

# Particle Discovery Opportunities at the International Linear Collider

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on behalf of the LCC Physics Working Group

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# The International Linear Collider

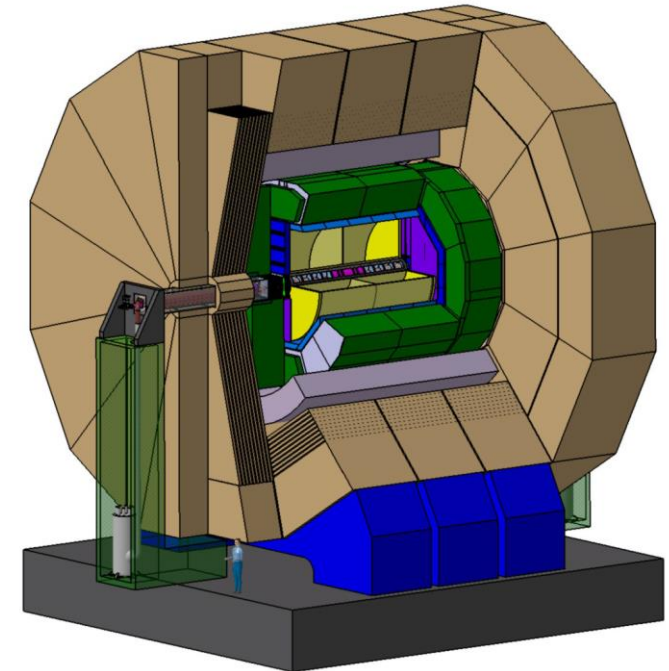
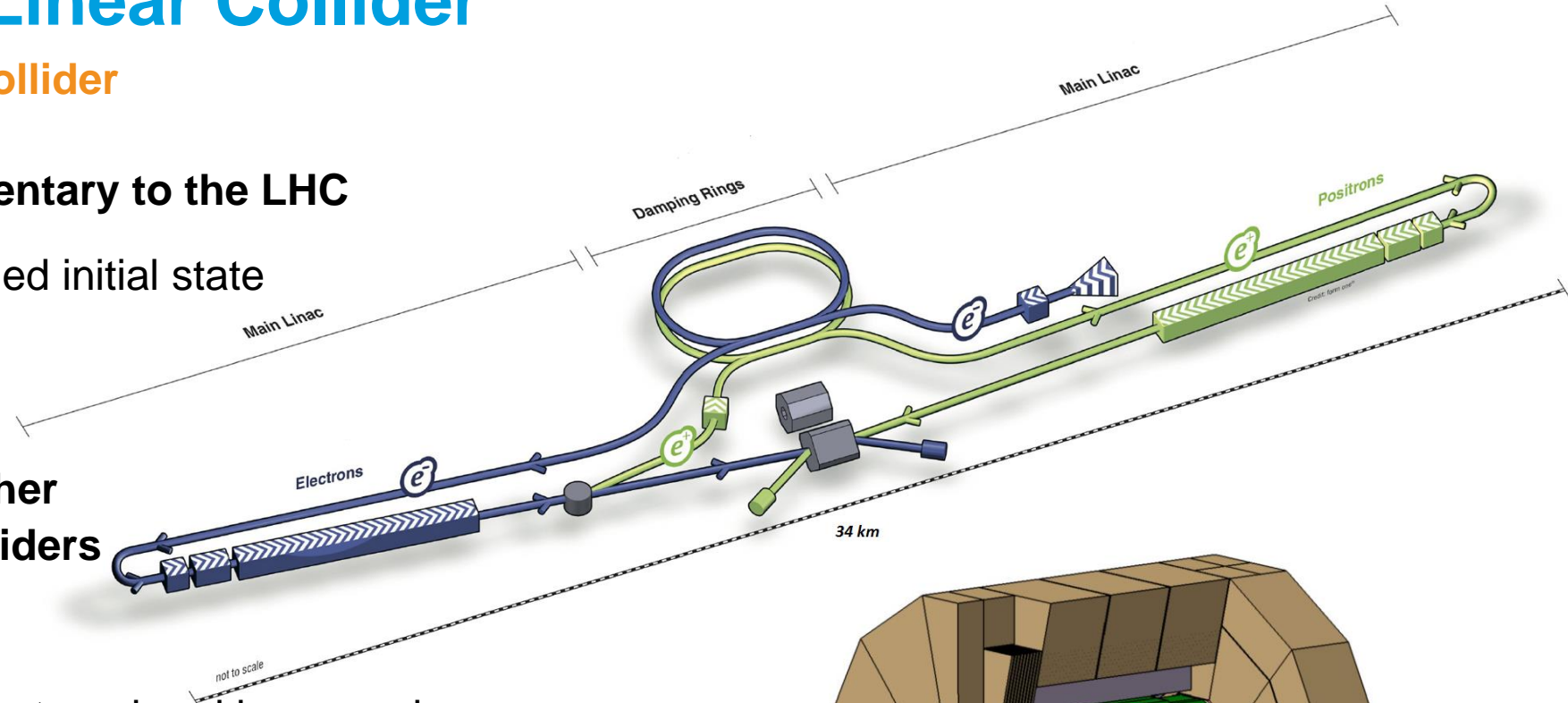
## A planned electron-positron collider

### Lepton colliders are complementary to the LHC

- cleaner environment, controlled initial state
- coupling to leptons is tested

### Advantages of the ILC over other planned electron-positron colliders

- mature technology
- centre-of-mass energy can be tuned and increased: 250 GeV in initial stage, upgrades to 500 GeV and 1 TeV
- polarisation of both beams:  $P(e^-)=\pm 80\%$ ,  $P(e^+)=\mp 30\%$
- triggerless operation
- hermeticity of detector down to lowest angles



# The BSM Physics Programme of the ILC

Large range of detailed studies

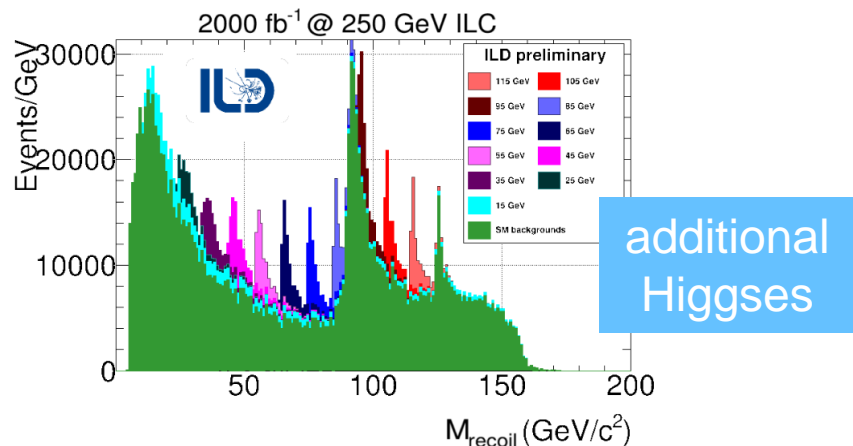
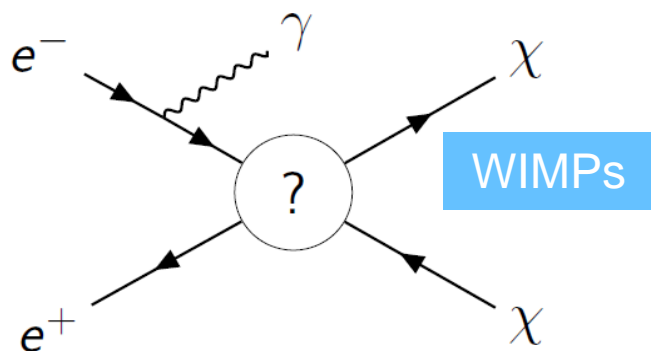
arxiv:1702.05333

The Potential of the ILC for Discovering new Particles → focus on 500 GeV

arxiv:1903.01629

The International Linear Collider: A Global Project → focus on 250 GeV

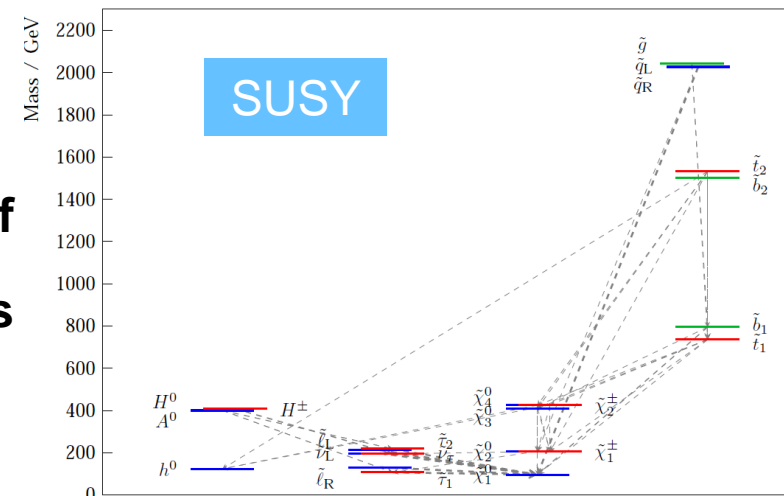
from generic searches ...



... to studies of complete BSM models

in addition: indirect constraints

- Higgs precision measurements **talk by S. Kawada**
- Standard Model precision measurements

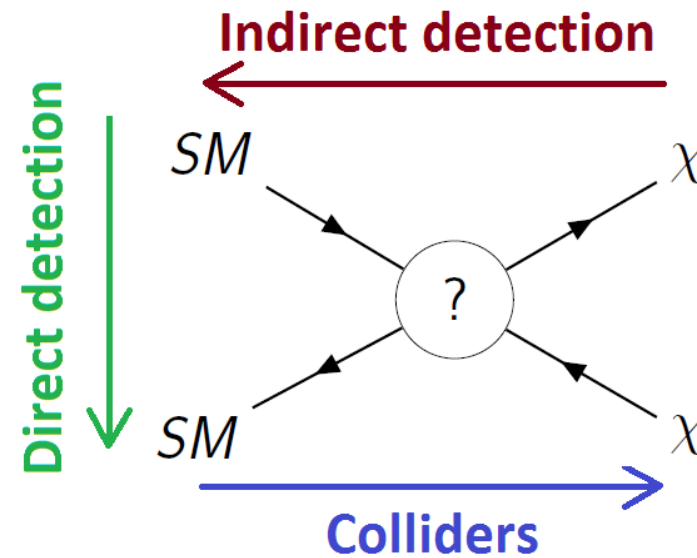


# Searches for WIMP Dark Matter

WIMPs = Weakly Interacting Massive Particles

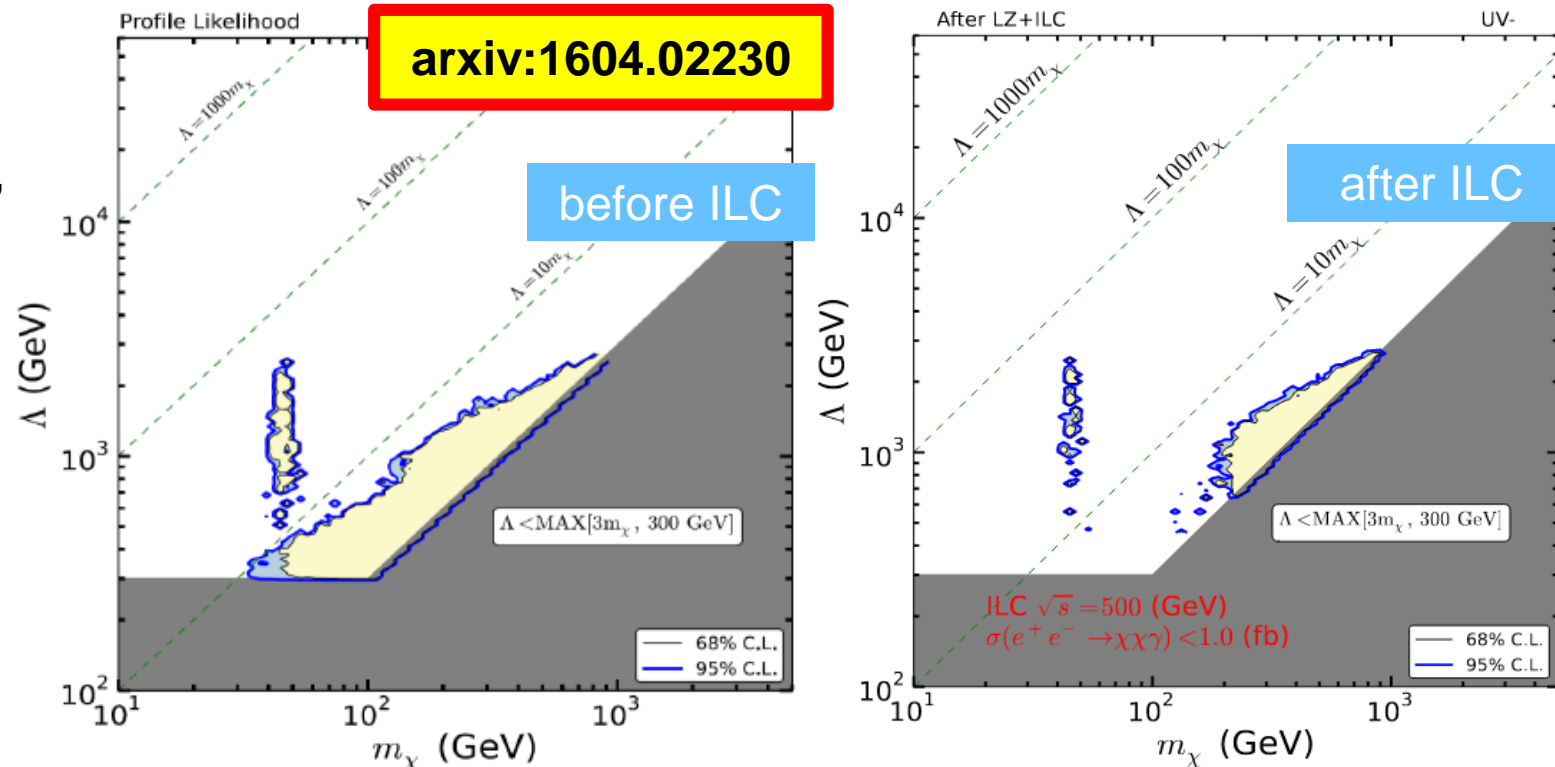
## Interplay between search channels

- direct and indirect detection
- collider searches



## Example: singlet-like fermion WIMP

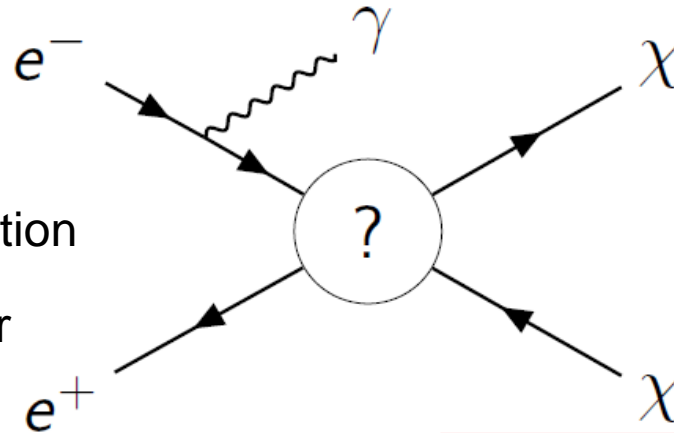
- likelihood analysis of Planck, PICO-2L, LUX, XENON100, LEP, LHC, plus LZ, PICO250 projections
- surviving region assuming no WIMP signals are detected  
→ can be tested at the ILC
- framework: effective operators ( $\Lambda$  – energy scale of new physics)



# WIMPs in the Mono-Photon Channel

## Generic collider search

- WIMP pair production
- with a photon from initial state radiation
- single photon in an “empty” detector



DESY-THESIS-2018-039

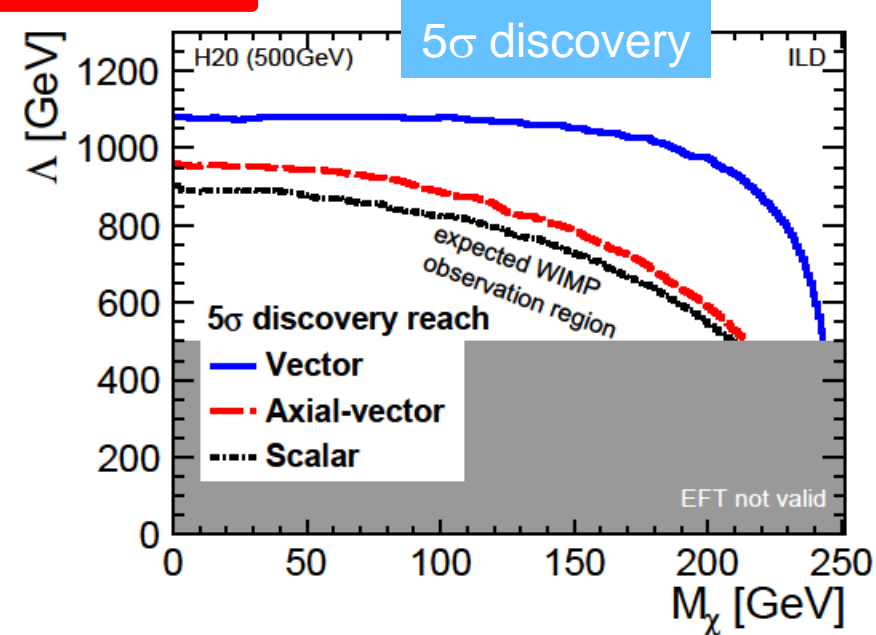
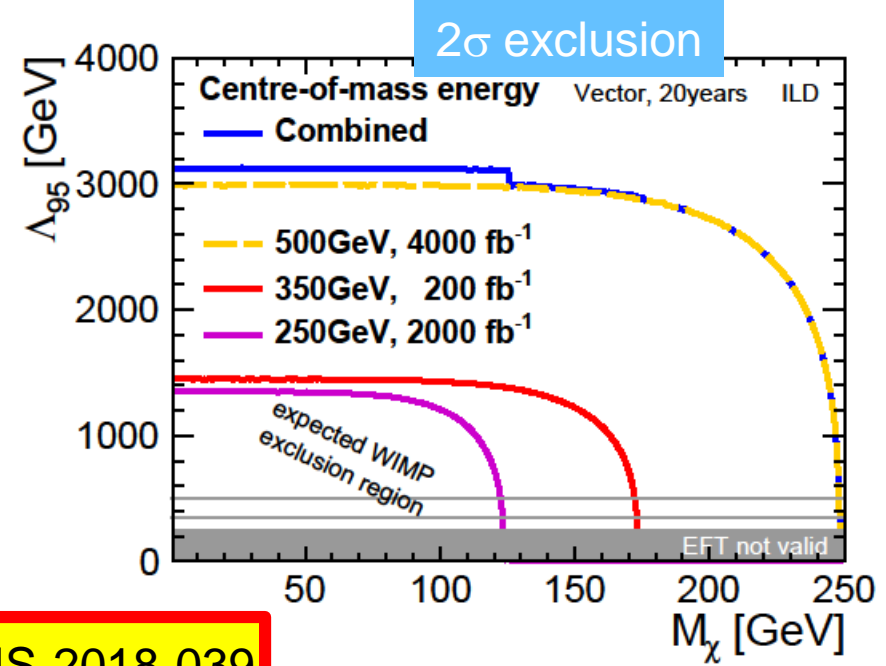
## Example: vector-like fermion WIMP

### effective operators

- valid: testable energies  $\gg \sqrt{s}$
- operators
  - vector
  - axial-vector
  - scalar

### full detector study at 500 GeV

- careful ISR modelling
  - several photons possible
  - double-counting avoided
- ILC accelerator environment
  - luminosity spectrum
  - beam-induced background



# Sensitivity to WIMP Dark Matter: Operation Scenarios

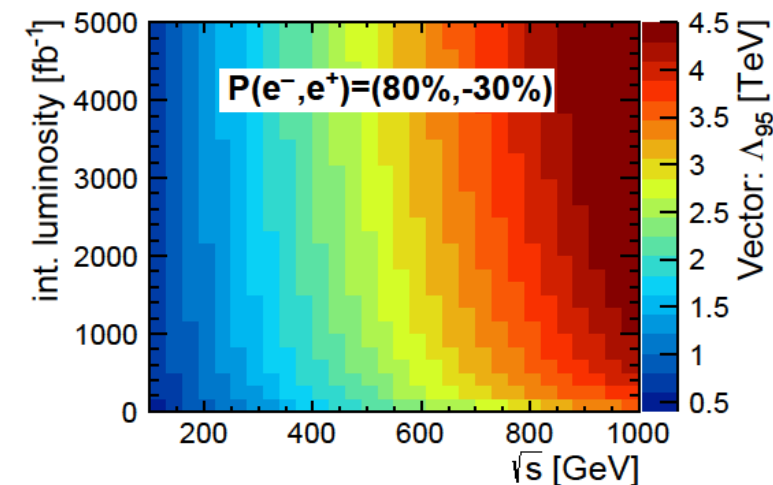
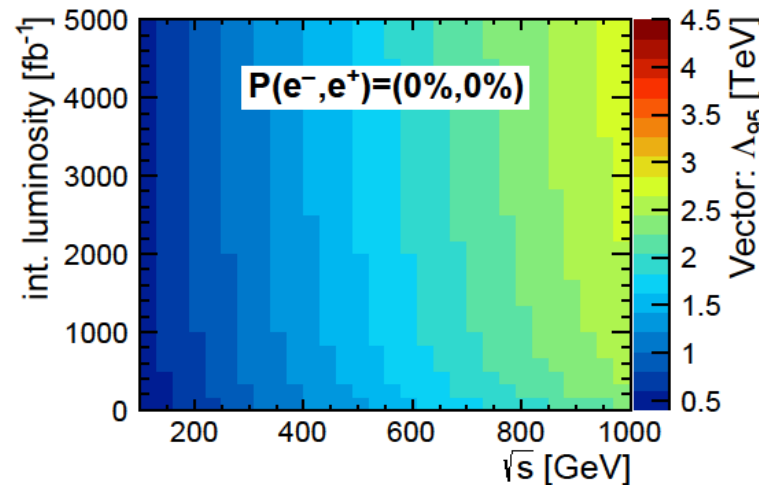
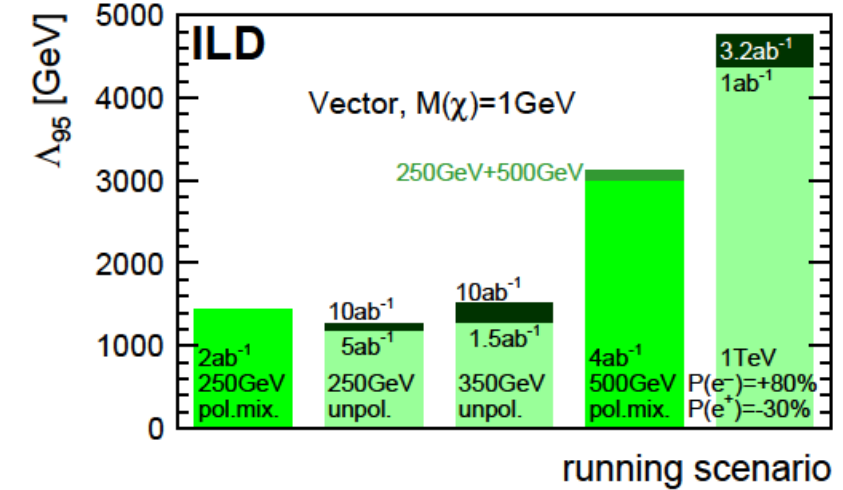
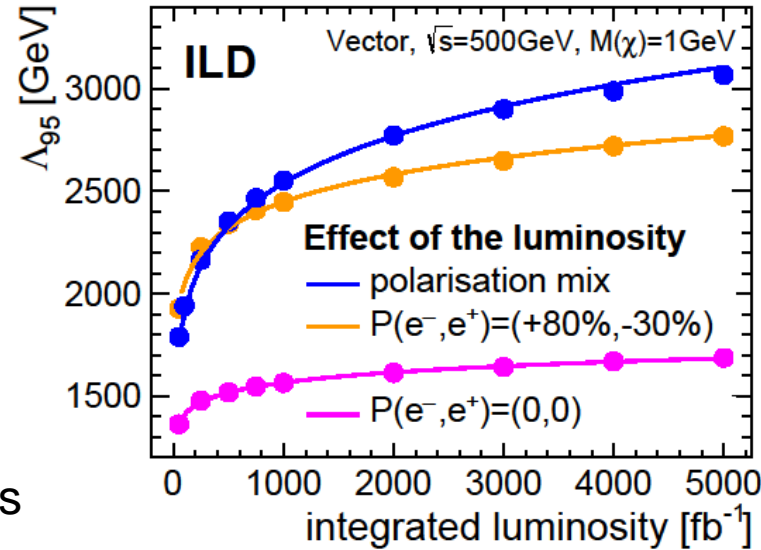
## Role of $\sqrt{s}$ , luminosity and polarisation

### Polarisation is crucial

- suppression of neutrino background
- enhancement of signal
- provides statistically independent data sets with different polarisation configurations  
→ control of systematic uncertainties

### Higher centre-of-mass energies are favored

- signal cross-section rises with energy
- collecting data for decades at a moderate energy is worse than running at higher energies and collect a smaller data set





# Detector Hermeticity

Background suppression crucial for BSM studies

## Bhabha scattering: background for WIMPs

- huge cross-section
- particles mainly in forward region  
→ challenging reconstruction  
→ mono-photon signal can be mimicked

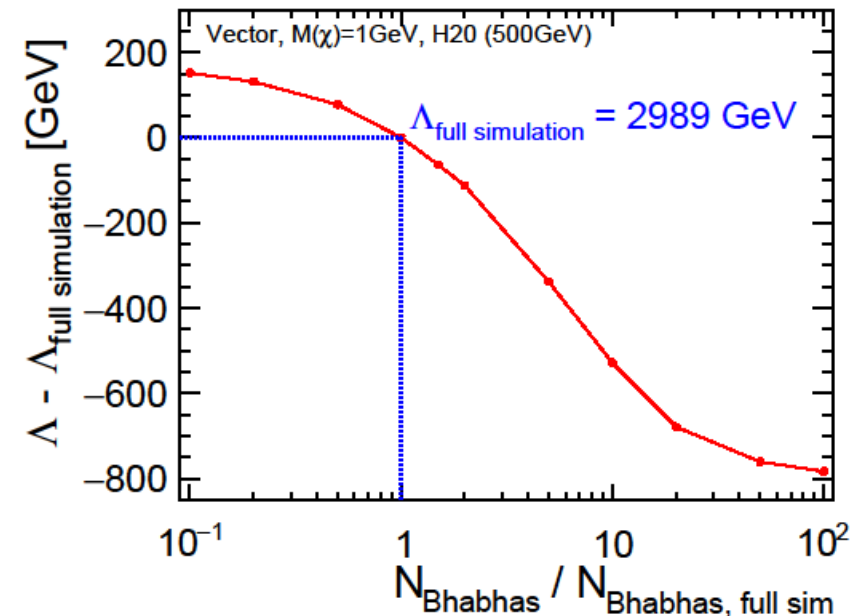
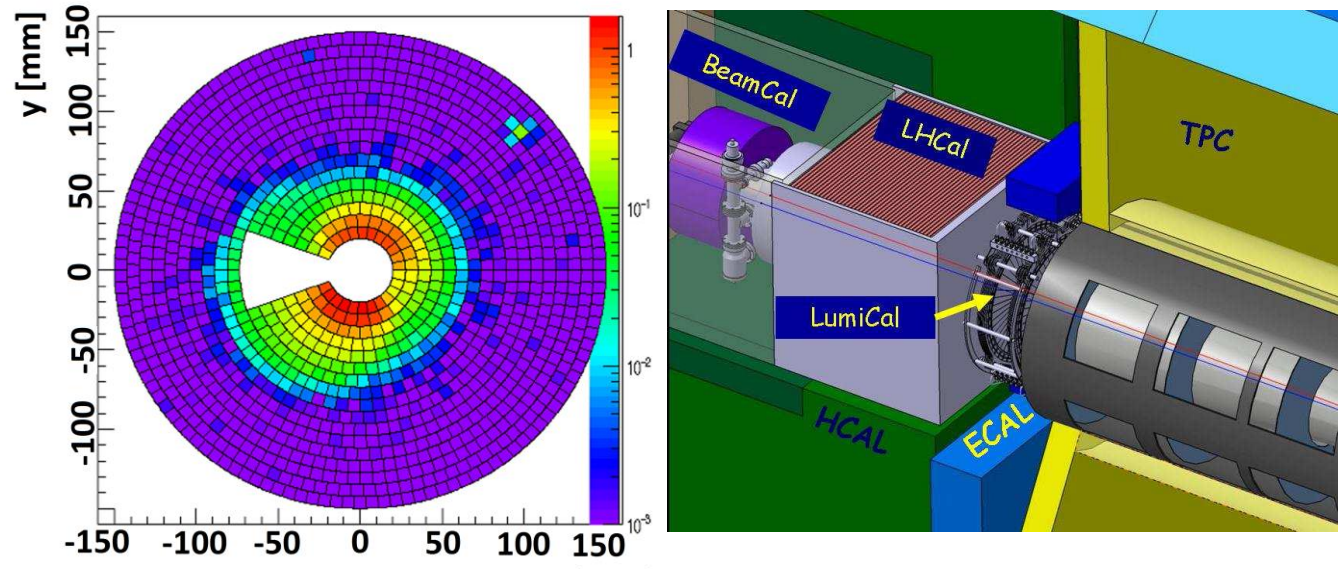
## Overlay

- pairs produced from beamstrahlung photons
- forward region is polluted

## Hermeticity study: WIMPs as example

- sensitivity depends on number of reconstructed Bhabha scattering events
- with a larger “blind region” around beam pipes: testable energy reach is significantly reduced

forward detector BeamCal



# Dark photon search

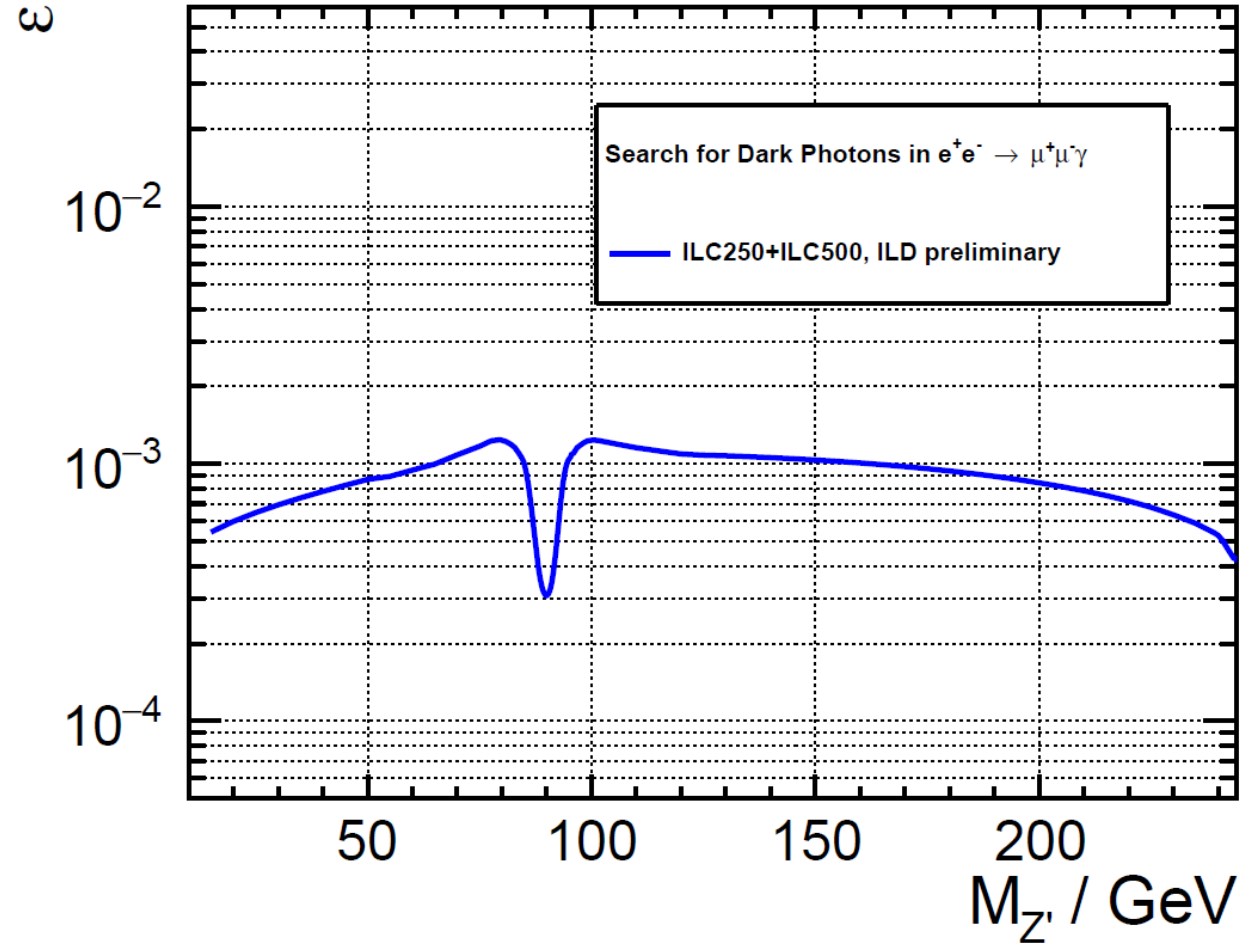
$$e^+e^- \rightarrow \gamma A' \rightarrow \gamma \mu^+ \mu^-$$

**95% exclusion limit** (no deviation from SM observed)

- amplitude  $\varepsilon$ : mixing of dark photon with hypercharge gauge boson
- assumes full ILC programme  
→ shown mass range dominated by run at 250 GeV

## role of polarisation

- polarisation not considered in study  
→ sensitivity around  $Z$  mass could improve
- for invisible decay products: polarisation crucial to suppress SM neutrino background





# Additional Higgs Bosons

## Search for extra light scalars

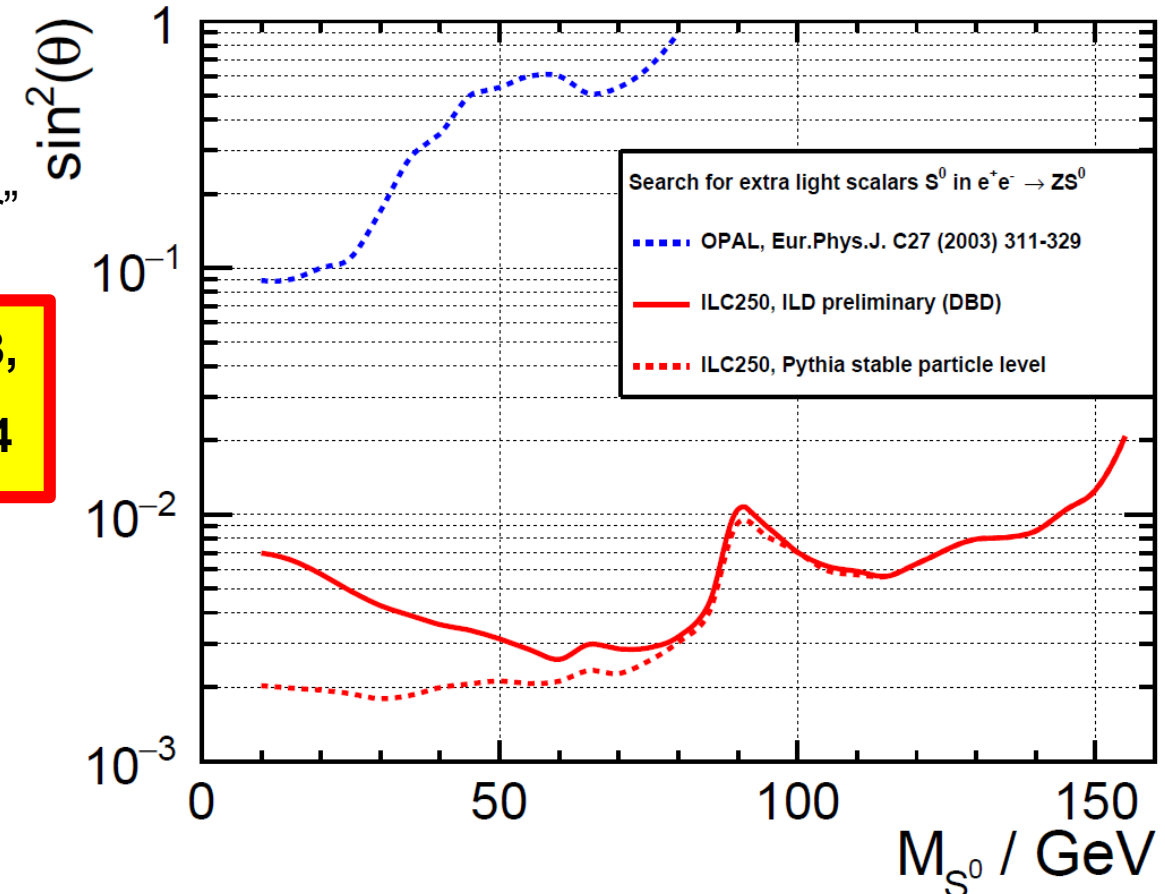
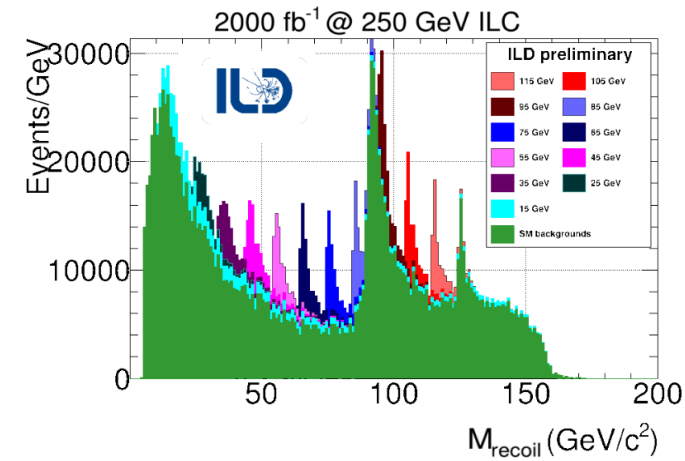
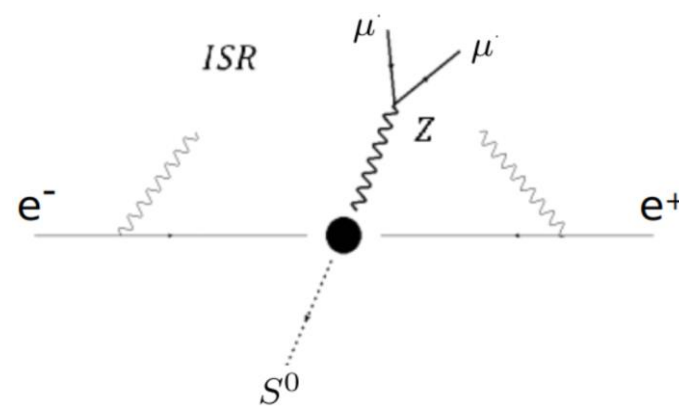
### Recoil against Z

- lepton collider: initial state 4-mom. is known
- Z reconstructed from its decay products  
→ Higgs can be reconstructed as the missing 4-mom.
- reconstruction of the scalar without “looking at the scalar”  
→ highly model-independent

**arxiv:1902.06118,**  
**arxiv:1801.08164**

### Exclusion limit

- $\sin^2(\theta)$ : cross-section relative to a SM Higgs with corresponding mass
- full detector simulation  
→ for low masses: detector effects play a role



# Supersymmetry

## UV-complete BSM models

**assumption: discovery of several new particles**

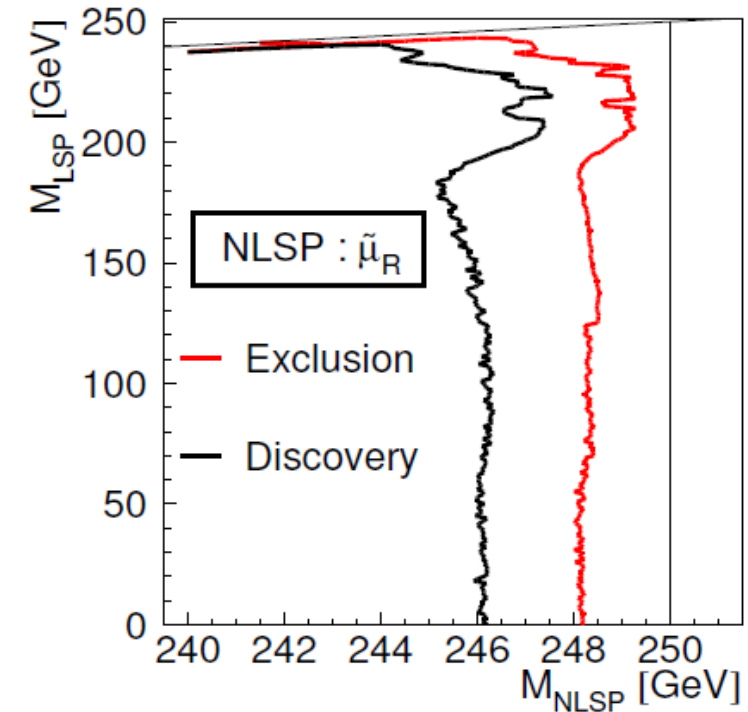
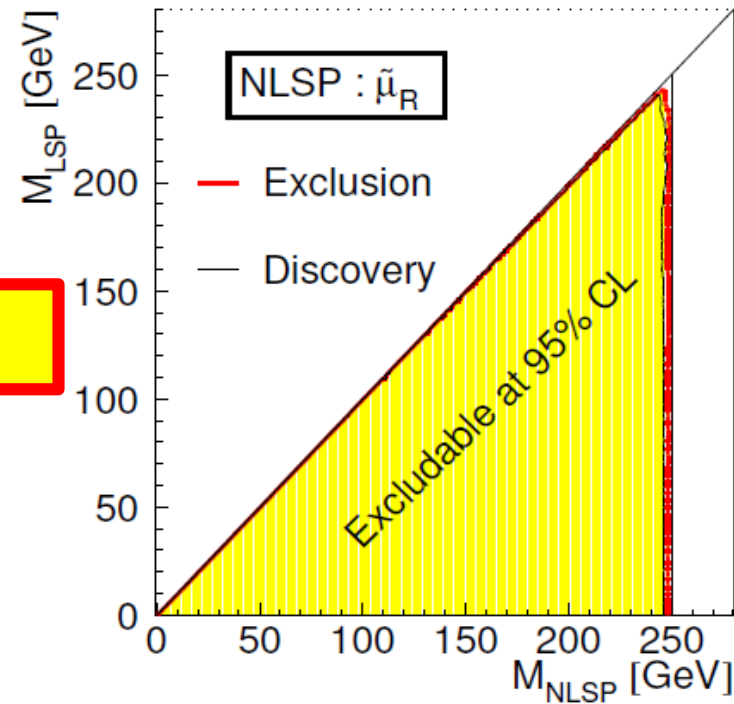
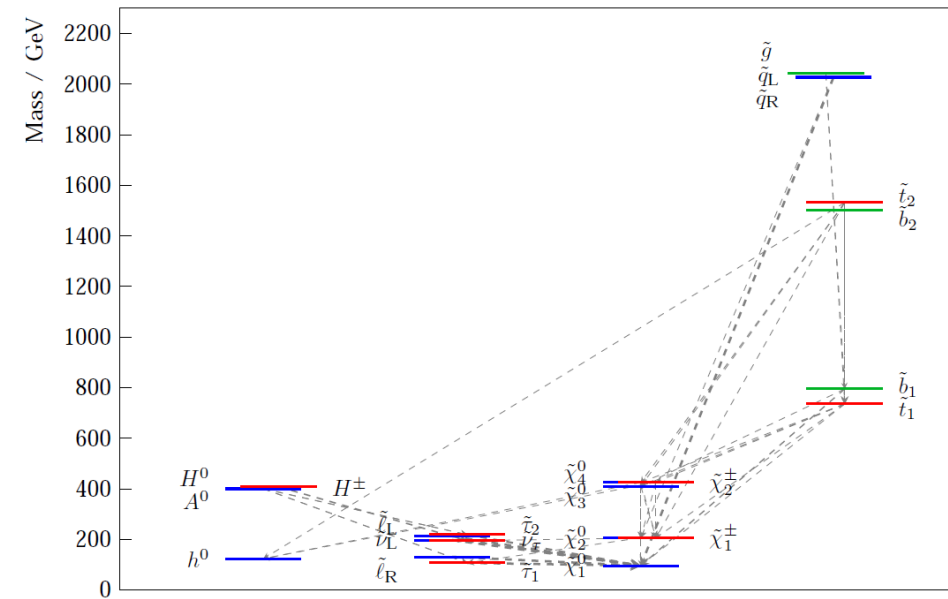
- nature of new physics can be tested
- conclusions about underlying parameters

**detector simulations of the complete model**

- complete particle spectrum
- model branching ratios (instead of just assuming 100% for dominant channel)

**loop-hole free searches** arxiv:1308.1461

- exclusion and discovery close-by
- in case of a discovery: accurate measurements



# SUSY: Fitting the Dark Matter Relic Density $\Omega$

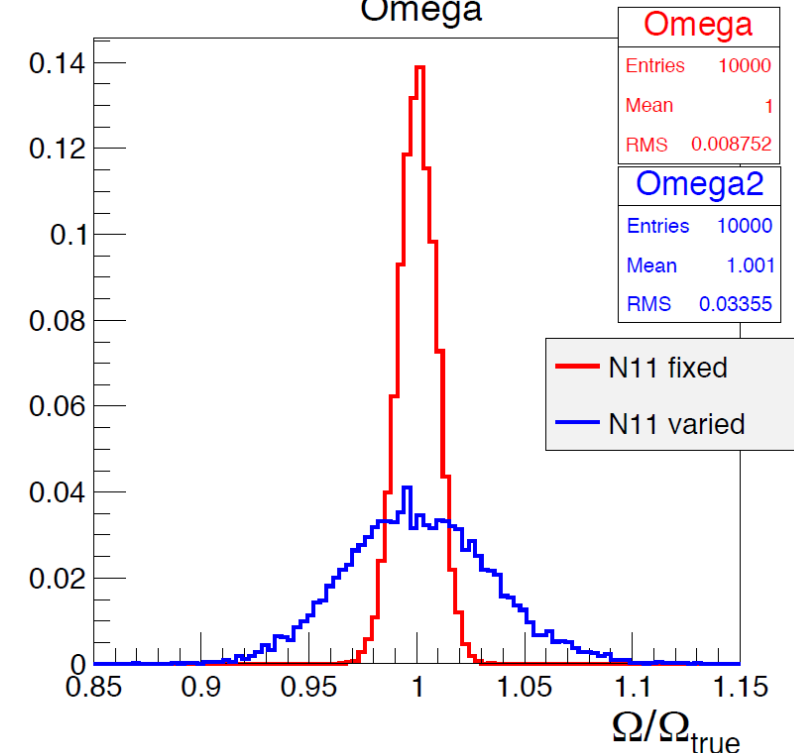
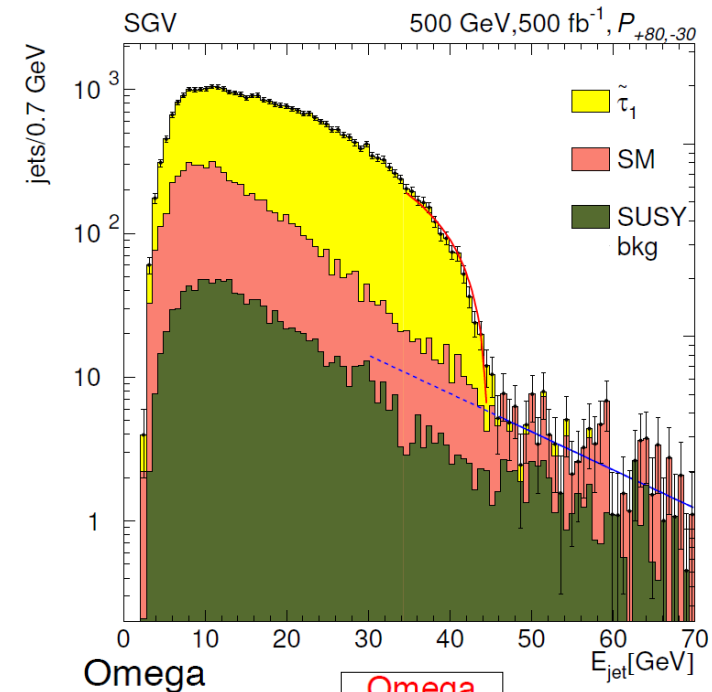
## Stau coannihilation scenario

example for precision measurement:  
stau coannihilation

- study at 500 GeV **arxiv:1508.04383**
- $\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_1^0$  endpoint  $\rightarrow$  stau mass precision 0.15%

lightest supersymmetric particle (LSP) is *the* dark matter

- with SUSY observables as input dark matter relic density can be fitted **arxiv:1602.08439**
  - using micrOMEGAs (arxiv:1305.0237)
  - input: discovery of all sleptons, sneutrinos,  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_1^\pm$  with permille mass precision
  - fit precision 2%  $\rightarrow$  same precision as Planck
- clear identification of LSP as dark matter constituent



# SUSY: Testing Gaugino Mass Unification

Natural SUSY with light Higgsinos

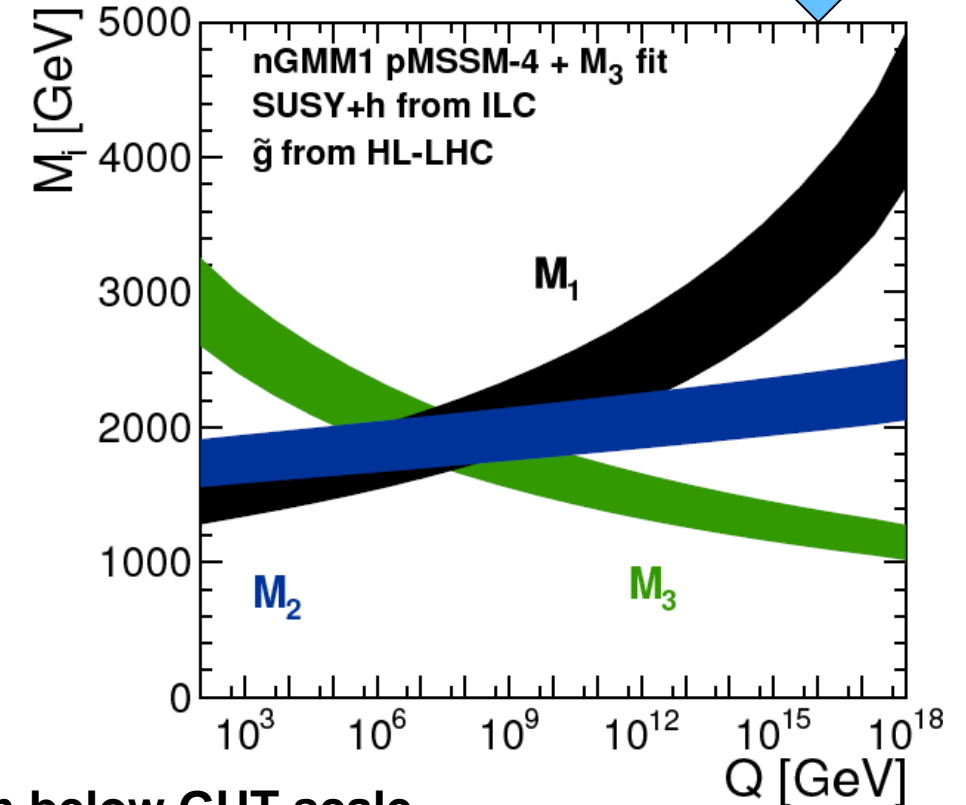
talk by S. Sasikumar

## The studied scenario

- mirage mediated breaking model
- not excluded

## Running gaugino masses

- gaugino masses are fitted (at 1 TeV)
  - using Fittino (arxiv:hep-ph/0412012)
  - with Higgsino masses and polarised cross-sections as input
- evolving gaugino masses to higher scales
  - using renormalisation group equations
  - bands show  $1\sigma$  confidence levels



## Unification below GUT scale

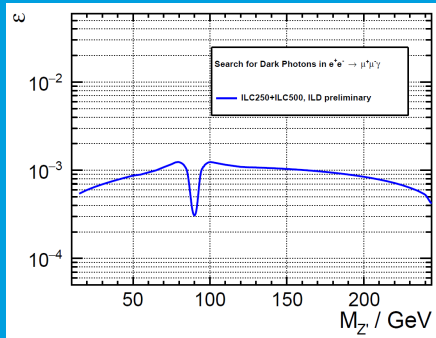
- running of  $M_1$ ,  $M_2$  and  $M_3$
- unification at GUT scale can be excluded from fit
- good precision with 10% measurement of gluino mass from HL-LHC

# Conclusion

new particle that couple preferentially to leptons

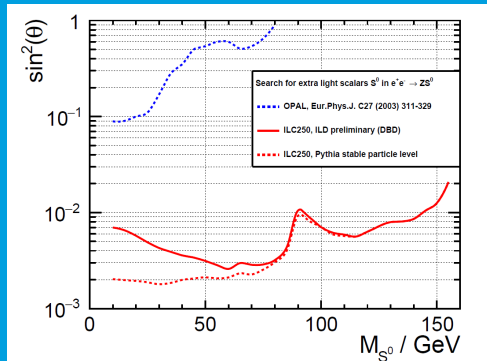
polarisation of both beams  
 → chirality of new process can be tested

The ILC has the potential to find ...

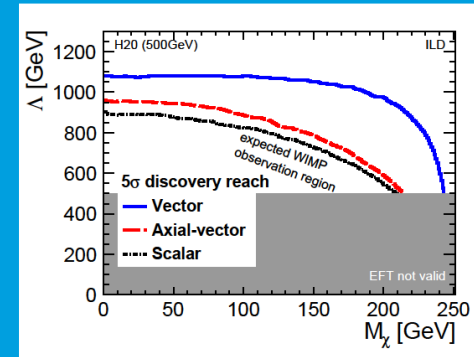


precision measurements

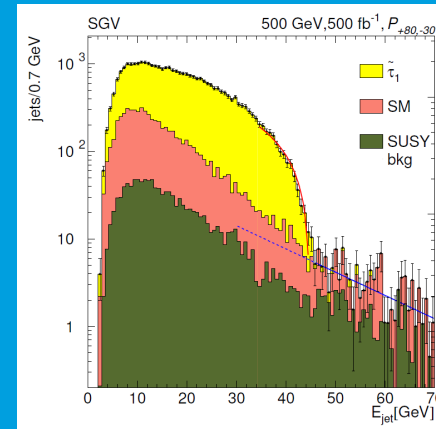
exclusion limits



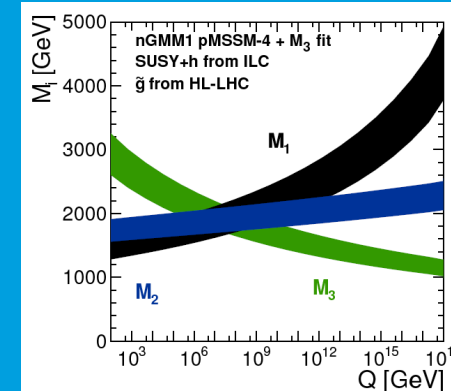
polarisation: control of systematics



new particles



loop-hole-free searches



new physics

Lepton colliders cover unique parameter space → complementary to the LHC

Polarisation of both beams is crucial for many searches → ILC

## Contact

**DESY.** Deutsches  
Elektronen-Synchrotron

[www.desy.de](http://www.desy.de)

Moritz Habermehl  
FLC  
[moritz.habermehl@desy.de](mailto:moritz.habermehl@desy.de)



# Possible additional material

$\Delta m$  vs.  $m\chi_1^+$

## Exclusion plot

- Susy, no specific model
- Mass difference vs. Chargino mass
- ...in the making

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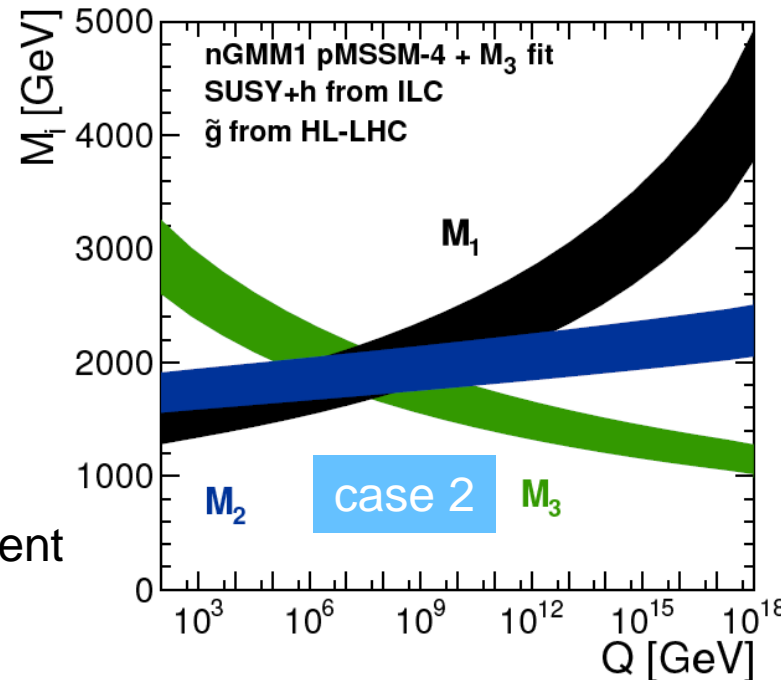
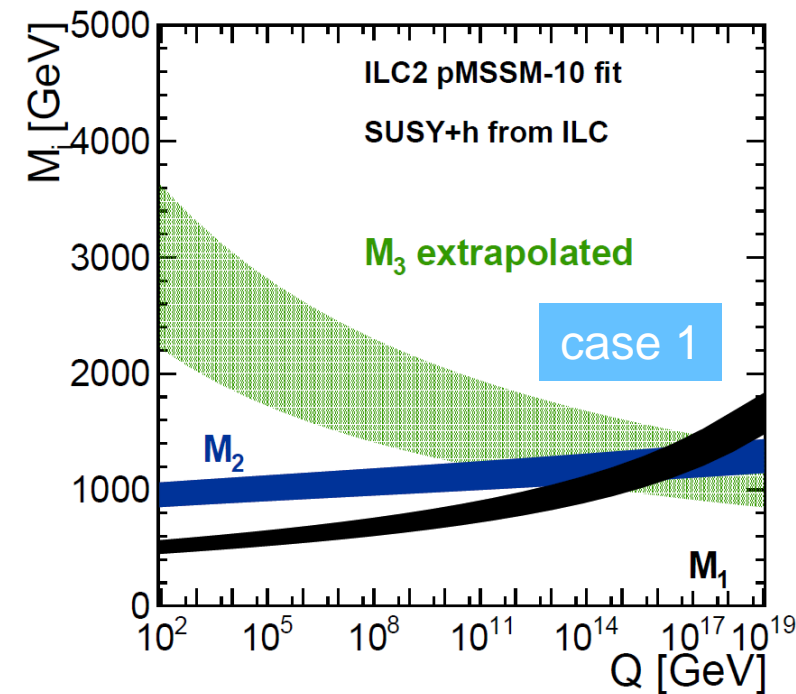
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## Running gaugino masses

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- evolving gaugino masses to higher scales
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  - bands show  $1\sigma$  confidence levels

## Case 2: unification below GUT scale

- unification at GUT scale can be excluded from fit
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## Case 1: unification at GUT scale

- running of  $M_1$  and  $M_2$
- unification at GUT scale can be fitted
- running of  $M_3$  from unification to lower energies
  - matches model point at 1 TeV
  - could be cross-checked with LHC results

# SUSY: Testing Gaugino Mass Unification

Natural SUSY with light Higgsinos

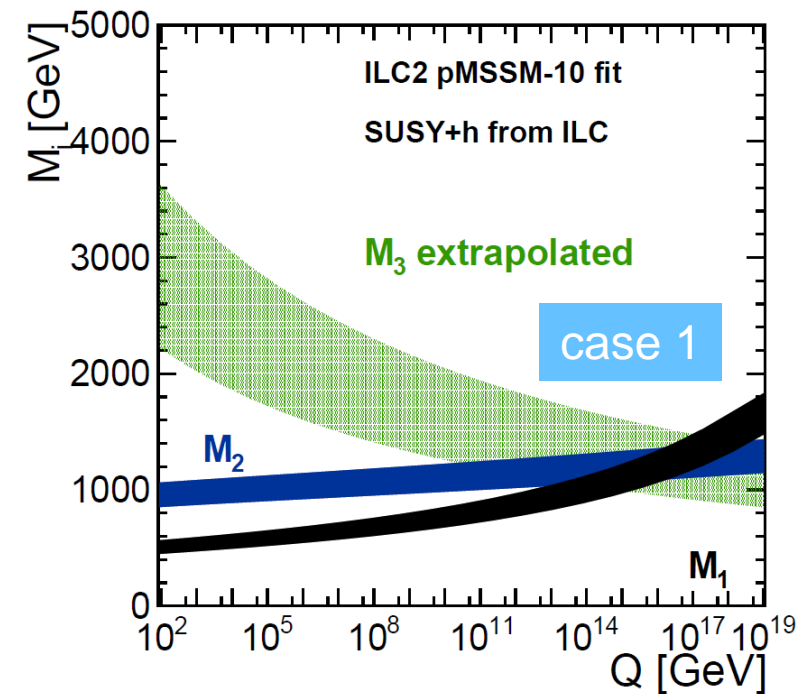
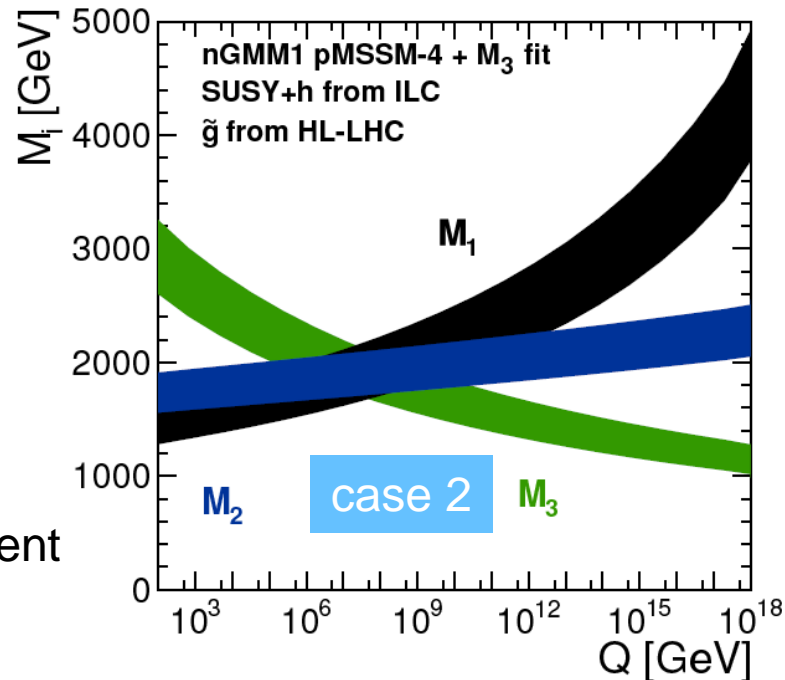
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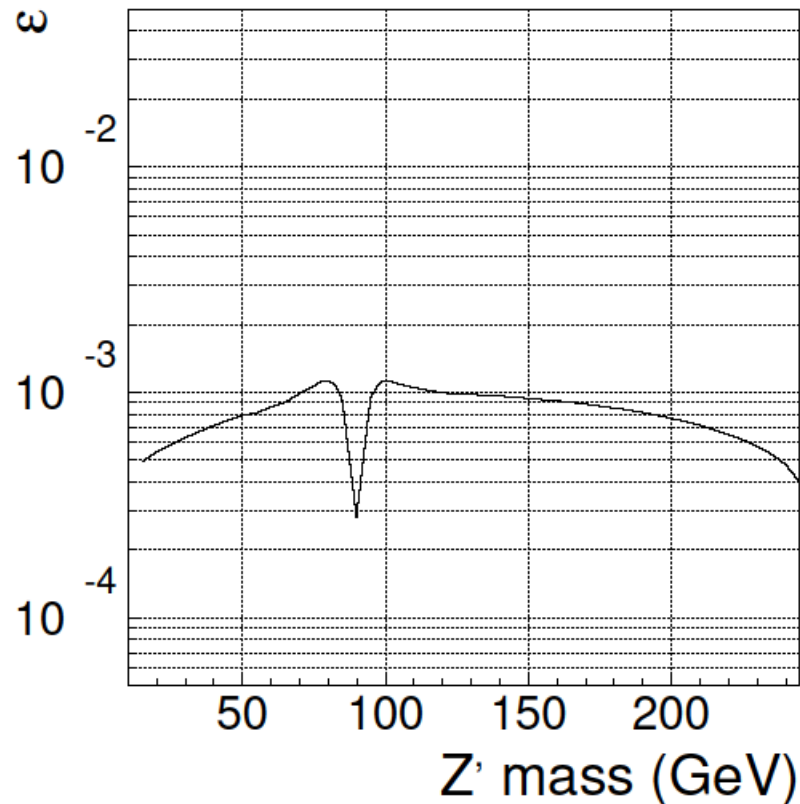


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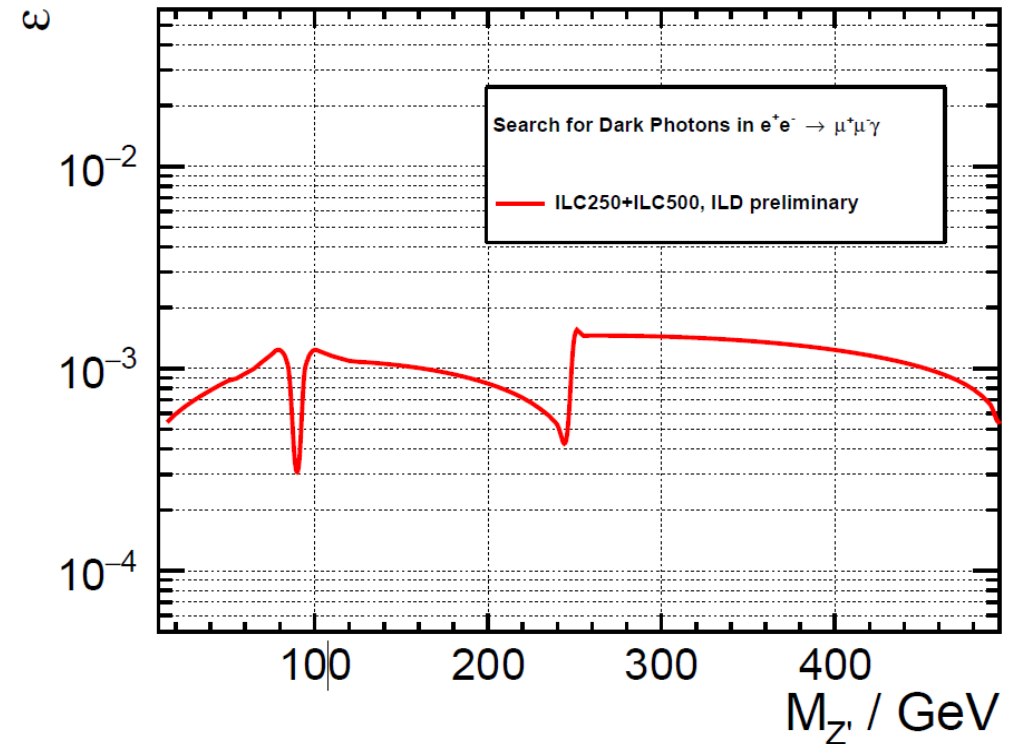
# BACKUP: Dark photon search I

Limits below 250 GeV dominated by 250 GeV run



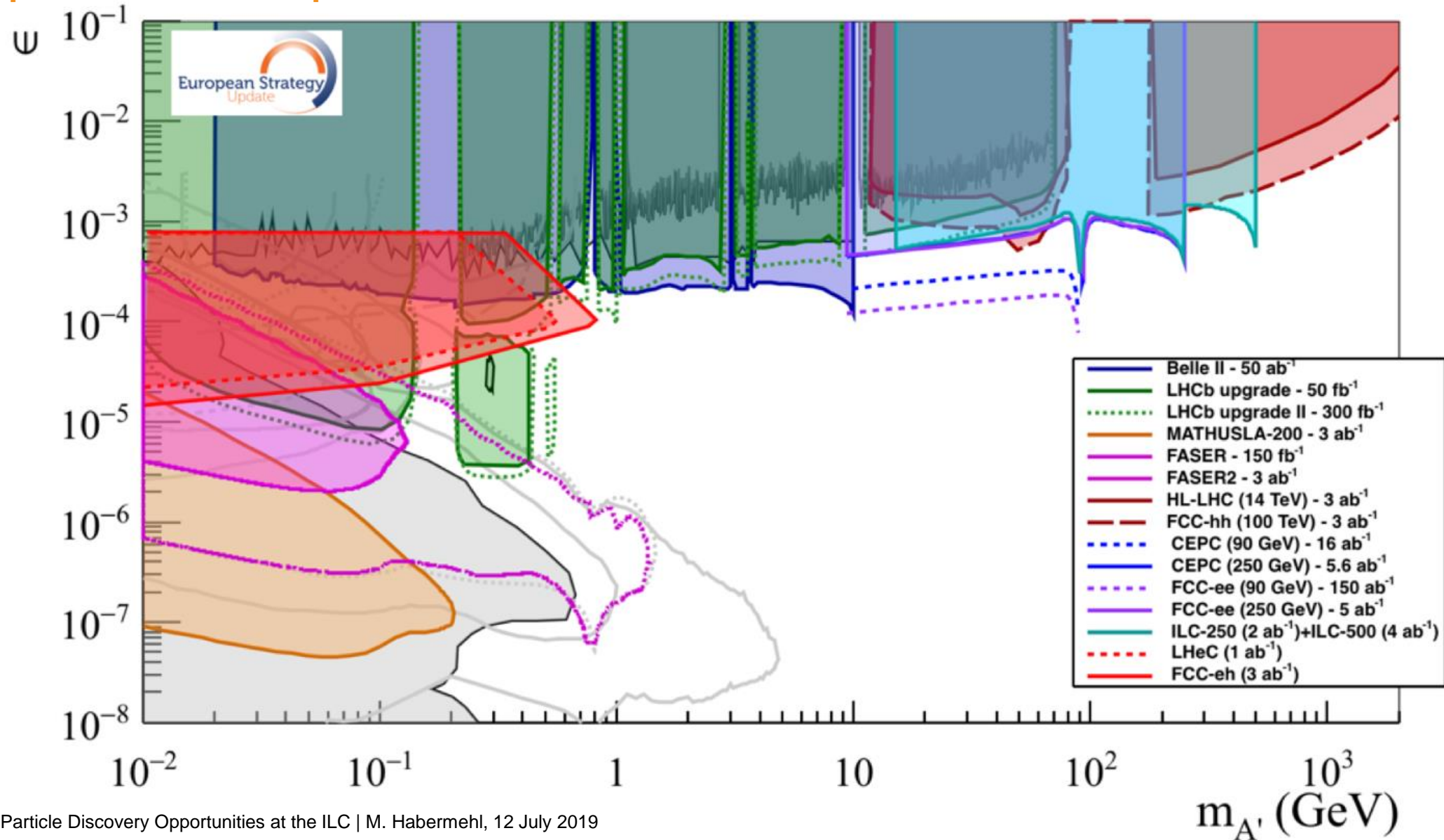
## approach

- muon momentum resolution taken from full detector simulation  $\rightarrow$  propagated to mass peak width
- energy dep. BG cross-section from generator level
- around  $Z$  mass
  - shape taken from CEPC study (arxiv:1503.07209)
  - more background, but interference of  $Z$  and dark photon



# BACKUP: Dark photon search II

## Comparison to other experiments



# BACKUP: Additional Higgs Bosons

## Search for extra light scalars

arxiv:1902.06118, arxiv:1801.08164

- black curve: update with 500 GeV and IDR detector model

