CLIC detector & physics
Status and Plans

Marcel Vos, IFIC (UVEG/CSIC) Valencia,
for the CLIC detector & physics collaboration

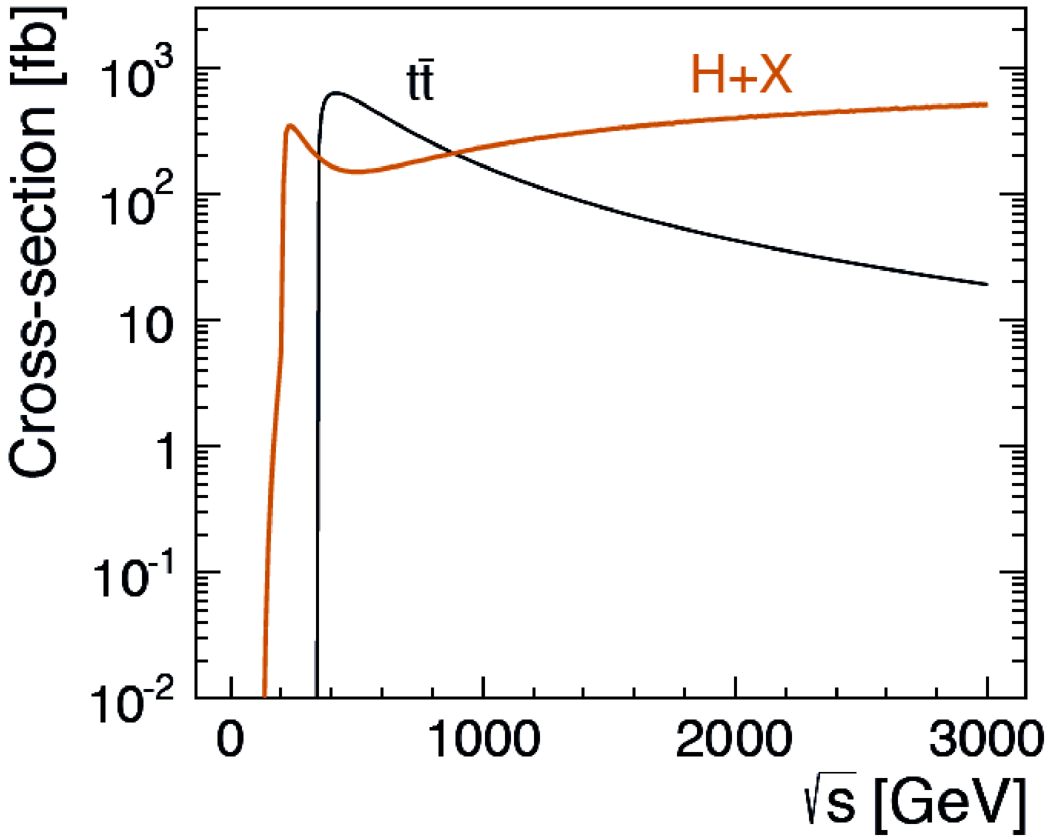
CLIC Workshop, CERN, january 2016

LINEAR COLLIDER COLLABORATION

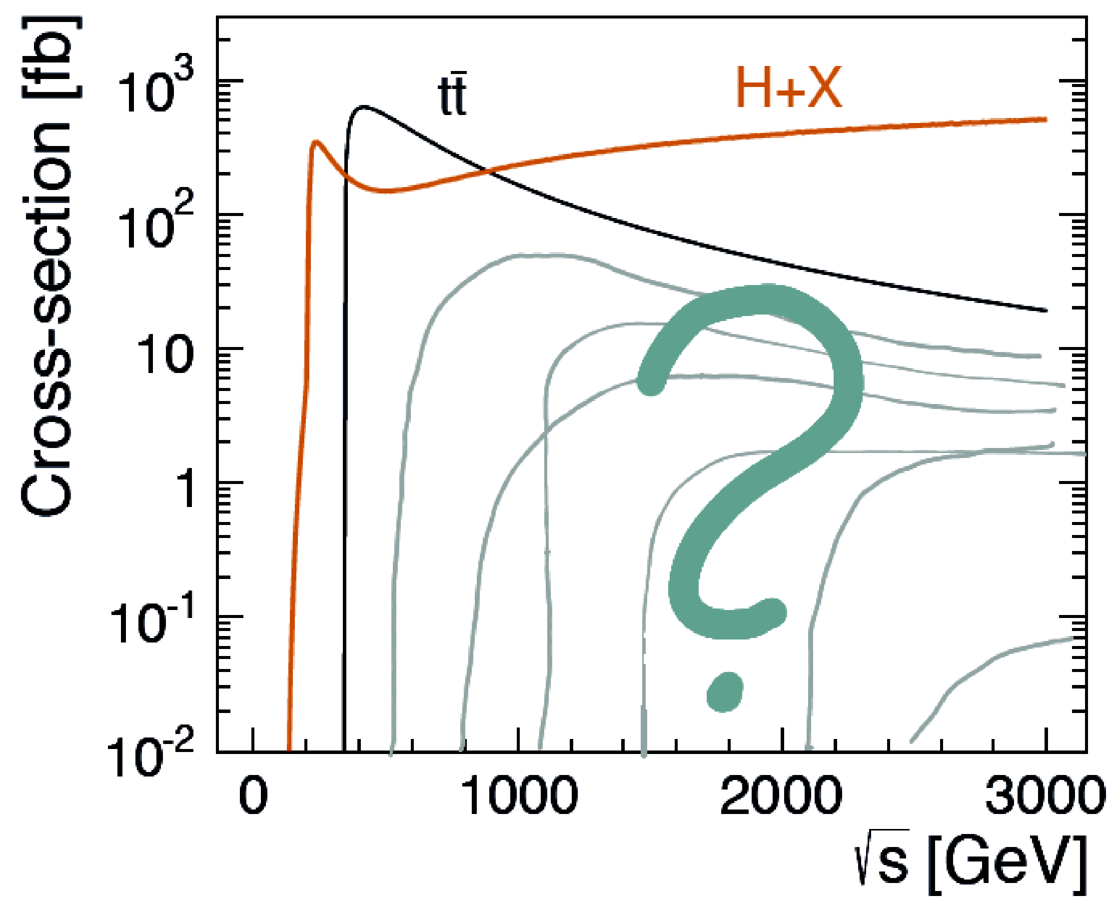
Compact Linear Collider

Physics programme

CLIC has a “guaranteed programme” based on known particles and processes: a precise knowledge of couplings and properties of Z, W, H, t provides indirect sensitivity to BSM physics at very high scale



Physics programme

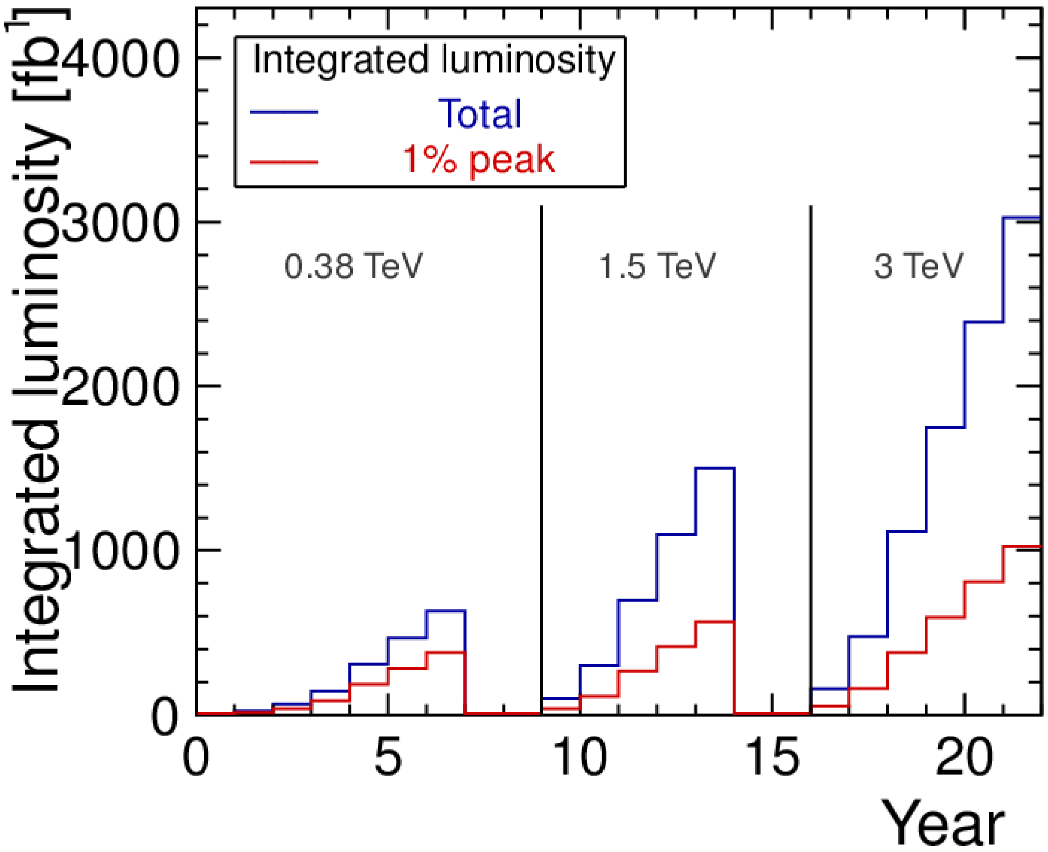


R&D for future colliders must be ready for the unexpected:
enable direct production of new particles with mass up to $\sqrt{s}/2$

A tentative programme

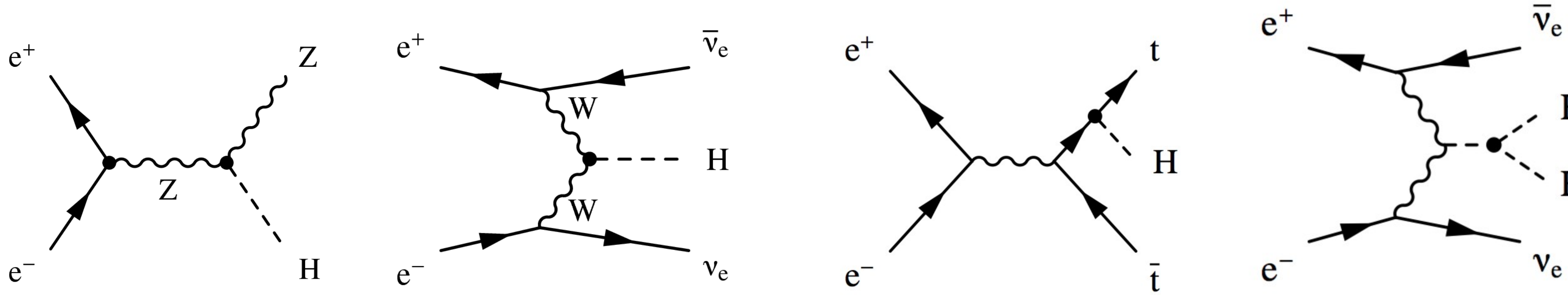
The CLIC programme envisages a start at relatively low energy (380 GeV), and quickly ramps up to ultimate lepton collider reach (1.5 TeV, 3 TeV)

Expected soon: staging document, see talk by Eva Sicking on Friday



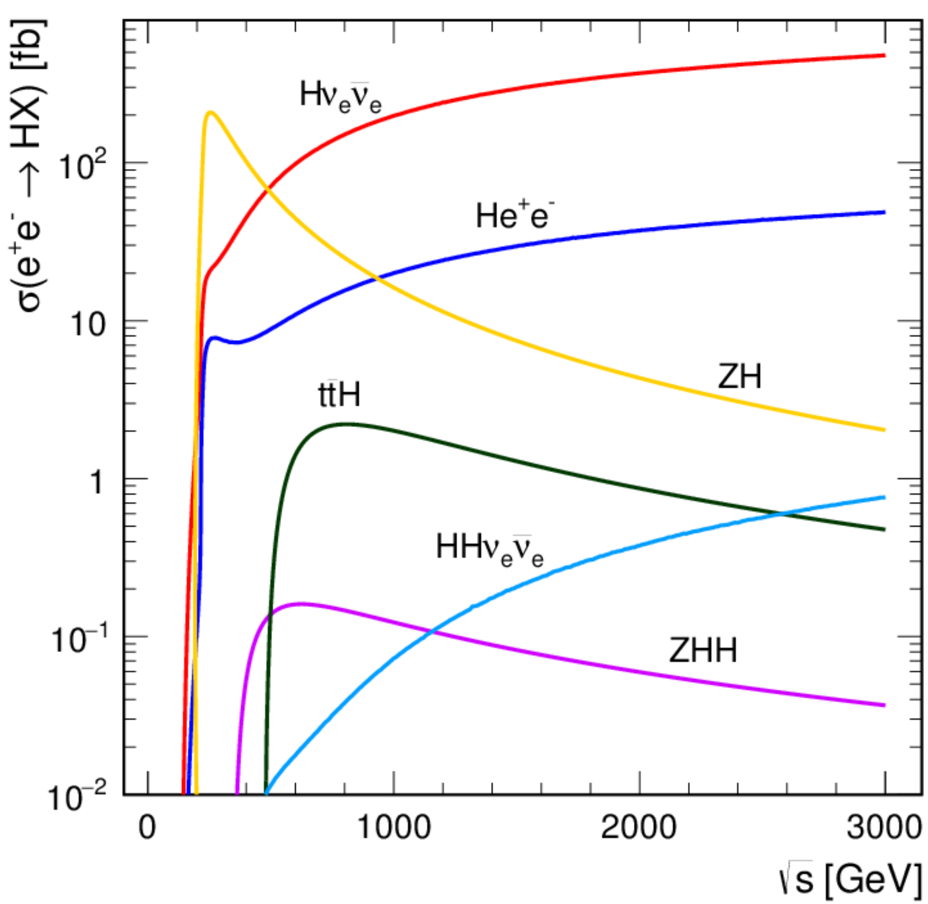
Note: benchmark studies were performed at 350 GeV and 1.4 TeV

Higgs physics

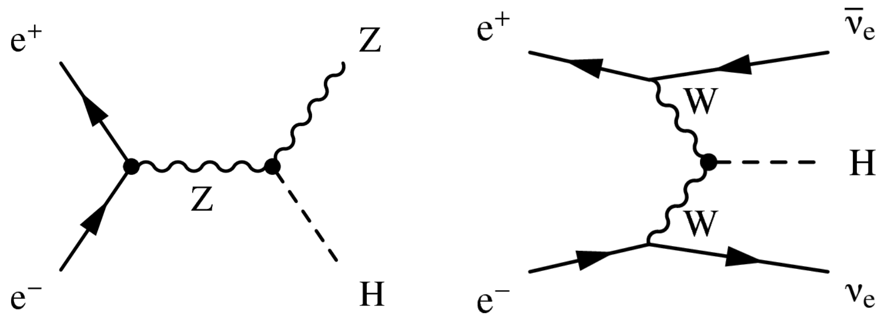


CLIC programme provides access to different Higgs boson production mechanisms:
- Higgstrahlung
- vector-boson fusion
- associated $t\bar{t}H$ production
- di-Higgs production

Expected soon: CLIC Higgs paper



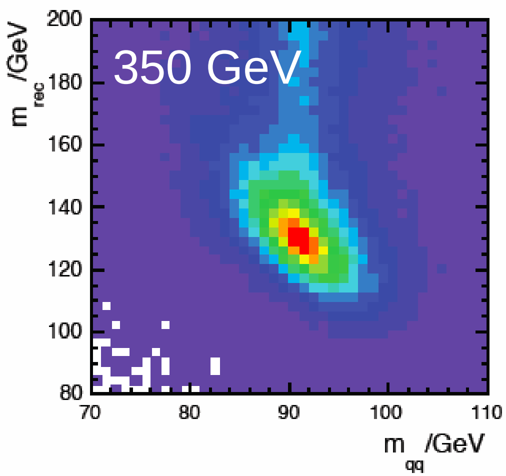
Higgs physics at 350 GeV



Analysis of Higgsstrahlung and vector-boson fusion events provides model-independent measurement of Higgs couplings

$Z \rightarrow \mu\mu$ BR~3.5%
$Z \rightarrow ee$ BR~3.5%
$Z \rightarrow qq$ BR~70%

$\Delta(\sigma_{HZ}) = \pm 4.2\%$
$\Delta(\sigma_{HZ}) = \pm 1.8\%$

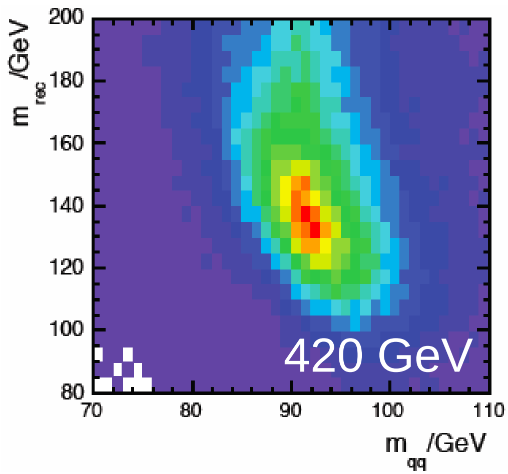


New: hadronic recoil analysis
M. Thomson, CLICdp-Pub-2015-004, arXiv:1509:02853

Jet energy resolution prefers 350 GeV over 420 GeV

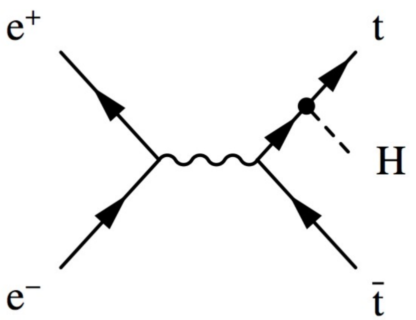
Jet clustering and tagging performance prefers 350 GeV over 250 GeV

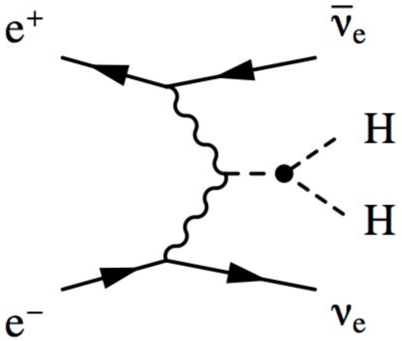
$\Delta(g_{HZZ}) = \pm 0.8\%$
BR(H=>inv) < 1%



Higgs physics

High-energy programme (1.4 – 3 TeV) provides opens up ttH production and di-Higgs production





ttH production: $e^+e^- \rightarrow$ ttH
- Extraction of top Yukawa coupling
- Best at $\sqrt{s} \gtrsim 700$ GeV

Projected precision:
- **$\Delta(g_{Htt})$ = ±4.5%** at 1.4 TeV

Double-Higgs production:
$e^+e^- \rightarrow HH\nu_e\nu_e$
- Simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
- Needs high $\sqrt{s} \gtrsim 1.4$ TeV

Projected precision:
Δ(λ) = ±10% for 1.4 TeV and 3 TeV operation combined (incl. polarisation)

CLIC's internal complementarity

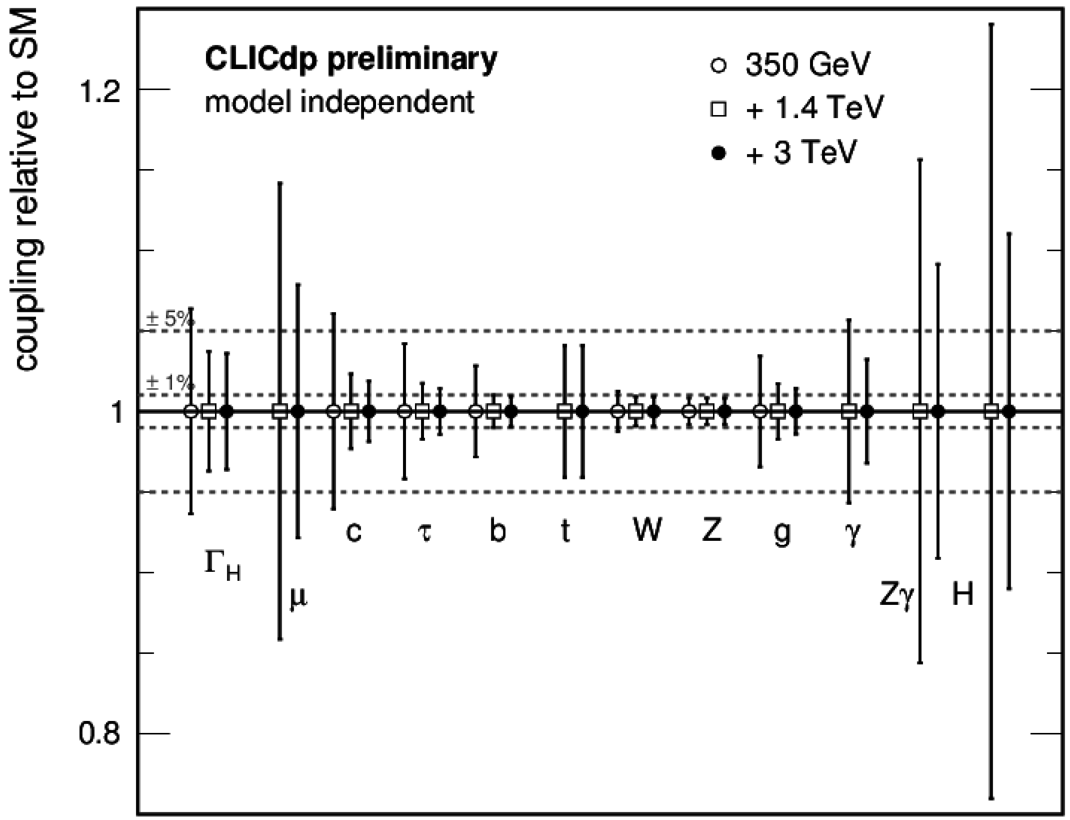
CLIC improves on its own low-energy results for most couplings

first stage provides crucial model-independent Z coupling measurement, and couplings to most fermions and bosons; higher-energy stages improve them, and add t, μ, g couplings

NEW: result for Higgs paper

includes hadronic recoil analysis

See talk by Ph. Roloff



Model-independent: width is free parameter
Model-dependent: assuming SM decays parameterizing perturbations as κ

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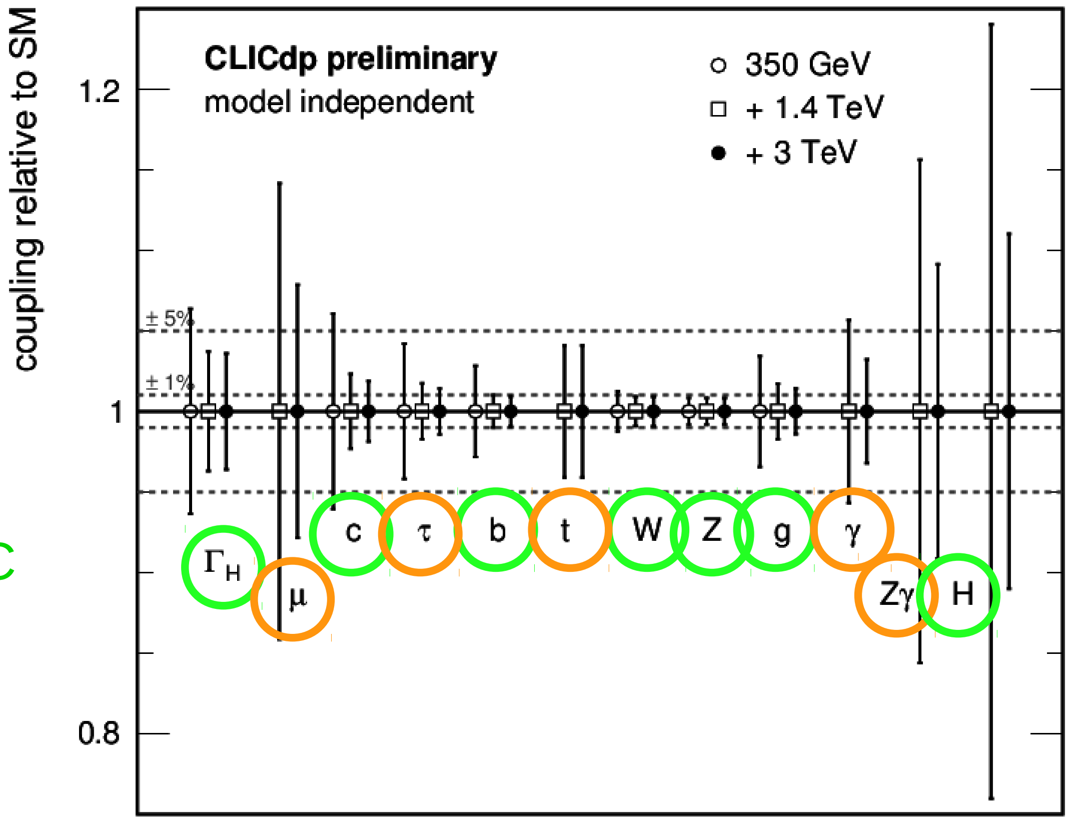
much more accurate than HL-LHC

similar accuracy as HL-LHC



Model-independent: width is free parameter

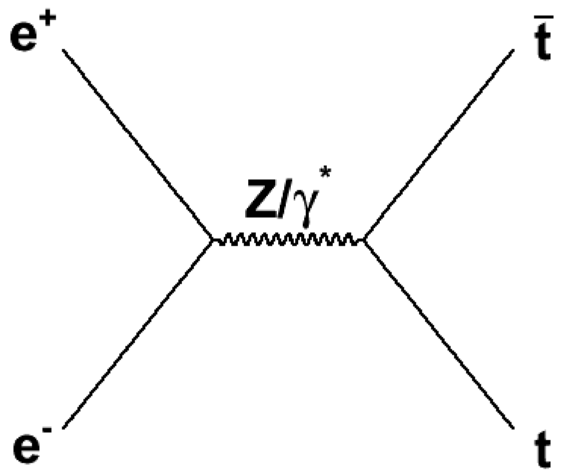
Model-dependent: assuming SM decays parameterizing perturbations as κ

Top quark physics

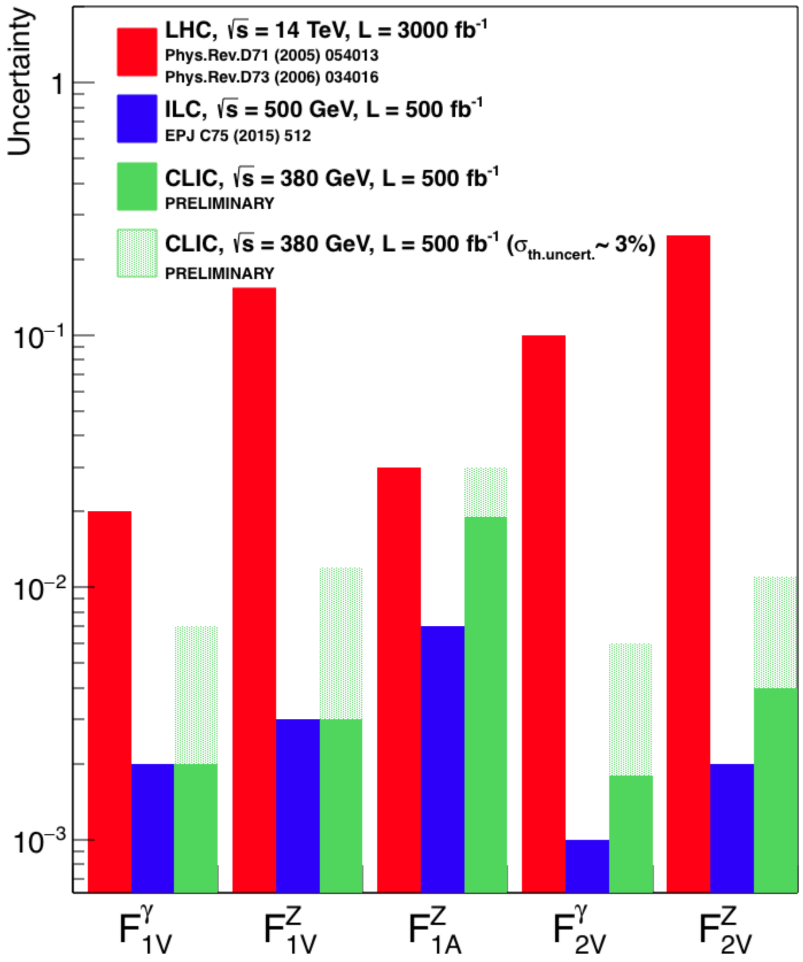
Top quark pair production

- $t\bar{t}Z$ coupling is a sensitive probe that may

present sizeable deviations for BSM at 10-30 TeV

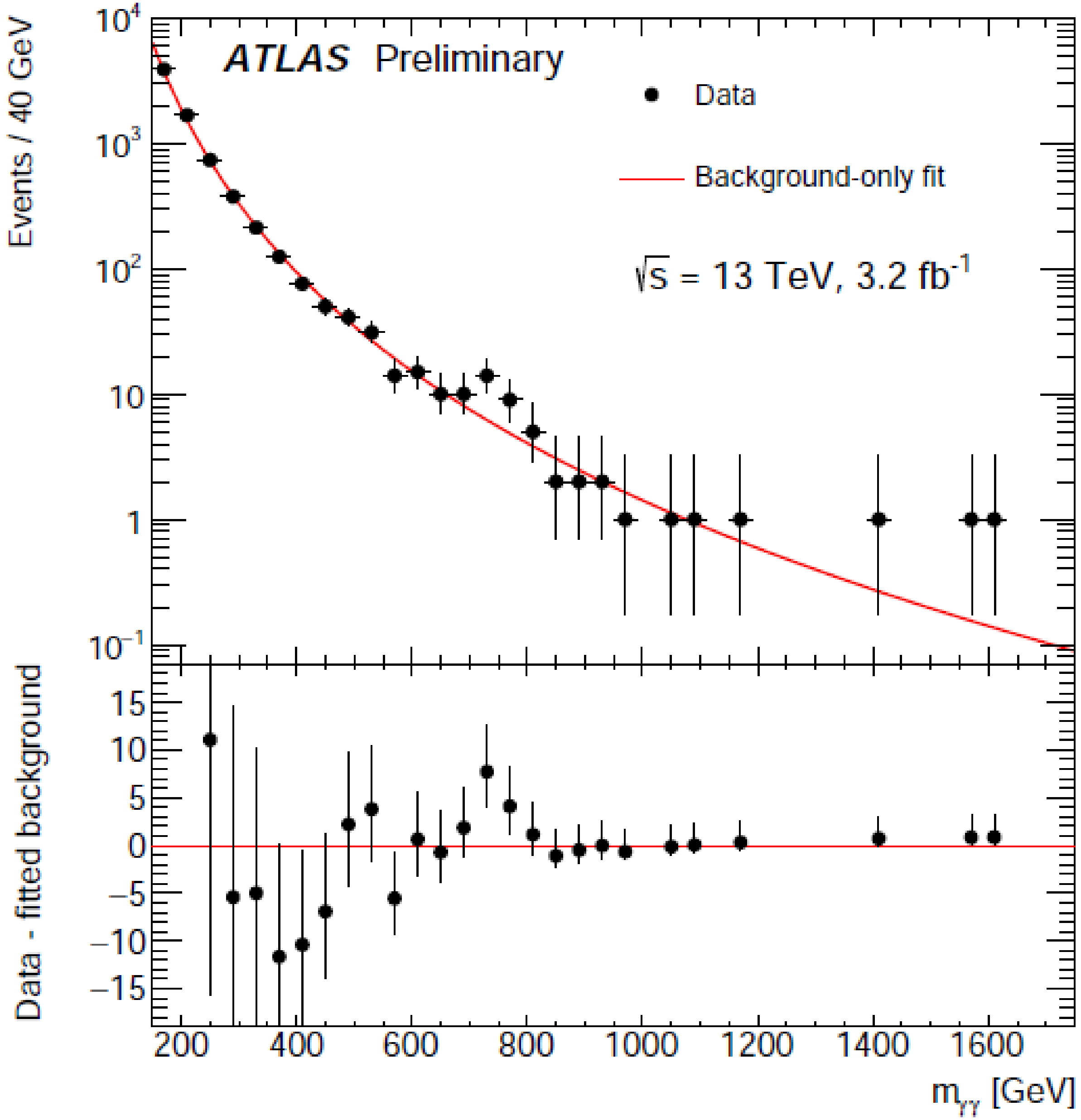


+top mass to 50 MeV, t → cH to 10^{-5}
Coordinated effort towards a top paper
See talk by I. Garcia



LC prospects are an order of magnitude better than LHC
500 GeV: larger boost and smaller theory uncertainty

New physics?

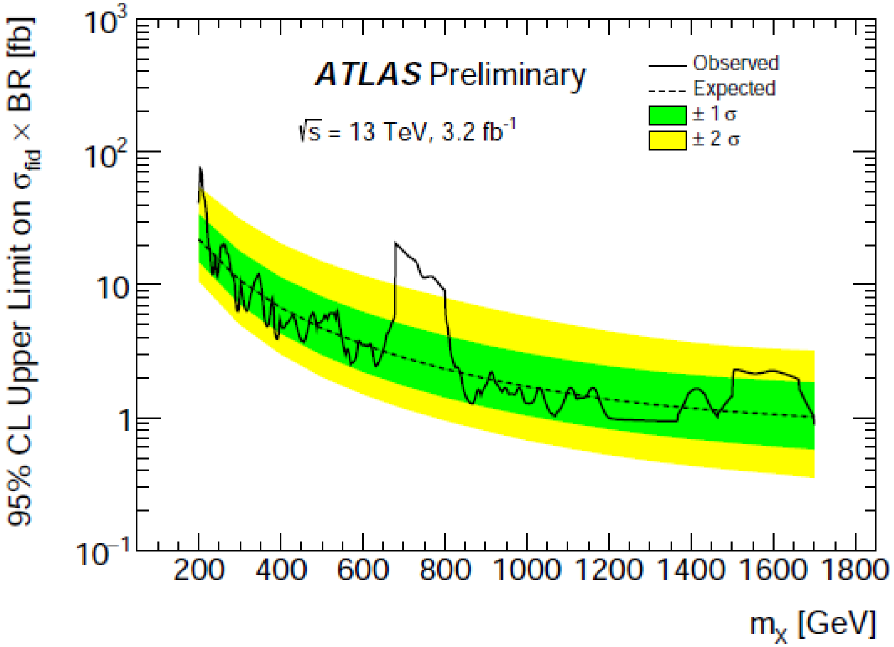


ATLAS di-photon spectrum

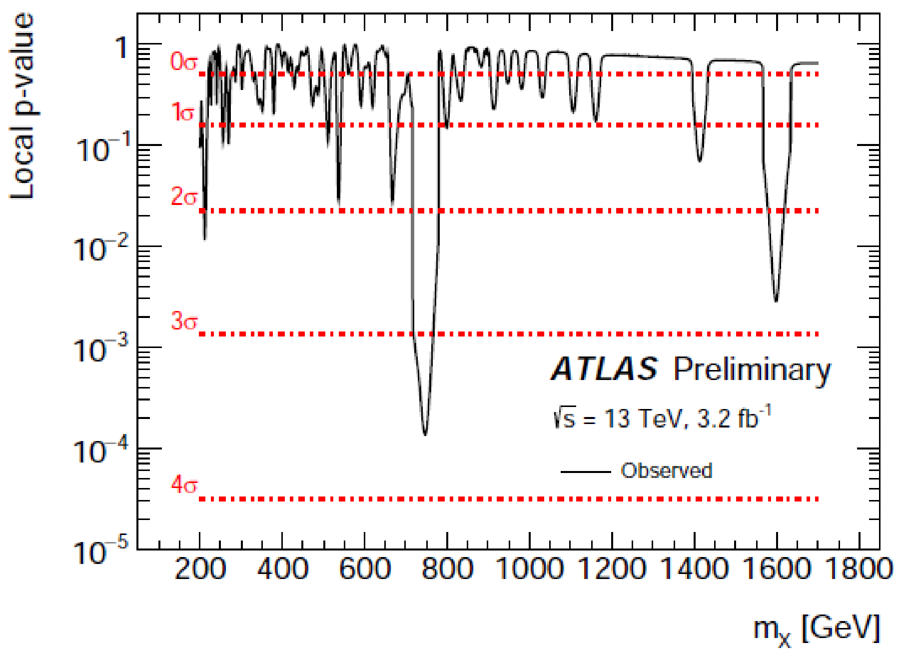
2015 data
3.2/fb of 13 TeV pp collisions

fit to smooth background

New physics: limits & p-values

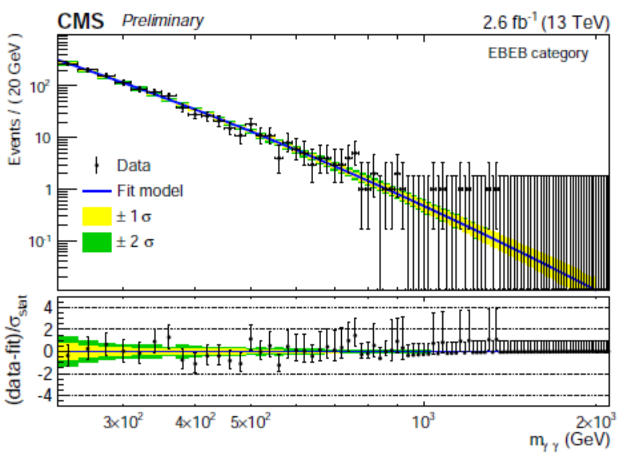


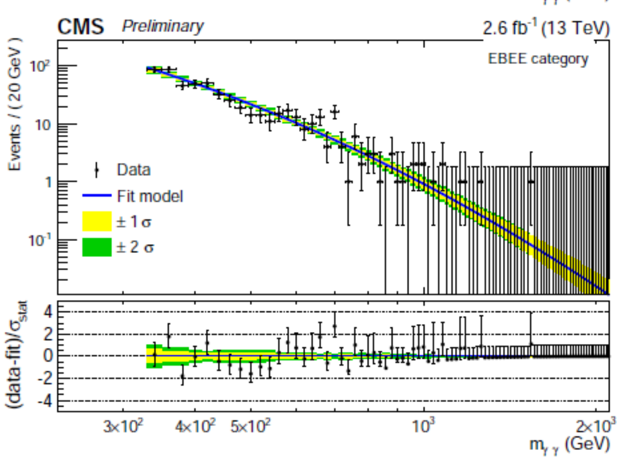
Limit on producion rate of a narrow state...
Clearly the limit around 750 GeV is quite poor

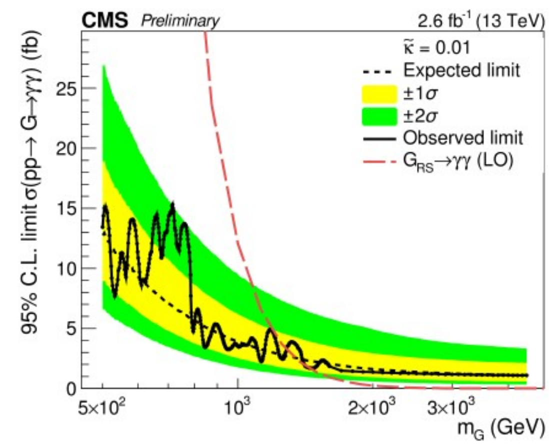


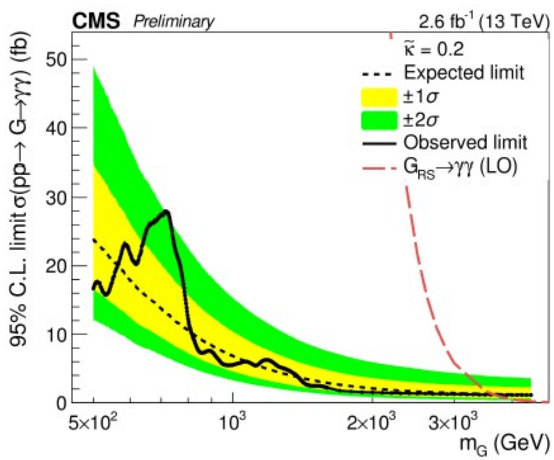
Local p-value = probability observations are compatible with background-only hypothesis.... without Look-Elsewhere-Effect

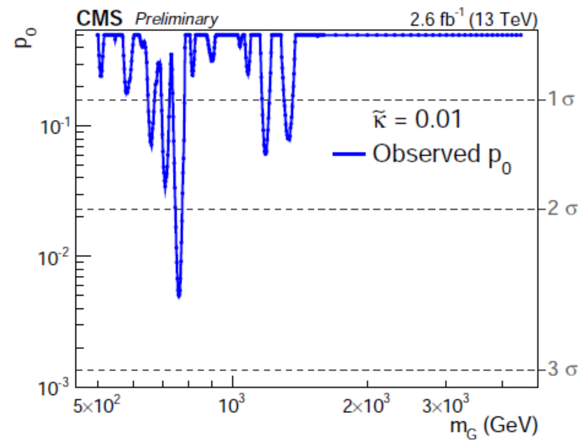
New physics... in CMS?

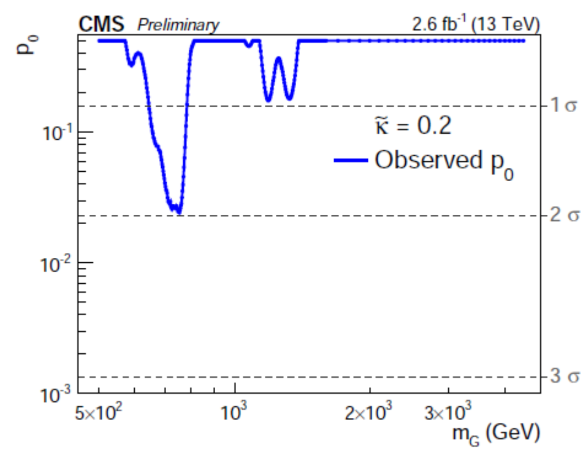












Discovery?

Poor signficance in ATLAS (<4σ locally) and none in CMS (2σ locally)

Look-Elsewhere-Effect reduces significance:

4σ → 2σ, 2σ → 1σ

200 theory papers can't all be wrong :)

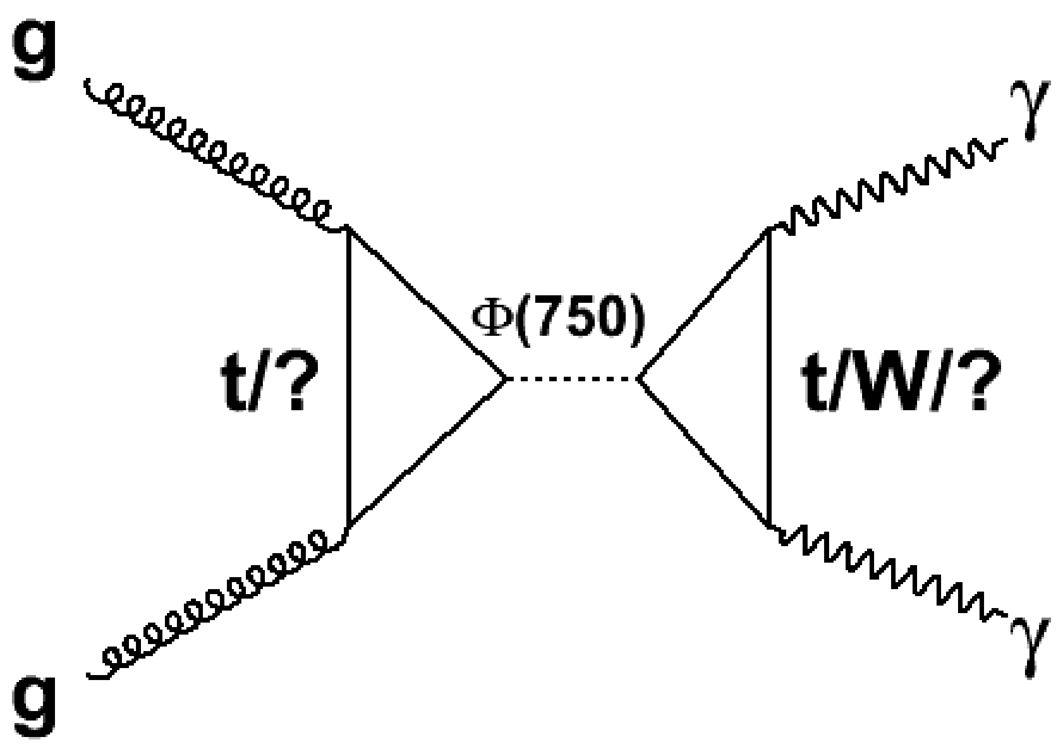
Wait six months and we'll know

New physics: be prepared for surprises

From the LHC, with love: a new scalar with m=750 GeV

The new state – if it exists - couples to photons, presumably through loops

So we might be seeing something like this:



New physics: be prepared for surprises

CERN-PH-TH/2015-302 IFUP-TH/2015

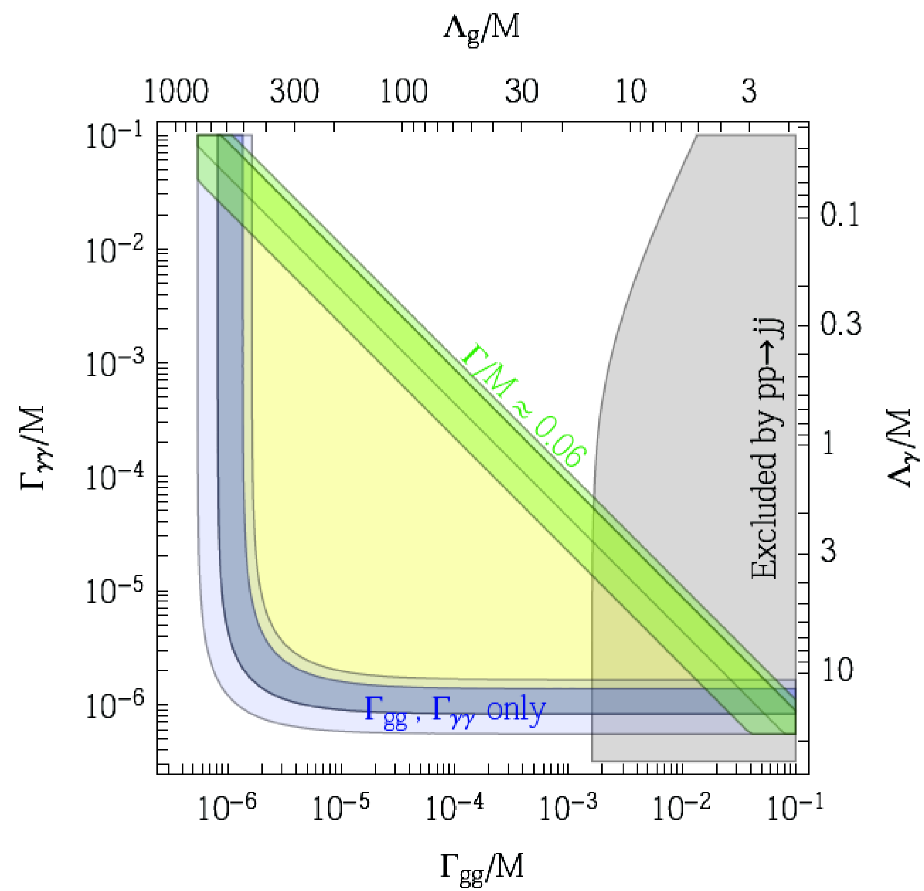
15 Dec 2015

What is the $\gamma\gamma$ resonance at 750 GeV?

Roberto Franceschini[a], Gian F. Giudice[a],
Jernej F. Kamenik[a,b,c], Matthew McCullough[a], Alex Pomarol[a,d],
Riccardo Rattazzi[e], Michele Redi[f], Francesco Riva[a],
Alessandro Strumia[a,g], Riccardo Torre[e]

[a] *CERN, Theory Division, Geneva, Switzerland*
[b] *Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*
[c] *Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19,*

Franceschini, Giudice et al., arXiv:1512.04933v1

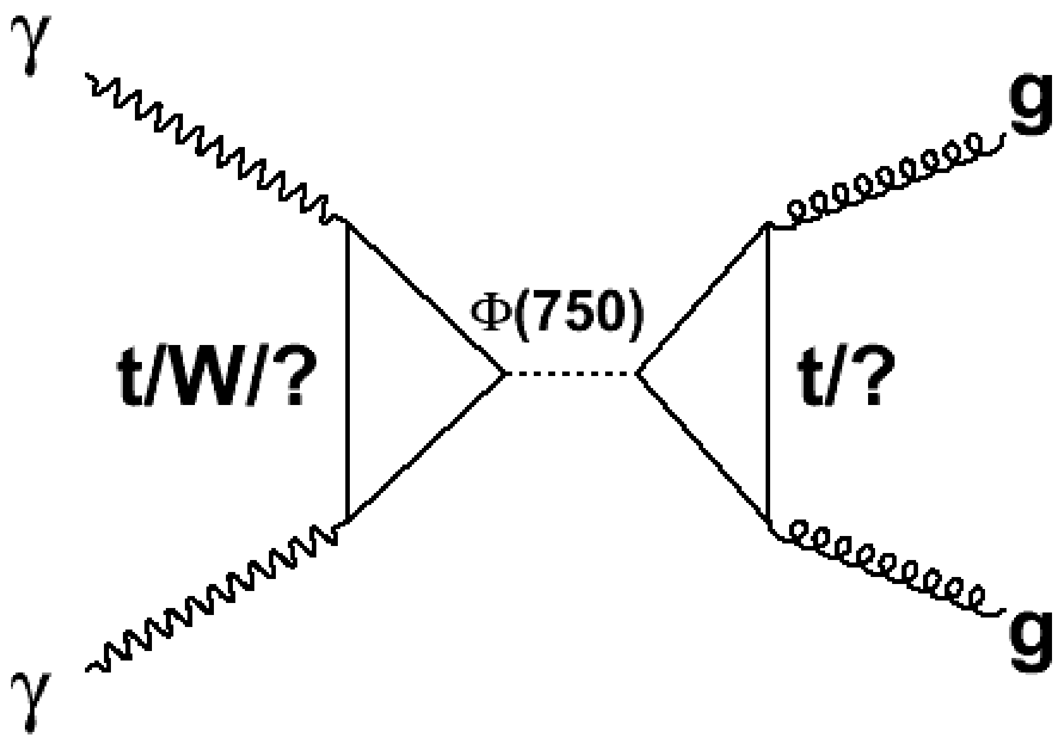


New physics: be prepared for surprises

From the LHC, with love: a new scalar with m=750 GeV

The new state – if it exists - couples to photons, presumably through loops

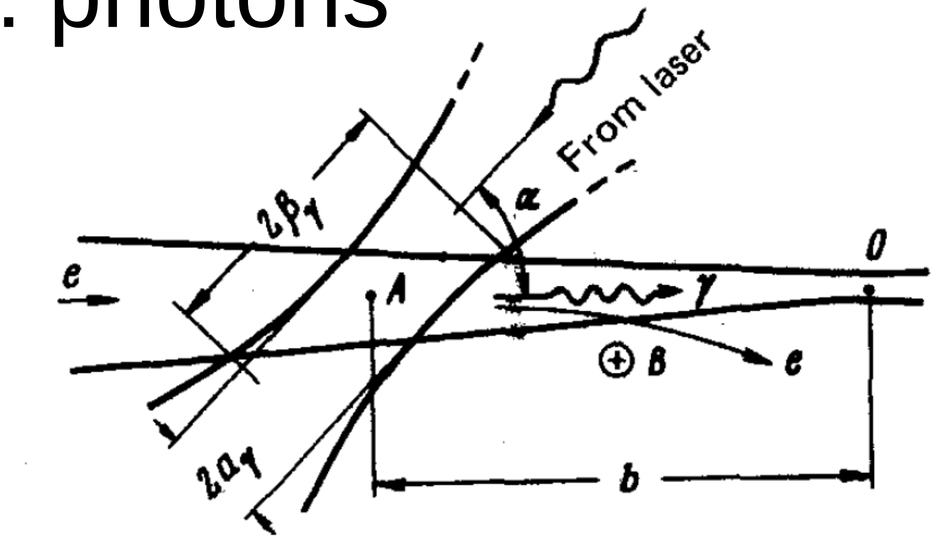
Then this other process should also have a sizeable rate:



New physics: photons

A 1 TeV $e^+ e^-$ collider + couple of lasers

= 750 GeV photon collider



Ginzburg et al., NIM 205, NIM 219, JETP Lett. (early 80s)
TESLA TDR, V. Telnov, JINST 9 (2014) 09 C0909

Production rate expected to be O(100) fb

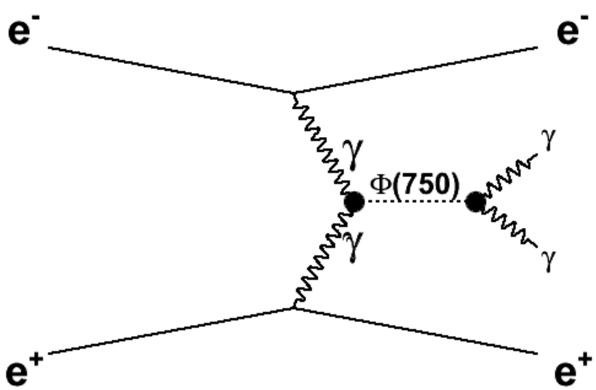
F. Richard, private comm.

Ito, Moroi, Takaesu, arXiv:1601.01144

Djouadi el a., arXiv:1601.03696

CLIC $\gamma\gamma$ option: https://indico.cern.ch/contributionDisplay.py?contribId=145&confId=175067

Photon fusion at high energy collider



Sizeable cross-sections possible if photon dominates the Φ(750) width
Requires rather high energy (2 TeV)

New physics: more speculative

A new scalar with m=750 GeV can be many things:

- **If the new state couples to W or Z, vector-boson fusion production of such a heavy state requires a high-energy $e^+ e^-$ machine**

  Cross section typically O(1) fb at 2 TeV

- **If it is accompanied by, say, vector-like leptons**

  these can be pair-produced if $\sqrt{s} > 2m$

- **If it talks to the Standard Model (Higgs and top)**

  sizeable deviations in precision measurements at “low” energy

Illustration: Higgs couplings in several scenarios (with Λ = 1 TeV)

Snowmass Higgs report (arXiv:1310.8361)

LCC physics WG is working out more specific cases

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

New physics: more speculative

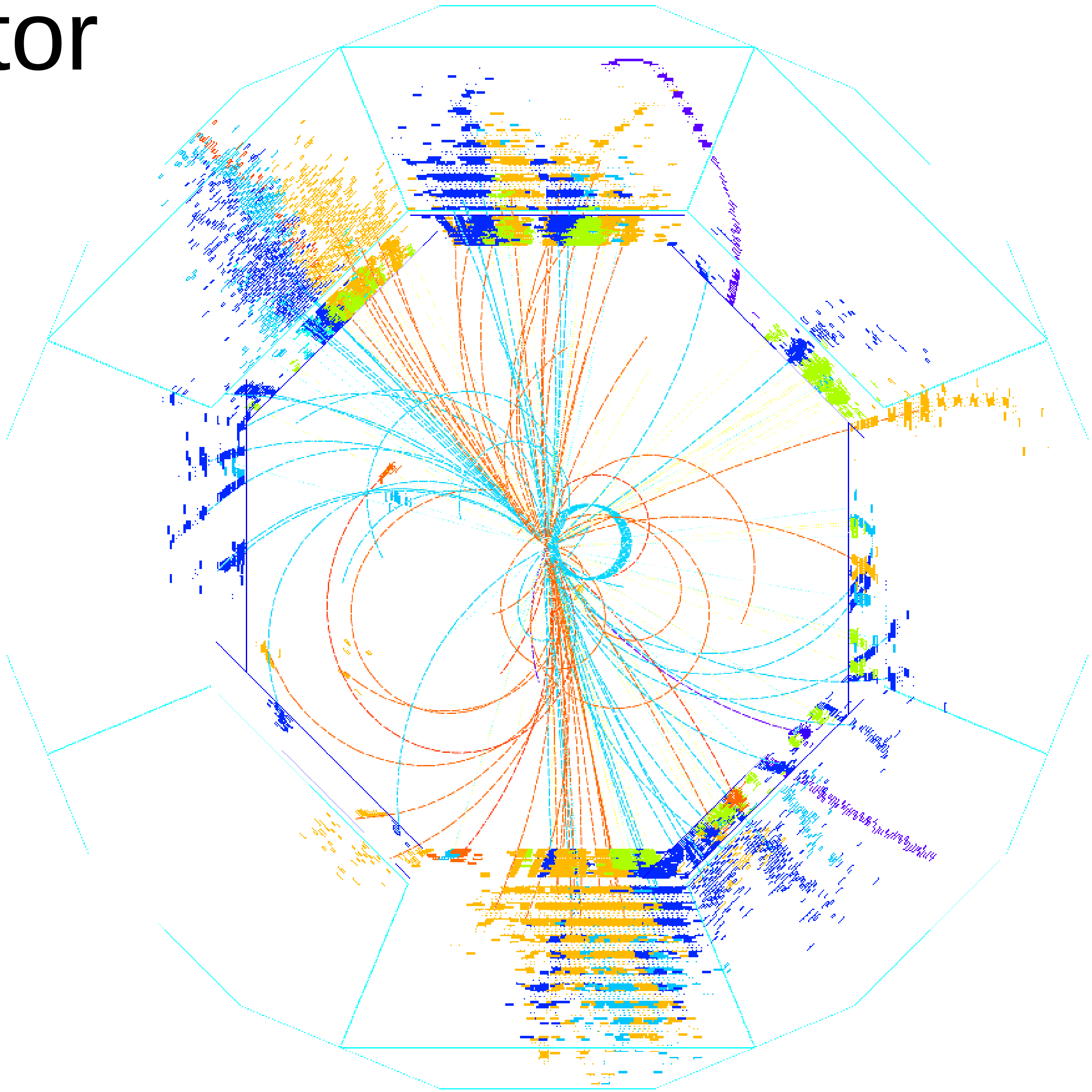
A new scalar with m=750 GeV can be many things:

Potentially very rich phenomenology,
both at low (250-500 GeV) and high energy (1-3 TeV)

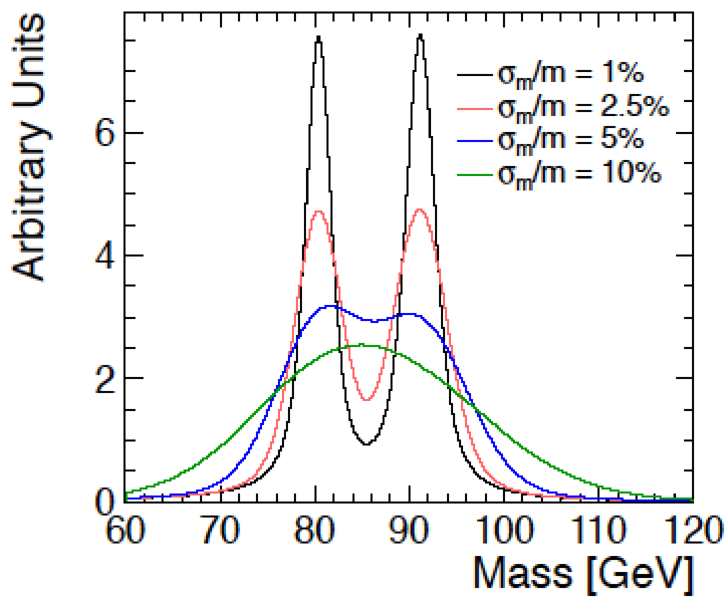
Djouadi, Ellis, Godbole, Quévillion, arXiv:1601.03696
"If the discovery is confirmed, it will shine a new light on options for possible future colliders, placing a premium on those with sufficient energy to produce the new particles, while also suggesting a new motivation for precision low-energy experiments."

See talks by F. Simon, M. Berggren for more conventional new physics prospects

CLIC detector



CLIC detector requirements



★ **momentum resolution:**

endpoints, Higgs recoil mass, Higgs → $\mu\mu$

$$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\,\mathrm{GeV}^{-1}$$

★ **jet energy resolution:**

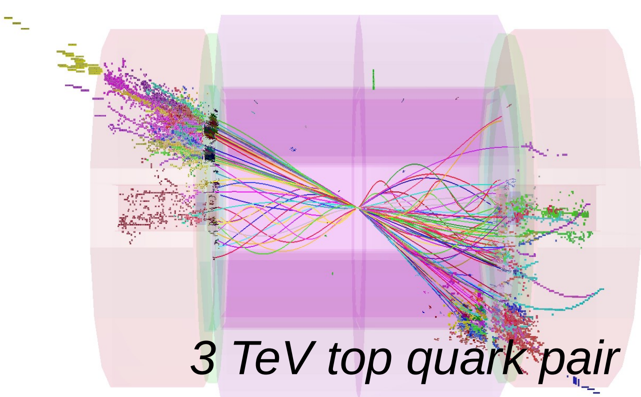
W/Z/h di-jet mass separation

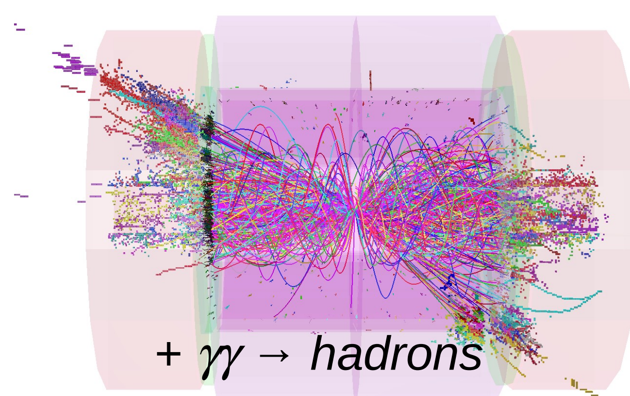
$$\frac{\sigma_E}{E} \sim 3.5 - 5\ \%$$ (for high-E jets)

★ **impact parameter resolution:**

c/b-tagging, Higgs BR

$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$





+ time stamping for $\gamma\gamma \rightarrow$ hadrons and pair production

★ **Forward coverage!!**

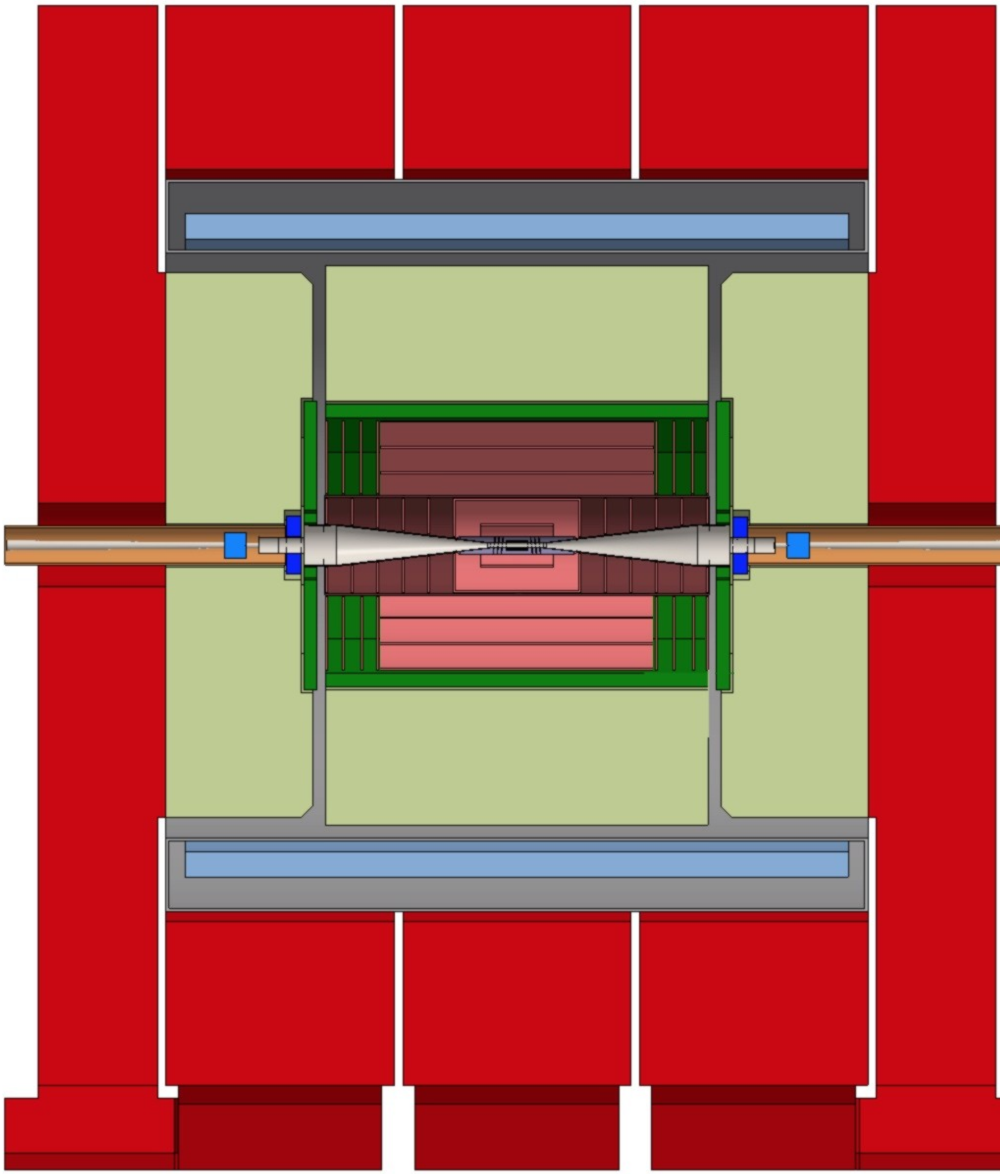
CLIC Detector Concept

Adapt the ILC concepts to a single CLIC detector

- 4 Tesla solenoid
- highly granular and deep calorimeter (1+8Λ)
- low-mass silicon tracking system
- precision vertexing (starting at R=3 cm)
- precise 10 ns time stamping
- QD0 outside detector (forward coverage)

For overview:
CLIC CDR, arXiv:1202.5940

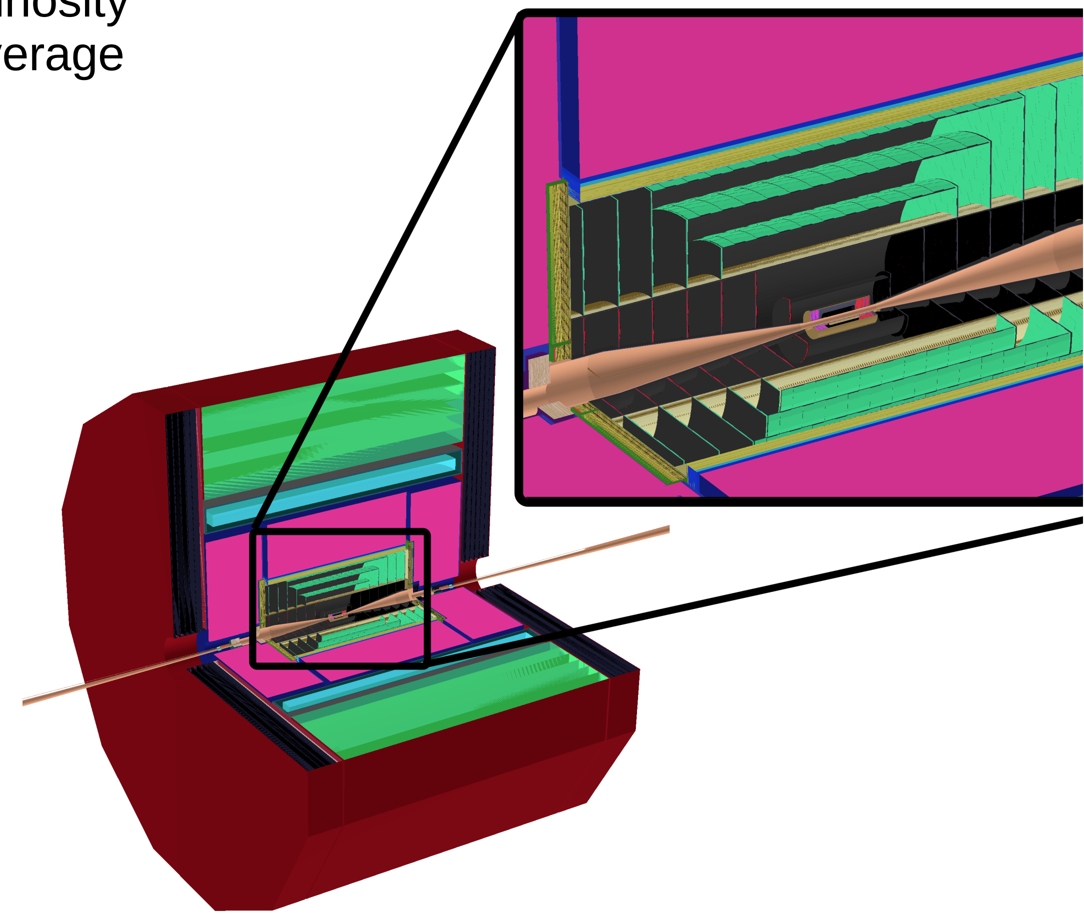
For up-to-date details:
Marko Petric, Friday plenary session



New Detector Design

Position of final quadrupole QD0 represents a trade-off

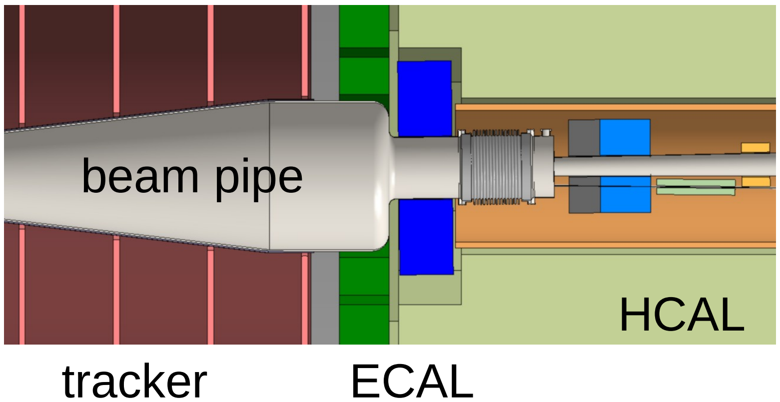
- QD0 inside detector → maximal luminosity
- QD0 outside detector → forward coverage (important at high energy!)



new CLIC detector model:

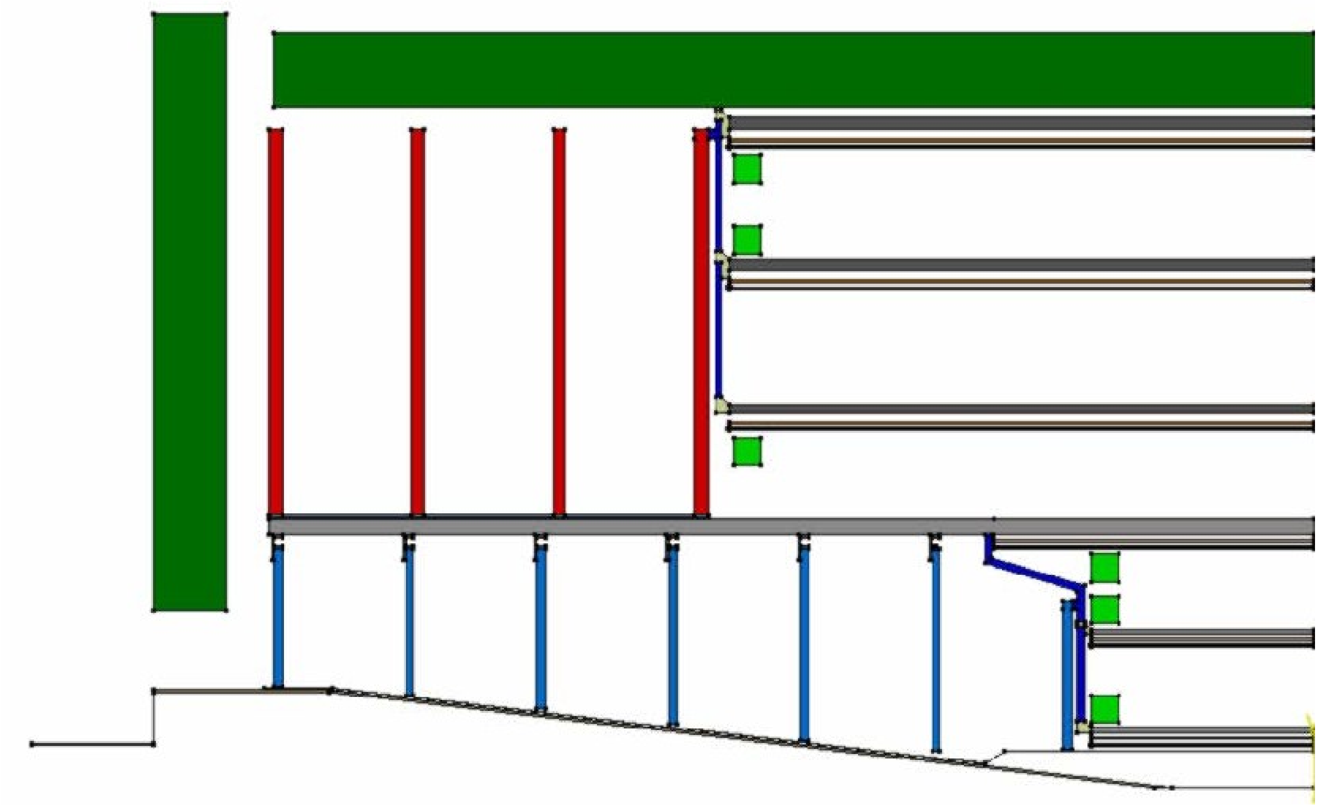
R (HCAL) decreased, 500 → 250 mm

L* = 6 m, minor loss of luminosity

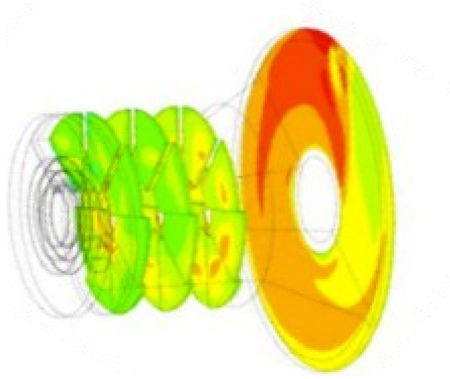


See talk by Marko Petric

New tracker layout



Increased realism from engineered studies of services: power, supports, cooling

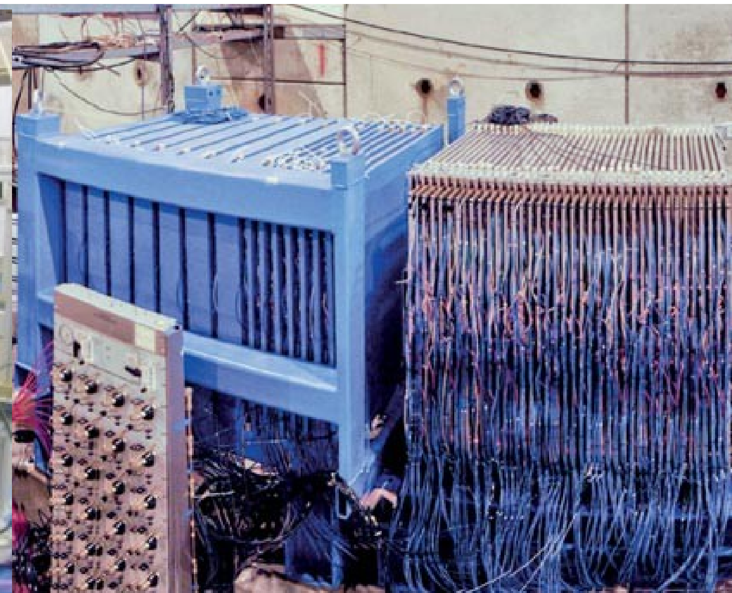


All-silicon tracker, divided in an inner and outer system

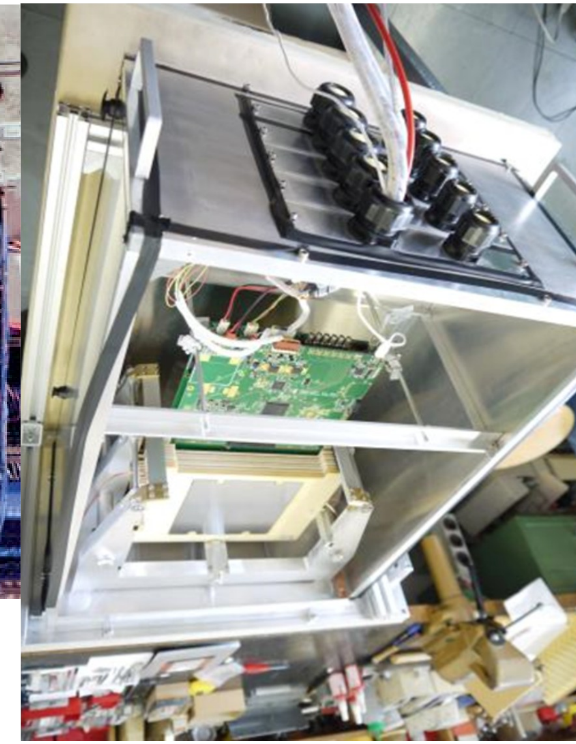
- 3 short + 3 long barrel layers
- 7 inner + 4 outer endcaps

At least 8 hits (Vertex + Tracker) for > 8◦

CLIC Detectors: calorimetry



CALICE

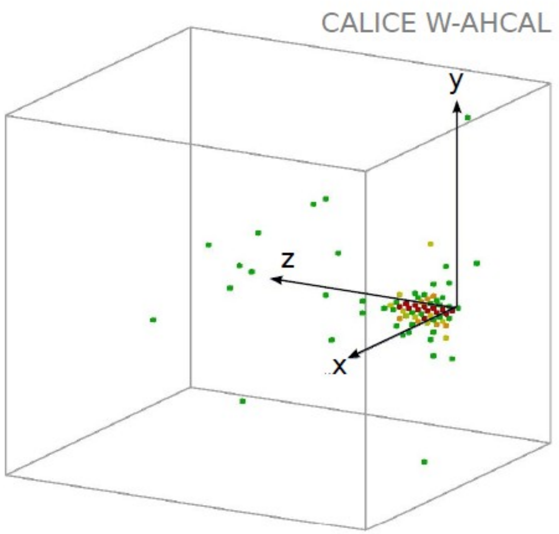


FCAL

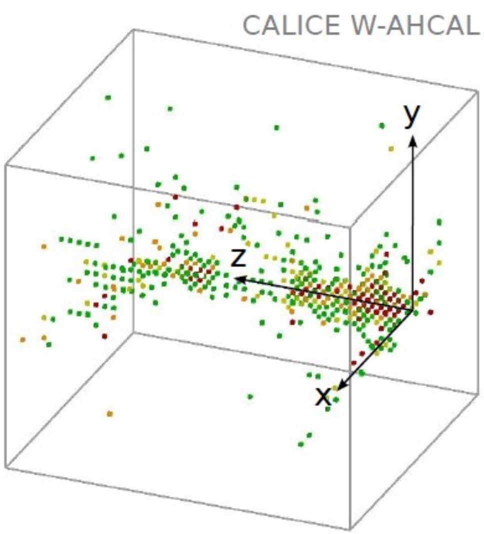
Ultra-granular calorimeters: from science fiction to science

The **CLICdp group contributes to the CALICE and FCAL** R&D collaborations, which have constructed and tested ultra-granular SiW EM calorimeters, a 1 m^3 prototype ScW hadronic calorimeter and forward calorimeter prototypes

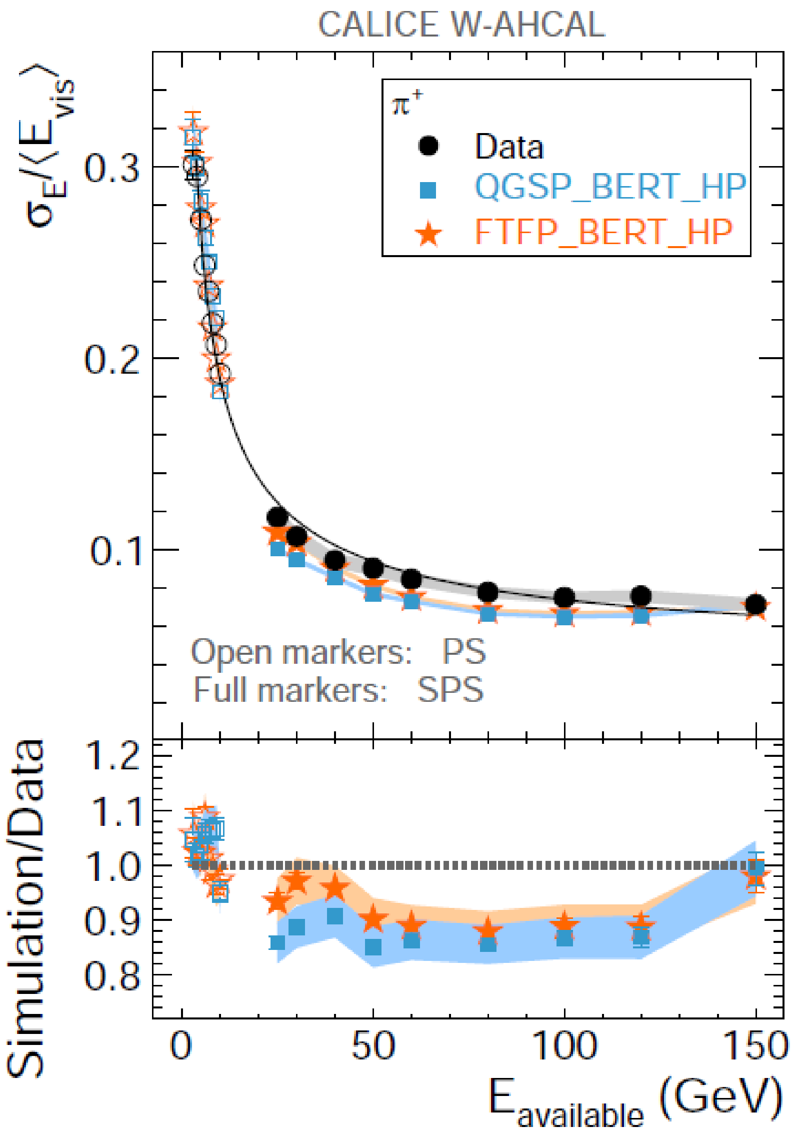
CLIC detectors: calorimetry



EM shower



hadronic shower



Unique opportunity to understand hadronic shower (longitudinal profile, time structure)

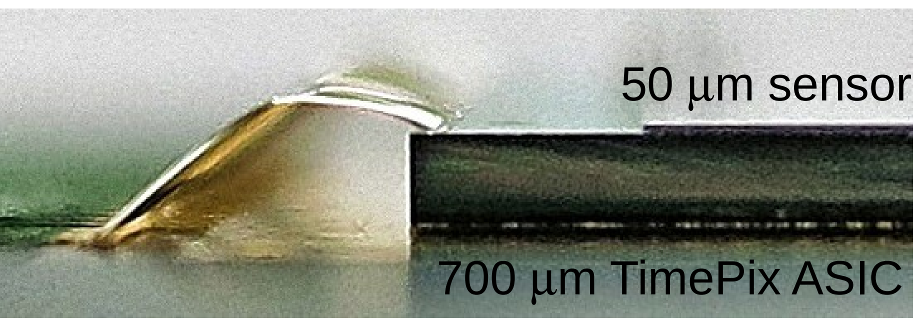
CALICE, JINST10 (2015) 12, P12006

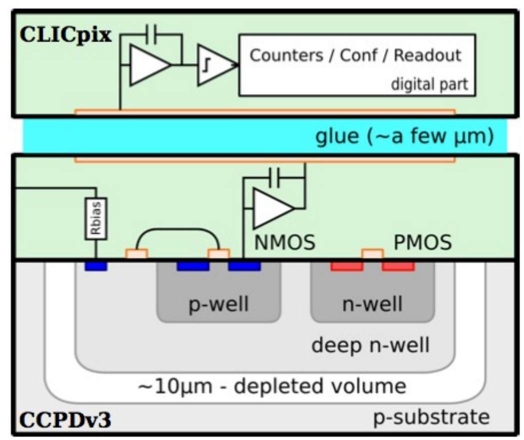
See contributions in this workshop:
F. Sefkow (CALICE), M. Manelli (CMS)

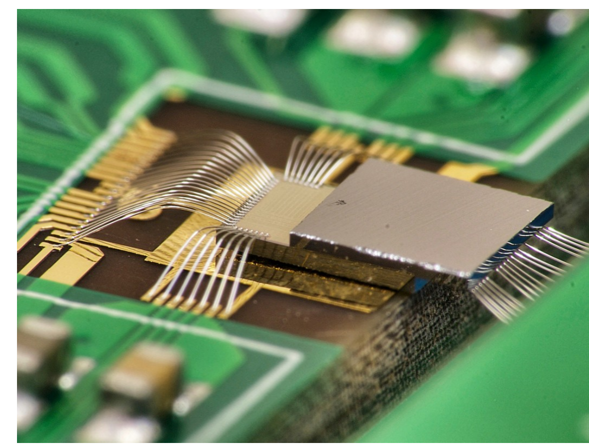
Vertex detector/tracker

Hybrid pixels & active R&D on CMOS, active, 3D integrated, SOI,...
(precise & fast within a challenging material budget)

CLICpix
(evolution of TimePix to 25 x 25 µm2 pixels)







capacitive signal connection to CMOS detector

Can we build a demonstrator that meets all challenging specifications
– 10 ns time stamping, 3.5 µm resolution, low power, 0.2% X_0/layer?

presentation by M. Campbell in this session
See also: review by N. Wermes

Reconstruction software

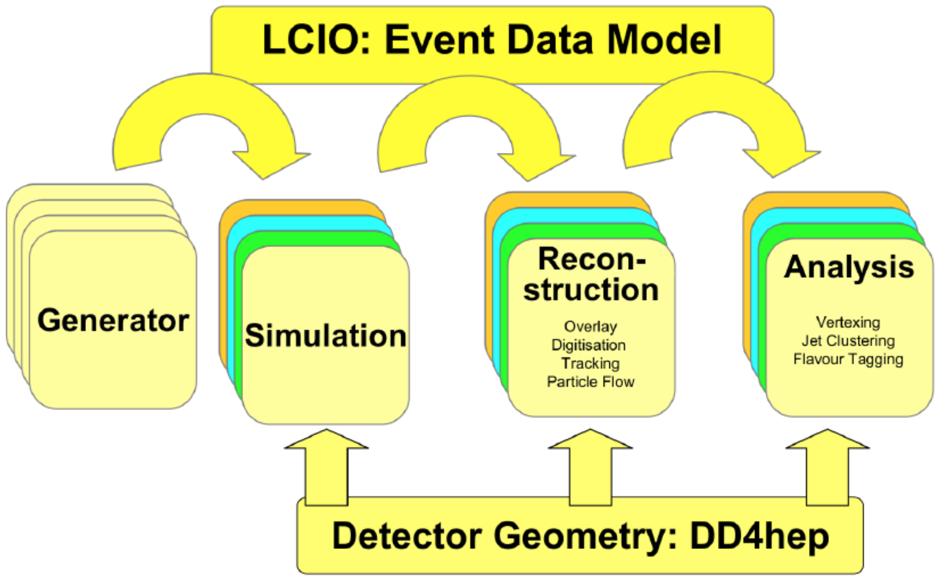
- Track reconstruction in dense jets
  - Adopt solutions from LHC
- Particle flow “under pressure”
  - Confusion limits high-energy resolution
- Jet reconstruction with background
  - New algorithms

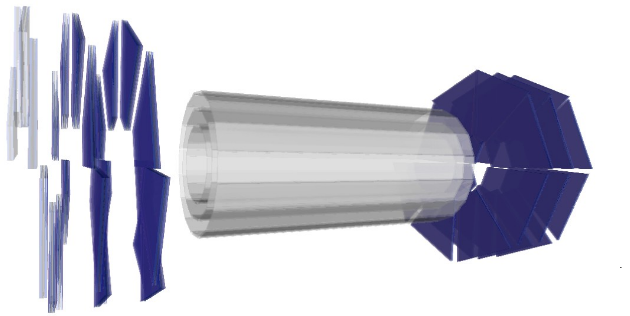
overlap with LHC experiments

FCC-hh is forced to find solutions

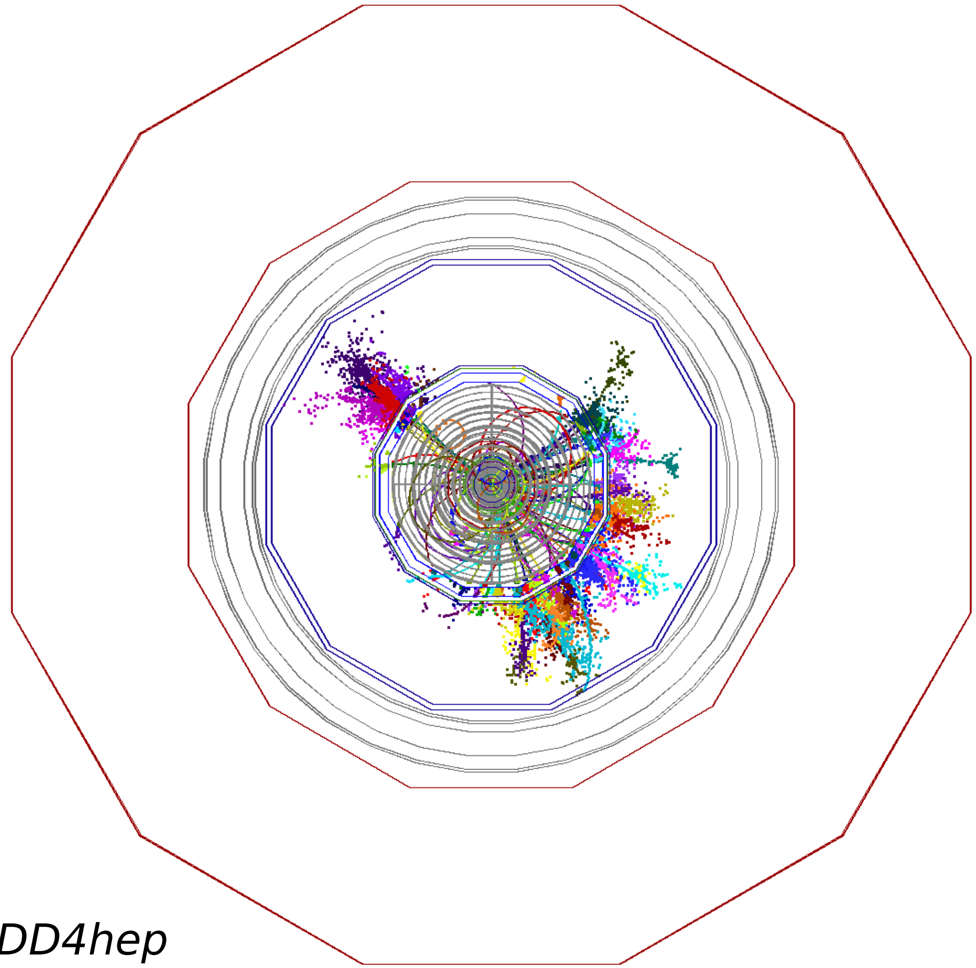
Track reconstruction

Continuous improvement of **Linear Collider software** for simulation/reconstruction
Strong common ILD/CLICdp effort. Emphasis: **DD4hep** and **track reconstruction**





CLIC vertex detector in DD4hep



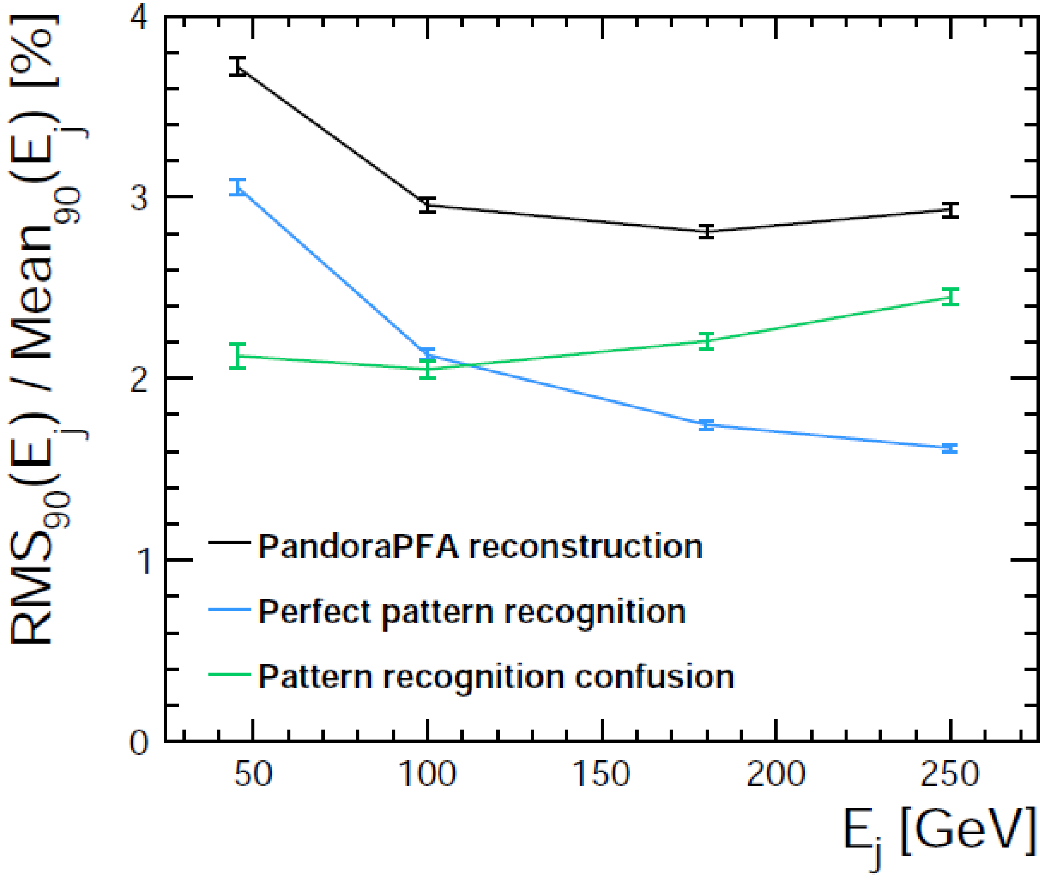
CLIC event simulated, reconstructed, visualised with DD4hep

PFA/jet reconstruction

Pandora Particle Flow

EPJC75 (2015) 9, 439

- Energy resolution: ΔE/E~3%
- Powerful jet substructure analysis



- Excellent jet reconstruction performance in 50-250 GeV range
- Confusion degrades energy resolution at TeV scale
- Clustering limits performance of 4, 6 and 8-jet final states (vvHH, ttH)

Summary

- CLIC's low-energy stage provides very competitive precision Higgs and top physics, probing new physics at very high scales
- CLIC opens up the possibility of e^+e^- collisions with $\sqrt{s} >> 1$ TeV, giving access to ttH and HH production and extending the direct discovery reach
- In the next years the CLIC detector and physics collaboration will:

  - finalize a realistic detector model (~2016)

  - pursue detector R&D for the most challenging components (calorimetry, vertexing)

  - complete physics case studies on Higgs, top and BSM physics (~2017)

  providing inputs for the next European Strategy discussion (2019/20)

See: Lucie Linssen's talk on Friday

CLICdp plans up to next European Strategy

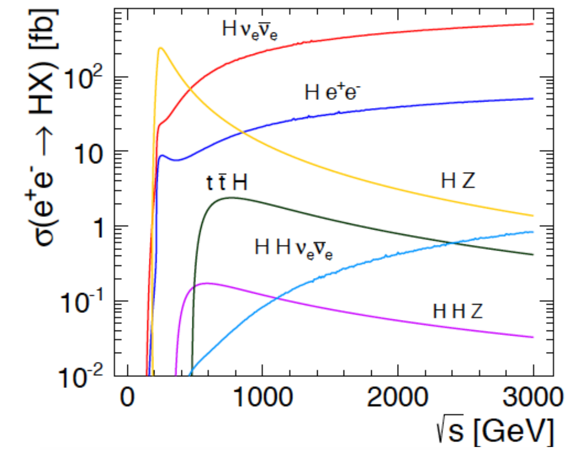
CLICdp reports serving as ingredients for a summary report:

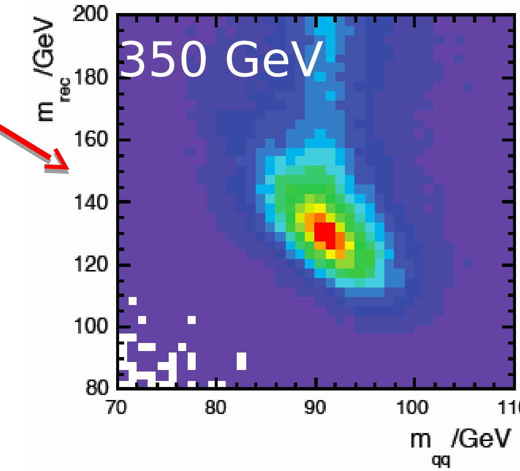
- 2015 CLIC re-baselining report †
  - In preparation, together with accelerator. Draft by end-2015. Publication tbc.
- The 2015 CLIC detector model †
  - Nearly complete draft exists. Technical note.
- The CLIC Higgs physics overview publication of 2015 †
  - Nearly finished. End-2015. Publication
- An overview of CLIC top physics
  - Foreseen CLIC top physics publication in 2016/2017?
- Extended BSM studies (hopefully motivated by LHC discoveries)
  - Foresee publication in 2017?
- CLIC R&D report => with main CLIC technology demonstrators
  - Summary report, 2017, Note or Publication tbc.
- Plan for the period ~2019-2025 in case CLIC would be supported by next strategy
  - 2017/2018, Note to be included in the CLIC input report for the Strategy

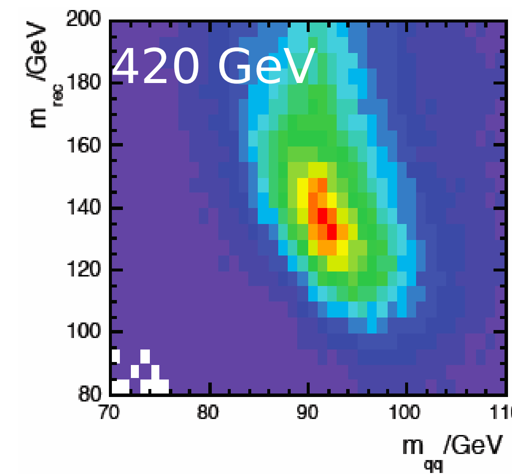
choice of lower CLIC energy stage (1)

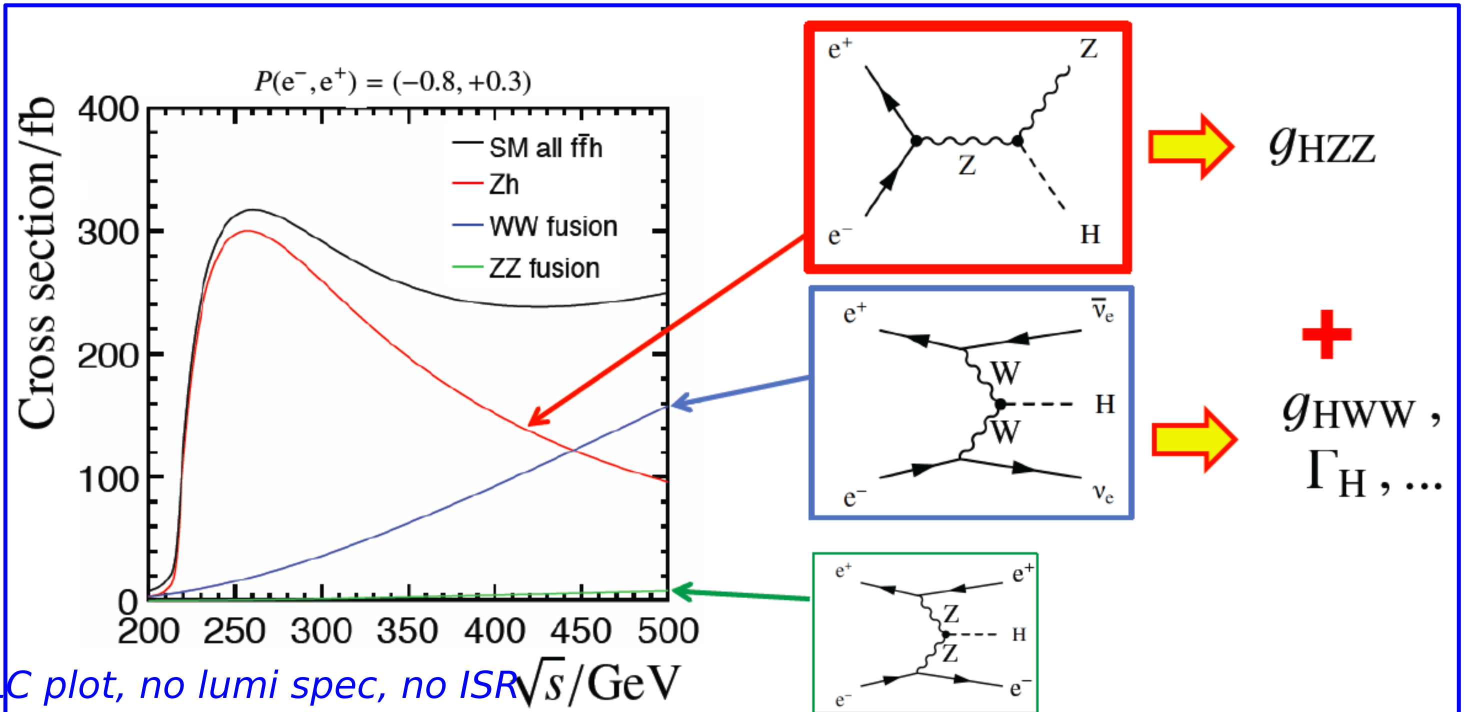
Guaranteed physics case #1: Higgs physics

- **HZ production** => $\sqrt{s}$ ~ 250 – 450 GeV
- **Recoil mass measurement** => $\sqrt{s}$ < 400 GeV
- **H from WW fusion** => $\sqrt{s}$ > 350 GeV





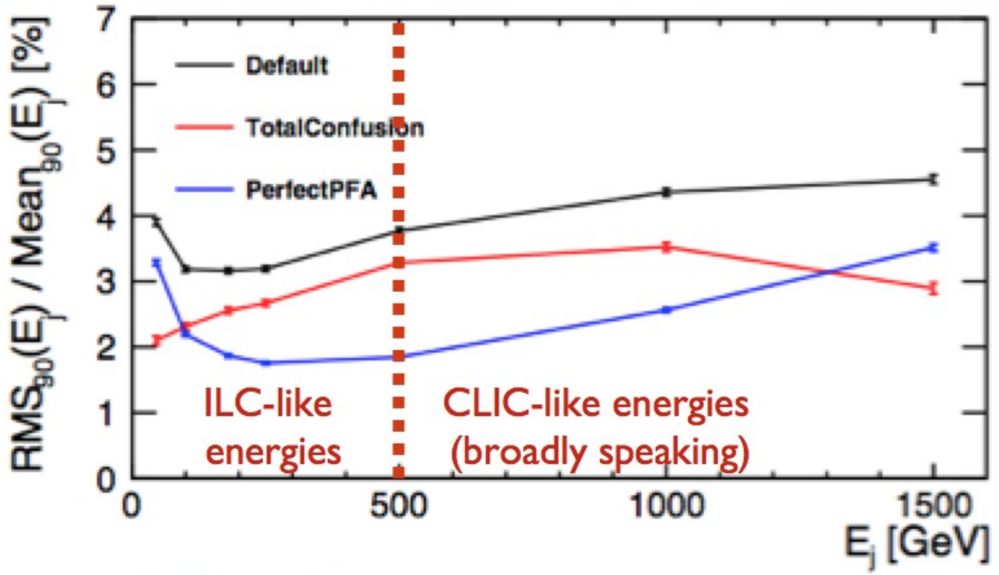




CLIC jet reconstruction

High-energy performance dominated by confusion in PFA pattern recognition

Improvements in software may change (and indeed have changed) the overall picture in a qualitative fashion!

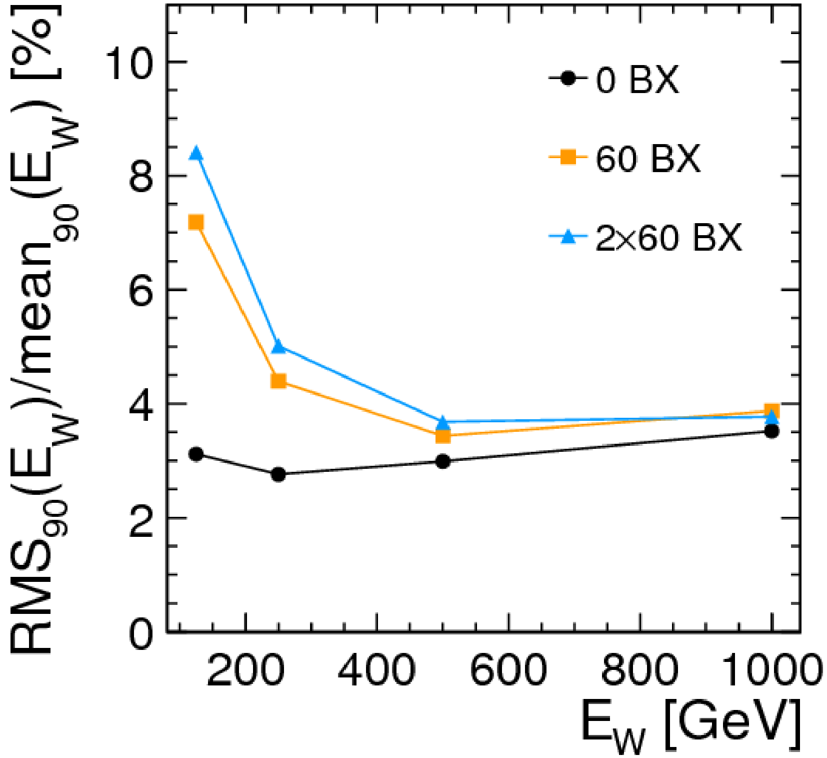


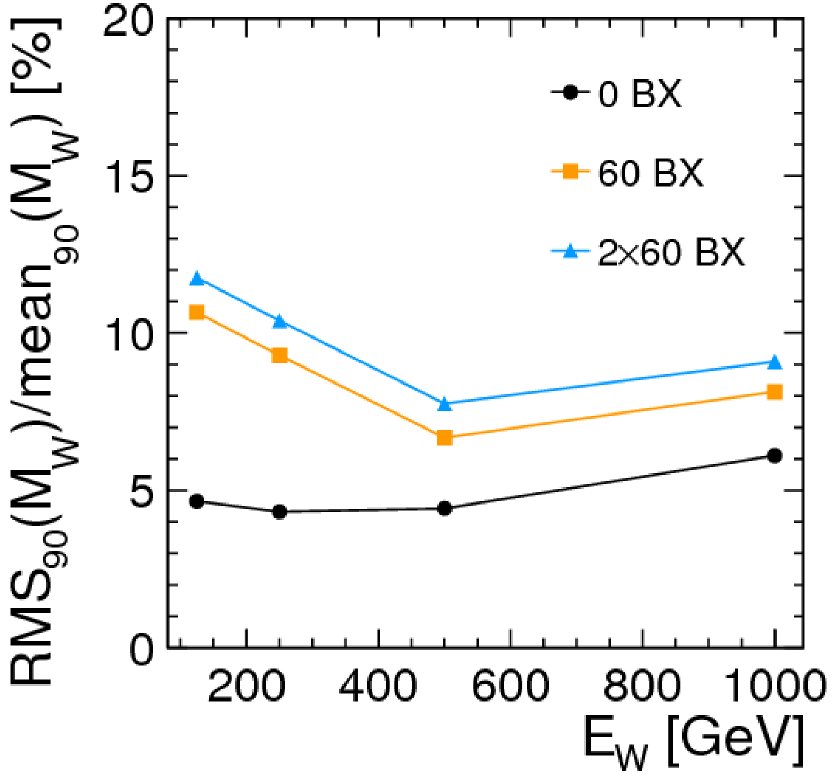
Reap the rewards of this approach with detector optimisation studies…

Jet energy resolution (with intrinsic energy resolution and confusion terms) as a function of jet energy, for $45\,\text{GeV} \leq E_j \leq 1.5\,\text{TeV}$

Impact of background on jets

$e^+e^- \rightarrow W^+W^- \rightarrow l\nu q\bar{q}$ events at CLIC at 3 TeV with W energies of 100, 250, 500 and 1000 GeV
Overlay 60 (120) BX worth of $\gamma\gamma \rightarrow$ hadrons, select in-time reconstructed particles, remove lepton
Reconstruct long. inv. k_t jets exclusively (N=2, R=0.7)

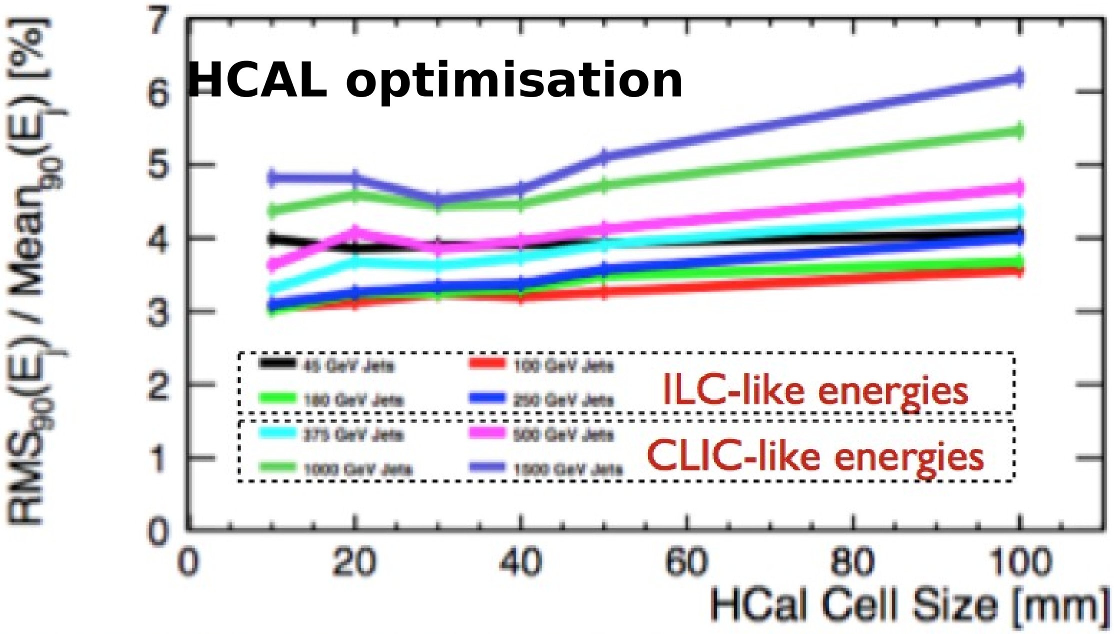




Energy resolution at high energy is not too badly affected, but can deteriorate strongly at low energy. Mass resolution suffers.

[CLIC CDR, Marshall, Münnich & Thomson, arXiv:1209.4039],
See also: M. Boronat et al., PLB750 (2015) 95-99

Pandora ILC/CLIC synergies



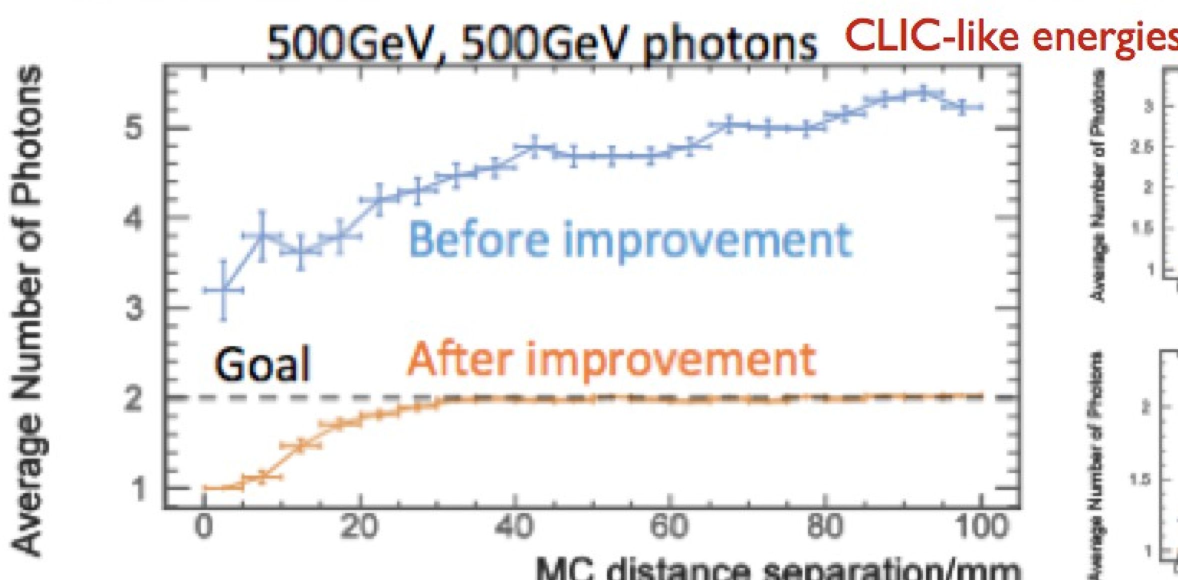
Jet energy resolution vs HCAL cell size, for 45 GeV ≤ E_j ≤ 1.5 TeV

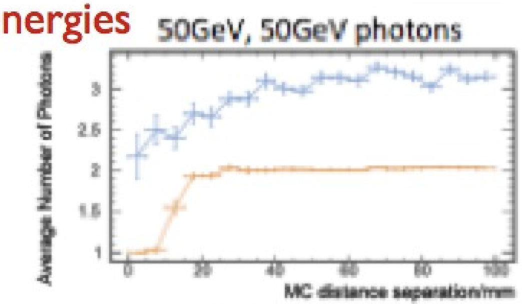
(The Devil's in the detail for these kinds of plots)

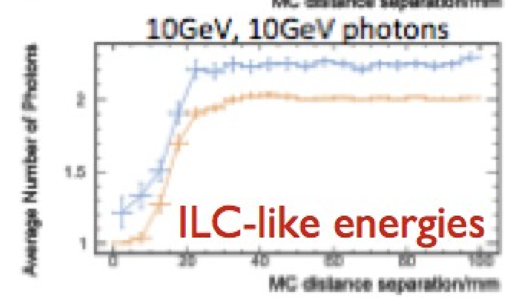
HCal Timing Cuts: 10 ns
ECal Timing Cuts: 20 ns
Hadronic Energy Truncation: 10^6 GeV
Software: ilcsoft_v01-17-05
Digitiser: ILDCaloDigi, without new realistic options,
Calibration: As documented in PandoraAnalysis v02-00-00

Photon reconstruction

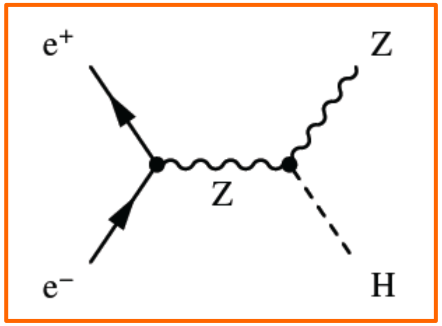
e.g. photon fragment removal algorithms



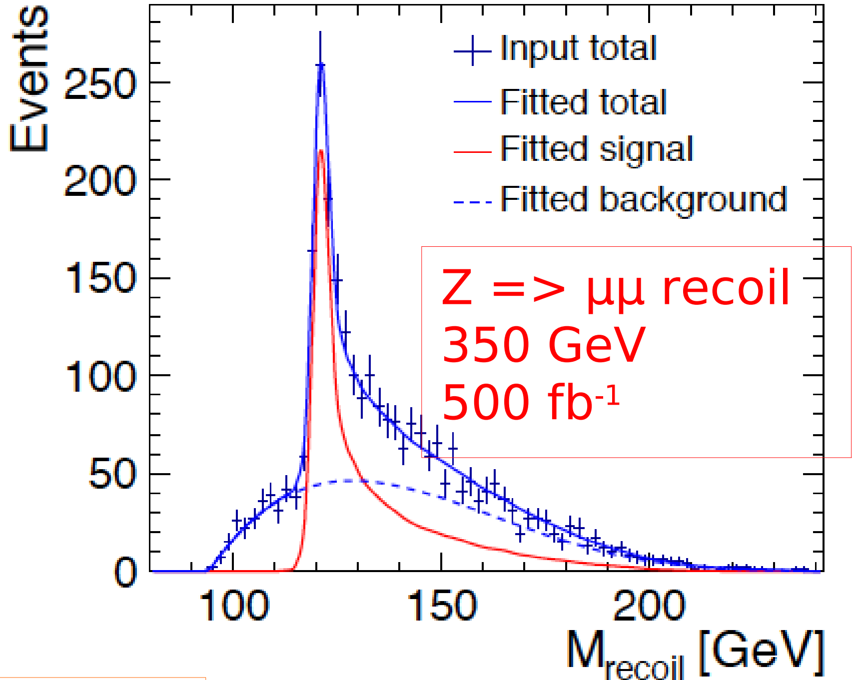




Higgsstrahlung $e^+e^- \to HZ$ @ 350 GeV



HZ events, selected through **Z recoil**
model-independent measurement
=> g_{HZZ} coupling and Higgs mass

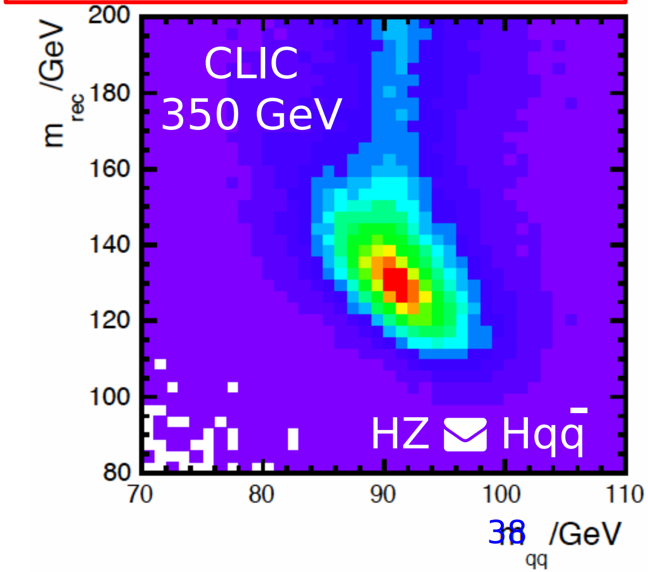


Z => μμ BR~3.5% very clean
Z => ee BR~3.5% very clean
} $\Delta(\sigma_{HZ}) = \pm 4.2\%$

Z => $q\bar{q}$ BR~70% almost model independent $\Delta(\sigma_{HZ}) = \pm 1.8\%$

$\Delta(g_{HZZ}) = \pm 0.8\%$

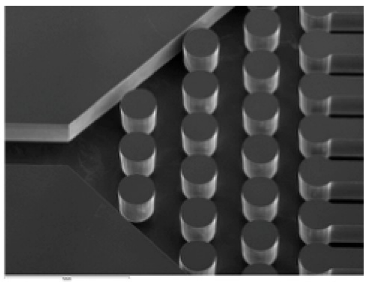
$HZ \to Hq\bar{q}$: better precision found at 350 GeV than at 250 GeV or 420 GeV
(trade-off between detector resolution and physics bkg)

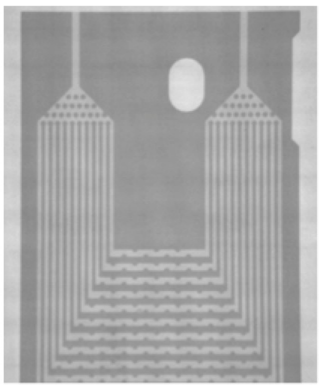


HZ => $Hq\bar{q}$ also gives access to invisible Higgs decay

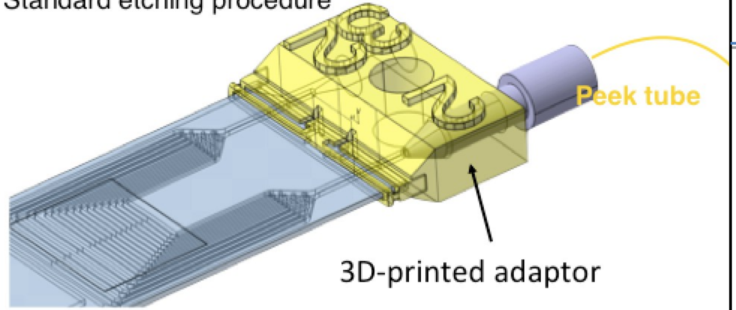
Vertex engineering

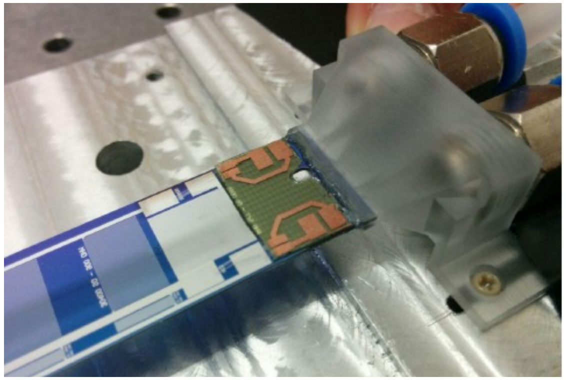
micro-channel cooling



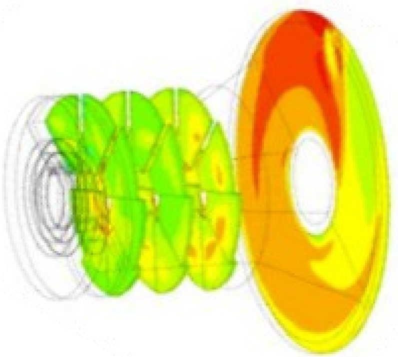


Micro-channel pattern in
handle wafer
Standard etching procedure

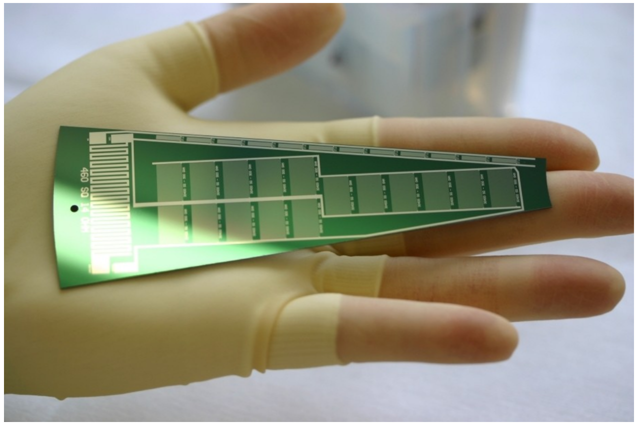


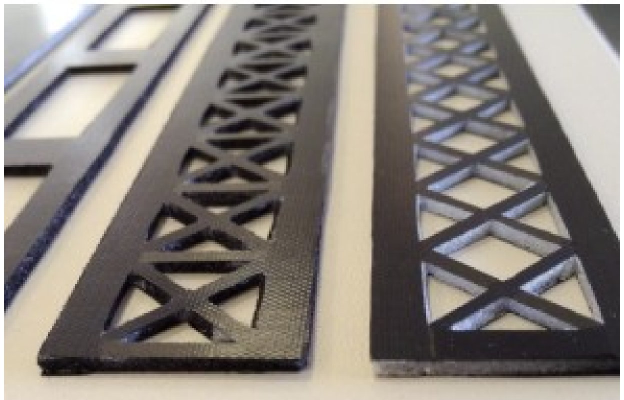


air cooling simulations/tests



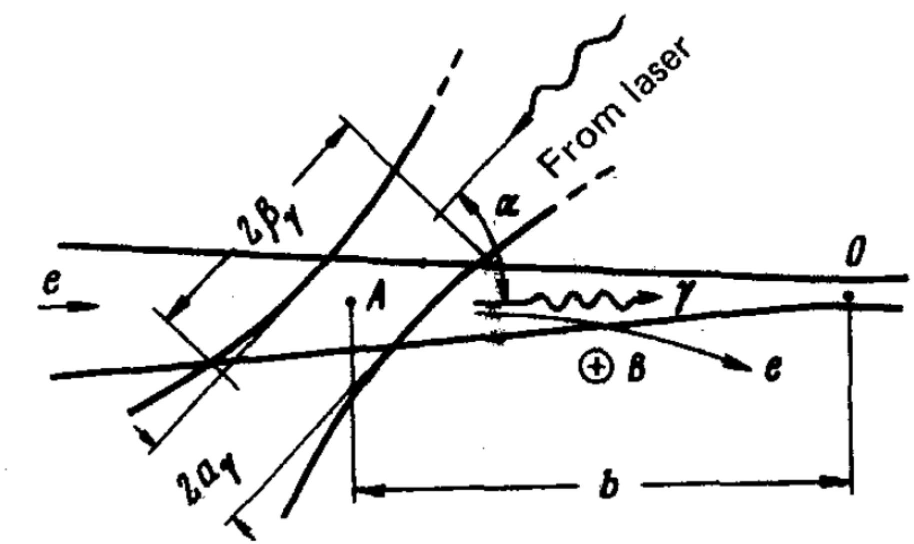
thin supports





Photon Collider

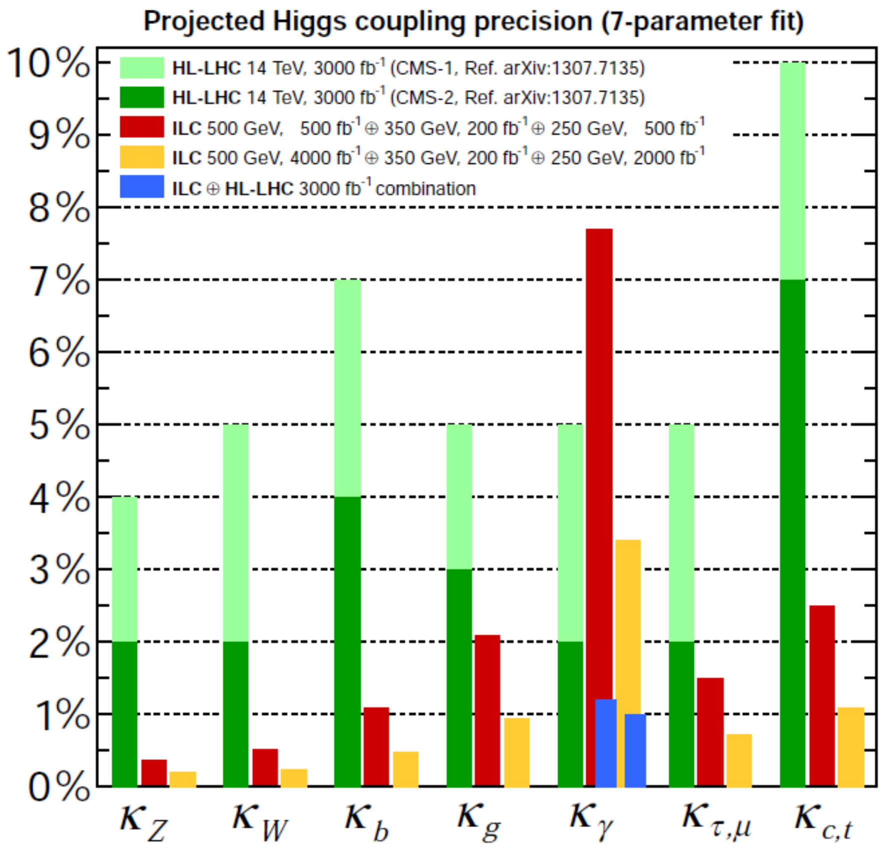
- Idea goes back to Novosibirsk in the early 1980s
- Extensively studied in TESLA TDR and still part of the ILC TDR design considerations. See V. Telnov, JINST9 (2014) C09029

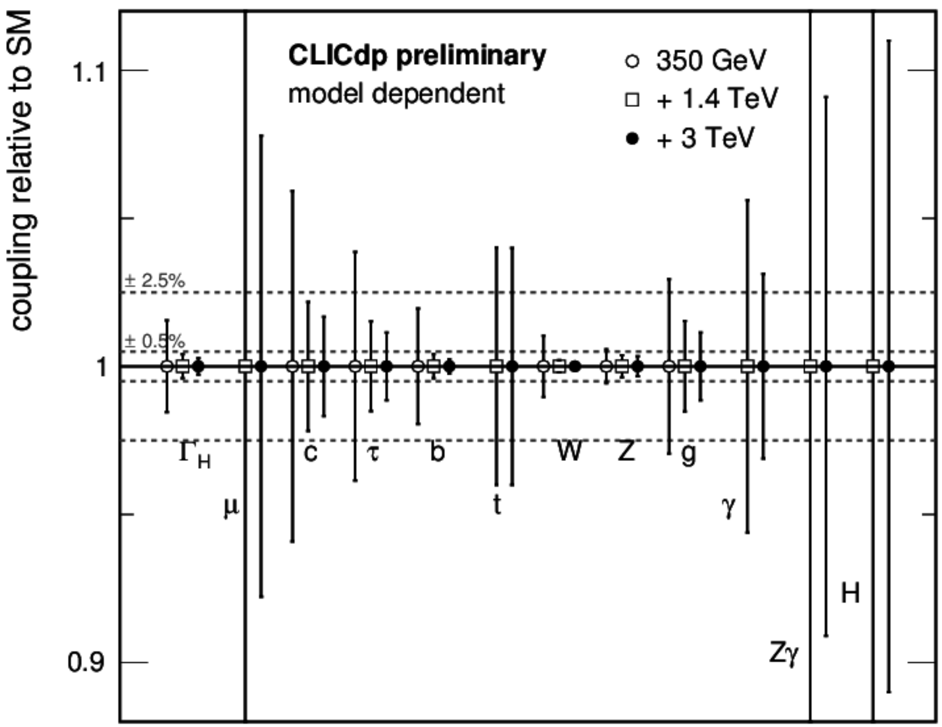


High-energy, high-lumi electron beam transfers its energy to photons from a laser through Compton back-scattering

Resulting photon beam has $E_\gamma \sim 0.8\ E_b$ and a luminosity that's not too different from the parent e^+e^- collider

Higgs couplings - comparisons





Channel	Measurement	Observable	Statistical precision		
			350 GeV $500\ fb^{-1}$	1.4 TeV $1.5\ ab^{-1}$	3.0 TeV $2.0\ ab^{-1}$
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \rightarrow b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \rightarrow b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \rightarrow \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \rightarrow q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.85%	–	–
ZH	$\sigma(H+X) \times BR(H \rightarrow c\bar{c})$		10.7%	–	–
ZH	$\sigma(H+X) \times BR(H \rightarrow gg)$		4.1%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	5.1%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.8%	0.4%	0.3%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	6.1%	6.9%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow gg)$		–	5.0%	4.3%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	4.2%	4.4%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	25%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \gamma\gamma)$		–	15%	10%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow Z\gamma)$		–	42%	30%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*)$	g^4_{HWW}/Γ_H	tbd	1.0%	0.7%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	5.6%	3.9%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \rightarrow b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1.8%	2.3%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \rightarrow b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%	3%
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarization	λ	–	24%	12%

CLIC Higgs coupling measurements Overview for Higgs paper as per 18-01-2016