Hadronic interaction at LHC: Review for the LHCf and air shower related measurements

Takashi Sako

(ICRR, Univ. of Tokyo)

History? No, +Future

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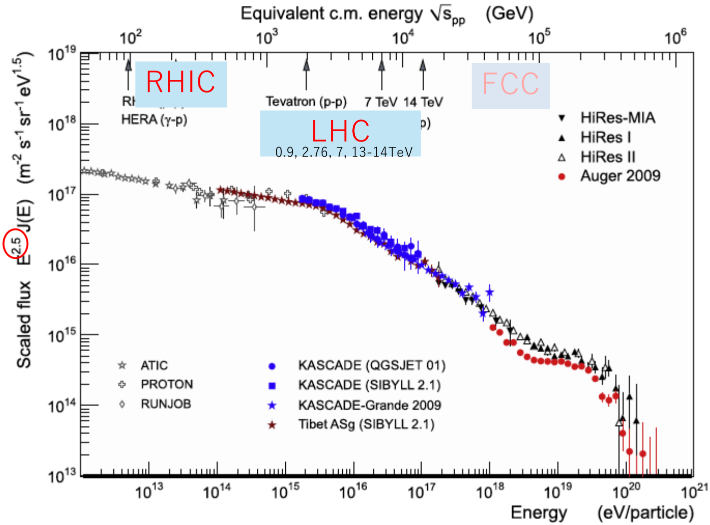
Cosmic-ray spectrum and collider energy

(D'Enterria et al., Astropart. Phys., 35,98-113, 2011)



In CMS

$E, m, \vec{p}$ ⟶ ⟵ $E, m, -\vec{p}$

$$\sqrt{s_{CMS}} = \sqrt{(E+E)^2 - (\vec{p}-\vec{p})^2} = 2E$$

In Lab

$E_{lab}, m, \vec{p}_{lab}$ ⟶ $m, m, 0$

$$\sqrt{s_{lab}} = \sqrt{(E_{lab}+m)^2 - (\vec{p}_{lab}-0)^2}$$
$$= \sqrt{2m(m+E_{lab})} \cong \sqrt{2mE_{lab}}$$

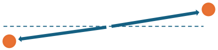
$$\sqrt{s_{CMS}} = \sqrt{s_{lab}} \qquad E_{lab} = \frac{2E^2}{m} = 2\gamma E$$

In case of LHC max energy (E=7TeV),

$$E_{lab} = 2\times 7000 \times 7TeV \cong 1\times 10^{17} eV$$

What do we want to measure, what can we measure at the colliders?

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$



- very small scattering angle
- not directly related to the shower development (no energy transfer)
- **dedicated forward detectors** are required

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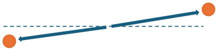
$$\sigma_{diffractive} + \sigma_{non-diffractive\ (ND)}$$



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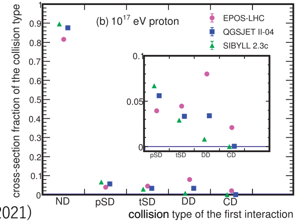
- particles are produced into the beam direction
- small number of particles **with high energy**
- important to determine the **shower core** structure
- **dedicated forward detectors** are required

- particles are produced in **wide angle**
- large number of particles with **low energy**
- related to the shower spread
- measured by the **central General Purpose Detectors**

(Theoretical definition is strict. In this talk, experimental "diffractive-like" events are discussed.)



Ohashi et al., PTEP (2021)

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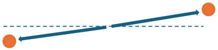

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$$\frac{d\sigma_{ela}}{dt}$$

Differential cross sections as a function of kinematic variables of final state particles

- particles are produced into the beam direction
- small number of particles **with high energy**
- important to determine the **shower core** structure
- **dedicated forward detectors** are required

$$\frac{d\sigma}{dE\,d\eta}$$

what is this?

(Theoretical definition is strict. In this talk, experimental "diffractive-like" events are discussed.)

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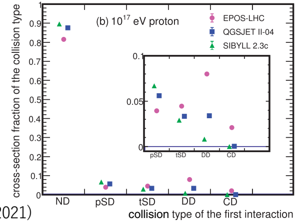


Ohashi et al., PTEP (2021)

$$\frac{dN}{d\eta} \quad \frac{dE}{d\eta}$$

Rapidity (y) and pseudorapidity (η) !? are your friends from today

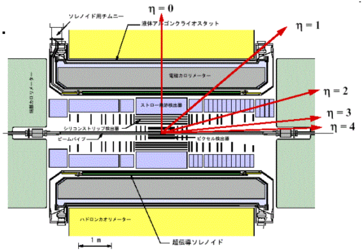
- What we want to measure is : $\frac{d^3\sigma}{dp_x dp_y dp_z}$ (z is along the beam direction)
- Because of a symmetry around the beam direction : $\frac{d^2\sigma}{dp_T dp_z}$ (p_T momentum transverse to z)
- p_T is Lorentz invariant but p_z is not. Any **Lorentz invariant variable** related to p_T??

- rapidity is defined as : $y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right)$
- In $E \rightarrow E', p_z \rightarrow p_z'$ transform, $y' = y + \frac{1}{2} ln\left(\frac{1+\mathrm{B}}{1-\mathrm{B}}\right)$ (B : relative velocity/c of two frames)
- y is NOT Lorentz invariant, but $\boldsymbol{dy}$ **IS Lorentz invariant** $(dy' = dy)$.

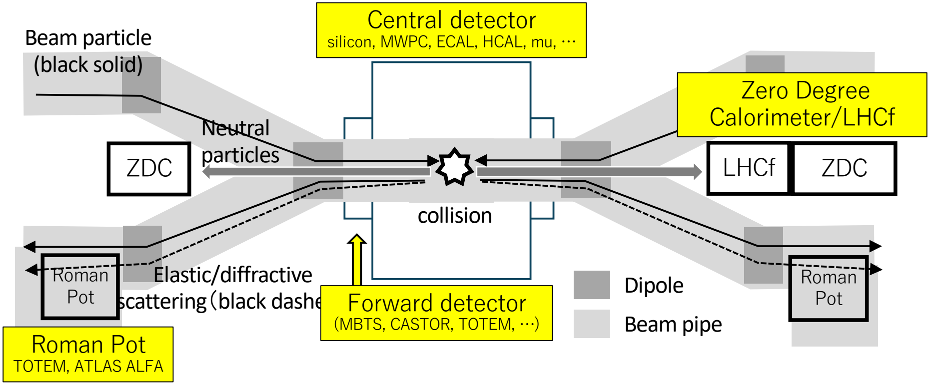
- $\frac{d^2\sigma}{dp_T dy}$ is a Lorentz invariant cross section including all kinetic information.

- Because $\frac{dy}{dp_z} = \frac{1}{E}$, $E\frac{d^2\sigma}{dp_T dp_z}$ is also a Lorentz invariant cross section.

- When $E \gg m$, $y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right) \sim -ln\tan\frac{\theta}{2} \equiv \eta$: pseudorapidity
  - corresponding to the angle
  - $|\eta| \lesssim 2$: central region, $2 \lesssim |\eta| \lesssim 5$: forward, $5 \lesssim |\eta|$: very forward

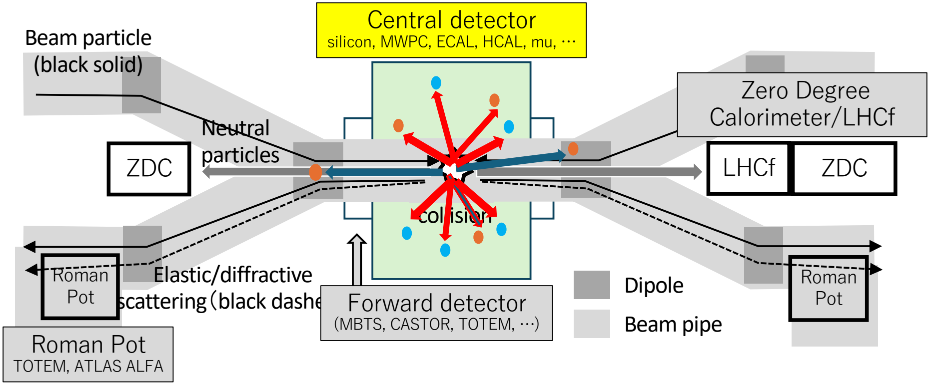


Detectors surrounding the collision point



- **Charged particles with large angles** are detected by the central general purpose detectors (main detector of ATLAS and CMS).
- **Charges forward particles** are detected by the forward calorimeters and counters such as CMS CASTOR, Minimum Bias Trigger Scintillators and TOTEM T1/T2.
- **Neutral forward particles** are detected by the zero-degree forward calorimeters such as ZDC and LHCf.
- **Elastically scattered particles** are detected by the Roman pot detectors inserted in the beam pipe such as TOTEM RP and ATLAS ALFA.

Detectors surrounding the collision point



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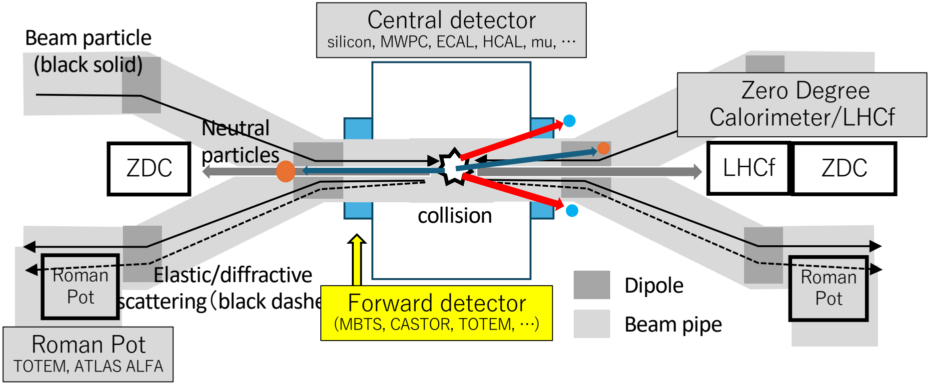

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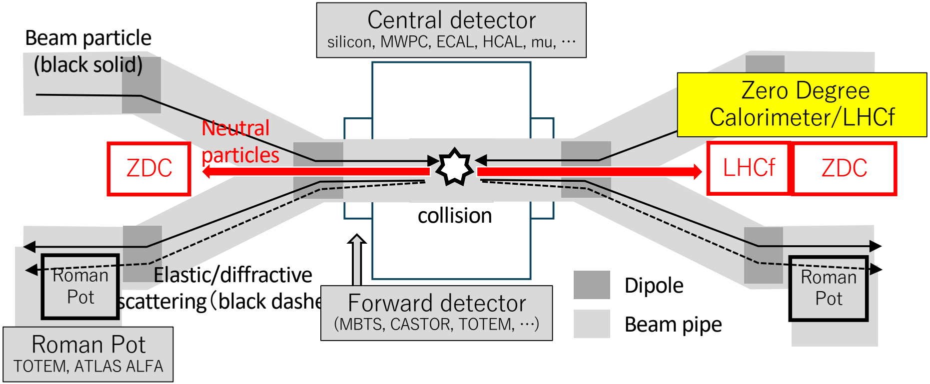

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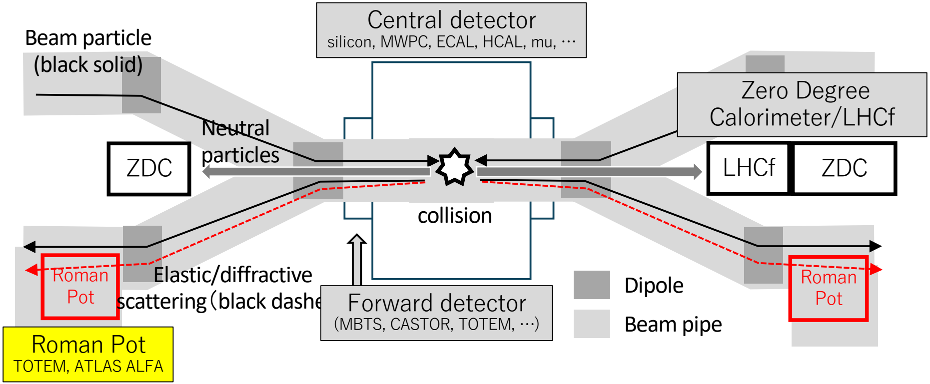

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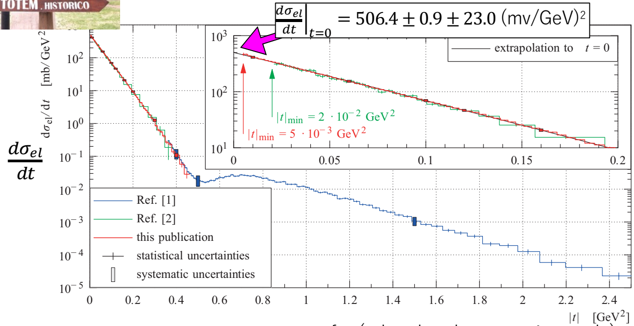
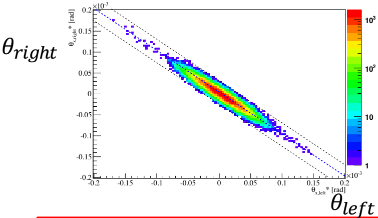
$\sigma_{tot}, \sigma_{ela}, \sigma_{ine}$ measurements by TOTEM

TOTEM Collaboration, EPL, 101 (2013) 21002



transverse momentum transfer (related to the scattering angle)



$\sigma_{el} = \int \frac{d\sigma_{el}}{dt} dt = 25.43 \pm 0.03 \pm 1.07\text{(mb)}$

[Optical theorem]

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$$

$\rho = 0.141 \pm 0.007$
(COMPETE collaboration)

$\sigma_{tot} = 98.58 \pm 2.23\text{(mb)}$

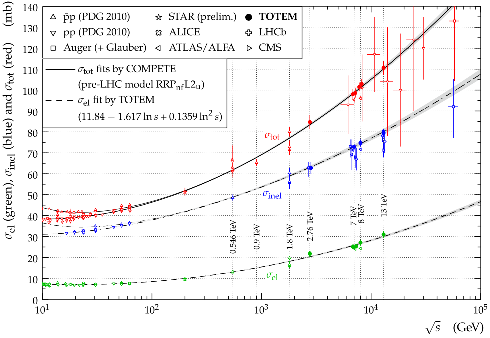
$\sigma_{ine} = \sigma_{tot} - \sigma_{ela}$
$= 73.15 \pm 1.26$ (mb)

- Precise measurement of $\frac{d\sigma_{el}}{dt}$ by roman pot=> σ_{el}
- Extrapolation to t=0 gives $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$
- Optical theorem relates $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$ to σ_{tot}
- $\sigma_{ine} = \sigma_{tot} - \sigma_{ela}$

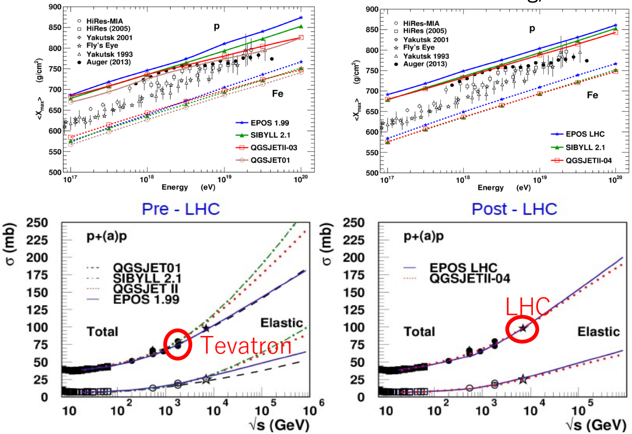
- Measurement of elastic scattering gives us the information of inelastic scattering important for air shower development

Impact on AS physics

TOTEM Collaboration, EPJC (2019) 79:103



T.Pierog, HESZ2015



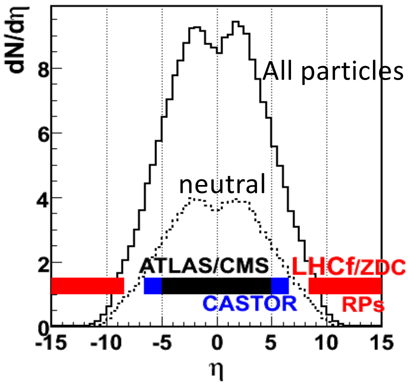
- One of the best successes of LHC to the air shower physics
- How "post-LHC" models improve the prediction power

Particle production at LHC

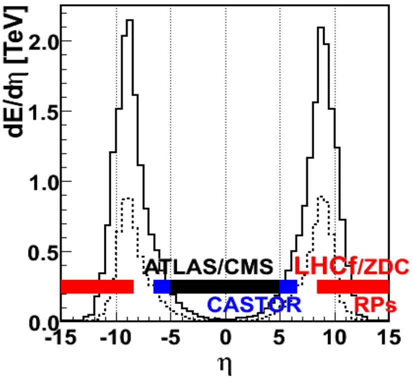
multiplicity and energy flux at LHC 14TeV collisions

pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$

Multiplicity

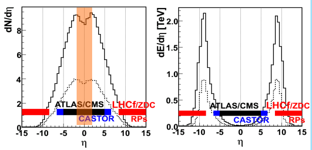


Energy flux

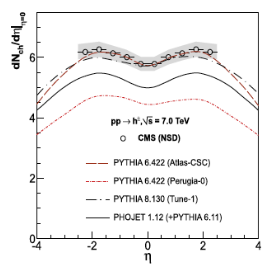


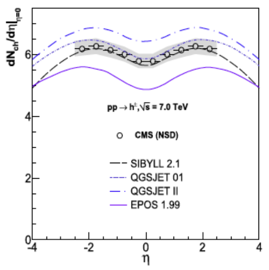
- Most of the particles are produced into central (ND events)
- Most of the energy flows into **forward** **(diffractive-like events)**

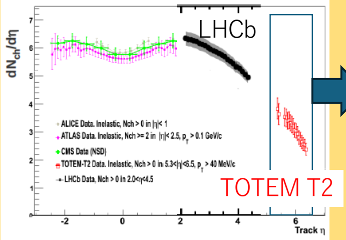
Multiplicity

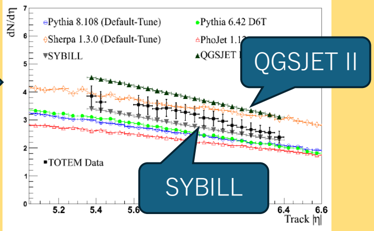


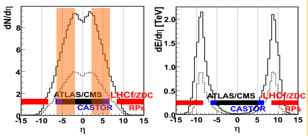
D.D'Enterria et al., Astropart. Phys., 35 (2011) 98-113





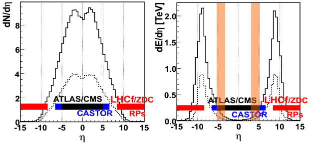




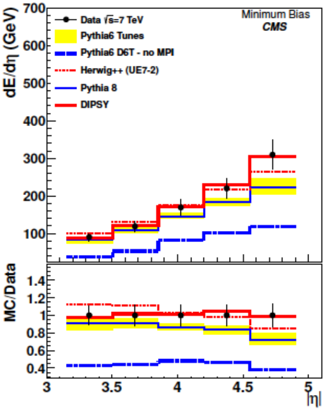


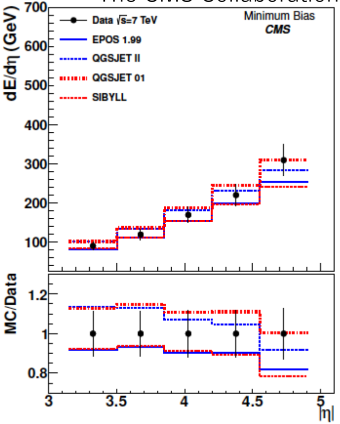
- Early LHC results were described by pre-LHC CR models than the HEP models

Forward Energy Flow
(Hadronic Forward Calorimeter)



The CMS Collaboration, JHEP, 11 (2011) 148





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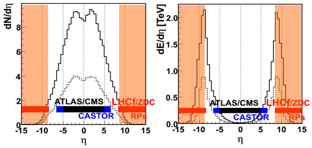
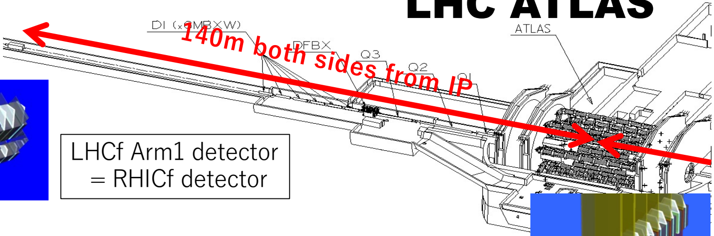
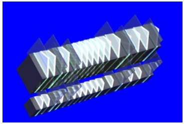


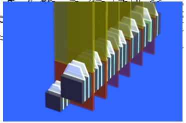
LHC forward

LHC ATLAS





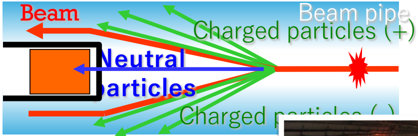
LHCf Arm1 detector
= RHICf detector



LHCf Arm2 detector

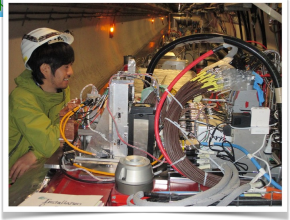
Location

- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo rapidity $\eta > 8.4$

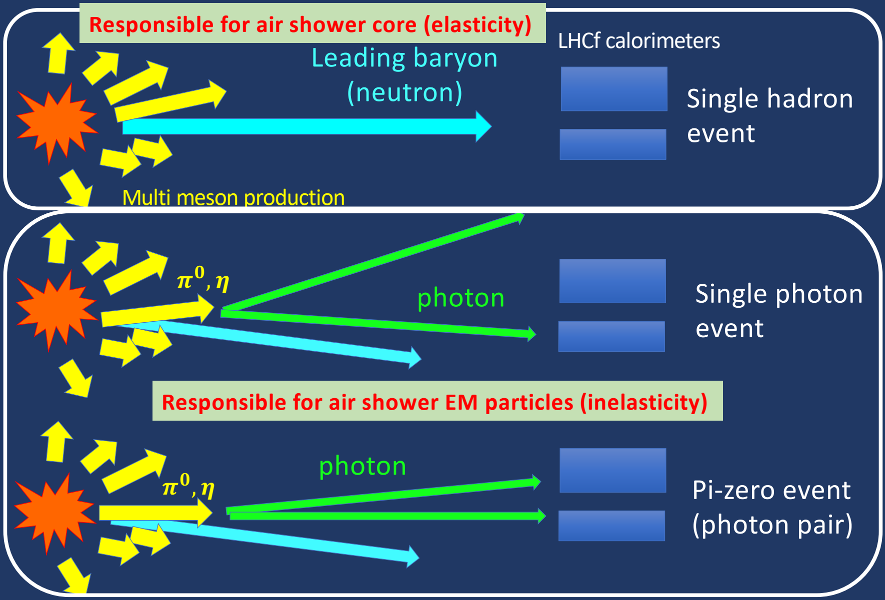


Detectors

- Sampling and positioning calorimeters
- Two towers, 20mmx20mm, 40mmx40mm (Arm1) , 25mmx25mm, 32mmx32mm(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

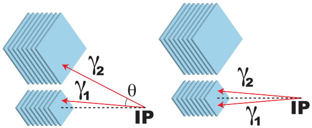


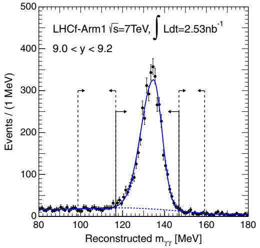
Event categories of LHCf

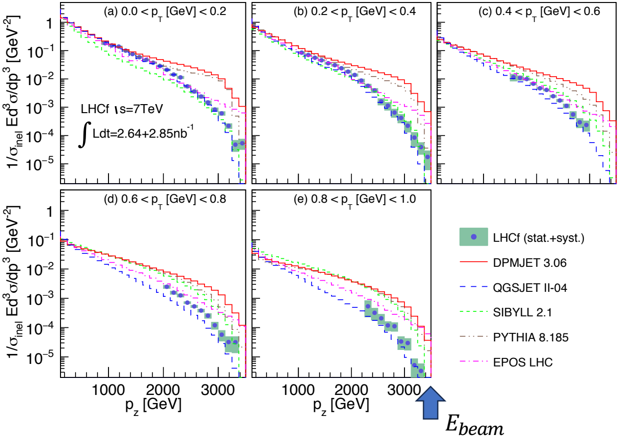


$\pi^0 p_z$ spectra in $\sqrt{s} = 7\mathrm{TeV}$ p-p collisions

LHCf Collaboration, PRD 94, 032007 (2016)



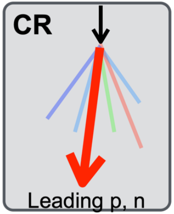




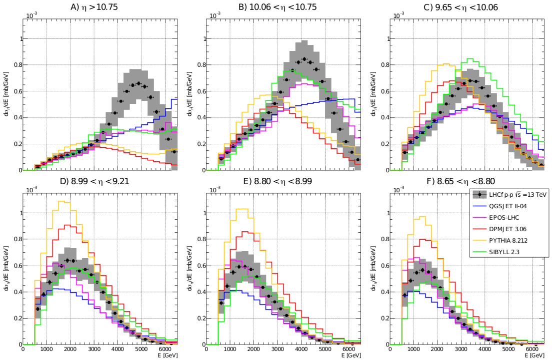
- Experimental result is between EPOS-LHC and QGSJET II-04
- Cross section with $E_{\pi^0} \sim E_{beam} = 3.5TeV$ => γ-like proton shower unavoidable

Forward neutrons by LHCf (elasticity)

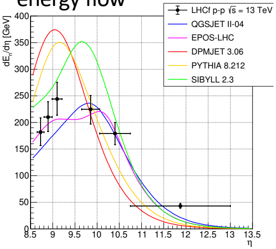
O. Adriani et al., JHEP07 (2020) 016



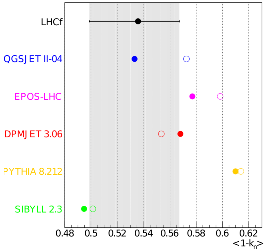
energy spectra



energy flow



inelasticity

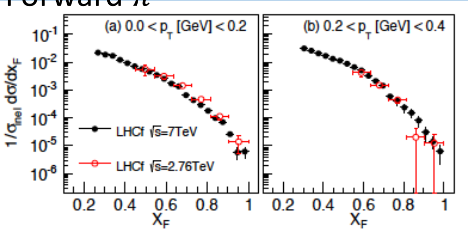


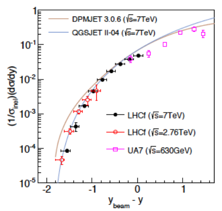
- ● neutron inelasticity
- ○ all particles inelasticity

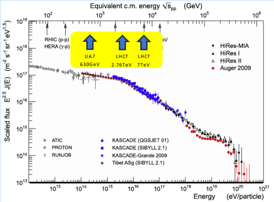
- Energy of the leading baryon (elasticity) determines the penetrating power of shower core.
- Inelasiticity ($k = 1 - E_{leading}/E_{CR}$)
- Energy spectra show a large model variation.
  - Some models (QGS, DPM) are trying to tune to this result
- Integrals (energy flow and inelasticity) show good agreements with EPOS and QGS

$\sqrt{s}$ dependence

Forward π^0

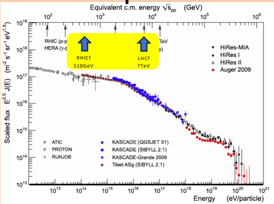


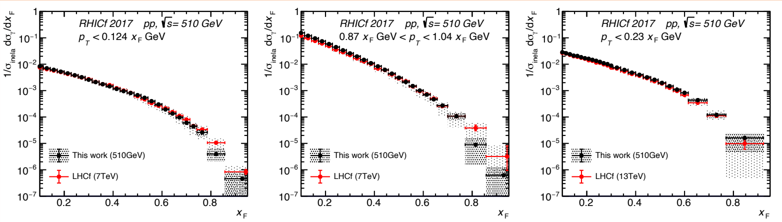




LHCf Collaboration, PRD 94, 032007 (2016)

Forward photon





RHICf Collaboration, arXiv:2203.15416

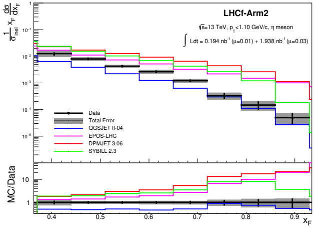
- Very weak dependence on the collision energy
- Smooth extrapolation to the UHECR energy range is expected (?)

Quick summary

- σ_{ine} measurements led successful post-LHC models and a less model-dependent elongation rate predictions.
- CR models are recognized to have a reliable prediction power at the LHC energies than the other HEP models.
- First successful very forward measurements by LHCf.
- **Good News!** : Generally, CR models show good agreements with measurements.
- **Bad News** : How can we solve the muon puzzle?

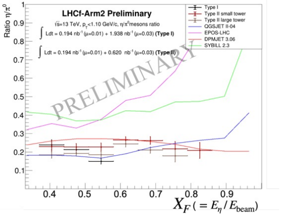
- What can we do next?
  - Heavy (strange) flavor hadrons (so far, mostly p, n, π) => different behaviers in AS
  - Correlation of multiple particles => process-by-process study
  - p-O collisions => First "Air-CR" collisions at colliders

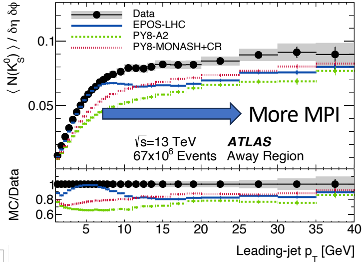
strange hadron productions



LHCf Collaboration, JHEP 10 (2023) 169.

very forward η production, η/π^0 ratio

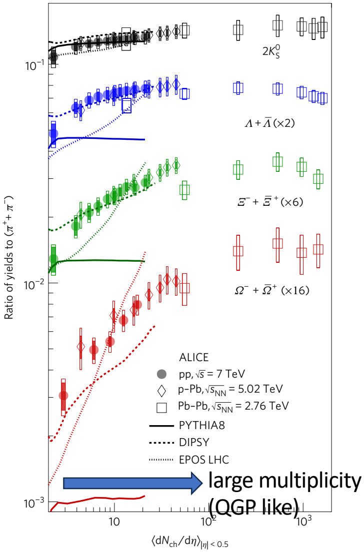




ATLAS Collaboration, EPJC submitted; CERN-EP-2024-105 (2024).

central K production in the Minimum Bias events

central $K,\Lambda,\Xi,\Omega/\pi^{\pm}$ ratio

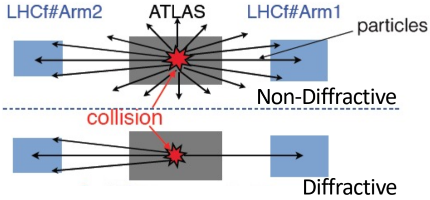


ALICE Collaboration, Nature Phys., 13 (2017).

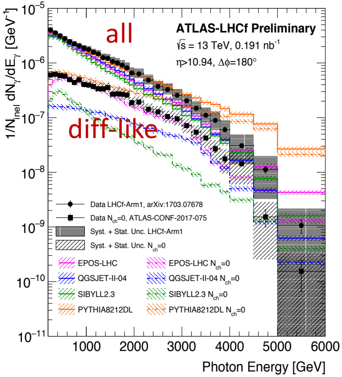
- Cross sections and/or production ratio of η, K, Λ production
- Larger difference than pion production (?)
- Hint to the muon puzzle??

ATLAS-LHCf joint analysis
- forward-central correlation -

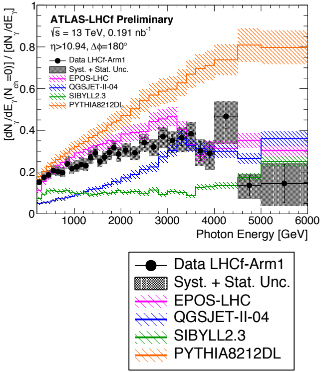
ATLAS-CONF-2017-075



Very forward photons classified with the central activity
LHCf (all; ●+solid lines), LHCf diffractive-like (■+dashed lines)



diffractive-like/ all

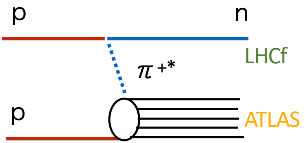


- Using the particle multiplicity in the ATLAS central detectors, LHCf photon events can be classified into diffractive-like and others
- Test models by processes

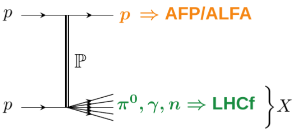
More joint analyses by ATLAS/LHCf

Fisibility study using MC
ATL-PHYS-PUB-2023-024

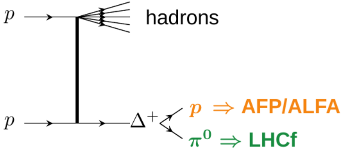
One Pion Exchange (OPE)



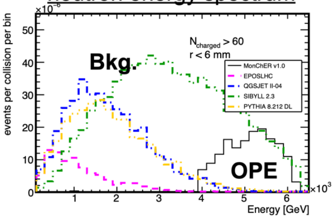
Single diffraction

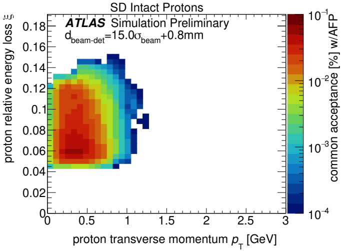


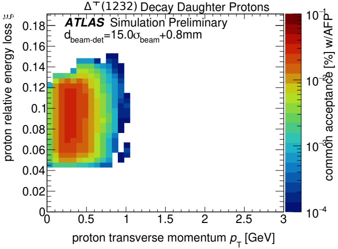
$\Delta^+(1232)$



neutron energy spectrum







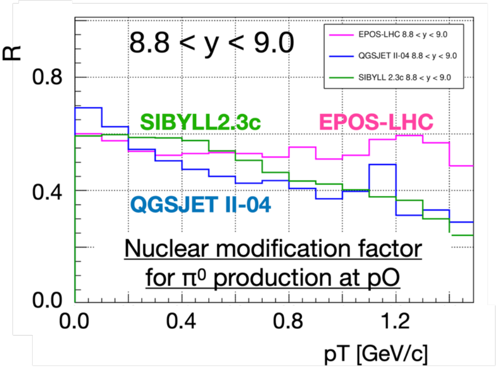
- Test models by processes (more examples)

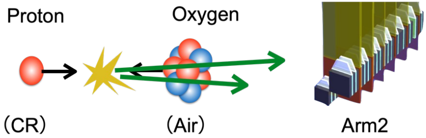
LHC proton-Oxygen collisions

Nuclear Modification Factor

$$R = \frac{\sigma_{pO}}{A\,\sigma_{pp}}$$

A: average number of nucleon collision





Jul 2025

Wk	27	28
Mo	VdM program (30)	O-O & p-O Ions run (7)
Tu		
We	O Ion setting up	
Th		
Fr		
Sa		
Su		

- p-O collision is **scheduled in July 2025**
- Nuclear modification factor depends on the model
- Big effort by Hans Dembinski and supports from the community

First discussion in 2012

first contact during UHECR2012 at CERN => meeting in August

差出人: Django Manglunki <django@cern.ch>
件名: Re: LHCf and light ion in LHC
日時: 2012年8月31日 0:39:19 JST
宛先: Takashi Sako <sako@stelab.nagoya-u.ac.jp>, Simone Gilardoni <Simone.Gilardoni@cern.ch>, Takashi Sako <Takashi.Sako@cern.ch>, Detlef Kuchler <Detlef.Kuchler@cern.ch>, John Jowett <John.Jowett@cern.ch>, Johannes Peter Wessels <j.wessels@uni-muenster.de>, Michaela Schaumann <michaela.schaumann@cern.ch>, Reine Versteegen <reine.versteegen@cern.ch>
Cc: Django Manglunki <django.manglunki@cern.ch>

Dear all,
here's a summary of our discussion, corrections/ comments welcome.
Cheers
Django
==
Preliminary discussion on the feasibility of N–N, p–N and Fe–N collisions in the LHC

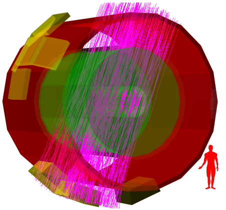
Present:
Sako, Hannes, Detlef, Simone, John, Reine, Michaela, Django.

Introduction by Sako:
The experiment LHCf is motivated to understand the interaction between cosmic-rays and atmosphere, and hence the origin of the cosmic-ray particles up to 10^20 eV. The p-p and p-Pb collisions at LHC give important fundamental information for this study. However, clearly, in the atmosphere the target of the interaction is light nuclei like Nitrogen and Oxygen. The direct measurements of p-N, N–N to Fe–N are very interesting to understand the nuclear effect in the interaction but there are no such experiment carried out using colliders. LHCf is interested in using the LHC as a light ion collider in the future.
Of course, these collisions are not prime target of the LHC science. But is it technically possible? And what is necessary to realize such experiments in future?

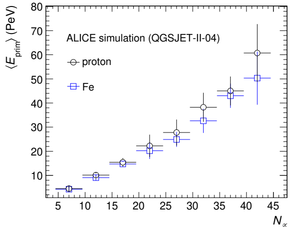
Discussion:
– As there is only one ion source at present, only p–N and N–N can be considered in the near future.
– Production of nitrogen in the ECR source is not a problem as it is a gas, neither is Fe as there are techniques to produce it easily (MIVOC). But afterwards the source needs several weeks to repliably produce Pb in a stable manner.
– LHCf does not need a lot of running time, only a few days, and since it is looking at high cross-section events, the luminosity does not need to be very high.
– ALICE is not interested in other ions than Pb, but an N–N ion run would not take many days out of the LHC programme. It would, however, use a lot of resources from the injectors team. In fact the schedule would be dominated by the setting up and commissioning in the injectors, not by the collisions. Preparation of a N–N run would also take a lot of time from the regular fixed target programme.
– One can imagine to start preparing the source with N in early January, commission the circular accelerators, and have a N–N or p–N run in autumn, before switching to Pb. But then it would take too long for the source to stabilise to have a Pb–Pb run before Xmas. This would only work during a year where there is no Pb–Pb run, or when it is postponed to after Xmas like this year.
– Oxygen on the other hand is also abundant in the atmsophere and could be a viable alternative. It is used in the ECR as a support gas for Pb production. One can consider tuning the source and transport systems for oxygen while preparing for a Pb run, still using Pb in order to keep conditions optimal. A short O–O or p–O run could be compatible with a "normal" collider schedule, possibly in 2020.
– Nitrogen could be used as support gas too, but would be less efficient for Pb production so the idea is not retained.
– In the longer term future, if the medical facility is approved, a switchyard and a second source, able to provide any ion from p to Ne, will be built. It should then be possible to collide Pb–N, or even Fe–N, after 2022.
– As a conclusion, there is no technical show-stopper, and LHCf can go ahead with a letter of intent.

Minutes by Django

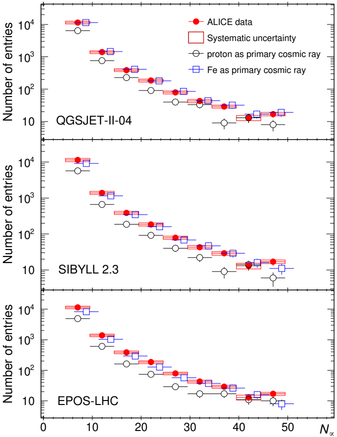
ALICE muon bundle observation



under 80 m.w.e. rock, >16GeV

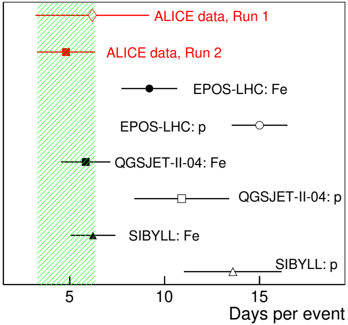


$E_{prim} = 4\times10^{15} \sim 6\times10^{16}$eV



ALICE Collaboration, CERN-EP-2024-263
arXiv:2410.17771.

Event rate of multiplicity>100
$\langle E_{prim} \rangle \sim 10^{17}$eV



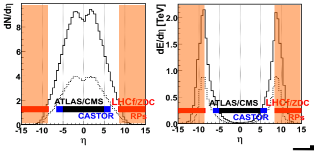
- AS muon measurement by a collider detector
- No AS measurement => no event-by-event energy determination
- Model comparison suggests pure or heavier than Fe => another sign of muon excess?

Summary

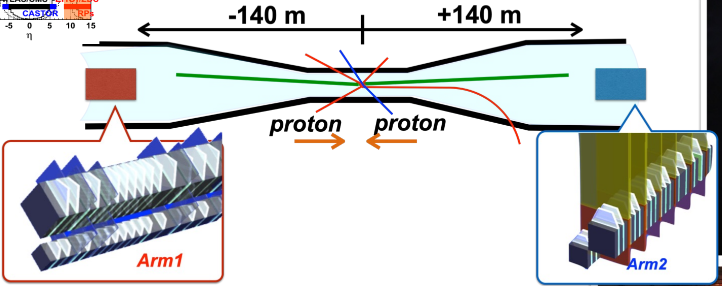
- 15 years have past since the first LHC collisions.
- CR motivated interaction models are widely compared with various measurements and recognized to explain the results better than the HEP models.
- Early LHC results are immediately implemented in the post-LHC models and the AS analyses became less model dependent than before.
- No apparent discrepancy means no hint to solve the muon puzzle raised.
- More analyses (strange hadrons, process specific,…) are on-going.
- First **p-O (O-O) run in 2025** will make next major update of the interaction models.
- CR-HEP collaborations become more important.

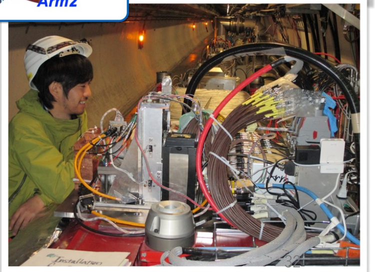
Pierre Auger street at CERN

Backup



LHCf experiment





Location

- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo rapidity $\eta > 8.4$

Detectors

- Sampling and positioning calorimeters
- Two towers, 20mmx20mm, 40mmx40mm (Arm1) , 25mmx25mm, 32mmx32mm(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ