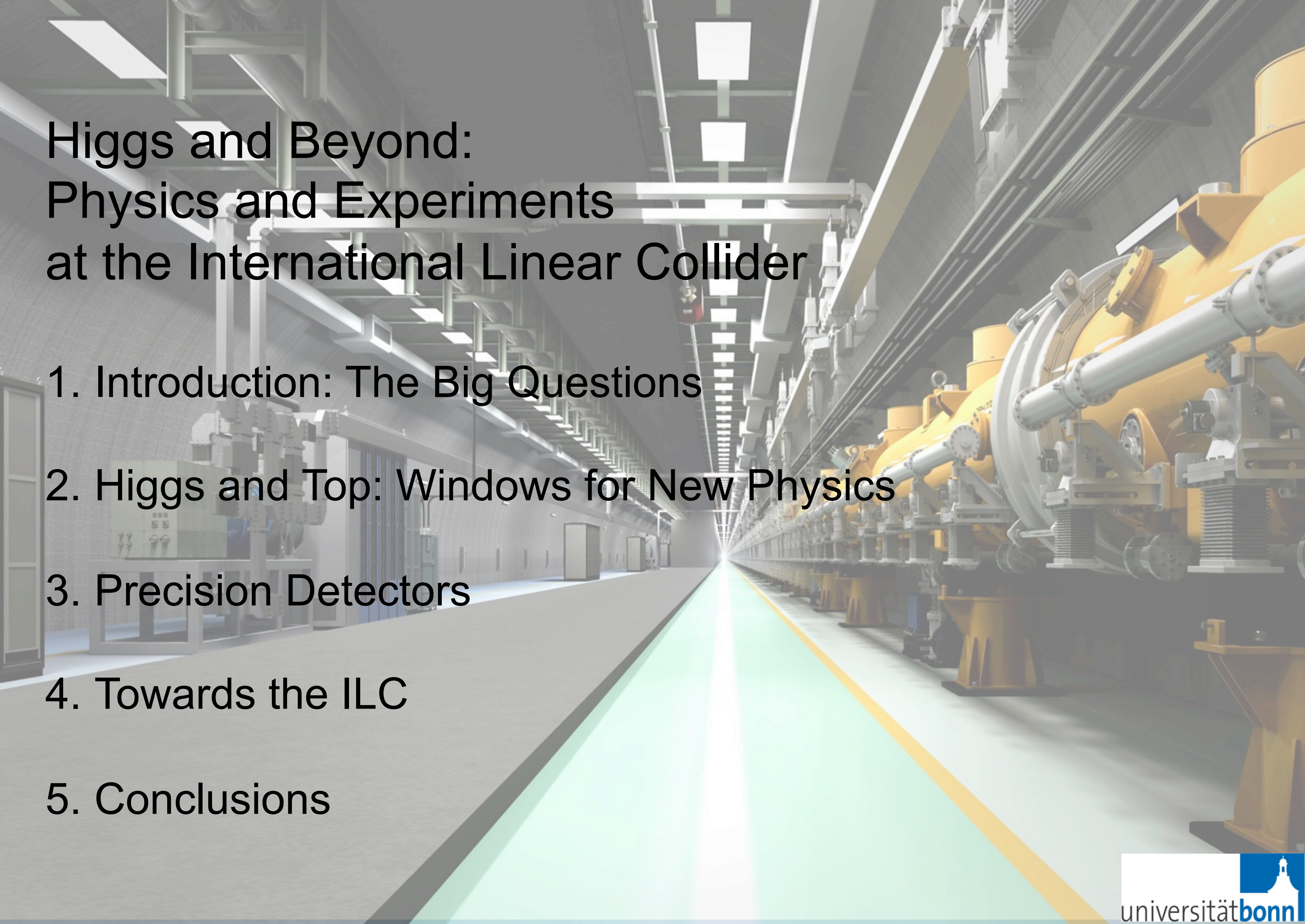


Higgs and Beyond: Physics and Experiments at the International Linear Collider

1. Introduction: The Big Questions

2. Higgs and Top: Windows for New Physics

3. Precision Detectors

4. Towards the ILC

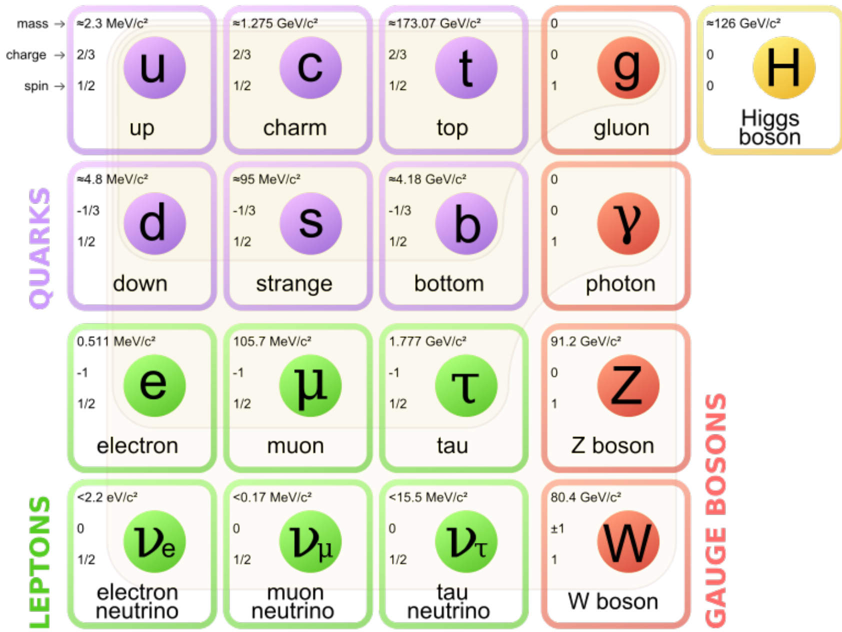
5. Conclusions

universitätbonn

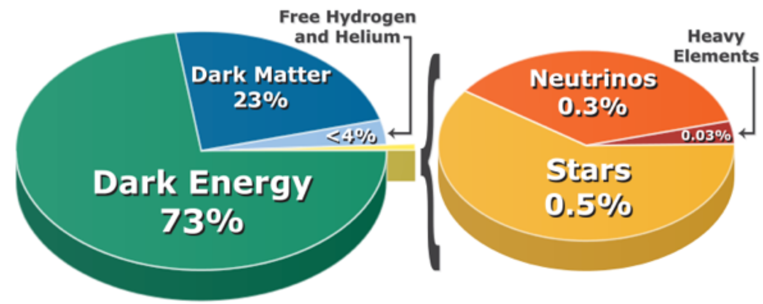
Fundamental Physics in 2015

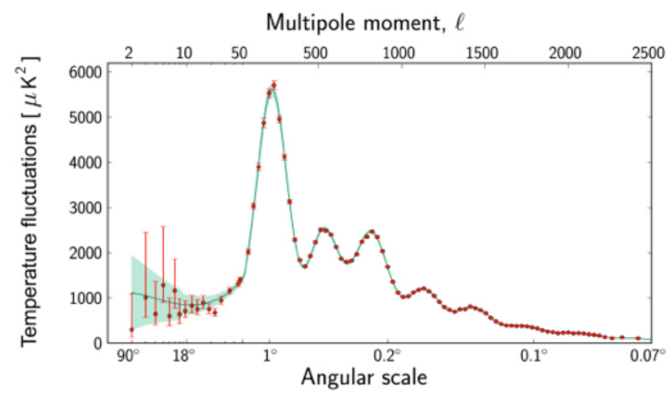
Triumph of the two Standard Models

Standard Model of Particle Physics



Standard Model of Cosmology





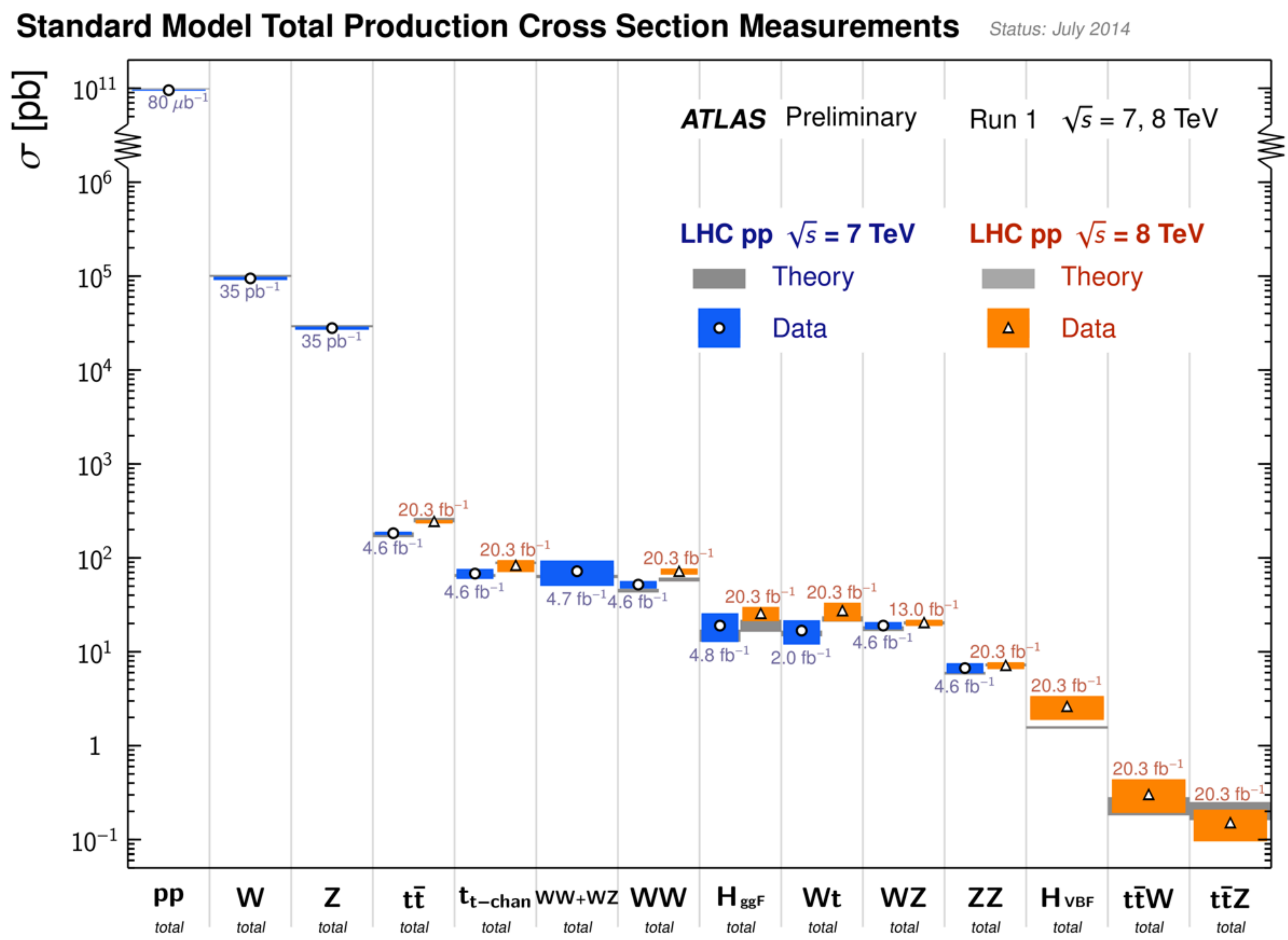
⇔

cross talk

Latest triumph:
A Higgs boson!

Lately re-confirmed by Planck

SM at work!


Standard Model Total Production Cross Section Measurements
Status: July 2014
σ [pb]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Data
LHC pp √s = 8 TeV
Theory
Data
80 μb⁻¹
35 pb⁻¹
35 pb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.7 fb⁻¹
4.8 fb⁻¹
2.0 fb⁻¹
13.0 fb⁻¹
pp total
W total
Z total
tt̄ total
t t−chan total
WW+WZ total
WW total
H ggF total
Wt total
WZ total
ZZ total
H VBF total
tt̄W total
tt̄Z total

Are we done?

Beautiful – but incomplete

(Experimental findings)

- What is the dark matter made of?
- What is dark energy?
- What produced the Baryon asymmetry?
- What makes neutrinos (a bit) massive?
- ...

(Theoretical nuisance)

- What is stabilizing the Higgs mass?
- Is there a unification of forces?
- How can we describe quantum gravity?
- ...

Multiple approaches

My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

M. Mangano (2014)

→ need multiple approaches

- energy frontier (hadron colliders)
- precision at high energy (e^+e^- colliders)
- precision at low energy (e.g. rare B decays, LFV, ...)
- astroparticle physics, lab-based experiments, „crazy" ideas...

Top and Higgs: heavy stuff

The two latest and heaviest additions to the set of fundamental particles

$$v = \left(\sqrt{2}G_F\right)^{-1/2} = 246 \text{ GeV}$$

$$\mathrm{m}_{top} \approx v/\sqrt{2} \qquad (<1\%) \qquad y_t \approx 1$$

$$m_H \approx v/2 \qquad (<2\%) \qquad \lambda \approx 1/8$$

by chance?

Study their properties to the best possible experimental precision
... even if we don´t know today what it is good for (in fact we do...)

Exploit them as windows for new physics

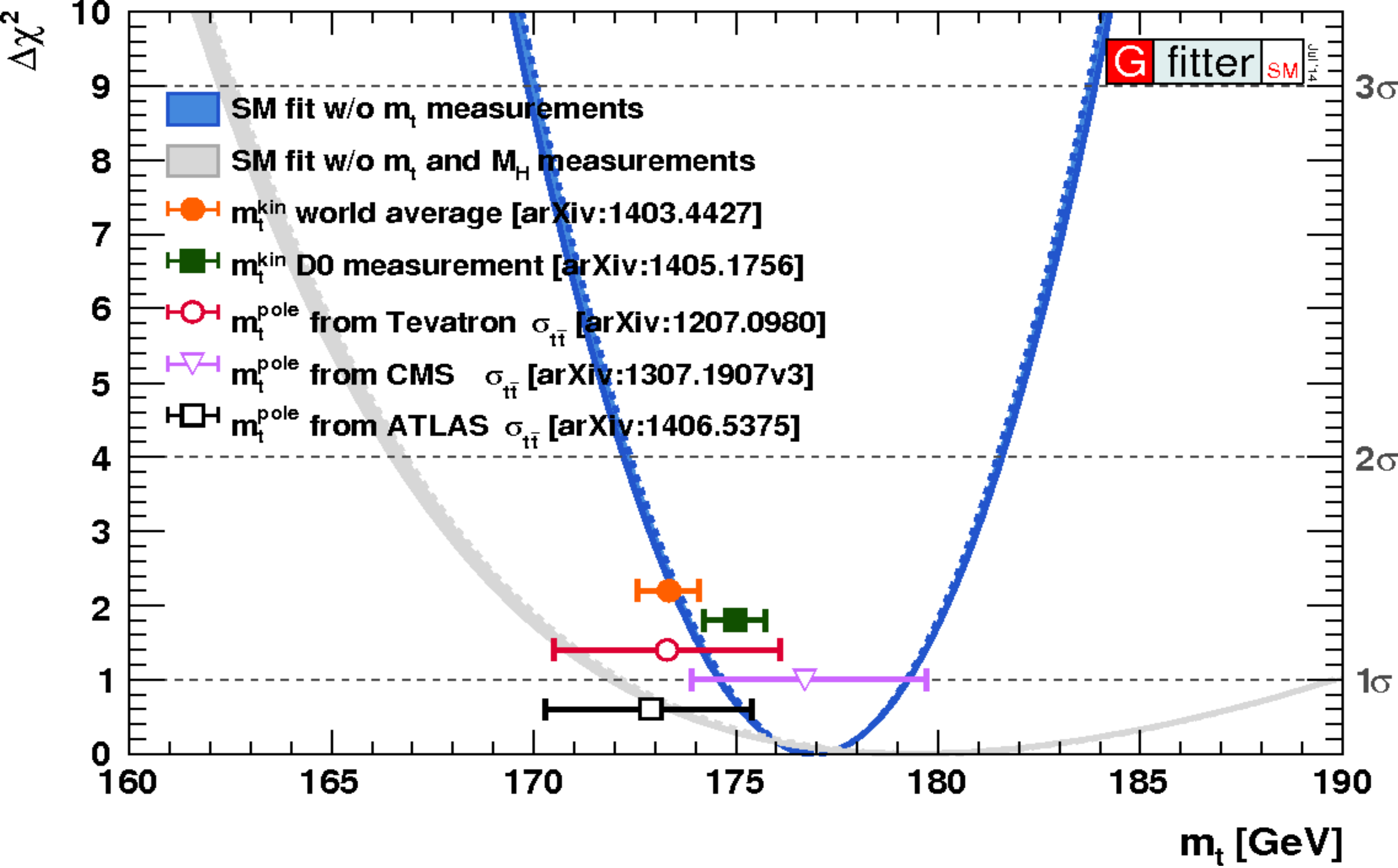
Electron Positron Collisions

Electron positron collisions at high energy provide a powerful tool to explore TeV-scale physics complementary to the LHC

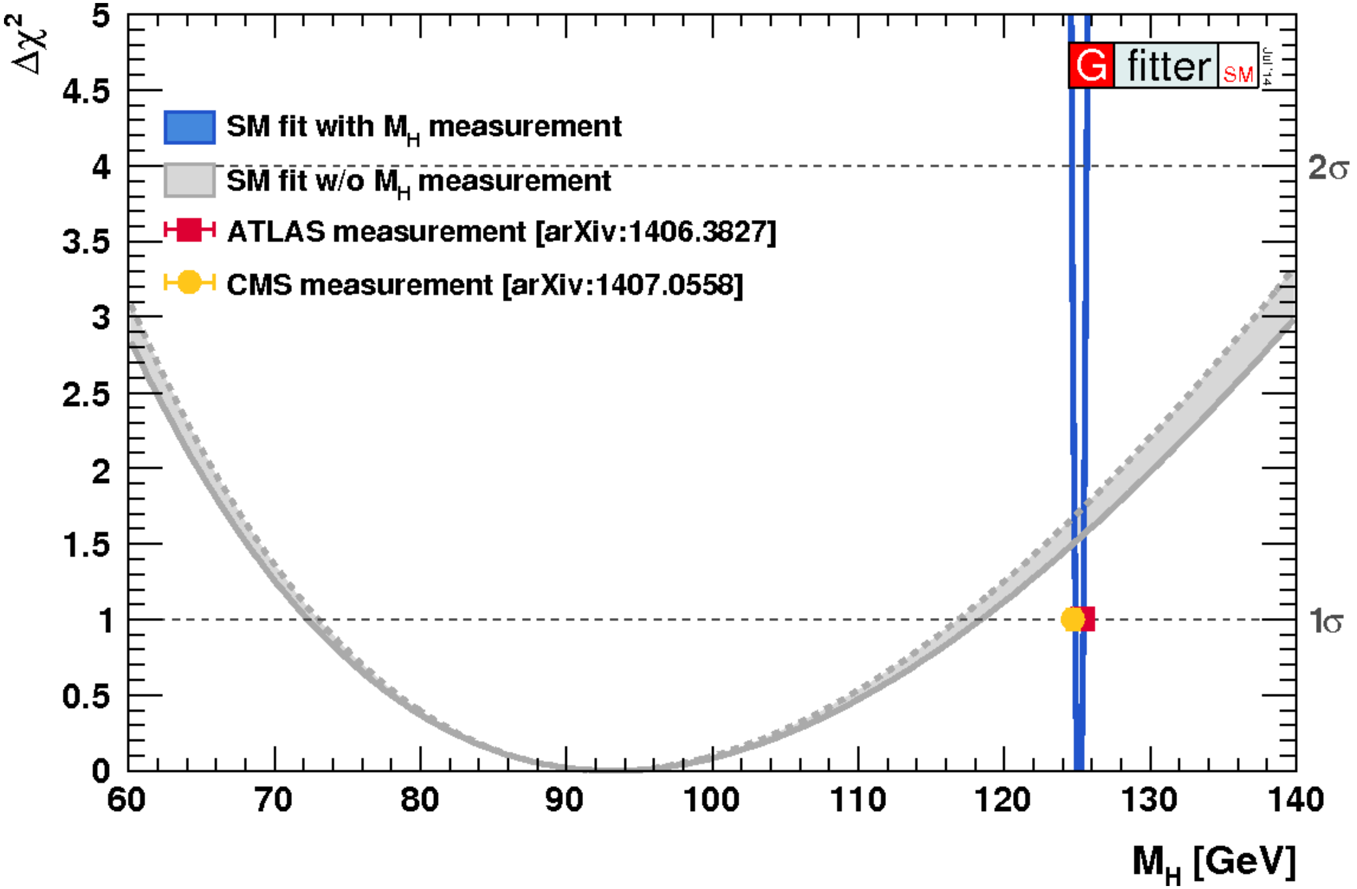
Due to their point-like structure and absence of strong interactions there are clear advantages of e^+e^- collisions:

- known and tunable centre-of-mass energy
- clean, fully reconstructable events
- polarized beams
- moderate backgrounds
  → no trigger
  → high efficiency (higher “effective” luminosity)

e^+e^- History: predicting m_{top}



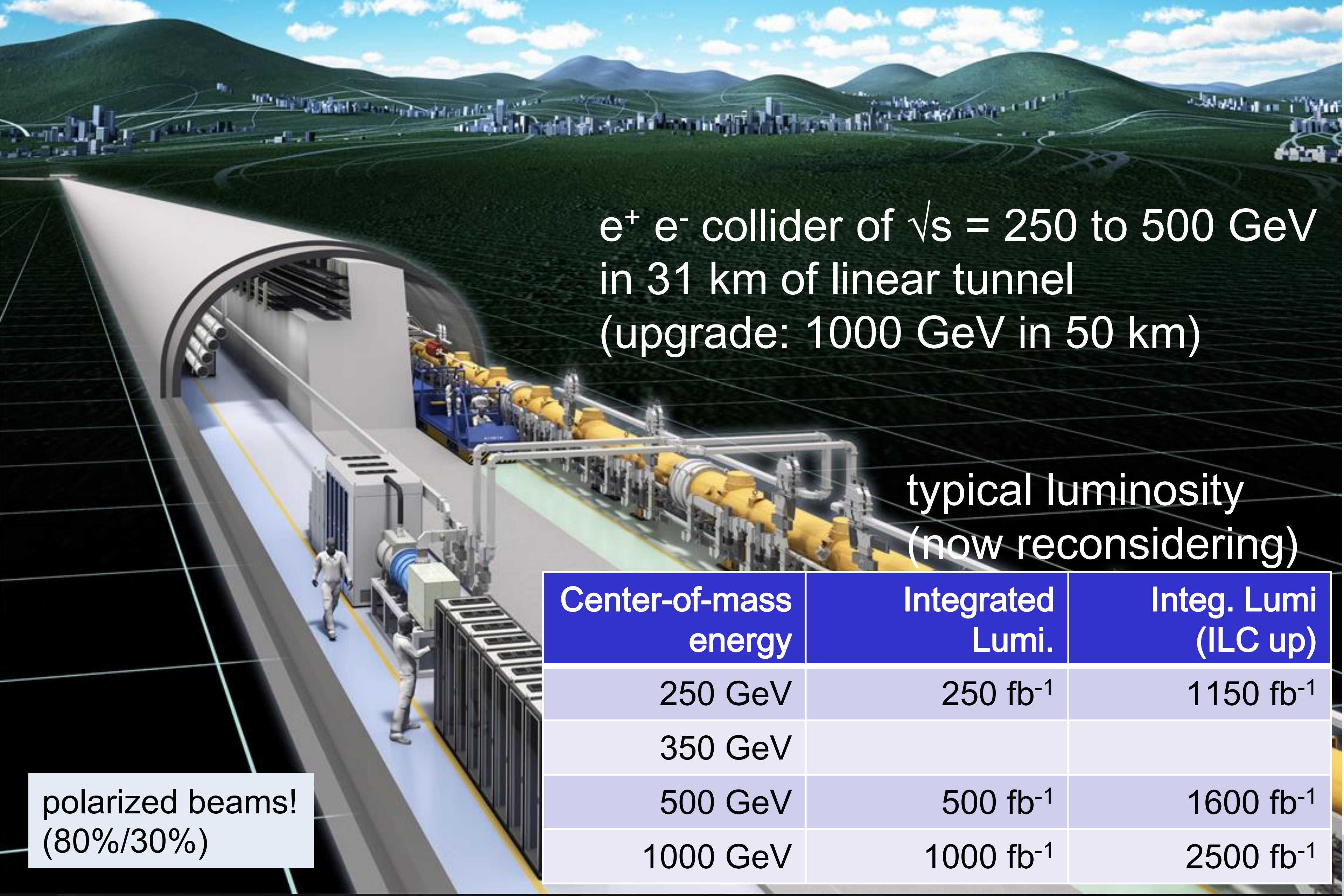
e^+e^- History: predicting m_{Higgs}



Grey band (used to be „blue band") was there before Higgs discovery!
Only possible through interplay of LEP/SLC and Tevatron (mainly m_{top})

Proof-of-principle: sensitivity of e+e- for New Physics in loops

International Linear Collider



$e^+ e^-$ collider of $\sqrt{s}$ = 250 to 500 GeV
in 31 km of linear tunnel
(upgrade: 1000 GeV in 50 km)

typical luminosity
(now reconsidering)

Center-of-mass energy	Integrated Lumi.	Integ. Lumi (ILC up)
250 GeV	250 fb^{-1}	1150 fb^{-1}
350 GeV		
500 GeV	500 fb^{-1}	1600 fb^{-1}
1000 GeV	1000 fb^{-1}	2500 fb^{-1}

polarized beams!
(80%/30%)

ILC History & Status

1980's-2001: Studies and proposals of TESLA, NLC & JLC

2005: Efforts unified to ILC based on the cold technology

2007: ILC Reference Design Report

2009: Letter of Intent of ILC detectors

- First optimization done here

2012: ILC Accelerator TDR & Detector DBD

- Realistic detector report with cost estimation

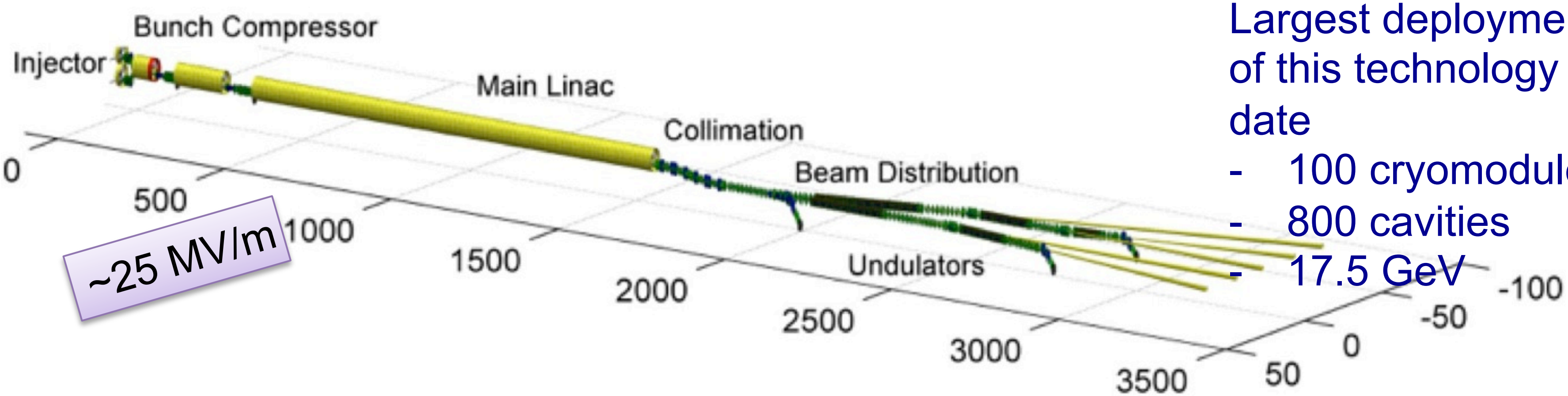
2012: Higgs Discovery

~2013: Interest of Japanese government raised

- Japanese site candidate endorsed to Kitakami (Tohoku)

Physics targets and site/political conditions clearer now
- re-optimization towards "Green sign" expected in a few years!

European XFEL at DESY



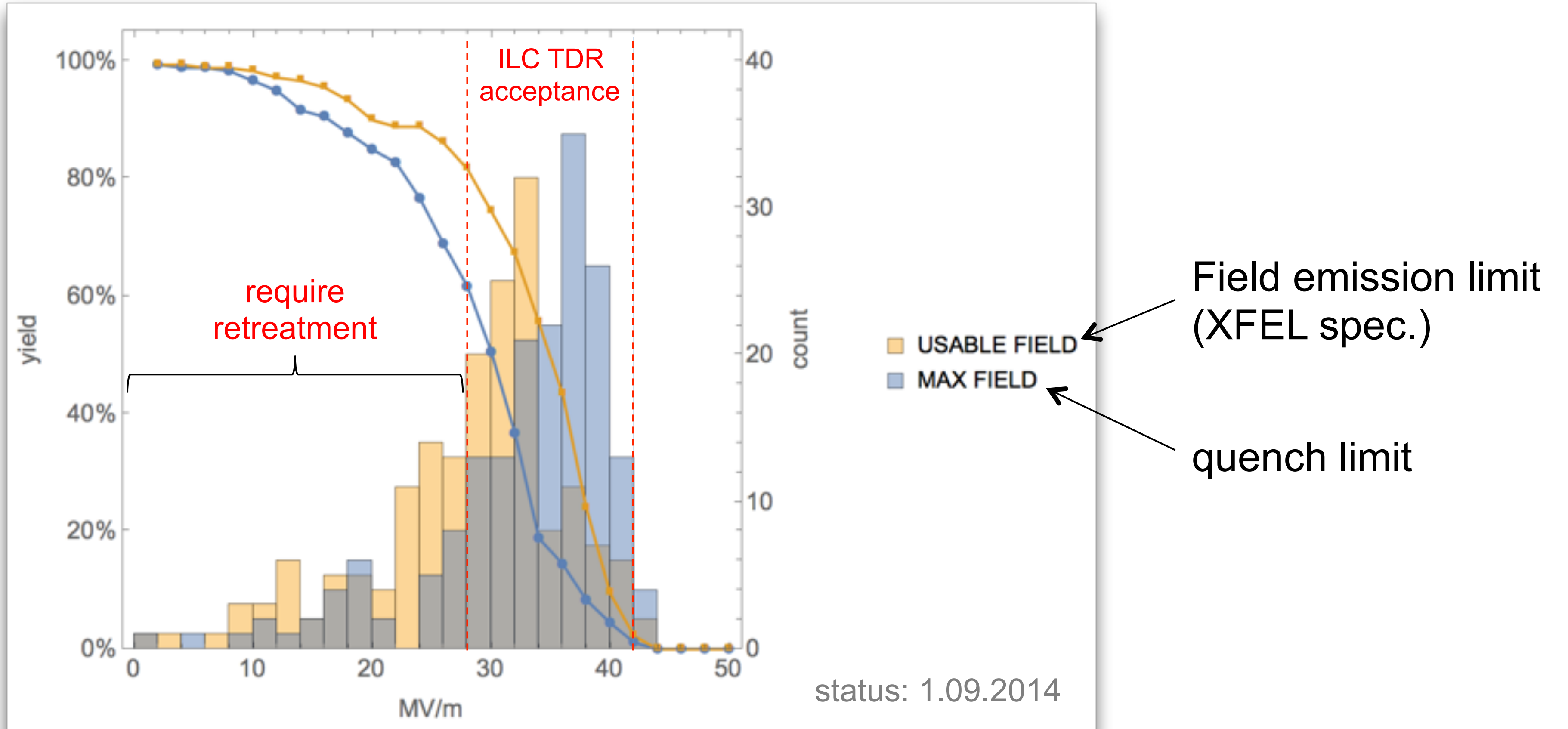
Largest deployment of this technology to date

- 100 cryomodules
- 800 cavities
- 17.5 GeV

The ultimate ‘**integrated systems test**’ for ILC.

XFEL Industrial Cavity Production

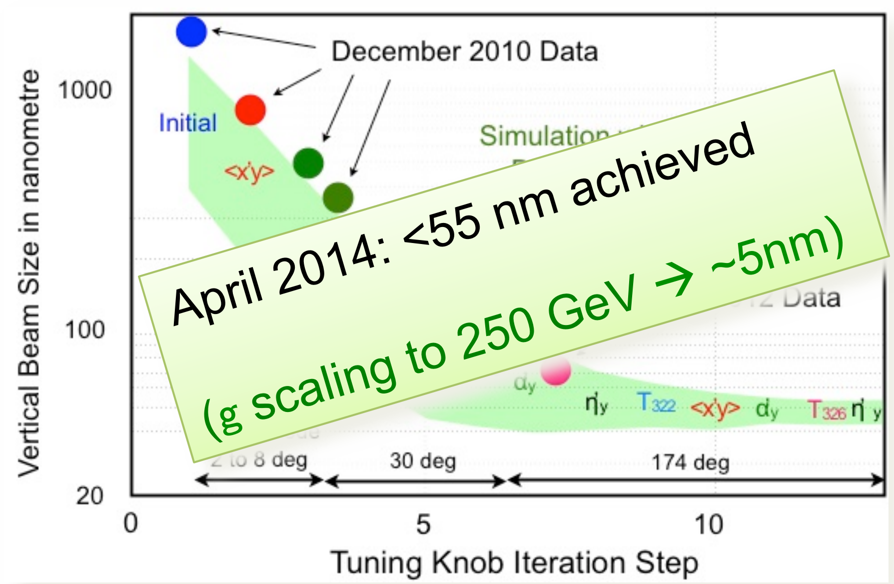
One vendor following ILC baseline recipe (4 per week, final total: 400 cavities)



	Tests	Average	rms	Yield@28	Yield@31.5	Yield@35
Max	148	32.8	7.6	82%	69%	48%
Usable	148	28.6	8.1	63%	41%	18%

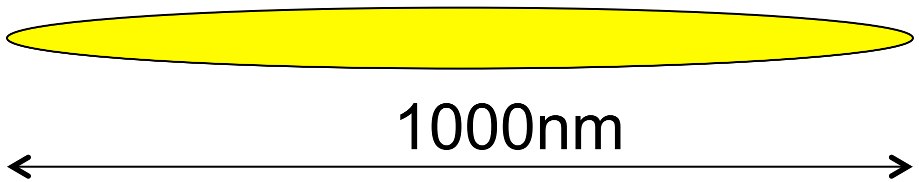
Luminosity needs focussing

- Design: $\mathcal{L}$=1.74·10^{34} cm^{-2}s^{-1} requires:
- Very small beams at interaction RMS size is 500 nm x 6 nm!
- This needs:
  – Beams with extremely low emittance
  – Extremely strong focusing at interaction point

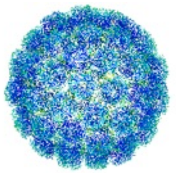


DNA: 2.5 nm

ILC Beam Spot



12nm



Virus: 20nm

1000nm

Higgs: Experimental Questions

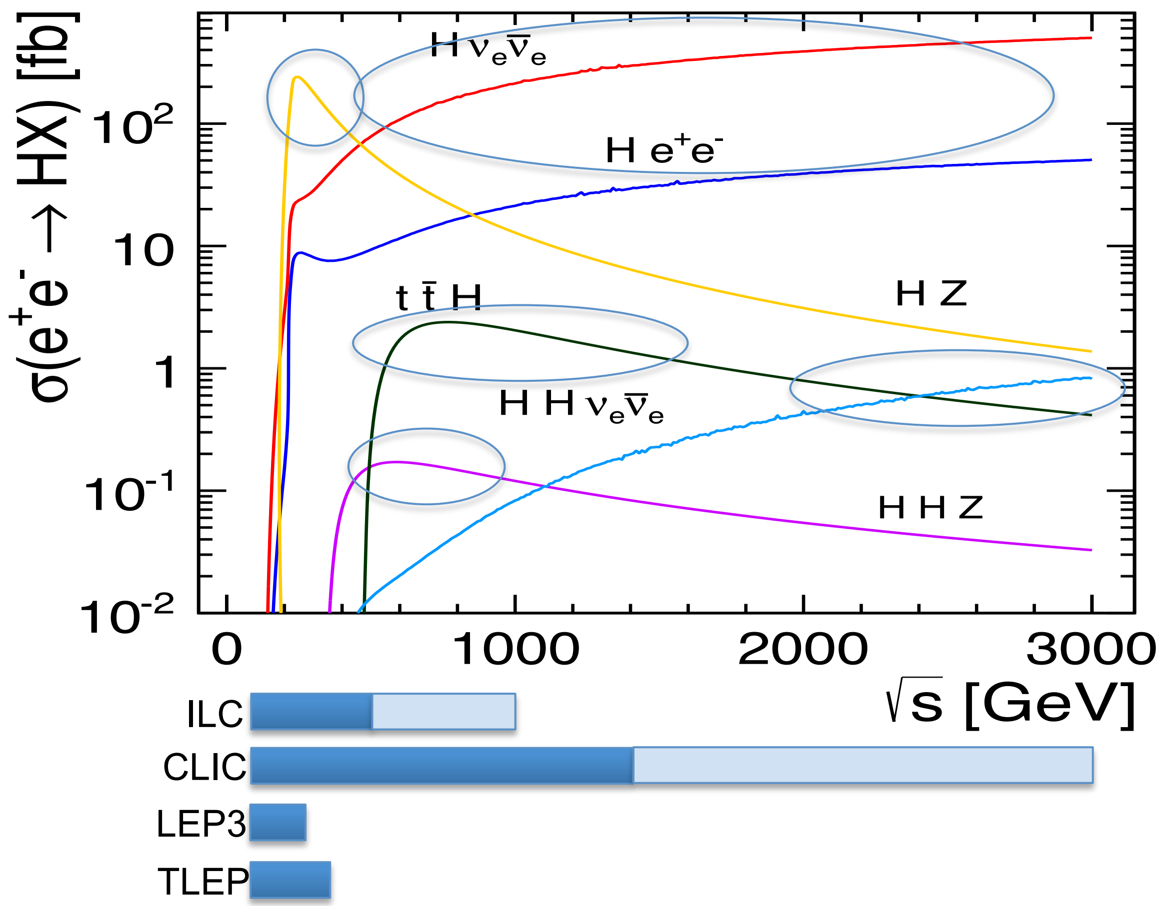
KD´s personal view

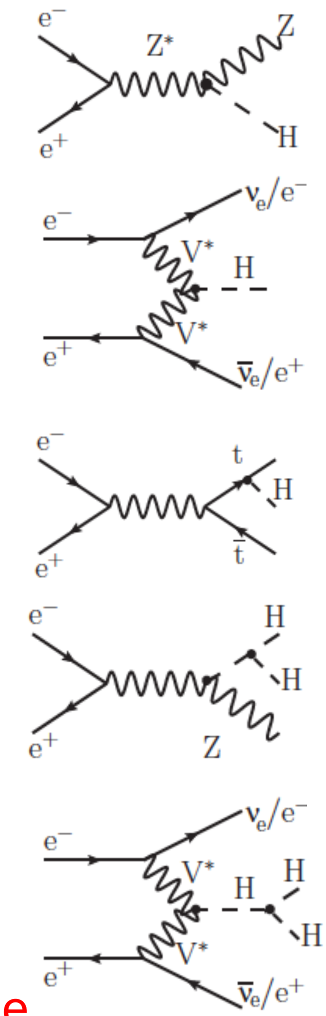
	(HL)LHC	ILC
Mass		
Spin		
CP		
boson couplings		
fermion couplings		
new decays		
self coupling		

legend:

- sufficiently precise for N.P. sensitivity/unambigous
- not precise enough for N.P. sensitivity/model-dependent
- challenging

e^+e^- Higgs processes





Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

Γ_{tot}

g_t (ILC,CLIC)

g_{HHH} (ILC500)

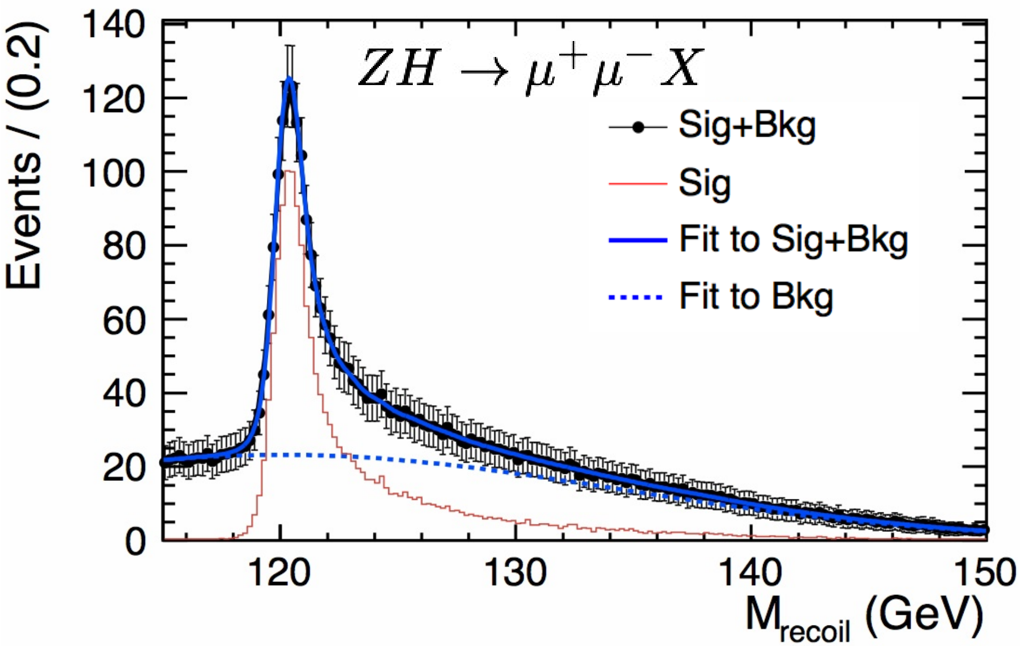
g_{HHH} (ILC1000, CLIC)

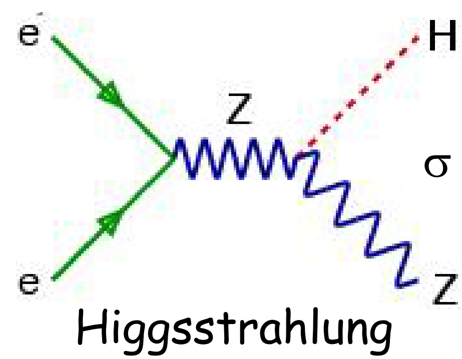
- Many processes at different √s needed & accessible

The LC flagship measurement

LHC: no known (to me) method to extract absolute Higgs BRs

LC: Recoil mass technique in $e^+e^- \rightarrow HZ$ allows us to measure σ_{HZ} indep. of H-decay





$\sigma \propto\sim 1/s$

$$m_H^2 = (p_{\ell\ell} - p_{initial})^2$$

250 fb^{-1}@250 GeV

$\Delta\sigma_{ZH}/\sigma_{ZH} = 2.6\%$

$\Delta m_H = 30$ MeV

1/10 LHC

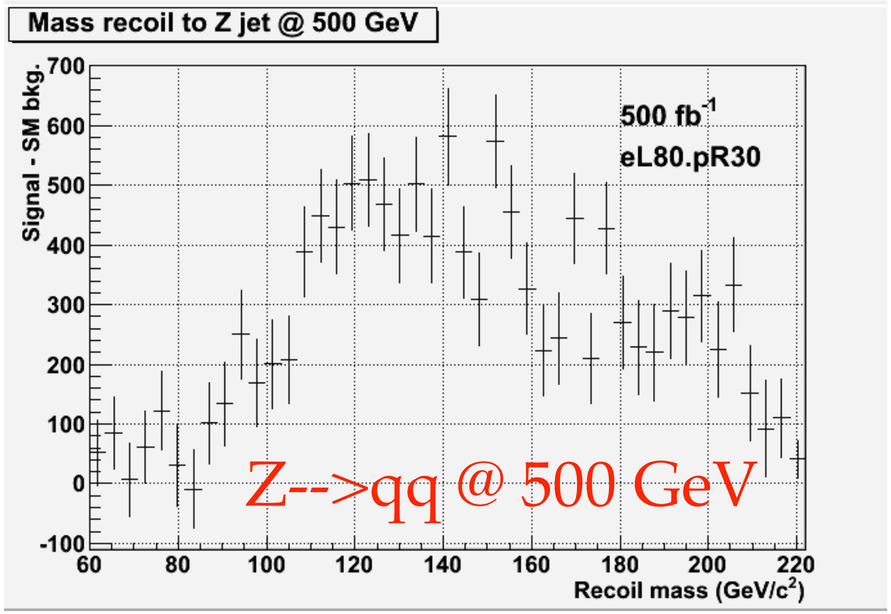
Once σ_{HZ} is known, any signal strength measurement can be turned into absolute BR´s measurement: $BR_X = (\sigma \times BR_X)_{meas} / \sigma(tot)_{meas}$

unique to lepton colliders (needs (E,p) constraint from initial state)

[Li, Poeschl]

HZ recoil from Z→qq (new!)

Very preliminary:
Extend the recoil mass technique also to Higgs recoiling against Z→qq
Advantage: large BR(Z→hadrons)
Challenge: unbiased selection of jets from Z (→ jet reconstruction,later)

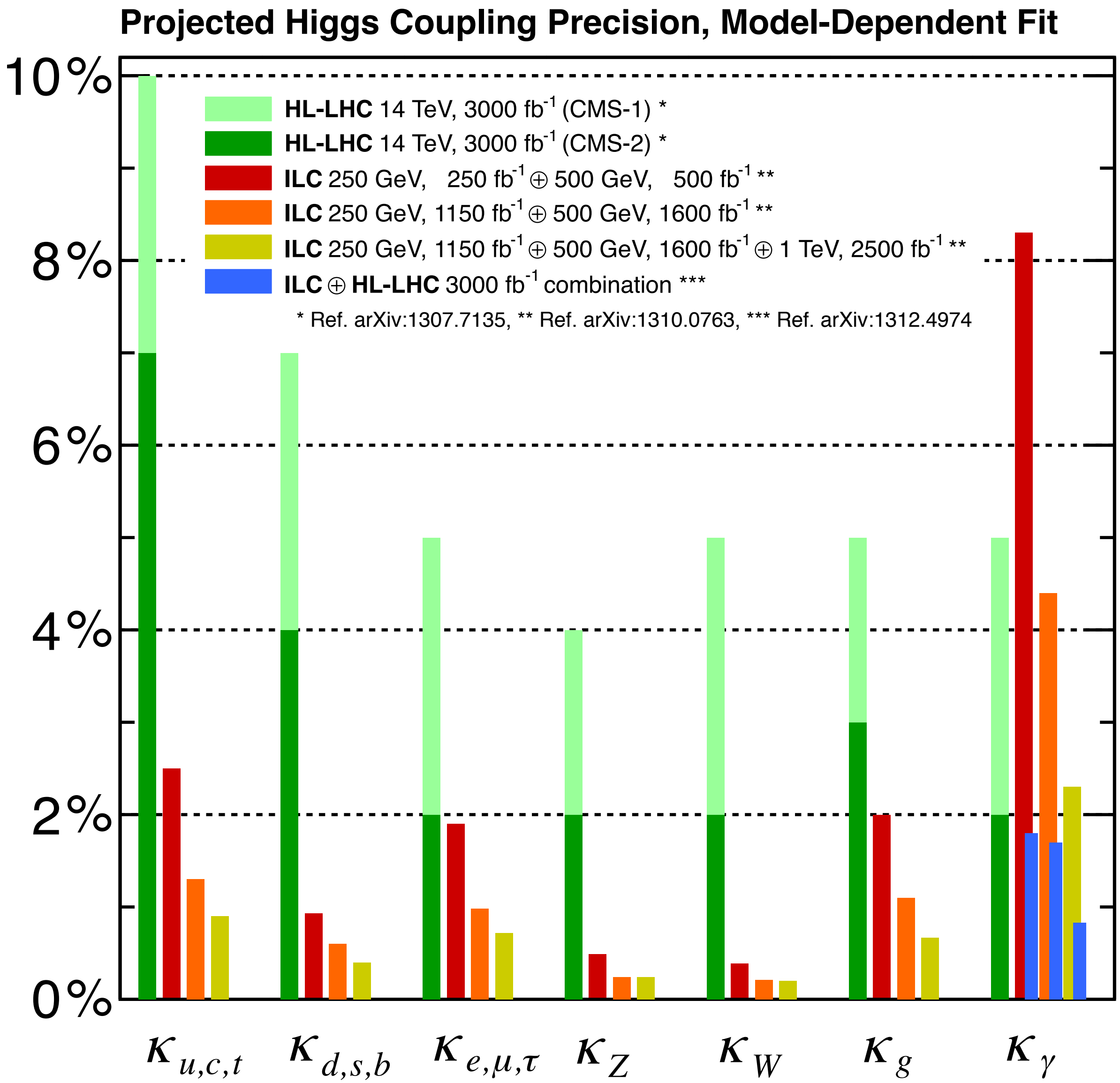


(signal only)

mode	before	after
H->all (100%)	216,195 (41.2%)	53.0%
H->bb̄ (55.6%)	128,085 (44.0%)	51.1%
H->WW (l) (2.4%)	1,331 (10.7%)	58.2%
H->WW (sl) (10.0%)	13,588 (25.8%)	61.0%
H->WW (h) (10.5%)	16,471 (29.9%)	41.3%
H->gg (9.0%)	24,154 (51.0%)	52.8%
H->$\tau\tau$ (6.7%)	18,354 (52.3%)	69.6%
H->ZZ (3.0%)	5,696 (36.4%)	54.0%
H->cc̄ (2.6%)	7,503 (54.2%)	54.0%
H->$\gamma\gamma$ (0.4%)	1,135 (56.9%)	54.8%

[Watanuki et al.], Tomita – also Thompson, Barklow

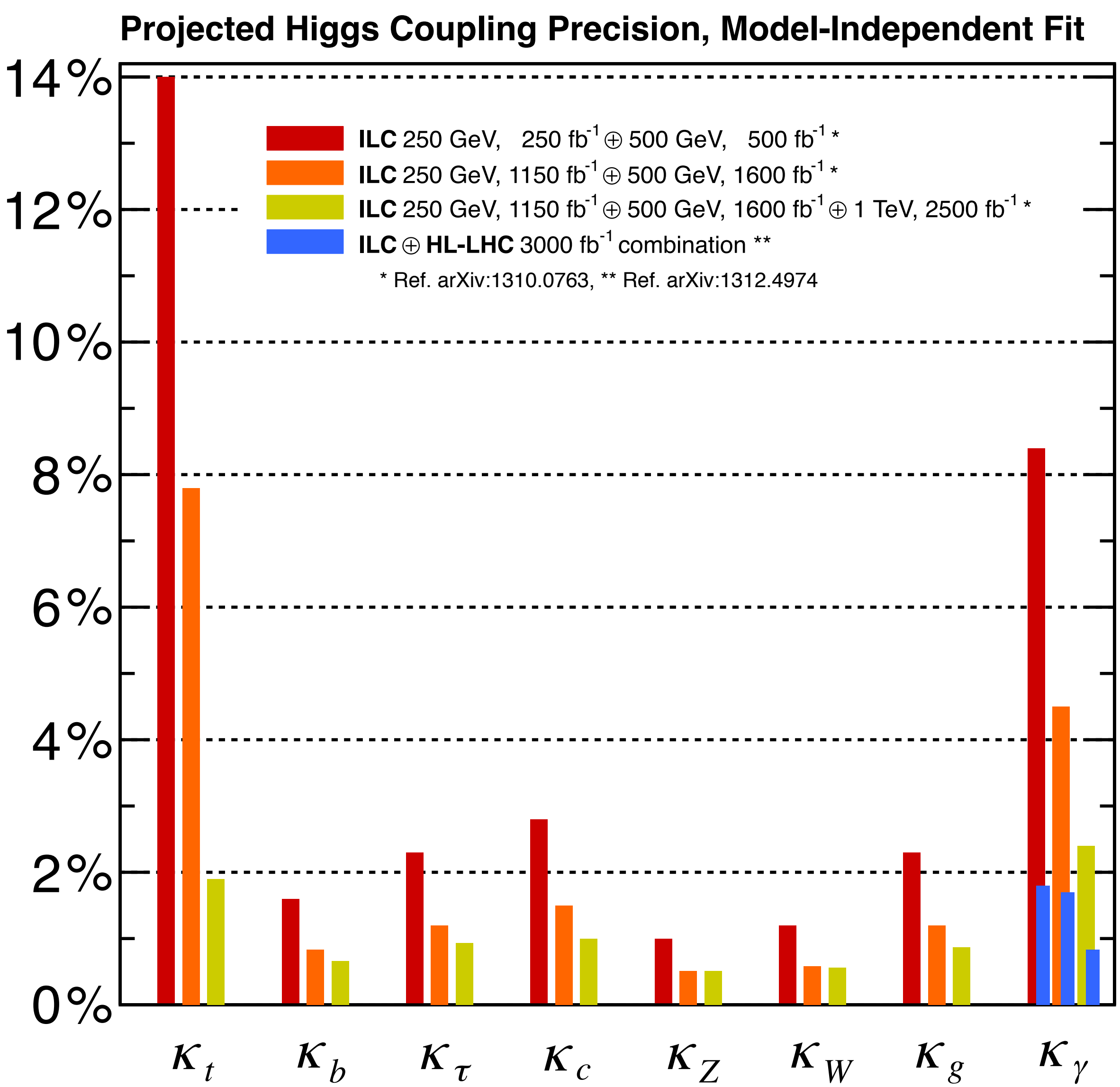
LHC vs LC: model-dep. couplings (κ)



typically one order-of-magnitude improvement w.r.t. HL-LHC

[LCC Physics Group]

ILC: model-independent couplings



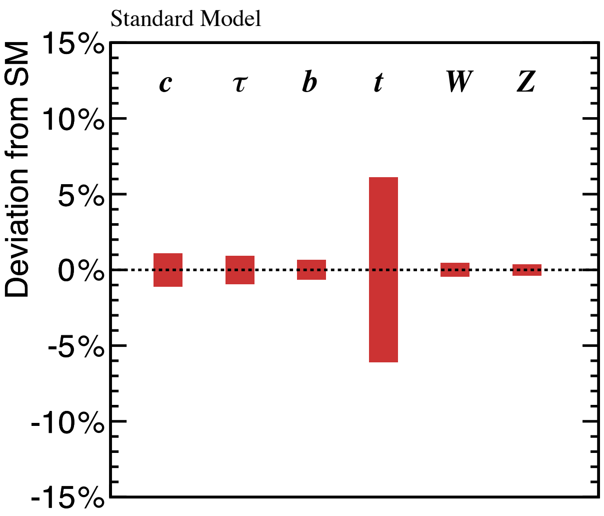
this cannot be done at LHC

At ILC:
only possible due to
a) recoil method g_{HZ}
and
b) total width measurement

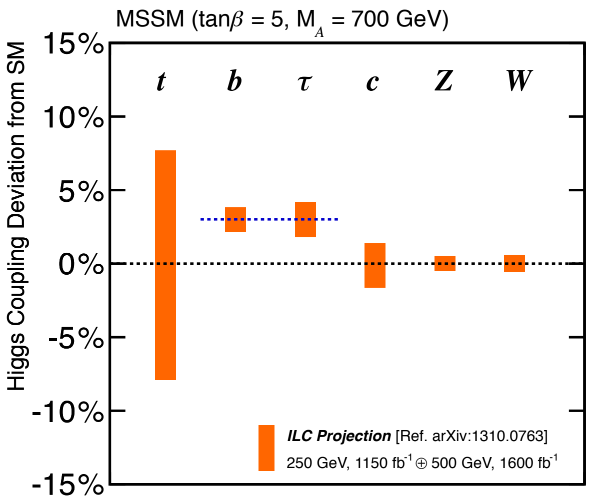
[LCC Physics Group]

Impact of BSM on Higgs Sector

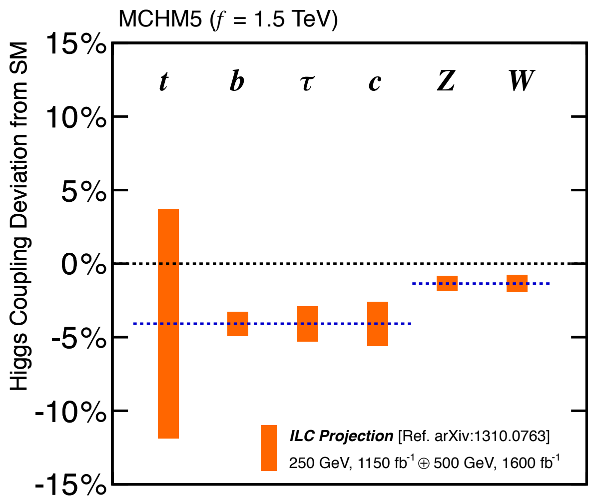
Standard Model



Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



[LCC Physics Group]

Composite Higgs: Reach

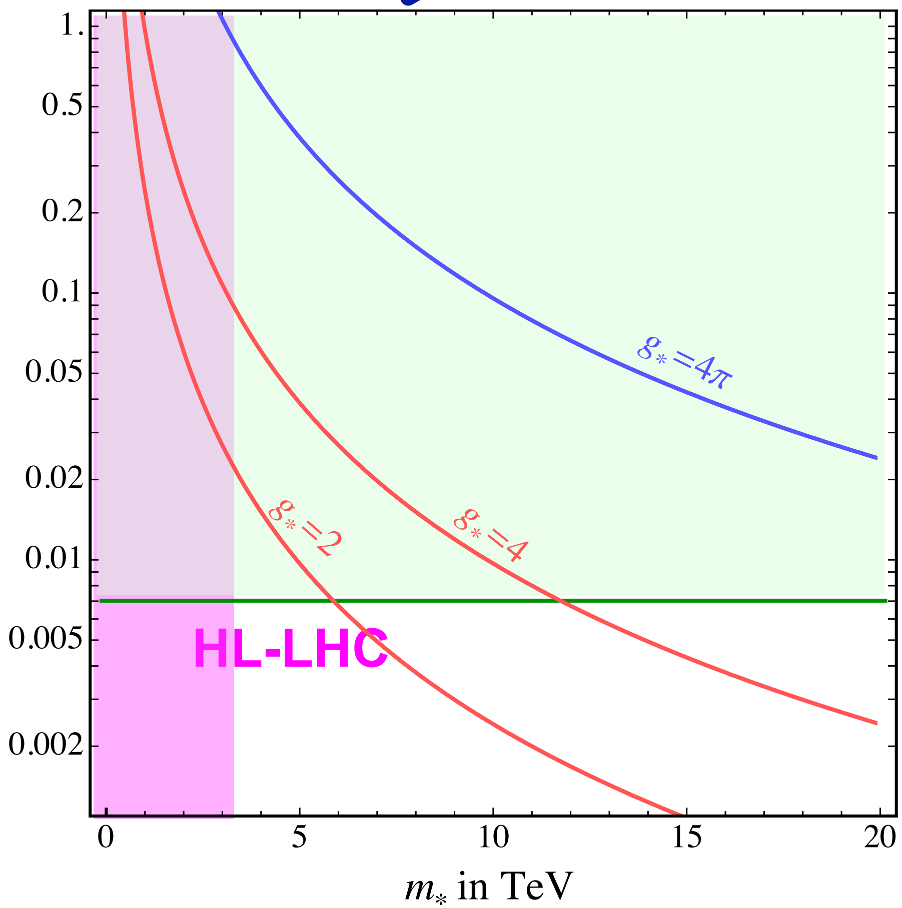
Complementary approaches to probe (e.g.) composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)

Direct Search

Higgs Couplings



$$\xi = \frac{g_*^2}{m_*^2} v^2$$

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

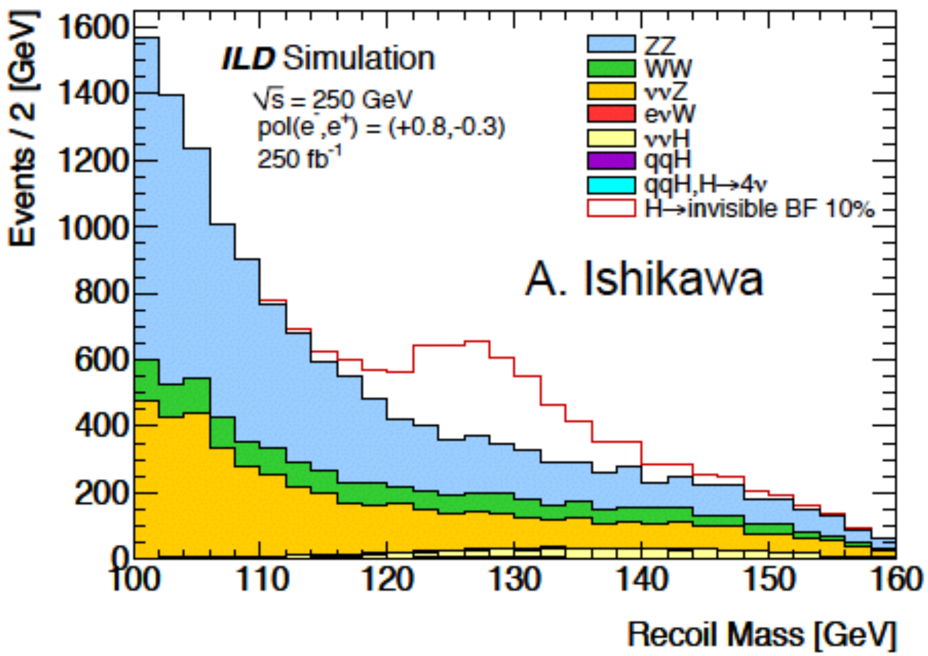
ILC

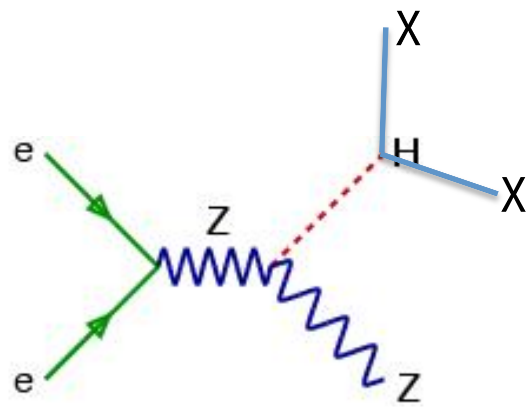
$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

[LCC Physics Group]

Invisible Higgs

The recoil mass technique also allows for unbiased observation of any non-SM decay, e.g. H→invisible:





UL on BF [%]	"Left"	"Right"
250GeV	0.95	0.69
350GeV	1.49	1.37
500GeV	3.16	2.30

Exclusion for BR(H→inv.) < 0.69% (95%CL)

also (qualitatively) applies to „LHC-invisible" decays, e.g. H→gg, H→qq etc.

The Higgs self coupling

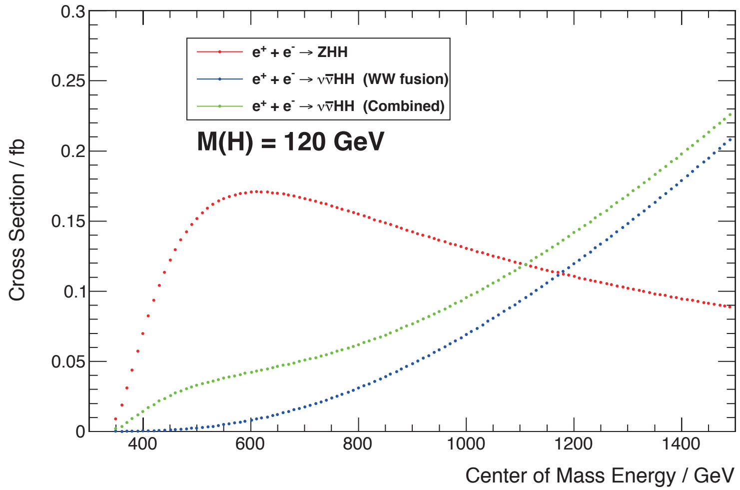
HL-LHC: prospects: currently no public result, seems very difficult

LC:

two choices:

$e^+e^- \rightarrow ZHH$
(maximum of σ around $\sqrt{s} \approx 600$ GeV)
→ ILC500 (~75 events in 500 fb^{-1})

$e^+e^- \rightarrow HH\nu\nu$
(log. rise of σ, need at least 1 TeV)



analyses ongoing!

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Baseline	83%	21%
LumiUP	46%	13%

challenges:
- huge number of different final states (huge effort needed)
- „dilution“ due to interference with non-HHH diagrams (not sensitive to λ_{HHH}) (can be mitigated by phase space weighting)

[Dürig; Kurata; Tian]

Top: Experimental Questions

KD´s personal view

	(HL)LHC	ILC
Mass		
Width		
EW (neutral) couplings		
FCNC		
tt resonances		
rare decays		

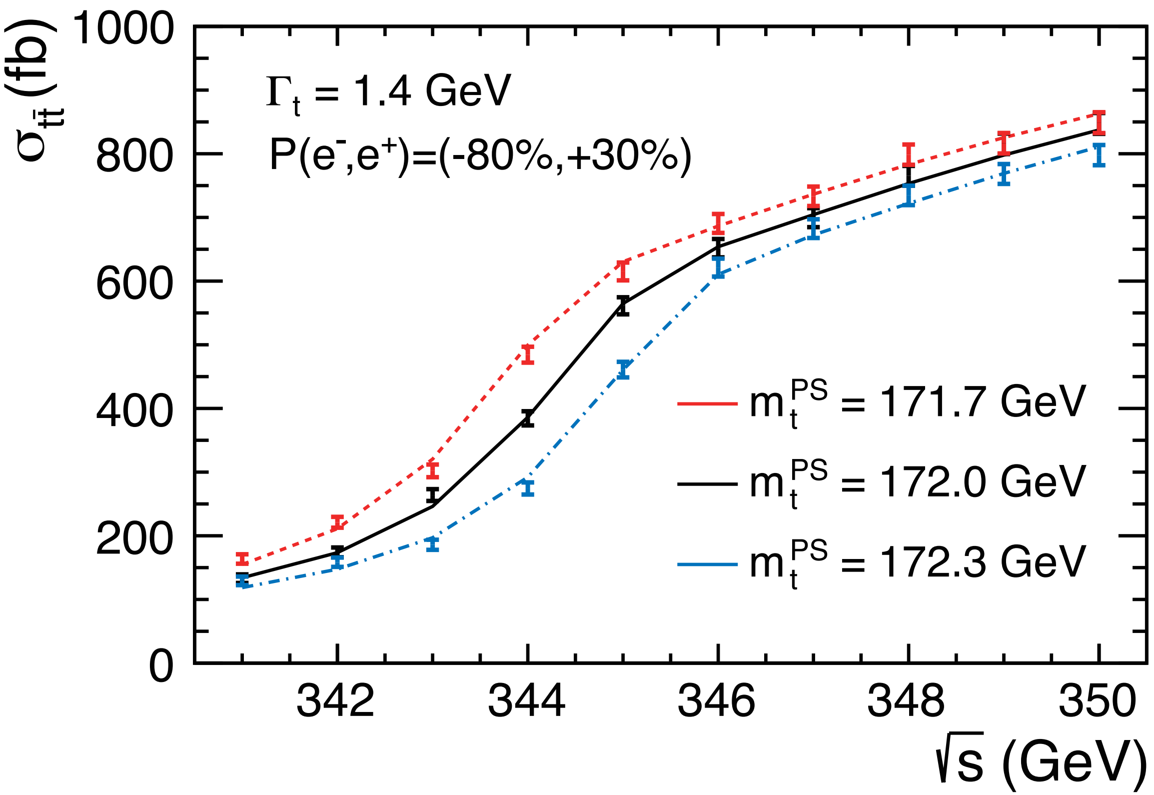
legend:

- sufficiently precise for N.P. sensitivity/unambiguous
- not precise enough for N.P. sensitivity/model-dependent
- challenging

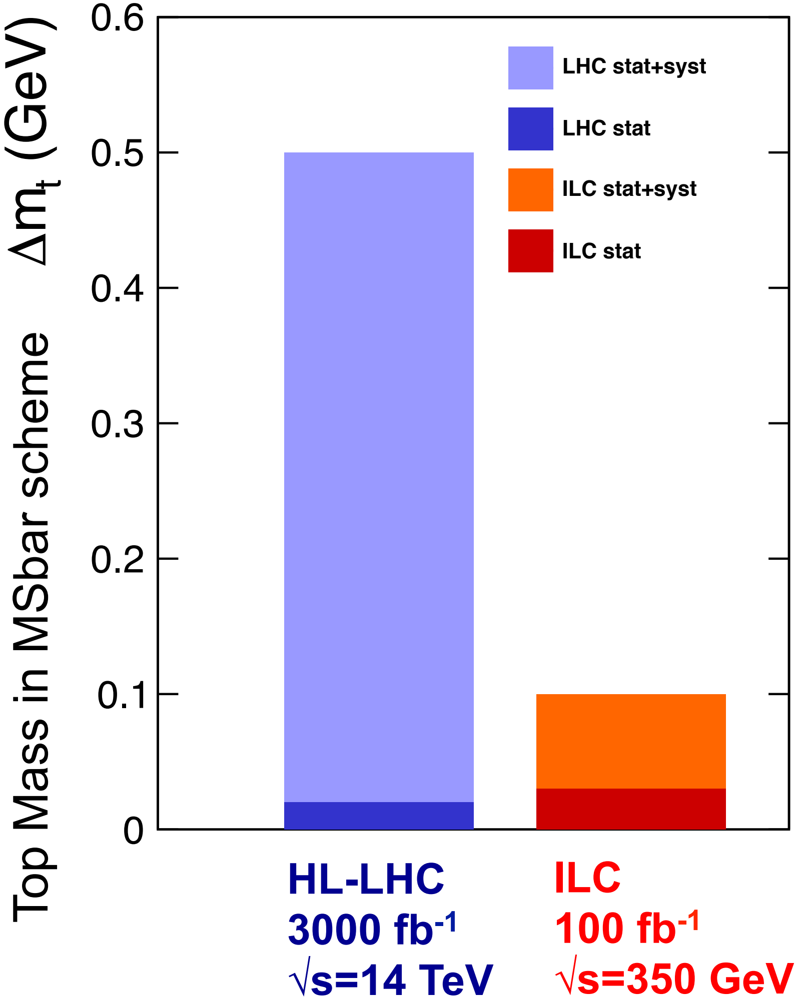
Top Quark Mass

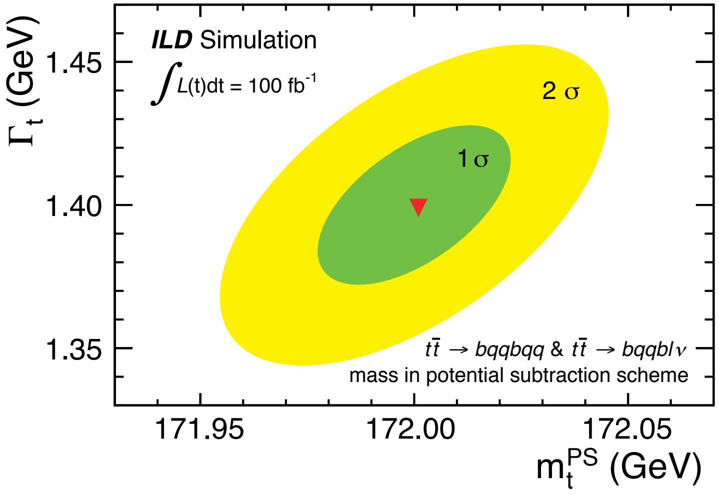
Top Quark mass from cross section at tt production threshold

- experimental limitation: beam energy spread, beamstrahlung – precision ~30 MeV
- theoretically well-defined (pole mass, „potential subtraction“) – precision ~100 MeV



Top Quark Mass





HL-LHC:
arXiv:
1311.2028

ILC:
Seidel, Simon, Tesar, Poss,
EPJ C73 2530 (2013)

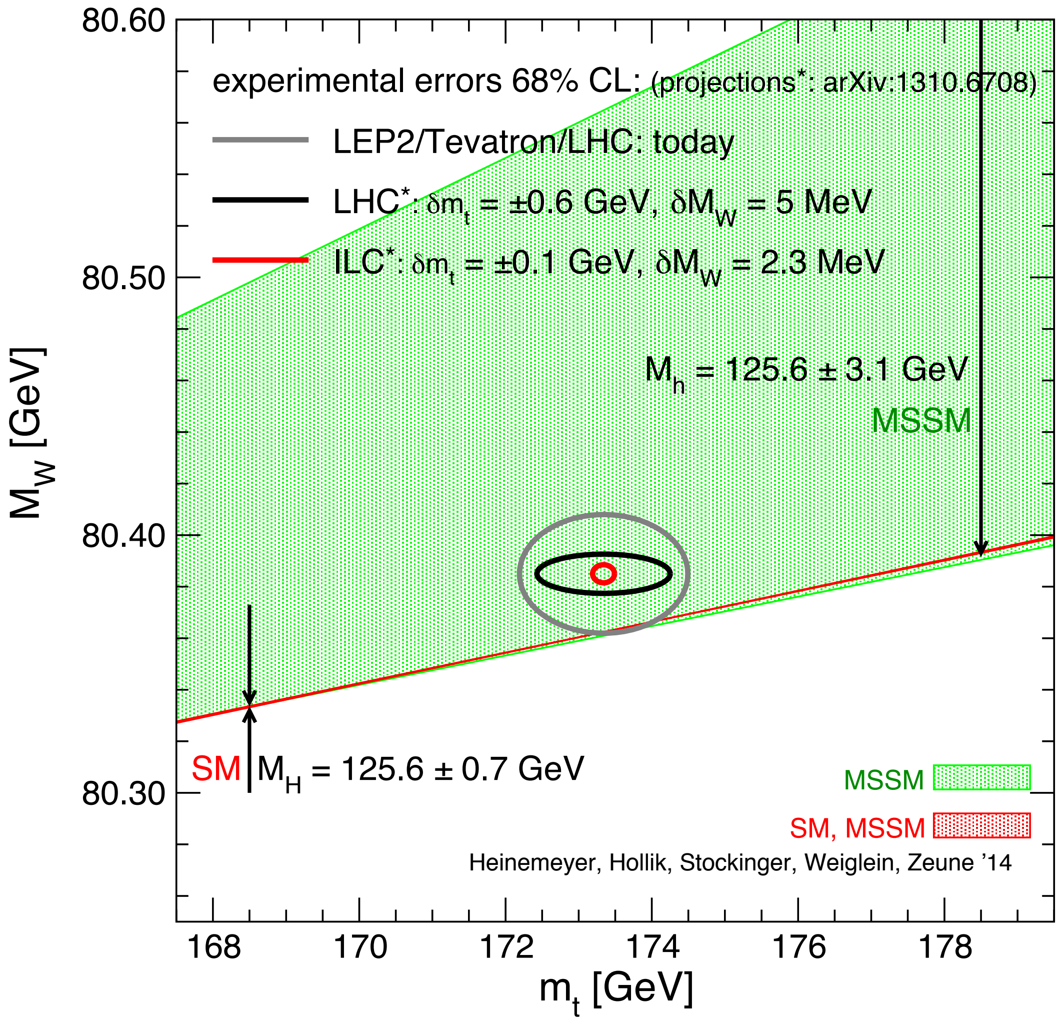
T. Horiguchi et al.

m_{top} impact

Example:

Electroweak observables can be also used to test the consistency of the MSSM/SM.

The W boson mass and the top quark mass are important measurements. They will be both improved by the ILC.



Top Quark: EW couplings

- **The process $e^+e^- \rightarrow t\bar{t}$ involves only $t\bar{t}Z_o$ and $t\bar{t}\gamma$ primary vertices**
- A way to describe the current at the $t\bar{t}X$ vertex:
- See details in: arxiv.org/abs/hep-ph/0601112

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

where:

V = Vector coupling

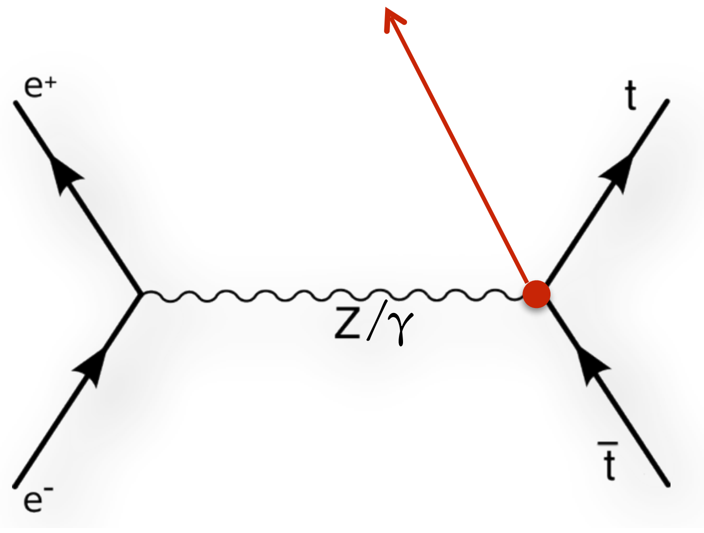
A = Axial coupling

X = Z,γ

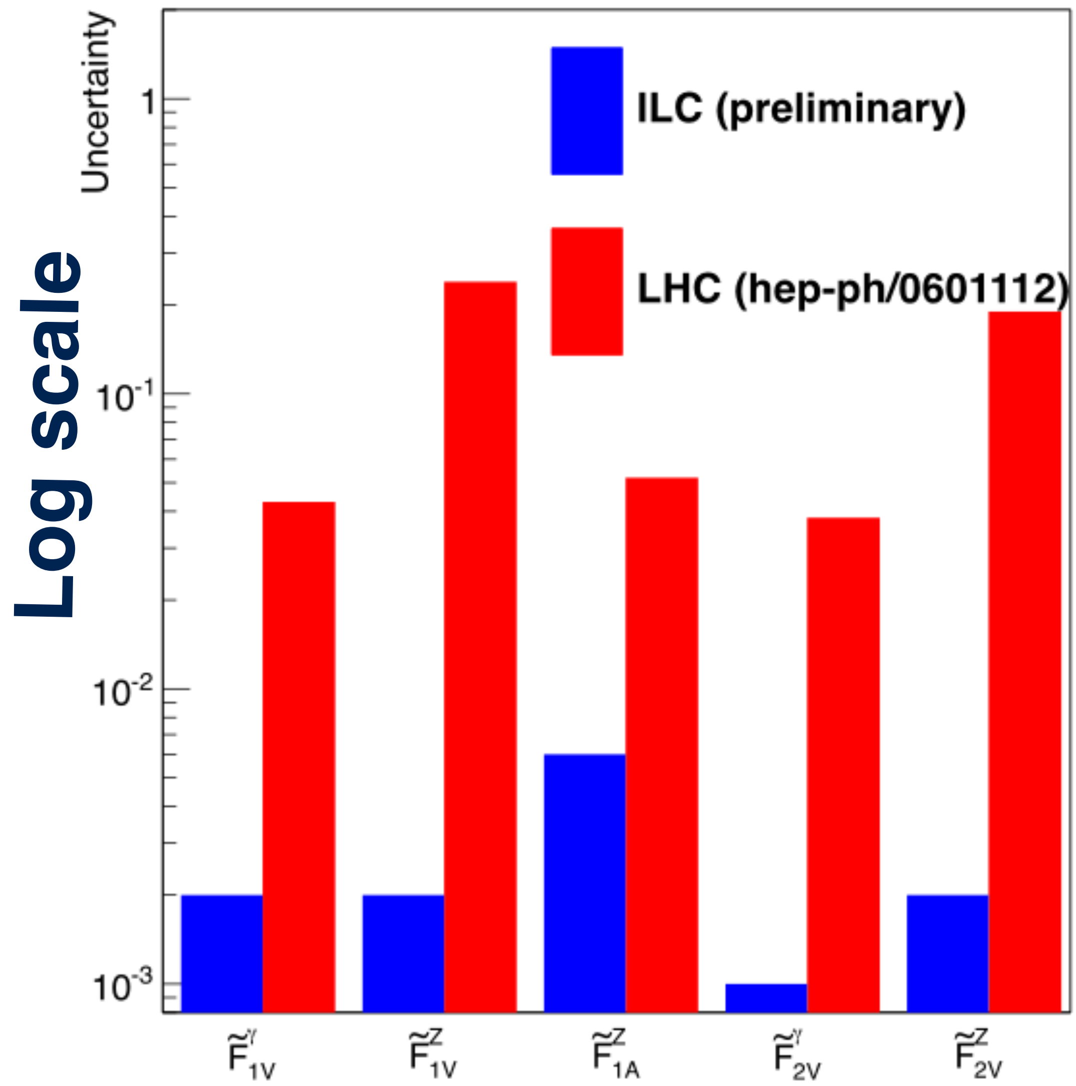
$$F_{1V}^{\gamma} \quad F_{1A}^{\gamma} \quad F_{2V}^{\gamma}$$

$$F_{1V}^{Z} \quad F_{1A}^{Z} \quad F_{2V}^{Z}$$

Non CP violating top quark couplings

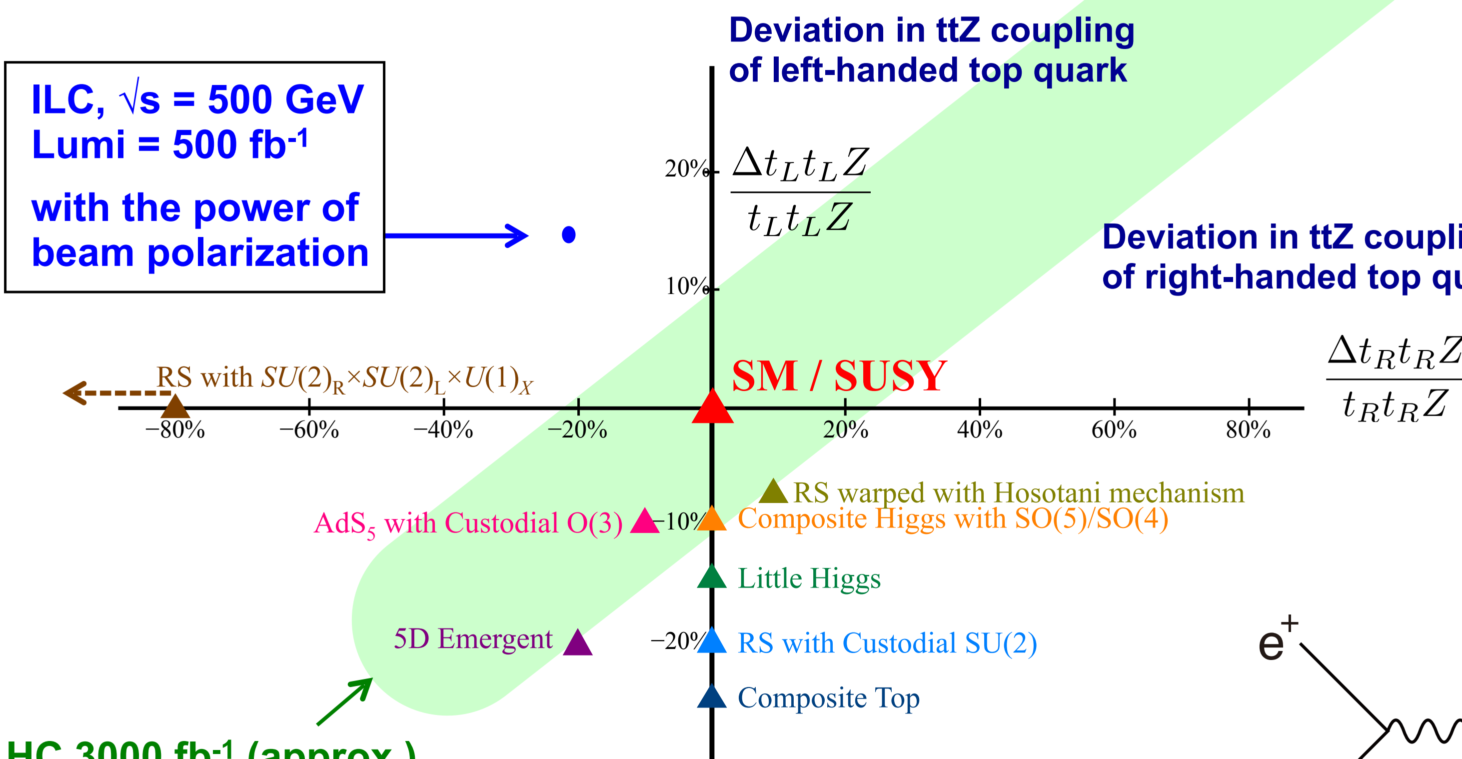


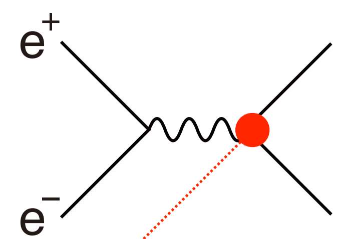
Top Quark at ILC



Impact of BSM on Top Sector

In composite Higgs models, it is often said that ***the top quark is partially composite***, resulting in ***form factors in ttZ couplings***, which can be measured at ILC. ***Beam polarization is essential*** to distinguish the ***left- and right-handed couplings***.





HL-LHC 3000 fb-1 (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

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

slide from K. Fuji, LCWS14

Discovery of new particles

KD´s personal view

	(HL)LHC	ILC
X	?	?
Y	?	?
Z	?	?
…	?	?

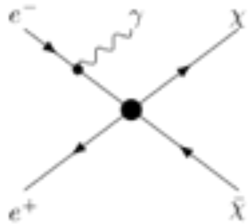
legend:

- (green) discovery
- (yellow) 3σ effect
- (red) no discovery

there is ample complementarity between LHC and ILC in discovery reach

we simply don´t know which NP Nature has chosen

DM: Effective Operator Approach

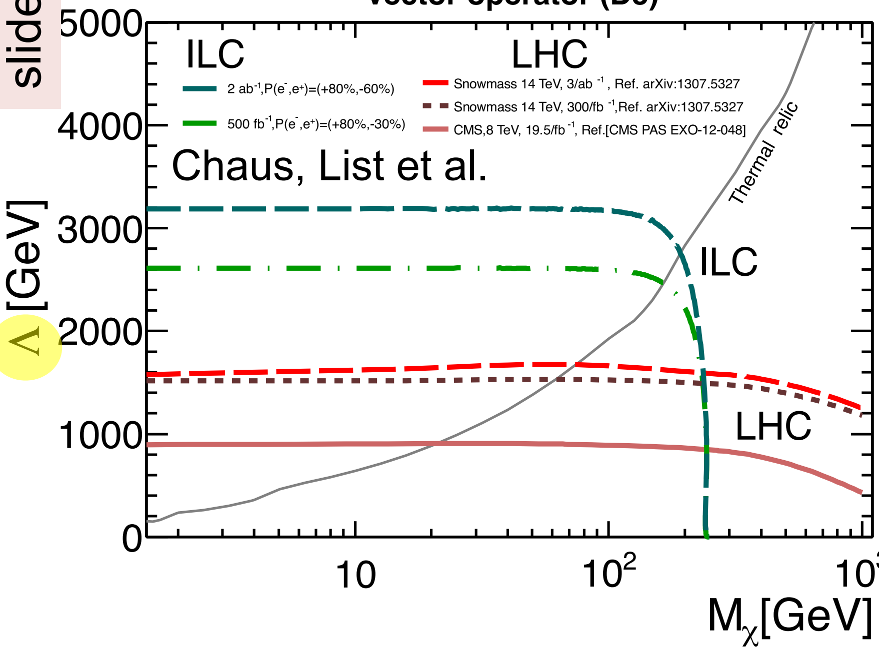


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

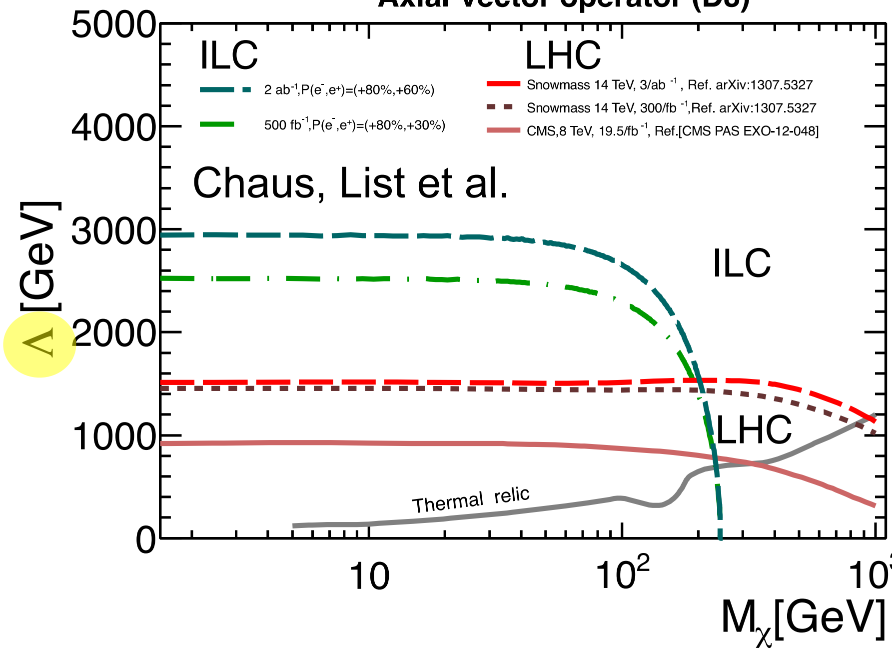
$$\mathcal{O}_V = (\overline{\chi}\gamma_\mu\chi)(\overline{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}_A = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{\ell}\gamma^\mu\gamma^5\ell)$$

Vector operator (D5)



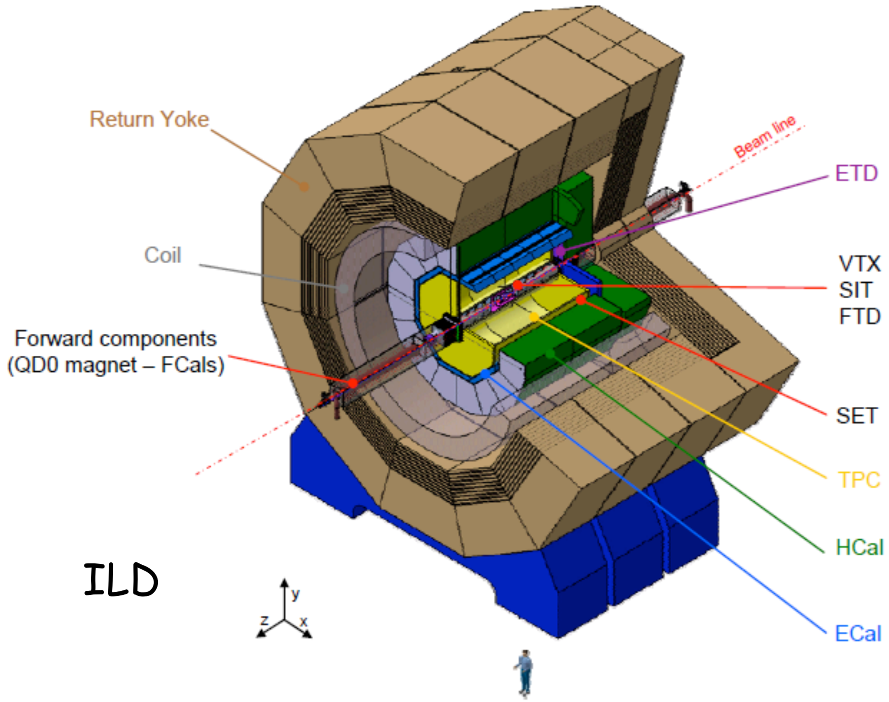
Axial-vector operator (D8)

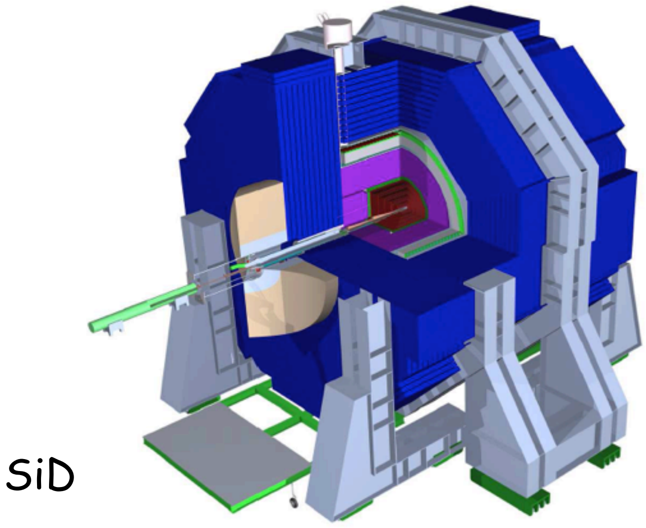


LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~√s/2***

Detector Concepts for the ILC





(Somewhat) complementary approaches

- gaseous vs. Si tracking
- „large"/moderate B vs. „compact"/huge B
- both share approach for vertexing and particle flow reconstruction

Off the beaten track...

Traditionally, collider detectors are reconstructing jets (as the witnesses of quarks, gluons)
But what is a jet?? It´s a man-made object.

Particle flow

To the best of our knowledge, a high energy particle collision results in a list of quasi-stable hadrons, leptons, photons.

Ideally, reconstruct all of them to the best possible precision!

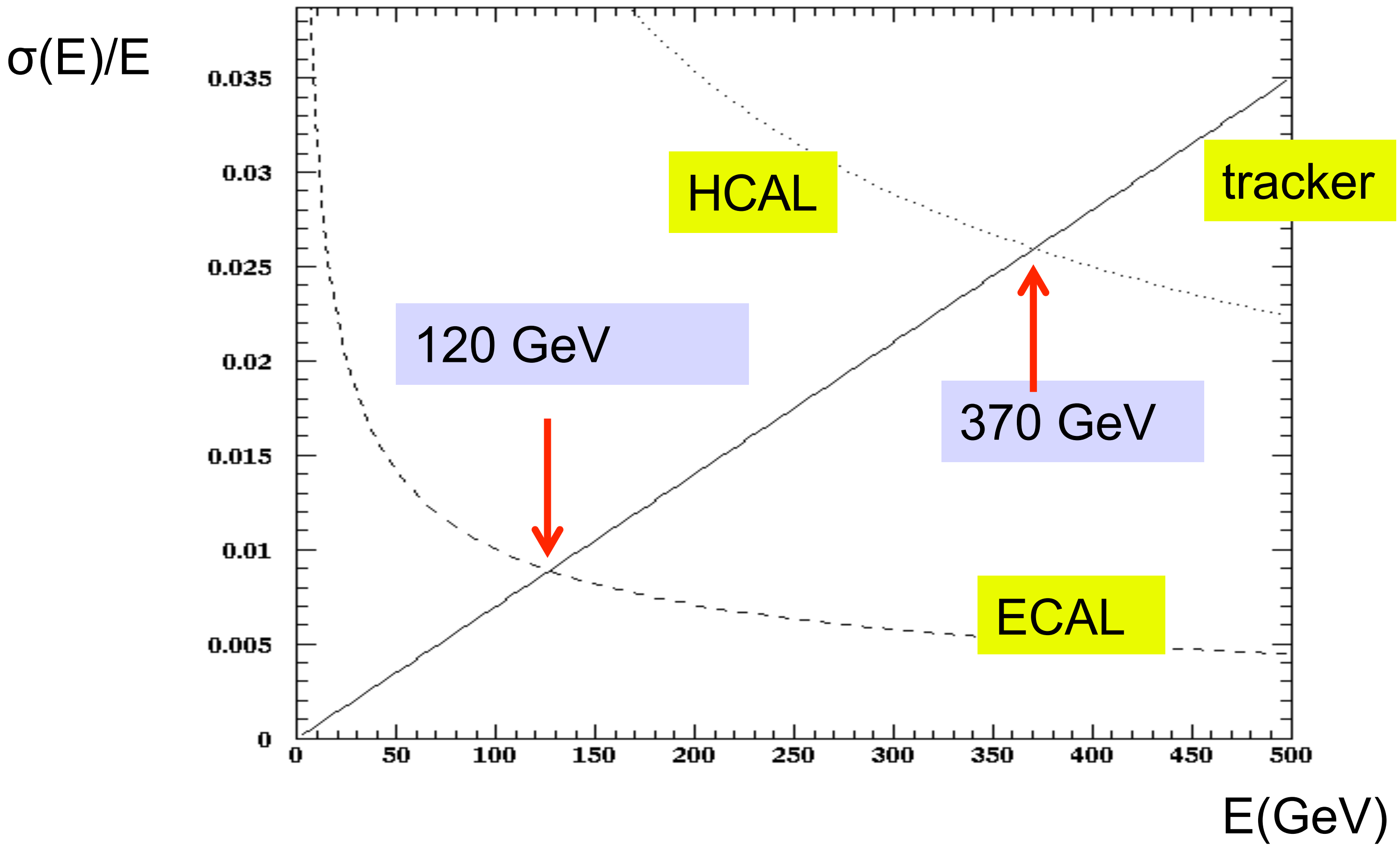
That is „particle flow".

As a byproduct, this yields:

- an improved energy resolution for „jets" at typical LC jet energies (compared to traditional calorimetry)
- allows for most flexible definitions of jets, sub-jets, etc.
- allows for excellent exclusive reconstruction of hadronic tau leptons

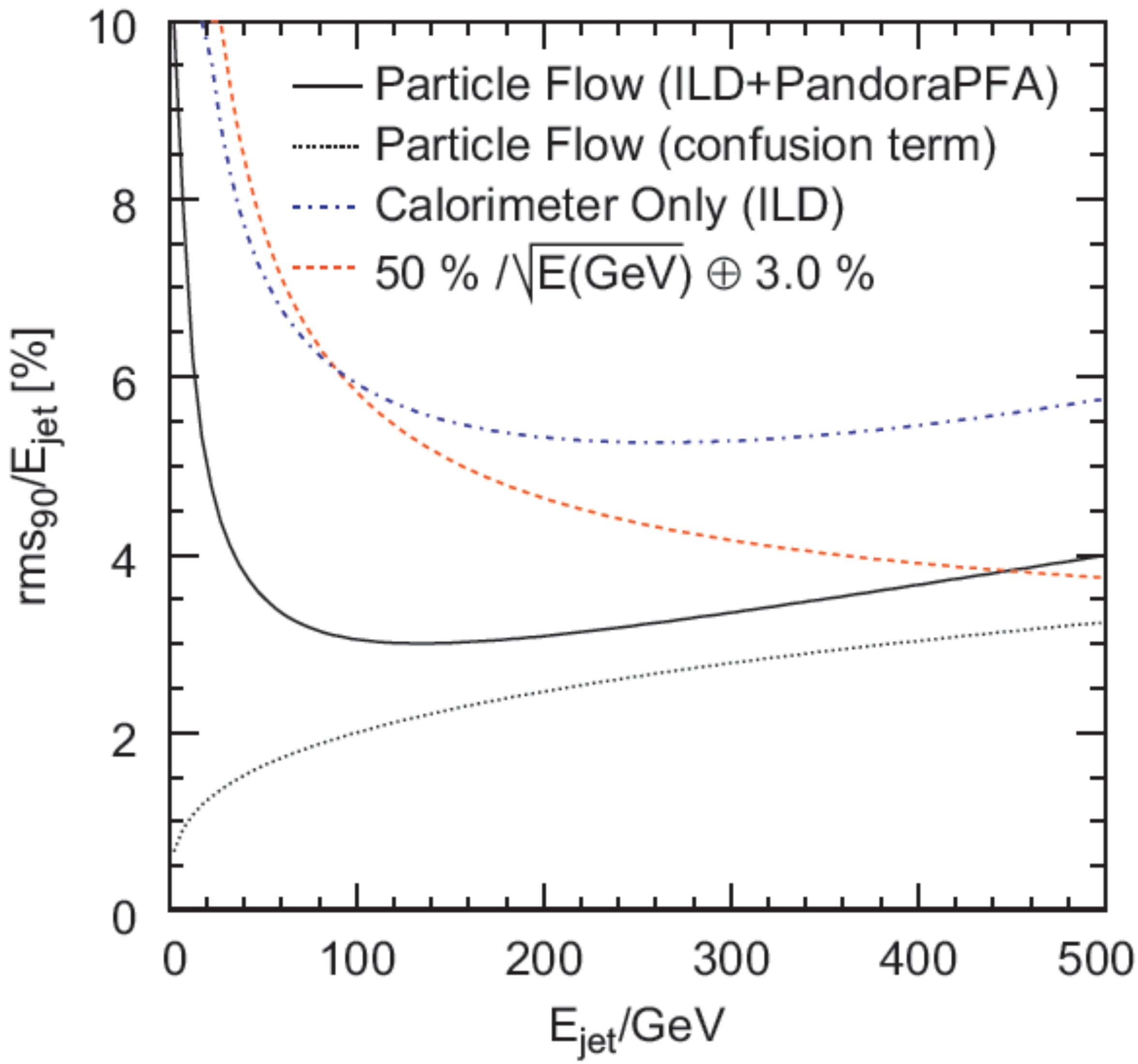
How does it work?

Resolution tracker - Calorimeter



[T. Behnke]

Particle Flow: performance



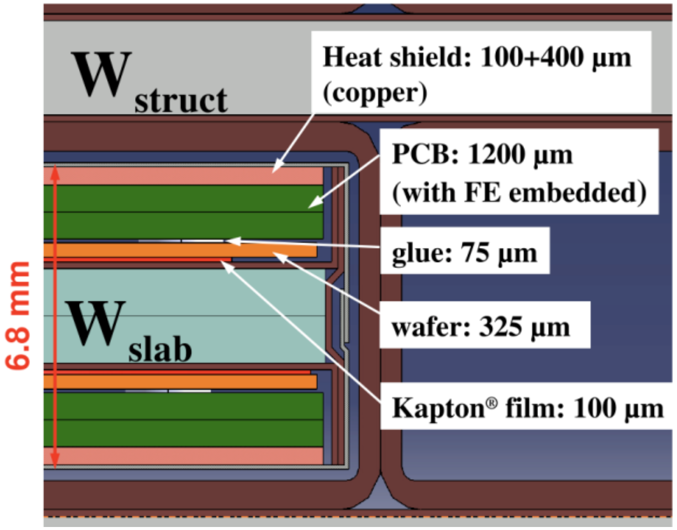
Particle flow is clearly superior to pure calorimetry, especially at low energies

How is it done?

sampling calorimetry with „ultimate“ transverse & longitudinal segmentation

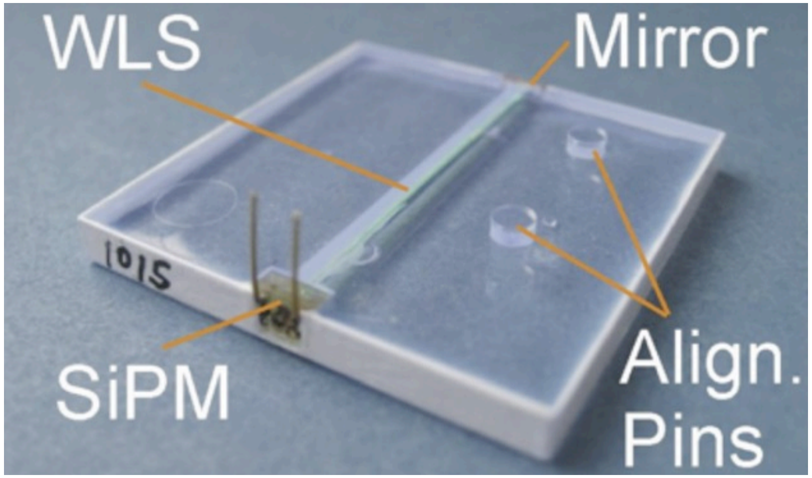
ECAL (one option):

Tungsten absorber
Silicon sensors as active material
30 layers / $24X_0$
Si sensor: $5x5mm^2$ pixel size

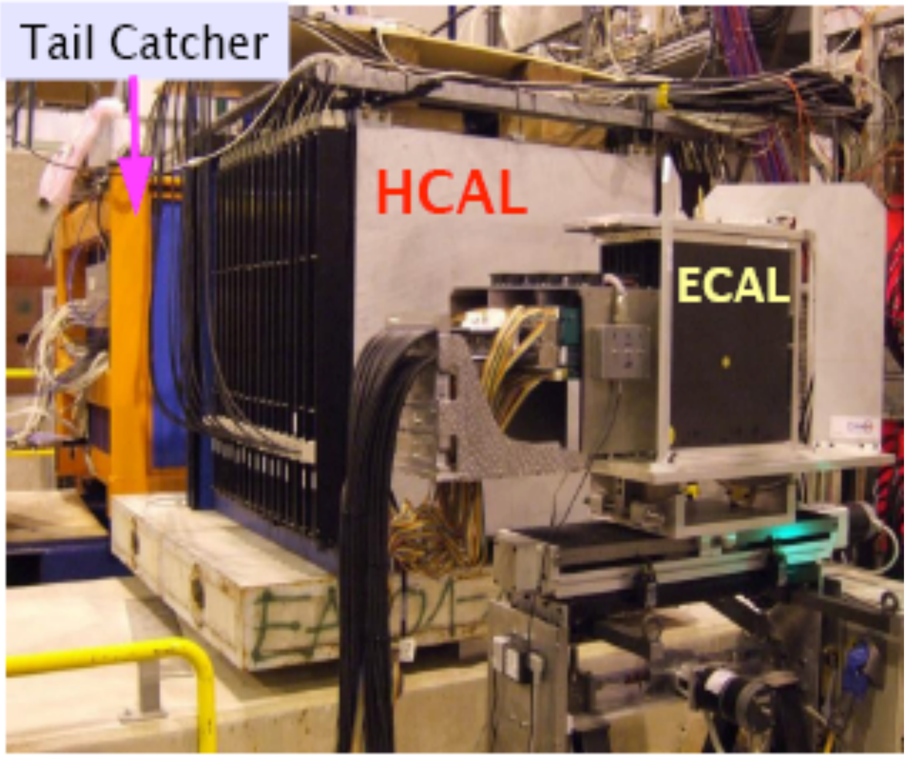


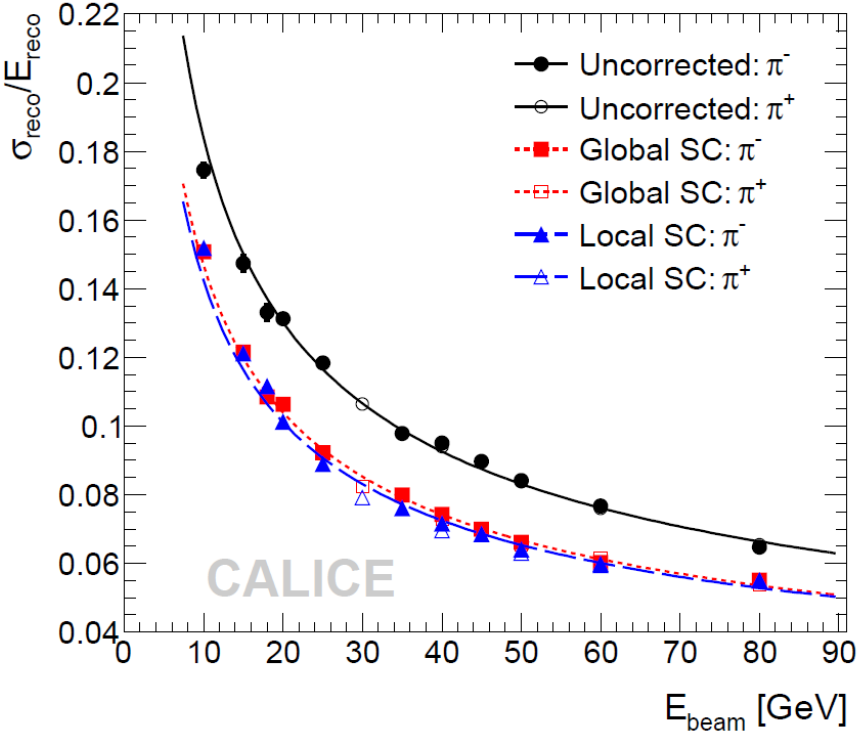
HCAL (one option „AHCAL“):

Steel absorber
Scintillating tiles ($3x3\ cm^2$) as active mat.
readout with Silicon Photomultipliers
48 layers / 6 λ



R&D: CALICE



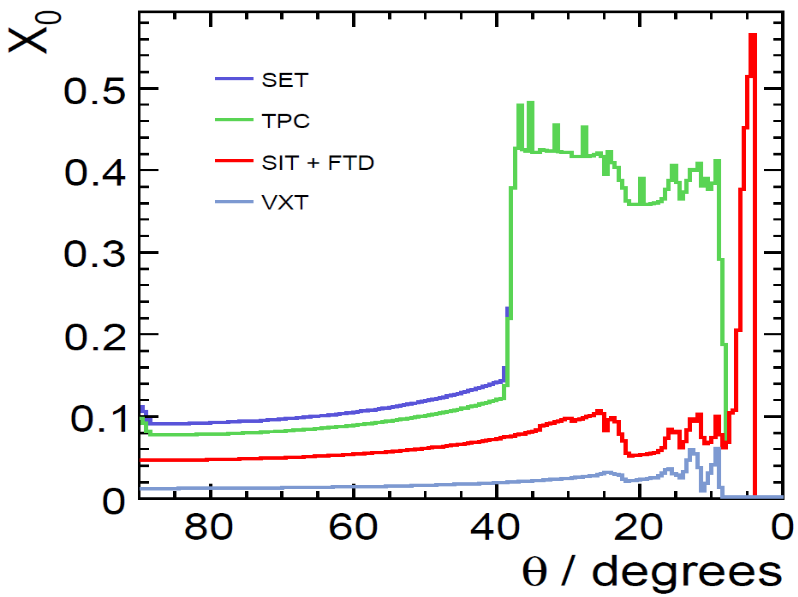


1 m^3 prototype in testbeam (CERN, Fermilab)

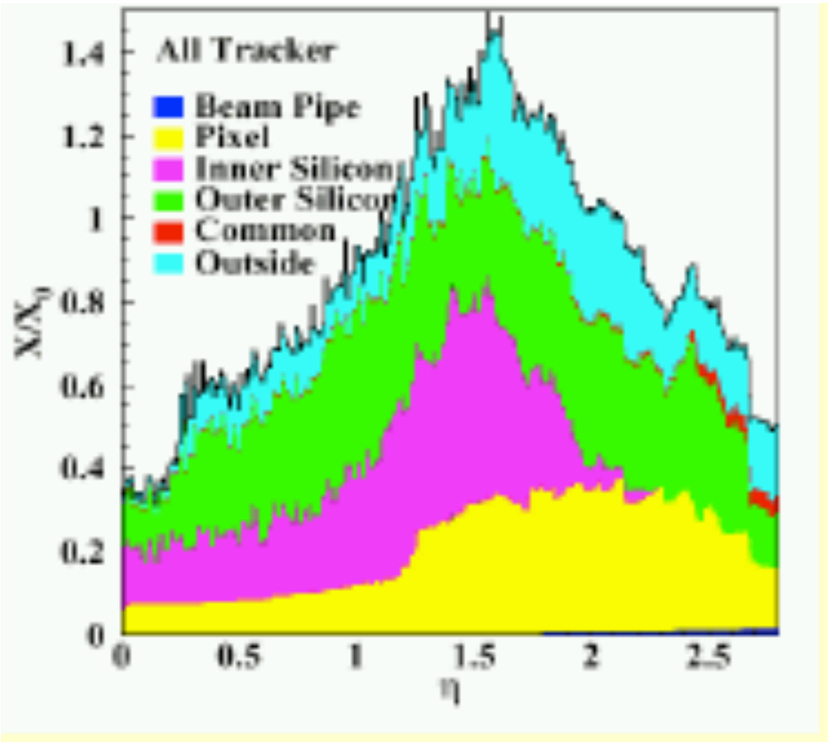
Need to validate/improve fine details of complicated hadronic showers (→ GEANT4)

Tracking: material is the challenge!

ILD



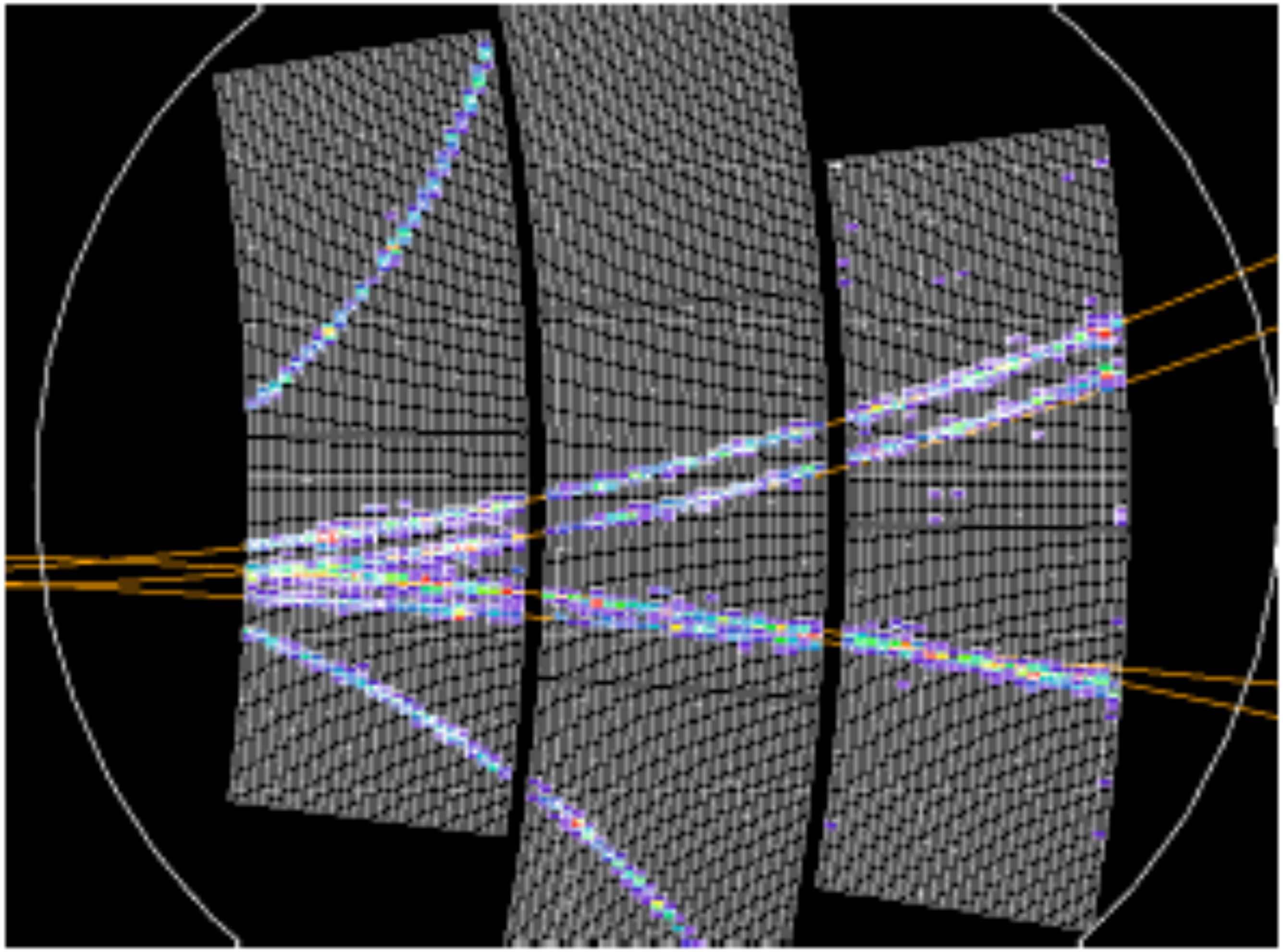
CMS



- ~ factor 4(3) less material in barrel/endcap
- remember material budget for ATLAS/CMS increased time...

TPC ideal for barrel (but keep an eye on endplate)

TPC



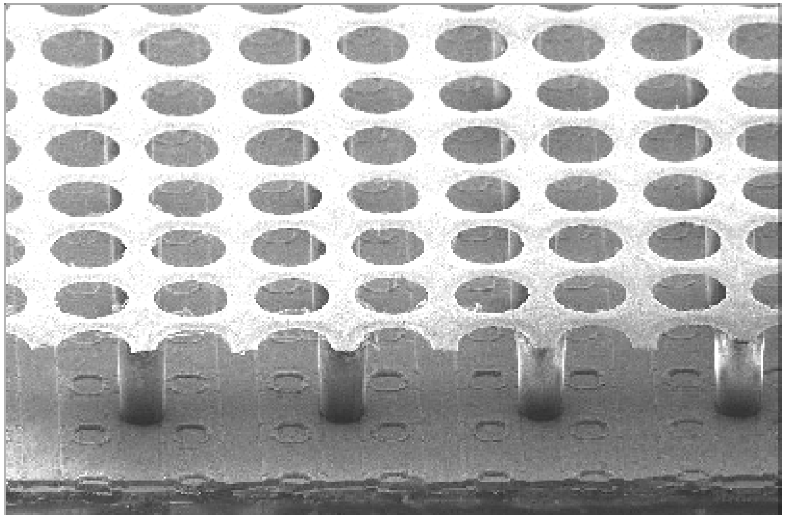
real data
from
„Large Prototype“
at DESY
(Micromegas
 modules)

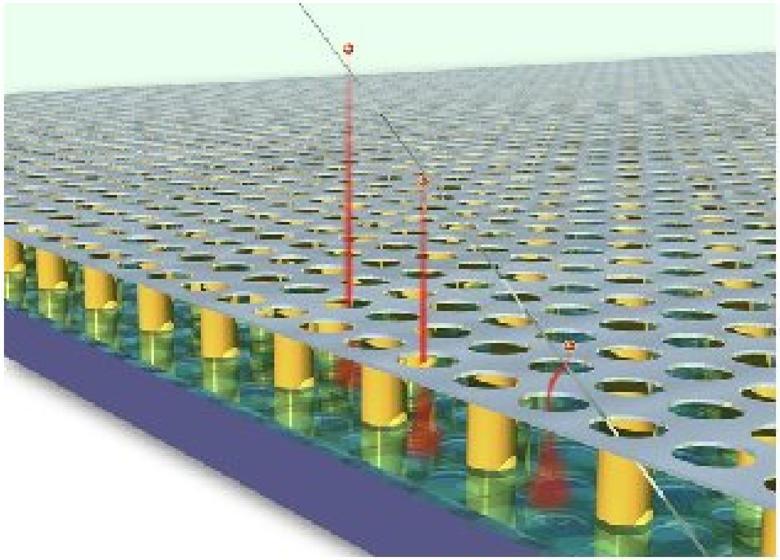
The Pixel-TPC

GridPix

Micromegas on a pixelchip

- Insulating pillars between grid and pixelchip
- One hole above each pixel
- Amplification directly above the pixelchip



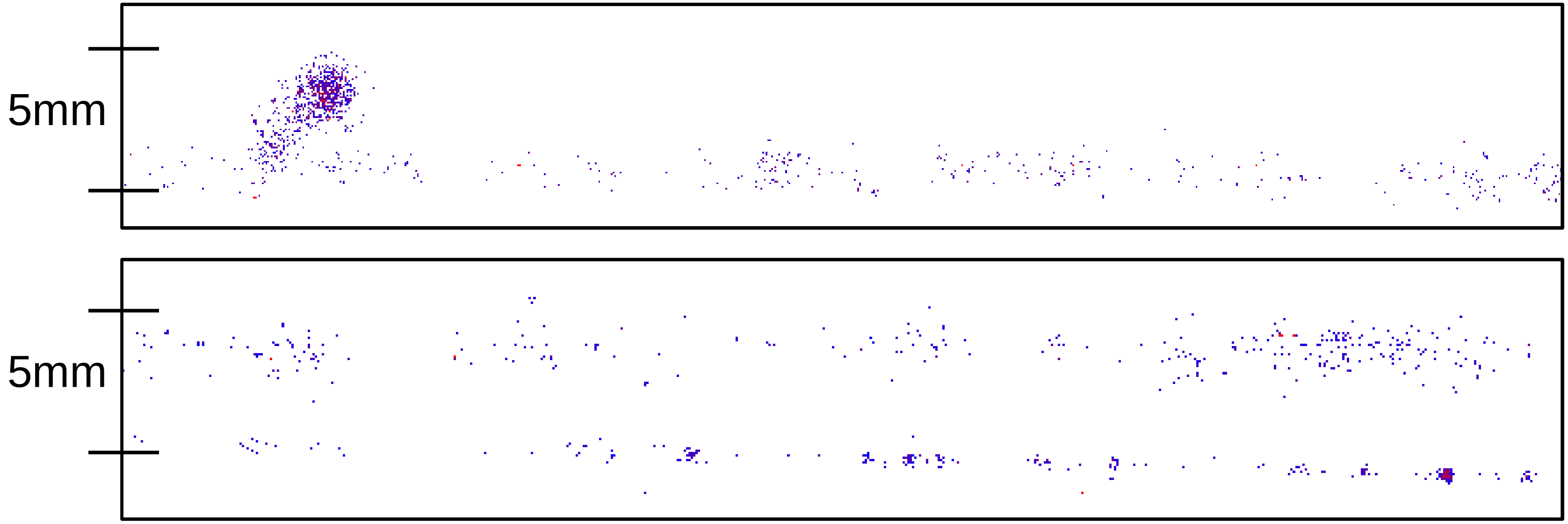


Advantages

- Very high single point resolution
- Perfect alignment
  - Each primary e^- is detected on one pixel
  - Nearly 100 % single e^- efficiency
  - Low occupancy

The Pixel-TPC

Real events from 8-chip module in DESY LP testbeam

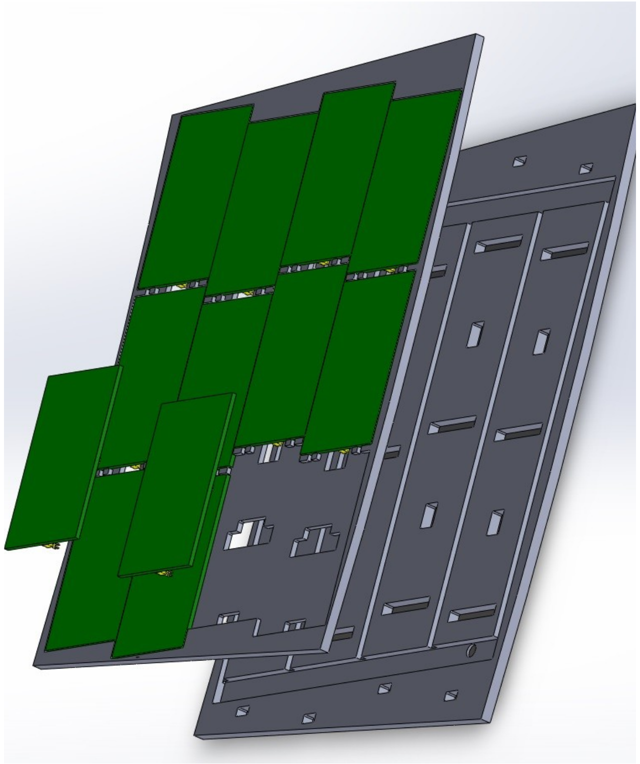


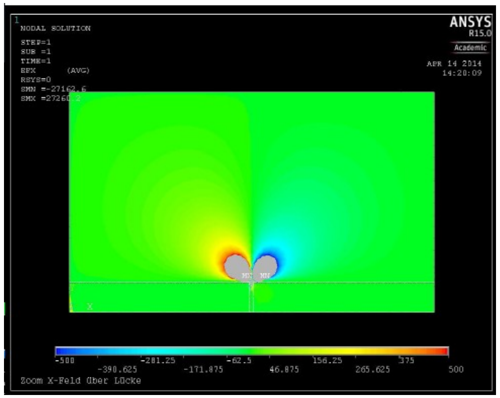
The Pixel-TPC

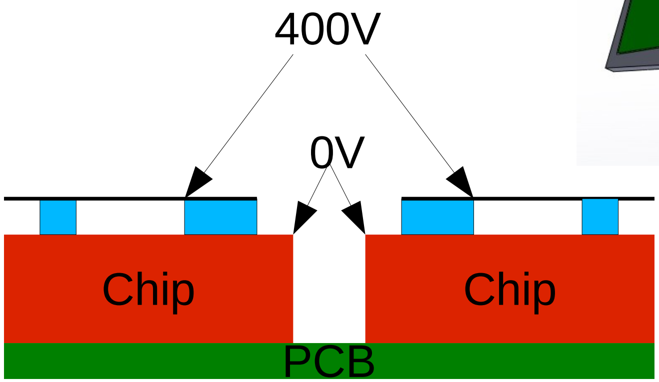
Equip larger area → demonstrate the pixel-TPC concept

Detector:

- 32 / 96 InGrid chips
- Mechanical design / cooling
- Powering
- Readout
- Edge effects

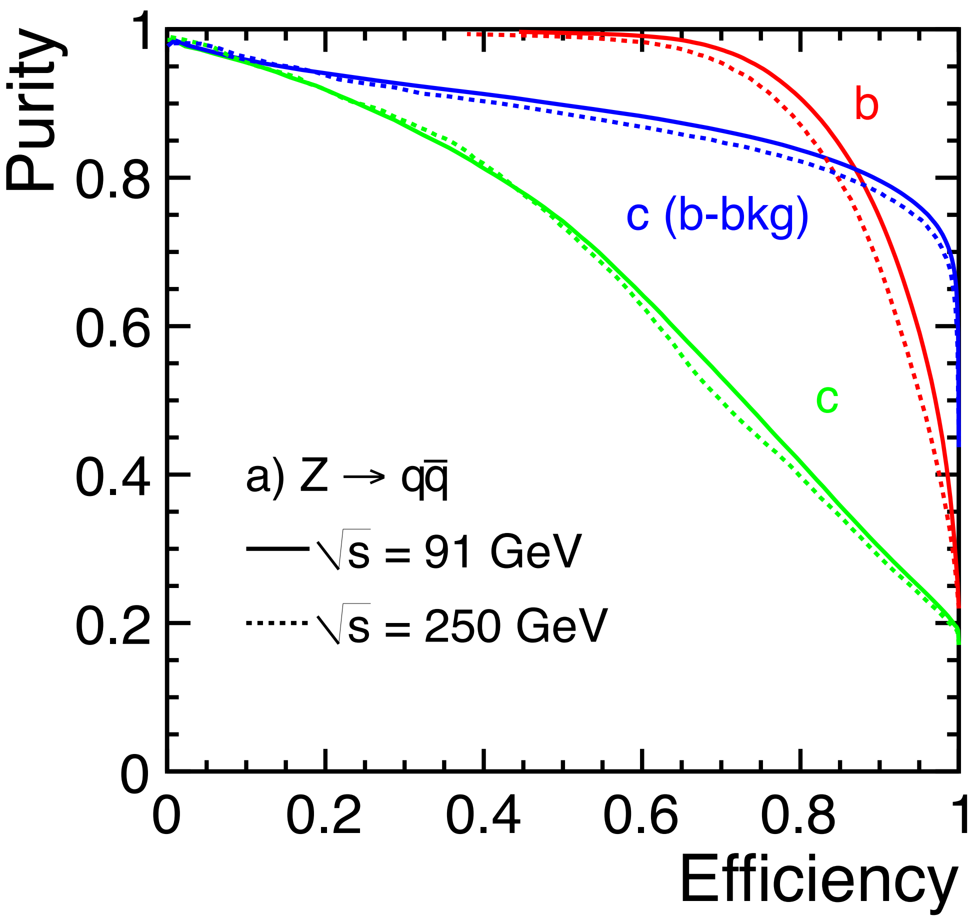






Michael Lupberger TIPP 2014

Vertex detectors - motivation



Goal:

$$\sigma_{r\phi} = 5\ \mu\mathrm{m} \oplus \frac{10}{p(\mathrm{GeV}\sin^{3/2}\theta)}\ \mu\mathrm{m}$$

- Bottom + Charm tagging for Higgs branching ratios
- Bottom tagging in fully hadronic tt-event
- Vertex charge!
  - forward-backward asymmetries
  - combinatorics in (e.g.) ZHH

Vertex detectors - implementation

Moderate radiation levels

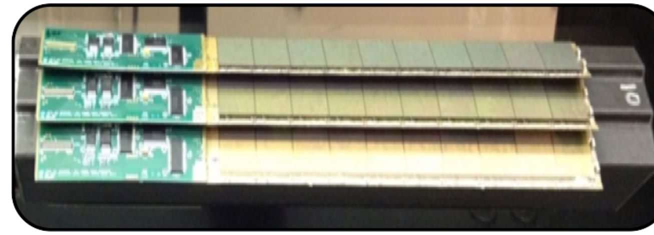
→ Monolithic pixel detectors

→ pixel sizes ~< 20x20 μm^2
→ < 0.3% X_0 per layer
→ < 130 μW/mm^2
→ single bunch time resolution
→ gas cooling

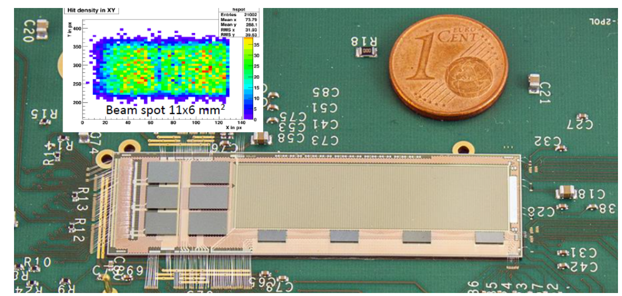
Several technologies under development (and being used in other experiments)

- CMOS pixels
- DEPFET
- FPCCD
- VIP

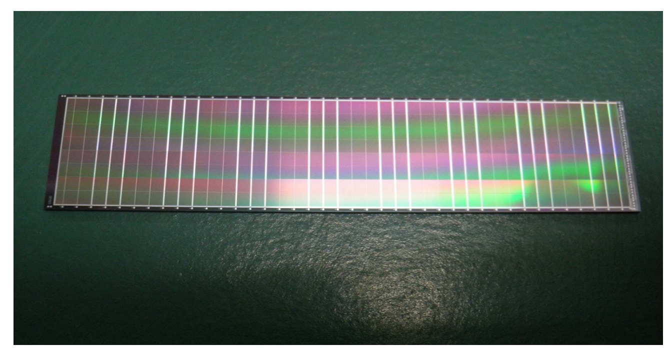
...



MAPS (for STAR)



DEPFET (for Belle II)



FPCCD

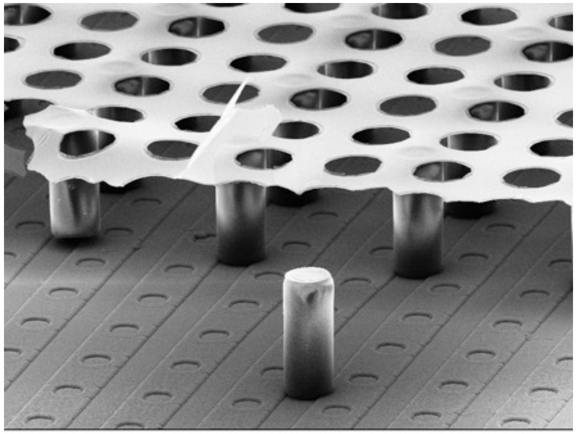
Technology advances

New detector technologies were invented since design of LHC detectors, e.g.

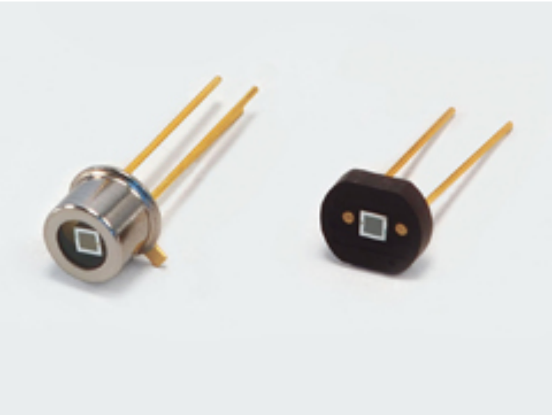
- highly-granular ultra-thin pixel devices (CMOS, DEPFET, ...)
- MPGDs (GEMs, Micromegas, InGrids) for gaseous detector r/o
- Silicon Photomultipliers (SiPM)

→ „spin-off“ of LC detector R&D to other experiments and v.v.

CMOS Pixels
(STAR)

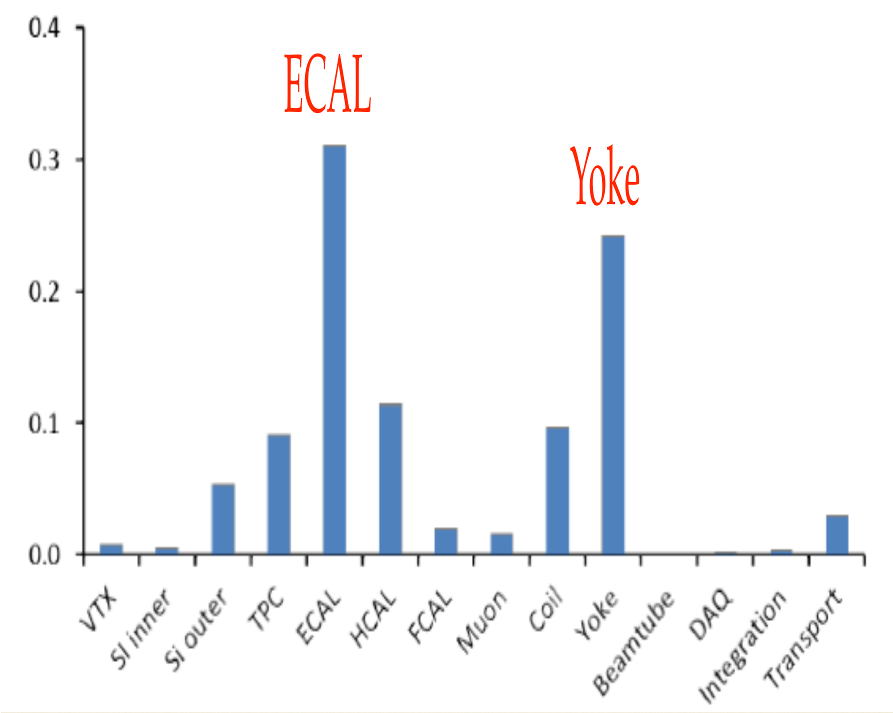


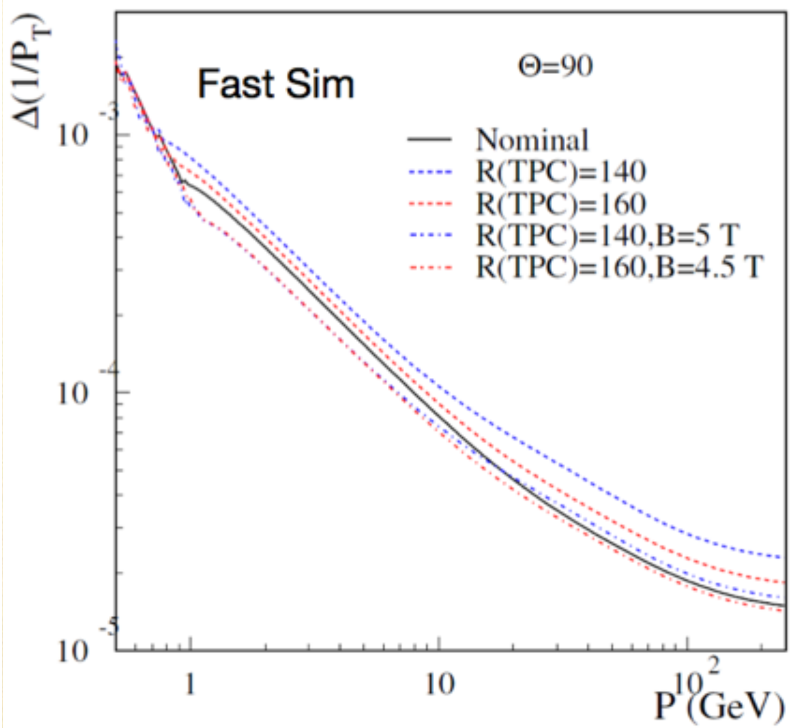
InGrid
(CAST)



SiPM
(LHCb)

Detector optimization





ECAL and Yoke are the cost drivers of ILD (correlated)

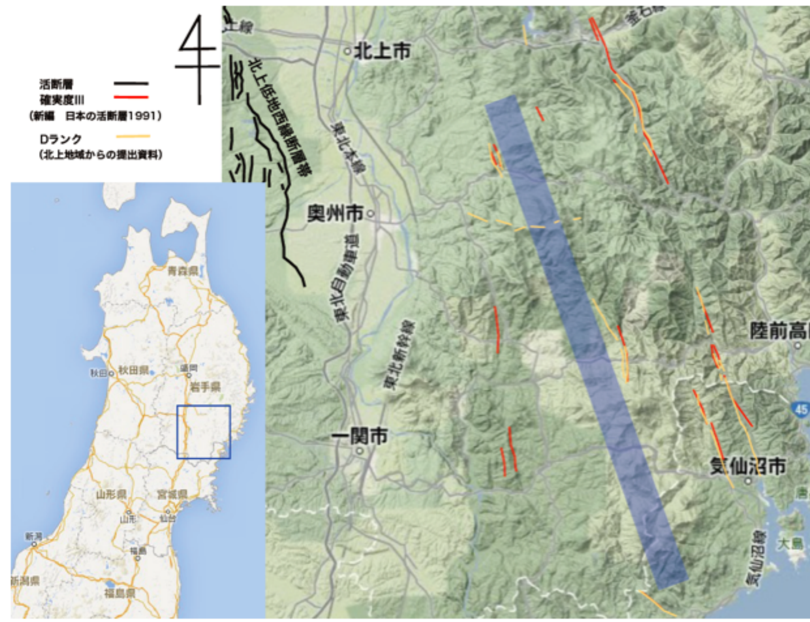
Critical parameter: $R_{coil} \sim R_{TPC}$

→ optimization of cost vs. detector performance is a major post-TDR/DBD issue

Realizing the ILC

ILC: Technical Design Report (Accelerator and Detector) is ready
New organisation led by Lyn Evans in place.
Goal: realize of the ILC a.s.a.p.

Northern Japanese Site



Geologically very stable area
Thinly populated, still well accessible through major roads and high speed rail roads
Close-by big city: Sendai

International Situation

EU: European Strategy:
strong support for a Japanese initiative to host the linear collider

US: P5 process just finished
- strong support for the physics case of the ILC
- in any scenario ILC plays a role in the US
- for being a leading partner additional funding would be needed

Japan: <u>MEXT has initiated internal study group</u>
ILC has become an official project in Japan in MEXT
Detailed investigation is ongoing about the possibility to host
Budget for siting studies etc. is being prepared
Official letters have been sent to US, and recently to Europe

ICFA: Endorsement of regional strategies – reiterated its support for ILC

Slide from S. Komamiya (LCSW14)

LCB

Current ILC Activities in Japan

Japanese government wants to understand and convince themselves that about the ILC project, before engaging the international community.

“Academic Expert Committee” to have meetings to the public and to produce a report by 31 March 2016.
This group is not international.
This committee is studying total ILC cost, human resources, the Japanese domestic ILC organization, and social and economical impact of the project of the ILC in Japan.

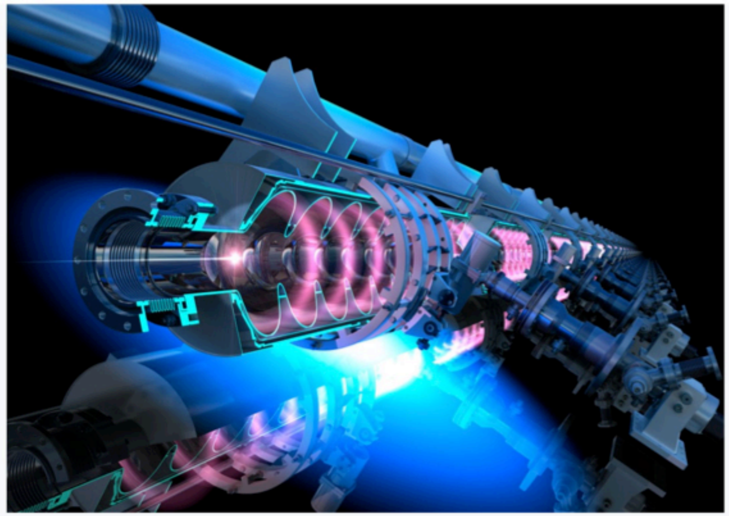
ALCW in April 2015

ALCW 2015

Asian Linear Collider Workshop

20-24 April '15 KEK Tsukuba, Japan

- Welcome
- Bulletins
- Poster
- ILC Tokyo Event
- Committees
- Program and Conveners
- Time table
- Registration
- List of Registrants
- Accommodation
- Access
- Visas
- Past workshops
- Sponsors



The Asian Linear Collider Workshop 2015 (ALCW2015) will take place at KEK in April 20-24, 2015. The workshop will be devoted to accelerator, physics and detector aspects of future high energy electron-positron linear colliders. This workshop is the first Asian regional workshop since the start-up of LCC. Being different from the past regional workshops in Asia this workshop is co-organized by KEK, ACFA, and LCC and a new session organization is attempted; detector sessions consists of several mini-workshops of detector concept and R&D

News

2015.1.27
"Poster" is Uploaded!
Poster

2015.1.15
"Draft program" is added.
See! program page

2014.12.18
Online Registration is Now Open!

Contact

KEK

Conclusions

- Discovery of H(125) and t(174) present a quest for precision at high energy

  → a strong and guaranteed physics case for ILC (clearly beyond HL-LHC)
  → additional potential for discovery of new particles (direct + indirect)

- ILC is technically ready

- Japanese initiative is highly welcome by large international community

- Political process has started – not entirely transparent to us physicists(?)

- Timeline (for major investments)

Conclusions

a small dark spot on the sky