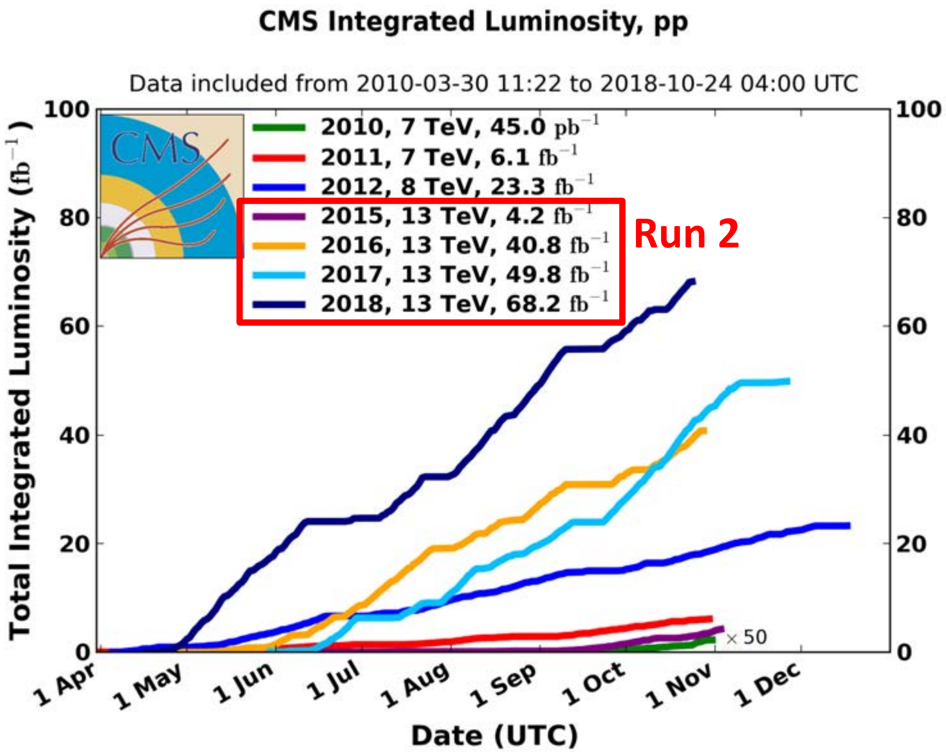
LHC experiments and future high-energy frontier

K. Österberg,

HIP town meeting 3.10.2019

Input & slides provided by M. Aicheler, F. Djurabekova, T. Linden, P. Luukka, S. Räsänen, F. Tuomisto & M. Voutilainen

Excellent LHC performance: ~ 160 fb^{-1} at $\sqrt{s}$ = 13 TeV in Run 2 (2015-18). [goal: 100 fb^{-1}]



LHC

- Long Shutdown 2 (LS2): 12/2018 – 03/2021
- **Run 3: 2021-23**
- LS3: 2024-25 with High Luminosity LHC (HL-LHC) installation
- **Run 4: 2026 →**

- **Logical to fully exploite LHC (CMS, ALICE & TOTEM) as highest priority** (incl. detector R&D, experiment upgrades, detector lab, computing etc…)
- **Make sense to leave no ”stone” unturned to look for indications of BSM physics** (hence prioritize both searches & precision measurements)

ALICE@HIP

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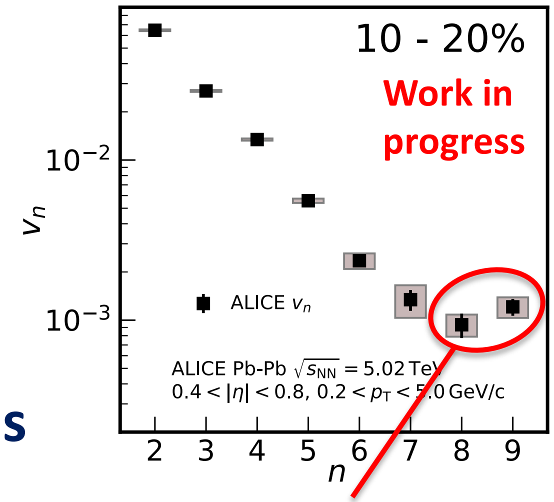
ALICE

S. Räsänen

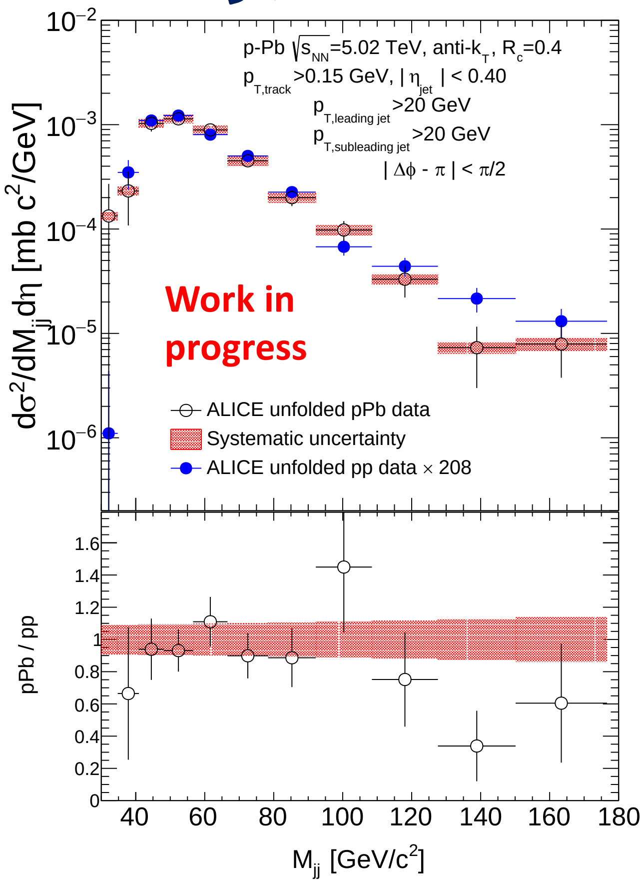
- **Physics**
  - **High-p_T correlations**
  - **Jets**
  - **Flow**
- **Detector contributions**
  - QA for TPC GEM foils
  - **Fast Interaction Trigger (FIT)** for run 3 & 4
  - Forward Calorimeter (FoCal) for run 4 (?)
- **Highlights**
  - Flow physics analysis group coordination
  - Flow results very visible at major conferences
  - FIT project leadership

QM-19 @ Wuhan
High flow harmonics



$v_9 > v_8$: acoustic peak?

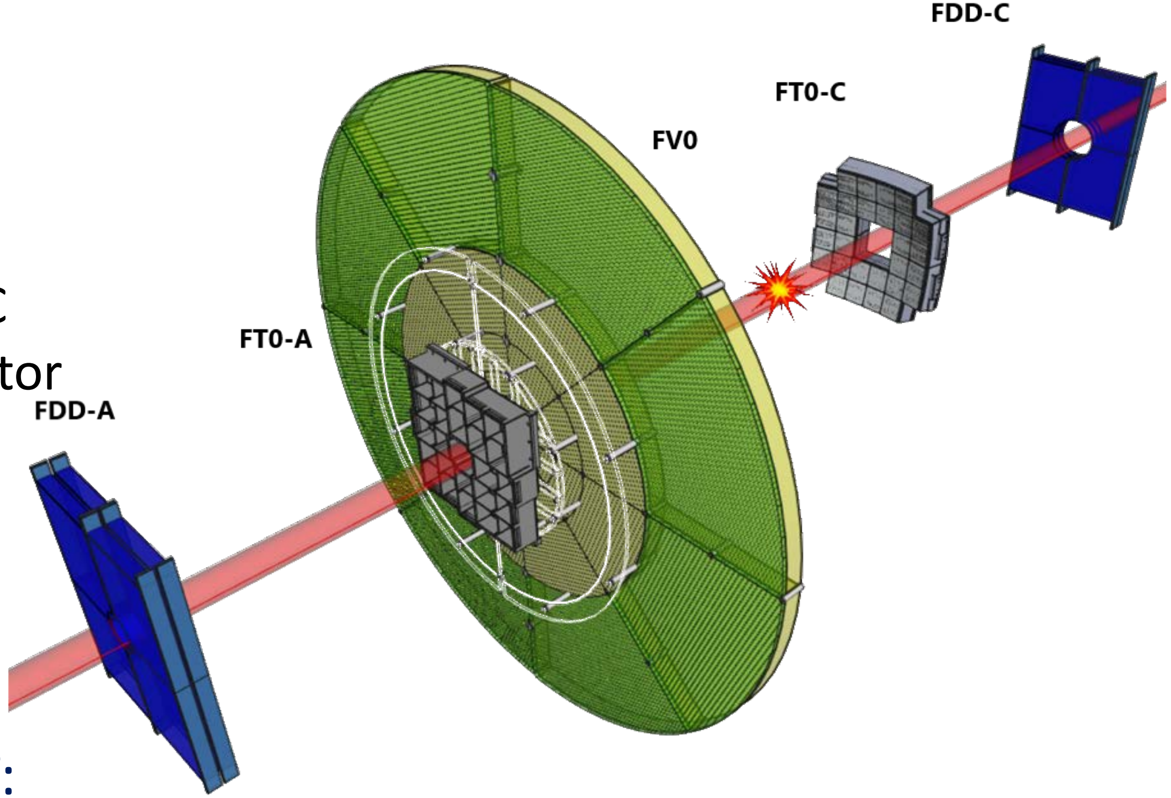
QM-19 @ Wuhan
Di-jet mass in p+Pb



Fast Interaction Trigger - FIT

S. Räsänen

Role of FIT in ALICE:
- **Minimum Bias trigger**
- Beam-gas event rejection
- **Vertex reconstruction**
- On-line luminosity info to LHC
- Wake up trigger to TRD detector
- **Centrality & event plane determination in heavy-ion**



Role of Finnish Team in FIT:
- Timing detector T0 in Run 1 & 2 success

=> initiated proposal of FIT for Run 3 & 4
- Developing Detector Control System, raw data format, detector geometry implementation, test MPC's, commissioning, …
- Studies on centrality resolution & event plane determination

FoCal upgrade for Run 4

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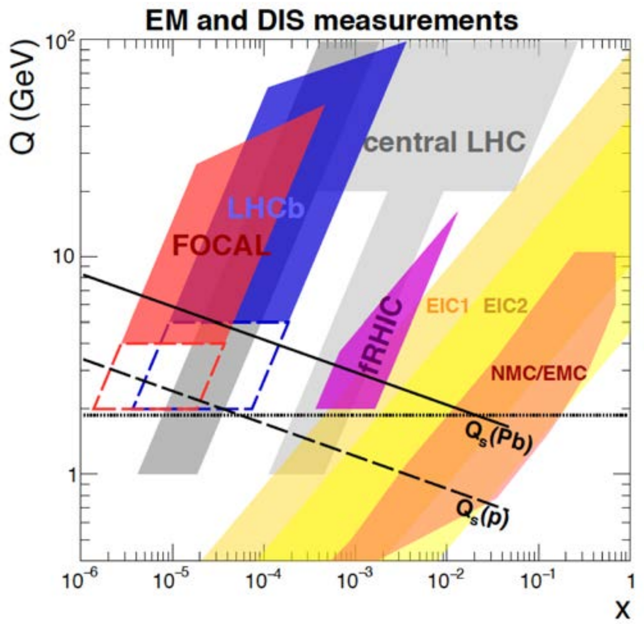

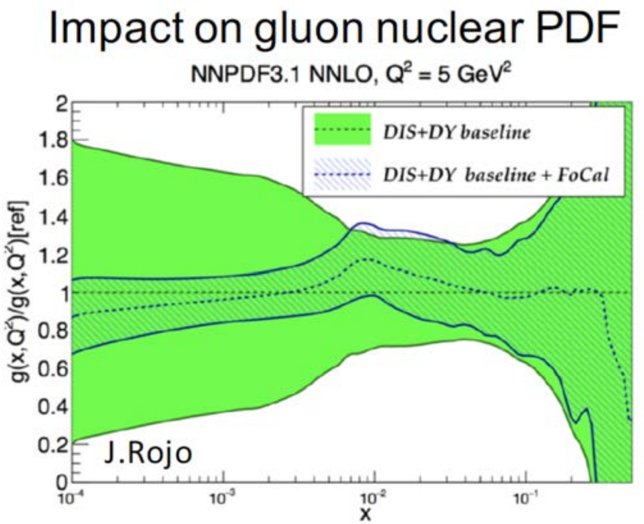

New forward calorimeter at 3.2 < η < 5.8:

- High-granularity EMCal for π^0 & γ measurement, HCal for γ isolation, EMCal & HCal for forward jets
- **Deep reach into saturation region; small x & momentum transfer Q**, only LHeC/FCC better
- **Good synergy with JyU theory group:**
  - Color glass condensate studies – enter saturation region (prof. T. Lappi)
  - nuclear parton distribution functions (PDFs) – constraints to gluon distributions (prof. K. Eskola)
- Letter of Intent expected by end of 2019

To reduce secondaries in FoCal:

- Move FIT close to FoCal, 3.3 m → 6.4 m from IP
- Reconstruct FIT support structures
- Change beam pipe

→ **significant work required also on the FIT side**

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TOTEM@HIP

- **Proton Precision Spectrometer (PPS)** (high luminosity part of TOTEM) became **CMS sub-detector** May 2018 ⇒ **continue in Run 3** (& HL-LHC?).
- **Low luminosity part of TOTEM** including vertical RPs & their equipment **continue as a separate running experiment** until 2021-22 focusing on physics of high β^* runs aiming for a σ_{tot} & ρ @$\sqrt{s}$ = 14 TeV (in 2021-22).
- **Physics priorities:**
  - Confirmation & characterisation of t-channel exchange of a colourless C-odd 3-gluon compound state (”Odderon”) in elastic scattering.
  - Study of glueball candidates (together with CMS).
- **Detector upgrade:** new T2 for σ_{tot} & ρ measurement @ $\sqrt{s}$ = 14 TeV.
- **Highlights:** evidence for colourless C-odd 3-gluon compound (from both diffractive minimum $pp \neq p\bar{p}$ & ρ parameter), TOTEM physics coordination
- TOTEM **continue for a few years** (until 2024?) analysing data & publishing.

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LUT University

CMS@HIP

CMS

❑ Physics

- New physics searches: charged & neutral Higgses, SUSY
- Precision measurements: jet cross-sections, m_{top}
- Forward physics: BSM searches in $\gamma\gamma$ fusion processes

❑ Detector operations & tools

- Jet energy corrections, Level-1 trigger, Alignment, Calibration & DataBase (AlCaDB)
- Deep learning applications in HEP
- Open access data

❑ Detector upgrades (”phase1” 2021-, HL-LHC ”phase 2” 2024-) & operation

- Charged particle tracker: rad-hard pixel detectors & electronics (phase 1 & 2)
- Minimum Ionizing Particle timing detector: Low Gain Avalanche Detectors
- Forward proton detector: diamond timing detectors

❑ **Responsibilities:** collaboration board vice-chair, career committee co-chair, data preservation & open access coordinator, AlCaDB co-convener, top mass & properties co-convener, standard model physics-hadronic co-convener…

CMS detector operations

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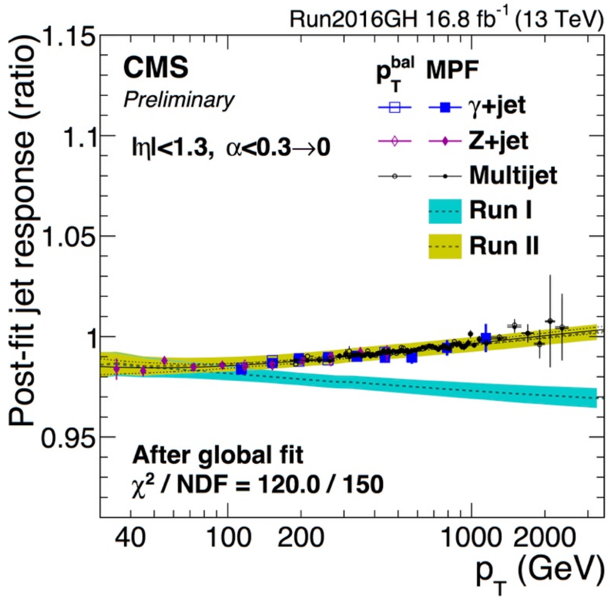
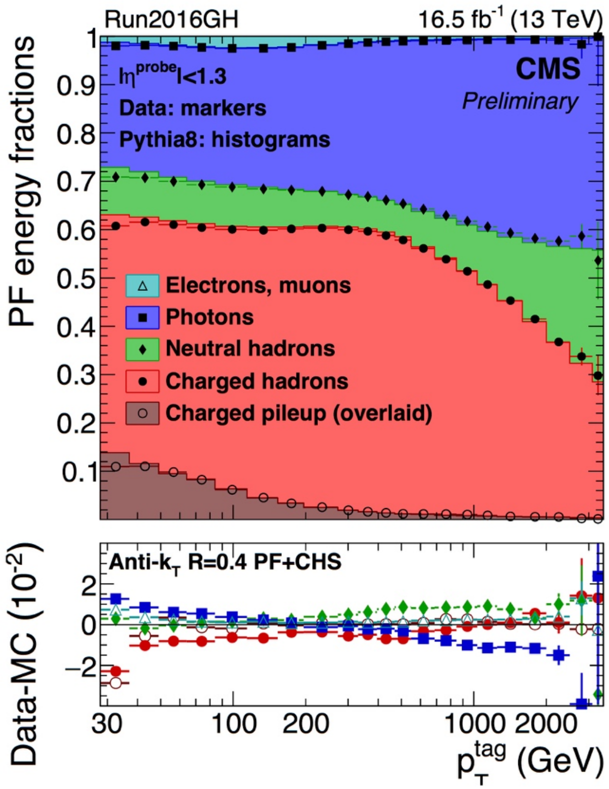
M. Voutilainen

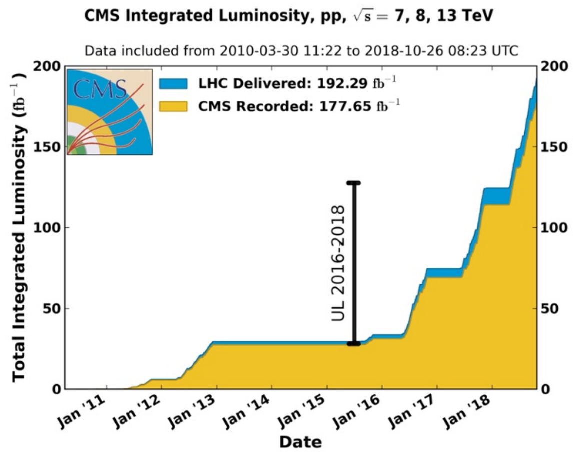
- **Jet energy corrections**
- Critical contributions tailored to our physics program:
  - Global fit of absolute JEC
  - Uncertainty sources
  - PFJet composition
  - High p_T with multijet balance
  - b-jet scale with Z+b (new)



- **Level-1 trigger**
  - J. Heikkilä & S. Laurila, CMS Achievement Award for Level-1 offline certification coordination
  - Continuity into LS2



- **AlCa/DB**
  - T. Lampén L2 co-convener
  - UltraLegacy 2016—2018 campaign to re-reconstruct data at highest possible precision



- **Outreach:**
  - Organisation of Physics Days 2019 (>300 participants)
  - CERN BootCamp 2019 @ CERN IdeaSquare

CMS physics

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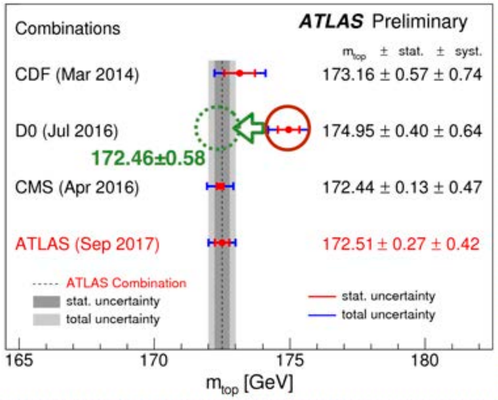
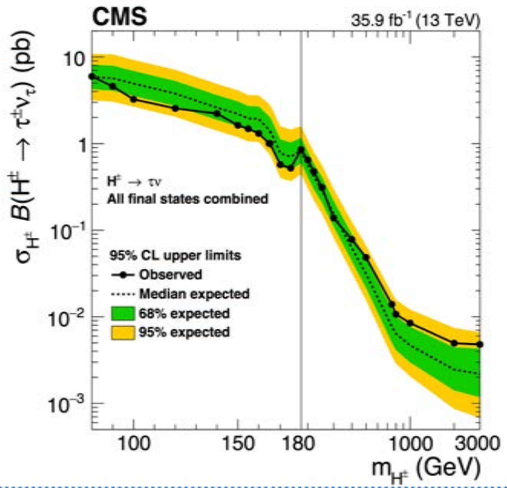
M. Voutilainen

- **Charged Higgs bosons**
  - Additional Higgs bosons predicted in many BSM models
  - Publication on 2016 data, $H^+ > \tau\nu$ on-going with full Run2
  - New search in WH channel more sensitive to type-I models
- **Neutral Higgs bosons**
  - $A \to ZH \to 2l2\tau$ channel with CERN and Wisconsin
  - Expected sensitivity +40% compared to Run I methods
  - Public results on 2016 data
- **SUSY**
  - Gluino pair to tttt with Athens, CERN, DESY, FNAL
  - Most sensitive single lepton channel, advanced ML
  - On-going with full Run2 data
- **Top quark mass**
  - Key parameter in SM, for vacuum stability
  - Aiming at ±0.2 GeV at CMS, in lepton+jet channel
  - Address key systematics: b-JES, final state radiation, underlying event
- **Strong coupling α_s**
  - Also key parameter in SM, for vacuum stability
  - Least precisely known coupling in SM (~1%)
  - Running at high p_T: inclusive jet cross section
- **Parton distribution functions (PDFs)**
  - Key input to all LHC predictions
  - High-*x* gluon least precise
  - Gluon jet cross section: α_s - gluon PDF anticorrelation at high p_T

- MSc thesis (T. Mäkelä) re-analyzed D0 m_t results using public internal notes on b-JES



- Search for $H^\pm \to \tau^\pm \nu_\tau$, JHEP 07 (2019) 142



CMS physics future plans

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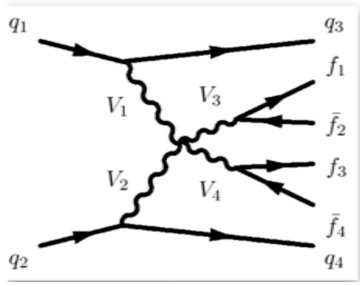
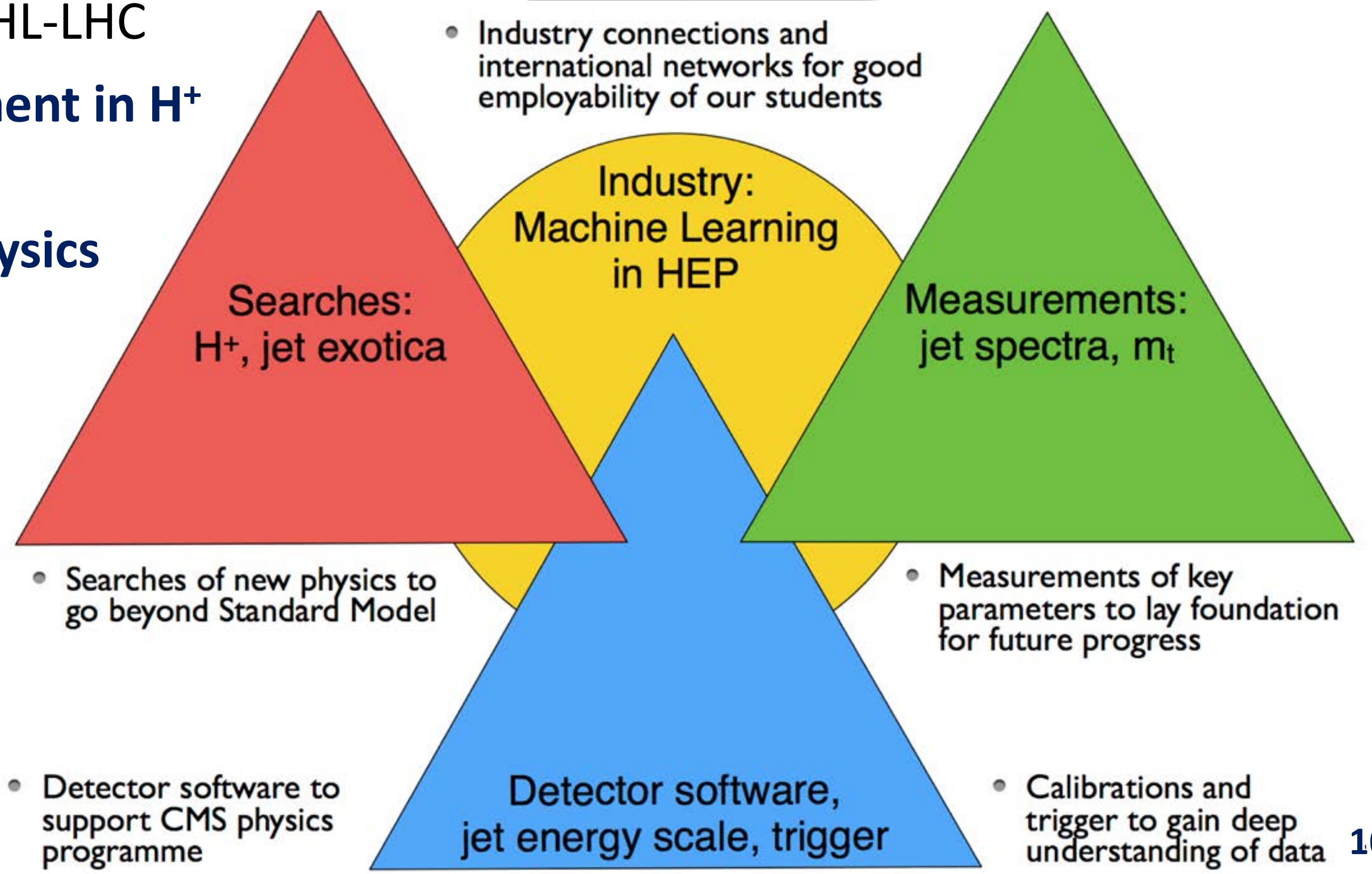
❑ Capitalize on Helsinki expertise in H^+, jet physics & Machine Learning (ML)

- **Fully explore electroweak symmetry breaking, targeting vector boson fusion channels in all-hadronic mode**: prove in run 3, measure at HL-LHC
- **Continue engagement in H^+**
- **Support jets for the whole CMS physics programme:** novel methods with ML, dijet & $Z(\mu\mu)$+jet measurements to combat forward region radiation damage, high rates & high pile-up.



M. Voutilainen

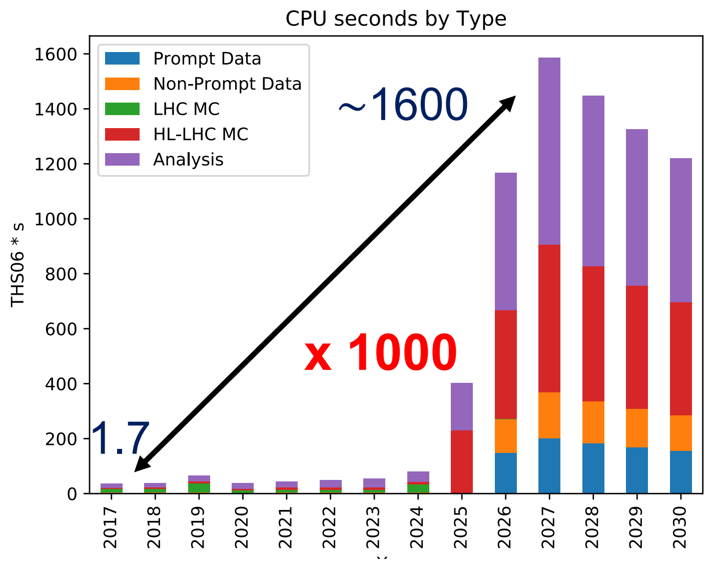


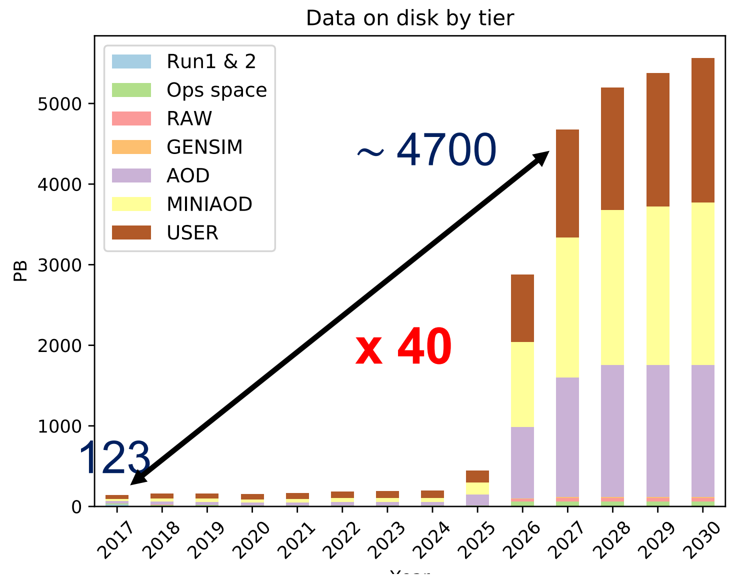
LHC computing & HL-LHC challenge

- ❑ **Worldwide LHC Computing Grid (WLCG) resources through Nordic Tier-1 (NGDF, provides ALICE) & HIP Tier-2 (T2_FI_HIP, provides CMS) centers**
  - Finnish Grid and Cloud Infrastructure (FGCI) collaboration crucial for developing & maintaining necessary national grid infrastructure.

T. Lindén

  - Collaboration with CSC important to satisfy data intensive LHC computing needs
- ❑ **HL-LHC computing & data challenge** [roadmap: arXiv:1712.06982]





- ❑ **Challenging to fund & meet increased LHC computing demands**
- ❑ **Need changes in computing models & software**

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LUT University

Detector R&D for HL-LHC

❑ Main challenges at HL-LHC:

- radiation damage due to higher integrated luminosity
- higher pile-up (= multiple pp collisions in same bunch crossing) coming from the higher instantaneous luminosity

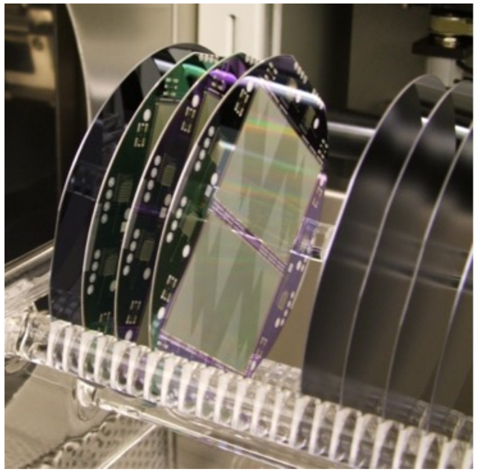
❑ Crucial to develop detector technologies that:

- can stand the harsh radiation environment
- have higher granularity than existing devices (to keep occupancy reasonable)

❑ Another improvement: add info about precise arrival time of the particles to the detector (”4D” vertexing) to mitigate pile-up.

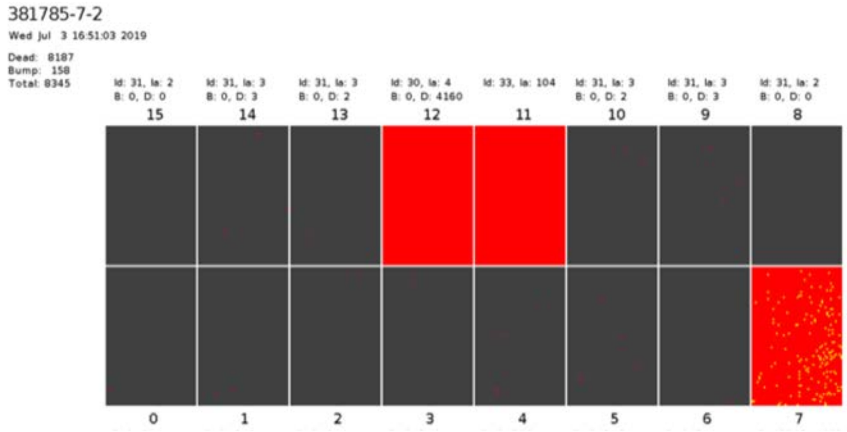
❑ Important aspects:

- **Proper facilities:** Kumpula detector laboratory & Micronova, Espoo
- **Collaboration with industry**
- **Technology & knowledge transfer** towards industry, other sciences & applications e.g. medical imaging & nuclear safety

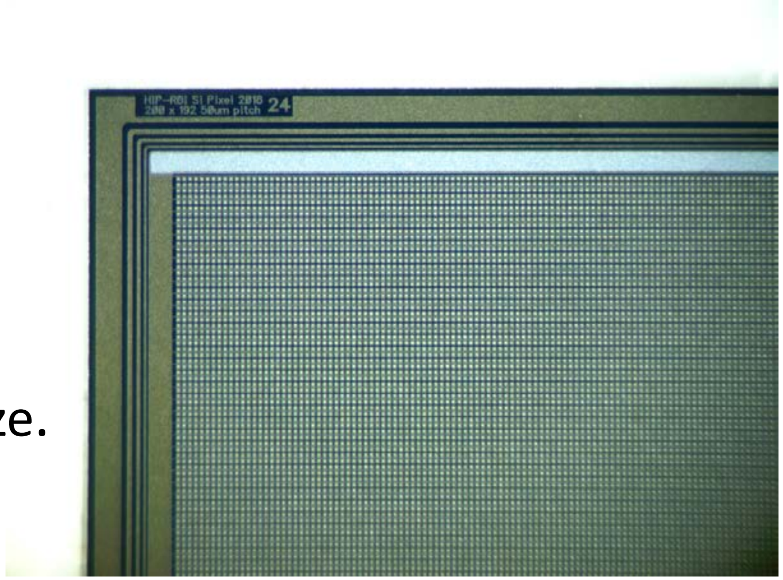


CMS charged particle tracker

- **The CMS pixel layer 1 needs to be refurbished during LS2 to achieve the best possible performance during Run3 starting in 2021**
  - bare pixel modules currently being flip-chip bonded @ Advacam in Espoo
  - first quality assurance (QA) step in Kumpula Detector Laboratory
  - HIP contribution: work force for QA

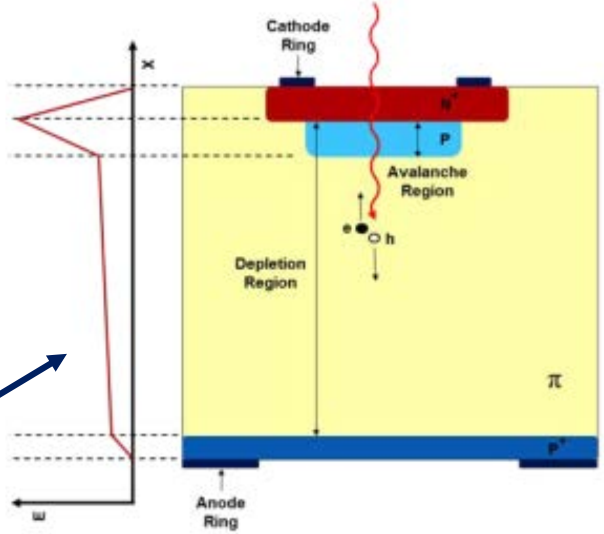


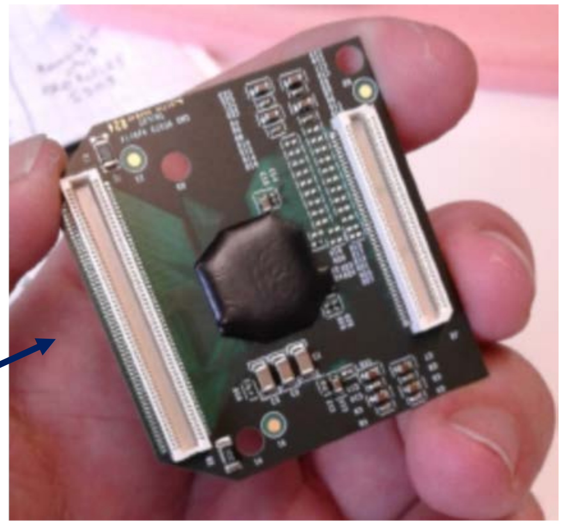
- **The whole CMS tracker needs to be rebuilt during LS3 to achieve best possible performance during HL-LHC**
  - detector R&D: ALD grown thin films on thin p-type pixel sensors with very small pixel size.
  - module contruction & QA
  - mechanics contribution
  - electronics contribution ?



CMS endcap precision timing layer

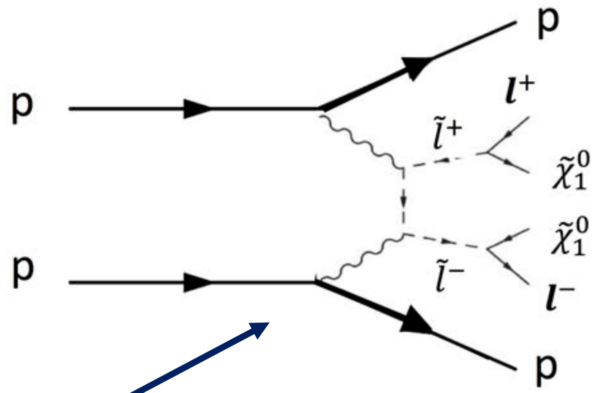
- To reduce impact of pileup at HL-LHC, CMS will use precise time stamping of particles with precision timing layer both in barrel & endcap region
  - Finland will participate to endcap timing layer (MTD-ETL)
- Planned technology: pixelated Low Gain Avalanche Detector (LGAD)
- Finnish responsibilities include:
  - detector R&D (optimizing & testing devices)
  - testing of module components (readout chips, sensors)
  - module construction
- Also trigger electronics for CMS GE1/1 muon station to be installed for Run 3

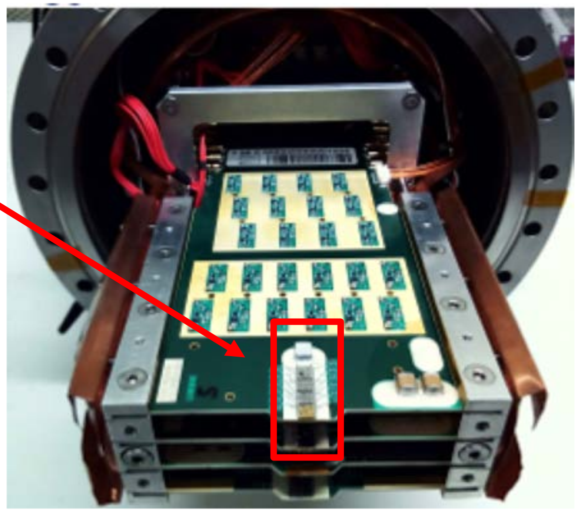




CMS forward proton precision timing

- **Increase the CMS sensitivity to central exclusive processes in Run 3 (& HL-LHC?)**
  - precise proton arrival time measurement in CMS Proton Precision Spectrometer (PPS) allows reconstruction of proton longitudinal vertex position & associate it with particle vertices in central part (to mitigate pile-up)
- **Physics:** anomalous quartic gauge couplings, axion-like particles, **low-mass SUSY searches**
- **Technology: single-crystal CVD diamonds**
- **Finnish responsibilities include:**
  - detector procurement, metallization & QA
  - detector module testing & assembly
- **PPS @ HL-LHC ?**
  - A completely new system with increased radiation tolerance & timing precision requirements
  - Expression of Interest to be submitted to CMS 2019





HIP strategy draft : Extracts from LHC part

Main focus of HIP in the coming decade is to fully exploit the participation in the LHC experiments. To this end the WLCG resources and detector R&D are essential.

…**The full physics exploitation of these, including their preparations for the high luminosity LHC (HL-LHC), constitute at the time being the highest priority of the Finnish high-energy physics community.**

Computing and data access are an integral part of this physics exploitation …

The HL-LHC upgrades of the experiments, requiring continued detector R&D, are also key elements for successful exploitation...

It is essential that the HIP Detector Laboratory is maintained and developed to support the detector R&D and the experimental upgrades.

Finland supports the continuation of heavy ion collisions at the LHC beyond 2029.

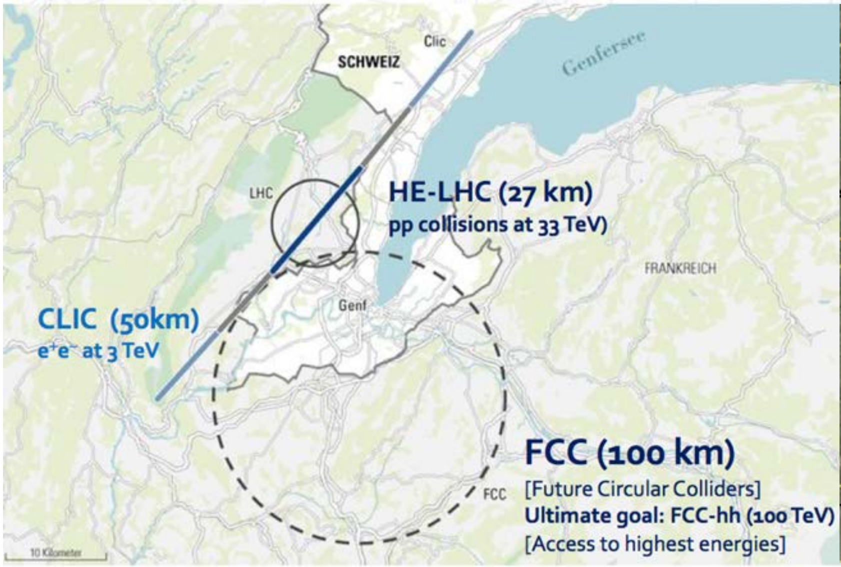
Next high energy frontier machine(s)?

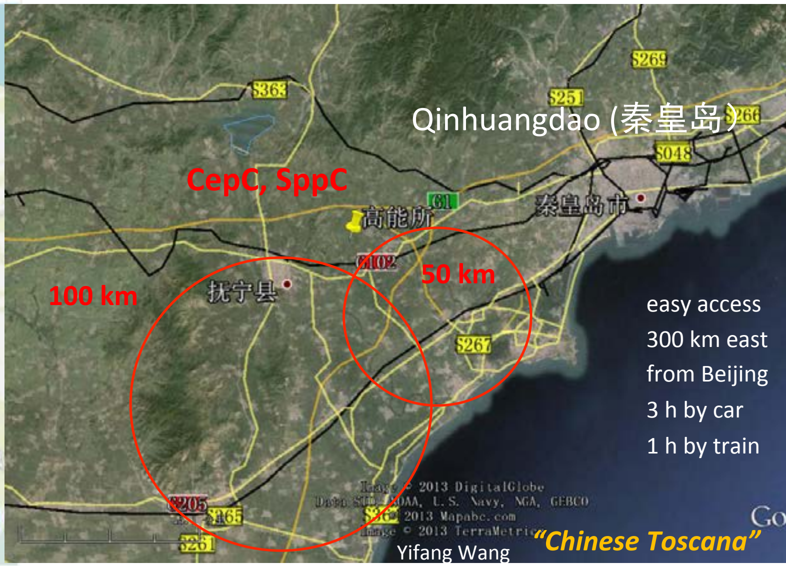
Circular colliders:

- FCC (Future Circular Collider), CERN hosts
  - FCC-hh: $\sqrt{s} = 100$ TeV proton-proton collider, ion operation possible
  - FCC-ee: First step $\sqrt{s} = 90 - 365$ GeV e^+e collider
  - HE-LHC: Stronger bending magnets in LHC, $\sqrt{s} = 27$ TeV proton-proton collider
- CEPC (Circular Electron-Positron Collider) : e^+e^- $\sqrt{s} = 90 - 240$ GeV, China hosts
- SppC (Super proton-proton Collider): proton-proton $\sqrt{s} = 70$ TeV, China hosts

Linear colliders:

- ILC (International Linear Collider): e^+e^- $\sqrt{s} = 250 - 500$ GeV, Japan hosts
- CLIC (Compact Linear Collider): e^+e^- $\sqrt{s} = 380$ GeV - 3 TeV, CERN hosts



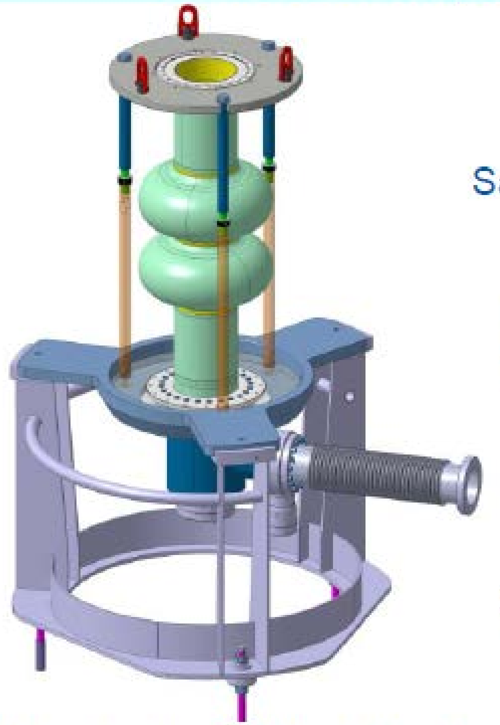


Material science: Q-slope mitigation of superconducting cavities

F. Tuomisto & F. Djurabekova

- **Replace DC Magnetron Sputtering (DCMS) used for LHC cavities by High Power Impulse Magnetron Sputtering (HIPIMS)?**
- study interplay between nano- (even pico-) porosity profiles & residual resistivity
- study HIPIMS Nb coatings deposited in varying conditions & thicknesses, characterize vacancy & vacancy cluster profiles (if any). Correlate vacancies with resistivity & other parameters

FCC cavities (400 & 800MHz)



Integration of a 800MHz double cell cavity on LHC coating bench

Same coating hardware as for LHC cavities

Identical for 400MHz
Upgraded for 800MHz

HiPIMS?
(Q-slope mitigation)

Spun seamless cavities
(Q_0 increase)

Material science: Multiscale physics modelling of breakdown

❑ Focus of the group:

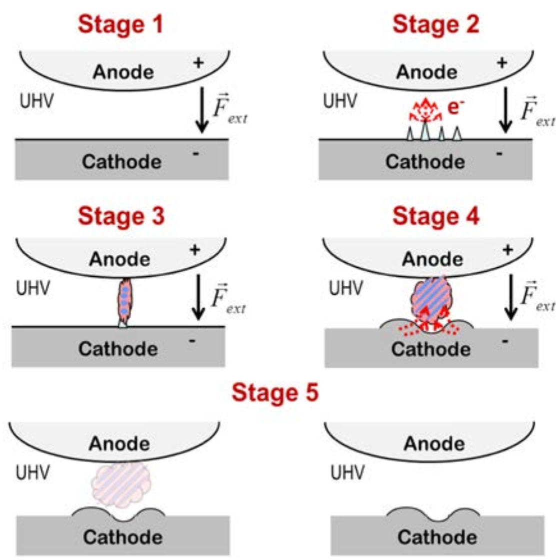
F. Djurabekova

- Mechanisms of vacuum arcing near metal surfaces to increase efficiency of CLIC accelerating structures.
- **Plans:** dynamic dislocation models under pulsing electric field (↔ experiments); experimental study of surface conditioning dependence on surface treatments.

❑ Previous activity:

- Developed multiscale & multiphysics model describing vacuum arcing

Scenario:



Model:

Multiscale multiphysics model

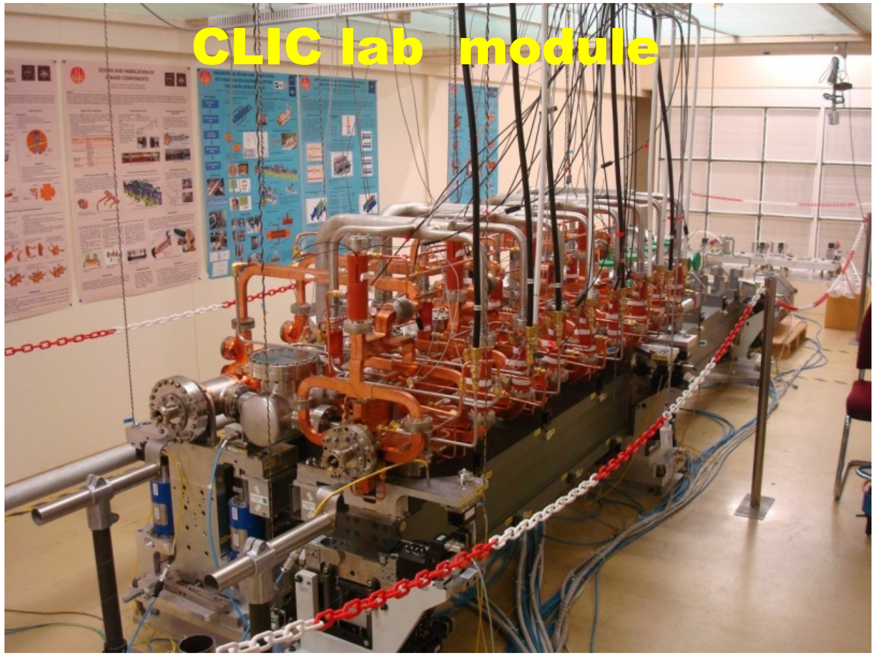
Stage 1 Charge on surface atoms **Method:** SIESTA (DFT), helmod (ED-MD)	~few fs
Stage 2a Onset of FE tip growth: Dislocation-mediated mechanism of surface protrusions **Method:** Comsol (FEM), parcas (MD), helmod	~few ns
Stage 2b Long time evolution of surface morphology affected by surface charge **Method:** kimocs (Kinetic Monte Carlo)	~10s ns
Stage 3 Field assisted evaporation of atoms & Joule heating, electromigration due to FE currents **Method:** helmod (ED-MD)	~ s/hs
Stage 4 Plasma evolution **Method:** Arc-pic (Particle-in-Cell)	~ s/min
Stage 5 Surface damage due to intense ion bombardment from plasma and heating by FE currents **Method:** Arc MD	~100s ns

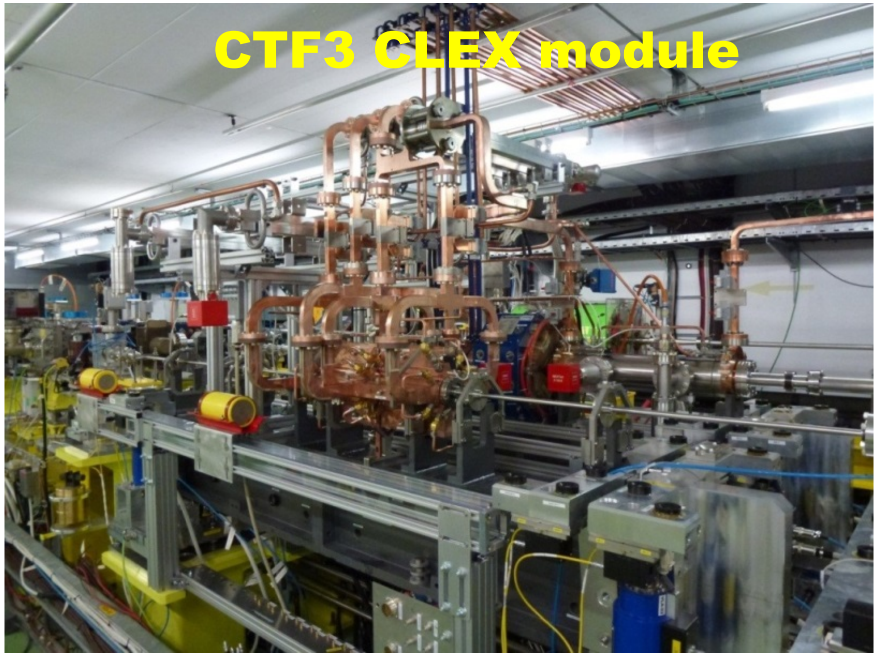
CLIC@HIP

Engineering: Module, RF structures & manufacturing

M. Aicheler

- ❑ **CLIC RF structure & module assembly**
- ❑ **Diagnostics of CLIC RF structure**
- ❑ **Industrialisation**
- ❑ **Other applications of high-gradient linear technology:** eSPS (Light Dark Matter eXperiment, LDMX) & future free electron lasers (Compact Light)





- **Logical to continue CLIC R&D involvement & FCC engagement** in view of a future decision on next high energy frontier machine.

HIP strategy draft: Extracts from future collider part

HIP intends to participate in future leading high-energy frontier experiments, based on physics driven decision

…Two independent and conceptually different designs of the next generation particle collider, which meet these requirements, compact linear electron-positron collider (CLIC) and high-energy future circular collider (FCC), are currently under development at CERN. HIP contributes to the CLIC and FCC R&D programme.

These activities are multidisciplinary and intersectorial, and includes material physics, superconductivity and engineering aspects as well as collaboration with the industry.

The development and preparation of the CLIC and FCC options as the next high-energy frontier facility should continue in parallel until a physics driven decision based on the LHC results can be taken…

We emphasize that CERN, as the European Particle Physics Laboratory, should play a key role in any international post-LHC high-energy facility…

Backup

Next high energy frontier machine(s)?

D. Schulte

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	0.06 / 7	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

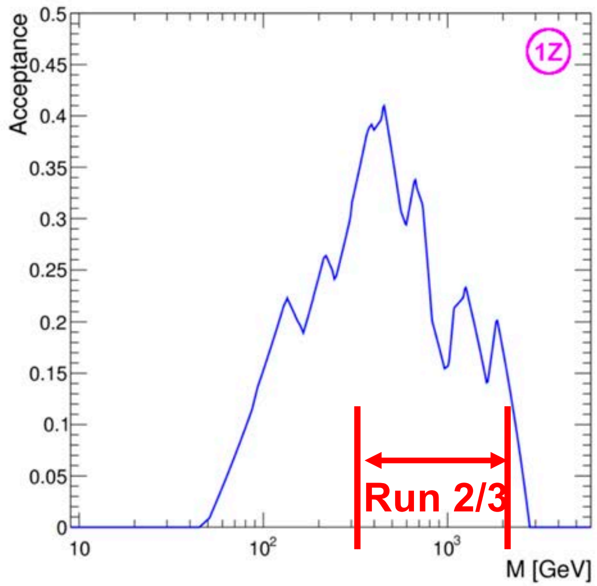
ILCU = 1€ (2012)

Proton tagged physics @ HL-LHC ?

Physics motivations (300 $\mathrm{fb}^{-1} \leftrightarrow$ 3000 fb^{-1}, improved low mass acceptance)

- High-mass searches: increased sensitivity to anomalous couplings ($\gamma\gamma\gamma\gamma$, $\gamma\gamma\gamma Z$ …) by $\sim$ a factor 10 & to couplings of axion like particles ("ALPs") by $\sim$ a factor 4
- Higgs/EWK: measure Higgs quantum numbers in a completely independent way
- Low-mass searches: extend SUSY searches in compressed scenarios to lower masses

e.g. HL-LHC mass acceptance assuming proton detectors at 210-250 m & 400-450 m; β_x^* = 0.15 m & vertical crossing



Completely new system: new (compact?) Roman Pots @ 400 m, improved radiation hardness of the tracking detectors (3D Si detectors?), radiation hard timing detectors with $\sim$ 5 ps timing resolution (?) $\Longrightarrow$ R&D required to find adequate solutions

The CMS Proton Precision Spectrometer at HL-LHC – Expression of Interest

(intended to be submitted for CMS internal review)