

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

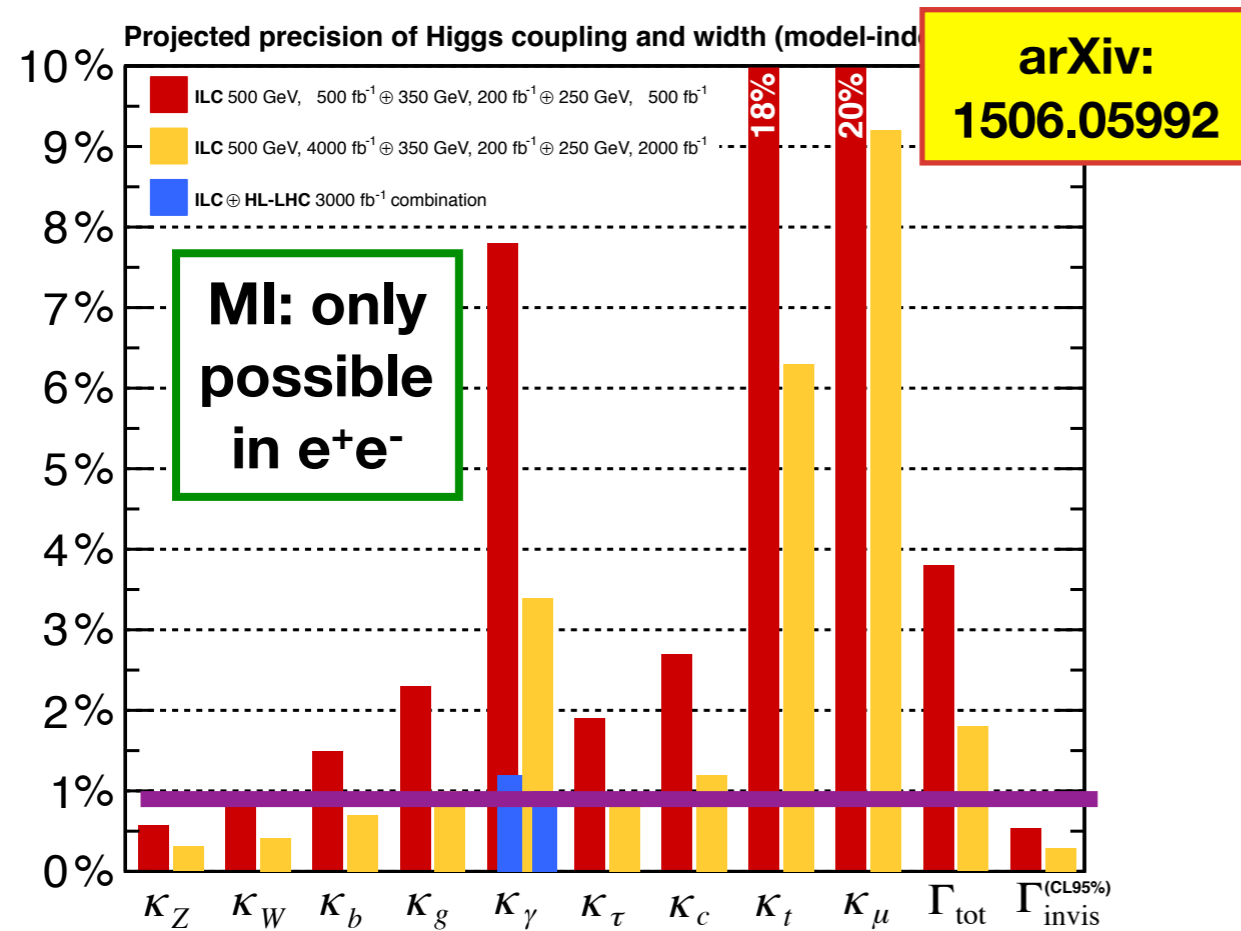
- e^+e^- centre-of-mass energy
 - 200....500 GeV
 - tuneable
 - upgradable to 1 TeV
- luminosity at 500 GeV:
 - $1.8 \times 10^{34} / \text{cm}^2 / \text{s}$
 - upgrade $3.6 \times 10^{34} / \text{cm}^2 / \text{s}$
- beam polarisation
 - $P(e^-) \geq 80\%$
 - $P(e^+) = 30\%$,
upgradable to 60%
- total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



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

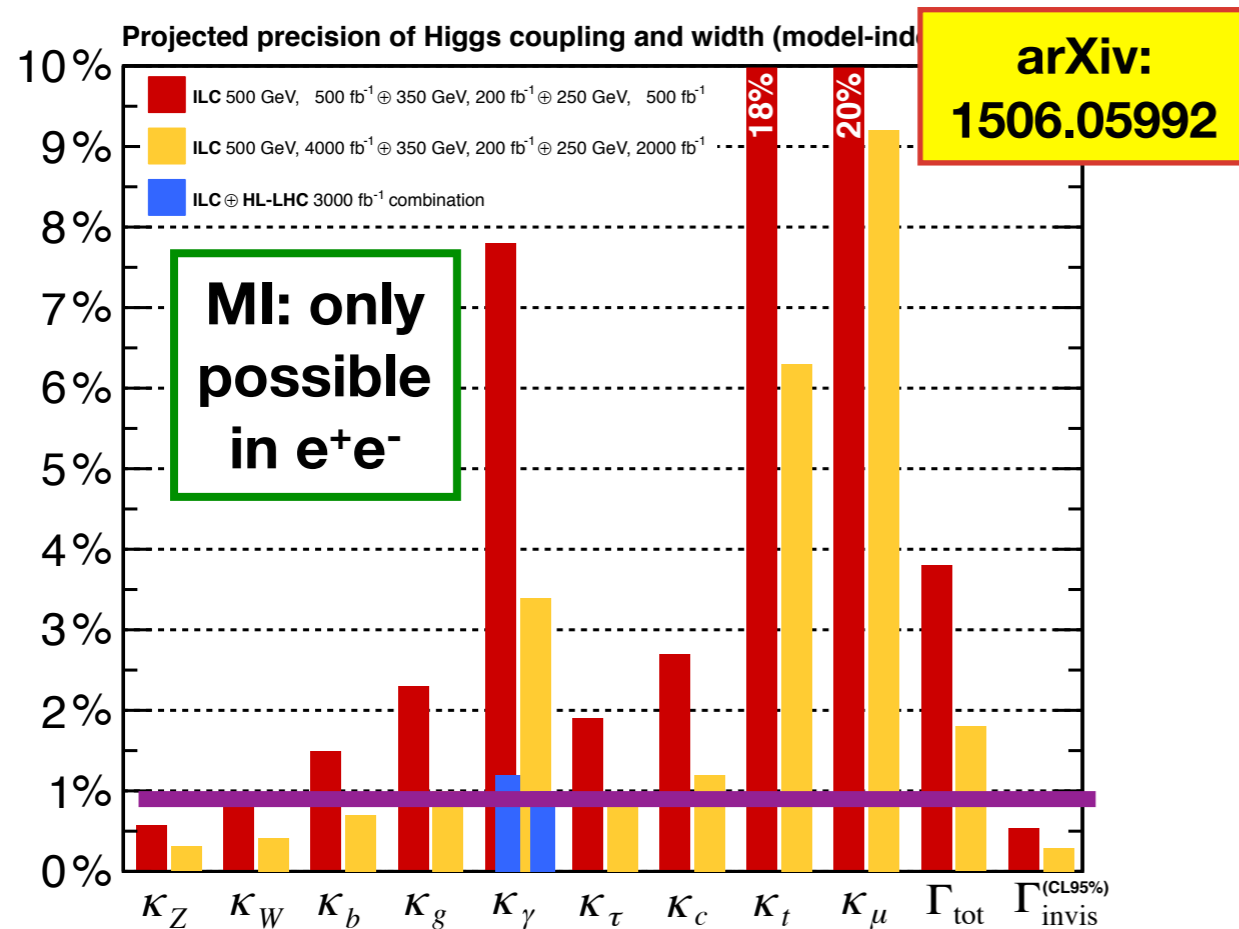


New Properties of the Higgs Boson





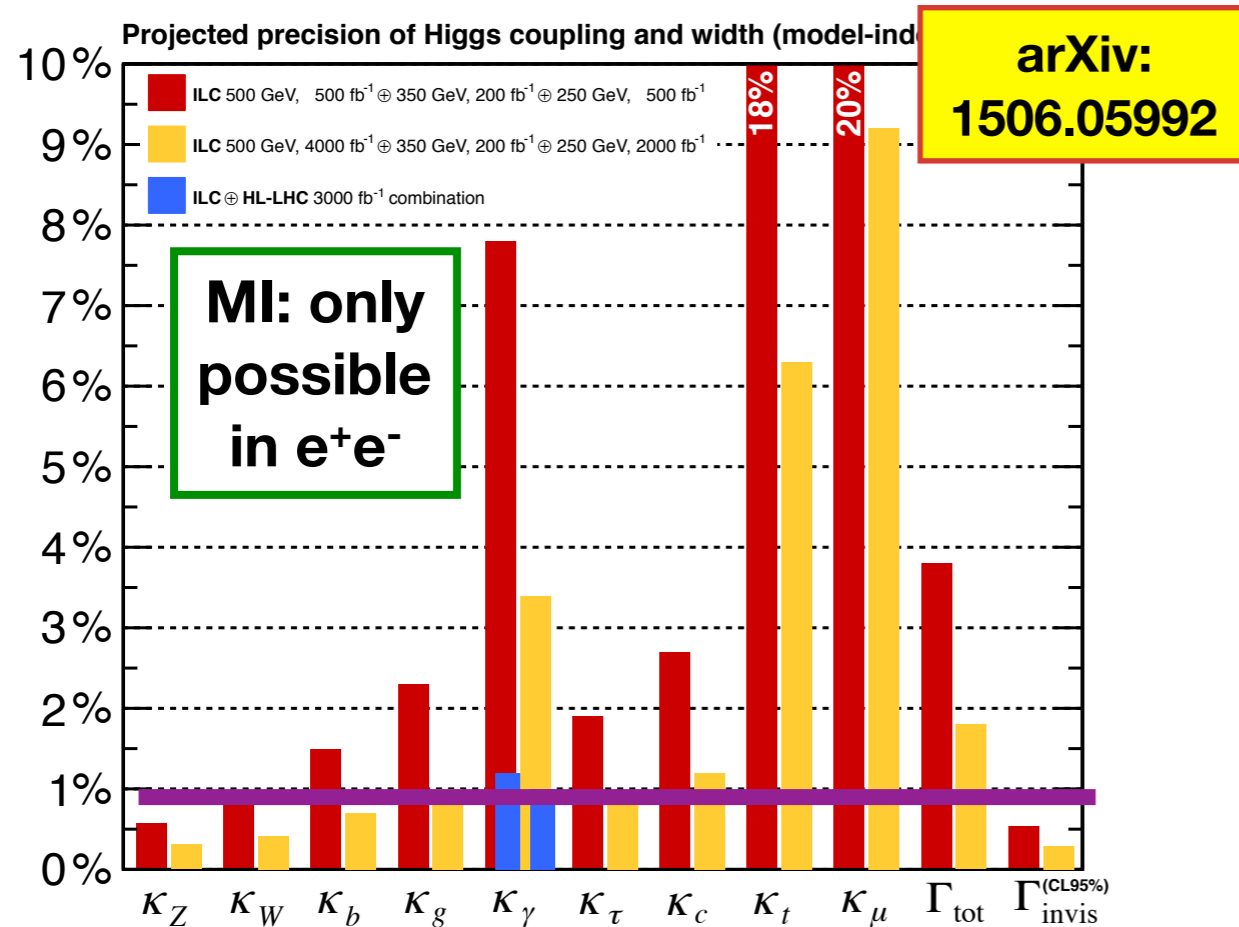
New Properties of the Higgs Boson



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



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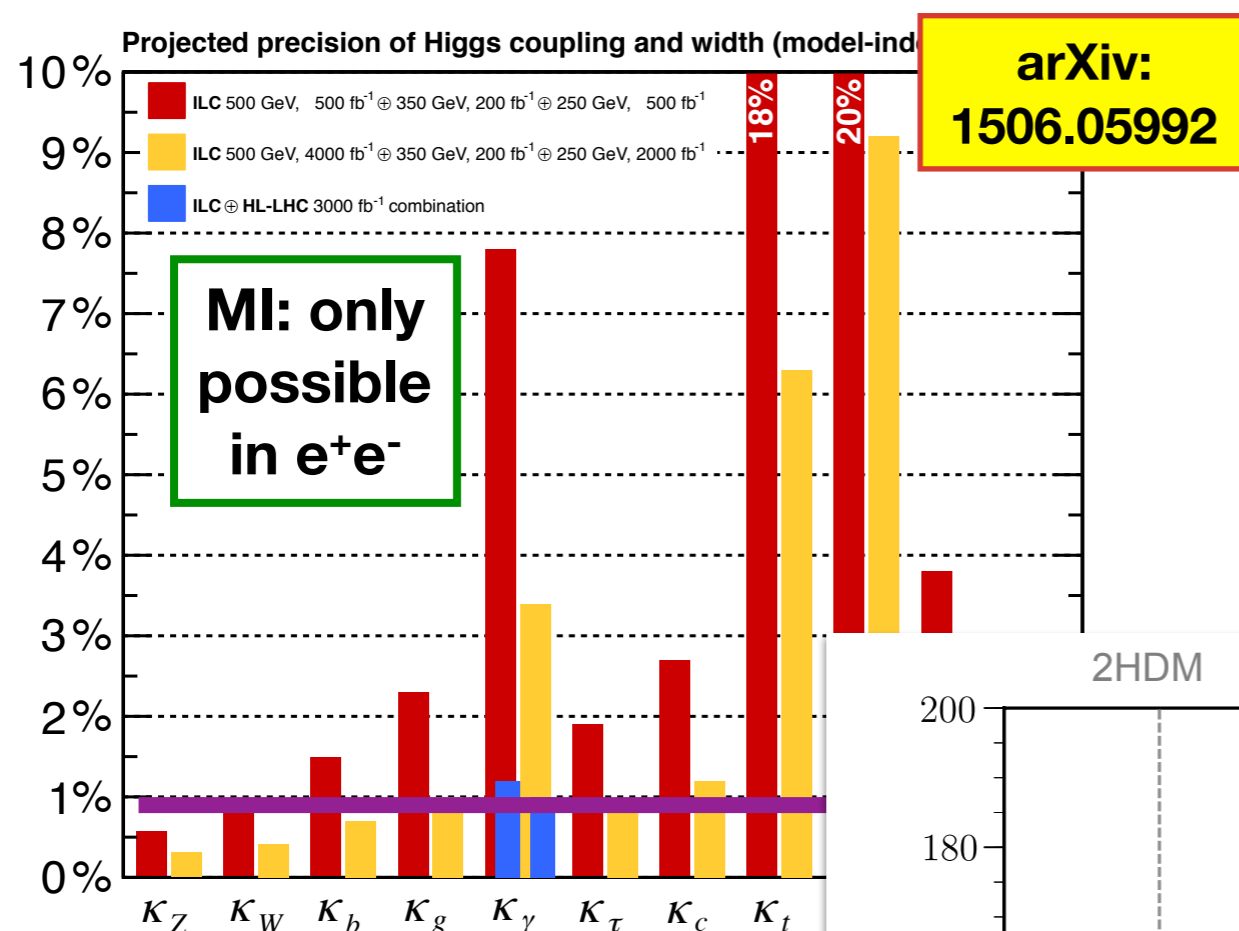


- not included here:
triple Higgs coupling
=> $\delta\lambda/\lambda_{\text{SM}} = 27\% @ 500\text{GeV}$
(-> 10% @ 1 TeV)
- important to probe EW
baryogenesis

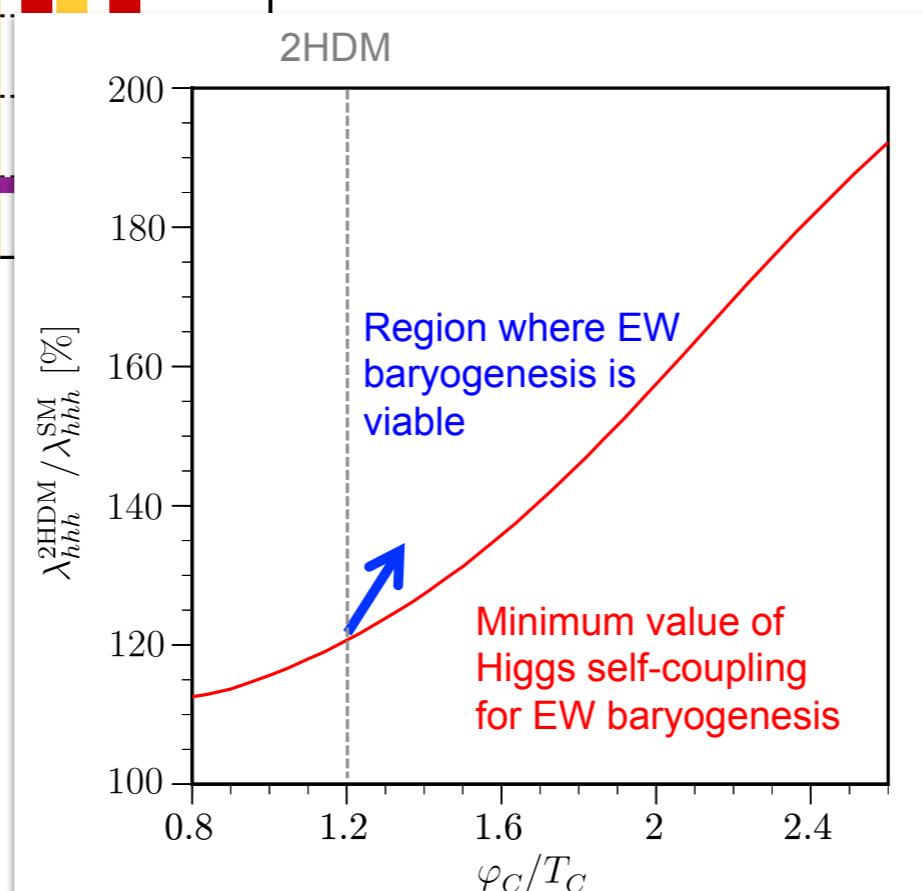
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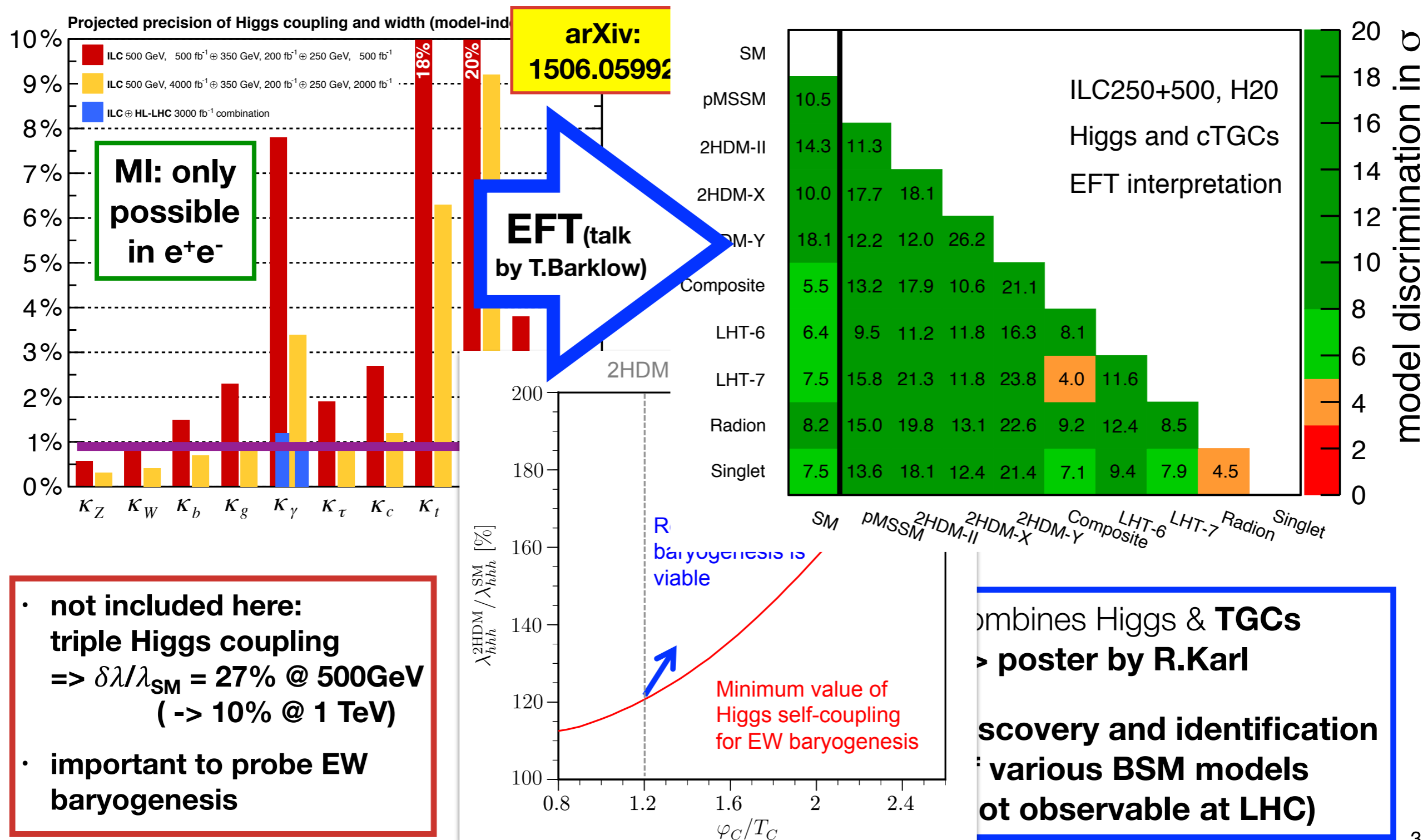


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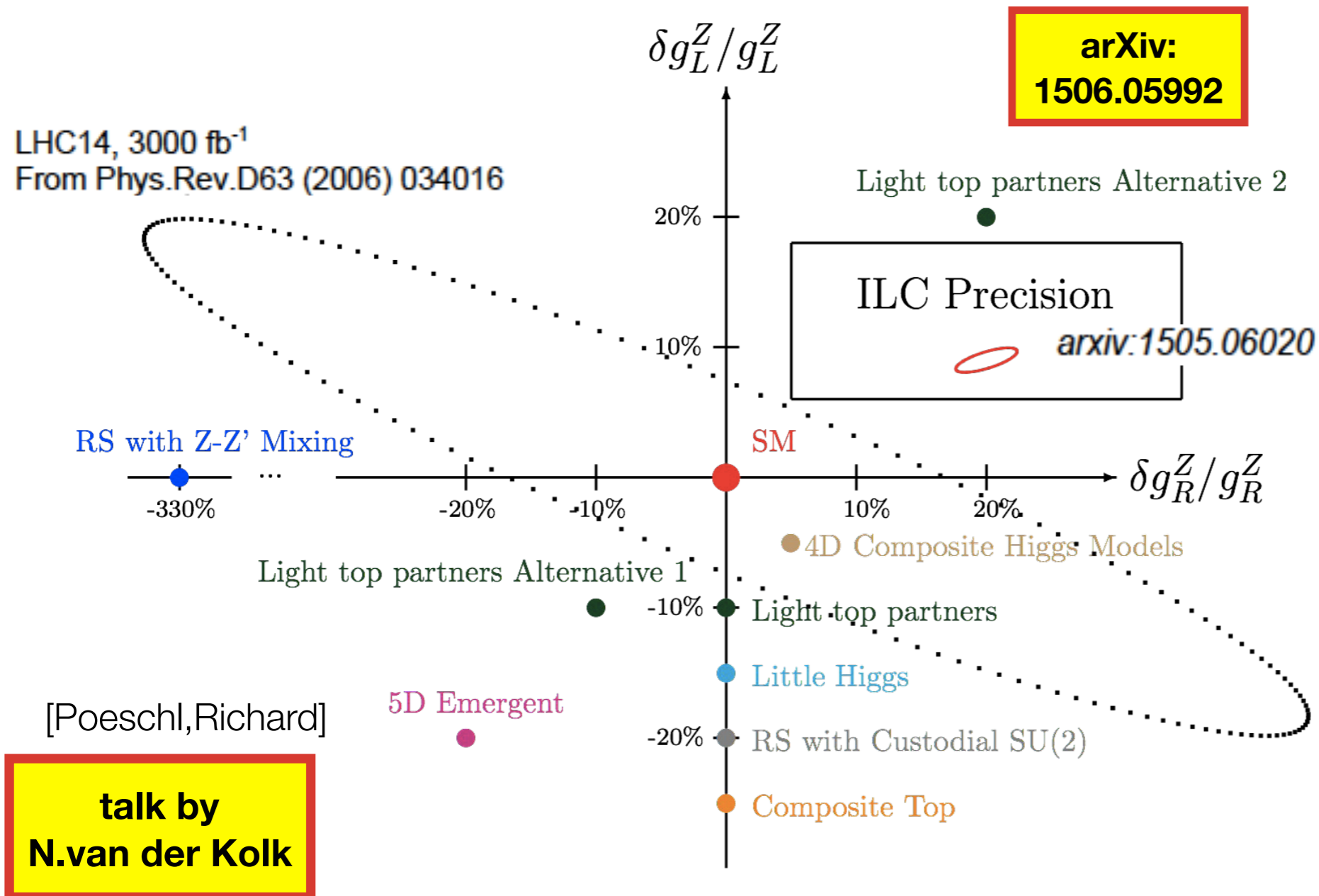


New Properties of the Higgs Boson





New Properties of the Top Quark

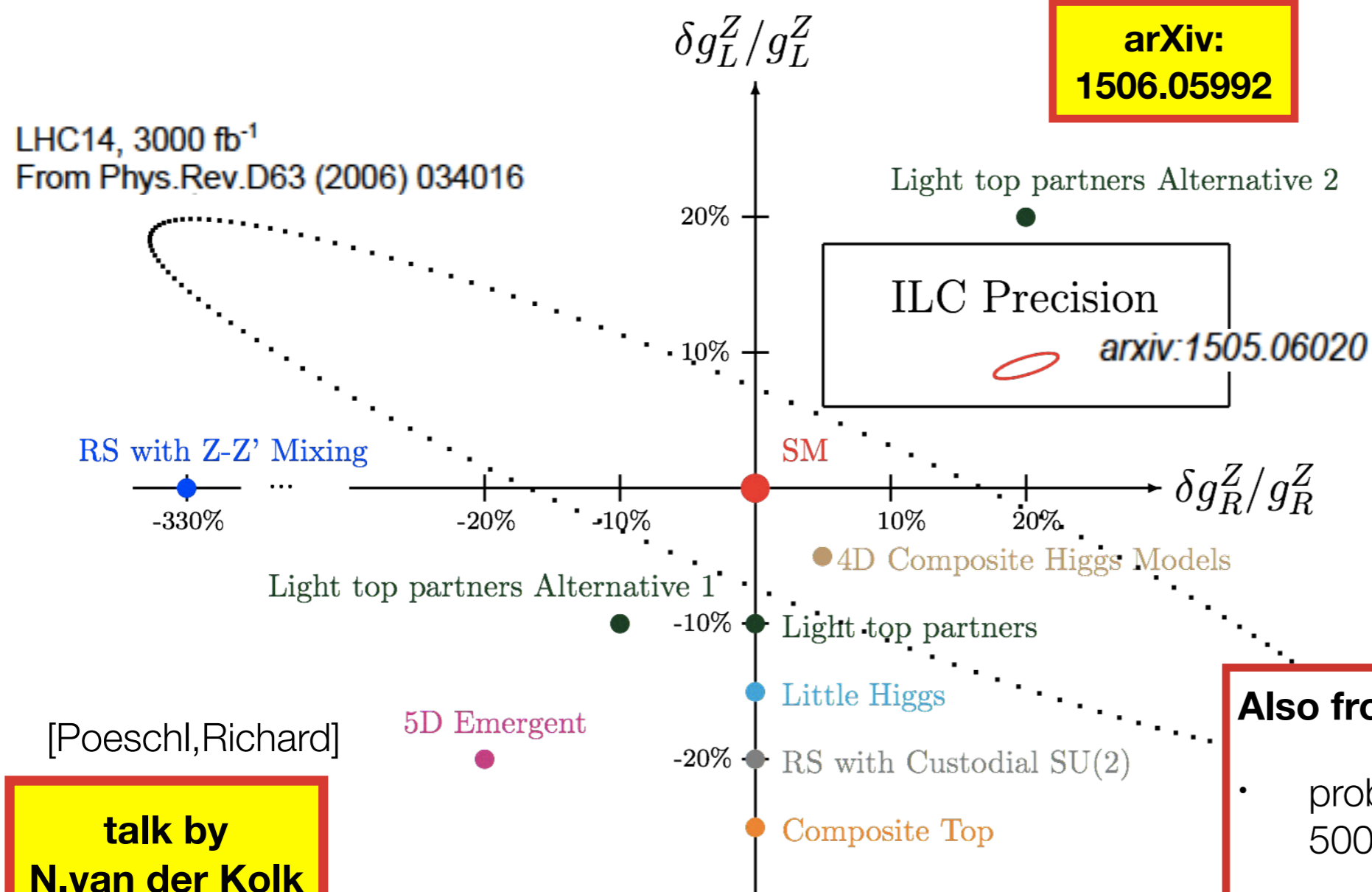


Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

- ILC precision allows model discrimination
- sensitivity in g_L^Z, g_R^Z plane complementary to LHC



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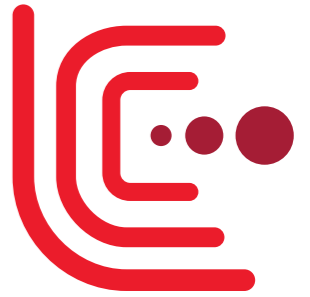
Also from other e⁺e⁻ -> ff:

- 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

talk by
N.van der Kolk

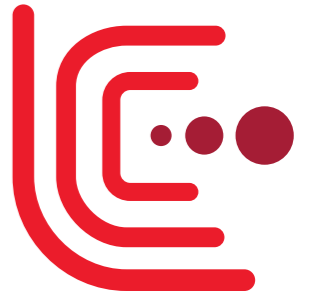
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poster by
S.Bilokin



Additional Higgs Bosons

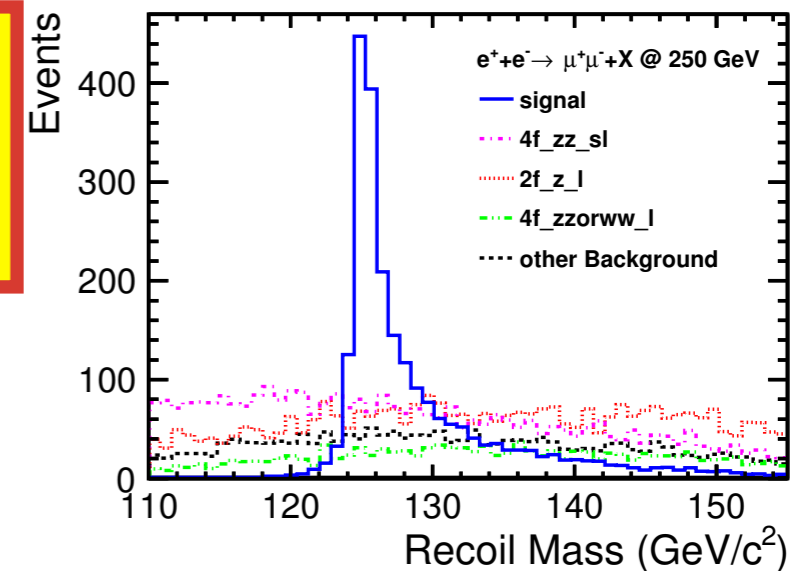
- eg from 2HDMs or additional singlets
(as in NMSSM)
- pair production:
 - loophole-free search for additional Higgs bosons up to masses of $\sim\sqrt{s}/2$
 - regardless of $\tan\beta$
- **or recoil against Z**
 - **even if coupling strongly reduced!**
 - quantitative studies in full detector simulation ongoing

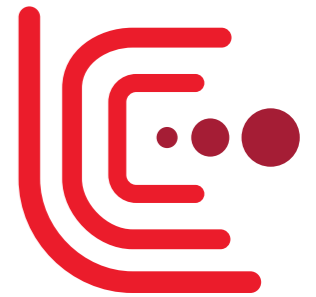


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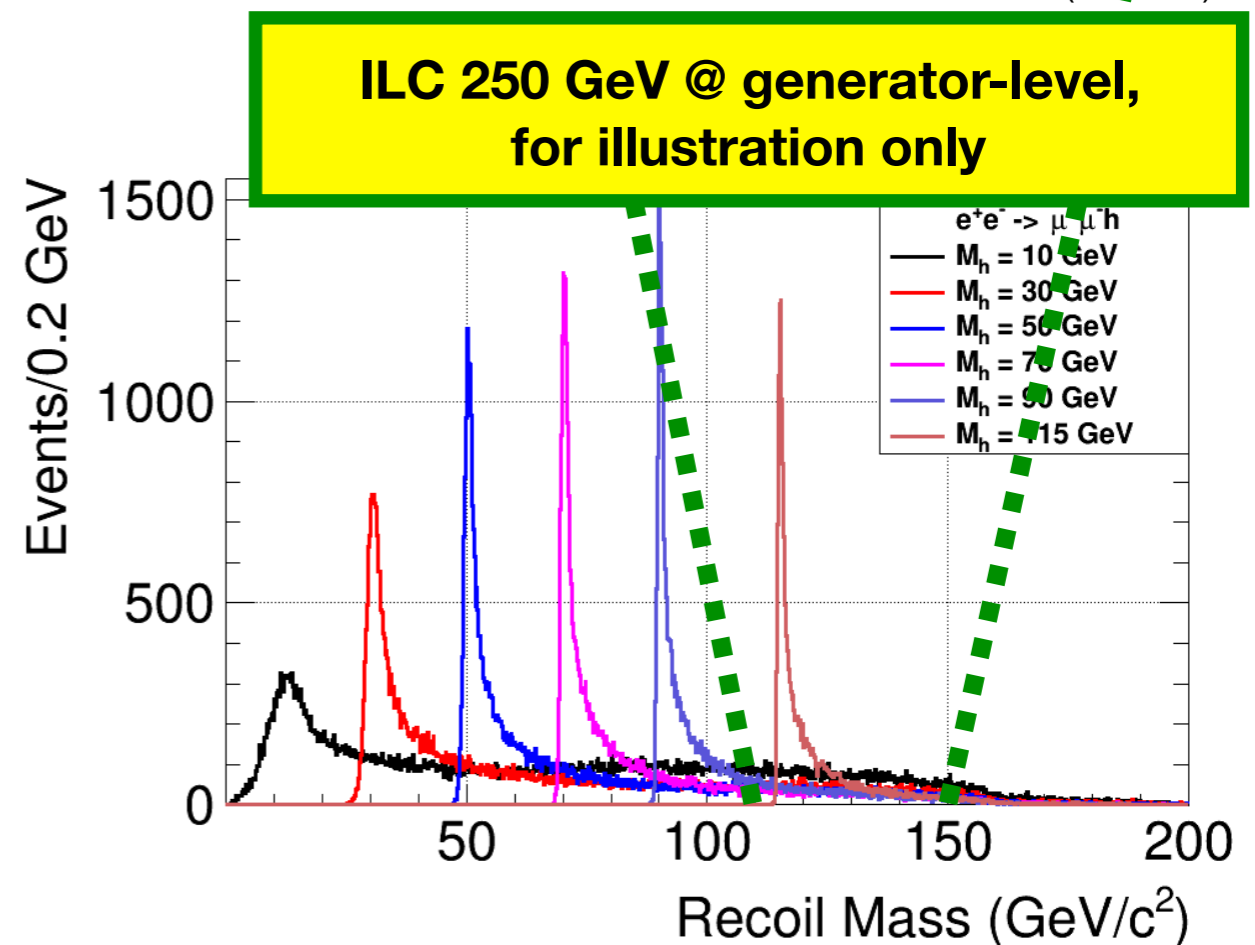
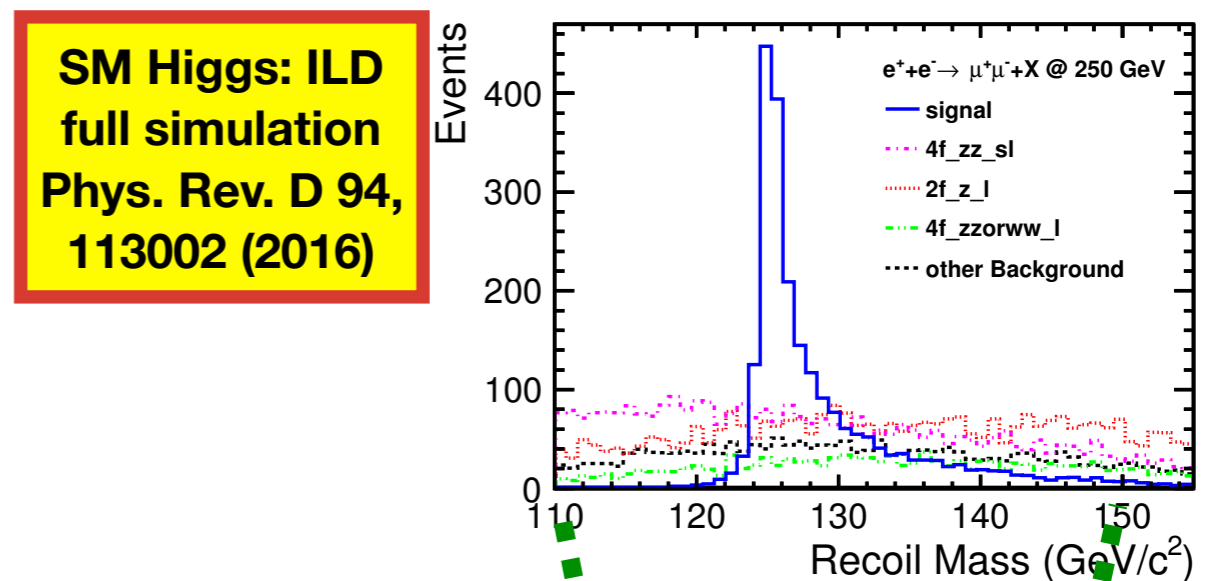
**SM Higgs: ILD
full simulation
Phys. Rev. D 94,
113002 (2016)**





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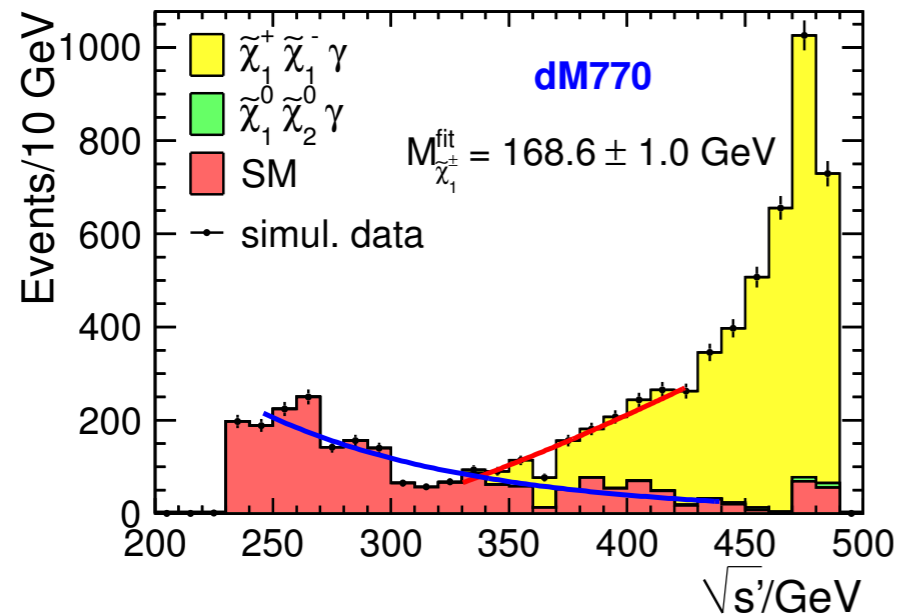
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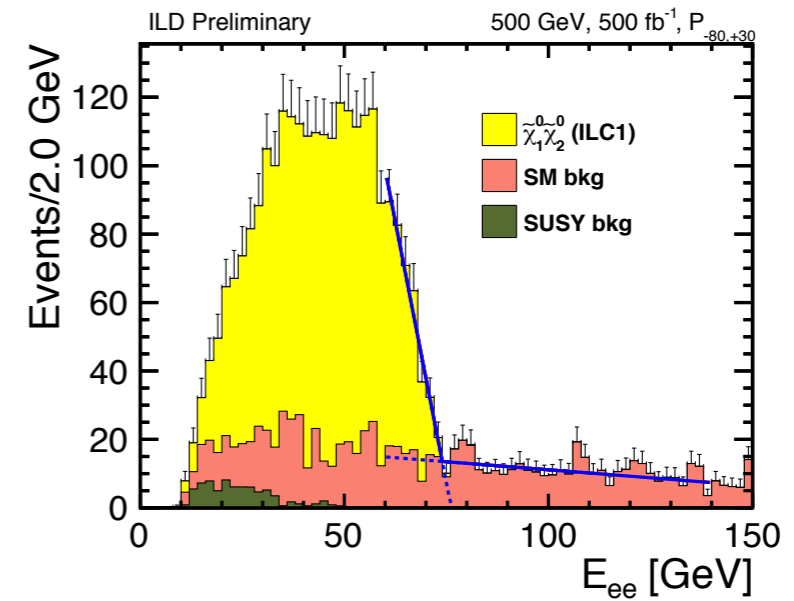
Supersymmetric Partners of the Higgs Boson



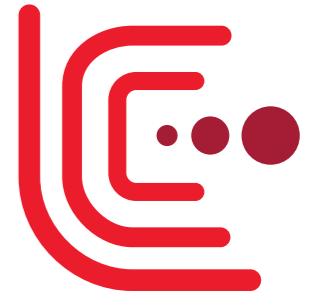
higgsinos with sub-GeV mass splitting
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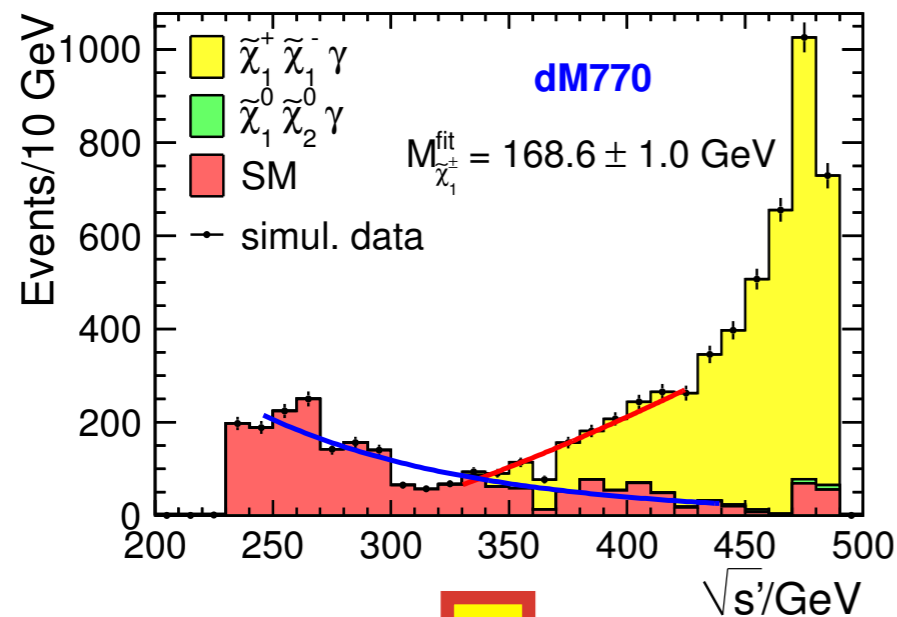
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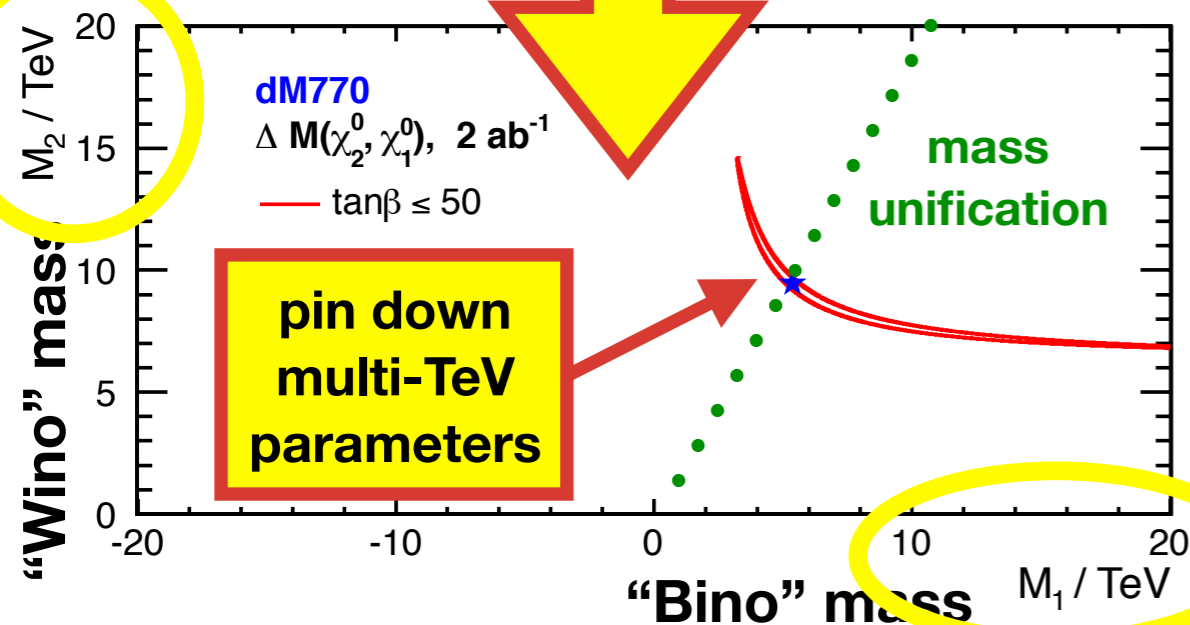
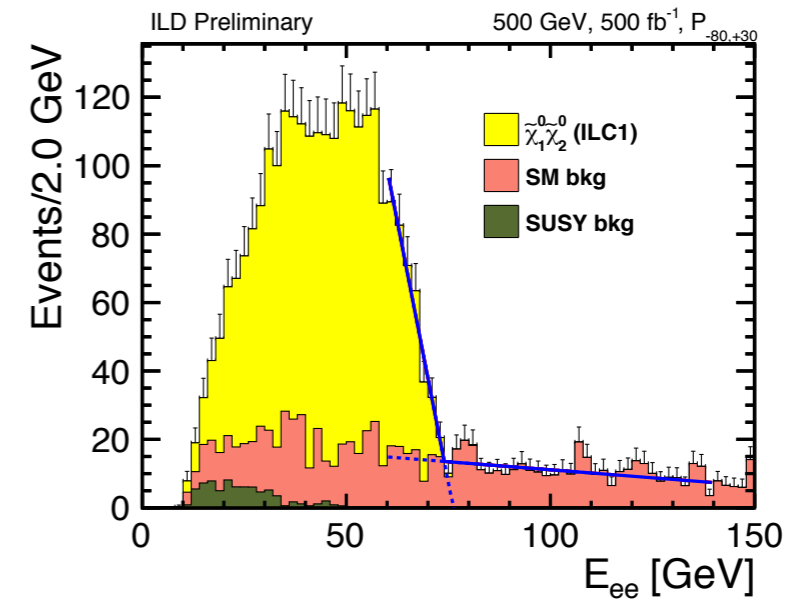
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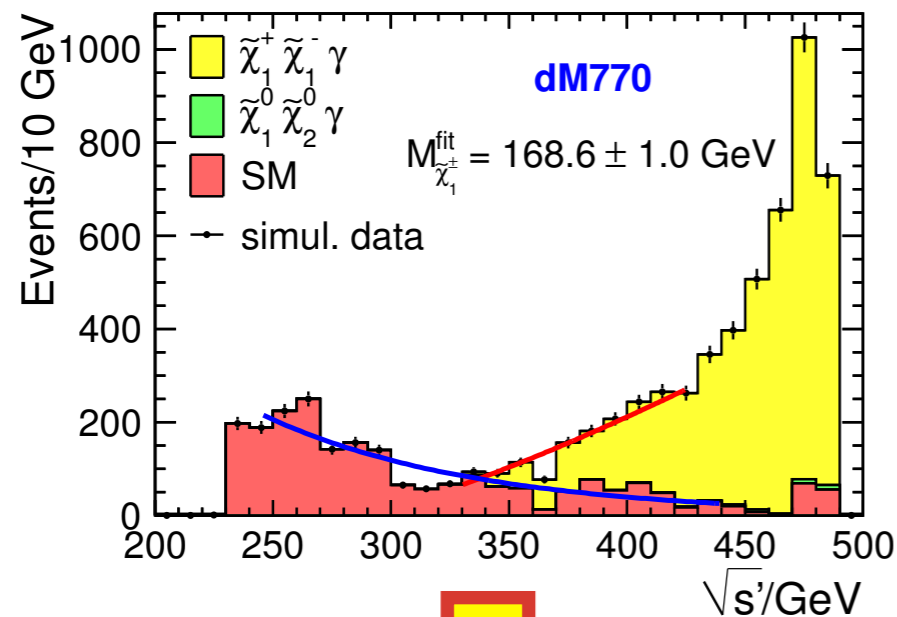
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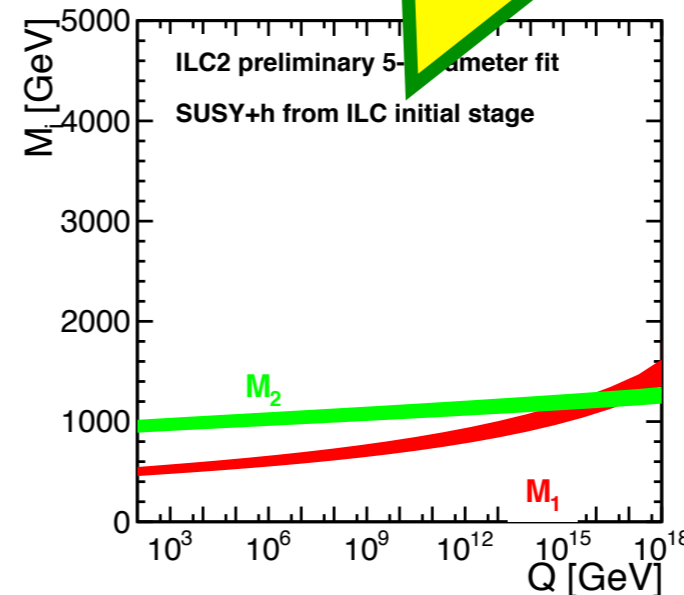
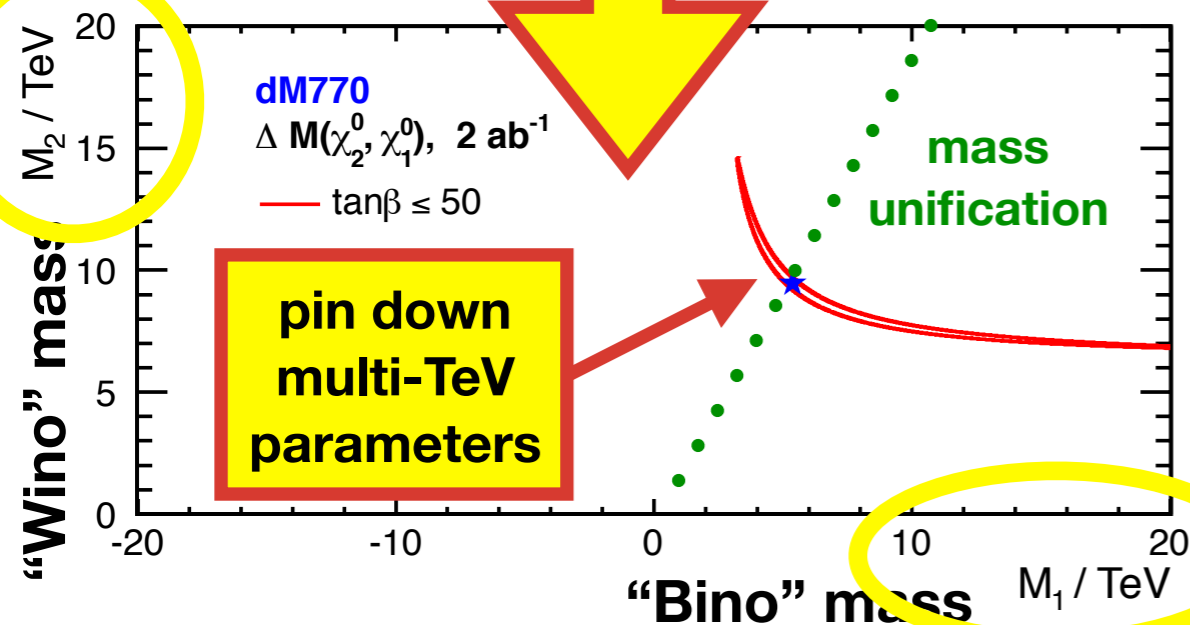
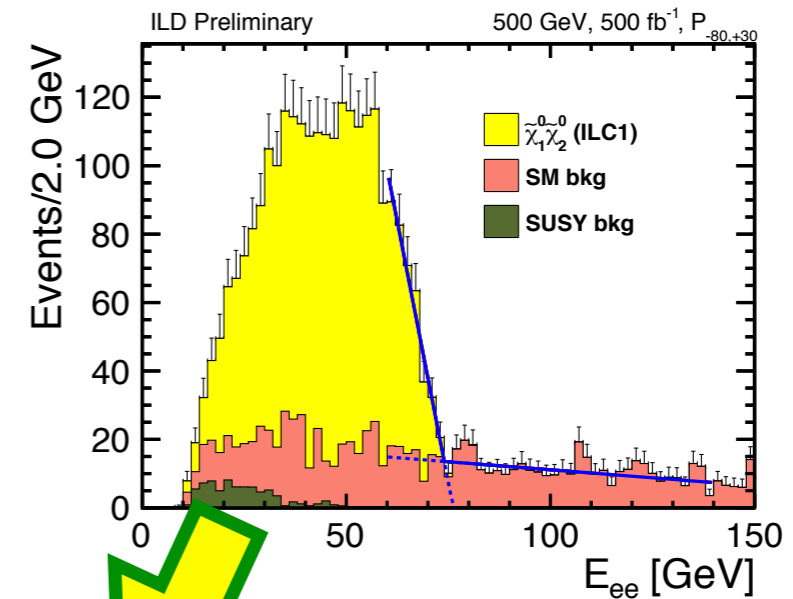
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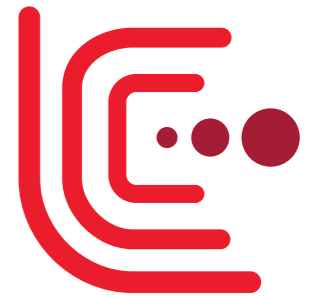
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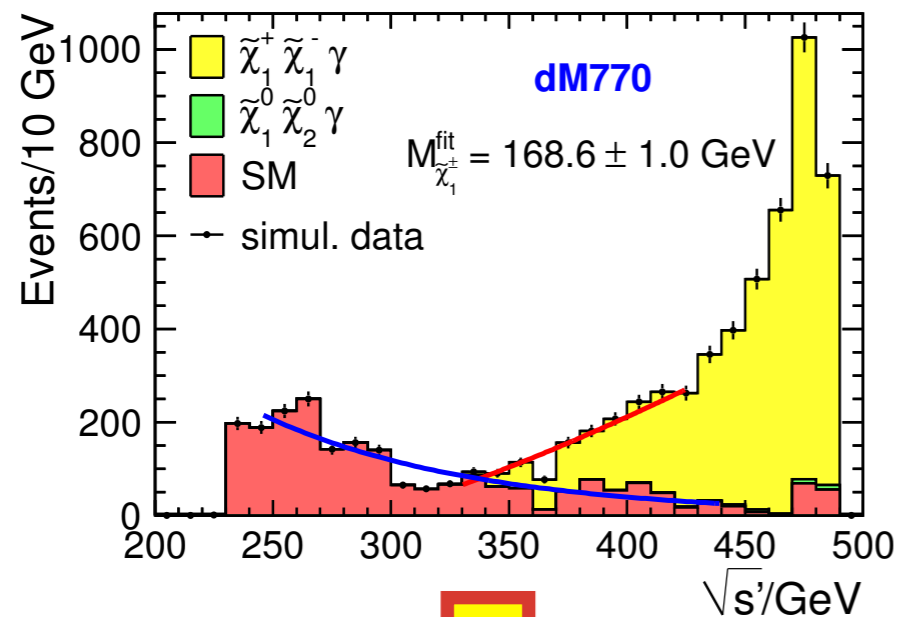
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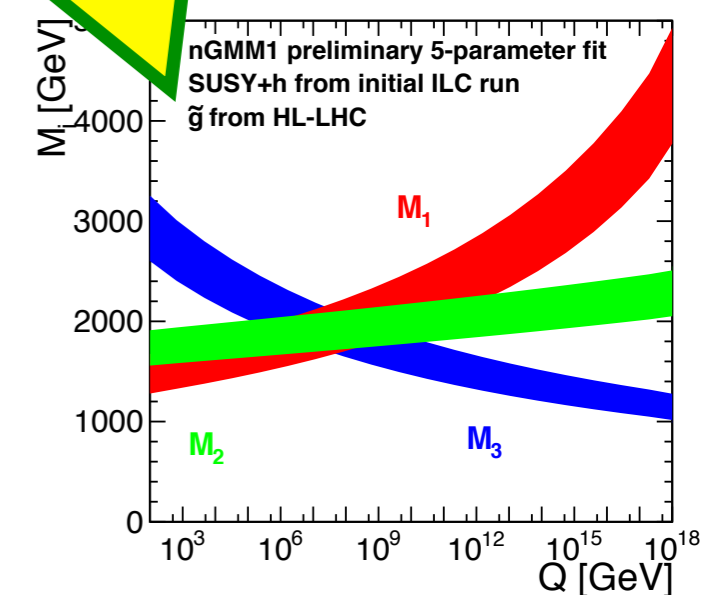
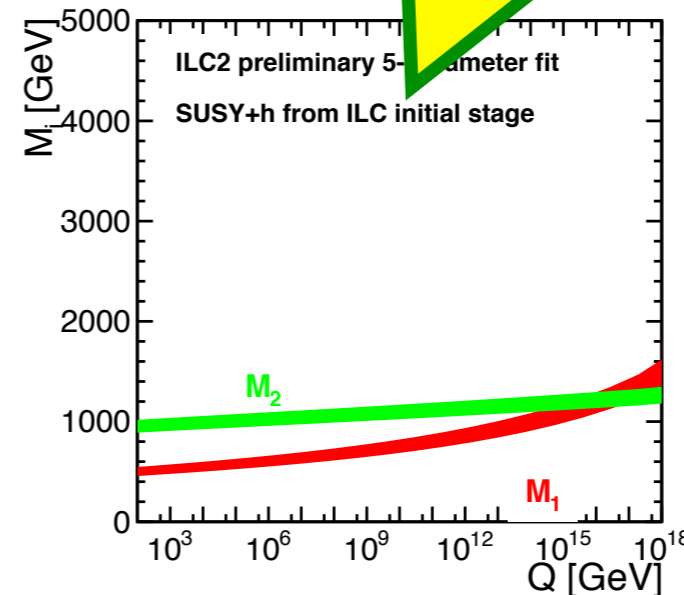
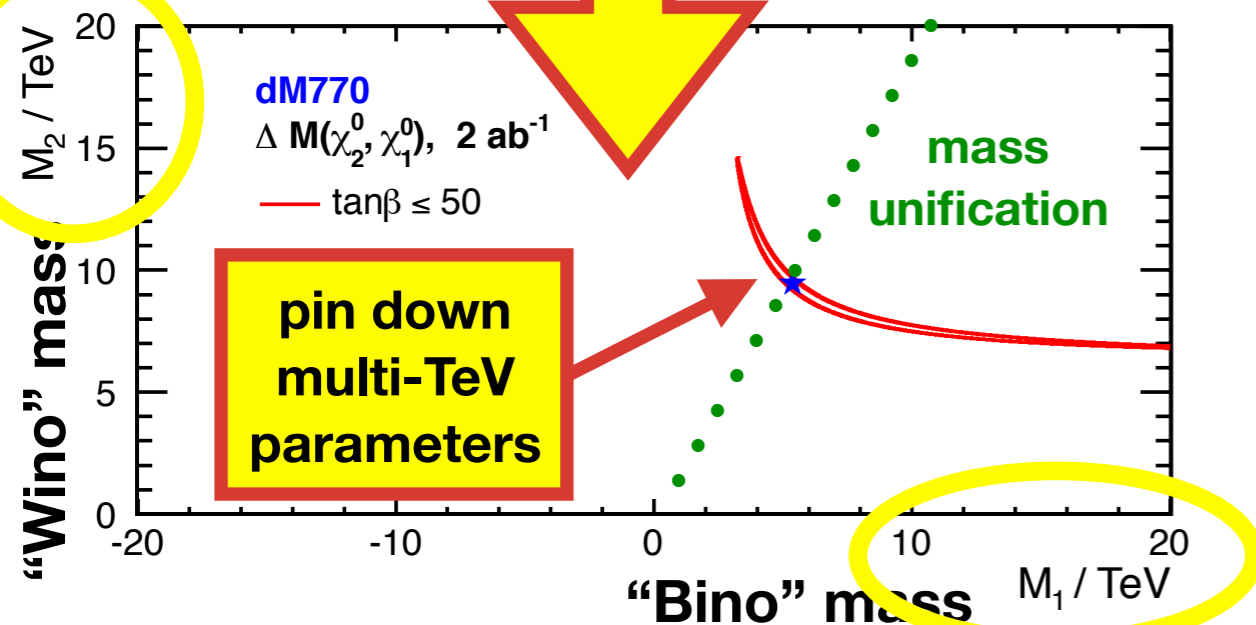
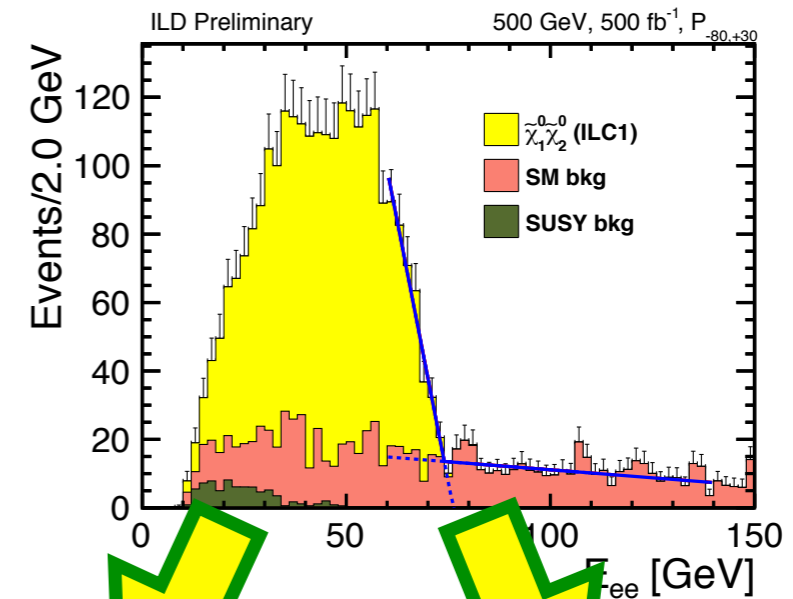
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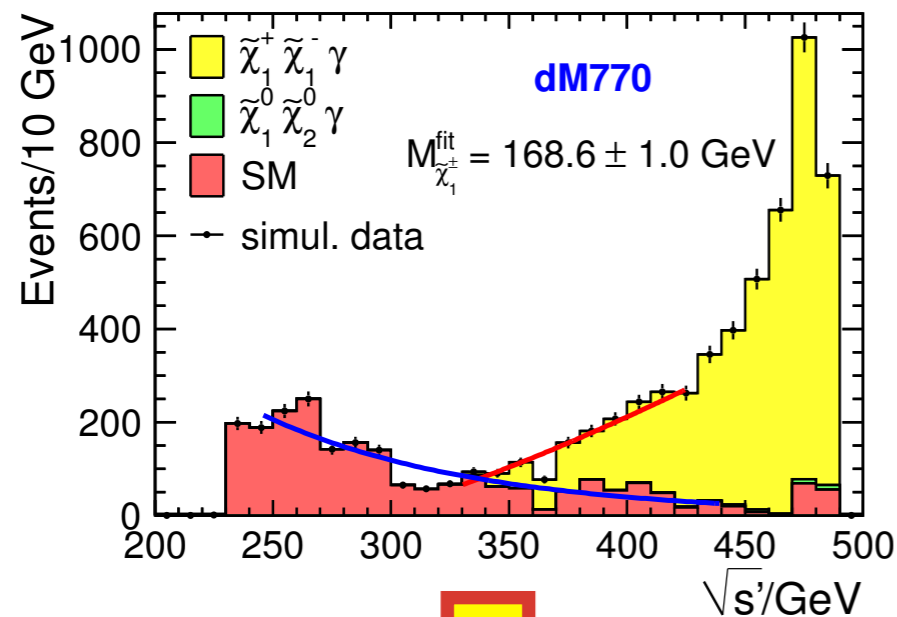
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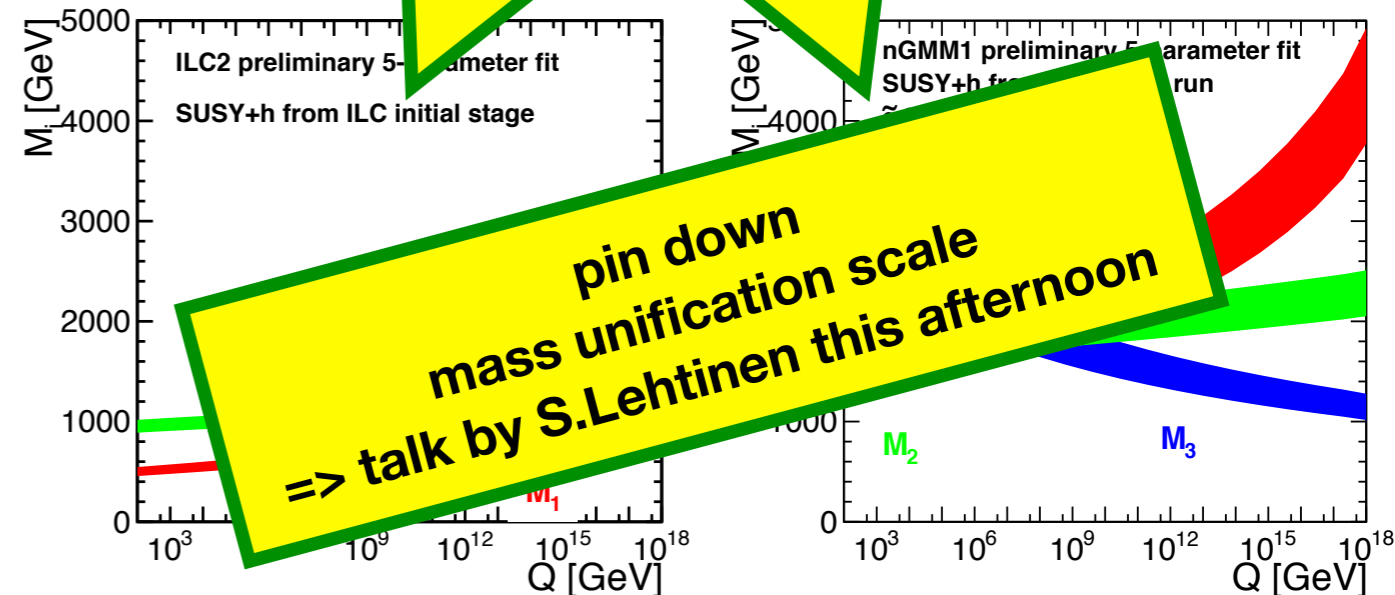
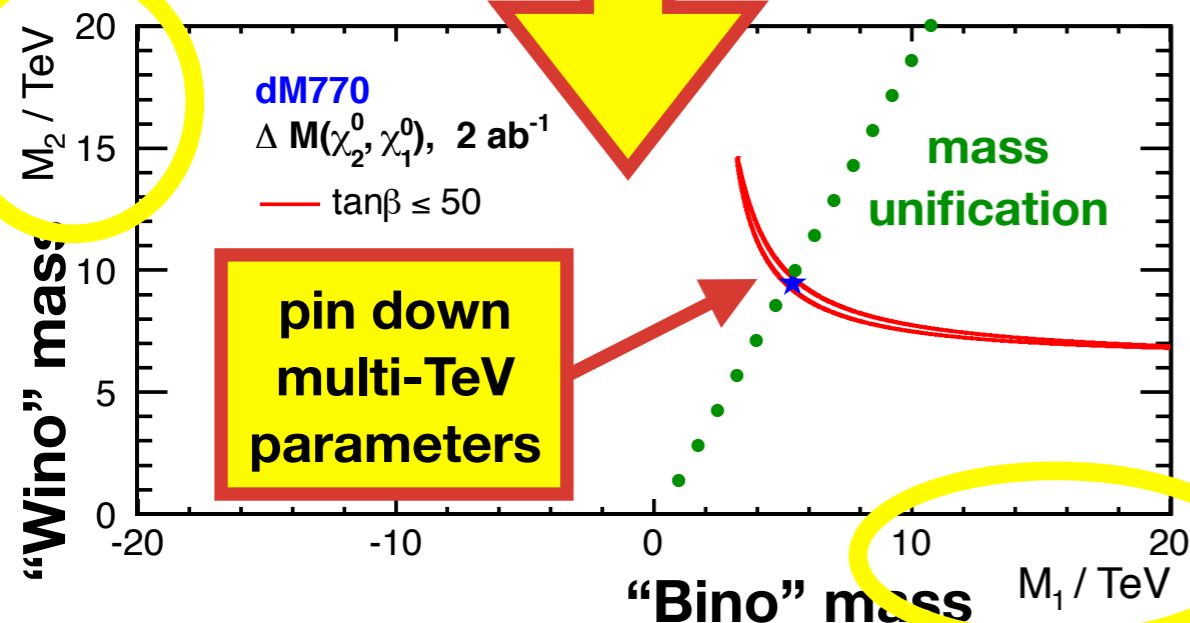
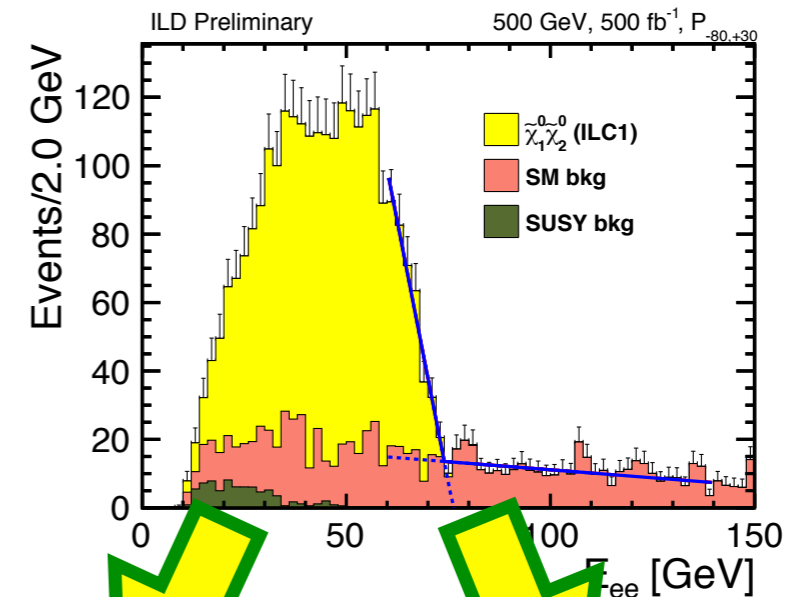
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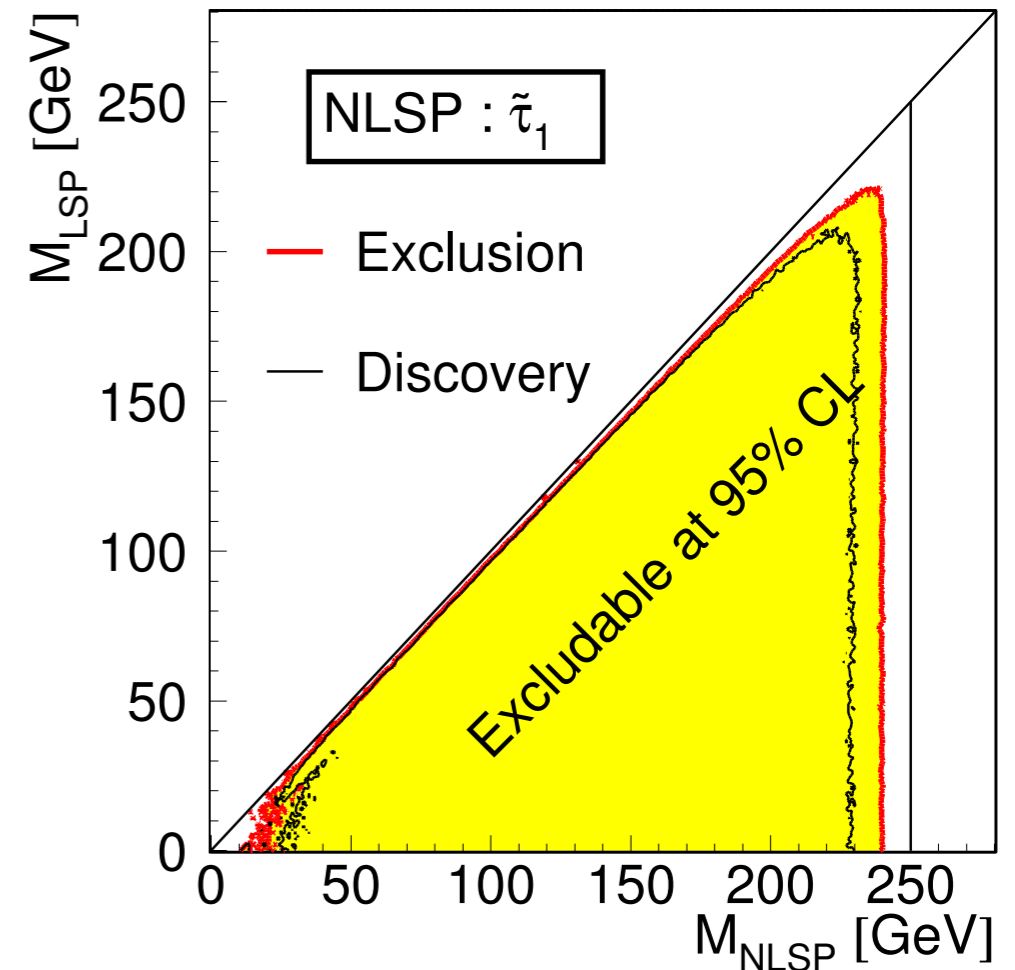
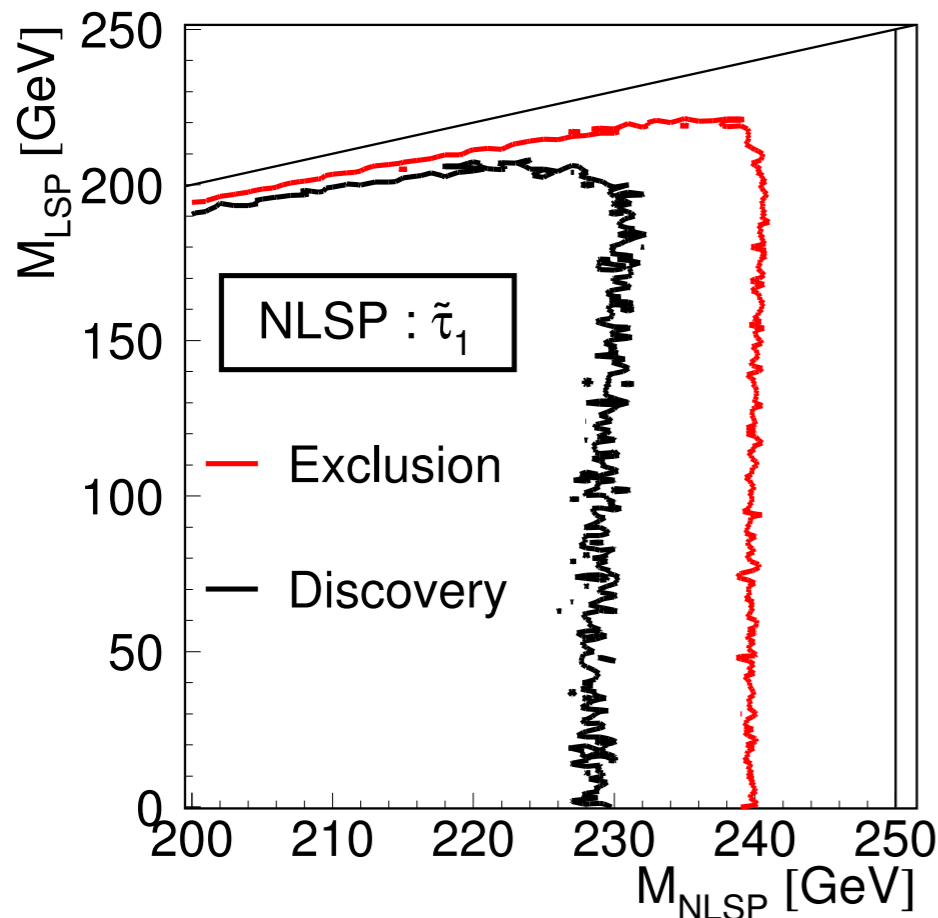
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SUSY without Loop-Holes

- pair production of new, weakly coupled particles
- special case SUSY: couplings are known
- R parity conservation: NLSP \rightarrow SM partner + LSP



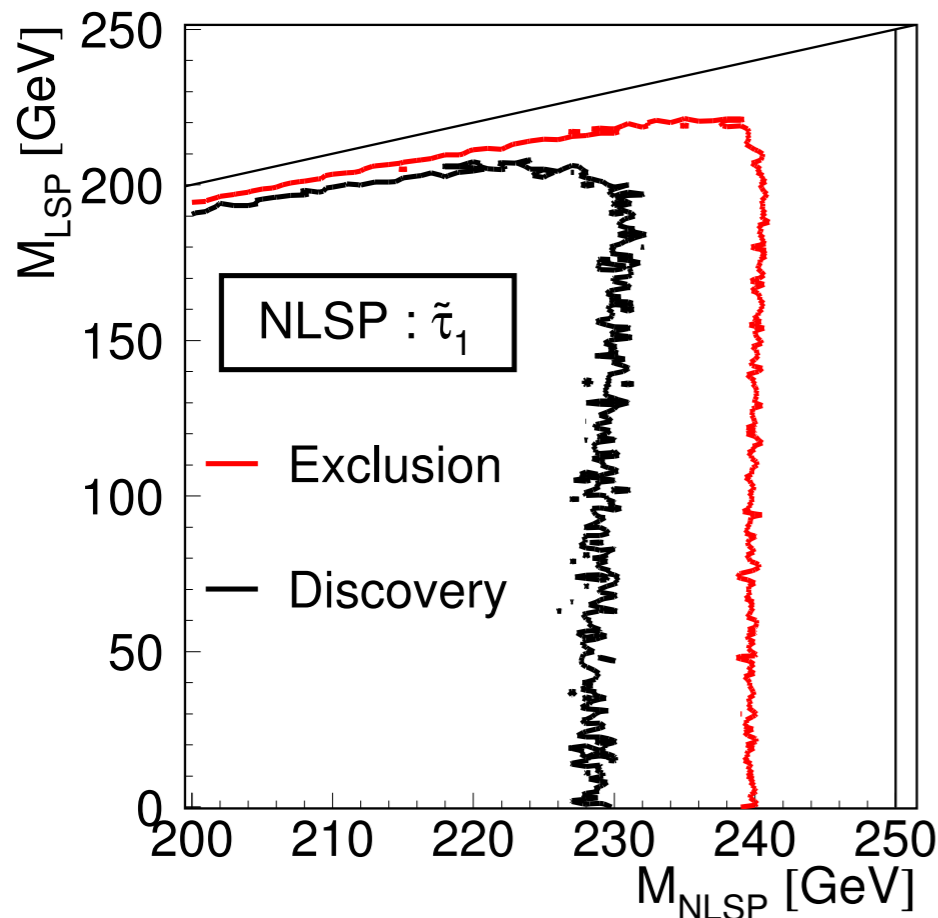
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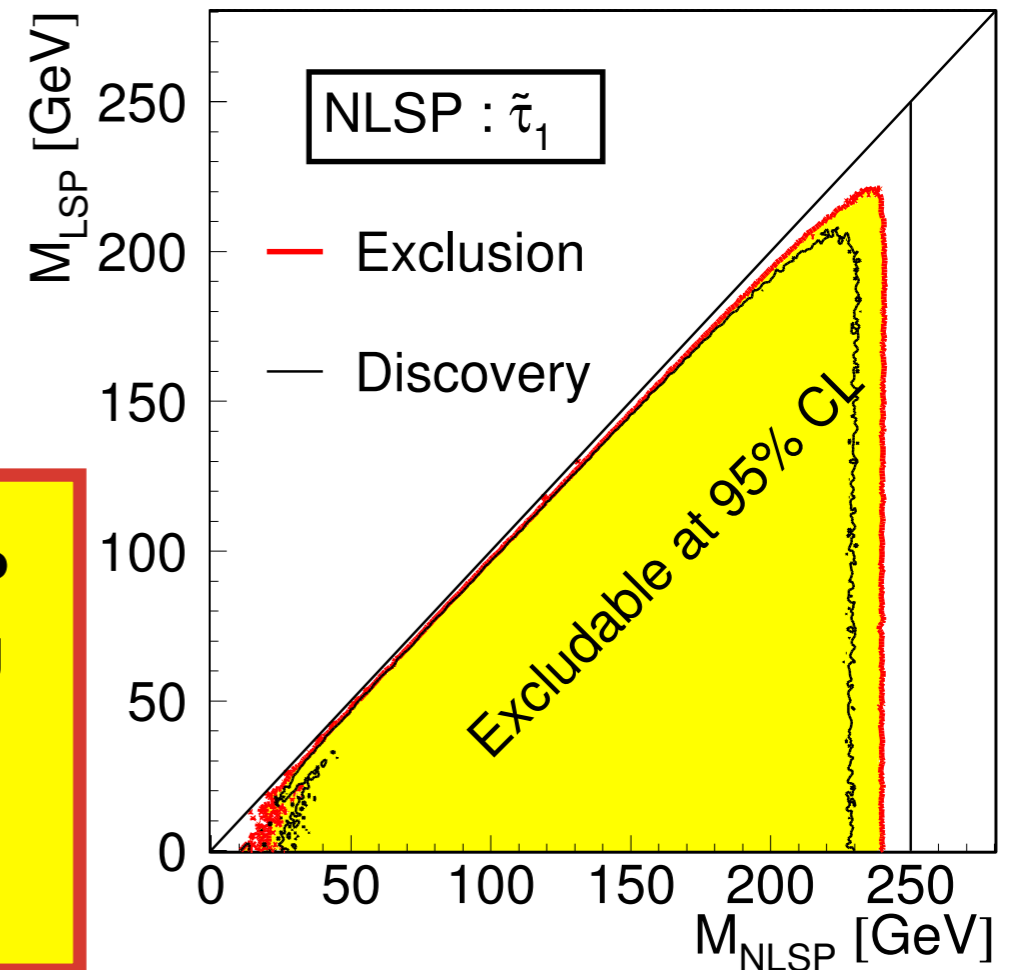


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**HERE: stau NLSP
most challenging
case -
for others even
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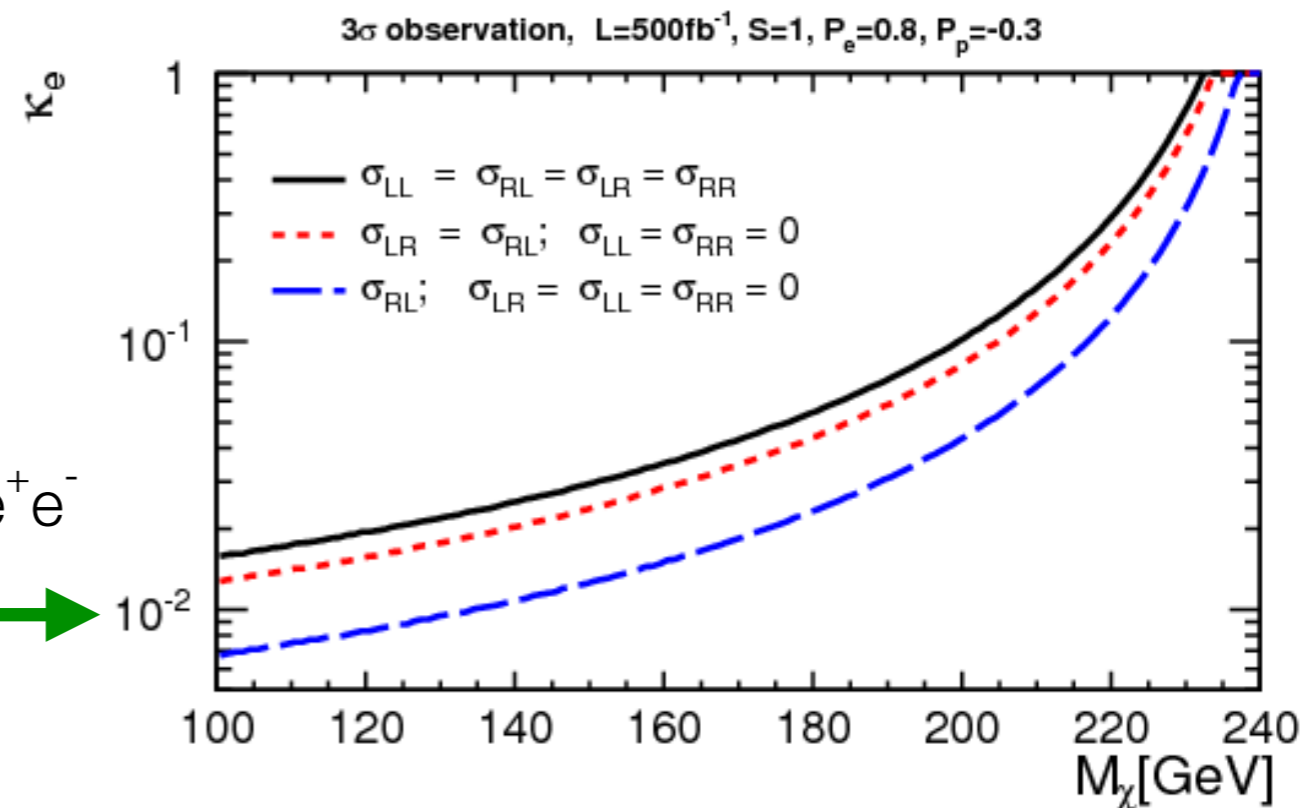
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Discovering Dark Matter Particles

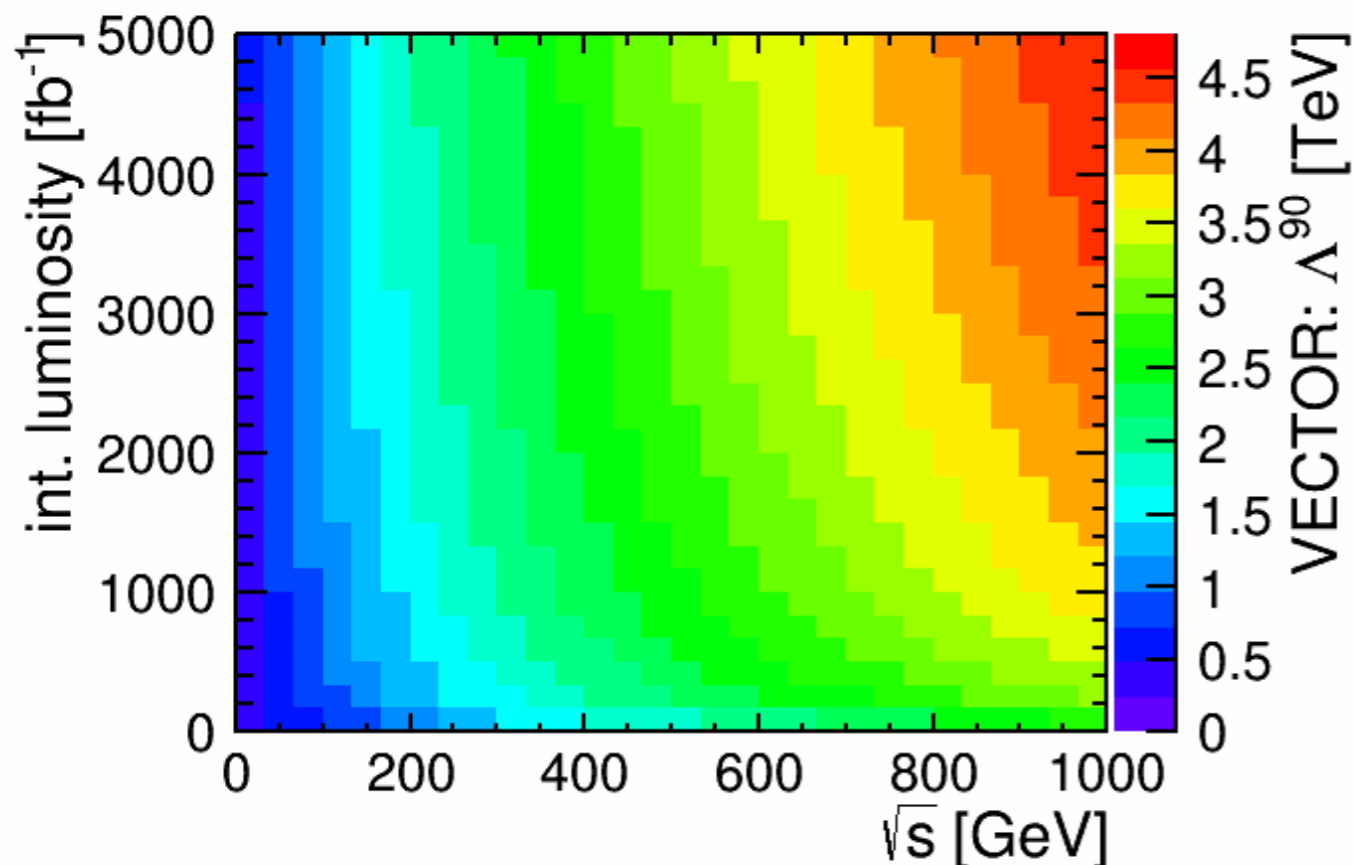
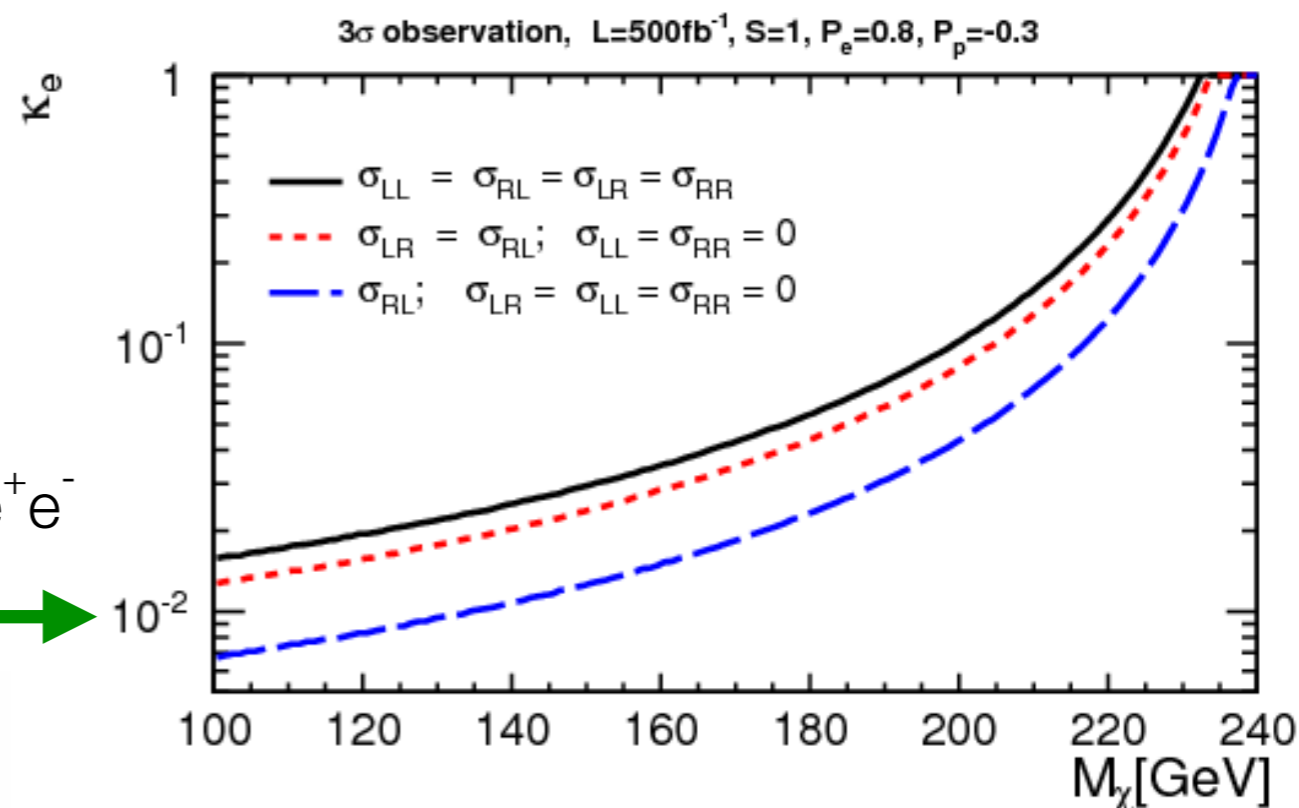
- $e^+e^- \rightarrow \chi\chi\gamma$ “mono-photons”
- probes WIMP coupling to *leptons*
- **cosmological interpretation:**
 - fix cross-section to saturate relic density
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- **Effective operator interpretation**
[nota bene: valid at e^+e^- colliders]
- for $M_\chi = 100$ 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

=> compare to cosmological observation (Planck, $\delta\Omega/\Omega \sim 2\%$)



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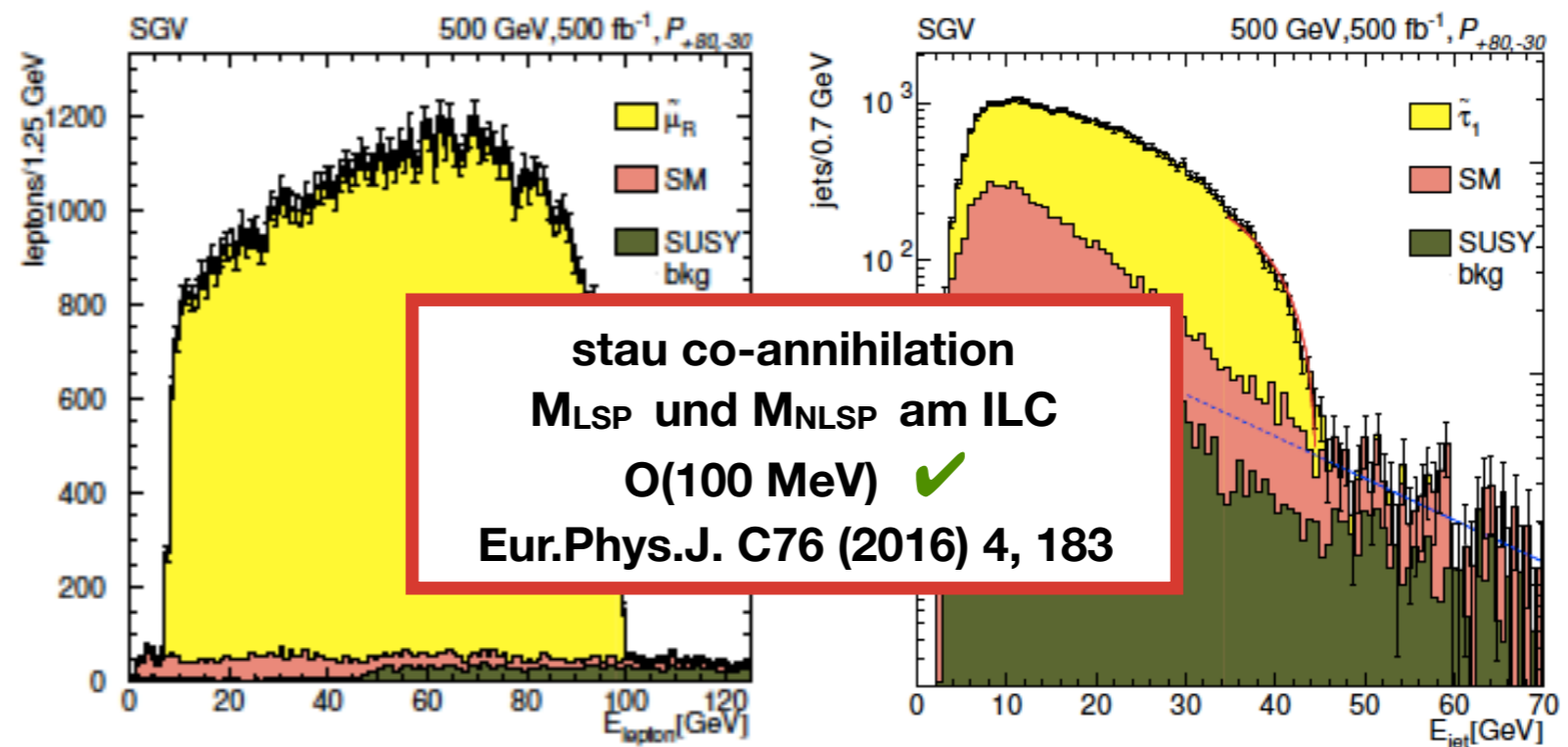
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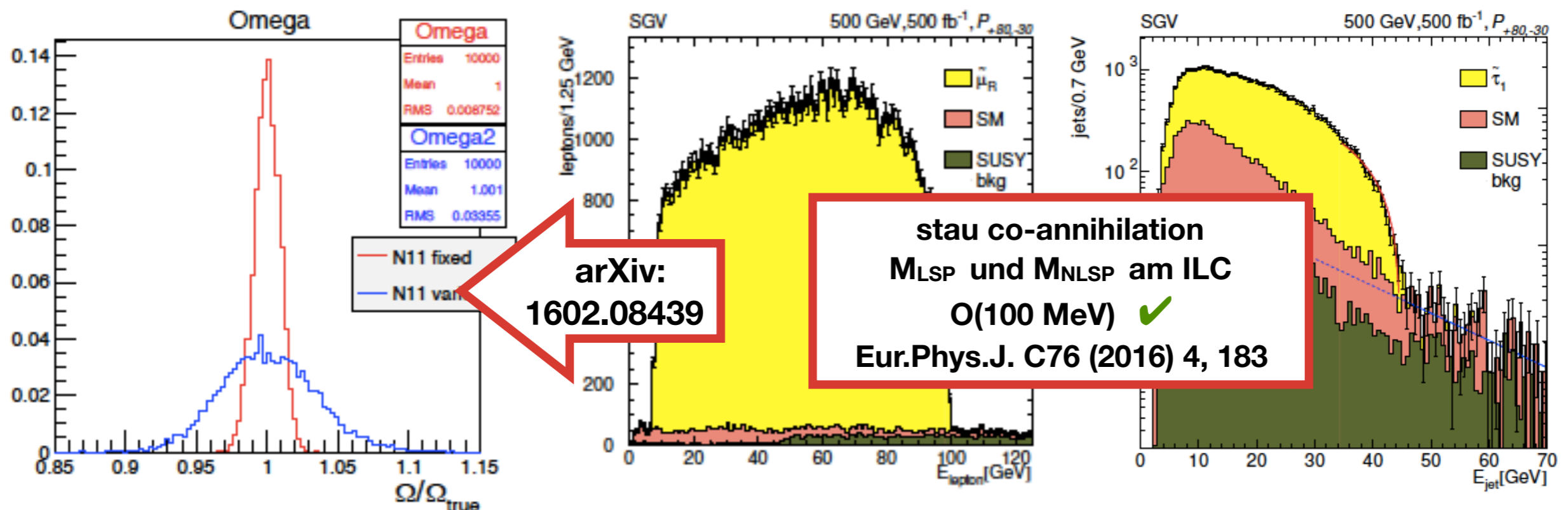
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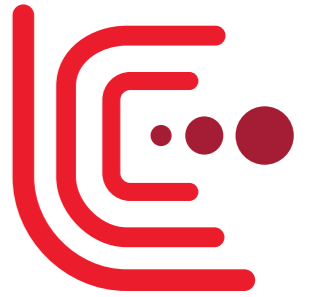




Neutrinos

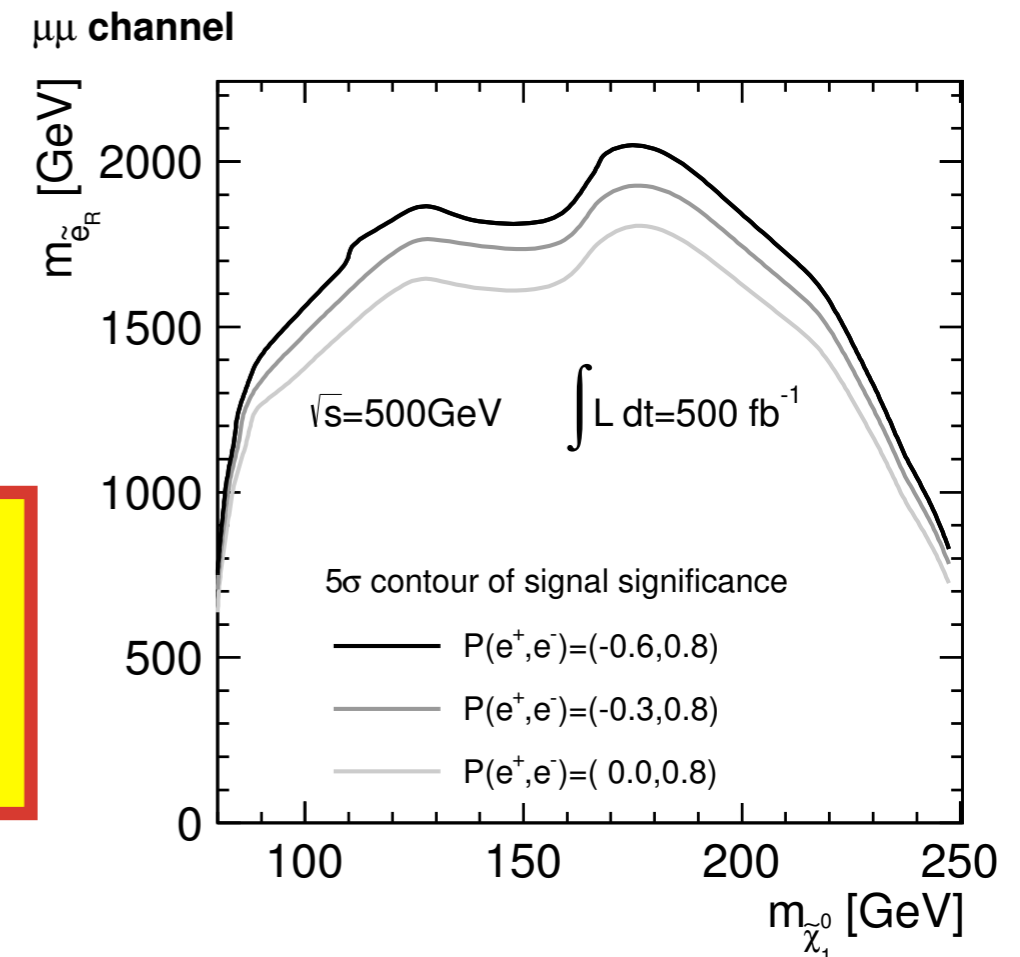
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**bRPV: ILD full
simulation
Eur.Phys.J. C74
(2014) 2720**

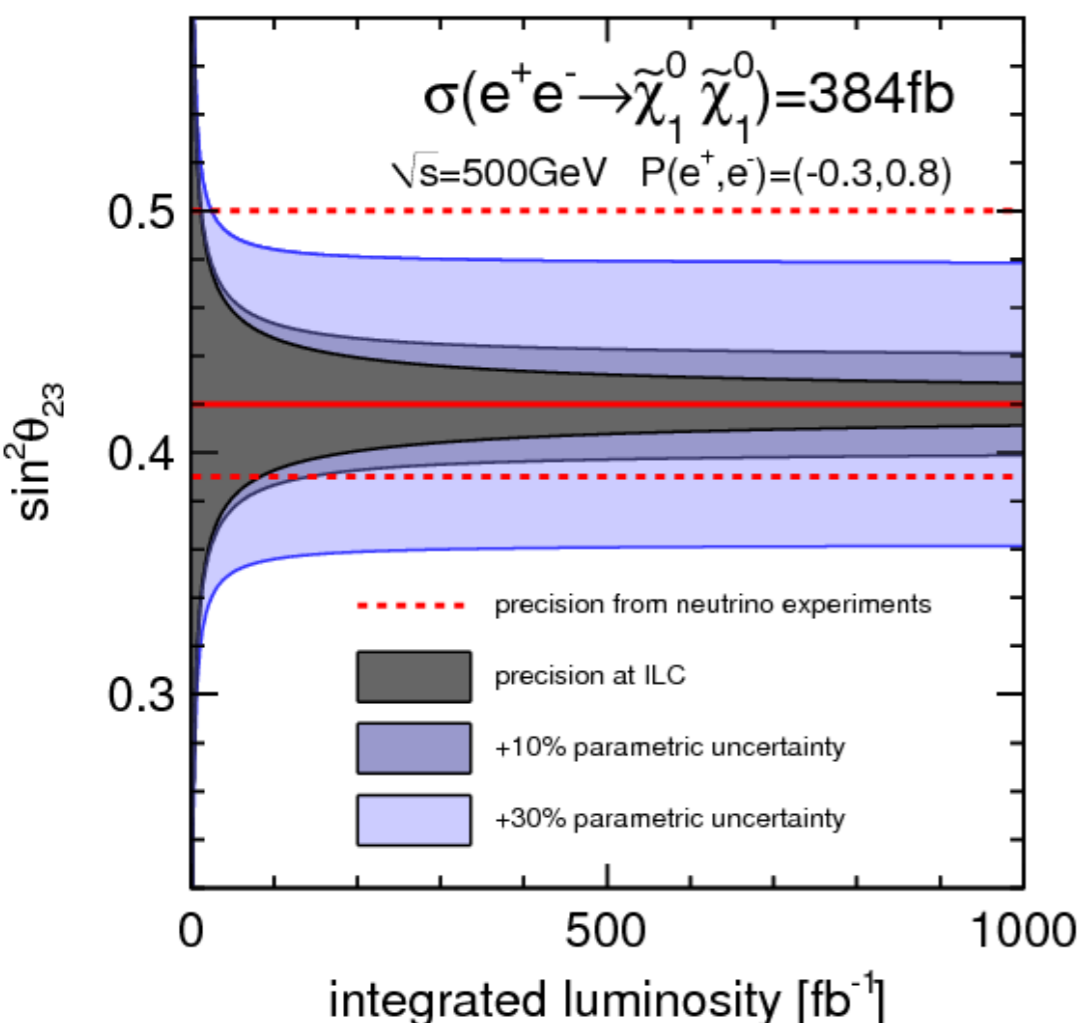


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- measure visible decays of LSP $\Rightarrow \sin^2 \theta_{23}$
- compare of collider measurement with neutrino oscillation data \Rightarrow **verify or falsify bRPV as mechanism of neutrino mass generation**

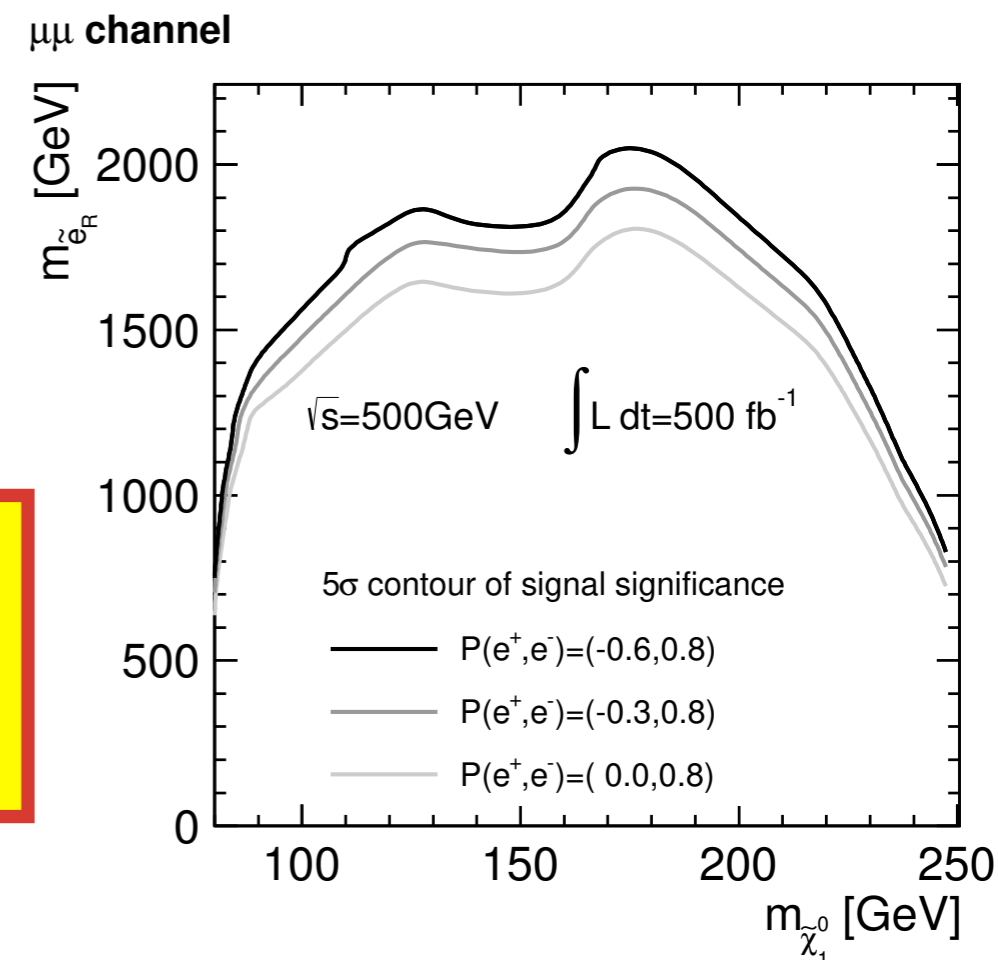


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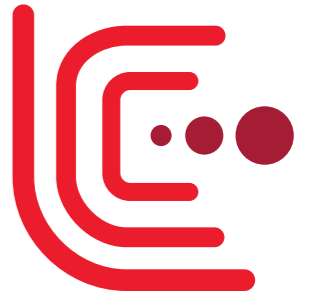


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Conclusions

- 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 e^+e^- 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:
 - extendability in energy
 - polarised beams
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arXiv:1702.05333**



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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!

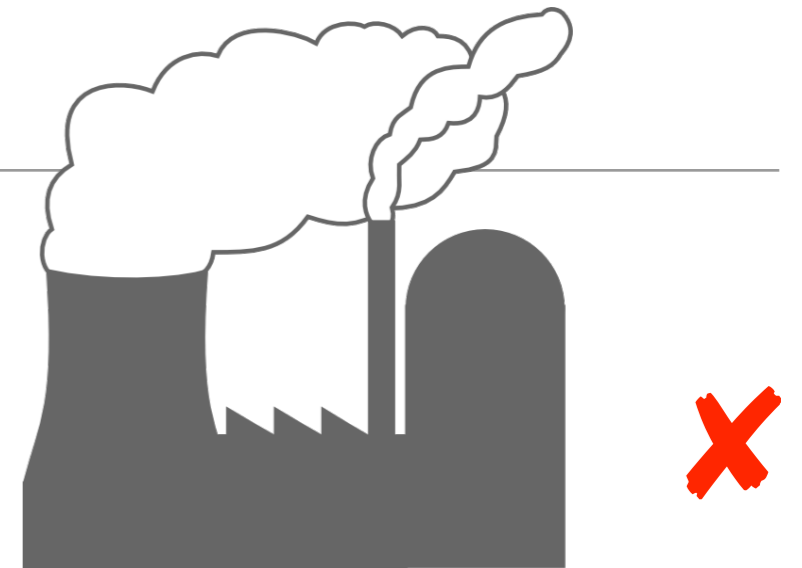
- **ILC design driven by *self-imposed* limits on total site power:**

- **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
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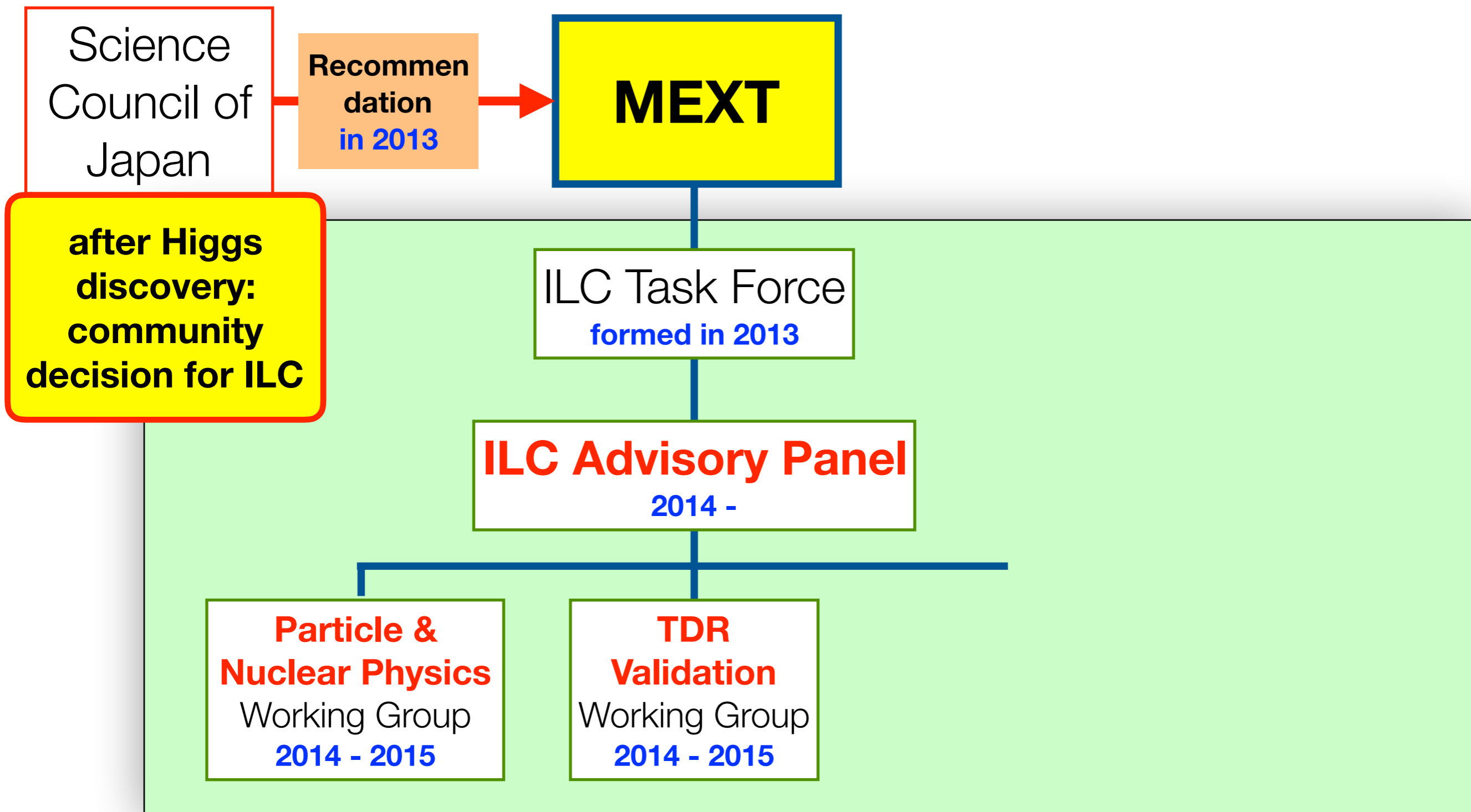
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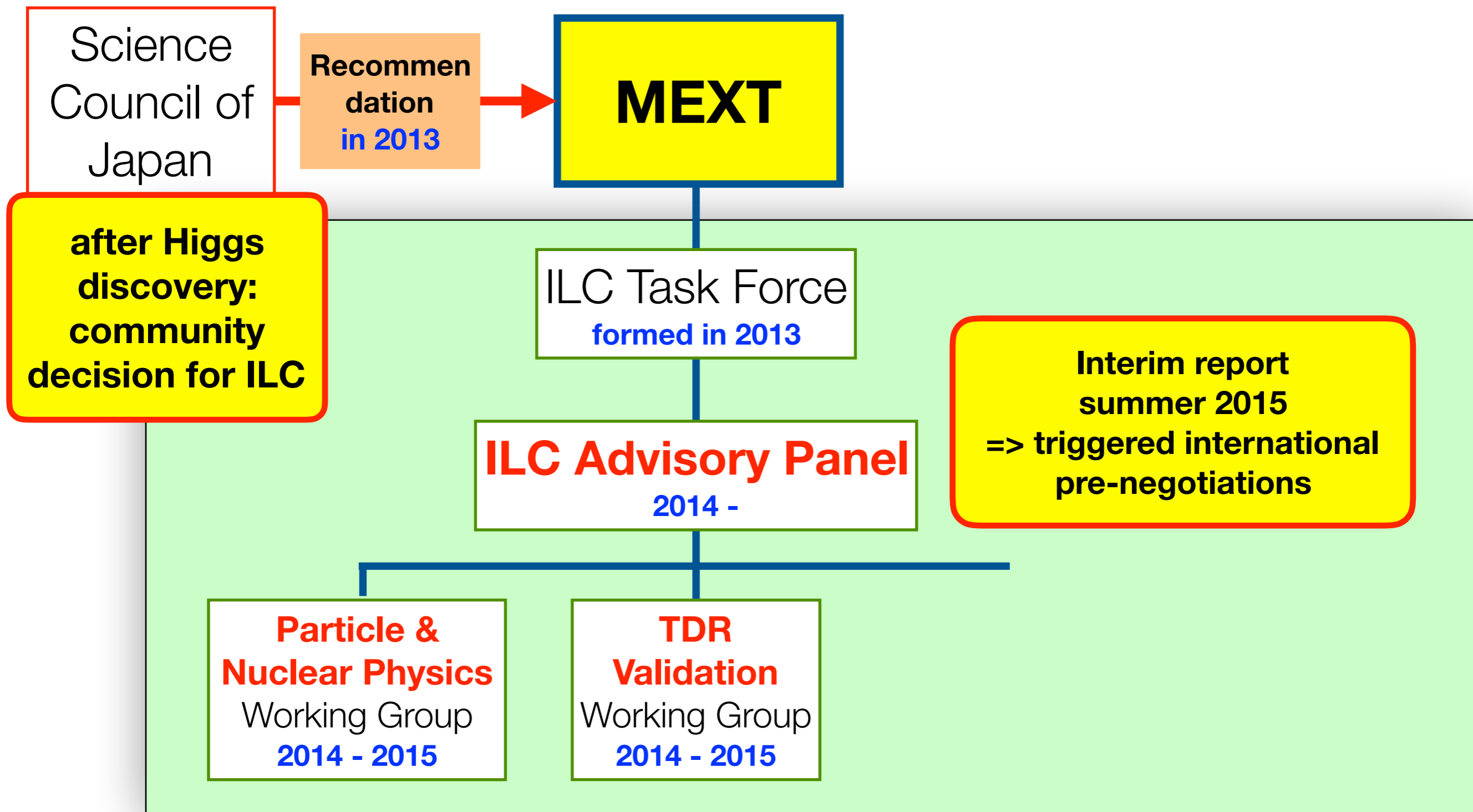
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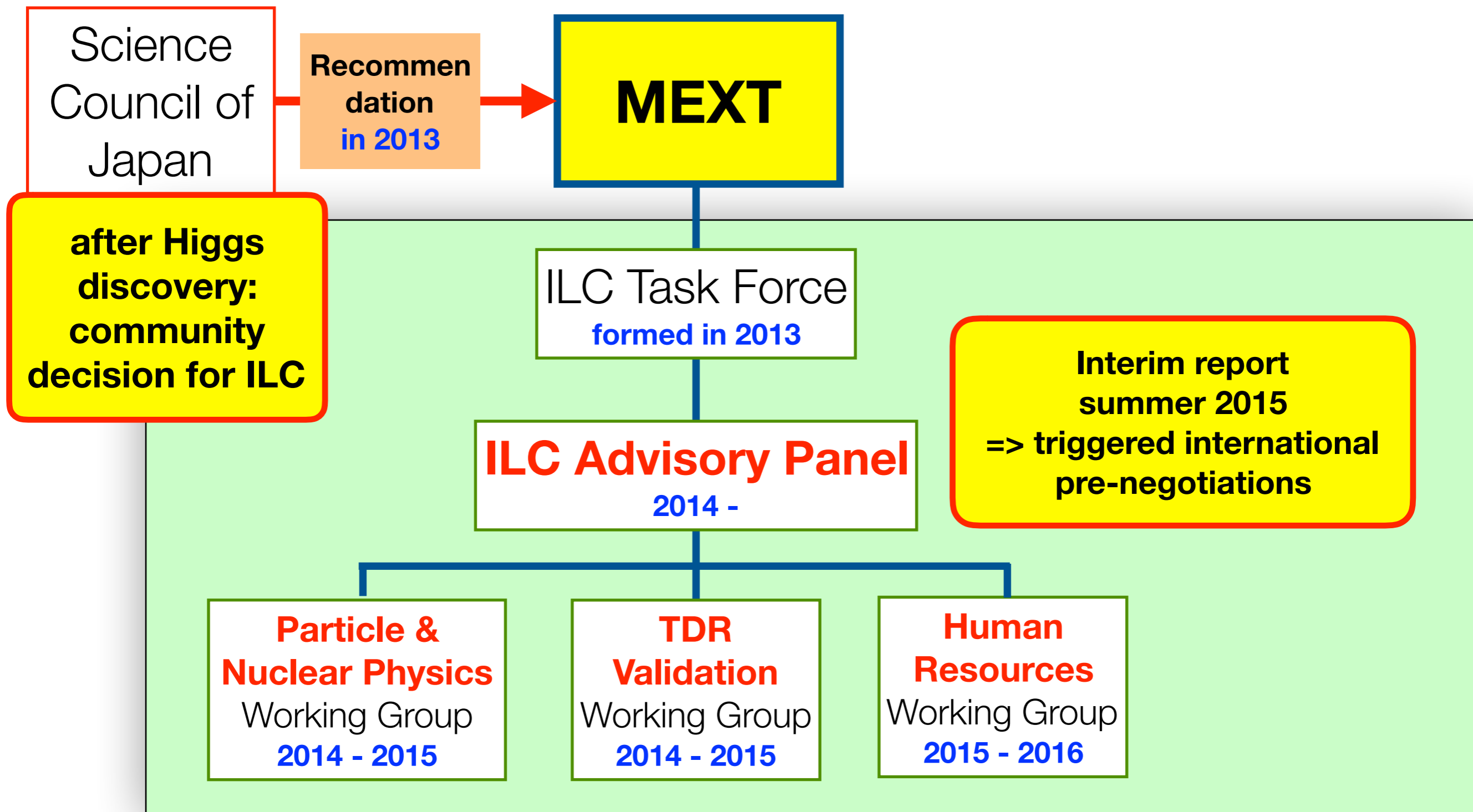
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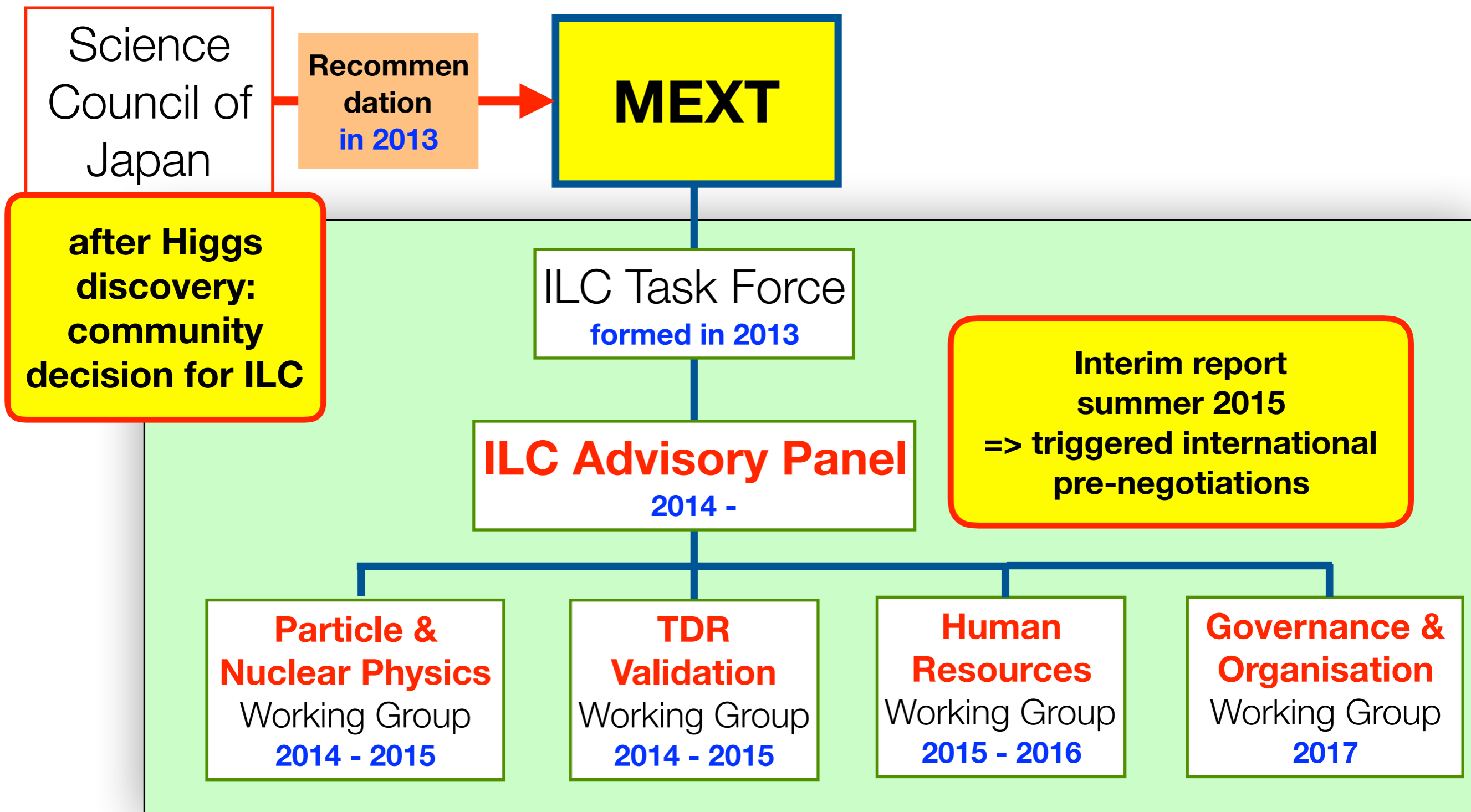
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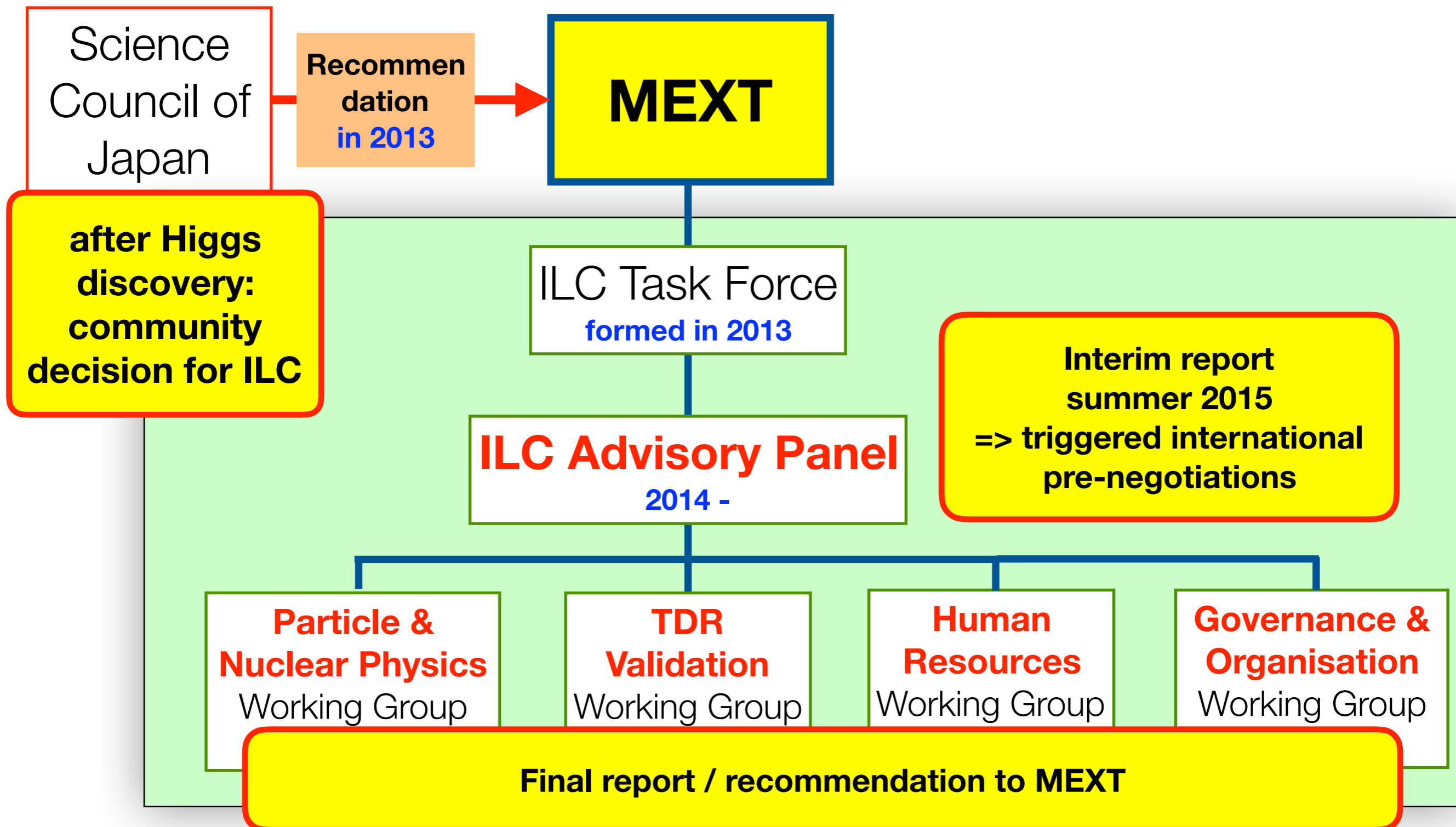
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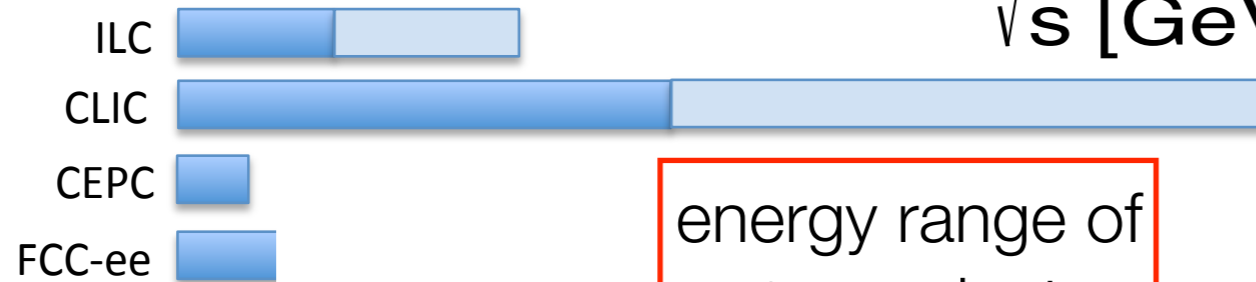
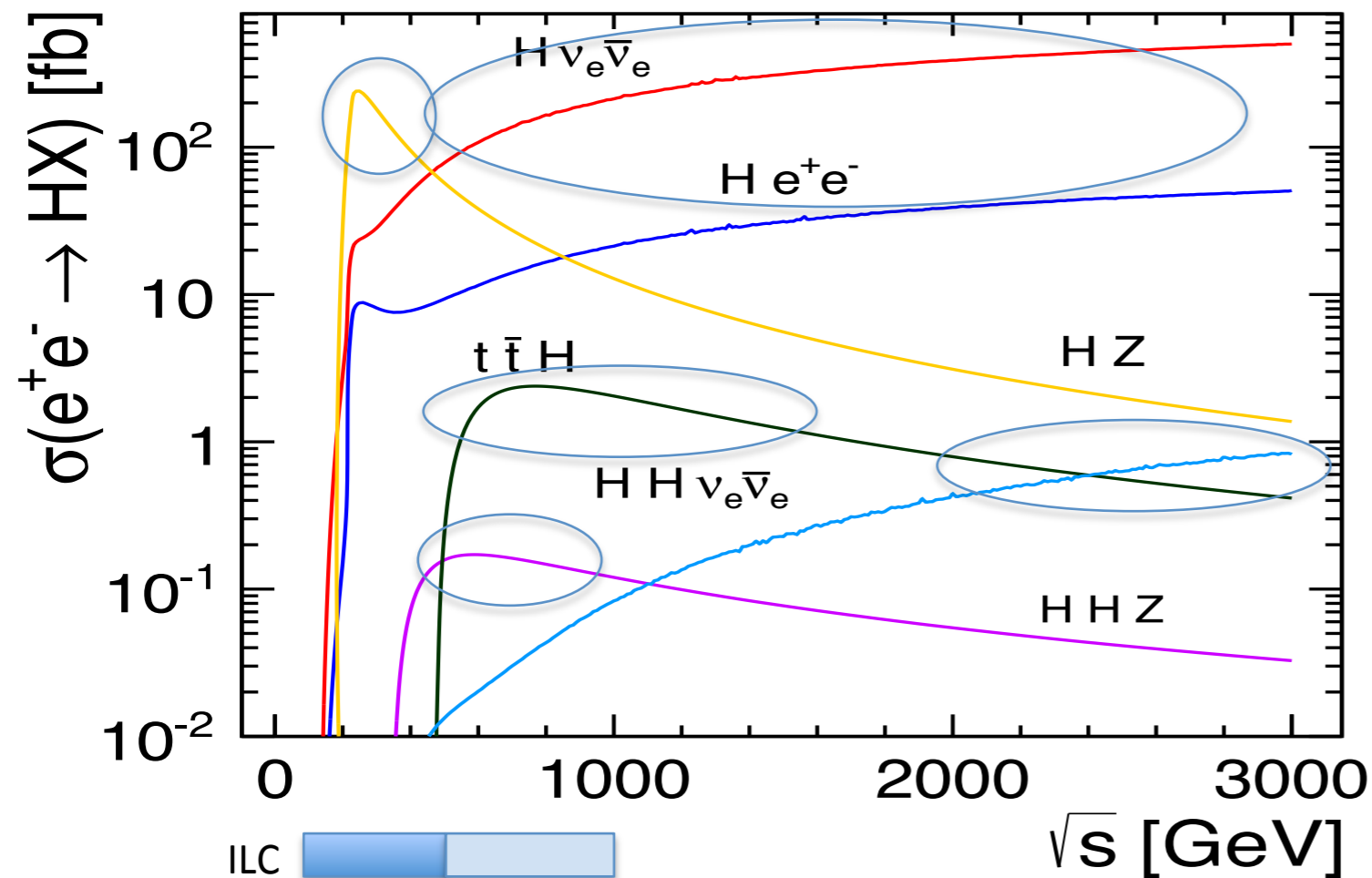
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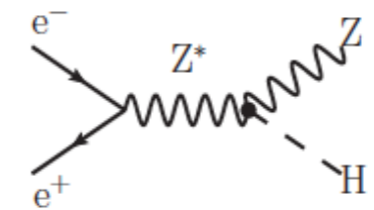
Review by Japanese Science Ministry (MEXT)



Higgs production in e^+e^- collisions

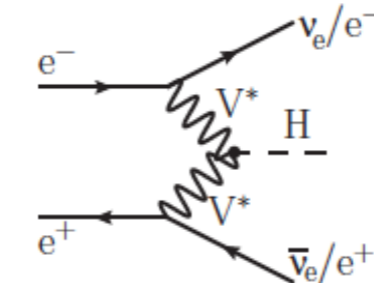


energy range of e^+e^- projects



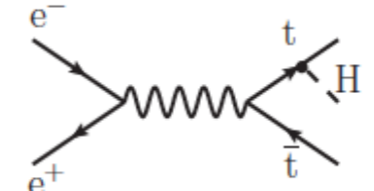
Mass $g_Z(\text{m.i.})$
BR's
(LHC)-invisible

$\geq 250 \text{ GeV}$



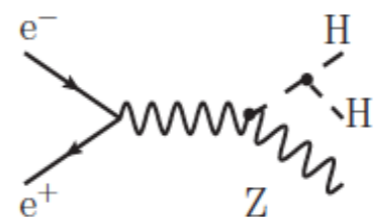
Γ_{tot}

$\geq 350 \text{ GeV}$



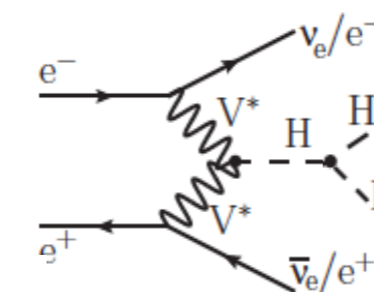
g_t

$\geq 500 \text{ GeV}$



g_{HHH}

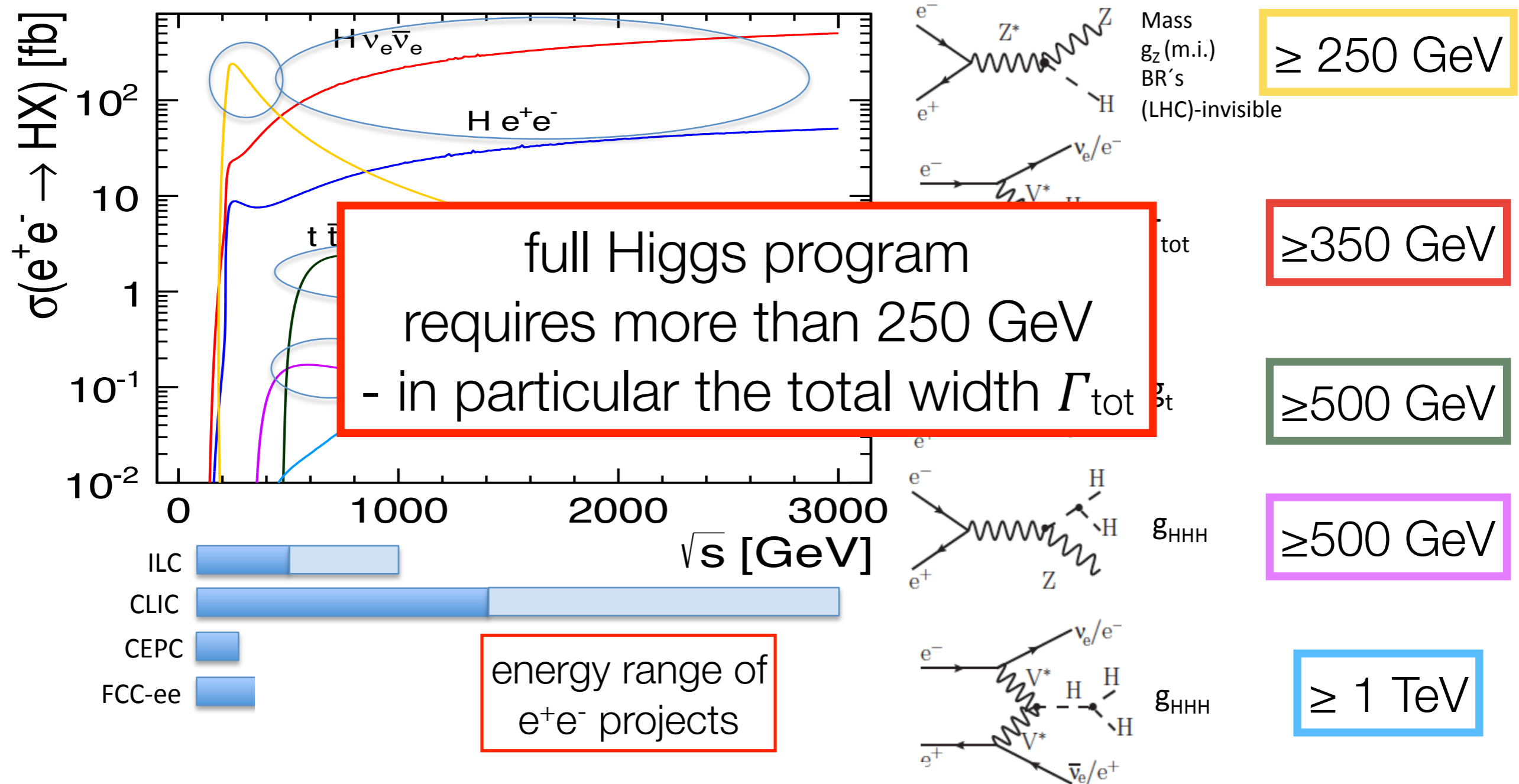
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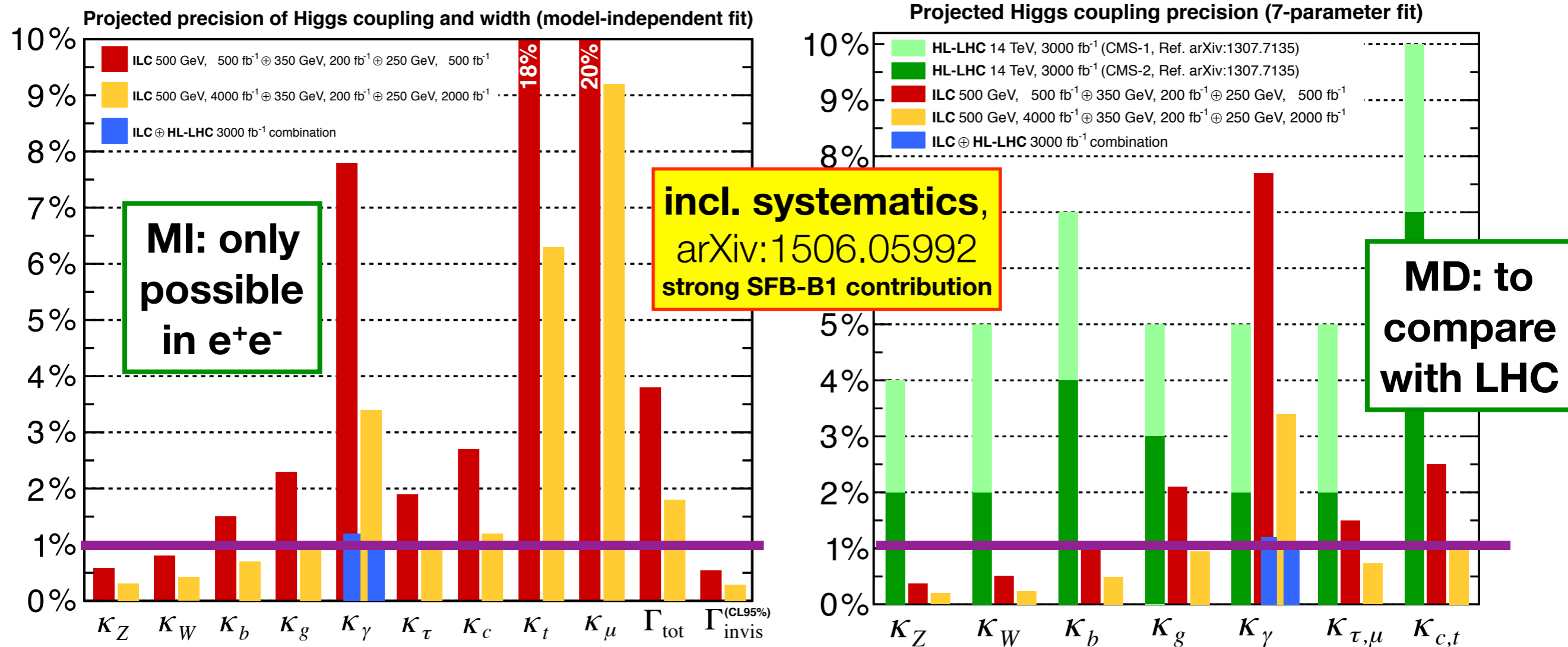
g_{HHH}

$\geq 1 \text{ TeV}$

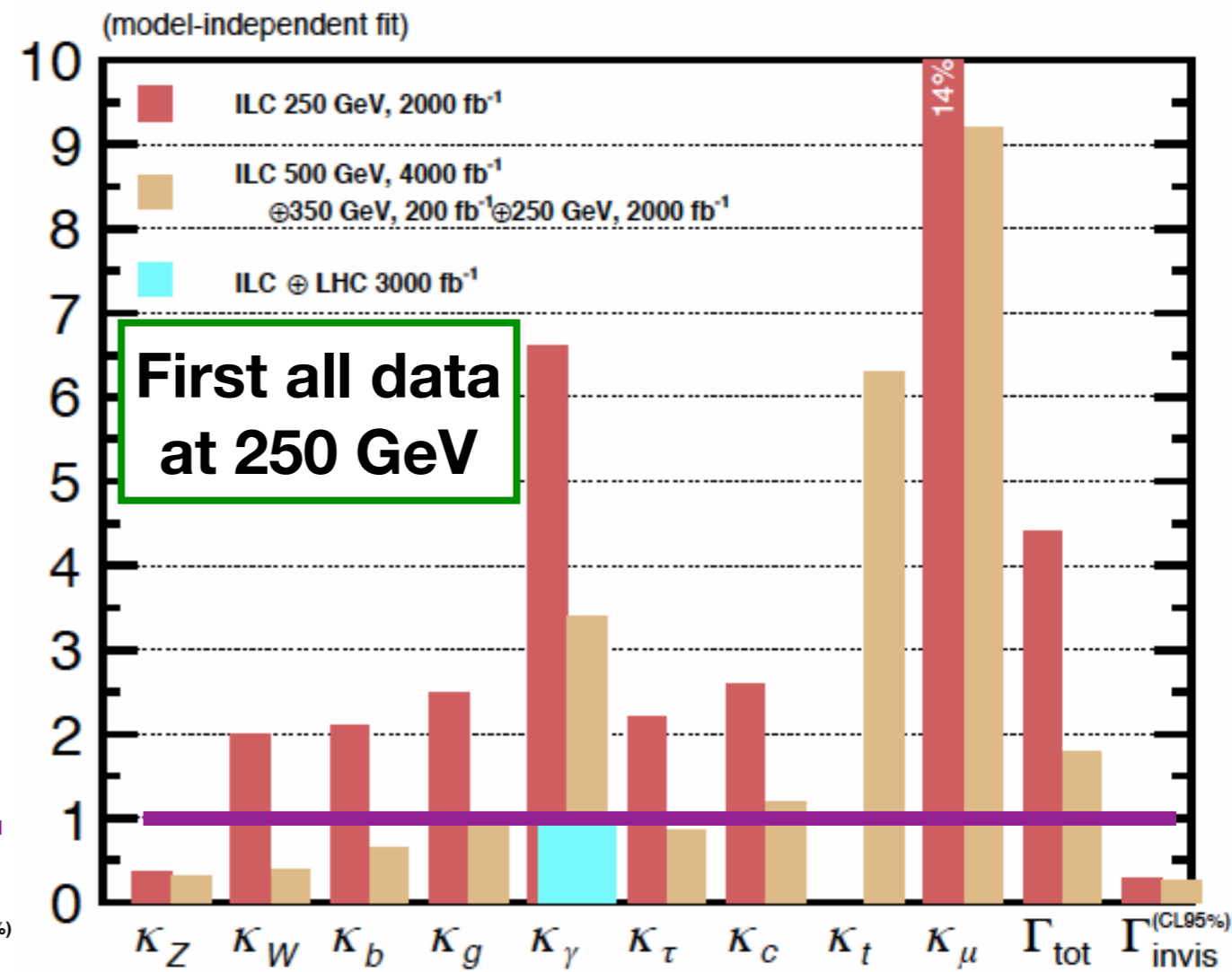
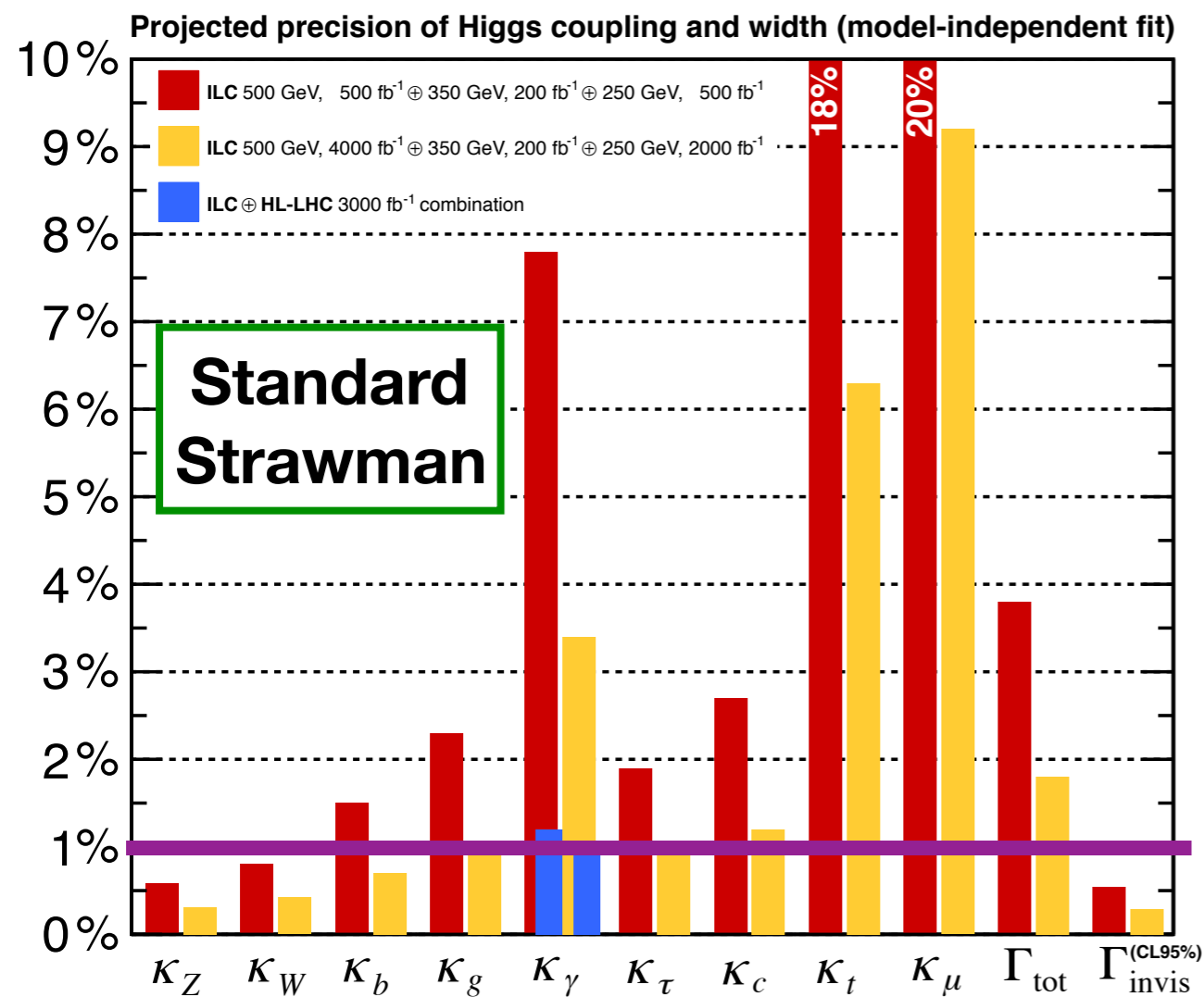
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Absolute (!) Higgs Couplings at the ILC



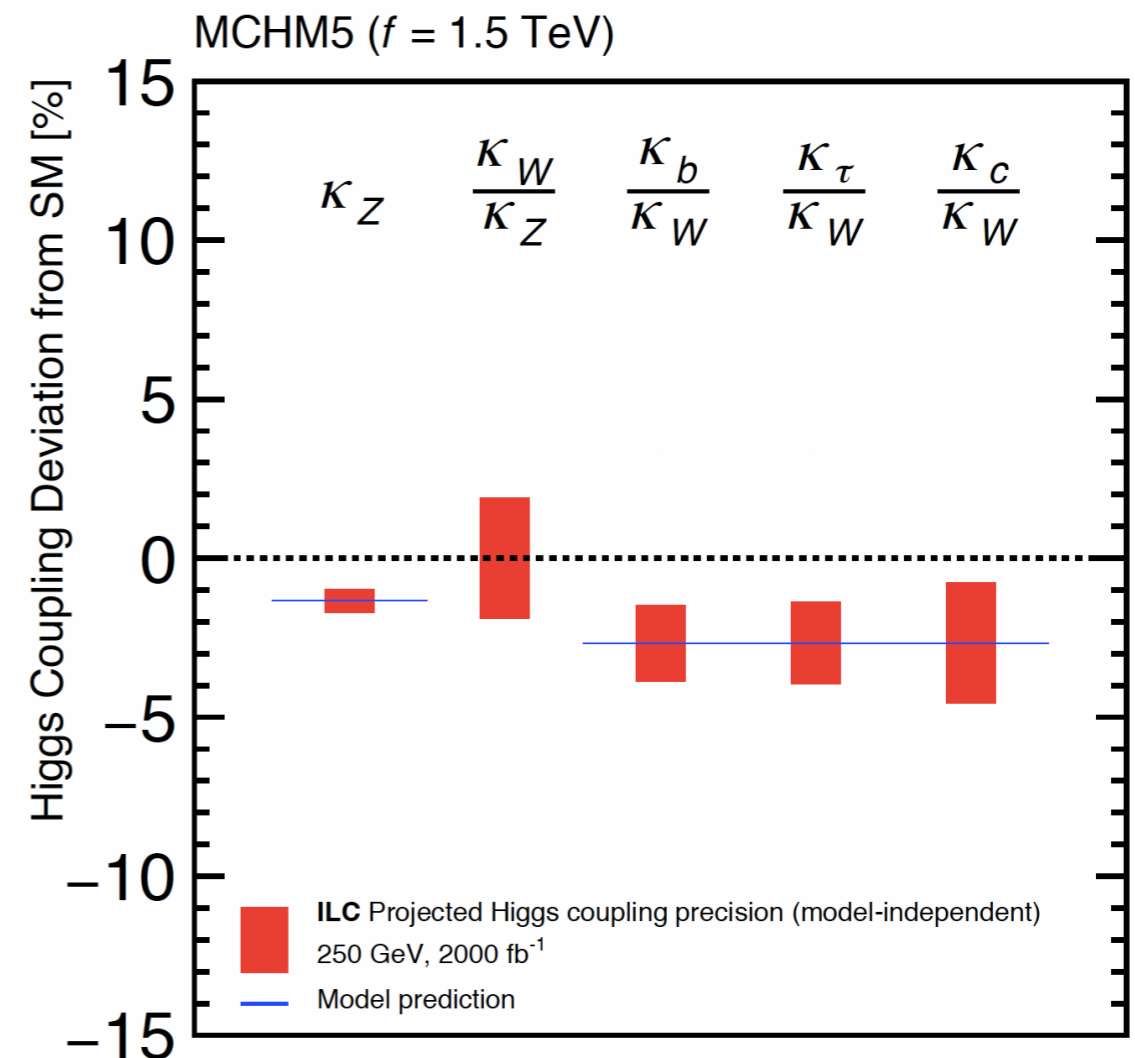
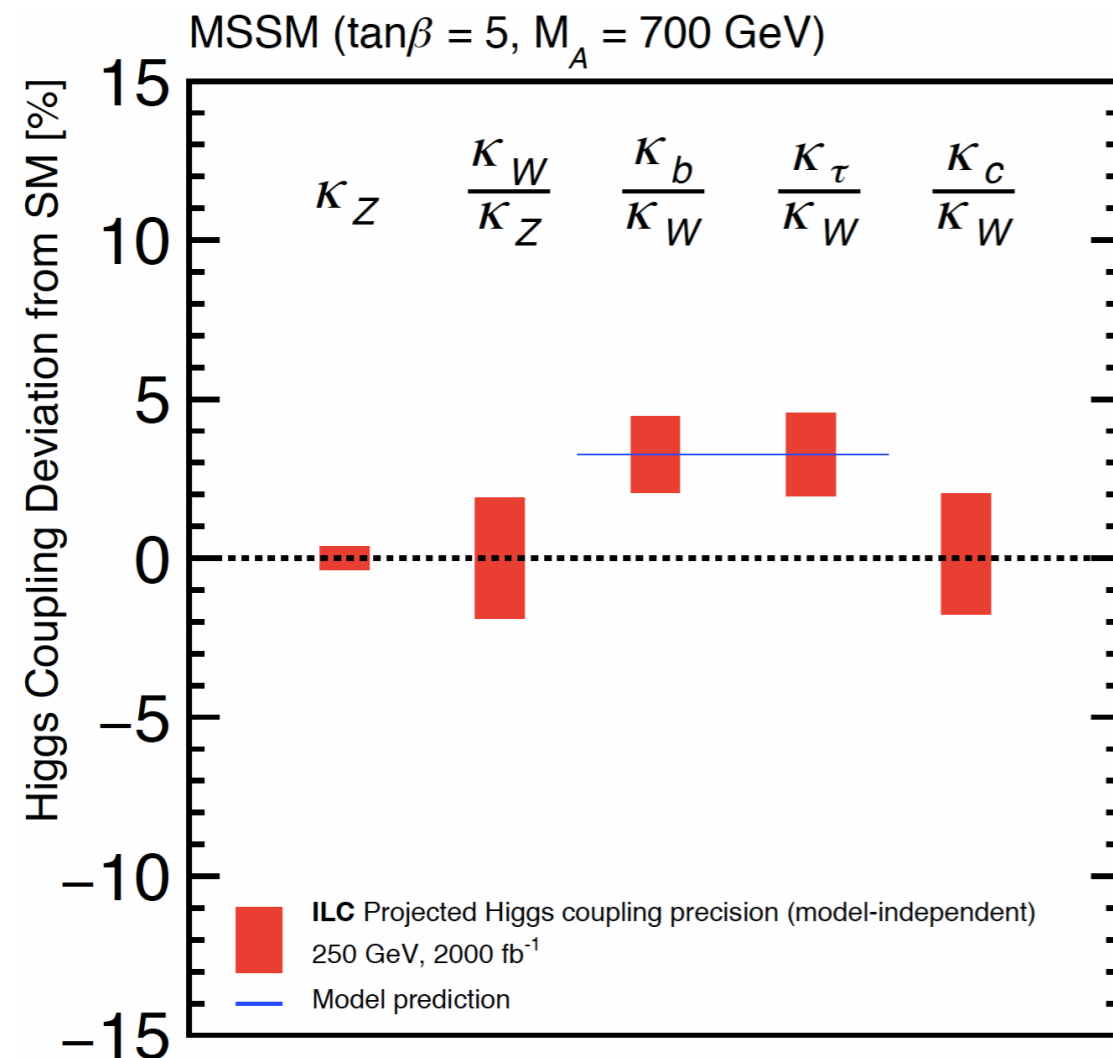
Higgs Couplings and Staging - Model-independent



Precisions roughly similar - most notable exceptions: κ_W , κ_t

But note: red bars compare **8yrs** \Leftrightarrow **15yrs**

Finger-printing the Higgs: SUSY or Composite?

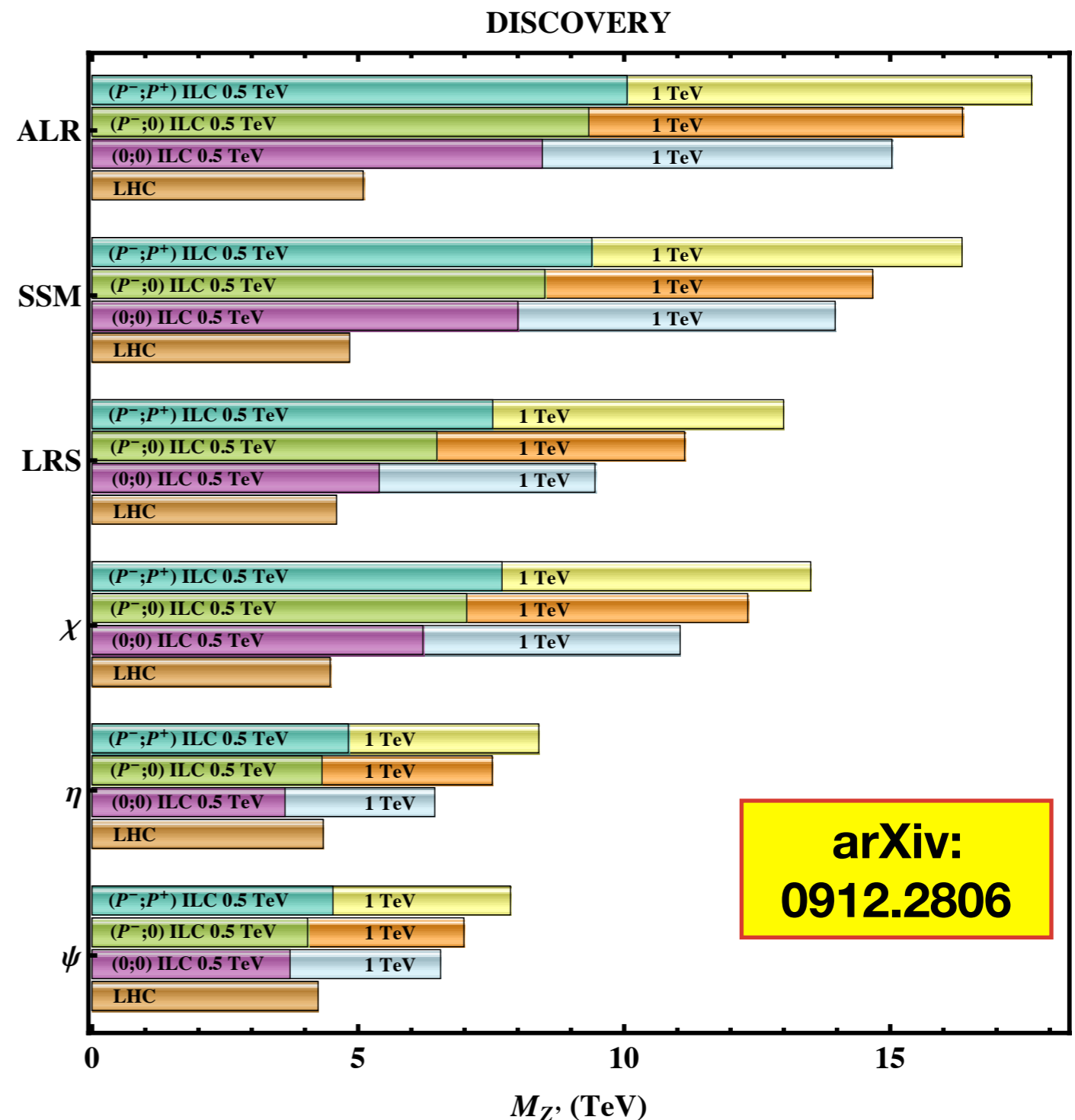


The full ILC250 stage gives significant BSM discrimination power

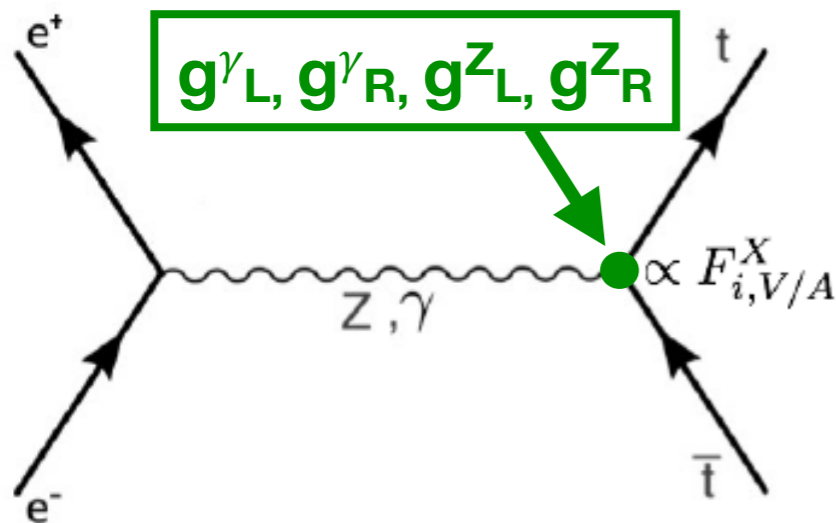


New Force Carriers

- via $e^+e^- \rightarrow f\bar{f}$: 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



Electroweak Couplings of the Top Quark



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

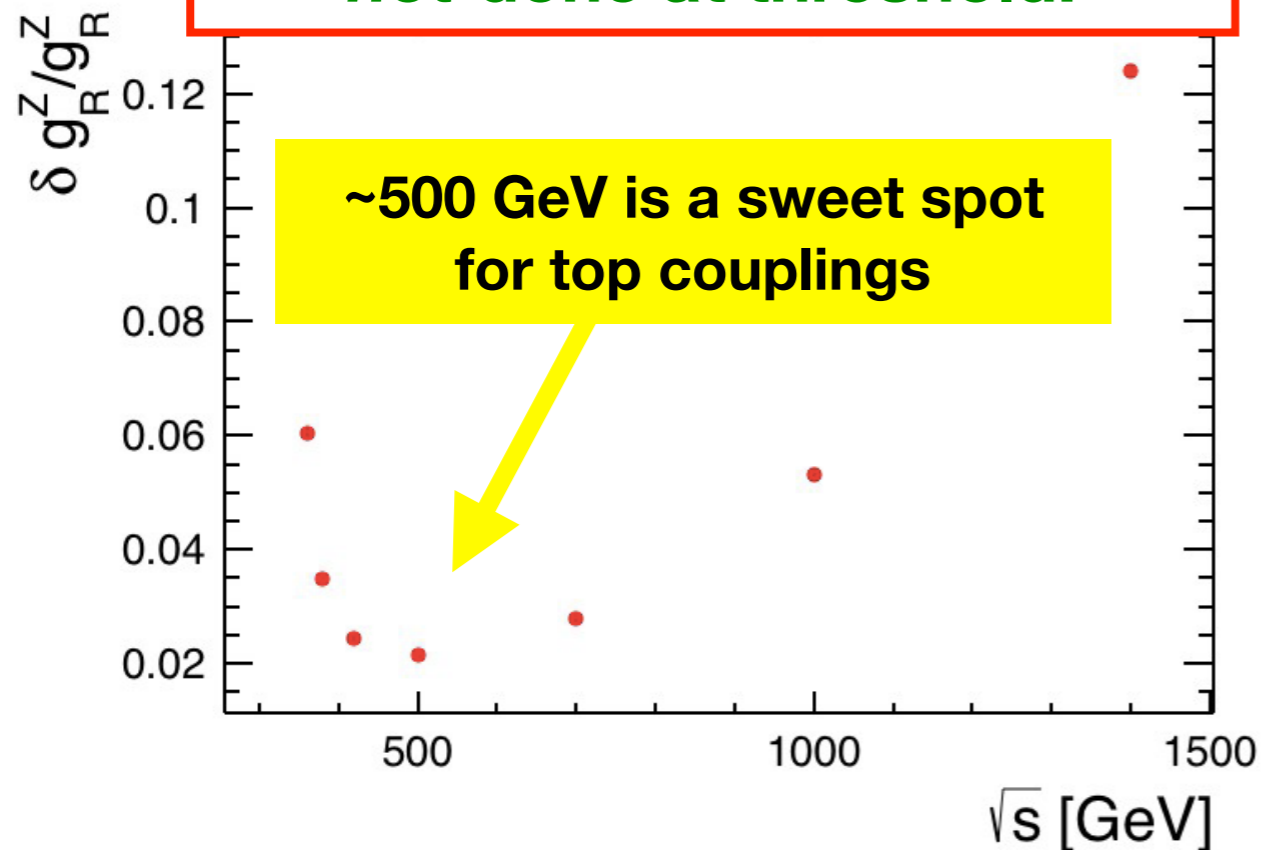
Z^0/γ interference : $\sigma \propto (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

ILC 'provides' two beam polarisations

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

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

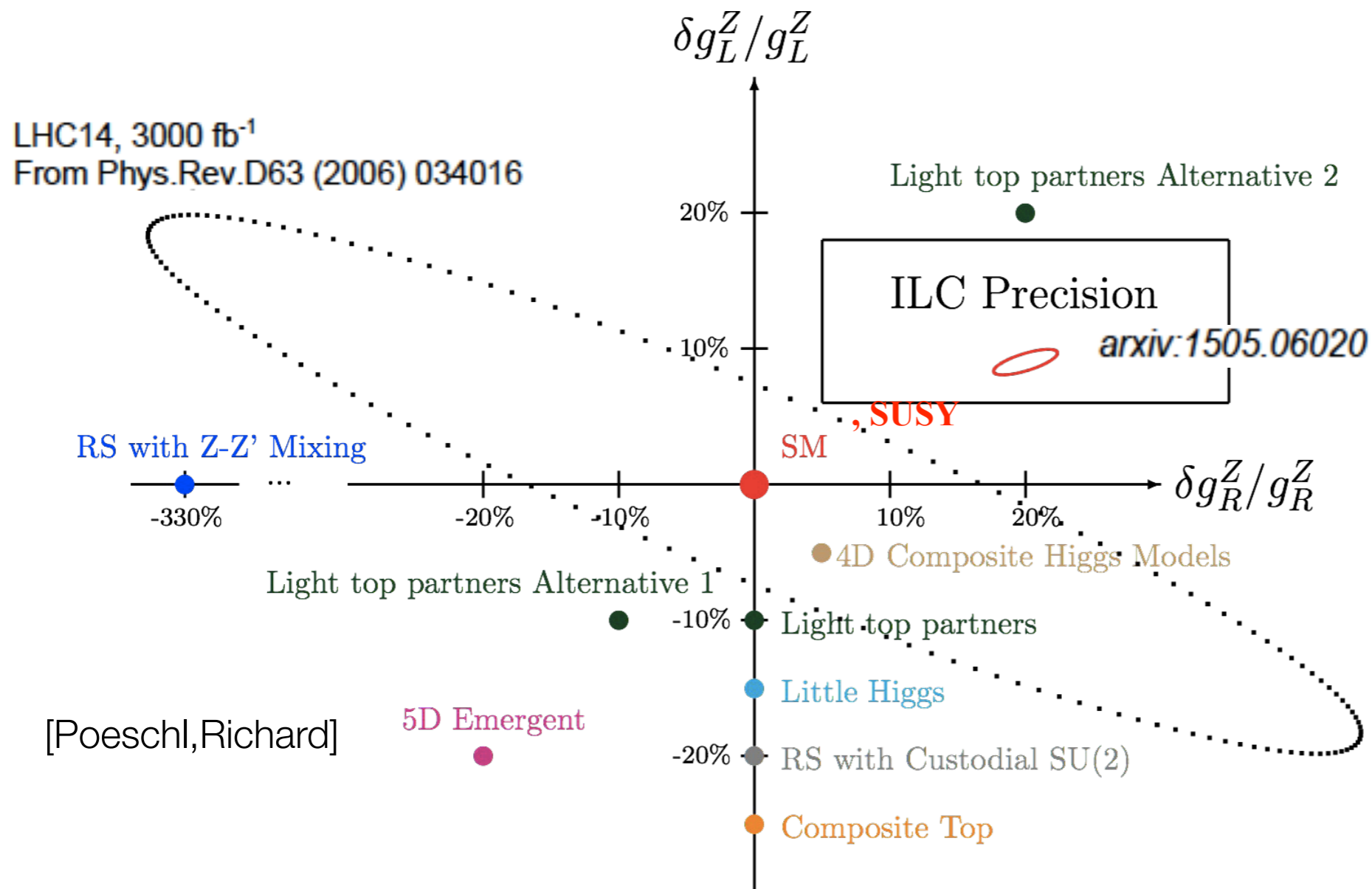
\sqrt{s} dependency: top physics is *not* done at threshold!



Polarised beams

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

ILC Prospects on Top Couplings and BSM

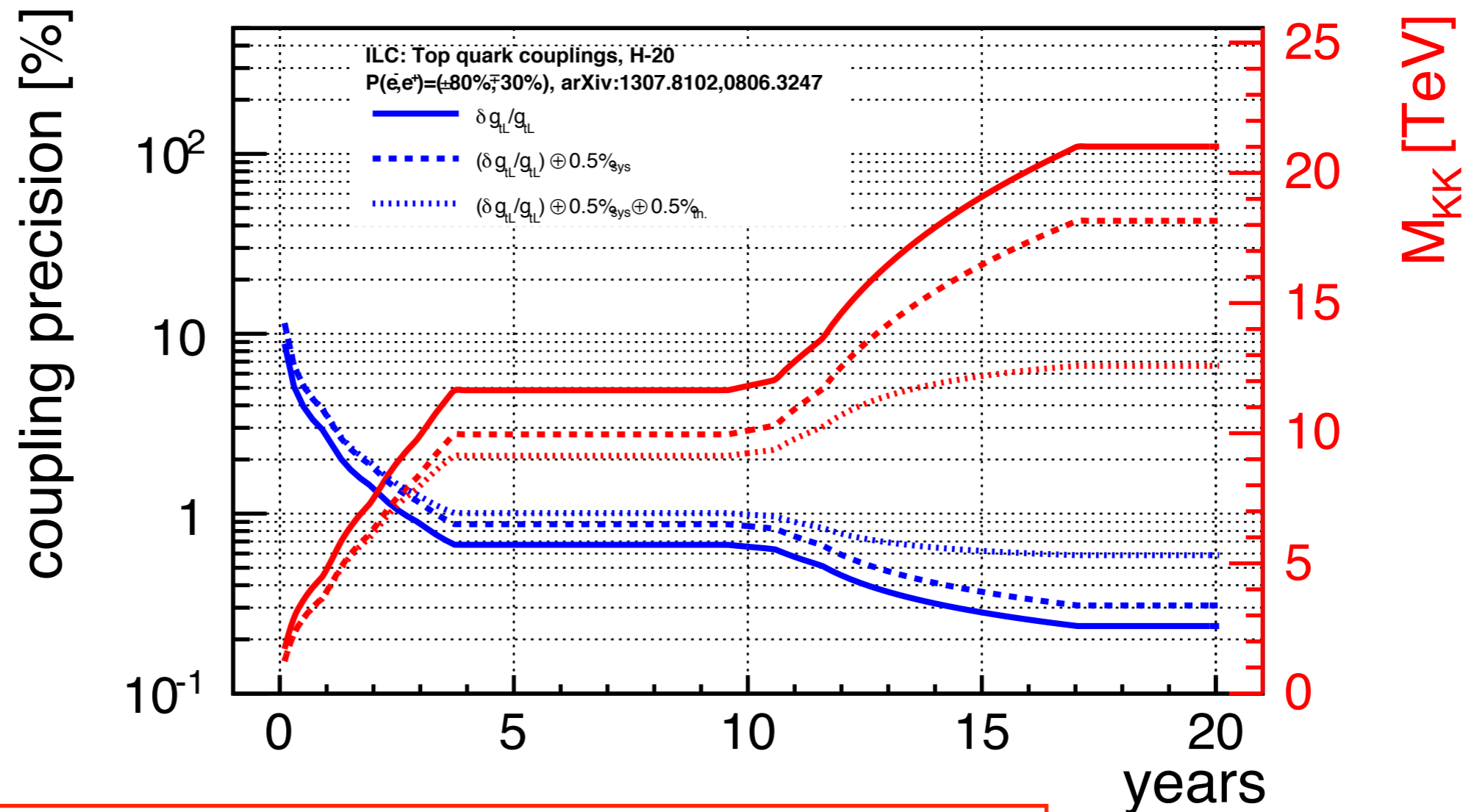


Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

- ILC precision allows model discrimination
- sensitivity in g_L^Z, g_R^Z plane complementary to LHC

New Physics Reach of full ILC500 Program

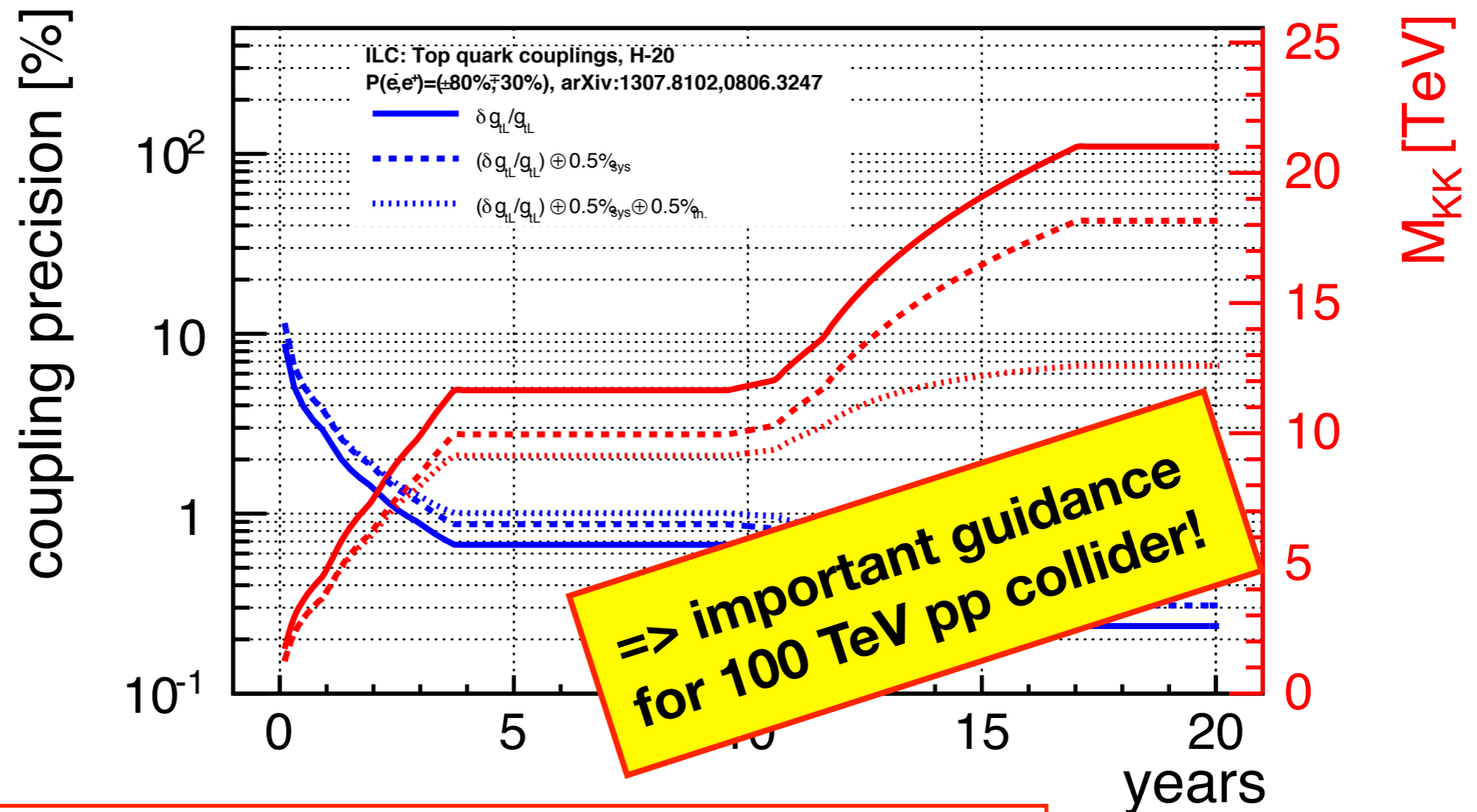
....for typical BSM scenarios with **composite Higgs/Top and/or extra dimensions**
based on phenomenology described in Pommerol et al. arXiv:0806.3247



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

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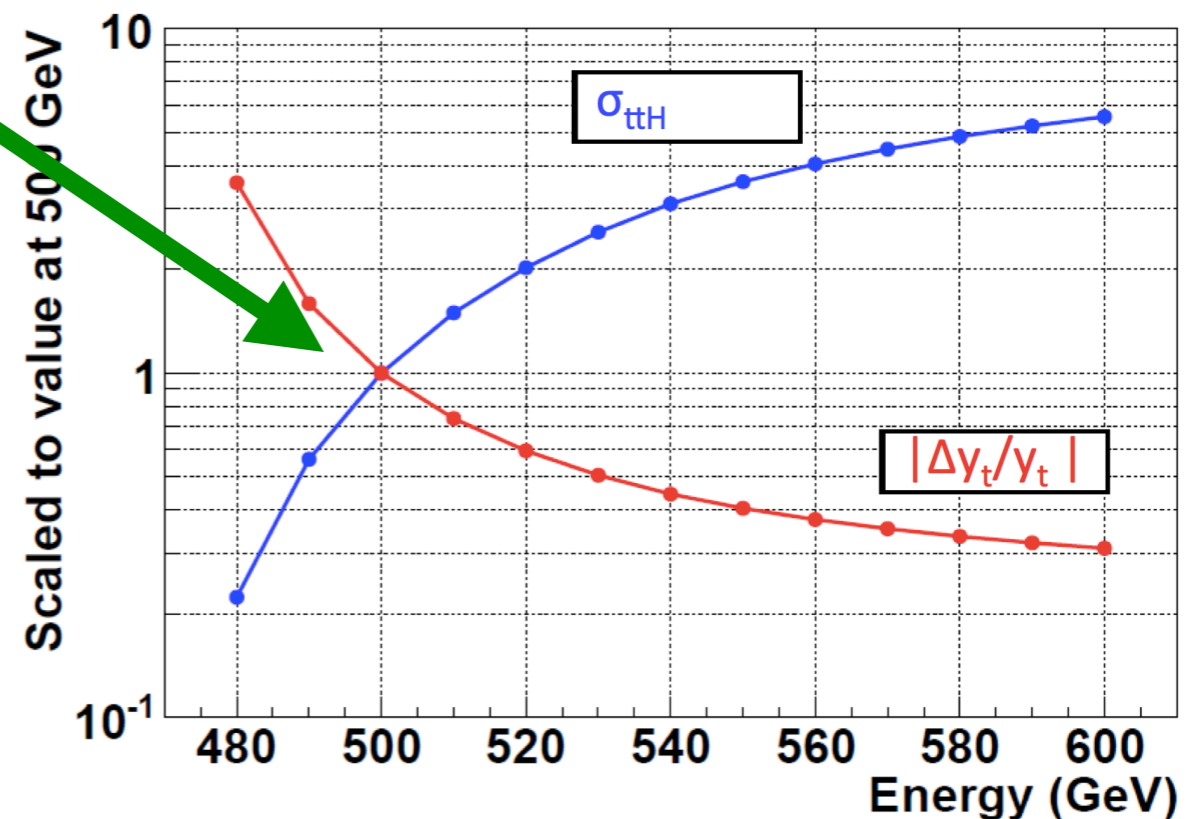
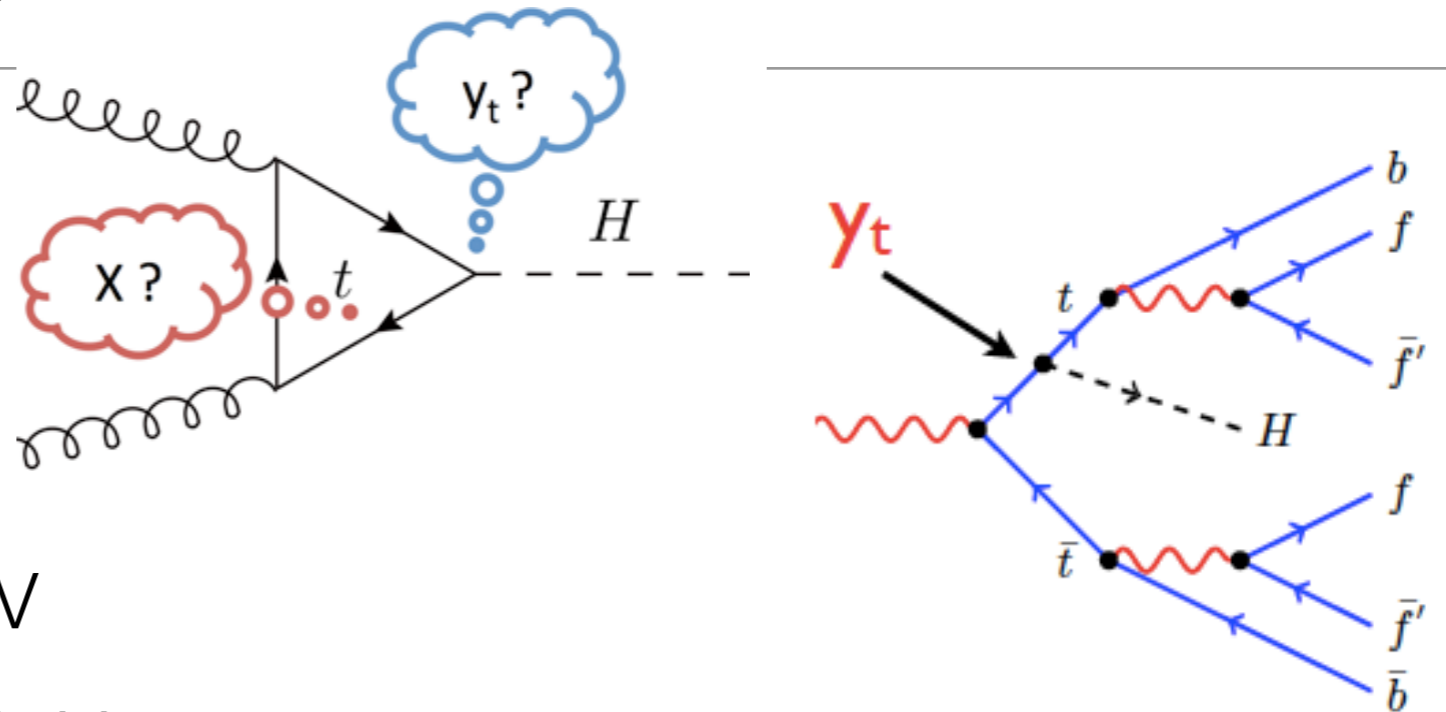
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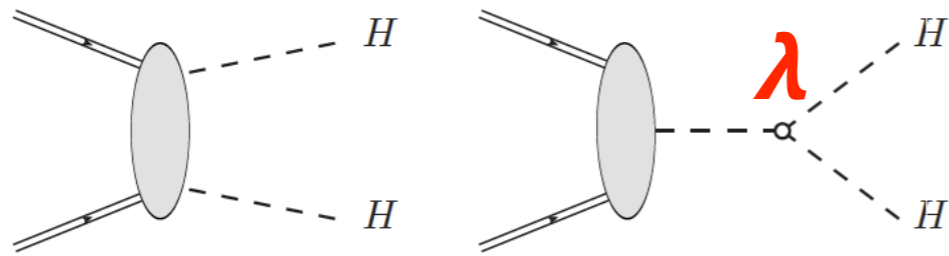
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Top Yukawa Coupling

- **Indirect:** loop couplings, top threshold scan ...
=> is it *really* y_t ?
- **Direct:** $t\bar{t}H$ production
=> possible for $\sqrt{s} \geq 500$ GeV
- SM $\sigma(t\bar{t}H) = 0.45\text{fb}$ @ 500 GeV
=> ILC500 full running scenario, geant4-based detector simulation:
 $\delta y_t = 6.3\%$
- 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**



Double Higgs Production & Higgs Self-Coupling



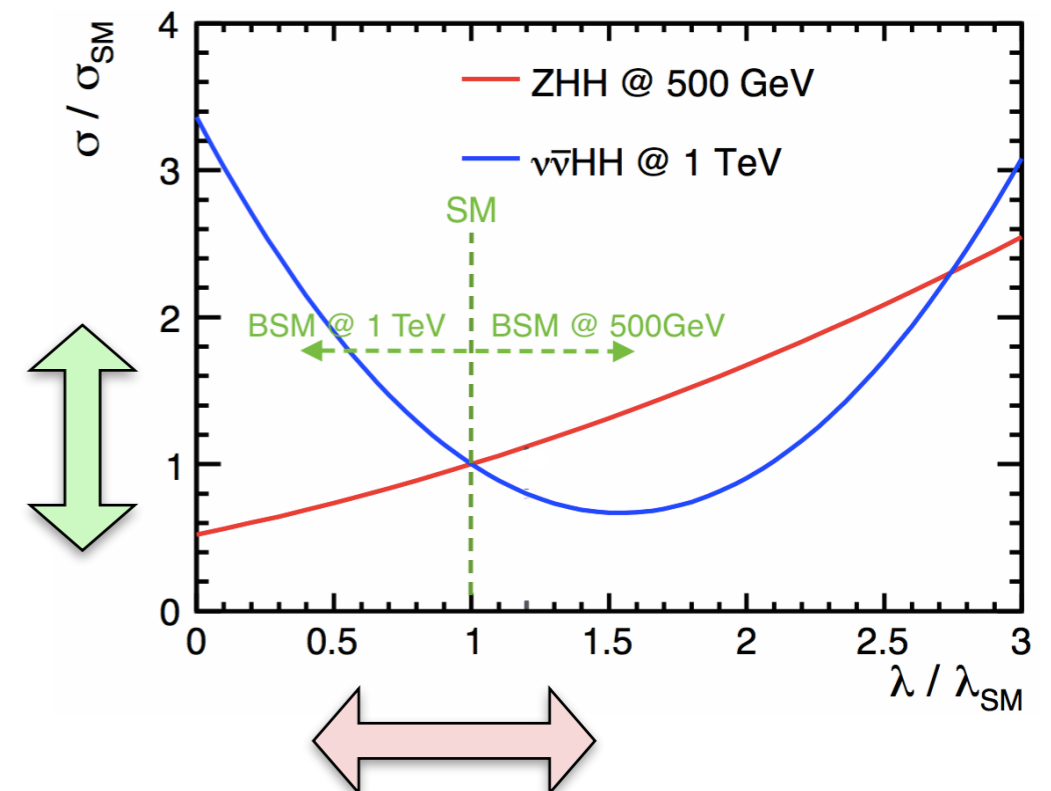
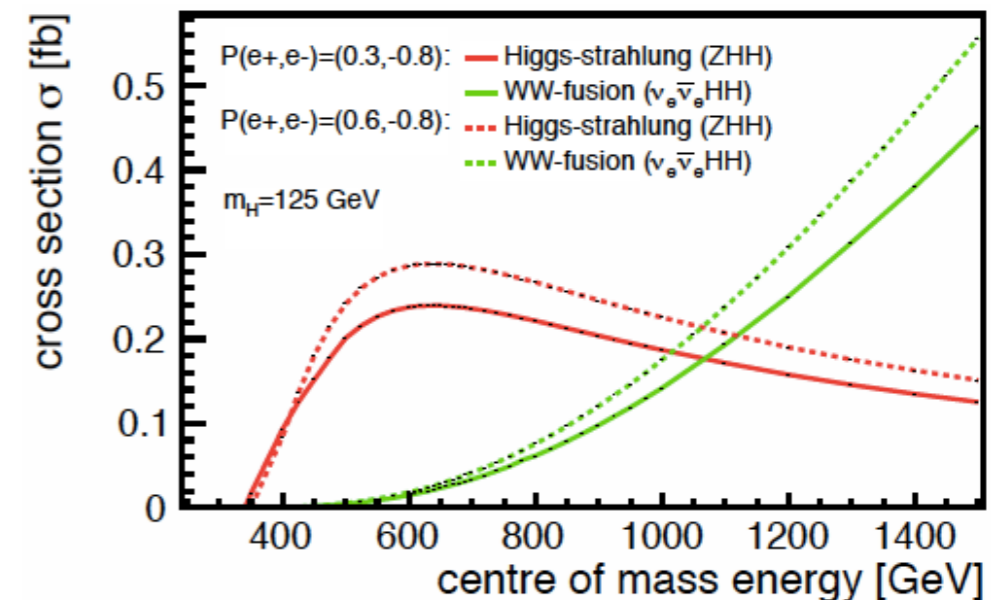
two **complementary** production processes:

- **ZHH @ ~500 GeV**
 - unique feature: *increases* if $\lambda > \lambda_{\text{SM}}$
 - $\delta\sigma/\sigma = 16\%$: **> 5 sigma discovery**
 - $\delta\lambda/\lambda = 27\%$: **3 sigma observation**
- **vvH (VBF) @ ECM > 1 TeV**
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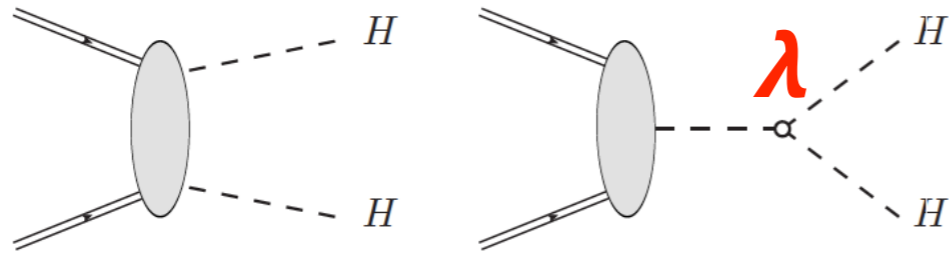
BSM changes the picture: e.g. $\lambda = 1.5 \lambda_{\text{SM}}$

500GeV: $\delta\lambda/\lambda = 20\%$, 1TeV: $\delta\lambda/\lambda \rightarrow \infty$

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



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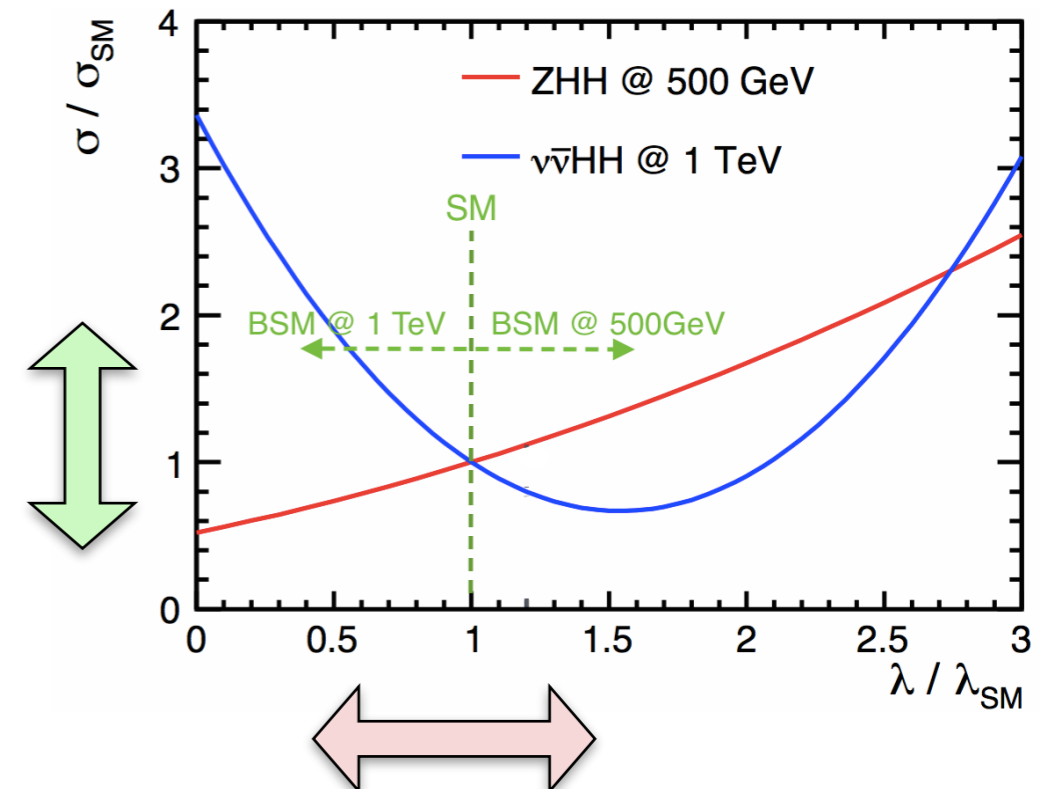
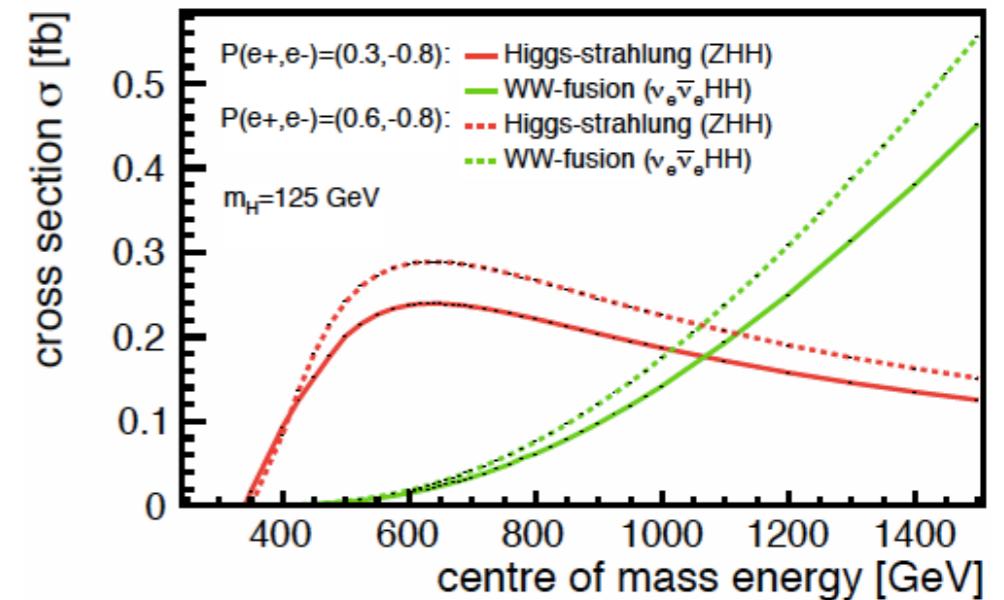
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sensitivity
to λ largest
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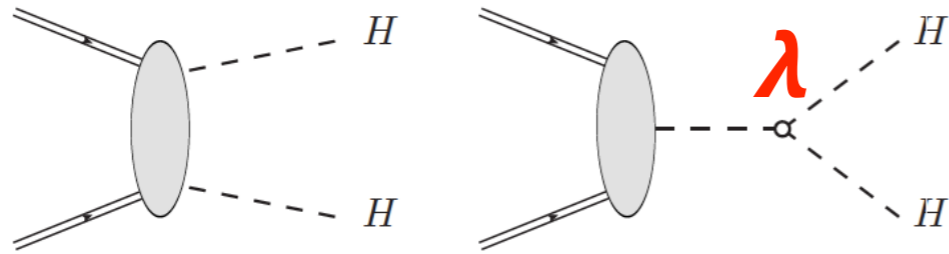
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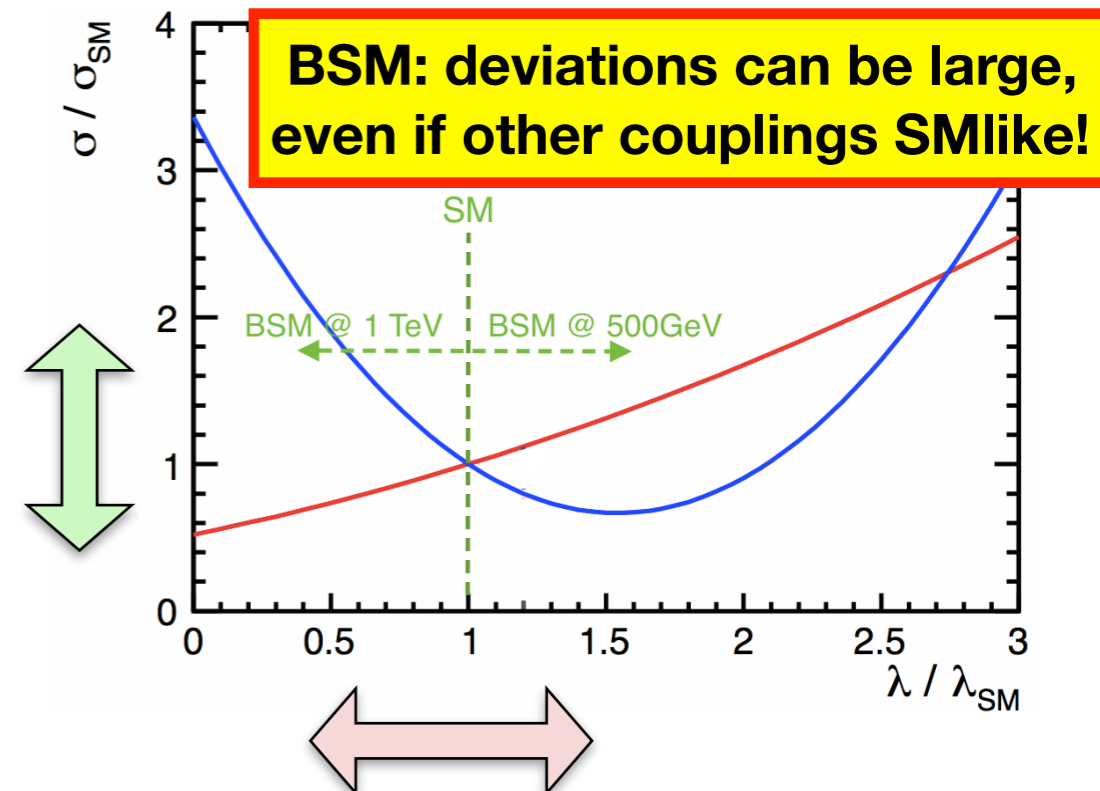
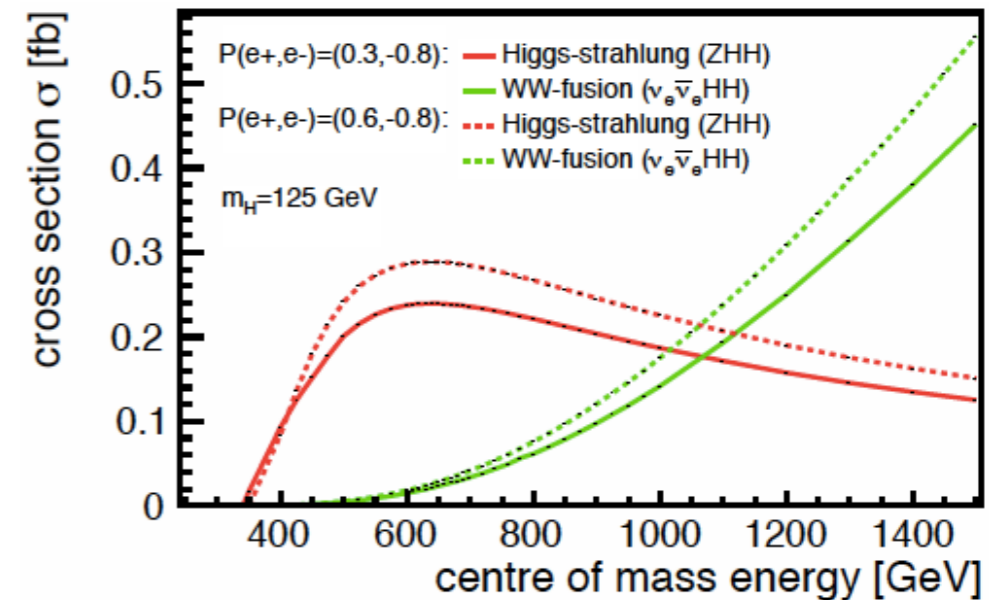
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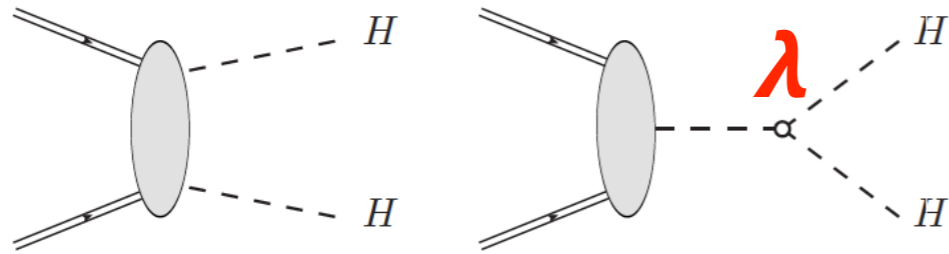
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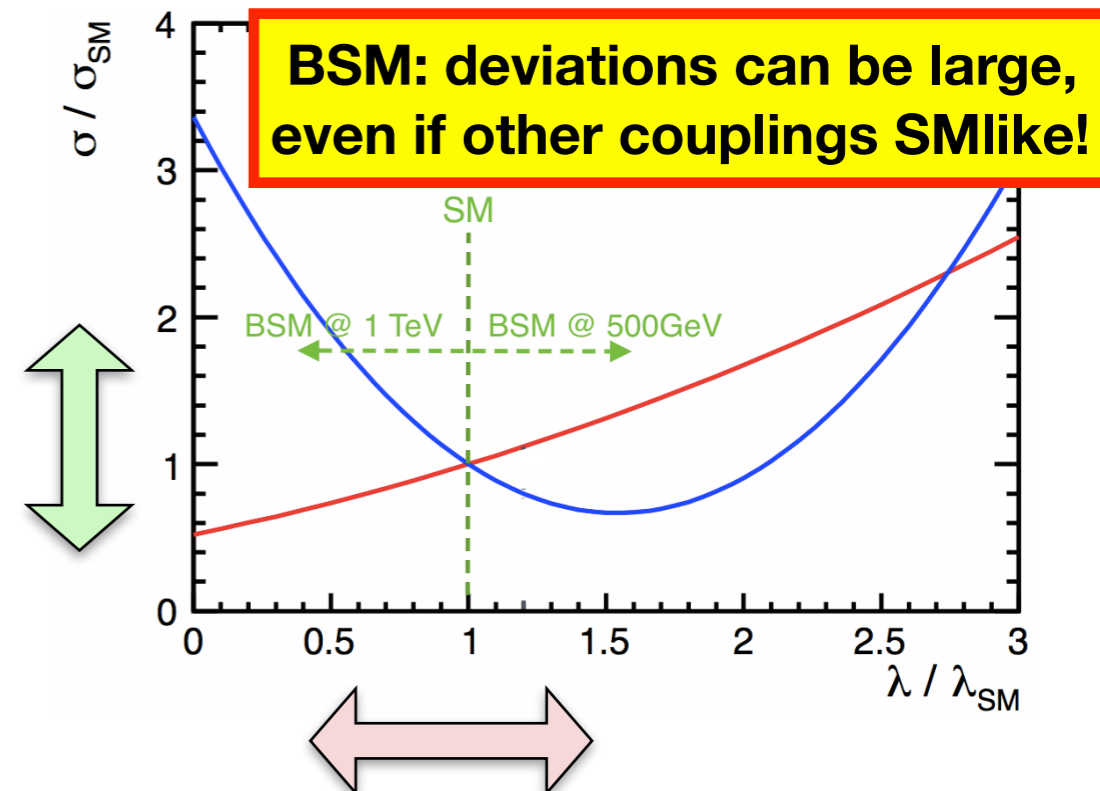
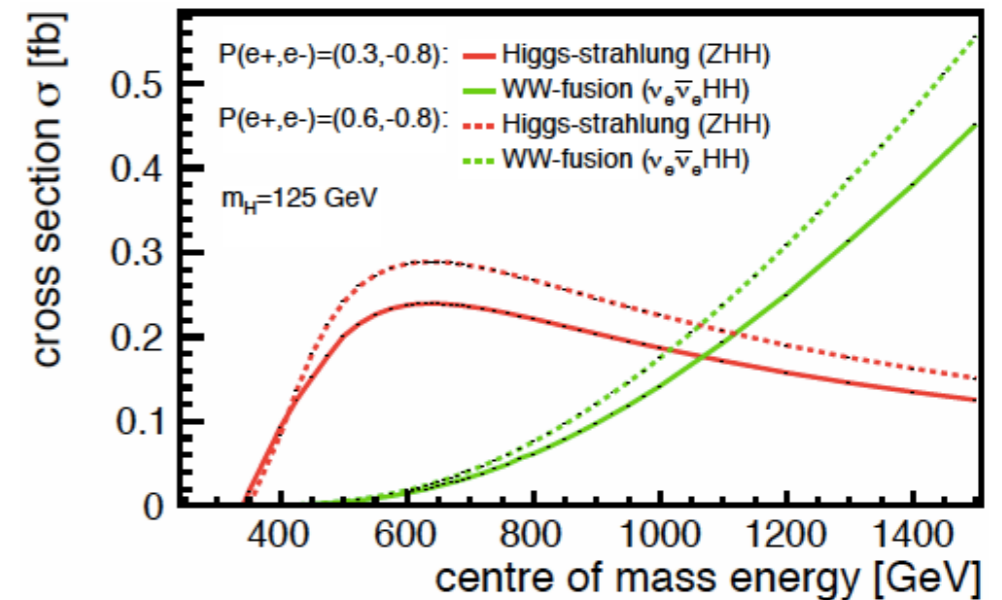
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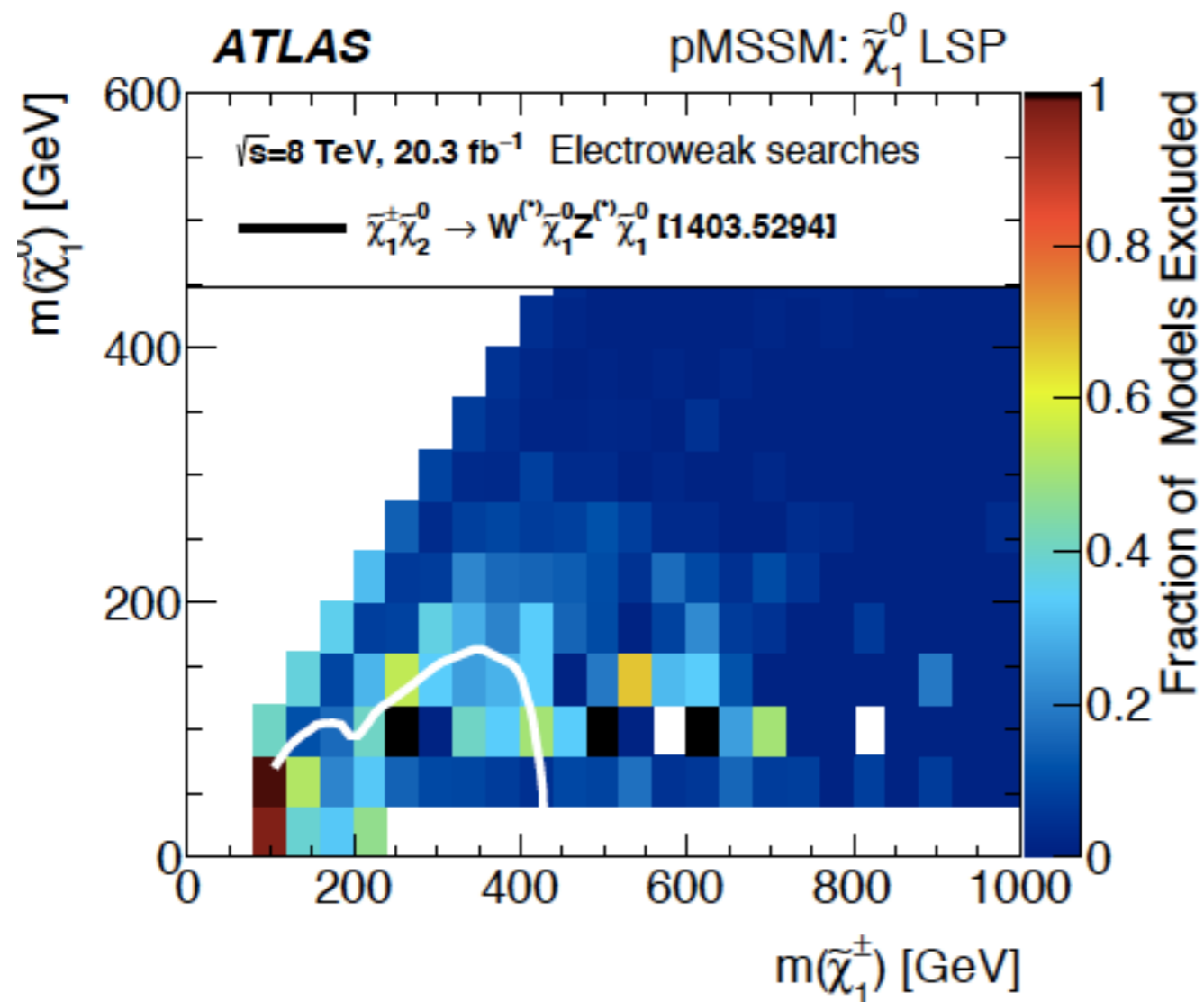


Plenty of room left for SUSY

simplified models don't give the full story

(e.g. 100% BR assumption rarely fulfilled)

-> c.f. pMSSM scan by ATLAS, arXiv:1508:06608

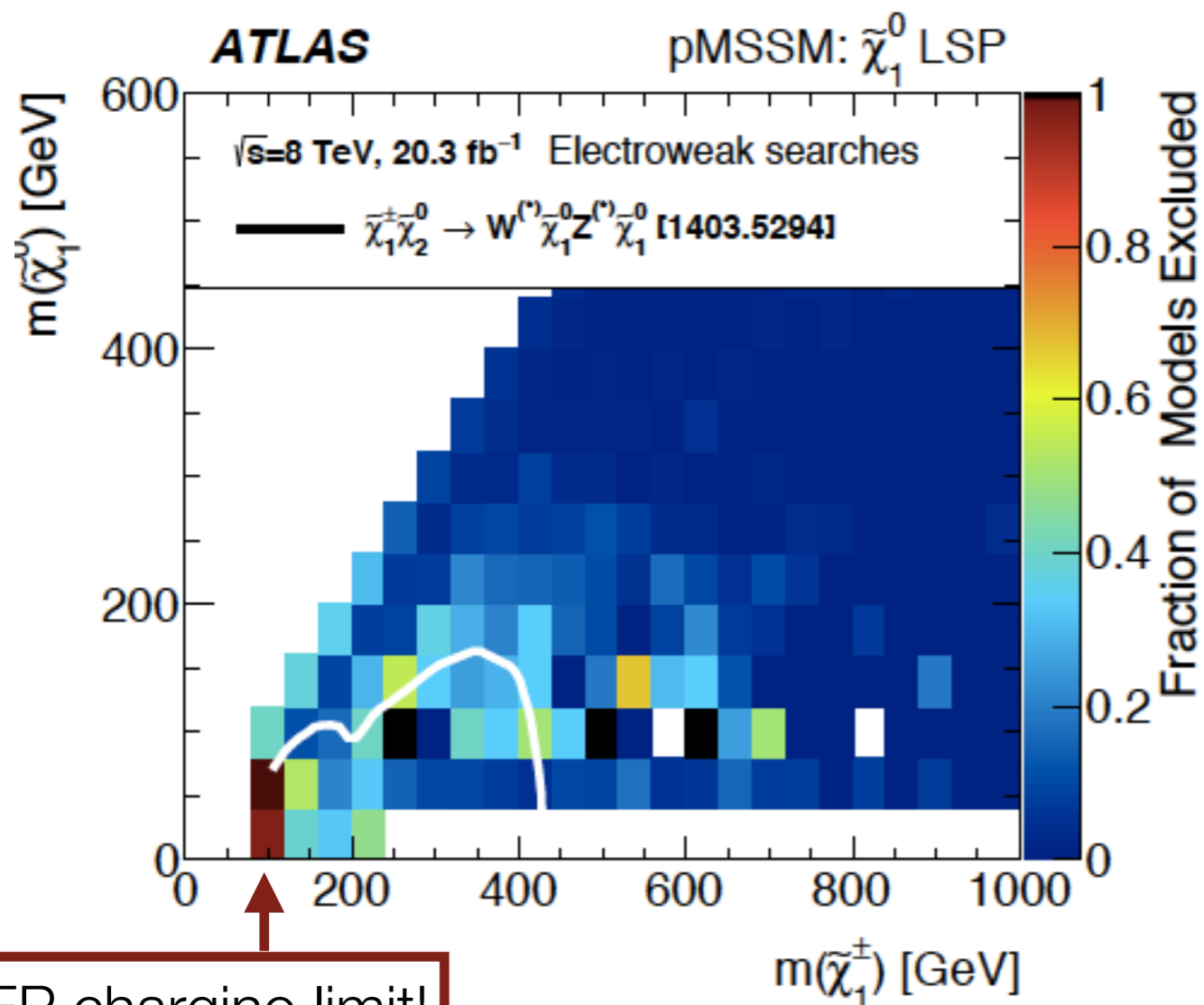


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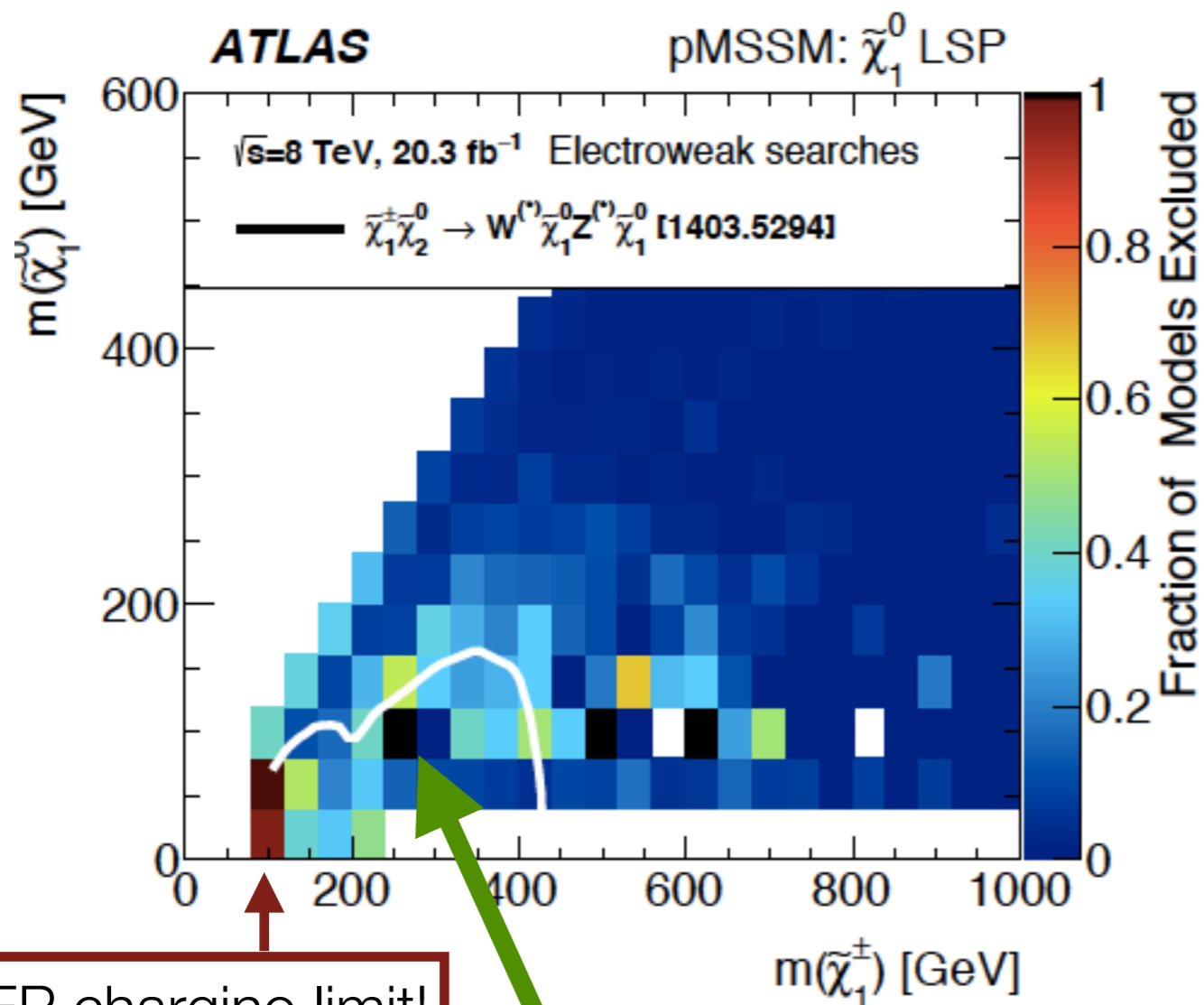


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LEP chargino limit!

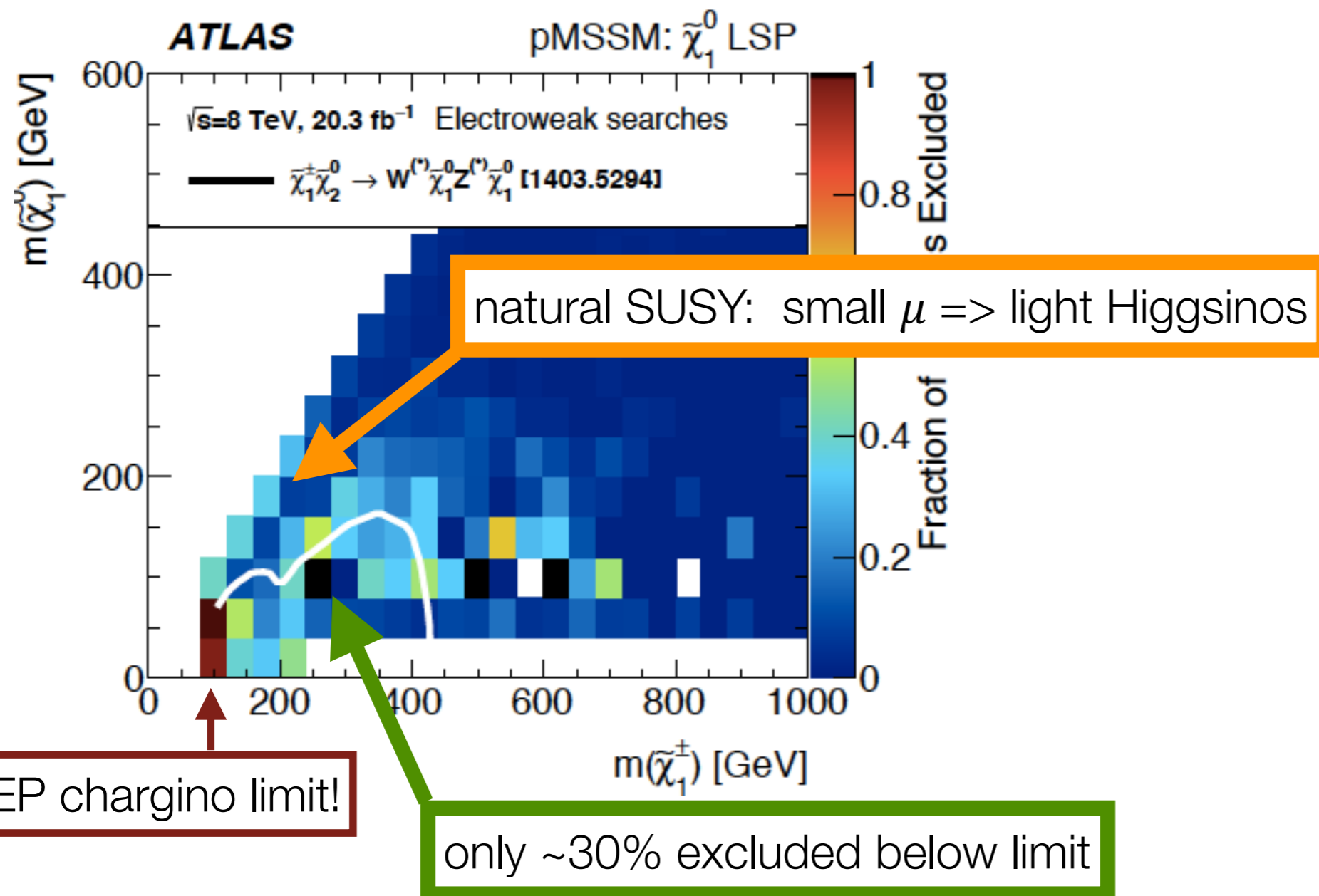
only ~30% excluded below limit

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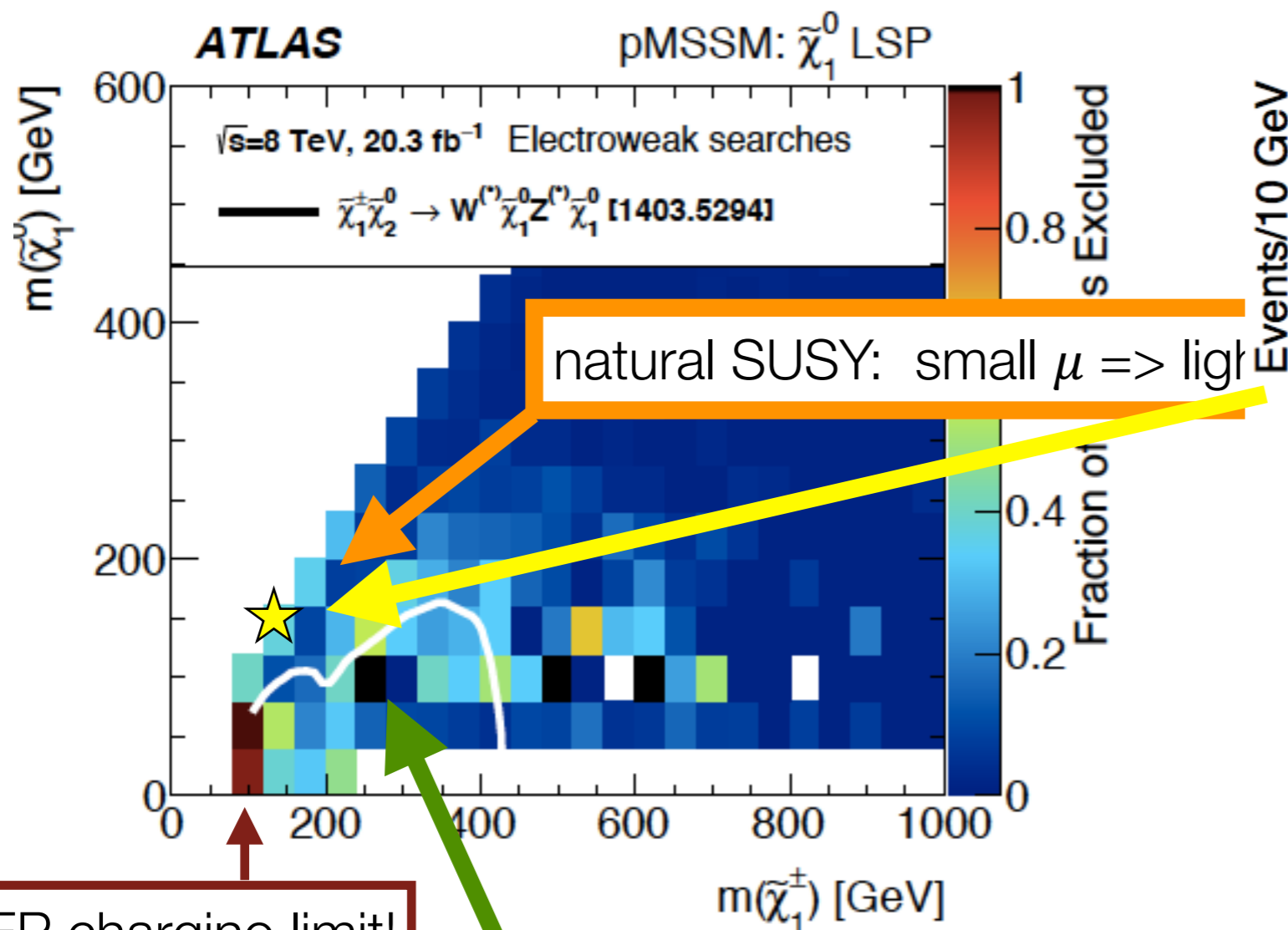


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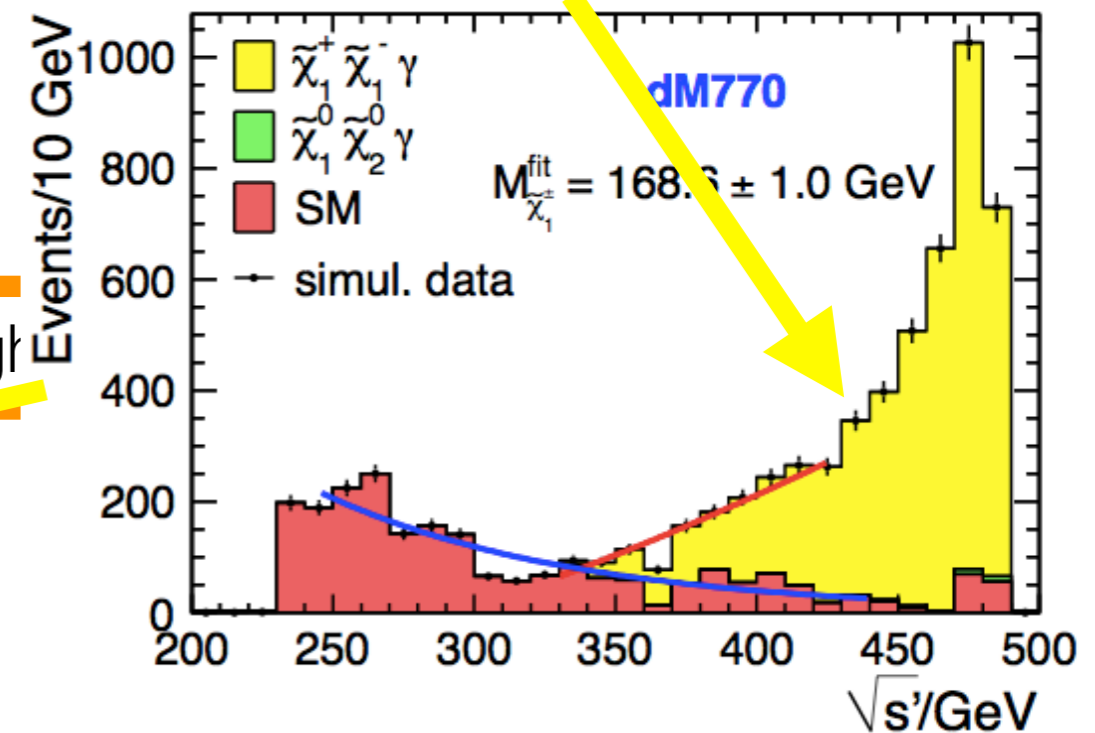
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Light Higgsinos at ILC



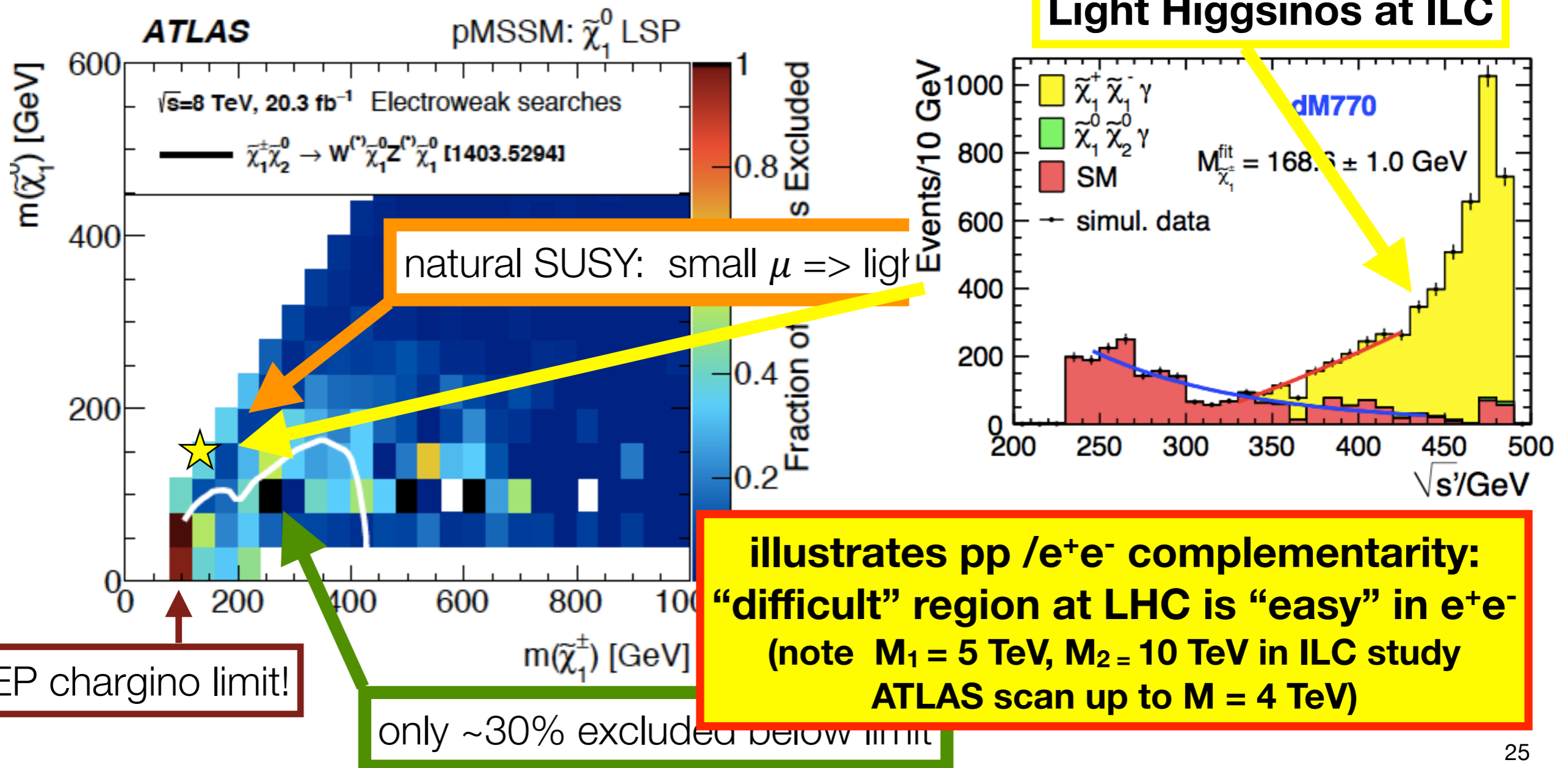
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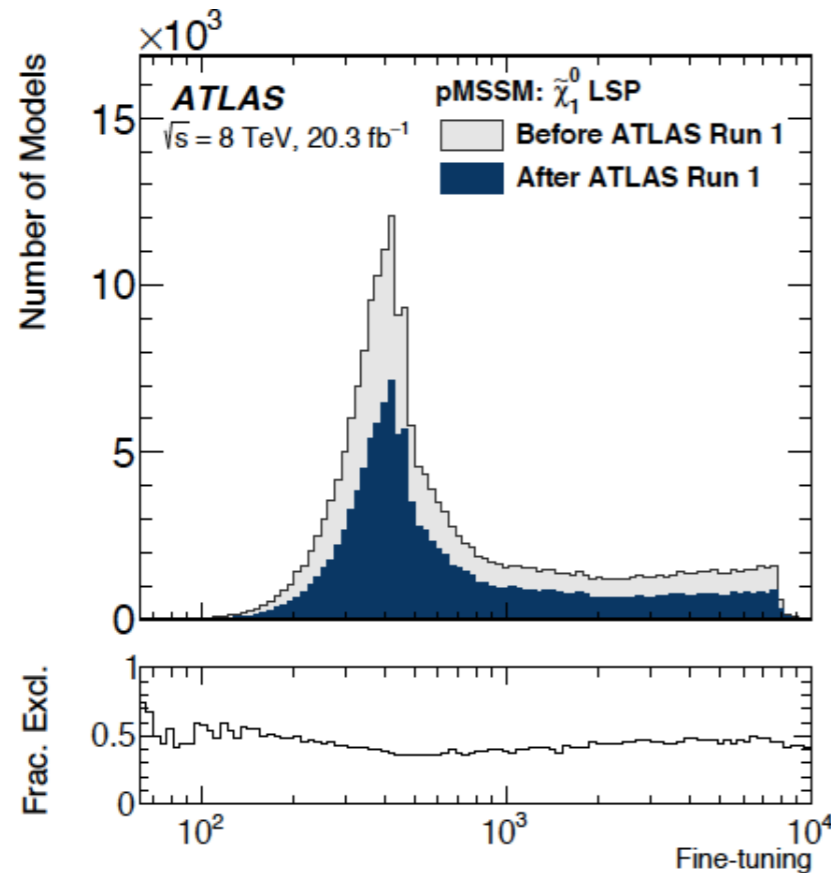
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Is SUSY still natural?

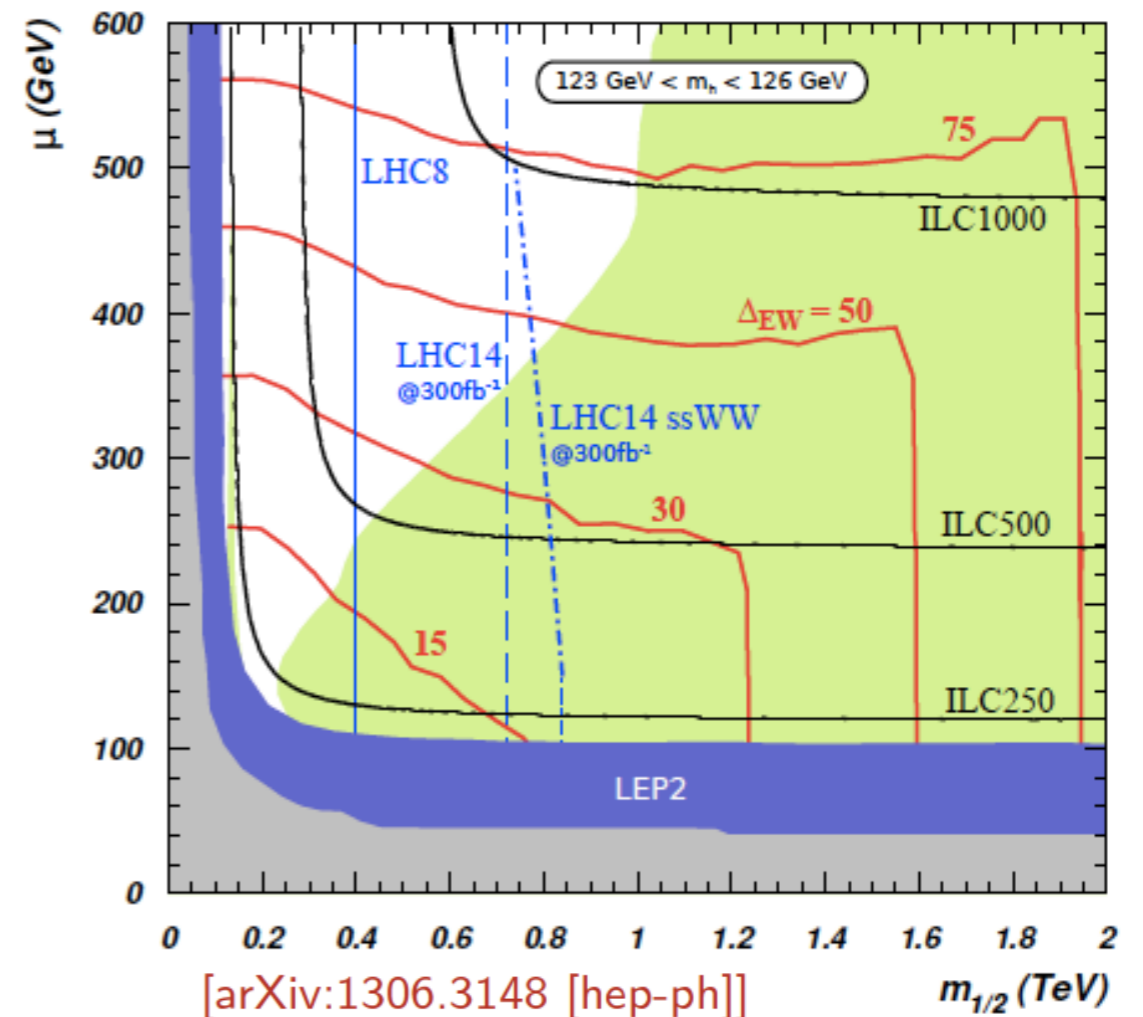


=> no dramatic change in level of fine-tuning due to ATLAS exclusions (Barbieri-Giudice measure)

e^+e^- colliders:

directly & unambiguously probe naturalness by discovery or exclusion of Higgsinos up to $\approx \sqrt{s} / 2$

NUHM2: $m_0=5 \text{ TeV}, \tan\beta=15, A_0=-1.6m_0, m_A=1 \text{ TeV}, m_t=173.2 \text{ GeV}$



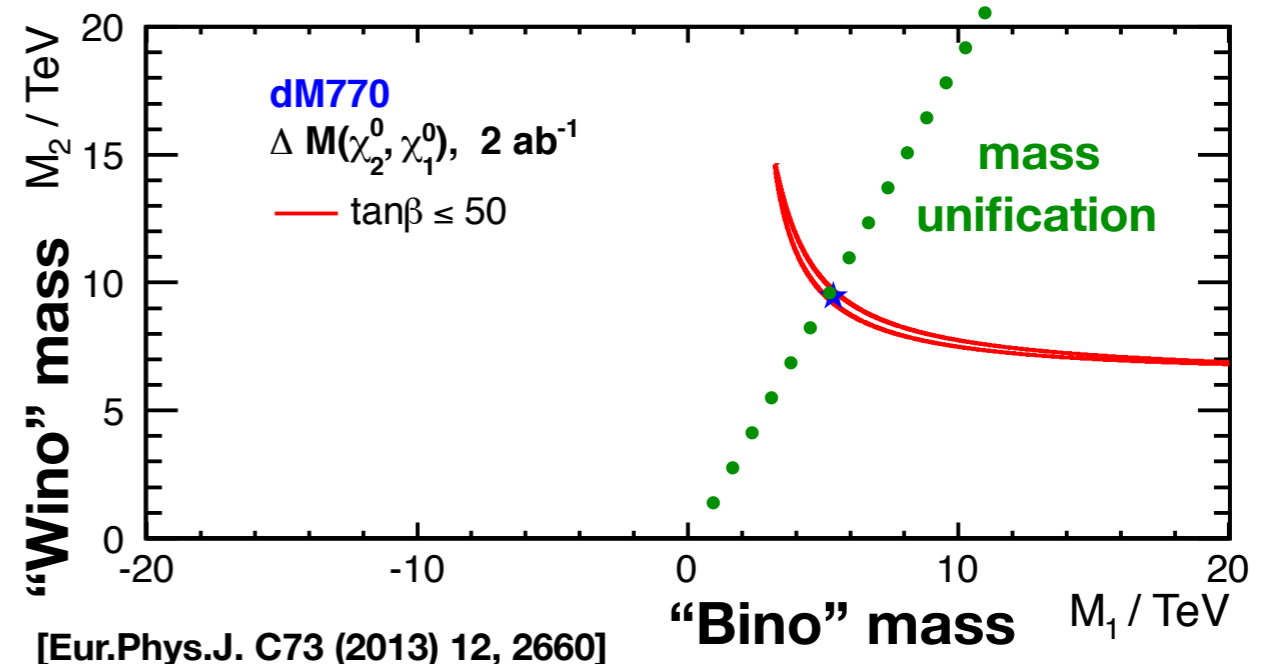
Probing the GUT scale with light Higgsinos

various benchmarks

- with $\Delta M = 0.77 \dots 20$ 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
 $\Rightarrow M_1, M_2, M_3, M_{\text{stop}}, M_A, \dots$
- test mass unification
- determine unification scale: GUT
scale? Or additional “mirage” scale?



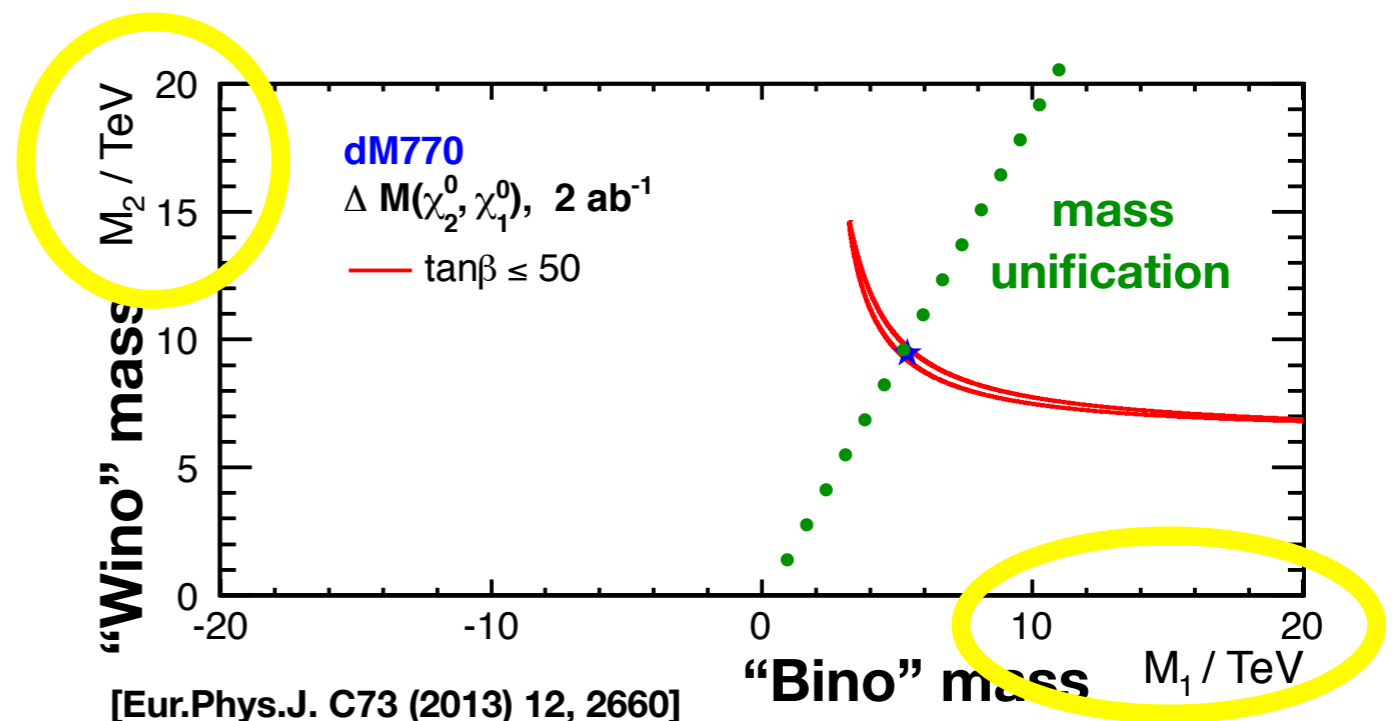
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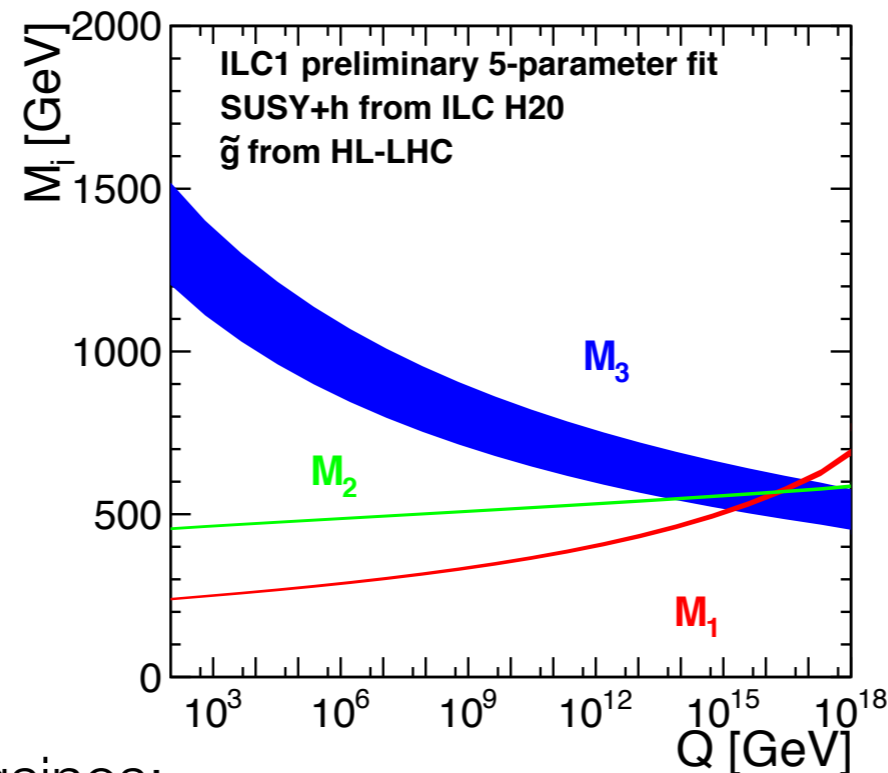
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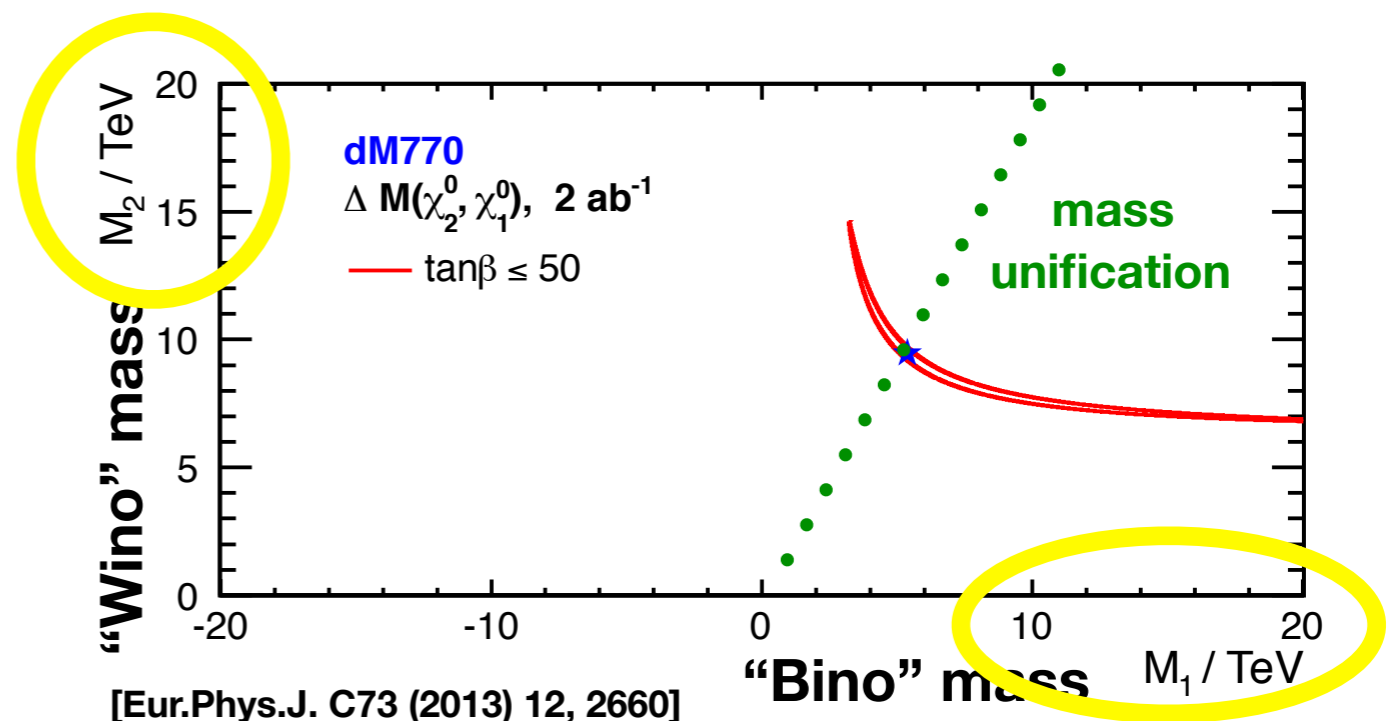
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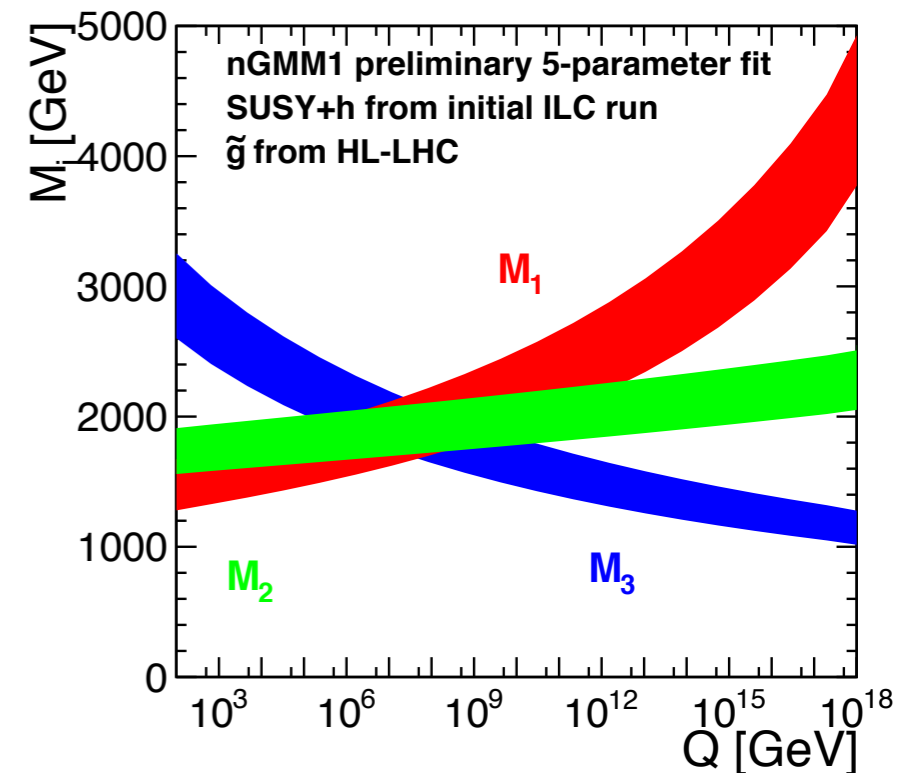
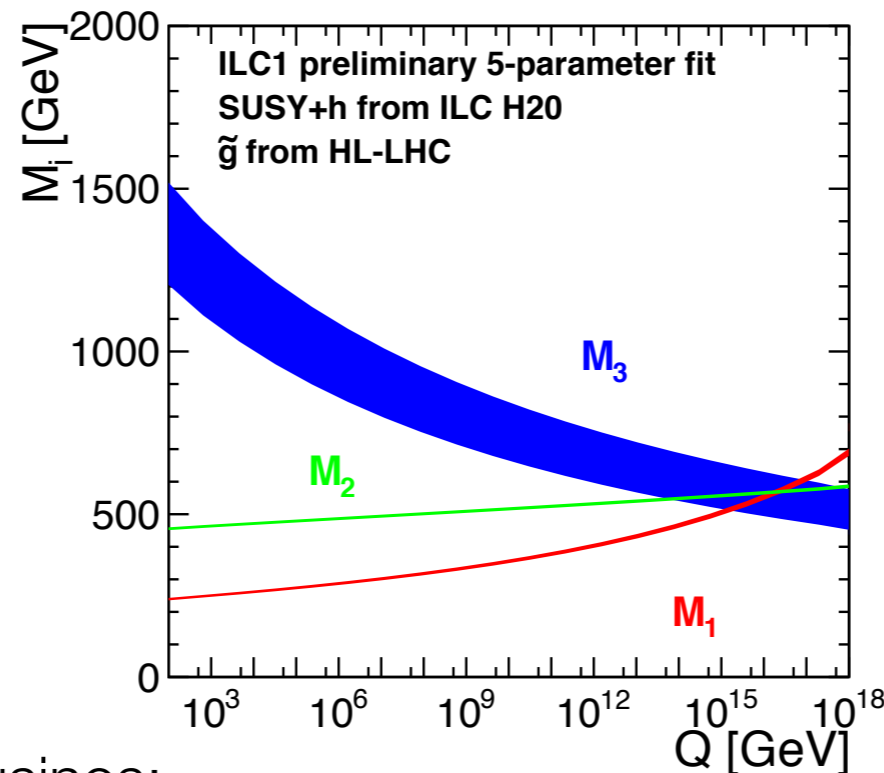
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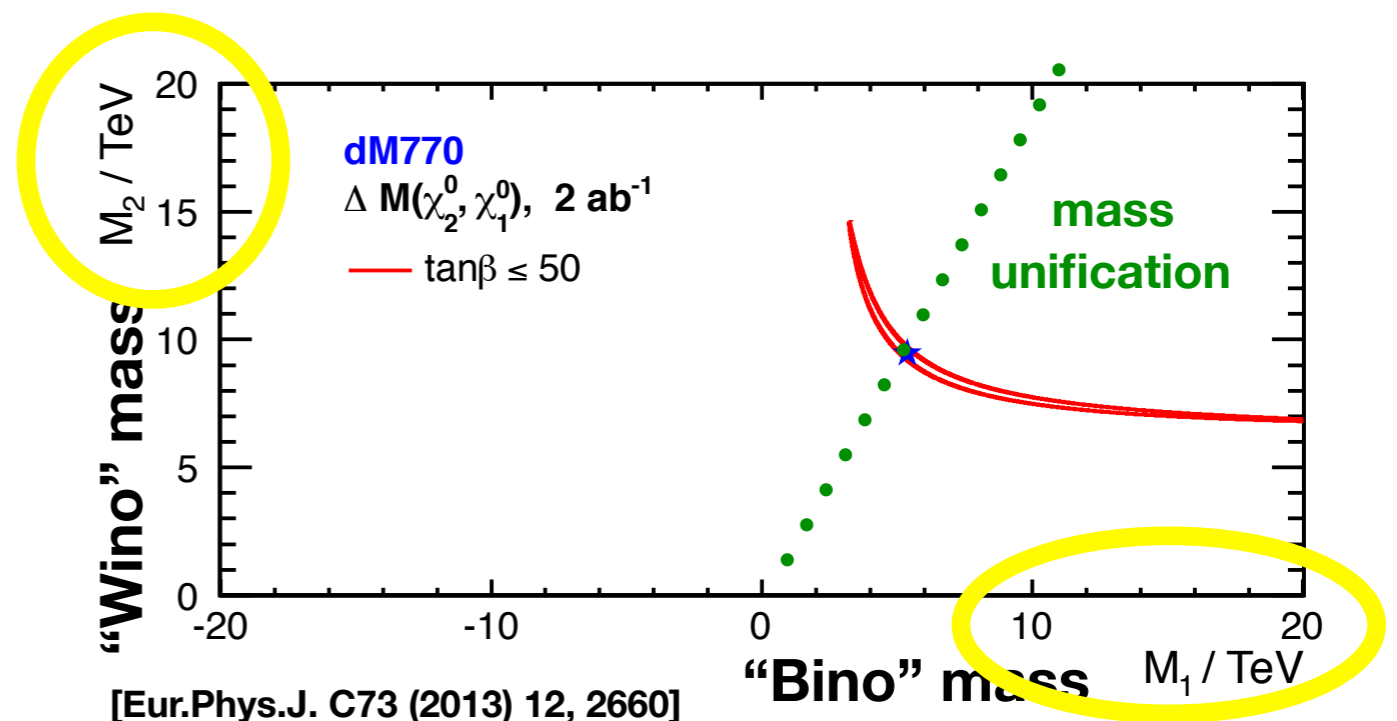
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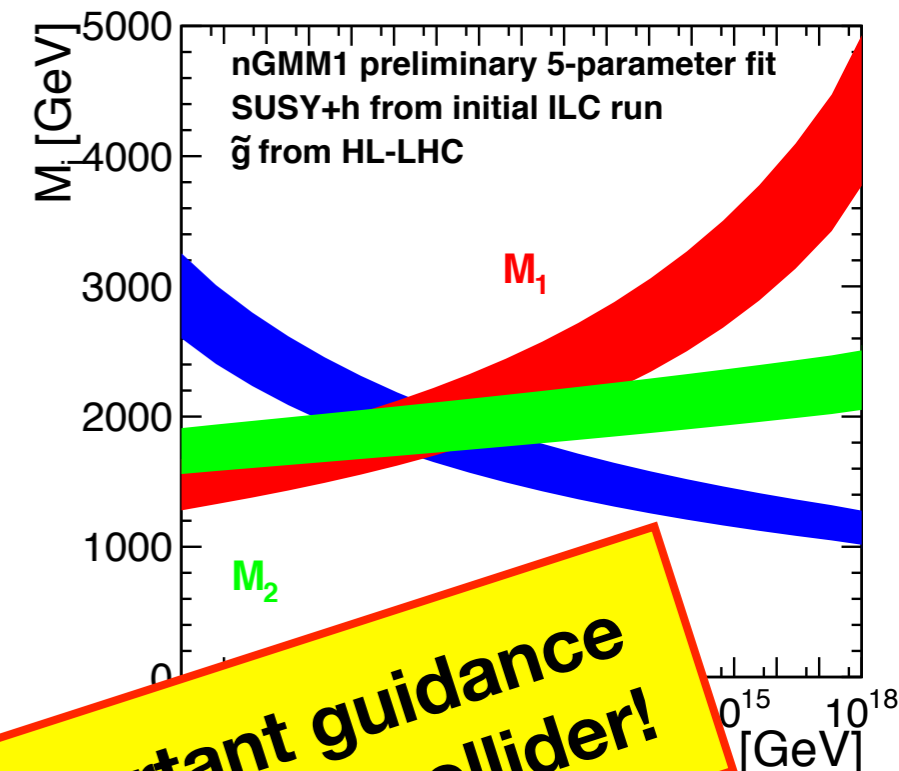
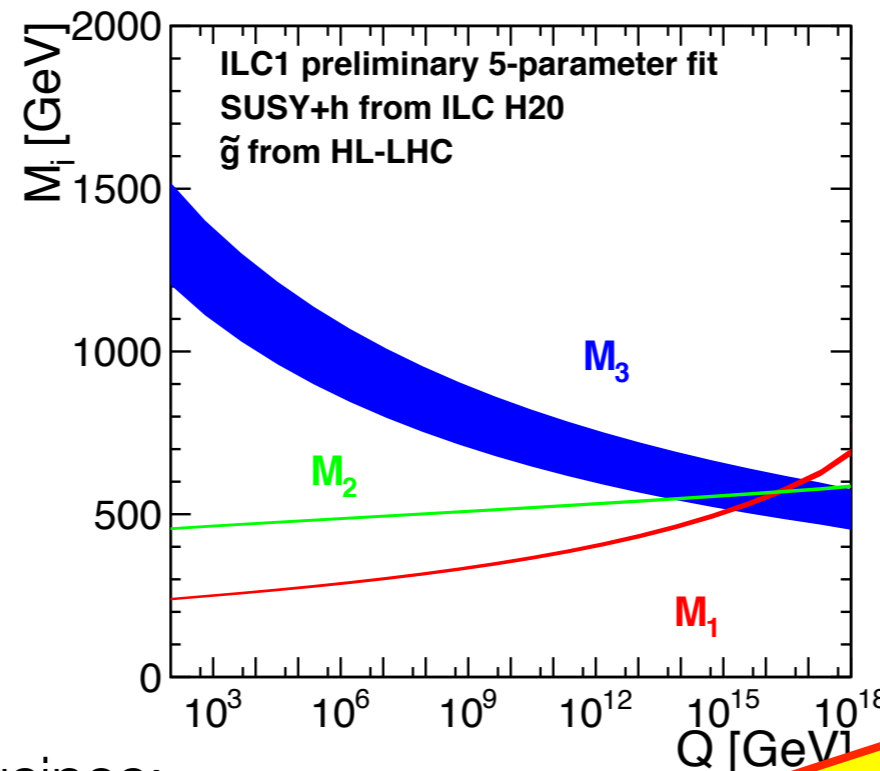
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\Rightarrow important guidance for 100 TeV pp collider!

