Development of Detectors

for Physics at the Terascale

Beijing, 4 September 2015

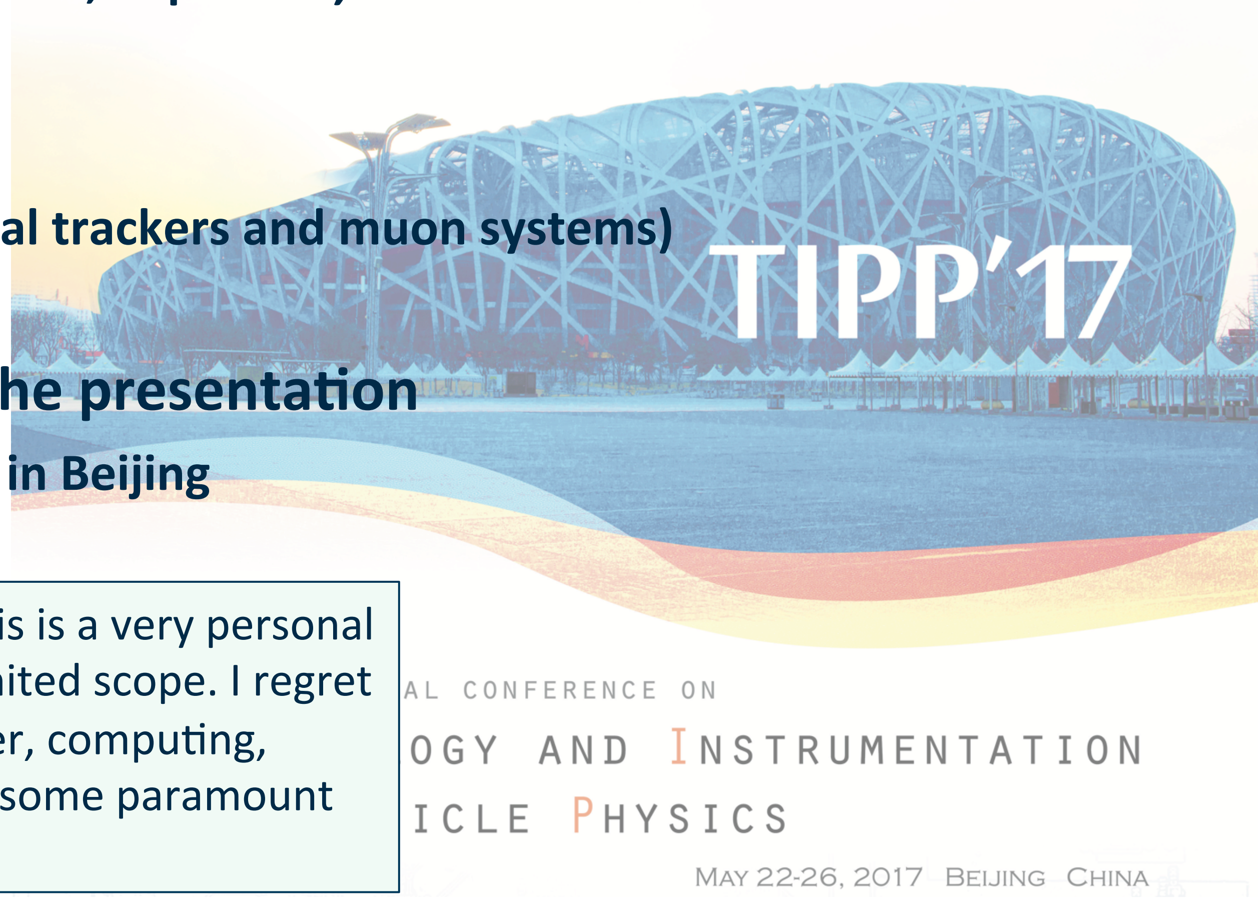
Attilio Andreazza

INFN Sezione di Milano
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Outline

- **Focused in scope:**
  - **technologies for the High-Luminosity LHC upgrades**
    - **They are the R&D for high-energy hadron colliders**
  - **and for lepton colliders: FCC-ee, CepC. ILC, CLIC**
- **Sections:**
  - **Silicon trackers**
  - **Gas tracking systems (central trackers and muon systems)**
  - **Calorimetry**
- **References at the end of the presentation**
  - **many from TIPP 2017, here in Beijing**

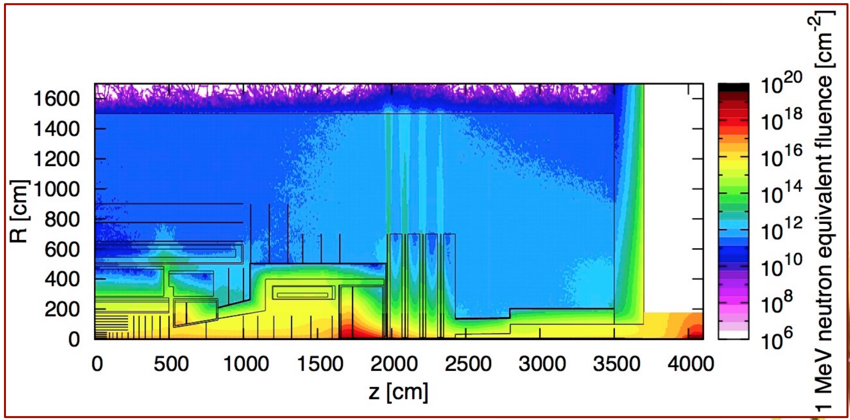


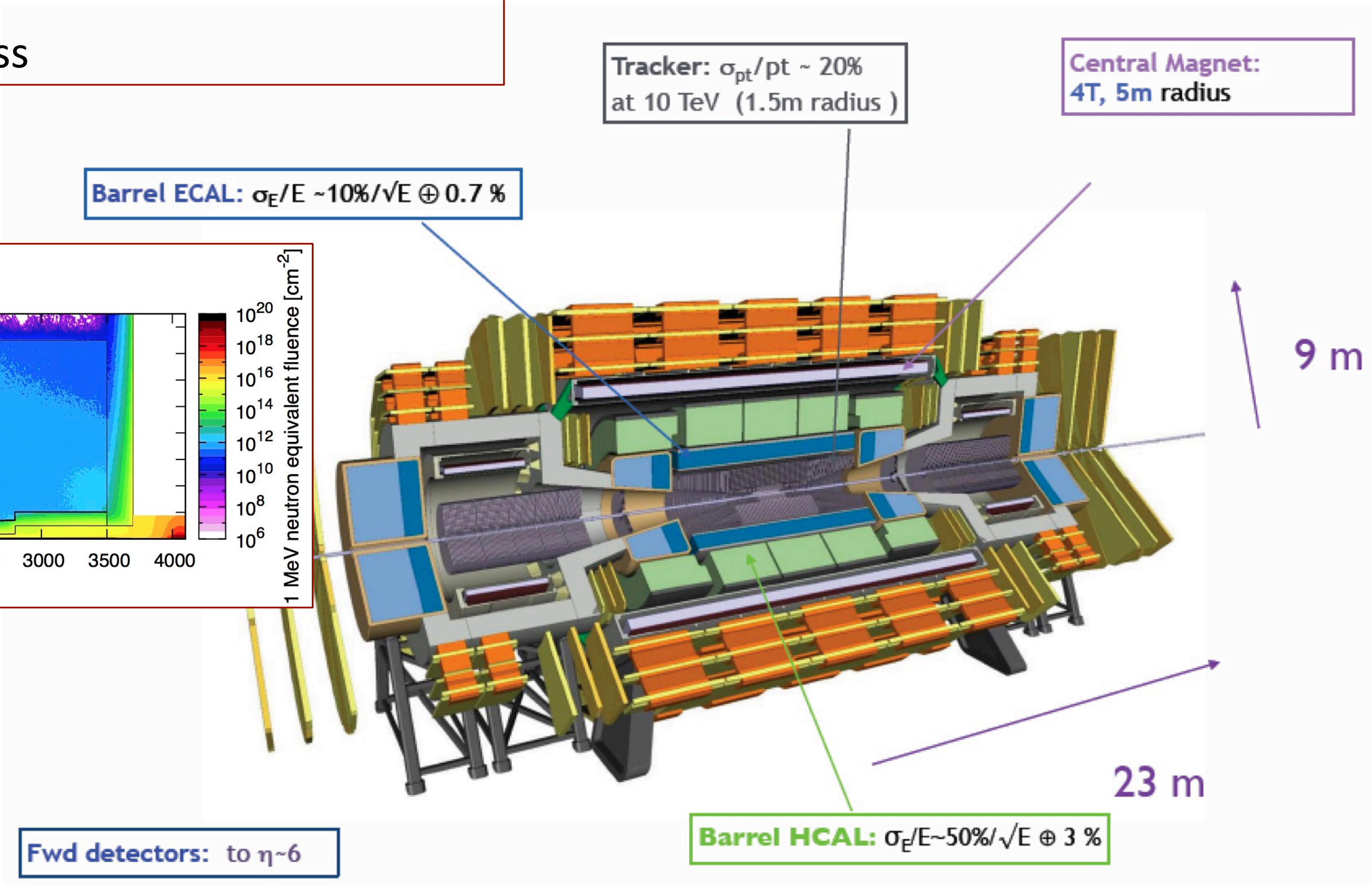
Disclaimer: due to the limited time, this is a very personal selection of topics, even within the limited scope. I regret that I'll not be able to talk about trigger, computing, particle ID and that I'll not cover even some paramount LHC experiments.

Hadron Colliders

Ref. 1, 35

- Inelastic p-p cross-section 100—120 mb
- Luminosity 7—30 $\times 10^{34}$ cm^{-2}s^{-1}
- **Pileup** 200—1000 interactions in 25 ns
- Radiation hardness





Lepton Colliders

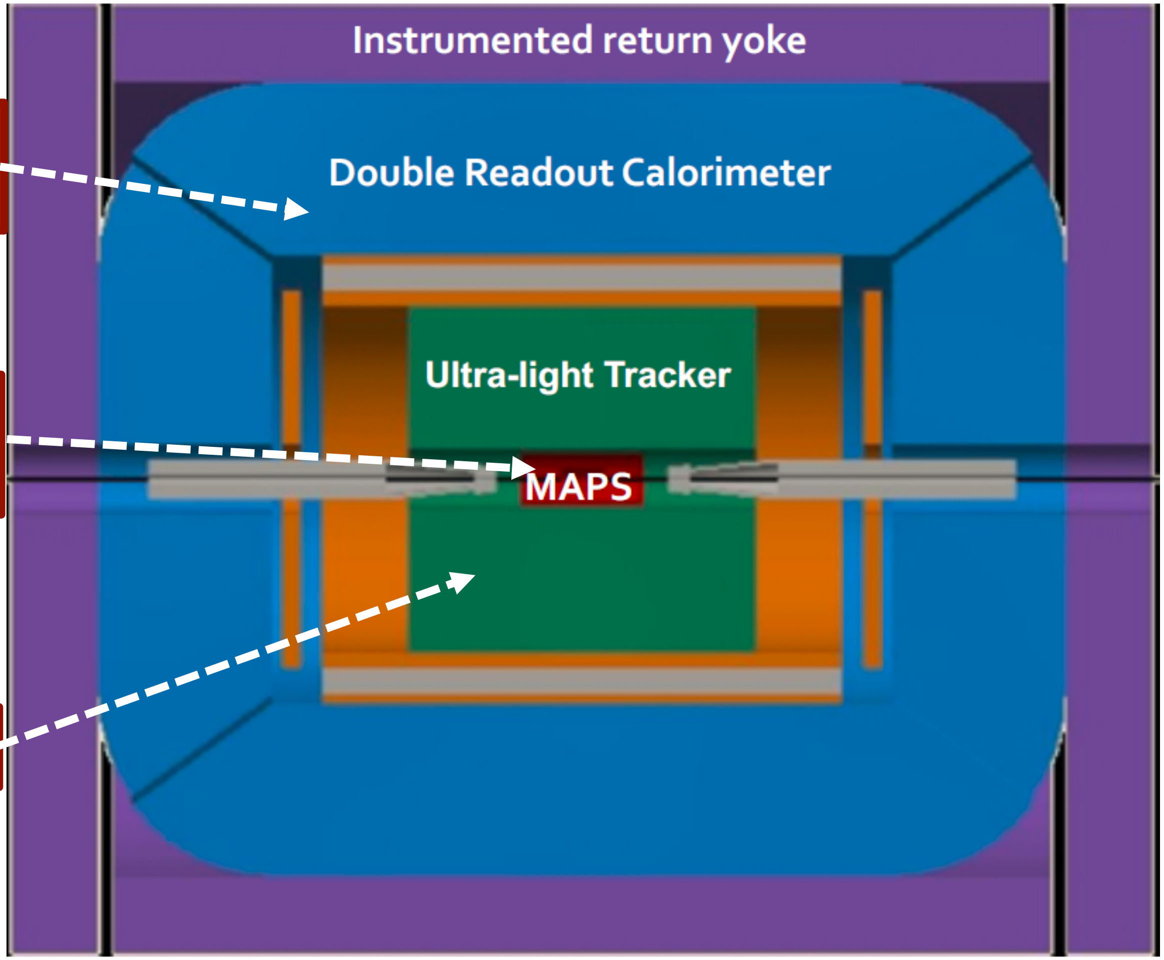
Ref. 1 –3, 23

- Emphasis on high precision, even at low p_T (for LHC standards)
- Cross section: 30 nb (Z peak) – 100 fb (high energy processes like ZH, tt)
- Luminosity: 1—20 $\times 10^{34}$ cm^{-2}s^{-1}

$$\frac{\sigma_E}{E} = 3-4\% \text{ at } {\sim}40 \text{ GeV}$$

$$\sigma_{d_0} = 5 \oplus \frac{10-15}{p[\mathrm{GeV}]\sin^{3/2}\theta}\ \mu\mathrm{m}$$

$$\sigma_{1/p} = 2-5\times 10^{-5}\mathrm{GeV}^{-1}$$



Silicon detectors are still the standard solution for:

- **precision tracking**
- **high-density, high-rate and high-radiation environments**

New solutions for pixel detectors and timing layers

PRECISION TRACKING

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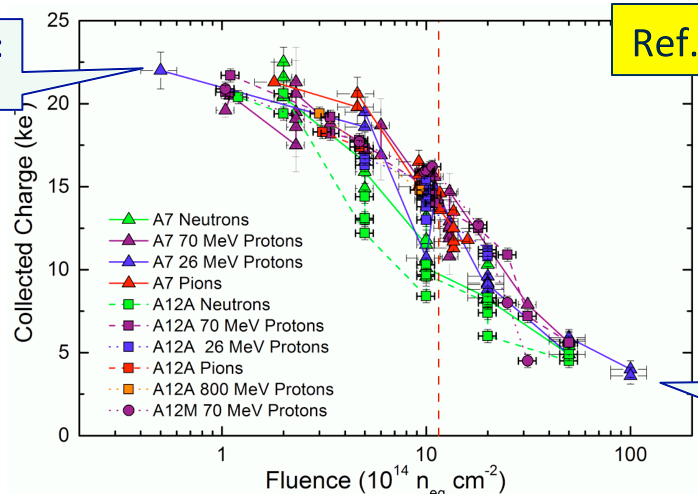
The two frontiers of silicon detectors

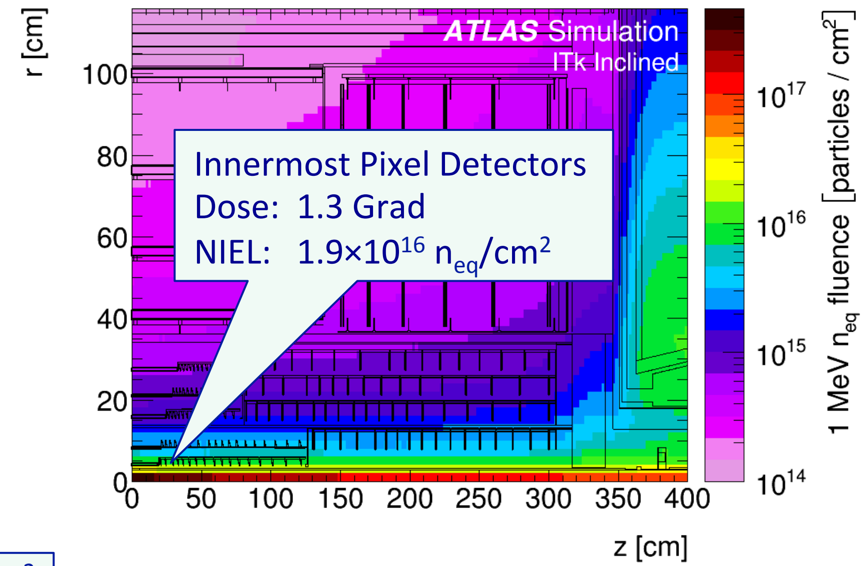
- **High radiation hardness**
  - Combined with high particle flux: O(10 MHz/mm^2)
  - Example: ATLAS Strip Detectors

Non-irradiated: 22 ke

Ref. 4

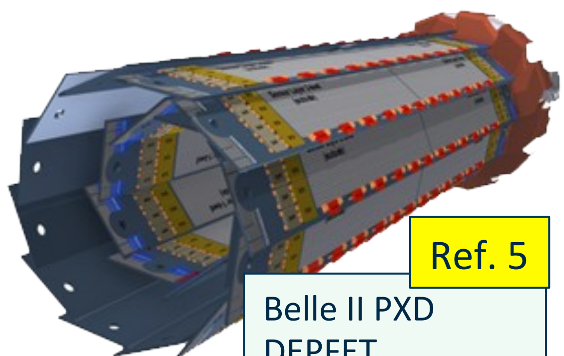


10^{16} n_{eq}/cm^2
4 ke



Innermost Pixel Detectors
Dose: 1.3 Grad
NIEL: 1.9×10^{16} n_{eq}/cm^2

- **High resolution**
  - small pitch
  - low material
  - low power consumption

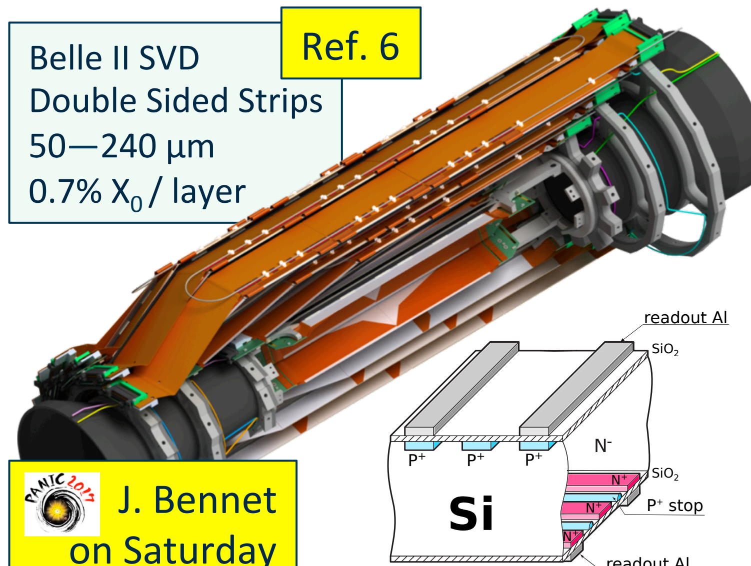


Ref. 5

Belle II PXD
DEPFET
55—85×50 µm^2
N_2 flow cooling
0.1% X_0 / layer

Belle II SVD
Double Sided Strips
50—240 µm
0.7% X_0 / layer

Ref. 6

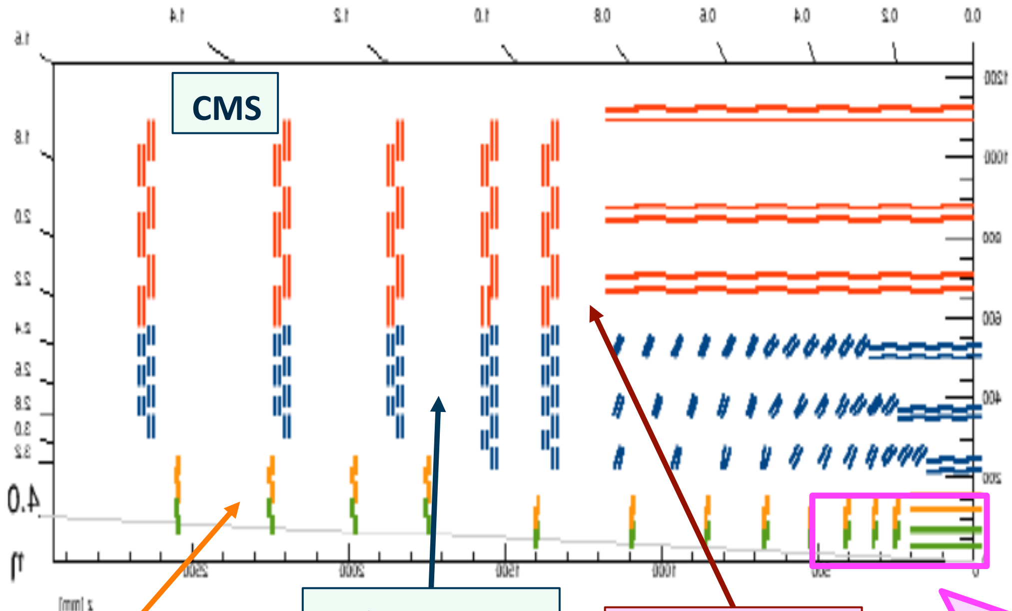


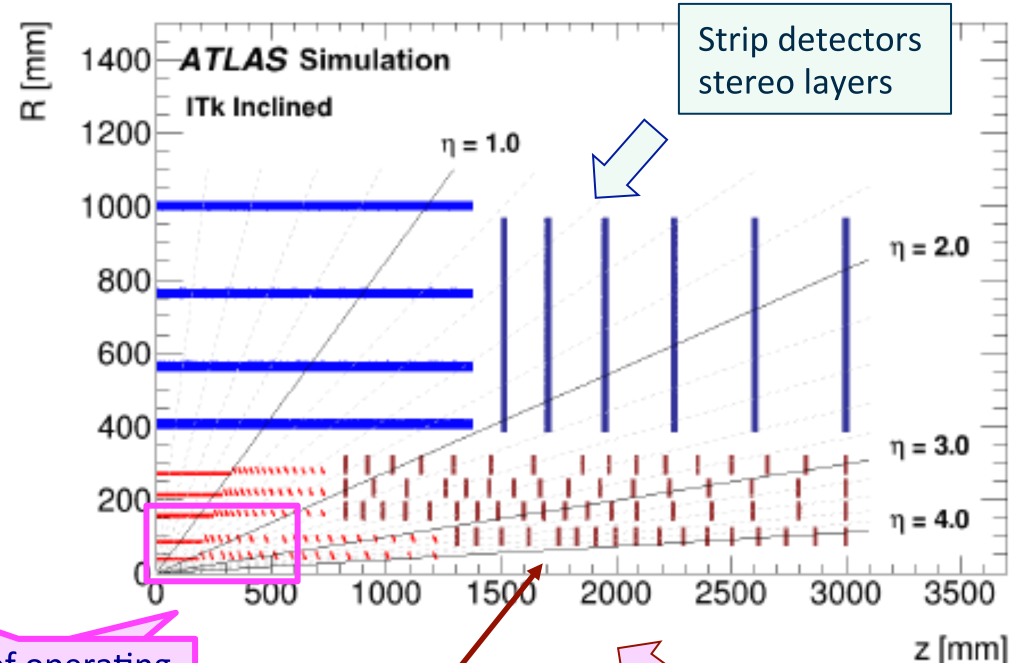
J. Bennet on Saturday

HL-LHC Trackers Upgrade

Ref. 7, 8

- High particle flux:
  - extend pixel layer
  - reduce pixel size
- Full Silicon Trackers
- Extended coverage up to $|\eta|=4$





Strip detectors stereo layers

Pixel sensors

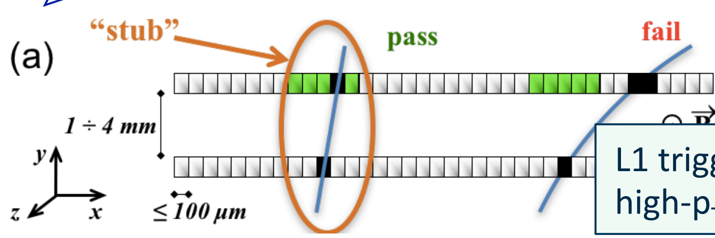
Strip + macro pixel doublets

Strip doublets

Size of operating pixel layers

Rings to optimize position of measurements

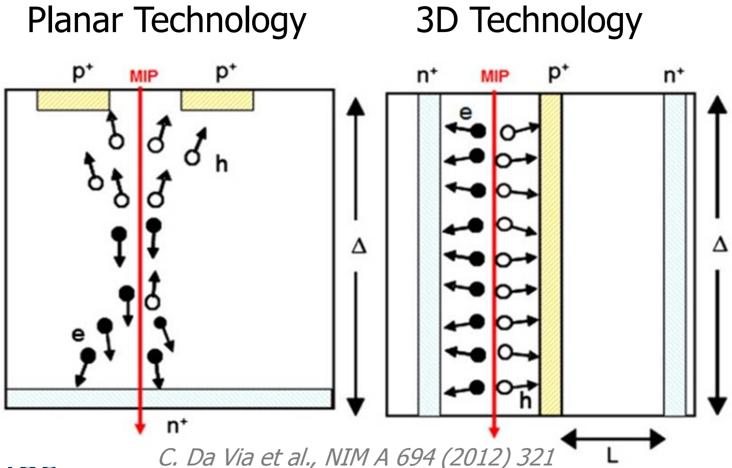
Pixel detectors (prototype with FE-I4)



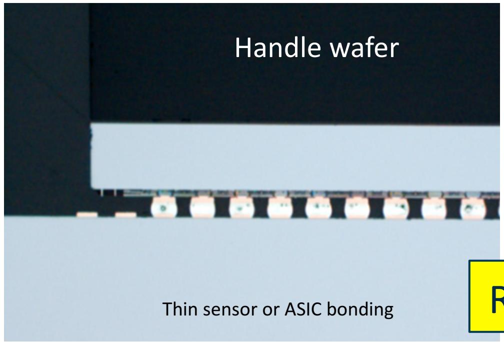
L1 trigger using high-p_T stubs

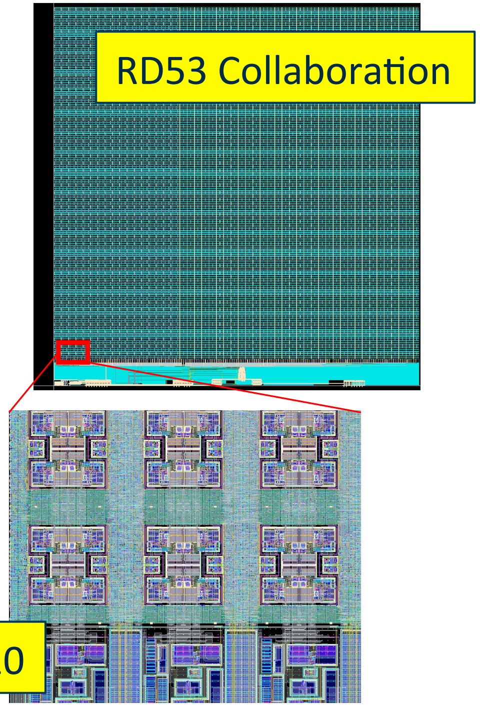
HL-LHC Trackers Upgrade

- Main technologies to cope with high radiation damage:
  - Thin (100-150 μm) planar sensors
    - better signal efficiency
    - lower leakage current
  - 3D sensors:
    - **L<Δ**: can be fully depleted with moderate bias
    - more complex fabrication: potential yield and cost issues
    - **innermost layers**
- Hybrid pixel sensor:
  - Readout chip in TSMC 65 nm CMOS
  - Bump bonding interconnection

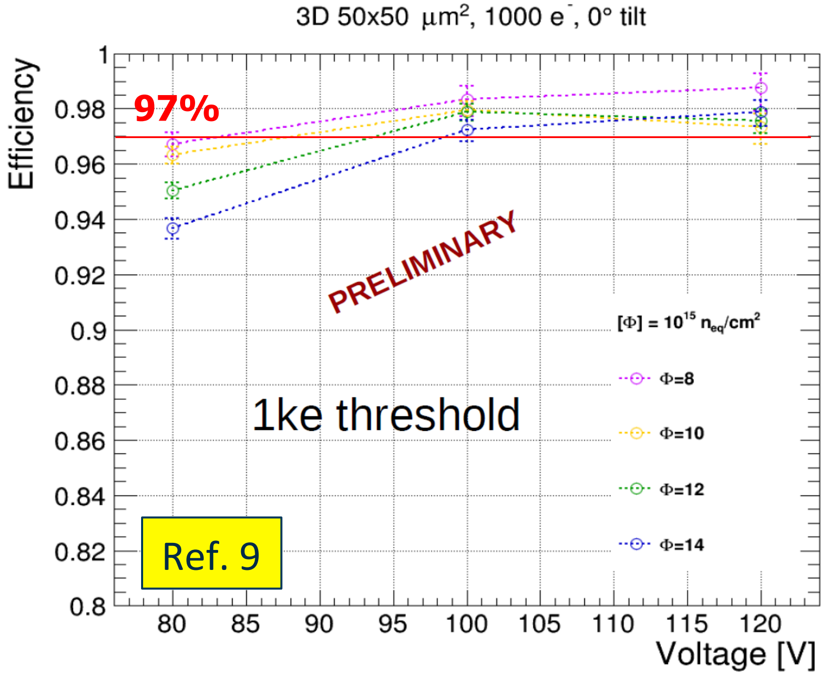


C. Da Via et al., NIM A 694 (2012) 321





Ref. 10



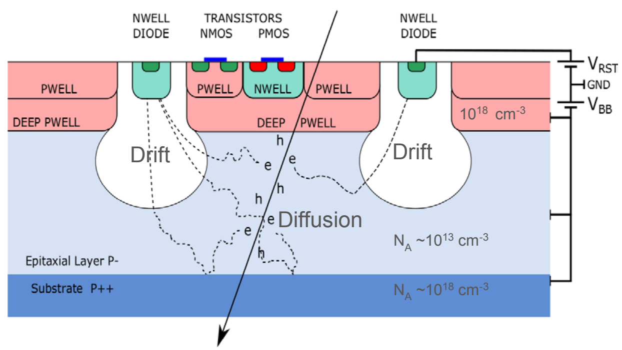
Ref. 9

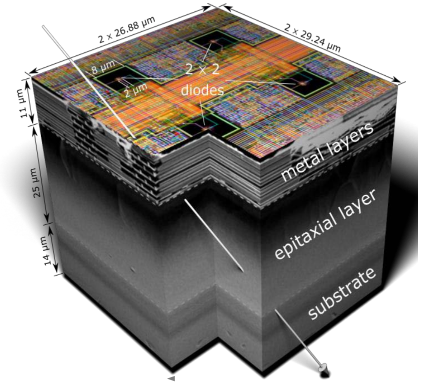
Monolithic Active PixelS

ALICE ALPIDE Ref. 11

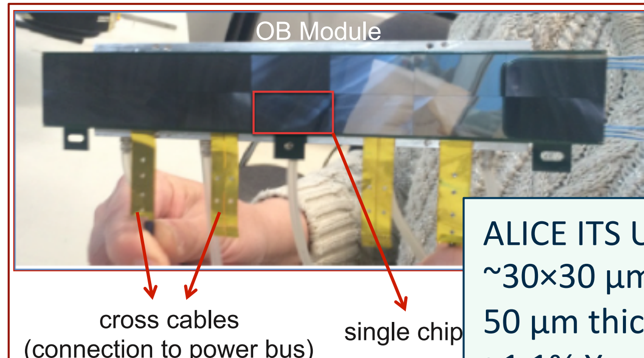
- MAPS are a possible choice for environments with lower rates:
  - Heavy ion experiments: STAR, **ALICE**
  - Interesting for FCC-ee, CepC, ILC, CLIC
- Small multiple scattering term:
  - Low mass detector:
    few tens of μm active region
  - Low power consuption:
    little or no cooling system material

Pixel Sensor produced using TowerJazz 0.18μm CMOS Imaging Process





	RD53	ALPIDE
Pixel size	50 × 50 μm^2 or 25 × 100 μm^2	27 × 29 μm^2
Readout	synchronous	asynchronous
Power	1 W/cm^2	<40 mW/cm^2
Time stamping	25 ns	~2 μs



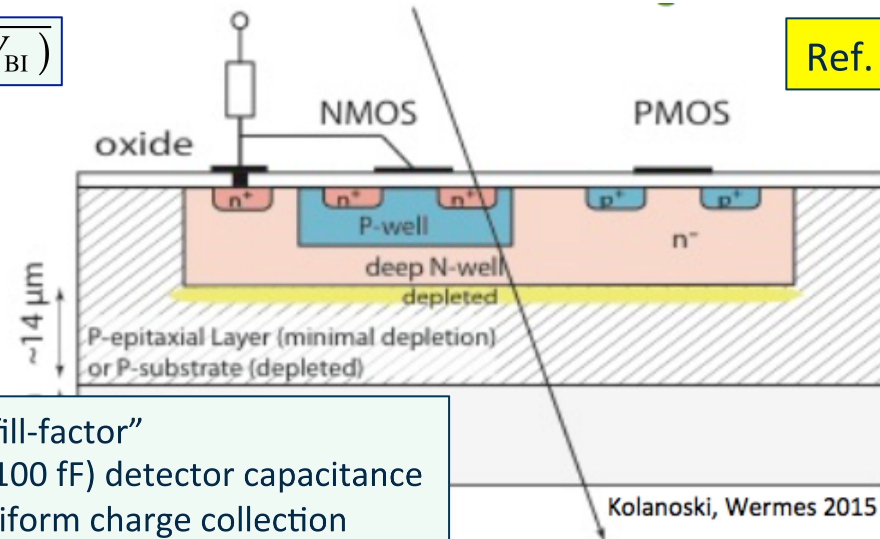
ALICE ITS Upgrade
~30×30 μm^2
50 μm thickness
~1.1% X_0
→ ~0.3 X_0

- Typical requirements for future lepton colliders:
  - point resolution < 3 μm → pixel size < 10 μm
  - material < 0.15% X_0/layer

Depleted Monolithic Active PixelS

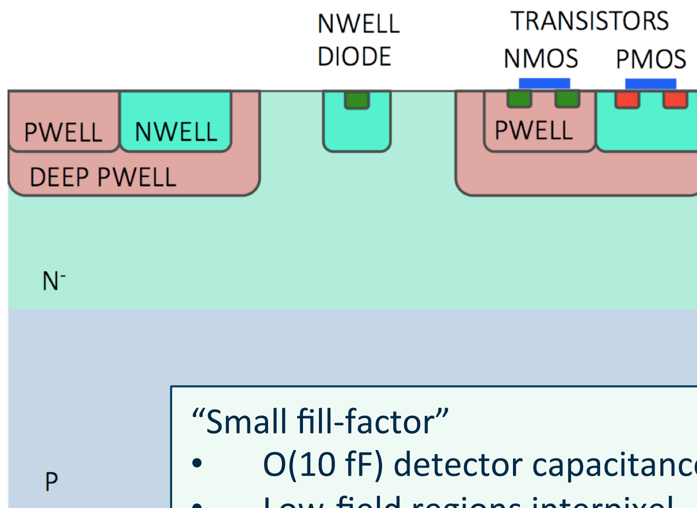
- **MAPS+Depleted Layers** $d = \sqrt{\varepsilon_{Si}\varepsilon_0\mu_{carrier}\rho(V+V_{BI})}$
  - **Collection by drift: faster, less trapping**
- High Voltage processes
  - Availability of processes with high voltage capability, driven by automotive and power management applications
- High Resistivity substrates
  - Foundries accepting/qualifying wafers or epitaxial substrates with mid-high resistivity
- 130-180 nm feature size
  - deep submicron technologies needed for the design of radiation hard electronics
  - multiple-well process to decouple front-end electronics from the sensitive region
- *Also SOI processes* Ref. 14

Ref. 12



"Large fill-factor"
- O(100 fF) detector capacitance
- Uniform charge collection

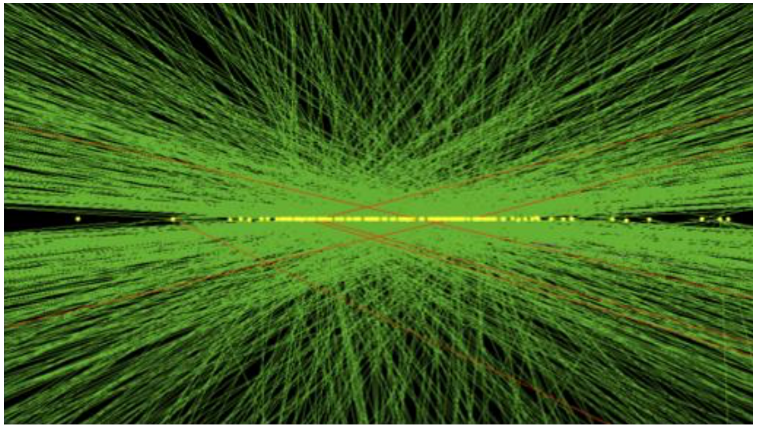
Ref. 13

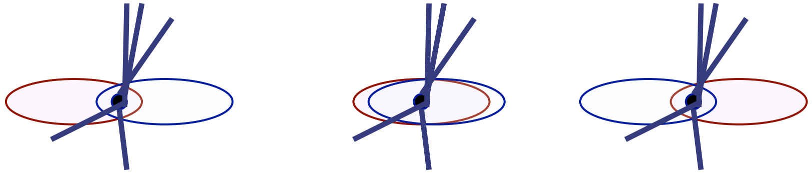


"Small fill-factor"
- O(10 fF) detector capacitance
- Low-field regions interpixel
- Special processing to improve performance

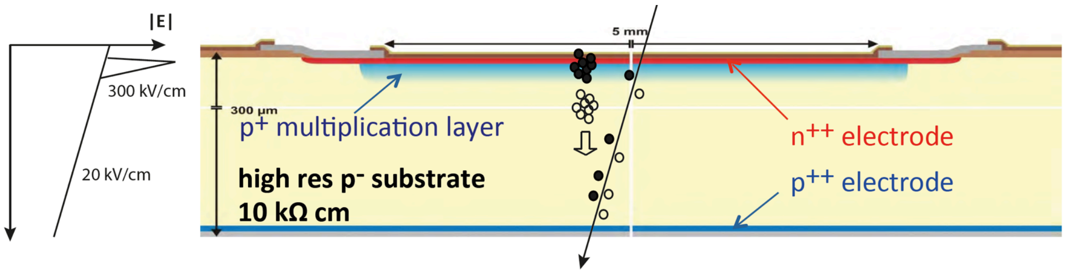
Timing and pileup

- With increasing rate of multiple interactions, individual pile up events cannot be anymore separated spatially
- But some separation can be achieved by precise timing information:
  - Events in the same position can be displaced in time by $$\sigma_t = \frac{\sigma_z}{c} \approx \frac{5\ \text{cm}}{c} \approx 180\ \text{ps}$$
  - State-of-art is NA62 GigaTracker σ_t≈200 ps





- Need to achieve σ_t=10-30 ps
- **Low Gain Avalanche Diodes** Ref. 15
  - exploit local amplification in silicon to increase **d*V*/dt**



$$\sigma_t^2 = \underbrace{\left(\frac{V_{th}}{dV/dt}\bigg|_{rms} \right)^2}_{\sigma^2_{\text{time walk}}} + \underbrace{\left(\frac{\text{Noise}}{dV/dt} \right)^2}_{\sigma^2_{\text{noise}}} + \sigma^2_{\text{arrival}} + \sigma^2_{\text{dist}} + \sigma^2_{\text{TDC}}$$

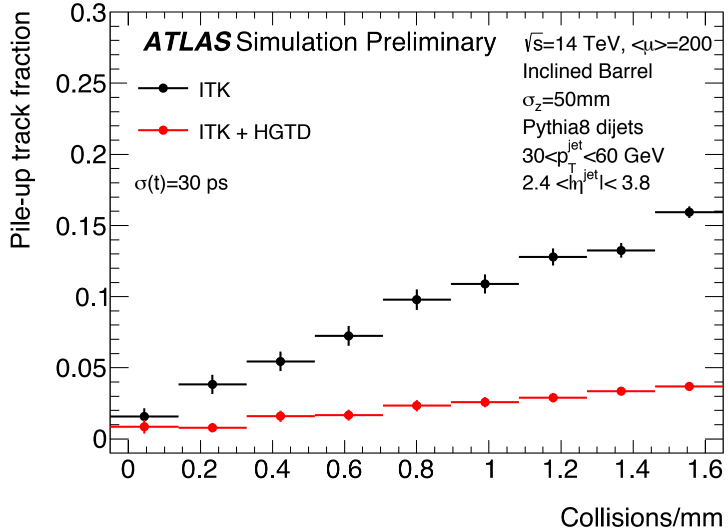
arrival fluct. — distortion low w-field

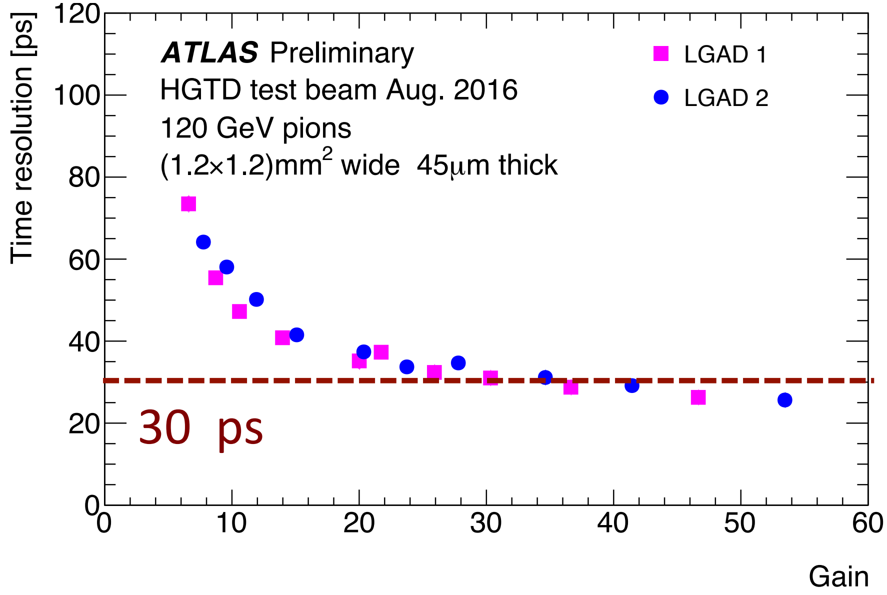
  - Radiation hardness still to be addressed (acceptor removal affects the multiplication layer)

ATLAS High Granularity Time Detector

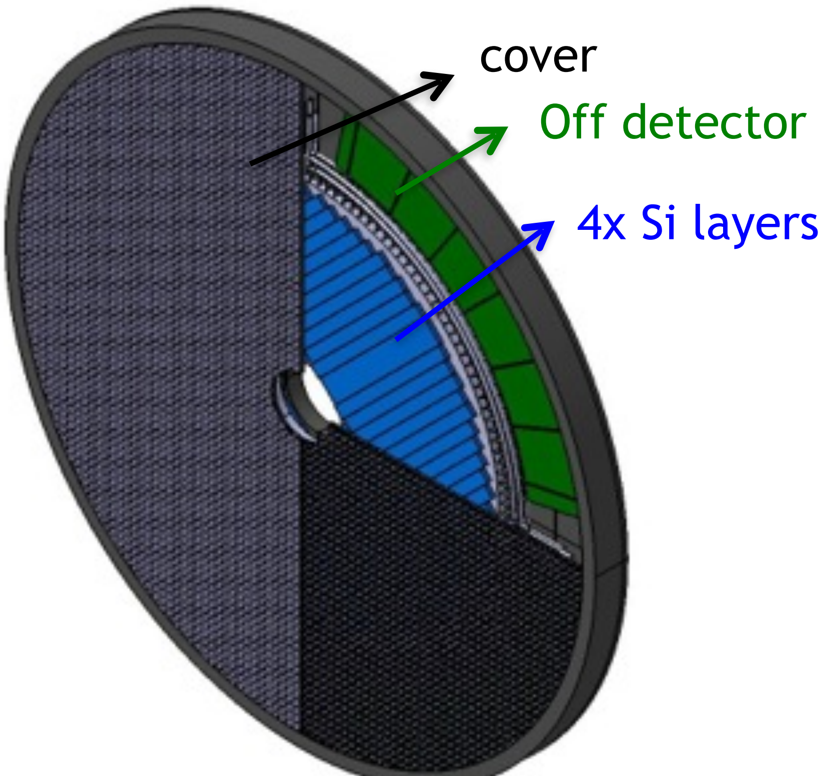
Ref. 16

Tracks in jets, σ_t = 30 ps





- Identify pileup track at $2.4<|\eta|<4.2$
  - tracking loose discriminating power
- 4 layers of LGAD, 1×1 mm^2
- Option for a W absorber (3 X_0)



Large volume / moderate density environment:

- central tracking of lepton collider, heavy ions experiments
- muon systems

TRACKING WITH GAS DETECTORS

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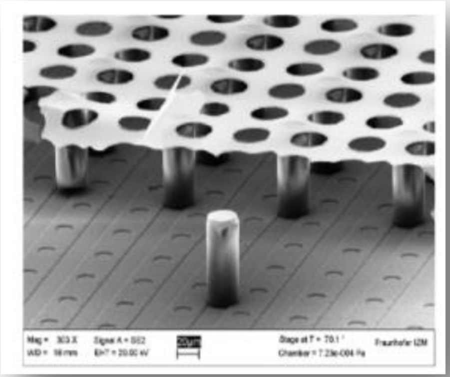
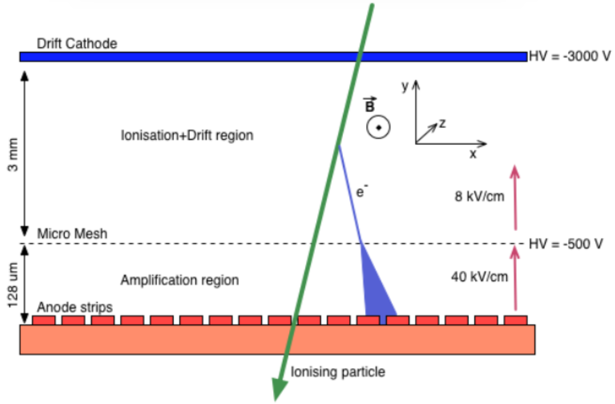
Micro-Pattern Gas Detector

Micromegas - Meshes

Giomataris (1998)

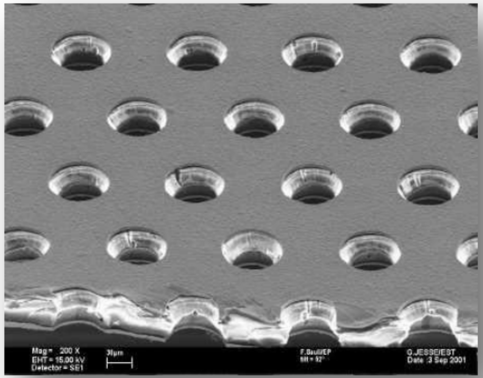




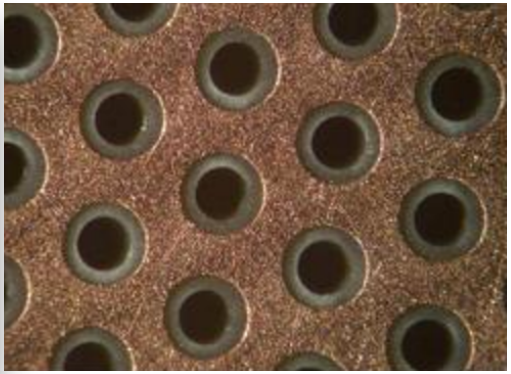
http://garfieldpp.web.cern.ch/garfieldpp/examples/mmlowenergypion/

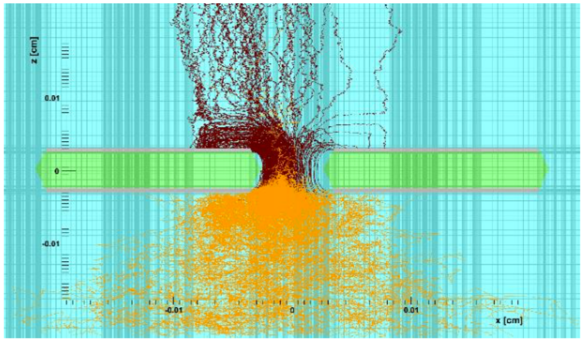
GEM/THGEM - holes

Sauli (1997)



Breskin (2004)
10 fold larger than GEM





http://www-flc.desy.de/tpc/projects/GEM_simulation/

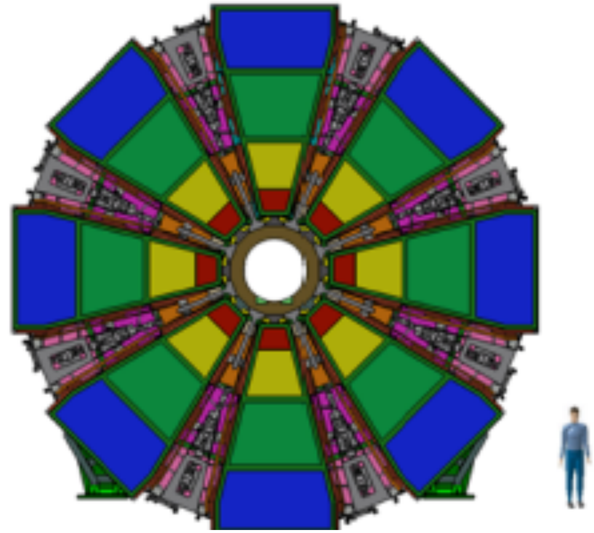
- Separation between drift and multiplication region
- Flexible techniques that can provide multiple incarnations

RD51 Collaboration

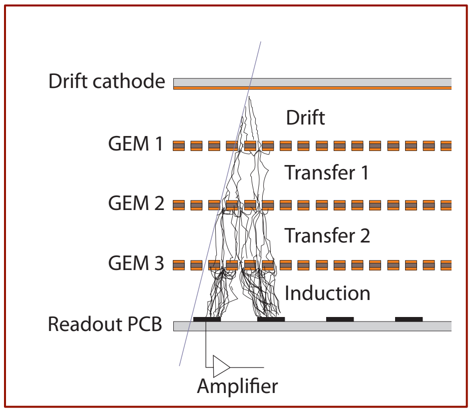
S. Bressler @ TIPP 2017

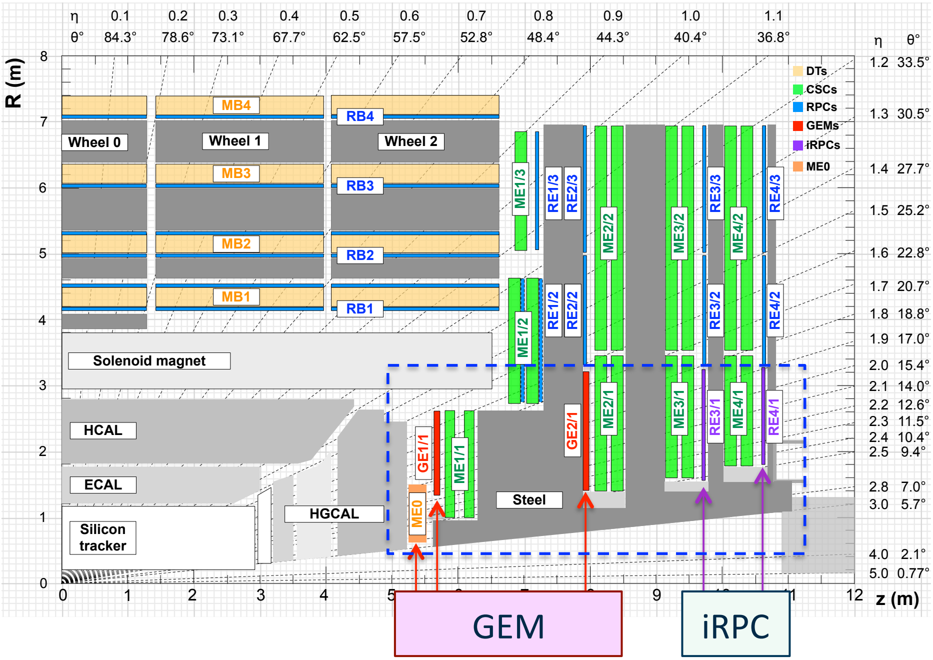
LHC Muon Systems upgrades

- ATLAS New Small Wheels Ref. 18
  - Cope with 15 kHz/cm^2
  - Tracking: 15% pT resolution at 1 TeV
  - Trigger: muon direction online with 1 mrad resolution
  - 8 layers of Thin Gap Chamber (trigger) and 8 of MicroMegas
  - 1200 m^2 / 2.4M readout channels



- CMS Ref. 19
  - Increase robustness in forward reagio
  - Rate 10 kHz/cm^2
  - Triple GEM amplification

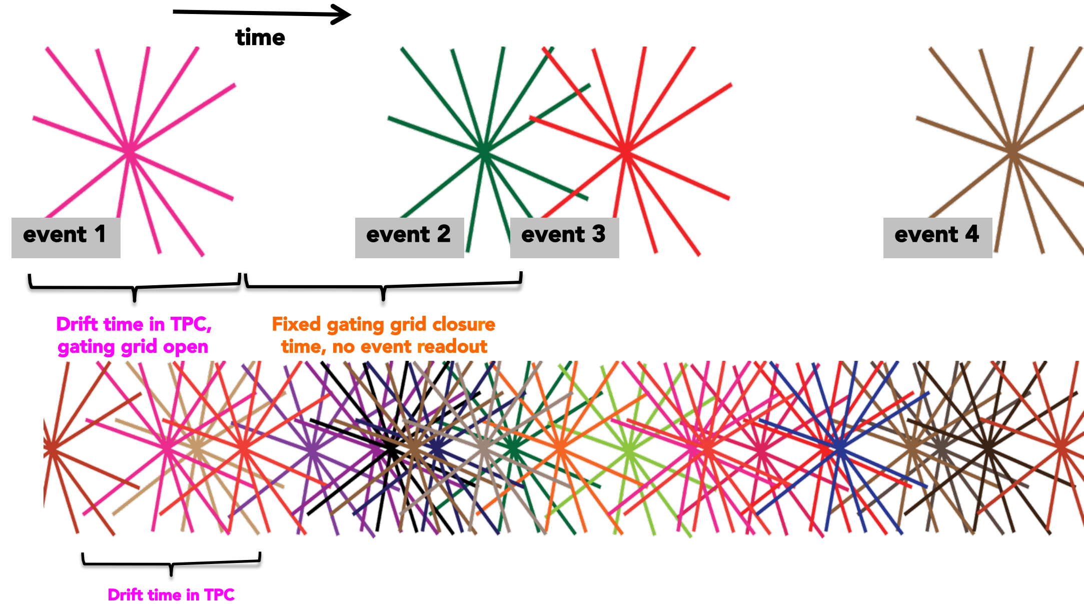


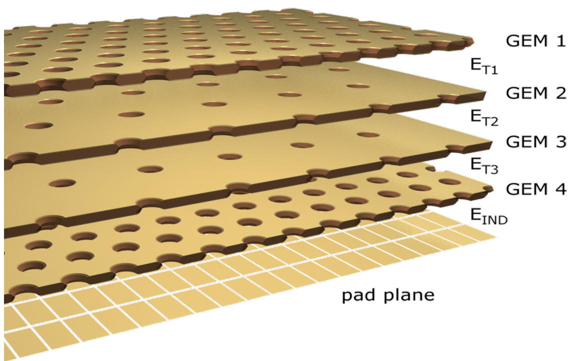


ALICE TPC continuous readout

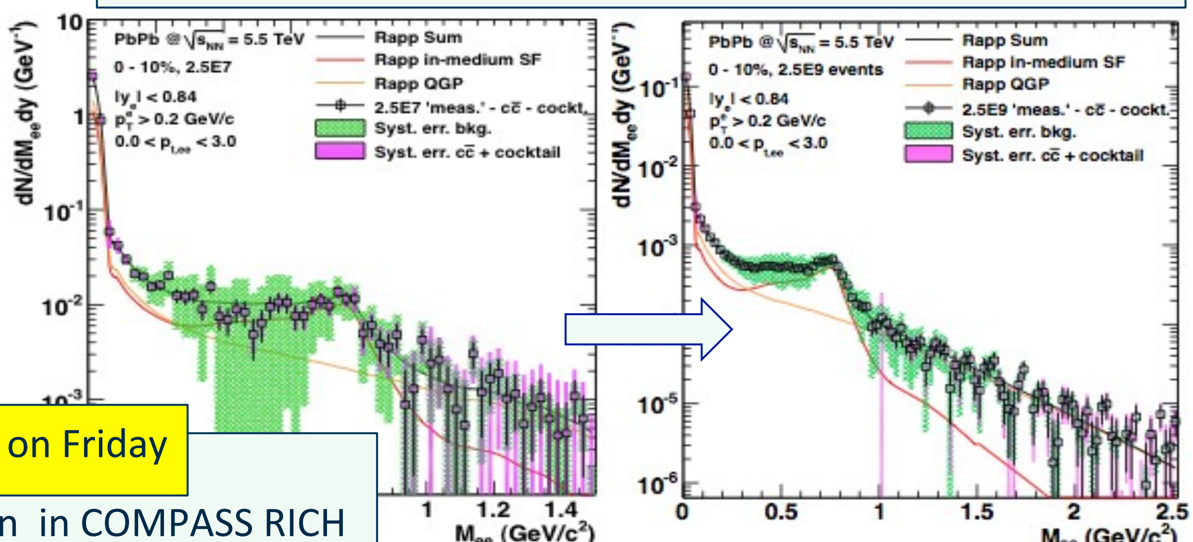
Ref. 20

- Typical operation mode for TPC:
  - MWPC readout planes
  - Gating grid to avoid ion backflow (10^{-5} suppression)
  - Rate limitation few kHz
- At Run3 many events will overlap
- Multiple GEM stacks
  - ion backflow <1%
  - maintaining good dE/dx resolution
  - continuous readout!





Run 1 Low-mass dileptons Run3 (expected)



Alco considered for ILC and CepC

H. Qi on Friday

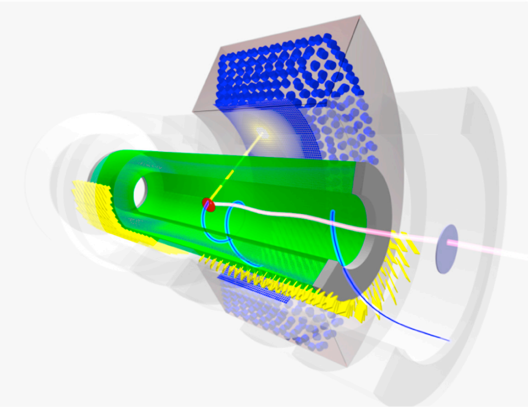
MPGD readout (GEM+MM) photon detector in in COMPASS RICH

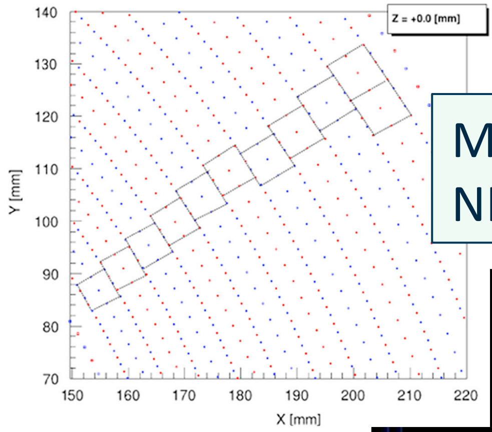
Drift Chambers

- Drift chambers continue to be attractive detectors for low material systems

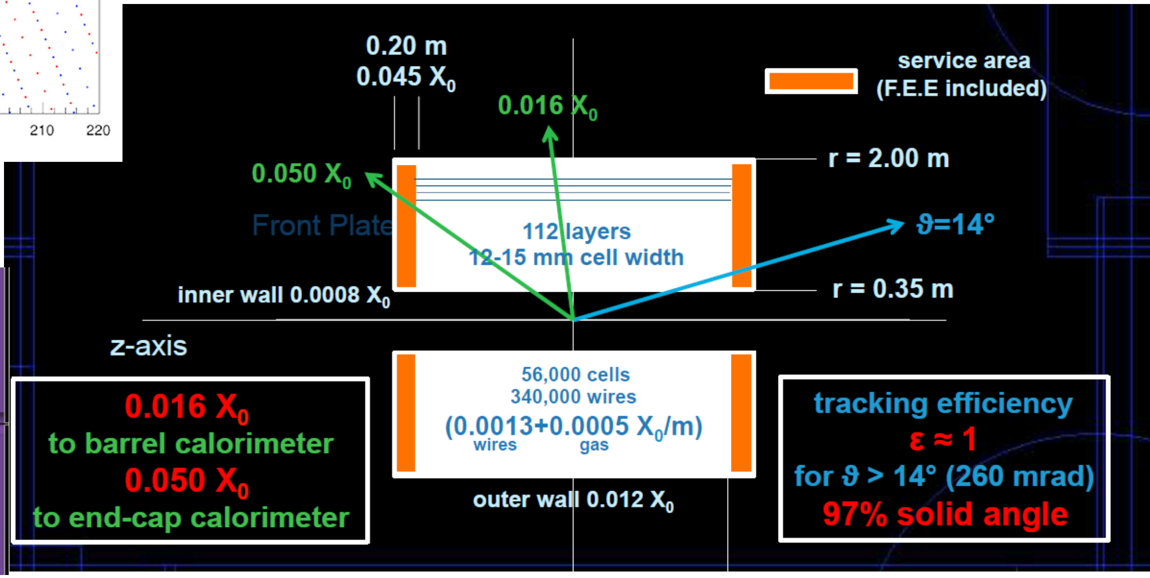
BELLE II

J. Bennet on Saturday



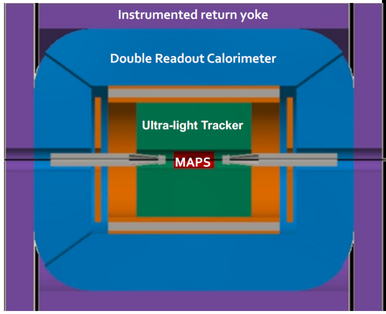


MEG drift Chamber
NIM A824 589—591



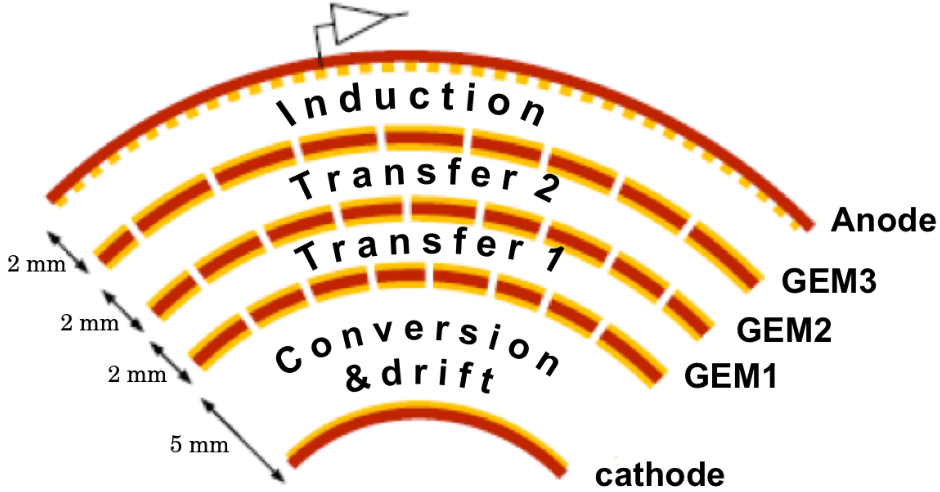
IDEA detector
FCC-ee, BepC

Ref. 22

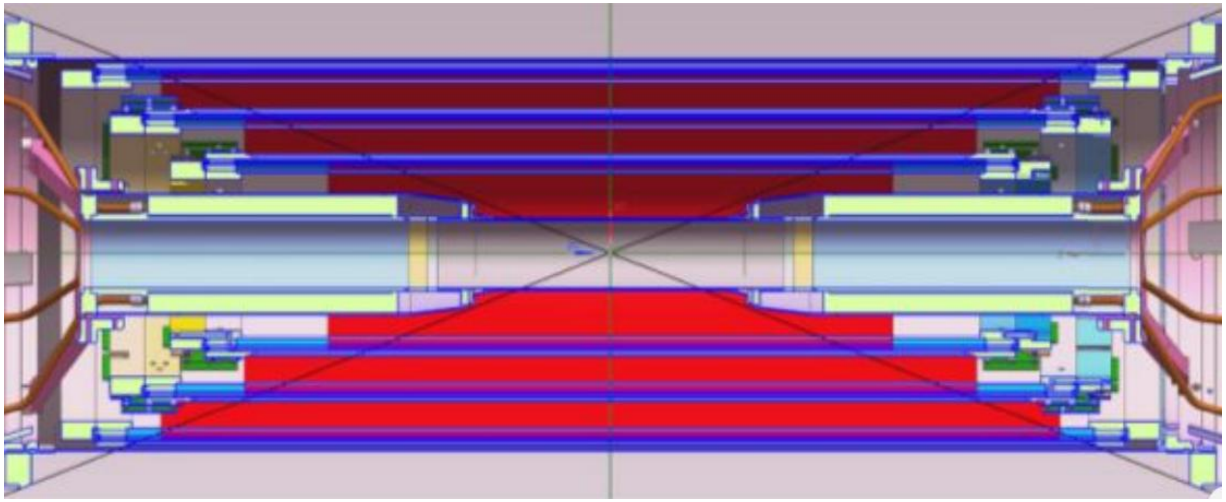


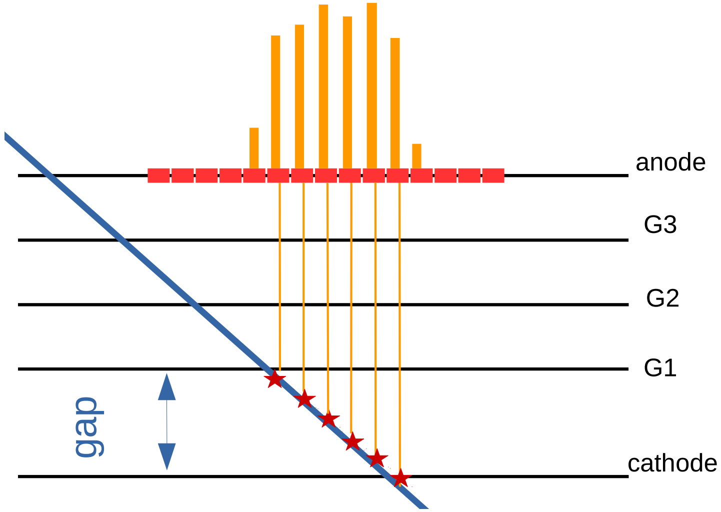
Cylindrical GEMs

L. Lavezzi on Sunday



- Support internal layers of drift chamber:
  - KLOE-2 @ DAFNE, **BESIII Upgrade @Beijing**, CLAS12 @JLAB, ASACUSA @CERN, MINOS @FERMILAB, CMD-3 Upgrade @ BINP
- Possibile to implement stereo readout on anode
- Timing on electrode: µTPC mode





The quest for higher granularity:

- **in space and time**

and for the ultimate hadron jet energy resolution

CALORIMETRY

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HL-LHC Calorimetry upgrades

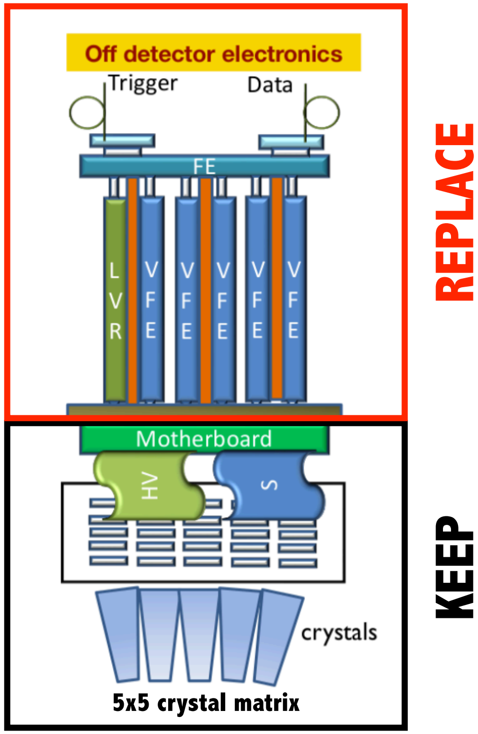
- Calorimeters are a structural asset of an experiment
- Most of the sensors capable to cope with aging and radiation at the HL-LHC
- Upgrade of the readout electronics can improve performance for the more demanding HL-LHC conditions:
  - increase data bandwidth (more information: timing, granularity)
  - trigger algorithms on off-detector high performance FPGAs

- **CMS barrel ECAL**

  D. A. Petyt and P. Meridiani on Saturday

  - $PbWO_4$ crystals APD readout:
  - **Run with colder APD:** 18 °C → 9 °C, 35% noise reduction
  - **New Very Front End cards**
    - reduce shaping time
    - local digitization

    Target 30 ps time resolution
  - **New Front-End cards**
    - Streaming of data: Single channel data link at 160 MHz
  - **Off-detector signal processing, with full granularity**

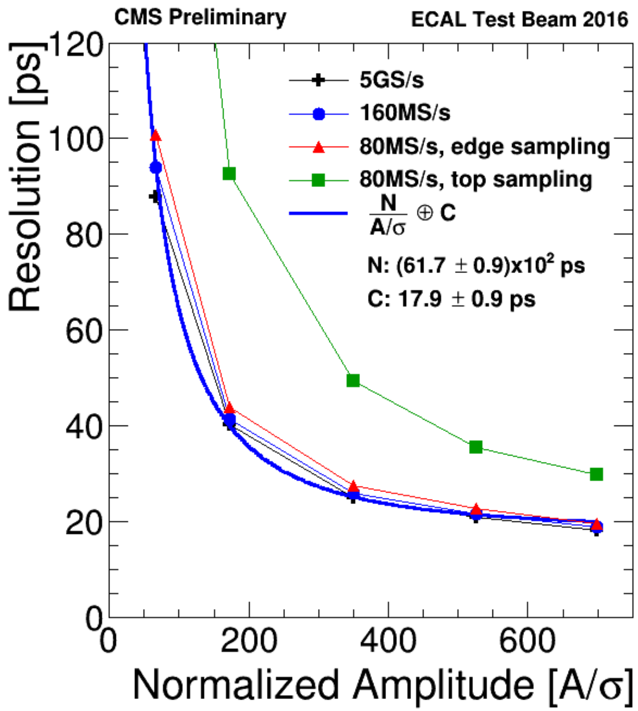


Similar plans for ATLAS LAr and Tile calorimeters

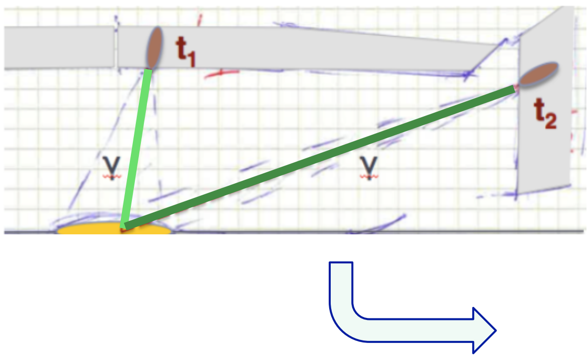
Ref. 27-28

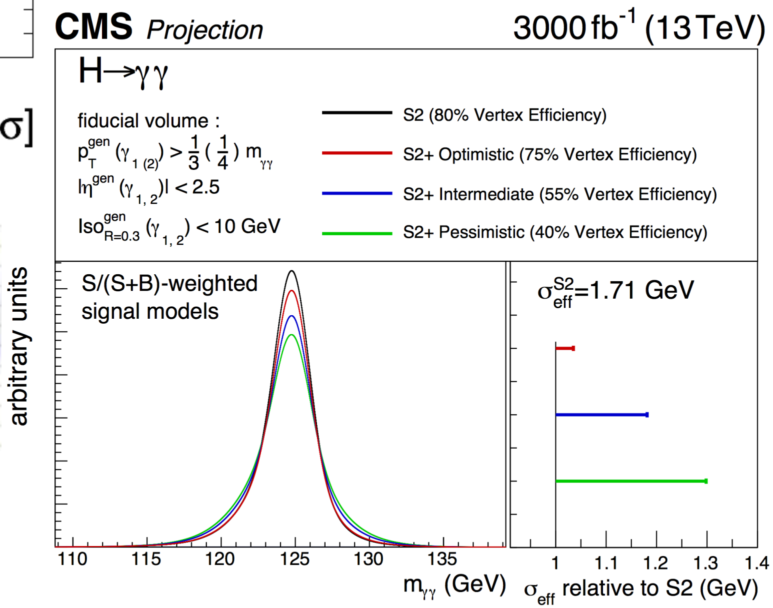
CMS ECAL upgrade

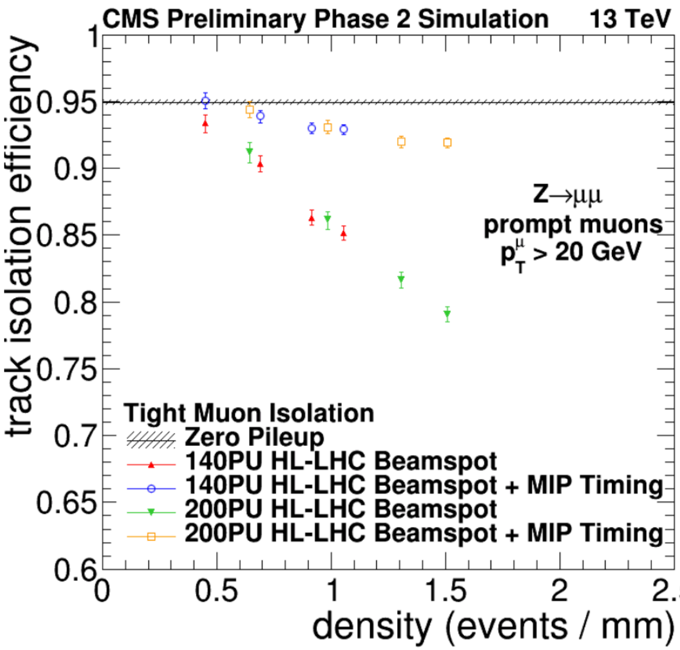
D. A. Petyt and P. Meridiani on Saturday



- Combination of faster shaping time and 160 MS/s allows to reach the 30 ps resolution
  - achieved in 2016 testbeams
  - provide performance at 200 pileup HL-LHC similar to the ones of LHC running
  - need to ensure it at the whole system level





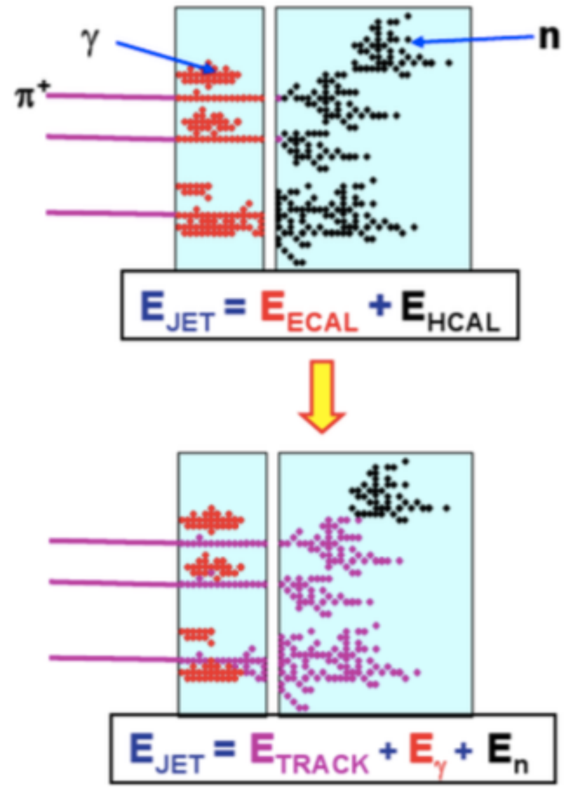


Jet reconstruction in e^+e^- experiments

- A requirement for high-precision physics at e^+e^-colliders is $W \rightarrow jj$ / $Z \rightarrow jj$ separation.
  - 3 — 4% jet energy resolution at 50 GeV

Ref. 29

- Particle-Flow:
  - jet energy sharing:
    - ≈60% charged particles → **central tracker**
    - ≈30% photons → **electromagnetic calorimeter**
    - ≈10% neutral hadron → **hadronic calorimeter**
    - **90% of the energy may be obtained from high precision measurements**
  - requires complex reconstruction algorithms
    - very high granularity detectors to reconstruct the shower development

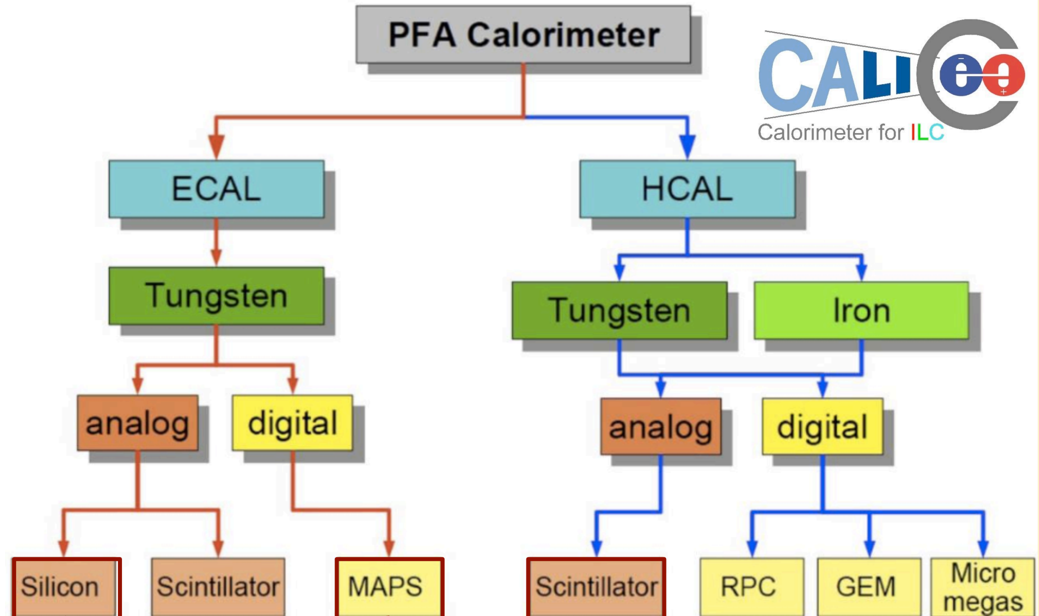


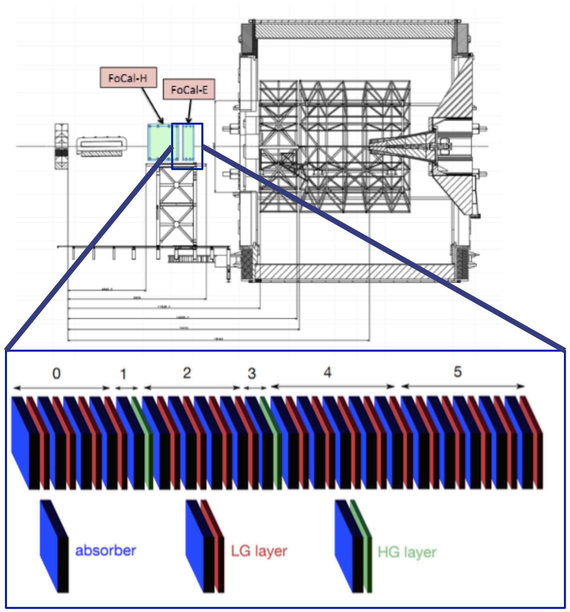
- Dual readout:
  - determine e.m. and had. components of hadronic showers by reading out two different signals (for example: **scintillation** and **Cherenkov** light)

High-Granularity Calorimeters

Ref. 30

- R&D by CALICE Collaboration (**Calorimeter for ILC**)
  - different technologies explored
  - reconstruction algorithms
  - Baseline for ILD (RPC) and SiD (Si-W)
  - concepts now being applied also to current experiments!

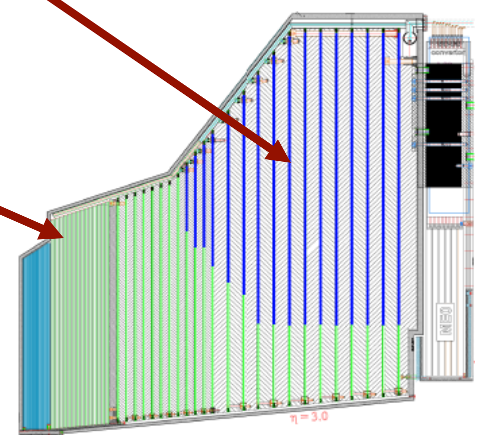




ALICE FoCAL
- **3.5 mm W absorbers**
  - 1 X_0
  - R_M 9.3 mm
- **Low Granularity layers**
  - Si Pad 1×1 cm^2
- **High Granularity layers**
  - CMOS Maps 30×30 μm^2
- Few mm 2-particle separation

Ref. 31

CMS HGCal
- Replacement for forward ECAL
- **Silicon** + Cu, W, Pb
  - 28 layers
  - 25 X_0 ~1.3 λ
- **Scintillators** and **Silicon** + Steel
  - 24 layers, 8.5 λ

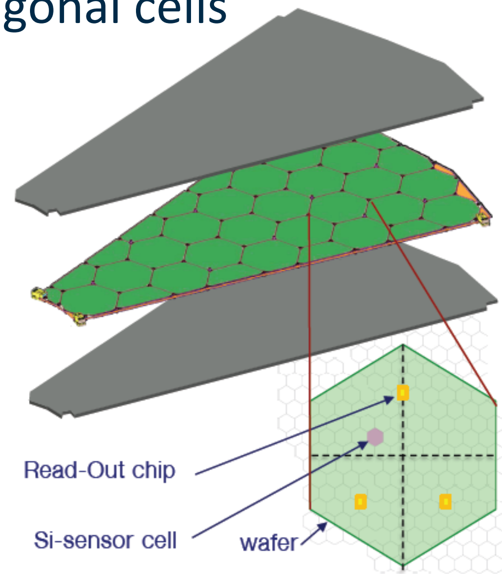


L. Mastrolorenzo and S. Jain on Saturday

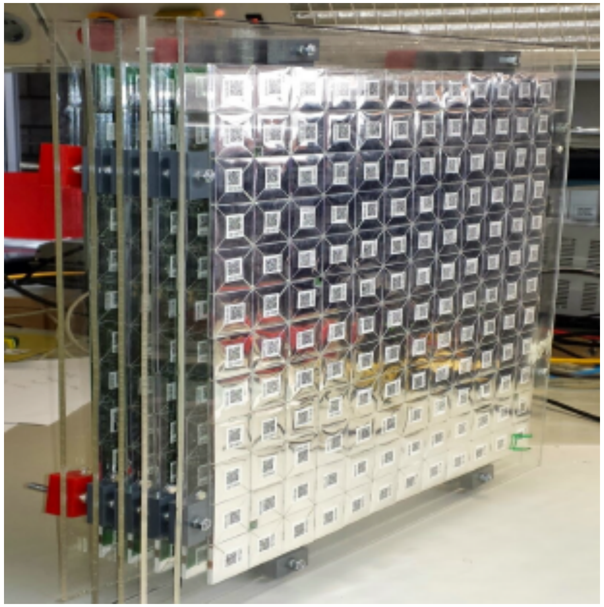
CMS HGCal for HL-LHC

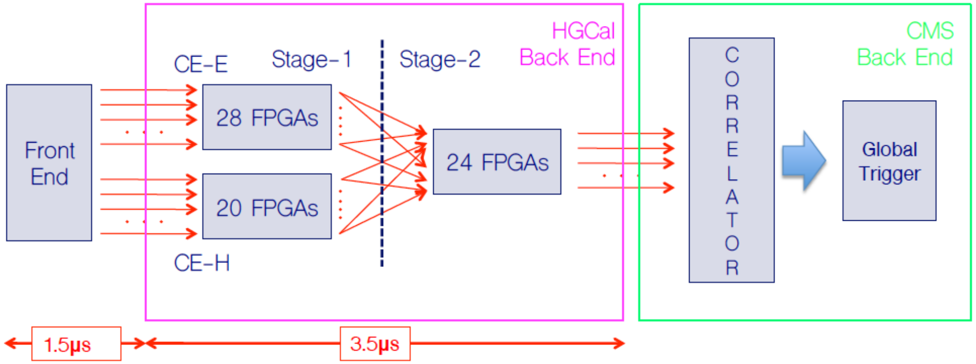
L. Mastrolorenzo and S. Jain on Saturday

- **Silicon sections**
  - hexagonal modules (from 8” wafers)
  - thickness 100—300 µm
  - 0.5-1.0 cm^2 hexagonal cells
  - 11-bit ADC/TOT
  - Time of Arrival O(50 ps)



- **Scintillator-SiPM section**
  - 3×3 cm scintillator tiles
  - interleaved with steel plates





- **Level-1 trigger**
  - Trigger cells in FE chip
  - 2D (1st stage) and 3D (2nd stage) clusterization on FPGS (Vitrtex7)
  - **Trigger decision in 5 µs**

Dual Readout Approach

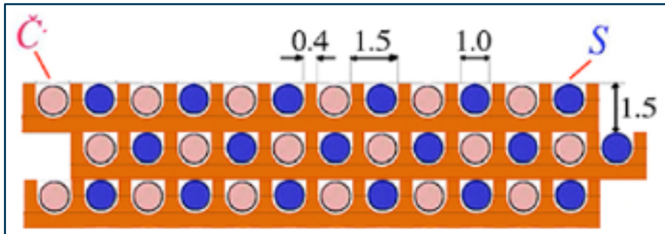
- RD52 – DREAM
  (**D**ual **REA**dout **M**ethod)
  - Scintillation light:
    d*E*/dx of charged particles
  - Cherenkov light:
    from *e*, e.m. component of shower

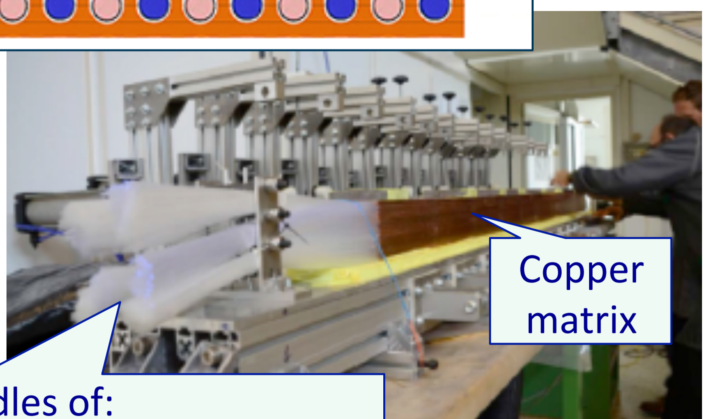
Test beam results and simulations show a 30%/√*E* resolution can be achieved for a 4π detector.

Under study readout with SiPM (instead of PM):

- more compact readout
- it allows longitudinal segmentation and operation in magnetic field
- higher granularity

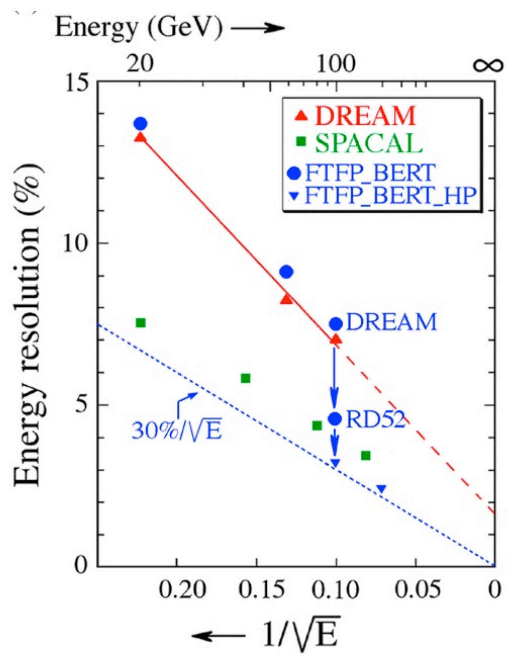
Proposed for IDEA detector at FCC-ee



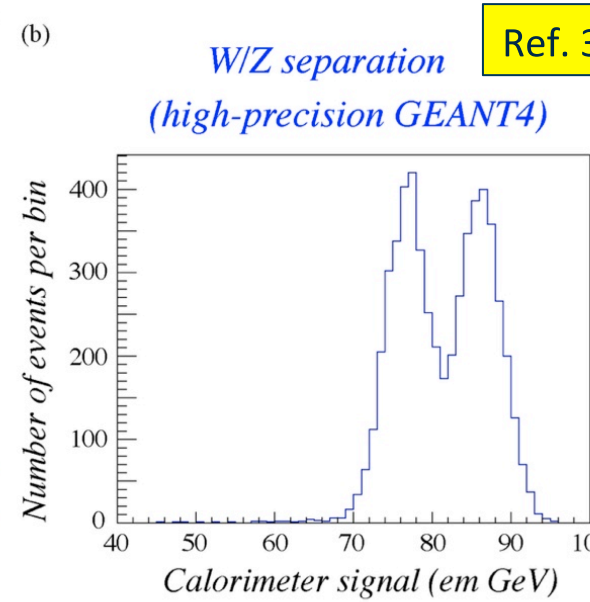


Copper matrix

Bundles of:
- Scinitillating fibers
- Cerenkov fibers

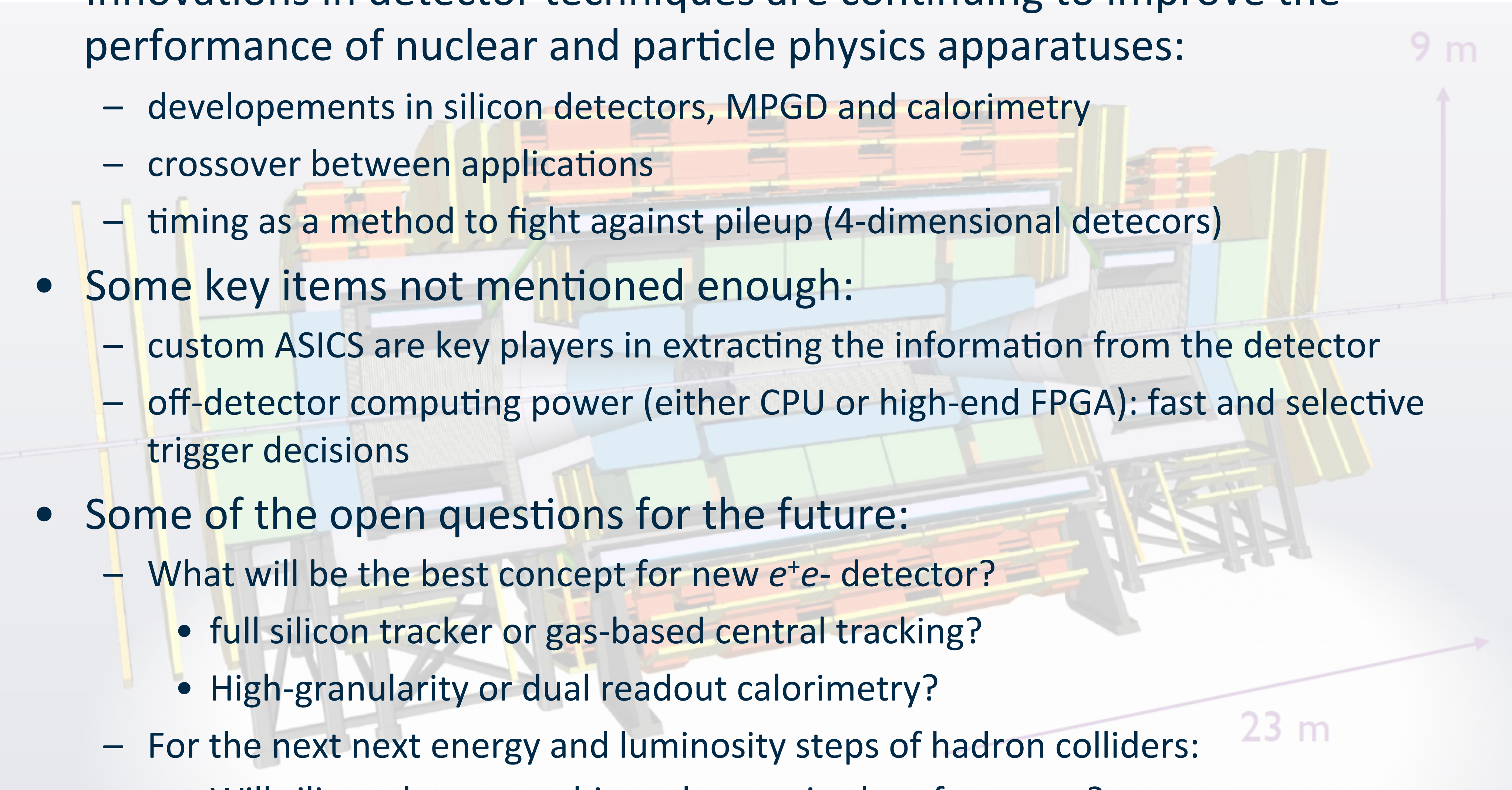


Ref. 34



Summary and outlook

- Innovations in detector techniques are continuing to improve the performance of nuclear and particle physics apparatuses:
  - developements in silicon detectors, MPGD and calorimetry
  - crossover between applications
  - timing as a method to fight against pileup (4-dimensional detecors)
- Some key items not mentioned enough:
  - custom ASICS are key players in extracting the information from the detector
  - off-detector computing power (either CPU or high-end FPGA): fast and selective trigger decisions
- Some of the open questions for the future:
  - What will be the best concept for new $e^{+}e$- detector?
    - full silicon tracker or gas-based central tracking?
    - High-granularity or dual readout calorimetry?
  - For the next next energy and luminosity steps of hadron colliders:
    - Will silicon detector achieve the required performance?
    - Which technology for high rate muon system?



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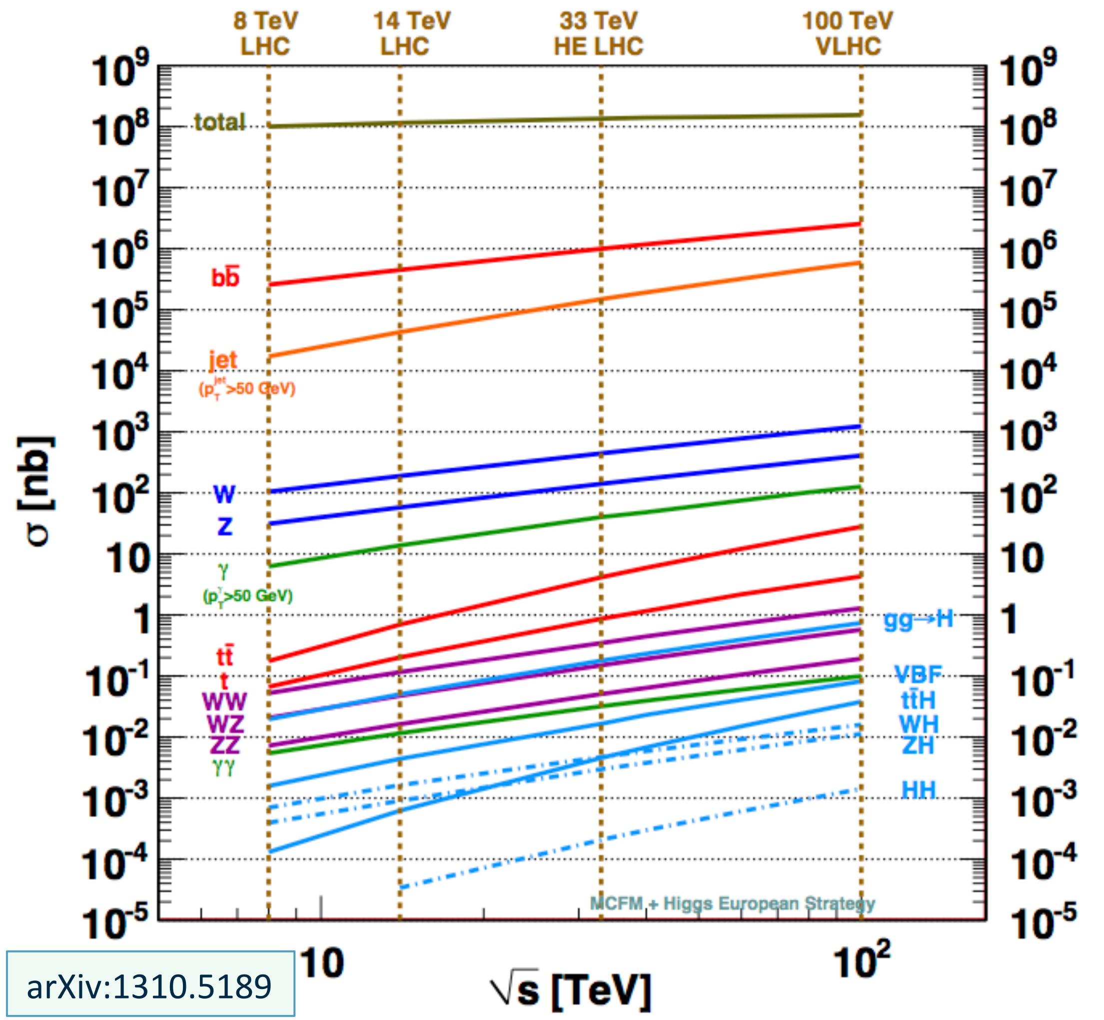
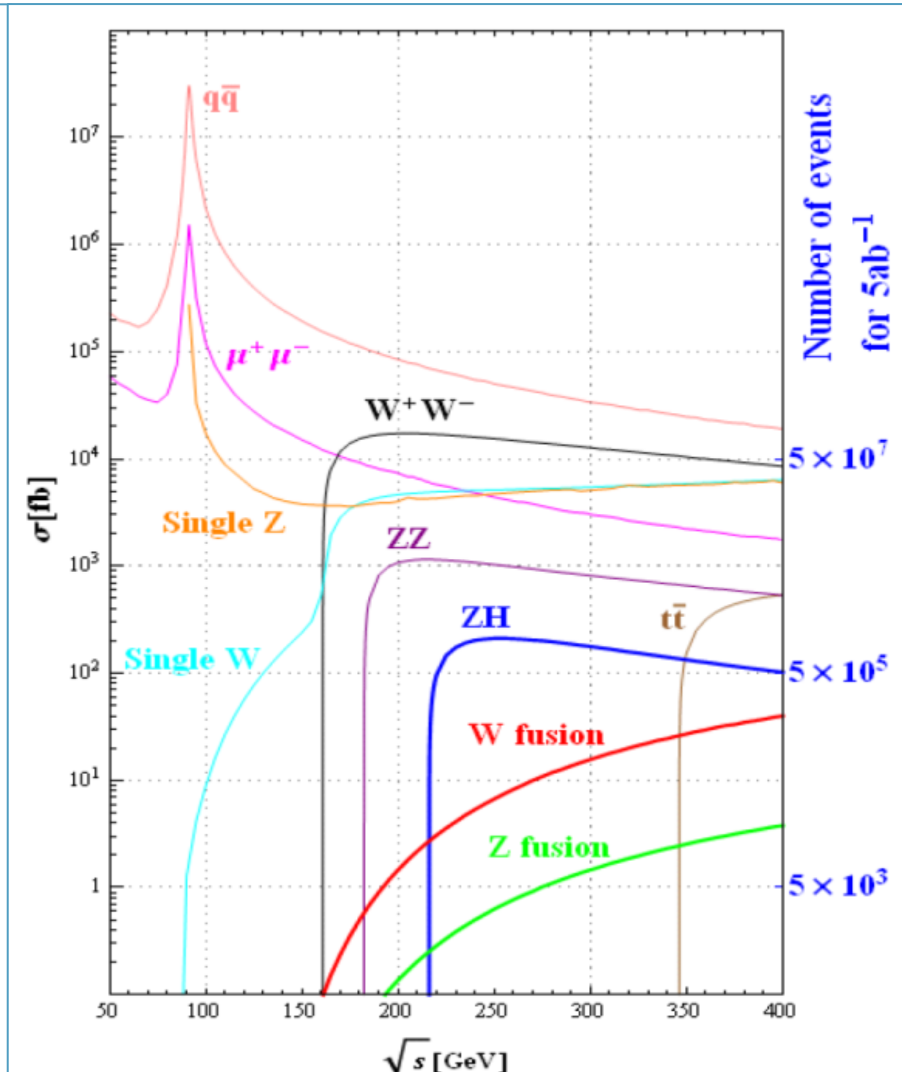
BACKUP

pp and ee Cross Section

- pp+ee interaction cross sections



arXiv:1310.5189



Linear collider detector needs

Eva Sicking @ TIPP2017

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons

  → $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\,\text{GeV}^{-1}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios

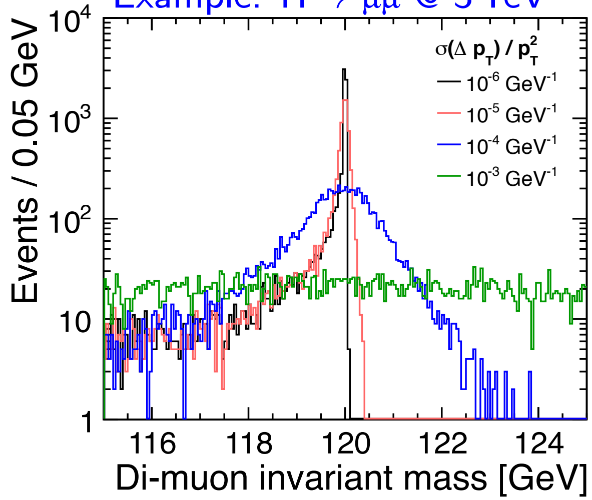
  → $\sigma_{r\varphi} \sim a \oplus b/(p[\text{GeV}] \sin^{\frac{3}{2}} \theta)\,\mu\text{m}$
  - $a = 5\,\mu\text{m}$, $b = 10 - 15\,\mu\text{m}$
- Jet energy resolution
  - Separation of W/Z/H di-jets

  → $\sigma_E/E \sim 3.5\%$ for jets at 50-1000 GeV
- Angular coverage
  - Very forward electron and photon tagging

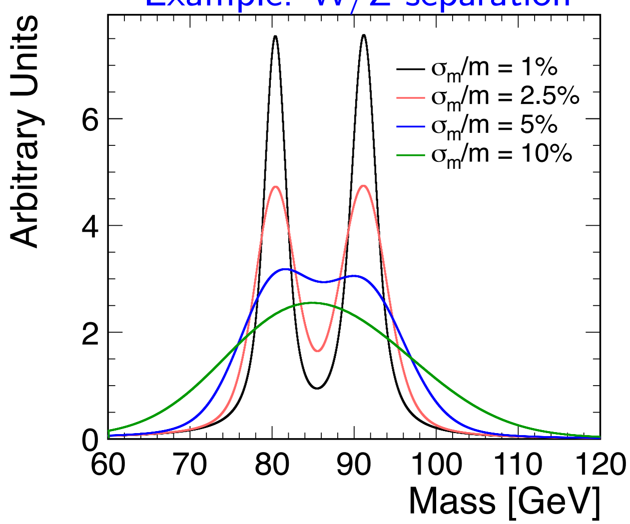
  → Down to $\theta = 10$ mrad ($\eta = 5.3$)
- Requirements from beam structure and beam-induced background

→ Note: Ongoing study to re-define needs for precision measurements

Example: H→ μμ @ 3 TeV

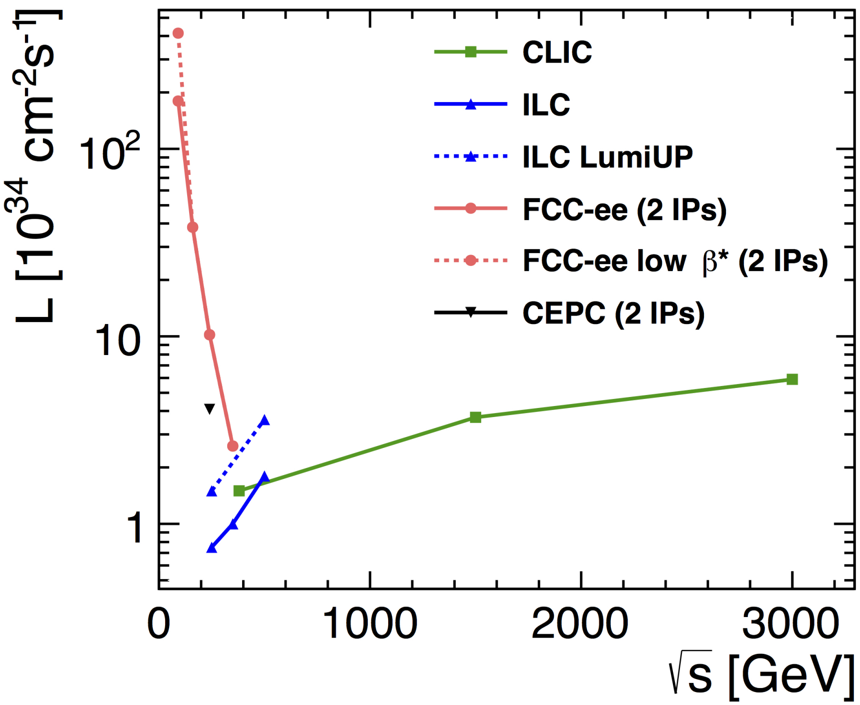


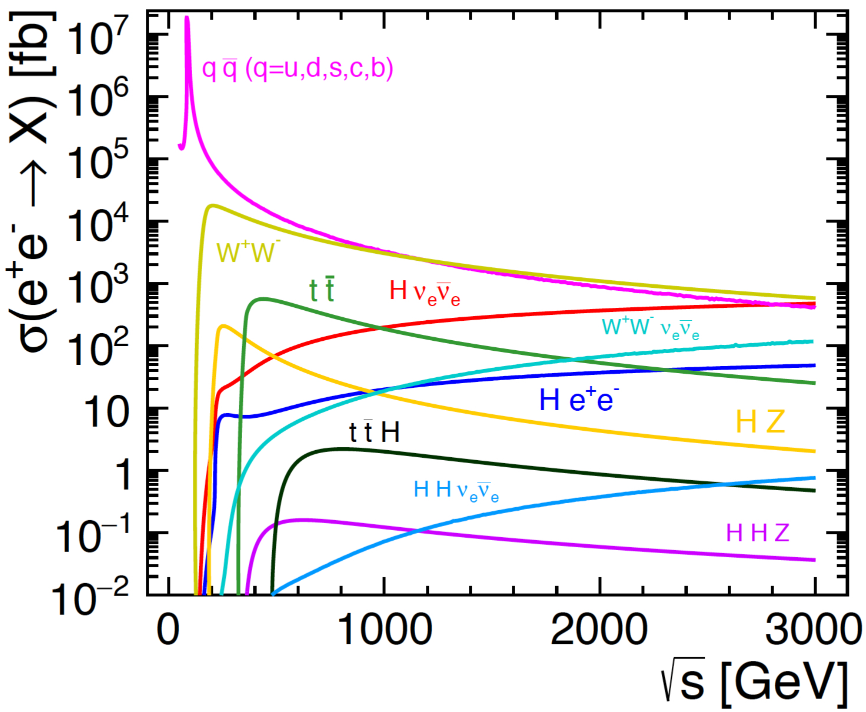
Example: W/Z separation



Energy reach → physics programmes

Eva Sicking @ TIPP2017





- Physics programmes focus on **precision measurements** of
  - FCC-ee: Z, W, Higgs, top
  - CEPC: Higgs (Z, W under discussion)
  - ILC: Higgs, top, direct high-mass BSM searches
  - CLIC: Higgs, top, direct high-mass BSM searches

FCC-ee and CepC parameter lists

	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population [10^{11}]	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm]	0.267	0.26	0.61	1.33, 2.03
Vertical emittance ε [pm]	1.0	1.0	1.2	2.66, 3.1
Momentum comp. [10^{-6}]	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP				
- Horizontal β^* [m]	0.15	0.20	0.5	1
- Vertical β^* [mm]	0.8	1	1.2	2
Horizontal beam size at IP σ^* [μm]	6.3	7.2	17	45
Vertical beam size at IP σ^* [nm]	28	32	38	79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%]				
- Synchrotron radiation	0.038	0.066	0.10	0.145
- Total (including BS)	0.130	0.153	0.14	0.194
Bunch length [mm]				
- Synchrotron radiation	3.5	3.27	3.1	2.4
- Total	11.2	7.65	4.4	3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor $H(L_i)$	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	215	31.0	7.9	1.5
Beam-beam parameter				
- Horizontal	0.004	0.007	0.033	0.092
- Vertical	0.134	0.126	0.141	0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

Parameters for CEPC double ring for CDR Goal

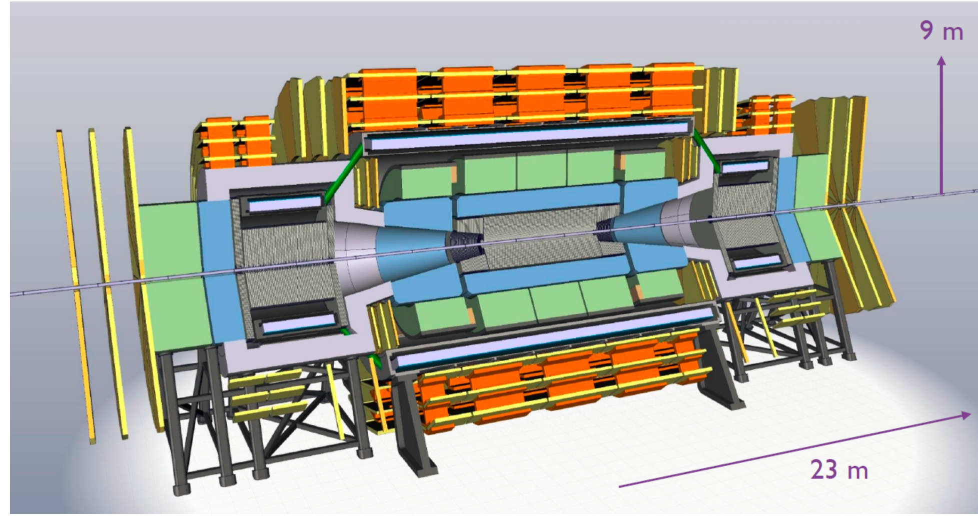
（wangdou20170426-100km_2mmβy）

	Pre-CDR	***Higgs***	***W***	***Z***	
Number of IPs	2	2	2	2	
Energy (GeV)	120	120	80	45.5	
Circumference (km)	54	100	100	100	
SR loss/turn (GeV)	3.1	1.67	0.33	0.034	
Half crossing angle (mrad)	0	16.5	16.5	16.5	
Piwinski angle	0	3.19	5.69	4.29	11.77
N_e/bunch (10^{11})	3.79	0.968	0.365	0.455	0.307
Bunch number	50	412	5534	21300	2770
Beam current (mA)	16.6	19.2	97.1	465.8	408.7
SR power /beam (MW)	51.7	**32**	**32**	**16.1**	**1.4**
Bending radius (km)	6.1	11	11	11	11
Momentum compaction (10^{-5})	3.4	1.14	1.14	4.49	1.14
β_{IP} x/y (m)	0.8/0.0012	0.171/0.002	0.171 /0.002	0.16/0.002	0.171 /0.002
Emittance x/y (nm)	6.12/0.018	1.31/0.004	0.57/0.0017	1.48/0.0078	0.18/0.0037
Transverse σ_{IP} (um)	69.97/0.15	15.0/0.089	9.9/0.059	15.4/0.125	5.6/0.086
ξ_x/ξ_y/IP	0.118/0.083	0.013/0.083	0.0055/0.062	0.008/0.054	0.006/0.054
RF Phase (degree)	153.0	128	126.9	165.3	136.2
V_{RF} (GV)	6.87	**2.1**	**0.41**	**0.14**	**0.05**
f_{RF} (MHz) (harmonic)	650	650	650 (217800)	650 (217800)	
Nature σ_z (mm)	2.14	**2.72**	**3.37**	**3.97**	**3.83**
Total σ_z (mm)	2.65	2.9	3.4	4.0	4.0
HOM power/cavity (kw)	3.6 (5cell)	0.41(2cell)	0.36(2cell)	1.99(2cell)	0.12(2cell)
Energy spread (%)	0.13	0.098	0.065	0.037	
Energy acceptance (%)	2	1.5			
Energy acceptance by RF (%)	6	2.1	1.1	1.1	0.68
n_γ	0.23	0.26	0.15	0.12	0.22
Life time due to beamstrahlung_cal (minute)	47	52			
F (hour glass)	0.68	0.96	0.98	0.96	0.99
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	2.0	5.15	11.9	1.1

Experimental conditions

Ref. 1 –3

- Hadron colliders
  - inelastic p-p cross-section 100—120 mb
  - luminosity 7—30 $\times 10^{34}$ cm^{-2}s^{-1}
  - **pileup** 200—1000 interactions in 25 ns
  - radiation hardness

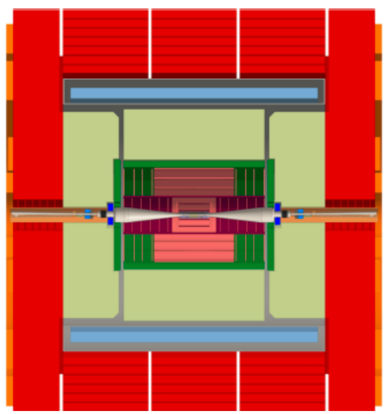


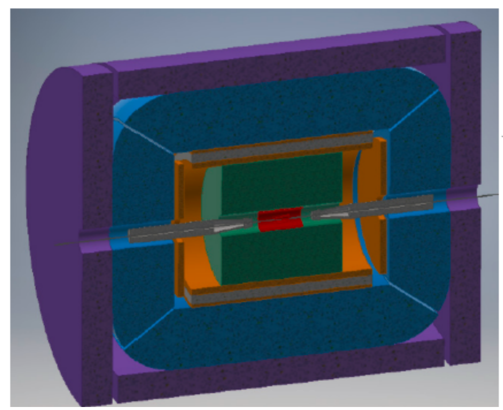
- Lepton colliders - Emphasis on high precision, even at low p_T (for LHC standards)
  - cross section: 30 nb (Z peak) – 100 fb (high energy processes like ZH, tt)
  - luminosity: 1—20 $\times 10^{34}$ cm^{-2}s^{-1}

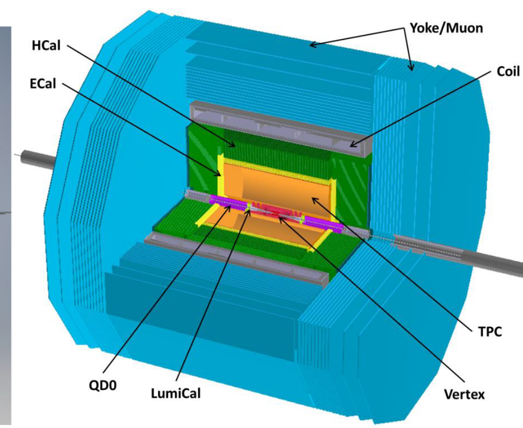
$$\sigma_{d_0} = 5 \oplus \frac{10-15}{p[\mathrm{GeV}]\sin^{3/2}\theta}\ \mu\mathrm{m}$$

$$\sigma_{1/p} = 2-5\times 10^{-5}\,\mathrm{GeV}^{-1}$$

$$\frac{\sigma_E}{E} = 3-4\%\ \text{at} \sim 40\ \mathrm{GeV}$$



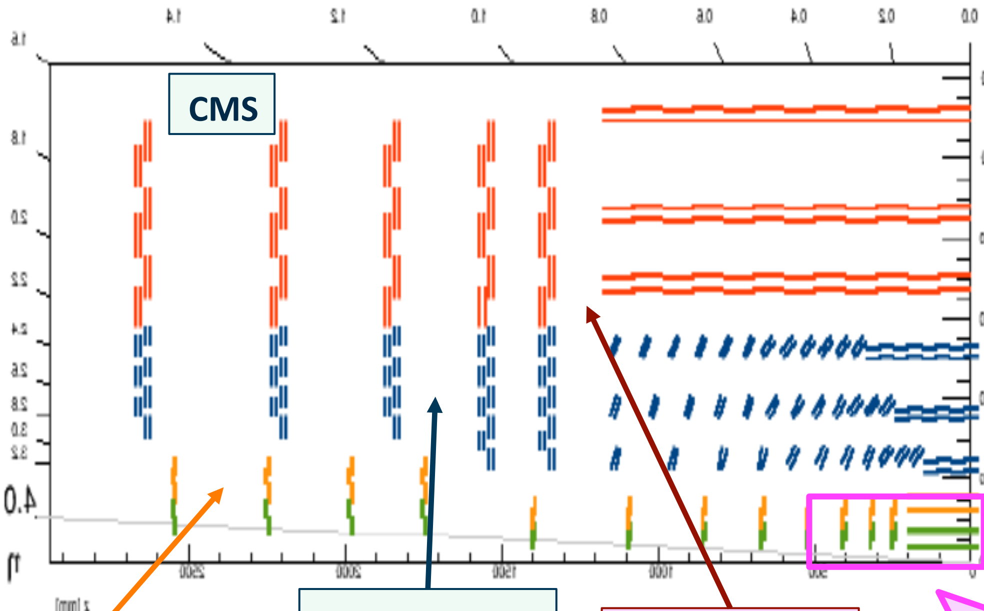


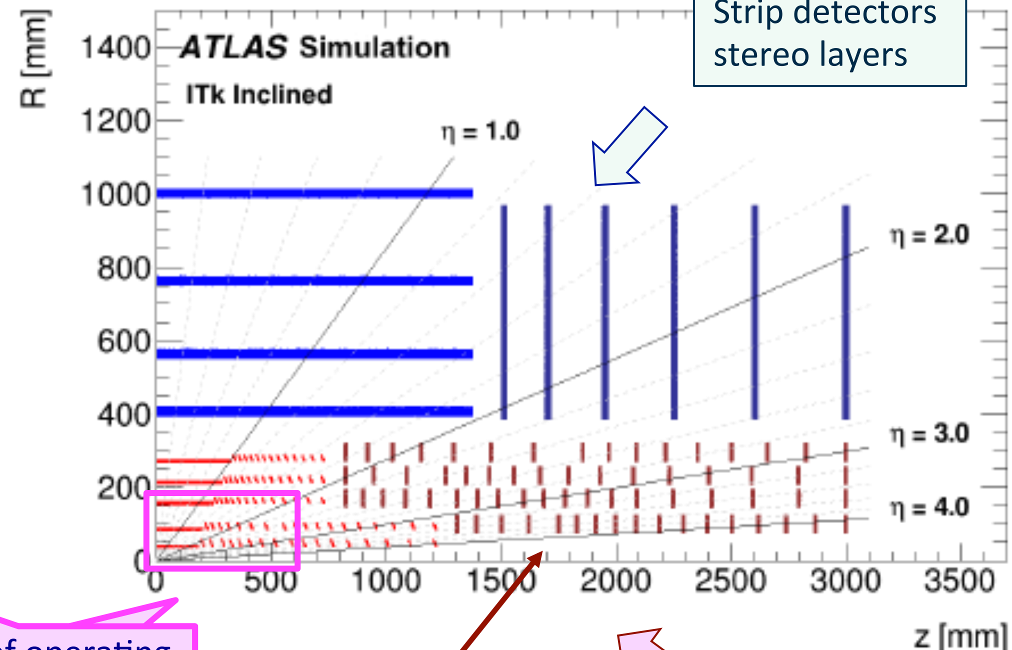


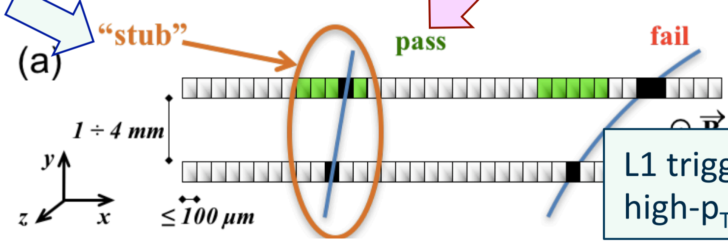
HL-LHC Trackers Upgrade

Ref. #

- High particle flux:
  - extend pixel layer
  - reduce pixel size
- Full Silicon Trackers
- Extended coverage up to $|\eta|=4$

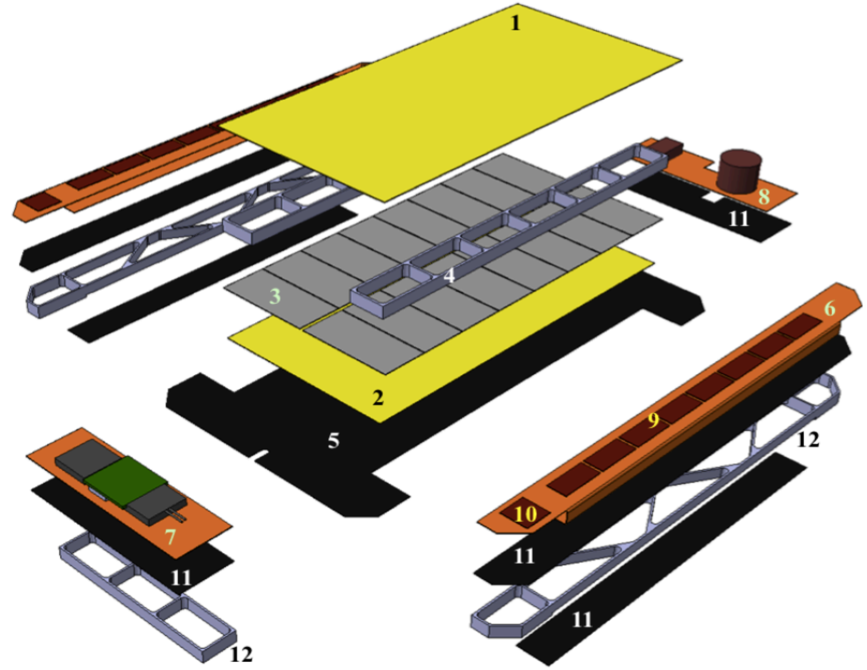


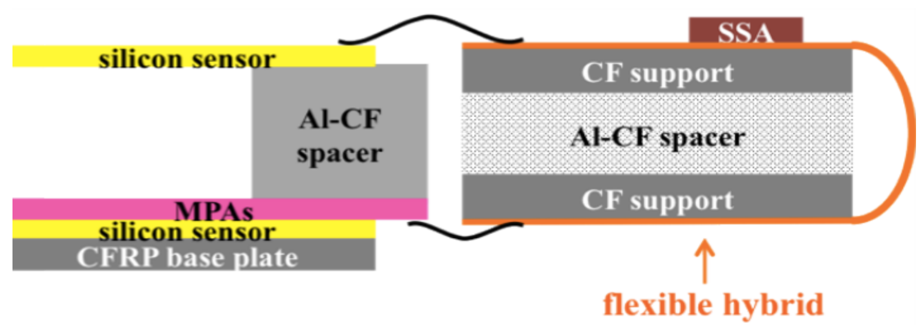




p_T modules: PS module

- **One silicon strip sensor (PS-s) and one silicon macro pixel sensor (PS-p) stacked** [pic. #1, #2]
  - AC-coupled PS-s: 2.4 cm x 100 µm
  - DC-coupled PS-p: 1.5 mm x 100 µm
- **Front-end electronics:**
  - PS-s readout → Short Strip ASIC (SSA)
  - PS-p readout → Macro Pixel ASIC (MPA)
    - ➢ Bump bonded to PS-p
    - ➢ Performs hit correlation
    - ➢ Cooling via carbon fibre reinforced polymer (CFRP) base plate [pic. #5]
  - Concentrator ASIC (CIC) [pic. #10]
    - ➢ Buffer, aggregate and format data
  - DC/DC converter [pic. #8]
  - Low-power gigabit data transceiver (LpGBT) [pic. #7]



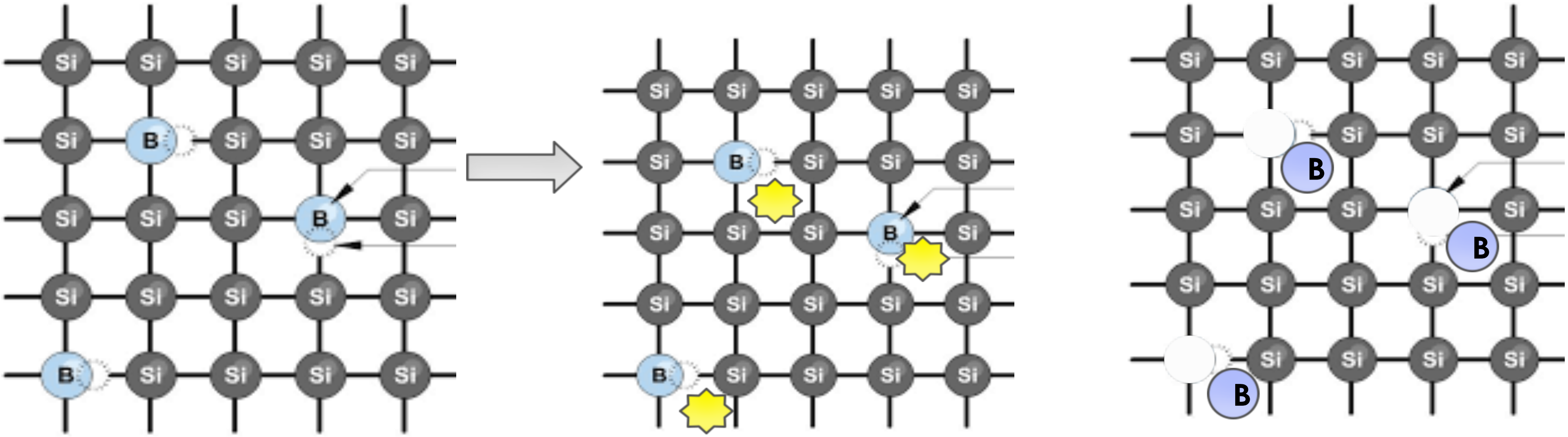


Radiation issue: Initial acceptor removal

This term indicates the “removal” of the initially present p-doping.

For UFSD this is particularly problematic as it removes the gain layer

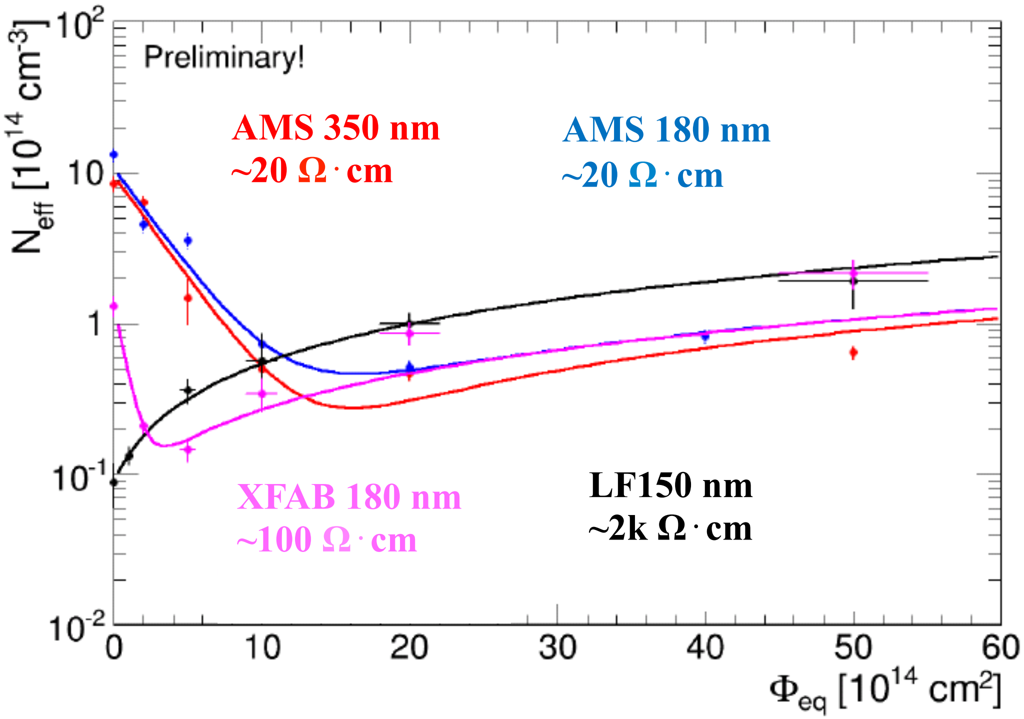
Irradiation ➔ Defects ➔ Boron becomes interstitial



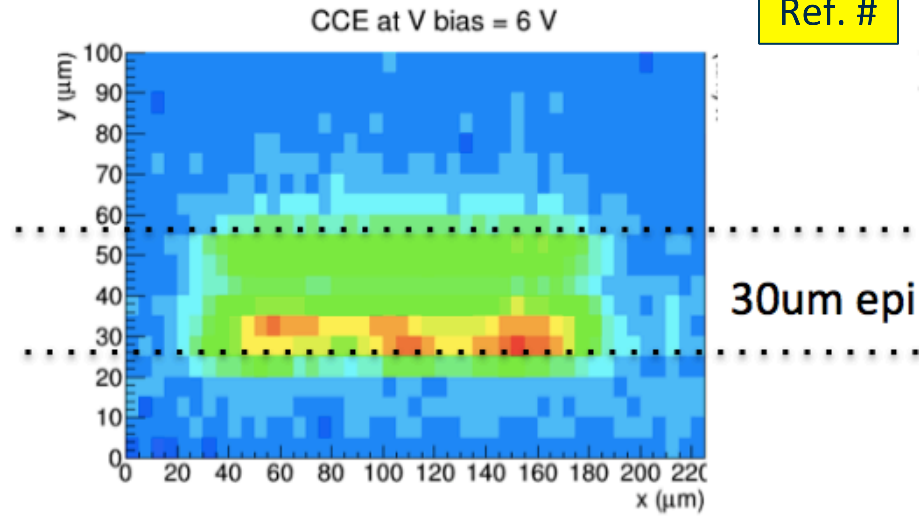
The boron doping is still there, only it has been moves into a different position and it does not contribute to the doping profile, it is inactive

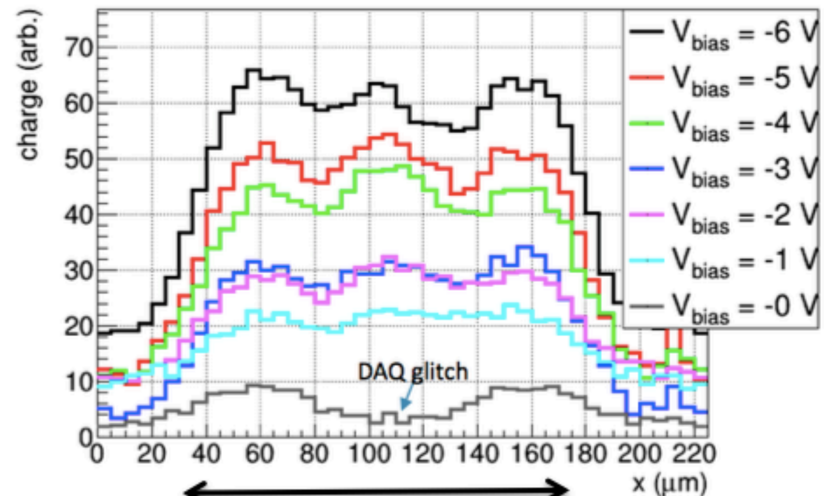
Depleted Monolithic Active PixelS

Ref. #



Igor Mandić, Jožef Stefan Institute, Ljubljana Slovenia
11th "Trento" Workshop, February, Paris, 2016





H. Pernegger CERN EP -

3x50um pitch

Large fill-factor: sizeable depleted region after irradiation

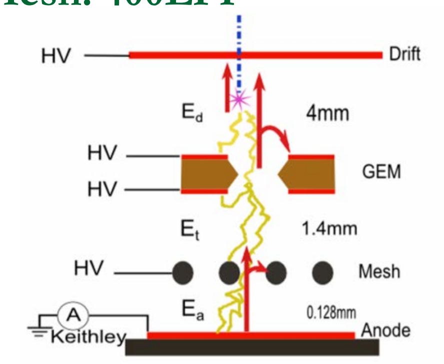
$$d = \sqrt{\varepsilon_{Si}\varepsilon_0 \frac{V + V_{BI}}{qN_{A,eff}}}$$

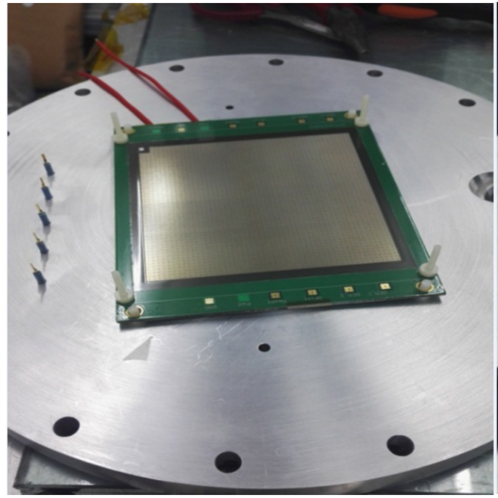
Small fill-factor: uniform charge collection even after 10^{15} n_{eq}/cm^2

H. Qi on Friday

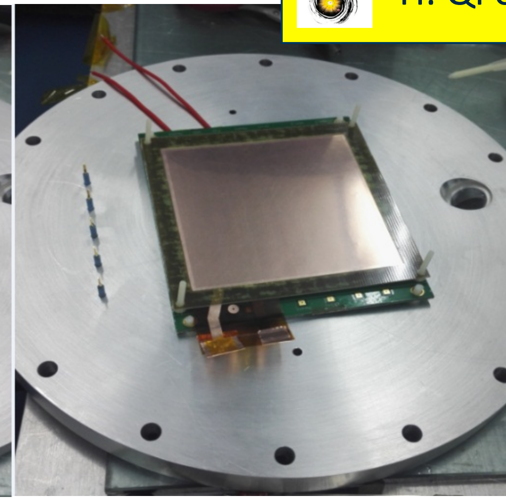
Test of the new module

- Test with GEM-MM module
  - New assembled module
  - Active area: 100mm × 100mm
  - X-tube ray and 55Fe source
  - Bulk-Micromegas from Saclay
  - Standard GEM from CERN
  - Additional UV light device
  - Avalanche gap of MM:128μm
  - Transfer gap: 2mm
  - Drift length:2mm~200mm
  - Mesh: 400LPI

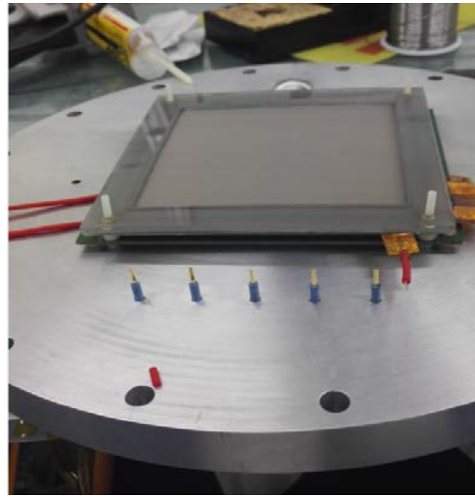




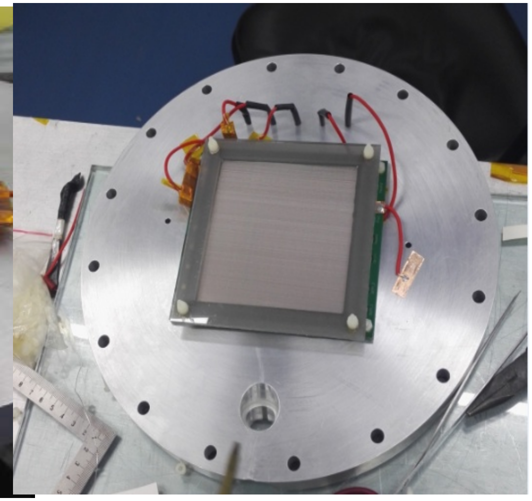
Micromegas(Saclay)



GEM(CERN)

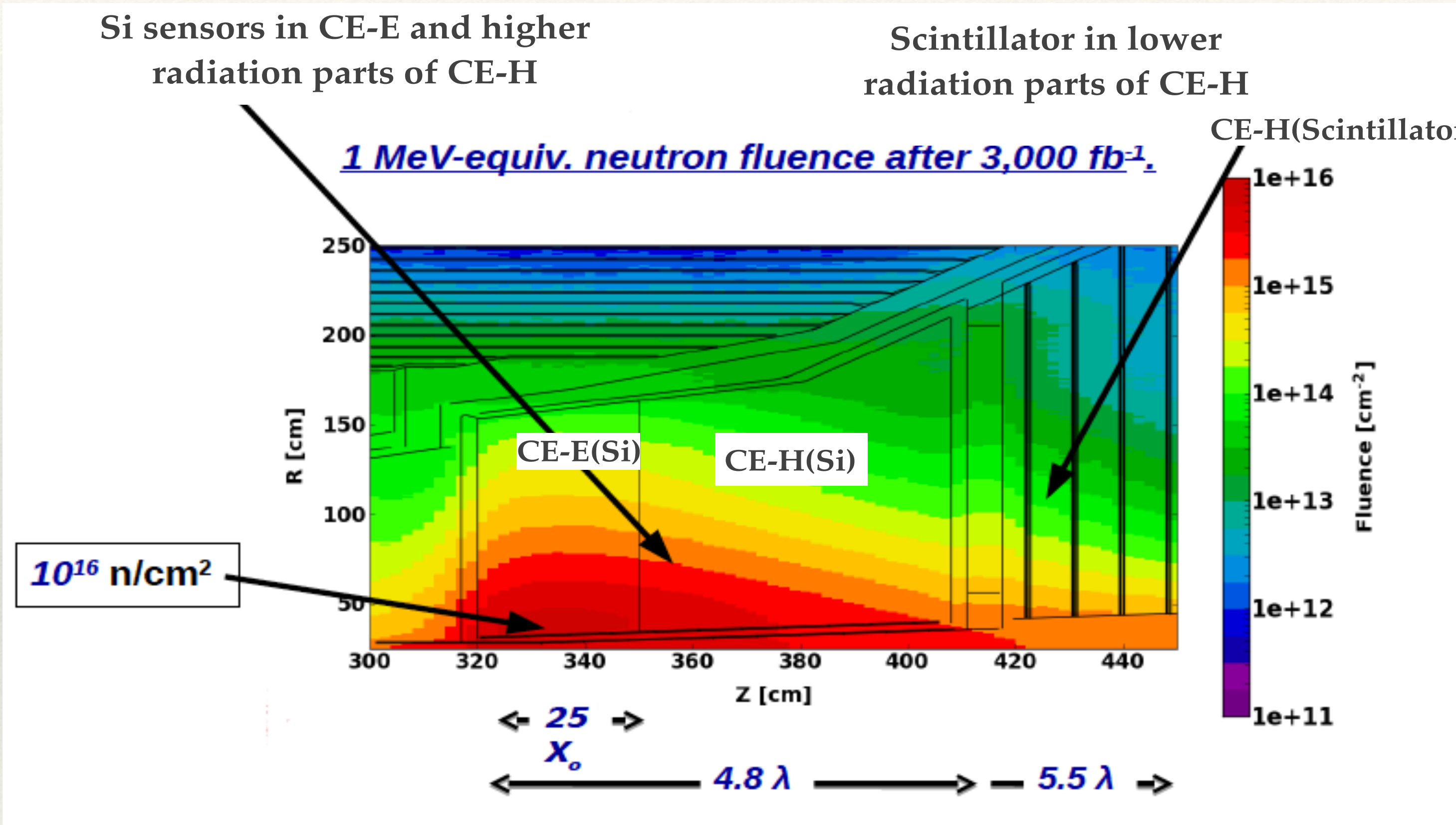


Cathode with mesh



GEM-MM Detector

Why High Granularity Calorimeter (HGCAL) in HL-LHC

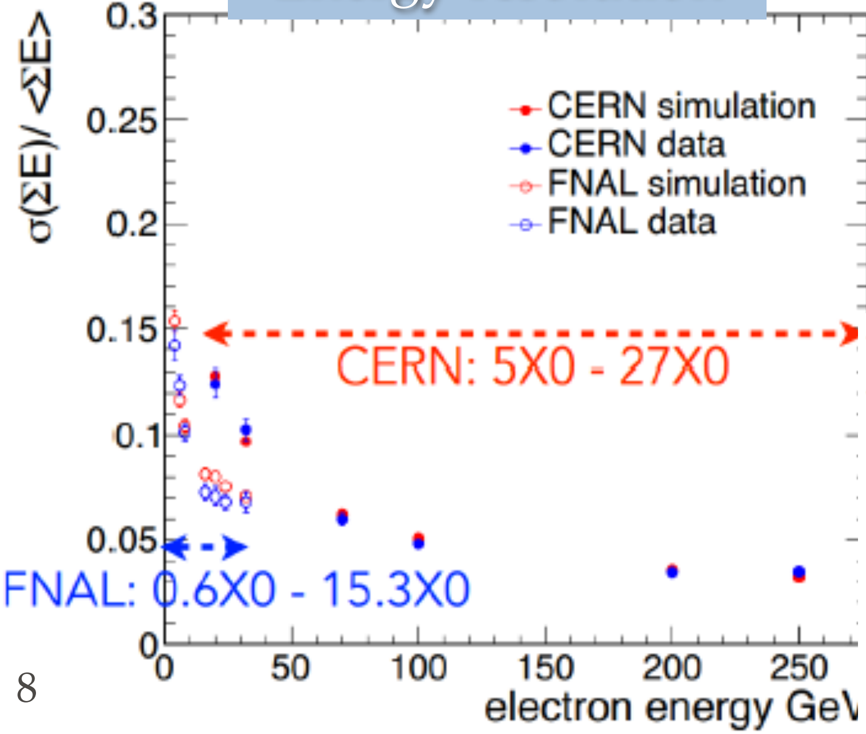


Detailed review of HGCAL in Luca's talk

- Important role of the forward calorimeter for physics at the HL-HLC
- Current CMS calorimeters will suffer radiation damage by the end of LHC running
- Detector upgrade important to maintain excellent performance in the harsh HL-LHC

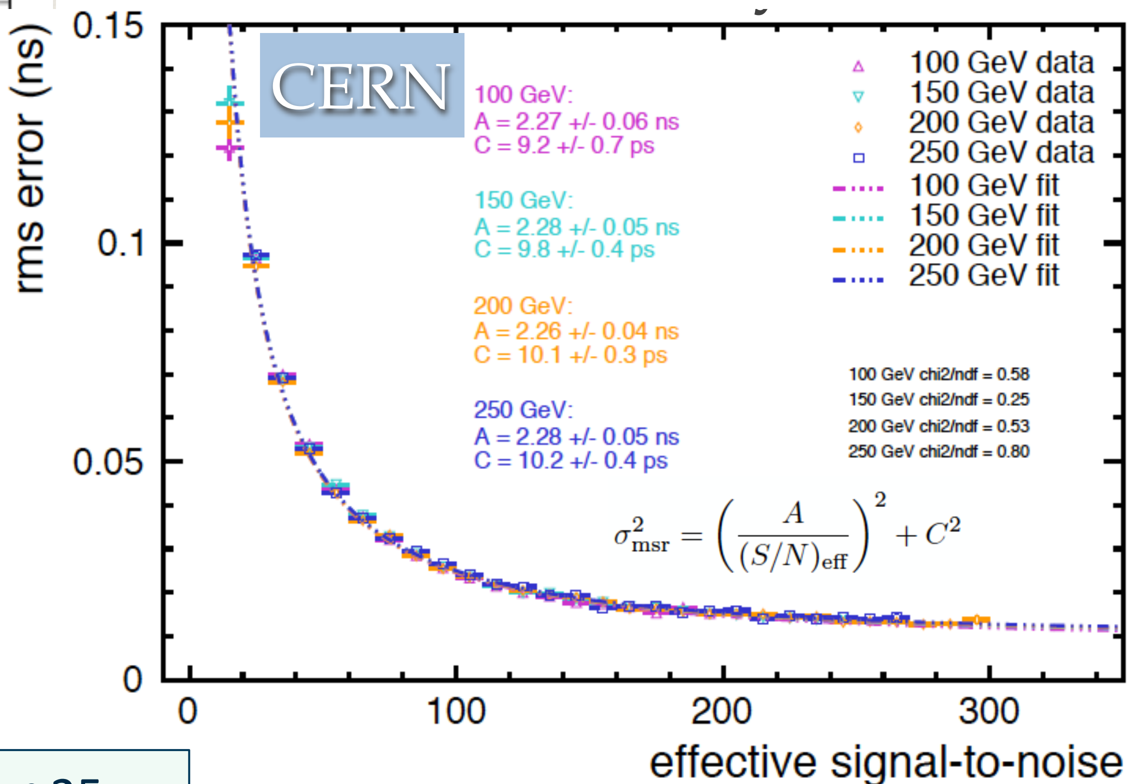
CMS HGCal for HL-LHC

Energy resolution



8

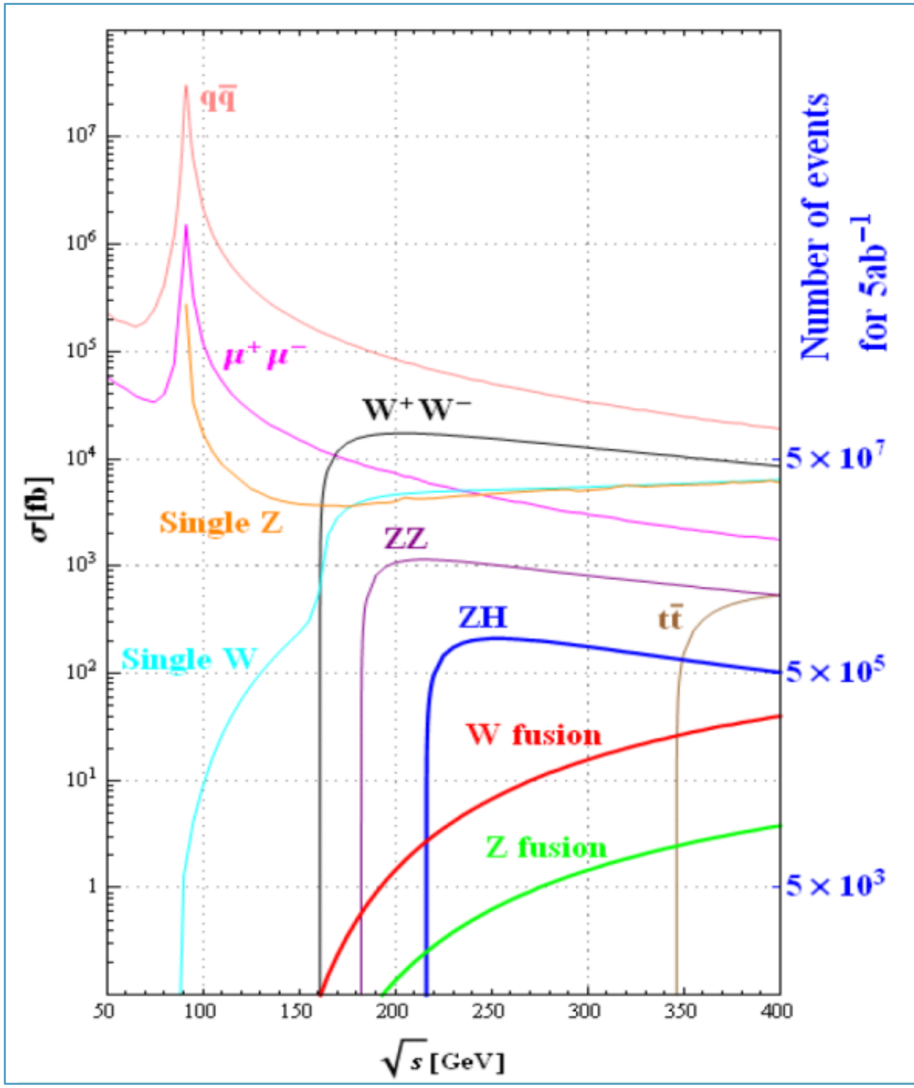
Excellent agreement between simulation and testbeam result

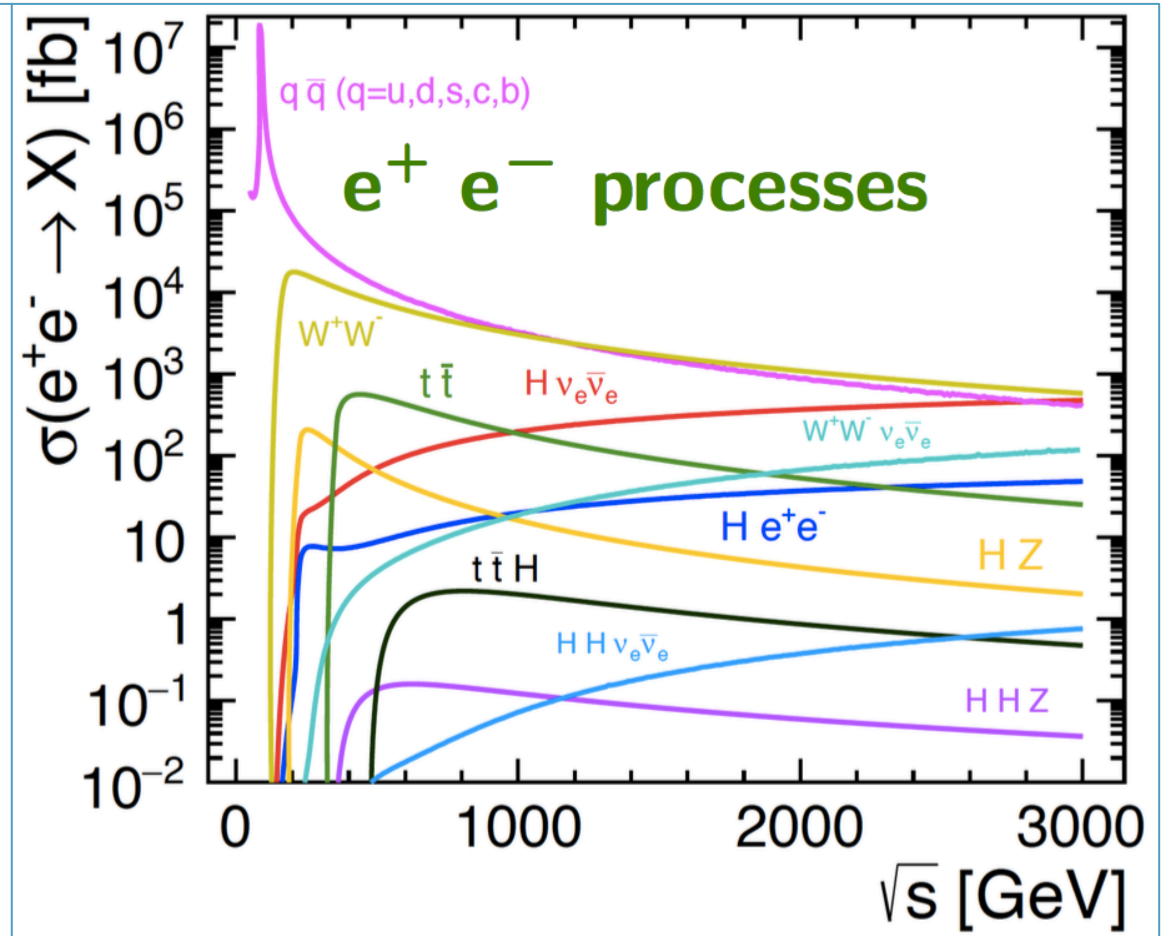


Time resolution ~25 ns

pp and ee Cross Section

- ee interaction cross sections





CMS HGCal for HL-LHC

- First full slice of HGCal tested on beam at CERN in 2017
- Very preliminary results!

S. Jain on Saturday