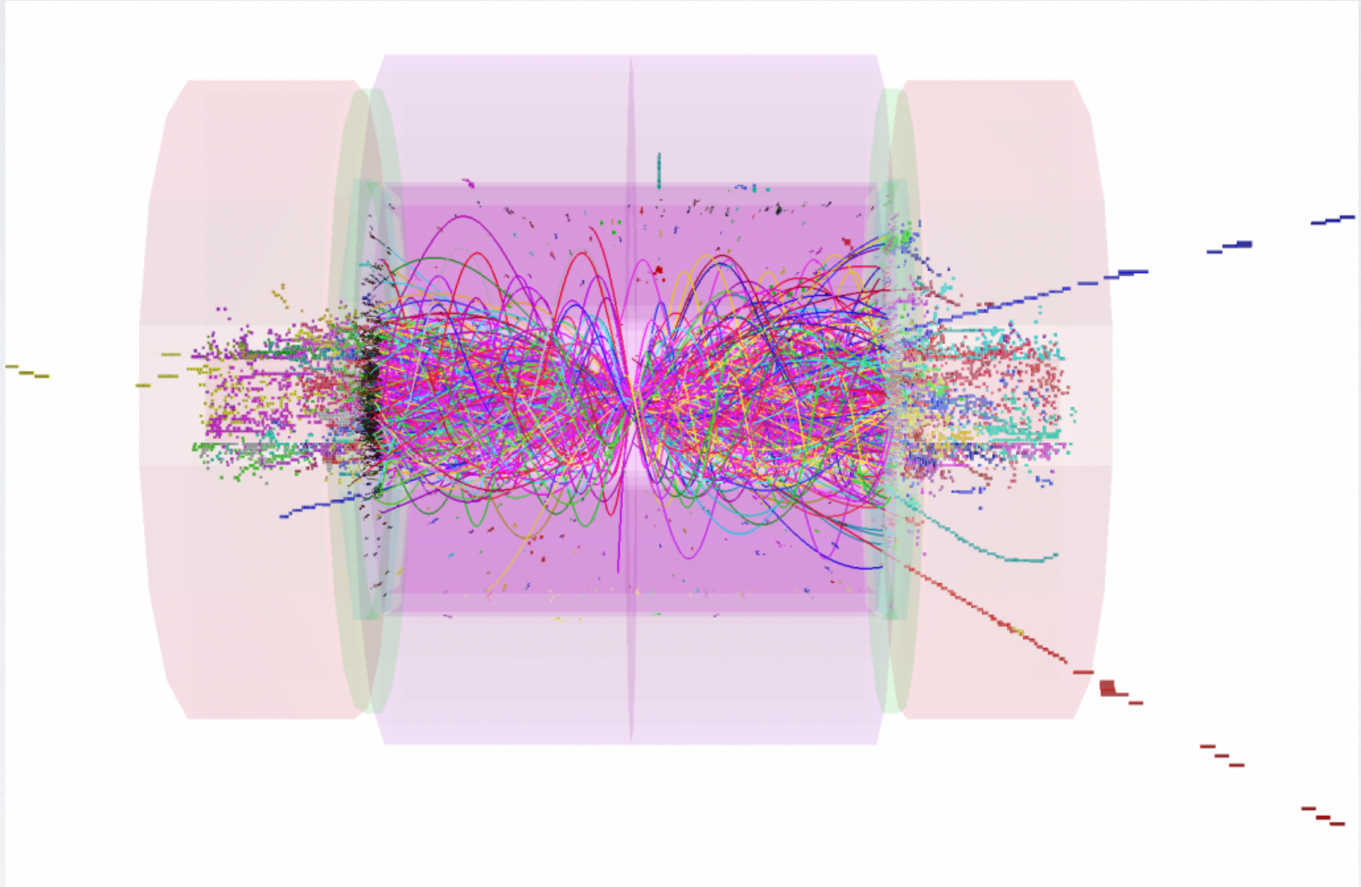
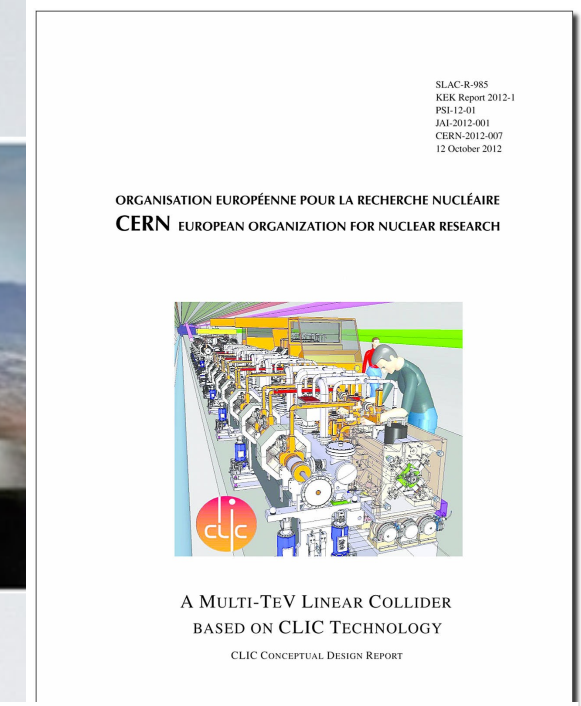
BSM Physics at High-Energy e^+e^- Colliders



Jürgen R. Reuter, DESY

Physics at High-Energy e+ e- Colliders



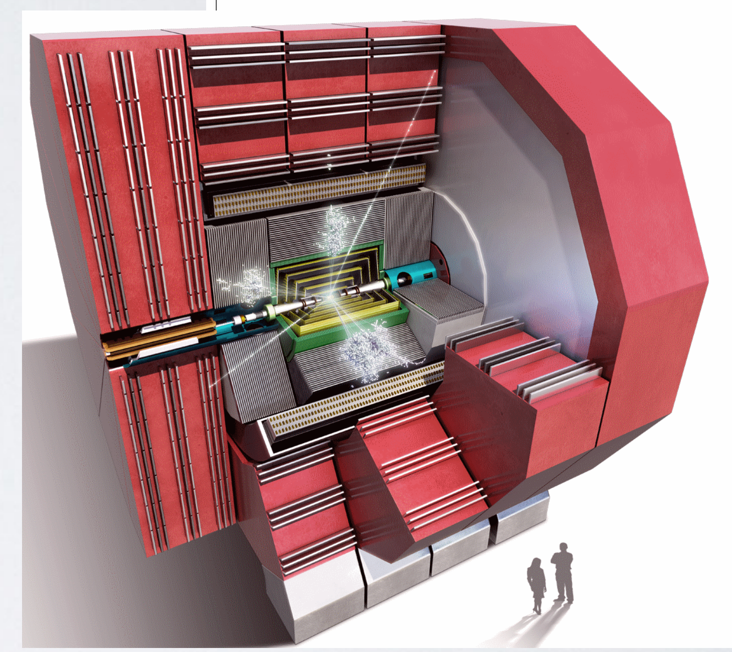
SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

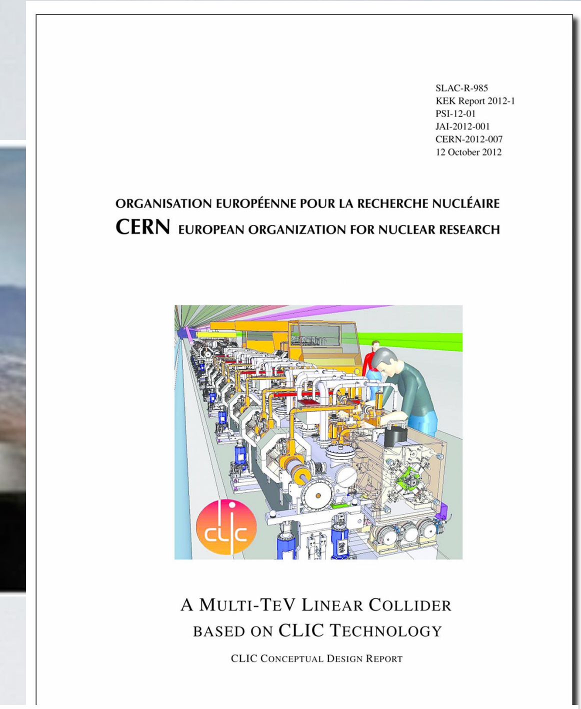
A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

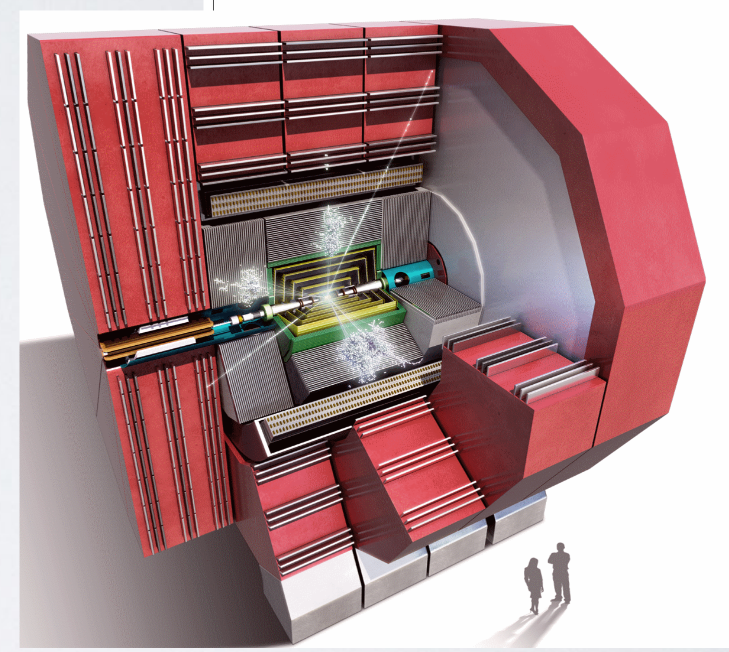
- High-energy e+ e- collider, c.m. energy: 200 GeV - 3000 GeV
- Polarisation: 80% e- and at least 30% e+
- Integrated Luminosity: 100-250-500 / fb / yr
- Experimental setup:
  - ✳ Well-defined initial state
  - ✳ Pure electroweak production (small theory errors)
  - ✳ Triggerless operation
- Physics programme: Higgs physics, top physics, Electroweak physics, QCD physics (jets, α_s, fragmentation), BSM searches
- Offers only possibility to scan over all states with EW quantum numbers in a certain range



Physics at High-Energy e+ e- Colliders



- High-energy e+ e- collider, c.m. energy: 200 GeV - 3000 GeV
- Polarisation: 80% e- and at least 30% e+
- Integrated Luminosity: 100-250-500 / fb / yr
- Experimental setup:
  - ✳ Well-defined initial state
  - ✳ Pure electroweak production (small theory errors)
  - ✳ Triggerless operation



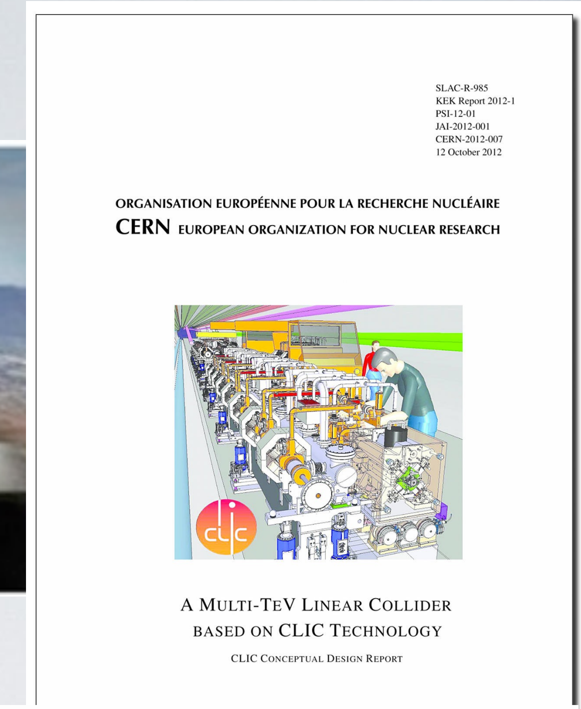
- Physics programme: Higgs physics, top physics, Electroweak physics, QCD physics (jets, α_s, fragmentation), BSM searches
- Offers only possibility to scan over all states with EW quantum numbers in a certain range

PROCEEDINGS OF THE WORKSHOP ON PHYSICS AT FUTURE ACCELERATORS

La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2} s^{-1}$)
LHC	pp	16	$10^{33} \to 10^{34}$
	ep	1.3	10^{32}
		1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \to 10^{34}$

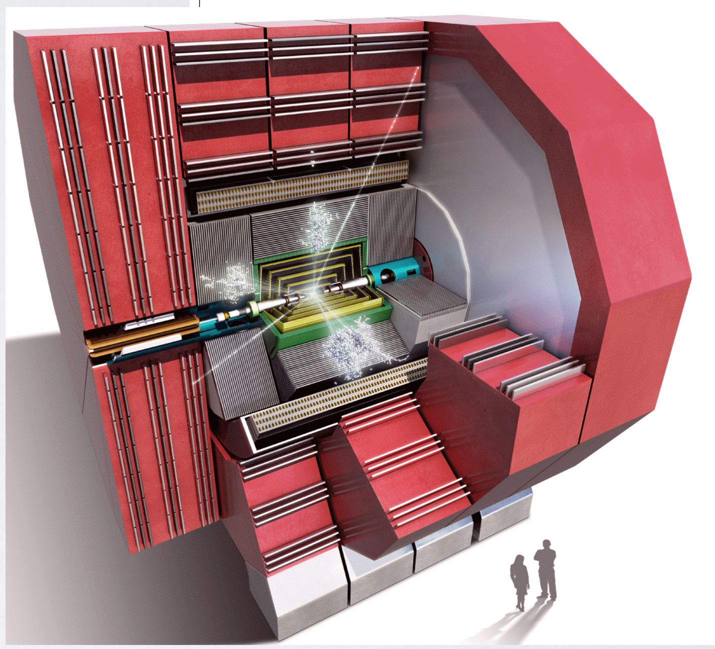
Physics at High-Energy e+ e- Colliders


SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

- High-energy e+ e- collider, c.m. energy: 200 GeV - 3000 GeV
- Polarisation: 80% e- and at least 30% e+
- Integrated Luminosity: 100-250-500 / fb / yr
- Experimental setup:
  - ✳ Well-defined initial state
  - ✳ Pure electroweak production (small theory errors)
  - ✳ Triggerless operation



- Physics programme: Higgs physics, top physics, Electroweak physics, QCD physics (jets, α_s, fragmentation), BSM searches
- Offers only possibility to scan over all states with EW quantum numbers in a certain range

PROCEEDINGS OF THE WORKSHOP ON PHYSICS AT FUTURE ACCELERATORS

La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2} s^{-1}$)
LHC	pp	16	$10^{33} \to 10^{34}$
LHC	ep	1.3	10^{32}
		1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \to 10^{34}$

Opportunities and Requirements for Experimentation at a Very High Energy e^+e^- Collider
May 1988

The Virtue of Lepton Beams / Colliders

(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*

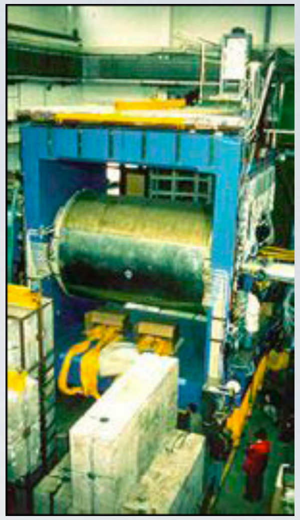
The Virtue of Lepton Beams / Colliders

(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*

A) Deep Inelastic Scattering: 1969,
SLAC: **QCD/Quark Substructure**
(e^- beams)

The Virtue of Lepton Beams / Colliders

(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*



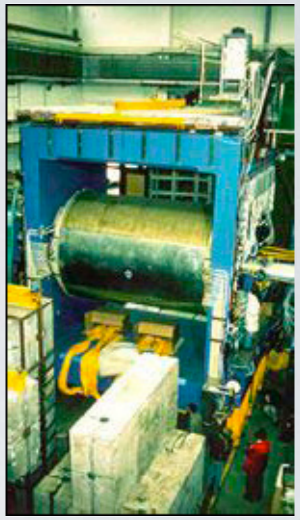
A') e+ e- → jets: 1979

DESY: **QCD Force Carrier**

($e^- e^+$ beams)

The Virtue of Lepton Beams / Colliders

(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*



A') e+ e- → jets: 1979

DESY: **QCD Force Carrier**

($e^- e^+$ beams)

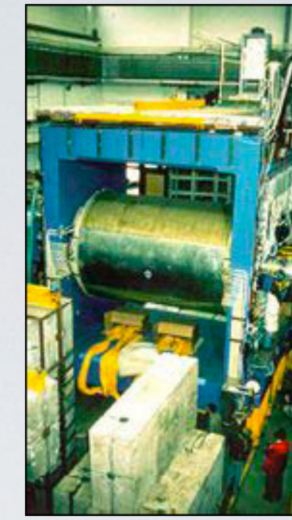
B) Neutral currents: 1973, Gargamelle,

CERN: **Weak Gauge Structure**

(ν_μ beams)

The Virtue of Lepton Beams / Colliders

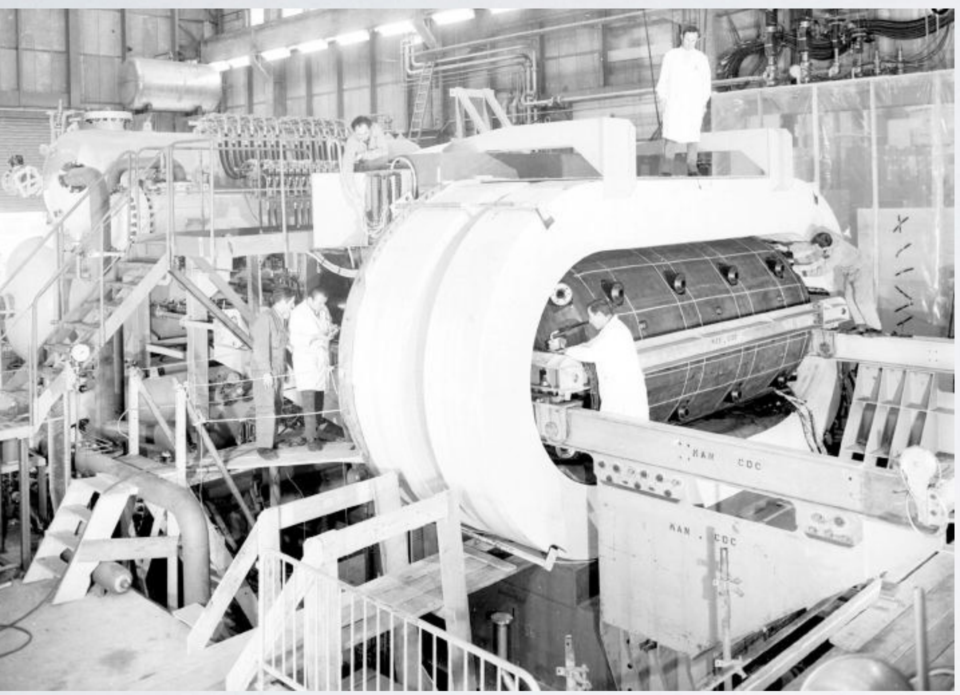
(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*



A') e+ e- → jets: 1979

DESY: **QCD Force Carrier**

($e^- e^+$ beams)



B) Neutral currents: 1973, Gargamelle,

CERN: **Weak Gauge Structure**

(ν_μ beams)

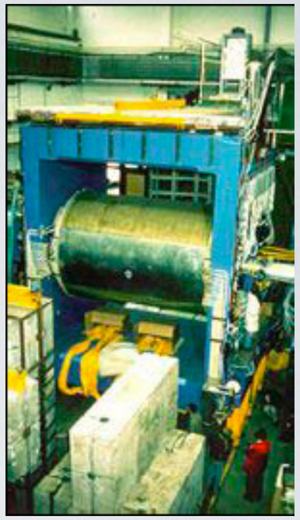
C) Charm/tau discovery: 1974/76

SLAC: **SM flavor structure**

($e^- e^+$ beams)

The Virtue of Lepton Beams / Colliders

(FALSE) PARADIGM: *"Hadron colliders are discovery machines, lepton colliders are precision machines."*



A') e+ e- → jets: 1979
DESY: **QCD Force Carrier**
($e^- e^+$ beams)

B) Neutral currents: 1973, Gargamelle,
CERN: **Weak Gauge Structure**
(ν_μ beams)

C') Bottom oscillations: 1987
DESY: **Top Quark mass**
($e^- e^+$ beams)

“Minimum Bias” BSM physics

- No obvious guideline for New Physics:
  compared to W/Z, top or Higgs searches
- Several possible paths:

“Minimum Bias” BSM physics

- No obvious guideline for New Physics:
  compared to W/Z, top or Higgs searches
- Several possible paths:

★ Electroweak sector: spontaneously broken gauge sector (still unexplored)
★ Is there a Higgs sector ? Is the Higgs *the Higgs* ? [Higgs potential tomography]
★ Are there any particles with EW quantum numbers in a certain energy range?
★ Flavor sector: connection to the High-energy frontier ?
★ Existence of new neutral or charged currents ?
★ Is there a collider connection to the baryon asymmetry ?
★ Is there a collider connection to the Dark Matter sector ?
★ Do gauge interactions unify?
★ Is there a new layer of matter (a.k.a. compositeness) ?
★ Are there new symmetries (global, super, space-time) ?

“Minimum Bias” BSM physics

- No obvious guideline for New Physics:
  compared to W/Z, top or Higgs searches
- Several possible paths:

★ Electroweak sector: spontaneously broken gauge sector (still unexplored)
★ Is there a Higgs sector ? Is the Higgs *the Higgs* ? [Higgs potential tomography]
★ Are there any particles with EW quantum numbers in a certain energy range?
★ Flavor sector: connection to the High-energy frontier ?
★ Existence of new neutral or charged currents ?
★ Is there a collider connection to the baryon asymmetry ?
★ Is there a collider connection to the Dark Matter sector ?
★ Do gauge interactions unify?
★ Is there a new layer of matter (a.k.a. compositeness) ?
★ Are there new symmetries (global, super, space-time) ?

Make best possible use of LHC data (historical hadron-lepton collider duality:
SPEAR+DORIS/AGS, PETRA+PEP/AGS+SPS, SppS/SLC+LEP I, Tevatron/LEP II

High-energy e+e- only option of re-confirmation and diagnosis of LHC discoveries

Paradigmatic Standard Candle Telescopes

3 main pillars of e+e- physics:

1. Higgs Physics
   ↪ Heidi Rzehak's talk
2. Top Physics

3. BSM Physics
   ("direct searches")

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

Paradigmatic Standard Candle Telescopes

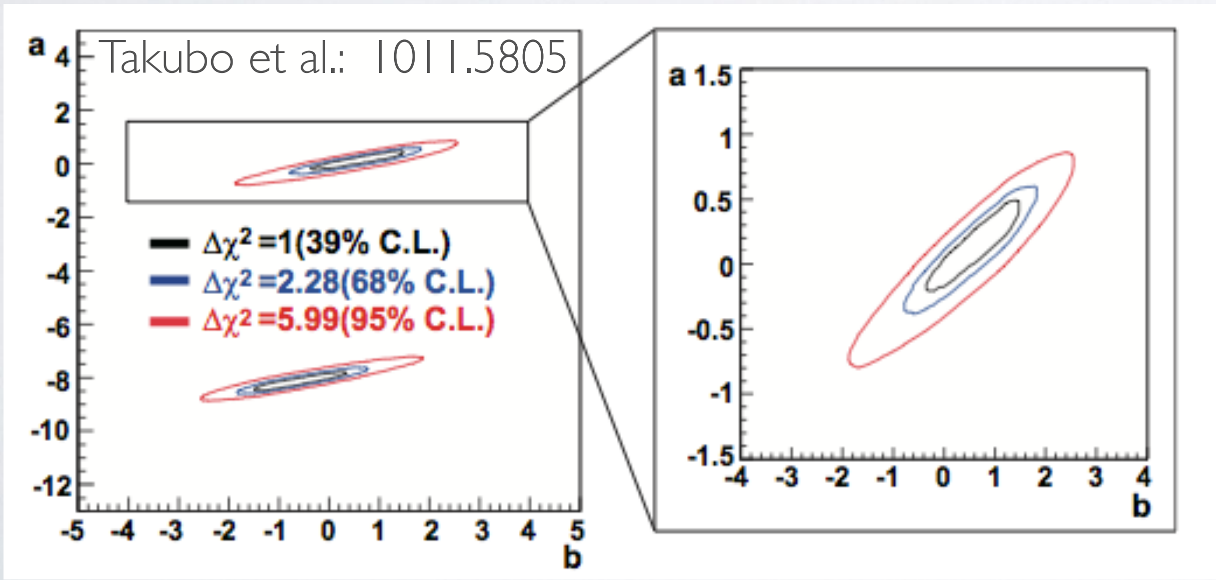
3 main pillars of e+e- physics:

1. Higgs Physics
   ↪ Heidi Rzehak's talk
2. Top Physics
3. BSM Physics
   ("direct searches")

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

Search for anomalous Higgs couplings

$$\mathcal{L}_{hWW} = 2m_W^2 \left(\frac{1}{v} + \frac{a}{\Lambda}\right) h W_\mu^+ W^{\mu,-} + \frac{b}{\Lambda} W_{\mu\nu}^+ W^{\mu\nu,-}$$



Paradigmatic Standard Candle Telescopes

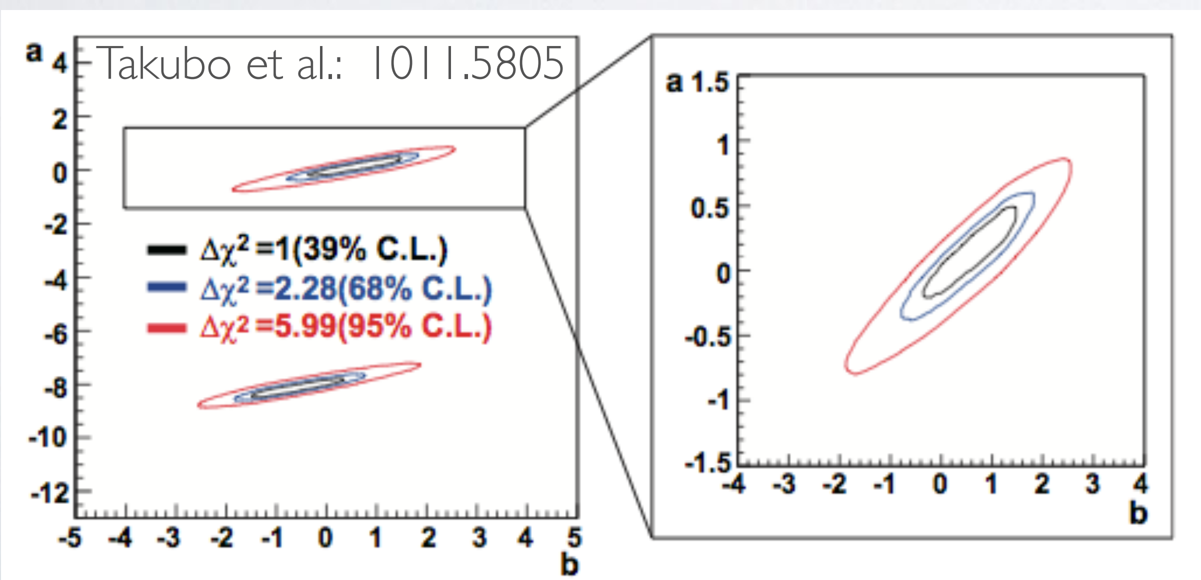
3 main pillars of e+e- physics:

1. Higgs Physics
   ↪ Heidi Rzehak's talk
2. Top Physics
3. BSM Physics
   ("direct searches")

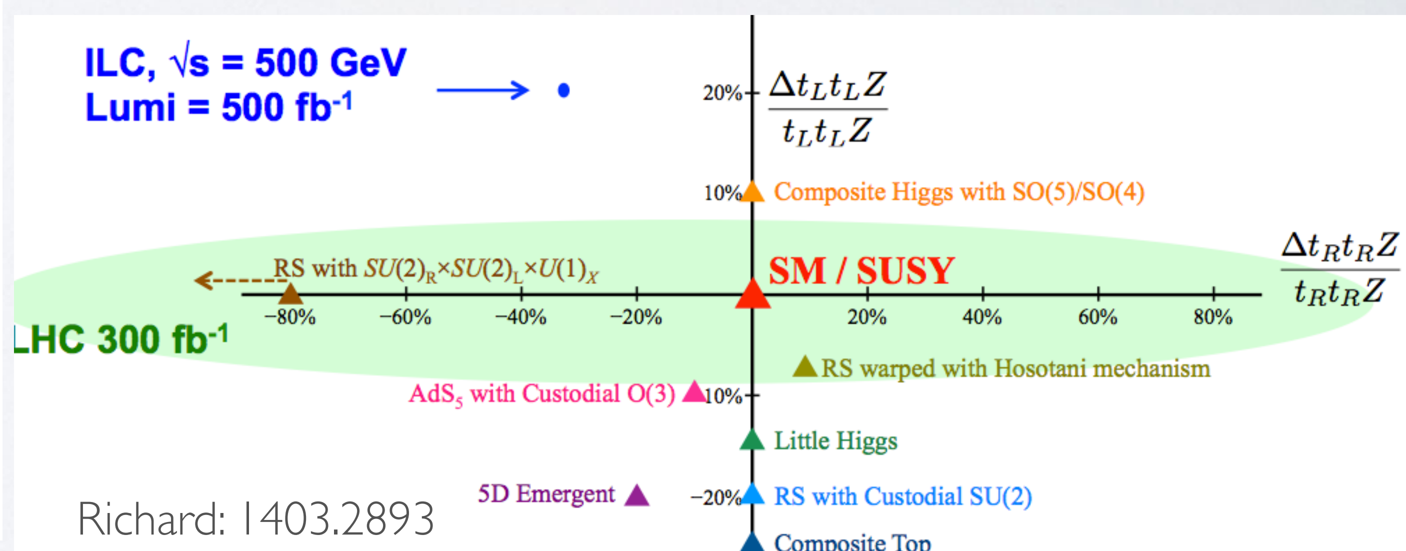
Standard (Model) candles can be used as Telescopes for [indirect] BSM searches

Search for anomalous Higgs couplings

$$\mathcal{L}_{hWW} = 2m_W^2 \left(\frac{1}{v} + \frac{a}{\Lambda}\right) h W_\mu^+ W^{\mu,-} + \frac{b}{\Lambda} W_{\mu\nu}^+ W^{\mu\nu,-}$$



Anomalous Top couplings as BSM probes



Dark Matter Searches

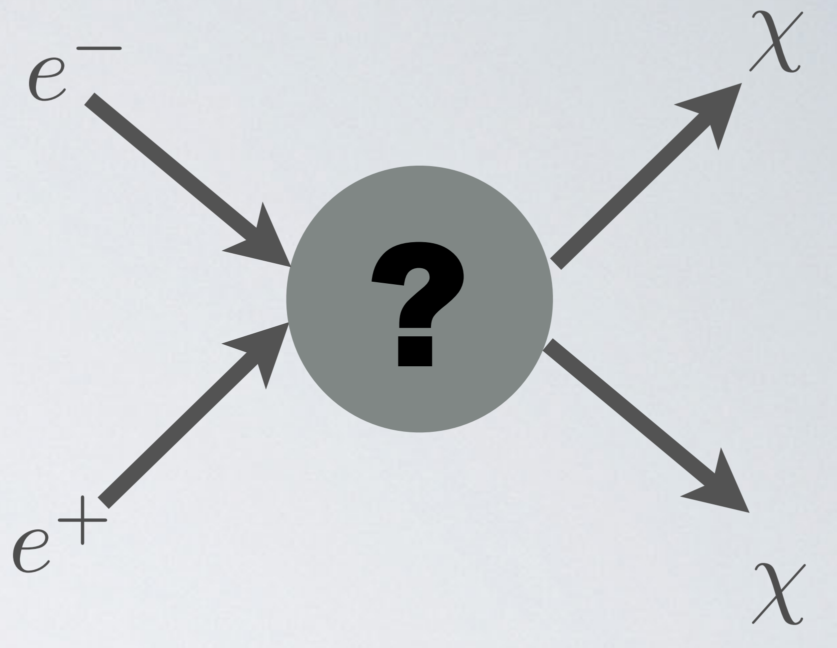
↪ Itay Yavin's talk

- 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 → $\nu\nu\gamma$,

  ee → eeγ with ee lost in the beampipe
- Polarisation to suppress backgrounds: *W* exchange killed a lot by P(e+,e-)

Bartels/Berggren/List: arXiv: 1206.6639



Dark Matter Searches

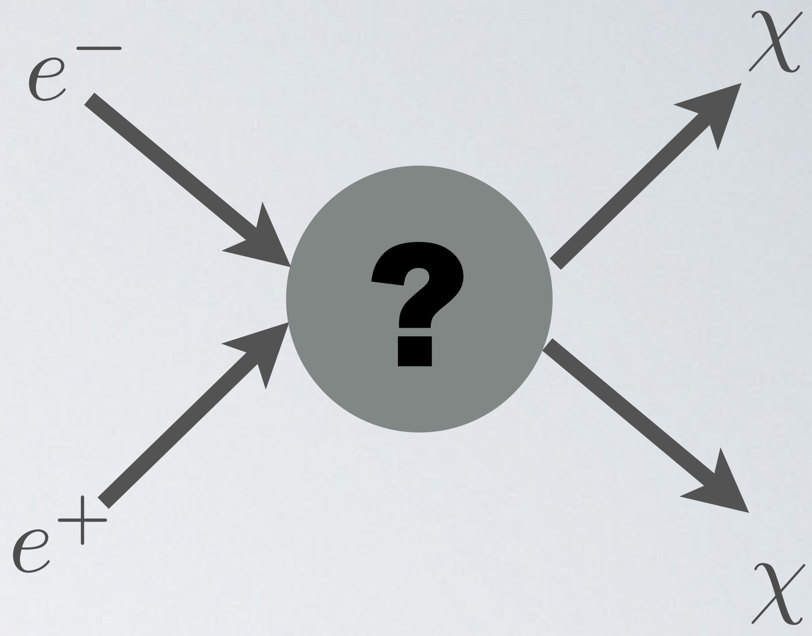
↪ Itay Yavin's talk

- Assumption: weakly interacting particle χ
- ee → χχ invisible, use bremsstrahlung:

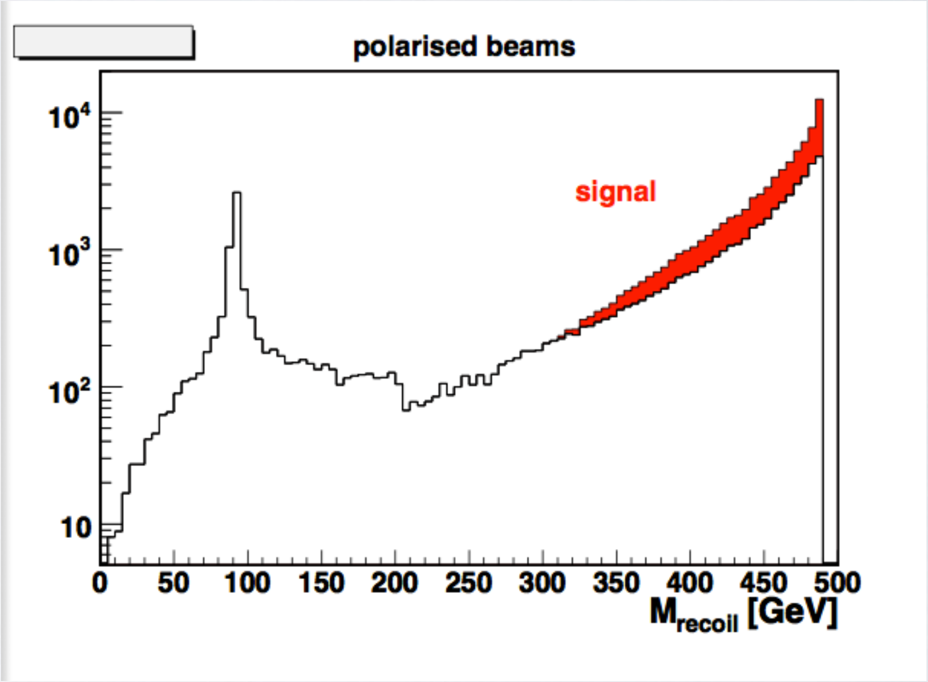
  ee → χχγ (analogous to LHC: pp → χχj)
- Irreducible backgrounds: ee → ννγ,

  ee → eeγ with ee lost in the beampipe
- Polarisation to suppress backgrounds: *W* exchange killed

  a lot by P(e+,e-) Bartels/Berggren/List: arXiv: 1206.6639



- Veto from low-angle calorimeter hits against radiative Bhabha
- **Search for signals in the photon recoil spectrum**



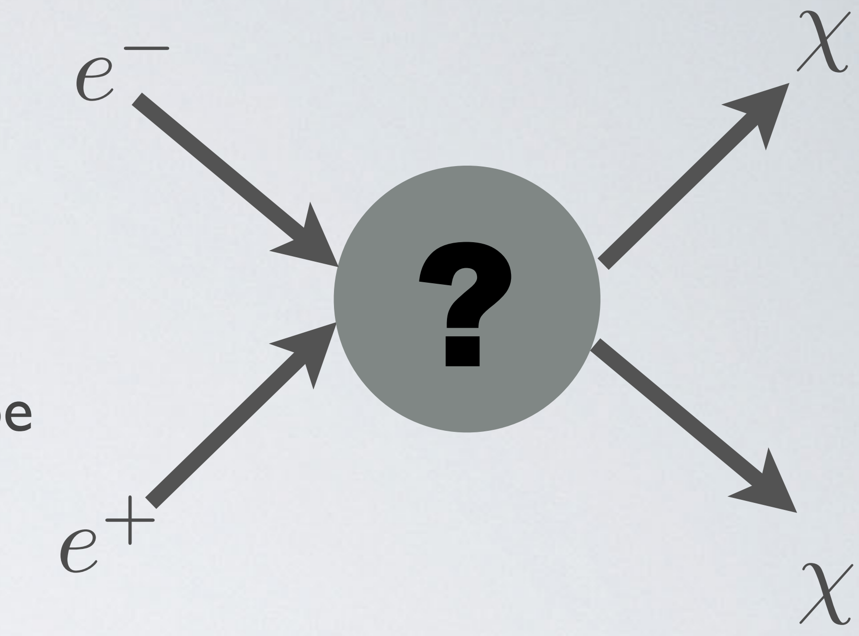
Dark Matter Searches

↪ Itay Yavin's talk

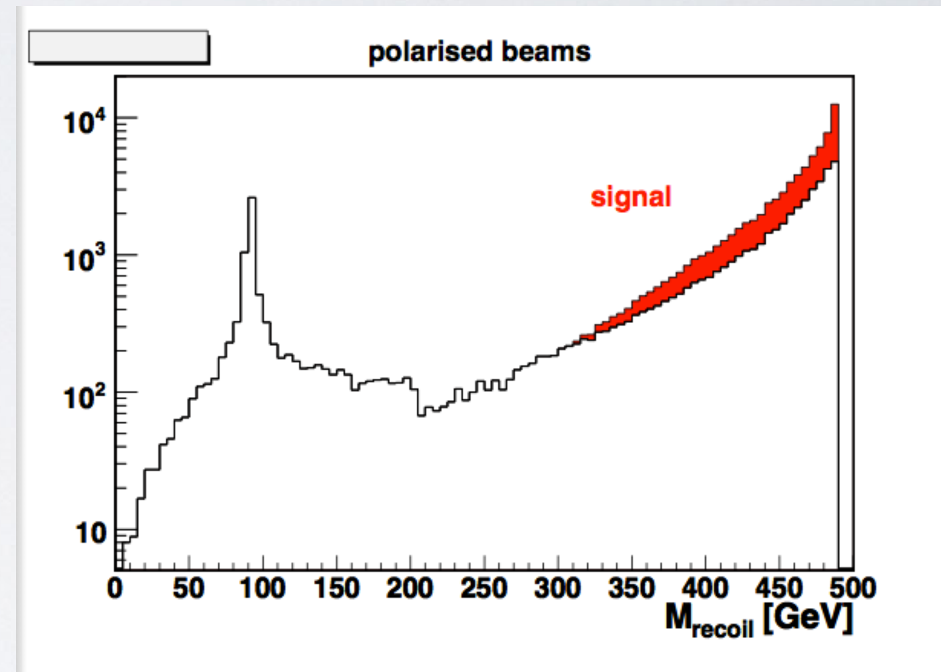
- Assumption: weakly interacting particle χ
- ee → χχ invisible, use bremsstrahlung:

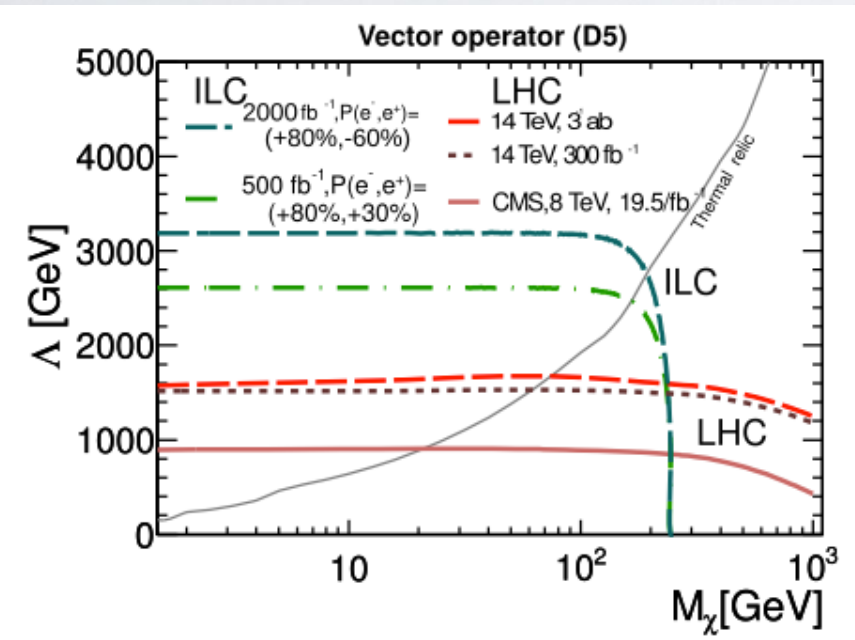
  ee → χχγ (analogous to LHC: pp → χχj)
- Irreducible backgrounds: ee → ννγ,

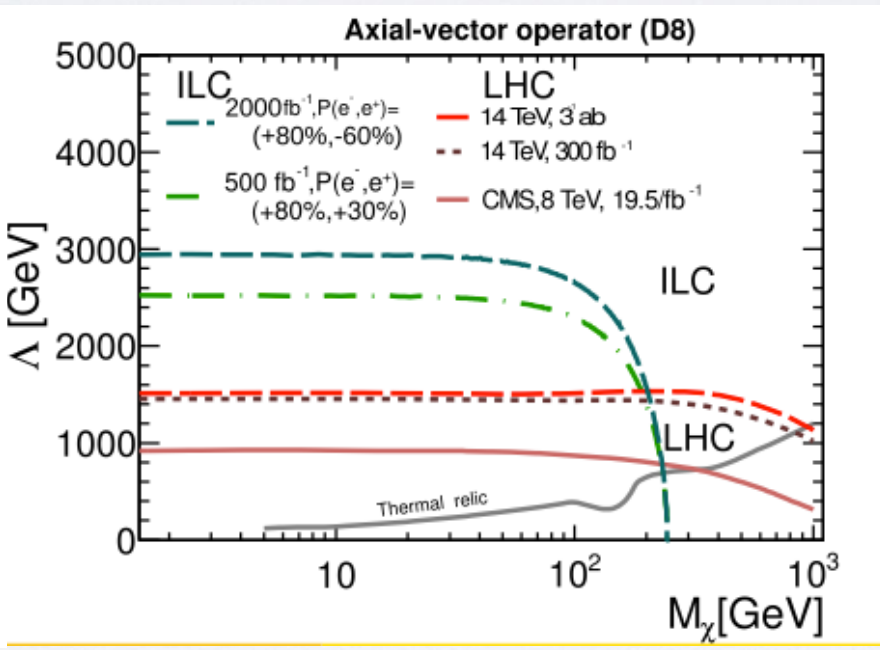
  ee → eeγ with ee lost in the beampipe
- Polarisation to suppress backgrounds: *W* exchange killed a lot by P(e+,e-) Bartels/Berggren/List: arXiv: 1206.6639



- Veto from low-angle calorimeter hits against radiative Bhabha
- **Search for signals in the photon recoil spectrum**







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

LHC accesses higher masses, TeV e+e- lower cross sections (few caveats)

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

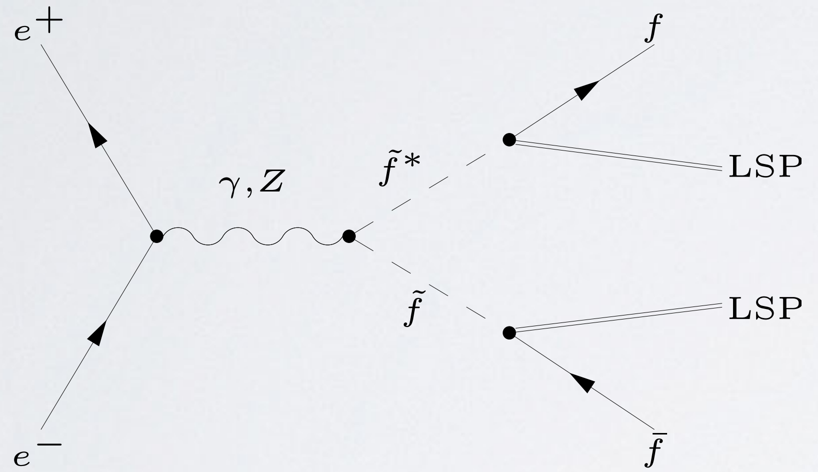
Model-Independent Electroweak Searches

- 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

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

  $\tilde{\tau}_1$ NLSP min. χsec

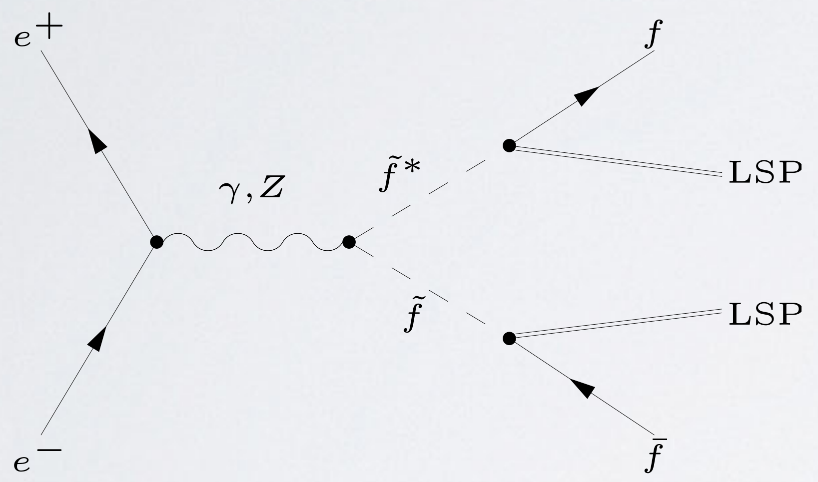
Berggren, arXiv:1308.1461



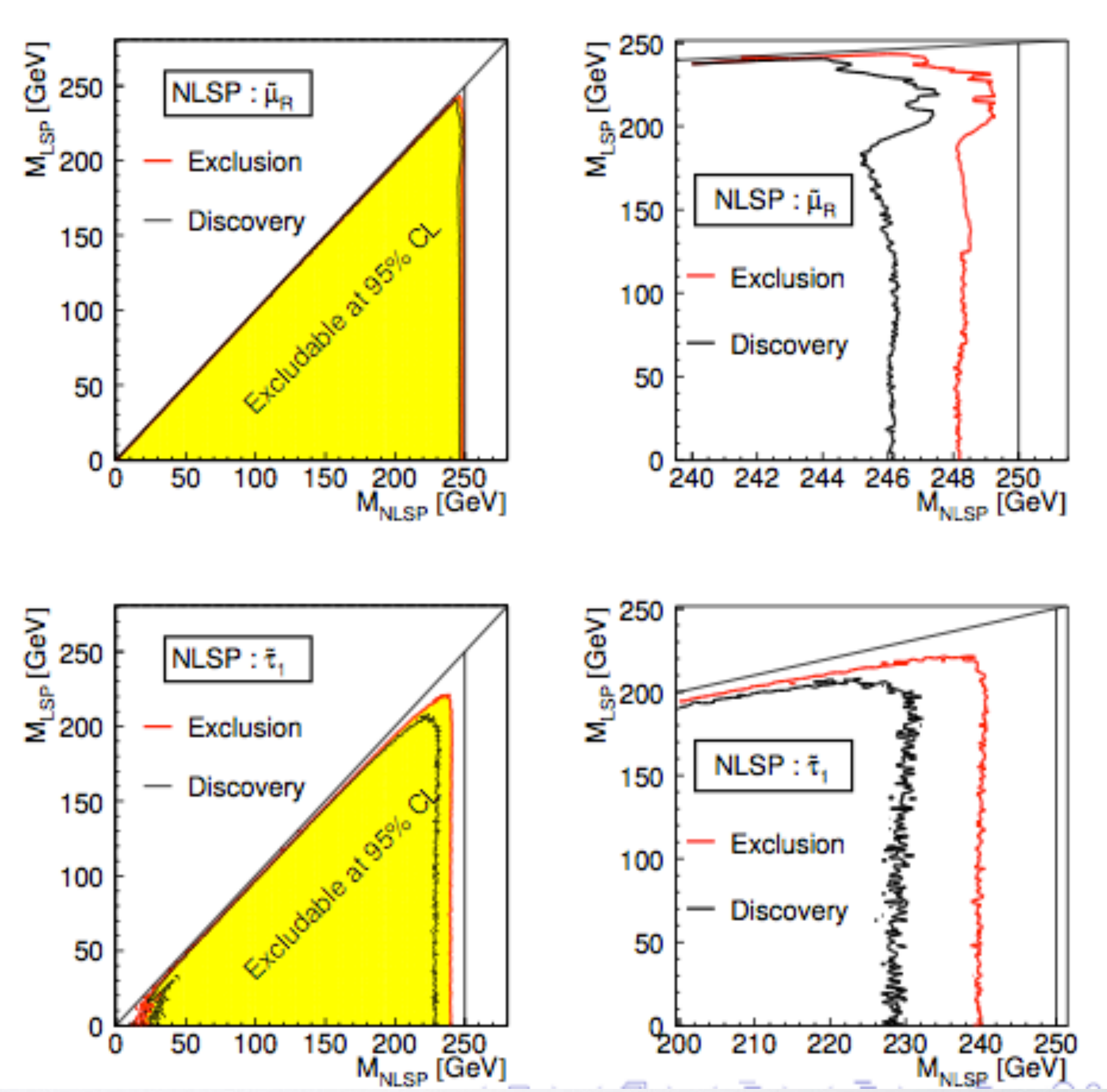
Model-Independent Electroweak Searches

- 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
  $M_{\text{NLSP}} - M_{\text{LSP}}$ plane
- Examples: $\tilde{\mu}_R$ NLSP
  $\tilde{\tau}_1$ NLSP min. χsec

Berggren, arXiv:1308.1461

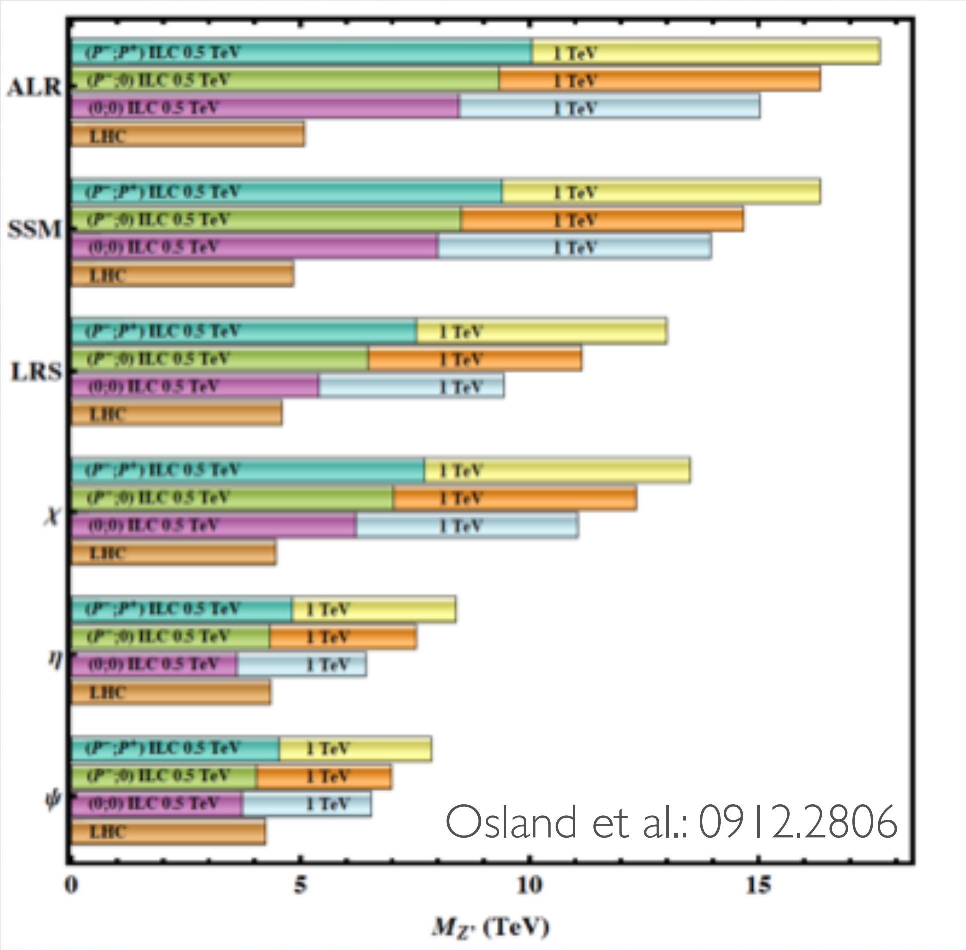


Discover/exclude close to kinematical limit



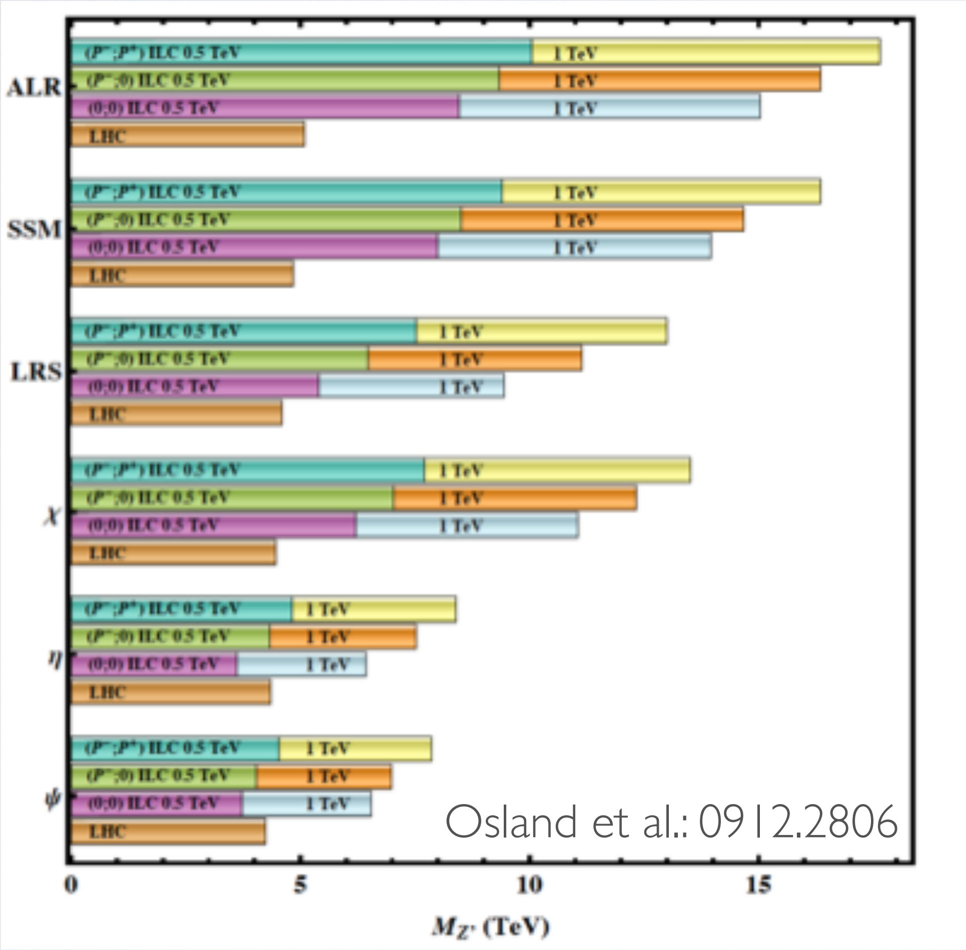
New Neutral Currents: *Z'* searches

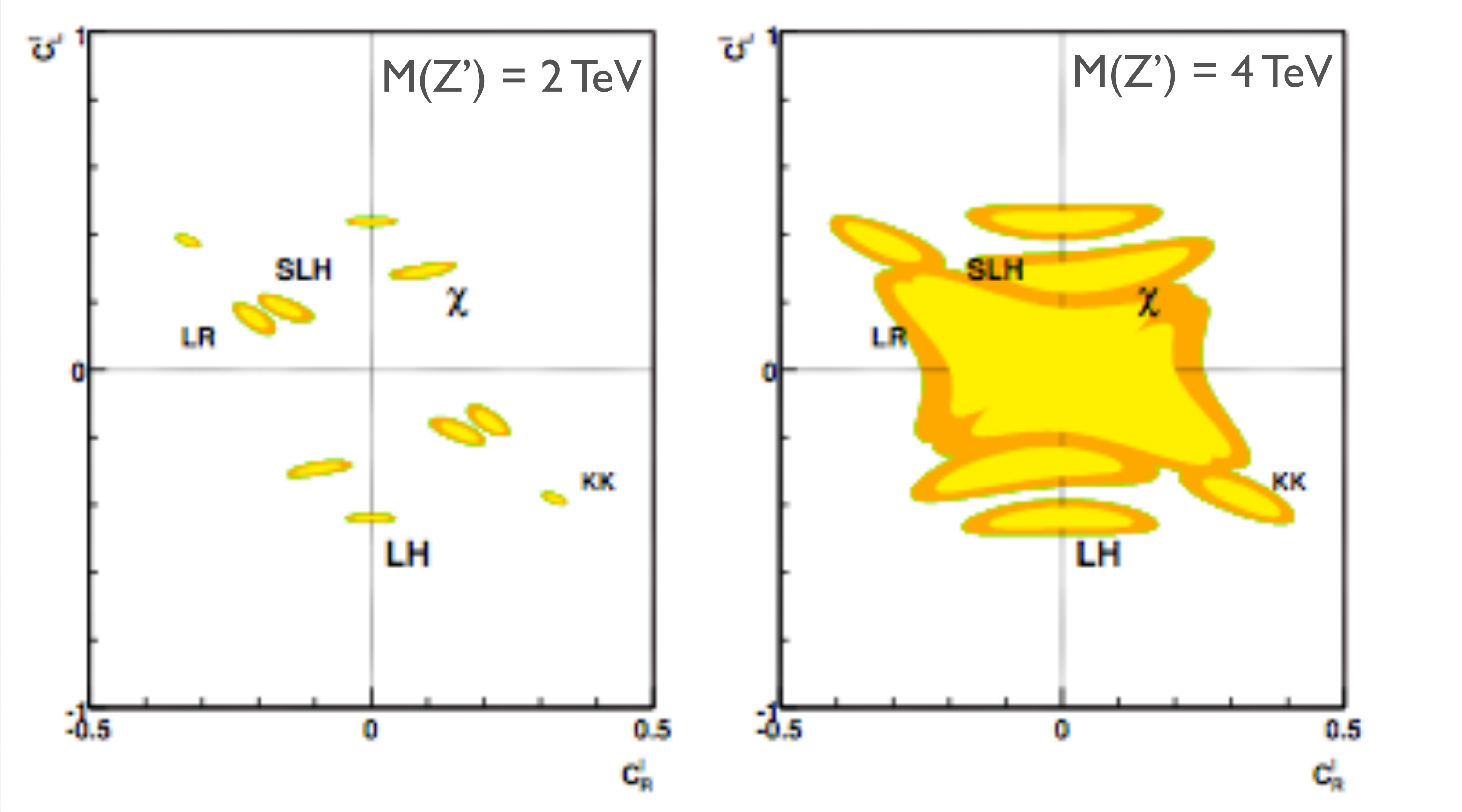
- ★ Neutral current paved path to understanding gauge structure of the SM
- ★ Promising way to go beyond: many GUT models predict additional neutral currents (Z')
- ★ High-precision high-energy e+e- measurements allows model discrimination
- ★ Access to scales up to several tens of TeV!!



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 high-energy e+e- measurements allows model discrimination
- ★ Access to scales up to several tens of TeV!!

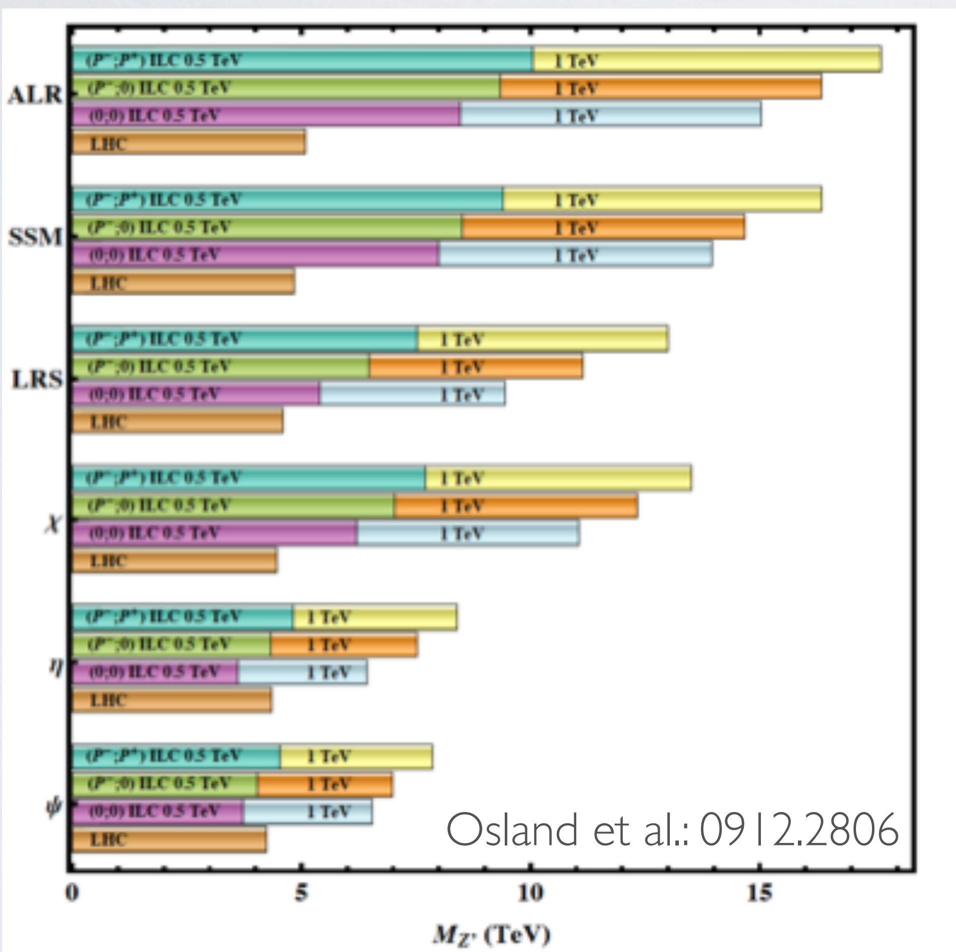


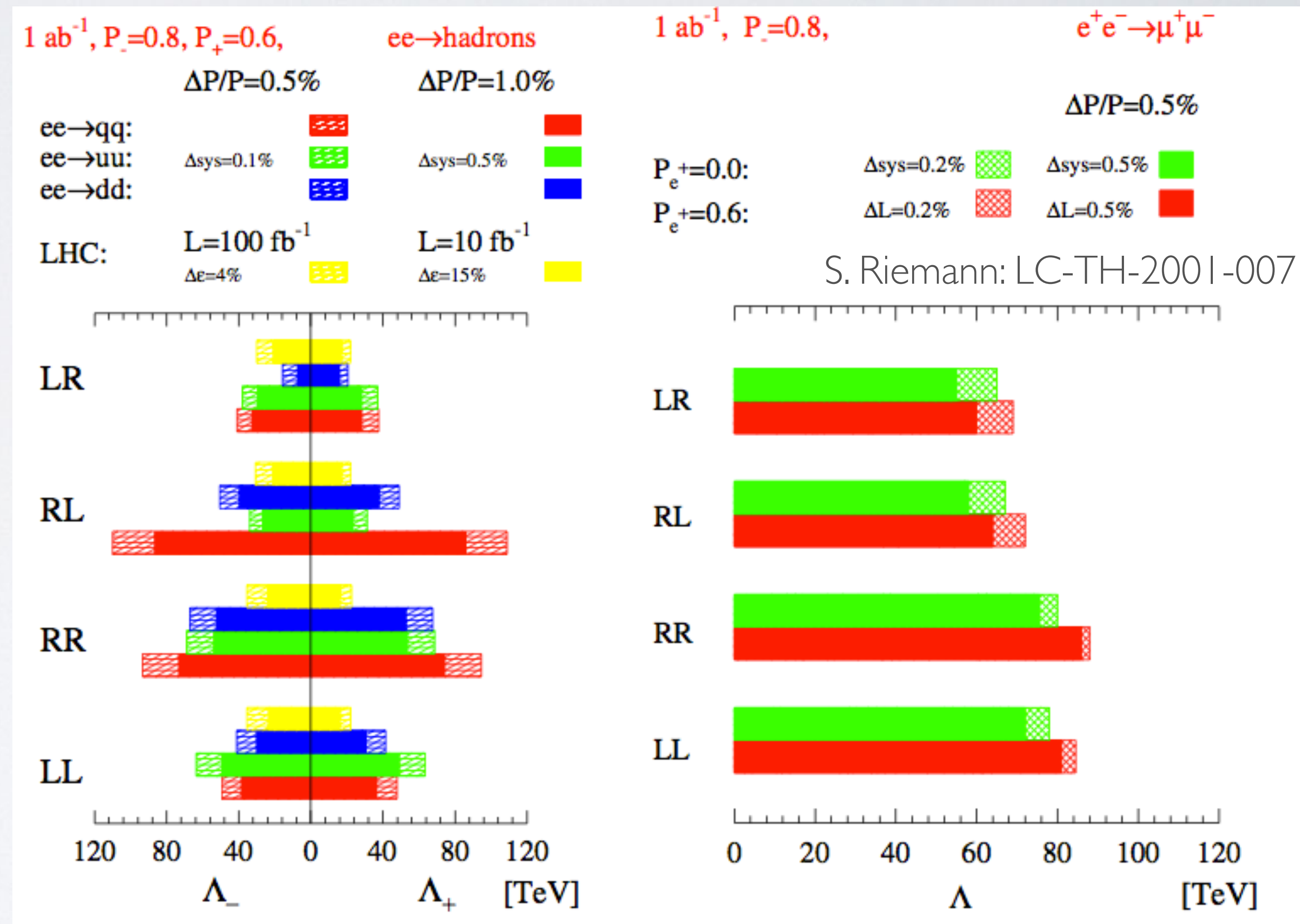


Godfrey/Kalyniak/Tomkins: 0511335

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 high-energy e+e- measurements allows model discrimination
- ★ Access to scales up to several tens of TeV!!





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

High-Energy Electroweak Sector

- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Longrightarrow$ Higgs physics, trilinear Higgs etc.)
- Dynamics of electroweak interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Processes: Dibosons, Tribosons, Vector Boson Fusion, Vector Boson Scattering
- By vector bosons EW bosons are meant, not the photon (though generally higher rate)
- Existing studies assume: $\mathcal{P}(e^-) = 80 - 90\%$ $\mathcal{P}(e^+) = 30 - 60\%$

High-Energy Electroweak Sector

- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Longrightarrow$ Higgs physics, trilinear Higgs etc.)
- Dynamics of electroweak interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Processes: Dibosons, Tribosons, Vector Boson Fusion, Vector Boson Scattering
- By vector bosons EW bosons are meant, not the photon (though generally higher rate)
- Existing studies assume: $\mathcal{P}(e^-) = 80 - 90\%$ $\mathcal{P}(e^+) = 30 - 60\%$
  - ⋆ longitudinal polarization of beams: *(V-A)* couplings of *W/Z*
  - ⋆ e_L and e_R different multiplets $\Rightarrow$ access completely different couplings

High-Energy Electroweak Sector

- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Longrightarrow$ Higgs physics, trilinear Higgs etc.)
- Dynamics of electroweak interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Processes: Dibosons, Tribosons, Vector Boson Fusion, Vector Boson Scattering
- By vector bosons EW bosons are meant, not the photon (though generally higher rate)
- Existing studies assume: $\mathcal{P}(e^-) = 80 - 90\%$ $\mathcal{P}(e^+) = 30 - 60\%$
  - ★ longitudinal polarization of beams: *(V-A)* couplings of *W/Z*
  - ★ e_L and e_R different multiplets $\Rightarrow$ access completely different couplings

Exploration of E-frontier →look for heavy objects, including high-mass $V_L V_L$ scattering:
❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

F. Gianotti, CLIC Workshop, CERN, 02/2014

High-Energy Electroweak Sector

- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Longrightarrow$ Higgs physics, trilinear Higgs etc.)
- Dynamics of electroweak interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Processes: Dibosons, Tribosons, Vector Boson Fusion, Vector Boson Scattering
- By vector bosons EW bosons are meant, not the photon (though generally higher rate)
- Existing studies assume: $\mathcal{P}(e^-) = 80 - 90\%$ $\mathcal{P}(e^+) = 30 - 60\%$

  ★ longitudinal polarization of beams: *(V-A)* couplings of *W/Z*
  ★ e_L and e_R different multiplets $\Rightarrow$ access completely different couplings

Exploratio
❑ require

attering:
/s)

orkshop, CERN, 02/2014

$$\sigma(e^+e^- \to VVV) \propto \frac{1}{s}$$

Limits usefulness to subprocess energies in the lower range where cross section of fusion process still small

$$\sigma_{\mathrm{VBS}}(e^+e^- \to \nu\bar{\nu}W^+W^-) \propto \log(s)$$

$$e^+e^- \to ZZZ$$
$$\to WWZ$$

ZH $\hookrightarrow WW$ $\hookrightarrow ZZ$ — Present in spectrum

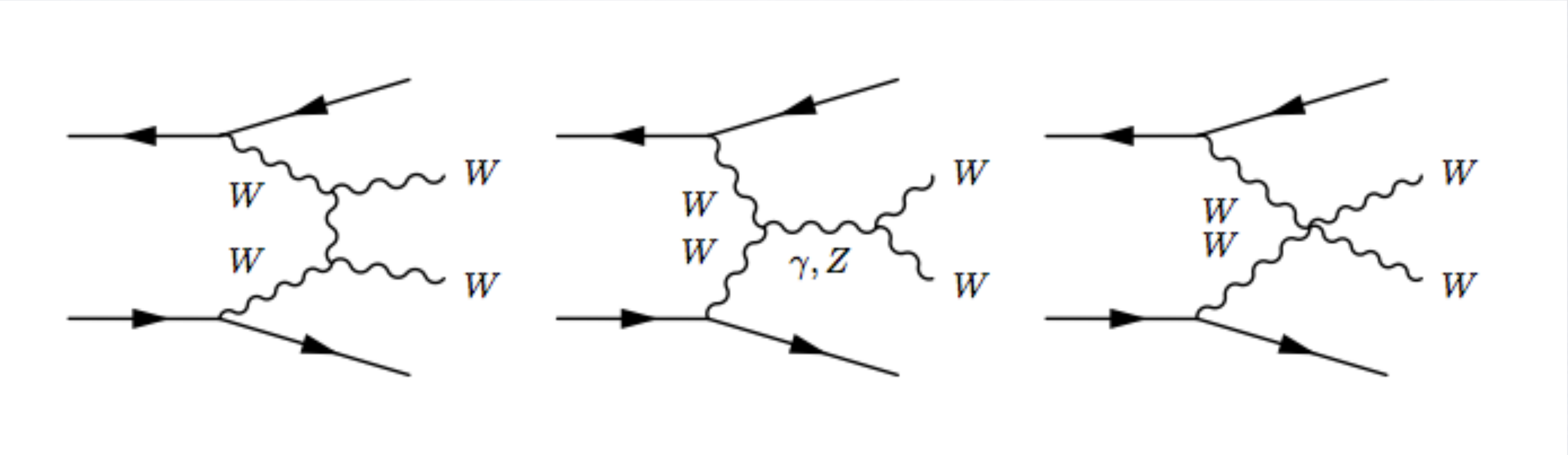
$$\to WW\gamma$$

Complementary (and present at lower energies)

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

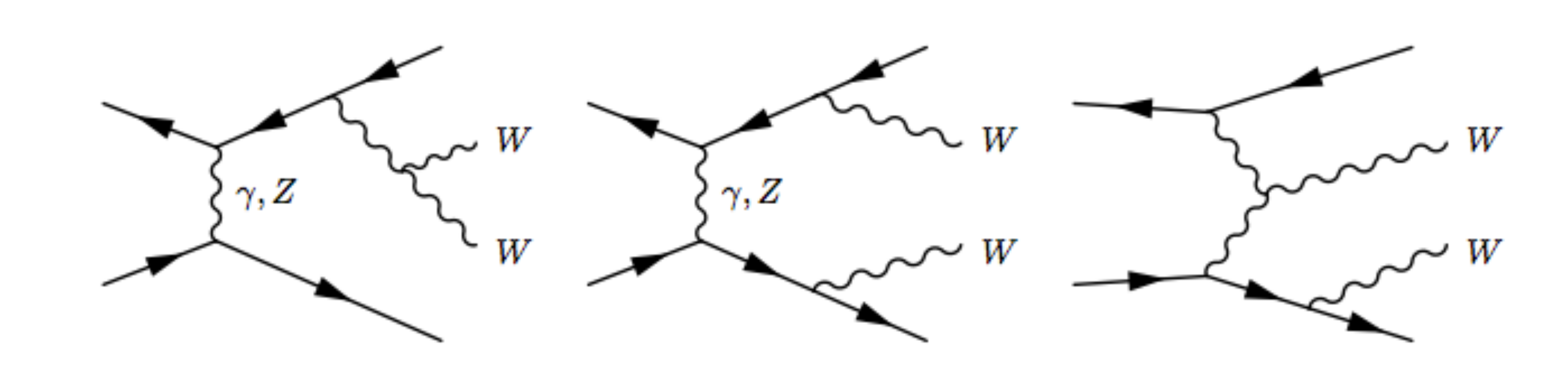
Signal



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

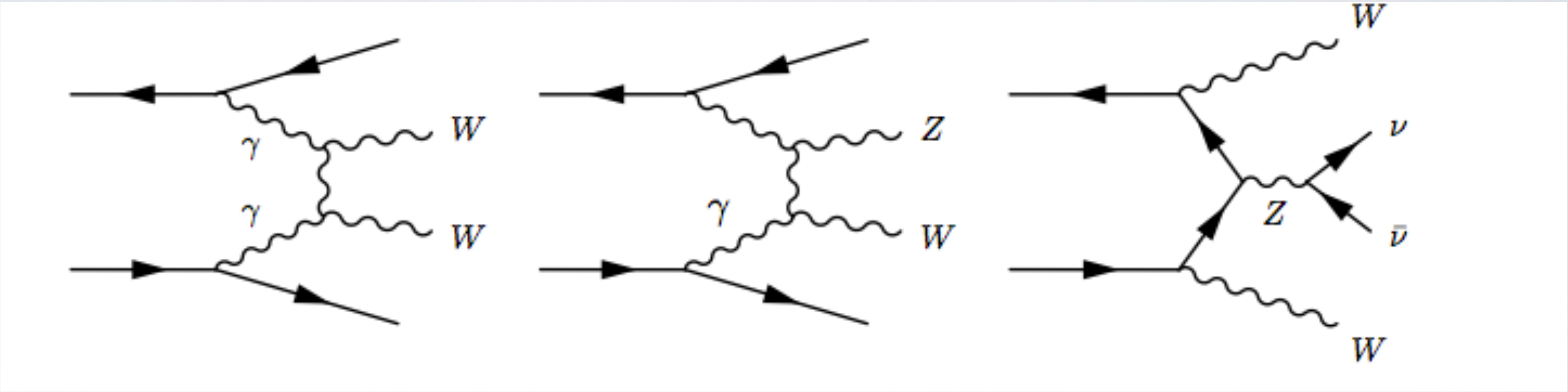
Irreducible Background



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

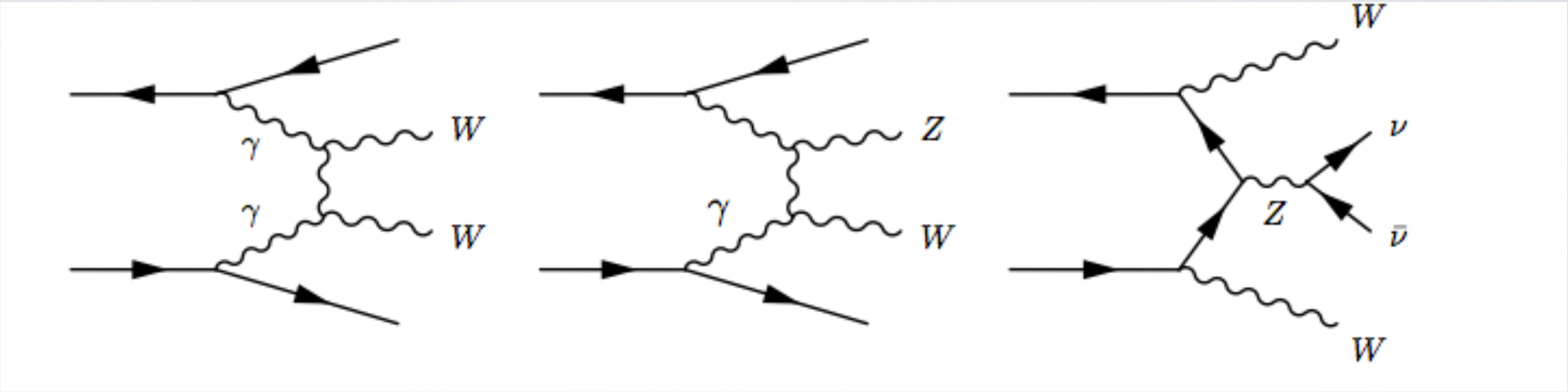
(Partially) reducible Background



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

(Partially) reducible Background

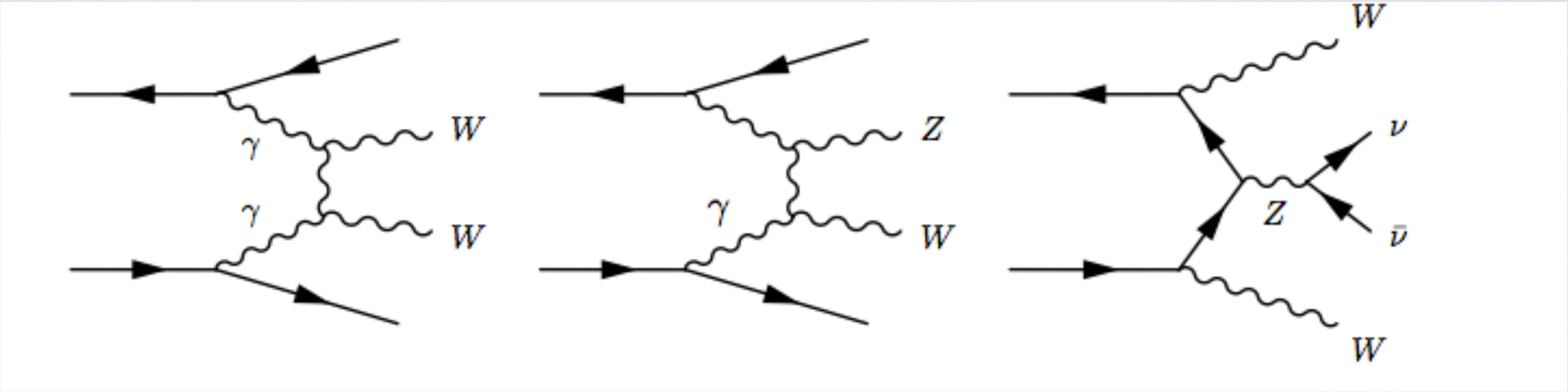


Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	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

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

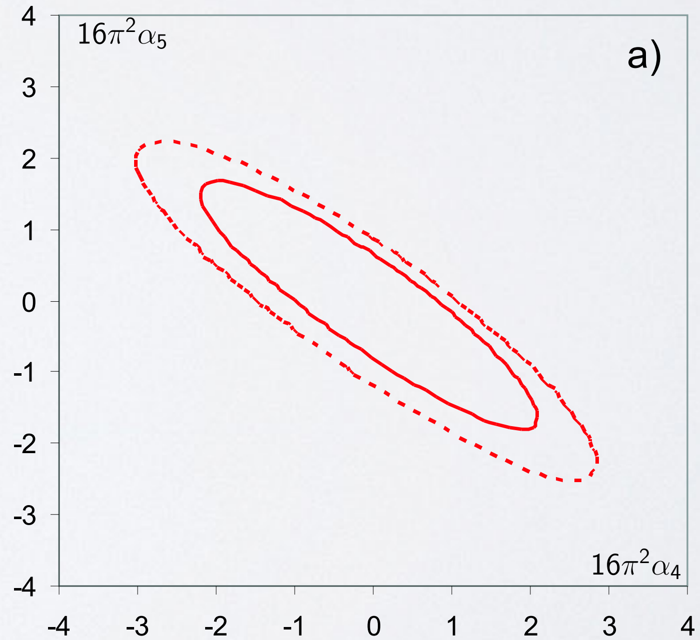
(Partially) reducible Background



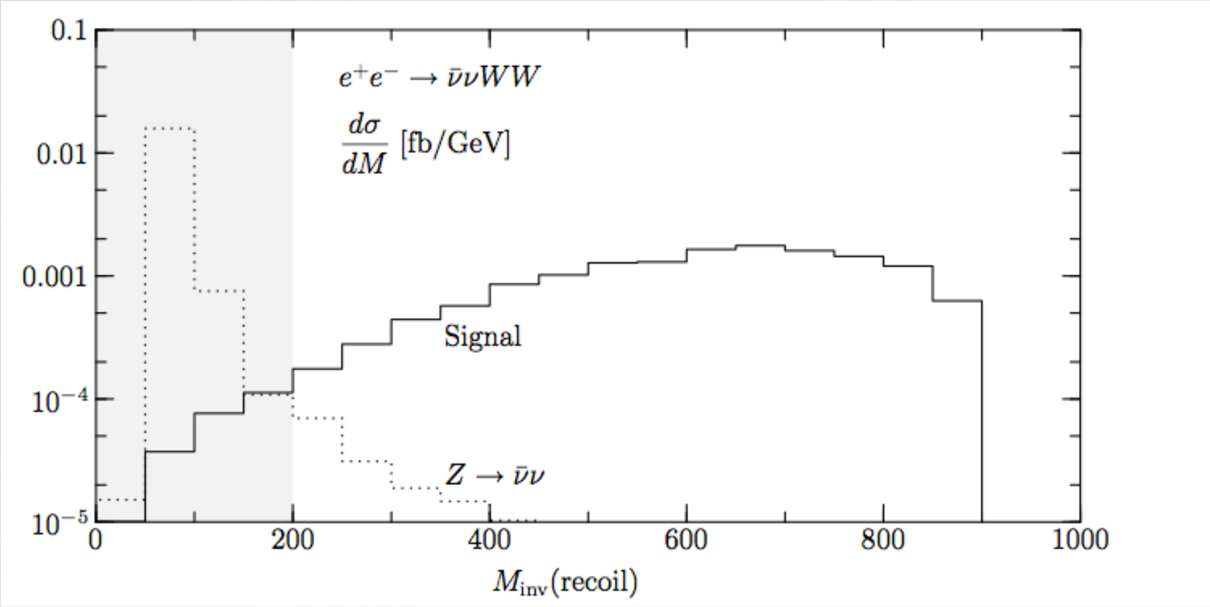
Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	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

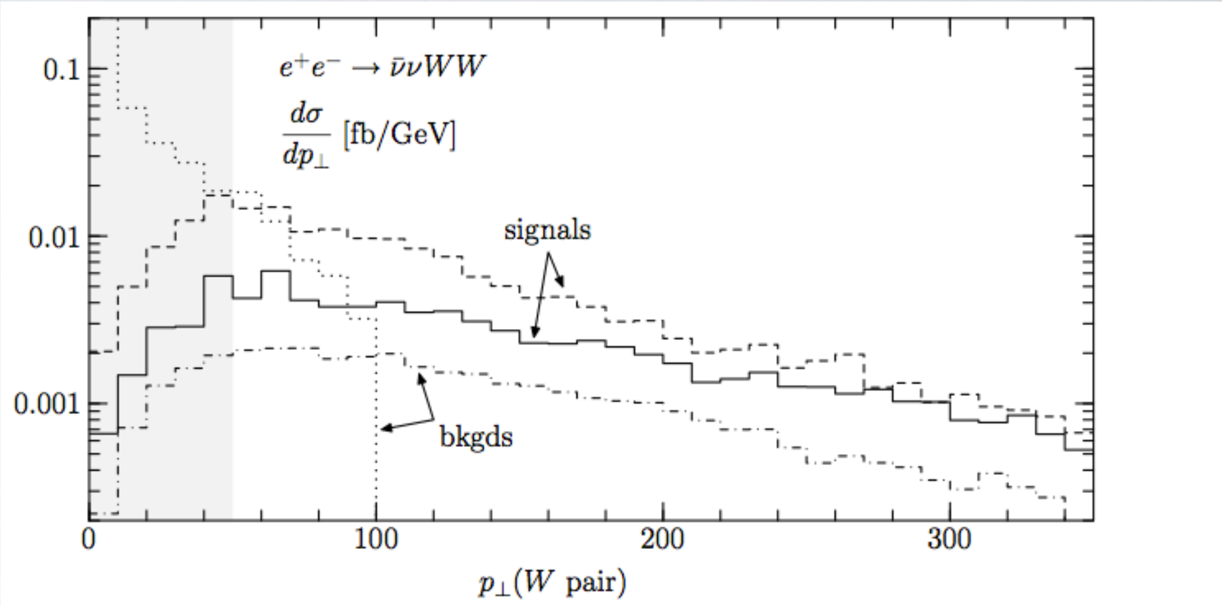
$SU(2)_c$ conserved case, all channels

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



High-Energy Electroweak Sector

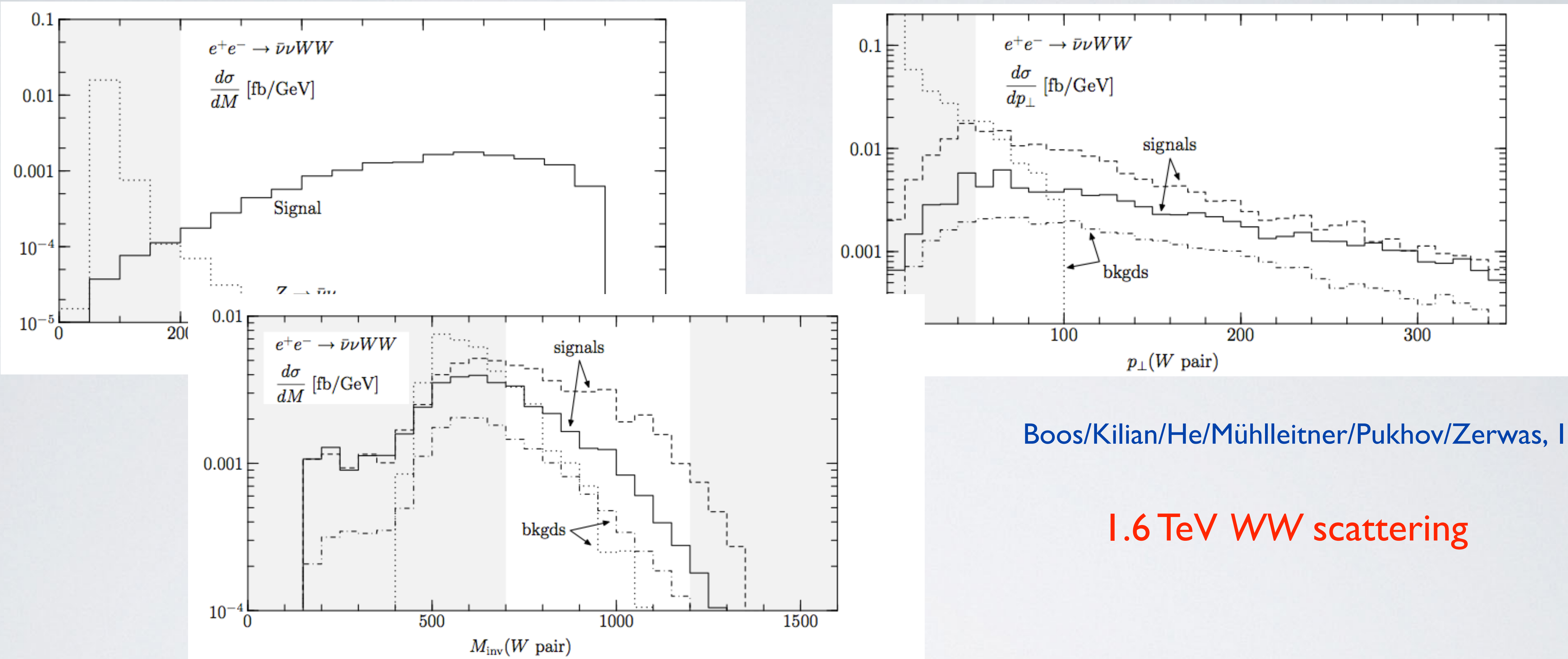




Boos/Kilian/He/Mühlleitner/Pukhov/Zerwas, 1998

1.6 TeV *WW* scattering

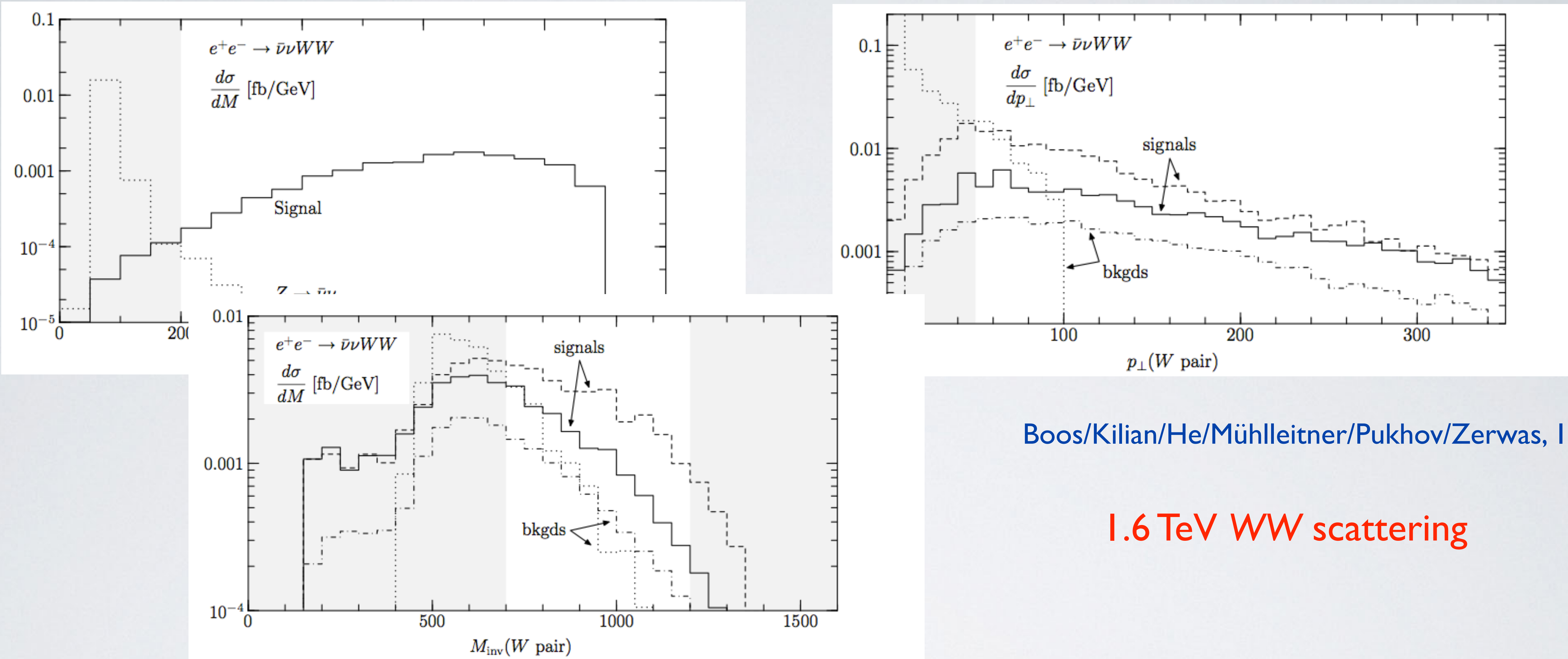
High-Energy Electroweak Sector



Boos/Kilian/He/Mühlleitner/Pukhov/Zerwas, 1998

1.6 TeV *WW* scattering

High-Energy Electroweak Sector



Boos/Kilian/He/Mühlleitner/Pukhov/Zerwas, 1998

1.6 TeV *WW* scattering

✳ Interpretation as limits on Electroweak Resonances (1 TeV):

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

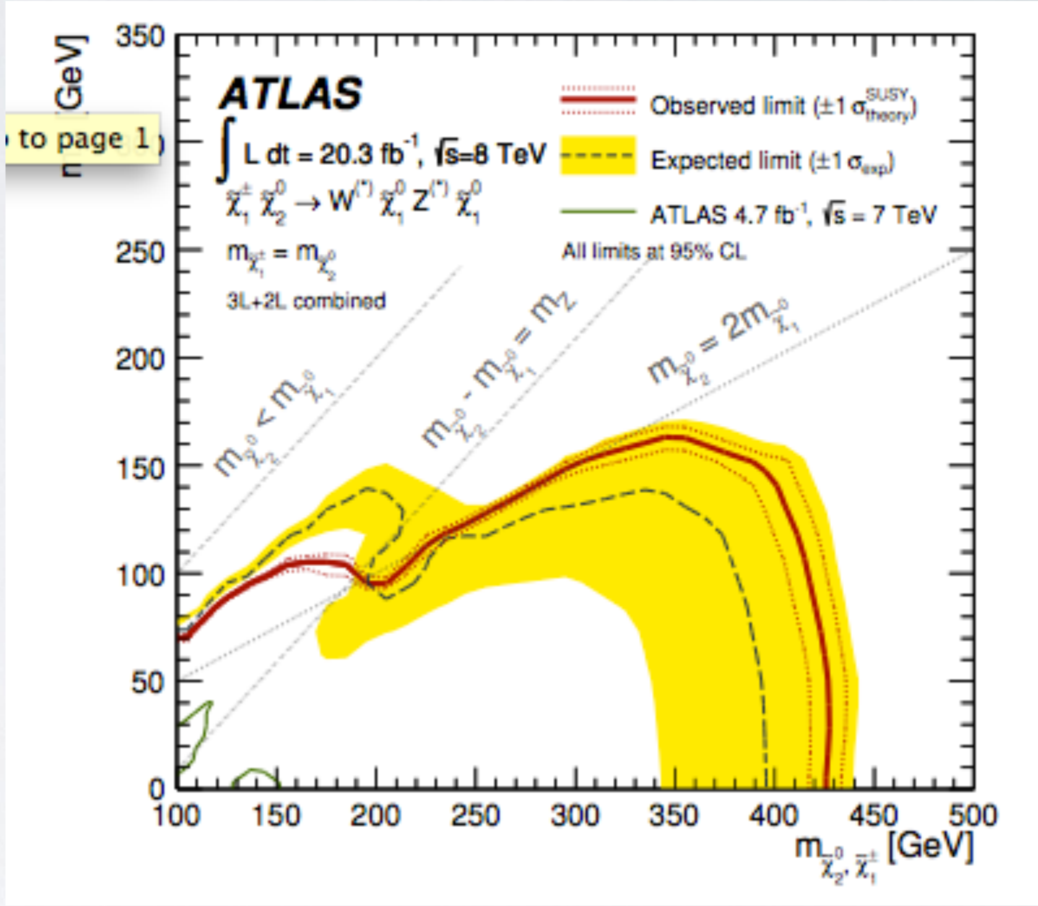
Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

✳ Results for 1 TeV, probably the best-possible measurement at Multi-TeV e+e-

✳ 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)

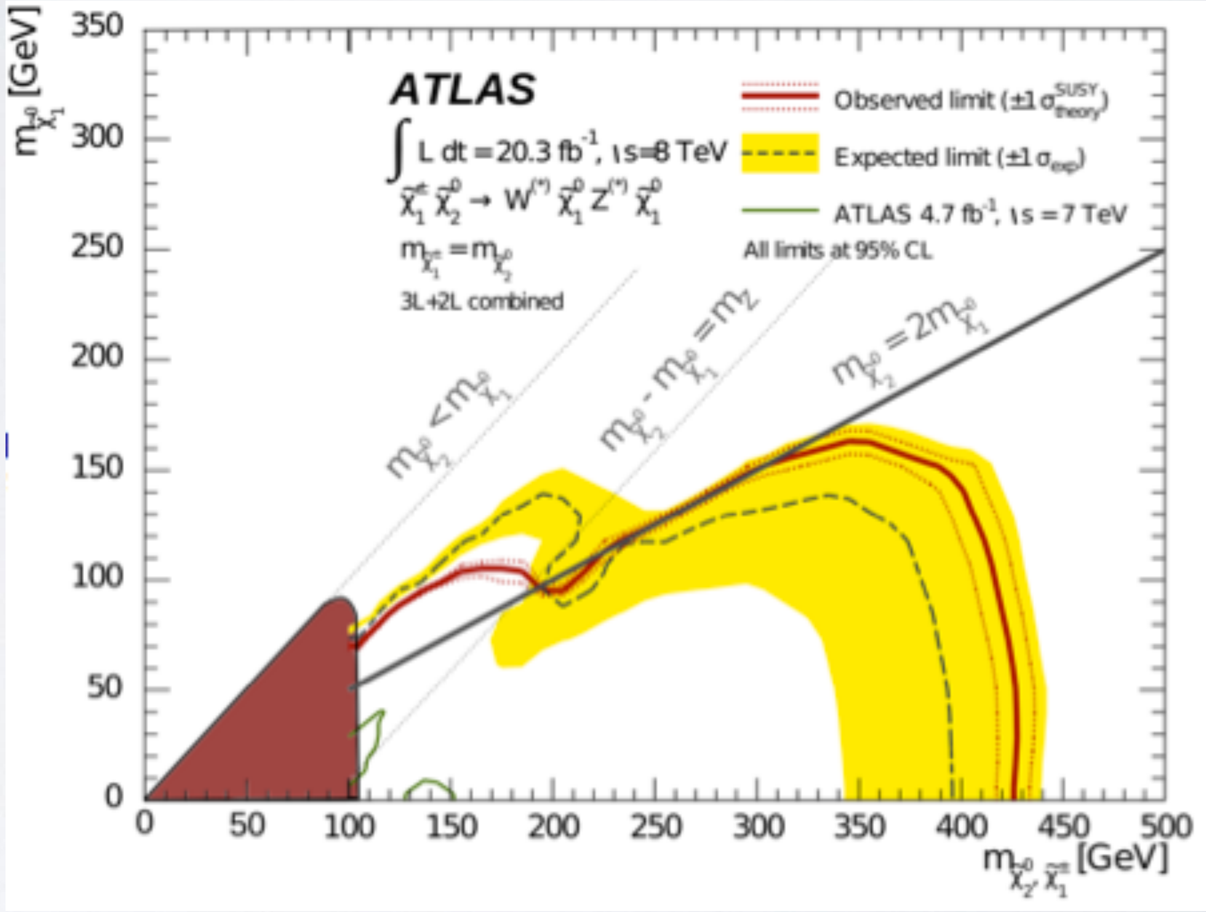
- e+e-: electroweak production ⇒ allows (more) model-independent searches for EW particles
- Example: SUSY searches for partners of electroweak particles (EW gauginos / Higgsinos)
- LHC searches: assumptions $M_{\tilde{\chi}_1^0} = M_{\tilde{\chi}_1^\pm}$ $\quad \mathrm{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_{2,3,4}^0 \to Z^0 \tilde{\chi}_1^0) = 1$



Search for New Weakly Interacting Particles (I)

- ✳ 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 $M_{\tilde\chi_1^0} = M_{\tilde\chi_1^\pm}$ $\mathrm{BR}(\tilde\chi_1^\pm \to W^\pm \tilde\chi_1^0) = \mathrm{BR}(\tilde\chi_{2,3,4}^0 \to Z^0 \tilde\chi_1^0) = 1$

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



Search for New Weakly Interacting Particles (I)

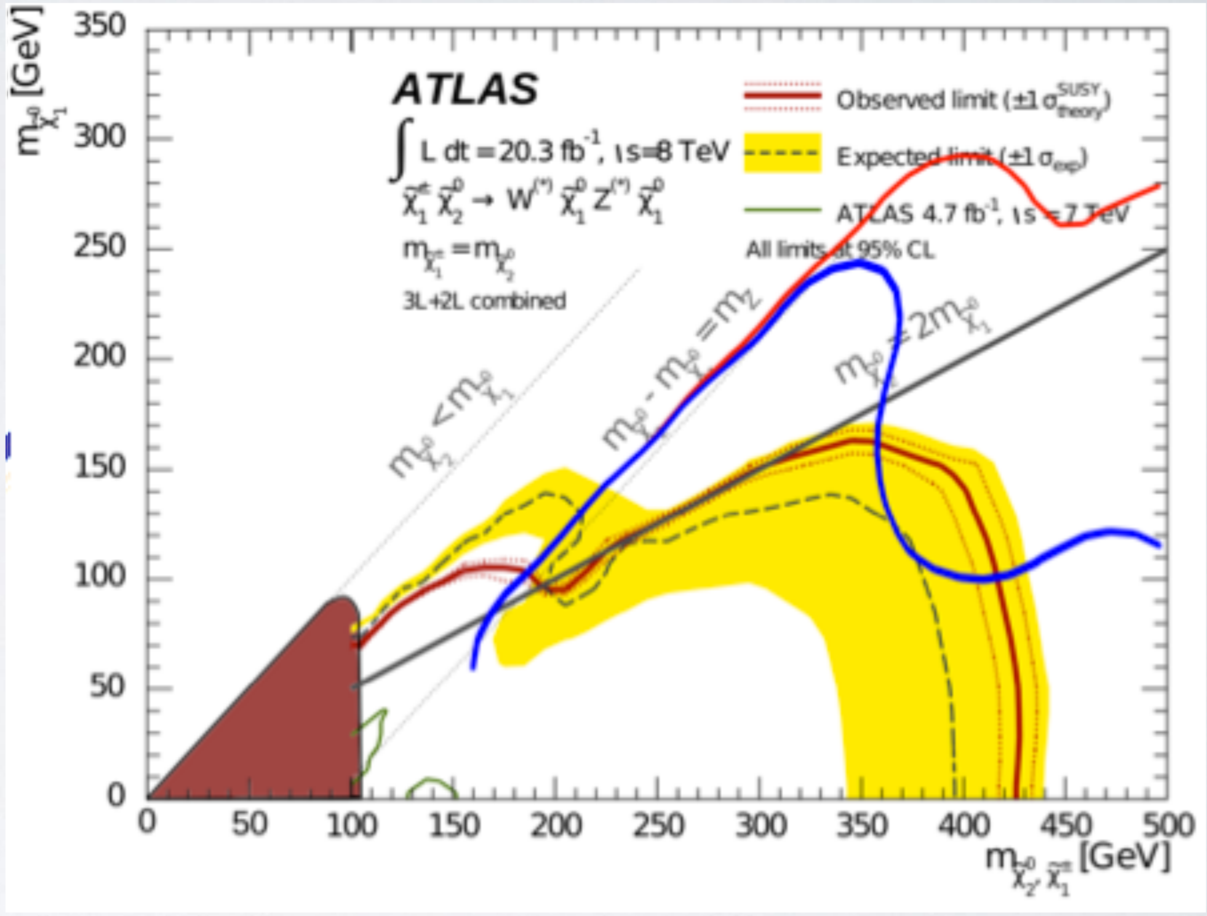
✳ e+e-: electroweak production ⇒ allows (more) model-independent searches for EW particles

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

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

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

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



Search for New Weakly Interacting Particles (I)

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

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

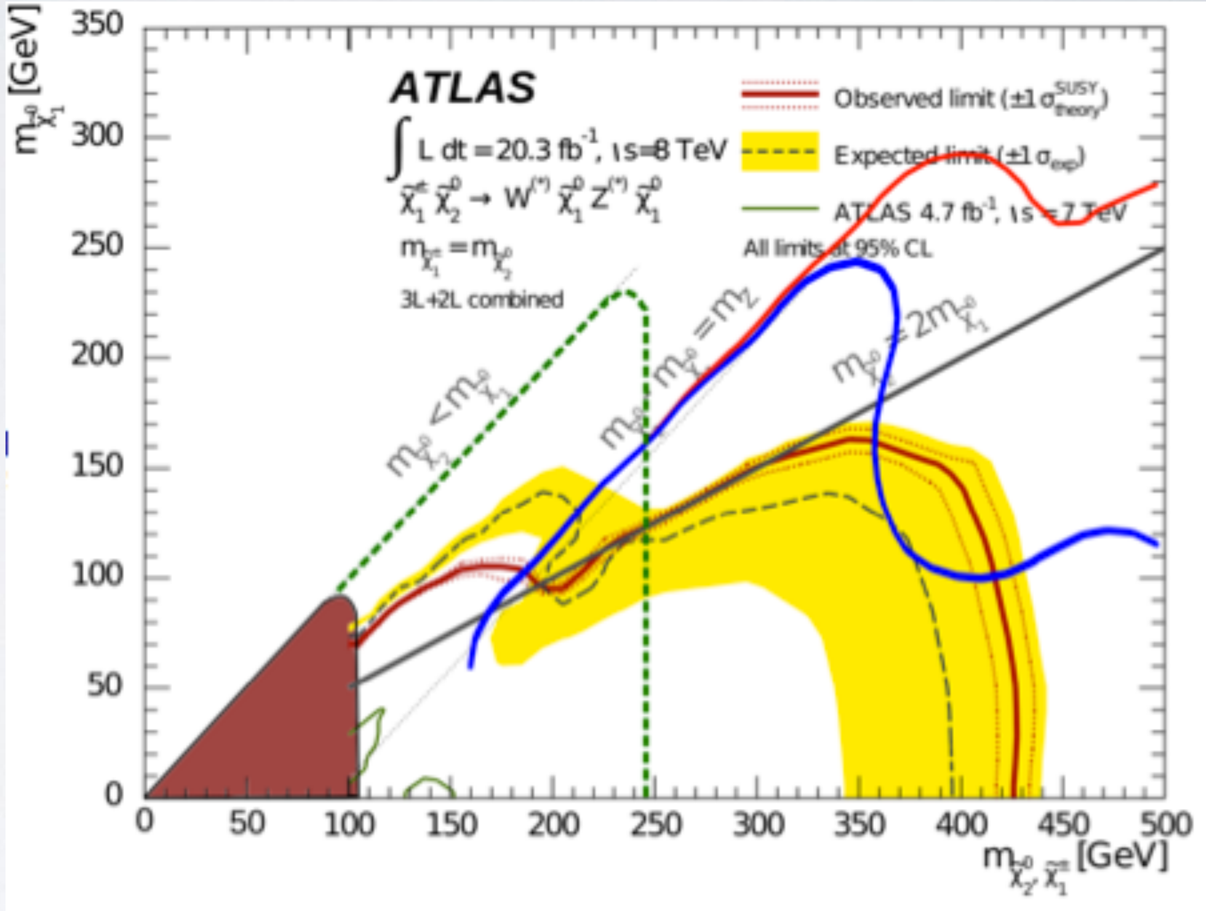
✳ LHC searches: assumptions $M_{\tilde{\chi}_1^0} = M_{\tilde{\chi}_1^\pm}$ $\mathrm{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0) = \mathrm{BR}(\tilde{\chi}_{2,3,4}^0 \to Z^0 \tilde{\chi}_1^0) = 1$

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

★ LHC projections to 14 TeV (arXiv: 1307.7292)

300 / fb and 3000 / fb

500 GeV e+e- generic searches



Search for New Weakly Interacting Particles (I)

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

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

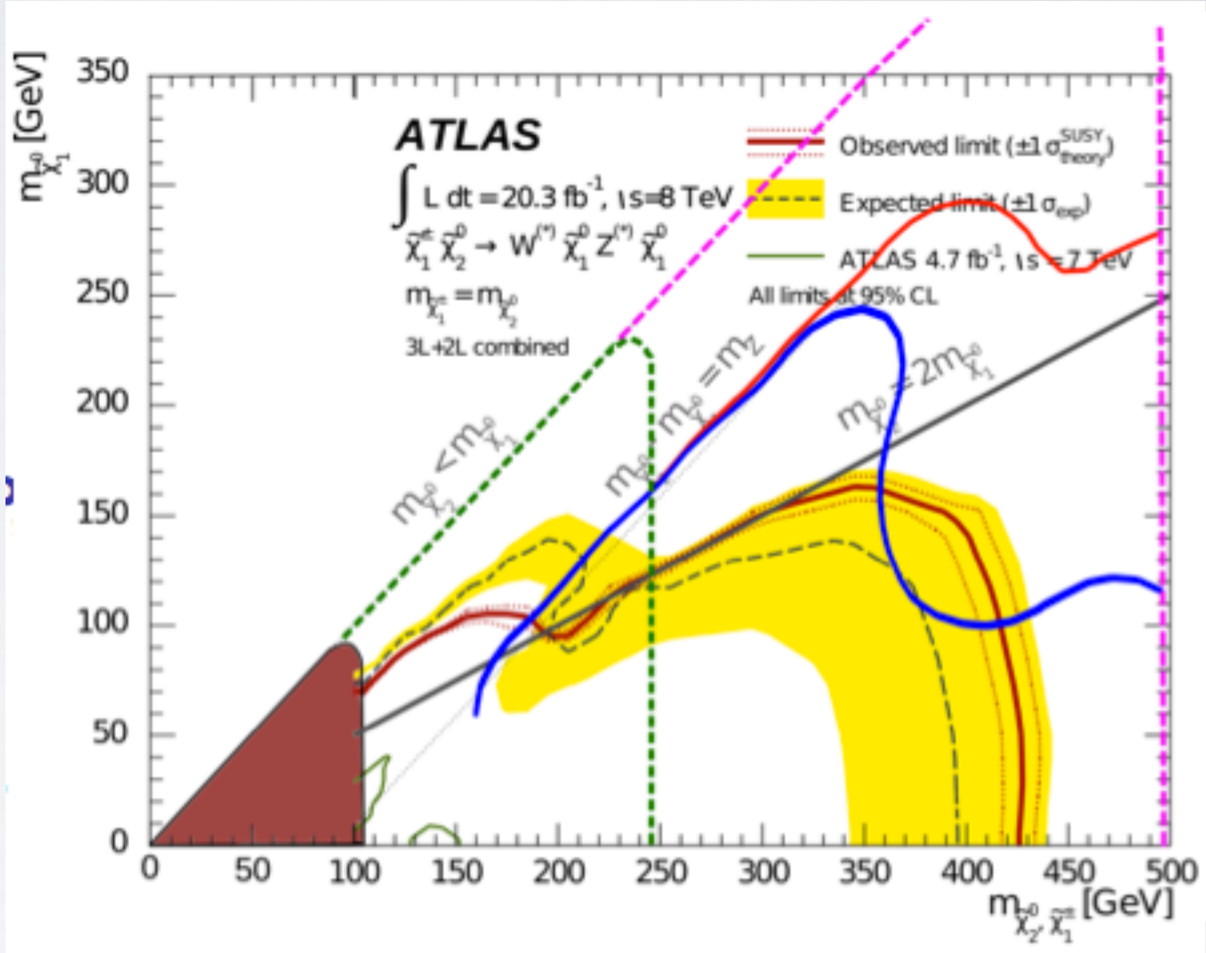
✳ LHC searches: assumptions $M_{\tilde\chi_1^0} = M_{\tilde\chi_1^\pm}$ $\mathrm{BR}(\tilde\chi_1^\pm \to W^\pm \tilde\chi_1^0) = \mathrm{BR}(\tilde\chi_{2,3,4}^0 \to Z^0 \tilde\chi_1^0) = 1$

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

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

500 GeV e+e- generic searches

Upgrade to 1 TeV covers parameter space



Search for New Weakly Interacting Particles (I)

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

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

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

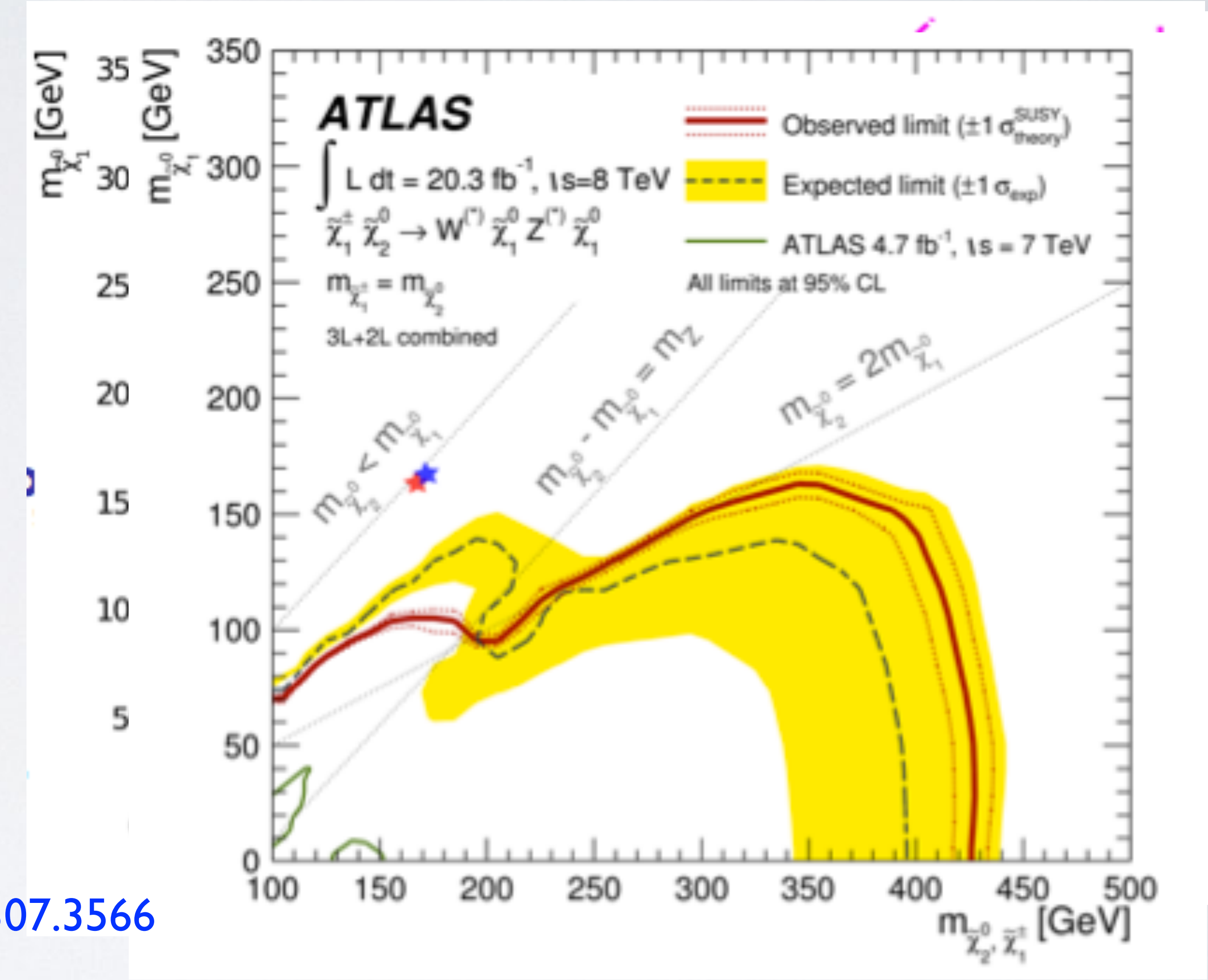
500 GeV e+e- generic searches

Upgrade to 1 TeV covers parameter space

- Benchmark searches for degenerate EW-inos

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

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



Sert et al.: arXiv:1307.3566

Search for New Weakly Interacting Particles (I)

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

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

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

500 GeV e+e- generic searches

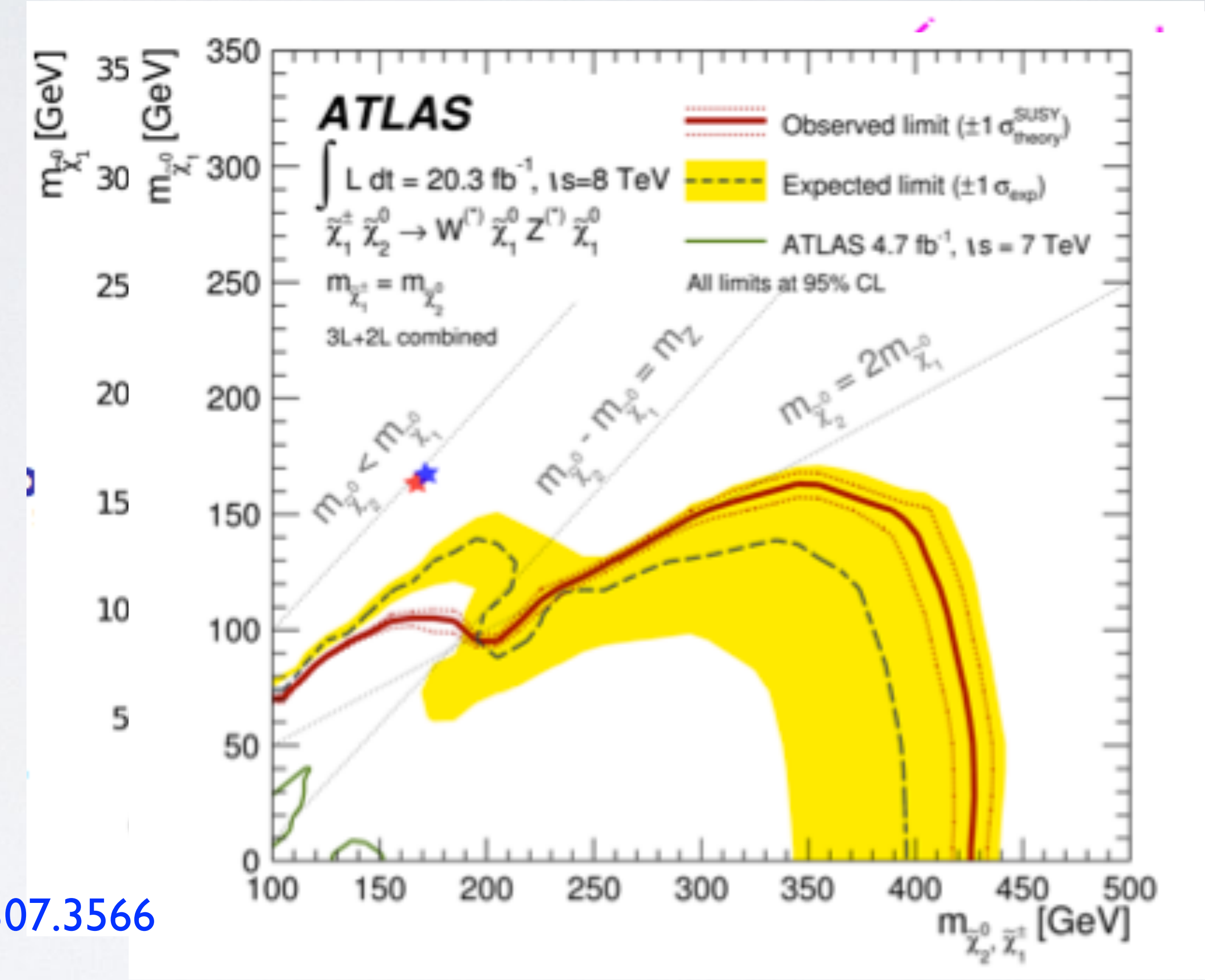
Upgrade to 1 TeV covers parameter space

- Benchmark searches for degenerate EW-inos

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

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

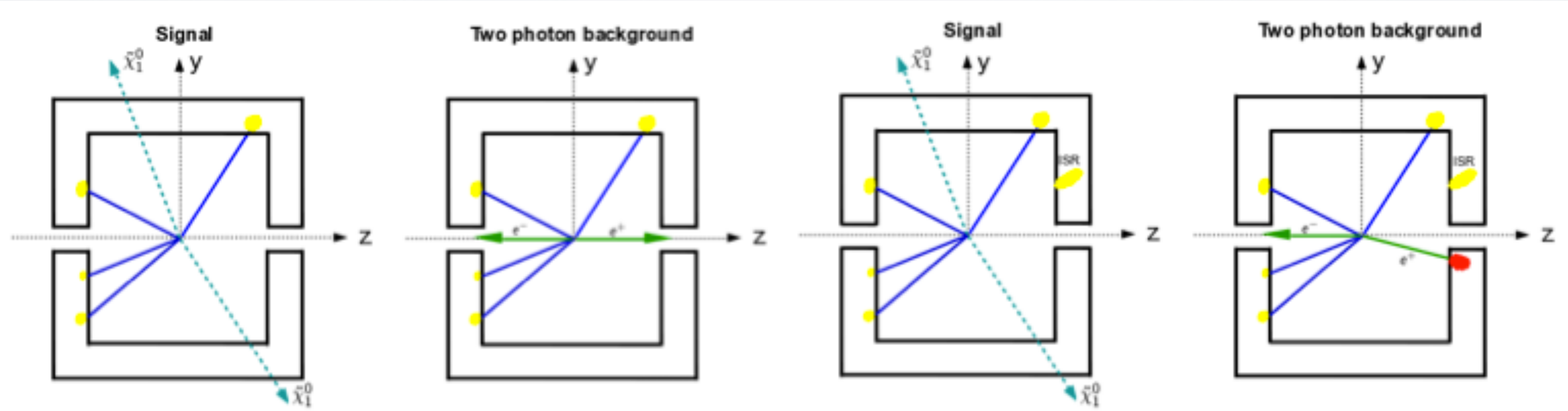
Sert et al.: arXiv:1307.3566



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])

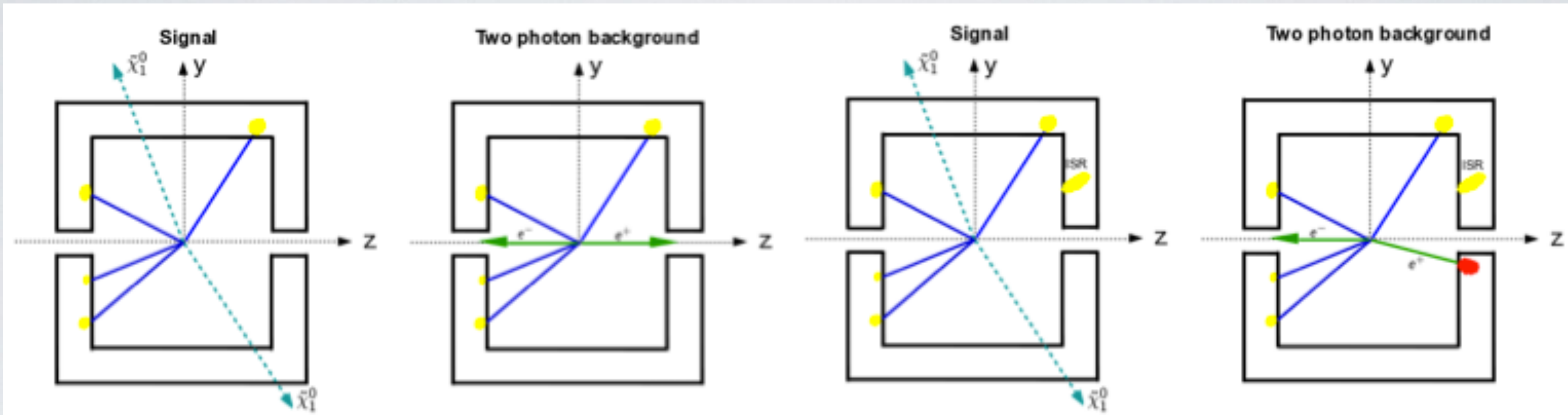
Search for New Weakly Interacting Particles (I)

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



Search for New Weakly Interacting Particles (I)

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

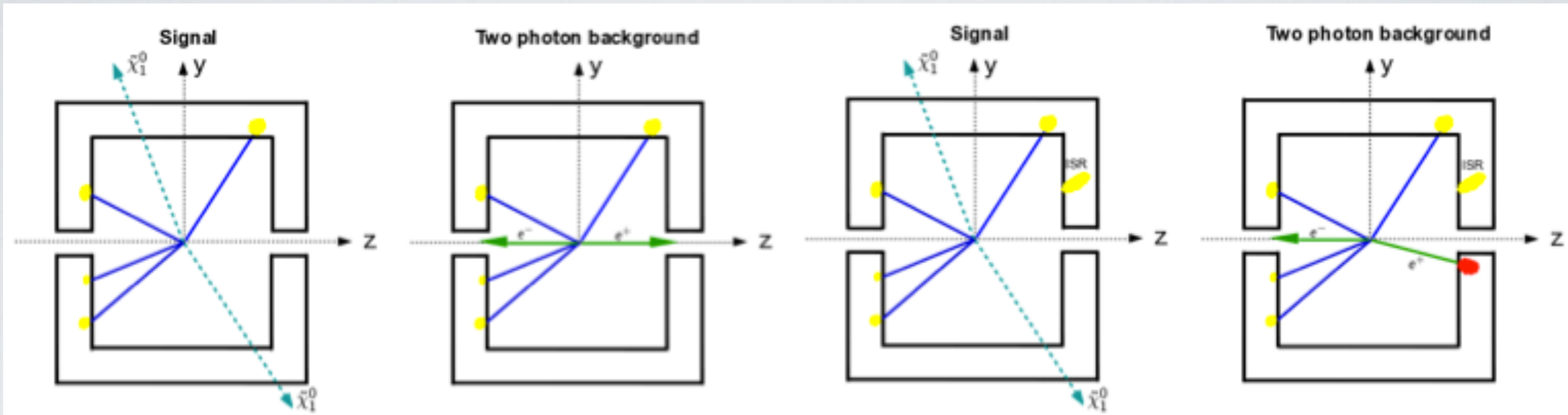


- Select chargino (semi-leptonic mode) vs. neutralino (radiative decay)

$$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 jj, \tilde{\chi}_0^1 \ell^\pm \nu$$
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$$

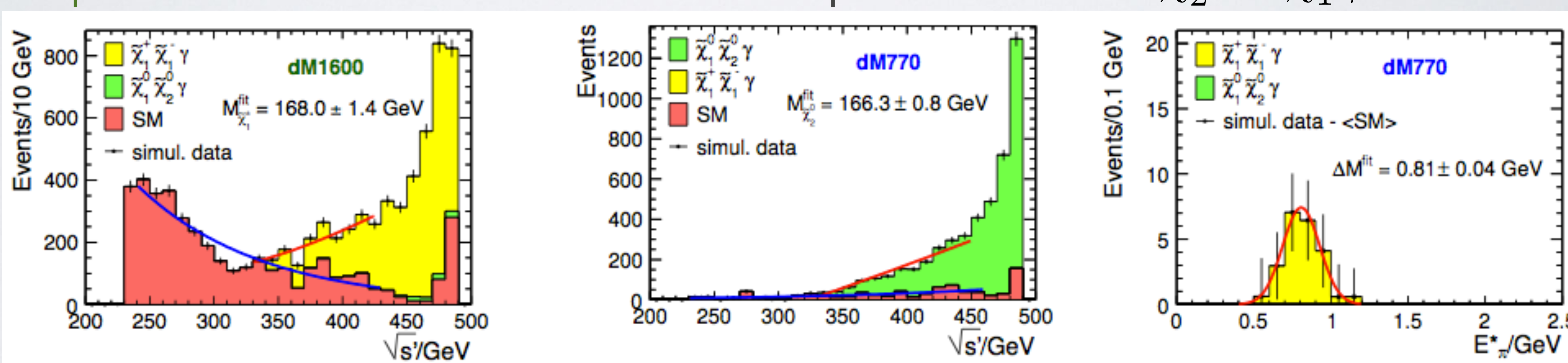
Search for New Weakly Interacting Particles (I)

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



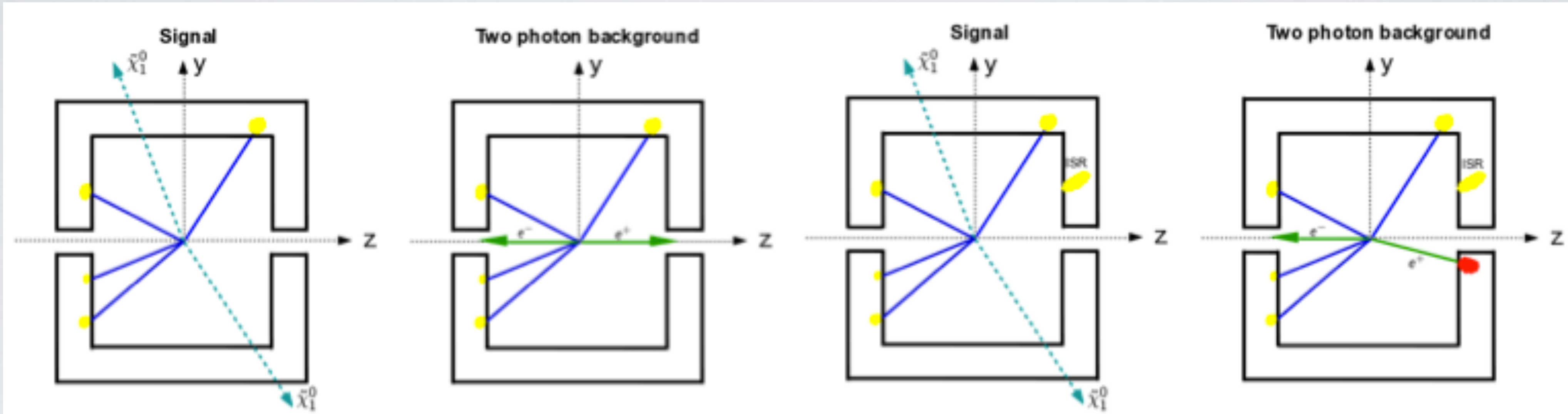
- Select chargino (semi-leptonic mode) vs. neutralino (radiative decay)
- ISR quasi-'scan': linear fits allow to extract masses up to ≃ 1 GeV

$$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 jj, \tilde{\chi}_0^1 \ell^\pm \nu$$
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$$



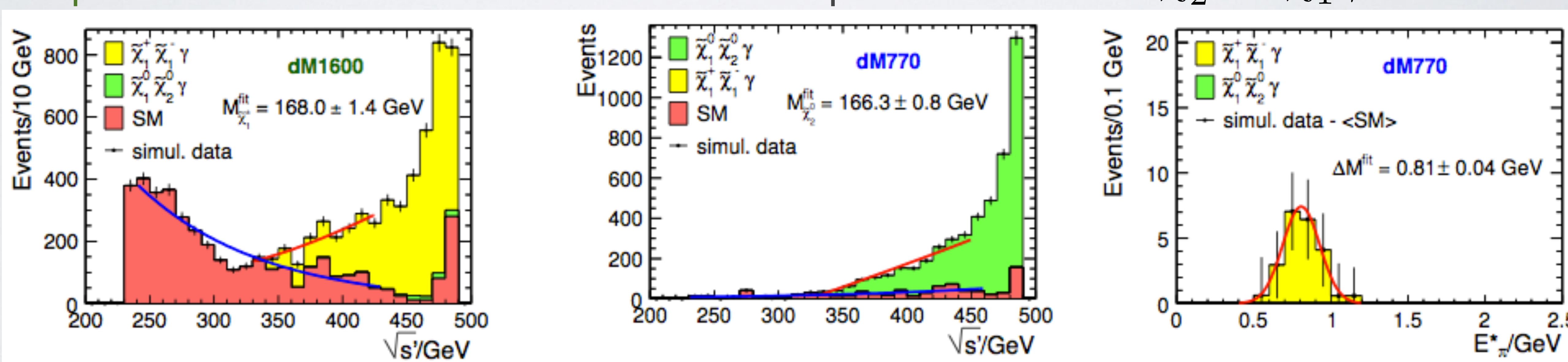
Search for New Weakly Interacting Particles (I)

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



- Select chargino (semi-leptonic mode) vs. neutralino (radiative decay)
- ISR quasi-'scan': linear fits allow to extract masses up to ≃ 1 GeV

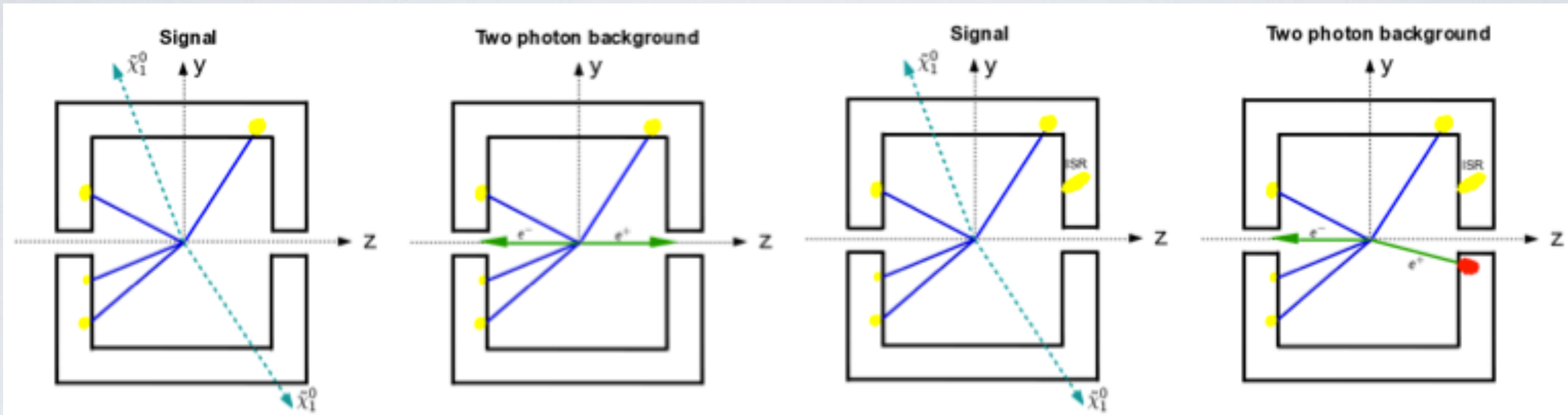
$$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 jj, \tilde{\chi}_0^1 \ell^\pm \nu$$
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$$



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

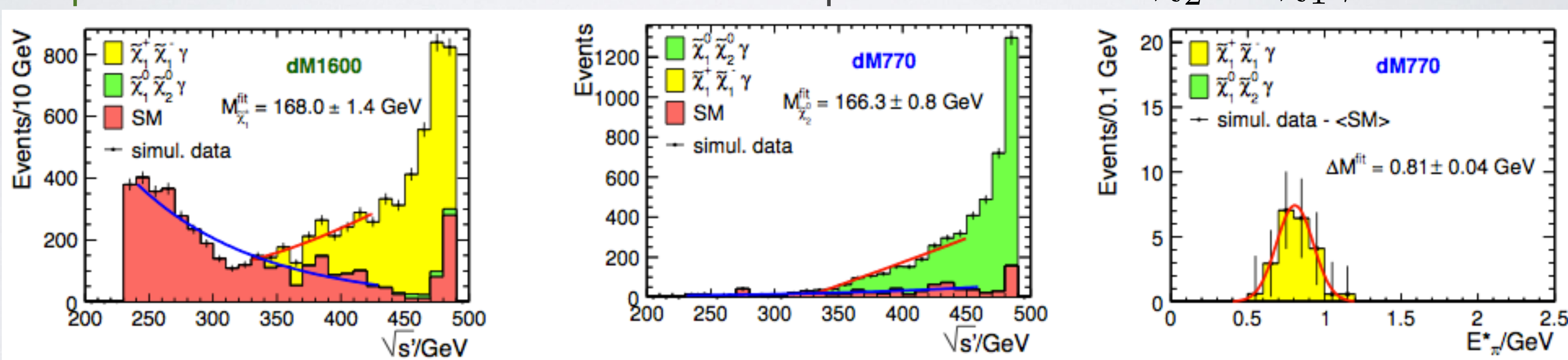
Search for New Weakly Interacting Particles (I)

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



- Select chargino (semi-leptonic mode) vs. neutralino (radiative decay)
- ISR quasi-'scan': linear fits allow to extract masses up to ≃ 1 GeV

$$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 jj, \tilde{\chi}_0^1 \ell^{\pm} \nu$$
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$$



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

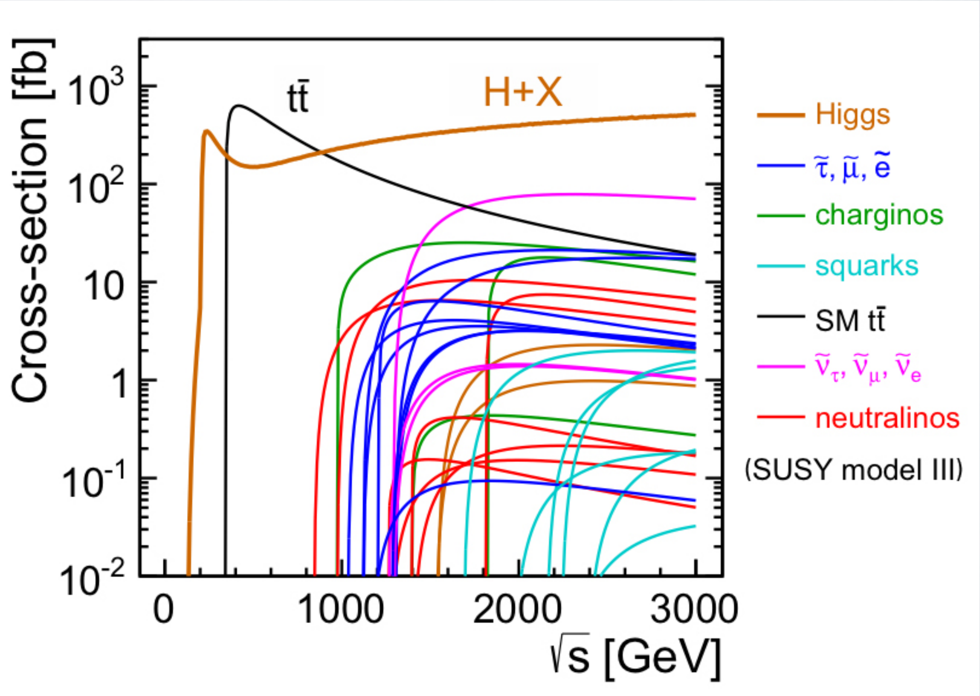
  Even for invisibly decaying sneutrino NLSP

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

Search for New Weakly Interacting Particles (II)

Tomography of all EW states in a certain energy range:

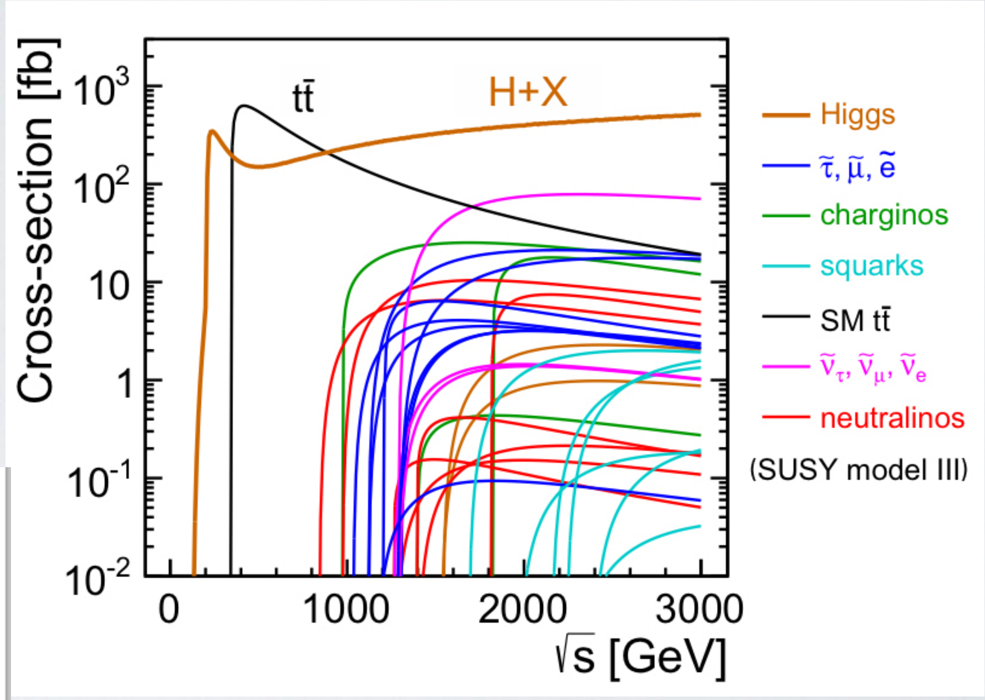
- depending on energy range covers EW and QCD states
- known initial state ⇒ clean mass determination

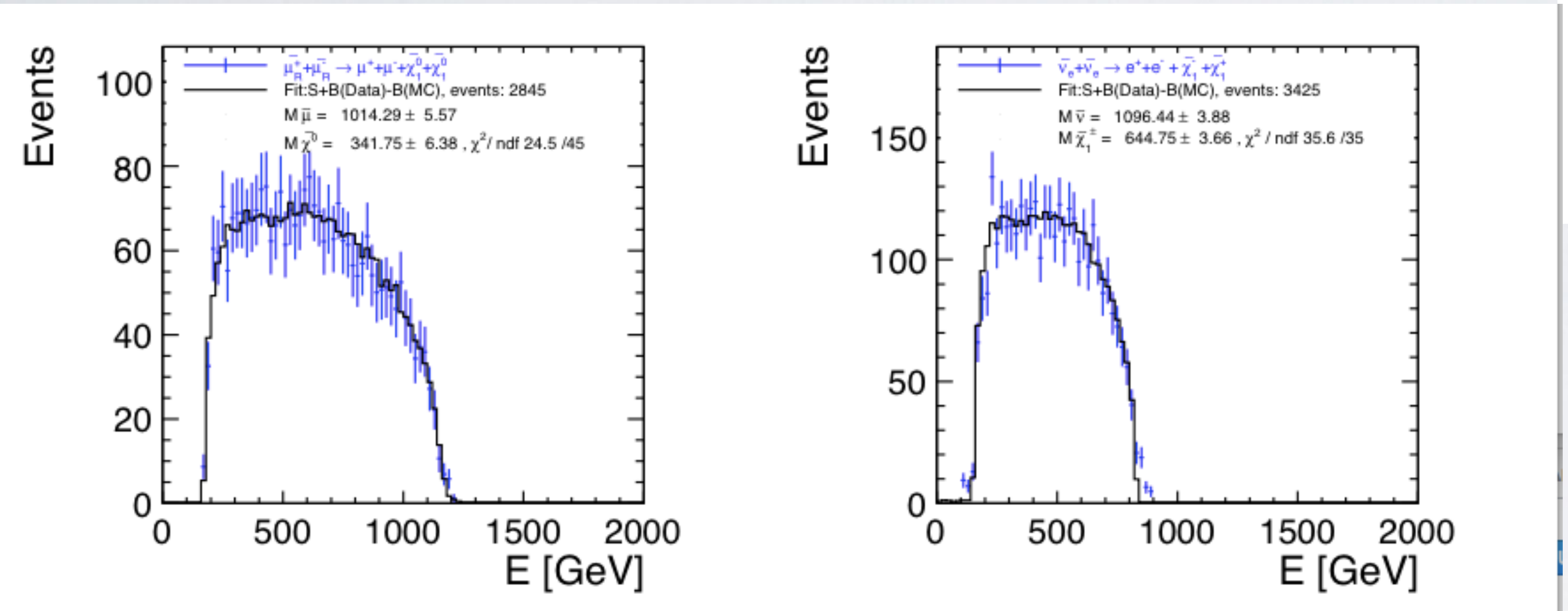


Search for New Weakly Interacting Particles (II)

Tomography of all EW states in a certain energy range:

- depending on energy range covers EW and QCD states
- known initial state ⇒ clean mass determination





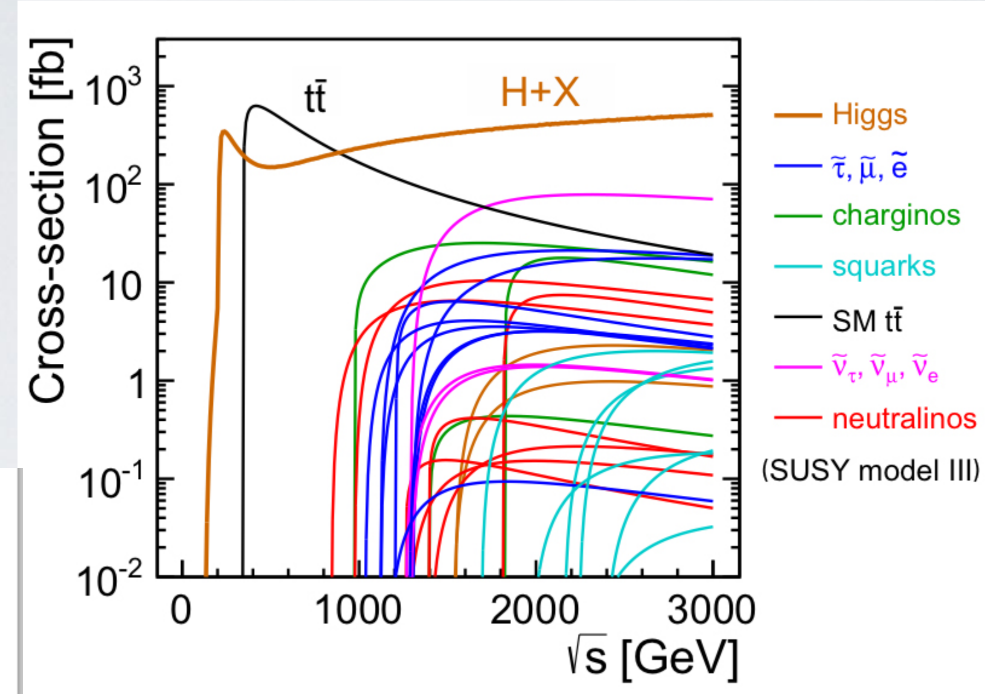
(a) $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$ (b) $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$

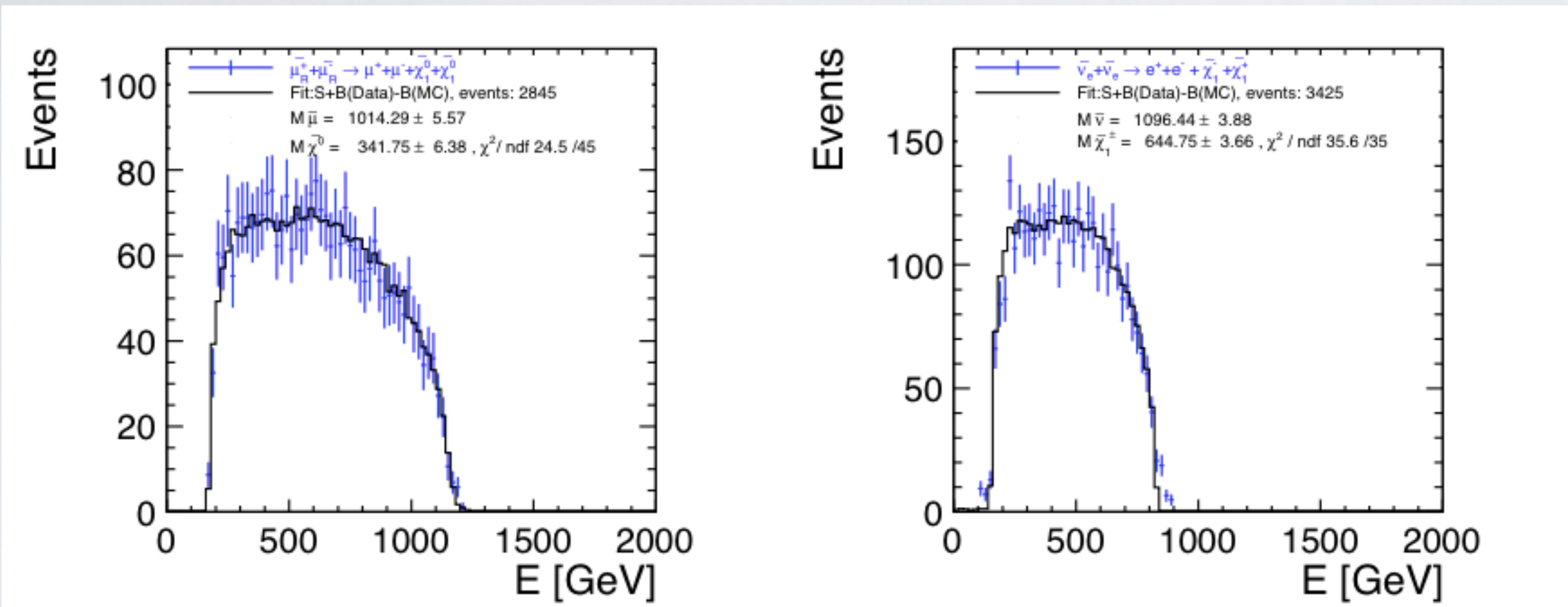
CLIC CDR, arXiv:1202.5940

Search for New Weakly Interacting Particles (II)

Tomography of all EW states in a certain energy range:

- depending on energy range covers EW and QCD states
- known initial state ⇒ clean mass determination





(a) $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$

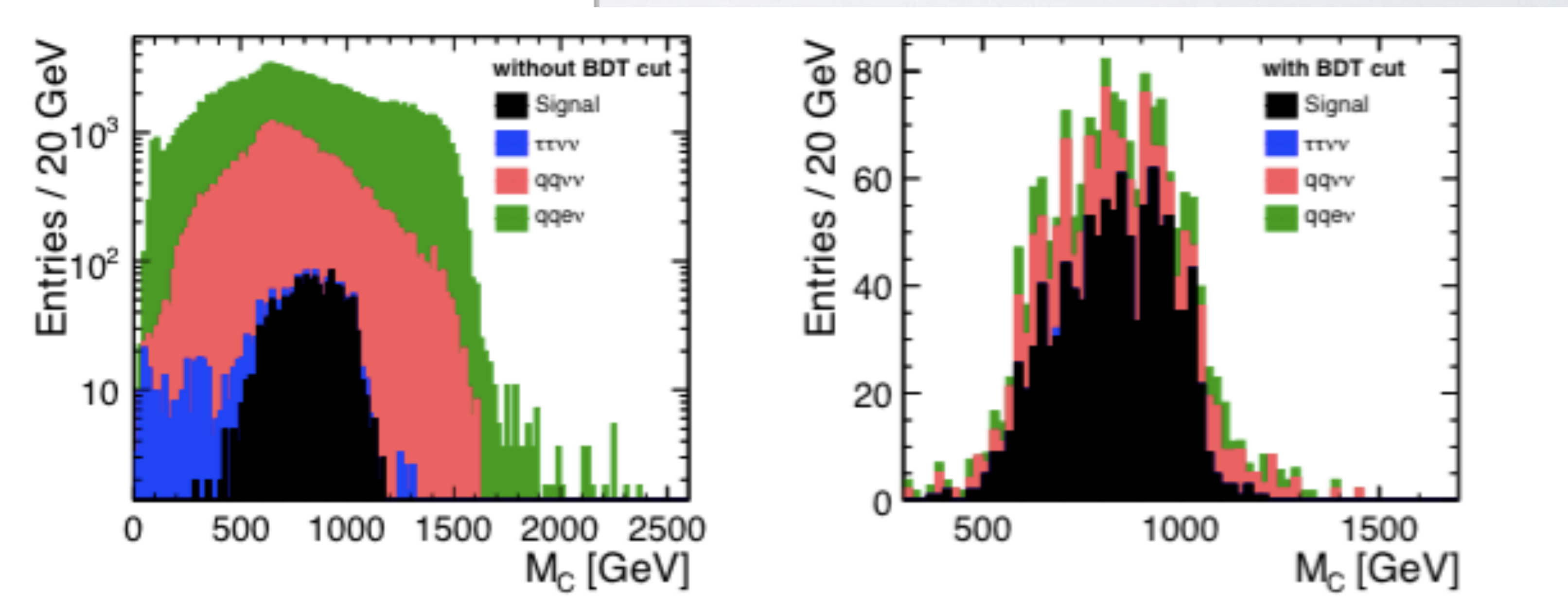
CLIC CDR, arXiv:1202.5940

$$M_C = \sqrt{E_{j,1}E_{j,2} - \vec{p}_{j,1}\cdot\vec{p}_{j,2}}$$

Mass determination for particles with strong and weak quantum numbers, e.g. squarks:

Template fit: $m_{\tilde{q}_R} = 1127.9 \pm 5.9$ GeV

(input value: 1123.7 GeV)



(a) $p_T > 600$ GeV (b) $p_T > 600$ GeV and BDT Cut

Search for New Weakly Interacting Particles (III)

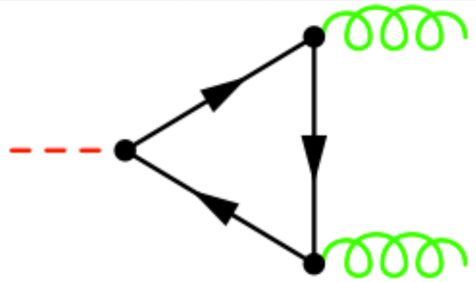
- ⋆ Other candidates: axion-like particles in strongly-interacting models
- ⋆ Prime example: Little Higgs Models Kilian/Rainwater/JRR, arXiv: hep-ph/0411213, hep-ph/0609119
- ⋆ Axion-like particles:

Search for New Weakly Interacting Particles (III)

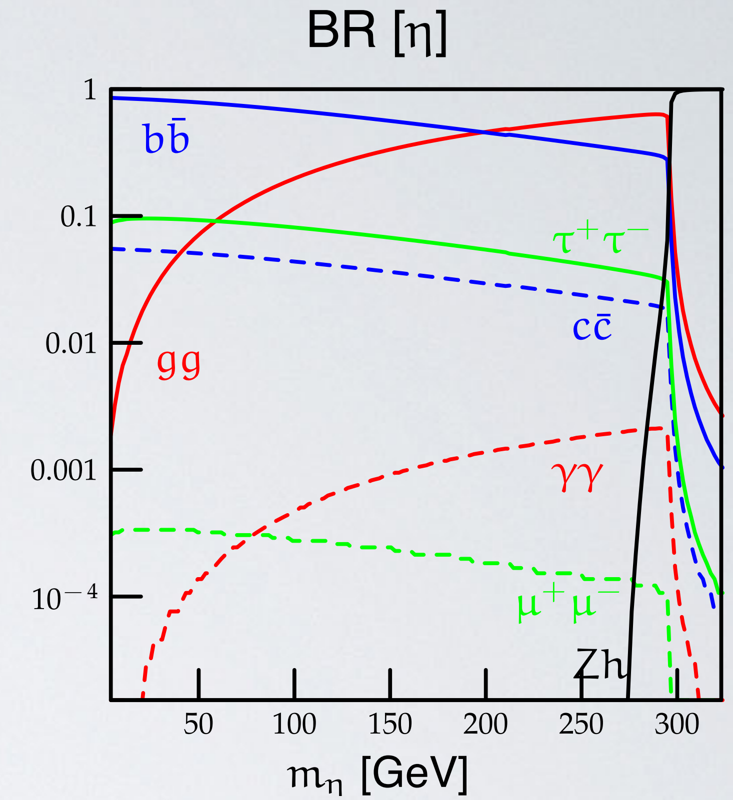
- ★ Other candidates: axion-like particles in strongly-interacting models
- ★ Prime example: Little Higgs Models

Kilian/Rainwater/JRR, arXiv: hep-ph/0411213, hep-ph/0609119

- ★ Axion-like particles:
  - Gauged *U(1)* group: Z' $\longleftrightarrow$ Ungauged *U(1)* group: η
  - Couples to fermions like pseudoscalar
  - $m[\eta] \lesssim 400$ GeV (at LHC only accessible for $\gtrsim 200$ GeV)
  - SM singlet, couplings to SM fermion suppressed v / F



$$\longrightarrow \frac{1}{F}\frac{\alpha_s}{8\pi^2}\eta F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

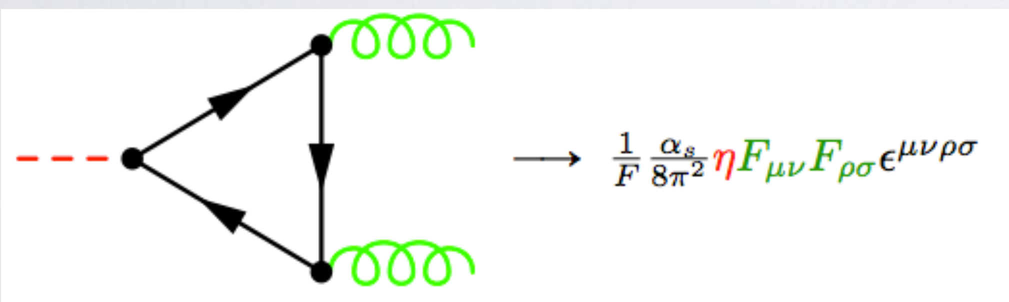


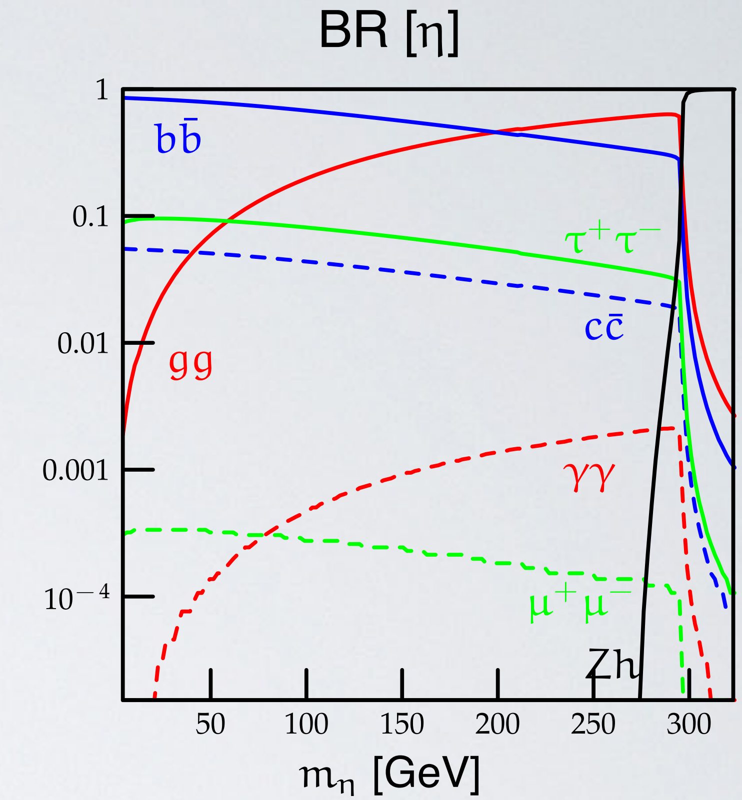
Search for New Weakly Interacting Particles (III)

- ★ Other candidates: axion-like particles in strongly-interacting models
- ★ Prime example: Little Higgs Models

Kilian/Rainwater/JRR, arXiv: hep-ph/0411213, hep-ph/0609119

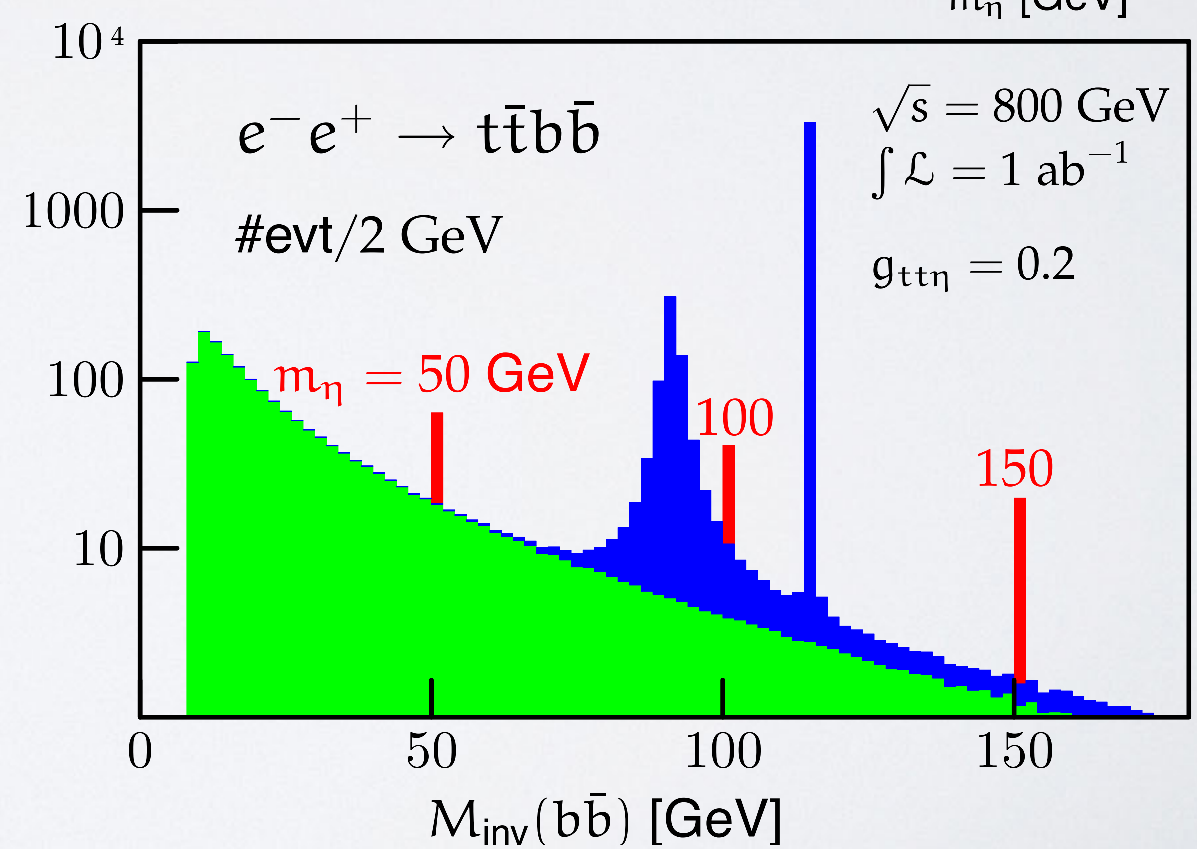
- ★ Axion-like particles:
  - Gauged *U(1)* group: *Z'* $\longleftrightarrow$ Ungauged *U(1)* group: η
  - Couples to fermions like pseudoscalar
  - *m*[η] ≲ 400 GeV (at LHC only accessible for ≳ 200 GeV)
  - SM singlet, couplings to SM fermion suppressed *v / F*





★ High-energy e+e- allows detection in the low-mass regime:

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



Conclusions and Outlook

- TeV-/Multi-TeV e+ e- machines offer large BSM discovery potential
- Model-independent electroweak searches
- Dark Matter direct searches
- High-energy e+e- resolves many LHC search constraints
- (Multi-)TeV e+e- surpasses LHC energy reach for EW sector and neutral current searches
- Search for light electroweak particles not covered by LHC
- High-energy e+e- is a mandatory tool for discovery and discrimination of New Physics

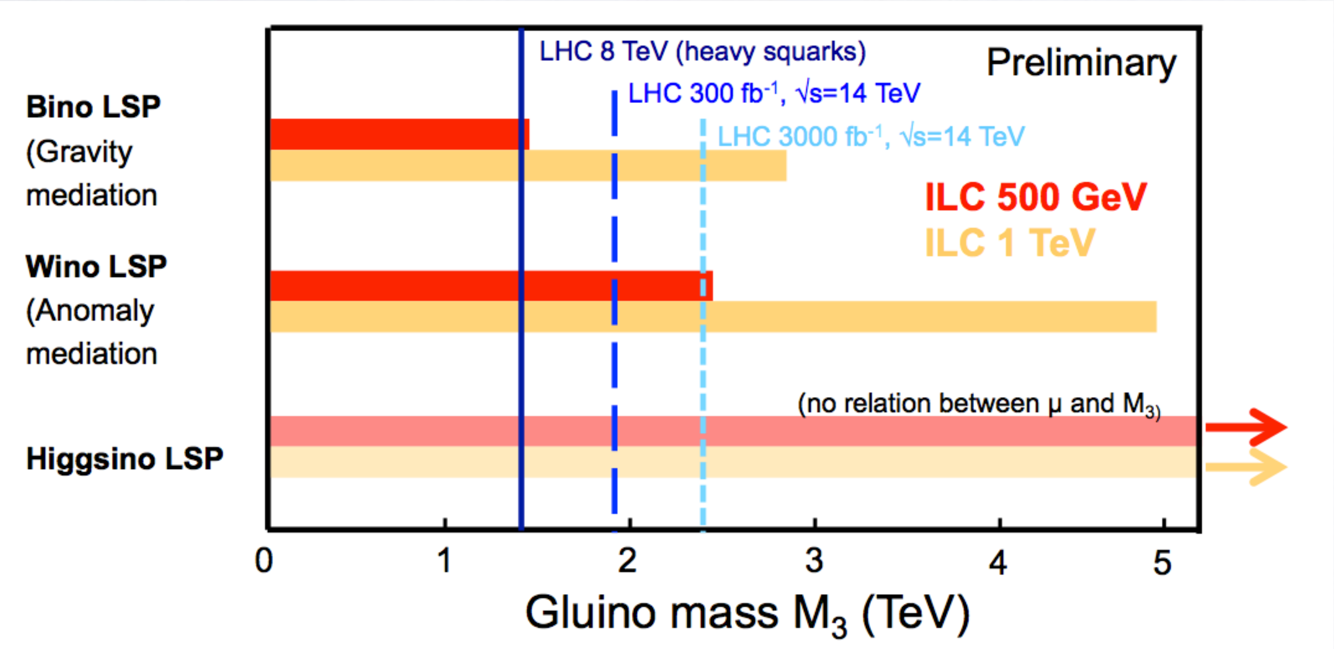
Conclusions and Outlook

- TeV-/Multi-TeV e+ e- machines offer large BSM discovery potential
- Model-independent electroweak searches
- Dark Matter direct searches
- High-energy e+e- resolves many LHC search constraints
- (Multi-)TeV e+e- surpasses LHC energy reach for EW sector and neutral current searches
- Search for light electroweak particles not covered by LHC
- High-energy e+e- is a mandatory tool for discovery and discrimination of New Physics

Conclusions and Outlook

- TeV-/Multi-TeV e+ e- machines offer large BSM discovery potential
- Model-independent electroweak searches
- Dark Matter direct searches
- High-energy e+e- resolves many LHC search constraints
- (Multi-)TeV e+e- surpasses LHC energy reach for EW sector and neutral current searches
- Search for light electroweak particles not covered by LHC
- High-energy e+e- is a mandatory tool for discovery and discrimination of New Physics

Synergistic potential from both LHC & e+e-



Conclusions and Outlook

- TeV-/Multi-TeV e+ e- machines offer large BSM discovery potential
- Model-independent electroweak searches
- Dark Matter direct searches
- High-energy e+e- resolves many LHC search constraints
- (Multi-)TeV e+e- surpasses LHC energy reach for EW sector and neutral current searches
- Search for light electroweak particles not covered by LHC
- High-energy e+e- is a mandatory tool for discovery and discrimination of New Physics

Synergistic potential from both LHC & e+e-