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on behalf of the CLIC and CLICdp collaborations

Lepton Photon 2017, Sun Yat-sen University, Guangzhou, China

中国广州中山大学

Contents

Overview
What is CLIC?
The CLIC run plan

The CLIC detector

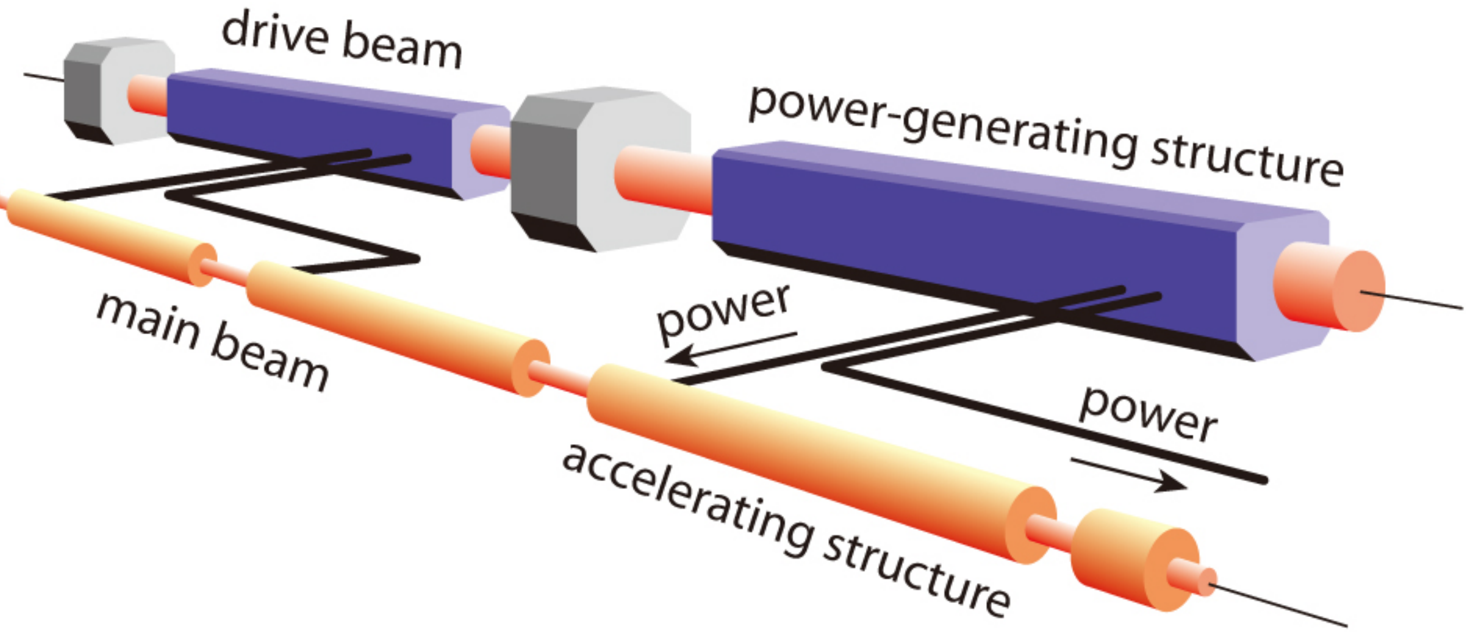
CLIC accelerator:
status & developments

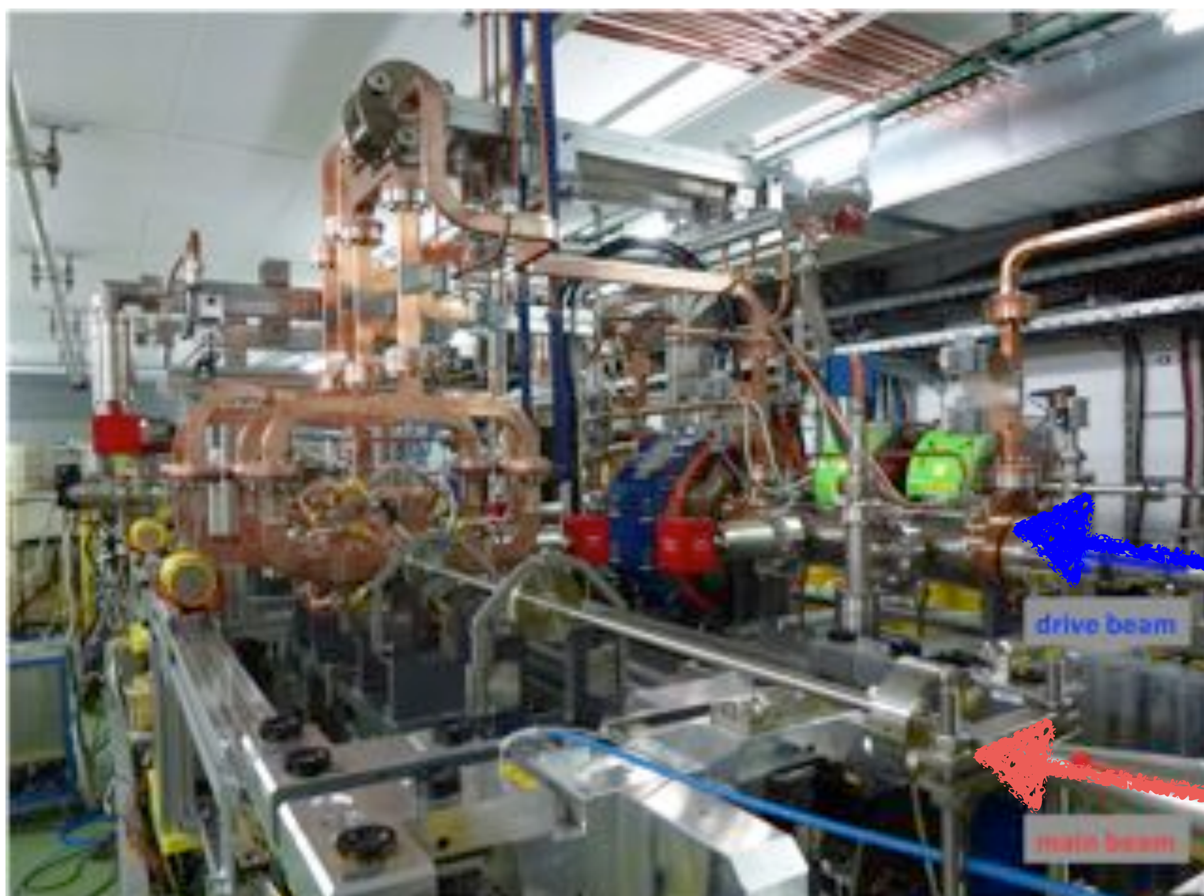
The CLIC physics program:
Higgs
top
BSM

Compact Linear Collider: CLIC

e^+e^- collider with up to 3 TeV collisions

- **100 MV/m** accelerating gradient is required for compact (**~50 km**) machine.
- Based on normal-conducting accelerating structures and a two-beam acceleration scheme.





CLIC foreseen as a staged machine:

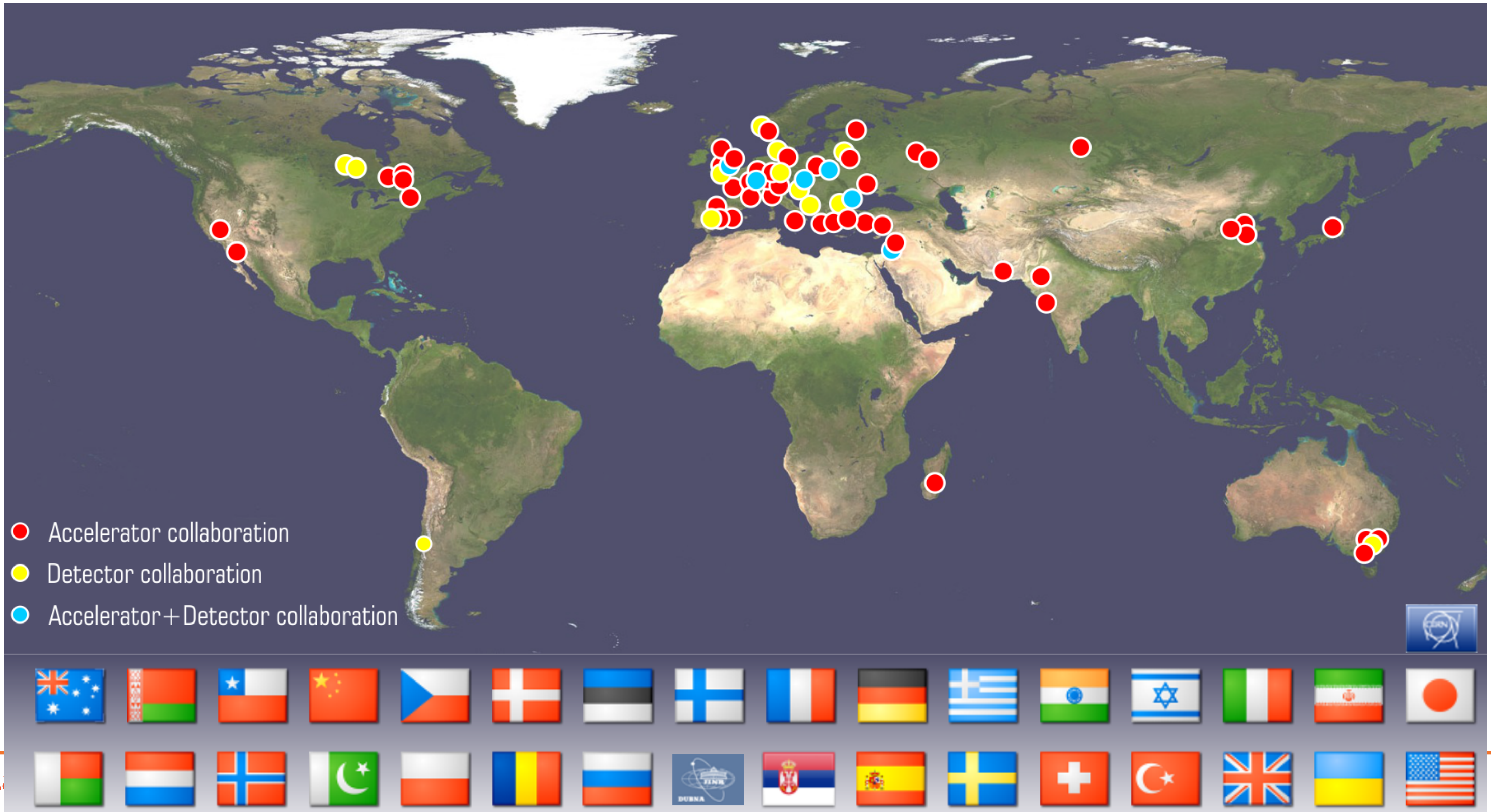
- Stage 1: $\sqrt{s} = 380$ GeV
  ➡precision SM physics: top & Higgs
- Stage 2 & 3 baseline: **1.5 TeV, 3 TeV**

drive beam

main beam

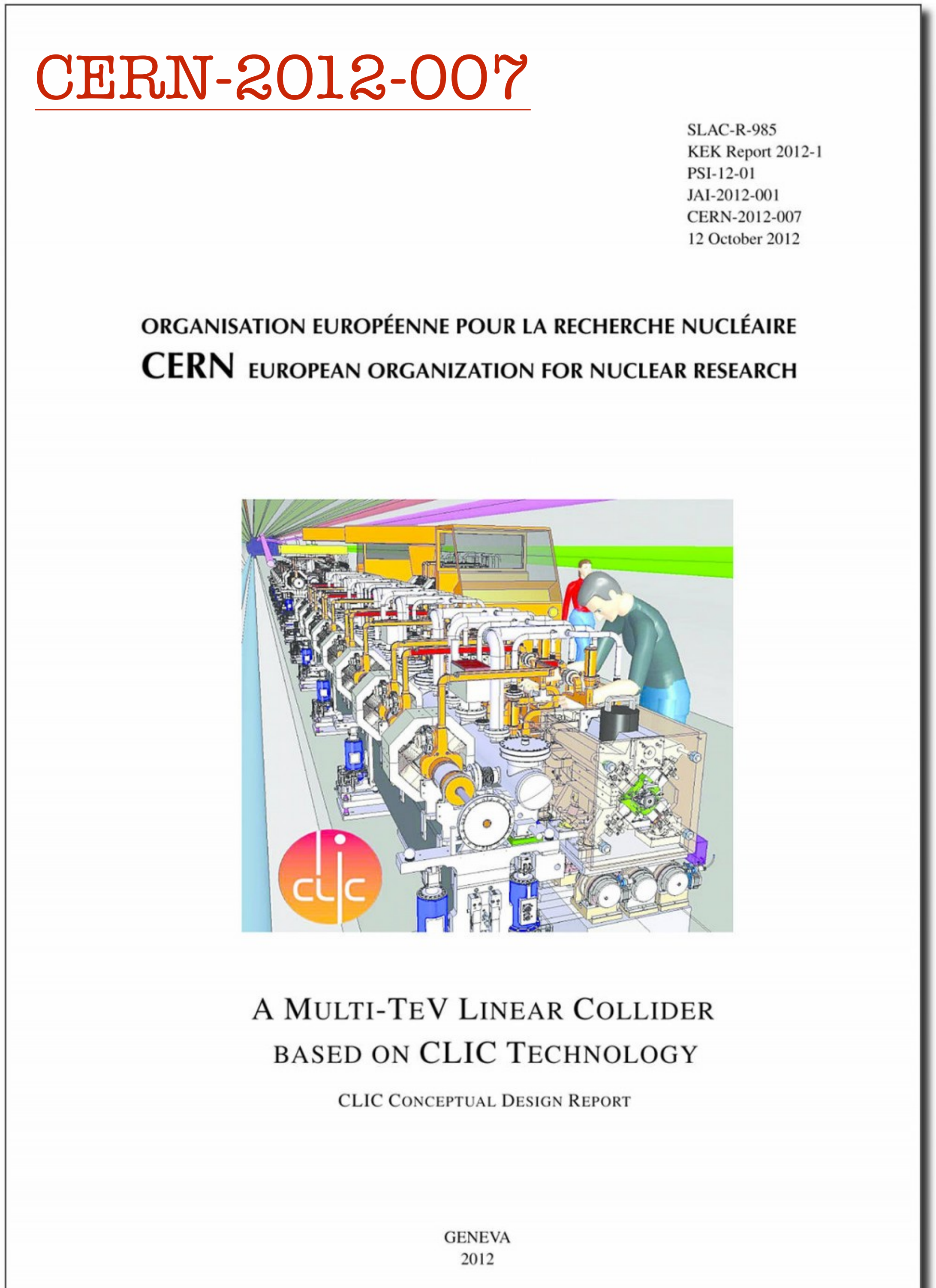
CLIC Collaborations

- **CLIC/CTF3 collaboration:**
  - 62 institutes from 28 countries
  - http://clic-study.web.cern.ch/
  - ➡ Design & development of CLIC
  - ➡ Construction & operation of CTF3
- **CLIC detector & physics (CLICdp):**
  - 29 institutes from 18 countries
  - http://clicdp.web.cern.ch/
  - ➡ CLIC-specific studies of physics prospects
  - ➡ Detector development & optimisation



CDRs for Machine & Detector (2012)

CERN-2012-007


SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

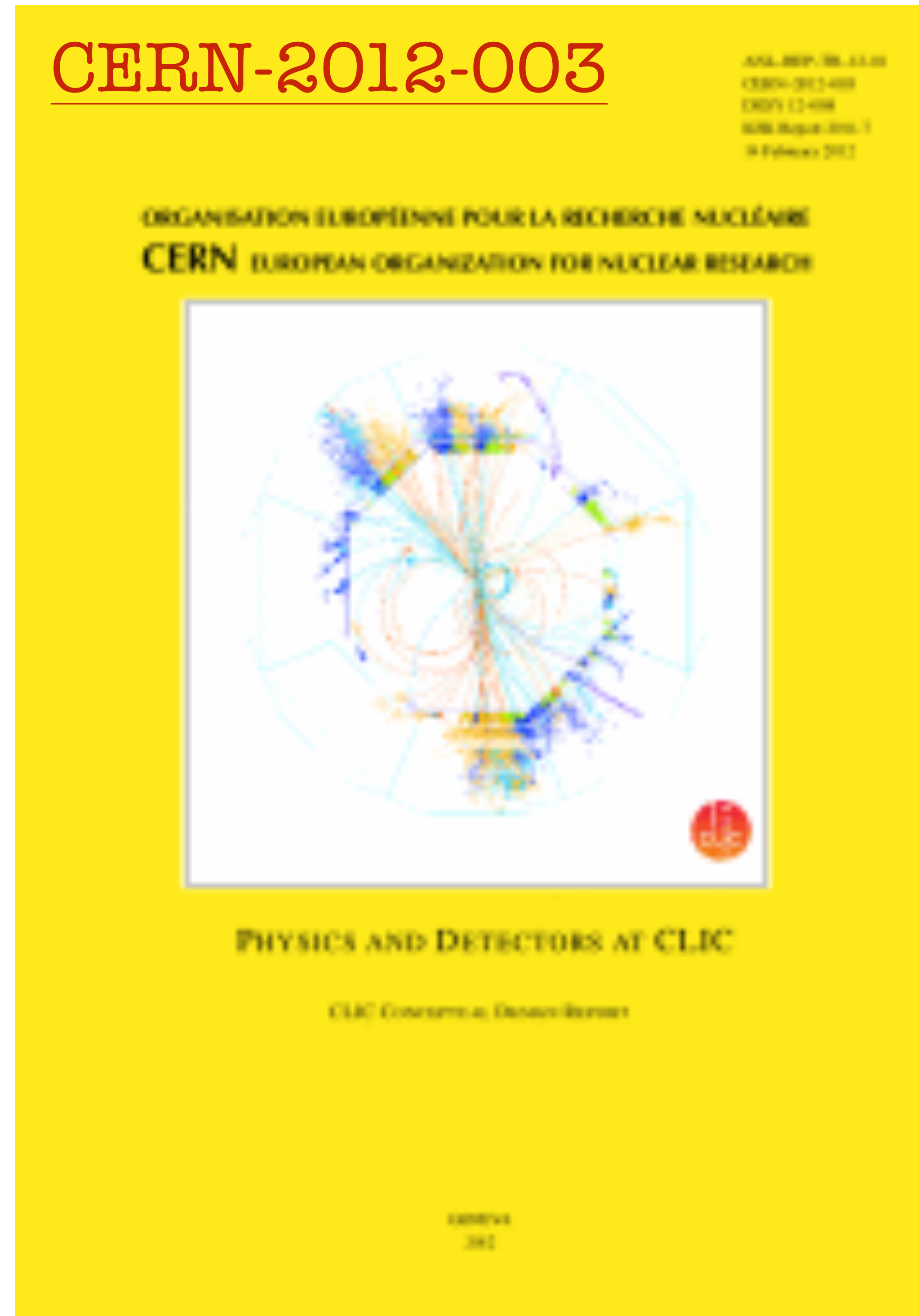
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

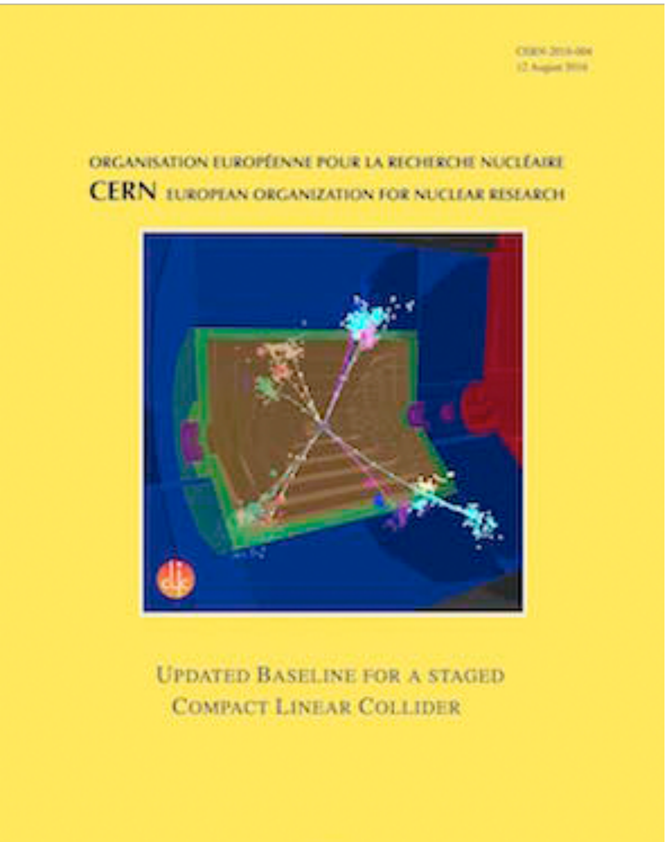
GENEVA
2012

CERN-2012-003



arxiv:1202.5940

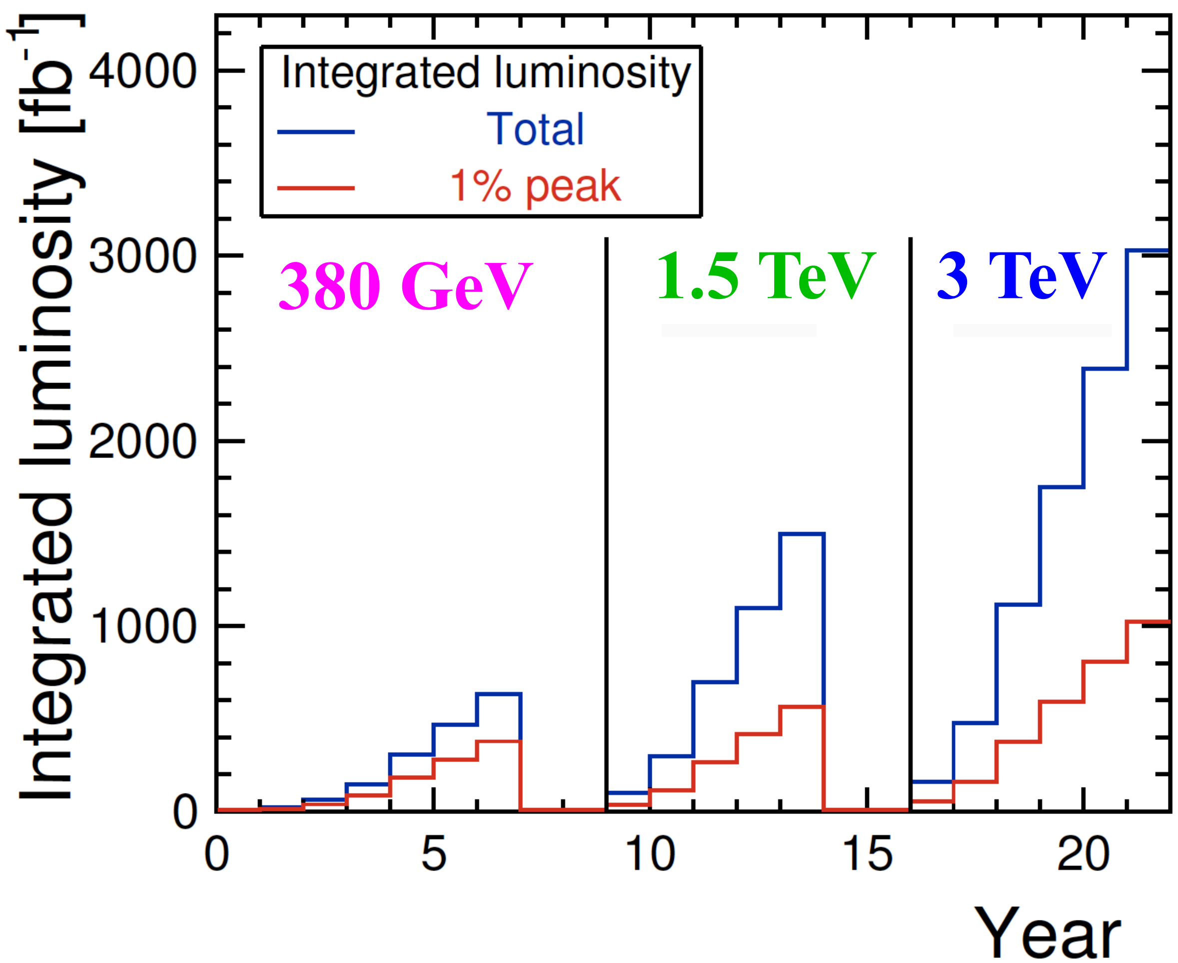
Updated CLIC Baseline Plan (2016)



arXiv:1608.07537

Three stages: **380 GeV, 1.5 GeV, 3 TeV**

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000



CLIC accelerator parameters

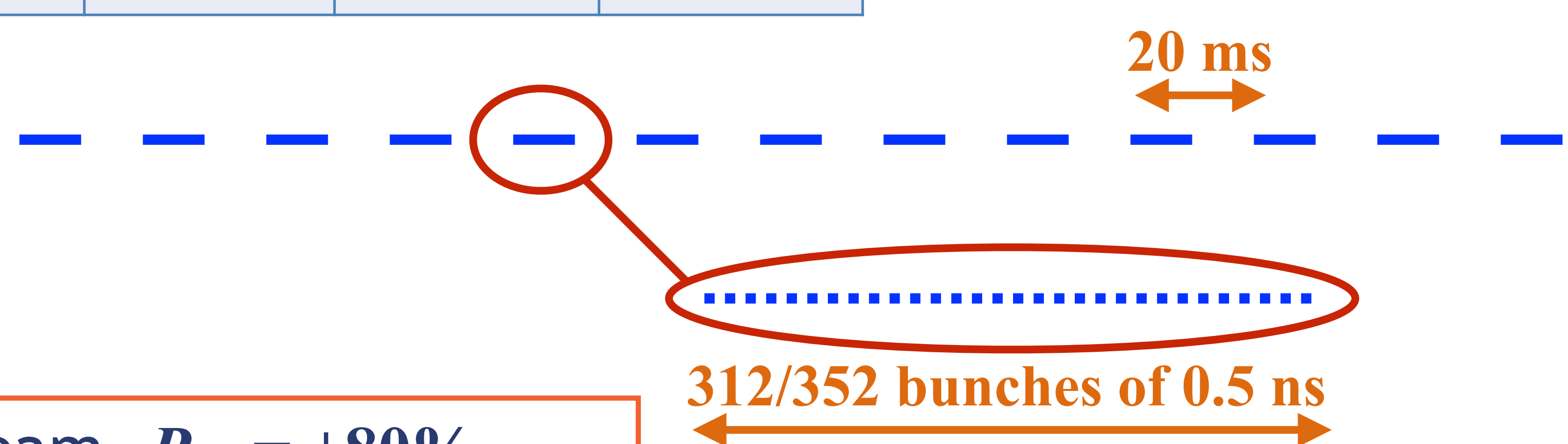
Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathcal{L}$ ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
$\mathcal{L}$ above 99% of $\sqrt{s}$ ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	11.4	29	50
Repetition frequency (Hz)	50	50	50
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	70	44	44
Estimated power consumption* (MW)	252	364	589

**scaled from CDR, actively being improved!*

Drives required detector timing resolution

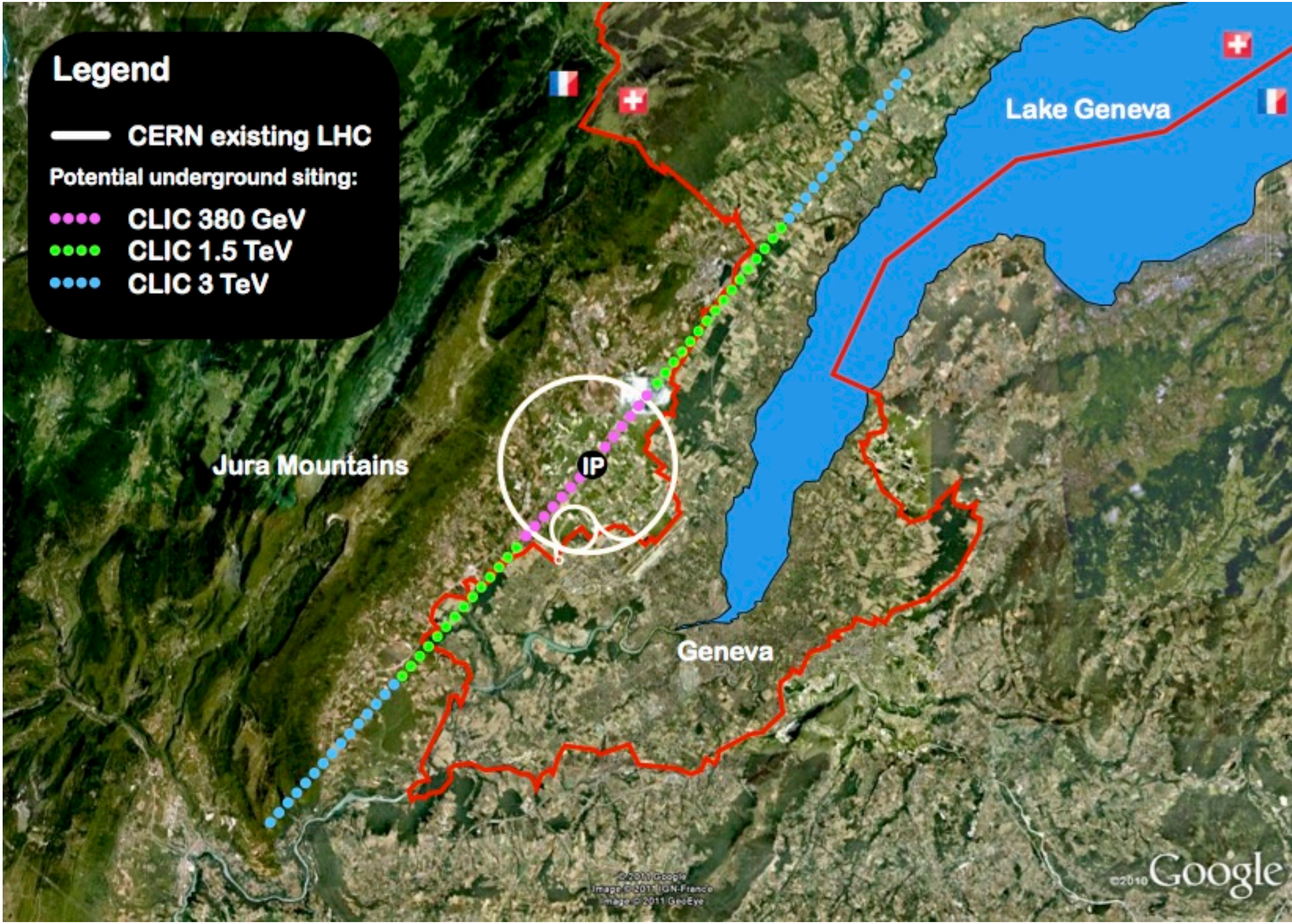
Very small beam

beam structure (not to scale!)

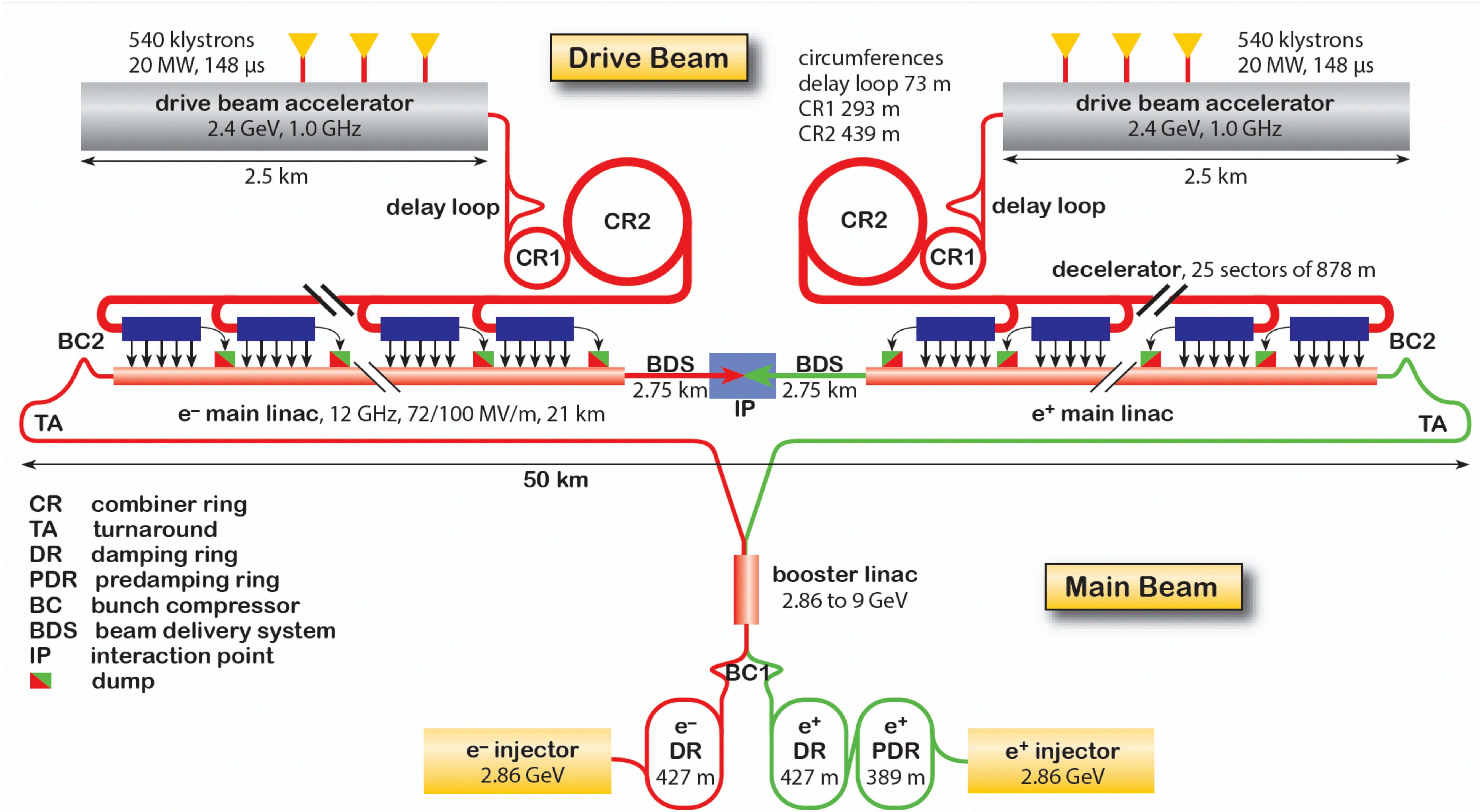


Polarised electron beam, $P_{e-} = \pm 80\%$

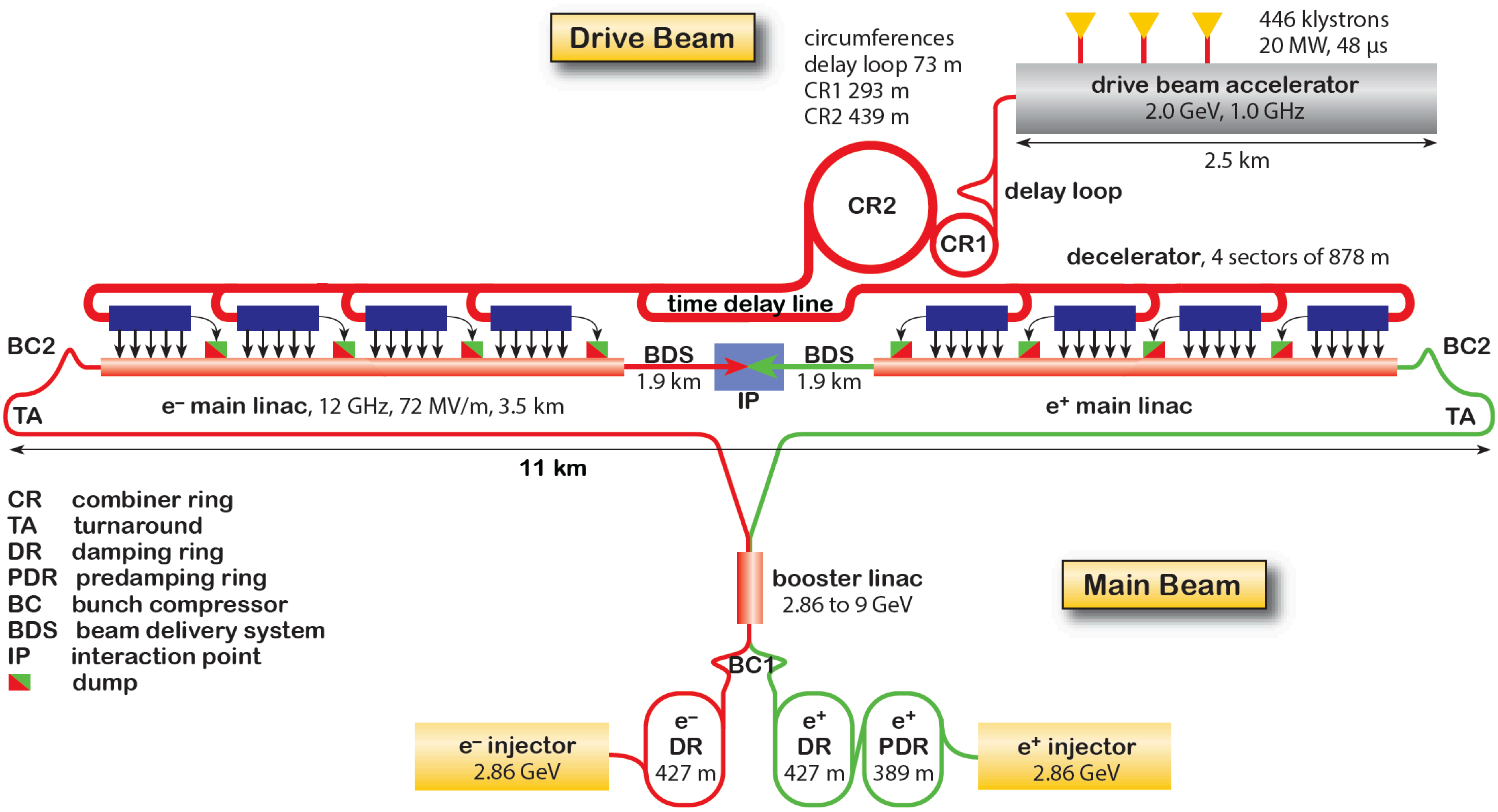
Positron polarisation is an upgrade option


Legend
CERN existing LHC
Potential underground siting:
CLIC 380 GeV
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2010 Google

CLIC Layout at 3 TeV

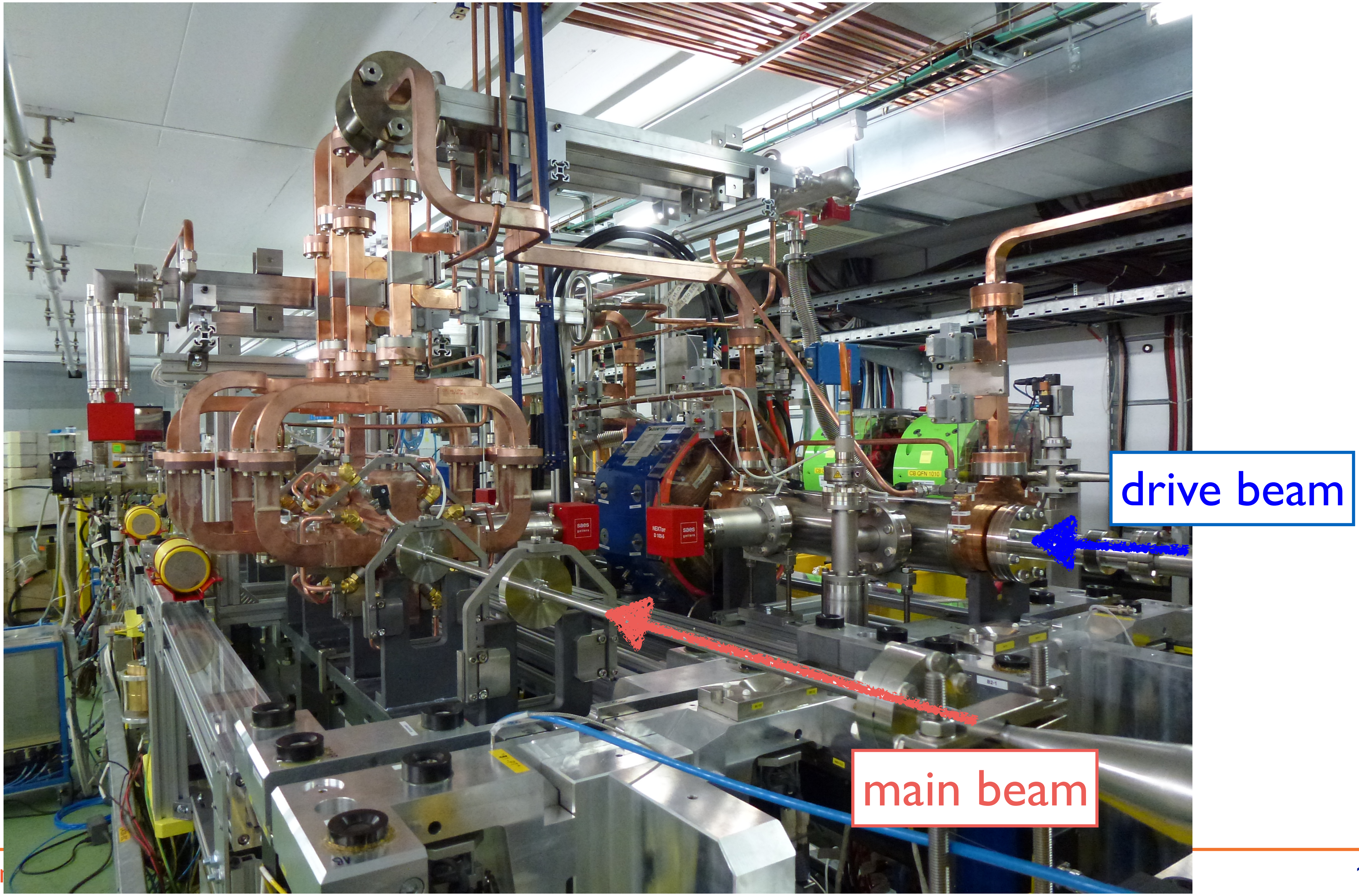


CLIC Layout at 380 GeV



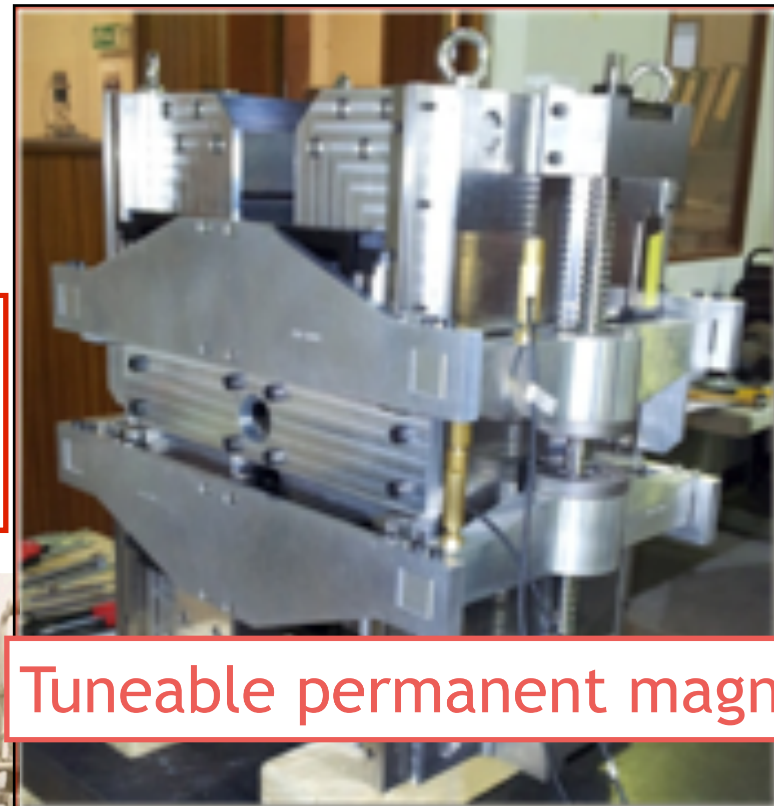
CTF3 (CLIC Test Facility 3)

CTF3 test facility at CERN has demonstrated drive beam generation, RF power extraction and two-beam acceleration scheme up to **145 MV/m**

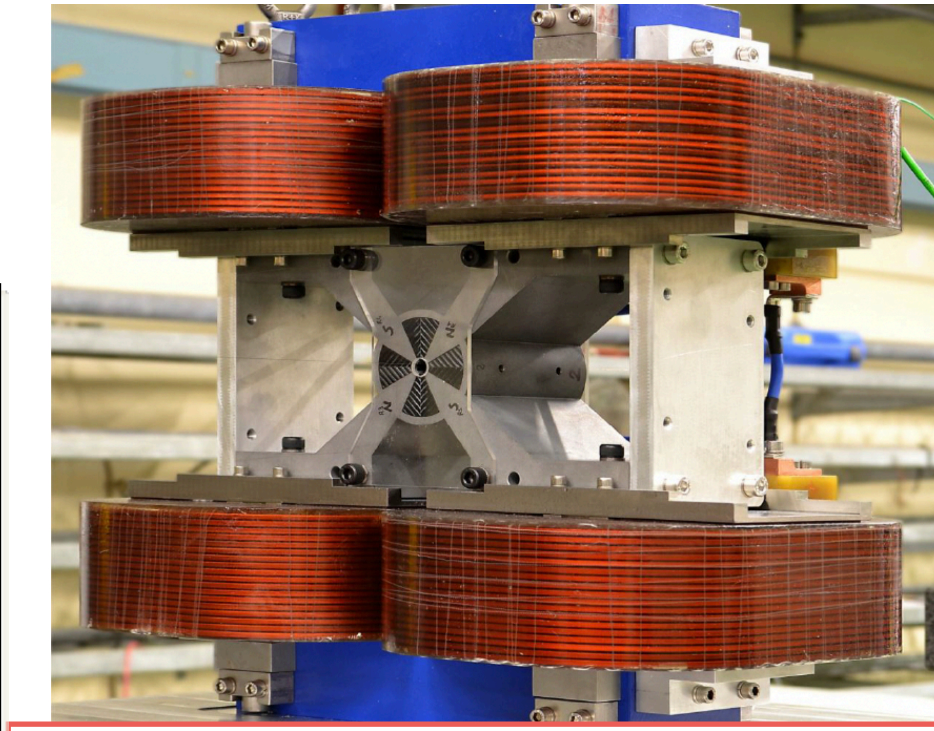


Accelerator Components

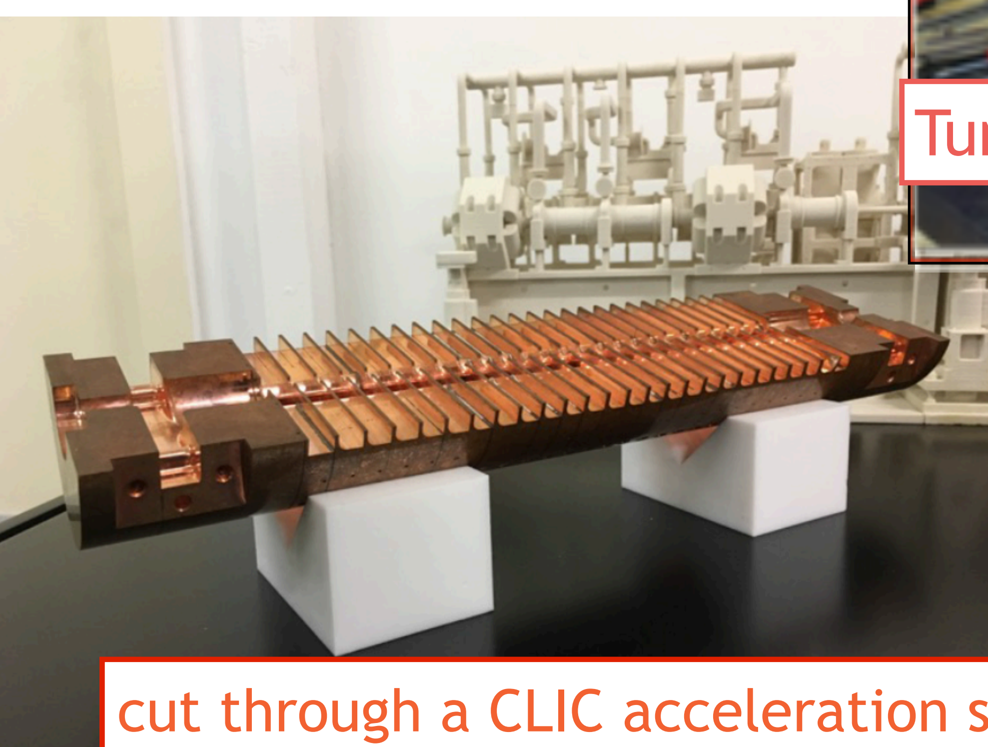
accelerating structure, 1 disk



Tuneable permanent magnet



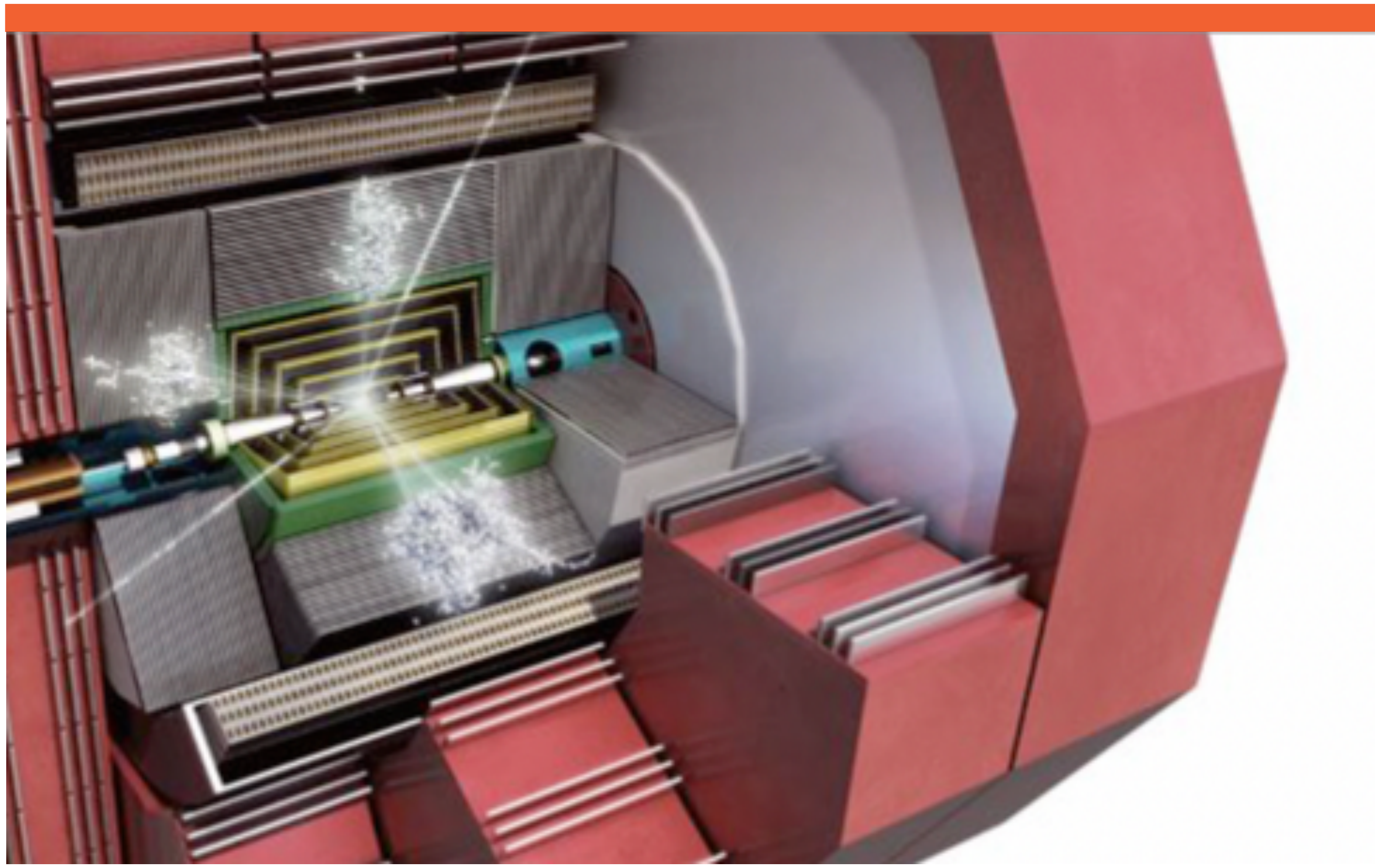
Prototype final-focus quadrupole



cut through a CLIC acceleration structure

Mechanical tests of 2-beam module: active alignment and stabilisation

Detector



Detector Motivations

Detector goals: high precision…

- jet energy resolution
  - ➡ fine grained calorimetry

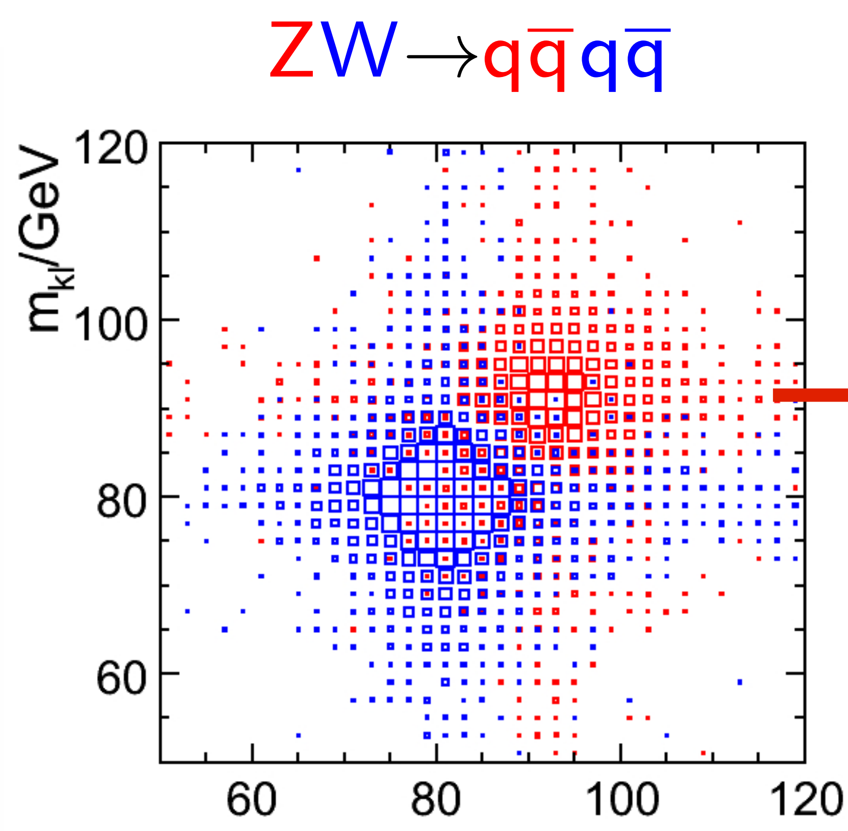
$\sigma(E)/(\mathrm{E}) \sim 3.5\%$ for $E > 100$ GeV

- momentum resolution

$\sigma(p_\mathrm{T})/p_\mathrm{T}^2 \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$

- impact parameter resolution

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



CALICE calorimetry

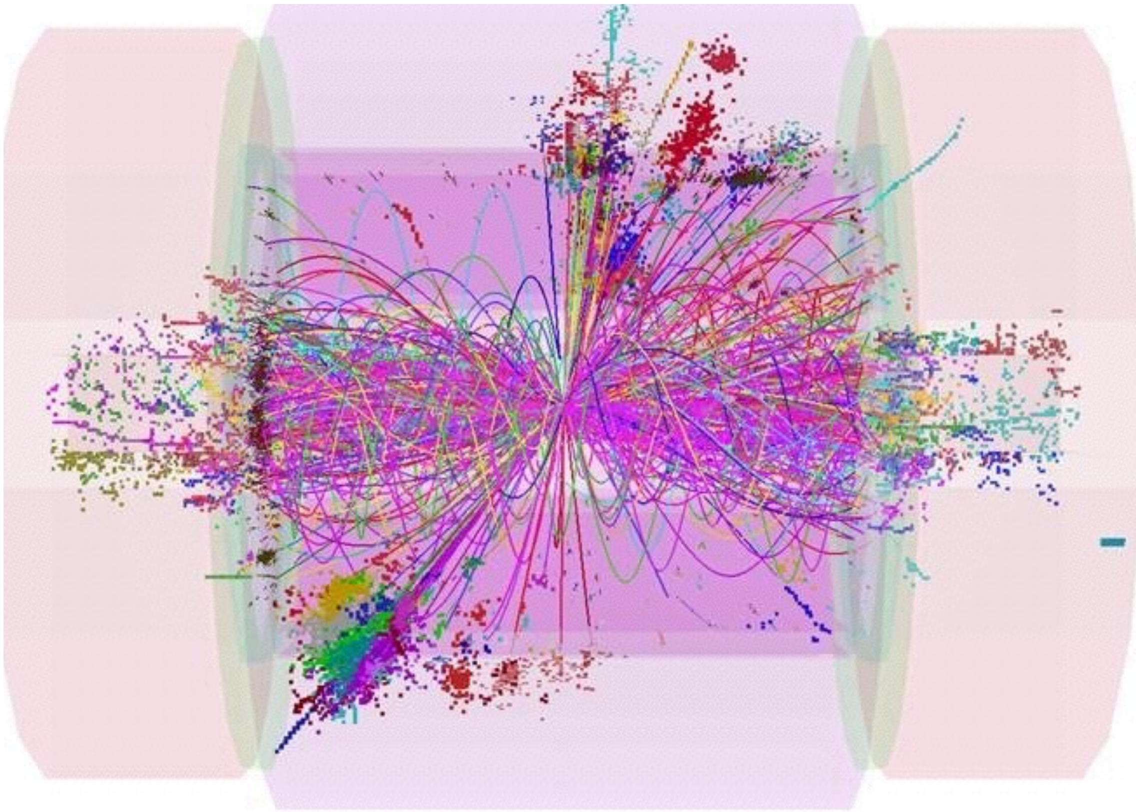
CLICdp vertexing & tracking programme

Small pixels ($\sim$25 μm^2) ultra-low material

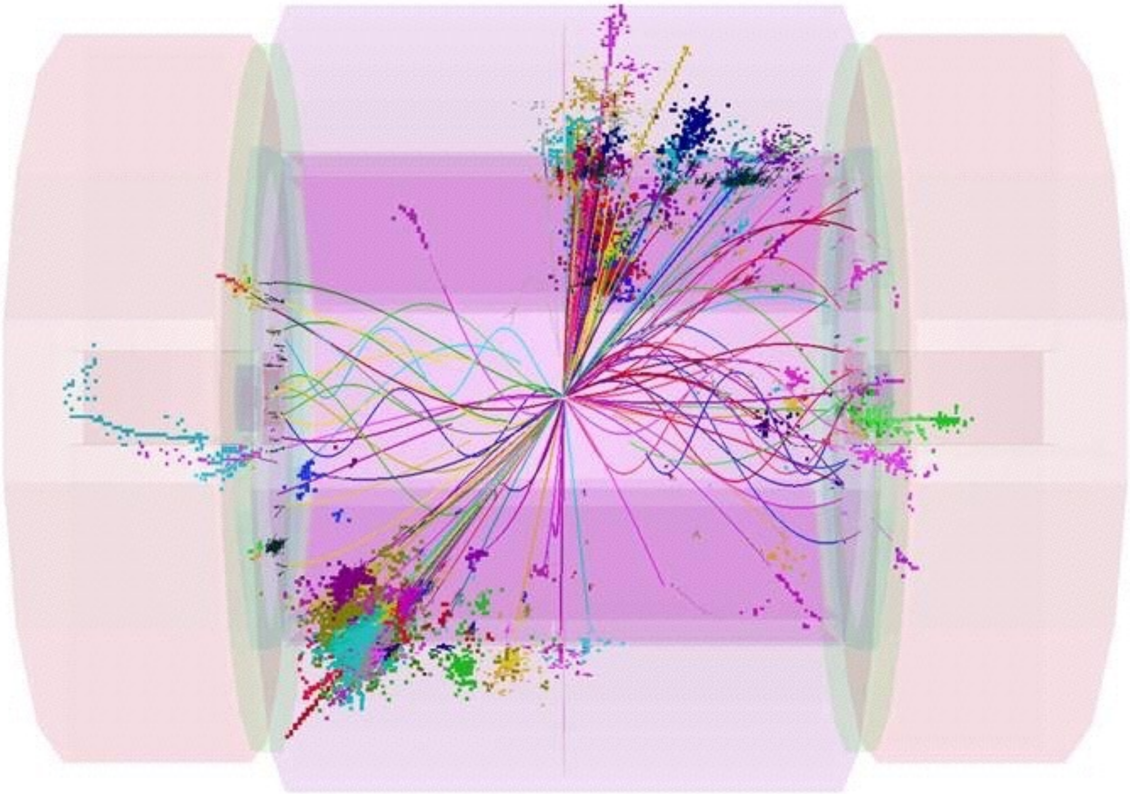
Background Suppression

Beam-induced background from $\gamma\gamma \rightarrow$ **hadrons** can be efficiently suppressed by applying ***p_T* cuts and timing cuts on individually reconstructed particles** (particle flow objects)

e.g. $\mathrm{e^+e^-} \rightarrow \mathrm{H^+H^-} \rightarrow \mathrm{t\bar{b}b\bar{t}} \rightarrow 8\,\mathrm{jets}$



1.2 TeV background in reconstruction window (**10 ns**) around main physics event



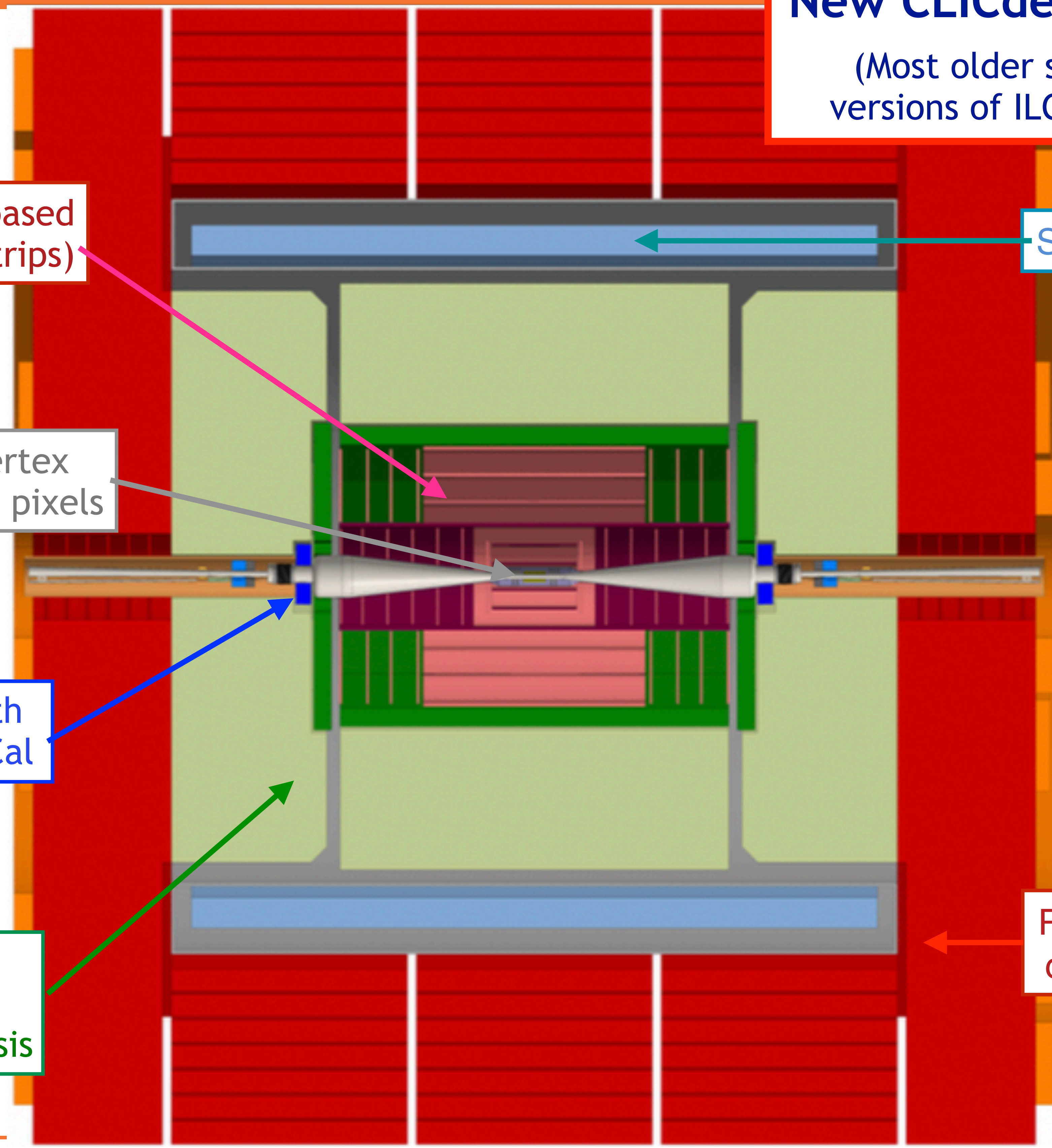
100 GeV background after tight cuts

Timing resolution
1 ns in calorimeter
10 ns in vertex & tracker

CLICDet

New CLICdet detector model

(Most older studies use modified versions of ILC ILD & SiD detectors)



Main tracker, silicon-based (large pixels and/or strips)

Solenoid magnet B=4 T

Ultra low-mass vertex detector with 25μm pixels

End coils for field-shaping

Forward region with LumiCal and BeamCal

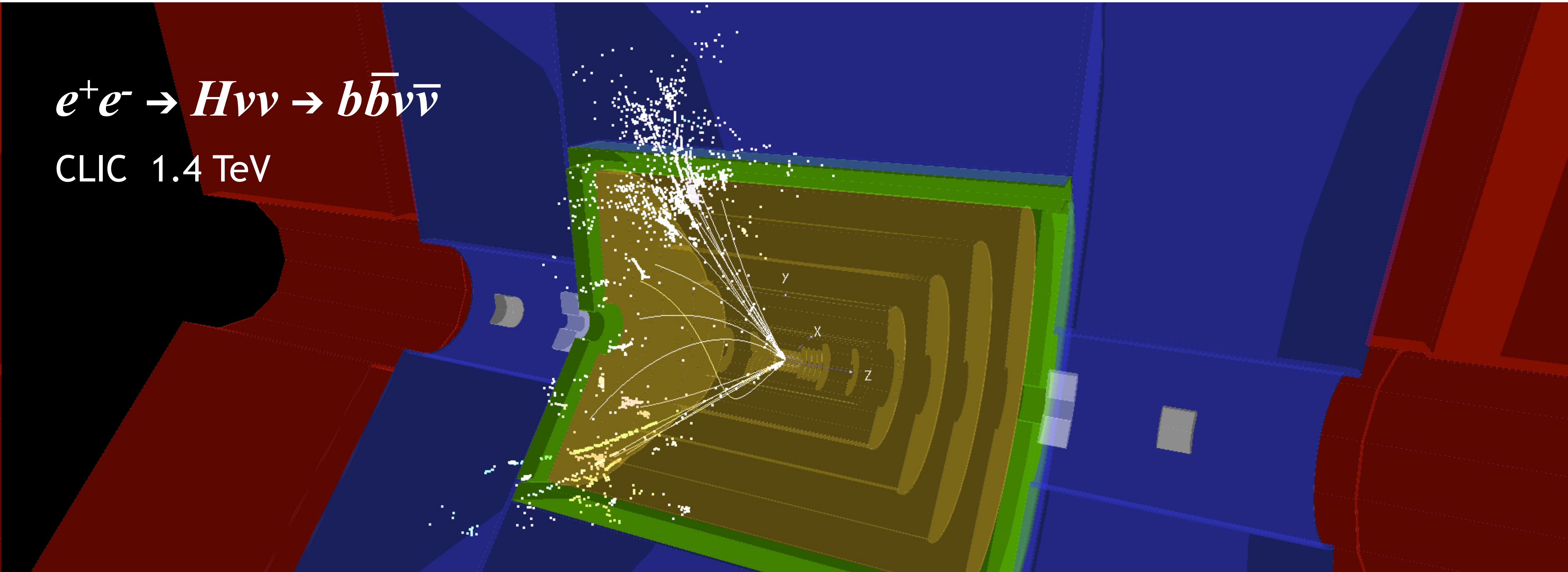
Return yoke (iron) with detectors for muon ID

Fine-grained calorimetry for Particle Flow Analysis

Physics

Higgs	top	BSM

Higgs


$e^+e^- \rightarrow H\nu\nu \rightarrow b\bar{b}\nu\bar{\nu}$
CLIC 1.4 TeV
y
x
z

New Paper on Higgs physics at CLIC

Eur. Phys. J. C (2017) 77:475
DOI 10.1140/epjc/s10052-017-4968-5

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

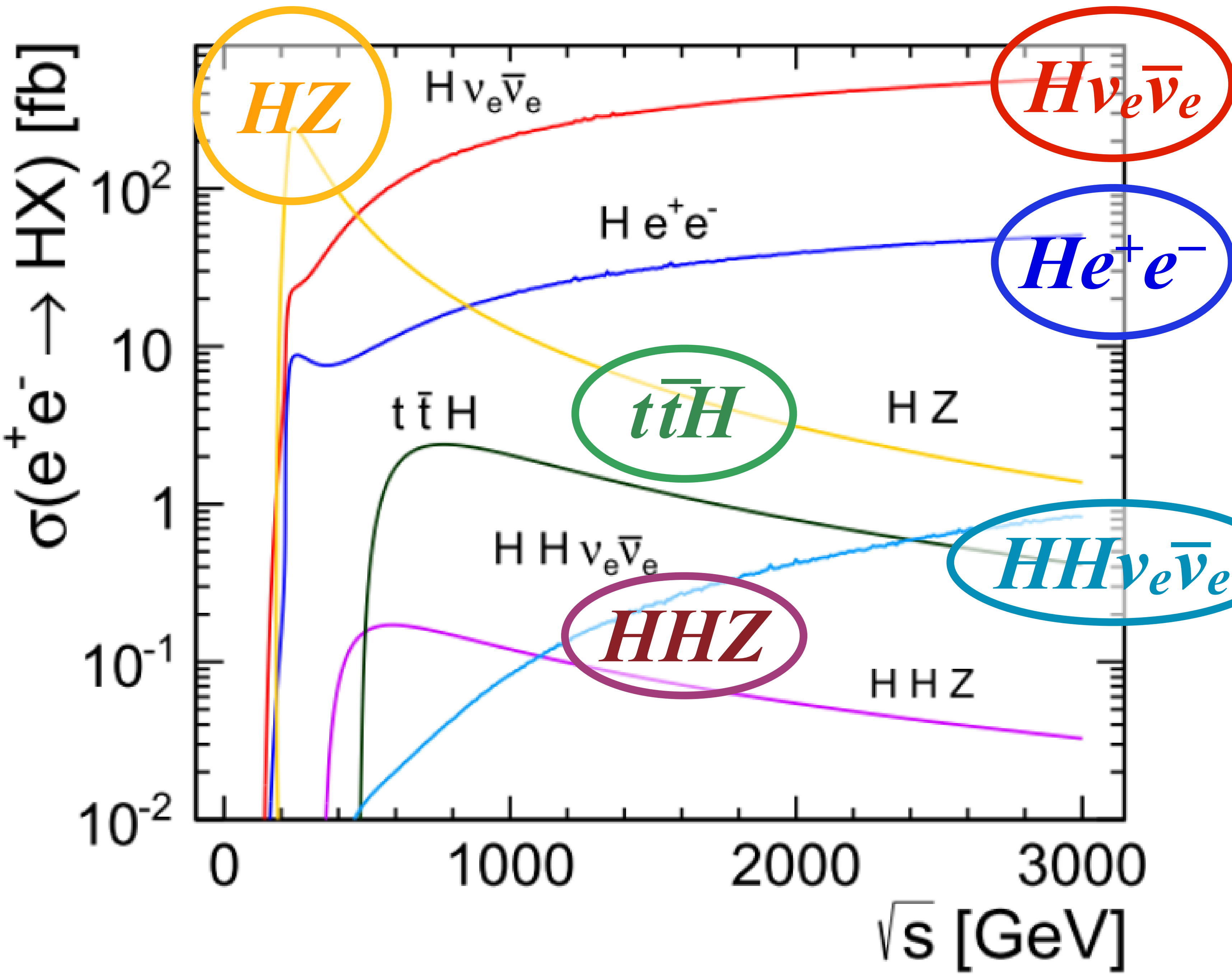
Regular Article - Experimental Physics

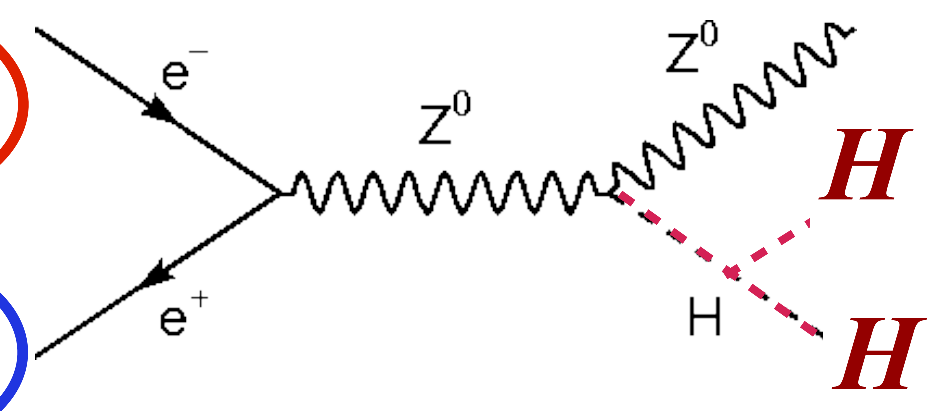
Higgs physics at the CLIC electron–positron linear collider

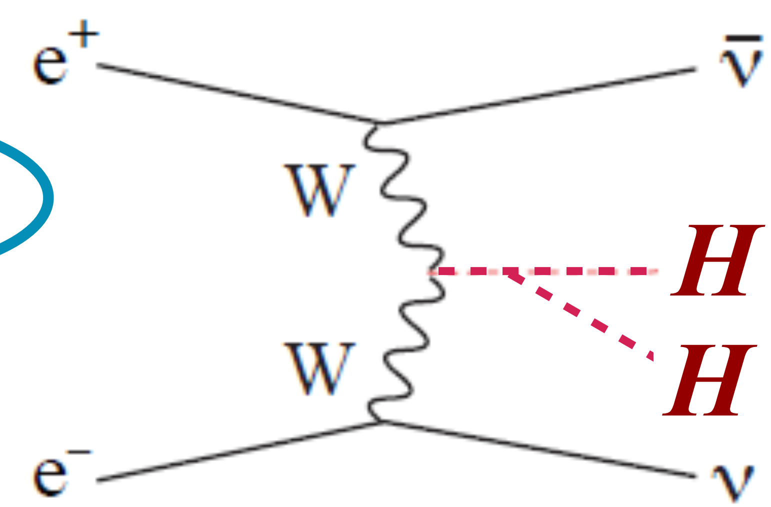
H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], N. Alipour Tehrani[4], C. Balázs[5], Y. Benhammou[1], M. Benoit[6], B. Bilki[7], J.-J. Blaising[8], M. J. Boland[9], M. Boronat[10], O. Borysov[1], I. Božović-Jelisavčić[11], M. Buckland[12], S. Bugiel[13], P. N. Burrows[14], T. K. Charles[5], W. Daniluk[15], D. Dannheim[4], R. Dasgupta[13], M. Demarteau[7], M. A. Díaz Gutierrez[2], G. Eigen[16], K. Elsener[4], U. Felzmann[9], M. Firlej[13], E. Firu[17], T. Fiutowski[13], J. Fuster[10], M. Gabriel[18], F. Gaede[4,19], I. García[10], V. Ghenescu[17], J. Goldstein[20], S. Green[21], C. Grefe[4,b,d], M. Hauschild[4], C. Hawkes[23], D. Hynds[4], M. Idzik[13], G. Kačarević[11], J. Kalinowski[24], S. Kananov[1], W. Klempt[4], M. Kopec[13], M. Krawczyk[24], B. Krupa[15], M. Kucharczyk[15], S. Kulis[4], T. Laštovička[25], T. Lesiak[15], A. Levy[1], I. Levy[1], L. Linssen[4], S. Lukić[11,b], A. A. Maier[4], V. Makarenko[3], J. S. Marshall[21], V. J. Martin[22], K. Mei[21], G. Milutinović-Dumbelović[11], J. Moroń[13], A. Moszczyński[15], D. Moya[26], R. M. Münker[4,e], A. Münnich[4,f], A. T. Neagu[17], N. Nikiforou[4], K. Nikolopoulos[23], A. Nürnberg[4], M. Pandurović[11], B. Pawlik[15], E. Perez Codina[4], I. Peric[27], M. Petric[4], F. Pitters[4,g], S. G. Poss[4], T. Preda[17], D. Protopopescu[28], R. Rassool[9], S. Redford[4,b,h], J. Repond[7], A. Robson[28], P. Roloff[4,a,b], E. Ros[10], O. Rosenblat[1], A. Ruiz-Jimeno[26], A. Sailer[4], D. Schlatter[4], D. Schulte[4], N. Shumeiko[3,c], E. Sicking[4], F. Simon[18,b], R. Simoniello[4], P. Sopicki[15], S. Stapnes[4], R. Ström[4], J. Strube[4,i], K. P. Świentek[13], M. Szalay[18], M. Tesař[18], M. A. Thomson[21,b], J. Trenado[29], U. I. Uggerhøj[30], N. van der Kolk[18], E. van der Kraaij[16], M. Vicente Barreto Pinto[6], I. Vila[26], M. Vogel Gonzalez[2,j], M. Vos[10], J. Vossebeld[12], M. Watson[23], N. Watson[23], M. A. Weber[4], H. Weerts[7], J. D. Wells[31], L. Weuste[18], A. Winter[23], T. Wojtoń[15], L. Xia[7], B. Xu[21], A. F. Żarnecki[24], L. Zawiejski[15], I.-S. Zgura[17]

arXiv:1608.07538 (Eur. Phys. J. C 77, 475 (2017))

A Higgs Factory

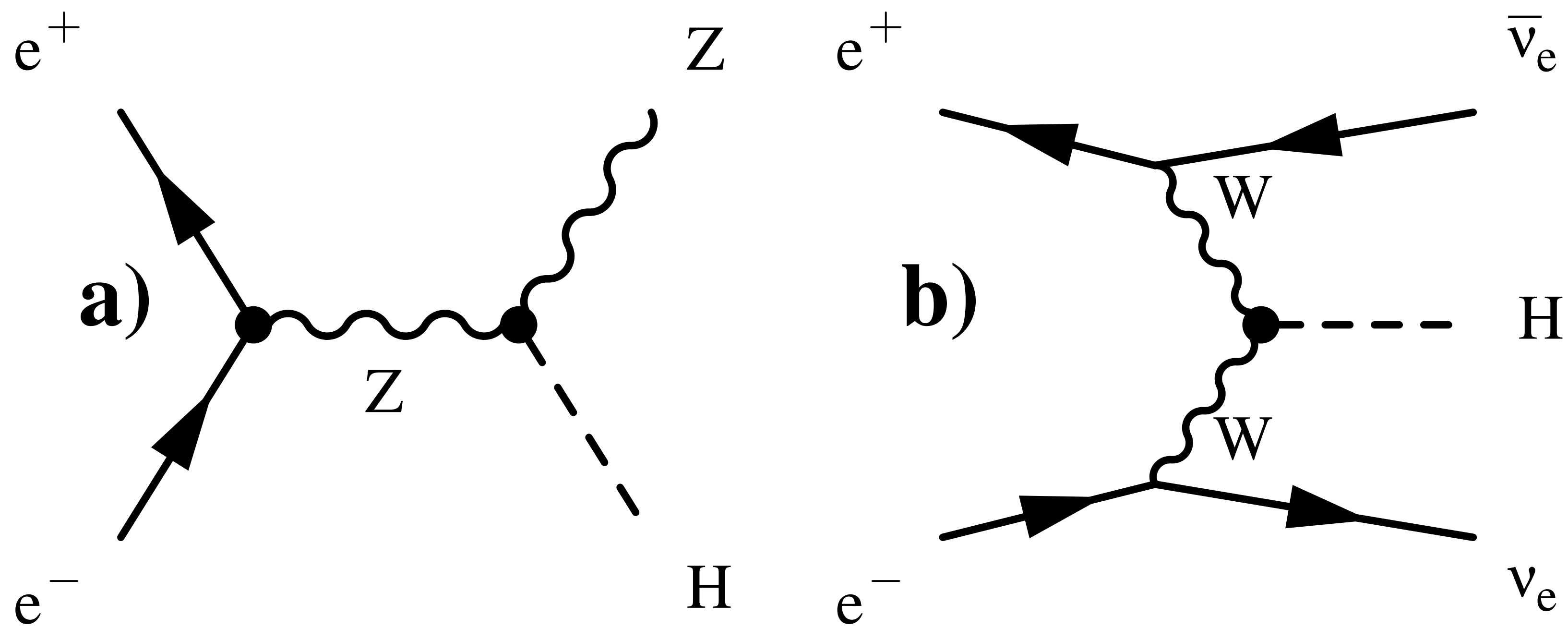






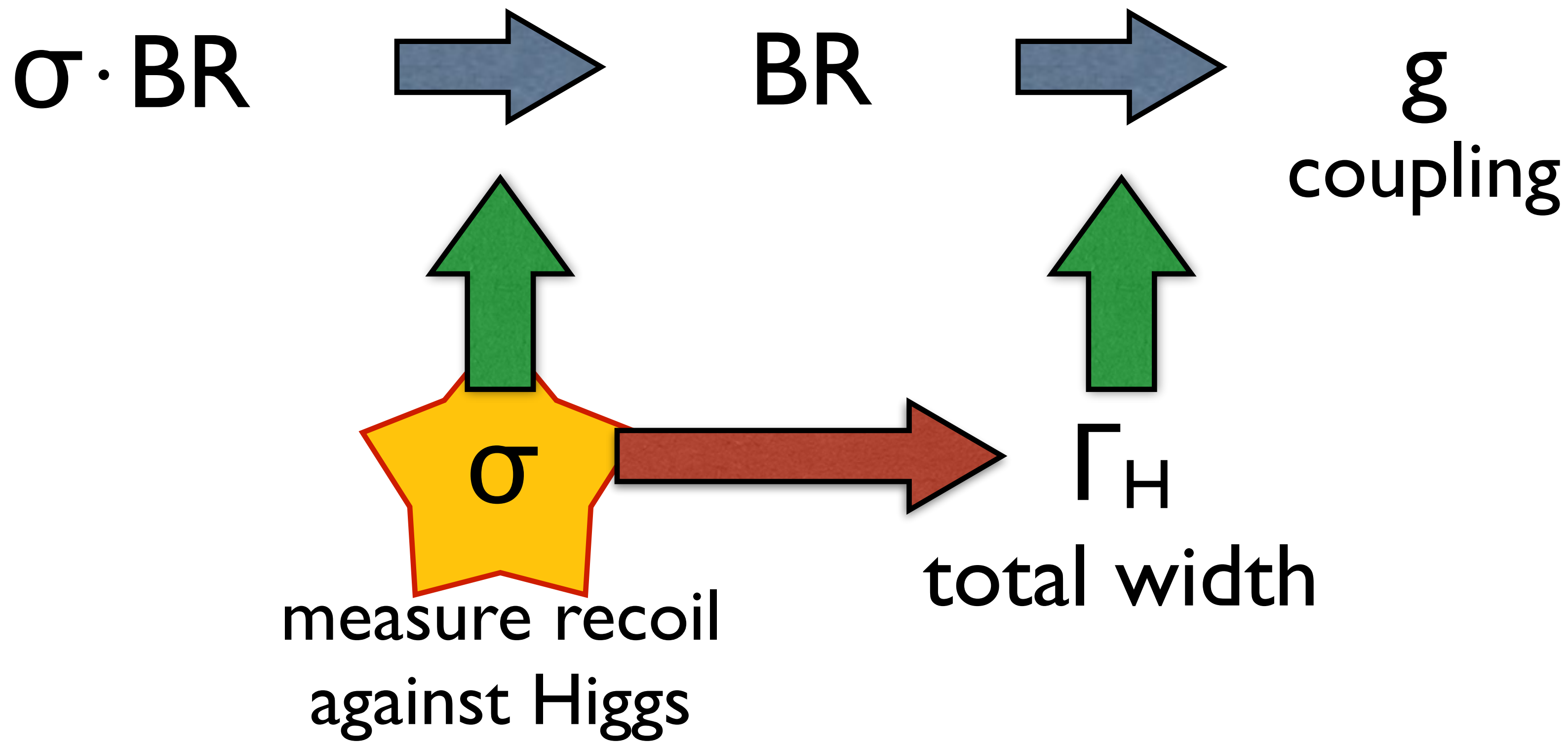
Higgs at CLIC380

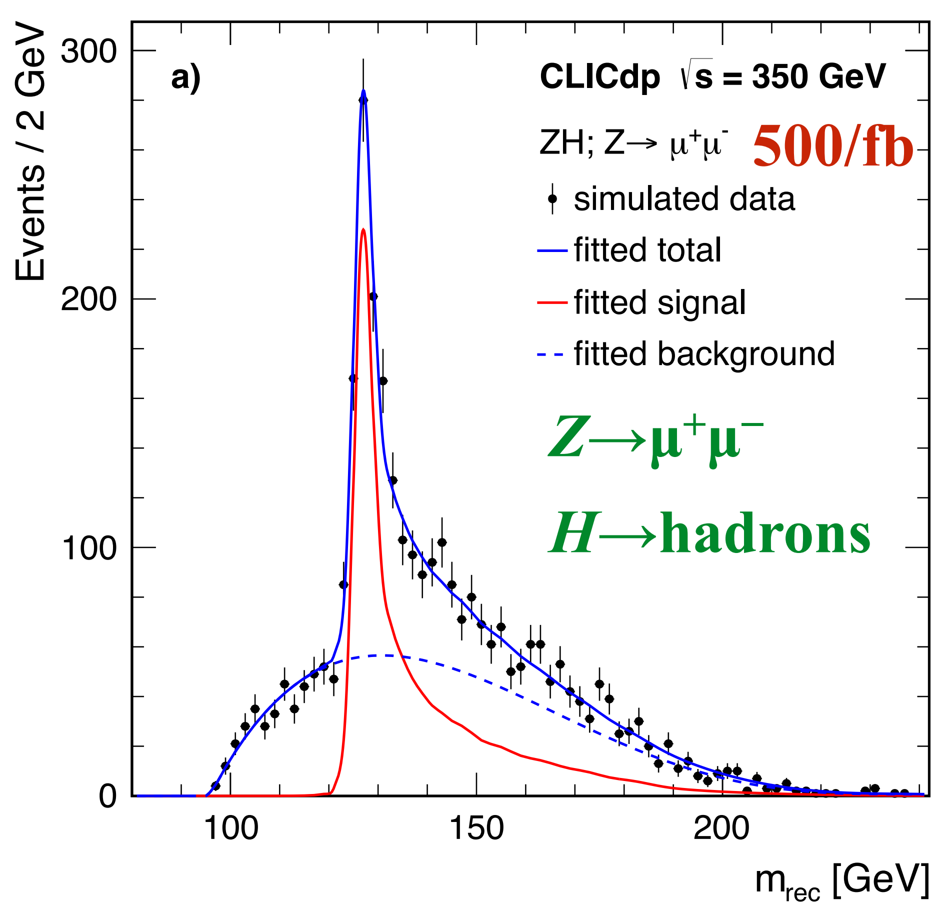
- Lower ZH production cross section at 380 GeV *cf* 250 GeV compensated by increased luminosity
- Boost enables discrimination between $H \to jj$ and $Z \to jj$ production
- Access to $H\nu_e\bar{\nu}_e$ production ⇒ increases precision on coupling measurements

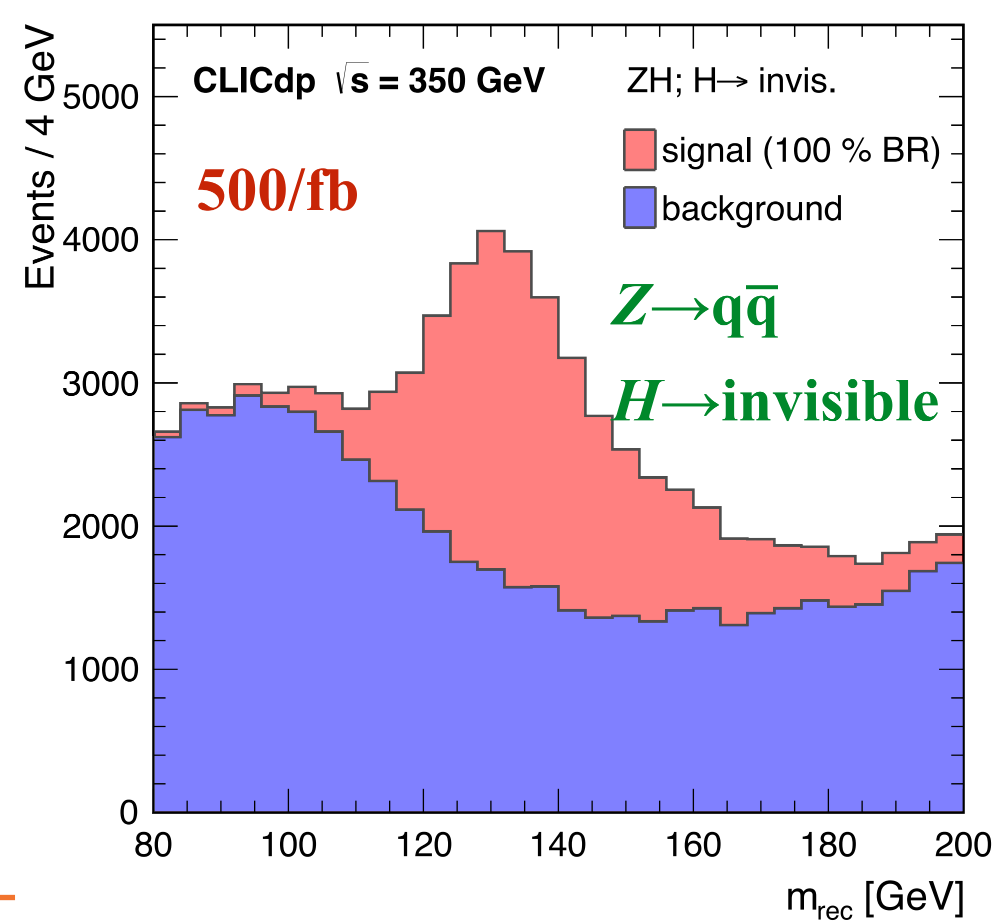


Model-independent Higgs Couplings

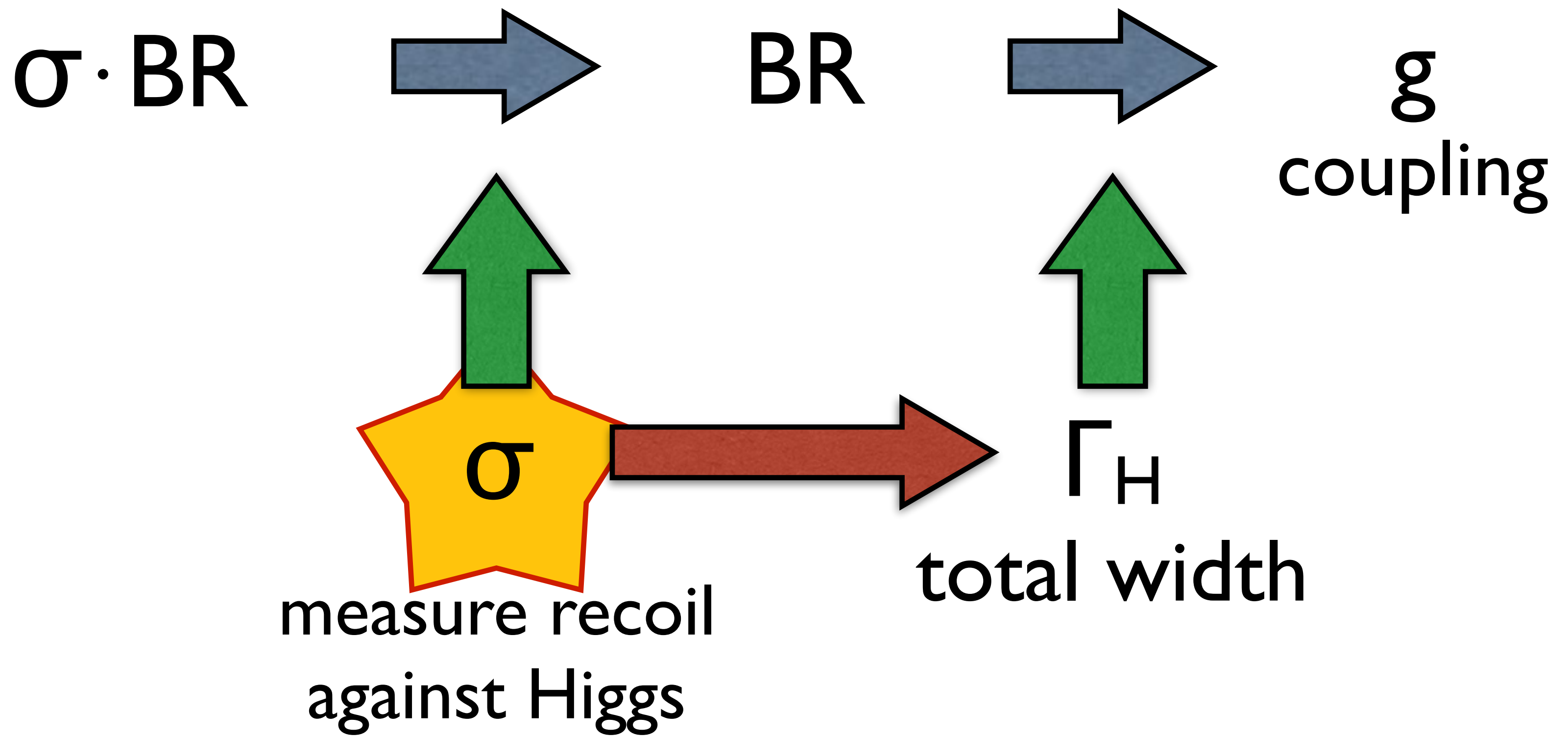
arXiv:1608.07538







Model-independent Higgs Couplings



$$\frac{\sigma(e^+e^- \to ZH) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to \nu_e\bar{\nu}_e H) \times BR(H \to b\bar{b})} \propto \left(\frac{g_{HZZ}}{g_{HWW}}\right)^2$$

$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

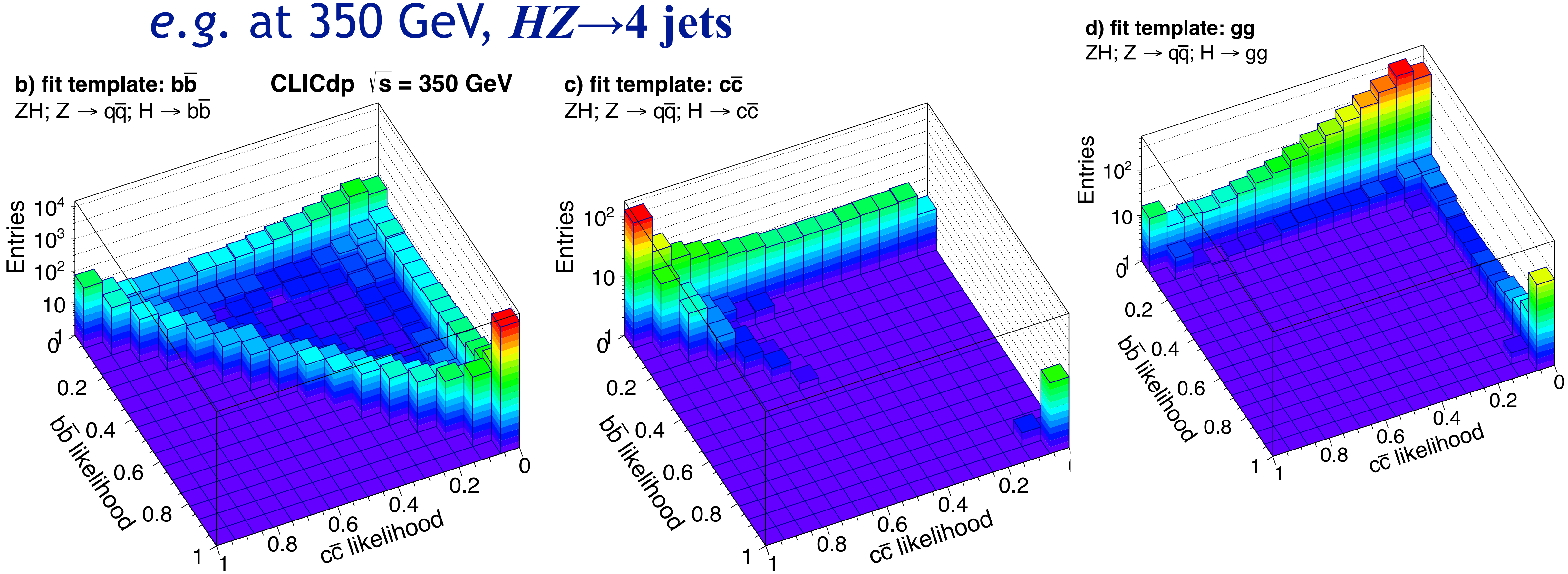
$$\sigma_{ZH} \propto g^2{}_{HZZ}$$

Higgs Hadronic BRs

arXiv:1608.07538

- Aim: resolve $H\rightarrow 2$ jets signal into $H\rightarrow b\bar{b}$, $H\rightarrow c\bar{c}$ and $H\rightarrow gg$
- Fit to multivariate-derived templates using flavour tagging info

e.g. at 350 GeV, $HZ\rightarrow 4$ jets



Also with:

➡ $HZ\rightarrow 2$ jets + 2 ℓ,

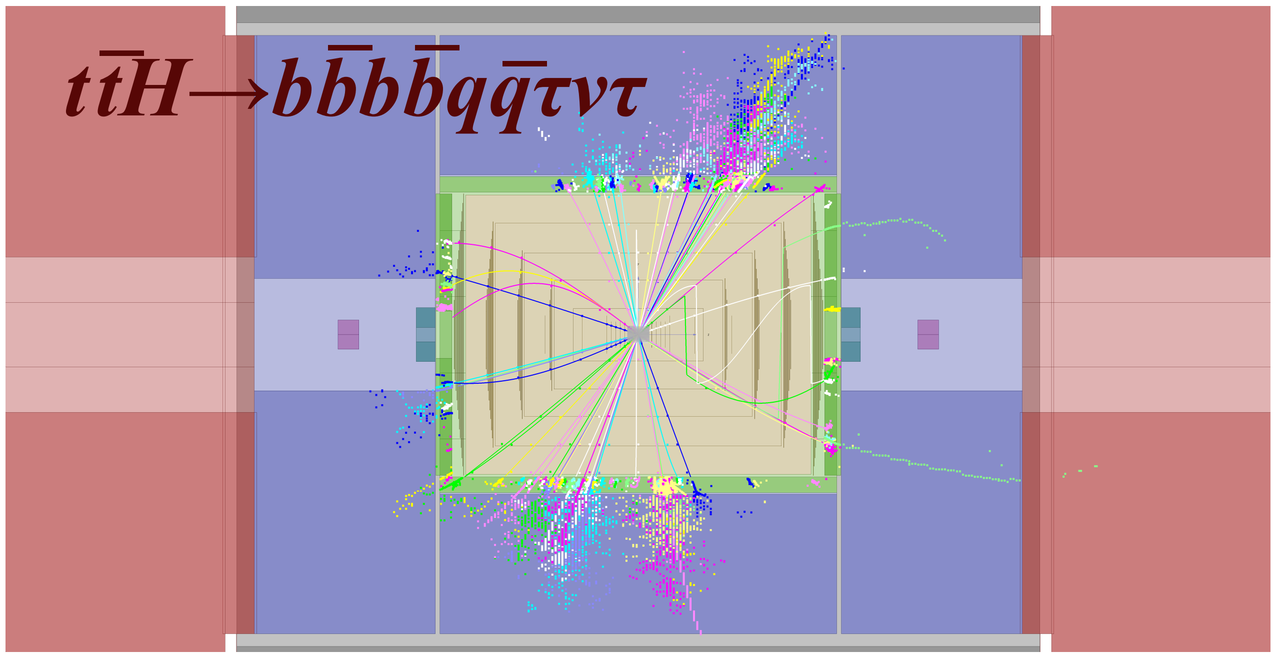
➡ $\nu\nu H\rightarrow \not{E}$ + 2 jets

With **500/fb** at **350 GeV**

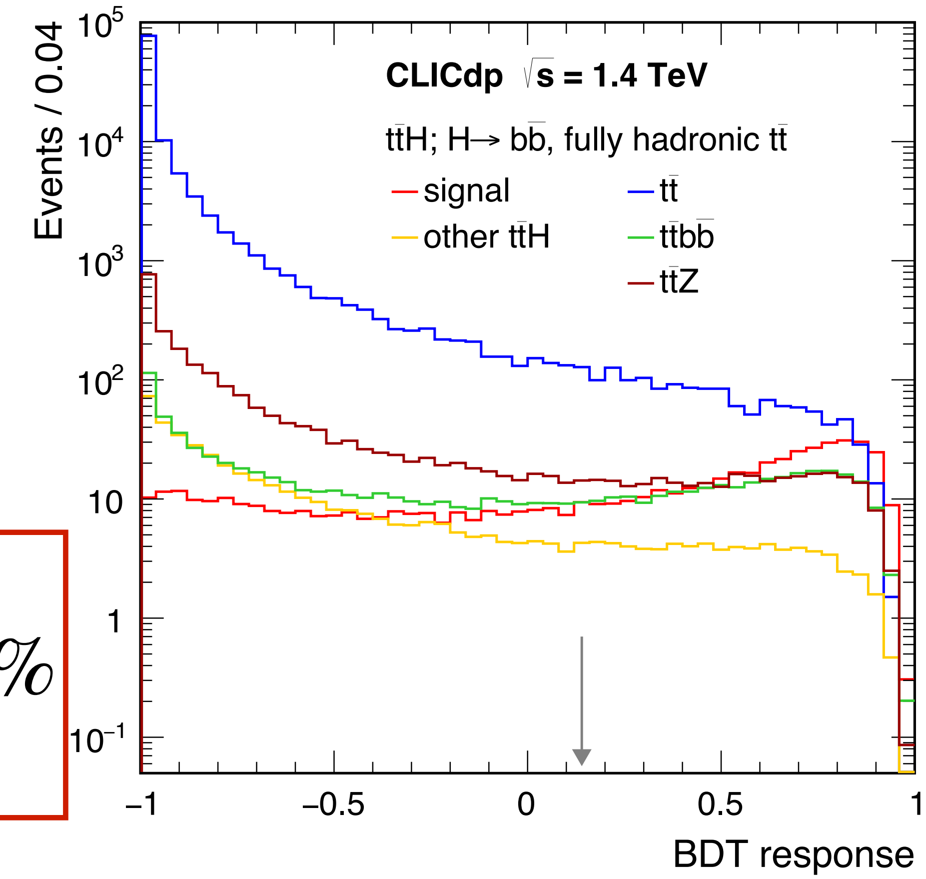
Decay	Statistical uncertainty Higgsstrahlung	Statistical uncertainty WW-fusion
$H\rightarrow b\bar{b}$	0.86 %	1.9 %
$H\rightarrow c\bar{c}$	14 %	26 %
$H\rightarrow gg$	6.1 %	10 %

Higher Energy: $t\bar{t}H$ and HH arXiv:1608.07538

$t\bar{t}H$ production at 1.4 TeV



$$\frac{\Delta y_t}{y_t} = 4.2\,\%$$



$\nu\bar{\nu}HH$ production at 1.4 and 3 TeV

- **Preliminary results**, working on combination and scale to full luminosity

	$\nu_e\bar{\nu}_eHH$, $HH\rightarrow b\bar{b}b\bar{b}$	backgrounds
1.4 TeV (1.5/fb)	16	37
3 TeV (2/fb)	61	97

$$\frac{\Delta[\sigma(\mathrm{HH}\nu_e\bar{\nu}_e)]}{\sigma(\mathrm{HH}\nu_e\bar{\nu}_e)} = 44\,\% \text{ at } 1.4\,\mathrm{TeV},$$

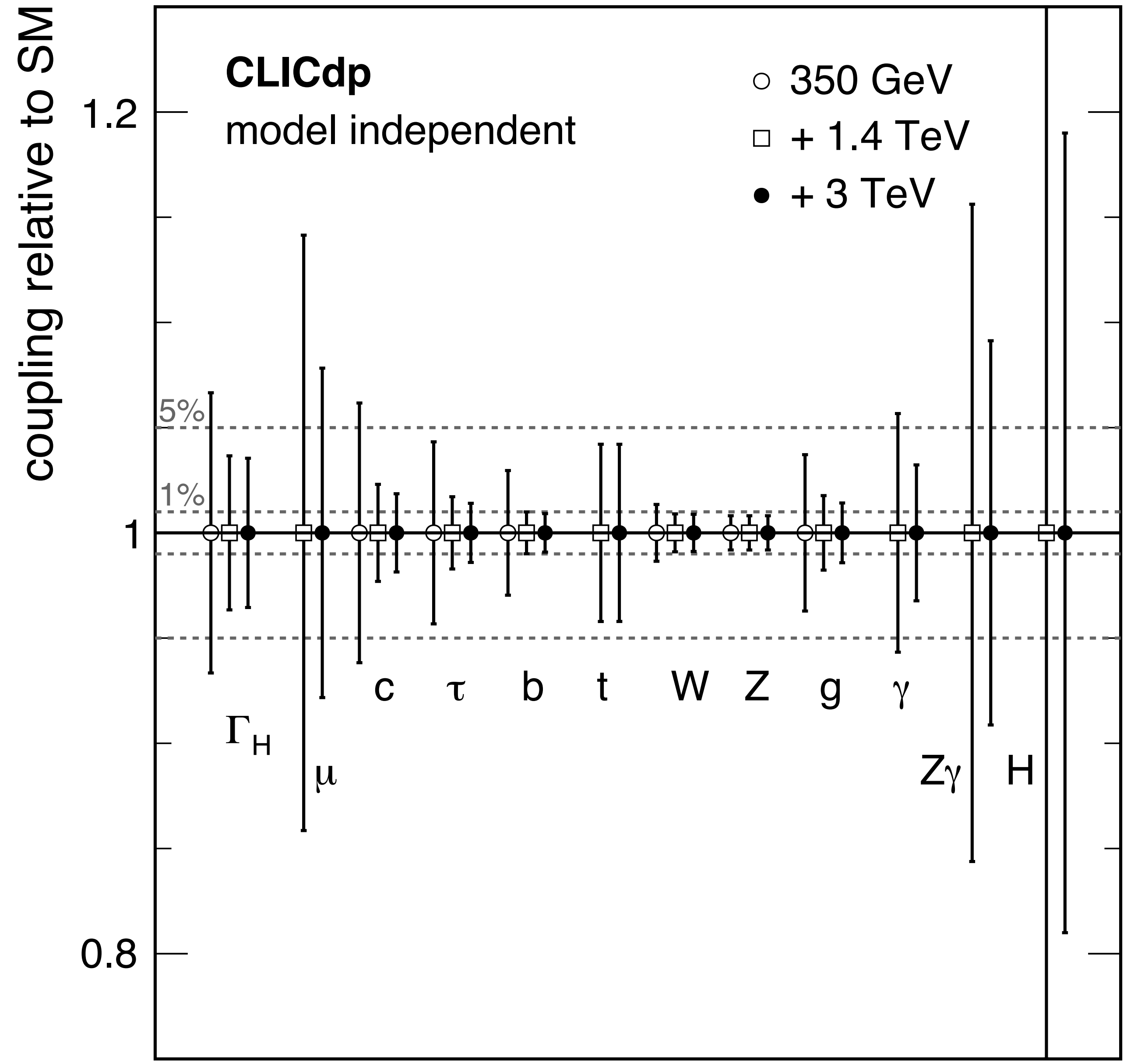
$$\frac{\Delta[\sigma(\mathrm{HH}\nu_e\bar{\nu}_e)]}{\sigma(\mathrm{HH}\nu_e\bar{\nu}_e)} = 20\,\% \text{ at } 3\,\mathrm{TeV}.$$

Higs Couplings Precision

arXiv:1608.07538

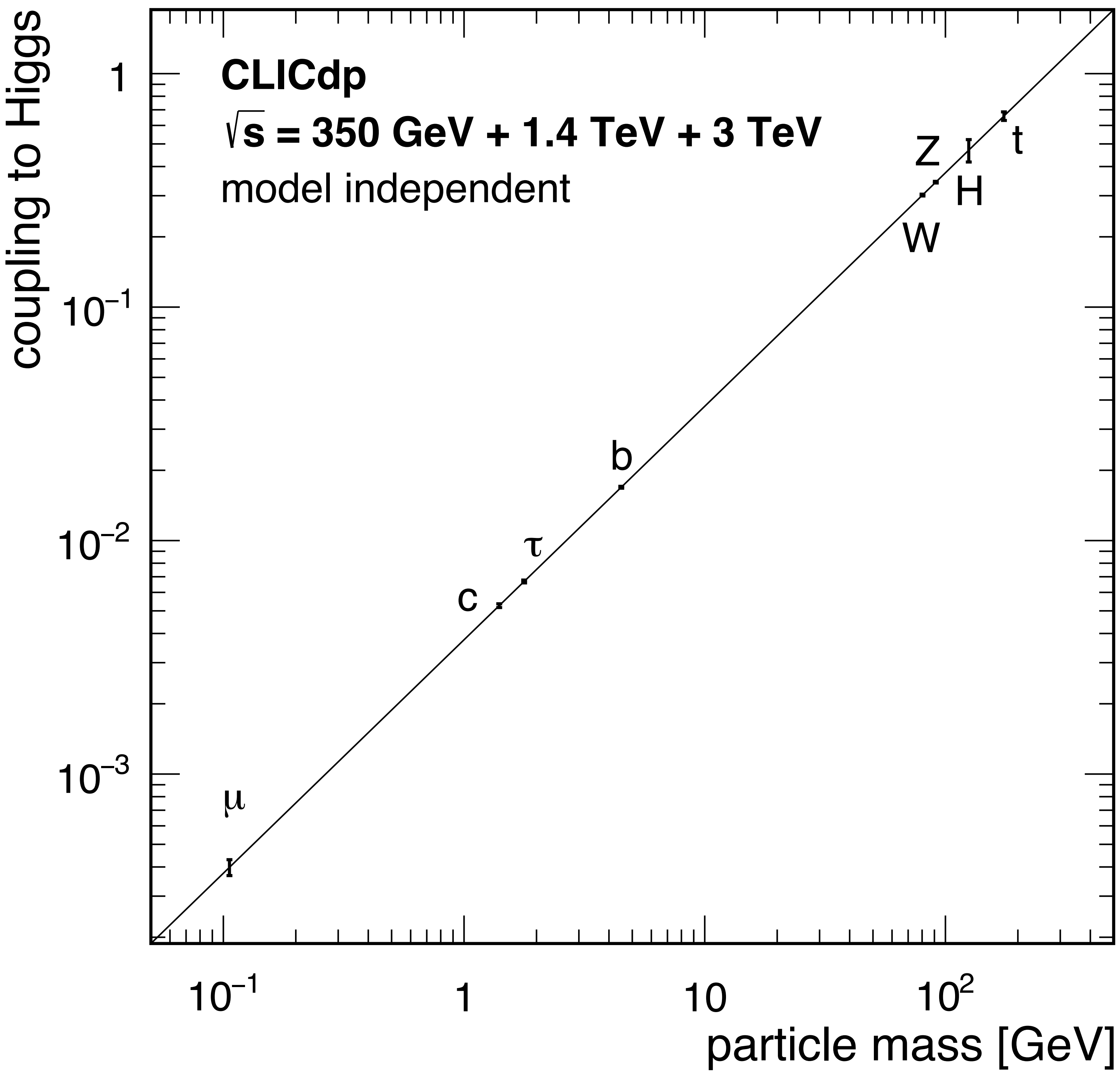
- Model-independent fit using recoil mass to measure Γ_H

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.4 %	0.9 %	0.9 %
g_{Hbb}	3.0 %	1.0 %	0.9 %
g_{Hcc}	6.2 %	2.3 %	1.9 %
$g_{H\tau\tau}$	4.3 %	1.7 %	1.4 %
$g_{H\mu\mu}$	–	14.1 %	7.8 %
g_{Htt}	–	4.2 %	4.2 %
$g^{\dagger}_{Hgg}$	3.7 %	1.8 %	1.4 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	3.2 %
$g^{\dagger}_{HZ\gamma}$	–	15.6 %	9.1 %
Γ_H	6.7 %	3.7 %	3.5 %



Higgs Couplings Precision

arXiv:1608.07538



Higgs Couplings Precision

arXiv:1608.07538

- Model-dependent à la LHC
- No theoretical or systematic uncertainties

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.4 %	0.9 %	0.9 %
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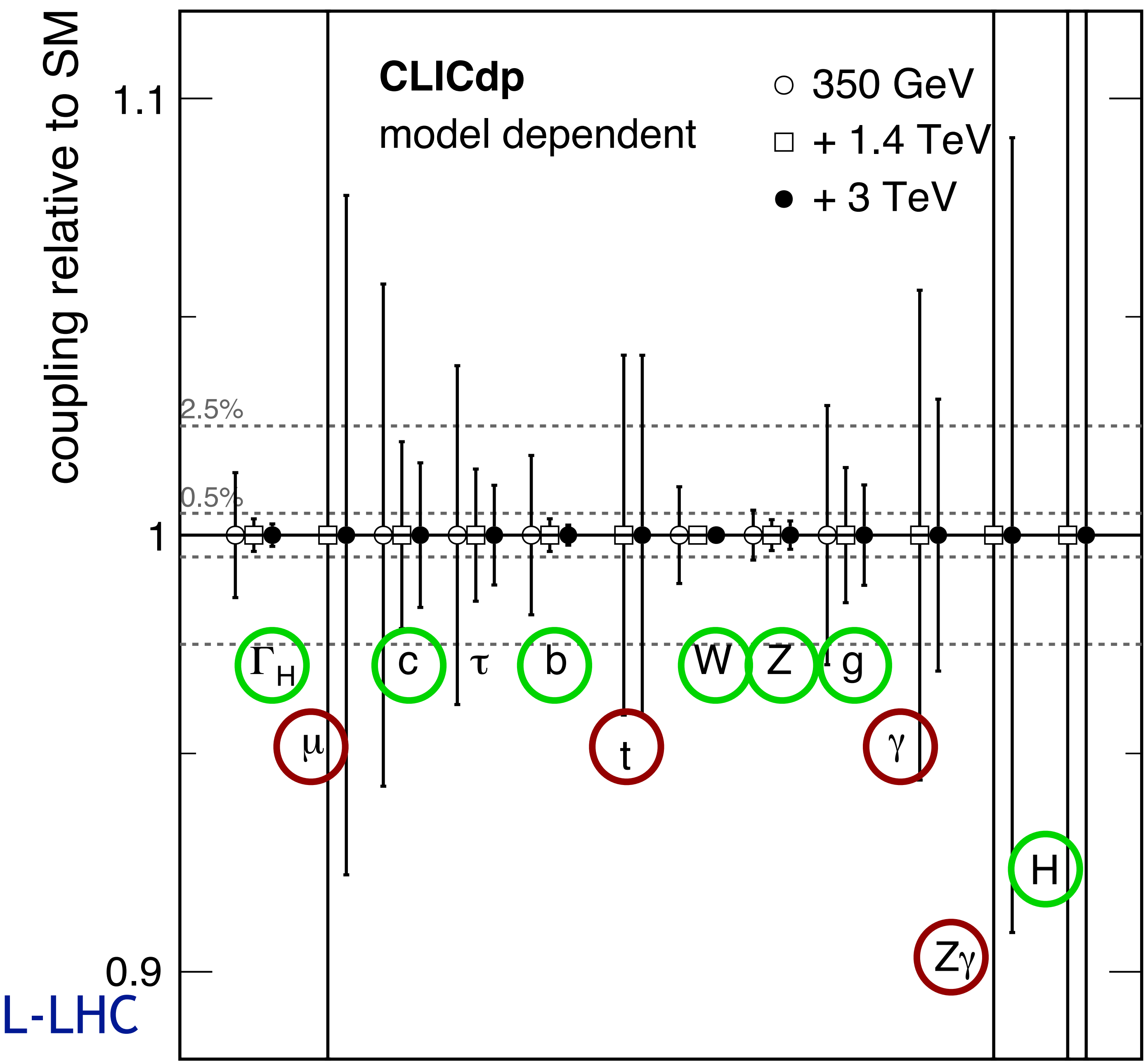
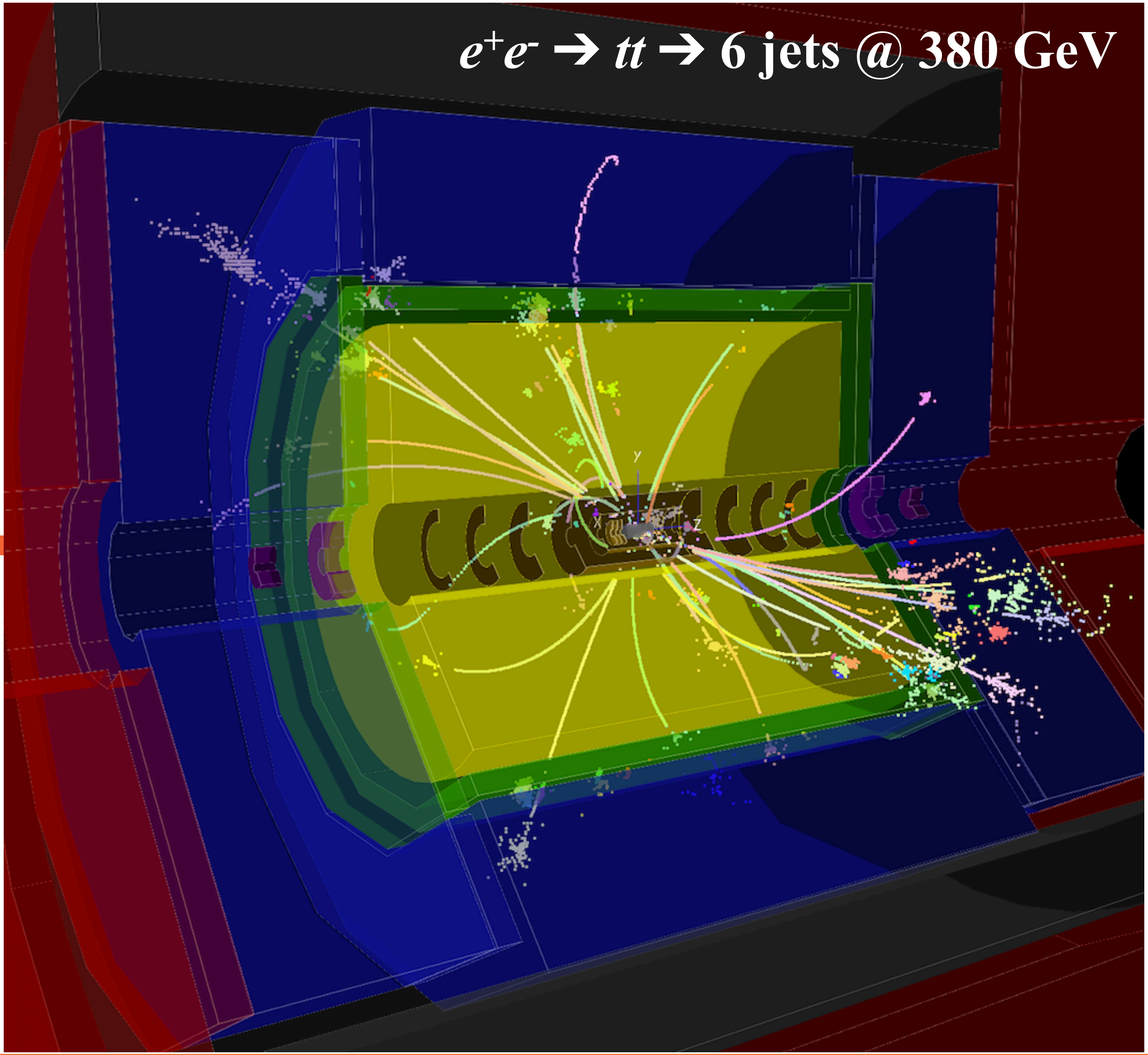
g_{Hcc}	6.2 %	2.3 %	1.9 %
$g_{H\tau\tau}$	4.3 %	1.7 %	1.4 %
$g_{H\mu\mu}$	–	14.1 %	7.8 %
g_{Htt}	–	4.2 %	4.2 %
$g^{\dagger}_{Hgg}$	3.7 %	1.8 %	1.4 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	3.2 %
$g^{\dagger}_{HZ\gamma}$	–	15.6 %	9.1 %
Γ_H	6.7 %	3.7 %	3.5 %



Precision significantly better than HL-LHC

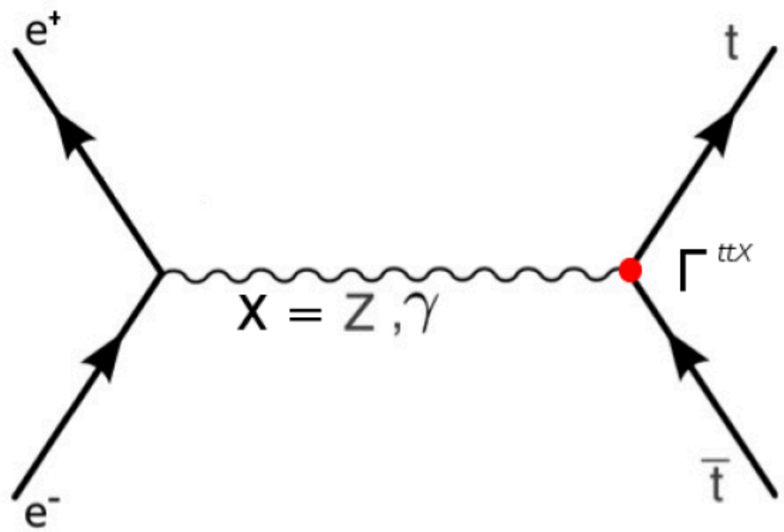
Precision comparable to HL-LHC

Top

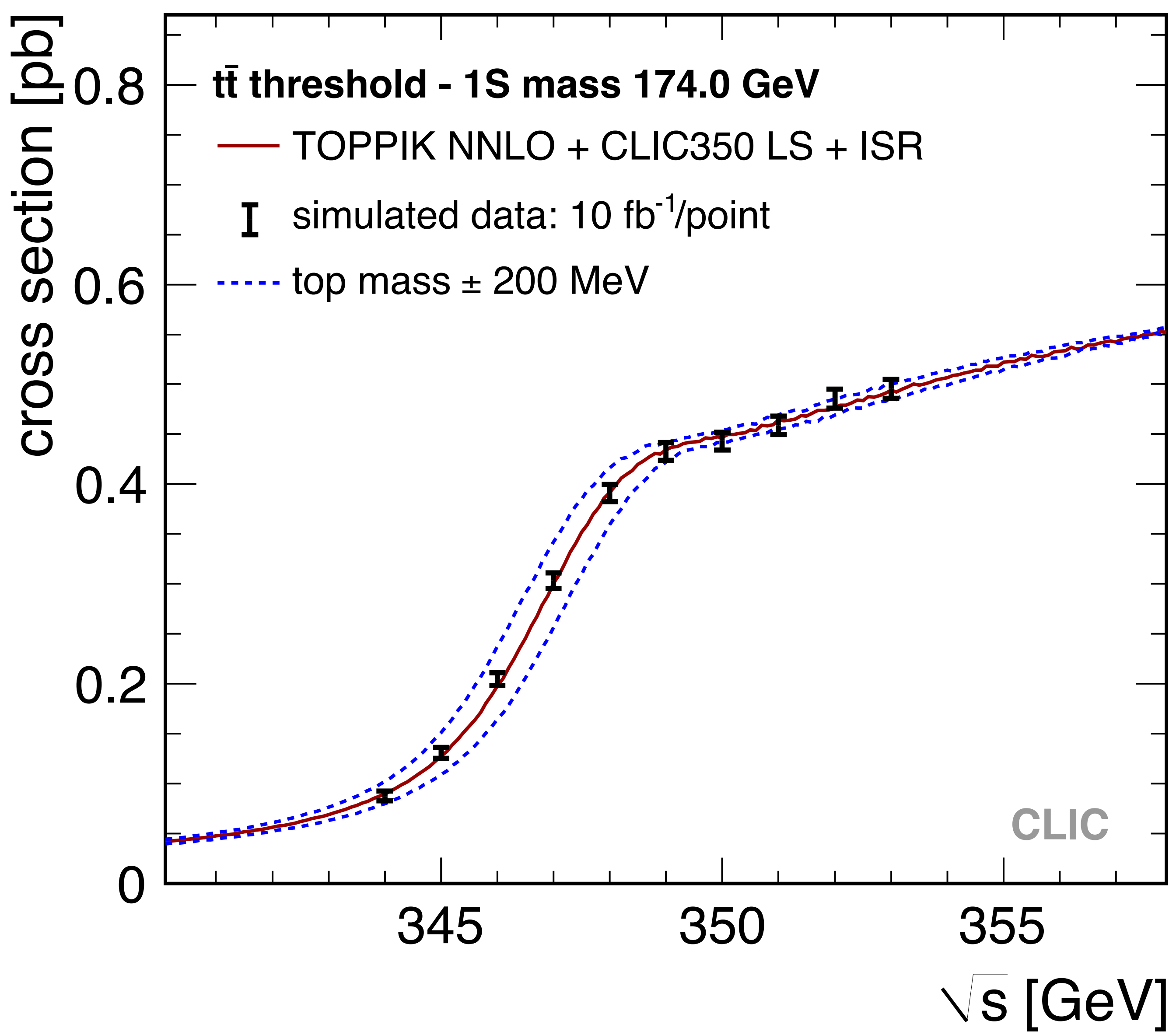


Top Production Threshold Scan

- CLIC380 will make a dedicated scan at $\mathbf{E \sim 350\ GeV}$ to measure top pair production
- Cross section *turn on* very sensitive to the top quark **pole mass.**



- 10 energies with $\mathbf{10/fb}$
- ≲1 year of data-taking in total
- Resulting uncertainty $\mathbf{\Delta m_t \sim 50\ MeV}$



Precision Top Physics

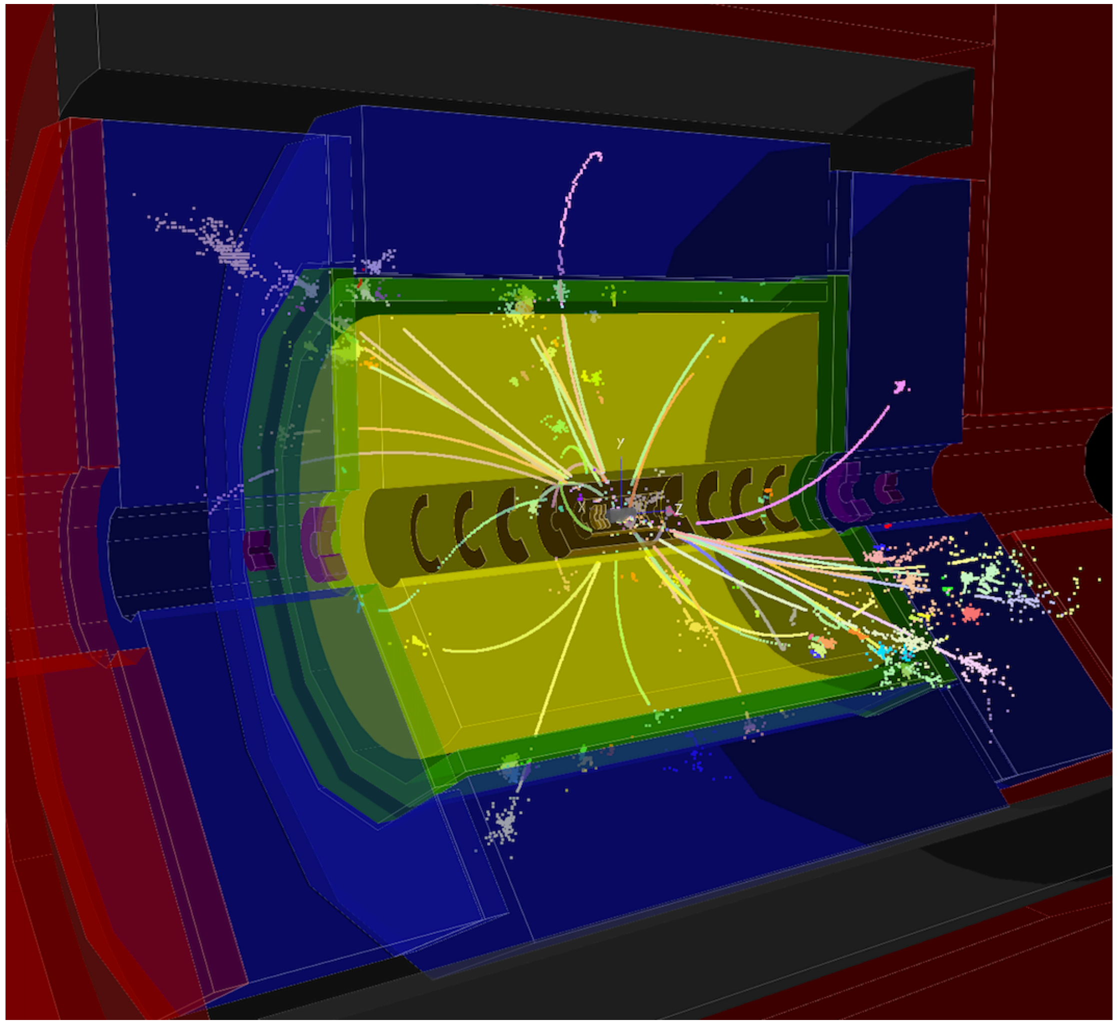
- Clean environment at CLIC facilitates precision measurements & search for rare phenomena.
- *e.g.* New physics in $t\bar{t}V$ and $t\bar{t}\gamma$ vertices, measurements with polarised beam can disentangle γ and Z form factors

$$\Gamma^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\underbrace{\gamma_\mu\left(F^X_{1V}(k^2)\right.}_{\text{vector}} + \underbrace{\left.\gamma_5 F^X_{1A}(k^2)\right)}_{\text{axial}} - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \underbrace{\left(iF^X_{2V}(k^2)\right.}_{\text{tensor}} + \underbrace{\left.\gamma_5 F^X_{2A}(k^2)\right)}_{\text{CPV}}\right\}$$

- ***e.g.* $A_{fb}(e^+e^-\to t\bar{t})$**

$$A^t_{FB} = \frac{N(0<\theta_{top}\leq\pi/2) - N(\pi/2<\theta_{top}\leq\pi)}{N(0<\theta_{top}\leq\pi/2) + N(\pi/2<\theta_{top}\leq\pi)}$$

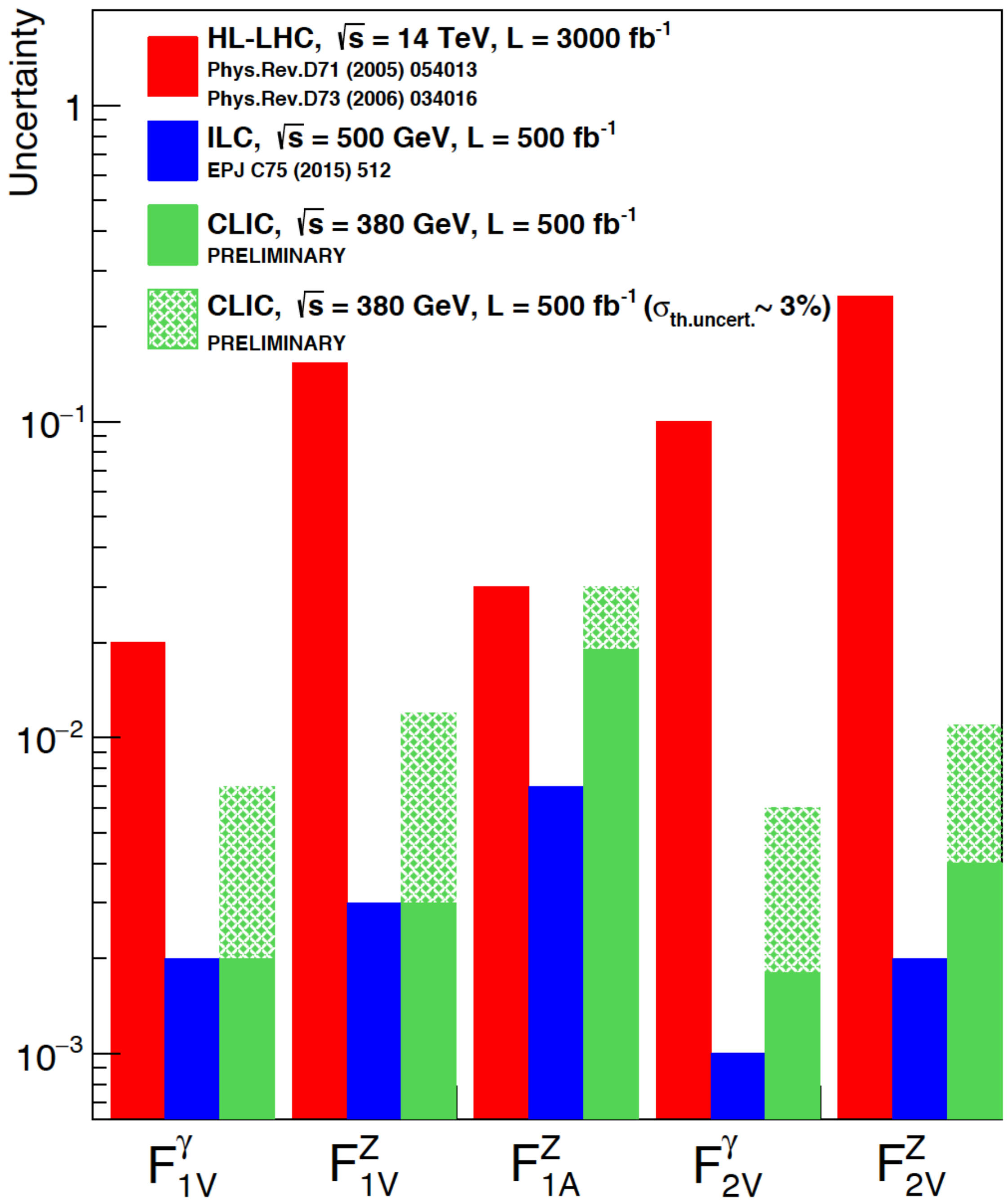
- Preliminary results at **1.4 TeV**: stat. precision **2-3%** for ***P*(e^-) = ±80%**



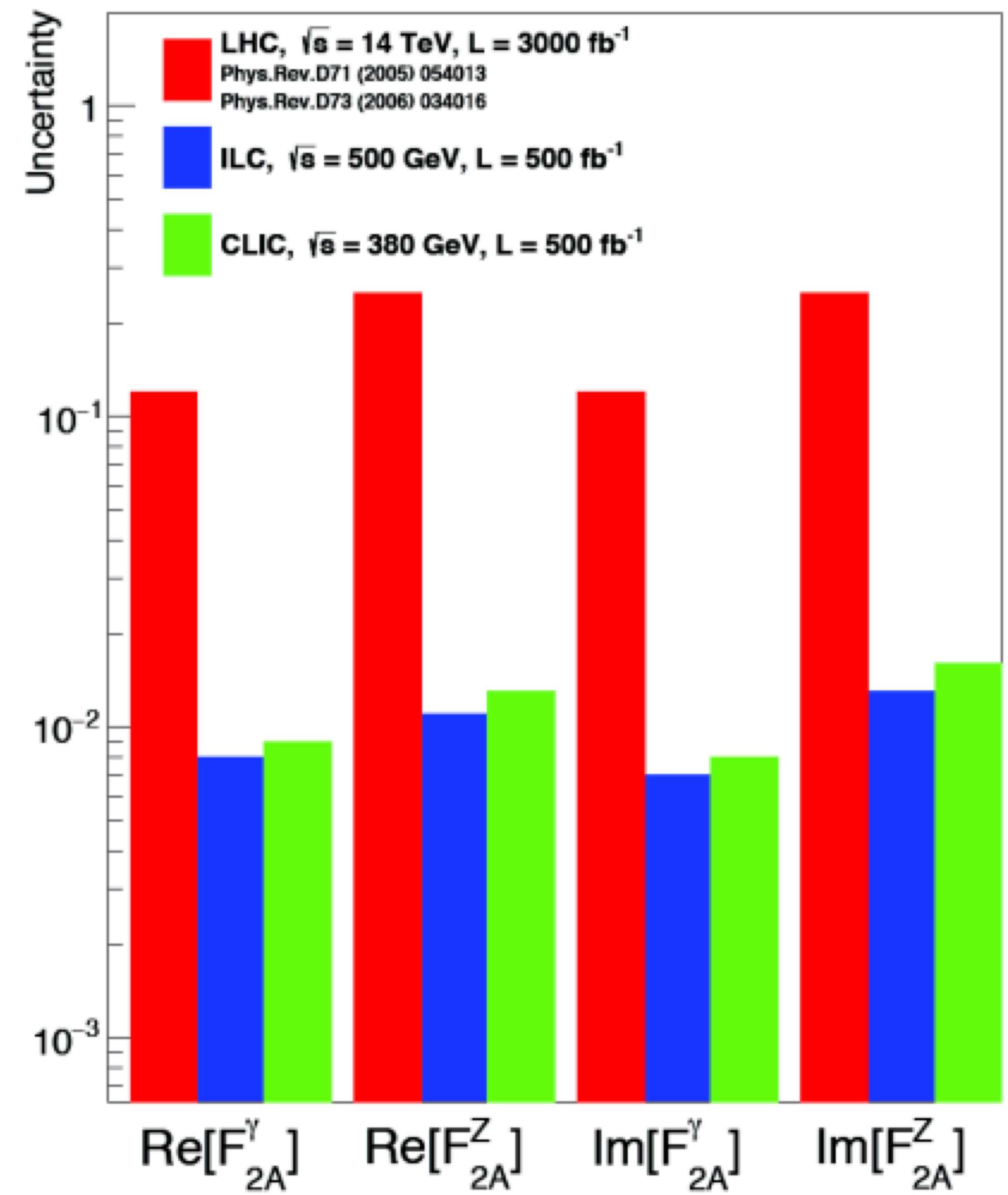
top quark couplings to Z and γ

Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)

CP-conserving couplings



CP-violating couplings



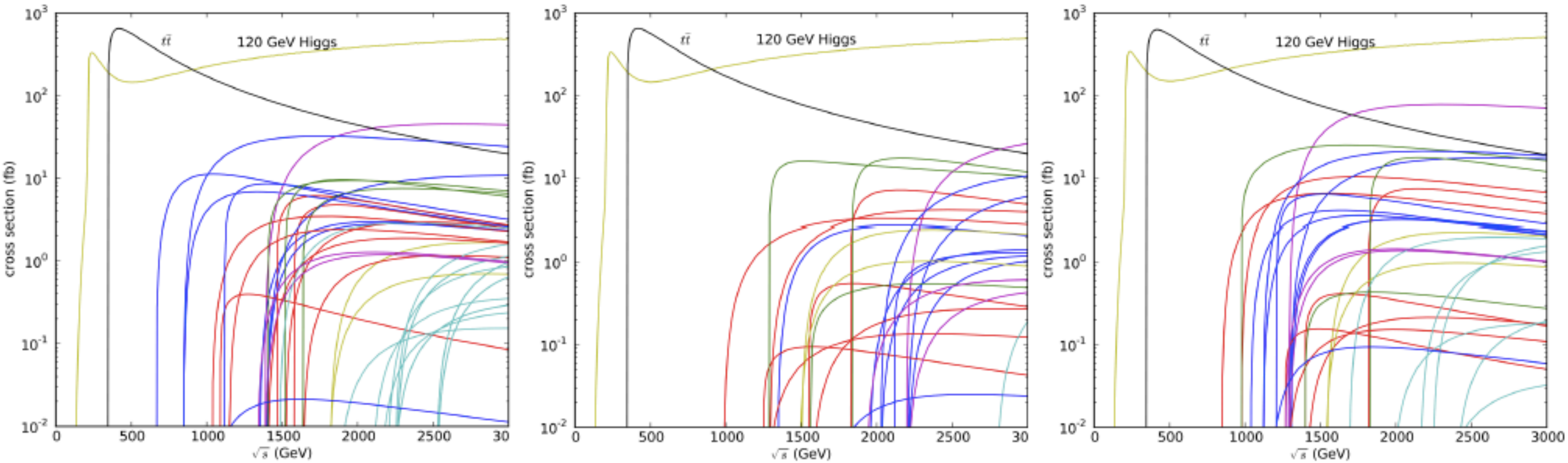
arXiv:1608.07537

M. Vos at ECFA LC 2016

BSM

Direct BSM Sensitivity

arxiv:1202.5940



"model I", 3 TeV:
- Squarks
- Heavy Higgs

"model II", 3 TeV:
- Smuons, selectrons
- Gauginos

"model III", 1.4 TeV:
- Smuons, selectrons
- Staus, Gauginos

Higgs
$\tilde{\tau}, \tilde{\mu}, \tilde{e}$
charginos
squarks
SM $t\bar{t}$
$\tilde{\nu}_{\tau}, \tilde{\nu}_{\mu}, \tilde{\nu}_{e}$
neutralinos

Wider capability than only SUSY: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"

→ In general, **O(1%)** precision on masses and production cross sections found

e.g. Di-jet masses: gauginos at 3 TeV

Chargino and neutralino pair production

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

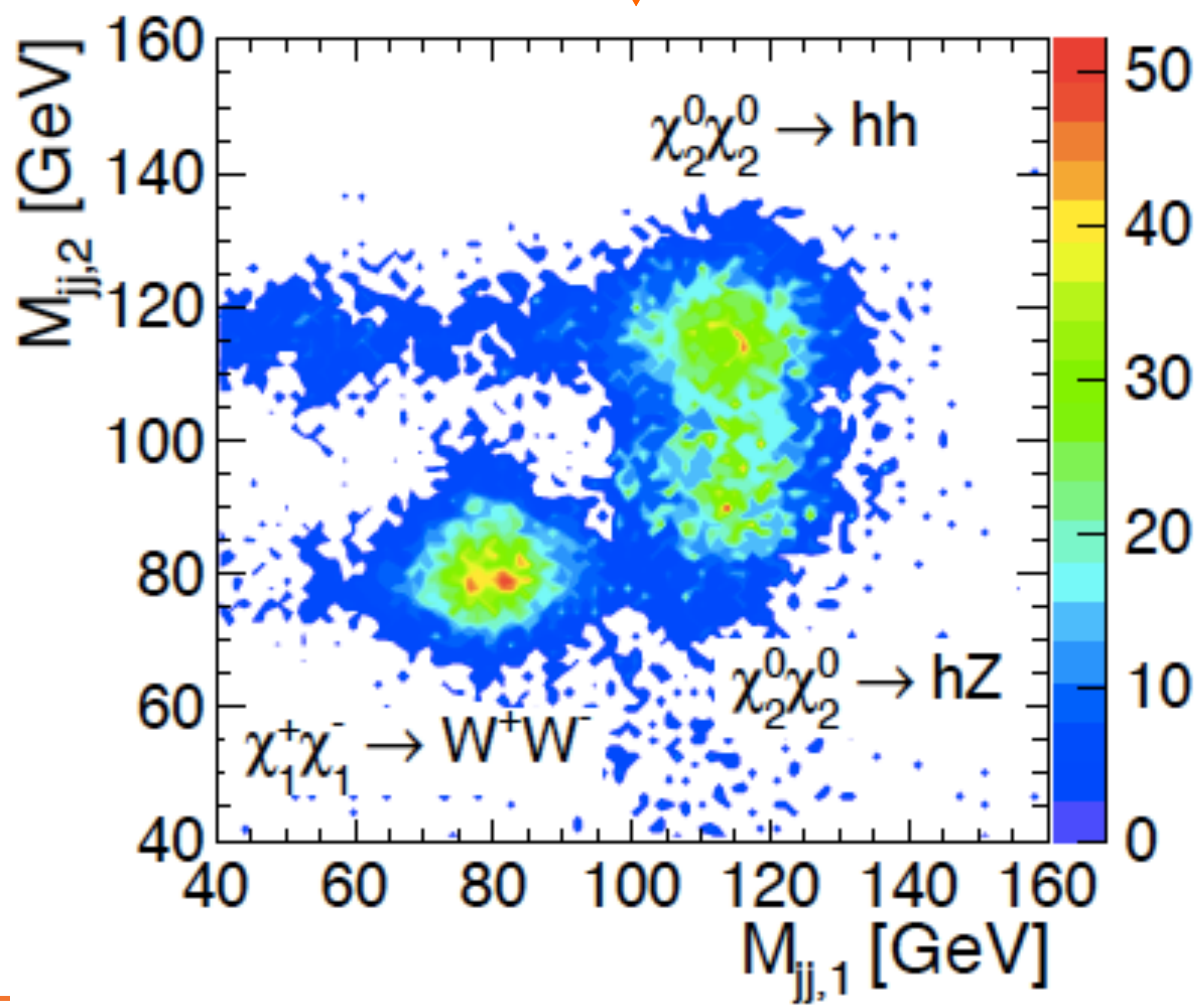
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \mathbf{82\ \%}$$

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

$$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$$

separation using di-jet invariant masses (test of PFA)



$$m(\tilde{\chi}_1^\pm) \ :\ \pm 7\,\mathrm{GeV}$$
$$m(\tilde{\chi}_2^0) \ :\ \pm 10\,\mathrm{GeV}$$

use slepton study result

$$m(\tilde{\chi}_1^0) \ :\ \pm 3\,\mathrm{GeV}$$

result: $\Delta m/m \leq 1\%$

LCD-Note-2011-037

SUSY benchmarking

arxiv:1202.5940

Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

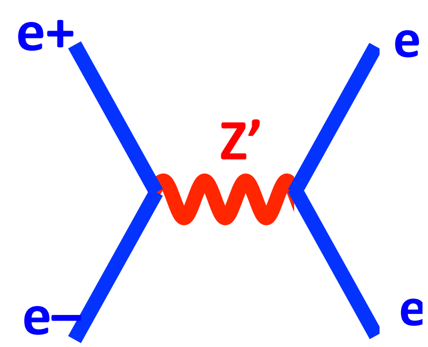
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ 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	$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ 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%

Large part of the SUSY spectrum measured at <1% level

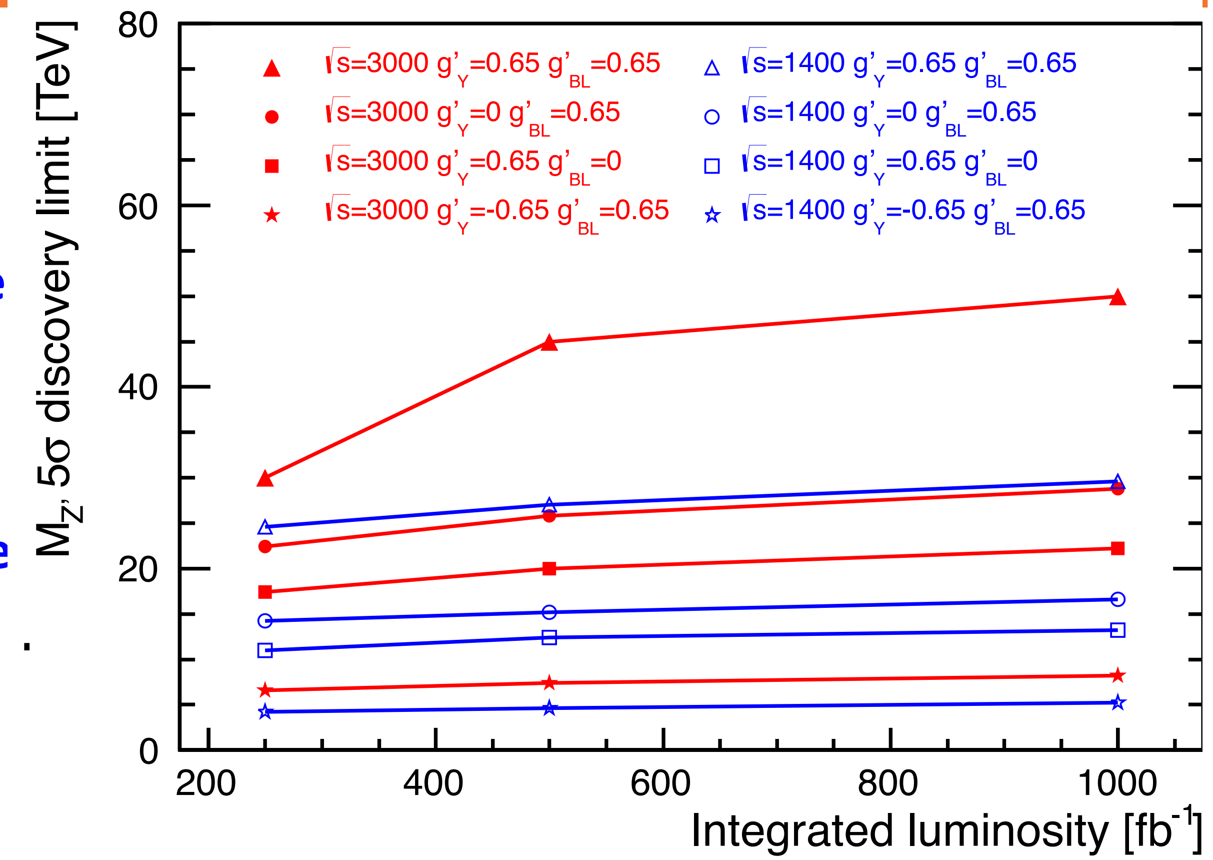
Indirect BSM - some examples

Precision studies of $e^+e^- \to \mu^+\mu^-$

- e.g. minimal anomaly-free Z' model, look at:
  - ➡ total $e^+e^- \to \mu^+\mu^-$ cross-section
  - ➡ forward-backward asymmetry
  - ➡ left-right asymmetry

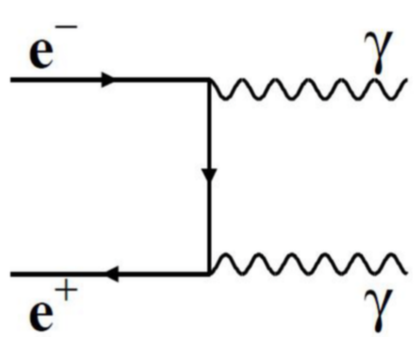


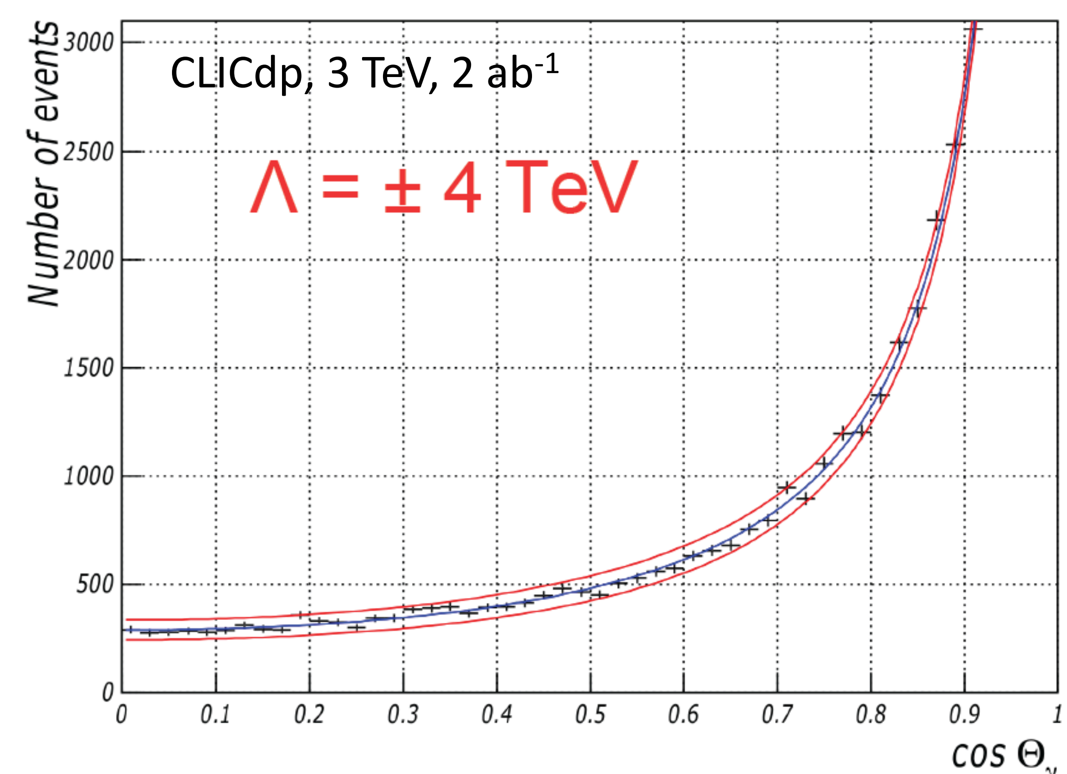
- ***Either***: precise measurements of effective couplings following multi-TeV LHC discovery
  or: discovery reach up to tens of TeV



Precision studies of $e^+e^- \to \gamma\gamma$

- Set limits on $$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)$$
- $\Lambda > 6 - 6.3$ **TeV** (or electron size less than $3\text{x}10^{-18}$ **cm**)
- also interpreting as limits on contact interactions, extra dimensions, ...

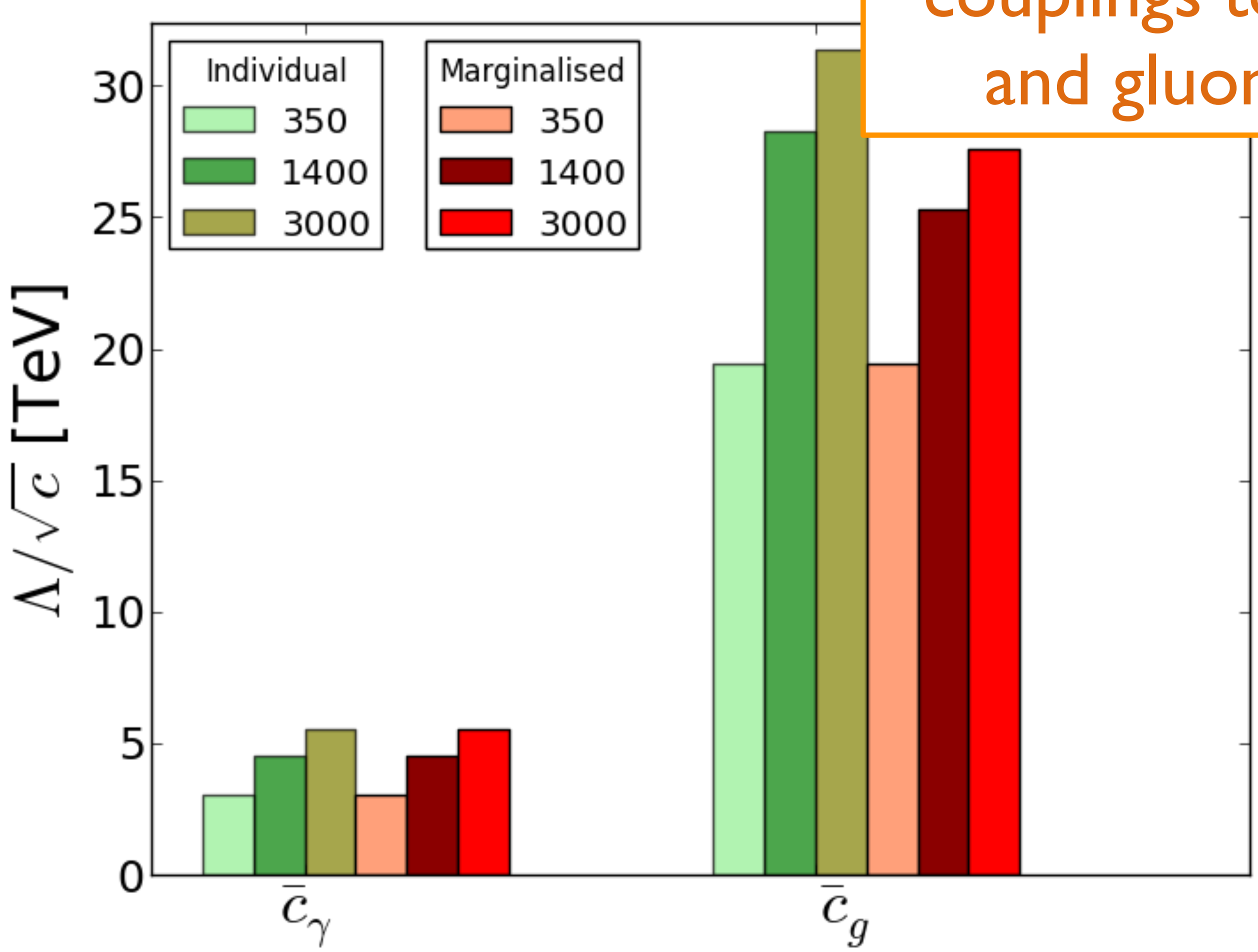




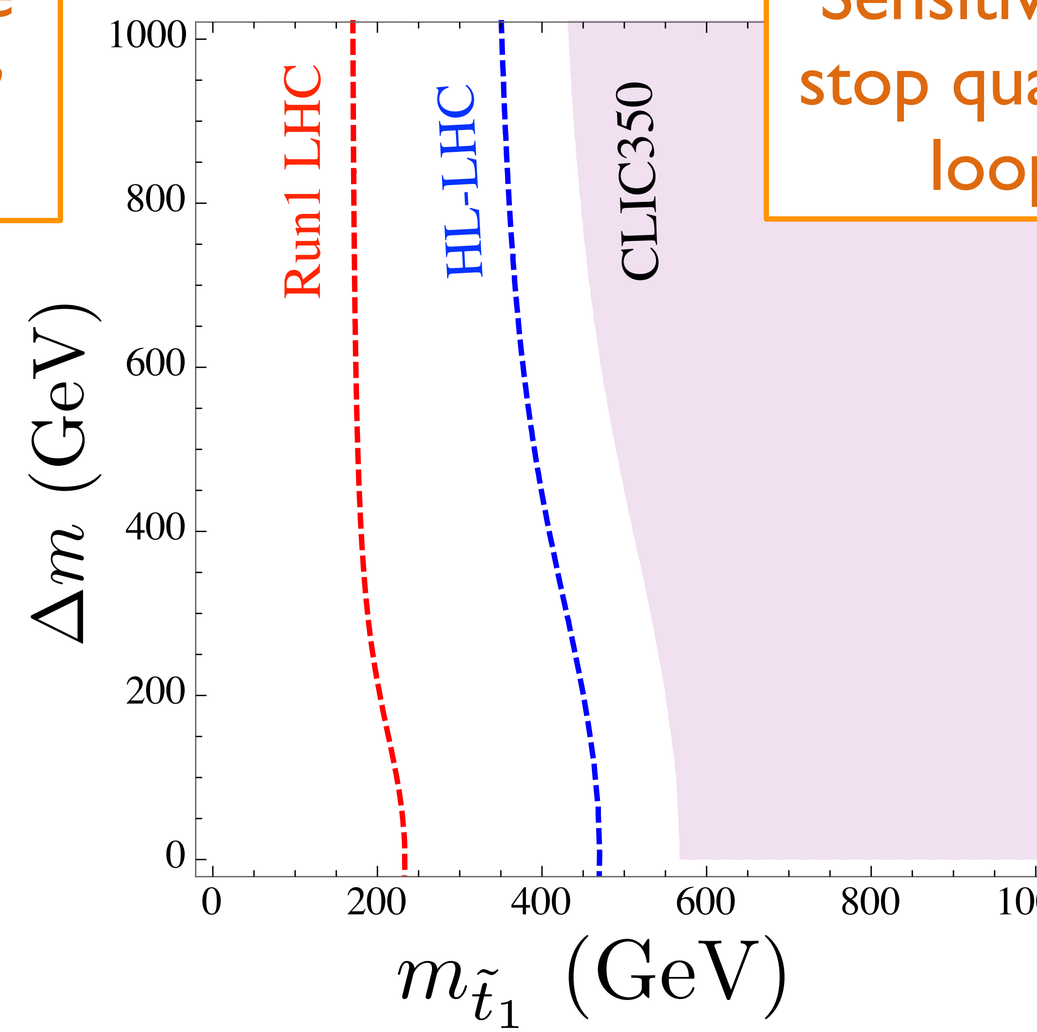
Effective Field Theory Interpretations

arXiv:1701.04804v1

- Higgs and W^+W^- production used to constrain effective field theories.
- The full CLIC program has sensitivity beyond other proposed e^+e^- colliders due to its higher energy.
- Dimension-6 Operator Analysis of the CLIC Sensitivity to New Physics



dim-6 effective couplings to γ and gluon



Sensitivity to stop quarks in loops

When & how much?

Timeline

2013 - 2019 Development Phase

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

2020 - 2025 Preparation Phase

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

2026 - 2034 Construction Phase

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

2019 - 2020 Decisions

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

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

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

Cost!

arXiv:1608.07537

- Baseline scoping document gives a cost estimate for the 380 GeV collider
- A new, bottom-up, cost estimate, including cost optimisations, is being prepared

Table 11: Value estimate of CLIC at 380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690

CLIC: Summary & Outlook

Design & development of the CLIC accelerator is in advanced state
Acceleration principle demonstrated at near required values
The detector concept is mature
⇒ CLIC is a realistic option for a post-LHC collider

CLIC baseline is for three stages:

380 GeV: precision Higgs measurements, top pole mass to 50 MeV

1.5 TeV, 3.0 TeV: HH, ttH, precision top couplings, BSM direct/indirect

The physics is complementary to the LHC program
CLIC offers a powerful tool to address the open questions in our field

The 380 GeV stage of CLIC is affordable
with a guaranteed physics return

Can be upgraded later to high energies 1.5 and 3 TeV

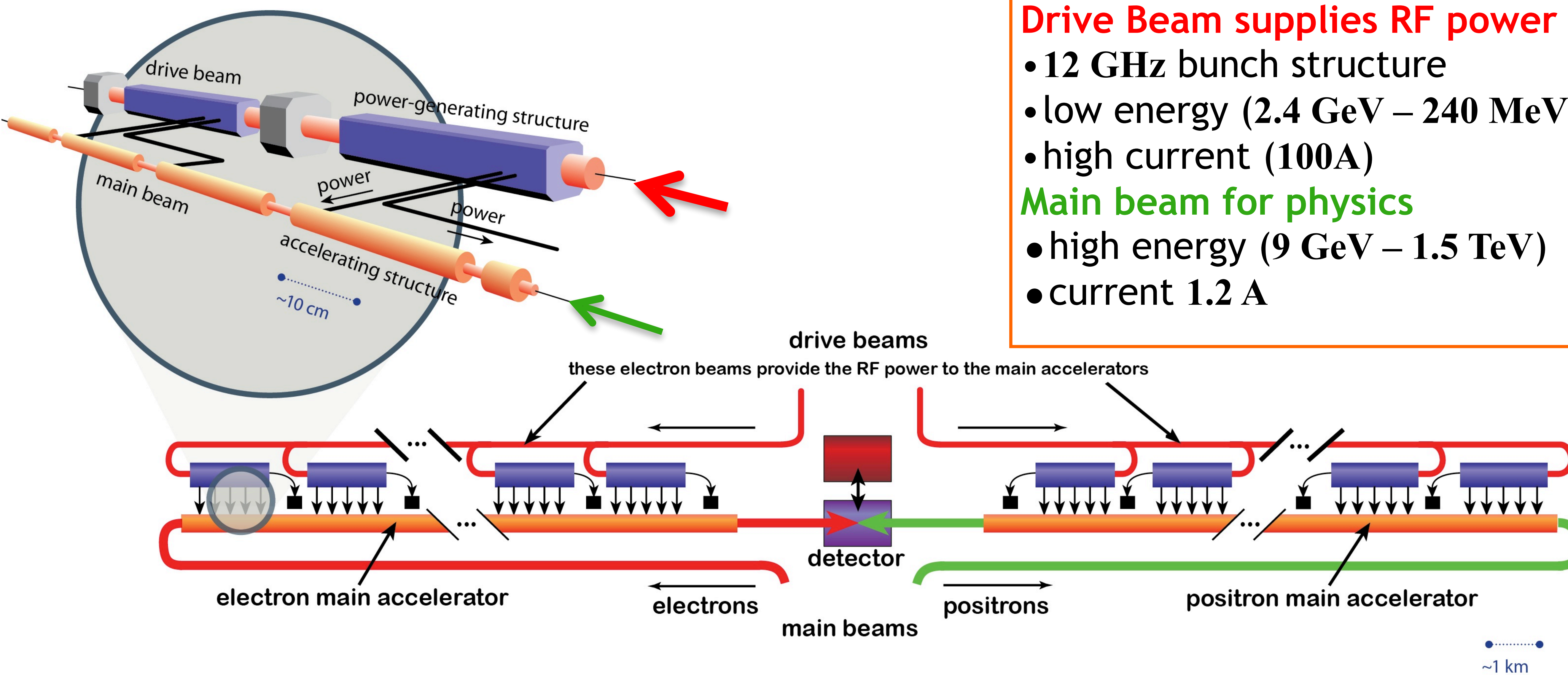

Thank you
谢谢

Backup Slides

CLIC 2-beam Acceleration Scheme

- **High centre-of-mass energy requires high-gradient acceleration**
- High gradients feasible in normal conducting structures with high RF frequency (12 GHz)
- Initial transfer from wall plug to beam (klystron) is efficient at lower frequency (~1 GHz)
- To keep power low, apply RF power only at the time when the beam is there.

CLIC uses a 2-beam acceleration scheme at 12 GHz, gradient of 100 MV/m



Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV – 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

CLEAR

- CTF3 programme ended at the end of 2016
- Electron beam maintained as new facility: *CLEAR*: CERN Linear Electron Accelerator for Research

  ➡ Beam test capability for CLIC (instrumentation, high gradient studies, components)

  ➡ Connected to 12 GHz RF for high-gradient studies

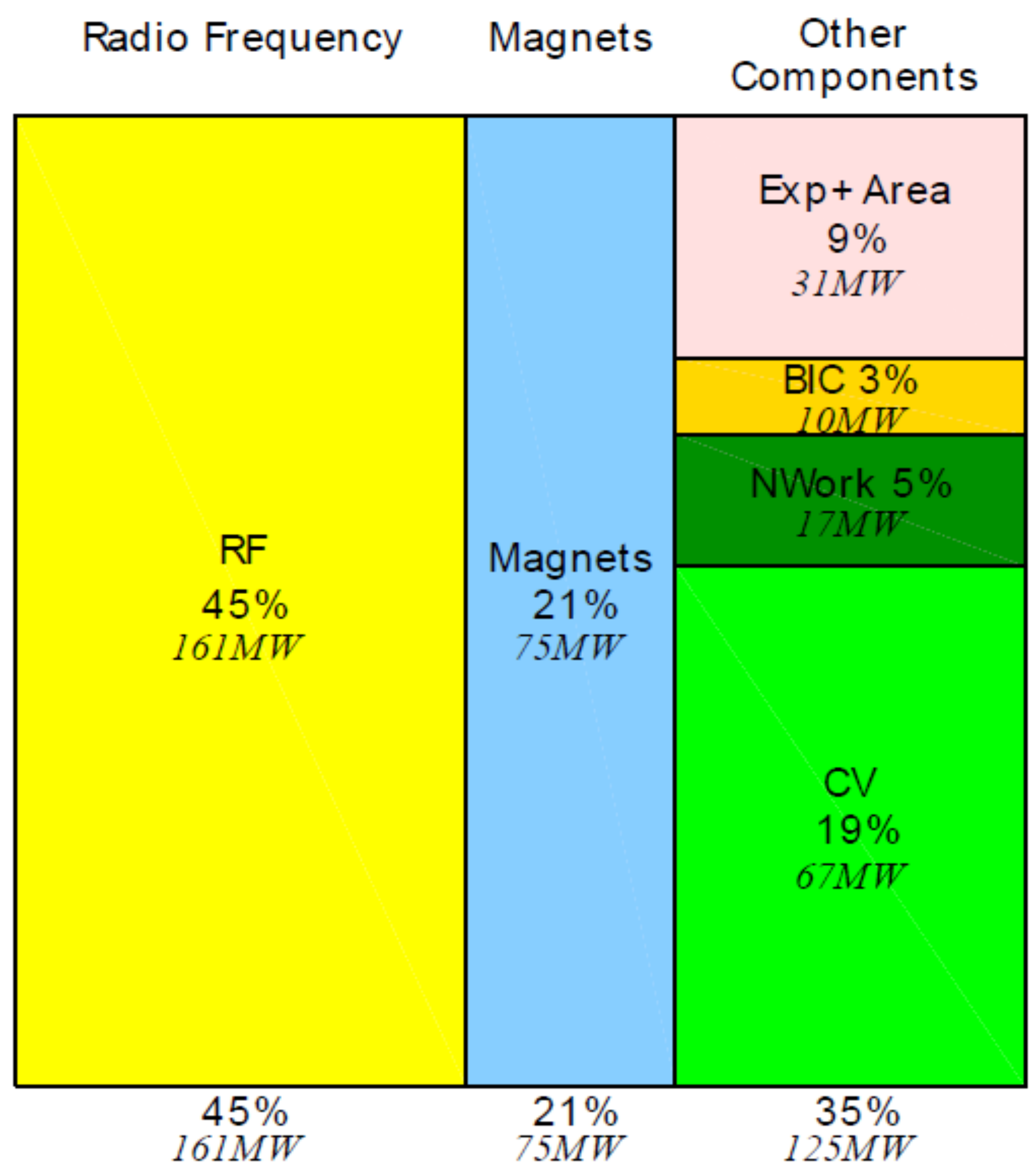
Power Consumption

arXiv:1608.07537

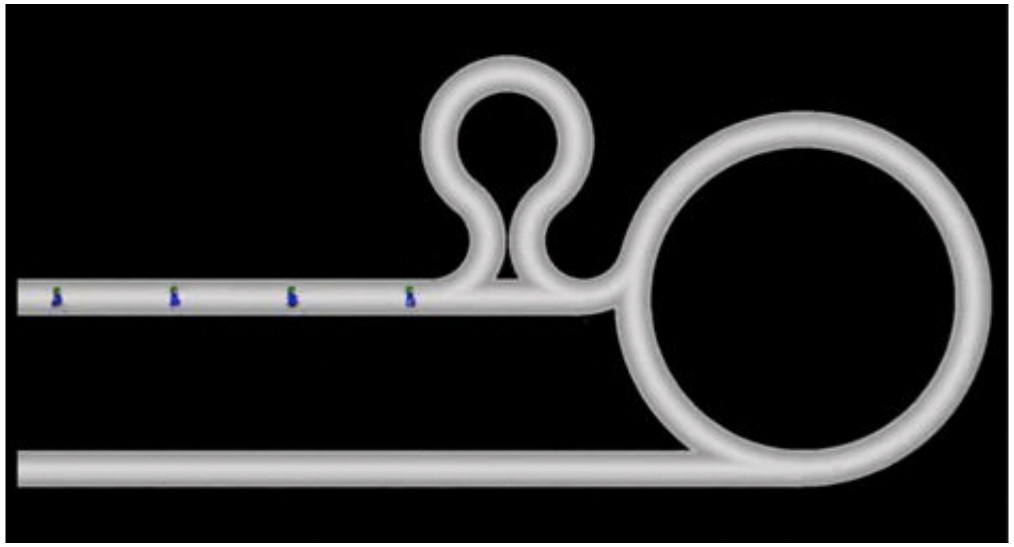
Table 9: Parameters for the CLIC energy stages. The power consumptions for the 1.5 and 3 TeV stages are from the CDR; depending on the details of the upgrade they can change at the percent level.

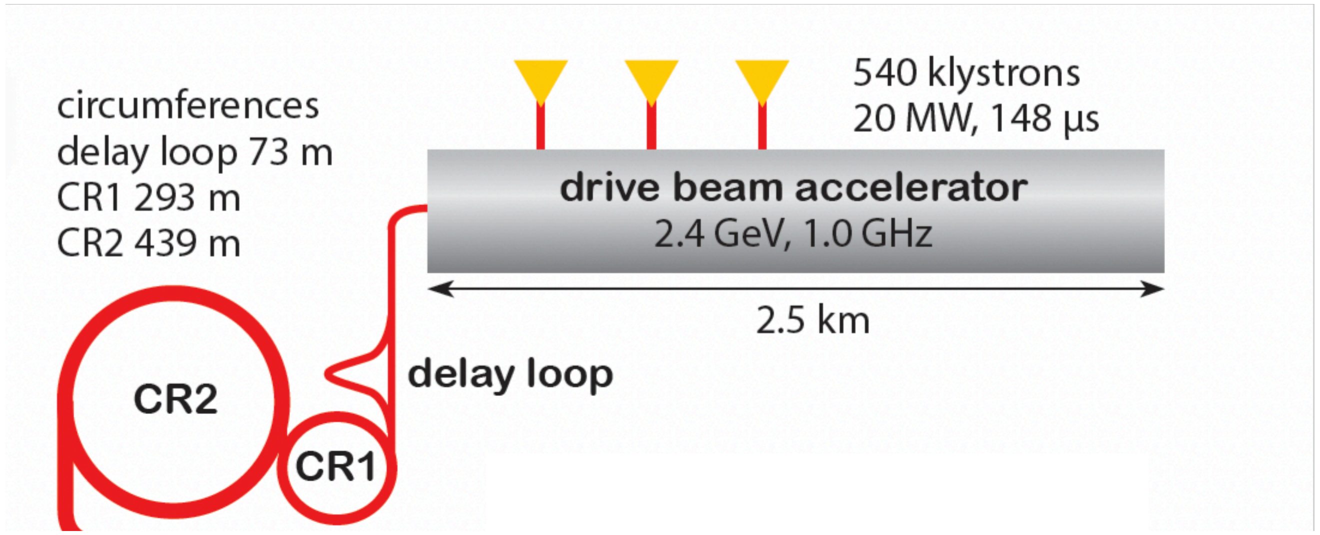
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total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

Power Consumption: 1.5 TeV

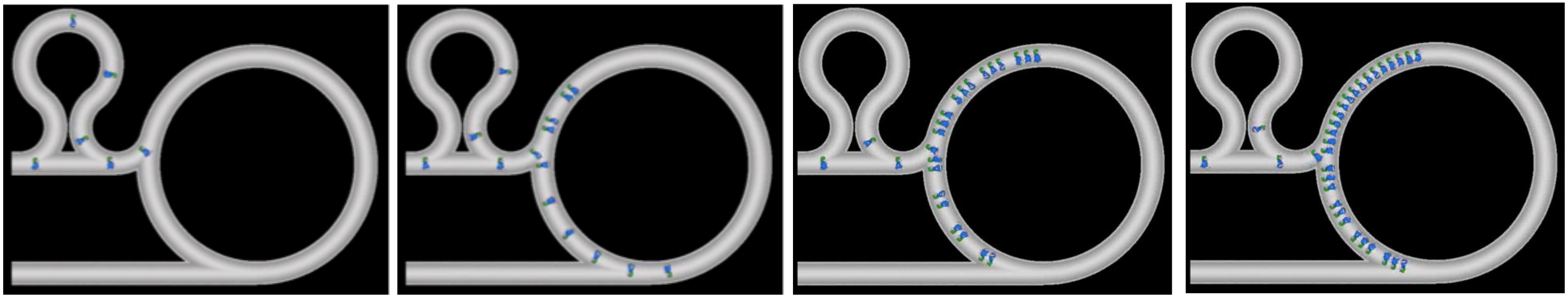


Drive Beam Production





Delay loops create drive beam bunch-structure



Low energy high current drive beam → high energy low current main beam

Costing

- A full bottom-up costing was done in 2011 for the CDR.
- A new costing will be made for the project plan in 2019.

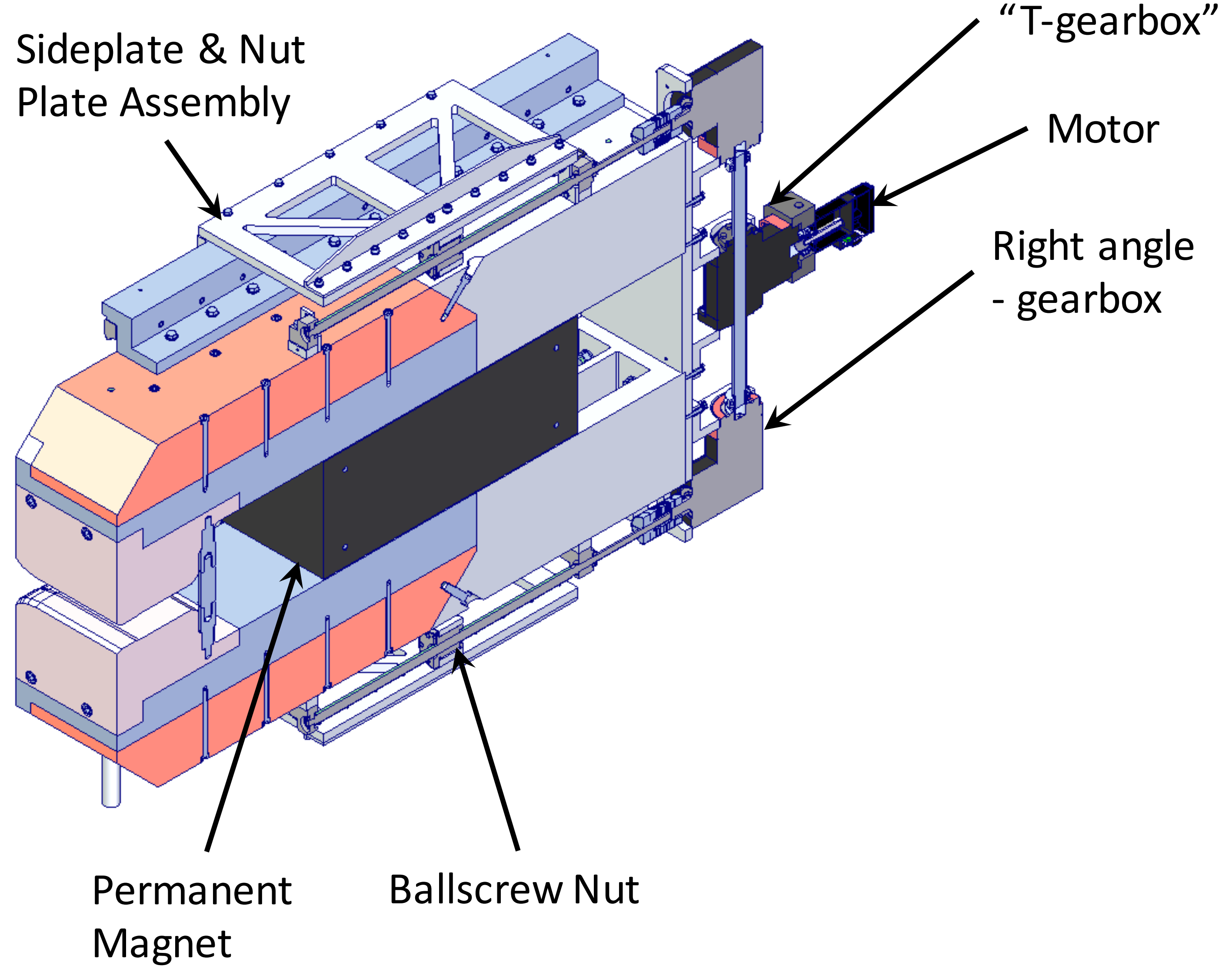
- Several options are actively being researched that could reduce the cost:
  - ➡ Klystrons instead of drive beam for 380 GeV
  - ➡ Using permanent magnets wherever possible

Adjustable-field Permanent Magnet Prototyping

High Energy Quad

Low Energy Quad

Dipole design



Klystron Option for 380 GeV

arXiv:1608.07537

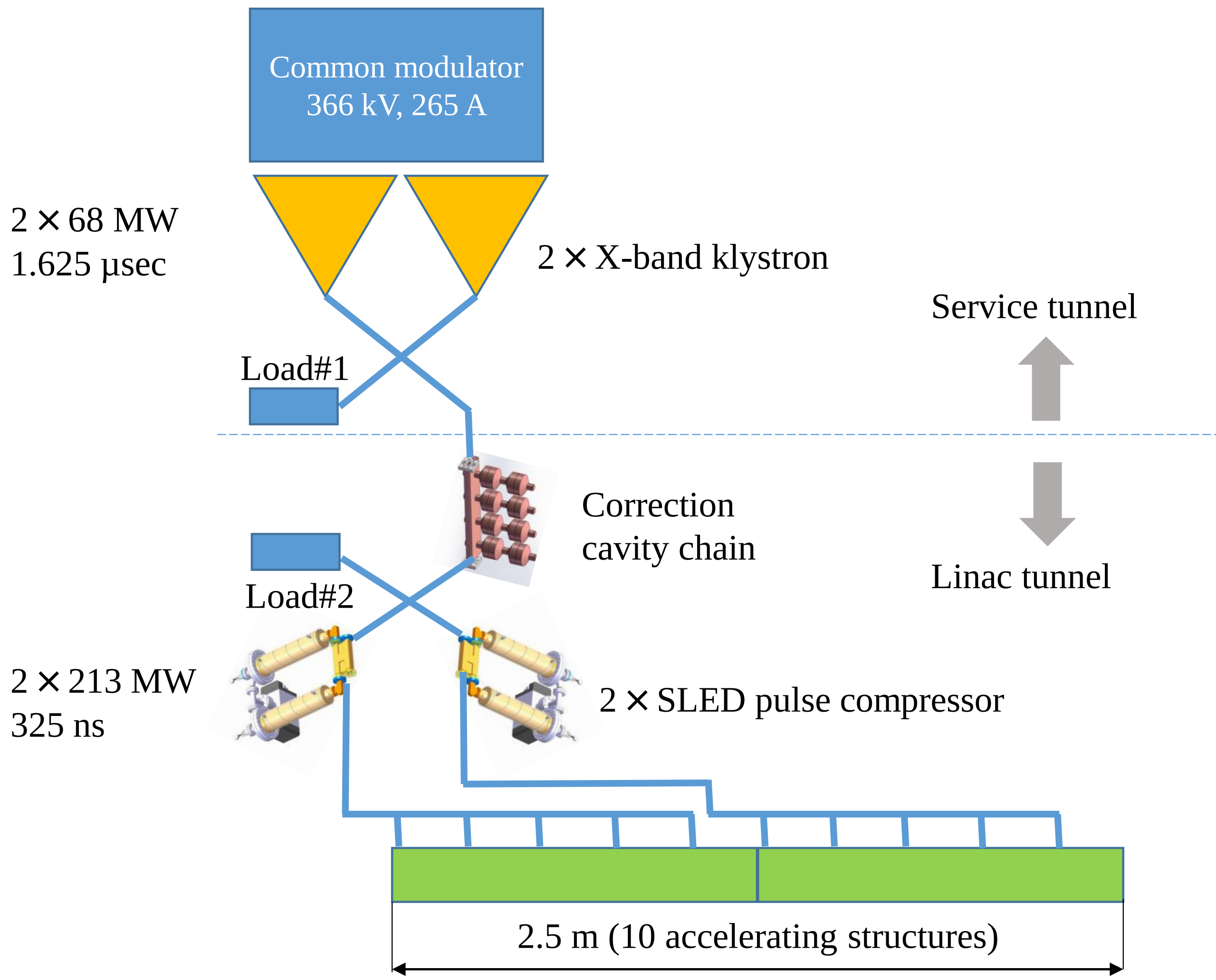
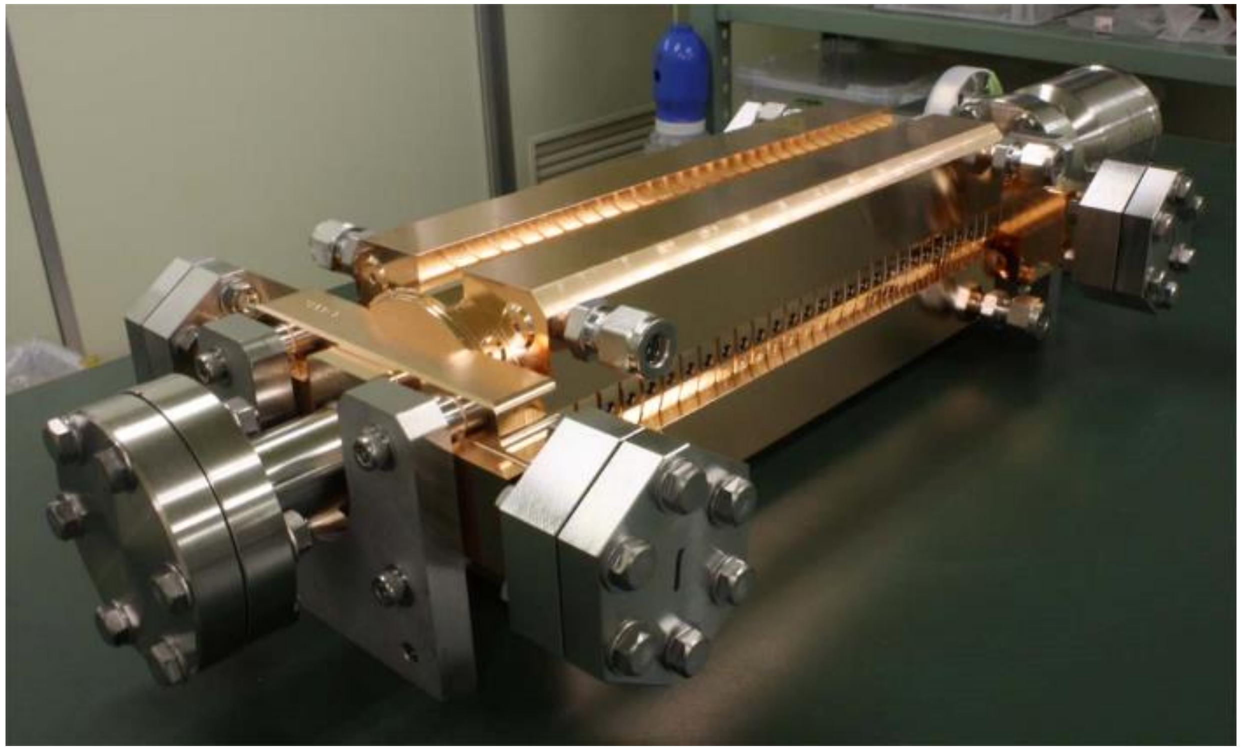


Figure 26: Conceptual Design of an RF unit for a klystron-based CLIC main linac. Two klystrons produce RF pulses, which are combined into a single double-power pulse. The pulse passes the correction cavities chain, which modifies the pulse shape, and is then split into two pulses of half the power in order to feed two SLED pulse compressors. Each SLED shortens the pulse by increasing the power; two compressors are used to limit the final power in each of them. Finally, the pulses are split and distributed into five accelerating structures.

CLIC Accelerating Structures

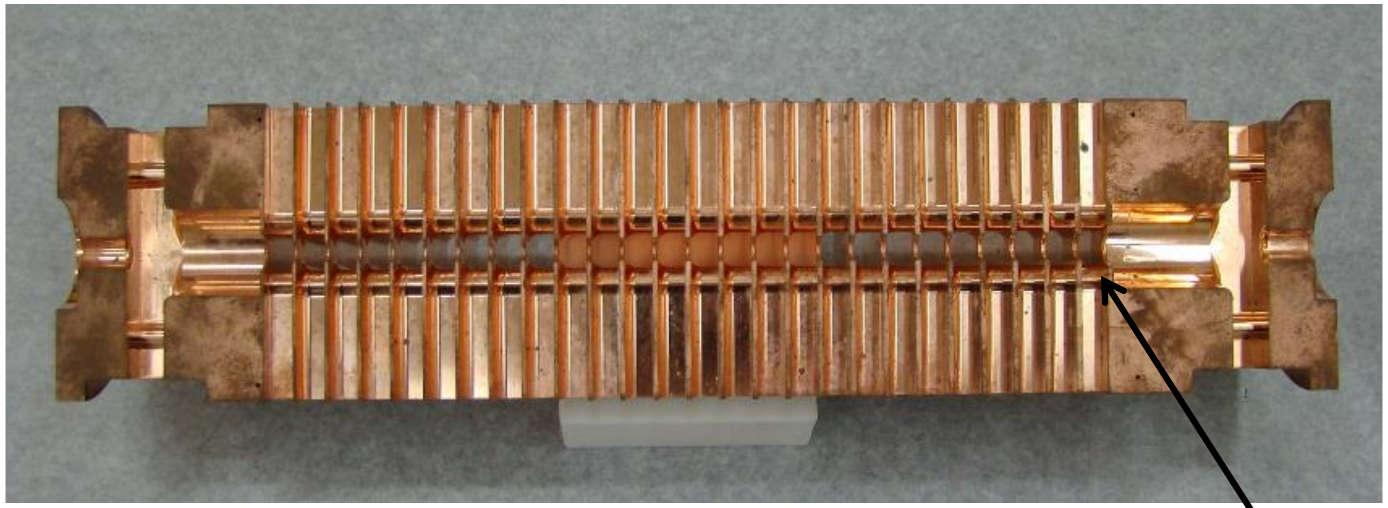
Outside

11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz



HOM damping waveguide

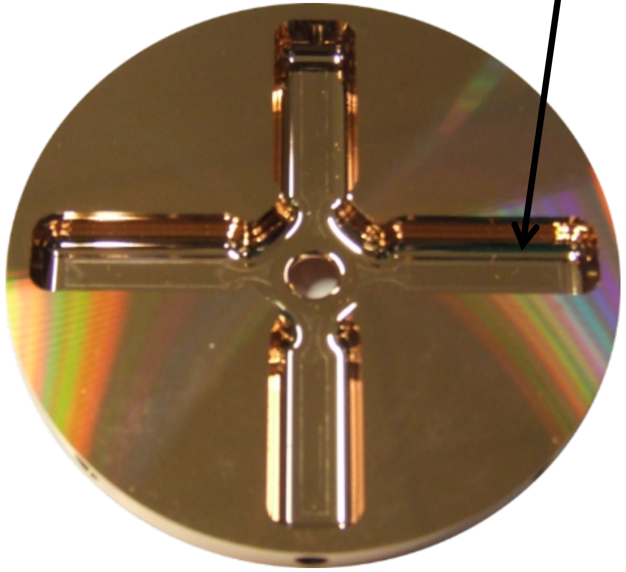
Inside



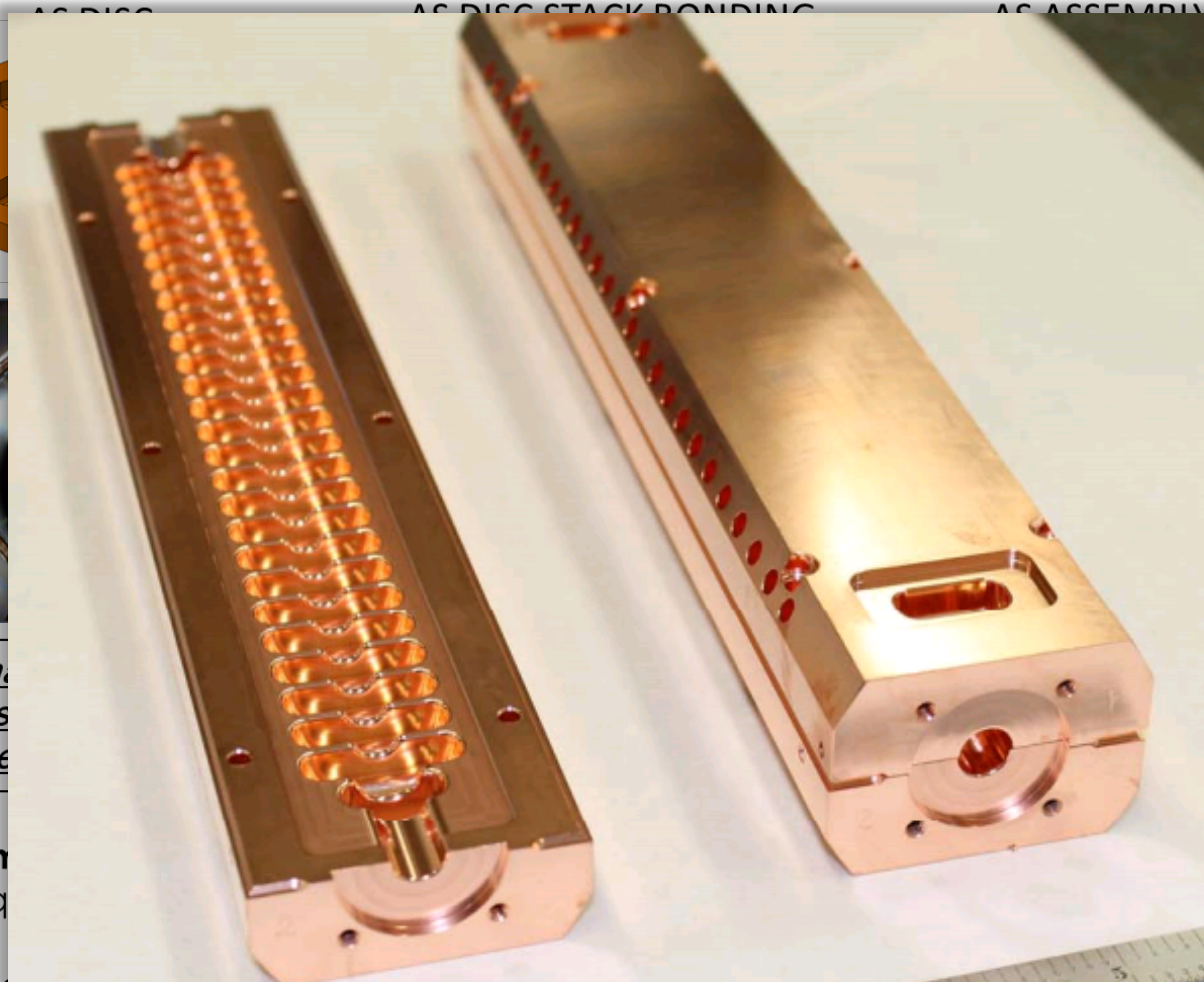
25 cm

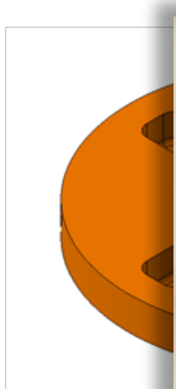
6 mm diameter beam aperture

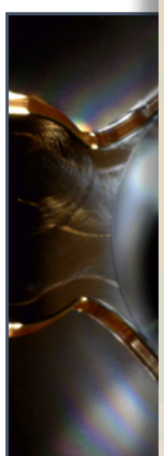
Micron–precision disk

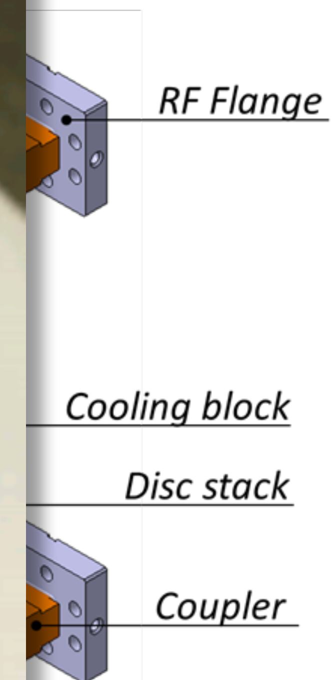


Assembly: towards industrialisation









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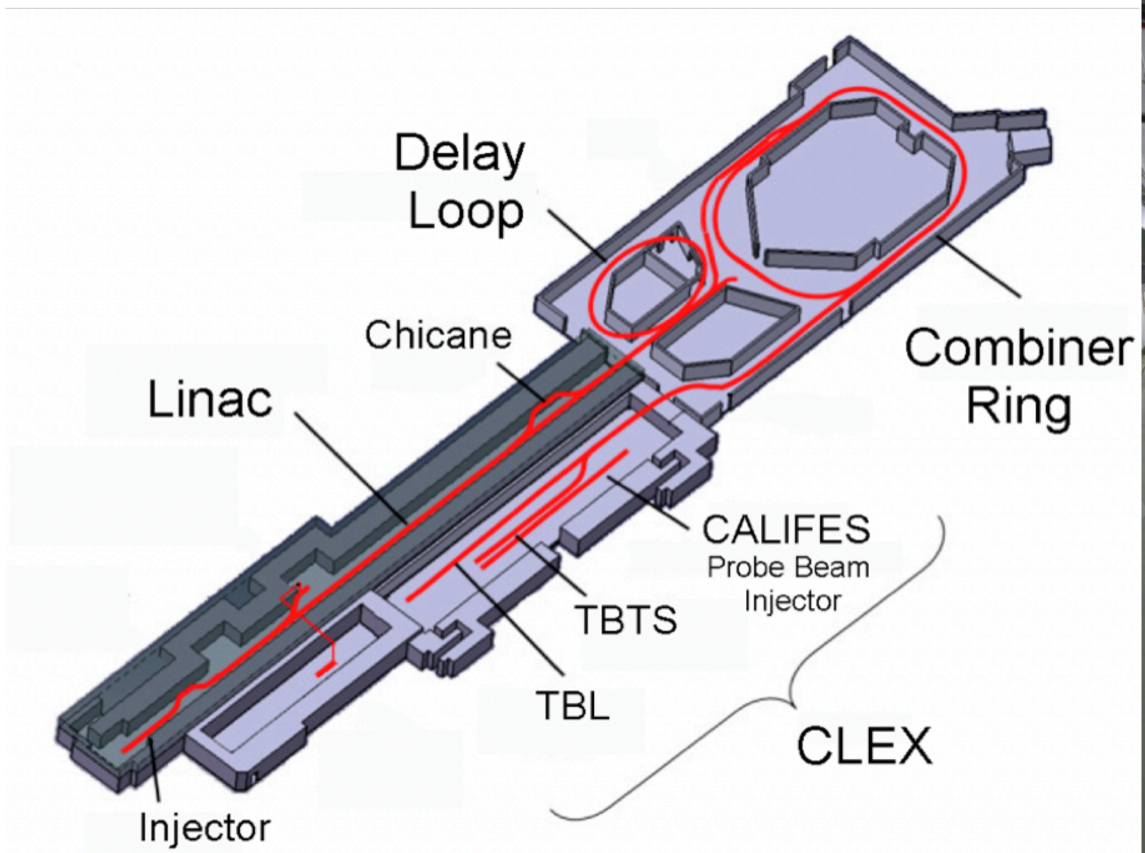
- Collaborators.

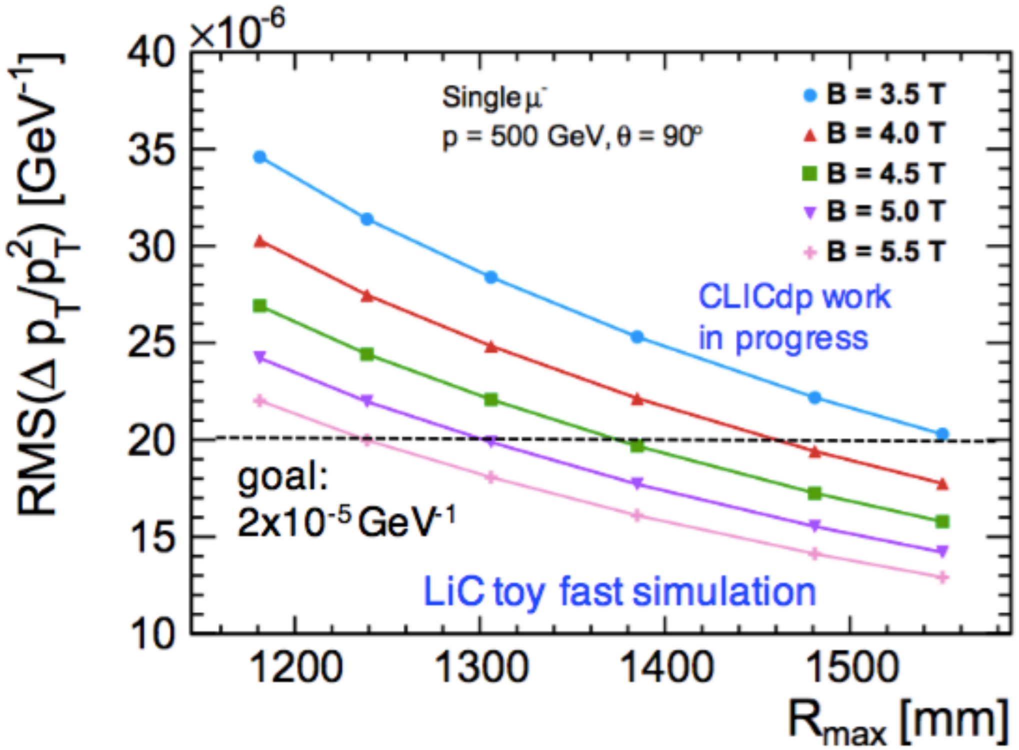
CLEAR

- CTF3 programme ended at the end of 2016
- Electron beam maintained as new facility: ‘CLEAR’:
  CERN Linear Electron Accelerator for Research
  - ➡ Beam test capability for CLIC (instrumentation, high gradient studies, components)
  - ➡ Connected to 12 GHz RF for high-gradient studies

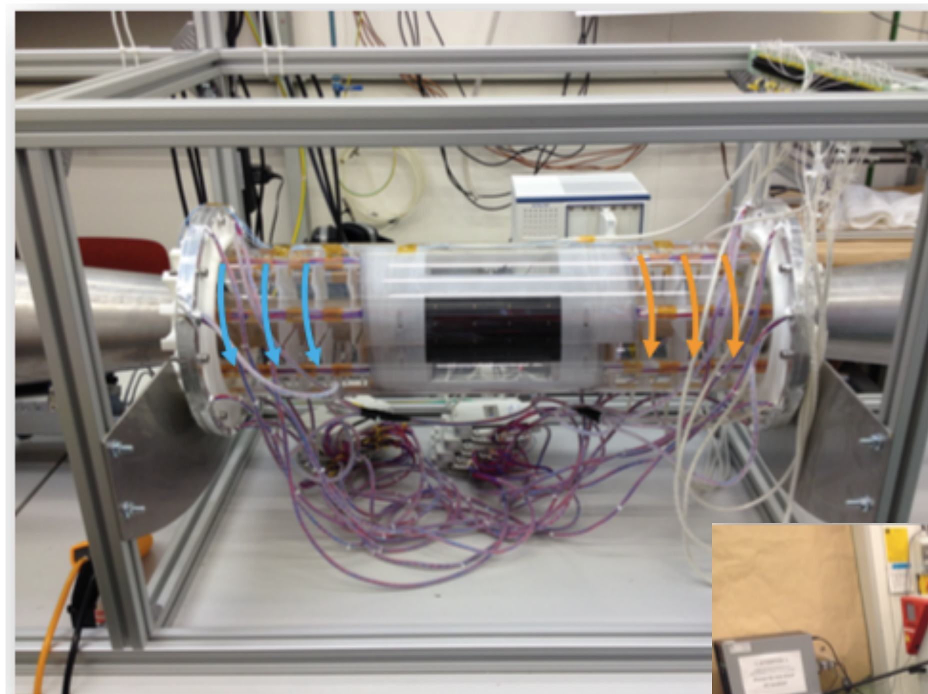


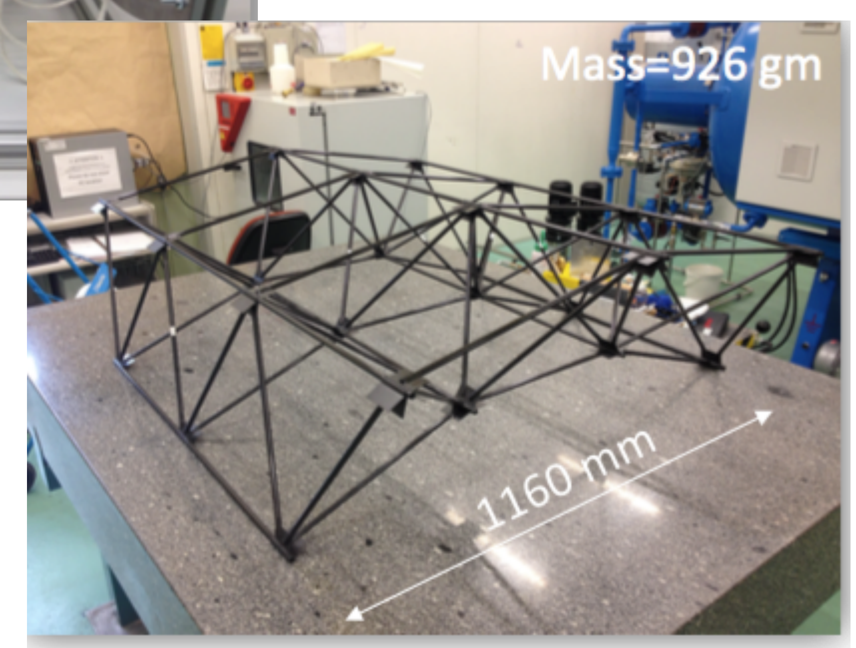
Detector Optimisation

Momentum resolution for different radii and B-fields

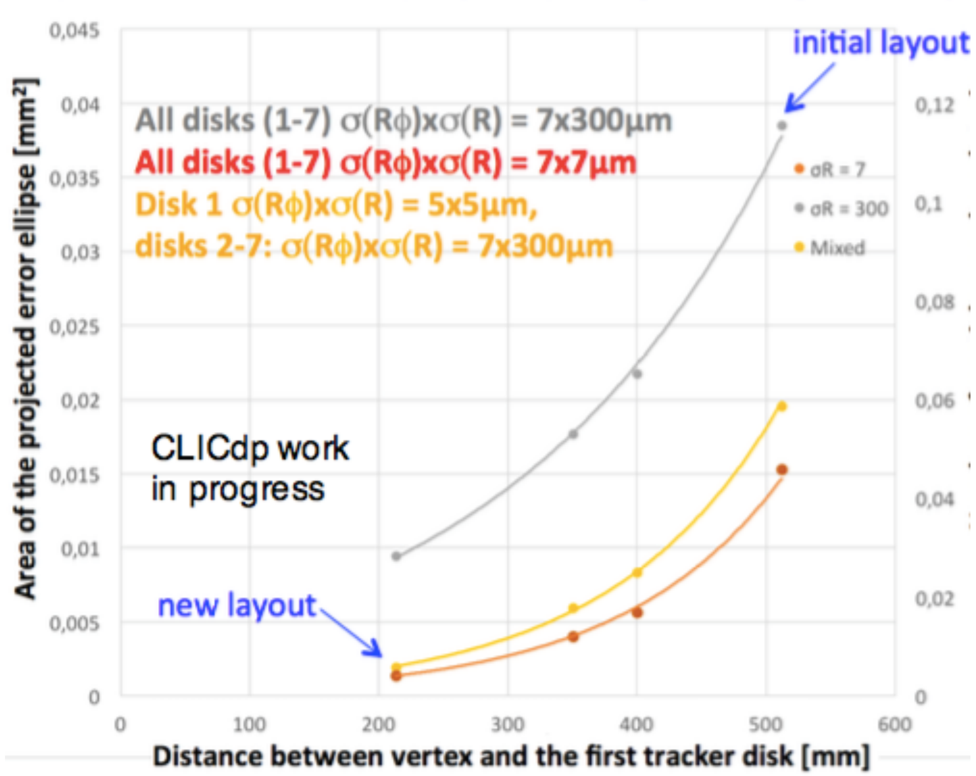


Optimizations of detector dimensions, spacings, granularities -> also informed by detector development, and full-scale cooling mockup and support structure development



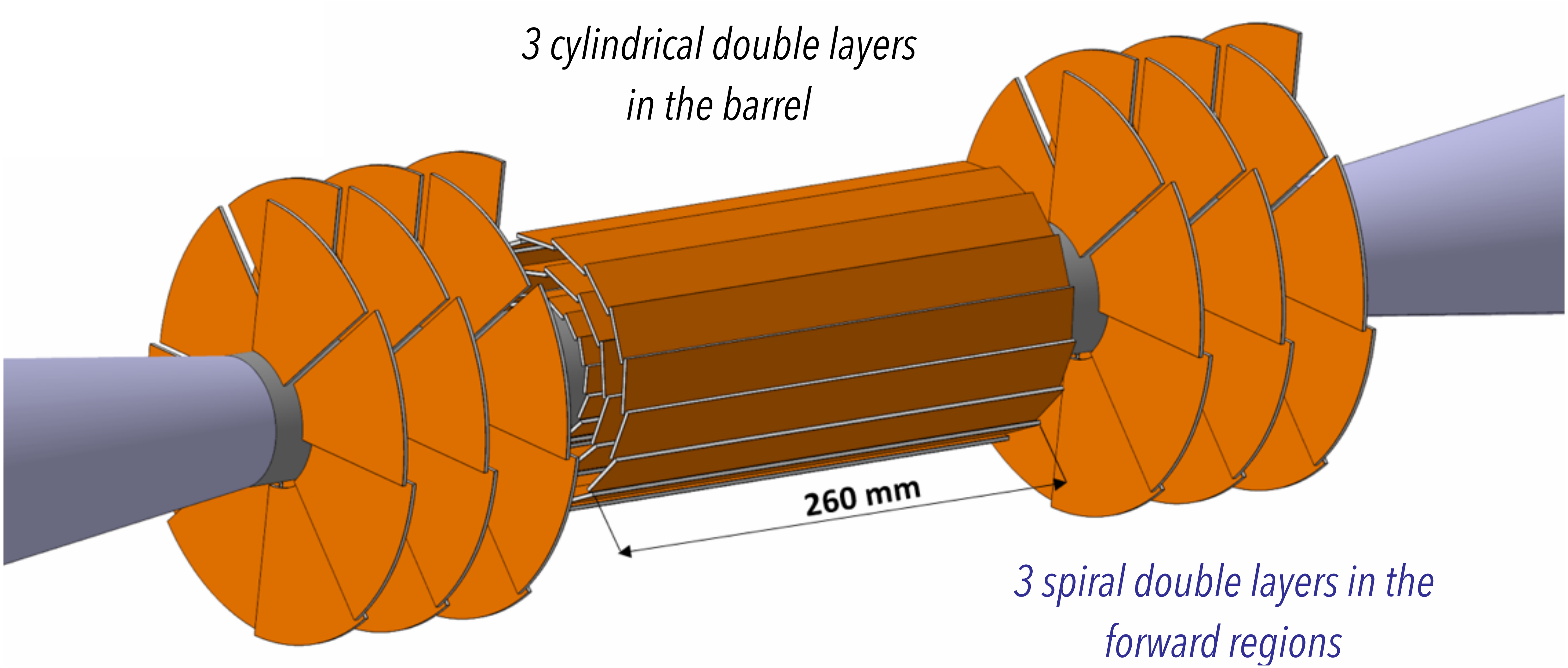


Optimization of end-cap layer spacing and r/o granularity



Vertexing and Tracking R&D

- Very thin materials/sensors: **0.2% X_0** material per layer
- ~2 billion pixels, each **25 μm** square
- 10 ns time slices
- CLICpix sensors and readout under development

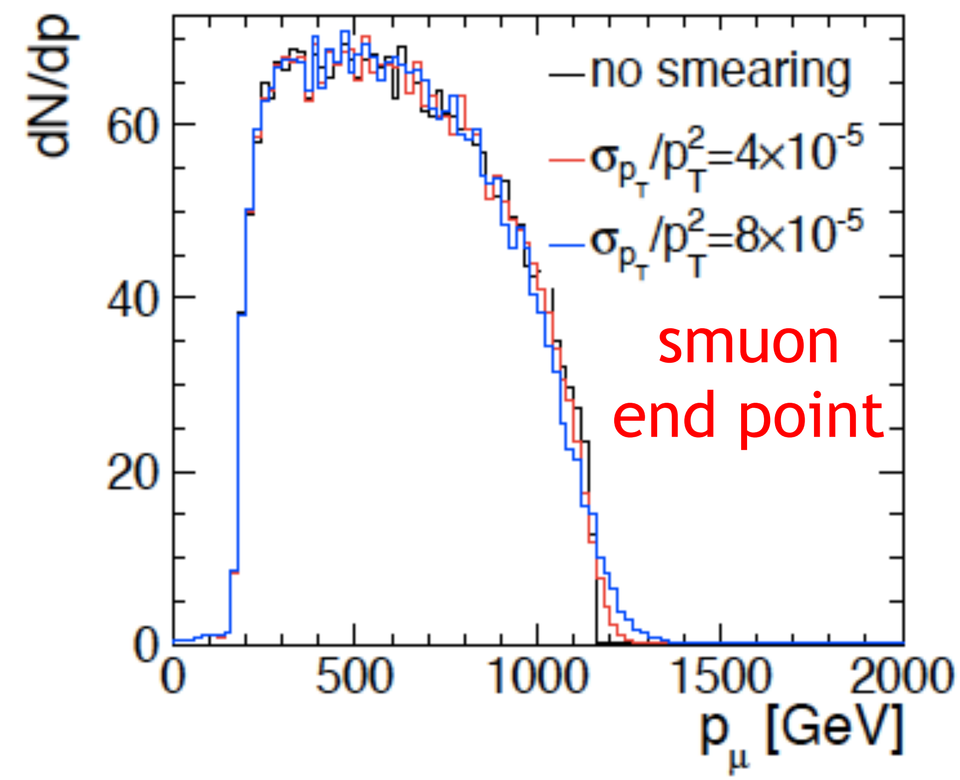


CLIC detector requirements (from physics)

★ **momentum resolution:**

e.g, $g_{H\mu\mu}$, Smuon endpoint

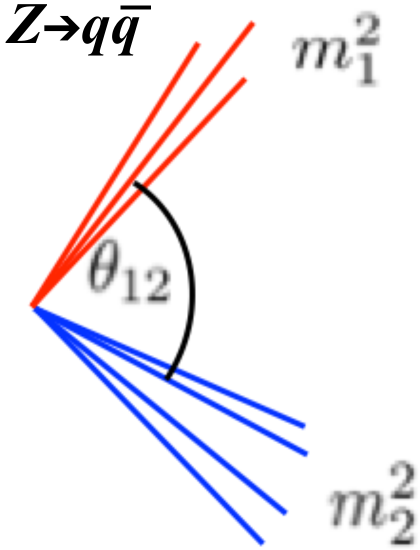
$$\boxed{\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}}$$



★ **jet energy resolution:**

e.g, ***W/Z/H*** di-jet mass separation, ***ZH*** with $Z\to q\bar{q}$

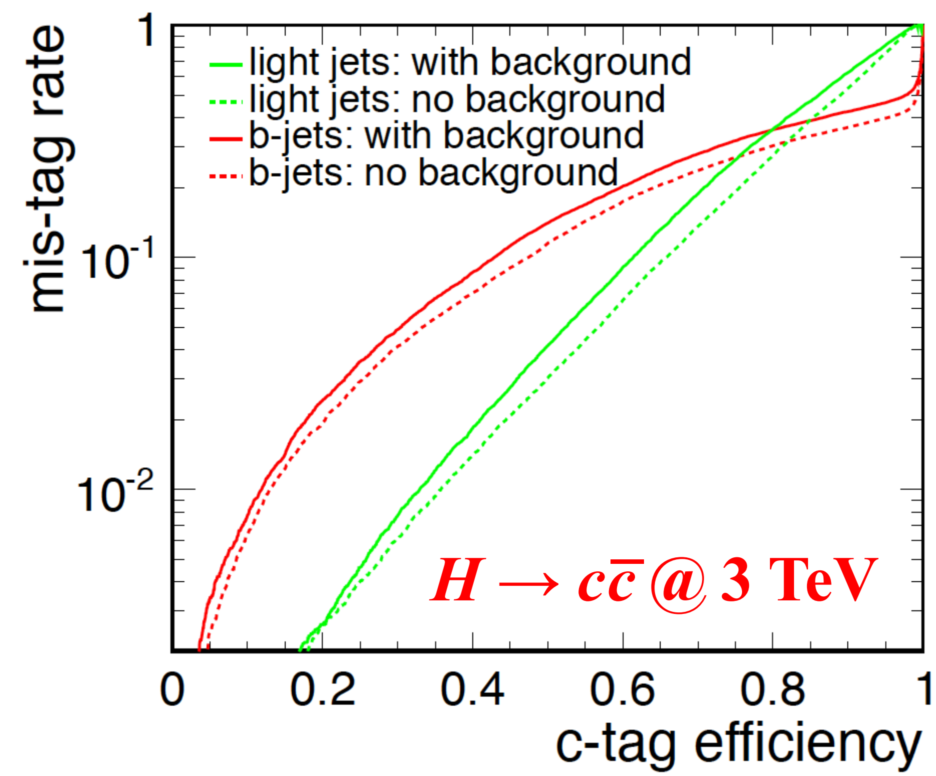
$$\boxed{\frac{\sigma_E}{E} \sim 3.5-5\ \%}$$ (for high-E jets, light quarks)



★ **impact parameter resolution:**

e.g. ***c/b***-tagging, Higgs BR

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



★ **angular coverage, very forward electron tagging**

Valencia Jet Clustering Algorithm

- Combines the good features of lepton collider algorithms:
  - ➡Durham-like distance criterion
  - ➡Background robustness of the long. inv. k_T algorithm

$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

$$d_{iB} = E^{2\beta} sin^{2\gamma}\theta_{iB}$$

- β: clustering order
- γ: evolution of jet area with polar angle

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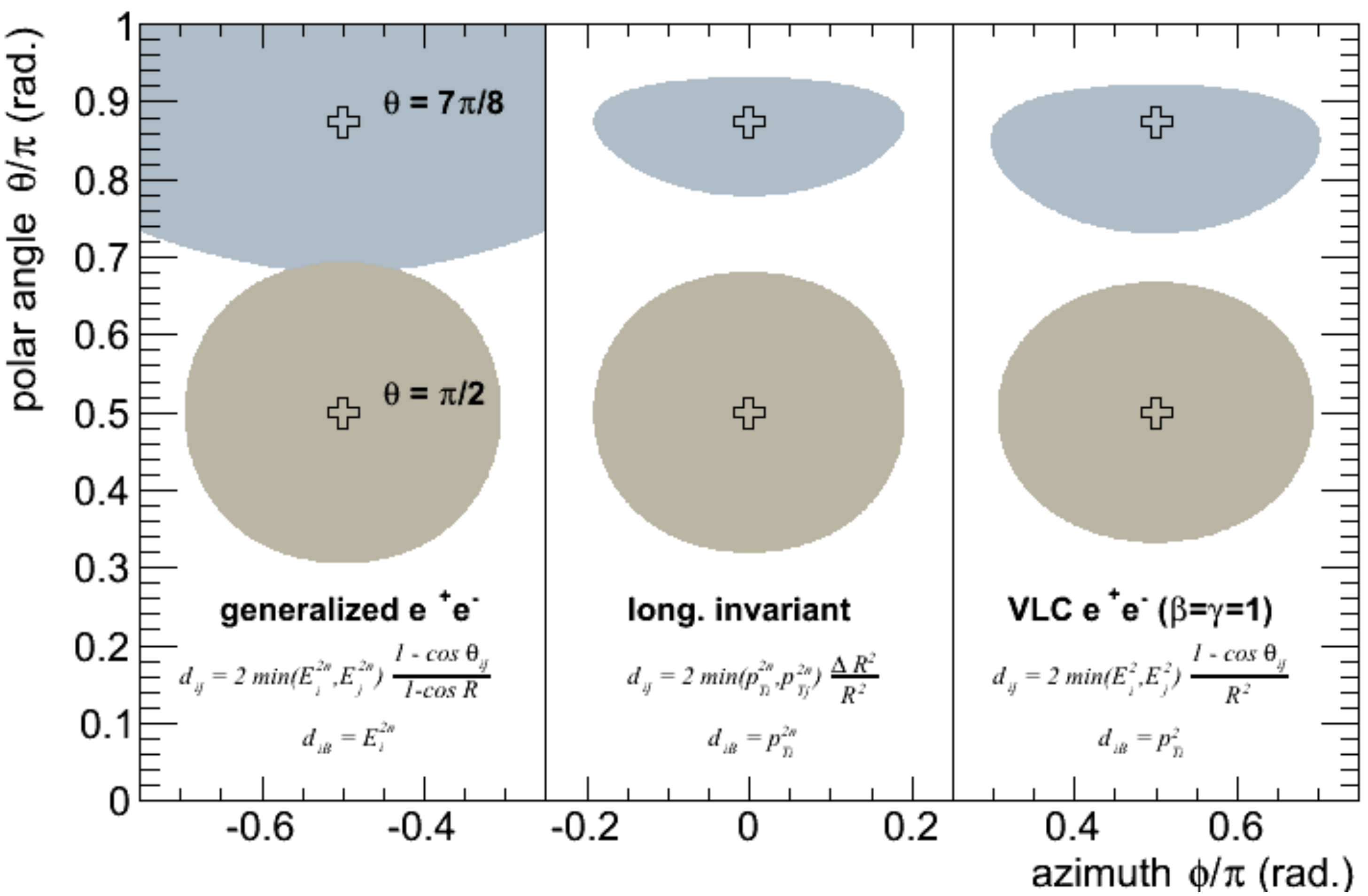
Footprint of jets reconstructed with R = 0.5



Top Reconstruction at high $\sqrt{s}$

- Under active study!
- $t \to Wb \to 3$ **jets**. Due to large boost, three jets will be close together
- Reconstruct one large jet, and look for *subjets*.
- e.g. using Valencia clustering algorithm developed for high-energy e^+e^- with R**=1.5**