Naturalness and light higgsinos: a powerful reason to build ILC!

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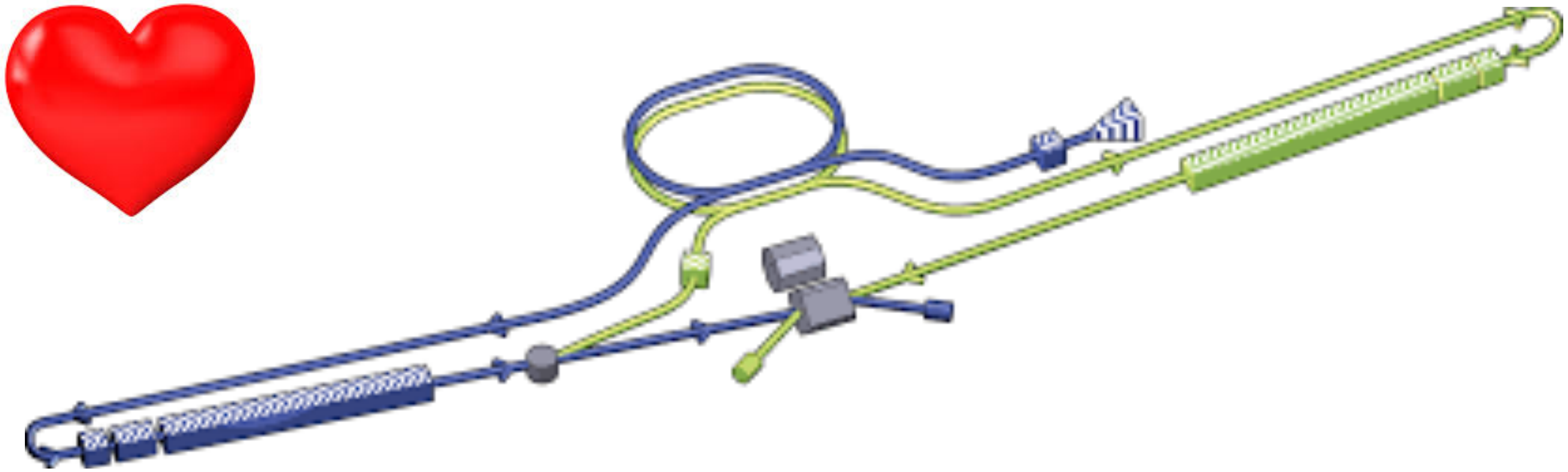
Jenny List (DESY)
with J. Yan (KEK), S.L. Lehtinen (DESY),
M. Berggren (DESY), K. Fujii (KEK) and
T. Tanabe (Tokyo)

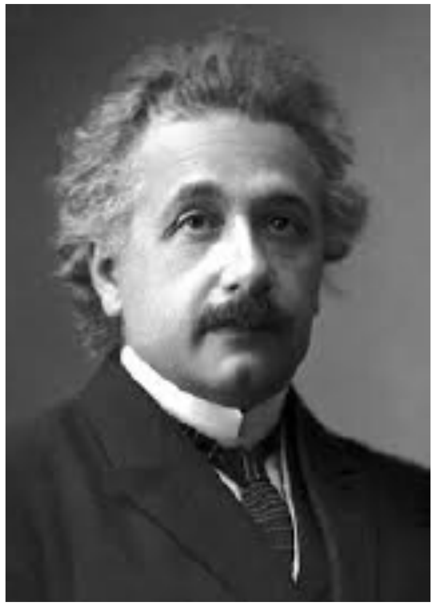
SUSY ❤



Motivation: simplicity and naturalness

``The appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained"

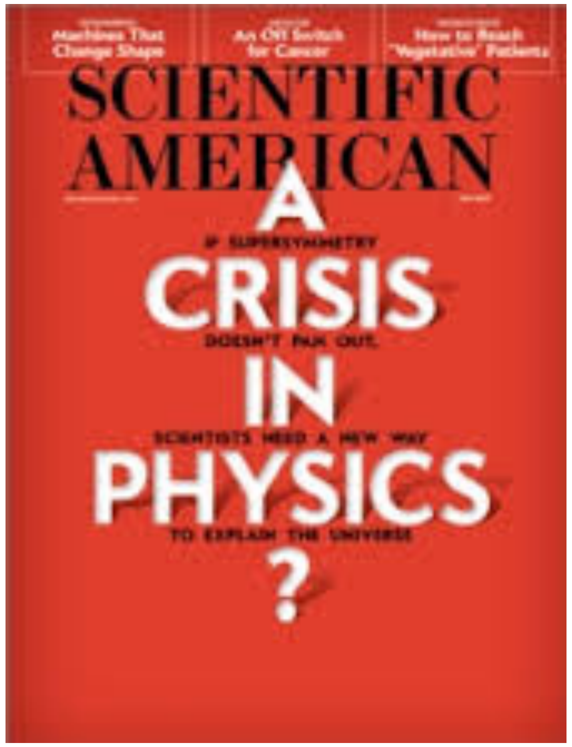
S. Weinberg



``Everything should be made as simple as possible, but not simpler"

A. Einstein

- The SM is *unnatural* beyond a scale $\Lambda \sim 1$ TEV due to well-known quadratic divergences in scalar sector
- simple extension to include larger spacetime symmetry (SUSY) renders SM natural: $\Rightarrow MSSM$!
- other attempts to gain naturalness typically involve baroque constructions- hard to believe nature follows those routes
- But: LHC hasn't found SUSY and Higgs mass $m_h(125)$ seems heavy:
- Is SUSY also unnatural? Little Hierarchy problem: $m(SUSY) \gg m_Z$



Machines That Change Shape

An Off Switch for Cancer

How to Reach "Vegetative" Patients

SCIENTIFIC AMERICAN

A CRISIS IN PHYSICS ?

IF SUPERSYMMETRY DOESN'T PAN OUT, SCIENTISTS NEED A NEW WAY TO EXPLAIN THE UNIVERSE

In the past several years, the notion of electroweak naturalness in SUSY has been clarified:

Most direct expression within MSSM:
minimize scalar potential to determine VeVs:
relate measured value of m(Z) to SUSY Lagrangian

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

weak scale soft term:

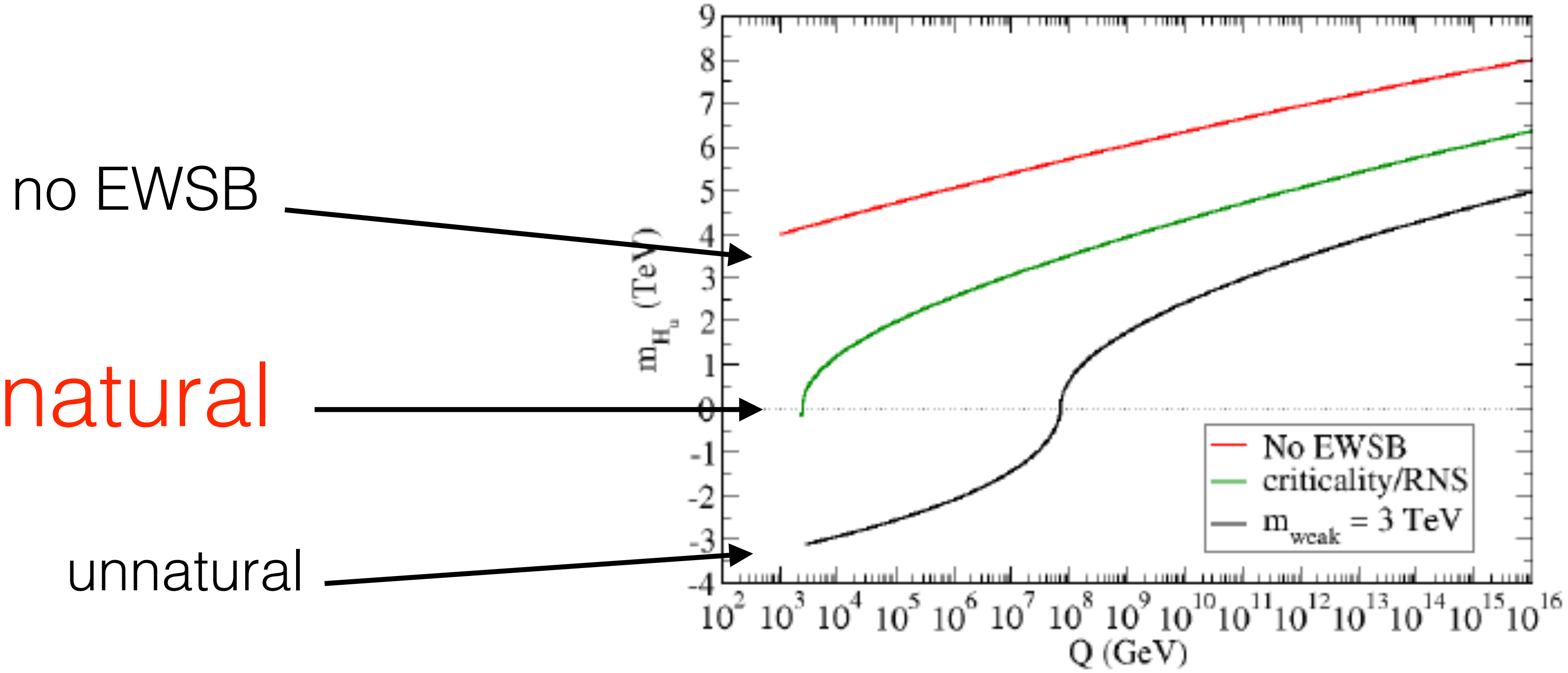
radiative corrections: biggest from t1,t2

SUSY conserving mu term

no large unnatural cancellations:
all terms on RHS are <~100-200 GeV

$$\Delta_{\rm EW} \equiv {\rm max}|{\rm each\ additive\ term\ on\ RHS}|/(m_Z^2/2)$$

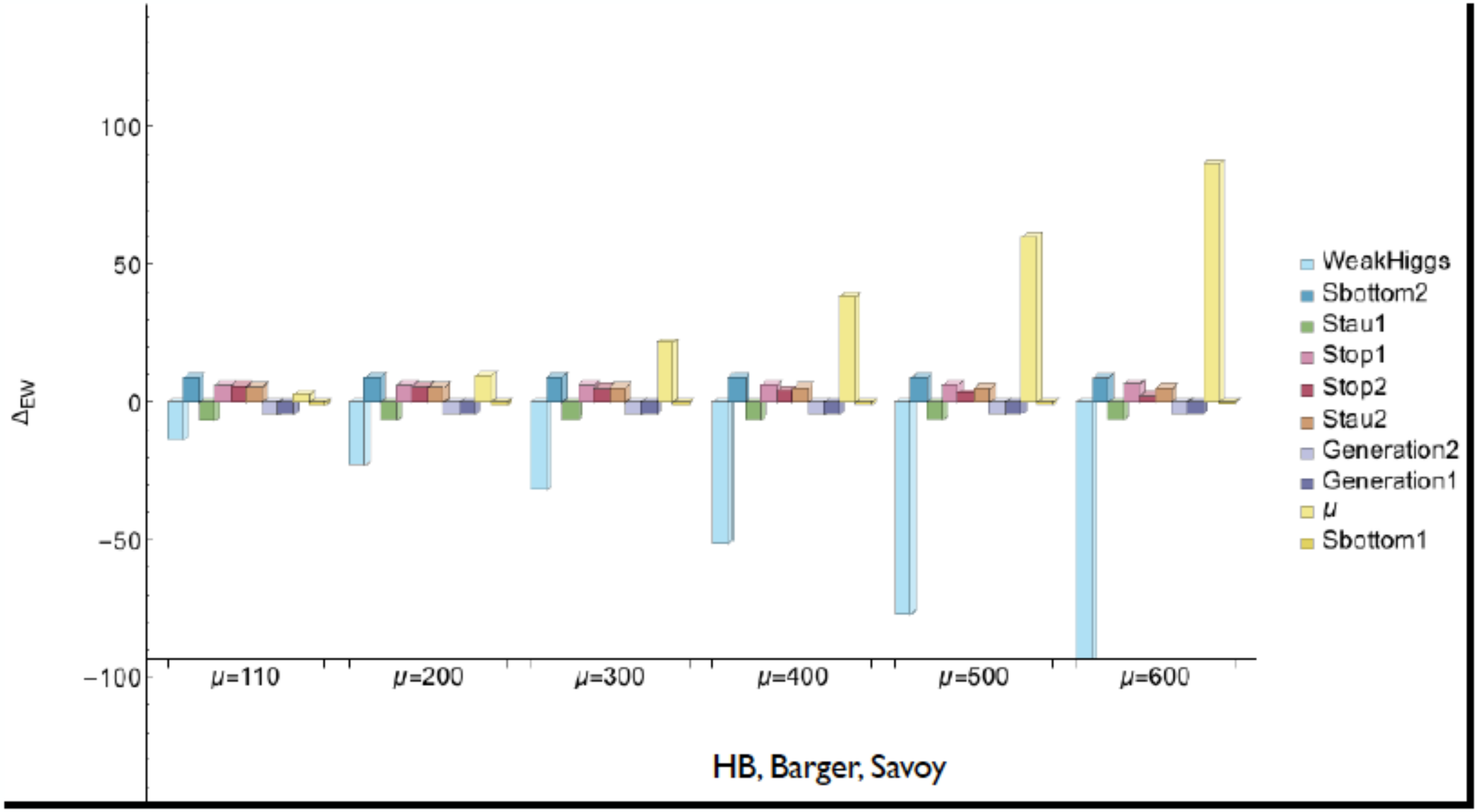
m_{H_u} : may be large ($\sim m_{3/2} \sim$ multi-TeV) at GUT scale but driven to natural values by radiative corrections at weak scale:
radiatively-driven naturalness) or RNS



$\Sigma_u^u(\tilde{t}_{1,2})$: small for TeV-scale highly mixed stops;
$m_{\tilde{g}} <\sim 4$ TeV ($\tilde{g}$ beyond LHC reach?)

SUSY μ term: feeds mass to W, Z, h and higgsinos:
higgsinos $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_{1,2}^0 \sim 100 - 200$ GeV!
soft decay products (due to small mass gaps) hard to see at LHC
but easy to see at ILC with $\sqrt{s} > 2m(higgsino)$

How much is too much fine-tuning?



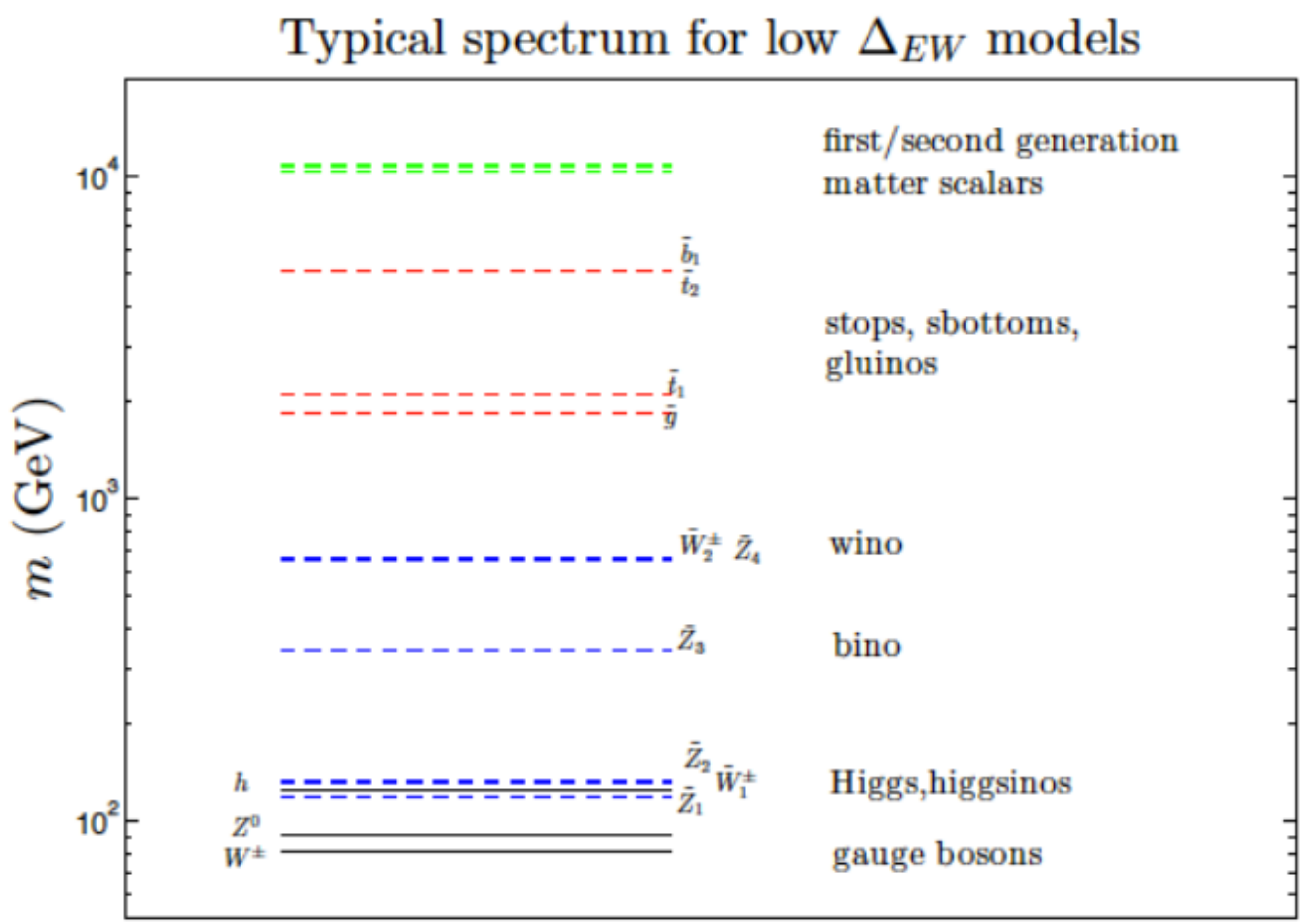
Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

higgsinos should be accessible to ILC!

Crisis averted:

* naturalness: only higgsinos need lie near ~100 GeV scale

stops, gluinos can safely lie ~1-4 TeV scale
at little cost to naturalness:
contributions suppressed by loop factors

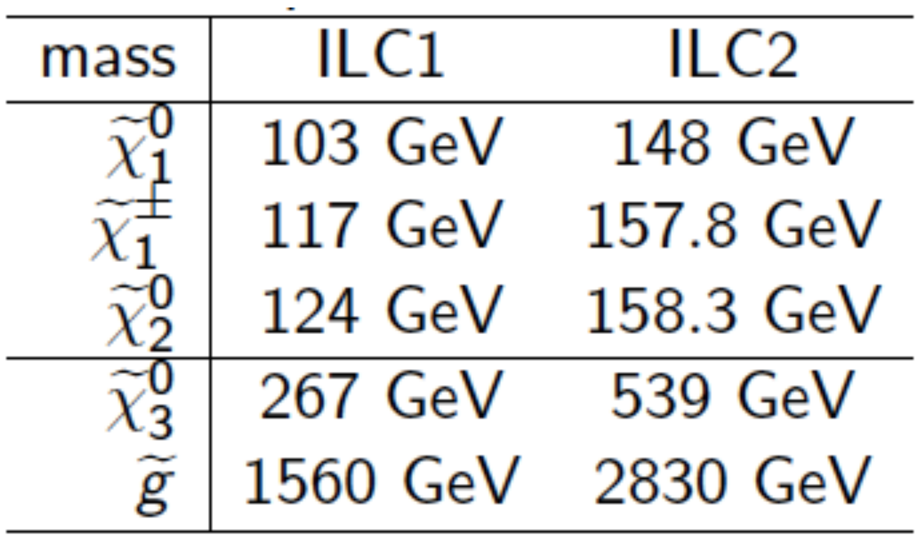


There is a Little Hierarchy, but it is no problem

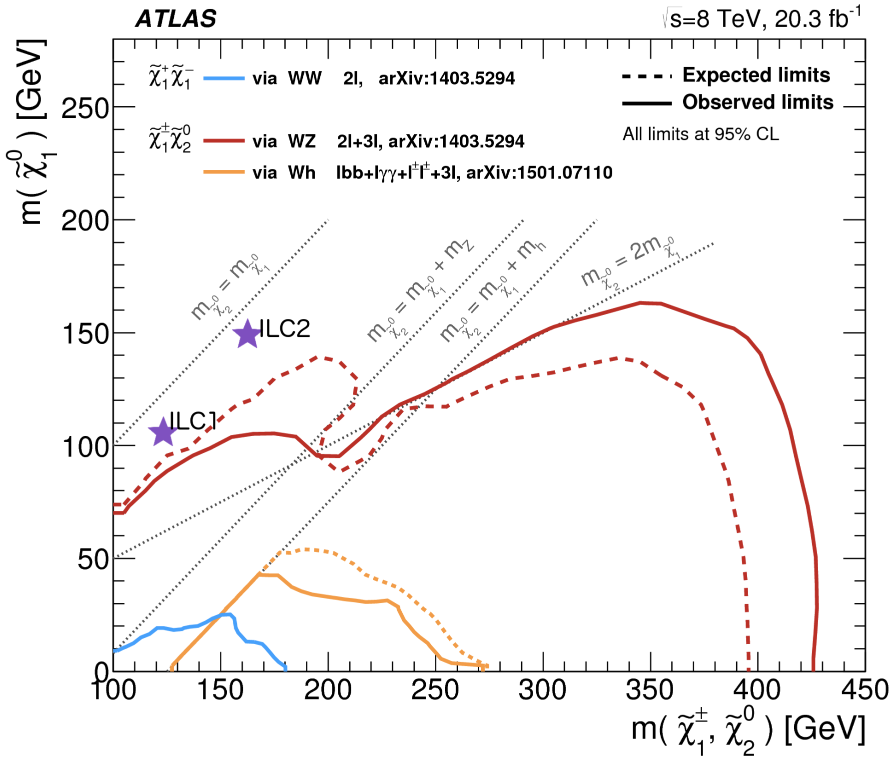
$$\mu \ll m_{3/2}$$

Natural SUSY Prospects at the ILC

- studied two benchmark scenarios



mass	ILC1	ILC2
$\tilde{\chi}_1^0$	103 GeV	148 GeV
$\tilde{\chi}_1^\pm$	117 GeV	157.8 GeV
$\tilde{\chi}_2^0$	124 GeV	158.3 GeV
$\tilde{\chi}_3^0$	267 GeV	539 GeV
$\tilde{g}$	1560 GeV	2830 GeV



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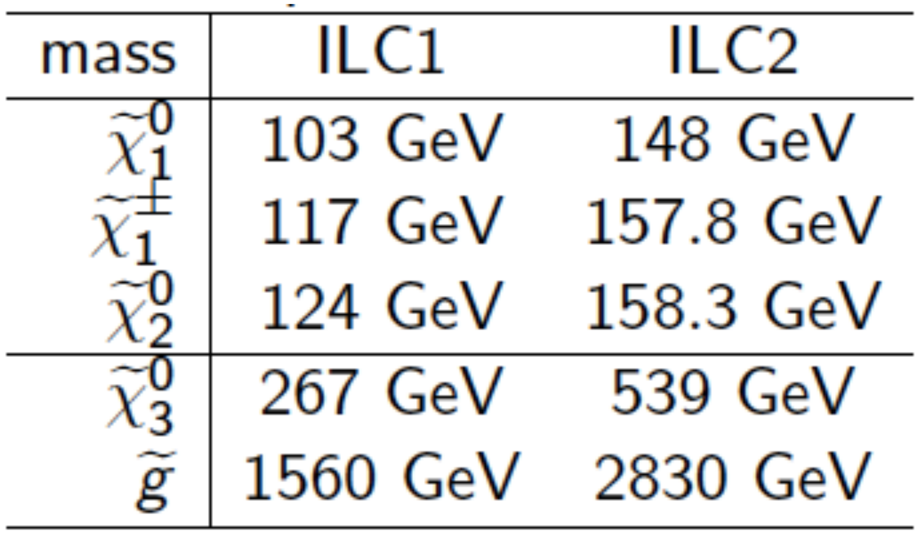

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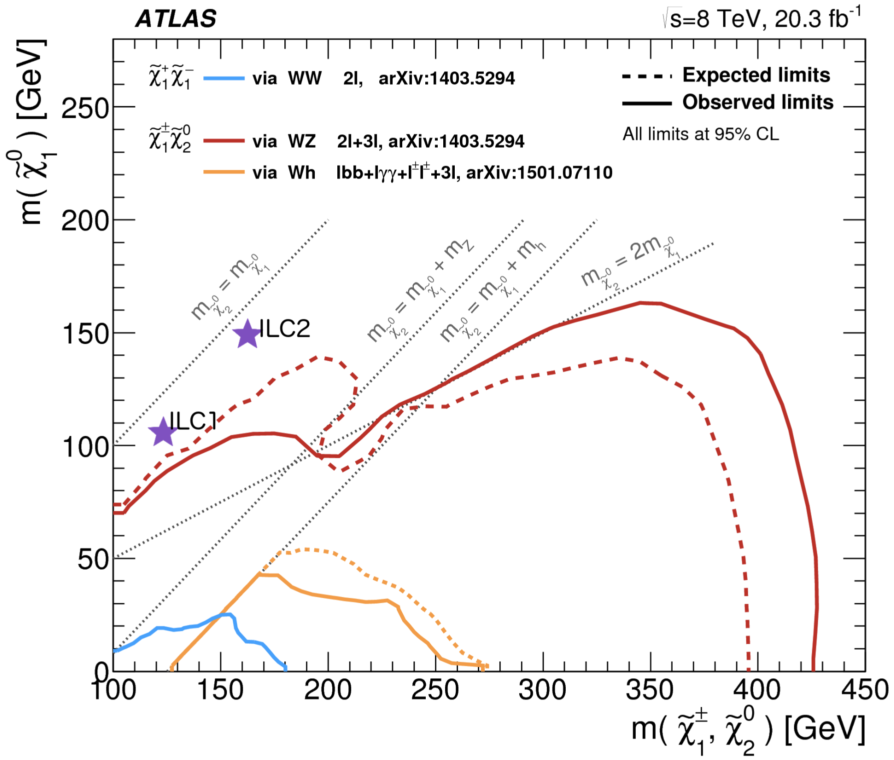

- $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ cross sections ~ few 100 fb
- mass gaps ~ 10…20 GeV
  - decay via virtual W*/Z*, e.g. $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0 e\nu_e$
  - visible decay products soft, small missing momentum
- other sparticles heavy

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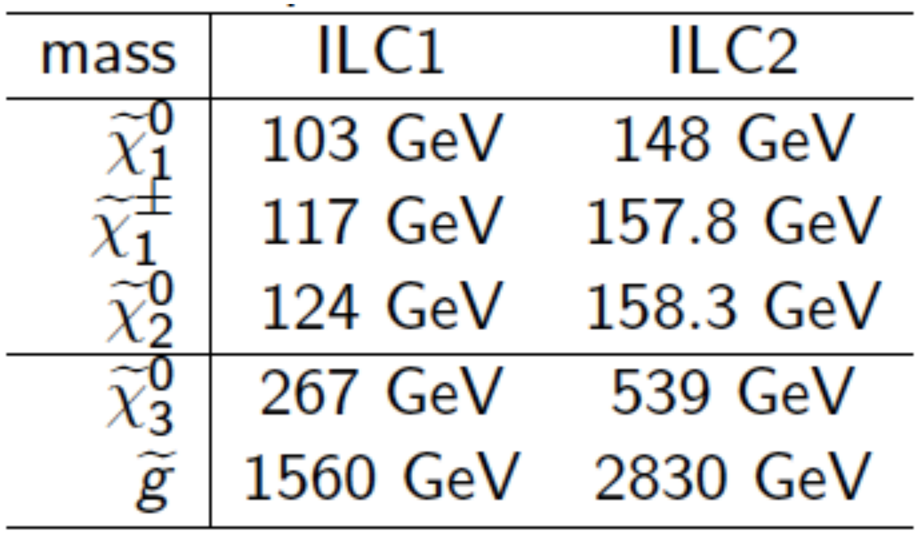

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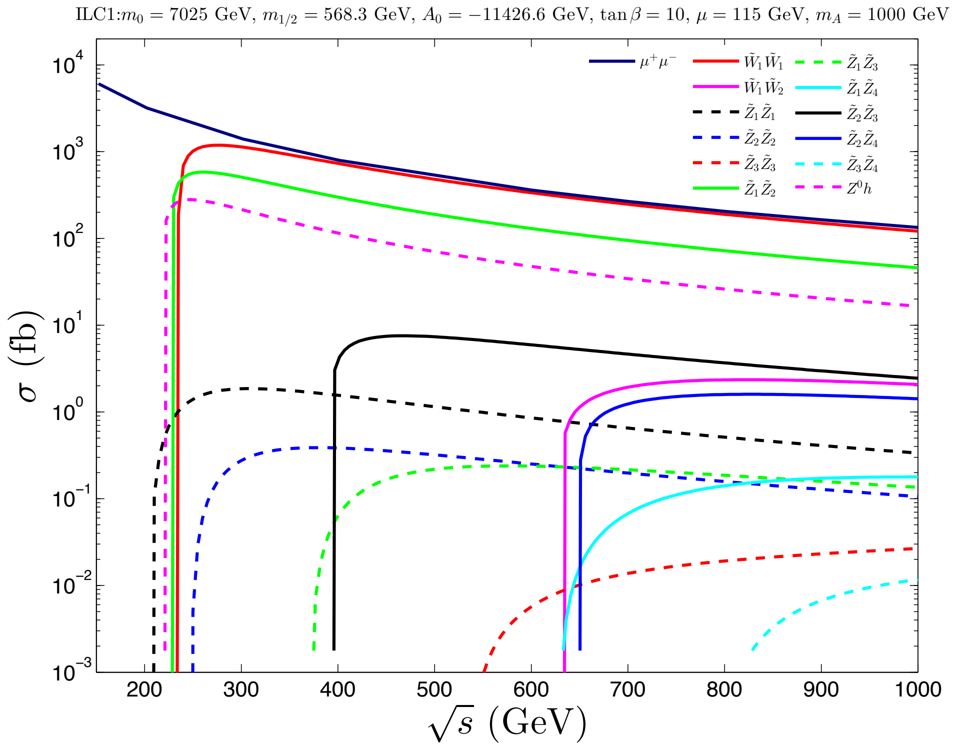

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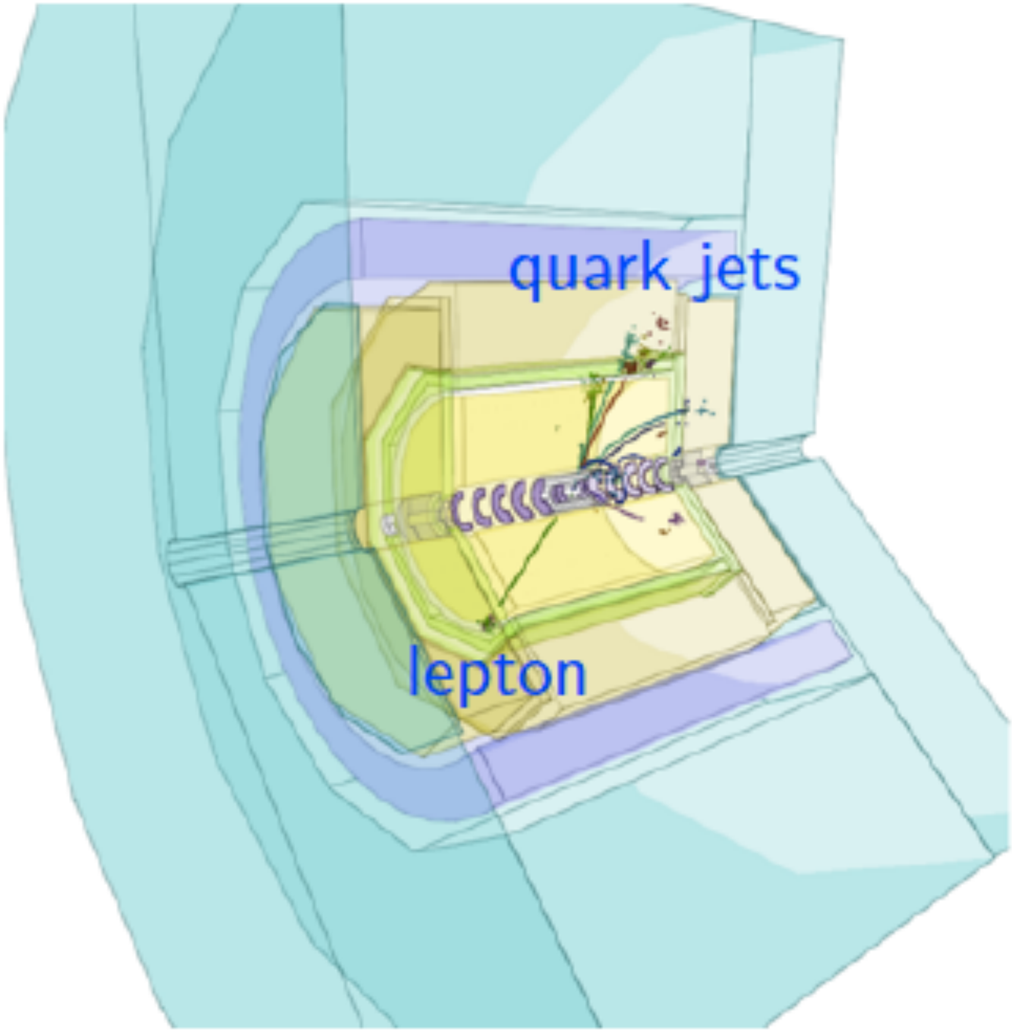
ILD Simulation Study

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0 e\nu_e$

in the International Large Detector



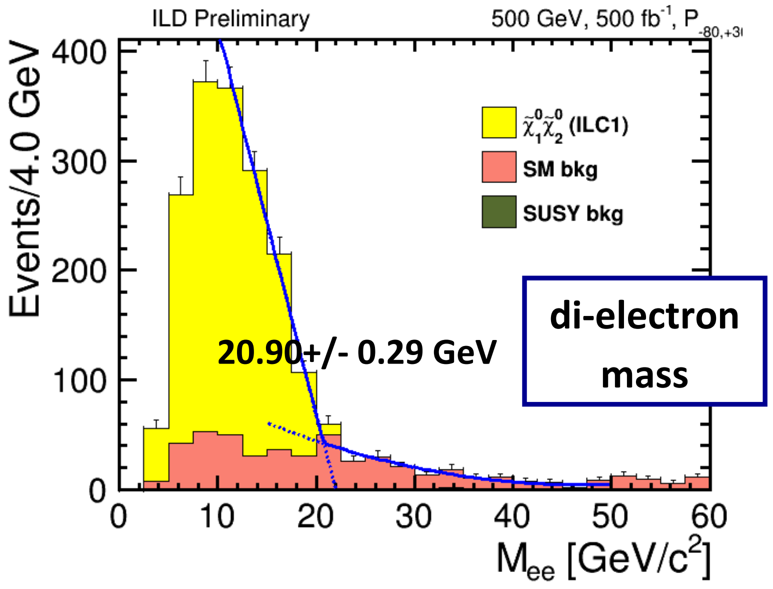
Soft tracks - no problem for ILC

- Event generation by **`Whizard 1.95`** & **`Pythia 6.422`** (hadronisation tuned to LEP)
- Detailed **`Geant4`**-based ILD simulation and reconstruction (**`Mokka`** & **`Marlin`**)
- Beam energy spectrum and ISR included
- Studied so far:
  - $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-(\mu^+\mu^-)$

    $e^+e^- \to \tilde{\chi}_1^-\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0 e\nu_e(\mu\nu_\mu)$

Mass and Cross Section Measurement

- **masses:**
    - maximum invariant mass of W*/Z* gives mass splitting
    - then maximum energy of W*/Z* gives absolute masses since initial state is known!
    - **preliminary precision for 500/fb @ GeV: δm/m ≈1%**
- **cross sections:**
    - fit overall shape to “count” events
    - **preliminary precision for 500/fb @ GeV: δσ/σ ≈ 3% (for P(e-,e+)=(±80%,∓30%)**
    - polarisation dependence reveals higgsino nature!



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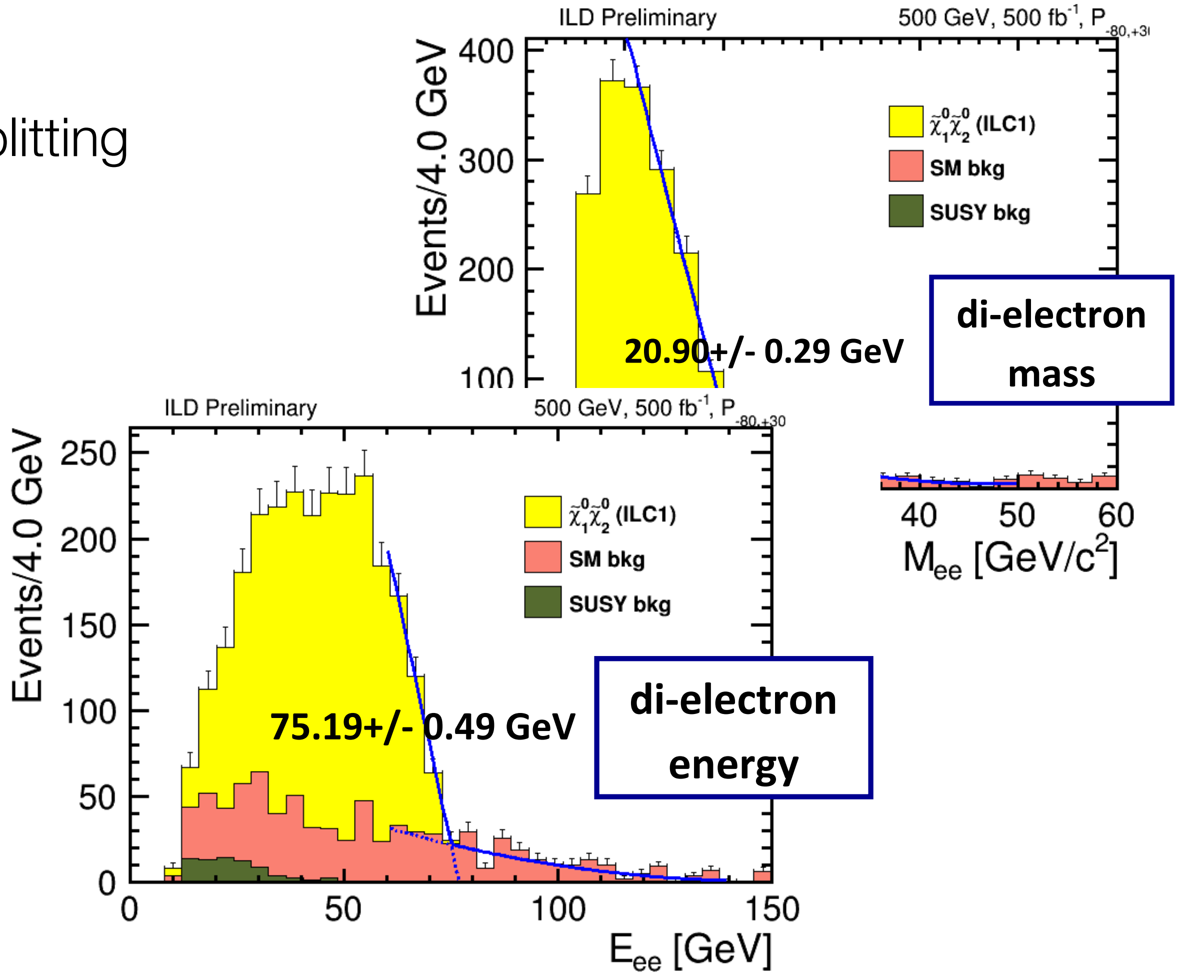

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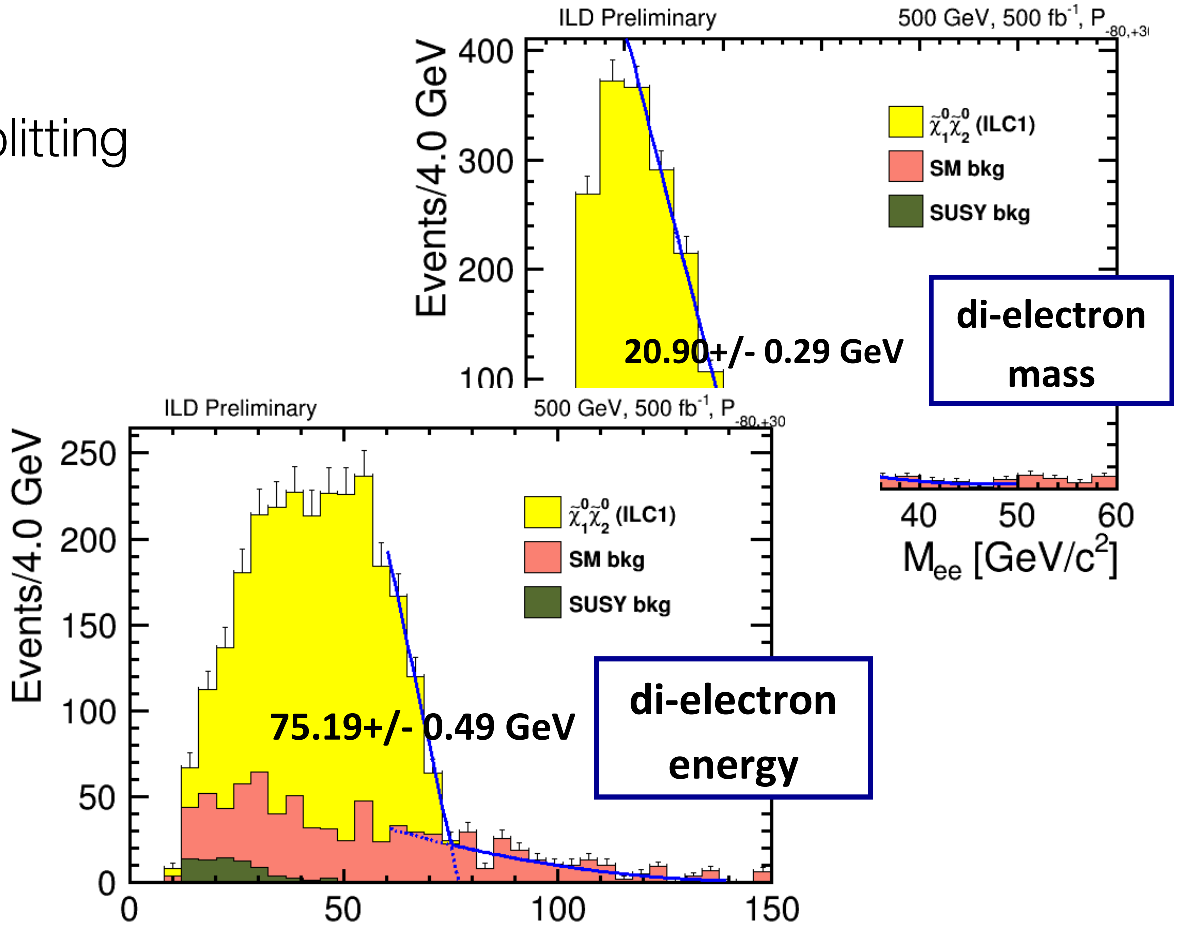
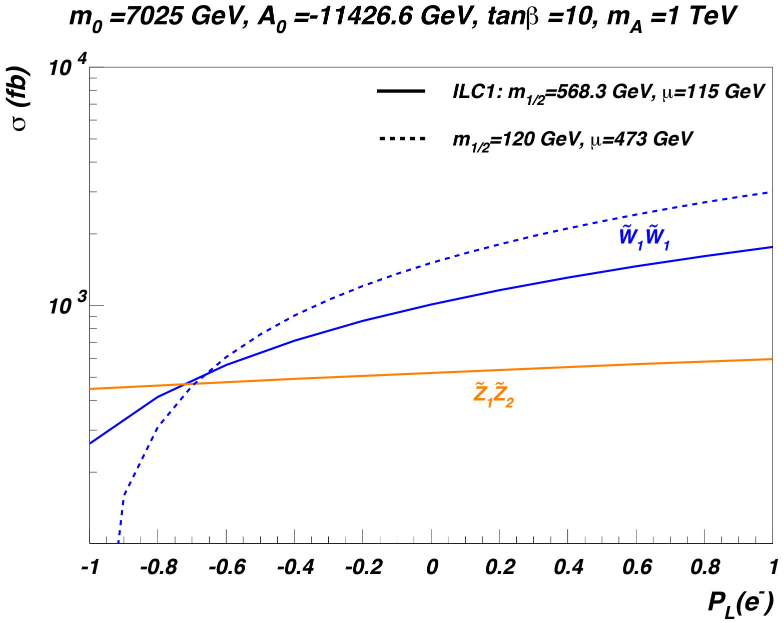
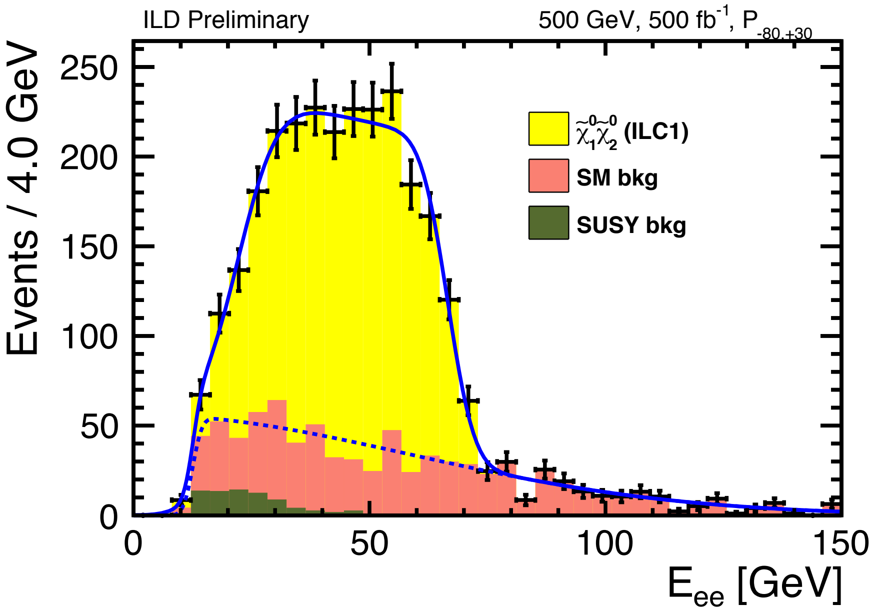


di-electron mass

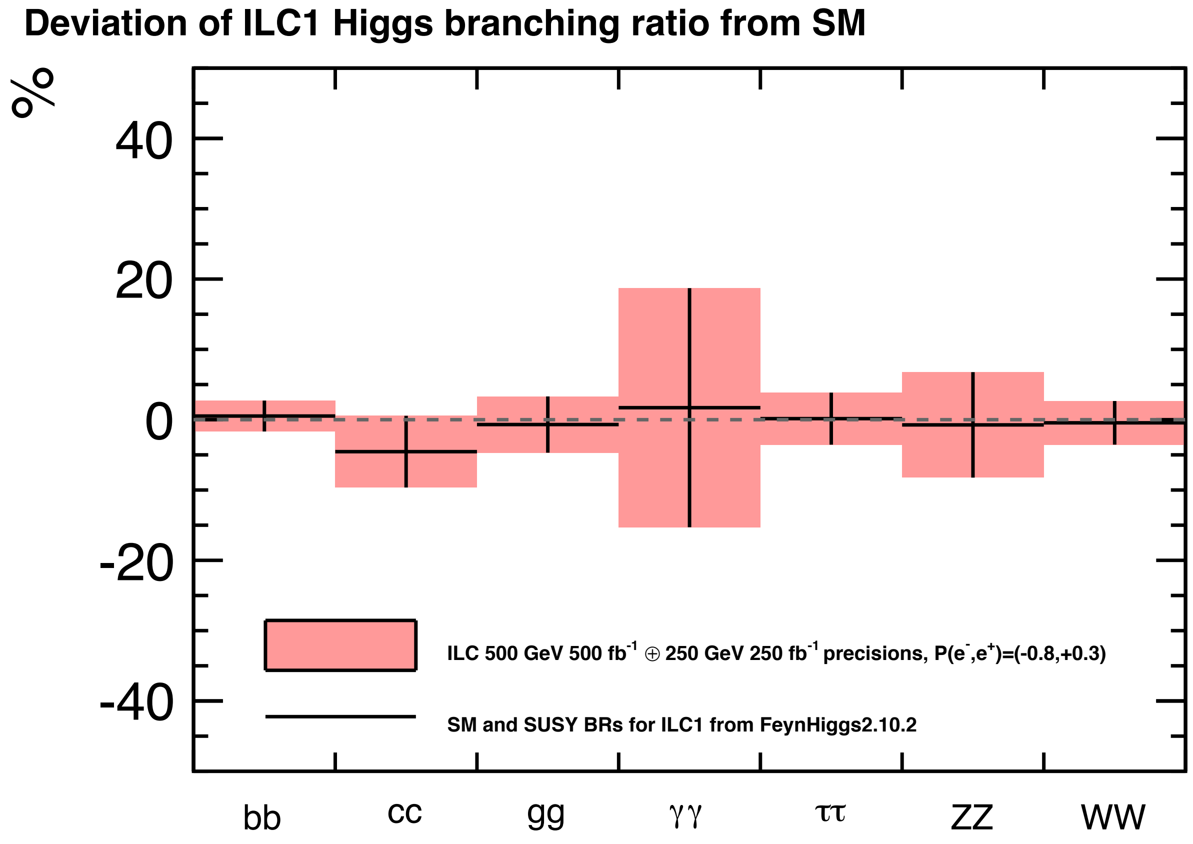
di-electron energy



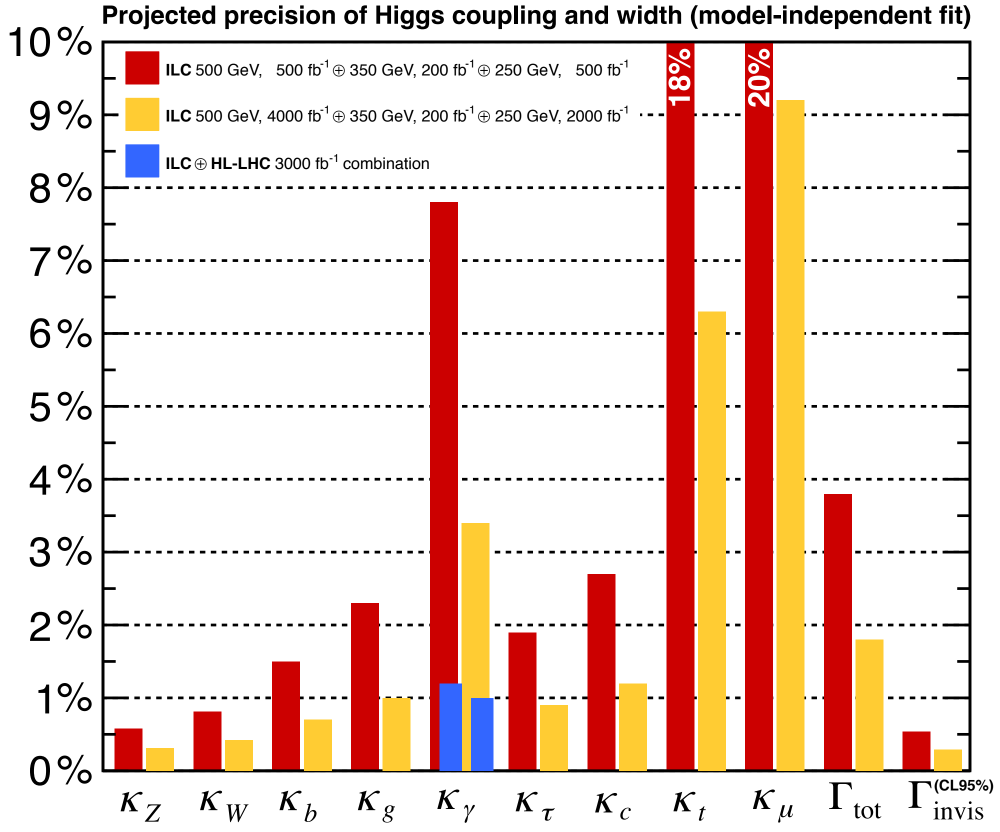


And the Higgs boson?

- only light higgsinos => H(125) SM-like:



ILC model-independent Higgs coupling determination [arXiv:1506.05992]



- here only conservative precisions corresponding to initial ILC dataset (red bars)

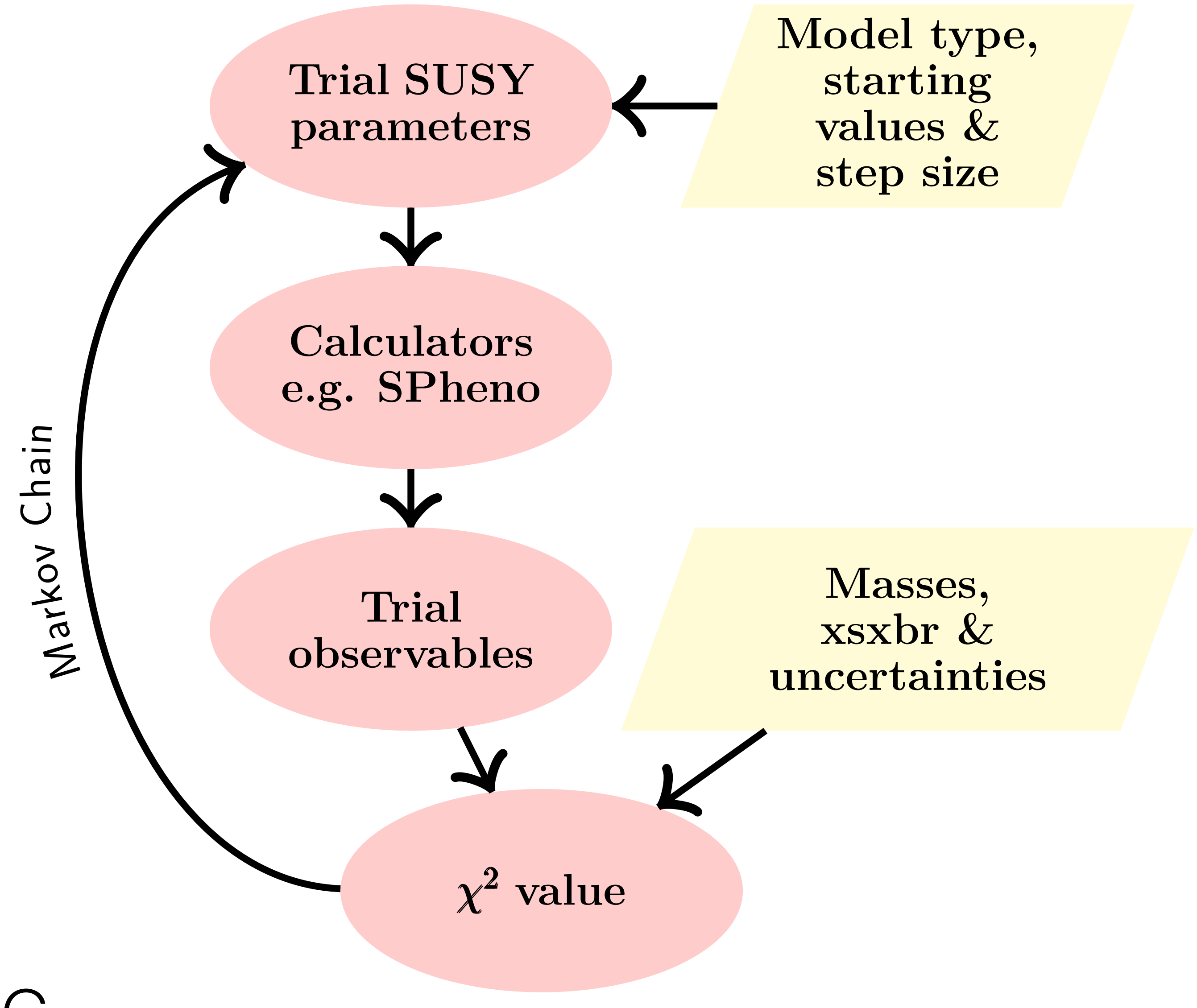
Parameter Determination with Fittino [arXiv:hep-ph/0412012]

calculators:

- SUSY spectrum:
  SPheno 3.3.9beta
- Higgs properties:
  FeynHiggs 2.10.2

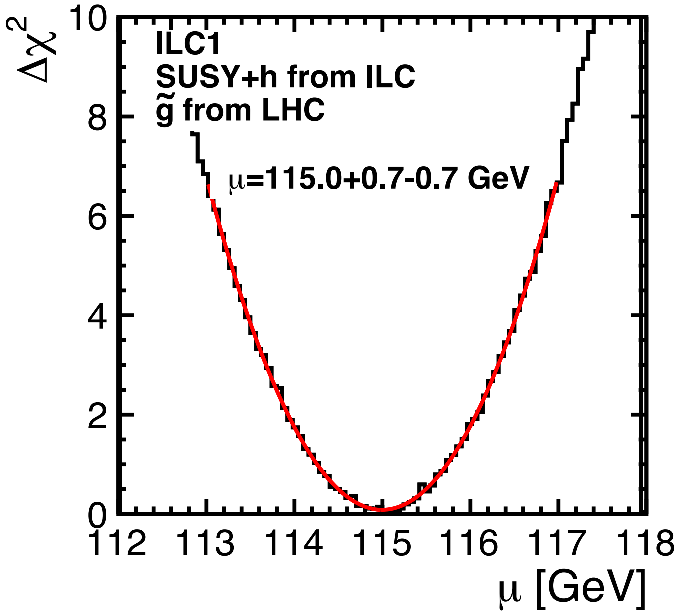
experimental inputs:

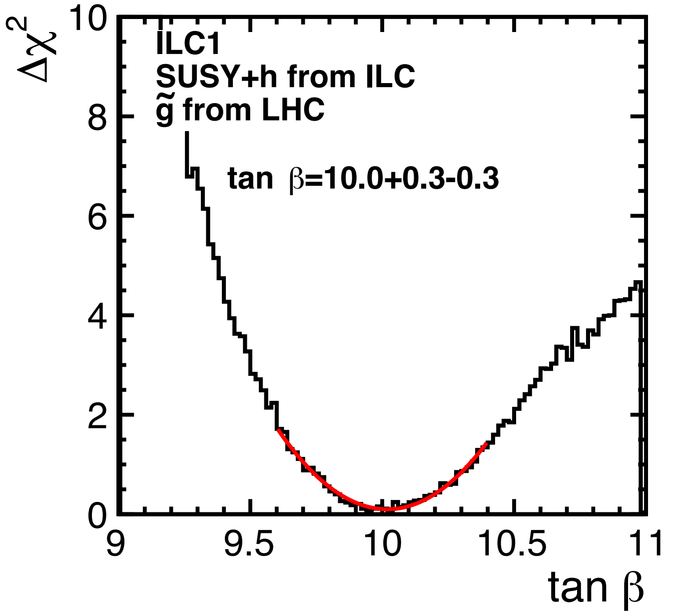
- δm(higgsinos) = 1%
- δσ(higgsinos) = 3%
- Higgs mass & couplings
- gluino mass to ~ 10% from LHC

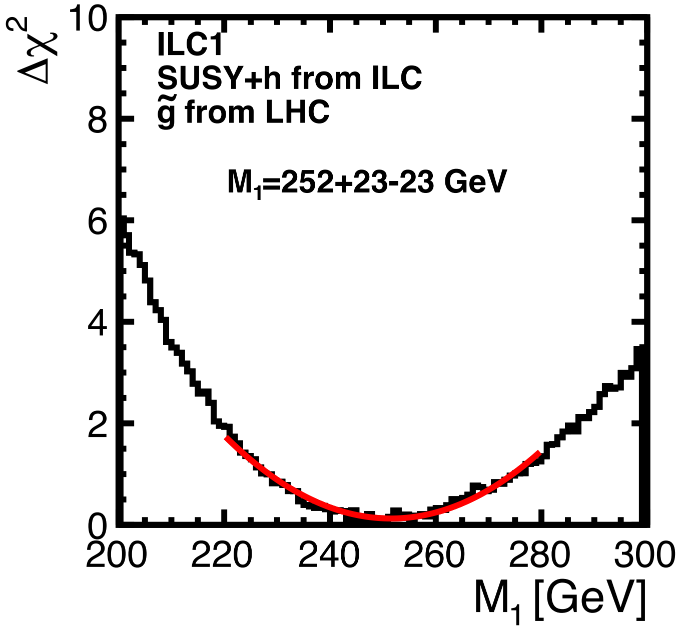


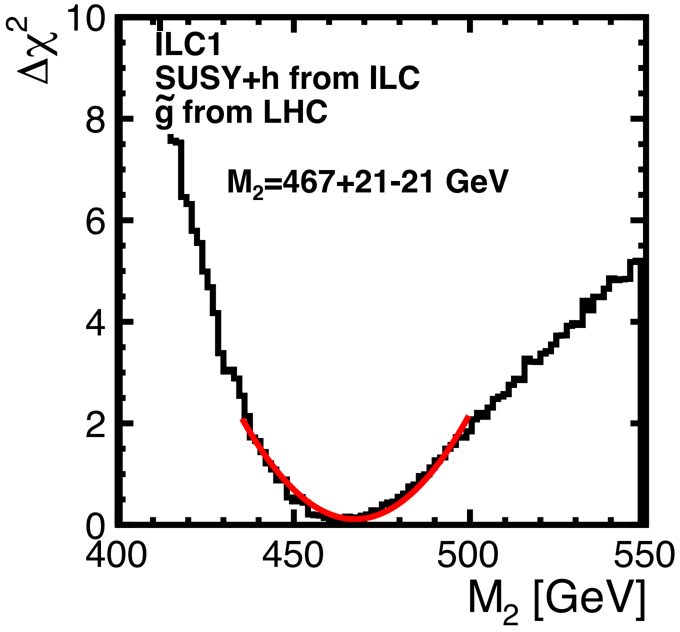
Weak Scale Parameter Determination

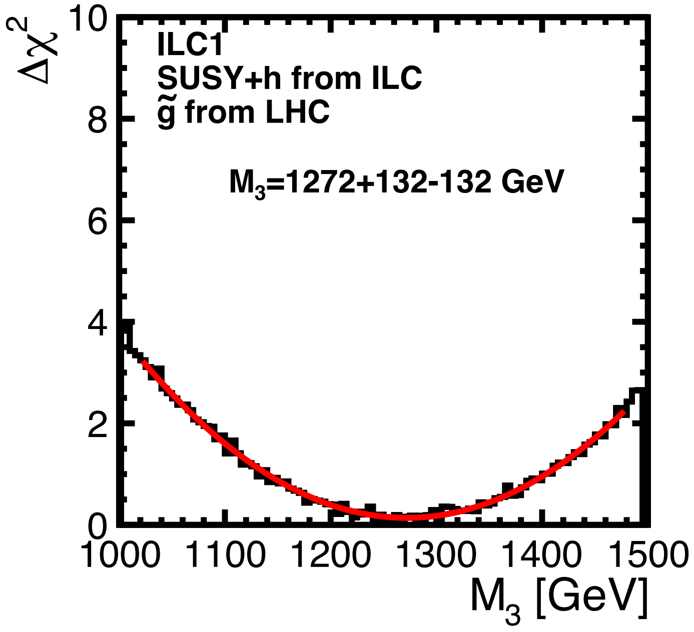
- fit all parameters which enter gaugino and higgsino sector at tree-level
- other SUSY parameters fixed
- only fraction of ILC standard running scenario assumed
  [c.f. talk by J.Brau in accelerator session today, and arXiv:1506.07830]
- μ determined to better than 1%
- Higgs properties very important









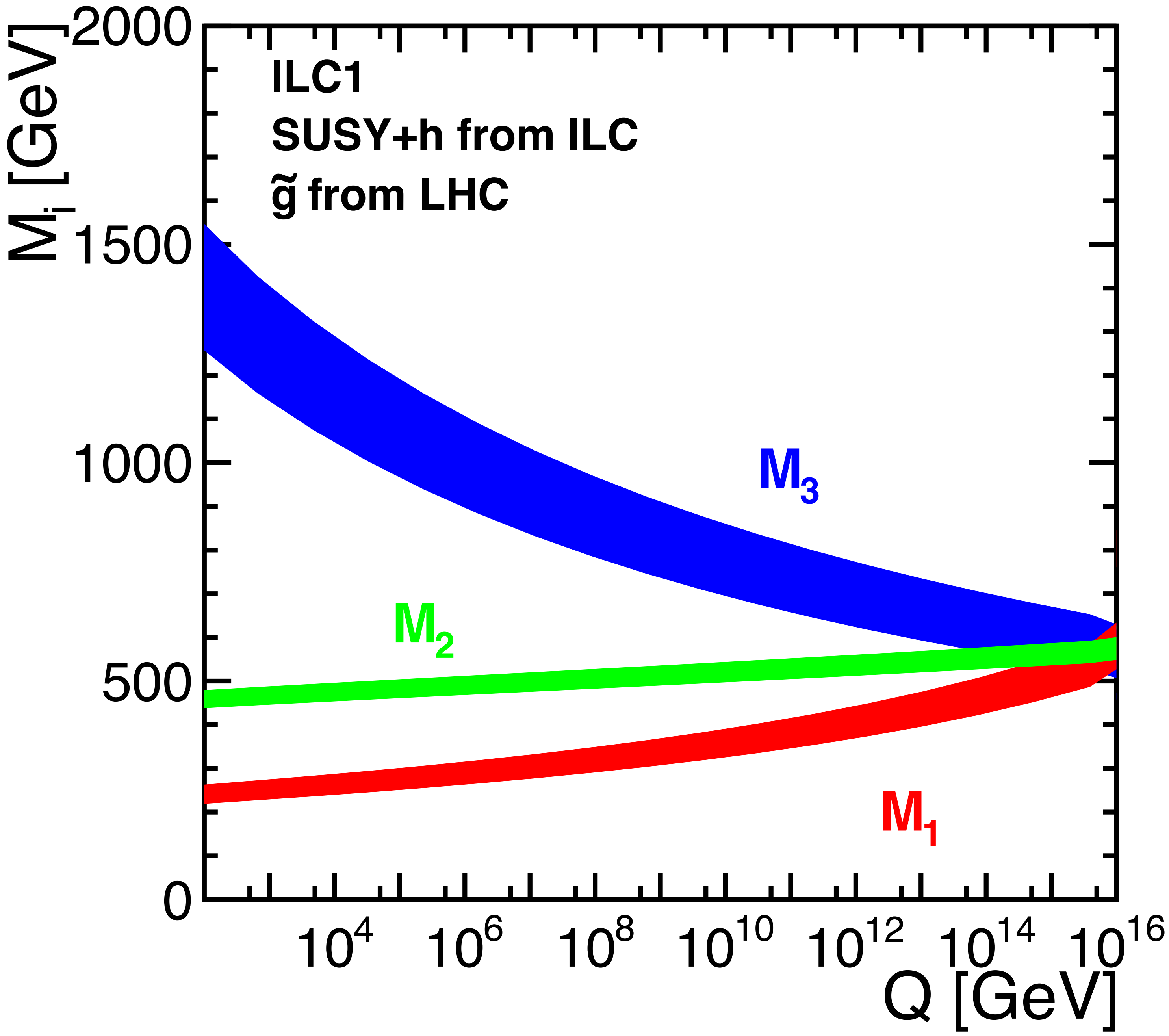


Probing the GUT scale with LHC & ILC

at 1 TeV:

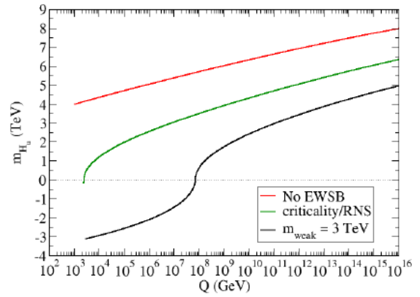
  - $\delta M_1 \approx 25$ GeV
  - $\delta M_2 \approx 20$ GeV
  - $\delta M_3 \approx 130$ GeV

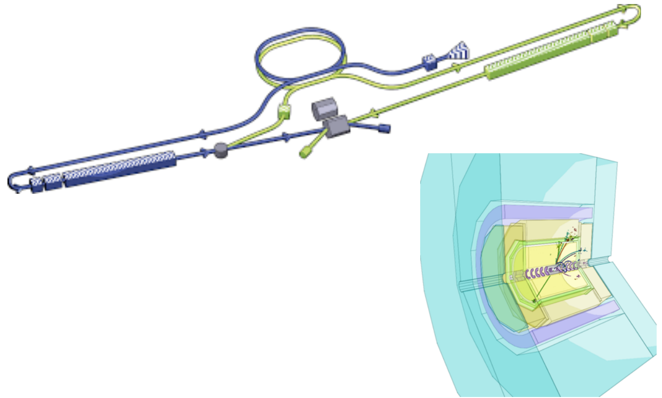
- run to high scale (SPheno):
  - do gaugino masses unify?
  - determine the GUT scale!

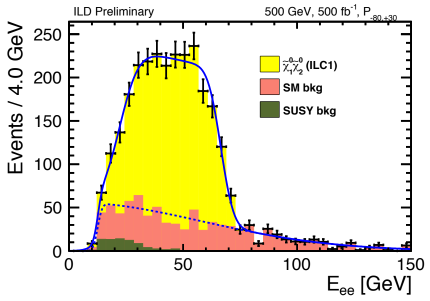


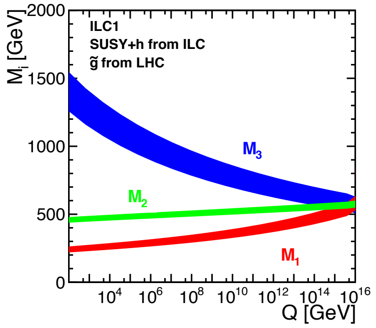
Conclusions

- naturalness: need to take high-scale relations between parameters and running into account
- SUSY can still be natural if higgsinos are sufficiently light
- stops, gluino can safely lie in the 1…4 TeV regime
  => **maybe discoverable at LHC - but don't panic if not!**
- if there is natural SUSY, ILC is a higgsino factory
  => **if no higgsinos at ILC, *then* need to re-think naturalness**
- and offers ideal environment for measuring higgsino properties at the percent-level
- together with the higgs couplings: full determination of electroweakino sector, including M_1 and M_2
- weak-scale parameter determination allows to test for unification and to probe the GUT scale





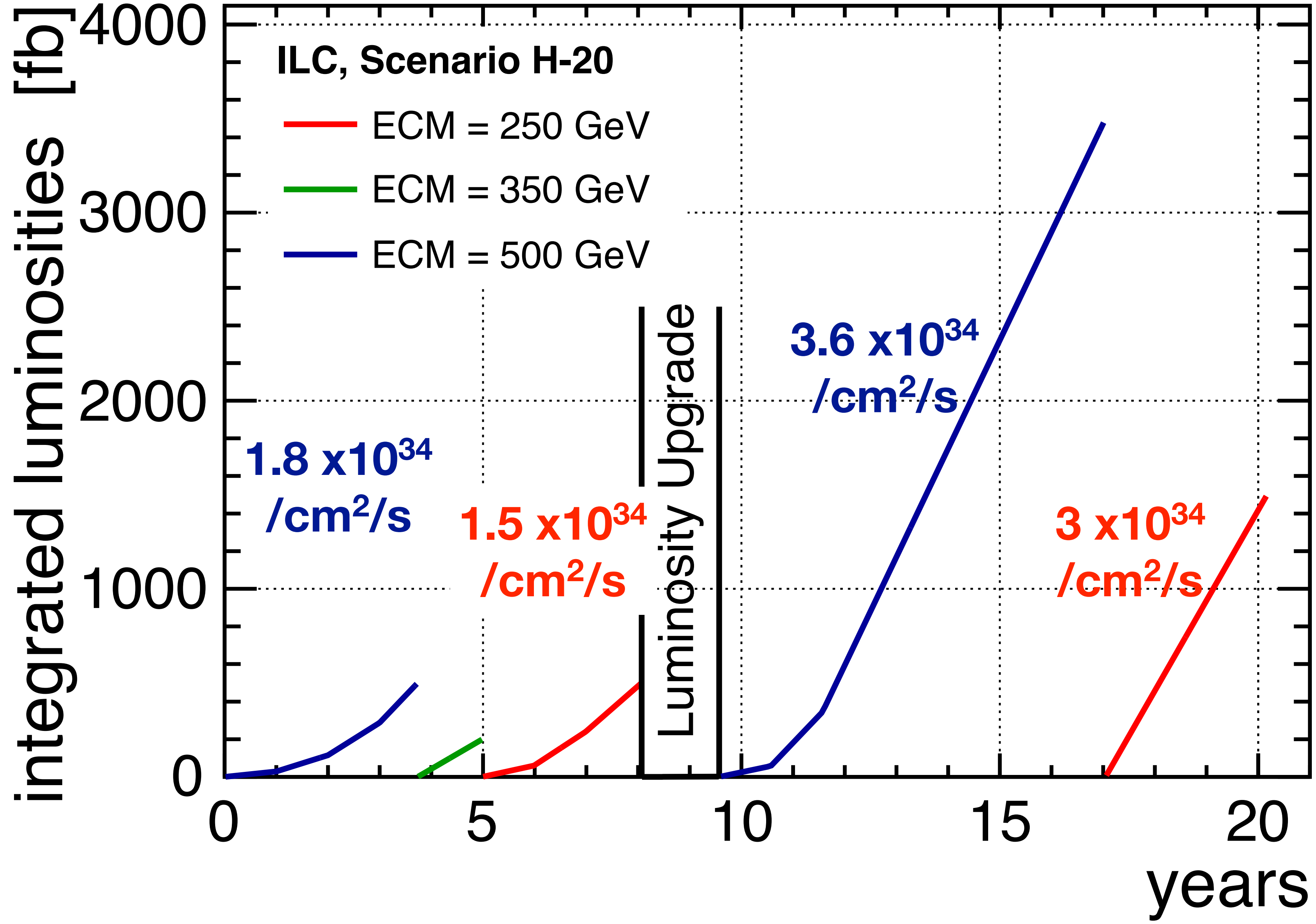




BACK UP

A 20 Year Strawman Running Program for the ILC

- **500 GeV:** general purpose - Higgs & top physics, **Higgs self-coupling, top-Yukawa, BSM**
- **350 GeV:** top threshold scan
- **250 GeV:** special Higgs measurements (mass, CP in H->$\tau\tau$)



Total integrated luminosities

$\sqrt{s}$	$\int \mathscr{L}\, dt$
250 GeV	2 ab^{-1}
350 GeV	200 fb^{-1}
500 GeV	4 ab^{-1}

refer to these as full ILC500 programme

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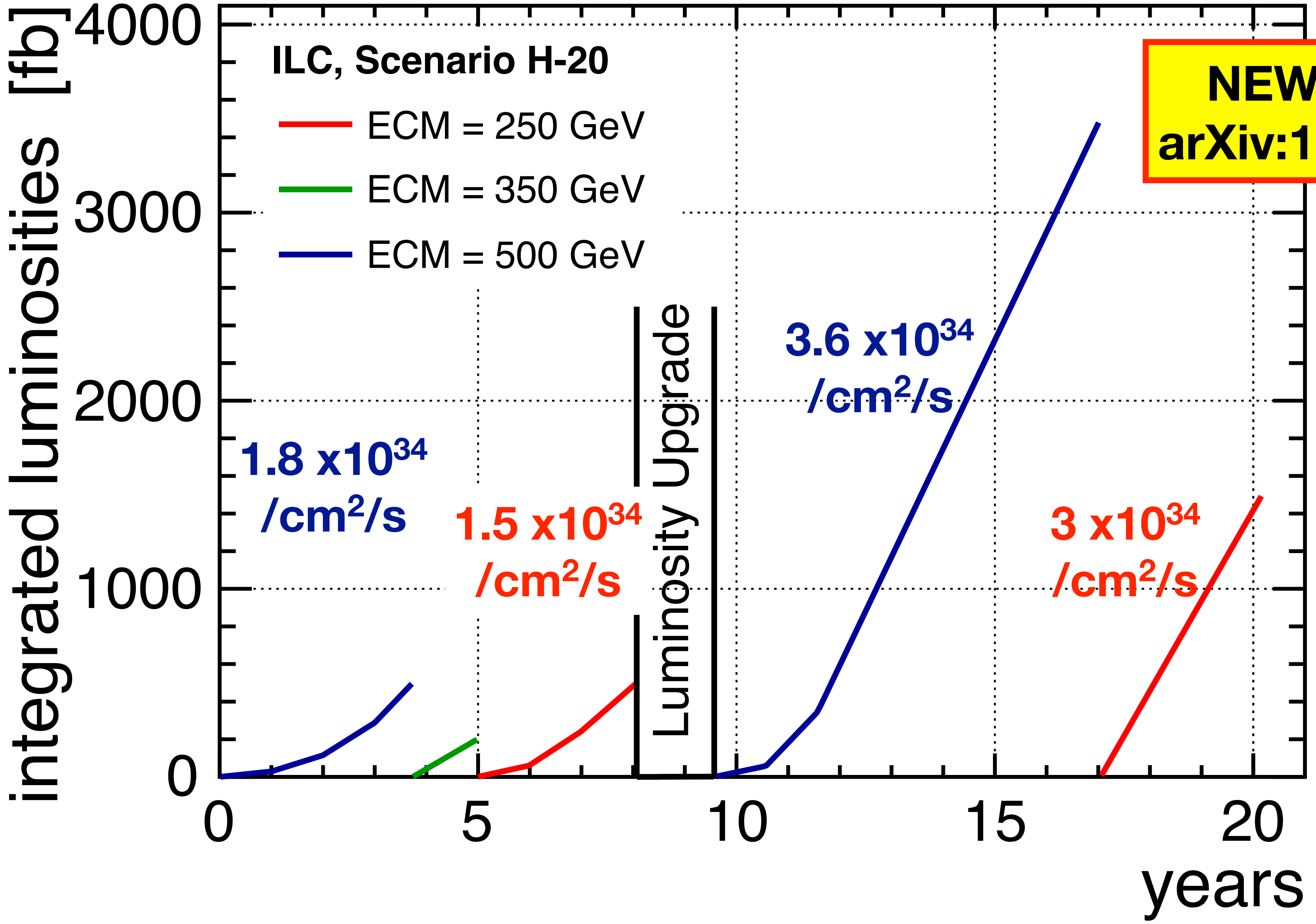

NEW in 2015
arXiv:1506.07830

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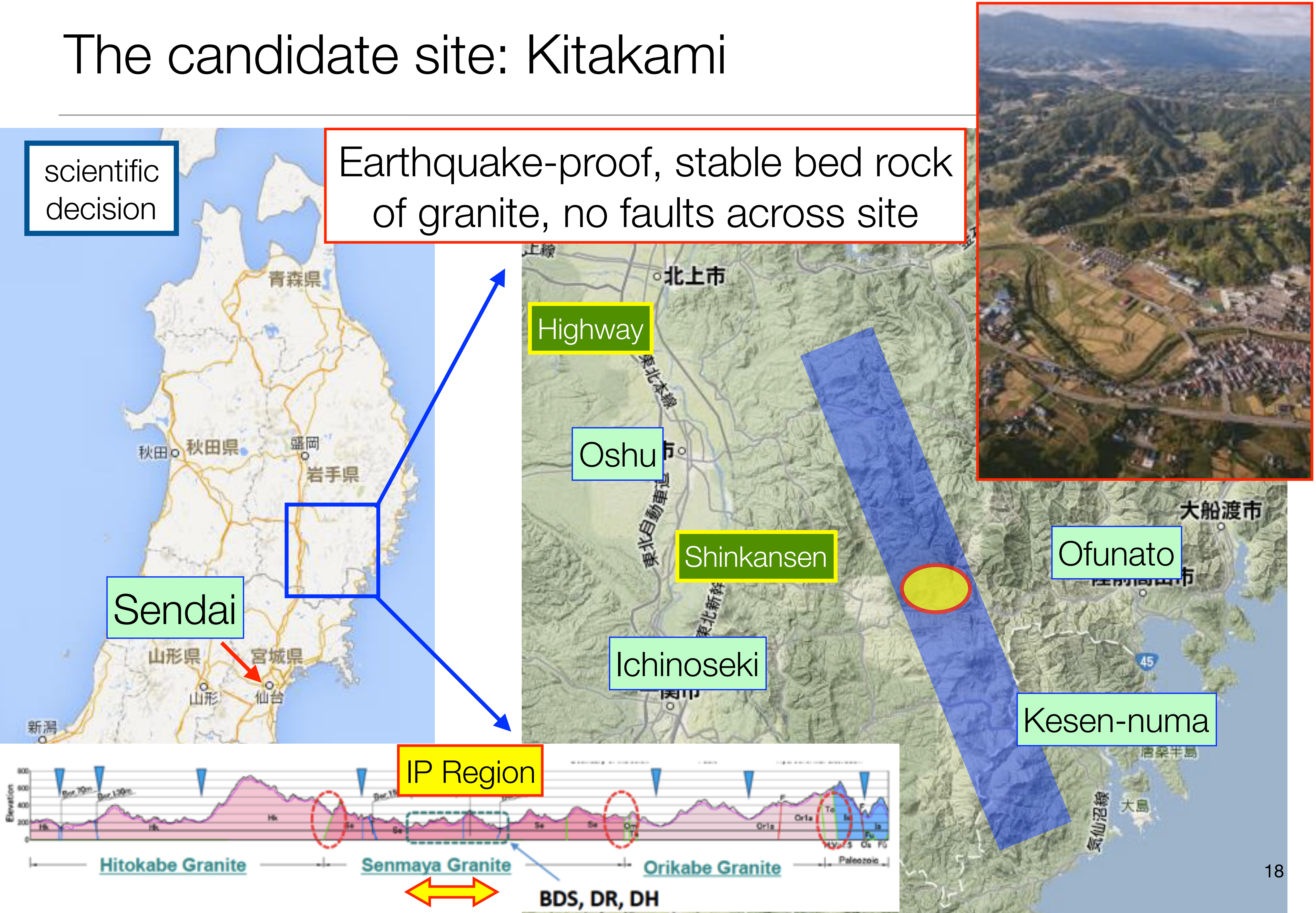

scientific decision

Earthquake-proof, stable bed rock of granite, no faults across site

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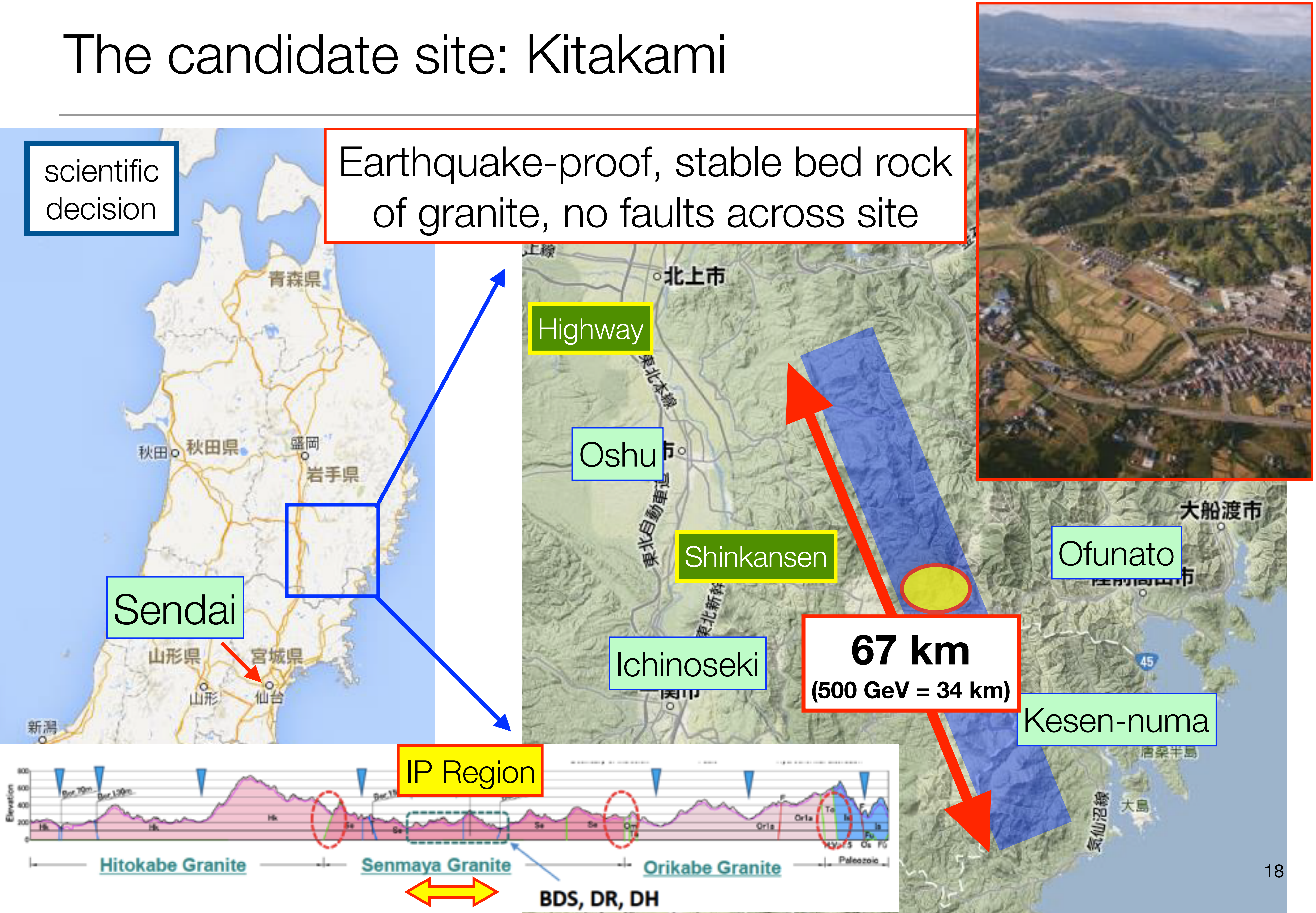

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67 km

(500 GeV = 34 km)

Review by Japanese Science Ministry (MEXT)

Science Council of Japan

after Higgs discovery: community decision for ILC

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Recommendation
in 2013

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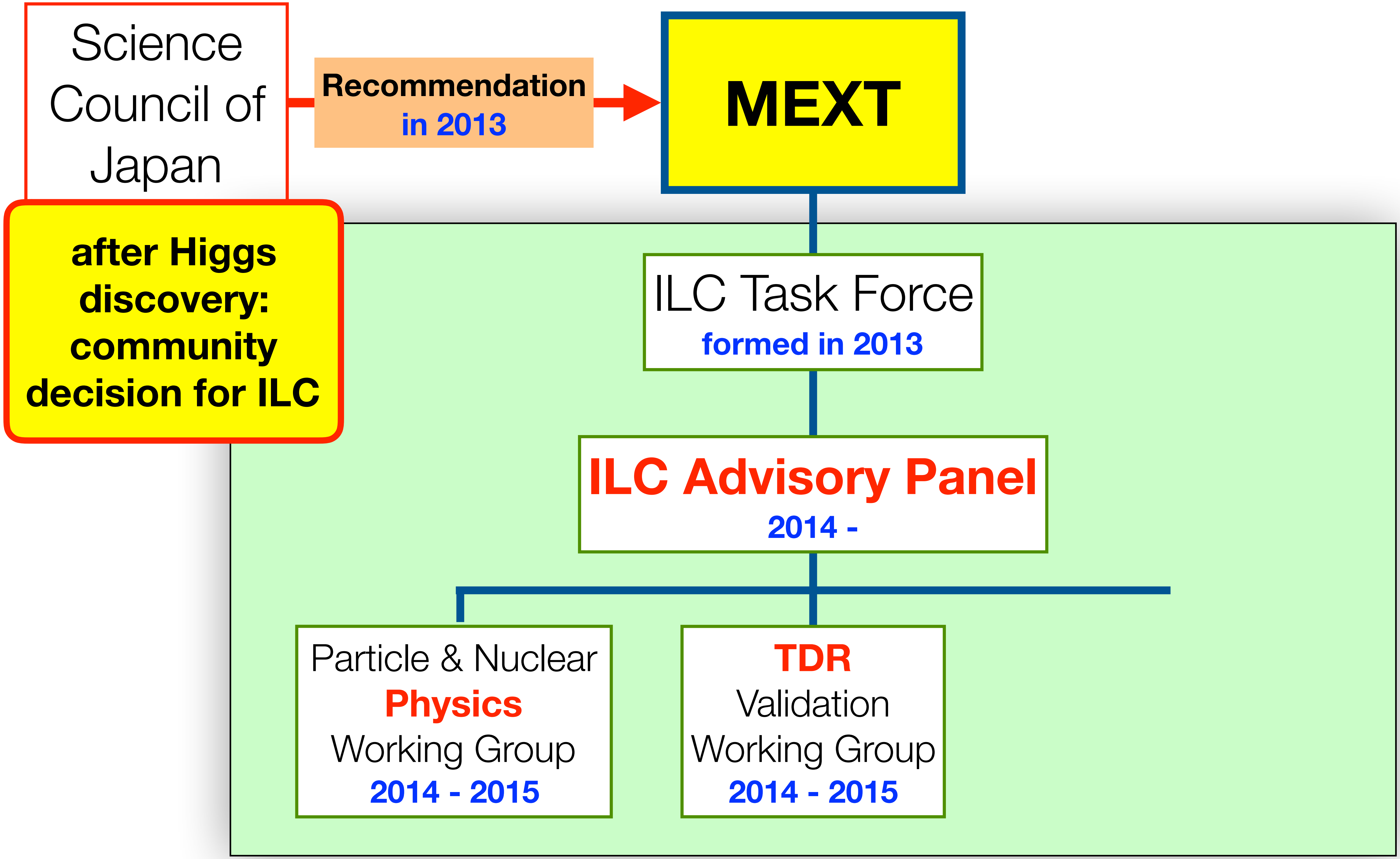

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Particle & Nuclear **Physics** Working Group
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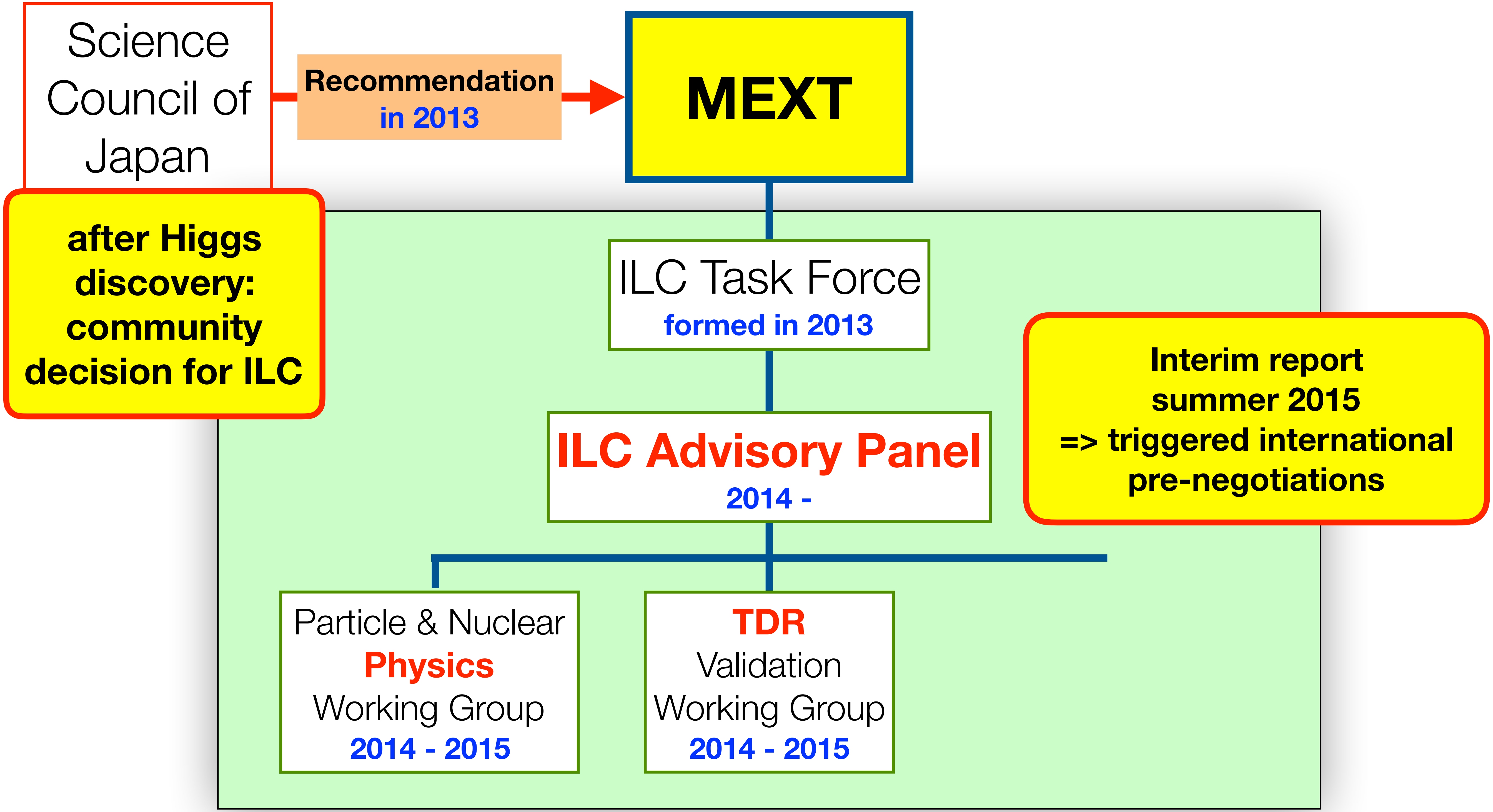

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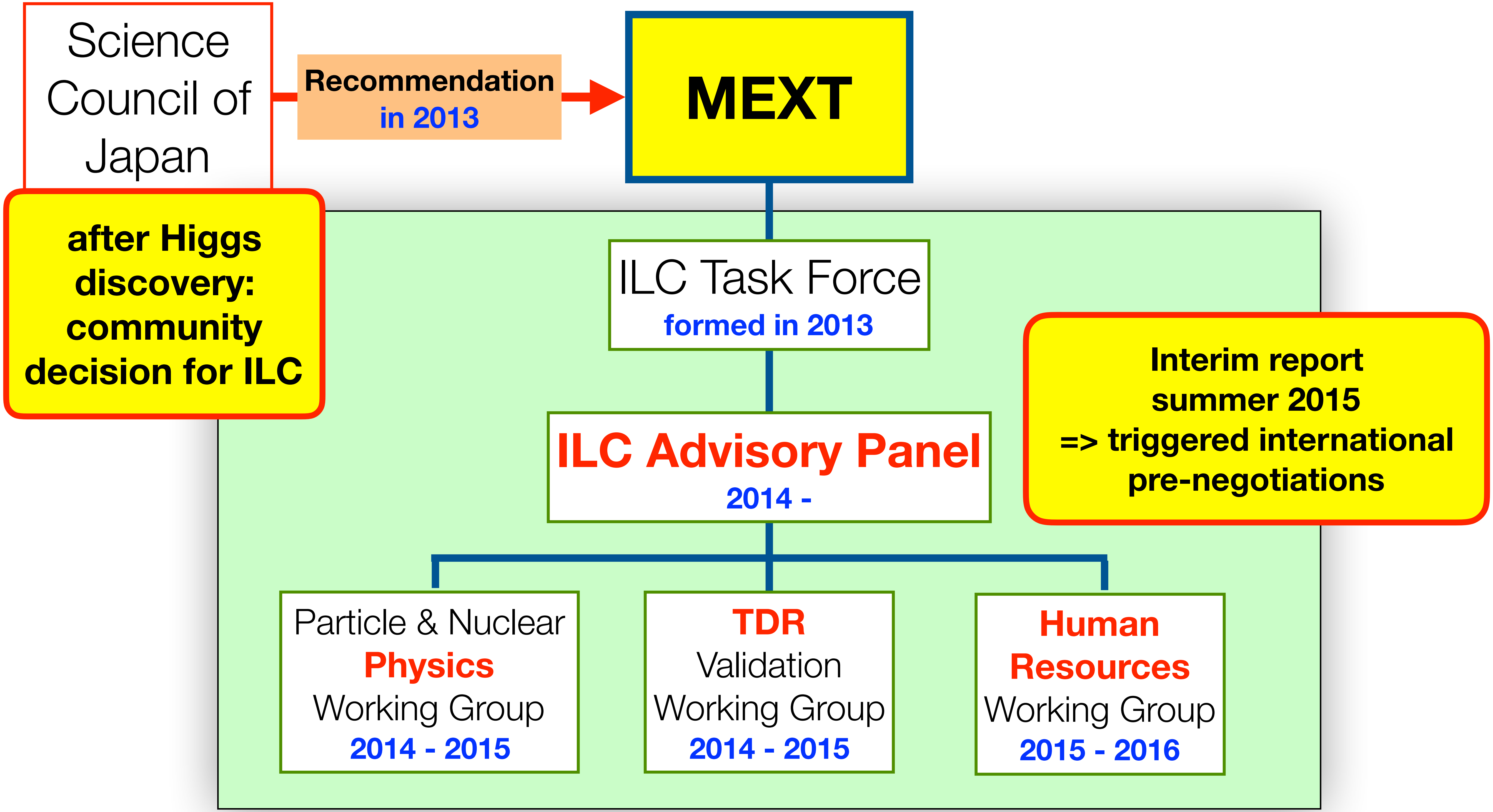

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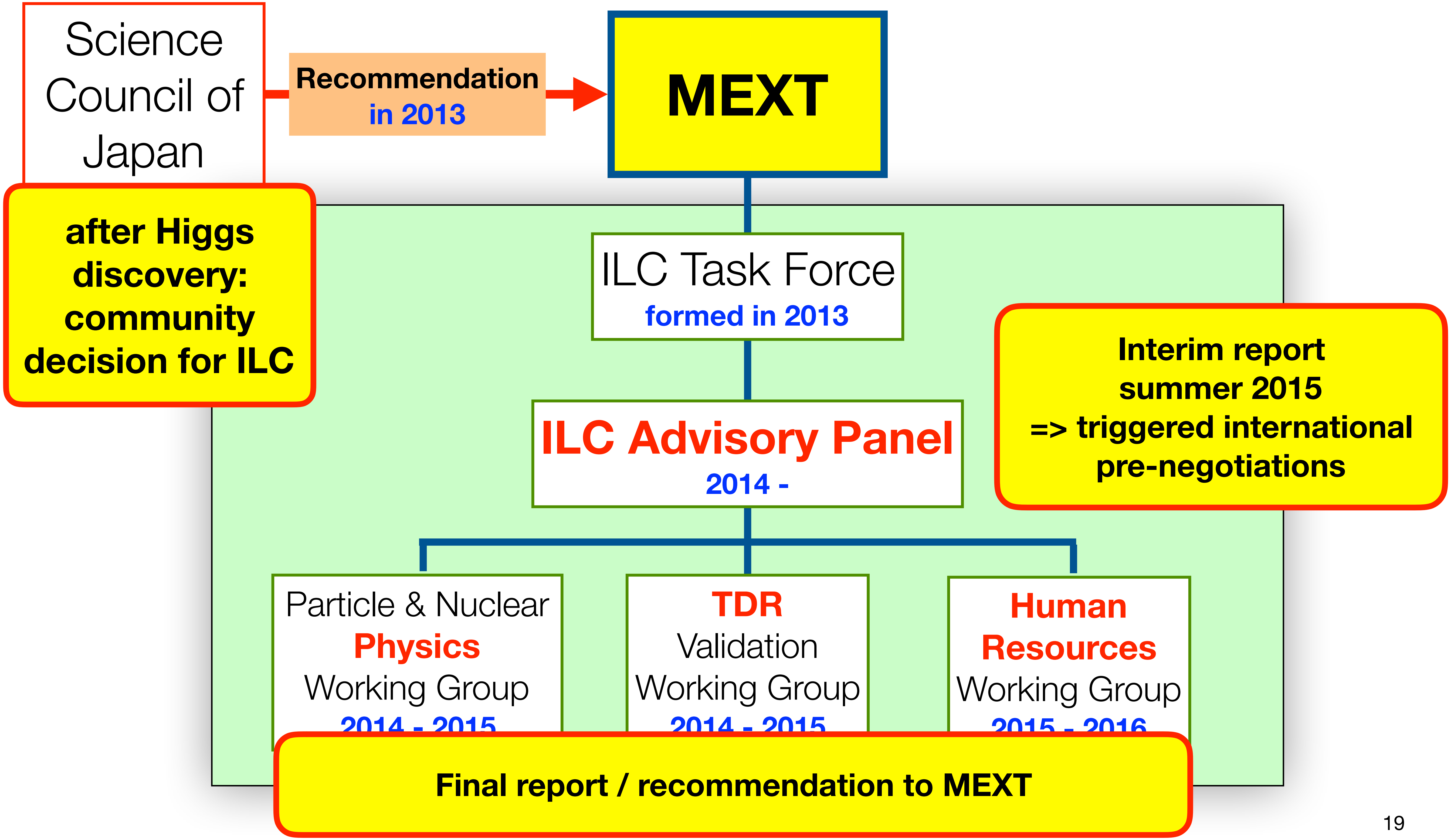

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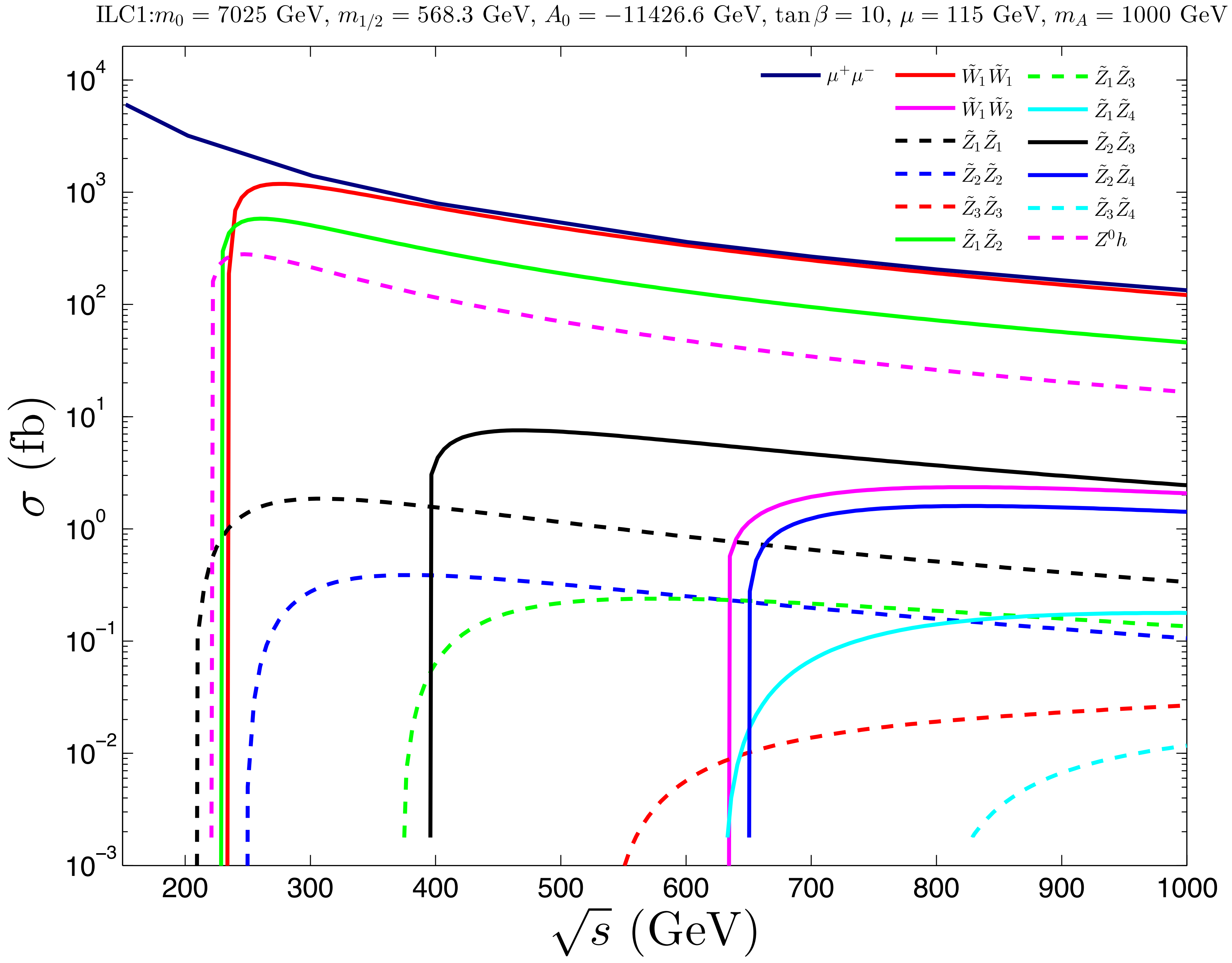
Human Resources Working Group
2015 - 2016

Final report / recommendation to MEXT

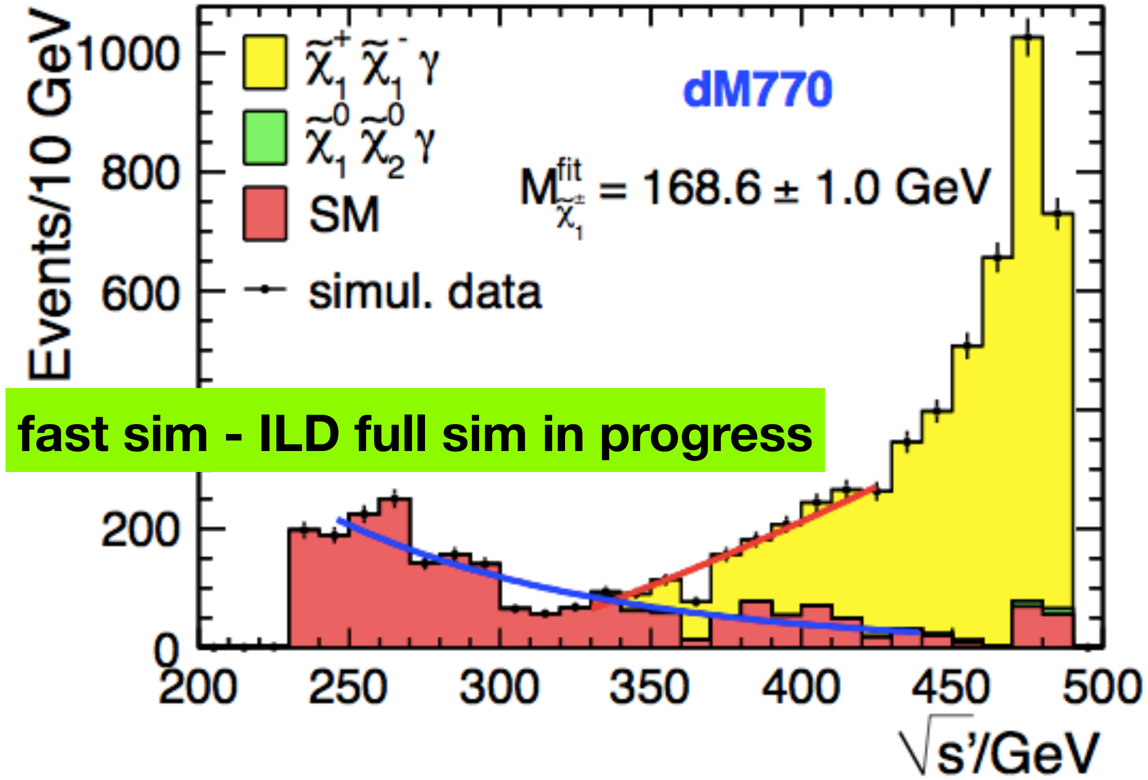
ILC1 Cross Sections in e⁺e⁻ Collisions



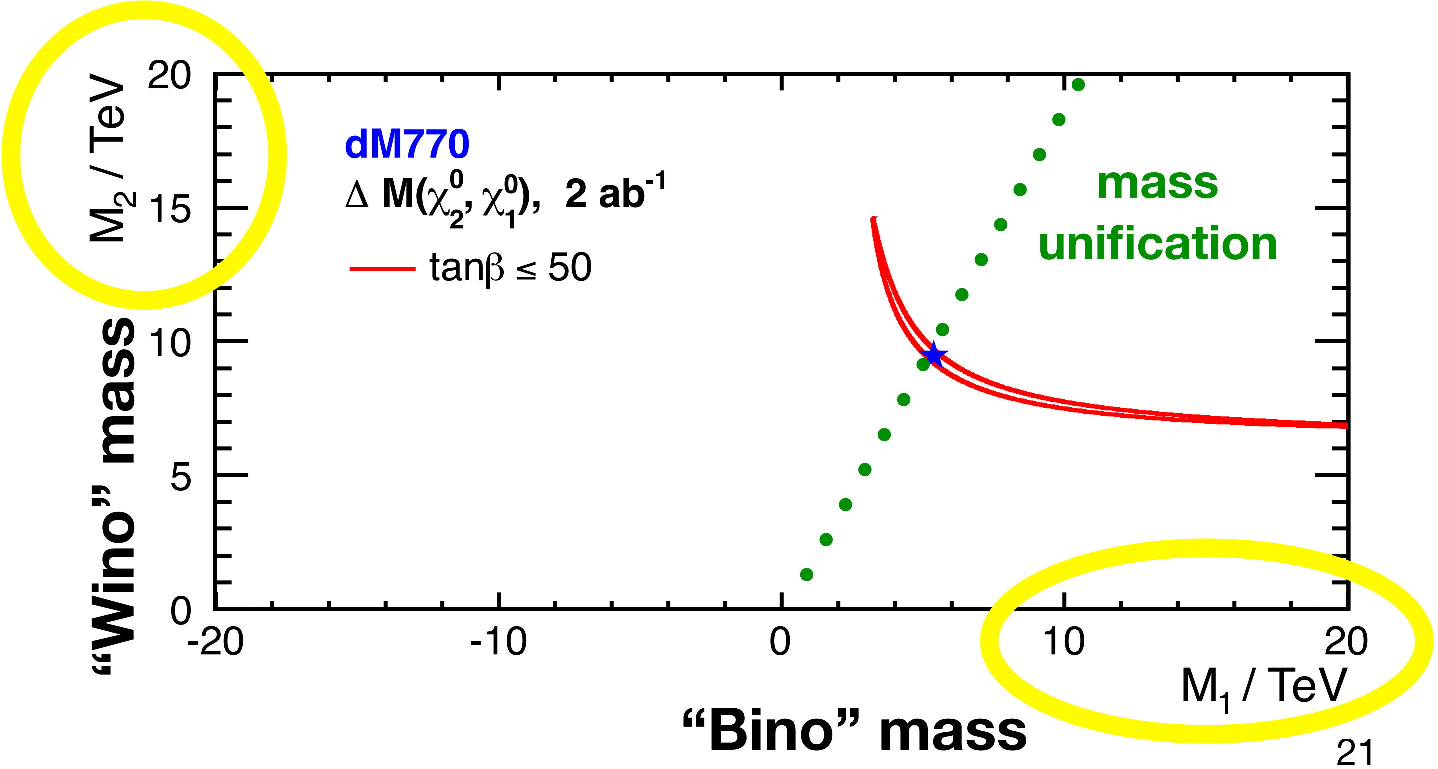
ILC1:$m_0 = 7025$ GeV, $m_{1/2} = 568.3$ GeV, $A_0 = -11426.6$ GeV, $\tan\beta = 10$, $\mu = 115$ GeV, $m_A = 1000$ GeV

Natural SUSY

- key prediction: small μ **=> 3 light Higgsinos with small mass differences**
- “invisible” at LHC
- **loop-hole free detection at ILC up to √s/2**
(clean environment & beam polarisation required!)
- determination of gaugino masses - even if in multi-TeV regime

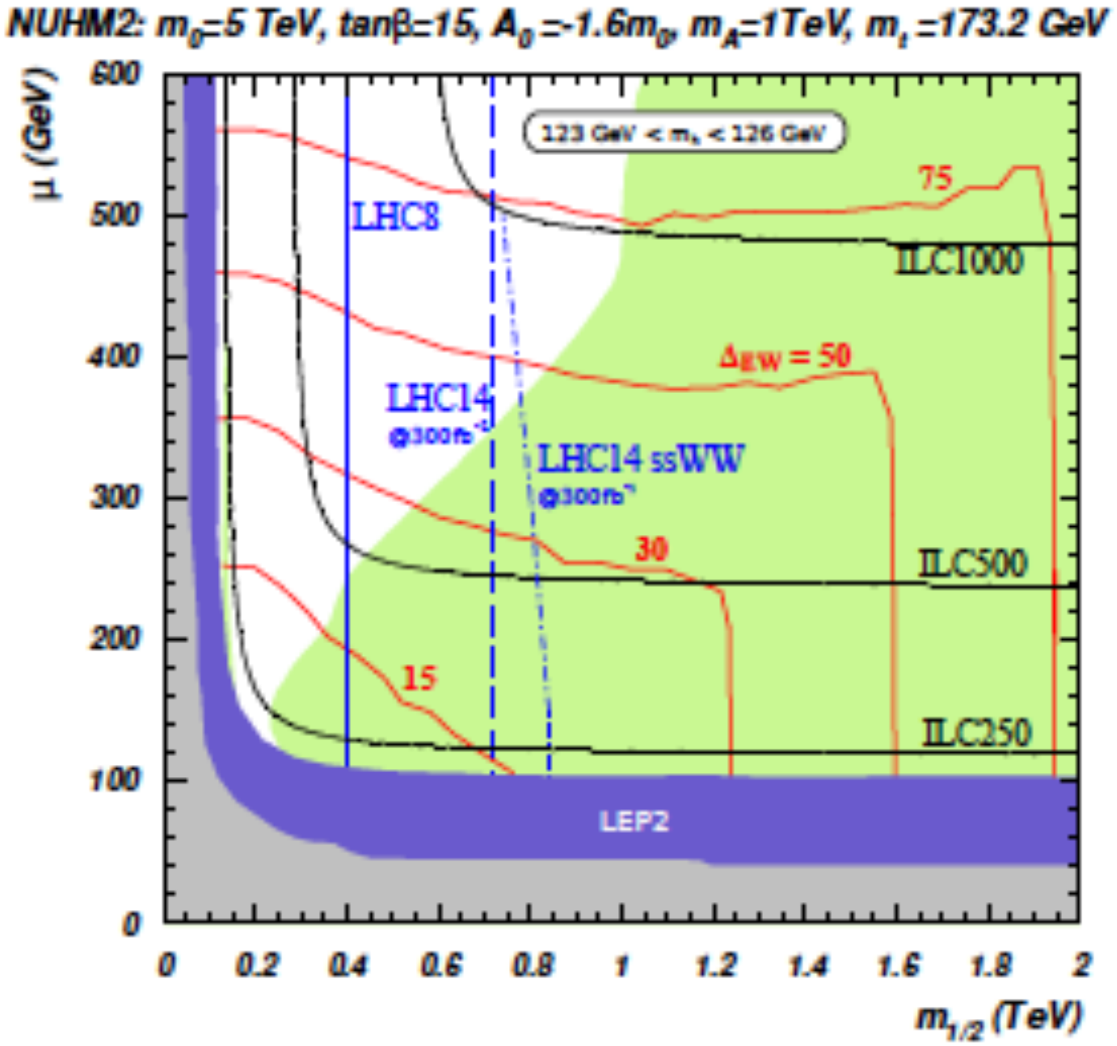


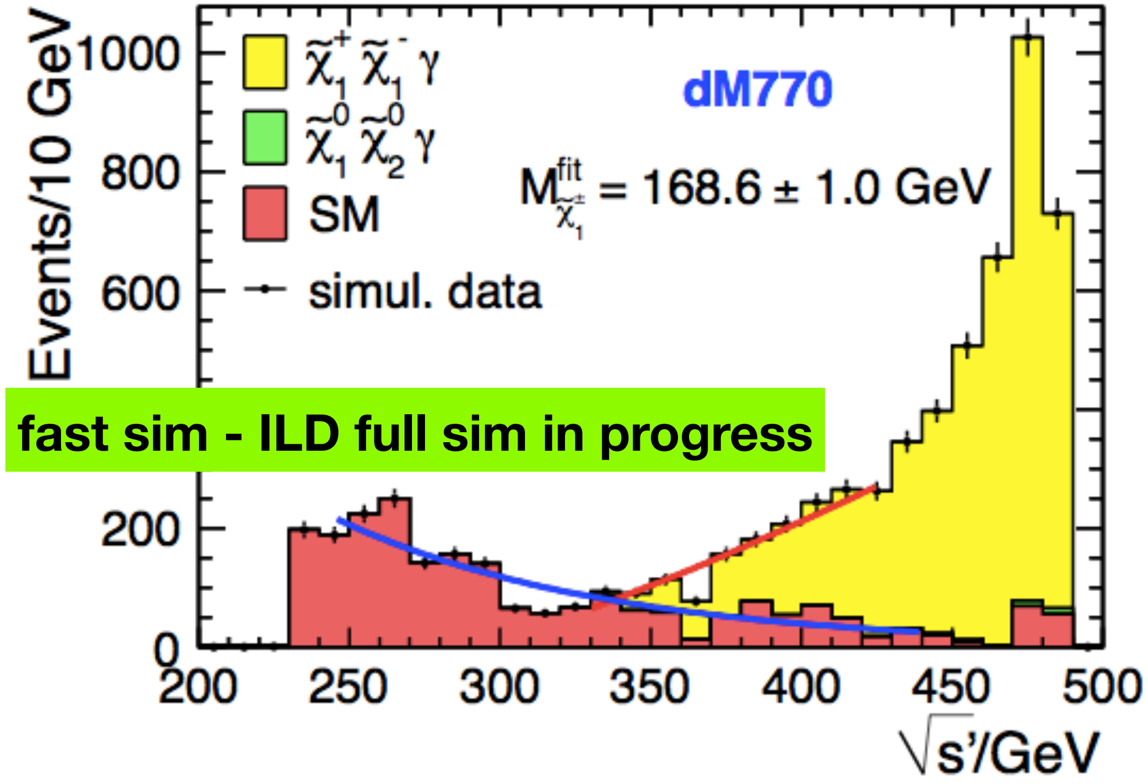
fast sim - ILD full sim in progress



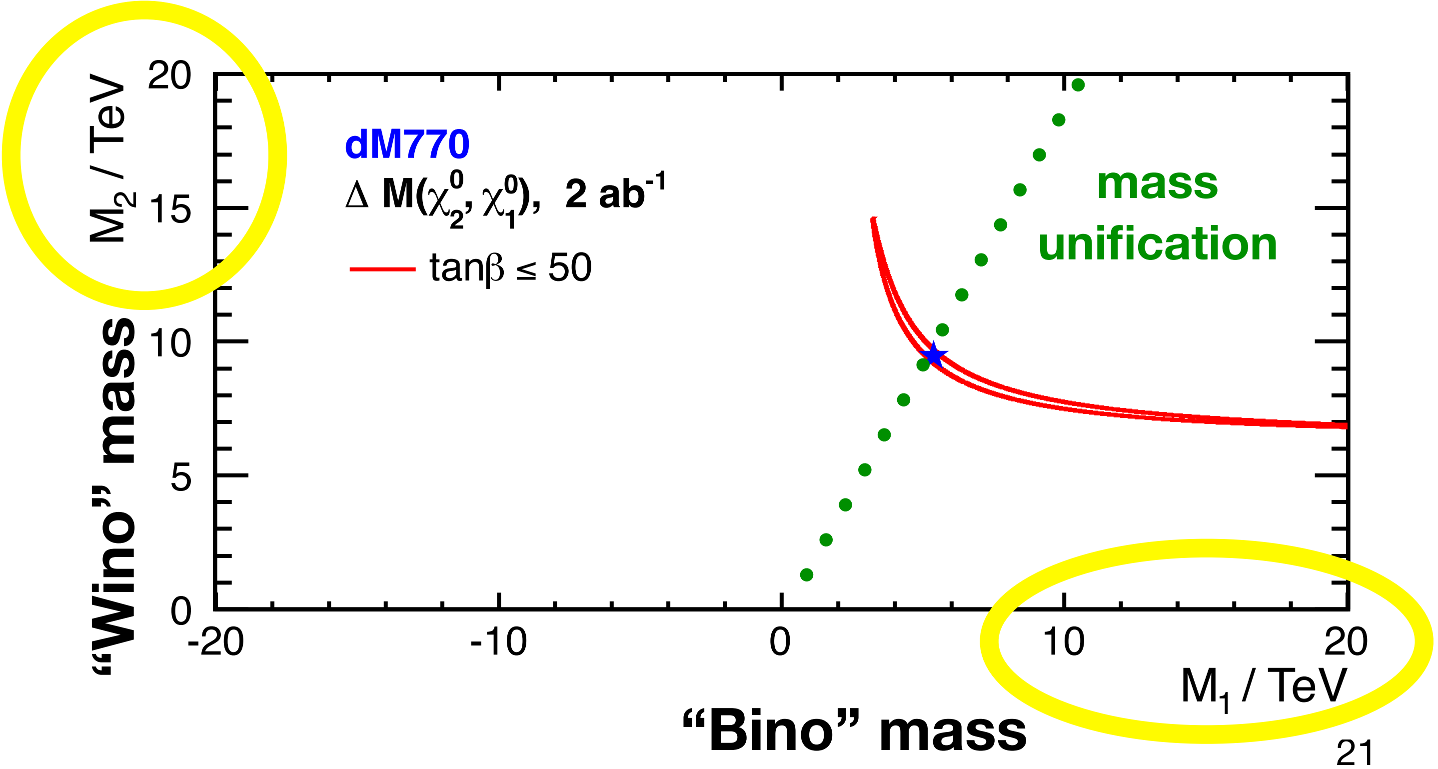
Natural SUSY

- key prediction: small μ => **3 light Higgsinos with small mass differences**
- "invisible" at LHC
- **loop-hole free detection at ILC up to √s/2**
  (clean environment & beam polarisation required
- determination of gaugino masses -
  even if in multi-TeV regime



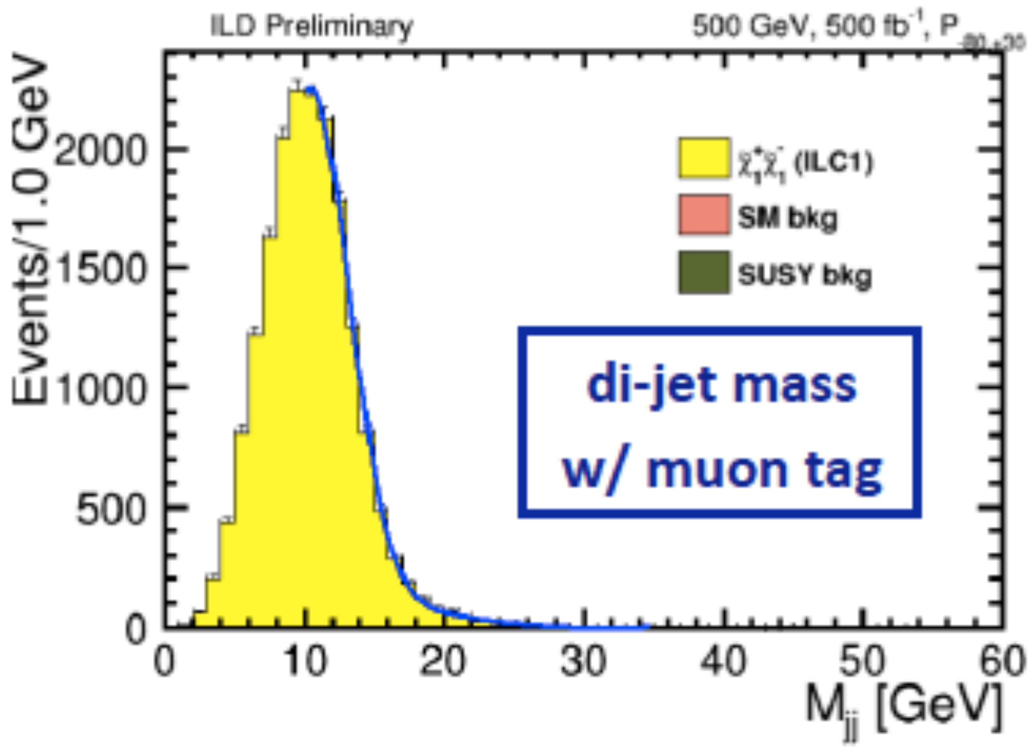


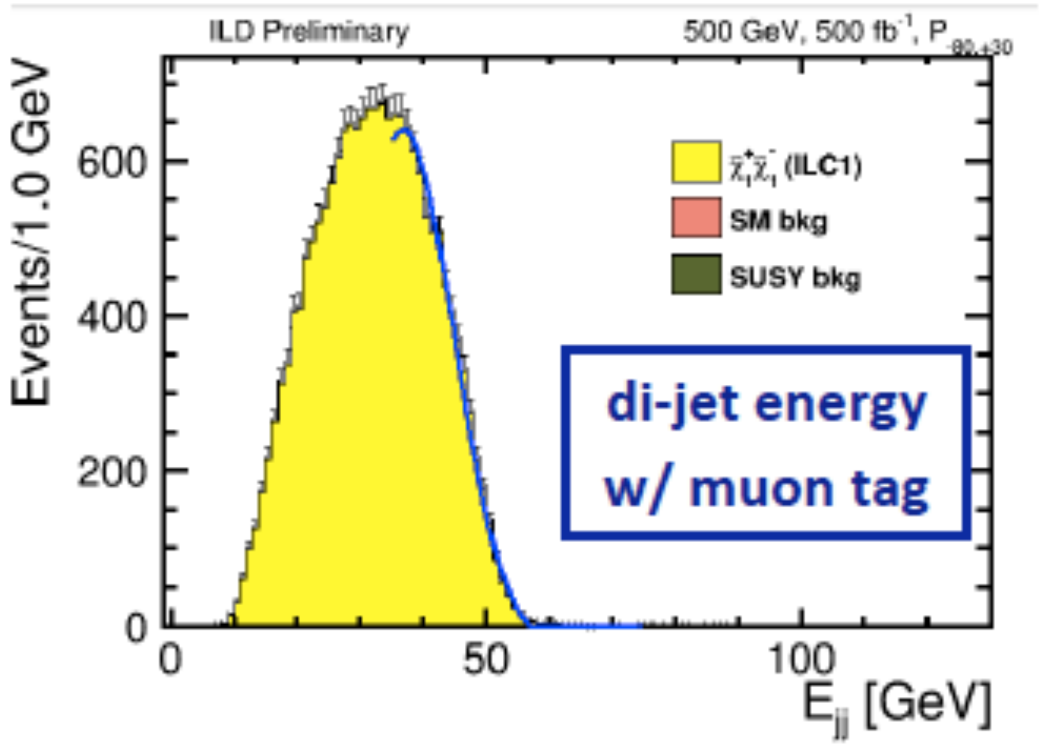
fast sim - ILD full sim in progress



Chargino Measurements

- Chargino signal: $e^+e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 q\bar{q}' \tilde{\chi}_1^0 e\nu_e(\mu\nu_\mu)$
- Characterised by large missing energy, two jets from one W* and a lepton from the other W*

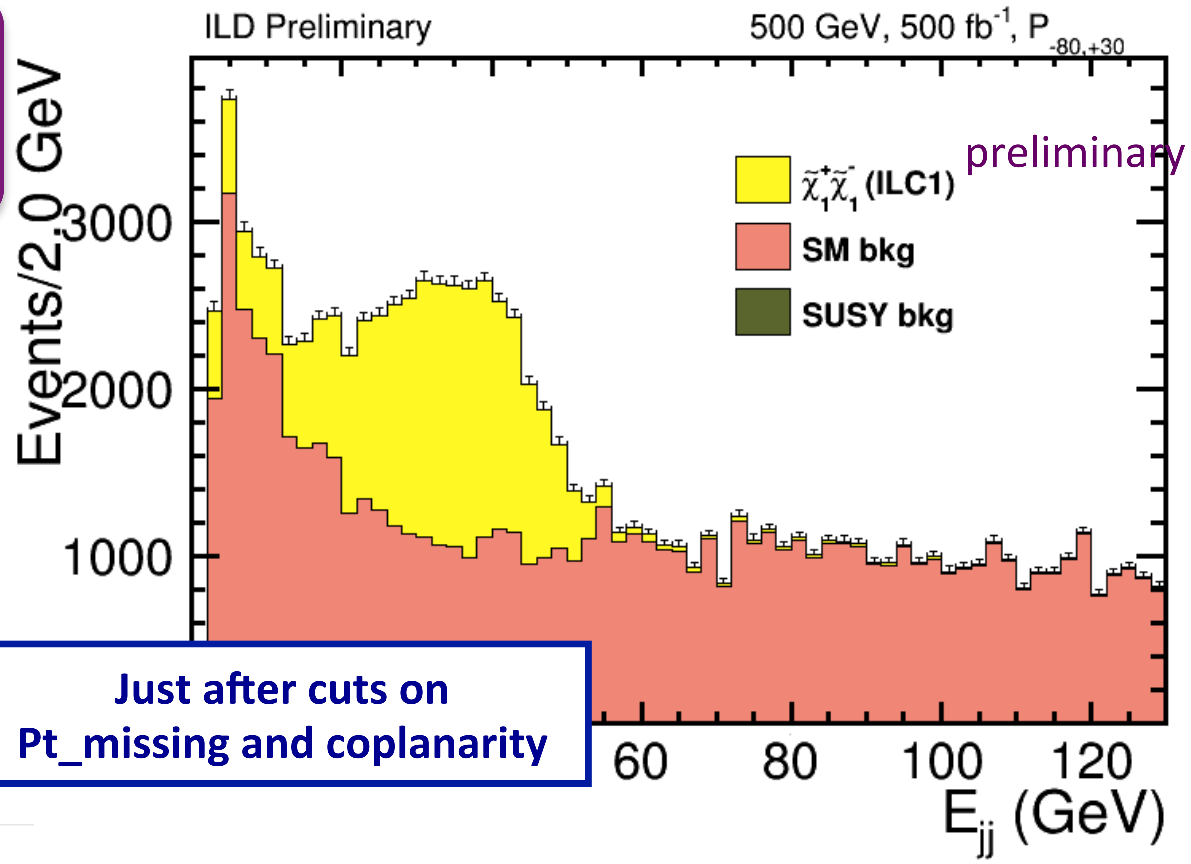




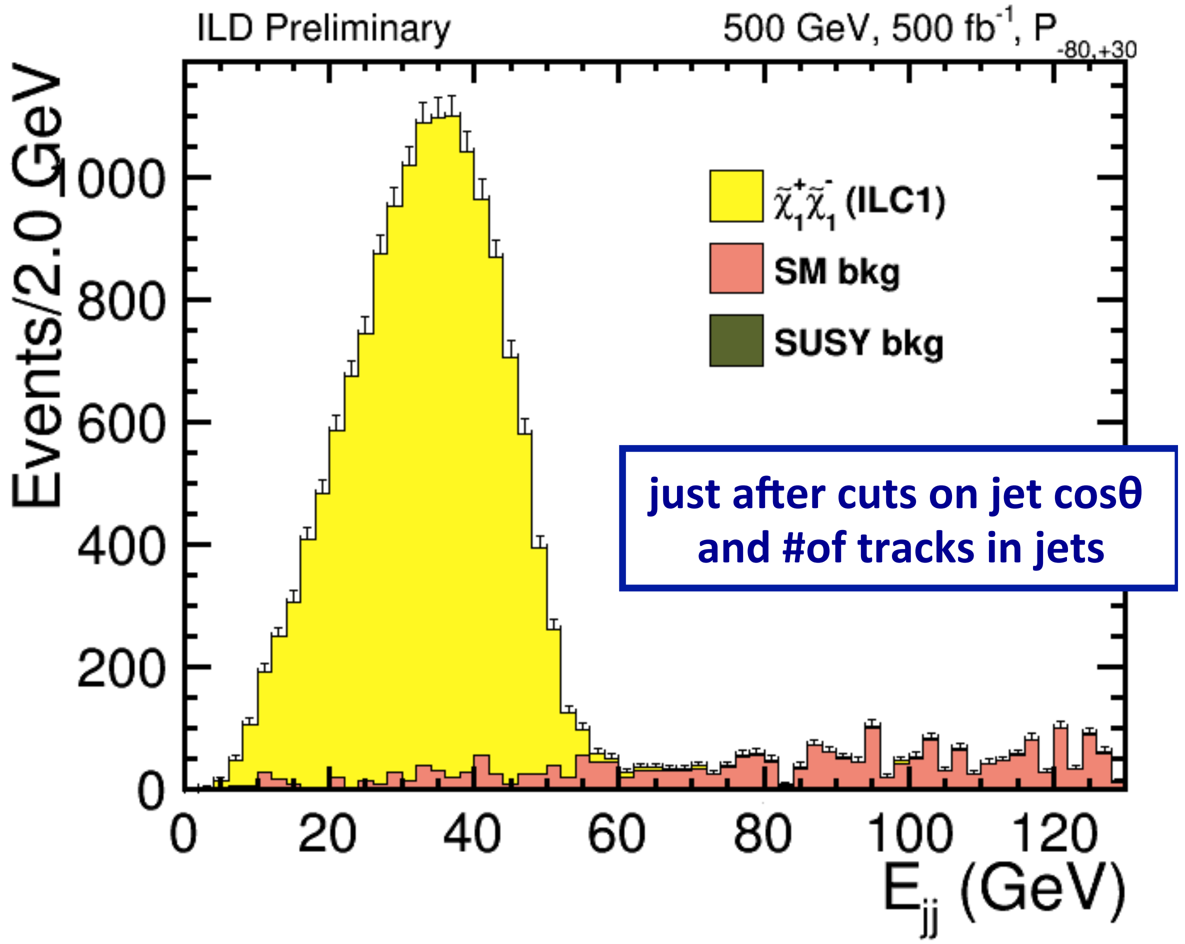
Chargino pair production with semileptonic decay

$$e^+e^- \to \widetilde{\chi}_1^+\,\widetilde{\chi}_1^- \to \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 qq'\ell\nu$$

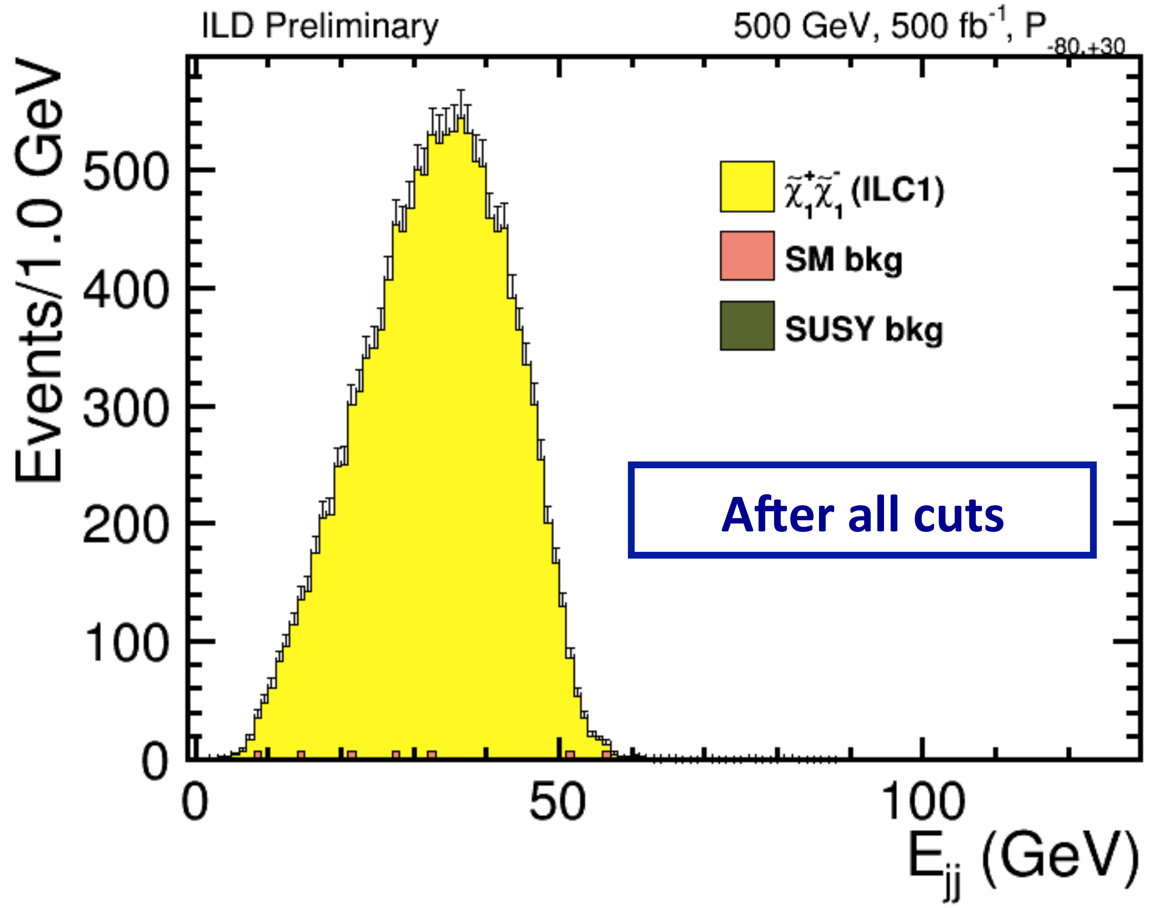
Polarization (Pe-,Pe+) = (-0.8, +0.3)



Just after cuts on Pt_missing and coplanarity



just after cuts on jet cosθ and #of tracks in jets



After all cuts