Detector Technologies
for
Future Collider Experiments

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Hızlandırıcı ve Algıç Fiziği Çalıştayı
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Outline

1. Introduction- Particle Physics-Status
2. Future Accelerators
3. Tracking
4. Calorimetry
5. Muon Detectors
6. Summary

1974-1984 The rise of cm energy

Collisions at large √s: A-priori obvious way to discover heavier particles

Year	Discovery	Experiment	√s (GeV)	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \rightarrow J/\Psi)$ $J/\Psi \rightarrow \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SLAC)	8	$e^+e^- \rightarrow \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \rightarrow \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (DESY)	30	$e^+e^- \rightarrow q\bar{q}g$ Three--jet events
1983	**W, Z** (m ~ 80, 91 GeV)	$p\bar{p}$ ring (CERN)	900	$W \rightarrow l\nu$ $Z \rightarrow l^+l^-$

- **Standard model particle spectrum is filling up quickly**
  - **Three families, but top quark missing**
  - **Higgs boson missing but $m_W \sim m_Z \cos\square_W$: smoking gun for the Higgs mechanism**
- **Quantum structure not tested: requires precision measurements**

1987-2011: The rise of precision

1995-2011: Testing the quantum structure of the standard model

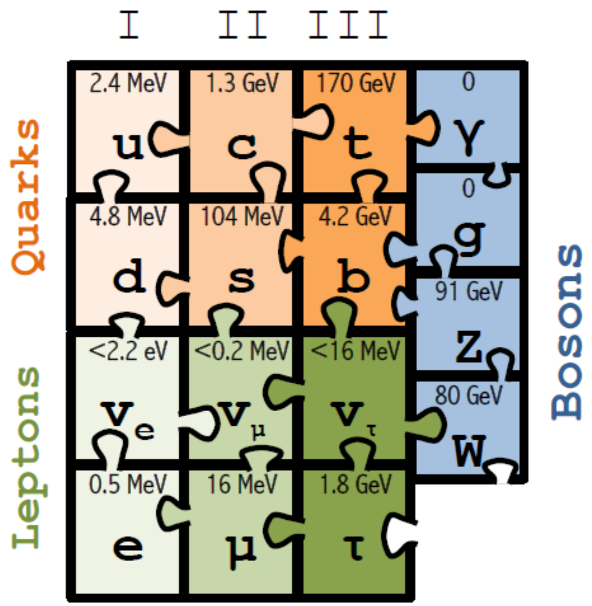
1995: Discovery of the top quark at the Tevatron (D□, CDF)1995-2011:
Measurement of m_{top} (Tevatron)

- **m_{top}(Obs.) = 173.2 ± 0.9 GeV**
- **m_{top}(Pred.) = 178.0 ± 4.3 GeV**

[LEP/SLD/m_W, for mH = 150 GeV]

1997-2011: Measurement of m_W (LEP2, Tevatron)

- **m_W(Obs.) = 80385 ± 15 MeV**
- **m_W(Pred.) = 80363 ± 20 MeV**



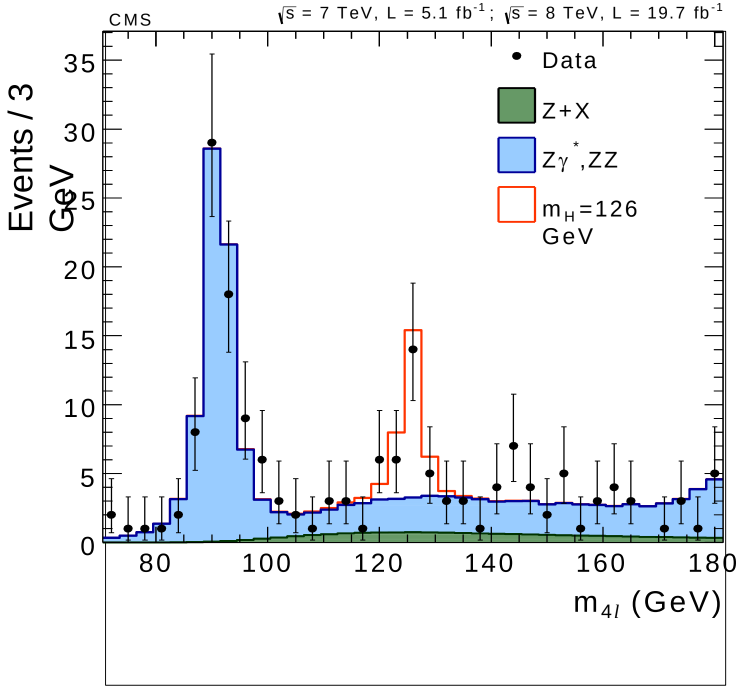
1999: Nobel Prize for t'Hooft and Veltman
Standard Model almost complete

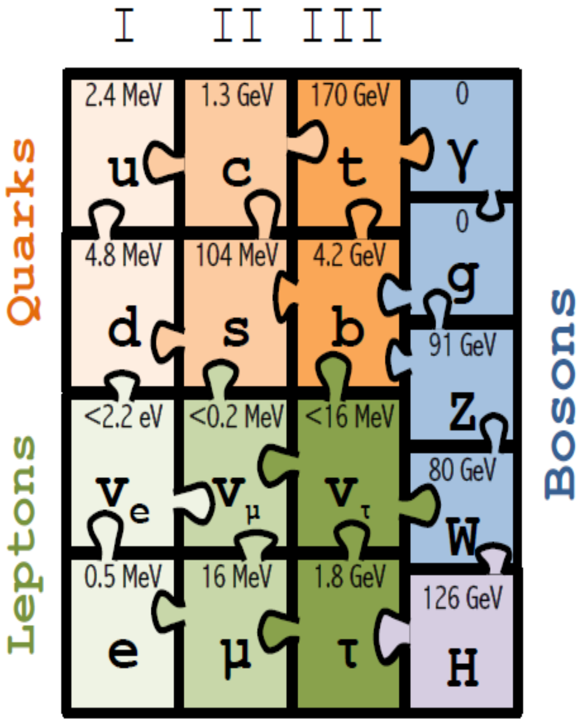
- **Only the Higgs boson is missing, but ...Prediction from Higgs mechanism**

2012-2014 The SM becomes the standard theory

2012-2014: The Higgs boson era

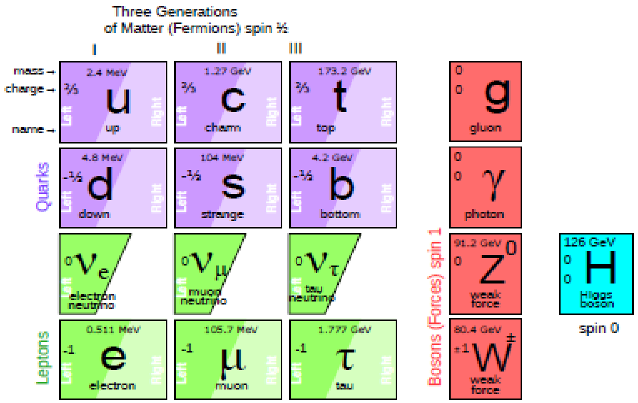
- **2012: Discovery of the standard model Higgs boson at the LHC (ATLAS, CMS)**
  - **m_H = 125.4 ± 0.5 GeV (ATLAS), 125.0 ± 0.3 GeV (CMS)**
  - **Mass, couplings, spin, width in agreement with Standard Theory predictions**
- **2010-2013: No new physics found at the LHC Run1 at the TeV scale**
- **2014: Nobel Prize to Englert and Higgs**

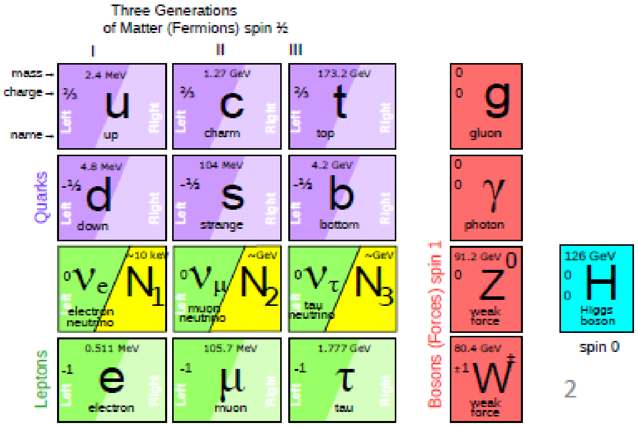




Precision vs Energy

The standard theory is complete? Obviously three pieces missing



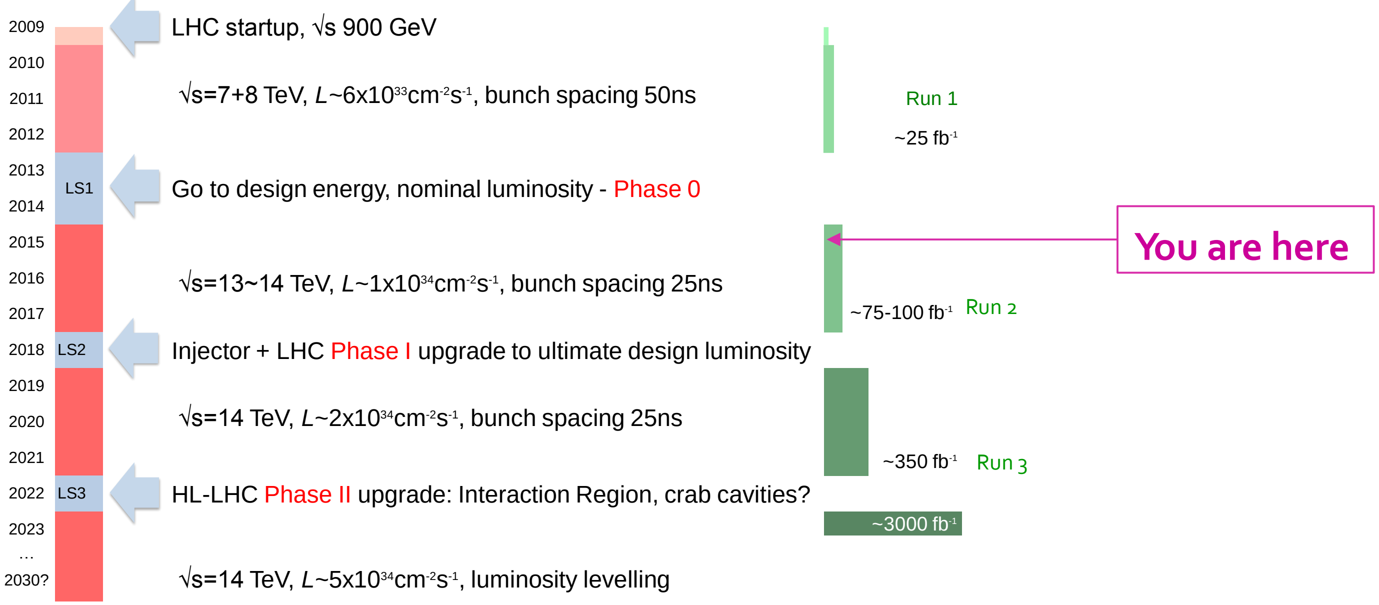


- **Three right-handed neutrinos ?**
  - **Extremely small couplings, nearly impossible to find, but could explain it all !**
    - → **Small $m_{\square}$ (see-saw), DM (light N_1), and B.A.U. (leptogenesis)**
- **Need very-high-precision experiments to unveil**
  - **Could cause a slight reduction (increase) of the Z (H) invisible decay width**
  - **Could open exotic Z and Higgs decays: Z,H → Possibly measurable / detectable in precision e^+e^- colliders→ Almost certainly out of reach for hadron colliders (small couplings)**

Can we do everything ??

The cost (10’s B$) and challenges of these projects are paramount

- **A choice will have to be made at one point, but it would be too early to make it now**
  - **The LHC, indeed, is still in its early infancy**



2009 LHC startup, √s 900 GeV

2010

2011 $\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns Run 1

2012 ~25 fb^{-1}

2013 LS1

2014 Go to design energy, nominal luminosity - Phase 0

2015 You are here

2016 $\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

2017 ~75-100 fb^{-1} Run 2

2018 LS2 Injector + LHC Phase I upgrade to ultimate design luminosity

2019

2020 $\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

2021 ~350 fb^{-1} Run 3

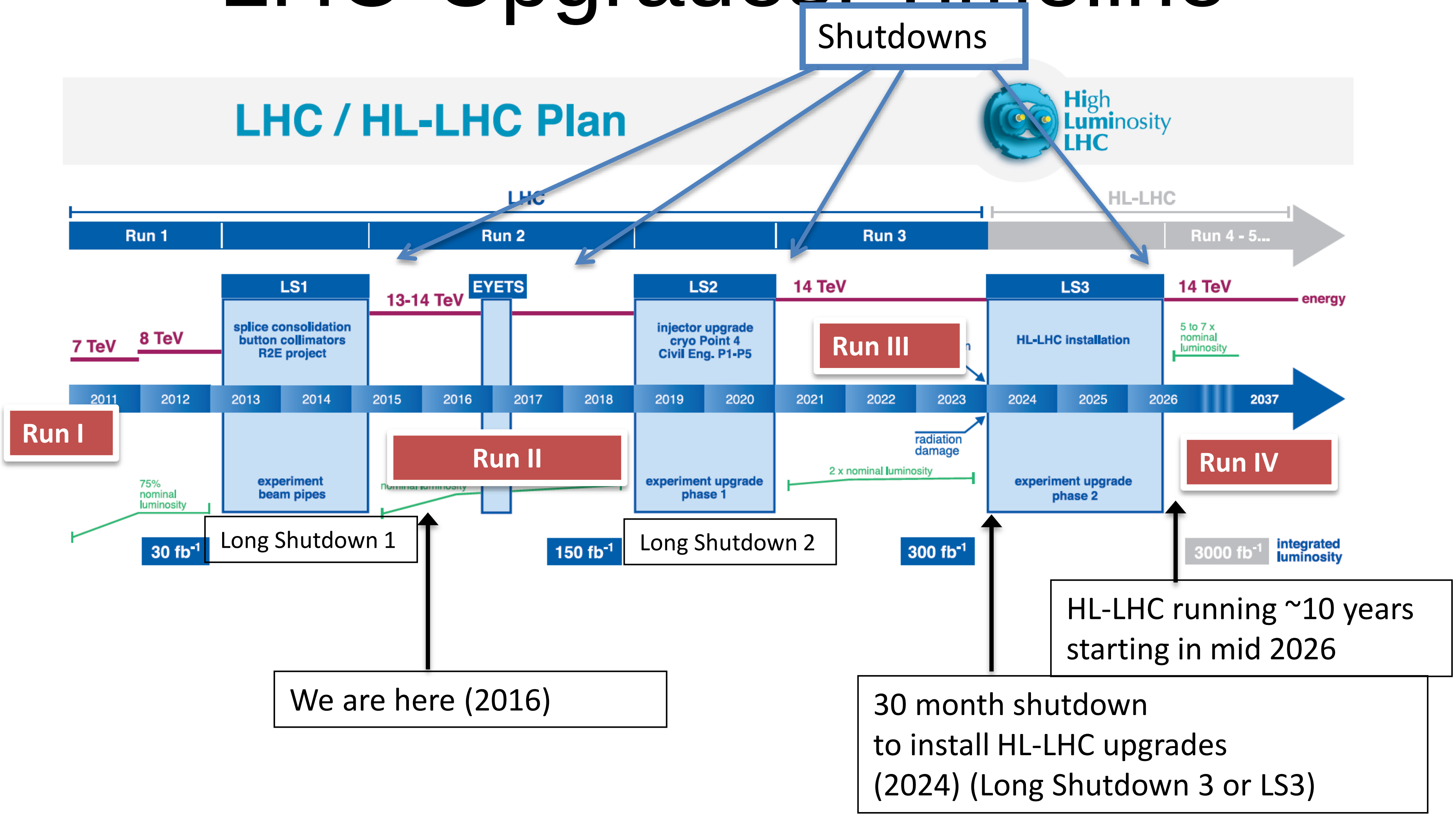
2022 LS3 HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2023 ~3000 fb^{-1}

…

2030? $\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling

LHC-Upgrades: Timeline



Shutdowns

Long Shutdown 1

Long Shutdown 2

HL-LHC running ~10 years starting in mid 2026

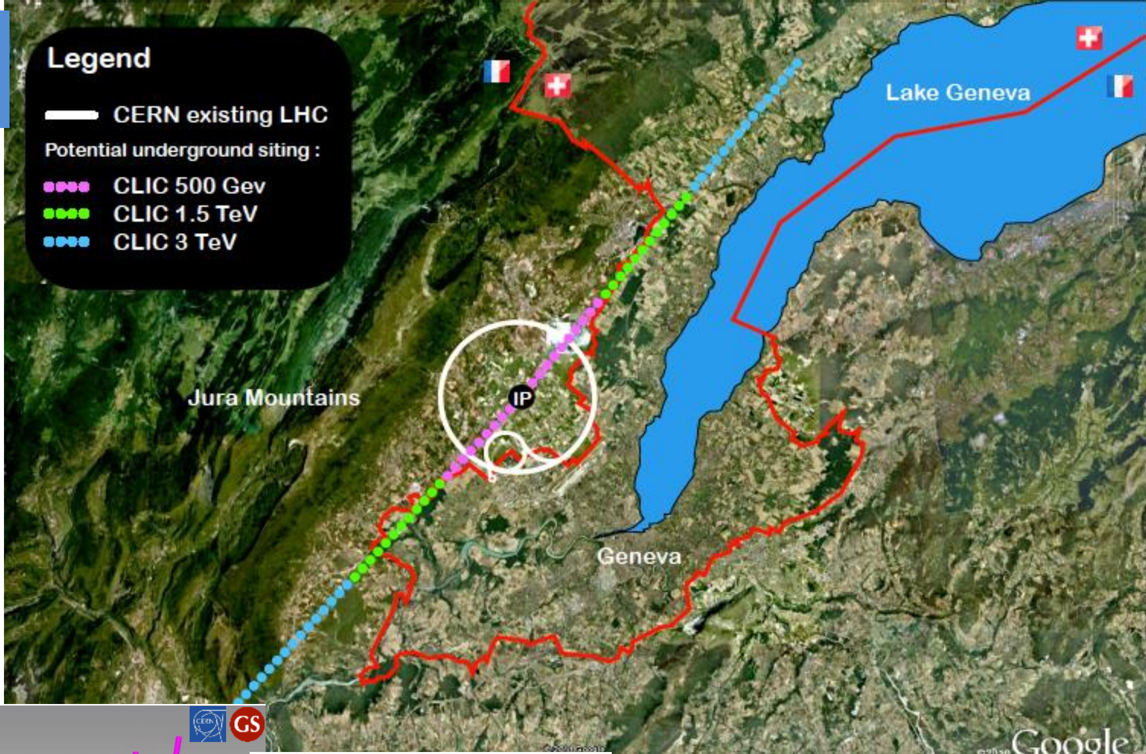
We are here (2016)

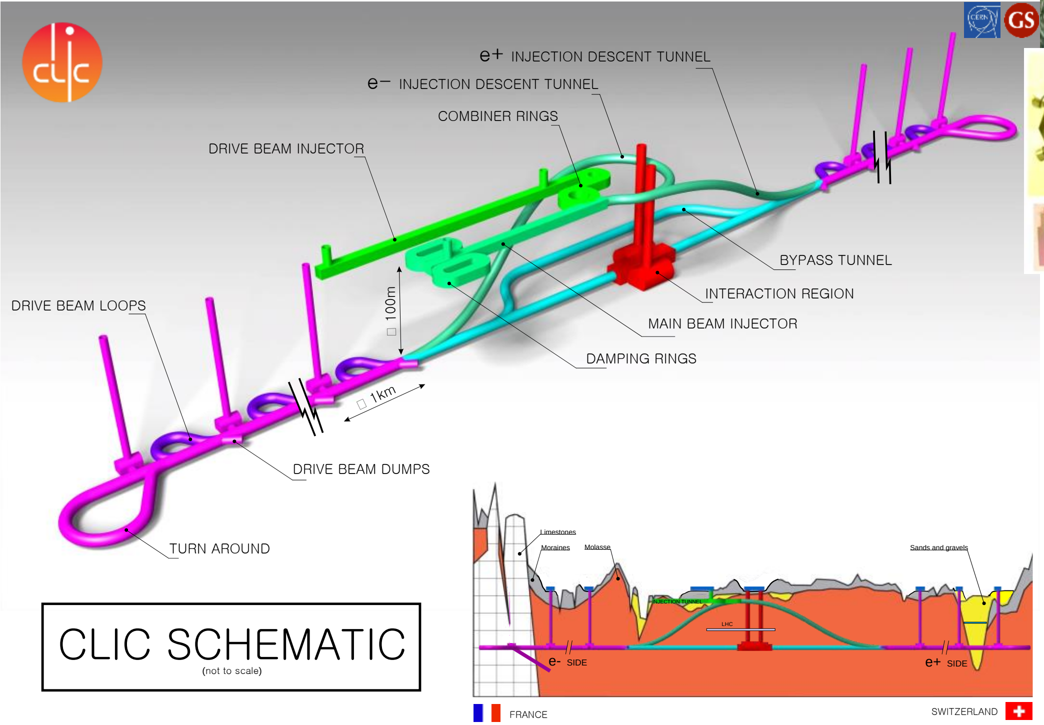
30 month shutdown
to install HL-LHC upgrades
(2024) (Long Shutdown 3 or LS3)

- High Luminosity (meaning many collisions) LHC (HL-LHC) running starts in mid 2026
- Expect to collect ~ 3000 fb^{-1} (compared to our current total of ~30 fb^{-1}) of data

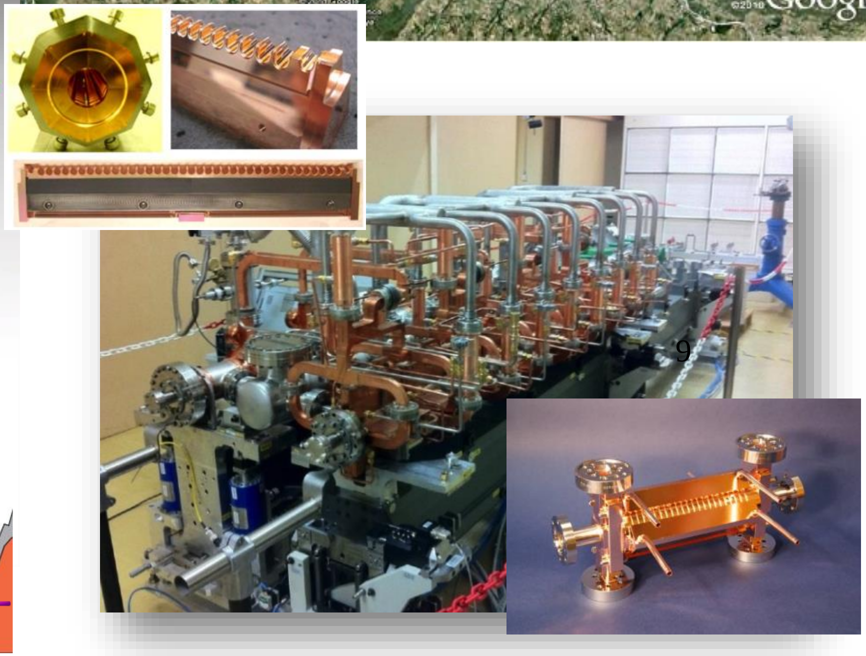
The CLIC project

Key features:
- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)



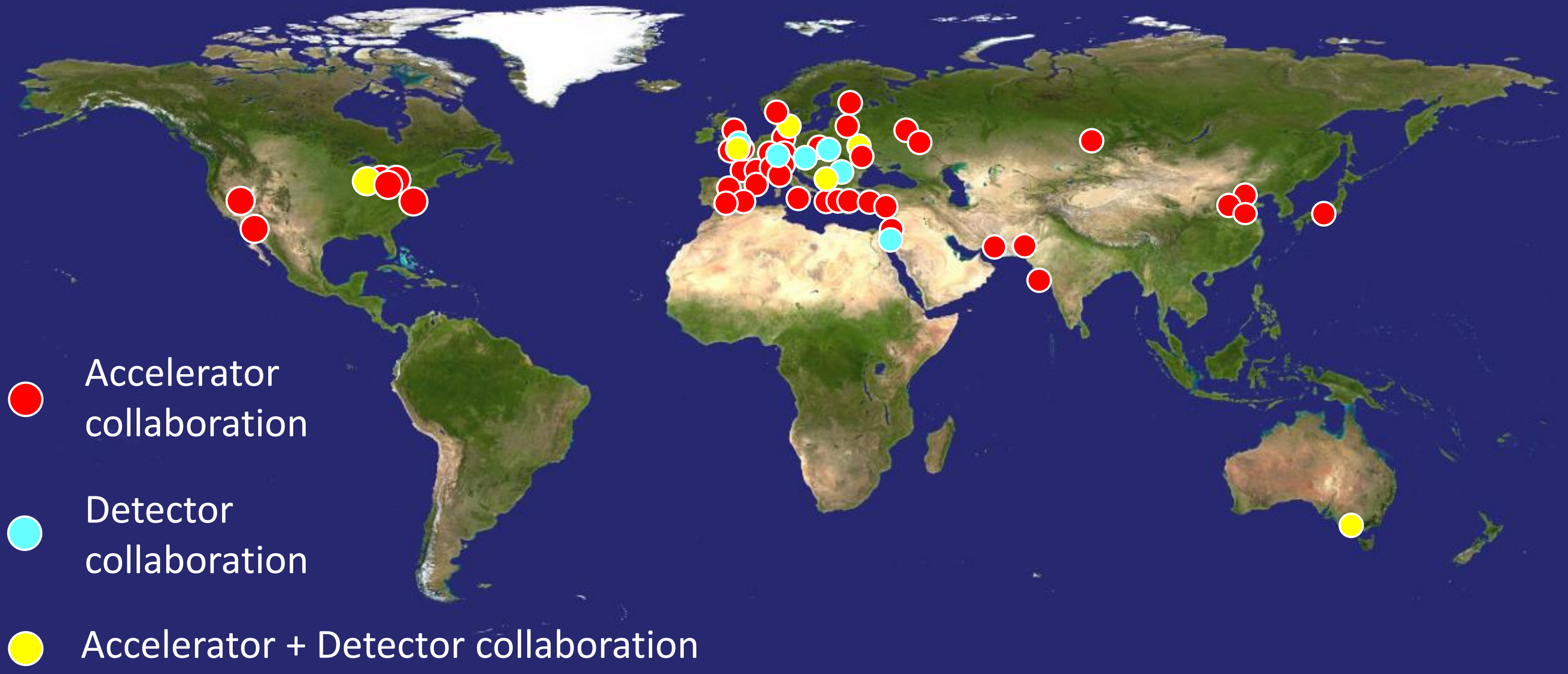


CLIC SCHEMATIC
(not to scale)



CLIC Collaboration

29 Countries – over 70 Institutes



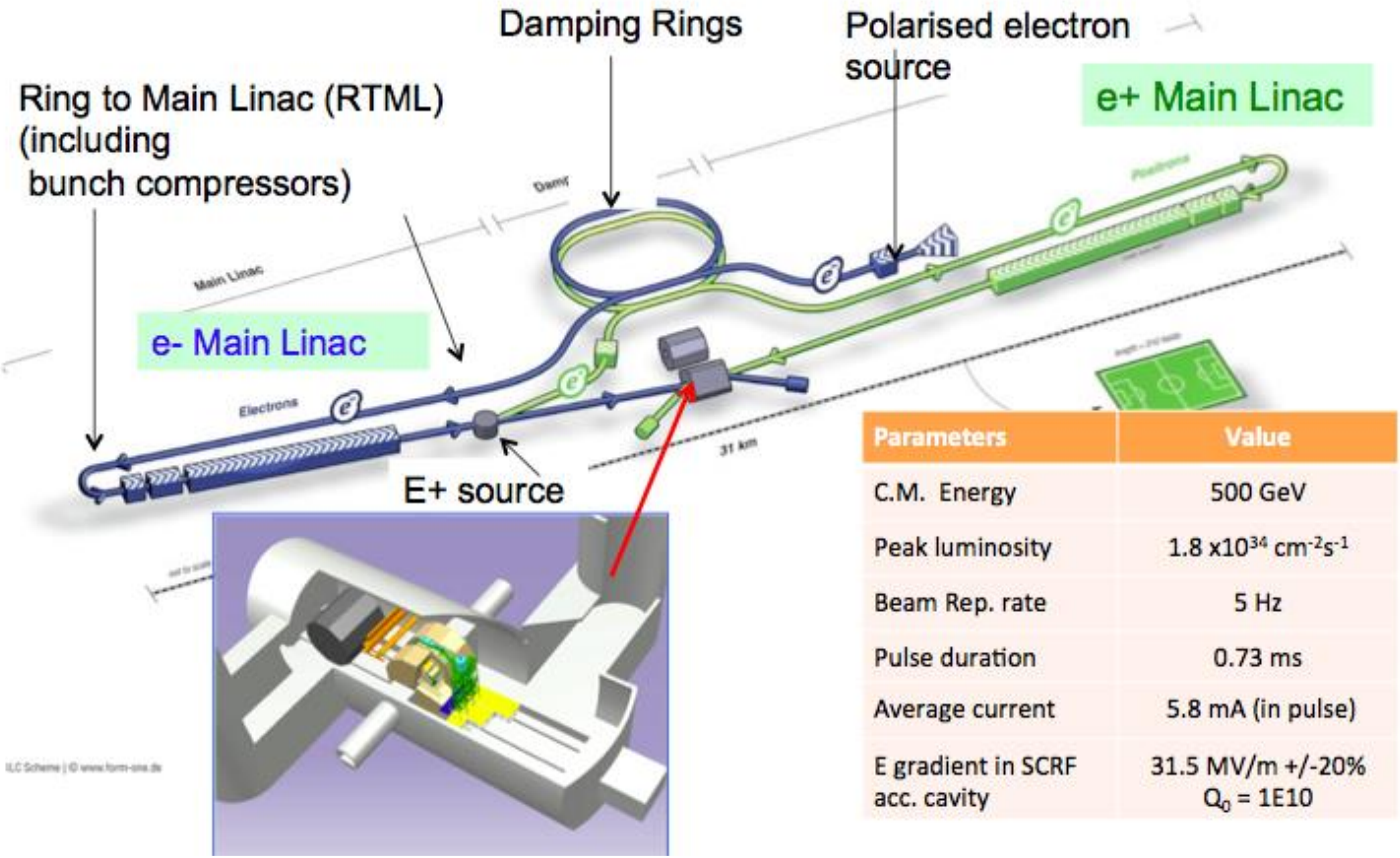
🔴 Accelerator collaboration

🔵 Detector collaboration

🟡 Accelerator + Detector collaboration

TDR: Technical
Design Report

ILC TDR Layout



Damping Rings

Polarised electron source

e+ Main Linac

Ring to Main Linac (RTML)
(including
bunch compressors)

e- Main Linac

E+ source

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

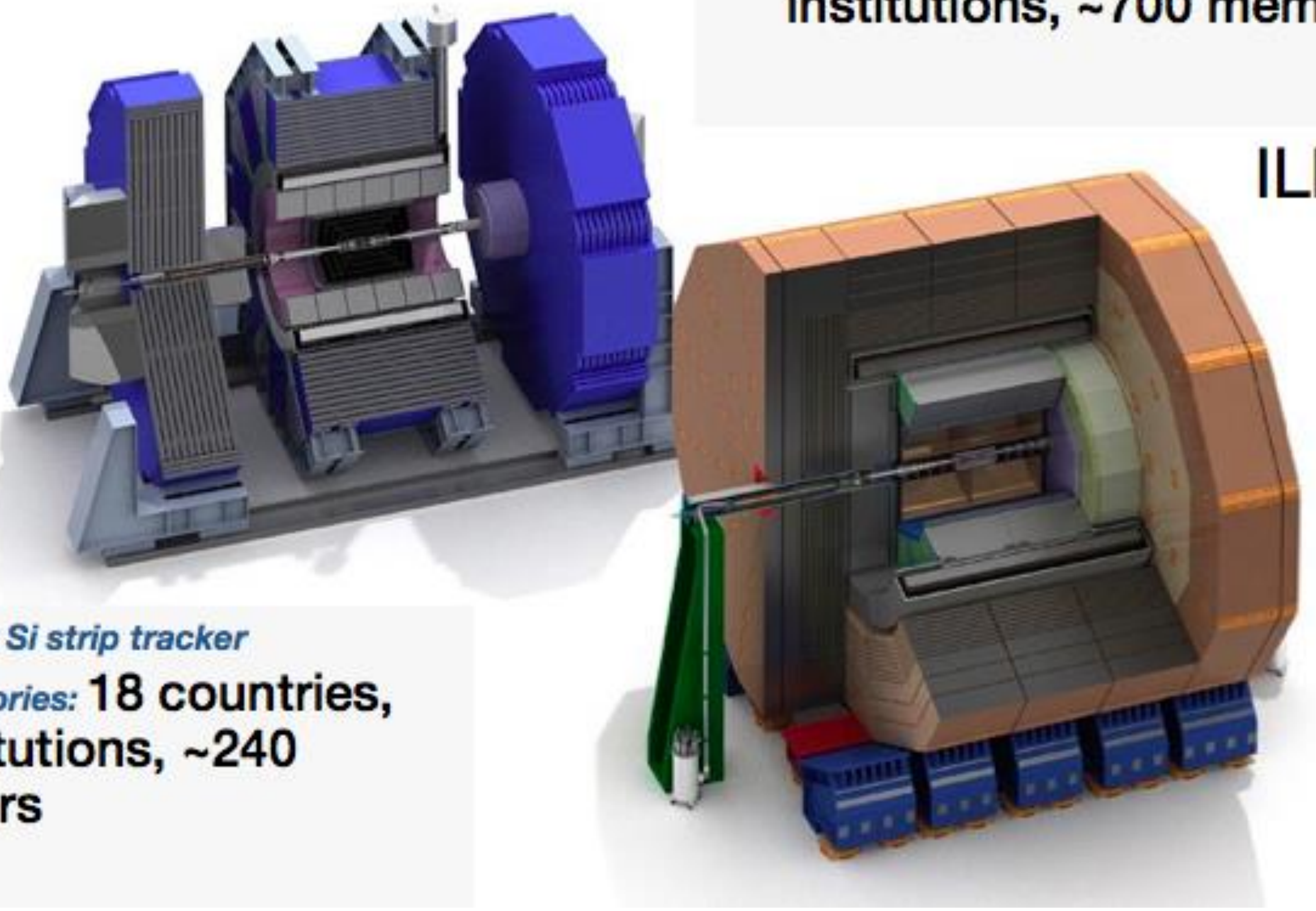
ILC Design Parameters

Beam Parameters	Collision Energy	500 giga-electron-volts (500 GeV = 250 GeV + 250 GeV)
	Luminosity	2 x 10^{34} cm^{-2} s^{-1}
	Bunch population	2 x 1010
	Number of bunches	1312
	Bunch spacing	554 ns
	Number of collision	6560 s^{-1}
	Number of beam acceleration	5 s^{-1}
	Acceleration gradient	31.5 MV/m
	Beam size at collision point	Width 474 nm
	Number of acceleration cavity unit	Thickness 5.9 nm
Accelerator unit	Number of cryomodules	14742
	Number of klystrons in	1701
	distributed klystron system	378
	Size of cryomodule	1m diameter, 12m length
Cryomodule	Cryomodule type	
	Type 1	9 units of 9-cell acceleration cavities
	Type 2	8 units of 9-cell acceleration cavities
		+ 1 unit of superconducting quadrupole magnet
	Frequency of pulsed RF	1.3 GHz
Operation	Power of pulsed RF	190 kW/cavity
	Operation temperature of acceleration cavity	2 K
Size of accelerator	Circumference of Damping ring	3.2 km
	Length of main linac	11 km (electron linac) + 11 km (positron linac)
Collision experiment	Number of Detectors	2 (push-pull alternation)

Two Detector Concepts in the ILC TDR

The number of Participants

- Large R with *TPC tracker*
  - *LOI signatories:* **32 countries, 151 institutions, ~700 members**



- High B with *Si strip tracker*
  - *LOI signatories:* **18 countries, 77 institutions, ~240 members**

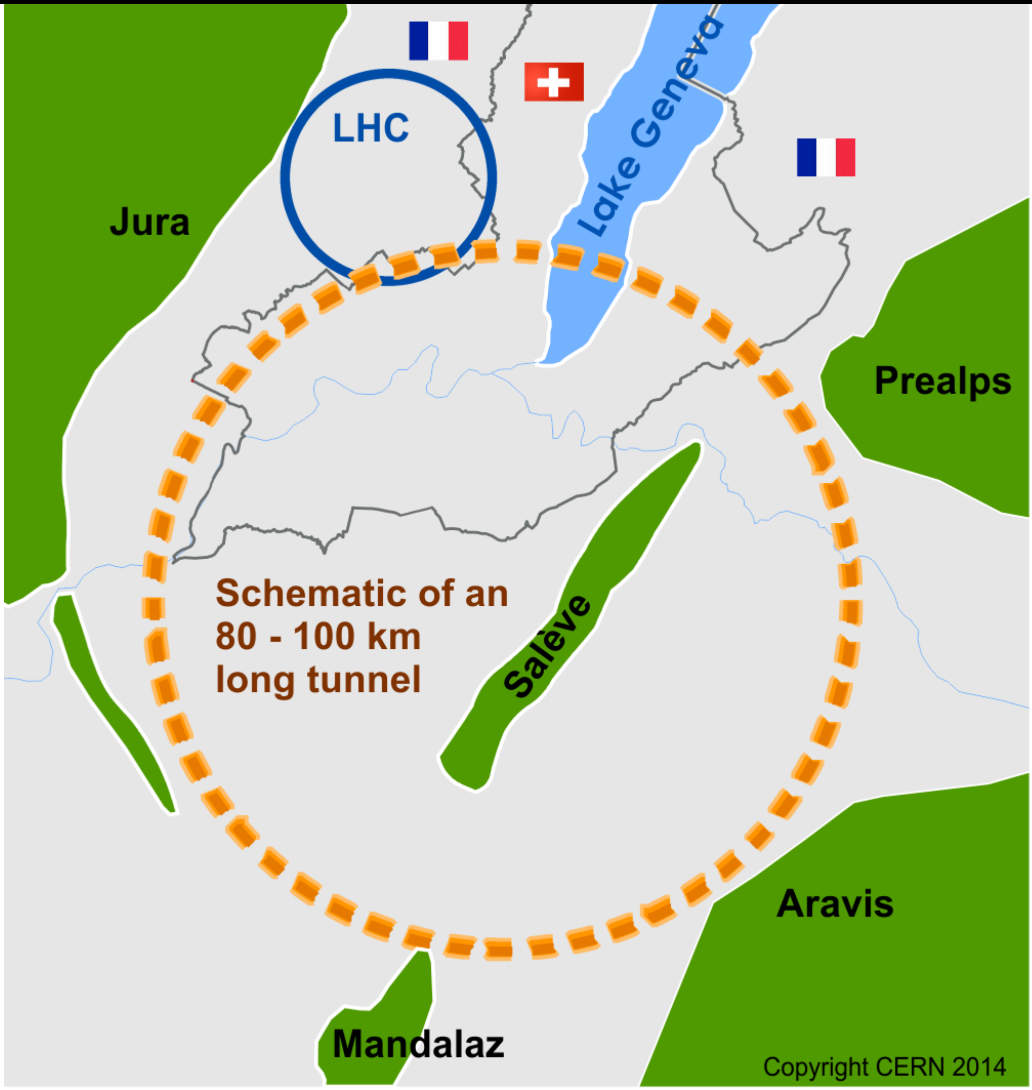
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **80-100 km infrastructure** in Geneva area
- ***e*$^+$*e*$^-$ collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**



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Key Parameters FCC-hh

Parameter	**FCC-hh**	**LHC**
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{\text{main}}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

M. Benedikt, FCC Week 2015

Key Parameters FCC-ee

Parameter	**FCC-ee**			**LEP2**
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.3-2.5	3.6-5.5	11	3.5

M. Benedikt, FCC Week 2015

FCC-hh and FCC-ee

Exceptionally on track for progression.

High physics reach with continuously evolving possibilities.

Unprecedented challenges on key technologies!

Muon Collider and Neutrino factories

Muon accelerator R&D is focused on developing a facility that can address critical questions spanning two frontiers…

The Intensity Frontier:

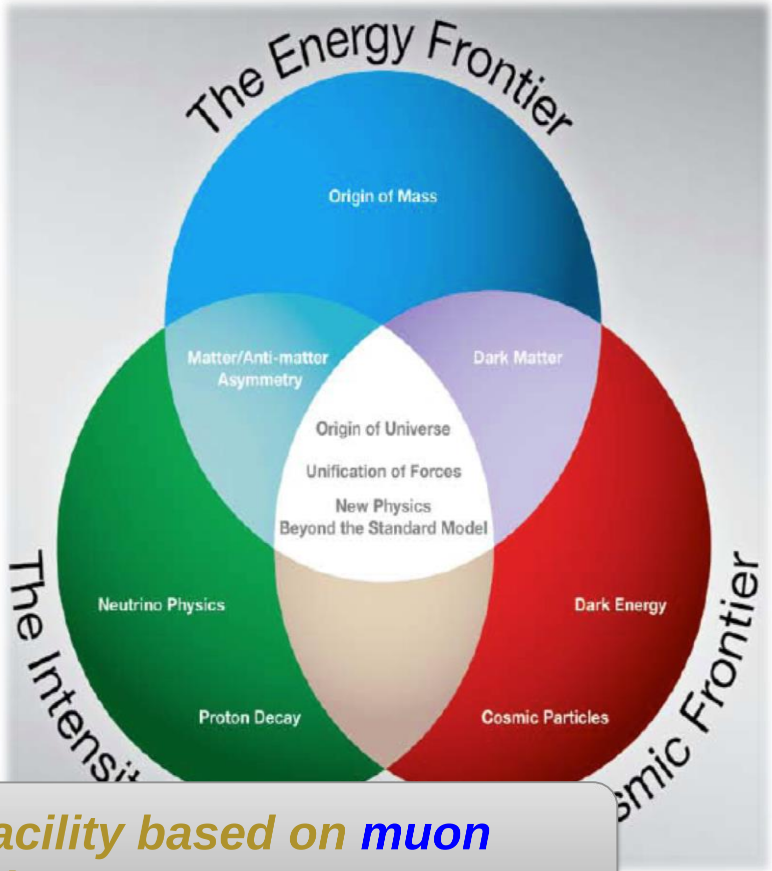
with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:

with a ***Muon Collider*** capable of reaching multi-TeV CoM energies

and

*a **Higgs Factory** on the border between these Frontiers*



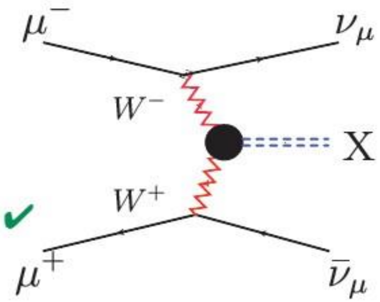
The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS

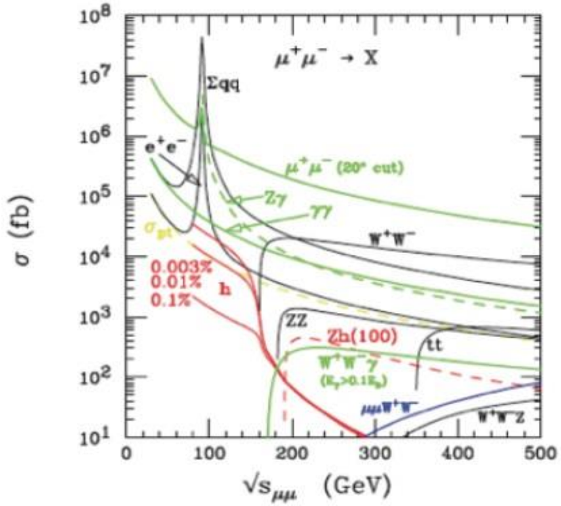
Muon Collider Reach

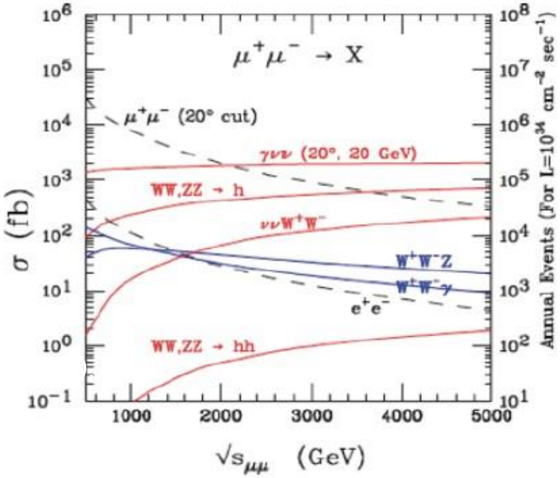
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx 126$ GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta| > 10°$) pair production ~ R × 86.8 fb/s(in TeV^2) ($R \approx 1$)
    - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For $\sqrt{s}$ > 1 TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$

  - An Electroweak Boson Collider ✔





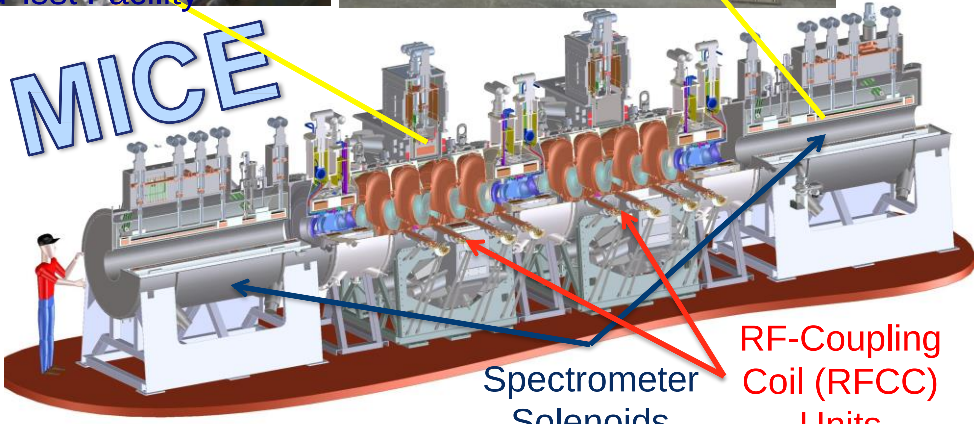


MICE

Fermilab Solenoid Test Facility

First Spectrometer Solenoid Now Commissioned!

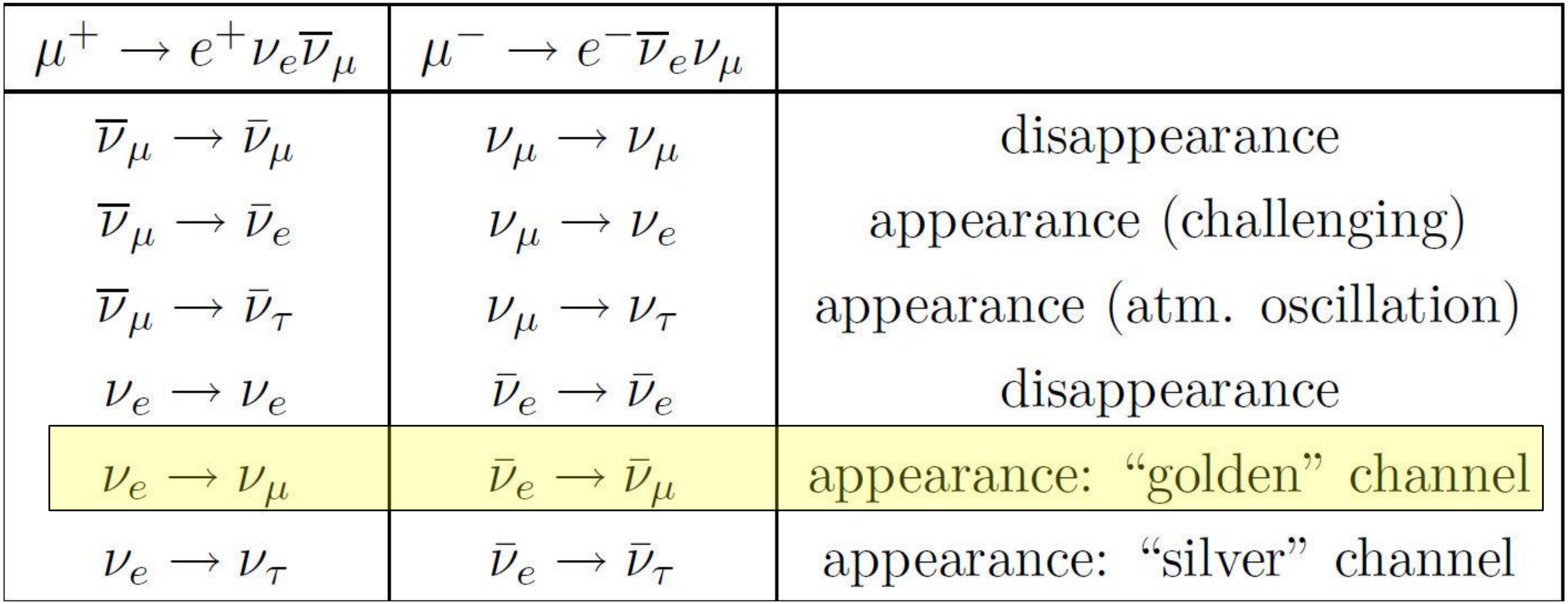
- Currently preparing for MICE Step IV
- Includes:
  - Spectrometer Solenoids
  - First Focus Coil
- Provides:
  - Direct measurement of interactions with absorber materials
  - Important simulation input



Spectrometer Solenoids

RF-Coupling Coil (RFCC) Units

ν physics with a μ storage ring



$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: “golden” channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: “silver” channel

Siting Concept

DETECTORS

Tracking

Tracking performance requirements

Time resolution

- a few ns hit timing accuracy assumed

Momentum resolution

- Assume $\sigma(p_T)/p_T$ of ~10% needed for isolated objects of very high energy

Impact parameter resolution

$\sigma(r\varphi) << 70\ \mu m$ at 1 GeV
$\sigma(r\varphi) << 10\ \mu m$ at 1 TeV

Tracking + Impact Parameter Resolution

Momentum resolution

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

=> to get p_T resolution similar to LHC => try to gain a factor 7 in $\sigma/(BR^2)$

Impact parameter resolution

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3\theta)}$$

dominated by
single-point resolution

multiple-scattering
term => low material!

=> impact of #material on accuracy is most important in the vertex region

Momentum Resolution at High p_T

Momentum resolution (assuming CMS-like solenoid geometry)

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

$\Rightarrow$ to get p_T resolution similar to LHC => try to gain a factor 7 in $\sigma/(BR^2)$

Increase B-field ?: =>=> very challenging/risky/expensive to go above 4T (CMS)

Increase single-point resolution ?:

Current CMS/ATLAS =>=> ~20-25 µm
Room for improvement =>=> **factor ≥4 (10??)** in central region

=>=> Resulting **increase in tracker radius** would be: **< √7/4 ≈ <30%**

What is the *p_T* resolution needed at large η ?

- Worth studying to stretch coil and tracker in z to increase coverage
- Penalty on #material (e.g. longer/stronger supports and longer cables)

Resolution in Vertex Detector

Impact parameter resolution

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3\theta)}$$

dominated by
single-point resolution

multiple-scattering
term => low material!

CLIC goal ***a* = 5 μm** ***b* = 15 μm**

	CLIC goal	ATLAS	CMS
$\sigma_{r\phi}$ [μm]			
$p_T = 1$ GeV	~20	75	90
$p_T = 1$ TeV	5	11	9

CLIC aims for: ~25 times smaller pixel size than current CMS/ATLAS
~10 times less material/layer than current CMS/ATLAS

Given the long time-scale, one can assume a CLIC-like accuracy goal for FCC-hh (??)

Si Technology Types

	Hybrid	**Monolithic**	**3D-integrated**
Examples	ATLAS, CMS, LHCb-Velo, Timepix3/CLICpix	HV-CMOS, MAPS	SOI, wafer-wafer bonded devices
Technology	Industry standard for readout; special high-Ω sensors	R/O and sensors integrated, close to industry standards	Currently still customised niche industry processes
Interconnect	Bump-bonding required	Connectivity facilitated	Connectivity is part of the process
Granularity	Max ~25 µm	Down to few-micron pixel sizes	Down to few-micron pixel sizes
Timing	Fast	Coarse, but currently improving with thin high-Ω epi-layers	Fast
Radiation hardness	“Feasible”	To be proven	??

Example: Integrated MAPS Technology

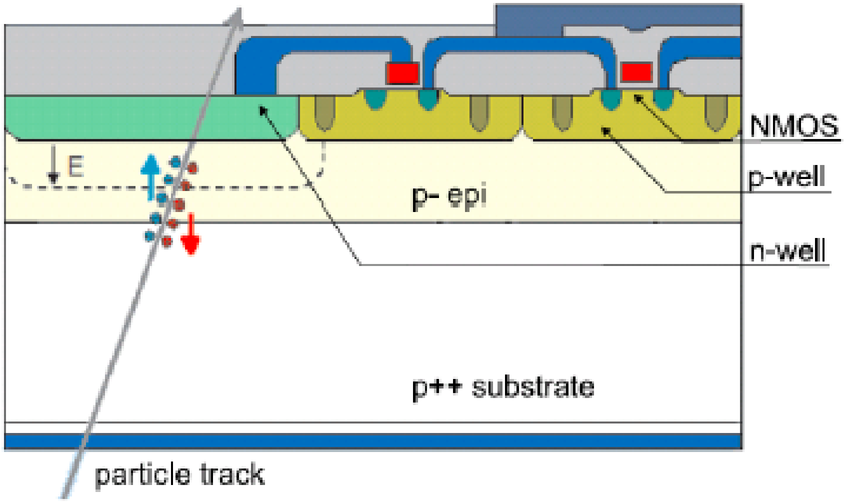
MAPS:

- Integrated electronics functionalities
- Allows for small pixel sizes
- No need for expensive bump-bonding

HV-CMOS:

- Possible in advanced 180 nm (350 nm) High Voltage process
- V_{bias} ~100 V, 10-20 µm depletion layer
- Fast signal collection from depleted layer

Radiation hardness improves when fully depleted, needs further R&D



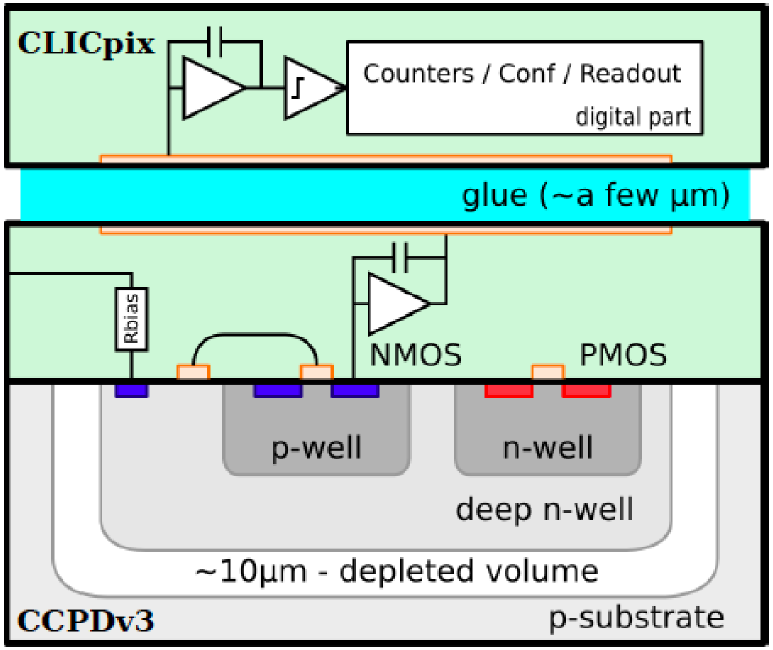
Example: Hybrid Vertex Detector with HV-CMOS

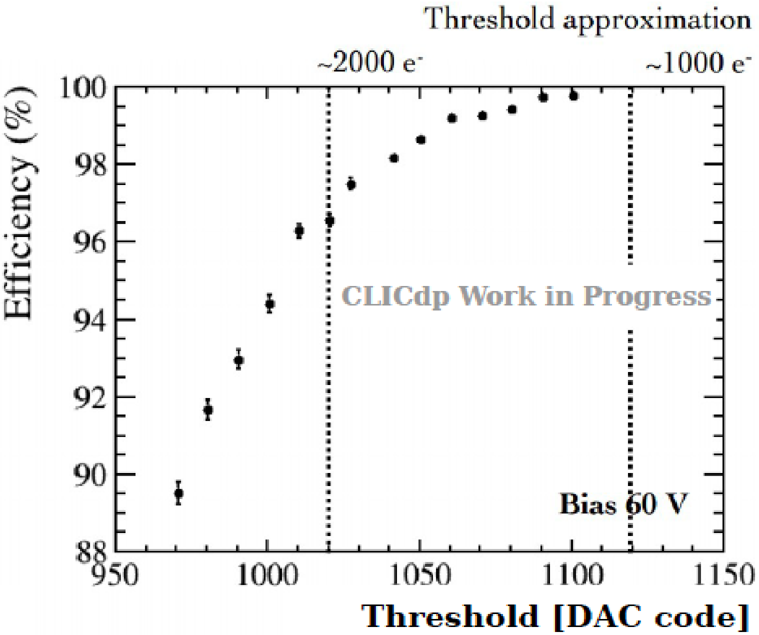
Hybrid option with HV-CMOS:

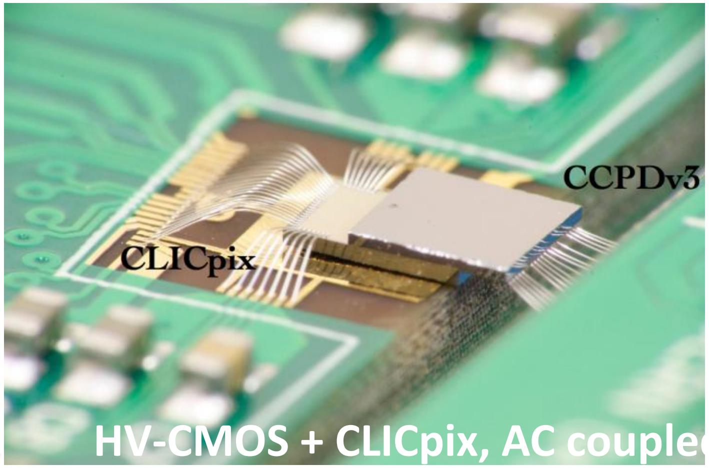
Capacitive Coupled Pixel Detector (CCPD)

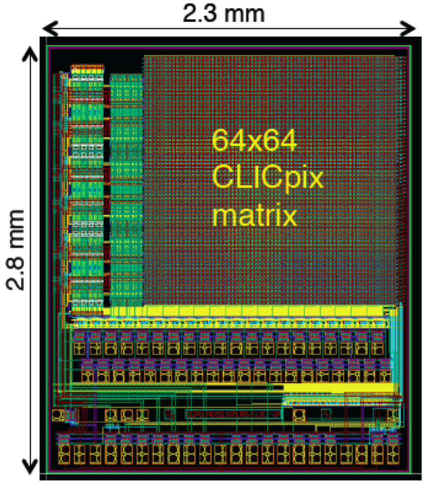
- HV-CMOS chip as integrated sensor + amplifier
- Capacitive coupling to CLICpix (or FEI4) ASIC through layer of glue => *no bump bonding*

R&D pursued by e.g. **ATLAS** and **CLIC**
successful initial beam tests



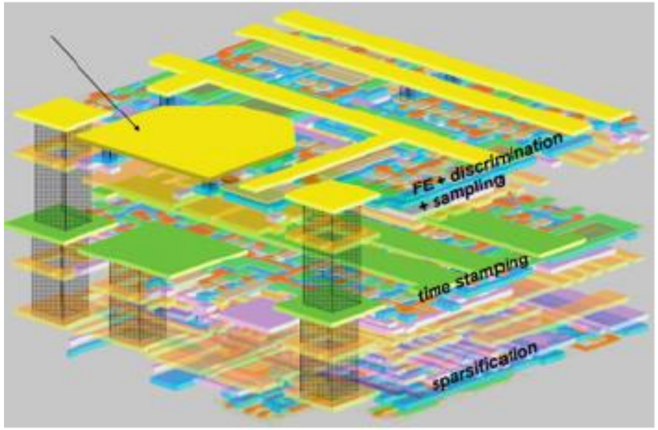




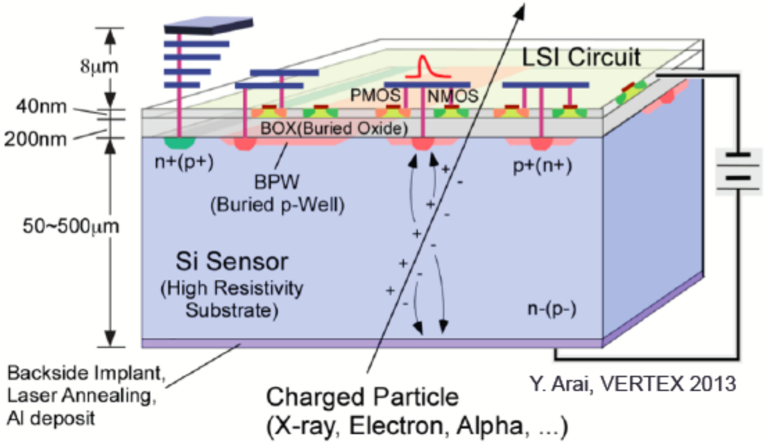


CCPDV3

Example: 3D Detectors, wafer-to-wafer bonding



3D-integrated, 3 tiers



Y. Arai, VERTEX 2013

SOI

3D technologies, wafer-to-wafer bonded ASIC + sensor

Main advantages:

Combining optimal sensor material (high-Ω) with high performance ASIC

Avoid bump-bonding

Profit from industrial CMOS trends towards very small feature sizes

Drawbacks:

Currently either still niche application (e.g. SOI) or fast-changing industrial R&D

(e.g. R&D for cameras with very small pixels)

Generally too high cost for particle physics R&D budgets

Calorimetry

(A Brief List of) Calorimetry Requirements

- Jet containment: Need ~12λ to contain 1 TeV hadrons at 98%
- Coverage up to η ~ 6.
- High granularity (a key factor!)
- Pileup mitigation
- Radiation tolerance
- …

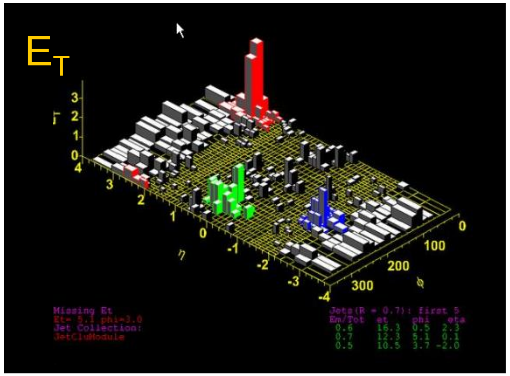
Trend in Calorimetry

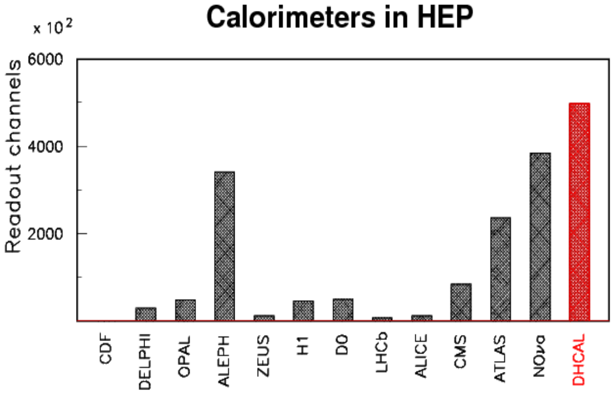
Tower geometry

Energy is integrated over large volumes into single channels

Readout typically with high resolution (> 10 bits/channel)

Individual particles in a hadronic jet not resolved



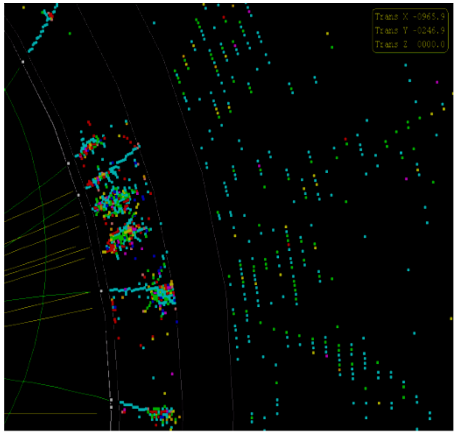


Imaging calorimetry

Large number of calorimeter readout channels (~10^7)

Particles in a jet are measured individually

Option to minimize resolution on individual channels (1, 2… bits/channel)



Particle Flow Algorithms (PFAs)

Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	If goal is to achieve a resolution of 30%/√E →		$\leq 0.24^2\ E_{jet}$

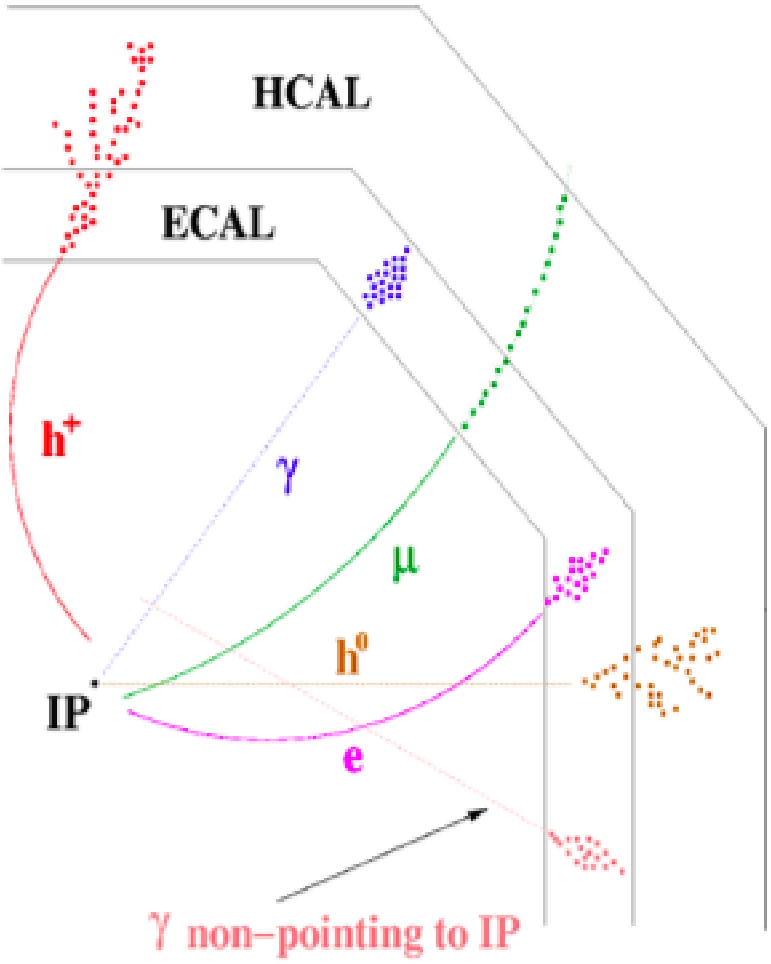
$$\boxed{\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}}$$

Particle Flow Detector

Maximum exploitation of precise tracking measurement

- Large radius and length
  to separate the particles
- Large magnetic field
  to sweep out charged tracks
- “no” material in front of calorimeters
  stay inside coil
- Small Moliere radius of calorimeters
  to minimize shower overlap
- High granularity of calorimeters
  to separate overlapping showers

Emphasis on tracking capabilities of calorimeters



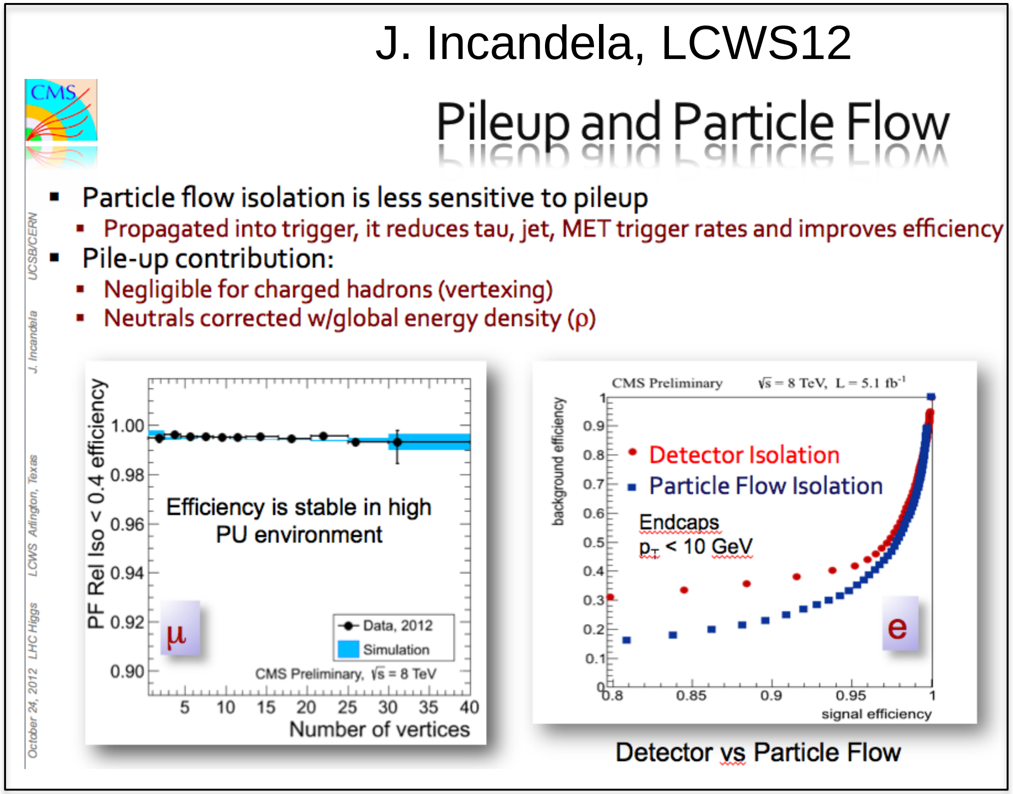
Imaging Calorimeters

Are needed for the application of **Particle Flow Algorithms** (PFAs) to the measurement of hadronic jets at colliders

In the past PFAs (or equivalent) have been used by ALEPH, ZEUS, CDF…

Now being applied by **CMS**
(← detector **NOT** optimized for PFAs)

Future colliders
(→ detectors to be **optimized** for PFAs)



J. Incandela, LCWS12

Pileup and Particle Flow

- Particle flow isolation is less sensitive to pileup
  - Propagated into trigger, it reduces tau, jet, MET trigger rates and improves efficiency
- Pile-up contribution:
  - Negligible for charged hadrons (vertexing)
  - Neutrals corrected w/global energy density (ρ)

Efficiency is stable in high PU environment

Detector vs Particle Flow

October 24, 2012 LHC Higgs LCWS Arlington, Texas J. Incandela UCSB/CERN

Assets of Imaging Calorimeters

- Detailed view into hadronic showers

- Lots of information to cope with shortcomings in energy resolution that may occur due to high sampling frequency
  - ➔ Opportunities for software compensation

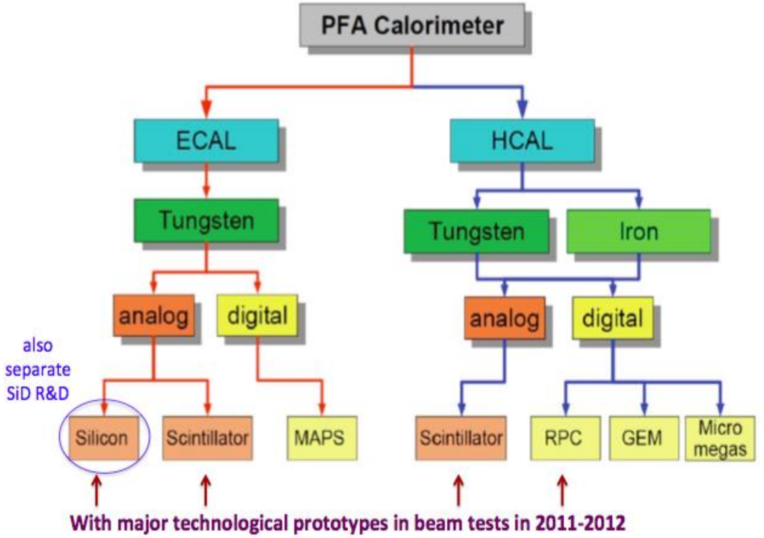
- Resolution of shower substructure allows for in-situ calibration of detectors with track segments
  - ➔ In situ calibration and no or few calibration runs needed during detector operation

- Leakage correction

- Particle ID

- Software Compensation

R&D for Imaging Calorimeters



PFA Calorimeter

- ECAL
  - Tungsten
    - analog
      - Silicon
      - Scintillator
    - digital
      - MAPS
- HCAL
  - Tungsten
  - Iron
    - analog
      - Scintillator
    - digital
      - RPC
      - GEM
      - Micro megas

also separate SiD R&D

With major technological prototypes in beam tests in 2011-2012

The CALICE Collaboration

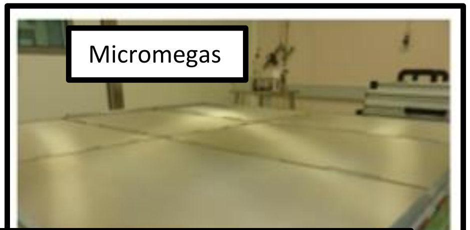
Calorimeter R&D for the ILC … and beyond

~360 physicists/engineers from 60 institutes and 19 countries from 4 continents

- Integrated R&D effort

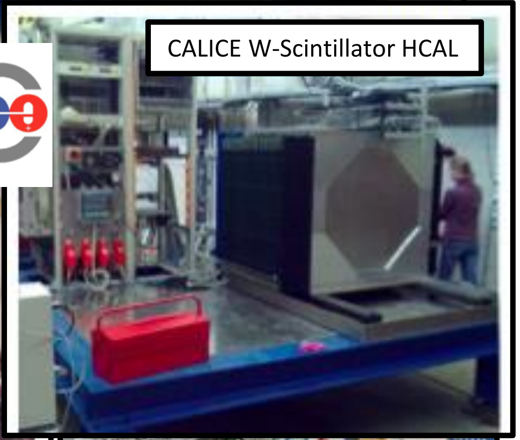
- Benefit/Accelerate detector development due to *common* approach


CALICE RPC SDHCal


Micromegas

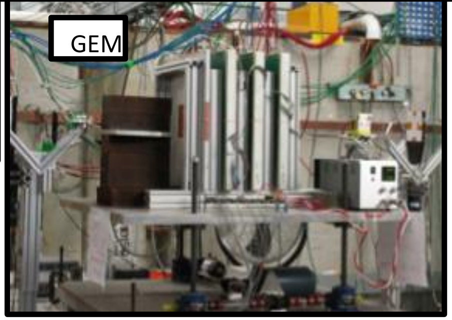

CALICE RPC DHCal

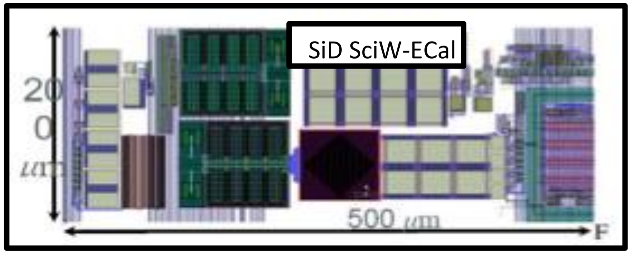

CALICE SciW-ECal


CALICE W-Scintillator HCAL

CALICE Calorimeter for ILC

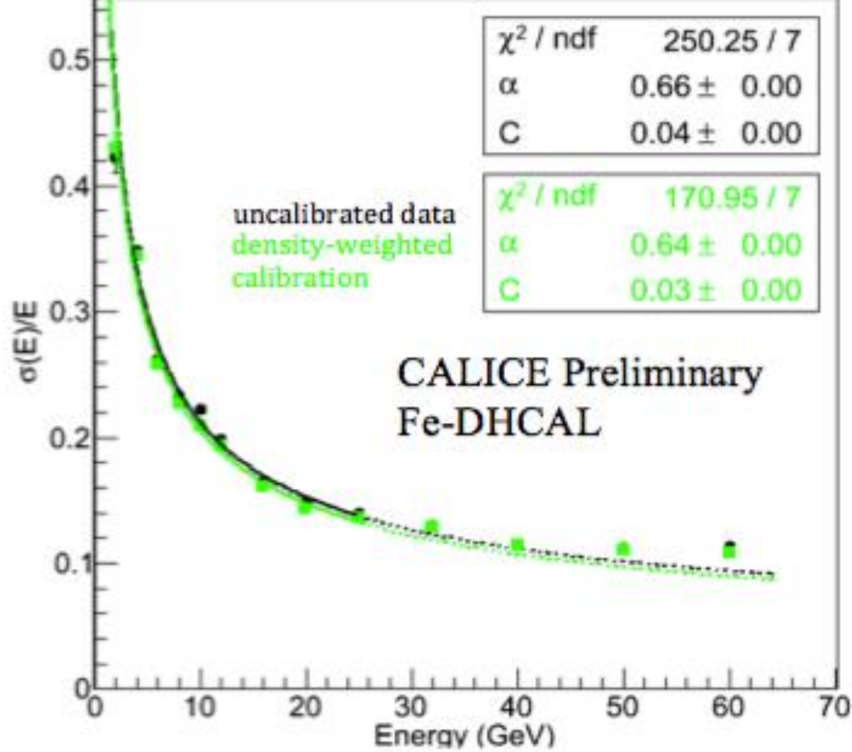

CALICE SiW-ECal

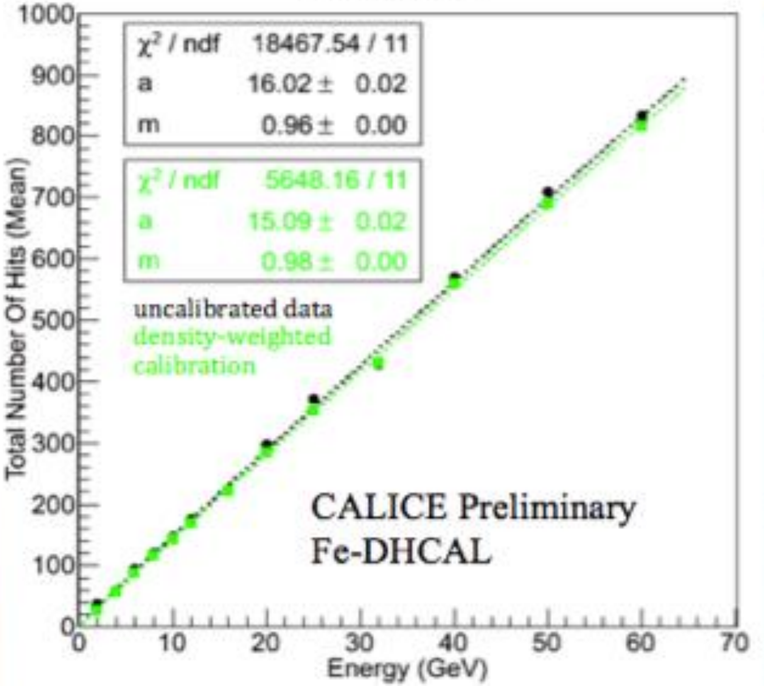

GEM


SiD SciW-ECal

CALICE Digital Hadron Calorimeter

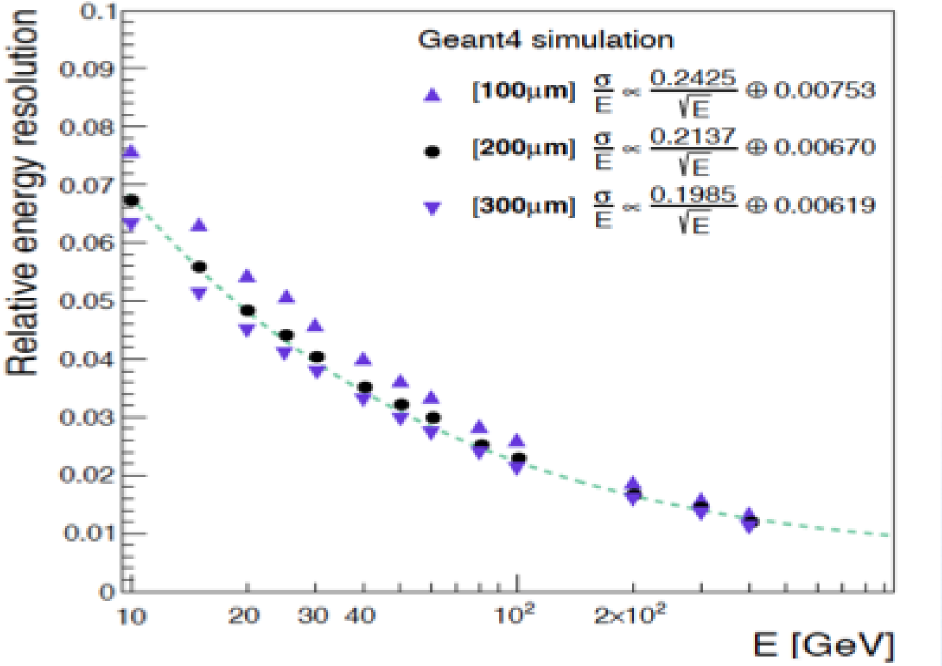
- Example DHCAL with Fe absorber on pion beam
- Close to linear response up to 60 GeV
  - Power law fit to measure saturation at high energies
- Energy resolution stochastic term ~64%/√E (adequate for PFA)





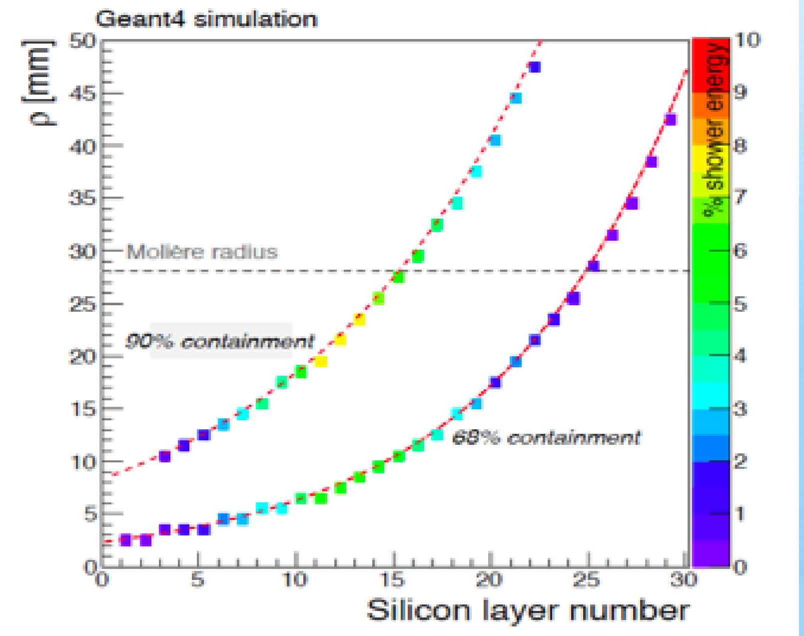
Silicon Based High Granularity Calorimeter - CMS

- ***Si-HGC extends Tracking into Calorimeter***
  - Provides good cluster energy resolution
  - Very detailed topological information
  - Excellent space resolving power for nearby clus
- ***Ideally suited for PF reconstruction in 'high-densit energy deposit environment***
  - Baseline choice for ILC/CLIC
  - Option for HL-LHC upgrade of CMS EC-ECAL
- Possible applications for EM calorimeters in the cer region of a FCC-hh experiment



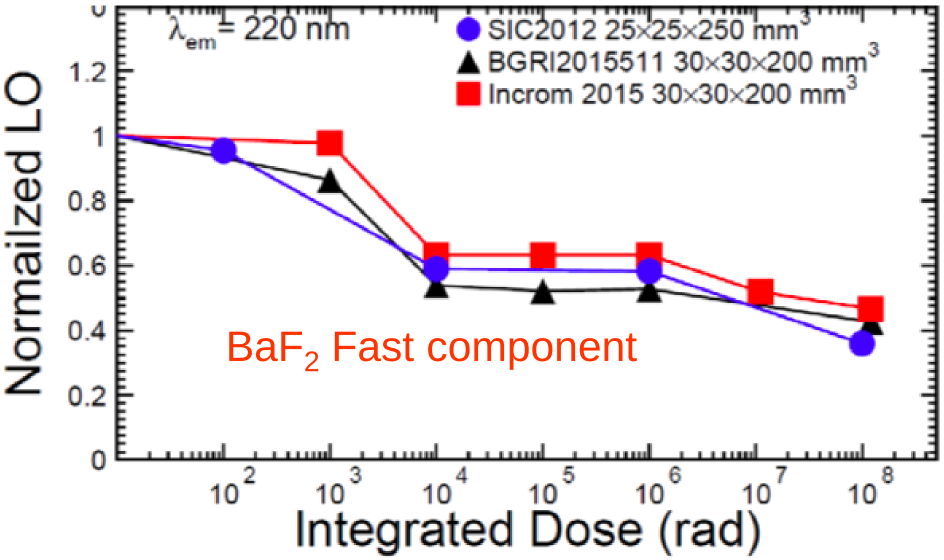
Potential Limitations and/or Challenges

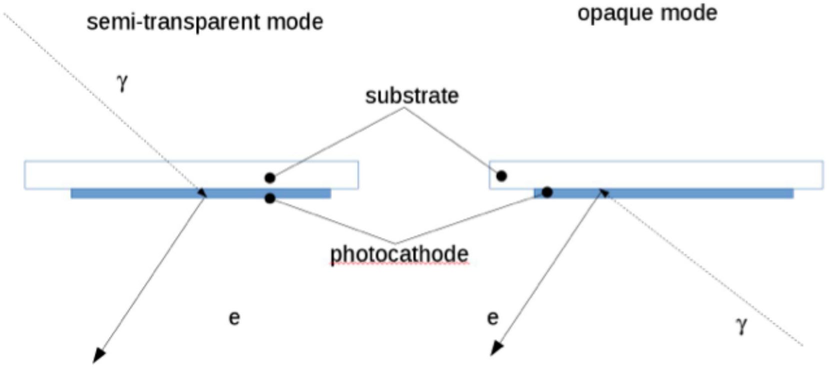
- Size and costs
- Cell size mm2-cm2 and no. of readout channels
- Radiation tolerance of sensors and electronics
  - Thin sensors vs. noise & MIP sensitivity
- Dynamic Range vs. technology
  - MIP to 100-200pC range
  - Complexity, dead-time & pileup sensitivity
- Power and cooling
- Analog vs. Digital readout (UHGC)



Crystal Calorimetry

- Several future crystal calorimeter implementations: LYSO for COMET (Mu2e, Super B and CMS at HL-LHC) BaF_2 and PbF_2 for Mu2e and g-2 respectively at Fermilab PbF_2, PbFCl, BSO and BGO for Homogeneous HCAL for LC.
- Extensive radiation damage studies were performed.
- Various crystals, inorganic scintillators, glasses and ceramics may offer solutions for future HEP experiments.



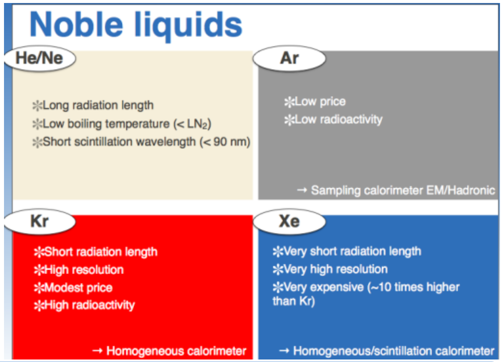


Deposit GaN photocathodes directly on the MCPs!

B. Bilki, CPAD Workshop, October 7, 2015

Noble Liquid Element Calorimetry

- Major impact points are the newly developed VUV-sensitive SiPMs and simultaneous utilization of scintillation and ionization signals in the noble liquids (segmented TPC).



Noble liquids

He/Ne

- ✻Long radiation length
- ✻Low boiling temperature (< LN_2)
- ✻Short scintillation wavelength (< 90 nm)

Ar

- ✻Low price
- ✻Low radioactivity

→ Sampling calorimeter EM/Hadronic

Kr

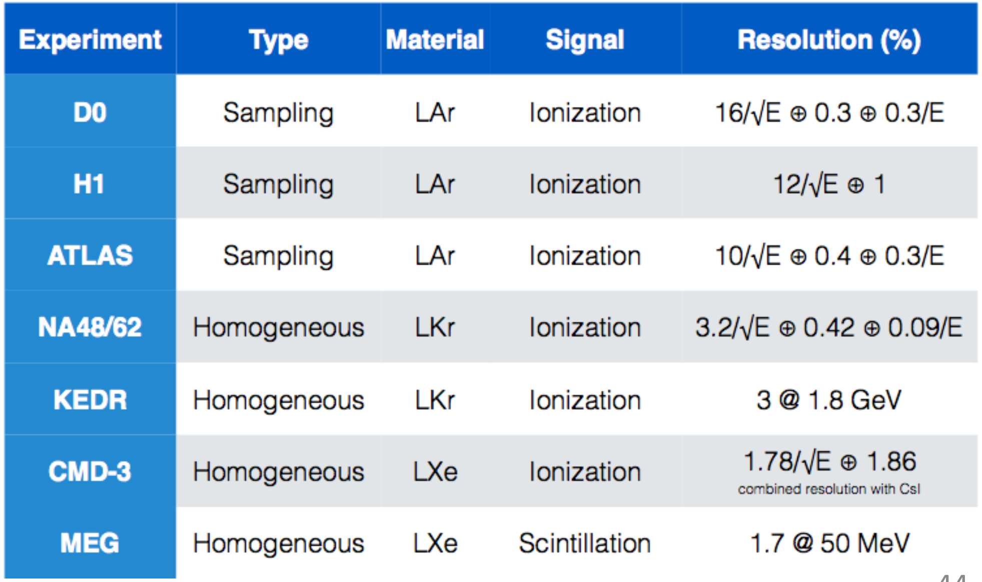
- ✻Short radiation length
- ✻High resolution
- ✻Modest price
- ✻High radioactivity

→ Homogeneous calorimeter

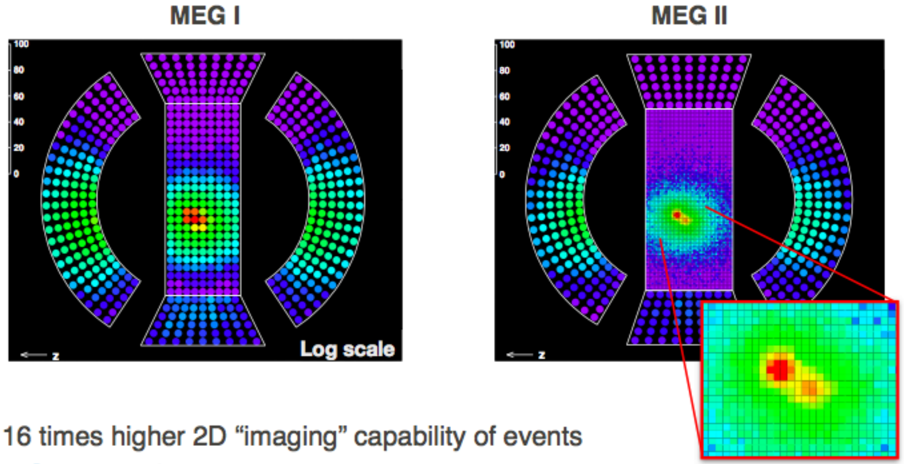
Xe

- ✻Very short radiation length
- ✻Very high resolution
- ✻Very expensive (~10 times higher than Kr)

→ Homogeneous/scintillation calorimeter



Experiment	Type	Material	Signal	Resolution (%)
D0	Sampling	LAr	Ionization	16/√E ⊕ 0.3 ⊕ 0.3/E
H1	Sampling	LAr	Ionization	12/√E ⊕ 1
ATLAS	Sampling	LAr	Ionization	10/√E ⊕ 0.4 ⊕ 0.3/E
NA48/62	Homogeneous	LKr	Ionization	3.2/√E ⊕ 0.42 ⊕ 0.09/E
KEDR	Homogeneous	LKr	Ionization	3 @ 1.8 GeV
CMD-3	Homogeneous	LXe	Ionization	1.78/√E ⊕ 1.86 combined resolution with CsI
MEG	Homogeneous	LXe	Scintillation	1.7 @ 50 MeV

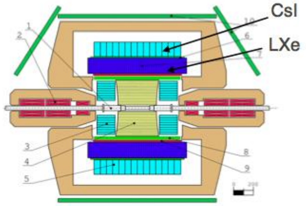


16 times higher 2D “imaging” capability of events

- ✱More uniform energy respose
- ✱Better position resolution with using the shower-shape information
- ✱Pileup identification

CMD-3 LXe calorimeter

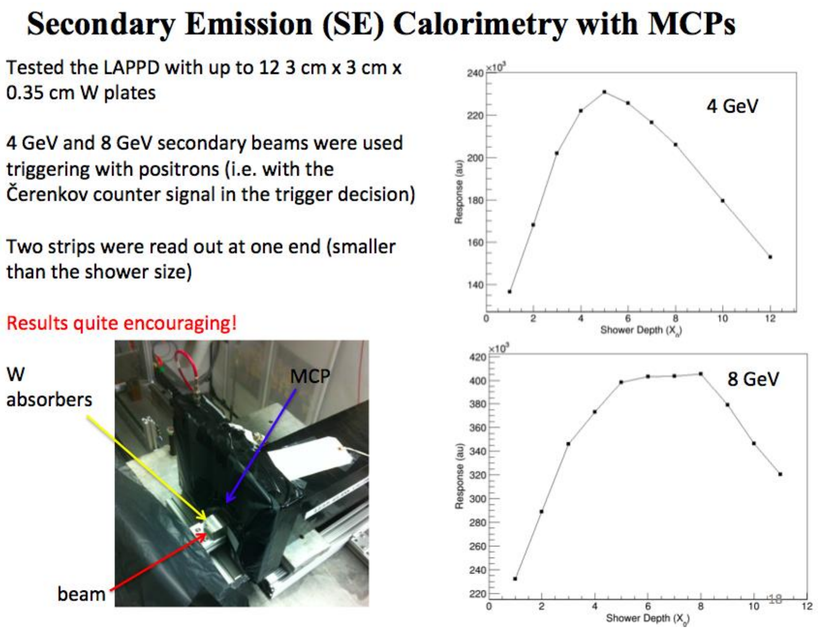
VEPP-2000 e+e- collider in Novosibirsk



- ✱ Combined calorimeter, LXe + CsI
  - ✱ 400 l LXe : 5.4 χ_0
  - ✱ LXe+CsI : 13.5 χ_0
- ✱ Successful operation since 2009
- ✱ another 5 — 10 years operation expected.
- ✱ Upgrade study of the readout electronics aiming at 1 ns time resolution is ongoing.

Secondary Emission Calorimetry

- Intrinsically radiation-hard and fast electromagnetic calorimetry option for harsh radiation conditions.
- Unique capabilities of precision shower timing and position measurements.
- Feasible for large-scale applications and fine readout segmentation hence imaging calorimetry.



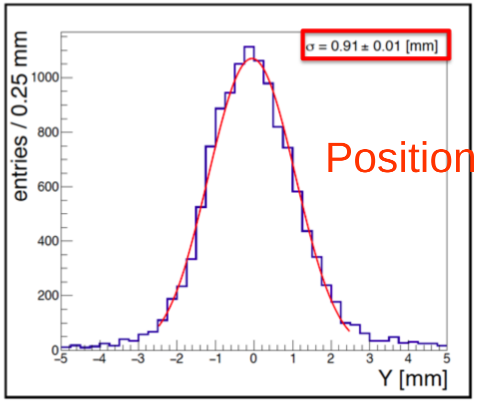
Secondary Emission (SE) Calorimetry with MCPs

Tested the LAPPD with up to 12 3 cm x 3 cm x 0.35 cm W plates

4 GeV and 8 GeV secondary beams were used triggering with positrons (i.e. with the Čerenkov counter signal in the trigger decision)

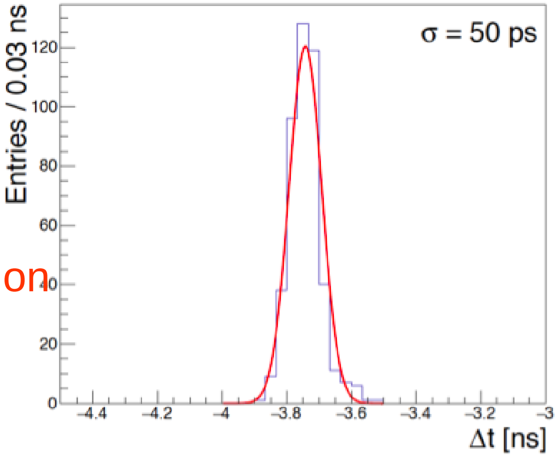
Two strips were read out at one end (smaller than the shower size)

Results quite encouraging!



Position resolution

Time resolution



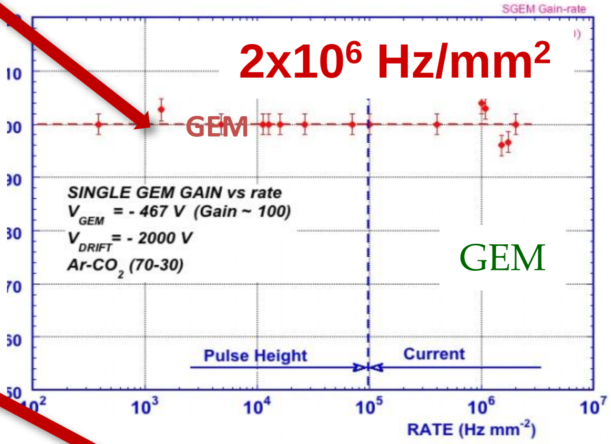
Muon Detectors

(A Brief List of) Muon System Requirements

- Very large area ~ 15000 m^2 → gaseous detectors
- O (100 ps) timing resolution
- Robustness → operate for ~ 20 years
- Pileup mitigation
- 10% p_T resolution at a few TeV
- …

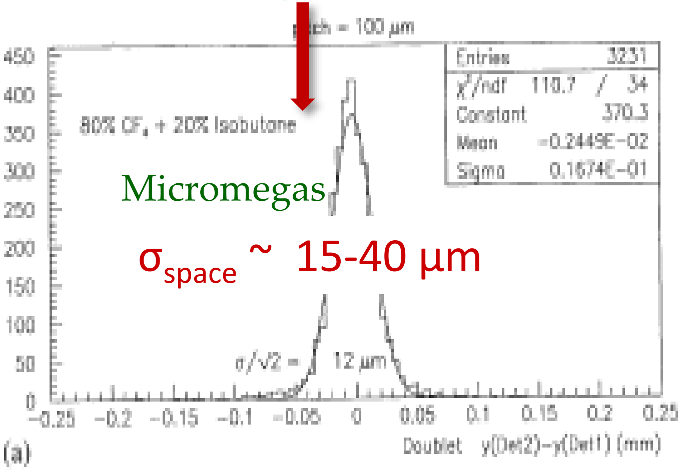
Why Micro-Pattern Gaseous Detectors are attractive

- ✓ High rate capability
- ✓ Excellent radiation hardness
- ✓ Large active areas / industrial production
- ✓ Good timing resolution
- ✓ Ion backflow/photon feedback reduction
- ✓ Excellent spatial resolution



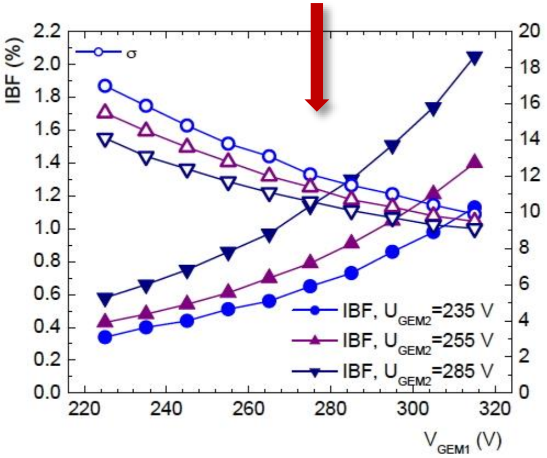
2×10^6 Hz/mm^2

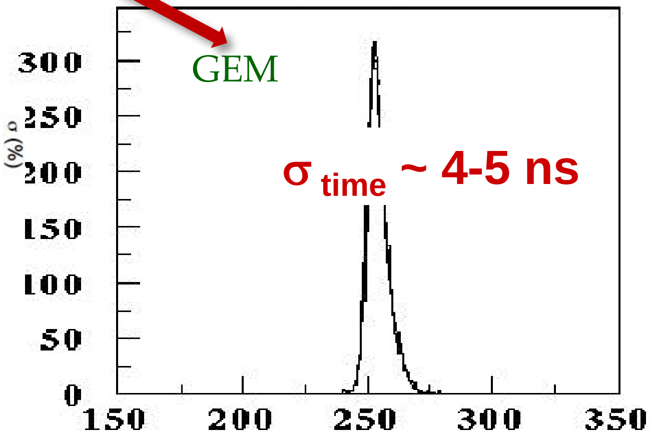
GEM



Micromegas

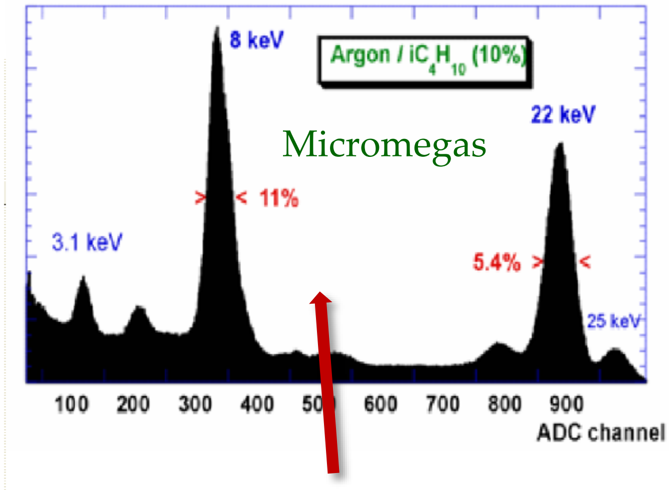
σ_{space} ~ 15-40 μm





GEM

σ_{time} ~ 4-5 ns



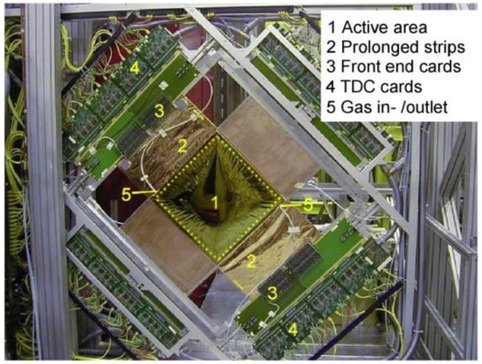
Micromegas

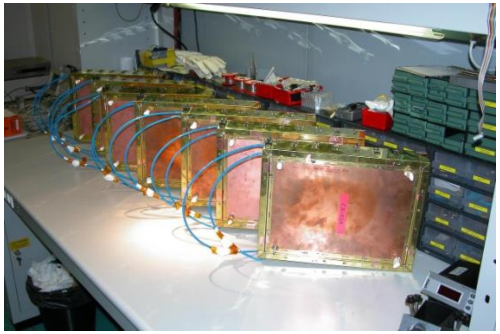
M. Abrescia, FCC Week 2015

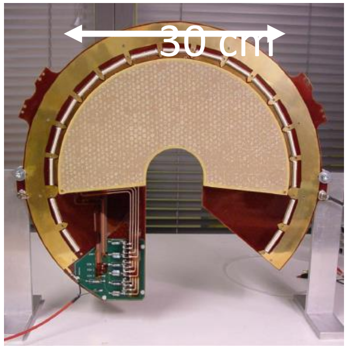
MPGDs in Running Experiments

Exp.	#	Type	Readout	# of ch.	Size (cm²)	Gas	σ_{space} (μm)	σ_{time} (ns)	ε (%)
COMPASS	22	GEM	2-D strips	1536	31×31	Ar/CO_2 (70/30)	70	12	>97
	12	MM	1-D strips	1024	40×40	$Ne/C_2H_6/CF_4$ (80/10/10)	90	9	>97
LHCb	24	GEM	pads	192	10×24	$Ar/CO_2/CF_4$ (45/15/40)		4.5	>97
TOTEM	40	GEM	pads + strips	1536 + 256	30 × 20	Ar/CO_2 (70/30)	~70 (θ)		>92

MPGDs have accumulated a lot of running experience with excellent results

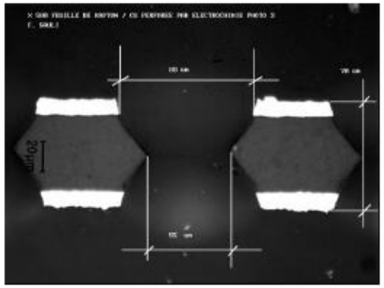




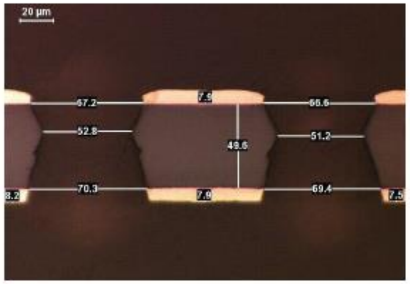


Example: GEMs: Technological breakthroughs

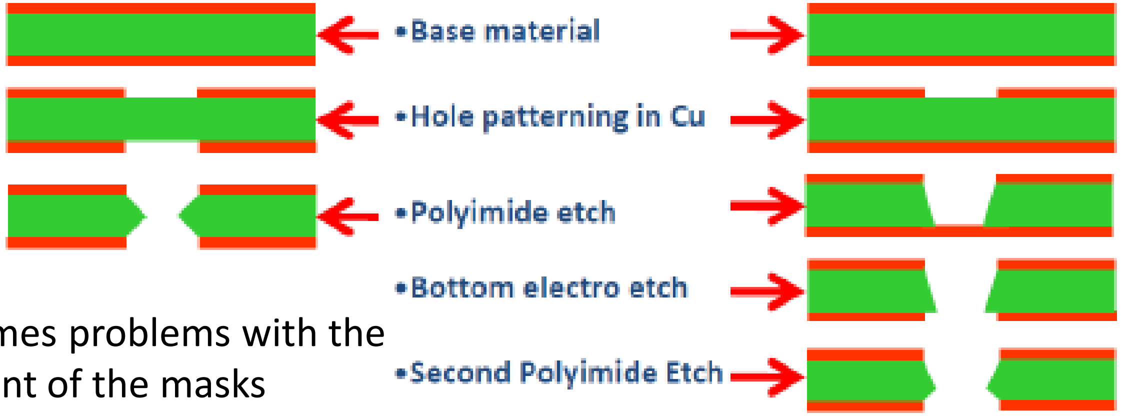
Achieved 40x40cm²



Achieved 200x60cm²



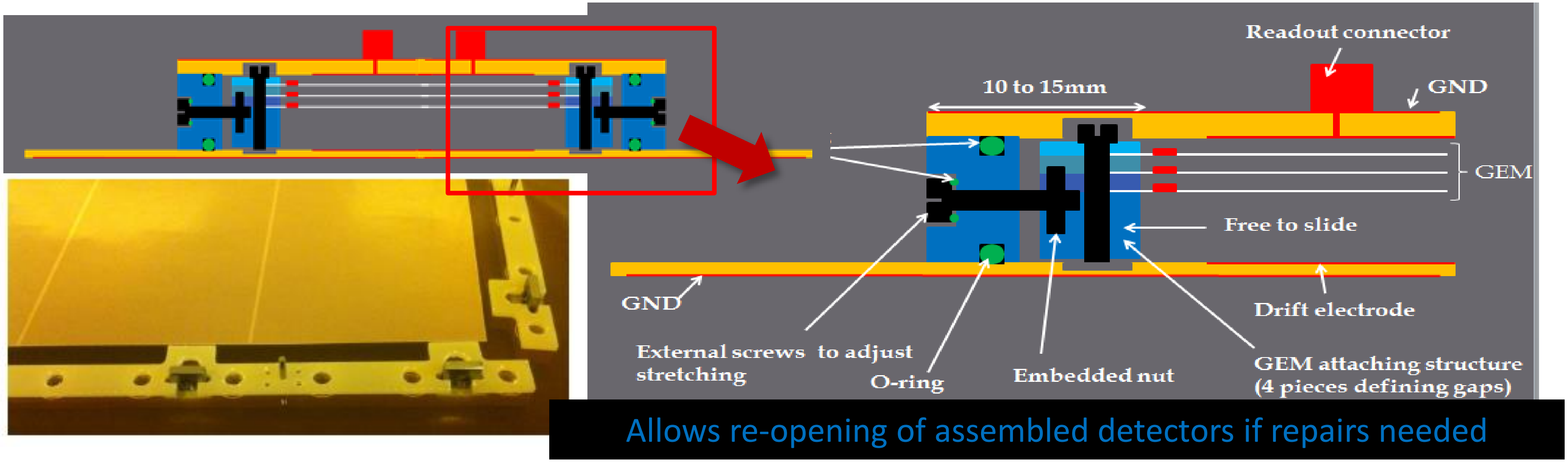
Single side etching technique



- Base material
- Hole patterning in Cu
- Polyimide etch
- Bottom electro etch
- Second Polyimide Etch

Overcomes problems with the alignment of the masks

Stretching assembly technique without glue without spacers (CERN)



Allows re-opening of assembled detectors if repairs needed

Example: MMs: technological breakthroughs

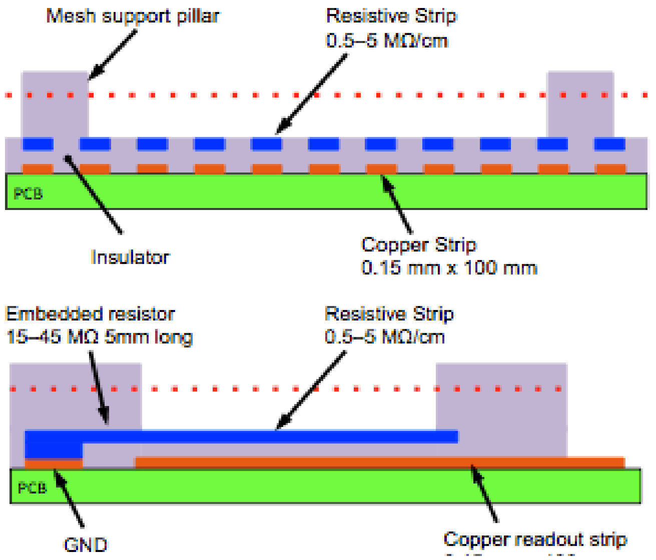
Resistive strips for spark immunity

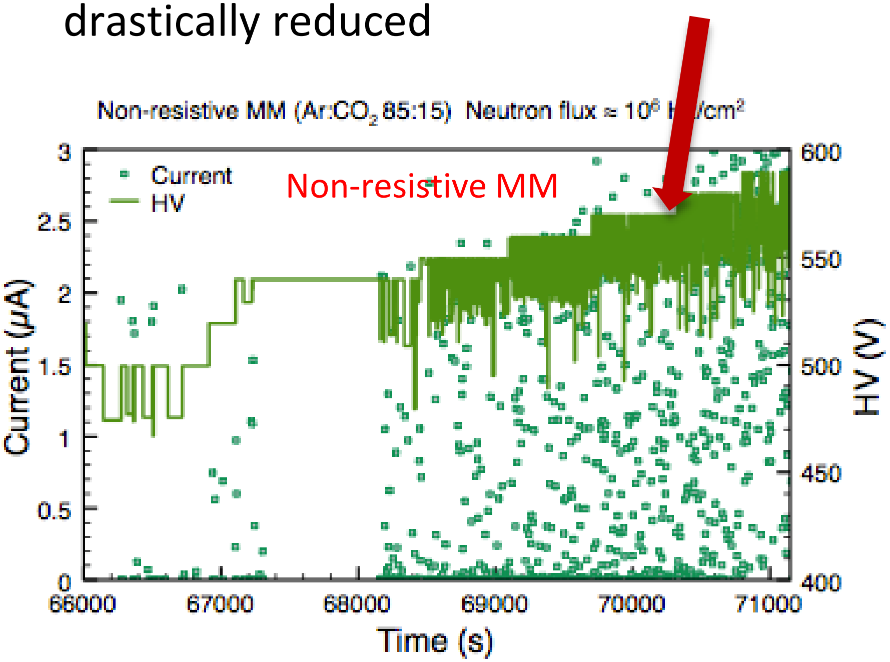
➢Same principle as resistive plates devices:

✓Put resistive strips on top of the readout (conductive) strip

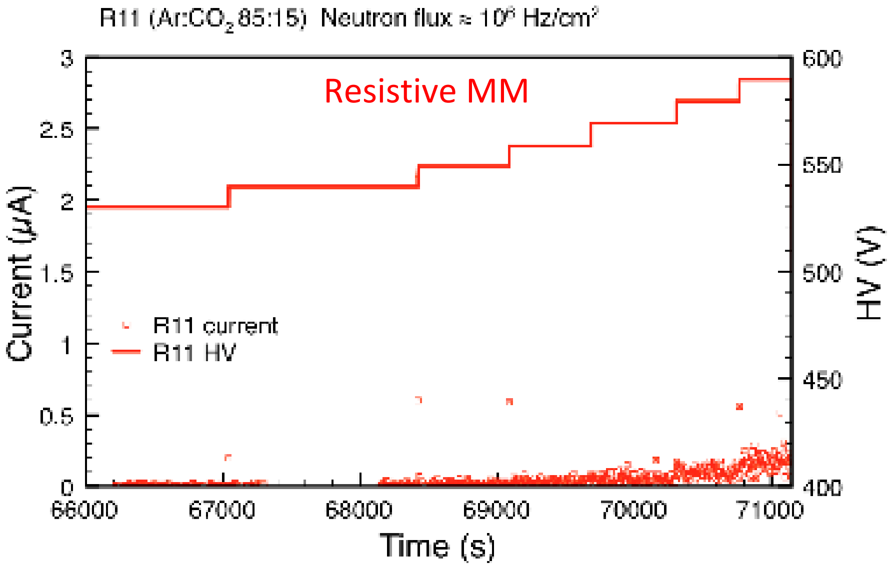
✓electric field is locally dumped in case of large discharges

Voltage drops due to small discharges drastically reduced





Non-resistive MM (Ar:CO$_2$ 85:15) Neutron flux ≈ 10^6 H/cm^2



R11 (Ar:CO$_2$ 85:15) Neutron flux ≈ 10^6 Hz/cm^2

Summary - Tracking

- Tracking detectors for FCC are considered feasible
- ~ns time resolution, ~micron-level space resolution and radiation tolerance to ~30x10^{16} appear as natural evolution of present technologies.
- Minimal FCC-hh target specifications are almost already achieved in dedicated detectors.
- No single technology reaches all design specs at the same time.
- The main issue: coverage at small radius with radiation hardness, fine granularity.
- Several sensor technologies are promising => consider them all
- Big technology step: integrated electronics => to be pursued closely

Summary - Calorimetry

- Several technologies exist for calorimetry
- Each technology requires a robust R&D program to satisfy all requirements of the FCC experiments
- Many active learning areas are available e.g. CMS HGC
- Integrated front-end electronics at this scale will be challenging
- High precision timing is necessary for pileup mitigation
- Rate capability, radiation-hardness, reliability and robustness of the detectors should be investigated at all stages of the R&D

Summary – Muon System

- Gaseous detectors seems to be the only option for the muon system
- Rigorous R&D is required to overcome existing limits for FCC conditions
- This R&D already evolves within HL-LHC upgrades but will need to be pushed forward for FCC
- Aging issues must be carefully studied and taken care of!
- Gas issues have to be taken care of: gas is the “core” of a gaseous detector

  - Resistive Plate Chambers:
    - Rate capability: will 10 kHz/cm^2 for 20 years be reachable?
  - Micro Pattern Gas Detectors
    - Large scale production: will o(several 100 m^2) production and operation (electronics, stability, …) of MPGD be feasable?
  - Wire Chambers
    - Size reduction due to occupancy and rate issues has a limit for FCC?