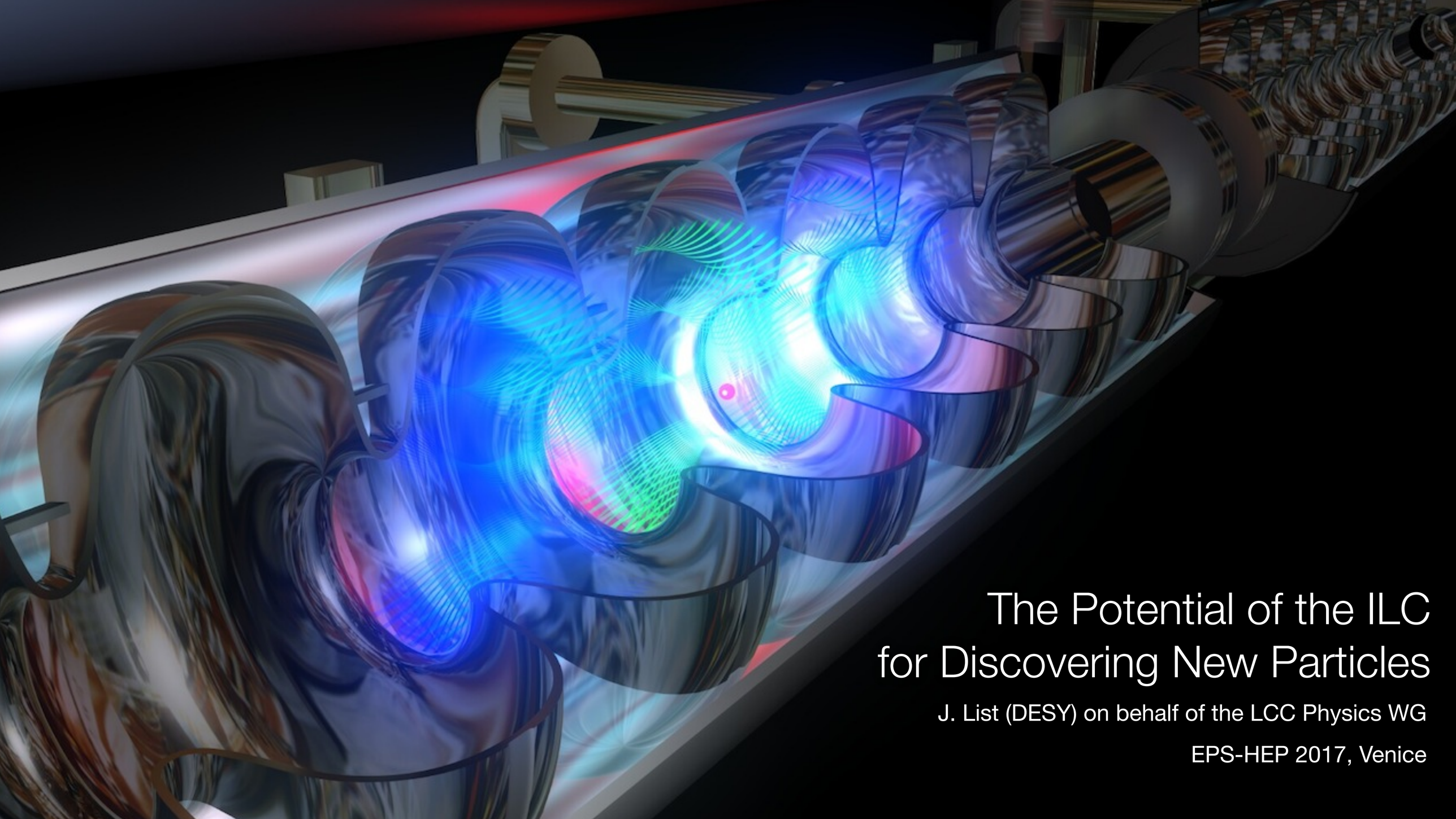


The Potential of the ILC for Discovering New Particles

J. List (DESY) on behalf of the LCC Physics WG

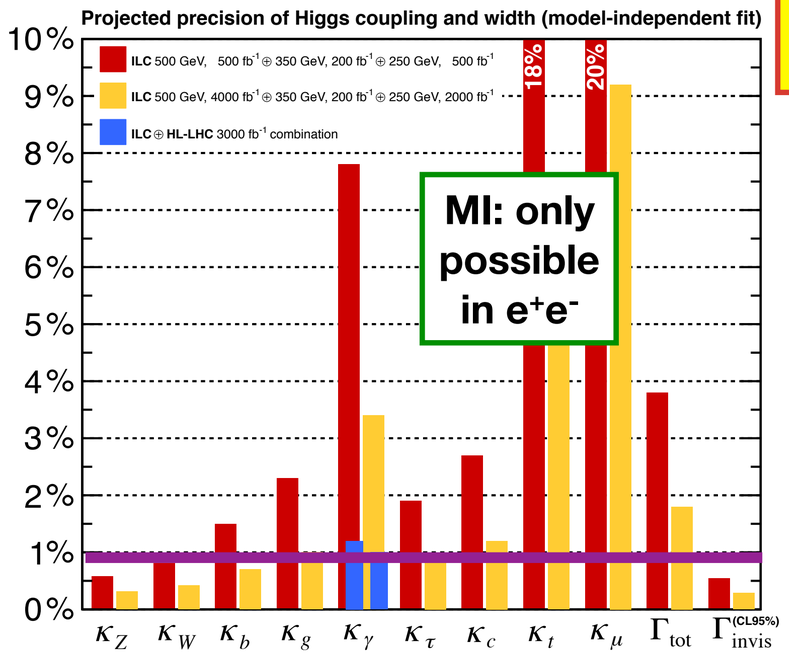
EPS-HEP 2017, Venice

The International Linear Collider

- e^+e^- centre-of-mass energy
  - 200….500 GeV
  - tuneable
  - upgradable to 1 TeV
- luminosity at 500 GeV:
  - 1.8×10^{34} /cm^2 /s
  - upgrade 3.6×10^{34} /cm^2 /s
- beam polarisation
  - $P(e^-) \geq 80\%$
  - $P(e^+) = 30\%$, upgradable to 60%
- total length (500 GeV): 34 km

TDR published in 2012
Ready to be built
Currently the only project under *political* consideration

New Properties of the Higgs Boson



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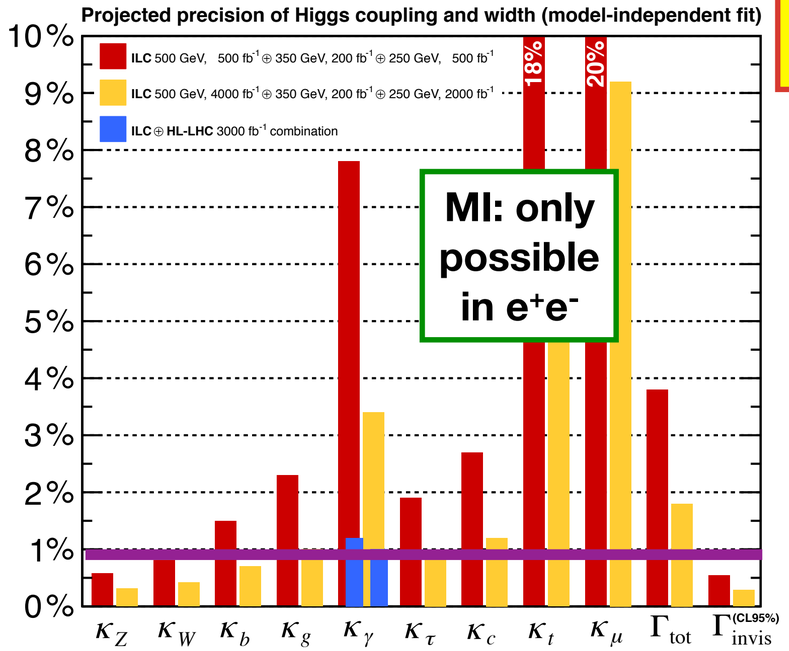

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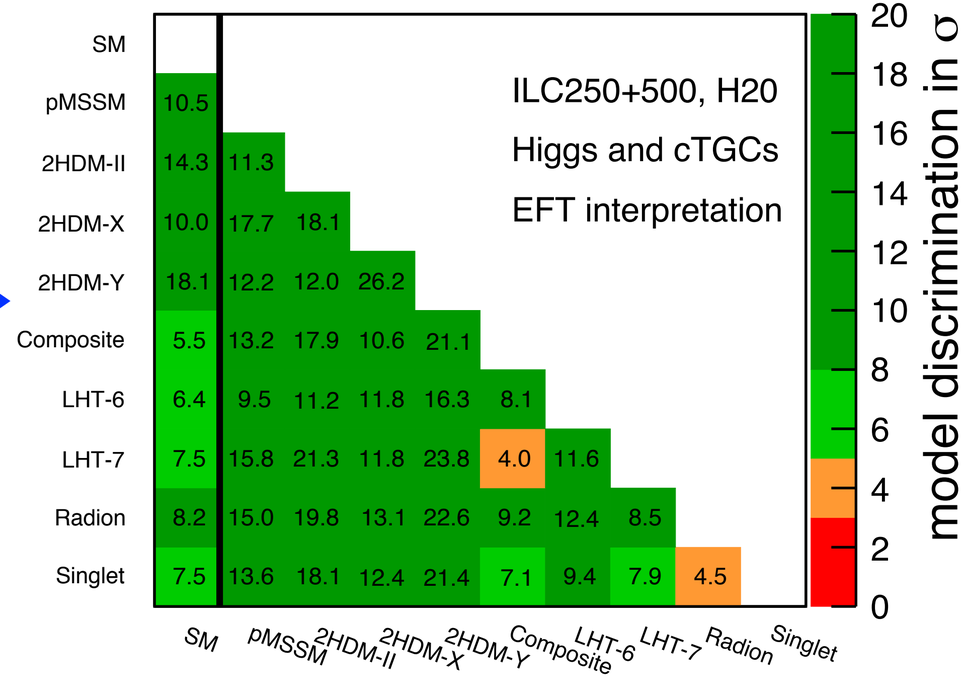

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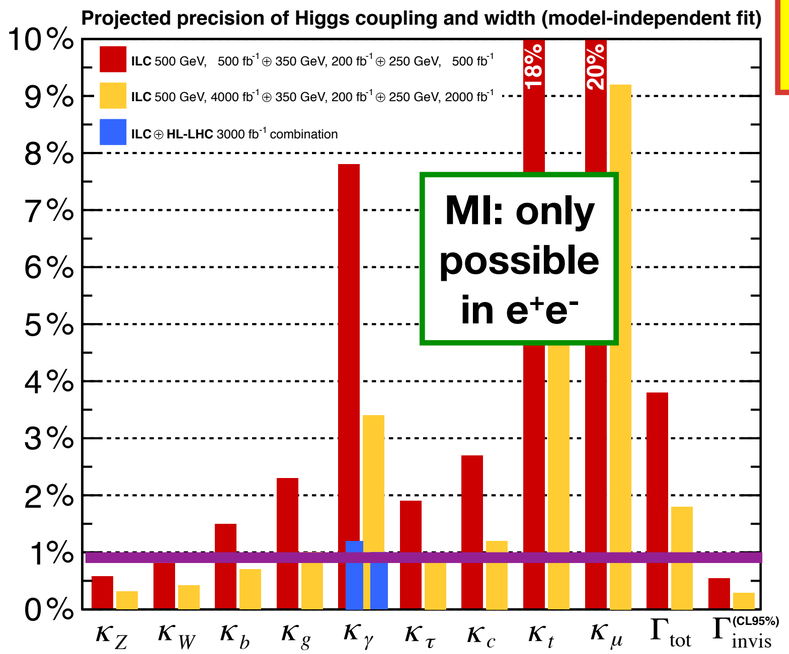

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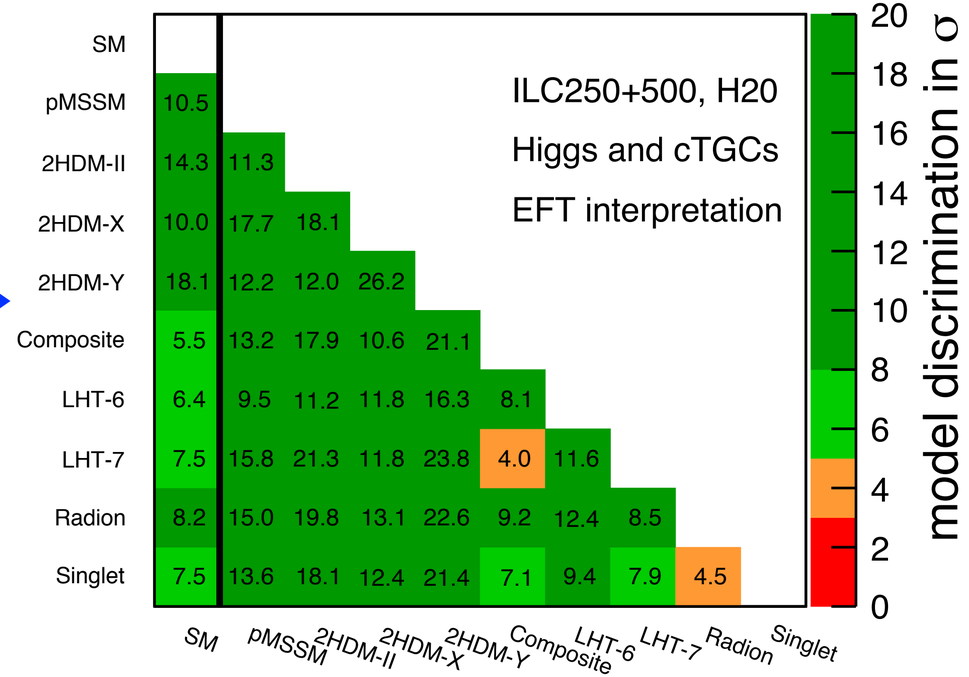

- combines Higgs & **TGCs**
  => poster by R.Karl
- **discovery and identification of various BSM models (not observable at LHC)**

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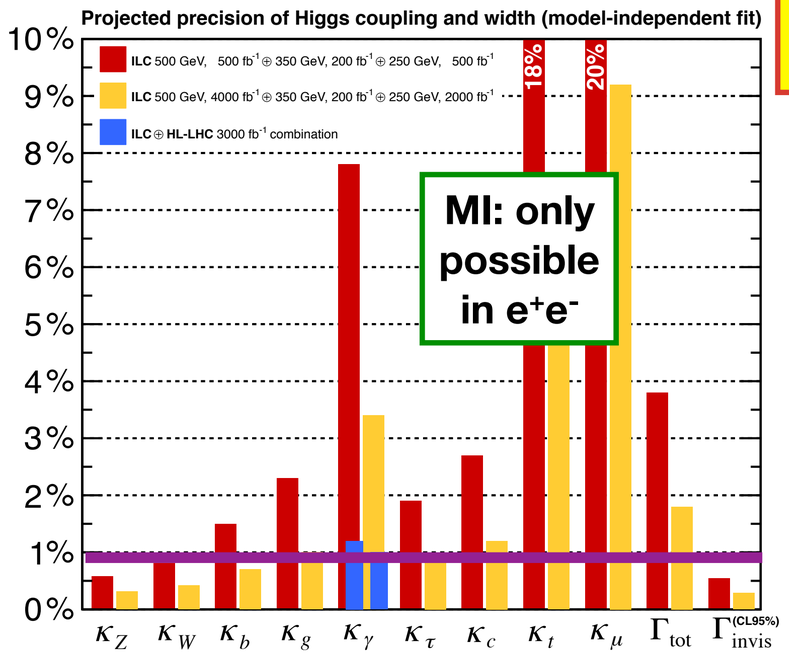

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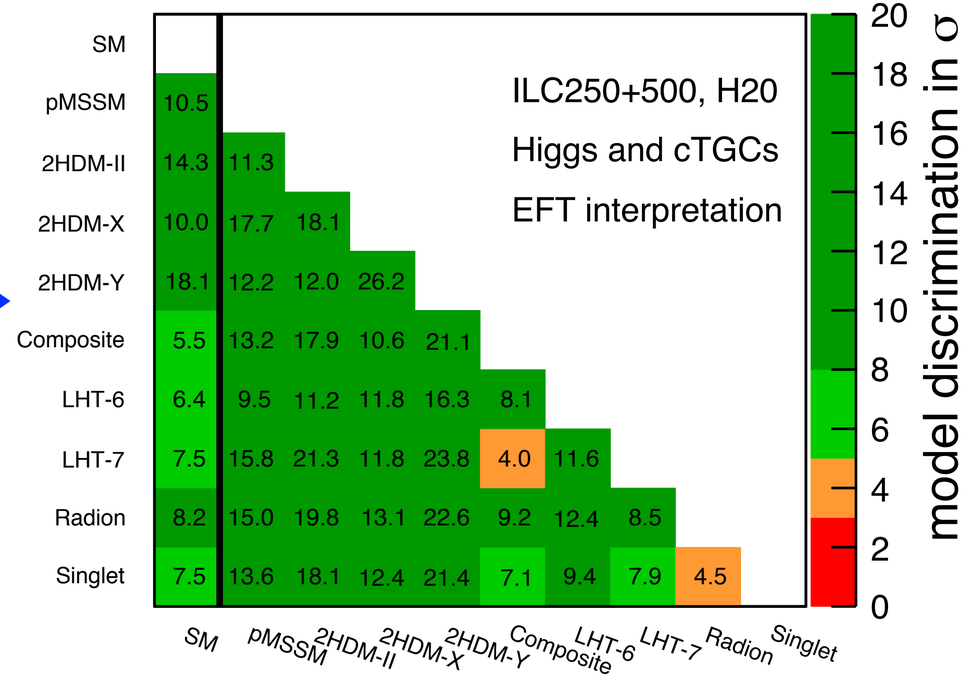

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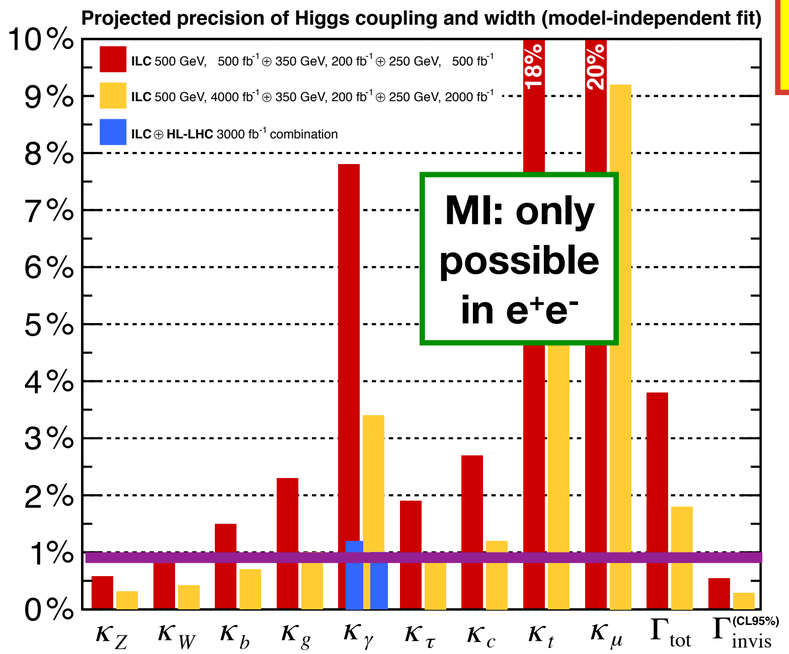

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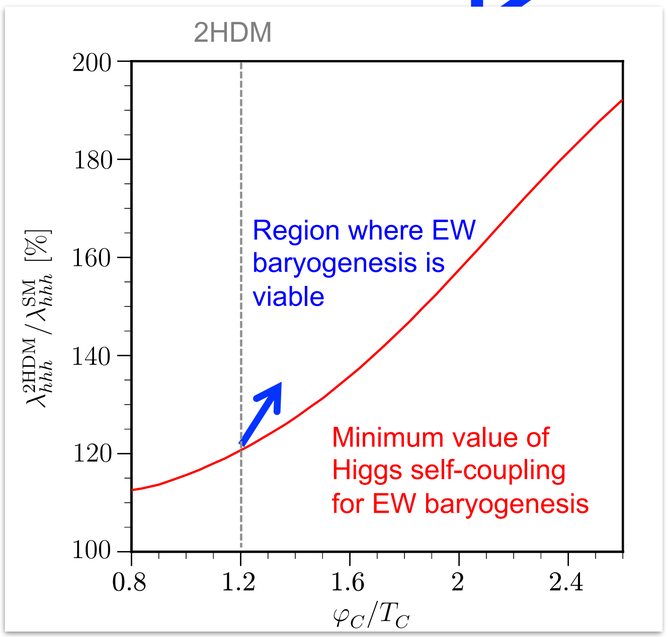

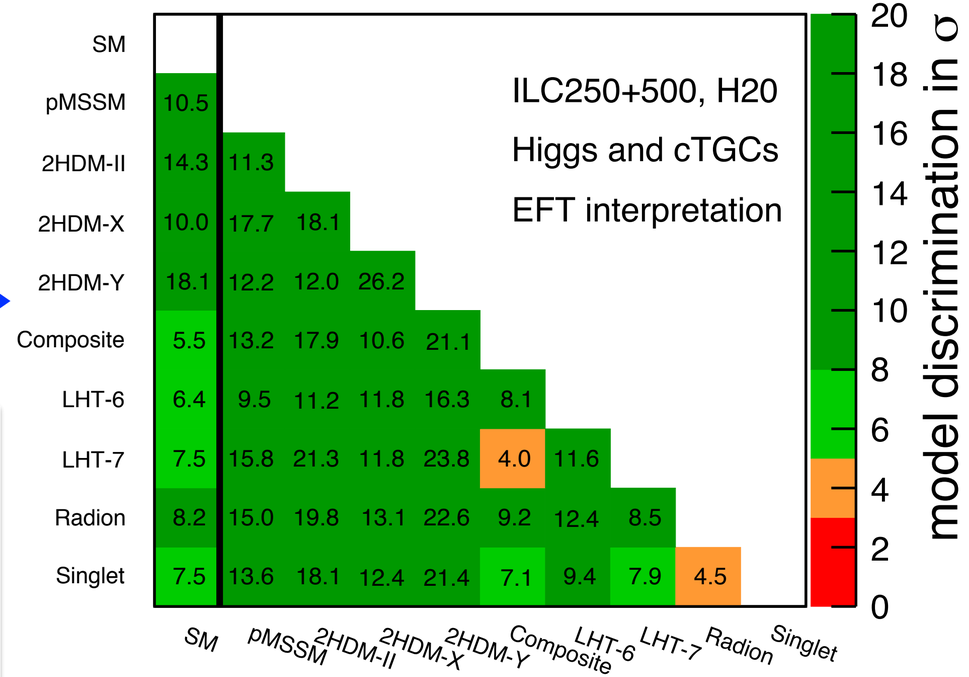

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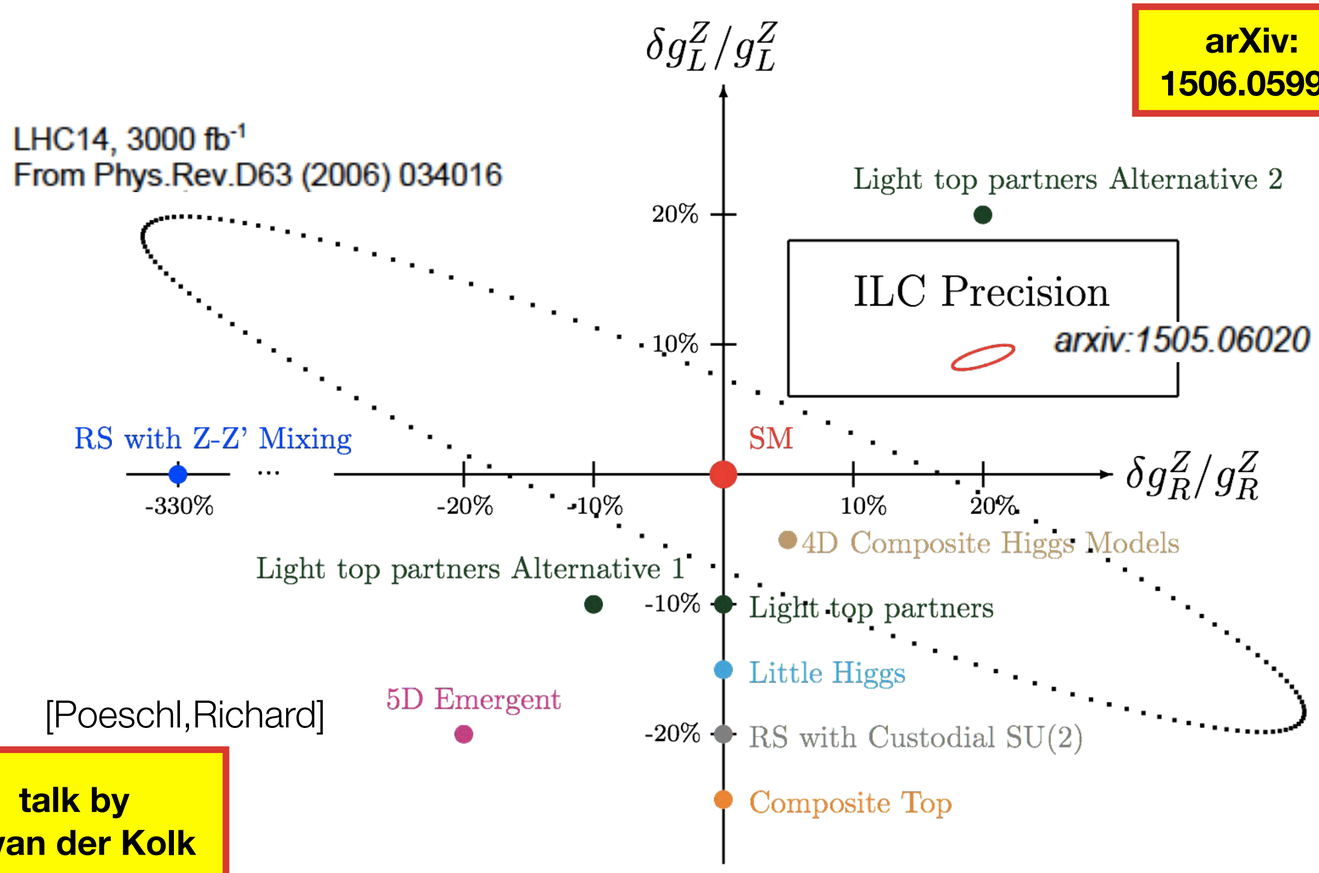

[Poeschl,Richard]

talk by N.van der Kolk

arXiv: 1506.05992

Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

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- **sensitivity in g^Z_L, g^Z_R plane complementary to LHC**

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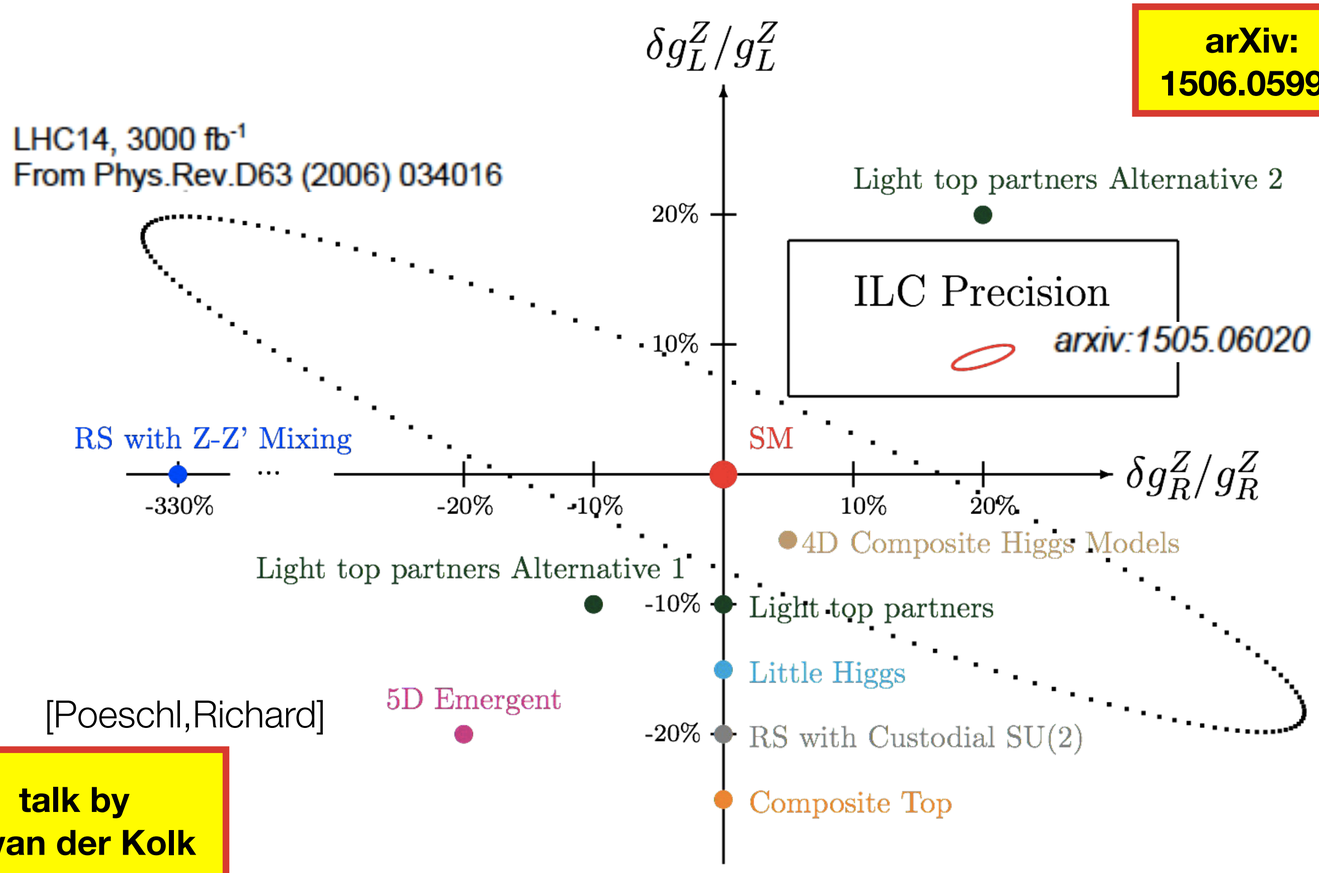

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Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

Also from other e^+e^- -> ff:

- probe Z' up to ~10 TeV 500fb^{-1} @ 500 GeV (initial run)
- up to ~17 TeV for 1ab^{-1} at 1 TeV
- polarised beams gain ~ 2TeV in reach

poster by S.Bilokin

Additional Higgs Bosons

- eg from 2HDMs or additional singlets (as in NMSSM)
- pair production:
  - loophole-free search for additional Higgs bosons up to masses of ~$\sqrt{s}/2$
  - regardless of tanβ
- **or recoil against Z**
  - **even if coupling strongly reduced!**
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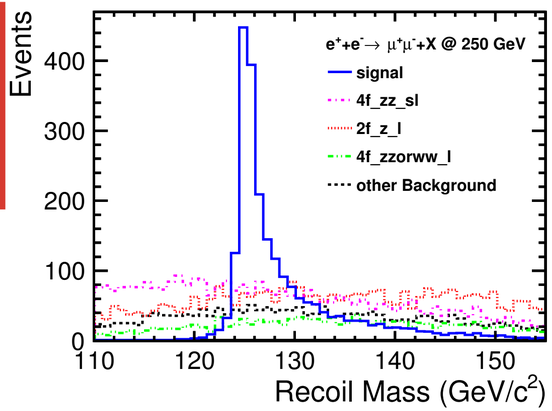
SM Higgs: ILD full simulation Phys. Rev. D 94, 113002 (2016)



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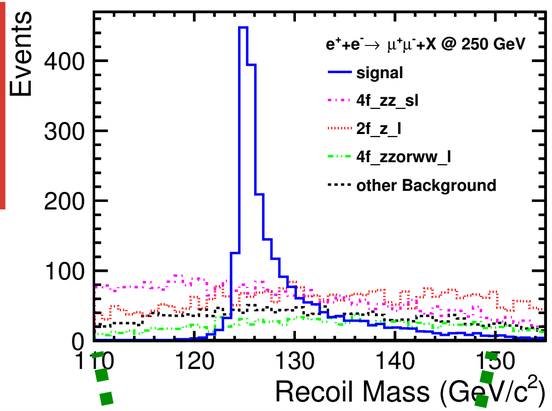
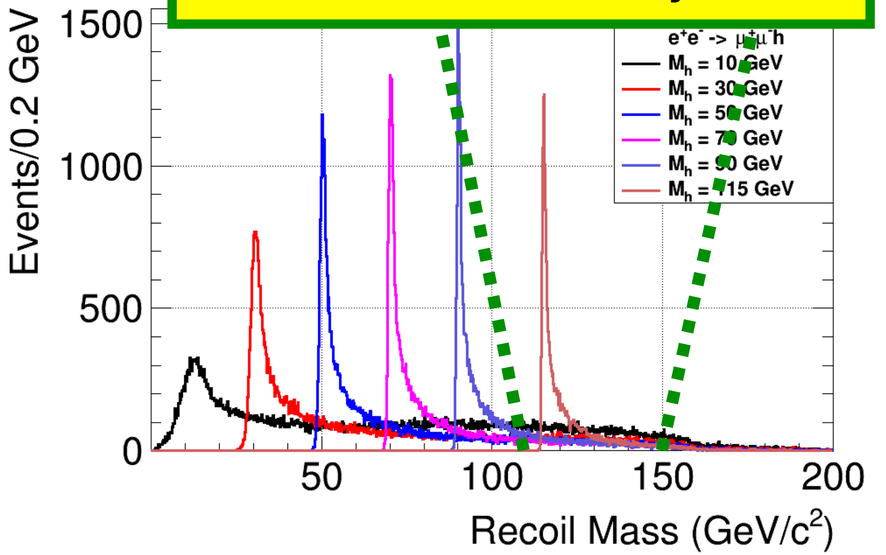
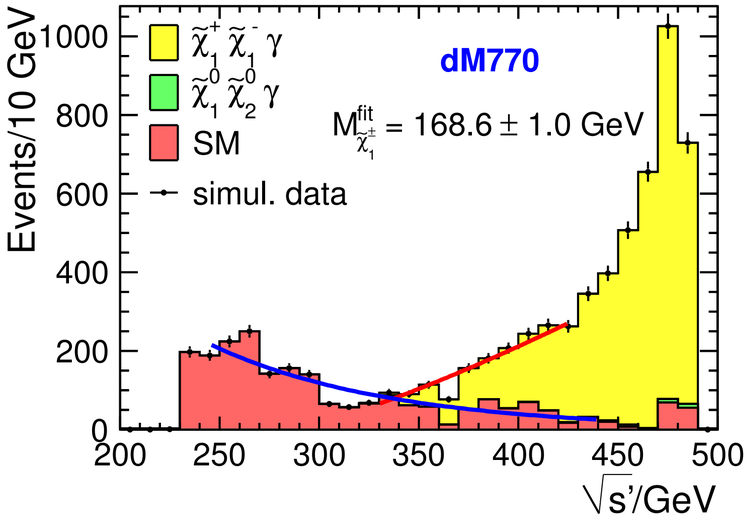


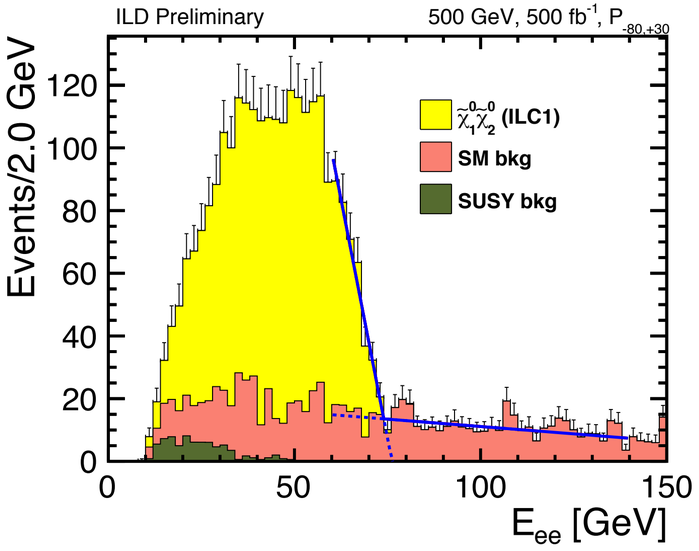
ILC 250 GeV @ generator-level, for illustration only



Supersymmetric Partners of the Higgs Boson

higgsinos with sub-GeV mass splitting Eur.Phys.J. C73 (2013) no.12, 2660





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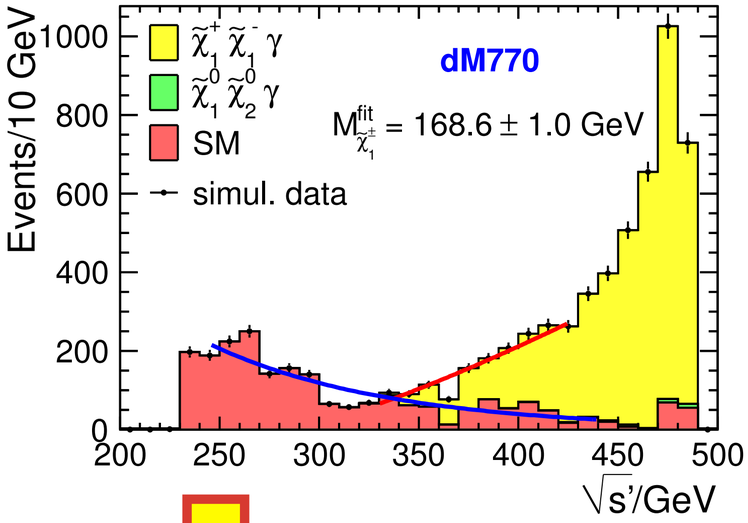

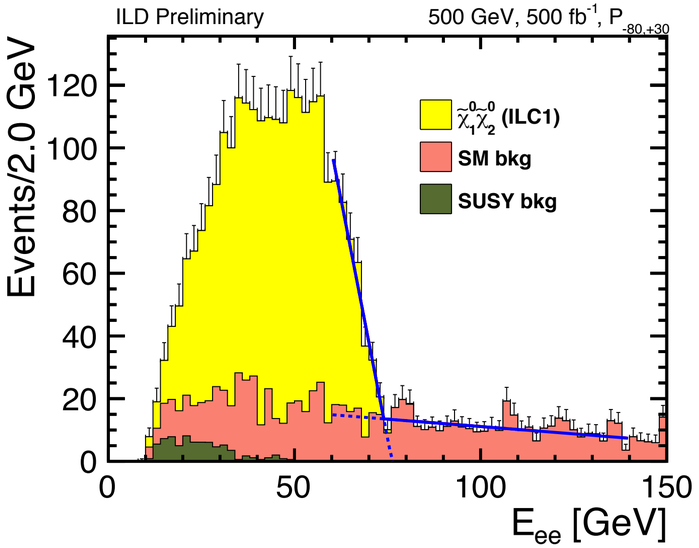

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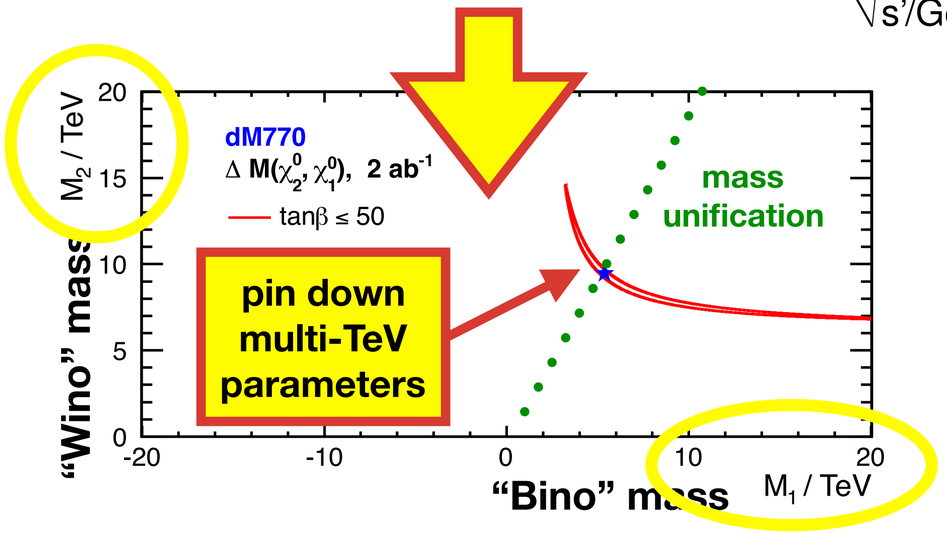

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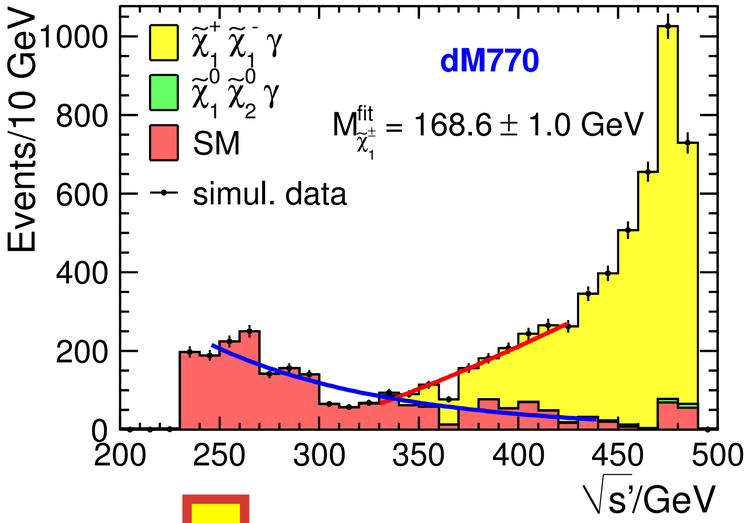

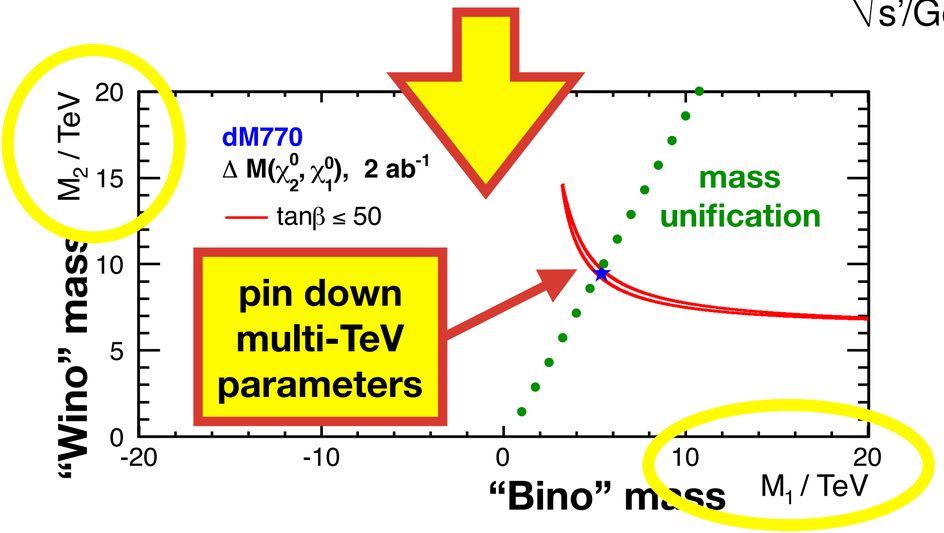

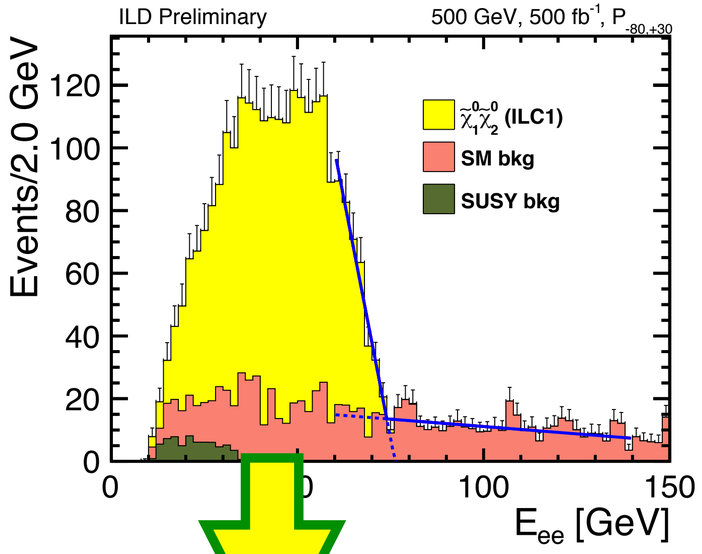

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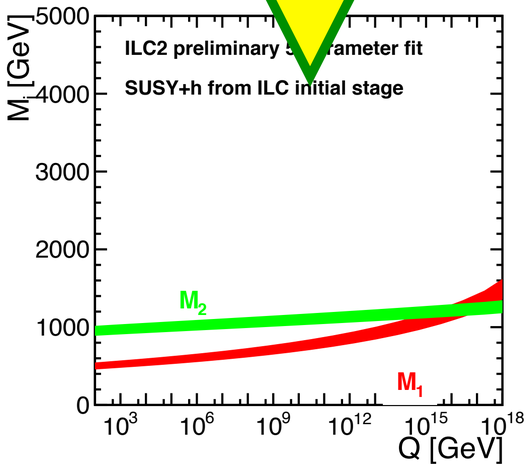

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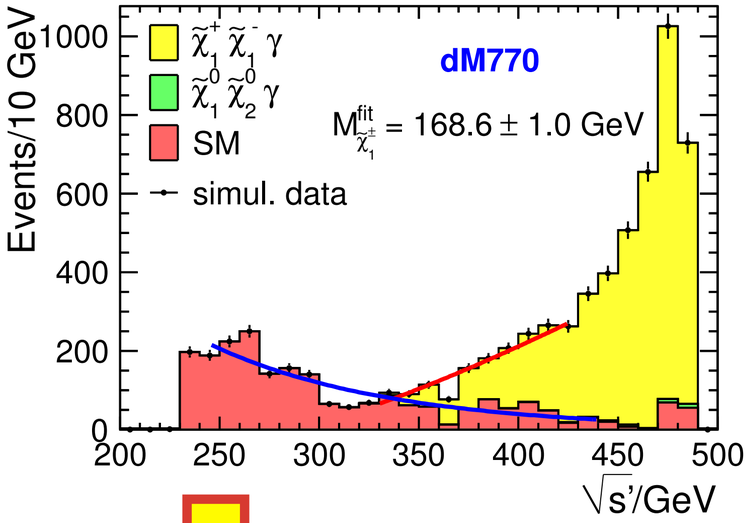

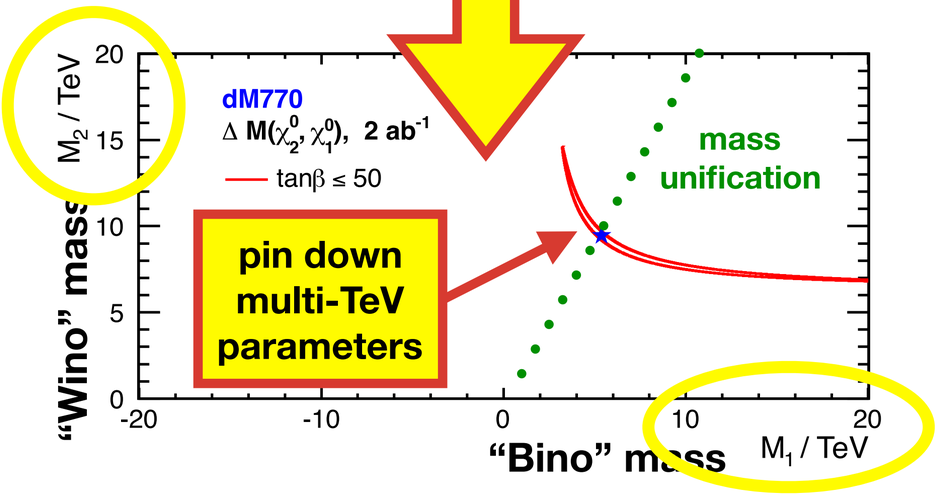

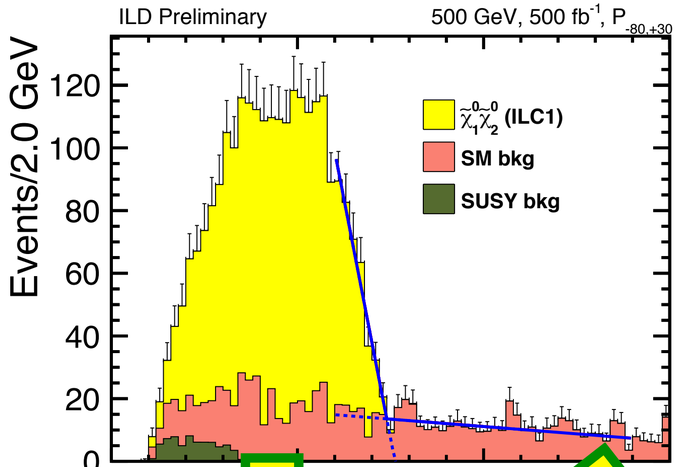

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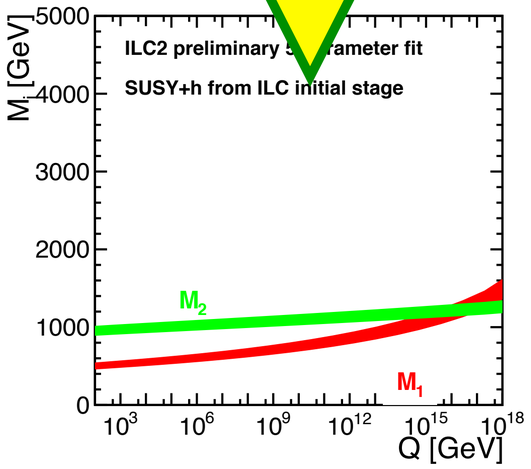

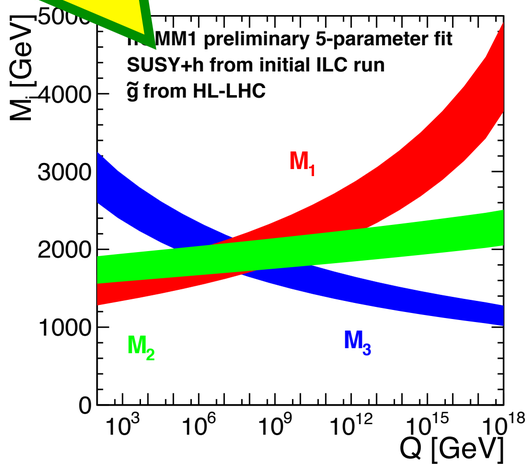

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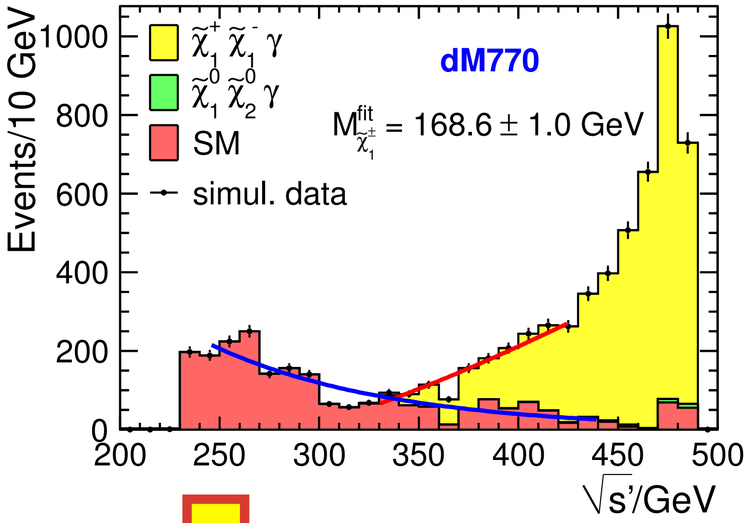
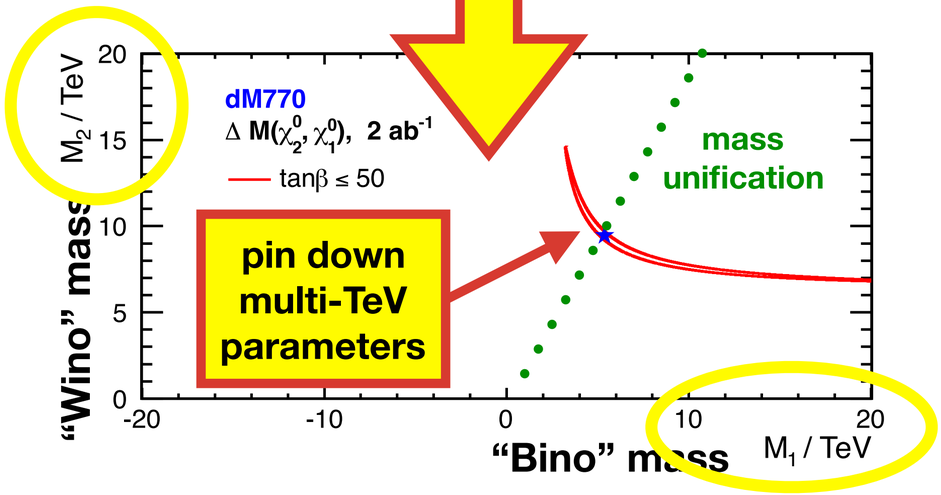
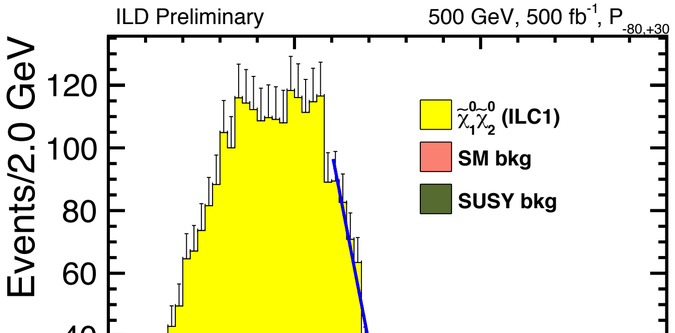




pin down multi-TeV parameters



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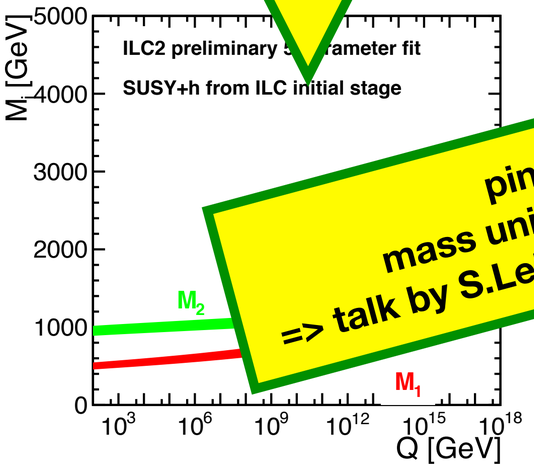
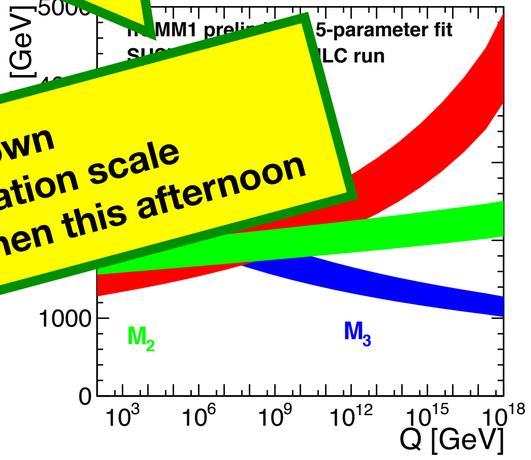
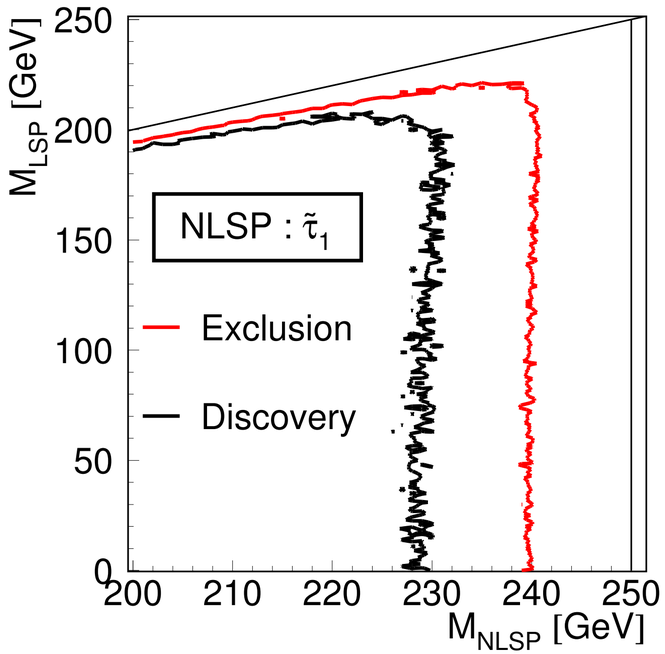




pin down mass unification scale => talk by S.Lehtinen this afternoon

SUSY without Loop-Holes

- pair production of new, weakly coupled particles
- special case SUSY: couplings are known
- R partity conservation: NSLP -> SM partner + LSP



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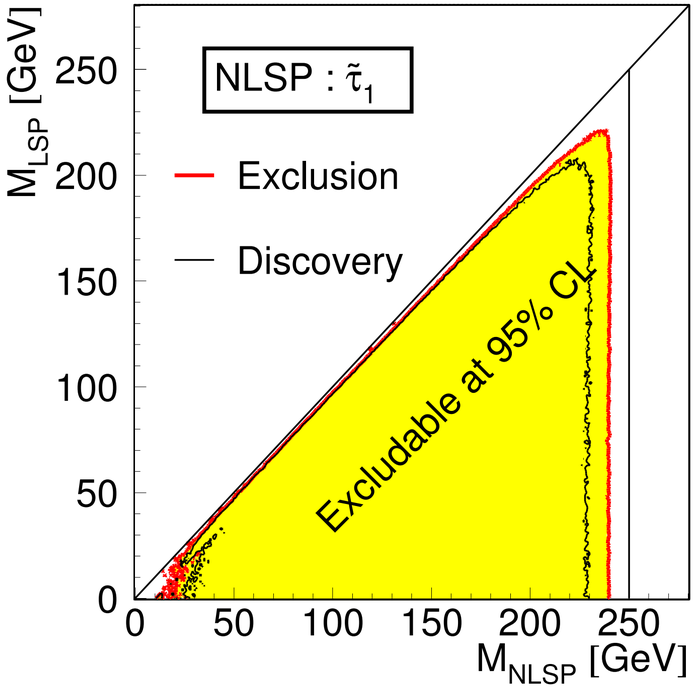

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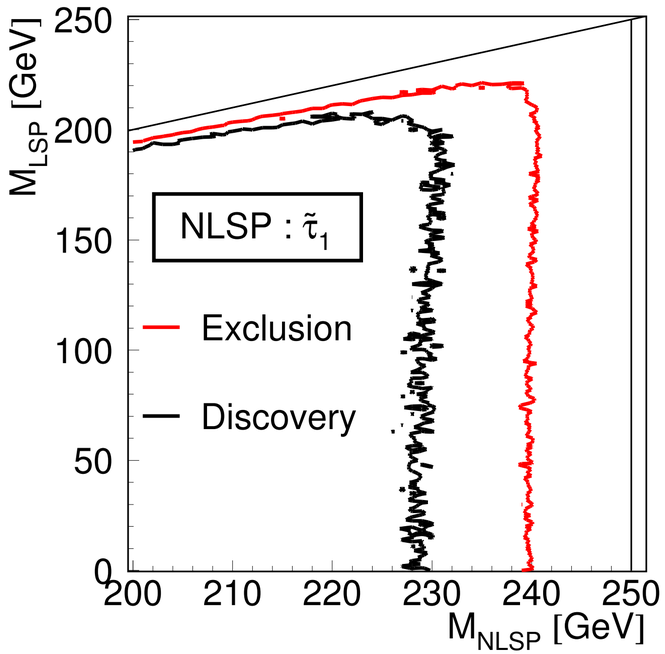
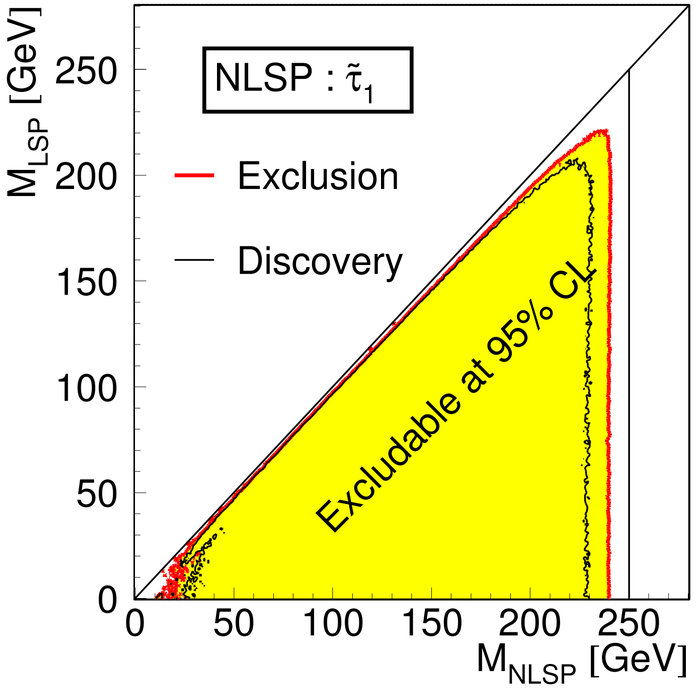


HERE: stau NLSP most challenging case - for others even closer to √s/2



Discovering Dark Matter Particles

- e^+e^- ->$\chi\chi\gamma$ “mono-photons”: probes WIMP coupling to *leptons*
- **cosmological interpretation**:
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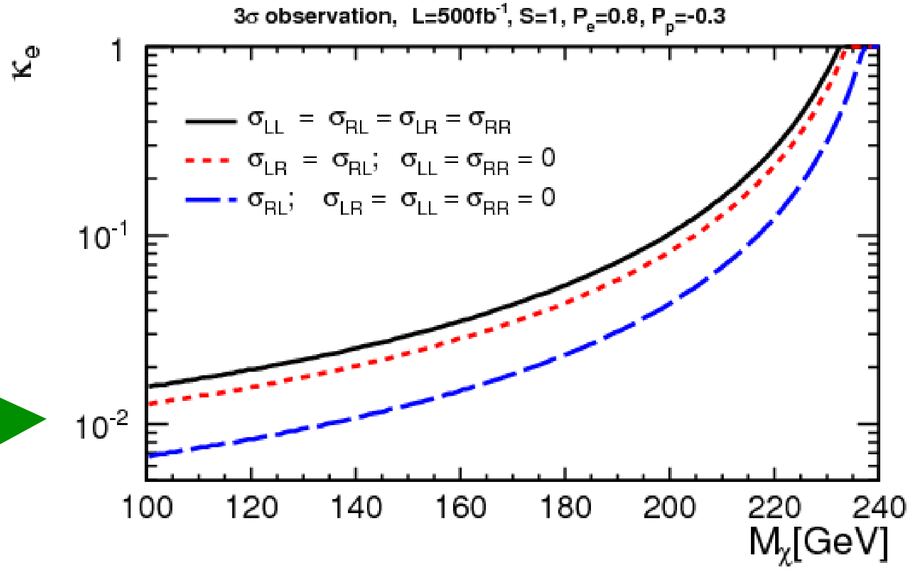

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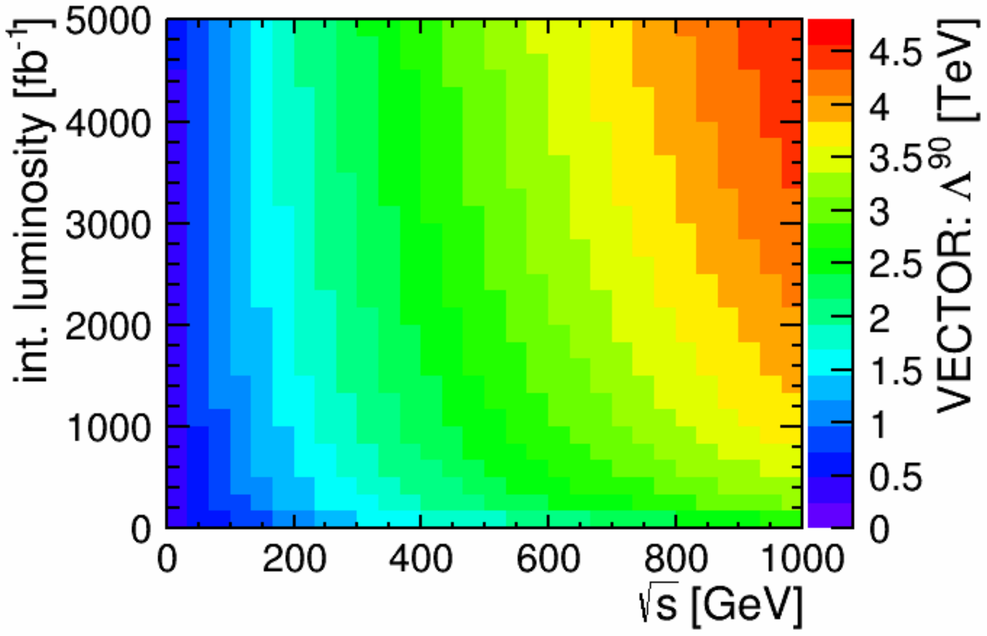

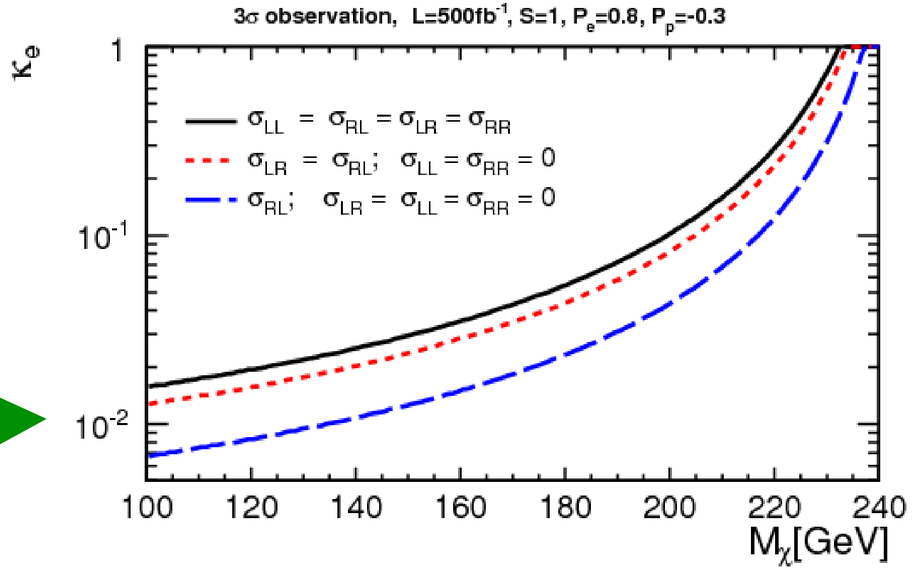

- **Effective operator interpretation**
  [nota bene: valid at e^+e^- colliders]
- for M_χ = 100 GeV ILC probes Λ
  - **up to ~3 TeV @ 500 GeV**
  - **up to ~4.5 TeV @ 1 TeV**

Identifying the Nature of Dark Matter

Does WIMP candidate really explain Dark Matter?

=> predict relic density from collider measurements
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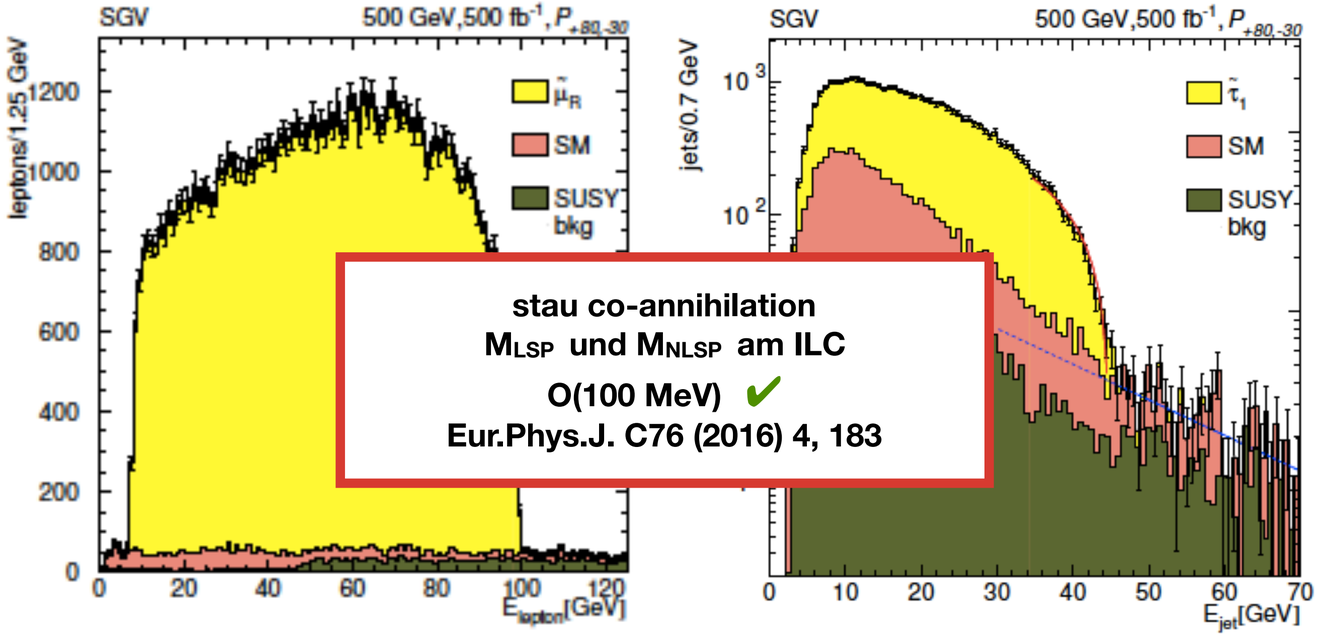


stau co-annihilation
M_{LSP} und M_{NLSP} am ILC
O(100 MeV) ✔
Eur.Phys.J. C76 (2016) 4, 183

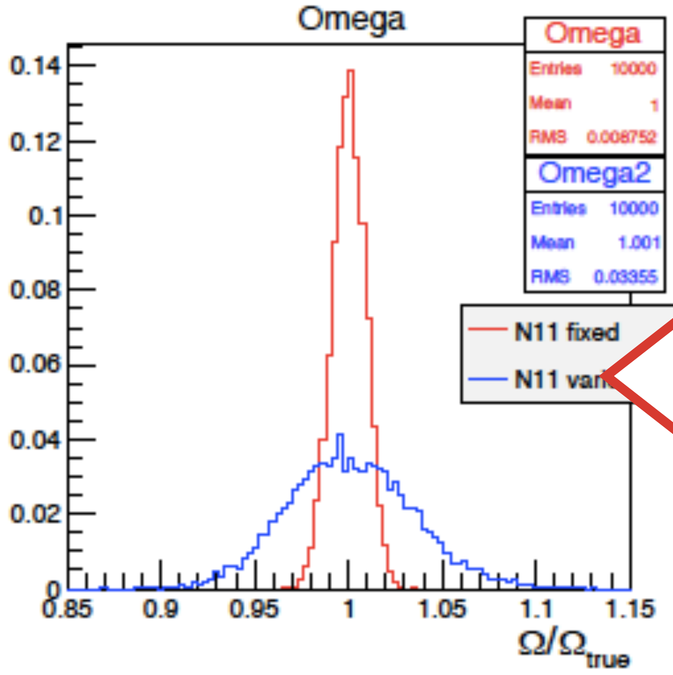
Identifying the Nature of Dark Matter

Does WIMP candidate really explain Dark Matter?

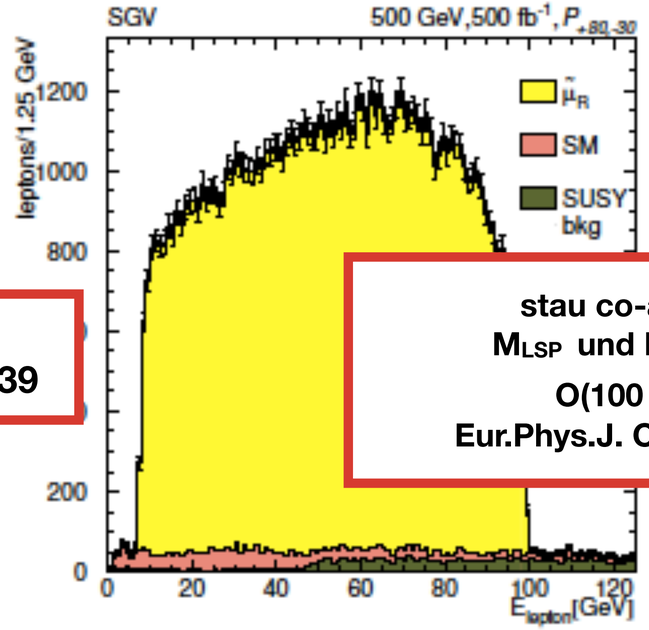
=> predict relic density from collider measurements
=> compare to cosmological observation (Planck, $\delta\Omega/\Omega \sim 2\%$)

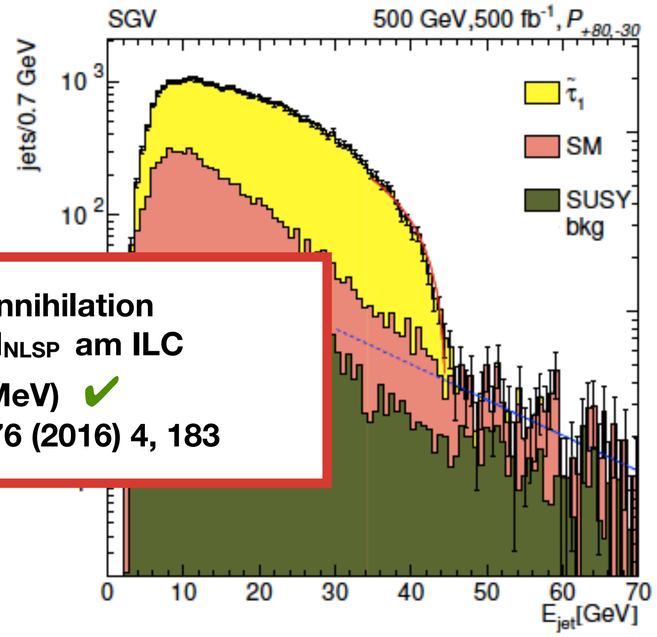
e.g. SUSY with co-annihilation:

- to match Planck precision need to know
  - masses of LSP and NLSP at permille level
  - mixings at percent level



arXiv: 1602.08439





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Neutrinos

- scale of neutrino mass generation still unknown
- some models testable at colliders
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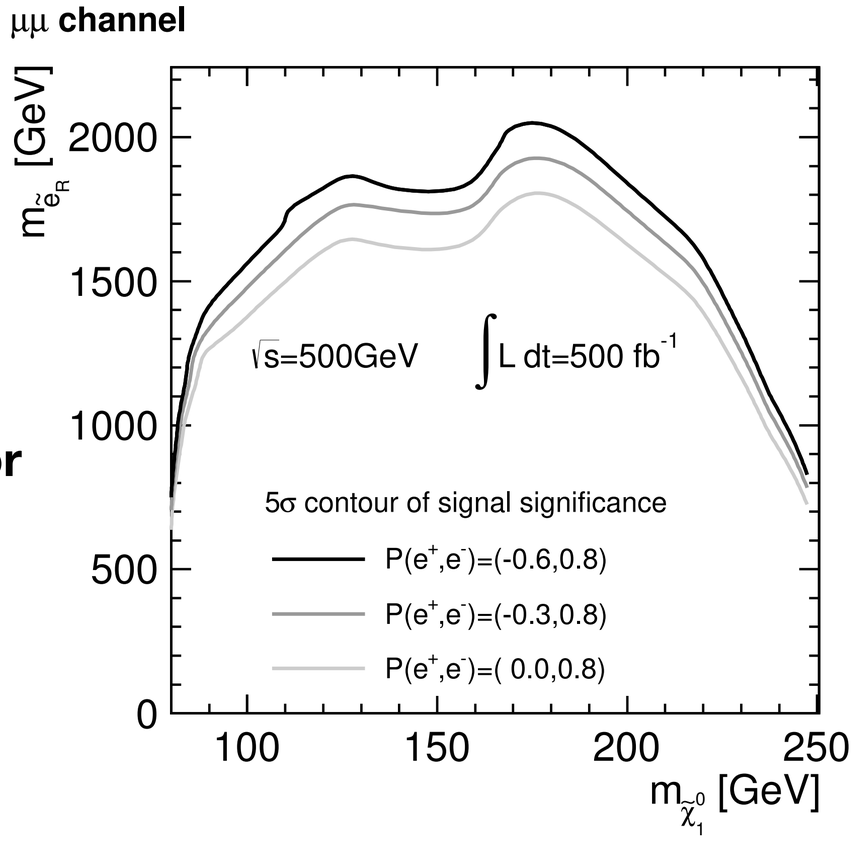
bRPV: ILD full simulation Eur.Phys.J. C74 (2014) 2720



- **LSP pair production discoverable for selectron masses up to ~ 2 TeV**
- measure visible decays of LSP => **$\sin^2\theta_{23}$**
- compare of collider measurement with neutrino oscillation data **=> verify or falsify bRPV as mechanism of neutrino mass generation**

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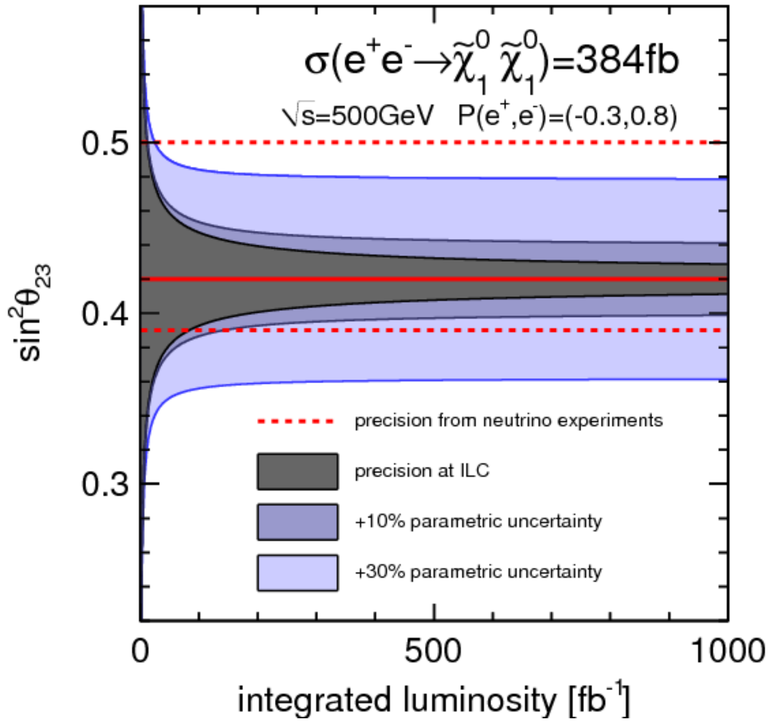

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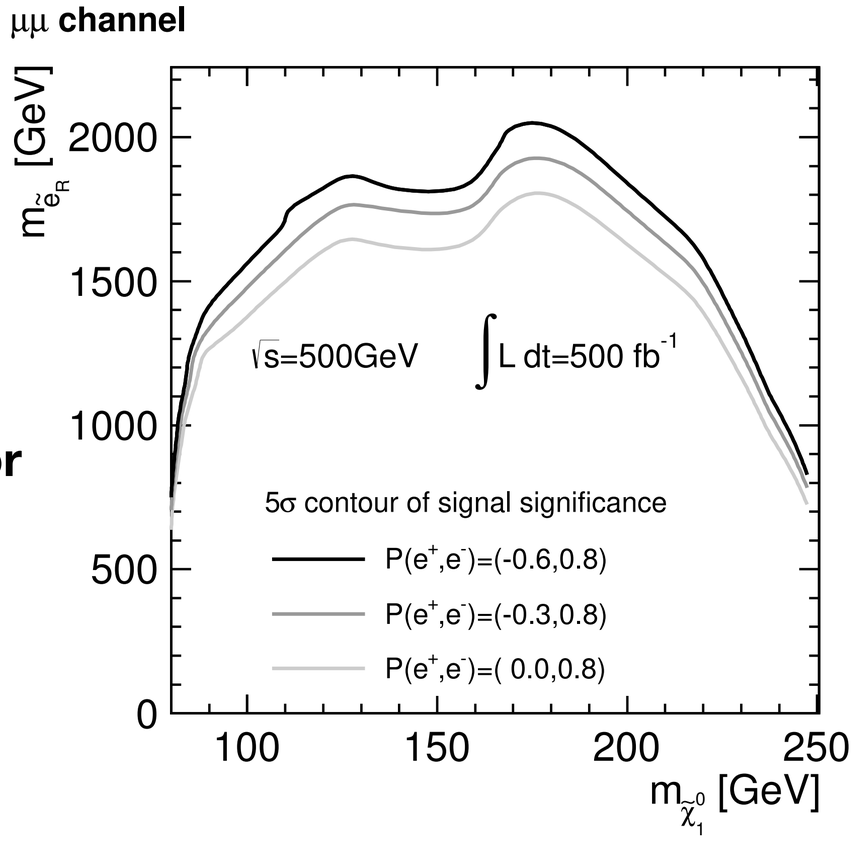

Conclusions

- The ILC offers significant discovery potential - both via indirect and direct searches

  => 10 examples discussed in this presentation

- Rely strongly on the well-appreciated properties of electron-positron colliders:
  - well defined initial state
  - clean environment, electroweak rates => trigger-less operation of detectors!
  - democratic production of particles with electroweak charges
- …and on the particular Linear Collider assets:
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  - polarised beams

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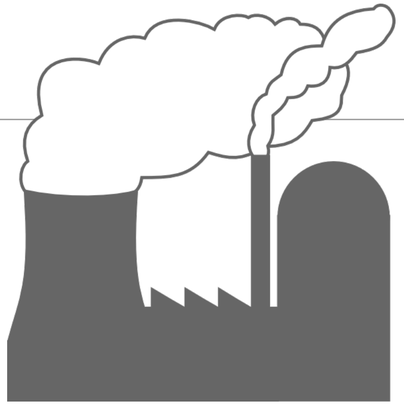
Even in the most pessimistic case that no evidence for new particles appears, the ILC offers distinct and powerful strategies for new phenomena, that will illuminate physics both at small scales and at the large-scale makeup of the universe.

Backup

Additional Design Considerations



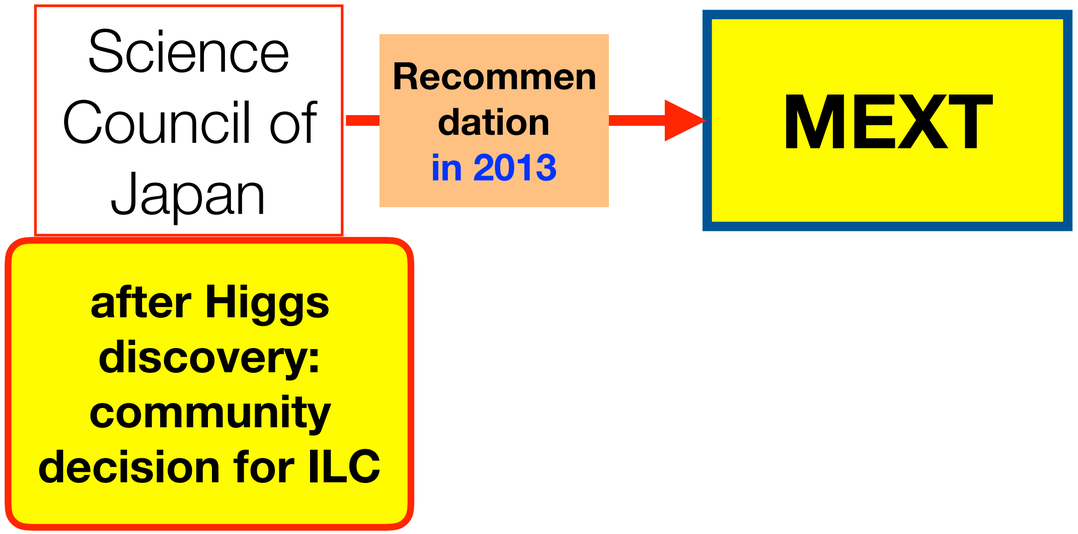
- **power consumption:**
  - public acceptance for large scale projects significantly challenged if (substantial fractions of) extra power plant required!
  - **ILC design driven by *self-imposed* limits on total site power:**
    - **200 MW for 500 GeV**
    - **300 MW for 1 TeV**
- **cost awareness:**
  - in years before TDR: critical review of design in order to reduce costs
  - value engineering
  - power reduction in favour of stronger focussing
- **at the end of the day: luminosity ~ power ~ money**

Review by Japanese Science Ministry (MEXT)

Science Council of Japan

after Higgs discovery: community decision for ILC

Review by Japanese Science Ministry (MEXT)



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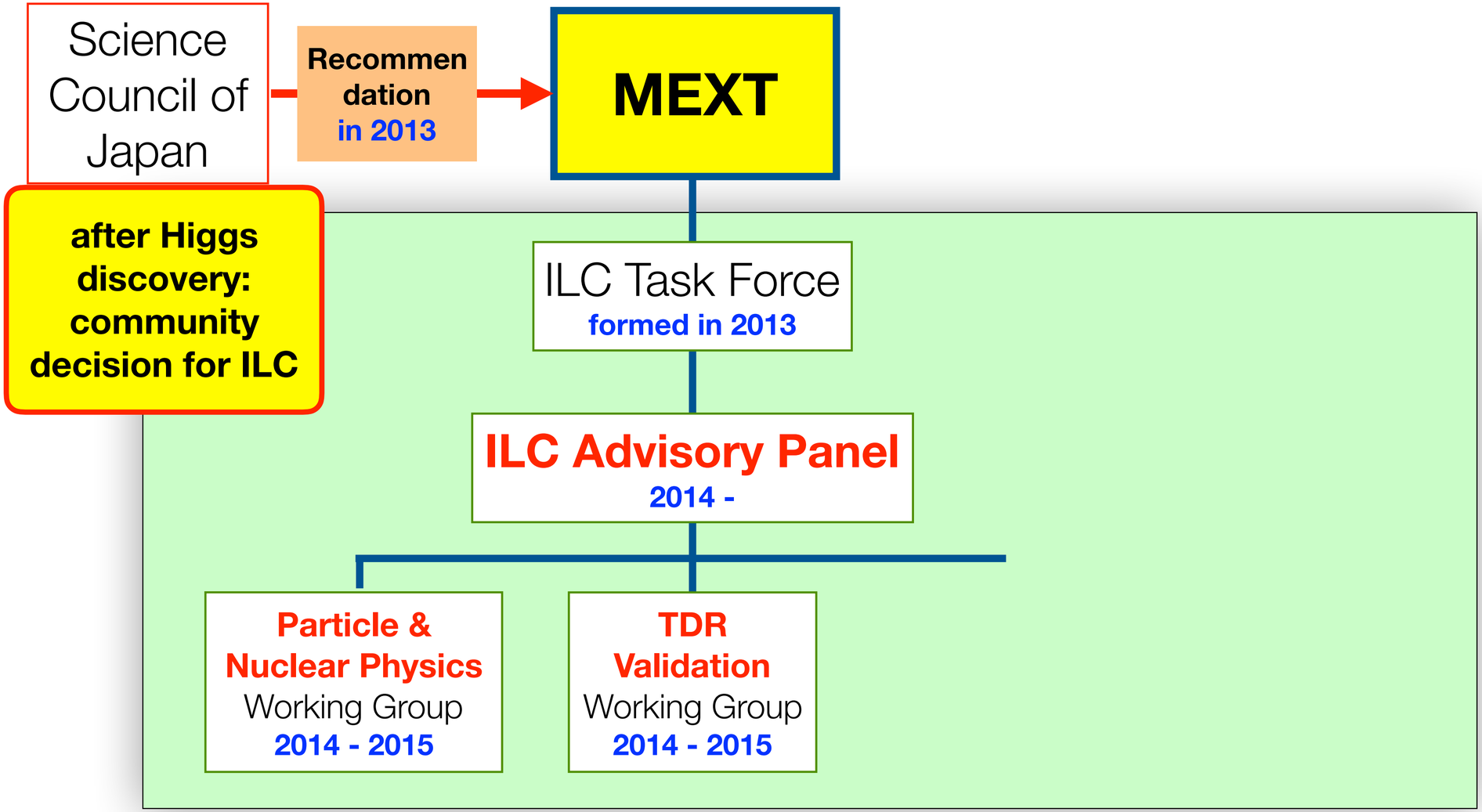

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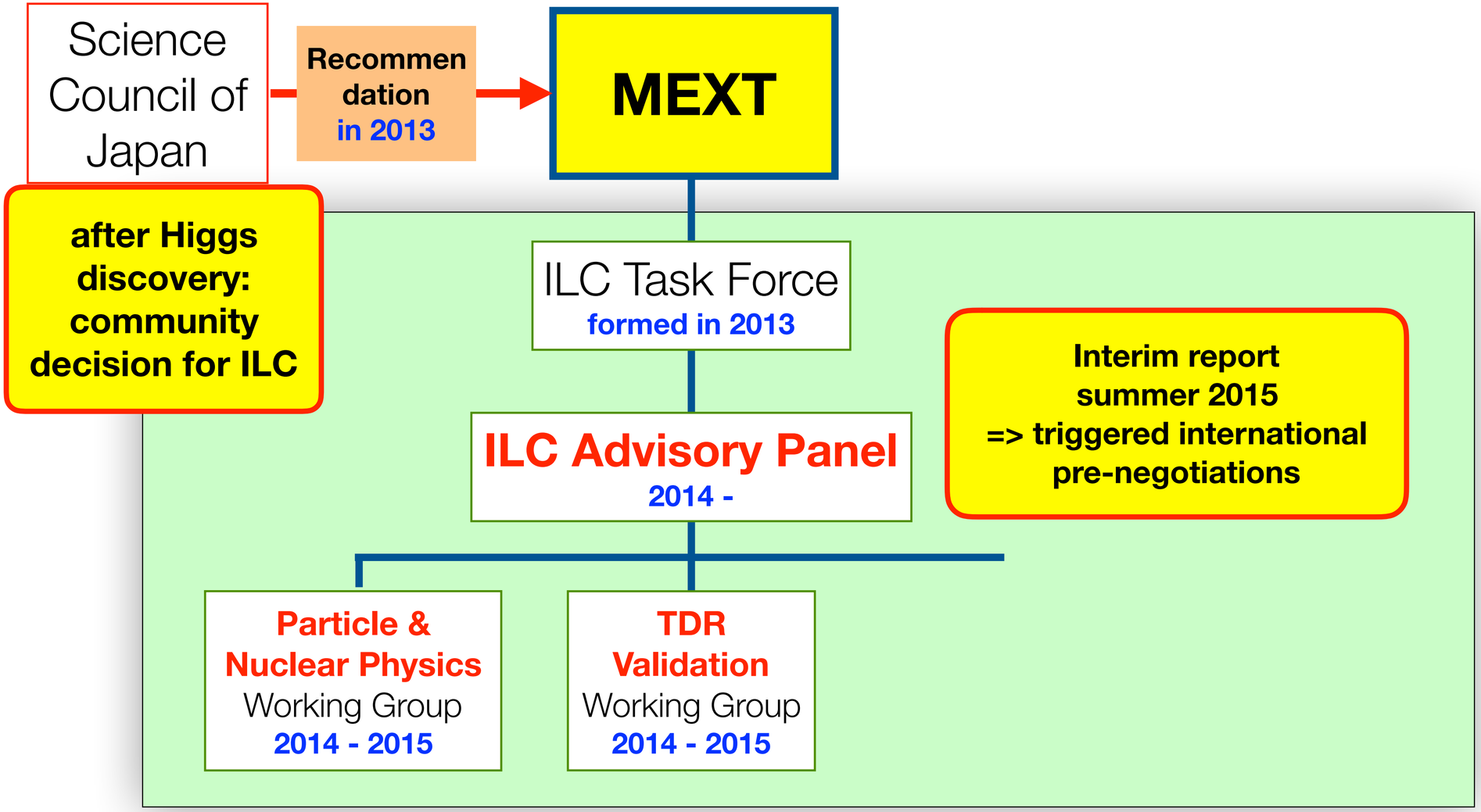

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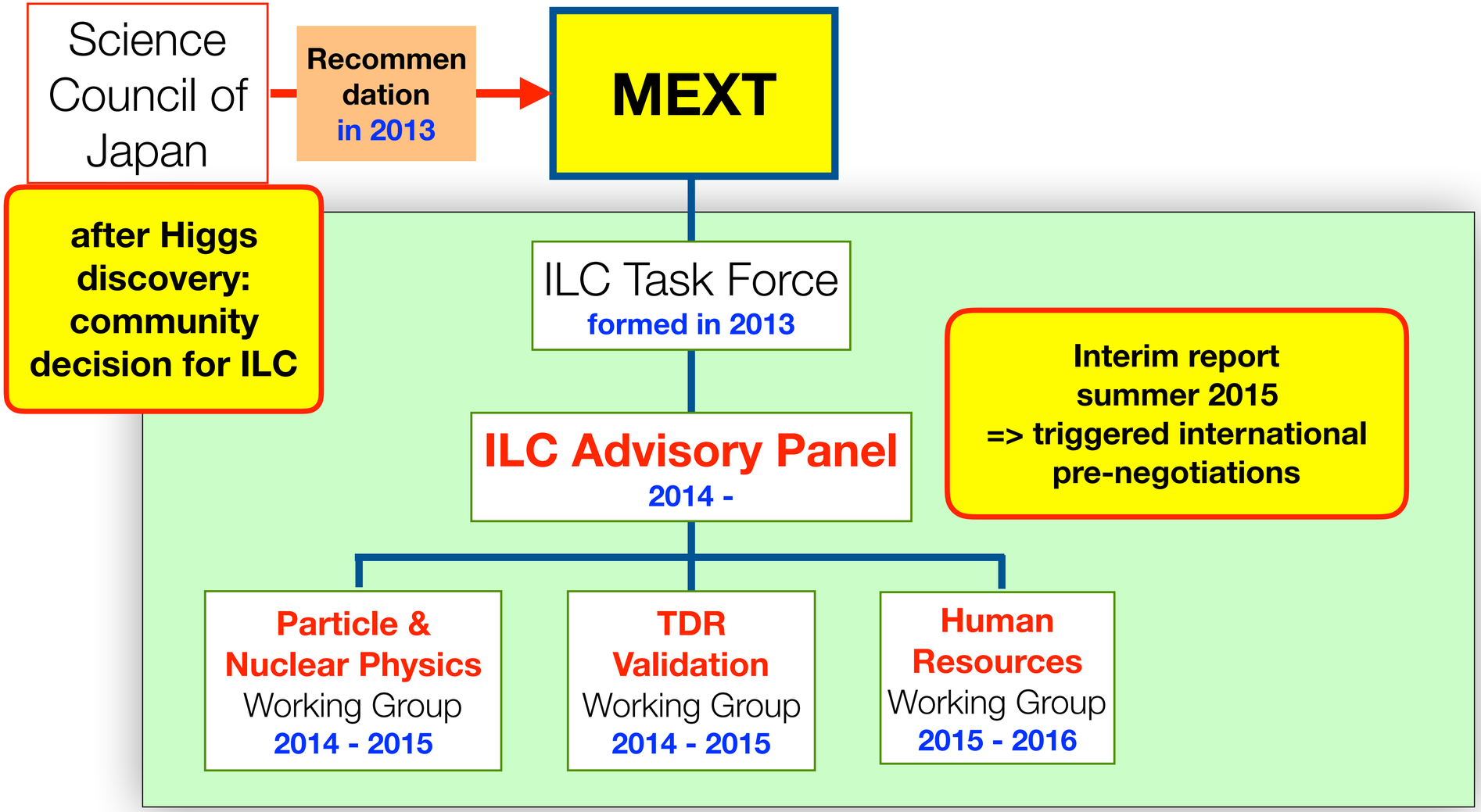

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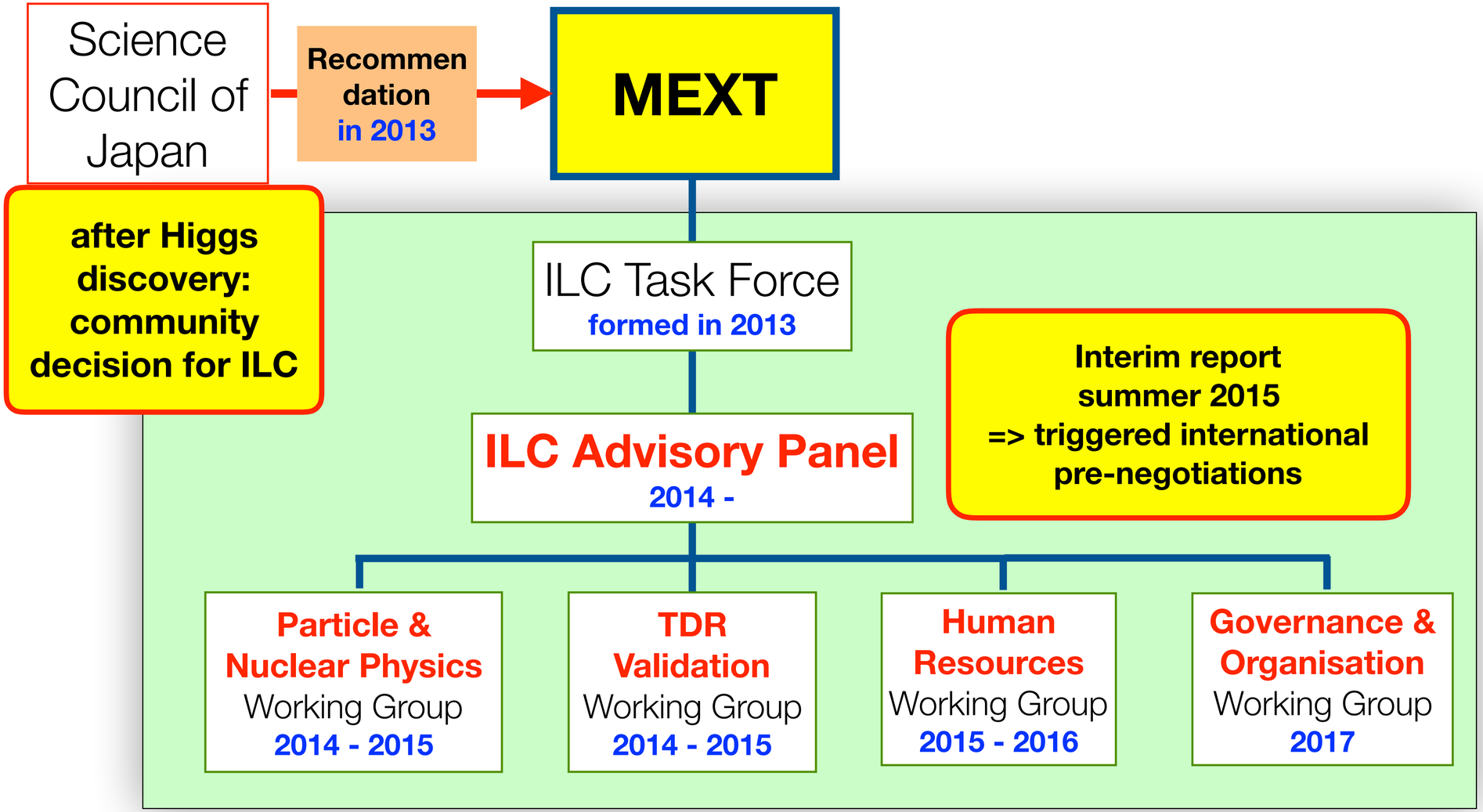

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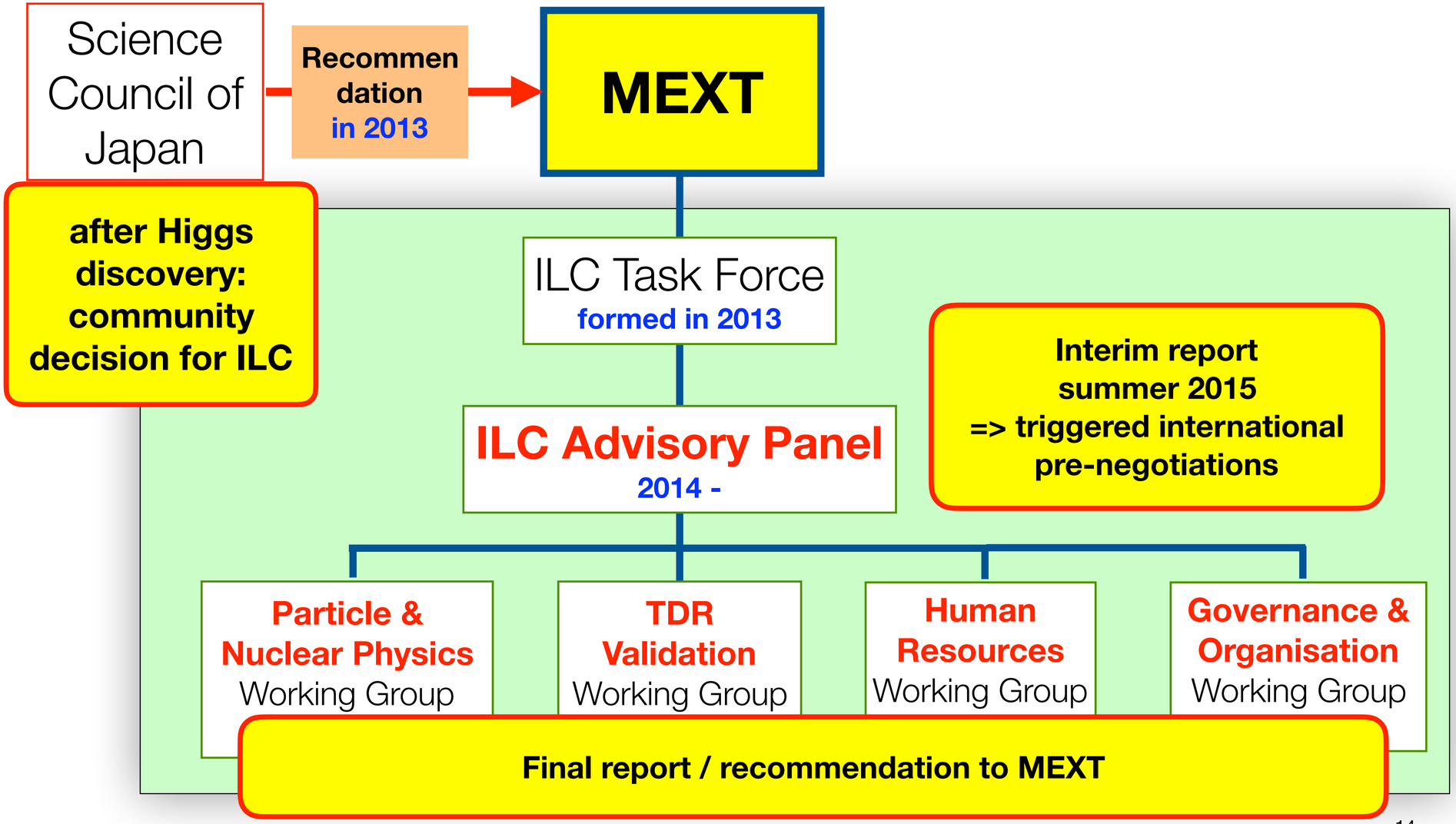
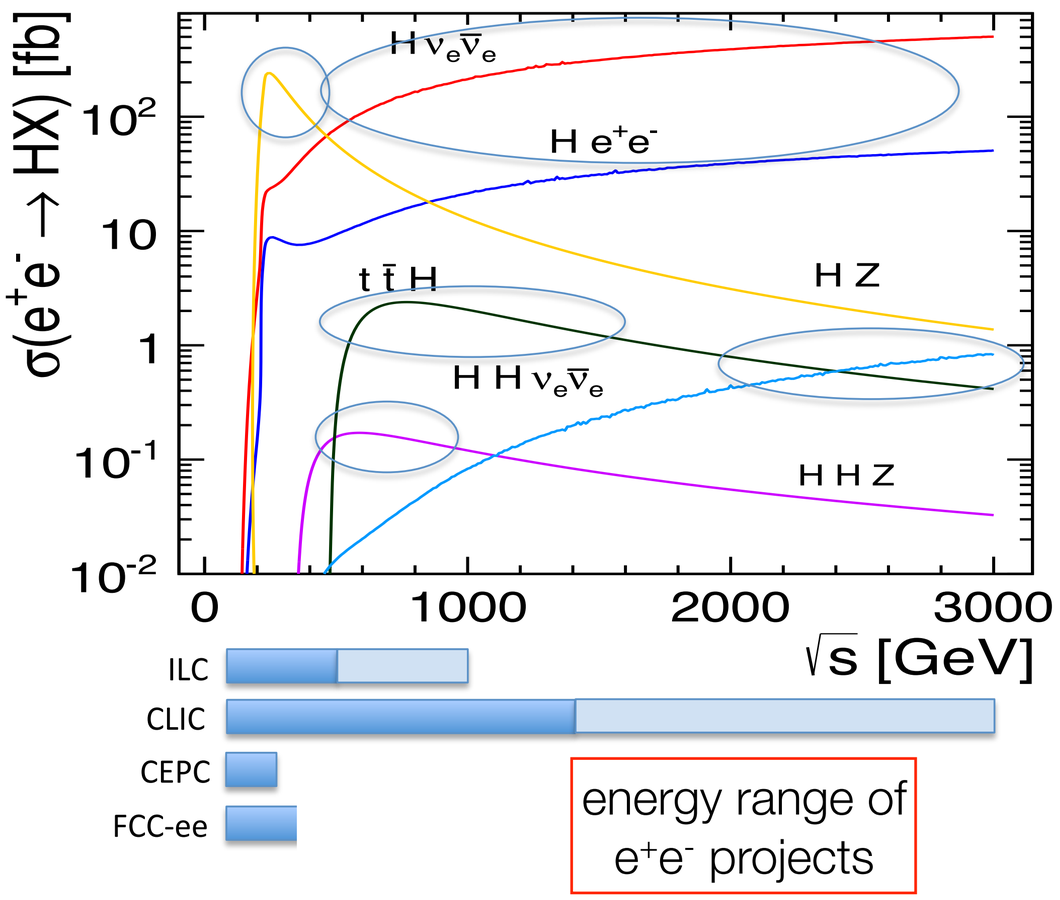
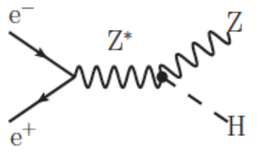


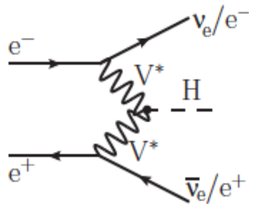
Higgs production in e^+e^- collisions





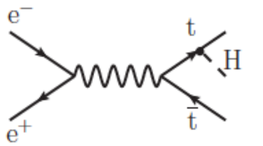
Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

≥ 250 GeV



Γ_{tot}

≥350 GeV



g_t

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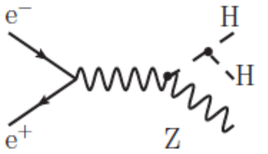

g_{HHH}

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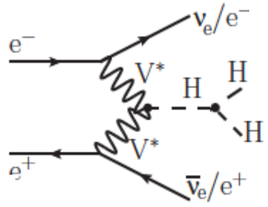

g_{HHH}

≥ 1 TeV

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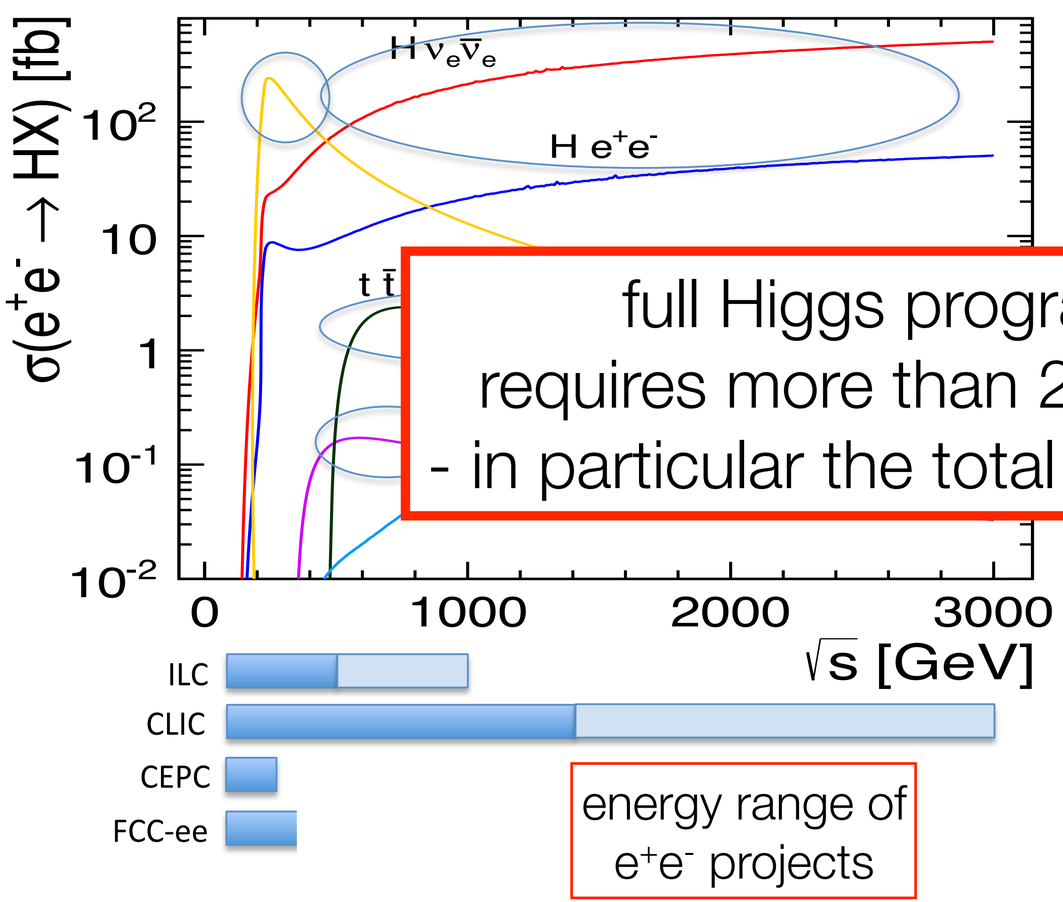
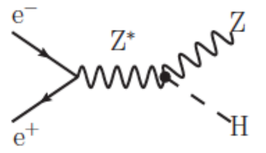


full Higgs program
requires more than 250 GeV
- in particular the total width Γ_{tot}

energy range of
e^+e^- projects



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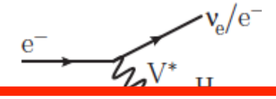

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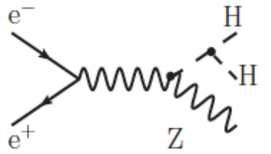

g_{HHH}

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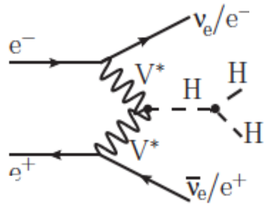
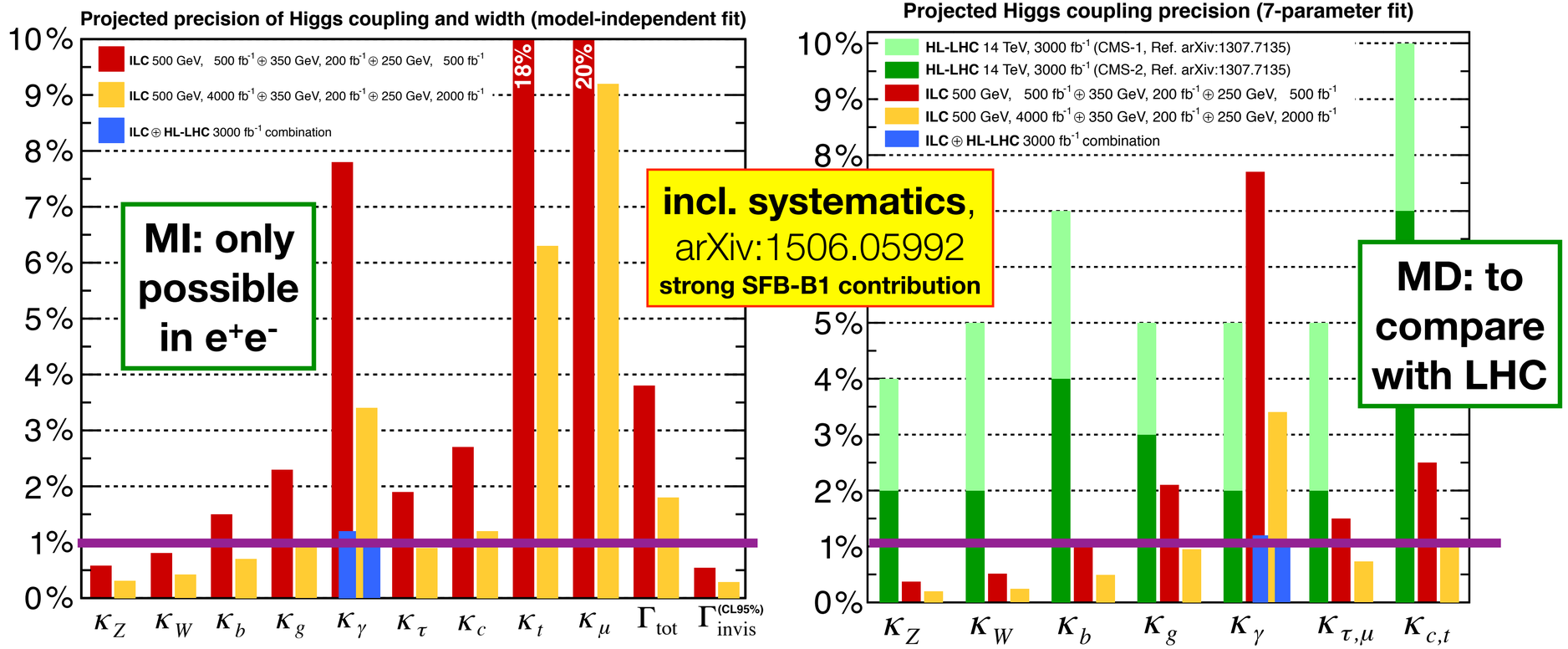


g_{HHH}

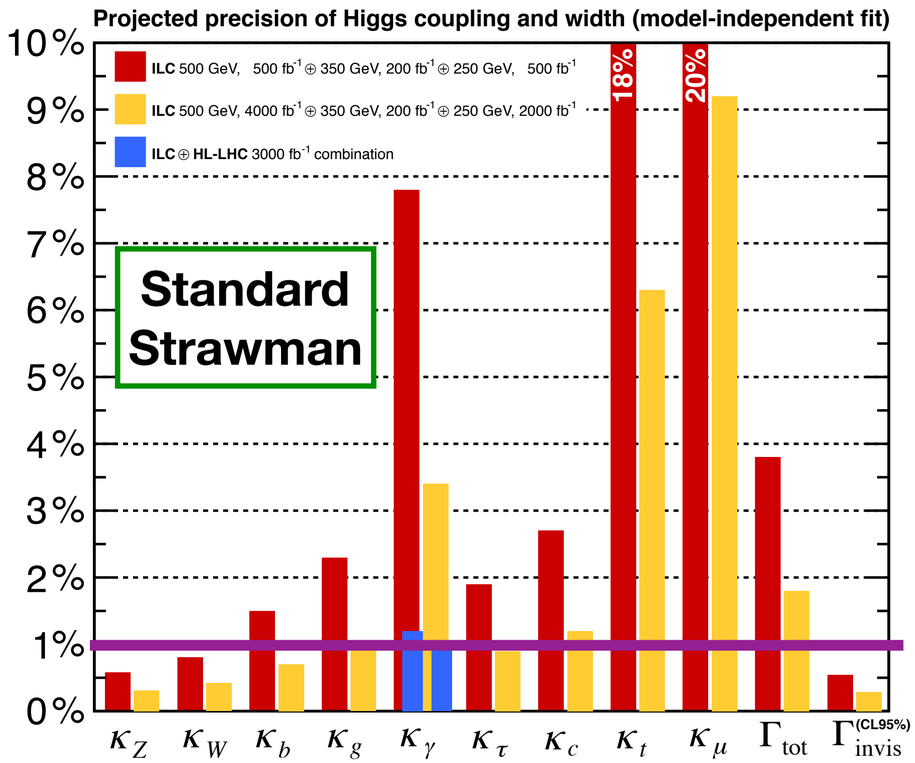
≥ 1 TeV

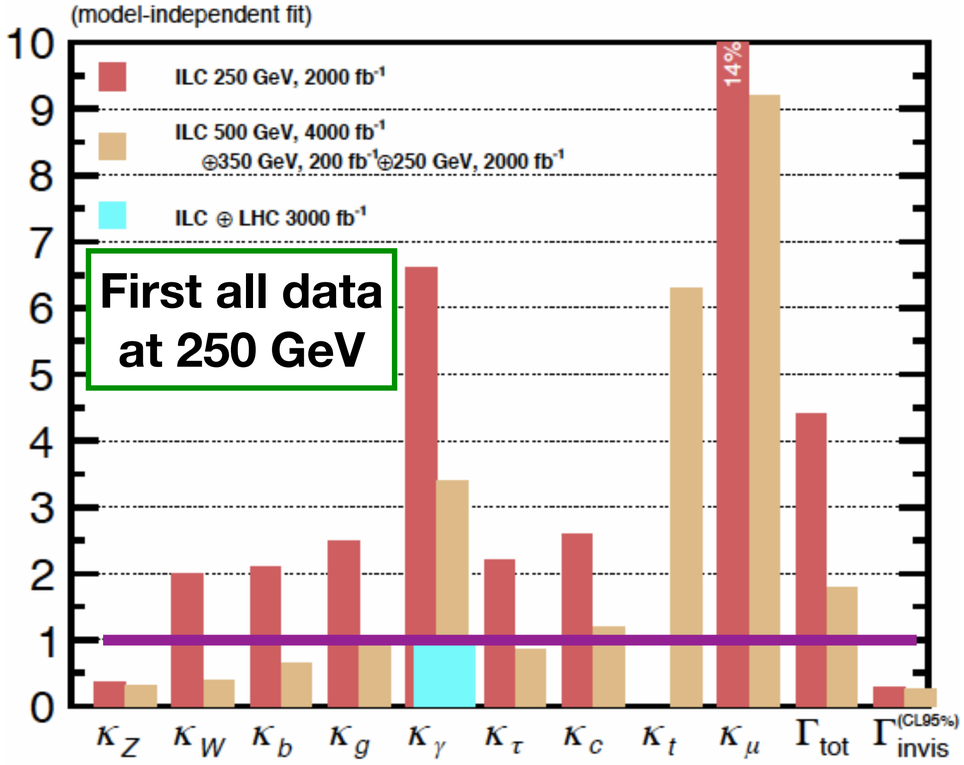
Absolute (!) Higgs Couplings at the ILC



The full ILC500 programme gives
sub-percent precision on most Higgs couplings

Higgs Couplings and Staging - Model-independent

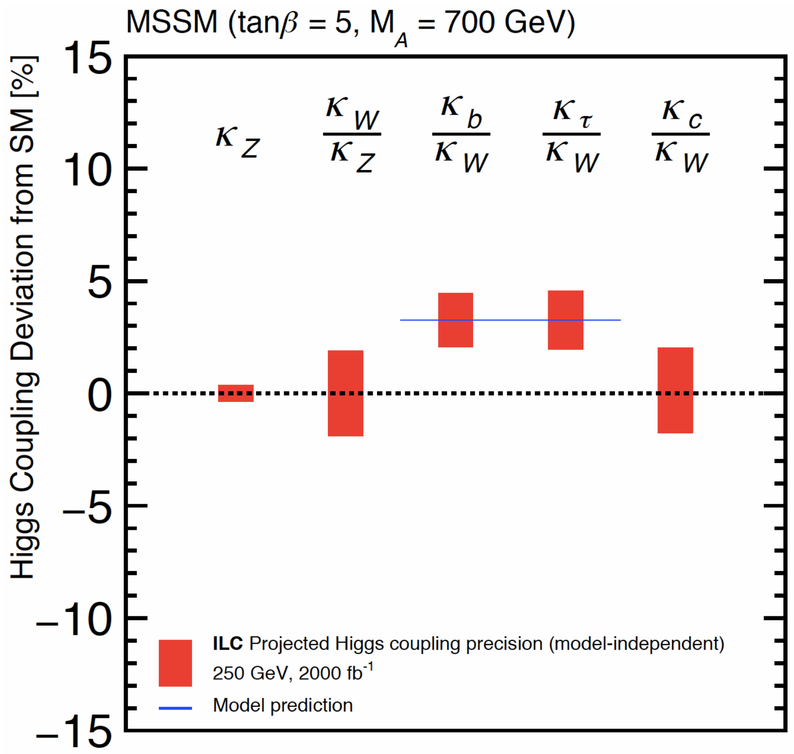


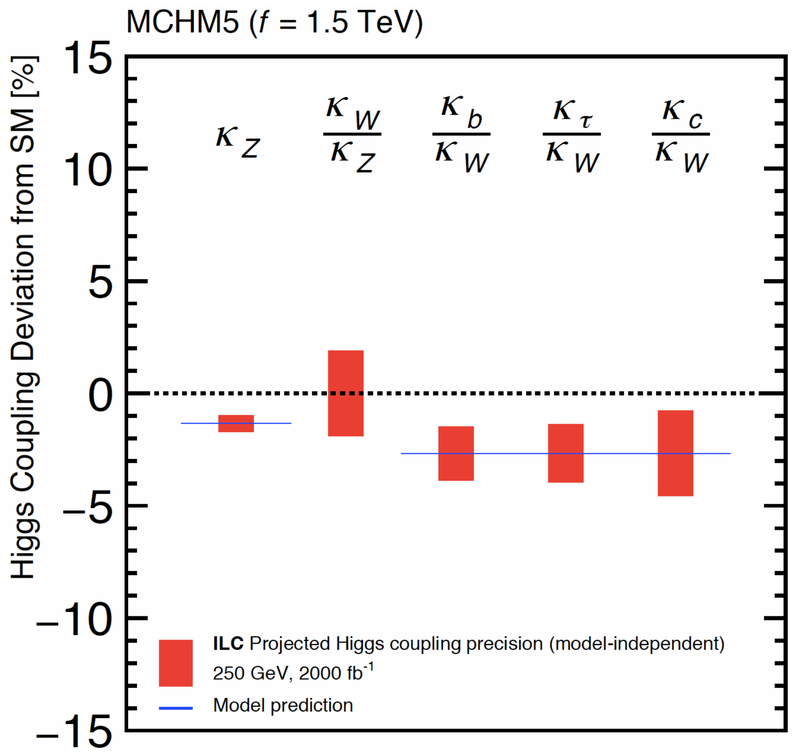


Precisions roughly similar - most notable exceptions: κ_W, κ_t

But note: red bars compare **8yrs** <=> **15yrs**

Finger-printing the Higgs: SUSY or Composite?

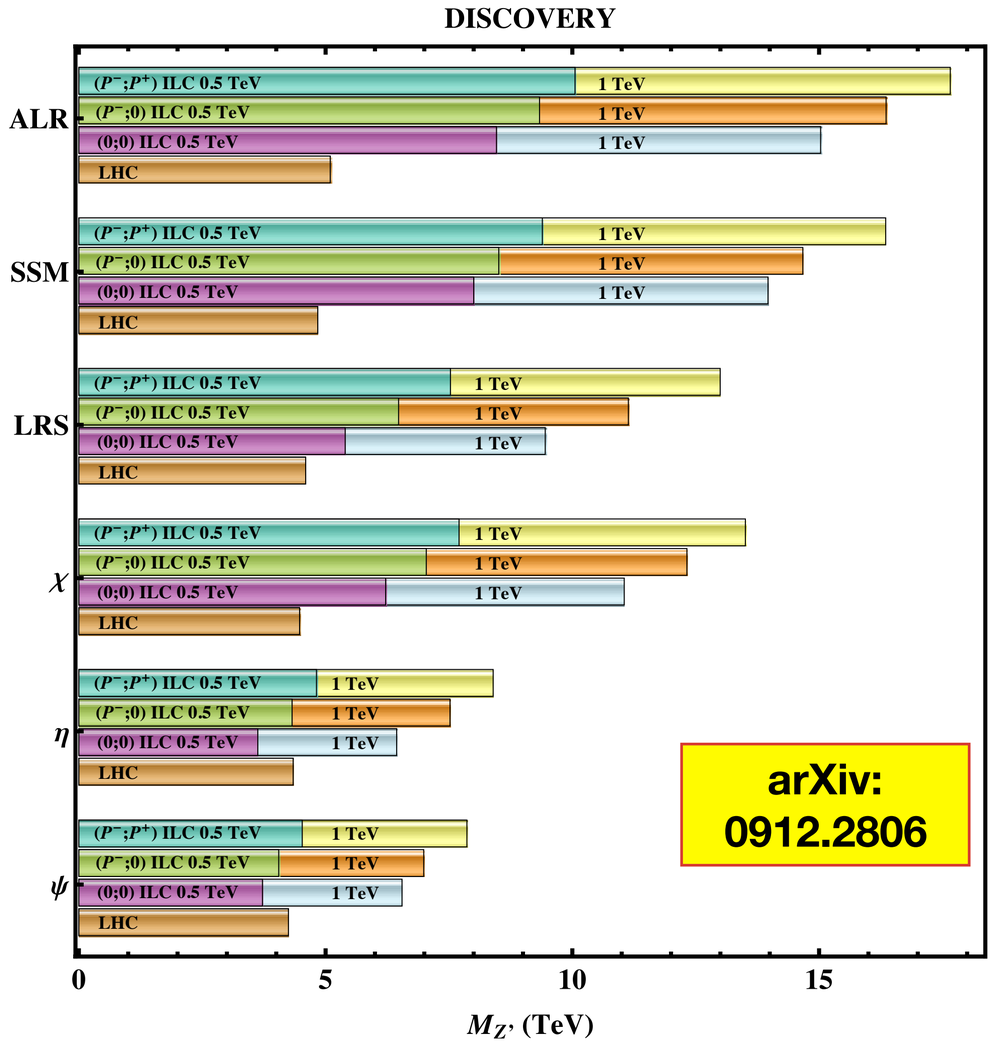




The full ILC250 stage gives significant BSM discrimination power

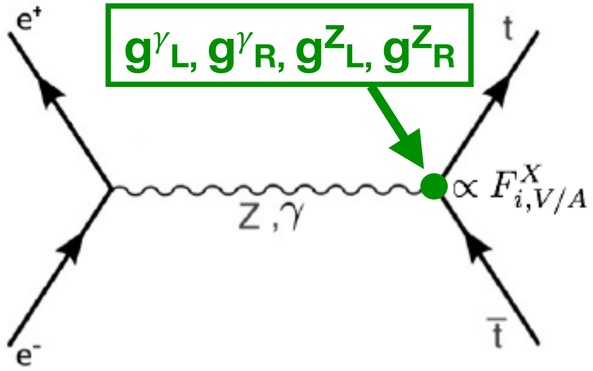
New Force Carriers

- via e^+e^- -> ff: sensitivity to Z' up to ~10 TeV
- already for 500fb^{-1} @ 500 GeV (initial run)
- increases to up to ~17 TeV for 1ab^{-1} at 1 TeV
- polarised beams typically gain ~2 TeV in reach



500 GeV

Electroweak Couplings of the Top Quark



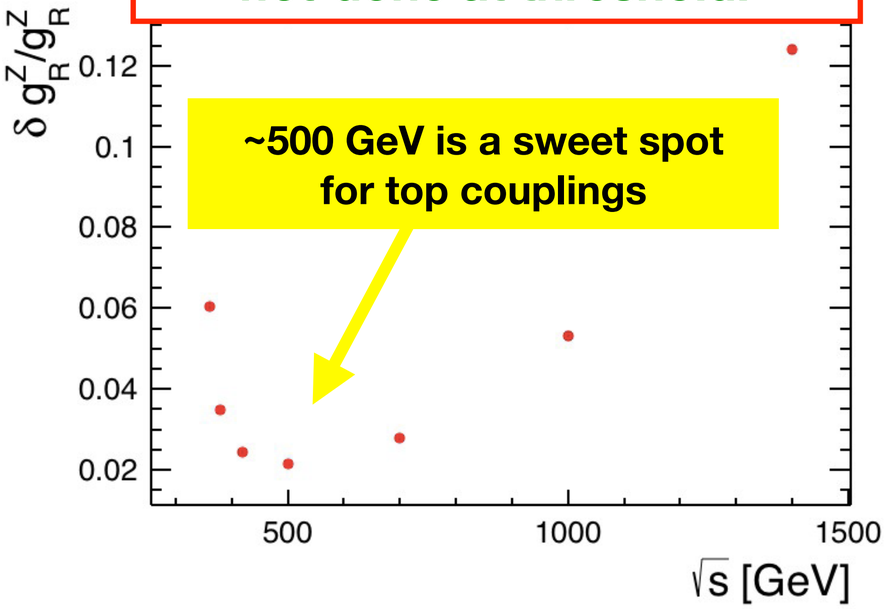
Pure γ or pure $Z^0 : \sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference $: \sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $P(e^+) = \mp 30\%$

√s dependency: top physics is *not* done at threshold!

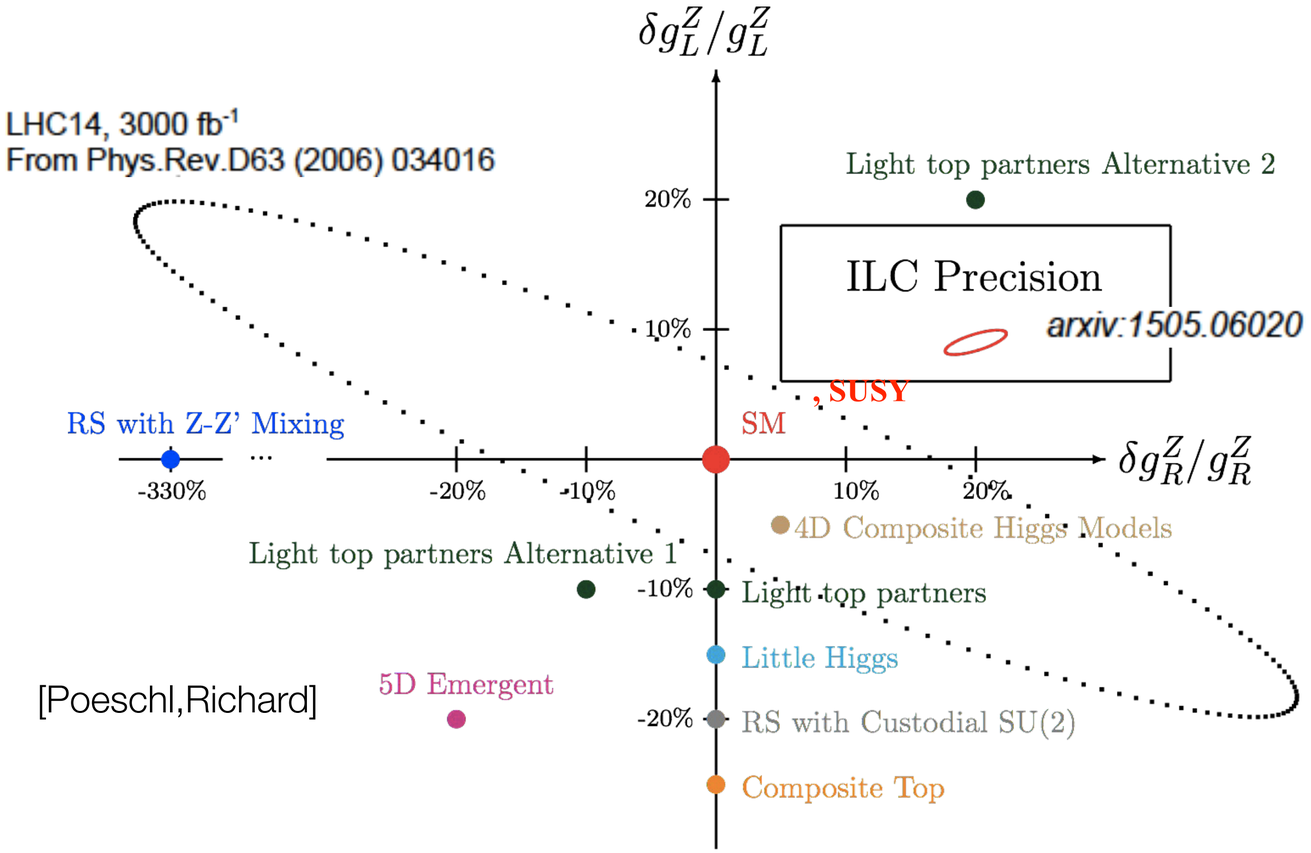


Polarised beams

- allow to disentangle g^{γ} vs g^{Z}
- provide robustness against systematic uncertainties
- minimise higher-order corrections

500 GeV

ILC Prospects on Top Couplings and BSM



[Poeschl,Richard]

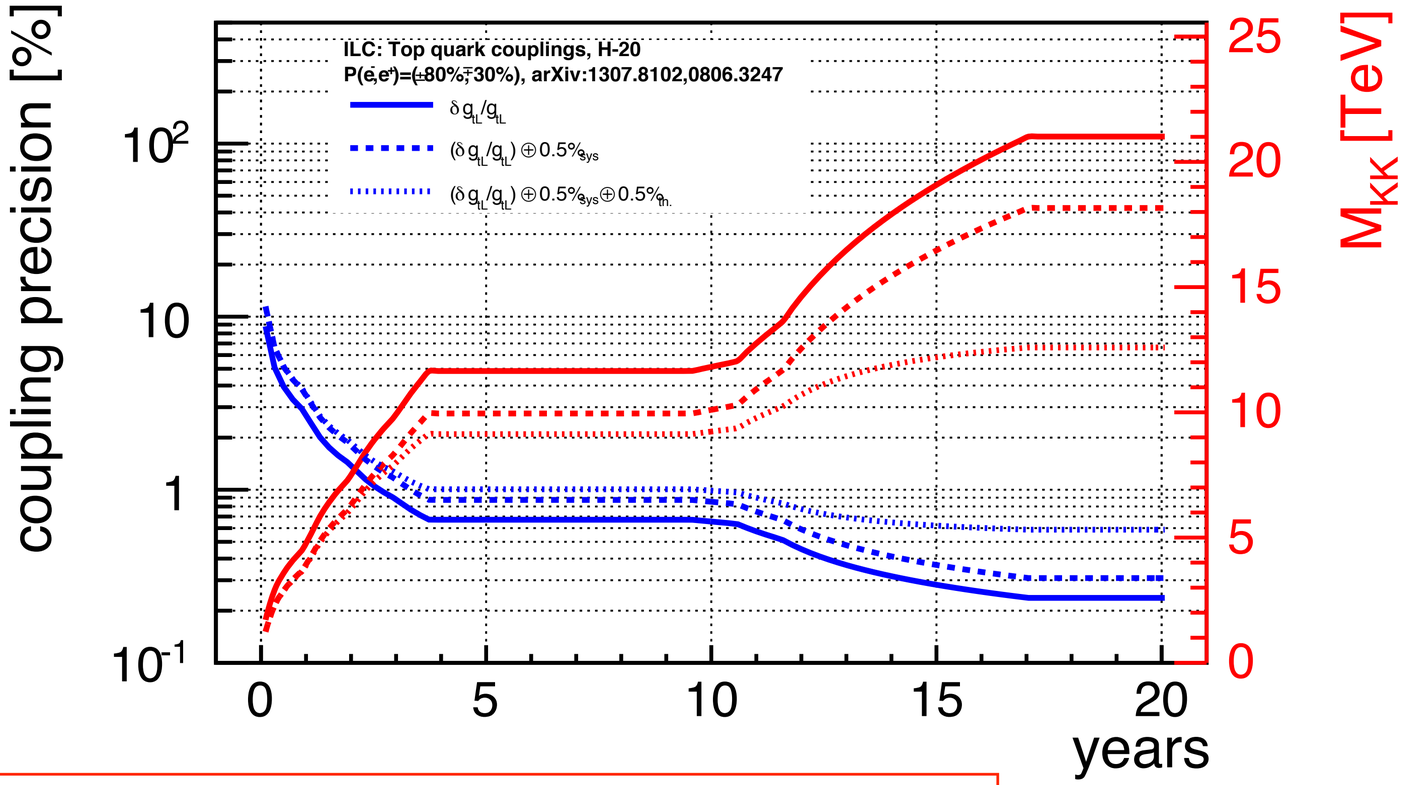
Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

- ILC precision allows model discrimination
- sensitivity in g^Z_L, g^Z_R plane complementary to LHC

500 GeV

New Physics Reach of full ILC500 Program

….for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**
based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~20 TeV in typical scenarios
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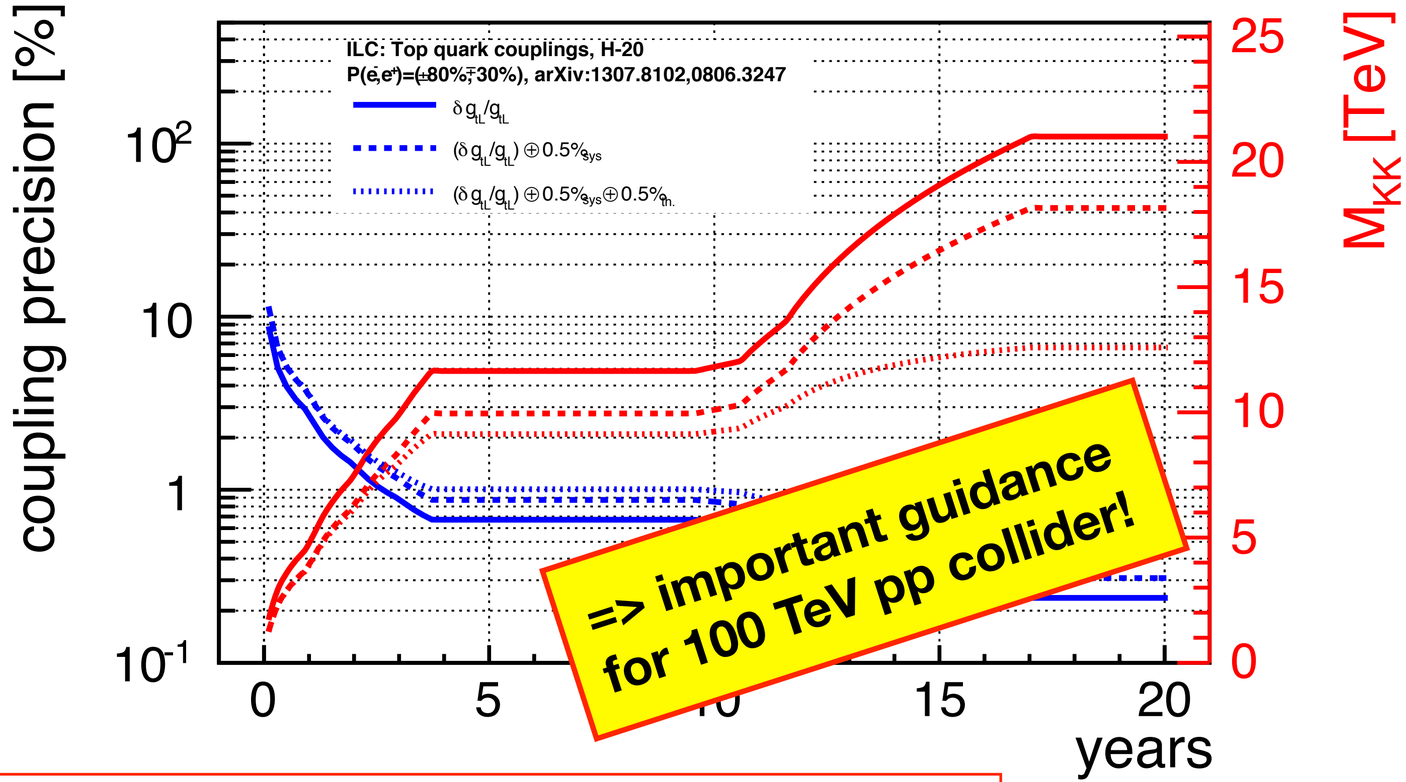
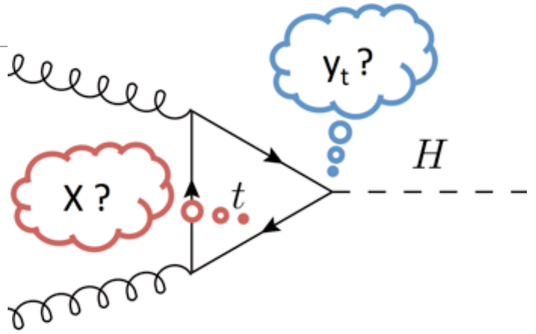


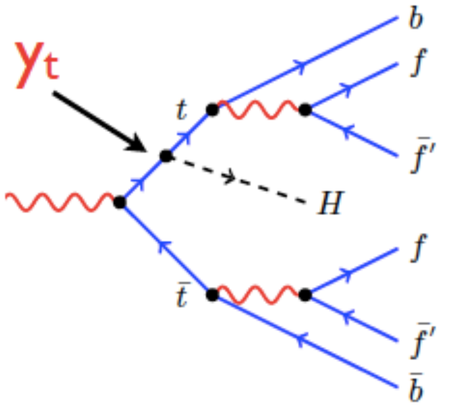
Can probe scales of ~20 TeV in typical scenarios
(… and up to 80 TeV for extreme scenarios)

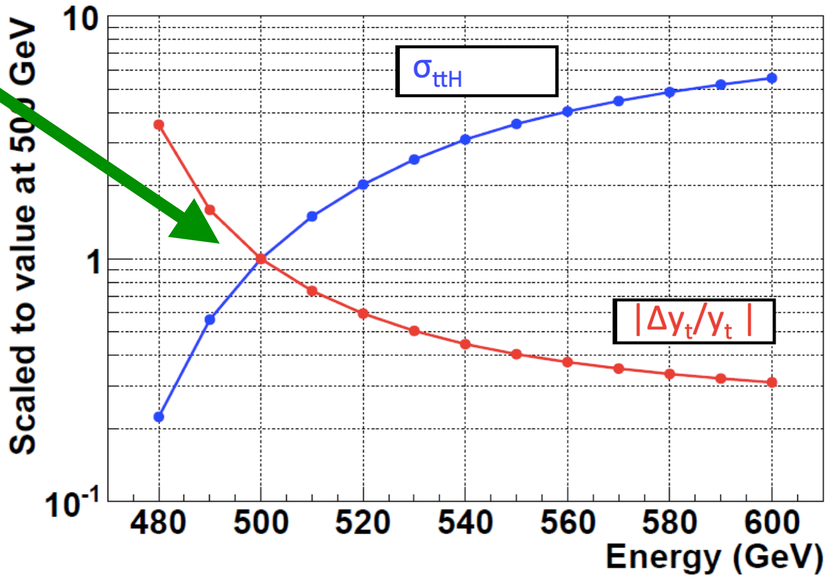
500 GeV

Top Yukawa Coupling

- **Indirect**: loop couplings, top threshold scan …
  => is it *really* y_t ?
- **Direct**: tth production
  => possible for $\sqrt{s} \geq 500$ GeV
- SM σ**(ttH) = 0.45fb** @ 500 GeV
  => ILC500 full running scenario, geant4-based detector simulation:
  δy_t **= 6.3%**
- ILC tunnel length contains 1.5 km reserve space on each side (at the moment "empty"…)
- δy_t could be **2.5% if $\sqrt{s}$ = 550 GeV**

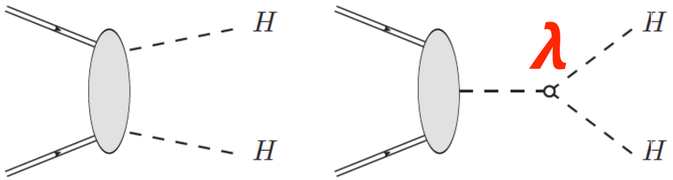






500 GeV

Double Higgs Production & Higgs Self-Coupling

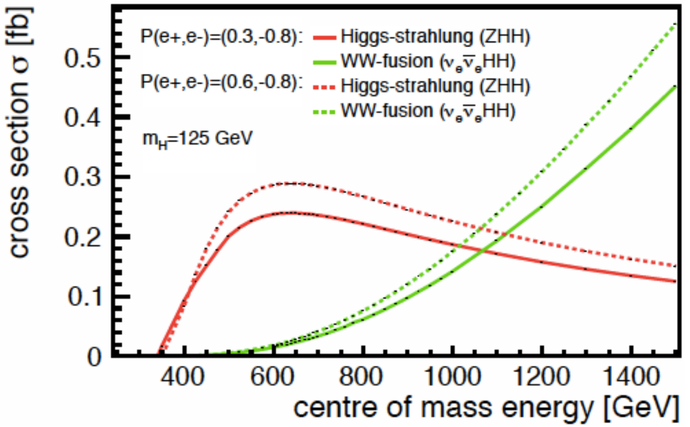


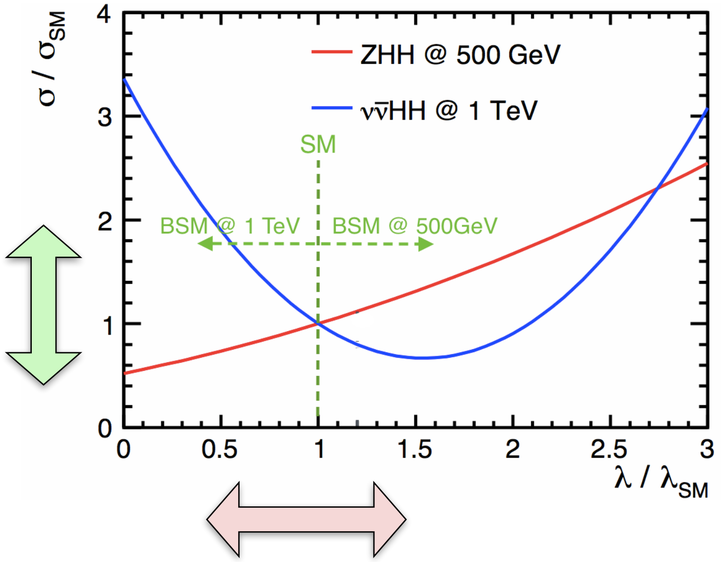
two **complementary** production processes:

- **ZHH @ ~500 GeV**
  - **unique feature: *increases* if $\lambda > \lambda_{SM}$**
  - **$\delta\sigma/\sigma$ = 16% : > 5 sigma discovery**
  - **$\delta\lambda/\lambda$ = 27% : 3 sigma observation**
- **vvH (VBF) @ ECM > 1 TeV**
  - **$\delta\sigma/\sigma$ = 13%**
  - **$\delta\lambda/\lambda$ = 10%**

BSM changes the picture: e.g. **λ = 1.5 λ_{SM}**
500GeV: $\delta\lambda/\lambda$ = 20%, 1TeV: $\delta\lambda/\lambda \to \infty$

=> with combination of 500 GeV and 1 TeV we're always on the safe side!





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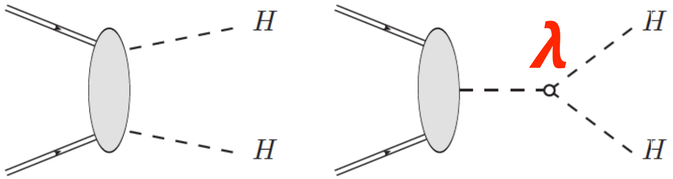
Double Higgs Production & Higgs Self-Coupling



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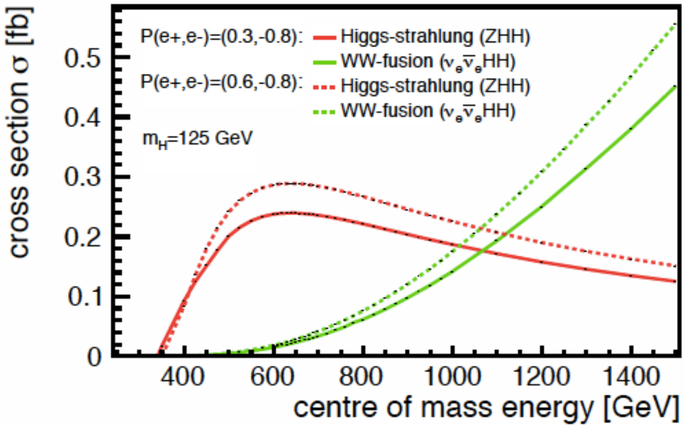

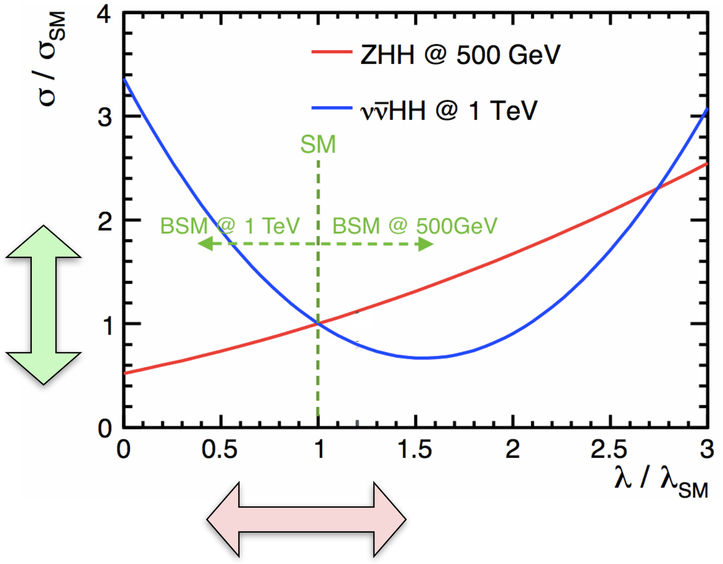

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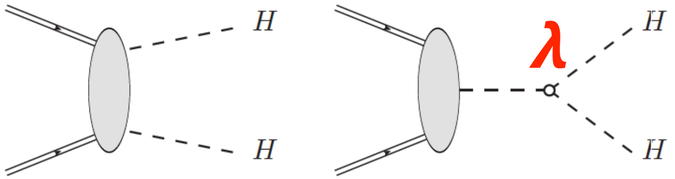

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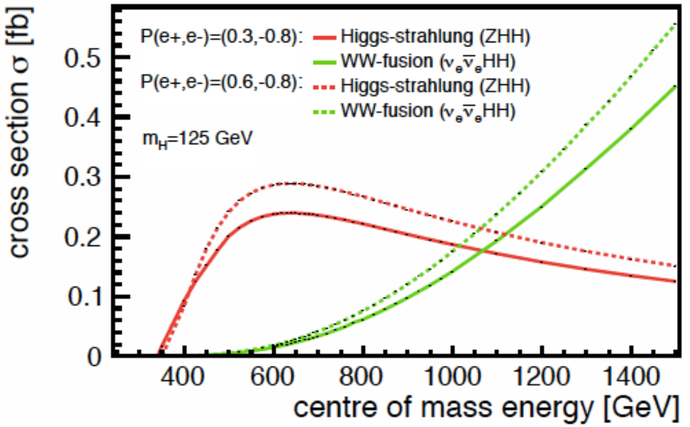

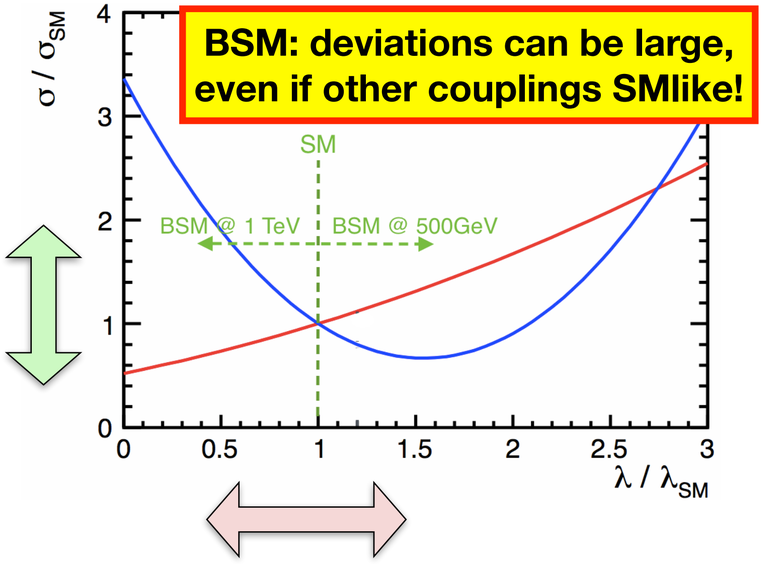

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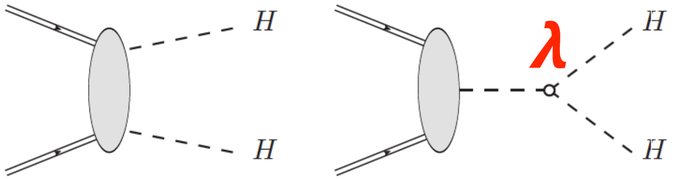

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SFB-B1 (PhD Th. C.Dürig)

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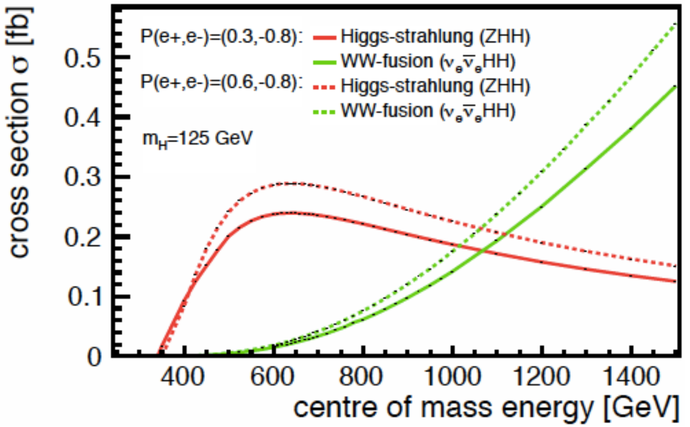

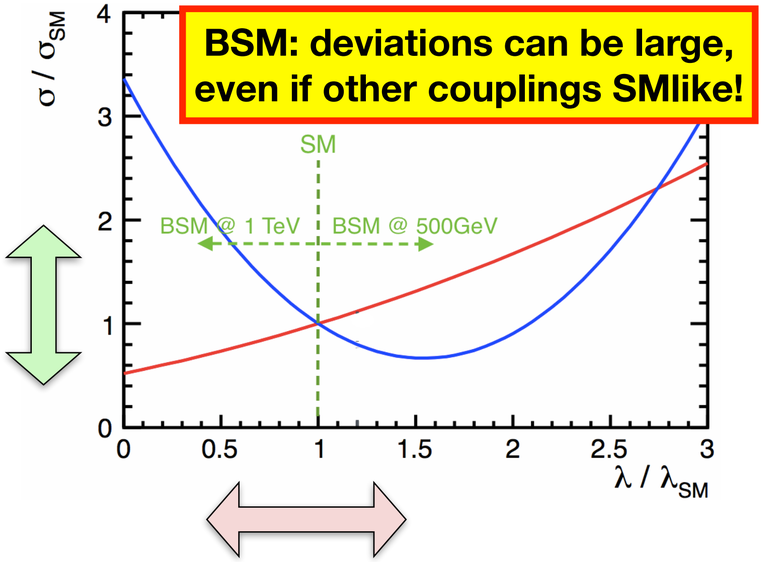

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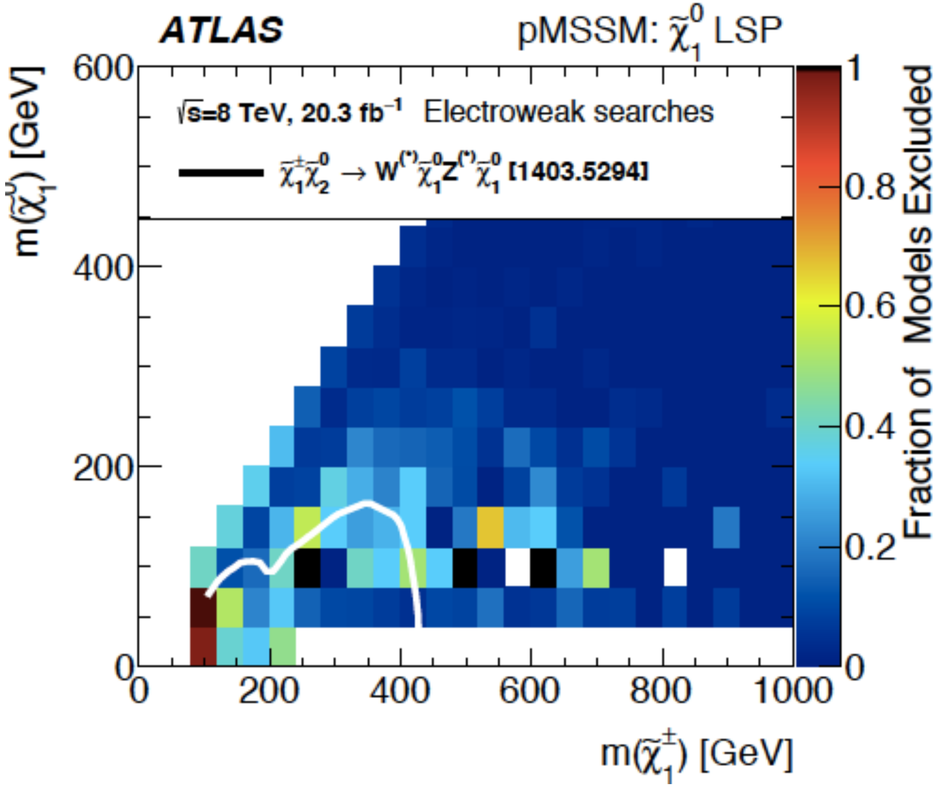
simplified models don't give the full story
(e.g. 100% BR assumption rarely fulfilled)
-> c.f. pMSSM scan by ATLAS, arXiv:1508:06608



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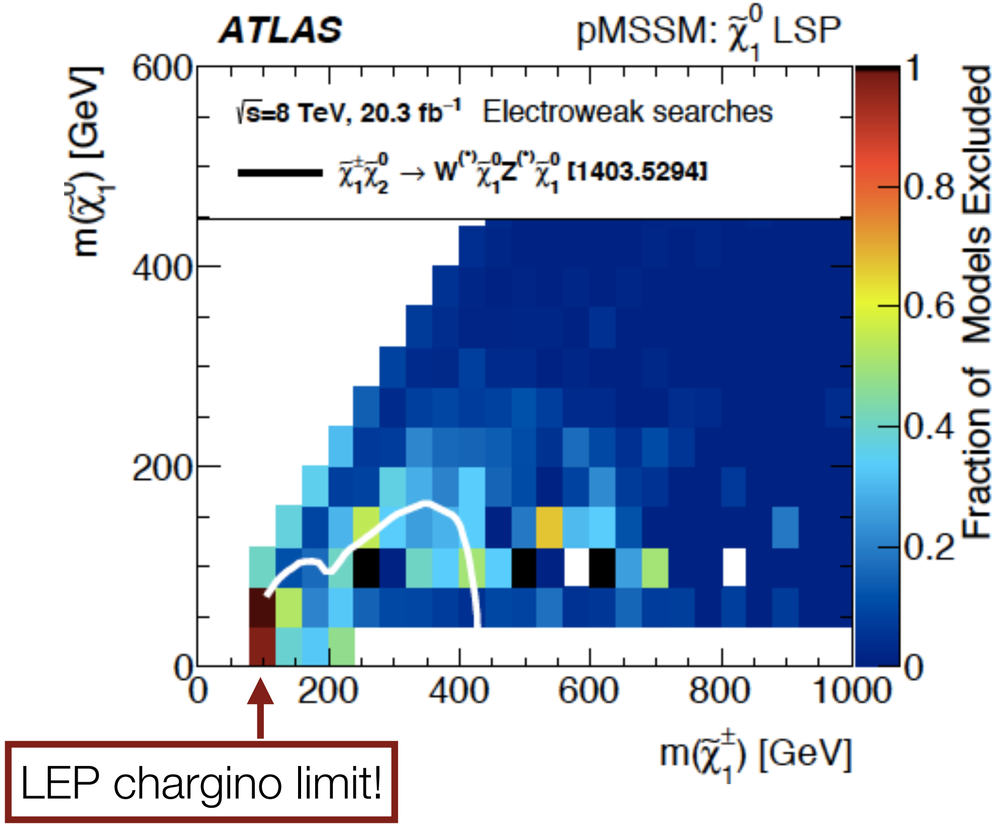

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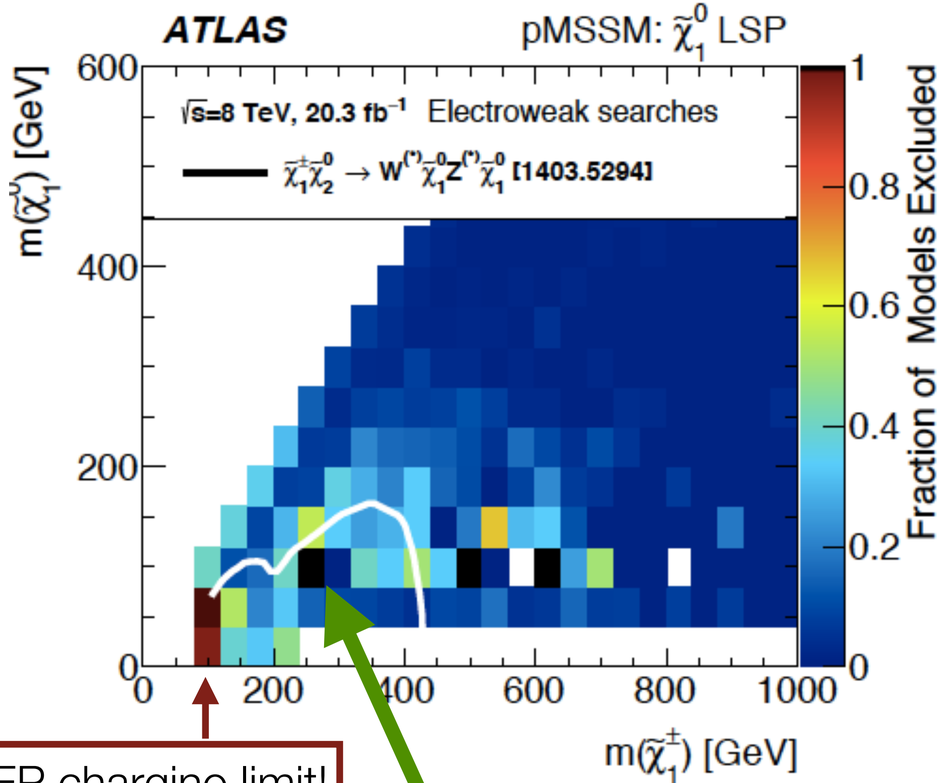

LEP chargino limit!

only ~30% excluded below limit

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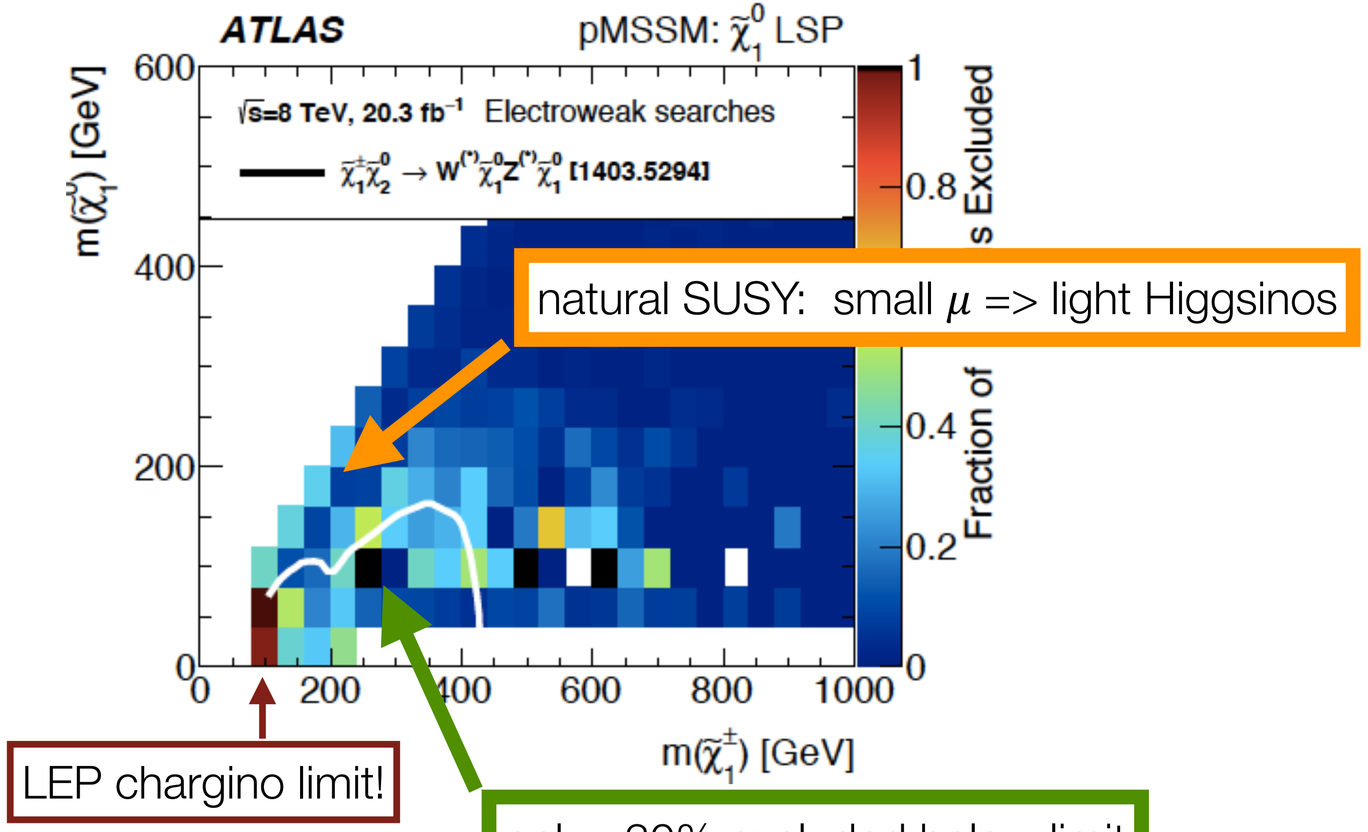

natural SUSY: small μ => light Higgsinos

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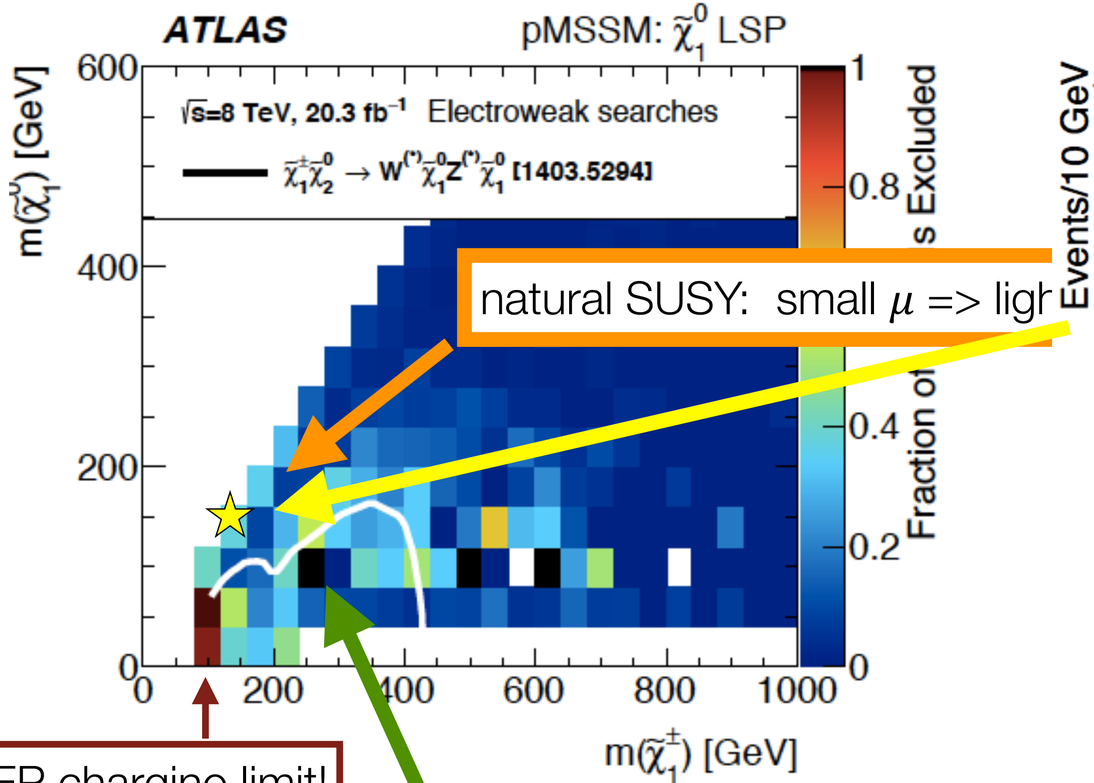

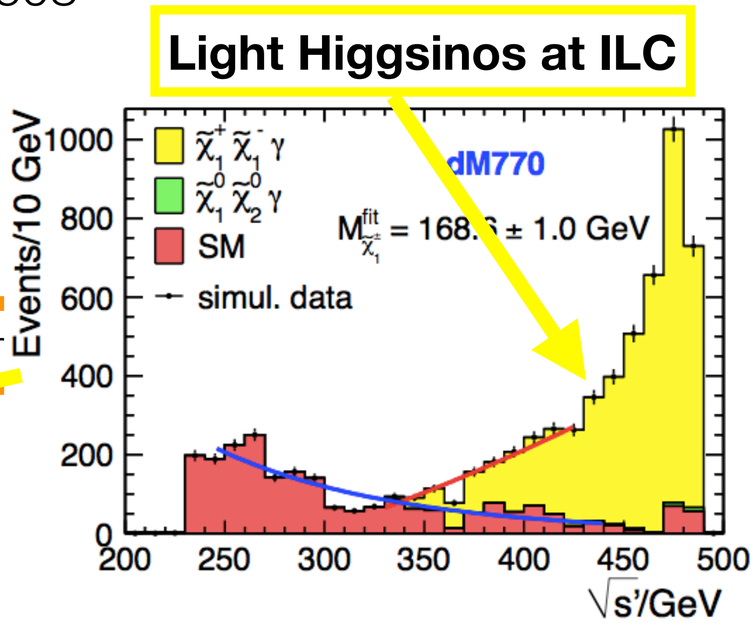

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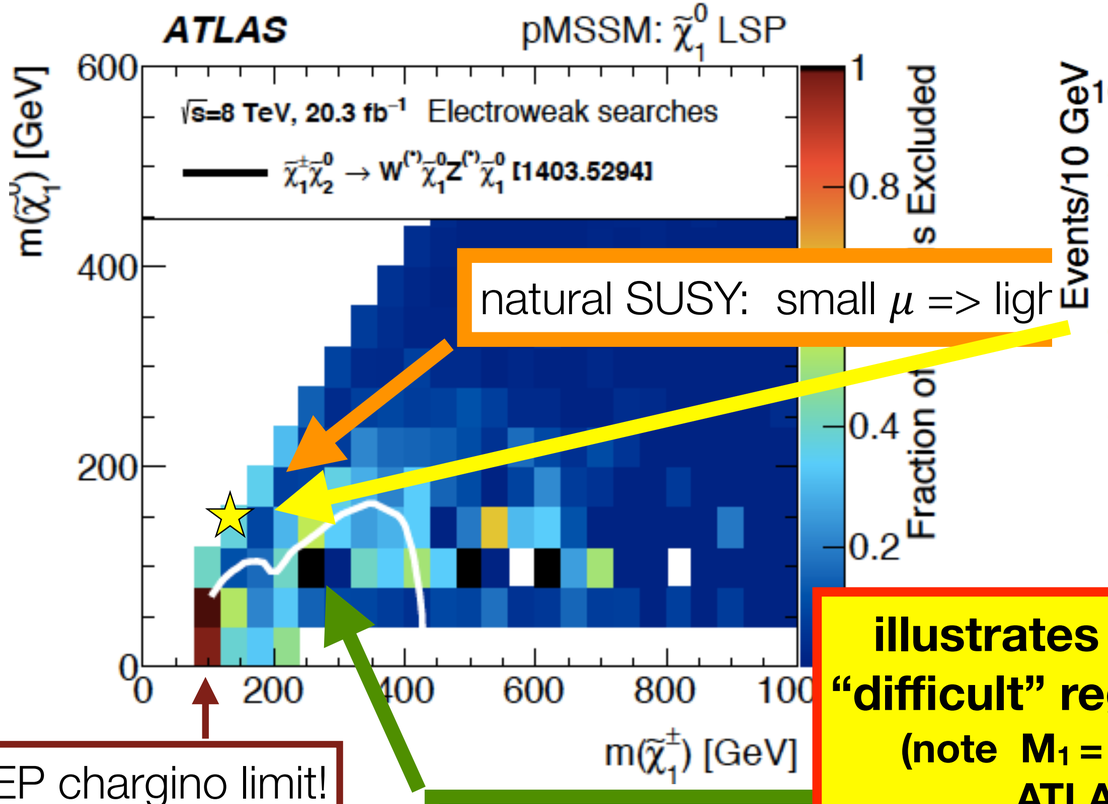

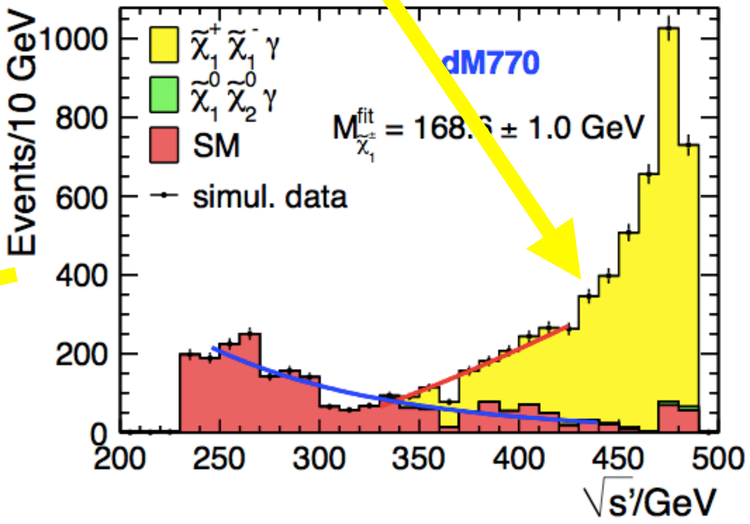

Light Higgsinos at ILC

natural SUSY: small μ => ligh

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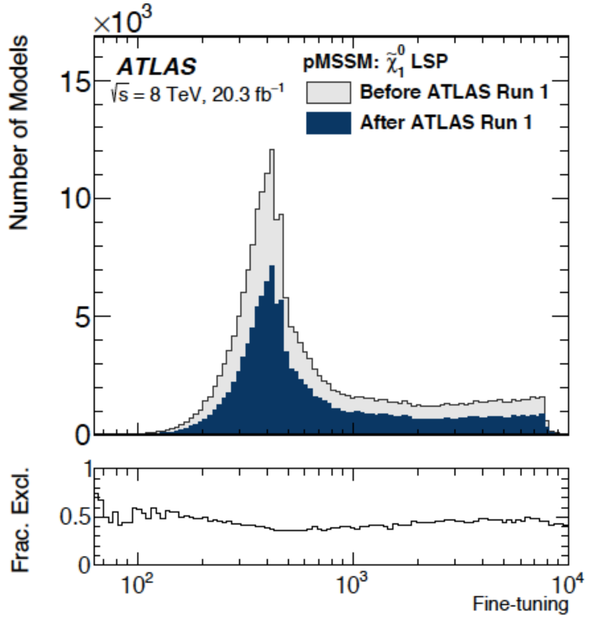
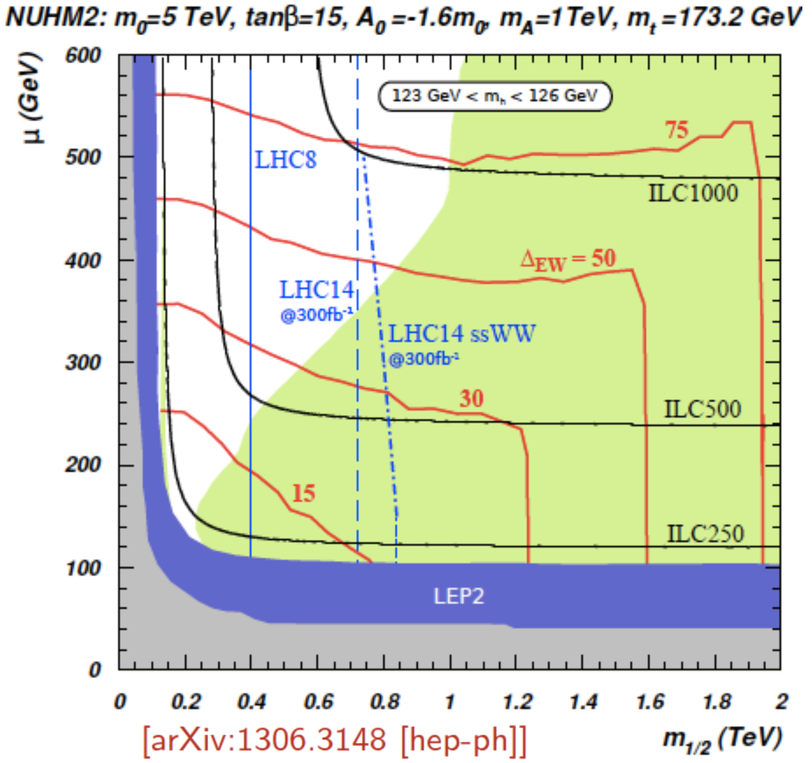
illustrates pp /e^+e^- complementarity:
"difficult" region at LHC is "easy" in e^+e^-
(note M_1 = 5 TeV, M_2 = 10 TeV in ILC study
ATLAS scan up to M = 4 TeV)

Is SUSY still natural?



=> no dramatic change in level of fine-tuning due to ATLAS exclusions (Barbieri-Giudice measure)



[arXiv:1306.3148 [hep-ph]]

e^+e^- colliders:

directly & unambiguously probe naturalness by discovery or exclusion of Higgsinos up to ≲ √s / 2

Probing the GUT scale with light Higgsinos

various benchmarks

- with ΔM = 0.77…..20 GeV
- in pMSSM / NUHM2 / hybrid gauge-gravity mediation / mirage unification
  [c.f. arXiv:1610.06205]

precision measurements of Higgsinos:

- determine weak scale SUSY parameters even if in multi-TeV regime
  => M_1, M_2, M_3, M_{stop}, M_A, …
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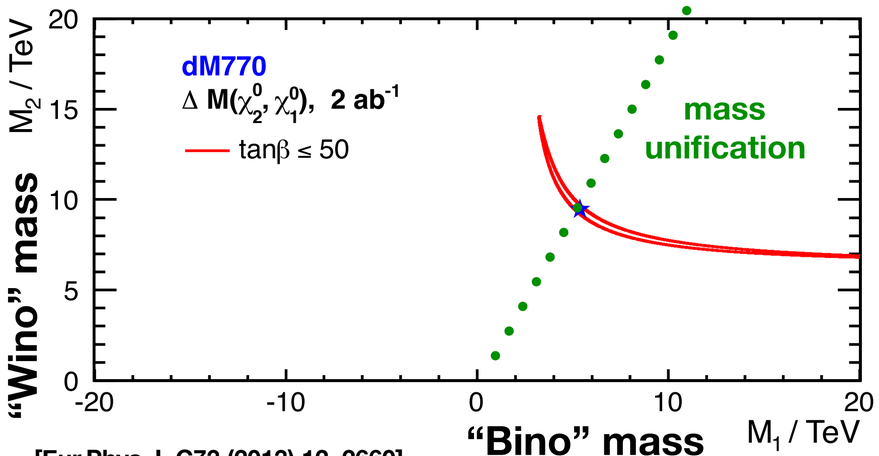

[Eur.Phys.J. C73 (2013) 12, 2660]

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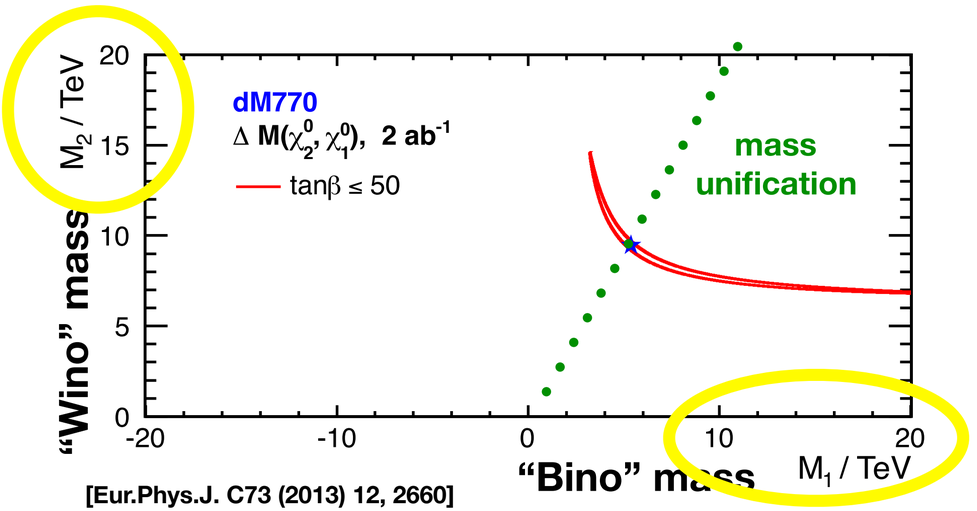

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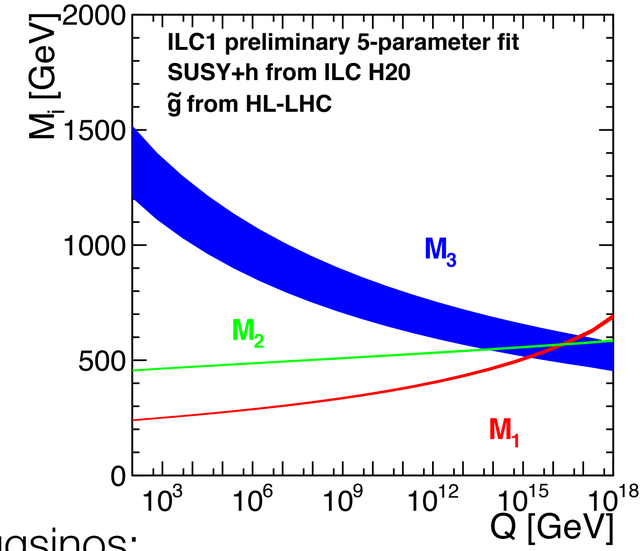

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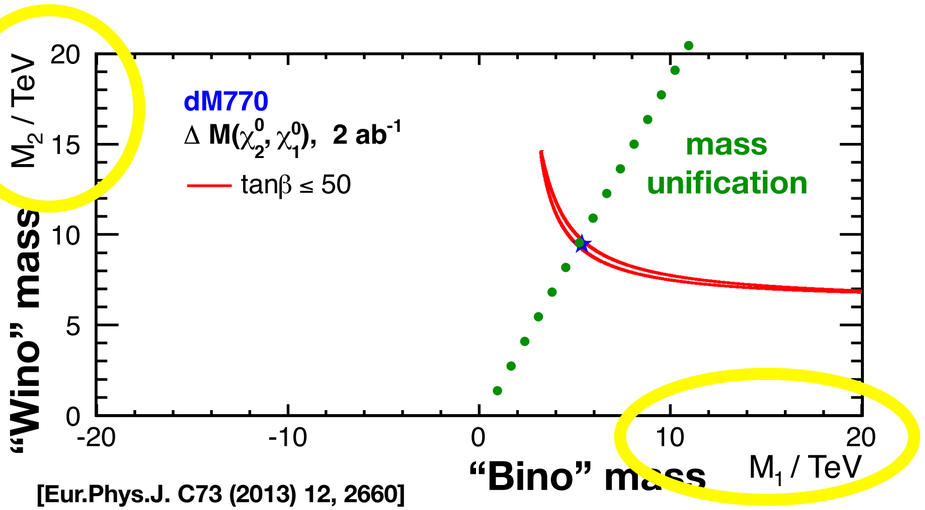

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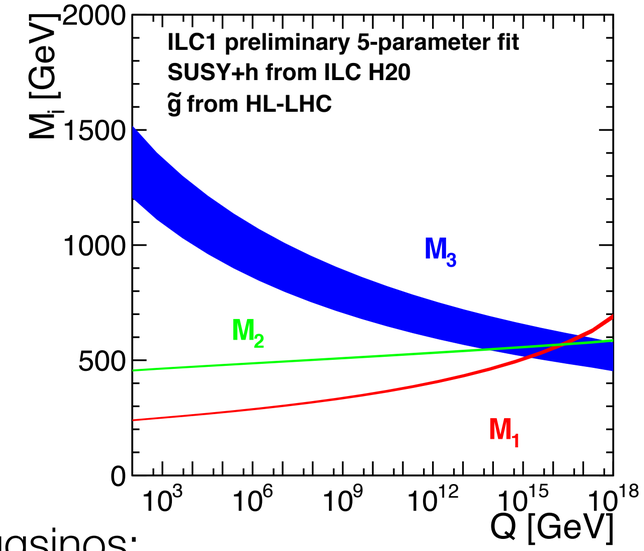

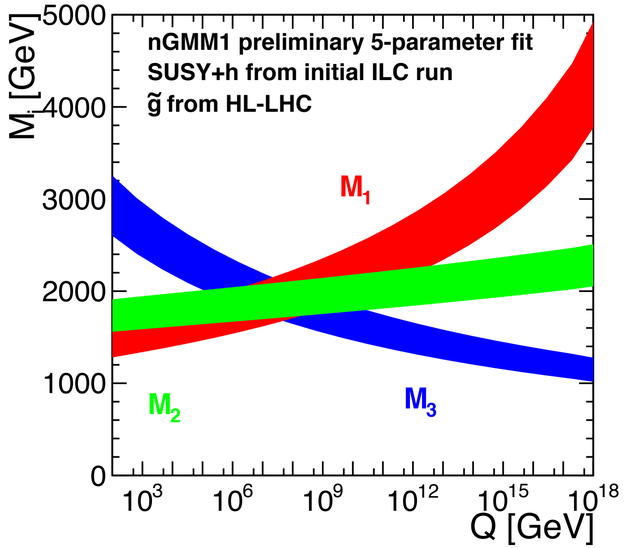

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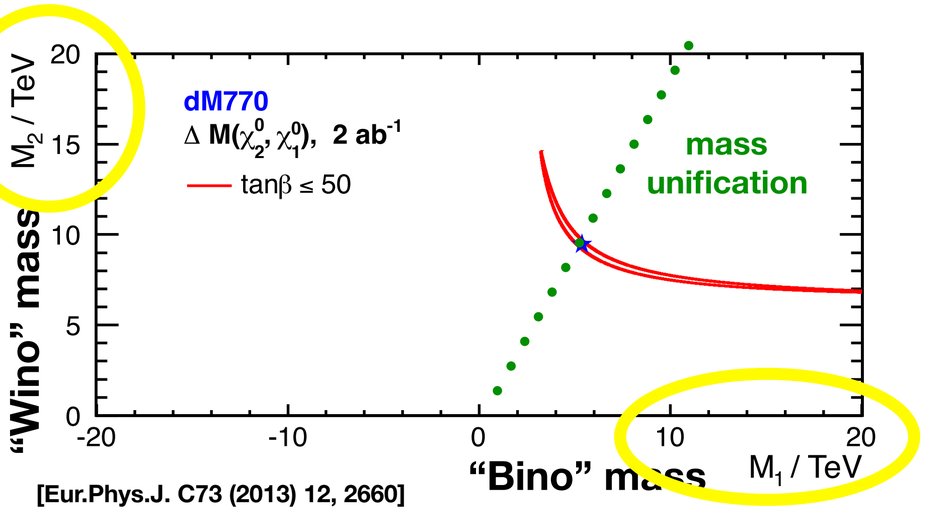

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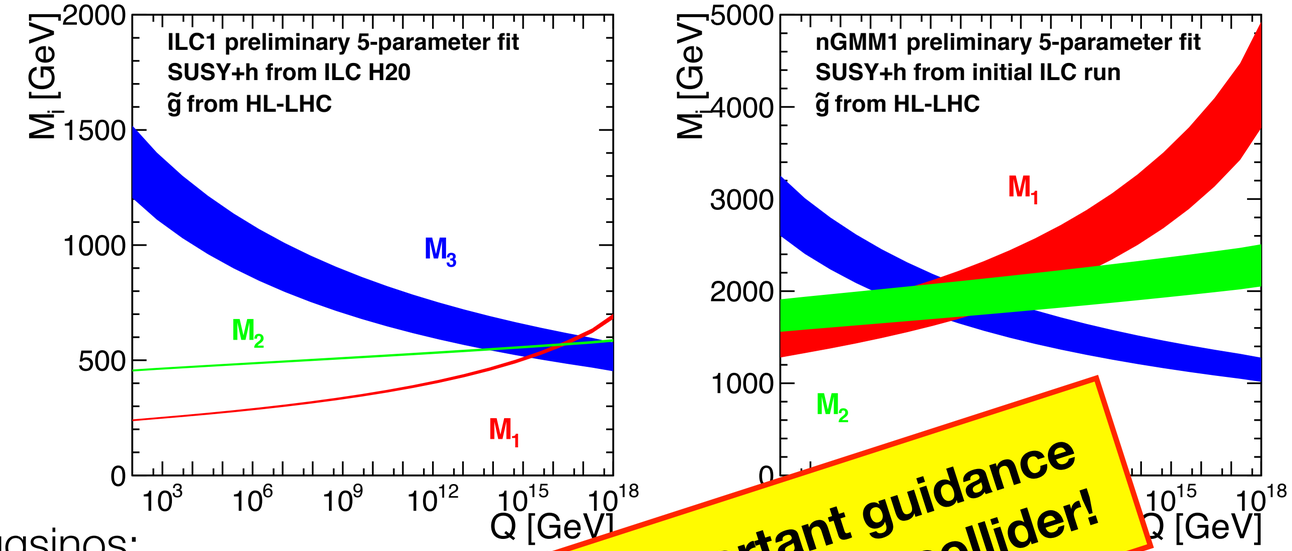

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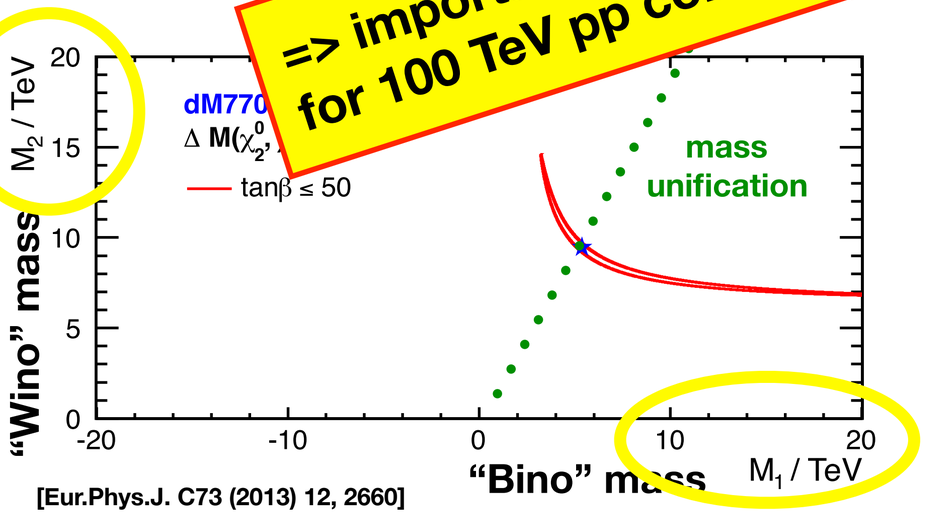
=> important guidance for 100 TeV pp collider!



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