Particle and Astroparticle Physics at the Large Hadron Collider --Hadronic Interactions--

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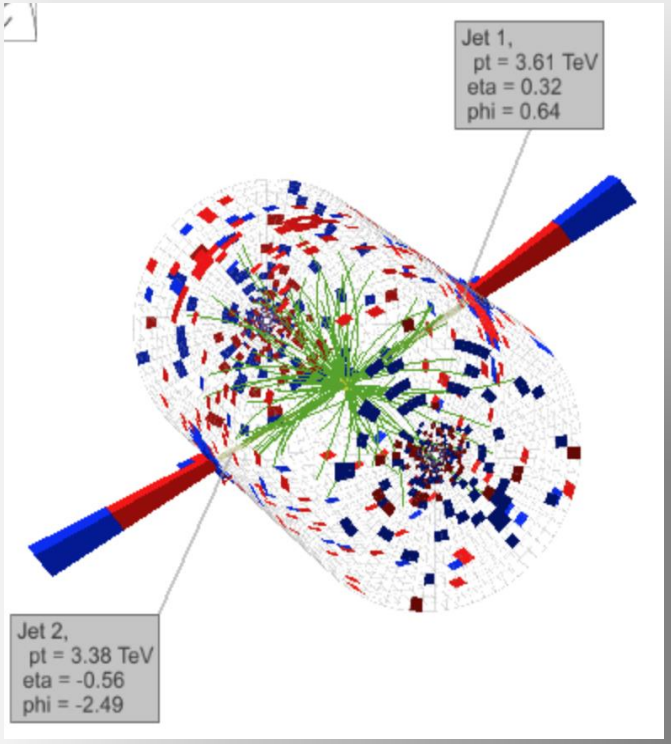
November 15th 2019

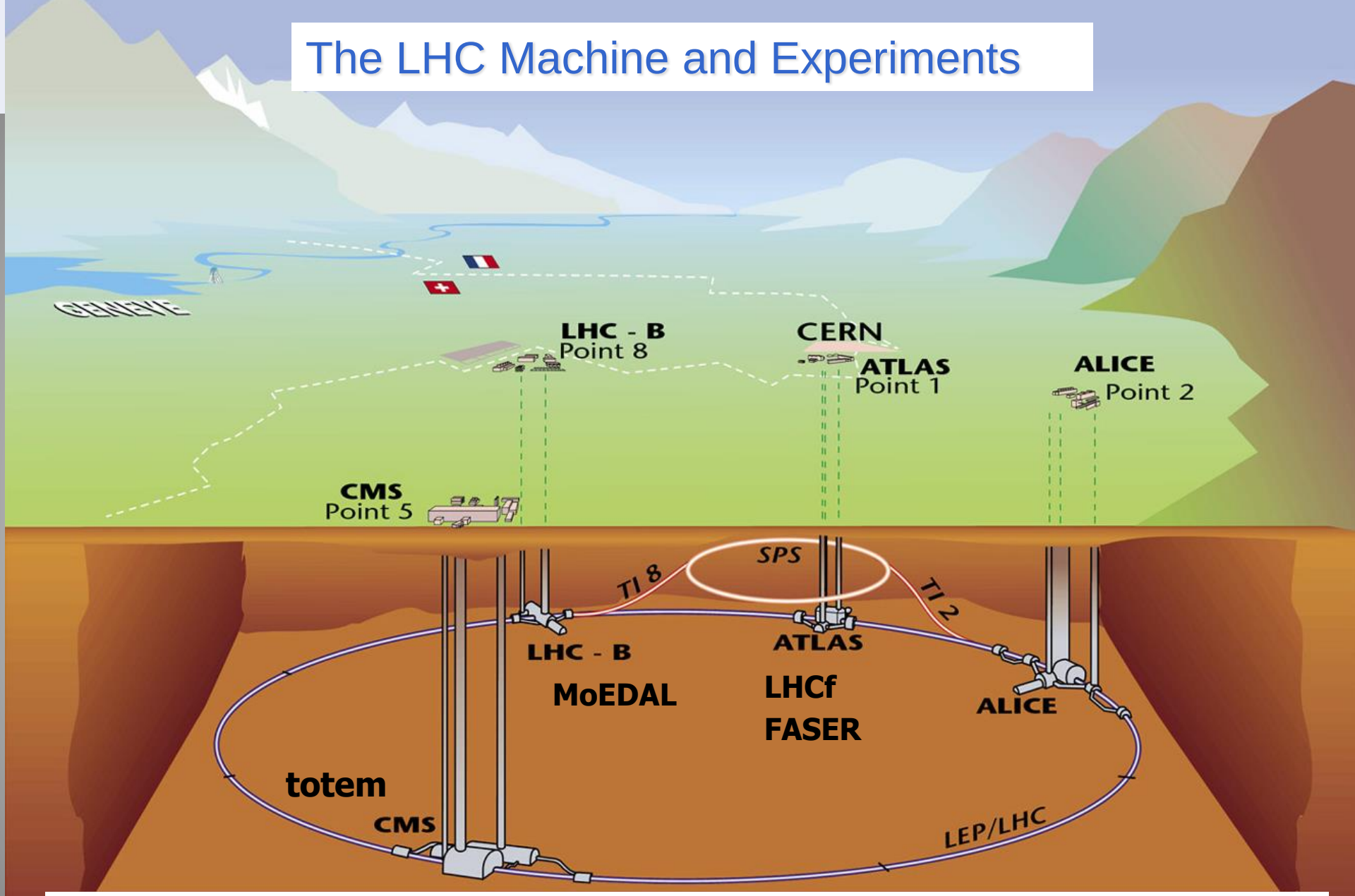
CERN



Outline

- Introduction on the LHC and LHC physics program
- LHC results for Astroparticle physics
  - Measurements of event characteristics at 13 TeV
  - Forward measurements
  - Cosmic ray measurements
  - LHC and light ions?
- Summary

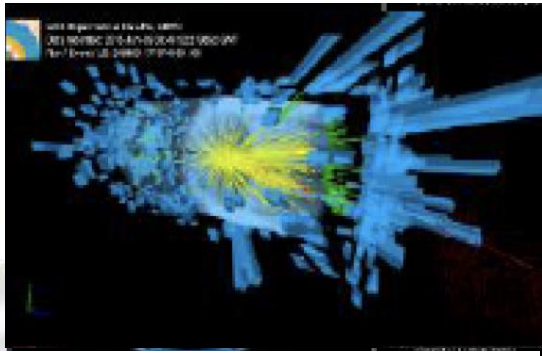
The LHC Machine and Experiments



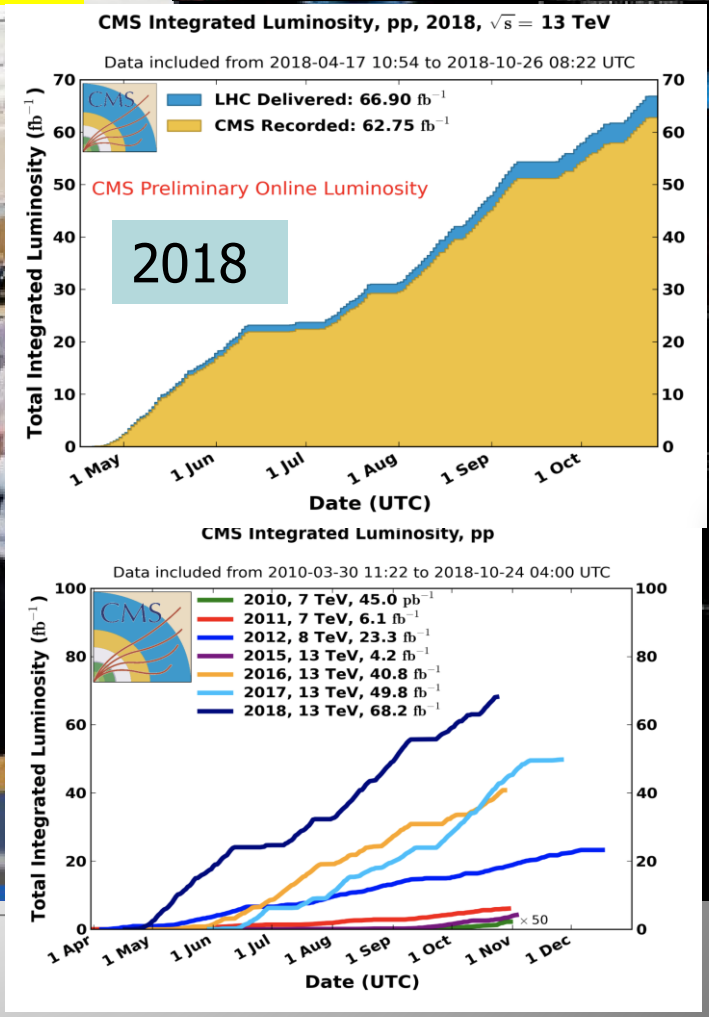
CM energy → Run-1: (2010-2012) 7/8 TeV Run-2: (2015-2018) 13 TeV
-> Now 8 experiments

LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts



proton-proton Run-2 finished 24/10/18 6:00am

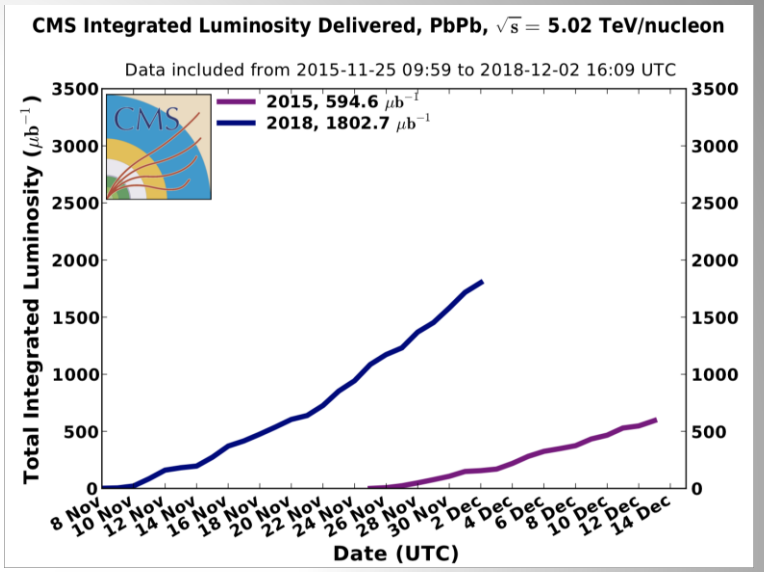


- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 27 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected ~ 140 fb^{-1}
- 2021-2023/24 : Run-3 Expect ⇨
  14 TeV CM Energy and ~ 200/300 fb^{-1}

The LHC is also a Heavy Ion Collider

ALICE

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	Recorded L_{int} (for muon triggers)
Pb–Pb	2010,2011	2.76	~75 μb^{-1}
	2015	5.02	~0.25 nb^{-1}
	2018	5.02	**~0.55 nb^{-1}**
Xe–Xe	2017	5.44	~0.3 μb^{-1}
p–Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}; ~25 nb^{-1}



Data taking during the HI run
- All experiments take AA or pA data (except TOTEM)

Expected for Run-3: in addition short pO and OO runs
⇨ pO certainly of interest for Cosmic Ray Physics Community!

10 years of LHC Operation

Two circulating beams bring first collisions in the LHC

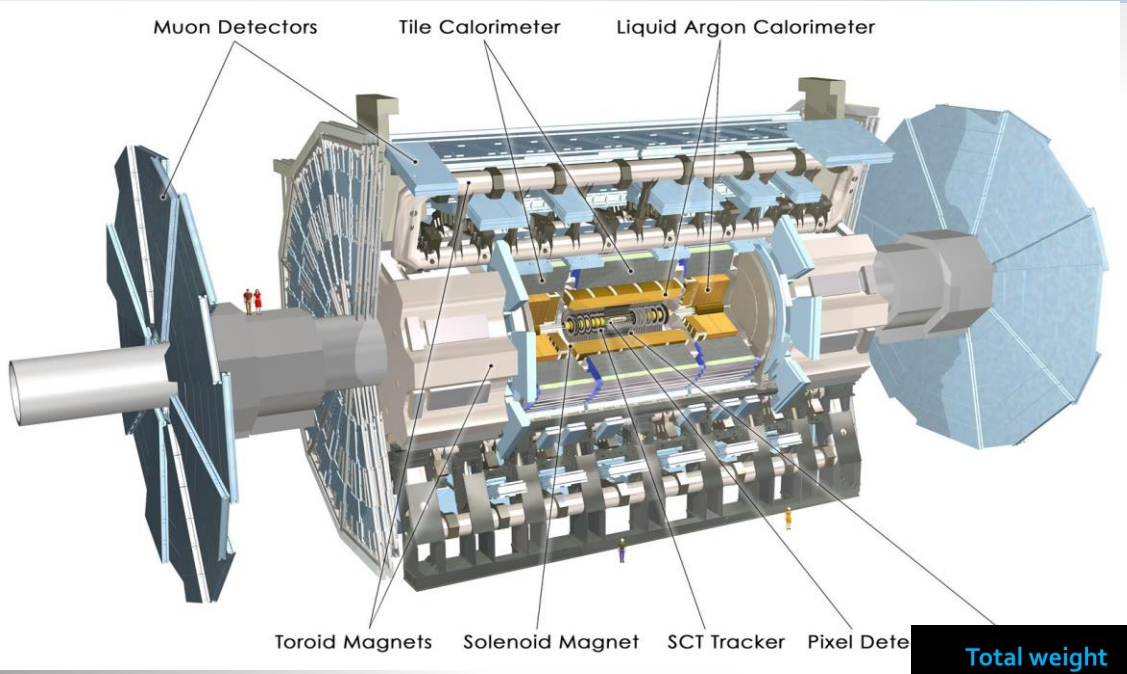
23 NOVEMBER, 2009

March 30 2010 …waiting..
…since 4:00 am

- LHC: 7 TeV in March 2010
  ->The highest energy in the lab!
- LHC @ 13 TeV from 2015 onwards
- Most important highlight so far:
  The discovery of a Higgs boson
- Many results on Standard Model process measurements, QCD and particle production, top-physics, b-physics, heavy ion physics, searches, Higgs physics
- Waiting for the next discovery…
  -> Searches beyond the Standard Model

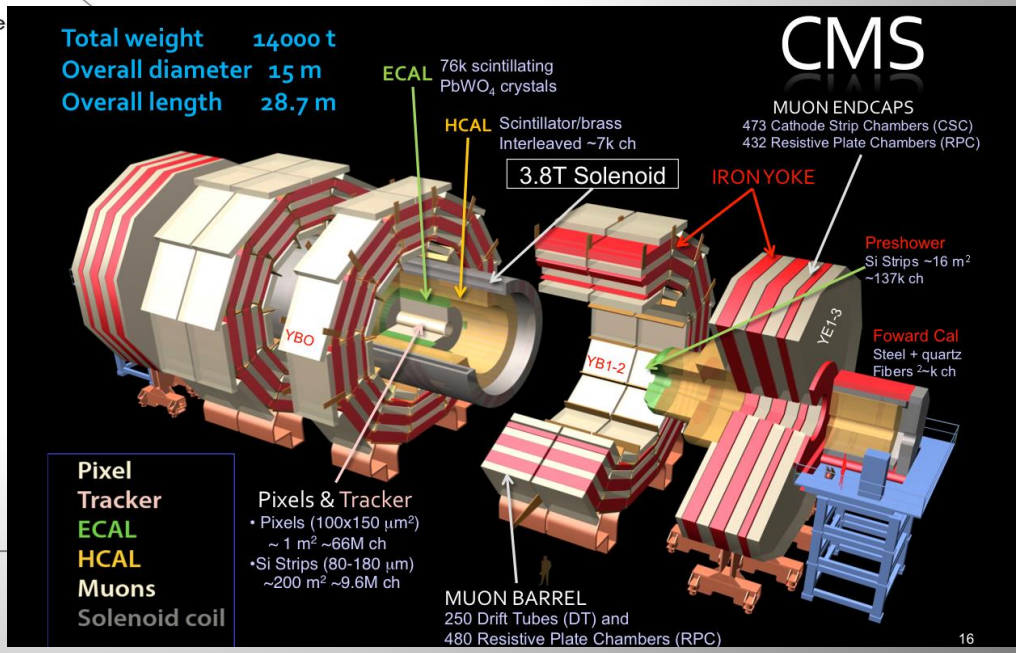
12:58 7 TeV collisions!!!

New Physics Hunters @ the LHC

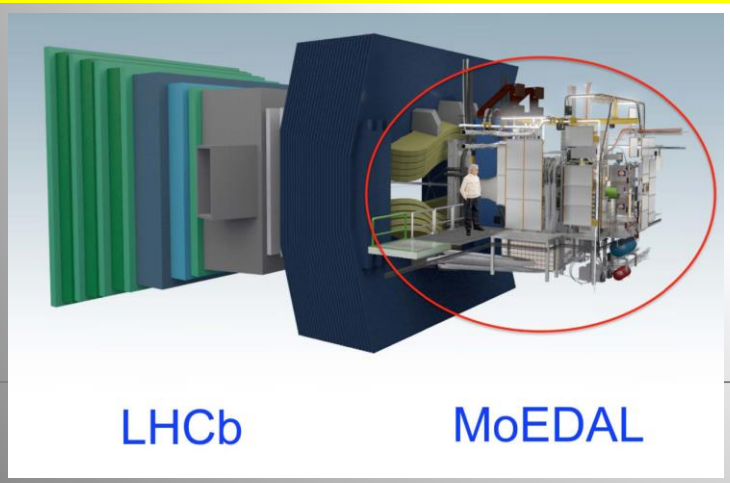


The ATLAS experiment

The CMS experiment

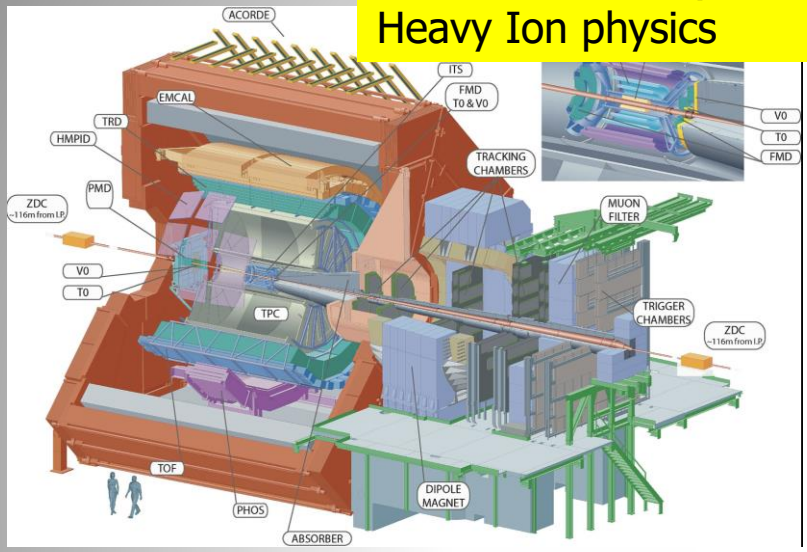


...And also LHCb and MoEDAL

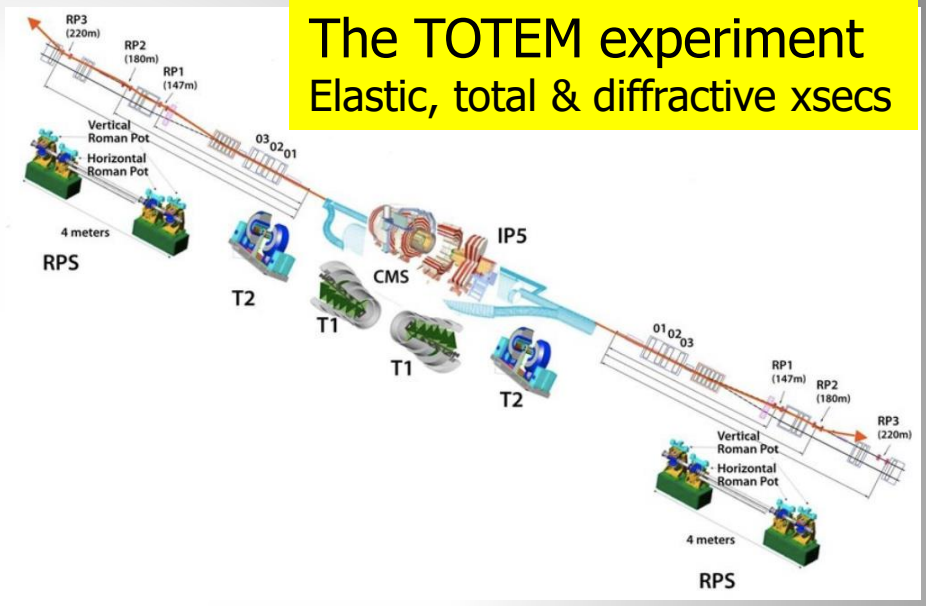


Other Experiments @ the LHC

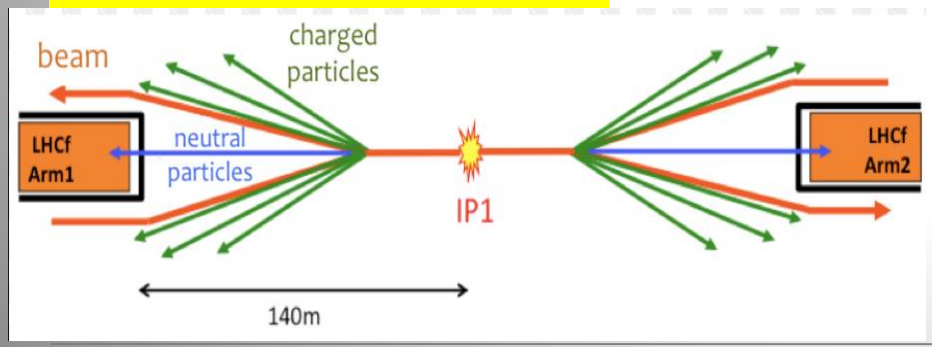
The ALICE experiment
Heavy Ion physics



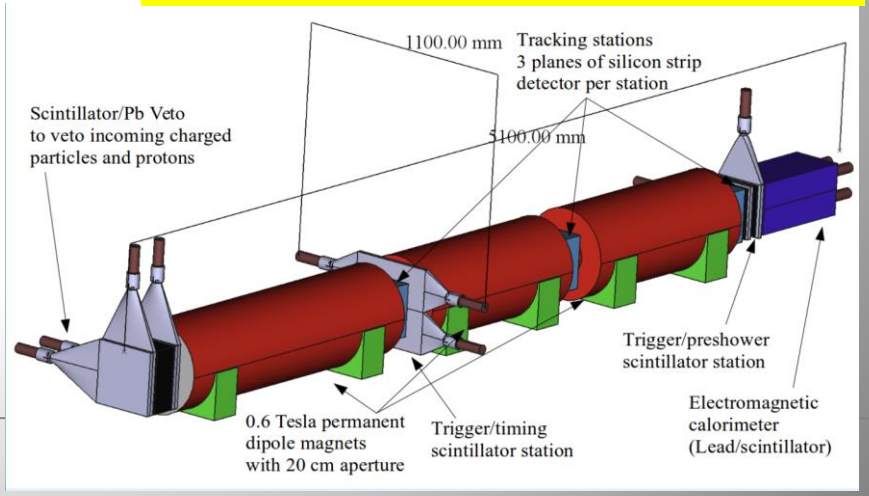
The TOTEM experiment
Elastic, total & diffractive xsecs



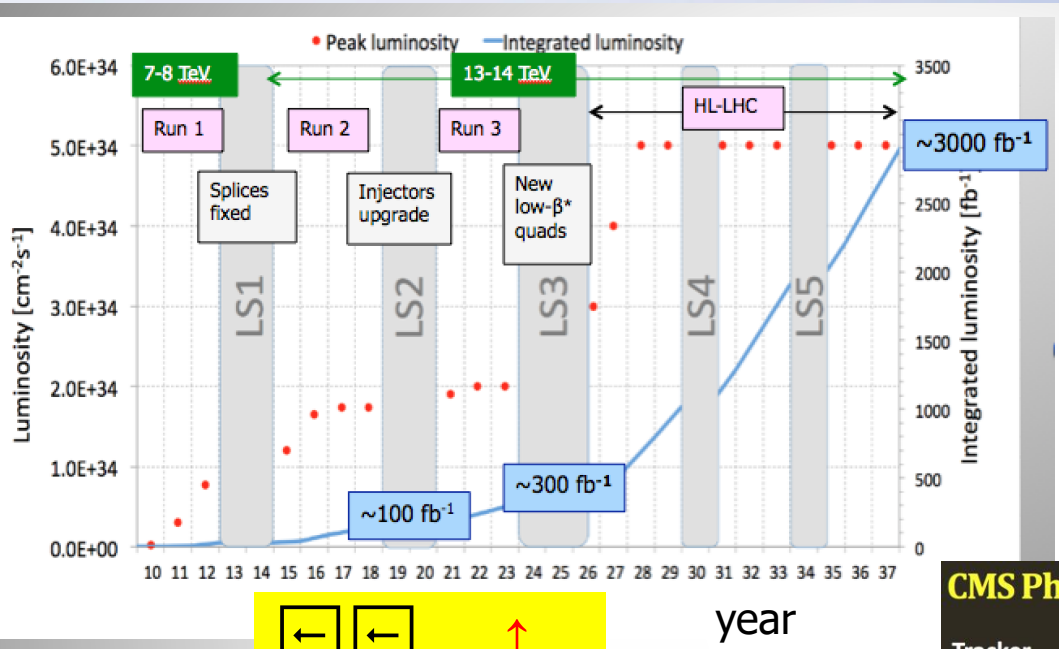
The LHCf experiment
Forward particle production



New: the FASER experiment
Dark photons Approved March 2019



LHC: Future Running

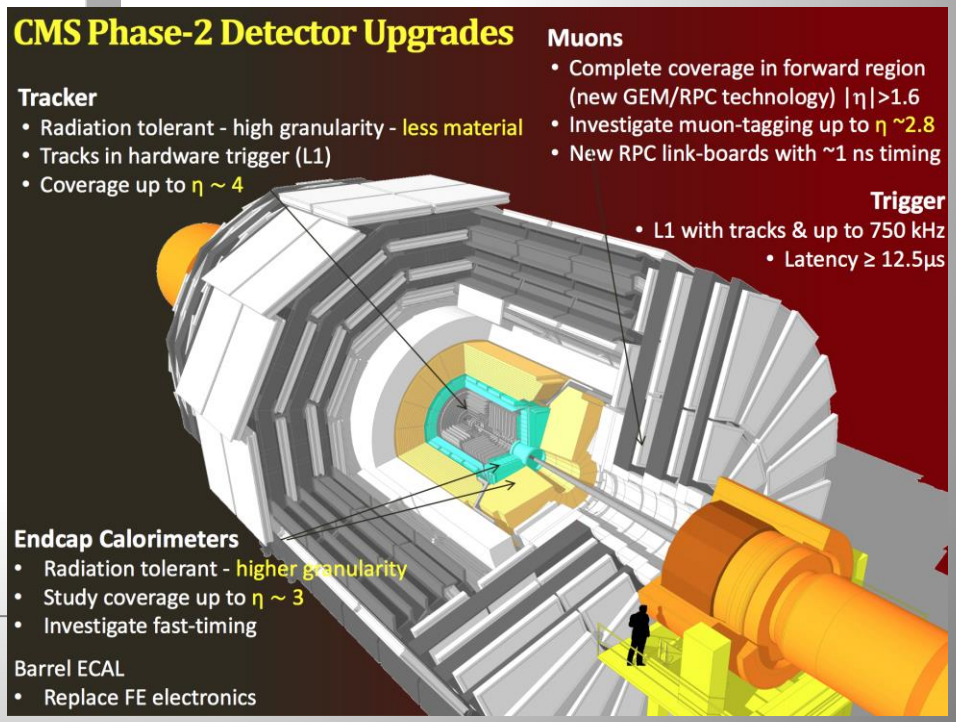


← ← ↑ you are here

High Luminosity LHC pile-up ->
~ 200 events per bunch crossing

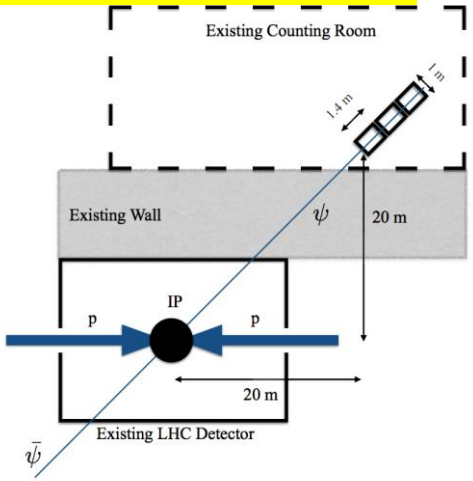
All LHC experiments plan upgrades for either 2019-2020 or 2024-2026 for the High Luminosity LHC upgrade (ATLAS, CMS and LHCb, ALICE)

LHC will run till ~2037
Expect to collect 3000 fb^{-1}
-> so far we have collected 5% only

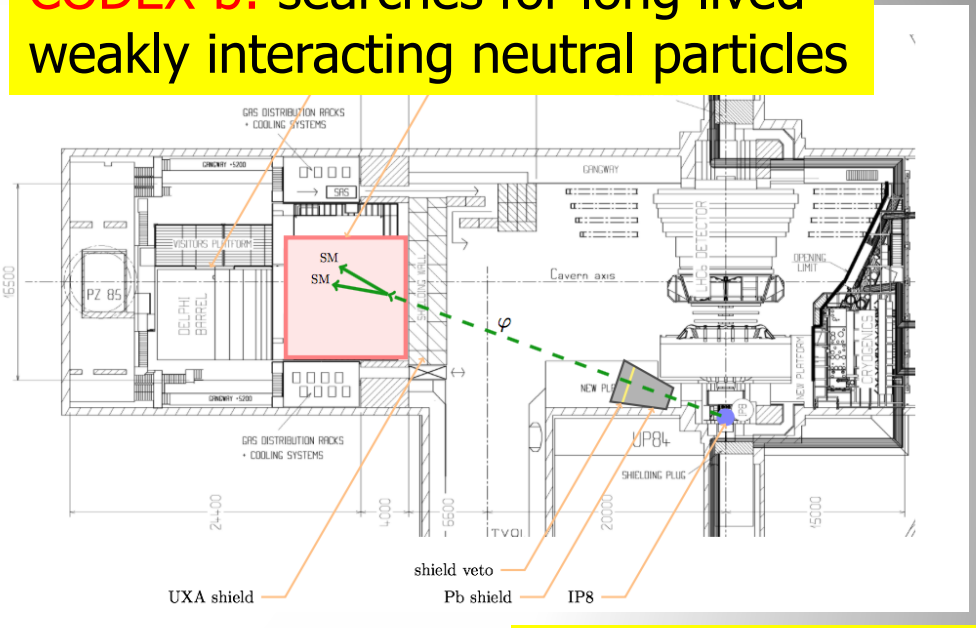


Proposals for New Experiments @LHC

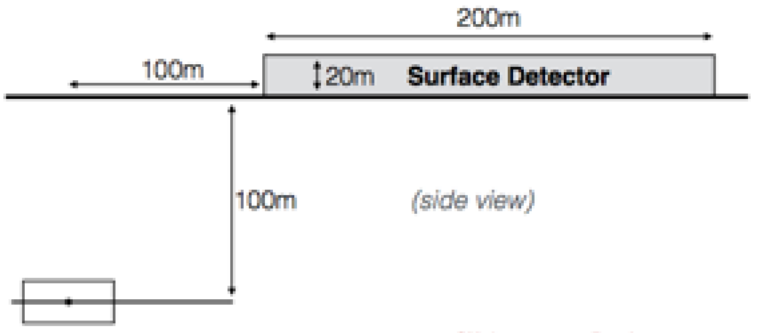
MilliQan: searches for millicharged particles

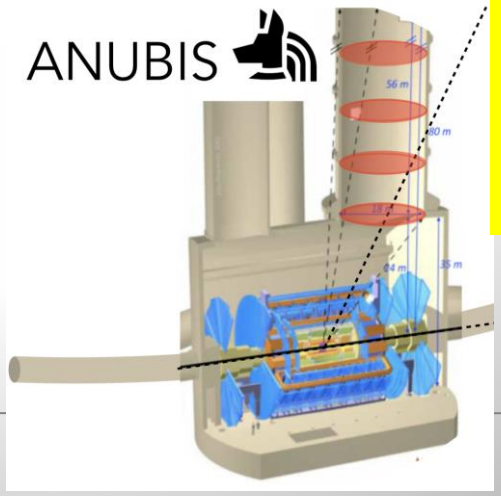


CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



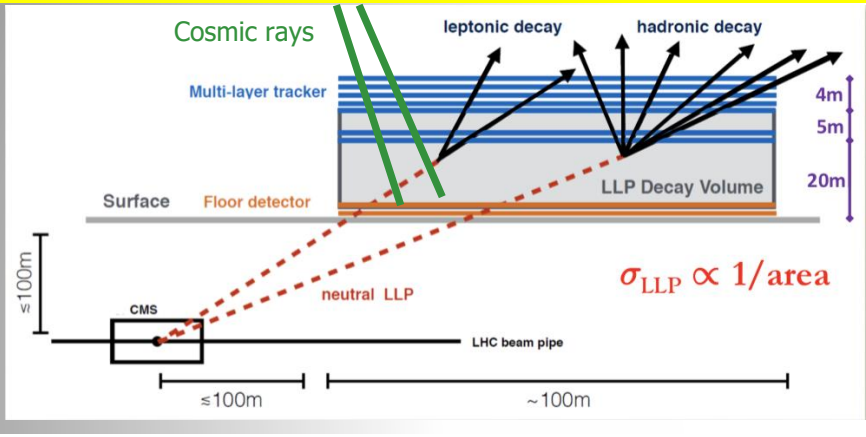


ANUBIS: searches for long lived weakly interacting neutral particles

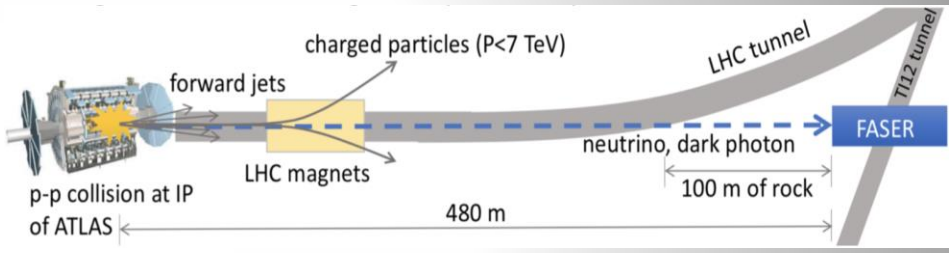
+ Experiment Proposals for TeV neutrinos

Cosmic Rays & TeV Neutrinos

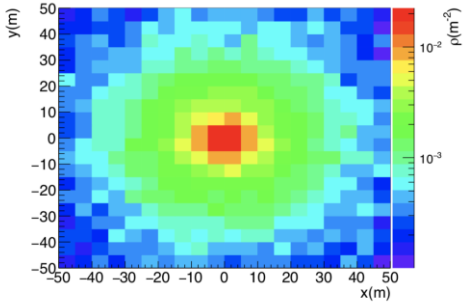
MATHUSLA and ANUBIS 'on surface' Cosmic Ray measurements possible



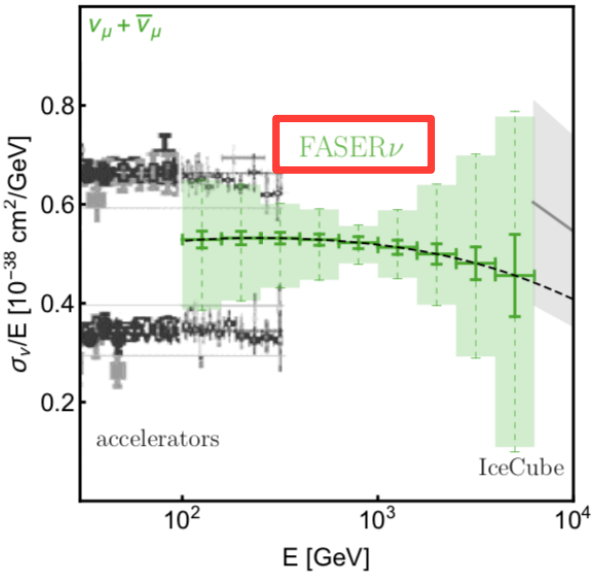
XSEN and FASER-Nu are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors



Observatory Observatory	Full coverage	Spatial resolution	Angular resolution	Energy precision	CR composition capabilities
MATHUSLA-100	100%	Very good	Very good	Good	Limited by statistics
ARGO-YBJ [204]	93%	Very good	Good	Good	Good
KASCADE [146]	$< 2\%$	Good	Good	Good	Very good
HAWC-Outrigger [86]	$0.8 - 62\%$	Good	Good	Good	In investigation
IceTop [88]	0.044%	Good	Good	Good	In investigation
TALE (TA) [89]	$O(1\%)$	Good	Good	Very good	In investigation

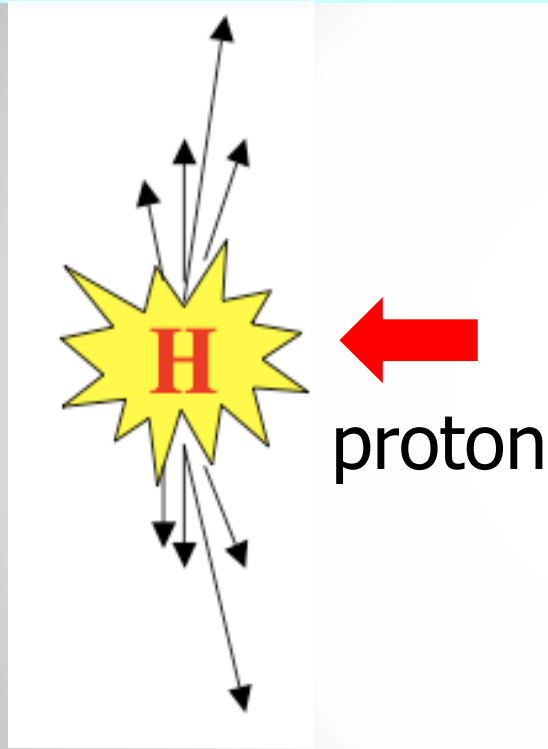


particle density in 10^{15} eV airshower



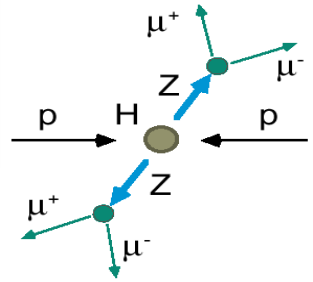
2012: A Milestone in Particle Physics

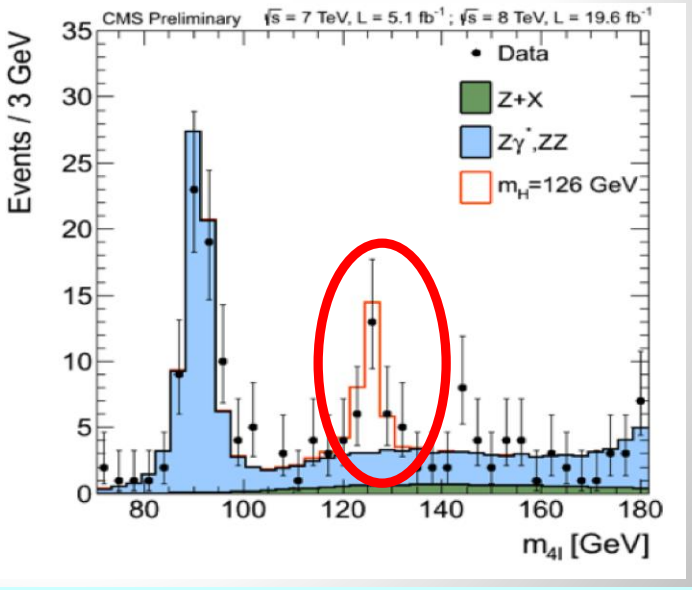
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

proton



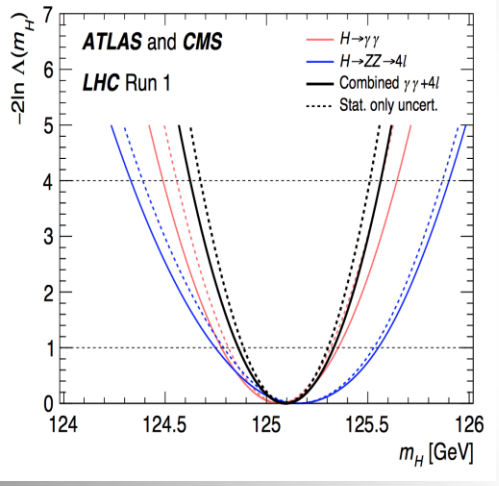


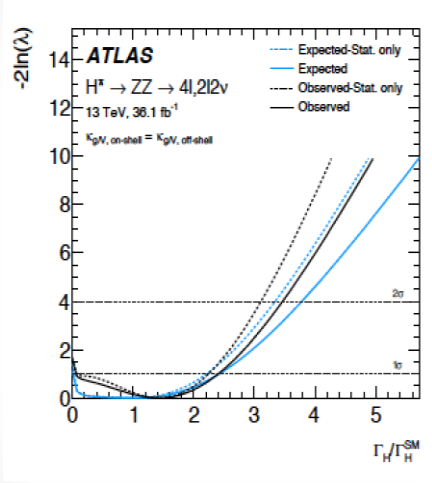
2013

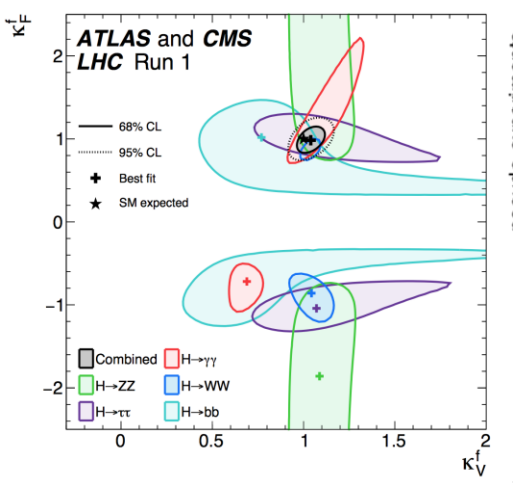
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

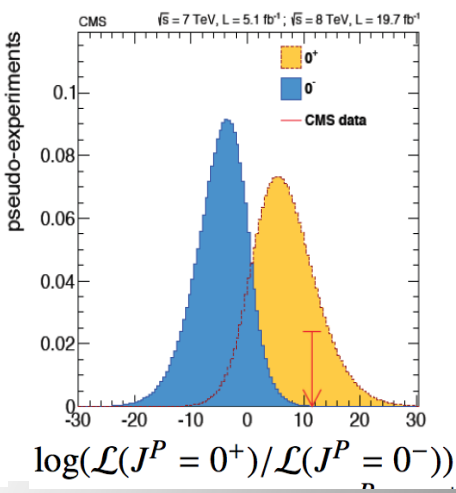
Brief Higgs Summary (so far)

We know already a lot on this brand New Higgs particle!!
So far this Higgs particle looks very Standard-Model like









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 9 MeV
(95%CL)

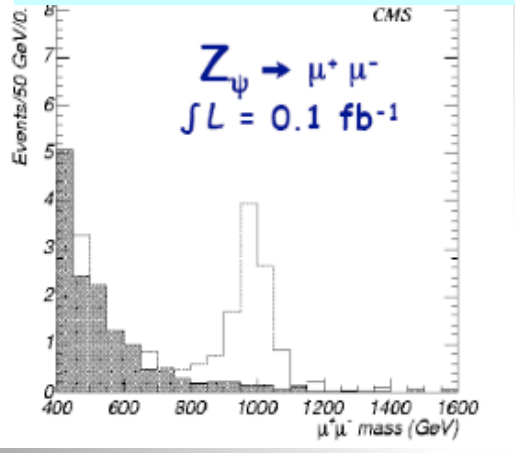
Couplings are within ~10-20% of the SM values

Spin =
$0^{+(+)}$ preferred over 0^-,1,2

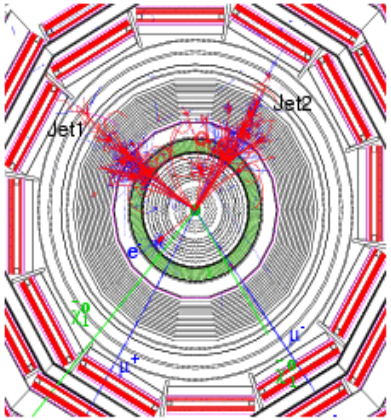
We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses…

New Physics?

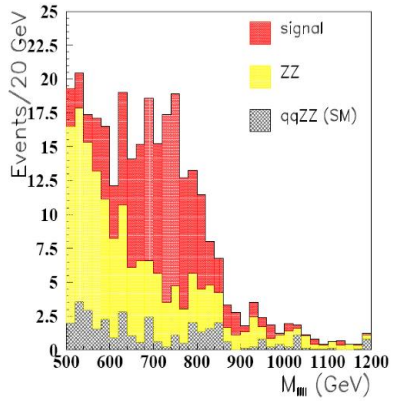
New Gauge Bosons?



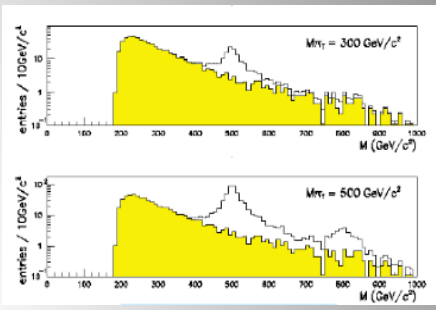
Supersymmetry



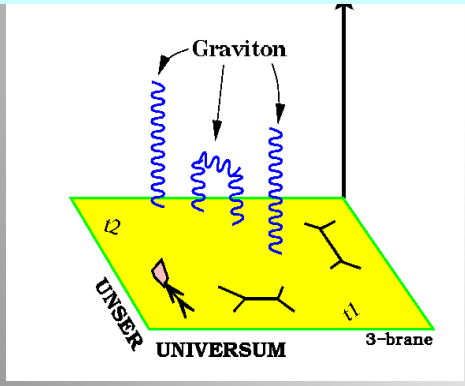
ZZ/WW resonances?



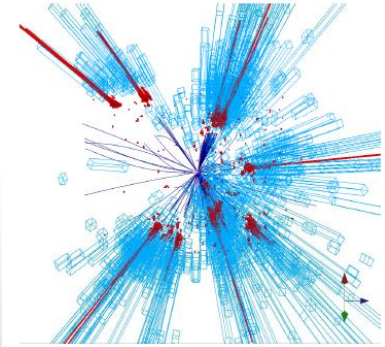
Technicolor?



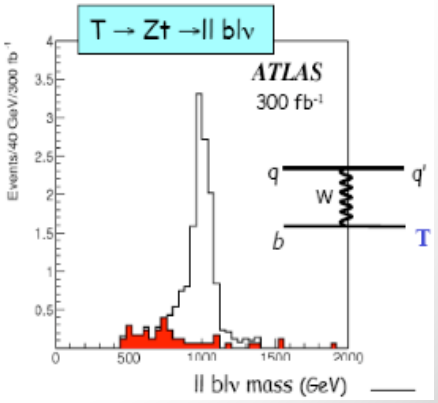
Extra Dimensions?



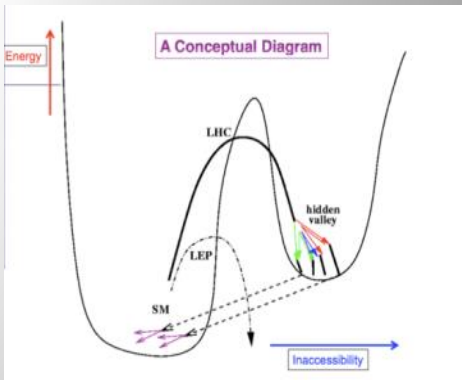
Black Holes???



Little Higgs?



Hidden Valleys?

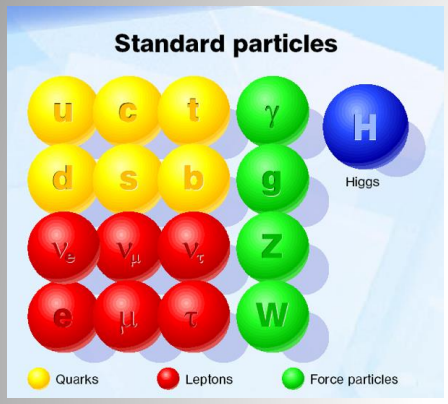


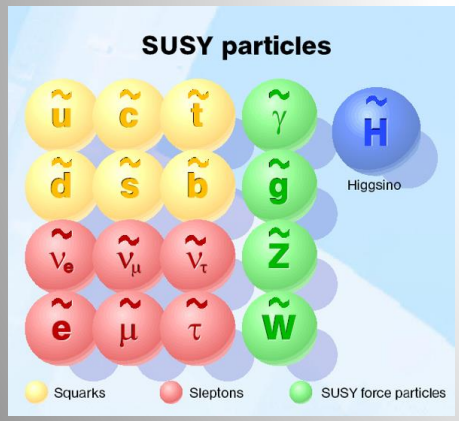
What stabelizes the Higgs Mass? Many ideas, not all viable anymore

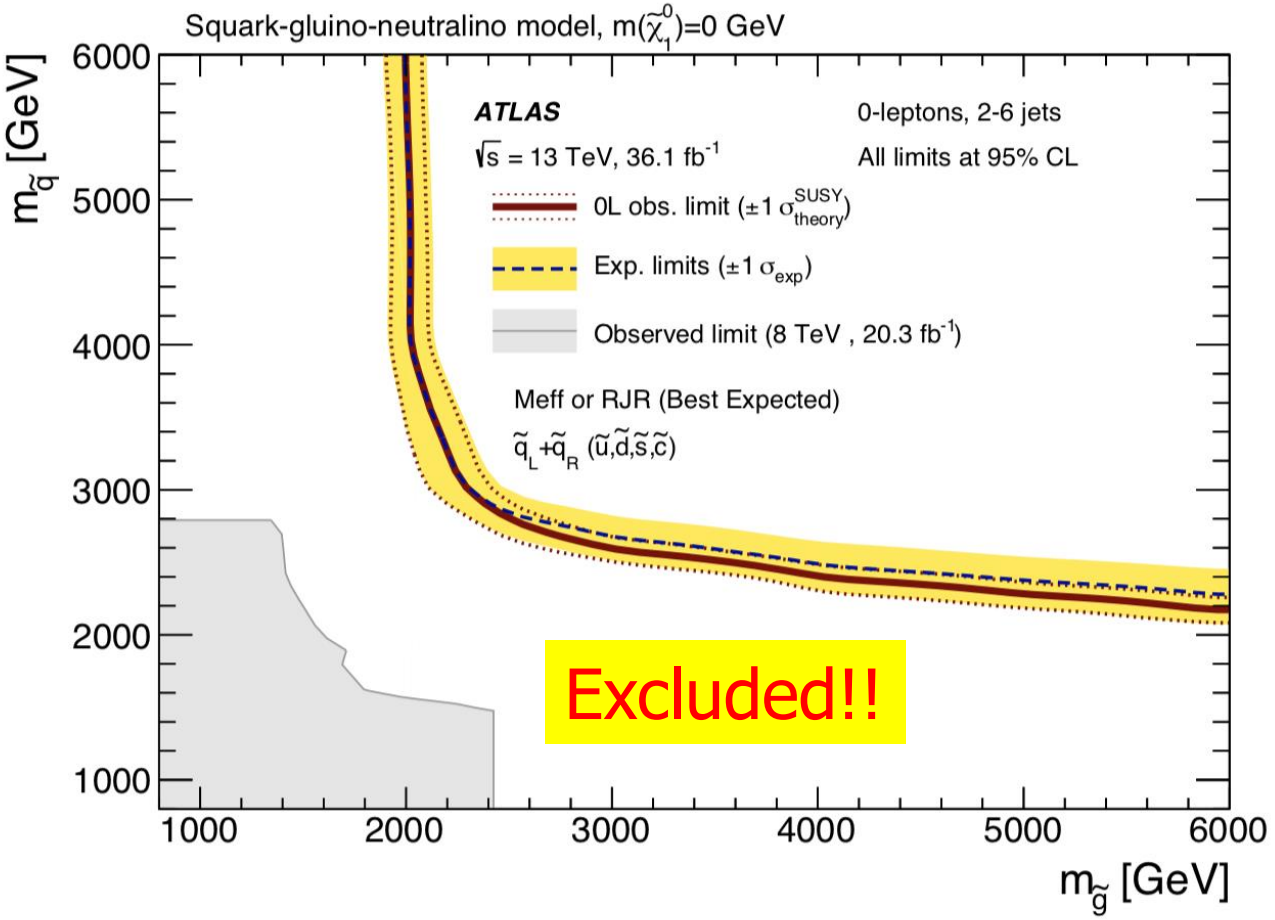
A large variety of possible signals. We have to search a wide phase space

The SUSY SEARCH Chart So Far…

No evidence for SUSY found yet. More than 100 different analyses performed
Excluded squark and gluino mass region:

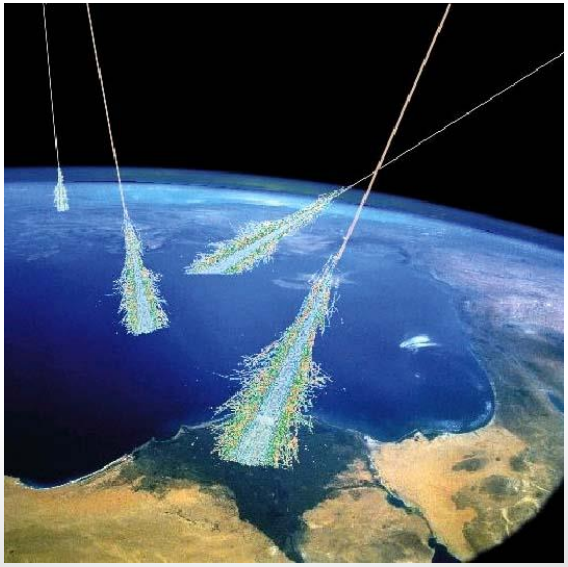




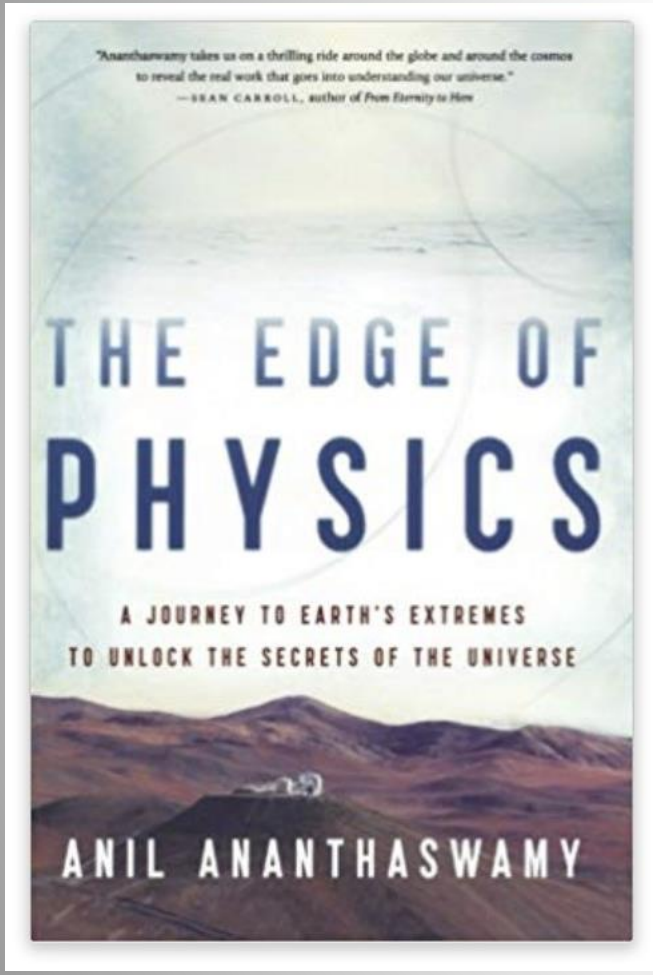


EPS19/LP19: Still no significant sign yet of SUSY with full run-2 data (140 fb^{-1})

LHC Results for Astroparticle Physics



Pierre Auger and LHC



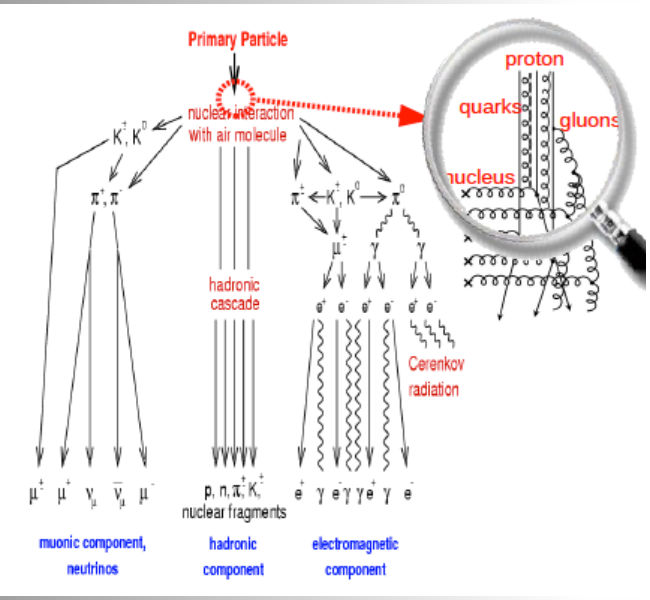
In this book (2011) the author visits and lived in --what he calls extreme places-- where physics can or needs to be done, to make ultimate measurements to unlock the secrets of the Universe.

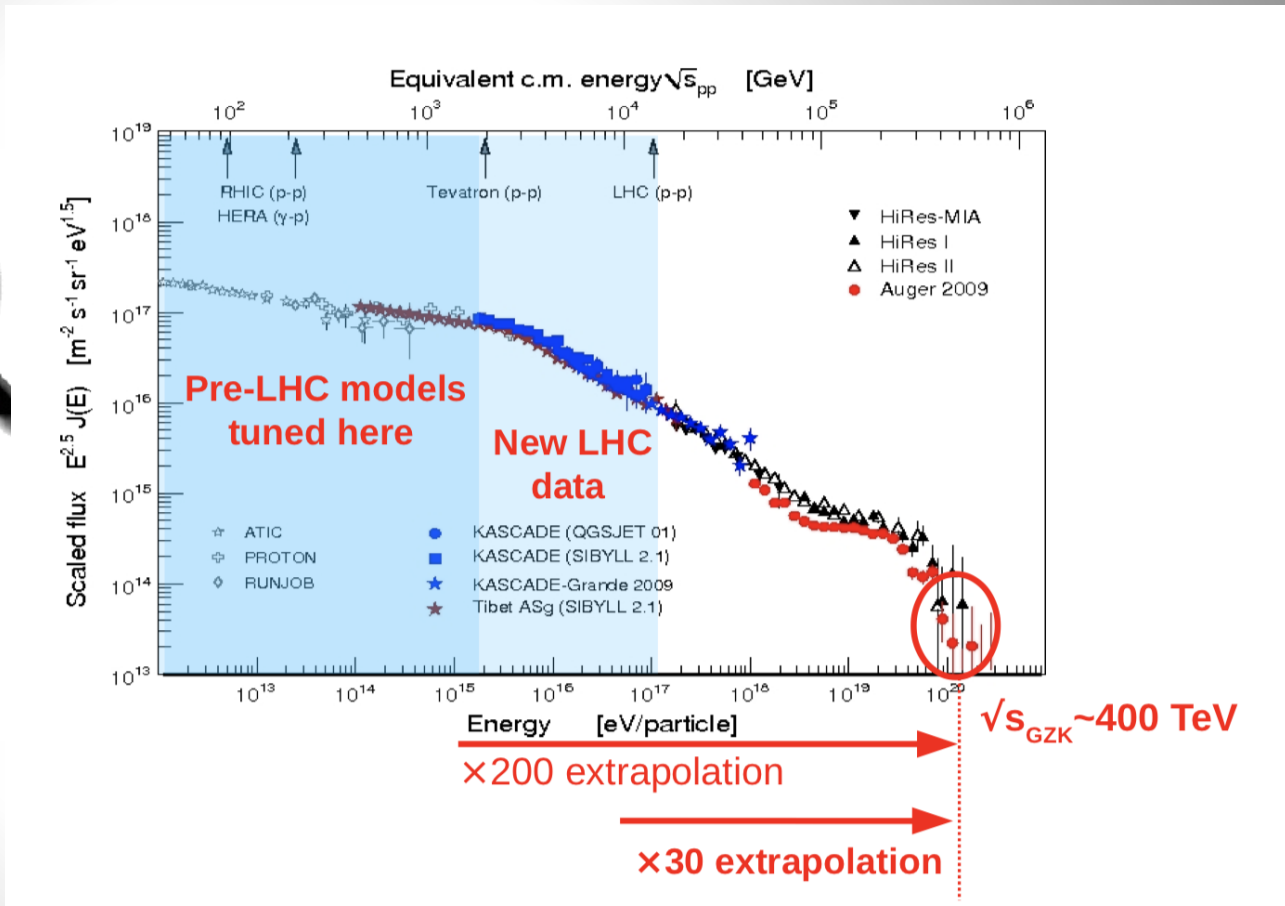
He visits seven experiments including Baikal, IceCube, Auger, telescopes in Chile...

His conclusion: physicists are willing to suffer in order to extract the best possible results!!

Interestingly: the LHC at CERN is one of the places he included in his book!!

LHC Results Relevant for Cosmic Rays



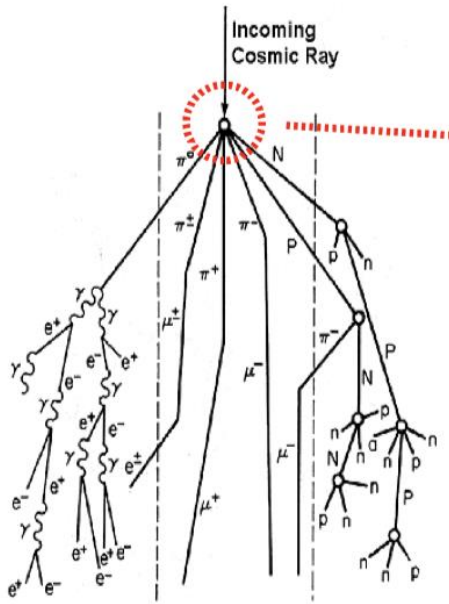


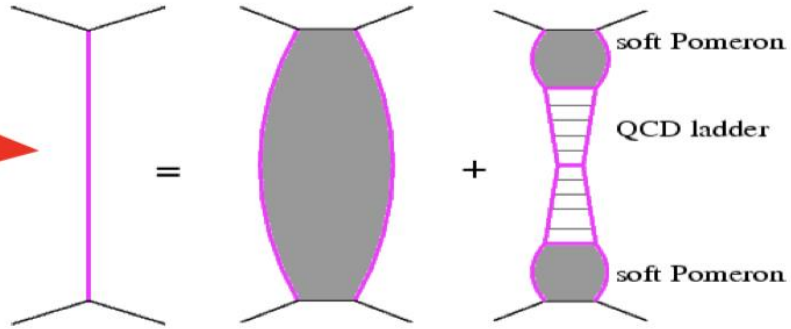
The LHC provides a significant lever-arm in providing data to constrain high energy cosmic ray Monte Carlo programs

Hadronic Monte Carlos for UHECRs

■ Primary hadronic collisions (p-p, p-A) = Complex QCD interactions:

D. d'Enterria





■ Theoretical basis :

- Reggeon Field Theory: soft, diffraction, eikonal (multi)parton ladders (pA, AA)
- pQCD LO: "(cut) hard Pomerons"
- Parton saturation in PDFs.

Kalnykov & Ostapchenko — QGSJET01

Engel et al. — SIBYLL 2.1

Ranft — DPMJET II.55

Werner — VENUS

soft

Drescher et al. — NEXUS

semi-hard

QGSJET II — *Ostapchenko*

(DPMJET III)

EPOS — *Pierog & Werner*

(T.Pierog, 2009)

■ Non-pQCD modeling:

- String hadronization.
- Beam-remnants.

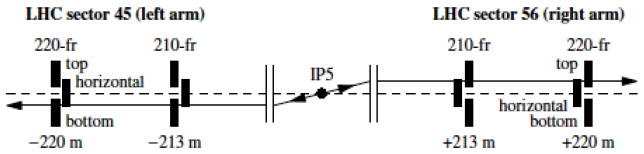
■ Model parameters:

- *O*(20-100) parameters tuned to multiple accelerator/ collider data.

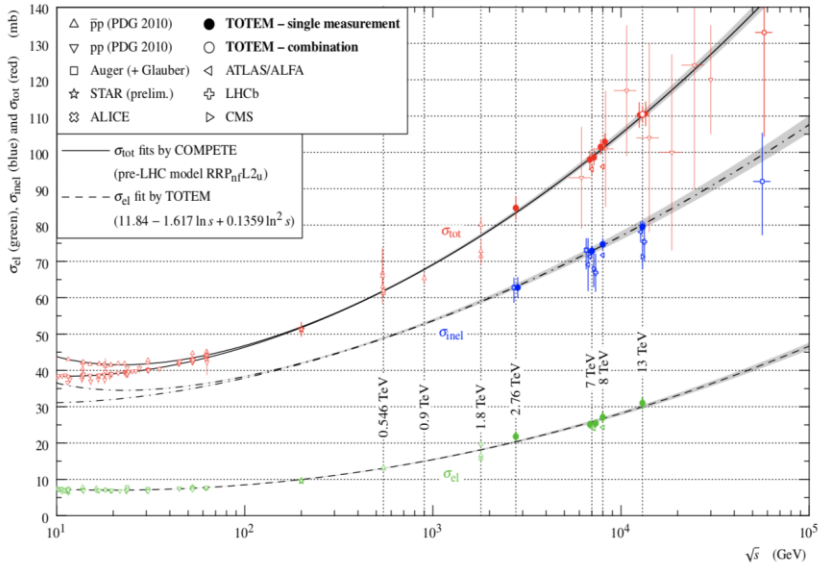
Total and Elastic Cross Sections

TOTEM experiment: Total cross section and elastic/diffractive scattering

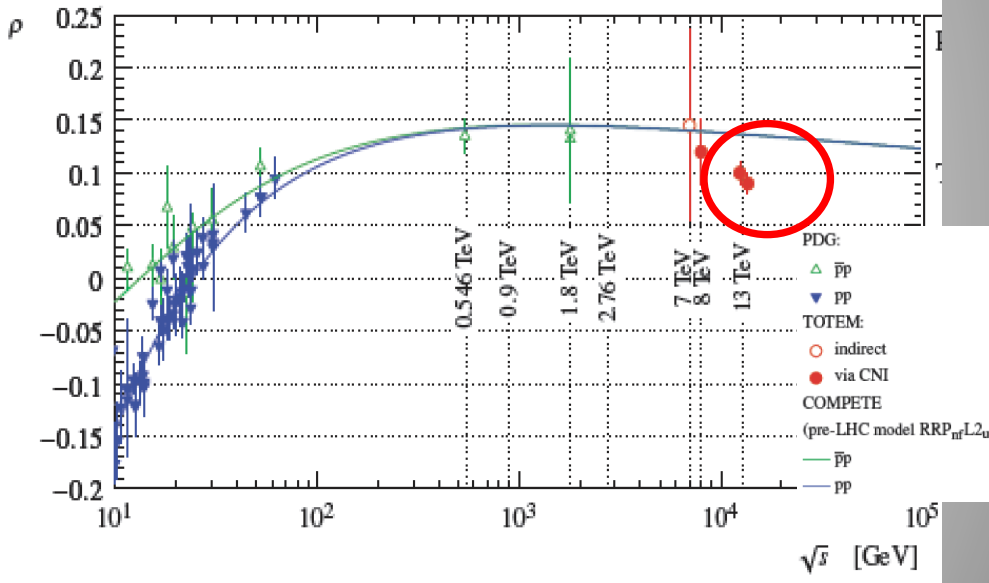
At $\sqrt{s}$=13 TeV: σ_{tot} = 110.6 ± 3.4 mb (σ_{inel} ~72%, σ_{el} ~28%).

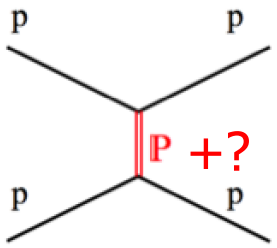


arXiv:1712.06153



arXiv:1812.04732





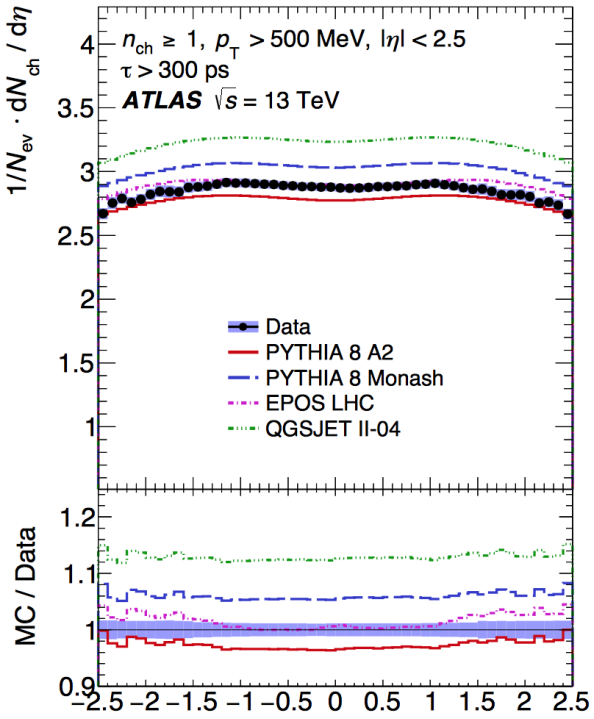
ρ: the ratio of the real to imaginary part of the nuclear elastic scattering amplitude at t=0, is lower that expected

First direct evidence for "odderon" exchange in elastic scattering??

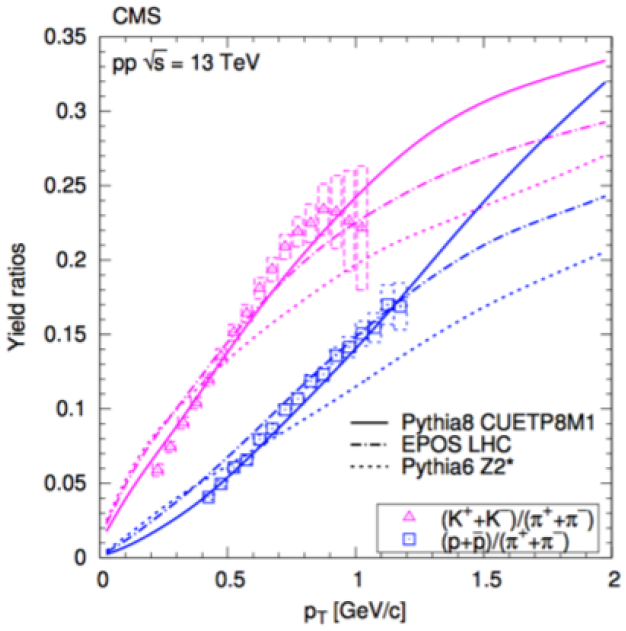
Inclusive Particle Spectra

LHC experiments have made measurements of charged particle spectra and energy flows in the central region for minimum bias pp collisions.

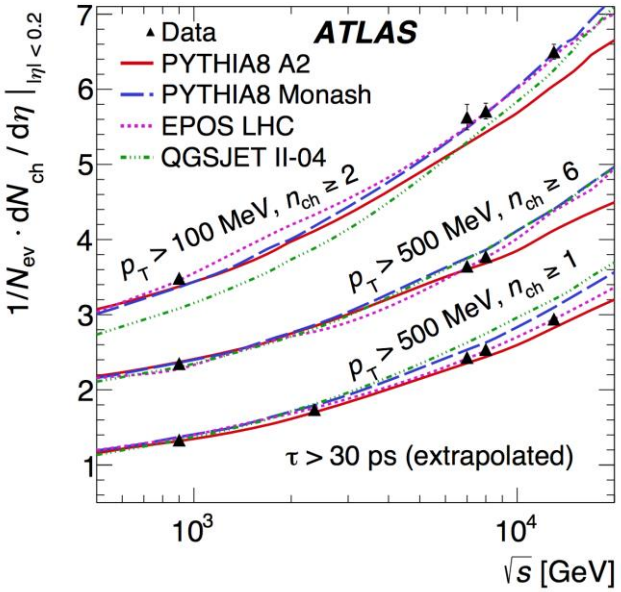
Some examples for data at 13 TeV:



arXiv:1602.01633



arXiv:1706.10194

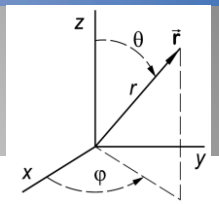


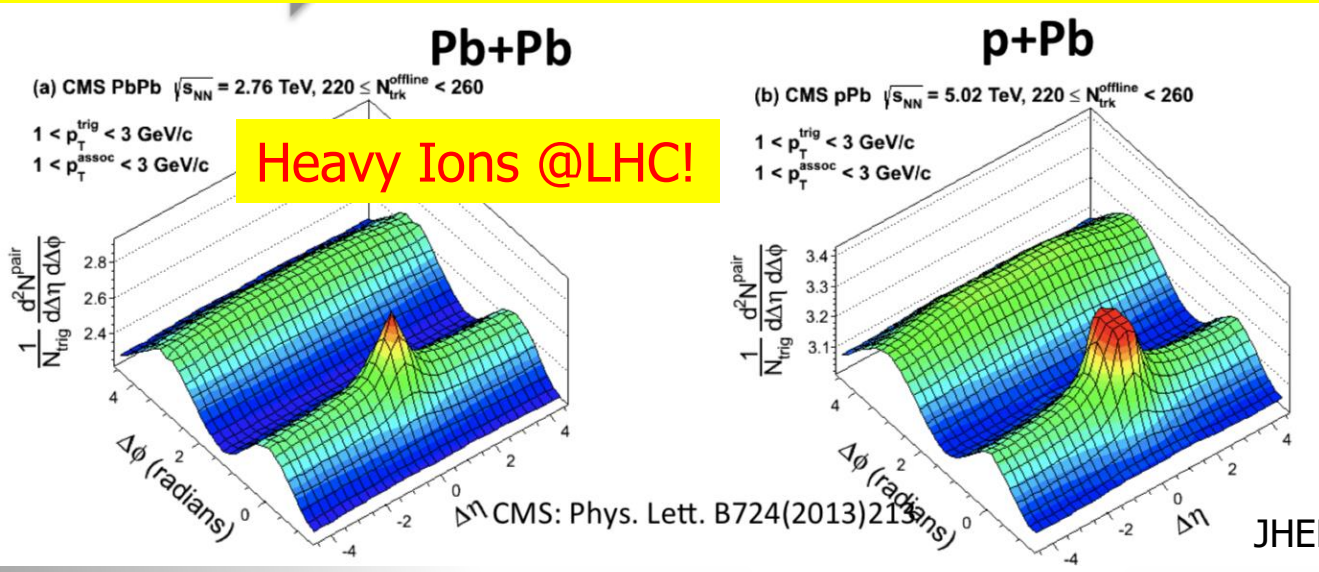
arXiv:1606.01133

- Useful for tuning of models.
- Any particular measurements still needed/required??

Correlations Between Produced Particles

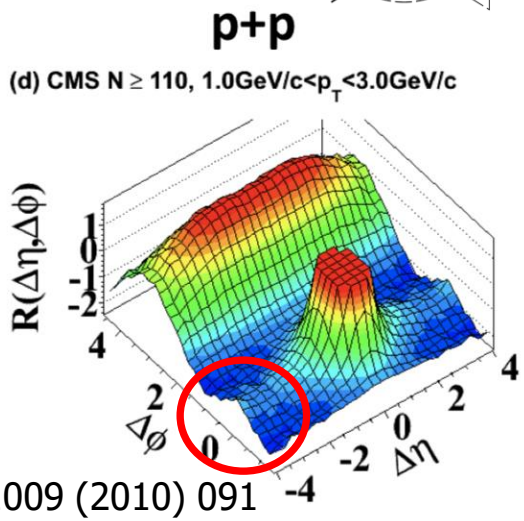
•Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ in PbPb, pPb and pp





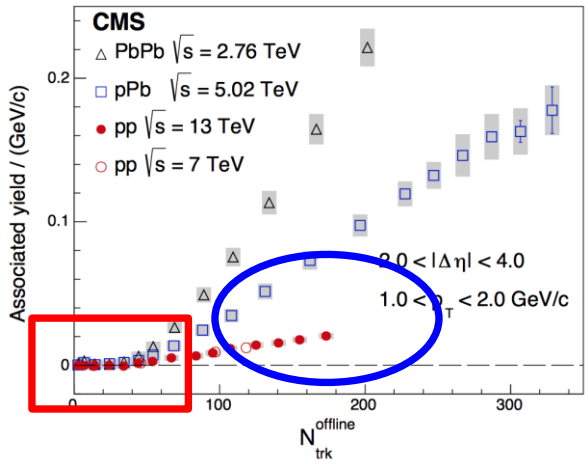
Heavy Ions @LHC!

CMS: Phys. Lett. B724(2013)213



JHEP 1009 (2010) 091

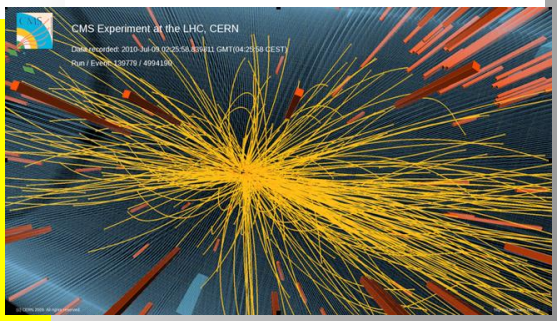
High multiplicity events



A new phenomenon in the 'stronge force'?

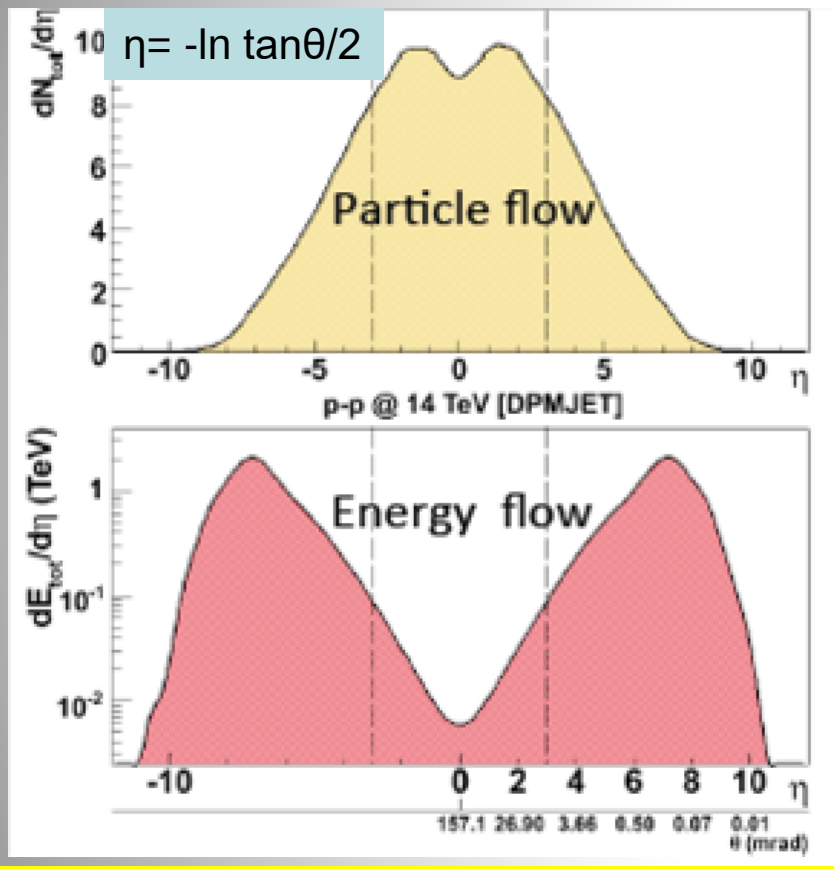
- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

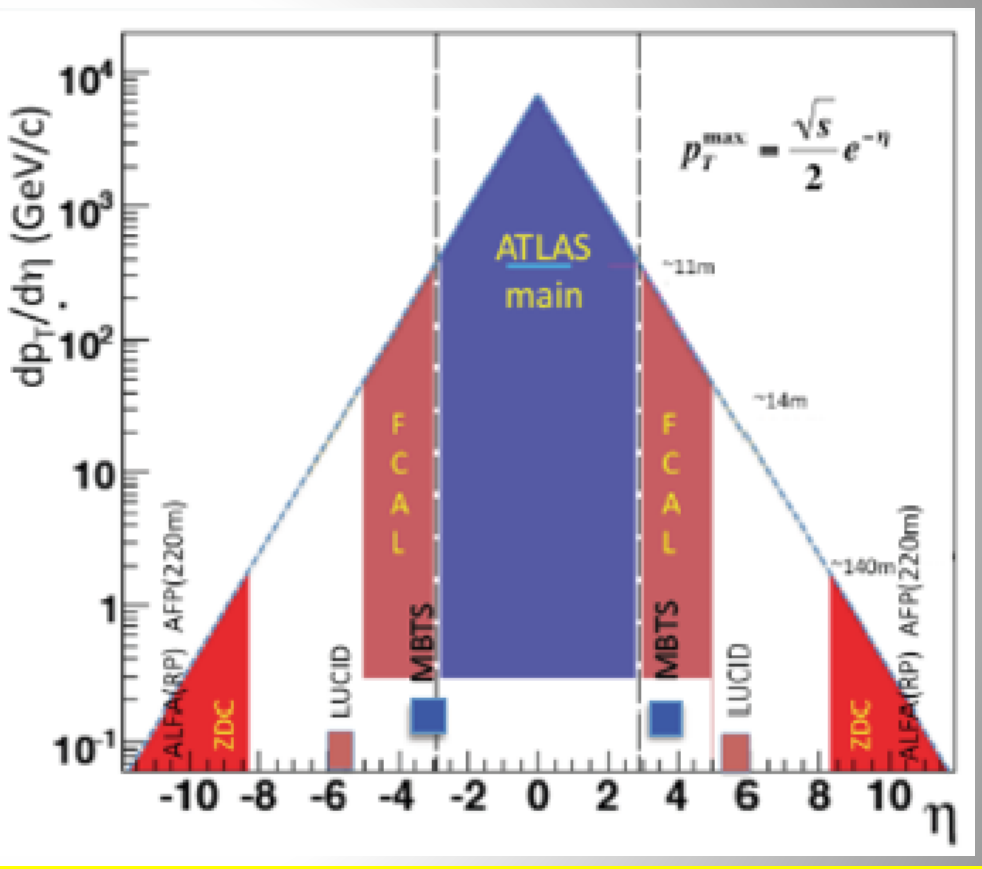
…



Forward Coverage of the Experiments

Particle and energy flow as function of pseudorapidity (polar angle)





- Most of the energy flow is in regions at large |η|, ie beam directions
- Particle density is highest in the central region
- Forward energy/particle flow of particular interest for cosmic ray air showers!
- Detectors @LHC extending up to |η|<5 + special detectors for larger |η|

Forward Detectors in CMS

Detector configuration during 2010 - 2011

CMS

Hadronic Forward (HF)

(3.0 < |η| < 5.0)

Hadronic Forward (HF)

140m

(5.2 < |η| < 6.6)

140m

ZDC

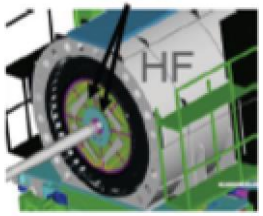
CASTOR

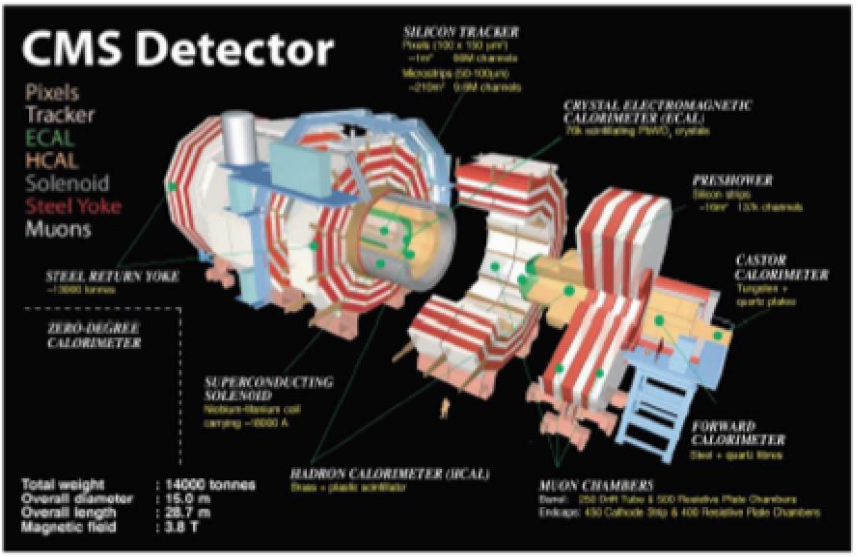
ZDC

(|η| > 8.1)

W-absorbers/quartz plates
12 longitudinal modules/16 azimuthal sectors

BSC





Hadron Forward:

@11.2m from interaction point

Rapidity coverage: 3 < |η| < 5

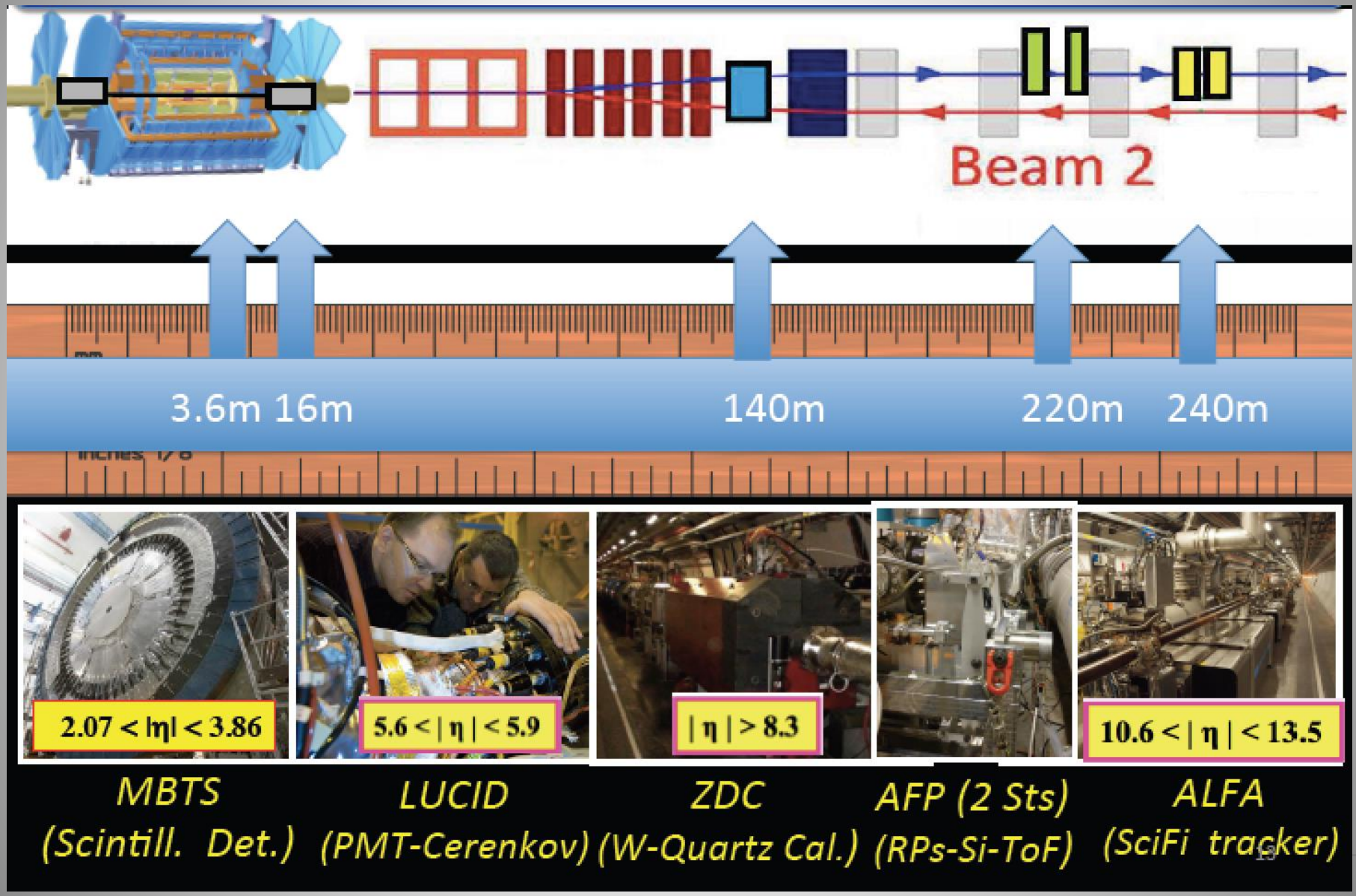
Steel absorbers/quartz fibers (Long+short fibers)

0.175x0.175 η/φ segmentation

Acceptance limited to |η| < 4.9 at analysis level

New: Precision Proton Spectrometer together with TOTEM (CT-PPS)

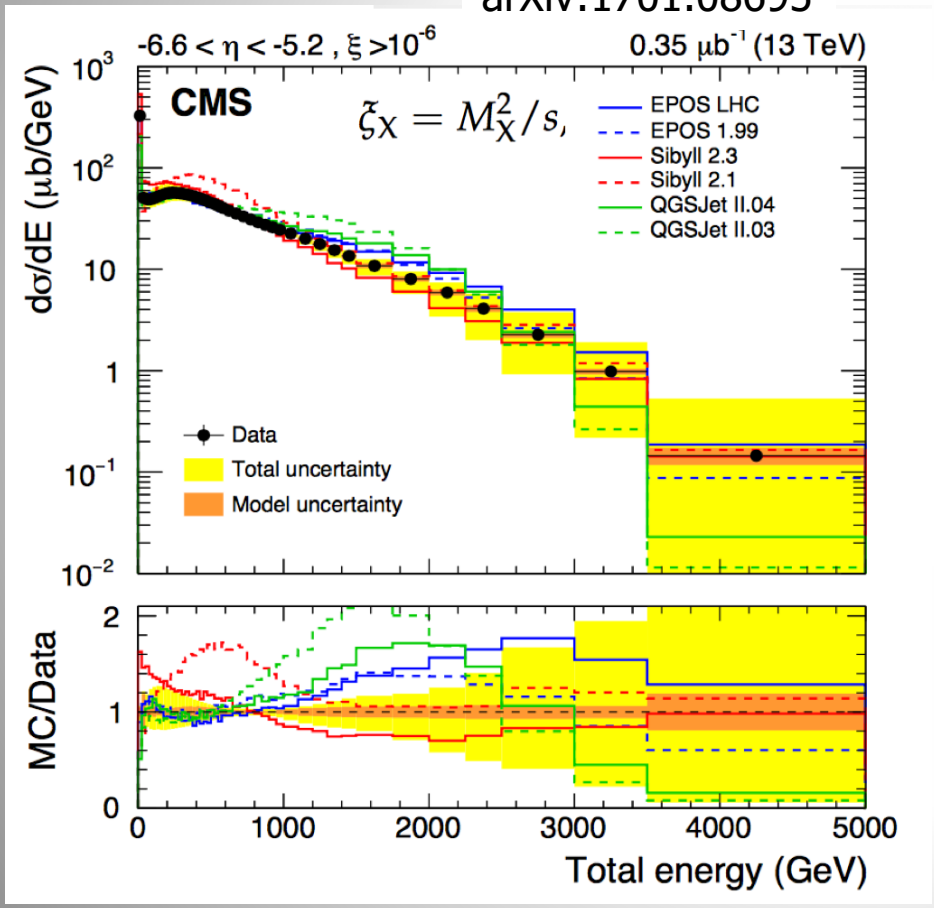
Forward Detectors in ATLAS



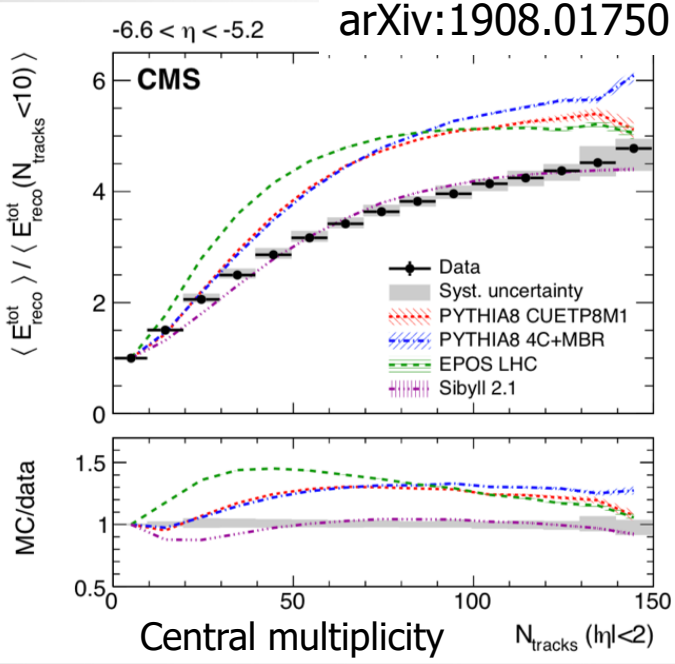
Event Characteristics in the Forward Region

Energy Flow in the extended forward region of CMS->compare with CR models

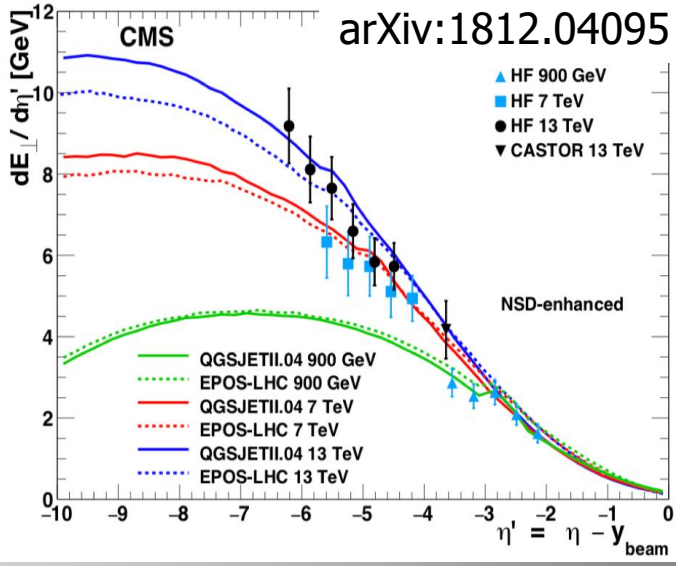
arXiv:1701.08695



arXiv:1908.01750



arXiv:1812.04095

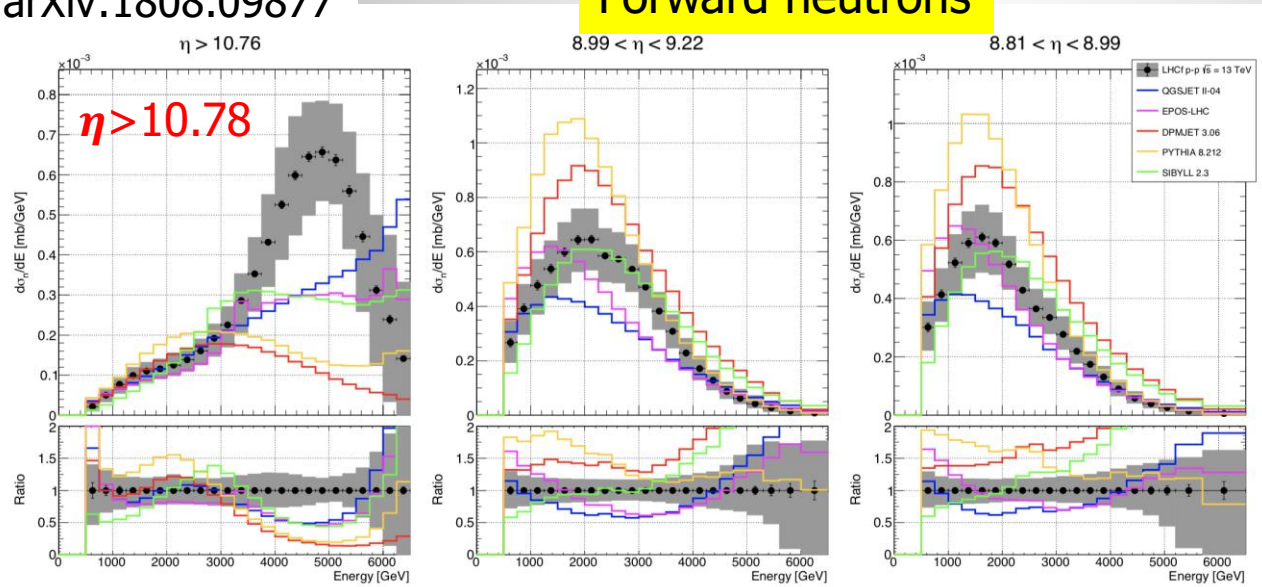


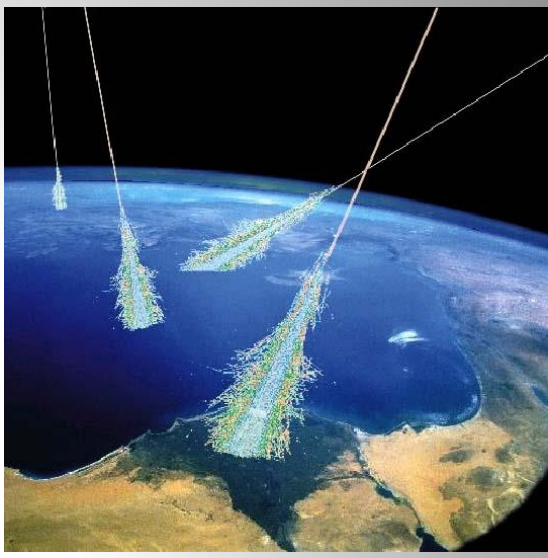
Pseudorapidity ranges: -6.6< η < -5.2

Forward Particle Production

arXiv:1808.09877

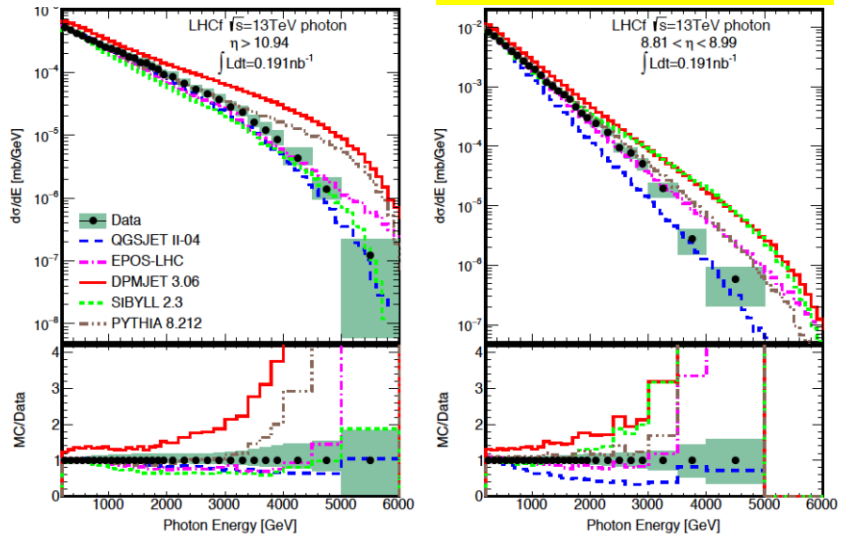
Forward neutrons

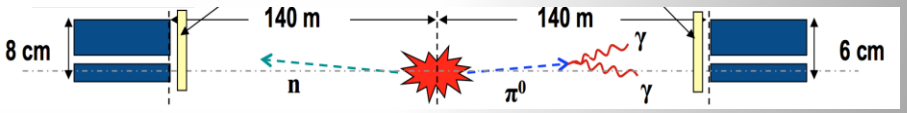




arXiv:1703.07678

Forward Photons

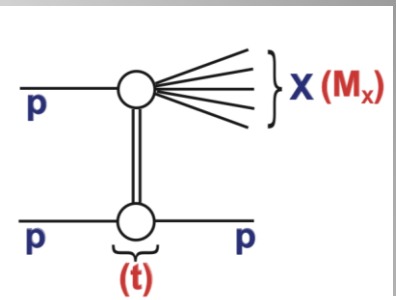




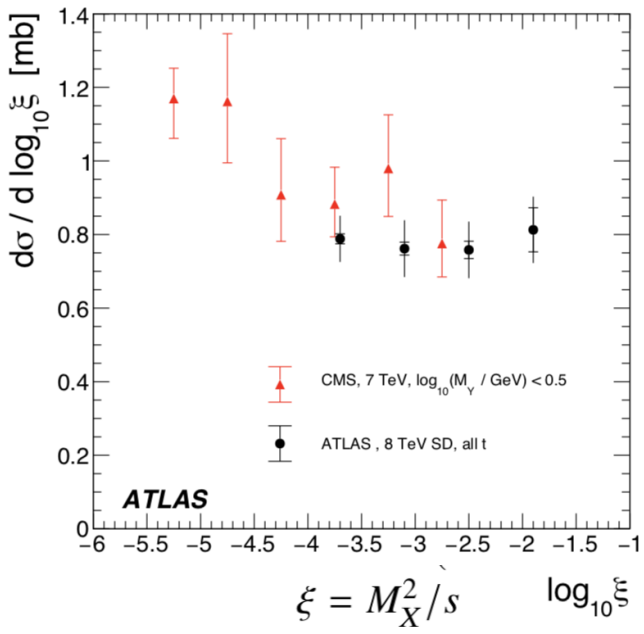
LHCf experiment:
Forward measurements in pp (and pA) compared to Monte Carlos for Cosmic Ray studies
No model reproduces the data well !!

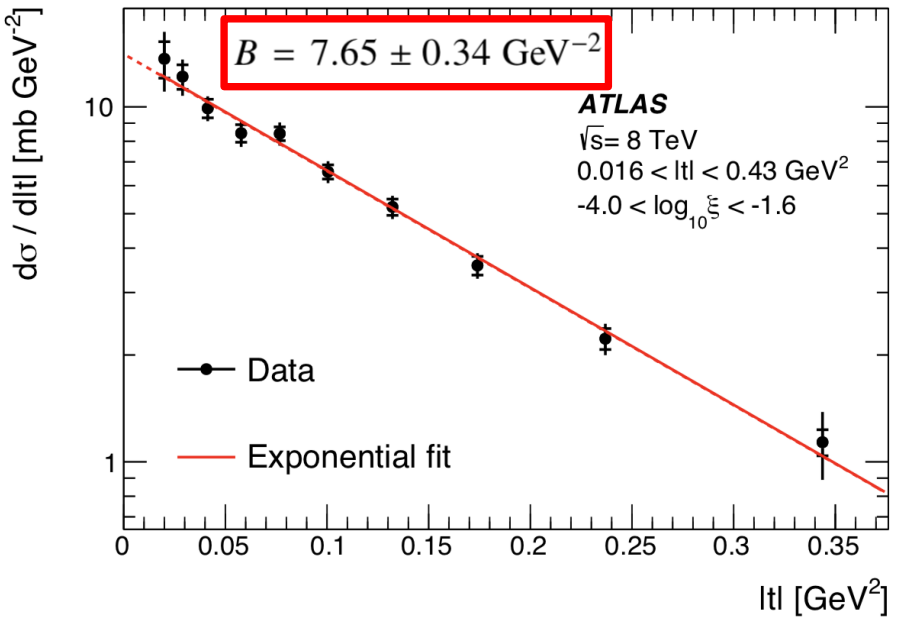
Single Diffractive Dissociation

Tagging Single Diffractive Dissociation via proton tagging in the ATLAS ALFA forward spectrometer, and with charged particles in the central detector



arXiv:1911.00453





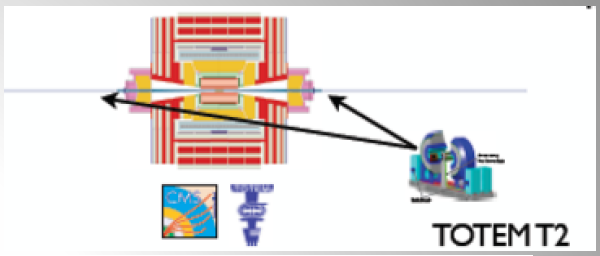
Distribution	$\sigma_{SD}^{fiducial(\xi,t)}$ [mb]	$\sigma_{SD}^{t\text{-extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
PYTHIA8 A2 (Schuler–Sjöstrand)	3.69	4.35
PYTHIA8 A3 (Donnachie–Landshoff)	2.52	2.98
HERWIG7	4.96	6.11

$-4.0 < \log_{10}\xi \leq -1.6$ and $0.016 < |t| \leq 0.43$ GeV^2

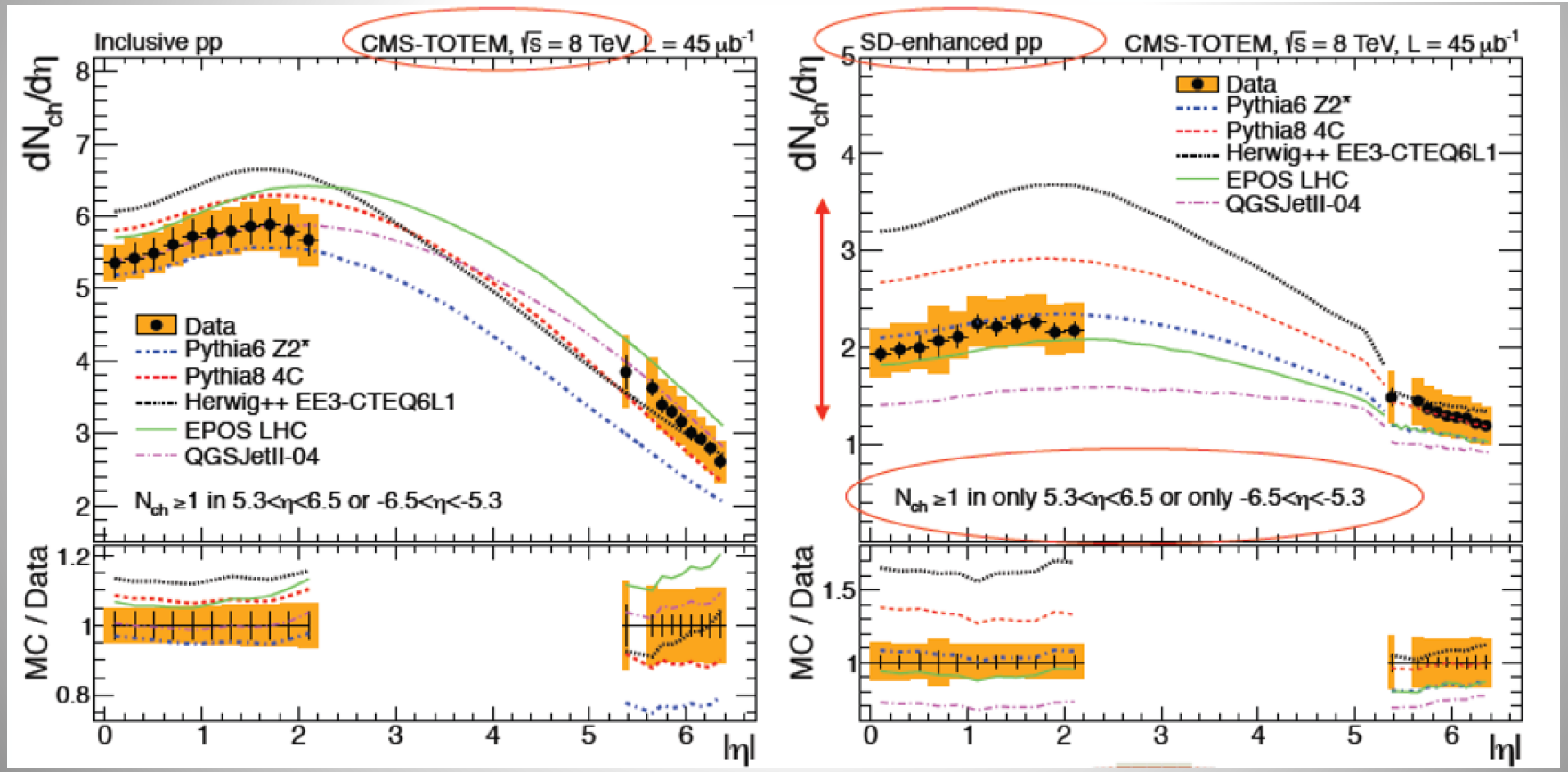
Data cross section substantially smaller than predicted by models

Central and Forward Particle Density

A common CMS+TOTEM measurement



arXiv:1405.0722

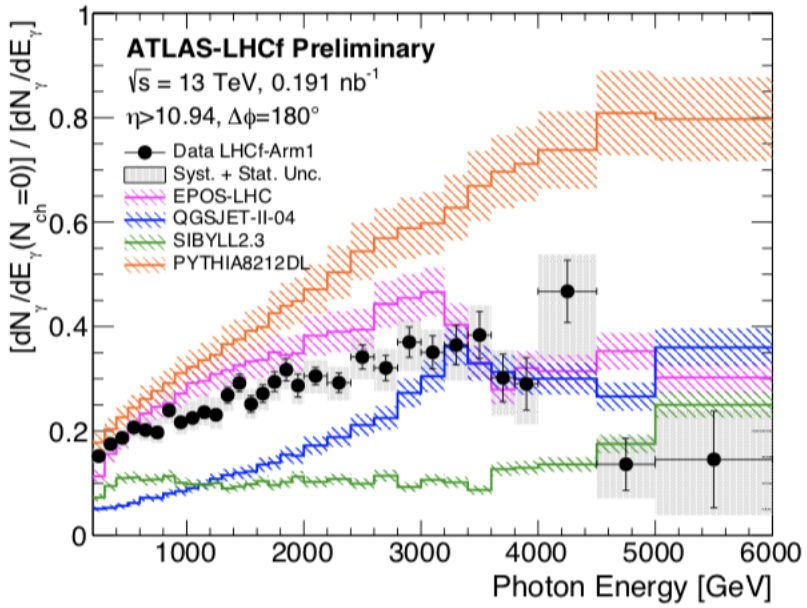


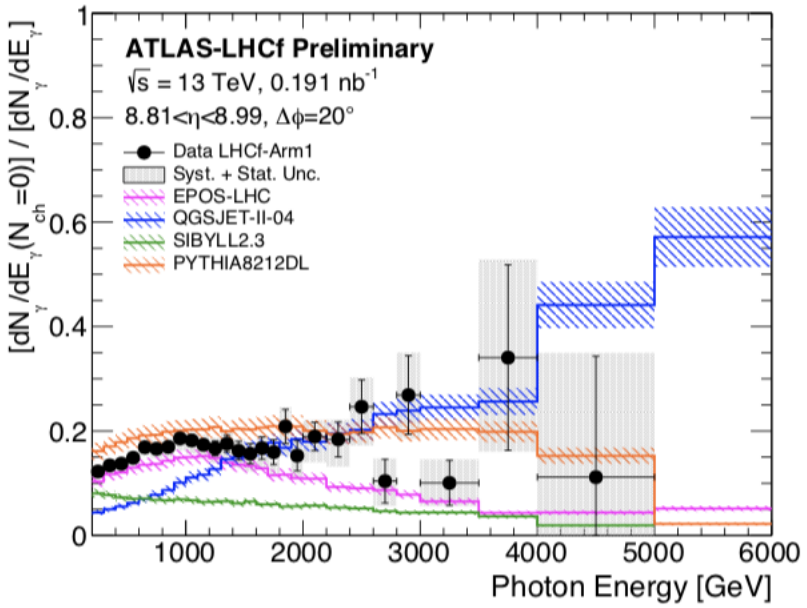
A challenge for the phenomenological models?

Combined ATLAS+LHCf Studies

Study of the contribution of proton diffractive dissociation to production of forward photons observed in LHCf

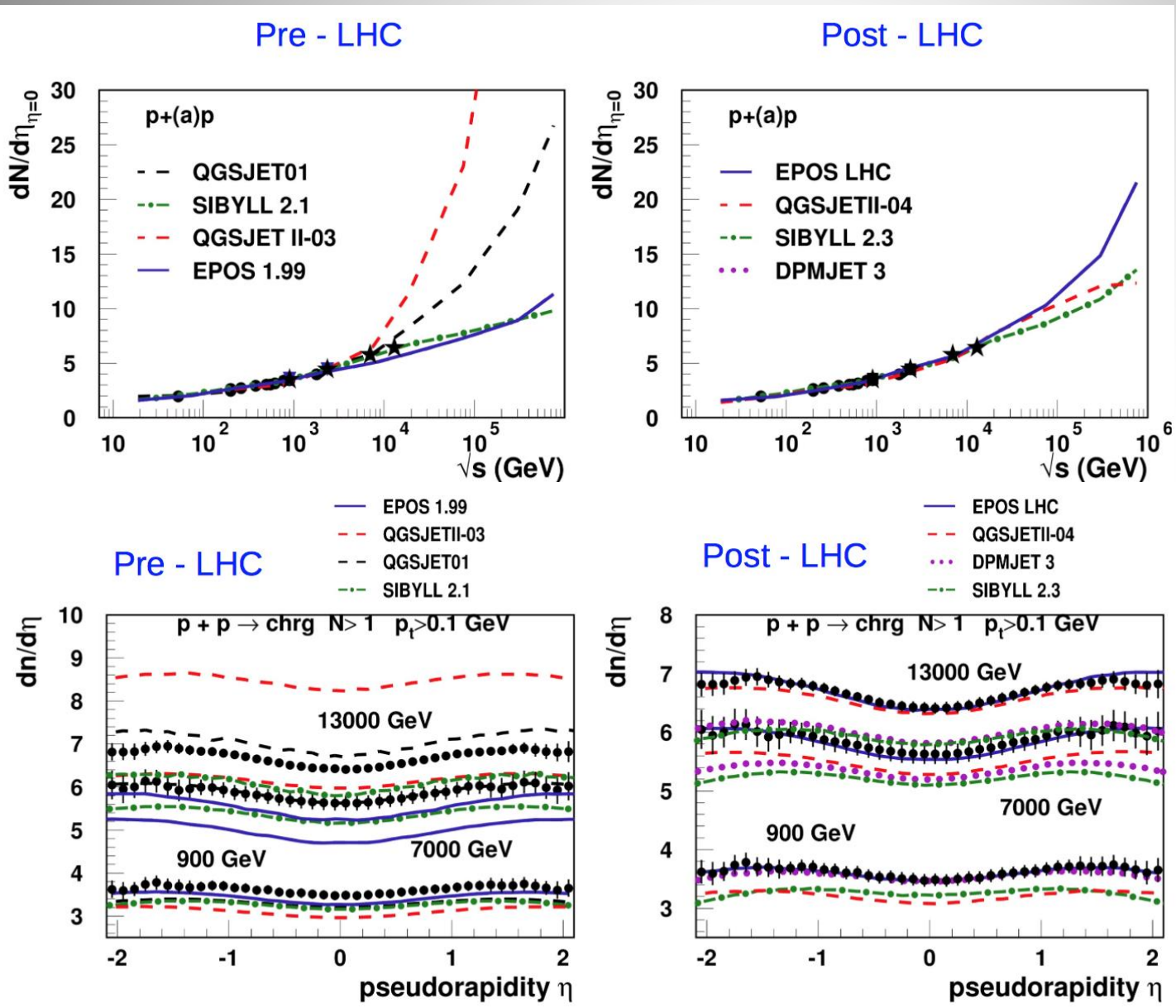
- Photon reconstruction in the LHCf-Arm1 detector, ATLAS for DD selection.
- Measure photons with $8.81 < \eta < 8.99$ or $\eta > 10.94$ for events with no charged-particle tracks with $p_T > 100$ MeV and $|\eta| < 2.5$.





A challenge for the phenomenological models

Does it Help? Yes!!



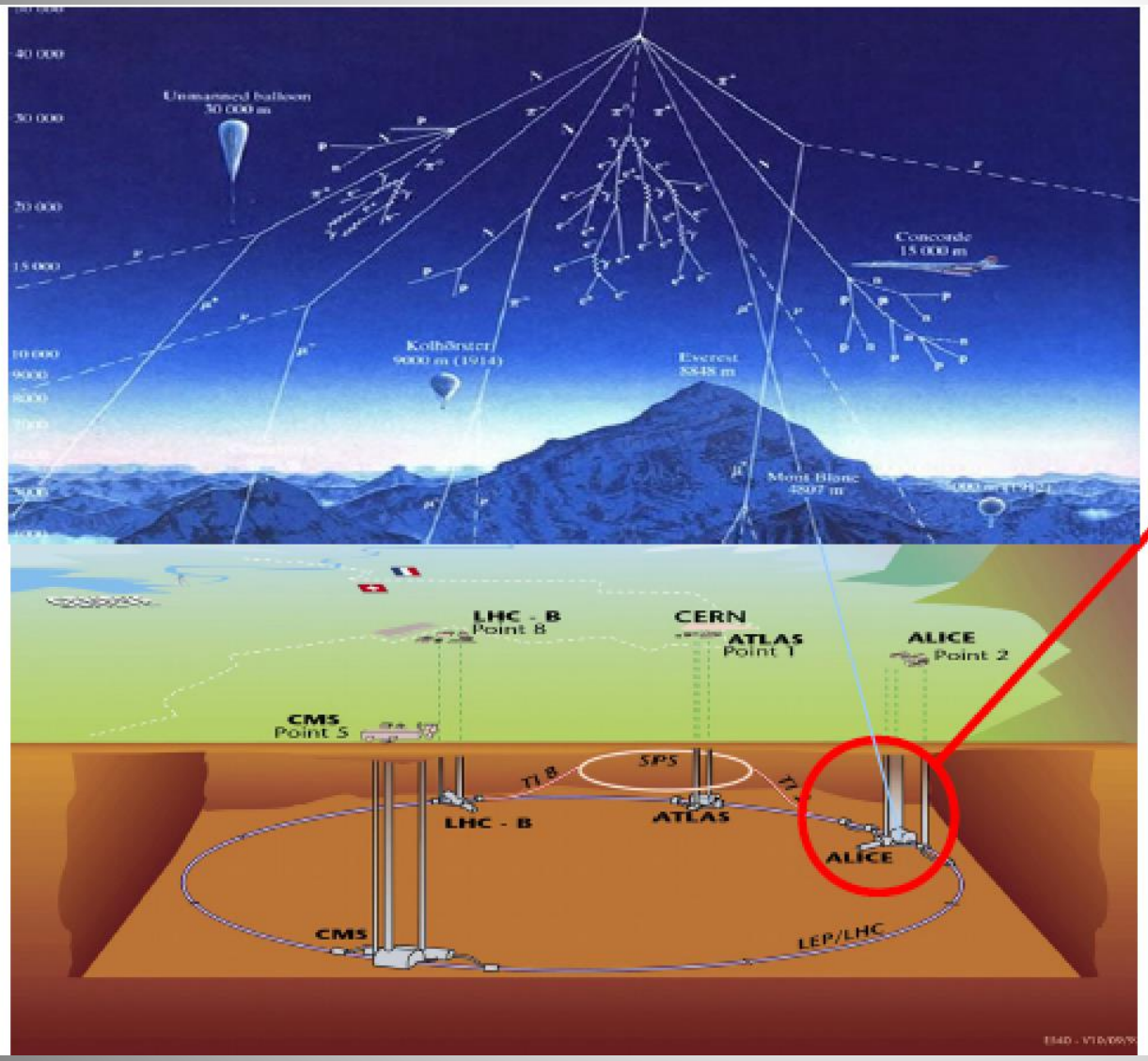
T. Pierog: UHECR meeting in Kyoto Japan

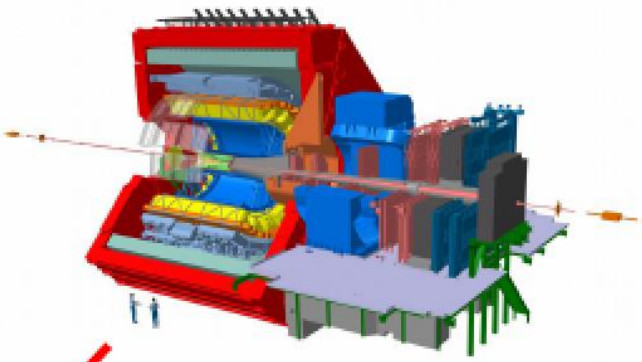
More ongoing by model tuners

- T. Pierog
- R. Engel
- S. Ostapchenko
- …

Expect continuous improvements!

Detection of Cosmic Rays at the LHC

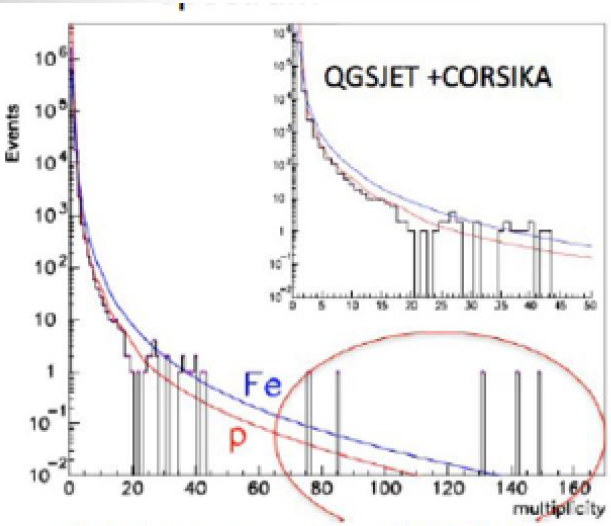




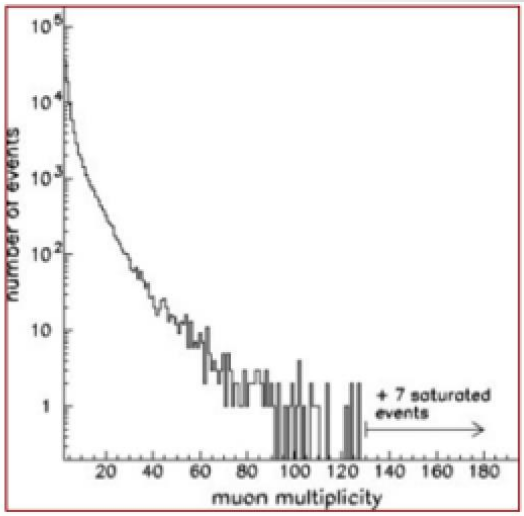
- ALICE is located at LHC Point2 52m underground (28m rock above)
- Muon energy threshold ~16 GeV

Detection of Cosmic Rays at the LHC

- To measure the cosmic charge ratio wrt momentum for single muons for two cases: near vertical and horizontal (central barrel)
- To measure the cosmic charge ratio wrt muon multiplicity.
- Study in detail the properties of muon bundles



ALEPH Coll., *Astrop. Phys.* **19** (2003) 513



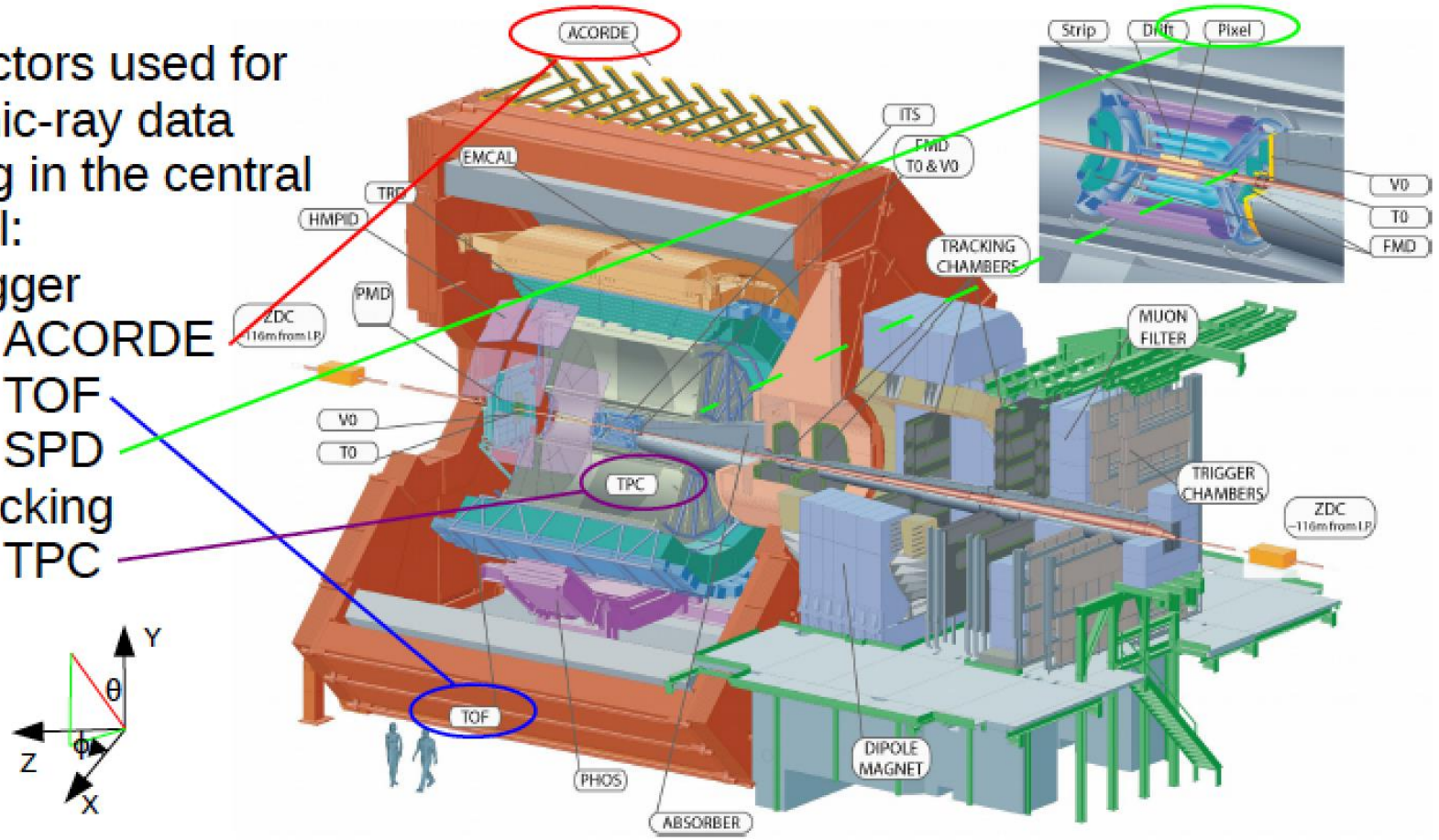
DELPHI Coll., *Astrop. Phys.* **28** (2007) 273

LEP detectors @ CERN have been used to study cosmic muons and in particular muon bundles passing the detectors.
These results were not understood at the time (even assuming pure Fe)

ALICE Detectors for Cosmic Rays

Detectors used for cosmic-ray data taking in the central barrel:

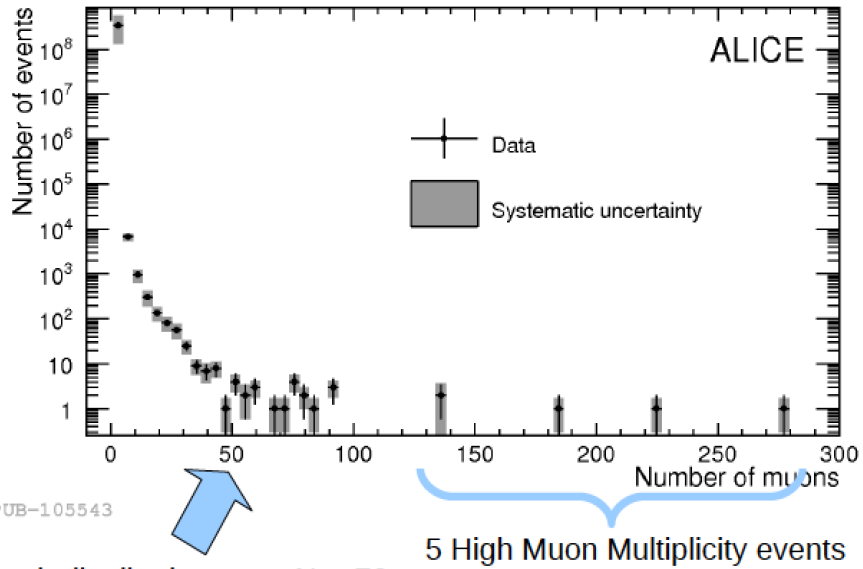
- Trigger
  - ACORDE
  - TOF
  - SPD
- Tracking
  - TPC



- 2010-2013 Recorded 30.8 days of cosmic triggers: ~7.5K events with > 4 μ's
- 2015-2018 63 days collected, including high mult. Trigger. Now being analyzed

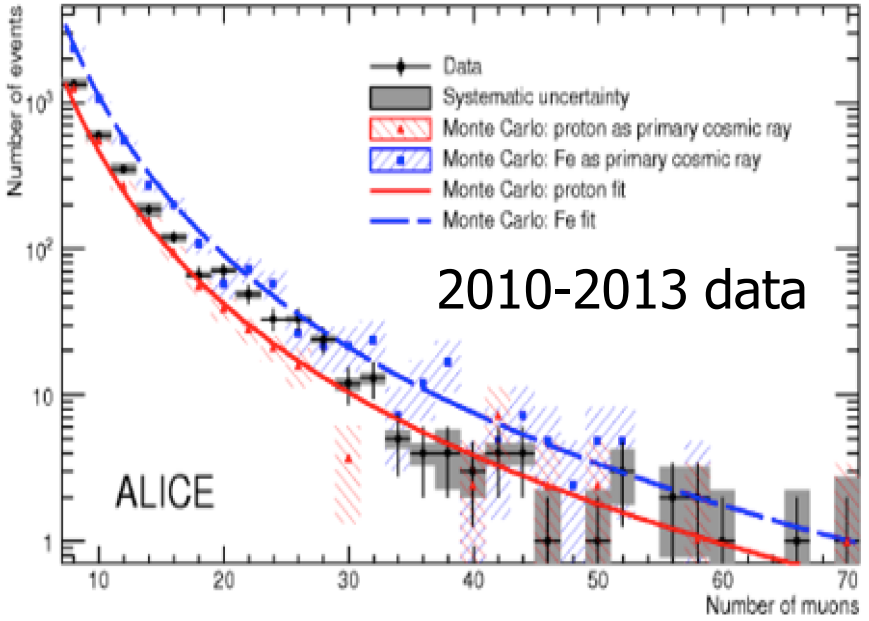
Muon Multiplicity Distribution

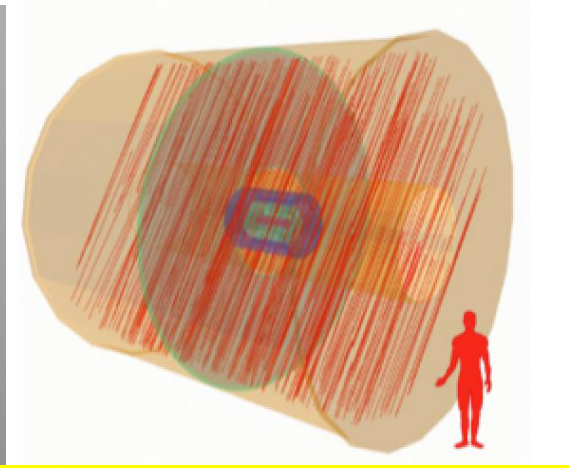
ALICE Coll., *JCAP* **01** (2016) 032



Smooth distribution up to N_μ ~70

5 High Muon Multiplicity events (defined when N_μ >100)



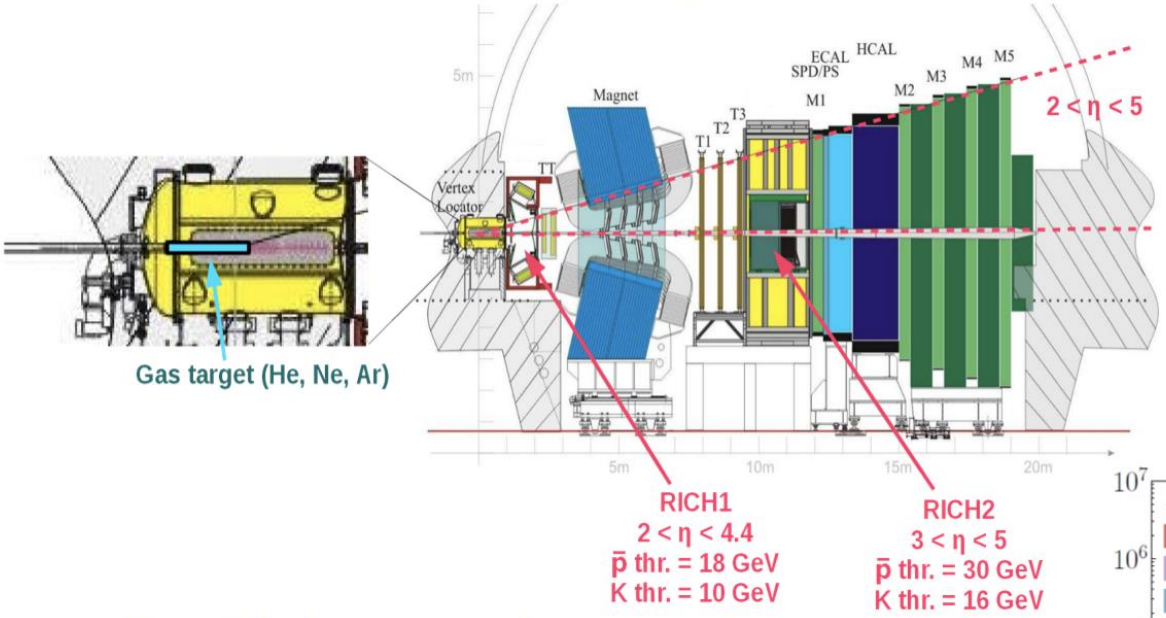


HMM events	CORSIKA 6990 QGSJET II-03		CORSIKA 7350 QGSJET II-04		Data
	p	Fe	*p*	Fe	
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [x10^{-6} Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (syst+stat) (%)	25	25	22	28	49

The observed rate is consistent with the predictions of CORSIKA 7350 with QGSJET II-04 model using pure Fe primary composition and energy >10^{16} eV

LHCb Fixed Target Data

LHCb as a fixed target experiment, thanks to the SMOG internal gas target



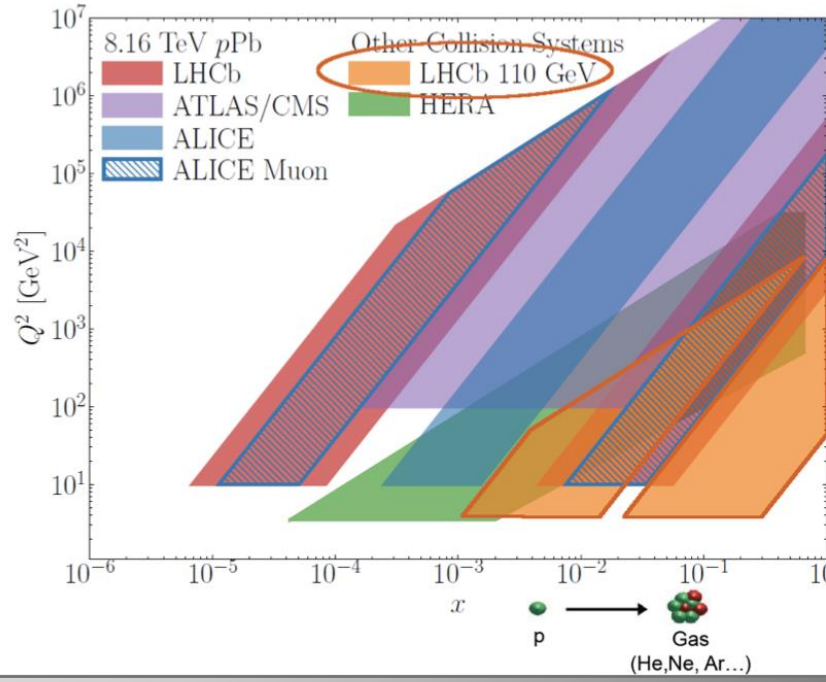
JINST 3, (2008) S08005

Int.J.Mod.Phys.A30 (2015) 1530022

Use "fixed target geometry" for… fixed target physics!

- pA collisions at unique energy scale

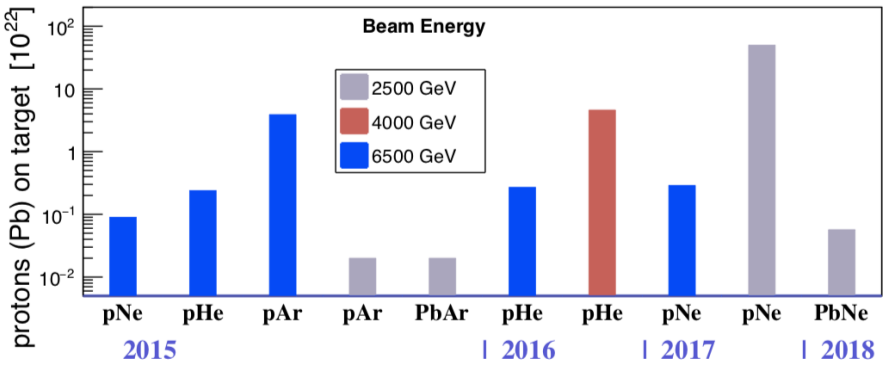
  $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV
- Unique coverage for (n)PDF at large x
- Exploiting LHCb specific features
  - forward geometry
  - extreme vertexing performance + complete particle identification : ideal for heavy flavours
- Possible targets (so far): He, Ne, Ar



LHCb Fixed Target Data

SMOG data samples

Final summary of fixed-target samples acquired with SMOG in Run 2



$$\int \mathcal{L}dt \sim 5\ \mathrm{nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\mathrm{mbar}} \times \mathrm{Exp\_Efficiency}$$

Largest sample (pNe 2017)
$\sim 100\ \mathrm{nb}^{-1}$

Main physics goals:

- charm production to investigate nuclear effects and (n)PDF at large x;
- studies of hadron production in novel kinematic regime and collision systems (notably proton - Helium), bringing crucial inputs to cosmic ray physics.

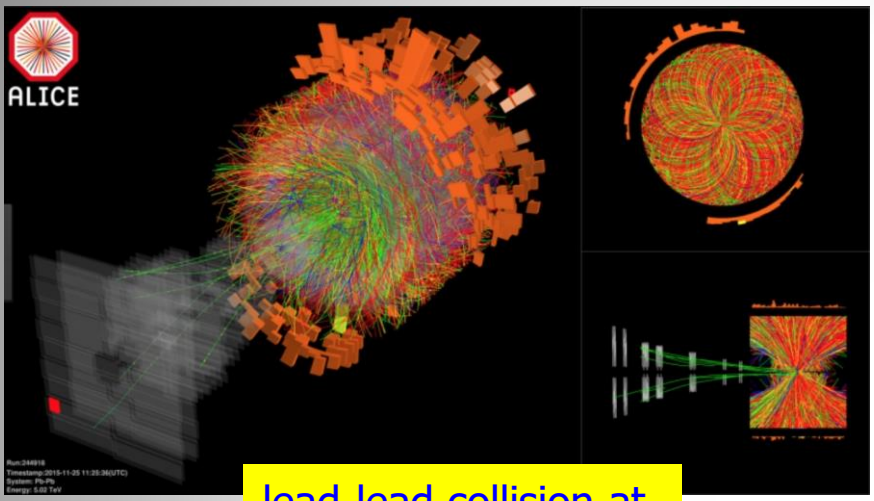
First two physics results published during the last year:

antiprotons in pHe, PRL 121 (2018), 222001

charm production in pHe and pAr, PRL 122 (2019) 132002

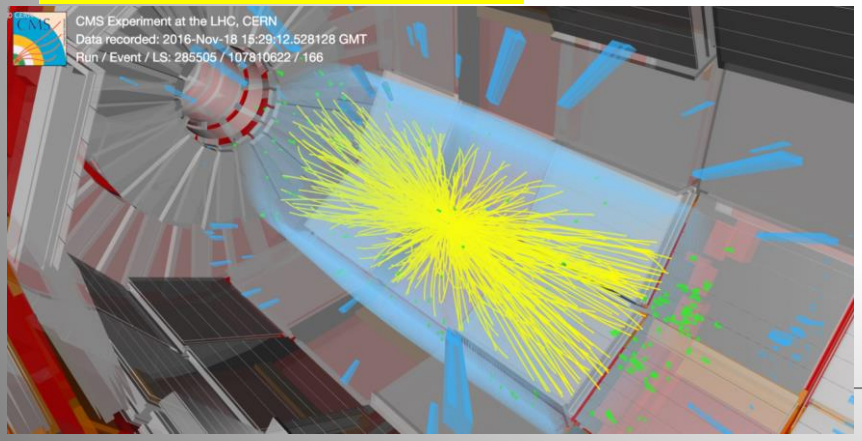
Upgrade planned for Run 3 with more targets (eg Nitrogen, Oxygen, Hydrogen, Deuterium…) and 100 times higher density (storage cell)

pp, pPb, PbPb and XeXe at the LHC

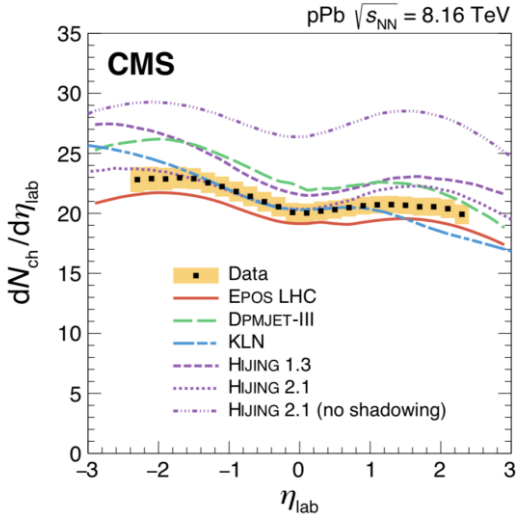


lead-lead collision at
5 TeV/nucleon

proton-lead collision at
8.2 TeV/nucleon

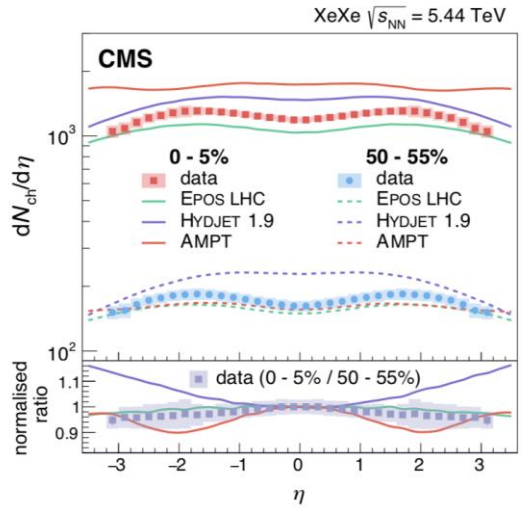


Many particle production results available by ALICE, CMS,ATLAS and LHCb



p-Pb

examples



Xe-Xe

Summary

- LHC has lots of data at 7,8, and 13 TeV. 14 TeV is next!!
- Many measurements are made which are useful for CR physics model tuning. LHC data has impact on these tunes.

Model	SIBYLL 2.1			QGSJET01			QGSJETII			EPOS 1.99		
$\sqrt{s}$ (TeV)	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7
σ_{inel}	✓	⇑	⇑	✓	✓	✓	✓	⇑	⇑	✓	✓	✓
$dN_{ch}/d\eta\|_{\eta=0}$	✓	✓	✓	✓	✓	✓	✓	✓	⇑	✓	⇓	⇓
$P(N_{ch}<5)$	⇑	⇑	⇑	⇑	⇑	⇓	⇑	⇑	⇑	✓	✓	✓
$P(N_{ch}>30)$	⇑	✓	⇑	✓	⇓	⇓	✓	✓	⇑	⇓	⇓	⇓
$\langle p_\perp \rangle$	✓	⇓	⇓	⇑	⇑	✓	⇑	⇑	⇑	✓	✓	✓

D. d'Enterria (2011)

- There are no doubt other measurements which can or should be done. Input welcome! Lots of data on tape!
- ALICE & other new LHC experiments for CR measurements?
- pPb, PbPb, XeXe, collisons on tape. Oxygen plans for Run-III
- SMOG2 approved for more fixed target data with LHCb

Happy 20th Anniversary to the Pierre Auger Observatory

Backup

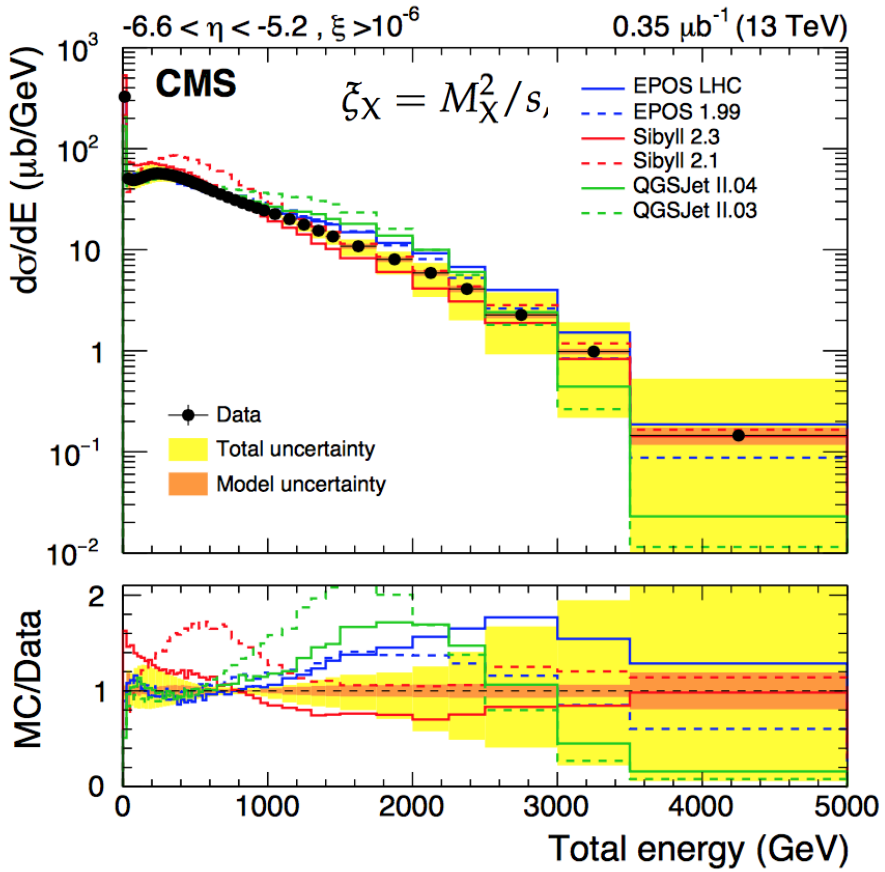
Event Characteristics in the Forward Region

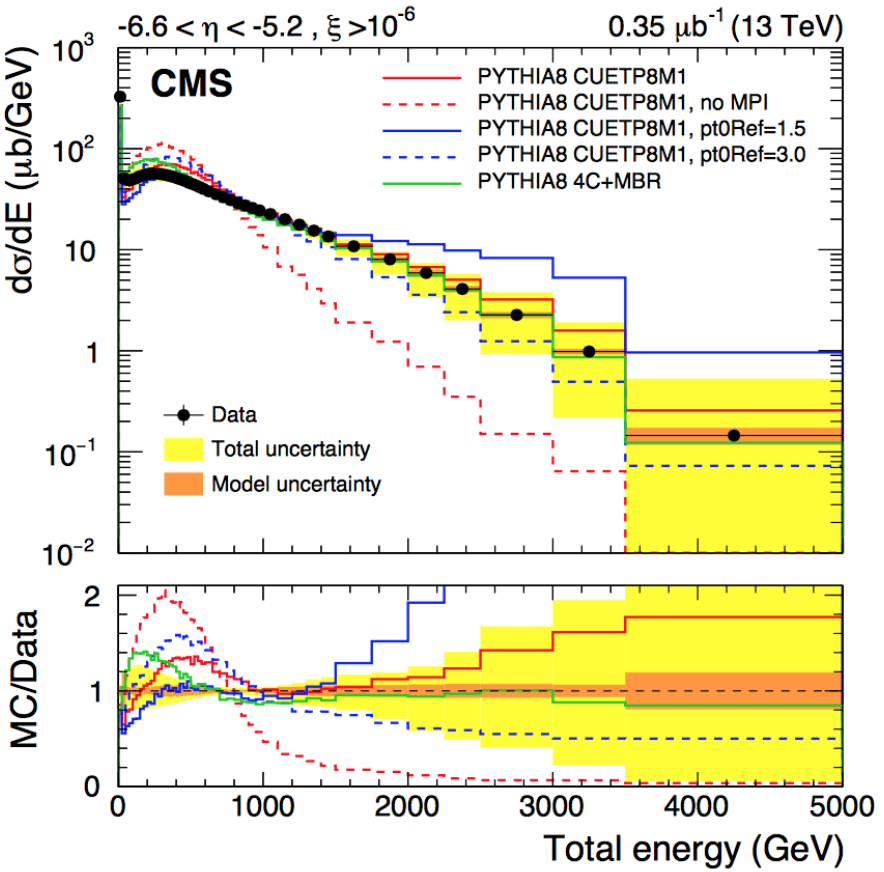
Energy Flow in the extended forward region of CMS

arXiv:1701.08695

Cosmic ray models

Pythia variations

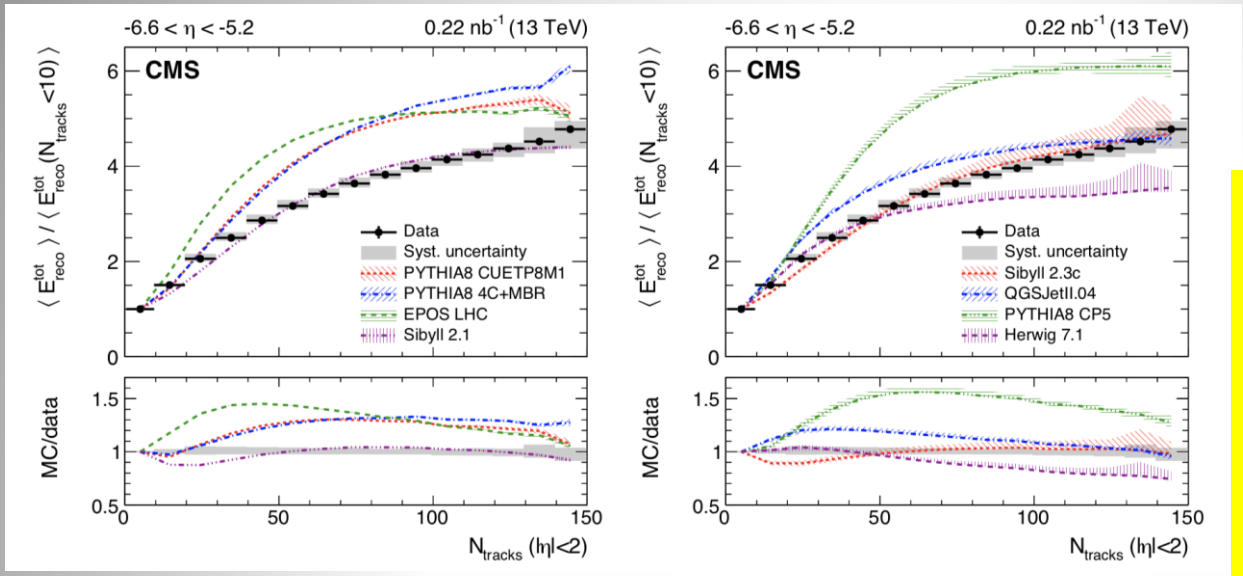


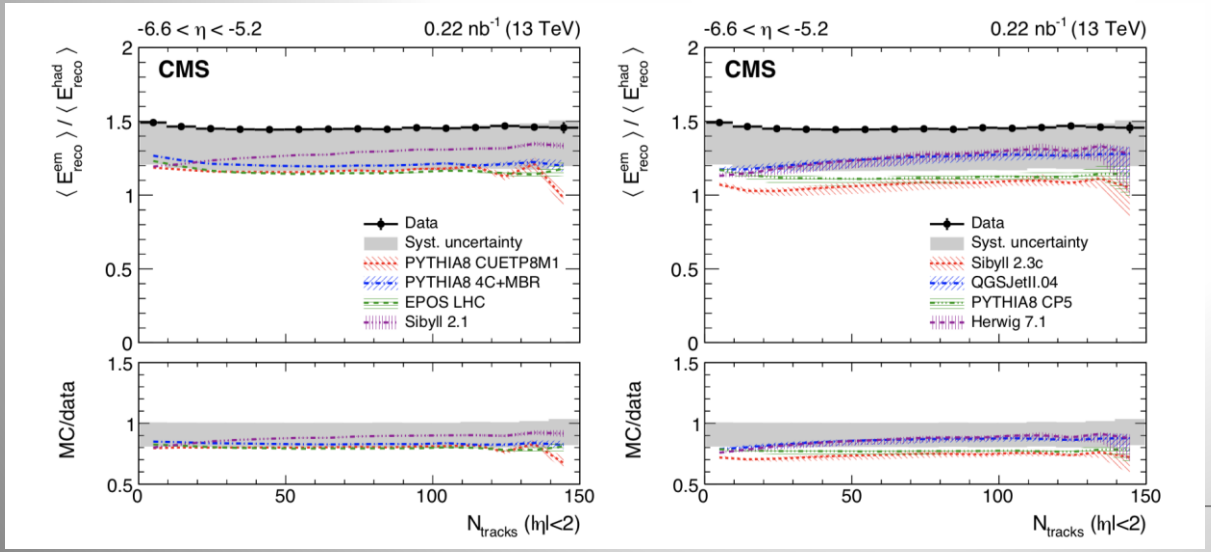


Pseudorapidity ranges: -6.6< η < -5.5

Stable particle results

Event Characteristics in the Forward Region





arXiv:1908.01750

Forward energy flow
$-6.6<\eta<-5.2$
as function of the central track multiplicity in region $|\eta|<2$

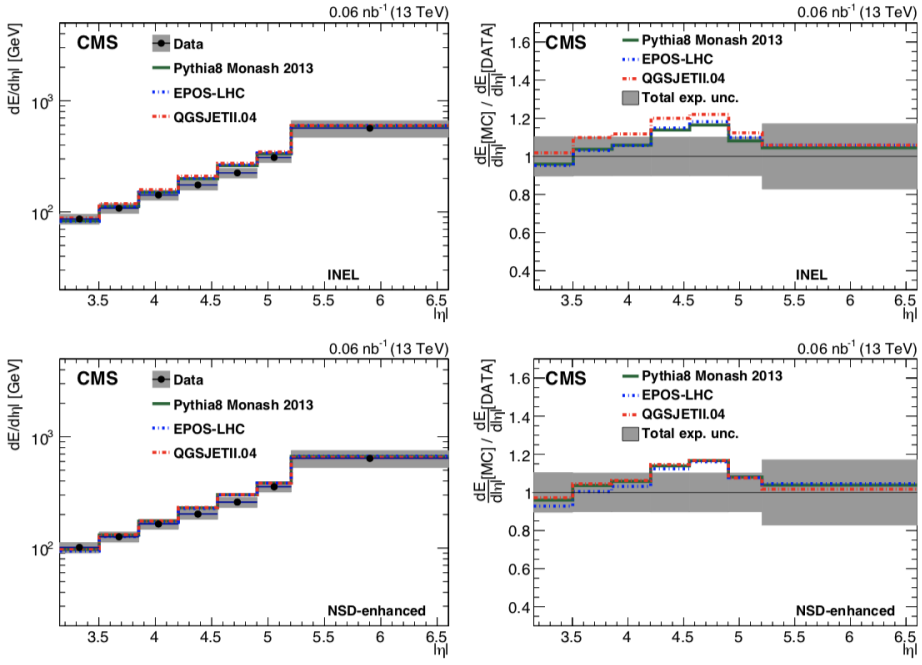
Total energy and relative EM/HAD fraction

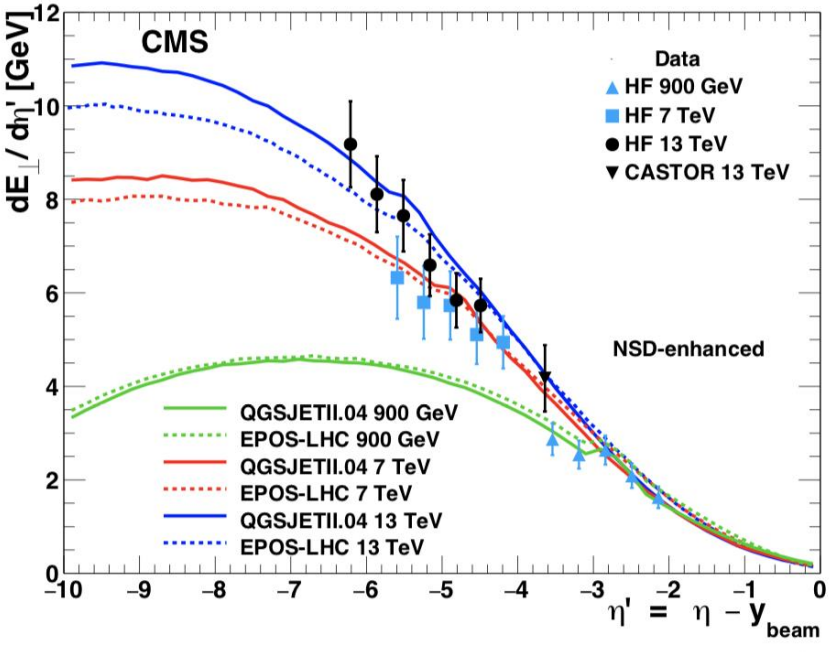
Compared to CR models:
Larger EM fraction in data compared to the models

Event Characteristics in the Forward Region

- Energy density as function of the pseudo-rapidity in 3.15 <|η|<6.6 for collisions at 13 TeV, and comparison with lower energies
- Compared with models used in cosmic ray physics for inelastic and non-single diffractive selected events

arXiv:1812.04095





Check limited fragmentation hypothesis

Standard Model Measurements

Grand Summary: The Standard Model works very well at 13 TeV!!