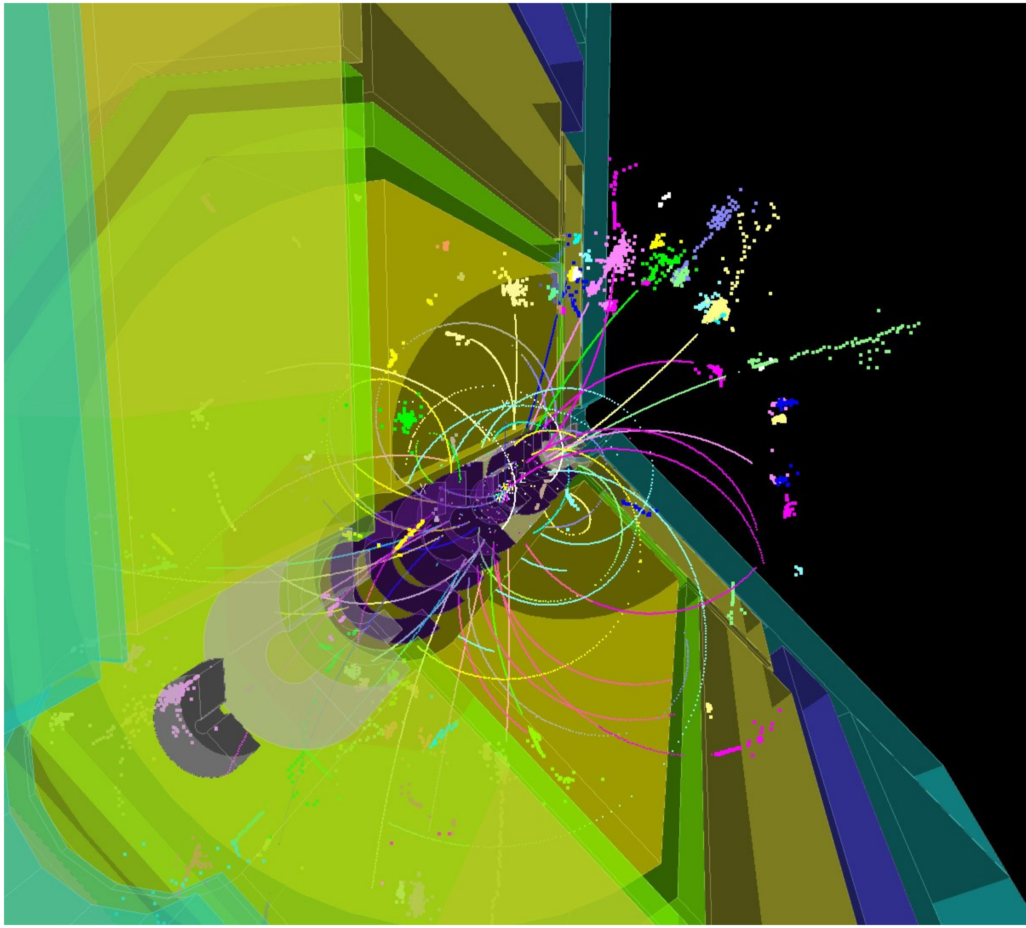
LINEAR COLLIDER COLLABORATION

A linear e^+e^- collider at the energy frontier: machine, physics and detectors



IVICFA experimental

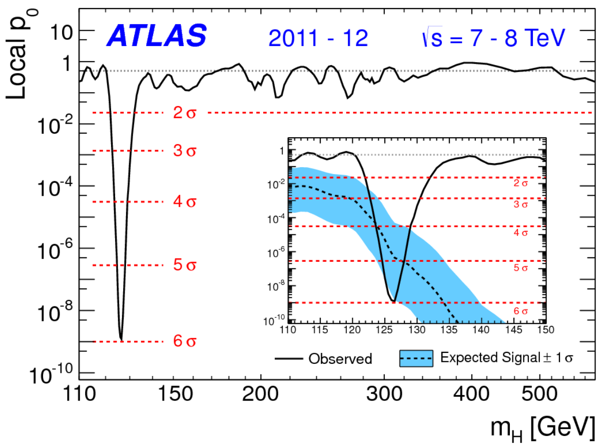
IFIC Valencia, October 25th 2013

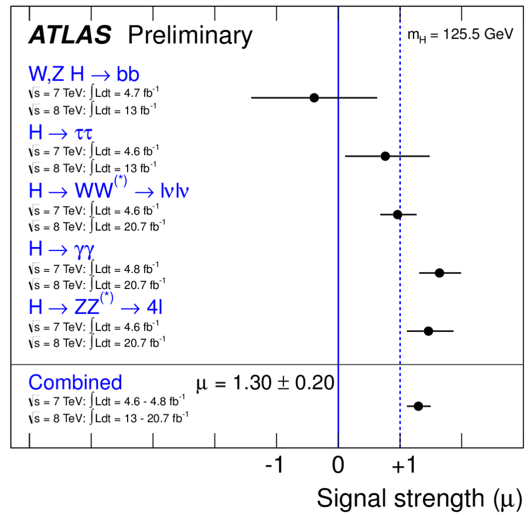
Marcel.Vos@ific.uv.es

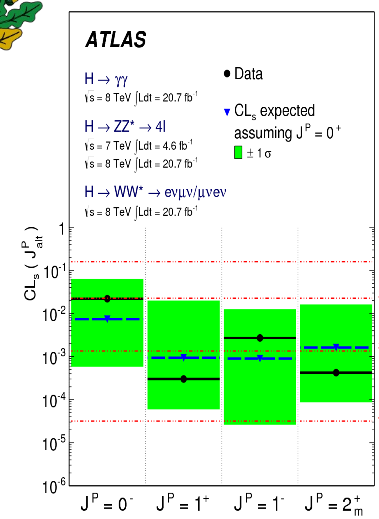
CSIC

IFIC

Big science!

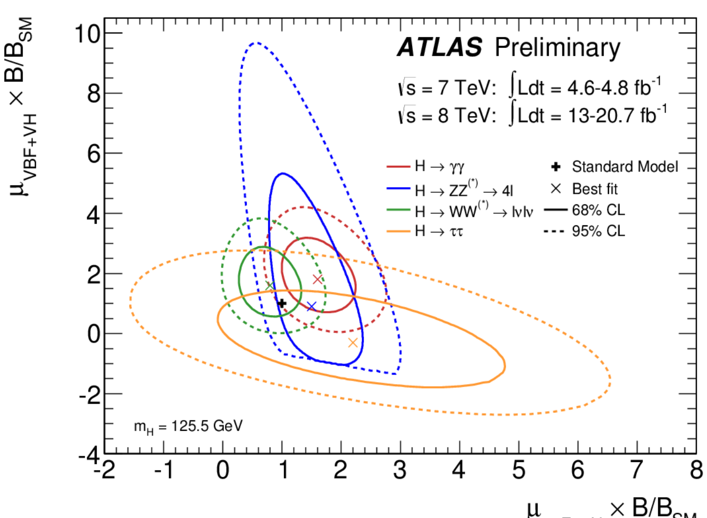


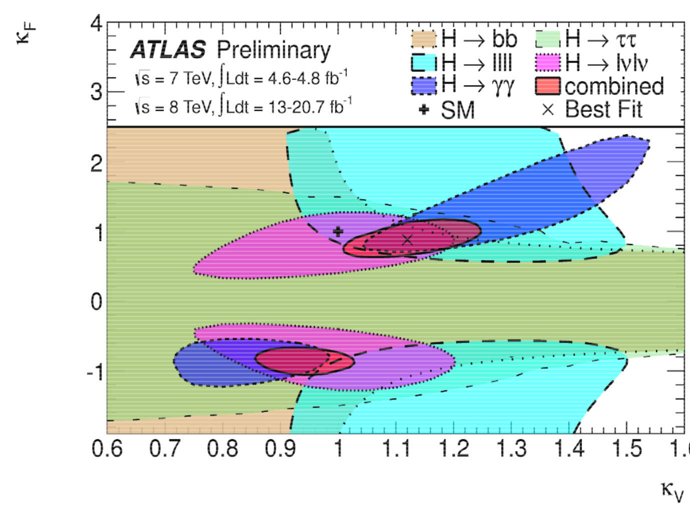




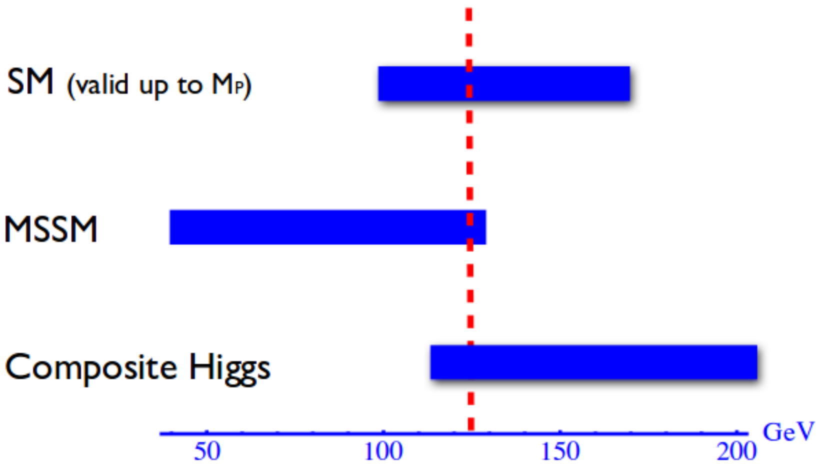
A Higgs boson; sure!
THE Higgs boson; let's wait and see...

See Andrea Bocci's talk today





Precision measurements of Higgs couplings



Fabiola Gianotti @ Higgs discovery: “nature has been kind to us”

Alex Pomarol @ ICHEP2012: “nature has been kind to experimentalists but not to theorists”

Generic size of Higgs coupling modifications from the Standard Model values when all new particles are M ~ 1 TeV and mixing angles satisfy precision electroweak fits. Higgs working group report Snowmass 2013.

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

The hottest area in particle physics for the next decades: clarify the nature of the new boson and the EWSB mechanism by measuring couplings to SM particles to sub-% precision

LHC potential for Higgs couplings

Higgs working group report Snowmass 2013.

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$
	additional parameters	
$\kappa_{Z\gamma}$	$41-41\%$	$10-12\%$
κ_μ	$34-35\%$	$9-11\%$
$\mathrm{BR}_{\mathrm{BSM}}$	$< 14-18\%$	$< 7-11\%$

LHC expectations from CMS and ATLAS. The 7-parameter fit assumes the SM productions and decays as well as the generation universality of the couplings. The precision on the total width is derived from the precisions on the couplings. The range represents spread from conservative and optimistic scenarios (no evolution in systematic errors vs. assuming them inversely proportional to integrated luminosity.

LHC prospects

(according to Snowmass Higgs group)

Can we overconstrain the system beyond the 7-parameter fit?

(i.e. determine κ_u κ_c and κ_t, or precise direct and indirect determination of κ_t)

Careful: prospects!

ATLAS prospects are more conservative than even the lower edge of these CMS intervals (ATL-PHYS-PUB-2012-004 vs. CMS-NOTE-2012-006)

Count on the largest value...

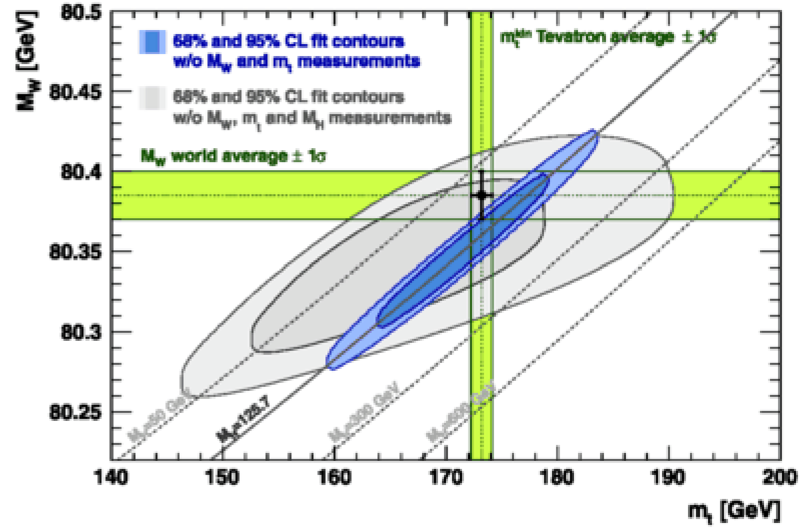
while we aim for the smallest

LHC precision on Higgs boson couplings is likely limited to the 5% level

Precision test of the SM

Relation H, W, t mass in EW fit

Driving the Higgs potential negative

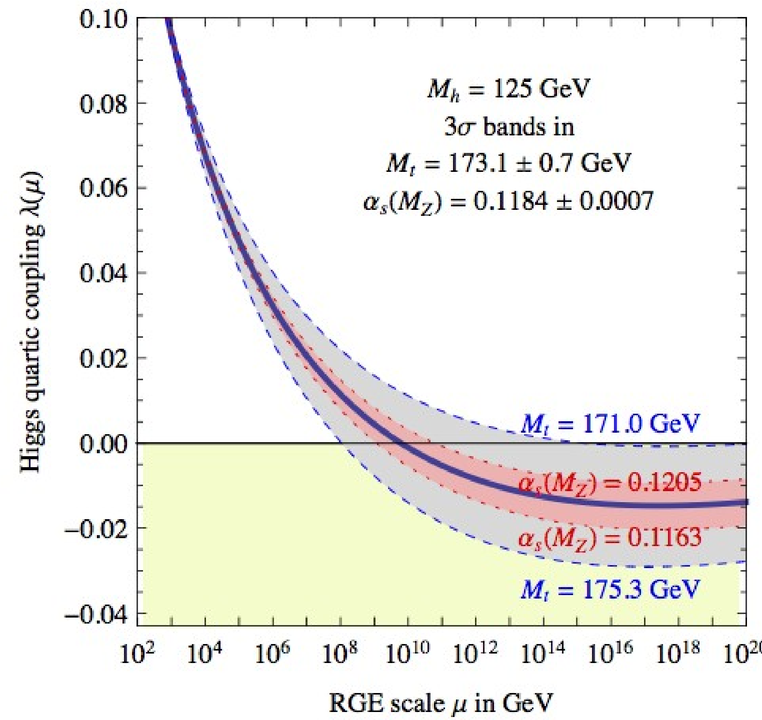


A quark we can characterize well

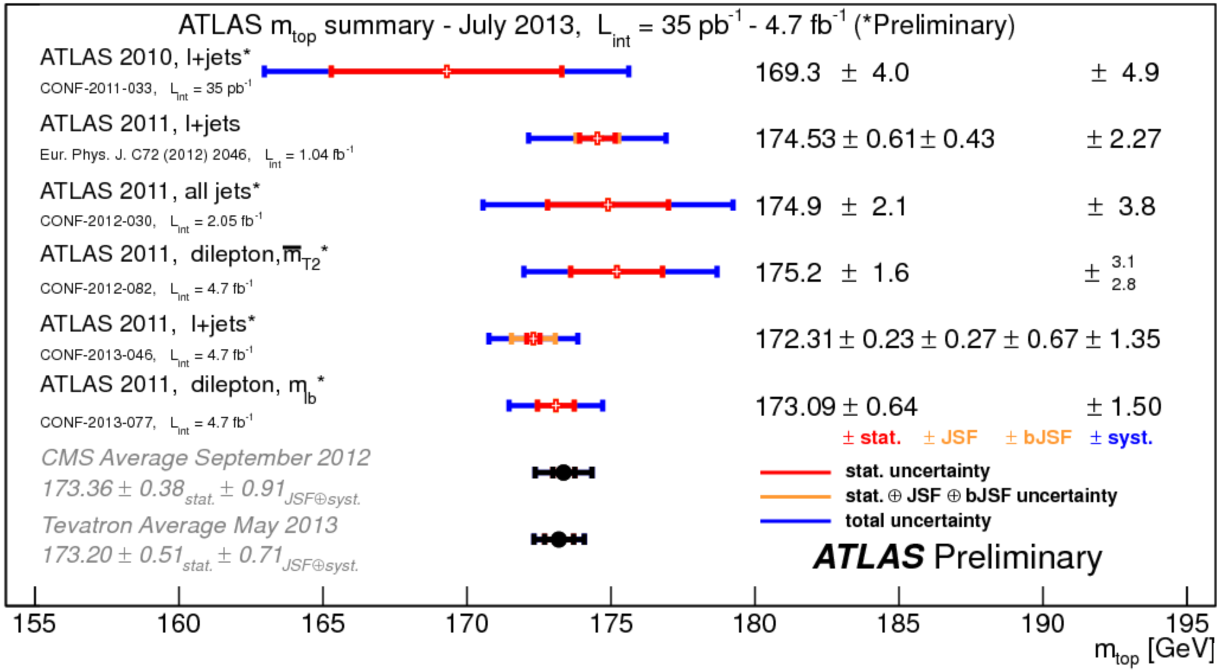
Escaped scrutiny at LEP

Produced by the millions at the LHC

Charge, polarization accessible

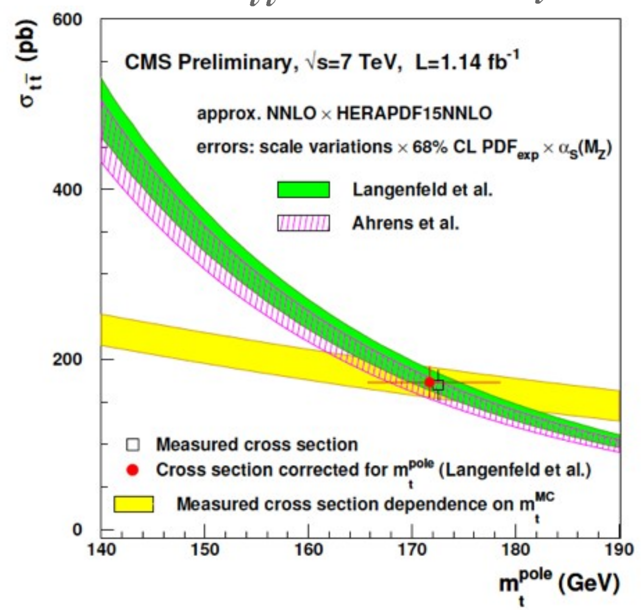


Top quark mass: classical approach



Classical approach:
Extract MC mass
Interpret as pole mass
Admit to a theory error
of order Λ_{QCD}

$$\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \approx 5\,\frac{\Delta m_t}{m_t}$$



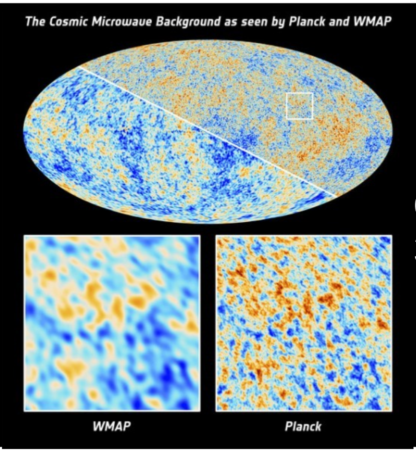
Current precision of the world average is sub-GeV, but has an uncertain interpretation
Extraction from cross-section yields a rigorously defined quark mass, but has insufficient sensitivity

Competing/complementing alternatives:
m_{bl} end-point, differential tt+jet x-section, J/ψ

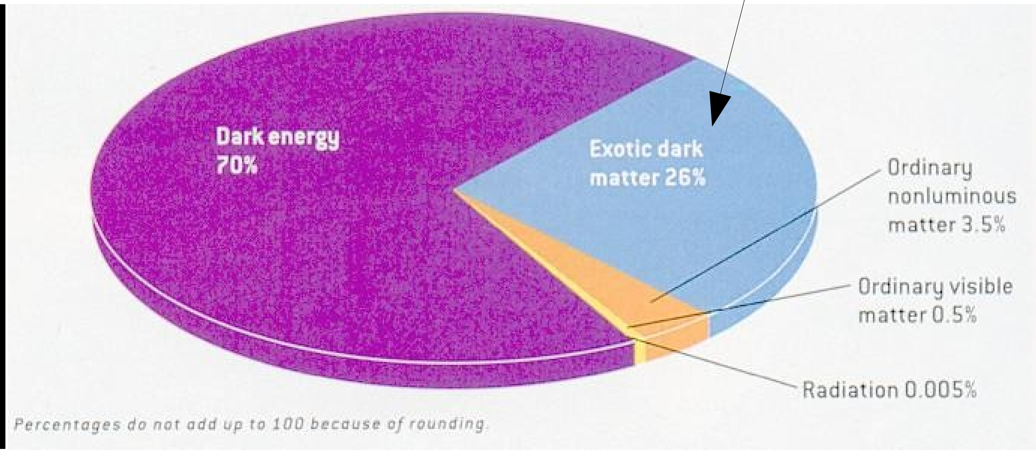
Juste, Mantry, Mitov, Penin, Skands, Varnes, Vos, Wimpenny, CERN-PH-TH-2013-226, arXiv:1310.0799 [hep-ph]

New physics searches

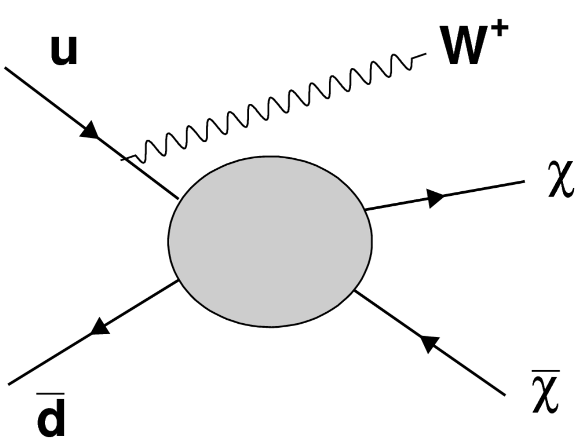
An electrically neutral, stable, massive, weakly interacting particle?



Rotation speed galaxies, gravitational lensing, 3K background...

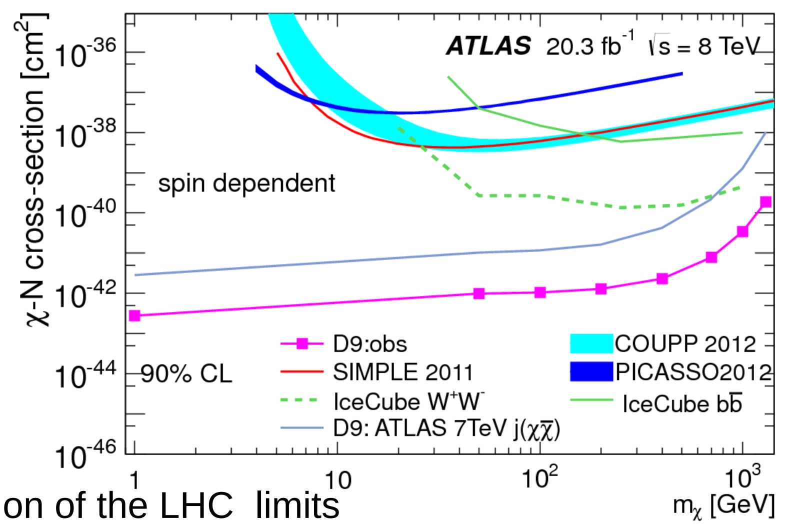


Solid empirical evidence for BSM physics...



Collider cosmology!

For light WIMPs the ATLAS mono-jet, mono-photon and V+MET analyses yields the tightest bounds on the market



See arXiv:1307.5327 for the prospects for the evolution of the LHC limits

Accelerator R&D:
find out HOW to build the next big machine,

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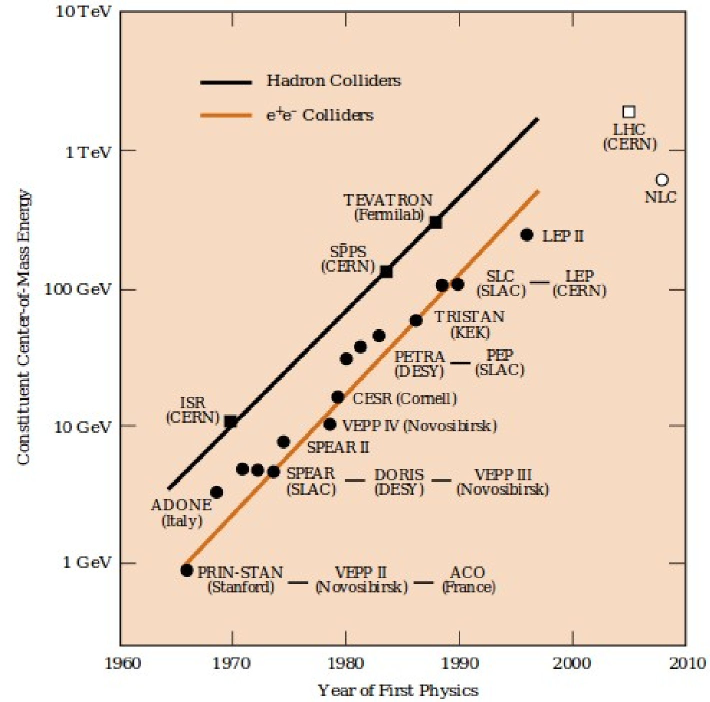
Before we discuss the future...



Back in 1984 people started to dream of a super-conducting hadron collider in the LEP tunnel at CERN

1984–Concept and preliminary studies (Lausanne LHC workshop)

1988–Model magnets demonstrate feasibility

1990–R&D program launched

1994–Project approved by the CERN council

1996-1999–Transfer of technology to industry

1998–Start civil engineering

1998–2001 –Main contracts signed

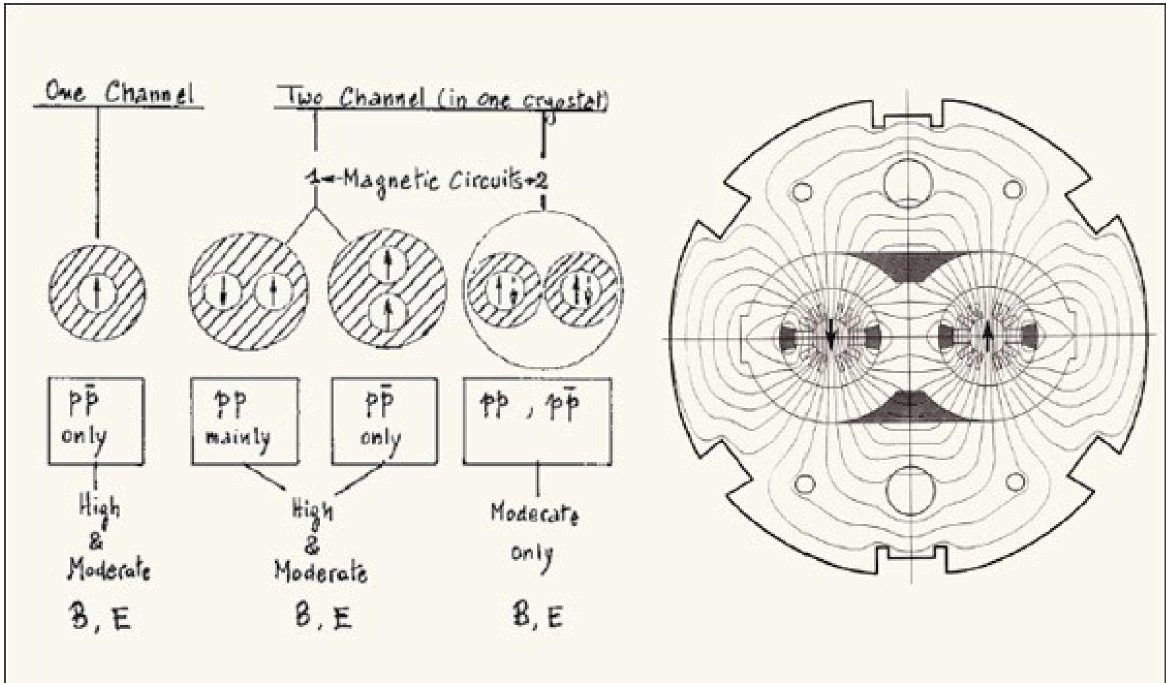
2003–Start tunnel installation

2005-2007 –Magnet installation

2007–First sector test

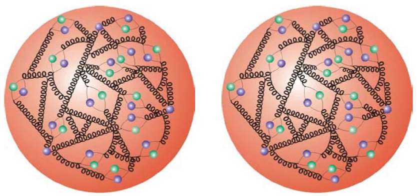
2008-2030 –Physics

LEP and SLC start in 1989
2 TeV Tevatron started in 1983 (to run until 2011)
maybe a 40 TeV SSC in Texas? (canceled 1992/3)

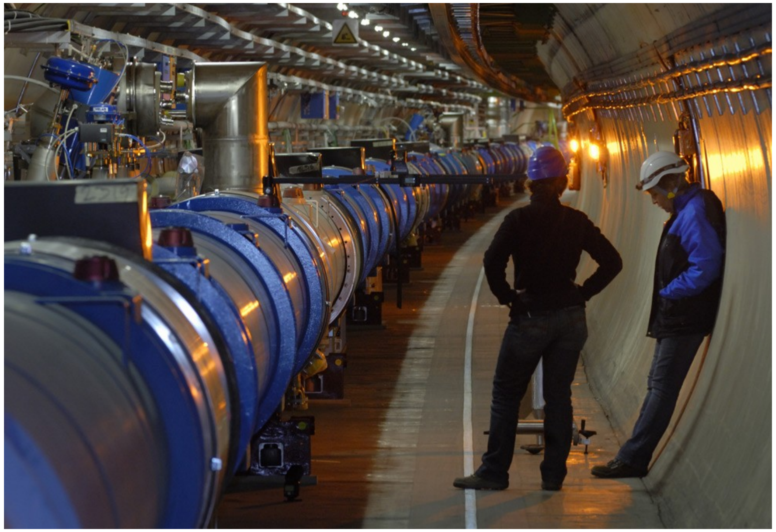


Hadron colliders

Proton proton collisions

p  p

LHC



A running machine!

Direct exploration of the energy regime up to 4-5 TeV

Today: ~30 fb-1 @ 7/8 TeV
~2021 300 fb-1 @ 14 TeV
~2030 3000 fb-1 @ 14 TeV
HL-LHC approval pending, but vigorously pursued

} Make the most of the investment made over the last three decades

? HE-LHC (33 TeV) → magnet R&D ongoing
????? VLHC (100 TeV) → visit www.vlhc.org

Lepton colliders: linear vs. circular

<u>Circular colliders:</u>

Proposal
LEP3 90..240GeV (27 km)
TLEP 90..240..350GeV (80 km)

Storage rings are great for luminosity (and beamstrahlung bkg)

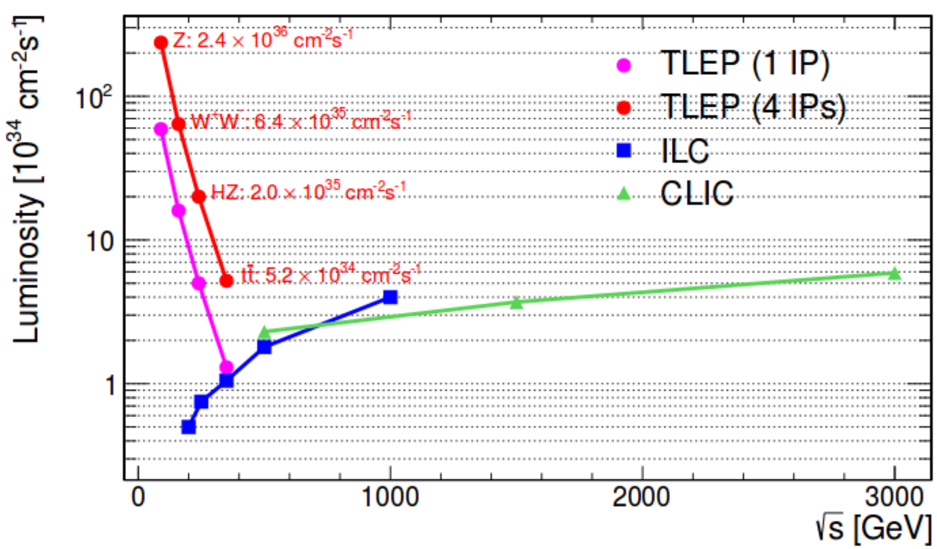
Limiting factor in a ring design for an e^+e^- collider is energy loss by synchrotron radiation:

Power loss P µ E^4/R (E=beam energy, R=radius)

Once the tunnel is built, the center-of-mass energy cannot exceed a maximum (cf. LEP)

TLEP: 100 km ring and continuous top-up can reach 350 GeV

(no $t\bar{t}$H, no Higgs self-coupling)



Comparison of the instantaneous luminosity for proposed lepton colliders
(source TLEP arXiv:1308.6176)

Wanted: heavier electron

Lepton colliders: electrons vs. muons

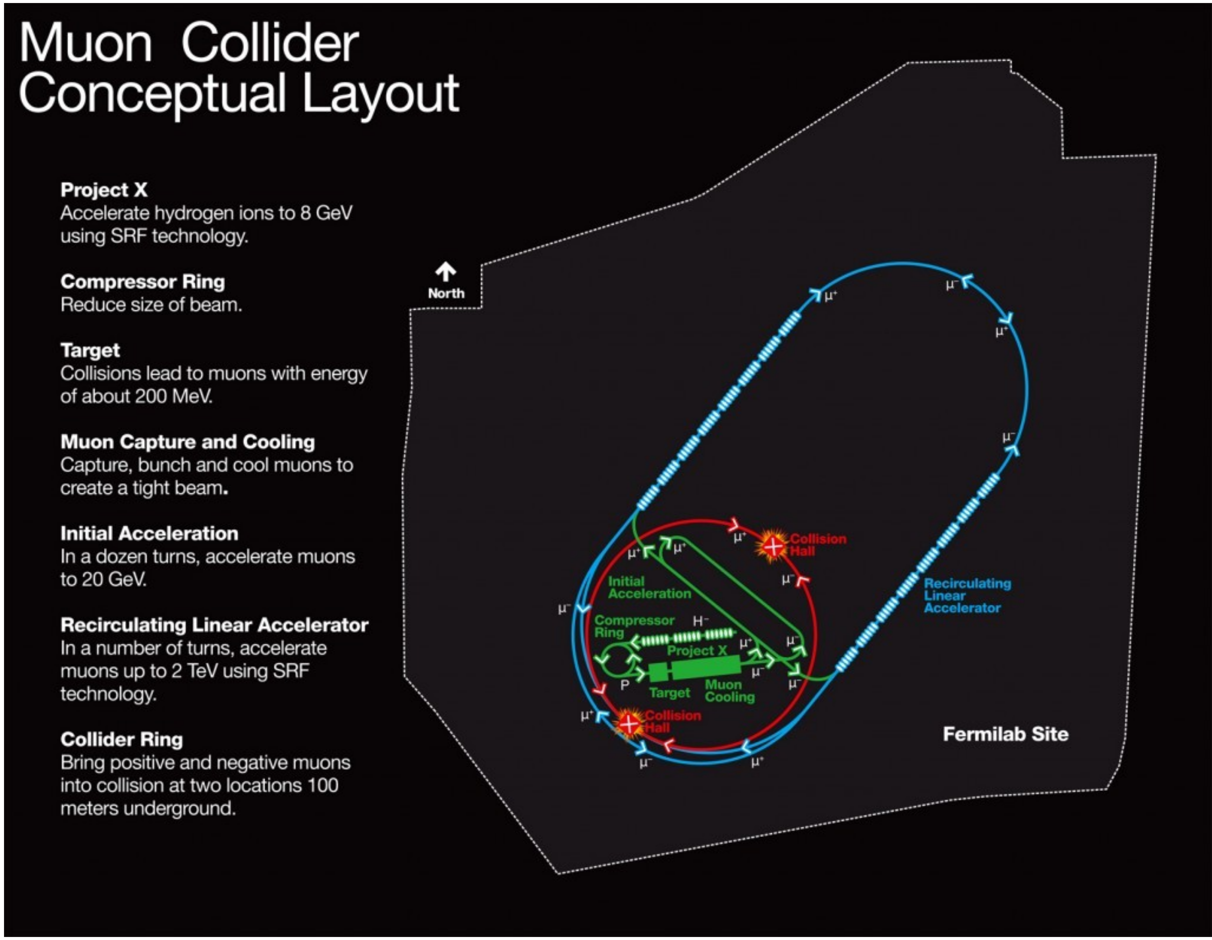
Muons can be accelerated to high energy in a relatively compact ring

Limiting factor in a muon collider is the muon lifetime

Little time to 'cool' and accelerate

No mature design yet, evolution might involve:

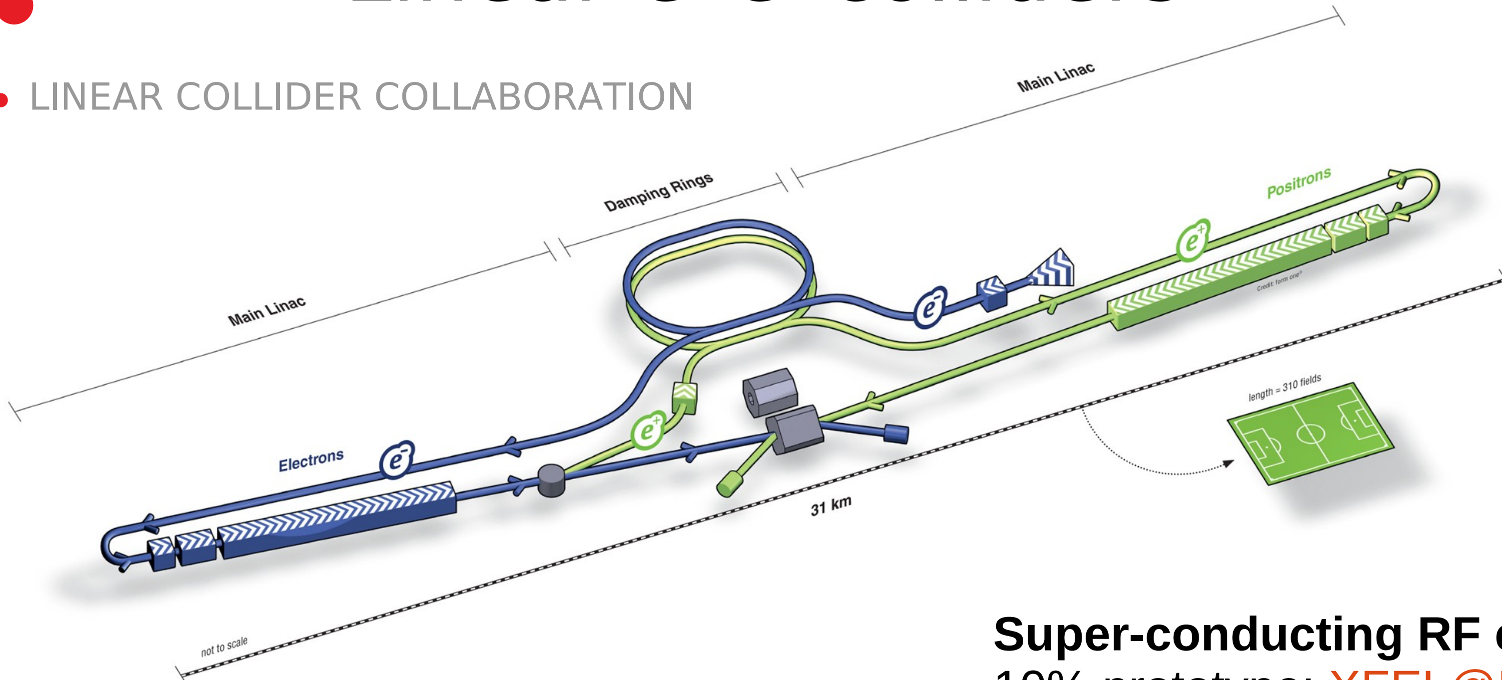
- ν-factory with neutrino's formed along the straight section of the racetrack ring
- Higgs factory (s-channel production, arXiv:1308.2143)
- multi-TeV collider



Wanted: longer-lived muon

Linear e^+e^- colliders

LINEAR COLLIDER COLLABORATION

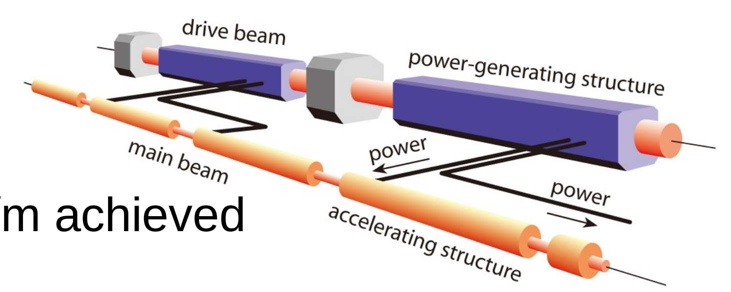


Super-conducting RF cavities
10% prototype: XFEL@DESY
production deployed in industry
ILC is shovel-ready

Linear colliders:

TDR ilc 250...500...1000 GeV

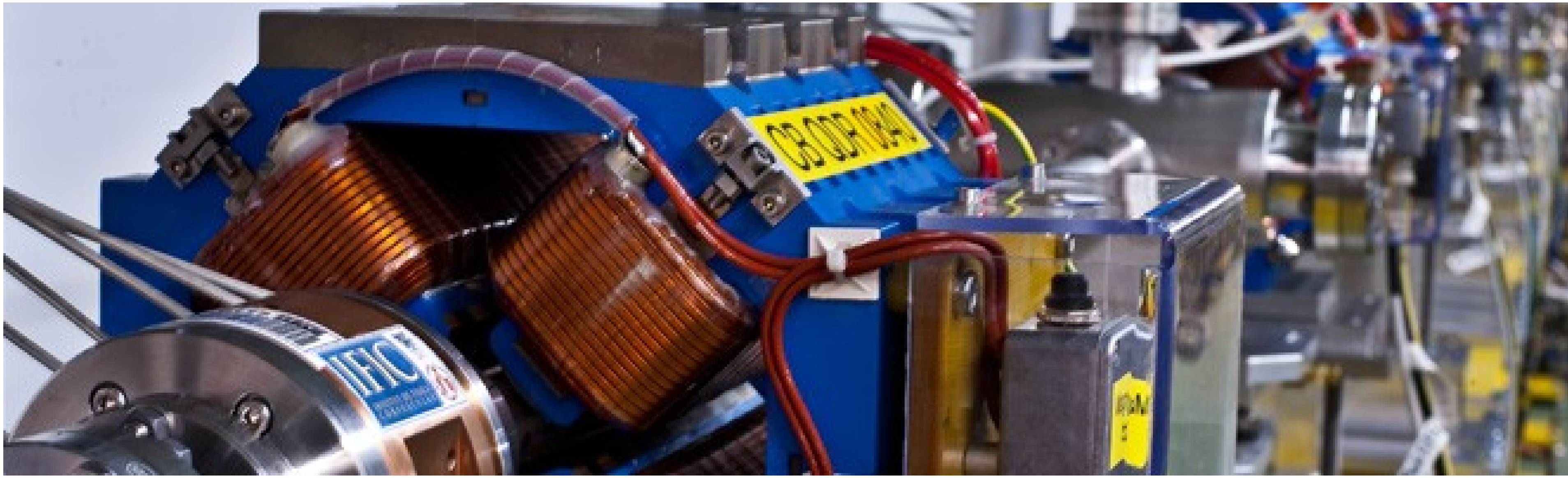
CDR clic 350...1400...3000 GeV



Gradients up to 100 MV/m achieved

Accelerator R&D at IFIC

Inductive Beam Position Monitors for CLIC Test Facility 3



Collimation, optics, instrumentation
Circular Colliders (LHC, HL-LHC) and
Future Linear Colliders (ILC, CLIC)
Contribution to test facility studies
(ATF2 at KEK, CTF3 at CERN)

IFIC Beam position monitor

GAP

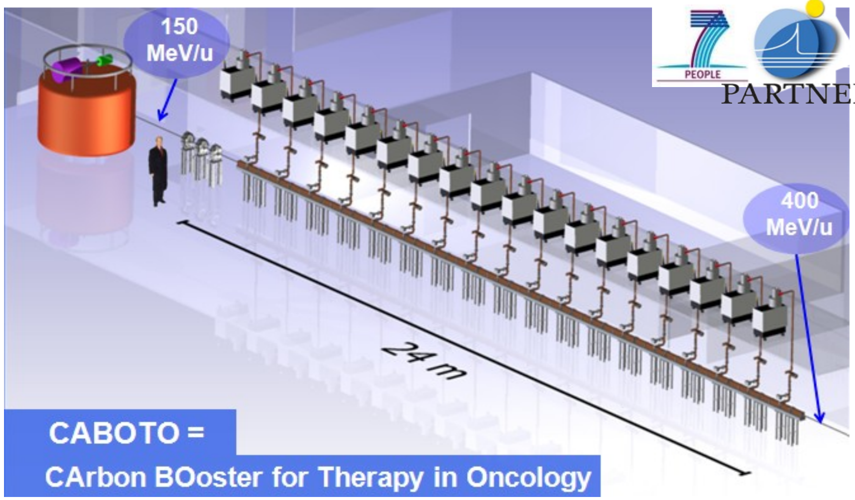
CSIC

IFIC

HIGH-GRADIENT RF STRUCTURES FOR MEDICAL APPLICATIONS

Cavities: gradient is (nearly) everything

Compact, energy-efficient accelerators for tumor treatment with hadrons (**hadrontherapy**)



Compactness *(about 24-m long)*

↑↓

high-gradient RF *(E_S ~ 200 MV/m)*

but

RF breakdowns?

S-band: 3 GHz

(electron linacs conventional radiotherapy)

- 3 GHz TERA **Single-Cell** Cavity

→ high-power **tested**

C-band: 5.7 GHz

(reduce size & cost)

- Three 5.7 GHz TERA **Single-Cell** Cavities

→ final production

- **Multi-Cell** Structure SPARC prototype

→ high-power **tested**

Test at CTF3

Detector R&D:
keep up with technology progress...

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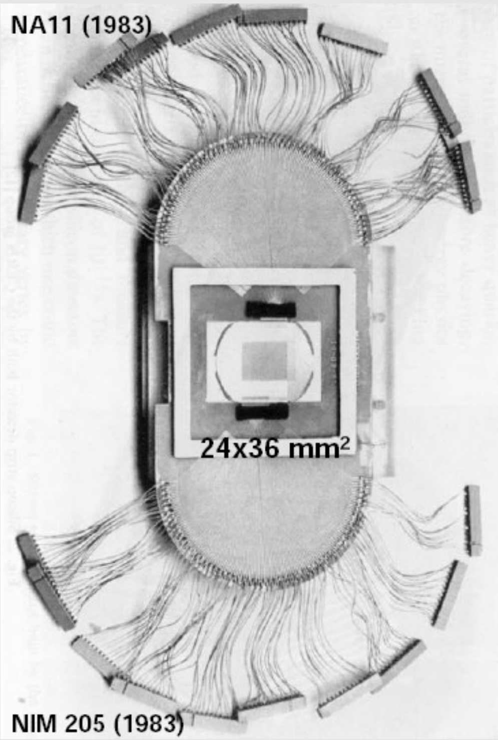
Back in 1984...

Detectors we now take for granted hadn't been conceived yet.

1983...



2000...

2015...

μ-strip detectors were in their infancy, pixels yet to be invented

Better detectors make a difference; in 1989 the LEP prospects expected a precision of 5-8%, but Γ ($Z \rightarrow b\bar{b}$) was measured to 0.5%

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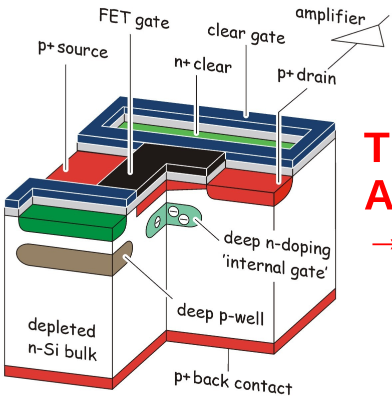
Detector R&D

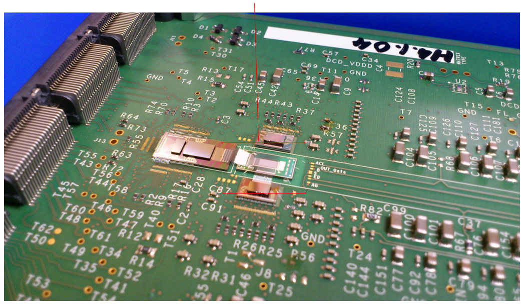


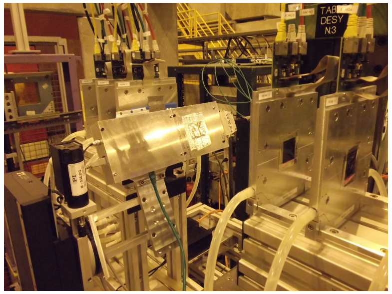
The DEPleted Field Effect Transistor
Amplification stage integrated in the sensor
→ Very low noise (single electron-level demonstrated)

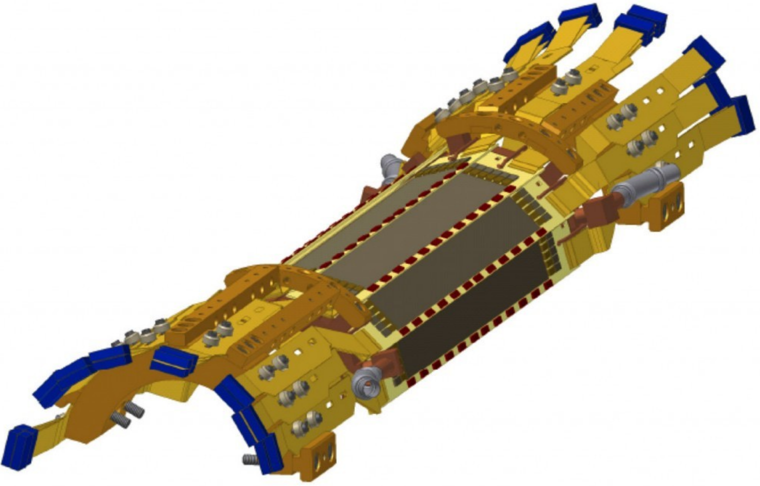
DEPFET
Active Pixel Detector

Proof-of-principle (2004-2010)
Sensor thickness: 50 µm
Pixel size: 20 x 20 µm^2
Resolution: 1-8 µm
Read-out speed: 80 ns/row

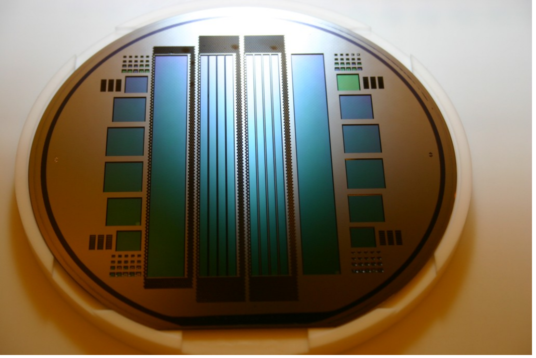
DEPFET sensor



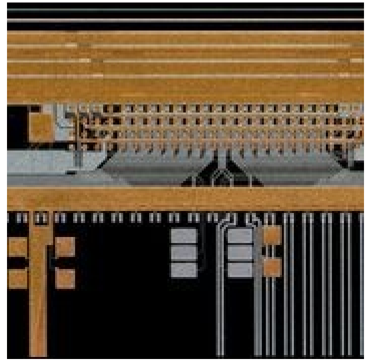


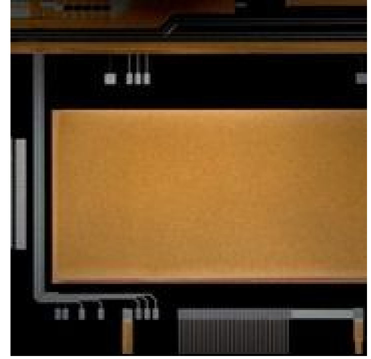


Building a complete system
Belle-II vertex detector (2011-2015)
...



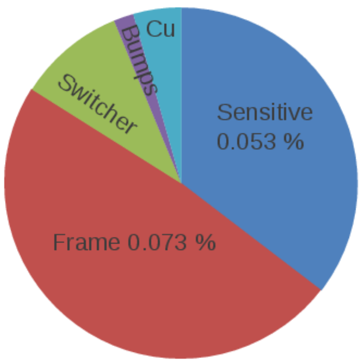
Self-supporting DEPFET ladders





Performance

Power and signal lines on sensor



Sensitive	0.053 % X_0
Frame	0.073 % X_0
Switcher	0.015 % X_0
Cu layer	0.007 % X_0
Bumps	0.003 % X_0
Total ladder	0.15 % X_0

Integration of functionality into sensor
→ reduction the material budget
Miniaturization of structures
→ competitive spatial resolution performance

Full ladder equivalent to 150 μm of Silicon
(order of magnitude better than LHC pixels)

Pushing vertexing performance to the level required for $H \rightarrow c\bar{c}$, $H \rightarrow b\bar{b}$, $H \rightarrow gg$ coupling measurements

	a (μm)	b (μm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
ILC	5	10

Constant term (spatial resolution)

multiple Coulomb scattering term (material budget)

DEPFET APS for a Future Linear e^+e^- Collider, IEEE Trans. Nucl. Sc. 60, 2
Building the Belle II vertex detector: Belle II TDR, arXiv:1011.0352 [physics.ins-det]
DEPFET Macropixel Detectors for MIXS IEEE Trans. Nucl. Sc. 59, 5 (2012)
DEPFET X-Ray Imager for the European XFEL, IEEE Trans. Nucl. Sc. 59, 6 (2012)

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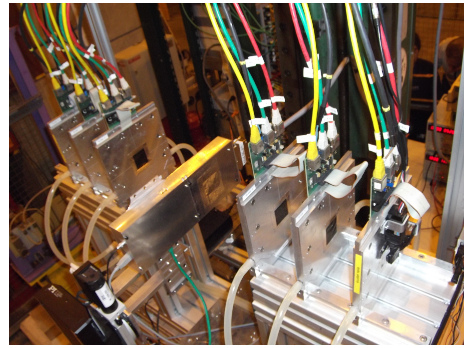
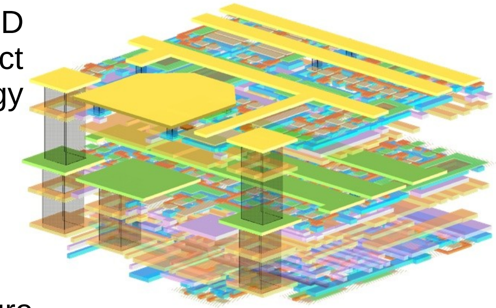
R&D infrastructure

AIDA
Advanced European Infrastructures for Detectors at Accelerators



Beam test infrastructure

Access 3D interconnect technology

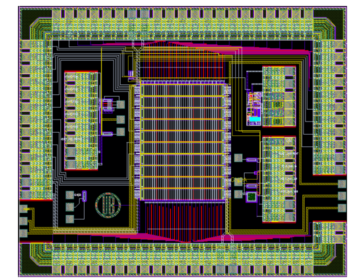


Spanish Future Collider network
coordination at national level

Spanish technological institutes
- ITA: grounding, power, ECM
- INTA: C-fibre support structures
- CNM: μ-strips, 3D pixels, …
- nano-photonics: bump-bonding

People: provide students with a background in “hardware”

ASIC design: electronics department UB



IFIC clean room

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The physics of a future (linear) e^+e^- collider

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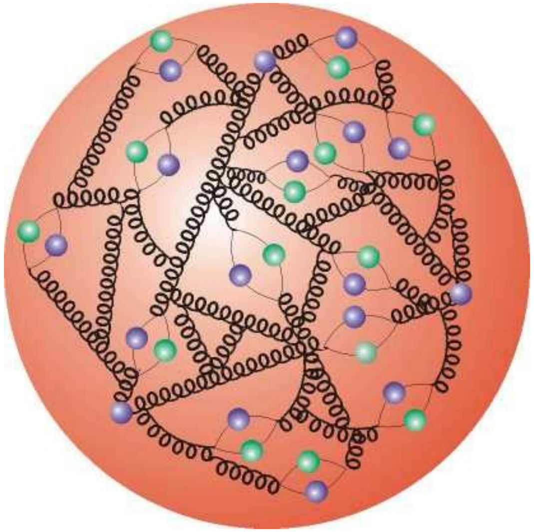
lepton vs. hadrons

Colliding (composite) hadrons is different from colliding (elementary) leptons in several important ways

At lepton colliders:

- **Every GeV delivered to the projectile is used**:
  a 2 TeV hadron collider is not enough to find a 126 GeV particle
  a 250 GeV lepton collider is!
- **The initial state is precisely controlled:**
  total energy sums up to 2 E_b
  beam polarization (at linear colliders)
- **Production rates are democratic**:
  Rate for Higgs, top and major backgrounds are ~ equal
- **Non-collision events are approximately empty:**
  ~no pile-up, relaxed read-out times, ~no radiation damage
- **Production rates are precisely calculable:**
  5% uncertainty on LHC $t\bar{t}$ cross-section is a milestone,
  per mil level is feasible at LC



Complementary strengths and weaknesses

The physics programme of a Linear Collider

91 GeV ***GigaZ*** (*optional*) high-lumi run at the Z-pole

- ➔ ultra-precise measurements of electroweak observables

250/350 GeV *Higgs factory*

- ➔ BR(h → VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)
- ➔ Absolute measurement of HZZ coupling (recoil mass)

345-355 GeV *top threshold scan*

- ➔ Precise top quark mass (width, α_s and top Yukawa coupling)

500 GeV *(nominal ILC energy)*

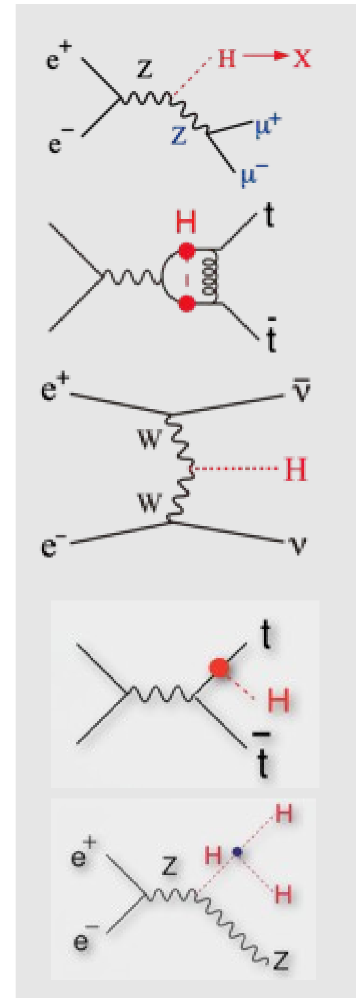
- ➔ HWW coupling → total width
- ➔ ttH → direct top Yukawa
- ➔ Top form factor measurements

1 TeV *(ILC energy upgrade)*

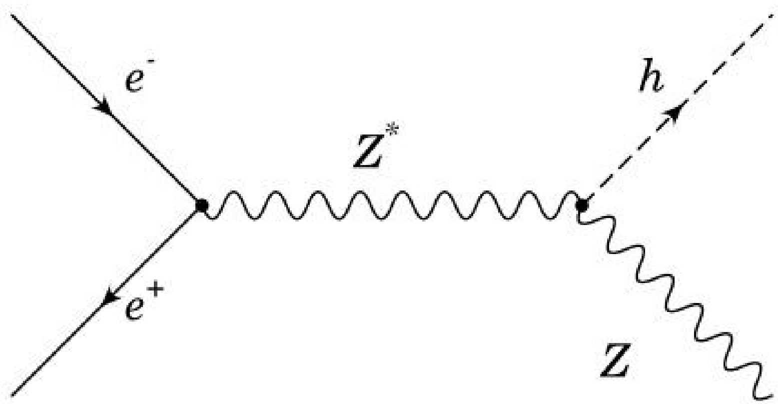
- ➔ Higgs self-coupling

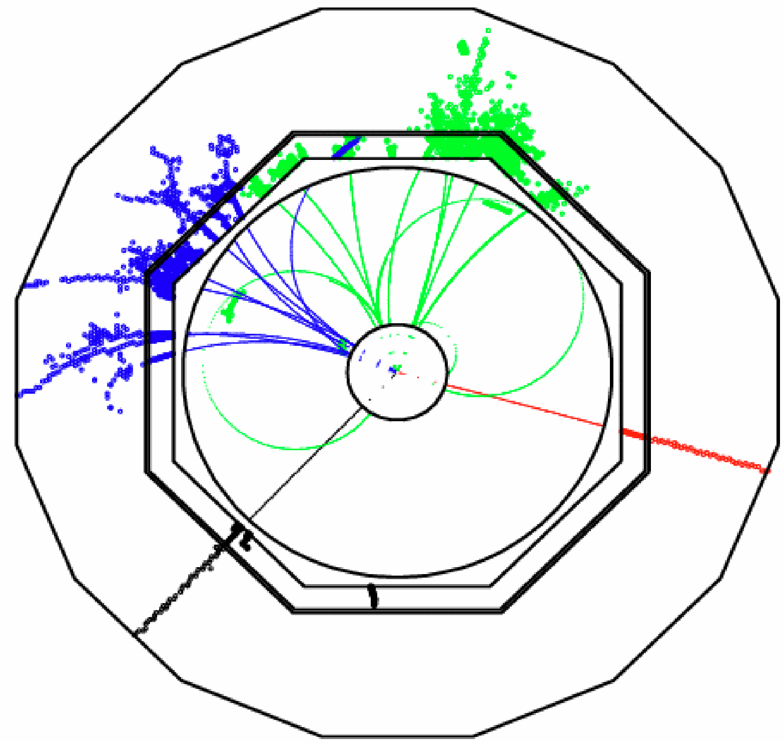
1.5 - 3 TeV *(CLIC only)*

- ➔ Running of λ, new physics



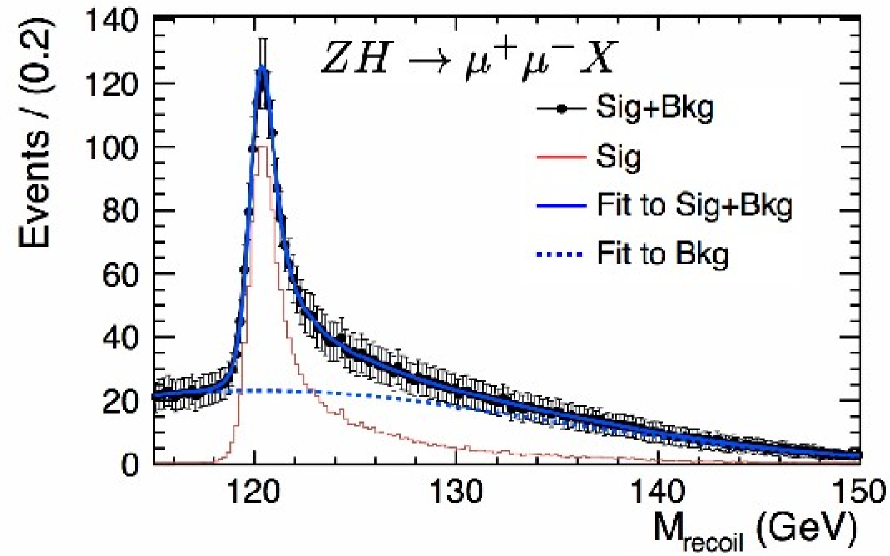
Recoil mass method





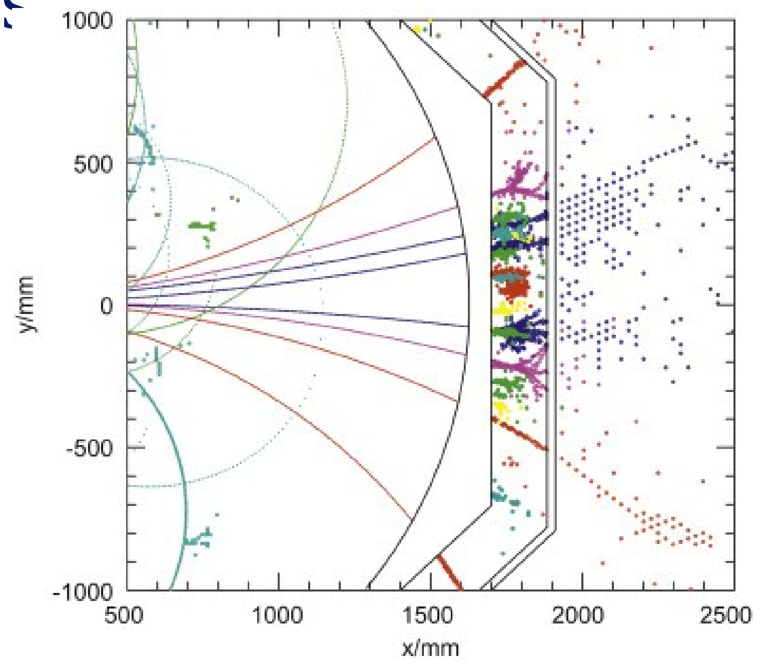
Infer the mass of the system recoiling against the Z boson from the known center-of-mass energy and the Z boson momentum

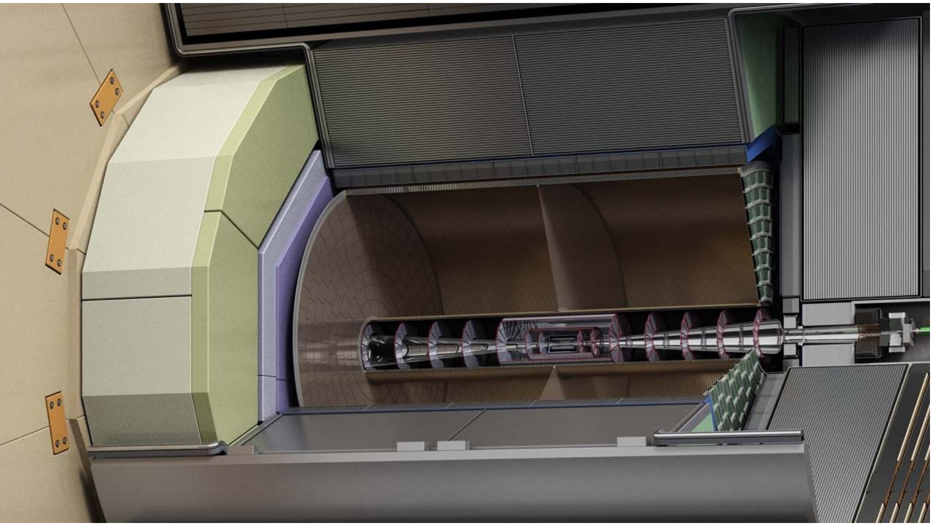
Count the relative frequency of Higgs decays, including invisible decays



LC detectors

Particle Flow: highly granular calorimetry inside a large 3.5-5 Tesla solenoid allows to follow every single particle produced from the cradle to the grave: $\Delta E/E \sim 3\text{-}5\%$





- **Transparent and precise tracking/vertexing:**

$\Delta(1/p_T) \sim 10^{-5}\ \mathrm{GeV}^{-1}$

$\Delta(d_0) \sim 5 \oplus 10\text{-}20 / (p \sin^{3/2}\theta)$

Detailed Geant4 model and sophisticated reconstruction software allow realistic estimates of performance

LC Higgs boson couplings

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality. The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of (−0.8, 0.3) at 250 and 500 GeV and (−0.8, 0.2) at 1000 GeV. CLIC numbers assume polarizations of (−0.8, 0) for energies above 1 TeV. TLEP numbers assume unpolarized beams.
Snowmass Higgs working group (same people, same assumptions everywhere)...

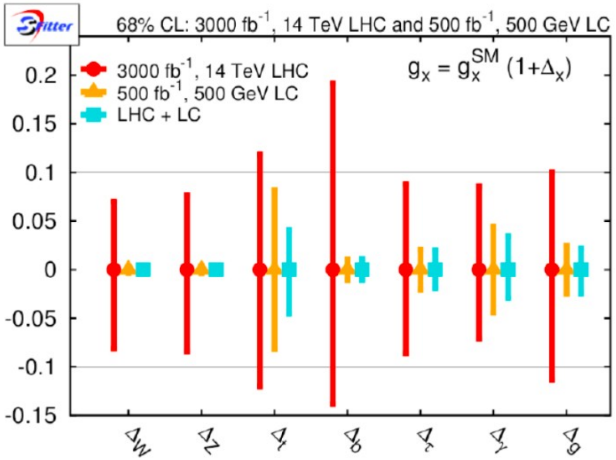
Order of magnitude better precision

LC complements LHC in several ways

(total width, $H \to gg$, $H \to c\bar{c}$, $H \to b\bar{b}$)

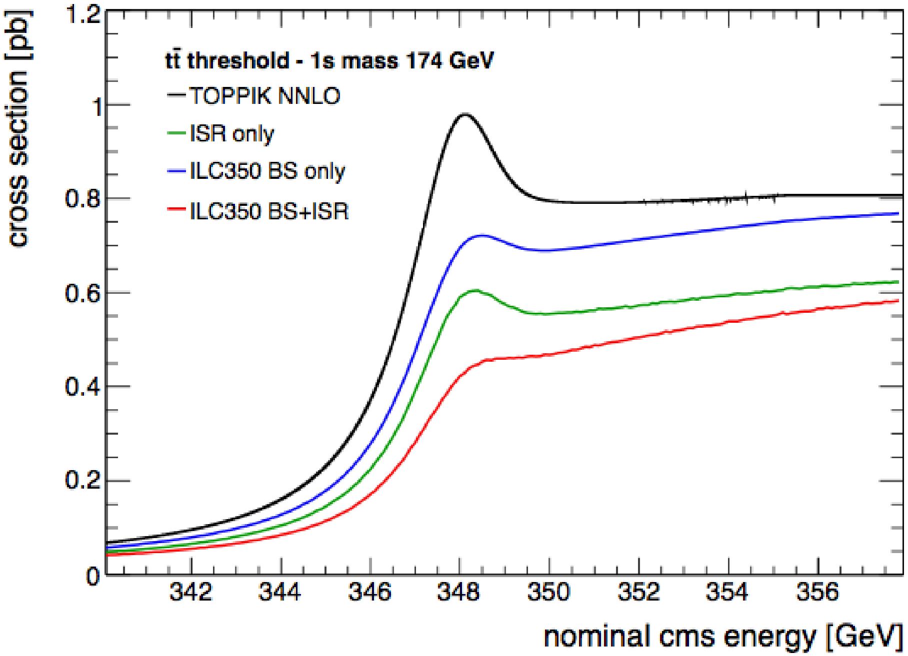
$H \to$ invisible: 6-17% at CMS, < 0.7% in ILC250

An excellent New Physics search channel



IFIC CSIC

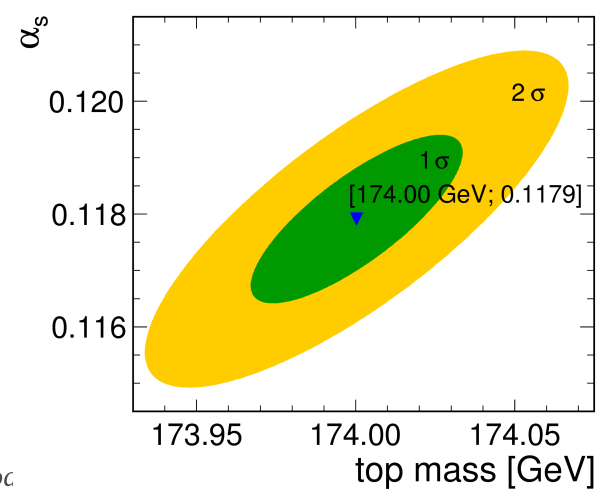
Top quark physics



Threshold scan @ 344-352 GeV
10 points x 10/fb each (< 1 year)

100 MeV precision on top quark mass
30 MeV stat., 50 MeV syst., 80 MeV theory
(don't let anyone tell you we can get to 10 MeV)
Rigorous interpretation, quantifiable theory error

Simultaneous extraction of α_s, Γ_t, y_t



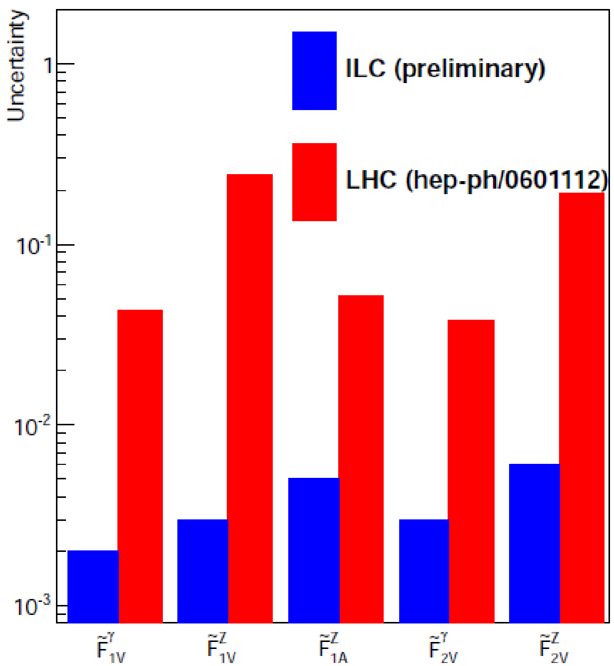
Mitov, Vos, Wimpenny et al., Determination of the top quark mass circa 2013: methoc subtleties, perspectives, CERN-PH-TH-2013-226, arXiv:1310.0799 (submitted to EPJC)
Asner, Hoang, Kiyo, Pöschl, Sumino, Vos, Top quark precision physics at the ILC, arXiv:1307.8265

Top quark couplings

$$\Gamma^{\mu}_{t\bar{t}(\gamma,Z)} = ie\left[\gamma^{\mu}\left[F^{\gamma,Z}_{1V} + F^{\gamma,Z}_{1A}\gamma^{5}\right] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}\left[F^{\gamma,Z}_{2V} + F^{\gamma,Z}_{2A}\gamma^{5}\right]\right]$$

Linear Collider:
$\sqrt{s}$ = 500 GeV, ∫L = 500/fb
Polarization:
P(e$^-$) = +/- 80%, P(e$^+$)= -/+ 30%

Large Hadron Collider: 14 TeV, 300/fb



Order of magnitude better precision on top quark couplings to photon and Z boson

Control over beam polarization is crucial to disentangle photon and Z components

A precise determination of top quark electro-weak couplings at the ILC operating at $\sqrt{s}$=500 GeV, Amjad, Boronat, Frisson, García, Pöschl, Ros, Richard, Rouëné, Ruiz Femenia, Vos, arXiv:1307.8102

Top Couplings: pre-Snowmass Energy Frontier 2013 Overview

Top quark precision physics at a linear e^+e^- collider, PoS (ICHEP2012) 208

Linear Collider TDR, arXiv:1306.6352

CSIC IFIC

World-wide strategy

Japan

"*We will call for inter-governmental negotiations with European and American governments in the first half of 2013*", Minister Shimomura (MEXT)

Kitakami site in Tohoku, North Japan selected in August 2013

AsiaHEP/ACFA (September 2013) Asia ≠ Japan

"AsiaHEP/ACFA believes that the ILC is the most promising electron positron collider to achieve next generation physics objectives […] AsiaHEP/ACFA welcomes the proposal by the Japanese HEP community [...and] looks forward to a proposal from the Japanese Government to initiate the ILC project [...]"

European Strategy (Cracow 2012, approved by CERN council)

"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. […] The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation."

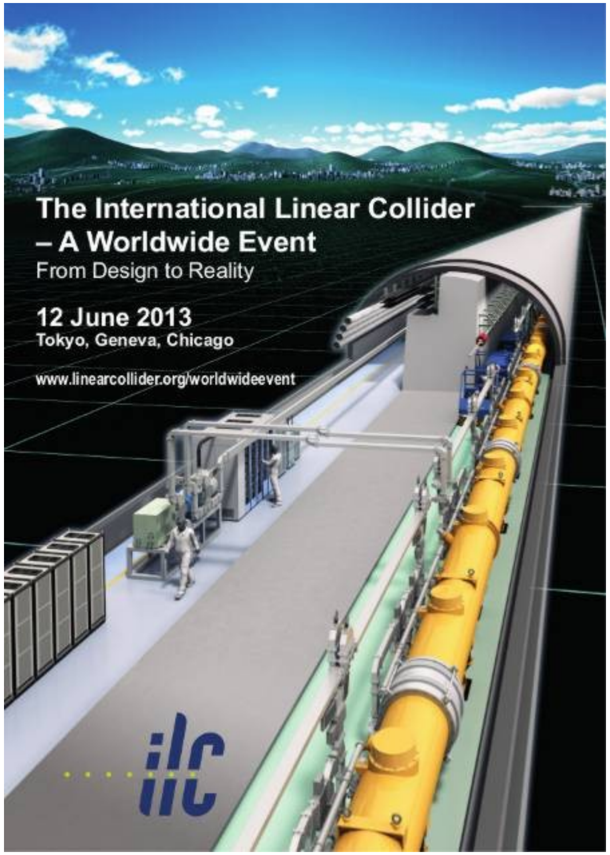
American Strategy (Snowmass 2013)

P5 (particle physics project priorization panel)
to hand in the report in May 2014

Physics may tell us otherwise at any time. Be ready for anything!

(still from promotional video of Sefuri site)

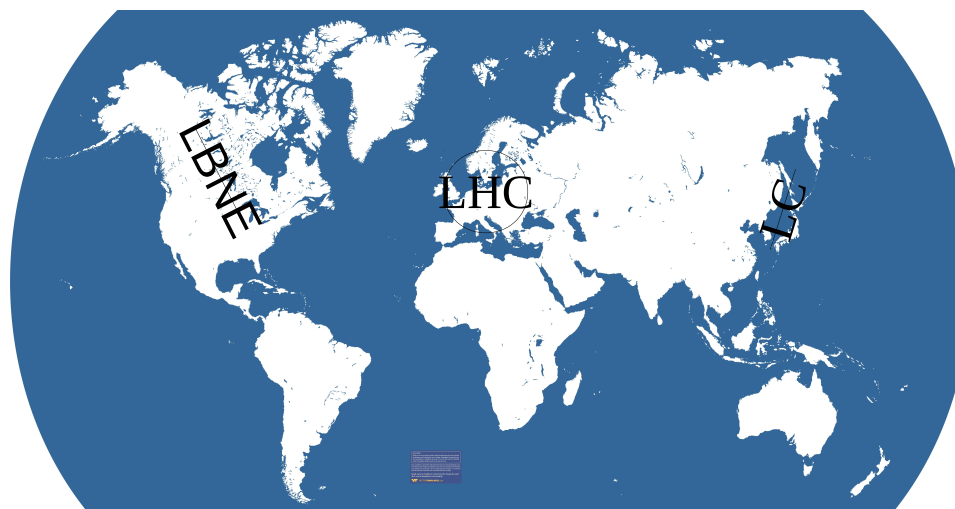
From design to reality – collider politics



June 2013:
ILC TDR

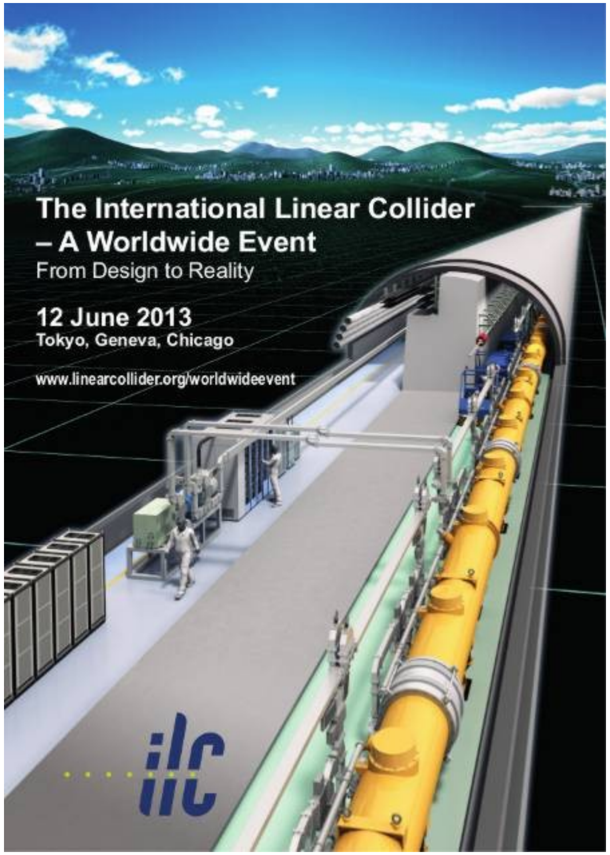
LCC: joint effort of CLIC & ILC (Lyn Evans)

A global program??



Marcel.Vos@ific.uv.es

From design to reality – collider politics



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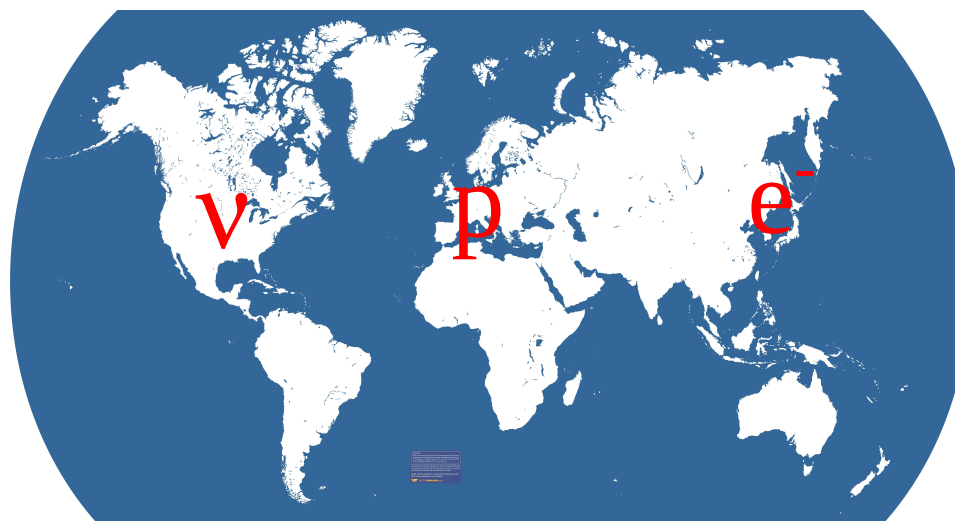

Marcel.Vos@ific.uv.es

Summary

Exciting times for particle physics
Expect a long LHC program (incl. upgrades)
yielding a ~5% level characterization of the Higgs boson couplings

Accelerators & detectors are crucial “tools for discovery”
- proposals take a lot of time & effort to mature
- better accelerators & detectors allow to extract more physics

The next big machine appears on the horizon:
A linear e^+e^- collider at the energy frontier offers:
- x10 increase in precision for known particles, including Higgs boson!
- a complementary opportunity to discover new physics