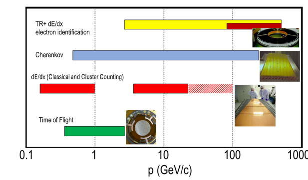
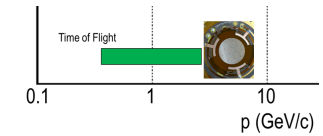
Time of flight measurements





Michele Gallinaro

LIP Lisbon

February 16, 2021

- ✓Precision timing and performance
- ✓Current and future experiments
- ✓Challenges and prospects

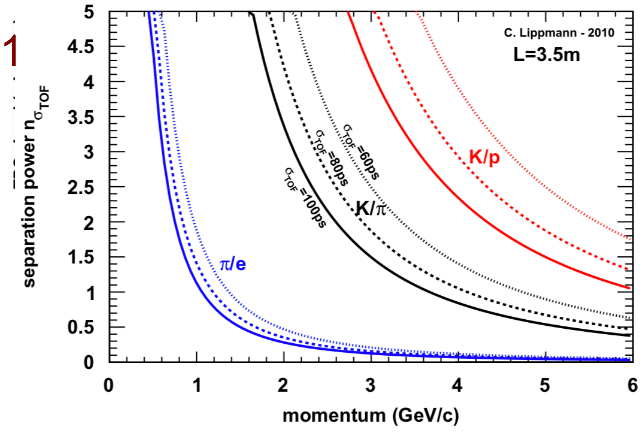
RD51 workshop on “on Gaseous Detector Contributions to PID”

ToF for Particle ID: Why?

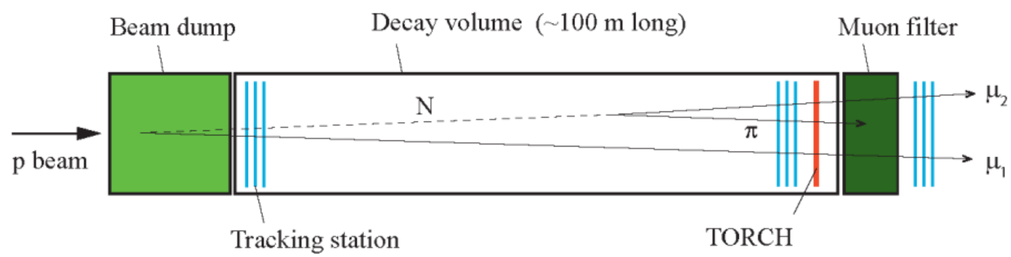
- Particle identification

dominant for $\gamma >> 1$

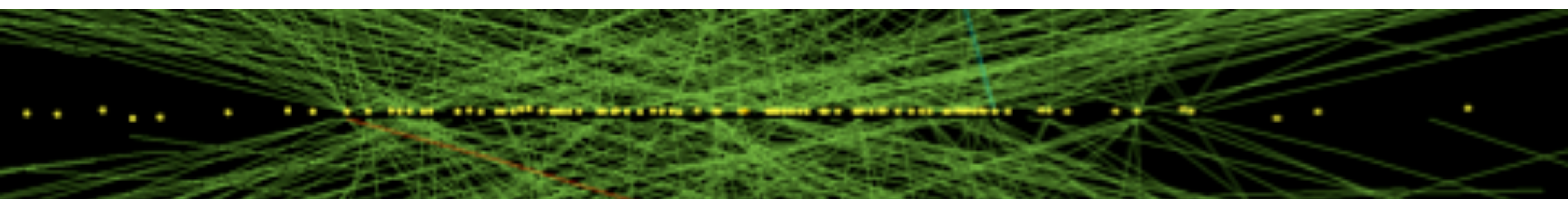
$$m = \frac{p}{c\beta\gamma} \longrightarrow \left(\frac{dm}{m}\right)^2 = \left(\frac{dp}{p}\right)^2 + \left(\gamma^2 \frac{d\beta}{\beta}\right)^2$$

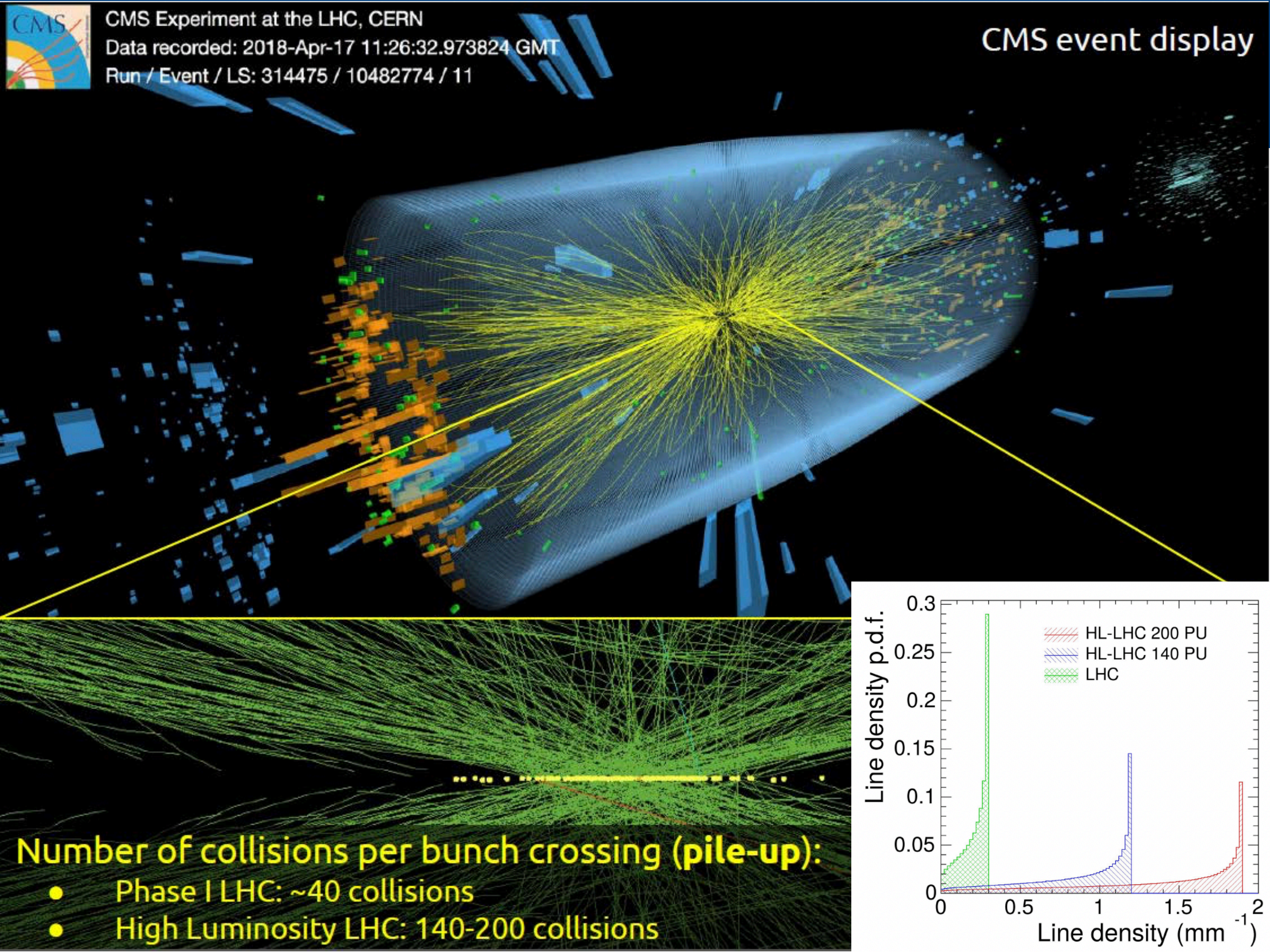


- Searches (e.g. long-lived-particles)
  - e.g. heavy neutrino (ToF~100ps): $D \longrightarrow N\mu X$, $N \longrightarrow \mu\pi$



- Beam background
  - Pileup rejection




CMS Experiment at the LHC, CERN
Data recorded: 2018-Apr-17 11:26:32.973824 GMT
Run / Event / LS: 314475 / 10482774 / 11
CMS event display
Number of collisions per bunch crossing (**pile-up**):
• Phase I LHC: ~40 collisions
• High Luminosity LHC: 140-200 collisions
Line density p.d.f.
0.3
0.25
0.2
0.15
0.1
0.05
0
HL-LHC 200 PU
HL-LHC 140 PU
LHC
0
0.5
1
1.5
2
Line density (mm^{-1})

Challenges and technologies

- Technologies:
  - Silicon, diamond, photodetectors, and gaseous detectors
- Challenges:
  - Large vs small systems
  - Aging effects
  - Rate capabilities
- Several contributions to time resolution

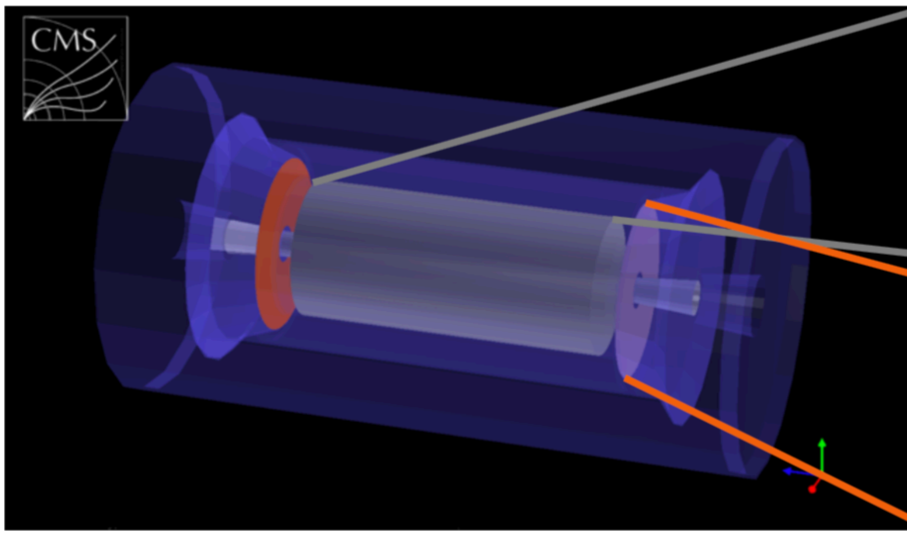
$$\sigma^2_{TOF} = \sigma^2_{t_0} + \sigma^2_{t_1} = \sigma^2_{t_0} + \sigma^2_{Intr} + \sigma^2_{Elec} + \sigma^2_{Clock} + \sigma^2_{Cal}$$

intrinsic det.
resolution

MIP Timing Detector @CMS

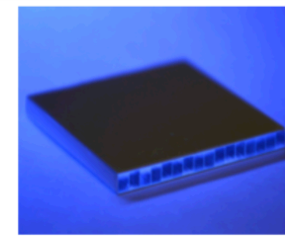
CERN-LHCC-2019-003

- High precision time measurement of MIPs
  - 30-40 ps at start, degrading to <60ps at 3000 fb^{-1}
  - Provide track-vertex association
  - Improve sensitivity to slow particles, add particle ID capabilities, etc.



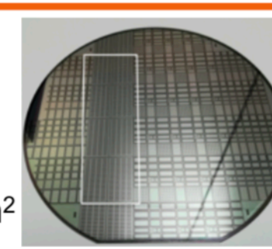
BTL: LYSO bars + SiPM read-out

▹ TK / ECAL interface ~ 45 mm thick
▹ $|\eta|< 1.45$ and $p_T > 0.7$ GeV
▹ Active area ~ 38 m^2 ; 332k channels
▹ Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



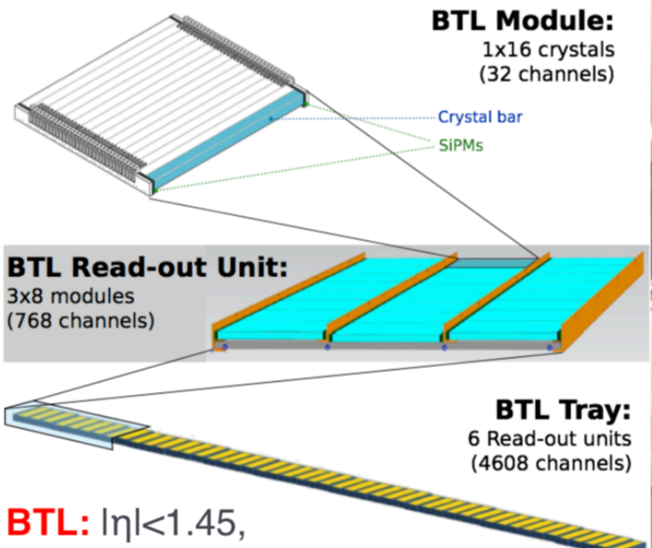
ETL: Si with internal gain (LGAD)

▹ On the HGC nose ~ 65 mm thick
▹ $1.6 < |\eta| < 3.0$
▹ Active area ~ 14 m^2; ~ 8.5M channels
▹ Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

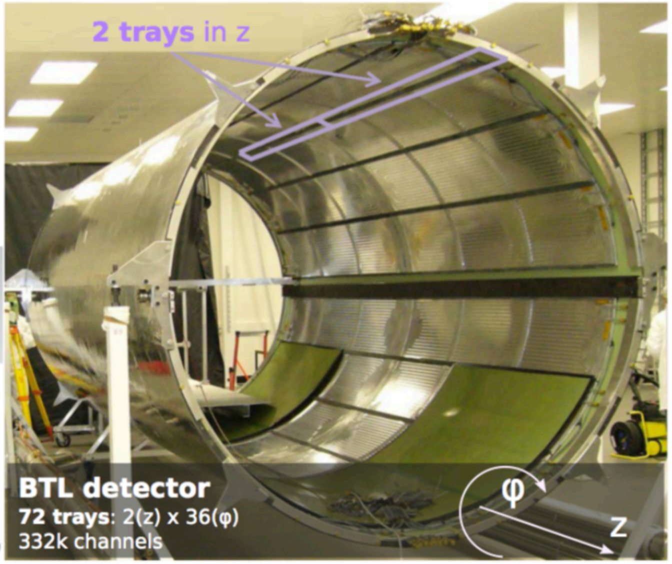


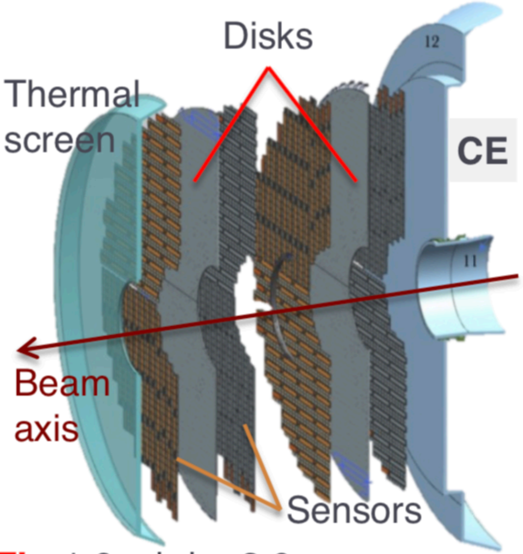
MIP Timing Detector

- Barrel Timing Layer (BTL):
  - Arrays of LYSO crystal bars with dual-end SiPM readout
  - Two meaurements per hit (improves resolution)
  - Mounted inside the Tracker Support Tube (independent cooling)
- Endcap Timing Layer (ETL):
  - LGAD modules bump-bonded to ASIC
  - Two layers (improves resolution and redundancy)



BTL: $|\eta|<1.45$,
surface ~38 m^2; 332k channels





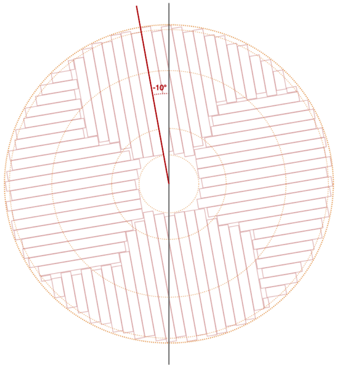
ETL: $1.6 < |\eta| < 3.0$,
surface ~14 m^2; ~8.5 M channels

Timing detector @ATLAS

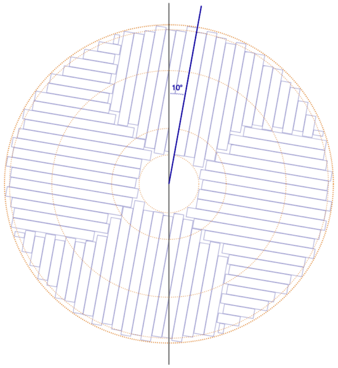
CERN-LHCC-2020-007

High Granularity Timing Detector (HGTD)

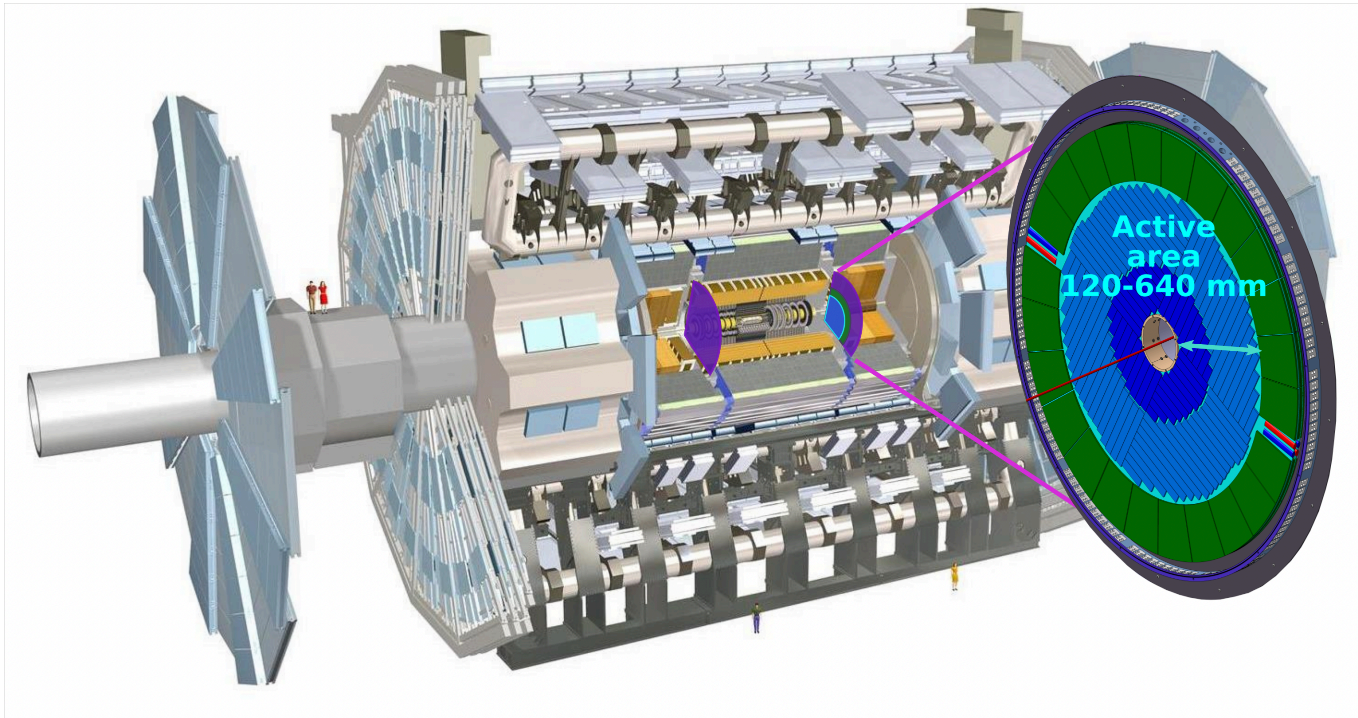
- Coverage: $2.4<|\eta|<4.0$
- Active area 6.3m^2, 3.6M ch
- Design based on 1.3x1.3mm^2 Si pixels optimized for <10% occupancy
- Rad hard up to $5\times10^{15} n_{eq}/cm^2$, 4.7MGy



(a) First layer

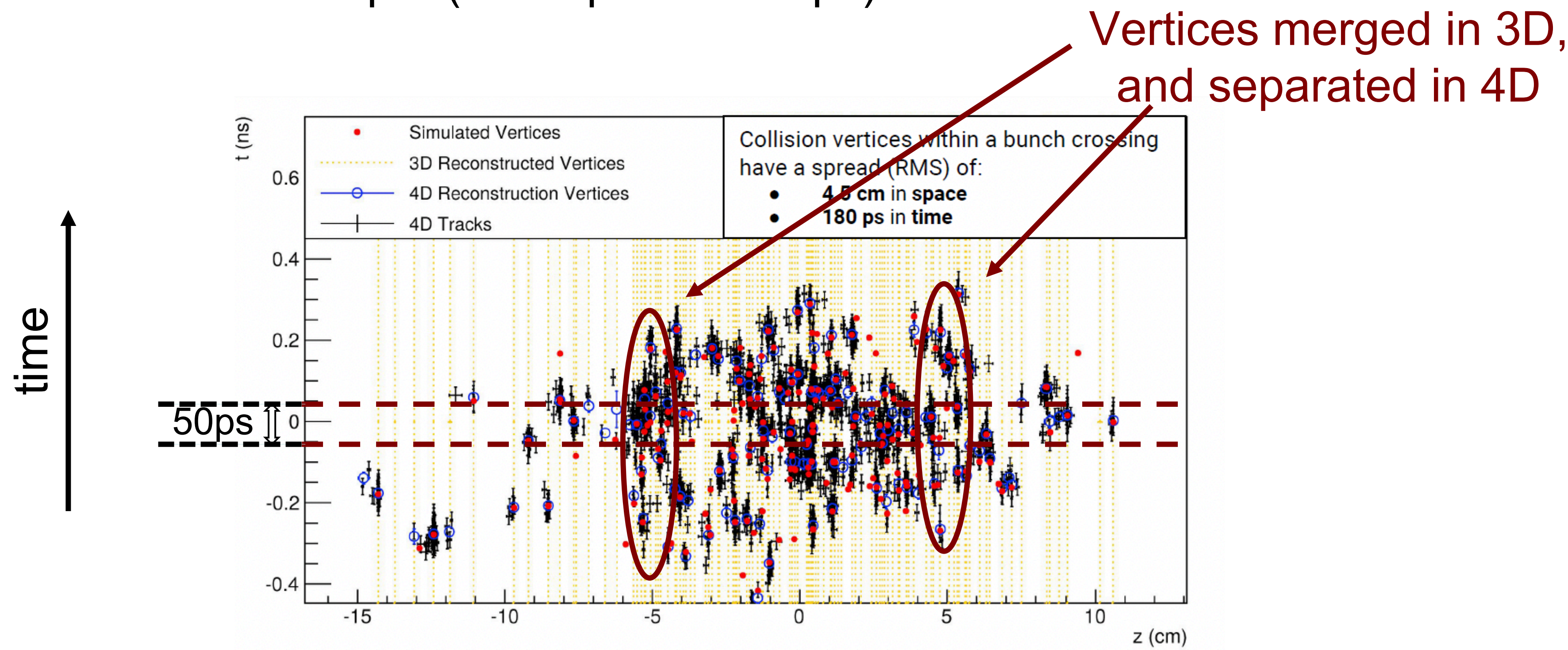


(b) Second layer



PU mitigation with ToF

- Time-tagging tracks with a resolution of ~30-40 ps
  - 4D vertex reconstruction
  - Track-vertex association
- Reduce effective PU to the LHC Run2 level
  - Slice beam spot (time spread 180 ps)



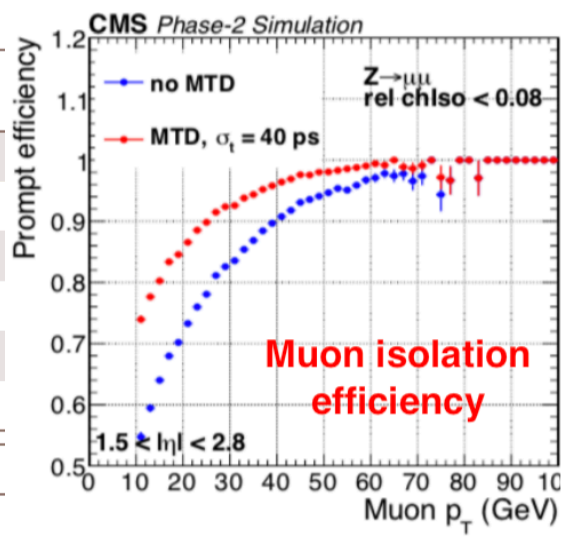
Particle reconstruction

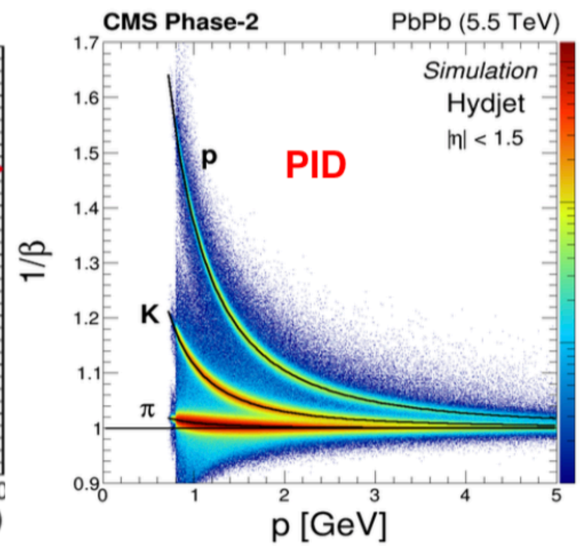
- Improve particle reconstruction/ID
  - Increase b-tagging efficiency
  - Increase photon and lepton Id, efficiency and isolation
  - Improve missing transverse momentum resolution
  - Reduce fake jet reconstruction
- 10%-20% gain in S/B in many Higgs decay channels

HH production sensitivity (sigmas) at 3 ab^{-1}

Channel	No MTD	$<\sigma_t>$ 35 ps	$<\sigma_t>$ 50 ps
bbbb	0.89	0.95	0.94
bbττ	1.3	1.58	1.48
bbγγ	1.7	1.85	1.83
bbWW	0.53	0.579	0.576
bbZZ	0.38	0.423	0.418
Combined	**2.4**	**2.71**	**2.63**
Luminosity gain	-	**+26%**	**+20%**

HL-LHC@140PU



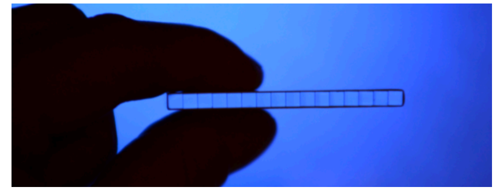


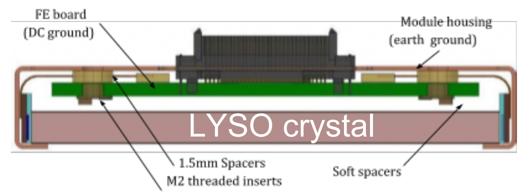
MTD: Time resolution

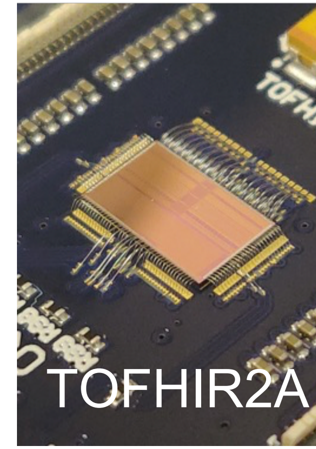
- Time resolution: ~30-40ps@start
- Dedicated on-detector electronics (TOFHIR and ETROC)

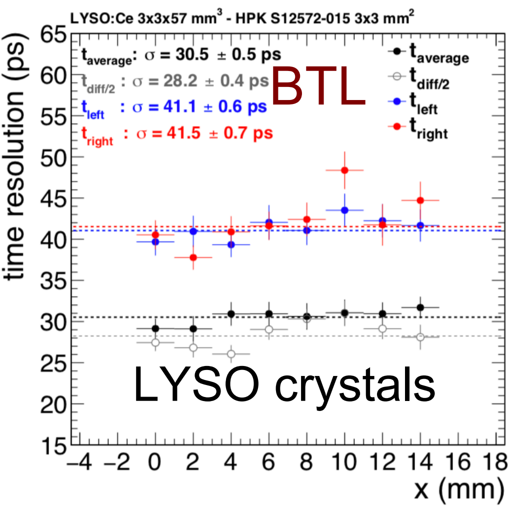
Different technologies in Barrel/Endcap:

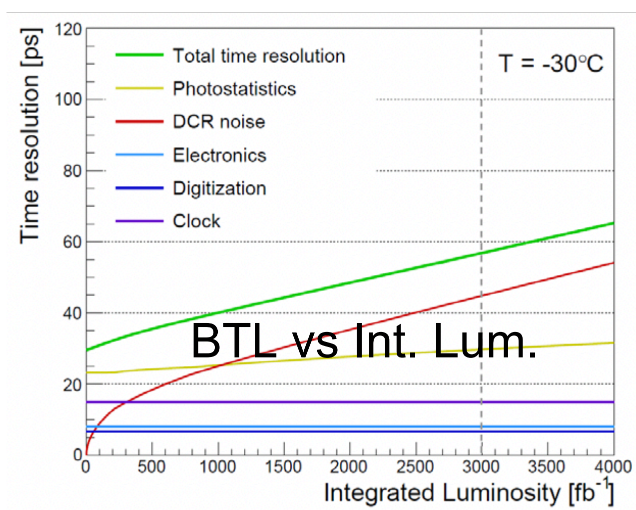
- LYSO crystals (BTL):
  - $3x3x57mm^3$ readout by two SiPMs
- LGAD: Low Gain Avalanche Diodes (ETL)
  - Si pixels $1.3x1.3mm^2$, $2x4cm^2$ module bonded to ASIC

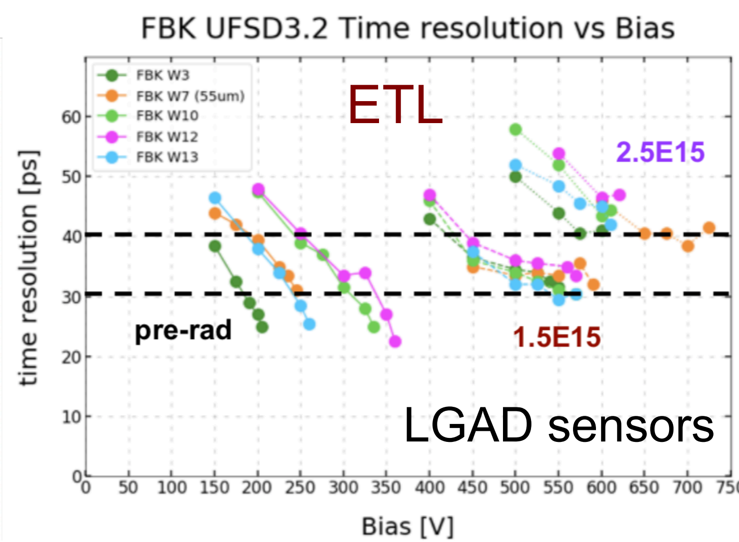






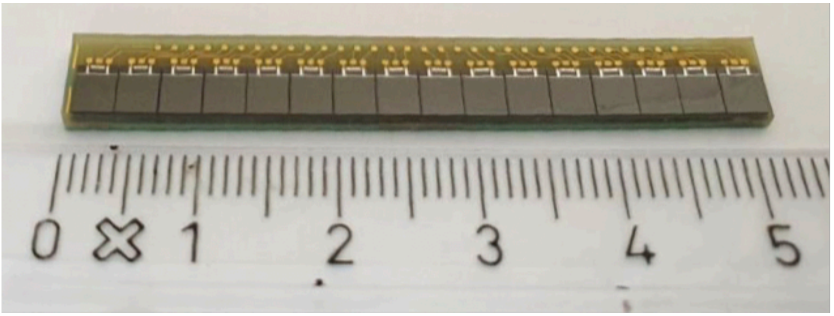


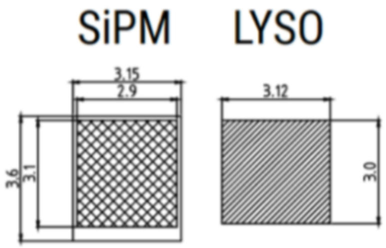




SiPMs

- SiPMs as photosensors
  - Compact, fast (single photon resolution ~100ps), insensitive to magnetic fields
  - Optimal cell size 15μm (balance btw radiation tolerance and photon detection efficiency
  - PDE: 20-40% at 420nm
  - Gain: 1.5-4x10^5
- **Drawback:** dark current noise due to radiation damage



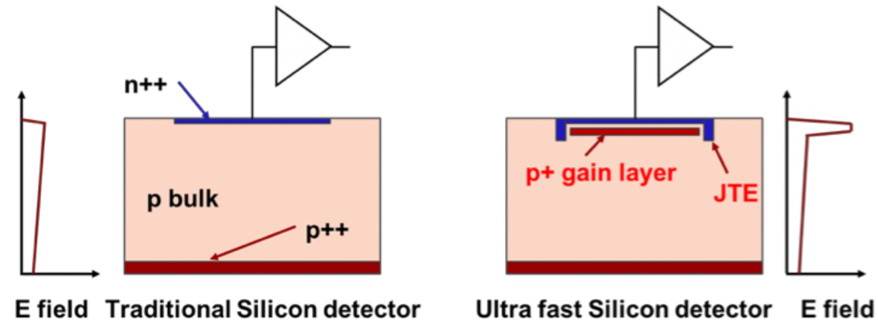


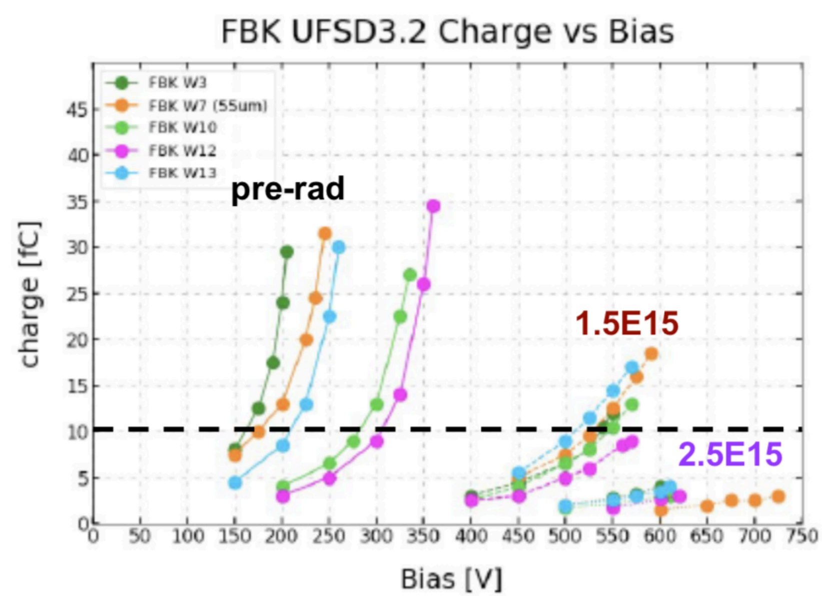
Integrated luminosity (fb-1)	Number of p.e.	SiPM gain	DCR (GHz)
0	9500	3.8×10^5	0
500	9000	2.9×10^5	20
1000	8000	2.5×10^5	30
2000	7000	1.9×10^5	45
3000	6000	1.5×10^5	55

end of operation → (3000 fb-1 row)

LGADs

- Gain is key ingredient to good time resolution
- High field obtained by adding an extra doping layer
  - E~300kV/cm, close to breakdown voltage
  - Exploit Carbon implant to extend lifetime
- Signal yield >10fC up to $1.5 \times 10^{15} n_{eq}/cm^2$
- Damage due to radiation:
  - Electric field decrease → compensate with higher bias
  - Increased leakage current
  - Doping creation/removal

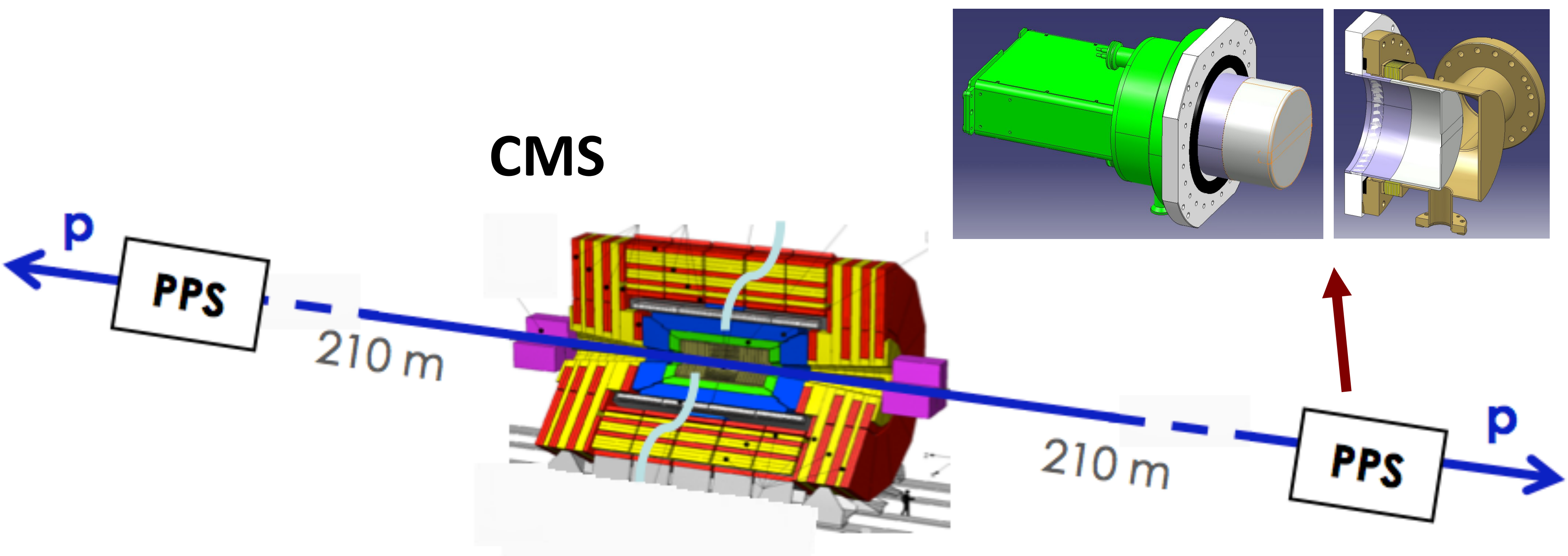




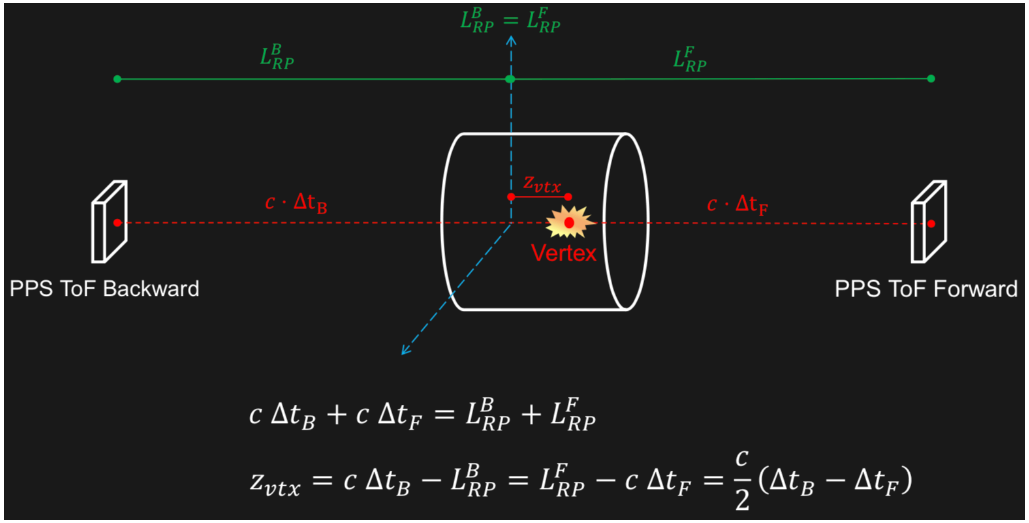
Precision Proton Spectrometer

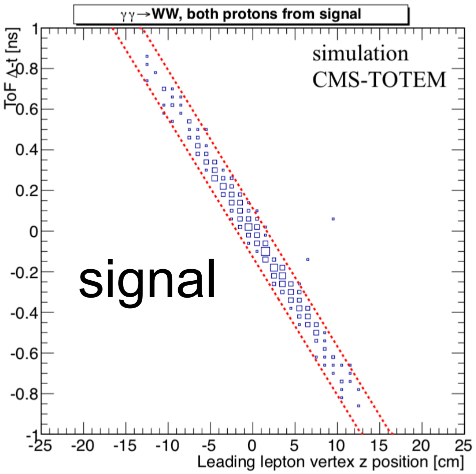
CERN-LHCC-2014-021

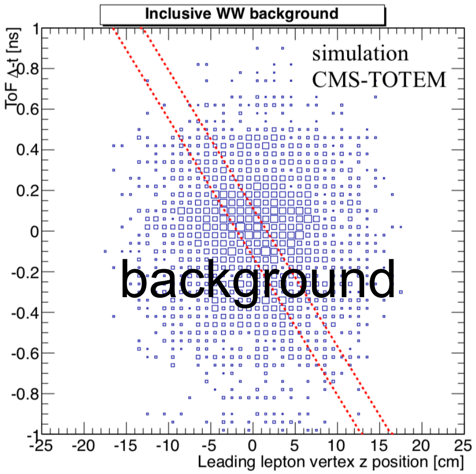
- Aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Close (~2mm) approach to LHC beams inside movable “Roman Pot” vessels



Time reconstruction





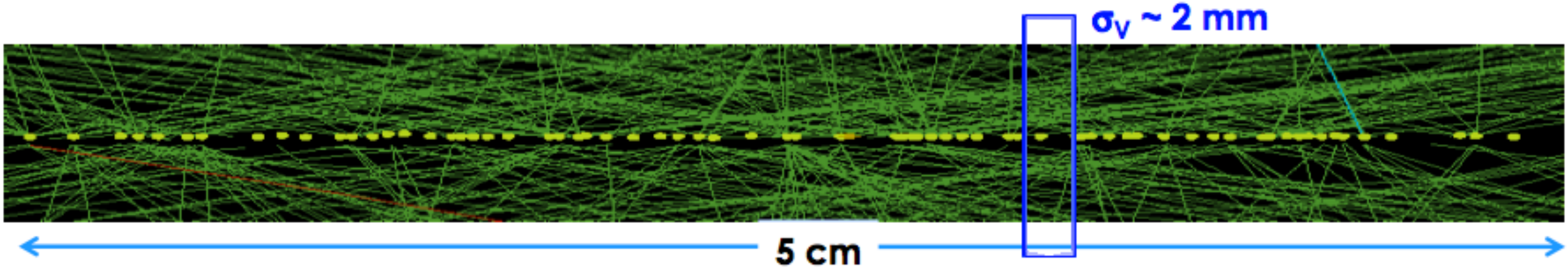


- A major background due to PU protons from other collisions in the same bunch crossing
  - PU~40-50 at LHC Run2
- Can be mitigated by precisely measuring the proton arrival time
  - For signal, Δt of the 2 protons is correlated with longitudinal vertex position measured in central detector

Timing detectors

Time-of-flight measurement to reject background in the high-pileup of normal LHC running (uncorrelated proton tracks)

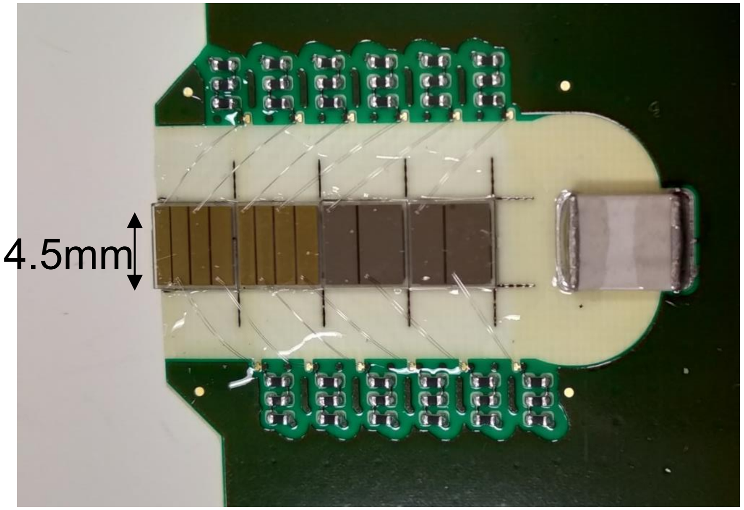
- Desired time resolution 20ps ⇒ 4mm (in z)
- Technology: diamond (rad-hard)
- Sustain high radiation levels
  - For 100/fb, proton flux up to $5x10^{15}cm^{-2}$

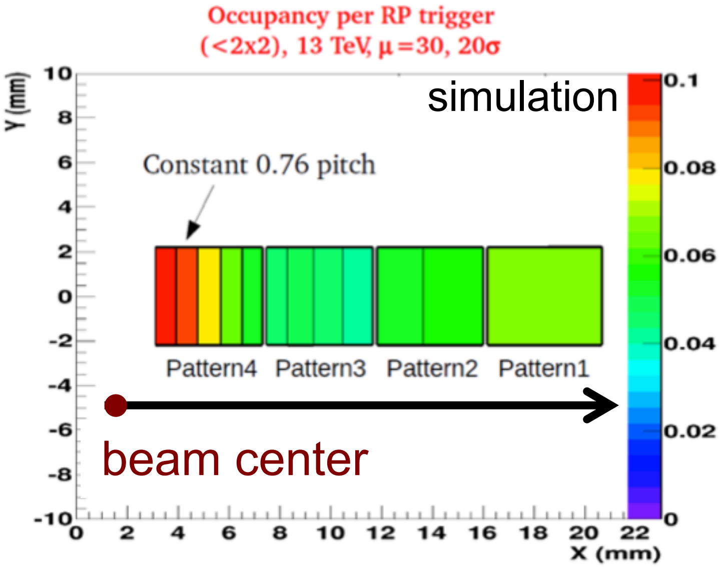


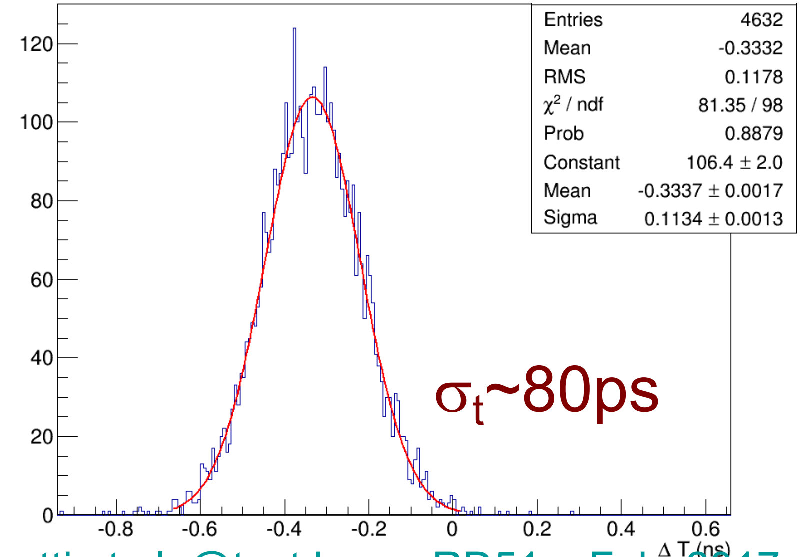
Diamond detectors

JINST12(2017)P03007

- Diamond detectors
  - single crystal CVD diamonds
  - 4 planes per station
  - pixels of different sizes
  - segmentation through crystal metallization
- Single plane resolution ~80ps
- Radiation hard





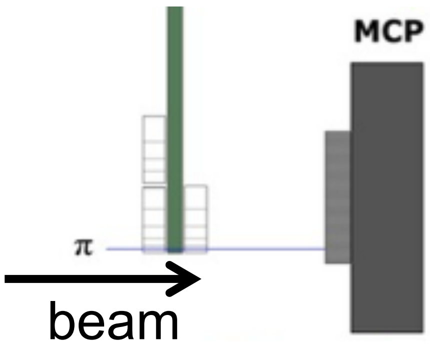


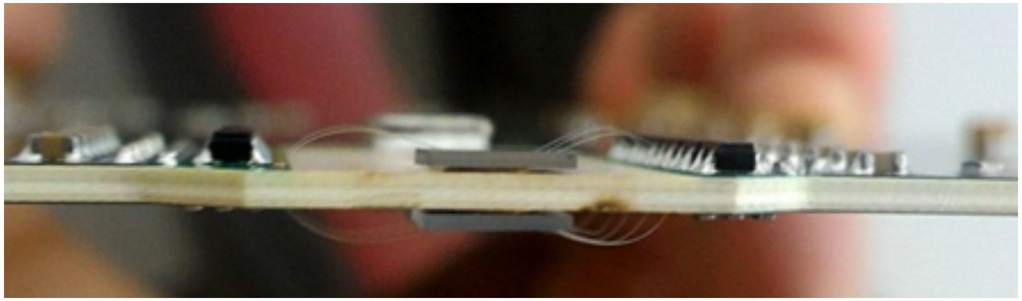
M. Berretti et al. @test beam RD51 – Feb. 2017

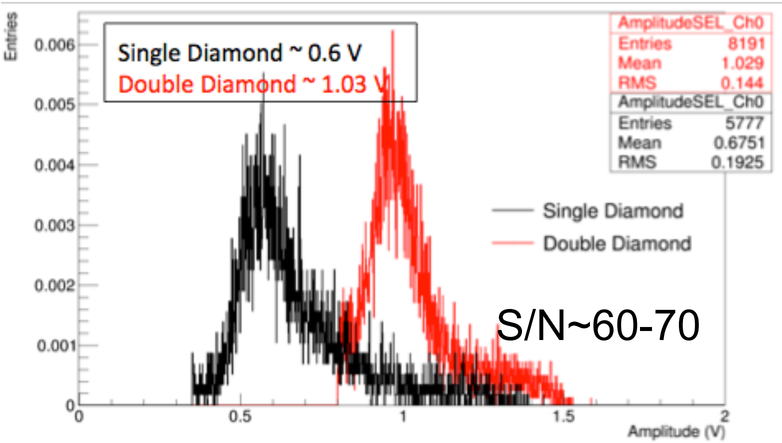
Double diamond layer

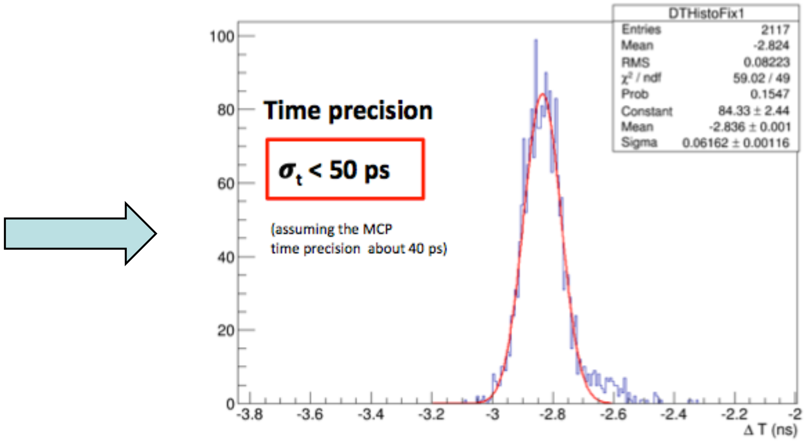
JINST12(2017)P03026

- Connected "sandwich" with two diamond sensors
- Beam tests in 2016/2017
- Performance improved (a factor of 1.7 wrt SD)
  - larger signal amplitude dominant over extra capacitance
- With 4 diamond sandwich-planes could reach 25 ps





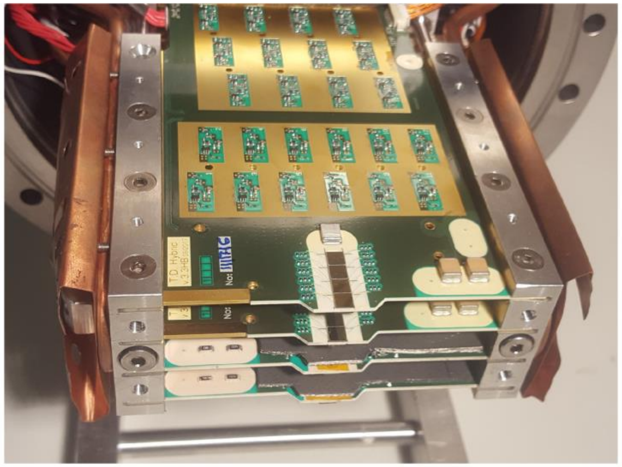


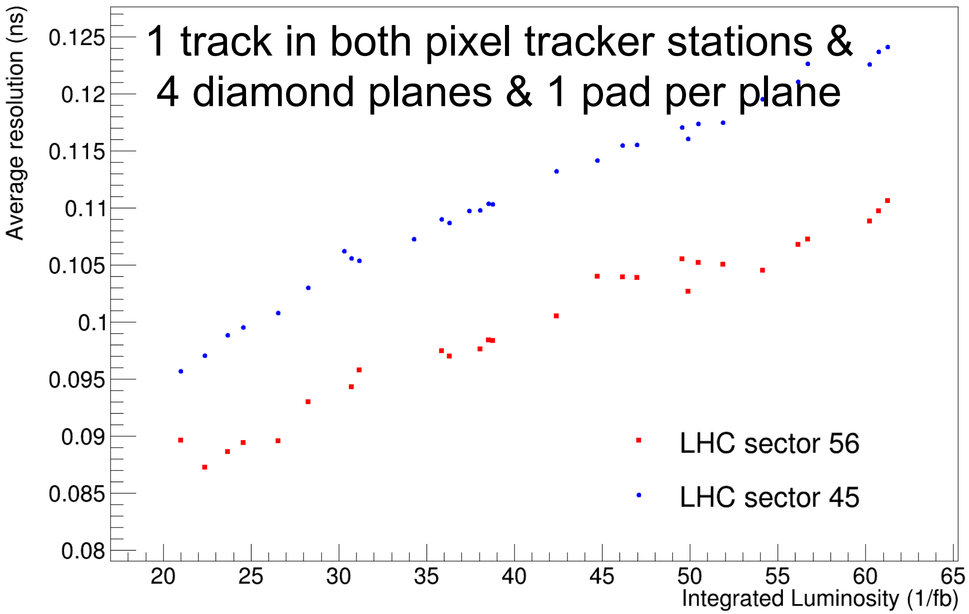


PPS: Time measurement in Run2

CERN-CMS-DP-2019-034

- Timing detectors installed in Run2 to measure proton ToF
  - Equipped with diamond detectors
  - One RP on each side, 4 planes in each RP (2DD+2SD)
- Reasonable efficiency maintained in 2018
- Expected 50ps/plane not yet reached
- Moderate loss of timing resolution from early to late 2018
  - Due to damage on the crystal and electronics (pre-amp, etc)



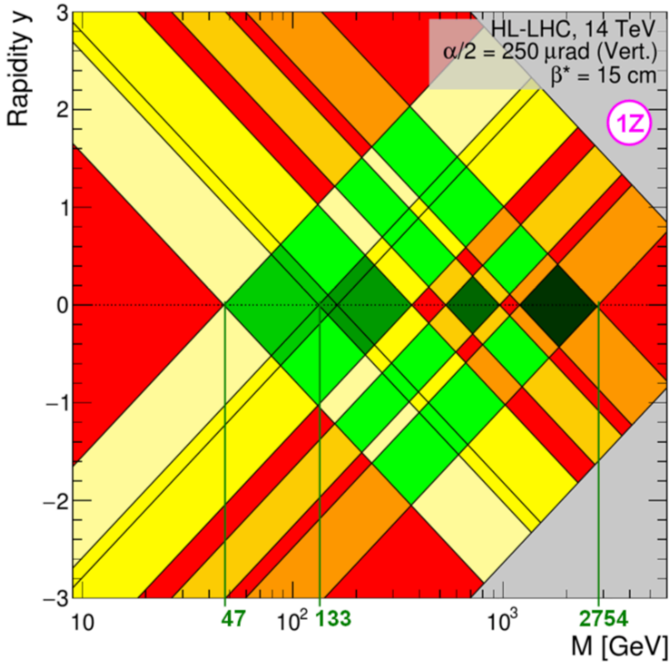


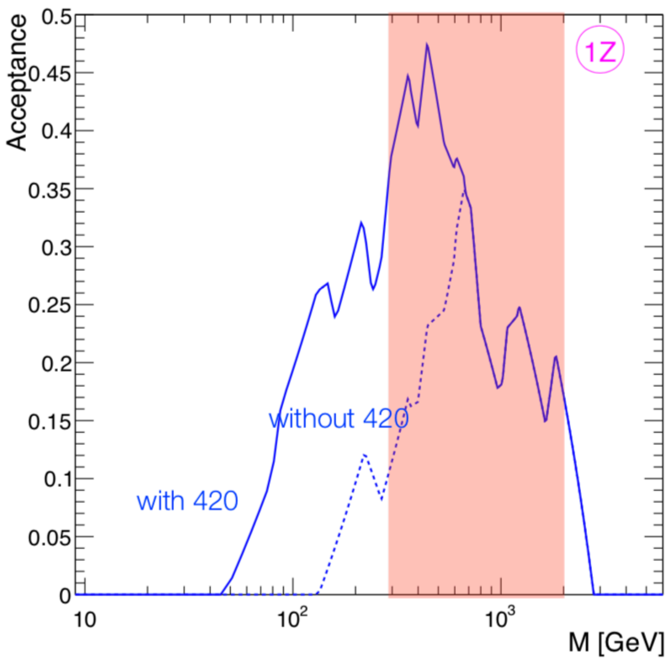
PPS at HL-LHC

CERN-CMS-NOTE-2020-008

Plan for an upgraded PPS detector at HL-LHC

- 4 possible locations in the HL-LHC tunnel
  - Roman Pots at 196, 220, 234m (+420m) from IP
- Fluence at ~1.5×10^{16}p cm^{-2} (~6×10^{15} $n_{eq} cm^{-2}$)





Significantly larger acceptance than in Run2/3

PPS at HL-LHC

- Synergies with central CMS upgrades
- PPS pixel tracking detectors already aligned with Phase-II tracker upgrade
- Several options for timing detectors: diamonds, LGAD (as in MTD-ETL)

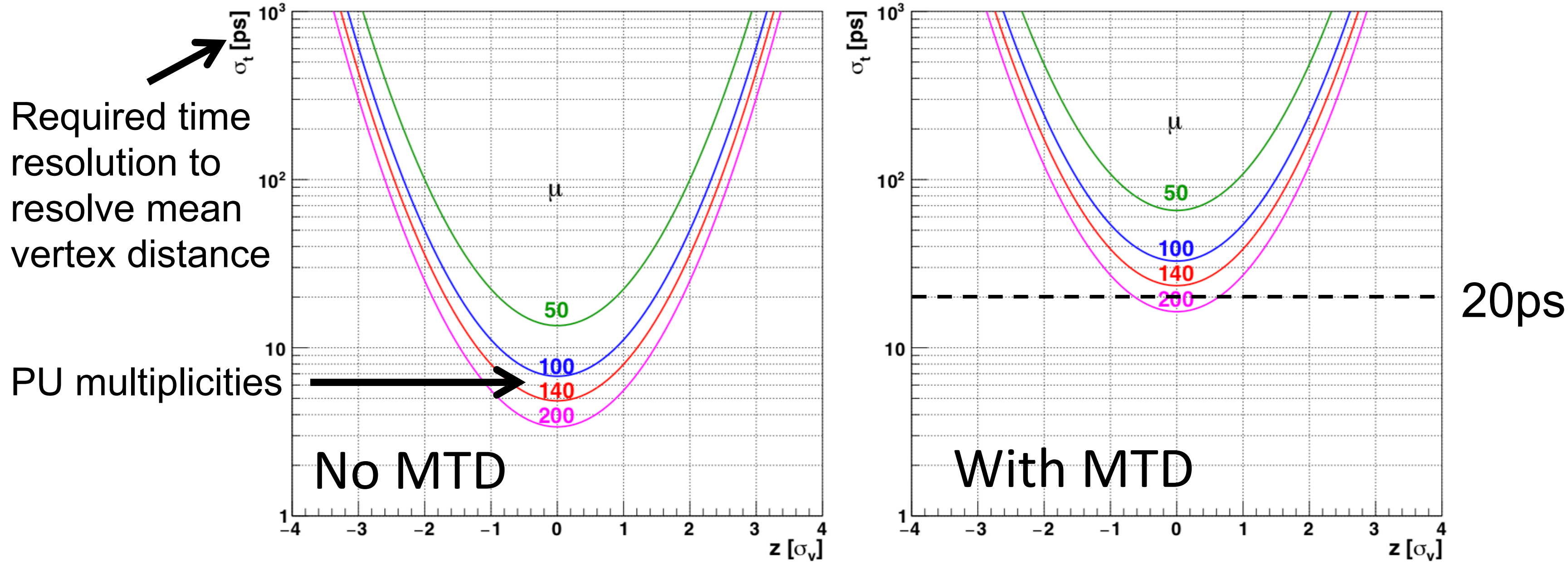


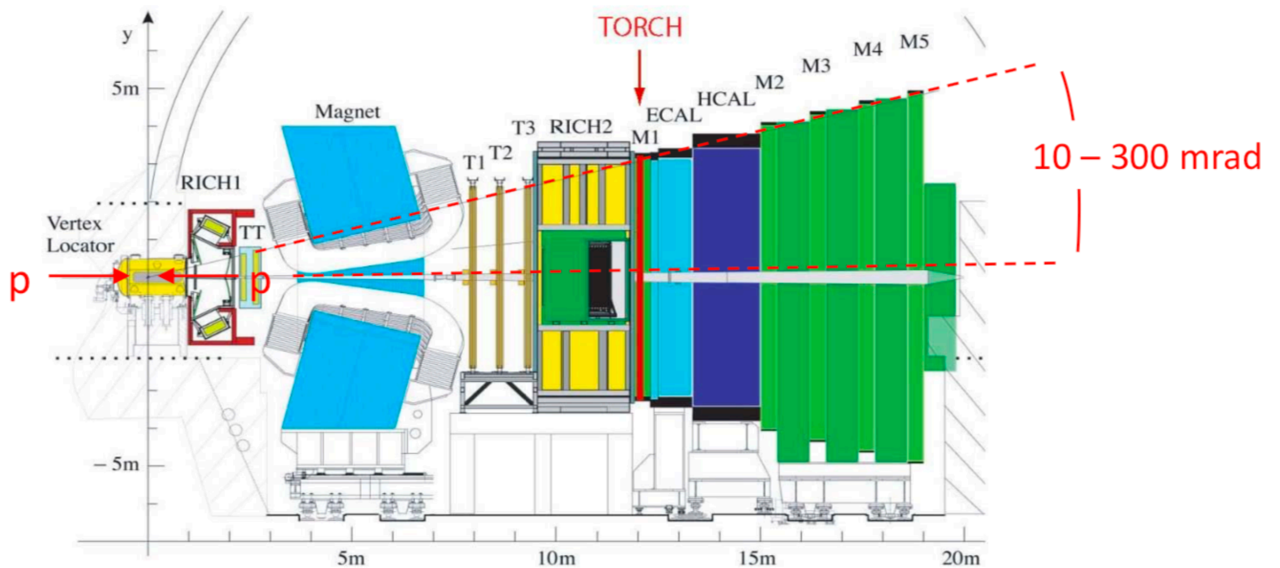
Figure 47: Time resolution required per spectrometer arm to resolve the mean vertex distance at a position z (in units of the longitudinal vertex width σ_v) from the IP centre. Four different pileup multiplicities are shown: $\mu = 50$ (LHC Run 2), 100, 140 (nominal HL-LHC performance), and 200 (ultimate HL-LHC performance). Left: for standalone PPS timing. Right: combining the PPS timing with the MTD system, selecting a time-slice of ± 50 ps around the central bunch crossing time.

TORCH @ LHCb

- Precise ToF measurement over a large area (~30m^2)
  - Time Of internally Reflected Cherenkov (TORCH) light
  - Exploit prompt Cherenkov light produced by charged particles
  - Single photon rates >10MHz/cm^2, integrated charge >5C/cm^2
- Particle ID (K-π separation) up to a momentum of 10GeV

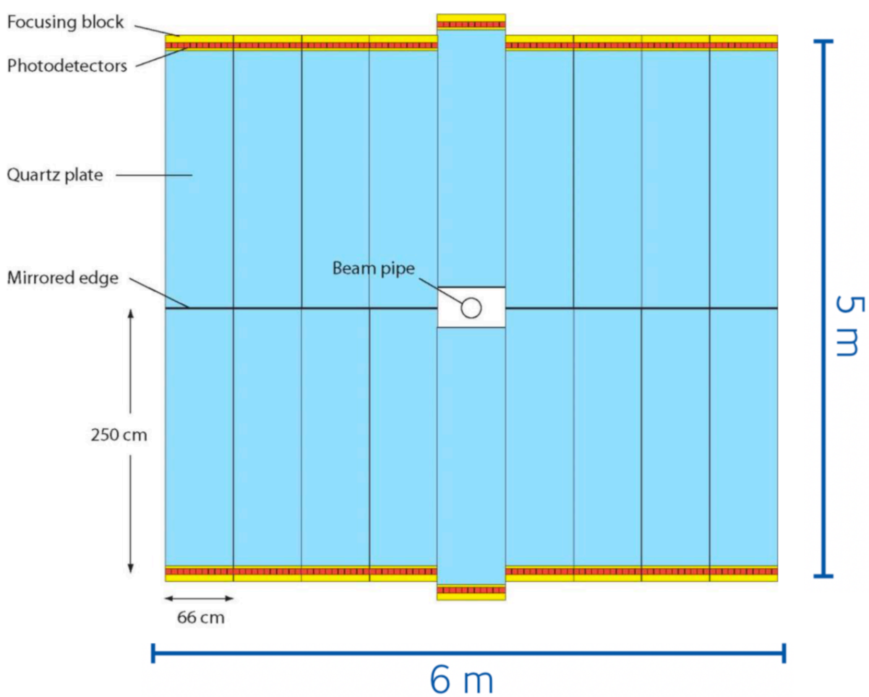
ΔToF(K-π)≈40ps over 10m at 10GeV

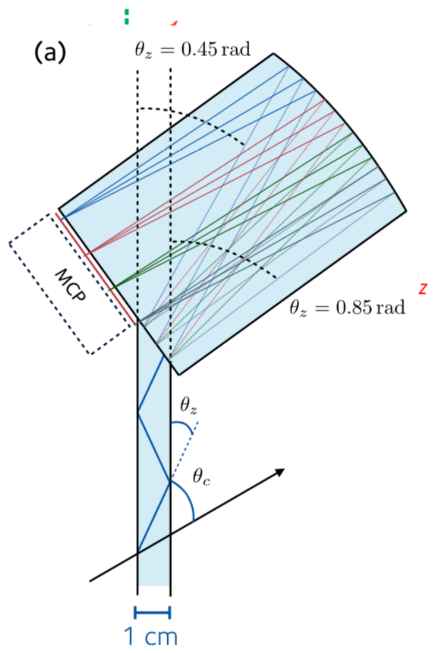
→require σ_t~10–15ps



TORCH design

- How to achieve 10-15ps time resolution?
- Cherenkov light: use quartz as source of fast signal DIRC-style detector with photon detector near edge
- Quartz of 1cm thickness enough to produce ~30 detected photons/track → require 70ps resolution/photon
- Spread arrival time due to different paths → need fine segmentation

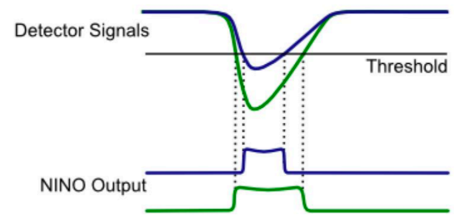


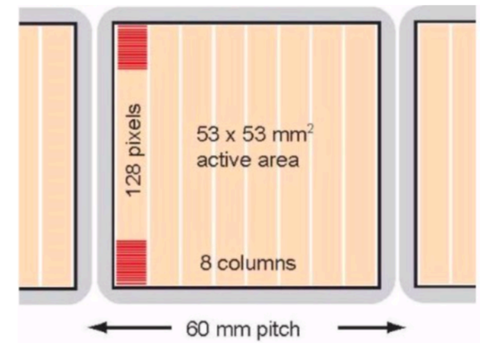


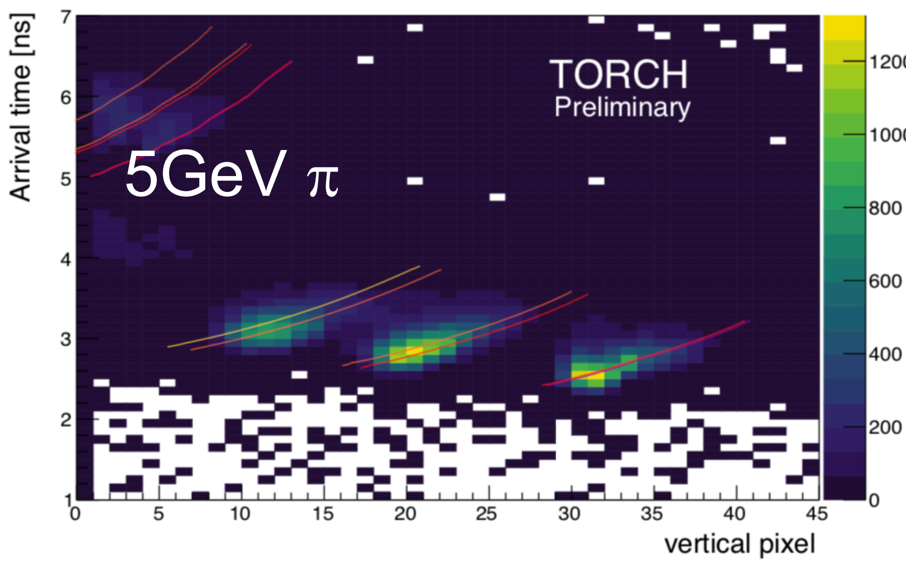
TORCH performance

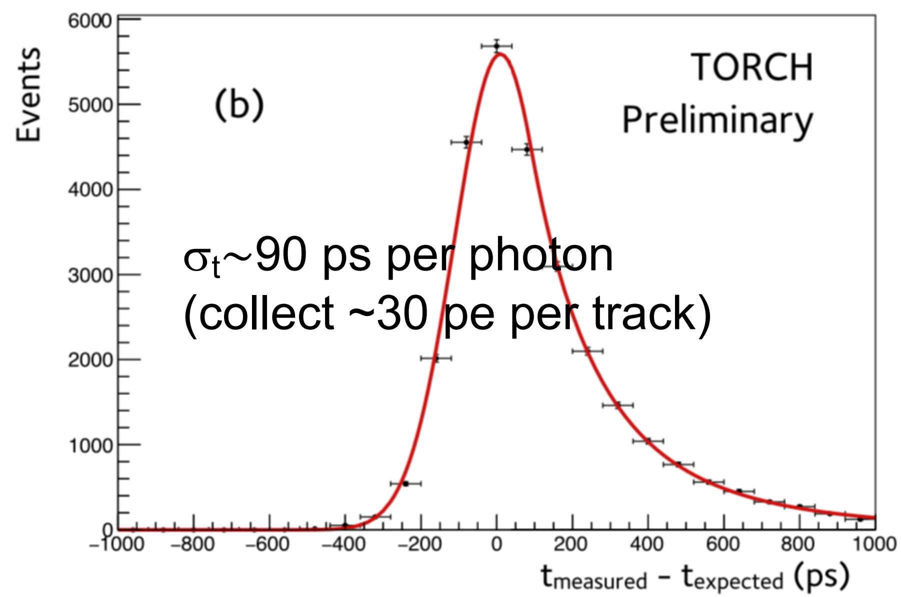
NIMA 952(2020)161692

- MicroChannel Plate (MCP) photon detectors
  - spatial resolution 6mmx0.4mm
  - ALD extends lifetime >5C/cm^2
- Approx 200k channels
- Readout NINO+HPTDC





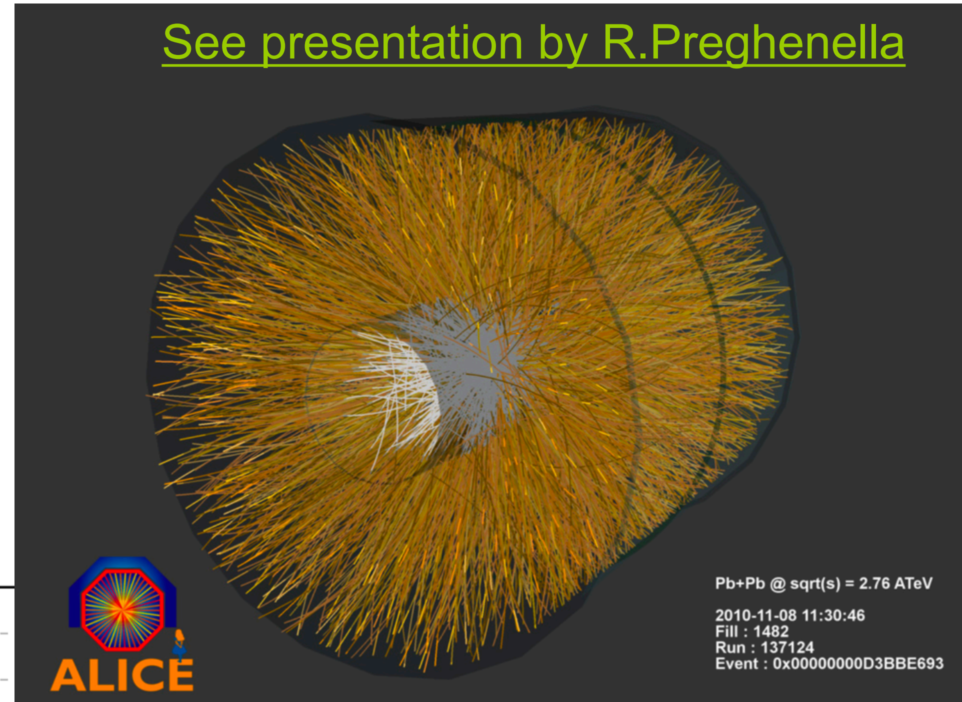


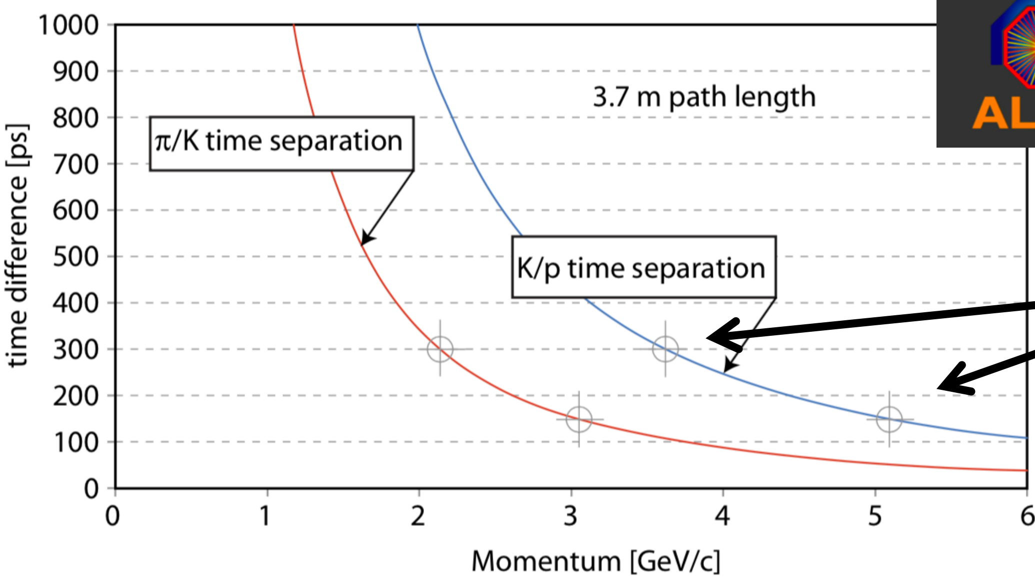


Particle ID at ALICE

JINST 14(2019)C06023, J.Phys.G 39 (2012) 123001

- Measure velocity (ToF) and p (tracking) → mass
- High multiplicities expected
  - highly segmented ToF array
  - operate in magnetic field
  - reasonable cost
  - low amount of material

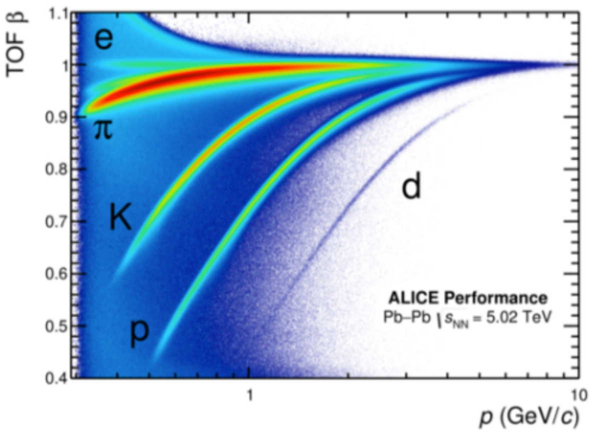


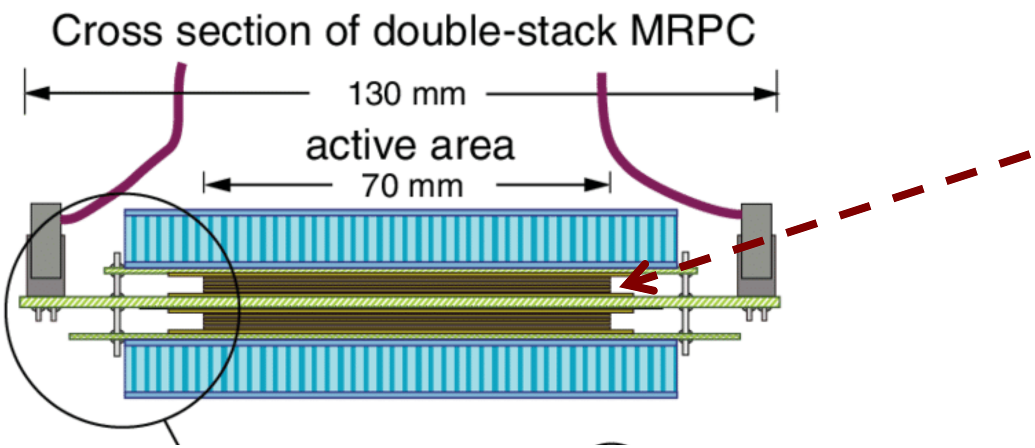


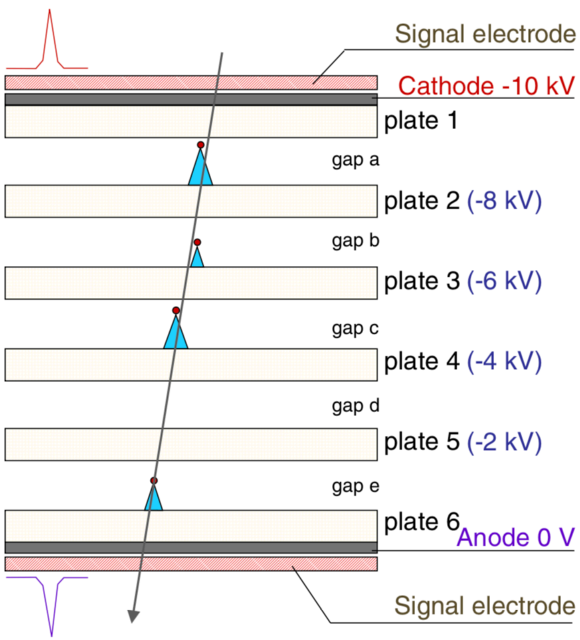
need time resolution of 100ps or 50ps

ALICE ToF

- PID: combination of ToF and dE/dx
- Multigap RPC (MRPC)
  - Many small gaps so that avalanches grow rapidly and detectable signals are generated
  - small gaps (250μm) give better timing
  - space-charge effects inhibit the growth of avalanches
- Approx 150k channels

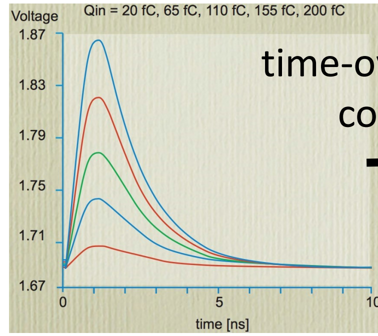


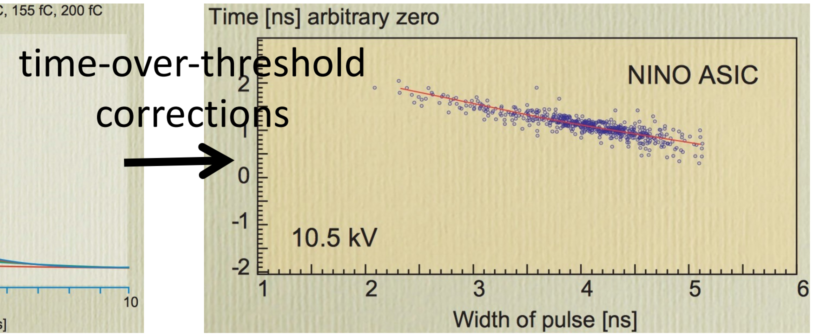


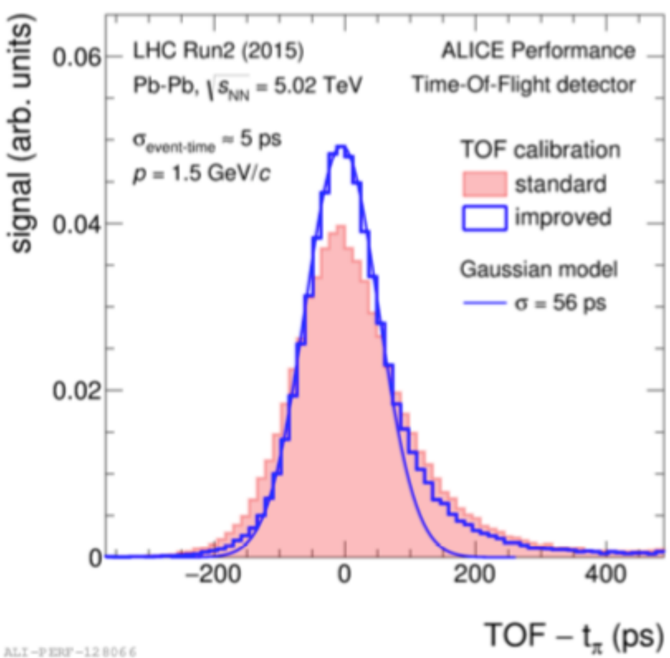


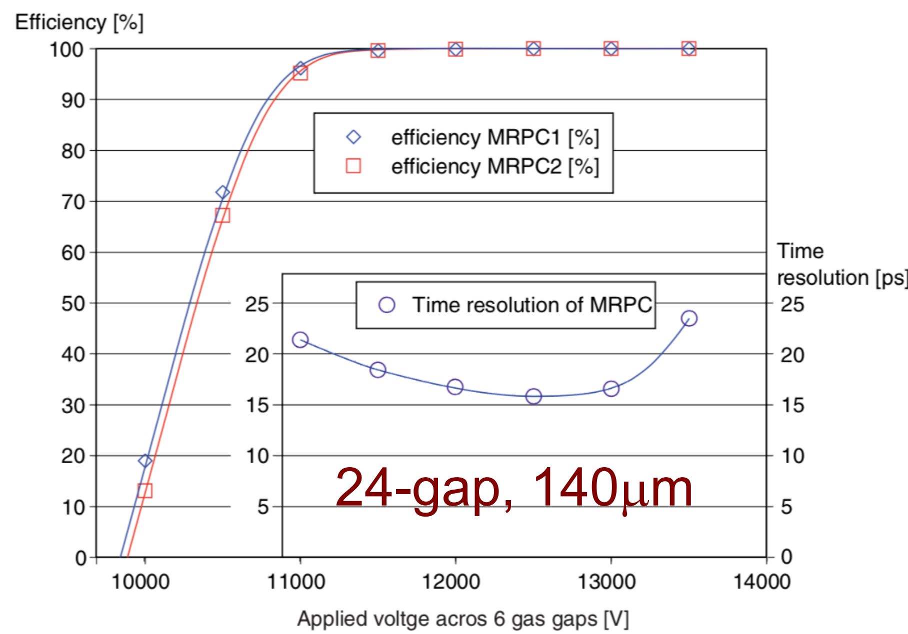
ALICE ToF performance

- 10-gap MRPC
  - σ_t~60ps @500Hz/cm^2
  - Efficiency ~100%
- For HL-LHC, 20-gap MRPC
  - Aim for ~20ps at 50kHz/cm^2







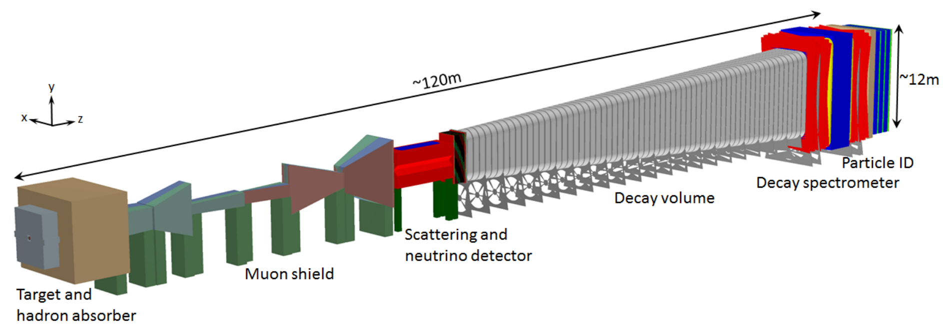


ToF @ SHiP

arXiv:1504.04956,CERN-SPSC-2019-010

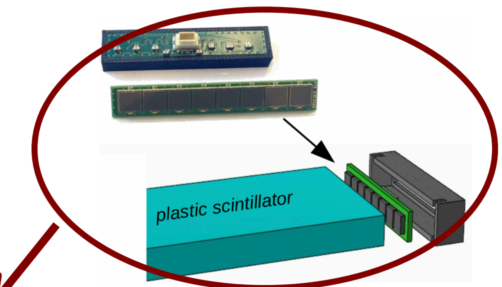
SHiP: Search for HIdden Particles

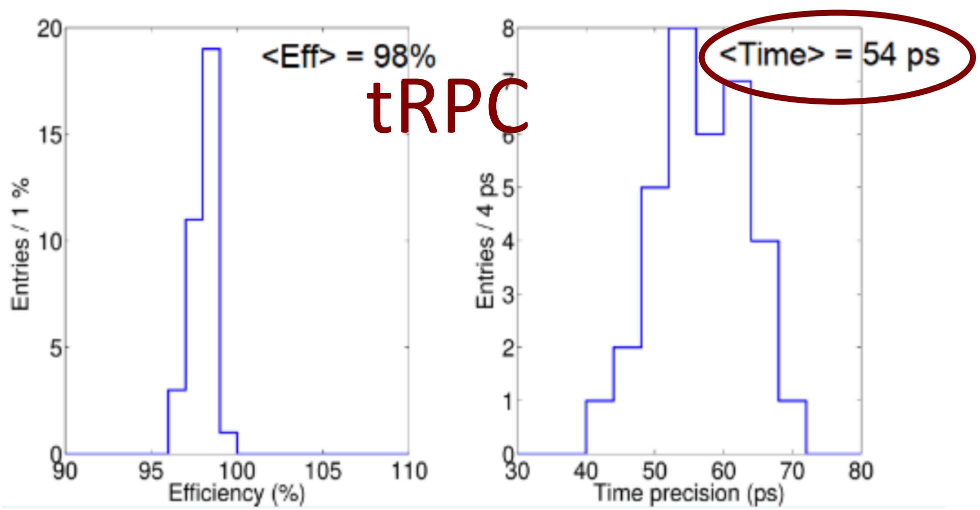
- Long-lived exotic particles, rare decays

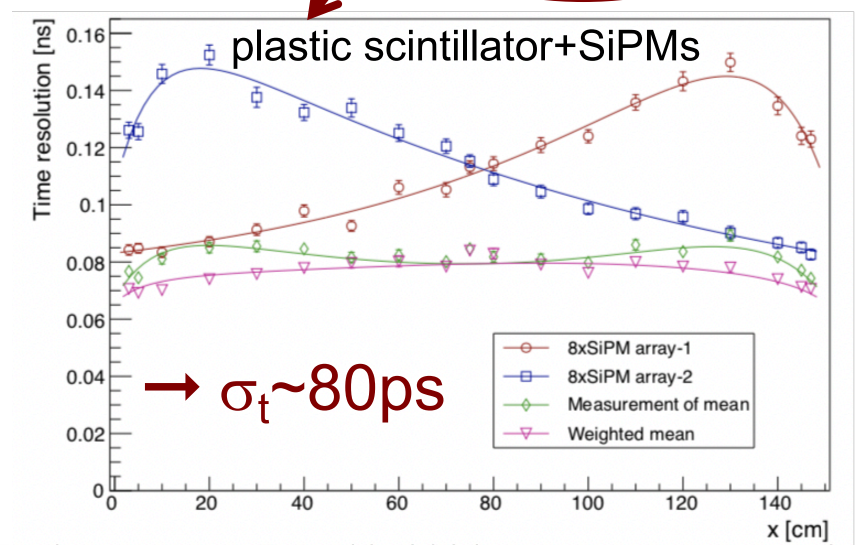


Two ToF options (~50m^2):

- Scintillator bars read by SiPM arrays
  - 1.7m bars, 6cmx1cm, 1.1k ch.
- Alternative option: timing RPCs (tRPC)
  - Sensitive module inside plastic box
  - Multi-gap RPC (12 gaps, 300μm)
  - Test beam shows high efficiency, σ_t~54ps



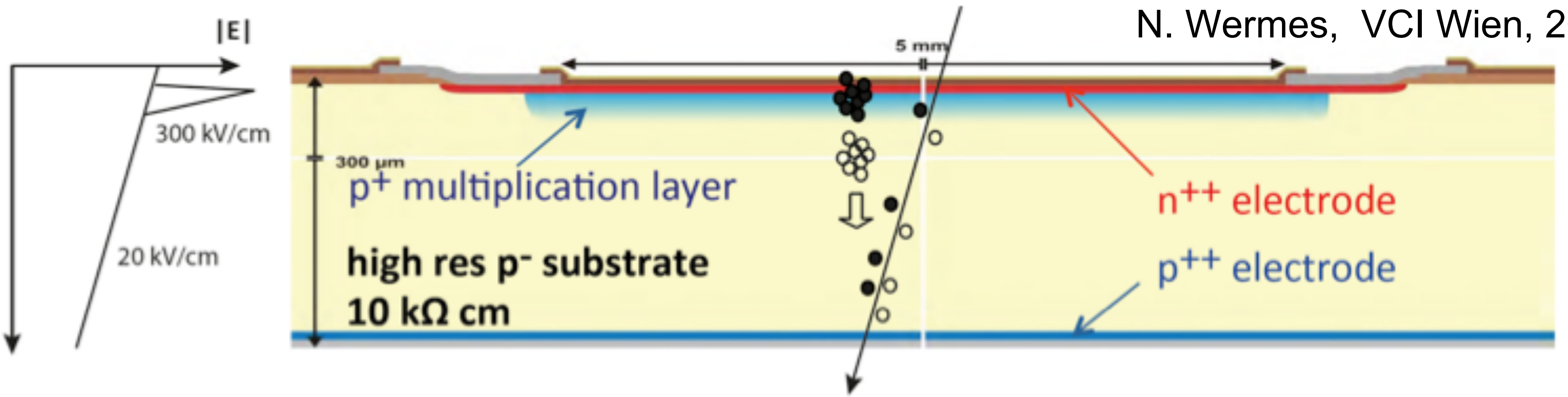




Fast timing with Si detectors

- How to reach “10ps range” with Si detectors
- Exploit “in-silicon” charge amplification
  - Geiger mode (as in gas RPC)
  - Linear mode (Low Gain Avalanche Detectors)

N. Wermes, VCI Wien, 2016

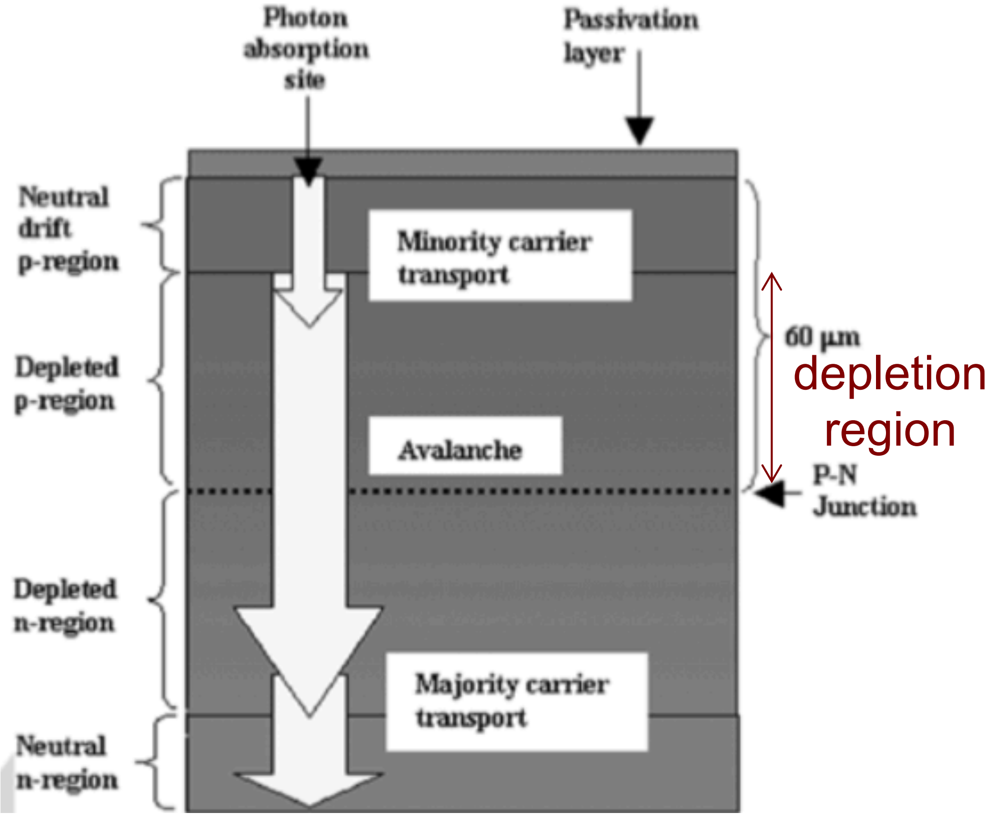


- Separate collection of charge from signal gain
- Fast drift, large signals, low noise
  - Collect electrons fast ⇒ thin
  - Large signals ⇒ amplified holes
  - Small C, small i_{leak}, low noise ⇒ small electrodes

Low-gain vs high-gain

Options for avalanche diodes

- Different amplification approaches
- “thin” layer: a few μm of depleted region
  - **Small gain** region near the surface (longer drift)
- “deep-depleted”: depletion region ~40μm
  - **High-gain** region deeper
  - shorter drift

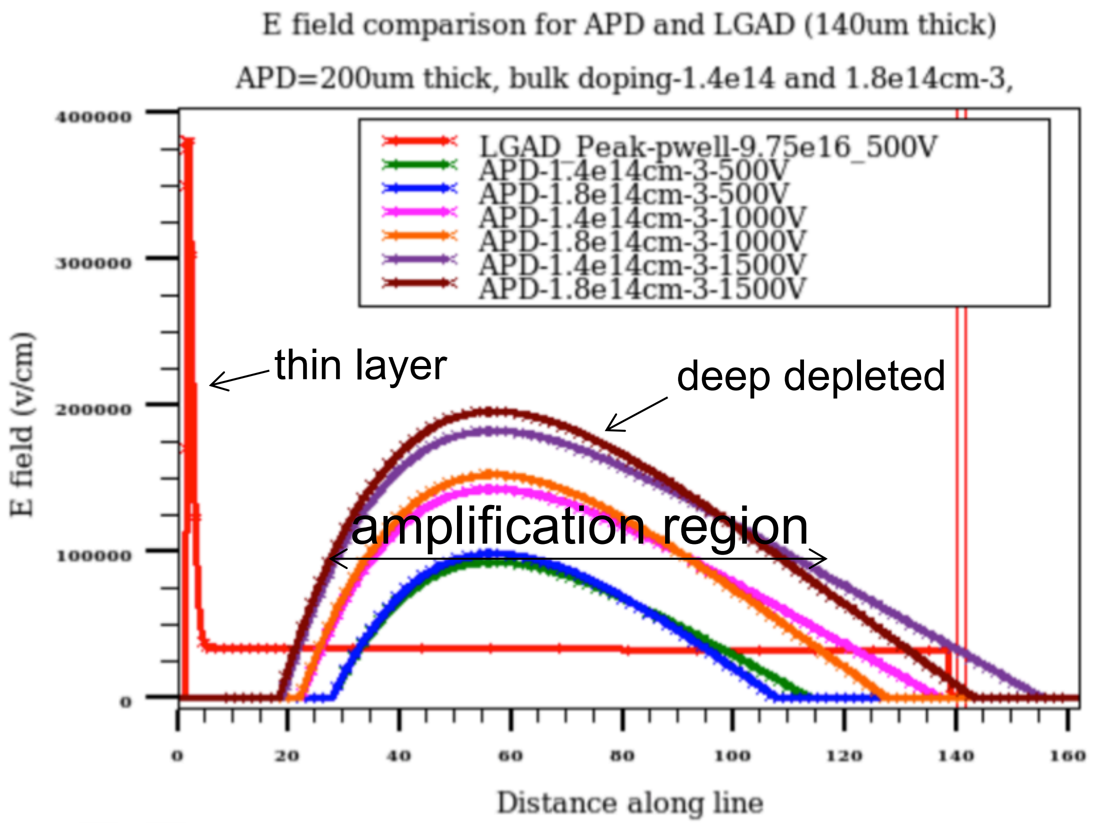


Low-gain vs high-gain

Options for avalanche diodes

- Different amplification approaches
- "thin" layer: a few μm of depleted region
  - **Small gain** region near the surface (longer drift)
- "deep-depleted": depletion region ~40μm
  - **High-gain** region deeper
  - shorter drift

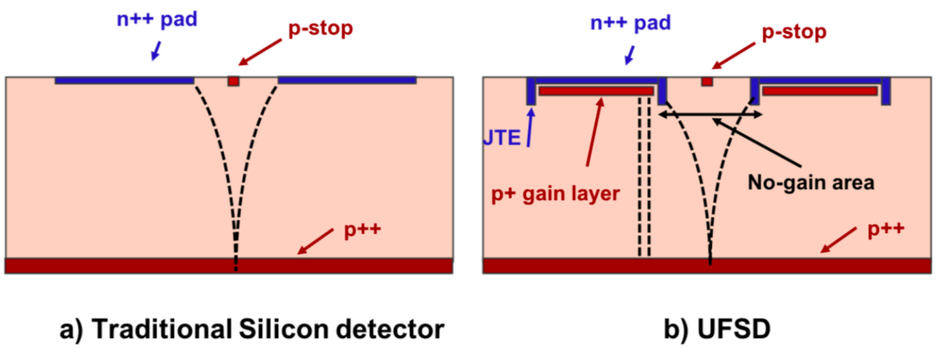
Electric field

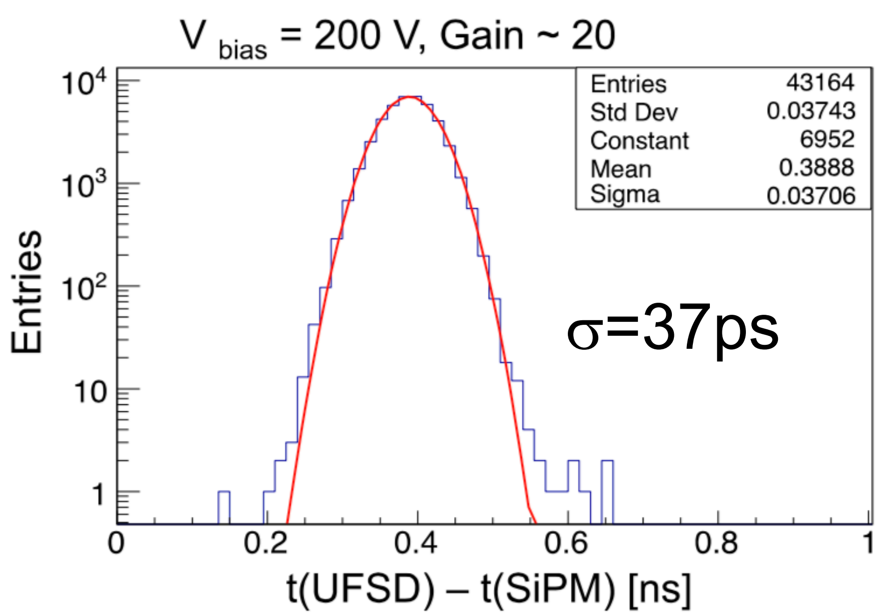


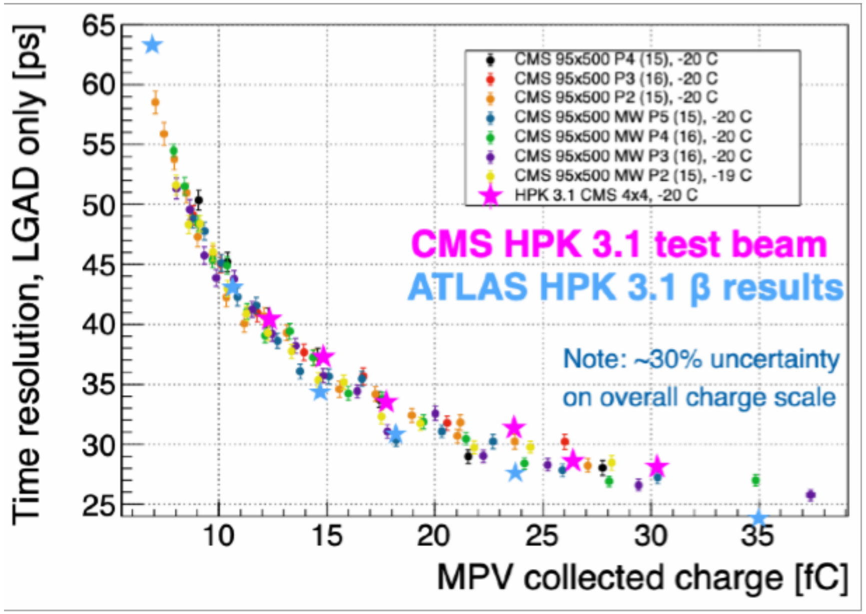
LGAD

NIMA 850(2017)83

- MTD: two layers of Si sensors 1.6<|η|<3.0
- Fast timing from Si with thin depletion region, ~50μm to reduce drift time
  - fast signal ~0.5ns
  - internal gain O(x10-30)

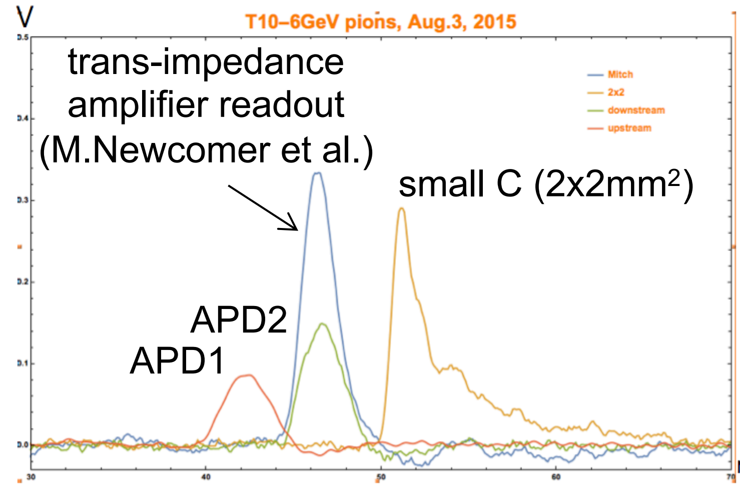


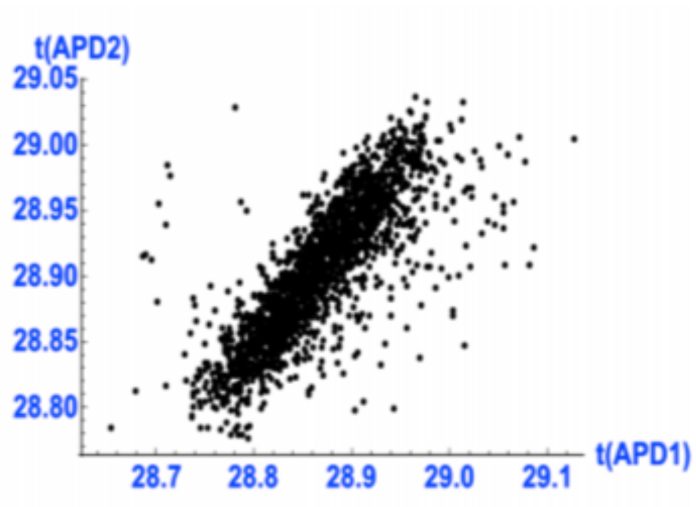


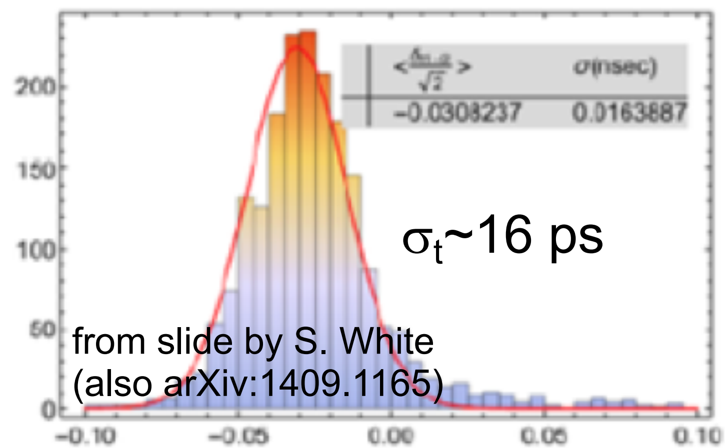


APD: Silicon Detectors

- Si sensors with amplification
  - Sensitivity to MIP in Si devices with internal amplification
- R&D on high gain APDs with field shaping to achieve fast timing
  - high gain devices (G~500)
  - “deep-depleted” technology
- Large S/N~100



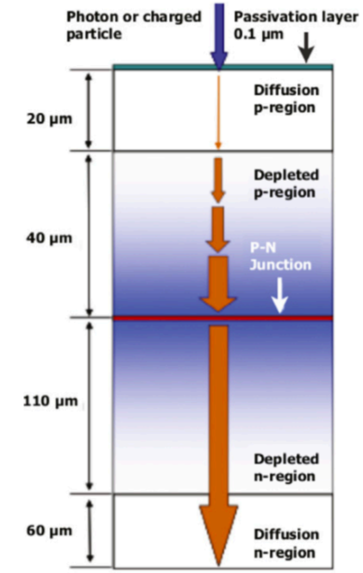


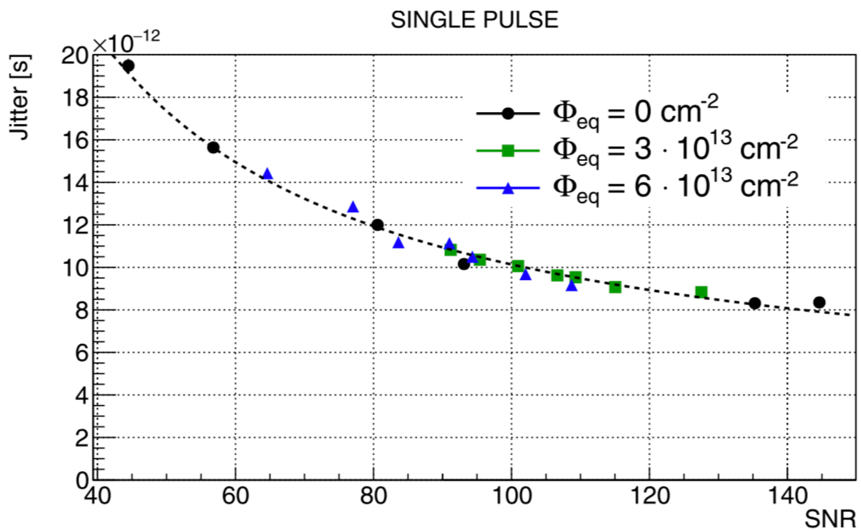


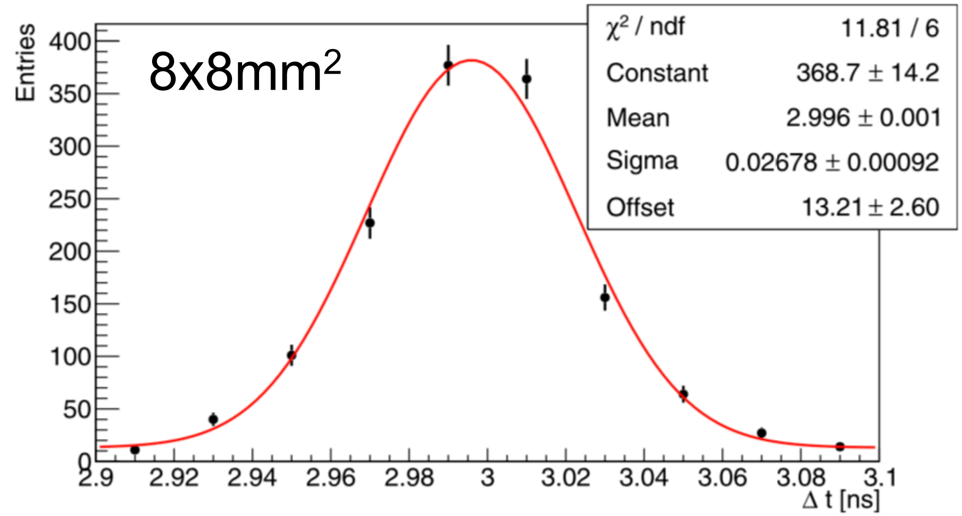
APD: Silicon Detectors

NIMA 949(2020)162930

- Si sensors with amplification
  - Sensitivity to MIP in Si devices with internal amplification
- R&D on high gain APDs with field shaping to achieve fast timing
  - high gain devices (G~500)
  - “deep-depleted” technology
- Large S/N~100



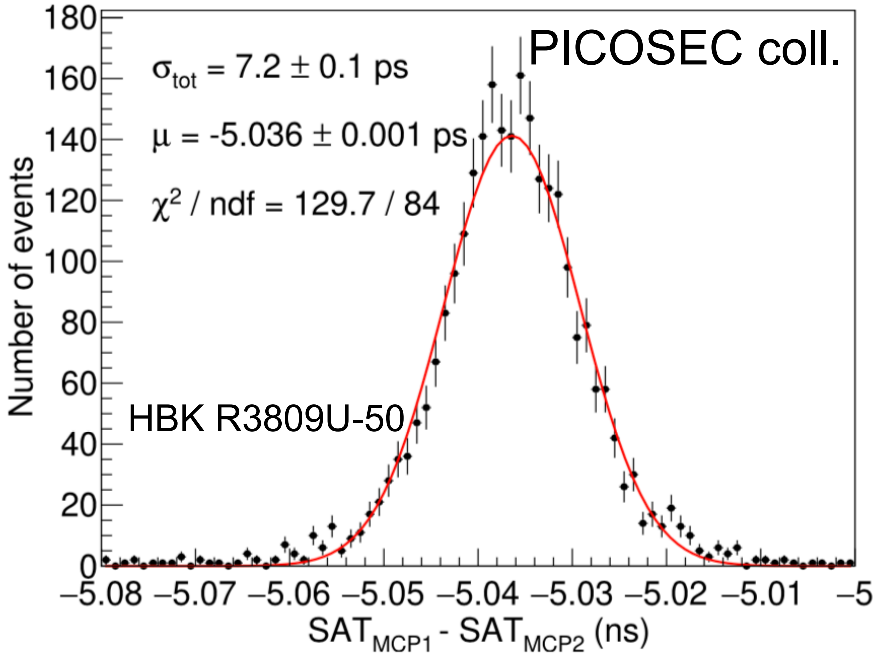




MCP PMT

NIMA 960(2020)163592

- Microchannel Plates can achieve best time resolution
- Better than 10ps in test beam



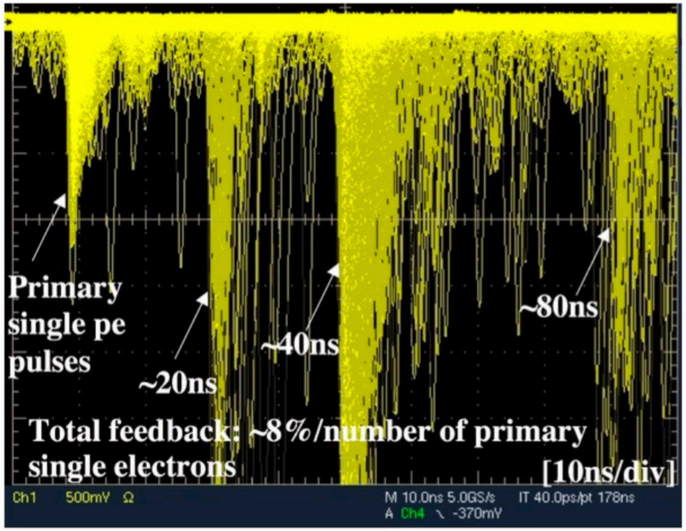
$$\sigma_{tot} = \sqrt{\sigma^2_{MCP1} + \sigma^2_{MCP2} + \sigma^2_{DAQ}}$$

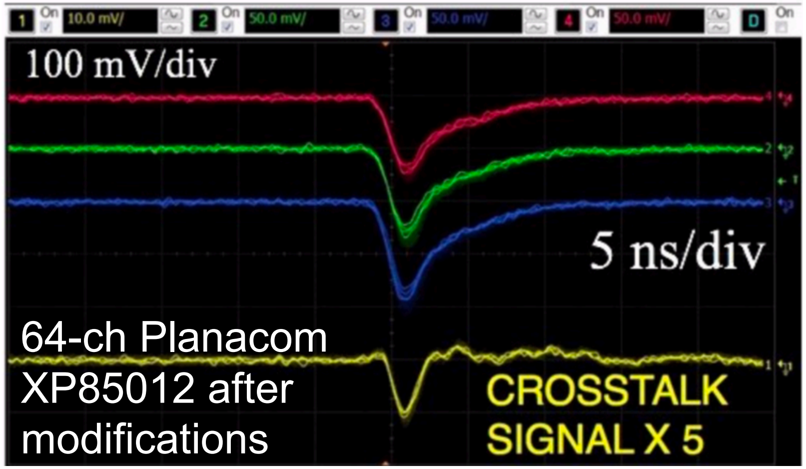
Gain	N_{pe}	total charge (electrons)	electronics resolution	final resolution	MCP type
$\sim 2 \times 10^6$	~ 70	1.4×10^8	4.1 ps	6.2 ps	HBK R3809U-59-11
$\sim 1 \times 10^6$	~ 80	8×10^7	2.0 ps	6.8 ps	PHOTEK 240
$\sim 8 \times 10^4$	~ 44	$3 - 4 \times 10^6$	2.2 ps	< 7.2 ps	HBK R3809U-50

MCP: Challenges

JPhys 1498(2020)012013

- S/N ratio crucial to time resolution
- Large total charge may cause large after-pulsing rates (due to ion-feedback)
  - After-pulses get worse at higher gain
- Multi-channel MCPs
  - Cross-talk btw pixels, charge sharing, ringing effects
- Problems relevant for use in experiments operating at high rates

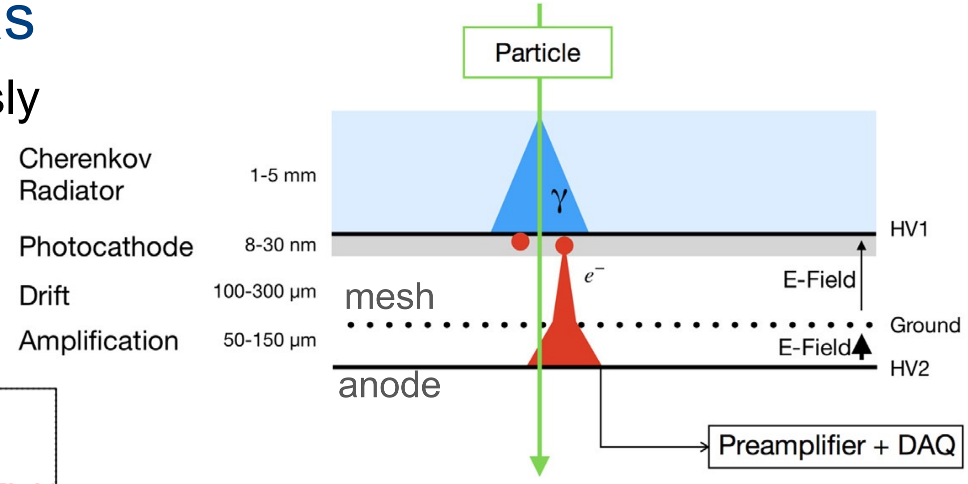


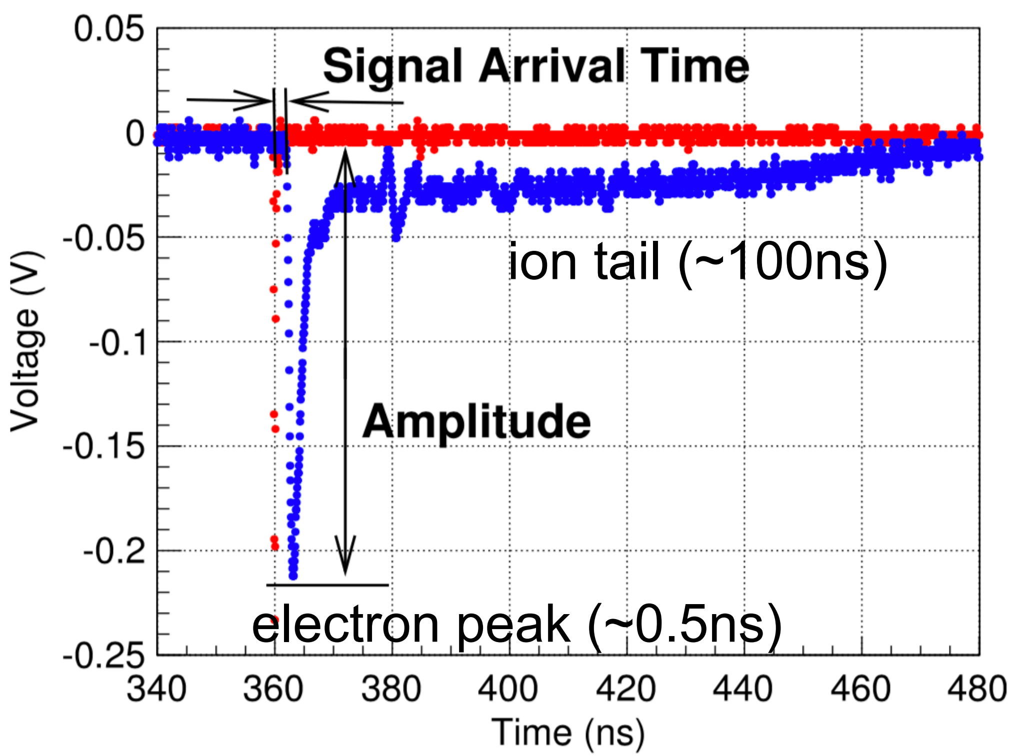


PICOSEC Micromegas

NIMA 903(2018)317

- Cerenkov radiator+Micromegas
  - photoelectrons emitted simultaneously by the photocathode
  - CsI photocathode on a thick 3mm MgF_2 window





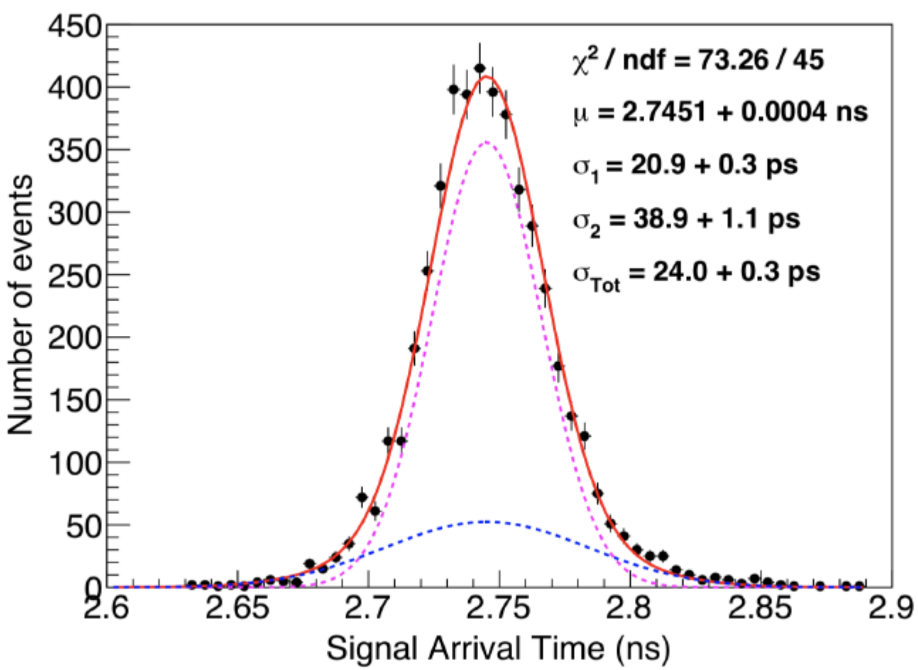
Two component signal: e-peak + ion-tail

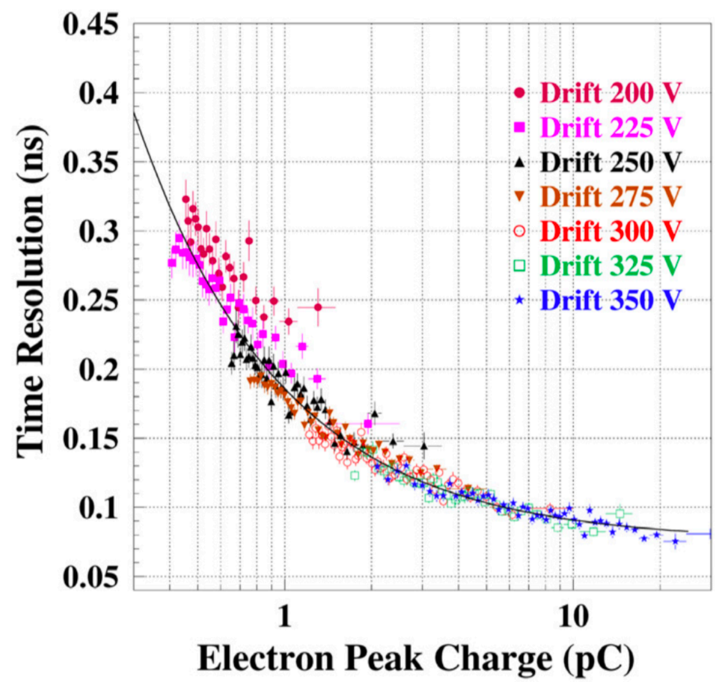
- Cerenkov radiator to produce synchrounous photons
- Short drift to reduce jitter

PICOSEC Micromegas (cont.)

NIMA 903(2018)317

- Fast MCP used as t_0 reference (<10ps resolution)
- σ_t~24ps with 150GeV muons, 76ps with single pe in laser tests (N_{pe}~10)
- Time resolution improves with higher drift field

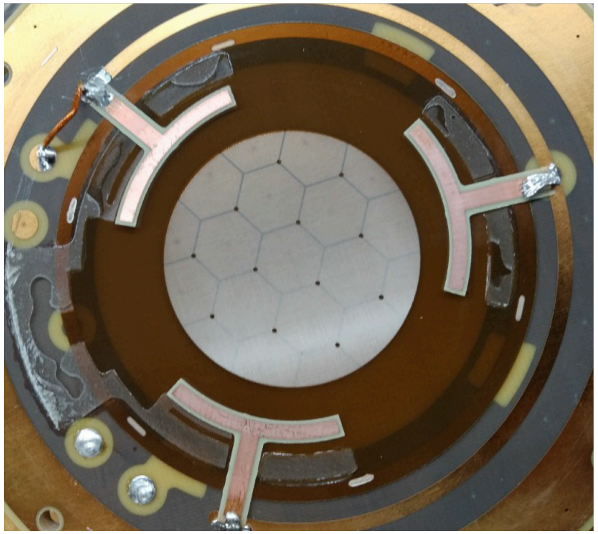




Further developments

NIMA 903(2018)317

- Resistive readout: employ resistive strips to limit effect of discharges
- Multipad readout: achieved σ_t~32ps for signal shared on 3 pads
- Photocathode lifetime: against discharges and ion feedback to increase photocathode lifetime. Different materials and protective layers under study

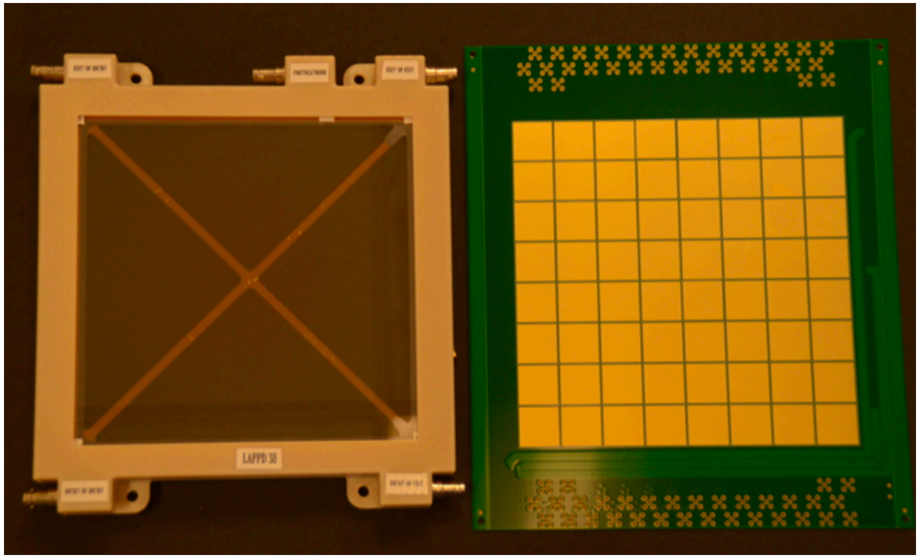


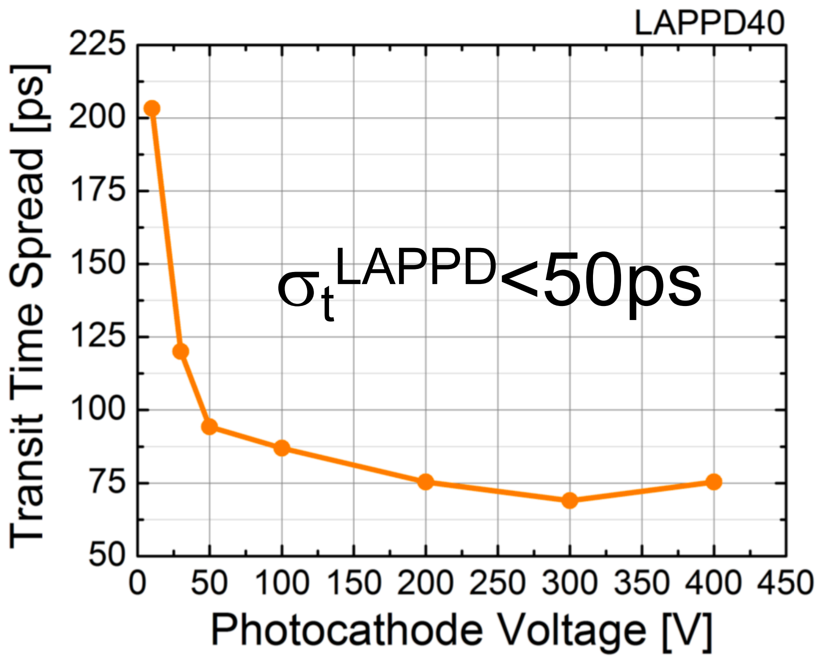
See presentation by A. Utrobicic

LAPPD: Large areas

arXiv:1603.01843, arXiv:1909.10399

- Large Area Picosecond Photo Detectors
- MCP based on planar geometry photodetector
- Design of 20x20cm^2 modules, gain >10^7, non-uniformity<15%, time resolution<50ps for single photons, spatial resolution 700μm





Fast timing at 20-30ps

- Good progress in small single-pixel devices
- More difficult in larger systems

$$\sigma_{time} \sim t_{risetime}/(S/N)$$

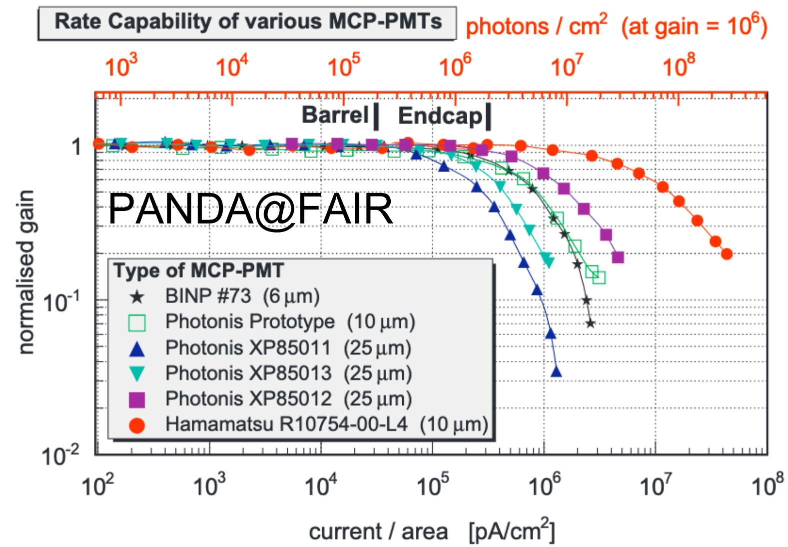
- Possible to obtain a good time resolution with large S/N ratio
  - for $t_{risetime}$= 200ps → need S/N~10 to get to 20ps
  - for slower risetime ~2ns, need S/N~100
- Many other effects also contribute (electronics, chromatic effects, #of pe, transit time, reference t_0, stability of clock system, etc)

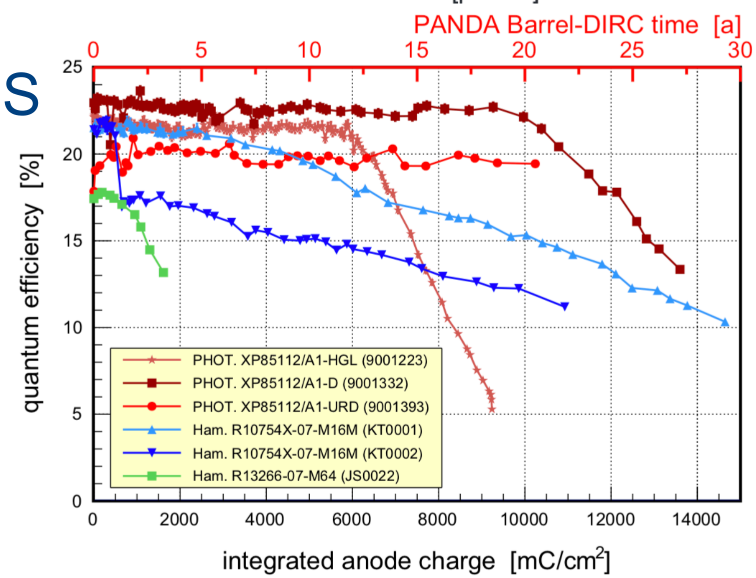
Time resolution, rates, aging

NIMA 939(2011)144, NIMA 876(2017)42

- MCPs currently provide best time resolution
- Micromegas gas detectors can reach 24ps

- High rates: Stable operation with MCPs to 200-300kHz/cm^2
- Aging: Expected radiation at ATLAS/CMS is challenging (~4x10^{15} n_{eq}/cm^2 and ~4MGy=400MRads)
- Large areas, complex systems: current tests w/ few pixels, small, less complex





Summary

- ToF measurements are key to particle ID
- Precise time determination
- Vast progress in many areas
  - Synchronous signal, high gain, thin drift, etc.
  - Across different technologies
- Several challenges (aging, rates, large areas, etc.)

- Average distance between vertices at z=0:
  - 1mm for HL-LHC (140 pileup)
  - 125μm for FCC-hh (1000 pileup)

Thank you!

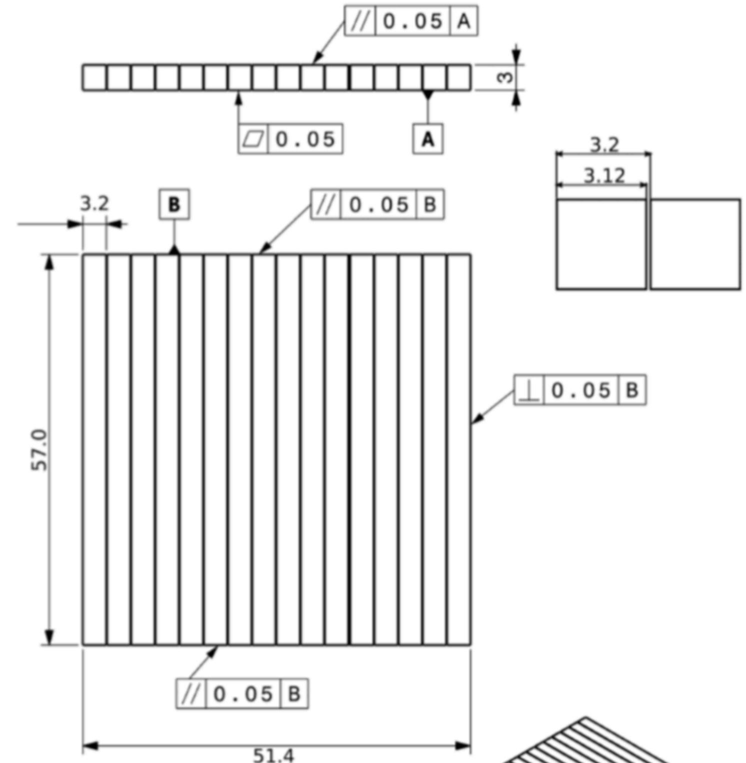
Questions?

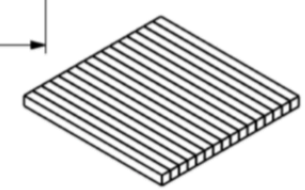
Many thanks to Eraldo Oliveri for
useful discussions and various inputs

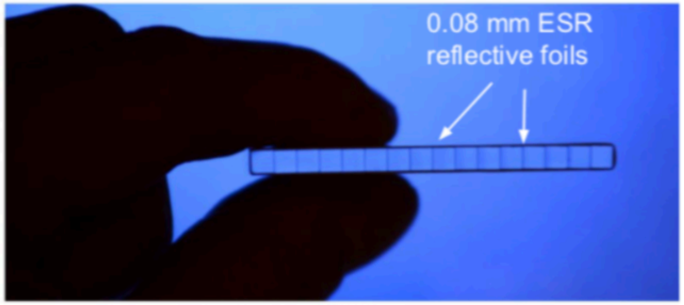
backup

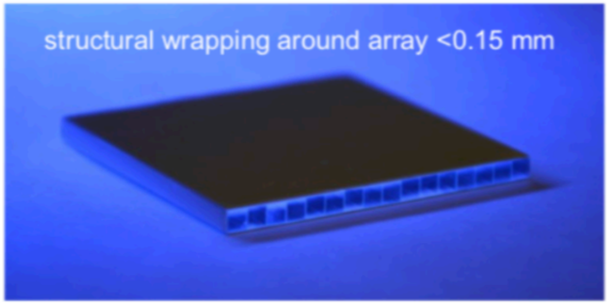
LYSO crystals

- **Lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) as scintillator**
    - Excellent radiation tolerance
    - Dense (>7.1 g/cm3): a MIP deposits ~4.2 MeV including impact angle (0.86 MeV/mm)
    - Bright: light yield (LY) ~40k photons/MeV.
    - fast rise time 100 ps and decay time ~40 ns



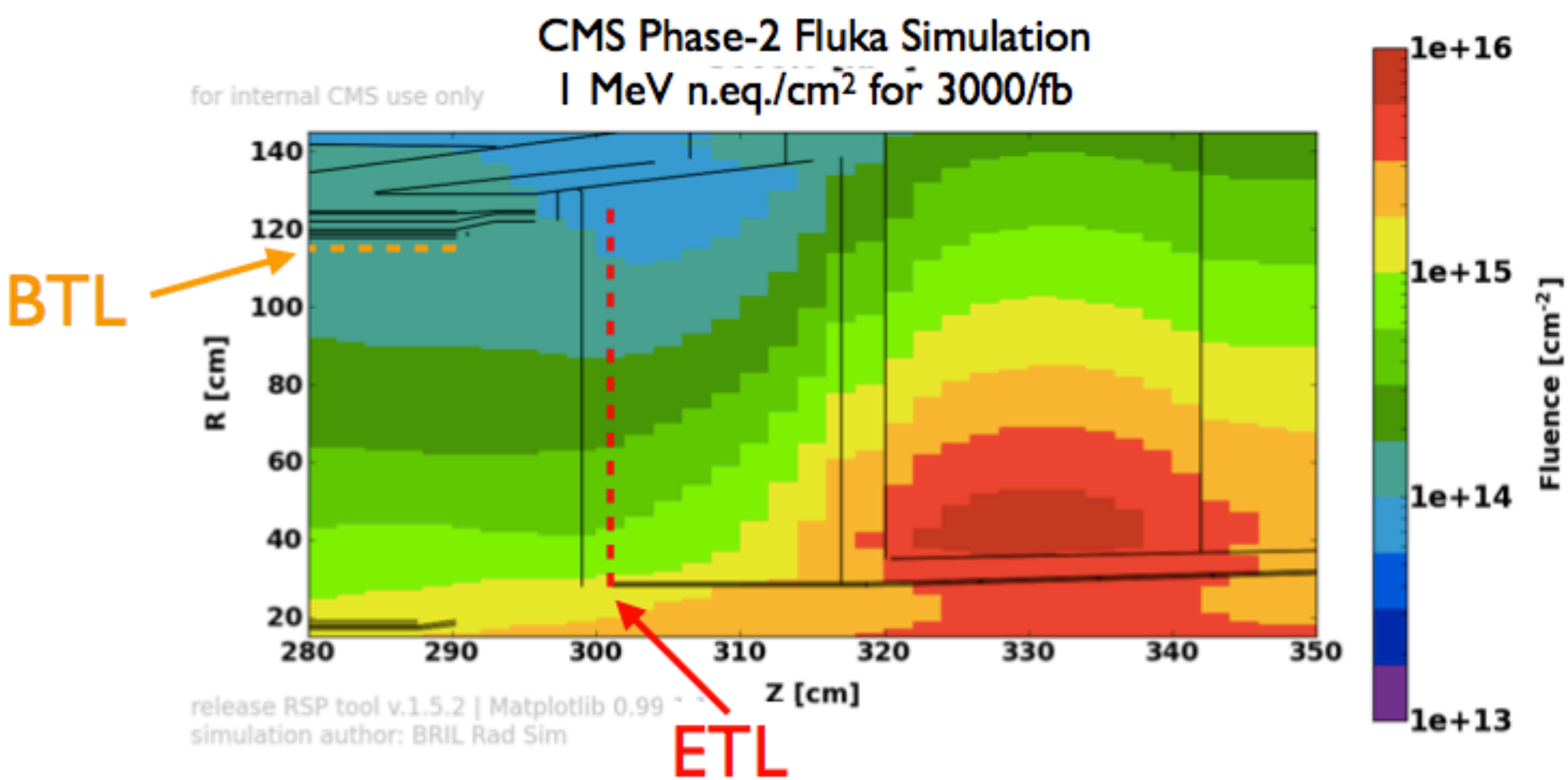






Radiation at HL-LHC

- Technology choices are driven by radiation and cost
  - BTL: LYSO + Silicon Photomultipliers (SiPM)
  - ETL: Low Gain Avalanche Detectors (LGAD)



Diamonds@PPS: Test beam

CERN-CMS-NOTE-2020-007

- Single crystal scCVD diamond sensors operated during Run2
- Sensors exposed to highly non-uniform proton radiation, fluence ~5×10^{15}p cm^{-2} (~2×10^{15} $n_{eq}cm^{-2}$)
- Test beam in 2019