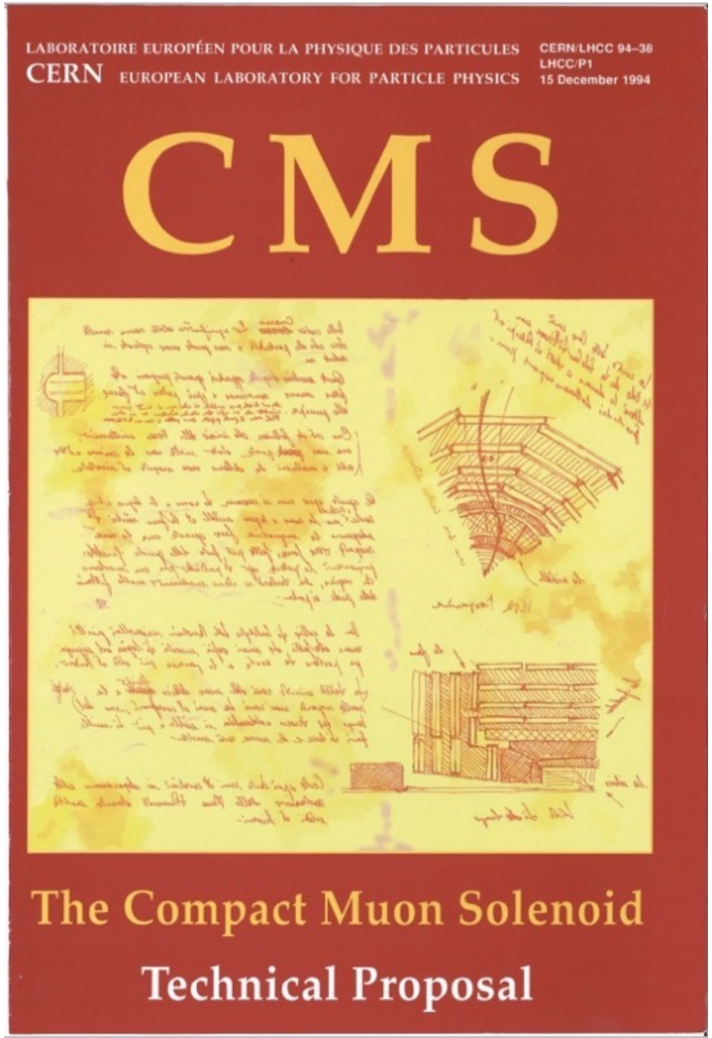
Activities of the Demokritos INPP CMS group

D.Loukas

On behalf of the CMS INPP group

The INPP CMS Group



A 28 years-activity, dating back to the inception of the CMS experiment at CERN

An experiment optimized for hunting the missing part of the Standard Model of particle physics: The higgs boson

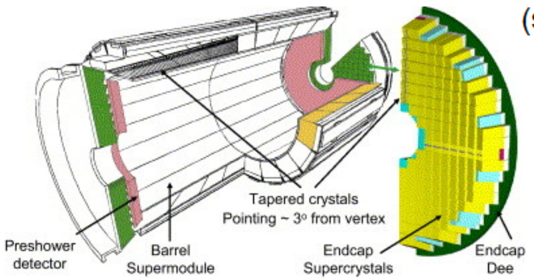
Contributions of the INPP CMS group:

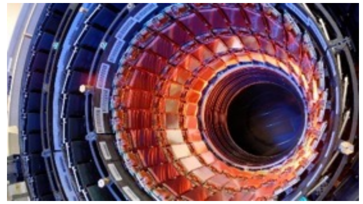
Detector&electronics development.
Commissioning & operation
Physics analysis & algorithms
Contribution to the Phase II Upgrade

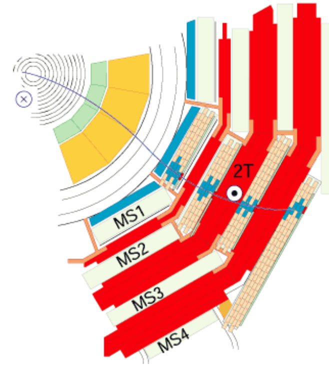
HL-LHC : A journey from now to 2035

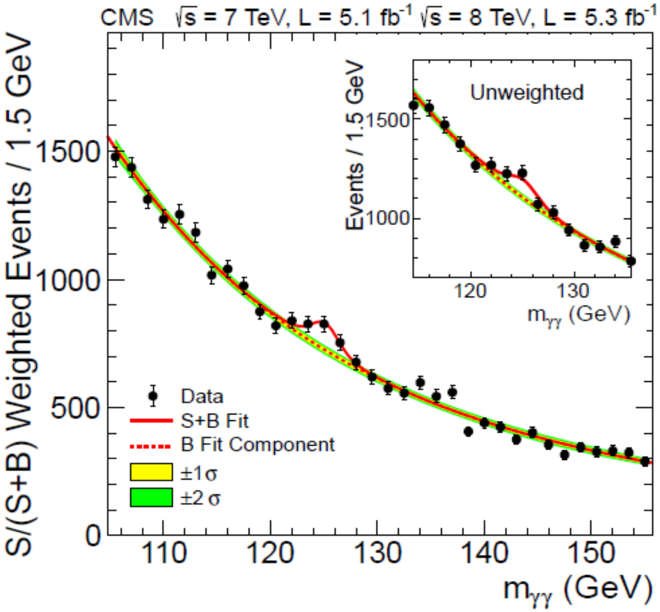
Higgs Discovery

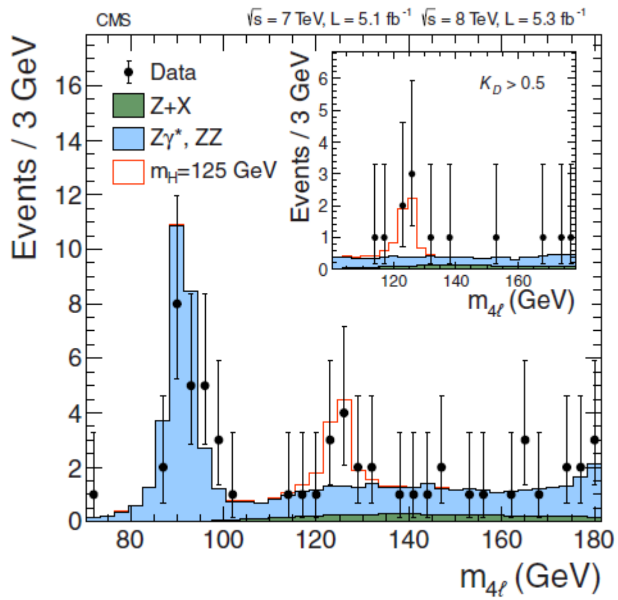
Higgs boson discovered and now well measured in H→ γγ, H→ZZ*→4l, H→ WW* → lνlν channels (small branching ratios but clean final states)











Higgs Discovery

Members:

Anagnostou	George	Physicist
Assiouras	Panagiotis	PhD student
Daskalakis	George	Physicist
Dizis	Angelos	MsC student
Gotsis	Konstantinos	Student
Kazas	Ioannis	ELE
Kyriakis	Aristoteles	Physicist
Loukas	Dimitrios	Physicist
Papadopoulos	Alkiviadis	PhD student
Papafilippou	Dimitrios	Student
Stakia	Anna	PhD student

A. Dizis obtained his M.Sc degree in 2021

Physics Analysis Overview

data : 2016-2017-2018 **13** TeV , **140** fb^{-1}

HIGGS

Study of the di-leptonic ttH(H→bb) channel **reconstructing the Higgs mass** and using a **data-driven background** prediction method. *AN-19-097, AN-20-047, AN-2021-166, FTR-21-002*

EXOTICA

Search for a **narrow resonance** in high-mass dielectron & dimuon final states. Analysis approved. **Publication:** JHEP06 (2018) 120 , JHEP07 (2021) 208

B2G

Searching **simultaneously** for both a **heavy top partner T'** and a **new gauge boson W'**.
ongoing *CMS AN -2017/343*

TOP

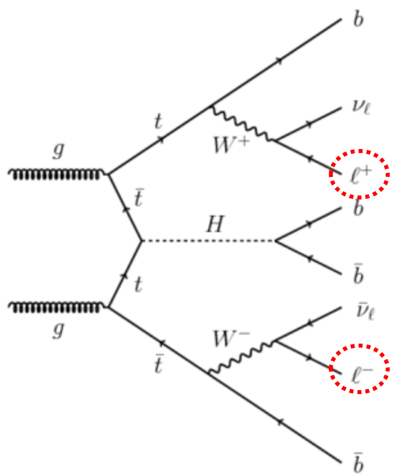
Measurement of the W helicities using semileptonic top-pair decays. **New Physics** from anomalous Wtb couplings. **New Methods** to improve systematics. ***ongoing*** *AN-19-066, TOP-21-002*

SUSY

Search for general gauge-mediated supersymmetry in final states with two photons and missing transverse momentum. **Publication:** JHEP06 (2019) 143, https://doi.org/10.1007/JHEP06(2019)143

HIGGS : ttH (H→bb)

data : 2016-2017-2018
13 TeV , 140 fb^{-1}



The team :
Charis Kleio Koraka (student)
Niki Saoulidou (UoA),
Georgios Anagnostou,
Georgios Daskalakis

The idea:
Study of the di-leptonic ttH(H→bb) channel **reconstructing the Higgs mass** and using a **data-driven background** prediction method.

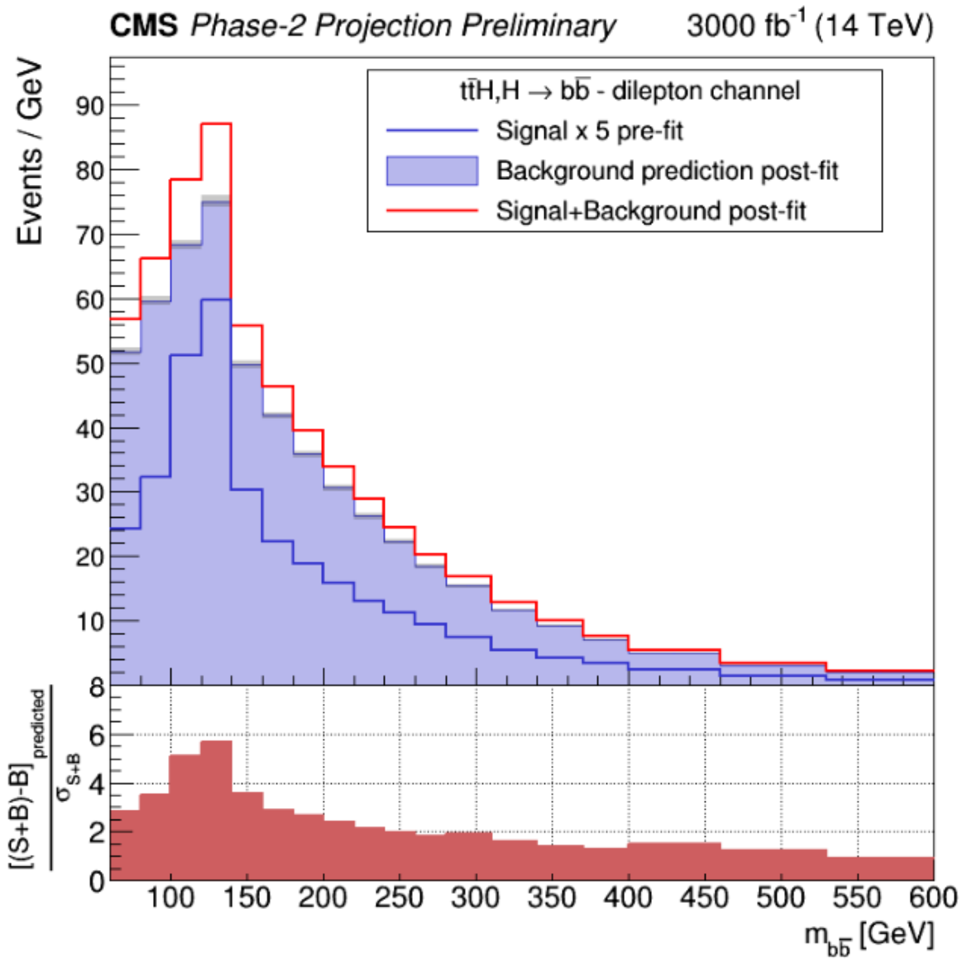
Higgs mass reconstruction : is performed by simultaneously solving analytically the ttH dileptonic decay system while scanning the M_t vs M_W mass plane searching for solutions.

Data-driven background: From events with exactly 2 b-tagged jets (ttbar enriched + Higgs contamination small) predict the ***shape*** and ***normalization*** of the m_{bb} distribution of events with exactly 3 / 4 b-tagged jets by applying probability weights (**T**agging **R**ate **F**unction method).

PhD : Charis Kleio Koraka

HIGGS : ttH (H→bb)

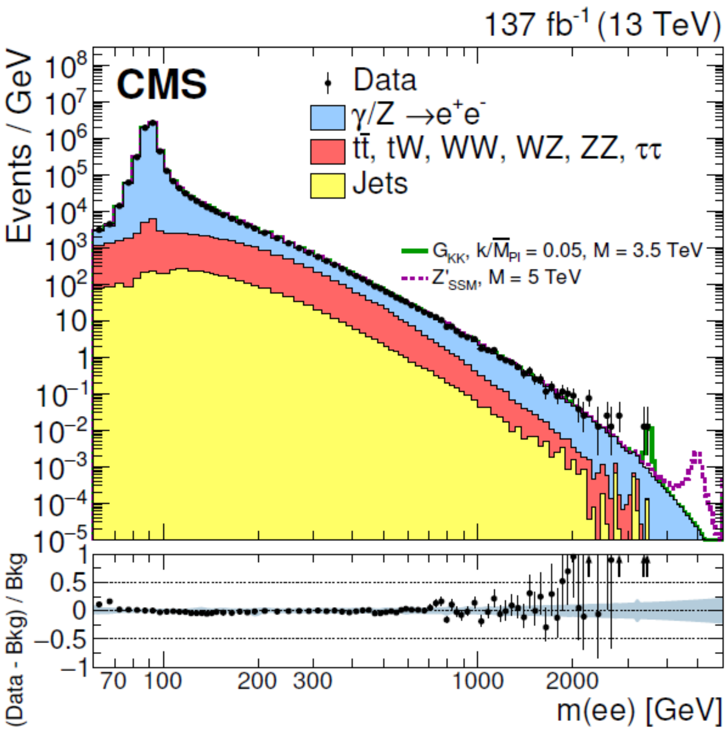
CMS PAS FTR-21-002

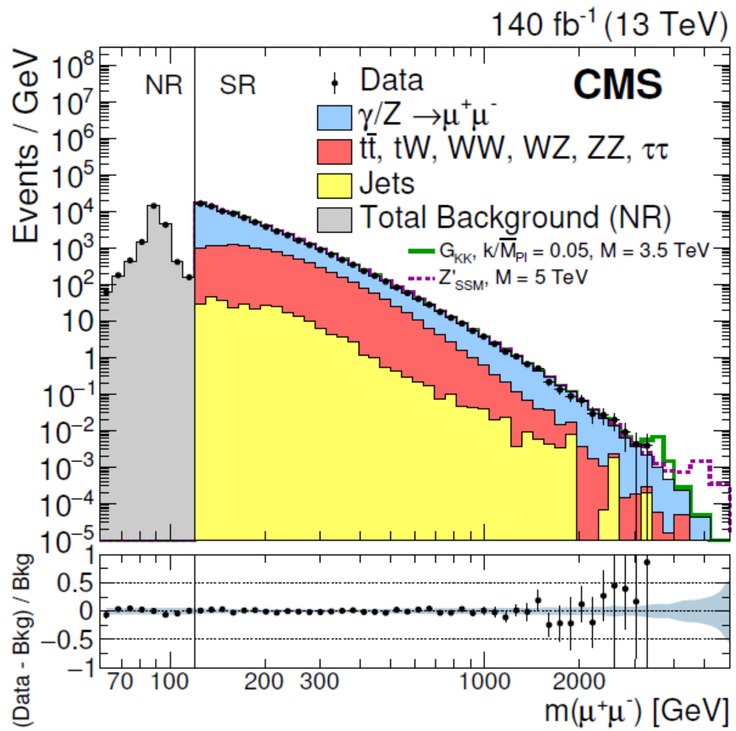


EXOTICA: Z'→e^+e^- , $\mu^+\mu^-$ Searches

data : 2016-2017-2018
13 TeV , **140** fb^{-1}

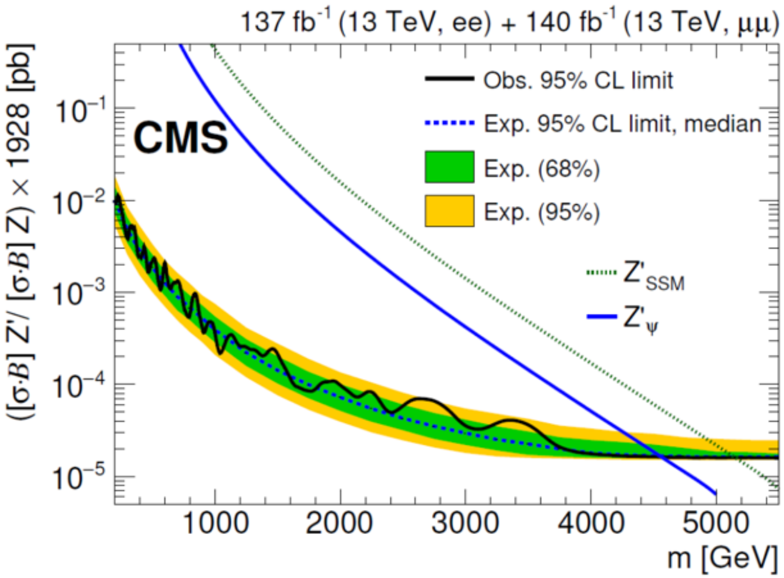
The team :
Georgios Daskalakis
IIHE-ULB, RAL, ENHEP,
University of Notre Dame, Purdue University





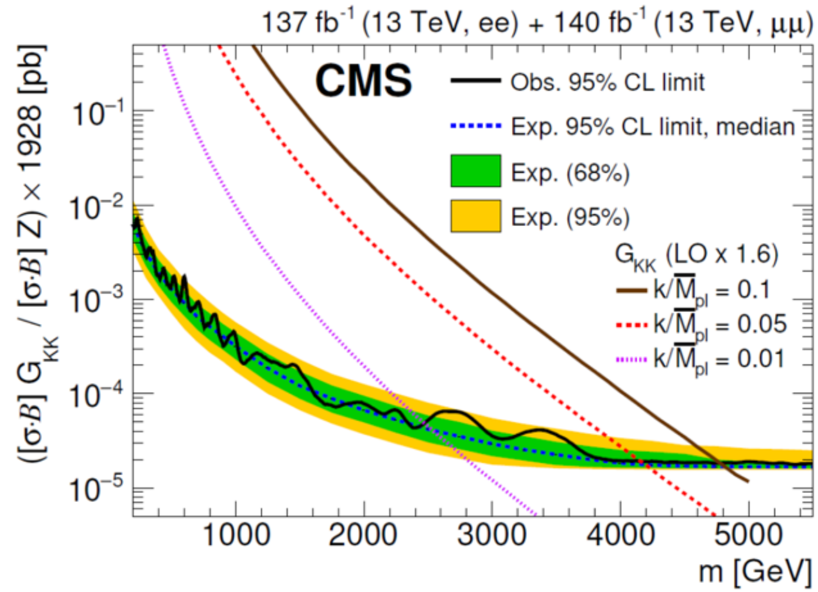
EXOTICA: $Z' \to e^+e^-$, $\mu^+\mu^-$ Searches

Spin-1



Channel	Z'_{SSM} Obs. [TeV]	Z'_{SSM} Exp. [TeV]	Z'_{ψ} Obs. [TeV]	Z'_{ψ} Exp. [TeV]
e e	4.72	4.72	4.11	4.13
$\mu^+\mu^-$	4.89	4.90	4.29	4.30
e e + $\mu^+\mu^-$	5.15	5.14	4.56	4.55

Spin-2



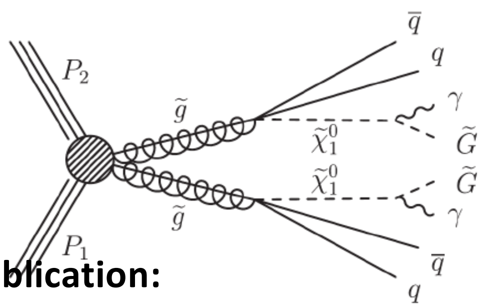
Channel	$k/\overline{M}_{Pl} = 0.01$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.01$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.1$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.1$ Exp. [TeV]
e e	2.16	2.29	3.70	3.83	4.42	4.43
$\mu^+\mu^-$	2.34	2.32	3.96	3.96	4.59	4.59
e e + $\mu^+\mu^-$	2.47	2.53	4.16	4.19	4.78	4.81

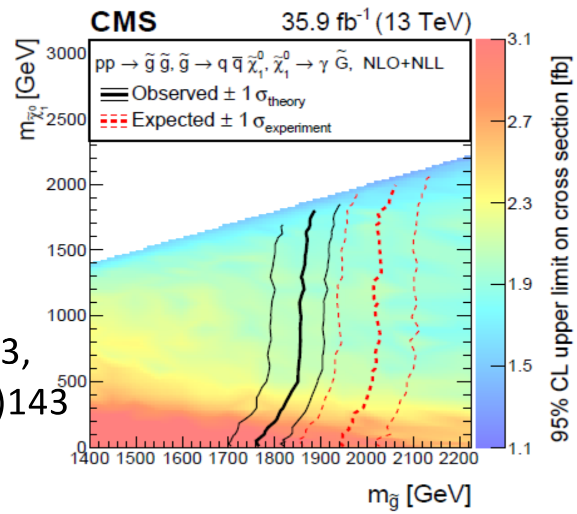
Ongoing PHYSICS analyses (2019)

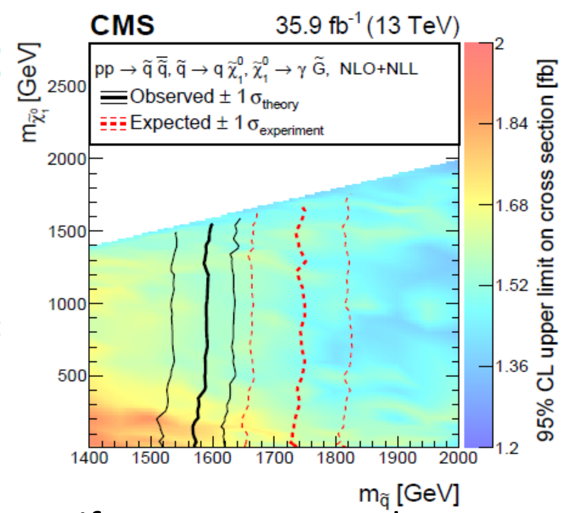
The team :
A. Kyriakis,
I. Topsis-Giotis,
G. Paspalaki (student)
Florida State University
University of Notre Dame

data : 2016 **13** TeV , **36** fb^{-1}

SUSY Search for general gauge-mediated supersymmetry in final states with two photons and missing transverse momentum.







Publication:
CMS Collaboration, JHEP06 (2019) 143,
https://doi.org/10.1007/JHEP06(2019)143

Conclusions

- Full analysis was performed using 2016 CMS data at 13TeV center if mass energy and integrated luminosity of 35.9 fb-1.
- Improved sensitivity with respect to previous analyses
- Exclude gluino masses below 1.86 TeV and squark masses bellow 1.59 TeV

B2G: Beyond Second Generation

Higgs discovery quite “straightforward” : Search mass peaks at “suspected ” regions

BUT:

Many models with dark matter particles (e.g. SUSY) have:
at least 2 invisible (undetectable) particles
and searches are done by using missing energy-observables

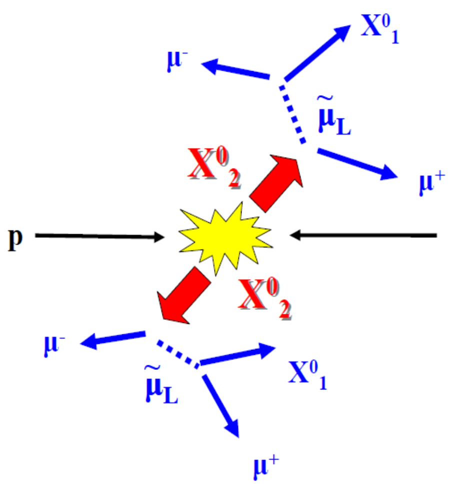
Discovery with missing energy is difficult to be established
due to the fact that we are looking for signal in the tail of the distribution.

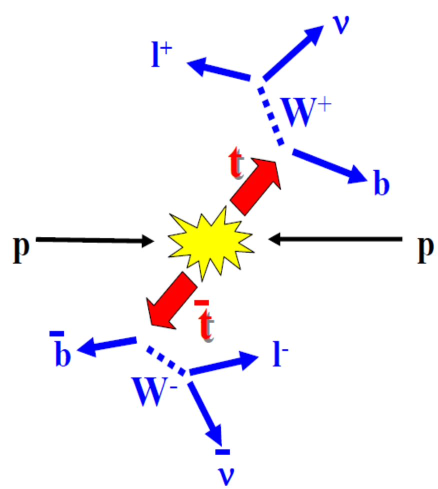
The Inverse way

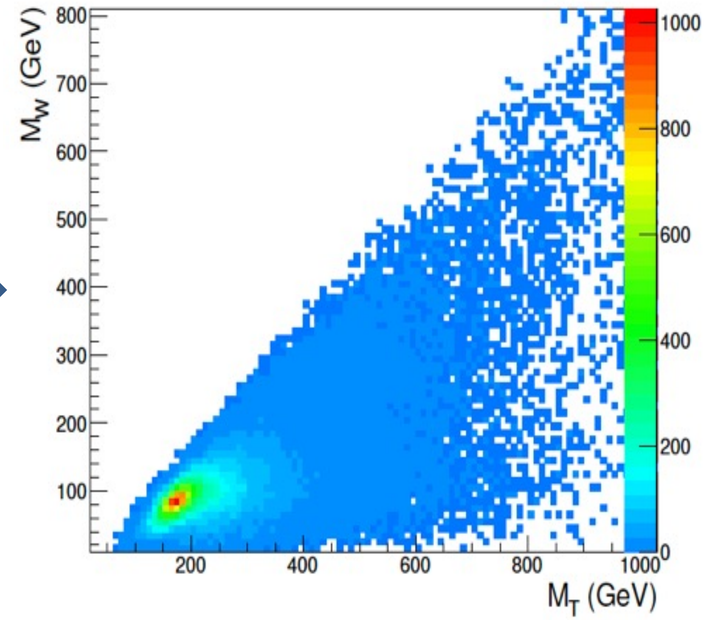
Proceed in the inverse way with respect to the analytical solution: given the visible particles and the topology, we are looking for the unknown masses per event.

B2G: Beyond Second Generation

Anagnostou, G. Searching in 2-Dimensional mass space for final states with 2 invisible particles. J. High Energ. Phys. 2021, 112 (2021)



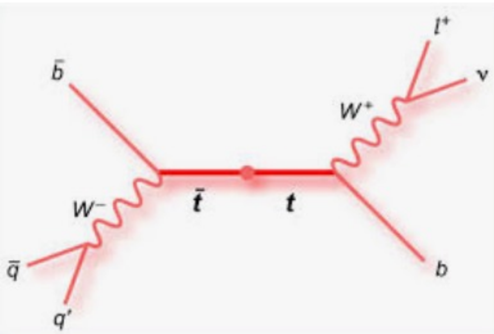




Proof of principle dilepton top pairs (left), as they have very similar topology with dark matter searches with two invisible particles (right).

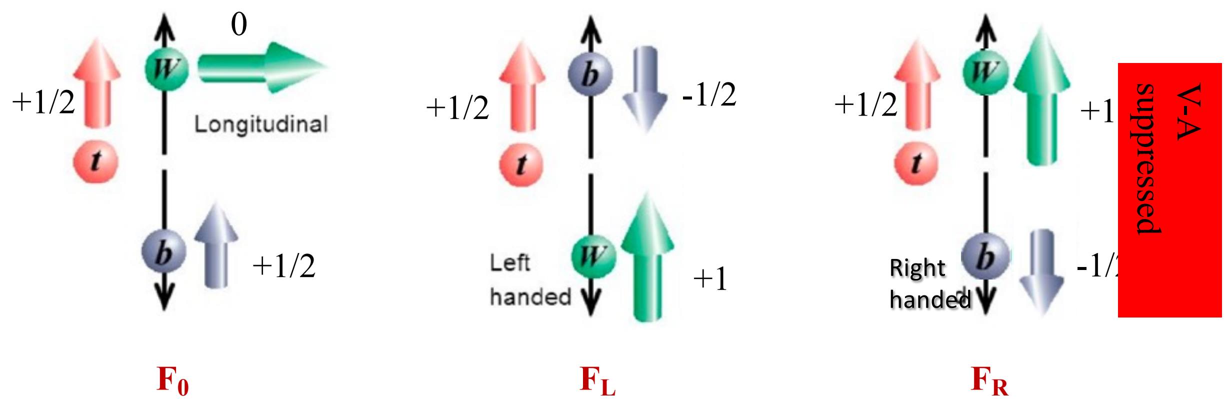
TOP : W helicities from ttbar events

data : full RUN-2
13 TeV , **140** fb^{-1}



Motivation:

i) The measurement is sensitive to the Wtb vertex structure;
new physics from anomalous Wtb couplings



The team :
J. Brochero (CIEMAT)
A. Stakia (PhD student),
G. Daskalakis

ii) **New methodology** to improve systematic uncertainties w.r.t. **7** & **8** TeV analyses

CMS (8 TeV)

Phys. Lett. B 762 (2016) 512

F_0 = 0.681 ± 0.012 (stat) ± 0.023 (syst),
F_L = 0.323 ± 0.008 (stat) ± 0.014 (syst), and
F_R = -0.004 ± 0.005 (stat) ± 0.014 (syst)

ATLAS (8 TeV)

Eur. Phys. J. C 77 (2017) 264

F_0 = 0.709 ± 0.019 (stat+syst),
F_L = 0.299 ± 0.015 (stat+syst), and
F_R = -0.008 ± 0.014 (stat+syst)

Analysis advanced.
Shown at TOP meetings.

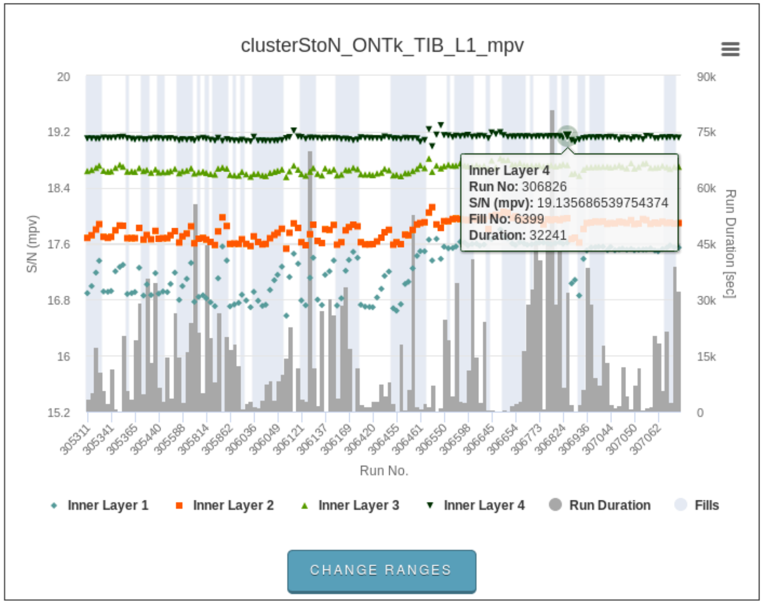
F_0 = 0.687±0.005, F_L = 0.311±0.005, F_R = 0.0017±0.0001
(Phys. Rev. D **81** (2010) 111503) , m_t = 172.8 1.3 GeV

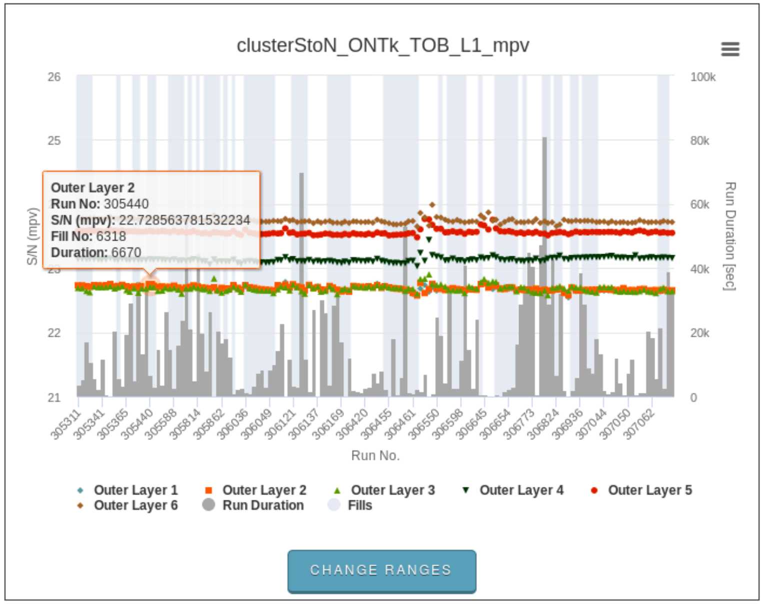
CMS Tracker Historic DQM

DEMOKRITOS

Historic Data Quality Monitor (HDQM) for the CMS Tracker

The Historic Data Quality Monitor (HDQM) of the CMS experiment is a framework (restructured, and further developed by our group) that permits a web-based monitoring of the time evolution of observables (S/N ratio, cluster size) in the CMS Tracker Silicon micro-strip and pixel detectors.





From LHC to HL-LHC

Phase-I: (2022-2025), Double the designed Luminosity: $2 \cdot 10^{34}\, cm^{-2}s^{-1}$, Integrated Luminosity: 450 fb^{-1} at Run 3.

Phase-II: (2025-2027) , Luminosity: $5 \cdot 10^{34} cm^{-2}s^{-1}$, $300\, fb^{-1}$ per year $3000\, fb^{-1}$ for 10 years of operation

CMS DETECTOR PHASE 2 UPGRADES

Trigger/DAQ

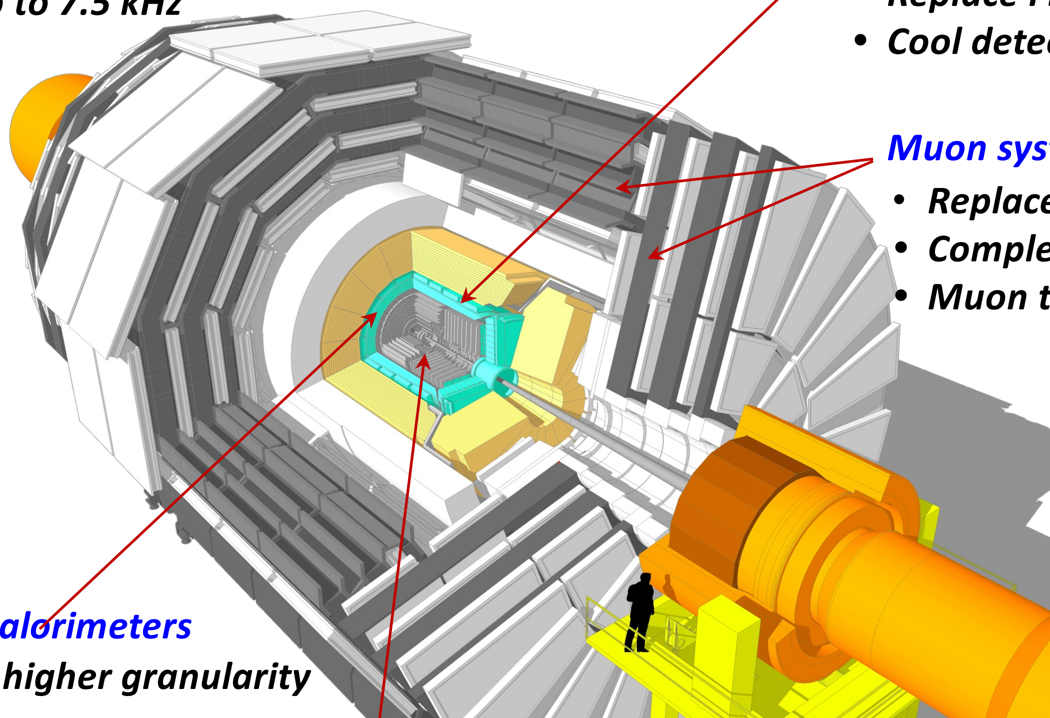
- *L1 with track up to 750 kHz - 12.5 μs latency*
- *HLT output up to 7.5 kHz*

Barrel EM calorimeter

- *Replace FE electronics*
- *Cool detector APDs*

Muon systems

- *Replace DT & CSC FE electronics*
- *Complete RPC coverage*
- *Muon tagging $2.4 < \eta < 3$*



Replace Endcap Calorimeters

- *Rad. Tolerant - higher granularity*

Replace Tracker

- *High granularity – less material- b eff- p_T resolution*
- *Selective readout of outer tracker at 40 MHz for L1 trigger*
- *Extend η coverage to 4*

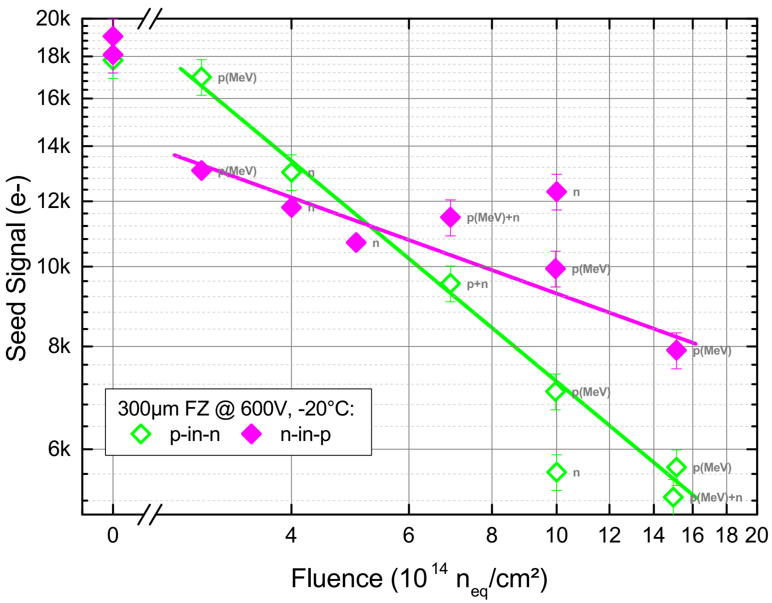
Total CMS Silicon Tracker Replacement

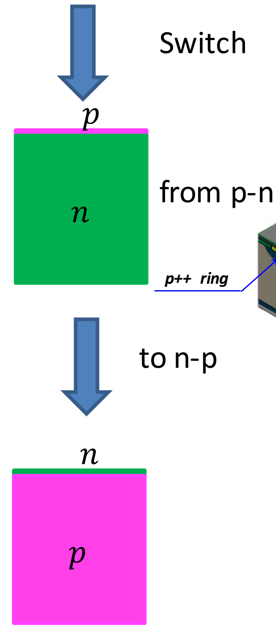
Radiation Tolerance up to $\int L dt = 3000\ fb^{-1}$	*Flip from p_on_n sensors to n_on_p*
Pile Up 140-200 , Occupancy < 1 %	*Increase granularity*
Longer Latency : from 3.2 μs to 12.5 μs	*Increase front end buffer depth*
Increase forward acceptance	*Mostly through pixel extension*
Improve CMS Trigger	*Provide tracking info to L1*
Improve resolution at low P_t	*Reduce material*
Improve resolution at high P_t	*Increase granularity*

layout by S. Mersi

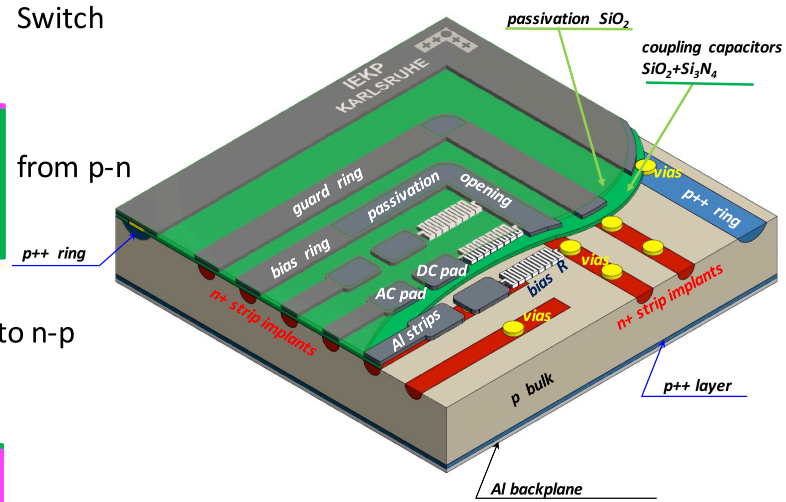
Silicon Sensors

2010: CMS campaign to identify sensors suitable for HL-LHC



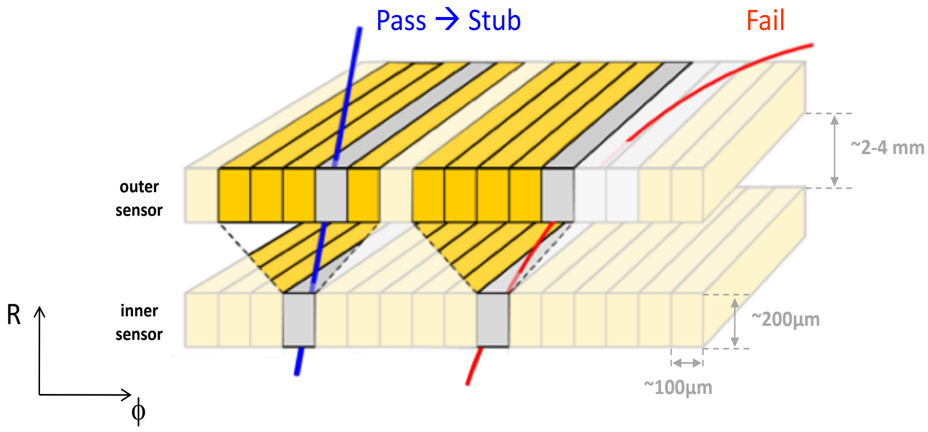


300 µm

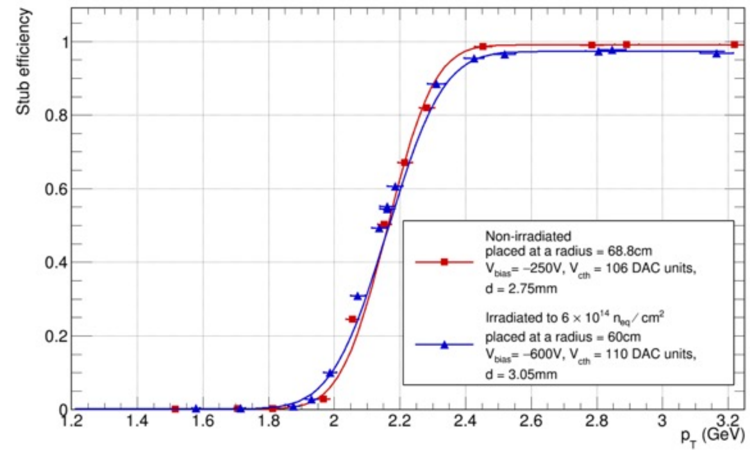


F. Hartmann, Evolution of Silicon Sensor Technology in Particle Detectors, Springer 2008

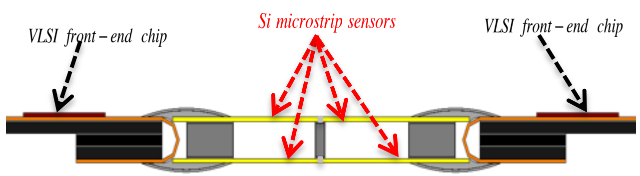
Provide Tracker info to L1 Trigger



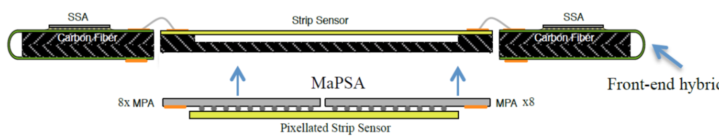
120 GeV/c pions



2S module



PS module

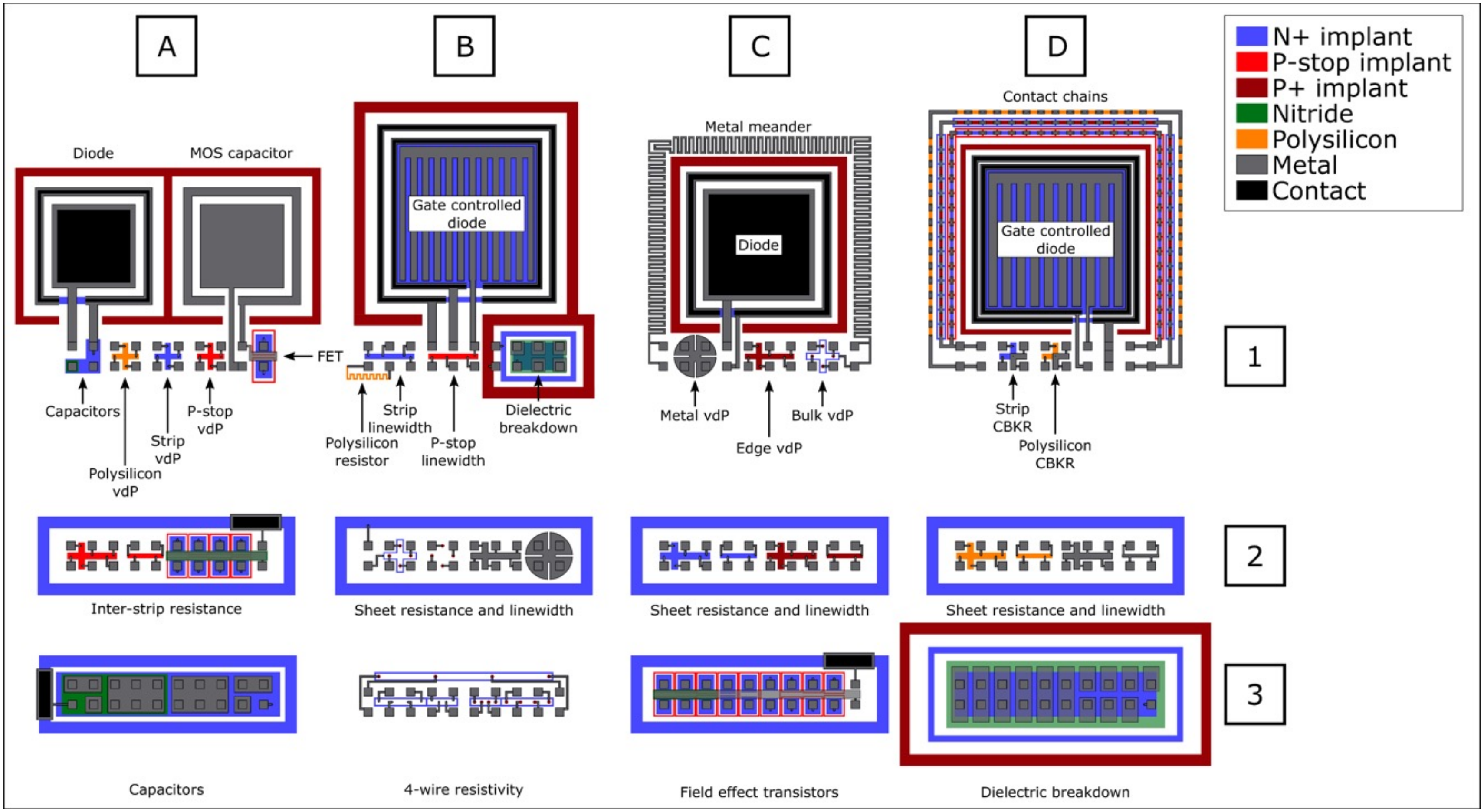


High-P_T tracks (stubs) can be identified if cluster centre in top layer lies within a search window in R-ϕ (rows)

- P_T cut is given by: module radius (z), sensor separation and correlation window

PQC Test Structures

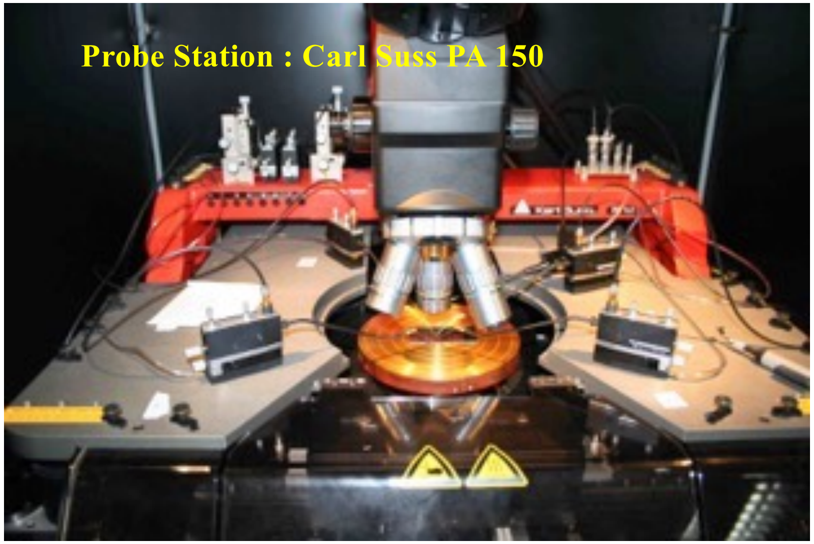
Mask Layout



Sensor Quality Control

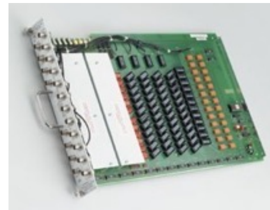
Bulk resistivity	Diode, van-der-Pauw, 4-wire
Oxide quality	MOS, GCD, capacitors with implant
Interstrip resistance	FET, van-der-Pauw
Sheet resistances	Meander, van-der-Pauw, linewidth
Contact quality	CBKR, contact chain, diode
Carrier lifetimes	GCD, diode, pulsed MOS
Dielectric strength	Dielectric breakdown

INPP Local Instrumentation



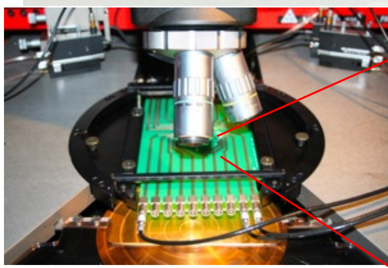
INPP Local Instrumentation

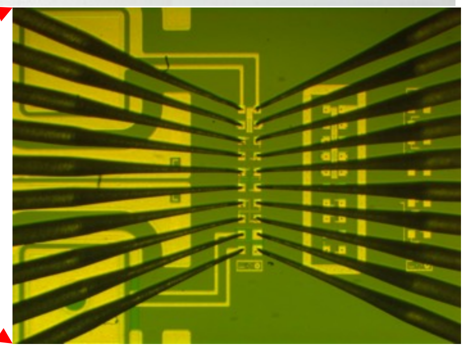
switching matrix



matrix cards

source measure units





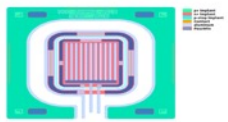
probe card

***EDA Tools :** Access via Europractice to EDA design tools (Cadence, Synopsys TCAD, OrCad)*

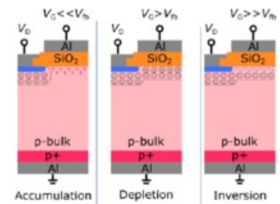
PQC Examples

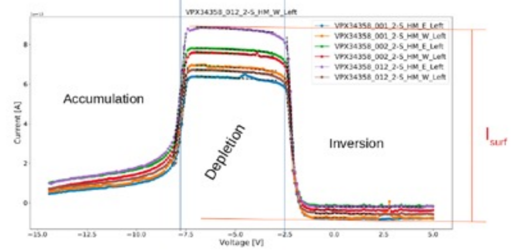
Gate controlled diodes

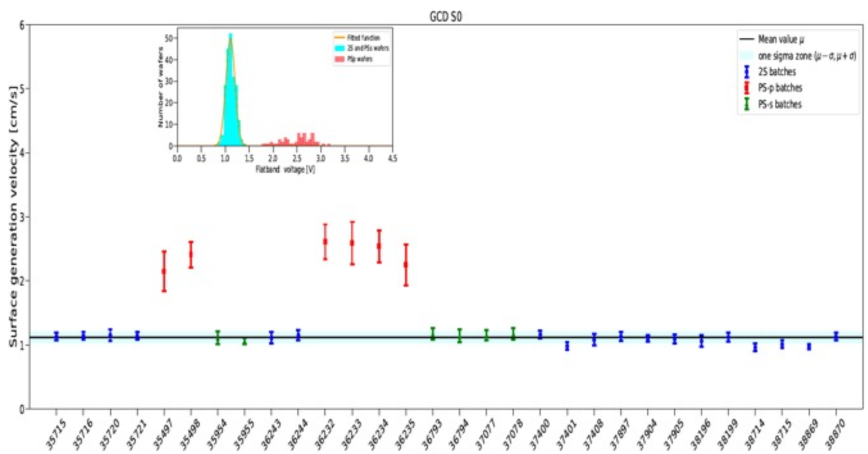
- GCDs are used to investigate the surface current and the number of interface traps
- Consisting of comb-shaped Diode with n+ strips, intertwined with comb-shaped MOS.



- Parameters measured with this device:
    - Surface current $I_{surf} = I_{depl} - I_{inv}$
    - Surface recombination velocity $S_0 \propto I_{surf}$
    - Interface trap density $D_{it} \propto S_0$





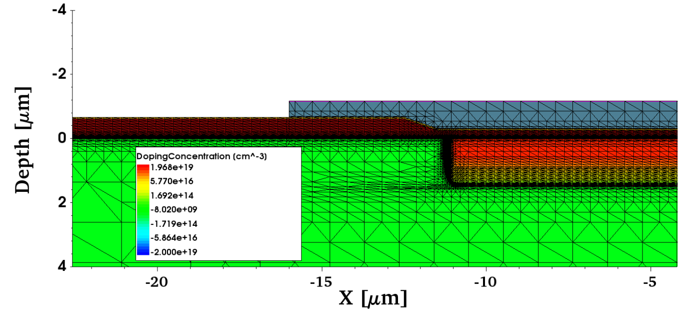


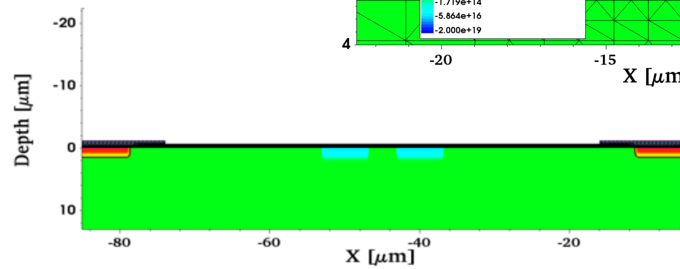
TCAD Simulation for 2S sensors

- 2D structure with 5 strips
  - Pitch: 90 um
  - Width: 22 um

- The capacitance between two neighboring strips i,j according to [2] is calculated by :

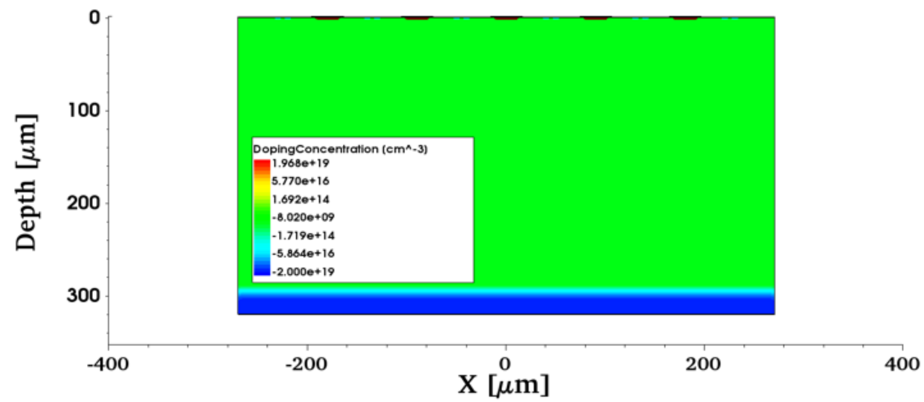
$$C_{int} = C_{I_j - I_i} + C_{M_j - M_i} + C_{I_i - M_j} + C_{I_j - M_i}$$





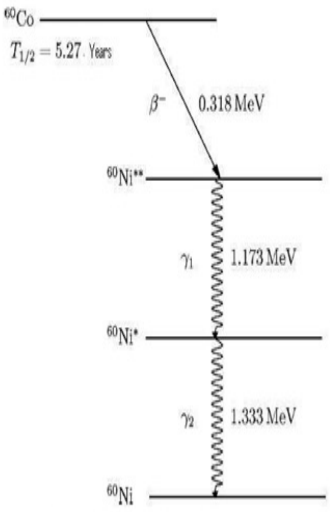
Geometrical characteristics and doping concentrations used for the TCAD simulations

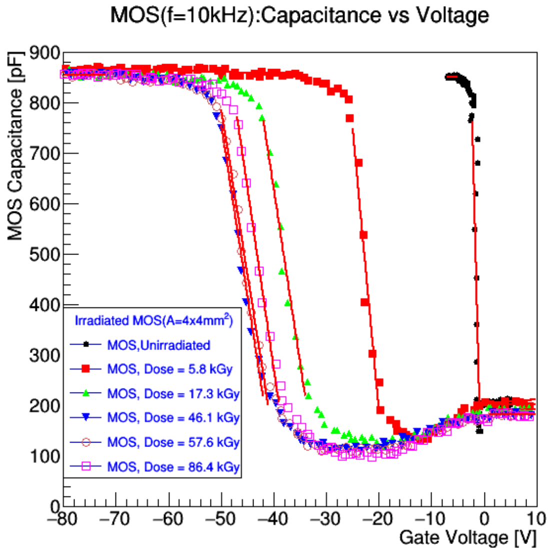
Bulk doping concentration [cm^{-3}]	4.0×10^{12}
Strip doping concentration [cm^{-3}]	1.0×10^{9}
Backplane doping concentration [cm^{-3}]	1.0×10^{19}
p-stop doping concentration [cm^{-3}]	1.0×10^{16}
SiO_2 thickness between strips [μm]	0.65
SiO_2 thickness between metal-strip [μm]	0.25
SiN_4 thickness [μm]	0.05
Aluminum thickness [μm]	0.5
Strip implant thickness [μm]	1.5



[2] S. Chatterji, A. Bhardwaj, K. Ranjan, Namrata, A. K. Srivastava and R. Shivpuri, Analysis of interstrip capacitance of si microstrip detector using simulation approach, Solid-State Electronics 47 (2003) 1491

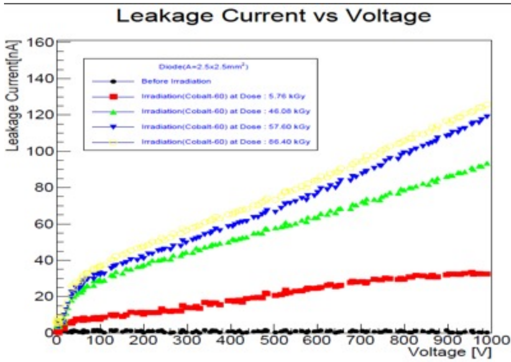
MOS and Diode irradiation studies for Phase 2 CMS Tracker Upgrade





^{60}Co source: Picker therapy unit 30 TBq (March 2012) horizontal orientation (~11 TBq October 2019) Greek Atomic Energy Commission (GAEC),

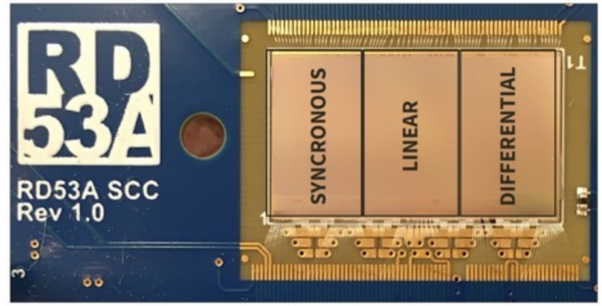
diodes



CMS Phase II Pixel Tracker ASIC

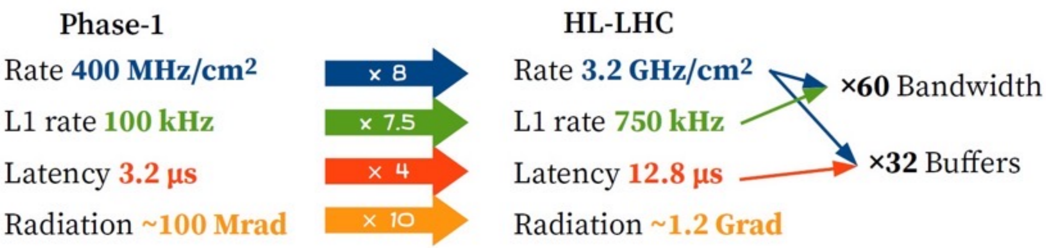
Developed by RD53 Collaboration: 19 Institutes (CMS + ATLAS)

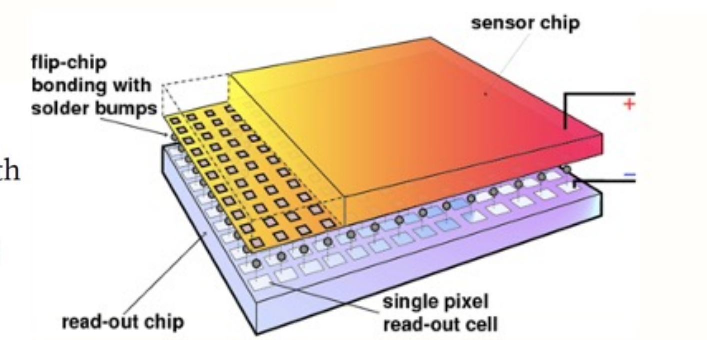
- RD53A Chip 65 nm CMOS successful demonstrator – used to develop Sensors, Modules and System
  - 20×12 mm² (~½ of final size)
  - 3-in-1 different Front-End architectures — accurate review process CMS (& Atlas) made their choice for the final chip *using dedicated DAQ system "μDTC"*



CMS Choice ATLAS Choice

- CMS Readout Chip v1 (CROCv1) received in September '21
  - 21.6mm x 18.6mm (336 rows x 432 columns)
  - Linear Front-End Architecture
  - Currently under characterization





The µDTC DAQ System

- The readout and control of the future front-end modules of the CMS Tracker, will be performed by the DAQ, Trigger and Control (DTC) System.
- The µDTC project was established to perform these tasks in the prototyping and production phases.
- Common framework for Outer Tracker (OT) and Inner Tracker (IT) based on FC7 board and IPBus* - this presentation focuses mostly on Inner Tracker implementation (IT-µDTC).

Software Suite
OT: INFL + DESY
IT: Milano + CERN + Demokritos
(*A.Papadopoulos*)

+

Firmware Suite
OT: DESY
IT: Demokritos
(*Y.Kazas*)

+

Hardware

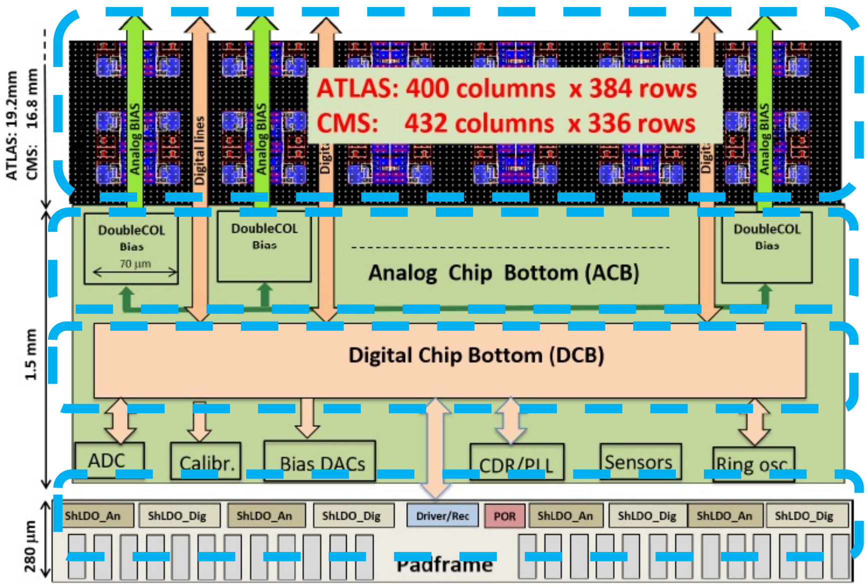
FC7 Board,
Developed by CERN

- **Demokritos has undertaken the responsibility to develop and maintain the DAQ for the Inner Tracker System Tests**

<u>*IPBus:</u> Ethernet-based communication protocol, developed by CERN.

CROC_v1 Characterization

For the new version of the CMS readout chip, Demokritos is leading the team for the characterization of the ASIC.



Pixel Matrix & Analog Front End:
CERN + Demokritos
(A. Papadopoulos)

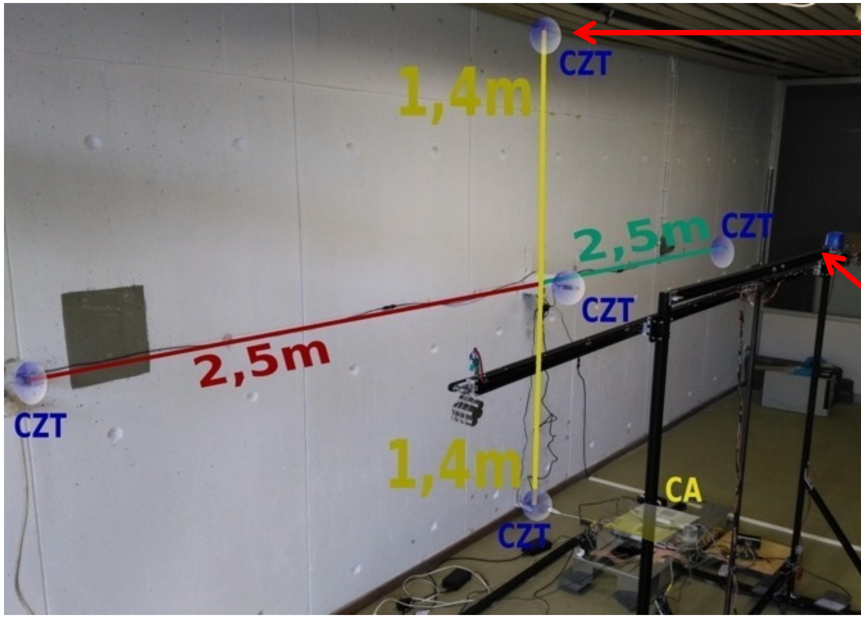
Analog Chip Bottom:
University of Zurich

Digital Chip Bottom:
Demokritos (Y. Kazas)

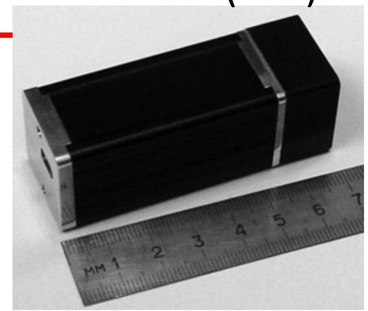
Power Supply Circuits:
Universita e INFN, Firenze

Coordinating the team:
Demokritos (Y. Kazas)

Artificial Intelligence for Radiation Detection Lab

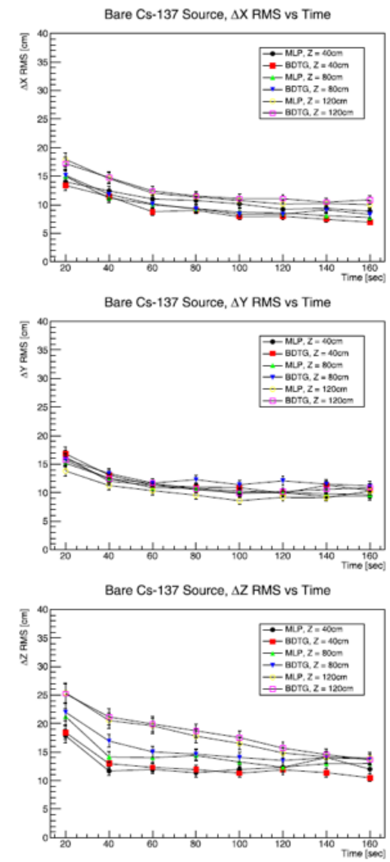


CdZnTe(CZT)



^{137}Cs, 180μCi

Bare Source Spatial Resolution vs exposure time



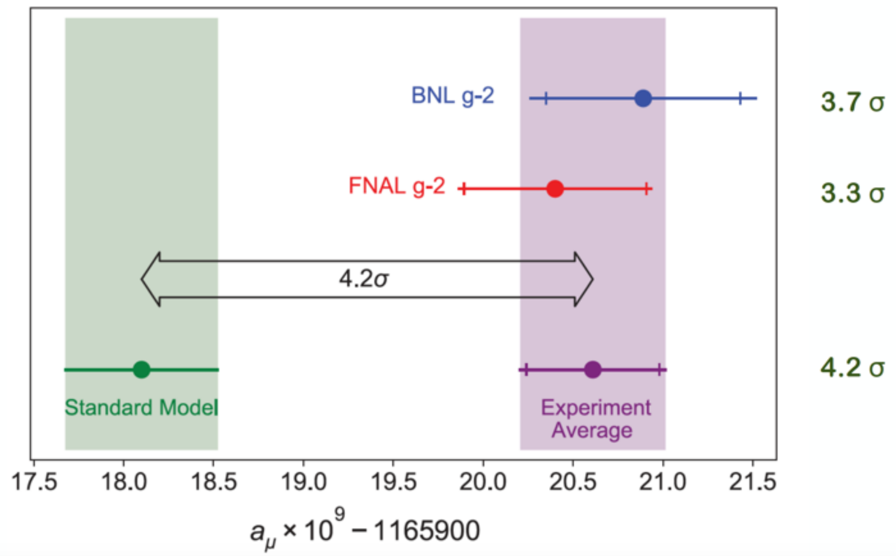
The localization resolution using AI after 40sec of exposure time:

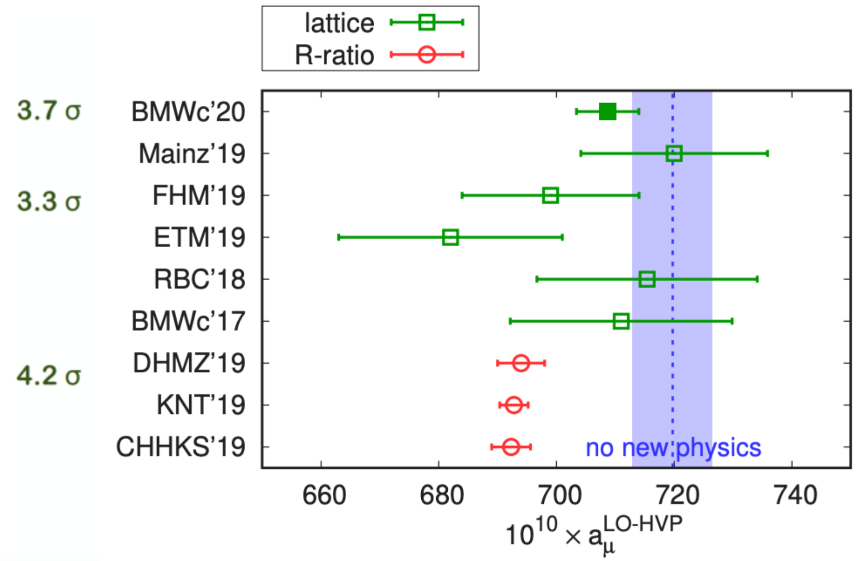
- Bare radioactive source :
  ~ 10 cm to 20 cm in 3D within a monitored volume of 5m × 2.8m × 2m
- Slightly shielded source:
  ~ 15 cm to 30 cm in 3D within a monitored volume of 5m × 2.8m × 2m

A. Kyriakis *et al* 2022 *JINST* **17** C03018

The MUonE Experiment

Muon g-2 measurements





BNL E821	$(116592089 \pm 63)\times 10^{-11}$	Dominant Statistical
FNAL E989 Run 1	$(116592040 \pm 54)\times 10^{-11}$	uncertainties
Weighted Average	$(116592061 \pm 41)\times 10^{-11}$	0.35 ppm

Expected improvements: factor 2 from FNAL Run 2+3; more from Run 4+5

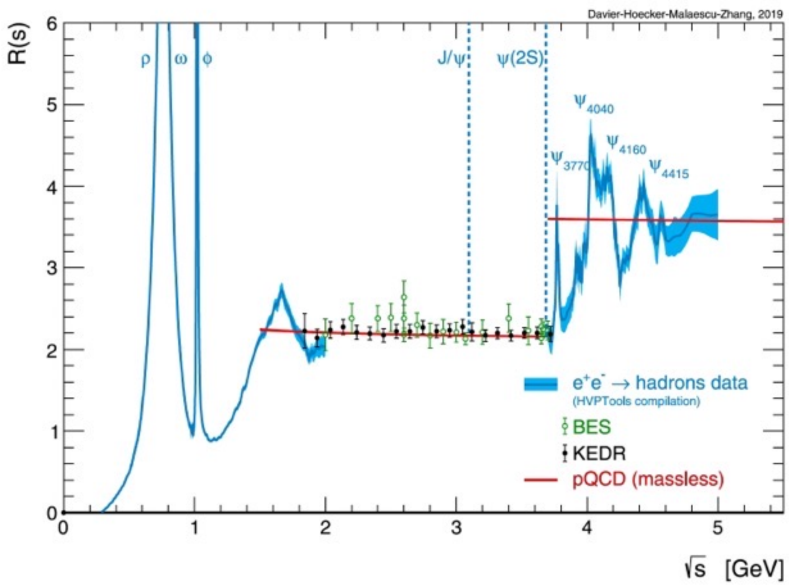
The MUonE Experiment

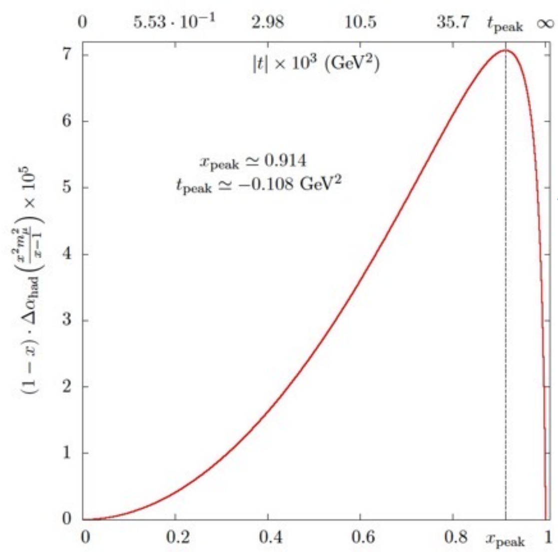
$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

$$a_\mu^{had} = (693.7 \pm 4)10^{-10}$$

Hadronic contributions give rise to main theoretical uncertainties. One relies on a dispersion relation approach to evaluate the lowest order contributions from corresponding cross section measurements.

An alternative approach has been proposed (by interchanging the order of Integration , which yields in a smooth function of $-Q^2(x)$





$$a_\mu^{had,LO} = \frac{\alpha}{3\pi}\int_0^\infty \frac{ds}{s} K_\mu^2(s) R(s)$$

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

The MuonE project

Measure the effective electromagnetic coupling in the space like region via scattering data* :

Scatter a 150 GeV muon beam on a Graphite (or Beryllium) fixed target

$$\mu^{\pm}(p_1)e^{-}(p_2) \rightarrow \mu^{\pm}(p_3)e^{-}(p_4)$$

The fundamental constrain

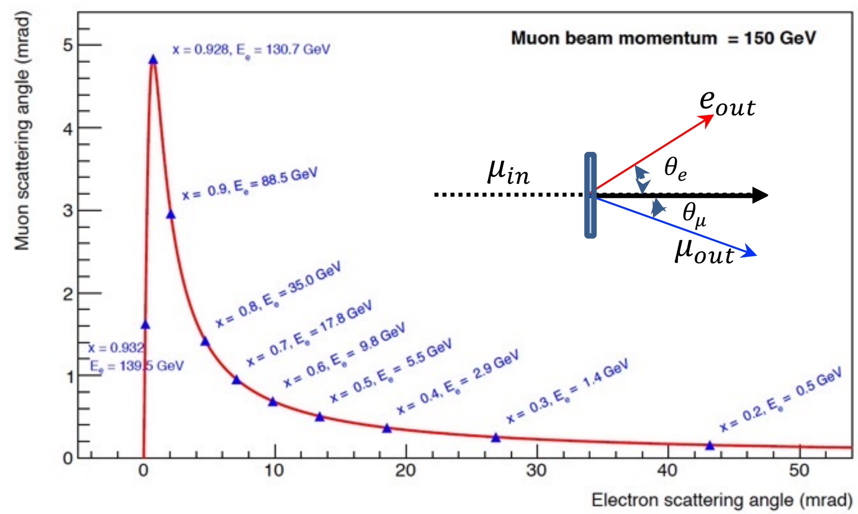
For elastic μe scattering

$$tan\theta_{\mu} = \frac{2tan\theta_e}{(1+\gamma^2 tan^2\theta_e)\left(1+\frac{E_1 m + M^2}{E_1 m + m^2}\right) - 2}$$

1. This is the fundamental constraint to discriminate elastic scattering events from the background of radiative events and inelastic processes.

2. At the same time, due to the small angles between the incoming muon and the the outgoing electron, a detector of medium to small transverse surface will suffice.

3. A statistical error of 0.3% for three years of run is expected

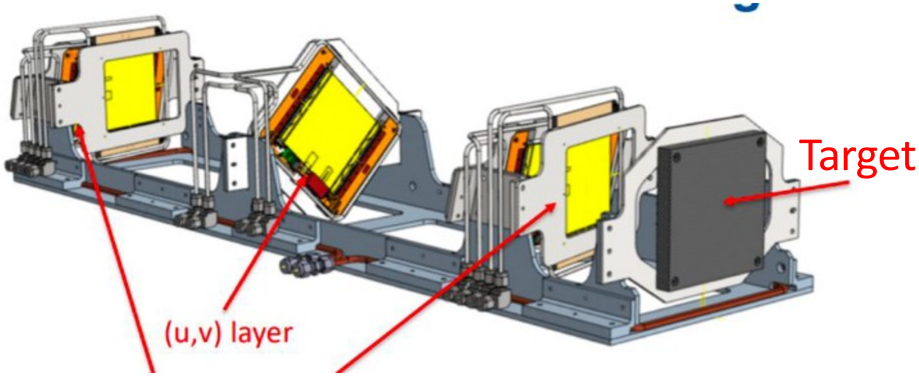


MUonE vs CMS

The MuOnE experimentL apparatus is a "byproduct" of the CMS Tracker project because the tracker modules of the Outer Phsae II CMS Trcaker will be used along with callorimetry modules based on the CMS ECAL crystals.

In principle :

Assuming a 150 GeV muon beam with intensity 1.3×10^{7} muons/s (presently available at CERN) incident on a Beryllium or Graphite target (40 layers, each 1.5 cm thick) and three years of data taking, one can reach an integrated luminosity of 1.5×10^{7} nb^{-1} , which would correspond to a statistical error of 0.3% on the value of $a_{\mu}^{HVP,LO}$. This will consolidate the muon g-2 and allow a firmer interpretation of upcoming measurements at Fermilab and J-PARC.



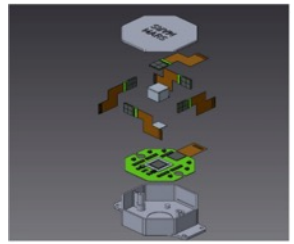
Tilted planes

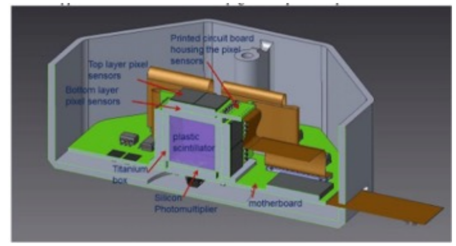
Calorimetry

The MIDAS Radiation Detector

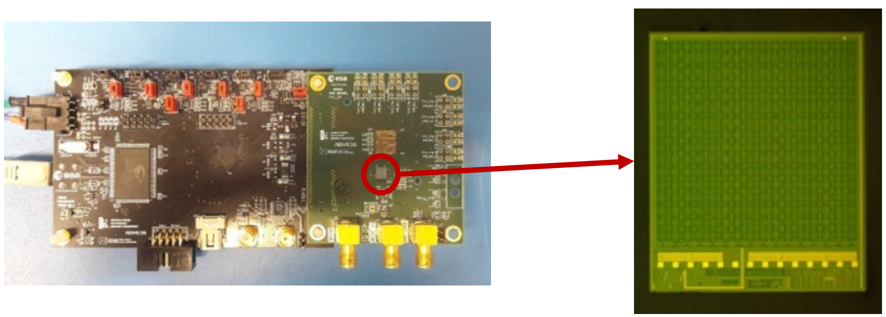
MIDAS is highly miniaturized radiation detector for use in space applications.

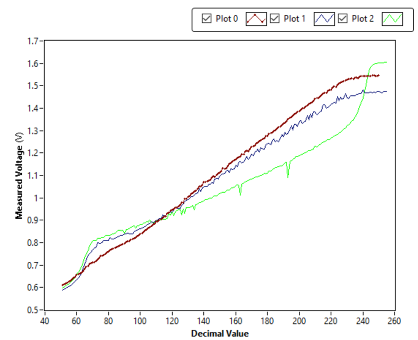
Detecting Head consists of 40 HVCMOS ASICs (32 x 32) & The Neutron Monitor subsystem.





Evaluation Board and DAQ system by I. Kazas.





https://www.sciencedirect.com/science/article/abs/pii/S1350448720301116

Conclusions

- *A strong Physics Analysis group is in place at INPP with several important contributions to the CMS physics program.*
- *Based on the expertise acquired in the course of the past fifteen years, the Instrumentation CMS-INPP group is established as the principal group in Greece in the field of solid-state sensors and related VLSI read out electronics for HEP radiation detector systems.*