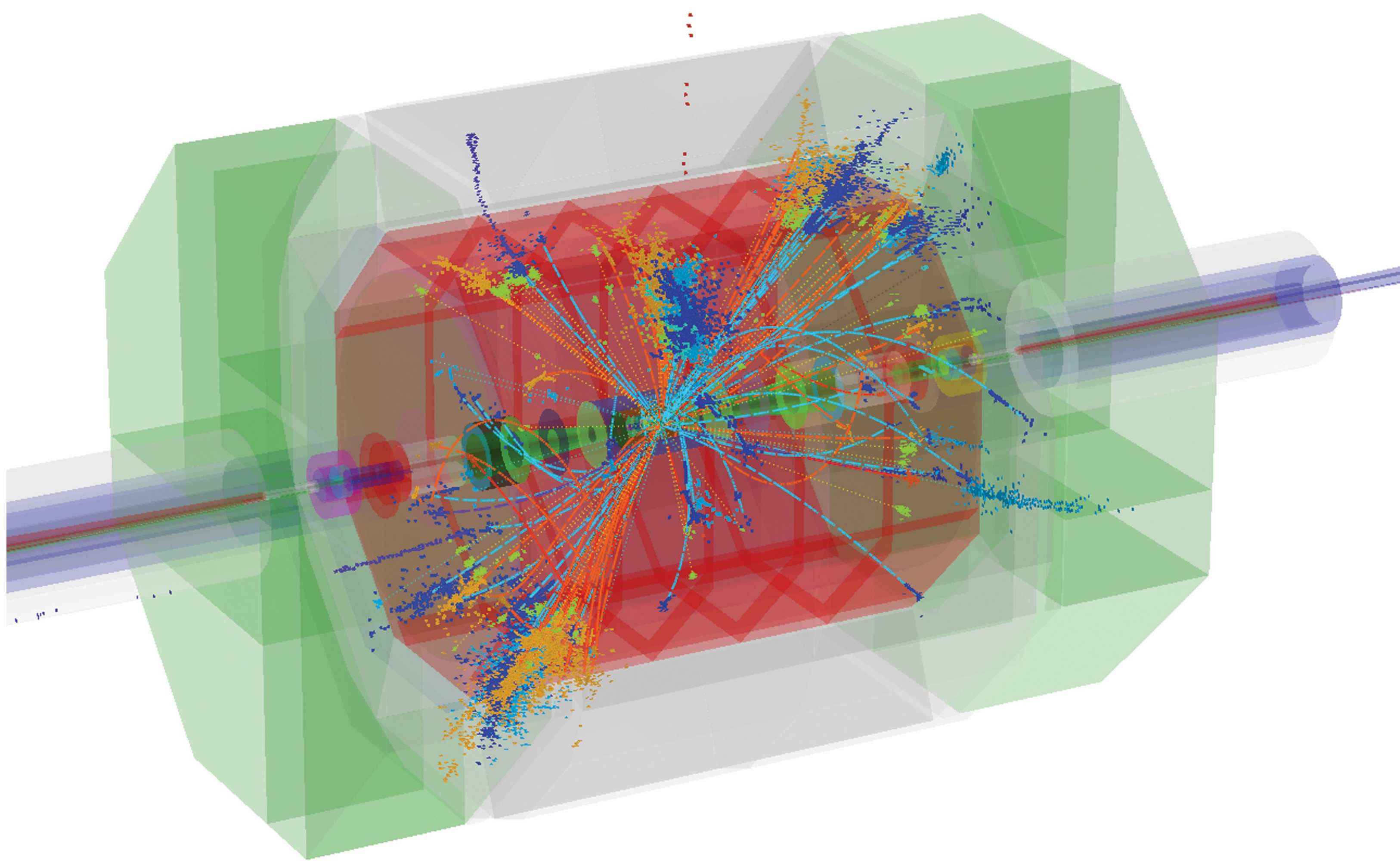
Overview of the CLIC physics potential

Marco Szalay - Max Planck Institute for Physics - München
On behalf of the CLICdp collaboration

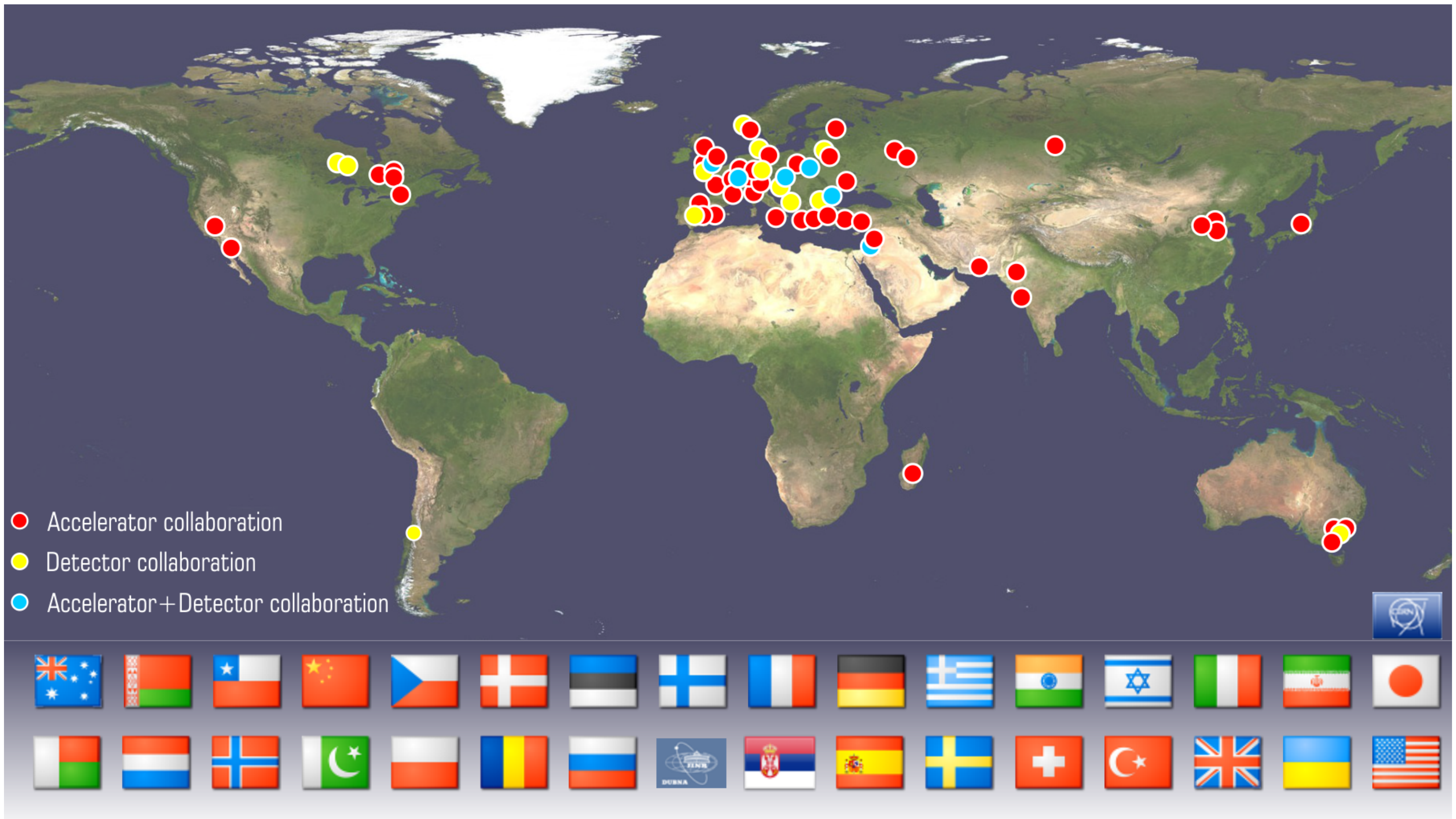
Le Rencontres de Physique de la Vallèe d'Aoste -
La Thuile, 12-03-2016

Outline

- CLIC Collaboration
- Accelerator Design
- Physics Requirements
- Detector Design
  - Vertex & Tracker
  - ECAL & HCAL
- Physics benchmarks
  - Top physics
  - Higgs physics
  - BSM physics



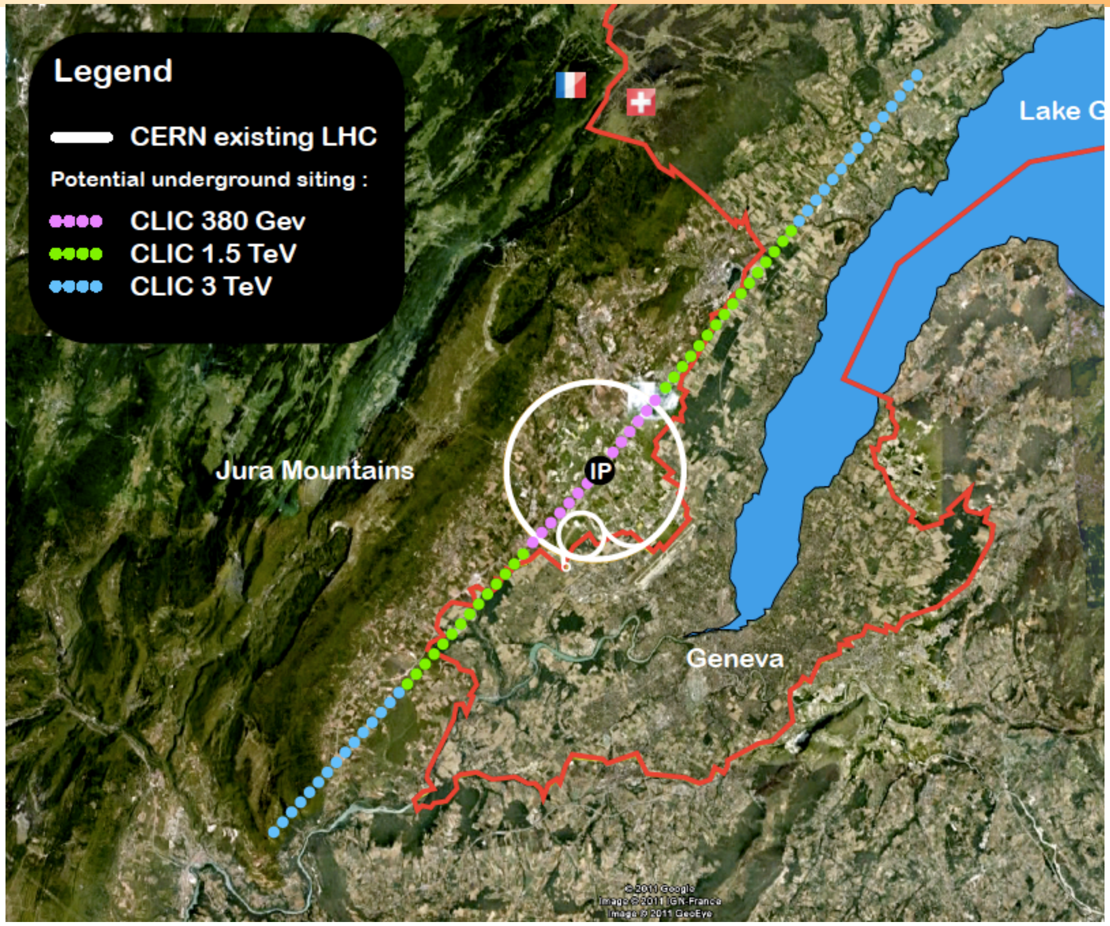
CLIC Collaboration



- Over 80 institutes from more than 30 countries
- Aim to develop and build multi-TeV e^+e^- collider and detector
- clic-study.web.cern.ch and clicdp.web.cern.ch for more information

Accelerator and Detectors

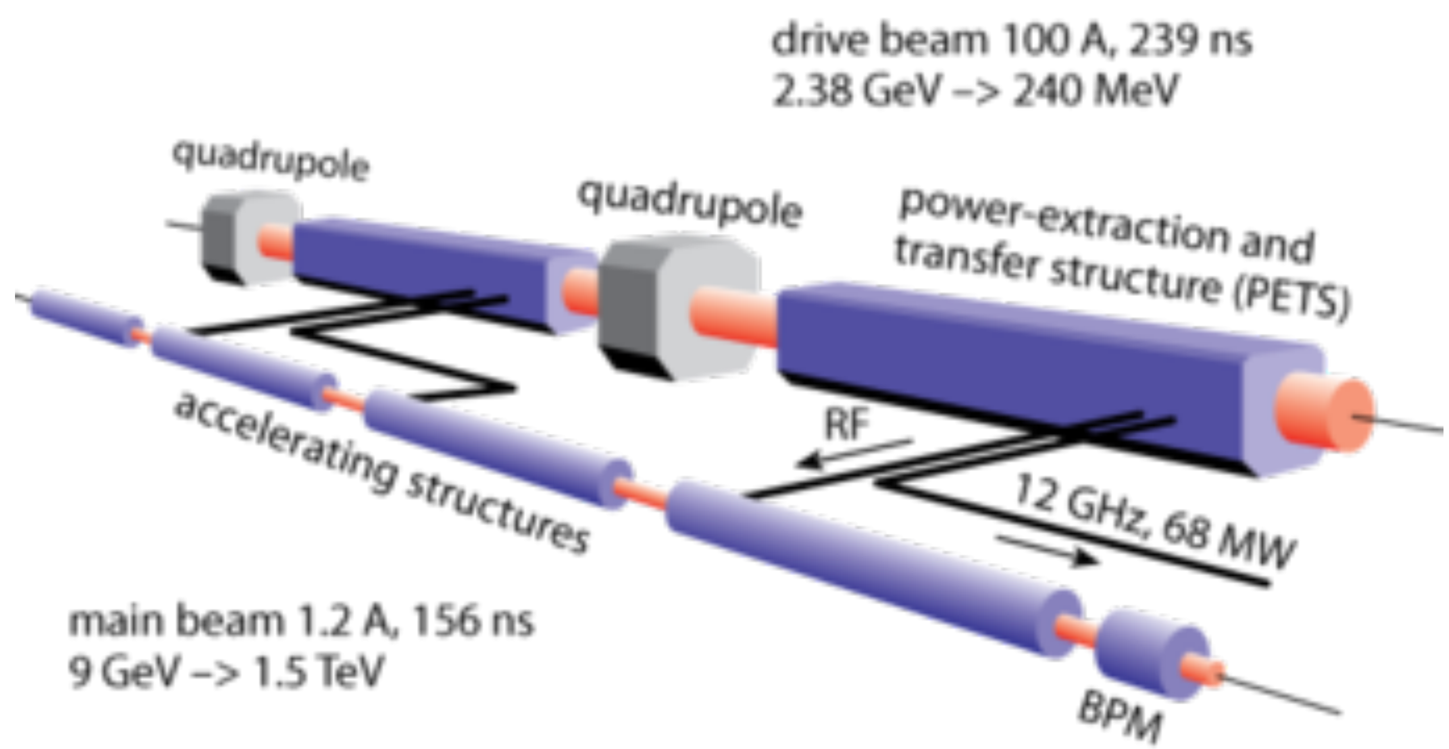
CLIC - Accelerator Design



CLIC (Compact LInear Collider)

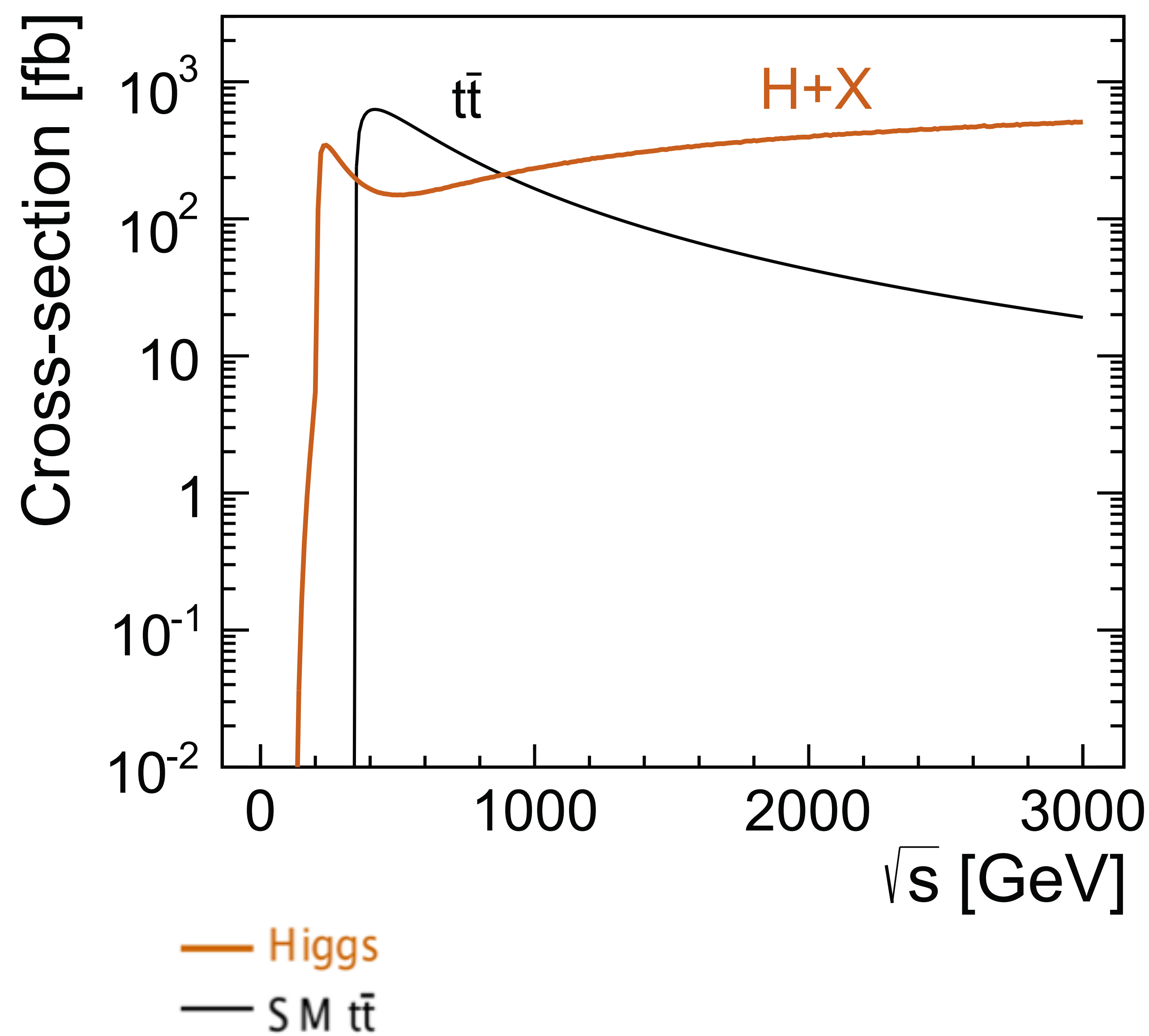
- 2-beam scheme:
  high-intensity, low-energy beam drives low-intensity, high-energy beam
- Warm RF technology
- Laser straight

	380 GeV	1.5 TeV	3 TeV
Lenght [km]	11.4	29	50.1
Bunch rate [ps]		500	
$\sigma_{x,y}$ [nm]	150x3	60x1.5	40x1
$\mathcal{L}$ [$10^{34}cm^{-2}s^{-1}$]	1.5	3.7	5.9
$\int\mathcal{L}$ [ab^{-1}]	0.5	1.5	3
Gradient [MV/m]	72	72-100	72-100
Power [MW]	252	364	589



Physics potential

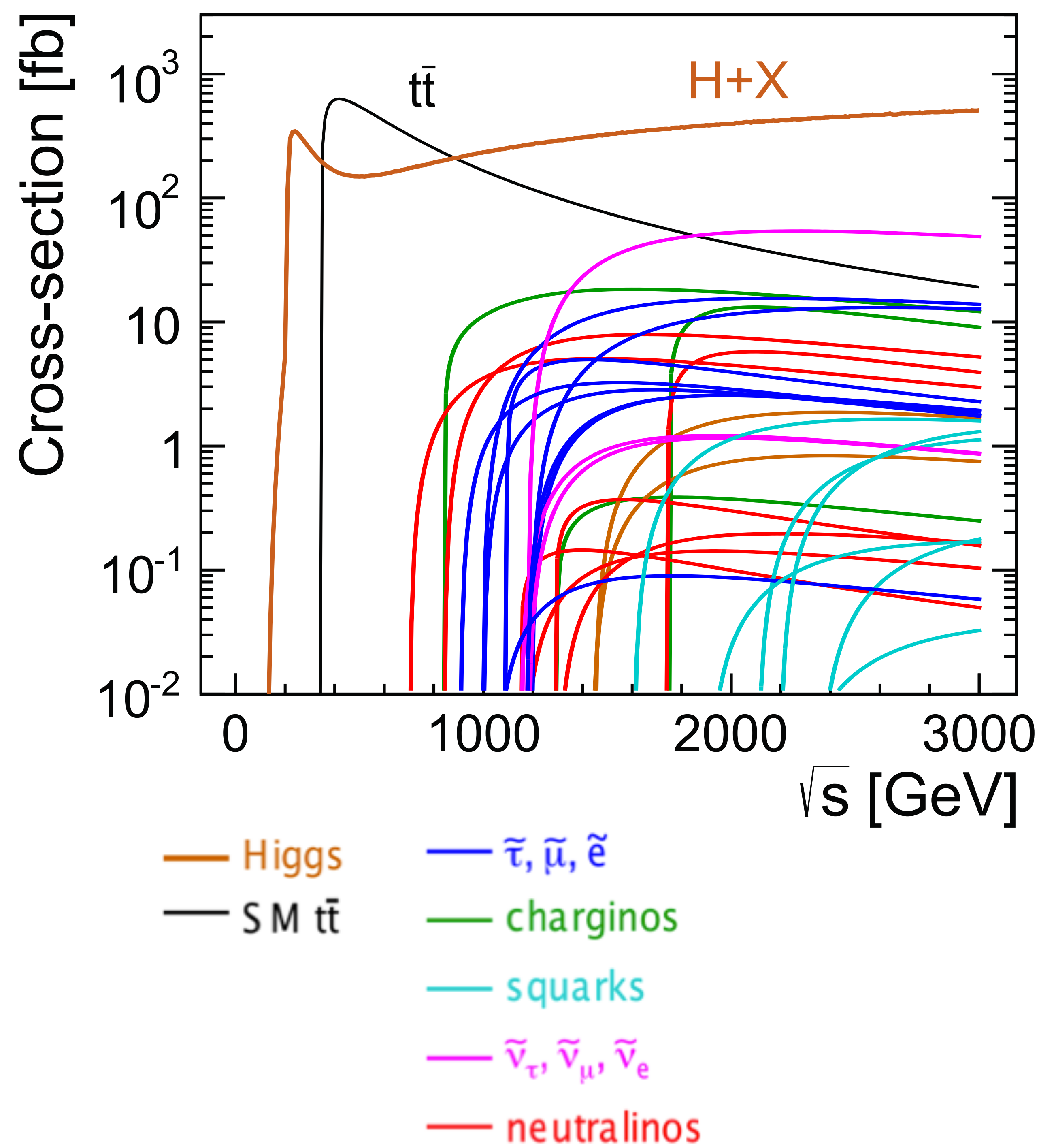
- Precision measurement of:
  - Higgs sector (couplings, mass, potential)
    - model independent H to Z coupling
  - Top quark (mass, width)
  - EW sector



Physics potential

- Precision measurement of:
  - Higgs sector (couplings, mass, potential)
    - model independent H to Z coupling
  - Top quark (mass, width)
  - EW sector

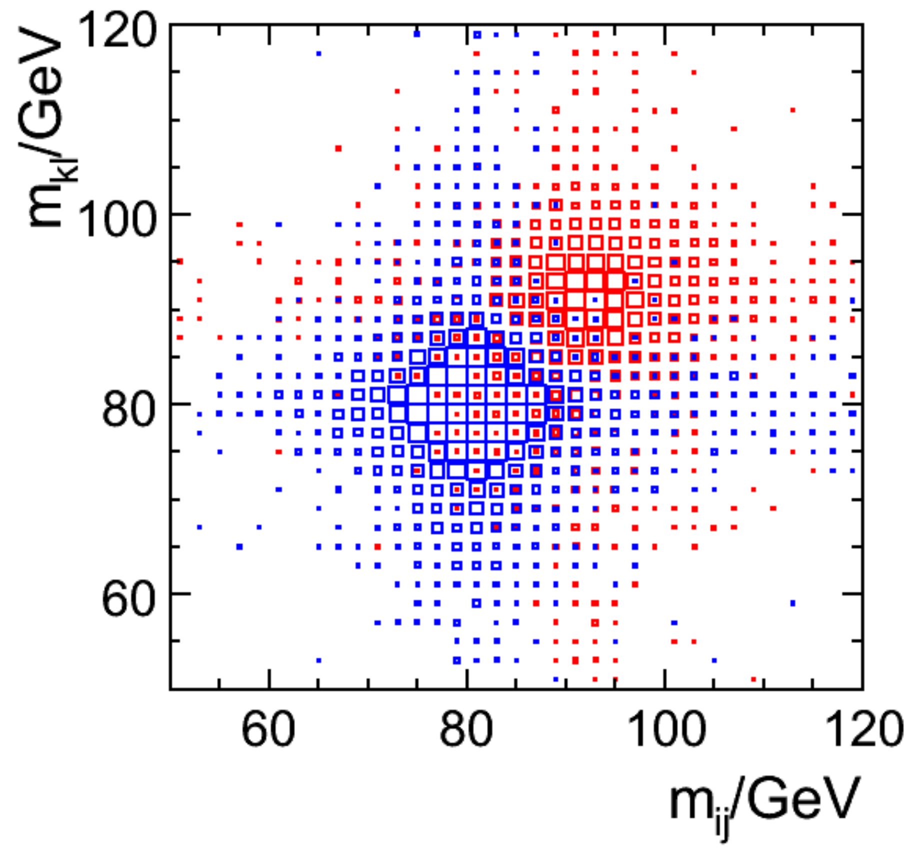
- Search for new physics:
  - Direct reach up to $\frac{\sqrt{s}}{2}$
  - Indirect reach far beyond $\sqrt{s}$

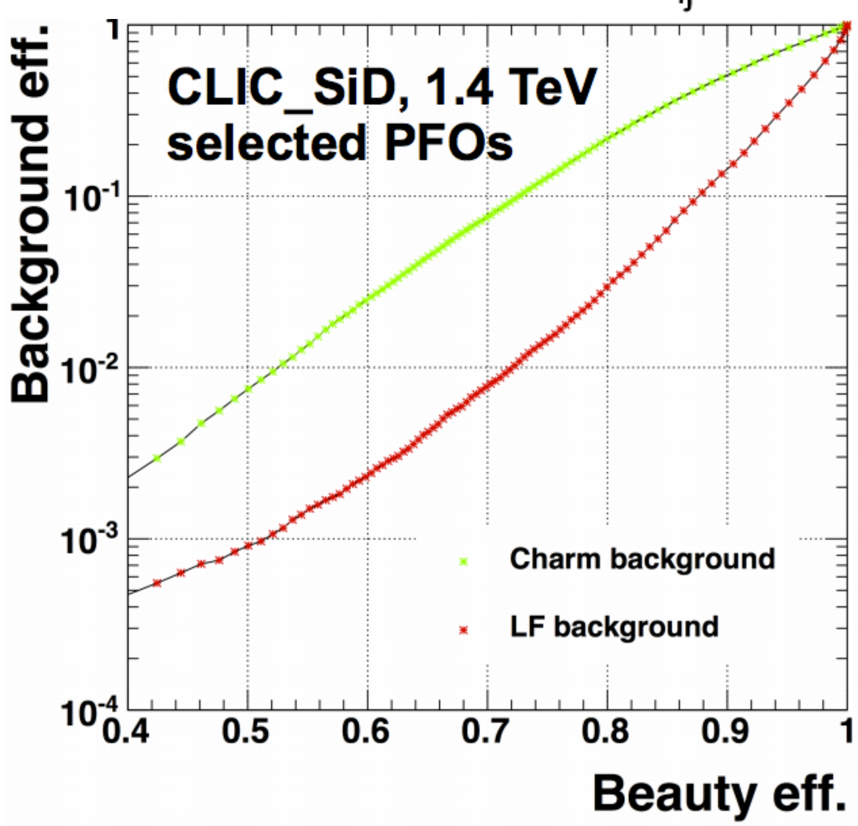


Detector Requirements

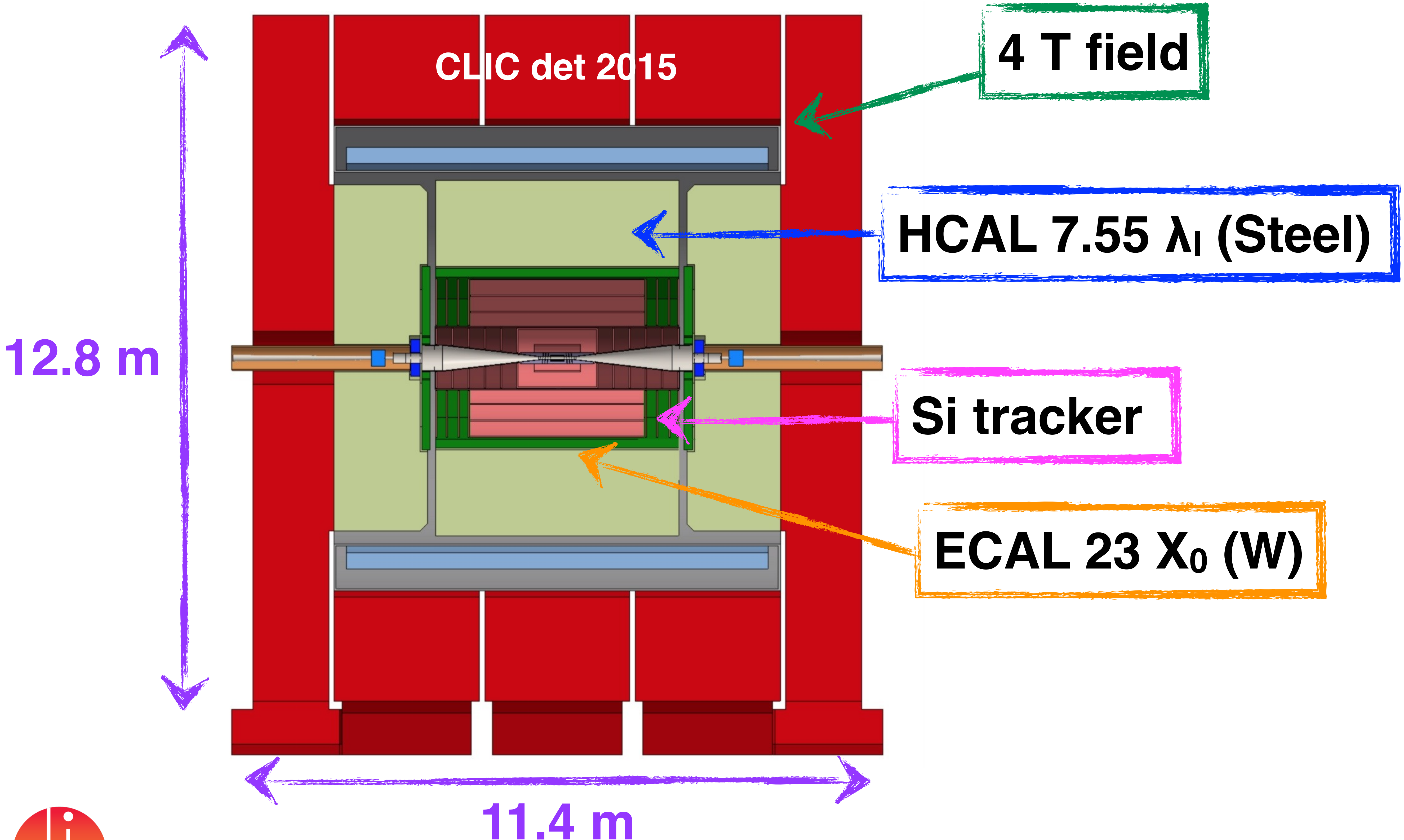
REQUIREMENTS

- Excellent tracking:
  $\sigma P_T / P_T^2 \sim 2 \times 10^{-5}\ \text{GeV}^{-1}$
  - M_H recoil measurement and H → $\ell^+\ell^-$
- Highly granular calorimeters
  $\sigma E/E \sim 3.5\%$ @ E ~ 100 GeV
  - Separation of W and Z hadronic decays
- Impact parameter resolution
  $\sigma R\phi \sim 5 \oplus 15\,/\,(p[\text{GeV}]\sin^{3/2}\theta)[\mu\text{m}]$
  - Efficient b and c jet tagging
  - Higgs couplings to fermions
- Precise time stamping ~ O(1-10ns)
  - Suppression of beam-induced background
    - Hadronic pile-up
    - Minimization of vtx occupancy



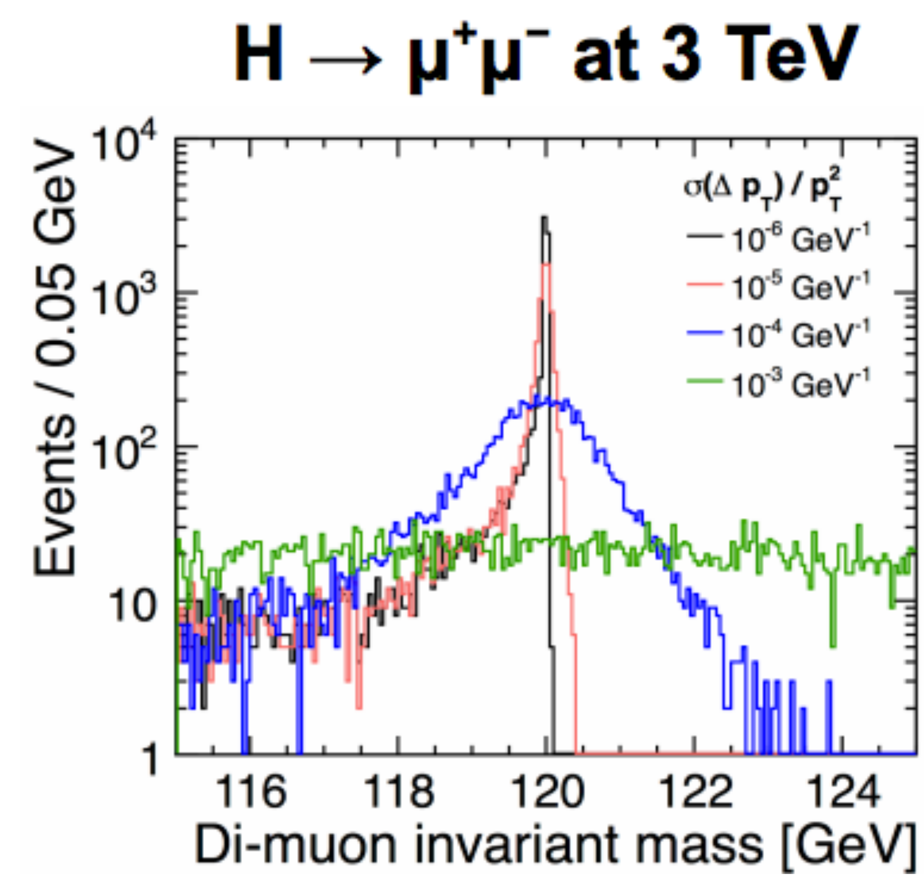


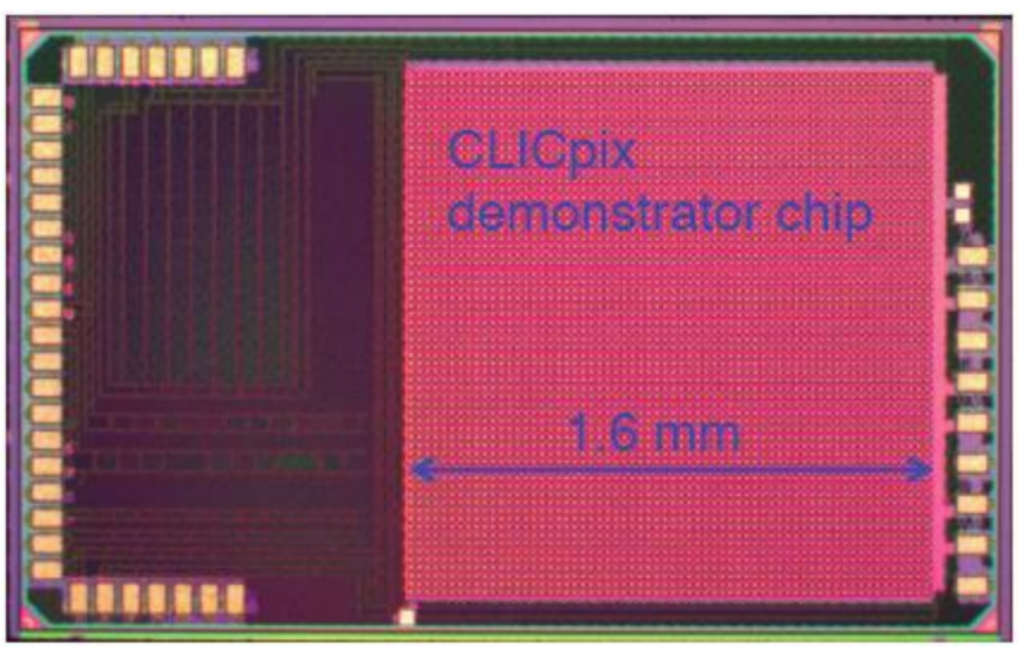
Detector - Overview

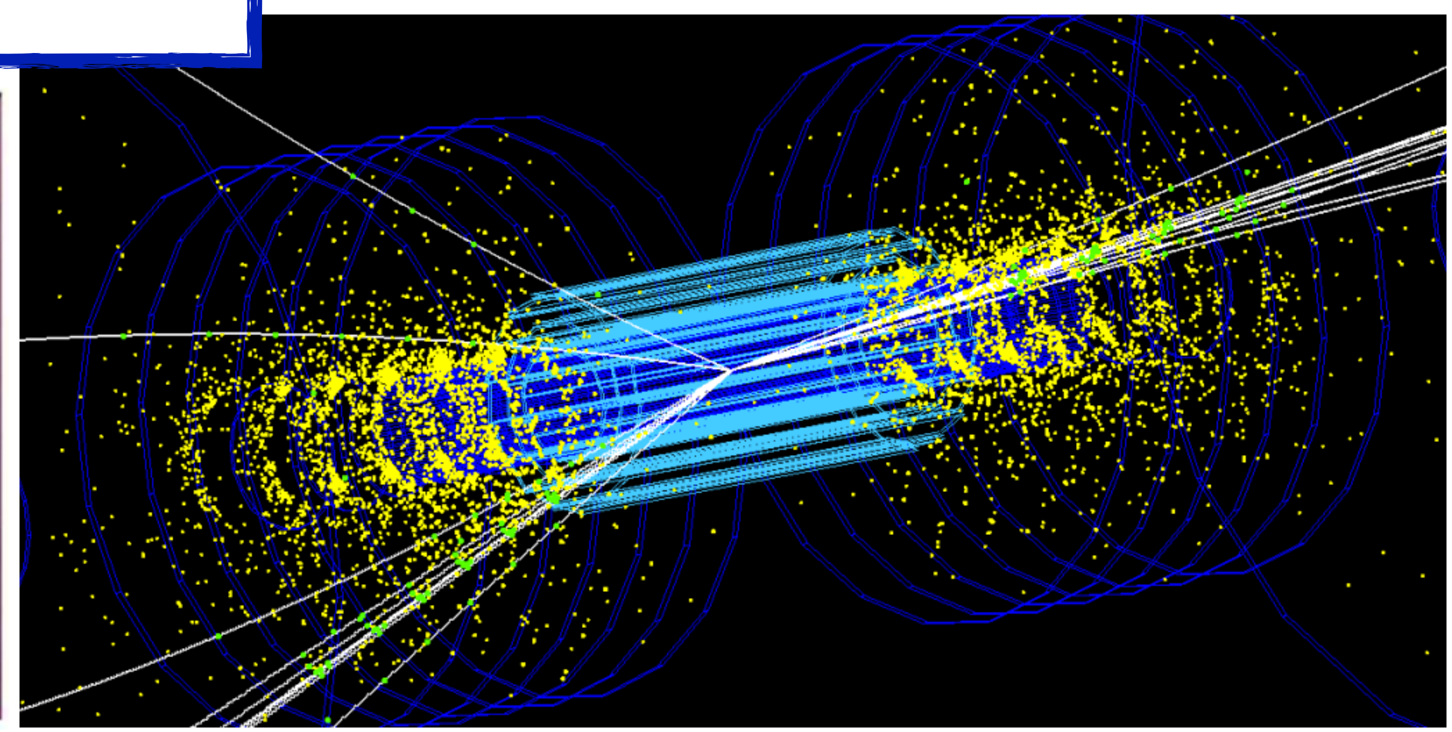


Detector - Vertex & Tracker

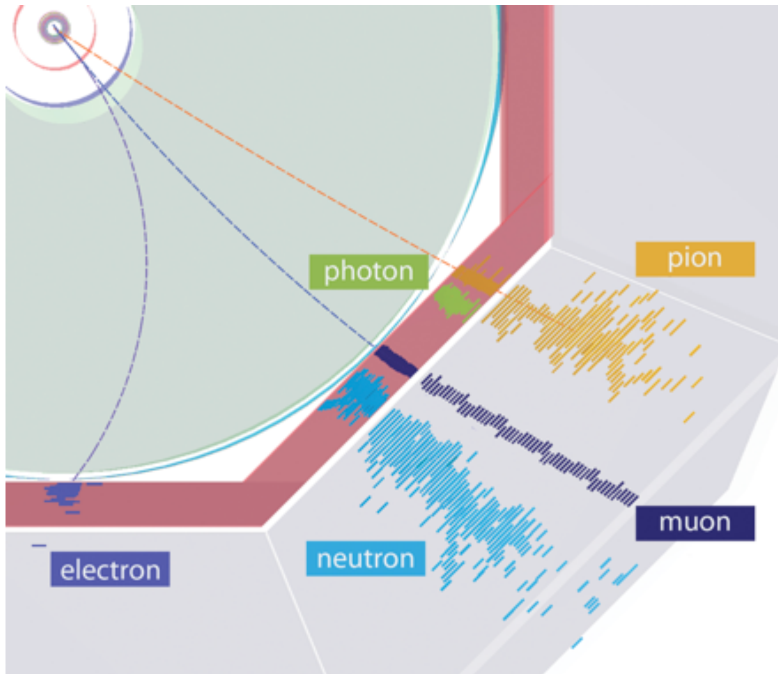
- 3μm single point resolution vertex
- 7μm single point resolution tracker
- 50 mW/cm^2 achieved with power pulsing
- $\leq$ 0.6% X_0 vertex total material budget
- $\leq$ 1-2% X_0 tracker material budget per layer
- Total of 1m^2 of silicon and O(10^9) pixels
- Silicon tracker:
  pixels or short strips options available
- Target resolution:
  $\sigma P_T / P_T^2 \sim 2 \times 10^{-5}$ GeV^{-1}





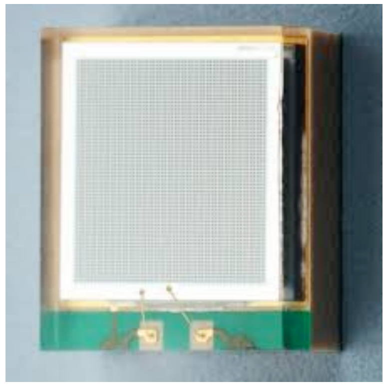


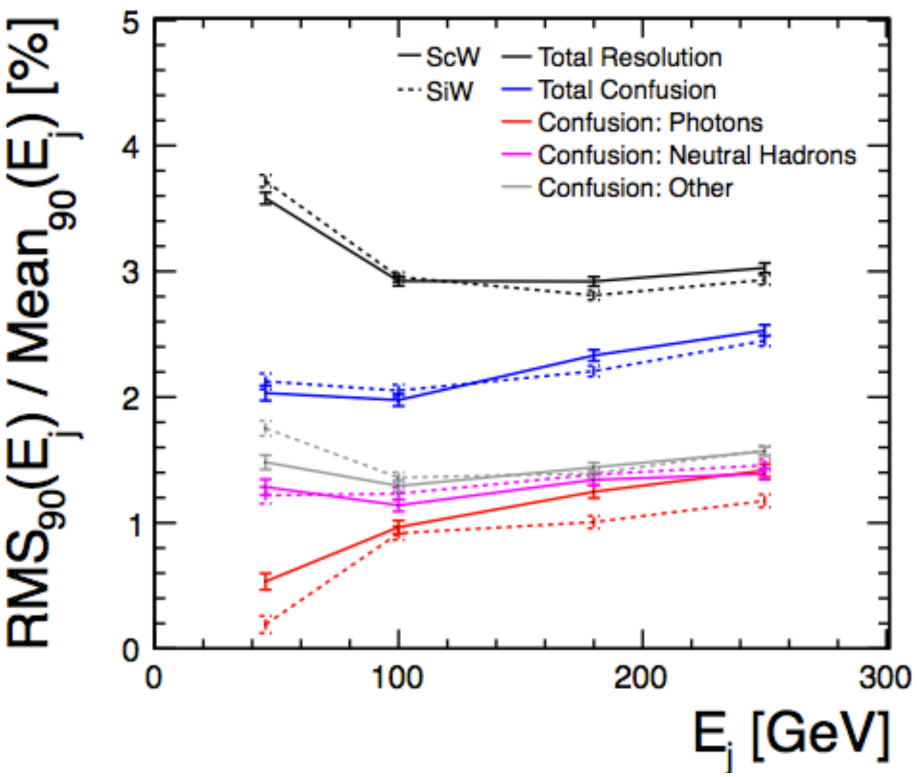
Detector - ECAL & HCAL

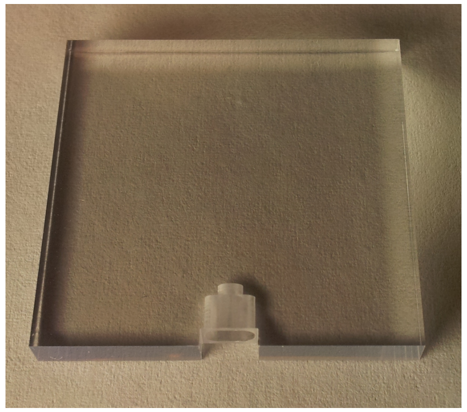


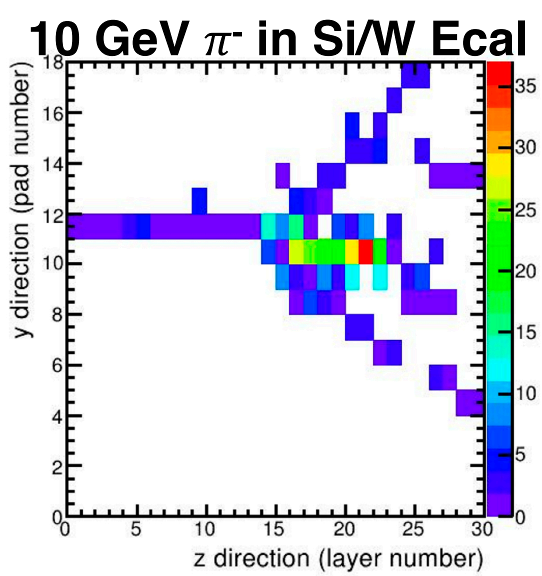
Calorimetric subsystem optimized for Particle Flow event reconstruction → high granularity

- Silicon/Tungsten ECAL (23 X_0 - 1 λ_I)
- 5.1x5.1 mm^2 pads
- Scintillator/SiPM steel analog HCAL
- 30x30x3 mm^3 scintillating tiles
- O(10^7) readout channels
- R&D and prototypes developed by the CALICE collaboration



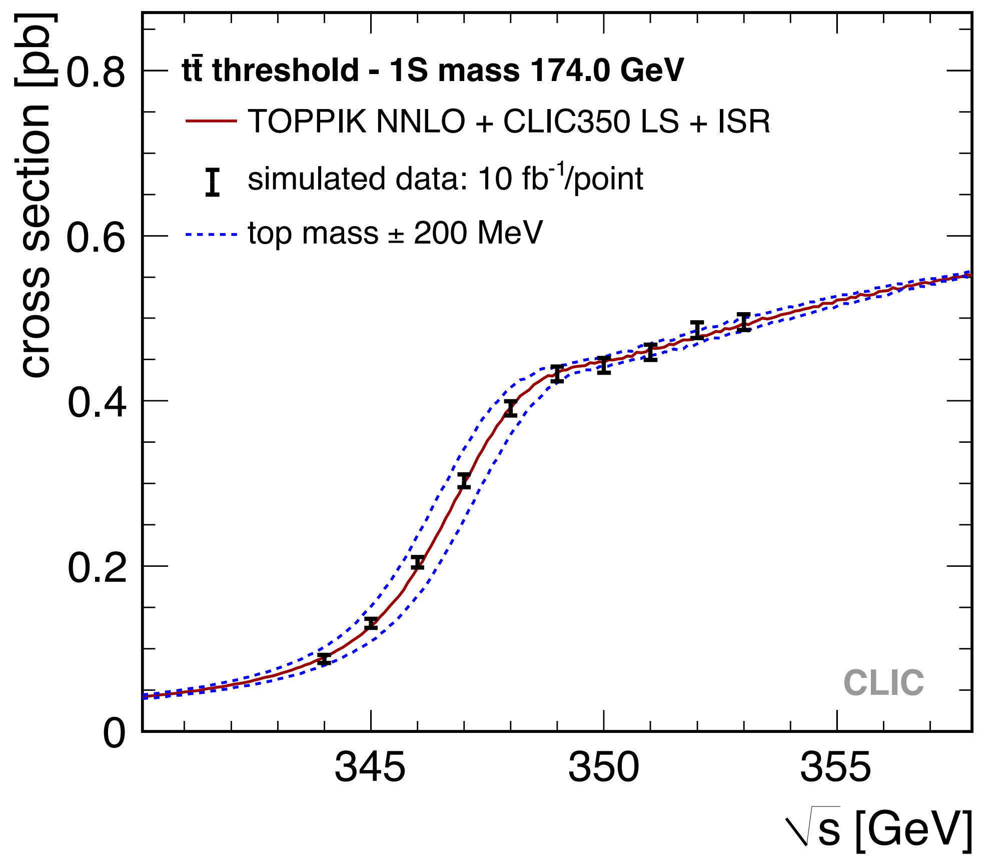






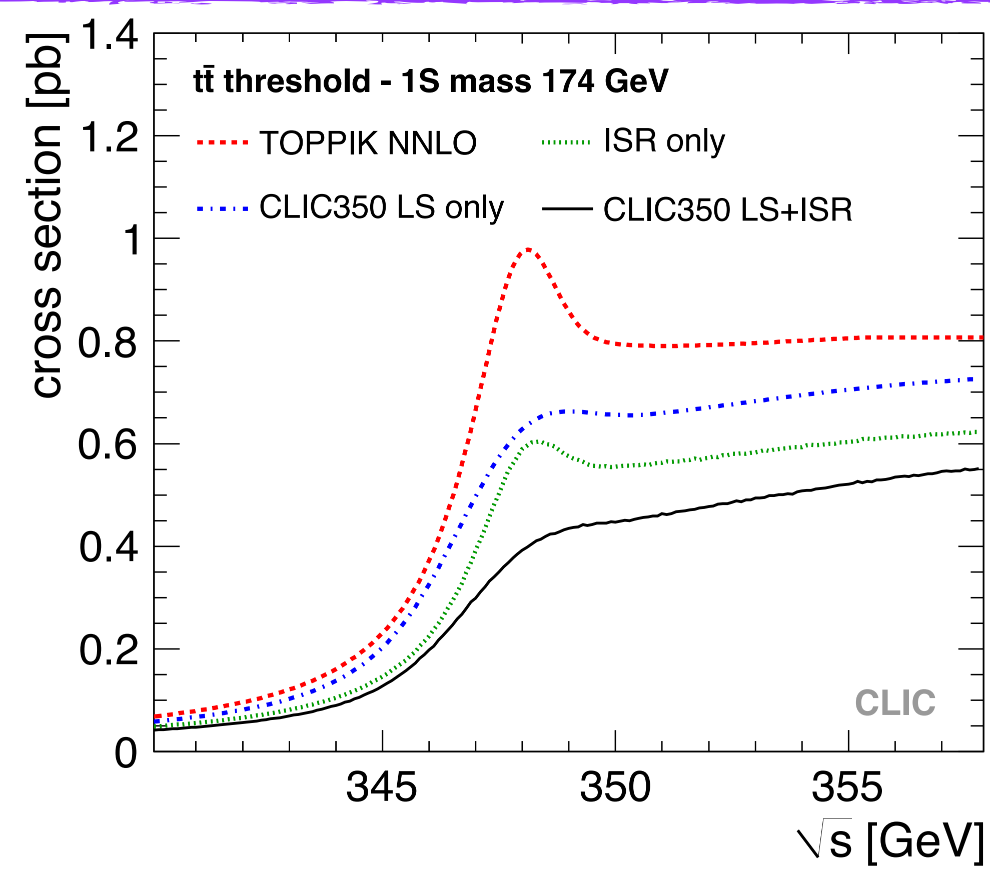
Physics benchmarks

Physics - Top



Top threshold scan

- Sensitive to top mass, width and couplings
- 10 measurements (100 fb^{-1} total ~ 1year)
- Δ_M O(30 MeV) both statistical and systematic



- Main uncertainties from theory:
  - O(50 MeV) from cross section
  - O(20 MeV) from strong coupling

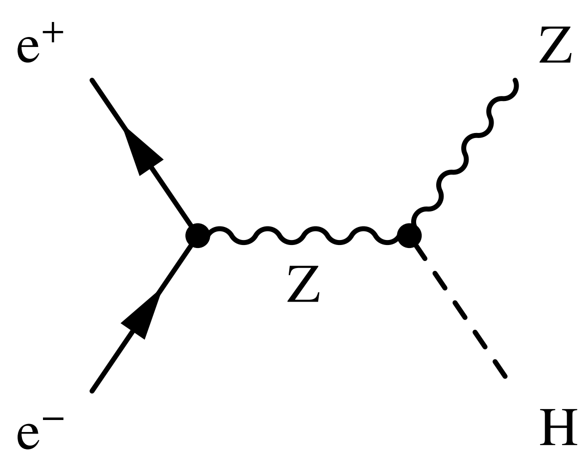
Total M_T uncertainty ~ 50 MeV

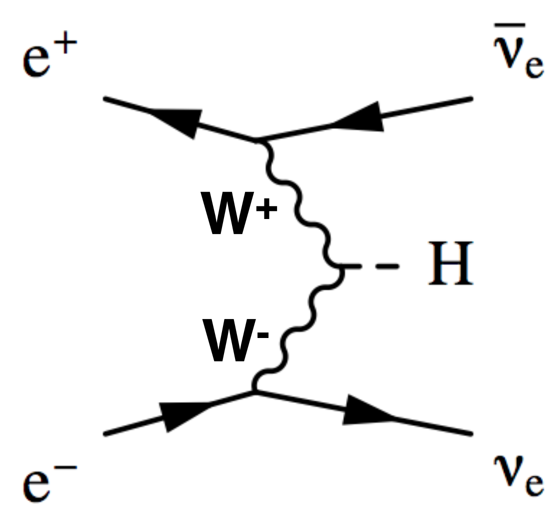
< 1 ‰ by far best quark mass measurement

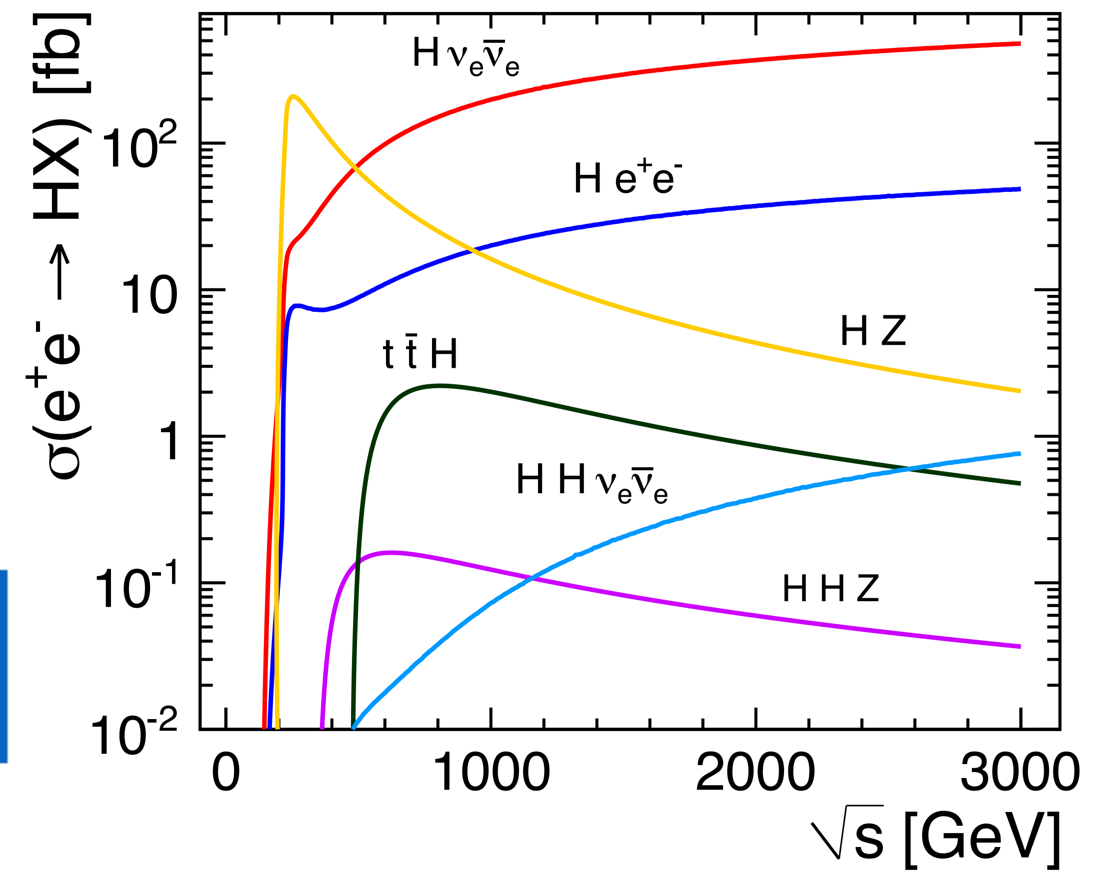
Other top studies include FCNC (e.g. t→cɣ), Yukawa coupling…

Physics - Higgs

380 GeV - Main Higgs production: Higgs strahlung and VBF
Combined measurements give model-independent access to H couplings to Z and W bosons and total Higgs width





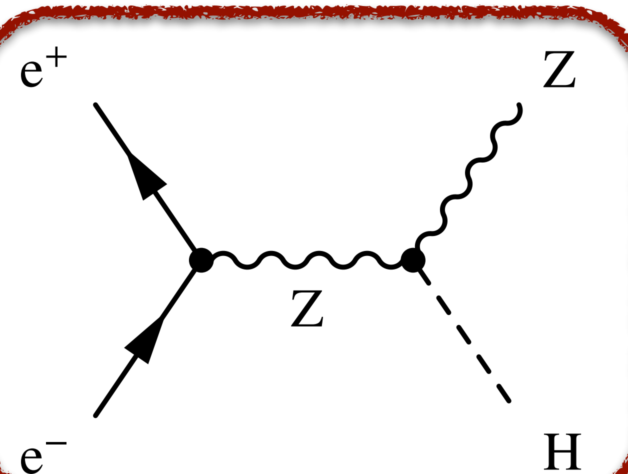


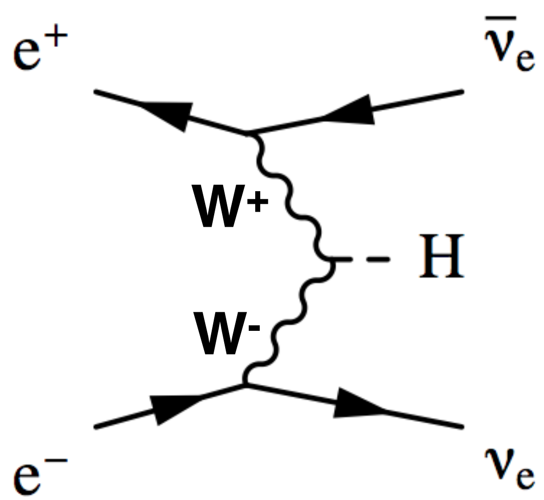
	350 GeV (500fb^{-1})	1.5 TeV (1.5ab^{-1})	3 TeV (2 ab^{-1})
#ZH events	68000	20000	11000
#H$\nu_e\nu_e$ events	17000	370000	840000
#He$^+$e$^-$ events	3700	37000	84000

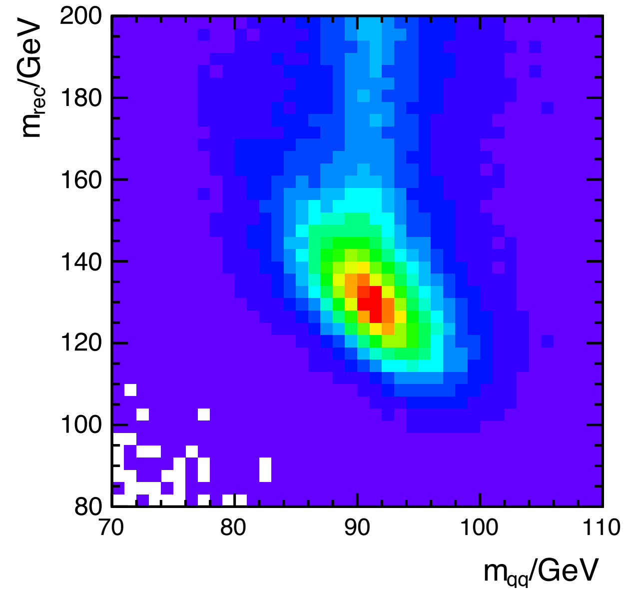
VBF increases by x1.8 with 80% e$^-$ polarization

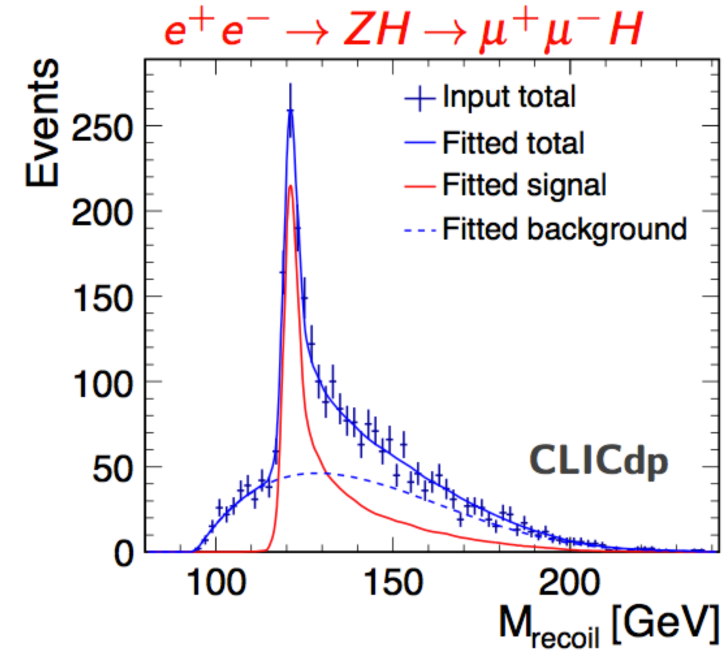
Physics - Higgs @ 350 GeV

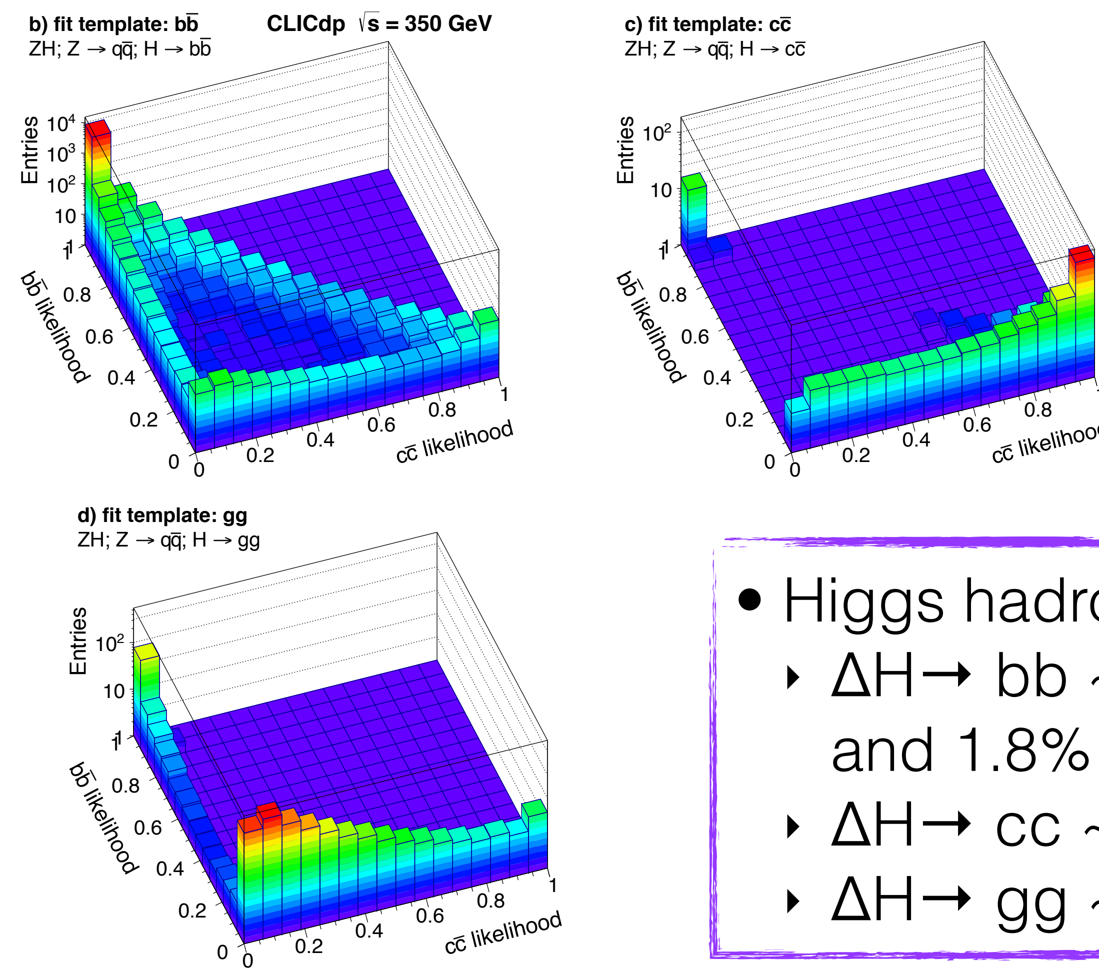
- Higgs recoil mass and Z coupling
  - $\Delta g_{HZ} \sim 4.2\%$ for $Z \rightarrow \ell^+\ell^-$
  - $\Delta g_{HZ} \sim 1.8\%$ for $Z \rightarrow qq$
  - 0.8% including all channels







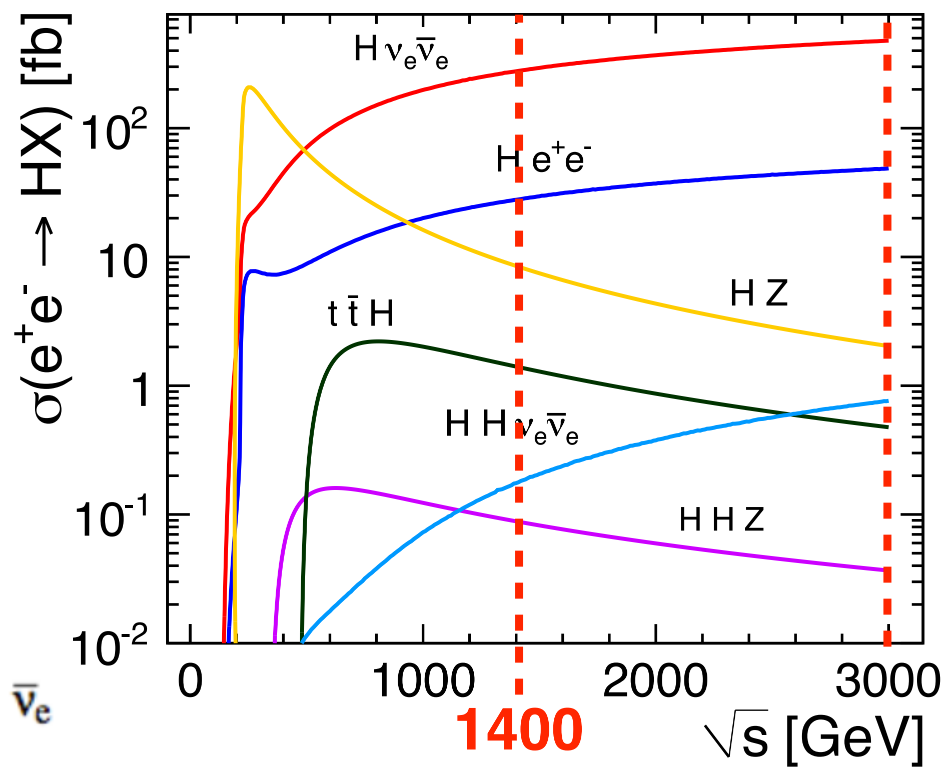


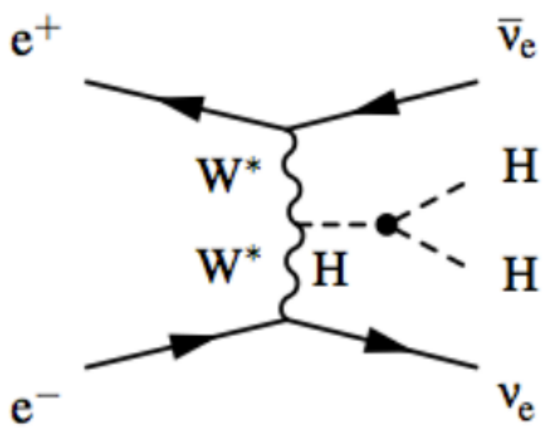


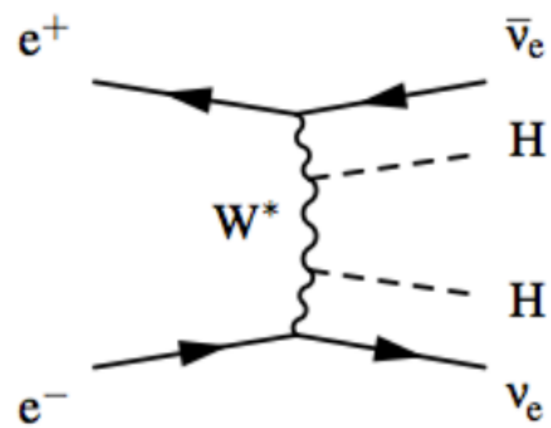
- Higgs hadronic couplings
  - $\Delta H \rightarrow bb \sim 0.75\%$ (ZH) and 1.8% (VBF)
  - $\Delta H \rightarrow cc \sim 11\%$
  - $\Delta H \rightarrow gg \sim 4\%$

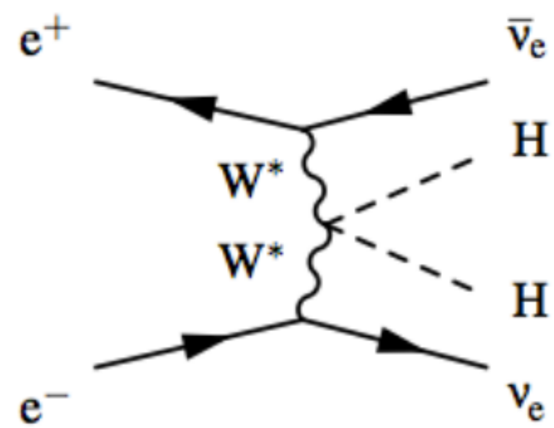
Physics - Higgs @ 1.4 & 3 TeV

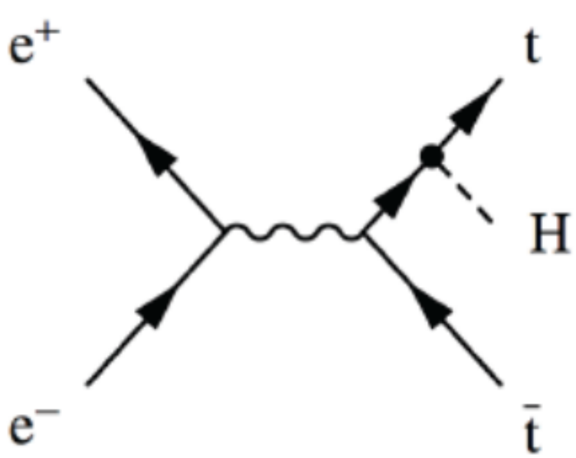
- Double Higgs production and H self-coupling (simultaneous extraction of g_{HHWW} and g_{HHH} couplings)
- Top Yukawa coupling







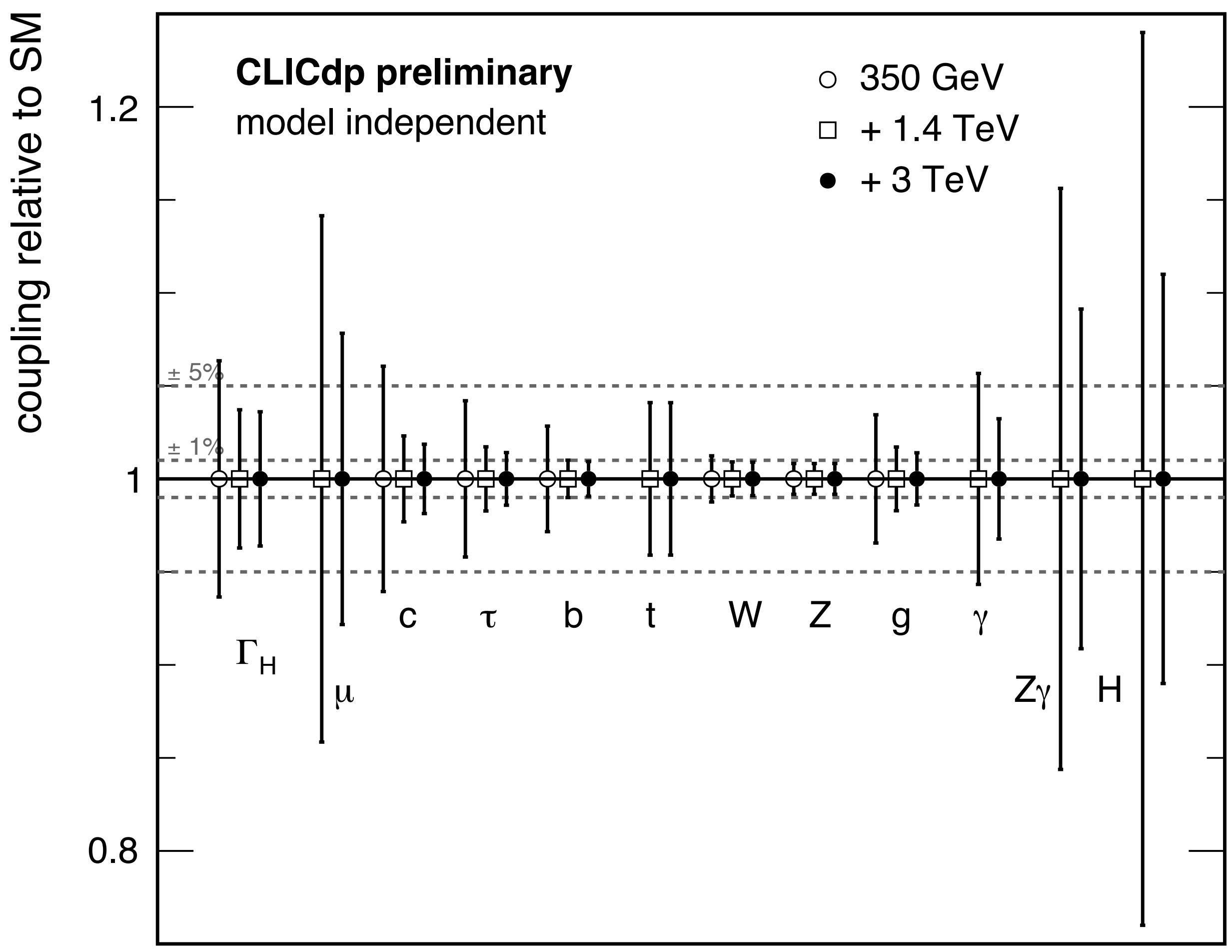


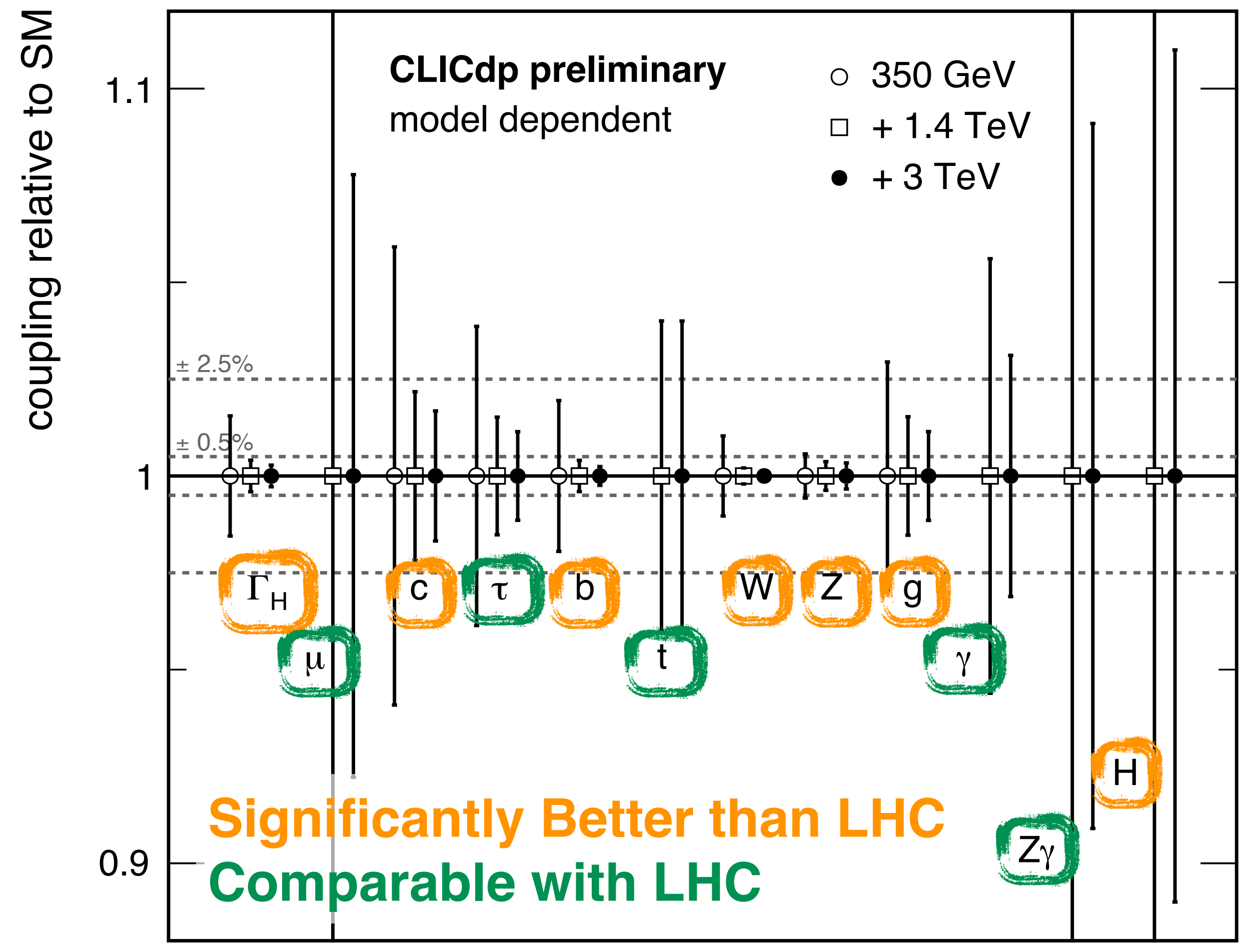


- Δg_{HHWW} ~ 3%
- Δg_{HHH} ~ 12%
- Δg_{ttH} ~ 4%

} 1.4 & 3 TeV combined (with e^- polarization)

Physics - Higgs Global fit





All previous Higgs measurements at all $\sqrt{s}$ energies (4 ab^{-1}, ~15 years of operations) of can be combined in a global fit, 2 strategies:

- Model independent (only at lepton collider):
  Γ_H as free parameter, most measurements to 1% precision, $\Delta\Gamma_H$ ~3.4%
- Model dependent (similar to LHC approach):
  Γ_H constrained by SM decays only, some measurements at ‰ level, $\Delta\Gamma_H$ ~0.2%

Physics - BSM Overview

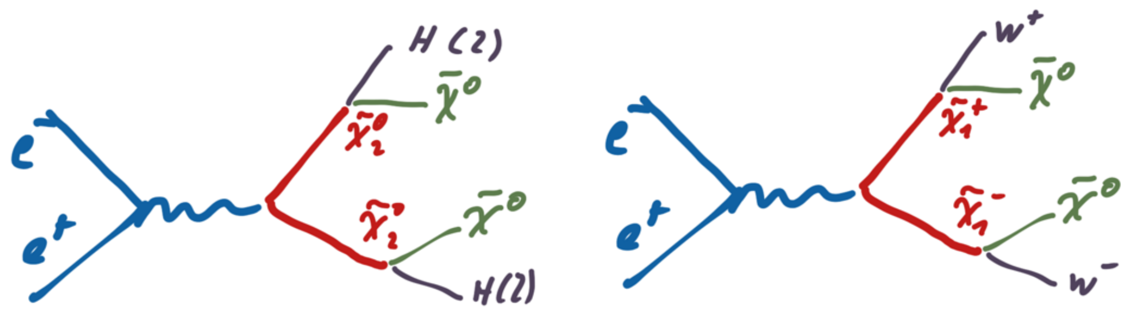
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Physics - BSM I

BSM direct measurement example:
mass degenerate gaugino/neutralino sector @ 3 TeV

$M(\tilde{\chi}_1^0) = 340 GeV$

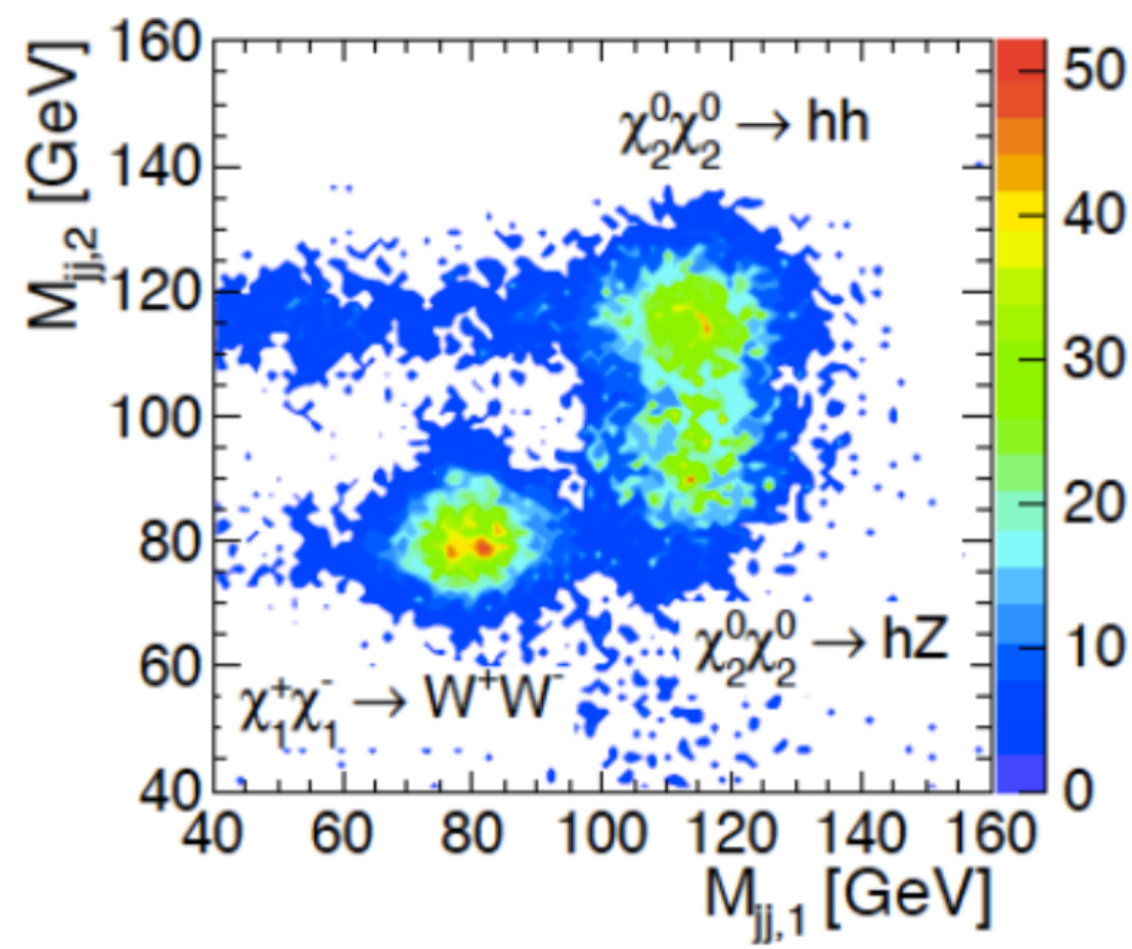
$M(\tilde{\chi}_2^0), M(\tilde{\chi}_1^+) = 643 GeV$



$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 hh$ **82%**

$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 Zh$ **17%**

$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$

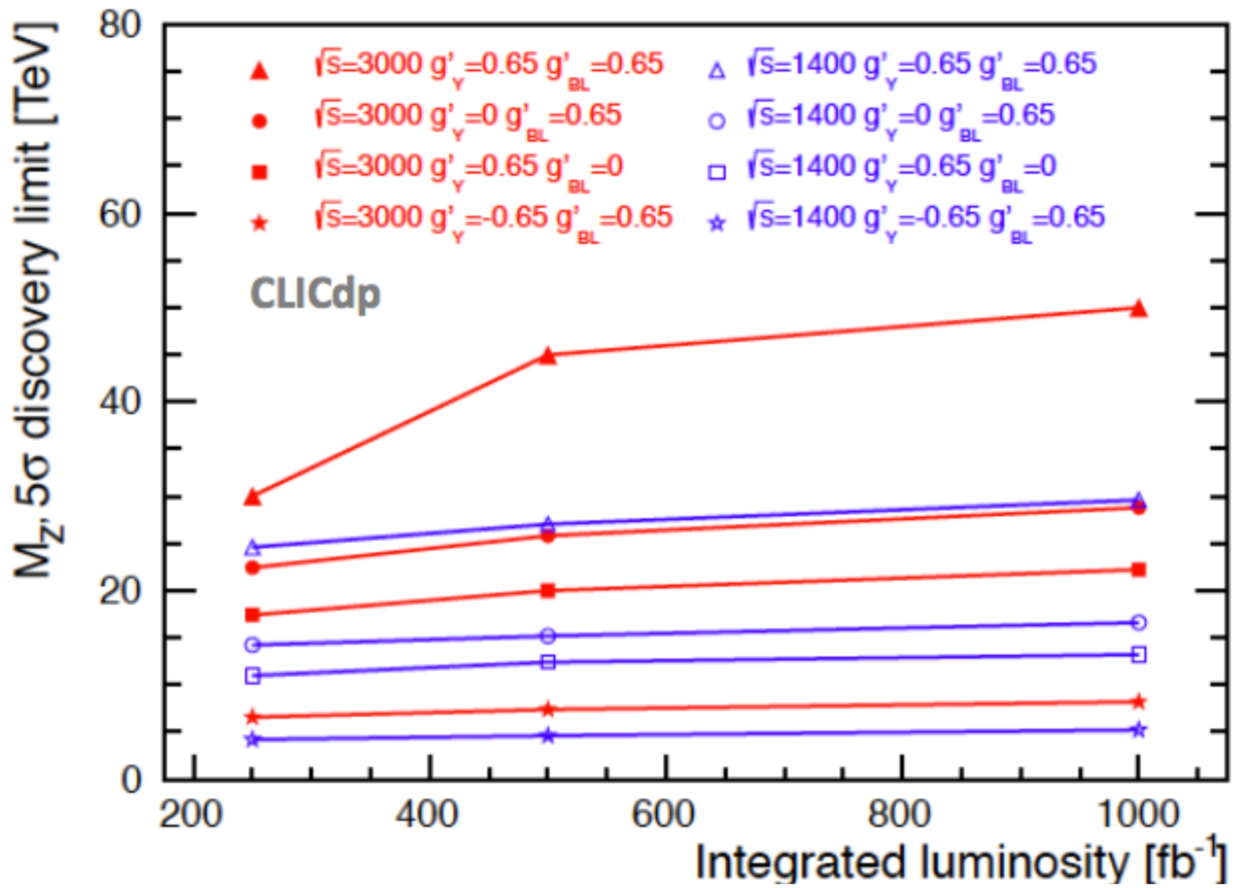


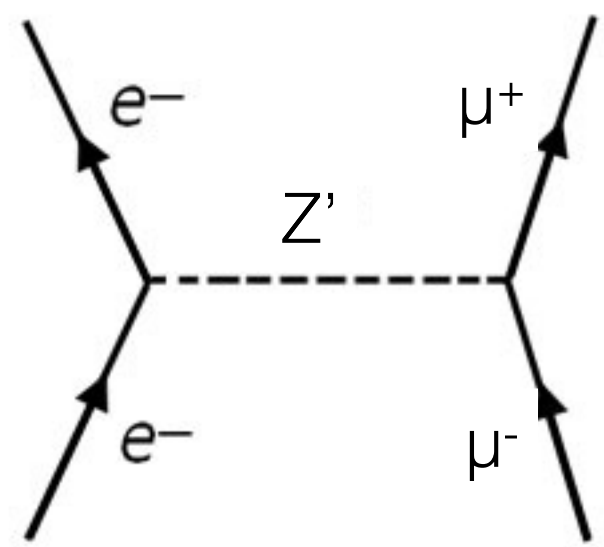
Mass uncertainty ~ 1-1.5%

particle flow algorithm benchmark scenario:
4 jets + missing energy

Physics - BSM II

BSM indirect measurement example: heavy Z’

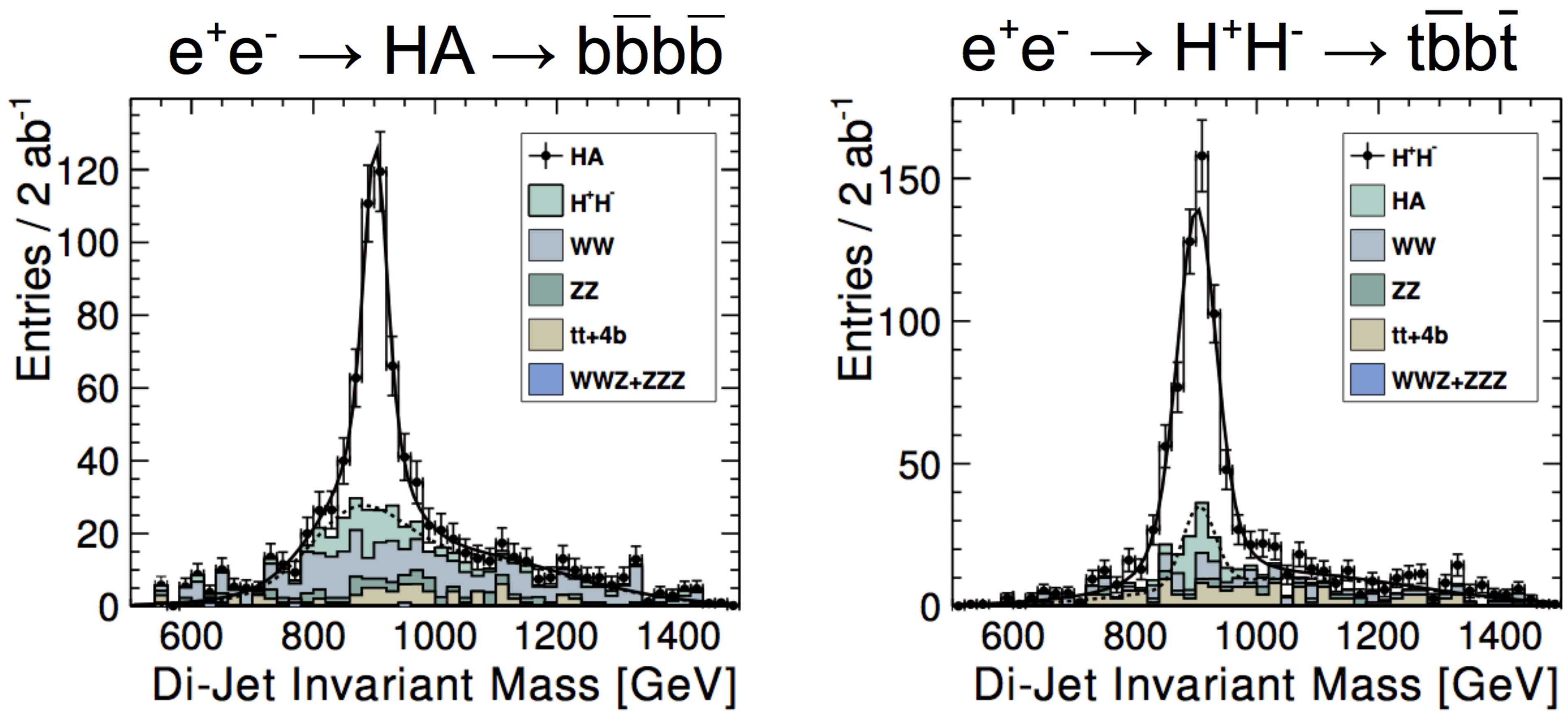




- Sensitive for discovery up to Z'_M of several 10 TeV via total e^+e^- -> $\mu^+\mu^-$ cross section
- Precision measurements for multi-TeV Z’ via:
  - forward-backward asymmetry
  - left-right asymmetry with e^- polarization

Physics - BSM III

Heavy Higgs Bosons with almost degenerate mass



- Complex hadronic final states
- Extremely challenging at an hadron machine
- Heavy Higgs mass resolution ~0.3% @ 2 ab^{-1}

Summary & Conclusions

- Well established physics case for TeV-scale lepton collider
  - Precision top physics
  - Model independent Higgs measurement
  - Higgs mass, width and couplings (including top-yukawa coupling and self-coupling)
  - Direct (up to 1.5 TeV) and indirect (multi-TeV, model dependent) BSM physics
- Complementary to LHC
- Very active R&D program both for accelerator and detectors
- Large-scale tests have demonstrated feasibility of CLIC as an option for CERN after the LHC

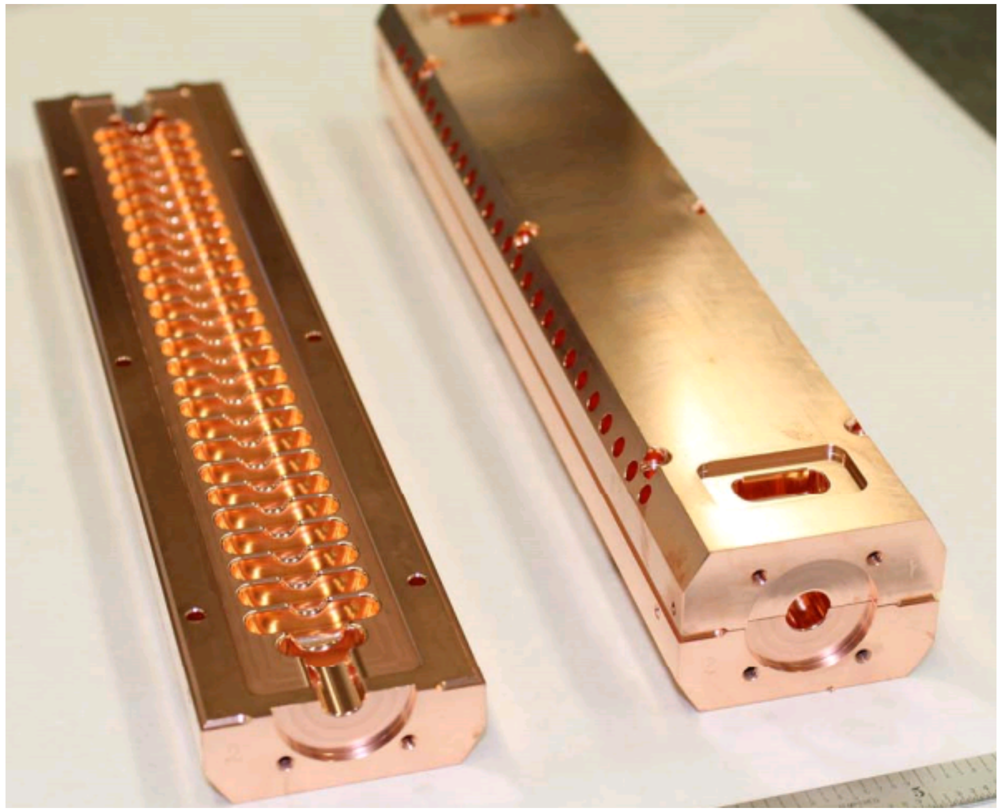
CLIC meeting - January 2016

Thank you!

References:
CLIC/CTF3 accelerator: clic-study.web.cern.ch
Physics and detectors: clicdp.web.cern.ch

Backup

CLIC - Accelerator Design II



A. Grudiev, H. Zha, V. Dolgashev

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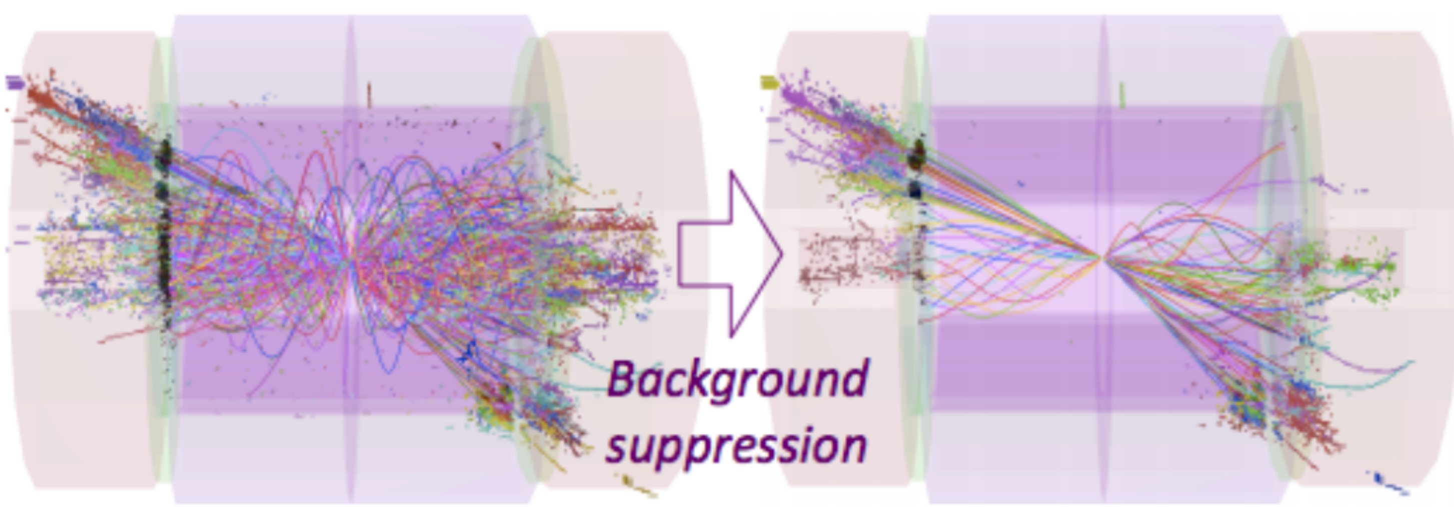
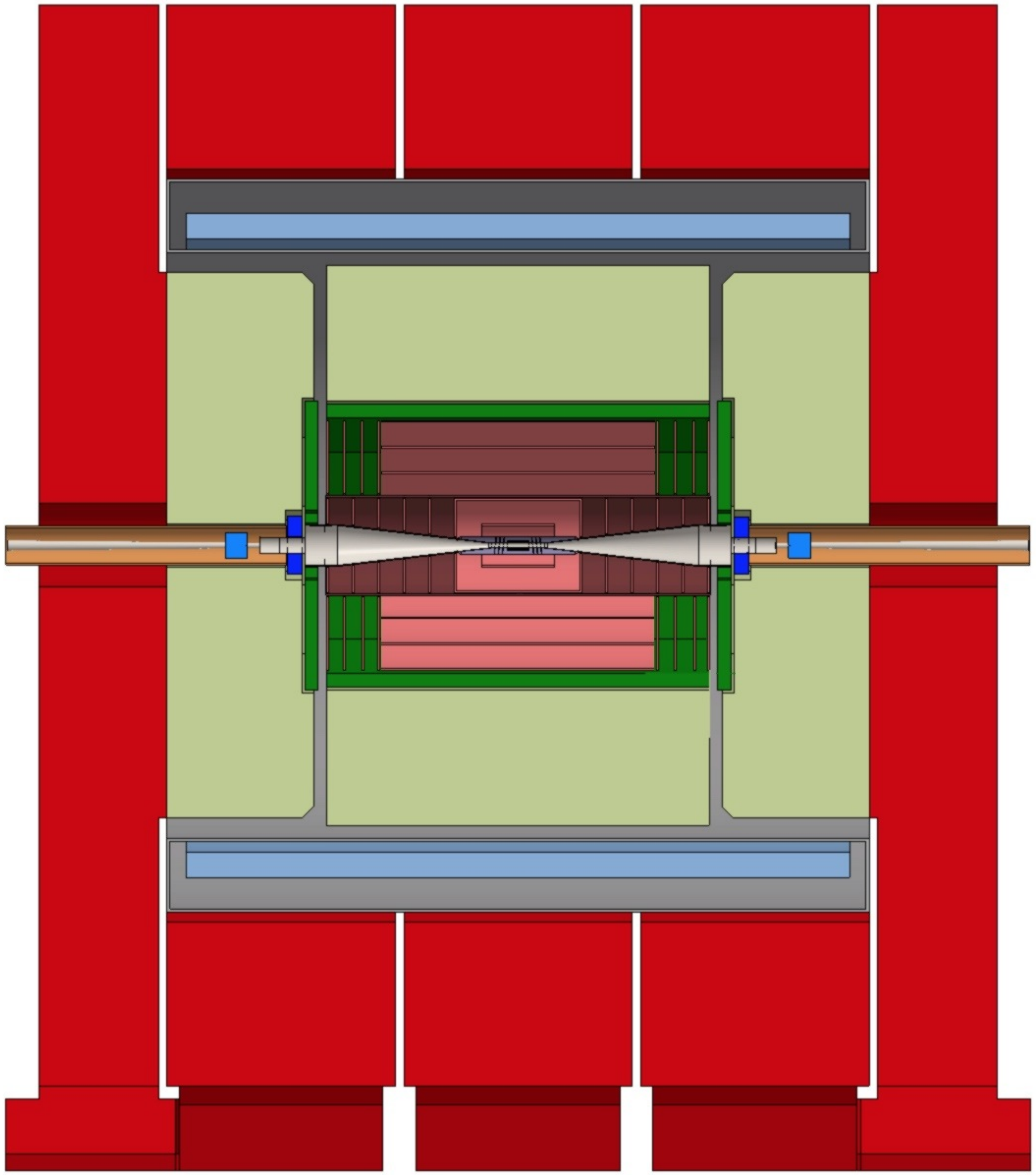
Lenght [km]	11.4	29	50.1
Bunch [ps]		500	
$\sigma_{x,y}$ [nm]	150x3	60x1.5	40x1
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	1.5	3.7	5.9
Top 1% Energy $\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	0.9	1.3	2.0
$\int\mathcal{L}$ [ab^{-1}]	0.5	1.5	3
Repetition f [Hz]		50	
Gradient [MV/m]	72	72-100	72-100
Power [MW]	252	364	589

- 12 GHz cavities
- micrometer tolerances
- Breakdown rate < 0.7 ppm
- Long low-energy beam spectrum tail due to beam-fields interactions
- High $\gamma\gamma$ background from luminosity and bunch crossing rate



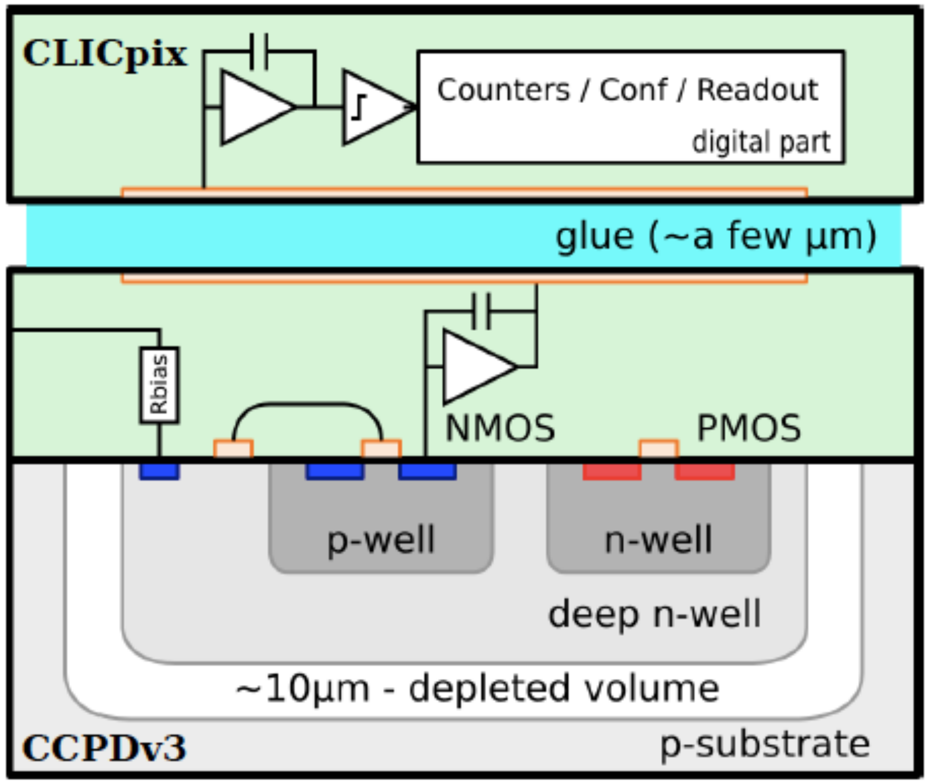
Detector - Overview

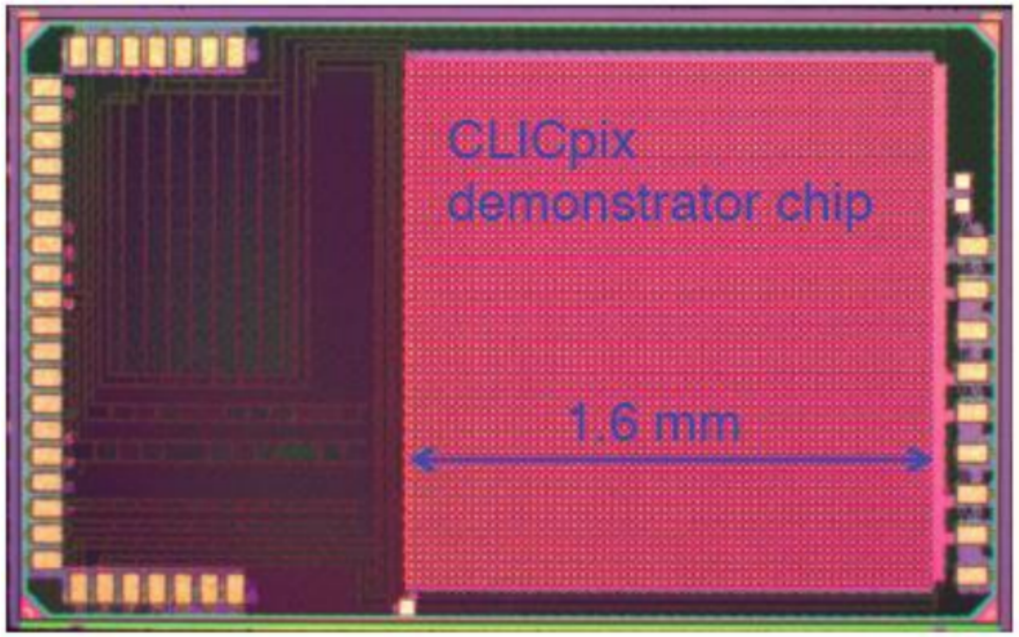


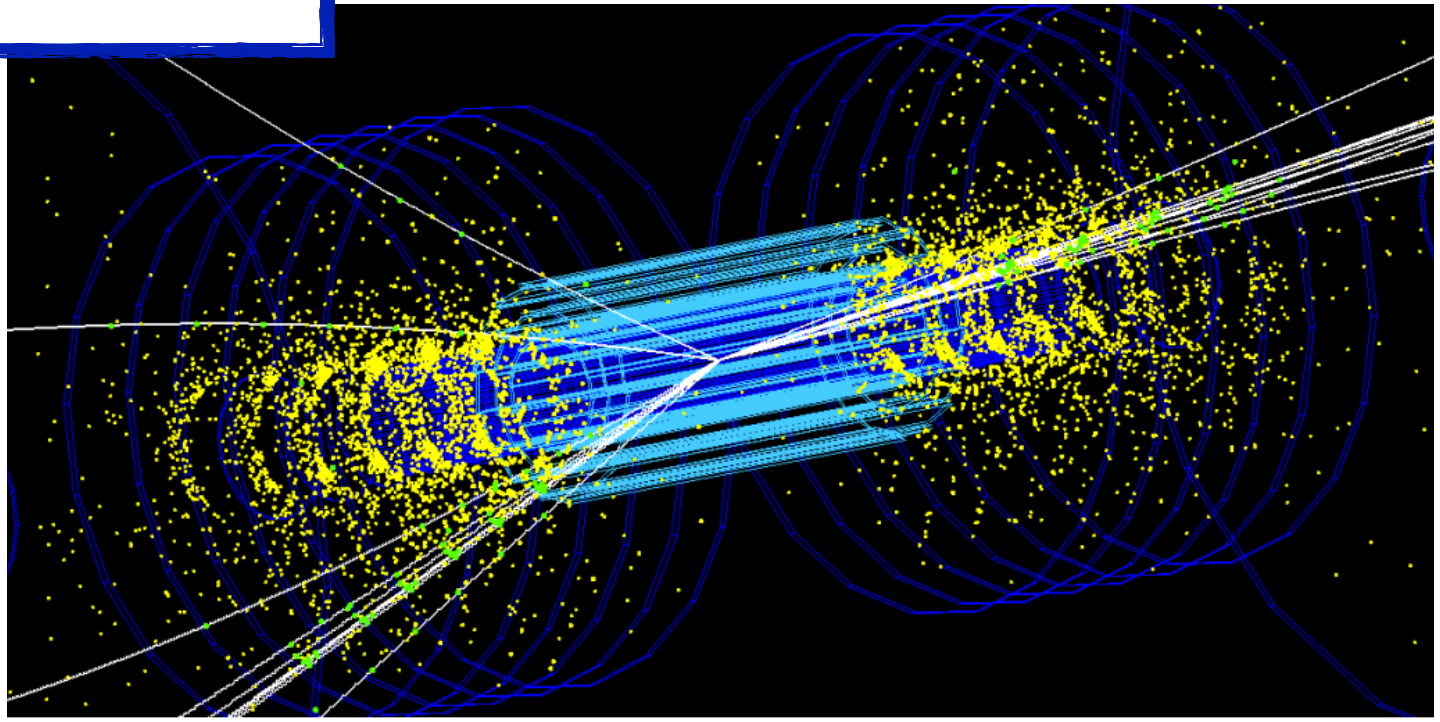
CLIC det 2015	
Tracker	Silicon
Solenoid Field [T]	4
Solenoid Free Bore [m]	3.4
Solenoid Length [m]	8.3
VTX Inner Radius [mm]	25-31
ECAL Absorber	W
ECAL Inner Radius [m]	1.5
ECAL ΔR [mm] (X_0)	159 (23)
HCAL Absorber	Steel
HCAL λ_I	7.55
Overall Height [m]	12.8
Overall Length [m]	11.4

Detector - Vertex

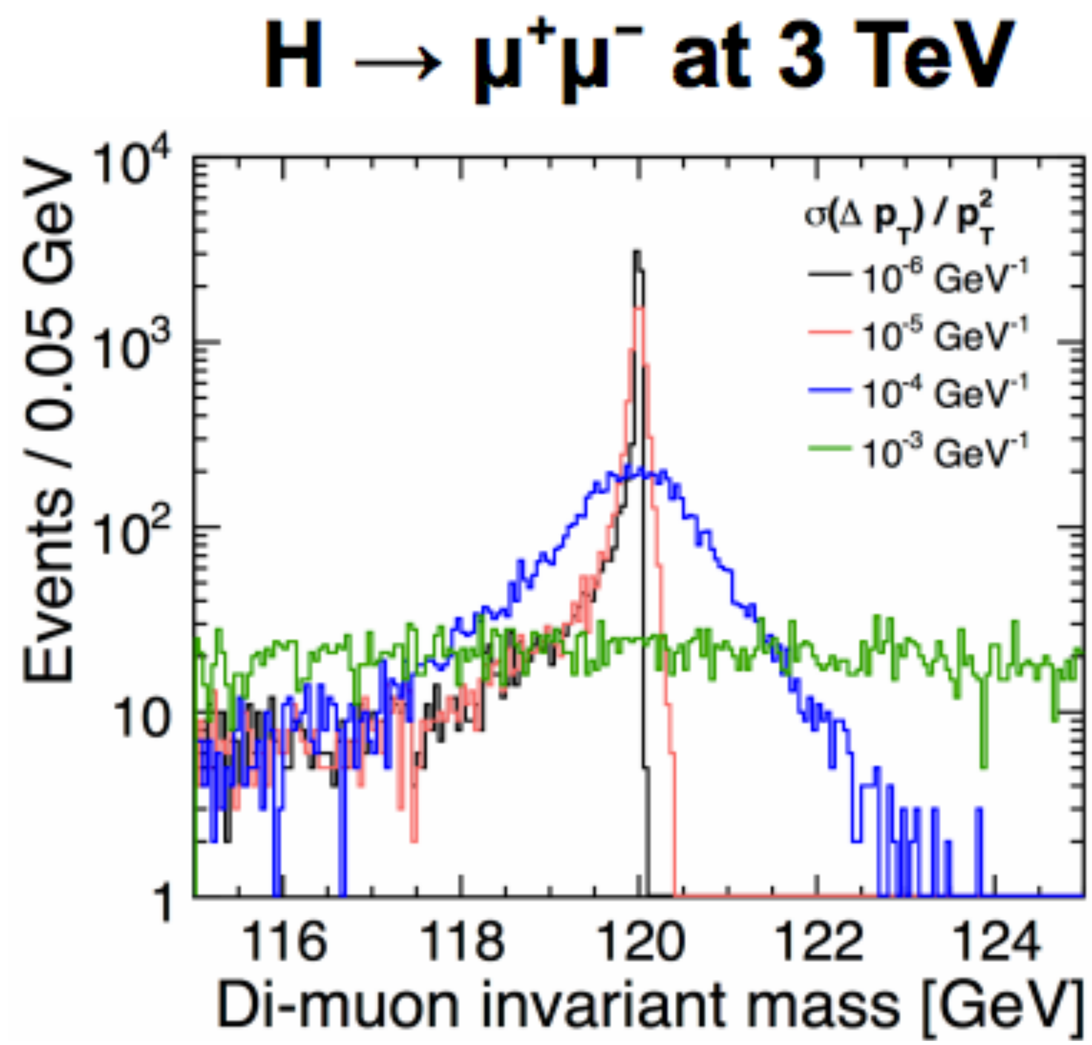
- CLICpix chip (collaboration with RD53)
  - 25µm pixel pitch HV-CMOS technology
  - 3µm single point resolution
  - 50 mW/cm^2 achieved with power pulsing
- 3 double-layers in barrel & endcap
  - $\leq$ 0.6% X_0 Total material budget
  - Total of 1m^2 of silicon and O(10^9) pixels
- Hybrid detector coupled (glued/bump bonded) to ASIC







Detector - Tracker

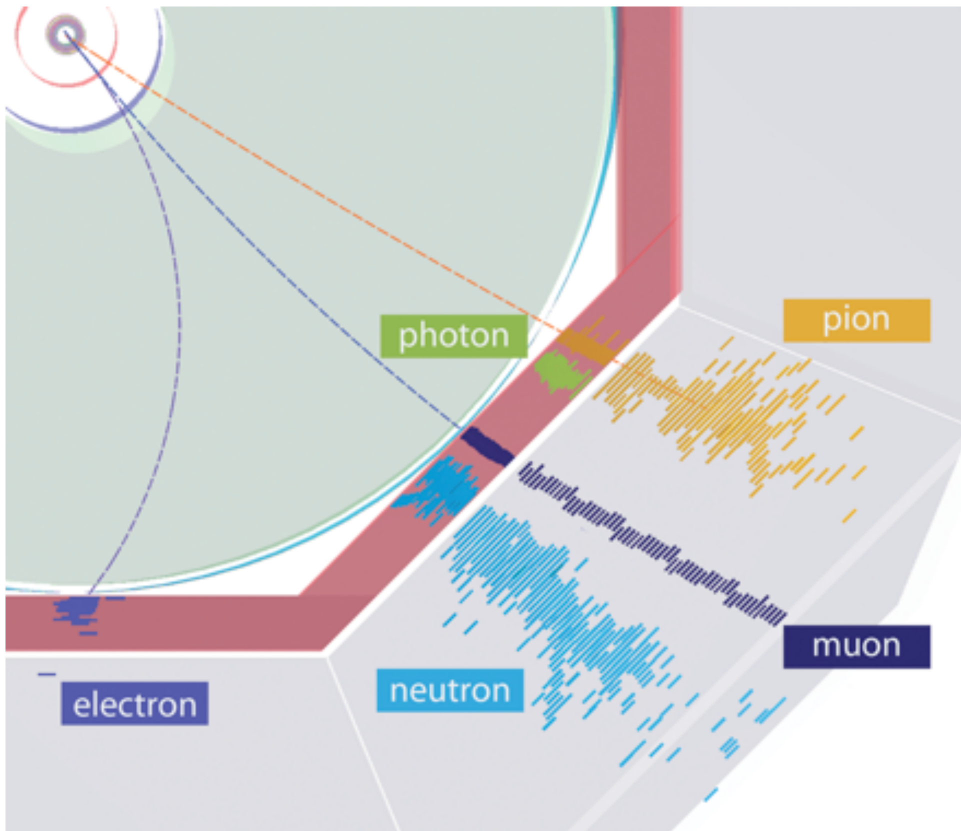


Example analysis of tracker requirements

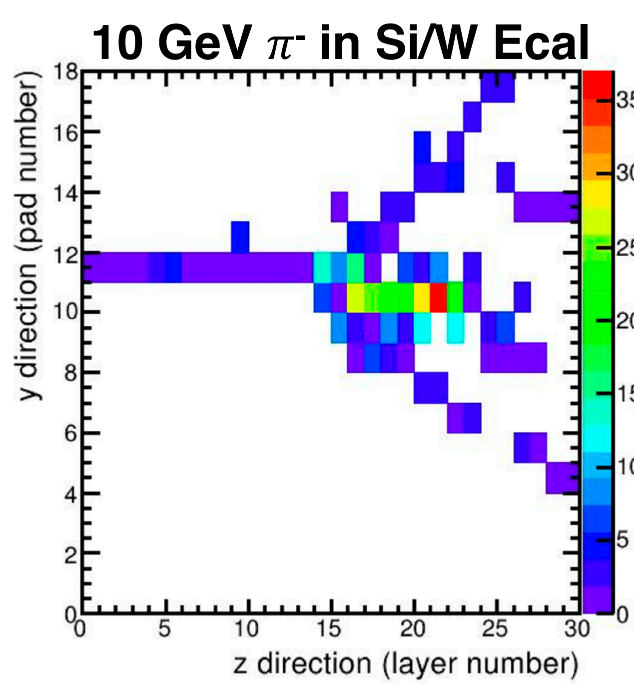
- Silicon tracker:
  pixels and strips options available
- 5 layers (7 in endcaps)
- 7μm single point resolution
- ≤ 1-2% X_0 budget per layer
- 1.5 m radius
- Target resolution:
  $\sigma P_T / P_T^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Inner layer radius:
  25 mm @ ≤ 500 GeV
  31 mm @ 3 TeV (to keep occupancy below 3%)

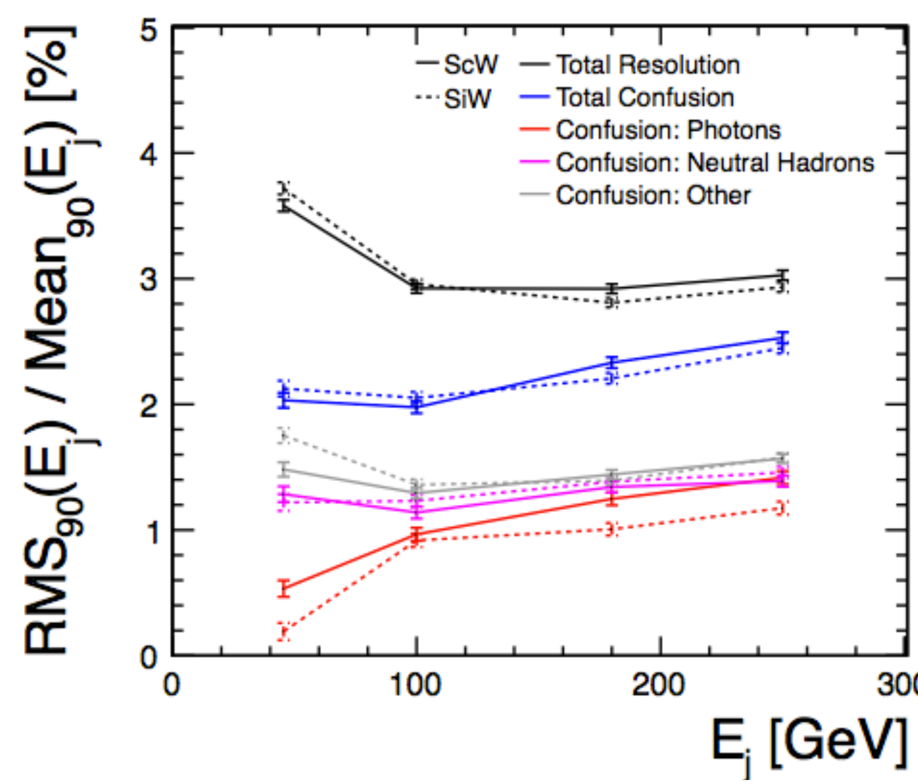
Detector ECAL

Calorimetric subsystem optimized for Particle Flow event reconstruction → high granularity



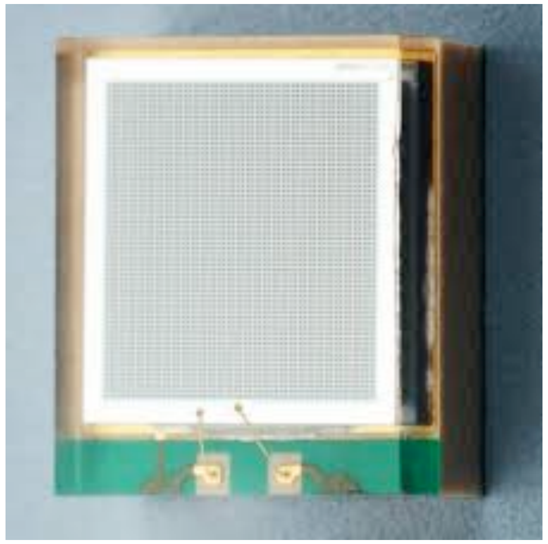
- Silicon/Tungsten ECAL
- 5.1x5.1 mm^2 pads
- 25 layers (23 X_0 - 1 λ_I)
- R&D and prototypes developed by the CALICE collaboration

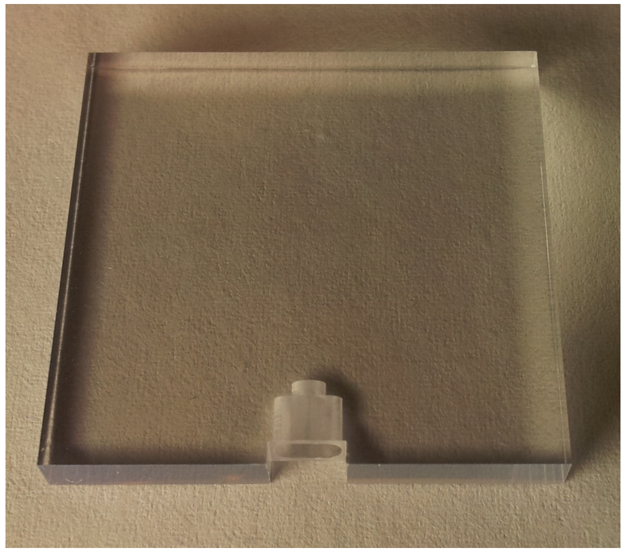




Detector HCAL

- Scintillator/SiPM steel analog HCAL
- 30x30x3 mm^3 scintillating tiles
- 60 layers (7.5 λ_I)
- 20 mm steel per layer
- Inside the magnet barrel
- $O(10^7)$ readout channels





Other technologies under investigation: (digital/semidigital RPC HCAL) not part of the current CLIC detector model