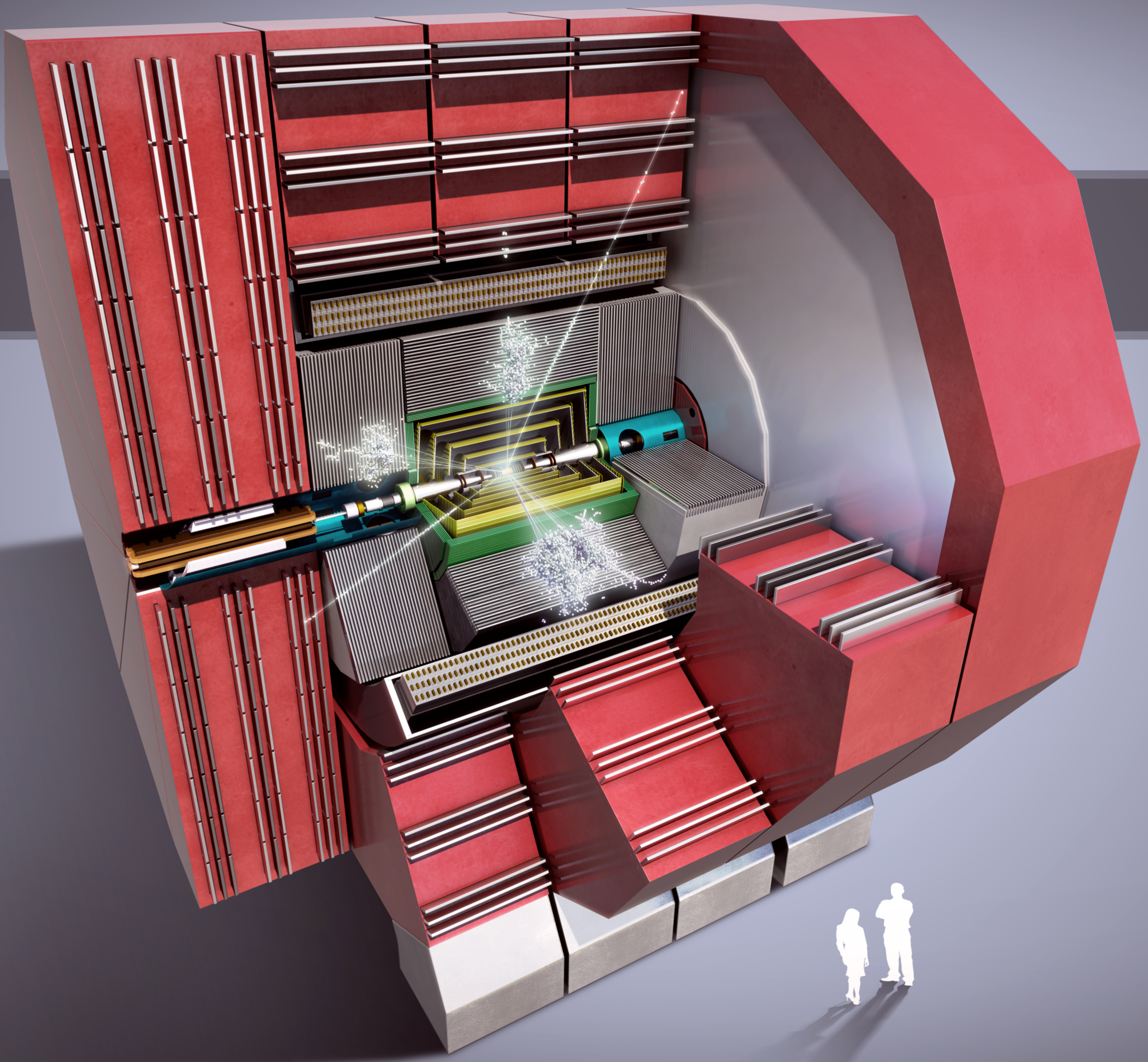


CLIC Detector

On behalf of the: CLICdp Collaboration:

'Overview of the CLIC detector and its physics potential'

Rickard Ström
EP-LCD Group, CERN
rickard.stroem@cern.ch

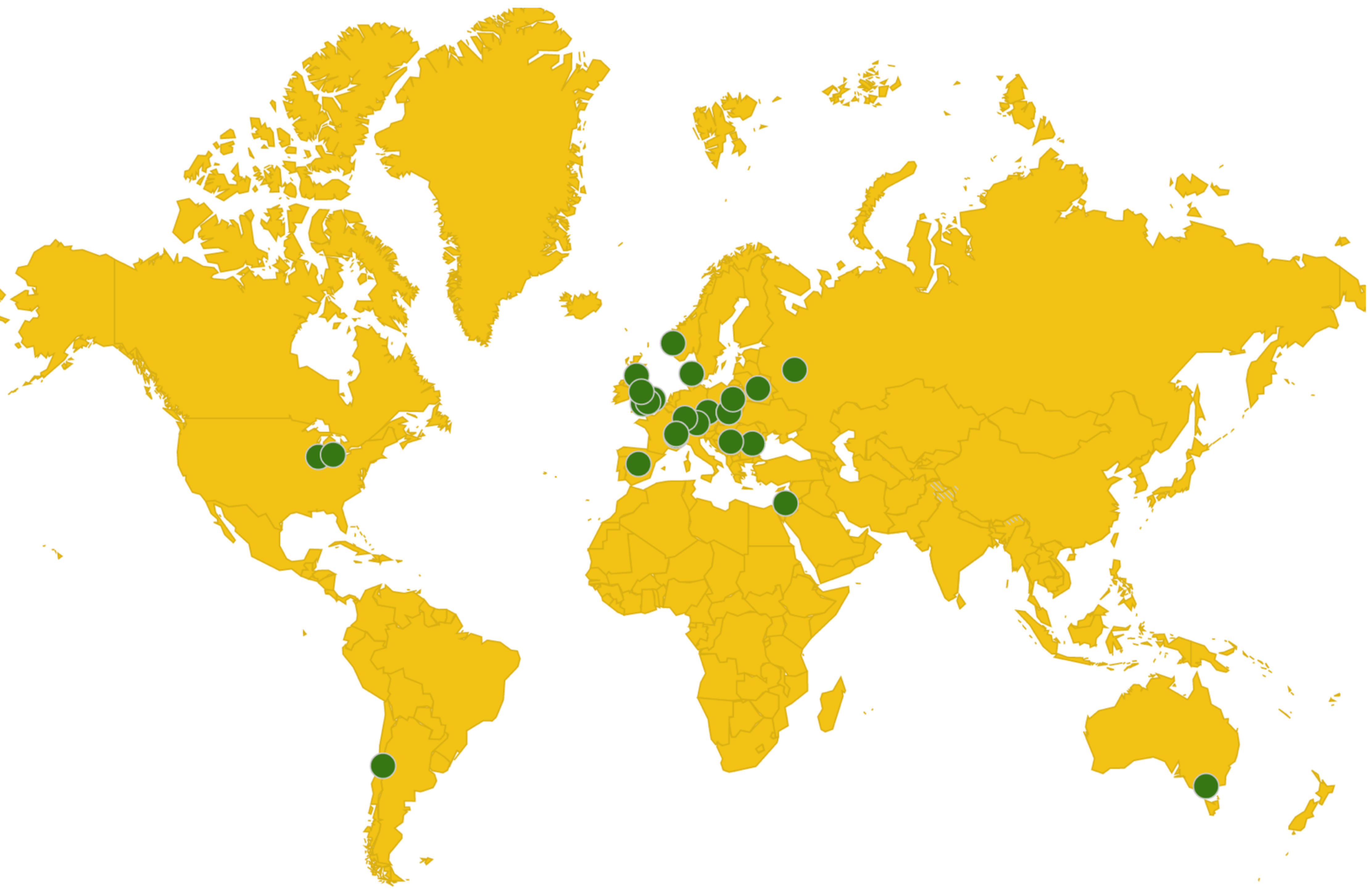
Uppsala University Seminar, 15 Dec. 2016

CLICdp Collaboration

CLICdp Collaboration:

150 members from 28 institutes

http://clicdp.web.cern.ch



CLIC **detector** and **physics** study:

- Physics prospects and simulation studies
- Detector optimisation and R&D for CLIC detector
- Aim to produce a series of reports for the European Strategy for Particle Physics around 2020. At this point seems like a feasible goal

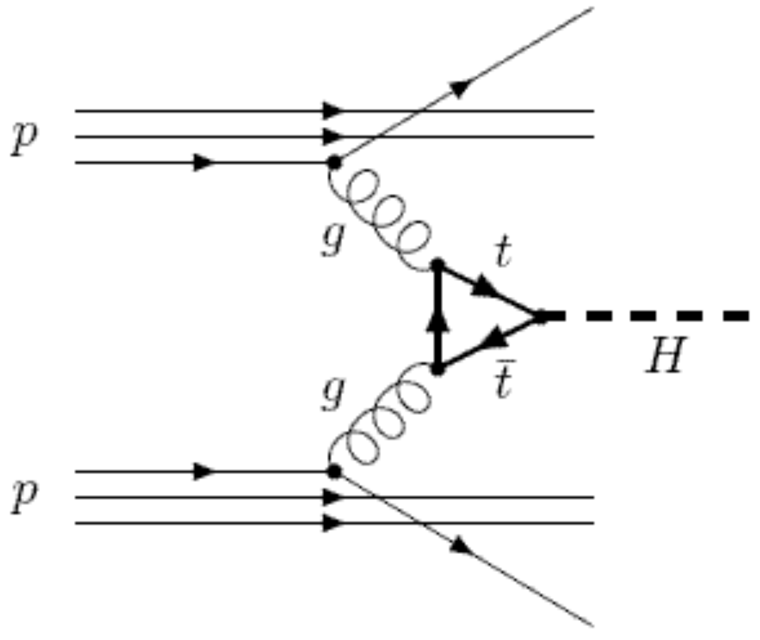
Outline

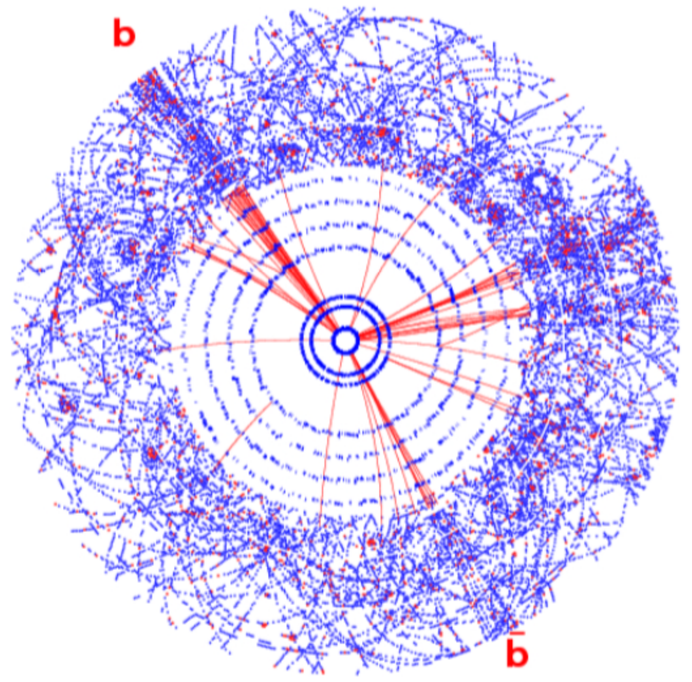
- Lepton Colliders and Future Projects
- CLIC - The Compact Linear Collider
- Detector Requirements
- CLIC Detector Overview - *NEW* CLICdet model
- A Staged Physics Program (Higgs, Top, Beyond)
- Reconstruction of Boosted Top Quarks at High-Energy CLIC
- Conclusions & Summary

Hadron vs. Lepton Colliders

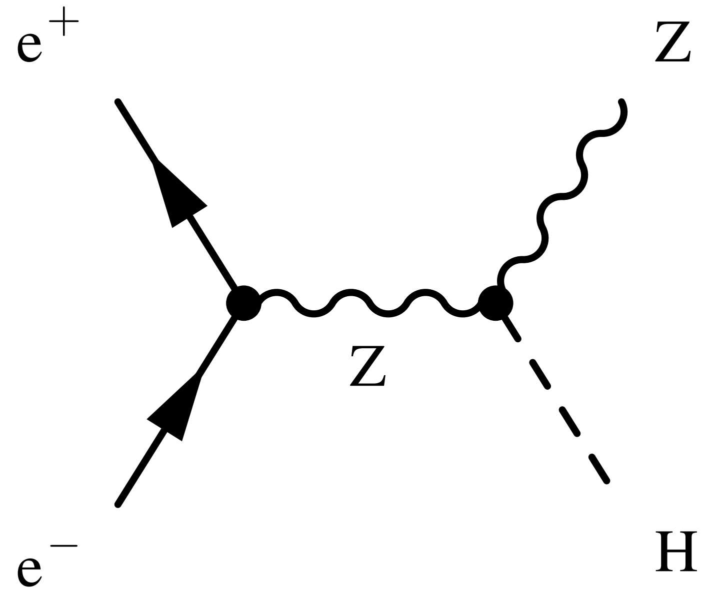
from discovery to precision

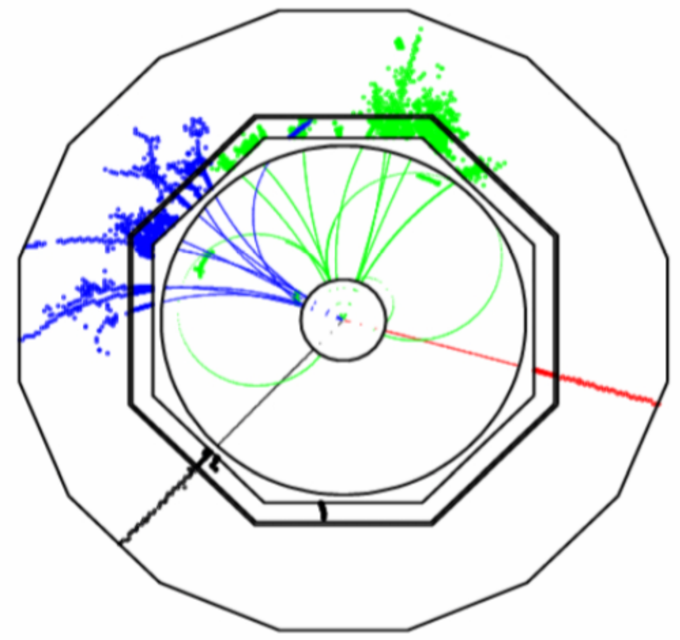
$H \rightarrow b\bar{b}$ @ LHC





$ZH \rightarrow \mu^+\mu^-b\bar{b}$ @ e^+e^-

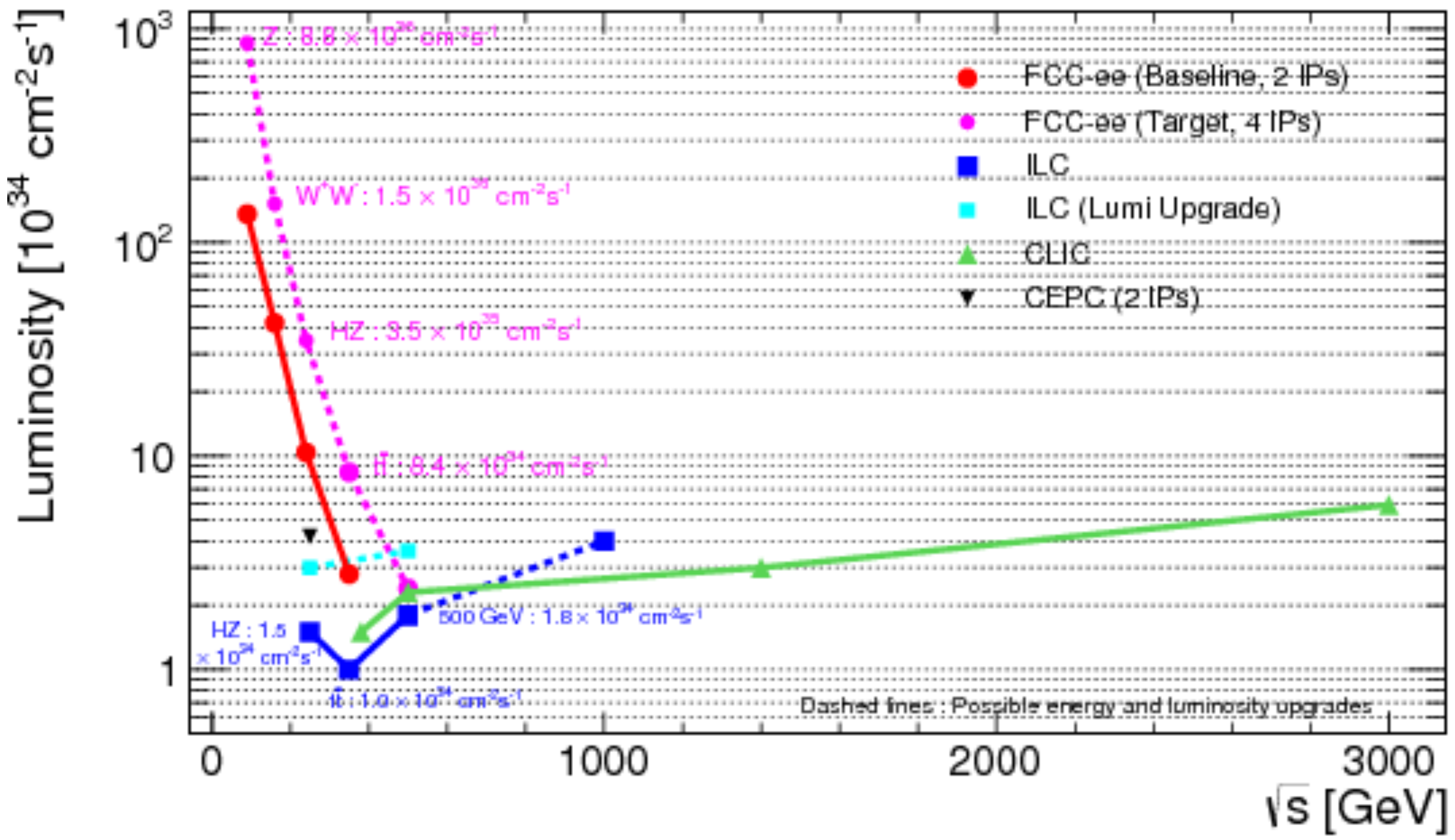




Protons are compound objects → Initial state not known event-by-event → Limits achievable precision	**Electrons/Positrons are point like** → Initial state well defined (energy, polarisation) → High-precision measurements
High-energy **circular colliders** feasible	High-energy requires **linear colliders**
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Cleaner experimental environment → Trigger-less readout → Low radiation levels
High cross-sections for **coloured states**	Superior sensitivity for **electroweak states**

Circular vs. Linear e^+e^- Colliders

- **Circular colliders**
  - Acceleration of the beams can happen gradually, over many revolutions. At the LHC this ramp phase takes around 30-45 min (16 (8 per beam) superconducting RF cavities at 5 MV/m)
  - Beams can be reused
  - Synchrotron radiation can be large, in particular for electrons (e.g. 2.75 GeV/turn lost at LEP for E = 105 GeV)

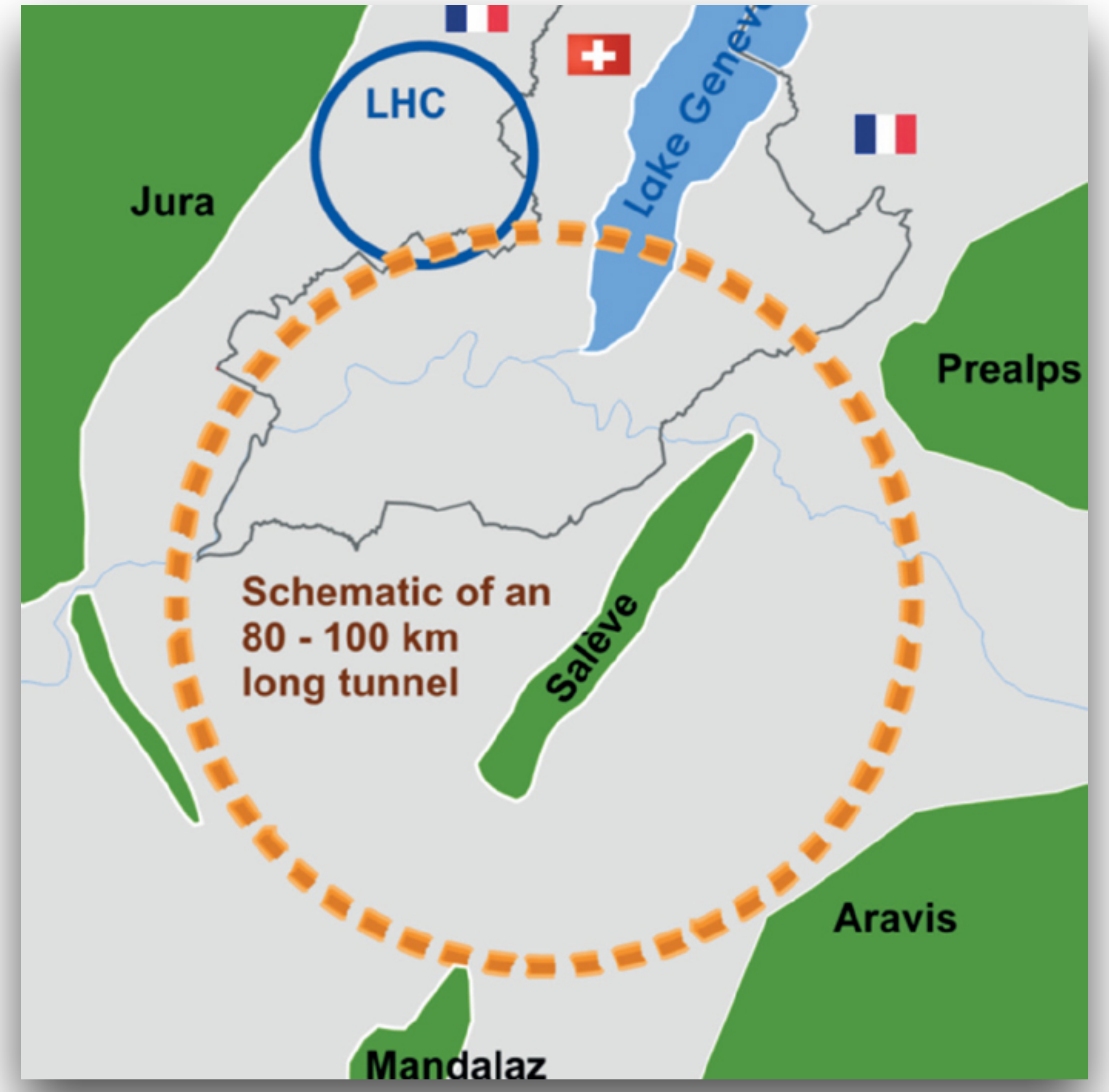


- **Linear colliders**
  - Full collision energy must be delivered in one passage through the accelerator. For CLIC this means in 70 μs. Requires many high accelerating gradient cavities (150’000 at 100 MV/m)
  - Likewise luminosity goal have to be achieved in a single pass (small beam size and high beam power needed). The luminosity of the accelerator scales as the wall-plug-to-beam efficiency, i.e. one needs at the same time a high-gradient acceleration and an efficient energy transfer

Proposed Projects - Circular

Several projects have been proposed for the era beyond LHC (post 2035)

- **HE-LHC** *High Energy LHC* - Proton-proton accelerator in the existing LHC tunnel, with centre-of-mass energy up to 30-35 TeV achieved by replacing the 1232 dipole magnets with new magnets of about 20 T
- **FCC-hh/ee/he** *Future Circular Collider* - hadron/lepton collider in new 80 - 100 km tunnel around CERN. Lepton collisions (f. TLEP) up to 350 GeV. Proton-proton collisions up to 100 TeV. Requires 16 T magnets
- **CEPC+SppC** *Circular Electron Positron Collider +* Super proton-proton Collider - Two phase collider in new 100 km tunnel in Qinghuada (?), China. First phase is an electron-positron collider (240-250 GeV). Second phase is a proton-proton collider with centre-of-mass energy of 50-70 TeV

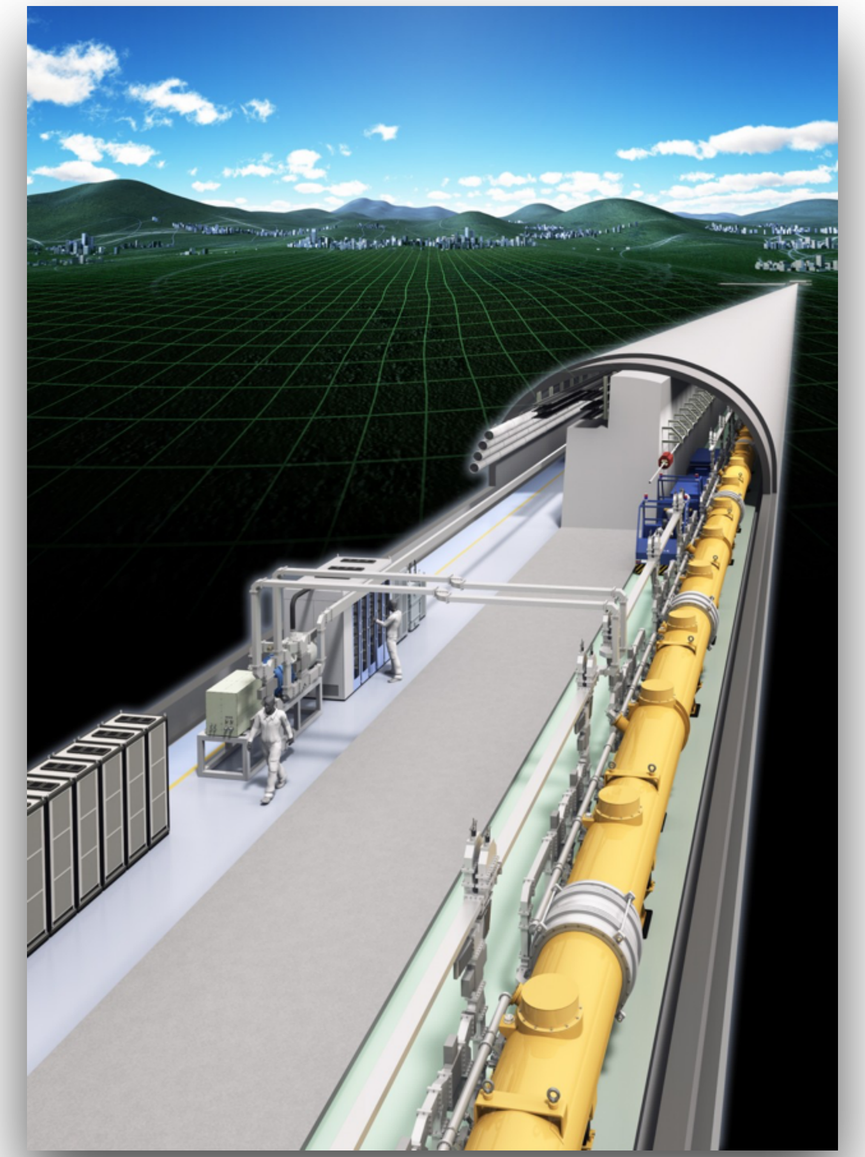


FCC - Future Circular Collider at CERN

Proposed Projects - Linear

- **ILC** *International Linear Collider* - A 500 GeV electron-positron linear collider in Japan, with centre-of-mass energy **up to 1 TeV** after upgrade. Conventional acceleration with superconducting RF cavities
- **CLIC** *Compact Linear Collider* - An electron-positron linear collider at CERN, with centre-of-mass energy **up to 3 TeV**. Two-beam accelerating technique with room temperature RF cavities

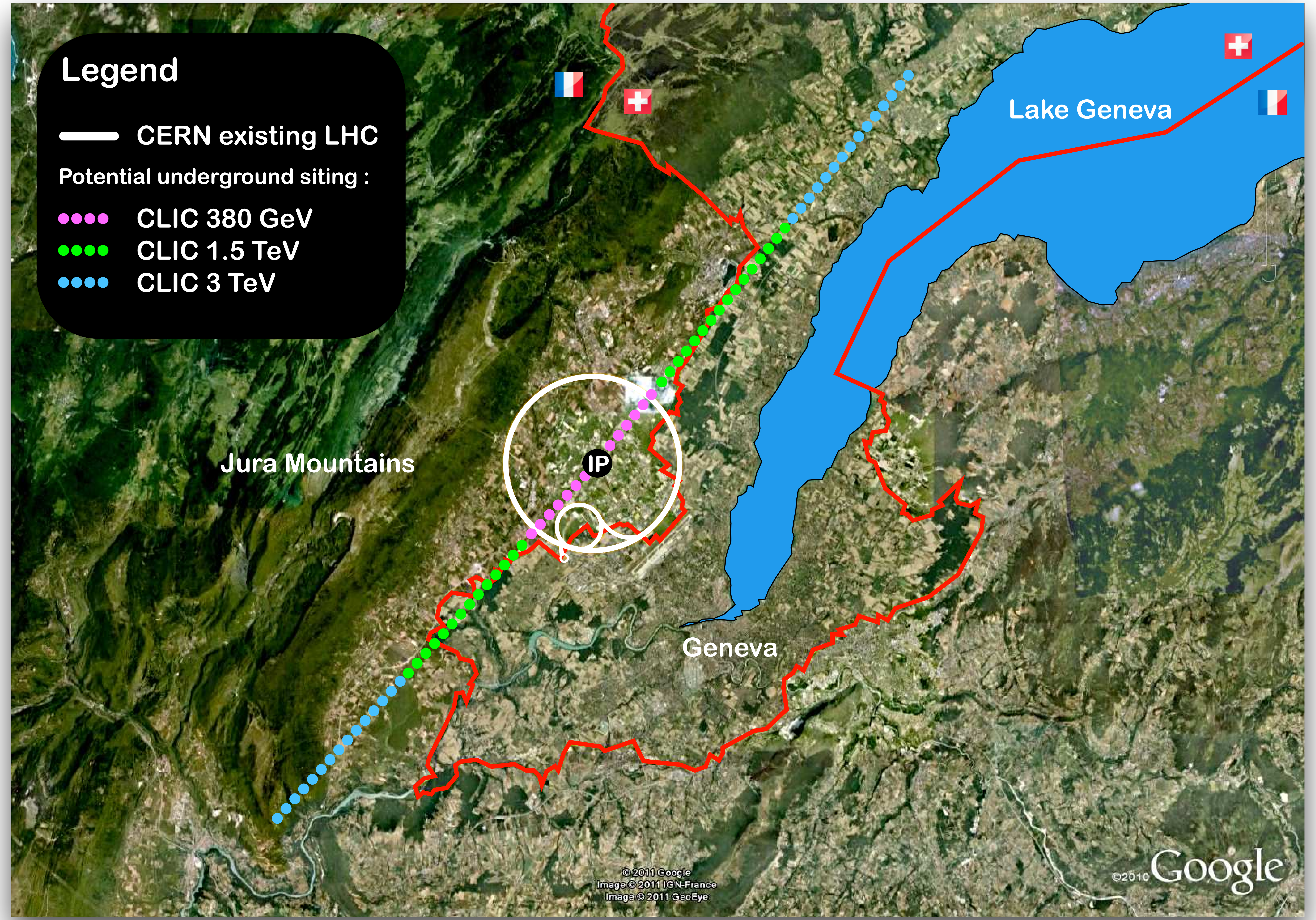
One of the 16'000 niobium-based 1.3 GHz superconducting RF cavities proposed to be used at the ILC



Kitakami - Proposed ILC Interaction Point

(~20 m below this point, shallowest point of the tunnel)

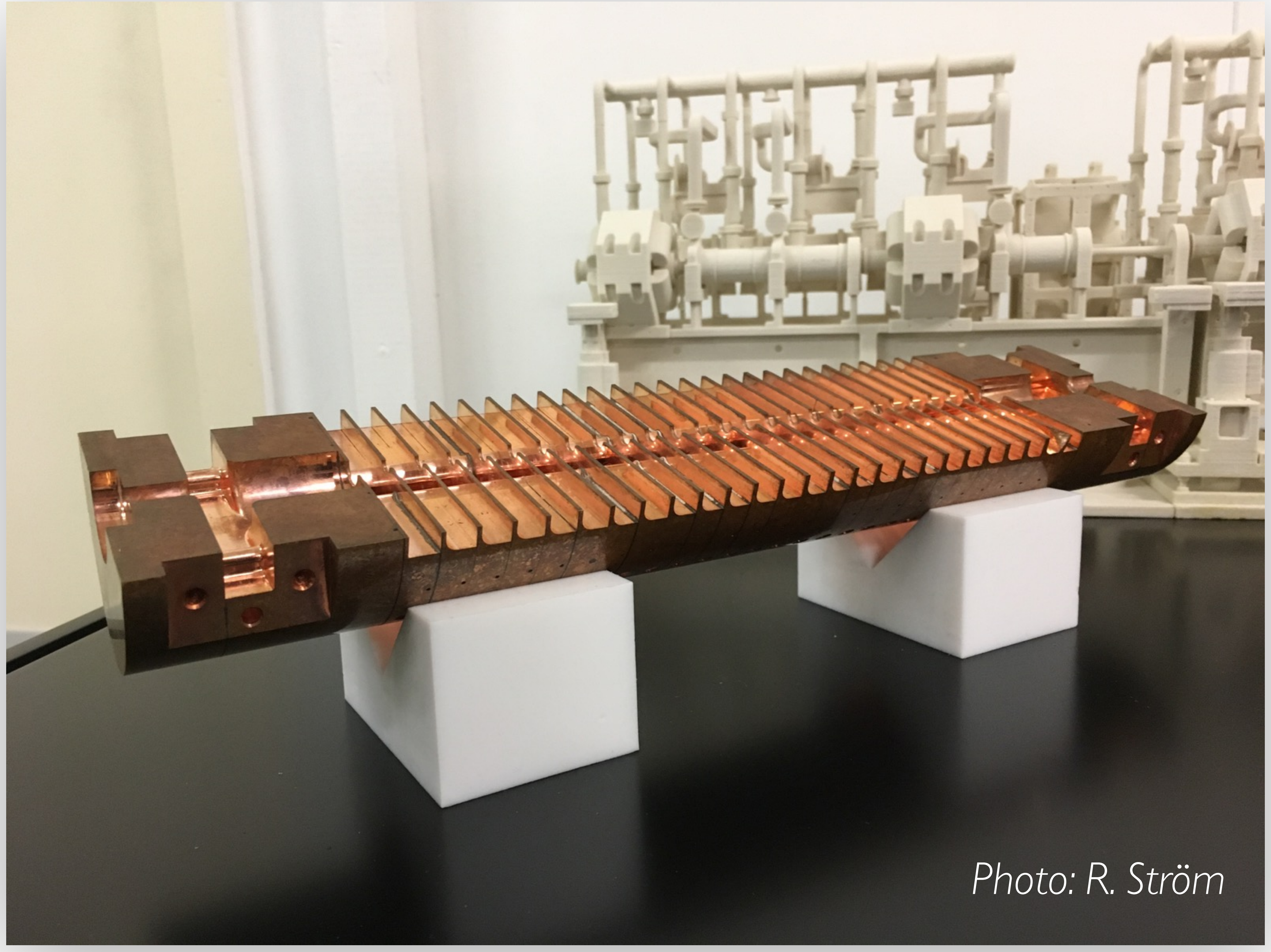
CLIC - Compact Linear Collider - e^+e^-



Centre-of-mass	Length
380 GeV	11.4 km
1.5 TeV	29.0 km
3.0 TeV	50.1 km

CLIC - Compact Linear Collider - e^+e^-

- CLIC is a proposed electron-positron linear collider at CERN
- Two-beam acceleration scheme (drive/main beams) to achieve a high accelerating gradient of 100 MV/m
- About 150’000 room temperature RF cavities
- Allows a 3 TeV collider to be built in *only* 50 km (compact)
- Staged construction optimal for physics:
  - 500 fb^{-1} at 380 GeV (+100 fb^{-1} at 350 GeV, ttbar threshold)
  - 1.5 ab^{-1} at 1.5 TeV
  - 3.0 ab^{-1} at 3.0 TeV
- Rich physics programme over ~ 20 years (with 5-7 years at each stage)



One of the 150’000 **copper** 12 GHz accelerating structures to be used at CLIC (L~20 cm)

Why do we need two-beam acceleration?

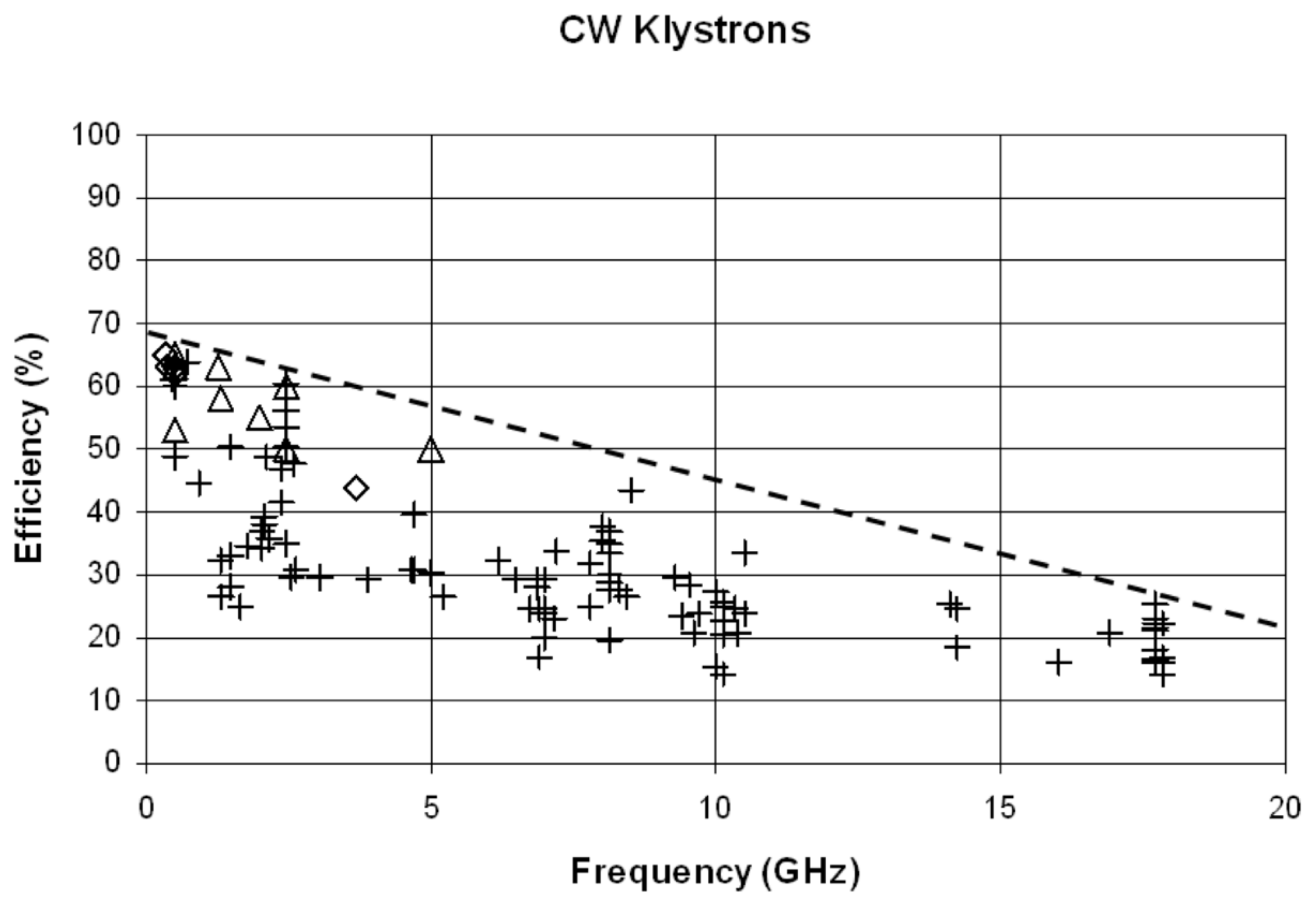
- Particle acceleration is typically carried out using RF cavities
  - RF waves matched to the cavity dimensions can be used to generate standing waves* inside them
  - A longitudinal electric field is produced, **accelerating** and **bunching** the incoming particles
- A compact TeV linear accelerator (~tens of km) requires high acceleration gradient (~100 MV/m)
- But the maximum accelerating gradient that can be achieved is limited
  - Ohmic losses in the conductor surface
  - Breakdown (sparks!)
- These issues can be addressed by moving to higher frequency RF but also requires careful "tuning"
- Note that superconducting cavities intrinsically limited to ~40 MV/m (depends on coating design, material, etc.)

**Technically CLIC uses a traveling wave*

Why do we need two-beam acceleration?

- Unfortunately it is not easy/efficient/practical to produce high frequency RF
  - **Klystrons** generally used for particle acceleration, but drop in efficiency beyond a few GHz
- CLIC approach is to use a **drive beam** powered by conventional klystrons to generate high-frequency RF (12 GHz)

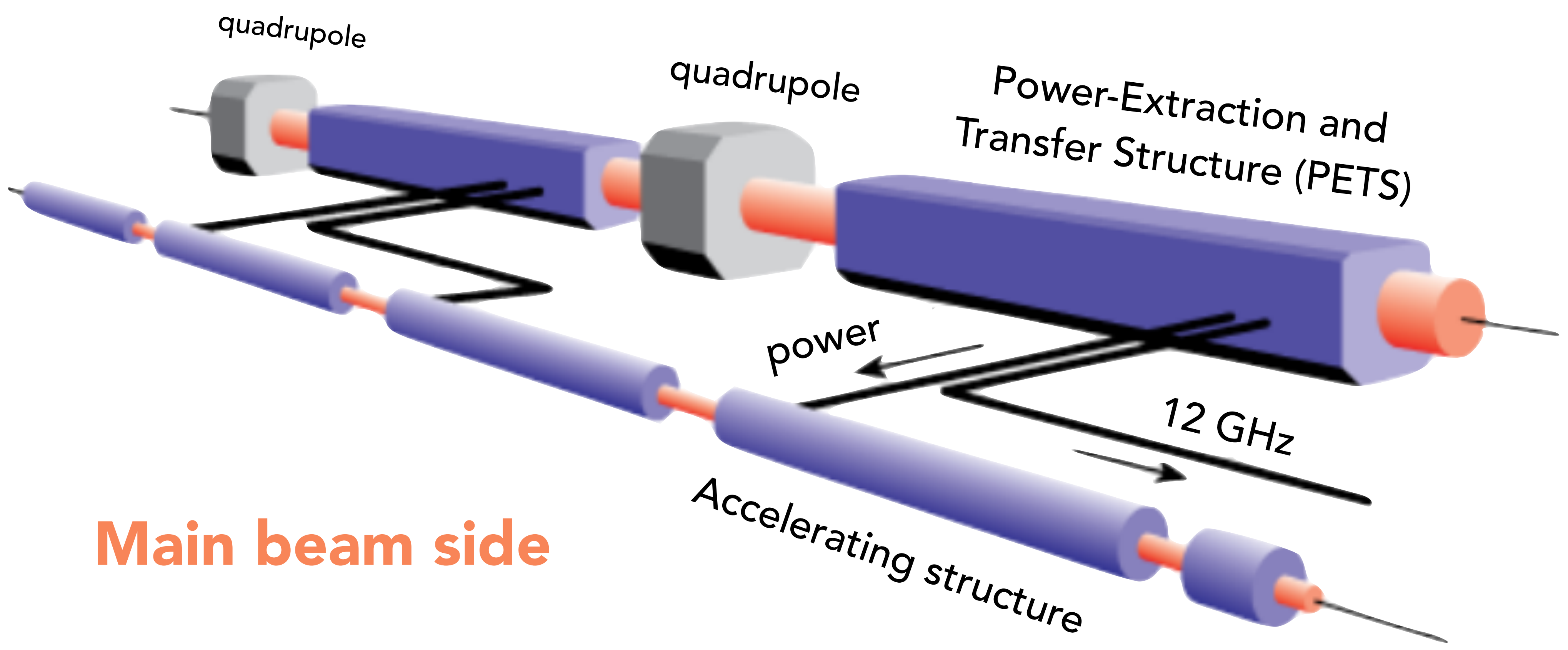
- Further, challenges of the CLIC accelerator complex come from the luminosity requirement, where a very small and dense beam, 40 nm x 1 nm in the transverse plane and 10^9 particles per bunch, is needed to reach high enough statistics for rare processes at high energy
- Constraints on both beam stability and alignment
- CLIC design has 43,250 quadrupoles in total
- LHC: 392 quadrupoles



Klystron

CLIC - Two Beam Acceleration Scheme

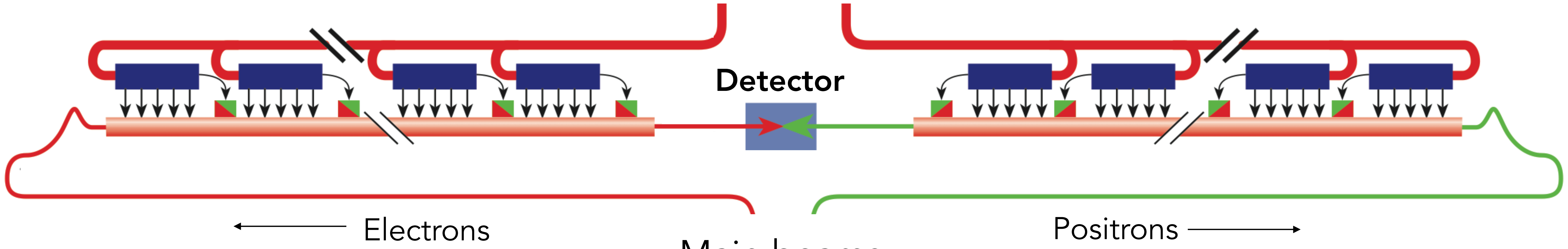
- Drive beam accelerated to a few GeV using conventional klystrons
- Frequency increased using a series of delay loops and combiner rings
- Drive beam decelerated through a series of Power Extraction and Transfer Structures (PETS) which decelerate the dense beam and extract its kinetic energy
- This energy is fed via an RF field in a waveguide to a second beam, which is much less intense. Since there are far fewer particles in this 'main beam', each one is accelerated to higher energy (from 9 GeV to 1.5 TeV)



- Concept demonstrated at a dedicated test facility at CERN (incl. step-up in frequency of the drive beam, power extraction, and acceleration of main beam in excess of the required 100 MV/m)

Drive beams

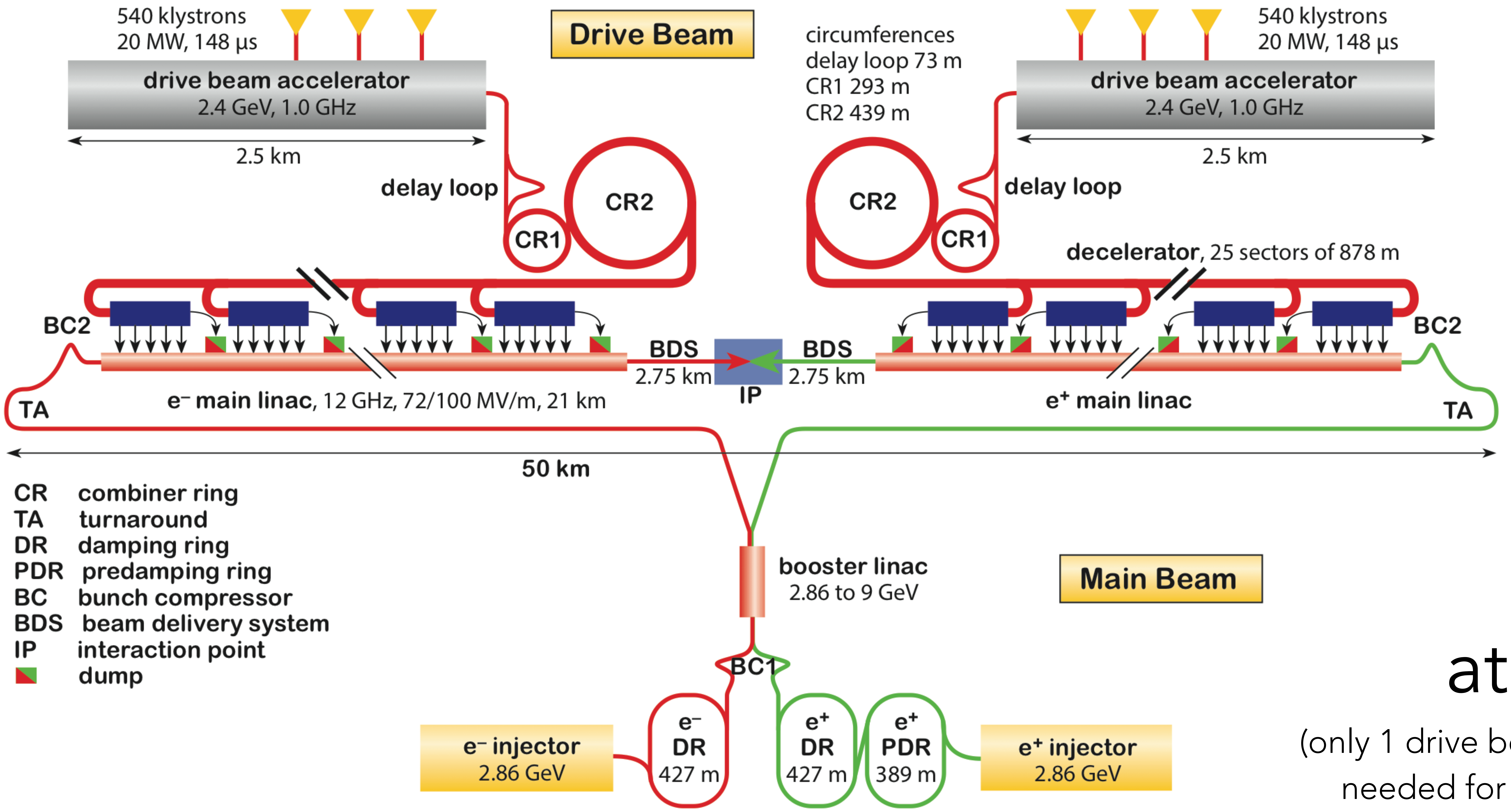
The electron drive beams supplies RF power



Main beams

The beam of electrons is set to collide with the beam of positrons after acceleration

CLIC - Two Beam Acceleration Scheme

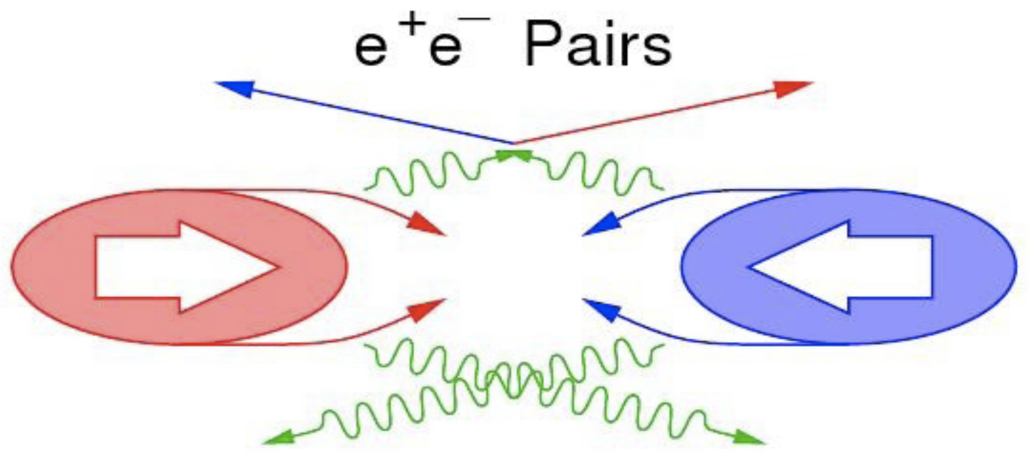


at 3 TeV

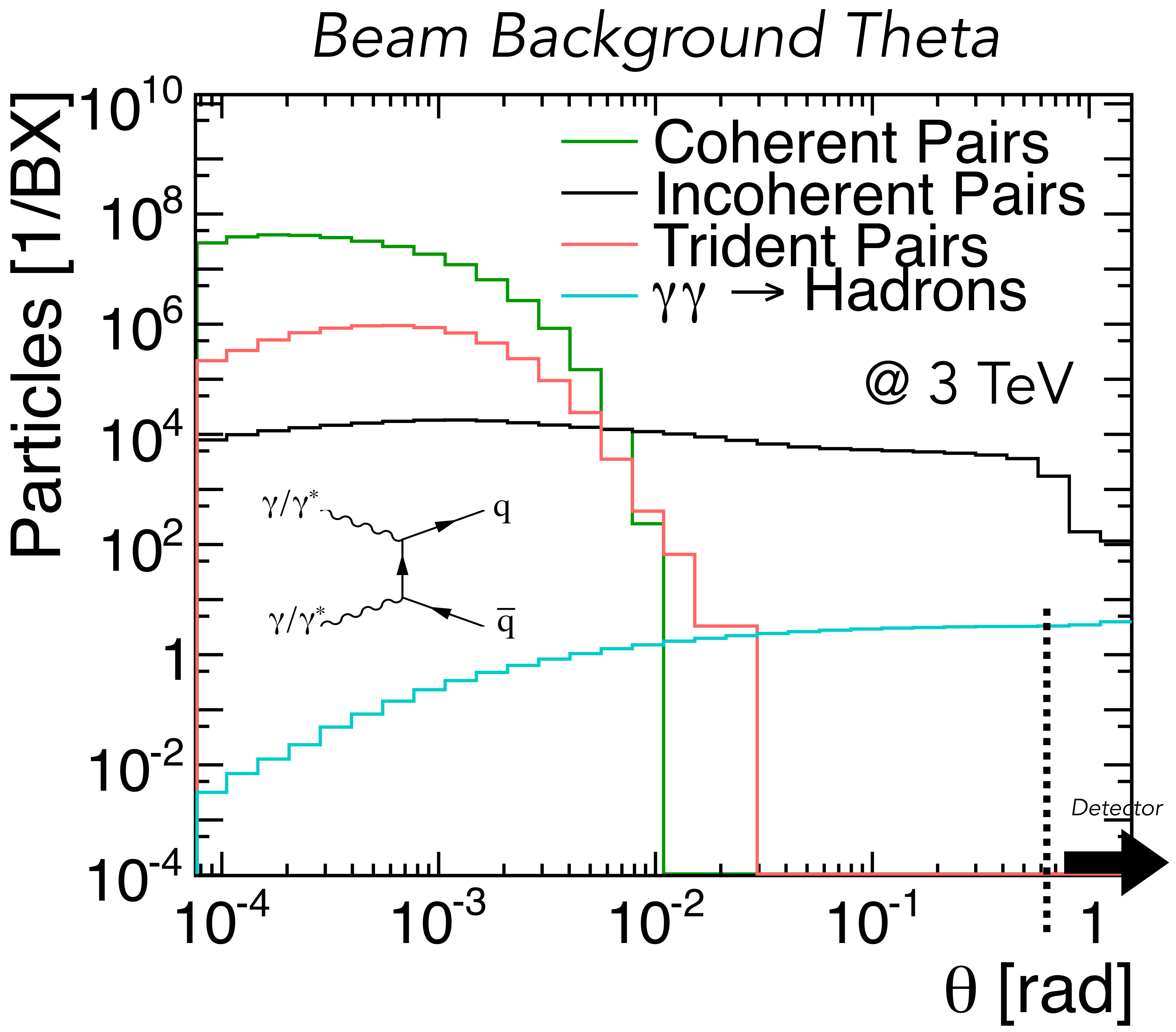
(only 1 drive beam complex needed for first 2 stages)

CLIC Accelerator Environment

- The beam (and bunch) structure is rather distinct, with a bunch-to-bunch spacing of 0.5 ns
- Very small beam size at IP leads to very high EM-fields, i.e. interactions between colliding bunches, so-called Beamstrahlung, even in the absence of a 'hard' interaction (~1 interesting event per bunch train)



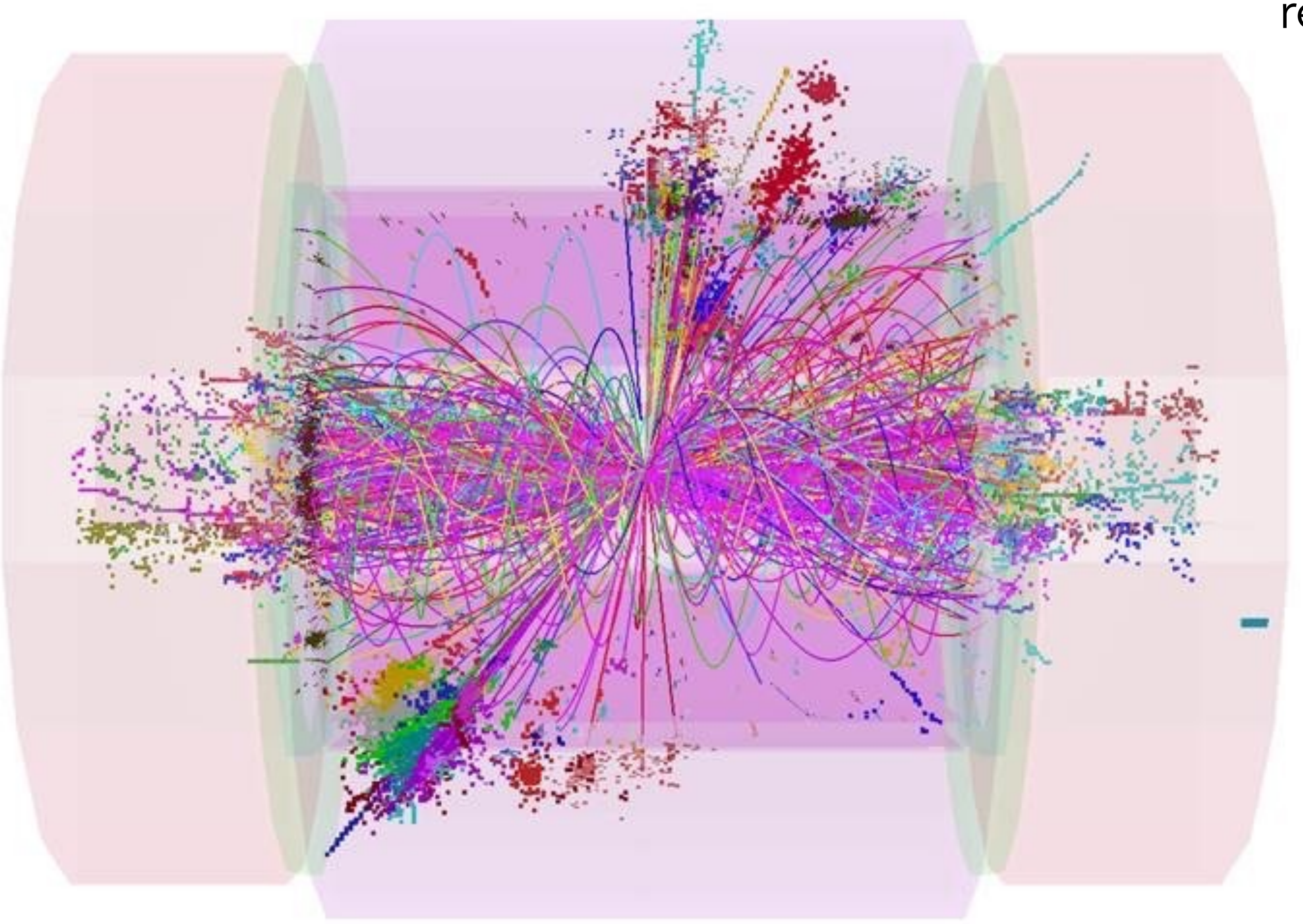
- **Coherent e^+e^- pairs:** 7 x 10^8 per BX, very forward
- **Incoherent e^+e^- pairs:** 3 x 10^5 per BX, rather forward, high occupancy, impact on detector design
- $\gamma\gamma$ → **hadrons:** 3.2 events per BX at 3 TeV (1.3 at 1.4 TeV), main background in calorimeters and trackers, impact on physics
- Reduced to manageable level by combined p_T and timing cuts in the sub-detectors



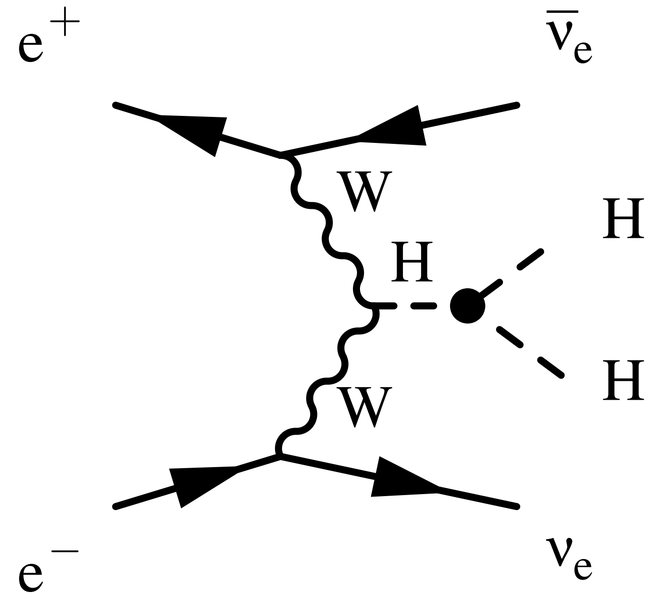
- Energy losses right at the interaction point leads to luminosity spectrum: most processes studied well above production threshold and profit from full luminosity, e.g. full luminosity at 3 TeV: 5.9 x 10^{34} $cm^{-2}s^{-1}$ (1% most energetic 2.0 x 10^{34} $cm^{-2}s^{-1}$)

Combined p_T and Timing Cuts

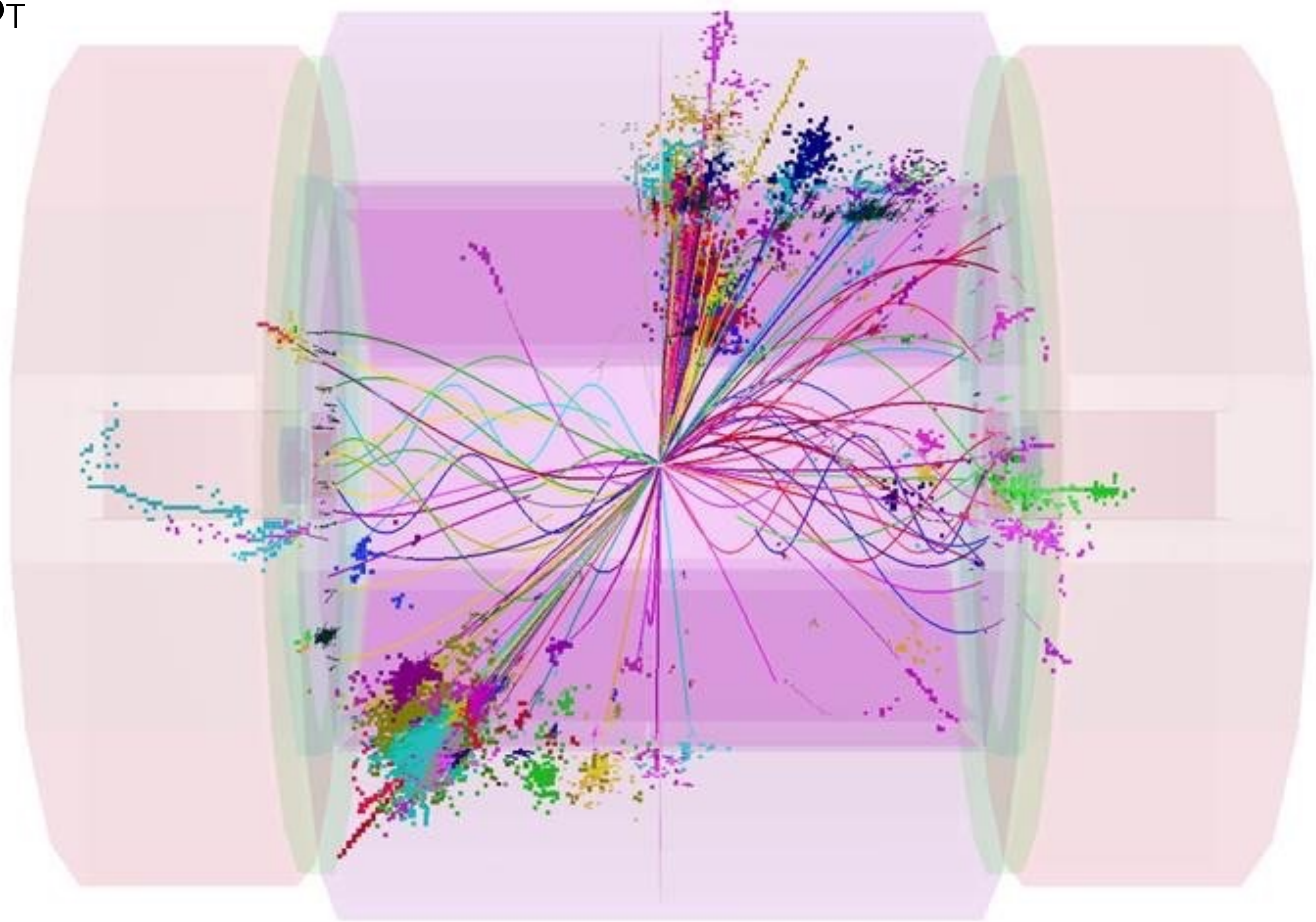
1.2 TeV background in reconstruction time window



Cuts depend on particle-type, p_T and detector region, protect high-p_T physics objects



85 GeV background after tight cuts



$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8\,\text{jets}$$

CLIC - Timeline

2013 - 2019 Development Phase

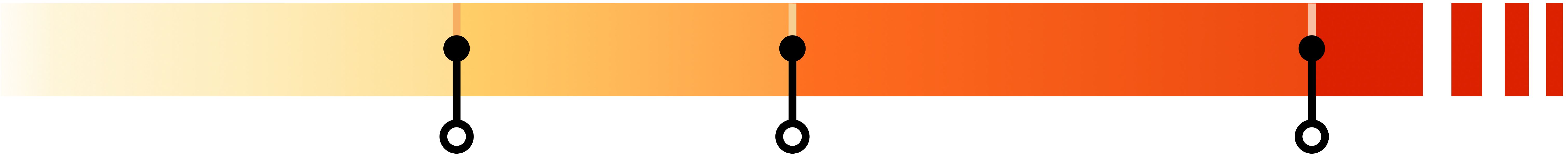
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

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

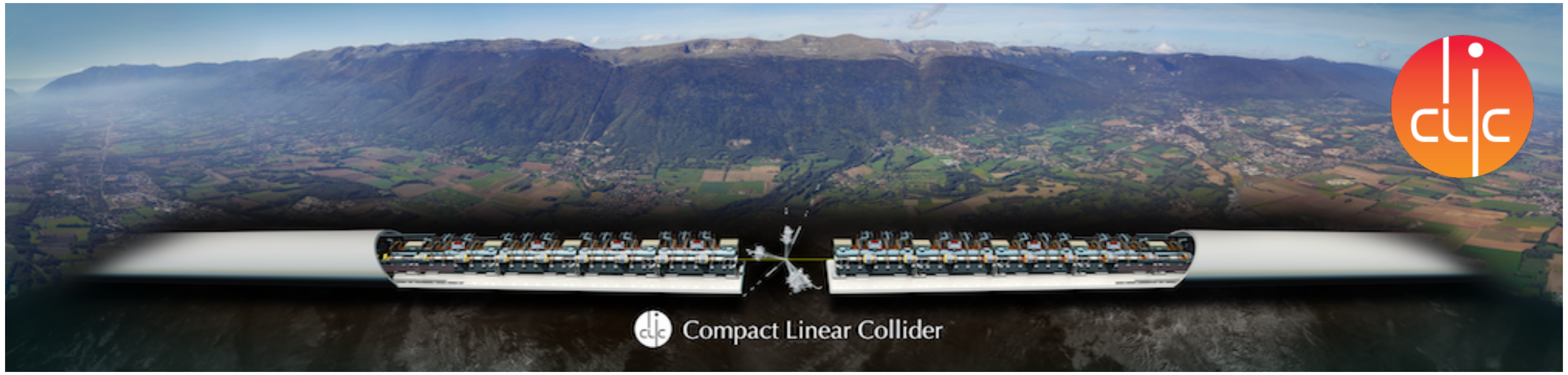
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

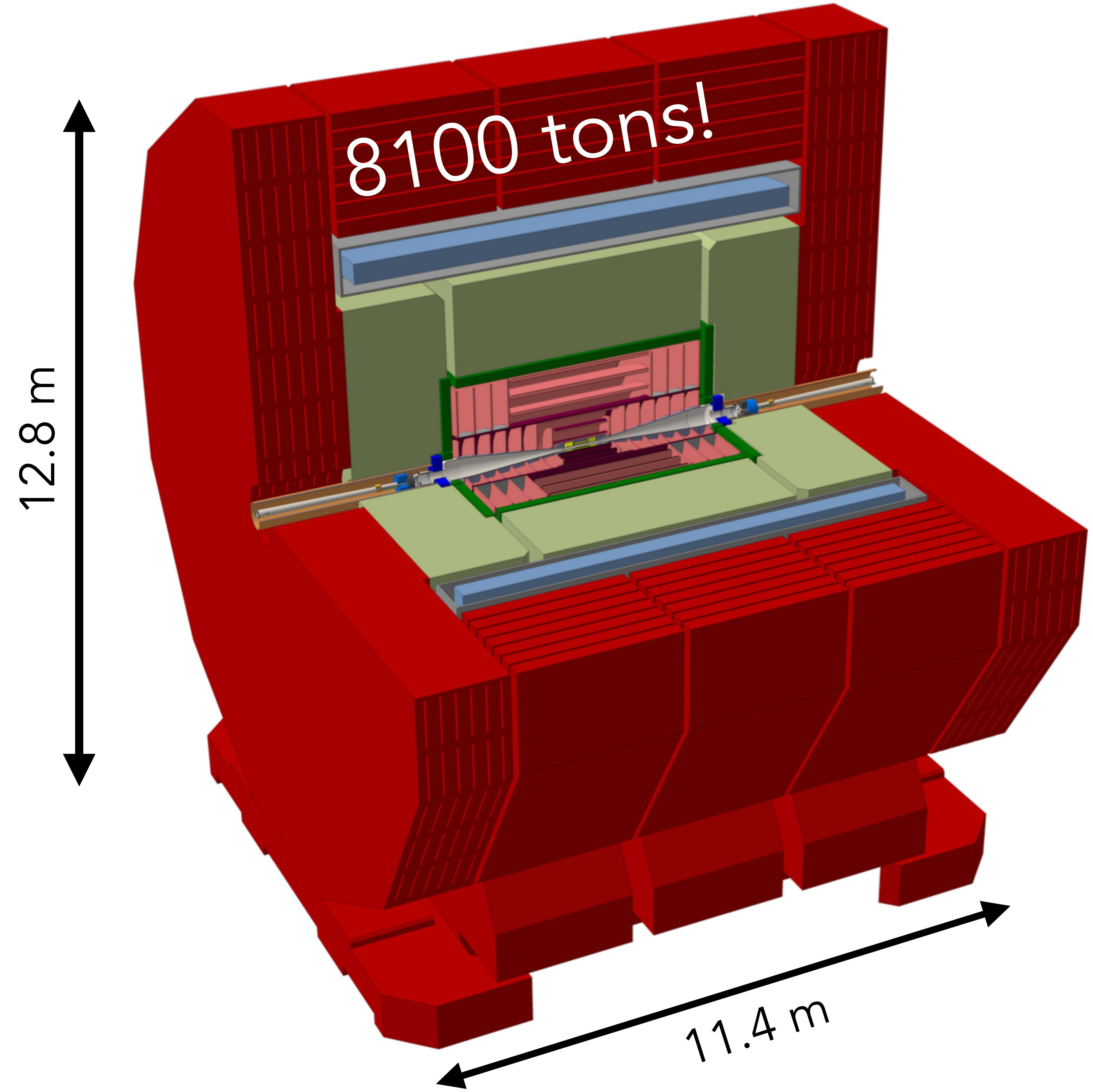
Ready for construction; start of excavations

2035 First Beams

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



CLIC Detector Overview

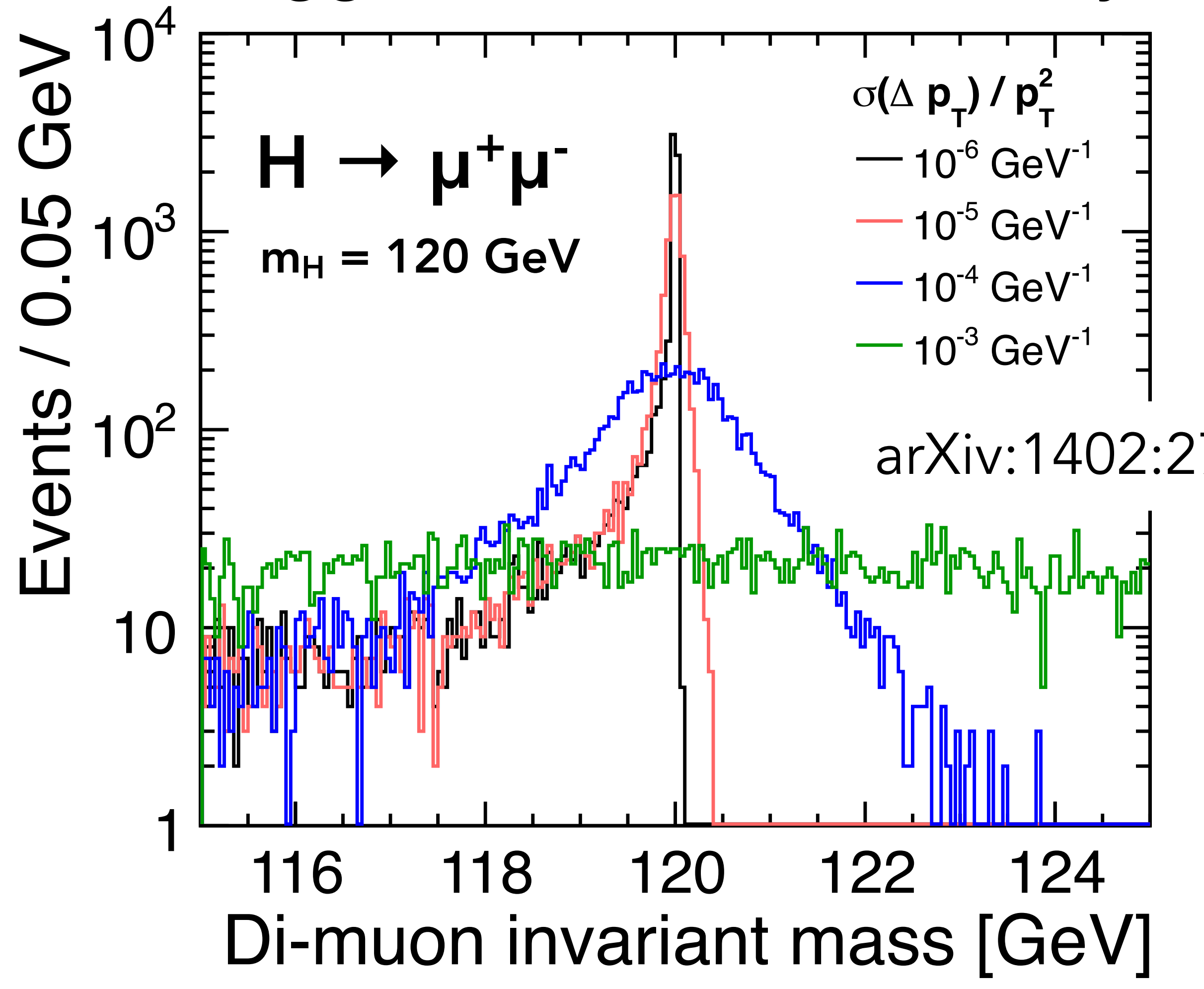


- The CLIC detector follows the overall design of GPDs at LHC
- Low mass tracking system with separate vertex detector and tracker for momentum measurement
- Fine grained calorimetry system (ECAL and HCAL) using particle flow
- Enclosed in a 4 T superconducting solenoid magnet (R_{in} = 3.4 m, L = 8.3 m)
- Iron return yoke instrumented with muon chambers, for muon identification
- Complex forward region: LumiCal (luminosity monitoring), BeamCal (extended coverage)

Detector Requirements

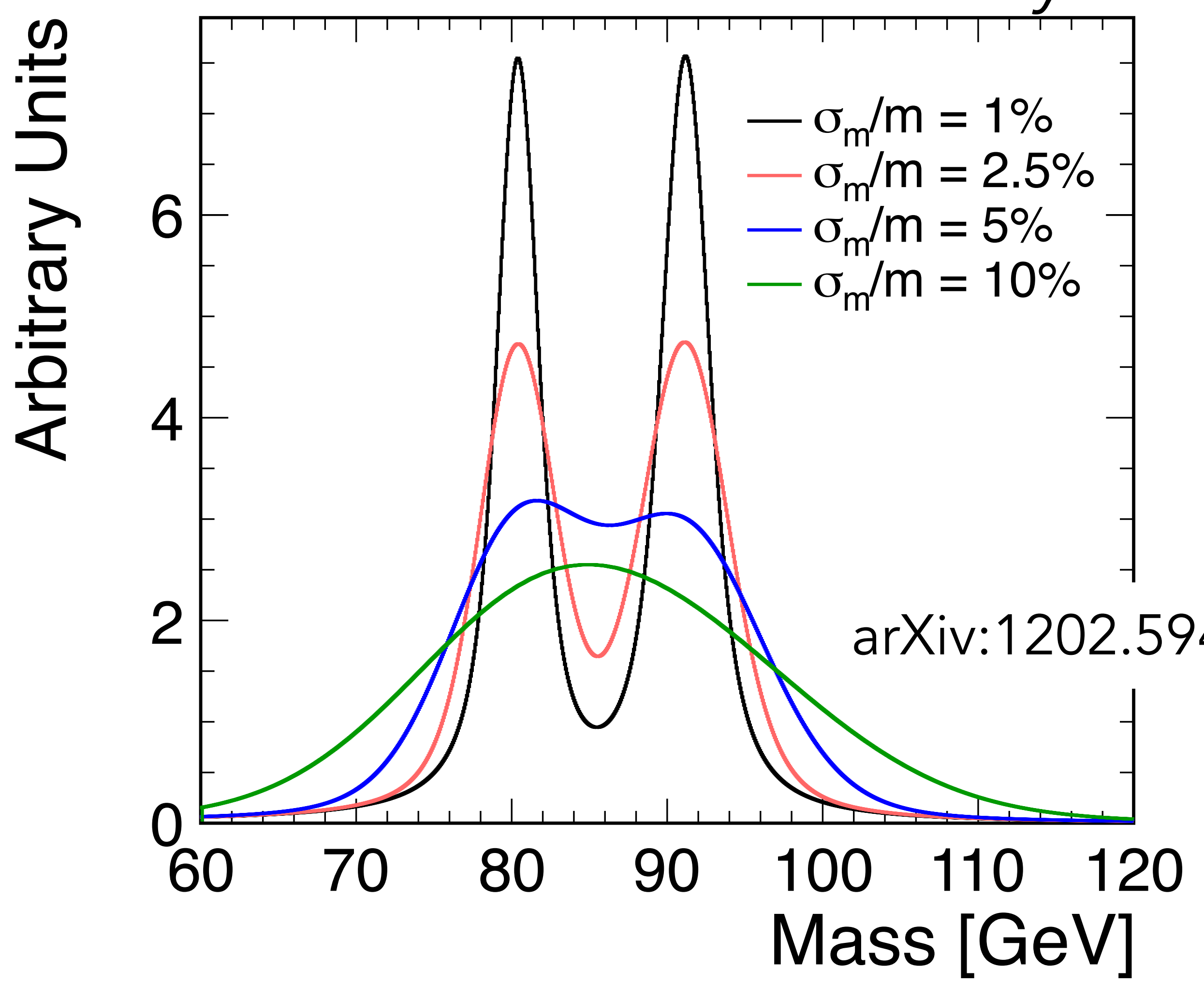
- **Impact parameter resolution** - High-resolution pixel detector for flavour tagging
- Small cell sizes needed for pattern recognition/background rejection (beyond what is needed for resolution since high tracker occupancy)
- **Track momentum resolution** - $\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}$ GeV^{-1}
- Need very good **jet-energy resolution** to distinguish W/Z di-jet decays, to be reached with Particle Flow Algorithm (PFA), $\sigma_E / E \sim 3.5$ % for jet energies in the range 100 GeV - 1 TeV
- Interactions between colliding bunches constitute large **experimental background** ($\gamma\gamma \rightarrow$ hadrons / e^+e^- pairs)
- Overall need for **precise timing** to suppress background:
  - ~10 ns hit time-stamping in vertex/tracker detector
  - 1 ns accuracy for calorimeter hits
- **Angular coverage** - Lepton identification, missing energy, very forward e-tagging

Higgs mass resolution study



arXiv:1402:2780

Jet mass resolution study



arXiv:1202.5940

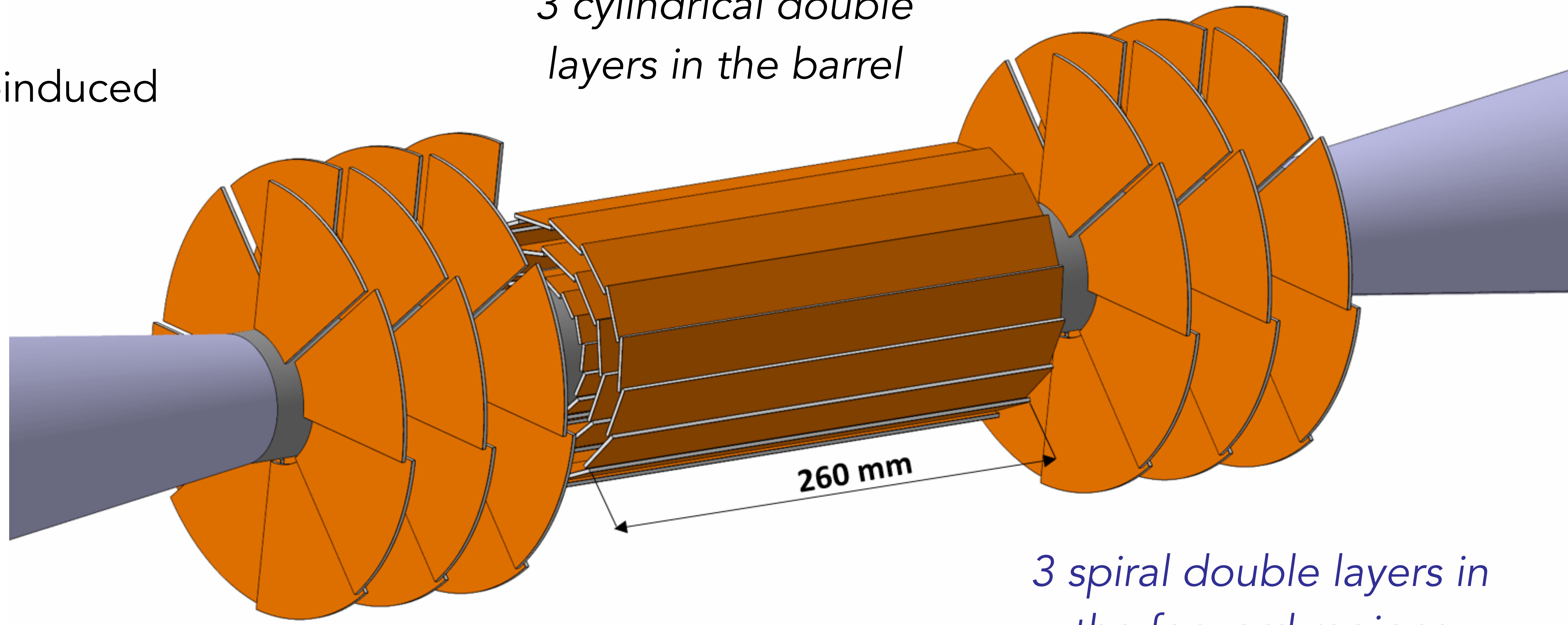
The CLIC Vertex Detector

- To reach impact parameter resolution: very thin materials/sensors: 0.2% X_0 material per layer (equivalent to 200 μm of Si)
- Roughly 2 billion pixels, each 25 μm square with a single point resolution of ~3 μm (needed for efficient flavour tagging)

- No material budget for liquid cooling. Cooling is achieved via:
  - Active air cooling strategy that induces a spiral airflow
  - Power-pulsing of the front-end electronics
- 10 ns time-tagging resolution to reduce beam-induced backgrounds

- Current technology choice assumes 25 μm square pixels, using hybrid pixel technology
  - ASIC thickness 50 μm connected to 50 μm sensor
  - Slim edge planar sensors and HV-CMOS both considered

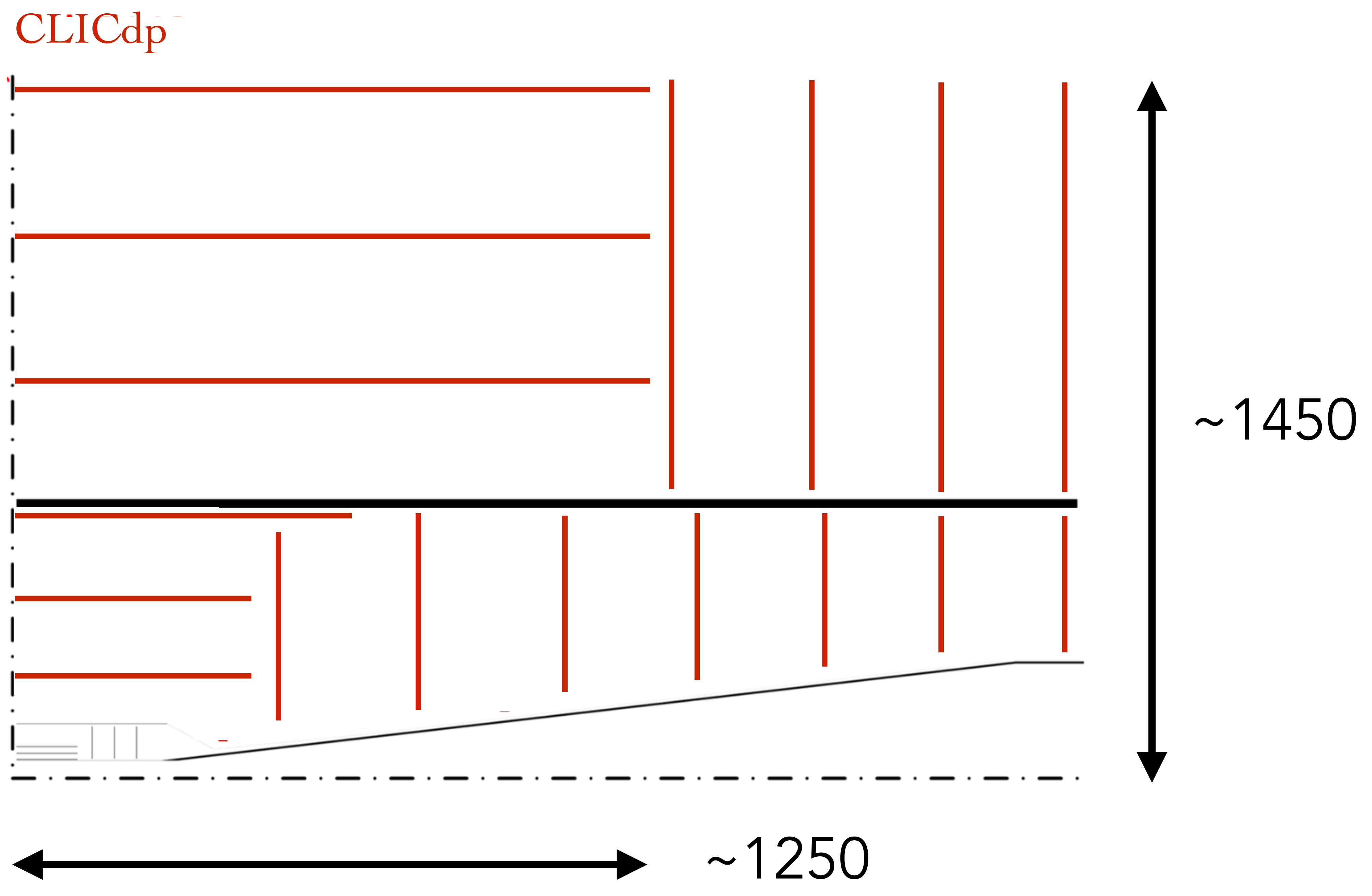
3 cylindrical double layers in the barrel



3 spiral double layers in the forward regions

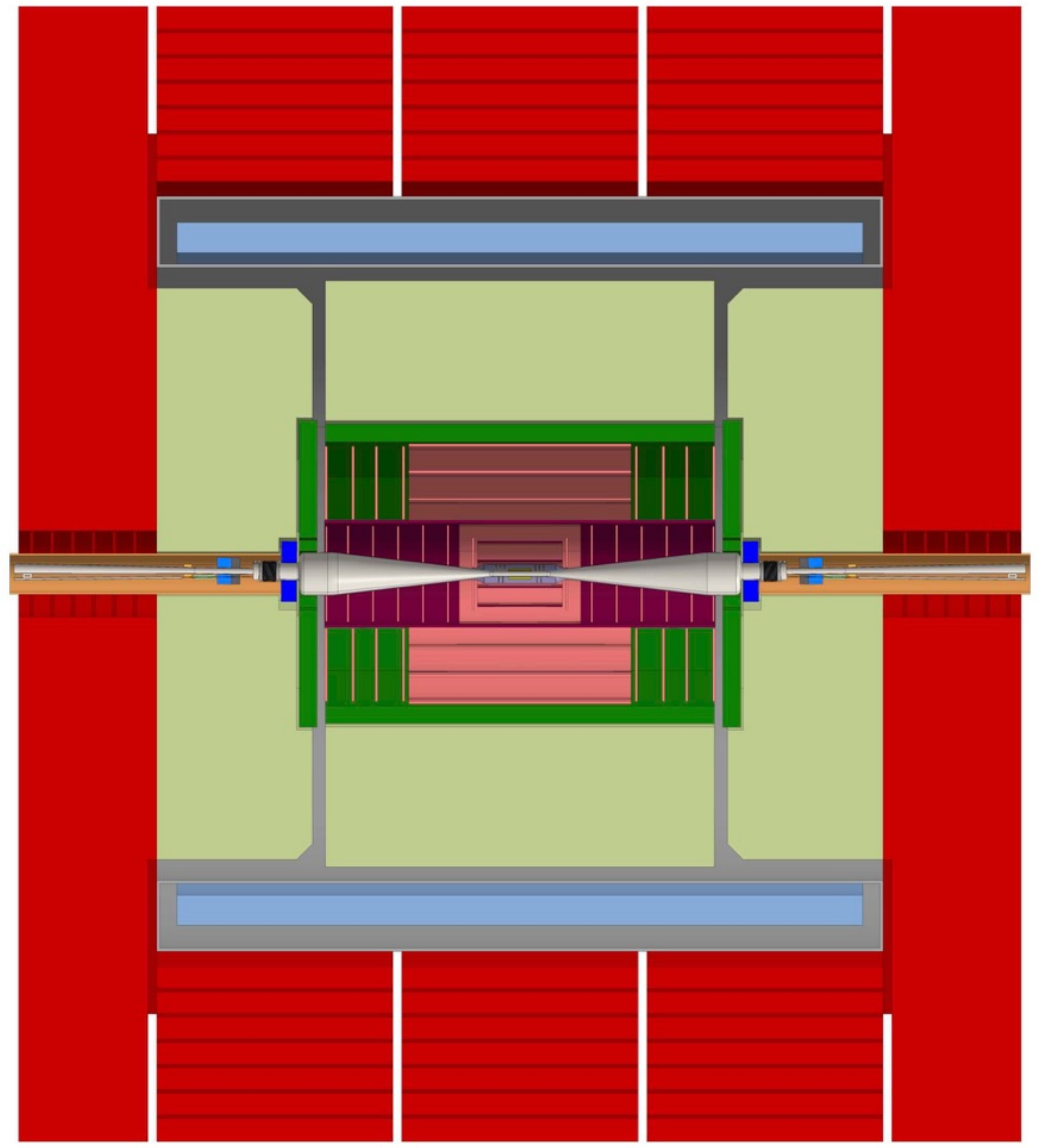
The CLIC Tracker

- To provide the required track momentum resolution of $\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}$ GeV^{-1} build a **large** Silicon tracking volume in a 4 T magnetic field
- Single point resolution of ~7 μm
- Large occupancy from beam-induced background - short strips/long pixels
- Low material budget 1-2% X_0 per layer



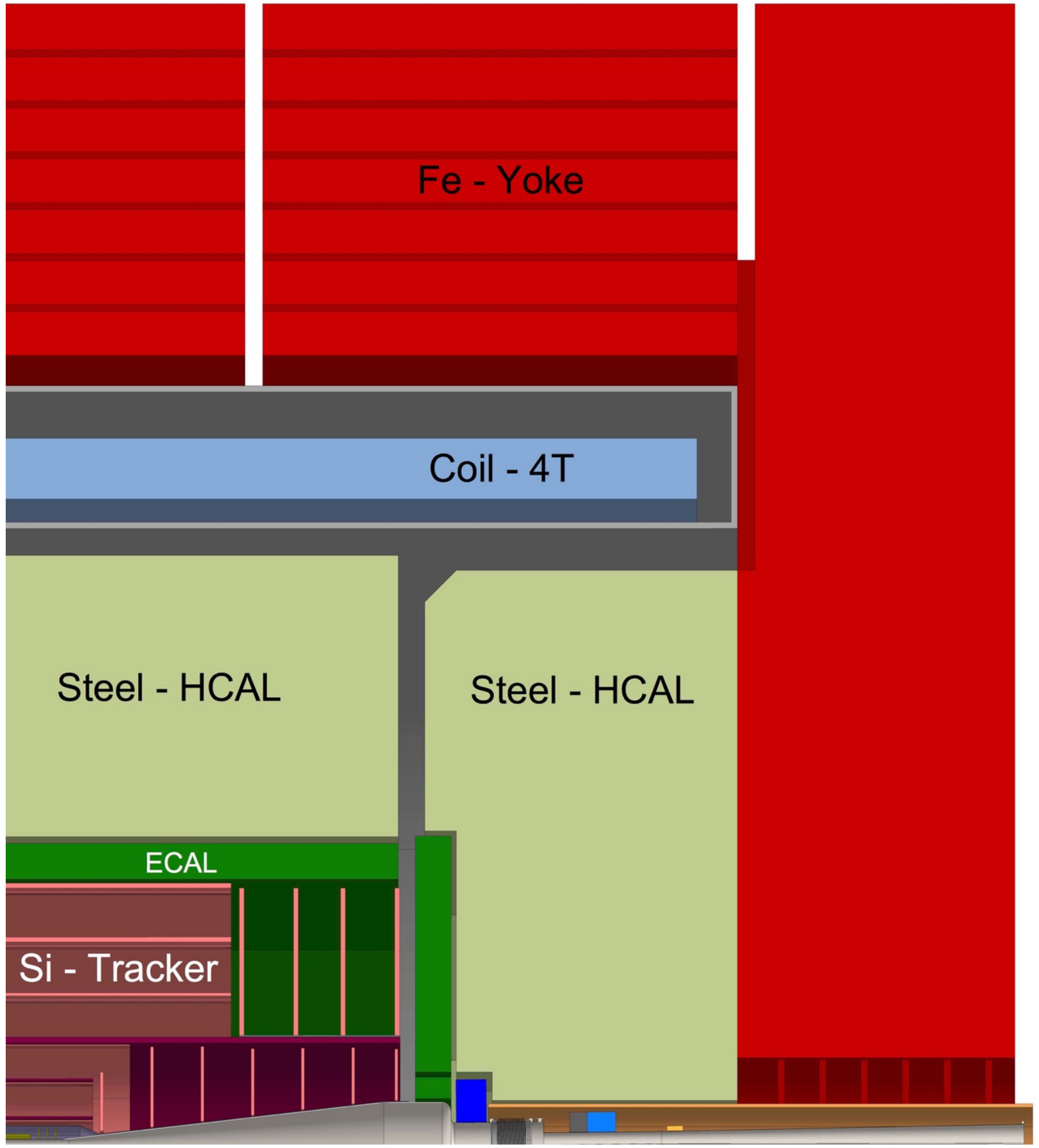
Larger radius than CMS tracker, same material budget as ALICE

Mechanically a great challenge



- Tracker expected to be split into two regions:
  - Inner tracker with 3 barrel layers and 7 forward disks
  - Outer tracker with 3 barrel layers and 4 forward disks
  - Support shell separating inner and outer trackers
- Integrated CMOS design being considered

The CLIC Calorimeter



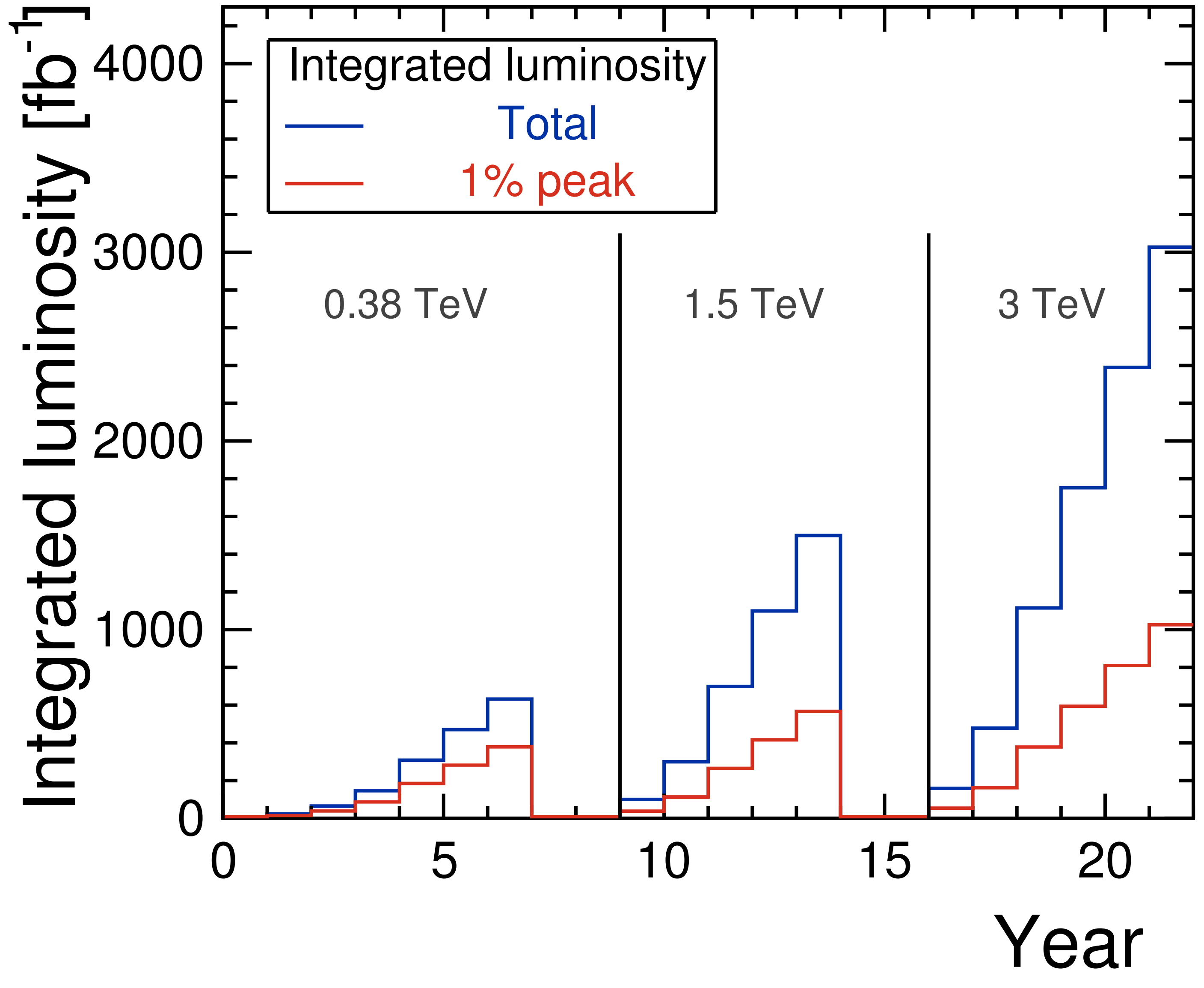
- ECAL - 40 layers of tungsten absorbers interleaved with silicon sensors of 5x5 mm^2 (corresponding to 23 X_0)
- Configuration re-optimised to ensure good resolution of high energetic photons
- HCAL - 60 layers of steel absorbers interleaved with scintillator tiles of 30x30 mm^2
- The CLICdp collaboration contributes to the CALICE and FCAL R&D collaborations, which have constructed and tested fine-grained SiW ECALs, a 1m^3 prototype ScW HCAL and forward calorimeter prototypes

- Jet energy resolution drives the overall detector design
  - Fine-grained calorimetry + Particle Flow Analysis (PFA)

Physics at CLIC - A Staged Programme

- To fully exploit physics case we need several energy stages going up to multi-TeV energies - defined by physics case w. considerations for technical constraints
- **380 GeV** / **1.5 TeV** / **3.0 TeV**
- Incl. 100 fb^{-1} at 350 GeV for top mass threshold scan

Each stage corresponds to 5-7 years



CLIC Integrated luminosity

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

1) $\sqrt{s}$ = 380 GeV (500 fb^{-1})

- Higgs/Top precision physics
- Top mass threshold scan (350 GeV)

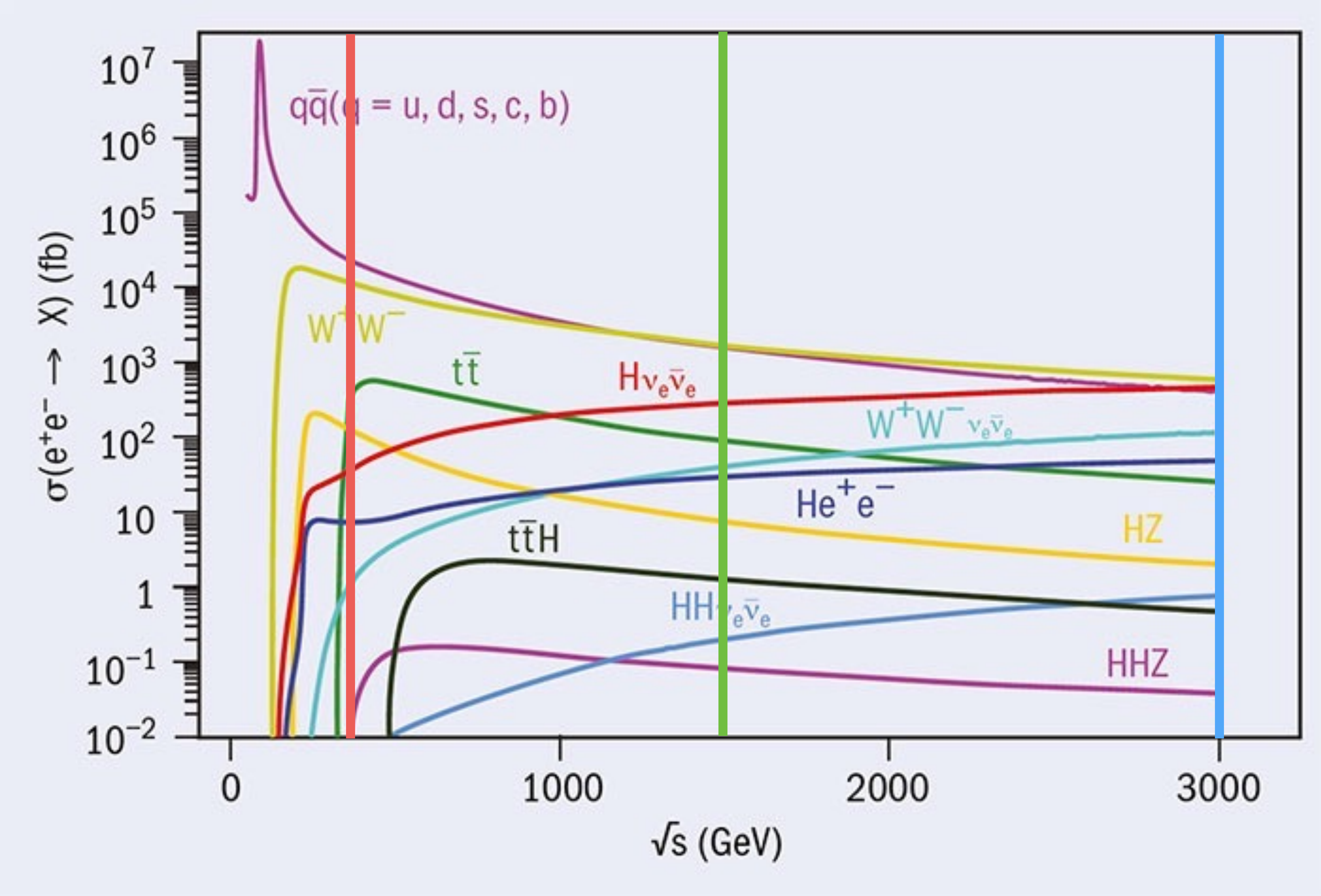
2) $\sqrt{s}$ = 1.5 TeV (1.5 ab^{-1})

- Target: Precision SUSY, BSM reach
- Higgs/Top precision physics
- Rare Higgs decays
- Top Yukawa coupling

3) $\sqrt{s}$ = 3 TeV (3.0 ab^{-1})

- Target: Precision SUSY, BSM reach
- Higgs self-coupling
- Rare Higgs decays

Physics at CLIC - A Staged Programme



Processes that will be there

- Standard Model
- Z, W, H, t production
- Understanding, "bookkeeping"

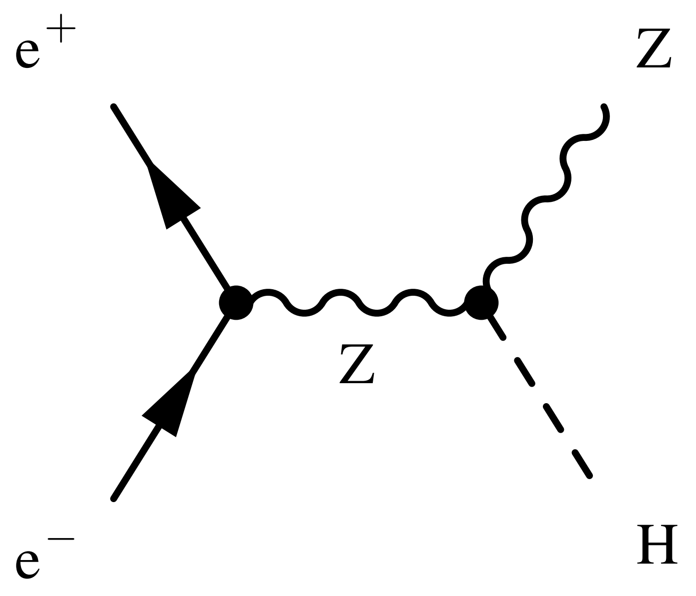
Top/Higgs measurements have exquisite discovery potential, often more than your favourite "*bump hunt*"!

Slow rise for t-channel processes:
$e^+e^- \rightarrow$ Hνν, He^+e^- , HHνν, WWνν

s-channel thresholds:
160 WW, 215 HZ, 340 HHZ, 350 tt, 500 ttH

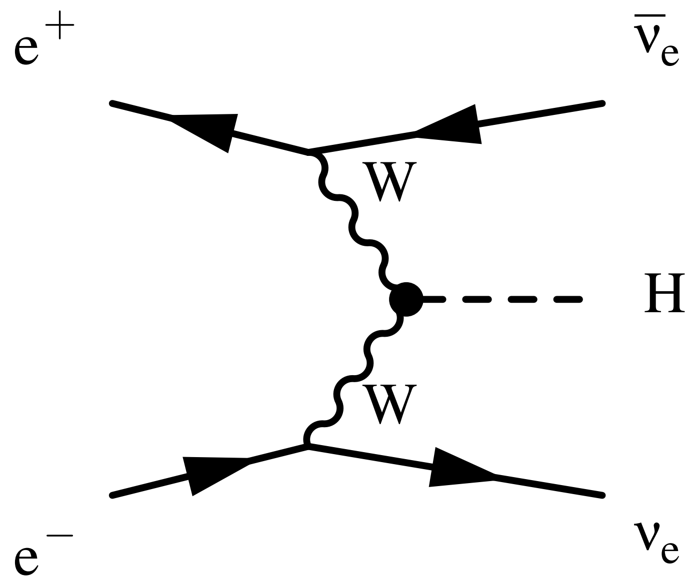
Higgs Physics at CLIC

Dominant Higgs production



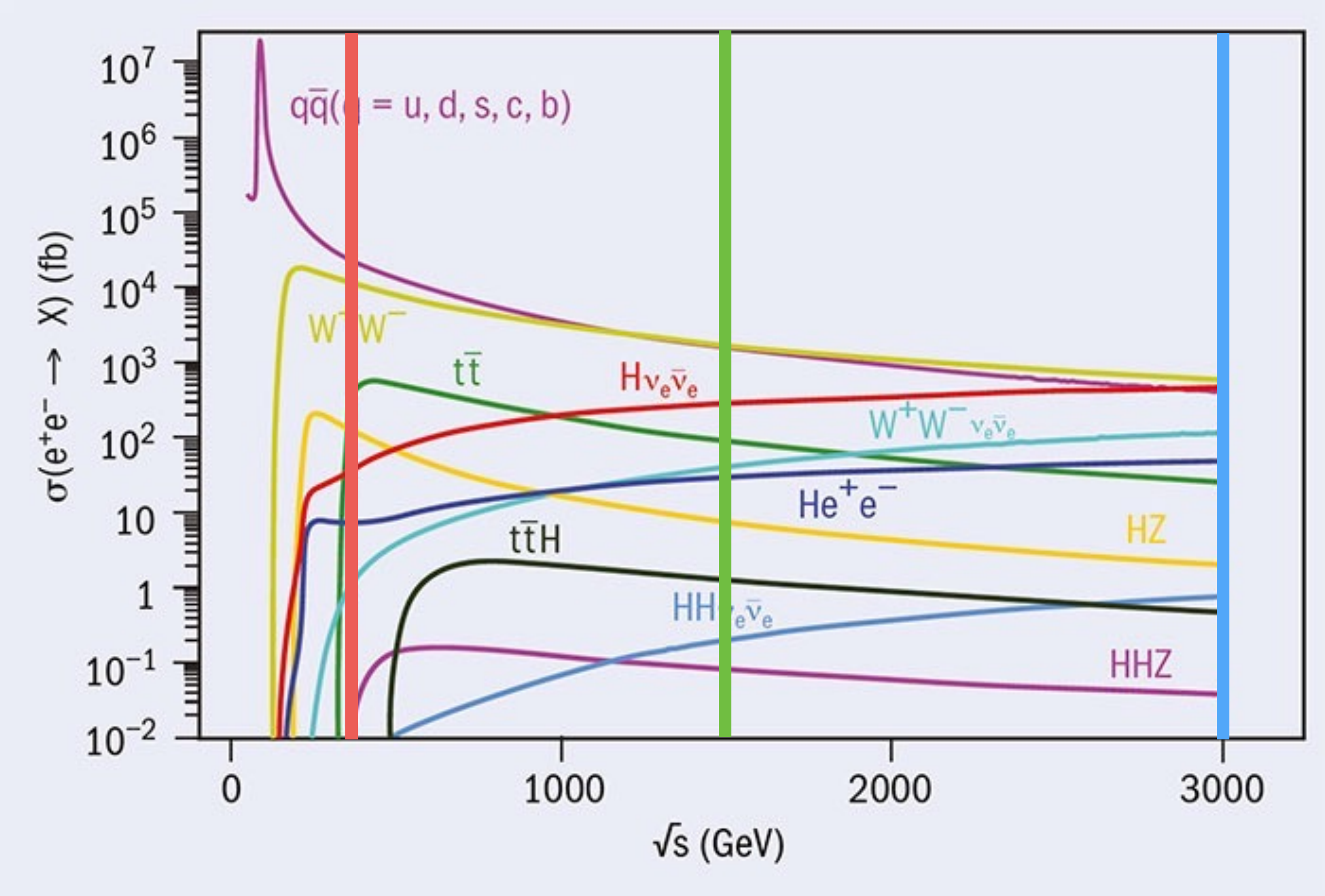
Higgsstrahlung $e^+e^- \rightarrow ZH$

σ~1/s, Higgs id. from Z recoil



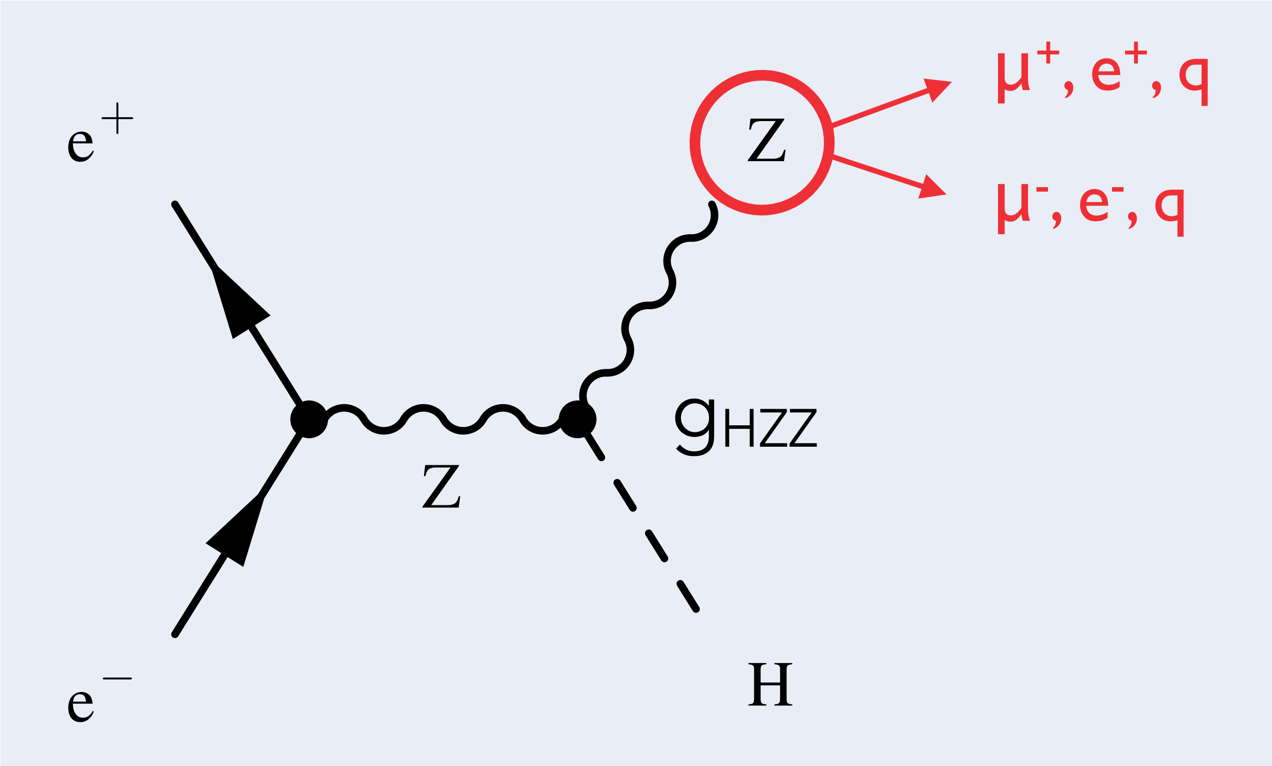
Vector-boson fusion

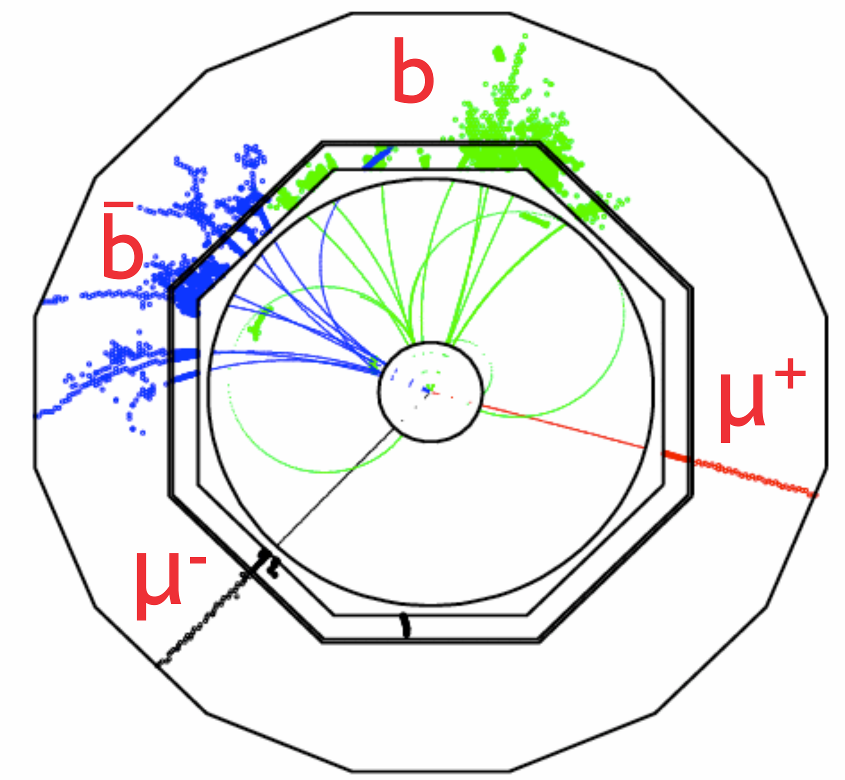
σ~log(s), large statistics at high energy

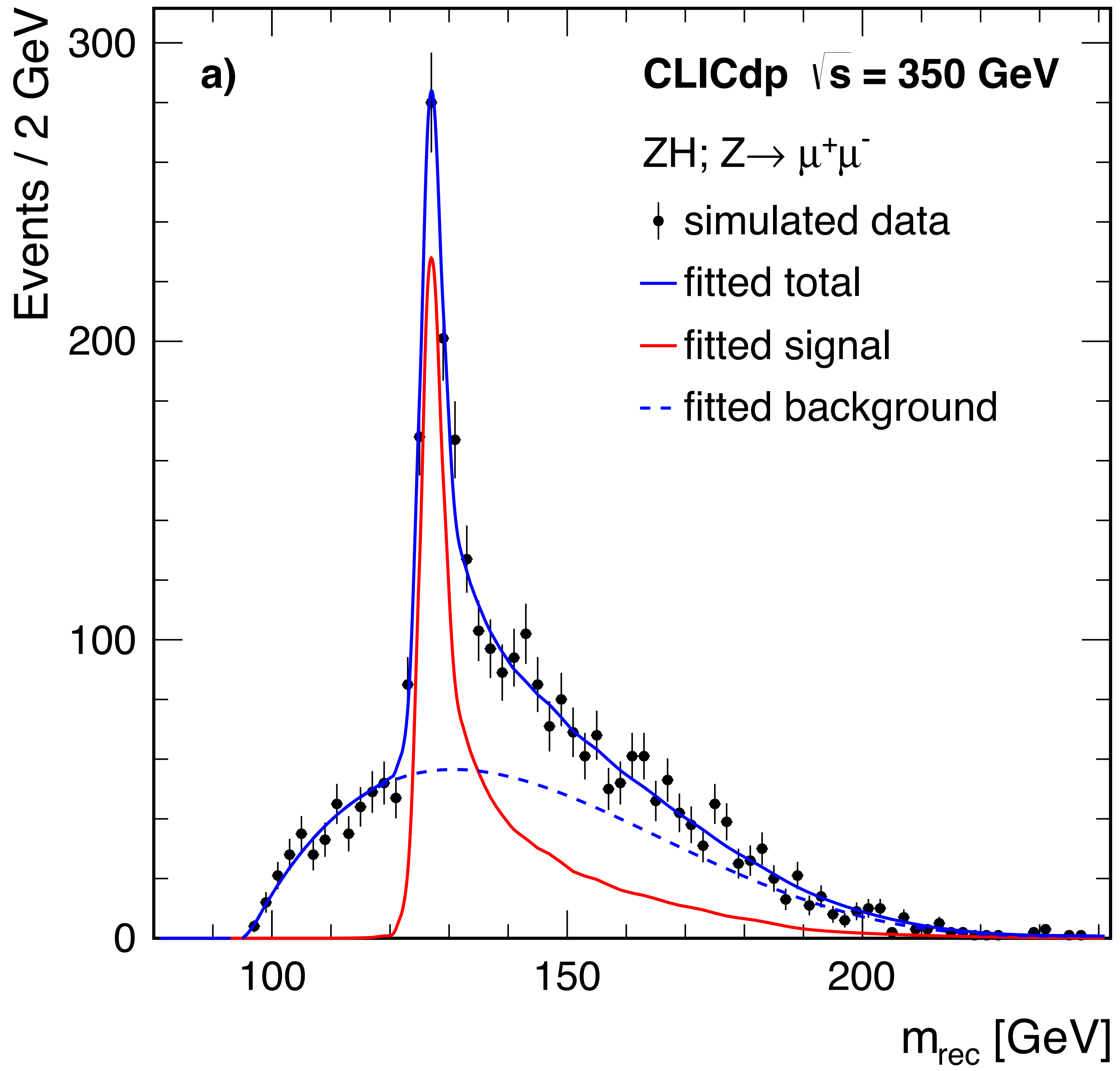


- Any deviation from SM Higgs couplings and its properties represents evidence for new physics
- Precision Higgs/top physics is the main motivation for CLIC operation at 380 GeV
- To fully exploit physics case we need several energy stages going up to multi-TeV energies
- CLIC covers several Higgs production processes, Higgs factory!
- Model-independent Higgsstrahlung process unique to lepton colliders
- Higgs couplings can be determined with a sub-percent statistical uncertainty

Higgsstrahlung $e^+e^- \to ZH$

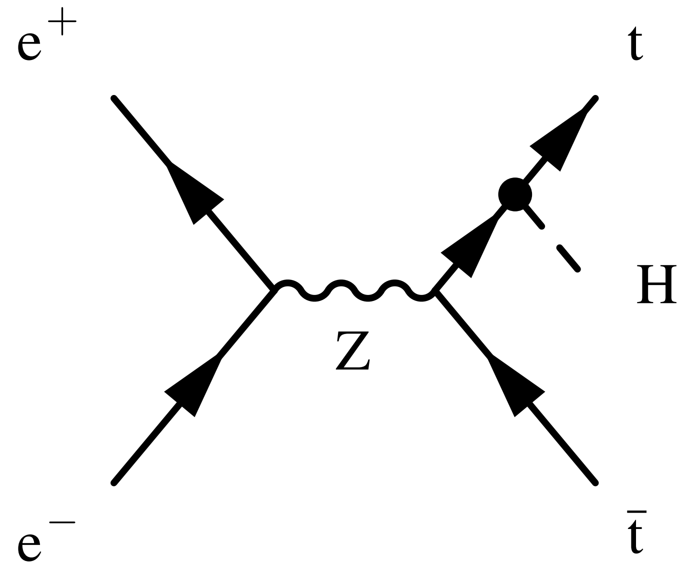






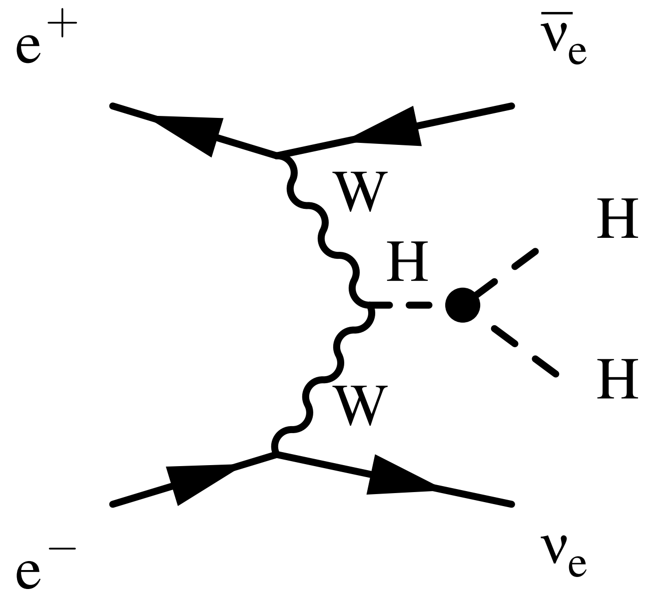
Z → μ⁺μ⁻ recoil

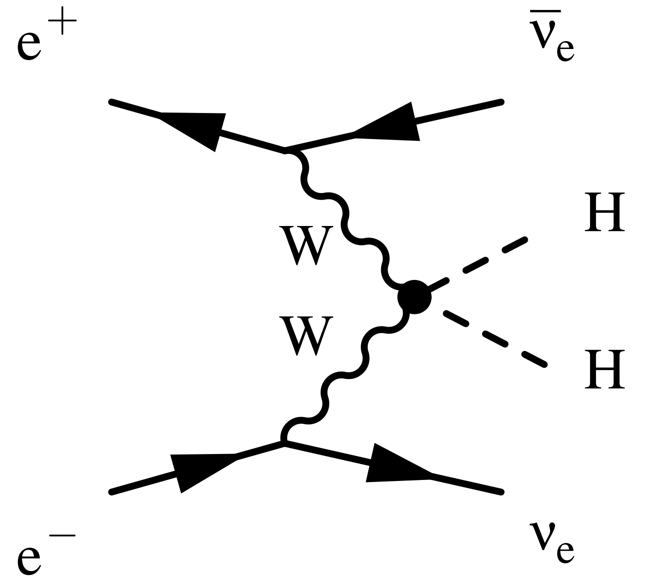
- Sets the absolute scale for all model-independent Higgs coupling measurements
- Model-independent measurements of Higgs properties from Z-recoil mass
- Independent of the Higgs decay mode
- Combined analysis ($Z \to e^+e^-$, $Z \to \mu^+\mu^-$, $Z \to qq$):
  - Absolute coupling of the H boson to the Z boson, $\Delta(g_{HZZ})$ = 0.8 % (stat.)
- Unique sensitivity to invisible decay modes: $\Gamma_{invis}/\Gamma_H < 1$ % at 90 % C.L.
- High flavour-tagging efficiencies → H branching fractions
- 6.3 % (stat.) precision on the total Higgs decay width



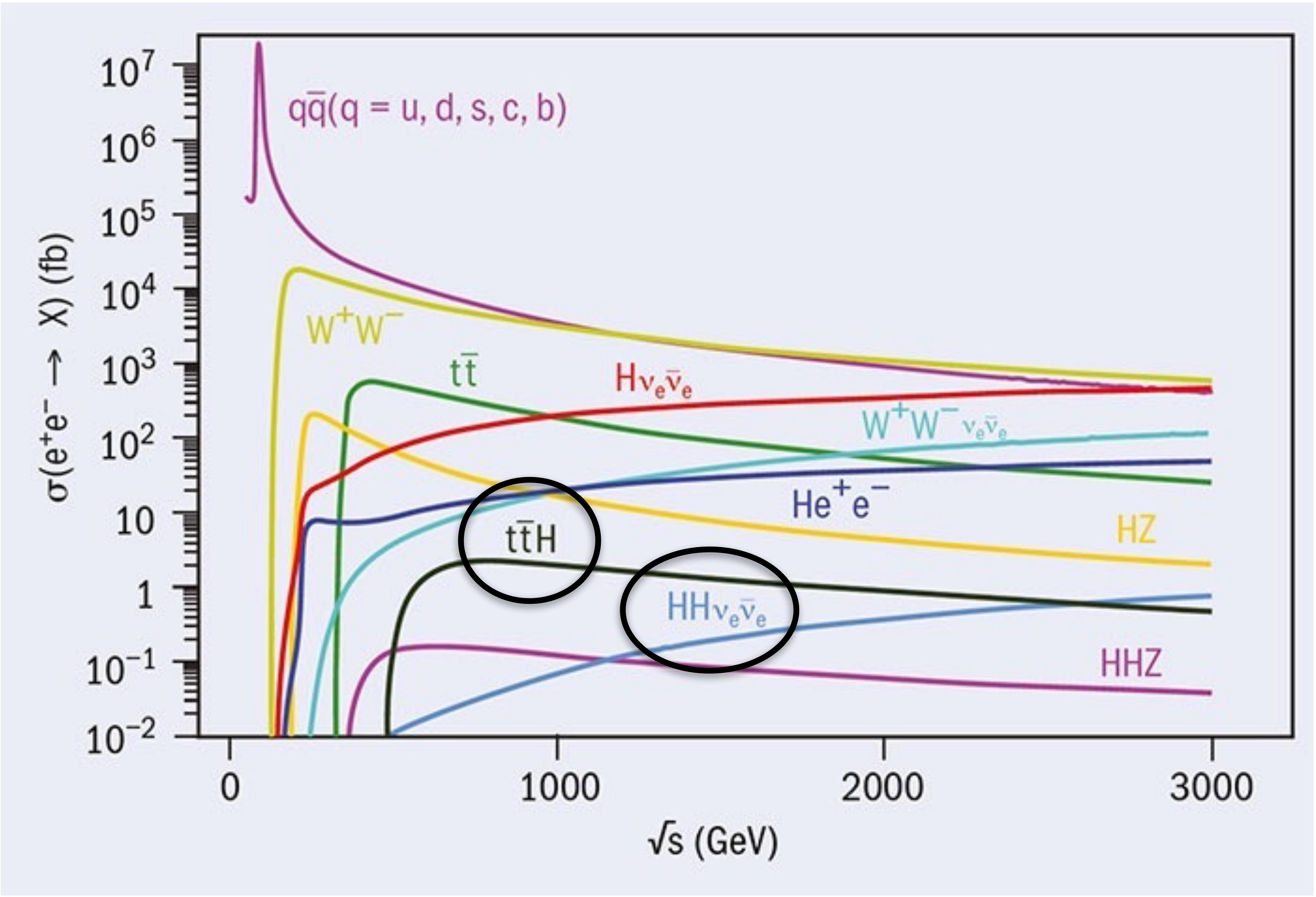
ttH production: $e^+e^- \rightarrow ttH$

- Extraction of top Yukawa coupling
- Best at centre-of-mass energy above 700 GeV
- $\Delta(g_{Htt})$ = 4-5% (stat.) at 1.4 TeV
- HL-LHC: 7-10 % (stat.) per experiment





Dominant Higgs production

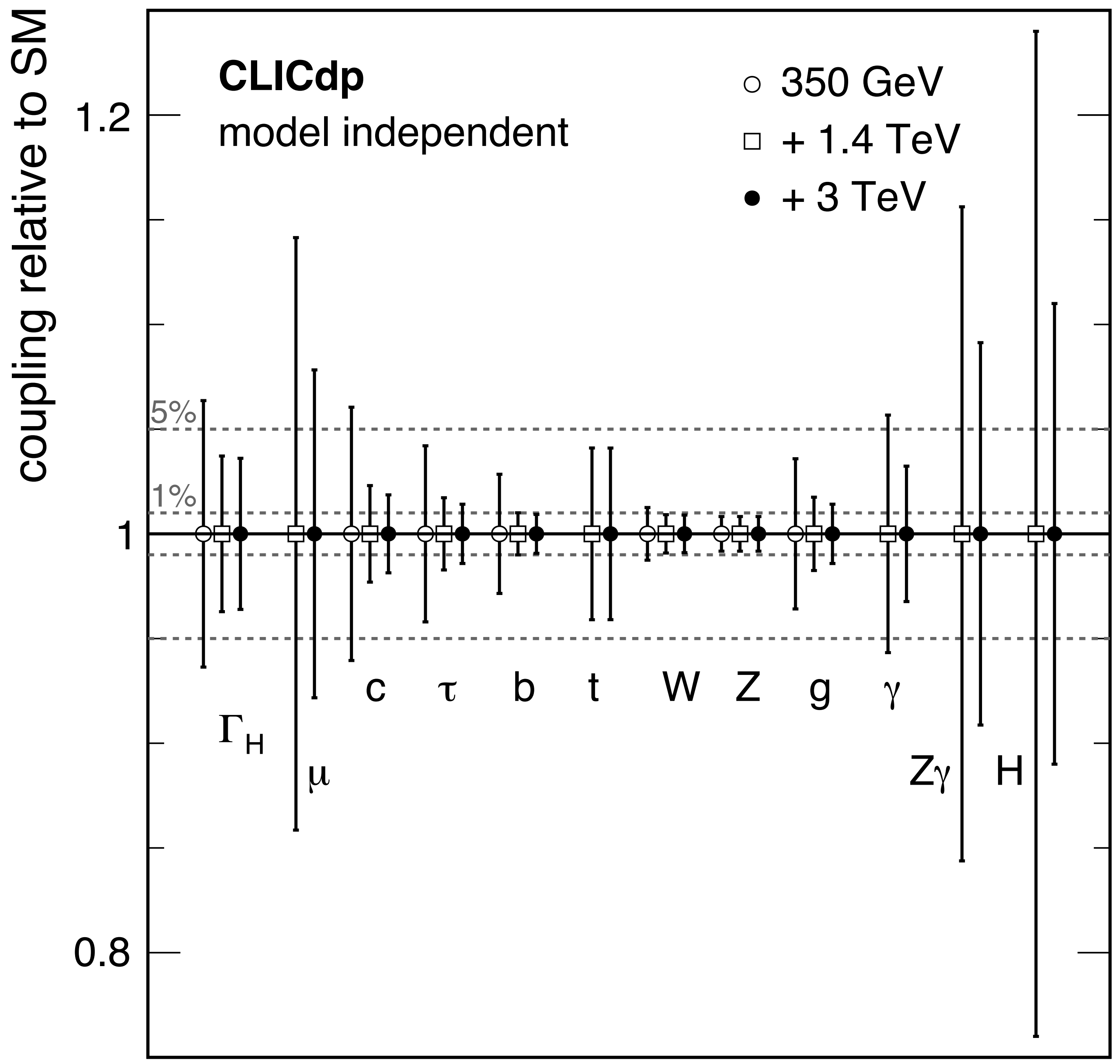


Double Higgs Production - Very high precision for CLIC

- High luminosity and high energy crucial for $e^+e^- \rightarrow HH\nu_e\nu_e$
- Only 225 (1200) $HH\nu_e\nu_e$ events at 1.4 (3) TeV
- Simultaneous extraction of tri-linear self-coupling and quartic coupling, direct probe of the Higgs potential
- Self-coupling: $\Delta(\lambda)$ = 11 % for 1.4 TeV and 3 TeV operation combined (HL-LHC: ~50 %)
- Quartic coupling g_{HHWW}: ~3 %

Combined CLIC Higgs Results

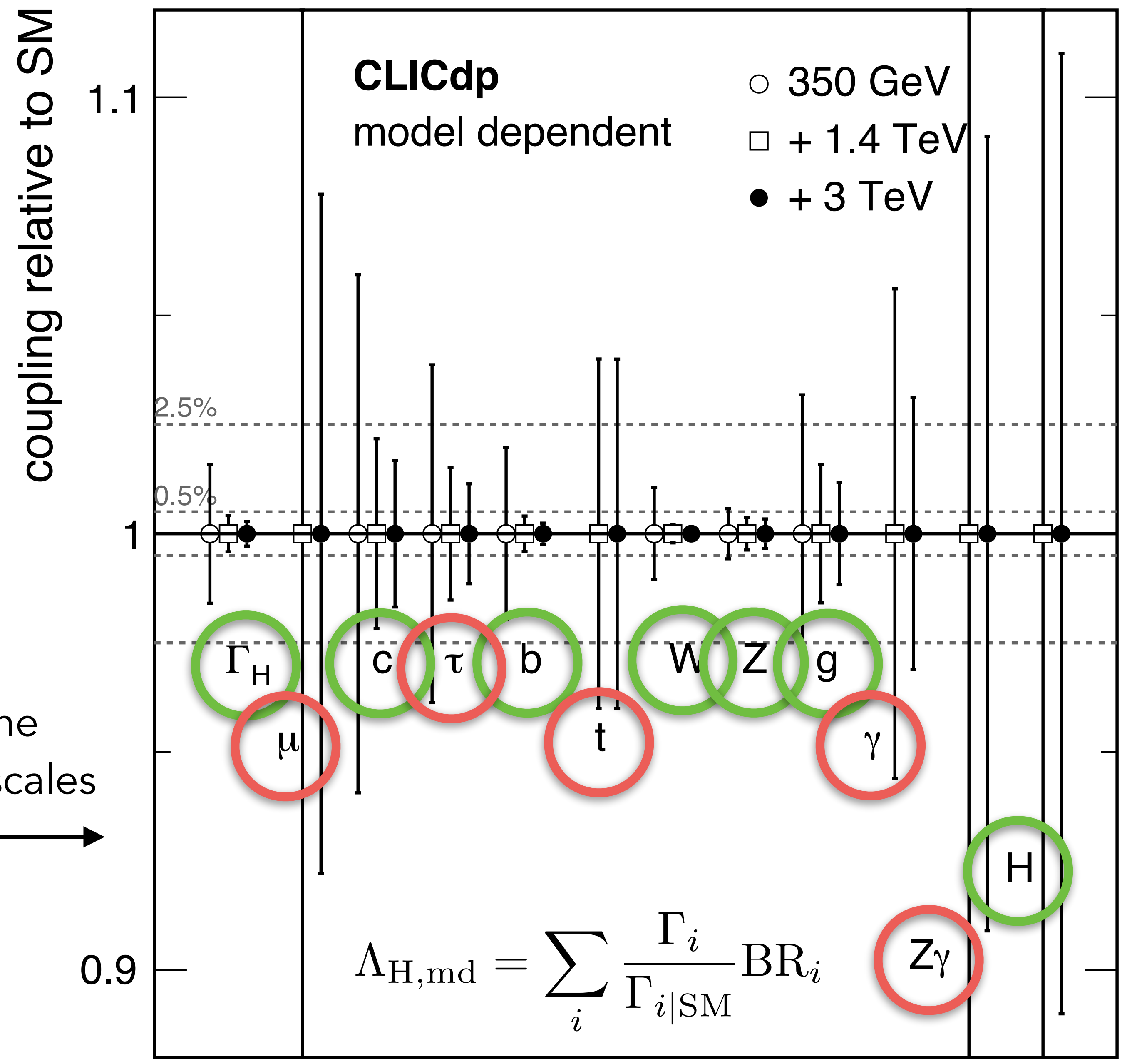
Model-independent (MI) global fits



Higgs width is a free parameter allows for additional non-SM decays.

Note the different scales

Model-dependent (MD) global fits



Constraining "LHC-style", assuming no invisible Higgs decays (model-dep.), fit to deviations from SM BR's

= *Accuracy significantly better than HL-LHC or not possible at hadron colliders*

= *Accuracy comparable to HL-LHC*

Full CLIC programme:

~5 years of running at each stage

incl. e⁻ polarisation above 1 TeV

- MI: down to ~2 % for most couplings (only at lepton colliders)
- MD: ~0.1-1 % for most couplings
- Accuracy on Higgs width:
  - ~3.6 % (MI)
  - ~0.3 % (MD, derived)
- Higgs mass with 24 MeV precision for 1.4 TeV and 3 TeV operation combined (HL-LHC: ~50 MeV per experiment)

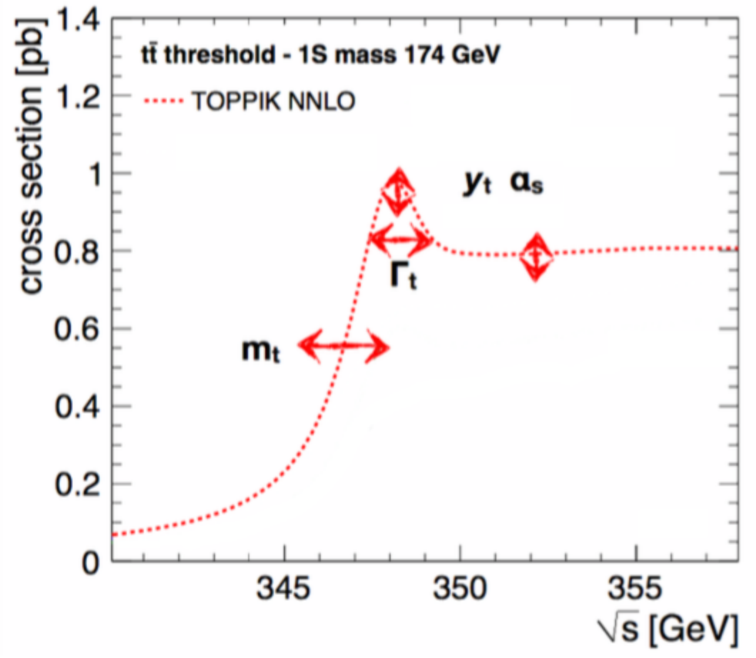
Top Physics at CLIC

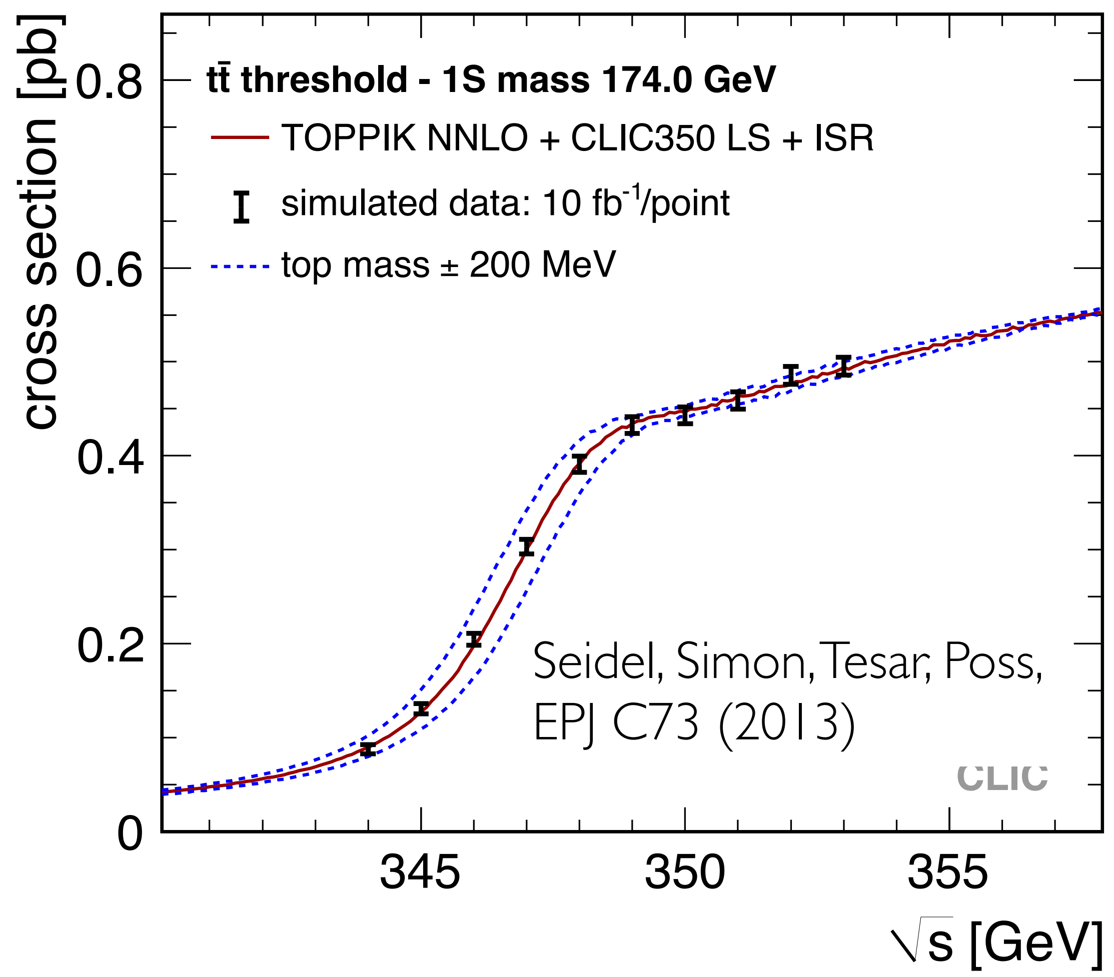
- The top quark is of particular interest - couples strongly to the Higgs field, key to understanding EWSB, relation to SM gauge bosons, compositeness
- Decays before hadronizing: the only naked quark - test ground for QCD - full advantage of the spin information
- Contributes via loops to processes that can be studied with high precision → Sensitive to BSM scenarios - may be first place a new particle shows up
- Top quark mass and the top quark couplings to Z and γ with high precision are among the main focuses of the initial stage of CLIC
- Ongoing effort to extend these studies to higher energy stages
- Competitive limits on rare decays such as $t \rightarrow cH$ and $t \rightarrow c\gamma$

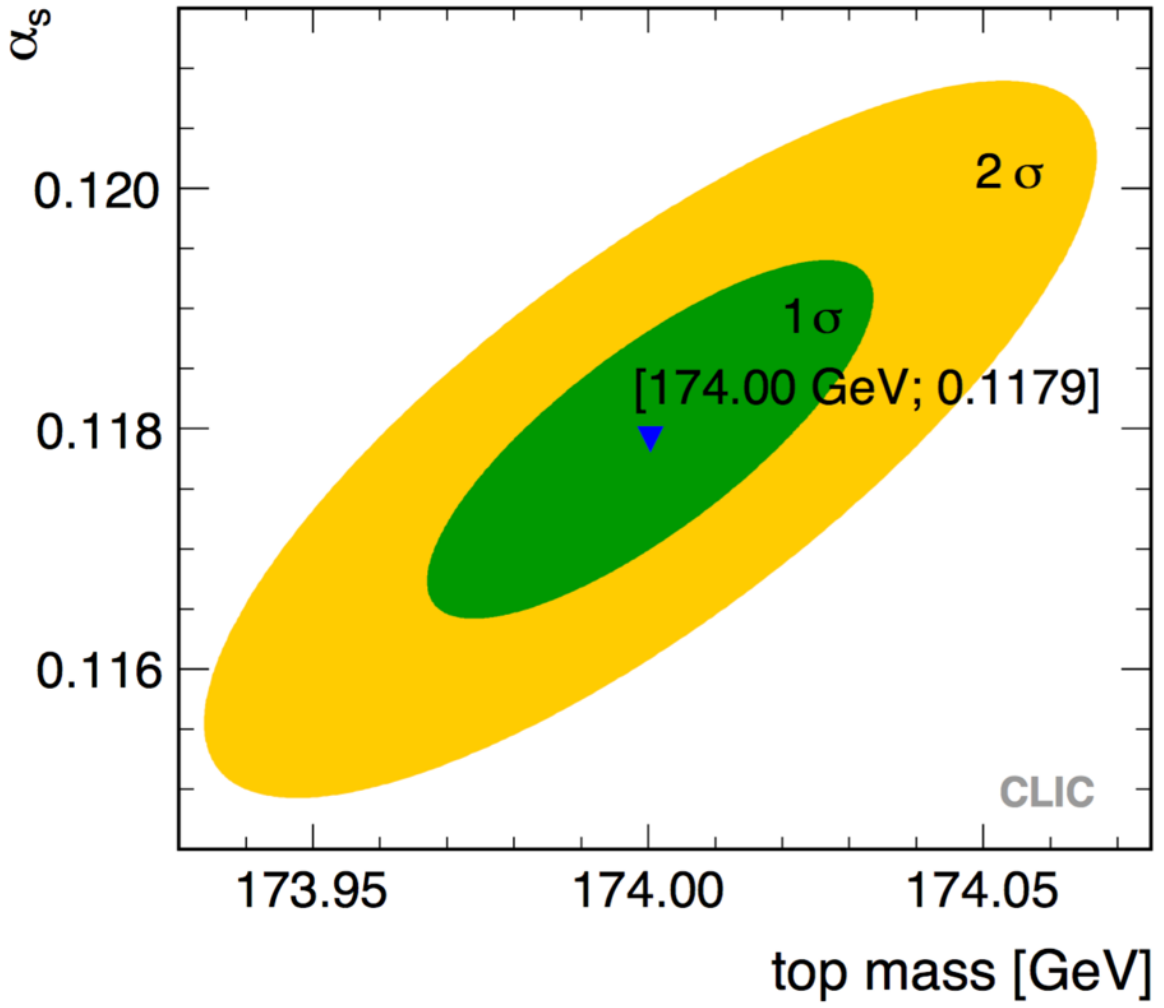
Top quark mass threshold scan

Top mass measurements (run at 350 GeV with 100 fb^{-1})

- Threshold scan (analogous to the LEP2 WW mass scan)
- Shape (position, slope) depends strongly on mass and width
- Normalisation sensitive to α_S and top Yukawa coupling
- Significant cross section smearing due to luminosity spectra and ISR
- Extraction of the theoretically well-defined 1S top mass with a statistical accuracy of about 20 MeV
- At this level of precision we expect experimental and theoretical systematic uncertainties to become important or even dominant
- Two main contributions:
  - The uncertainty in the NNNLO description of the threshold shape
  - The conversion of the threshold mass to the MS-bar scheme
- A total uncertainty on the top quark mass of about 50 MeV seems feasible
- Order of magnitude beyond the capabilities of HL-LHC

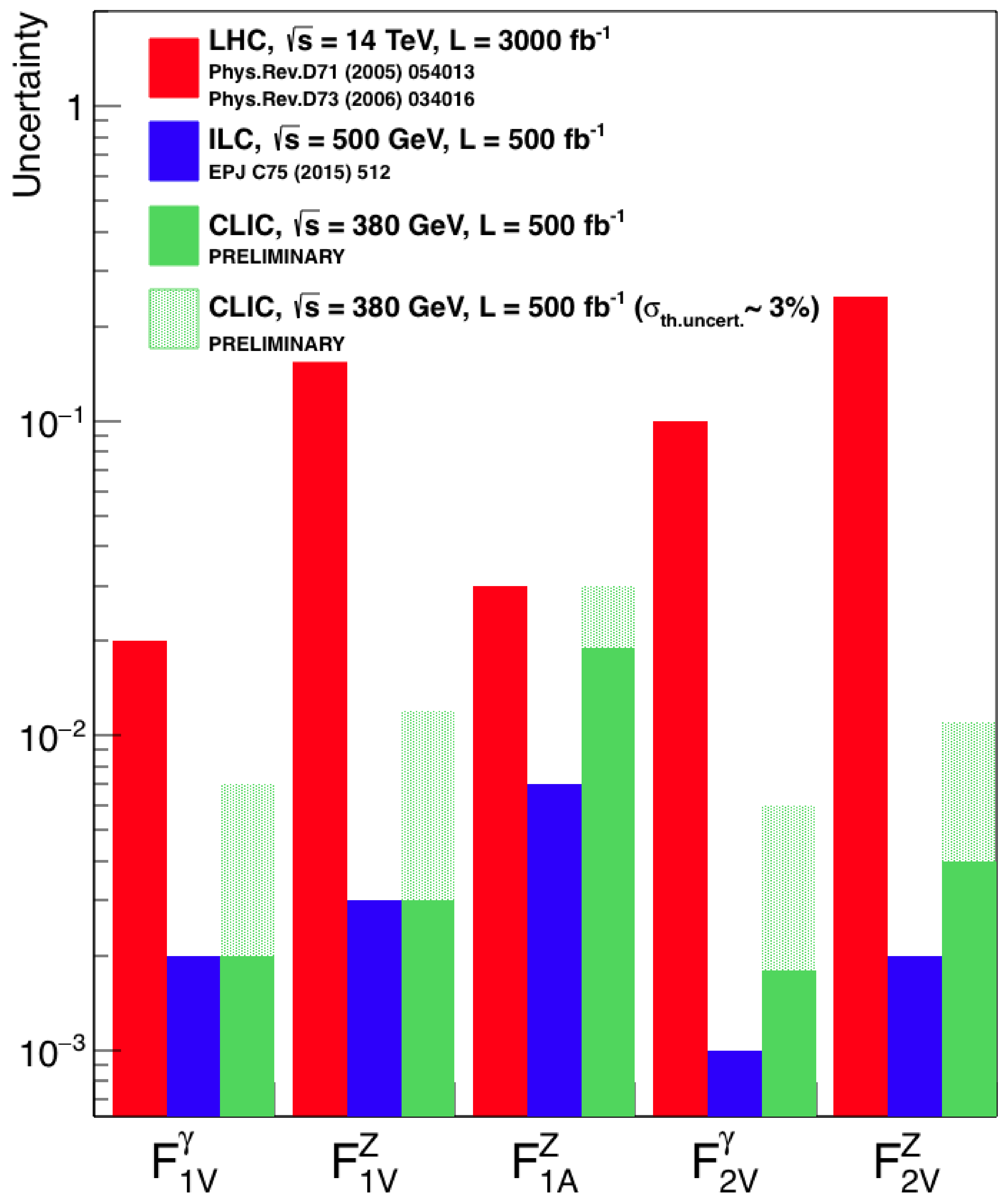






Top Physics at CLIC

Top quark couplings to Z and γ



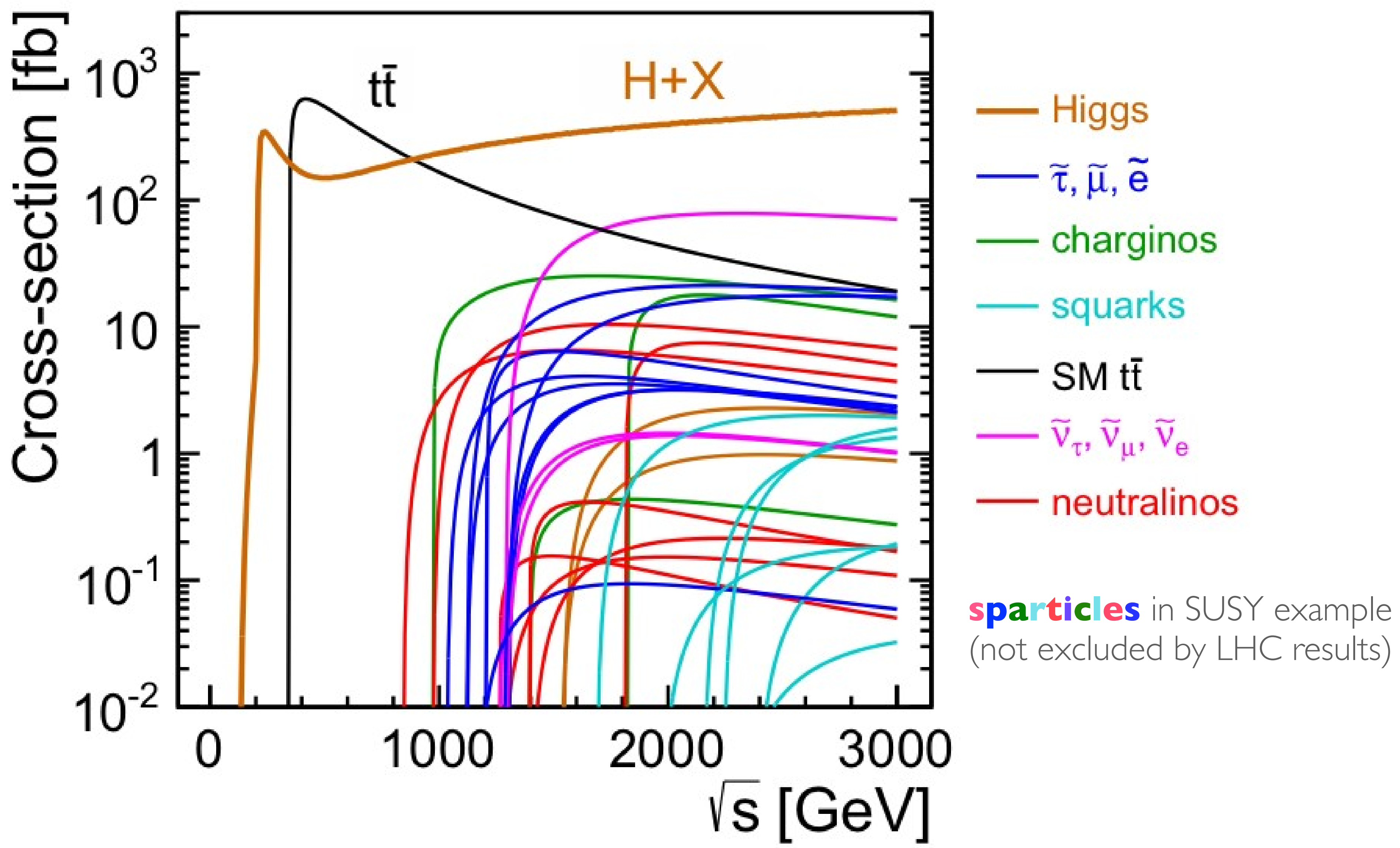
- Close to maximum of tt production cross section
- Determining top form factors through measurement of total cross-section, forward-backward asymmetry and helicity angle distribution for different polarisations
- In many BSM models top EW couplings substantially modified
- CLIC at initial stage (solid green) already an order of magnitude better than HL-LHC (red)
- Further, the fact that the top quark decays before it hadronizes allows access to its polarisation by measuring the angular distributions of the decay products. Sensitive probe for CP violation in the top sector.

Assume production is dominated by SM and NP scale is beyond direct reach, express in terms of form factors in general Lagrangian:

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

CP-violation

BSM Physics at CLIC



- The clean collision environment CLIC is particularly suited to study non-colored TeV-scale particles such as e.g. sleptons, gauginos, and neutralinos
- These might be hidden in the large QCD backgrounds at the LHC
- A small selection of the BSM benchmark analyses are highlighted on the following slides (constructed to show the CLIC detector capability)
- In general always able to measure the mass and production cross-sections to order of 1 %

Indirect searches

Indirect searches through precision observables

- Allow discovery of BSM signals beyond the centre-of-mass energy of the collider
- For example Z′ model and Higgs compositeness models can be probed up to scales of tens of TeV

Direct searches

Direct production of new particles

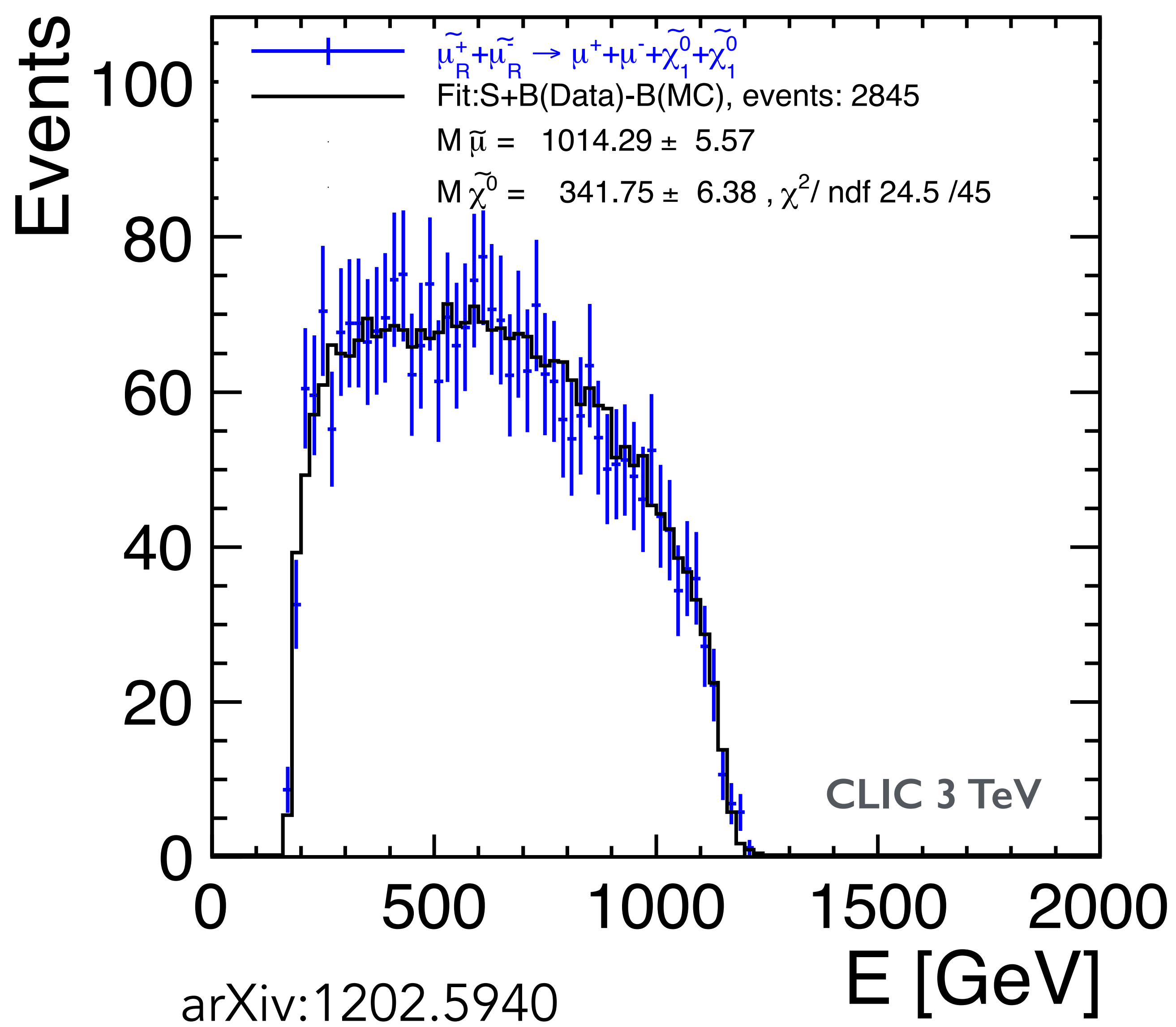
- Possible up to the kinematic limit ($\sqrt{s}/2$ for pair production)
- Precision measurements of new particle masses and couplings
- Complements the HL-LHC program to measure heavy SUSY partners

BSM Physics at CLIC - Direct Searches

Slepton production at CLIC very clean

- Leptons and missing energy
- The slepton and gauginos masses are extracted from the position of the kinematic edges of energy spectra
- Slepton mass precision Δm/m ≤ 1 % for sleptons

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



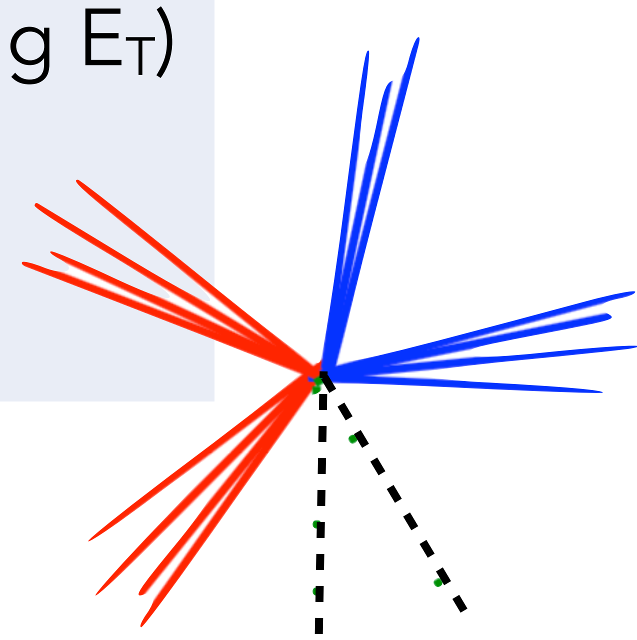
arXiv:1202.5940

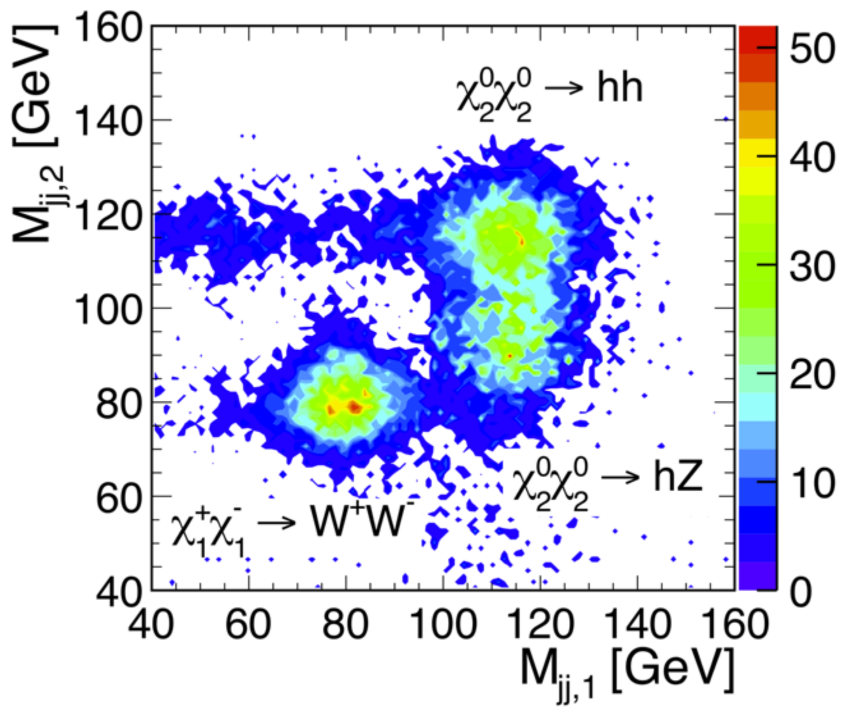
$m(\tilde{\mu}_R)$: ± 5.6 GeV
$m(\tilde{e}_R)$: ± 2.8 GeV
$m(\tilde{\nu}_e)$: ± 3.9 GeV
$m(\tilde{\chi}^0_1)$: ± 3.0 GeV
$m(\tilde{\chi}^\pm_1)$: ± 3.7 GeV

Slepton masses 1.0-1.1 TeV

Di-jet masses - gauginos at 3 TeV

- Reconstruct W/Z/H in hadronic decays (4j + missing E_T)
- Precision on the measured gaugino masses (few hundred GeV): Δm/m = 1 - 1.5%



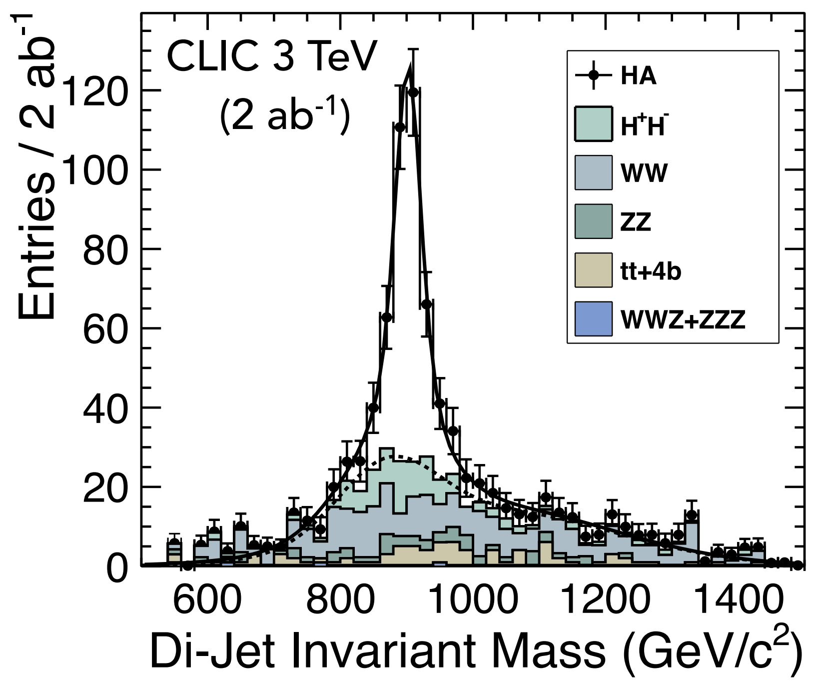


$$e^+e^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1 \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2 \rightarrow hh\,\tilde{\chi}^0_1\tilde{\chi}^0_1 \quad (82\ \%)$$
$$e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2 \rightarrow Zh\,\tilde{\chi}^0_1\tilde{\chi}^0_1 \quad (17\ \%)$$

Heavy Higgs bosons

- Mass precision, Δm/m = 0.3 %
- H^0, A^0, $H^{+/-}$ almost degenerate in mass, separation requires heavy-flavour tagging

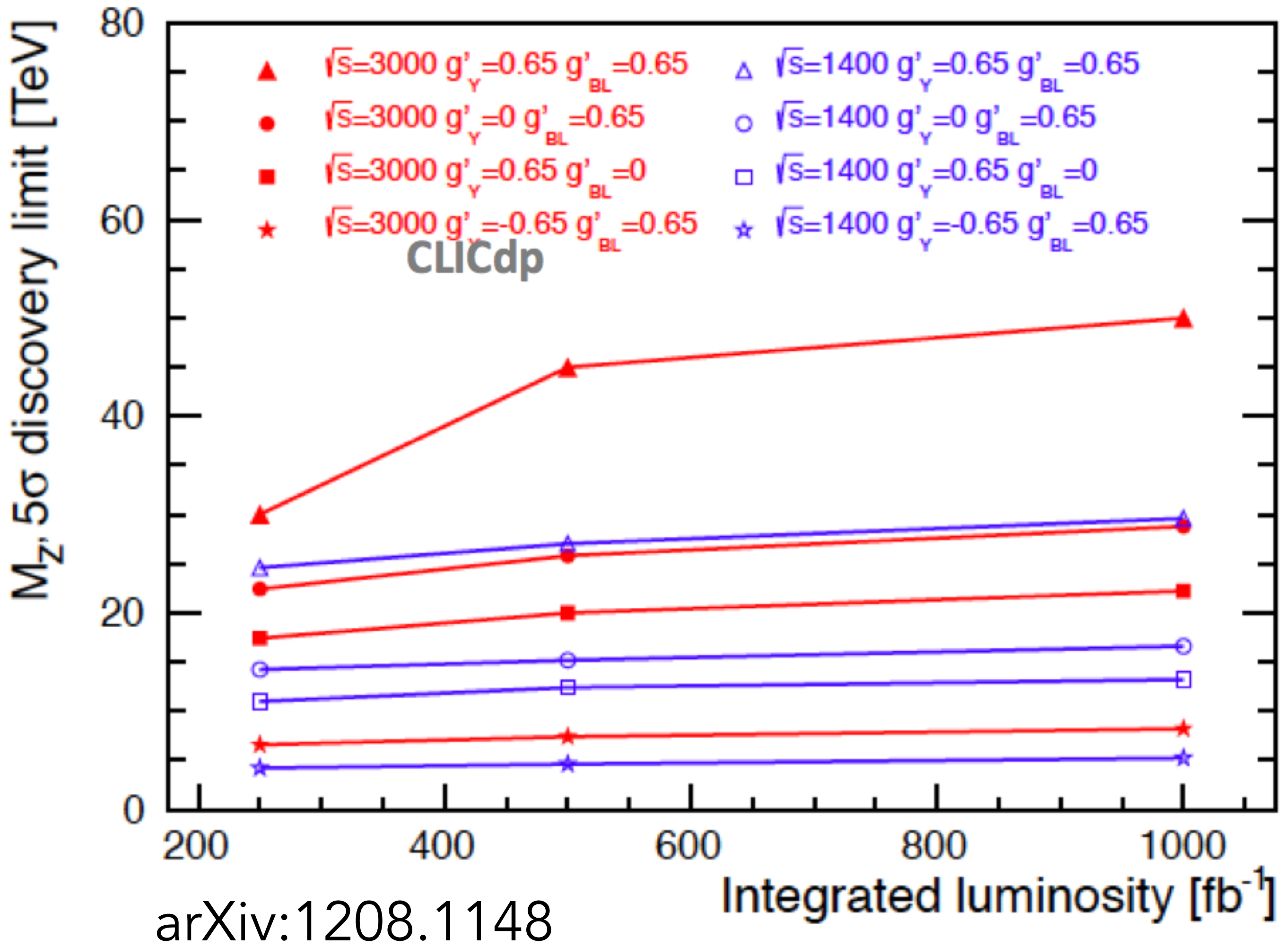
$$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$$



BSM Physics at CLIC - Indirect Searches

Z′ from fermion pair production

Precision study of $e^+e^- \rightarrow \mu^+\mu^-$

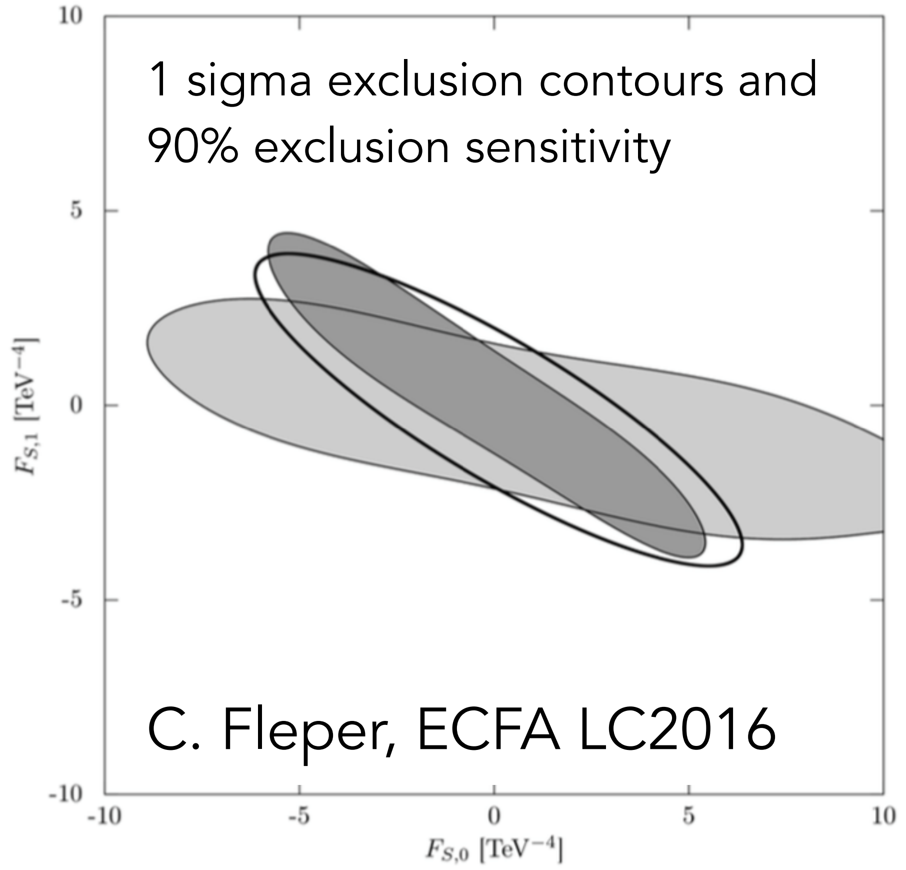


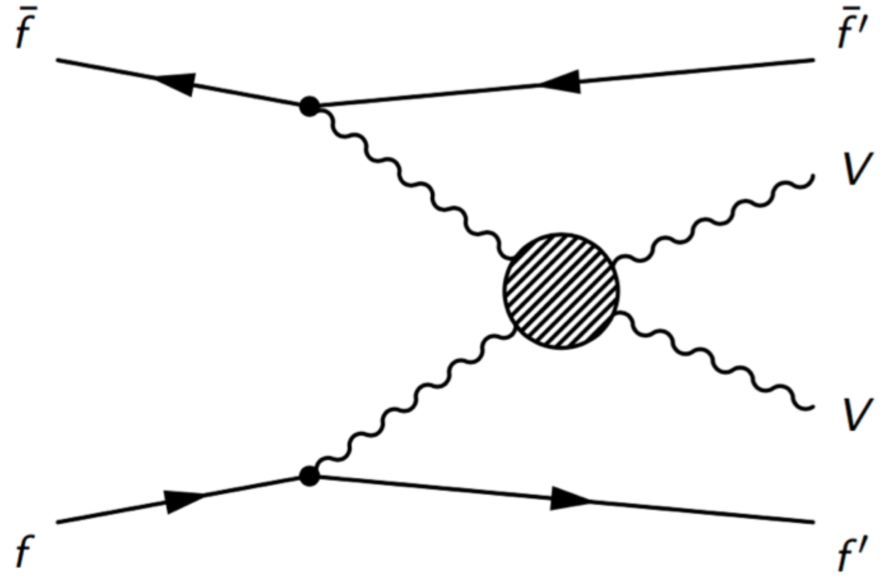
arXiv:1208.1148

- Hypothetical gauge boson arising from extensions of the electroweak symmetry of the SM
- High-precision measurement of the properties of the SM Z boson → model-dependence through Z′ and Z mixing (cross-section, forward-backward asymmetry, left-right asymmetry)
- Minimal anomaly-free Z′ (AFZ′) model: Discovery up to tens of TeV (HL-LHC reaches ~8 TeV with $3ab^{-1}$) (depending on the couplings)
- Precision measurement of effective couplings, if LHC discovers Z′ (e.g. for $M_{Z'}$ = 5 TeV)

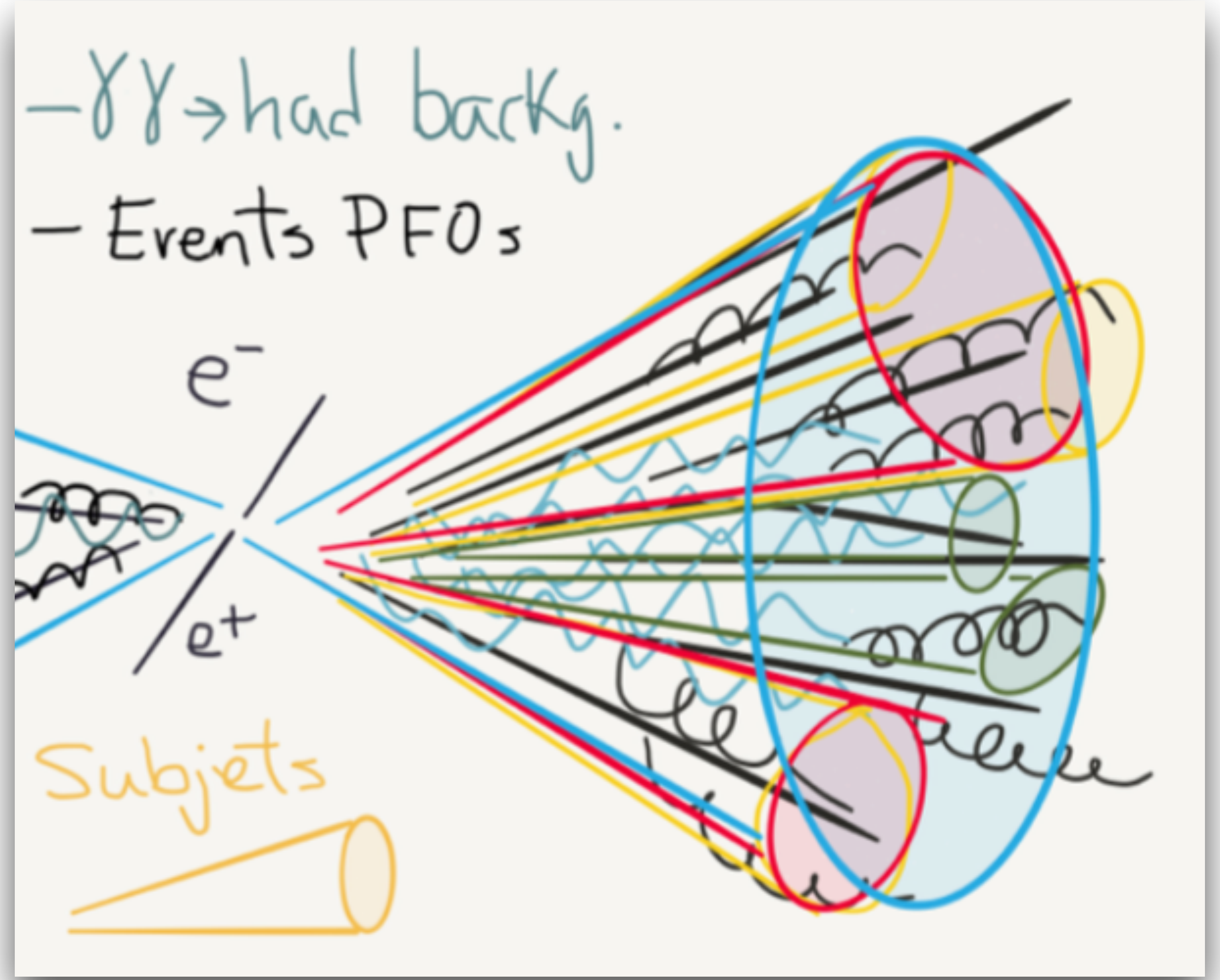
Vector boson scattering

- Vector boson scattering is sensitive to new physics in the Higgs sector
- Search for additional resonances or anomalous couplings
- At first glance, CLIC at 3 (1.5) TeV roughly two (one) orders of magnitude more precise than LHC at 8 TeV, for anomalous couplings





Drawing by I. Garcia

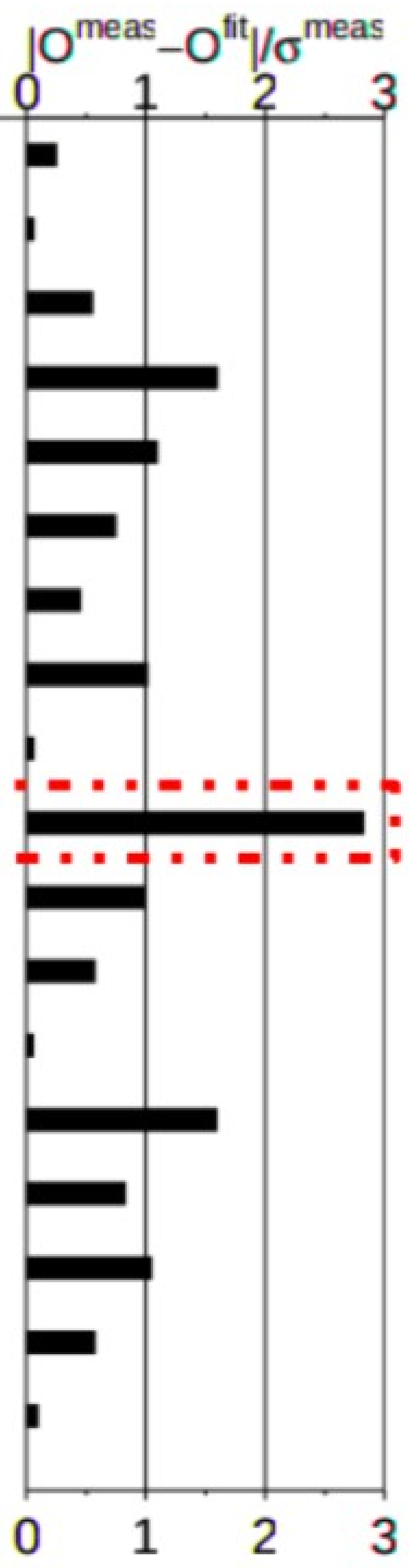


- Relative contribution from new physics may increase with centre-of-mass energy
- At high-energy CLIC operation, an increased **boost leads to separation** between the decay product of the two top quarks
- Top quark mass and the **top quark couplings** to Z and γ **with high precision** are among the main focuses of the initial stage of CLIC - plan to extend the top coupling study to high energy

SM Asymmetries

LEP Precision Measurements

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



- The measured value of A_{fb} for b-quarks has the highest tension with SM expectations - An indication of new physics?
- If so, t-asymmetry might show even larger deviation
- Determining top quark couplings through measurement of cross-sections and forward-backward and left-right asymmetries
- Sub-percent precision on anomalous EW couplings yields sensitivity to new physics at scales well beyond the direct reach
- Study of top quark couplings: form-factors or effective operators

Experimentally:

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

Measure 2 observables for 2 beam polarizations:

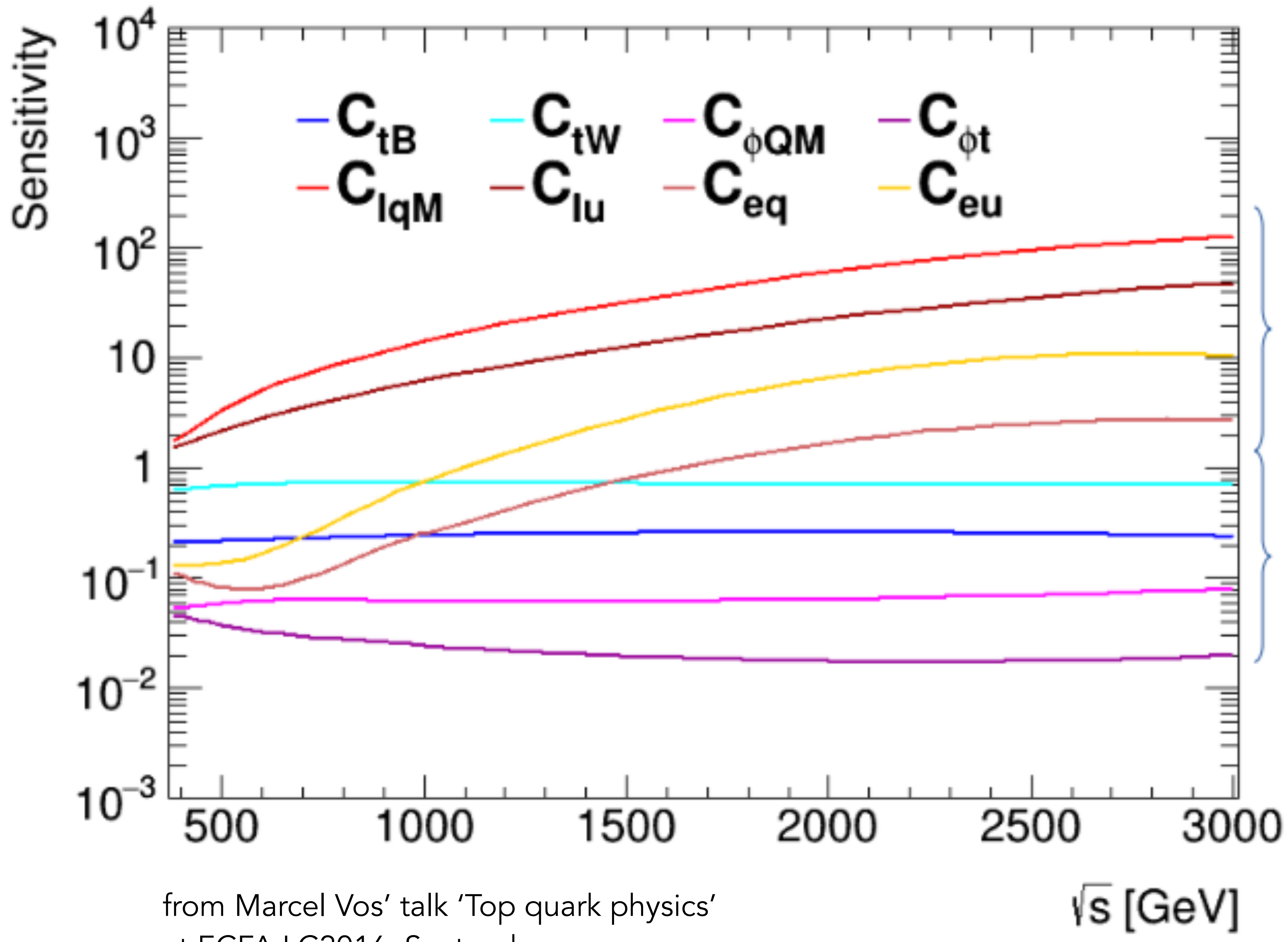
$F^{\gamma,SM}_{1A} = 0$ always because of the gauge invariance

$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & (+ = e^-_R) \\ \sigma(-) & A_{FB}(-) & (- = e^-_L) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^\gamma_{1V} & * & F^\gamma_{2V} \\ F^Z_{1V} & F^Z_{1A} & F^Z_{2V} \end{matrix}\right\}$$

SM Asymmetries

Describe BSM effect through effective D6 operators:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$



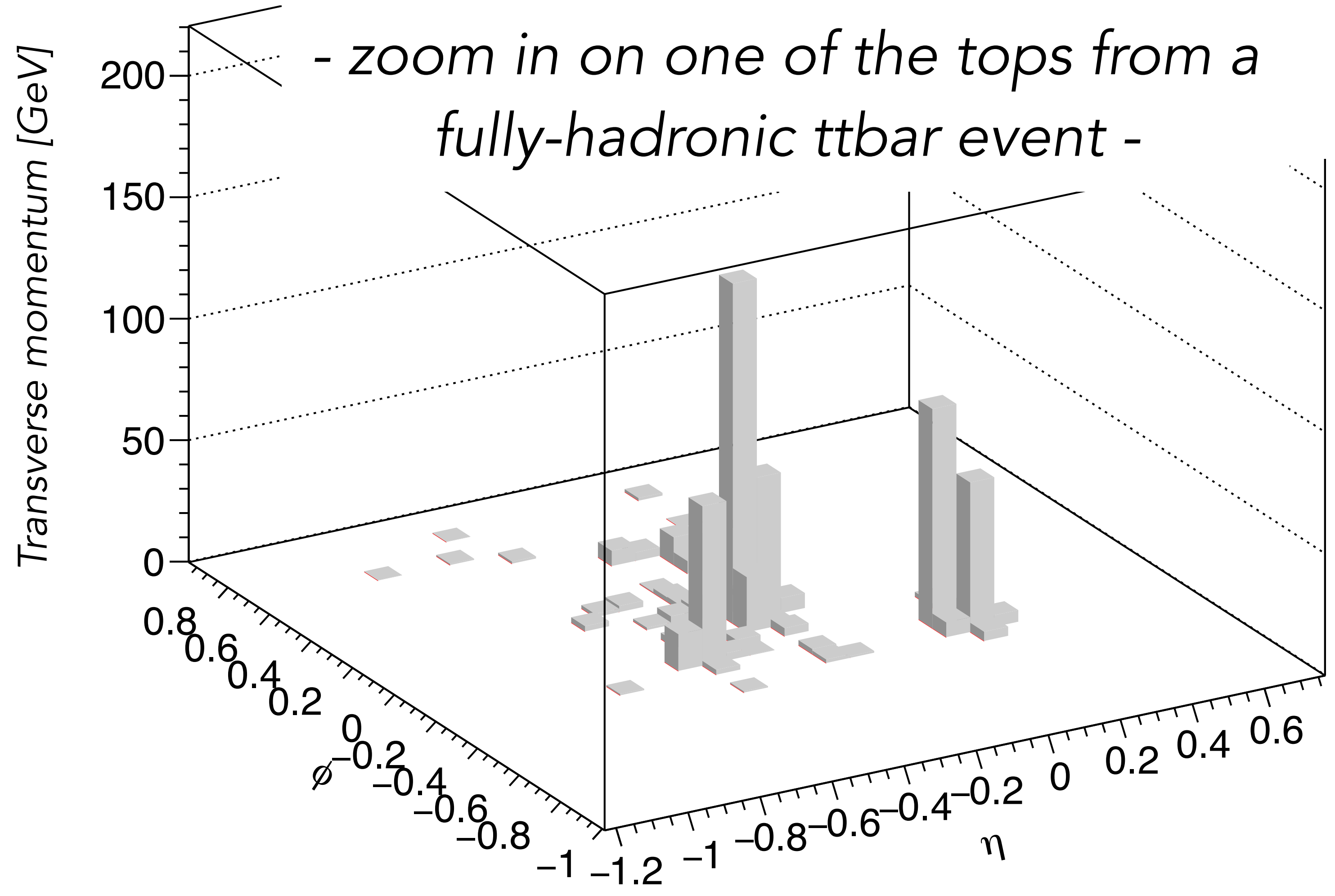
from Marcel Vos' talk 'Top quark physics' at ECFA LC2016, Santander

"4-fermion contact" operators - represent a massive, new mediator beyond direct reach

"2-fermion vertex" operators

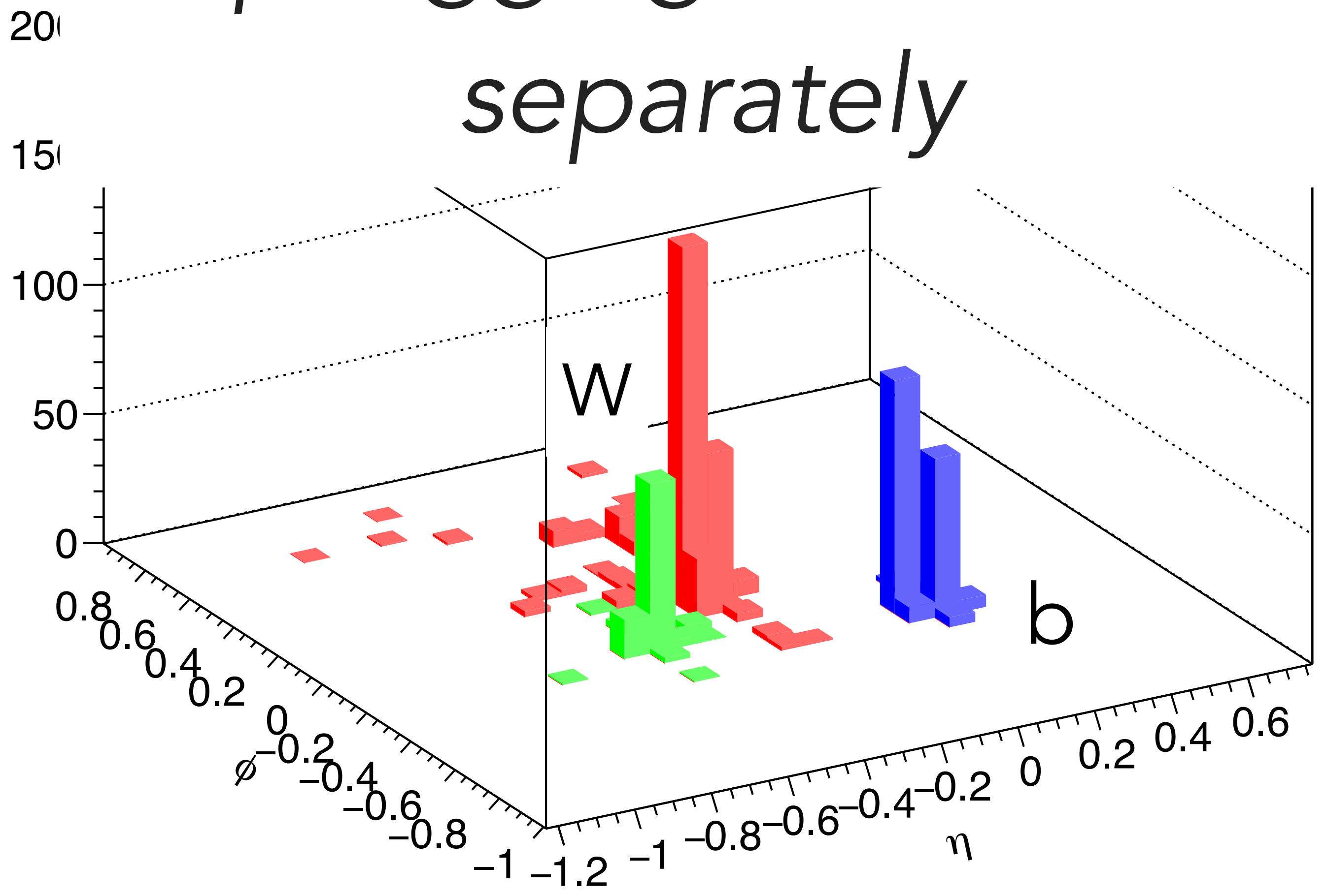
(multi-) TeV operation provides better sensitivity to "4-fermion" operators!

Parsing through jet cluster



Top Tagging

The three subjets after top tagging are shaded separately



- Top tagging is a powerful method to identity top quarks, in particular for boosted tops where the jet decay structure is complex (collimated collections of particles that look like single jets)
- Following the method from Kaplan et al. **DOI: 10.1103/PhysRevLett.101.142001**
- First attempt at using a top tagging algorithm with CLIC
- Distinguish boosted top jets from light-quark and gluon jets using jet substructure:
  - Parsing jet cluster + Imposing kinematic constraints

Top Tagging Algorithm

1) PFO objects are clustered into jets of size R (large jet) - any algorithm
   - Iteratively merge 4-vector pairs with closest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ until $\Delta R < R$

2) Iteratively decluster each resulting jet (reversing each step in the jet clustering) to search for subjets
   - Split into two parts, reject softest if .... $\frac{p_T^{\mathrm{subjet}}}{p_T^{\mathrm{jet}}} < \delta_p$
   - Declustering continues on the harder object until:

Both subjets are harder than $p_T^{\mathrm{jet}} \cdot \delta_p$	✔
Both subjets are too close $\lvert\Delta\eta\rvert + \lvert\Delta\phi\rvert < \delta_r$	✗
Both subjets are softer than $p_T^{\mathrm{jet}} \cdot \delta_p$	✗

3) If an original jet declusters into two subjets - step 2 is repeated on those subjets
   - Results in 1 (original jet), 2, 3, or 4 (additional soft gluon emission) subjets

1 ✗ → *Recover by other means?*
2 ✗ →
3 ✔
4 ✔

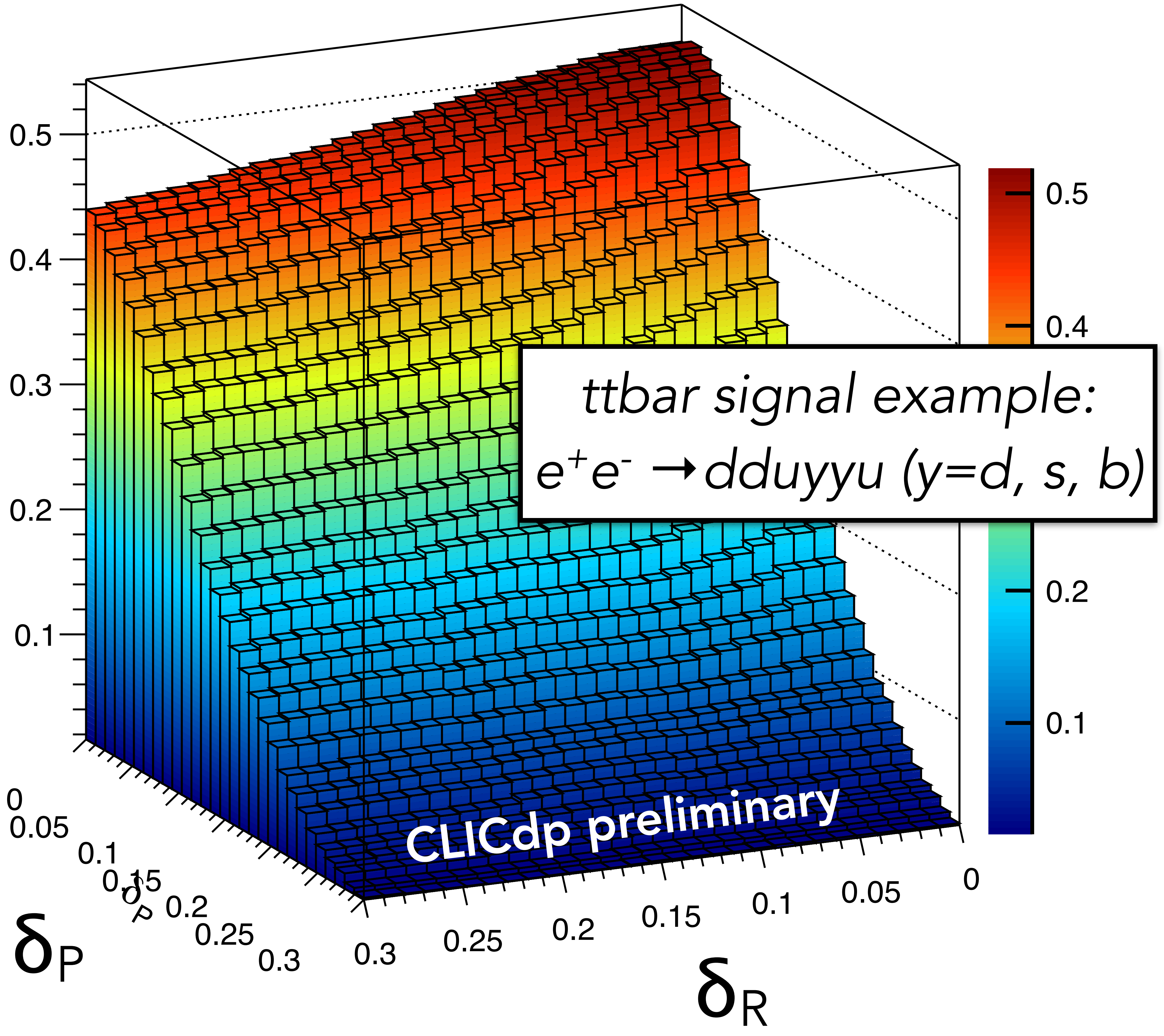
4) Additional kinematic cuts (make sure the resulting subjets are consistent with top mass, and that 2 are consistent with W mass)

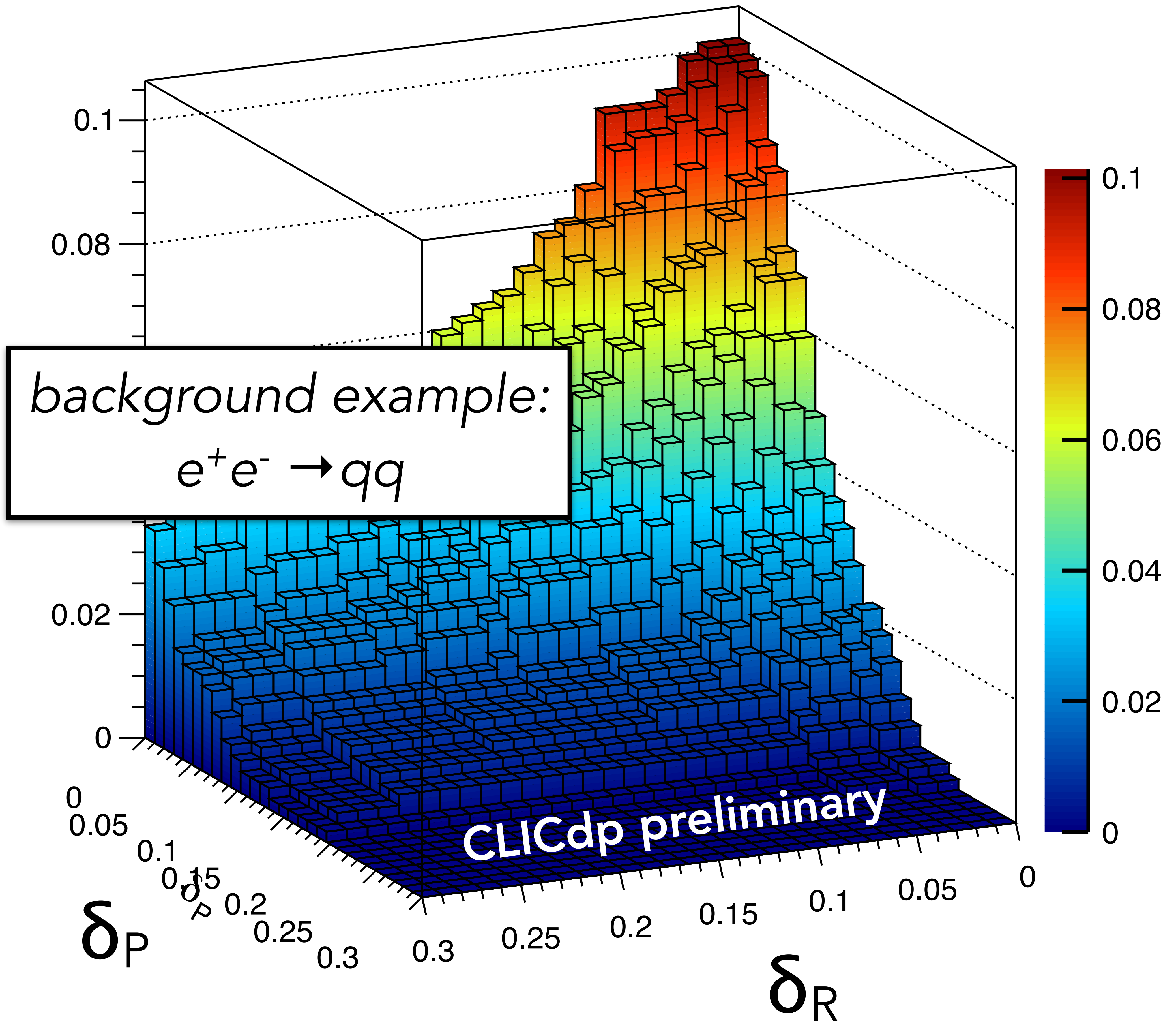
✗ = irreducible

Top Tagging Efficiency

VLC jet clustering algorithm (R=1.5, β=1, γ=1)

Top tagging efficiency



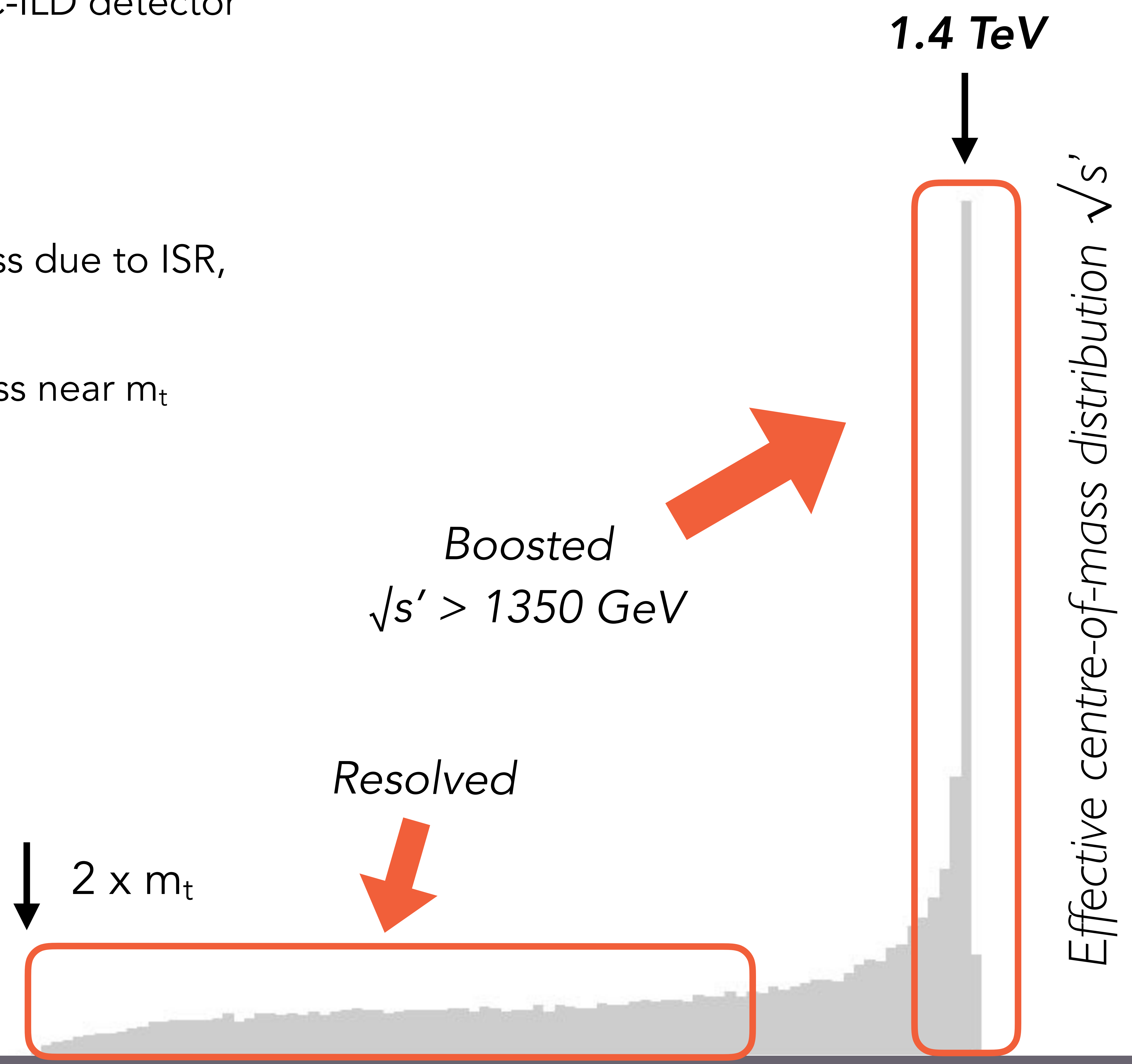


Analysis Strategy - 1.4 TeV

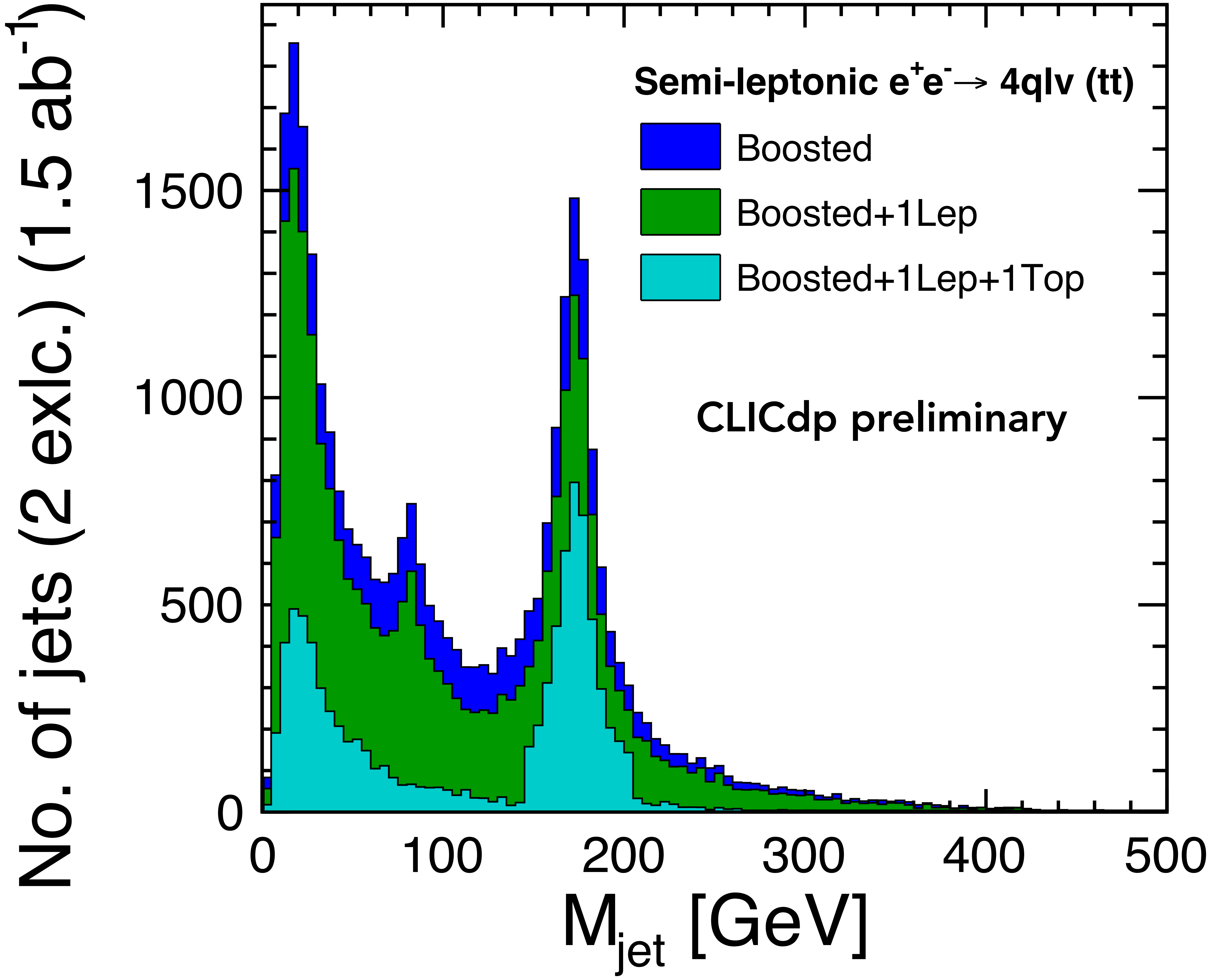
- Analysis concept studied at benchmark energy 1.4 TeV using the CLIC-ILD detector
- Using Default Selected Pandora PFO collection

- *Resolved analysis*
  - Production near threshold (events with lower effective centre-of-mass due to ISR, beamstrahlung, and/or luminosity spectrum)
  - Use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t

- *Boosted analysis (large R-jets/fat-jets)*
  - Standard top-quark identification techniques may not work:
    - b-tagging difficult since tracks are crowded and unresolvable
    - W decay products not isolated from each other or b-jet
  - Identify prongy structure that would be a signature of a top decay
  - Looking at $t \rightarrow W^{\pm}b$:
    - Fully hadronic decays $W^{\pm} \rightarrow qq$ (vertex charge challenging)
    - Semi-leptonic decays $W^{\pm} \rightarrow l\nu$



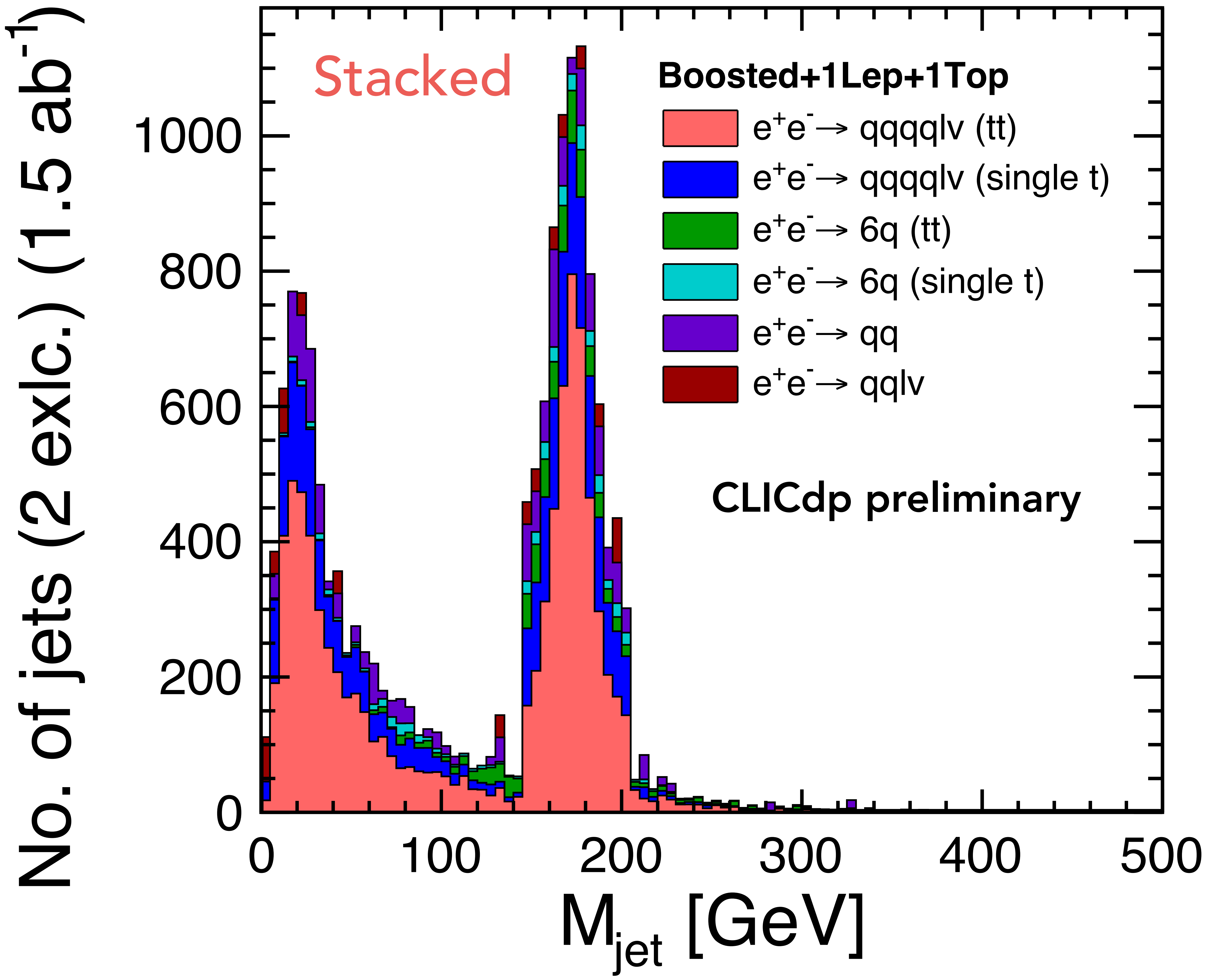
Analysis - Results for $P(e^-) = -80\%$



- *Technical cut: Boosted (√s'>1350 GeV)*
- *The following cuts are applied:*
  - 1 isolated lepton (electron or muon), incl. cuts on track energy, impact parameter, calorimeter information, and cone isolation
  - Jet clustering including trimming
  - 1 top tagged jet (VLC R=1.5, δ_r= 0.05, δ_p= 0.05), about 35 % signal efficiency
- Lepton charge can be used to reconstruct the charge of the top/anti-top

- Do same for P(e-) = +80%

Analysis - Results for $P(e^-) = -80\%$



	Signal [no. of events]	*Bkg [no. of events]*
No cut	140169	$2{,}42446 \times 10^7$
Boosted	32114	$5{,}12606 \times 10^6$
Boosted + 1Lep	25807	$1{,}59256 \times 10^6$
Boosted + 1Lep + 1 Top	**8942**	**7093**

- Plot shows $e^+e^- \rightarrow tt \rightarrow qqqqvl$ signal (light red) and backgrounds, all shown after cuts on previous slide have been applied
- Not including all backgrounds yet, e.g. missing $\gamma e \rightarrow qqqqe$ (forward)
- Further, event recovery possible if top tagger fails / b-tagging
- Preliminary results on forward-background asymmetry for the semi-leptonic ttbar decay channel to be expected soon!

Conclusions and Summary

- CLIC is a proposal **for a future e^+e^- collider** at CERN in the post-LHC era. It is the only mature option for an electron-positron multi-TeV accelerator with improved precision of many observables and access to rare Higgs decays + discovery machine for BSM physics at the energy
- Feasibility demonstrated through extensive simulation and prototyping, accelerator and detector R&D
  - The vertex R&D is well advanced, with several custom ASICs. Power consumption, cooling scheme and material budget constraints all seem feasible, single hit resolution still to be reached. Tracker R&D ramping up with realistic mechanical concepts. First tests on different silicon technologies (HV-CMOS, SOI). No time to mention the developments in software, simulation, etc.
- CLICdp has a well-established physics program that spans over several decades with a three-stage implementation - Current focus on top and BSM physics at high-energy CLIC stages
- Results from the LHC provide an important input for the CLIC physics program, a strategy that can be adapted to potential LHC/ HL-LHC discoveries

Don't miss our latest papers!

- Staging baseline document - 'Updated baseline for a staged Compact Linear Collider' (arXiv:1608.07537)
- Higgs physics paper - 'Higgs Physics at the CLIC Electron-Positron Linear Collider' (arXiv:1608.07538)

Find more information:

https://clicdp.web.cern.ch

http://clic-study.web.cern.ch

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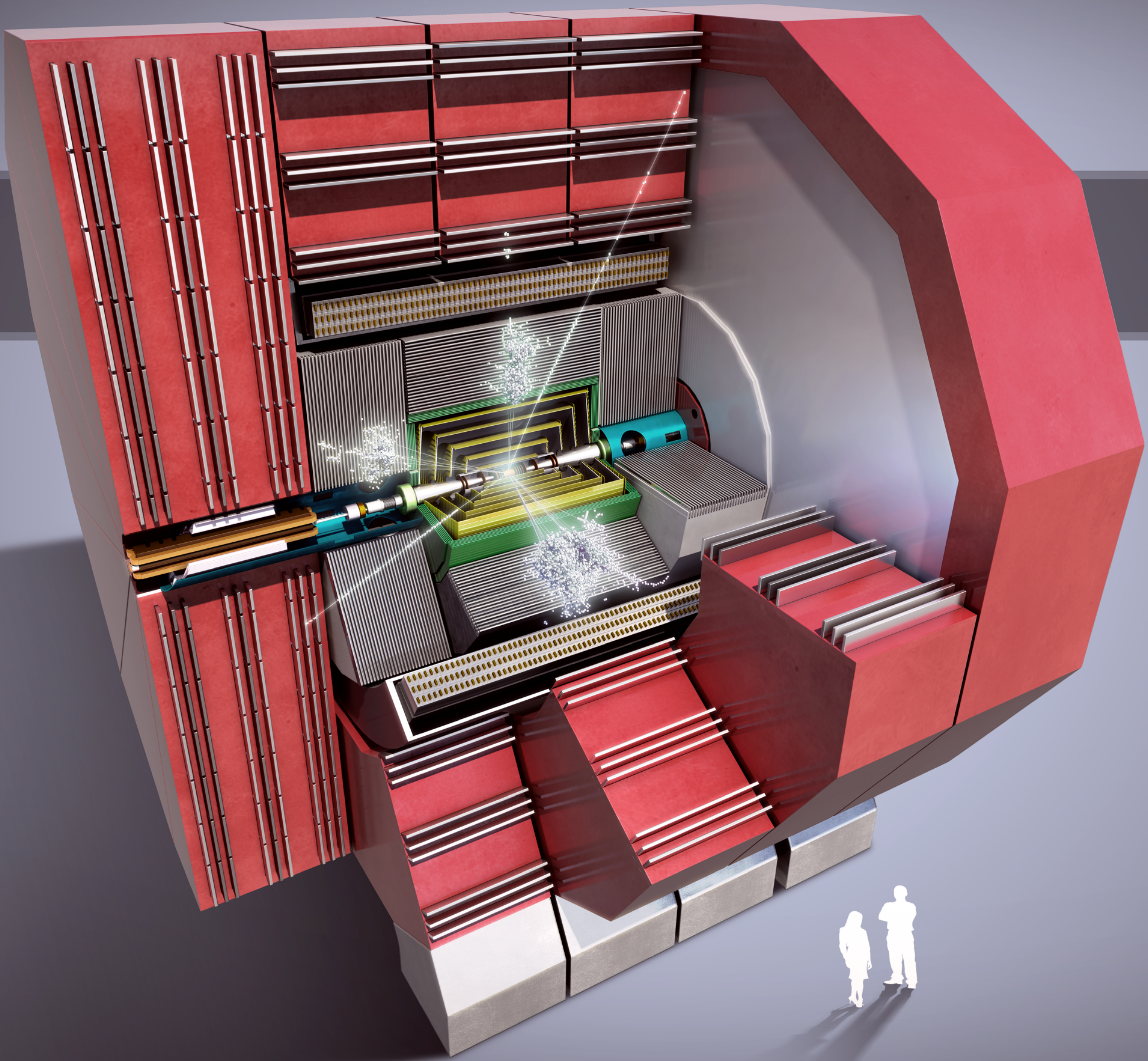


CLIC Detector

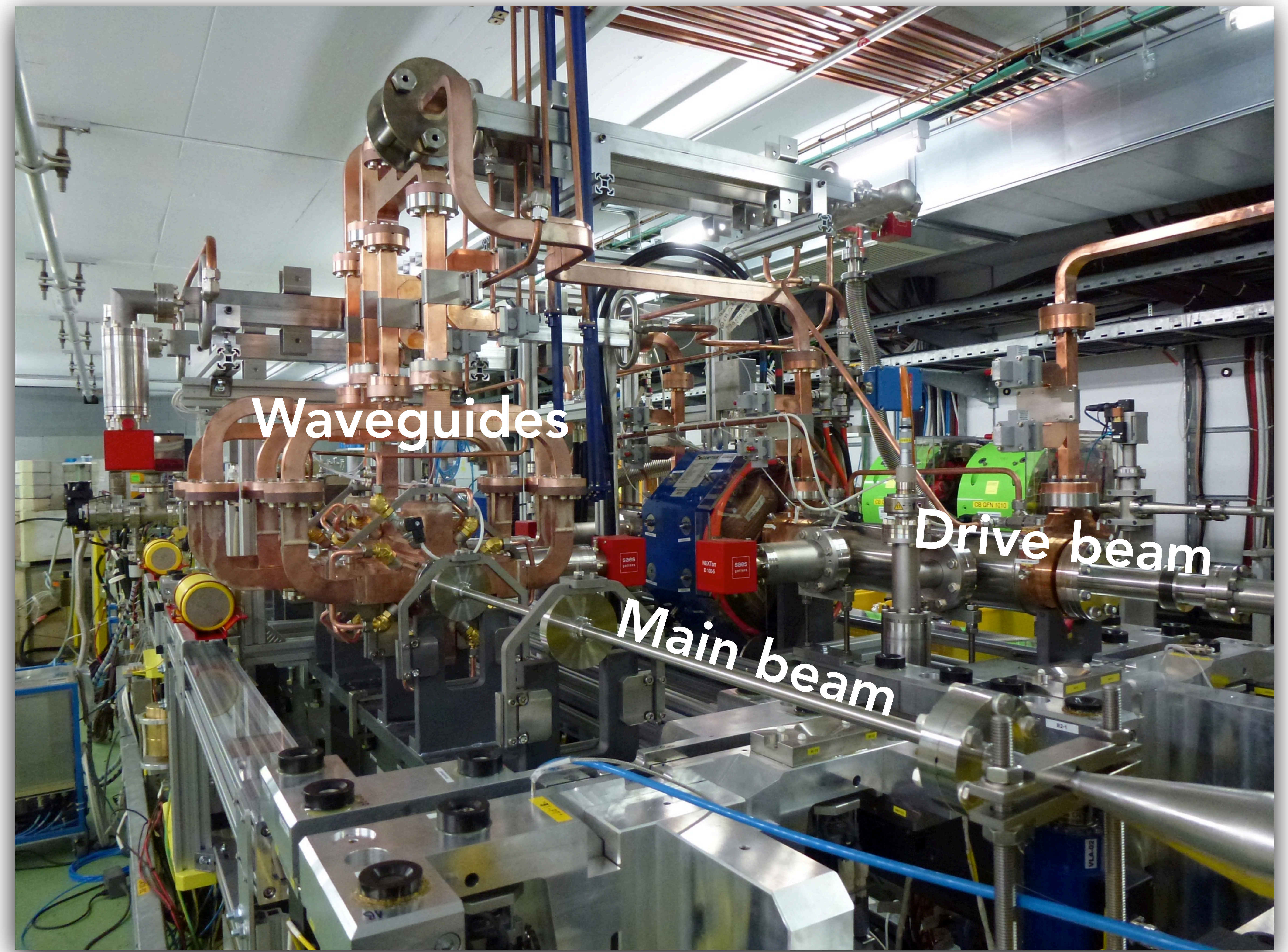
On behalf of the: CLICdp Collaboration:

Thank you for your attention!

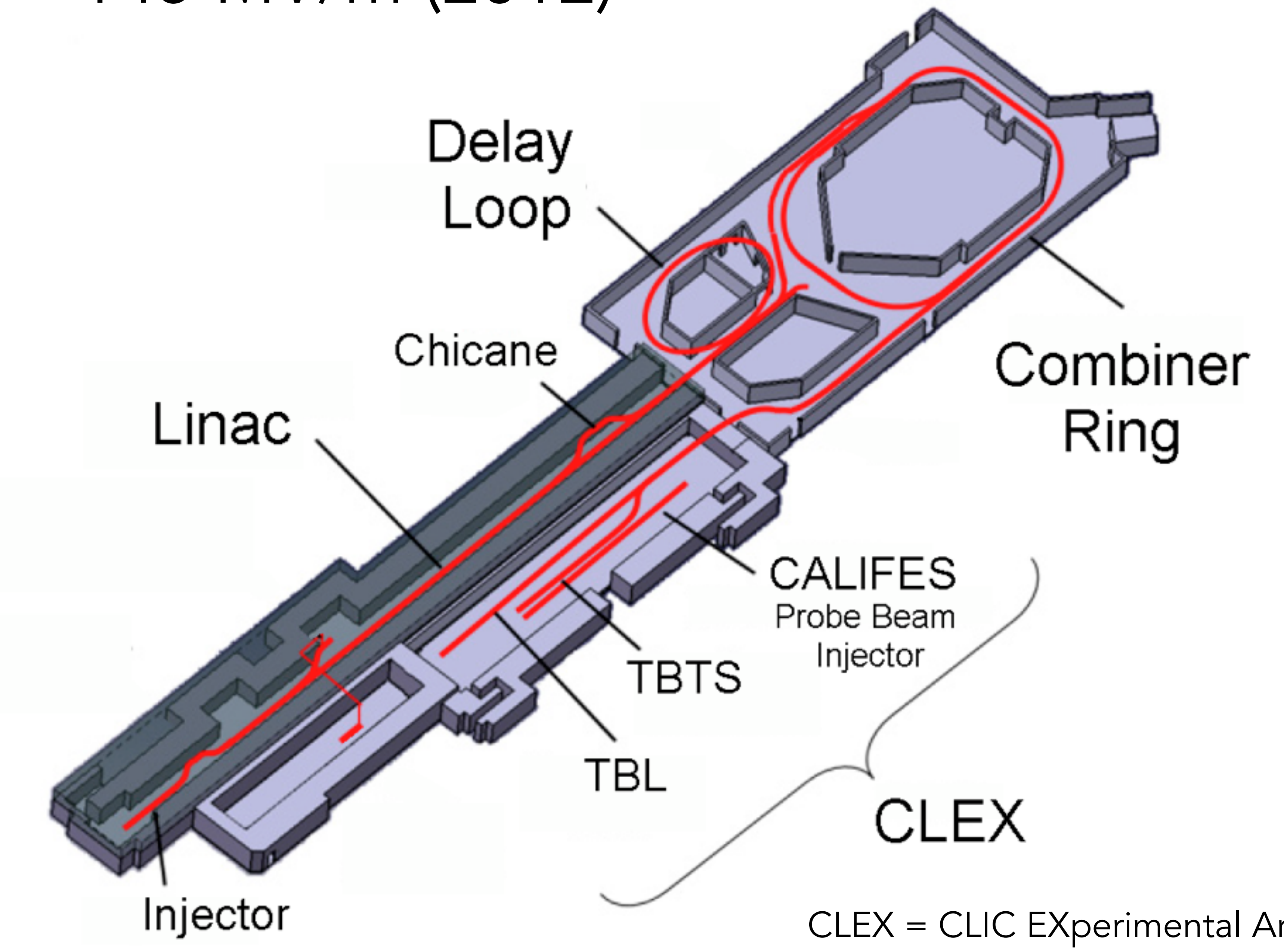
Rickard Ström
EP-LCD Group, CERN
rickard.stroem@cern.ch
Uppsala University Seminar, 15 Dec. 2016

Backup Slides

CTF3 - Two-beam Acceleration Module

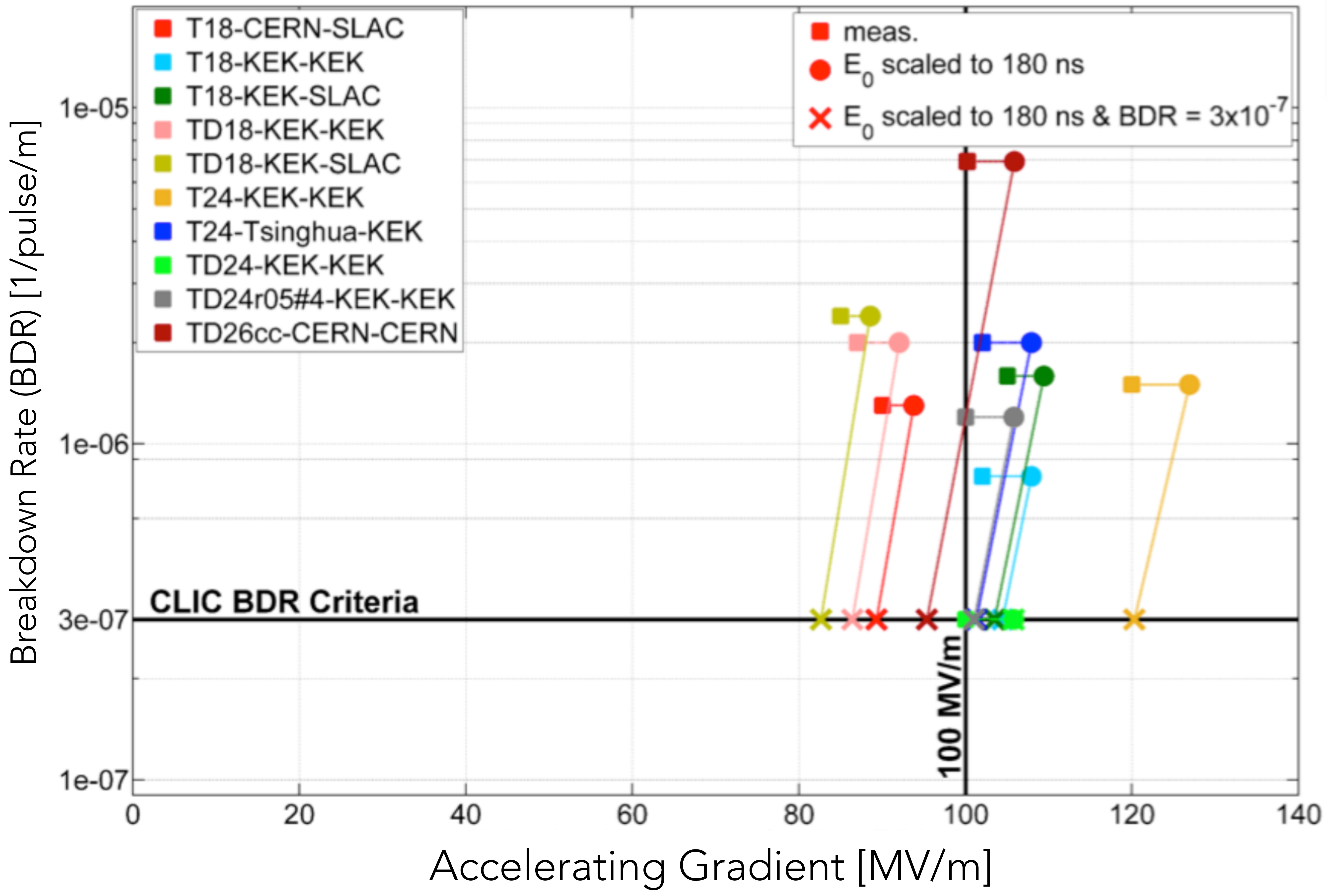


- Key stages of the CLIC acceleration demonstrated at CTF3
- Two-beam acceleration module in CTF3 (according to latest CLIC design)
- First two-beam tests stand reached 145 MV/m (2012)



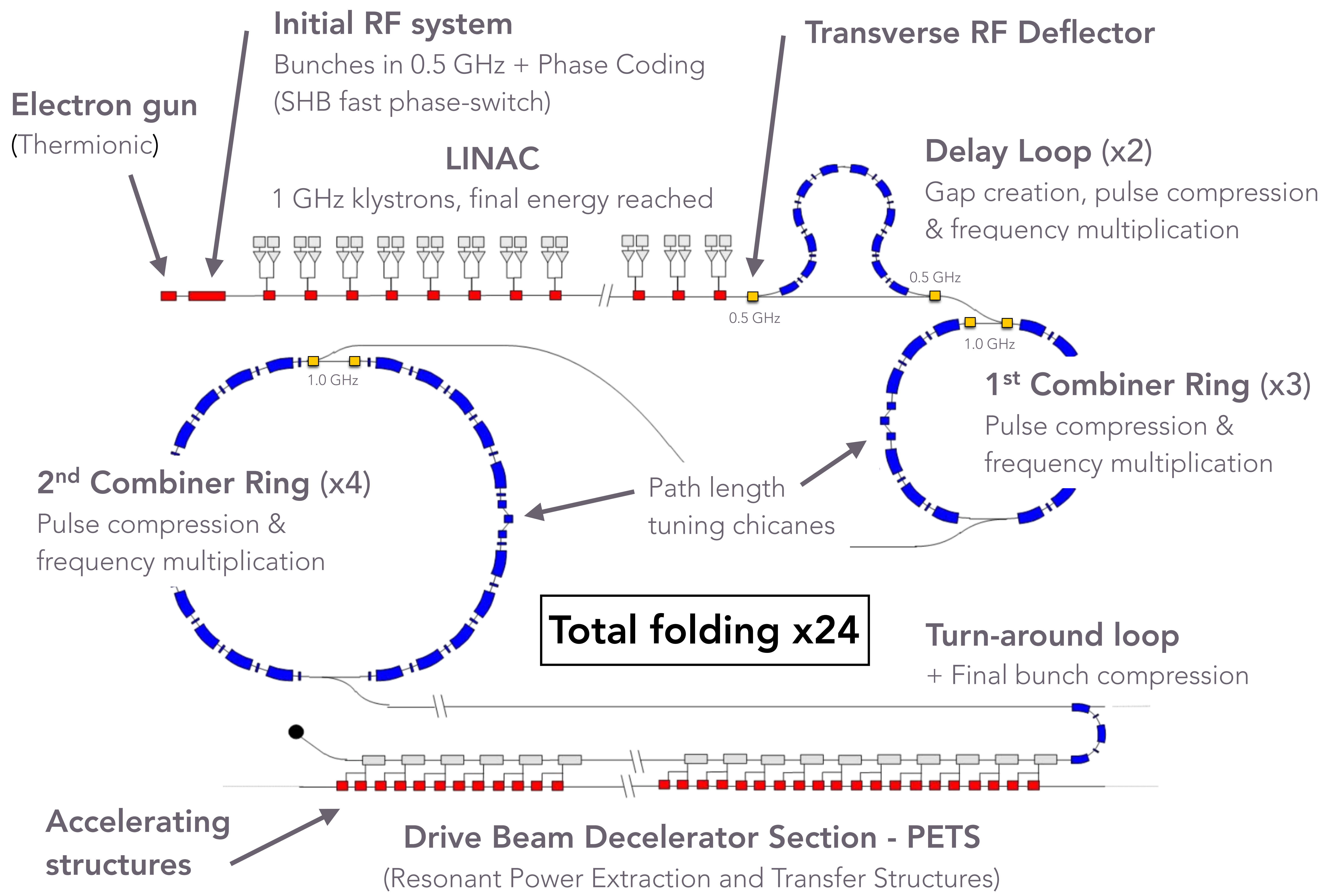
CLEX = CLIC EXperimental Area
TBTS = Two-Beam Test Stand (TBTS)
TBL = Test Beam Line (TBL)

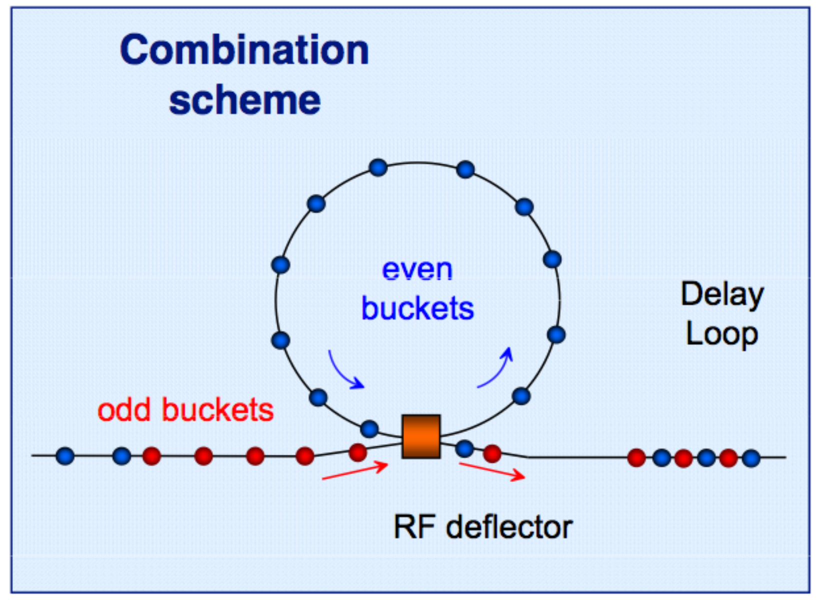
Why do we need two-beam acceleration?

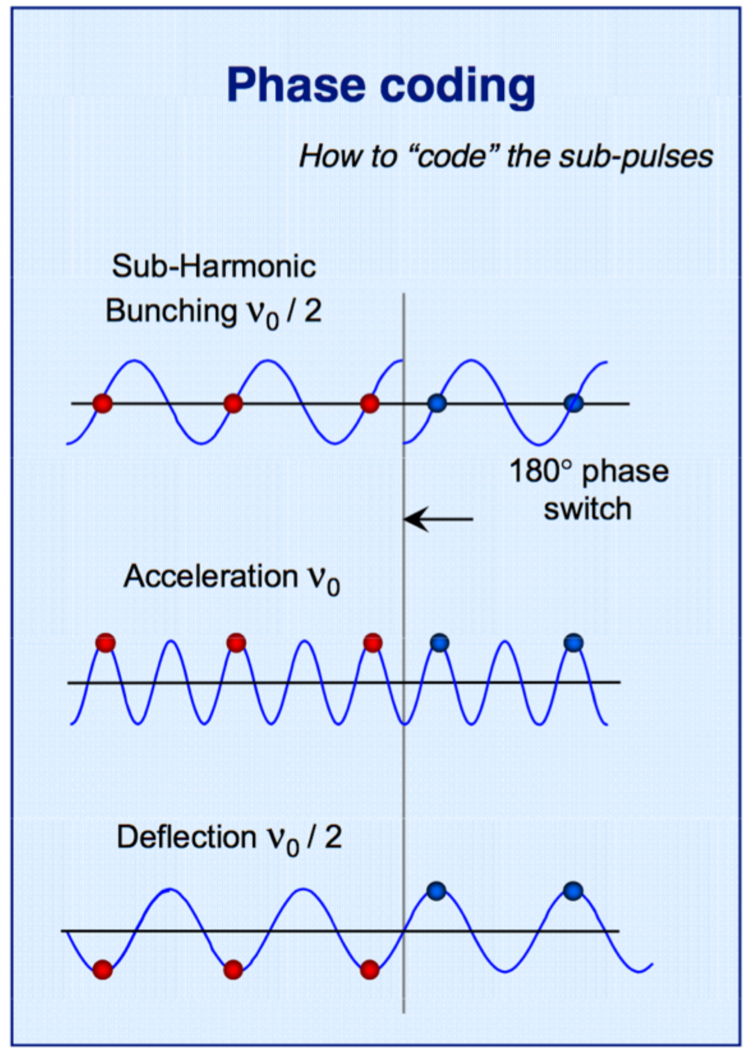


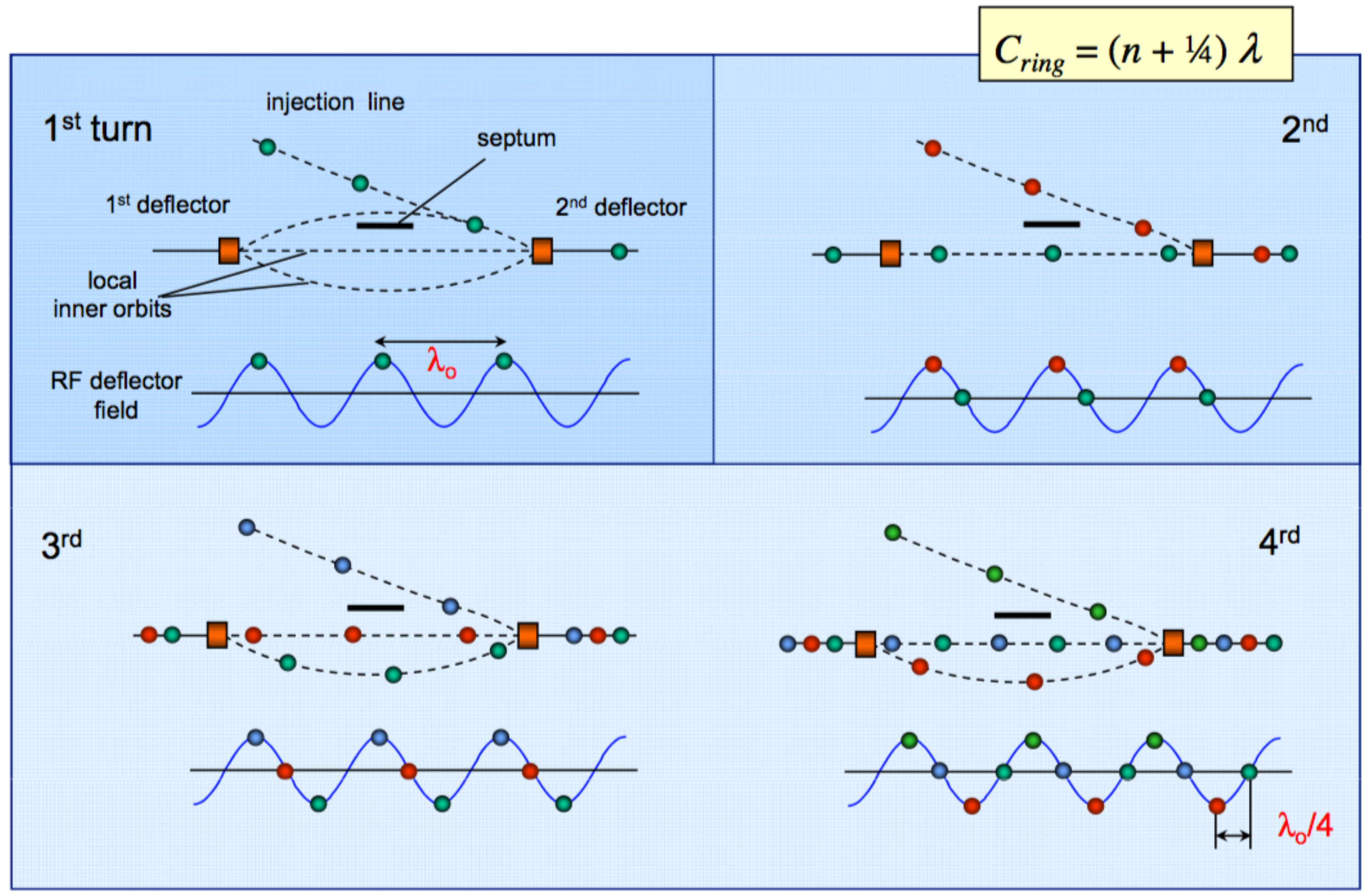
One cell of a CLIC 12 GHz structure and results of ongoing X-band module tests

Drive Beam Complex - Phase Coding and Bunch Folding









CLIC Cost and Power

How much will CLIC cost?

- The first stage of the *accelerator* is estimated to cost about 50% more than the cost for the LHC, ~6700 MCHF (~*60 miljarder SEK*). Most of this cost is in excavating the tunnels and caverns, and in the two-beam modules.
- The *detector* for CLIC is estimated to cost approximately the same as each of the LHC experiments ATLAS or CMS, ~500 MCHF (~*4.5 miljarder SEK*). Most of the detector cost is in the calorimeters, the superconducting coil and the yoke.

	CLIC_ILD (MCHF)	CLIC_SiD (MCHF)
Vertex	13	15
Tracker	51	17
Electromagnetic calorimeter	197	89
Hadronic calorimeter	144	86
Muon system	28	22
Coil and yoke	117	123
Other	11	12
Total (rounded)	560	360

arXiv:1202.5940

$\sqrt{s}$ (TeV)	$P_{nominal}$ (MW)	$P_{waiting\ for\ beam}$ (MW)	P_{stop} (MW)
0.38	252	168	30
1.5	364	190	42
3	589	268	50

How much power will CLIC use?

- Designed to be a high luminosity, high energy linear collider, CLIC will inevitably need high power.
- Low power consumption in stand-by or "waiting-for-beam" mode compared to superconducting technology.
- A preliminary analysis of the overall CLIC energy consumption per year:
  - The first stage would be similar to LHC, and the second stage similar to the total CERN energy consumption. Work is on-going to further reduce the anticipated power consumption of CLIC.

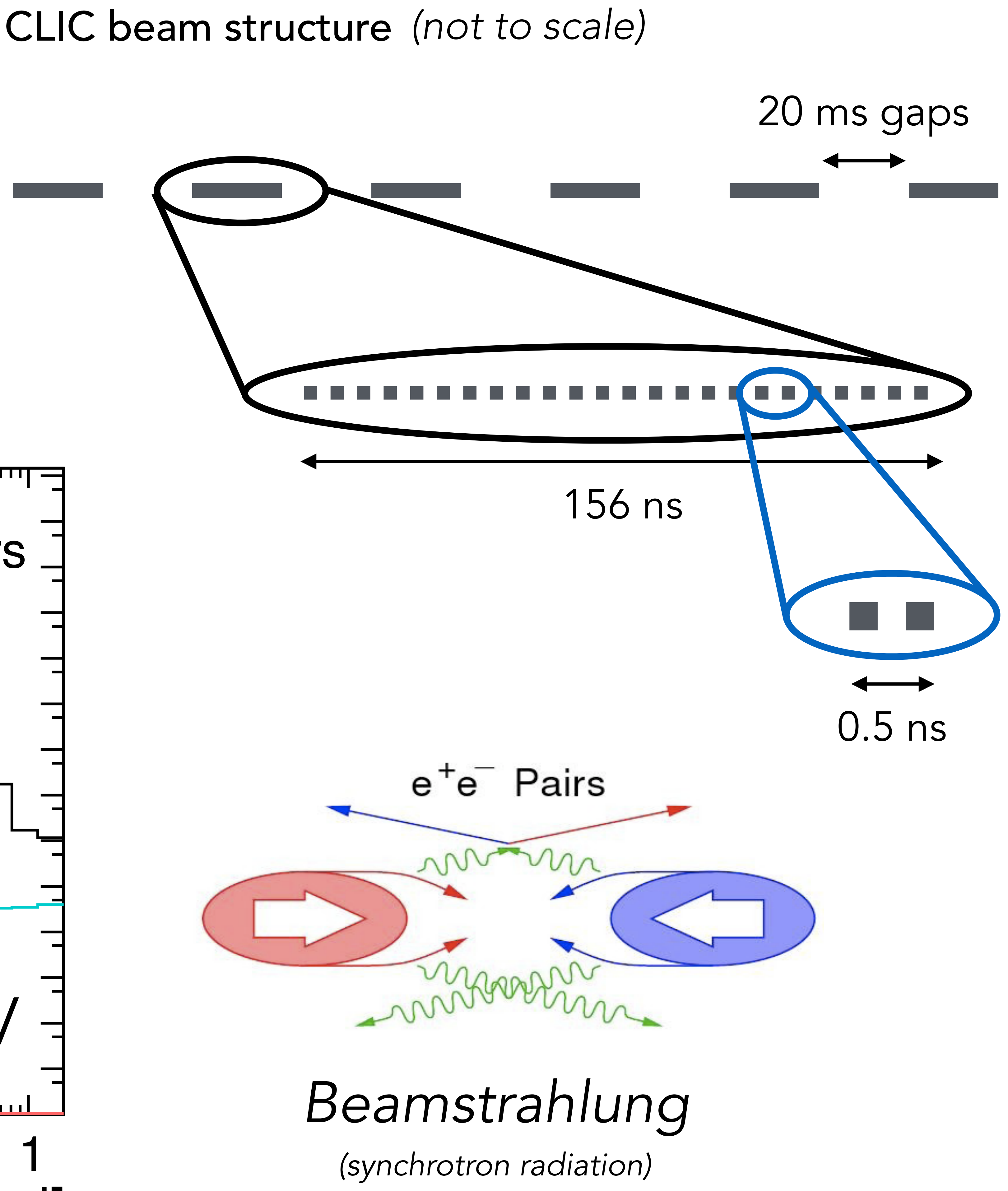
ILC and CLIC Accelerator Parameters

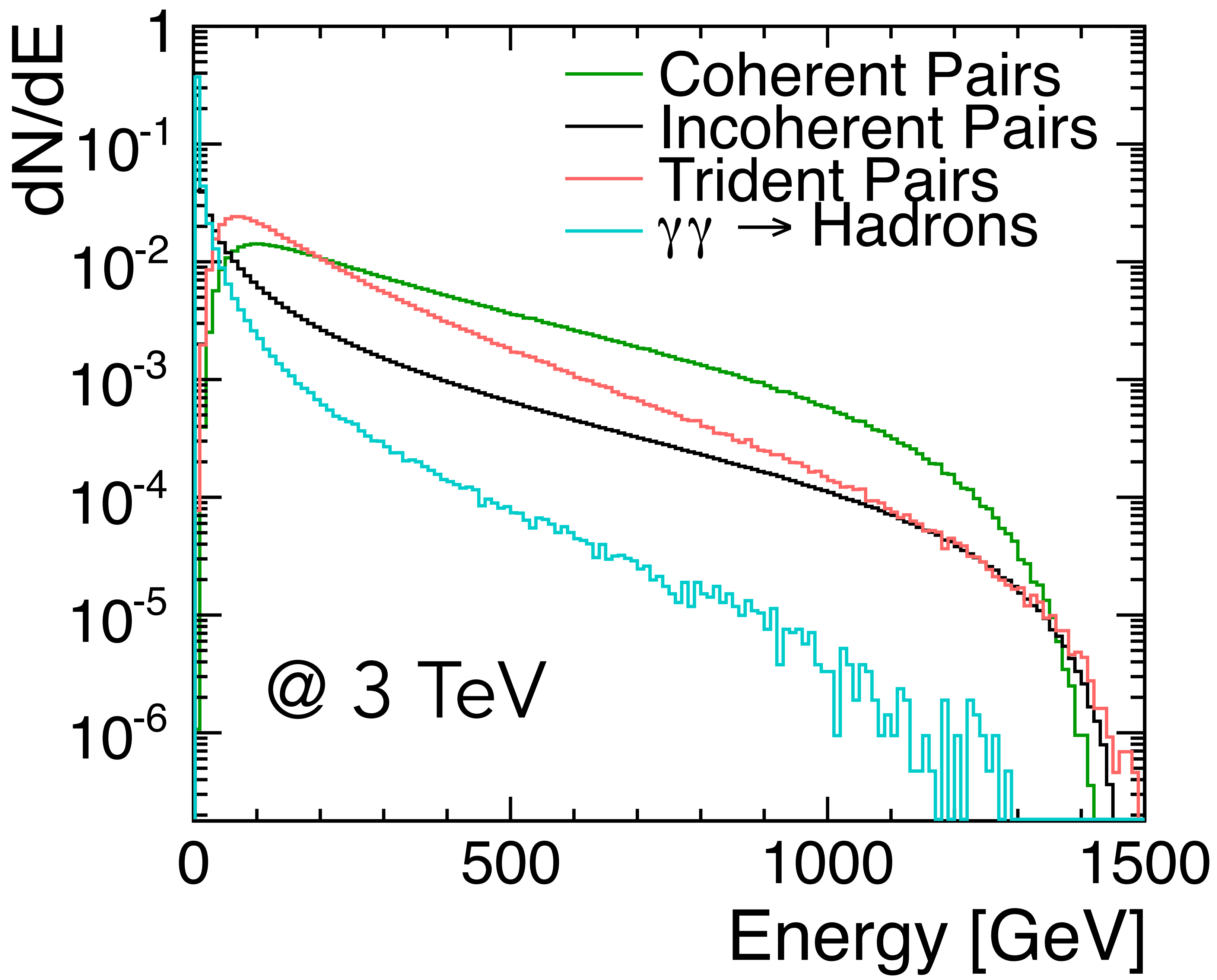
	ILC at 500 GeV	ILC at 1 TeV	CLIC at 380 GeV	CLIC at 3 TeV
L (cm^{-2}s^{-1})	1.8×10^{34}	3.5×10^{34}	1.5×10^{34}	5.9×10^{34}
$L_{0.01}$ (cm^{-2}s^{-1})	1.0×10^{34}	1.2×10^{34}	0.9×10^{34}	2.0×10^{34}
$L_{0.01}/L$	58%	59%	60%	34%
BX separation	554 ns	366 ns	0.5 ns	0.5 ns
#BX / train	1312	2450	356	312
Train duration	727 µs	897 µs	178 ns	156 ns
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Main linac gradient (MV/m)	31.5	38.2	72	100
Duty cycle	0.36%	0.36%	0.00089%	0.00078%
σ_x / σ_y (nm)	474/5.9	481/2.8	≈ 150 / 3	≈ 45 / 1
σ_z (µm)	300	250	70	44

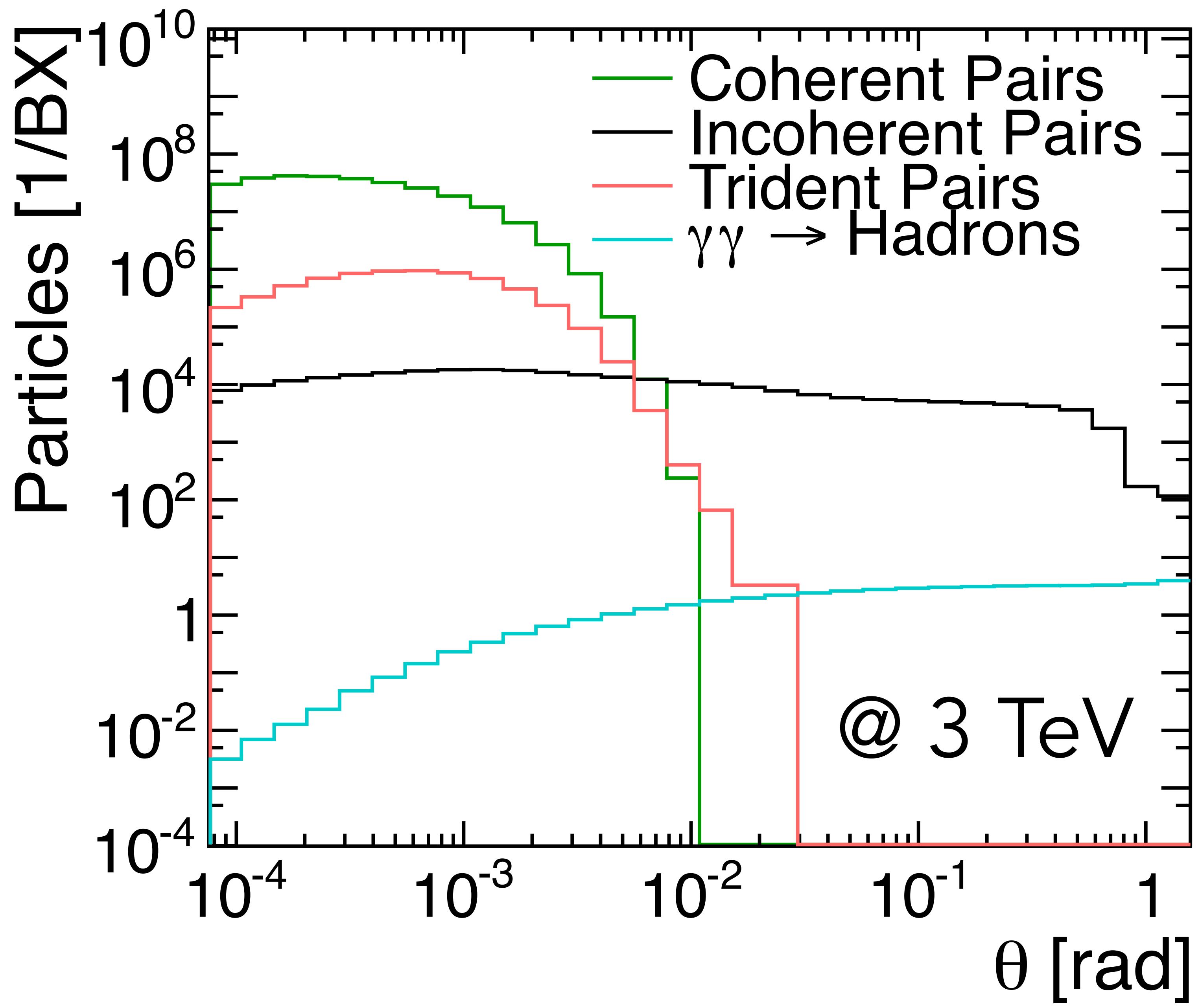
- *Parameters of the proposed CLIC staging scenario*
- *Can be adapted to changes in the physics landscape (e.g. LHC observations)*
- *Power estimates scaled from CDR, with room for improvement*

The CLIC Accelerator Environment

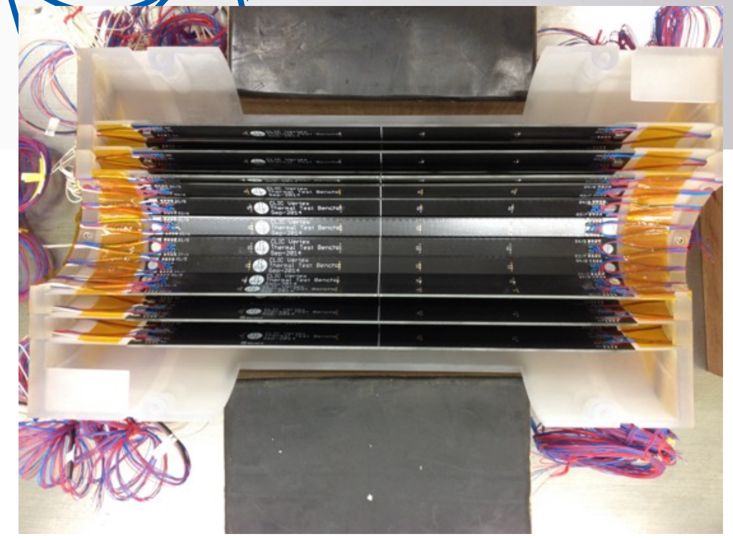
- The beam (and bunch) structure is rather distinct
- The spacing in between individual bunches is only 0.5 ns
- A train of 312 bunches collides with a repetition rate of 50 Hz



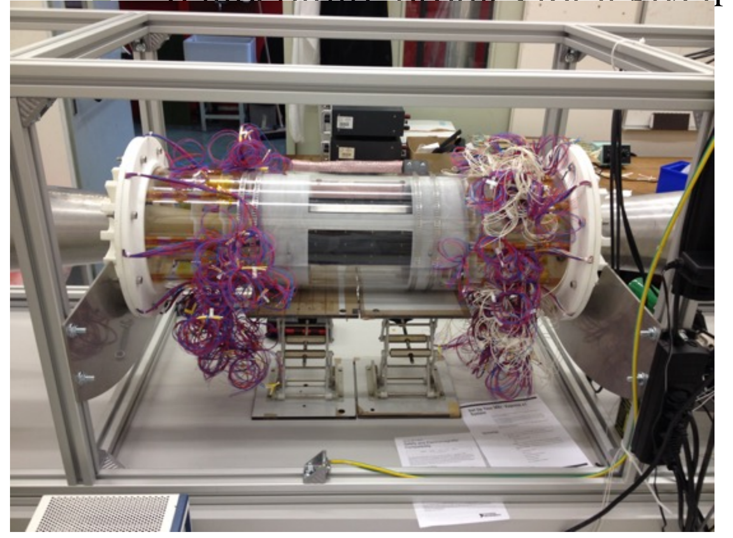


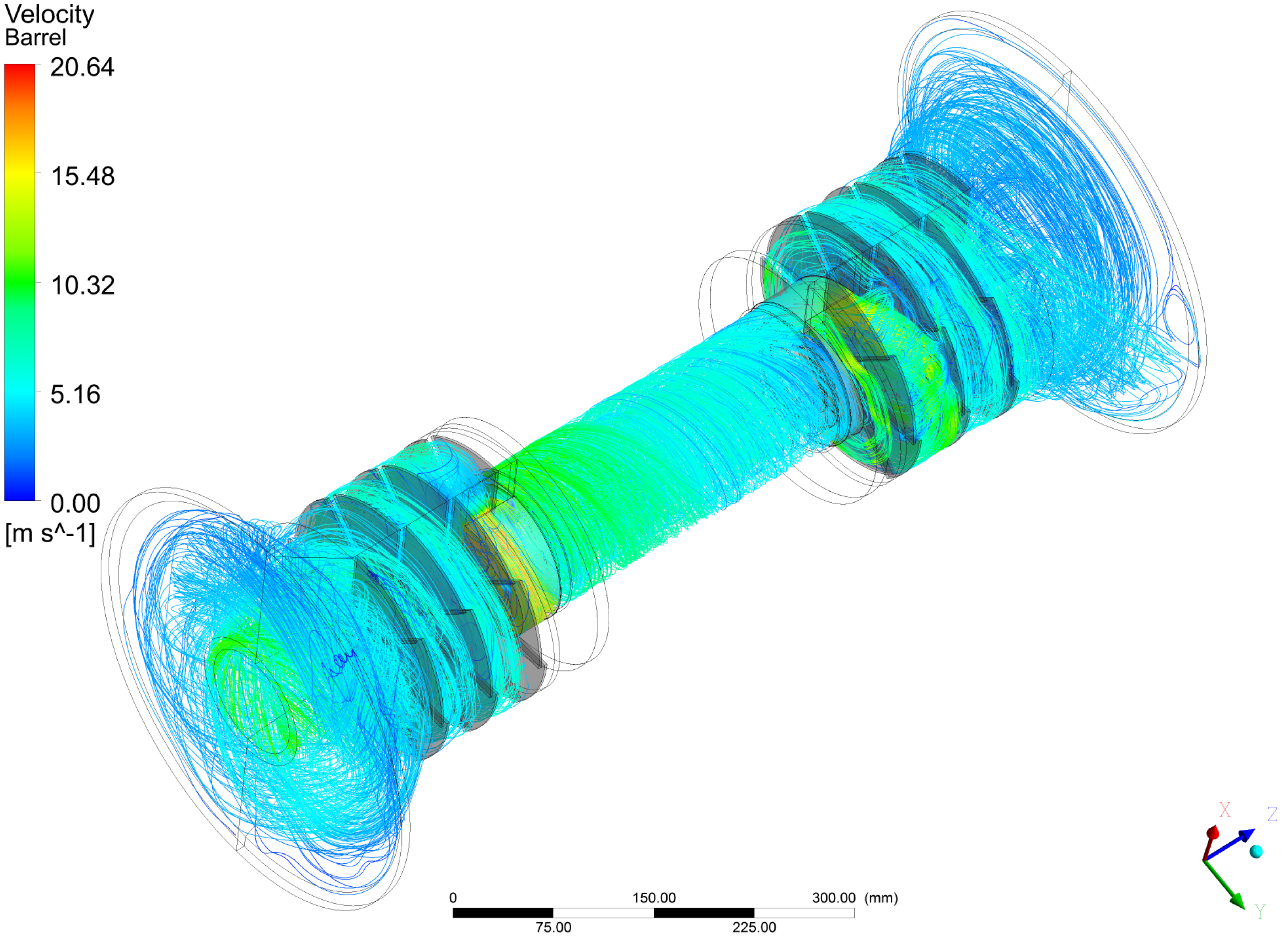


Spiral Air Flow



Temperature profiles for a given

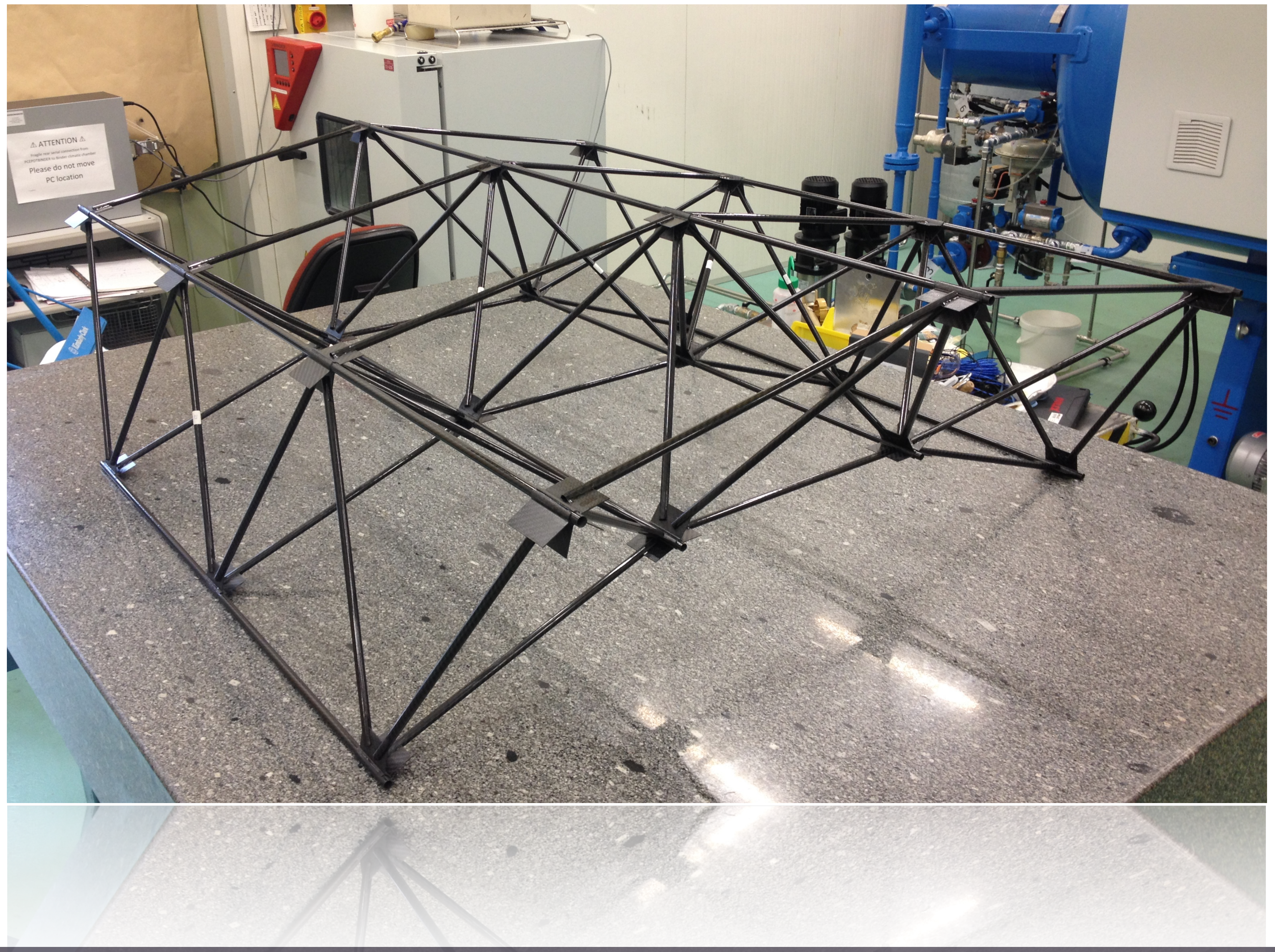


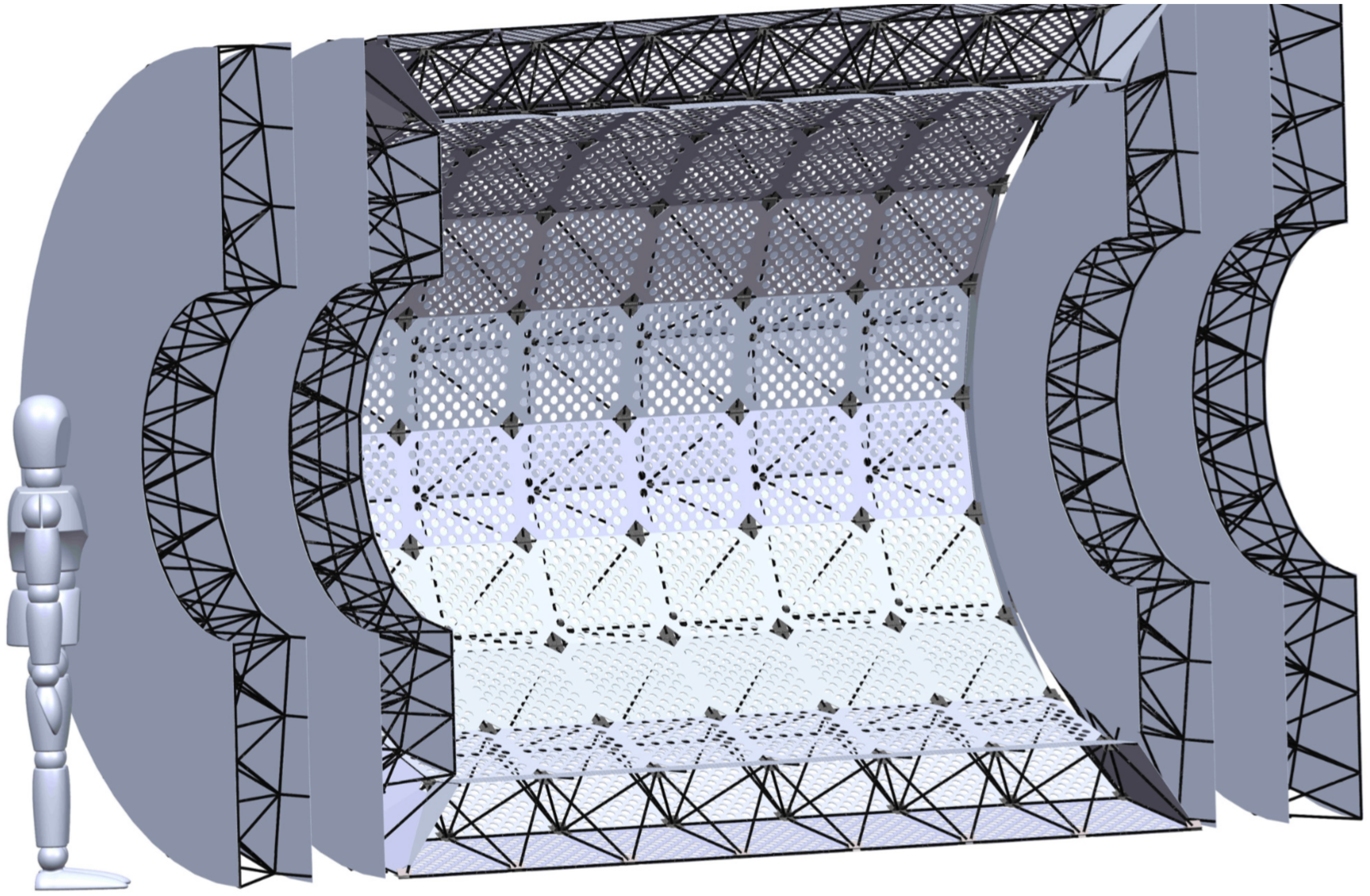


Rickard Ström - rickard.stroem@cern.ch

Tracker Mechanics

- One of the largest challenges in the tracker is holding it all together without a large increase in the material budget
  - Space frame proposed - signifiant savings (~factor 10) in material budget compared to filled foam sandwich
  - First simulation results for deformations (assuming 92 kg outer modules, 60 kg inner modules) give static deformation of < 70 μm, total mass of the support structure 0.125% X_0
  - Prototype constructed for comparison with simulations





CLIC BSM Discovery Reach

New particle / phenomenon	Unit	CLIC reach
Sleptons, charginos, neutralinos, sneutrinos	TeV	≈1.5 TeV
Z' (SM couplings)	TeV	20
2 extra dimensions M_D	TeV	20-30
Triple Gauge Coupling (95%) (λ_γ coupling)		0.0001
Vector boson scattering $\Delta F_{S,0,1}$	TeV^{-4}	5
μ contact scale	TeV	60
Higgs composite scale	TeV	70
Electron size (test of QED extension)	m	3.1×10^{-20}

- *CLIC discovery reach for BSM phenomena*
- *Studied for 2 ab^{-1} at 3 TeV*
- *Depending on the exact models used, quoted values generally extend significantly beyond the HL-LHC reach*

CLIC Conceptual Design Report

CDR - 3 volumes CLIC conceptual design report

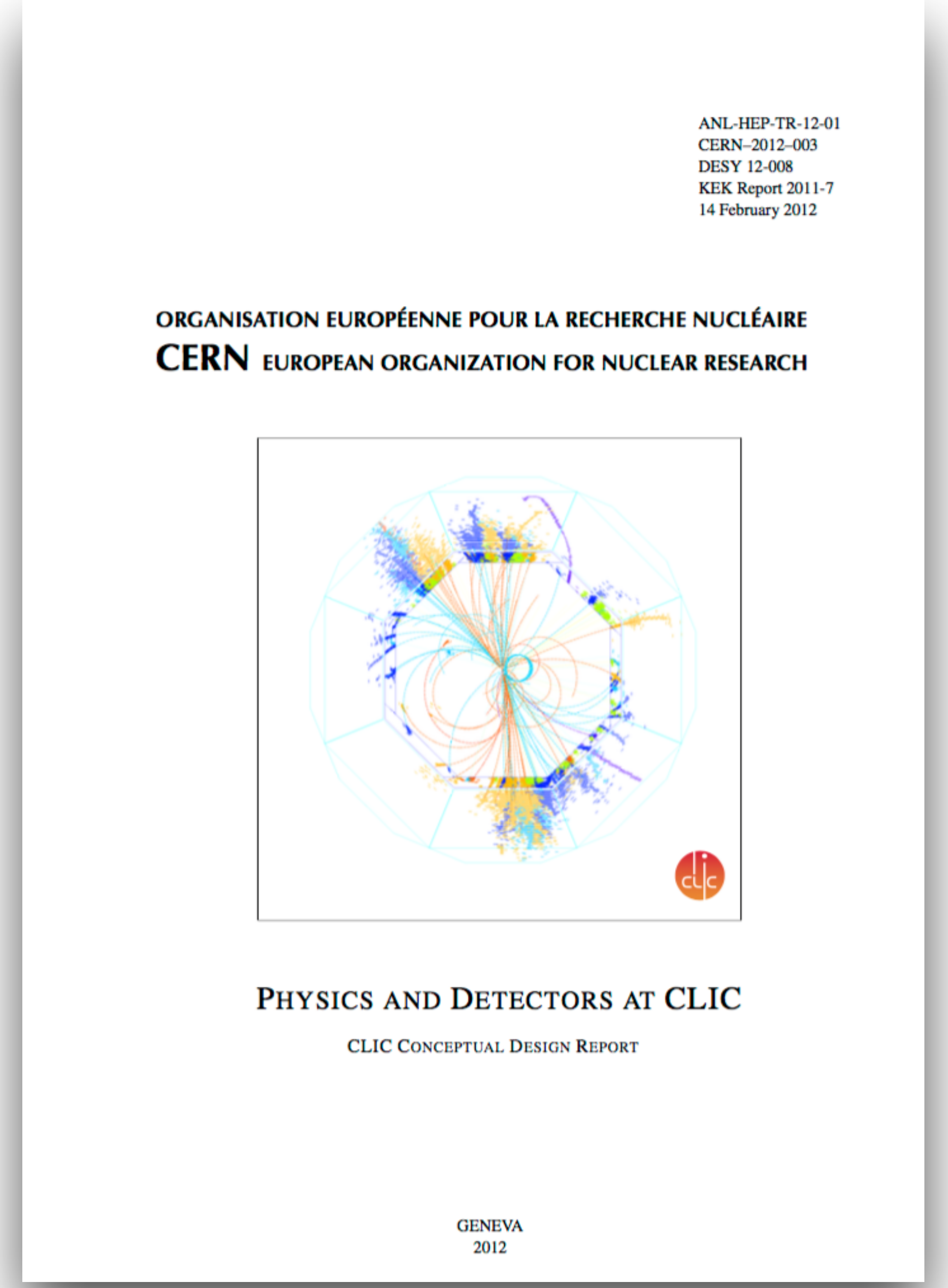

SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

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

Volume 1 "A multi TeV Linear Collider based on CLIC Technology"


ANL-HEP-TR-12-01
CERN–2012–003
DESY 12-008
KEK Report 2011-7
14 February 2012

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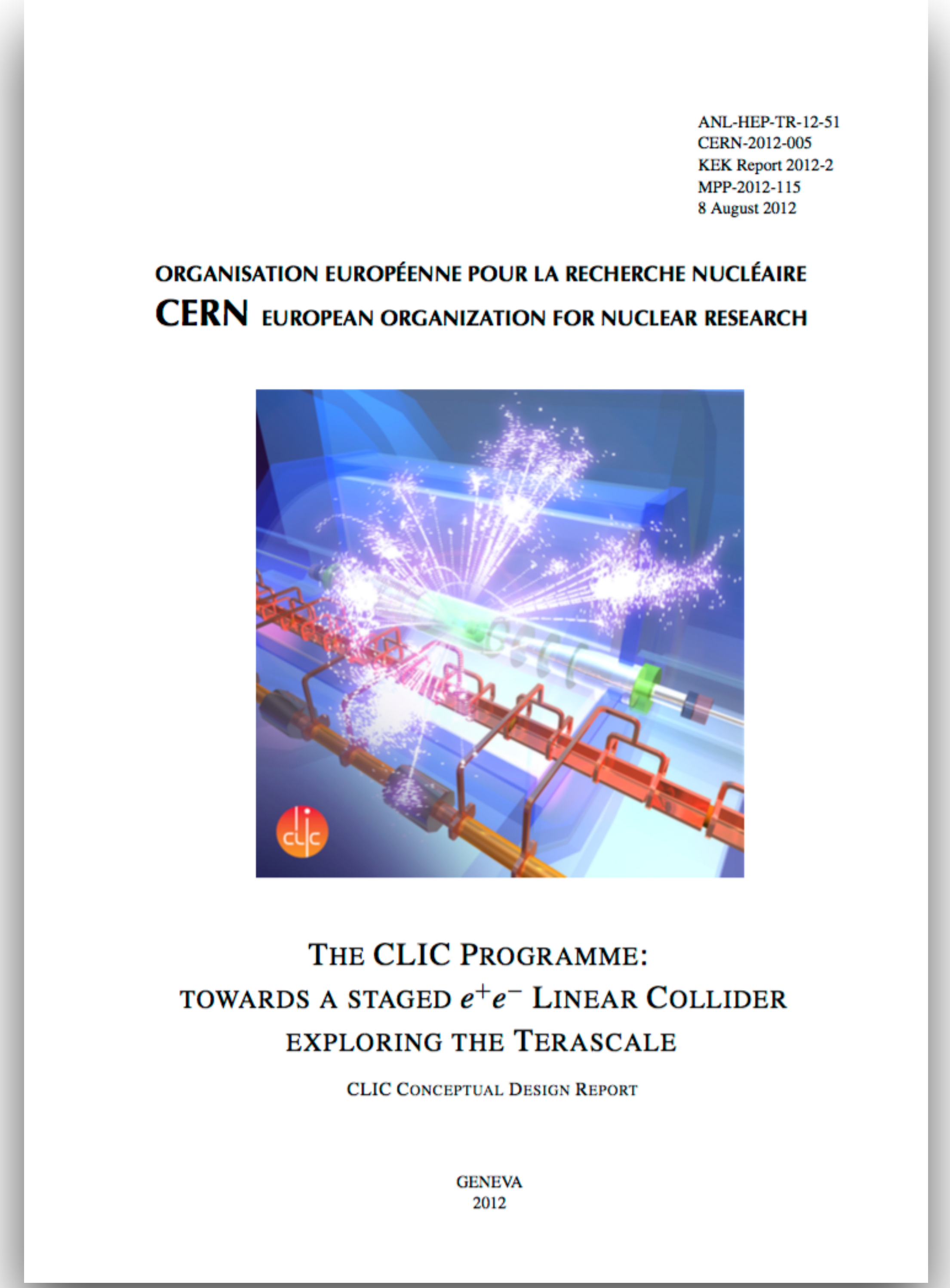
PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Volume 2 "Physics and Detectors at CLIC"


ANL-HEP-TR-12-51
CERN-2012-005
KEK Report 2012-2
MPP-2012-115
8 August 2012

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THE CLIC PROGRAMME: TOWARDS A STAGED e^+e^- LINEAR COLLIDER EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Volume 3 "The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale"

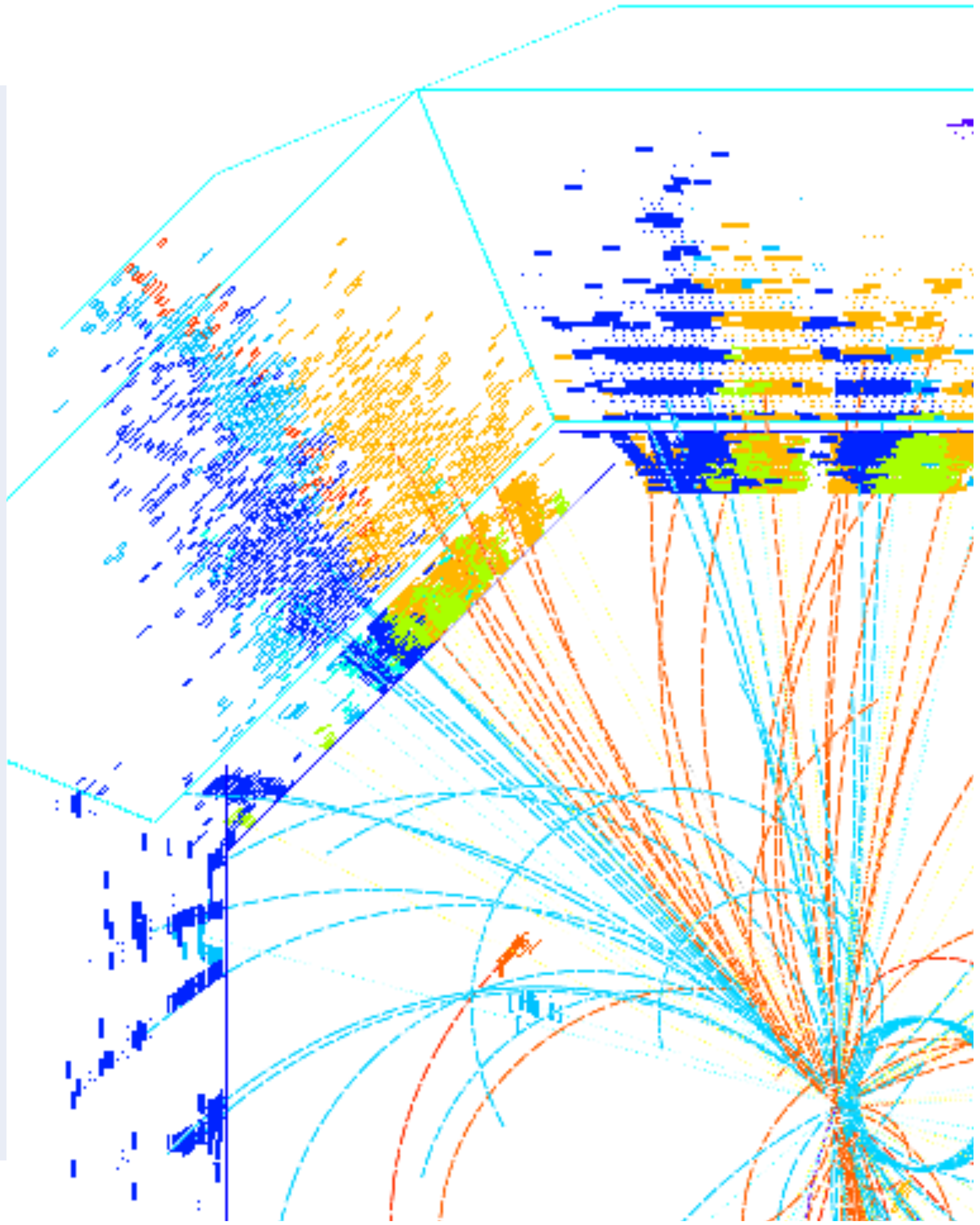
Background Suppression at CLIC

Trigger-less readout of full train

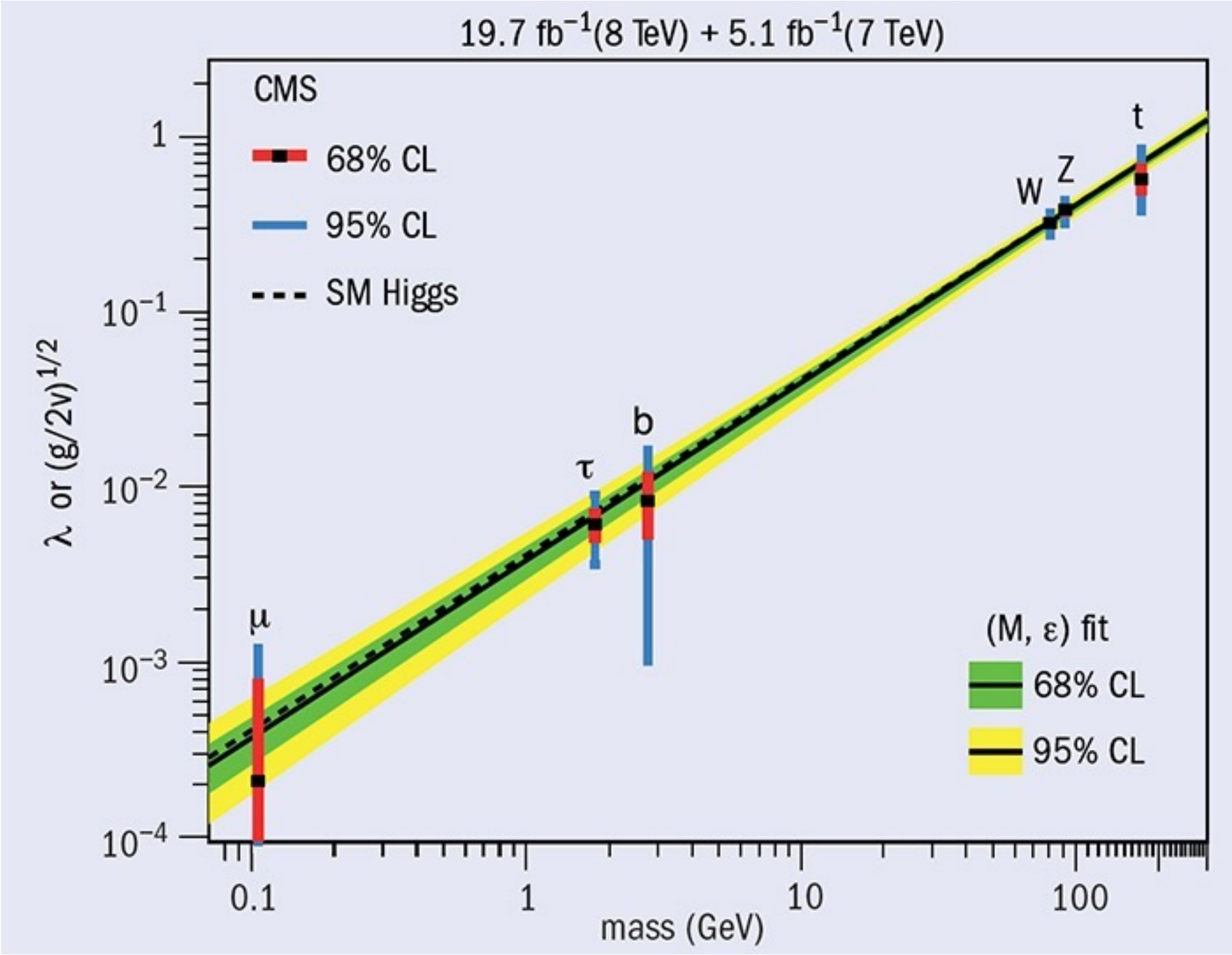
- Full event reconstruction + PFA analysis with background overlaid
  - Provide physics objects with precise p_T and cluster time information
  - Time corrected for shower development
- Then apply cluster-based timing cuts
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects
- Use well-adapted jet clustering algorithms

Particle Flow Calorimetry

- Typical jets contains 60 % charged hadrons, 30 % photons and 10 % neutral hadrons
- Intrinsically “poor” HCAL energy resolution typically limits jet energy resolution
- Identify contributions which come from charged hadrons and use information from the whole detector (charged particles most accurately measured in the tracker, etc.)
- Most popular algorithm ‘PandoraPFA’ developed at Cambridge, initially for use at linear collider
- The particle-flow approach yields optimal jet energy resolution
- CLIC will have very fine-grained calorimeters, allowing for the separation of individual particles in showers
- CMS successfully uses particle flow, though with less refinement as the CMS calorimeter cells are not small enough for a complete particle separation
- Particle flow algorithms (PFA) not a new concept → first used by ALEPH



Higgs Couplings - LHC run I Legacy



CERN COURIER, Jan 27, 2015, "CMS: final Run I results on the Higgs boson"

Linear Collider factor 5-10 better!

Kinematic Cuts

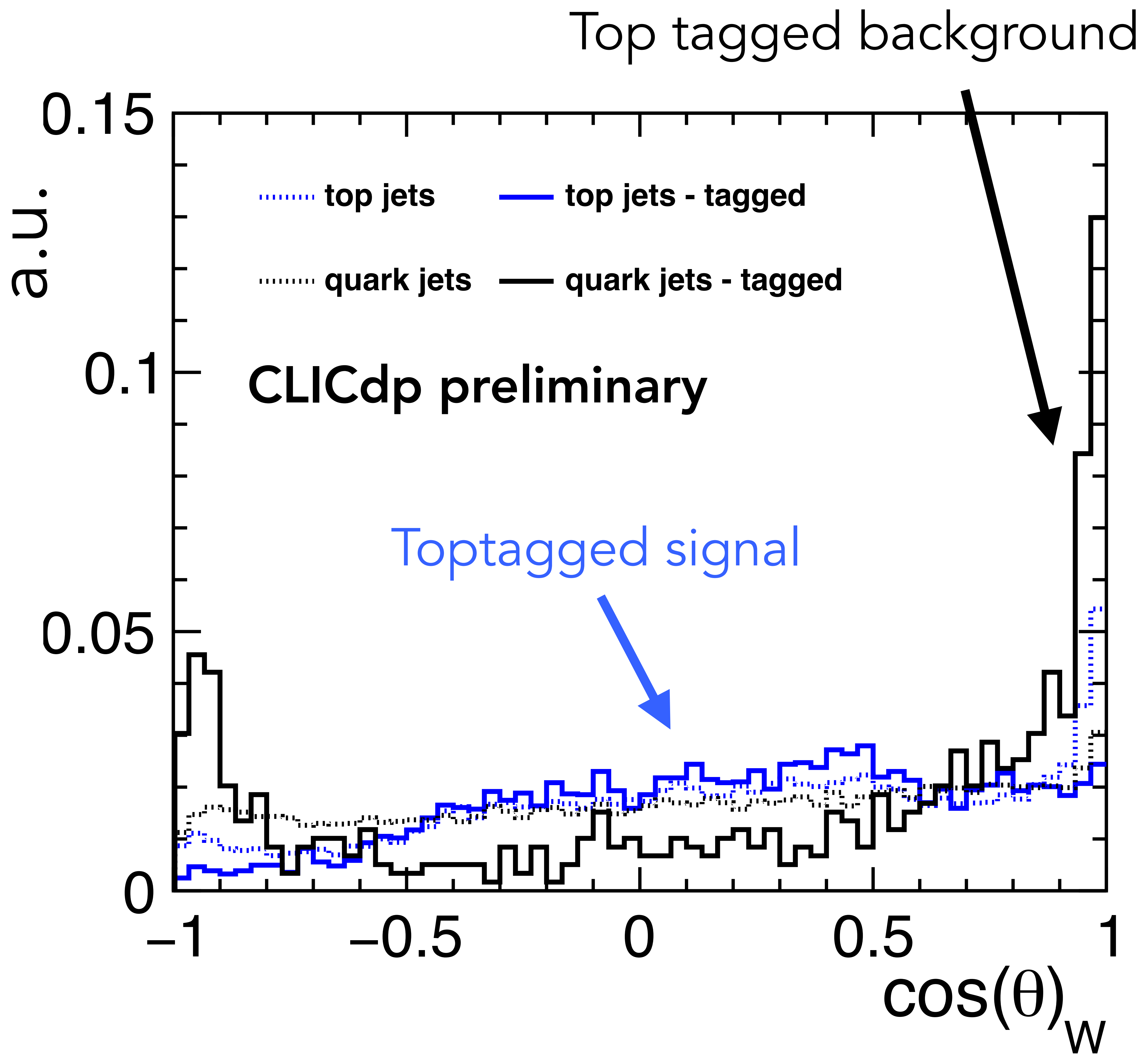
Purpose: make sure the resulting subjets are consistent with top mass, and that 2 are consistent with W mass

The following kinematic cuts are applied:

- Total invariant mass of 3-4 subjet system close to m_t:
  - 145 GeV ≤ m_t ≤ 205 GeV
- Two subjects which reconstruct the W mass within:
  - 65 GeV ≤ m_W ≤ 95 GeV
- W helicity angle consistent with top decay, angle < 0.7

General:

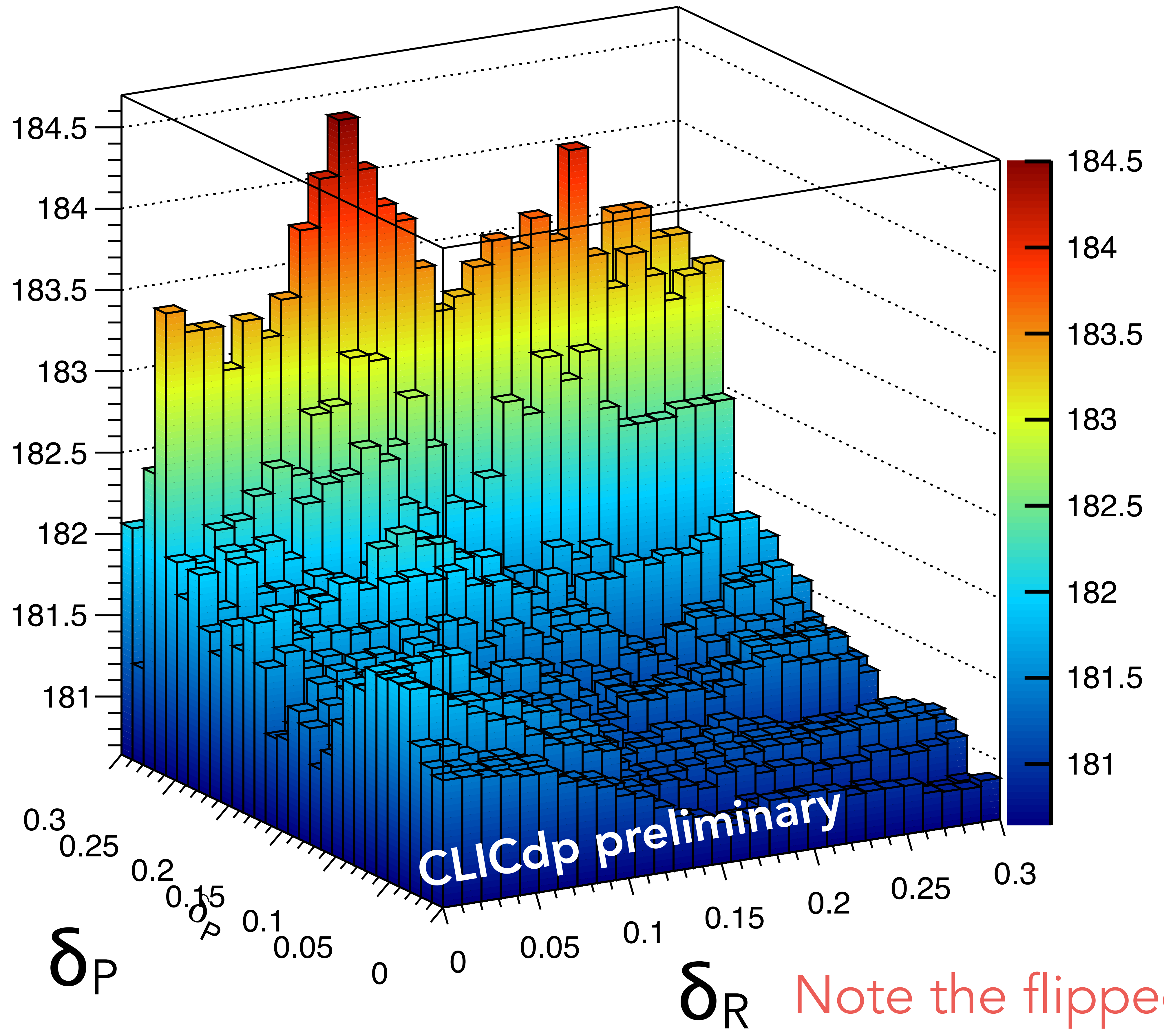
- Boosted events: Effective centre-of-mass > 1350 GeV
- |η| < 2.5
- Top tagger parameter optimisation (R, δ_p , $|\Delta\eta| + |\Delta\phi| < \delta_r$)



Reconstruction after Top Tagging

Top reconstruction

VLC jet clustering algorithm (R=1.5, β=1, γ=1)



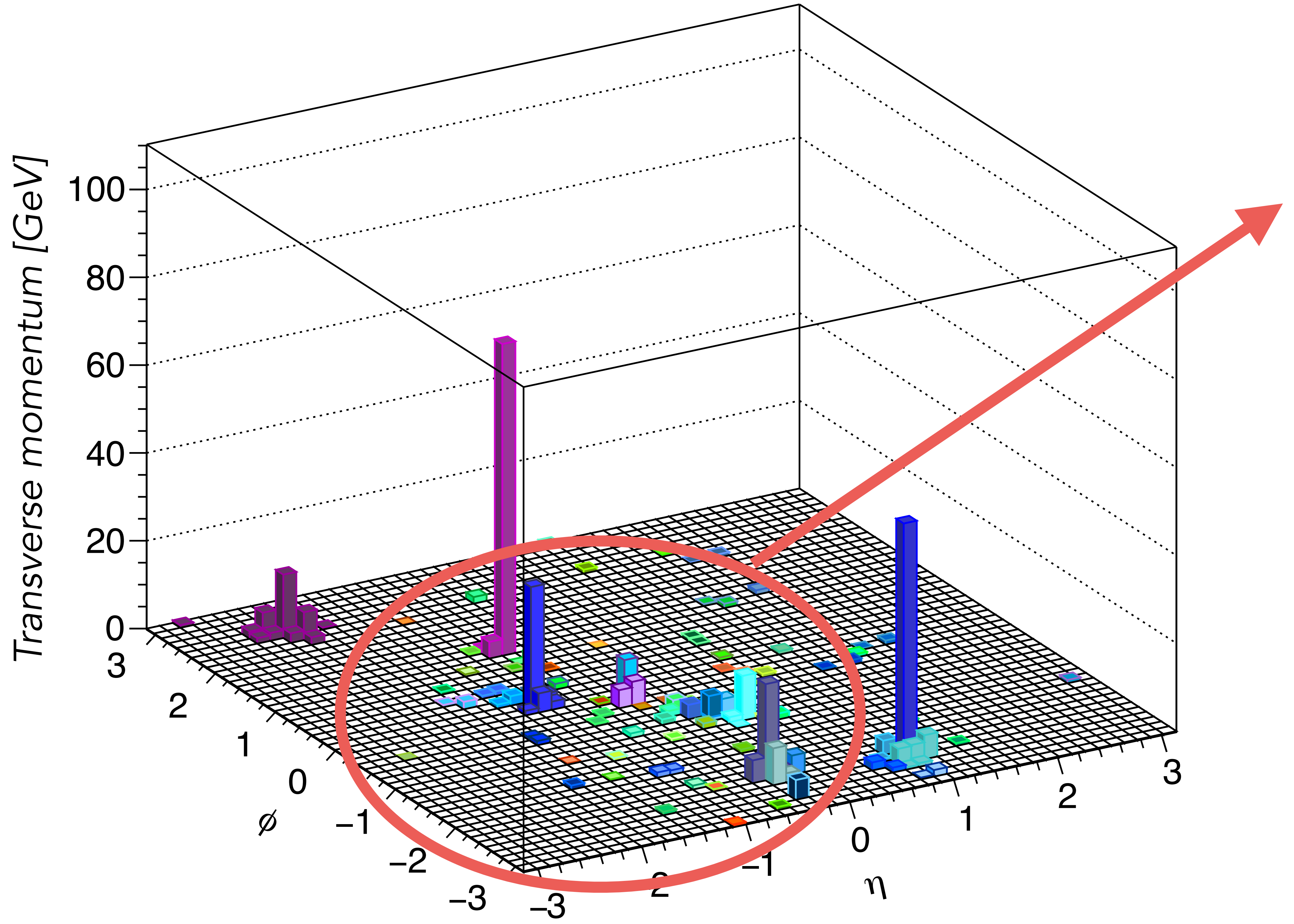
Note the flipped axis!

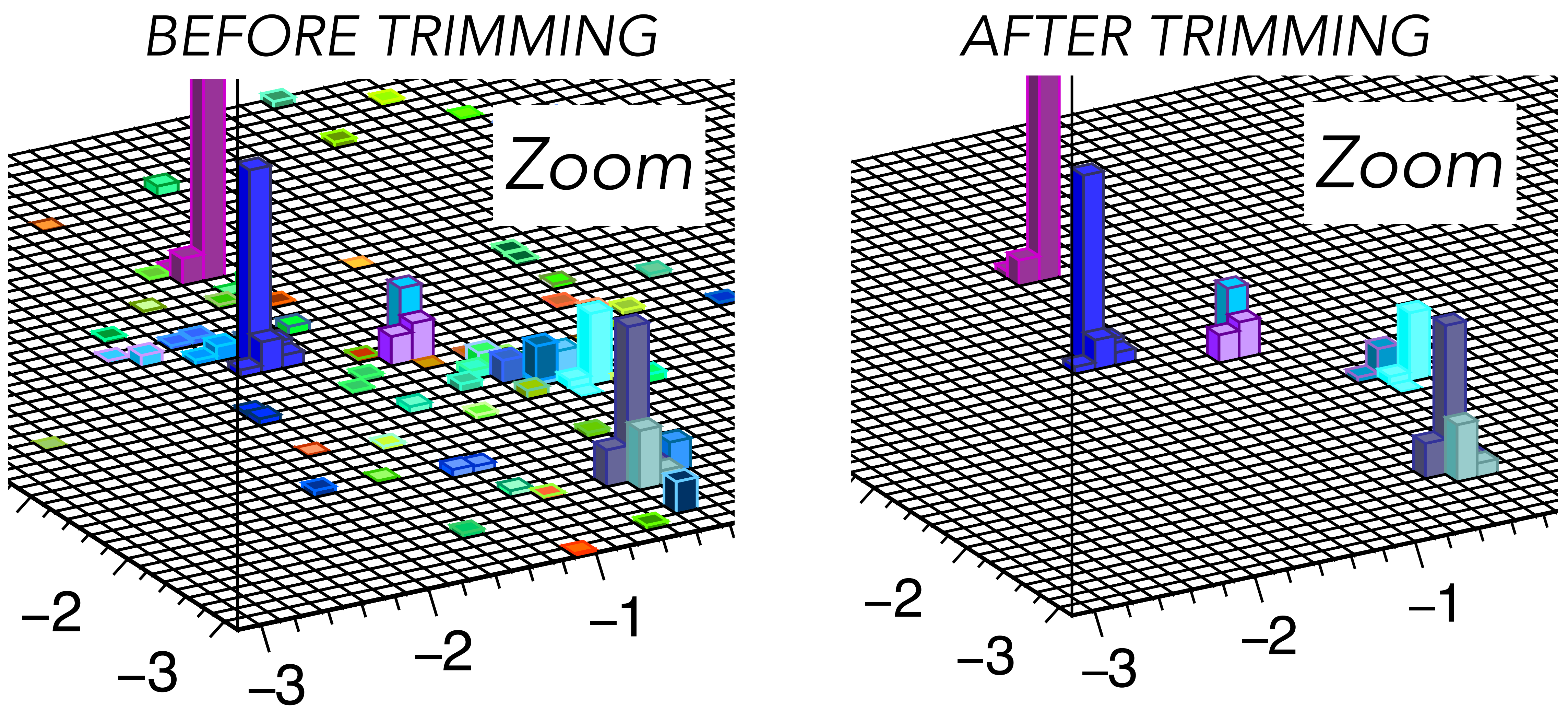
Reconstructed top mass position:

- Each point represents a gaussian fit to the reconstructed top mass (independent of the number of events)
- Using default (Selected) PFO collection gives a too high value of the top mass, can be overcome by by using tighter PFO selection or so-called jet trimming

Jet Trimming

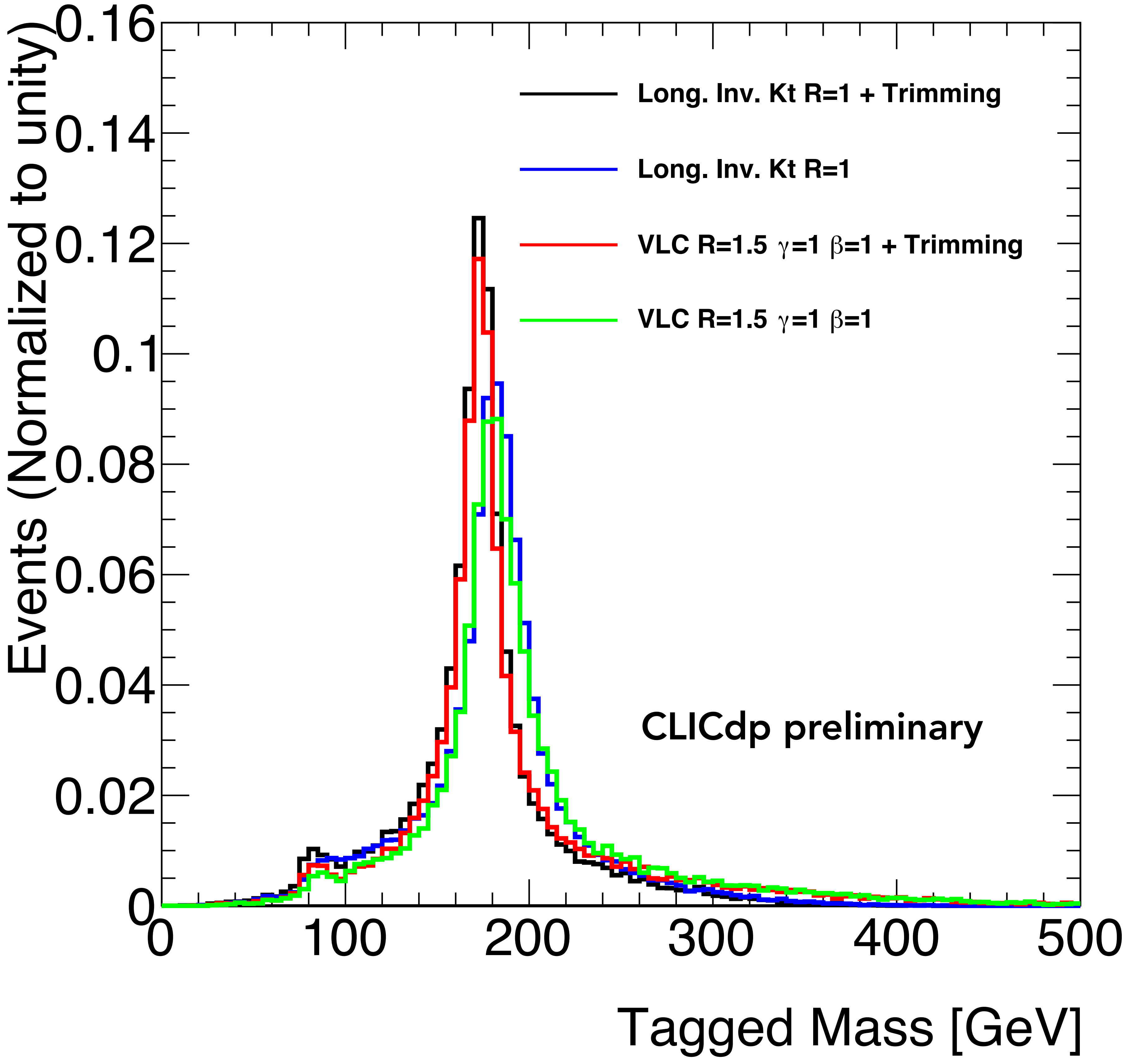
Full phi-eta space
fully-hadronic ttbar event





- Trimming of the jets is an alternative/complementary way to reduce the impact from the beamstrahlung background
- Pre-clustering into so-called microjets
- Inclusive pre-clustering of PFO objects into microjets
- Algorithm used: ee generalised kt
- Optimisation of:
  - Microjet energy threshold E_{th}
  - Jet radius R_{micro}

Jet Trimming Results



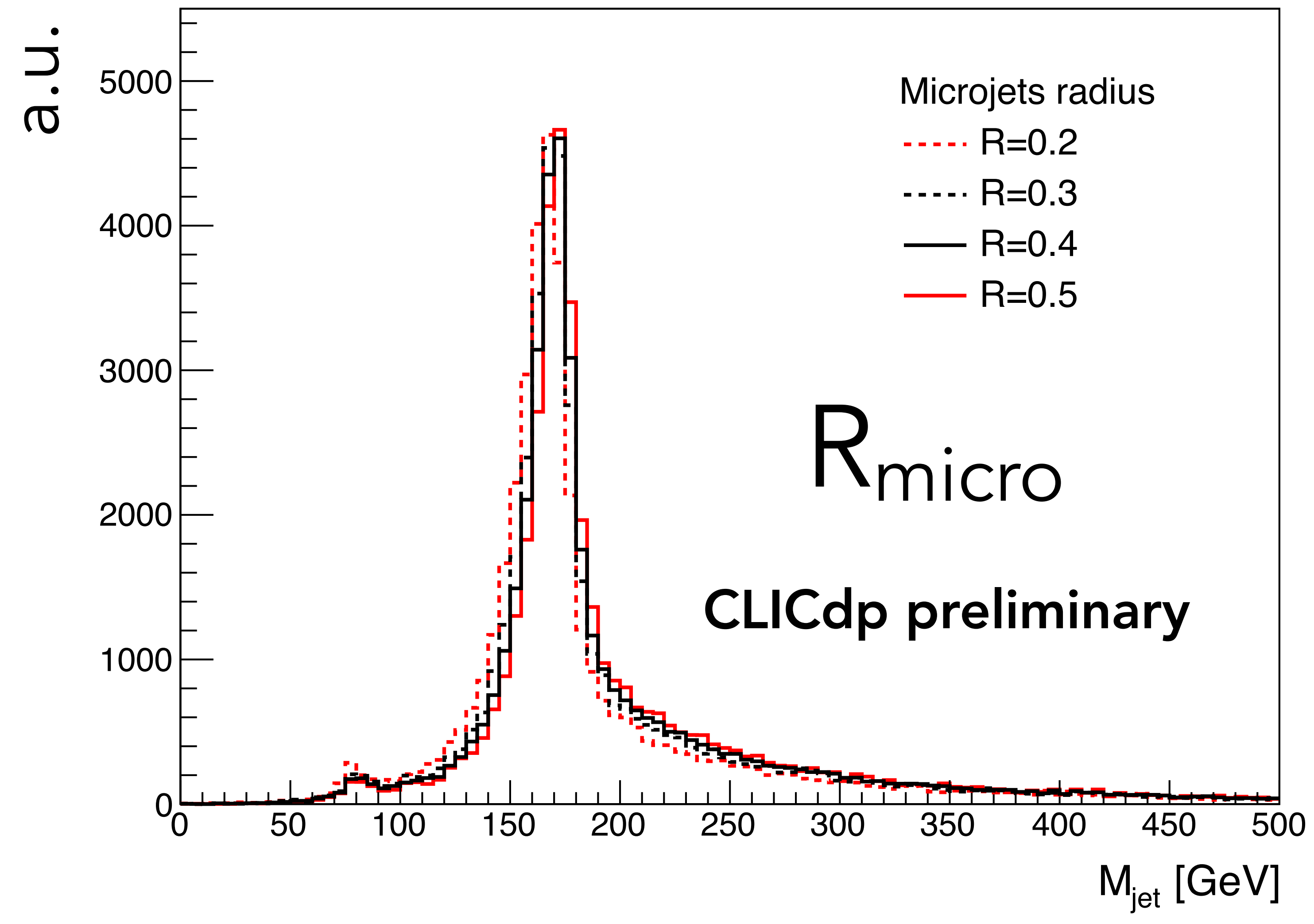
- Pushes the reconstructed mass towards m_t
- Additional Background rejection

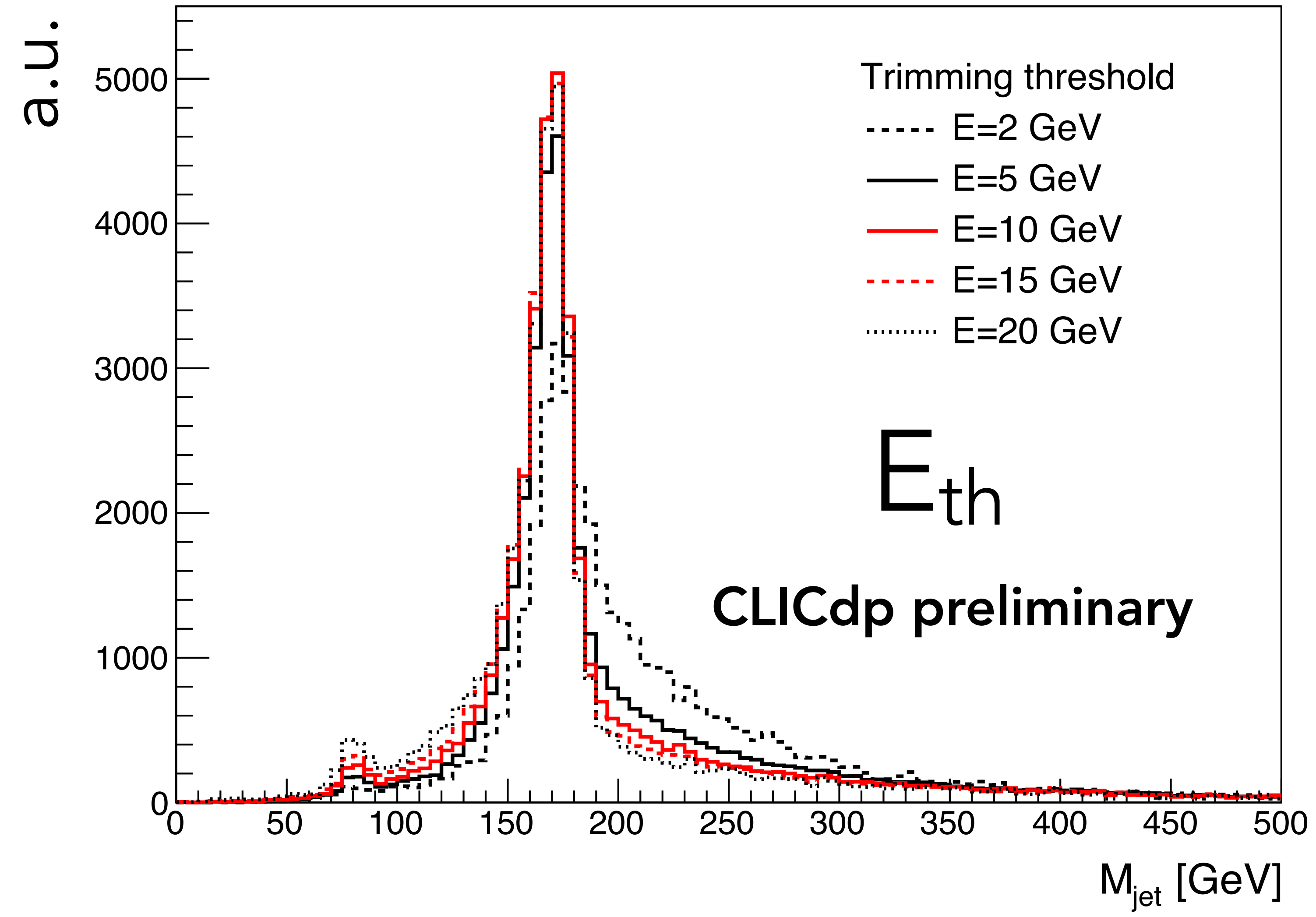
Trimming effect on top mass position

Optimisation of microjet parameters

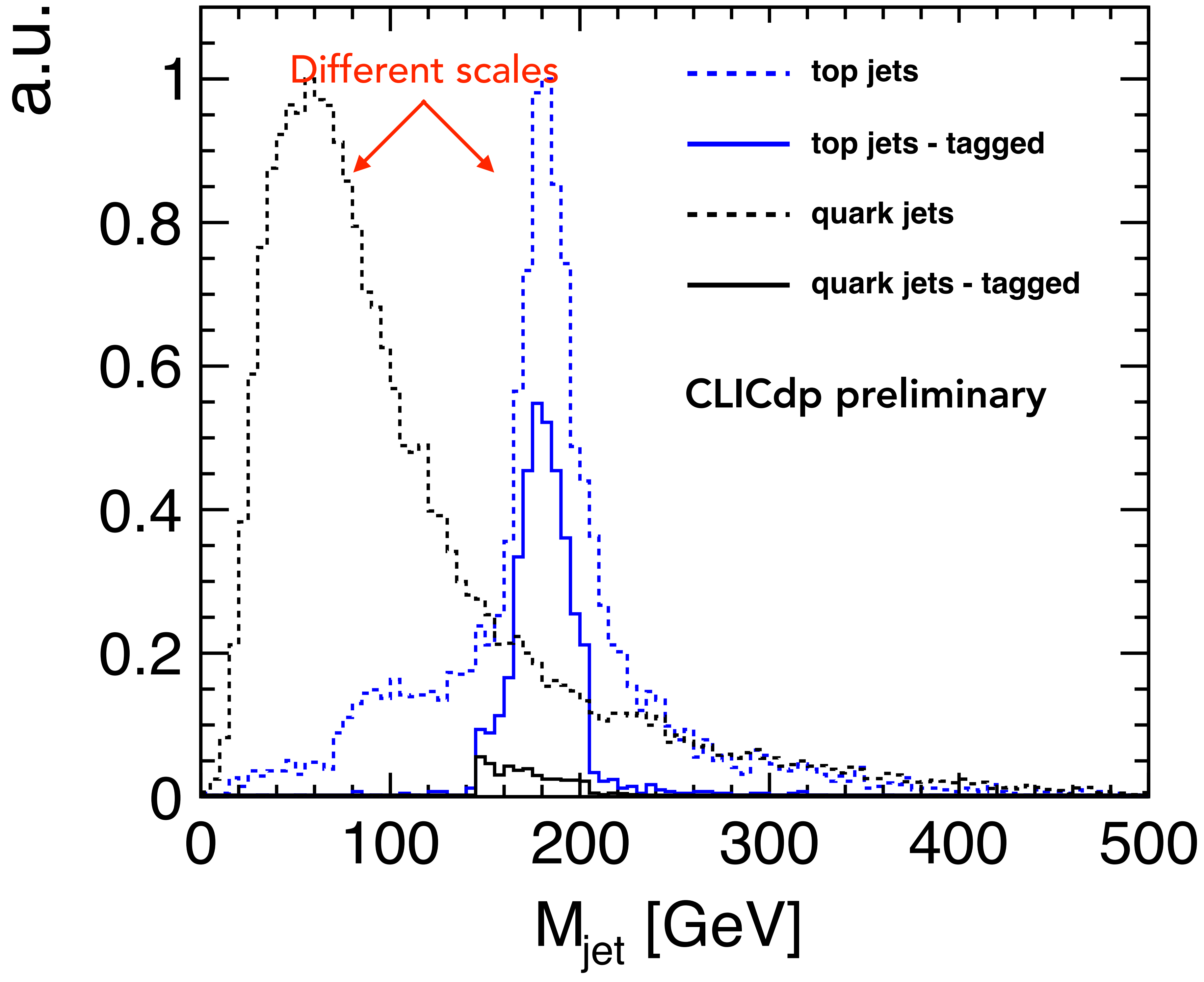
Optimal values:

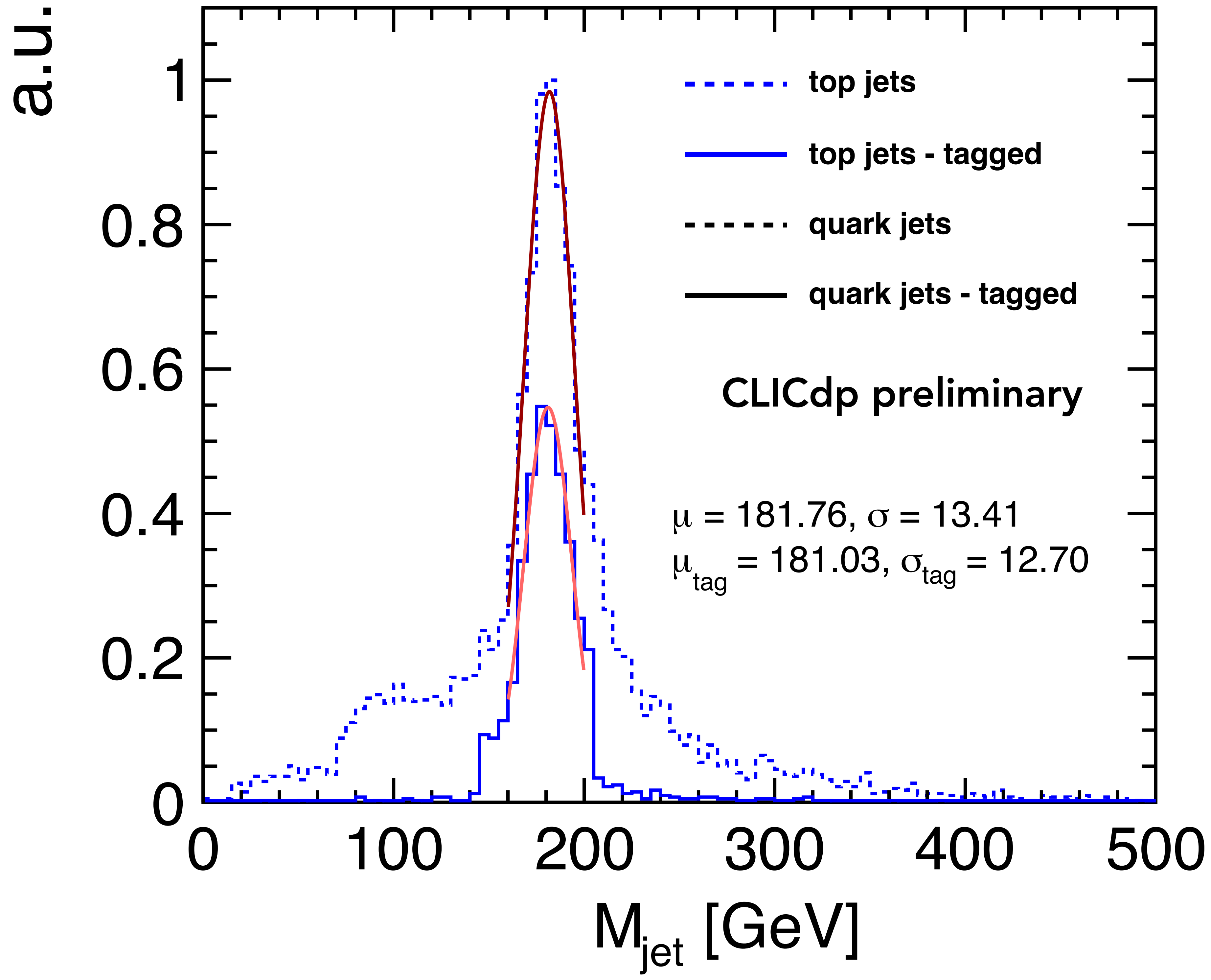
- E_{th} = 5 GeV
- R_{micro} = 0.4





Top Mass Reconstruction





NOTE: 2 Excl. jets per event, i.e. 2 entries per event in histograms

- Mass resolution in the order of 7.5%
- Final optimisation still pending
- Incl. trimming (mass peak position shift to 173.7 GeV, mass resolution in the order of 5%)