BSM physics at future e^+e^- colliders

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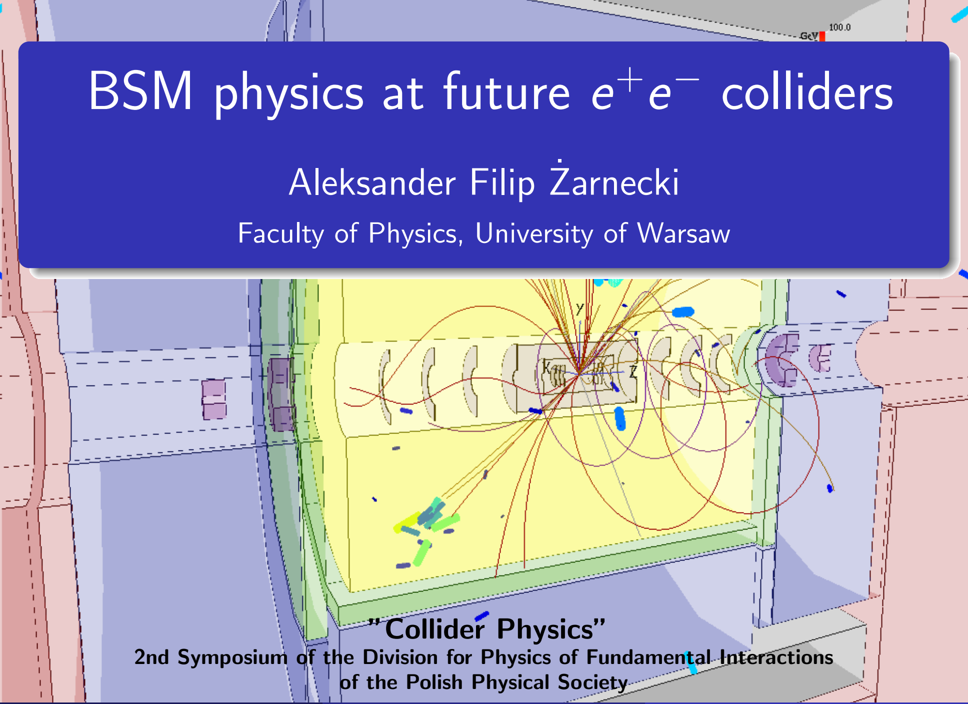


"Collider Physics"

2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society

Outline

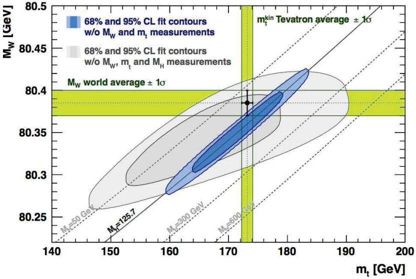
Motivation

Beyond Standard Model

Standard Model works perfectly at our laboratories (!).

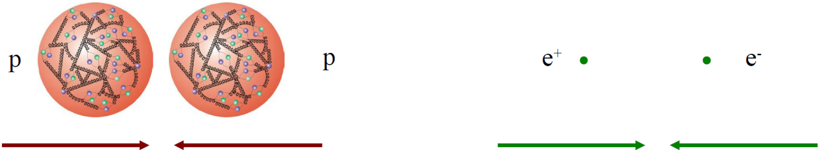
But we keep looking for hints of the "new theory" to understand:

- Dark Matter in the Universe
- origin of the EWSB
- hierarchy problem
- CP violation, matter-antimatter asymmetry
- flavour structure of SM
- nature of neutrinos



Motivation

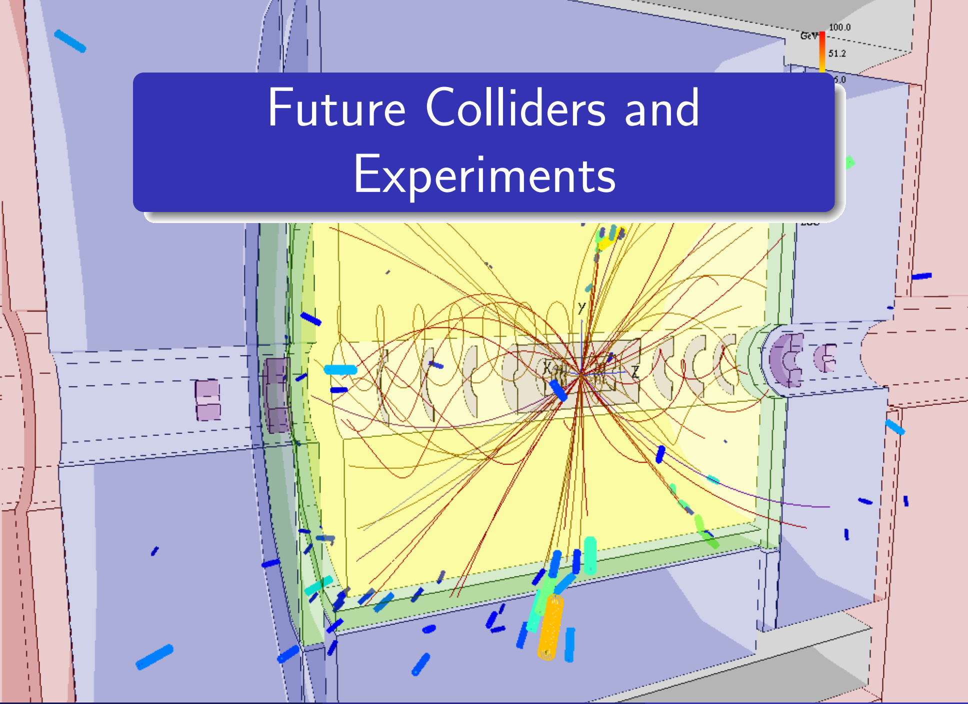
Lepton Colliders



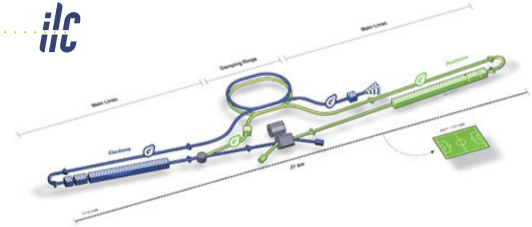
Advantages of the Lepton Colliders

- interactions of fundamental, point-like objects
- well defined (adjustable) initial state energy and polarisation
- low radiation levels (all instrumentation very close to the beam line)
- low background rates (trigger-less readout)
- electroweak interactions dominate
- precise theoretical predictions

Future Colliders and Experiments

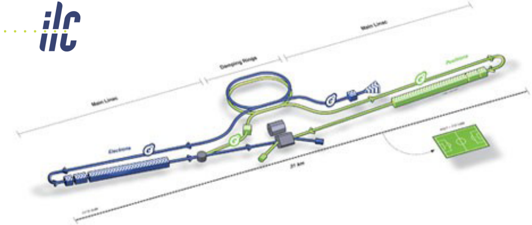


Linear Colliders



Technical Design (TDR) completed in 2013

- 500 GeV baseline
  1 TeV upgrade possible
- e^- and e^+ polarization



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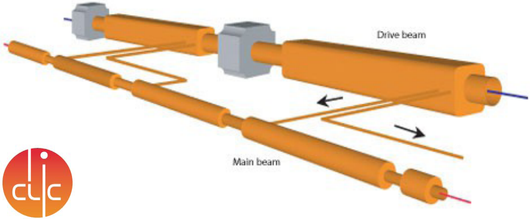
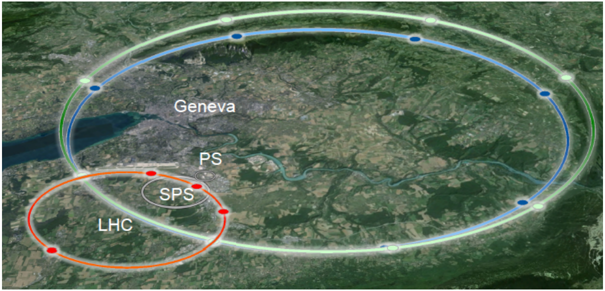


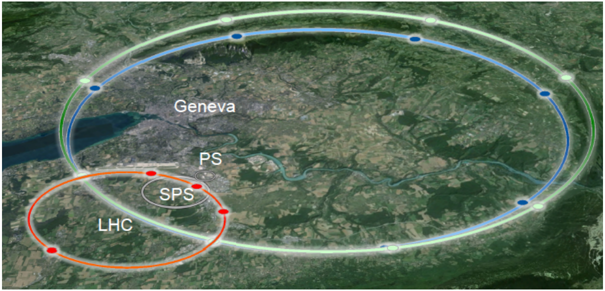
Conceptual design in 2012
Ongoing R&D towards TDR

- energy 380 GeV - 3 TeV
- e^- polarization



FCC-ee @ CERN

- 80-100 km ring
- focus on 250 GeV
  ⇒ Higgs factory
- 350 GeV possible
- no polarization



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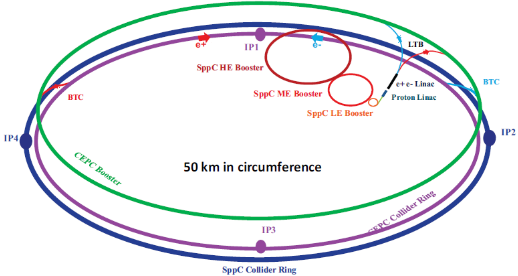


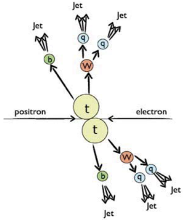
CEPC @ China

- 50 km ring
- up to 240 GeV
  $\Rightarrow$ Higgs factory

$t\bar{t}$ threshold not reachable

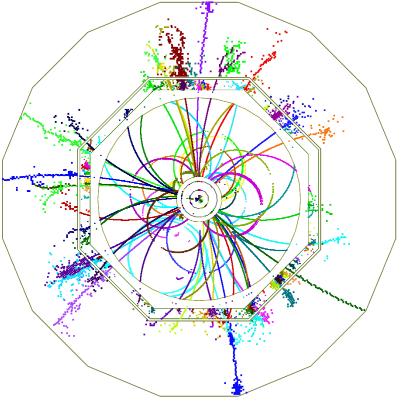
Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



High detector granularity
⇒ reconstruction of single particles

$e^+e^- \to t\bar{t} \to 6j$



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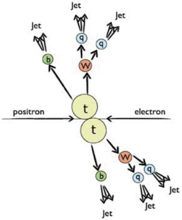

Jet reconstruction and jet energy measurement based on "Particle Flow" concept

High detector granularity
⇒ reconstruction of single particles

Excellent momentum measurement
⇒ best possible jet energy estimate

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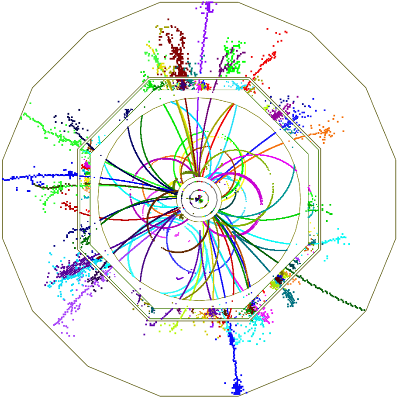

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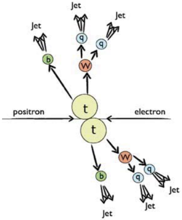

High detector granularity
$\Rightarrow$ reconstruction of single particles

Excellent momentum measurement
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High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

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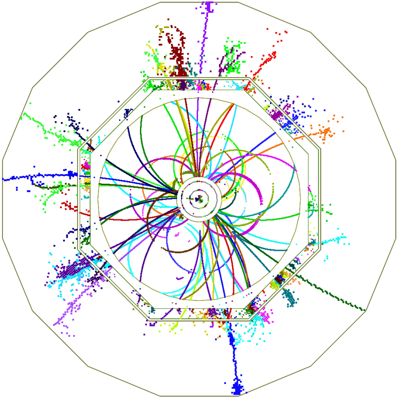

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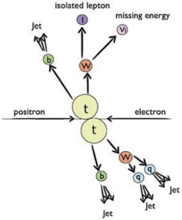
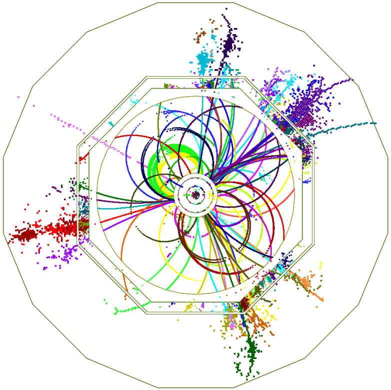


Jet reconstruction and jet energy measurement based on "Particle Flow" concept

$e^+e^- \rightarrow t\bar{t} \rightarrow 4j + l + \nu$



High detector granularity
$\Rightarrow$ reconstruction of single particles

Excellent momentum measurement
$\Rightarrow$ best possible jet energy estimate

High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

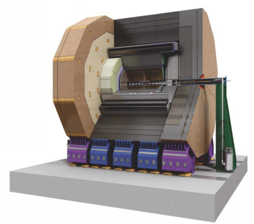
Hermecity
$\Rightarrow$ missing energy measurement

Detector Requirements

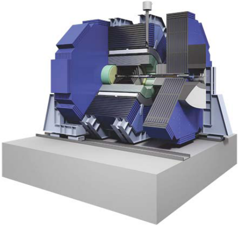
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Energy resolution: $\sigma_E/E = 3 - 4\%$
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed LC detector concepts:

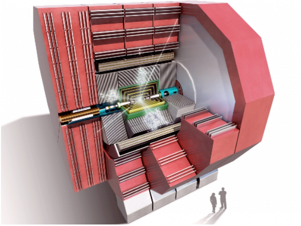
ILD



SiD



CLIC



Running scenarios

H-20 scenario for ILC

Initial stage

- $\sqrt{s} = 500$ GeV with 500 fb^{-1} in 3.7 years
- $\sqrt{s} = 350$ GeV with 200 fb^{-1} in 1.3 years
- $\sqrt{s} = 250$ GeV with 500 fb^{-1} in 3.1 years

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Additional 3'500 fb^{-1} at $\sqrt{s} = 500$ GeV and 1'500 fb^{-1} at $\sqrt{s} = 250$ GeV possible after luminosity upgrade (in about 11 years)

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Additional 3'500 fb^{-1} at $\sqrt{s} = 500$ GeV and 1'500 fb^{-1} at $\sqrt{s} = 250$ GeV possible after luminosity upgrade (in about 11 years)

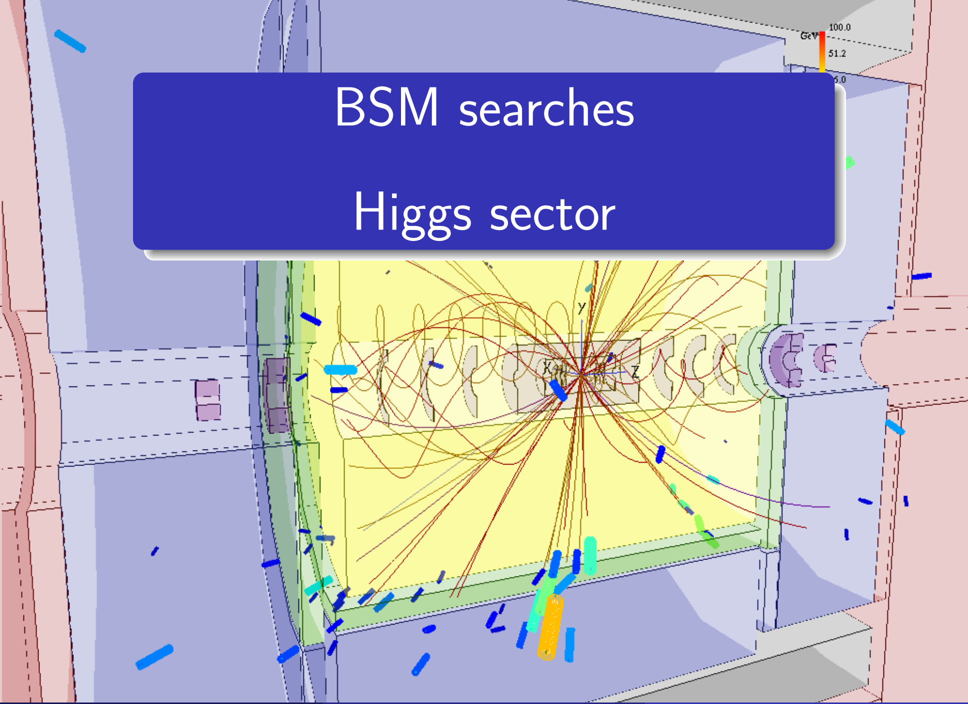
CLIC runnning scenario

Three construction stages:

- $\sqrt{s} = 380$ GeV with 500 fb^{-1} - initial stage
  selected as an optimal choice for precision Higgs and top physics
- $\sqrt{s} = 1.4$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 2000 fb^{-1}

BSM searches

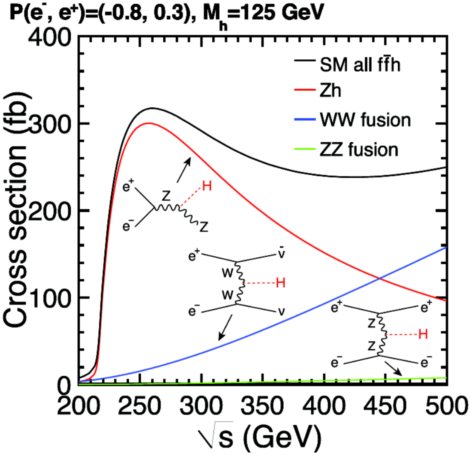
Higgs sector



Three major Higgs production channels

"Higgsstrahlung" ($e^+e^- \to Zh$) dominant at low energies

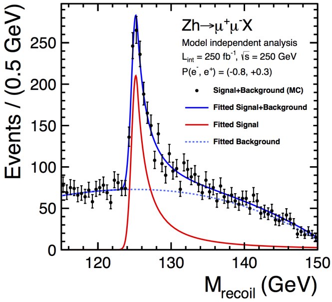
comparable with *WW* fusion for $\sqrt{s} \sim 400 - 500$ GeV

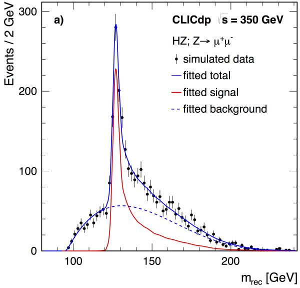


Zh reconstruction

Precise recoil mass measurement in $e^+e^- \to Z\ X$ events

$\Rightarrow$ model independent determination of Higgs production cross section and branching ratios (including $h \to cc,\ gg$, invisible)





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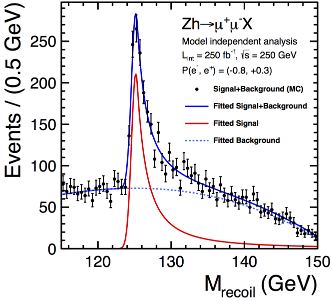
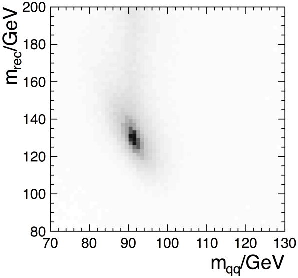




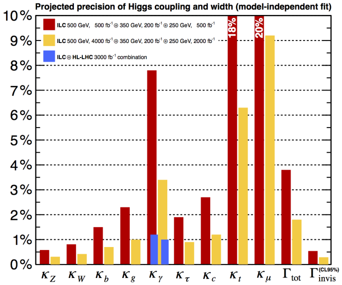
High purity also for hadronic Z decays $\Rightarrow$ large statistics

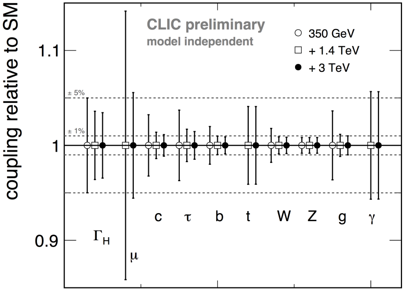
Higgs couplings

Recoil method

$\Rightarrow$ model-independent extraction of higgs couplings
and measurement of Γ^h_{tot}

Percent level precision expected for model-independent analysis



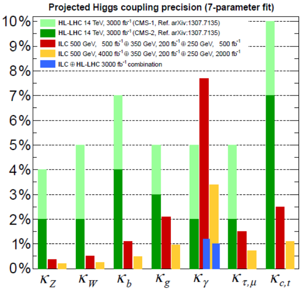


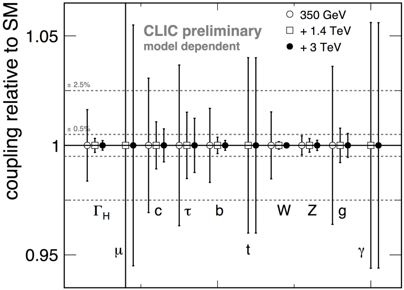
Keisuke Fujii et al. arXiv:1506.05992

Recoil method

⇒ model-independent extraction of higgs couplings
and measurement of Γ^h_{tot}

Sub-percent precision for constrained fit (as used in LHC analysis)





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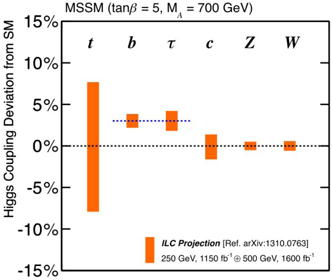
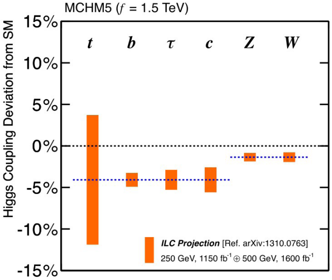
Deviations due to extended Higgs sectors expected in many models
Largest deviations typically 5% – 10%

⇒ LC should allow to discriminate between different models

Supersymmetry



Composite Higgs



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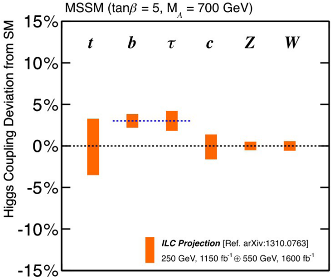

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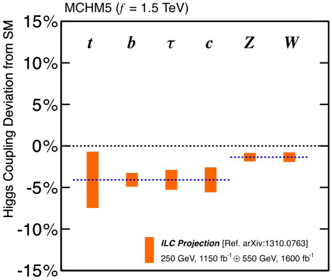
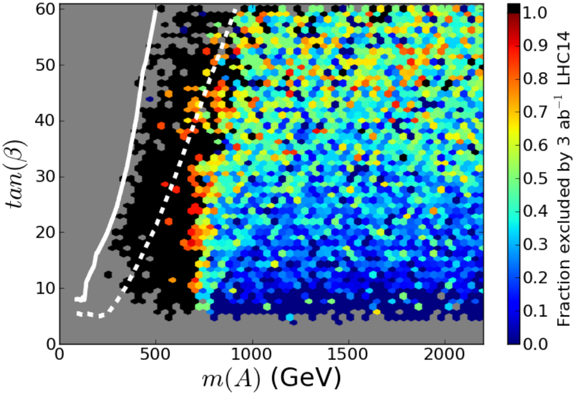


tth uncertainty @ ILC significantly reduced when running at 550 GeV.

Exclusion of pMSSM points: arXiv:1407.7021

fraction of models probed in $m_A - \tan\beta$ space

Higgs coupling measurements at HL-LHC



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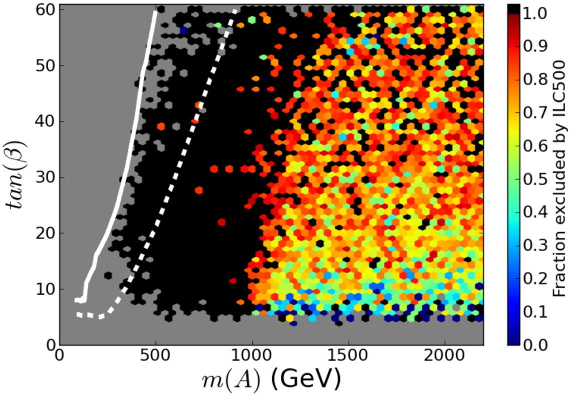
fraction of models probed in $m_A - \tan\beta$ space

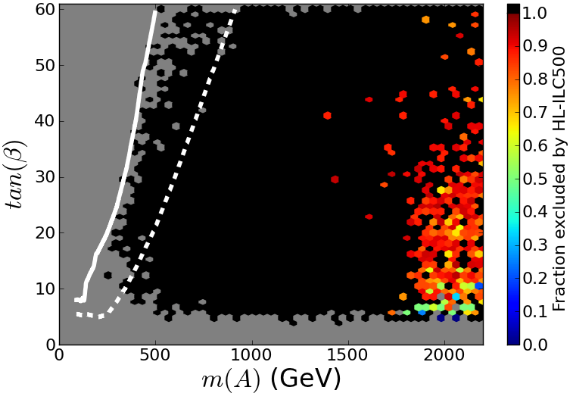
Higgs coupling measurements at ILC (initial stage)



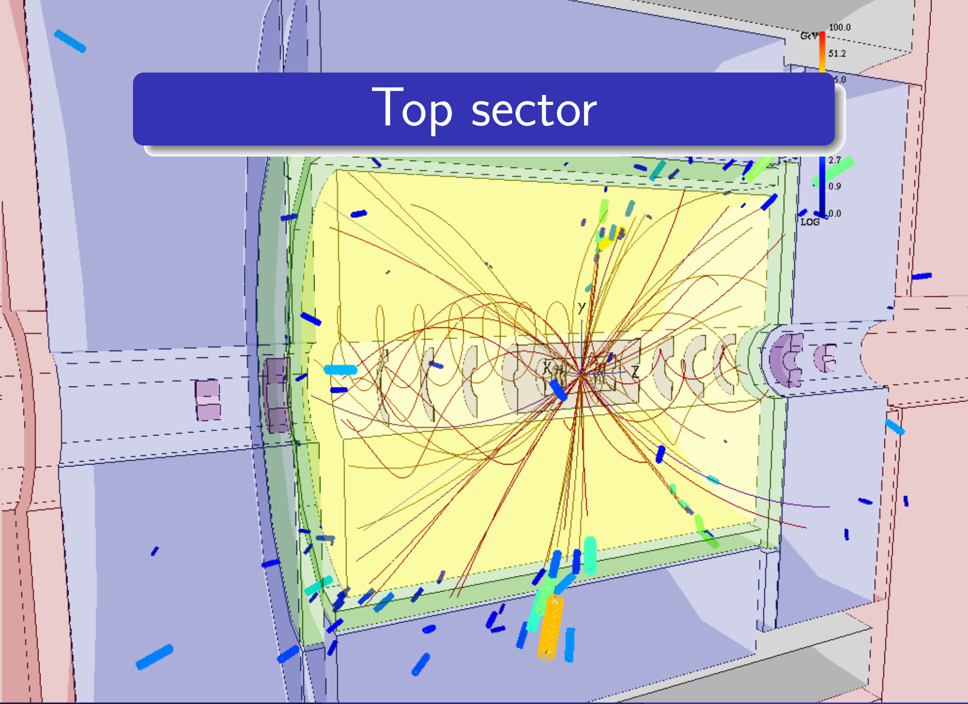
Exclusion of pMSSM points: arXiv:1407.7021

fraction of models probed in $m_A - \tan\beta$ space

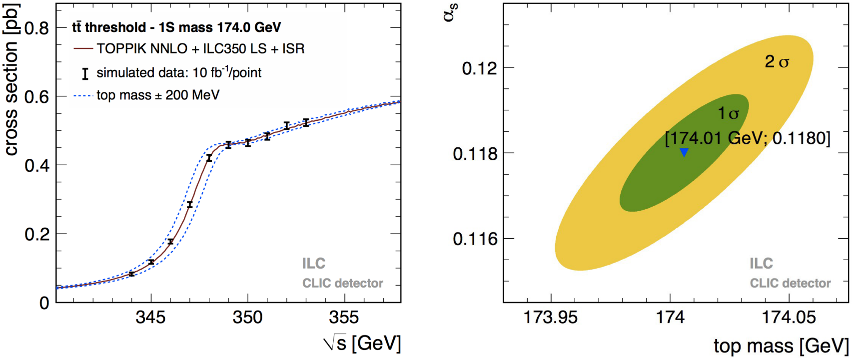
Higgs coupling measurements at ILC (Lumi upgrade)



Top sector



Top pair production cross section around threshold very sensitive to: strong coupling α_s, top quark mass m_t, width Γ_t and Yukawa coupling y_t

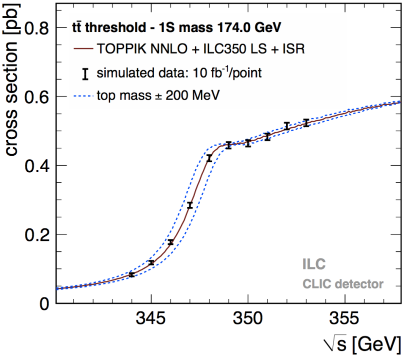


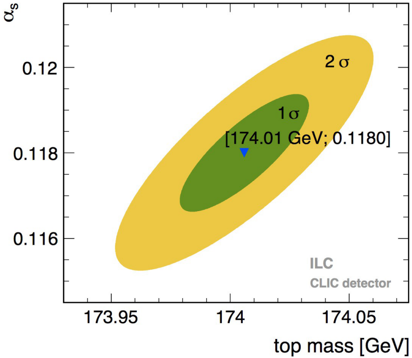
Precision mass measurement possible already with 100 fb^{-1}

$\Rightarrow \pm$ 10–30 MeV (stat) $\oplus$ 30 MeV (exp. sys.) $\oplus$ 20 MeV (theory)

Threshold scan

Top pair production cross section around threshold very sensitive to: strong coupling α_s, top quark mass m_t, width Γ_t and Yukawa coupling y_t





Precision mass measurement possible already with 100 fb^{-1}

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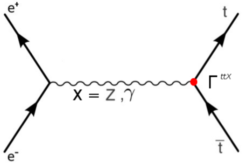
y_t can be extracted with statistical uncertainty $\sim$6% if α_s constrained from other measurements. Model dependent!

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics" contribution



General coupling form:

$$\Gamma_{\mu}^{ttX}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Electroweak couplings

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Possible higher order corrections
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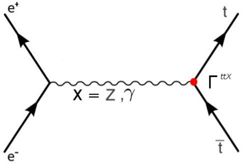

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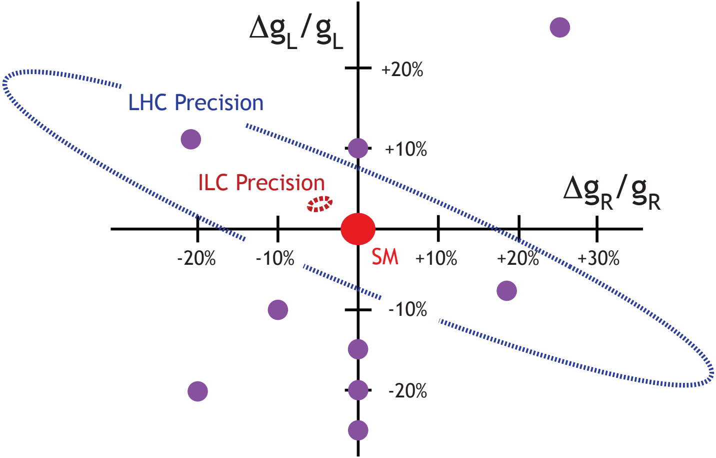
5 non-trivial form factors can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

for two polarization combinations: $e_L^- e_R^+$ and $e_R^- e_L^+$

Already the initial ILC running will allow for top coupling determination with 1-2% accuracy



In the Standard Model, FCNC top decays are strongly suppressed (GIM mechanism + CMK suppression):

$$\begin{aligned} BR(t \rightarrow c\,\gamma) &\sim 5\cdot 10^{-14} \\ BR(t \rightarrow c\,Z) &\sim 1\cdot 10^{-14} \\ BR(t \rightarrow c\,g) &\sim 5\cdot 10^{-12} \\ BR(t \rightarrow c\,h) &\sim 3\cdot 10^{-15} \end{aligned}$$

Significant enhancement possible in many "new physics" scenarios, due to modified couplings or loop contributions on new particles

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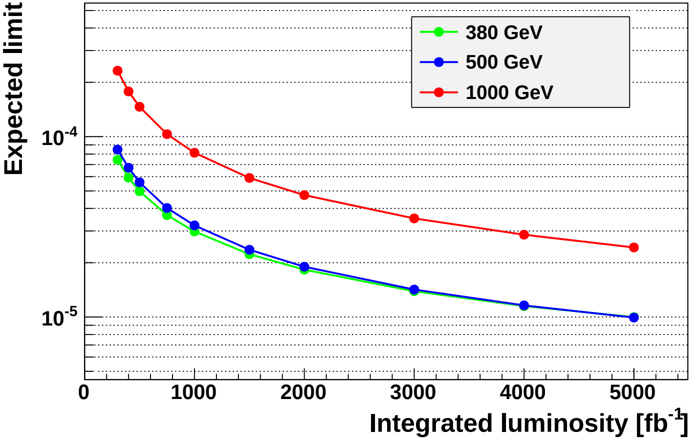
Decay $t \rightarrow c\,h$ looks promising:

- enhancement up to $BR \sim 10^{-5} - 10^{-2}$ possible
- test of Higgs boson couplings
- well constrained kinematics
- seems to be most difficult for LHC

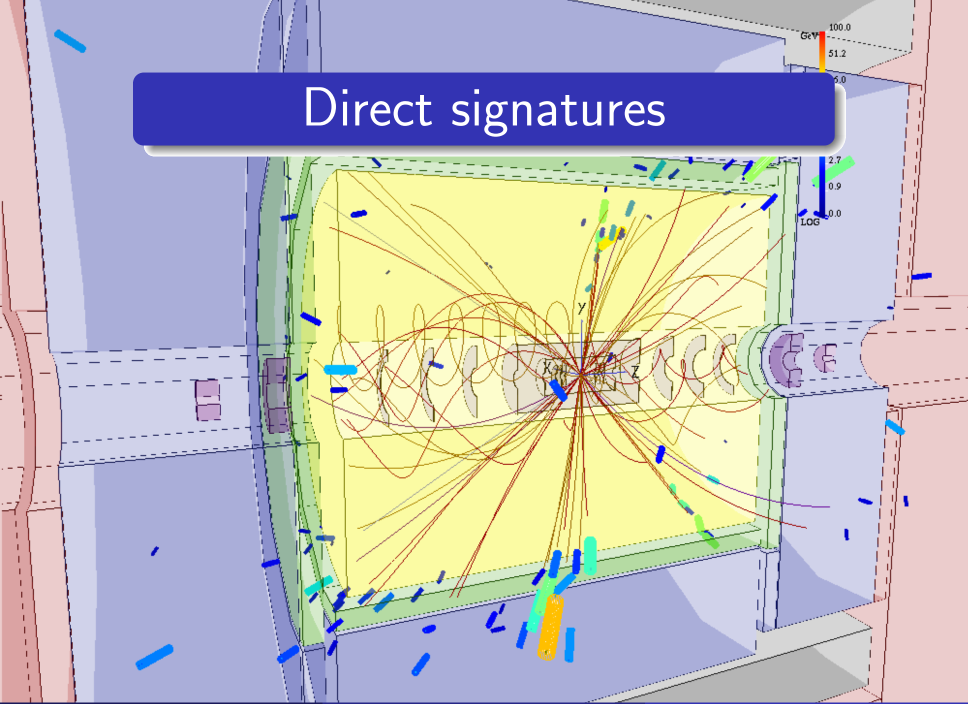
Tested for Two Higgs Doublet Model (2HDM) type III

Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 50%, different collision energies

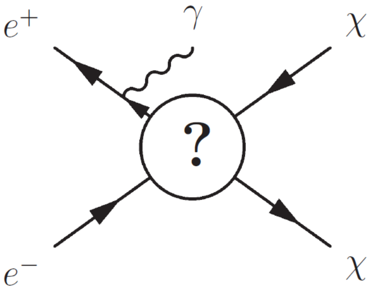


Direct signatures



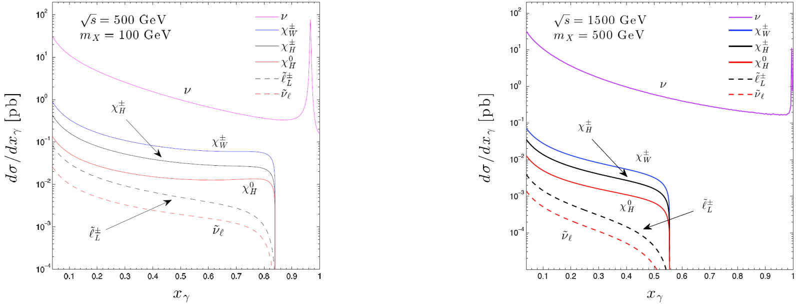
WIMP/DM/LSP Production

Single-photon processes at e^+e^- colliders:
possible signature for WIMP/Dark Matter/LSP production



Can be studied in detail thanks to: clean environment, detector hermecity, constrained kinematics, polarized beams

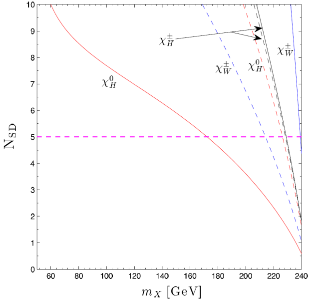
Expected cross sections for single photon production
for different signal scenarios and SM background

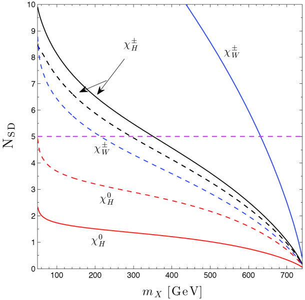


S.Y. Choi et al., PRD 92(2015)095006 [arXiv:1503.08538]
Updated for CLIC: J.Kalinowski @ CLIC Workshop 2016

WIMP/DM/LSP Production

Expected cross sections for single photon production
for different signal scenarios and SM background





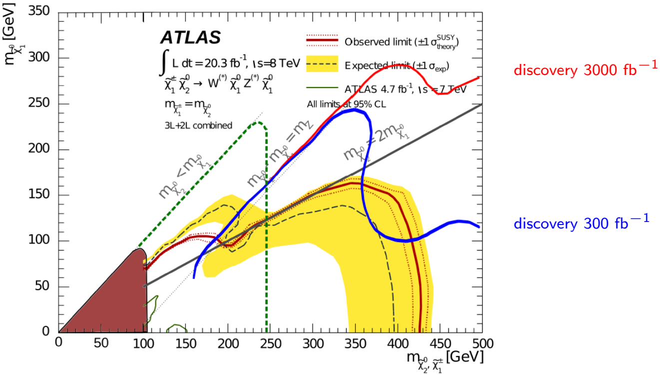
Background can be suppressed with recoil mass cut
and by using beam polarization

S.Y. Choi et al., PRD 92(2015)095006 [arXiv:1503.08538]
Updated for CLIC: J.Kalinowski @ CLIC Workshop 2016

In supersymmetric extensions of the Standard Model, higgsino-like charginos and neutralinos with EW scale masses are preferred

In cases where they are very close (degenerate) in mass

$\Rightarrow$ almost impossible to be observed at the LHC



arXiv:1403.5294, arXiv:1307.7292

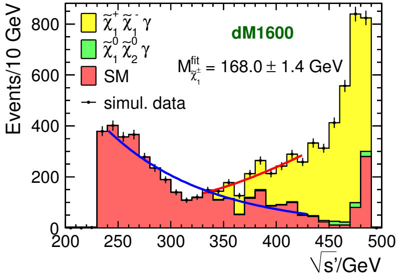
Higgsino Production

Chargino and neutralino pair production for model with

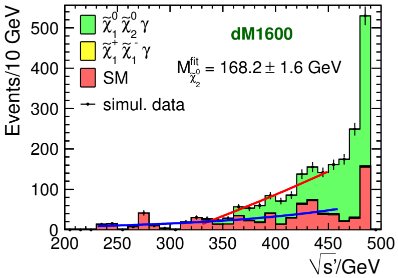
$$m_{NLSP} - m_{LSP} = 1.6\text{GeV}$$

Require: tagged ISR photon, large missing energy, "soft" final state

Chargino



Neutralino



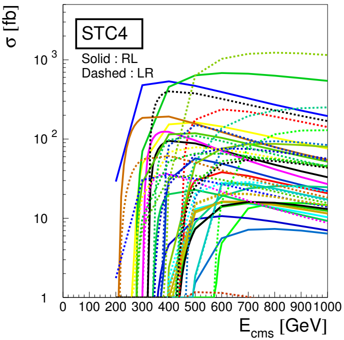
LSP mass resolution $\sim 1\%$

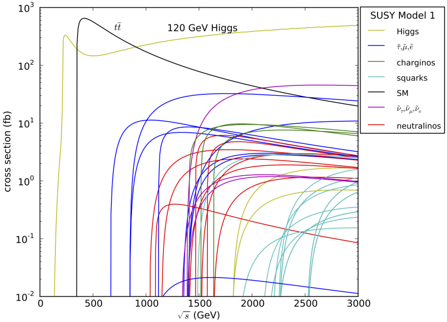
M. Berggren, et al., EPJC 73(2013)2660 [arXiv:1307.3566]

Sfermion Production

LHC can easily exclude strongly interacting squarks and gluinos
High energy LC can be competitive for sleptons and light bosinos

Many possible scenarios within the kinematic reach

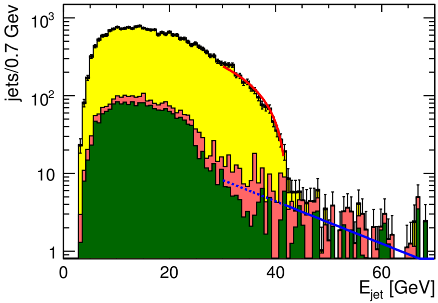




Sfermion Production

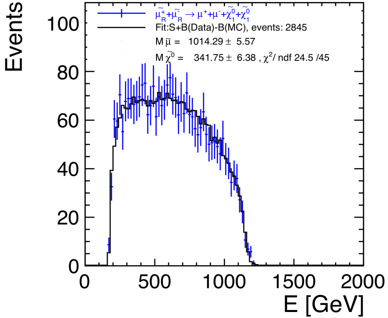
Very clean signatures with small backgrounds

Stau pair production



ILC, arXiv:1506.05992

Smuon pair production



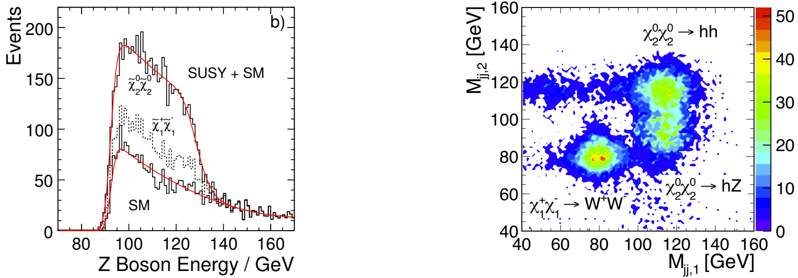
CLIC CDR, arXiv:1202.5940

Gaugino Production

Chargino and neutralino pair production: four jets and missing energy

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 h\, h$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 h\, Z$$

Very good reconstruction thanks to excellent jet energy resolution
Cross section determination to 1–3%, mass fit to 1–3 GeV



arXiv:0906.5508

Inert Doublet Model

One of the simplest extensions of the Standard Model (SM).
The scalar sector consists of two doublets:

- Φ_S is the SM–like Higgs doublet,
- Φ_D (inert doublet) has four additional scalars H, A, $H^{\pm}$.

$$\Phi_S = \begin{pmatrix} G^{\pm} \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} H^{\pm} \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

The most general scalar potential has seven real parameters
Two parameters fixed from Standard Model (v, M_h)
$\Rightarrow$ 5 new, free parameters: M_H, M_A, $M_{H^\pm}$ + 2 couplings.

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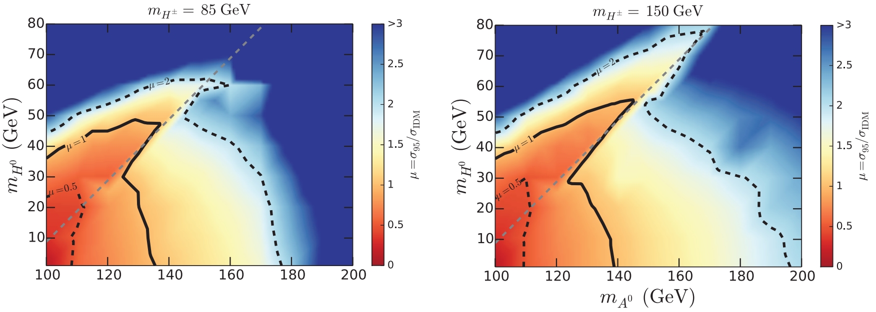
Assuming a discrete Z_2 symmetry (SM particles even, inert scalars odd)
$\Rightarrow$ Yukawa-type interactions only for Higgs doublet (Φ_S).
The inert doublet (Φ_D) does not interact with the SM fermions!
$\Rightarrow$ The lightest inert particle is stable: a natural candidate for dark matter!
Inert scalars couplings to γ, $W^{\pm}$ and Z determined by SM parameters

Inert scalars can be pair-produced at LHC via virtual Z or W exchange.
Recasting the results of ATLAS Run I dilepton analyses:

- SUSY-2013-11: Chargino, neutralino and slepton [arXiv:1403.5294]
- HIGG-2013-03: $ZH \to l^+l^- +$ inv. [arXiv:1402.3244]



Sabine Kraml, presented at "Scalars 2015", Warsaw, December 2015
G. Belanger et al., arXiv:1503.07367

Inert Doublet Model

Benchmark points (BP) for investigation at LHC Run II arXiv:1508.01671

- Benchmark point 1: low scalar mass

$$M_H = 57.5\,\mathrm{GeV},\; M_A = 113.0\,\mathrm{GeV}, M_{H^\pm} = 123\,\mathrm{GeV}$$

- Benchmark point 2: low scalar mass

$$M_H = 85.5\,\mathrm{GeV},\; M_A = 111.0\,\mathrm{GeV}, M_{H^\pm} = 140\,\mathrm{GeV}$$

- Benchmark point 3: intermediate scalar mass

$$M_H = 128.0\,\mathrm{GeV},\; M_A = 134.0\,\mathrm{GeV}, M_{H^\pm} = 176.0\,\mathrm{GeV}$$

- Benchmark point 4: high scalar mass, mass degeneracy

$$M_H = 363.0\,\mathrm{GeV}, M_A = 374.0\,\mathrm{GeV}, M_{H^\pm} = 374.0\,\mathrm{GeV}$$

- Benchmark point 5: high scalar mass, no mass degeneracy

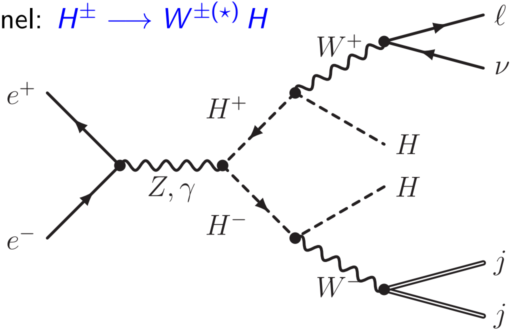
$$M_H = 311.0\,\mathrm{GeV}, M_A = 415.0\,\mathrm{GeV}, M_{H^\pm} = 447.0\,\mathrm{GeV}$$

H is DM candidate, A decays always to $Z\,H$, $H^\pm$ decays mainly to $W^\pm\,H$

Large cross section (up to 100 fb^{-1}) for charged scalar production

$$e^+e^- \to H^+H^-$$

Main decay channel: $H^\pm \longrightarrow W^{\pm(\star)}\,H$



For the low mass benchmark scenarios $M_{H^\pm} < M_W + M_H$

$\Rightarrow$ produced $W^\pm$ have to be virtual

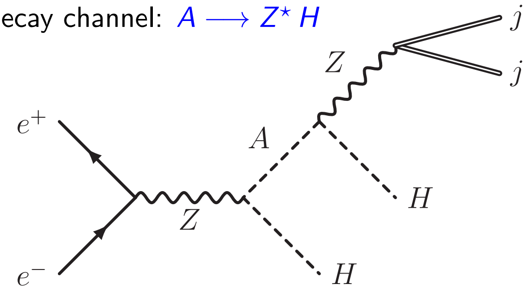
Final state topology depends on the $W^\pm$ decays (as for $t\bar{t}$ events)

Most promising channel: semi-leptonic decay

Neutral scala production:

$$e^+e^- \to AH$$

With only one decay channel: $A \longrightarrow Z^\star H$



For the low mass benchmark scenarios $M_A < M_Z + M_H$

$\Rightarrow$ produced Z have to be virtual

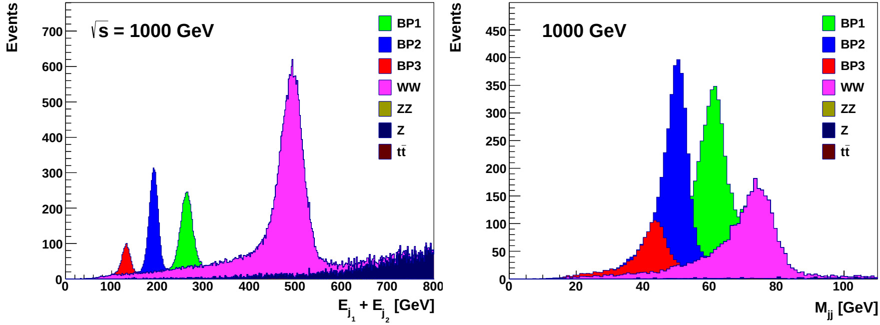
Both hadronic and leptonic Z decays can be considered.

Event statistics much higher in the hadronic channel.

Due to kinematic constraints, both for charged and neutral scalar production, we expect to observe maxima for signal events in

jet energy sum and jet invariant mass distributions

Charged scalar production



semi-leptonic channel

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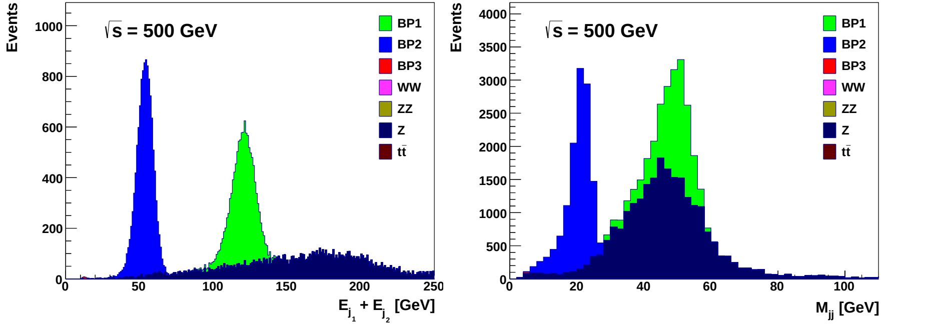
Neutral scalar production



hadronic channel

Due to kinematic constraints, both for charged and neutral scalar production, we expect to observe maxima for signal events in
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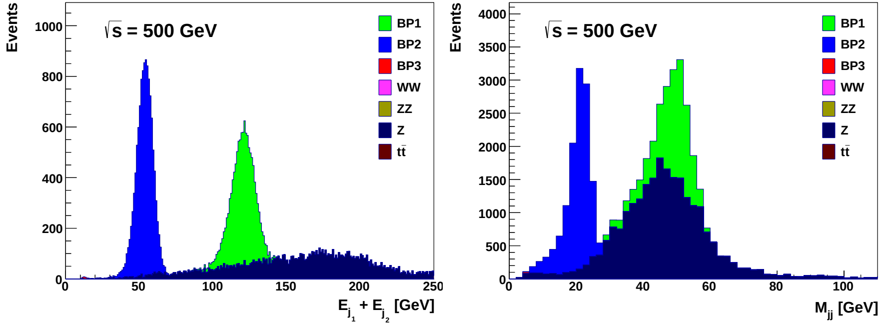
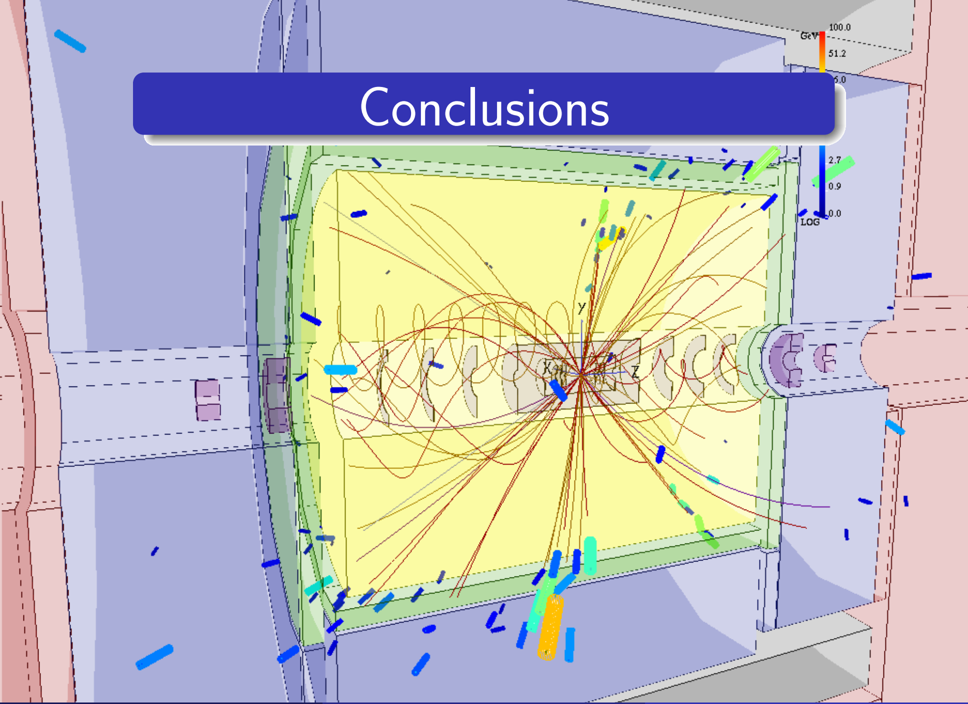
Neutral scalar production



hadronic channel

Clear signal separation ⇒ masses can be reconstructed to ∼100 MeV (stat)

Conclusions



Conclusions

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The ILC project is waiting for “green light”
could produce first result already in 20 years.

It has the potential to make major contributions to particle physics -
we should strongly support it and hope for the positive decision in Japan...

Thank you!