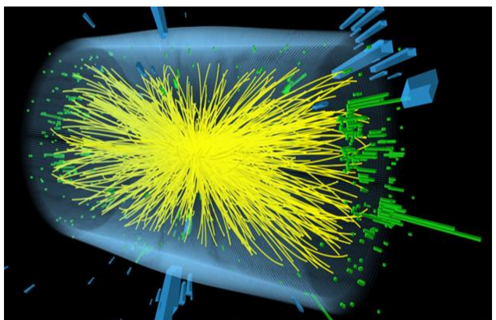
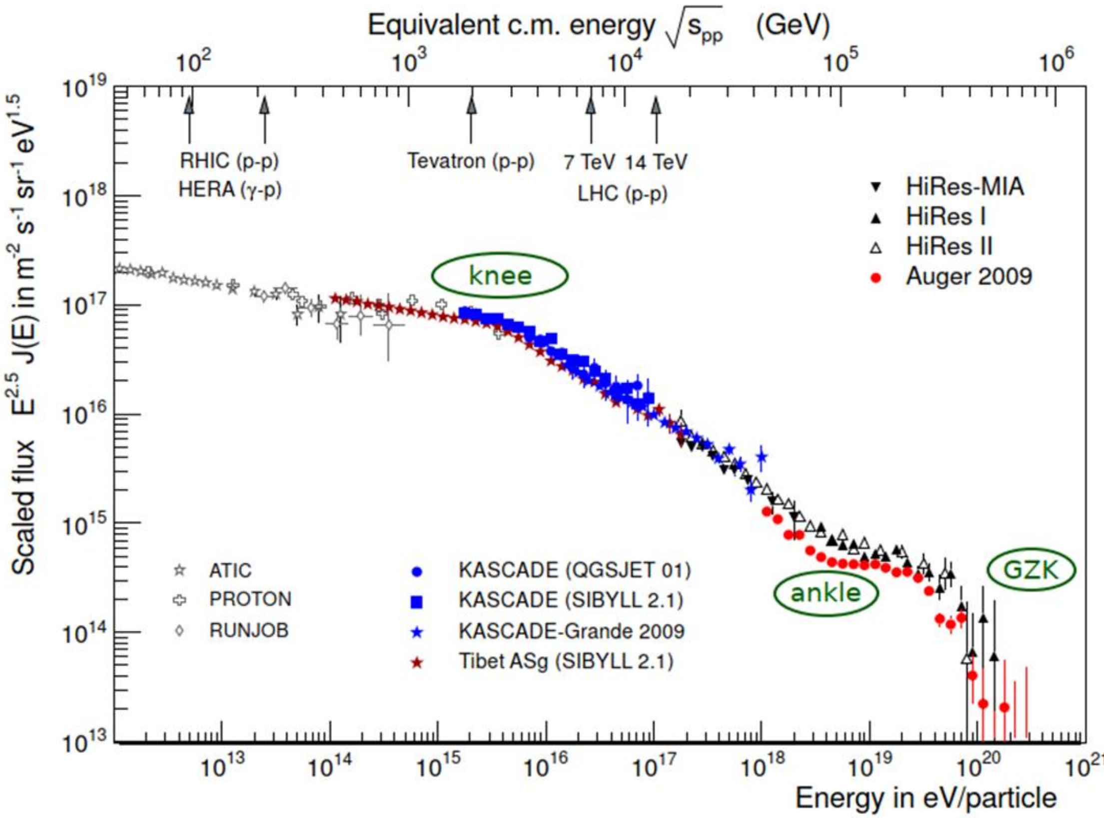
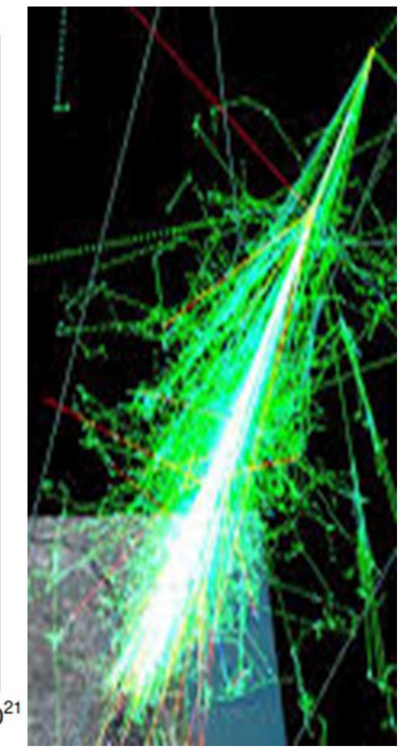
Forward Physics at LHC:
Intersection with Astrophysics

QCD24: 27th High Energy Physics International Conference in Quantum Chromodynamics, 8-12 Jul 2024, Montpellier (France)







Aldo Penzo, U. of Iowa (on behalf of the CMS Collaboration)

Preamble

At QCD-2016:

"Diffractive and Parton Processes with Forward Detectors at the LHC"

Focus on **partonic processes** in the new regime of LHC and simulation programs to describe them.

Use measurements of total/inelastic cross-sections to **constrain cosmic ray generators** and compare results of hadroproduction.

However, as we'll see, simulation programs tuned to the LHC regime, ended up in **underestimating the muon flux** at Auger Observatory....

On the other side we are flooded with messages (Siderei Nuncii!)(*) coming from cosmic events, remote in space and time... (**)

(*) Galileo (March 13, 1610)

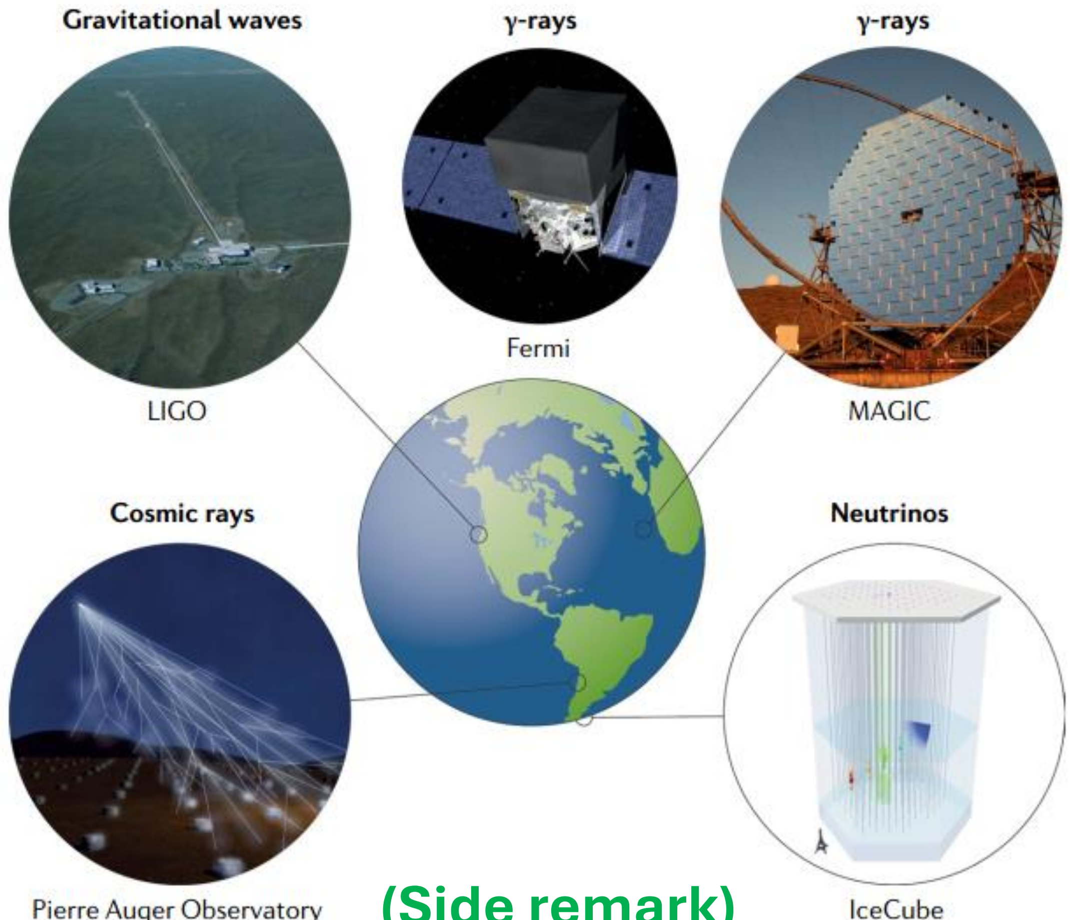
(**) Pierre Auger (1938)

Multi-Messenger Astrophysics

Some current instruments observing cosmic signals via the electromagnetic, gravitational, weak and strong forces

<u>LIGO:</u> Laser Interferometer Gravitational-Wave Observatory
<u>MAGIC:</u> Major Atmospheric Gamma Imaging Cherenkov Telescopes, Canary Islands
<u>Pierre Auger</u> Observatory: Cosmic Ray Arrays, Argentina
<u>IceCube</u>: cubic kilometre neutrino detector, Antarctica
Fermi: γ-ray space telescope (NASA)

Complementarity of information carried by photons, gravitational waves, neutrinos and cosmic rays about individual cosmic sources.

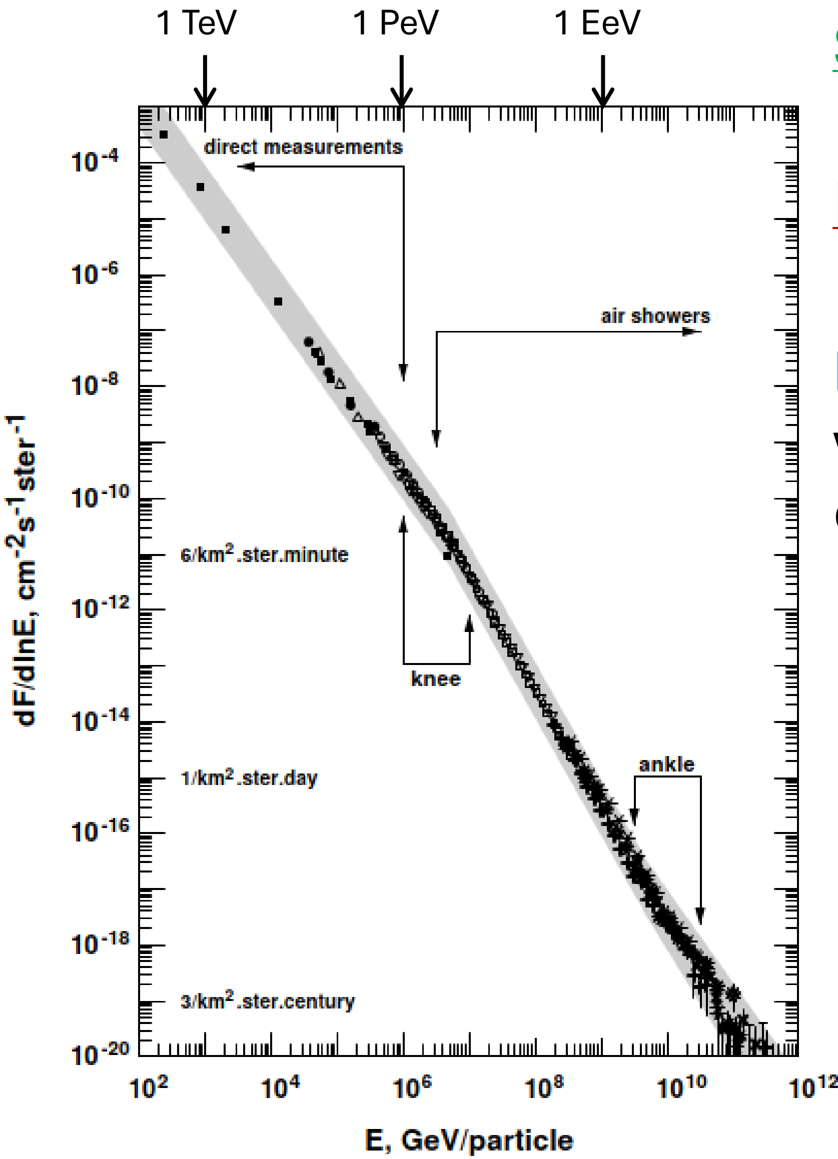


(Side remark)

Astrophysics detectors :
"... an ode to Cherenkov!"

Cosmic Rays: Origins

Seen as Extended Air Showers (EAS)



Sources: galactic up to the "knee"
extra-galactic above the "ankle"

Energies: Few PeV (10^6 GeV) at "knee"
Few EeV (10^9 GeV) at "ankle"

E. Fermi (1949): Acceleration from interaction with random magnetic fields of interstellar clouds; spectrum with inverse power low …
(Difficulties with "injection", mainly for heavy nuclei…)

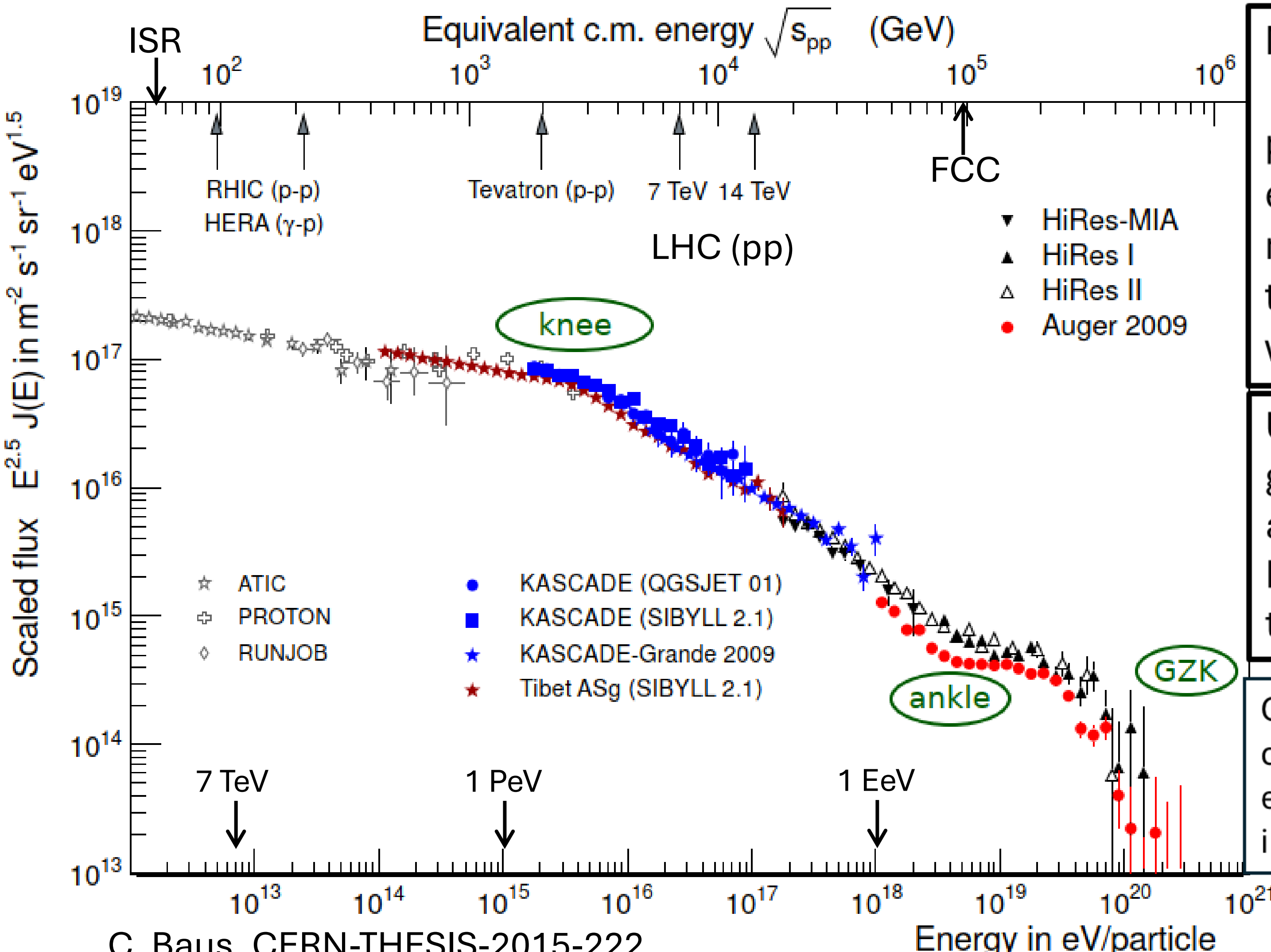
Further developments:

F. Bouchet et al., Minimal Stochastic Model for Fermi's Acceleration; Phys. Rev. Lett 92, 040601 (2004);
A.Marcowith et al., Multi-scale simulations of particle acceleration in astrophysical systems; Living Reviews in Computational Astrophysics (2020) 6:1 ;
M. Lemoine, First-Principles Fermi Acceleration in Magnetized Turbulence; Phys. Rev. Lett 129, 215101 (2022)

Particle Accelerators…

Cosmic vs (Under-)Ground

<u>Sideral messages</u> can be seized and reproduced, with new <u>decrypting machines</u>



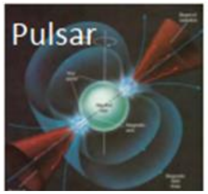
C. Baus, CERN-THESIS-2015-222

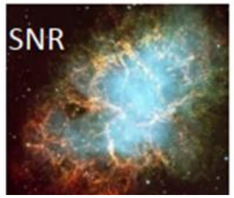
Man-made accelerators are approaching CR energies; in particular for equivalent CM energies of CR-atmospheric nuclei collisions. LHC covers the “knee” region and FCChh will cover the “ankle”region.

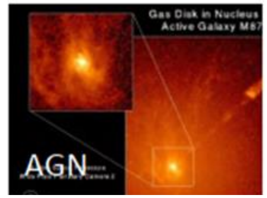
Up to “knee” region, CR are galactic, and extra-galactic above the “ankle” ;
Between “knee” and “ankle” there is a transition region

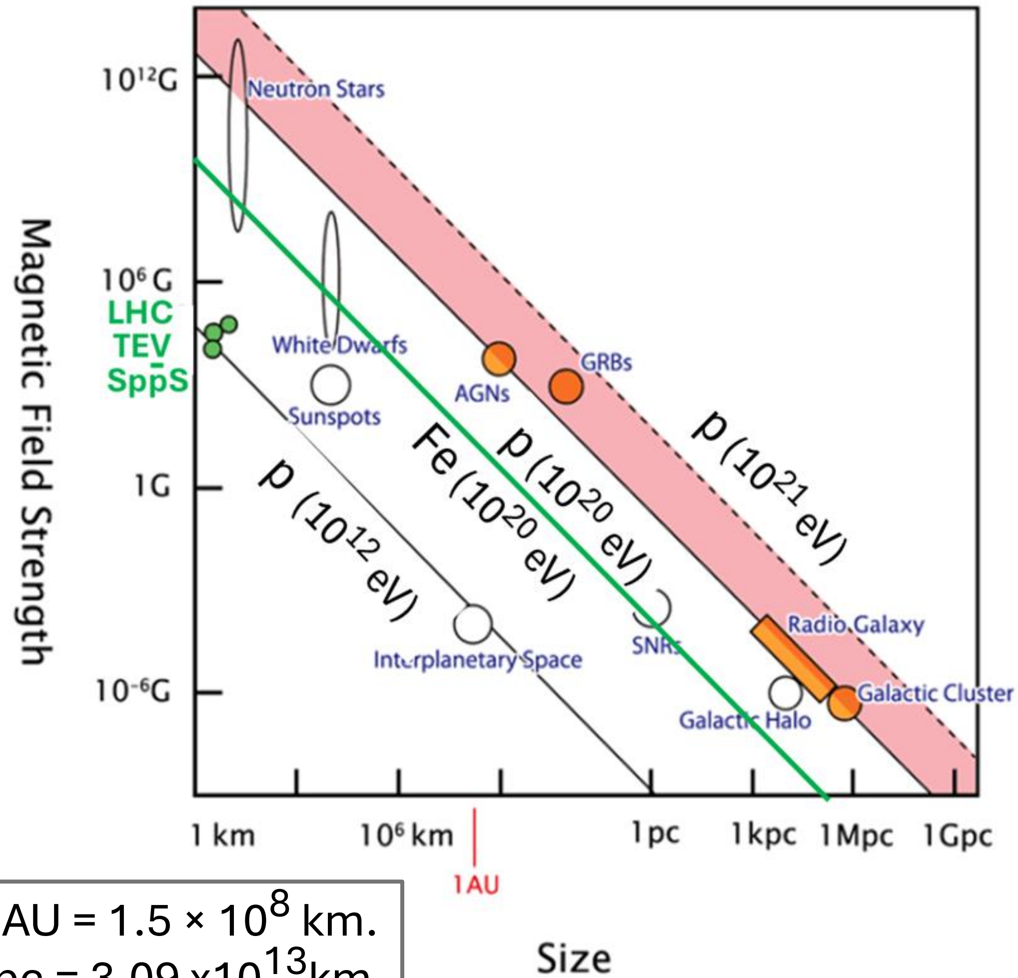
GZK (Greisen–Zatsepin–Kuzmin): cutoff on energy of protons from extra-galaxies (50 EeV), from their interaction with CMBR.

"Hillas plot" (1984) : UHECR sources







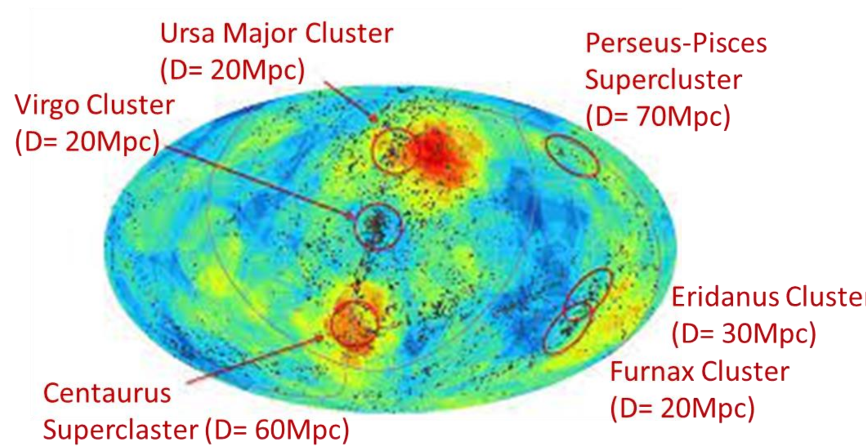


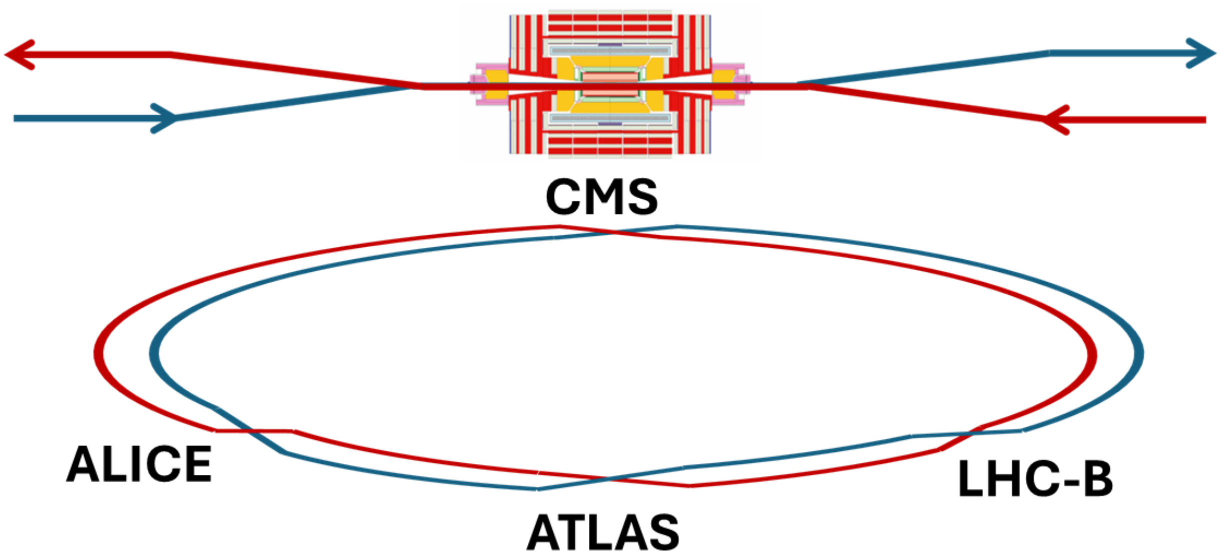
1 AU = 1.5 × 10^{8} km.
1pc = 3.09 x10^{13}km

"Hillas' Criterion":
Ions of charge Ze and energy E, in a magnetic field B, have curvature radius r = E/(ZeB) that should be less than the acceleration region size L:

$$E_{max} \sim Ze(BL)/2$$

Map of possible sources from Auger and Telescope Array



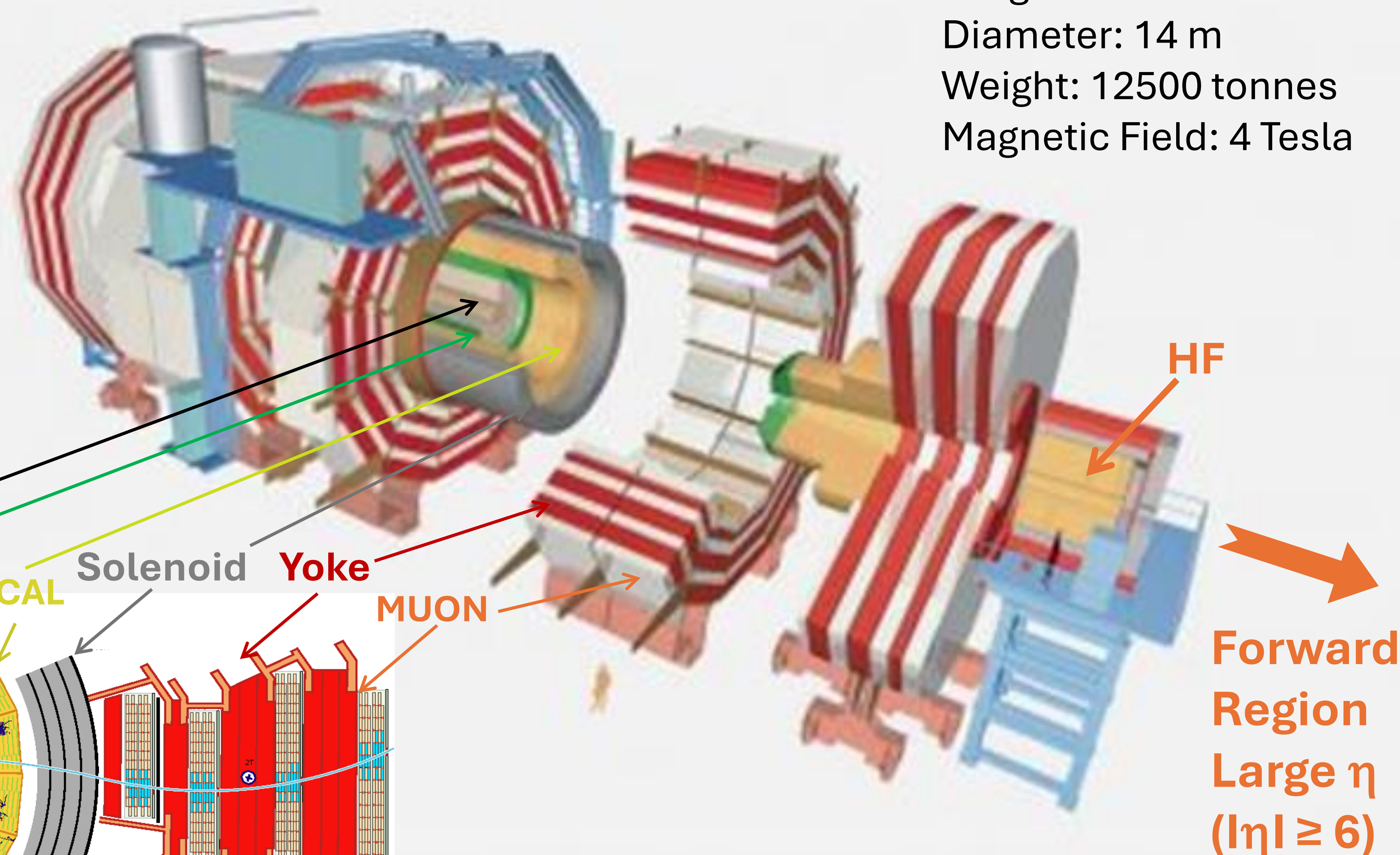


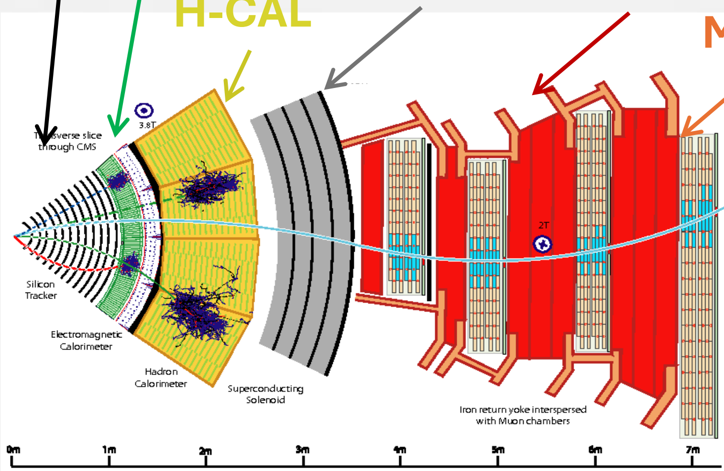
LHC : world largest accelerator/collider

Diameter : 8.6 km
Beam energy : 7 TeV
Intensity: 3.37×10^{14}
Collisions: 10^{12}/sec
(pp and PbPb)

CMS: Compact Muon Solenoid

Length: 21.6 m
Diameter: 14 m
Weight: 12500 tonnes
Magnetic Field: 4 Tesla





CMS Forward detectors

Quartz Cherenkov Calorimeters (HF, CASTOR, ZDC)

HF (3.0 ≤ IηI ≤ 5.2)

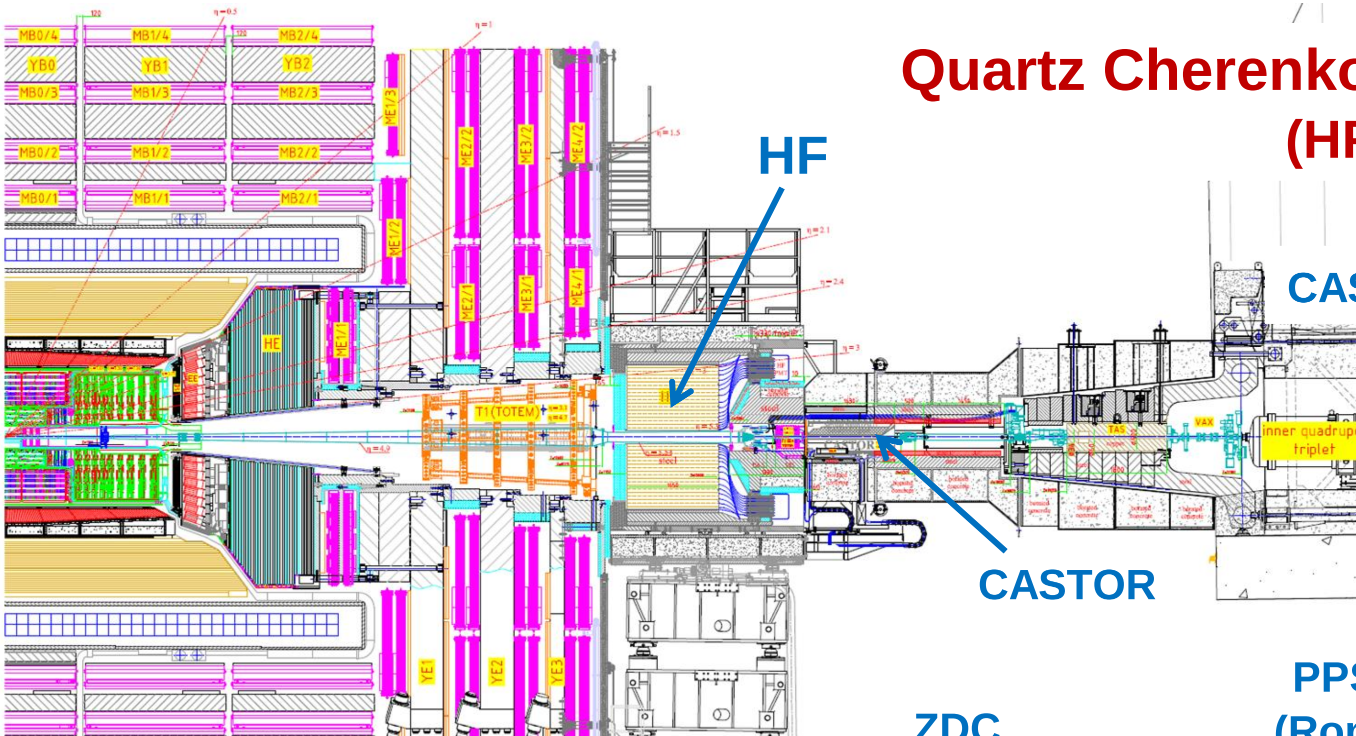
CASTOR (-5.0 ≥ η ≥ -6.65)

ZDC (IηI ≥ 8.0)

IP5

HF

CASTOR

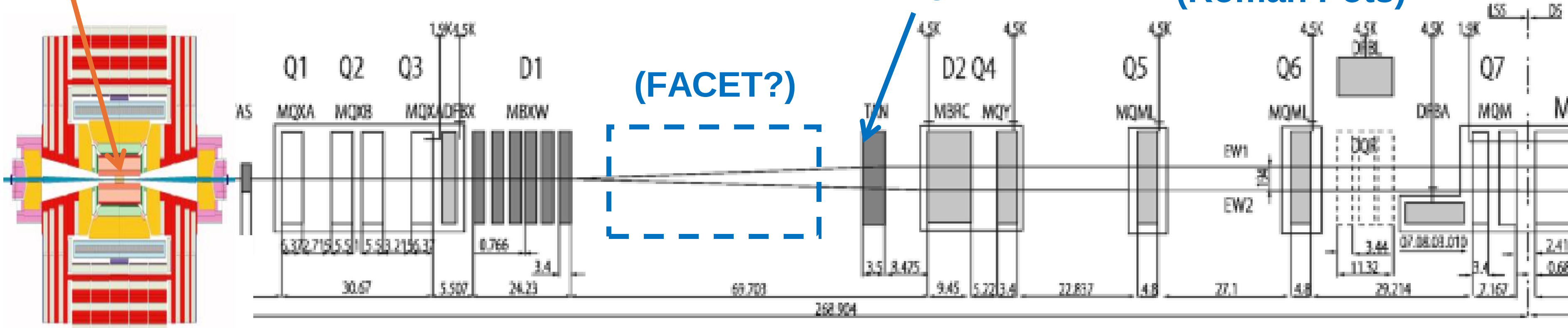


Forward Region (IηI ≥ 6)

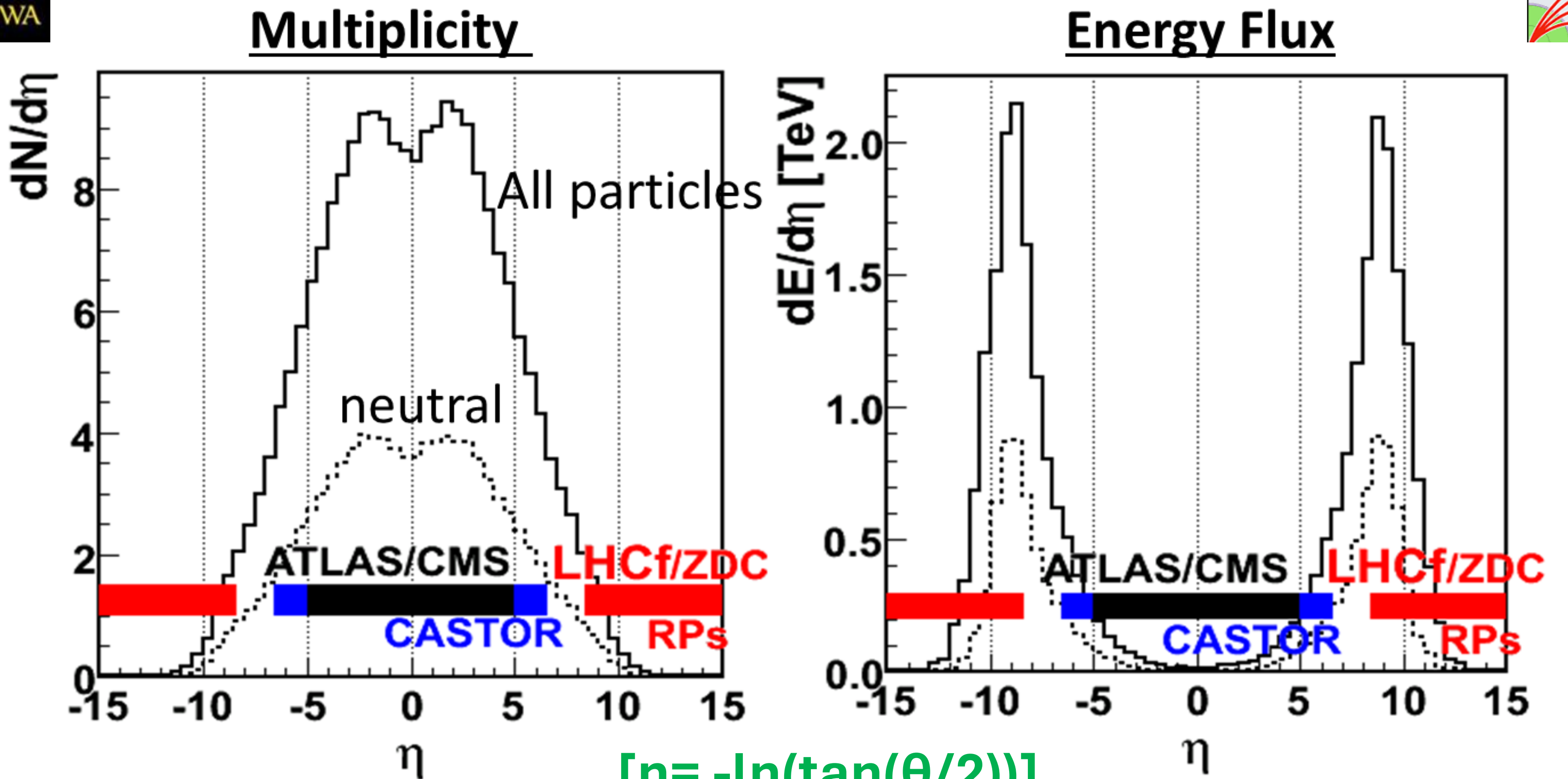
PPS-TOTEM (Roman Pots)

ZDC

(FACET?)



LHC: Multiplicity and Energy Flux at 14TeV



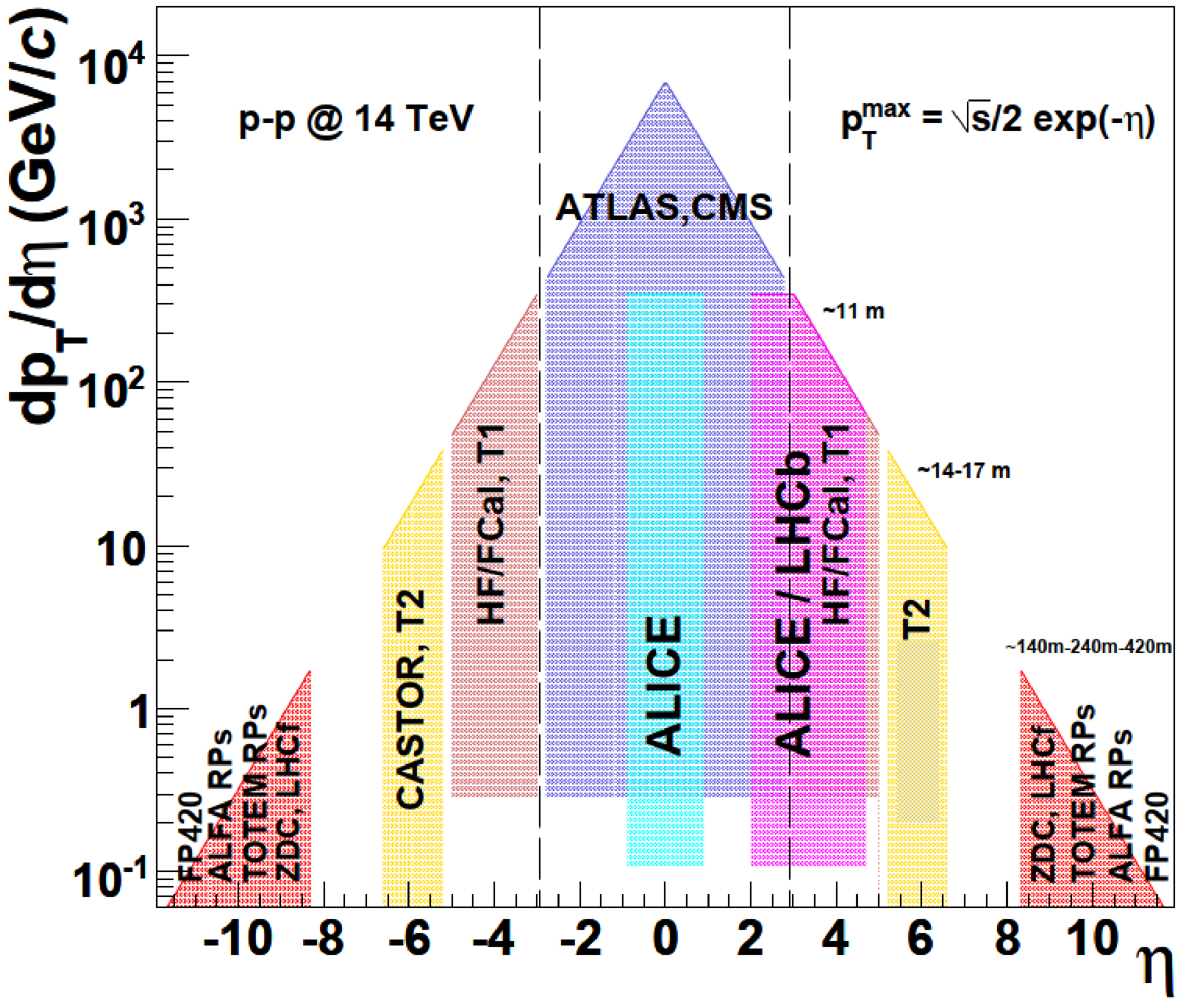
[η= -ln(tan(θ/2))]

Most particles produced in central region

Most energy flows into very forward region (= relevant to EAS)

(NB: Forward → soft interactions: experimentally &theoretically difficult!)

Large – η Coverage at LHC



[D. d'Enterria, arXiv:0806.0883v3 [hep-ex] 30 Aug 2008]

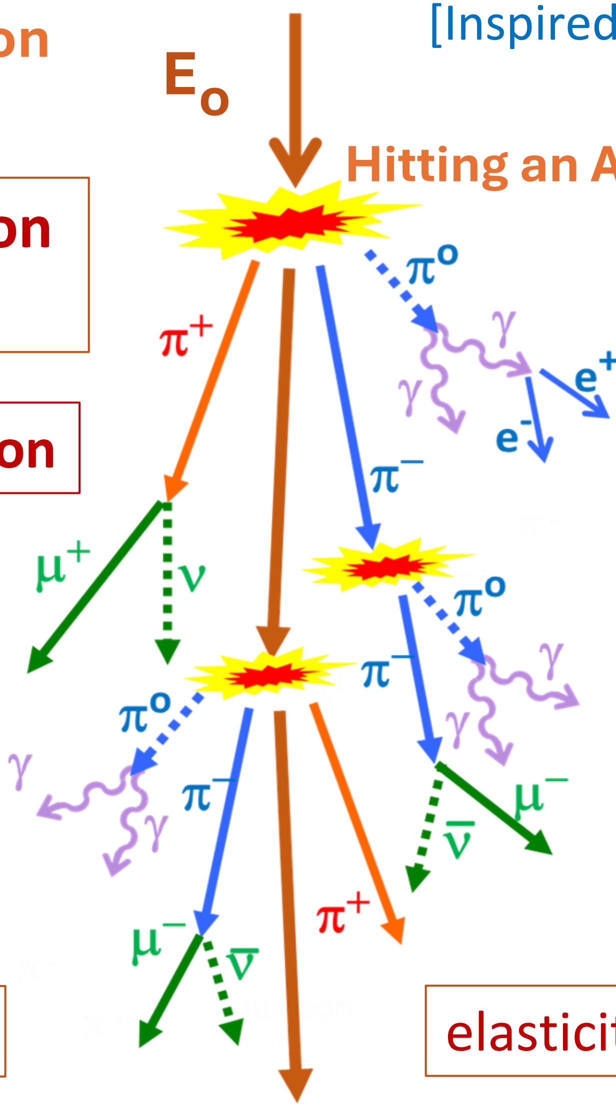
This is an early –stage snapshot of the "forward detectors" at LHC During the successive stages of Run1 /Run2/Run3 operations the configurations of some "forward detectors" changed drastically For instance: FP420 has not been implemented, CASTOR activity was discontinued in 2020, as well as the TOTEM trackers T1 and T2. On the other side important parts were added to LHCb and ALICE. The "gap" around $|\eta| \approx 7$ has been partially filled during Run1 (FSC), but now it extends over $5 \leq |\eta| \leq 8$ To be noted that the region $|\eta| \approx 7$ is being targeted by FACET....

The role of LHC in understanding UHECR
(and viceversa?)

[Inspired by T. Sako, UHECR2016@Kyoto,(2016)]

Primary proton
(or nucleus)

Hitting an Air molecule



1. **p–A interaction ($\sigma_{inel.} \rightarrow \lambda_{int}$)**

Multi meson production

2. **Particle production**

inelasticity (E_{meson}/E_0= 1-elasticity)
Multiplicity, meson spectrum

3. **π–A interaction**

π^os initiate EM showers

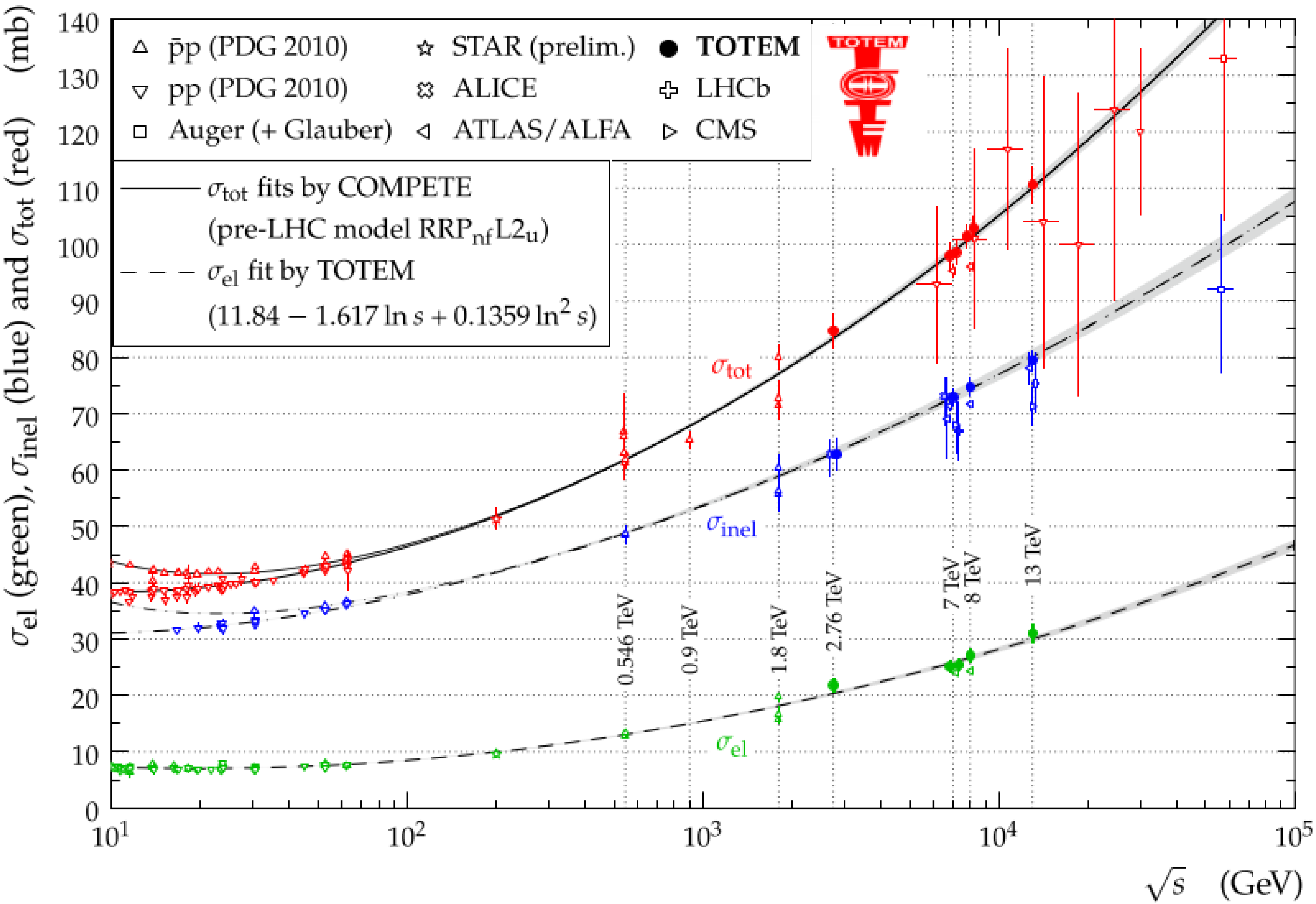
$\pi^{\pm}$s eventually decay to muons

4. **Nuclear effects**

5. **Leading baryons**

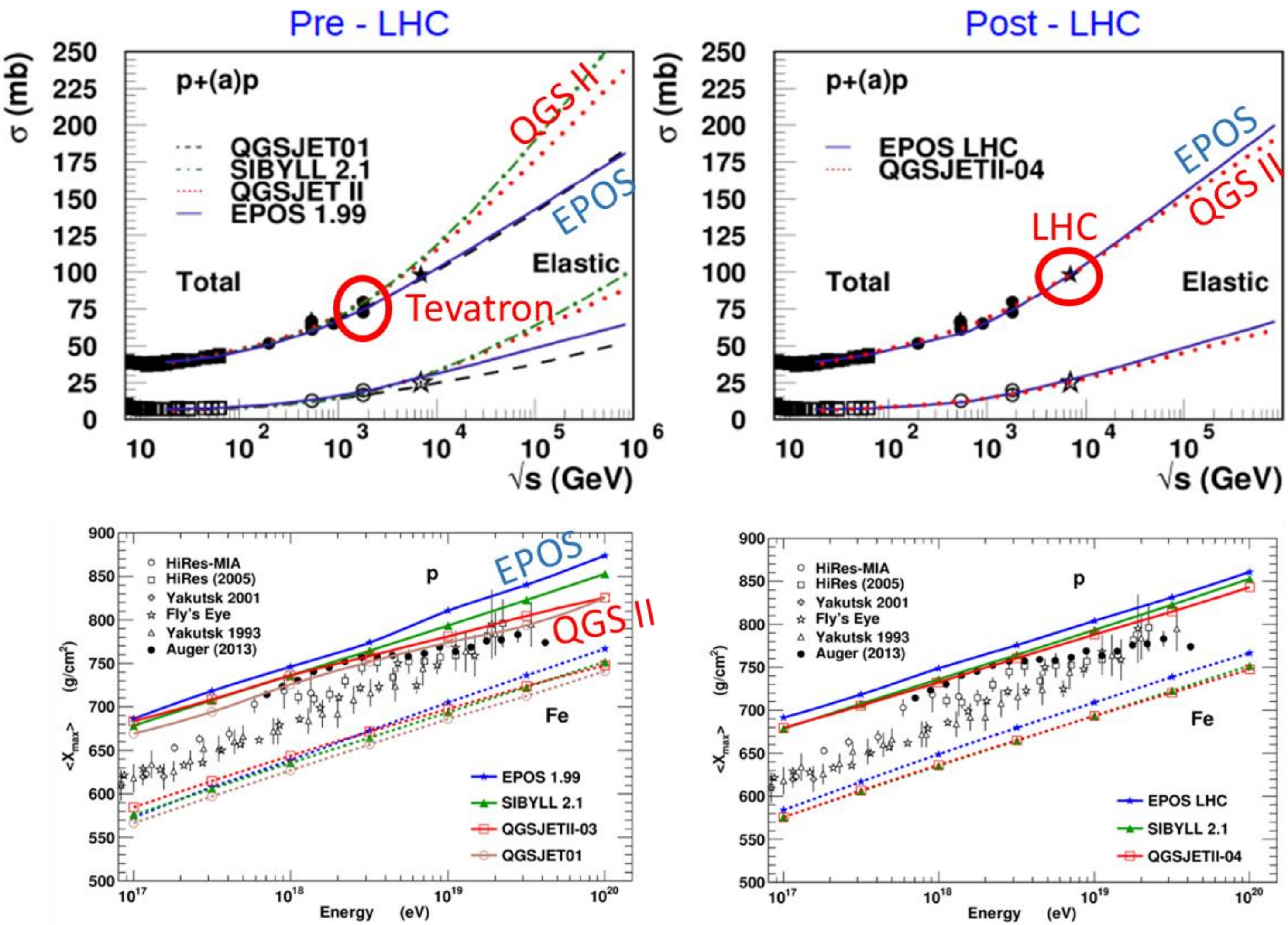
elasticity (E_{baryon}/E_0) → baryon spectrum

Basic cross-section results from LHC (TOTEM)



F. S. Cafagna (for the TOTEM Collaboration), Latest results for proton-proton Cross Section Measurements with the TOTEM experiment at LHC; PoS(ICRC2019)207; 36th International Cosmic Ray Conference -ICRC2019-July 24th - August 1st, 2019, Madison, WI, U.S.A.

$\langle X_{max} \rangle$ model estimates (T.Pierog, HESZ2015)

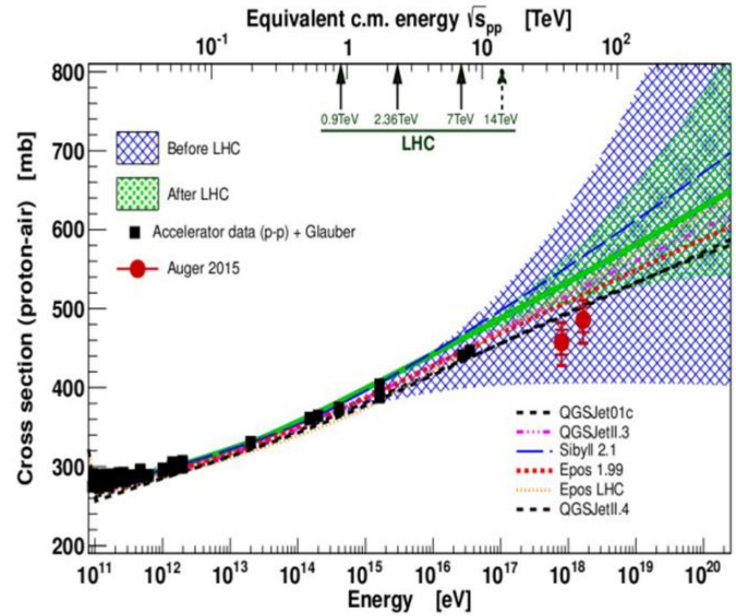


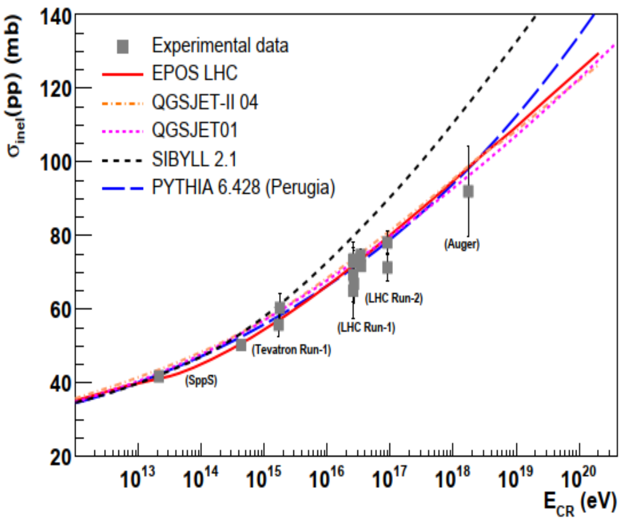
Using LHC σinel to tune "post-LHC" models, differences in <Xmax> model estimates are reduced.

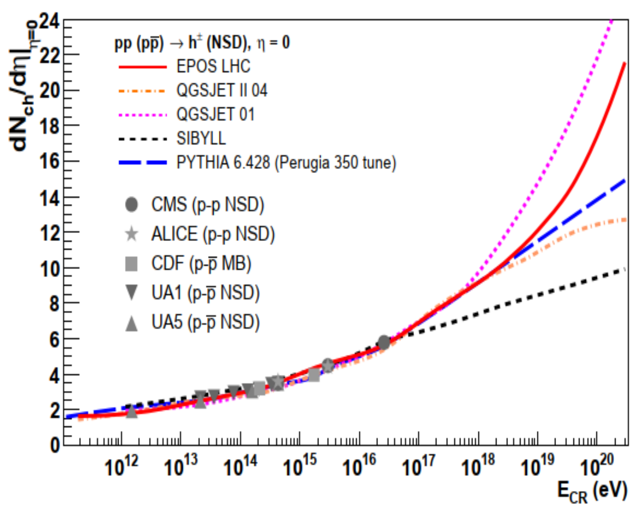
Model tuning with Inclusive LHC data

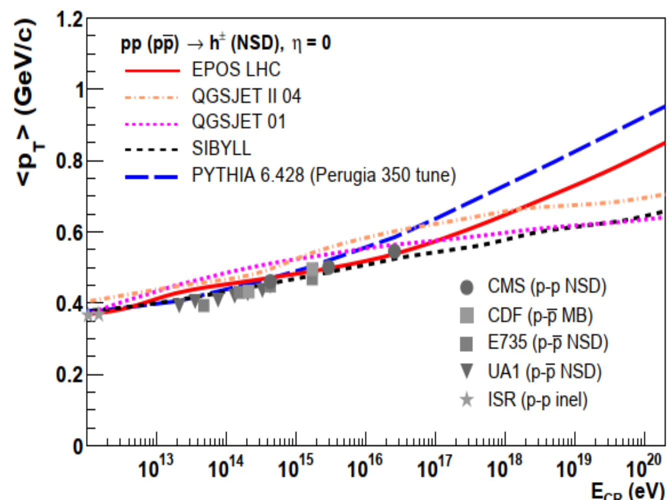
LHC is the first collider reaching energies higher than the knee in the UHECR energy spectrum. The LHC hadron multiplicity measurements do not indicate signs of any special change in the properties of hadronic interactions above √s ≈ 2 TeV; therefore the break in the power-law index is probably reflecting simply a change from light to heavier components of the showers.

The measured midrapidity charged-particle density is found to follow a simple power-law in energy, from 10 GeV up to 7 TeV c.m. energy, with exponent ≈ 0.10.



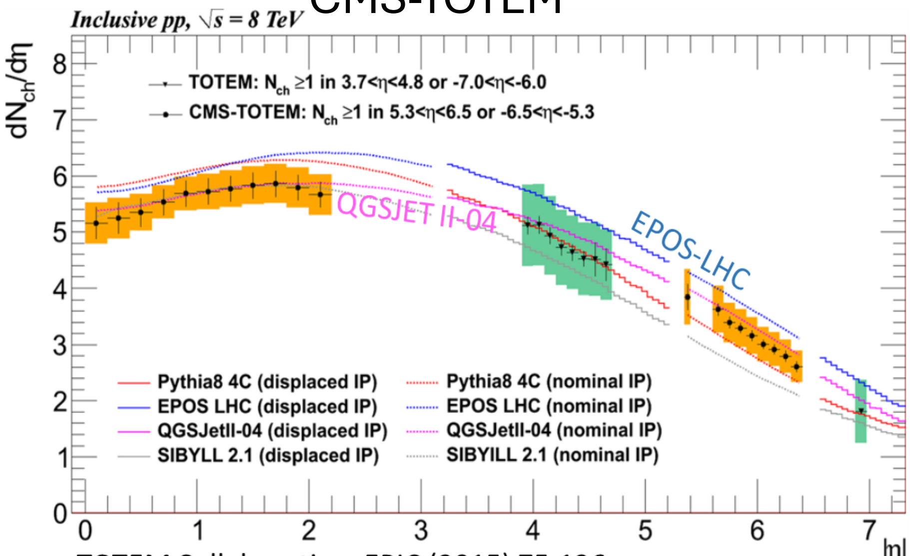






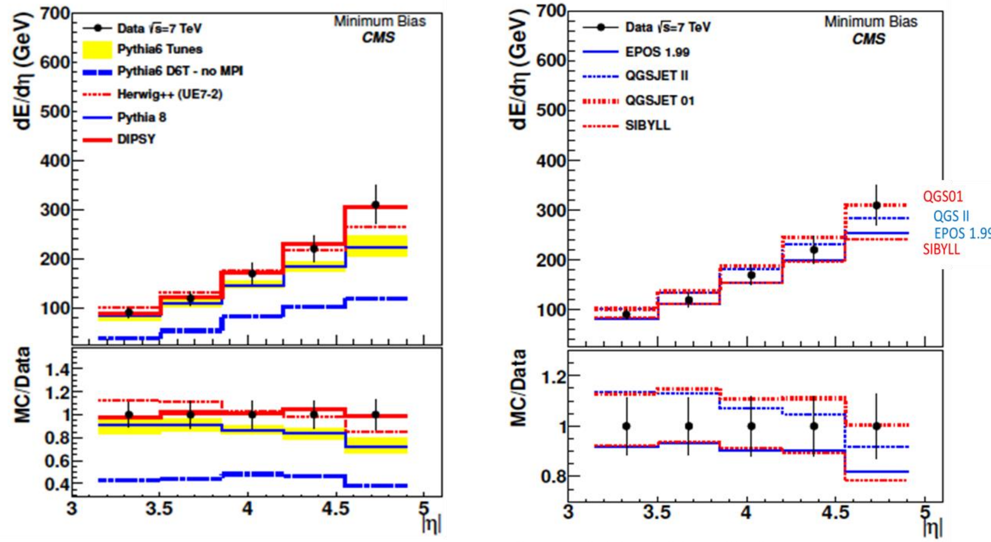
Inclusive measurements with forward detectors

CMS-TOTEM



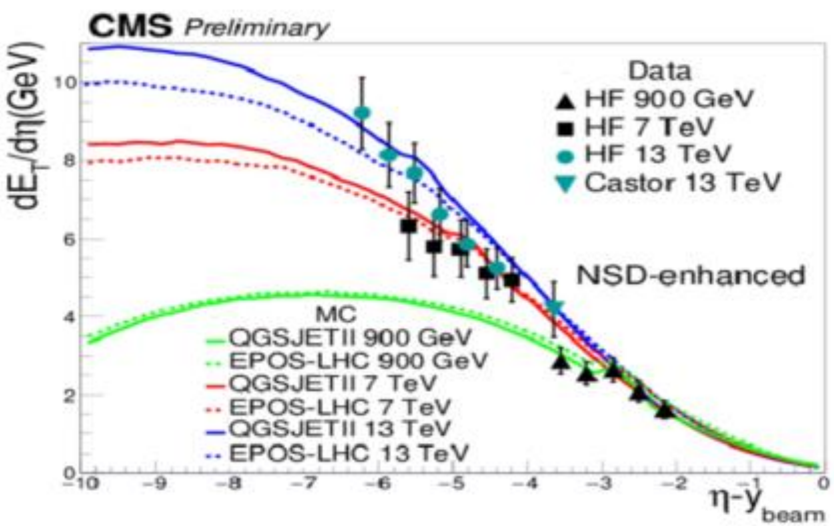
TOTEM Collaboration, EPJC (2015) 75:126

CMS-HF

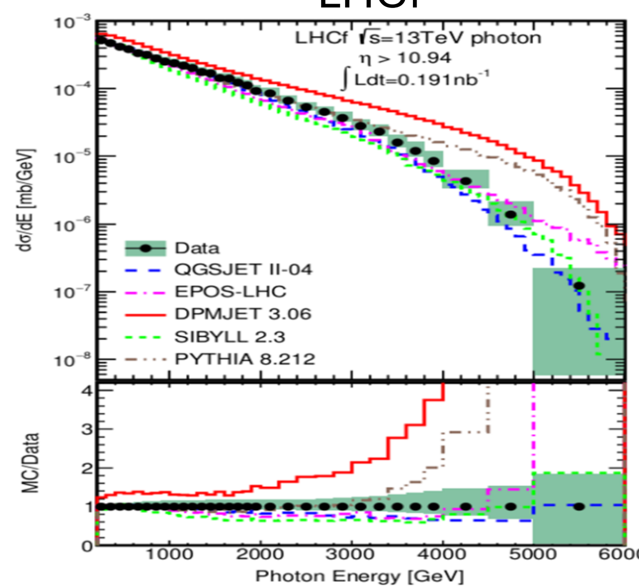


The CMS Collaboration, JHEP, 11 (2011) 148

CMS: HF and CASTOR

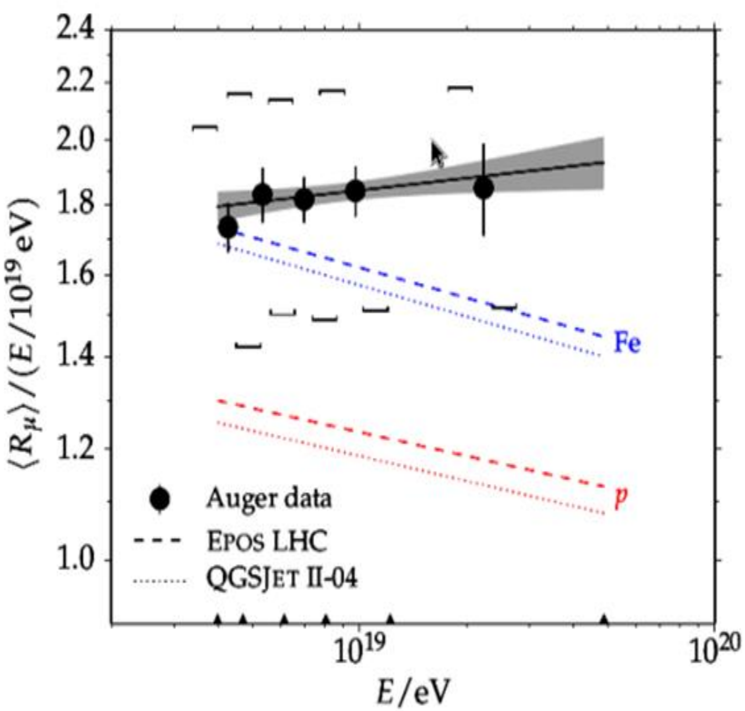


LHCf



Interim Conclusions on UHECR and LHC

This behaviour can be used to retune some basic model ingredients and improve their extrapolations to the highest energies. Such a result constrains in particular the way in which multiparton interactions and gluon saturation are implemented in various MCs (e.g. in pythia, phojet and sibyll), via an energy-dependent infrared transverse momentum cutoff, $Q_o(\sqrt{s})$ for (multi)parton scatterings.



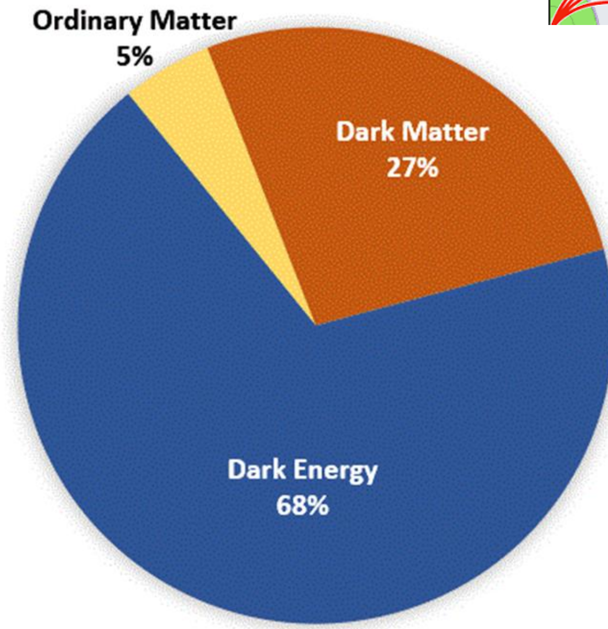
UHECR show muon excess (esp. at large axis distance): Impact of heavy-Q & pQCD minijet production on the muon excess?

PYTHIA-6 (tuned to LHC data) shows similar EAS as std. UHECR MCs, but produces more muons (at larger axis distances) than UHECR MCs. EPOS–QGSJET p-H, p-Air diffs. point to nuclear effects.

Solution of UHECR muon deficit requires pQCD minijet + nuclear effects combined (probably not missing heavy-quark production). Enough or new physics?

QGP is known for providing enhanced strangeness…

Other Sidereal Messages…



A multitude of effects, like, for instance: galactic rotation or gravitational lensing or anisotropies in the cosmic microwave background (CMB), provide overwhelming evidence for **“dark matter”** that influence gravitationally the ordinary matter. In fact dark matter should be roughly 5 times the ordinary one. Furthermore, 68% of energy in the universe is accounted for by **“dark energy”**, responsible for its accelerating expansion, while “dark matter” corresponds to 25% and the ordinary matter is only 5%. In particular “dark matter” (DM) would be composed by elementary particles as the ordinary one, which is well described by the Standard Model (SM). The “dark” particles however are beyond the Standard Model **(BSM).** They may interact with SM ones, albeit very weakly (small coupling) and via special portals.

From CERN-LHC Seminar on Tuesday 9 July 2024:

Jingyu Luo (Brown University) : Investigating the Physics of the Dark Sector with CMS

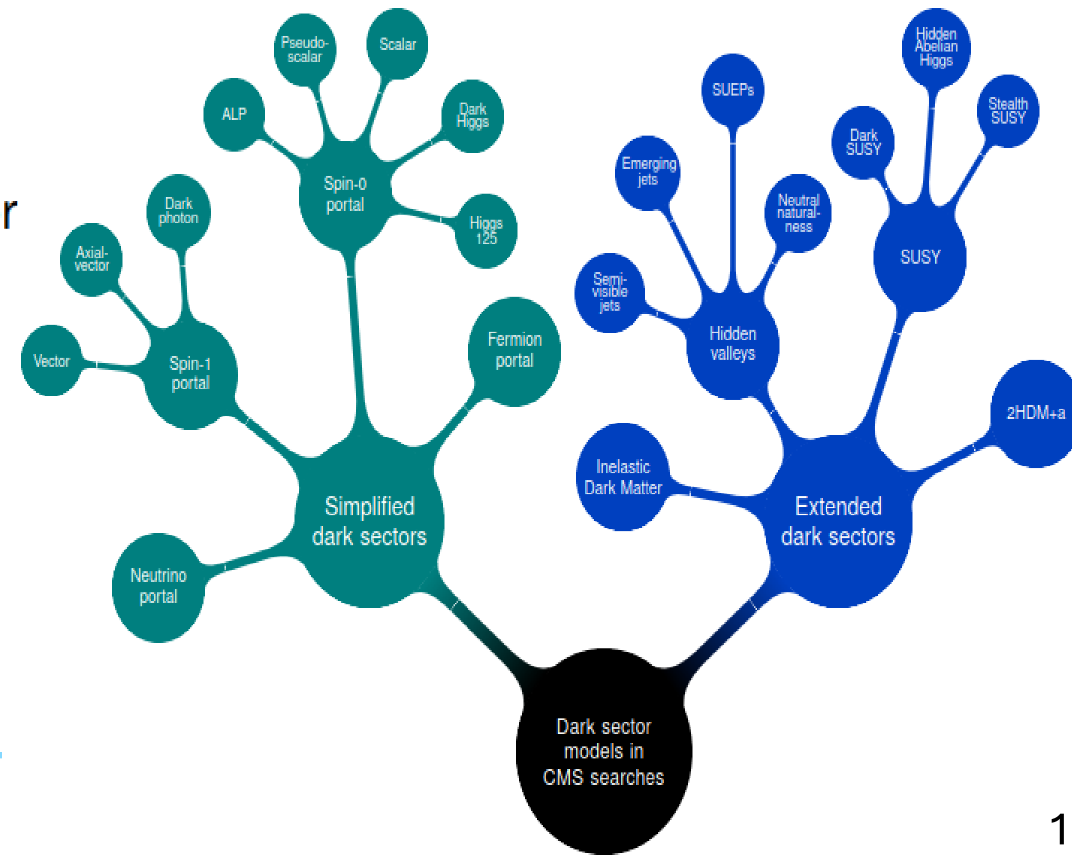
https://indico.cern.ch/event/1403078/

Dark matter/sector searches at CMS

❖CMS is a powerful experiment in exploring dark sectors

- Excellent detector performances
- Highly flexible data-taking system
  - Dedicated trigger algorithms;
  - Data scouting — trigger-level objects for high-rate "real-time" analyses;
  - Data parking — delayed reconstruction for lower trigger thresholds.
- Innovative reconstruction and analysis techniques
  - Displaced tracking, timing, etc.
  - Advanced machine-learning algorithms.

❖Map of CMS searches for dark sectors



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-106
2024/05/24

CMS-EXO-23-005

Dark sector searches with the CMS experiment

The CMS Collaboration*

arXiv: 2405.13778, submitted to Physics Reports

- Huge community efforts within CMS

  - ~20 editors
  - ~40 analyses
  - ~500 authors
  - 145 pages
  - 10 updated summary plots
  - 27 new reinterpretations

Covered analyses

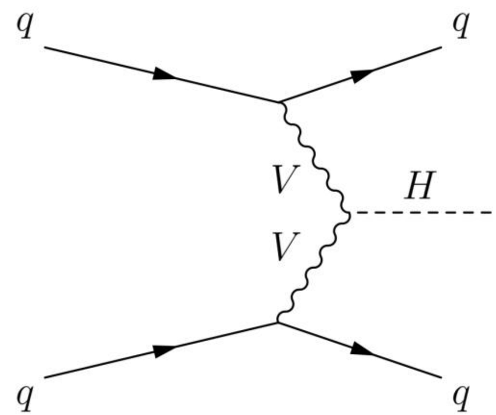
Invisible	Visible	Long-lived
Mono-X	**Low-mass resonances**	**Displaced leptons**
Monojet (EXO-20-004)	Boosted dijet (EXO-18-012)	Displaced ee, emu, mumu (EXO-18-003)
Mono-Z (EXO-19-003)	Dijet + photon (EXO-17-027)	Displaced dimuons (EXO-21-006, EXO-23-014)
Monotop (EXO-16-051)	Boosted bbbar (EXO-17-024)	H to aa to 4mu (HIG-18-003)
Monophoton (EXO-16-053)	Dimuon including scouting (EXO-19-018)	Displaced dimuon scouting (EXO-20-014)
Mono-H (EXO-18-011)	Dimuon scouting (EXO-21-005)	**Hadronic LLP decays**
Dark Higgs (WW) + MET (EXO-21-012)	**High-mass resonances**	Displaced jets (EXO-19-021)
H to invisible	Dijet + ISR (EXO-19-004)	Displaced vertices (EXO-19-013)
VBF (HIG-20-003)	Dijet (EXO-19-012)	Emerging jets (EXO-18-001, EXO-22-015)
ttH/VH (HIG-21-007)	Dilepton (EXO-19-019)	Stopped particles (EXO-16-004)
Dark photons: ZH (EXO-20-005), VBF (EXO-19-007)	**Other signatures**	Muon detector showers (EXO-20-015, EXO-21-008)
Hidden Valley	Fractionally charged part. (EXO-19-006)	**LLP + p_T^{miss}**
Semivisible jets (EXO-19-020)	SUEPs, offline (EXO-23-002)	Inelastic DM (EXO-20-010)
	Stealth/RPV stops (SUS-19-004)	Delayed jets (EXO-19-001)
	ALPs in PbPb (FSQ-16-012)	Trackless and OOT jets (EXO-21-014)
	CEP w/ TOTEM (EXO-19-009)	Displaced vertices + MET (EXO-22-020)

Forward Tags for New Physics

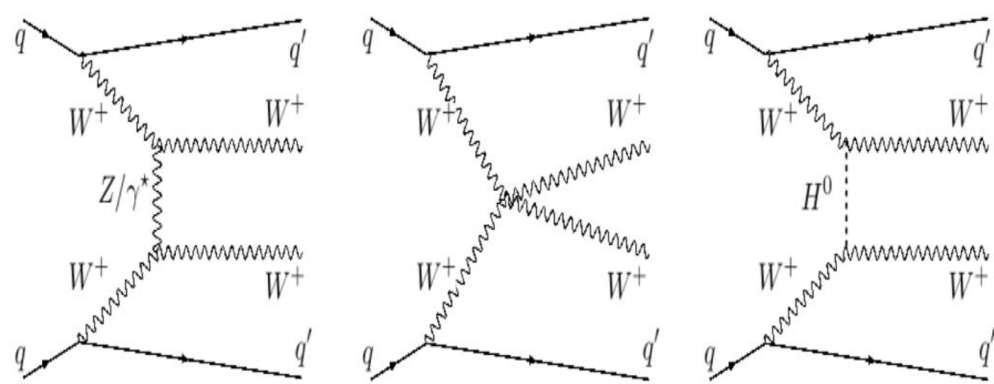
At colliders there are 2 categories of particles going into the forward direction (of the incoming beam particles) :

1 – Fragments of the interacting beams

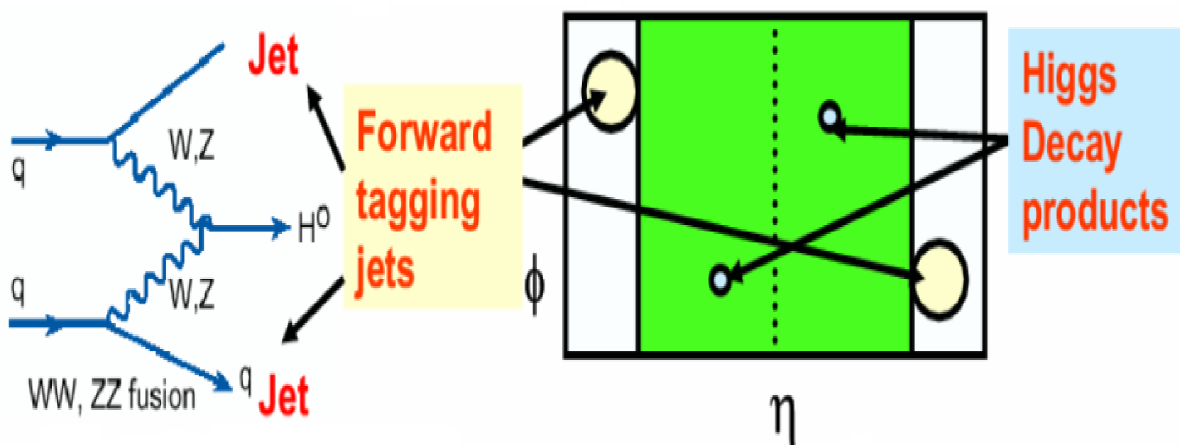
2 – Lorentz – boosted light particles

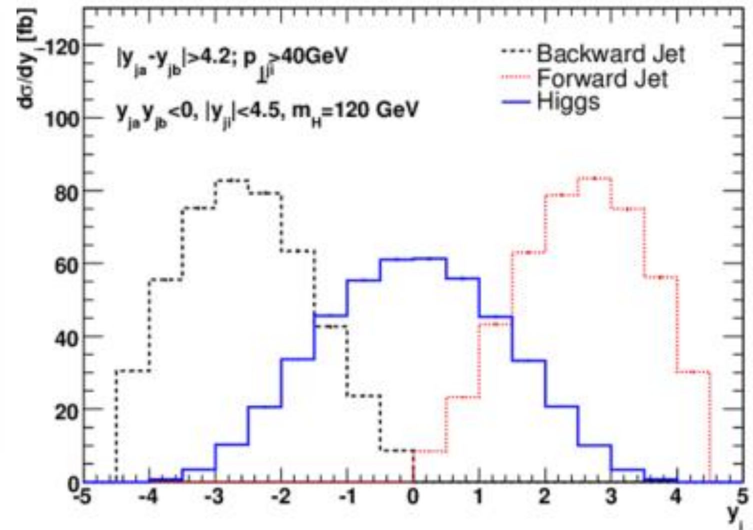


When the LHC proton beams collide, two gauge bosons may be emitted by quarks from each of the beams. These gauge bosons subsequently interact and may either scatter (VBS) or fuse (VBF). The quarks are deflected and fragmented and appear in the detector as jets of particles, typically emitted at a relatively small angle with respect to the beam direction.

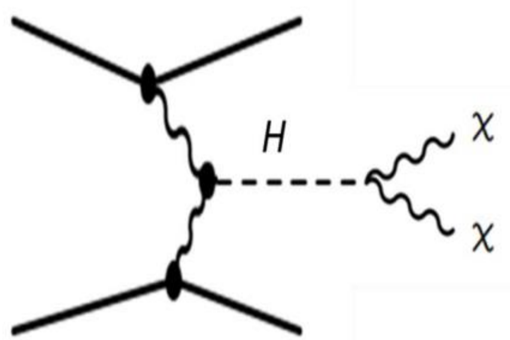


VBF, VBS and Higgs Portal processes

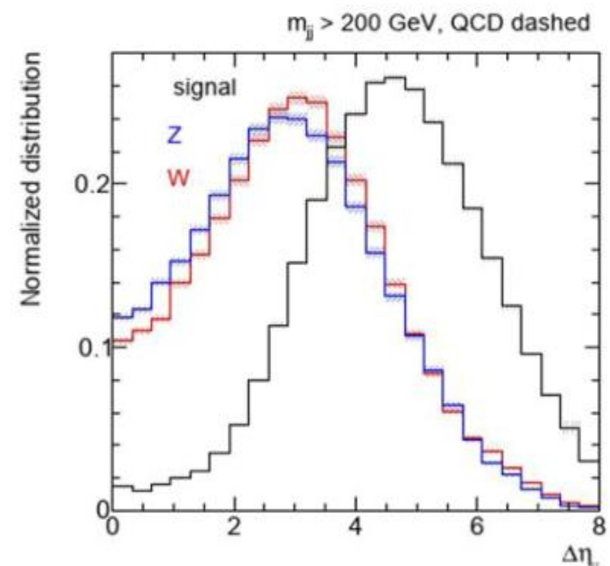




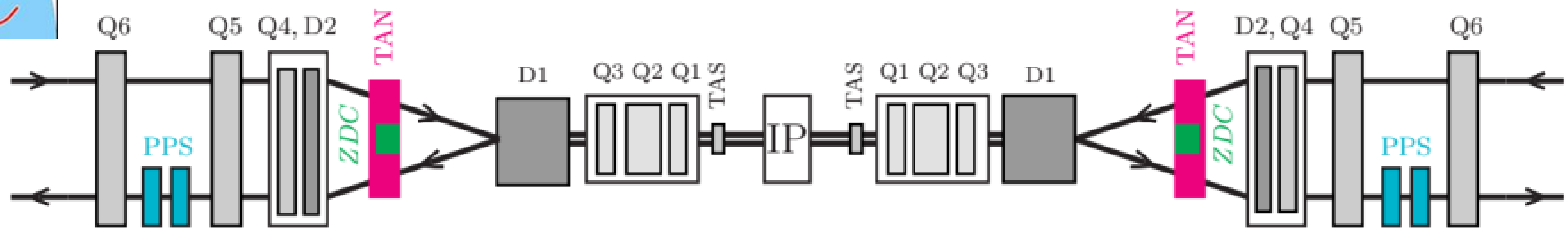
Ideas to implement HF with EM sections, to improve granularity, timing and shower resolution. With this, the HF calorimeters would be able not only of tagging Higgs VBF production, but also constrain the process in order to have the possibility of measuring Higgs “portal” events where the Higgs decay in BSM particle, f.i. dark matter.



Higgs Portal



Very Forward Detector: PPS

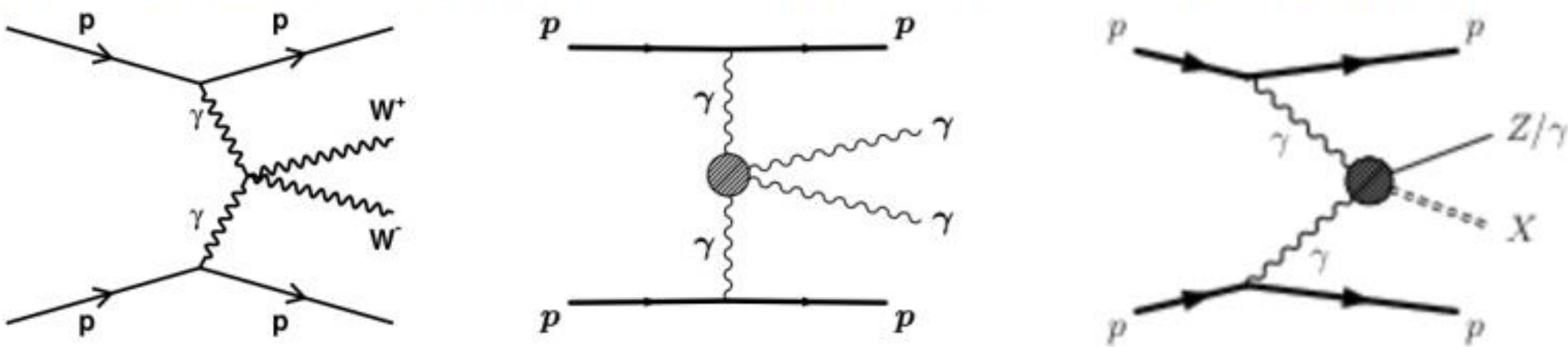


Central Exclusive Production at HL-LHC

Tag scattered (intact) protons with Roman Pot detectors in LSS5

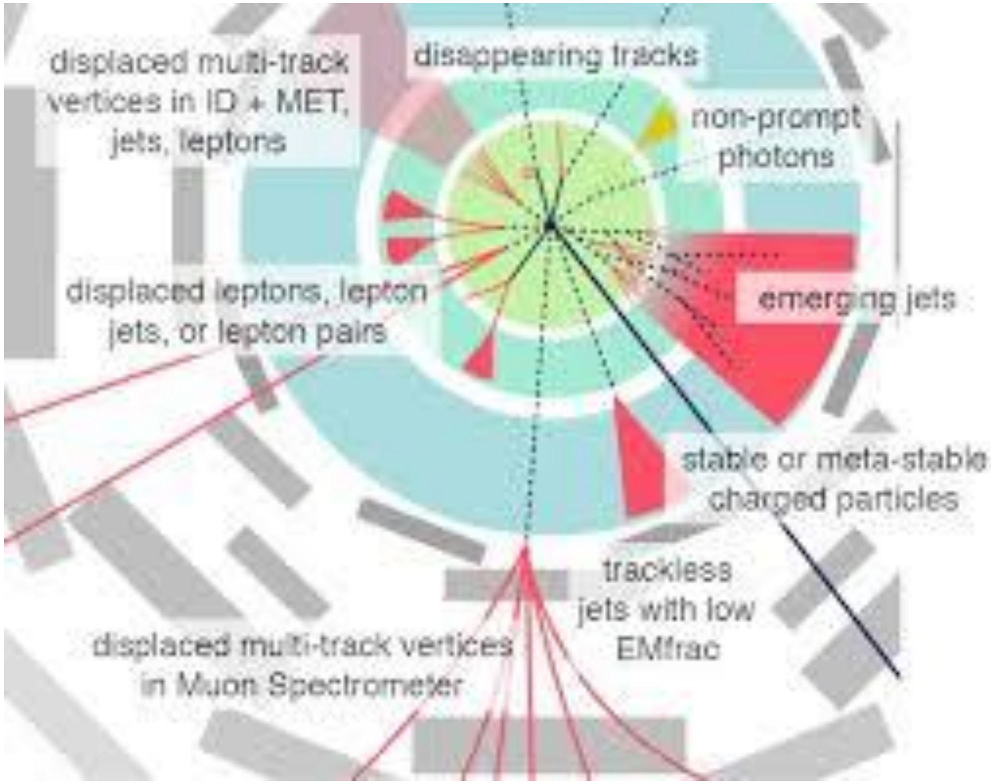
(Successfully done by TOTEM, PPS, AFP. A lot of experience gained)

Physics case: Central Exclusive Production of SM processes OR new particles



Exploring the Lifetime Frontier

https://arxiv.org/abs/1903.04497



Many search criteria

For the "standard" detectors

Also new detectors: FASER ....

FACET

Search for BSM long-lived particles (LLPs) in the forward direction of IR5 (CMS), penetrating 35 m - 50 m of steel (Q1-Q3) D1 yokes, and either decaying in a large vacuum pipe or interacting in an imaging calorimeter. Integrated in CMS and to be used either together with the central detector or as a standalone detector. Located around the LHC beam pipe, allowing to study unique physics processes not accessible to FASER, e.g., rare D meson decays. FACET will be built based on the CMS Phase 2 Upgrade concept, combining silicon tracker, timing detector, HGCAL-type EM/HAD calorimeter, and GEM-type muon system in a compact design.

F A C E T :

Forward Aperture CMS ExTension

Proposal for **LLP** searches ($c\tau \approx 0.1 - 100$ m)

- with a new detector 100 m from CMS
- fiducial volume ≈ 14 m^3 – high vacuum (10^{-10} mbar)
- forward direction ($7.6 > \eta > 6.2$)
- phase-2 upgrade equipment (tracker, calorimeter)

JHEP06(2022)110

FACET: A new long-lived particle detector in the very forward region of the CMS experiment

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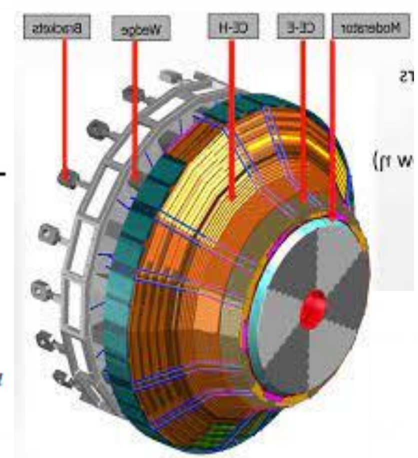
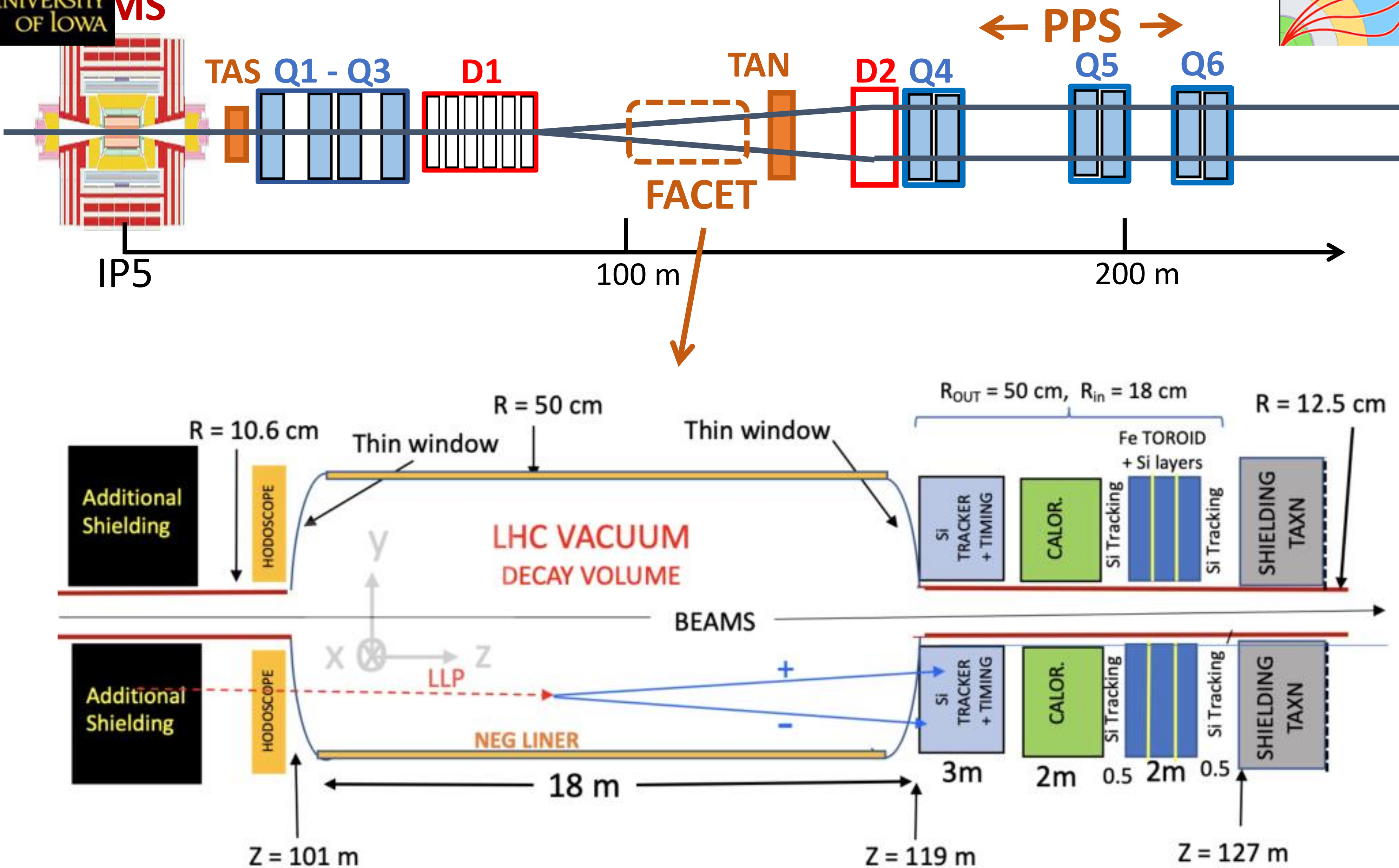


arXiv:2201.00019v2 [hep-ex] 18 Jun 2022

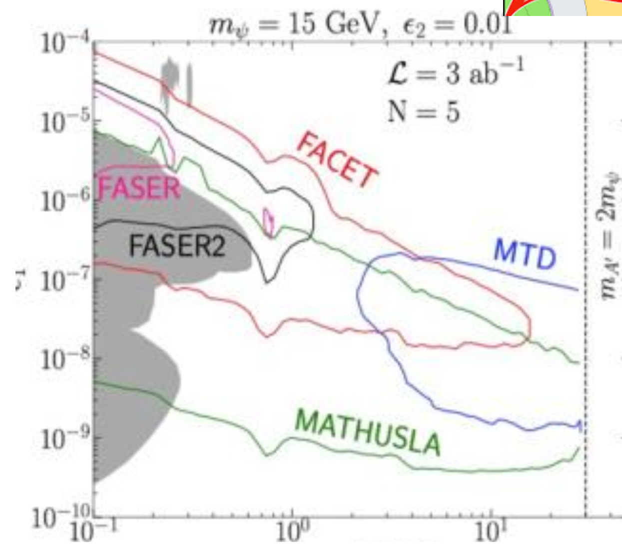
https://doi.org/10.1007/JHEP06(2022)110

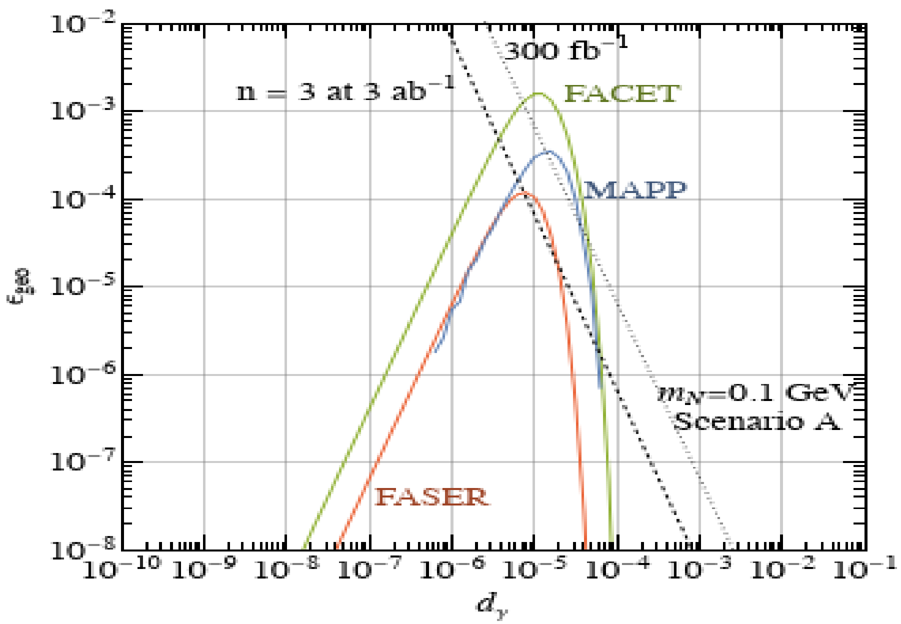
CMS Forward Region

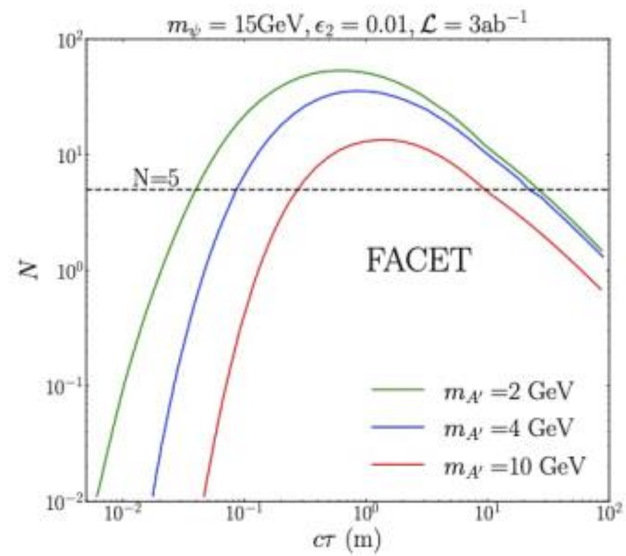


Some studies of channels accessible to FACET

Dark photon production model via dark fermion bremsstrahlung (arXiv:2111.15503, M. Du et al)
FACET has good reach and nice complementarity with CMS Phase-2 MIP Timing Detector(MTD)

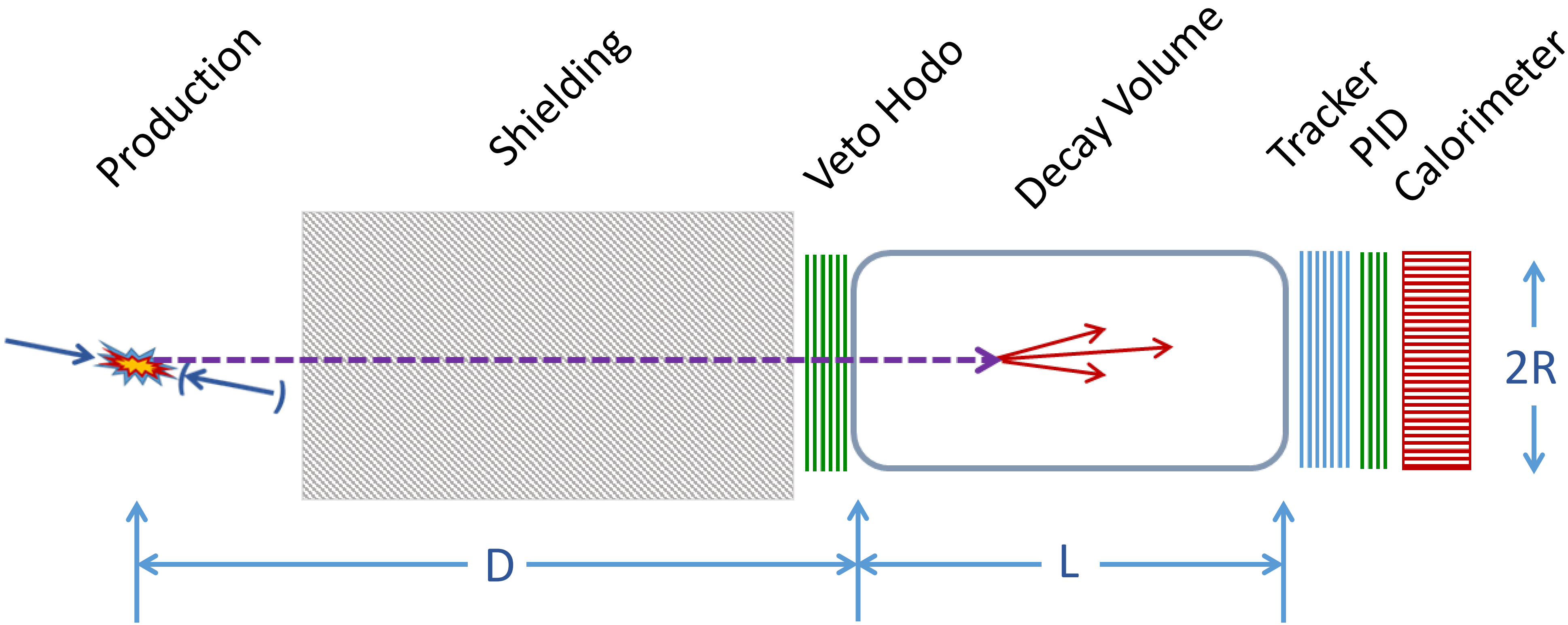






Wei Liu, Yu Zhang; aXiv:2302.02081v3 [hep-ph] 13 Apr 2023: production of heavy neutral leptons.

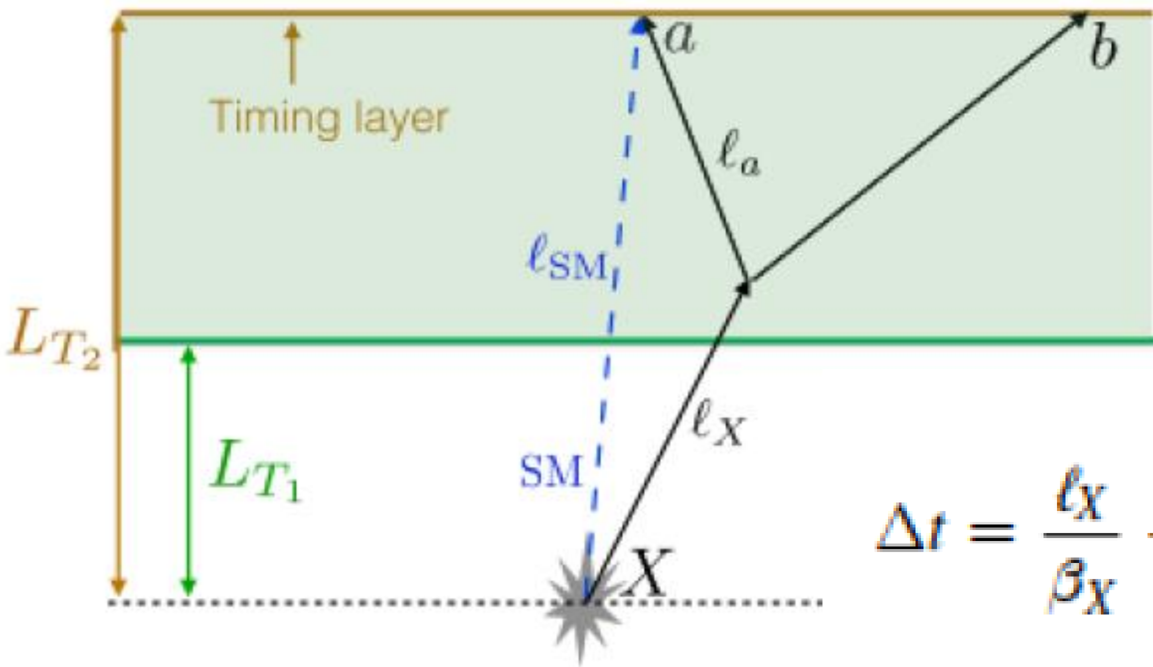
A Figure-of-Merit for LLP Search Experiments



Production Cross Section	No decay over distance D	Decay in chamber L	Solid angle
$d\sigma/d\eta$	$e^{-D/\beta\gamma c\tau}$	$1 - e^{-L/\beta\gamma c\tau}$	$(R/D)^2$

Delayed Jets

J. Phys. G: Nucl. Part. Phys. **47** (2020) 090501 J Alimena *et al*



$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}},$$

Figure 43. An event topology with an LLP X decaying to two light SM particles a and b. A timing layer, at a transverse distance L_{T_2} away from the beam axis (horizontal gray dotted line), is placed at the end of the detector volume (shaded region). The trajectory of a potential SM background particle is also shown (blue dashed line). The gray polygon indicates the primary vertex. Taken from [363].

[26] CMS Collaboration, “Search for long-lived particles using displaced jets in proton-proton collisions at √s = 13 TeV”, Phys. Rev. D 104 (2021) 012015

[32] CMS Collaboration, “Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at √s = 13 TeV”, Phys. Rev. Lett. 127 (2021) 261804,

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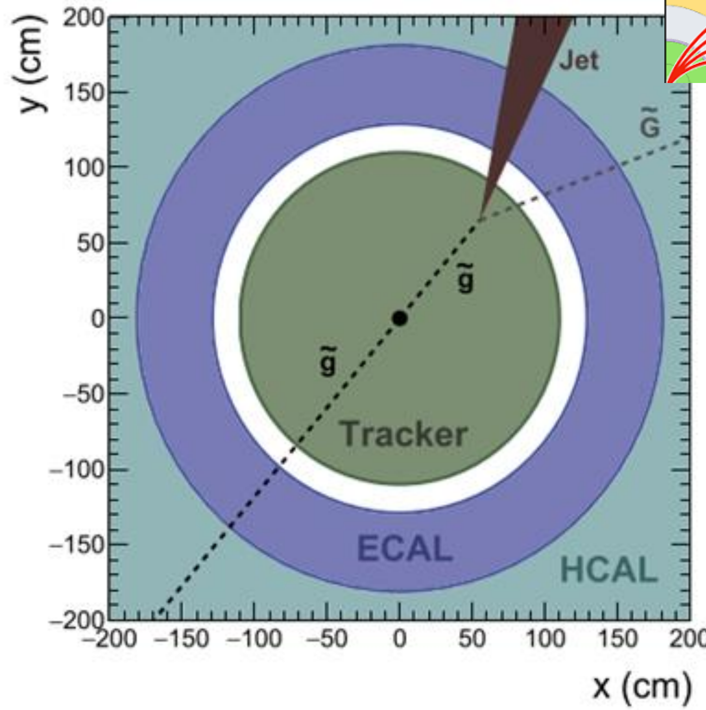
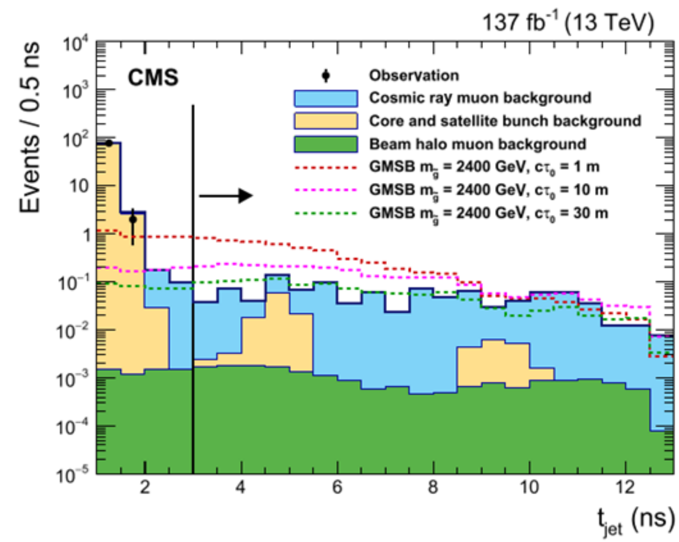
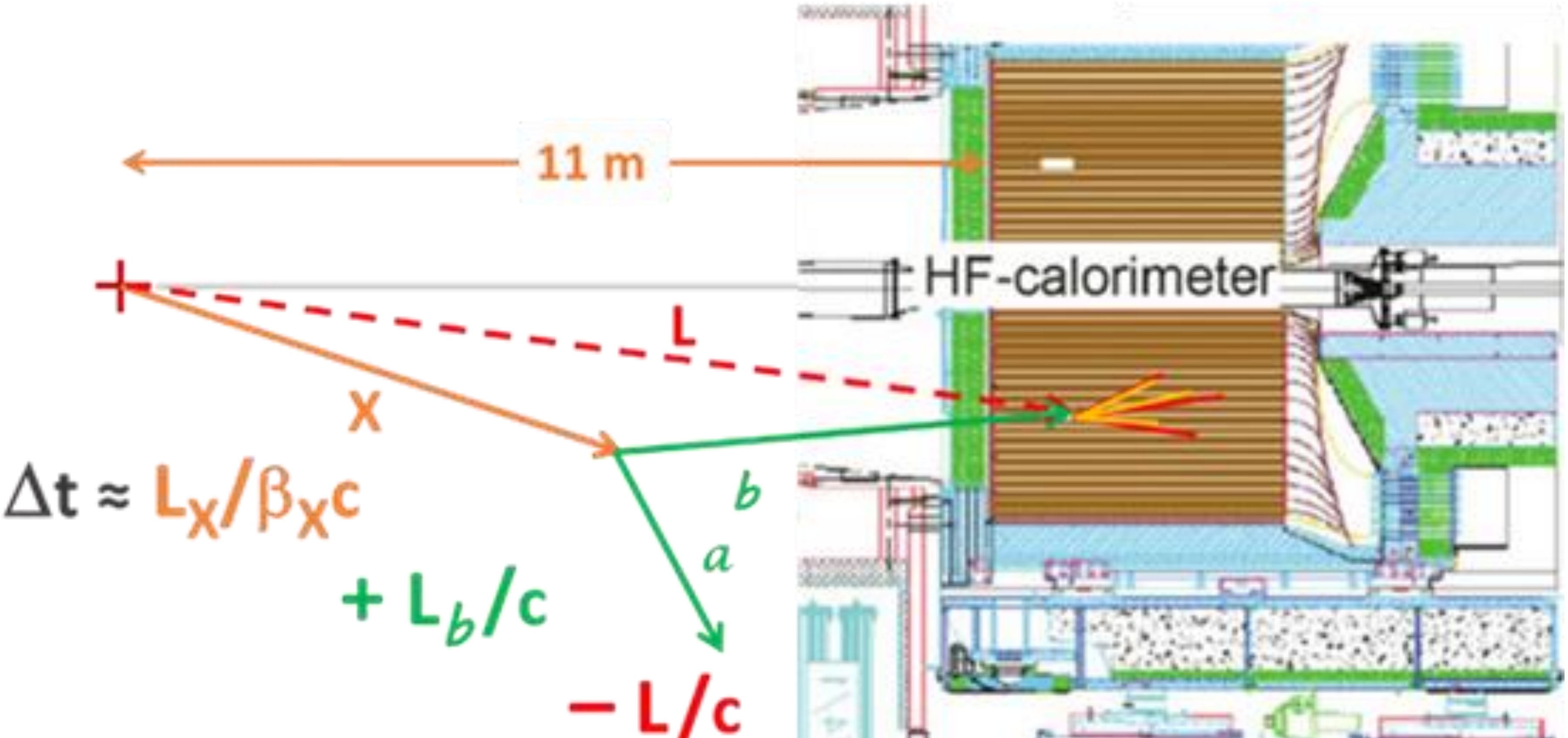
[[20] CMS Collaboration, Search for long-lived particles decaying into displaced jets in proton-proton collisions at √s = 13 TeV, Phys. Rev. D 99 (2019) 032011, https://doi .org/10.1103/PhysRevD .99 .032011, arXiv:1811.07991.





Long Lived Particle (LLP) X --> *a*+*b* (--> *jet*)



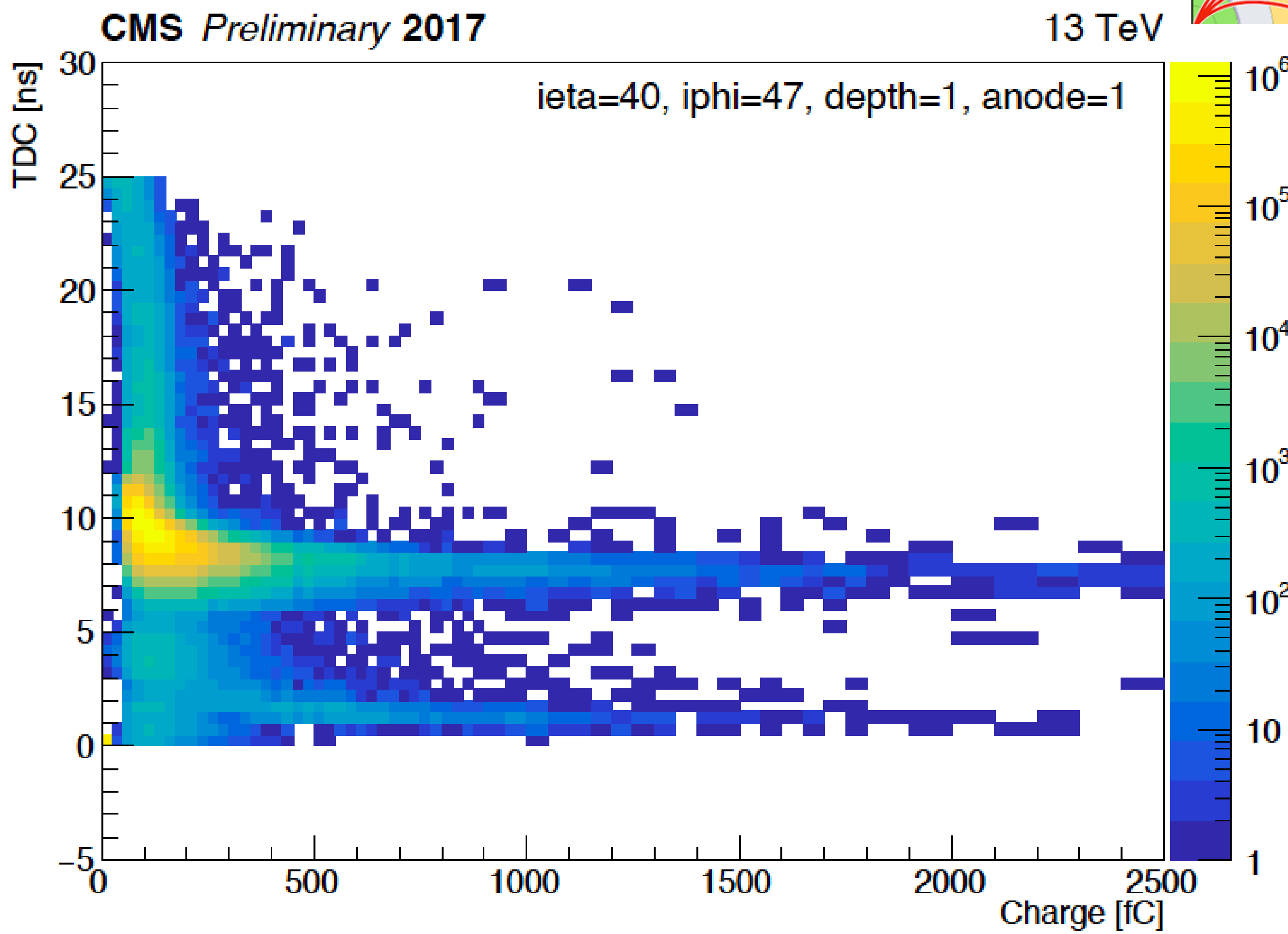
"Delayed" Jet Signature:

Jia Liu, Zhen Liu, Lian-Tao Wang, Long-lived particles at the LHC: catching them in time, Phys. Rev. Lett. 122, 131801 (2019)

[In CMS HCAL (barrel): C. Tully et al. , HCAL Trigger for LLPs]

Small time differences help a lot!

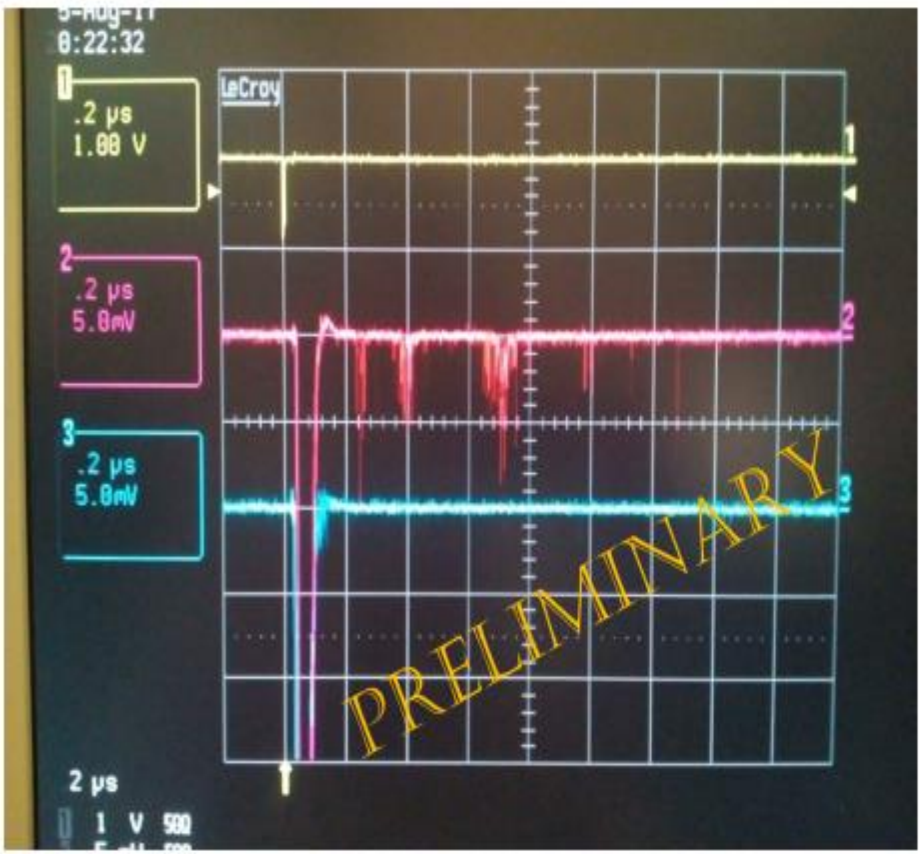
Particles hitting the HF PMTs, produce large pulses from Cherenkov in PMT windows



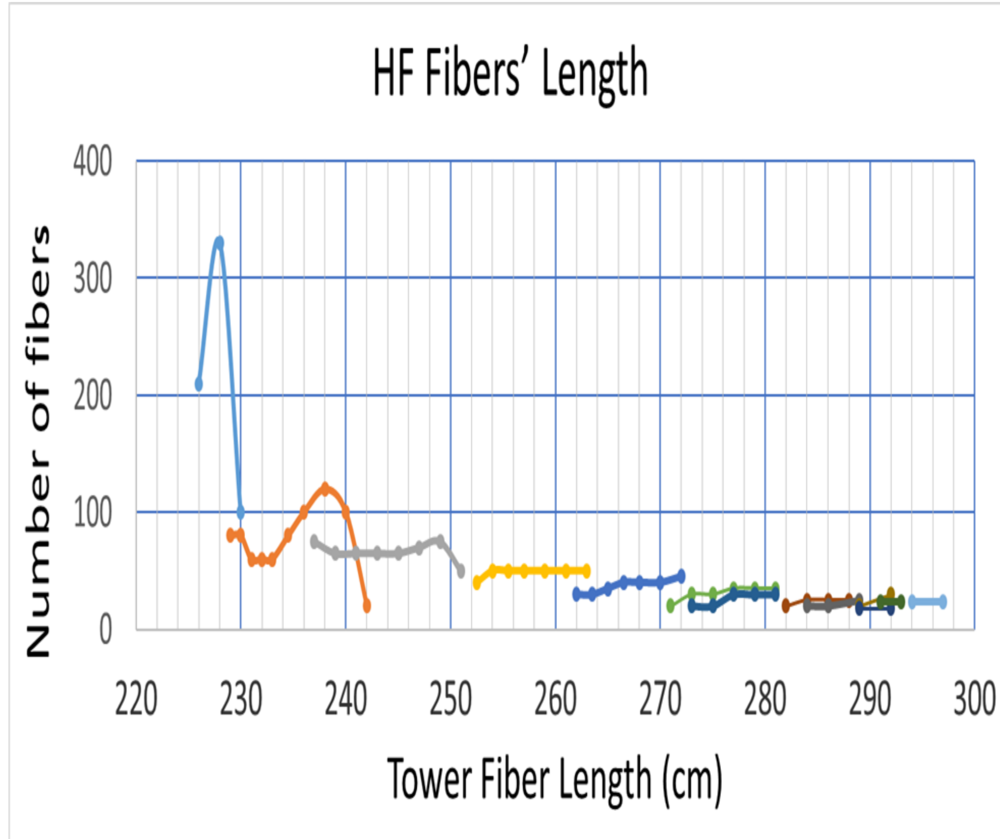
Time as measured by TDC vs anode charge in a given HF channel (ieta=40, iphi=47, depth=1). The contribution with low time values of <5 ns originate from particles directly hitting the PMT. Hits from collision particles populate timing values of around 8 ns

Beware of afterpulses… … and fiber length differences!

Afterpulses in R7525 and R7600 PMTs

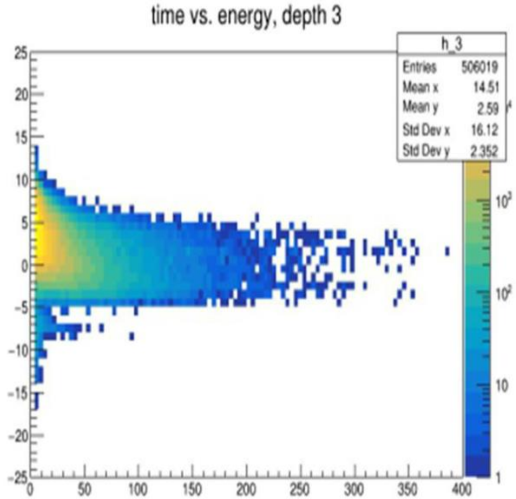


R7525 (magenta) : bands of afterpulses;
R7600 (blue) : no special pattern….

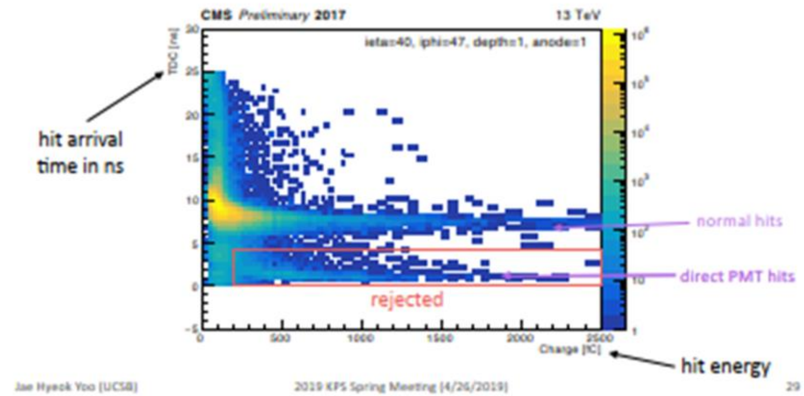


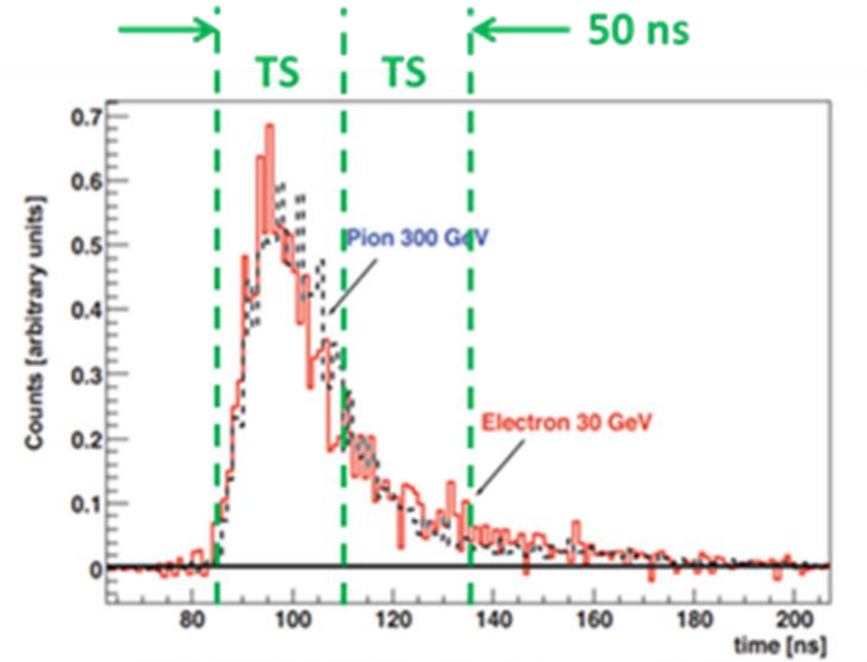
Can be corrected tower-to-tower, but not inside one tower!

Time slew in HB (2023D)

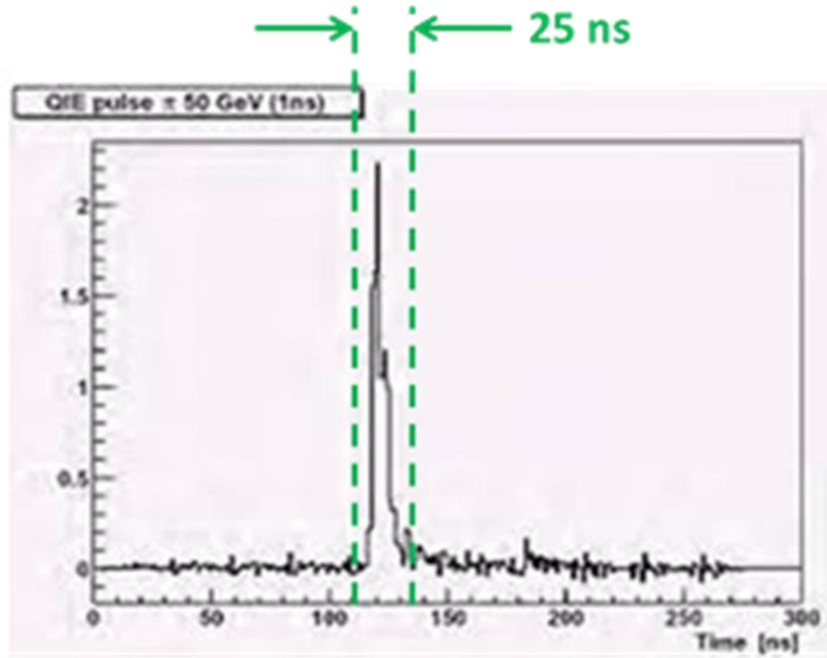


Direct PMT hits: early arrival





HB/HO/HE (scintillator tile)



HF (quartz fiber)

Acknowledgements

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P. De Barbaro, A. Mestvirishvili, Y. Onel, M. Ovchynnikov,
S. Ozkorucuklu, A. Skuja, D. Sunar Cerci +….

Credits: O.Aydilek, D. Druzhkin, B. Duran, B. Hacısahinoglu, B. Kaynak, O. Potok, I. Schmidt, R. Stefanovitch, T. Tichindelean, A. Toropin

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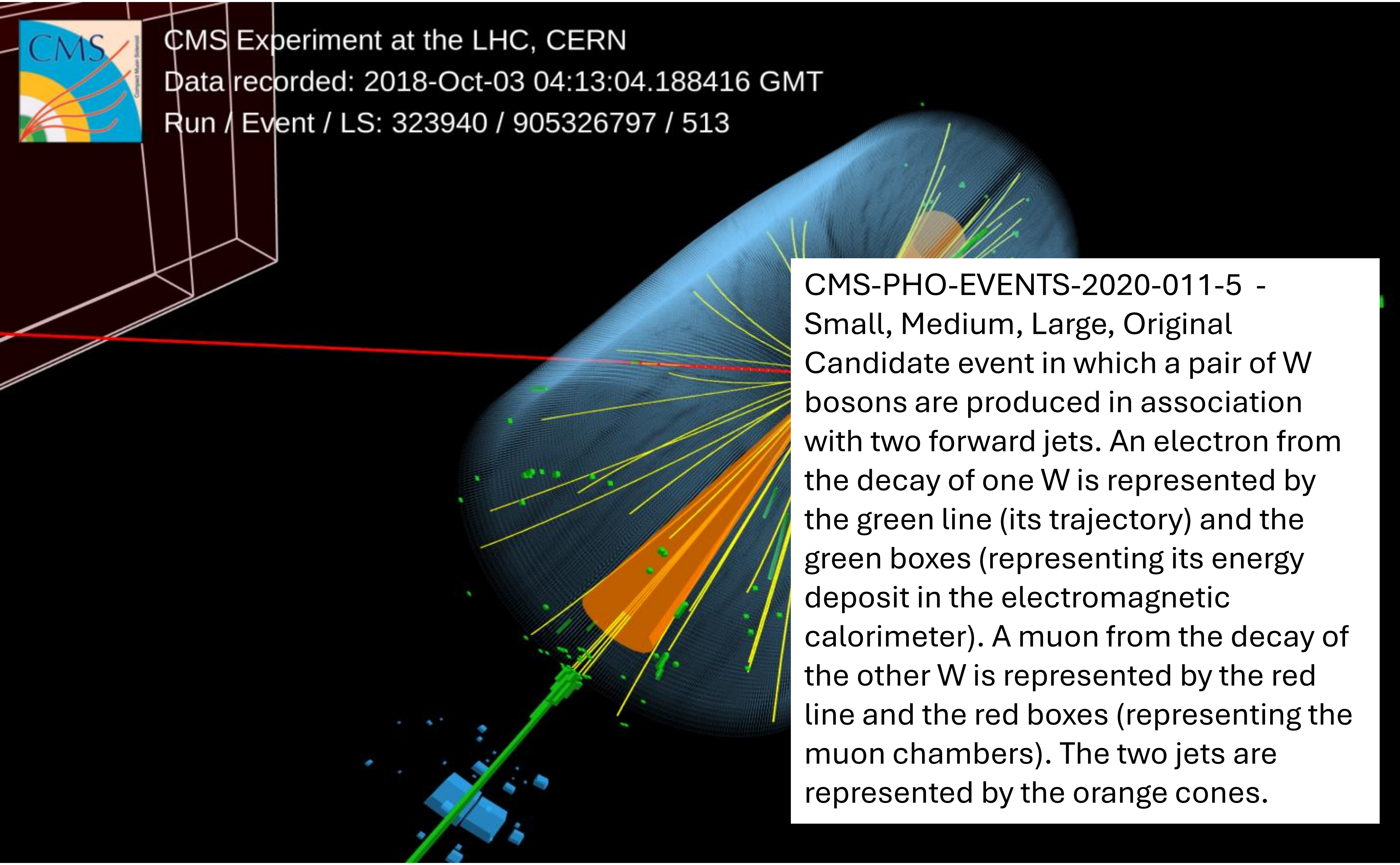
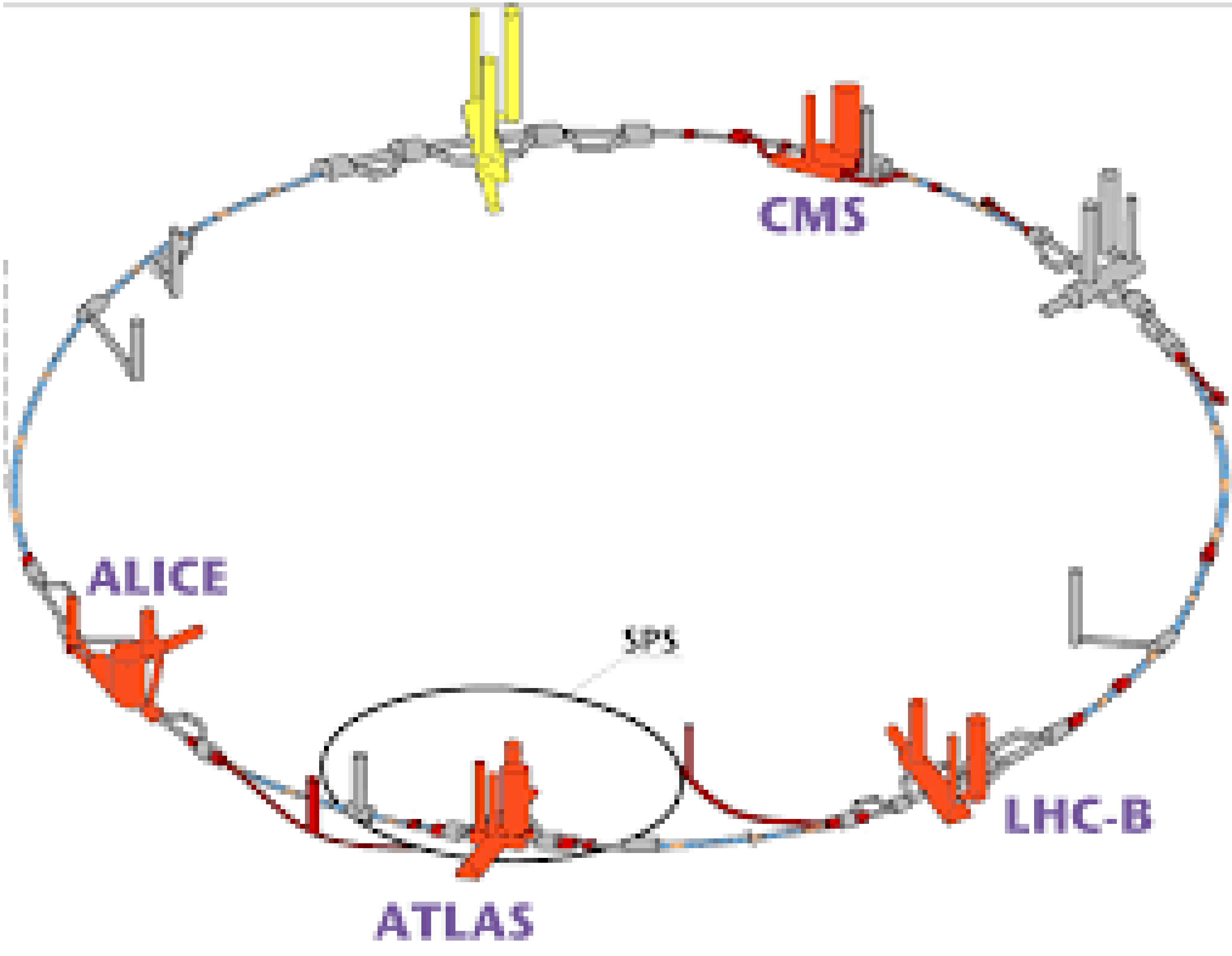
https://www.slac.stanford.edu/econf/C210711/reports/2209.13128.pdf



CMS-PHO-EVENTS-2020-011-5 - Small, Medium, Large, Original

Candidate event in which a pair of W bosons are produced in association with two forward jets. An electron from the decay of one W is represented by the green line (its trajectory) and the green boxes (representing its energy deposit in the electromagnetic calorimeter). A muon from the decay of the other W is represented by the red line and the red boxes (representing the muon chambers). The two jets are represented by the orange cones.

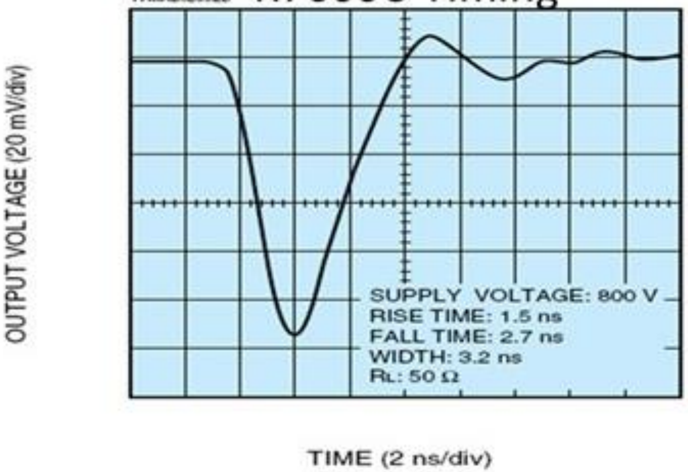


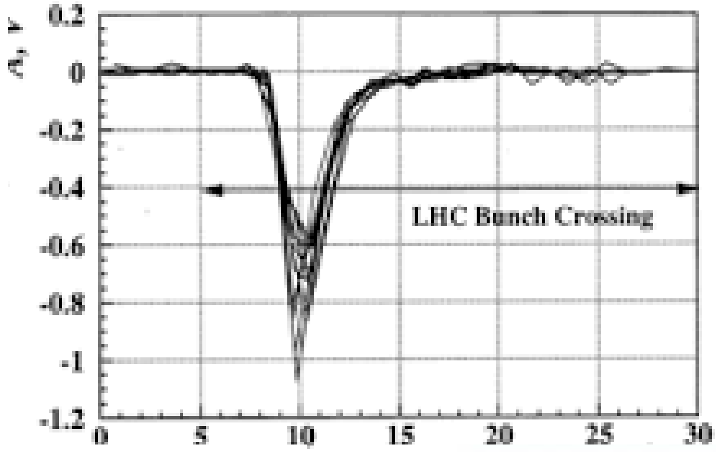
CMS
ALICE
SPS
LHC-B
ATLAS

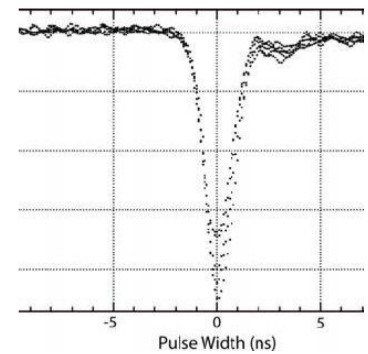

Google Earth

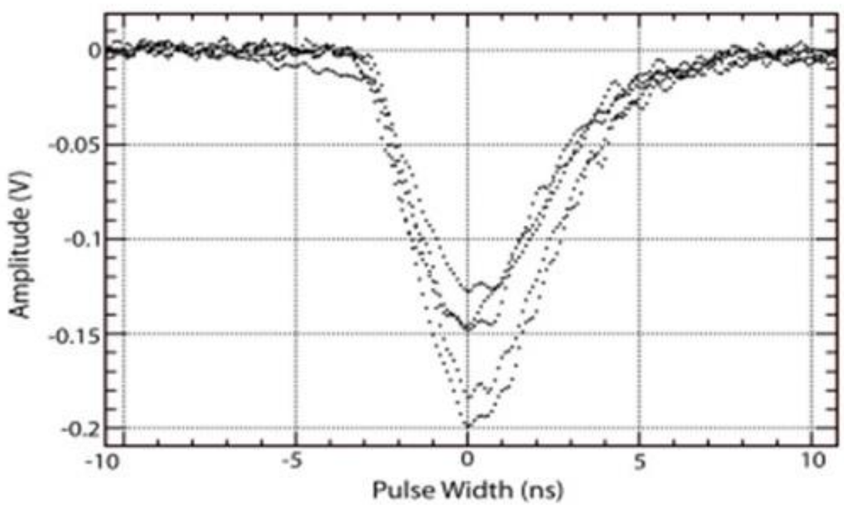
350 GeV Pion Signal

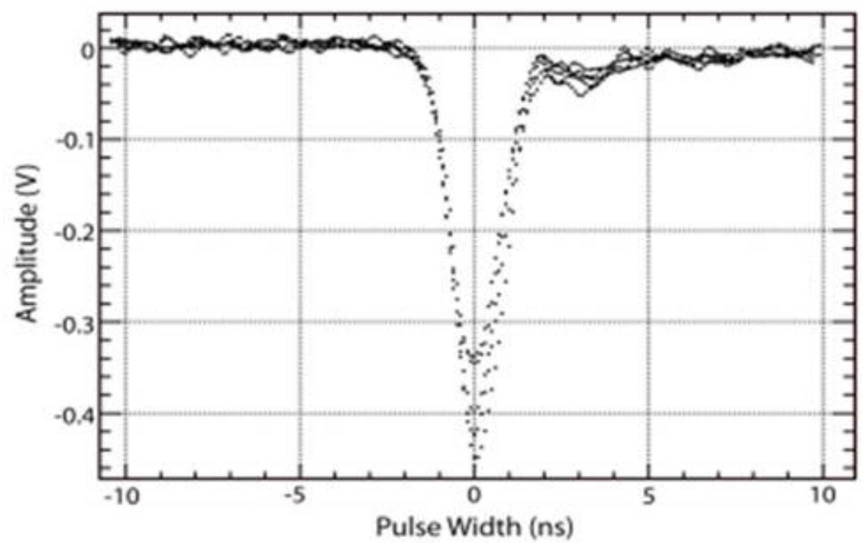
R7600U Timing











Normal HF Signal

Muon Signal on PMT