Future Linear Colliders
ILC & CLIC

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Max-Planck-Institute for Physics

on behalf of CLICdp and ILC

ALPS2017, Obergurgl, Austria, April 2017

Overview

- The Energy Frontier: Status, Ways Forward
- Linear Colliders: Overview
- A Closer Look at Linear Collider Physics
- Perspectives & Conclusions

Particle Physics at the Energy Frontier

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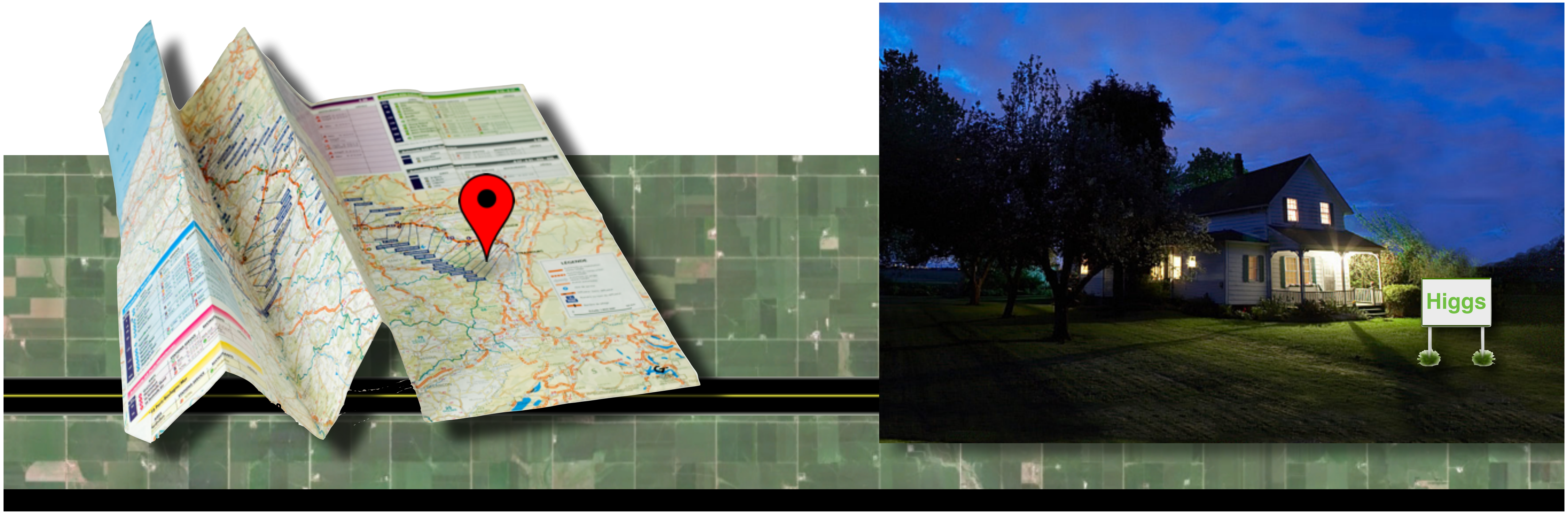

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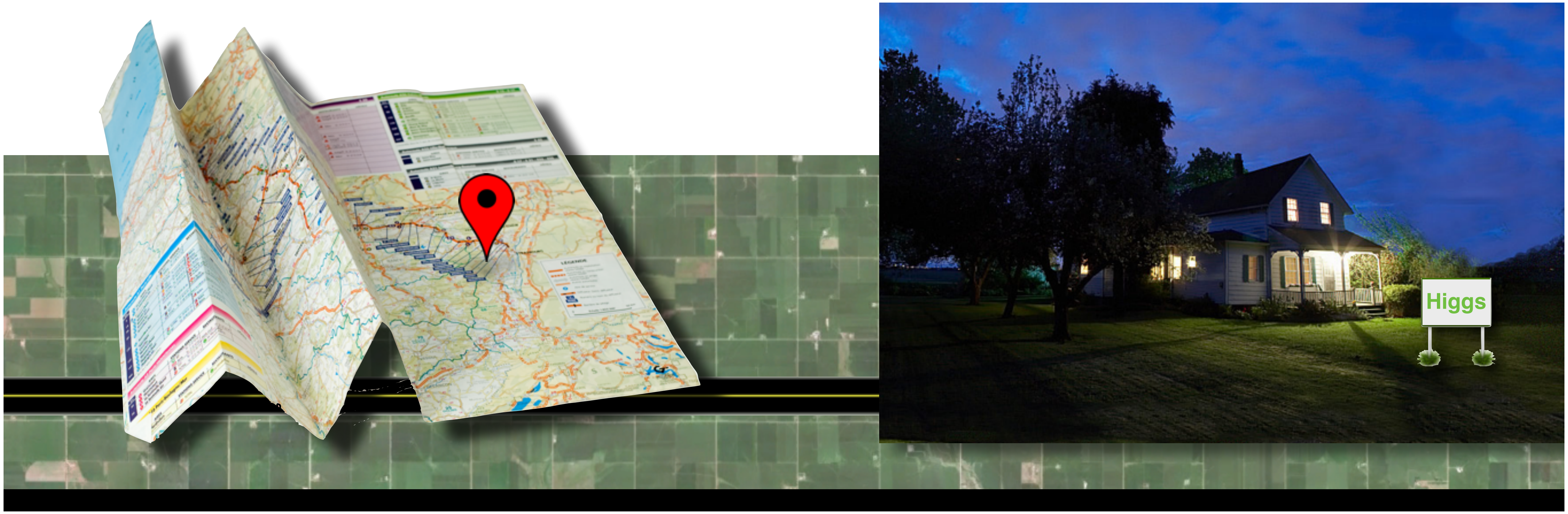
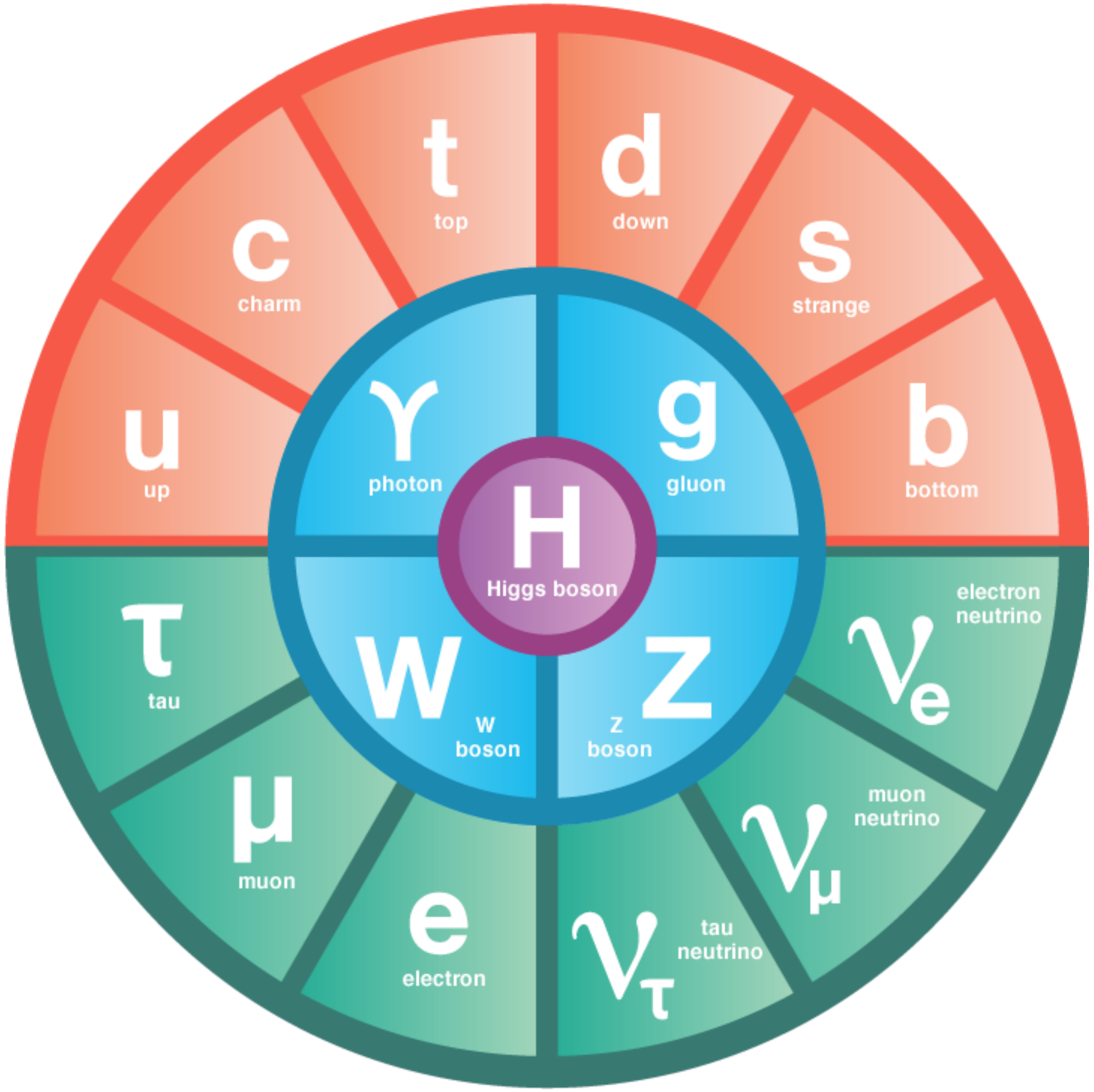


… and for the first time in 40 years we are left without clear guidance.

Answering Fundamental Questions



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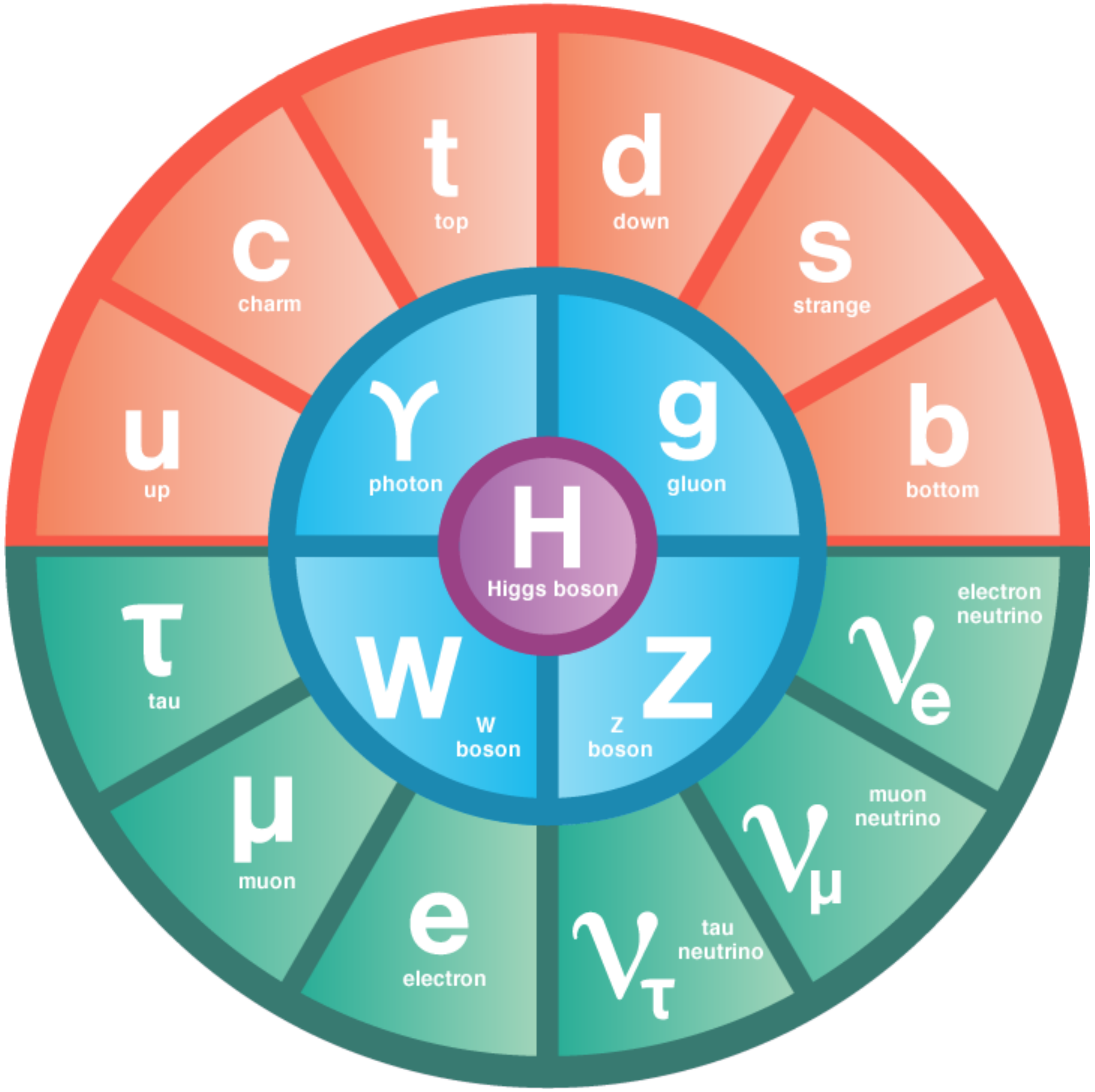

**the unknown:
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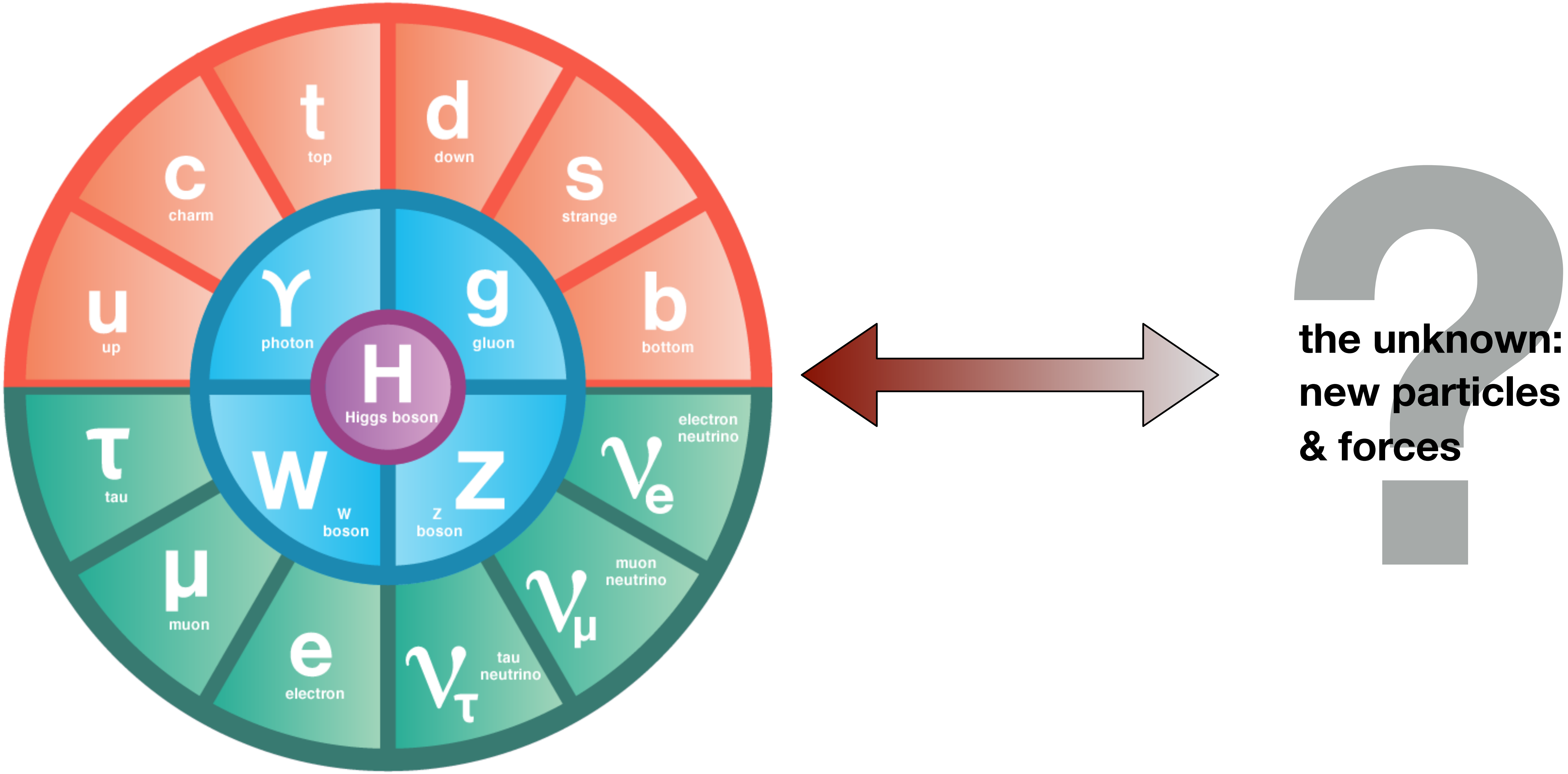

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Paths to discovery: Explore the interaction of New Physics with known fundamental forces - Now also extending to interactions with the Higgs boson

Ways Forward at the Energy Frontier

- Two main largely complementary strategies:

Highest energy: Direct production of new particles

Highest precision: Detection of new phenomena in deviations from expectations

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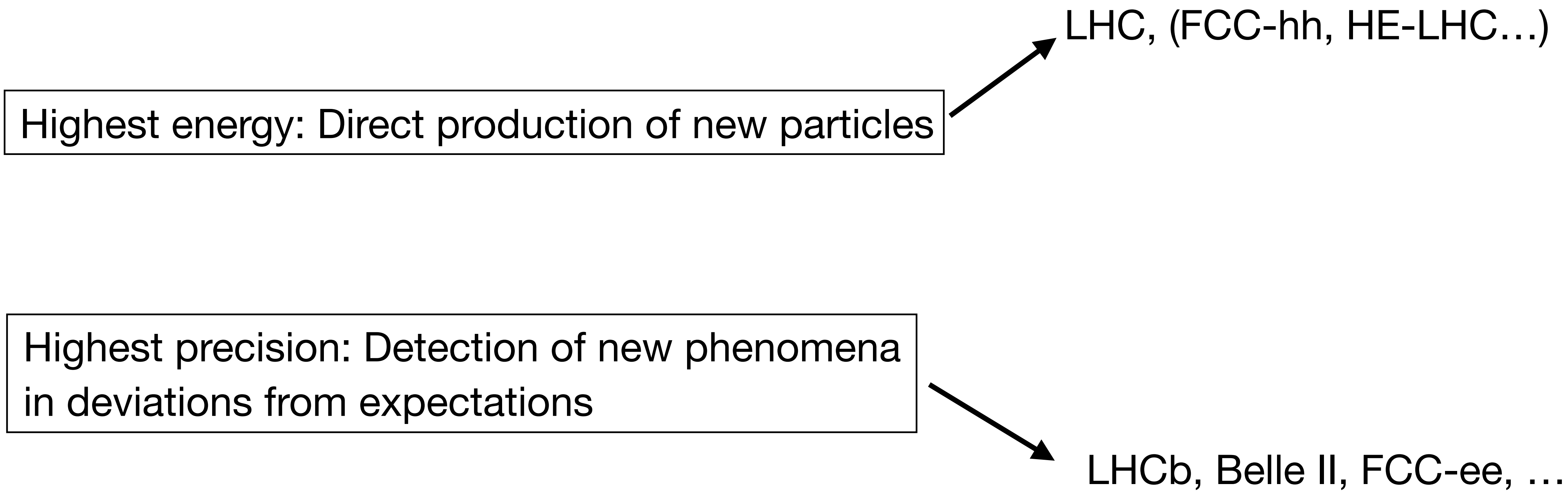

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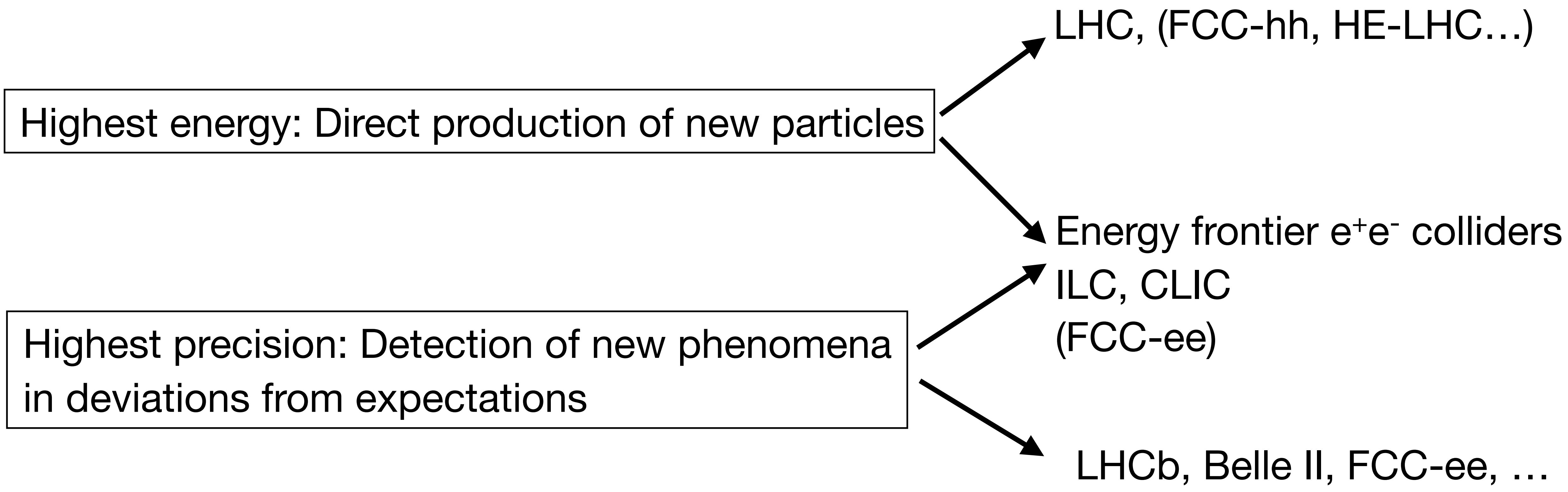

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Energy frontier e^+e^- colliders
ILC, CLIC
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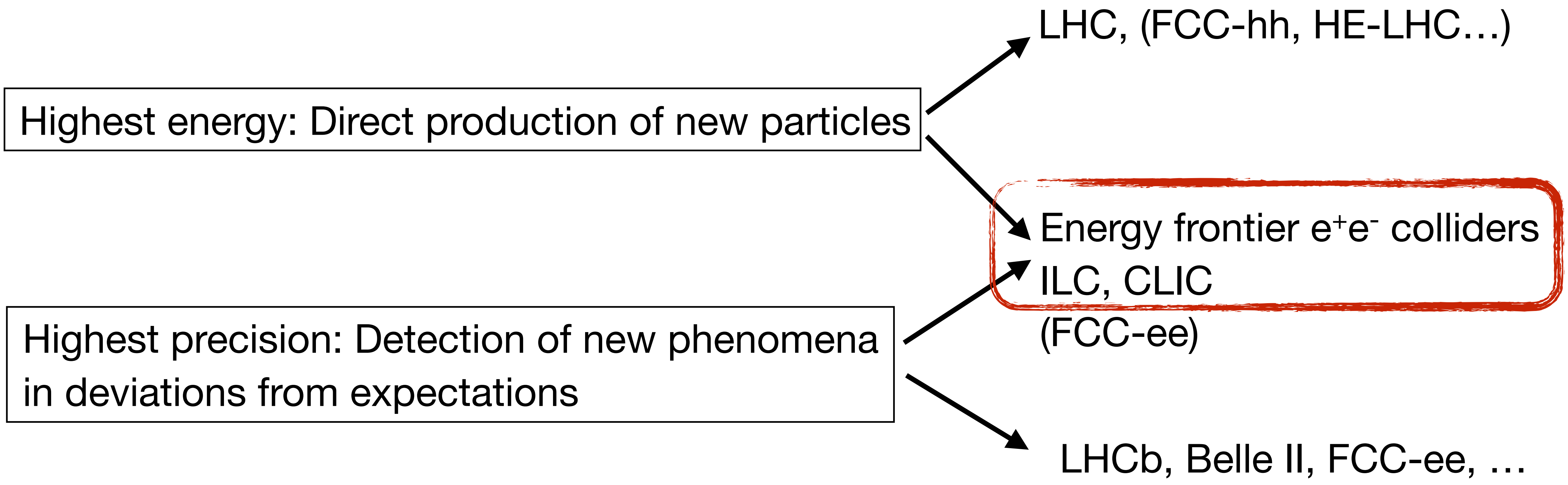

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This talk: Linear e^+e^- colliders - Combining precision and direct discovery potential

Physics at Linear Colliders - Overview

- Three main pillars:

Higgs

Full exploration of the Higgs sector:

a model-independent measurement of all relevant Higgs couplings

direct study of the Higgs potential: Measurement of the self coupling

top

Precision measurements of top quark properties in theoretically well-defined schemes

Use of top quark observables as an indirect probe for New Physics at high mass scales

electroweak precision measurements

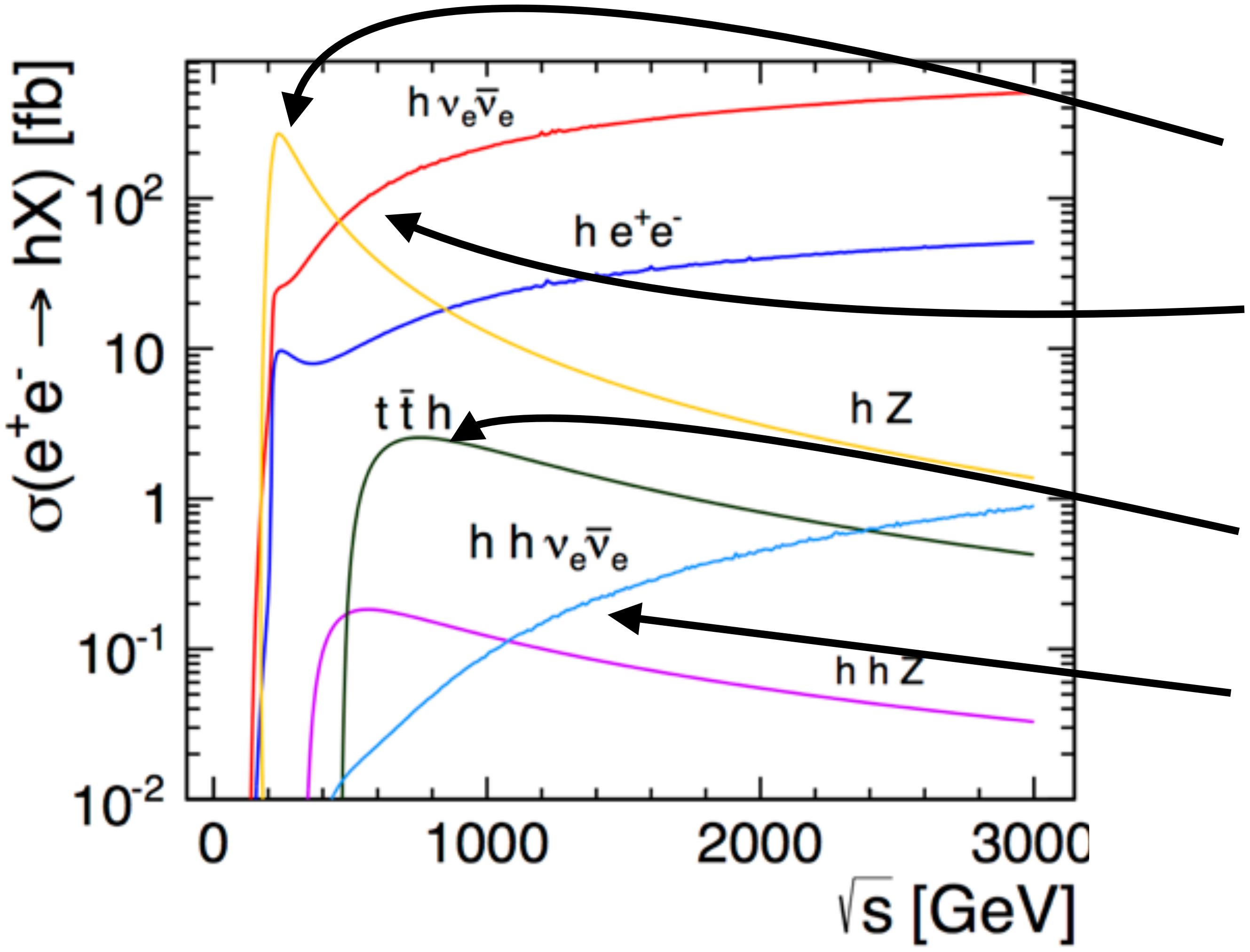
New Physics

Direct search for new particles complementary to the LHC: additional light Higgs bosons, electroweak states, Dark Matter candidates, …

Indirect search for new force carriers at high mass scales

Collider Requirements: Higgs as Example

- Energy reach and flexibility - high energy for possible direct access to new physics



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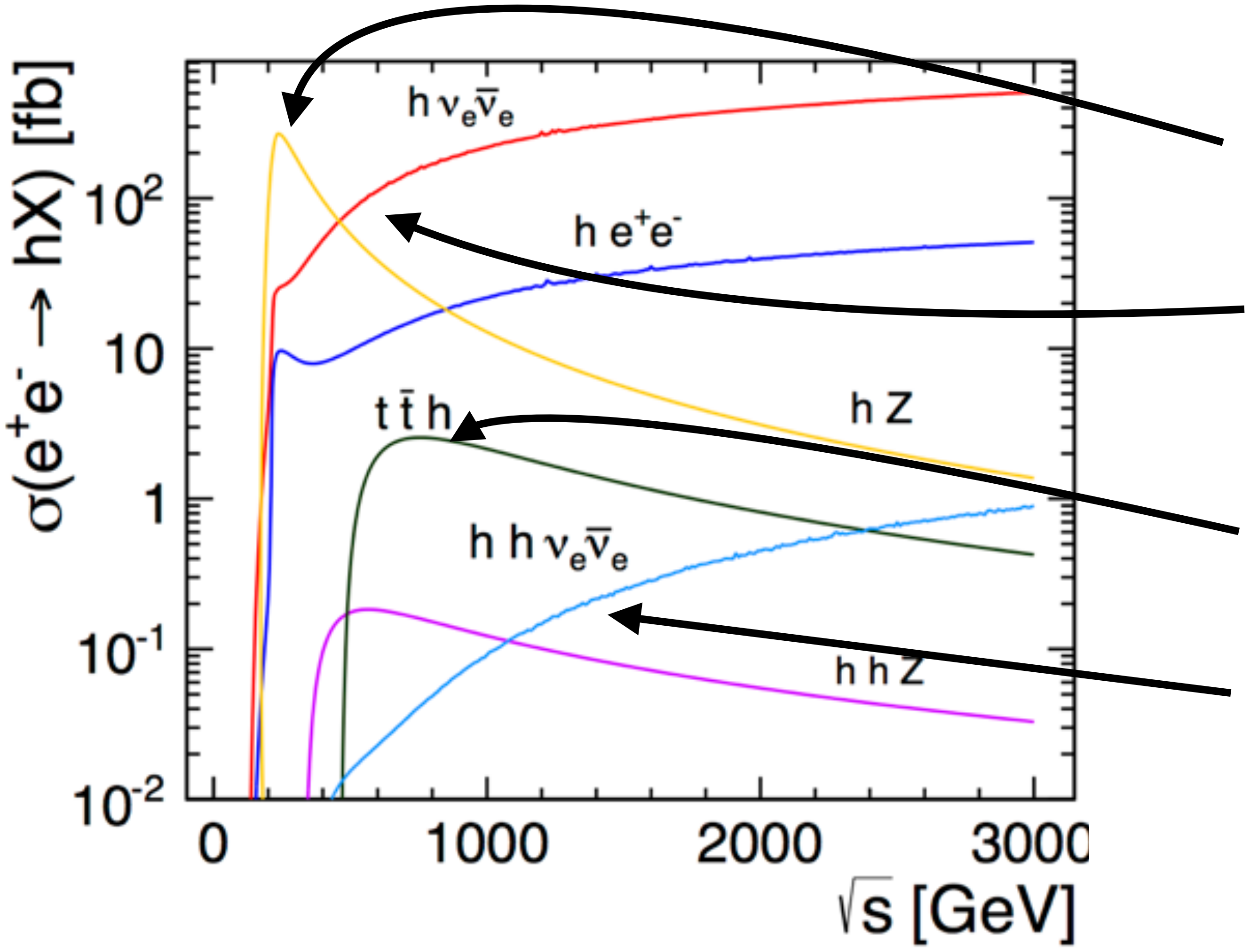

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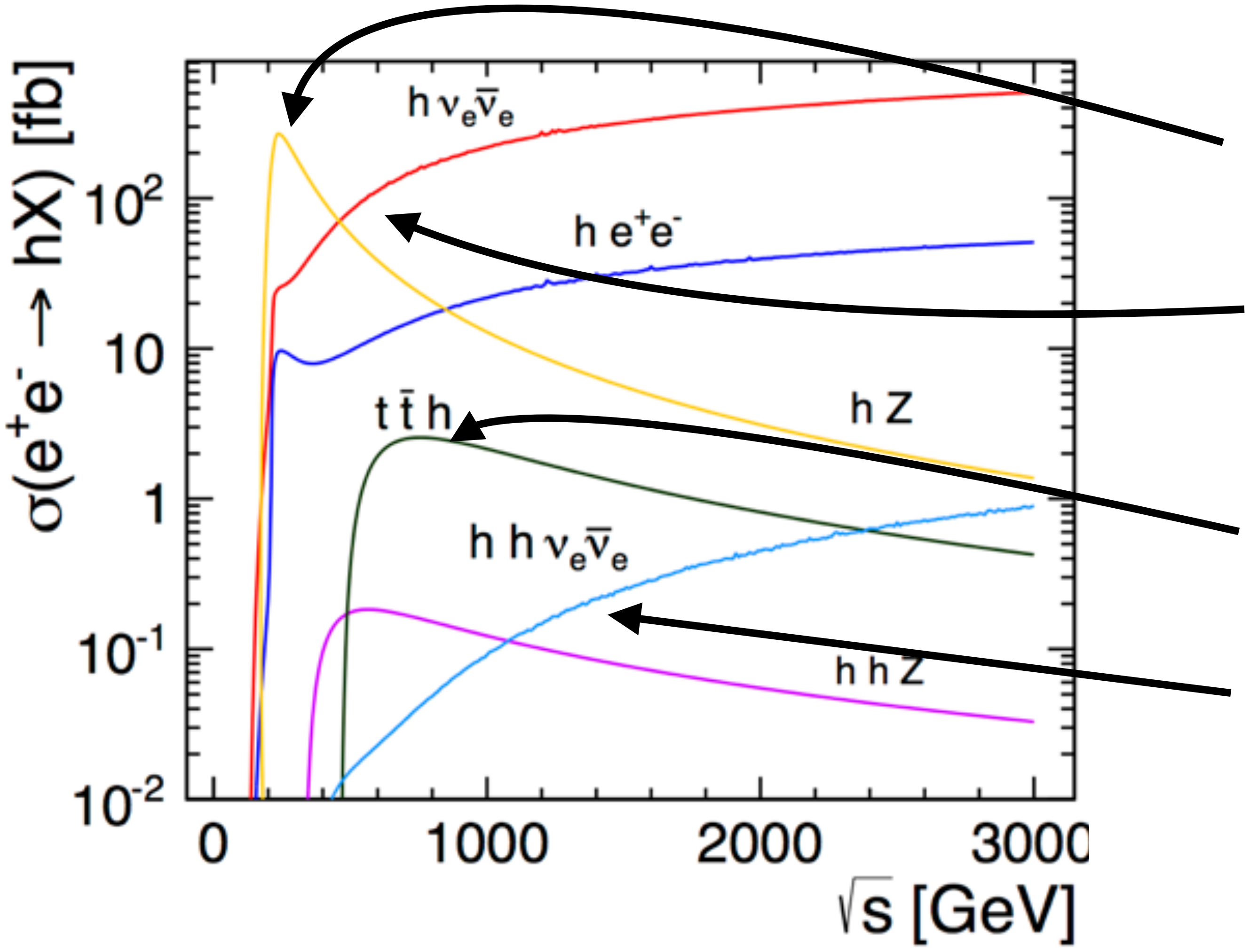

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Linear e^+e^- Colliders: Key Features

- “Single pass” acceleration: Accelerator length & acceleration gradient directly determine achievable energy
- No re-use of accelerated particles: High luminosity requires very small beam spots to achieve good overall energy efficiency: Beamstrahlungs-tail in luminosity spectrum

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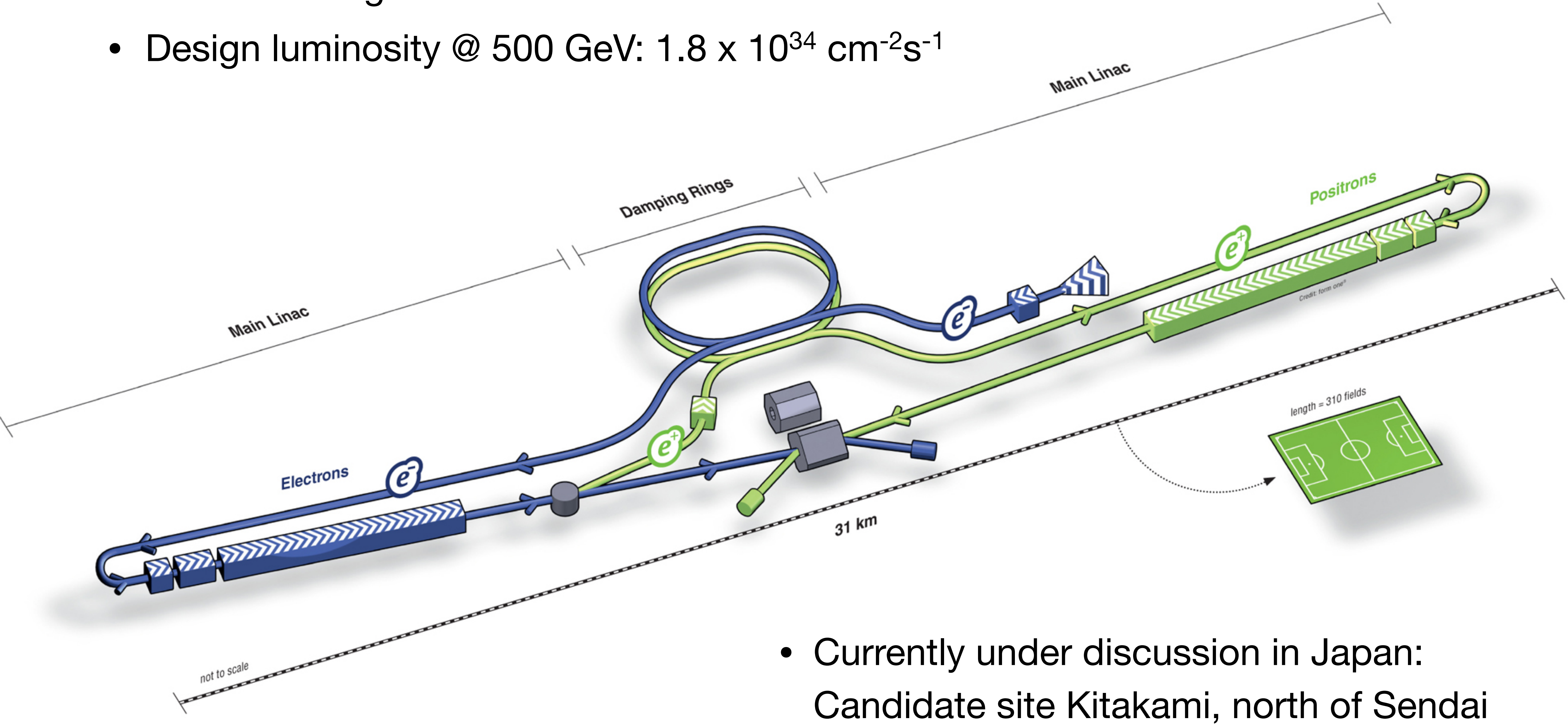
- "Trivial" upgrade path: If higher energy is needed, the two main linacs can be extended - possibly with higher-gradient modules if there is technological progress
- Well-suited for staging: Can start with a short machine, extend in steps to reach higher energy

Collider Concepts: ILC

- The International Linear Collider: A 500 GeV collider based on superconducting RF
  - Acceleration gradient ~ 35 MV/m
  - Design luminosity @ 500 GeV: 1.8 x 10^{34} $cm^{-2}s^{-1}$



Credit: form one®

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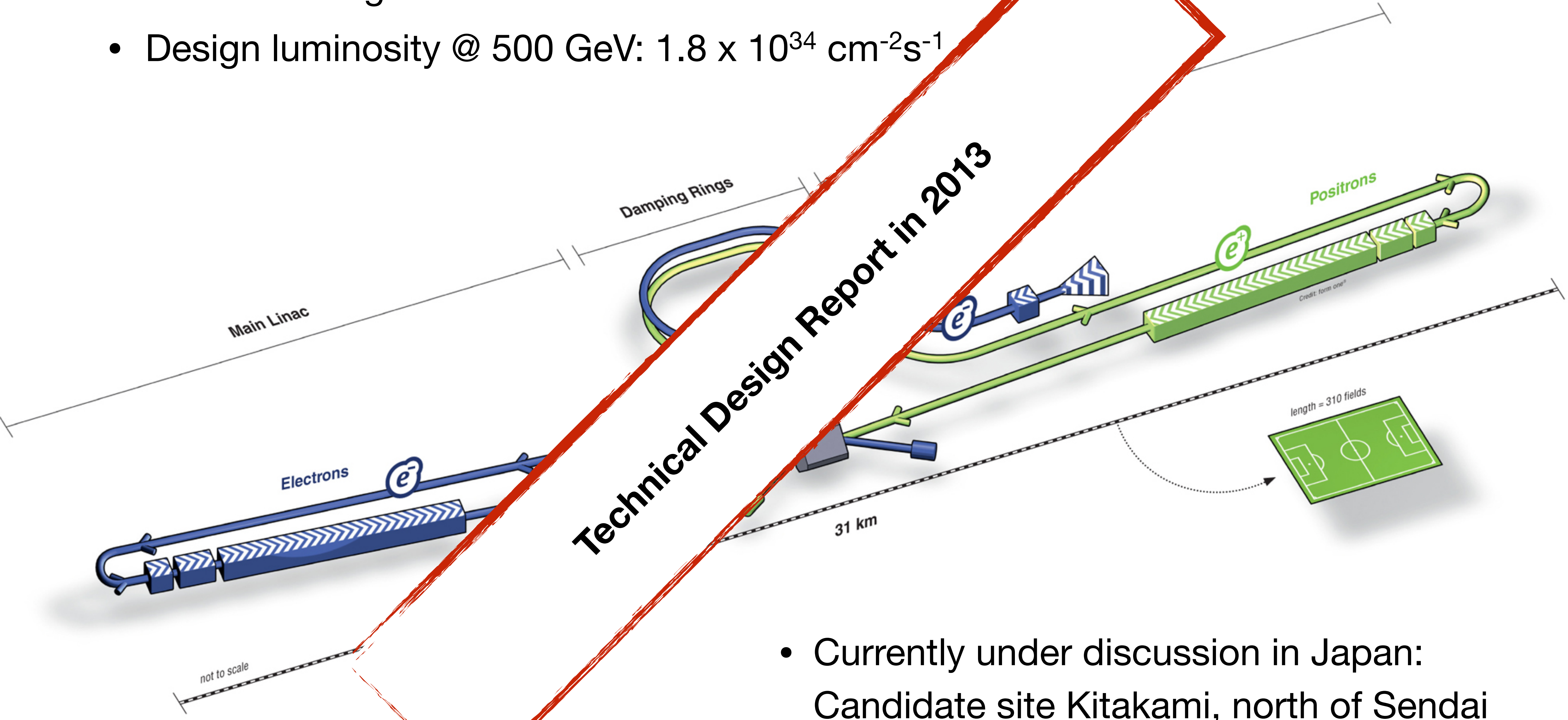

Technical Design Report in 2013

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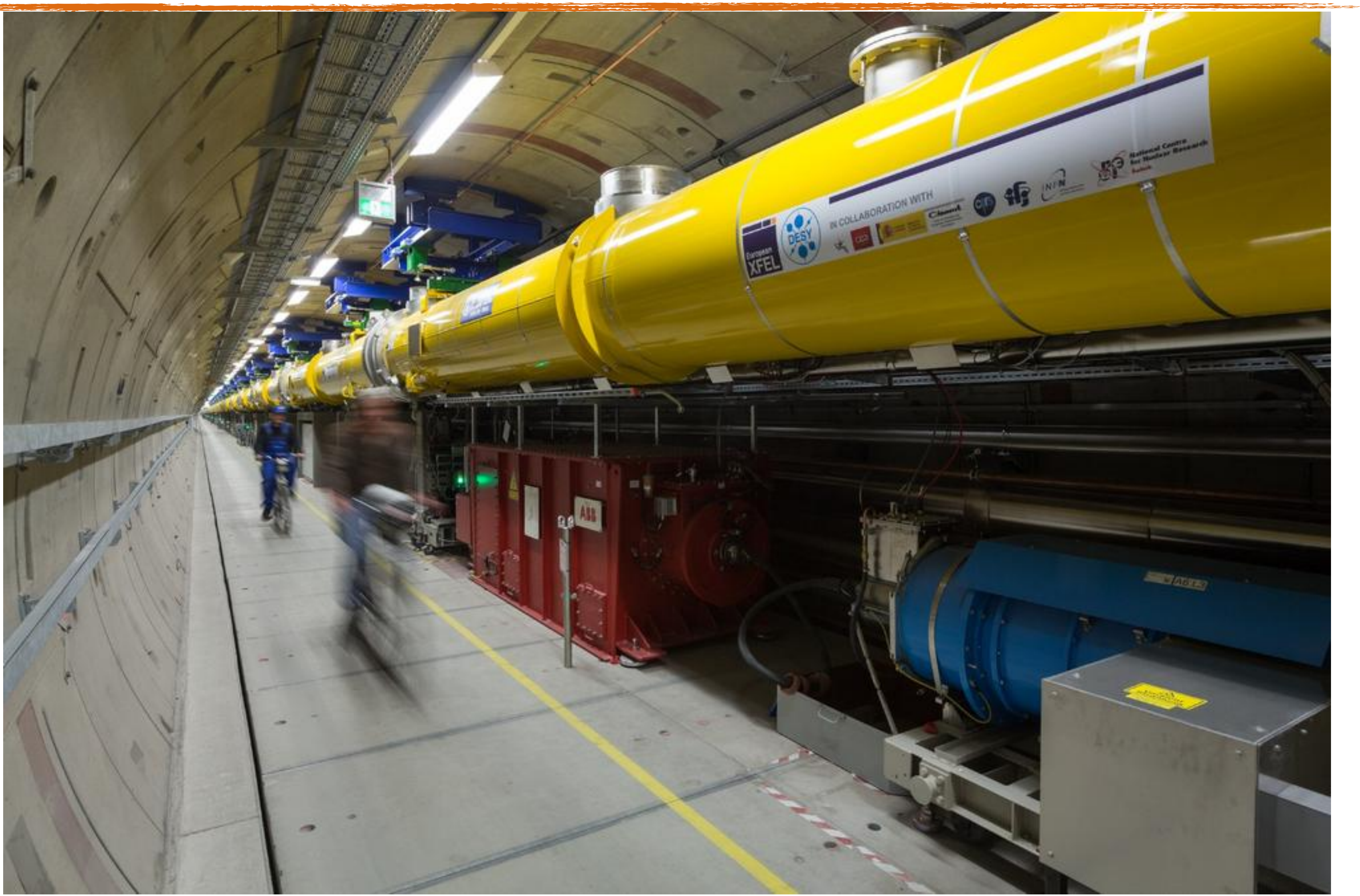
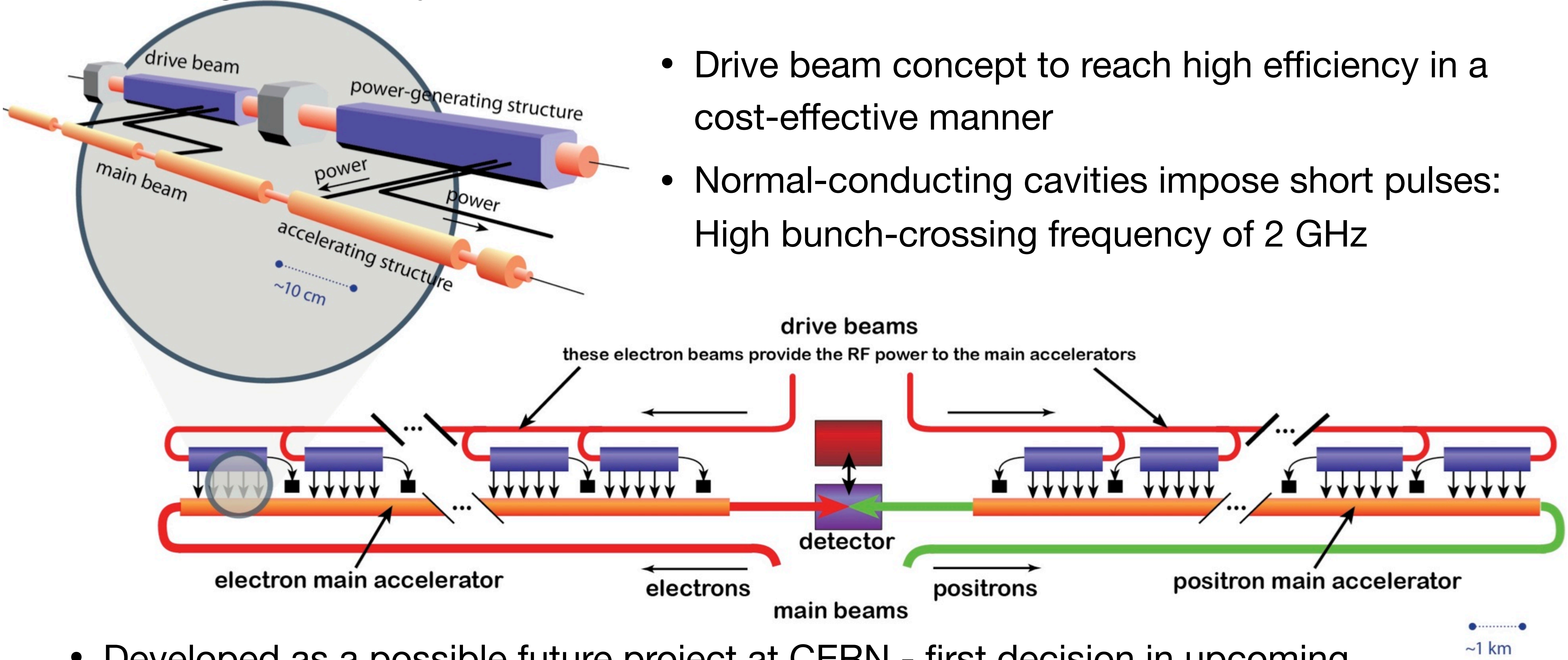
ILC: Technical Feasibility Demonstrated: XFEL



Collider Concepts: CLIC

- The Compact Linear Collider: A (up to) 3 TeV collider based on two-beam acceleration
  - Copper-based acceleration structures, acceleration gradient 100 MV/m
  - Design luminosity @ 3 TeV: 5.9 x 10^{34} $cm^{-2}s^{-1}$ [@ 380 GeV: 1.5 x 10^{34} $cm^{-2}s^{-1}$]
- Drive beam concept to reach high efficiency in a cost-effective manner
- Normal-conducting cavities impose short pulses: High bunch-crossing frequency of 2 GHz



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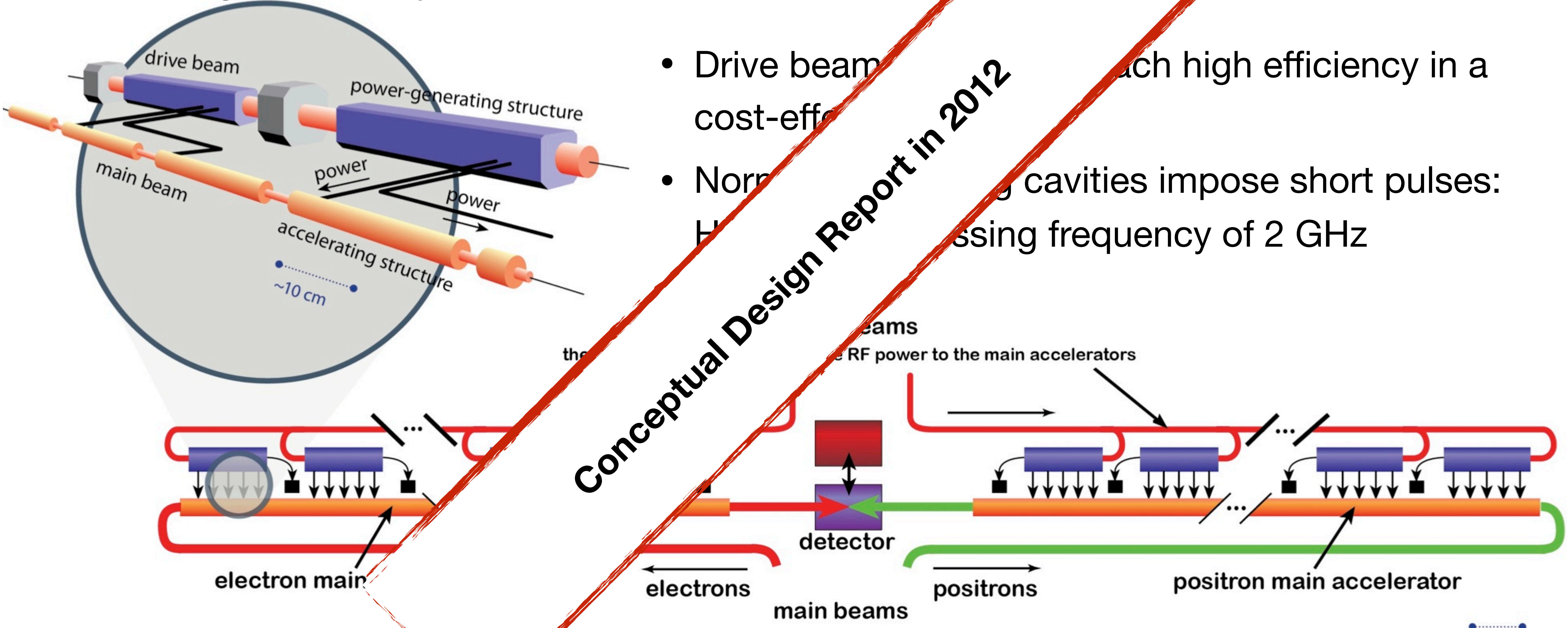

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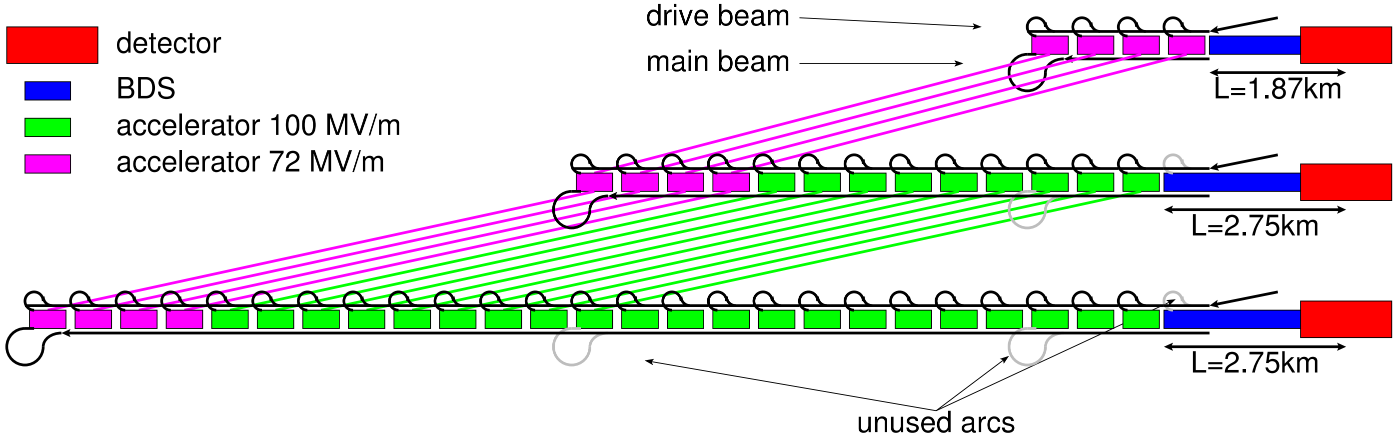

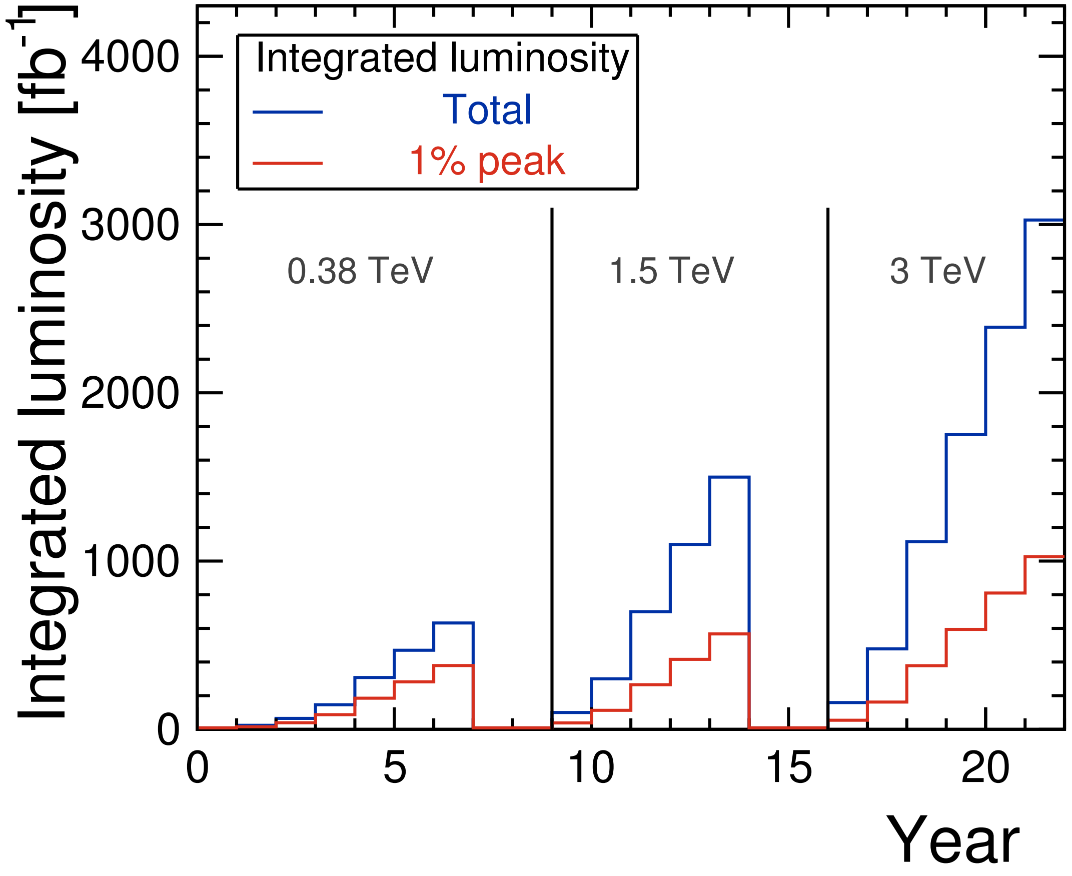

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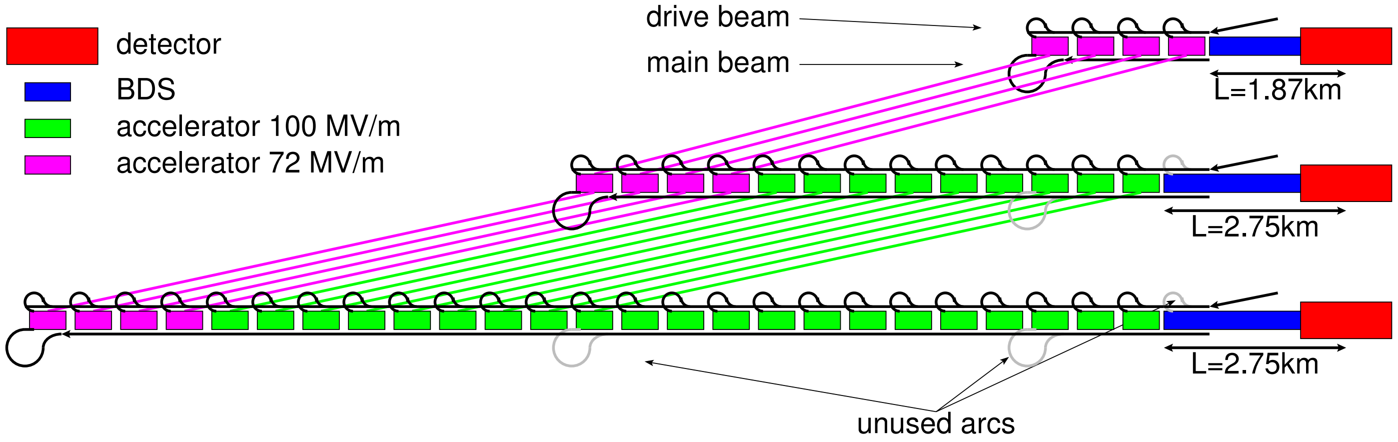
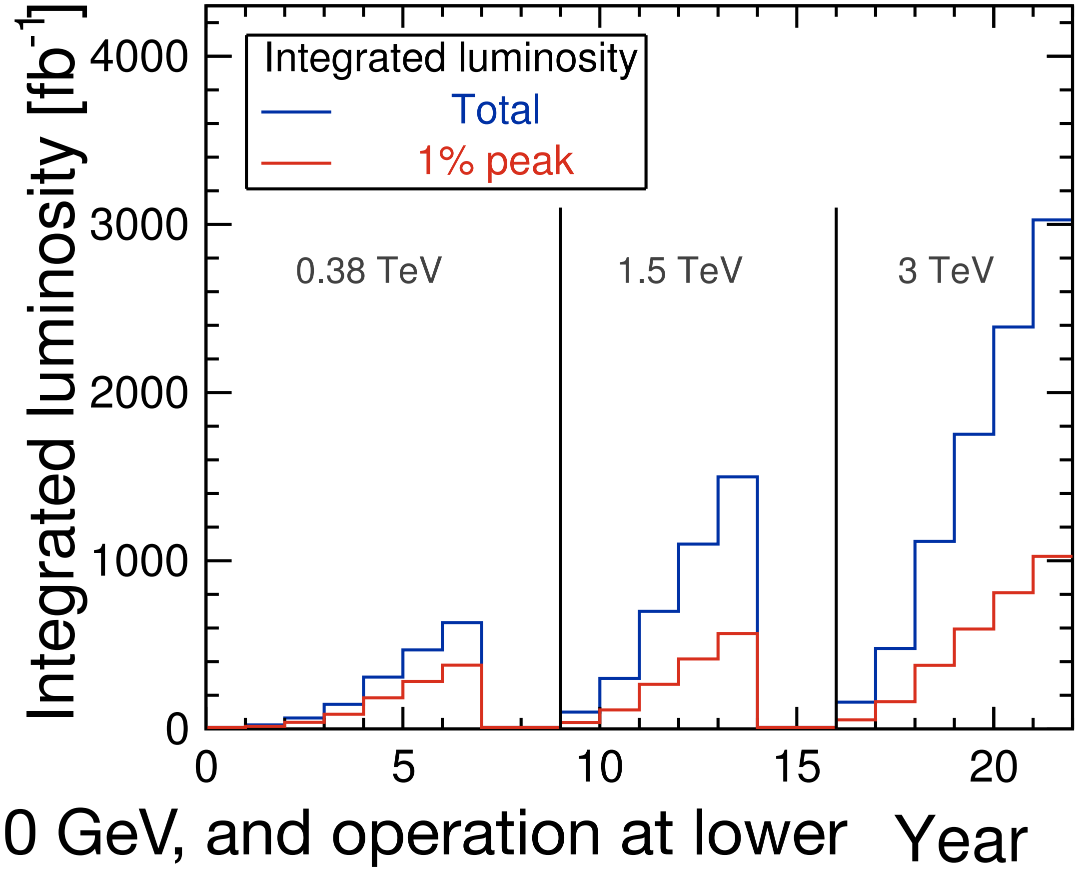
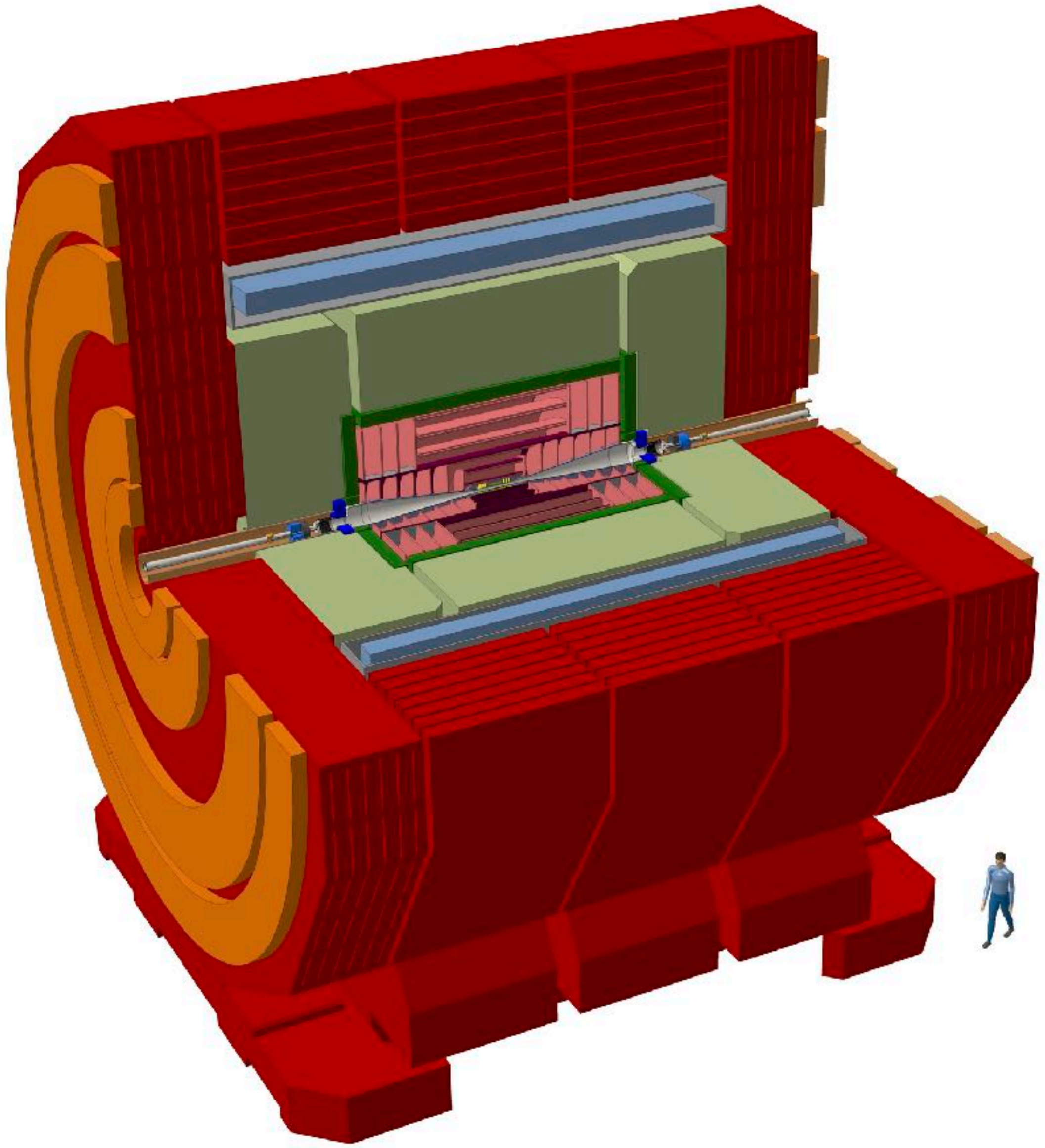




- Also considered for ILC - instead of start-up at 500 GeV, and operation at lower energies after an initial high-energy run:
  - Start at 250 GeV, increase length and energy in stages
  - Same overall final results

Detectors at Linear Colliders

- General-purpose collider detector systems, based on:
  - highly granular calorimeter systems optimized for particle flow reconstruction
  - precise vertexing to enable tagging of b, c and light flavors
  - precise, low mass tracking



- ILD & SiD detector concepts for ILC, CLICdp detector model
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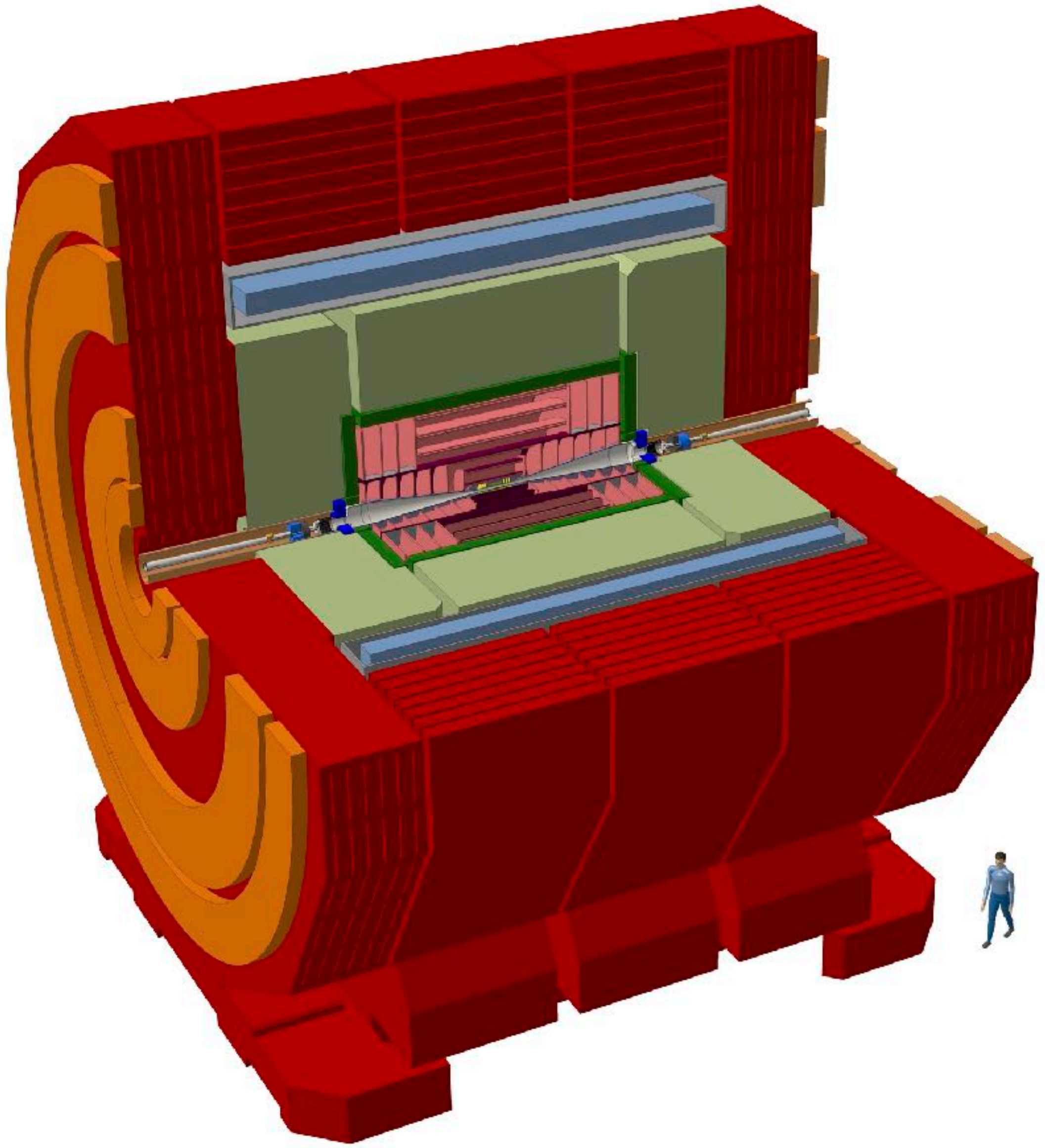

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Overall: interesting detector challenges, pushes the limits of current technology. A prime example: Highly granular calorimeters, an “LC idea”, now widely adopted also for LHC phase 2 upgrades

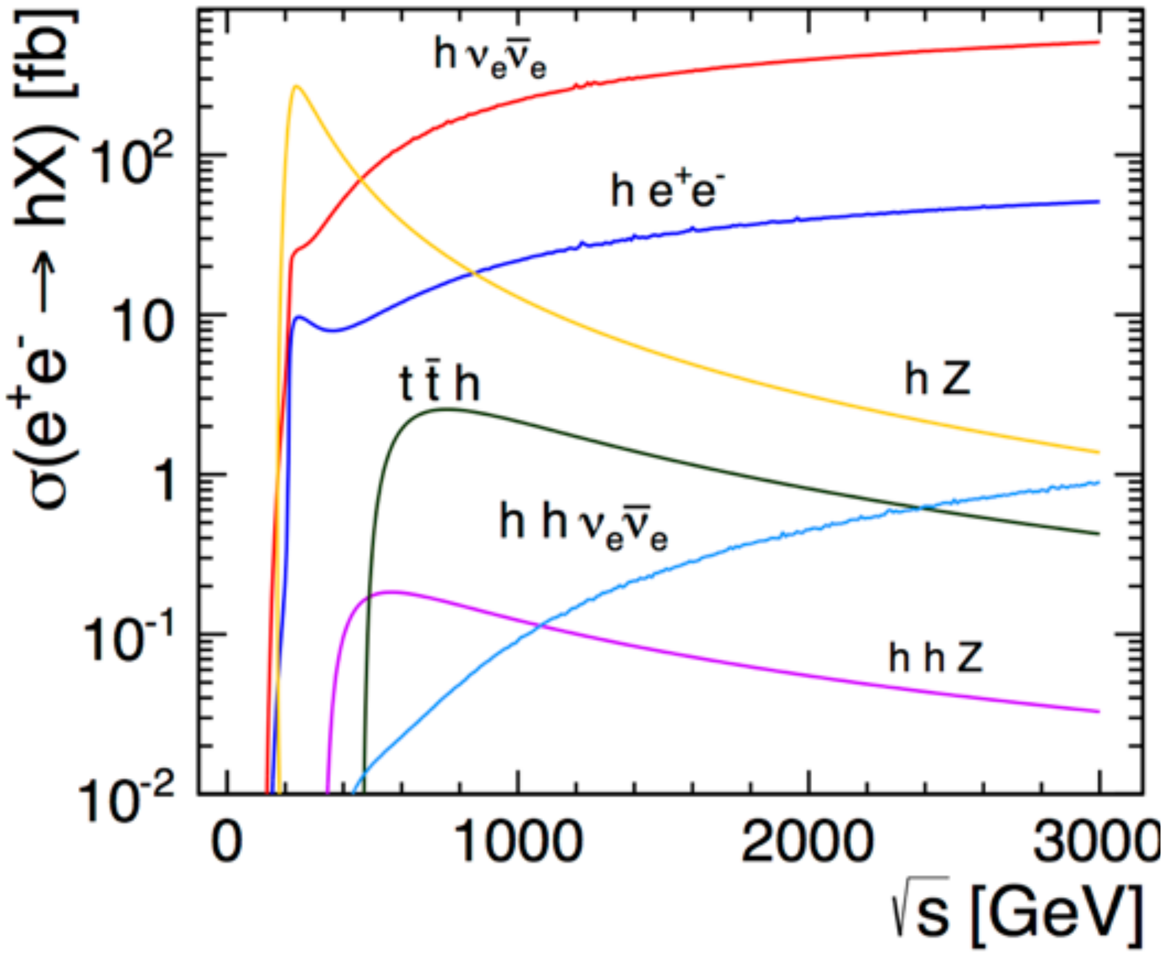
The Physics: A Closer Look

CLIC and ILC Physics Studies

- The projections of ILC and CLIC physics capabilities are based on an extensive program of physics studies - Almost entirely making use of full simulations:
    - Realistic detector models implemented in GEANT4
    - Full particle flow-based event reconstruction - not using MC truth or cheated reconstruction
    - Inclusion of physics and machine backgrounds
    - Event selection and analysis algorithms - often making use of multivariate techniques

Thoroughly Exploring the Higgs Sector: Couplings

- Access to Higgs couplings to fermions and bosons by explicit reconstruction of final states: A broad program at CLIC & ILC



covered in great detail
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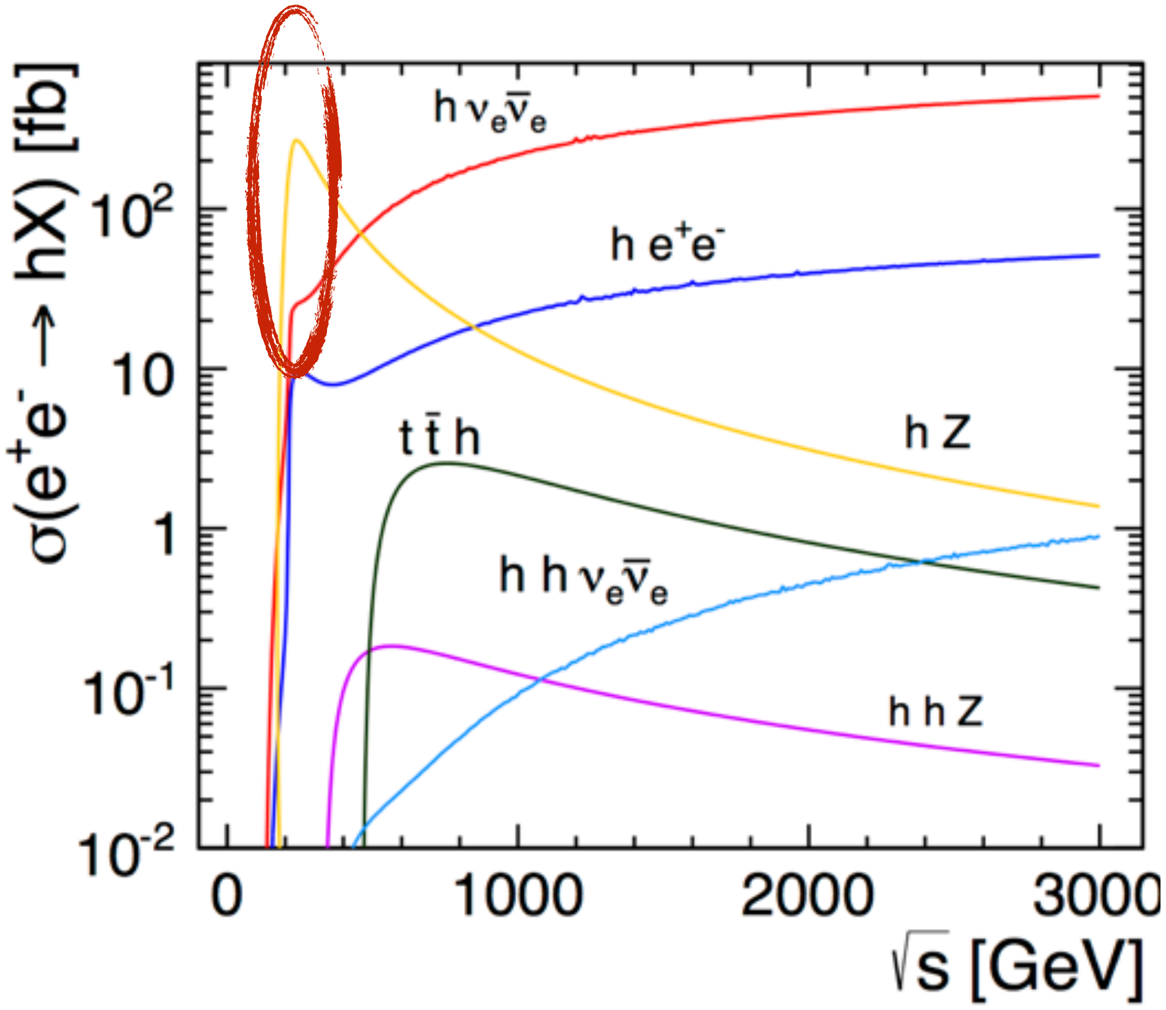

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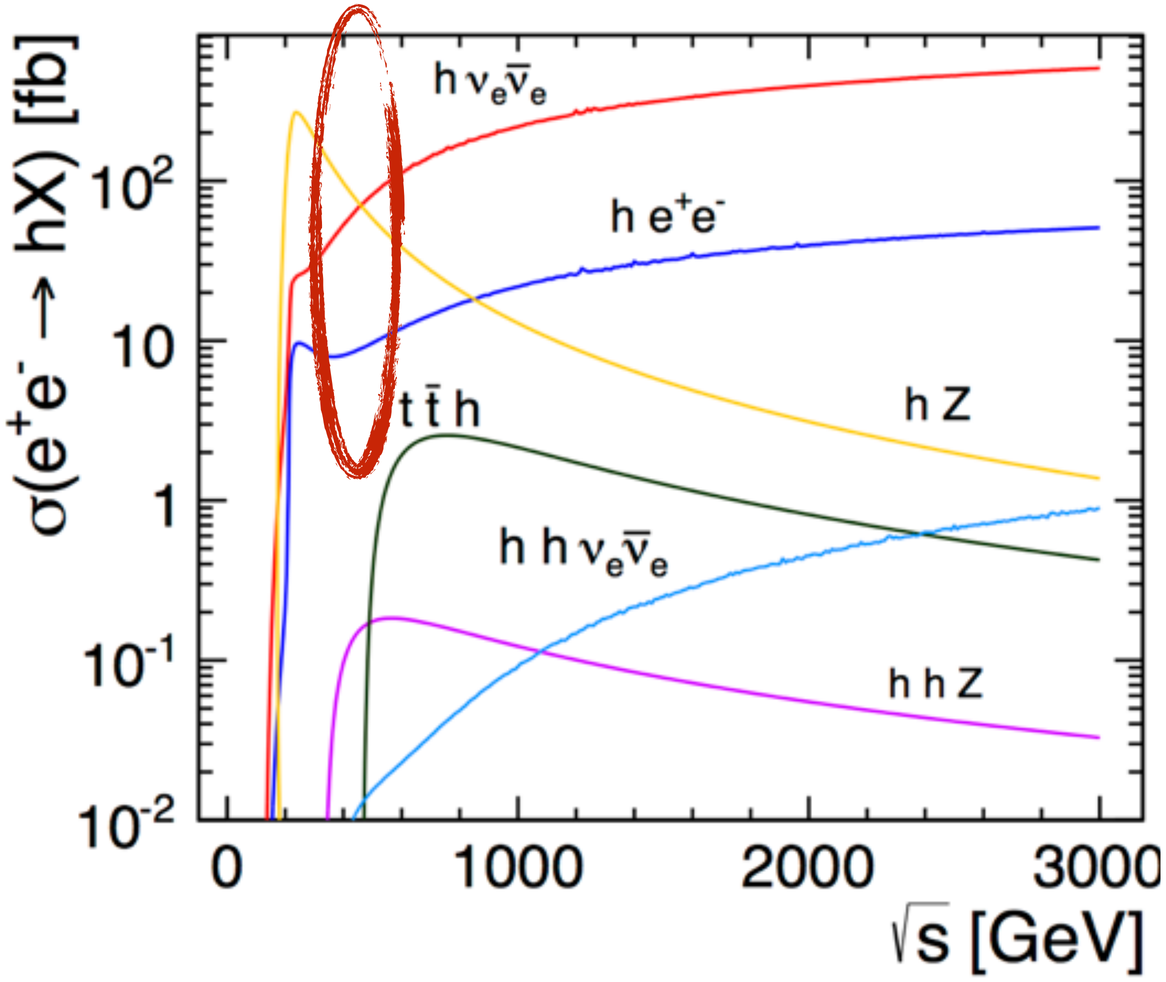

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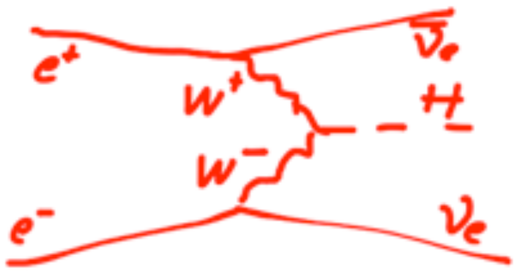

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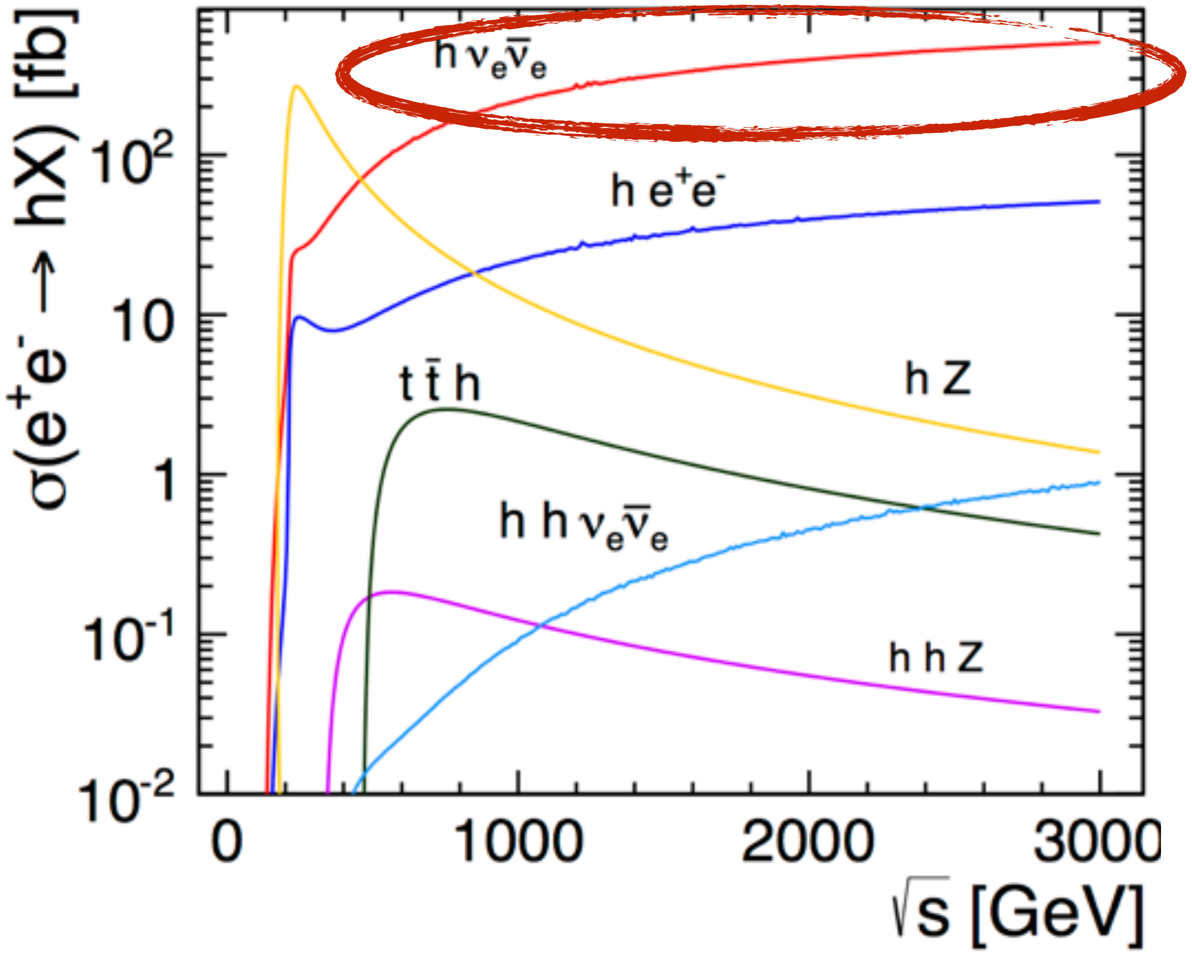

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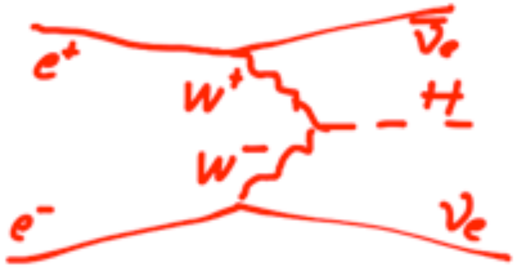

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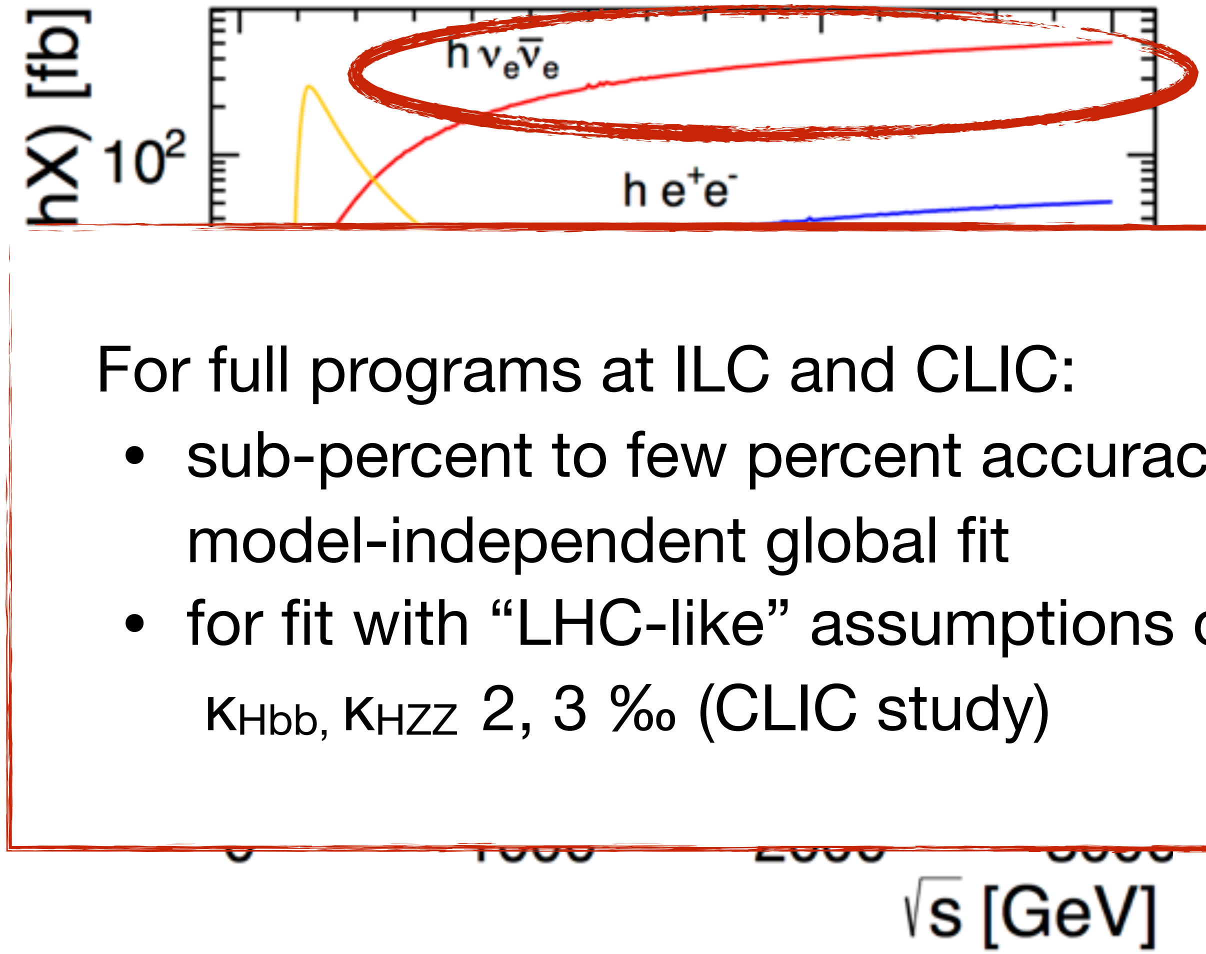

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For full programs at ILC and CLIC:

- sub-percent to few percent accuracy for most couplings in model-independent global fit
- for fit with “LHC-like” assumptions down to permille level for κ_{HWW}; κ_{Hbb}, κ_{HZZ} 2, 3 ‰ (CLIC study)

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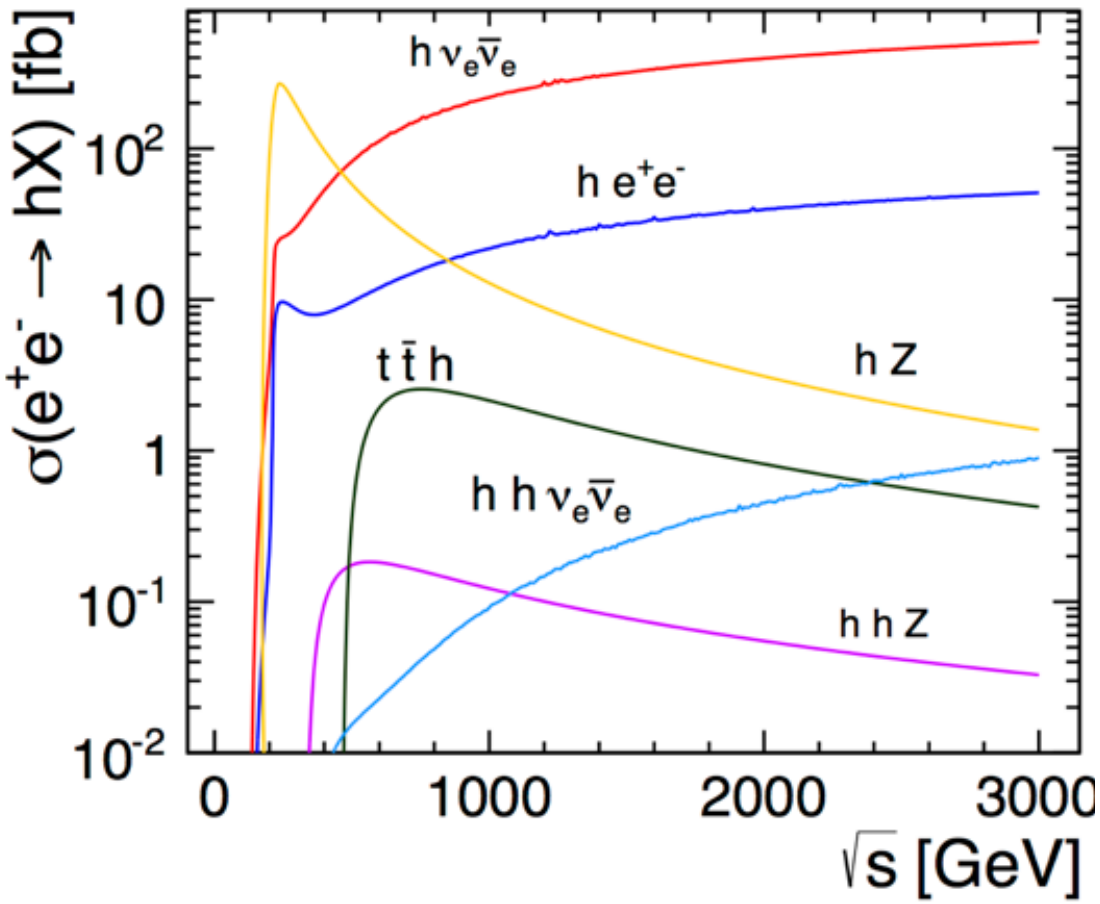
Beyond “Simple” Couplings: Top, Self-Coupling



- Energies of 500 GeV and above give access to the top Yukawa coupling and to the Higgs self-coupling

  - ~ 10% precision with 1 ab^{-1} @ 500 GeV - substantial improvement when going slightly up in energy

- 1 TeV ILC / 1.4 TeV CLIC ~ 4% precision or better, depending on running scenario

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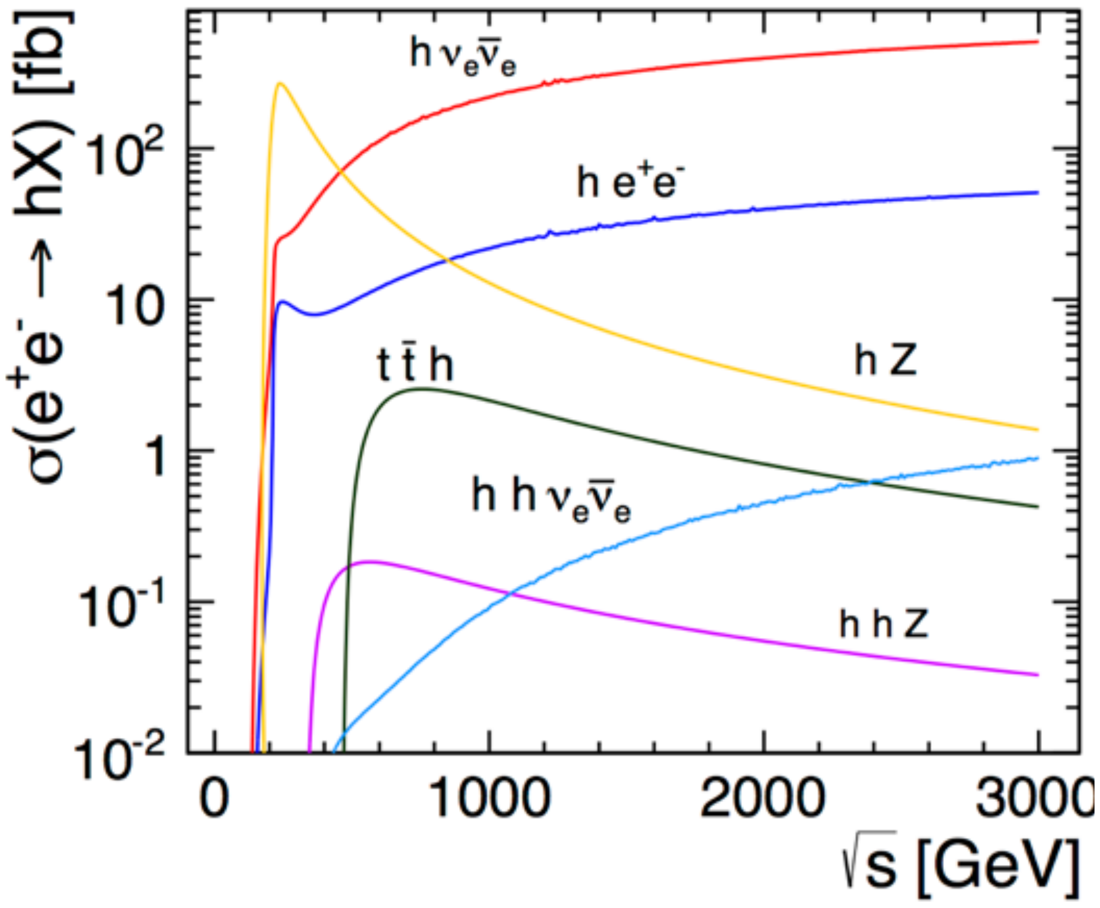

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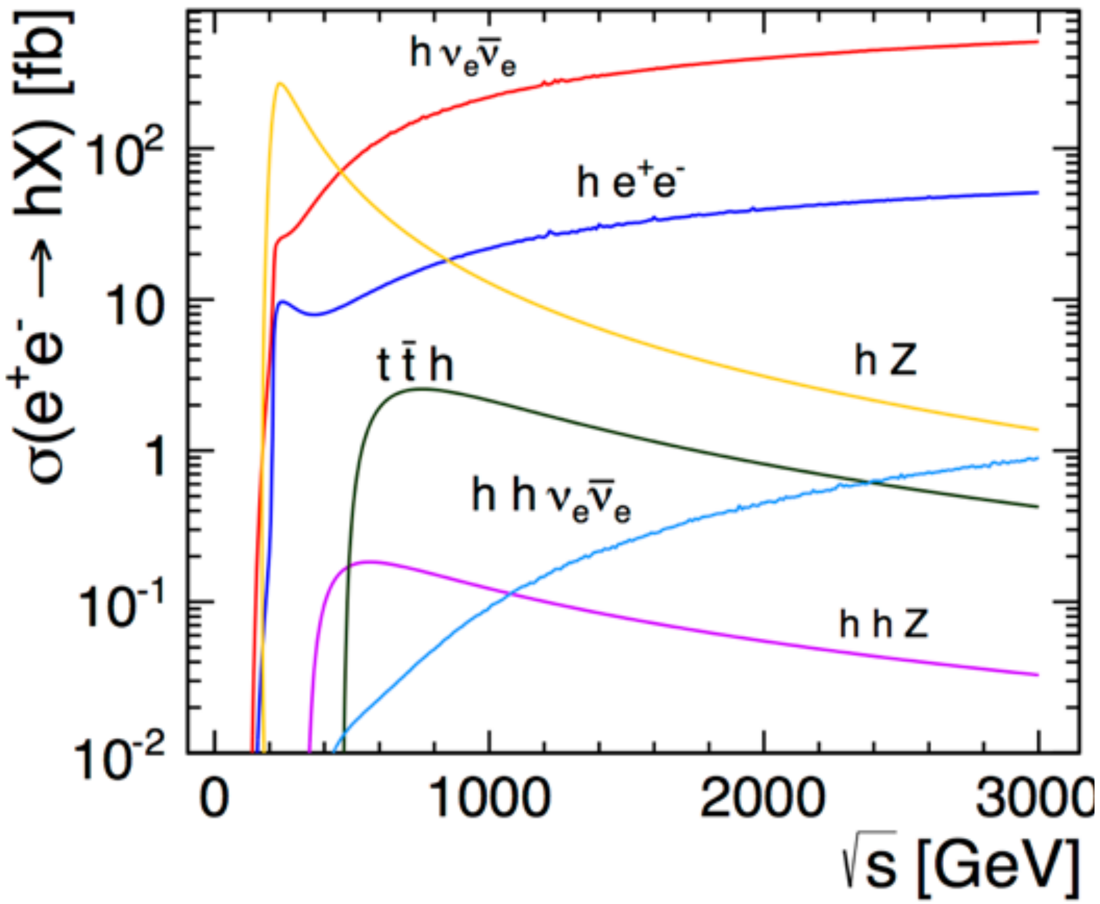

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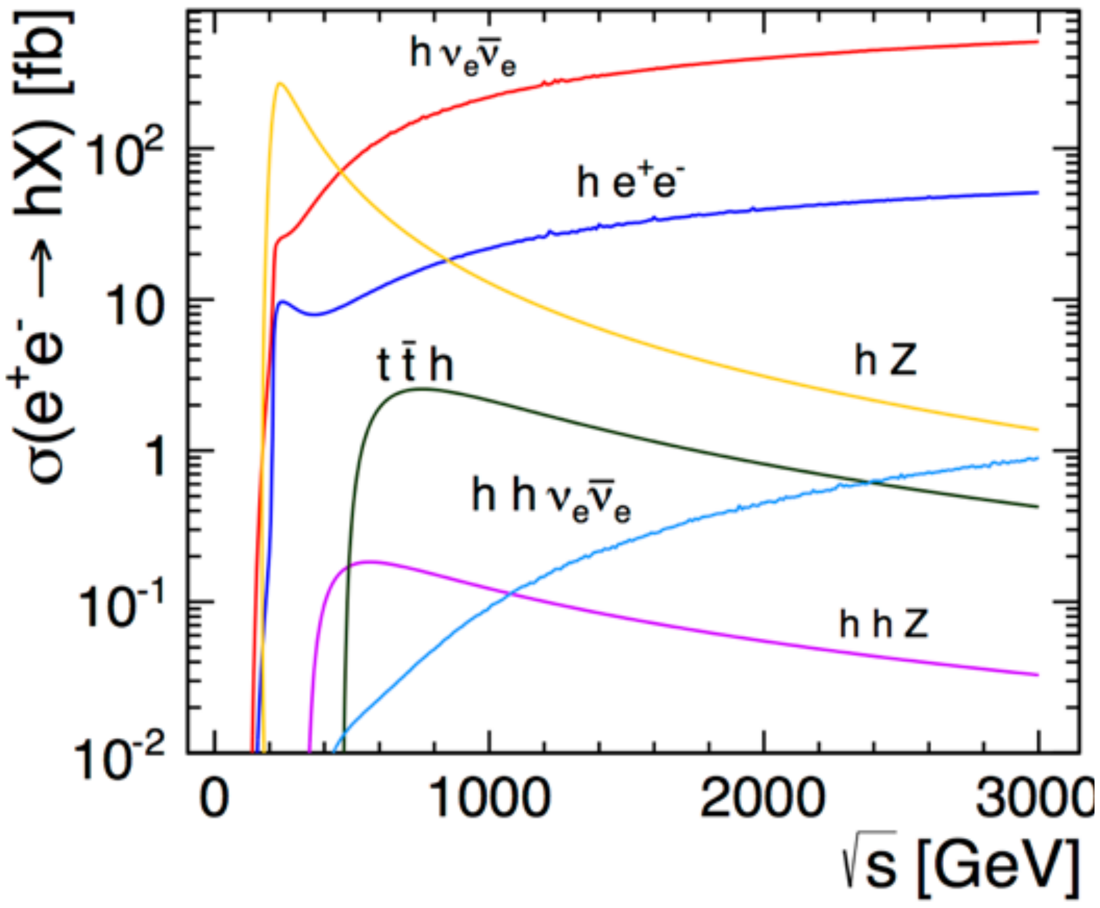

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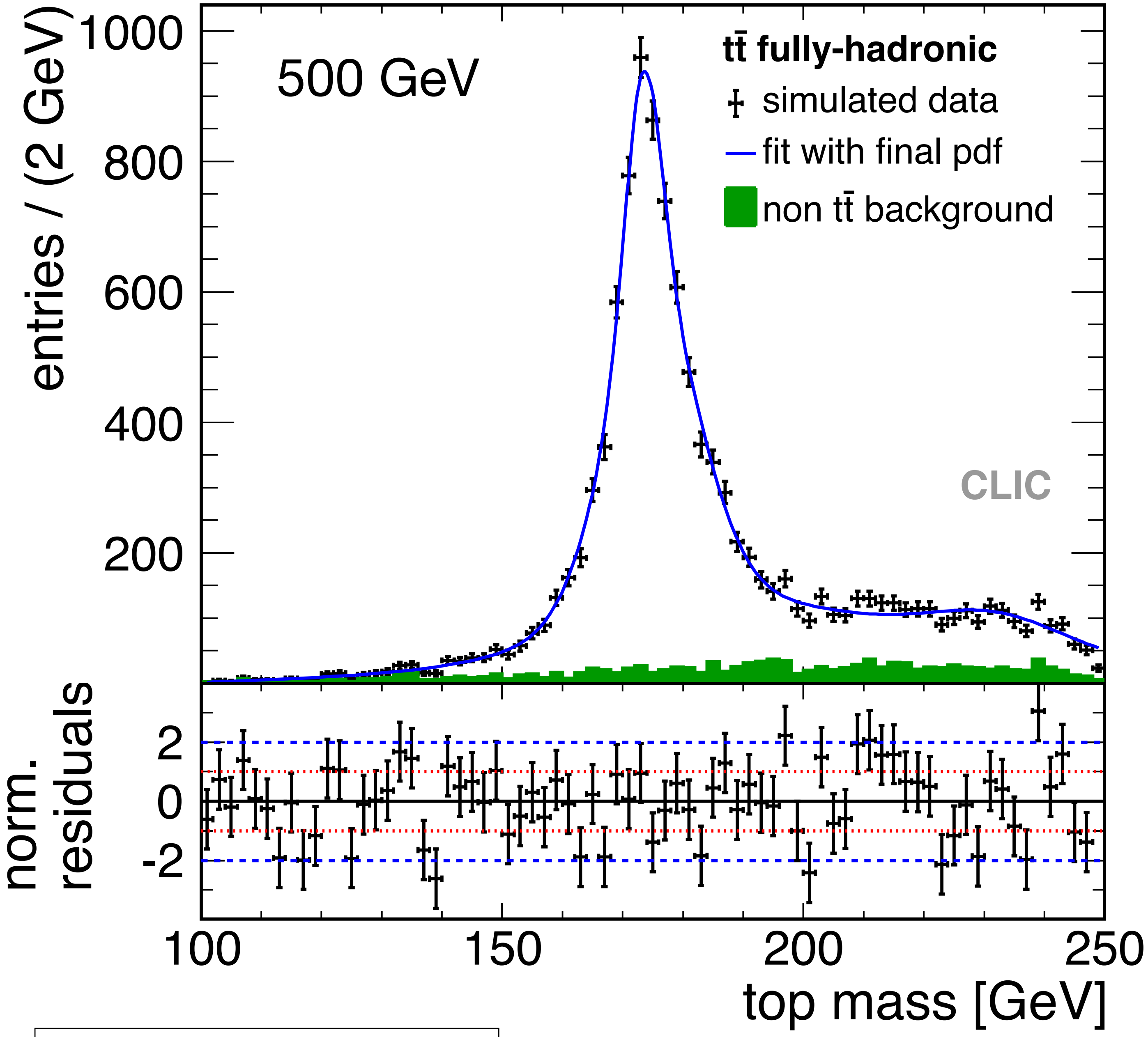
- ILC 1 TeV / CLIC 1.4 + 3 TeV: ~ 10% precision for near-SM values of λ

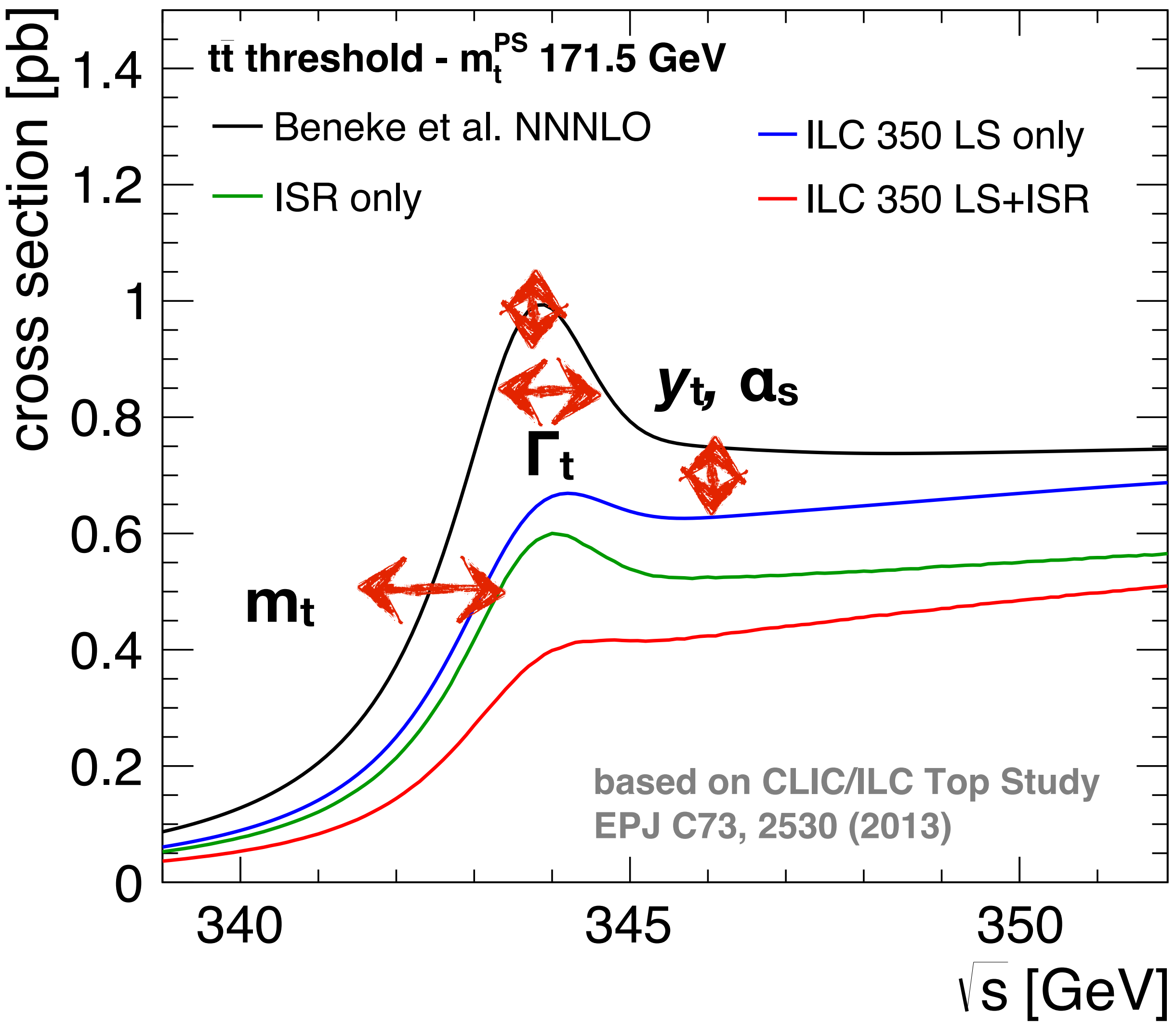
Identifying Top Quarks



EPJ C73 2530 (2013)

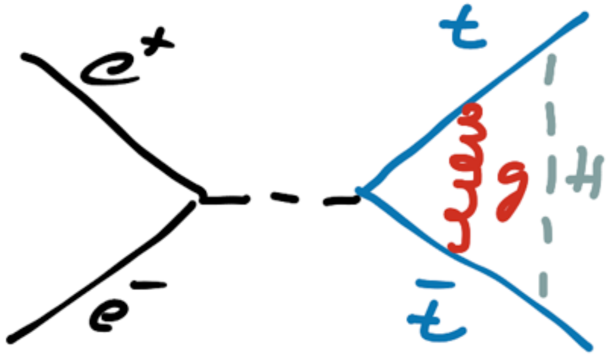
- Clean, highly efficient identification of top quark pair events
- Enables two classes of measurements:
  - Precise determination of top quark properties: mass, width, …
  - Use top quarks as a tool: high mass makes top potentially very sensitive to new physics, strong connection to EWSB

Top: Measuring the Mass



based on CLIC/ILC Top Study
EPJ C73, 2530 (2013)

- The best way to a theoretically clean, highly precise measurement of the top quark mass: a threshold scan



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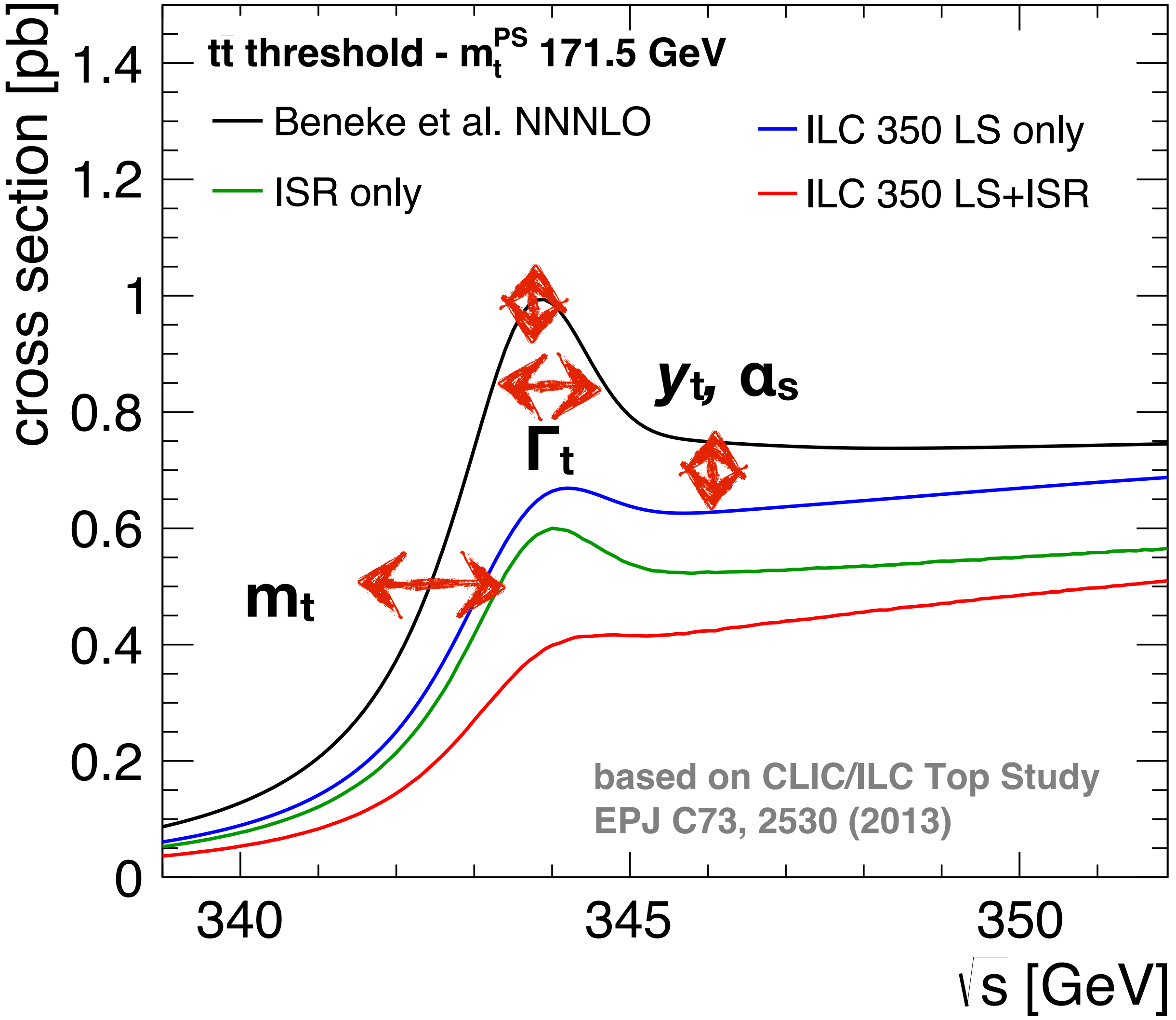
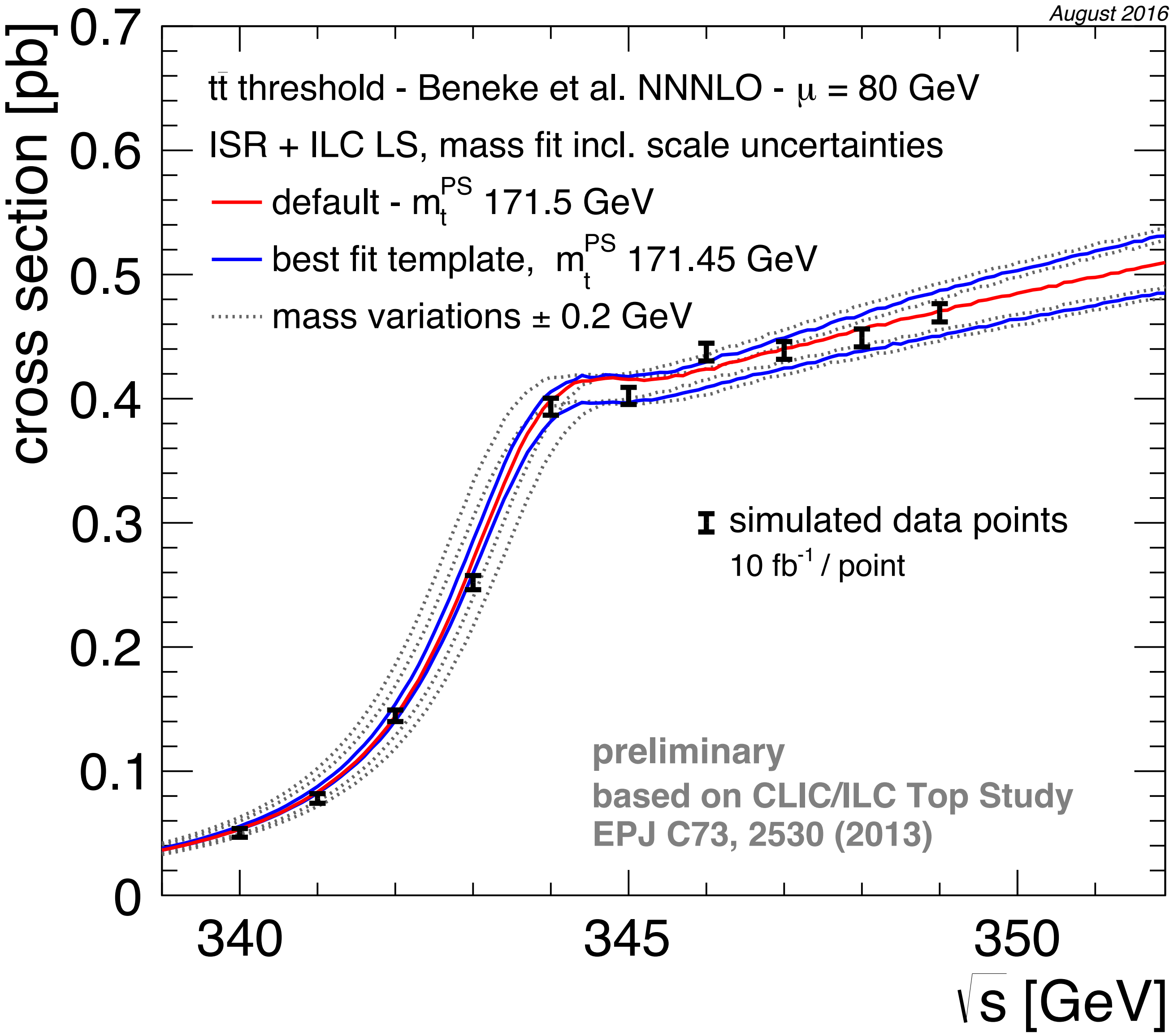


- The best way to a theoretically clean, highly precise measurement of the top quark mass: a threshold scan



- Theoretically relevant MSbar mass can be extracted with small uncertainties
- Total uncertainty including theoretical and experimental systematics ~ 40 - 75 MeV

Going Beyond the SM

- Two main paths for discovery
  - Direct detection of new particles
  - Observations of deviations from SM expectations, pointing to new phenomena at higher scales

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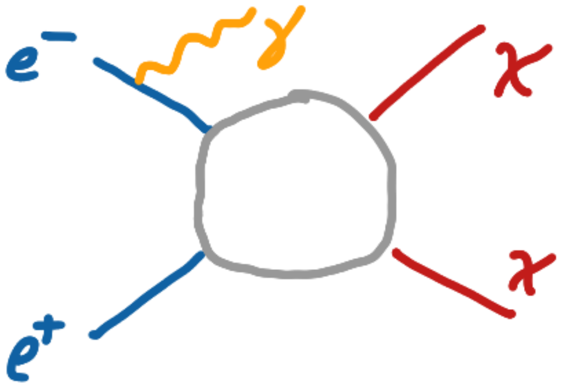
Additional LHC discoveries or not: Substantial potential for discovery of New Physics at Linear Colliders- but note: We are venturing out into the unknown - no guarantees!

For ILC: illustrated in arXiv:1702:05333

Dark Matter - You gotta have it…

- Direct production:



- Signature: A photon + nothing
    - requires a “hermetic” detector to suppress Bhabha background

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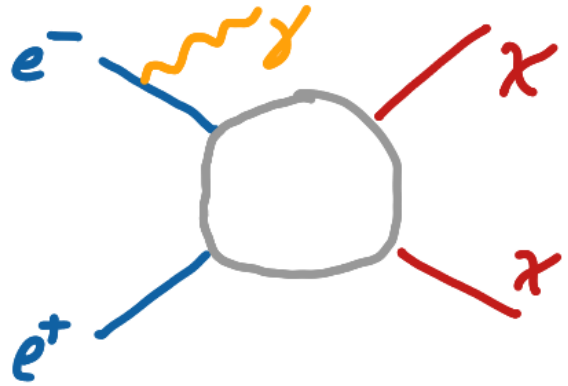

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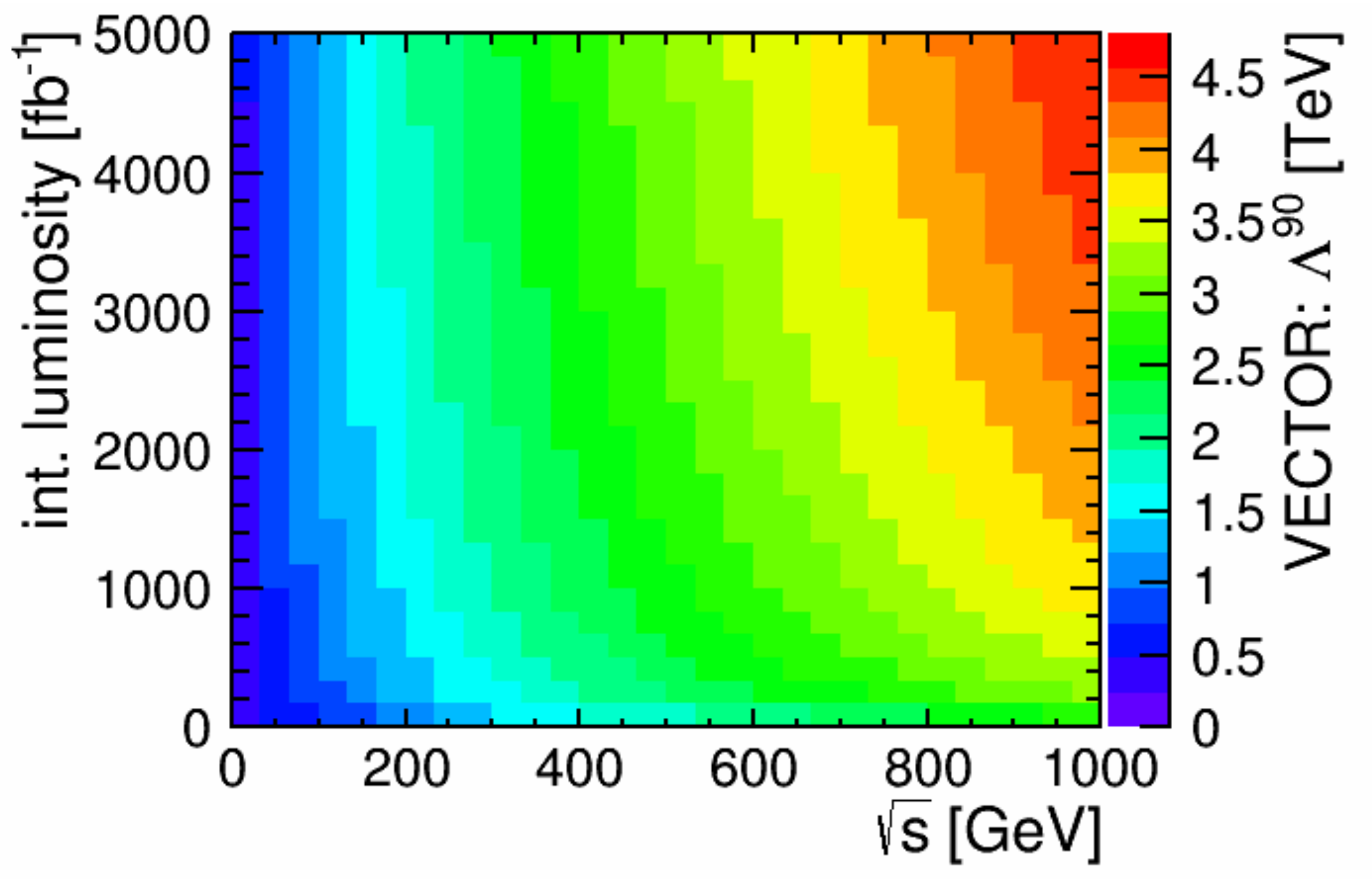
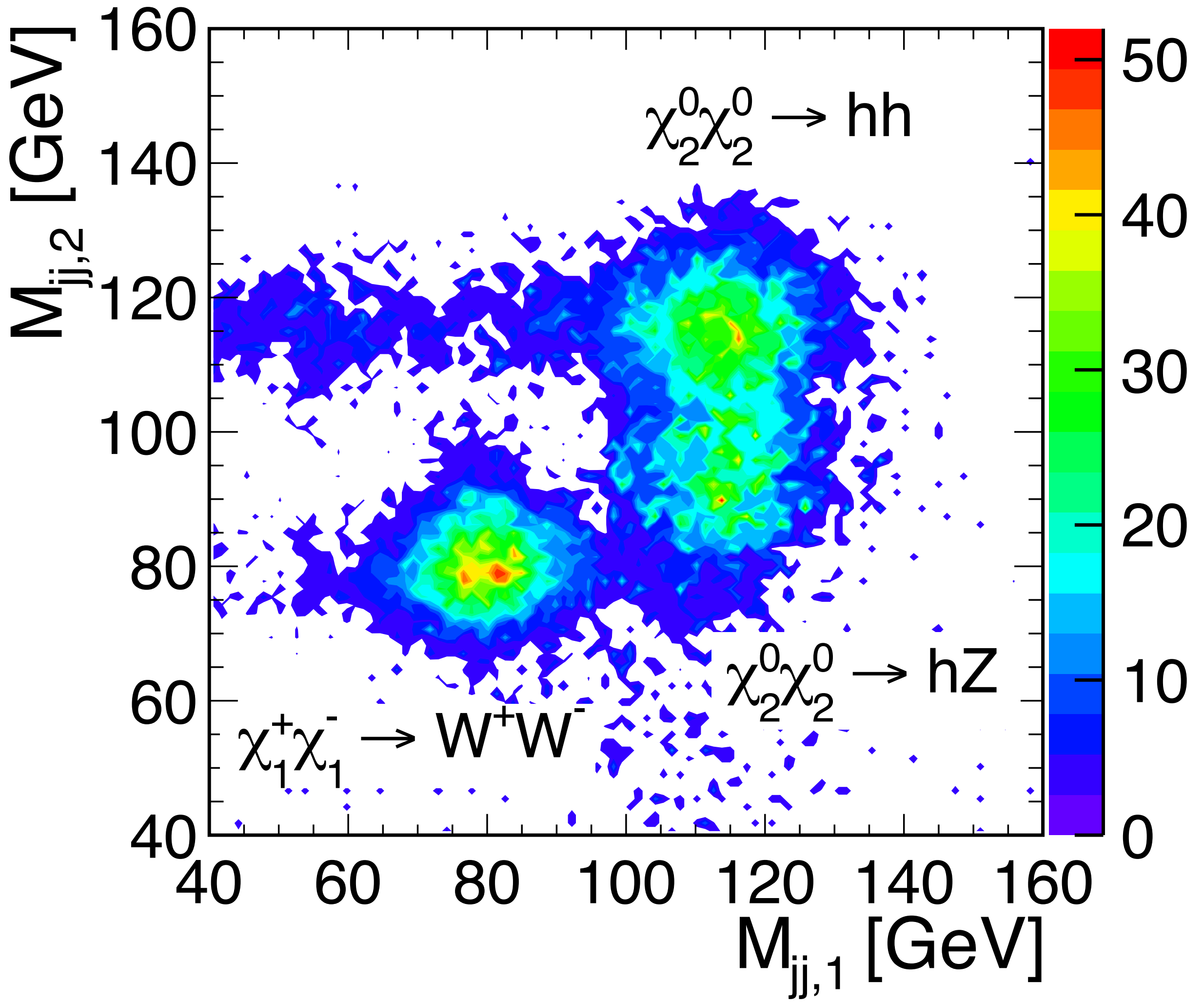
- Exemplary ILC study in a (well-motivated) EFT approach for a vector mediator and WIMP masses sufficiently (a few GeV) below the kinematic limit

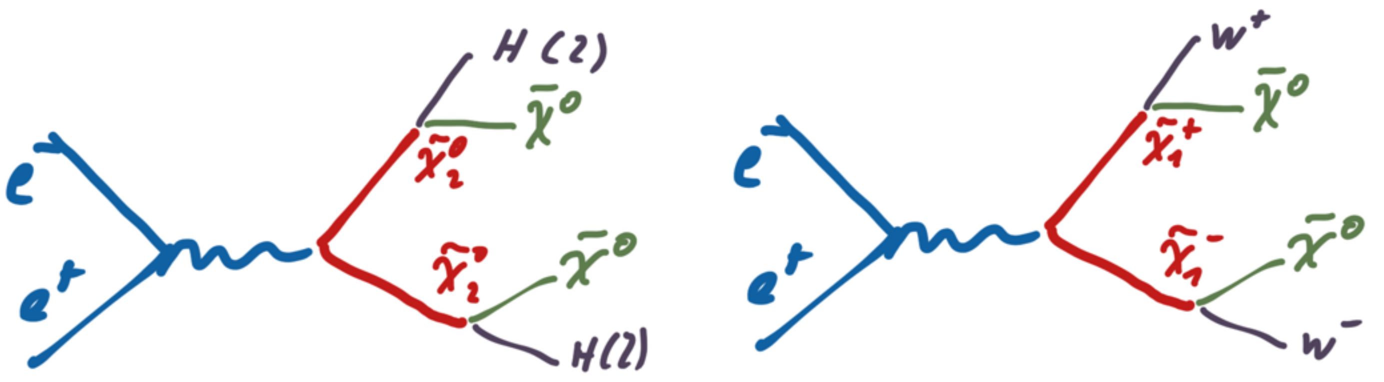


BSM Examples: Direct Measurements

- Potential for discovery directly linked to maximum energy: Sensitivity for pair-produced new particles up to ~ $\sqrt{s}/2$

A CLIC example: mass-degenerate gauginos - mass measurements at few GeV precision



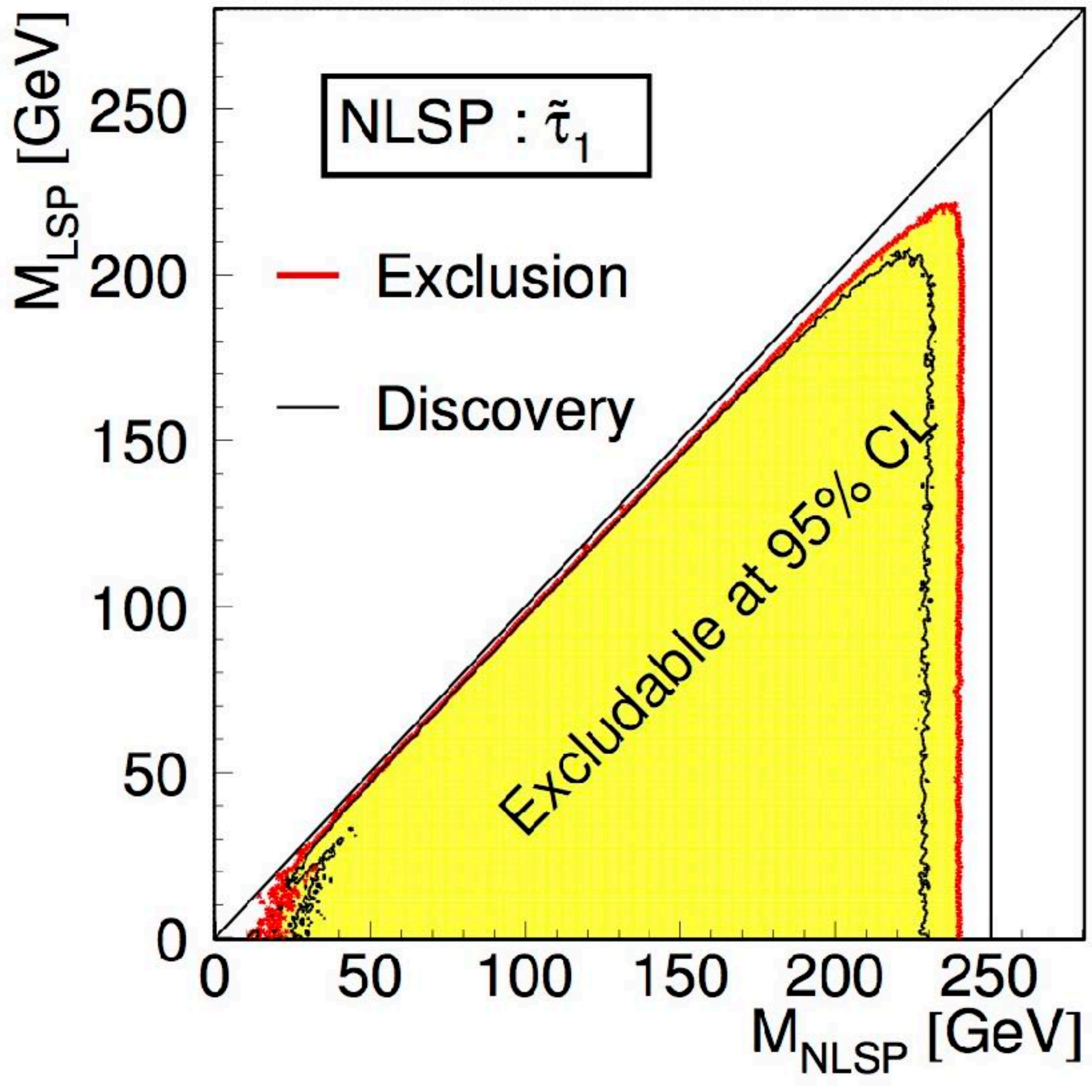


mass-degenerate charginos / neutralinos, $m_{gaugino}$ ~ 650 GeV (3 TeV benchmark)

Precise reconstruction of hadronic final states enables separation of different particles - capitalizes on PFA-optimized detectors

Direct Discovery Potential to the Kinematic Limit

- The clean environment and triggerless data acquisition enables discoveries also in scenarios with very small mass splittings
  - Here: Particularly challenging example with τ + neutralino final state



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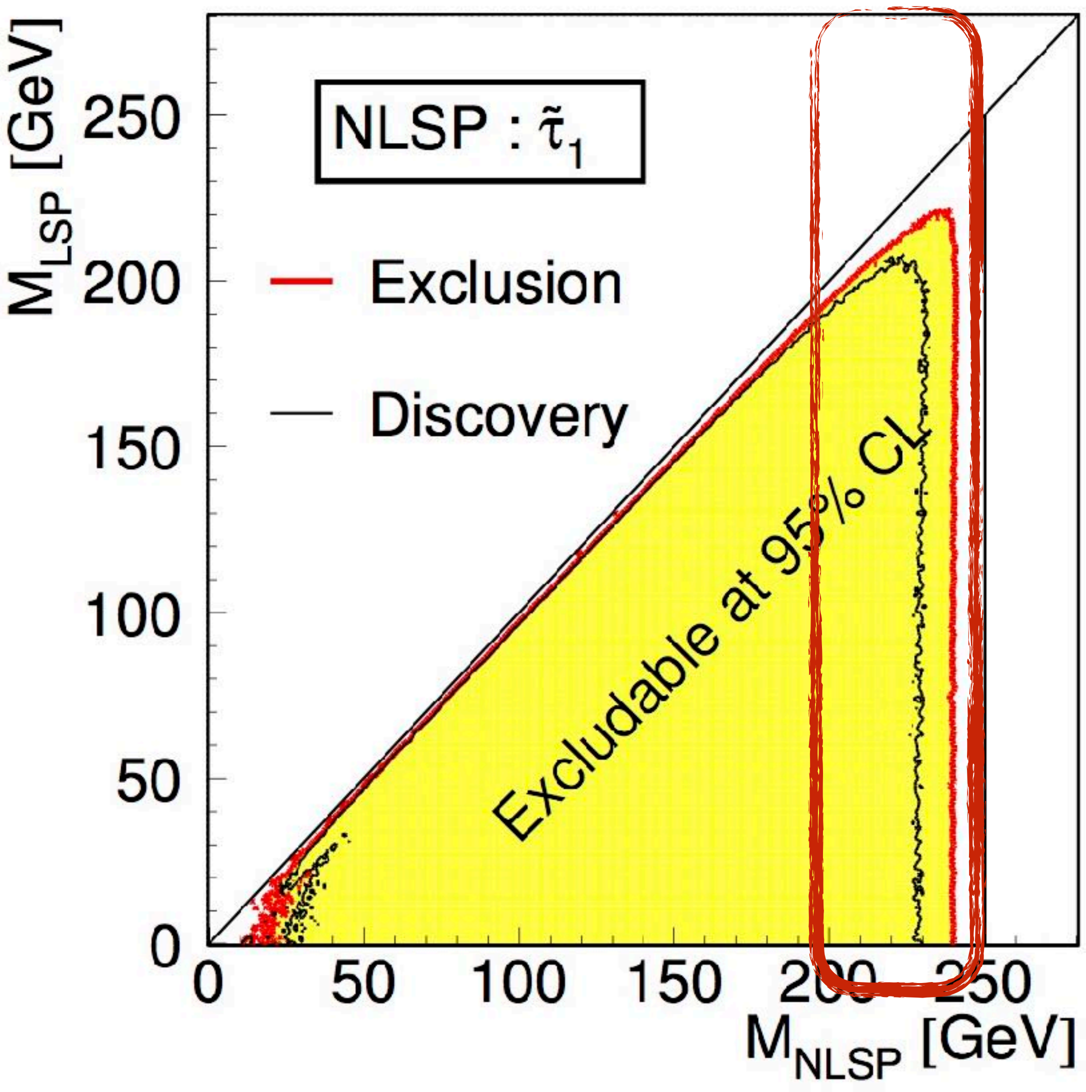
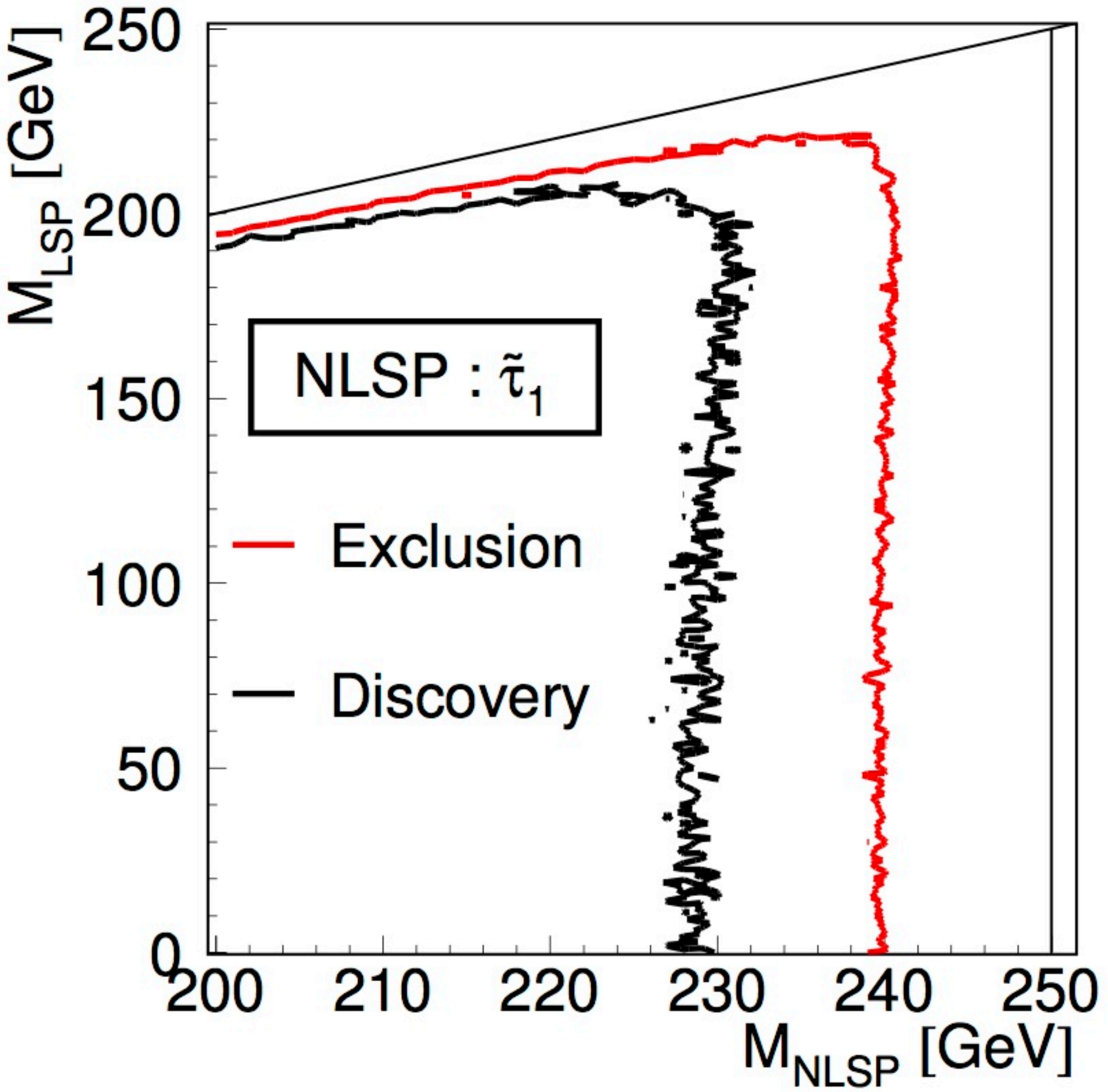
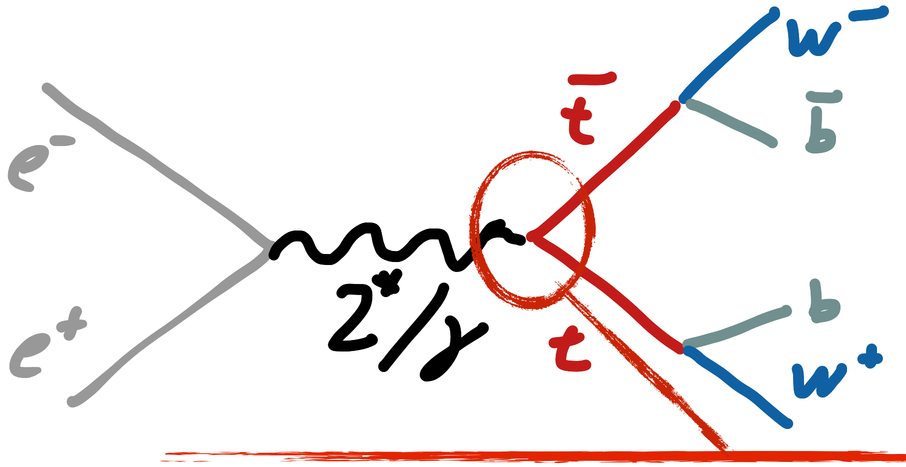




Indirect: Top Electroweak Couplings as BSM Probe



- The production of top pairs provides direct access to electroweak couplings - axial and vector form factors

$$\boxed{\Gamma_{\mu}^{ttX}(k^2,\, q,\, \overline{q}) = ie\left\{\gamma_\mu\,\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}}$$

X: Z, γ

A: axial coupling

V: vector coupling

- In total: 5 non-trivial CP-conserving form factors:

$$\begin{array}{ccc} F_{1V}^{\gamma} & \boxed{F_{1A}^{\gamma}} & F_{2V}^{\gamma} \\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z} \end{array}$$

= 0 due to gauge invariance

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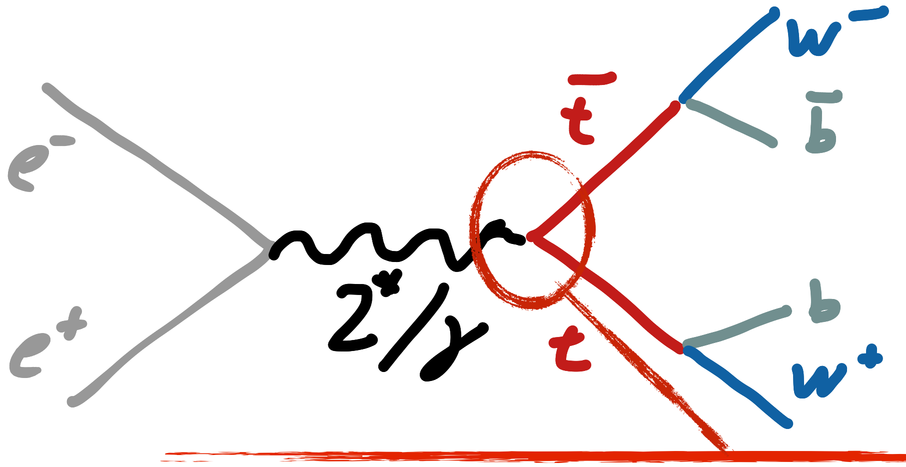

- The p
  acces
  vecto

$$\Gamma^{ttX}_{\mu}(k^2, q, \overline{q}) = ie\Bigg\{\gamma_\mu\ \Big(\widetilde{F}^X_{1V}(k^2) + \gamma_5\widetilde{F}^X_{1A}$$

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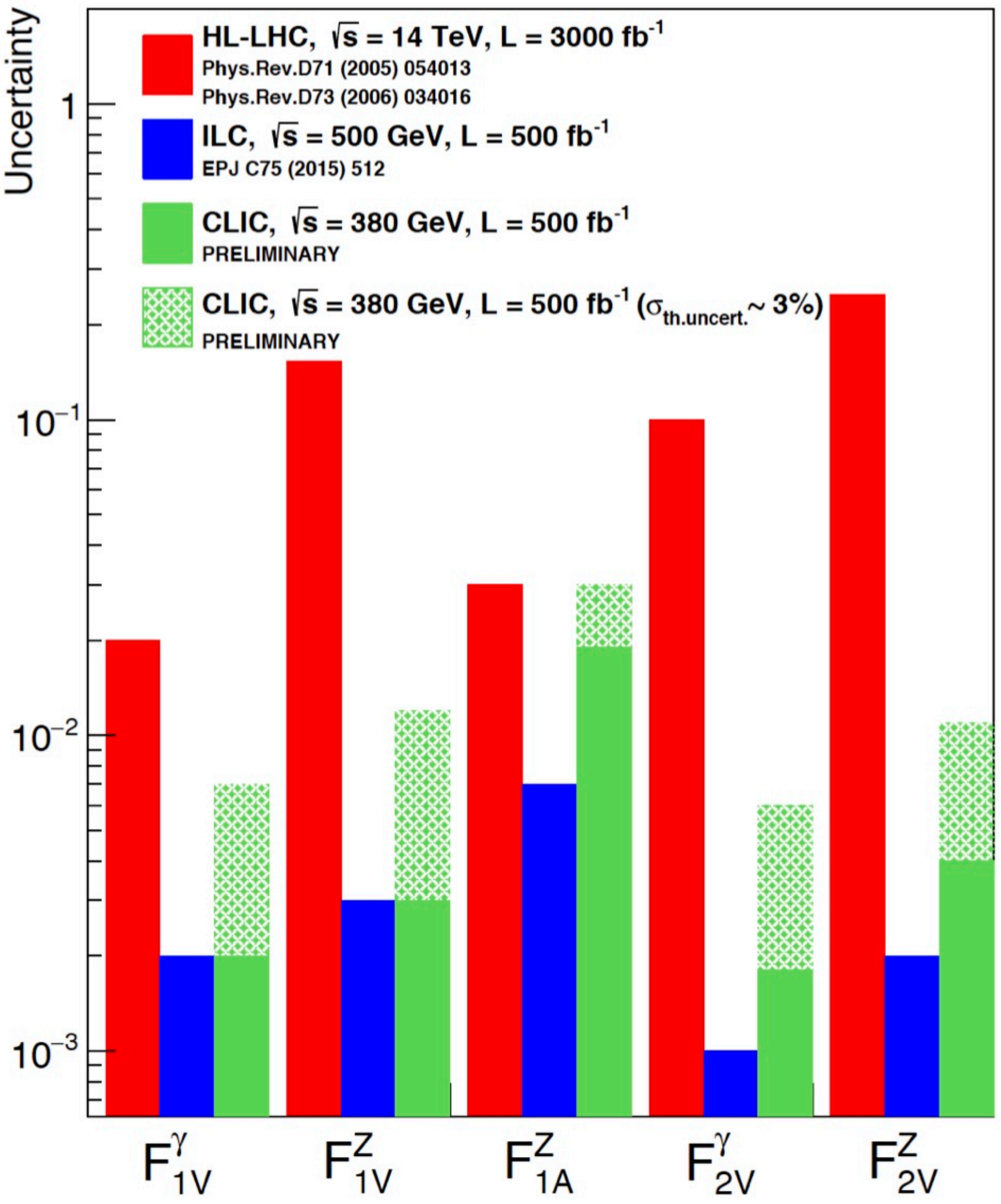

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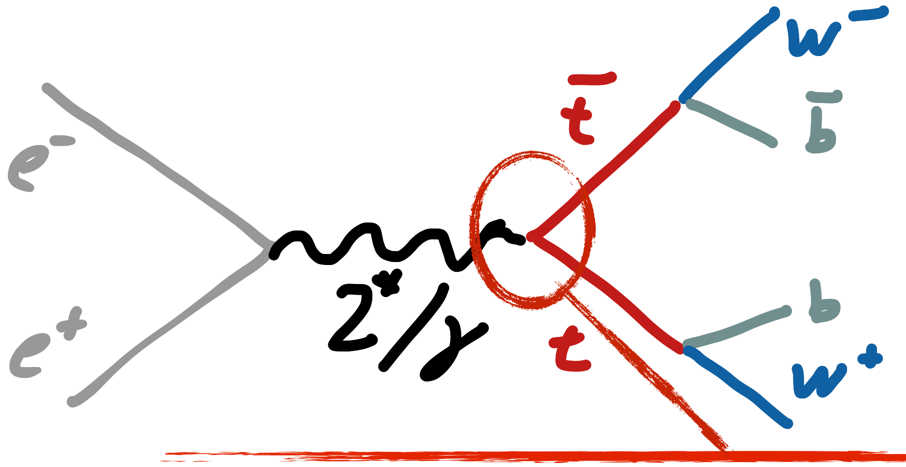

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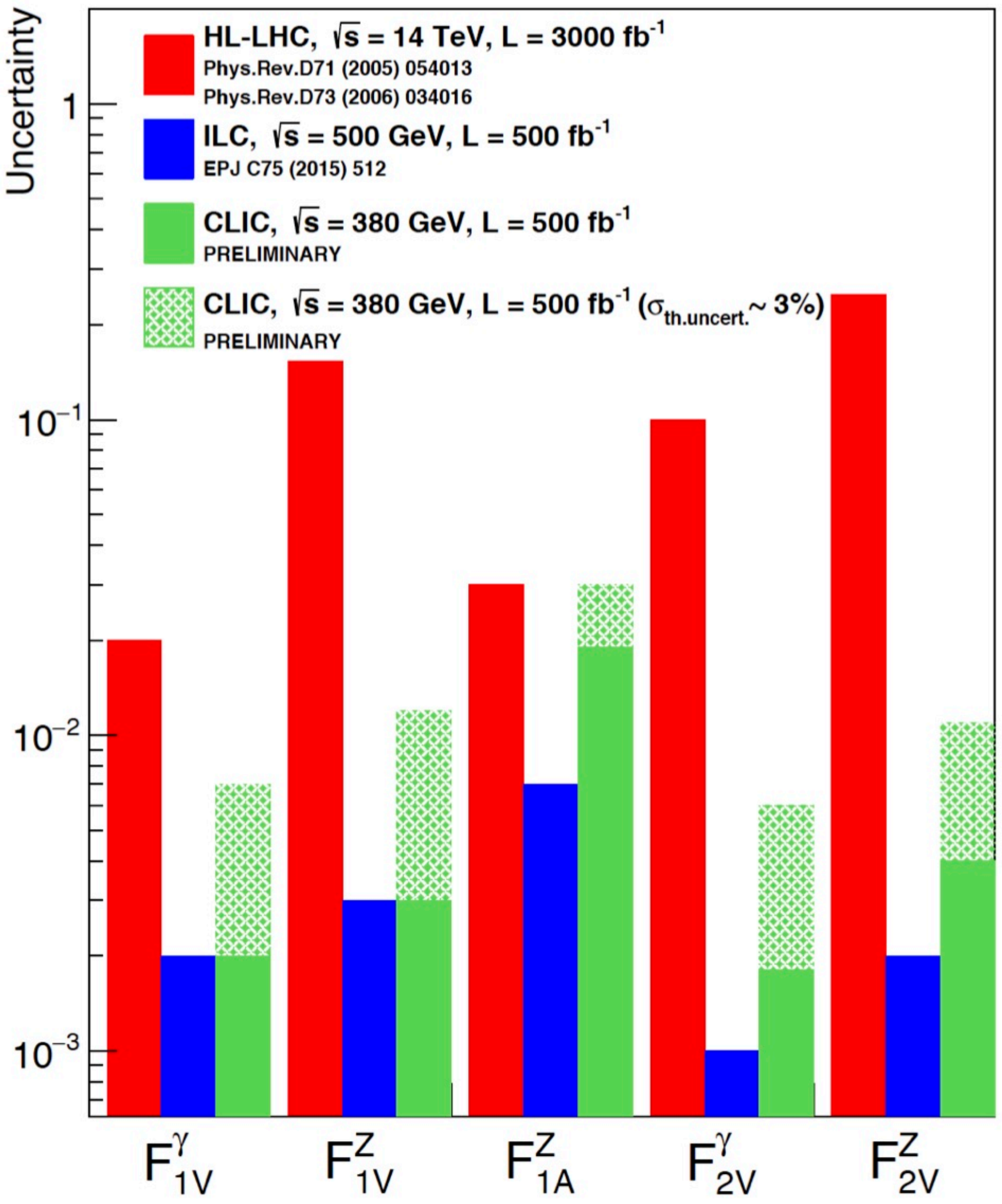
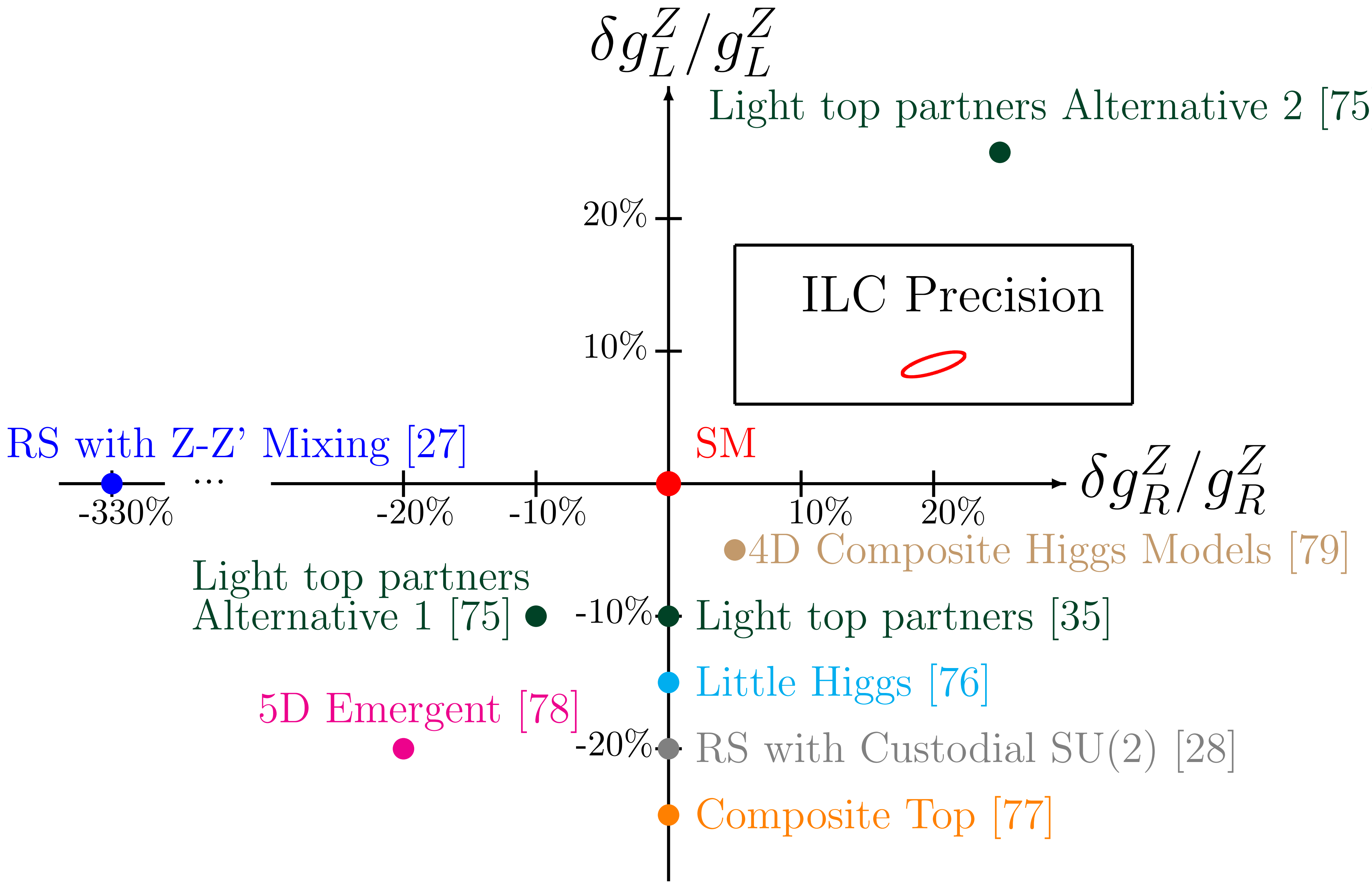
Requires polarized beams!

Requires boost: Measurement precision improves rapidly as one goes above threshold - excellent sensitivity from 380 GeV - 500+ GeV



Indirect: Top Electroweak Couplings as BSM Probe

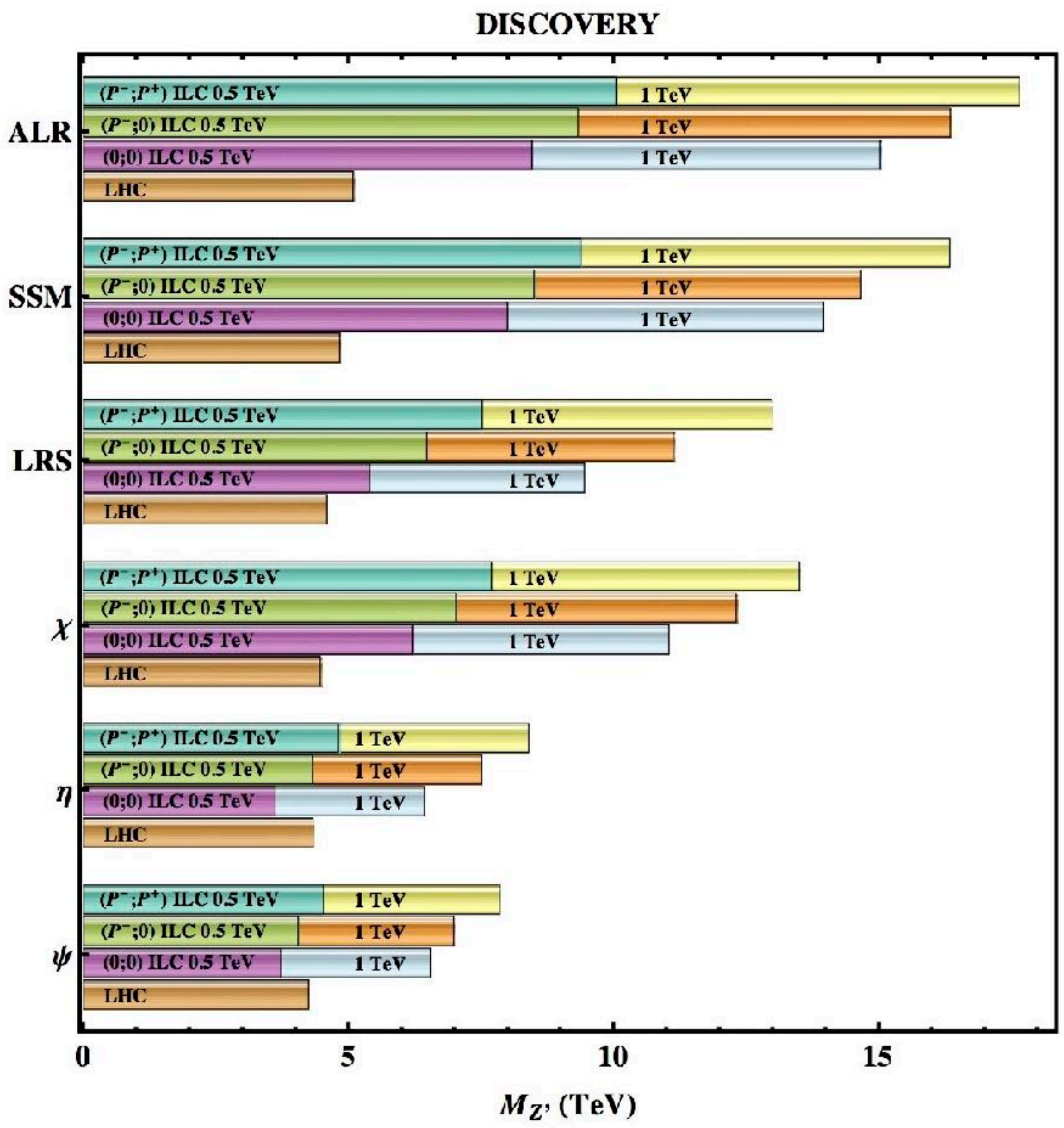
- Mapping this onto deviations in various models using the ILC example:

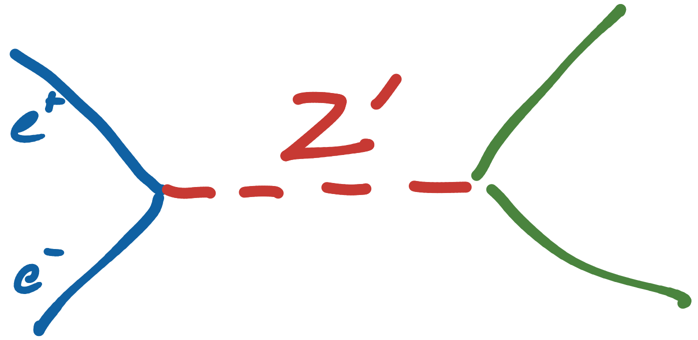


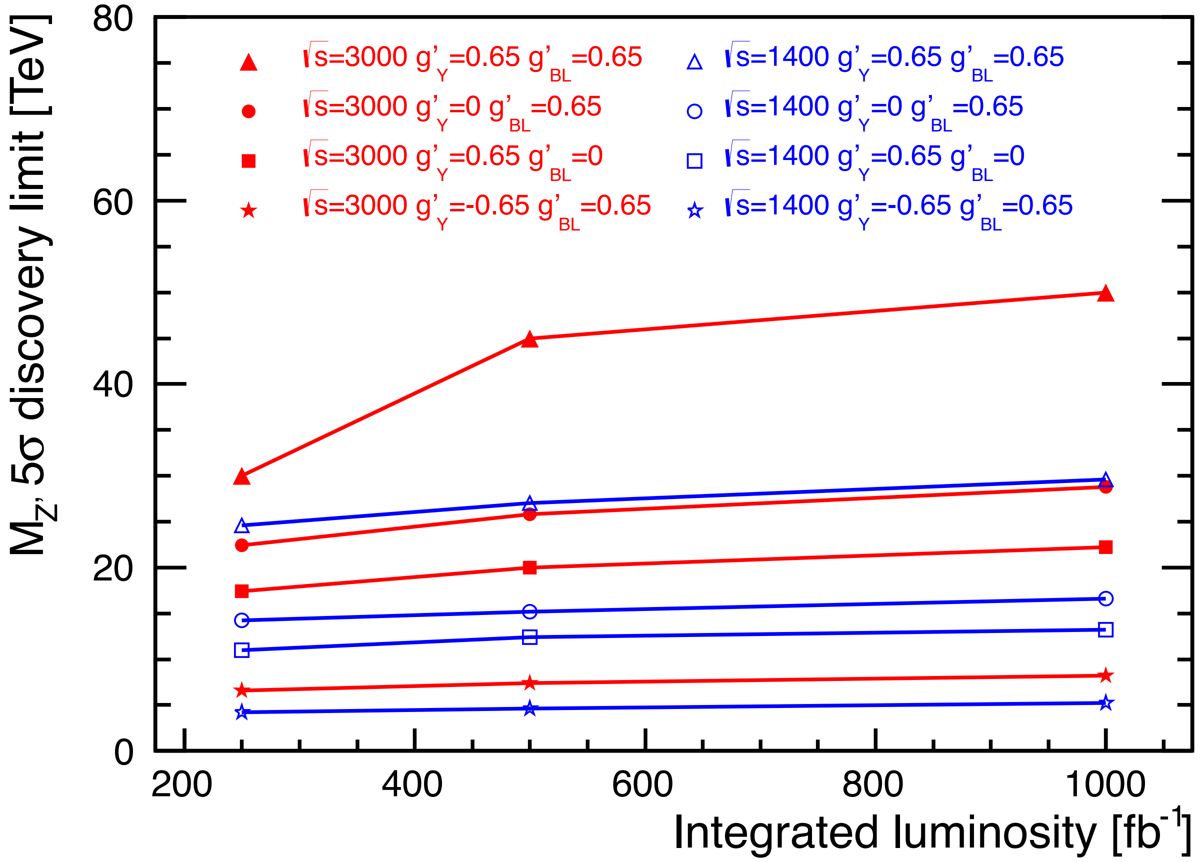
for references: see arXiv:1702:05333

BSM Examples: Indirect Reach

- Precision measurements may enable detections of significant deviations from SM expectations, pointing to new particles and/or new interactions at much higher energy scales







Sensitivity ~ 15 x collider energy

A Look Ahead, Conclusions

ILC: Perspectives

- ILC intensively discussed in Japan
    - Candidate site (Kitakami) identified
    - First international contacts established by MEXT

      … and a lot going on “behind closed doors”

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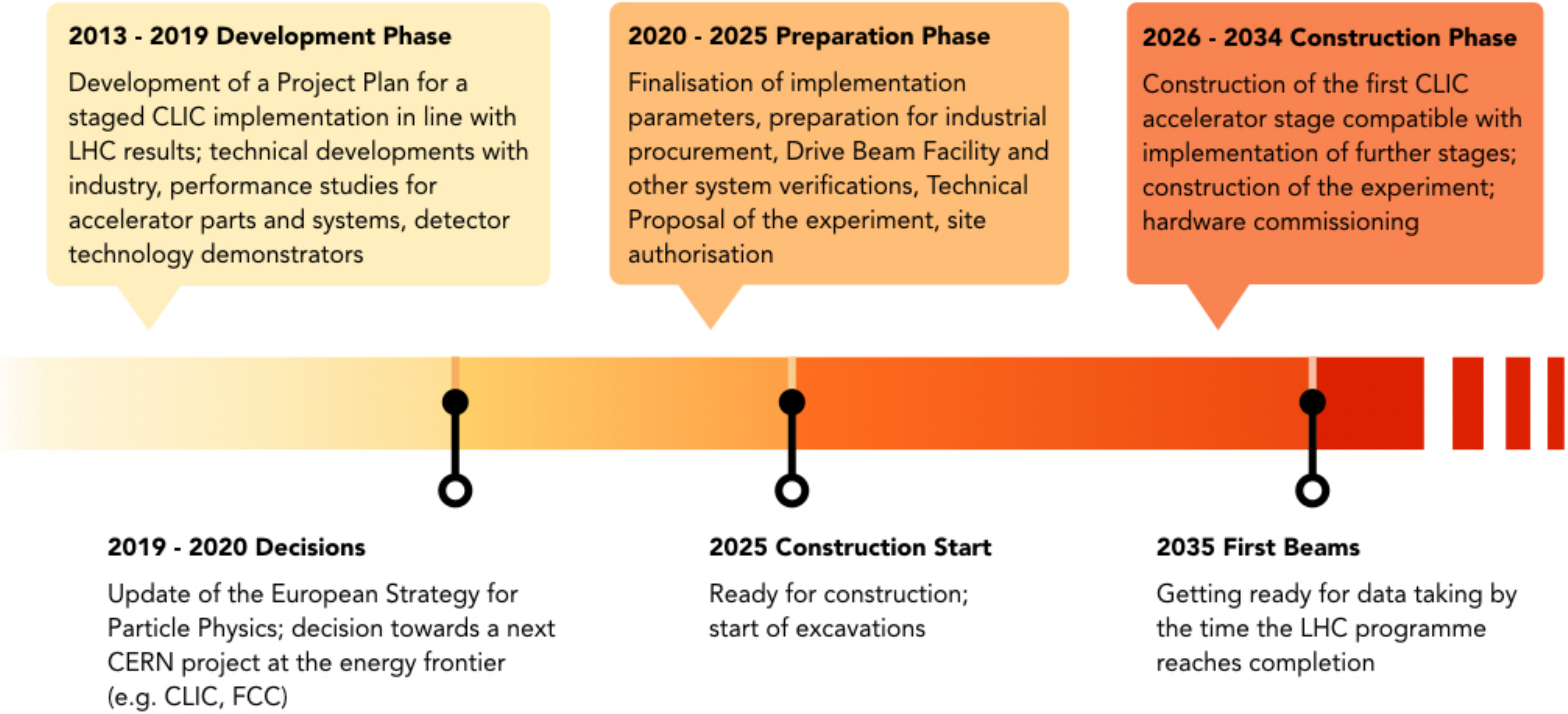
- Cost (obviously) a key factor - investigating staging as a means to lower project entry costs
- Continuing R&D, building on established technical design (TDR in 2013), profiting from XFEL construction experience

- After positive decision:
  - ~ 4 years of “preparation phase” - incl. international negotiations
  - ~ 9 years of construction

  ➪ Commissioning could begin 2031

CLIC: Perspectives



2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

- Over the next two years: Prepare for the update of the European Strategy for Particle Physics, to establish CLIC as a viable option for the future of CERN

Summary & Conclusions

- Linear Colliders offer a broad and ambitious experimental program at the energy frontier, combining precision measurements and discovery potential; highly complementary to the capabilities of LHC

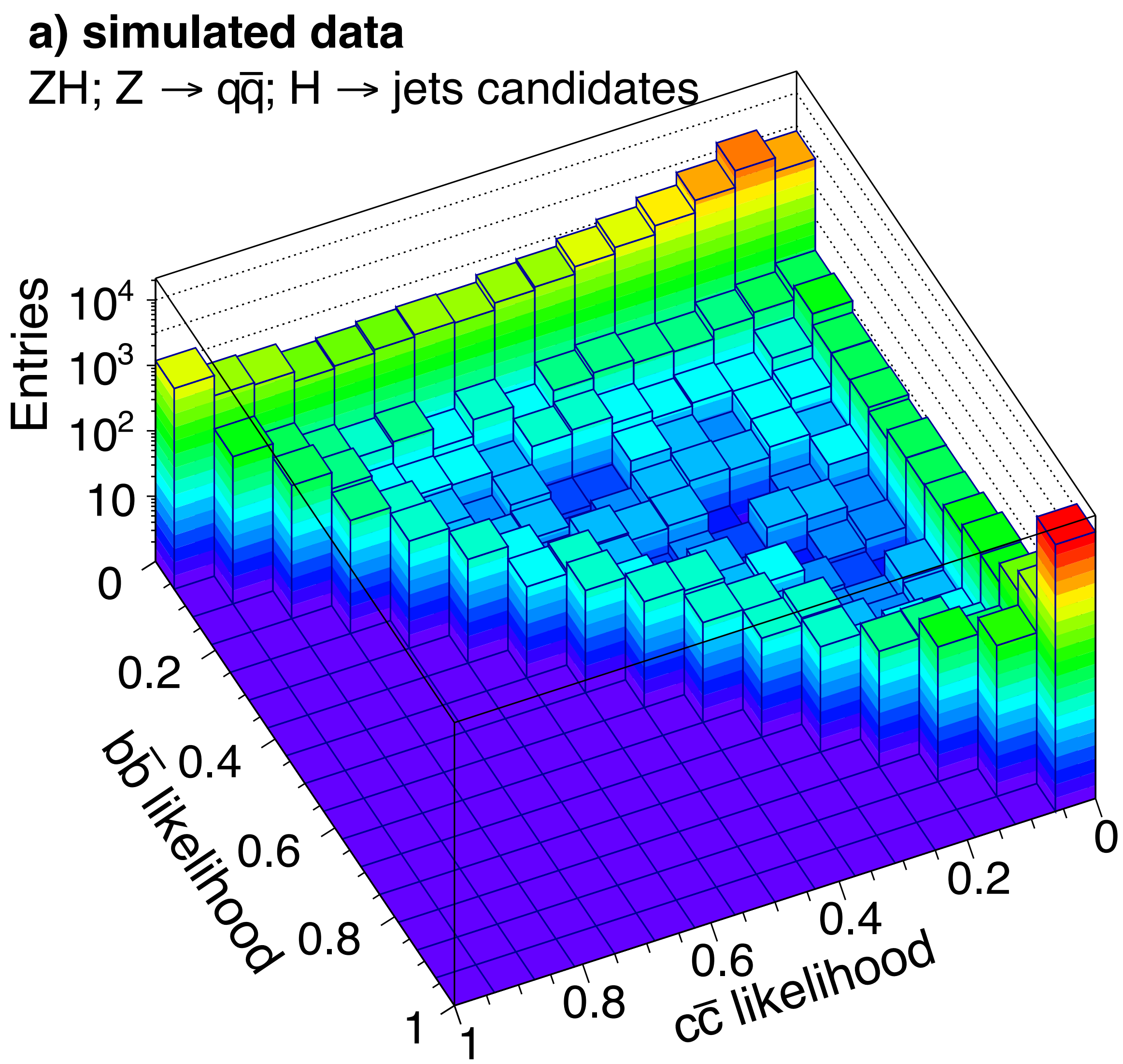
- Staged construction to maximize physics output and to match real-world funding profiles
- Linear Colliders provide the possibility to react to discoveries / indications: Energy reach can "easily" be extended if need arises
    - Ongoing studies to investigate novel acceleration concepts as "afterburner" for CLIC

- Decisions expected in the coming years:
    - Conclusions from Japanese review process of ILC in 2018
    - European Strategy in 2019/2020 to decide on future direction at CERN, with CLIC as one of the possibilities

Extras

Higgs -> Jets: b,c, gluon couplings

- Selection of hadronic final states, separated by flavor tagging: Example CLIC @ 350 GeV
    - BRs from template fit in flavor space



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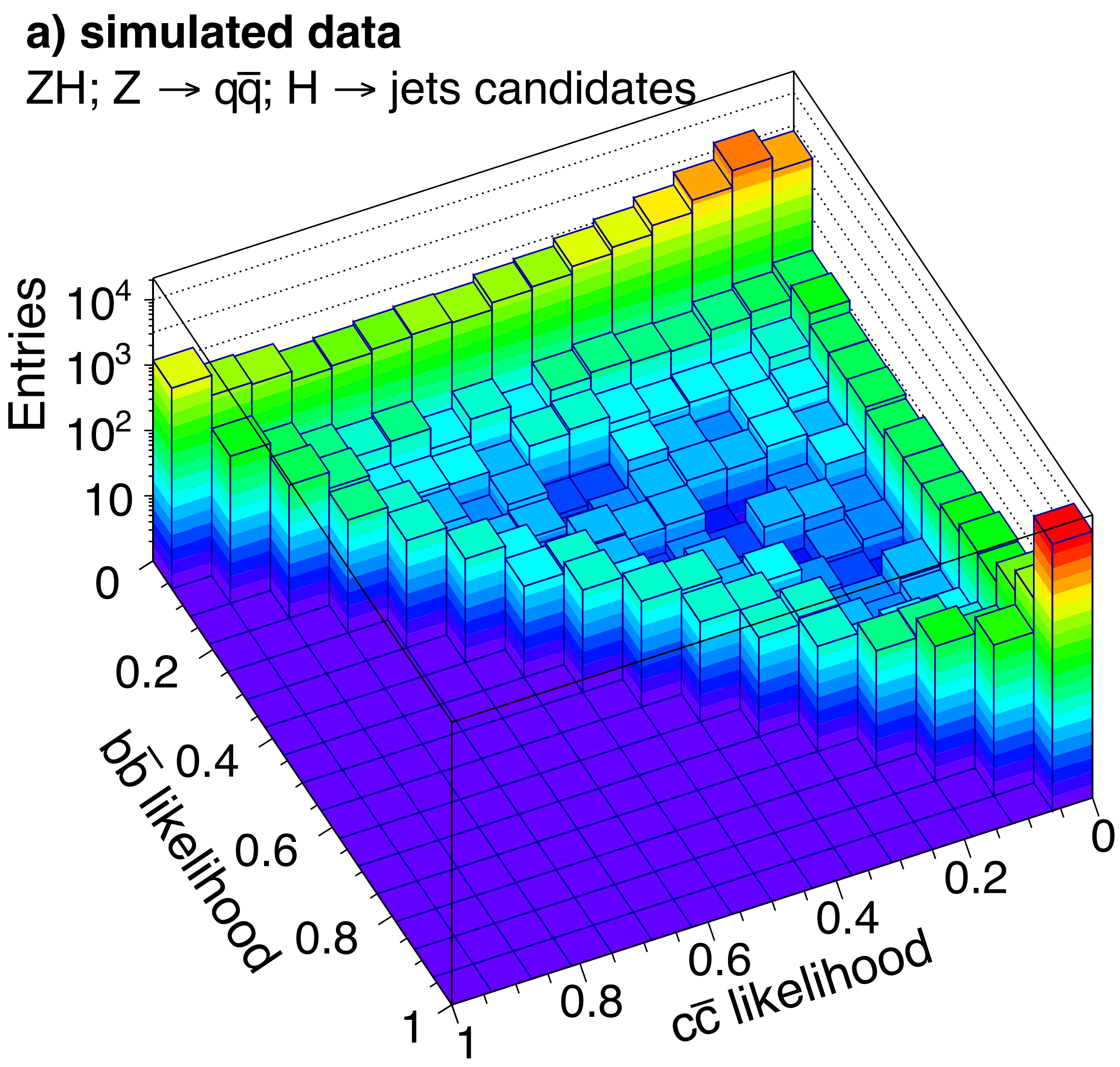
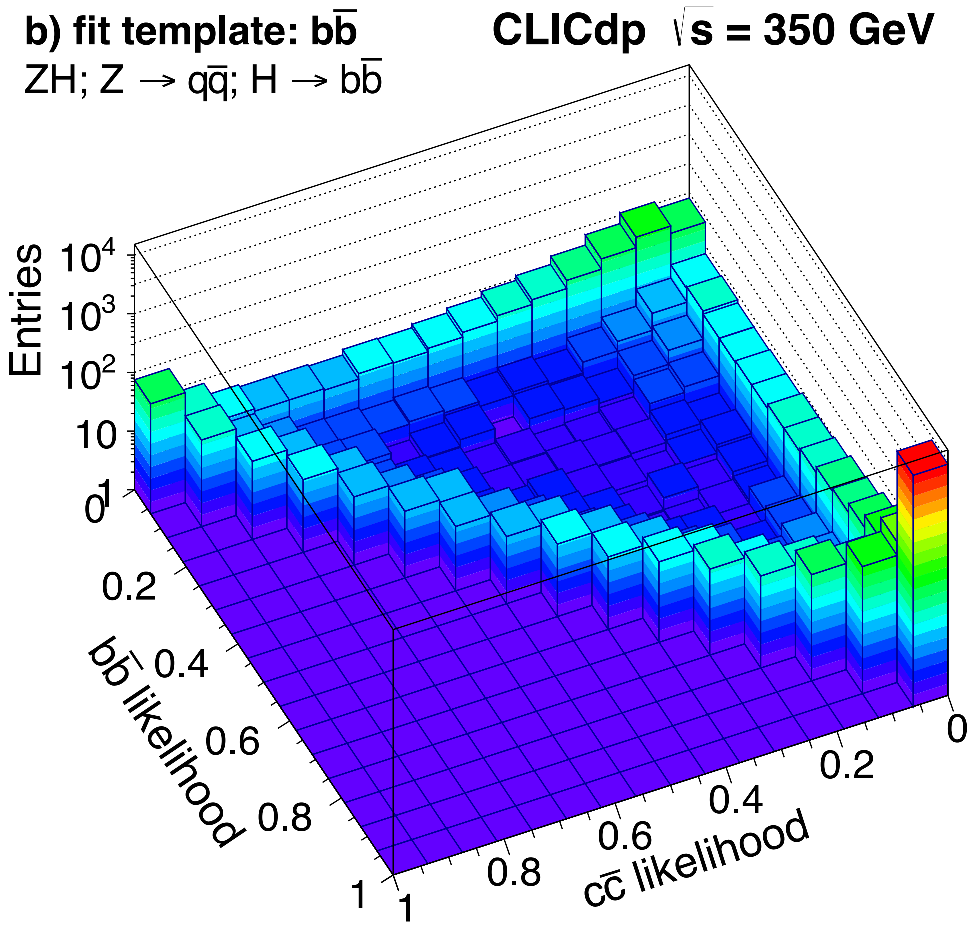


a) simulated data

ZH; Z → $q\bar{q}$; H → jets candidates



b) fit template: $b\bar{b}$

ZH; Z → $q\bar{q}$; H → $b\bar{b}$

CLICdp $\sqrt{s}$ = 350 GeV

Higgs -> Jets: b,c, gluon couplings

- Selection of hadronic final states, separated by flavor tagging: Example CLIC @ 350 GeV
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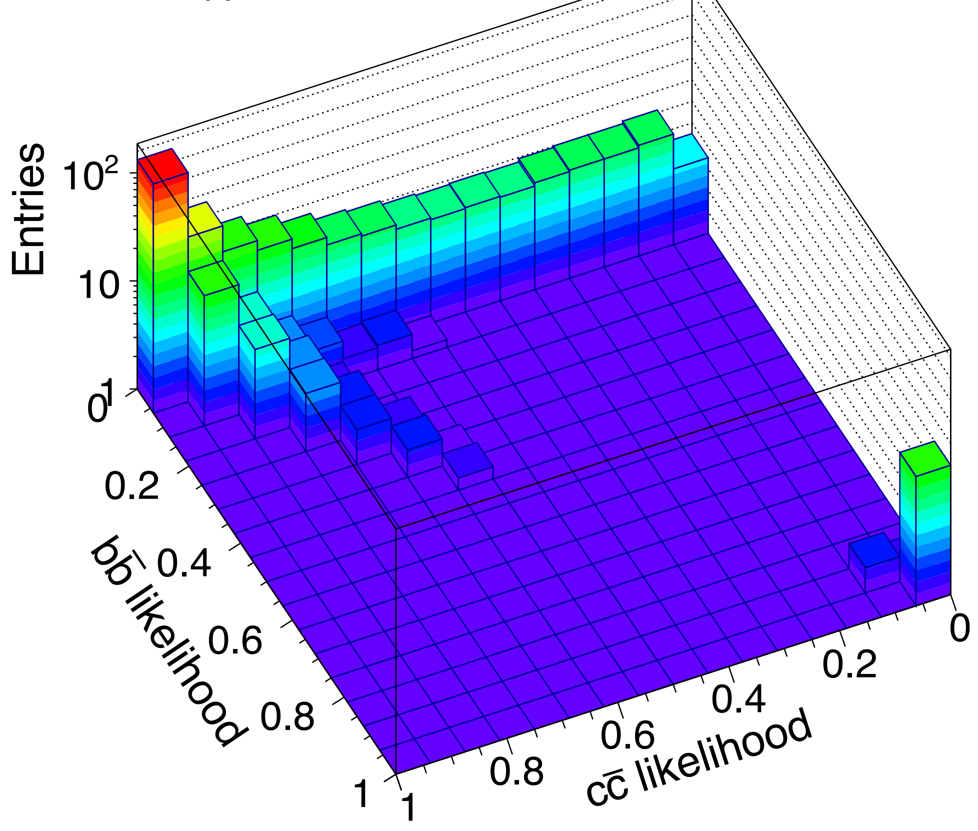
c) fit template: $c\bar{c}$

ZH; Z → $q\bar{q}$; H → $c\bar{c}$



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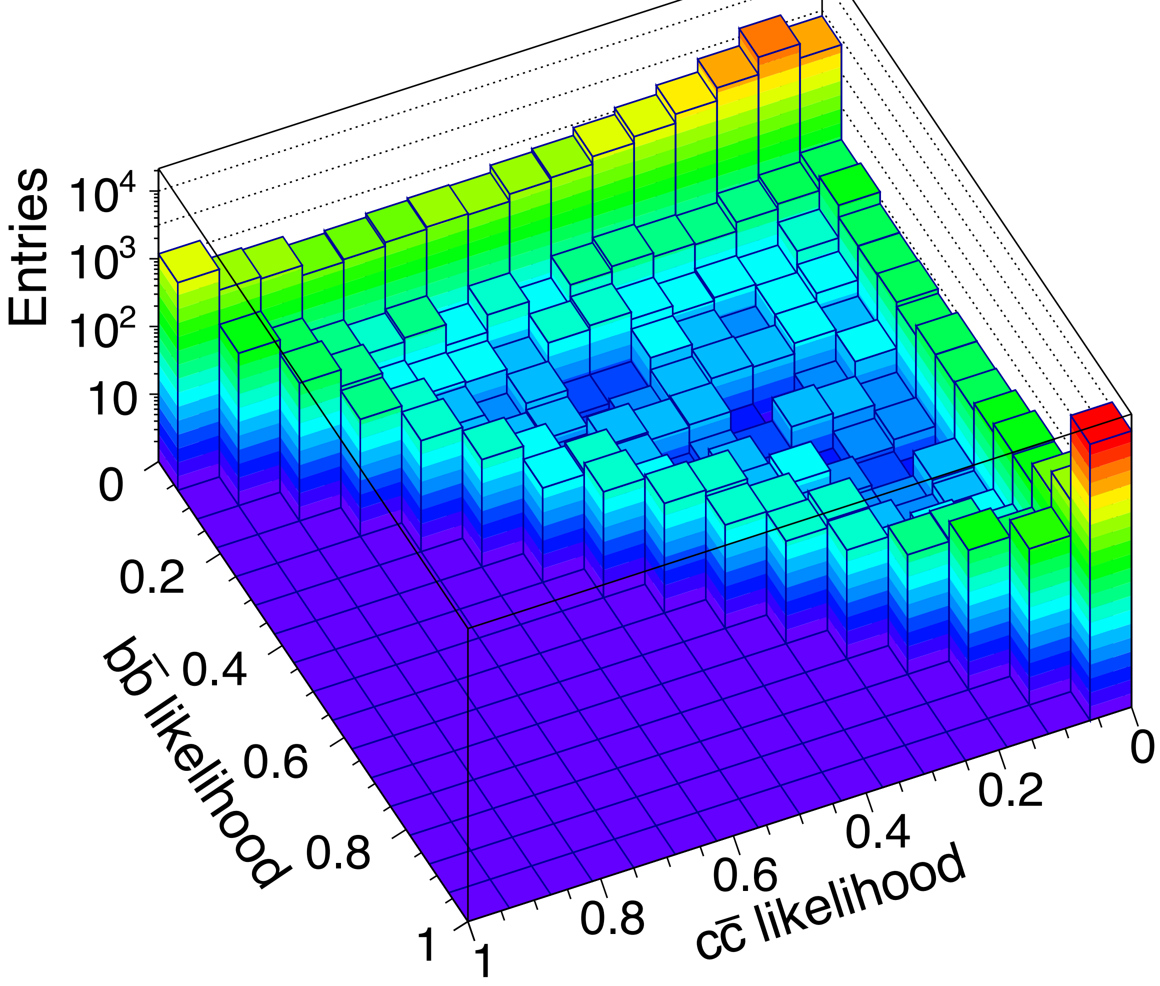

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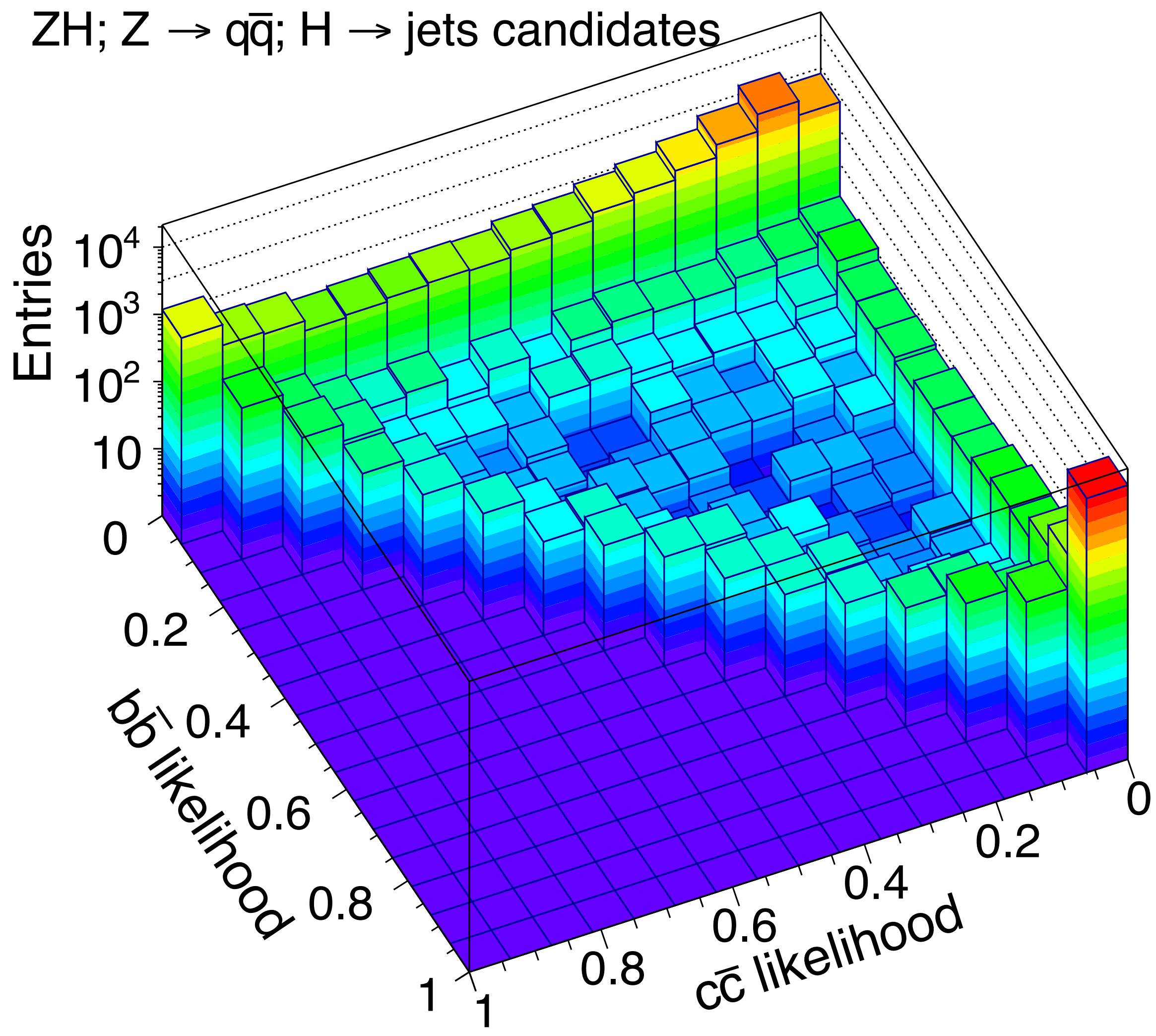

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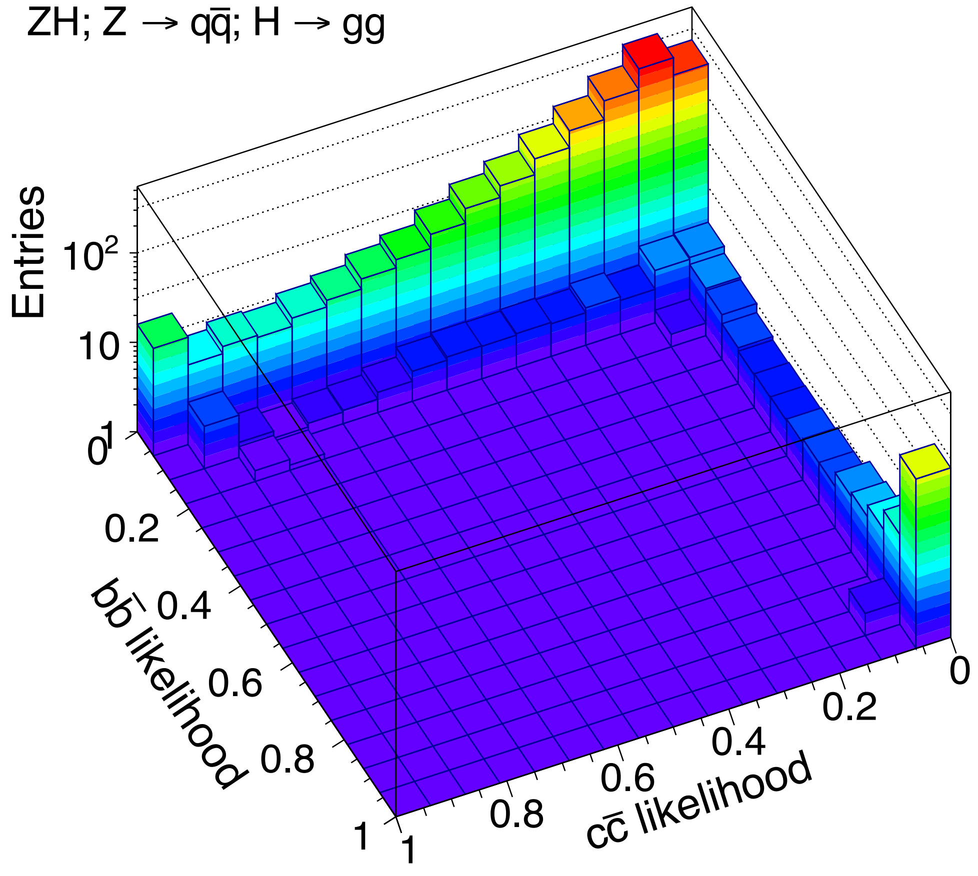

d) fit template: gg

ZH; Z → q$\bar{q}$; H → gg

Higgs -> Jets: b,c, gluon couplings

- Selection of hadronic final states, separated by flavor tagging: Example CLIC @ 350 GeV
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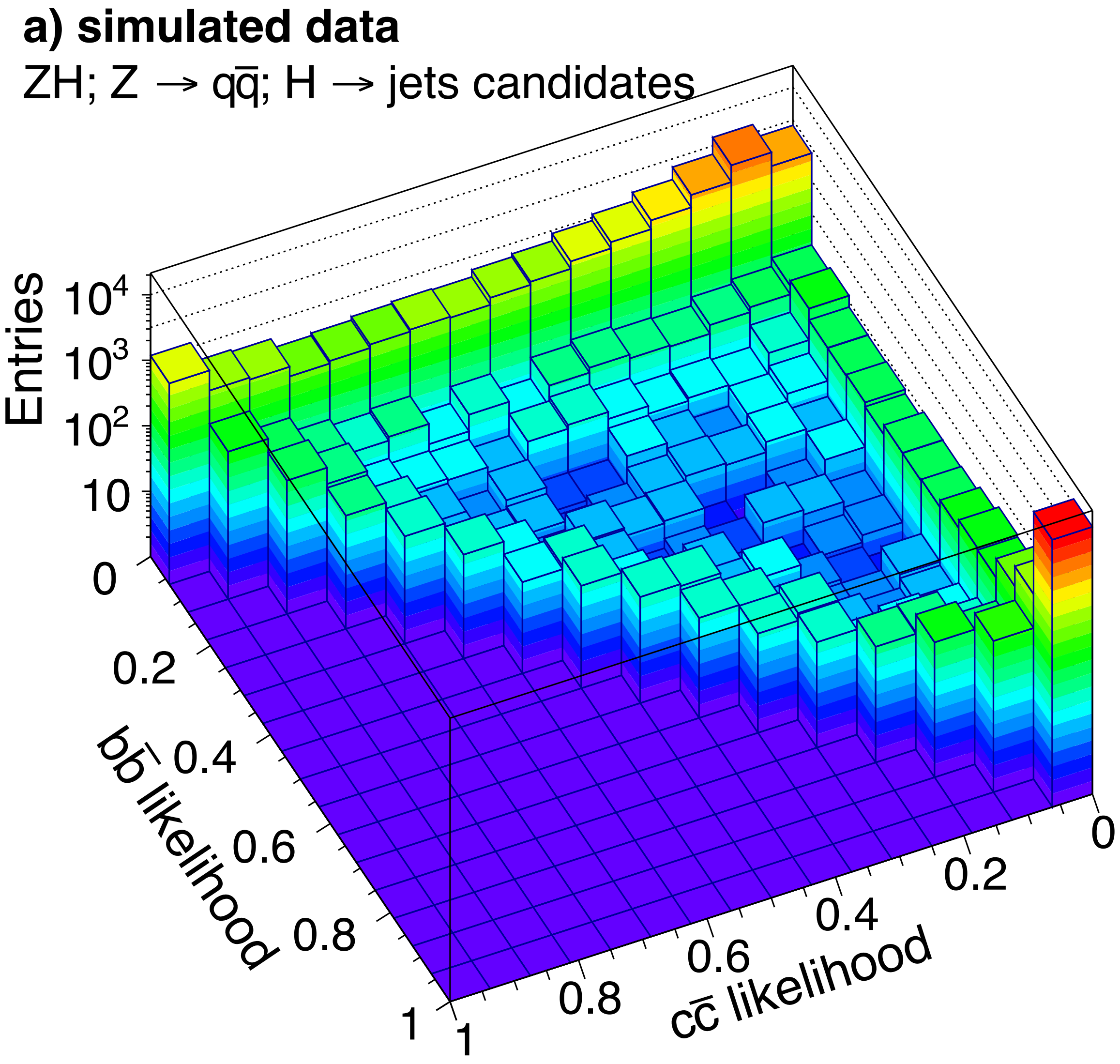

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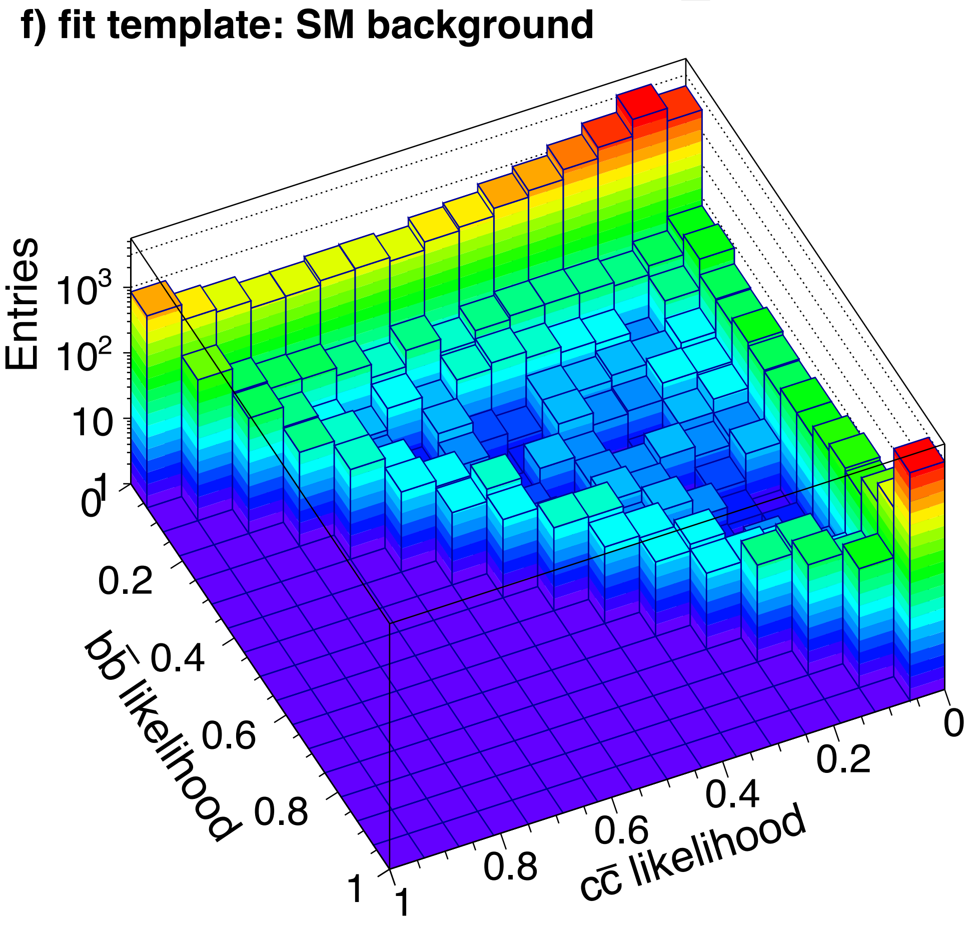

f) fit template: SM background

Higgs -> Jets: b,c, gluon couplings

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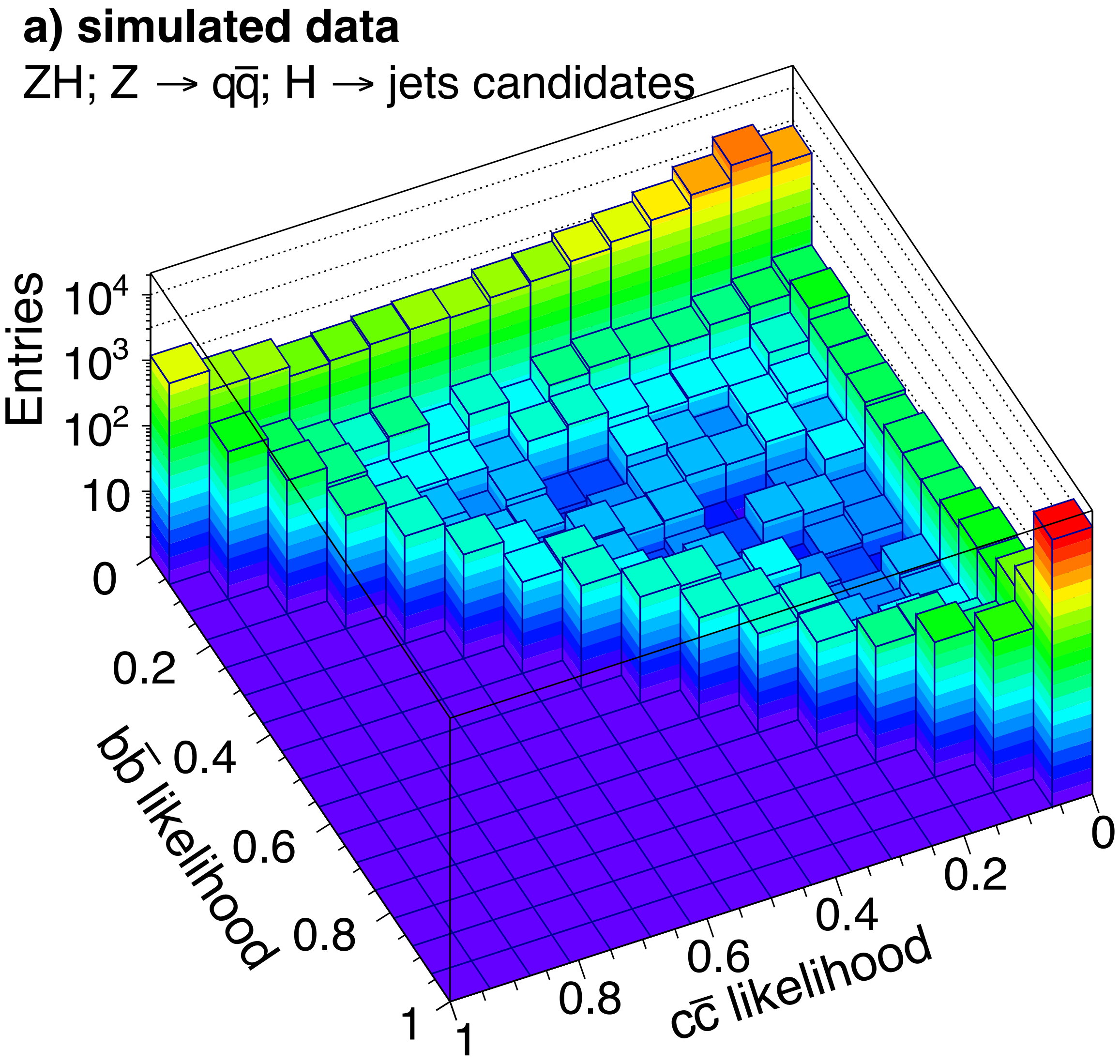
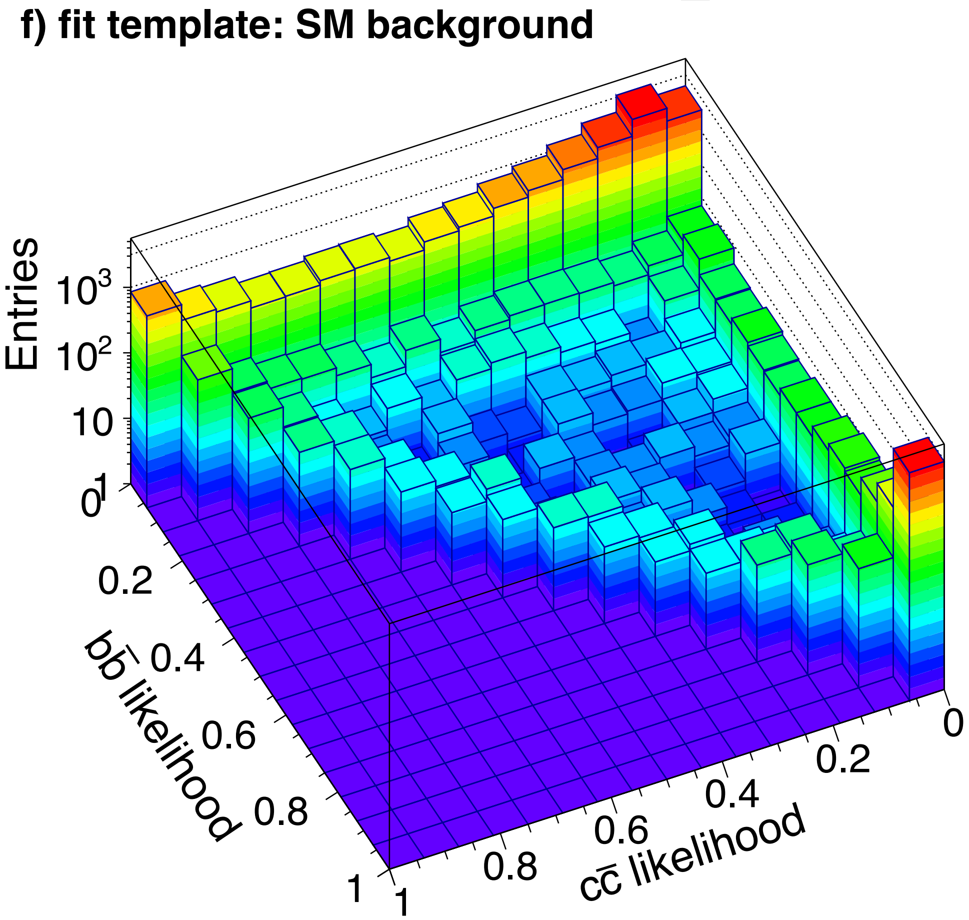
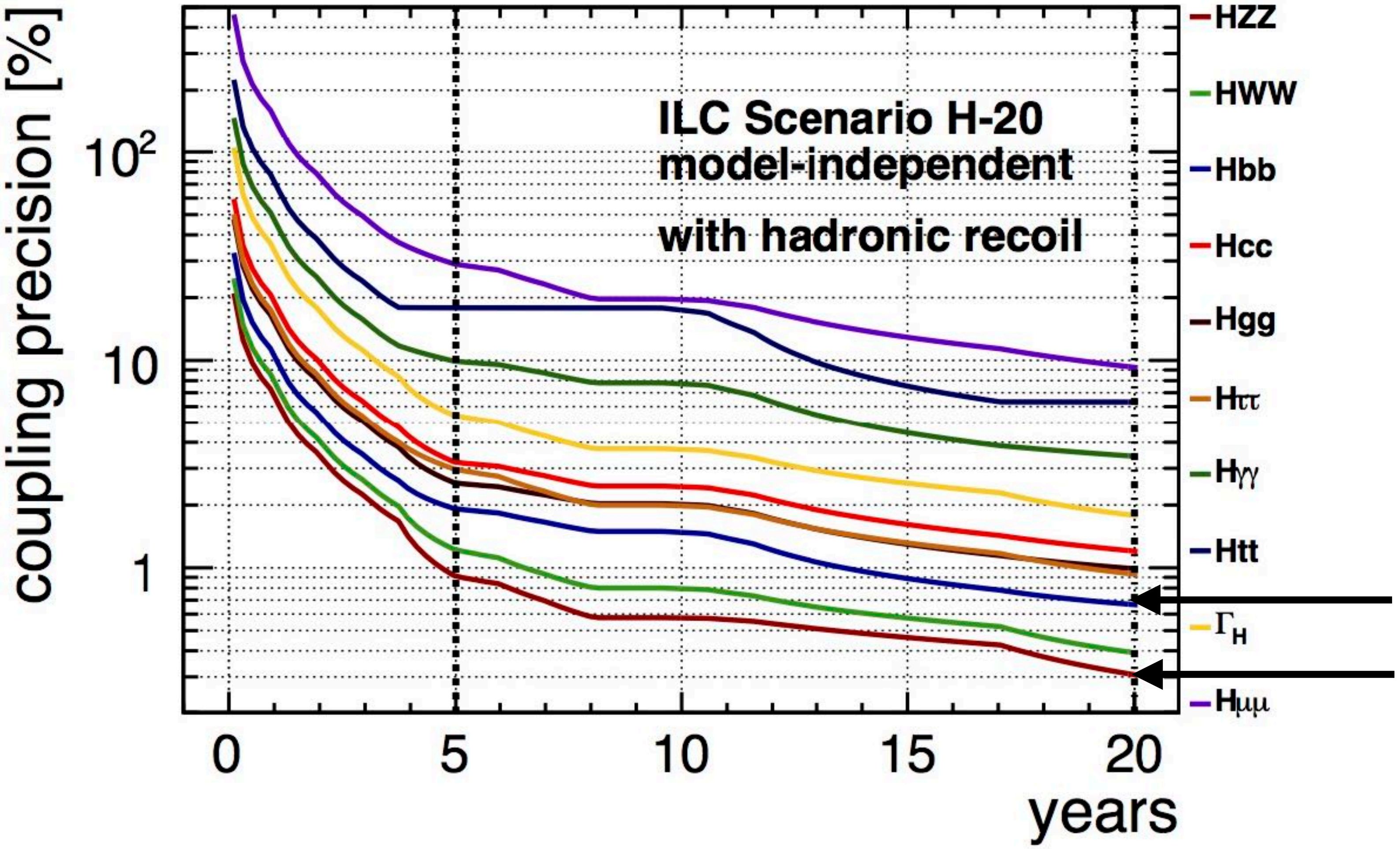




- … and the same for WW fusion: Combined extraction of 6 σxBRs, with full extraction of correlations (important for combined fits)

ILC Higgs Couplings

- Global fits of linear collider Higgs projections
    - NB: Non-trivial to compare between projects: Different assumptions on running scenarios



ILC "H-20" scenario:
after 20 years:

- 250 GeV: 2 ab^{-1}
- 350 GeV: 200 fb^{-1}
- 500 GeV: 4 ab^{-1}

polarized beams

g_{Hbb} ~ 0.7 %

g_{HZZ} ~ 0.31 %

- Model-independent fit: Minimal assumptions (zero-width approximation)
    - model-independent measurement of HZ coupling ("recoil measurement") serves as anchor: HZ coupling measurement in ZH process defines achievable precision

CLIC Higgs Couplings

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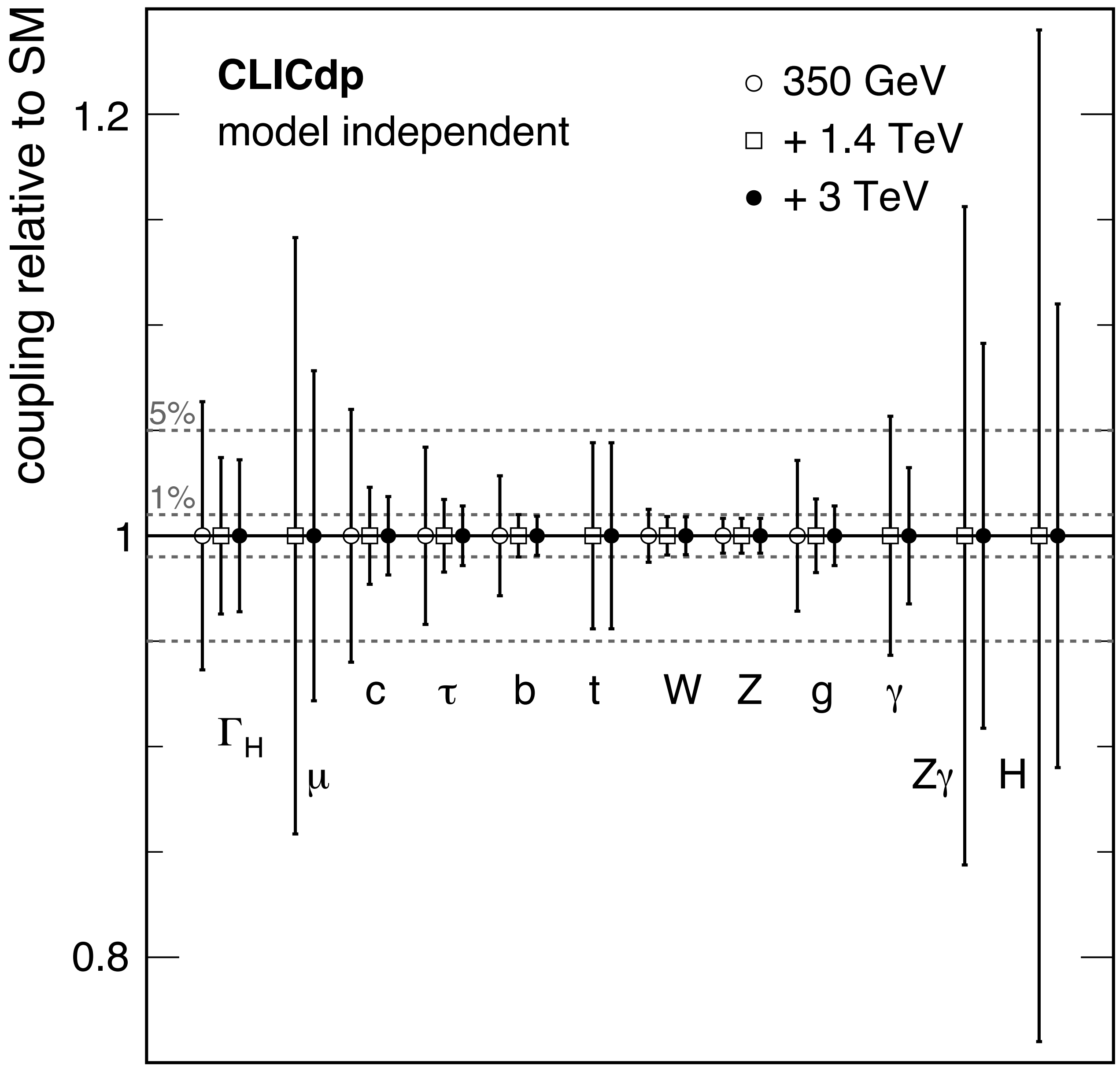
  - NB: Non-trivial to compare between projects: Different assumptions on running scenarios



CLIC modified CDR scenario:
after 23 years (incl. time for energy upgrades):

- 350 GeV: 500 fb^{-1}
- 1.4 TeV: 1.5 ab^{-1}
- 3 TeV: 2 ab^{-1}

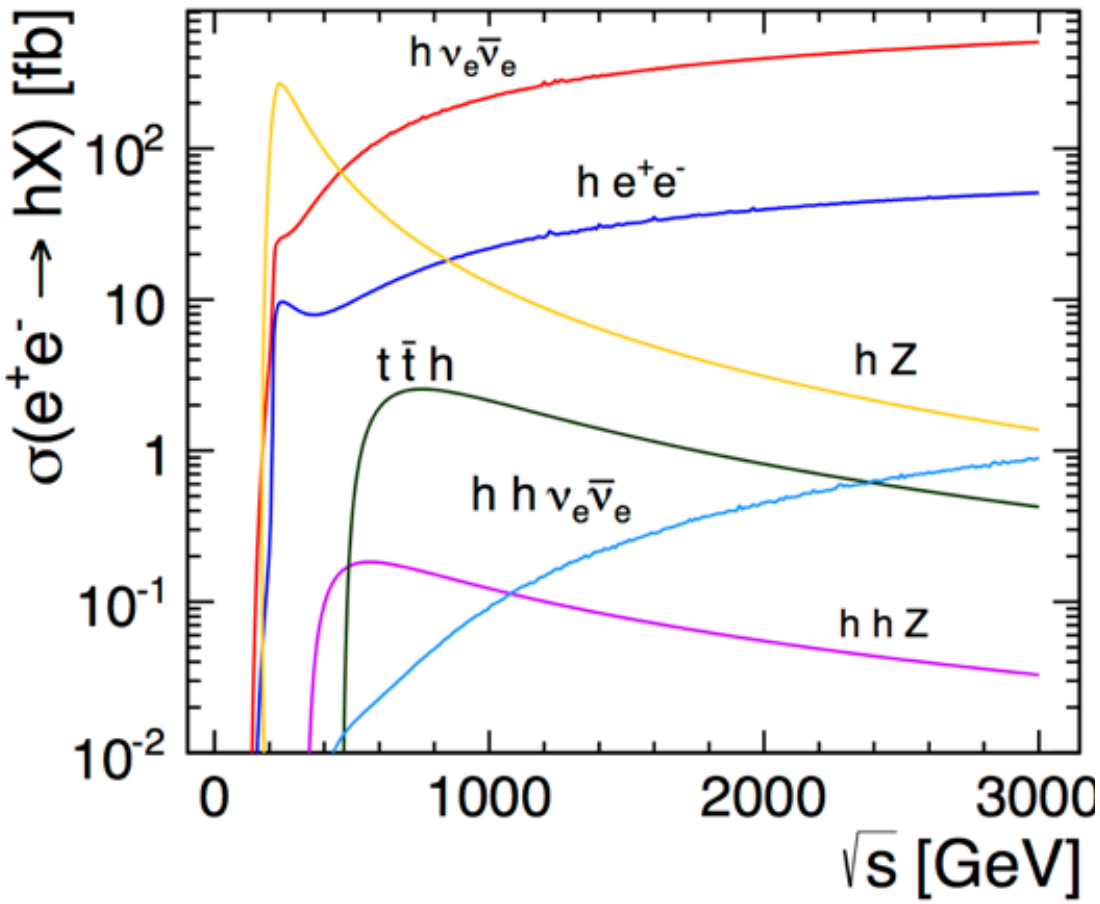
polarized electrons at 1.4 TeV and 3 TeV

- Model-independent fit

most couplings < 2% in full program

“LHC-like” assumptions bring κ_{HWW} to the permille level; κ_{Hbb}, κ_{HZZ} 2, 3 ‰, respectively

Higgs: Direct Access to Top Yukawa Coupling



- Energies of 500 GeV and above enable direct access to the top Yukawa coupling via nth production

- At ILC: 10% measurement with 1 ab^{-1} at 500 GeV, 6.3% in full running scenario (see later)

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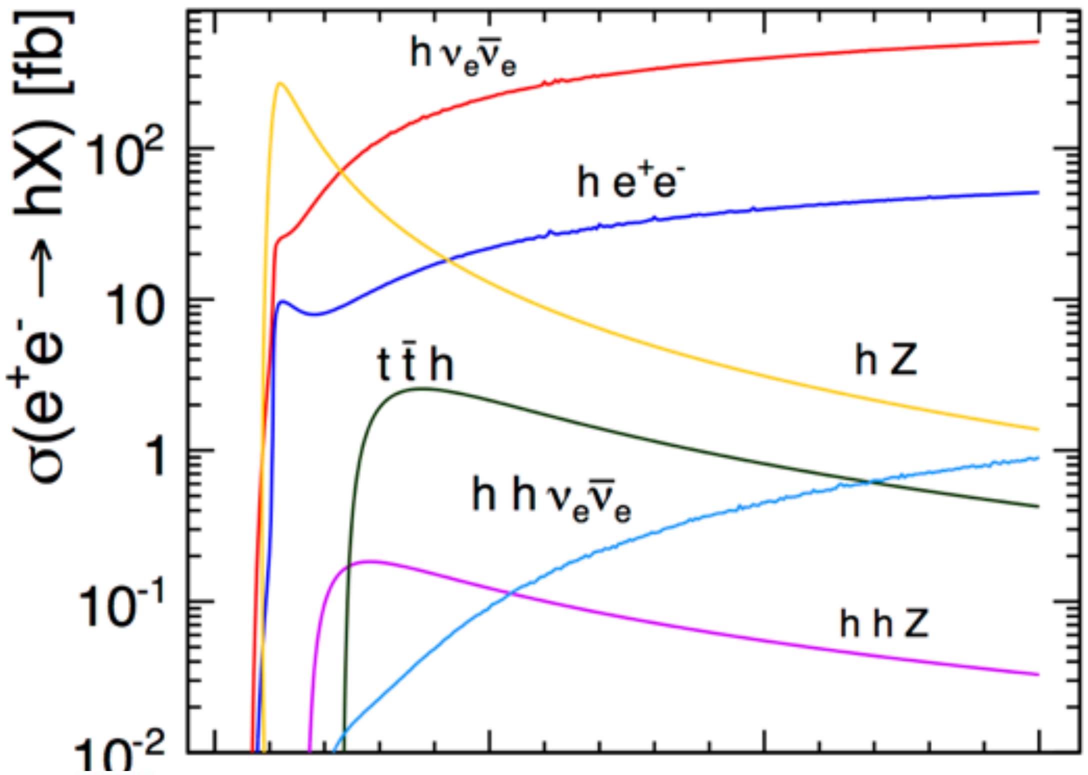
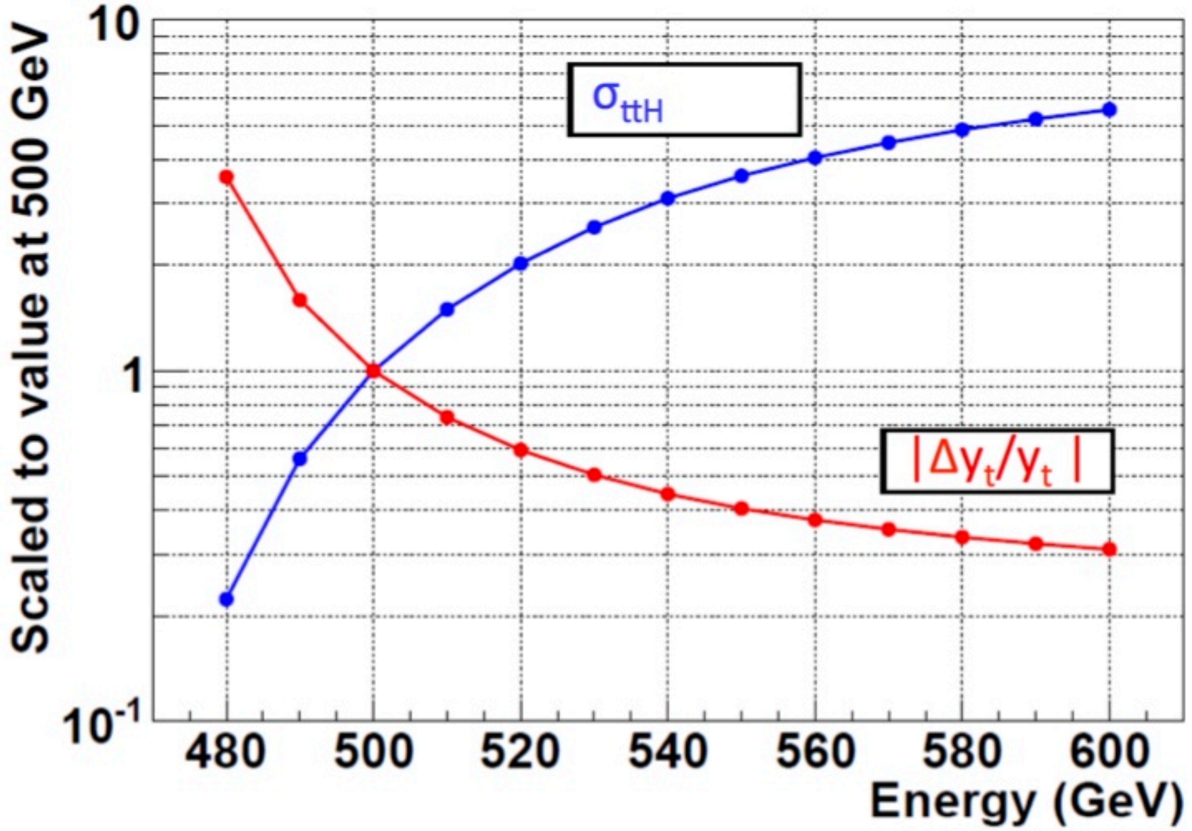
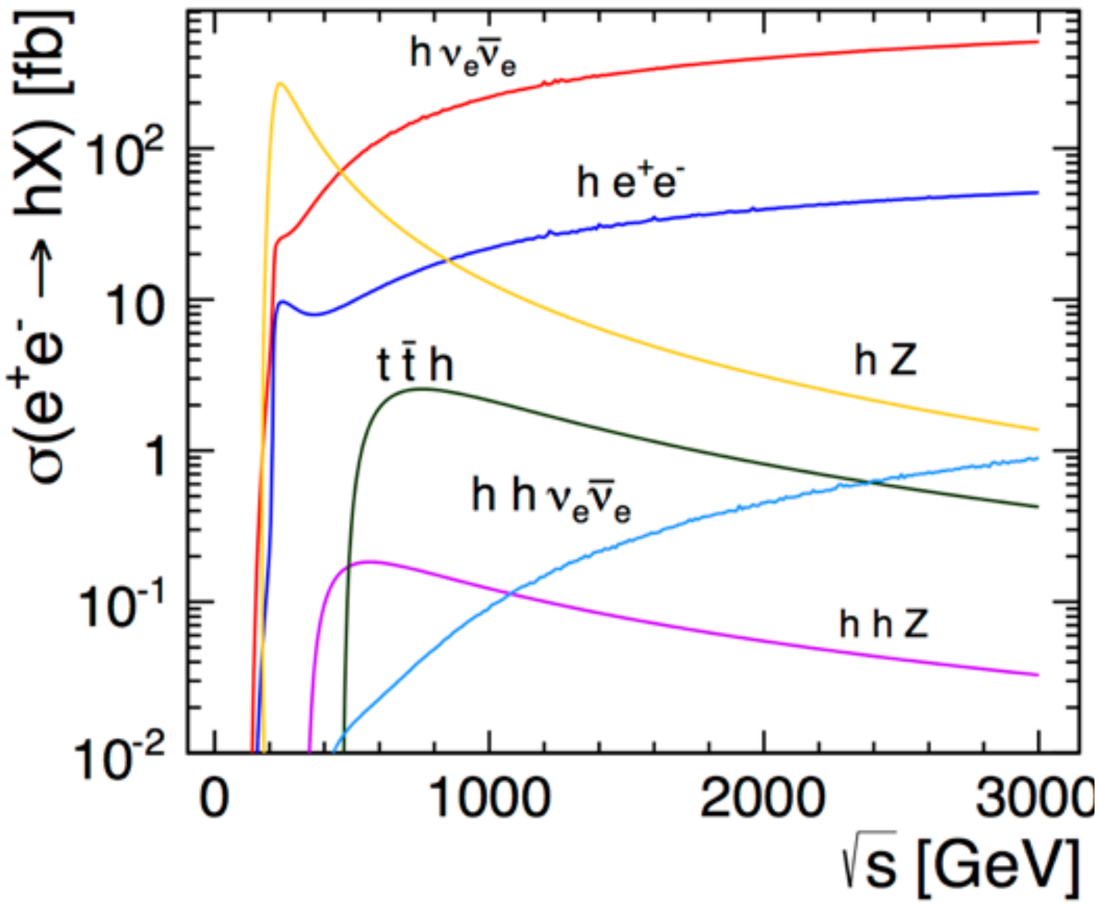




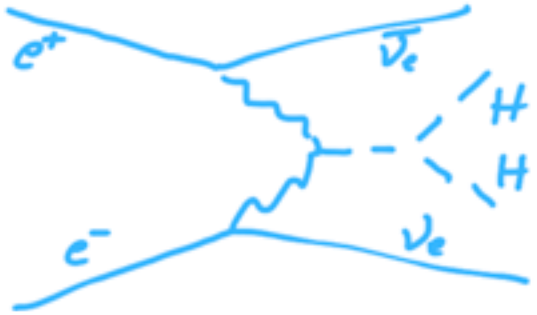
- Energies of 500 GeV and above enable direct access to the top Yukawa coupling via ttH production

- At ILC: 10% measurement with 1 ab^{-1} at 500 GeV, 6.3% in full running scenario (see later)
  - Slight increase of energy helps substantially
  - CLIC @ 1.4 TeV (1.5 ab^{-1}): 4.1% precision

Higgs Self Coupling



- Two processes for double Higgs production provide sensitivity to self coupling - in different energy regimes



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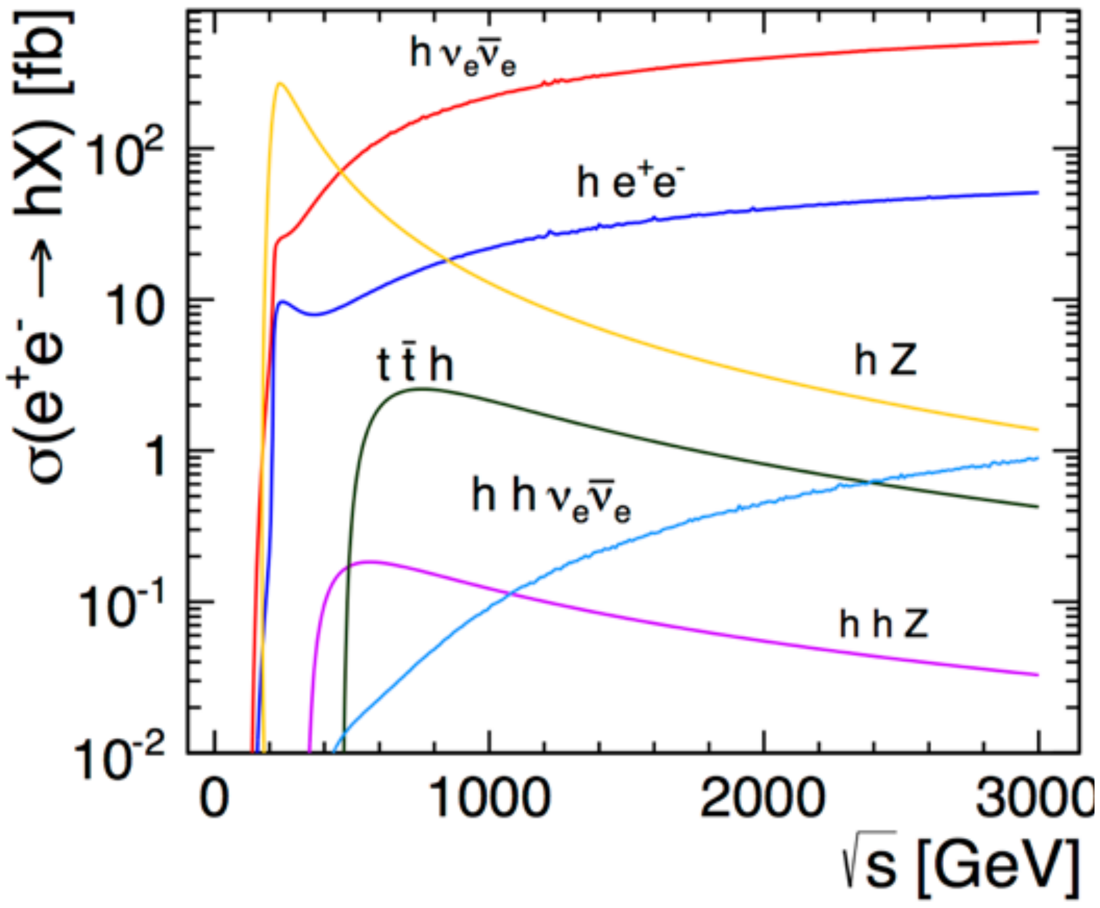

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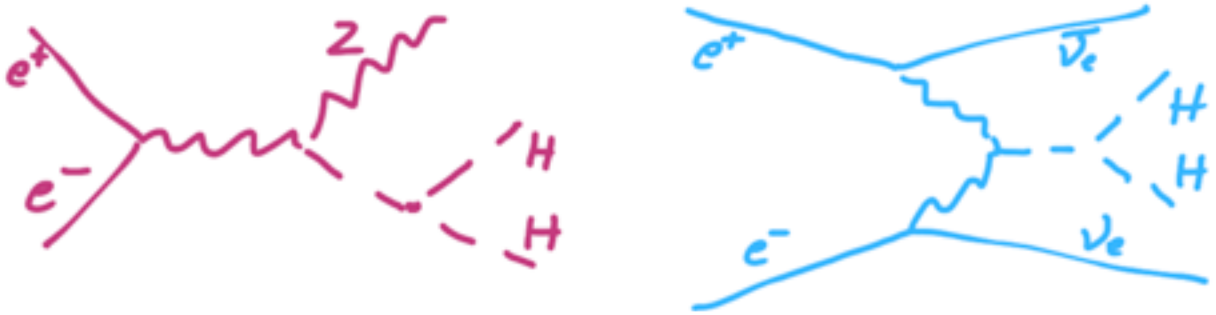
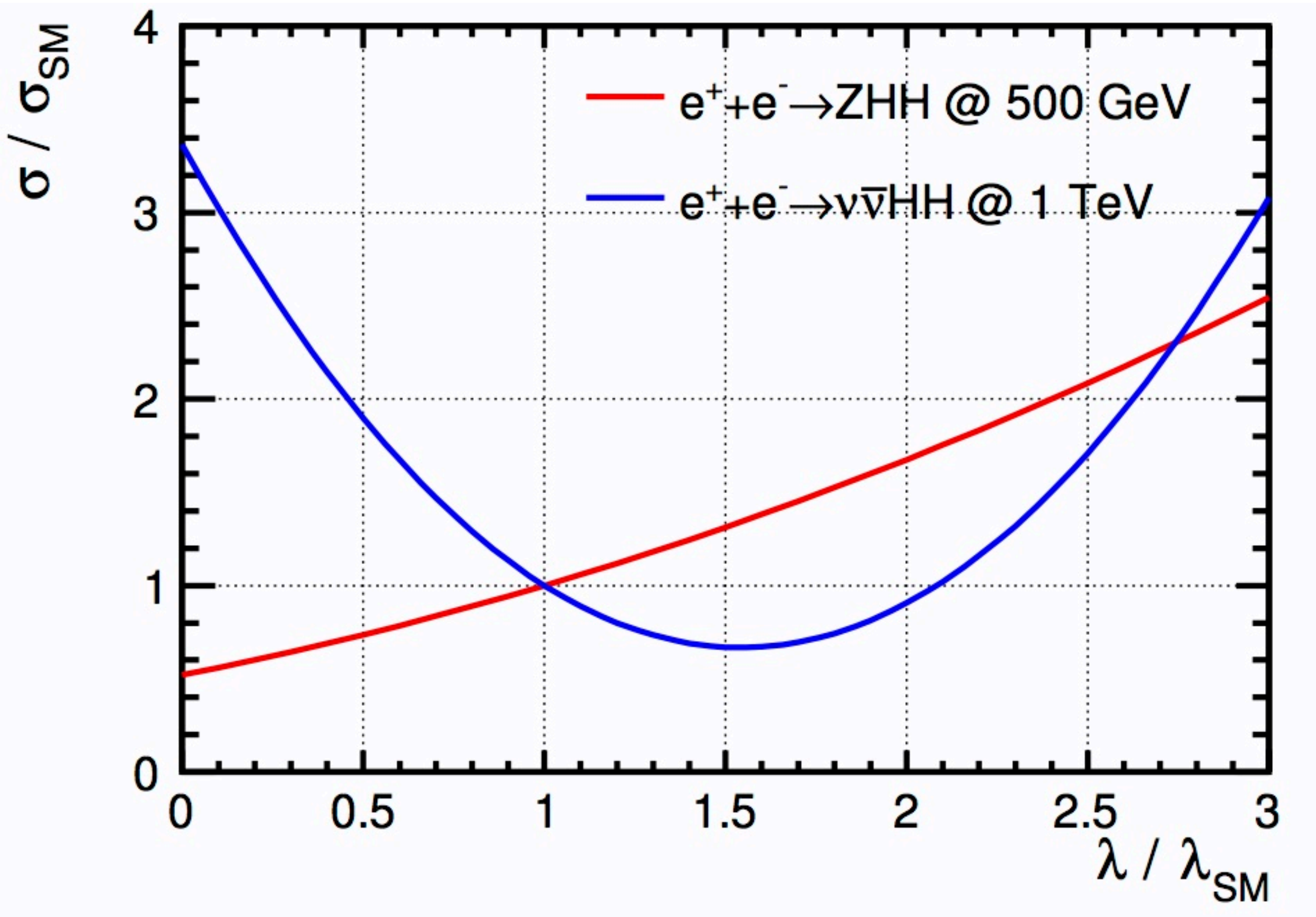


- Connection between cross section and self-coupling non-trivial: Depends on production process, energy and value of λ



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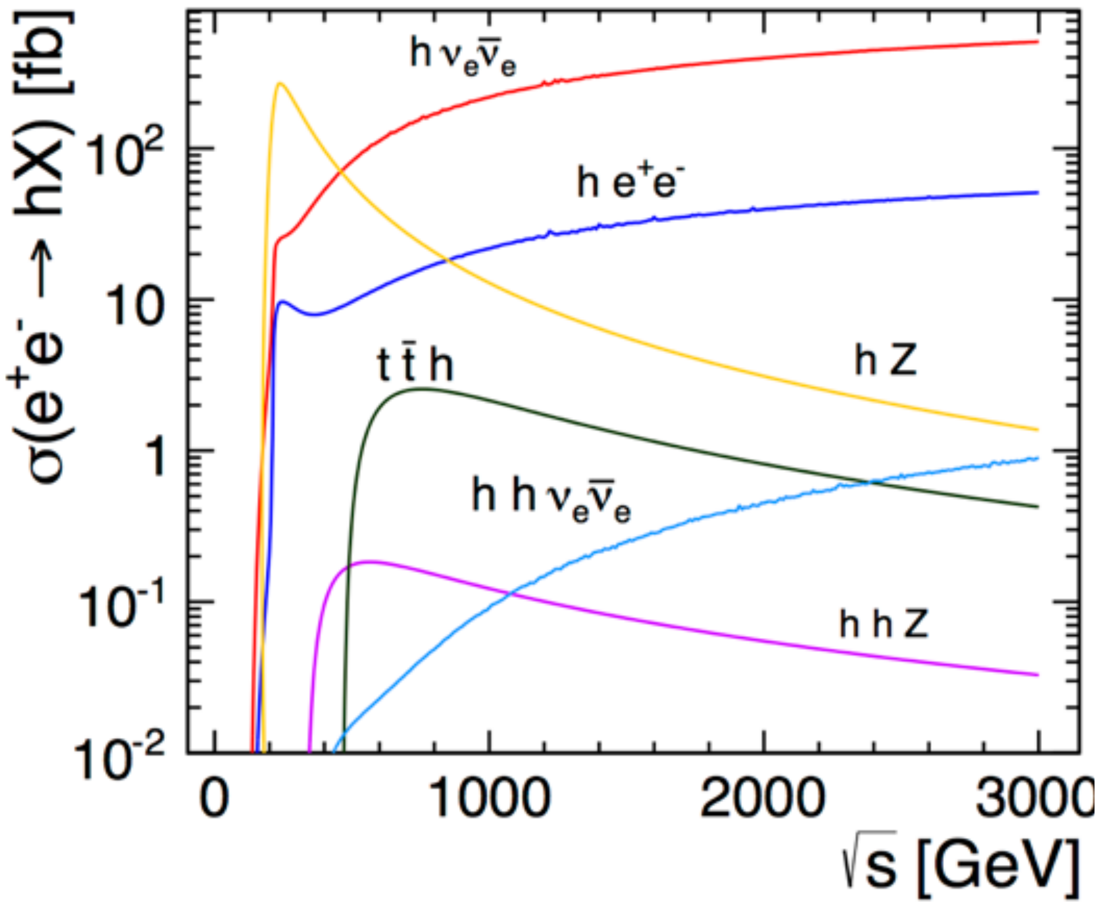

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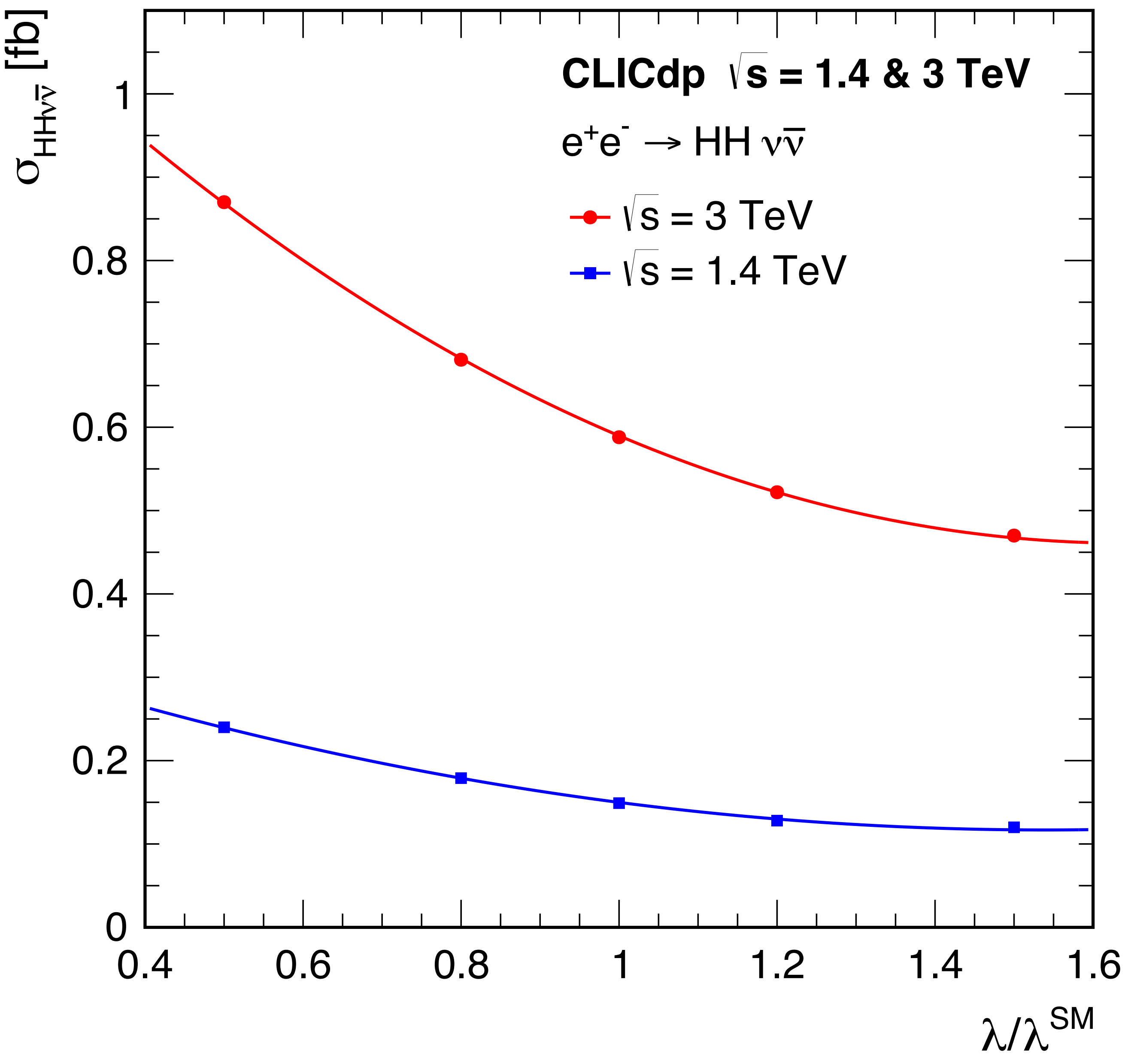

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  - 500 GeV $\kappa_{SM} = 1.64$, 1 TeV $\kappa_{SM} = 0.76$, 1.4 TeV $\kappa_{SM} = 1.22$, 3 TeV $\kappa_{SM} = 1.47$
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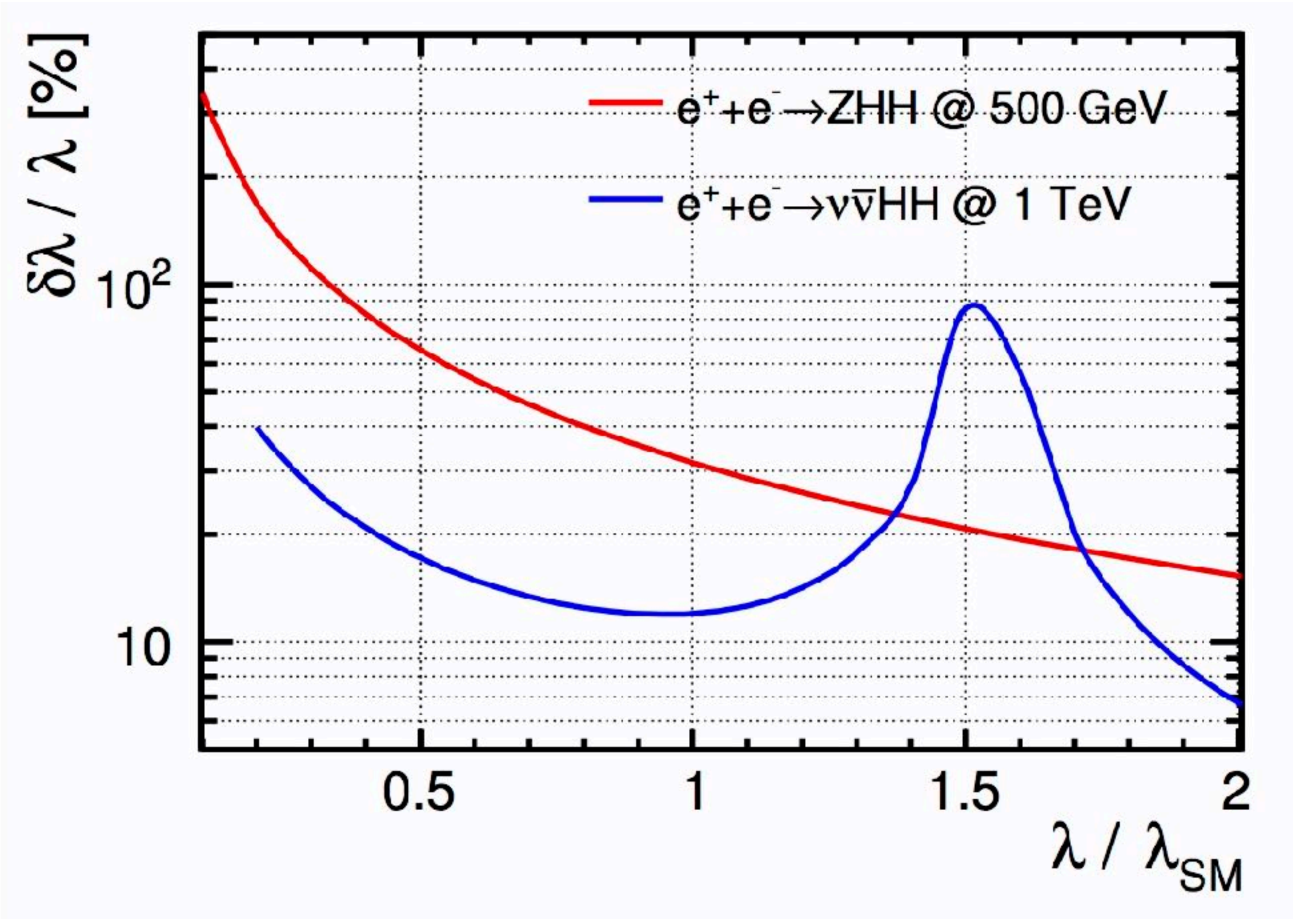
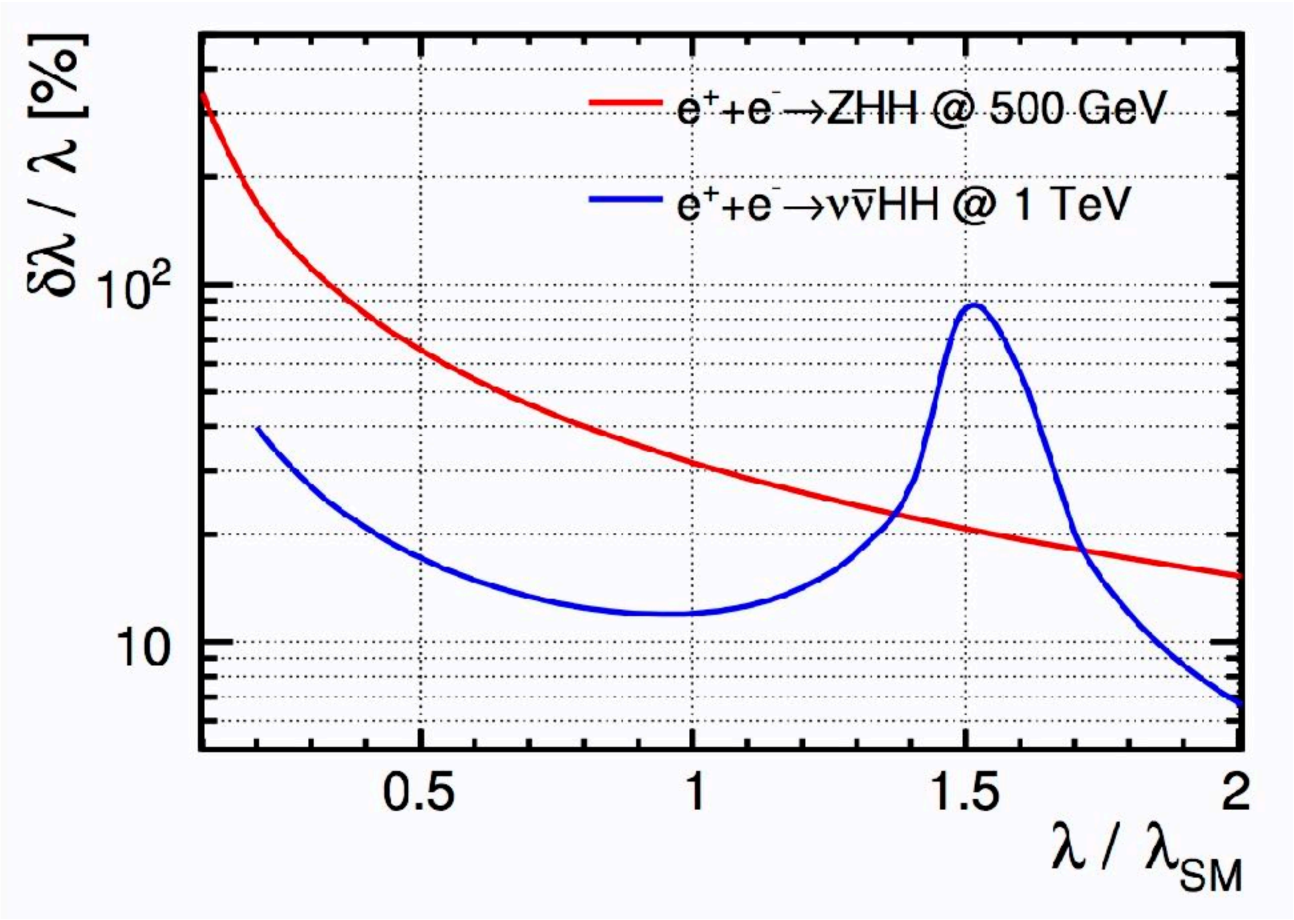


Small cross-section at 500 GeV makes measurement challenging in SM case: ~ 27% for 4 ab^{-1} - Interesting in BSM scenarios with substantially larger λ

Higgs Self Coupling

- From cross-sections to self coupling: “conversion factor” κ to illustrate sensitivity of changes in cross-section to self coupling assuming $\lambda = \lambda_{SM}$ [$\kappa = 1 / (\delta\sigma/\delta\lambda)$]
  - 500 GeV $\kappa_{SM} = 1.64$, 1 TeV $\kappa_{SM} = 0.76$, 1.4 TeV $\kappa_{SM} = 1.22$, 3 TeV $\kappa_{SM} = 1.47$
- NB: For a specific value of λ, sensitivity can essentially disappear: for $\lambda \sim 1.5\ \lambda_{SM}$ $\kappa \rightarrow \infty$ at 1 TeV, similar at higher energies



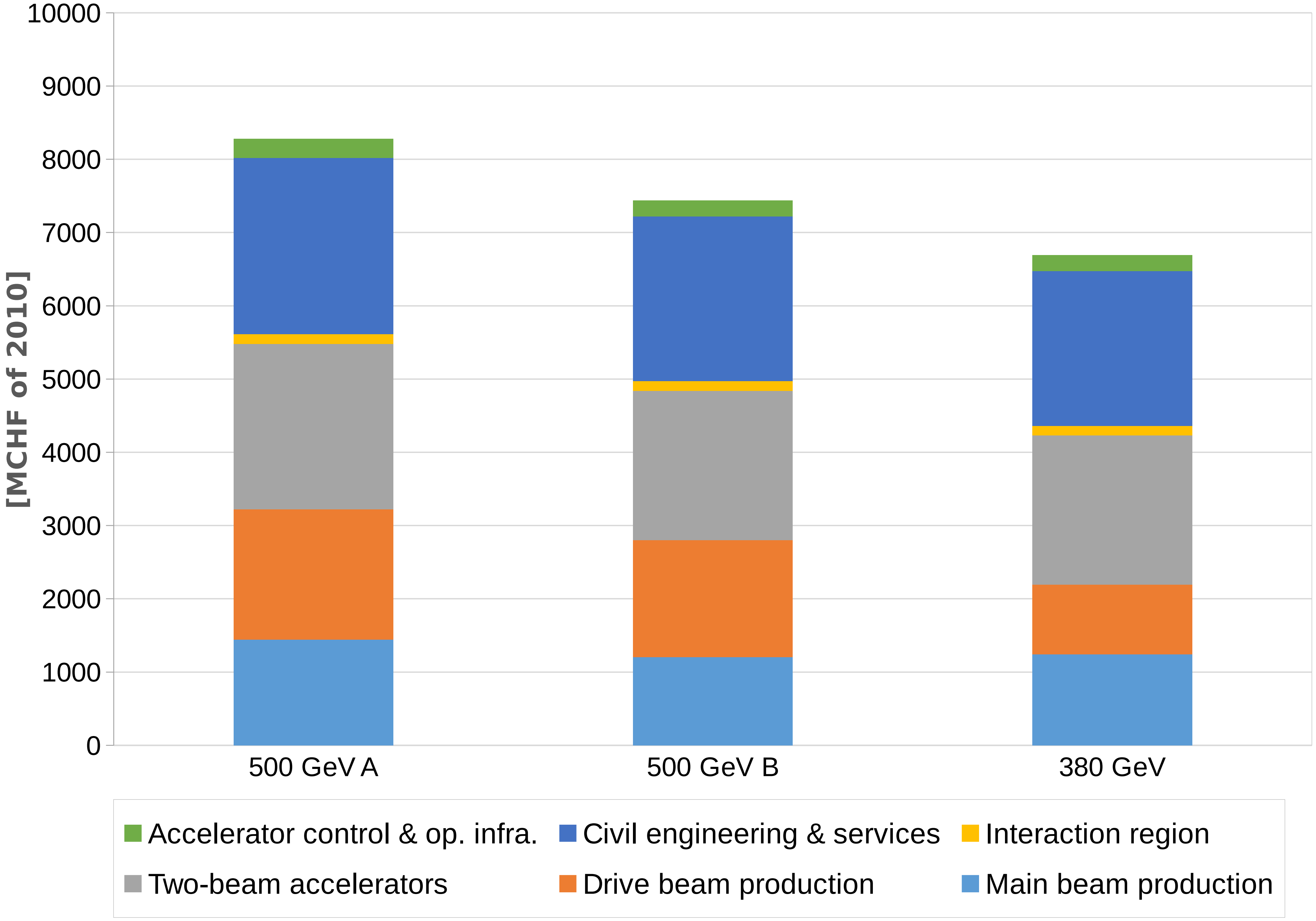
Small cross-section at 500 GeV makes measurement challenging in SM case: ~ 27% for 4 ab^{-1} - Interesting in BSM scenarios with substantially larger λ

Sweet spot at 1 TeV for λ_{SM}: ~ 10 % for 2.5 ab^{-1}

At CLIC: ~ 11% measurement in full program, extracted in analysis directly fitting λ (accounts for possible process bias introduced by event selection)

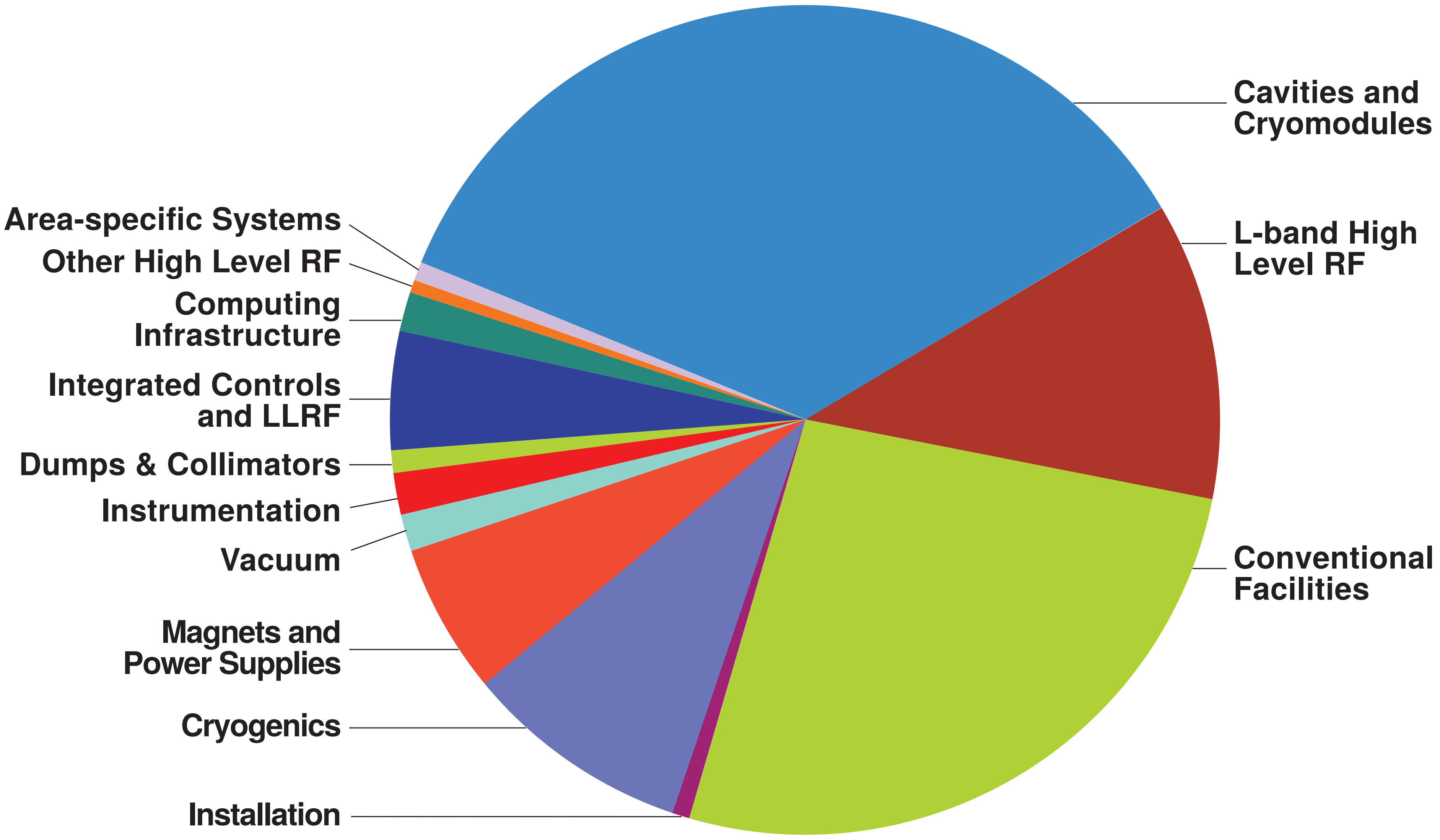
A Word On Cost: CLIC

- Thorough cost analysis for first stage done - CDR, and update for new energy of 380 GeV



ILC Cost

- Value estimate of TDR design (very thorough analysis!): 7.8 billion ILCU (2012 USD)
- + explicit labor estimate of 22.6 million person-hours (14 000 FTE - years)



Collider Parameters: CLIC

Parameter	**Symbol**	**Unit**	**Stage 1**	**Stage 2**	**Stage 3**
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	920/20	660/20	660/20
Normalised emittance (at IP)	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

Collider Parameters: ILC (TDR Parameters)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_{b}		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_{b}	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_{a}	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_{z}	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_{-}	%	80	80	80	80	80	80	80
Positron polarisation	P_{+}	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_{\mathrm{x}}$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β^*_{x}	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β^*_{y}	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ^*_{x}	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ^*_{y}	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0