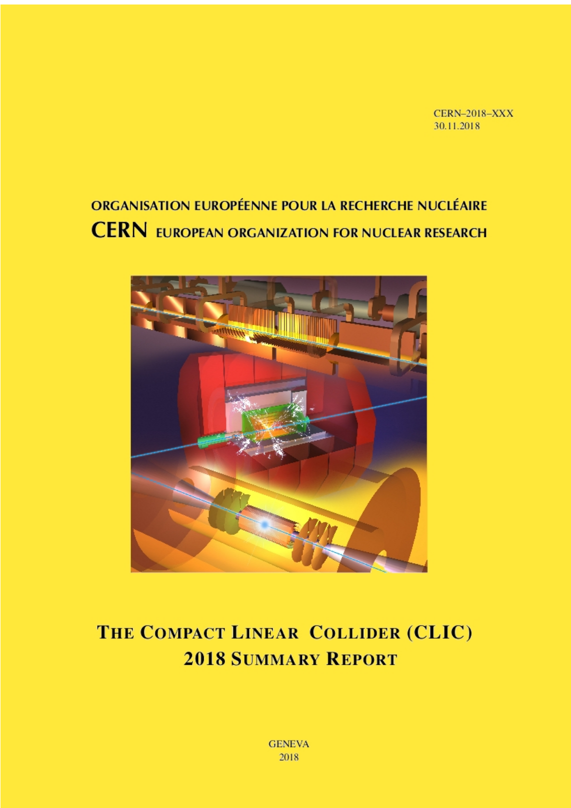
CLIC Detector & Physics


CERN–2018–XXX
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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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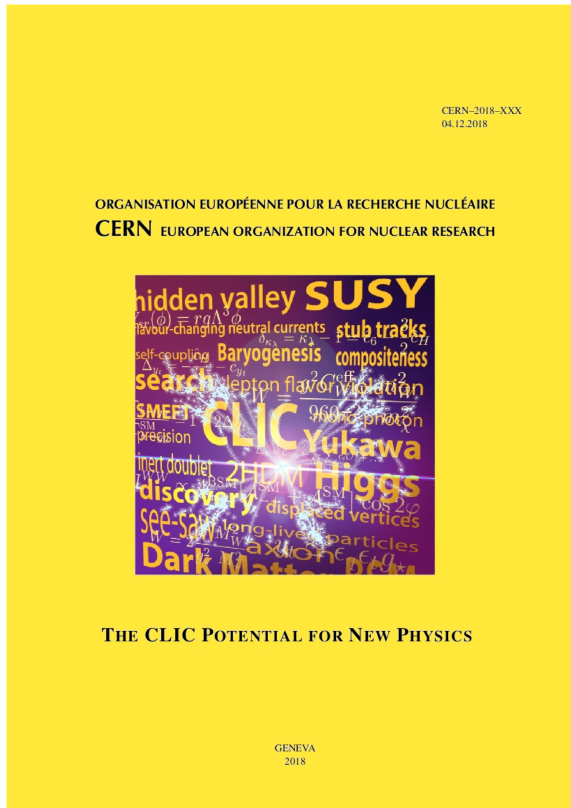
THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

GENEVA
2018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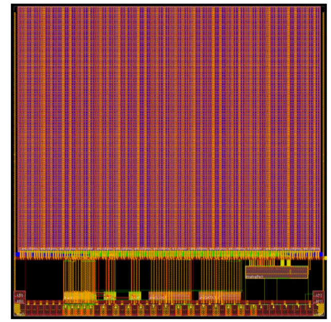
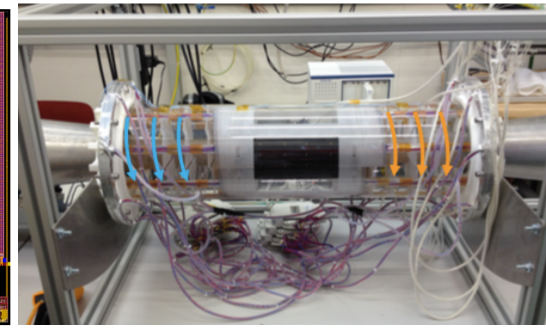
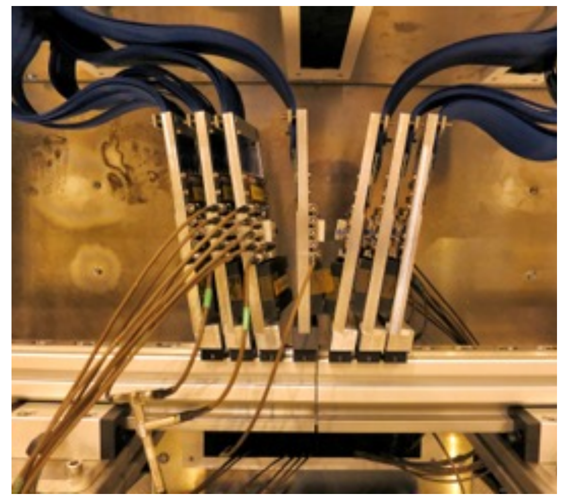
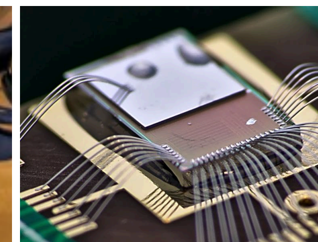
THE CLIC POTENTIAL FOR NEW PHYSICS

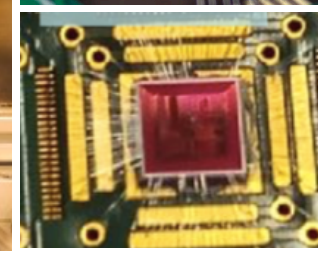
GENEVA
2018











CLIC Project Meeting, 6 December 2018

Aidan Robson, University of Glasgow & CERN
on behalf of the CLICdp Collaboration

CLIC 2018 Summary Report

CERN–2018–XXX
30.11.2018

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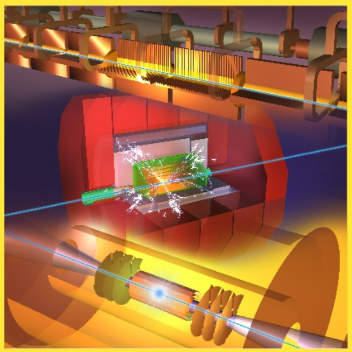


THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

GENEVA
2018

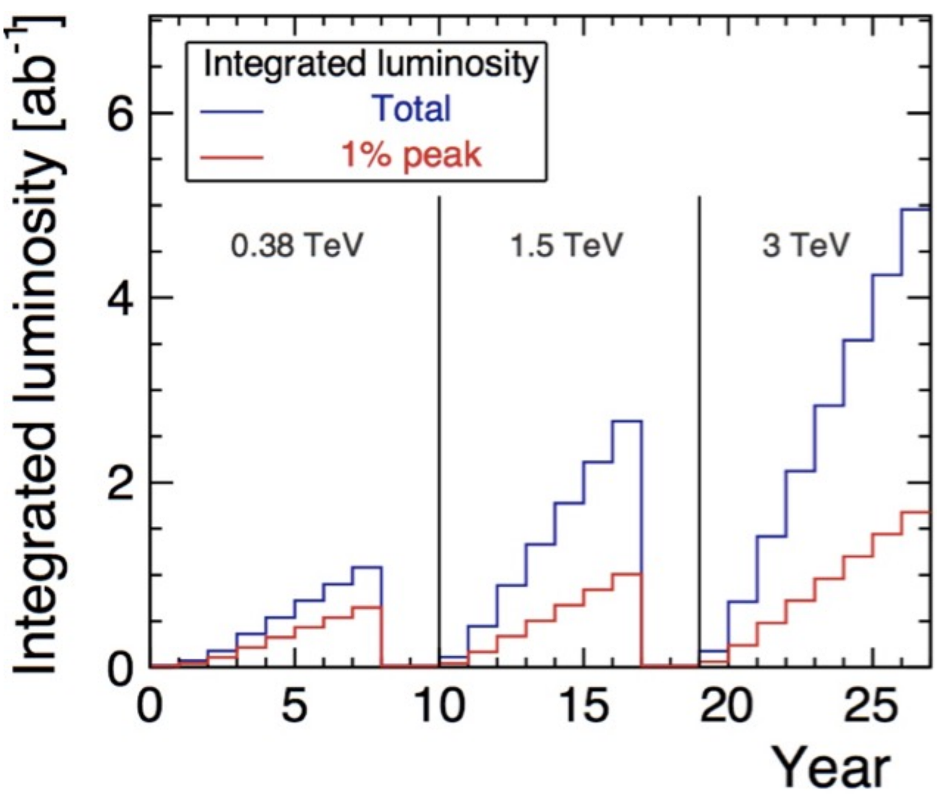
Submitted 30/11/18

Congratulations & thanks to all involved!

Contents

Updated CLIC Staging

New!



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

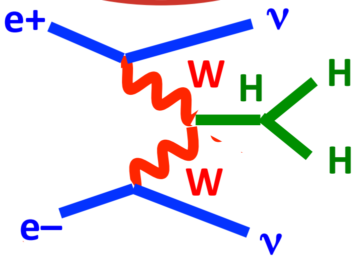
$\gamma\gamma$ collider using laser scattering also possible
Upgrades using novel accelerator techniques also possible

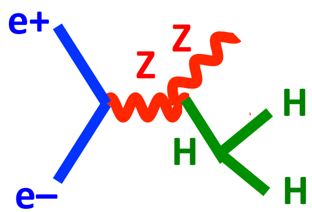
Staging and live-time assumptions following guidelines consistent with other future projects:
Machine Parameters and Projected Luminosity Performance of Proposed Future Colliders at CERN
arXiv:1810.13022, Bordry, Schulte, Stapnes et al.

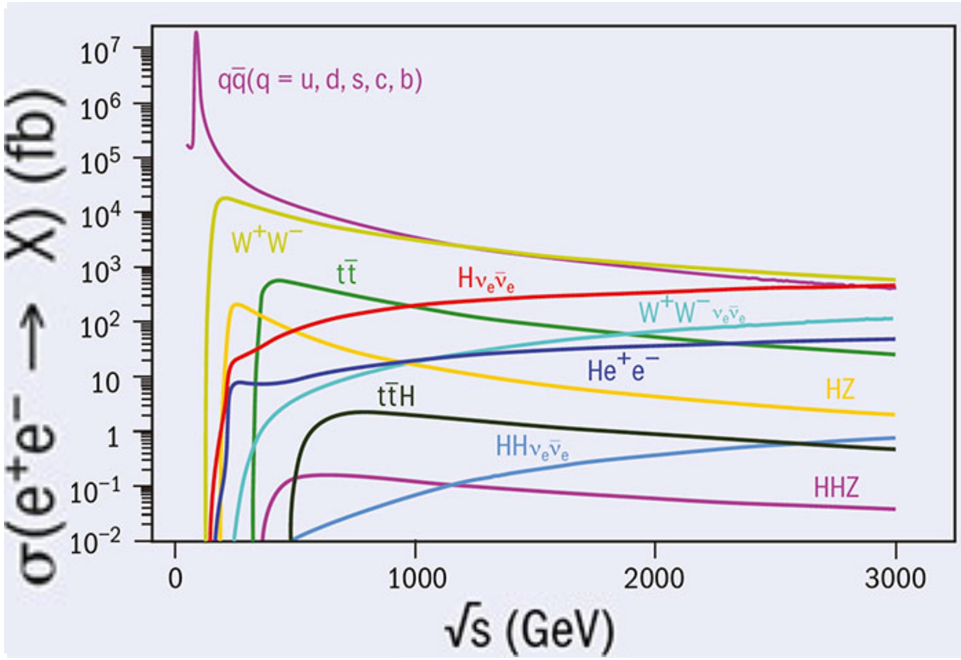
Updated CLIC luminosity staging baseline and Higgs coupling prospects
arXiv:1812.01644, Robson and Roloff

CLIC Physics

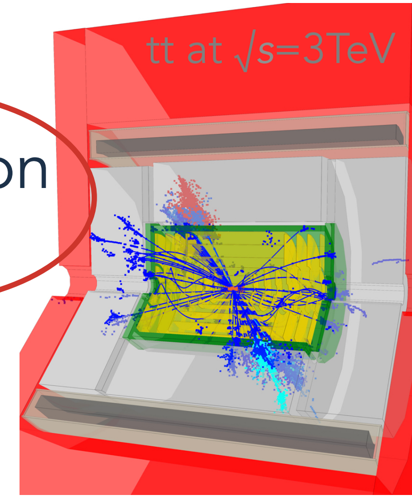
- Precision Higgs







- Precision top



- Beyond Standard Model

Issues not addressed by SM:
- origin of the weak scale interactions
- dark matter
- origin of matter/antimatter asymmetry

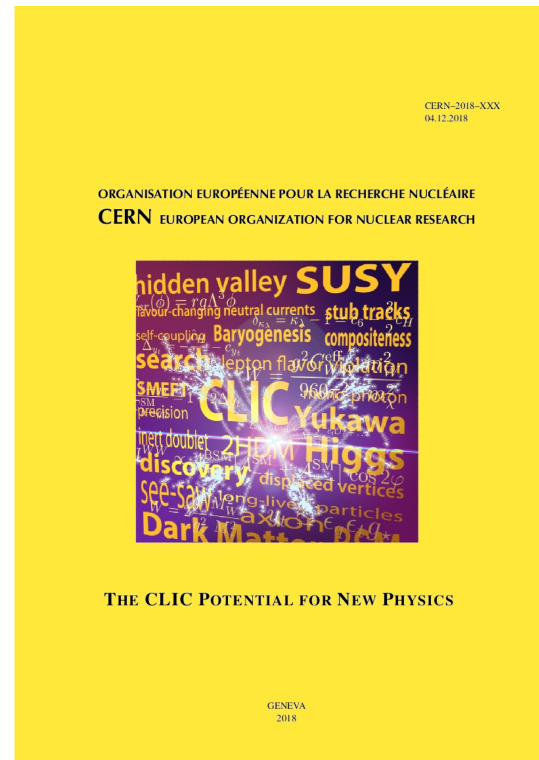
Many new studies focused on discovery prospects at CLIC; exploring the physics landscape as broadly as possible

New!

Yellow Report submitted 4/12/18

arXiv: 1812.02093

Congratulations & thanks to all involved!



Higgs coupling sensitivity

Full GEANT-based simulation studies including beam backgrounds of many channels at all 3 stages –> global fit including correlations;

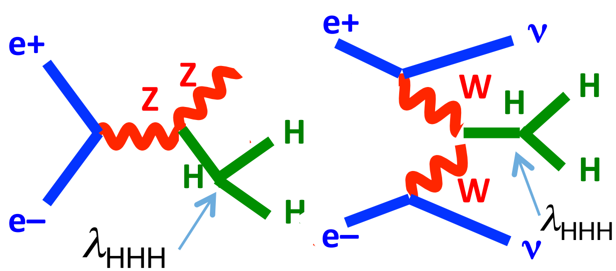
$\sigma(ZH) \sim g^2_{HZZ}$
$\sigma(ZH) \times BR(H \to VV/ff) \sim g^2_{HZZ} g^2_{HVV/Hff} / \Gamma_H$
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to VV/ff) \sim g^2_{HWW} g^2_{HVV/Hff} / \Gamma_H$

Precision $\lesssim$1% for most couplings

c/b/W/Z/g couplings significantly more precise than HL-LHC even after 380GeV stage

Γ_H is extracted with 4.7 – 2.5% precision

Higgs self-coupling requires high energy



complementary at 1.5TeV

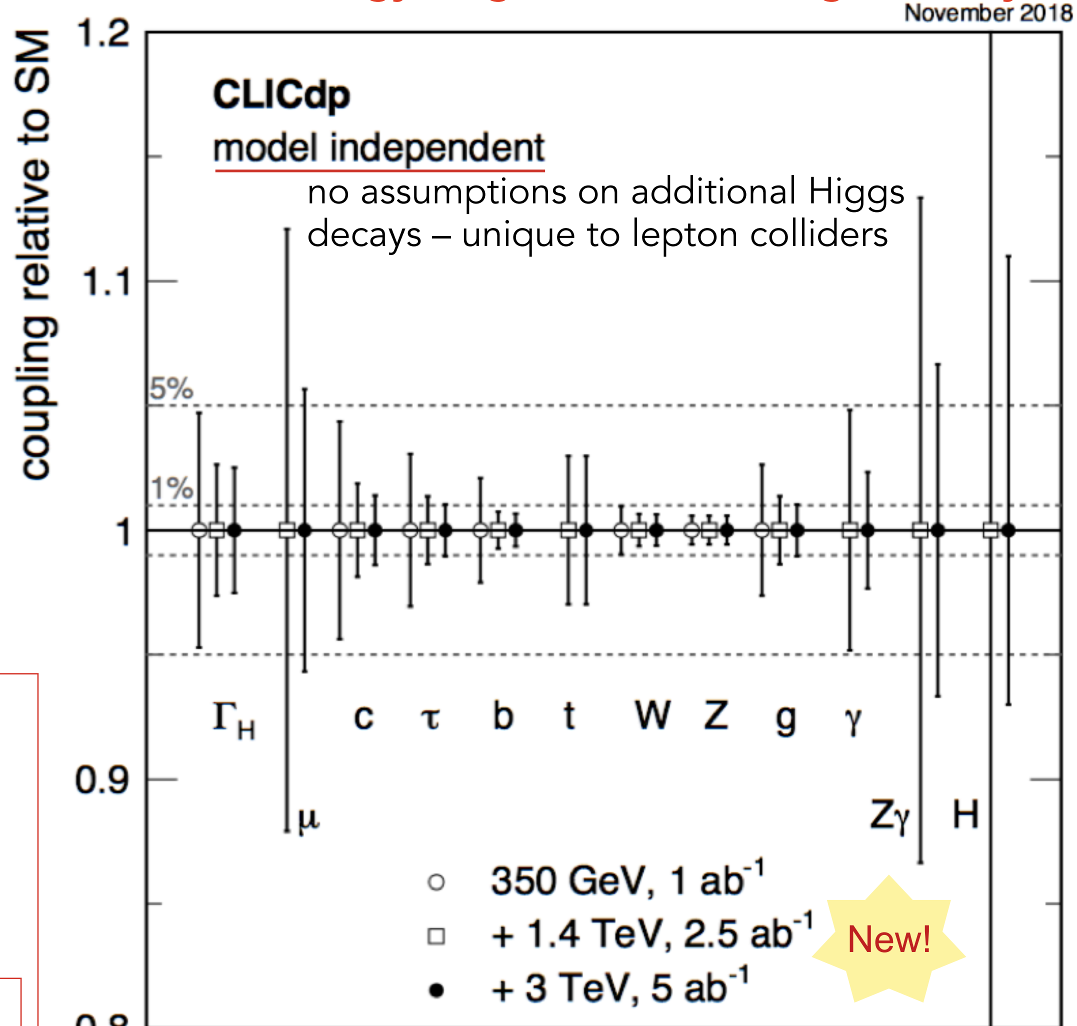
dominates at higher $\sqrt{s}$

Using *M*(HH) differential distribution:

$\Delta\lambda/\lambda = {}^{+11\%}_{-7\%}$

New!

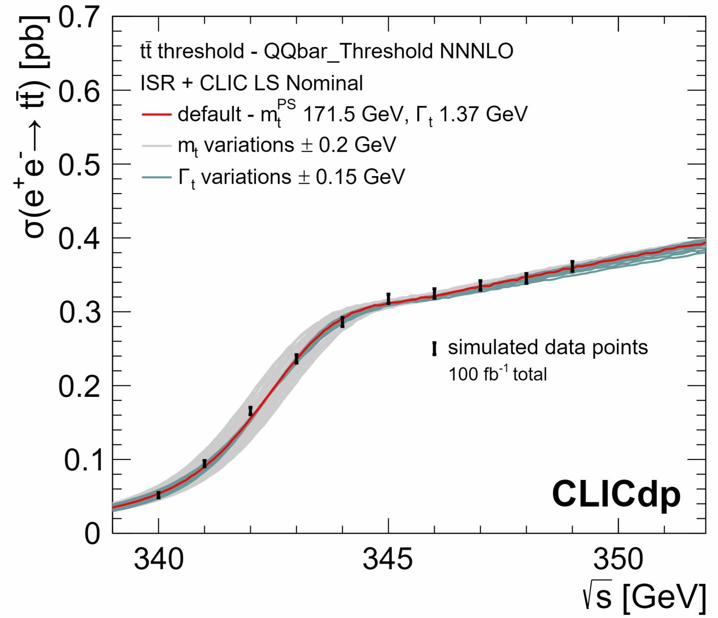
Each energy stage contributes significantly

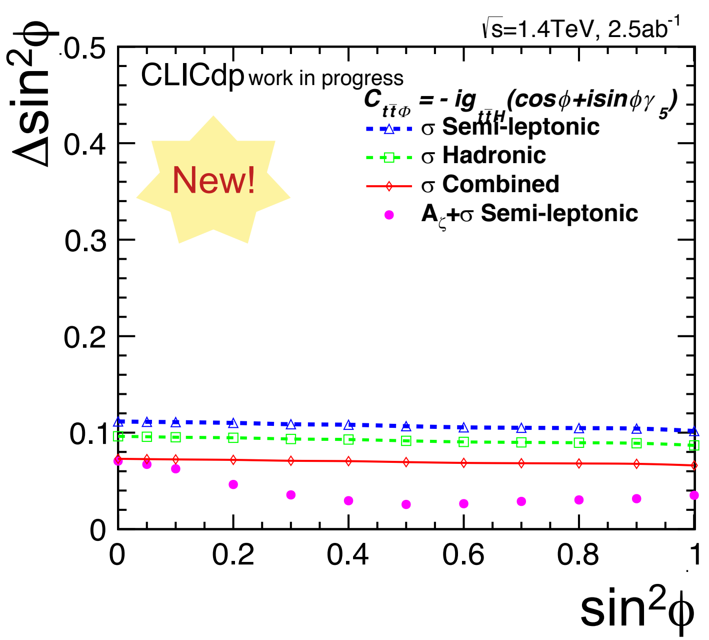


Based on Eur. Phys. J. C 77 475 (2017) updated to new luminosity scenario

Updated CLIC luminosity staging baseline and Higgs coupling prospects arXiv:1812.01644

Top





- Intending threshold scan around 350 GeV (10 points, ~1 year) as well as main initial-stage baseline $\sqrt{s}$=380GeV

- sensitive to top mass, width and couplings

- observe 1S 'bound state', Δm_t ~ 50 MeV

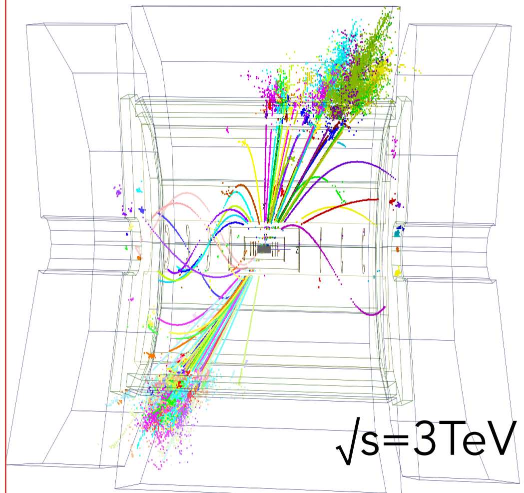
- FCNC decays
- CP properties of ttH
- cross-section and A_{FB}
  -> resolved, semi-resolved, boosted

- couplings to Z and γ
- EFT interpretation

–> initial and high-energy stages are very complementary

Polarisation provides new observables

First study of boosted top production in e^+e^-



e^+e^- -> $t\bar{t}$ -> $q\bar{q}q\bar{q}b\bar{b}$

Hadronic decays of high-energy top quarks do not lead to 3 separated jets
–> identify substructure

arXiv 1807.02441: Top-quark physics at the CLIC electron–positron linear collider

in journal review

Standard Model Effective Field Theory

Standard Model

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Scale of new decoupled physics

Dimension-6 operators

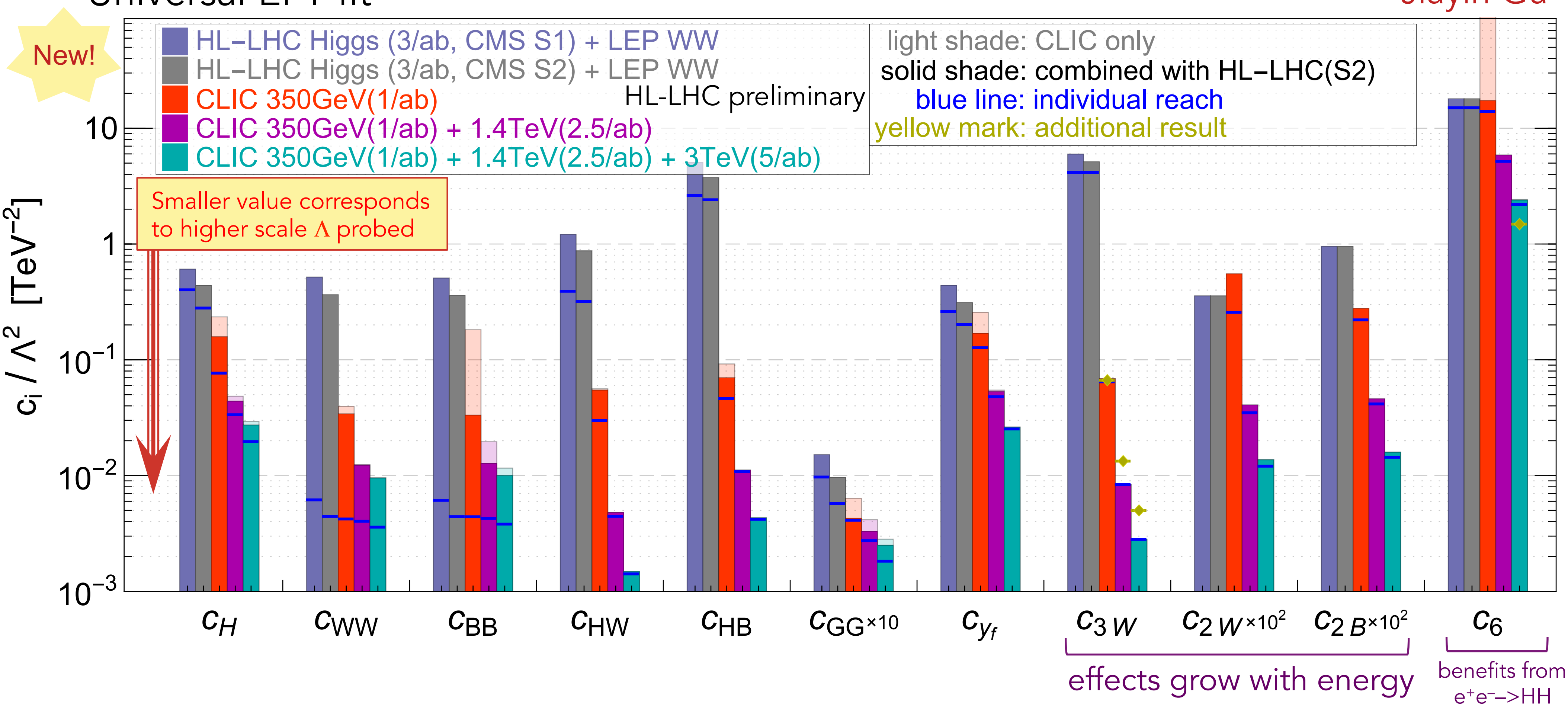
Includes CLIC Higgs, top, WW, and $e^+e^- \rightarrow f\bar{f}$ measurements

Strongly benefits from high-energy running

–> appears in 'The CLIC Potential for New Physics' Yellow Report

Jiayin Gu

Universal EFT fit



Standard Model

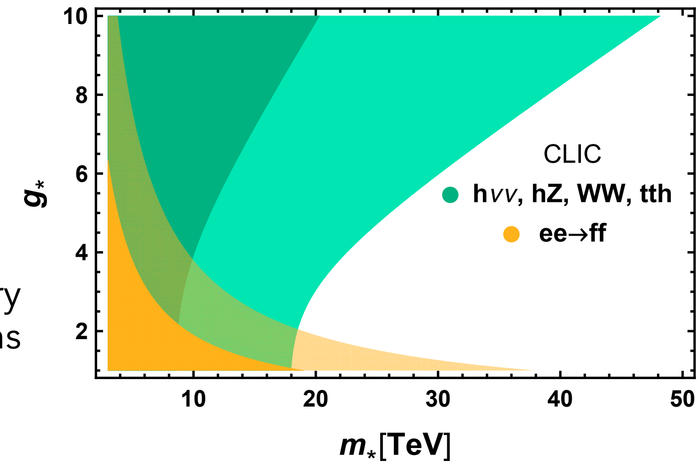
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Scale of new decoupled physics

Dimension-6 operators

Can interpret in concrete BSM scenarios
e.g. Higgs & top-quark compositeness

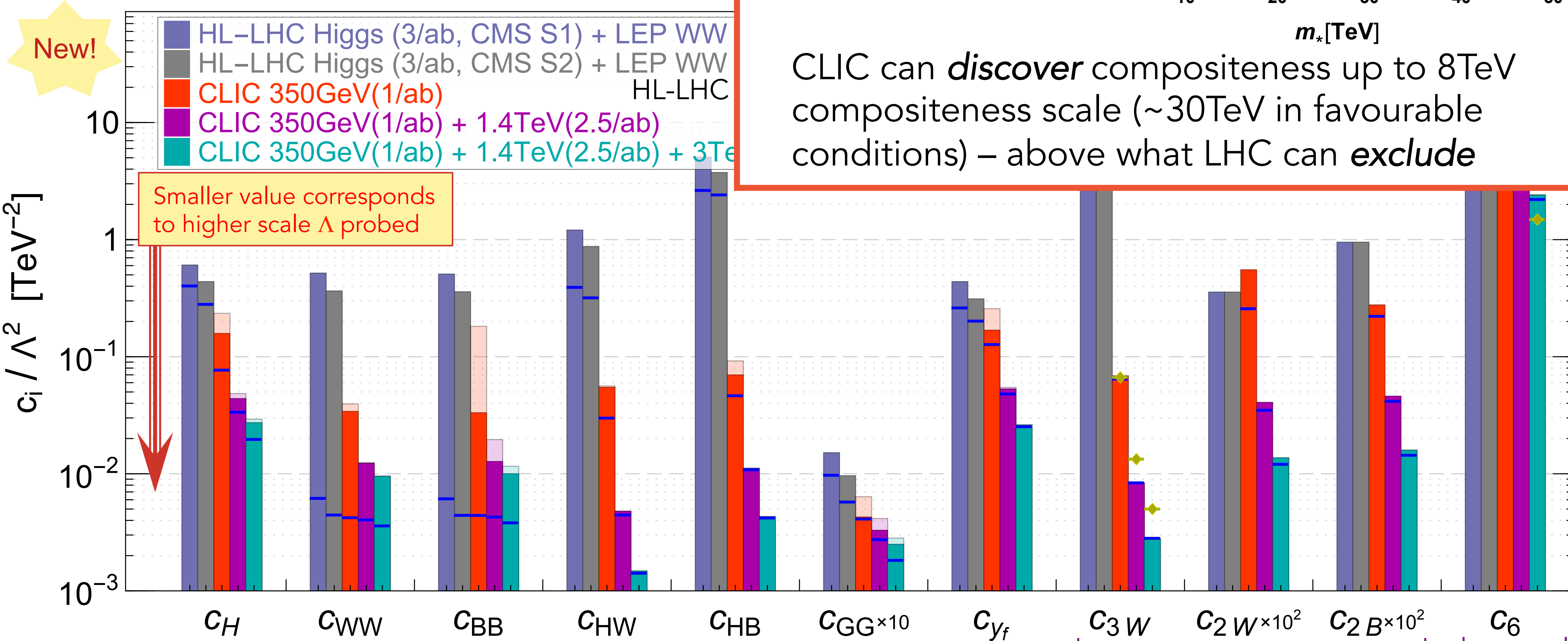
5-σ discovery regions



CLIC can ***discover*** compositeness up to 8TeV compositeness scale (~30TeV in favourable conditions) – above what LHC can ***exclude***

Universal EFT fit

New!



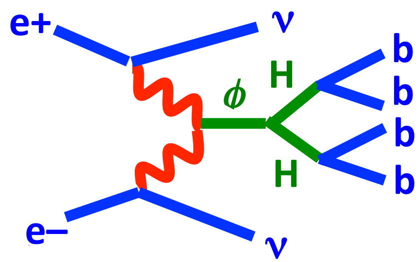
effects grow with energy

benefits from $e^+e^- \to HH$

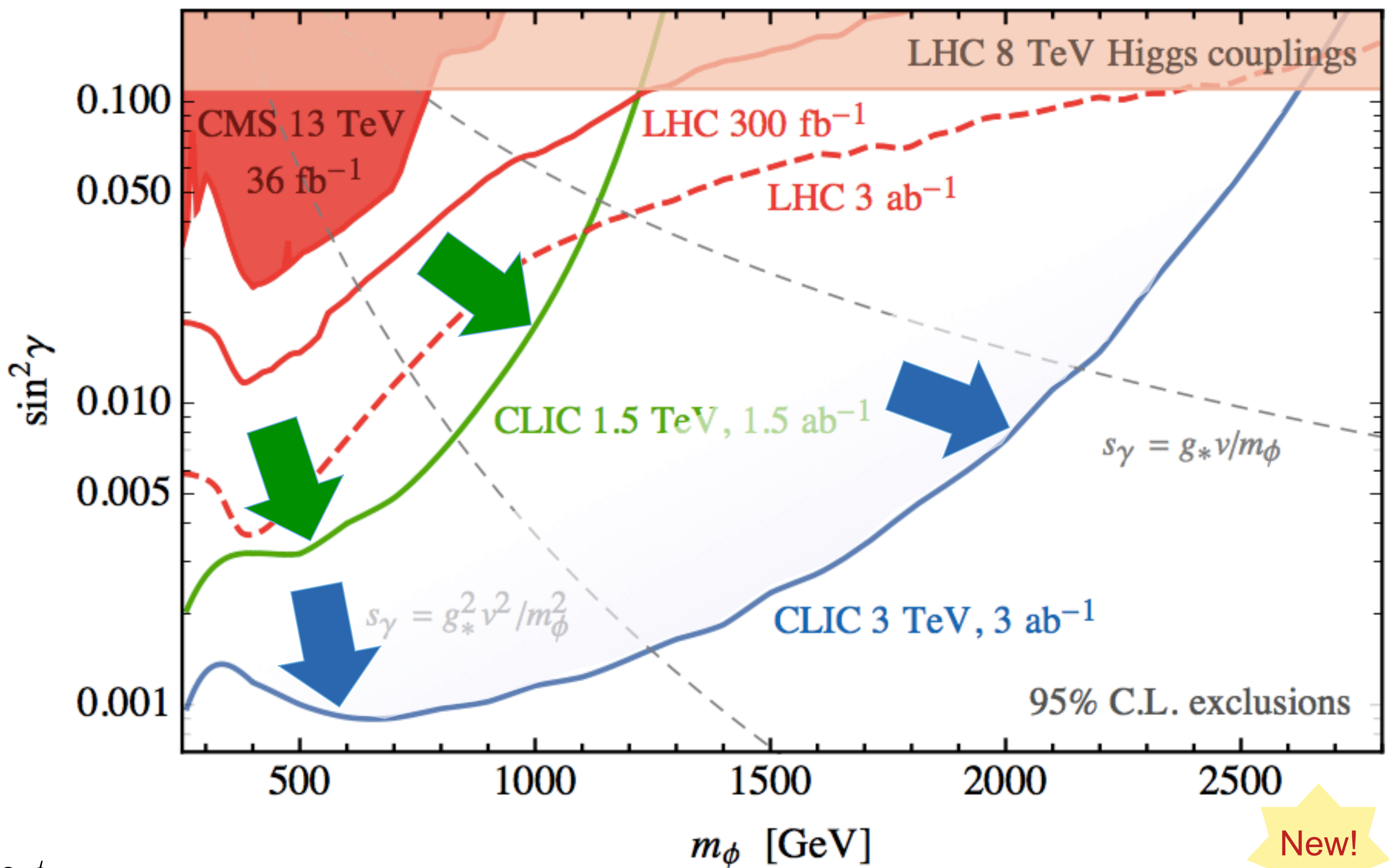
Higgs + heavy singlet

Direct search for real scalar singlet ϕ: new physics weakly coupled to SM

arXiv: 1807.04743 – Buttazzo, Redigolo, Sala, Tesi



(To be updated for new luminosities)



New!

$$h = h_0 \cos\gamma + S \sin\gamma$$

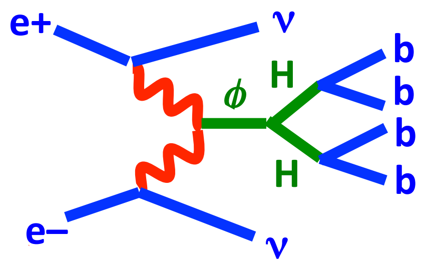
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

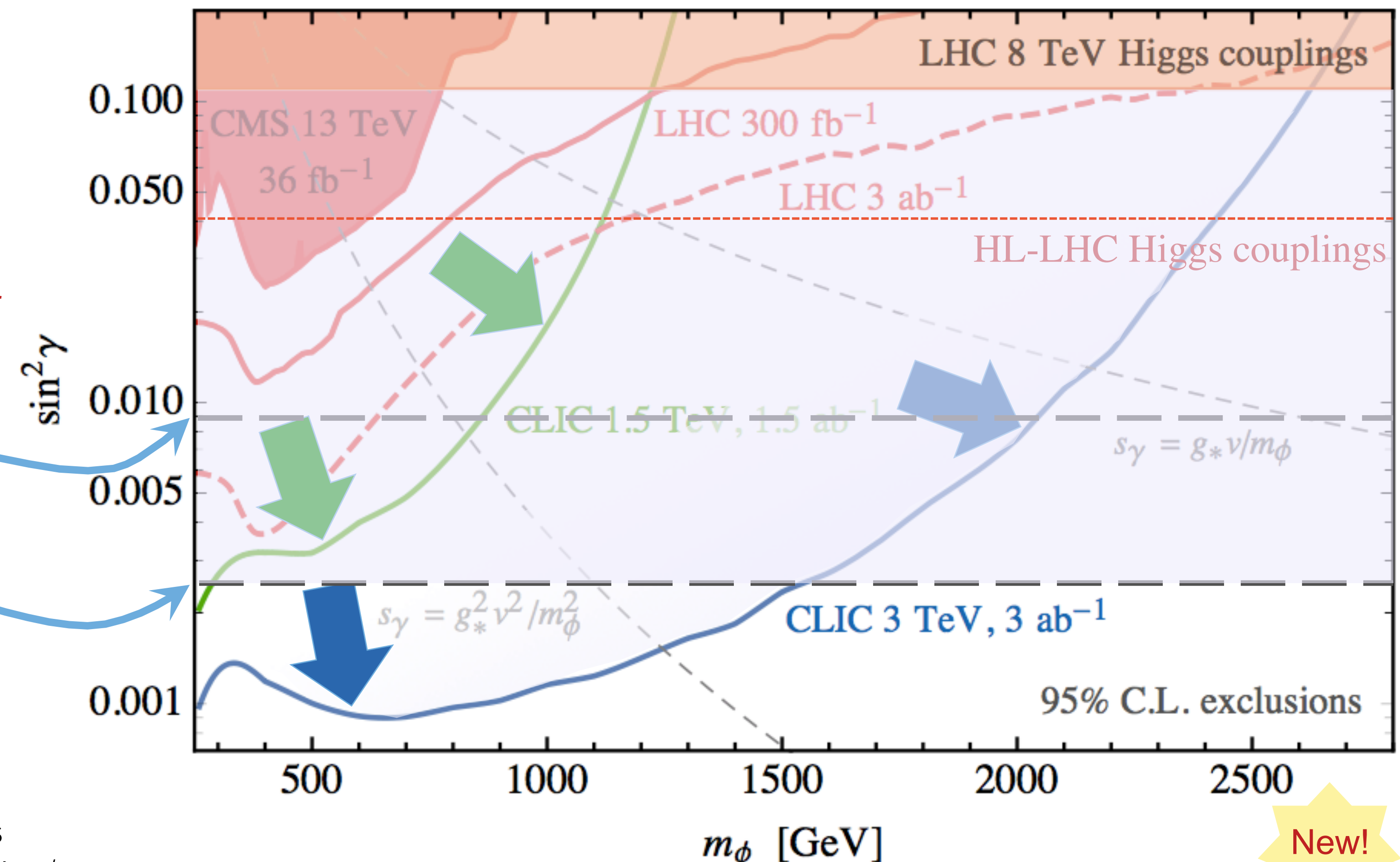
Higgs + heavy singlet

Direct search for real scalar singlet ϕ :
new physics weakly coupled to SM

arXiv: 1807.04743 – Buttazzo, Redigolo, Sala, Tesi



(To be updated for new luminosities)



Indirect search
very complimentary:
arXiv: 1608.07538 + Roloff

Higgs couplings give:

$\sin^2\gamma$<0.9% 95% CL (380GeV)

$\sin^2\gamma$<0.24% 95% CL (380GeV+1.5TeV+3TeV)

$$h = h_0 \cos\gamma + S \sin\gamma$$

$$\phi = S \cos\gamma - h_0 \sin\gamma$$

γ is mixing angle of SM-like Higgs (m_h=125GeV), and singlet-like state ϕ

New!

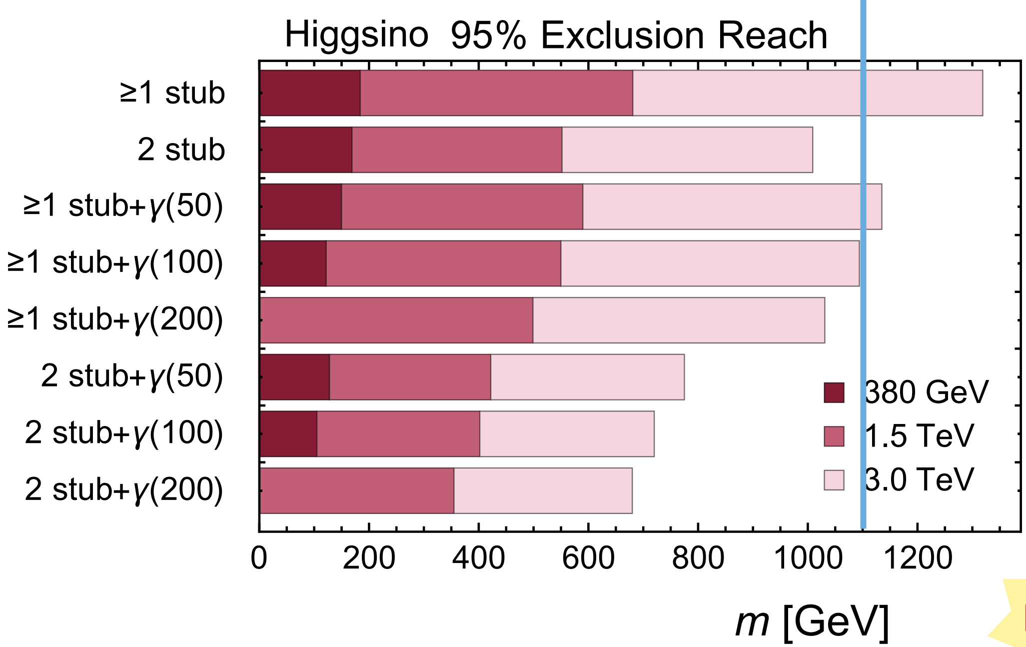
Dark matter

Higgsino:

WIMP dark matter candidate, connected to weak scale naturalness, and gauge coupling unification

When other superpartners decoupled:
$\chi^{\pm}$ slightly heavier than χ^0
$\chi^{\pm} \rightarrow \pi^{\pm}\chi^0$ **leaving 'charged stub' in detector**

reach Higgsino mass of 1.1TeV, required for DM relic mass density – even with some level of background



diverse experimentally

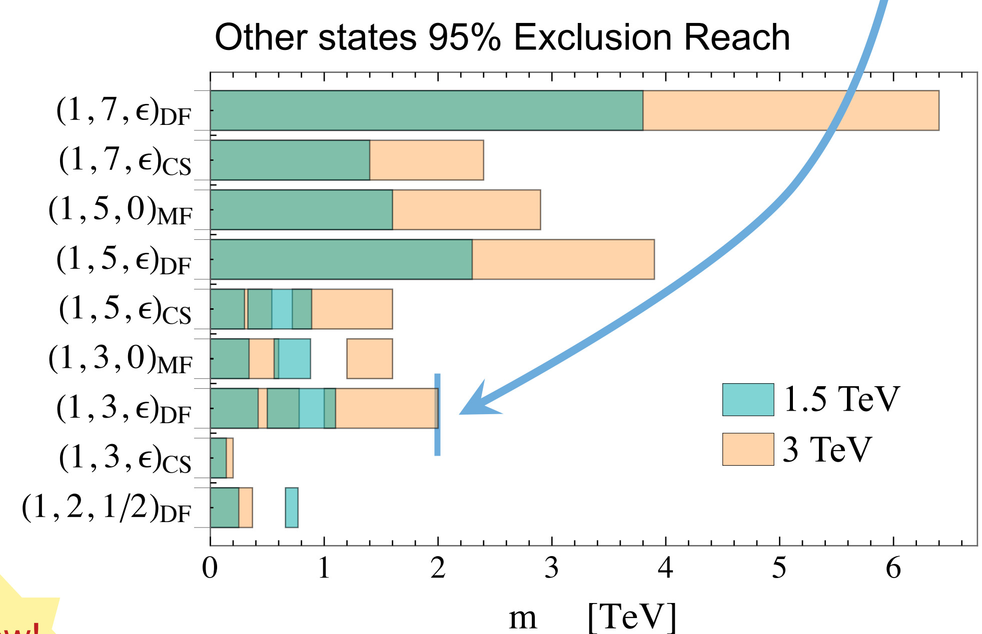
New!

Electroweak precision tests:

arXiv: 1810.10993 - Di Luzio, Gröber, Panico

Precision measurements of $d\sigma/d(\cos\theta)$ in $e^+e^- \rightarrow f\bar{f}$ sensitive to new states –> exclude mass ranges

e.g. for *n*=3 Dirac fermion, *m*=2TeV saturates DM relic mass density: can be excluded by CLIC



DF=Dirac Fermion, MF=Majorana Fermion, CS=Complex Scalar
SU(3)xSU(2)xU(1) representation; different *n*-tuplet multiplicities

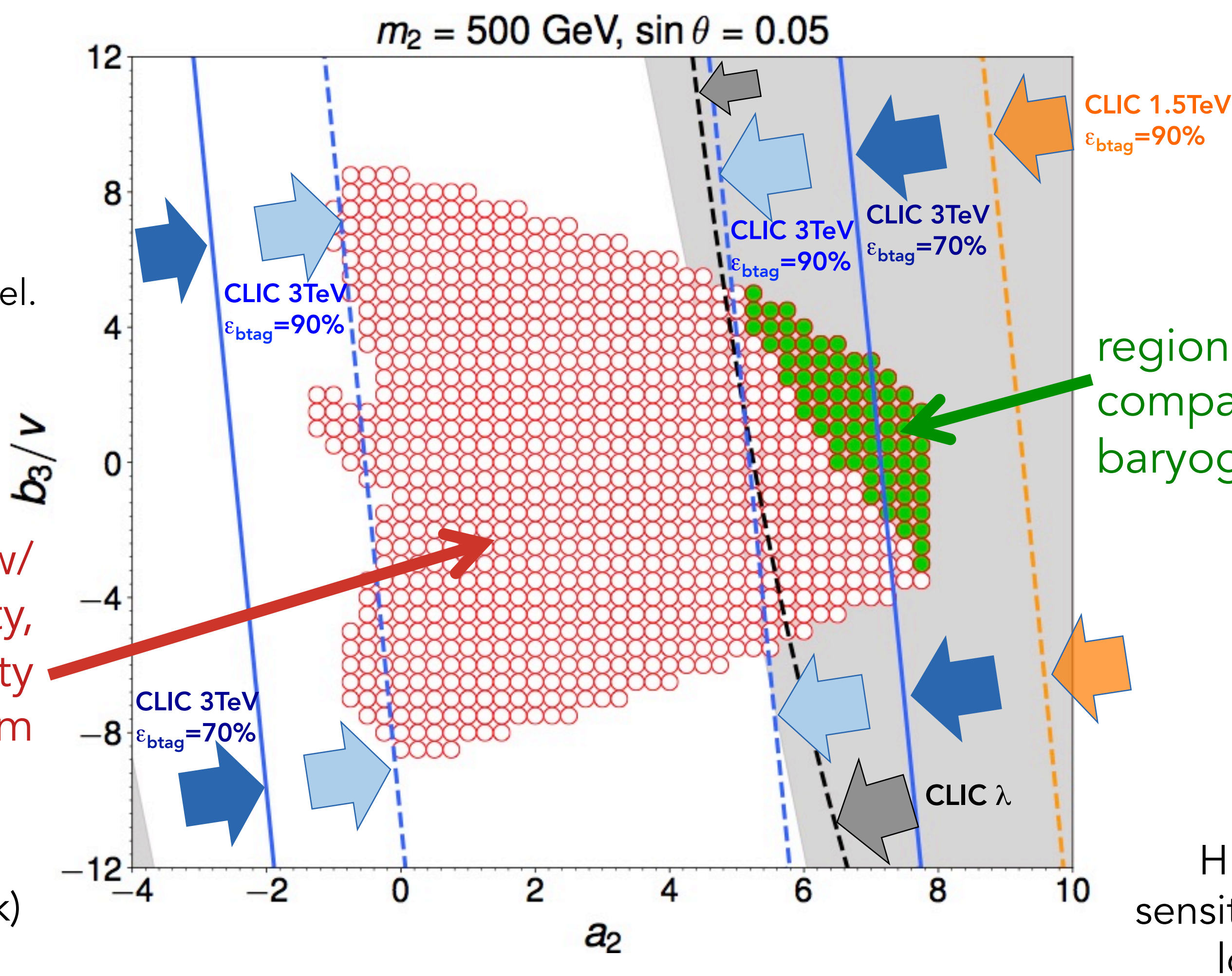
Baryogenesis

arXiv:1807.04284 No, Spannowsky

New!

A potential barrier between the symmetric vacuum and the vacuum after EW symmetry breaking, gives a first-order phase transition: a necessary condition for baryogenesis

Explored in the Higgs+singlet model.
CLIC resonant di-Higgs searches
CLIC Higgs self-coupling λ



regions compatible w/ unitarity, perturbativity, and absolute stability of the EW vacuum

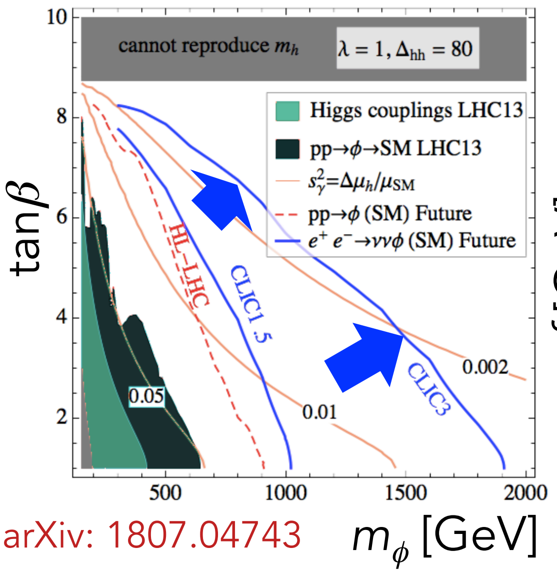
regions also compatible with baryogenesis

a_2 and b_3/v are parameters of the temperature-dependent effective potential; m_2 and θ are the singlet mass and mixing

well-constrained by CLIC Higgs self-coupling (black) and CLIC resonant di-Higgs searches at 1.5TeV and 3 TeV

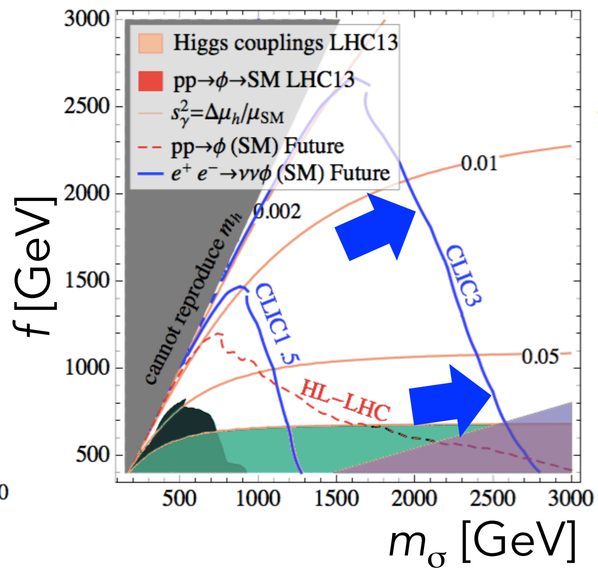
HL-LHC not sensitive at this low mixing sinθ=0.05

Interpretations and full programme

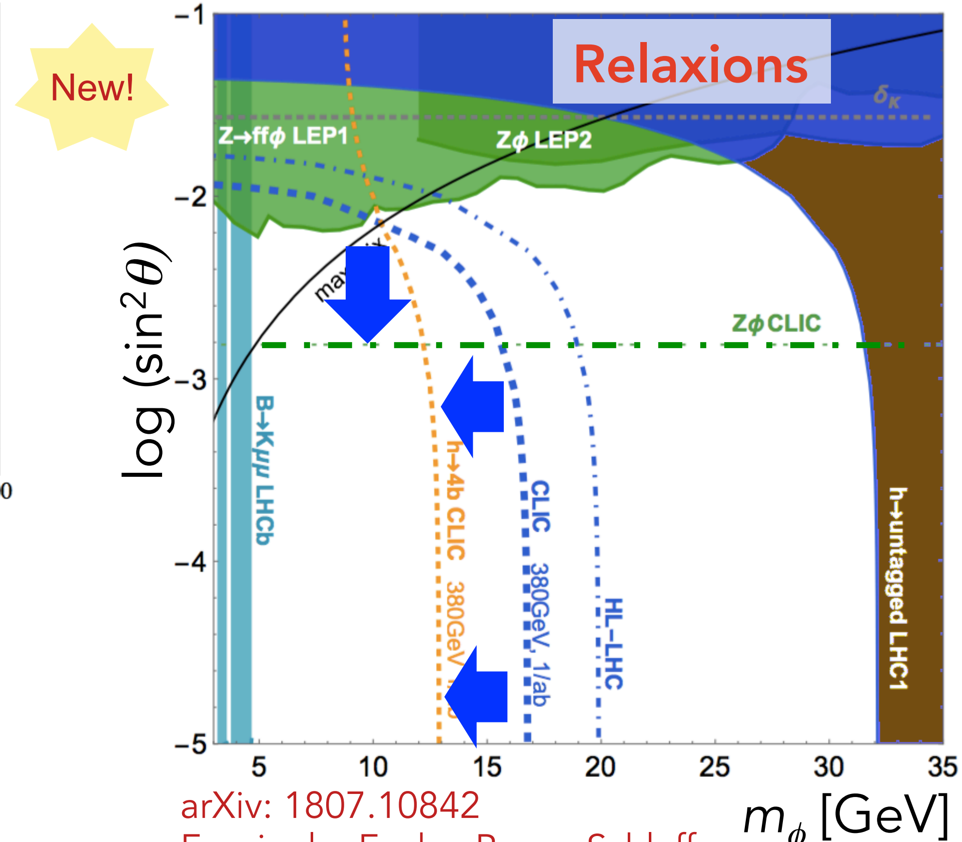


arXiv: 1807.04743

Higgs + singlet as **NMSSM**



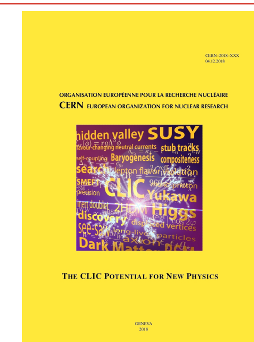
Higgs + singlet as **Twin Higgs** model



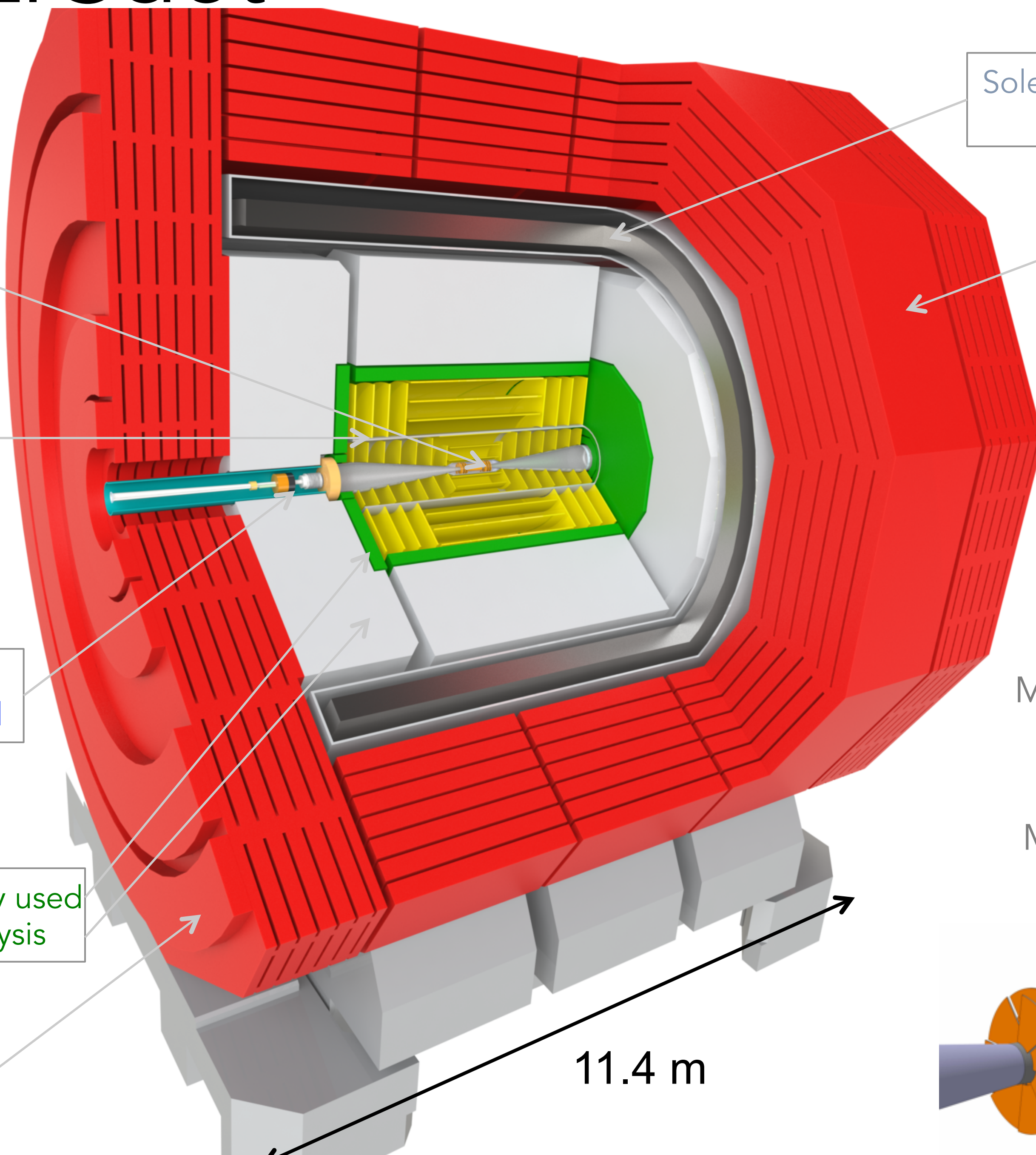
arXiv: 1807.10842
Frugiuele, Fuchs, Perez, Schlaffer

- Precision Higgs couplings and self-coupling
- Precision electroweak and top-quark analysis
- Sensitivity to BSM effects in the SMEFT
- Higgs and top compositeness
- Baryogenesis
- Direct discoveries of new particles
- Extra Higgs boson searches
- Dark matter searches
- Lepton and flavour violation
- Neutrino properties
- Hidden sector searches
- Exotic Higgs boson decays

Many more studies in Yellow Report (250 pages) – on arXiv this morning arXiv:1812.02093

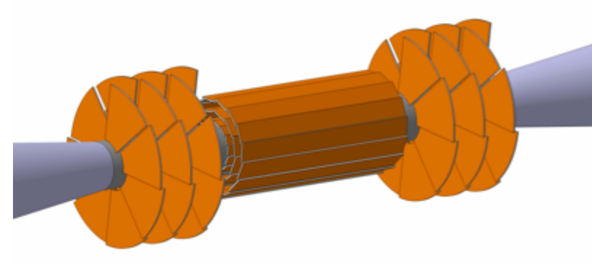


CLICdet



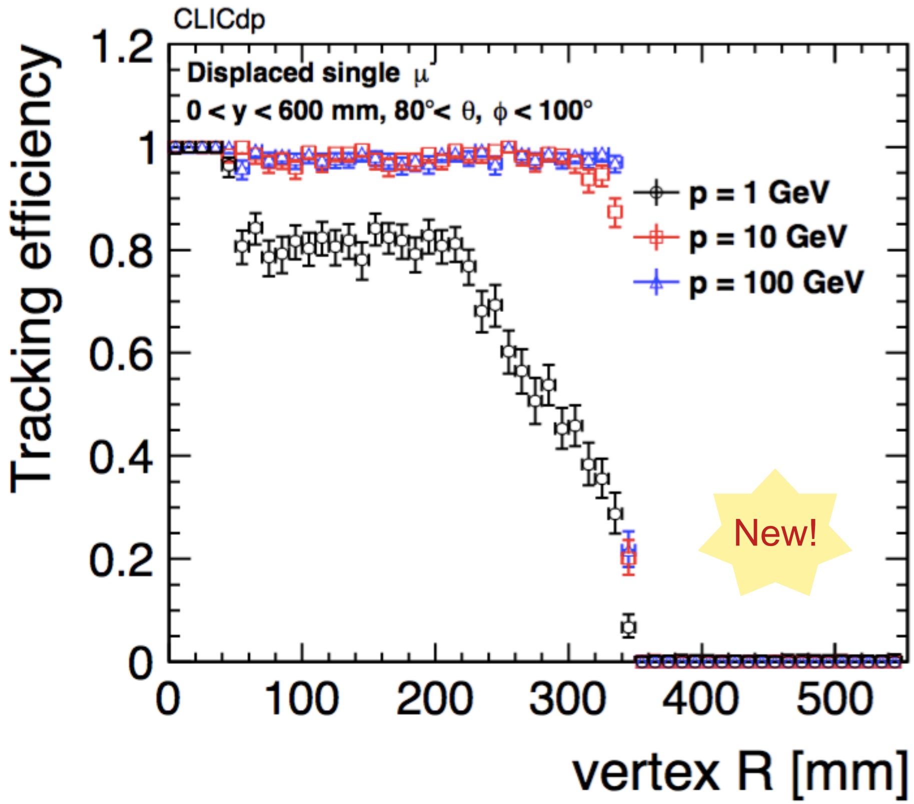
Tracker
spatial resolution: 7μm
Material: 1–2% X_0 / layer

Vertex detector
spatial resolution: 3μm
Material: 0.2% X_0 / layer
–> forced air cooling

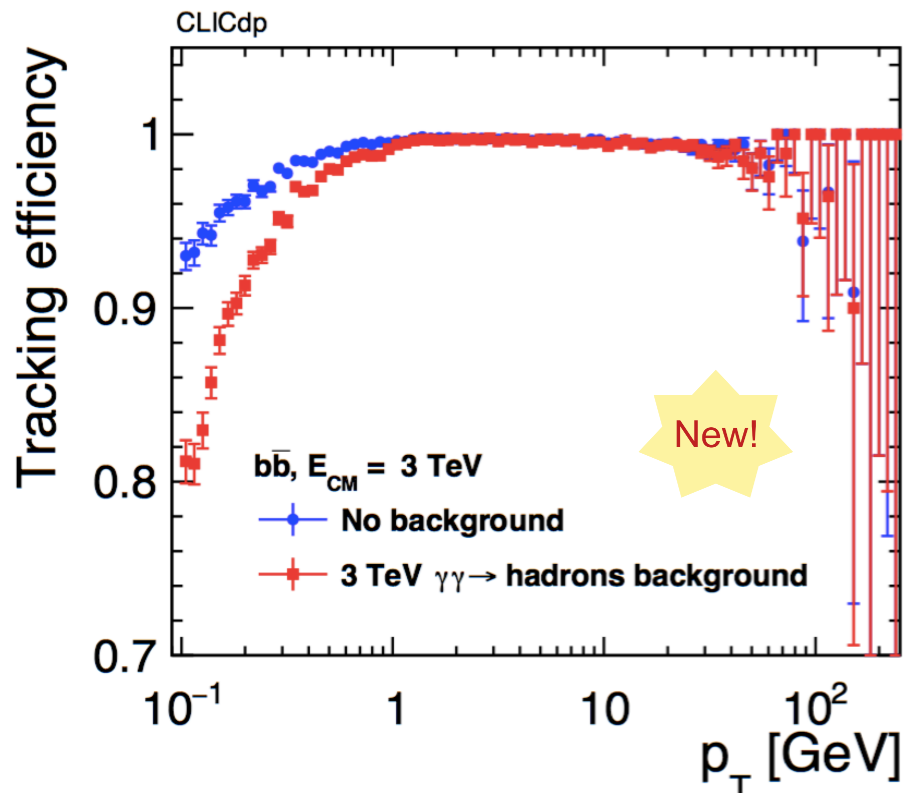


Tracking performance

Displaced track performance – single μ



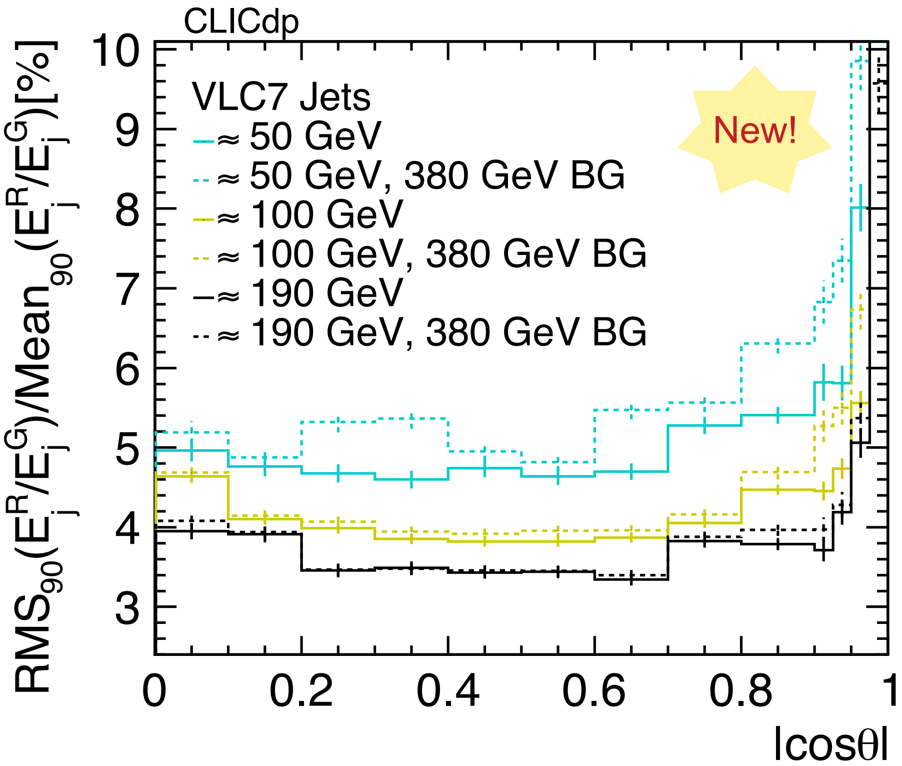
Effect of beam backgrounds on complex event reconstruction

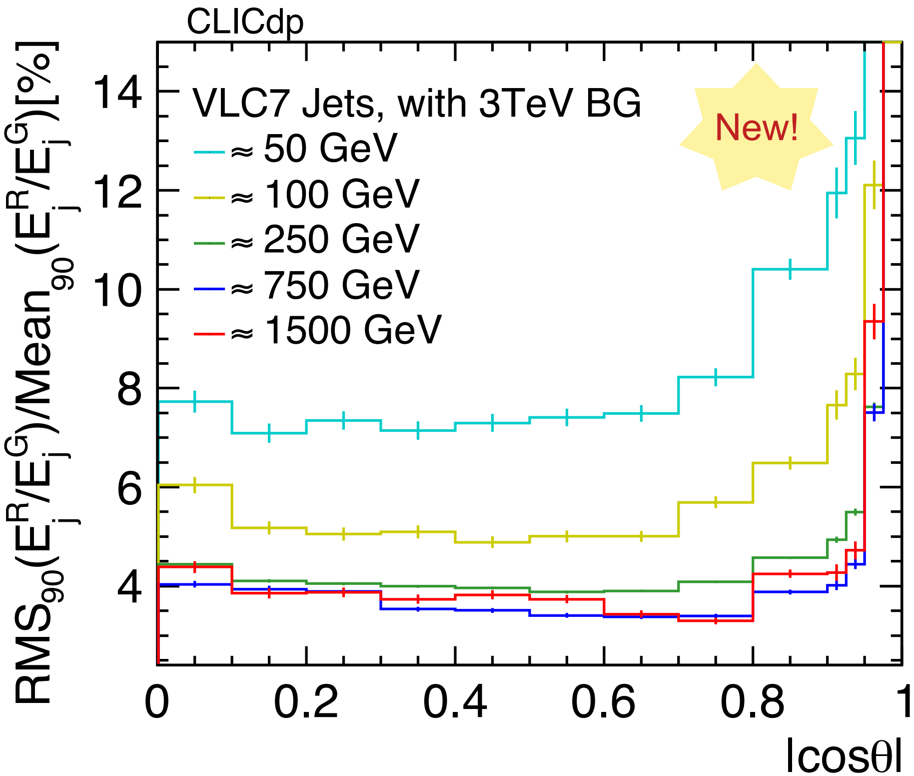


–> ongoing optimization of nearest-neighbour search to recover low-p_T tracks

Calorimetry performance

Studying effect of beam backgrounds on jet energy resolution



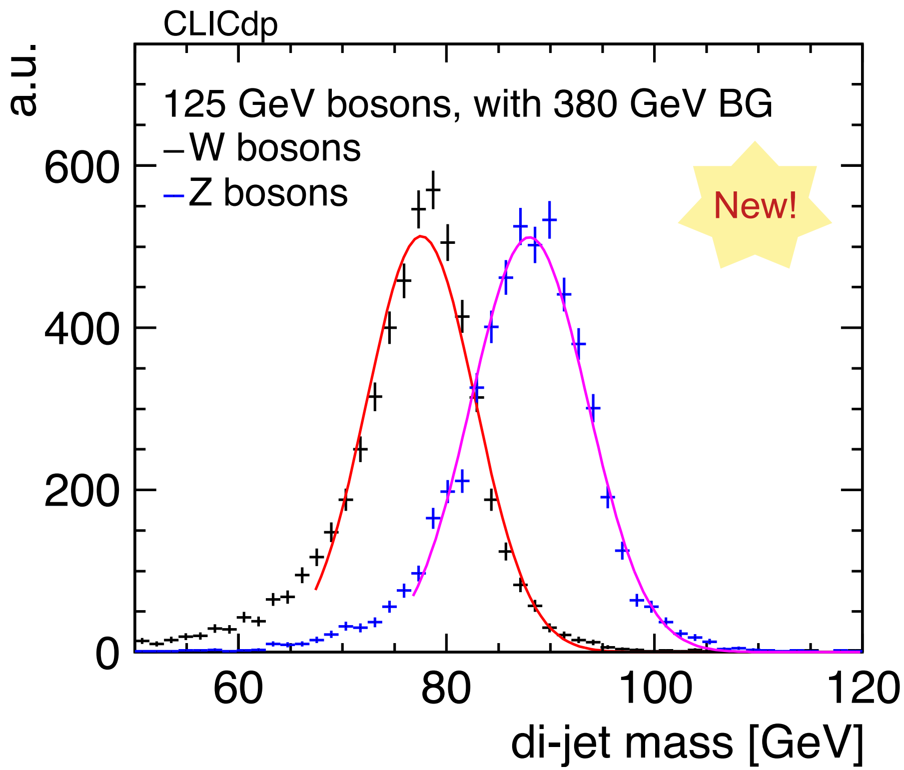


–> reaching target for higher-energy central jets

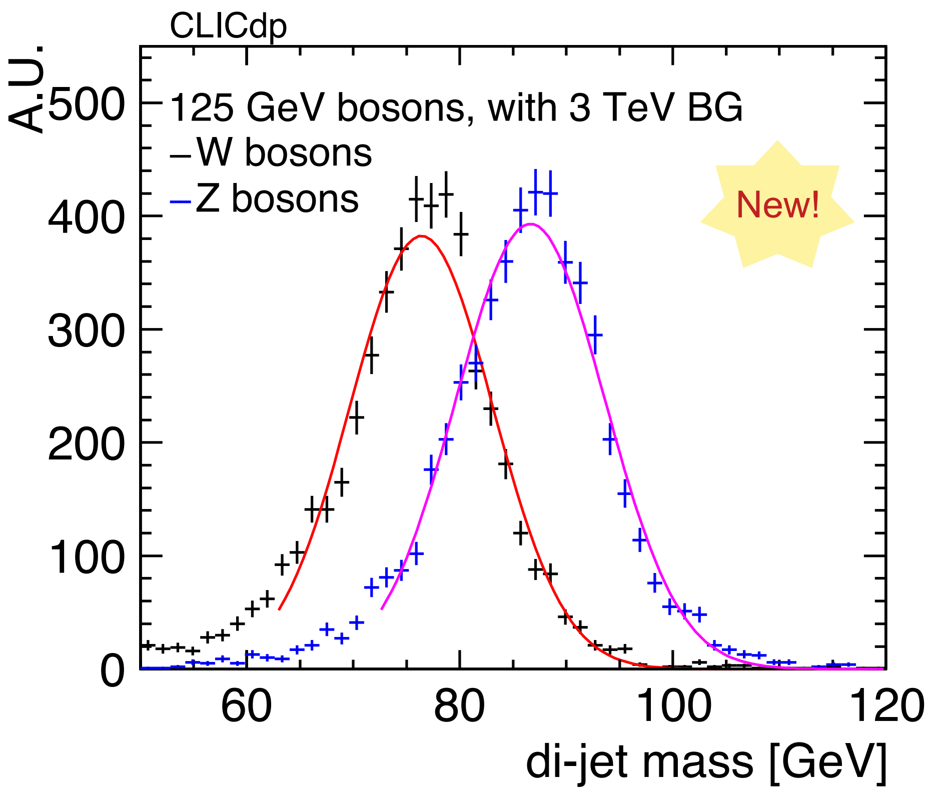
Calorimetry performance

Studying effect of beam backgrounds on W/Z separation

(Example: di-jet mass distribution of
250 GeV c.m. WW and ZZ events)



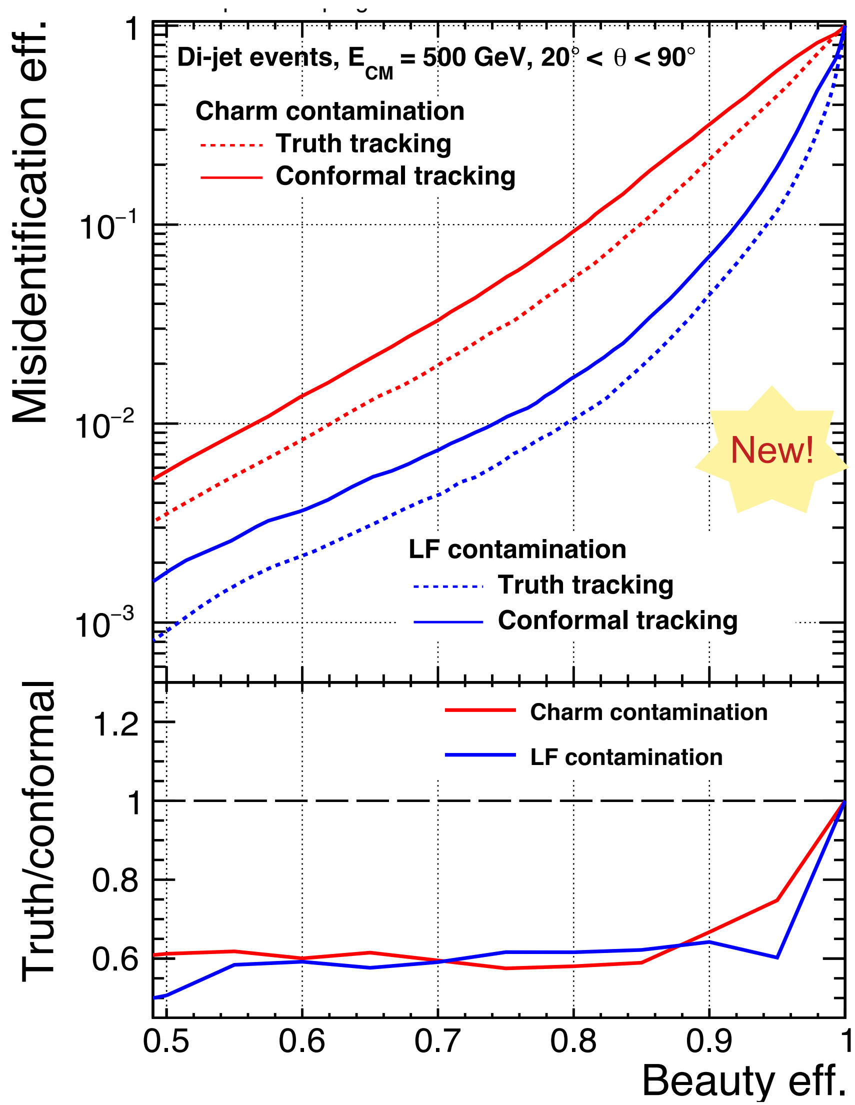
2.0σ separation

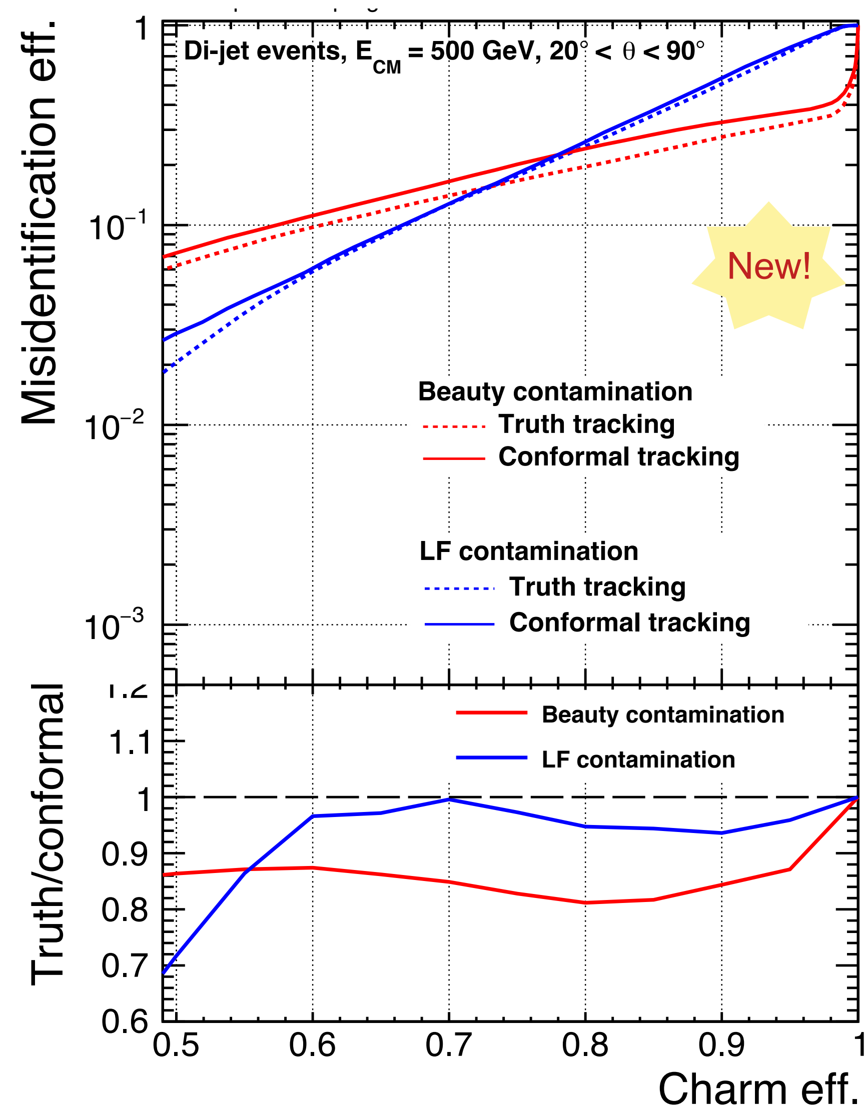


1.5σ separation

Flavour tagging performance

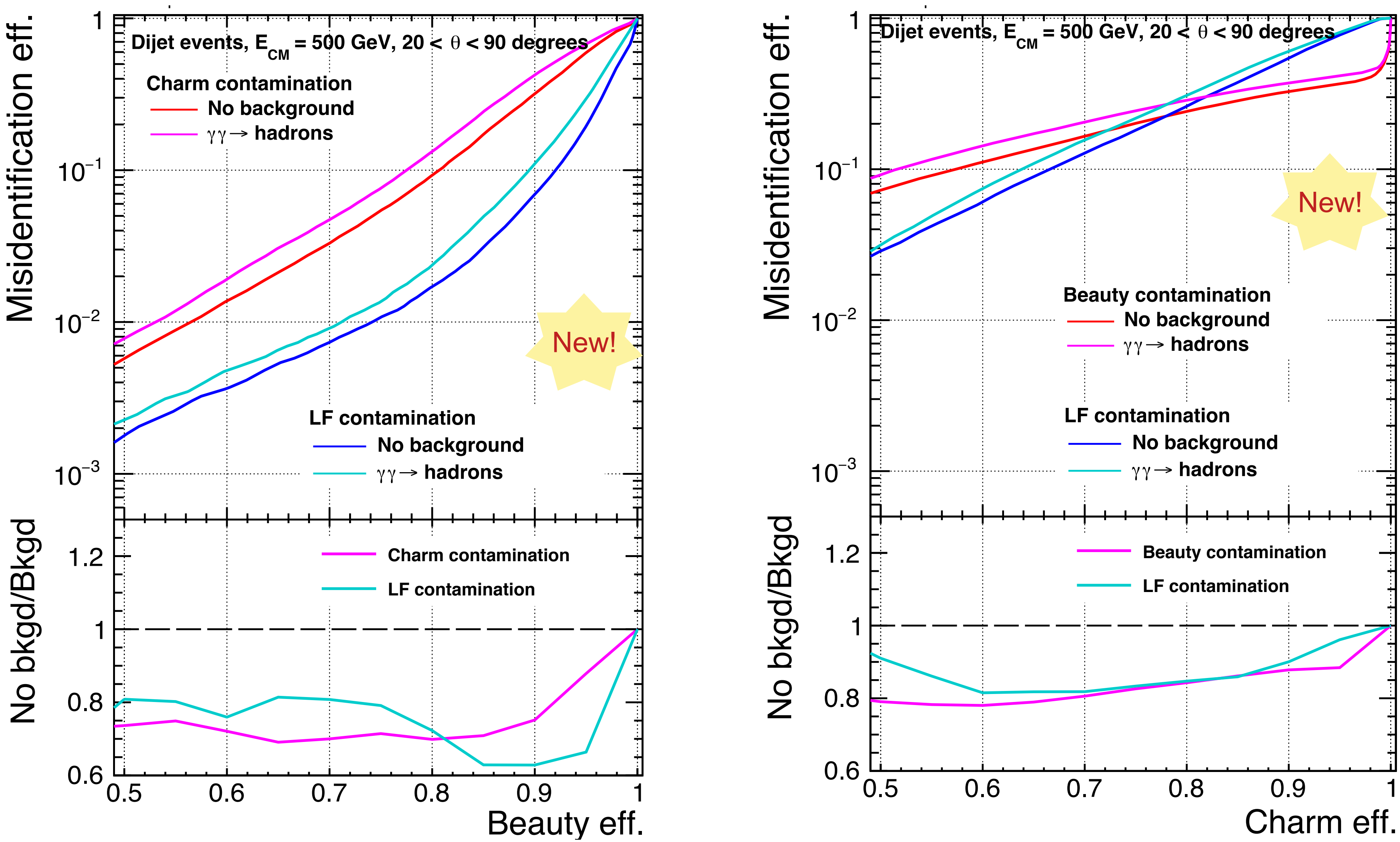
Studying effect of pattern recognition on flavour tagging
[no optimization yet of flavour tagging parameters]





Flavour tagging performance

Studying effect of beam backgrounds on flavour tagging
[no optimization yet of flavour tagging parameters]

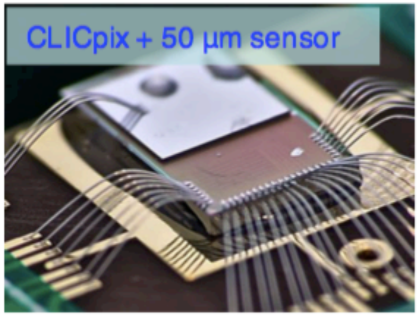


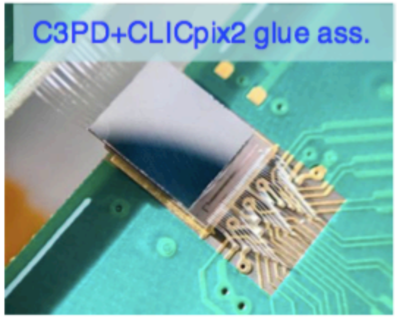
Vertex and Tracking R&D

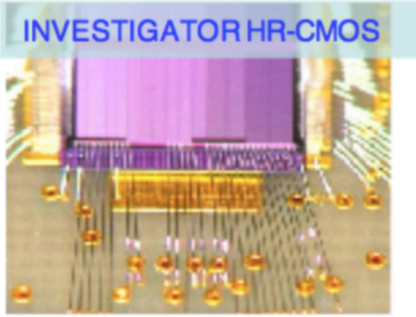
Sensor & readout technology:	**Considered for**:
Bump-bonded hybrid planar sensors	Vertex detector
Capacitively-coupled HV-CMOS sensors	Vertex detector
Monolithic HV-CMOS sensors	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensor	Vertex detector, Tracker

Various sensor + readout technologies under study for CLIC vertex + tracker detector

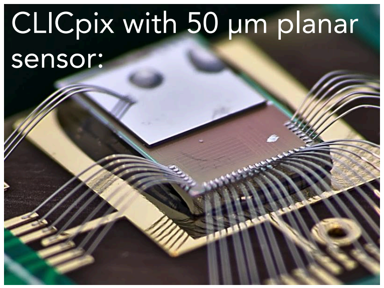
Examples of recent developments on the following slides



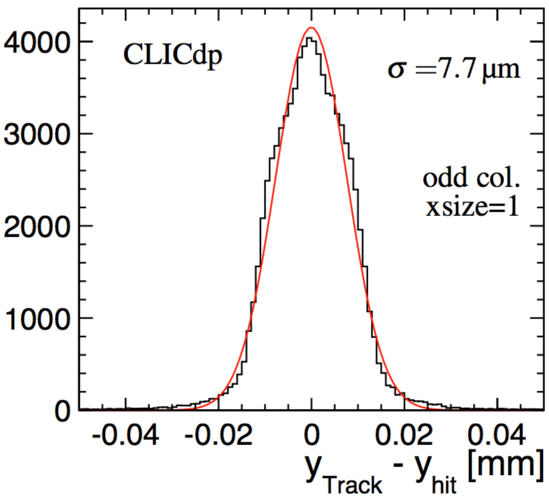




Hybrid technologies



CLICpix:
Prototype chip targeted at CLIC vertex detector, Timepix/Medipix family
- 65nm CMOS process
- 25x25μm pixels
- Power pulsing



Charge-sharing reduced with thinned sensors; challenging to achieve spatial resolution with low material budget

Testbeam results for CLICpix + 50μm sensor

CLICpix2:
5 bit ToA and 8 bit ToT measurement
Increased matrix size, 128x128 pixels
Improved noise isolation
Test pulse DACs; new bump-bonding process
Bump-bonded & capacitively-coupled assemblies
–> testbeam analysis in progress

Enhanced Lateral Drift sensors (ELAD)

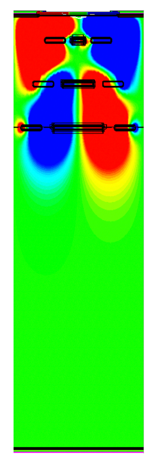
PIER Partnership of Universität Hamburg and DESY

DESY

Concept to improve spatial resolution for thin sensors (H. Jansen, DESY/PIER) Patent DE102015116270B4

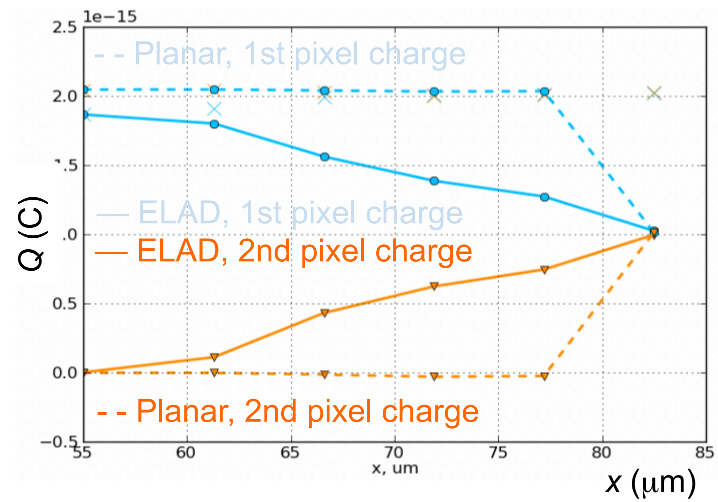
Deep implants to shape electric field in sensor

Electric field:



Current from MIP:

Charge as a function of MIP position:



TCAD simulations show increased charge sharing for given pitch and thickness.

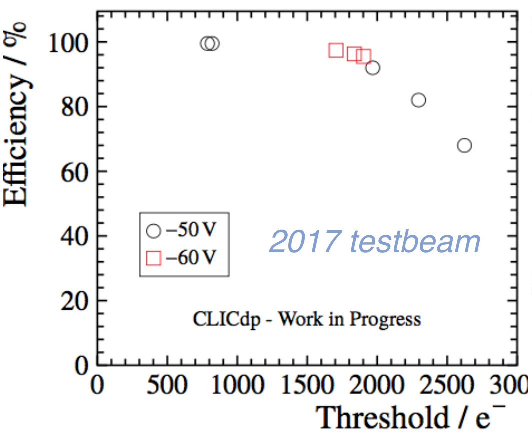
Next steps:
- integration into Geant simulation (Allpix²)
- production of wafer with various deep implant doping

Monolithic technologies

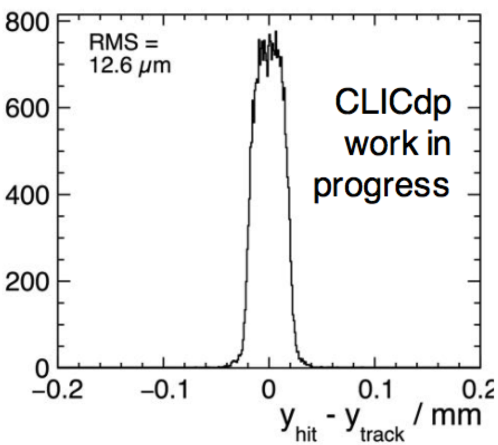
ATLASpix: HV-CMOS; electronics integrated in collection electrode

- high field around large collection electrode
  –> fast charge collection
- fully monolithic chip, designed for the ATLAS ITk upgrade
- 180 nm CMOS process
- Elongated pixels with size of 130 µm x 40 µm
- Isolated PMOS, in-pixel charge amplifier

Efficiency vs. threshold:



Residual along 40 µm row:



Integrated with Caribou universal readout system

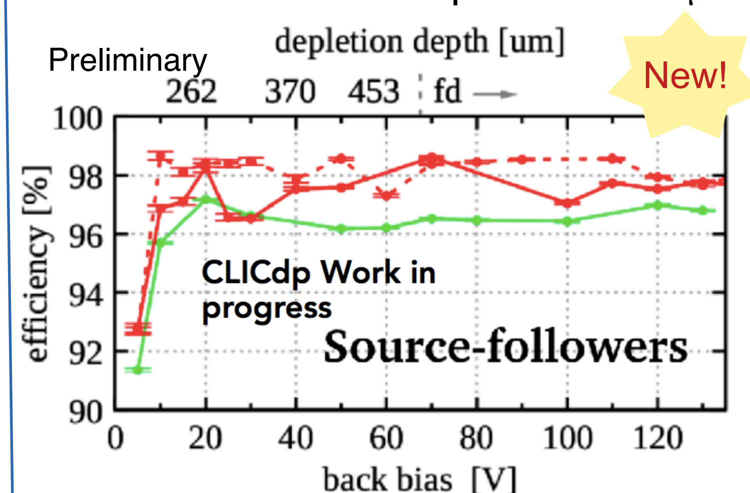
Large efficient operation window; almost no charge sharing –> resolution as expected from pixel size

In progress: timing studies with 160MHz clock and 2018 testbeam analysis

SOI: CMOS electronics and sensor on single wafer, separated by insulation oxide layer & buried p-wells

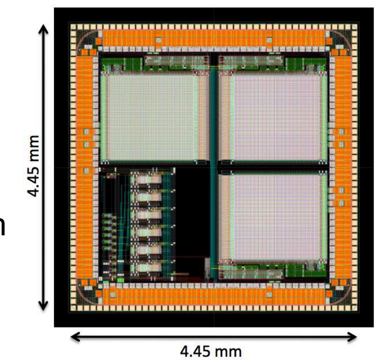
Cracow SOI test chip produced, different sub-matrices with various designs (different r/o schemes, single- and double-SOI, pixel size >= 30µm x 30µm) 500µm substrate [Test chip => external ADCs]

Test beam results for pixel size 30µm x 30µm :



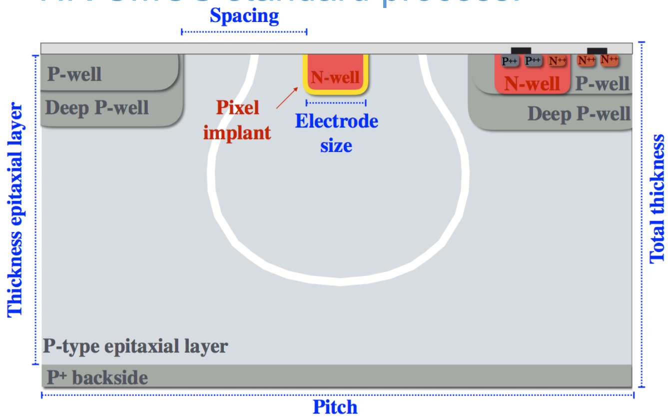
Efficiency > 90%, spatial resolution down to 2µm
Proof of principle of technology

Fully monolithic chip designed:
CLIPS [CLIc Pixel Soi]
Pixel size 20µm x 20µm
300µm wafer, could be thinned to 100µm
Designed; fabricated June 2018

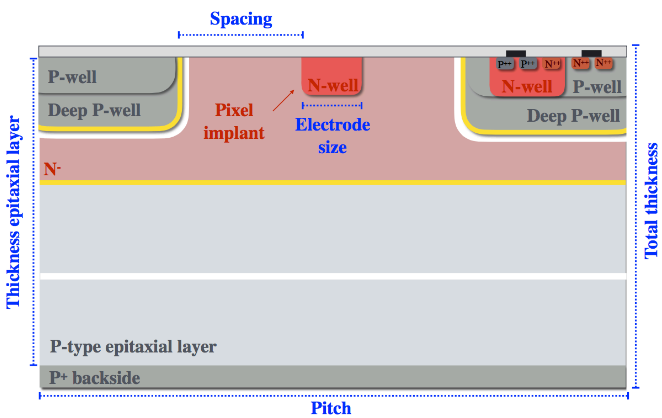


CLICTD

HR CMOS standard process:



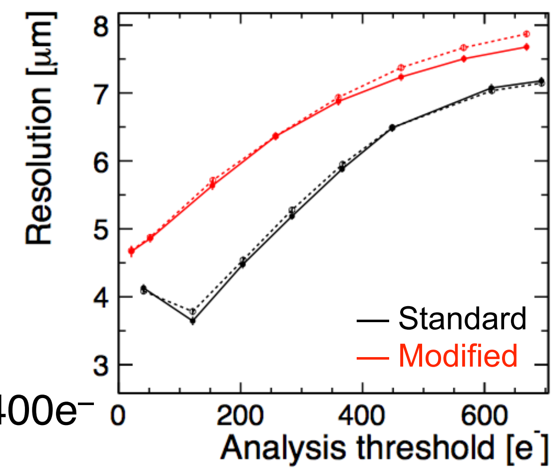
HR CMOS modified process:



HR-CMOS: electronics integrated in p-well, separated from collection electrode

Analogue 'Investigator' test-chip developed for ALICE ITS upgrade
180nm CMOS imaging process
Testbeam results for 2 process variants (pixel size 28μm x 28μm):
– spatial resolution down to 4μm
– fully efficient operation to threshold of ~400e⁻
– timing resolution of ~6ns

Resolution vs. threshold:



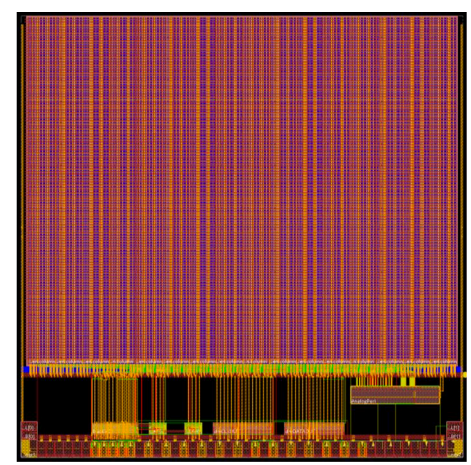
Promising results triggered **design of fully monolithic CLIC tracker chip: CLICTD**

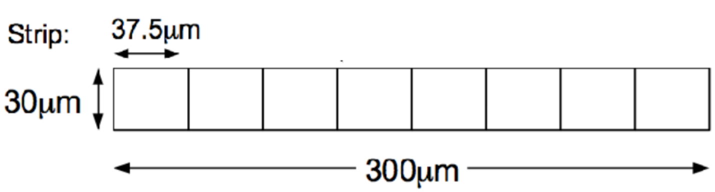
Super-pixels (30μm x 300μm) segmented into collection diodes (30μm x 37.5μm) to maintain fast charge collection while reducing digital logic

Sensitive area of 4.8 x 3.85 mm^2

Full chip verification is ongoing

Targetting submission in early 2019





Simulations

Allpix² – a generic simulation framework

Modular C++ framework to simulate silicon tracking detectors:

- stochastic simulation using GEANT4
- Full simulation chain from charge deposition to digitised charge
- Fast charge propagation with drift & diffusion models
- Uses results of finite element simulations (TCAD, COMSOL) for realistic description of device

Recent developments:

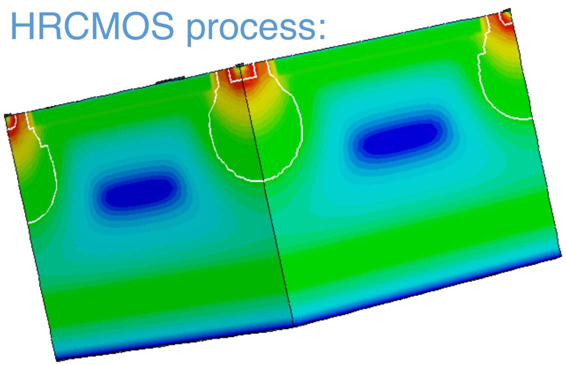
Capacitive transfer module for cross-coupling between pixels

Magnetic field / Lorentz drift

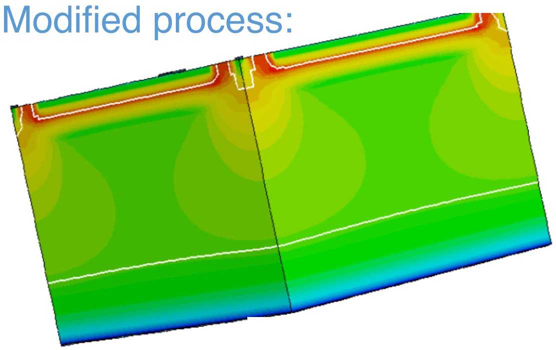
Multithreading, unit tests, geometry...

HR CMOS electrostatic TCAD simulations:

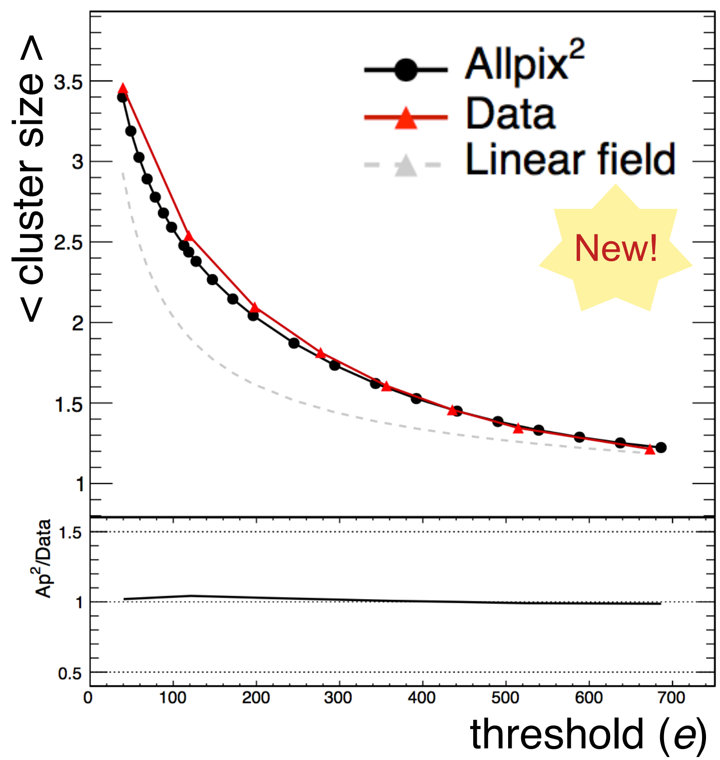
HRCMOS process:

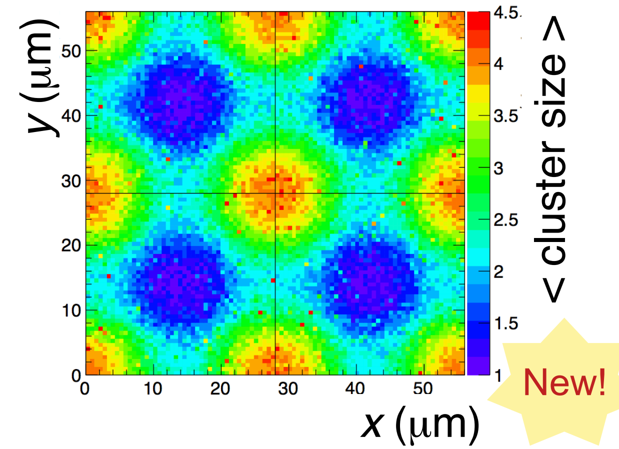


Modified process:



Use TCAD field maps for standard process in Allpix²

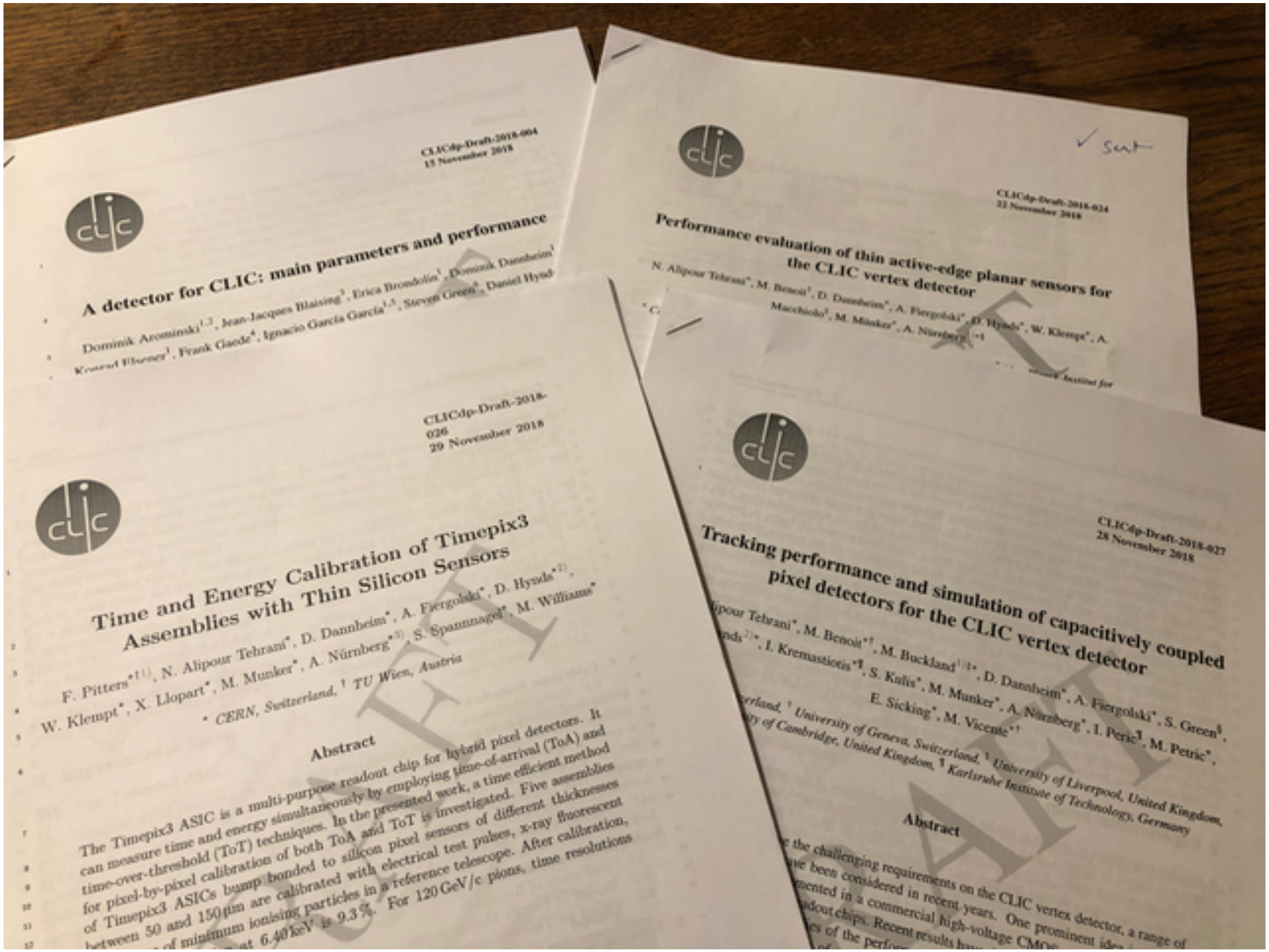




Excellent agreement with data, demonstrates relevance of field modelling in TCAD

High stats MC simulation allows detailed in-pixel resolved performance studies

Detector papers



Detector-related supporting papers in collaboration review.

Yellow Report “Detector Technologies for CLIC” is well advanced and will appear in early 2019

Detector Technologies for CLIC

ESU Input

Two 10-page documents form the formal CLIC input to the ESU:

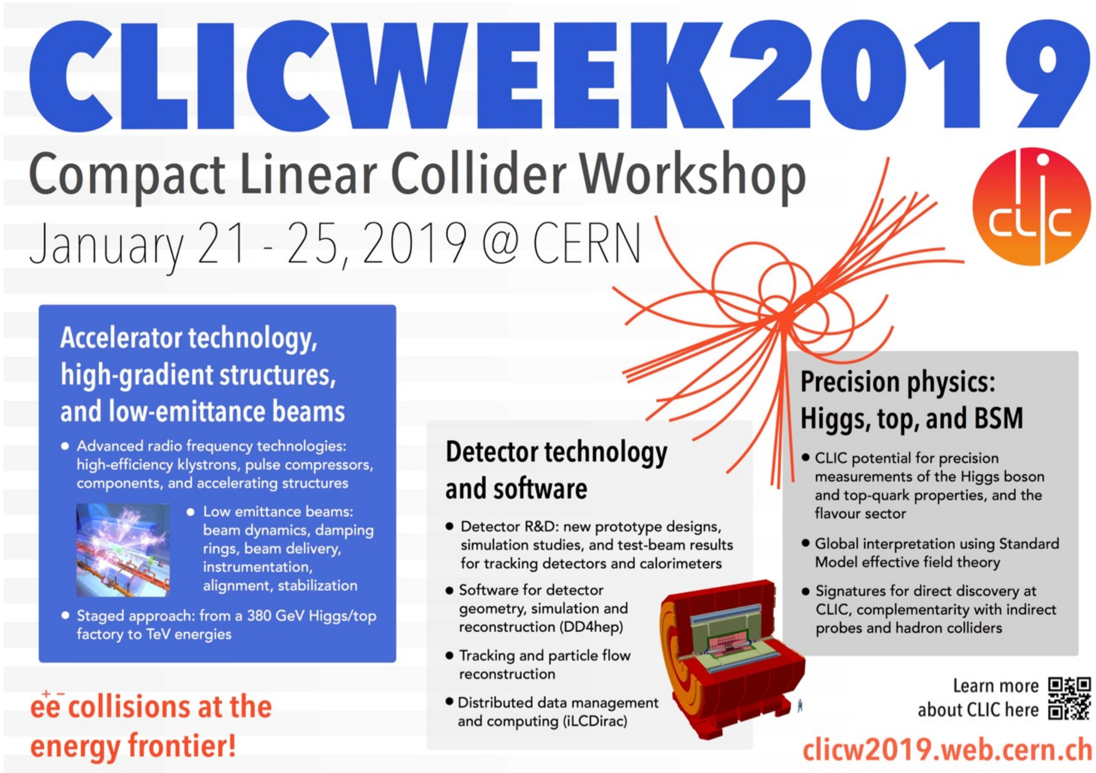
1. CLIC Physics
   – Eds. Philipp Roloff, Ulrike Schnoor,
   Andrea Wulzer, Roberto Franceschini

2. CLIC Accelerator and Detector
   – Eds. Aidan Robson, Lucie Linssen, Marko Petric,
   Daniel Schulte, Walter Wunsch

Format is constrained:
cover page + max. 10 pages “comprehensive and self-contained description”
separate addendum containing information on (where relevant):
interested community, timeline, construction and operating costs, computing requirements

Submission deadline is Tuesday 18th December
Writing teams aiming for circulation of draft to collaborations on Thursday 13th December
(content has already been through collaboration review
in the form of the CLIC Summary Yellow Report)

CLIC Workshop



Monday pm and Tuesday will be Vertex & Tracking, Calorimetry, and Software & Detector Validation sessions, and collaboration matters

Wednesday am and Thursday will be a CLIC Physics mini-workshop, following the "Physics at CLIC" workshop from summer 2017 and the "CLIC Potential for New Physics" Yellow Report

Topical session conveners:

Vertex & Tracking R&D:
Mathieu Benoit, Geneva
Andreas Nurnberg, KIT

Software & Detector Validation:
Emilia Leogrande, CERN
Matthias Weber, CERN

Calorimetry R&D:
Felix Sefkow, DESY
Erica Brondolin, CERN
Yan Benhammou, Tel Aviv

Physics:
Philipp Roloff, CERN
Marcel Vos, Valencia
Andrea Wulzer, CERN/EPFL
Roberto Franceschini, Rome