Università di Roma Tor Vergata



# Conceptual design of RPCs in future muon systems

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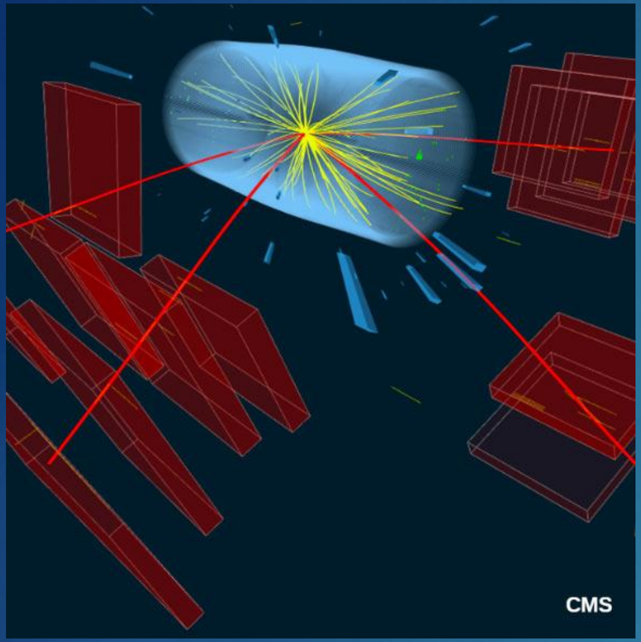
FIRST DRD1 COLLABORATION MEETING, JANUARY 30 2024, CERN

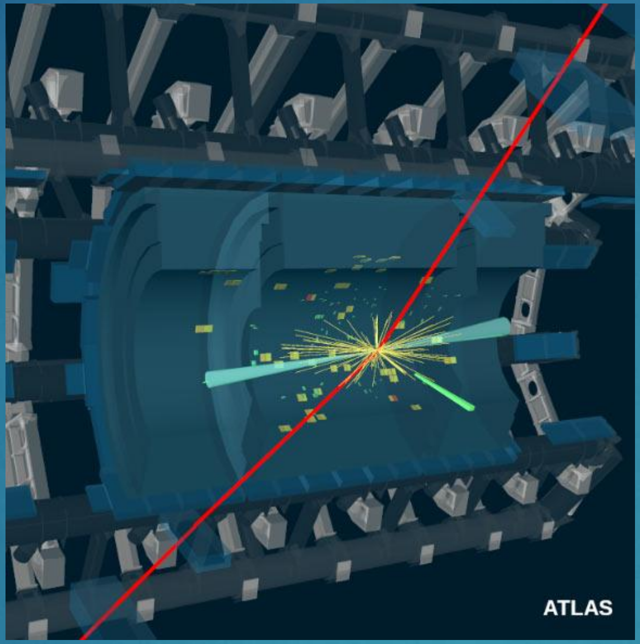


INFN Sezione di Roma Tor Vergata

# Introduction on muon systems






- Muon systems is whatever comes after the hadronic calorimeter, wrapping all the other detectors
- It is designed to provide a primary trigger on muons and measure their momentum spectrum
- It is done by measuring the muon trajectory deflection in a magnetic field

Typical features for HL-LHC

- measure of track curvature → thousands of m^2 instrumented surface
- Particle rate << than innermost detectors
- Typical tracking precision ~ 100 µm (with B ~1T and R=5m)
- Typical tracking trigger resolution 1 cm
- Typical trigger detector resolution < 5 ns

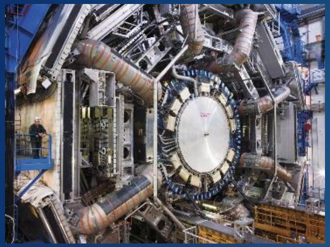
**How this will evolve in FFC scenarios and what are the consequences on the muon detector design?**

# State of the art of classic RPCs

- (some of)Present and recent past Application at colliders

- PRESENT AND RECENT PAST COSMIC RAYS AND UNDERGROUND

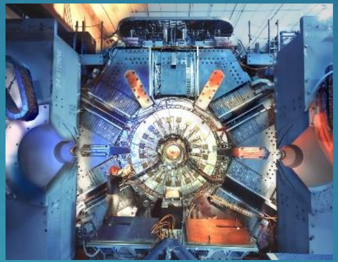




ATLAS
LHC 7000 $m^2$
HL-LHC1400 $m^2$
Tracking trigger

CMS
LHC 4000 $m^2$
HL-LHC1000 $m^2$
Tracking trigger

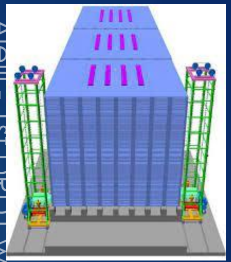
ALICE
LHC 144 $m^2$
HL-LHC new RPCs
Tracking trigger



BaBar
SLAC 2000 $m^2$
Instrum. iron
$\mu$ identifier

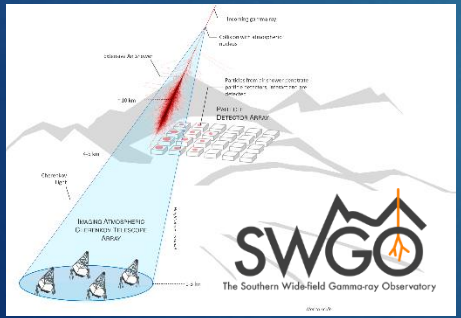
OPERA
CERN $\nu$ beam
Instrum. iron
$\mu$ spectrometer

ARGO Ybj
CR exp. 7000 $m^2$
4600 m altitude
3D reconstruct.

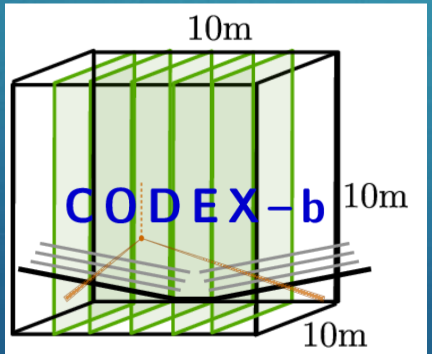


INO (staged)
$\nu$ observatory
150000 $m^2$
Instrum. Iron

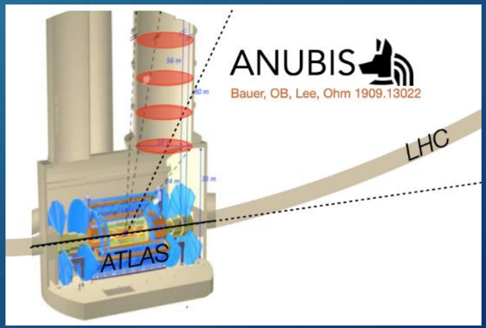
- ACTIVE PROPOSALS FOR FUTURE EXPERIMENTS USING PRESENT TECHNOLOGY




SWGO - STACEX
CR exp. 22500 $m^2$
5000 m altitude
3D reconstruct. +
Cherenkov



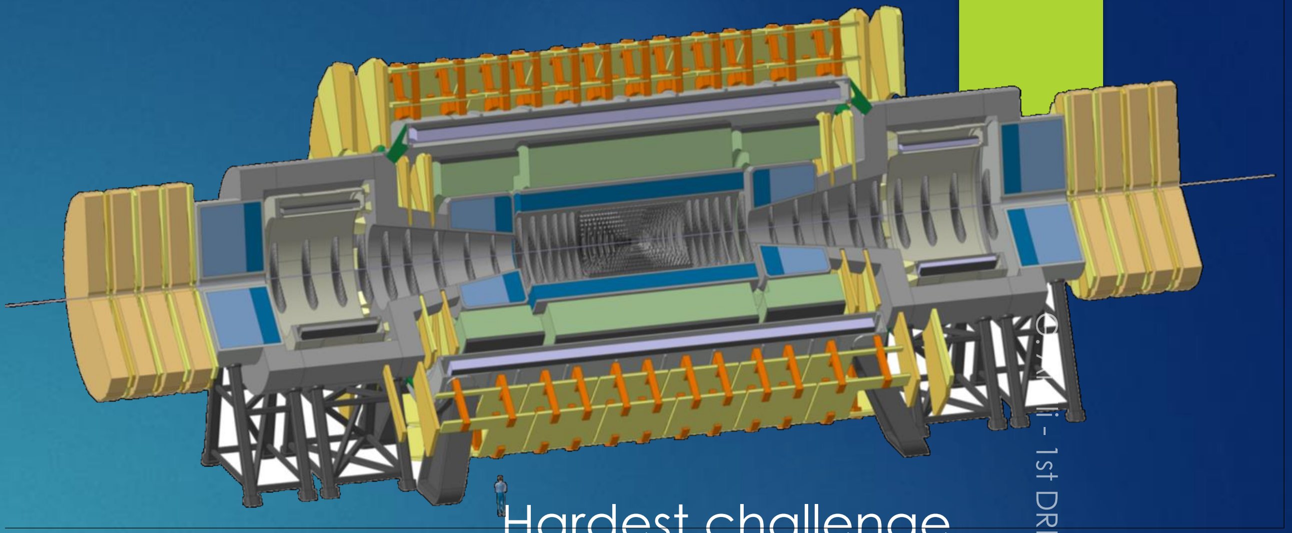

CODEX-B
HL-LHC. 3000 $m^2$
Search for DM
Sealed tracking
volume

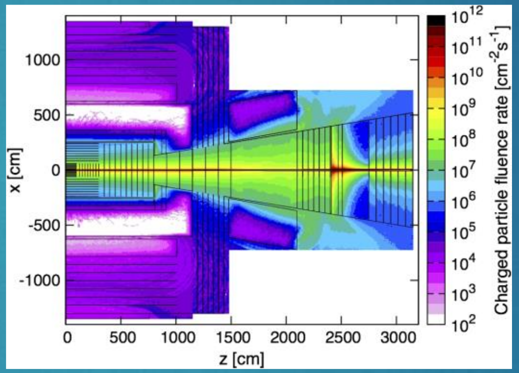


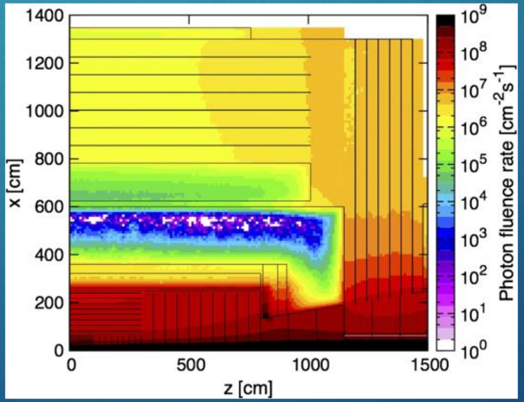

ANUBIS
HL-LHC. 5500 $m^2$
Search for DM
Sealed tracking
volume

# The quest for FCC

- RPC (all versions) is candidate technology for FCC experiments
- Key features
  - 50ps time resolution
  - (300 ps for single gap) Single Gap RPC Efficiency > 98%
  - 2D tracking, resolution up to 0.1 mm
  - Proportional response to high track density
  - Large size robust and Low cost
  - Thin and light
- RPCs underwent a substantial performance improvement from LHC to HL-LHC
- Can be further improved for FFC…
- R&D is needed






Hardest challenge

- pp collisions at 100TeV (FCC-hh)
- Pileup: 1000 events/bunch crossing → spatial resolution, timing

Muon barrel and endcap

- Charged rates ~ 5x$10^4$ cm$^{-2}$s$^{-1}$
- photon rates ~ 5x$10^{6-8}$ cm$^{-2}$s$^{-1}$
- N fluence ~$10^{14}$ cm$^{-2}$

Shielding can mitigate the effect on muon chambers

# FCC-hh parameters and constraints



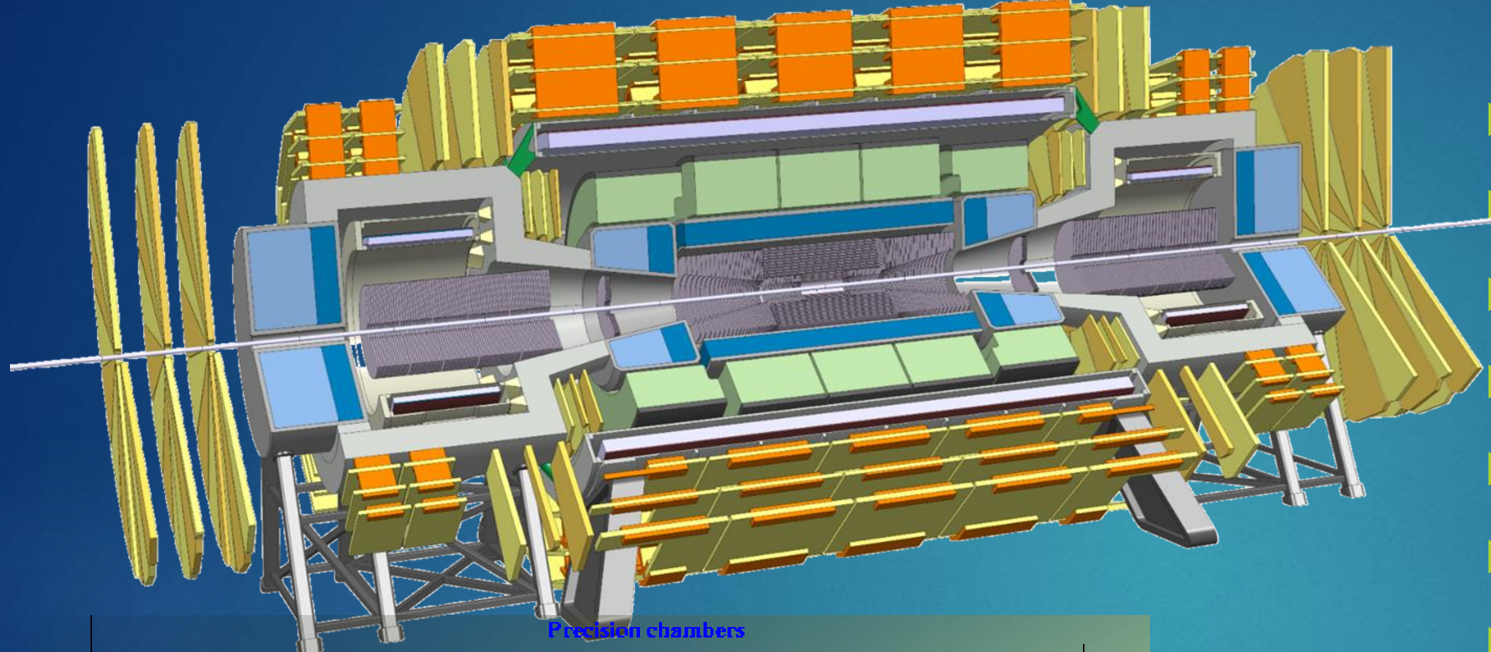
| parameter | FCC-hh | | HE-LHC | HL-LHC | LHC |
|---|---|---|---|---|---|
| collision energy cms [TeV] | 100 | | 27 | 14 | 14 |
| dipole field [T] | 16 | | 16 | 8.33 | 8.33 |
| circumference [km] | 97.75 | | 26.7 | 26.7 | 26.7 |
| beam current [A] | 0.5 | | 1.12 | 1.12 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 (0.2) | 2.2 (0.44) | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 (5) | 25 (5) | 25 | 25 |
| synchr. rad. power / ring [kW] | 2400 | | 101 | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 4.6 | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 1.8 | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.25 | 0.20 | 0.55 |
| normalized emittance [$\mu$m] | 2.2 (0.4) | | 2.5 (0.5) | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | 25 | 5 | 1 |
| events/bunch crossing | 170 | 1000 (200) | ~800 (160) | 135 | 27 |
| stored energy/beam [GJ] | 8.4 | | 1.3 | 0.7 | 0.36 |

- Constraints given by FCC-ee are less challenging for that concern the background rate and similar for the rest

- Highlighted in red → drivers for muon systems
- A factor 6 higher average rate w.r.t HL-LHC
- Physics boosted in the forward regions → muon precision $|\eta|$~4
- Combined muon tracking
- Stand-alone muon trigger
- X10 pileup → option to lower at 5 ns the BC to reduce the bunch intensity

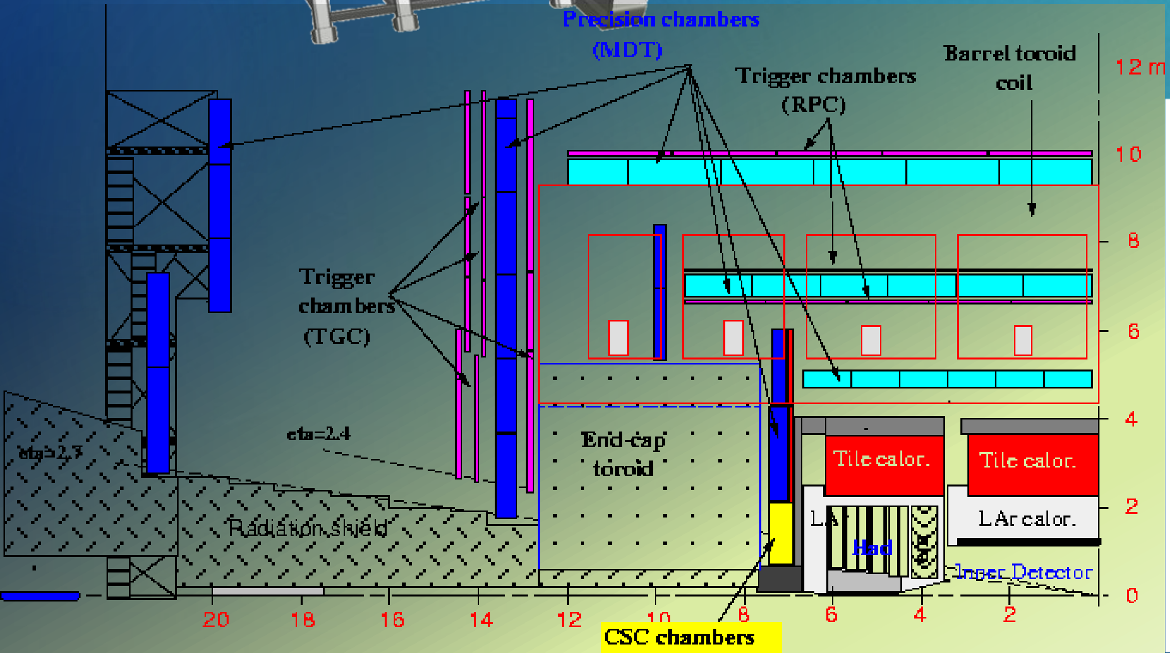
# FFC-hh reference detector

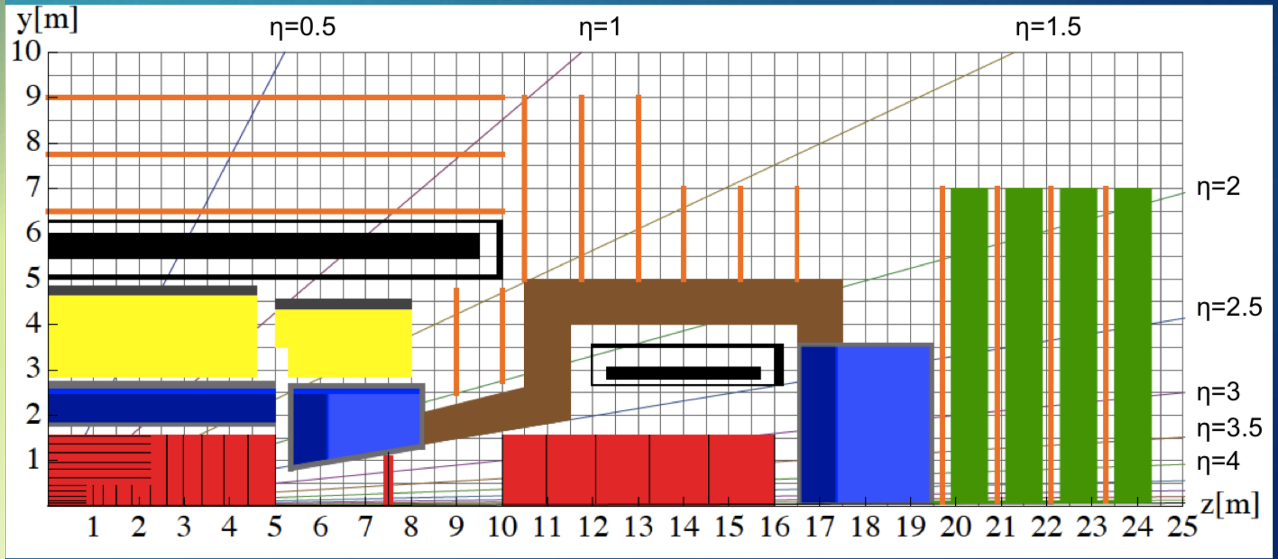




- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL Lar

- MUONS?
  - Barrel
  - Encap
  - Forward
- Various gaseous detectors



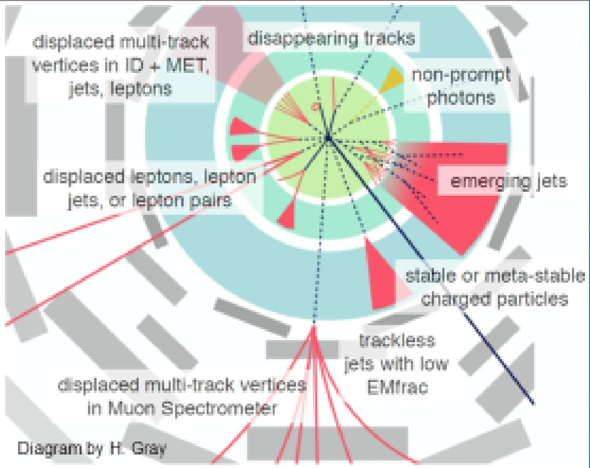



# Constraints from LLP and DM searches

# Beyond the muon detector: LLPs

## Why, how, where LLPs?

- Small couplings or small mass differences generically lead to LLPs
- Exact signature depends on LLP quantum numbers and decay modes → many possibilities, necessary to understand experimental sensitivity to these
- FCC-ee: charge, color neutral initial state → direct production of charge, color neutral BSM particles/ final states
  - Light color, electrically charged BSM particles heavily constrained
  - Consider looking for charge, color neutral particle
  - Displaced vertex signature
- FCC-hh: possible to also probe charged/colored BSM particles
  - Disappearing tracks
  - (Heavy) Heavy stable charged particles, stopped particles, R-hadrons as possible signatures
  - These exotic signatures are not covered in this talk




LLPs can also be looked for in MET and prompt final states

See talk by R. Gonzalez Suarez
See talks in the morning session

S. Kulkarni 3 31 May 2022

- Detector for long-lived particles at high energy of 100 TeV
- Has ca 500 times more sensitivity; 150 due to increased cross section and luminosity and factor 3-4 due to moving detector closer to IP

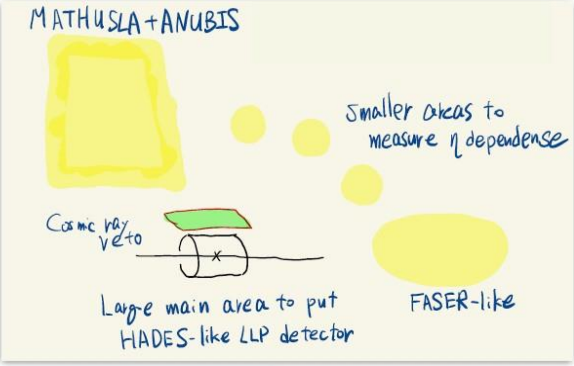
Impact on the muon system

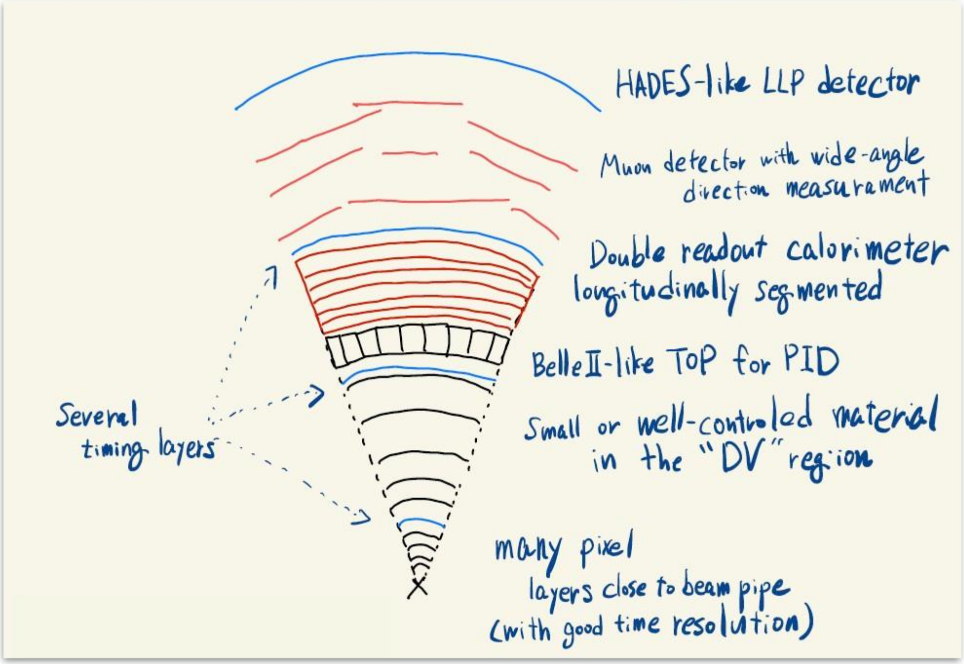
- Local vertex identification
- 3D tracking
- ~ 100 ps ToF capabilities
- Particle identification via ToF and pre-shower layers

# A dream LLP detector?

## A dream LLP detector?

Ryu Sawada's first example at the LLP workshop in November-2020



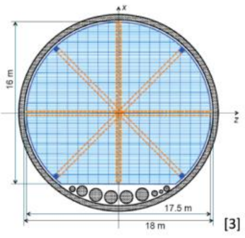




Adding a good timing and tracking layer extending the muon system...

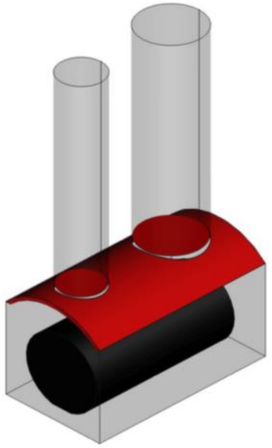
Dedicated detectors: ANUBIS

**ANUBIS – AN Underground Belayed In-Shaft search experiment**

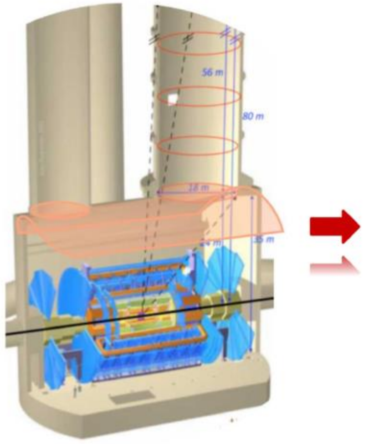
- Proposal to instrument the ceiling of the ATLAS Cavern at Point-1
  - > Include stations in the two service shafts (PX14, PX16)
  - > Ceiling approximately 20m away from the ATLAS IP
  - > Cavern ceiling proposal shown to be more sensitive (compared to Shaft only)
  - > Larger active volume (4.3 x $10^4$ $m^3$ vs 1.3 x $10^4$ $m^3$) and large detector area~$10^3$ $m^2$




PX14 Shaft: Cross sectional view



Proposal

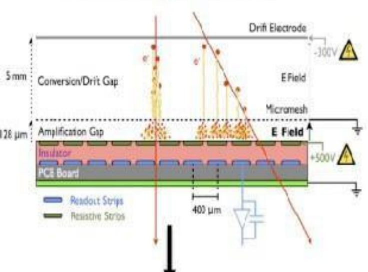


arXiv:1909.13022

https://twiki.cern.ch/twiki/bin/view/ANUBIS

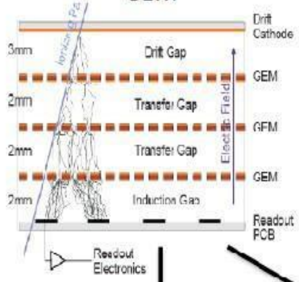
PX14 Shaft + Ceiling

MicroMegas (MM)



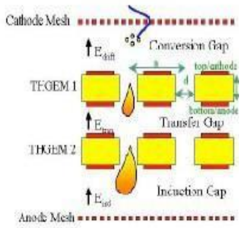

ATLAS new small wheels

GEM



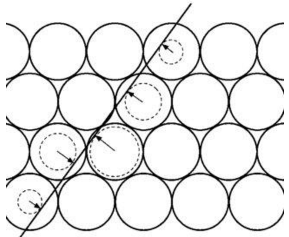

CMS GEM

THGEM



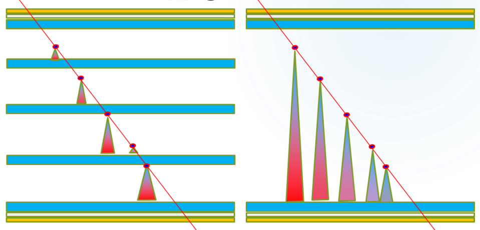

ALICE TPC upgrade

sMDT



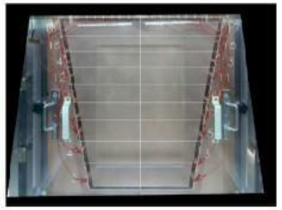
ATLAS Ph1 + Ph2 upgrade

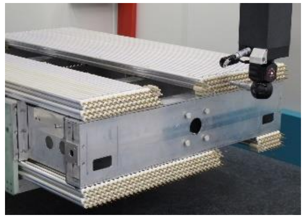
RPC

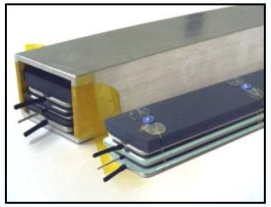


ATLAS Ph1 + Ph2 upgrade and CMS RE3/1 & RE4/1

Several experiments at GSI and RICH



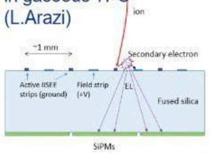




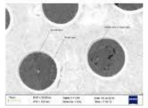
# Muon detector technologies

## AND NEW IDEAS

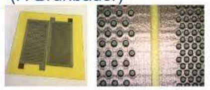
Positive Ion Detection in gaseous TPC (L.Arazi)



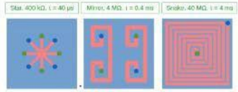
Charge transfer properties through graphene (P.Thuiner)



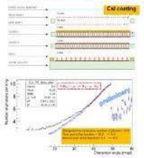
3D printed THGEM (F. Brunbauer)

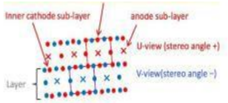


Scream mm (M. Chefdeville)



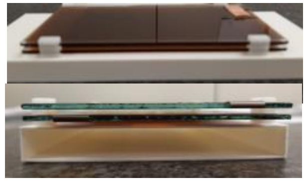
COMPASS RICH-1 (Compass)



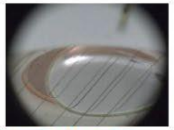


sRPC (Bencivenni

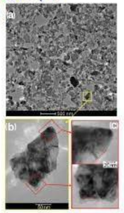
single gap semi-conductor R. Cardarelli



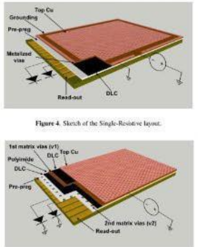
Bubble-assisted Liquid Hole-Multipliers (E. Erdal)



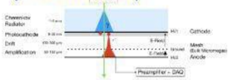
Nanodiamond photocathode (A. Valentini)



uRWELL (G. Bencivenni)

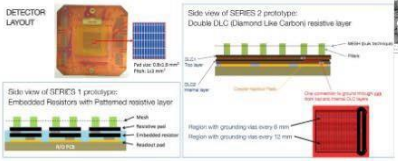


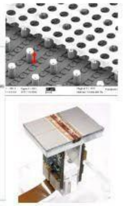
PICOSEC mm (PICOSEC coll.)

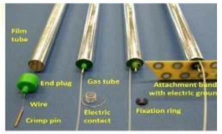


GridPix (J. Kaminski)

Small pad resistive mm (M. Iodice)

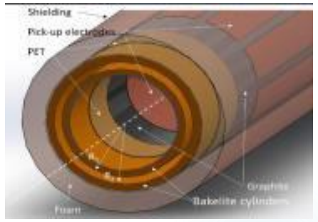




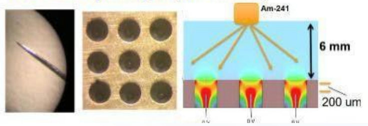


Straw tube components (for PANDA-STT [1])

RCC Cardarelli



TIP-HOLE prototype (M. Cortesi)

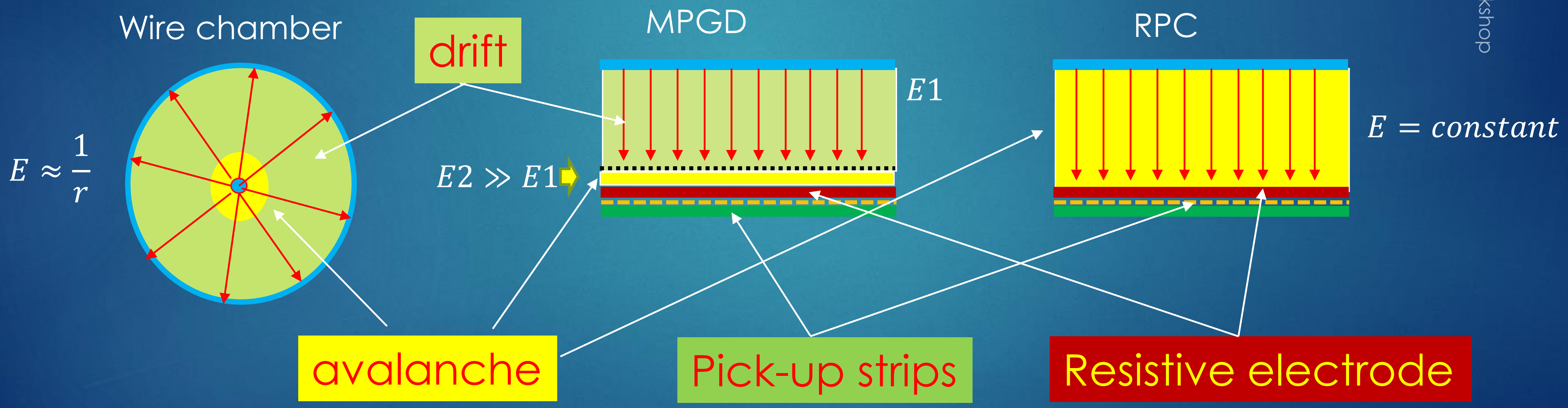


# Basic principles of muon detectors



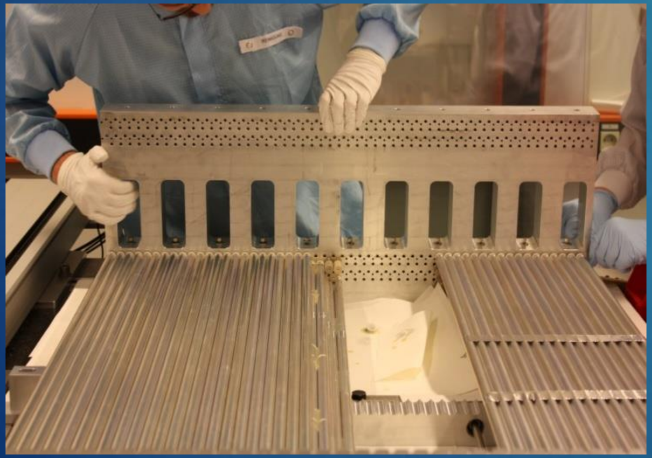
- All gaseous detectors designed for muons share the same base principle:
  - A gaseous target thick enough for a MIP to release a sufficient primary ionization
  - An electric field sufficiently strong to start an avalanche multiplication
  - A segmented pick-up electrode to readout the signal and extact a space-time information

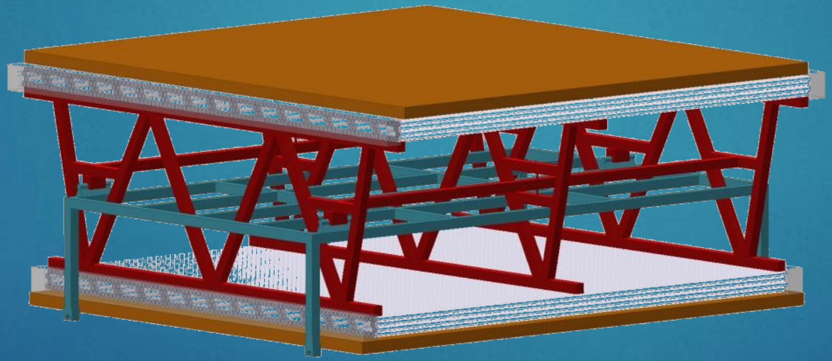


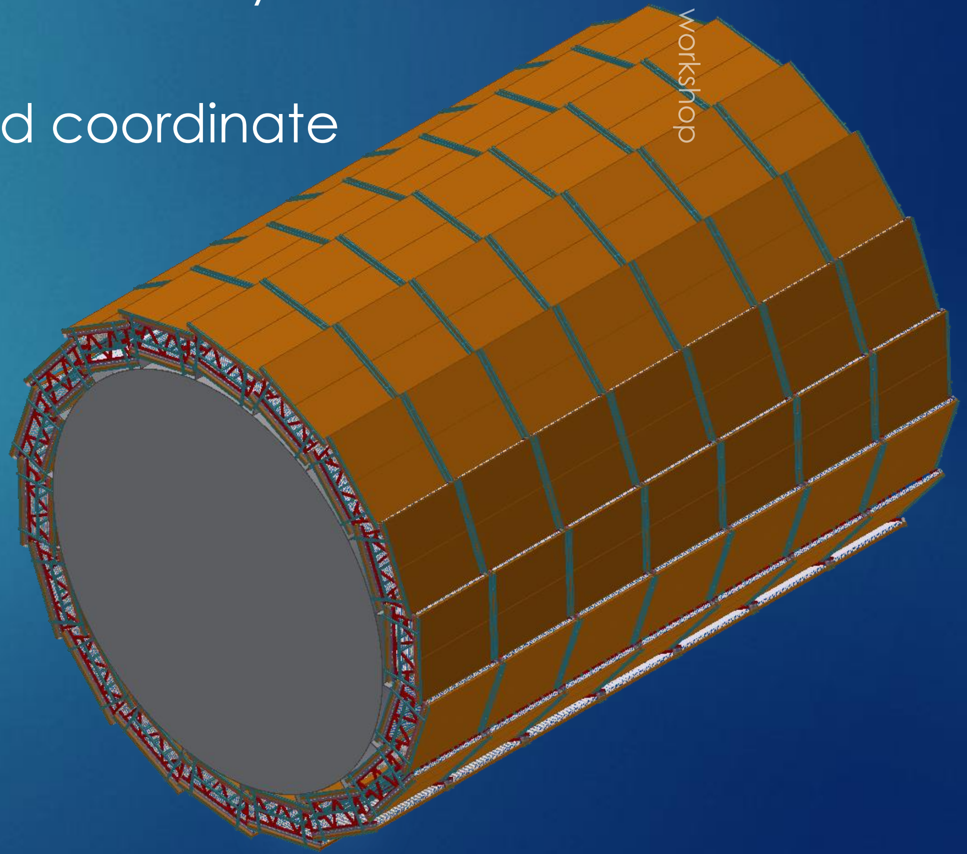


# A working proposal (doable now)

- **Barrel and outer endcaps of FFC-hh:**
- 2 x 4 layers of 2.8 m long drift tubes (axial in barrel, radial in outer endcaps) with 1.4 m multilayer distance provide 40 μm spatial resolution, 60 μrad angular resolution, 100% tracking efficiency up to the maximum background rates.
- Monolithic sMDT construction, no optical alignment of multilayers needed. Chambers well accessible.
- Embedded new RPCs for trigger, timing, and second coordinate







# R&D summary



| Facility | Technologies | Challenges | Most challenging requirements at the experiment |
|---|---|---|---|
| HL-LHC | RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC | Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost | **(LHCb)**: Max. rate: 900 kHz/cm$^2$<br>Spatial resolution: ~ cm<br>Time resolution: O(ns)<br>Radiation hardness: ~ 2 C/cm$^2$ (10 years) |
| Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF) | GEM, μ-RWELL, Micromegas, RPC | Stability, low cost, space resolution, large area, eco-gases | **(IDEA):** Max. rate: 10 kHz/cm$^2$<br>Spatial resolution: ~60-80 μm<br>Time resolution: O(ns)<br>Radiation hardness: <100 mC/cm$^2$ |
| Muon collider | Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC | High spatial resolution, fast/precise timing, large area, eco-gases, spark-free | Fluxes: > 2 MHz/cm$^2$ ($\theta<8^0$)<br>< 2 kHz/cm$^2$ (for $\theta>12^0$)<br>Spatial resolution: ~100μm<br>Time resolution: sub-ns<br>Radiation hardness: < C/cm$^2$ |
| Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+) | Micromegas, GEM, RPC | High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics | **(CBM@FAIR):** Max rate: <500 kHz/cm$^2$<br>Spatial resolution: < 1 mm<br>Time resolution: ~ 15 ns<br>Radiation hardness: $10^{13}$ neq/cm$^2$/year |
| FCC-hh (100 TeV hadron collider) | GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM | Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing | Max. rate 500 Hz/cm$^2$<br>Spatial resolution = 50 μm Time resolution: sub-ns<br>Angular resolution = 70 μrad ($\eta$=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c |

# Outlook of new RPCs for muon systems





- Muon systems tend to have large area (even larger in future)
- LLP systems are even larger…
- The BC timing could need to request resolving 5 ns BCs
- The rate expected is from a factor 2 up to a factor 6 with respect tp the HL-LHC values, depending on the region
- Higher eta higher rate but also smaller surface
- Classic RPCs can fit most to the regions with incremental improvement
- Newly proposed ideas can cope with all the areas of future colliders
- The R&D must focus mostly in getting rid of environmental unfriendly and expensive gases and in further improving the industrialization to cover such large areas

- Most of the FFC-hh requirements on muon detectors are fulfil
- In the regions with higher radiation a substantial improvement is needed
- Potential competitor: new generation of Si detectors
- Fine timing is needed in the 5 ns BC scenario and for the LLP searches
- Muon detector community is sparling new ideas

# Conclusions… and a small exercise

# Technology state of the art evaluation
(my personal view)

Useless = *
Poor = **
Sufficient = ***
Good = ****
Excellent = *****

Incremental R&D = *
Disruptive R&D = *

| State of the art | Rate capability | Longevity (hadrons) | Space resolution | Time Resolution | Cost | Industrialization | Scalability |
|---|---|---|---|---|---|---|---|
| DT | *** | **** | **** | * | *** | **** | **** |
| sTGC | **** | *** | *** | *** | *** | ** | **** |
| RPC | *** | *** | *** | ***** | ***** | **** | **** |
| MPGD | **** | *** | *** | *** | ** | *** | *** |

| R&D potential | Rate capability | Longevity (hadrons) | Space resolution | Time Resolution | Cost | Industrialization | Scalability |
|---|---|---|---|---|---|---|---|
| DT | *** | **** | ***** | ** | *** | **** | **** |
| sTGC | **** | *** | **** | *** | *** | *** | ***** |
| RPC | ***** | **** | **** | ***** | ***** | ***** | ***** |
| MPGD | ***** | **** | **** | **** | ** | **** | **** |

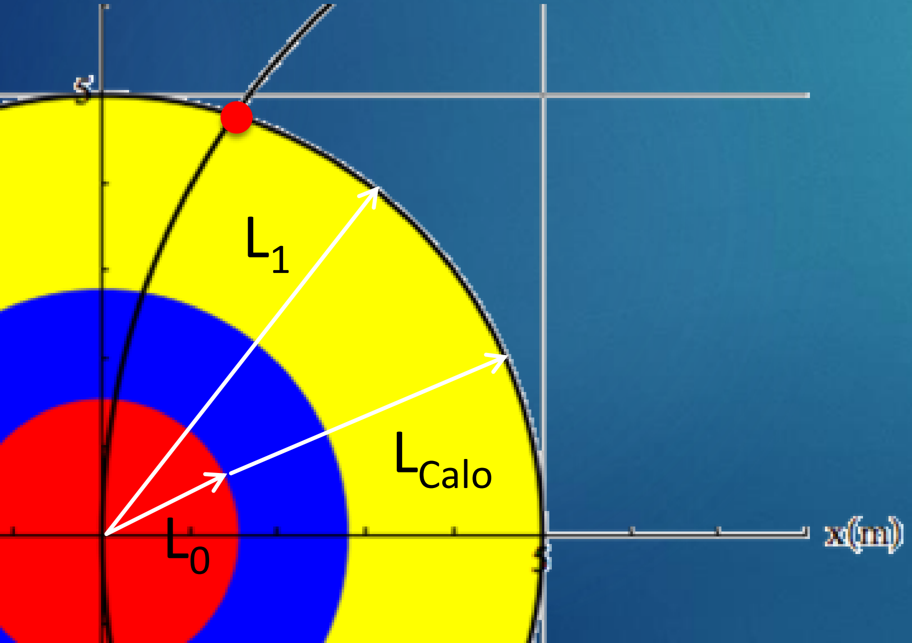
# Backup

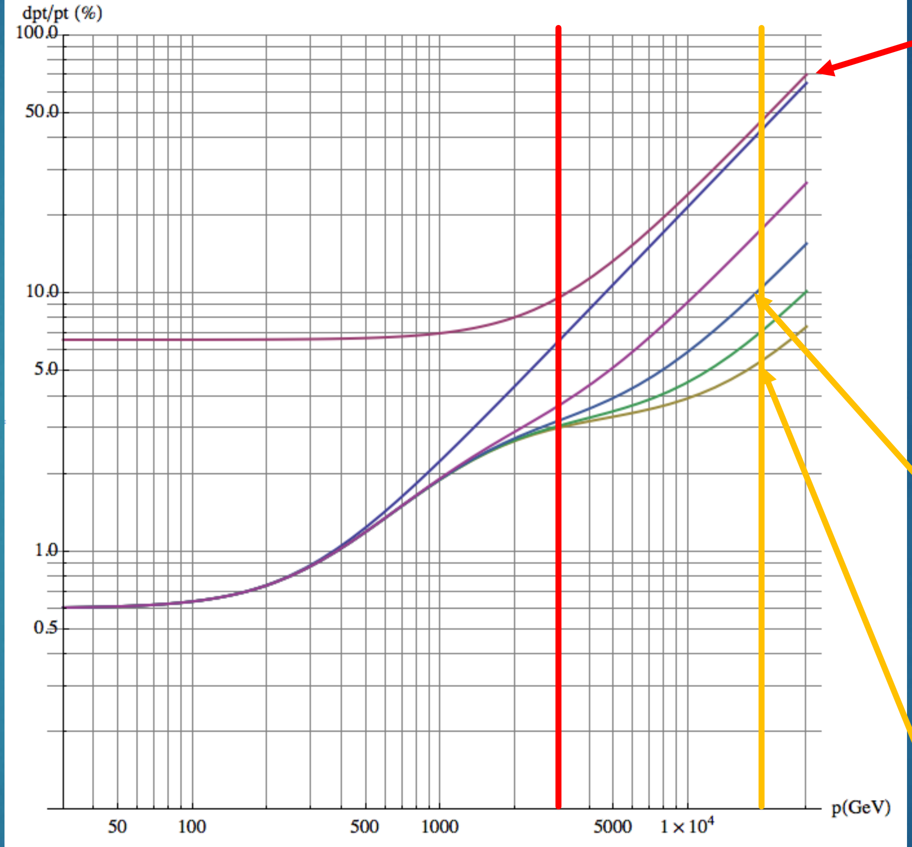
# Muon tracking performance



Three methods for the muon momentum measurement

- **Tracker only** with identification in the muon system
- **Muon system only** by measuring the muon angle where it exits the coil
- Tracker **combined** with the position of the muon where it exists the coil



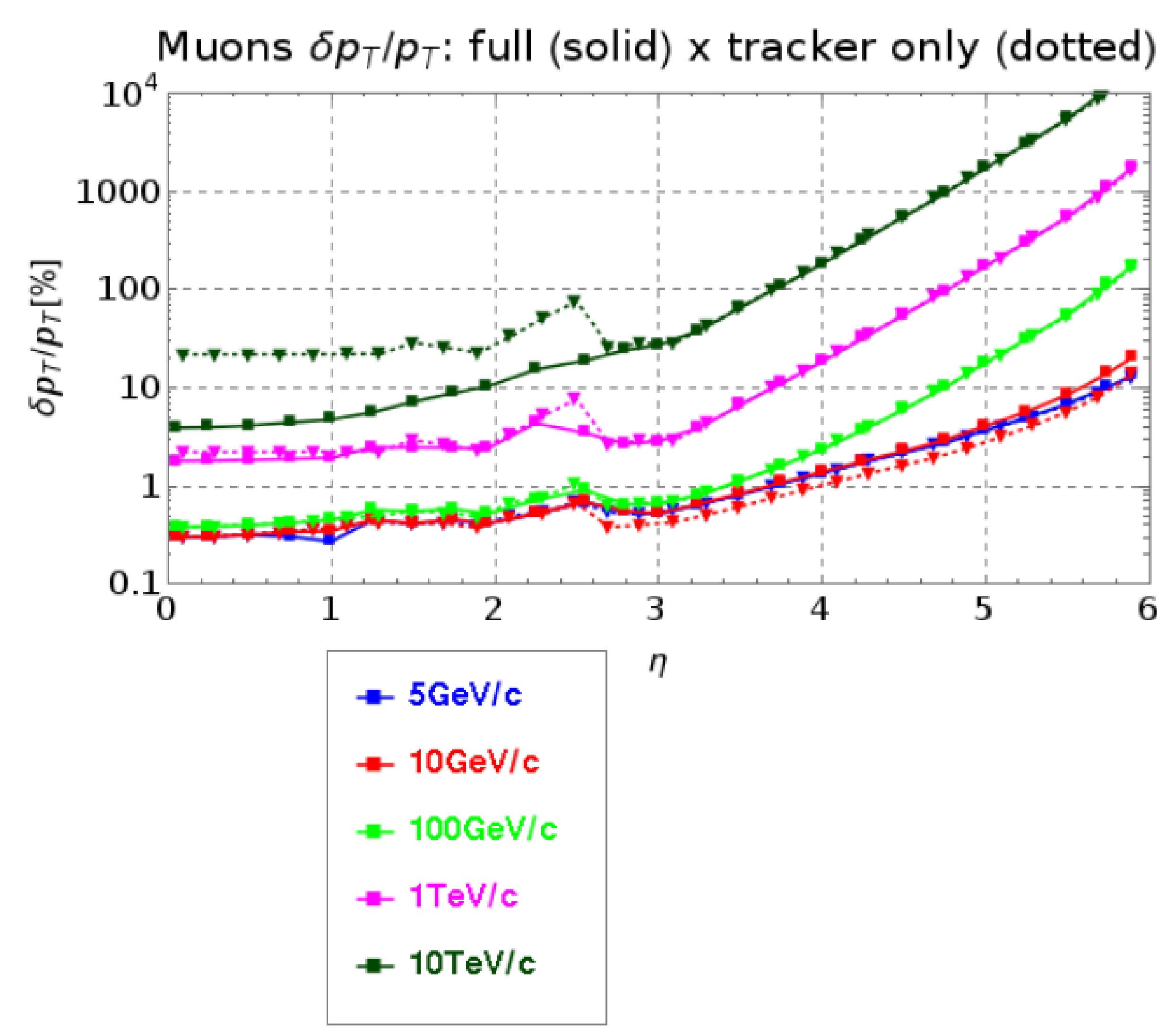




Analytical calculation,
Werner Riegler, FCC Week 2017

- 70 µrad muon detector angular resolution:
  - < 10% standalone momentum resolution up to 3 TeV, equal to tracker resolution
- 50 µm muon detector spatial resolution:
  - < 10% combined momentum resolution up to 20 TeV.
- Multiple scattering limit for track combination (infinite muon detector resolution)

# Muon system contribution






## Tracking

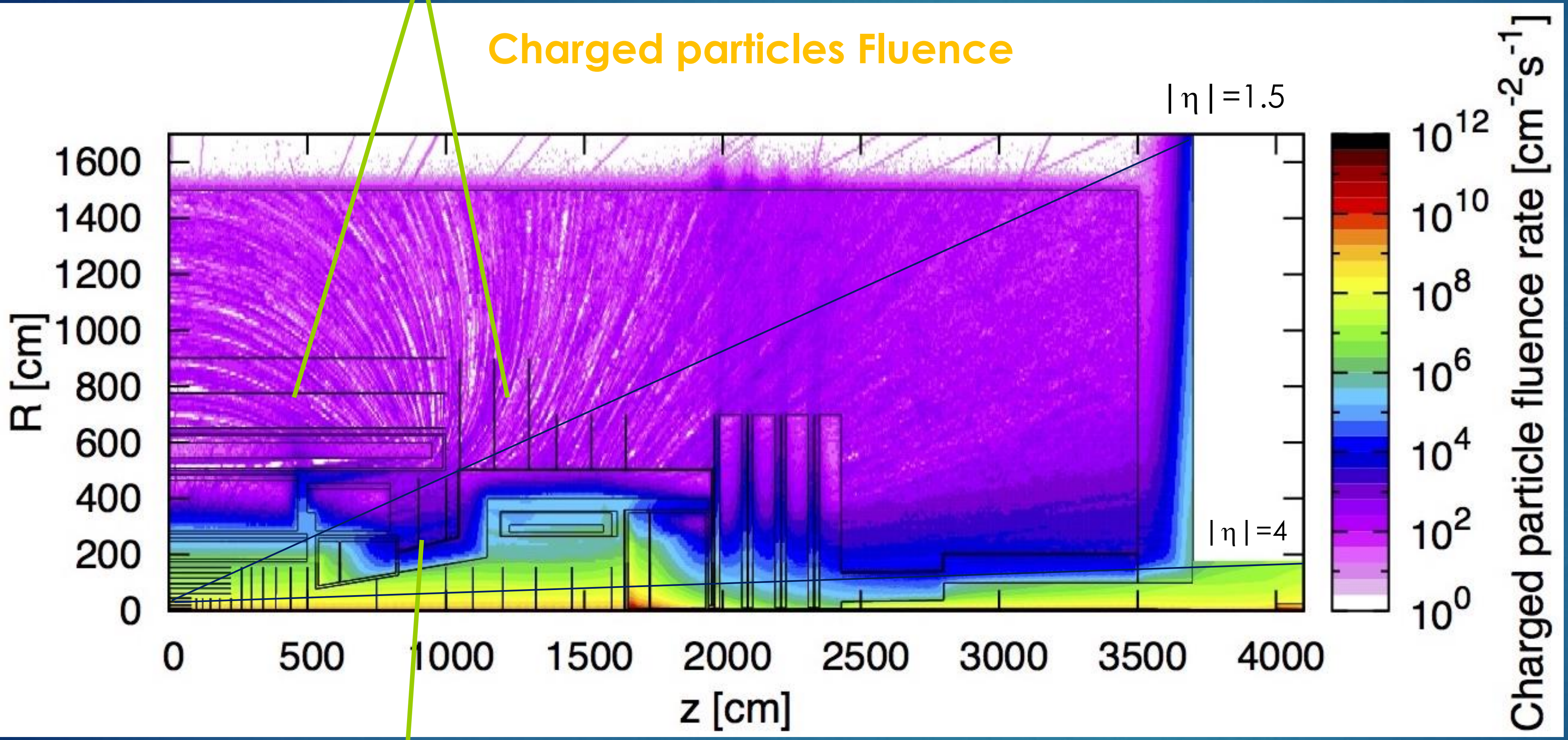
- Improvement by muon system for $p_T$ > 1 TeV and |η| < 2.5.
- Muon and Barrel endcap fully included
- Forward is meant principally for muon identification

## Trigger

- Momentum resolution at pT < 100 GeV dominated by multiple scattering, independent of detector resolution.
- For 200 X0 of scattering material in front of the muon system and perfect chamber resolution 5 - 25% standalone pT resolution from η =0 up to | η | = 2.5 for 1st level muon trigger.
- Solenoidal B field in forward direction (|η| > 2.5) not suitable for precise standalone momentum measurement for trigger ($p_T$ resolution > 80%).

# Particle Fluence @ L=30x10$^{34}$cm$^{-2}$s$^{-1}$

- Barrel muon chambers: ~300 cm$^{-2}$s$^{-1}$ to ~500 cm$^{-2}$s$^{-1}$




Endcap Muon Chambers: 10$^{4}$ cm$^{-2}$s$^{-1}$

Forward Muon Chambers: 5x10$^{5}$ cm$^{-2}$s$^{-1}$

- Charged rates
  - Up to 500 cm$^{-2}$s$^{-1}$ (R>3m |η|<1.5)
  - up to 10$^{4}$ cm$^{-2}$s$^{-1}$ (R>1m 1.5<|η|<3.5)
  - ~ 5x10$^{5}$ cm$^{-2}$s$^{-1}$ (R<1m |η|>4)
- photon rates
  - ~ 5x10$^{6-8}$ cm$^{-2}$s$^{-1}$
- N fluence
  - Up to10$^{14}$ cm$^{-2}$ (shielding to mitigate the effect)

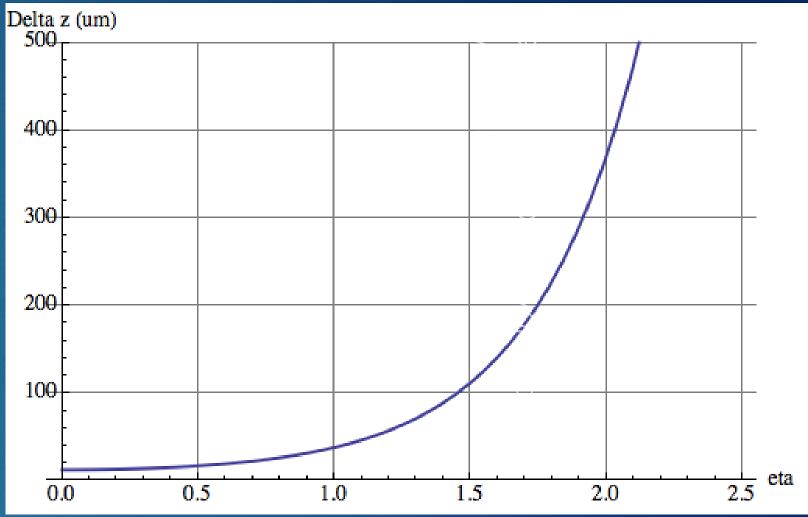
Present muon detectors close to fully satisfy this requirement → further R&D needed for completing

# Pileup of 1000 (25ns Bunchcrossing)



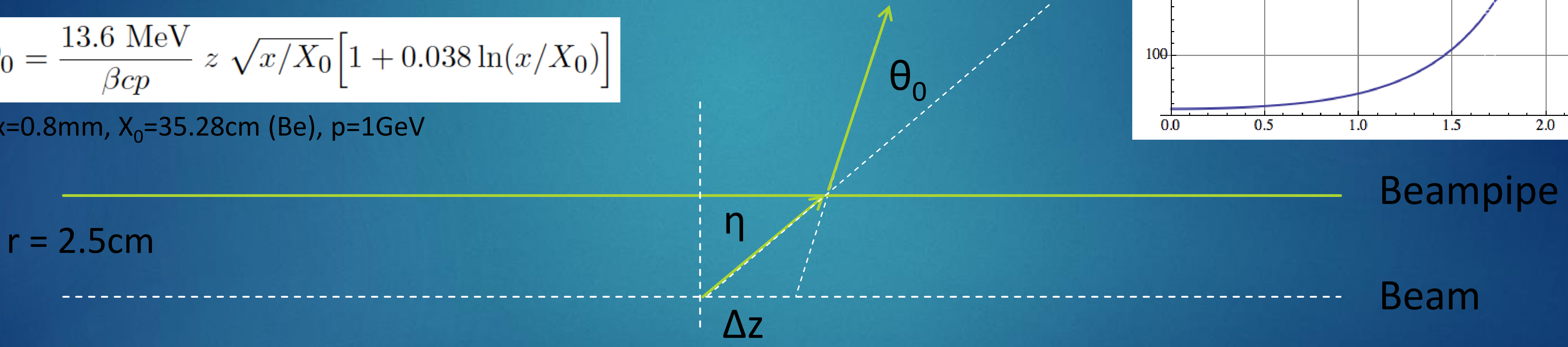
HL-LHC average distance between vertices at z=0 is
**≈ 1mm in space and 3ps in time.**

For 6 times higher luminosity at FCC-hh (an HE-LHC) this would become
**≈ 170µm in space and 0.5ps in time.**




$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

x=0.8mm, $X_0$=35.28cm (Be), p=1GeV



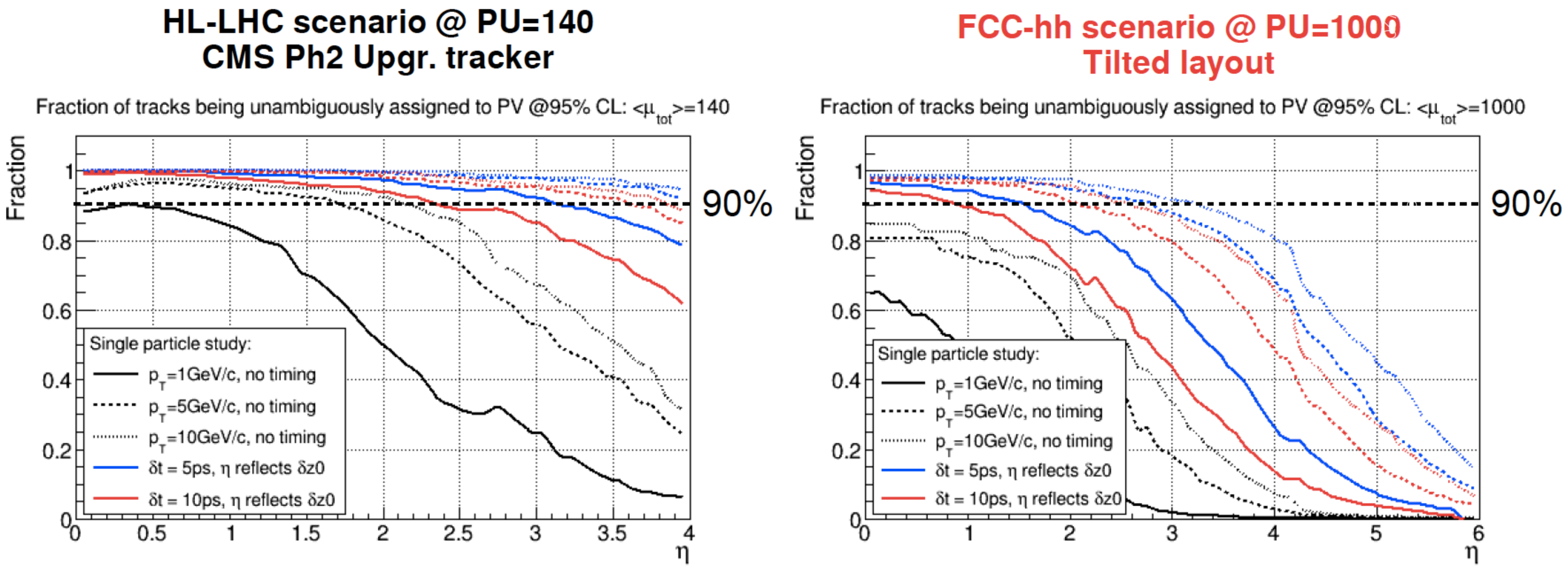

Even having a perfect tracking detector, the error due to multiple scattering in the beampipe for η > 1.7 is already larger than the average vertex distance !

Timing, very clever new ideas needed …

# Vertexing at Pileup of 1000, Timing



→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout



# Pileup mitigation - consequences

## Note: Other Bunch Spacings

Identified three main alternative scenarios, but need to study them

| | Initial | Nominal | Opt 1 | Opt 2 | Opt 3 |
|---|---|---|---|---|---|
| Bunch spacing [ns] | 25 | 25 | 12.5 | 5 | 5 |
| Protons per bunch [$10^{11}$] | 1 | 1 | 0.5 | 0.2 | 0.2 |
| Init. hor. transv. emittance [μm] | 2.2 | 2.2 | 1.1 | 1.1 | 0.44 |
| Init. vert. transv. emittance [μm] | 2.2 | 2.2 | 1.1 | 1.1 | 0.44 |
| Final hor. transv. emittance [μm] | 1.28 | 0.29 | 0.25 | 0.22 | 0.22 |
| Final vert. transv. [illegible] | [illegible] | [illegible] | 0.2 | 0.17 | 0.17 |
| Max. total beam-b[illegible] | [illegible] | [illegible] | 0.03 | 0.03 | 0.03 |
| IP beta-function [m] | [illegible] | [illegible] | 0.3 | 0.3 | 0.3 |
| Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$] | 5.01 | 25.2 | 23.2 | 14.5 | 20.1 |
| Max. number events per crossing | 170 | 857 | 394 | 99 | 137 |
| Optimum integrated luminosity / day [fb$^{-1}$] | 2.27 | 8.2 | 7.5 | 5.5 | 6.2 |

Much more study is required before we can conclude

D. Schulte FCC-hh, CERN, March 2019 12

- Shorter BC spacing proposal: 12.5 and 5 ns
- Correspondingly lower bunch intensity
- Pileup reduction
- Most of internal detector are developing at least sub ns timing
- The BC id. Will require sub-ns timing in the muon system too

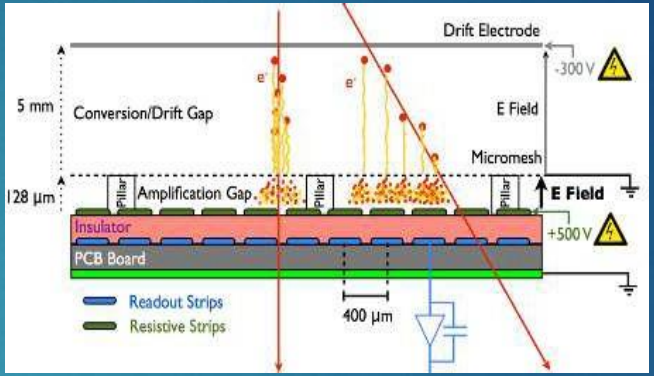
- At the moment just RPCs can provide this performance among the classical muon detectors → drive of new R&D effort

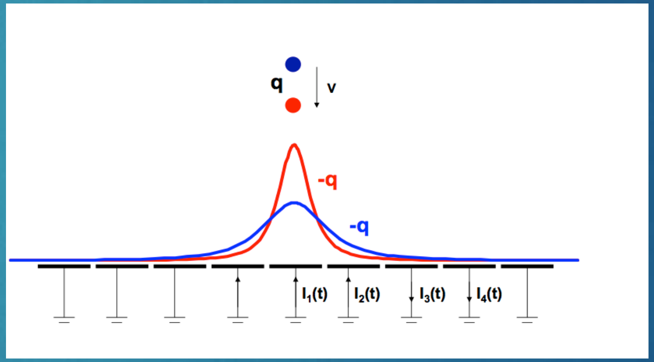
# Space resolution principles



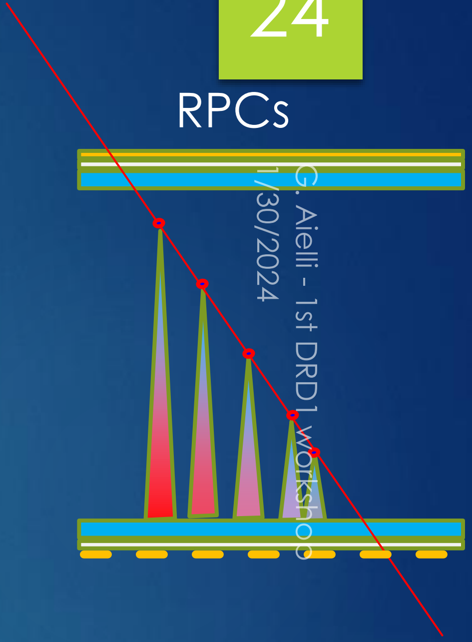
- Space resolution is driven by 2 factors
  - Intrinsic localization of the event
  - Precision of the chamber geometry

MPGD



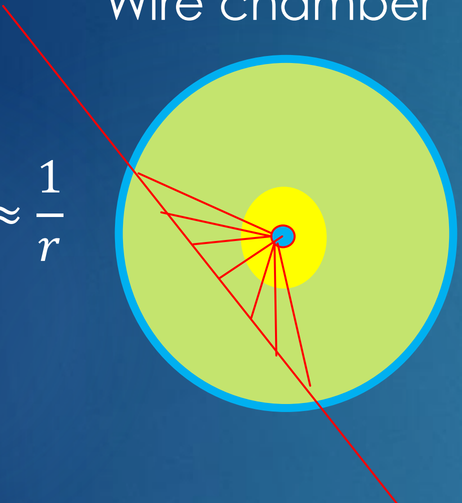



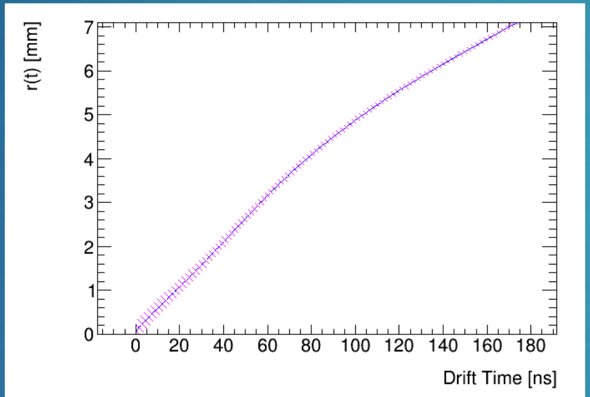

RPCs



Wire chamber

$$E \approx \frac{1}{r}$$






- Tubes and MWPC exploit the R-t relation of the ions drifting in the gas and rely on their metallic bulks which can be easily machined to offer a precise reference frame. Can obtain high precision with low channel density

- RPCs and MPGD exploit electrostatic induction of the moving charges to calculate the charge centroid. The resolution is driven by the readout system segmentation and mechanical precision preserving it on large multi-layer chambers made of composite materials. Can obtain high precision with high channel density

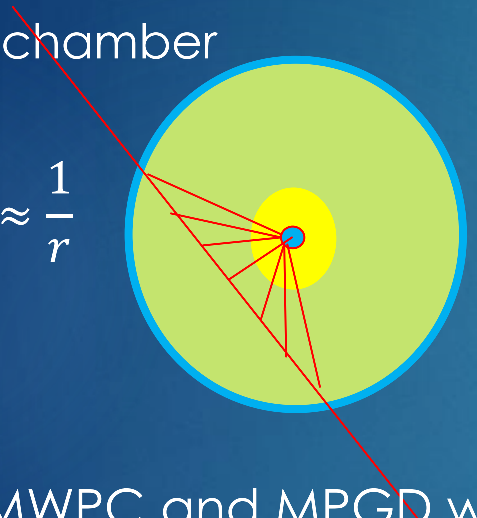
# Time resolution principles



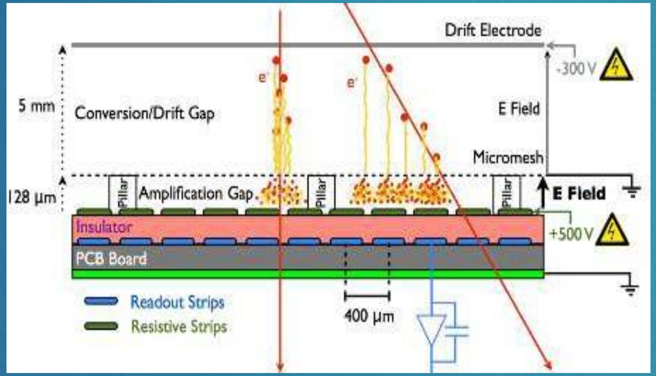
- Time resolution is driven by
  - Avalanche statistical fluctuations
  - Drift time (velocity x gap size)
  - Electronics noise

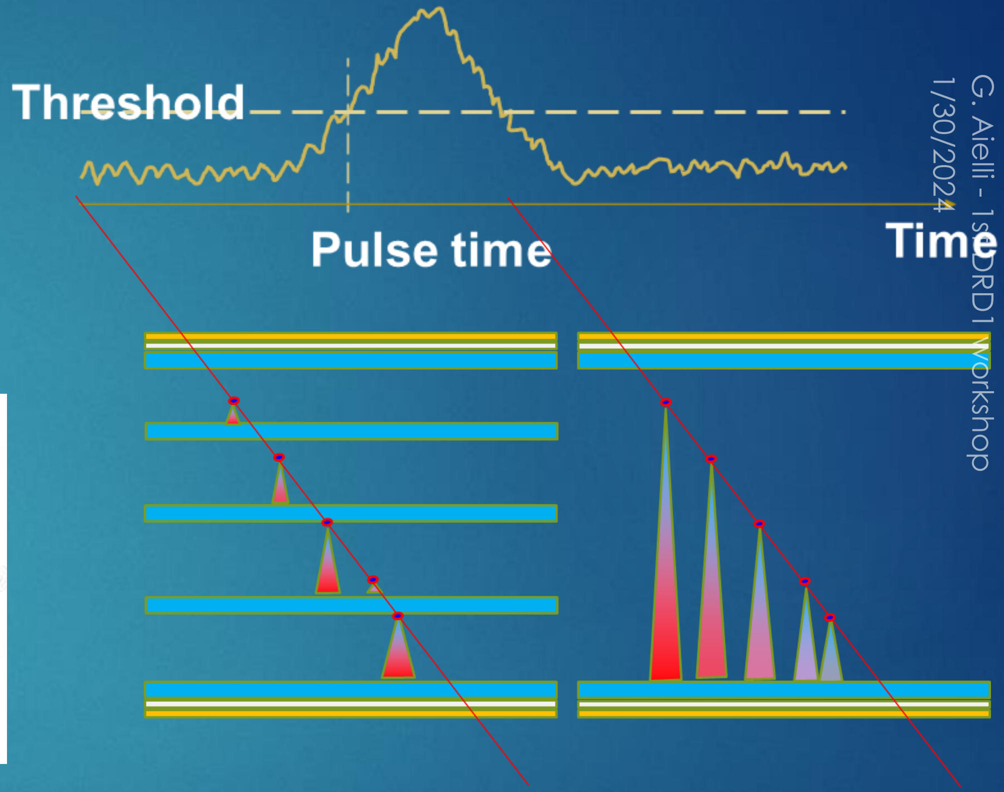
Wire chamber

$$E \approx \frac{1}{r}$$



MPGD




- MWPC and MPGD work on similar principles: the separation of the drift and multiplication introduces irreducible uncertainty on the time resolution, dependent on the drift width
- RPCs and MRPCs drift and multiplication space coincide. The multi-micro gap RPC segments the gas gap to further reduce the drift time