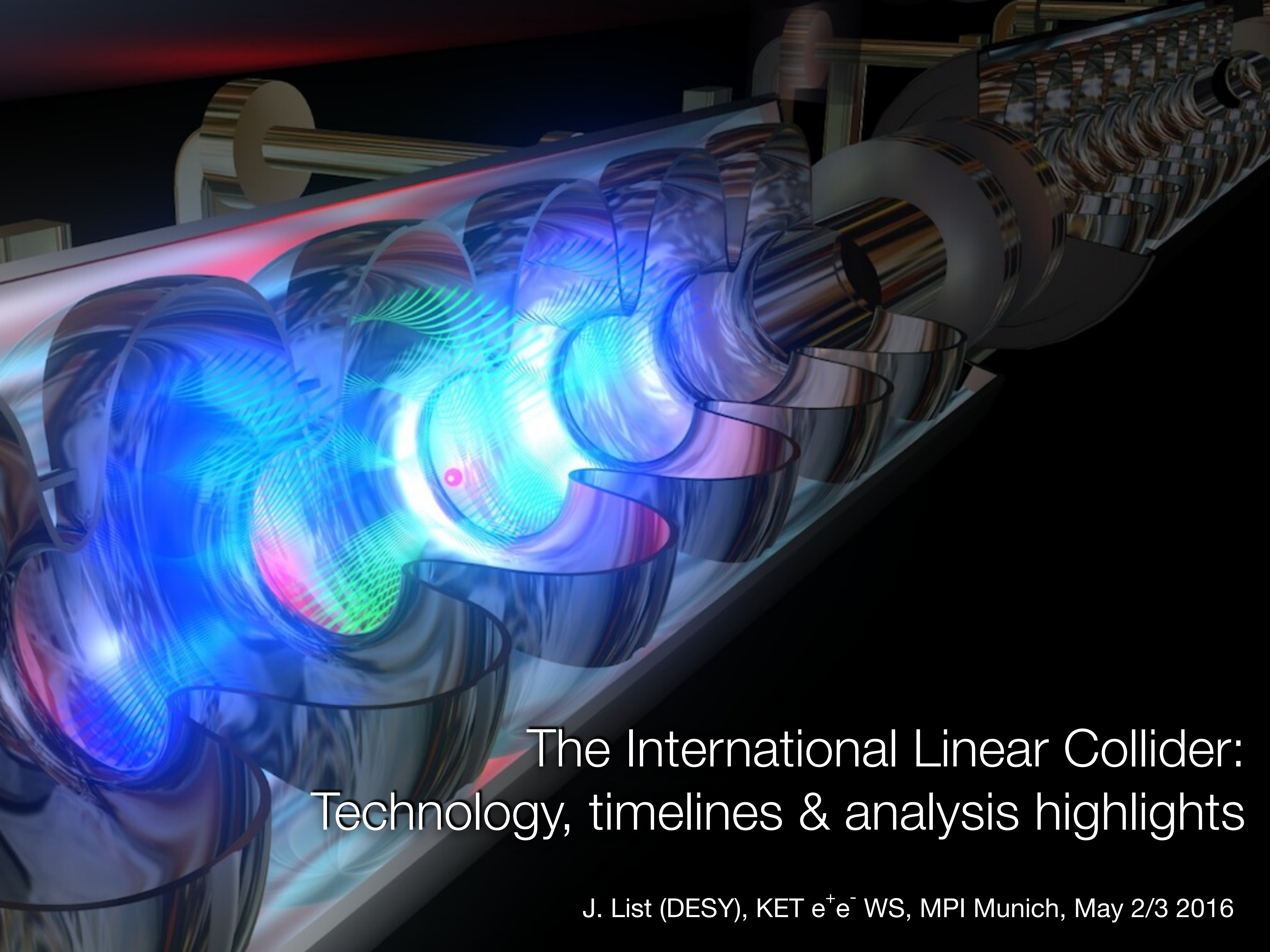


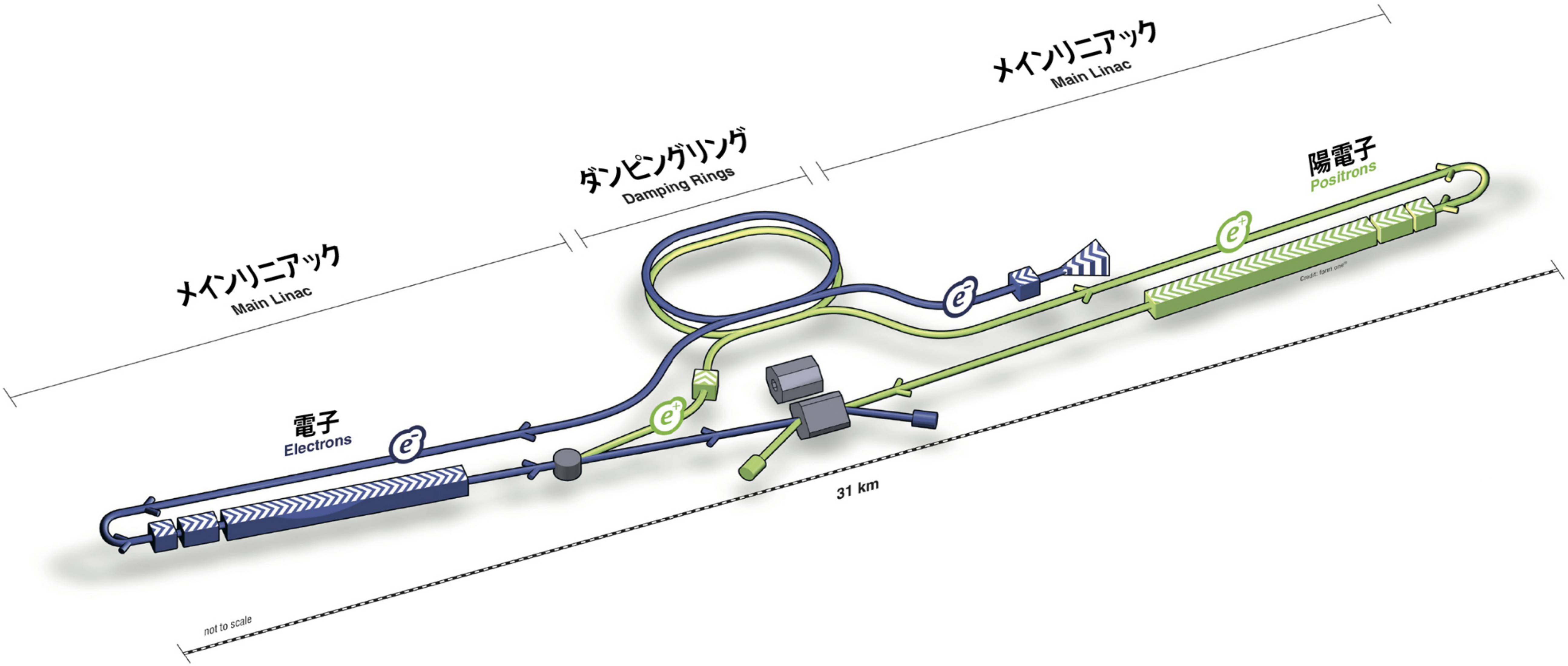
The International Linear Collider: Technology, timelines & analysis highlights

J. List (DESY), KET e^+e^- WS, MPI Munich, May 2/3 2016

Outline

- ILC Overview
- ILC Technology, Cost & Operation
- ILC Analysis Highlights
- ILC in Japan
- Conclusions

ILC Overview



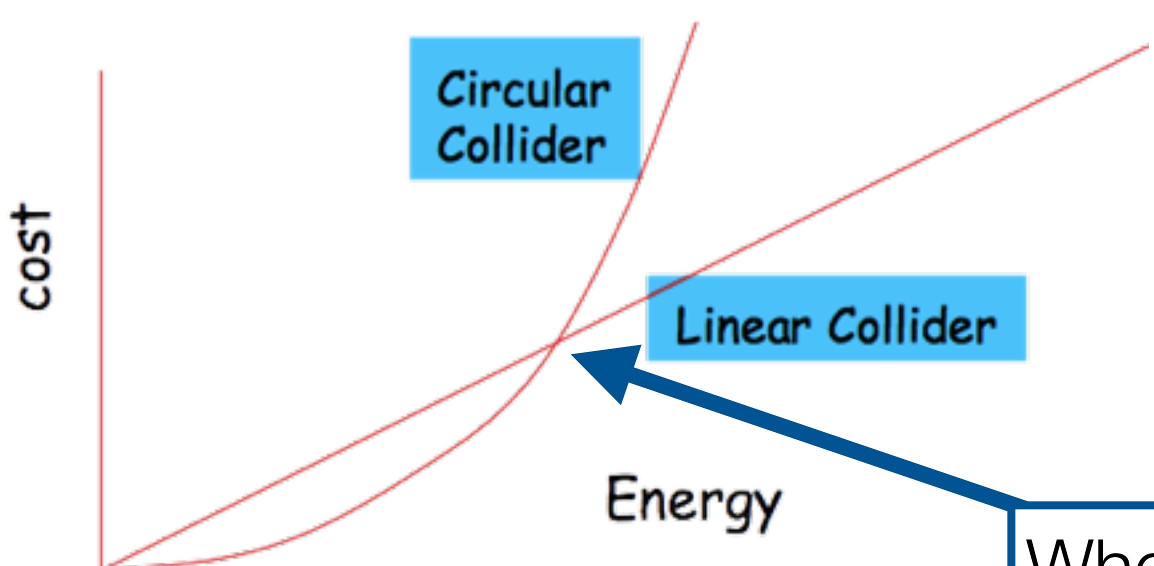
ILC Scheme | ©www.form-one.de

Why Linear?

- **synchrotron radiation:**
  - **$\Delta E \sim (E^4 / m^4 R)$** per turn => 2 GeV at LEP2
- **cost in high-energy limit:**
  - **circular :** \$\$ ~ a R + b **ΔE** ~ a R + b (**$E^4 / m^4 R$**)

    optimisation => $R \sim E^2$ => **\$\$ ~ E^2**
  - **linear :** \$\$ ~ **L**, with **L ~ E** => **\$\$ ~ E**

    => scalable



Where is the cross-over?

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND
LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

J.-E. Augustin*, N. Dikanski†, Ya. Derbenev†, J. Rees*,
B. Richter*, A. Skrinski†, M. Tigner**, and H. Wiedemann*

1978

Introduction

This note is the report of working Group I [...] ader). We were assisted at times by U. Amaldi and E. Keil of CERN. We concerned ourselves primarily with the technical limitations which might present themselves to those planning a new and higher-energy electron-positron colliding-beam facility in a future era in which, it was presumed, a 70-GeV to 100-GeV LEP-like facility would already exist. In such an era, we reasoned, designers would be striving for center-of-mass energies of at least 700-GeV to 1-TeV. Two different approaches to this goal immediately came to the fore: one, a storage ring based on the principles of PEP, PETRA, and LEP and the other, a system in which a pair of linear accelerators are aimed at one another so that their beams will collide. We realized early in the study that a phenomenon which has been negligible in electron-positron systems designed to date would become important at these higher energies - synchrotron radiation from a particle being deflected by the collective electromagnetic field of the opposing bunch - and we dubbed this phenomenon "beam-strahlung." During the rest of the week we investigated the scaling laws for these two colliding-beam systems taking beam-strahlung into consideration.

The International Linear Collider in a nutshell

- 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

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:**
  - from RDR to 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**

Top-Level Parameters for TDR Baseline

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

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ILC Challenges & Risks

- **Energy reach (and costs):**
  - Is design acceleration gradient realistic? -> next section
- **Luminosity:**
  - Can the few nm beam sizes be reached? -> next section
  - How to build target for positron source?
    -> engineering question, requires resources to answer
- **Beam energy spectrum / $\gamma\gamma$-pile up:**
  - Does the physics performance suffer? -> section after next
    -> all TDR benchmarks / physics studies include these effects

ILC Technology,
Cost & Operation

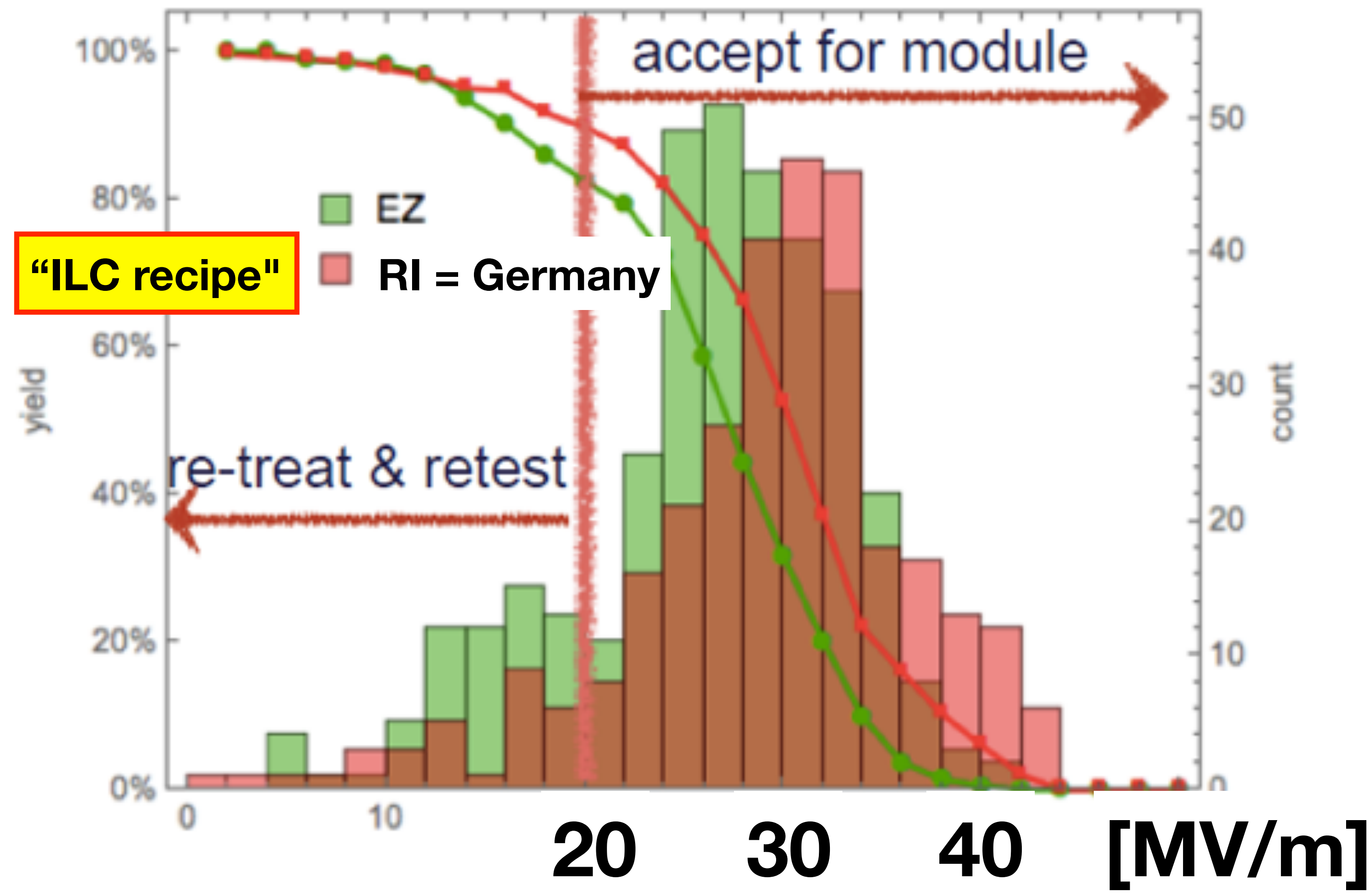
Technological Key: SCRF

- 16024 superconducting cavities

- > 10 years successful user operation in FLASH @ DESY
- European XFEL being commissioned in Hamburg
  ≈ 10% prototype
  of one ILC linac

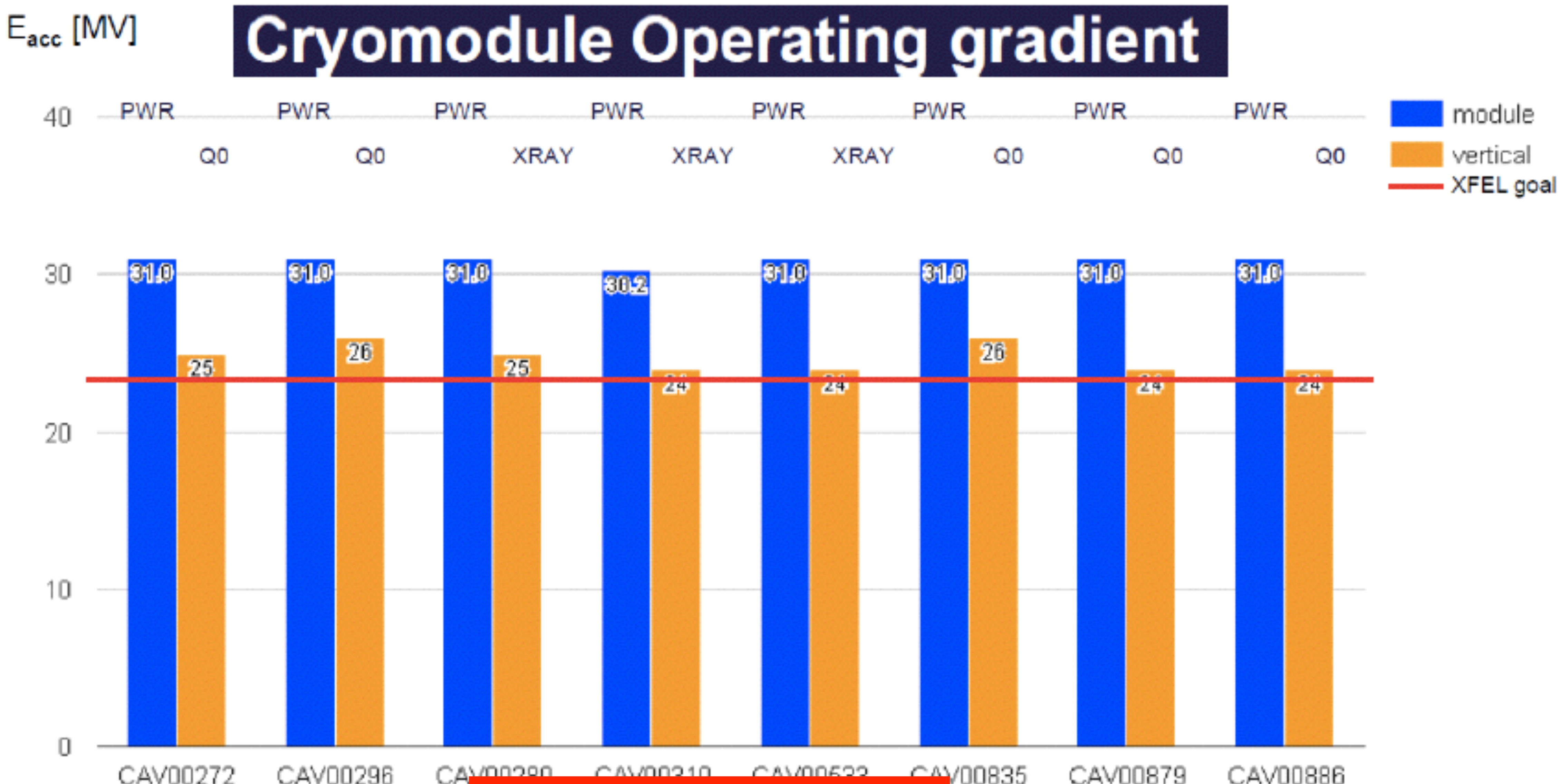
A mature and proven technology -
- ready to be built

XFEL cavities:
usable gradient “as received”



Average usable gradient
XFEL after rinsing: 30 MV / m
ILC operation: 31.5 MV / m (± 20%)

We put ILC-ready cryomodules into XFEL tunnel!



⟨E_{acc}⟩ = 31 MV/m

XM62 is an excellent module:
average gradient is +6 MV/m higher than in the Vertical Tests

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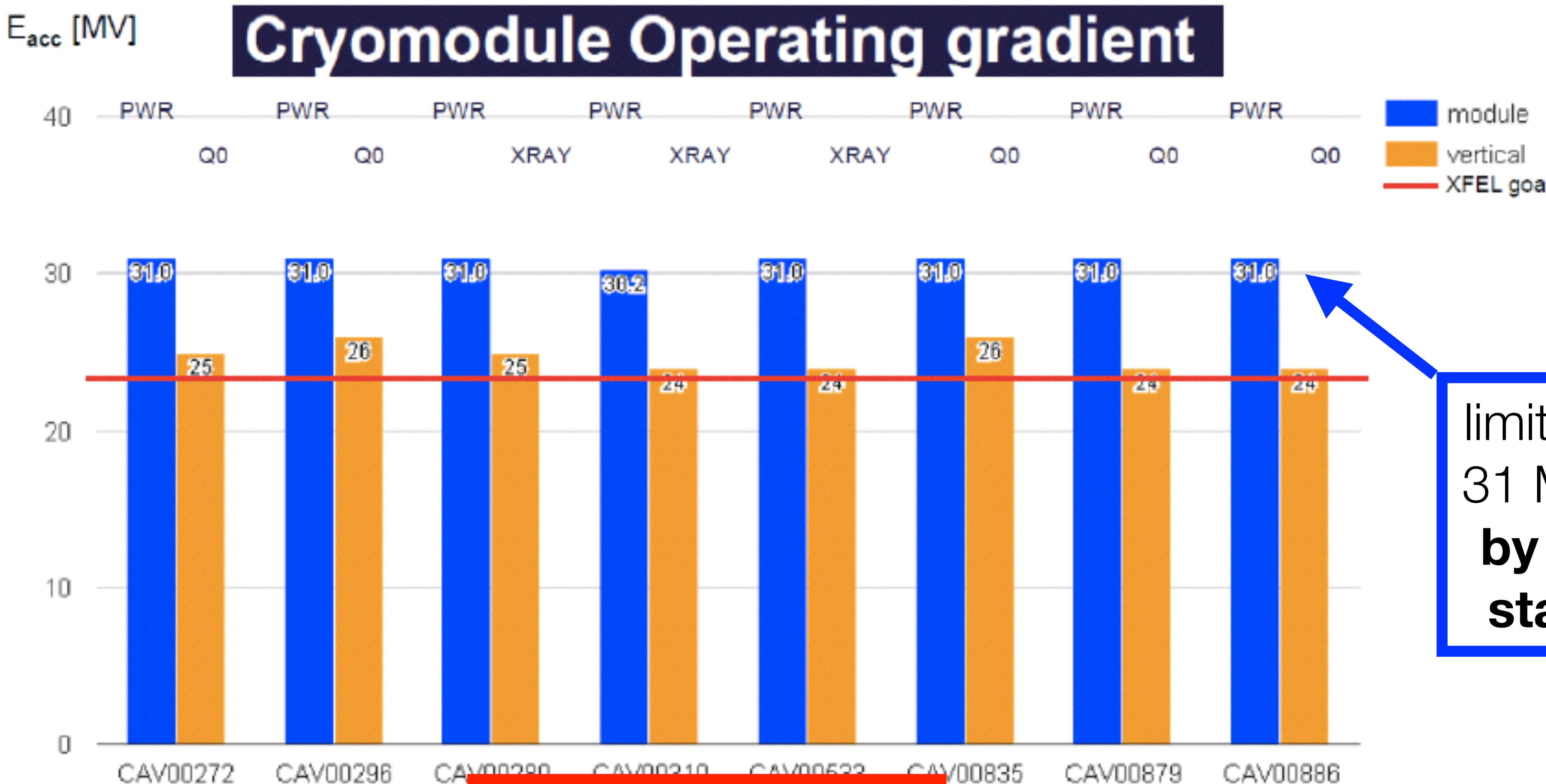

limited to 31 MV/m **by test stand!**

$\langle E_{acc} \rangle = 31$ **MV/m**

XM62 is an excellent module:
average gradient is +6 MV/m higher than in the Vertical Tests

XFEL: Industrial Mass Production of Cryomodules

XFEL cold masses at CEA Saclay

- nearly all 103 cryomodules delivered to DESY by now
- production rate:
  4 days / module achieved
- most have quality far above XFEL specifications
- costing for ILC cryomodules based on real XFEL costs

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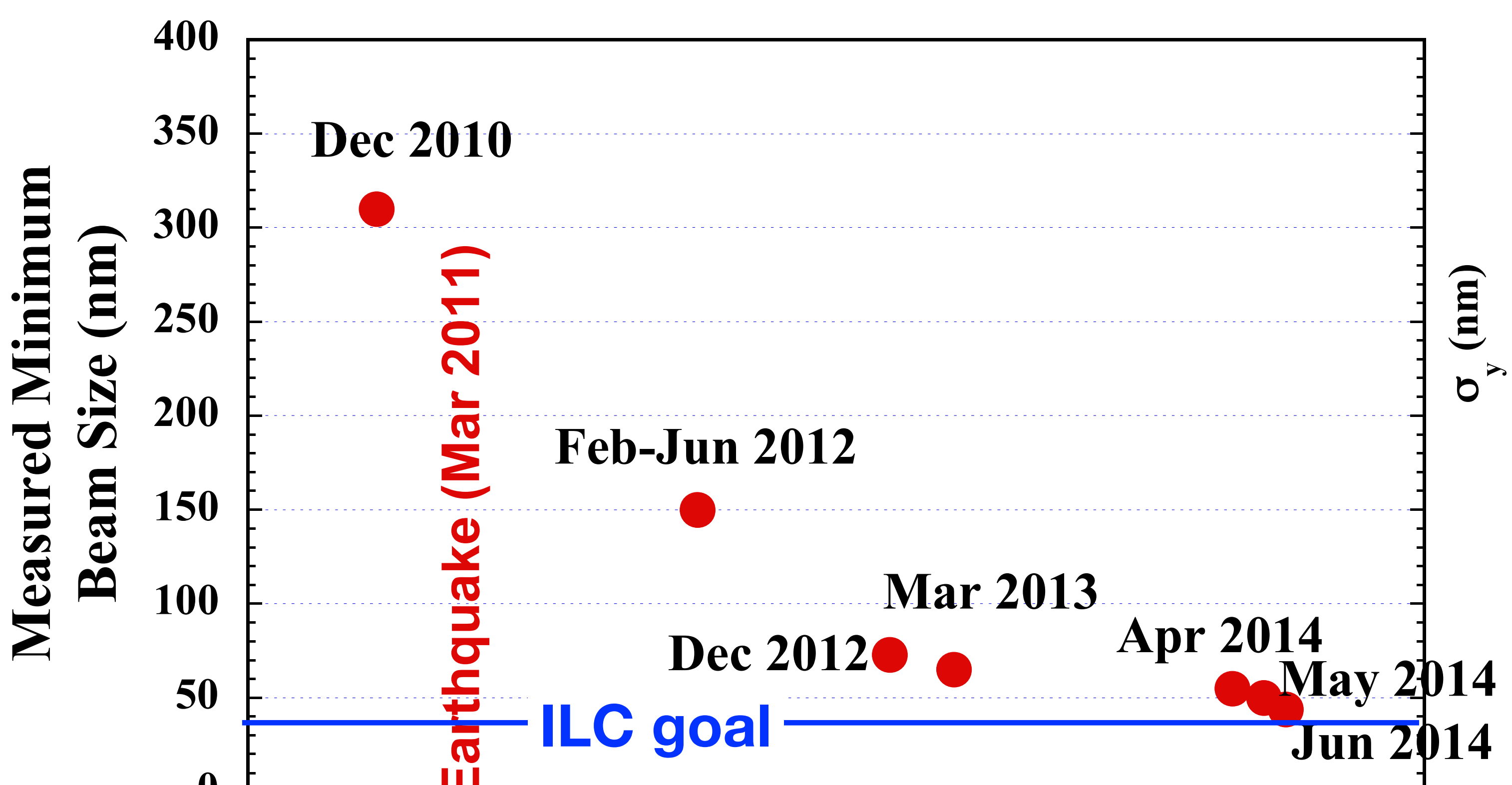
XFEL cold masses at CEA Saclay

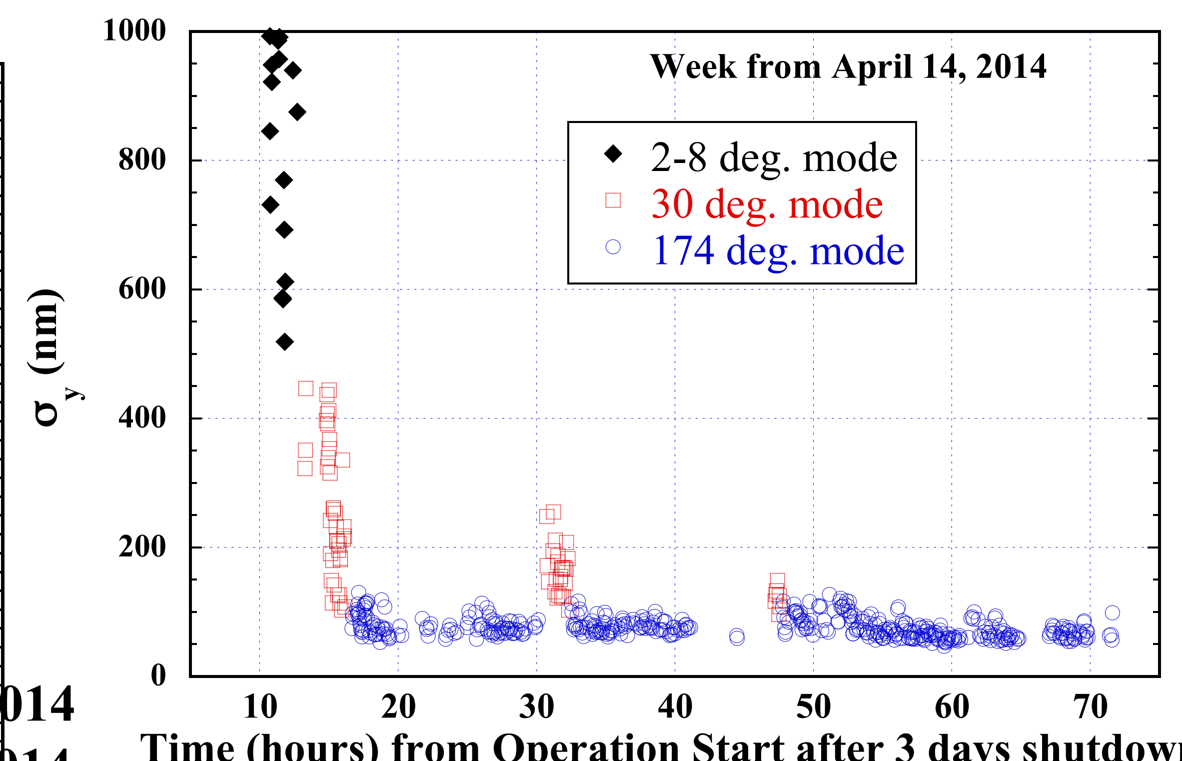
ILC-like cryomodules produced industrially by two European vendors, Germany leading

A real, linear tunnel full of cryomodules…..

Demonstrating the ILC Final Focus

- Test facility ATF2 at KEK
- 5nm @ ILC = 37nm @ ATF2
- R&D on
  - beam diagnostics
  - fast-feed back stabilisation

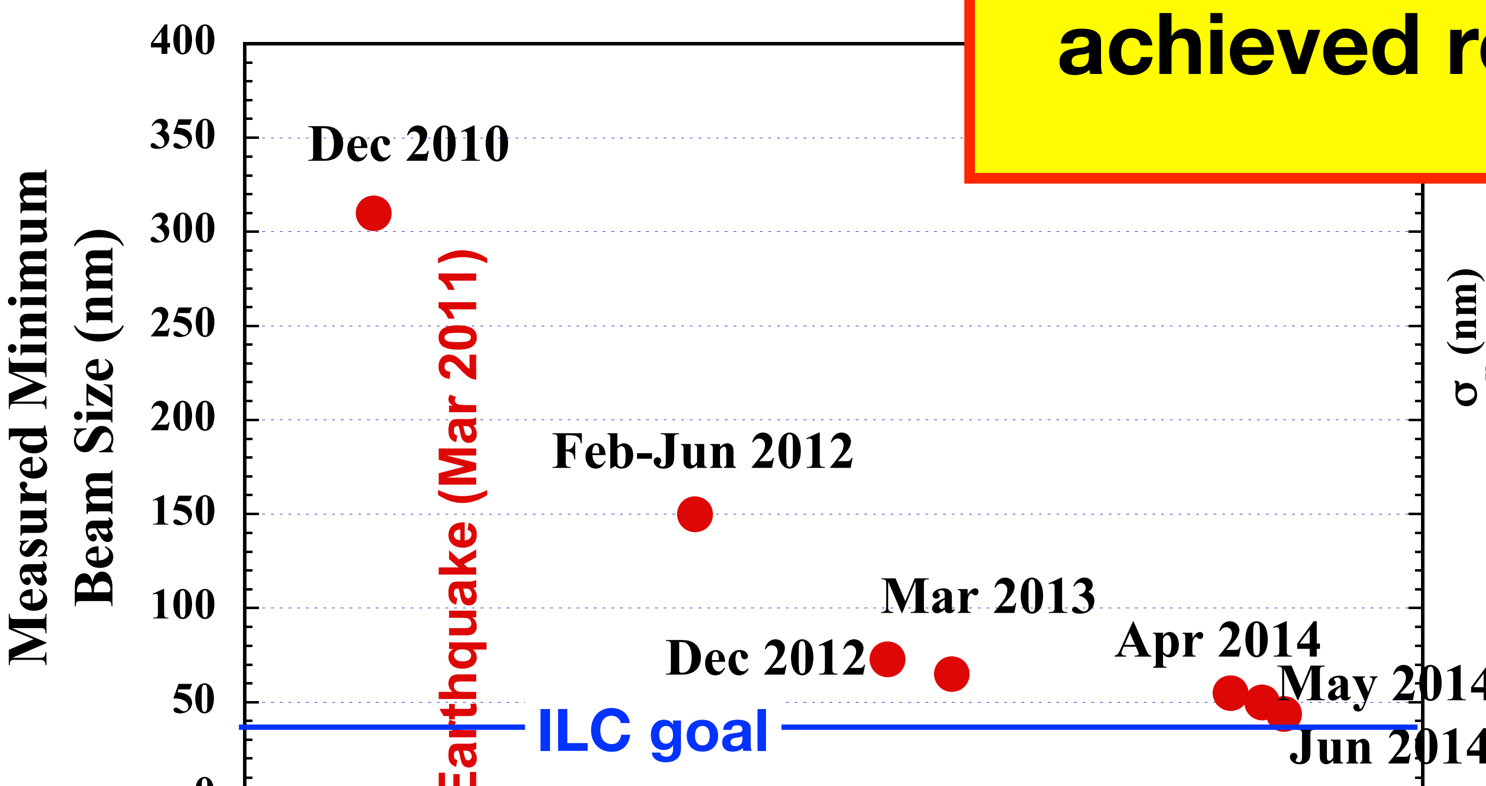


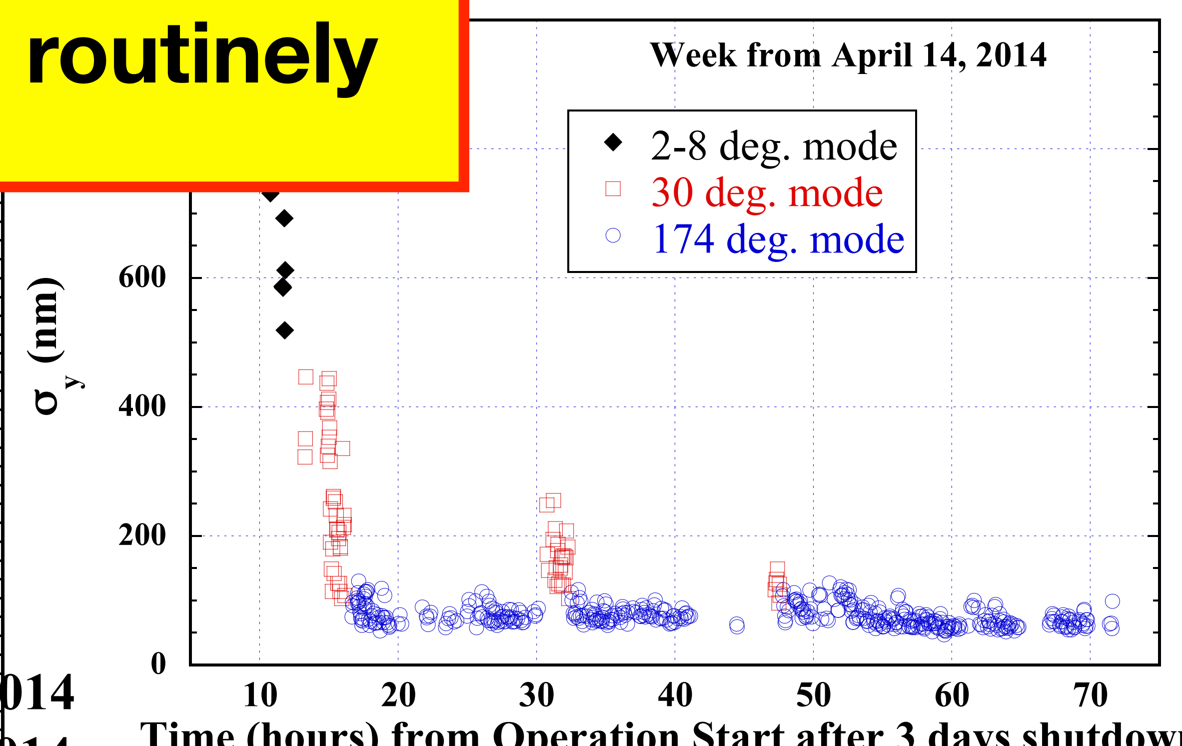


Demonstrating the ILC Final Focus

- Test facility ATF2 at KEK
- 5nm @ ILC = 37nm @ ATF2
- R&D on
  - beam diagnostics
  - fast-feed back stab

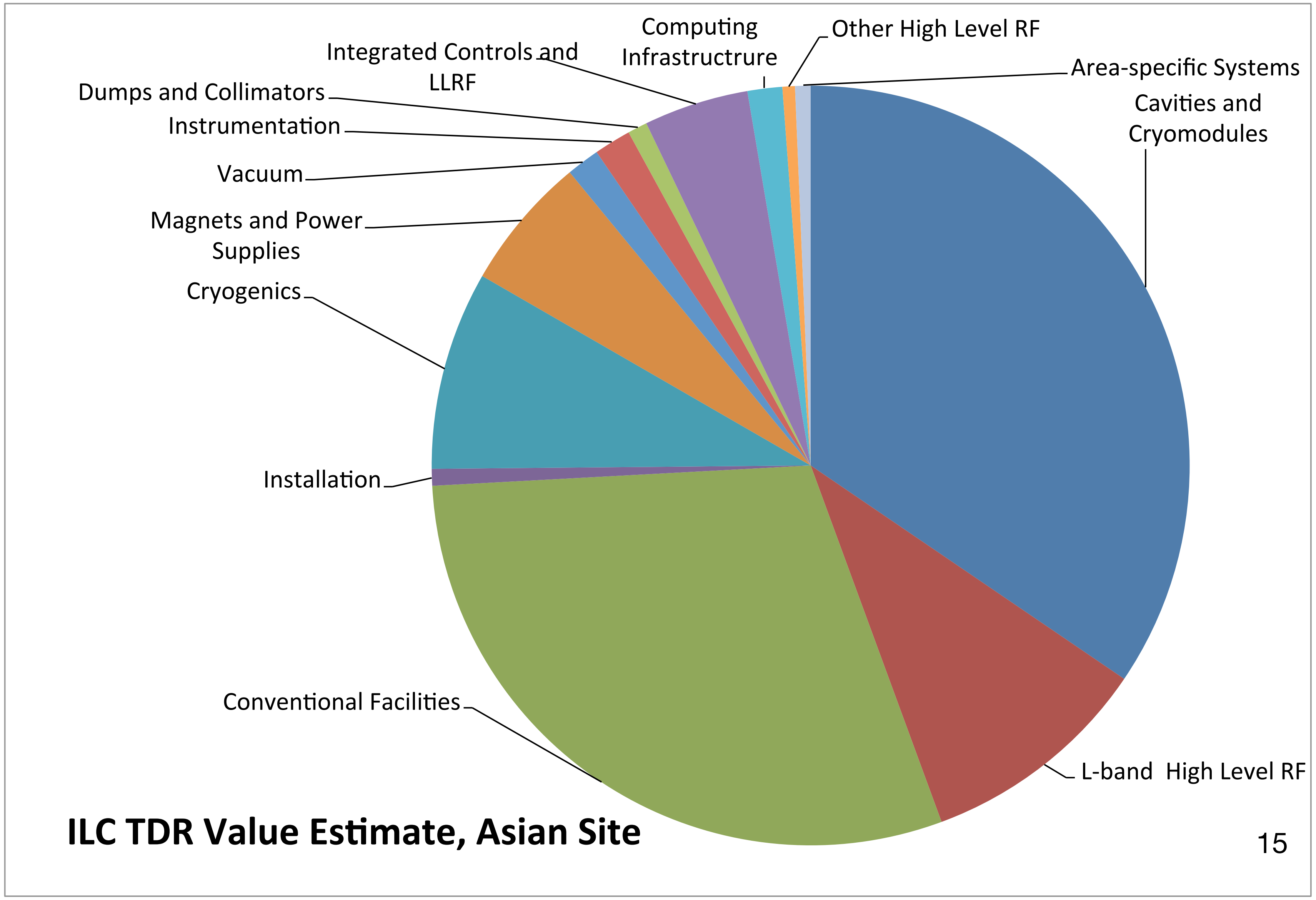
ILC-equivalent beam sizes achieved routinely





Costs

- Detailed “value estimate” costing of TDR baseline:
  - Value cost: **7.8 billion ILCU** (US$ in Jan 2012)
  - Labour: **23 million person hours** (~14 000 FTE years)
- not included:
  - R&D, detectors
  - real estate
    & development



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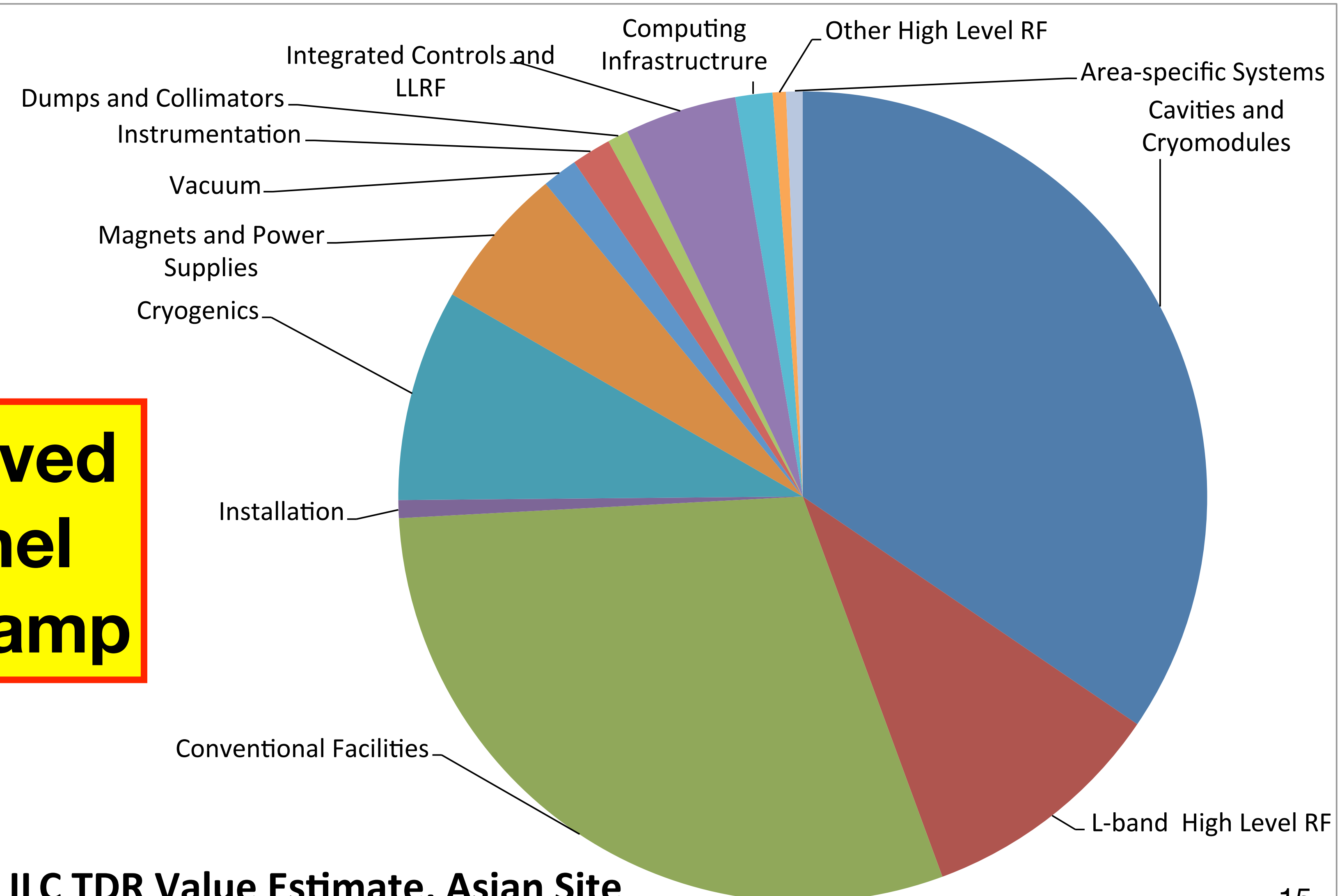
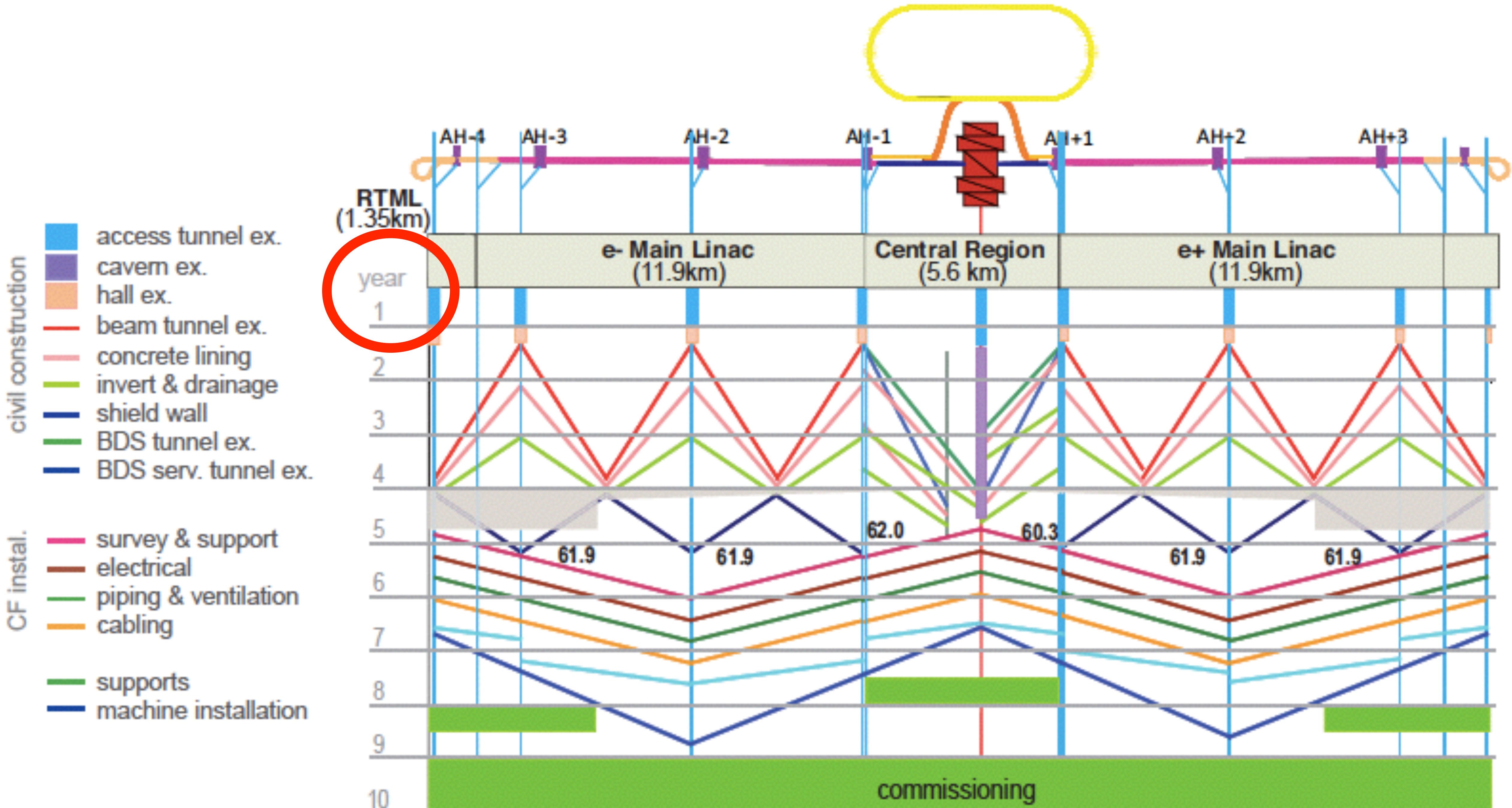
Reviewed and approved by independent panel - chaired by N. Holtkamp



ILC TDR Value Estimate, Asian Site

Construction Schedule (after ground breaking)

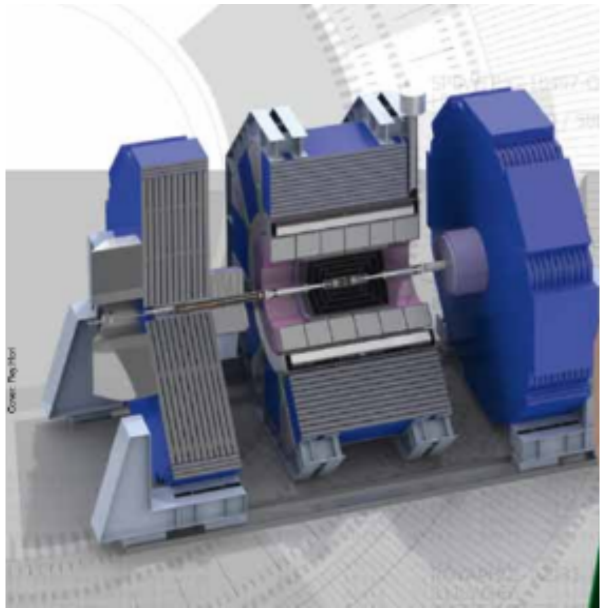


year 10 = commissioning

Operating the ILC

SCRF at high-gradients **=> pulsed operation:**

- trains of N_{bunch} = 1315 / 2625 bunches
  => 500 / 300 ns bunch spacing
- train repetition rate: 5 - 10 Hz **=> 199 - 99 ms gap**
- low duty cycle heavily exploited in detector design: **power pulsing**
- **saves factor 100 in detector power => cooling!**
- enables

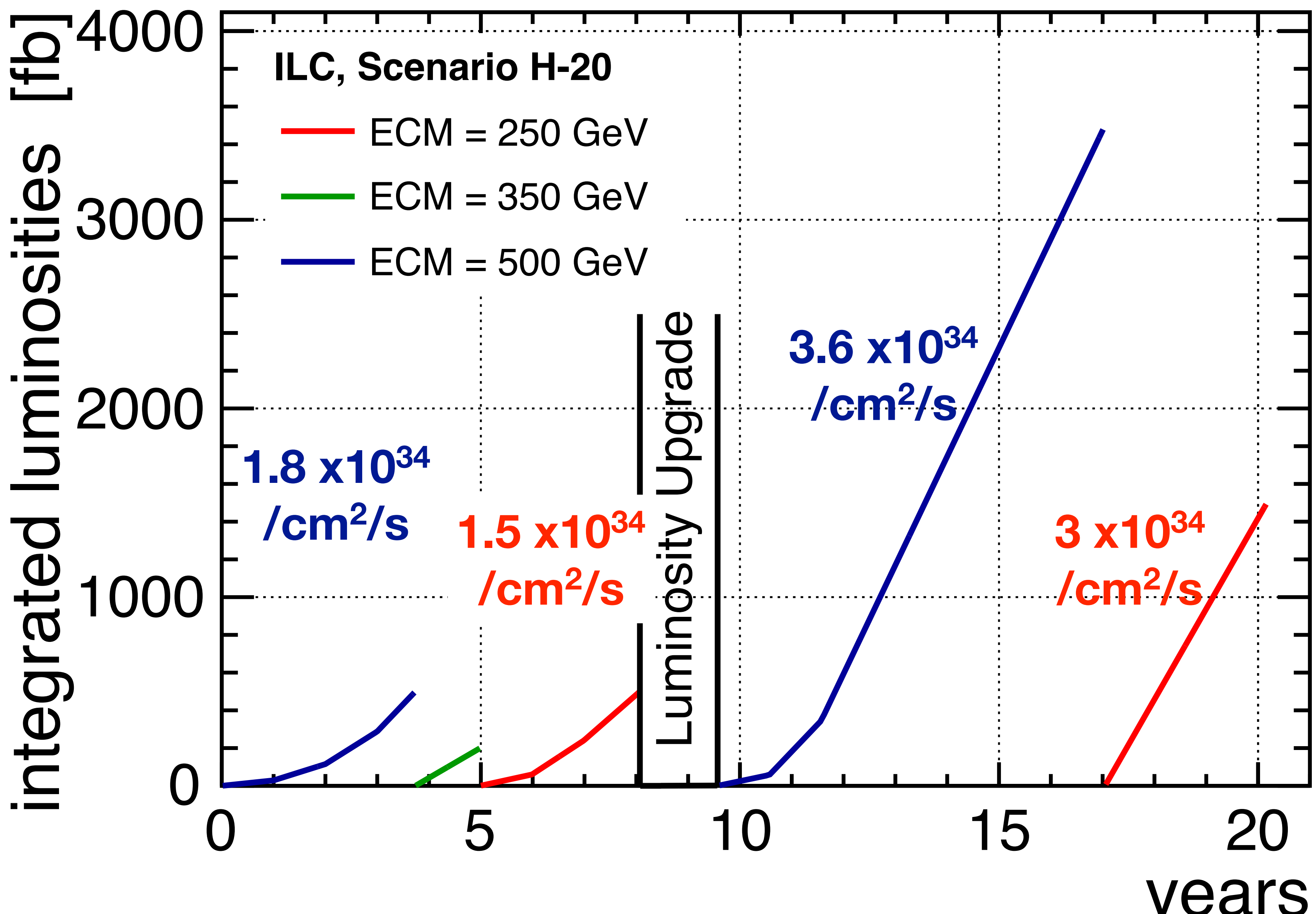


- **low-mass trackers**
- **dense calorimeters**

....at the heart of detectors optimised for particle flow

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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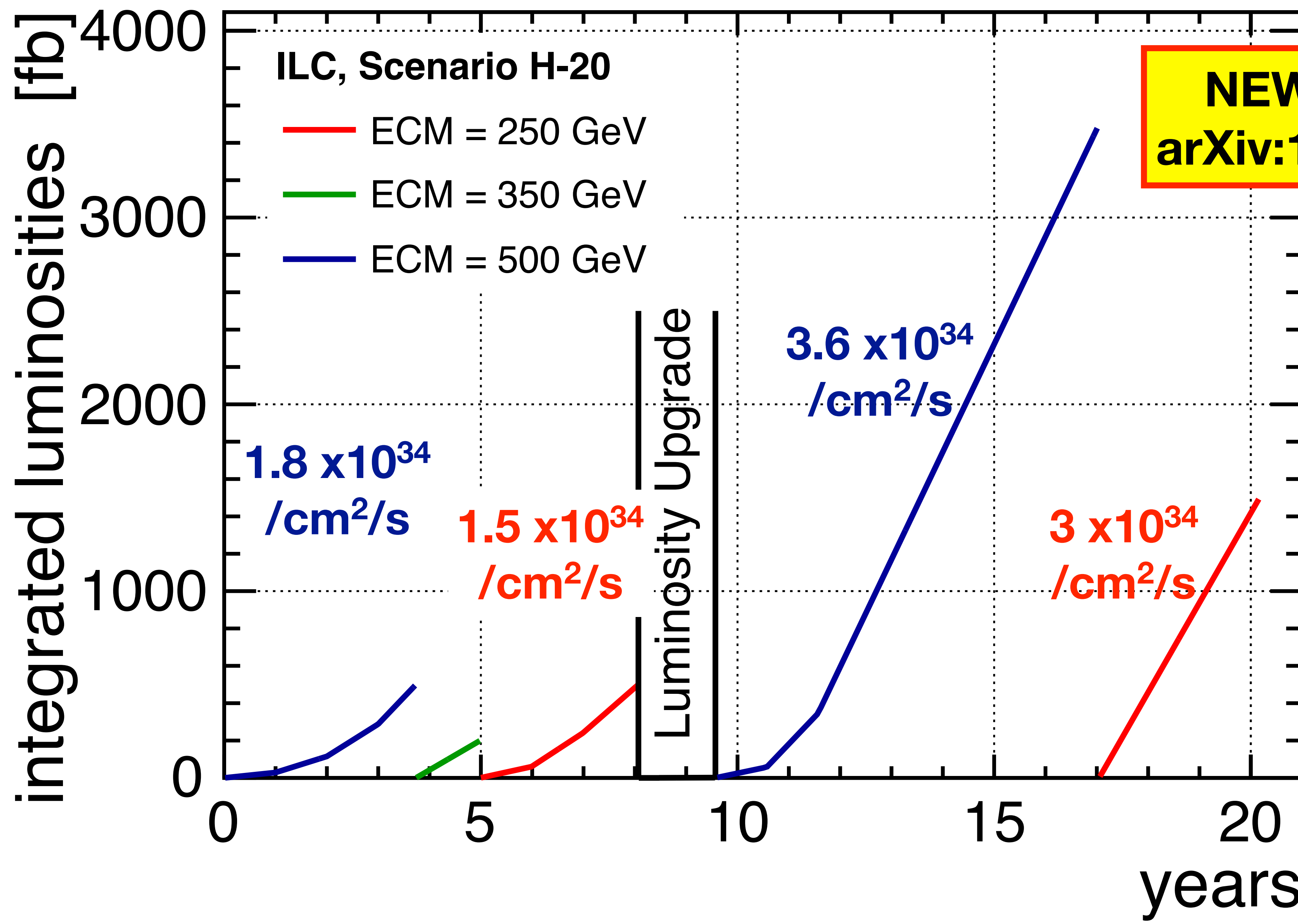

NEW in 2015
arXiv:1506.07830

Total integrated luminosities

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refer to these as full ILC500 programme

…. and beyond the Strawman Programme

also defined reference luminosities
to be used in physics studies for

- **$\sqrt{s}$ = 1TeV:** Higgs self-coupling, BSM
- **$\sqrt{s}$ = 91 GeV:** ew precision
- **$\sqrt{s}$ = 161 GeV:** W mass to few eV

for these energies, beam parameters are to be considered preliminary

Total integrated luminosities

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All with *both* beams polarised!

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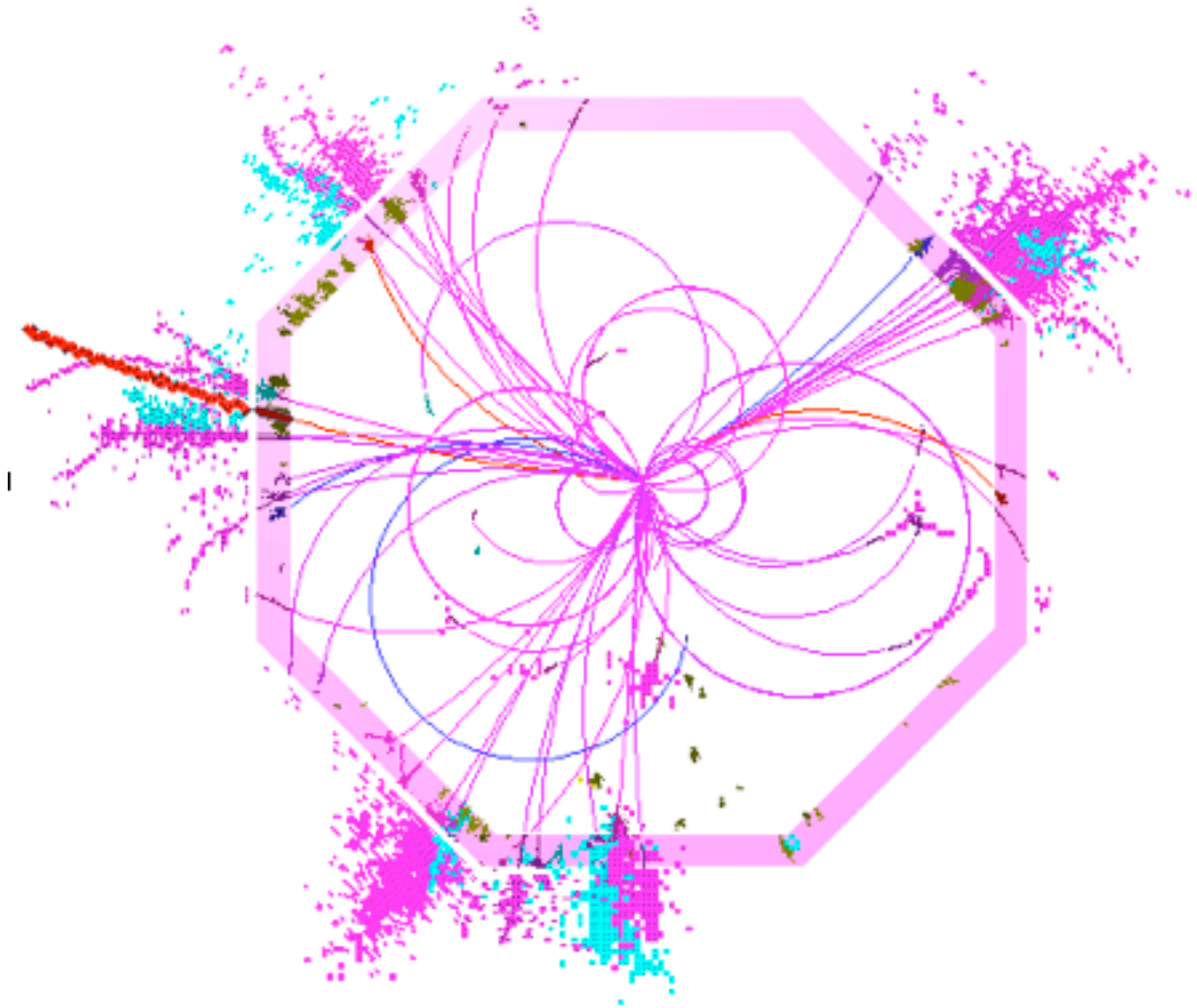
All with *both* beams polarised!

Discoveries at LHC (or at ILC itself!) might change run plan anytime

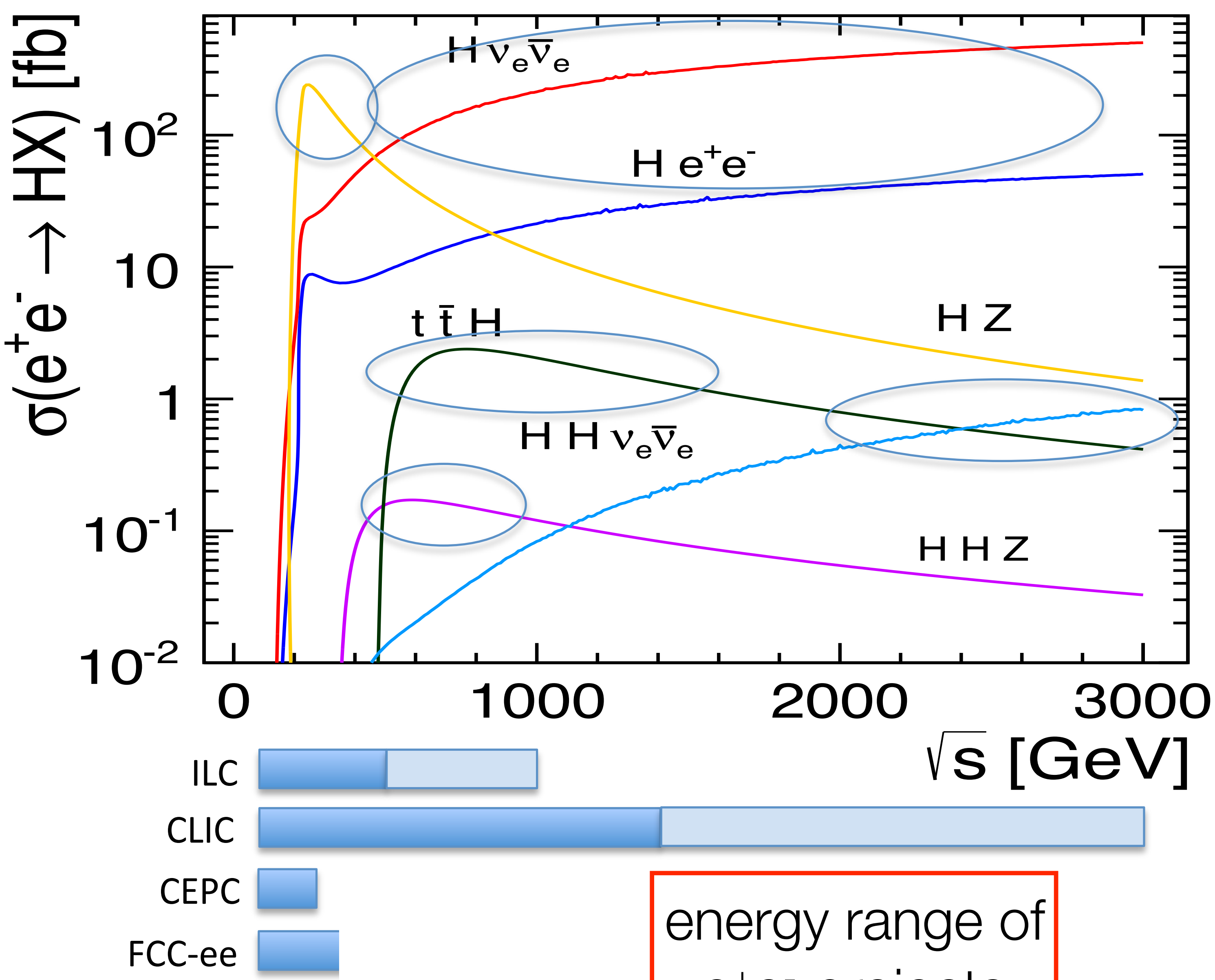
Flexibility remains a key asset of the ILC



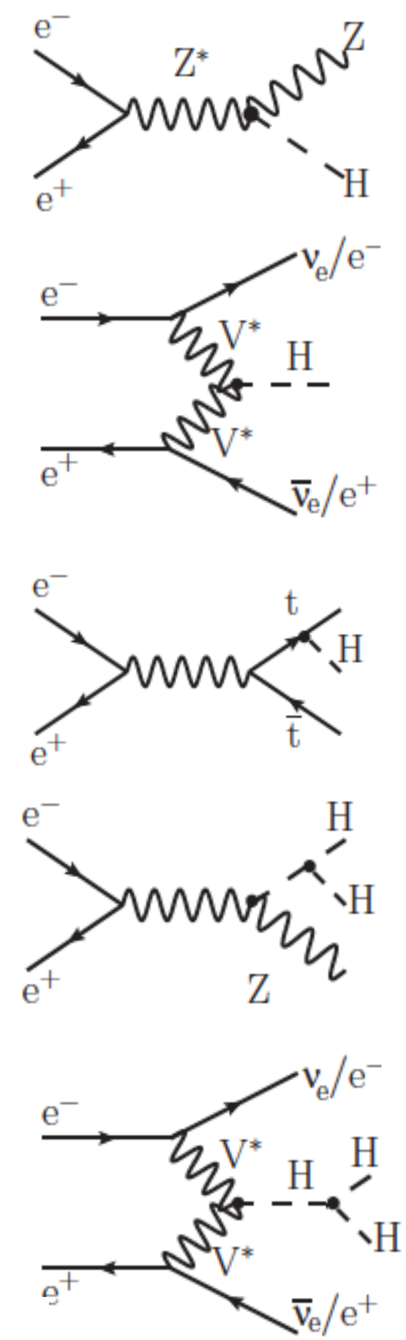
ILC Analysis Highlights

All plots & results based on **full, geant4-based detector simulation** gauged against **testbeam performance** of **prototype detectors** (unless stated otherwise)

Higgs production in e^+e^- collisions

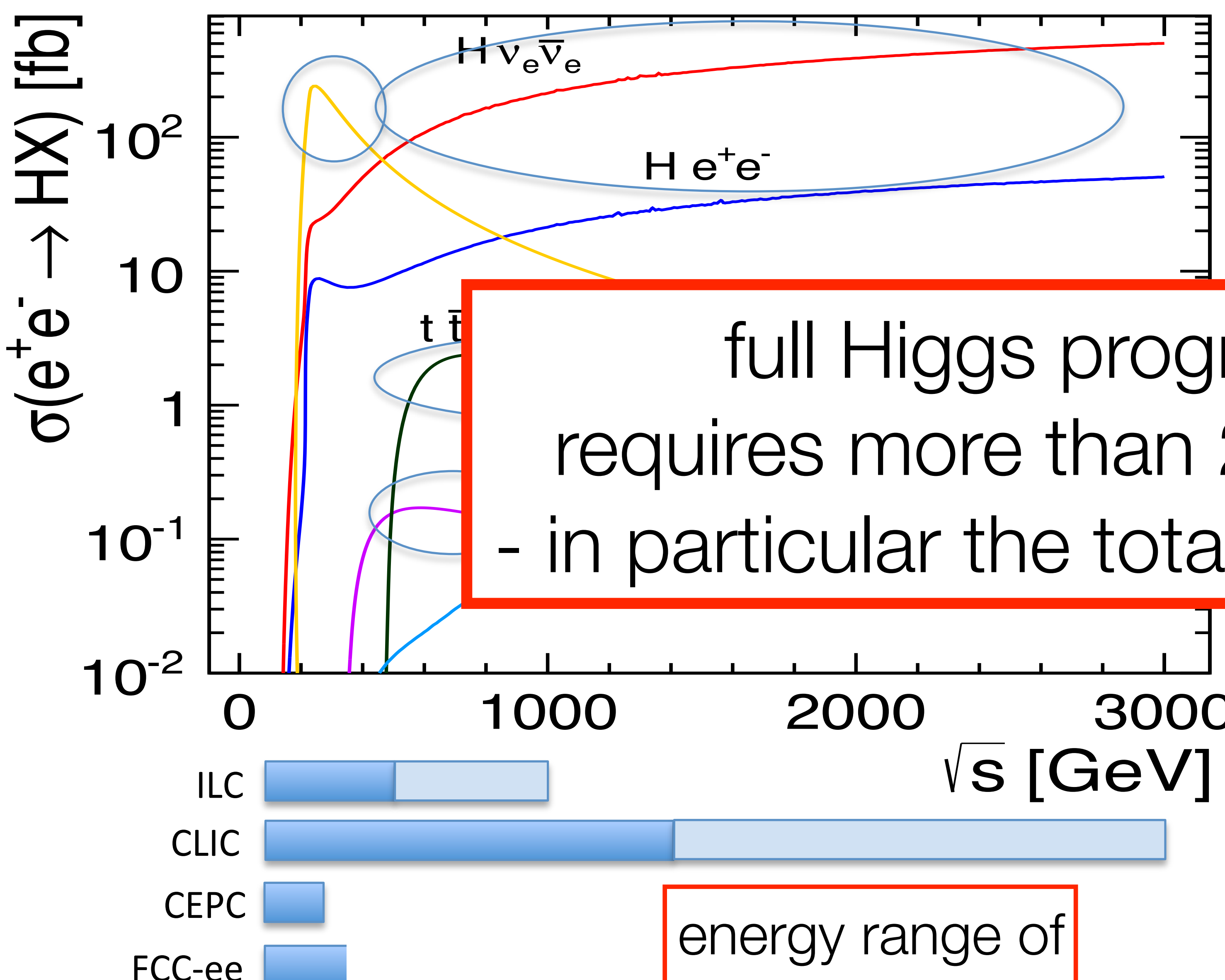


energy range of e^+e^- projects



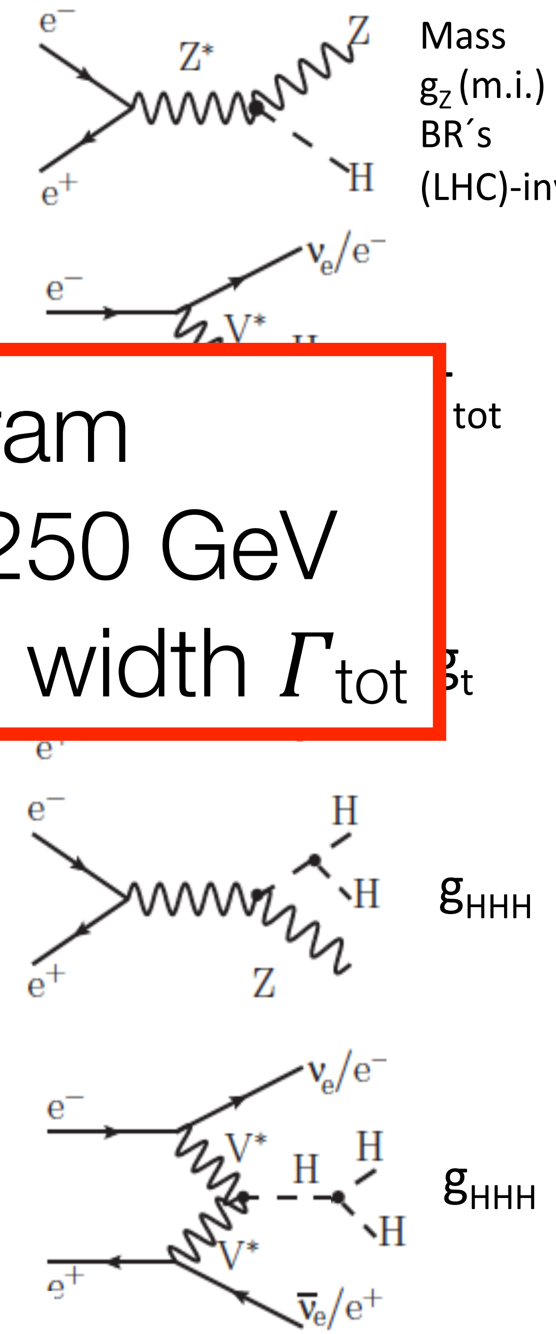
Mass g_Z (m.i.) BR´s (LHC)-invisible	≥ 250 GeV
Γ_{tot}	≥350 GeV
g_t	≥500 GeV
g_{HHH}	≥500 GeV
g_{HHH}	≥ 1 TeV

Higgs production in e⁺e⁻ collisions



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

energy range of e^+e^- projects



≥ 250 GeV

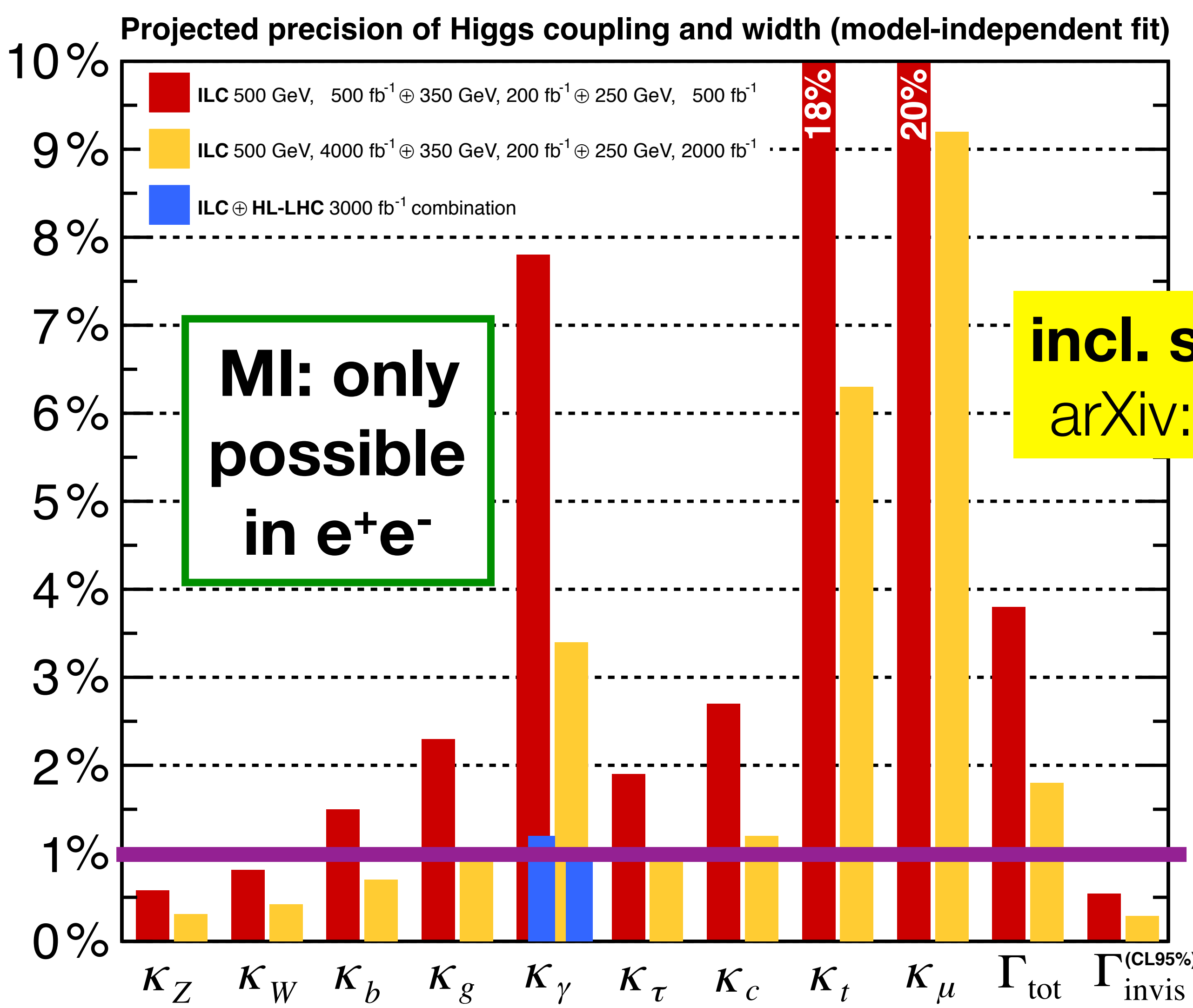
≥350 GeV

≥500 GeV

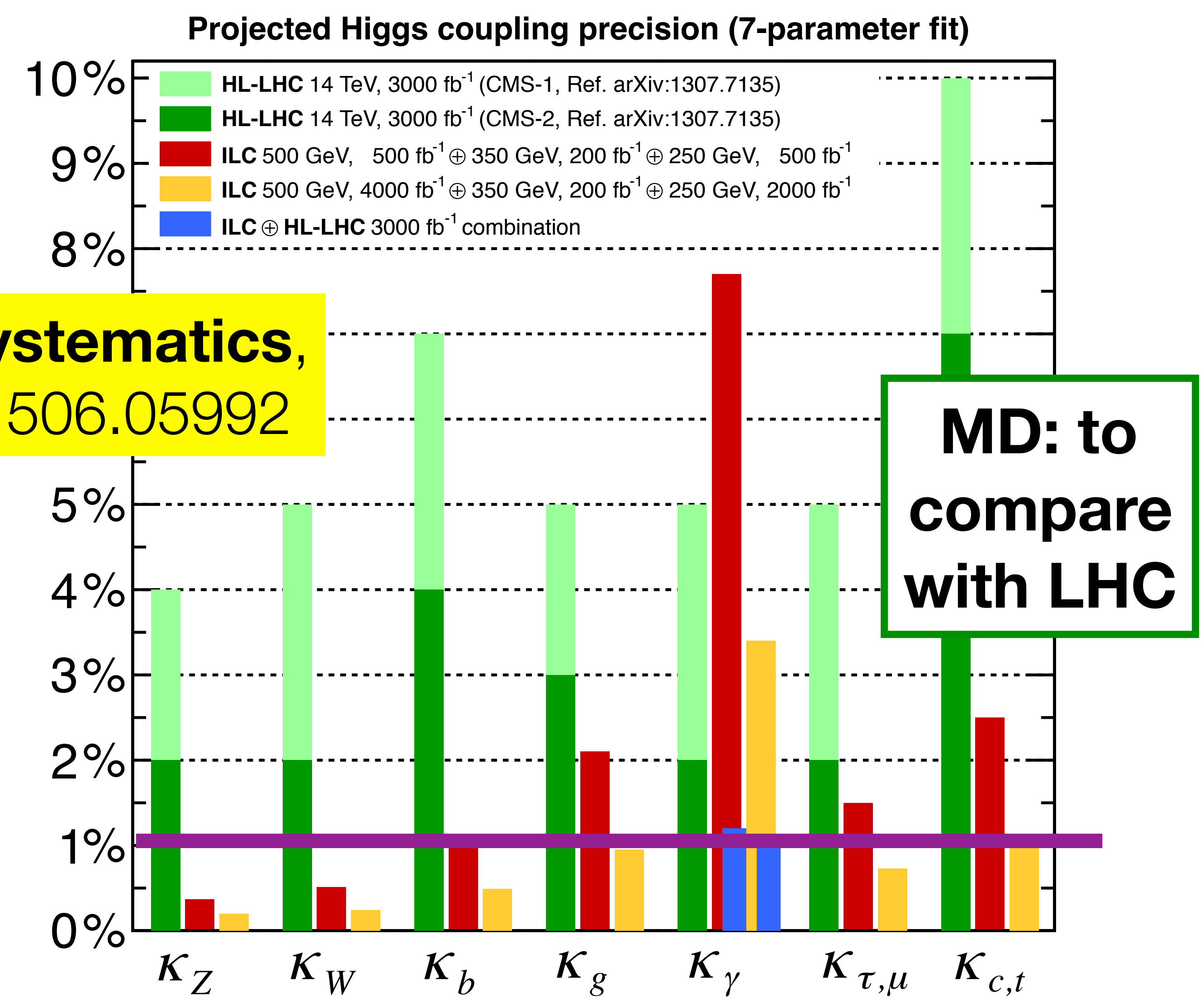
≥500 GeV

≥ 1 TeV

Higgs Couplings

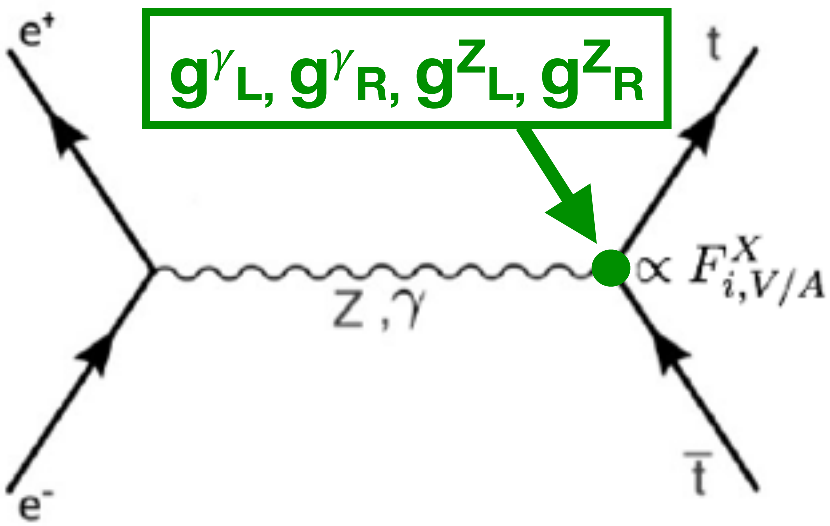


incl. systematics, arXiv:1506.05992



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

Electroweak Couplings of the Top Quark

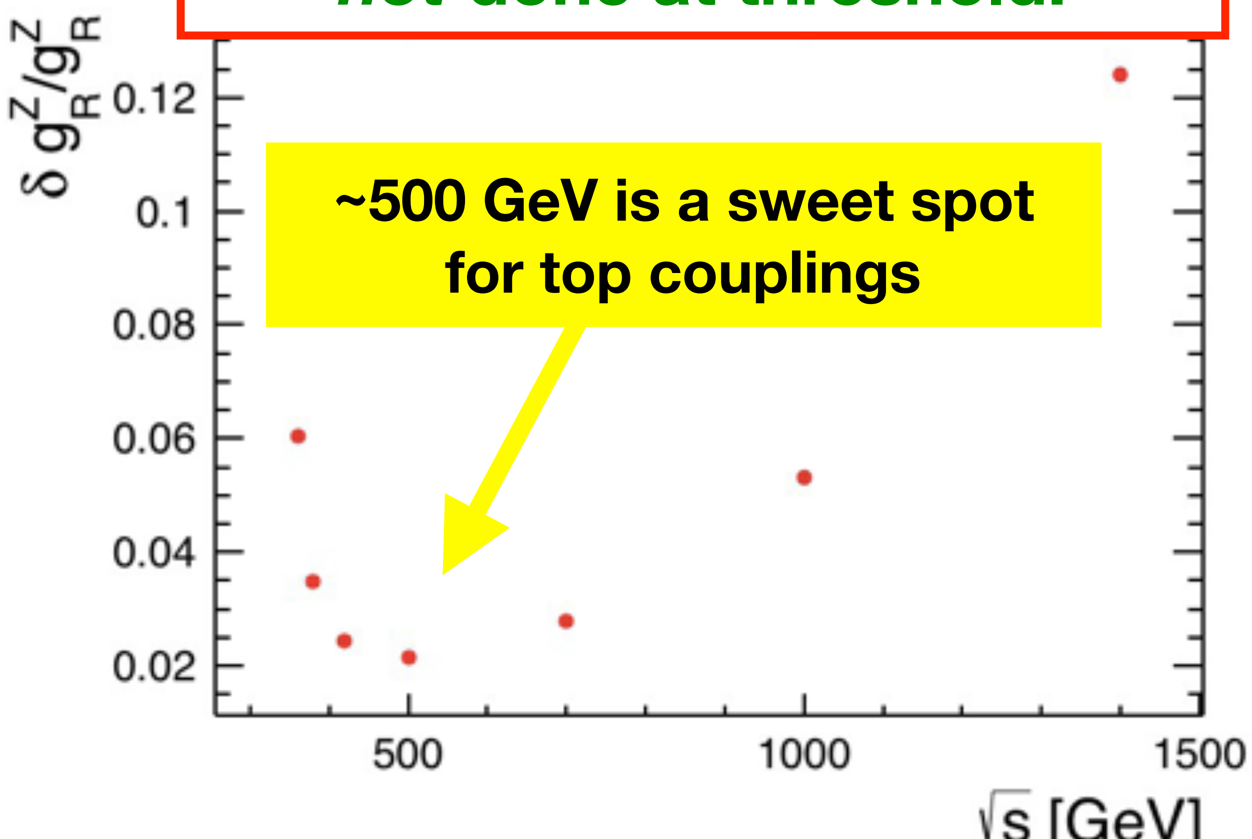


Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

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

ILC 'provides' two beam polarisations

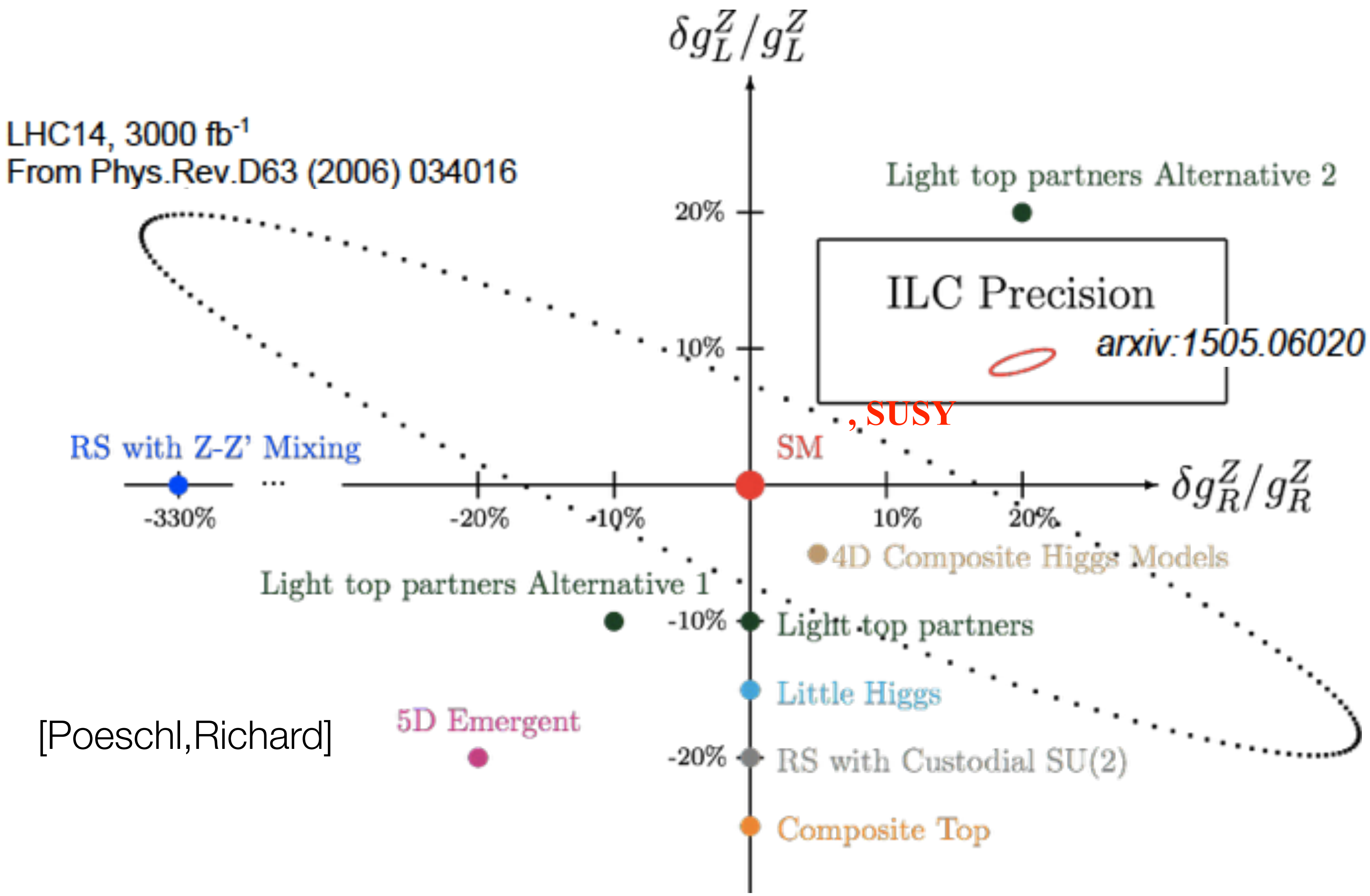
√s dependency: top physics is *not* done at threshold!



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

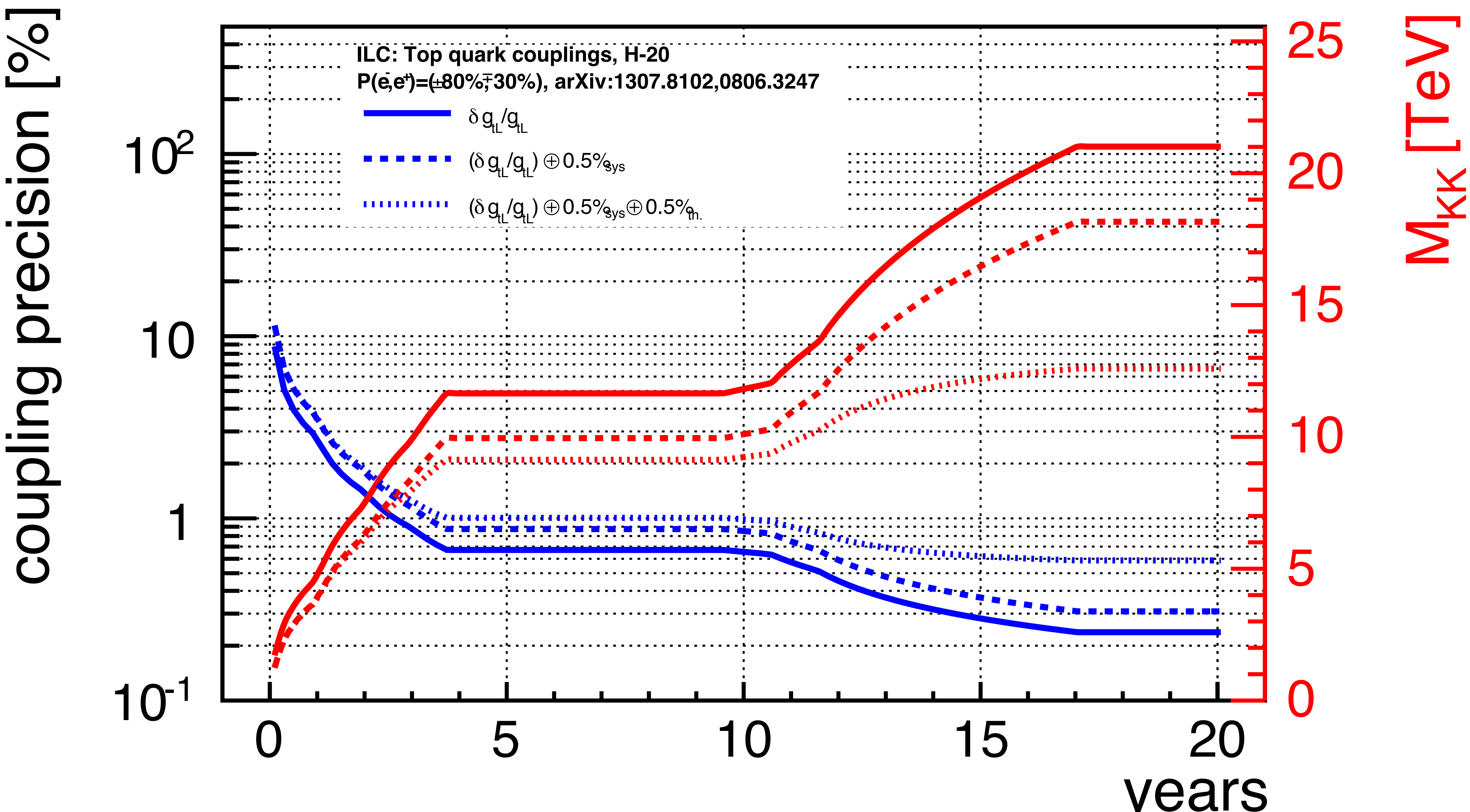


Sensitivity to huge variety of models with **compositeness and/or extra-dimensions** complementary to resonance searches

- ILC precision allows model discrimination
- sensitivity in g^Z_L, g^Z_R 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 Pomerol 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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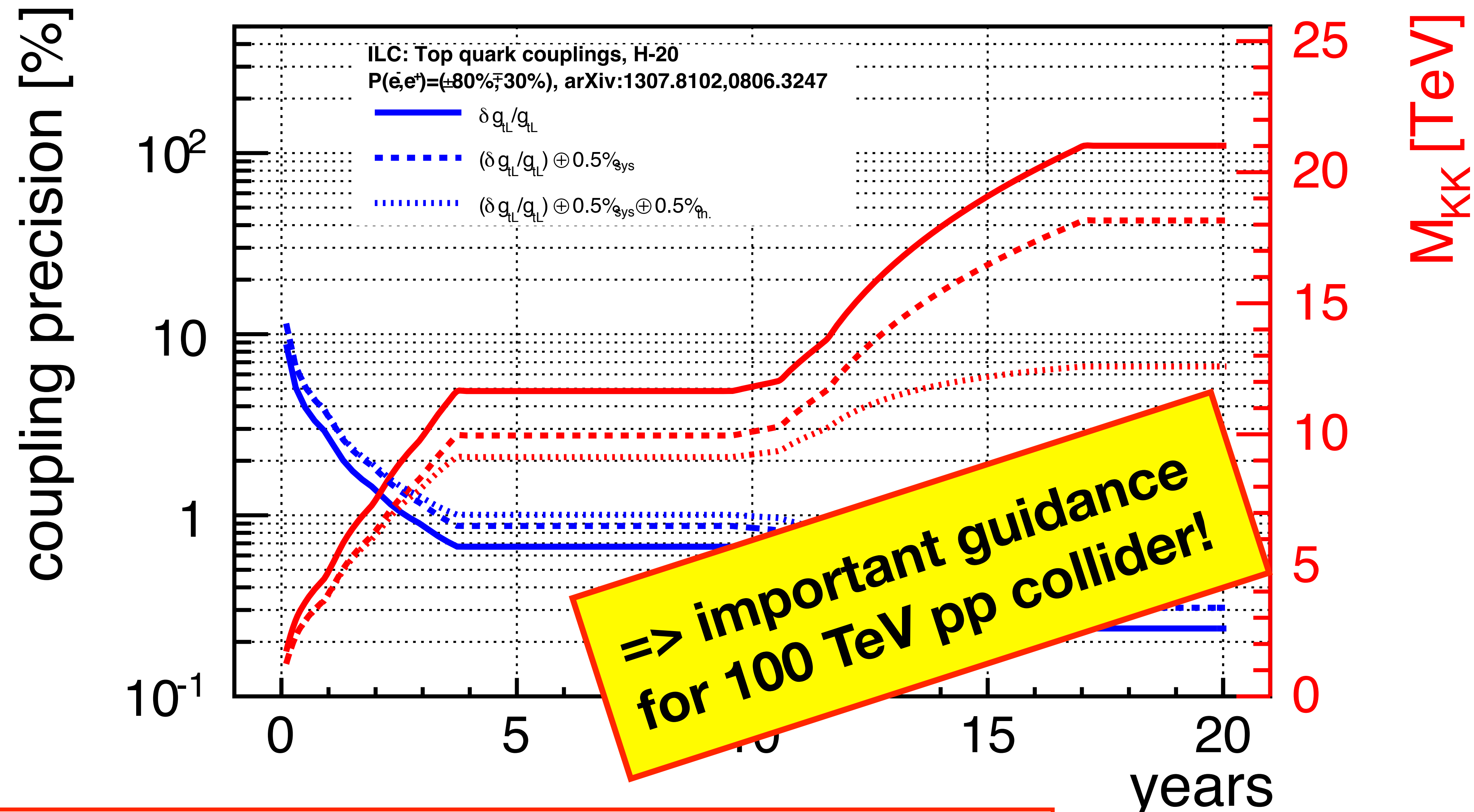

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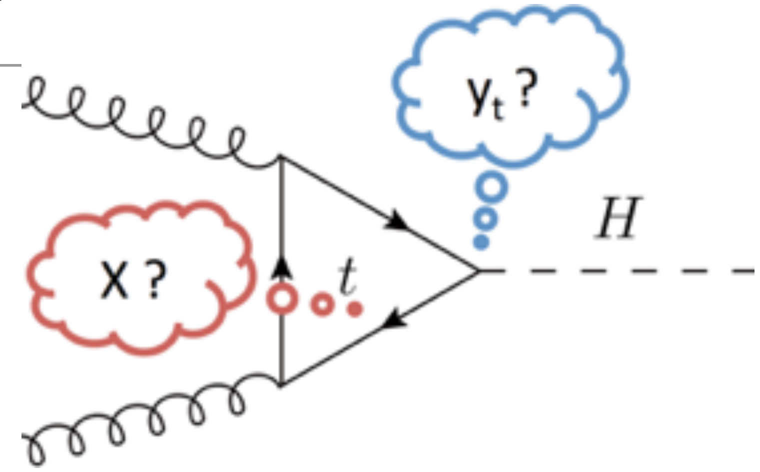
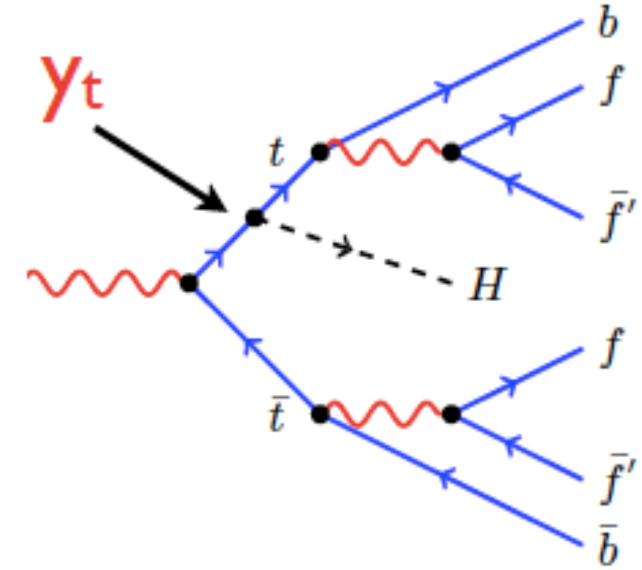
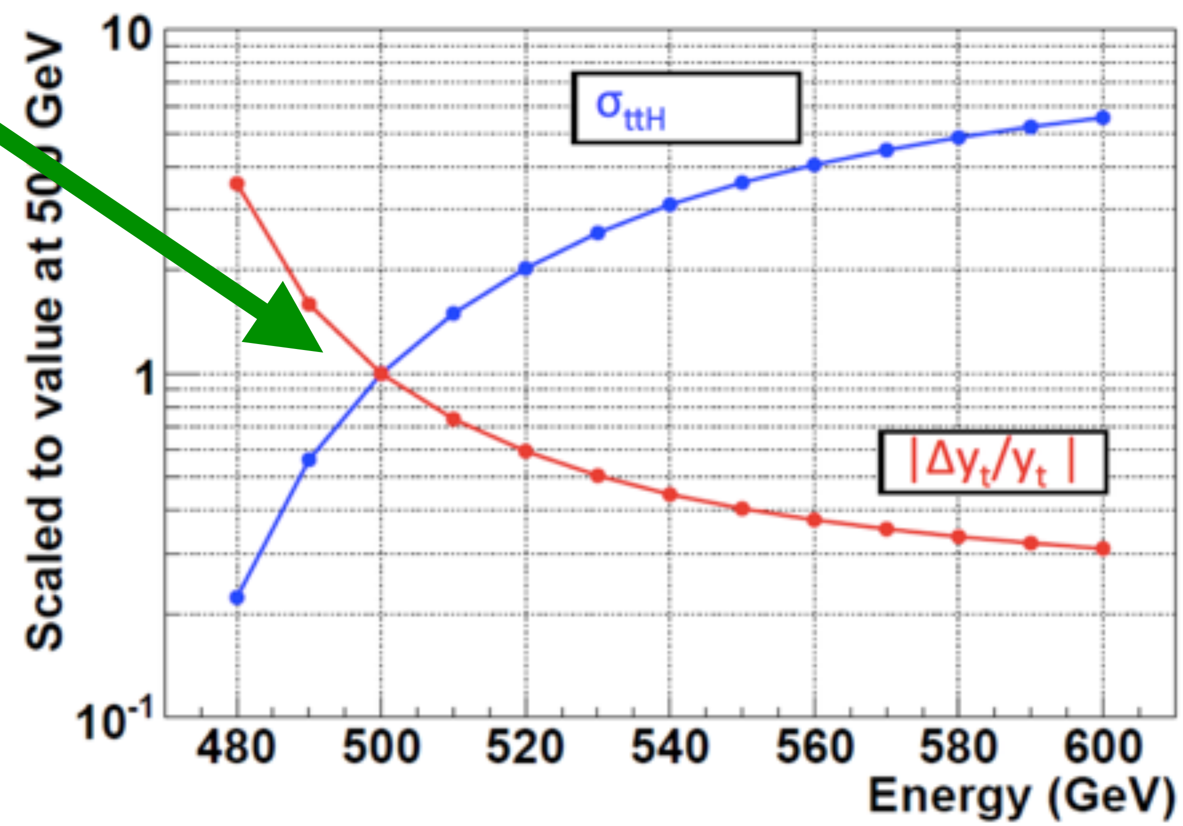
Top Yukawa Coupling

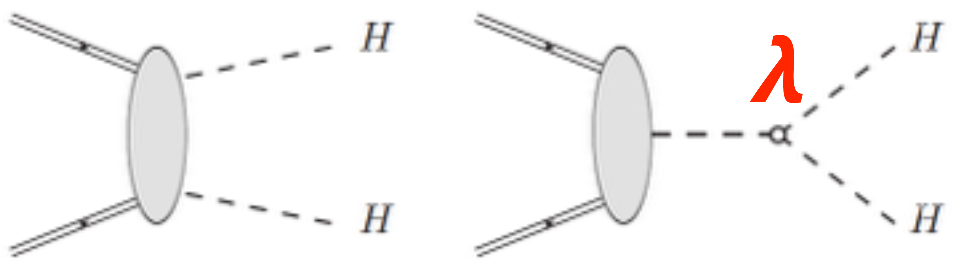
- **Indirect**: loop couplings, top threshold scan …
  => is it *really* y_t ?
- **Direct**: tth production
  => possible for $\sqrt{s} \geq 500$ GeV
- SM **σ(ttH) = 0.45fb** @ 500 GeV
  => ILC500 full running scenario, geant4-based detector simulation:
  δy_t = 6.3%
- ILC tunnel length contains 1.5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

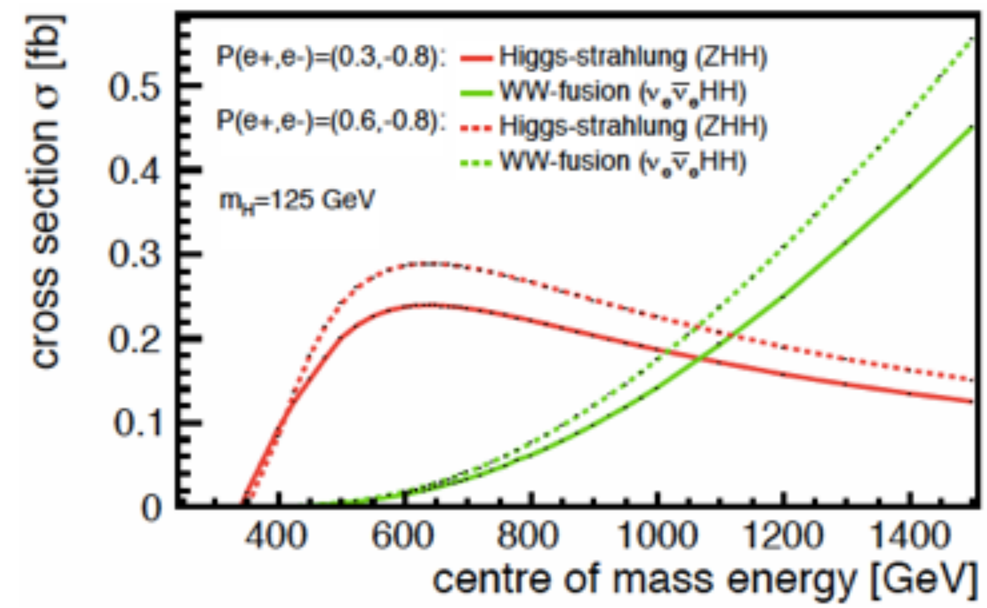






Double Higgs Production & Higgs Self-Coupling





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**
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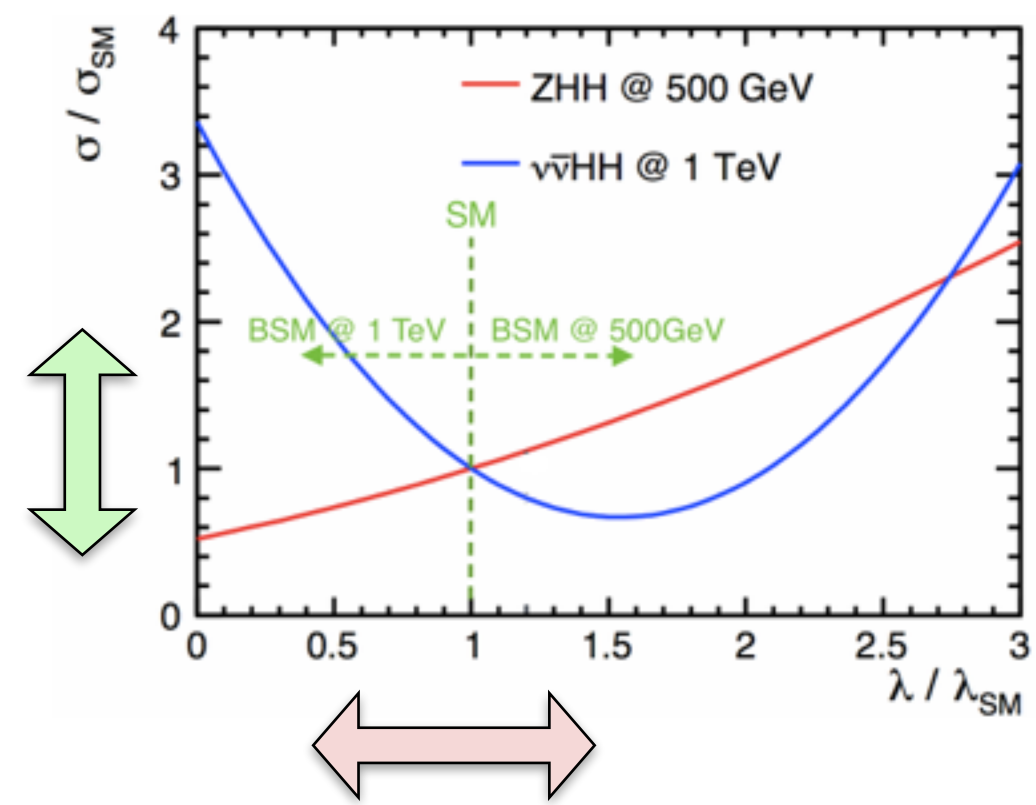

BSM changes the picture: e.g. λ = **1.5** λ_{SM}

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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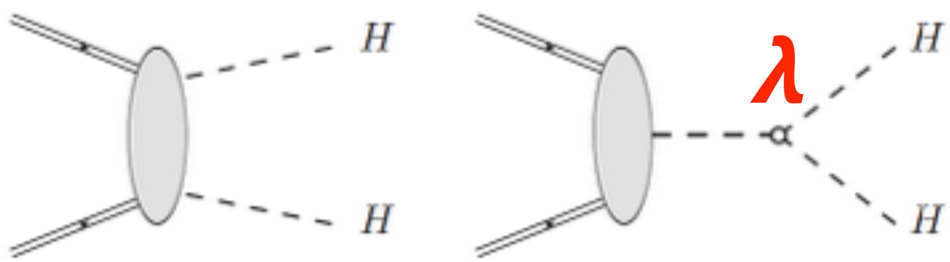

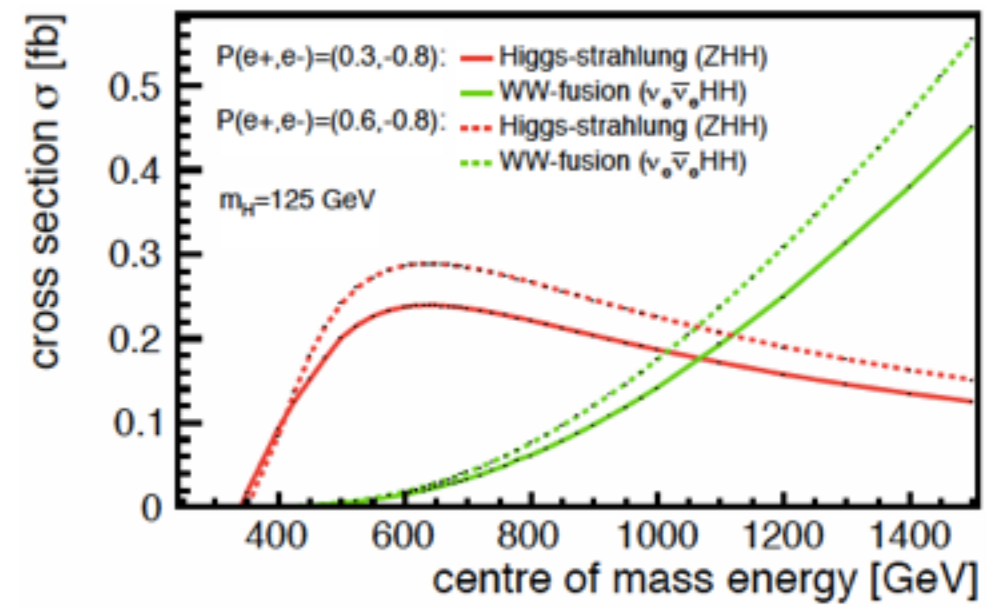

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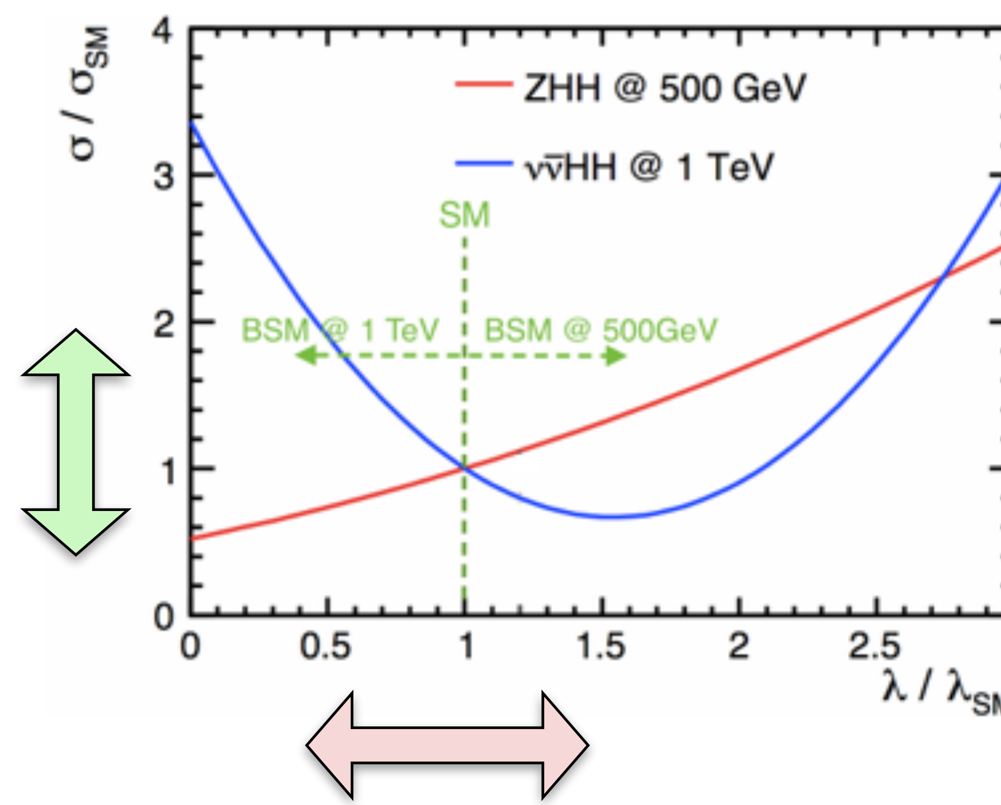

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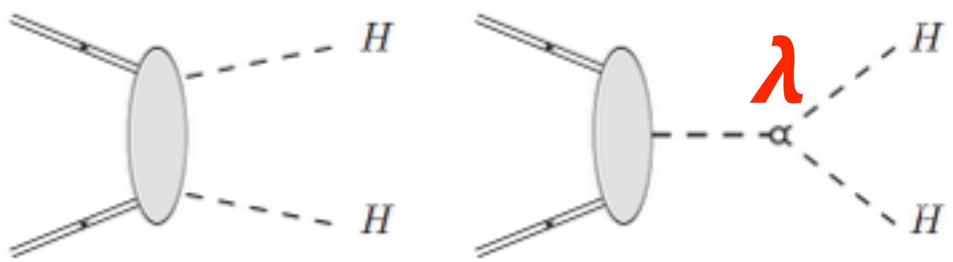

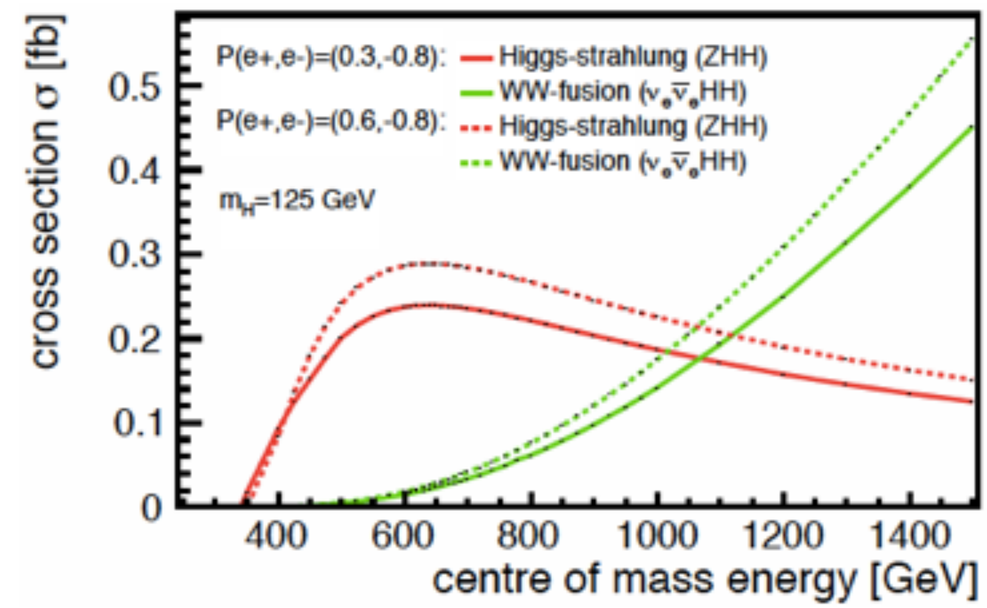

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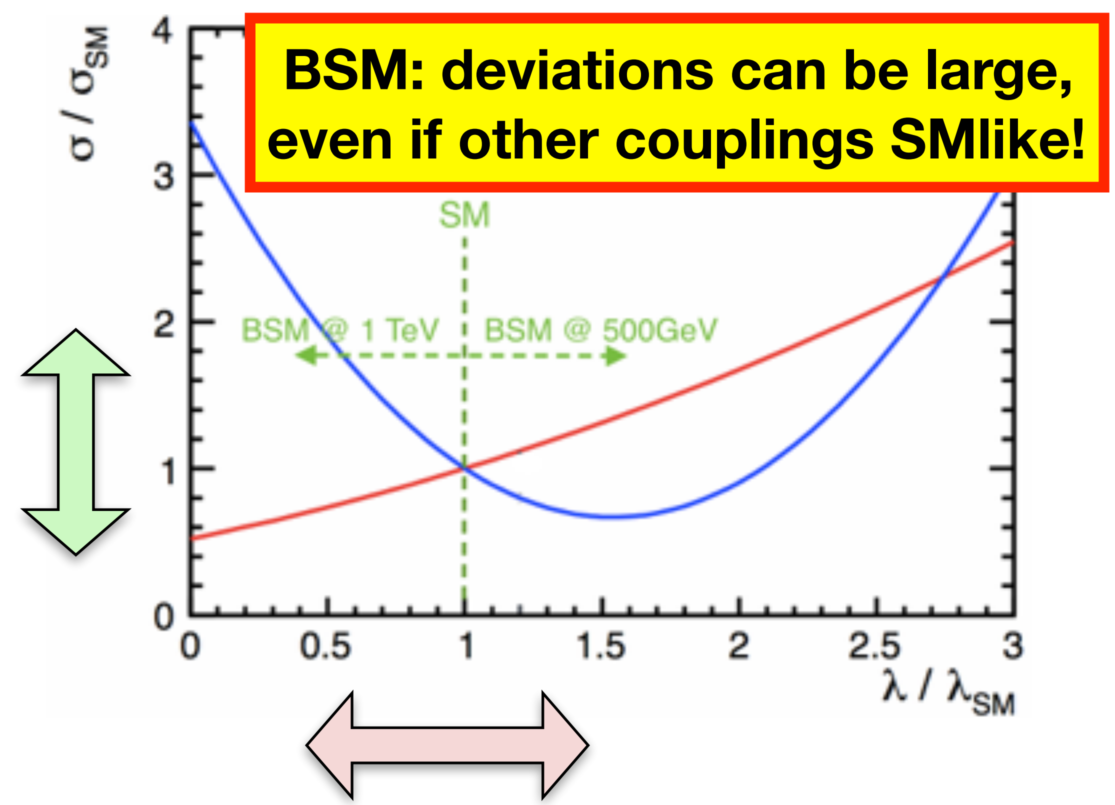

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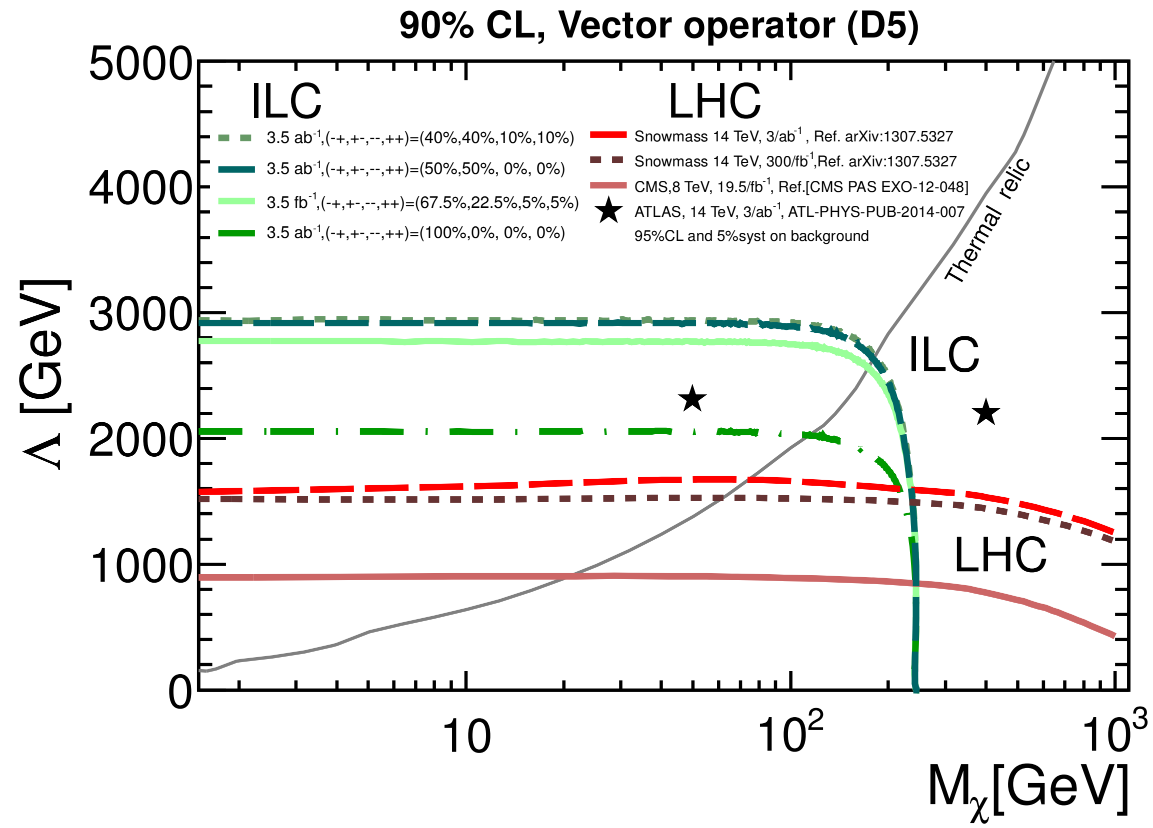
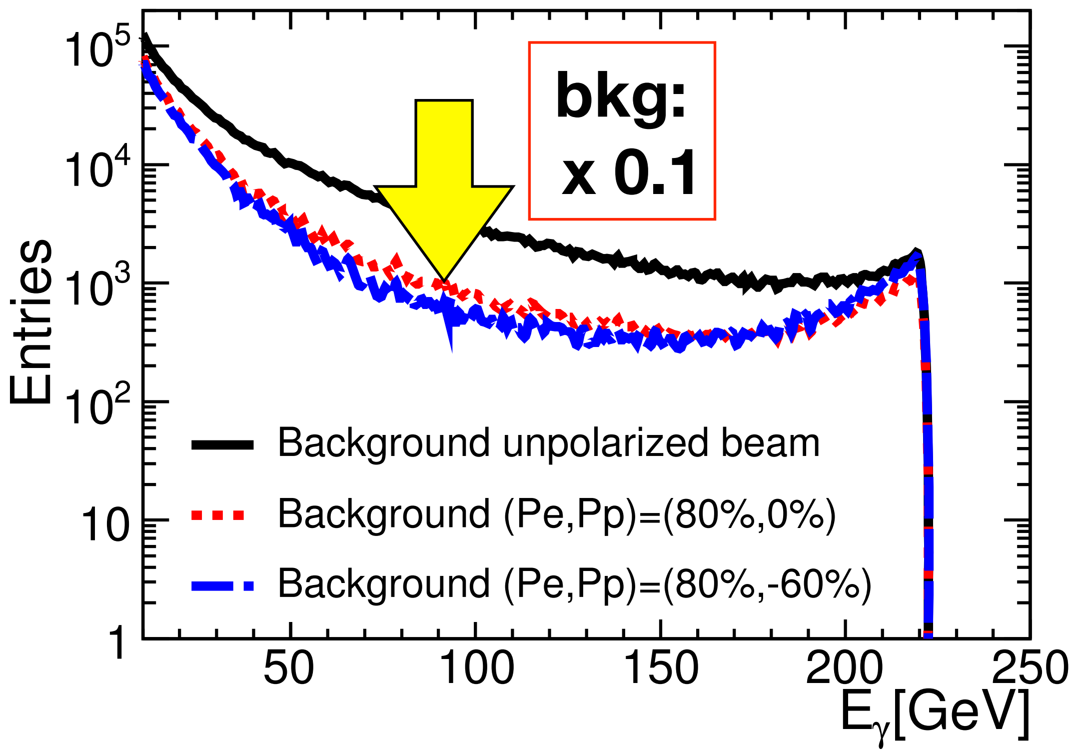
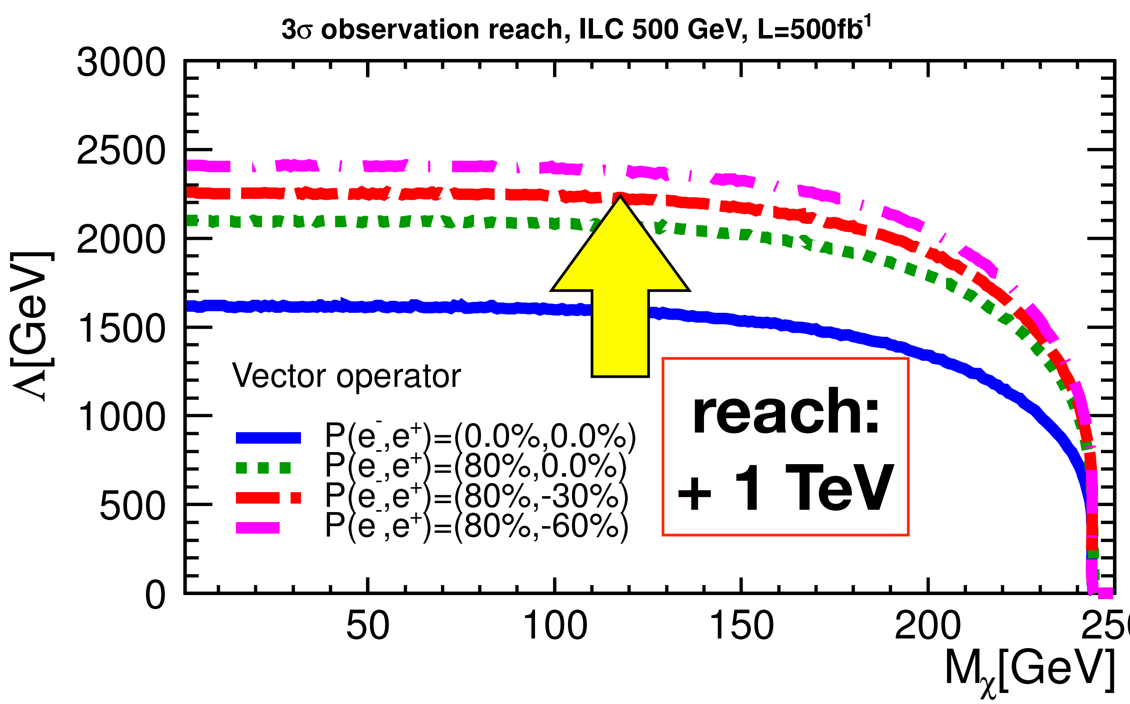
Generic Dark Matter

- **full complementarity to LHC / direct detection:**
  - lepton vs hadron couplings
  - large mediator scale vs large DM mass:
    ILC500: up to Λ = 3 TeV for M_χ < 250 GeV
- **beam polarisation is essential:**
  - suppress background by factor ~10
    => gains 1 TeV in reach!
  - *and:* analysis of potential signal

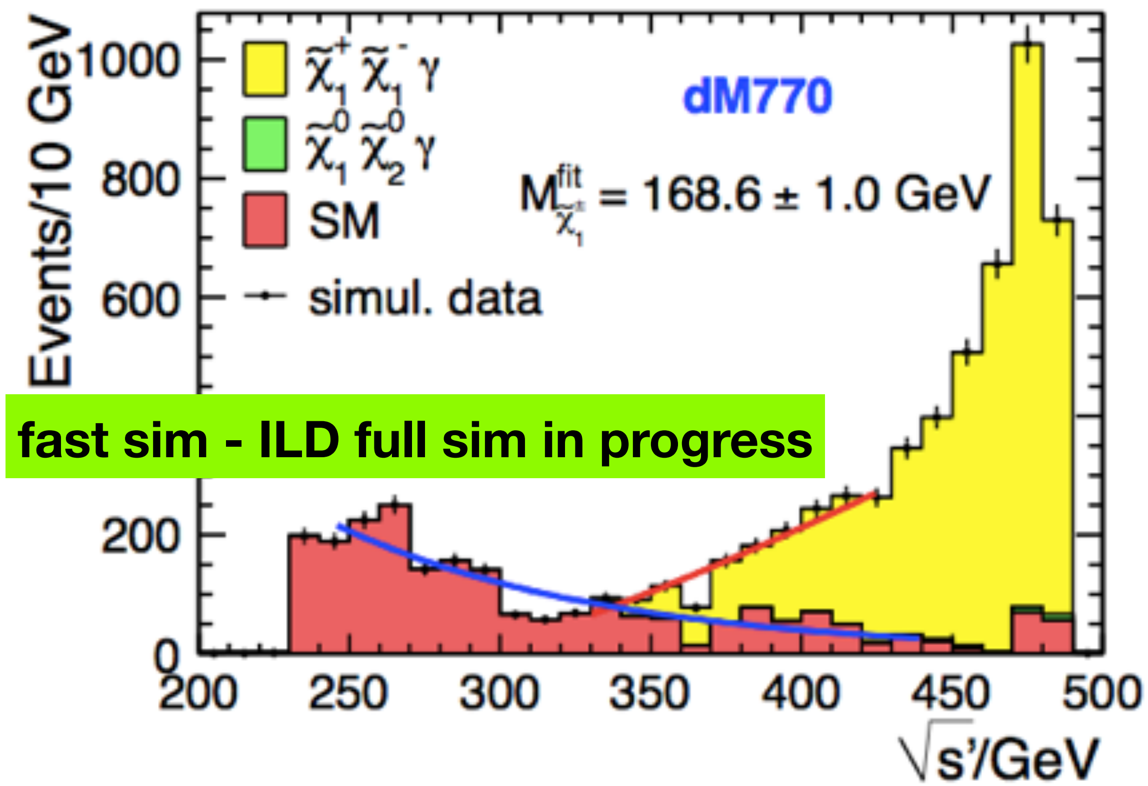


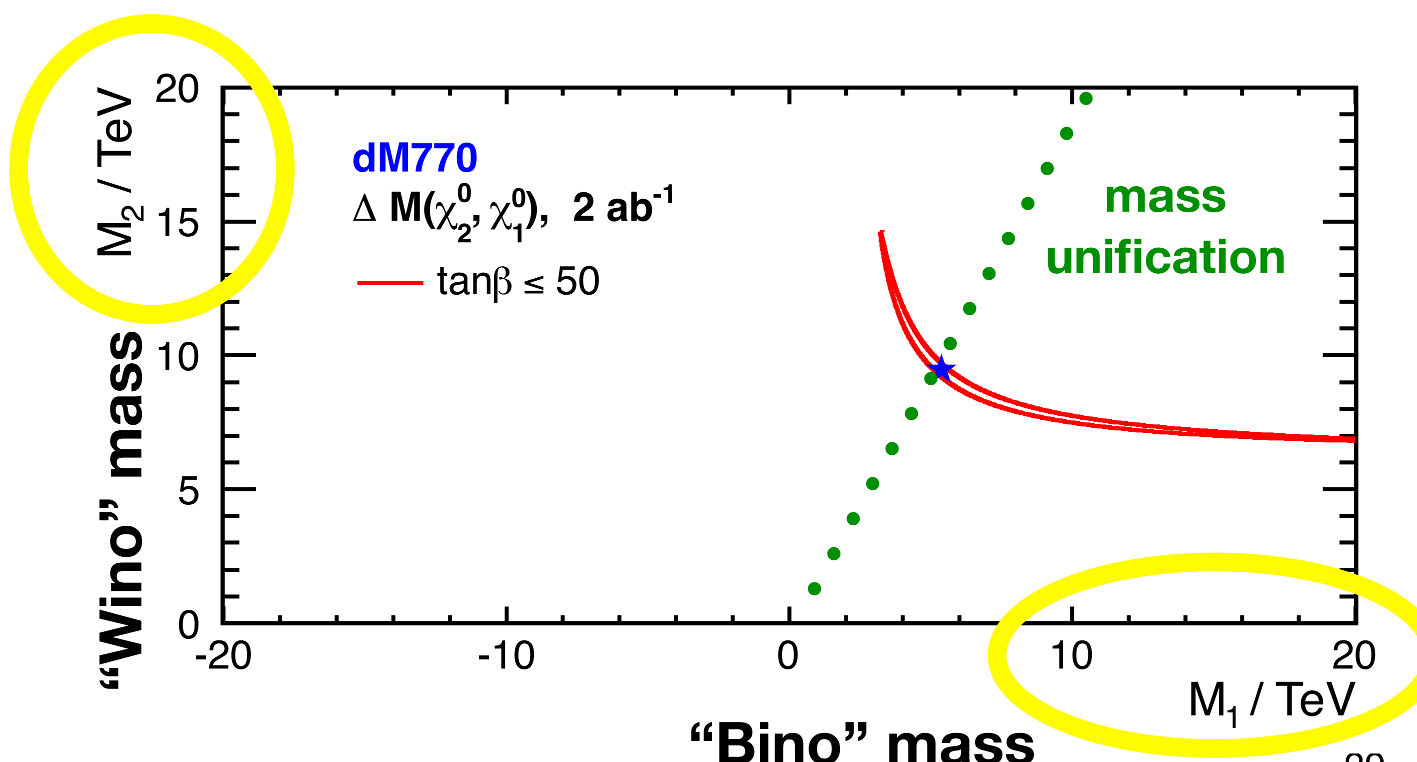




Natural SUSY

- 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





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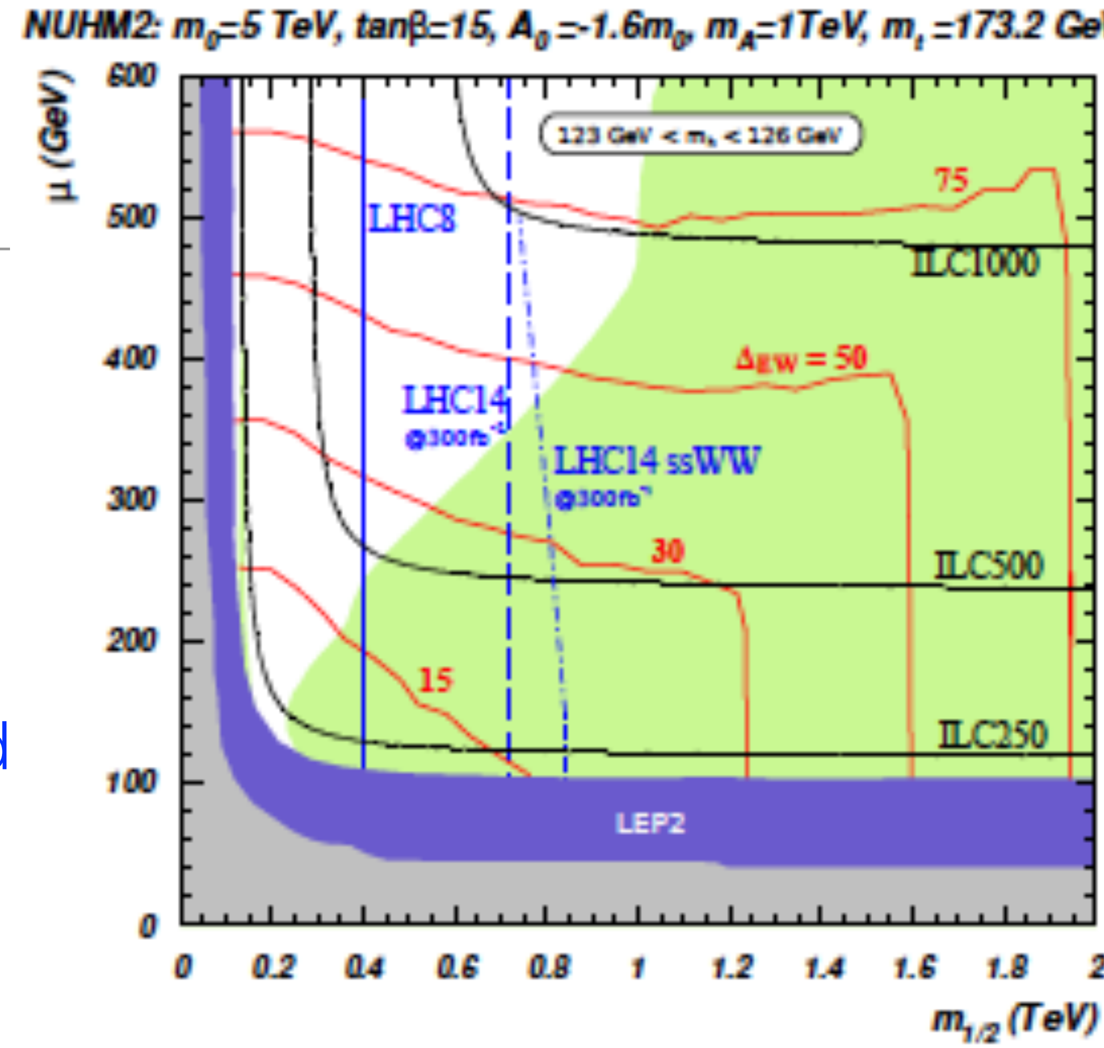

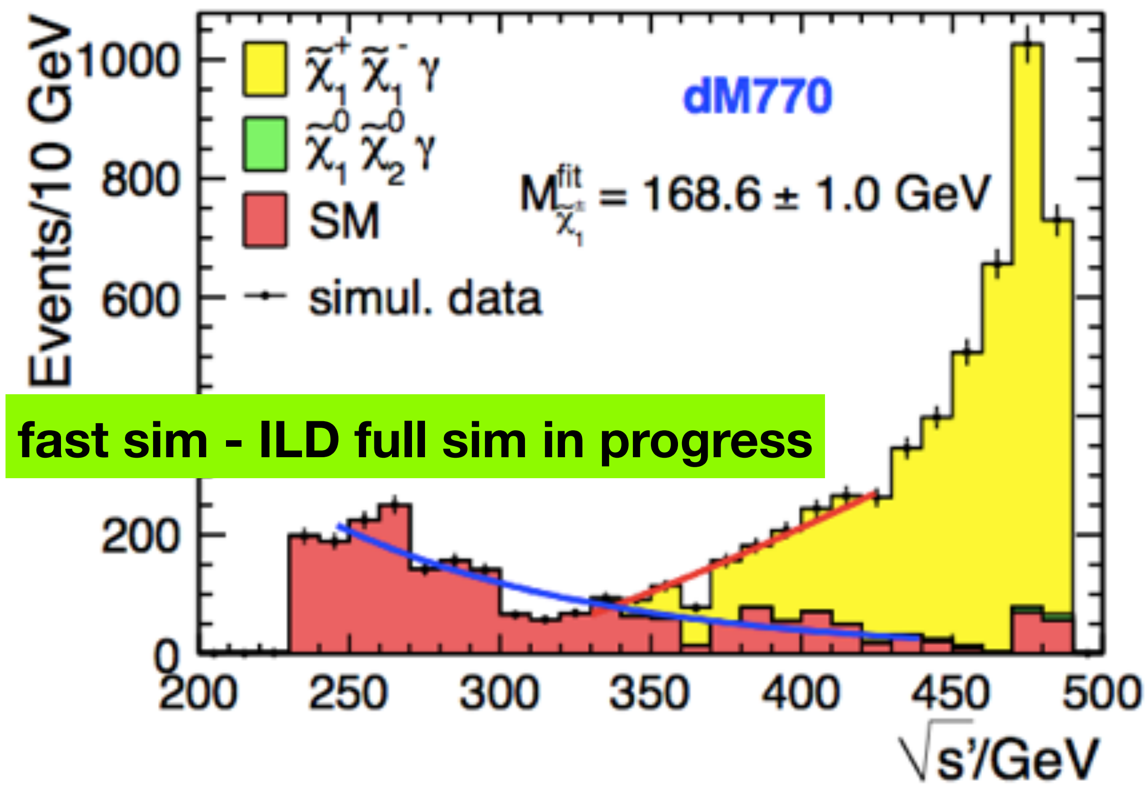

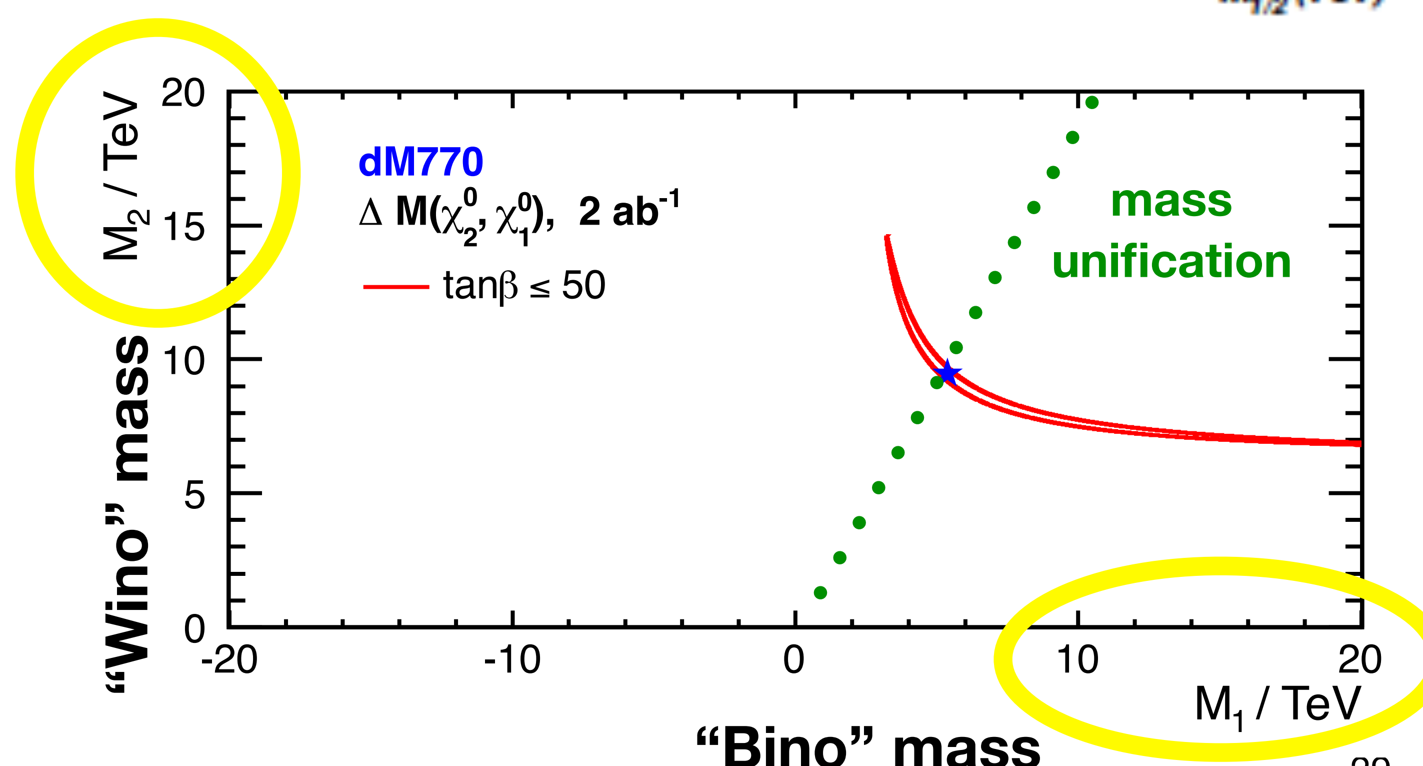

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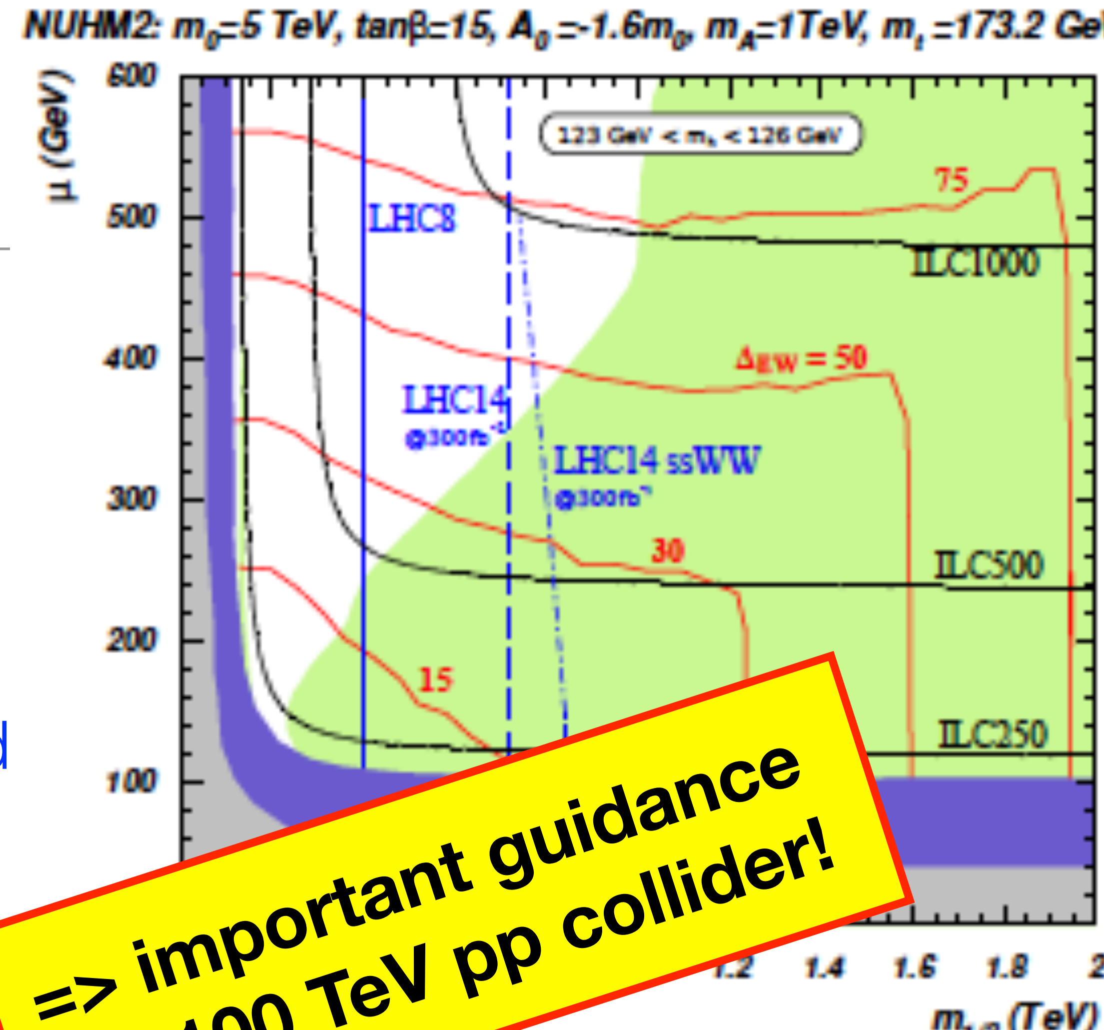
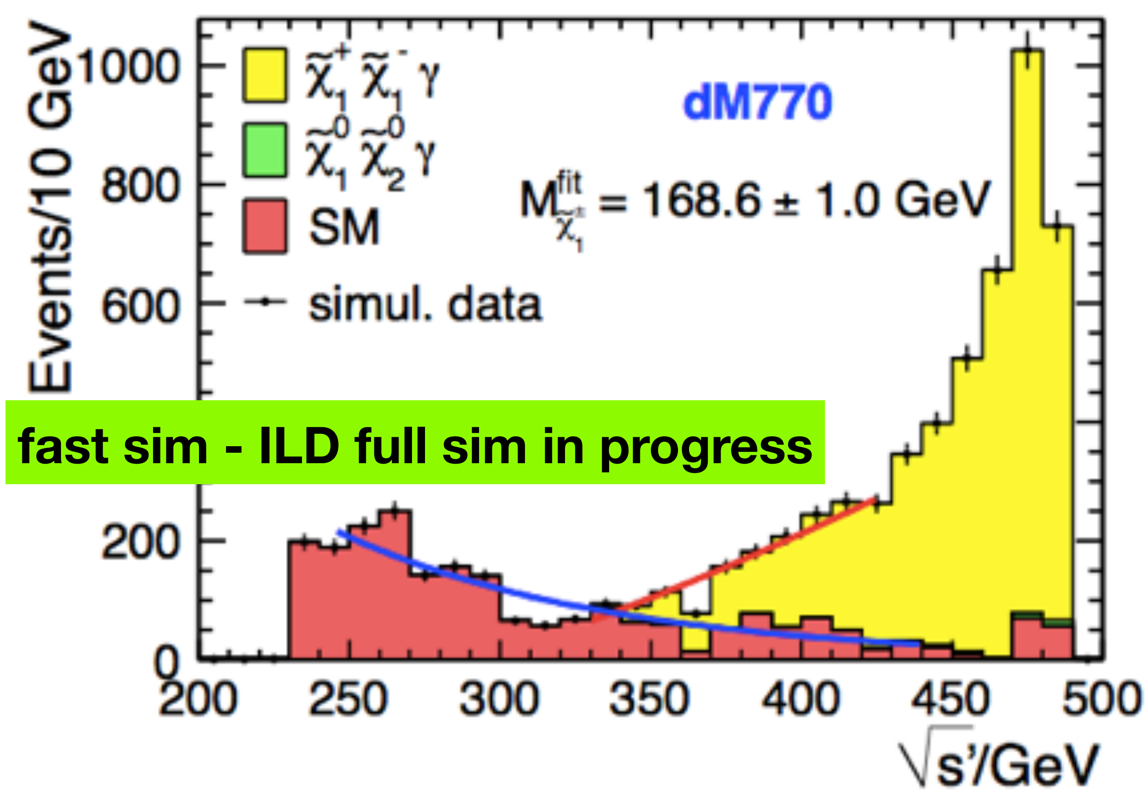
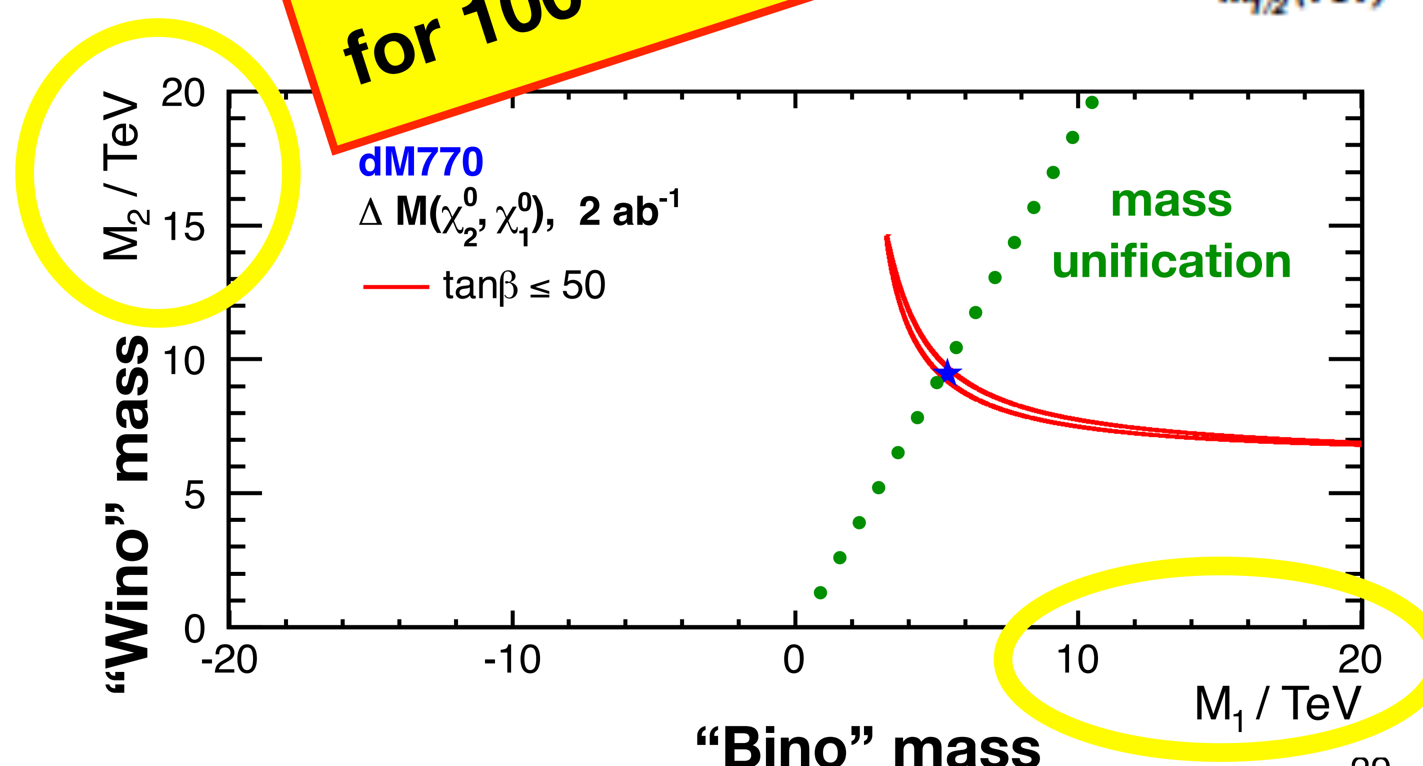


=> important guidance for 100 TeV pp collider!





Summary on ILC Analysis Highlights

The ILC energy range matches the guaranteed physics:

- Higgs couplings to ≲ 1% level
- top couplings => indirect reach to ~ 20 TeV NP
- Higgs self-coupling 27% … 10%
- top-Yukawa ≲ 6%
- … and many more!

In addition offers unique opportunities for direct discoveries, e.g.:

- Dark Matter
- natural SUSY

The ILC programme

- is extendable in energy and adjustable if physics requires
- is fully complementary to HL-LHC capabilities
- provides guidance for higher energy colliders
- rests on 500 GeV and polarised beams as key ingredients

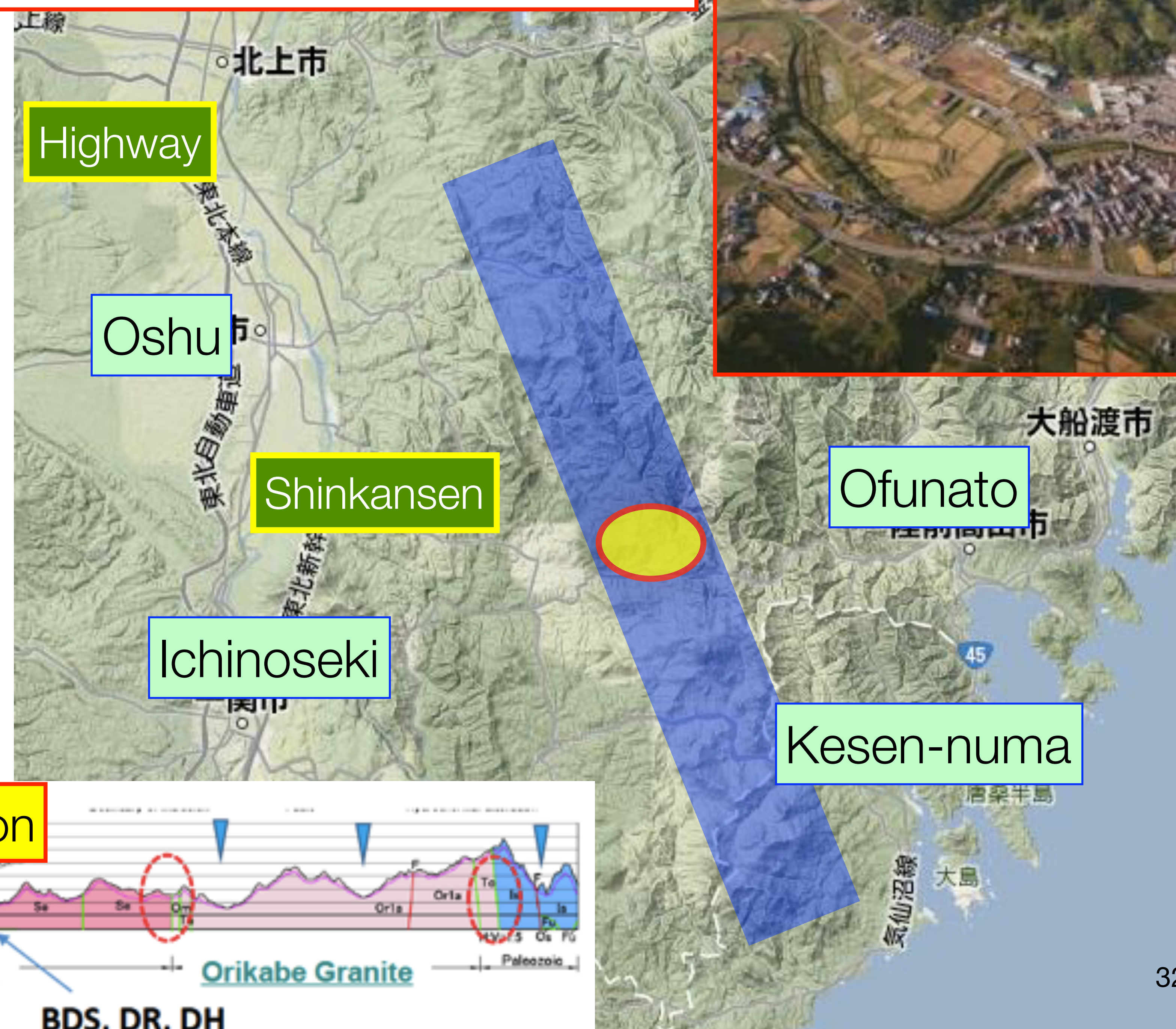
ILC in Japan

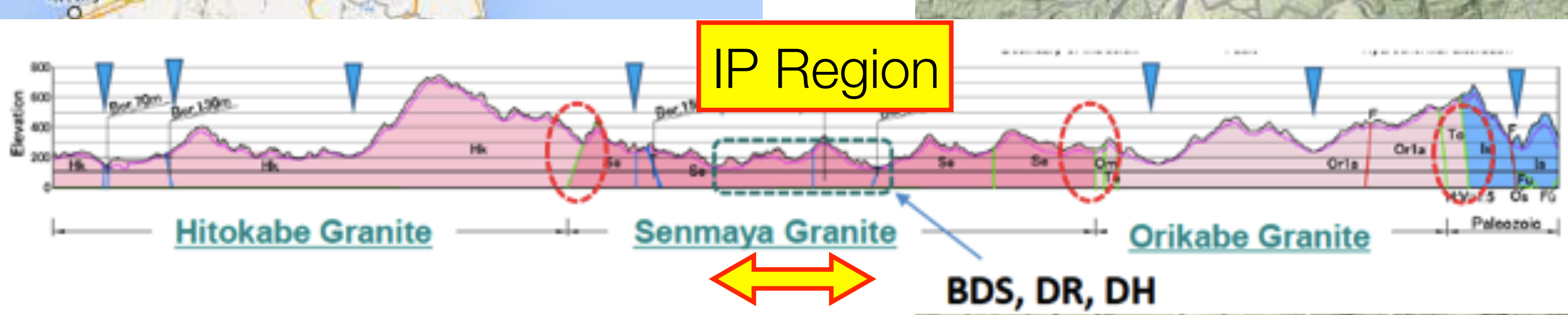

東北に
ILC実現を
（国際リニアコライダー）
We hope to realize plans of
the International Linear
Collider project in TOHOKU

The candidate site: Kitakami

scientific decision

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





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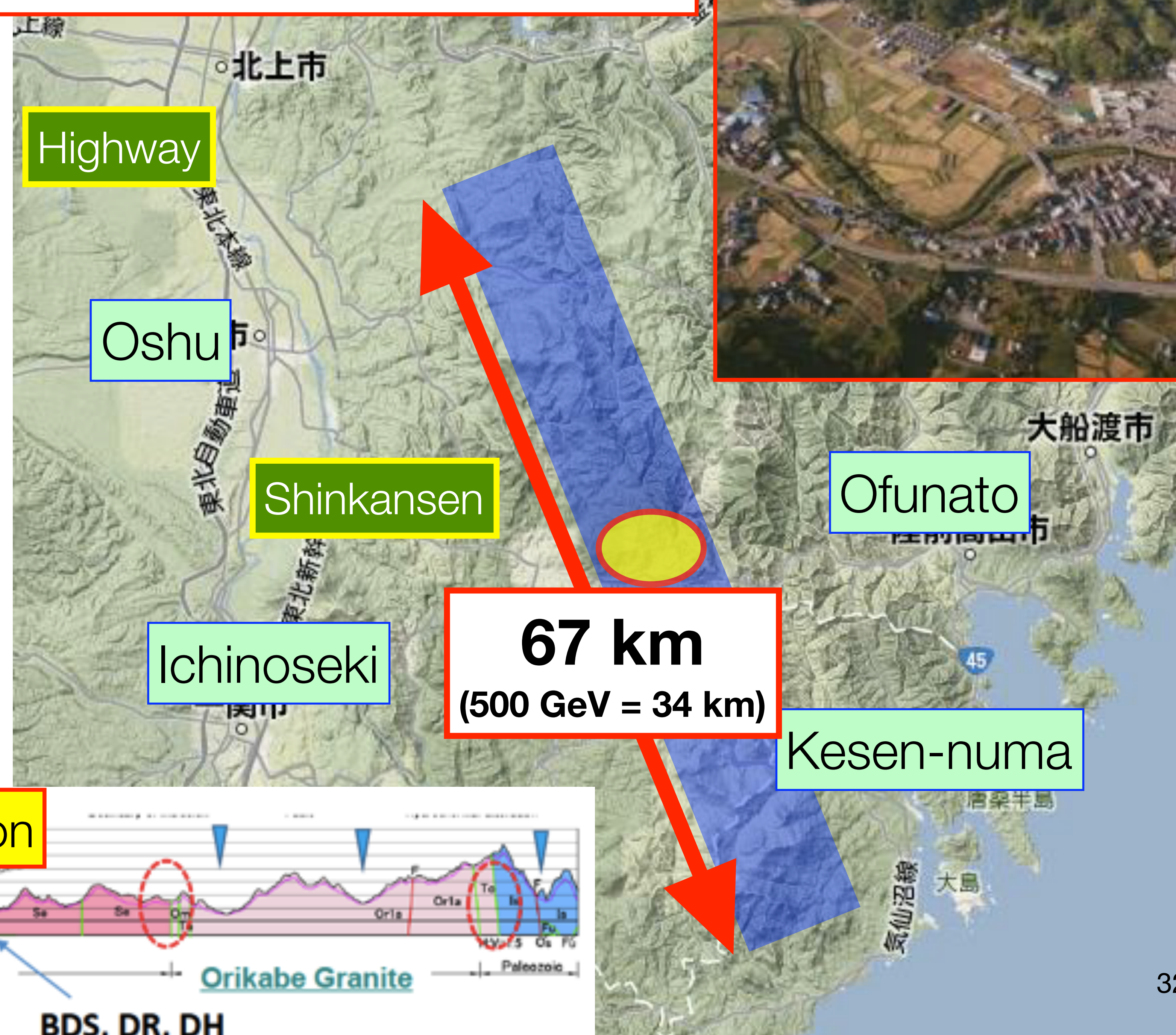
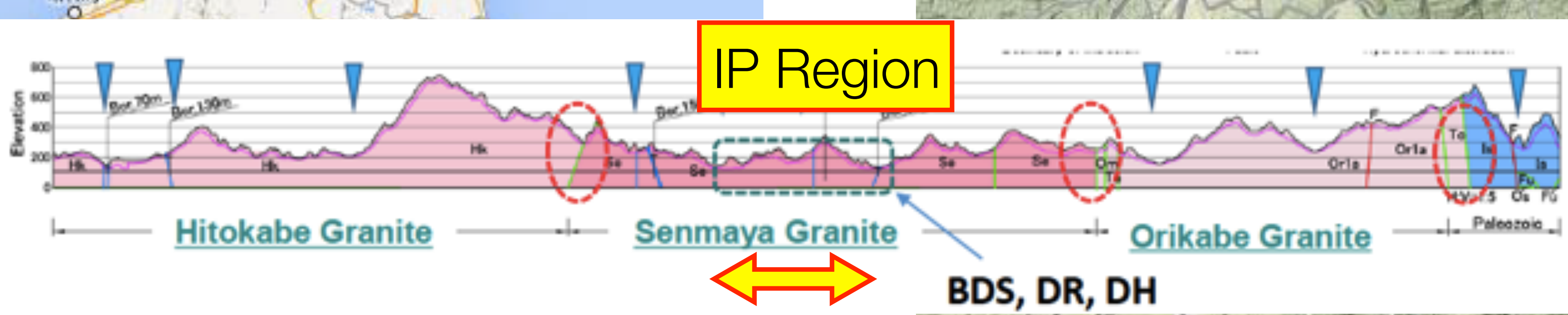




Ongoing site-related studies

new geological borings for main vertical shaft at IP

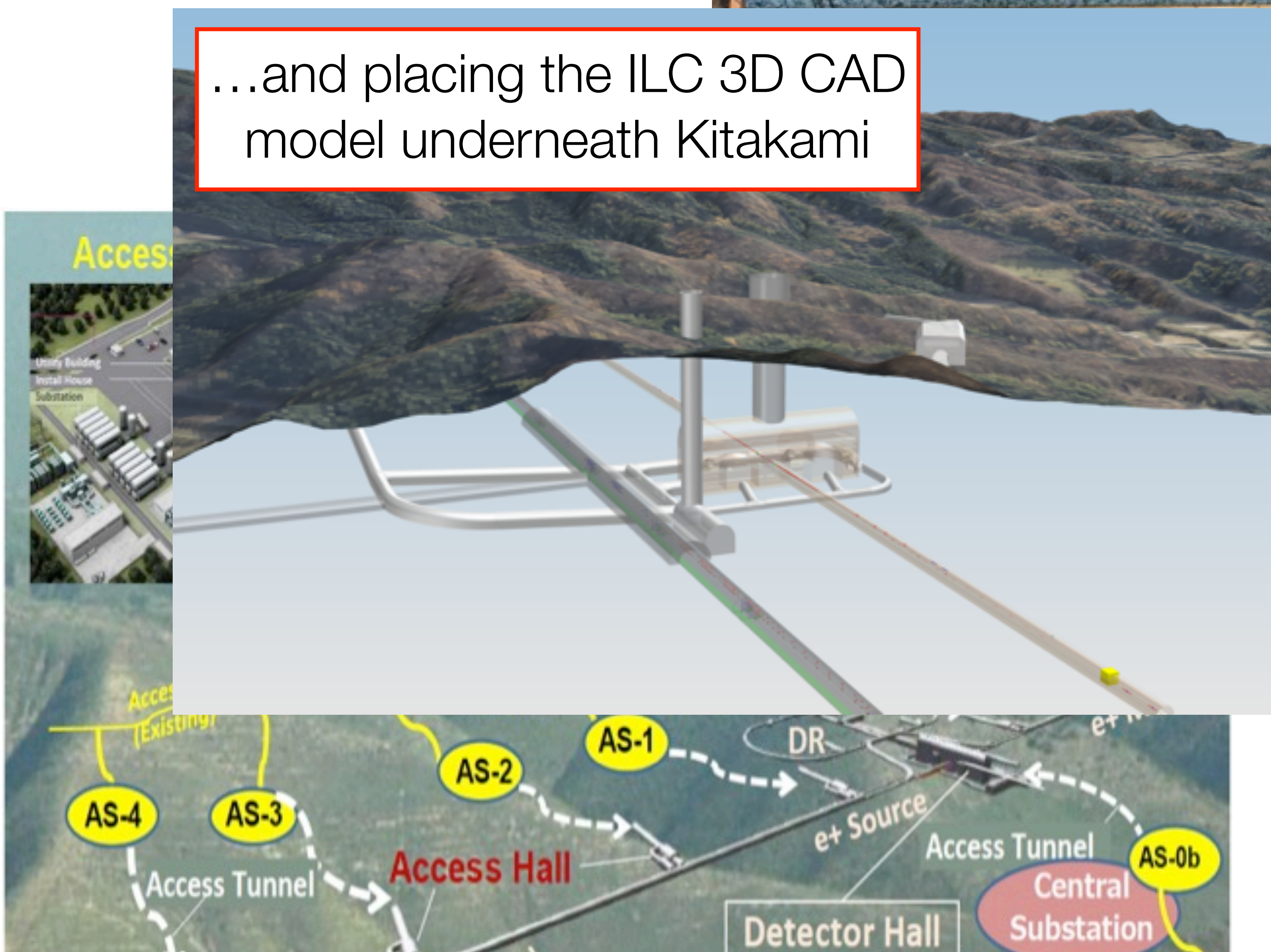
CERN/KEK/Industry Cooperation for:

- ILC Tunnel Optimisation Tool under development
- Focusing on access tunnel optimisation

Ongoing site-related studies

new geological borings for main vertical shaft at IP

…and placing the ILC 3D CAD model underneath Kitakami



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Review by Japanese Science Ministry (MEXT)

Science Council of Japan

after Higgs discovery: community decision for ILC

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Recommendation in 2013 →

MEXT

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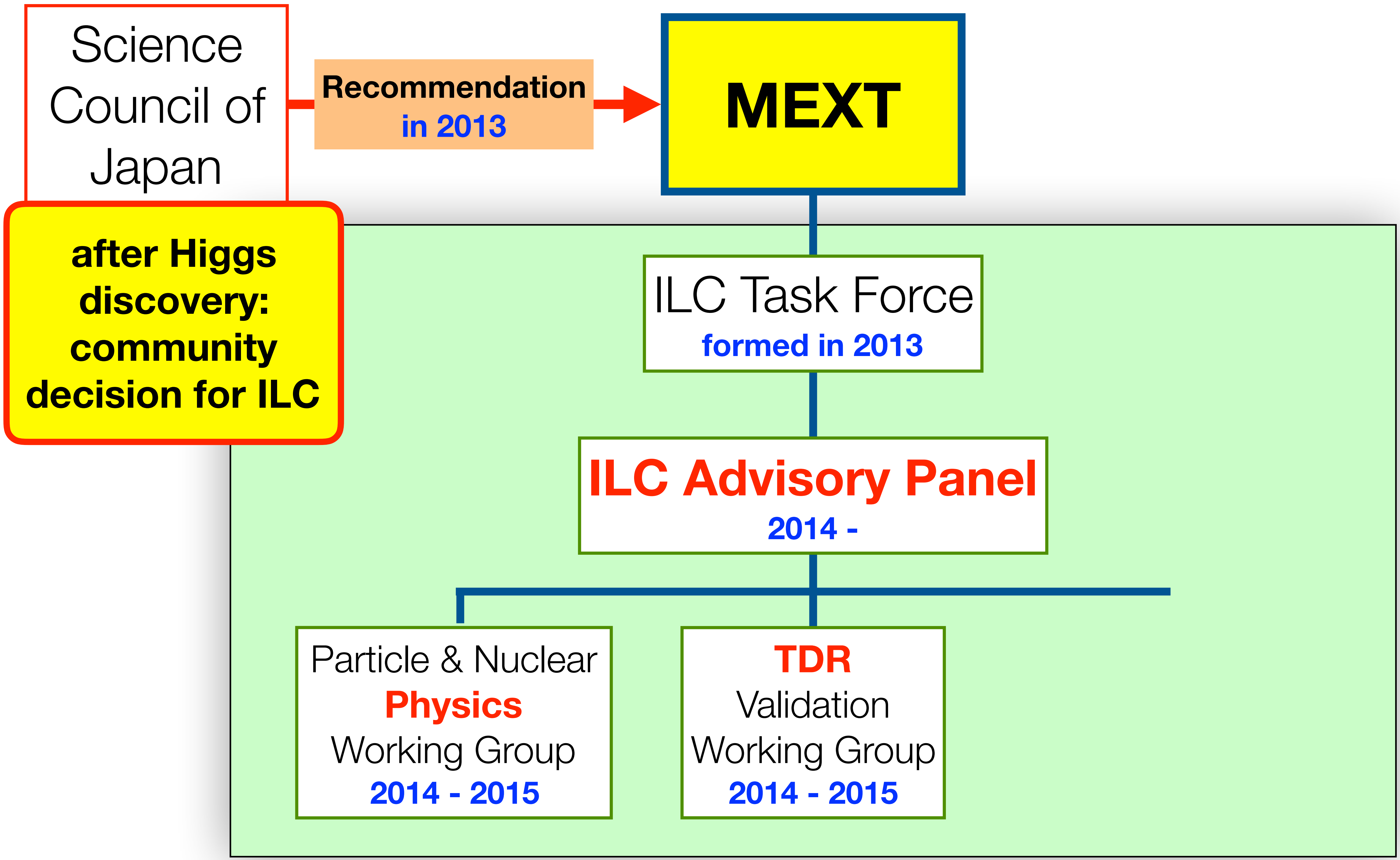

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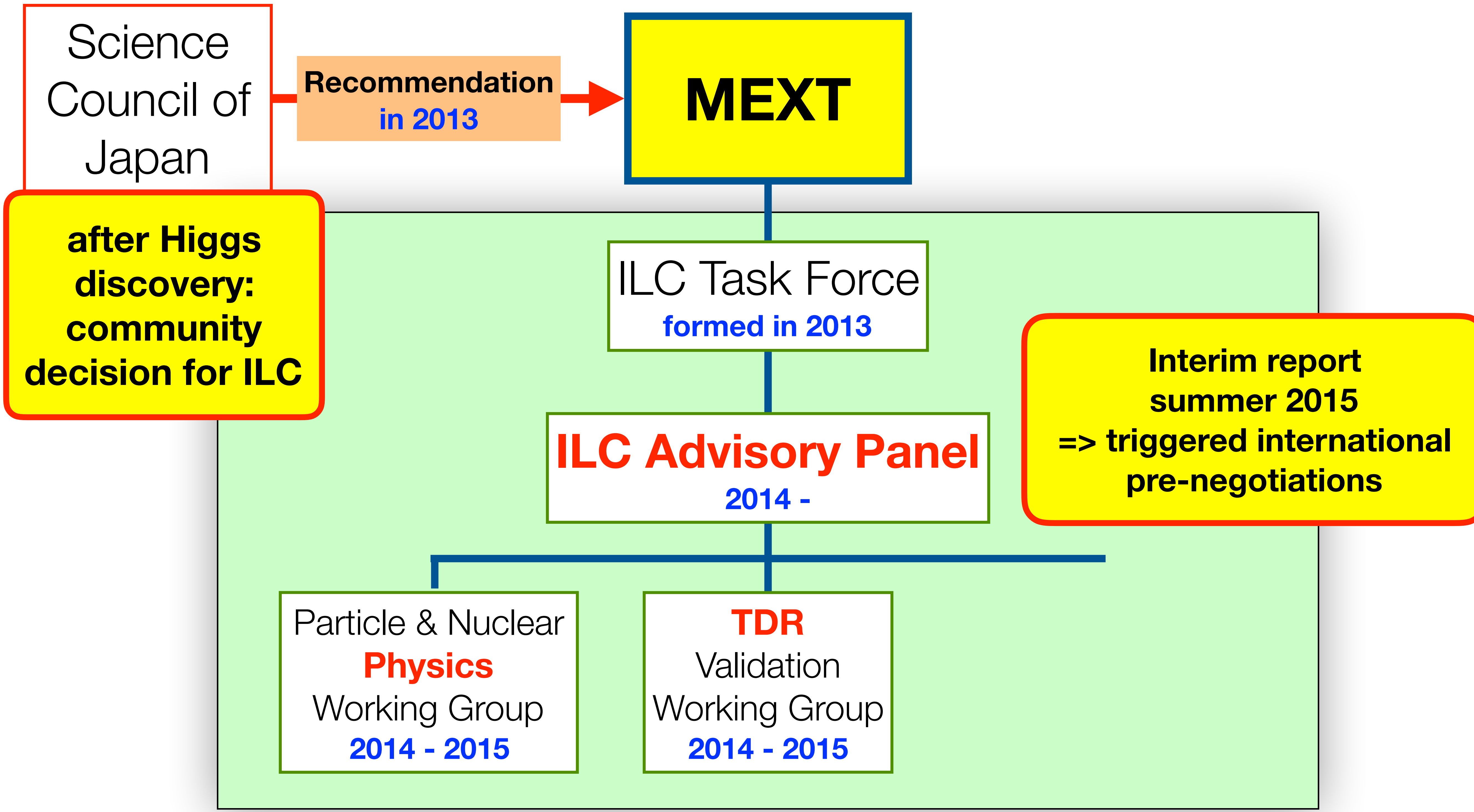

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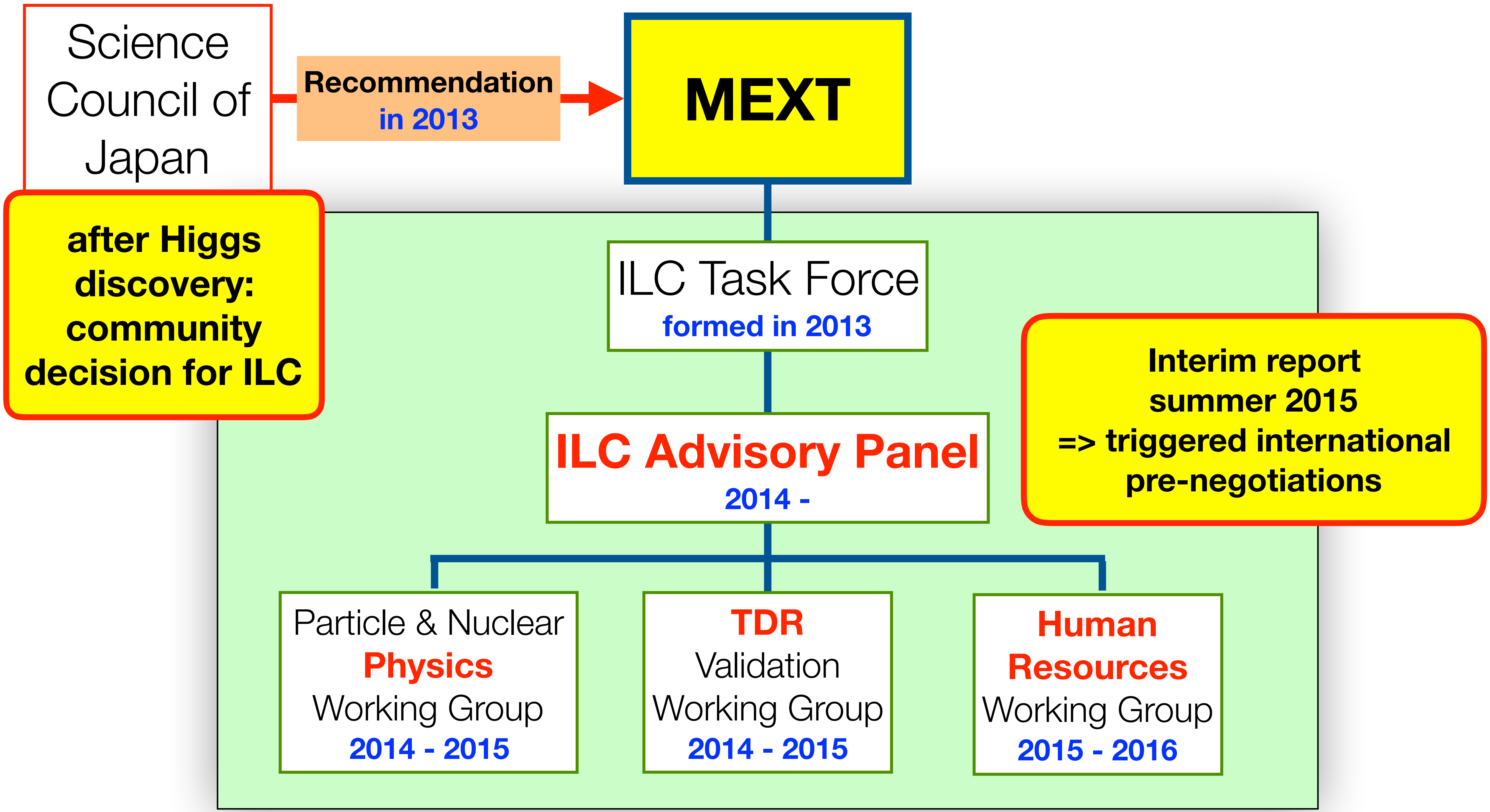

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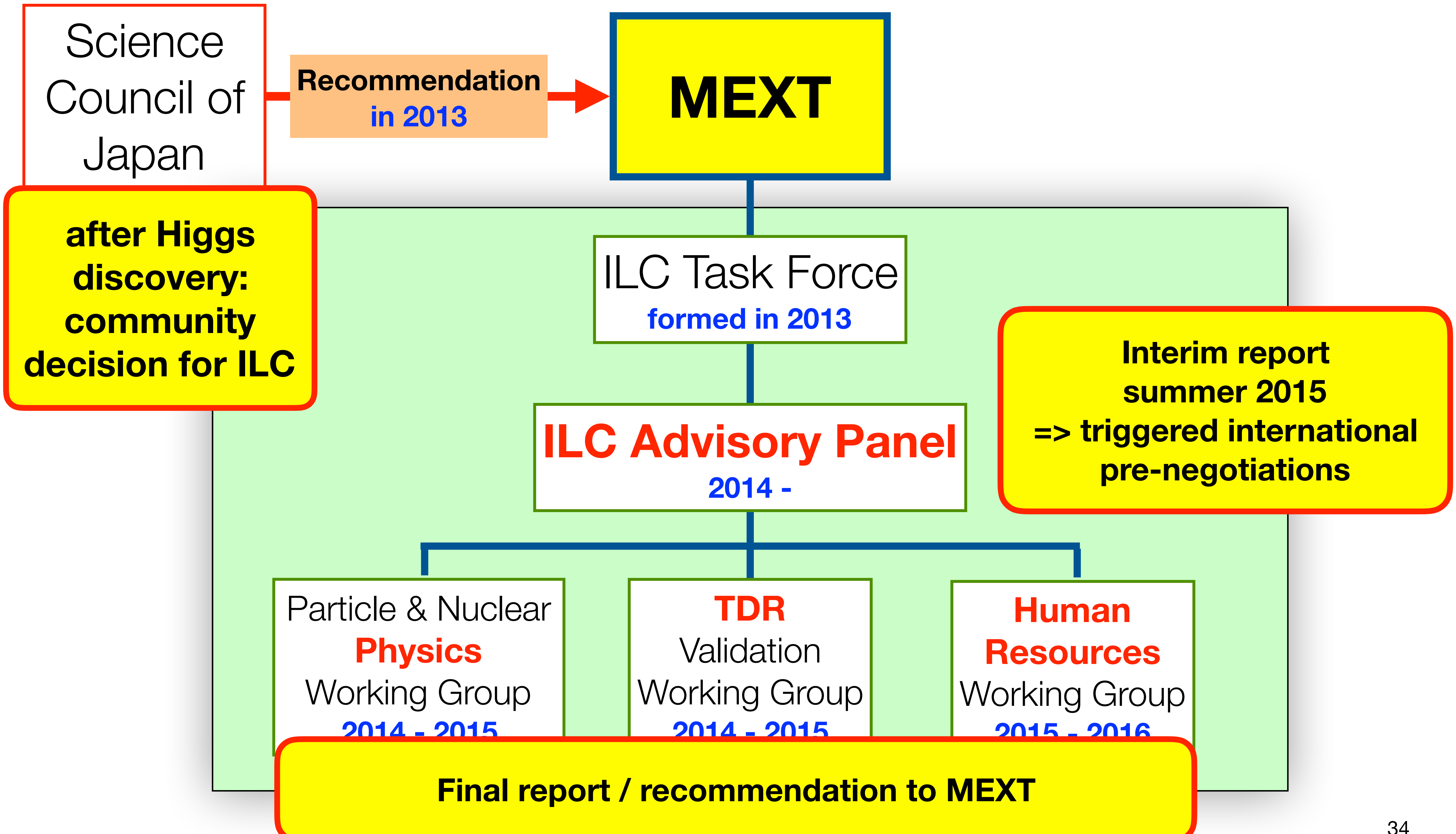

Reactions on Interim Report

- **Association of Diet Members for the ILC:**
  - **~150 diet (=Japanese Parliament) members across all parties**
  - approved resolution asking government to
    - define process towards a decision in 2017/18
    - **start international negotiations**
    - assign budget to address remaining questions
    - evaluate socio-economic impact of ILC

  => actions on all items are being taken, some still confidential

- **Letter from ICFA addressing questions on**
  - physics
  - accelerator technology

  which were raised in the interim report

Behind the Scenes: Diplomatic Actions

2013

- First survey through **Japanese embassy** in several countries in the world has been made by **Ministry of Foreign Affairs (MOFA) -> reported to Diet members**
- **MEXT officers'** survey trips to European countries

2014

- **EU-Japan-US intergovernmental** discussion (**officers' level**) has been tried

2015

- **Japan-EU** Parliamentary Assembly in Strasbourg
  => first political contact between Europe & Japan on ILC
- Focus on **US-Japan** discussions (next slide)

2016

- **Parliament-level** and **government-Level** discussions will be expanded to **Europe**, **Asia, Russia, South America and the rest of the world -> need counter-part in each country!**
- (The 2nd) Survey by **MEXT** will be conducted through **Embassy**, visits, interviews
- March: at Inter-Parliamentary Union meeting in Zambia contact with **German Bundestag member**
- **planned for autumn: meeting with other German politicians during possible visit to Japan**

Behind the Scenes: US-Japan

2014

- US-Japan **Ministers** (MEXT minister and US Secretary of Energy Dr. Moniz) discussion
- Visit of **Federation of diet members for the ILC** to Washington D.C.

2015

- US-Japan **undersecretary-level** discussion
- Visit of **Federation of diet members for the ILC** to Washington D.C.
- US-Japan high-level meeting (**ministers' level**) on Science & Technology
- **Presidential advisor Dr. Holdren's** visit to Japan
- **ILC introduced into annex of US-Japan S&T framework**

2016

- **Congress-Diet:** US-Japan Forum formed among members of **congress / diet** for collaboration in S&T, including ILC
- **US-Japanese inter-governmental activities:** meeting in Washington D.C. among US-DOE Office of Science director Dr. Murray, Dr. Siegrist, 3 Japanese diet members, MEXT officer & scientists

=> ILC discussion group between DOE and MEXT

In Japan

2015:

- MEXT minister changed in October -> **Mr. Hase**
- meeting with Mr. Hase, diet members, industry executives in December **=> support for the ILC**

2016:

- January: **cabinet approves national 5-year policy plan for S&T** (2016-2020)
  - highlights **importance of** S&T diplomacy and large-scale projects including **accelerator projects**
  - requests **increase of S&T budget to > 200B US$ / 5 years**
- January: **KEK presents action plan for ILC, including a budget for ILC at KEK**
- March: **MLIT** (Ministry of Land, Infrastructure, Transport and Tourism) **includes ILC in Tohoku Regional Plan** to promote advanced technology in the region

General considerations:

- Promotion of **local area development and local economy** is one of the central issues in the national cabinet policy, especially beyond Tokyo Olympic games 2020
- New position: **S&T Advisor of Minister of Foreign Affairs**

Oshu City

Ichinoseki Station

Morioka

Tohoku tourism ad seen on Tokyo Metro

Posters and "Toy ILC" by school children of Oshu City welcoming international workshop on ILC

Attempt of a Personal Assessment

Strong support from industry:
Advanced Accelerator Association

- founded in 2008
- 100 companies, 40 universities & institutes
- frequent meetings, hosted Tokyo ILC Event,study on “Green ILC”

Huge support from politics:

- Association of Diet Members for the ILC: ~150 diet members across all parties
- ILC in programme of LDP party
- Prime Minister Abe & several ministers

Enthusiastic local support in Tohoku, ILC part of rural development plan of MLIT

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Japanese government *is* serious about ILC

- but decision is complicated
- needs international, political reassurance before Japan officially “bids to host”
- next round LHC results imminent…

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Huge support from politics:

- Association of Diet Members for the ILC: ~150 diet members across all parties
- ILC in programme of LDP party
- Prime Minister Abe & several ministers

Enthusiastic local support in Tohoku, ILC part of rural development plan of MLIT

Japanese government *is* serious about ILC

- but decision is complicated
- needs international, political reassurance before Japan officially “bids to host”
- next round LHC results imminent…

Attempt of a Personal Assessment

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What we can do to support the process in Japan

- show continuous *scientific* support
- make sure politicians *know* about ILC
- be patient & acknowledge the “behind-the-scenes” activities

General Picture of Next Steps -
as consistently reported by Advisory Panel, MEXT, Diet Members

1. Japanese Government: official reviews and investigations (ongoing)
2. Government-To-Government:
   - discussions on issues and preparations (started)
   - **NEED NOW *prospects*** (not commitments) **for the international sharing of costs, human resources, technology**
3. Surveys in individual countries by Embassy, MEXT (2016)
4. Preparations and studies of management structure, etc. in bi-lateral government-government joint activities (2016-2017)
5. First LHC Run 2 results to come (2016-2018)
6. Decision to proceed by Japanese government, followed by official negotiations on the cost sharing
7. International agreement => International approval

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triggered by interim report & resolution by diet members

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From Presence to Future -
The ILC in the global HEP picture

LHC:

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- plan: ~3000fb^{-1} til **~2037**
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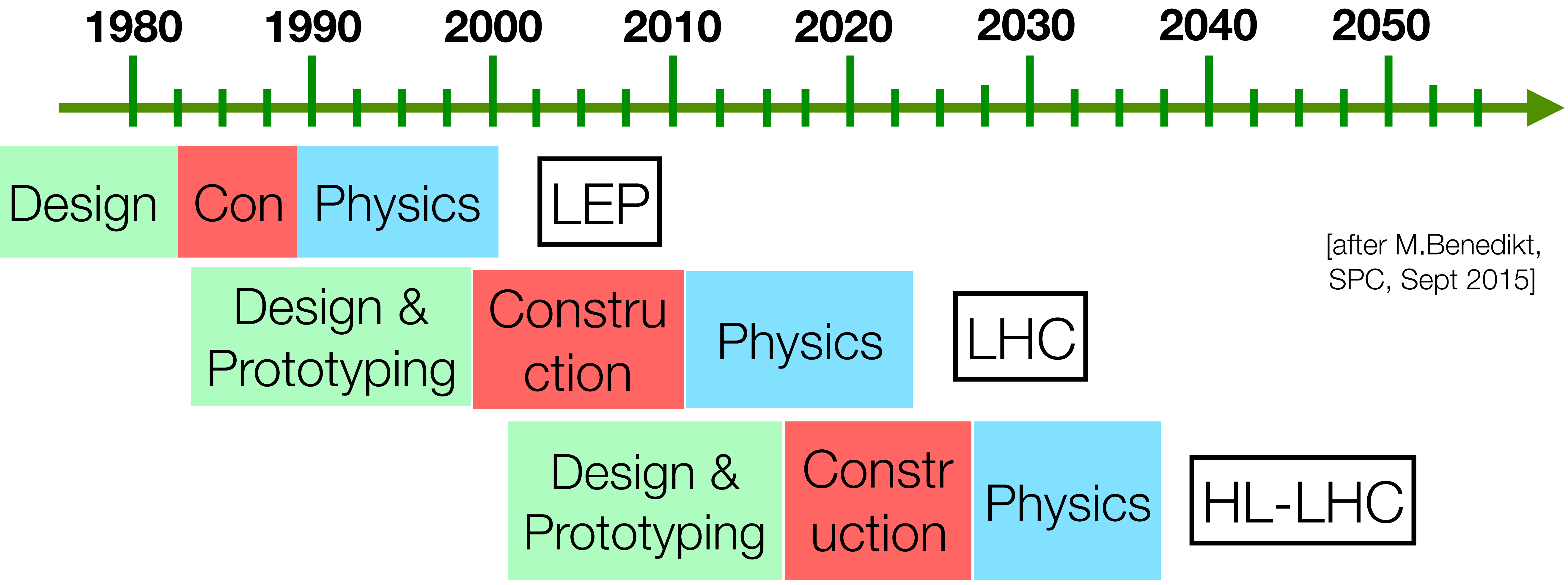
CEPC:

- great if realised in addition
- could allow for earlier energy upgrade of ILC
- but probably no polarisation?

Timelines: Past, Plans & Possibilities



[after M.Benedikt, SPC, Sept 2015]

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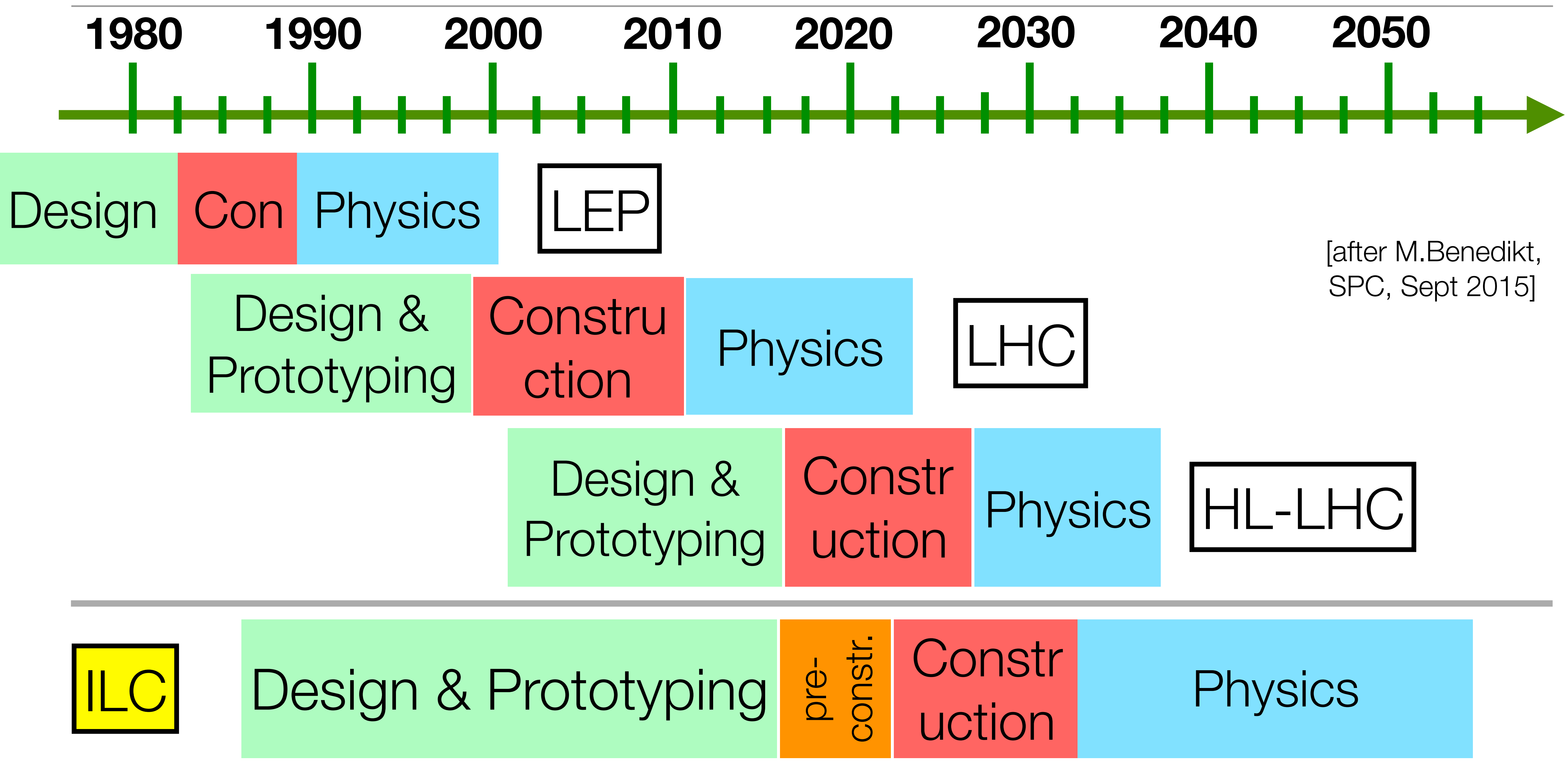

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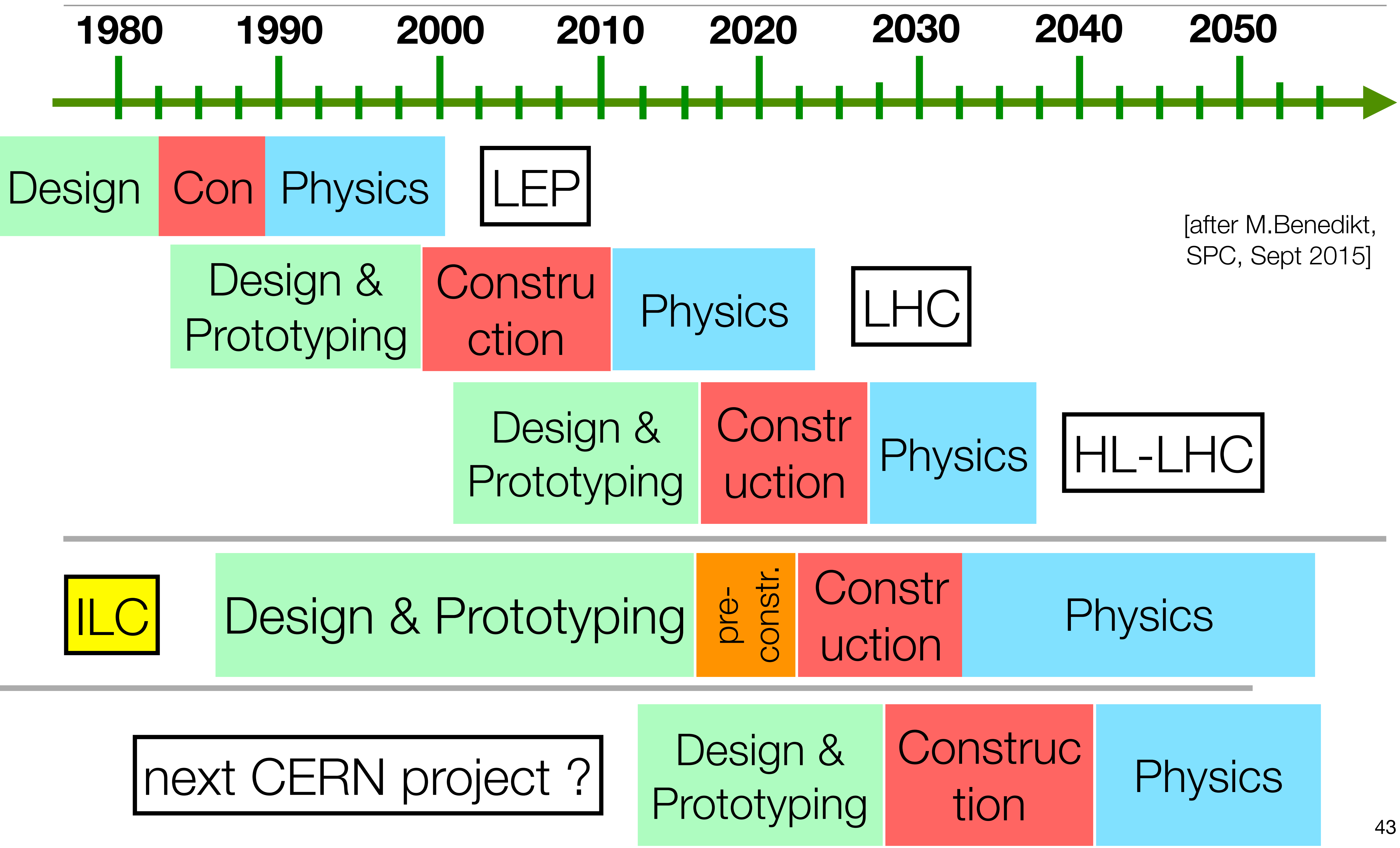

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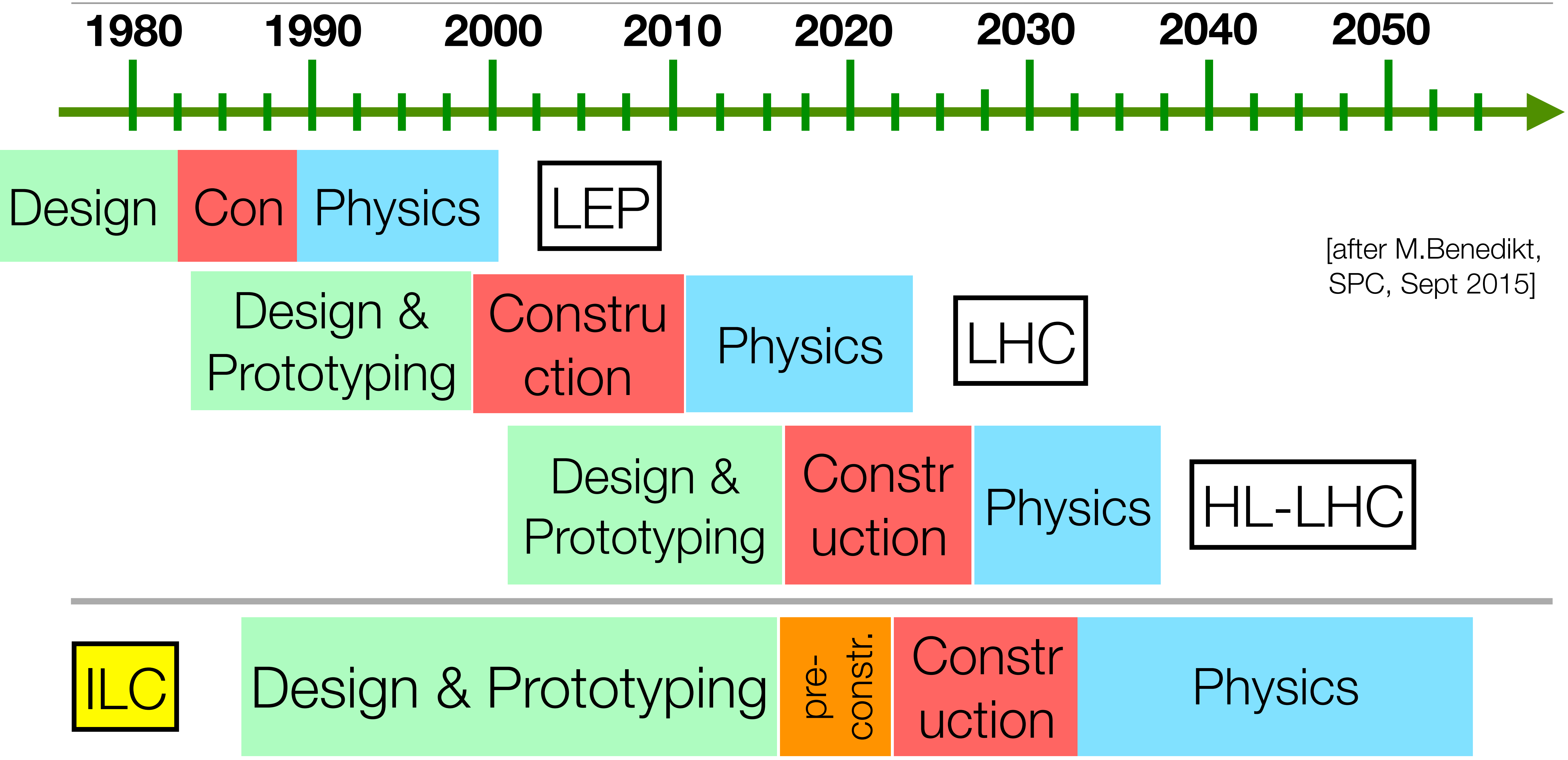

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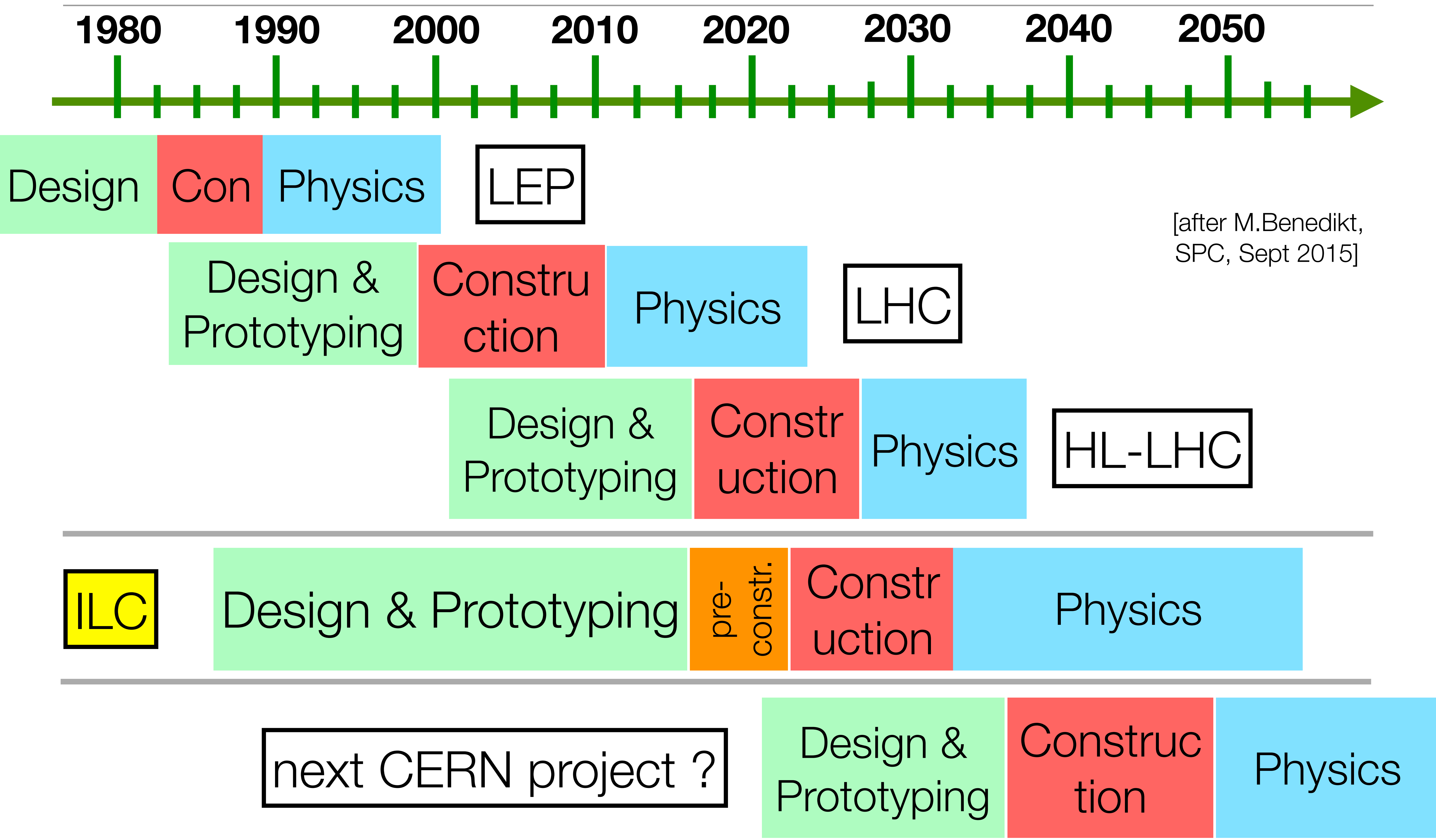
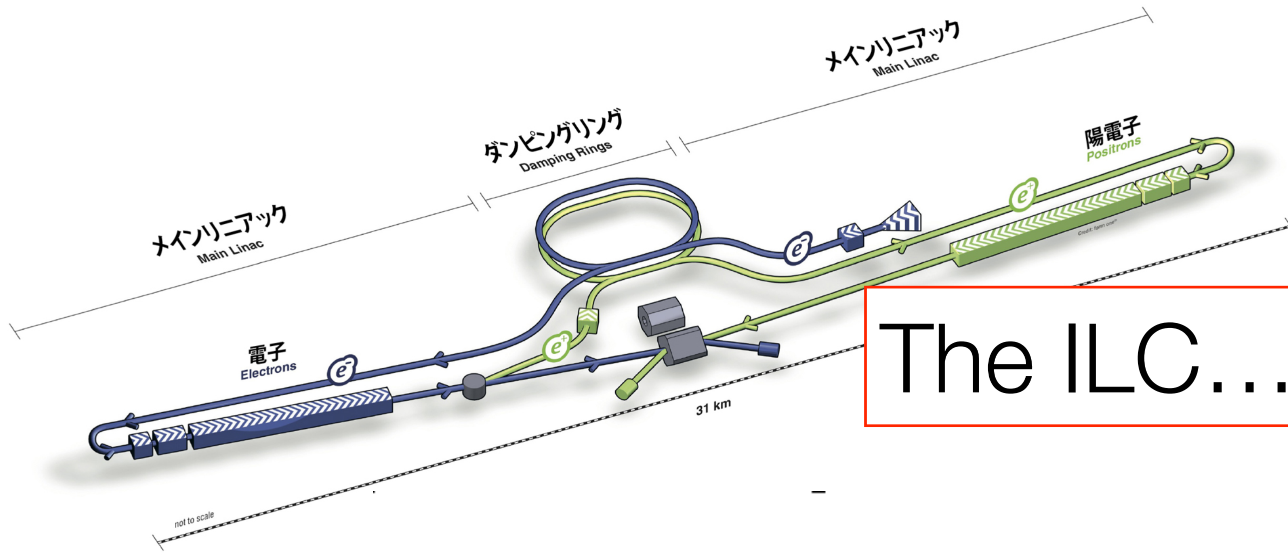
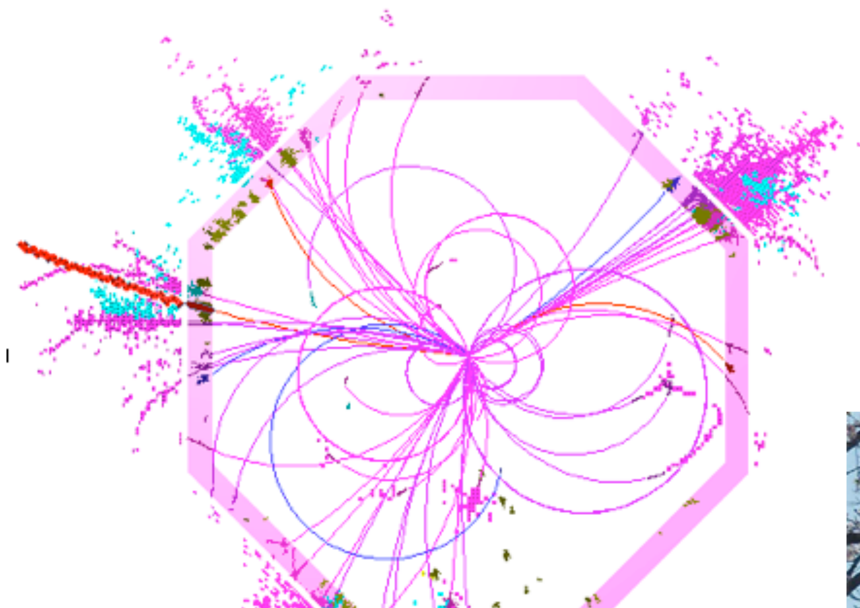


Conclusions



ILC Scheme | ©www.form-one.de

The ILC…



…is ready…

…to do great physics…

…in Japan!

Conclusions

The ILC has a solid physics case already now

- energy range matches *guaranteed* physics
  - and offers significant opportunities for "surprises"
- polarised beams, **upgradable in** luminosity and **energy**

Its technology is mature

- long standing user operation at FLASH
- industrialised for XFEL
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Strong international support
is vital for Japanese decision

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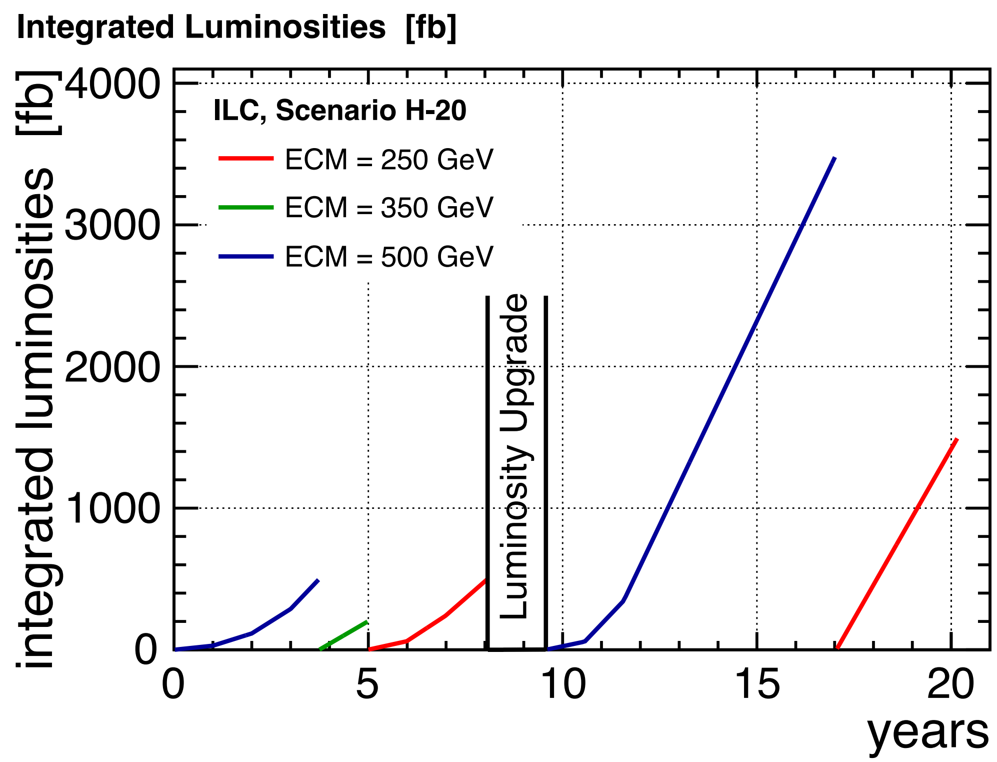
Still a lot to do - everybody is welcome to join!

Japan *is* serious - a lot is going on behind the scenes….

Strong international support is vital for Japanese decision

Backup

Details of Running Scenario



	$\sqrt{s}$	$\int \mathscr{L} dt$	L_{peak}	Ramp				T	T_{tot}	Comment
	[GeV]	[fb^{-1}]	[fb^{-1}/a]	1	2	3	4	[a]	[a]	
Physics run	500	500	288	0.1	0.3	0.6	1.0	3.7	3.7	TDR nominal at 5 Hz
Physics run	350	200	160	1.0	1.0	1.0	1.0	1.3	5.0	TDR nominal at 5 Hz
Physics run	250	500	240	0.25	0.75	1.0	1.0	3.1	8.1	operation at 10 Hz
Shutdown								1.5	9.6	Luminosity upgrade
Physics run	500	3500	576	0.1	0.5	1.0	1.0	7.4	17.0	TDR lumi-up at 5 Hz
Physics run	250	1500	480	1.0	1.0	1.0	1.0	3.2	20.2	lumi-up operation at 10 Hz

Operating the ILC

- SCRF at high-gradients => **pulsed operation:**
  - trains of N_{bunch} = 1315 / 2625 bunches, **530 / 270 ns bunch spacing**
  - train repetition rate: 5 - 10 Hz => 199 - 99 ms break

enables special detector features:
- **trigger-less readout => sensitivity to “subtle” signatures**
- **power pulsing => low mass trackers, dense calorimeters**

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ECM [GeV]	**250**	**250**	**500**	**250**	**500**	**1000**
rep. rate [Hz]	5	10	**5**	10	5	**5**
N_{bunch}	1315	1315	**1315**	2625	2625	**2625**
inst. lumi [10^{34} / cm^2 /s]	0.75	1.5	**1.8**	3	3.6	**3.6-4.9**
total power [MW]	**100**	**160**	**160**	**190**	**200**	**300**
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	staged	**ILC500@**	**TDR**			**TDR**
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	staged	ILC500@	TDR	lumi-upgrade		TDR
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The 20-year program for the ILC - and beyond

- **$\sqrt{s}$ = 250, 350, 500 GeV:**
  - int. luminosities to be used in physics studies
  - detailed run plan
- **$\sqrt{s}$ = 91, 161, 1000 GeV:**
  - int. luminosities to be used in physics studies
  - beam parameters preliminary

Total integrated luminosities

beam polarisation: sharing of luminosity between helicity configurations specified

$\sqrt{s}$	$\int \mathscr{L} dt$	P = (-0.8,+0.3) / (+0.8,-0.3) / (-0.8, -0.3) / (0.8, 0.3)
250 GeV	**2 ab^{-1}**	67.5% / 22.5% / 5% / 5%
350 GeV	**200 fb^{-1}**	67.5% / 22.5% / 5% / 5%
500 GeV	**4 ab^{-1}**	40% / 40% / 10 % / 10%
1 TeV	**8 ab^{-1}**	40% /40%/ 10% / 10%
91 GeV	**100 fb^{-1}**	40% / 40% / 10% / 10%
161 GeV	**500 fb^{-1}**	67.5 % / 22.5% / 5% / 5%

Flexibility remains a key asset of the ILC

Higgs Mass Measurement

WHY?

- fundamental (SM) parameter
  => deserves best possible measurement in its own right
- important source of parametric uncertainty on Higgs branching ratio predictions, e.g. within SM, δM_H = 200MeV
  => **parametric uncertainty** on:
  - BR(H->WW*): 2.2%
  - BR(H->ZZ*): 2.5%
  - reduce to 0.1% - level => **need δM_H = 10 MeV**

HOW?

- (HL-)LHC: currently ~200 MeV, eventually ~50 MeV from kinematic reconstruction of H -> $\gamma\gamma$ and H -> ZZ* -> 4l
- e+e- - two options:
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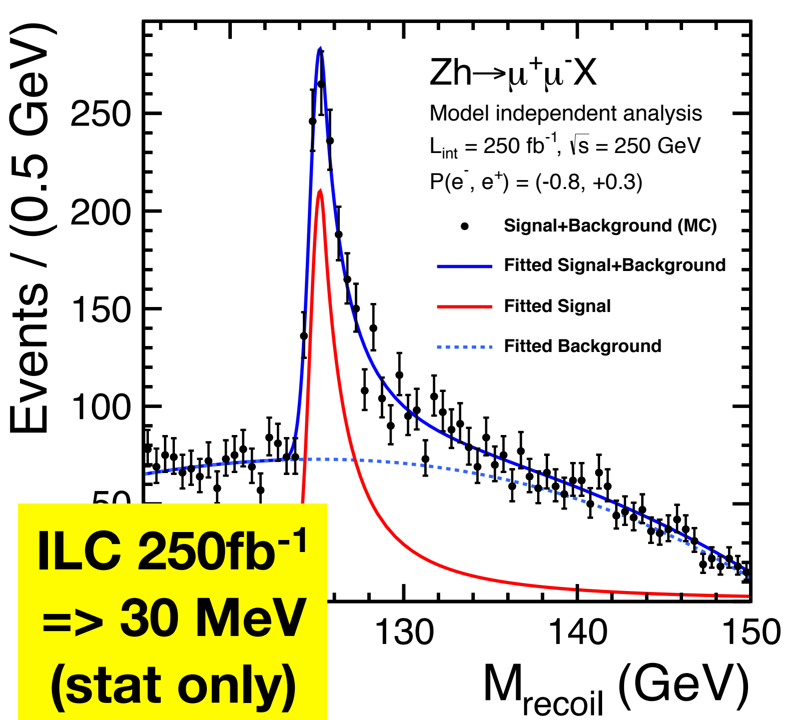

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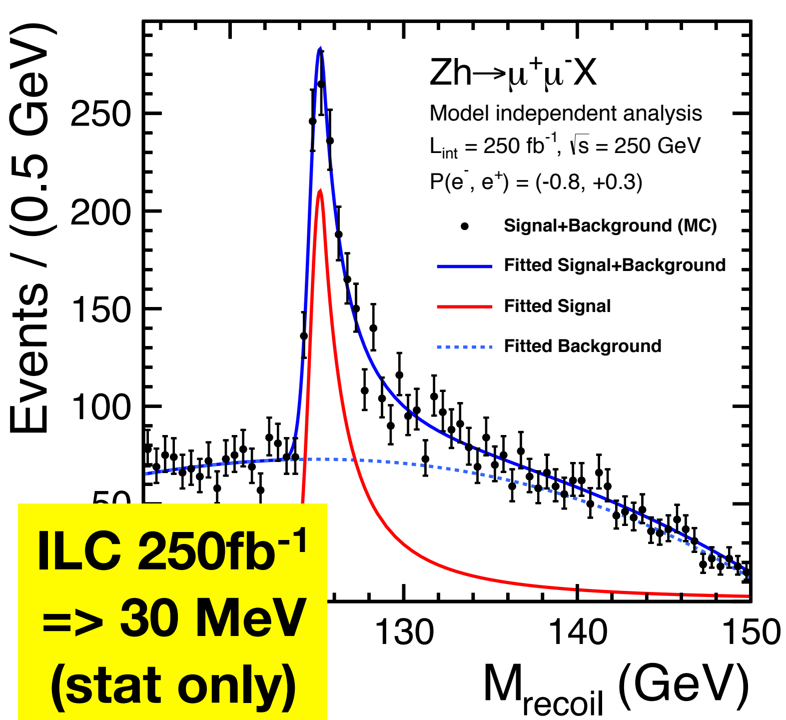

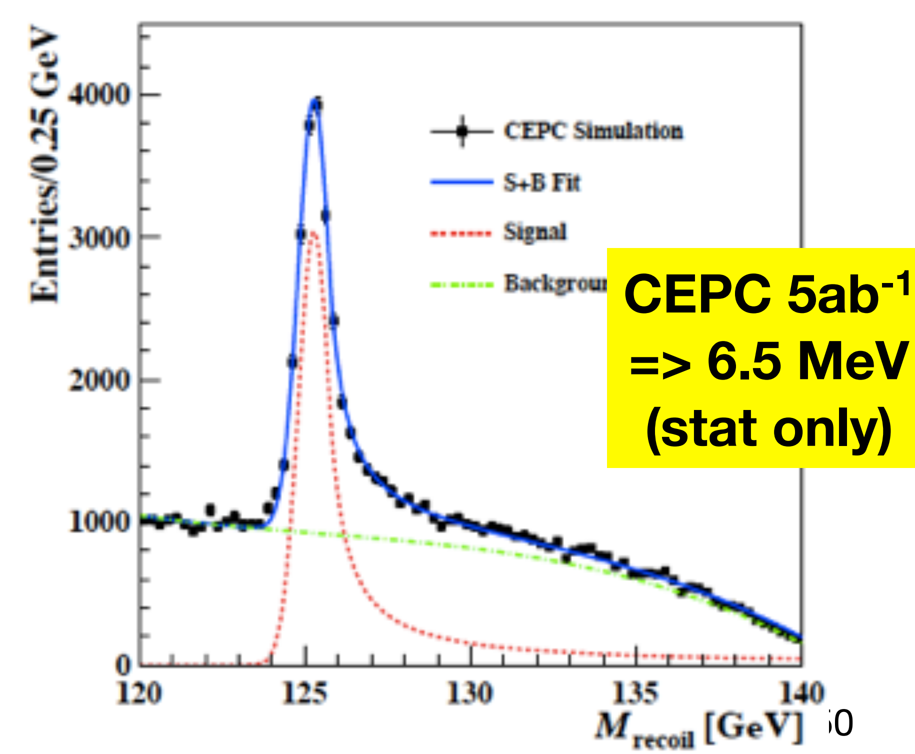

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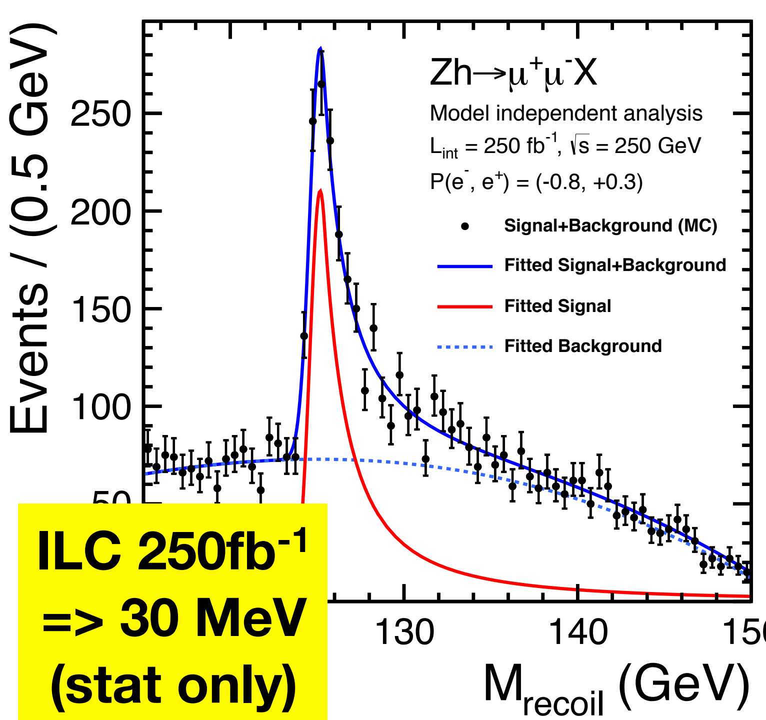

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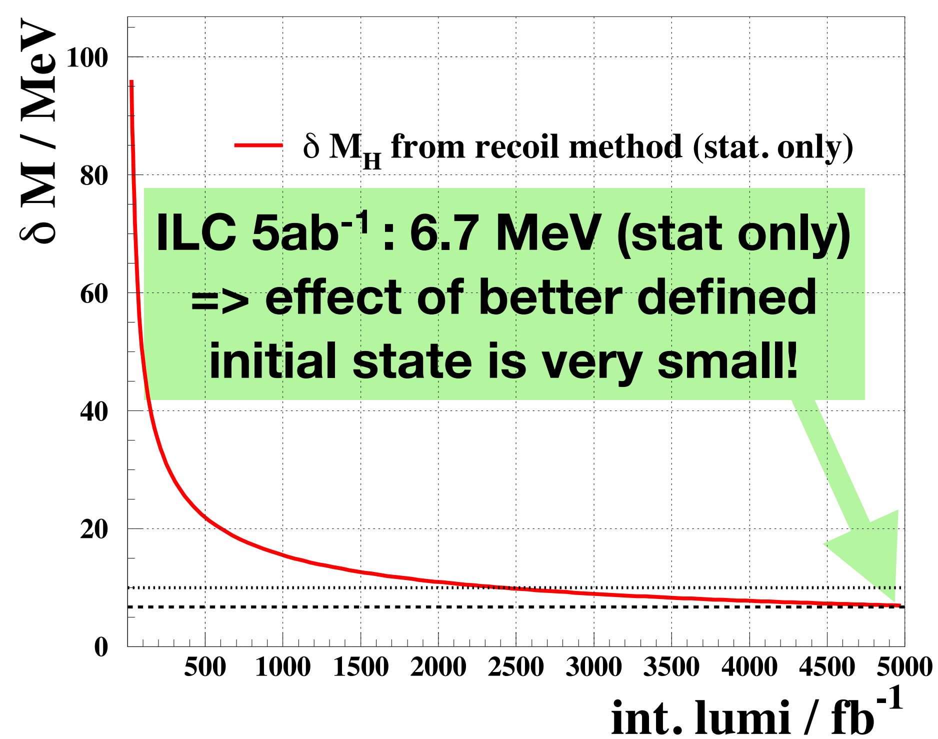
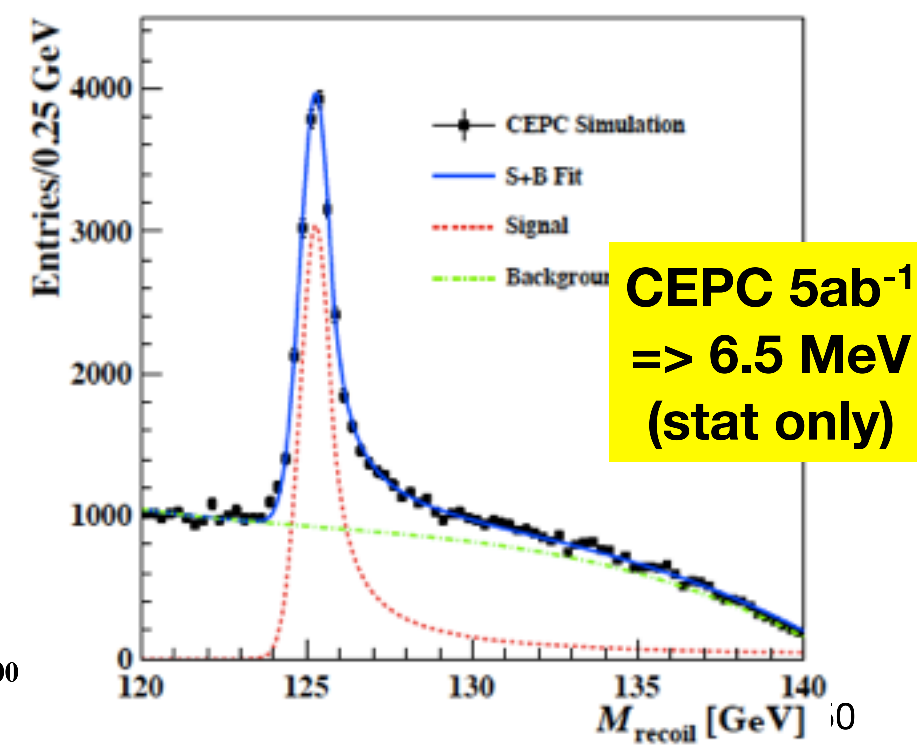


ILC 5ab^{-1} : 6.7 MeV (stat only) => effect of better defined initial state is very small!



CEPC 5ab^{-1} => 6.5 MeV (stat only)

Higgs couplings in e^+e^- collisions

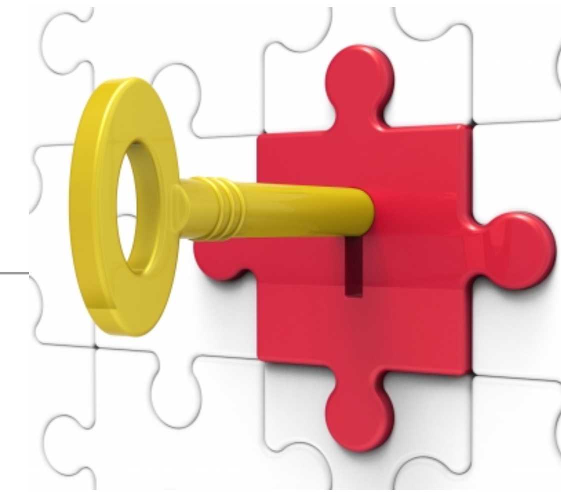


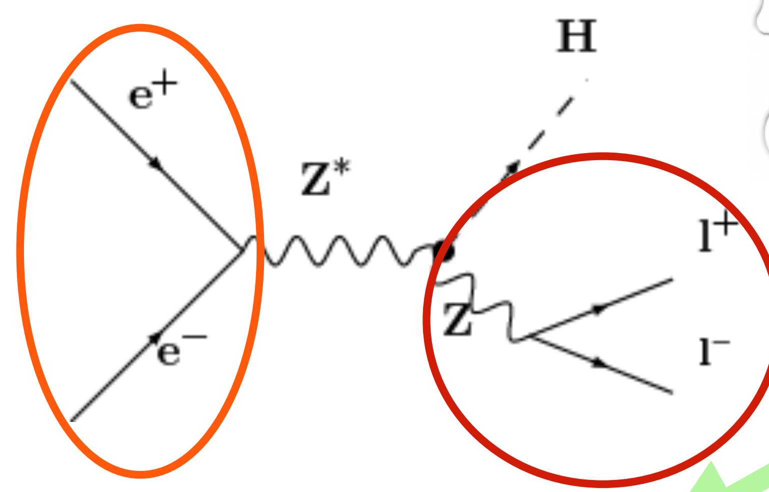
Image courtesy of Stuart Miles at FreeDigitalPhotos.net

- the **key**: measurement of *total* σ_{ZH} via recoil against **visible Z decay** => independent of Higgs decay!
- possible because **initial state** in *known*
- gives access to
  - total width Γ_H, e.g. via $\Gamma_H = \Gamma(H\to WW^*) / BR(H\to WW^*)$
  - thus *absolute* coupling measurements
  - …and H->invisible

=> all in a model-independent way!

- recent progress: [c.f. Eur.Phys.J. C76 (2016) no.2, 72]
  - can also **use Z->qq decays if √s > ~350 GeV**

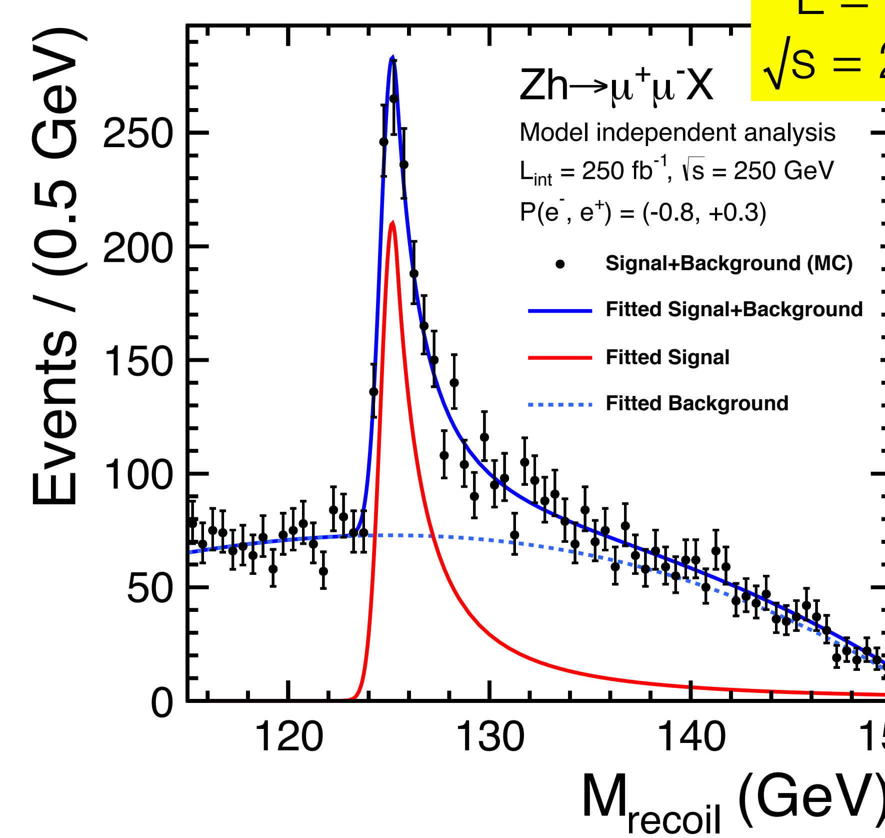
  => detector resolution dominates over initial state….
- furthermore: access to decay modes which are challenging at LHC (e.g. H->cc, gg)



circular e^+e^- colliders: initial state even better known! intrinsic advantage ?

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

L = 250fb[-1]
√s = 250 GeV



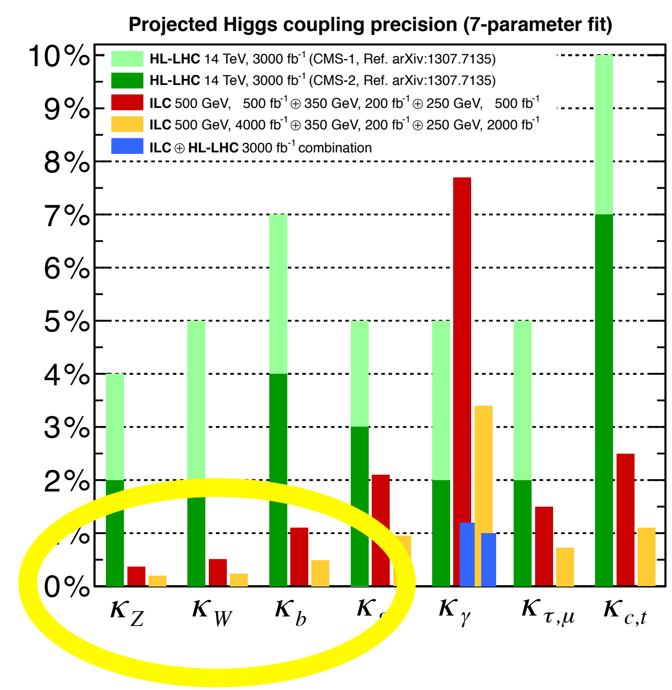
Beyond statistical uncertainties

- experimental systematics:
  - consider level of ~1% “easy” at e+e- collider (trust LEP)
  - what about ~0.1% ? Lots of data helps (trust LHC)
    - however need at least a clear strategy sketched out (control reactions, ….)
- theoretical uncertainties:
  - signal & background predictions entering the analysis itself (MC, …)
  - parametric uncertainties in interpretation (SM: e.g. other couplings at loop-level / BSM)
  - intrinsic uncertainties of calculations to compare to (HO, scales, …)

=> What is the appropriate *statistical* uncertainty to aim for?

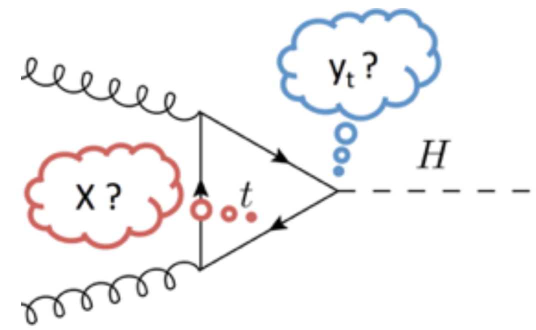
- example: ILC Higgs coupling fit assumes on σ x BR:
  - dL/L = 0.1%
  - dP/P = 0.1%
  - rel. uncert. on b-tag: 0.3%
  - rel. uncert. on theory: 0.1% (!)
  - => these are non-trivial to reach!

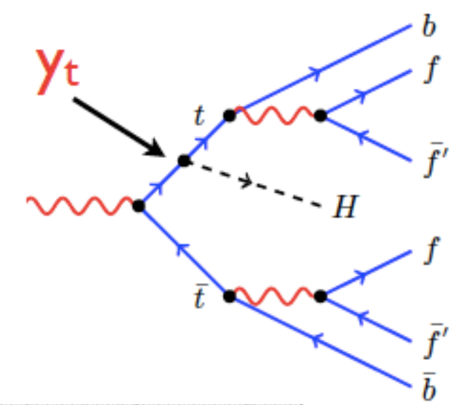
e.g. constrained fit
“LHC-style”
$\delta\kappa_Z = 0.2\%$
$\delta\kappa_W = 0.24\%$
$\delta\kappa_b = 0.5\%$

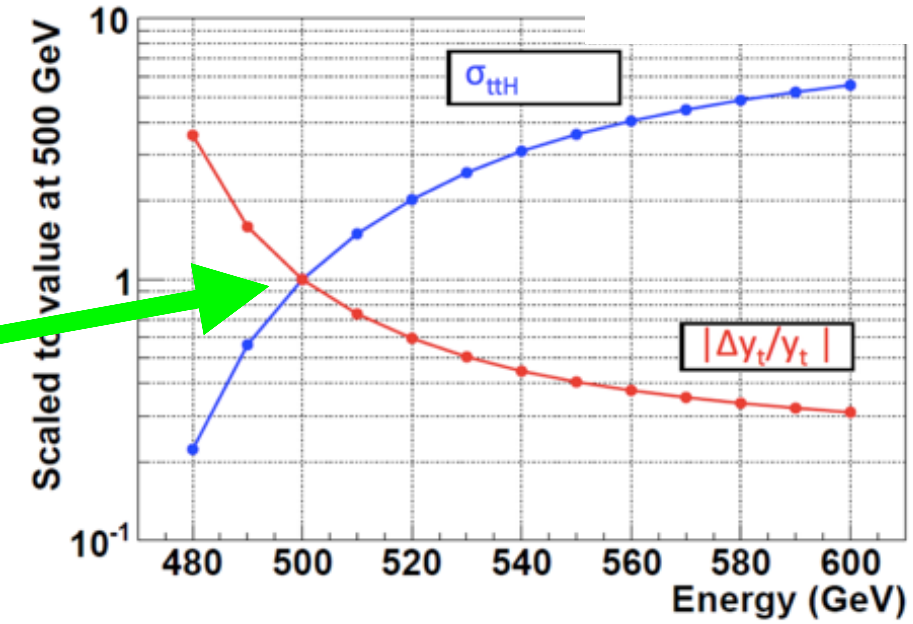


Direct Determination of the Top Yukawa Coupling

- **(HL-)LHC 14 TeV:**
  - SM σ(ttH) = 0.6 pb
  - “theory” studies indicate δ**y$_t$ ~15% (~10%)** with 300fb-1 (3ab-1) might be possible [arXiv:1310:8361]
- **pp 100 TeV:**
  - σ(ttH) increases by factor ~60
  - expect **~1%** from cross section scaling (20ab-1)
- **e+e-:**
  - **threshold at √s = 475 GeV**
  - SM σ(ttH) = 0.45fb @ 500 GeV
    => ILC full running scenario: **δy_t = 6.3%**
  - could be **2.5% if √s = 550 GeV**
  - ILC tunnel has recently been extended by 1.5km on each side (“empty”…)
  - **1 TeV, 4ab-1: δy_t = 2%**
  - **CLIC 1.4 TeV, 1.5 ab-1: δy_t = 4.4%** - no improvement at 3 TeV (σ drops)







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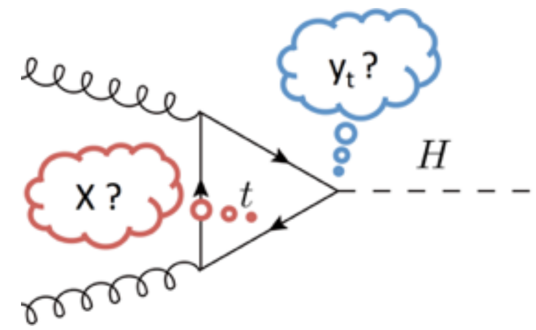
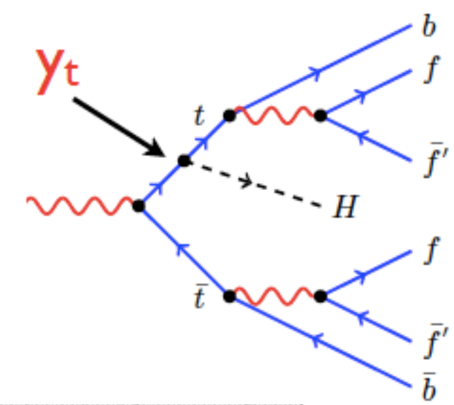
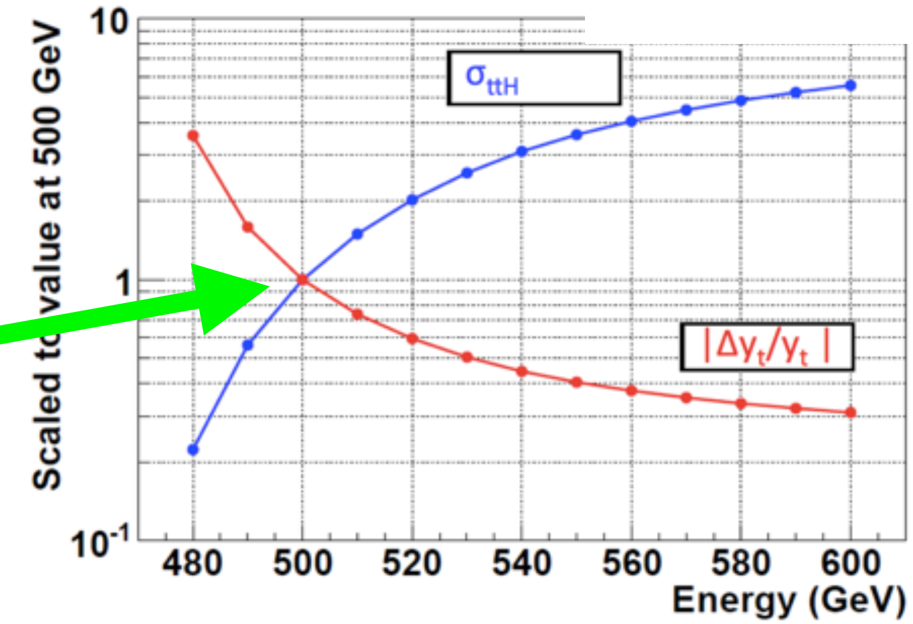
  - SM σ(ttH) = 0.45fb @ 500 GeV
    => ILC full running scenario: **δy_t = 6.3%**
  - could be **2.5% if √s = 550 GeV**
  - ILC tunnel has recently been extended by 1.5km on each side ("empty"…)
  - **1 TeV, 4ab-1: δy_t = 2%**
  - **CLIC 1.4 TeV, 1.5 ab-1: δy_t = 4.4%** - no improvement at 3 TeV (σ drops)







Direct Determination of the Top Yukawa Coupling

- **(HL-)LHC 14 TeV:**
  - SM σ(ttH) = 0.6 pb
  - "theory" studies indicate δ**y_t ~15% (~10%)** with 300fb-1 (3ab-1) might be possible [arXiv:1310:8361]
- **pp 100 TeV:** **=> simulation studies needed!**
  - σ(ttH) increases by factor ~60
  - expect **~1%** from cross section scaling (20ab-1)
- **e+e-:**
  - **threshold at $\sqrt{s}$ = 475 GeV**
  - SM σ(ttH) = 0.45fb @ 500 GeV
    => ILC full running scenario: **δy_t = 6.3%**
  - could be **2.5% if $\sqrt{s}$ = 550 GeV**
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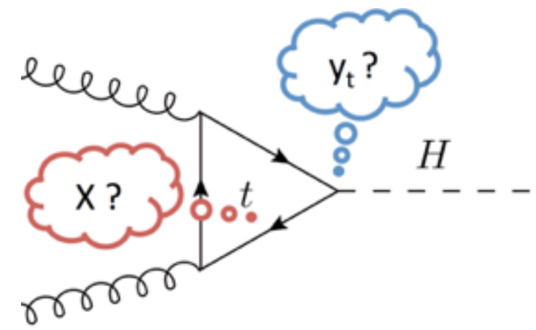
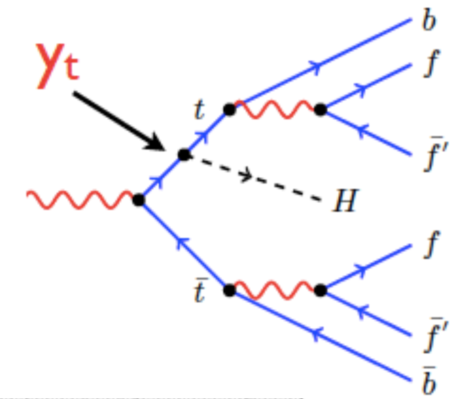
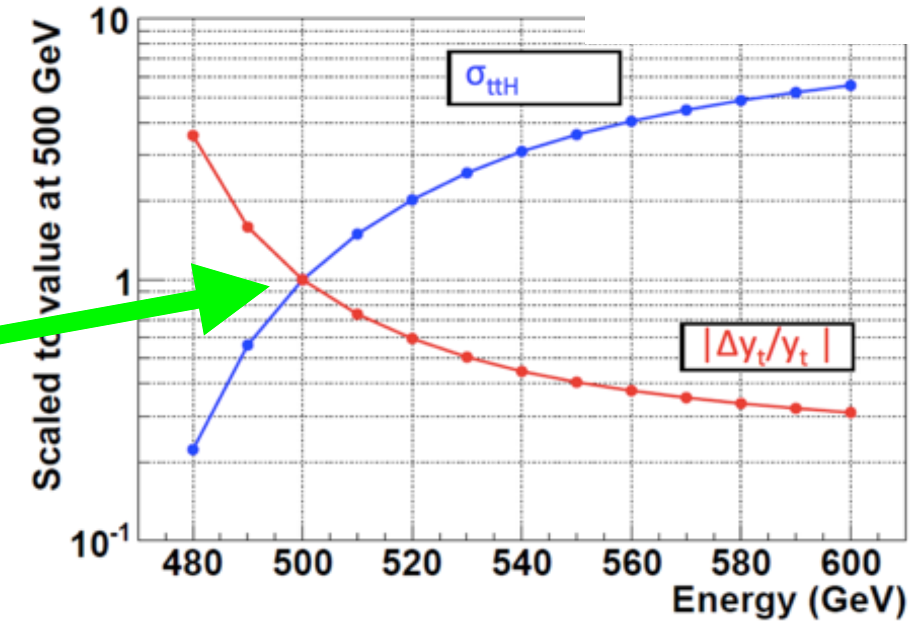


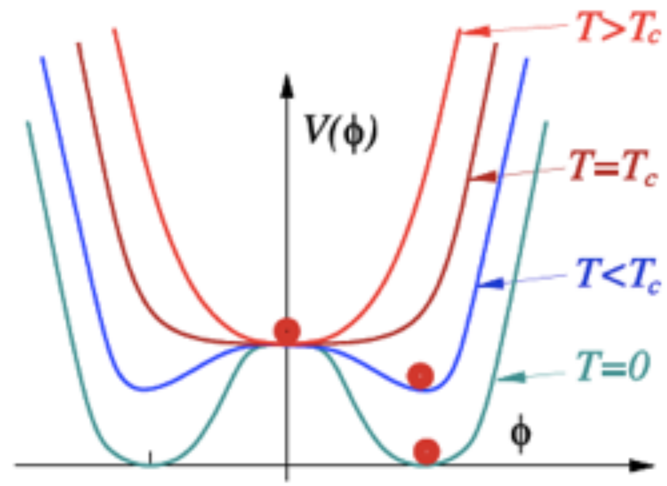




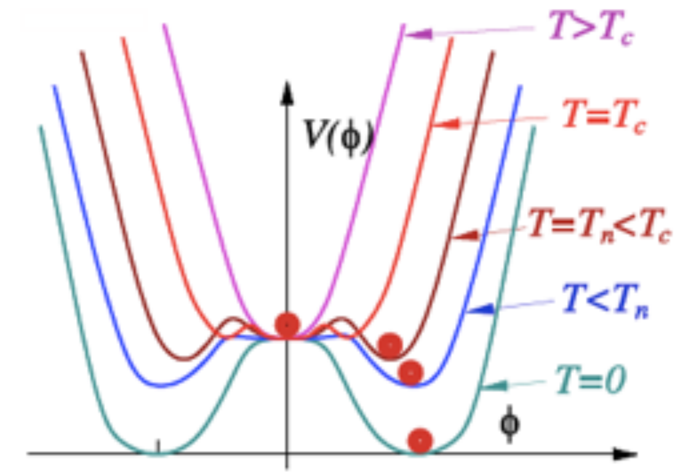
all ILC & CLIC projections from Geant4-based detector simulations benchmarked against performance of prototype detectors in testbeams!

Higgs self-coupling

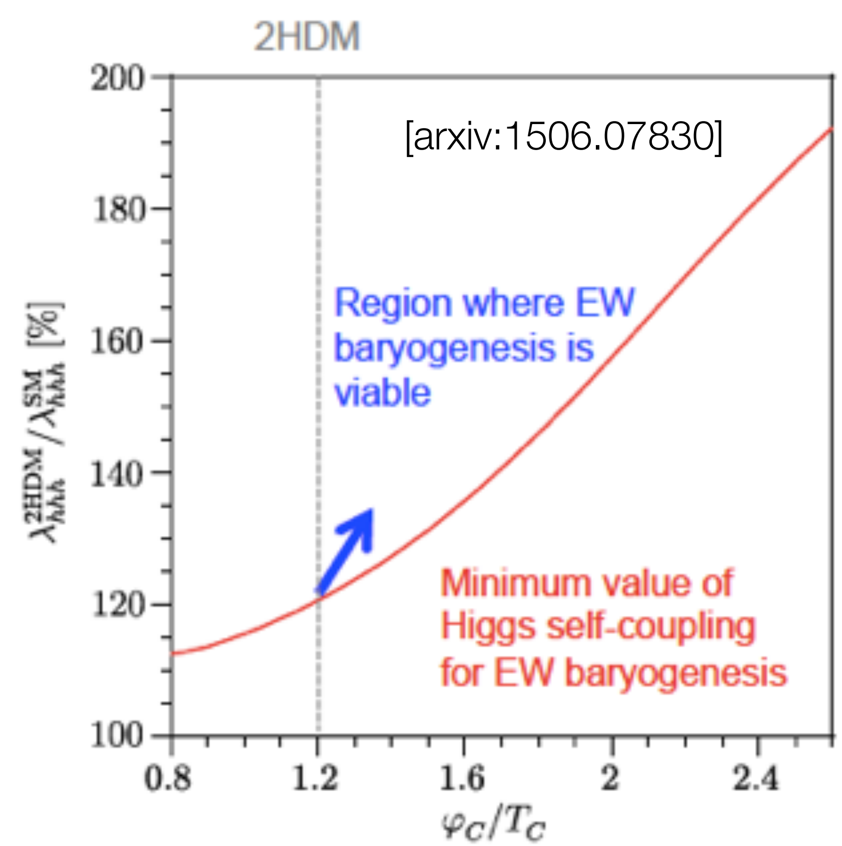
- determines shape and evolution of Higgs potential => cosmology!
- many BSM models influence λ, deviations from SM value can be **large**! E.g.:
  - up to O(100%) in general 2HDMs, even if other couplings are SM-like [c.f. e.g. Phys.Lett. B558 (2003) 157-164]
  - electroweak baryogenesis requires $\lambda > 1.2\ \lambda_{SM}$
- the experimental key: **Higgs pair production**!
  1. establish Higgs pair production at $>5\sigma$ level
  2. extract λ from cross section
- challenging at *any* collider!



1st order, required for EW baryogenesis

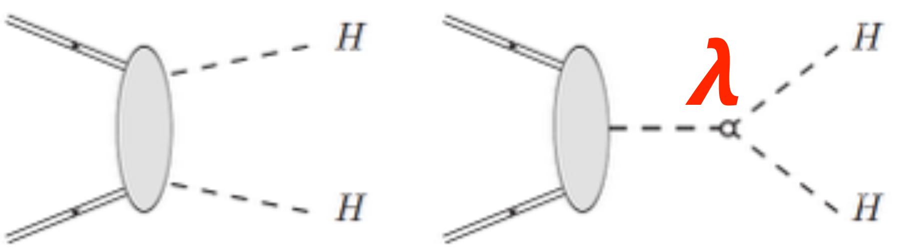


2nd order, SM with M_H = 125 GeV

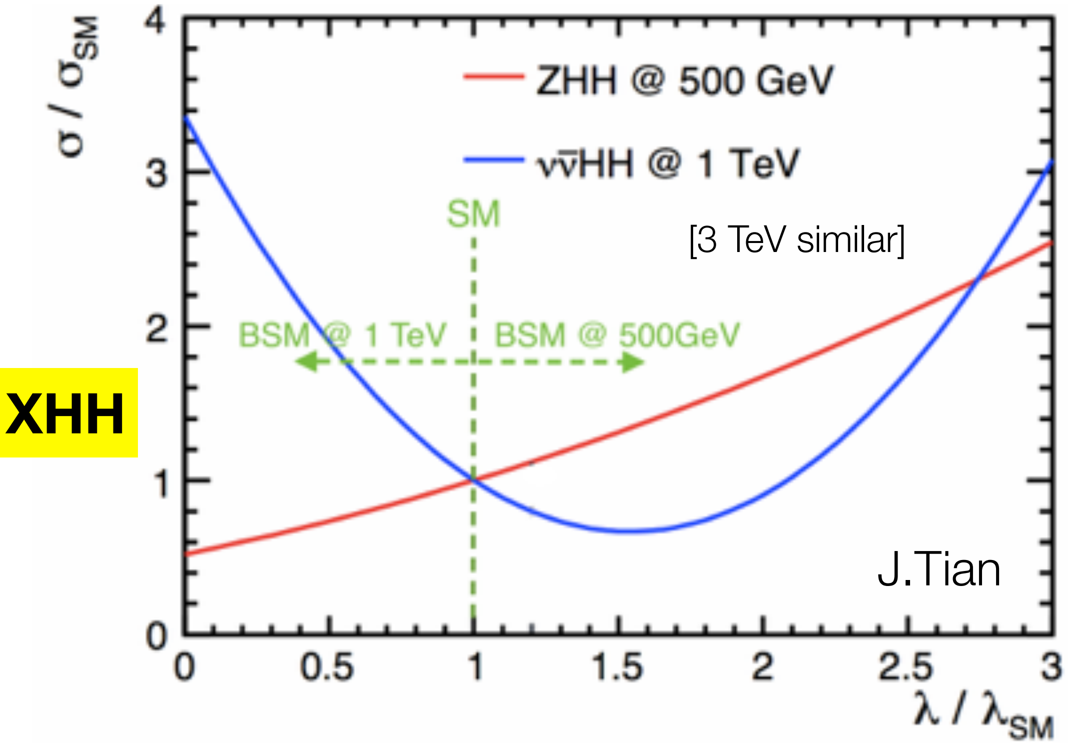


Higgs pair production

- always multiple diagrams contributing - with and without Higgs self-coupling λ
- interference induces *non-trivial relations* between cross sections and λ
- VHH has opposite behaviour to VBF /ggF=> important independent information!
- largest sensitivity to λ near threshold => restriction to high energy / high mass does not help
- **unique for e^+e^- @ 500 GeV: access to VHH**

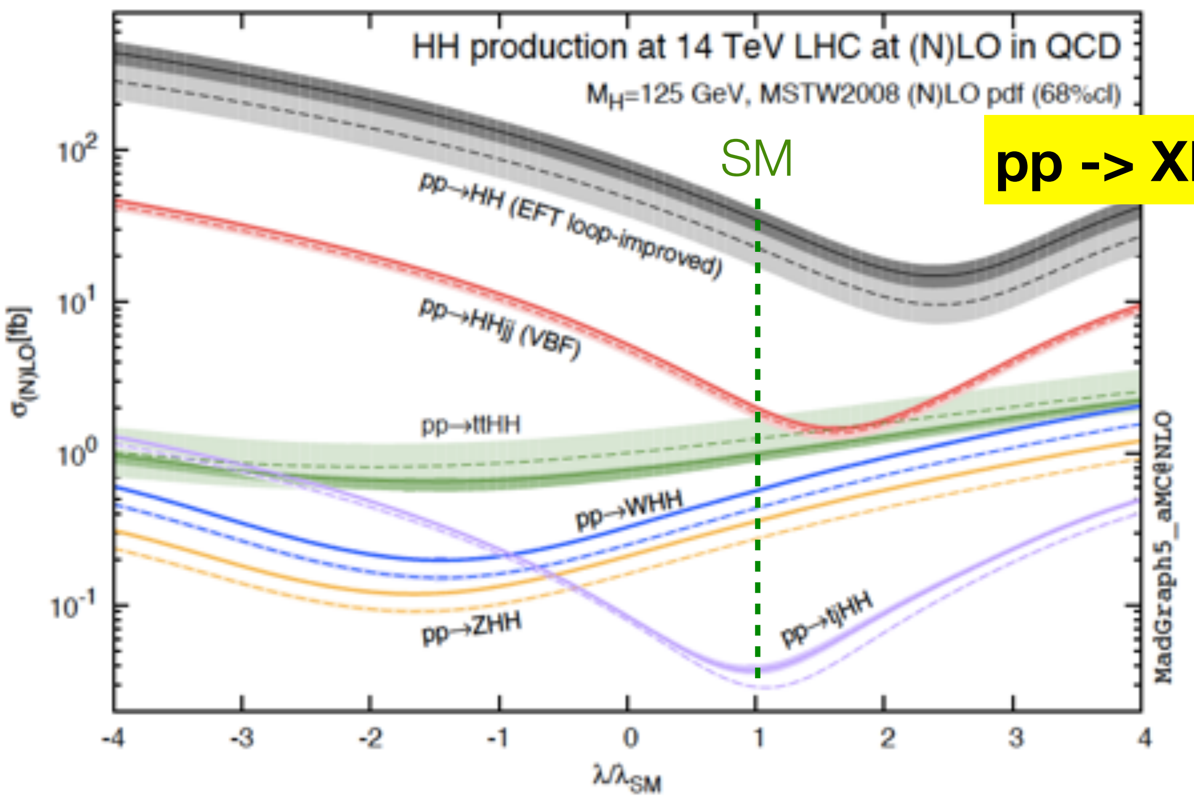


e^+e^- -> XHH



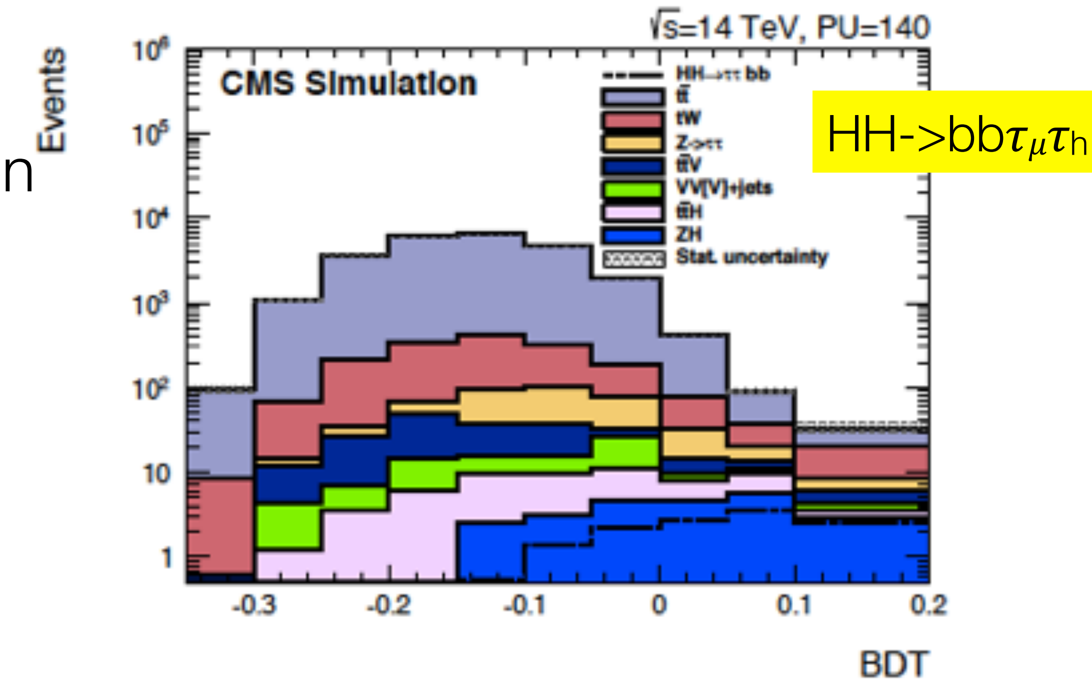
[arxiv:1401.7340]

pp -> XHH



Measurement prospects at pp colliders

- **HL-LHC:**
  - significance for observation of Higgs pair production **~1.9 σ / exp if λ = λ_{SM}** (bb$\gamma\gamma$ / bbWW / bb$\tau\tau$)
  - <=> uncertainty on **signal rate** ~54% / exp
    => **~38% combined**
  - *n.b.: this is not the uncertainty on λ!*



- **100 TeV:**
  - cross section ~40x larger
    => *aim for* 5-10% on signal rate
  - **NEW**: fast simulation study!
    (work in progress)
- **Common challenges:**
  - $\lambda > \lambda_{SM}$ => rate drops!
  - correlation with top Yukawa coupling y_t
  - large NLO k-factors….

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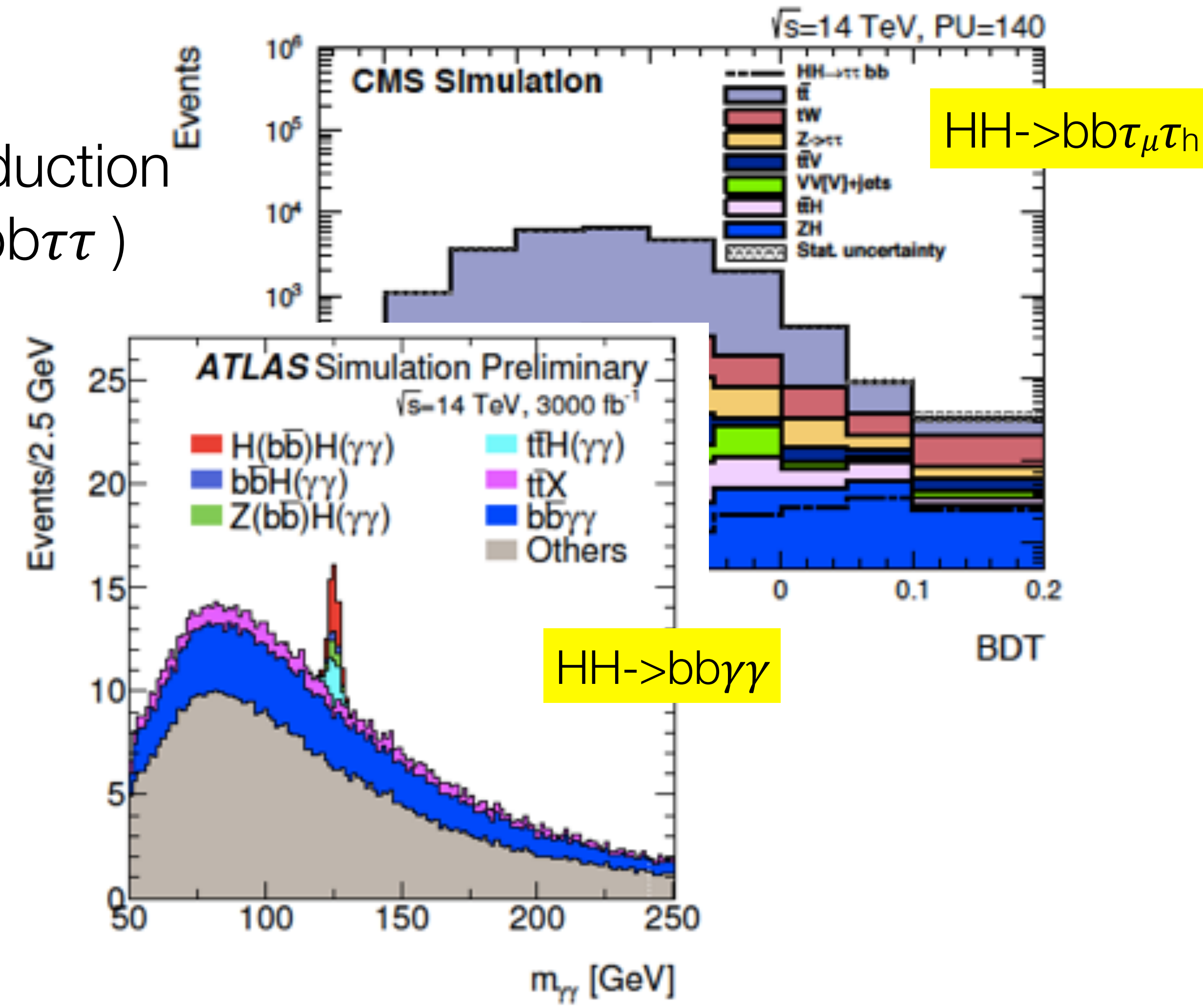

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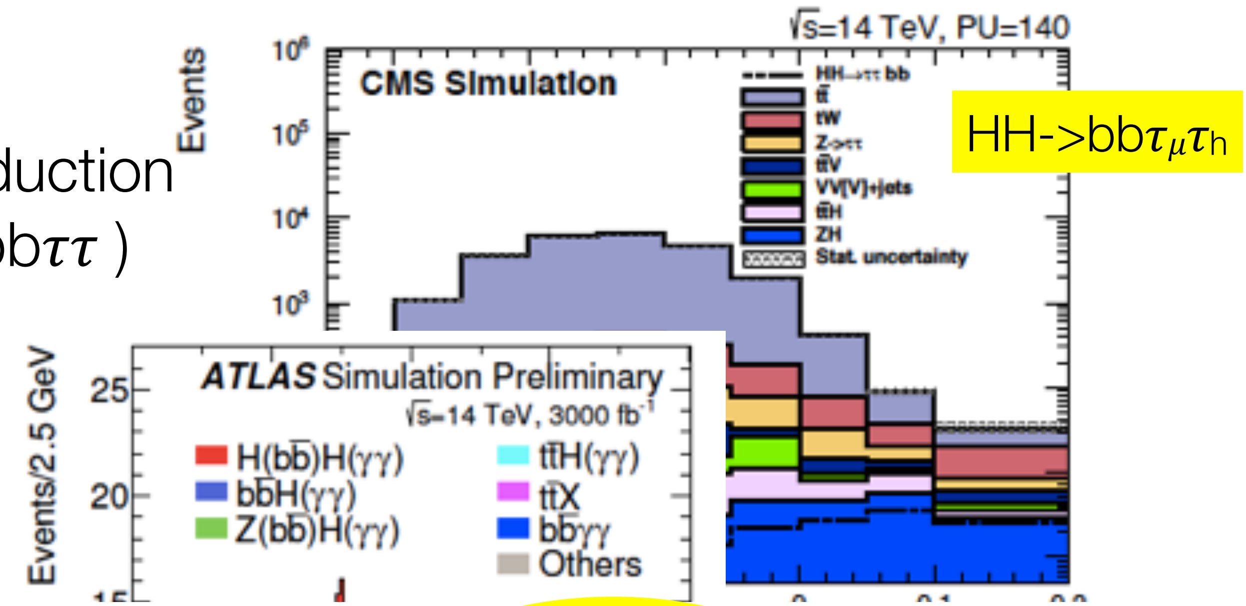

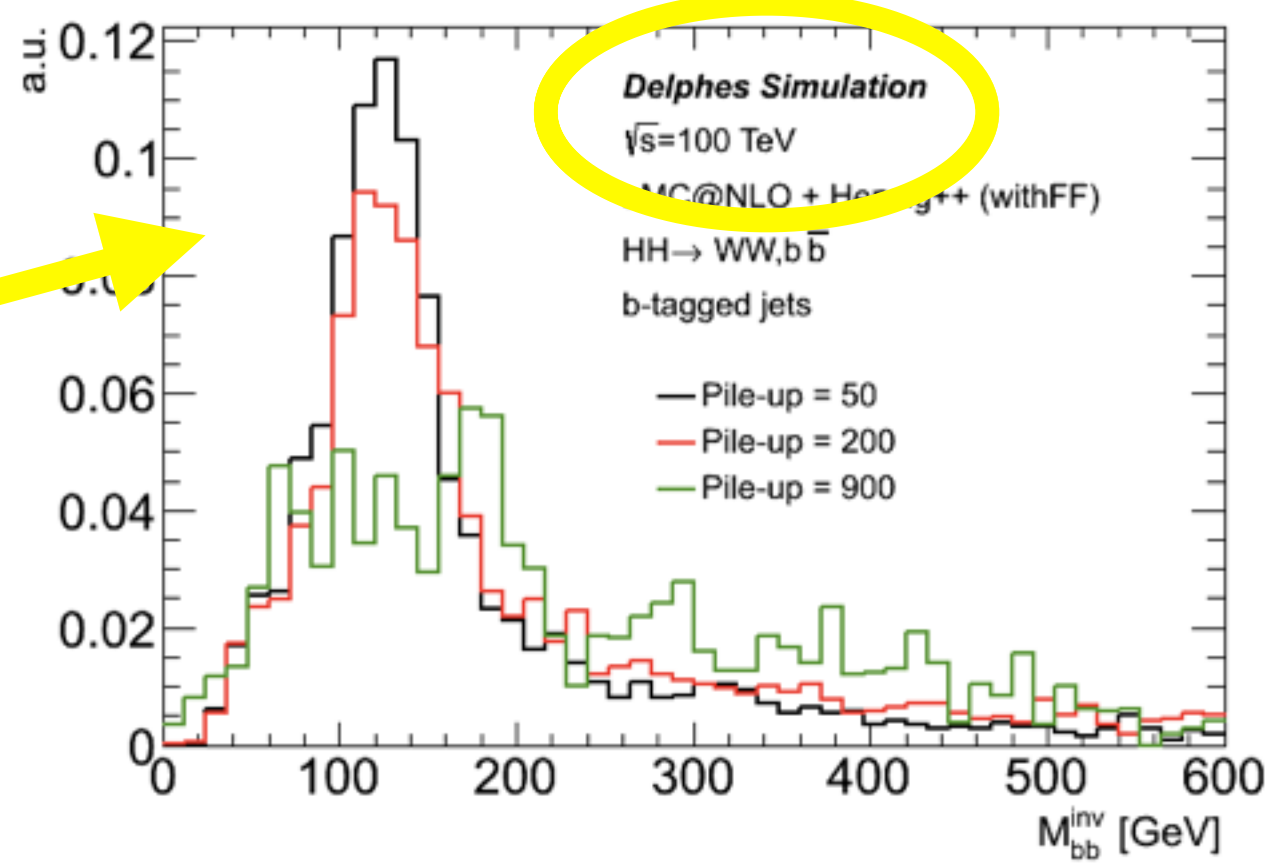

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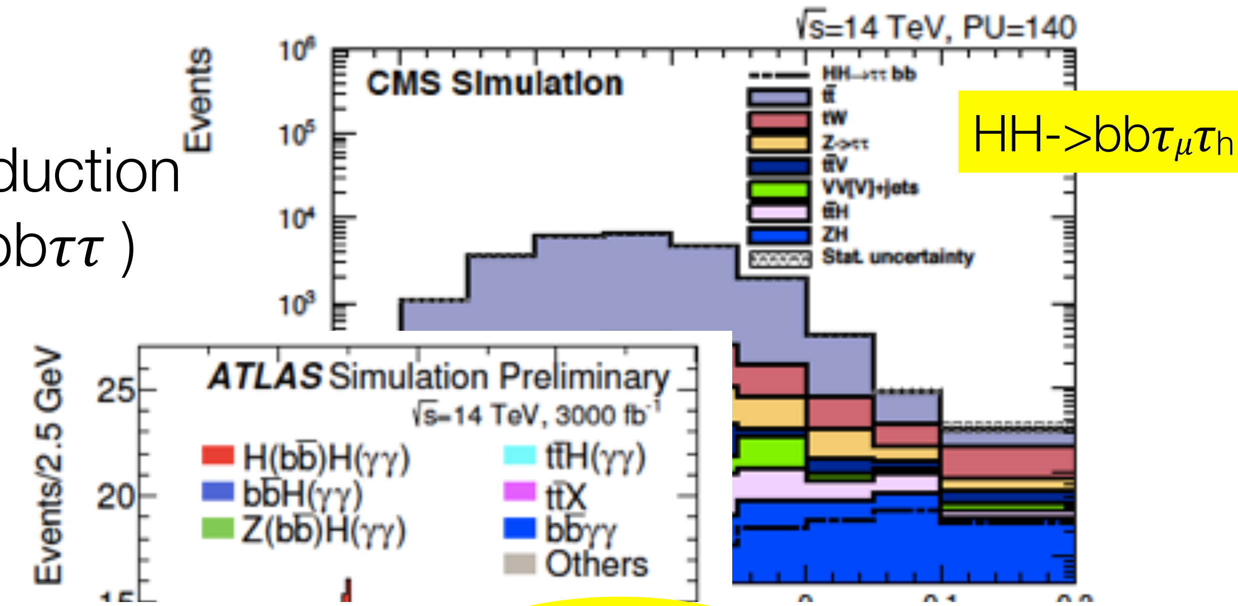
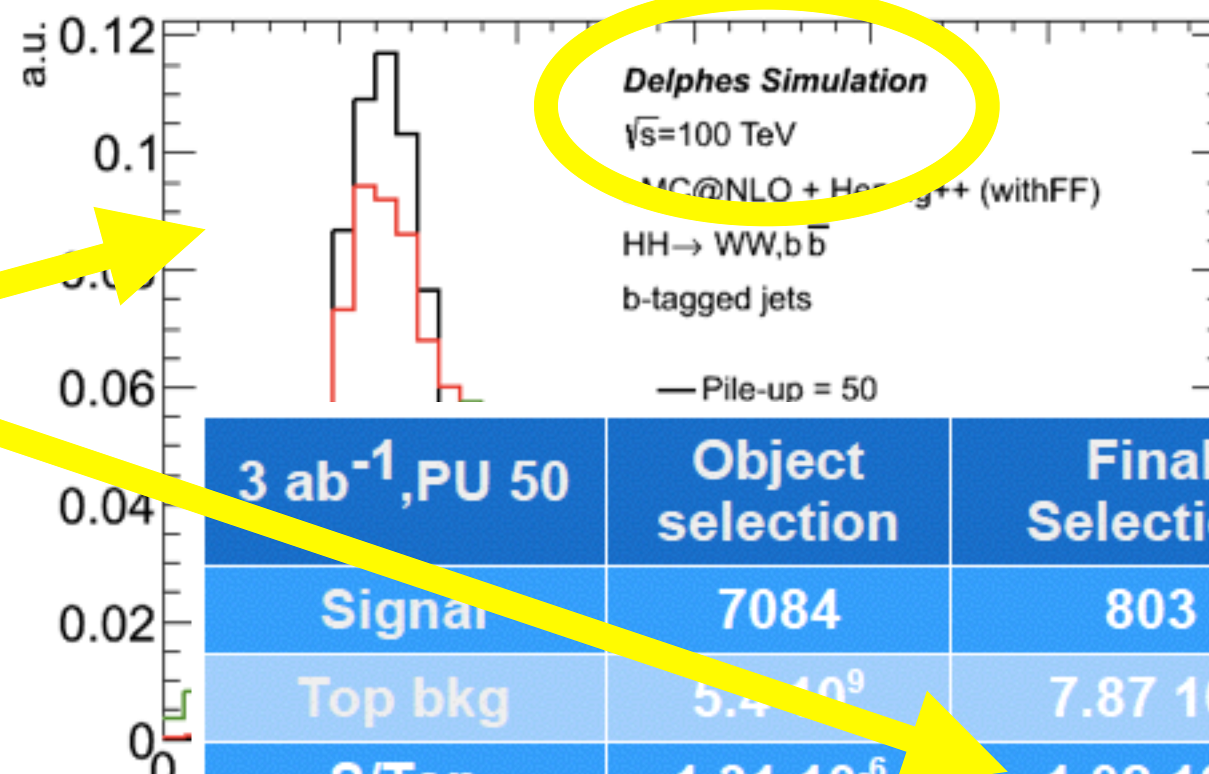
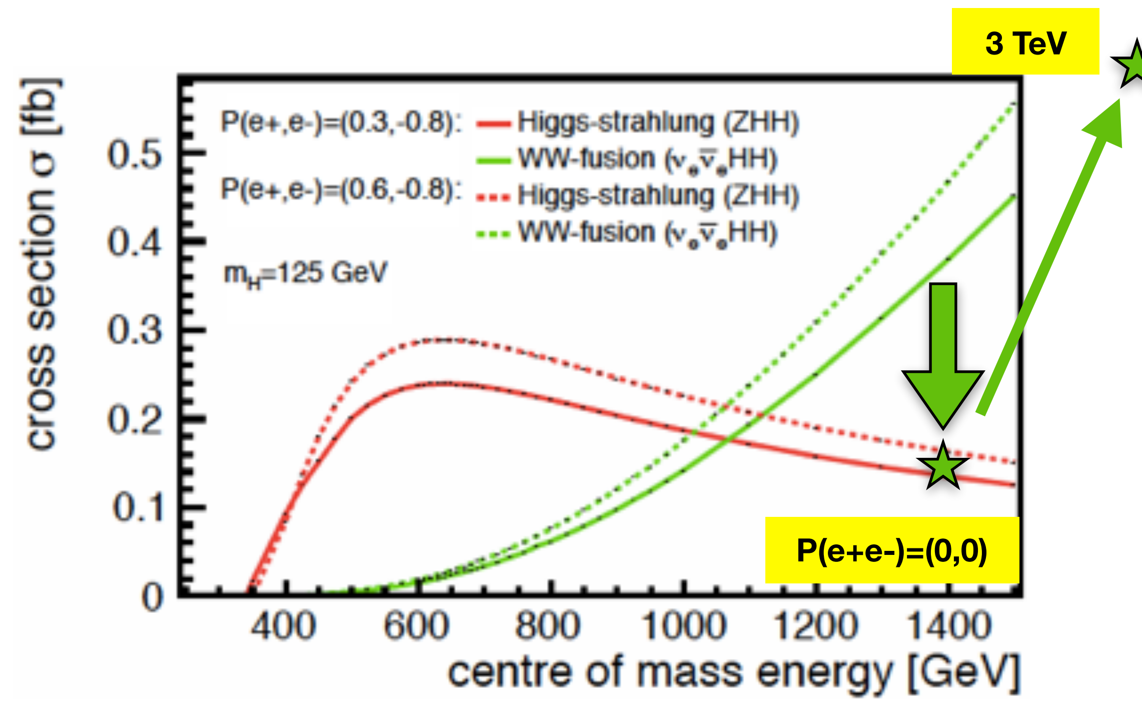


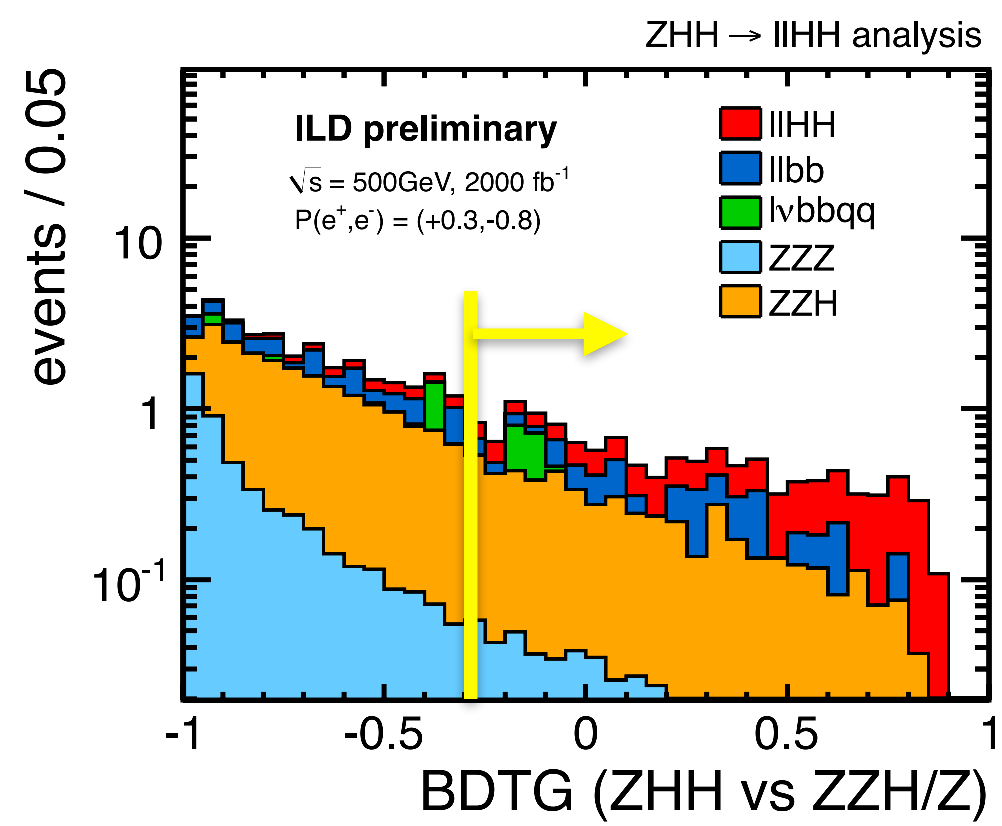


3 ab^{-1},PU 50	Object selection	Final Selection
Signal	7084	803
Top bkg	5.4 10^{9}	7.87 10^{5}
S/Top	1.31 10^{-6}	1.02 10^{-3}

Measurement prospects at e^+e^- colliders

- gives access to two complementary production processes:
  - **ZHH @ ~500 GeV**
    - unique feature: *increases* if $\lambda > \lambda_{SM}$
    - additional dependency on g_{ZZHH}
  - **vvH (VBF) @ ECM > 1 TeV: large cross section, in particular with polarised beams**
    - additional dependency on g_{WWHH}





- all decay modes of H and Z can be used (person power limited!), currently
  - main working horse: HH->bbbb
  - in addition: HH->bbWW*
  - after all cuts typical S/B ~ 1/2

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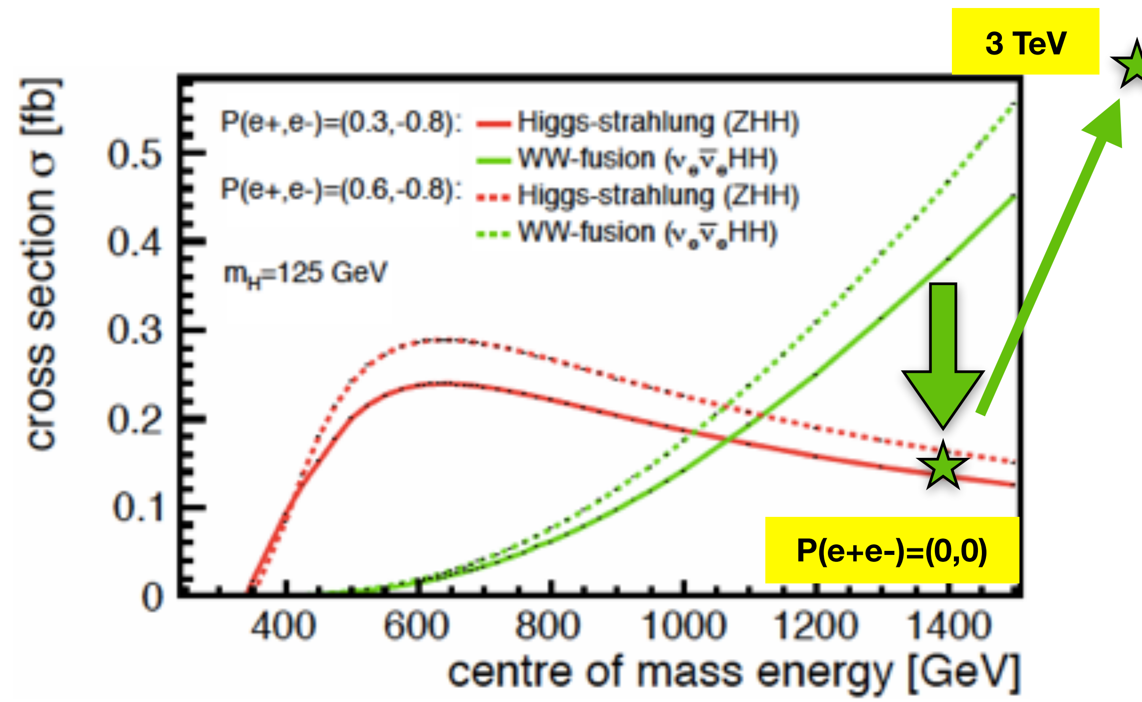

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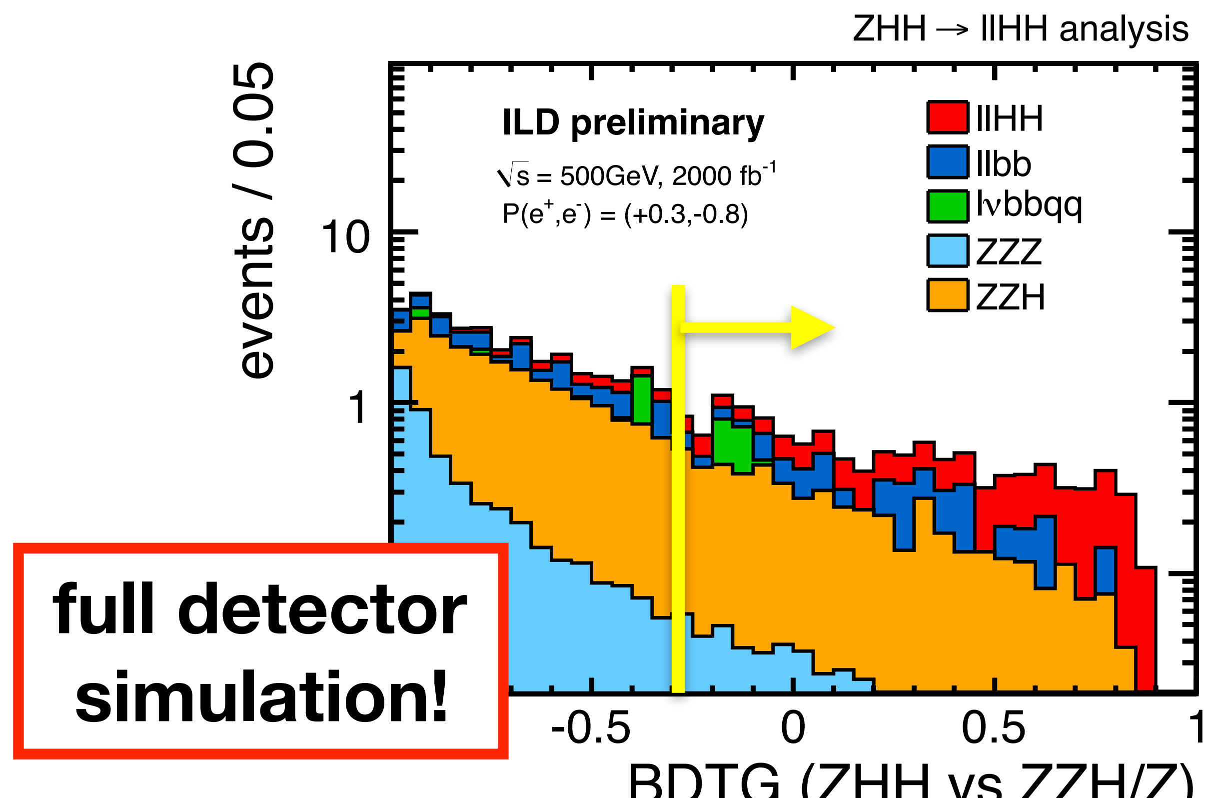
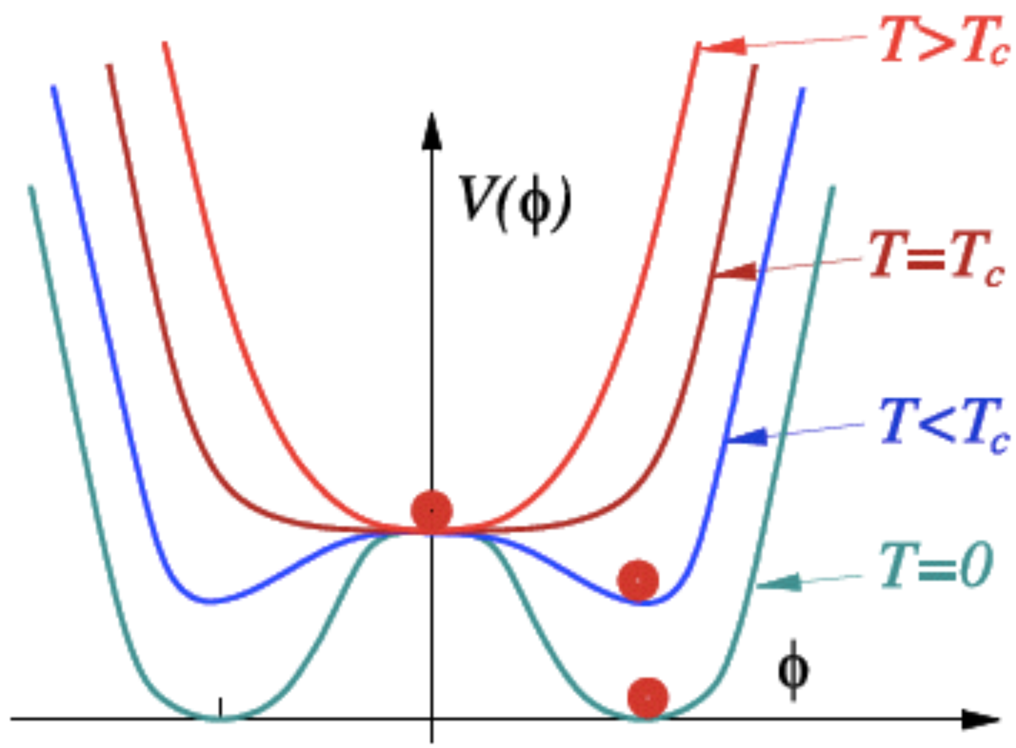
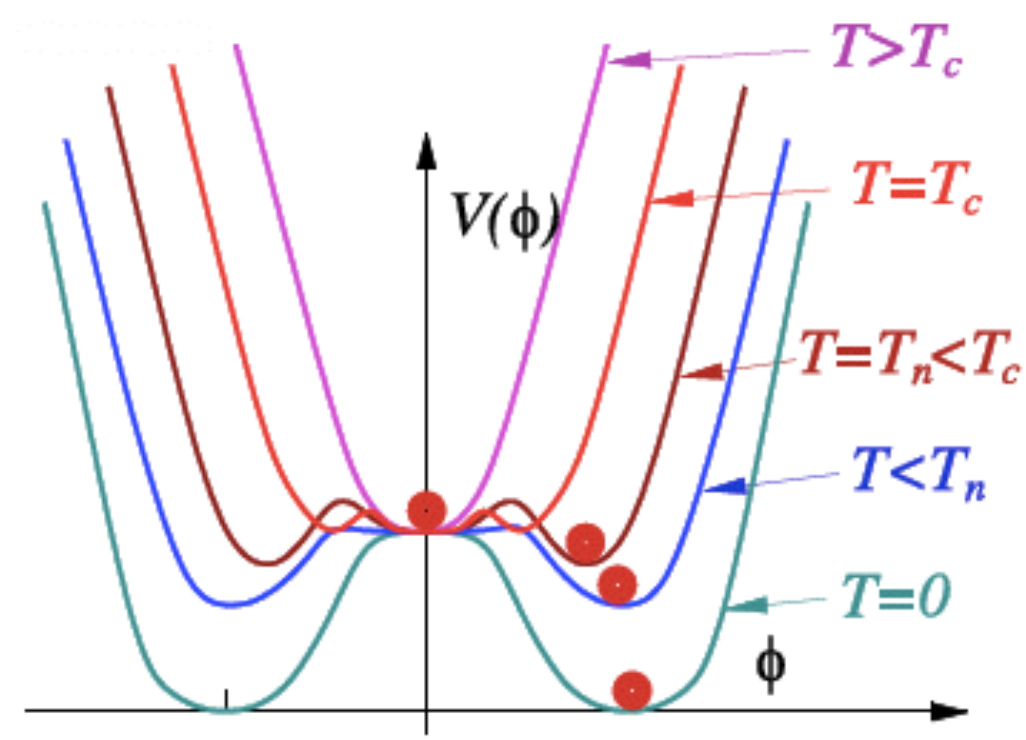


First or second order electroweak phase transition?



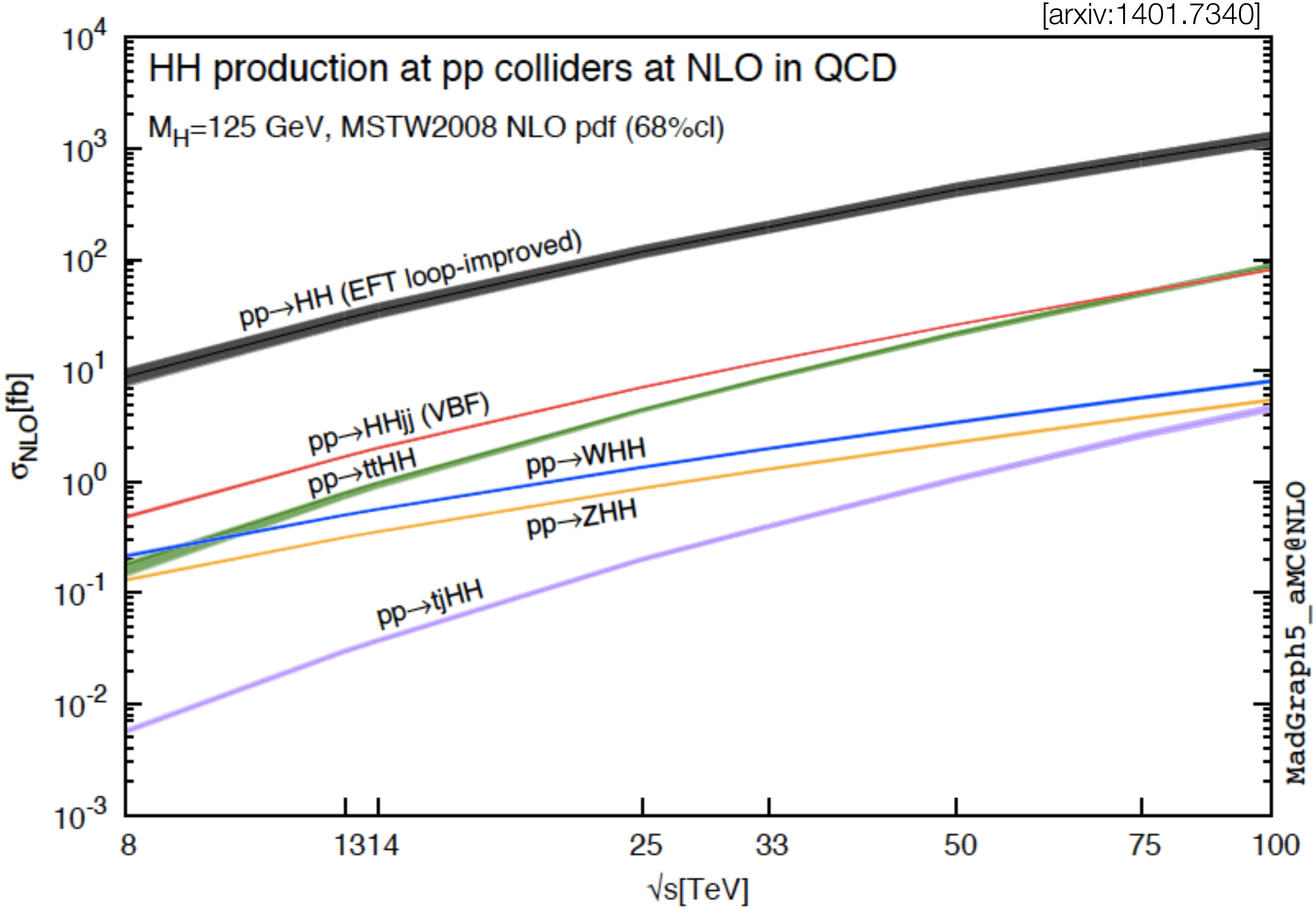


- first order
- required for electroweak baryogengesis

- second order
- SM with M_H = 125 GeV

Double Higgs Cross Section in pp vs ECM

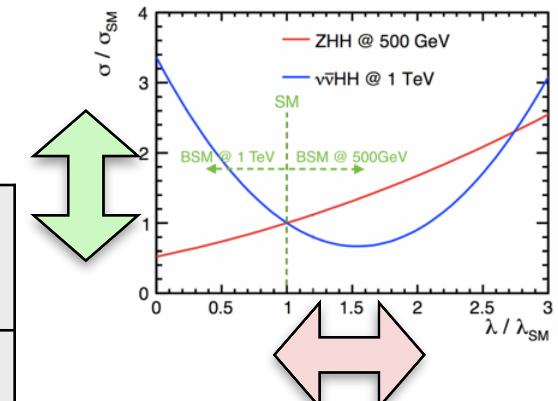
[arxiv:1401.7340]



From cross section to self-coupling in e^+e^-

- $\delta\lambda/\lambda = k\ \delta\sigma/\sigma$; n.b.: $k = \text{“}(\partial\sigma/\partial\lambda)^{-1}\text{”}\ |_{\lambda=\lambda obs}$

	500 GeV ZHH	1 TeV vvHH	1.4 TeV vvHH	3 TeV vvHH	1.4 TeV vvHH, pol	3 TeV vvHH,pol
$\int$Ldt	4 ab^{-1}	2.5 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}
$\delta\sigma/\sigma$	**16 %**	**13 %**	**26 %**	**11 %**	**20 %**	**8 %**
k_{SM}	1.64	0.76	1.22	1.47	1.22	1.47
$\delta\lambda/\lambda\ \|_{SM}$	27 %	10 %	32 %	16 %	24 %	12 %



HL-LHC 2 exp: 38%

HL-LHC : ?

- **$\delta\sigma/\sigma \leq$ 20% => $\geq 5\sigma$ discovery of Higgs pair production**
- for **SM** case, 1 TeV is a “sweet spot” with k < 1
  (sensitivity to λ largest close to threshold! - could analogous effect reduce the benefit of the factor 40 in σ from 14 TeV to 100 TeV?)
- **BSM** can change the picture: consider e.g. $\lambda = 1.5\ \lambda_{SM}$
  => 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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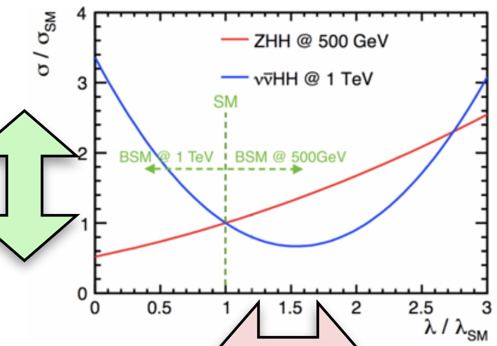

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Quantitative studies needed!

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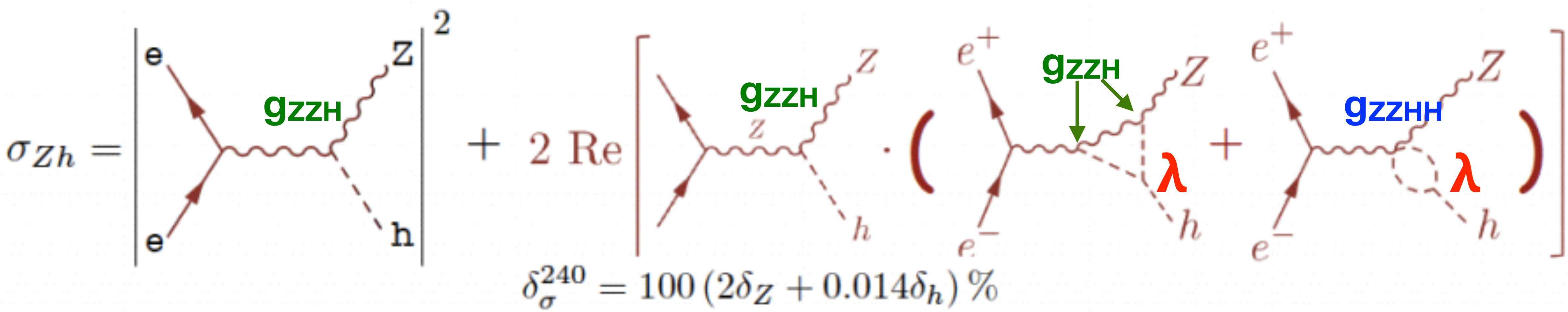
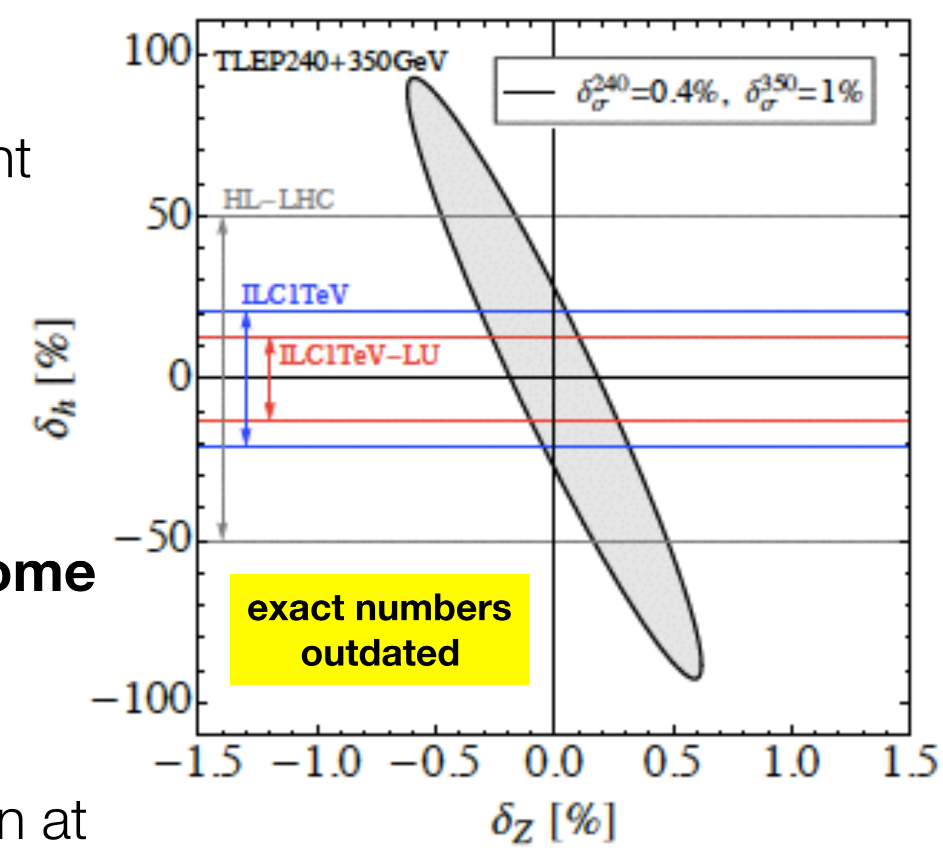
Higgs self-coupling from loop corrections?



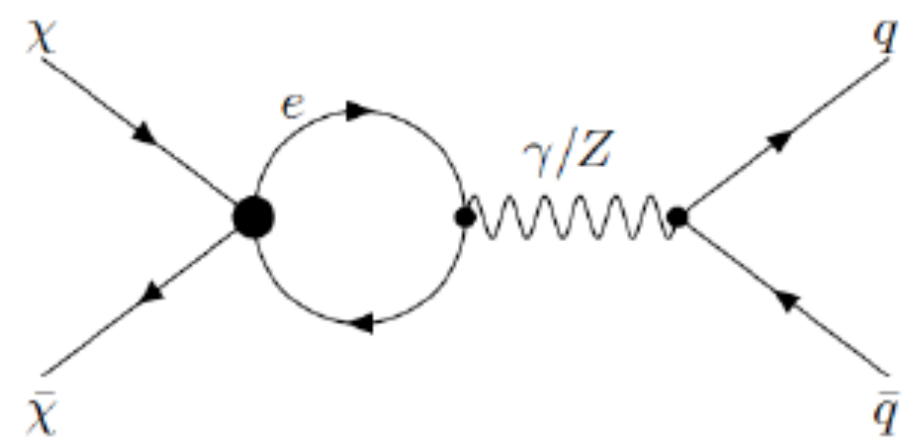
- sub-% precision on σ_{ZH} possible at all proposed e+e- colliders
- however: indirect and model-dependent method
- interesting consistency check, *not* an independent measurement
- what about other loop contributions?
  - top -> y_t ? W -> g_{WWH} ?
  - or even BSM ?
- **better look at plot the other way round: will we need at some point O(10%) direct measurement of λ in order to achieve permille-level extraction of g_{ZZH} from σ_{ZH} !?**
- at 500 GeV, NLO effects from λ on σ_{ZH} are ~7 times smaller than at 250 GeV **=> measuring σ_{ZH} at different ECM is more robust!**

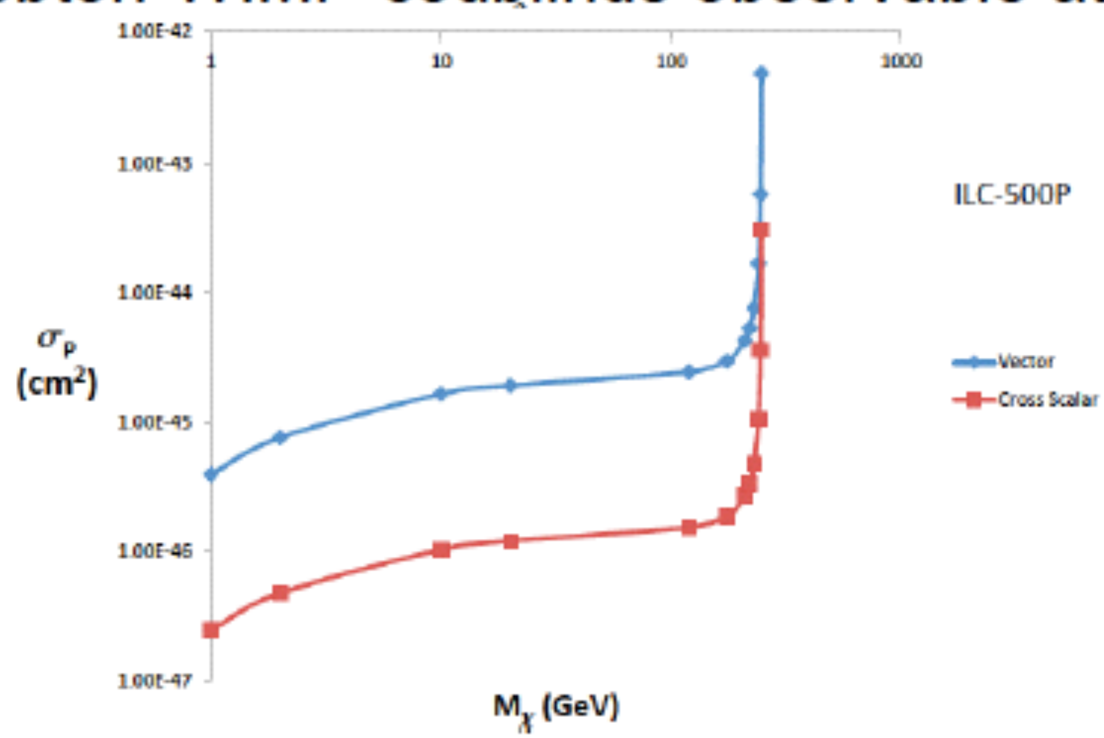
[arXiv:1312.3322]

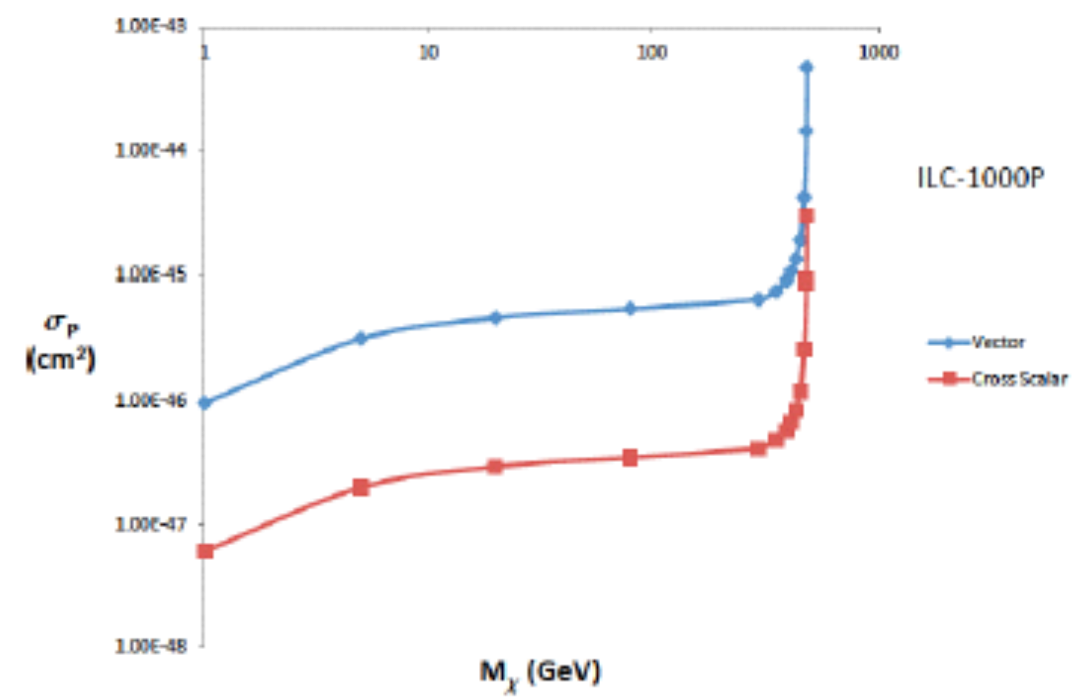


How to relate e^+e^- to Direct Searches?

- Will be model-dependent!
- Most conservative, ie minimal "unavoidable" X-Nucleon cross-section:
  - Assume no tree-level coupling to quark
  - Leaves us with loop contributions
- Direct searches need sensitivity of $\sim 10^{-46..47}$ cm^2 to rule out model-indepedently lepton-WIMP couplings observable at ILC



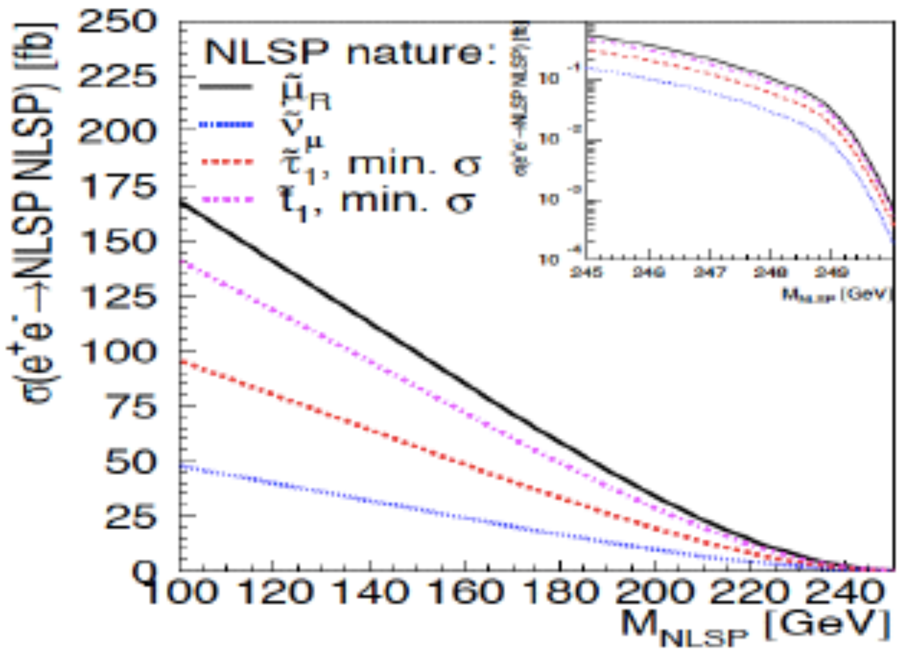


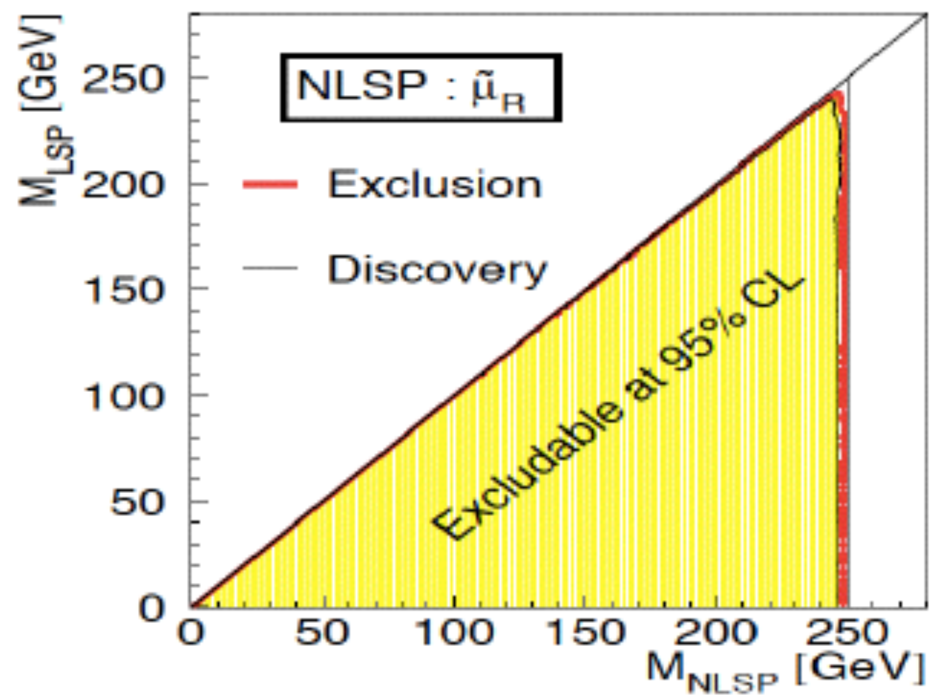


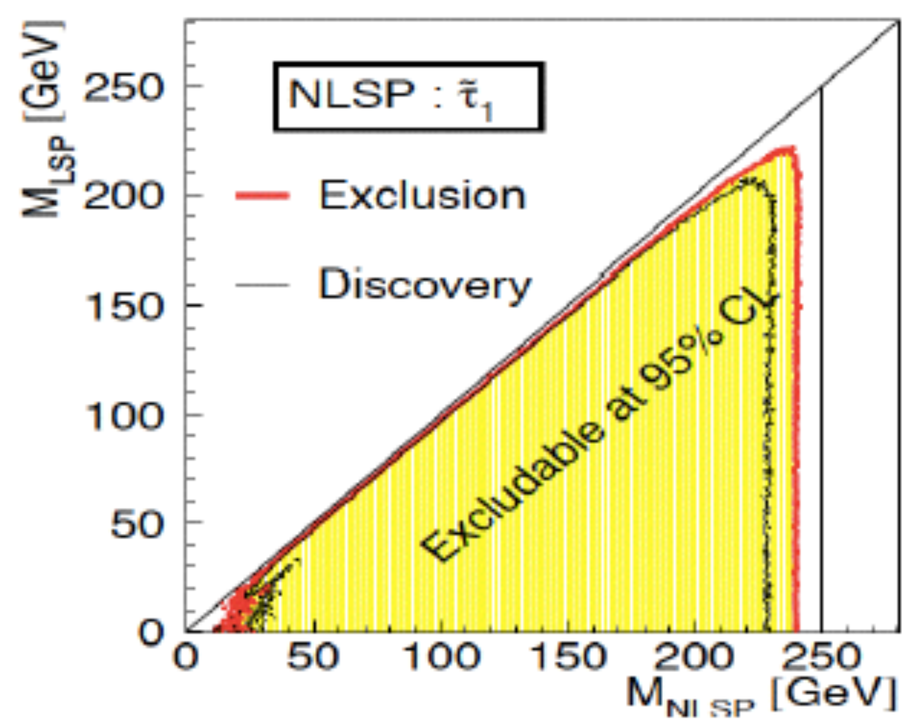
SUSY at the ILC

...is naturally simplified:

- NLSP pair production does only depend on mass of NLSPs:



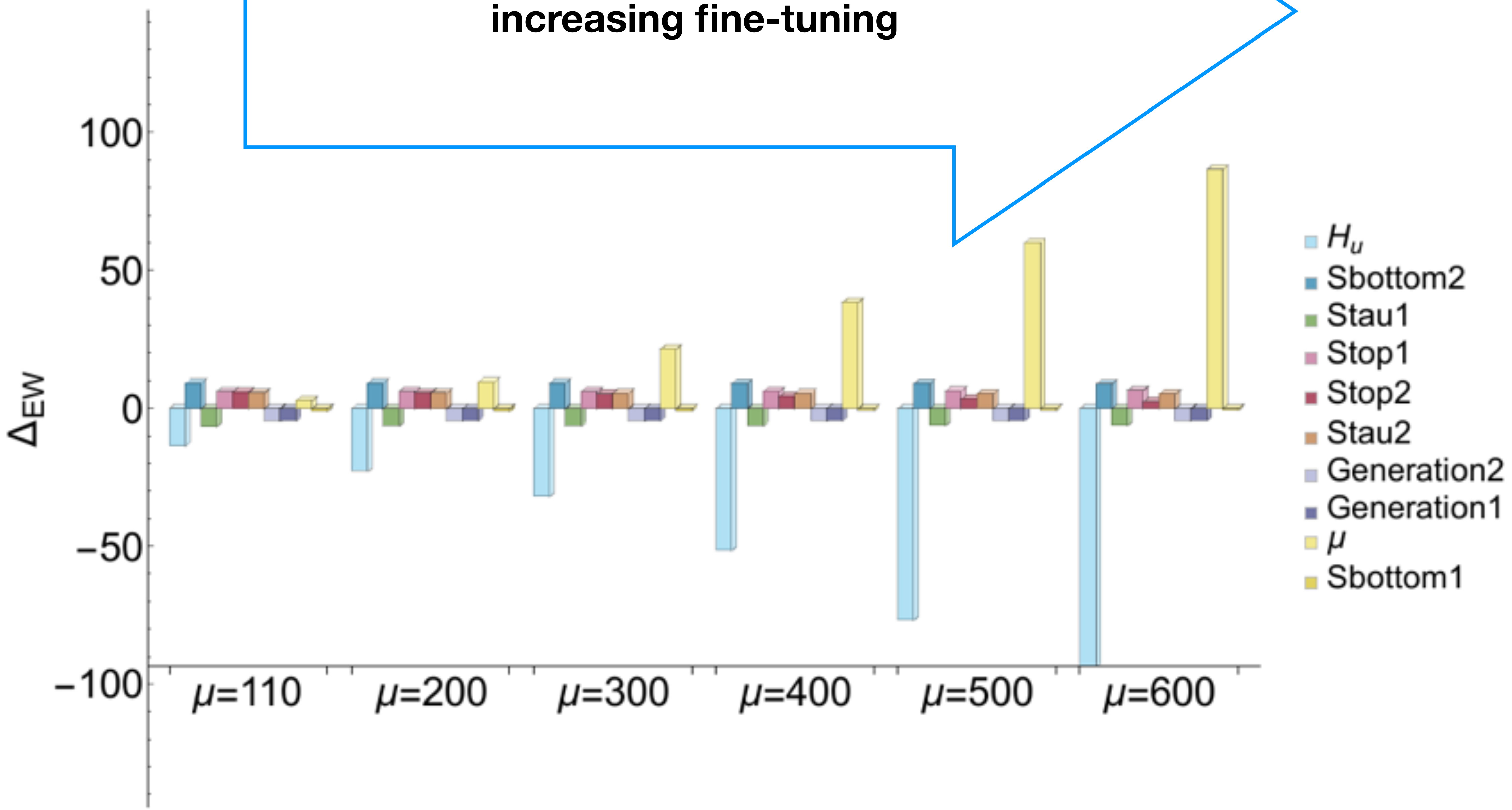




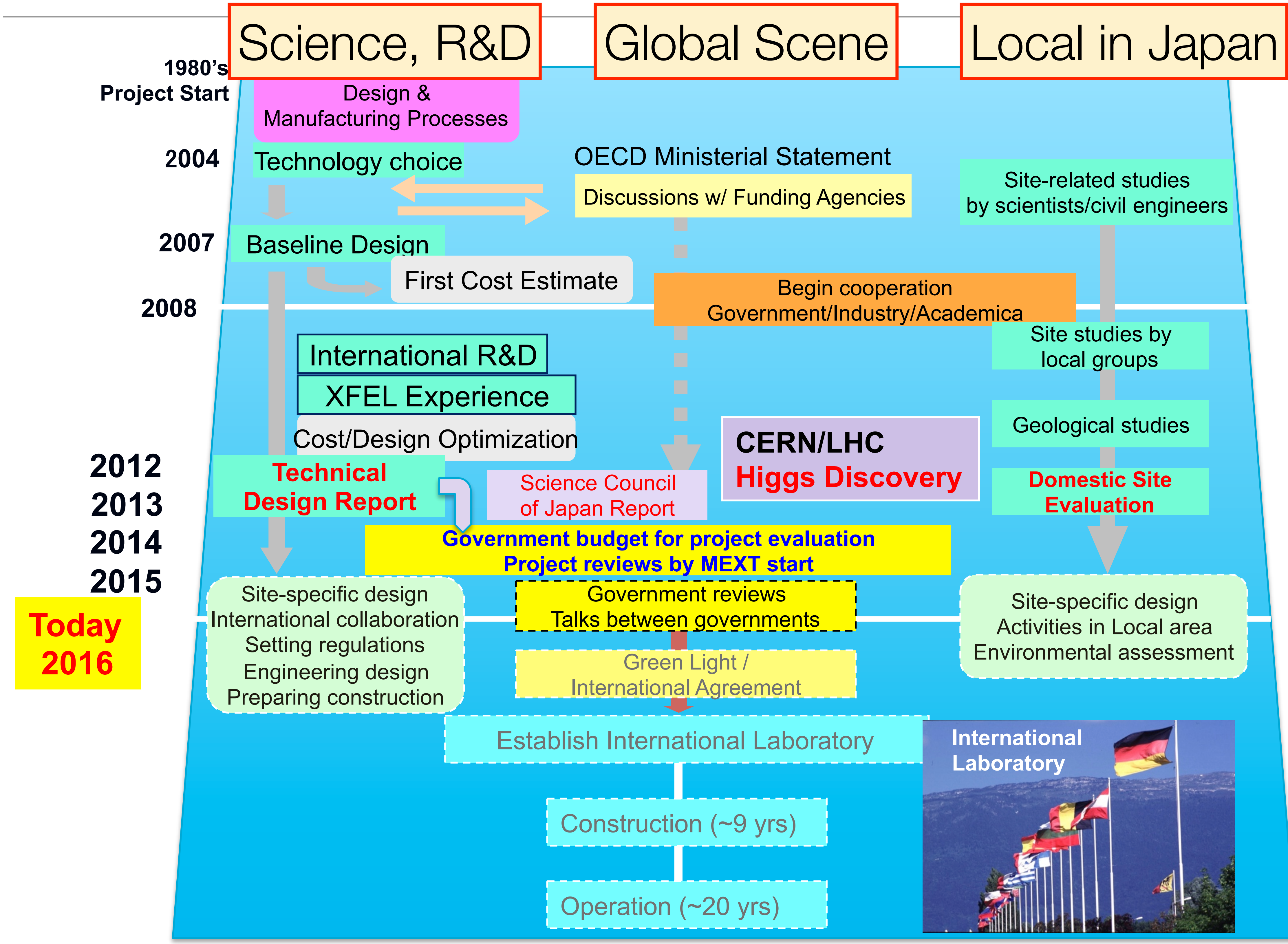
Loop-hole free, model-independent sensitivity down to very small mass differences

Naturalness

increasing μ
increasing fine-tuning



ILC Timeline - where are we now?

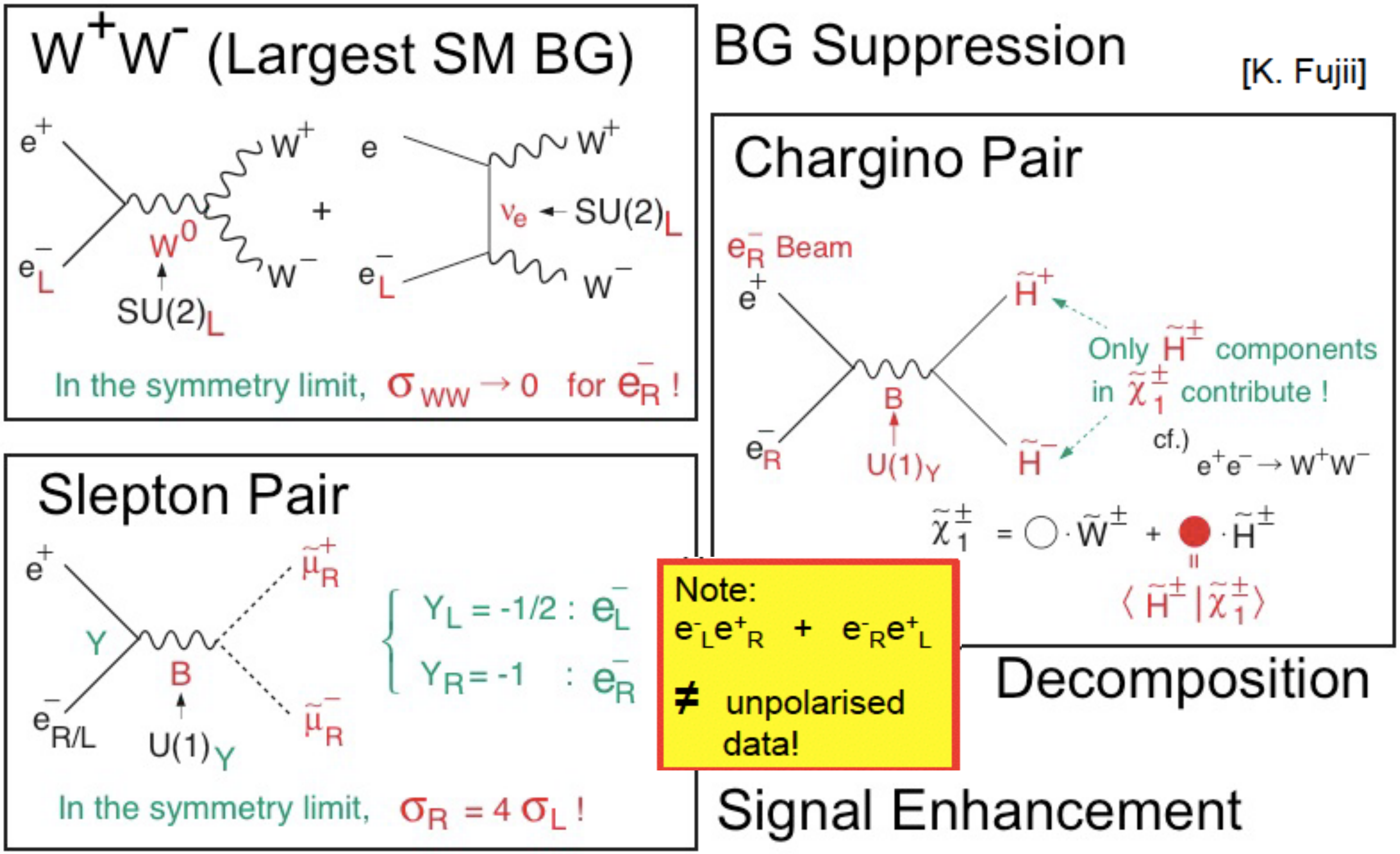


Luminosities vs power: CEPC & ILC at 250 GeV

	CEPC	5 Hz, 1315 bunches	10 Hz, 1315 bunches	10 Hz, 2625 bunches
inst. lumi [10^{34} / cm^2 / s]	**3.6 - 4**	0.75	1.5	**3**
total power [MW]	**498**	100	160 ?	**190**

=> ILC: 75% of CEPC luminosity with ~40% of CEPC's wall-plug power - not a bad deal!

Beam Polarisation



Note:
$e^-_L e^+_R$ + $e^-_R e^+_L$
≠ unpolarised data!

And what about 750 GeV?

- ATLAS and CMS report an excess in the di-photon invariant mass spectrum at 750 GeV

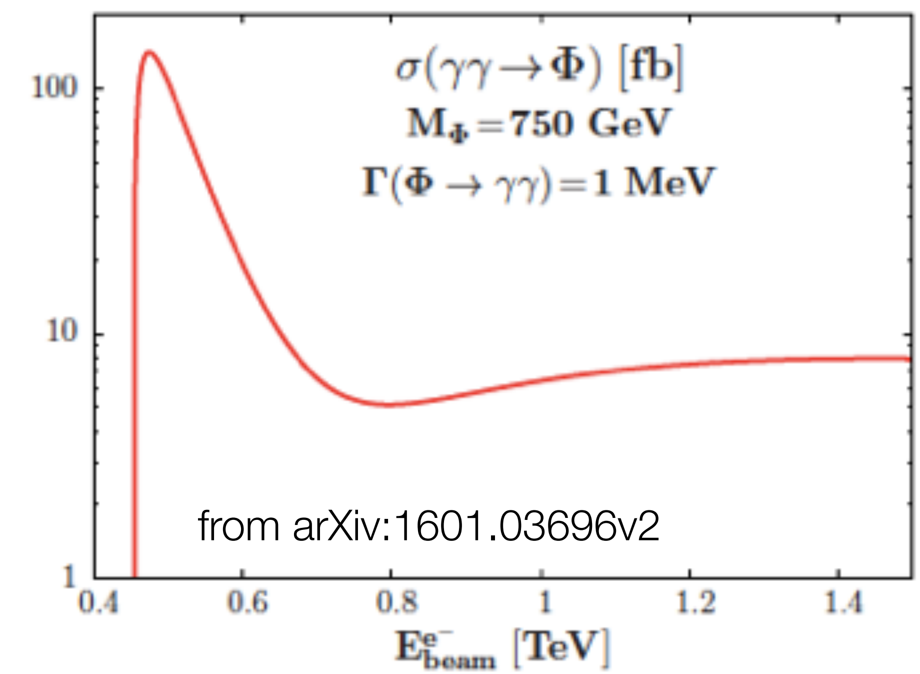
- As of today, this can be anything:
  - Narrow or broad? Spin 0 or 2?
  - Singlet or doublet?
  - Scalar or pseudo-scalar or CP violating?
  - Elementary or not?
  - A cousin of H125 or not?
  - Other decays than to di-photons?
  - …….
  - **real or statistical fluctuation?**

- By summer, we'll hopefully know the answer to the *last* question

=> If the signal proves to be real, we will need all complementary sources of information to fully unveil its nature!

Two “guaranteed” approaches to the 750-GeV particle

1. study the properties of the 750-GeV particle itself:
   - **LHC, HL-LHC will still provide a lot of information!**
   - FCC 100 TeV: increase cross section by factor 100
     => even more statistics, but still the same production mechanism (gluon-gluon fusion?)
   - the (only?) promising *alternative* way:
     $\gamma\gamma$ option of 1TeV e+e- Linear Collider !
     - ideal for *independent* precision determination of $\Gamma_{\gamma\gamma}$
     - and its CP properties



2. study its effects on other known particles, in particular Higgs, top, EWPO
   - in many possible models, deviations from SM well motivated
     - “tree-level”: e.g. in 2HDM
     - through loops involving the 750 GeV particle
   - even null result (i.e. agreement with SM) provides important constraints on interpretation

=> bread & butter programme of future e+e- colliders is as crucial as ever !

3. More speculative / model-dependent approach: additional new particles

- 750-GeV part of a 2HDM, NMSSM, ….:
  - more heavy Higgs bosons: e+e- at 3TeV? hh at 100 TeV? -> no guaranteed energy scale….
  - but possibly also some lighter ones
    => comprehensive, loop-hole free search for light Higgs bosons is core part of ILC programme
- new particles (e.g. vector-like fermions) in the loops creating gg and yy couplings
  - no guaranteed energy scale => e+e- at 3TeV? hh at 100 TeV?
  - large yy coupling could motivate that leptonic partners are lighter than coloured ones ?

=> Currently, still *everything* is possible here! - extreme cases:

- we could be lucky and find more new particles already in the current LHC run
- or we might need a full e+e- precision programme first to restrict the possibilities and thus to know where to look!