Highlight: Forward Physics (LHCf + FASER)

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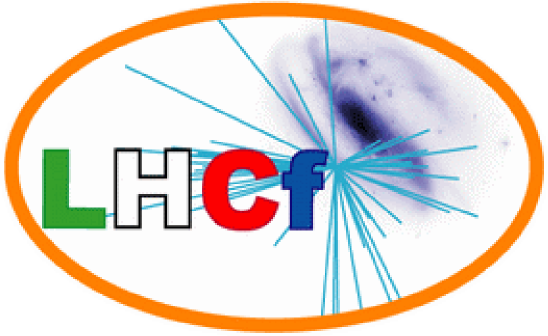
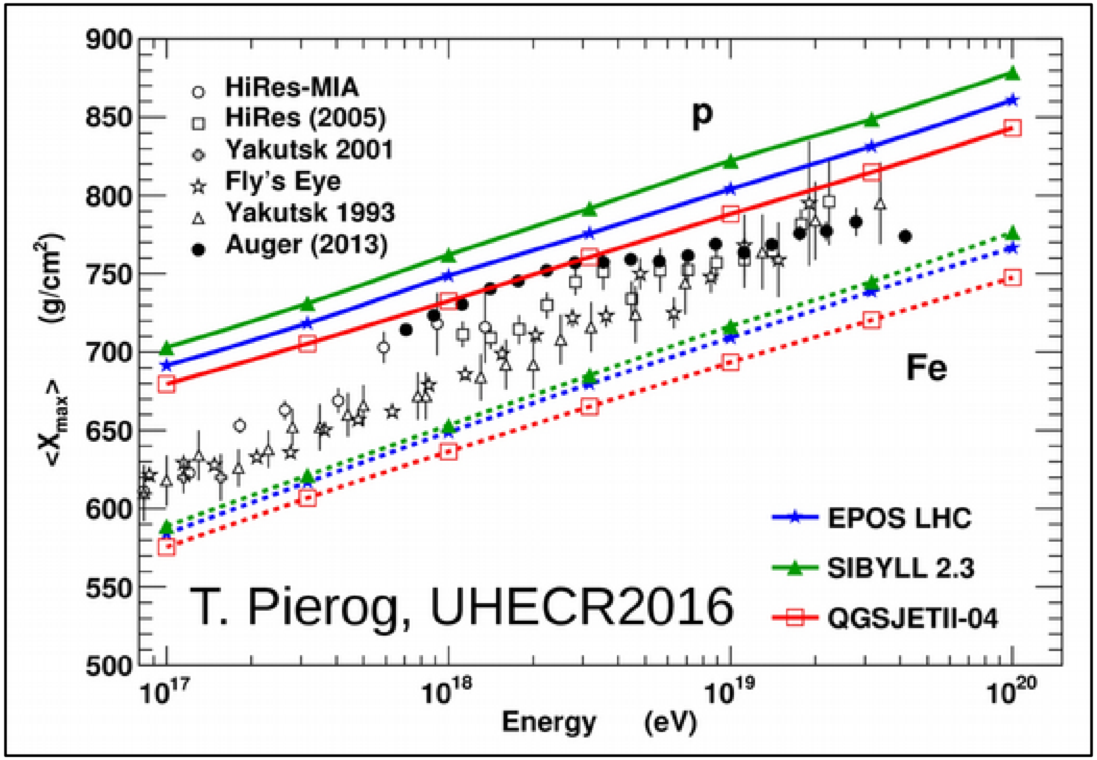
on behalf of the LHCf and FASER collaboration

LHCP 2021
June 7th-12th 2021

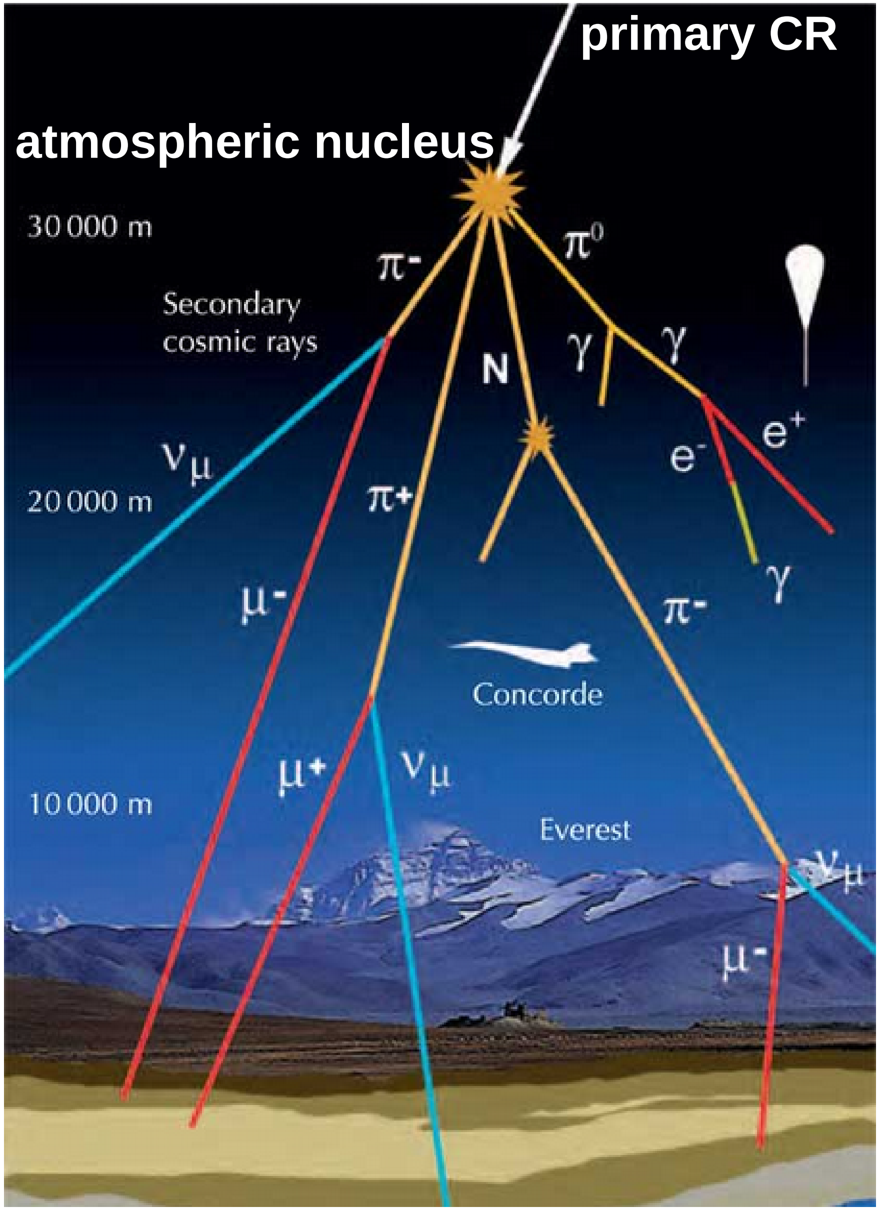

LHCf

Scientific motivation

Determination of **mass composition of Ultra High Energy Cosmic Rays** by indirect measurements are limited by the large uncertainty coming from the ability of **hadronic interaction models to simulate the Extensive Air Showers (EASs)**.



T. Pierog, UHECR2016



The LHCf experiment

EAS Input from LHC:

- Inelastic cross section
- Multiplicity

TOTEM, ATLAS, CMS, ...

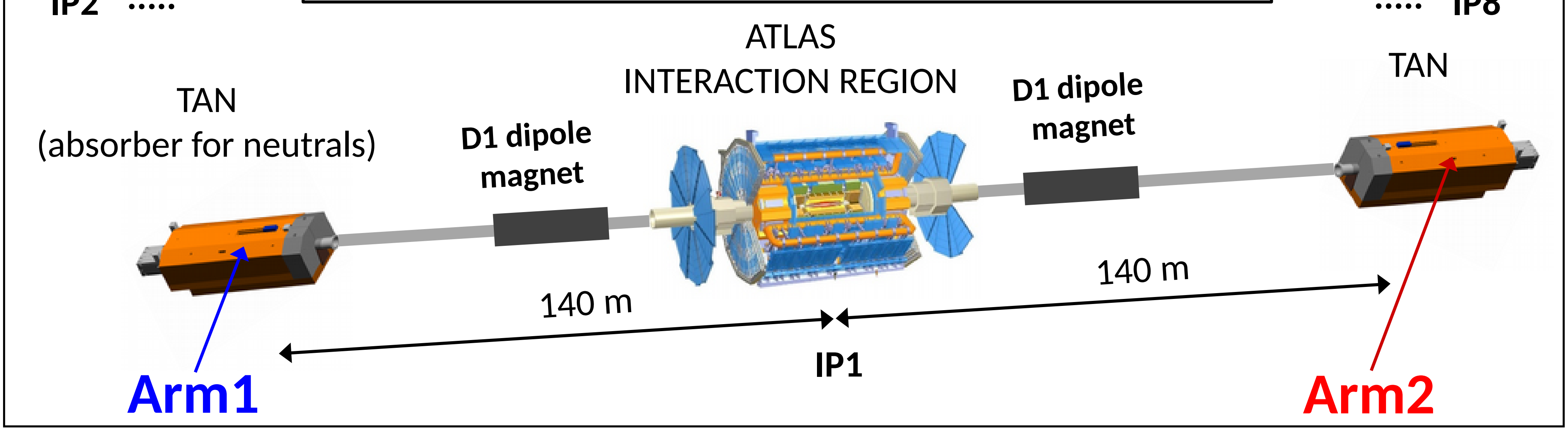
- Forward energy spectrum
- Inelasticity $k = 1 - p_{lead} / p_{beam}$
- Nuclear effects
- Extrapolation to $E > 10^{17}$eV

LHCf

*Neutrons, photons, π^0 in **η>8.4***

Forward region: **high energy** and **low multiplicity** of collision products

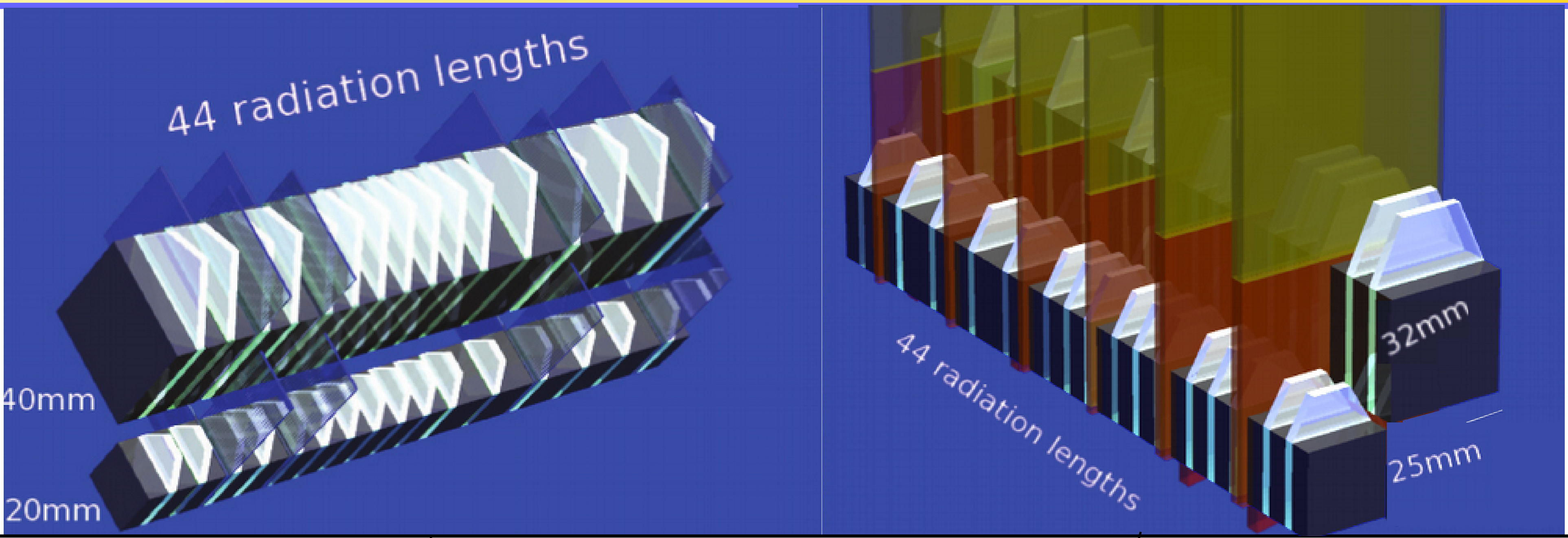
Two detectors installed in the **TAN regions** of IP1



The LHCf detectors

Arm1

Arm2



Two sampling calorimeters

Two towers: 22 tungsten and 16 GSO scintillators layers

Depth: 21 cm, 44 X_0, 1.6 λ_I

Energy resolution:

< 2% (photons)

~ 40% (hadrons)

Towers Size:

20 x 20 and 40 x 40 mm^2

Imaging layers:

4 x-y 1mm GSO bars

Position resolution:

< 200 μm (photons)

< 1 mm (hadrons)

Towers Size:

25 x 25 and 32 x 32 mm^2

Imaging layers:

4 x-y 160μm Si microstrip

Position resolution:

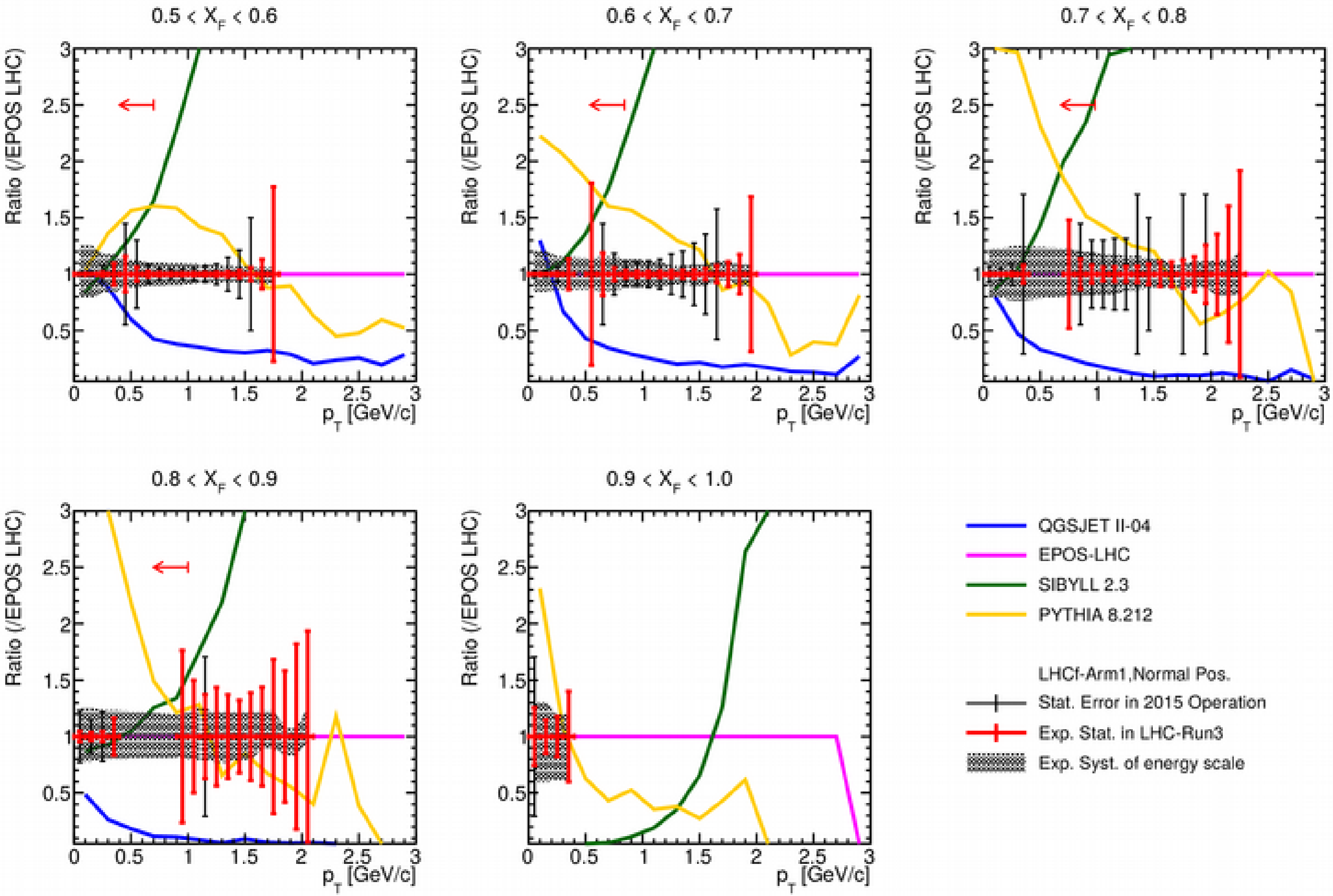
< 40 μm (photons)

< 800 μm (hadrons)

LHCf in Run III

p-p @ 14 TeV

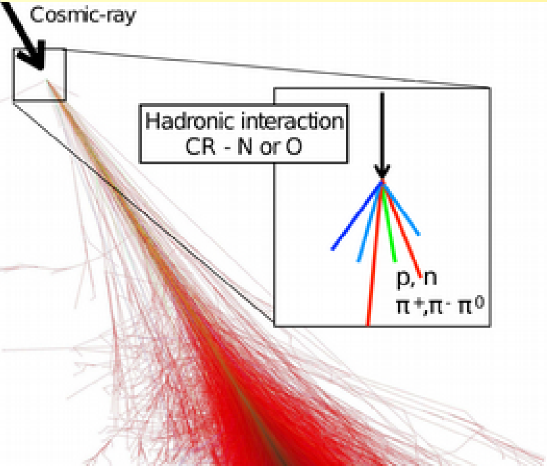
DAQ readout will be faster by a factor of 10 thanks to the new Arm2 silicon electronics based on Gb-Ethernet (~1 Gbps) instead of FOXI-Chip (~100 Mbps) protocol



Operating at L = 10^{29} $cm^{-2}s^{-1}$, in a couple of days LHCf will collect L_{int} = 20 nb^{-1}, *i.e.* a **statistics 10 times larger** than the one obtained from p-p collisions @ 13 TeV.

GOAL: significantly reduce the uncertainty on measurement of forward π^0 production, allowing for a better discrimination between different models.

In addition, it will be possible to detect ~5000 events of η->2γ and ~500 events of K^o_s->4γ



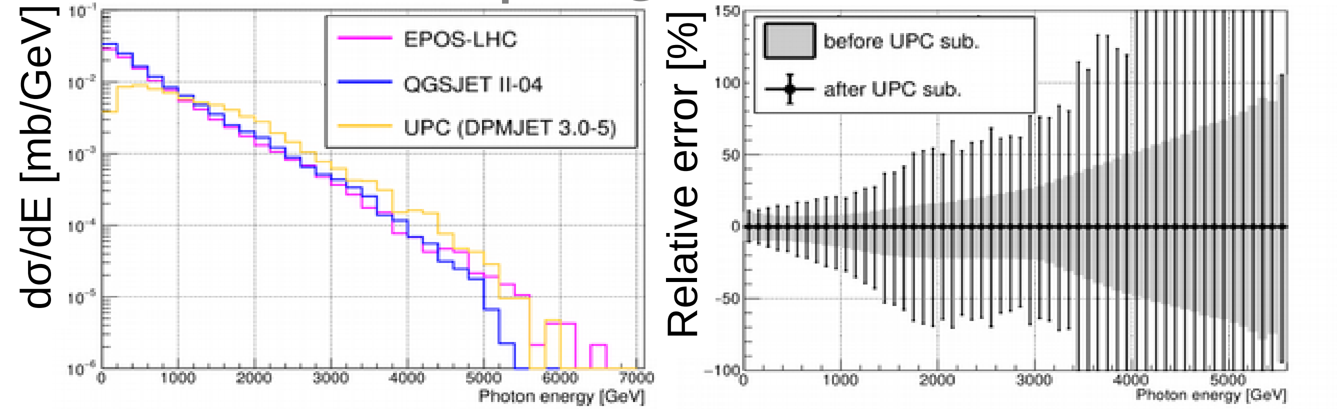
LHCf in Run III

p-O @ 9.9 TeV (Z*7 TeV)

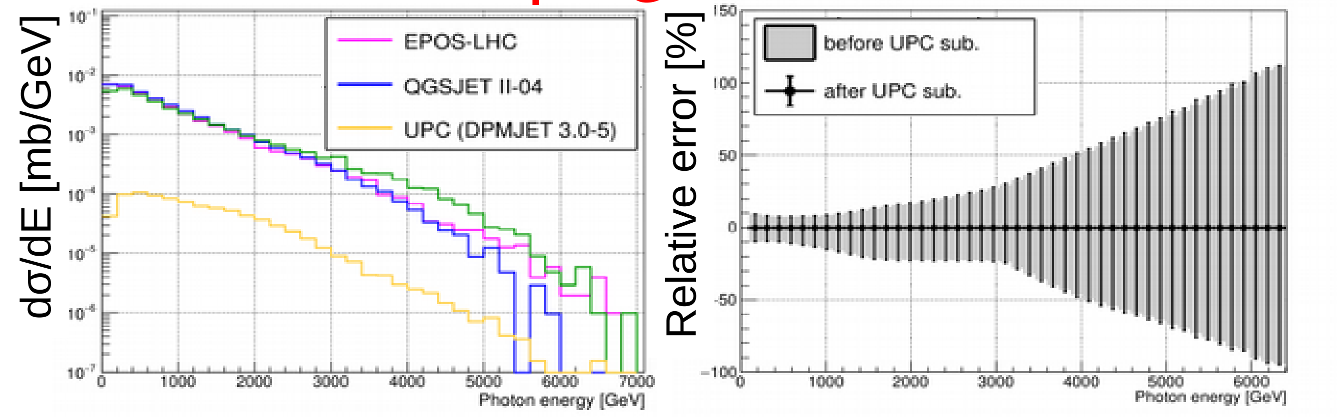
LHCf cannot operate after Run III: it is the (first and) last chance to **measure forward production in p-light nucleus collisions**!

Forward photon production in η > 10.94

p-Pb @ 8.16 TeV



p-O @ 9.9 TeV



GOAL 1: measure forward production in a configuration very similar to the first interaction of UHECR with an atmospheric nucleus (N or O)

GOAL 2: measure the effect of the target nucleus on forward production without a large contribution from UltraPeripheral Collisions

In p-O, UPC is negligible respect to QCD, thus strongly reducing the effect of this theoretical uncertainty respect to the p-Pb case.

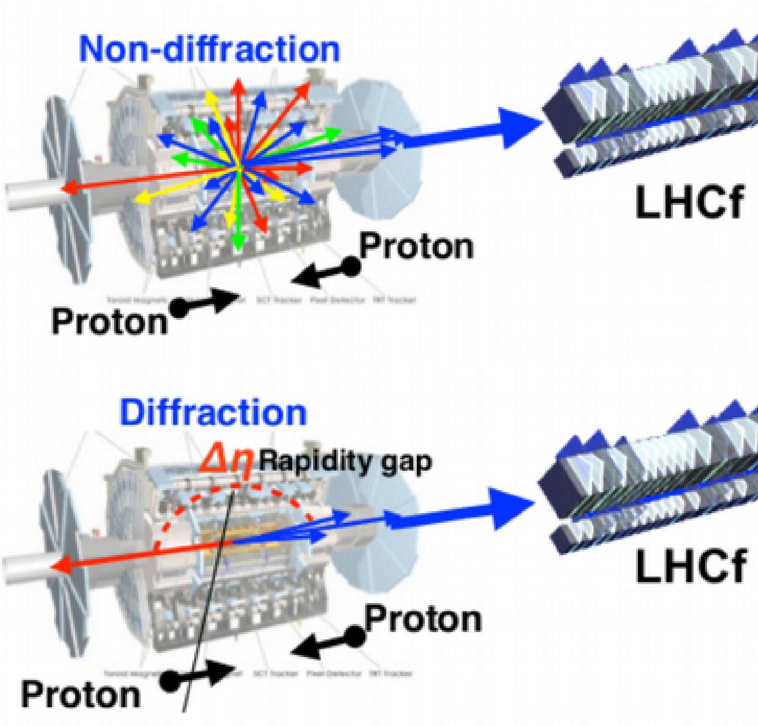
Operating at L = 10^{28} cm^{-2}s^{-1}, in a couple of days LHCf will collect L_{int} = 0.7 nb^{-1}

LHCf-ATLAS operation in Run III

In Run II, the LHCf and ATLAS experiments had **common operations** in p-p collisions @ 13 TeV so that, exploiting the information in the central region, it is possible to study forward production from different contributions, non-diffractive and diffractive (M_X<50GeV)

In Run II, the LHCf and ATLAS common data taking was not effective in p-Pb collisions because of the large UPC contribution (which has no activity in the central region).

In Run III, it will be possible to extend the LHCf-ATLAS joint analysis to p-O collisions, thanks to the negligible UPC contribution in case of p-O respect to p-Pb



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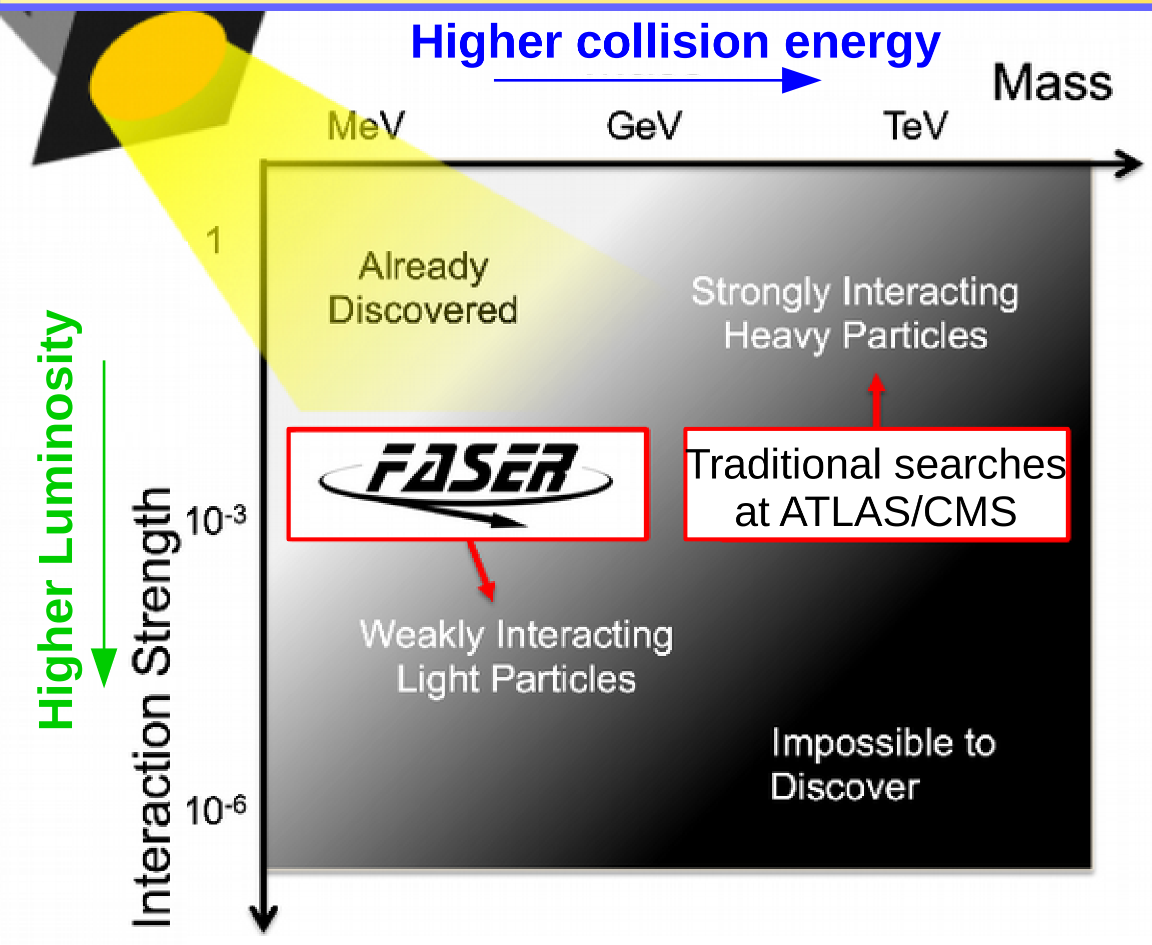
In Run III, this common operation will be extended including two ATLAS subdetectors:

- **ALFA roman pots**, for the identification of single diffractive events and measurements of Δ resonance ($p+p \rightarrow p+\Delta \rightarrow p+p+\pi^0$) and bremsstrahlung ($p+p \rightarrow p+p+\gamma$) contributions
- **ZDC**, in order to increase the depth of the combined calorimeter from 1.6 to 6.2 λ_I and consequently improve the hadronic energy resolution from about 40% to about 20%

FASER

Scientific motivation



Strongly interacting Heavy Particles, mainly produced at high p_T, are only accessible to central experiments

Weakly Interacting Light Particles, mainly produced at small p_T, are only accessible to forward experiment

In the forward region, a large amount of π, K, D and B mesons are produced.

These mesons could decay in BSM particles, *e.g.* a dark photon A' with mass $m_{A'}$ and coupling constant ε.

Being weakly interacting, A' travels large distances before decaying in e+e-.

A detector in the forward region, at a reasonable distance from interaction point and with a proper shielding from SM particles, can search for new physics.

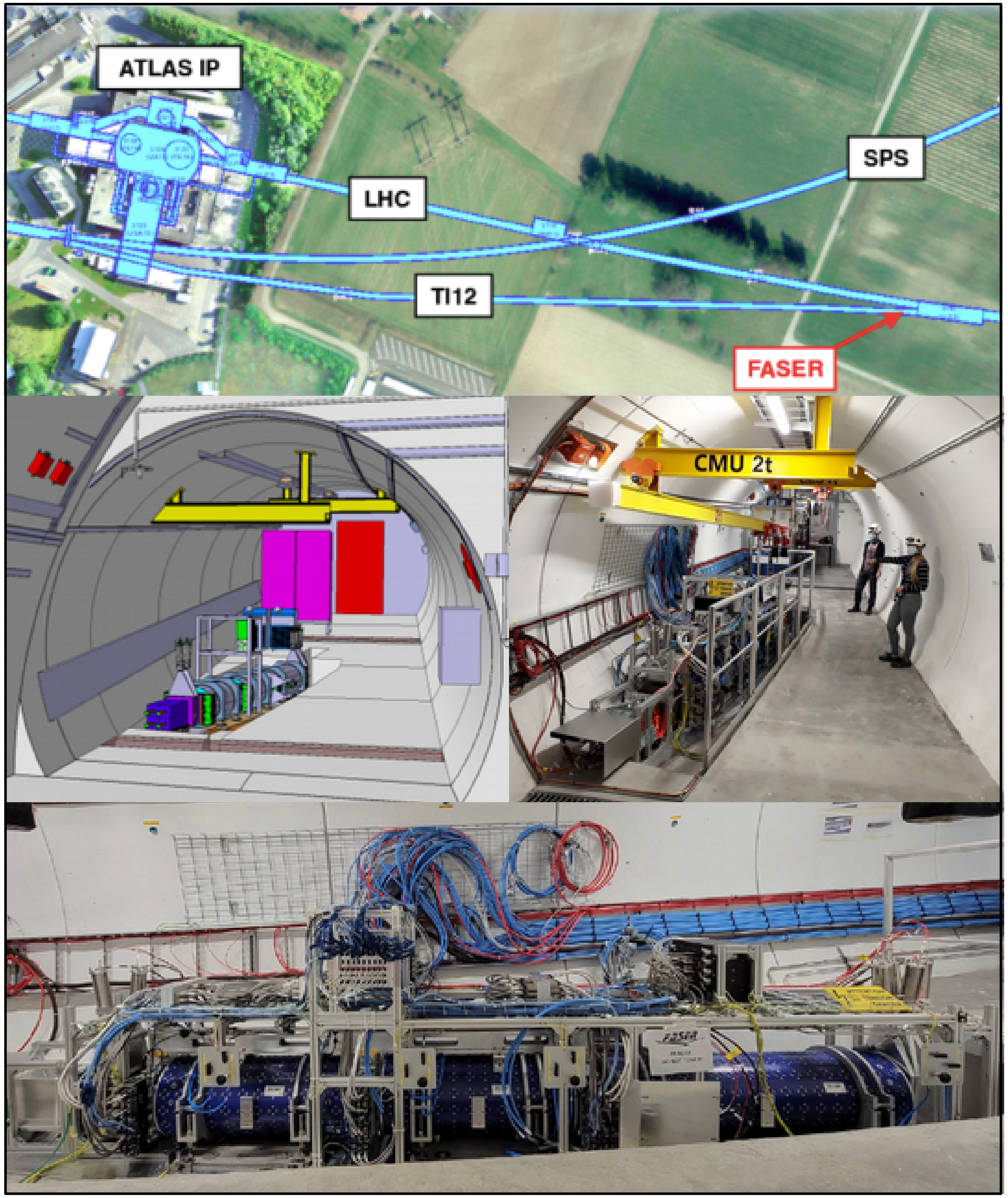
The FASER experiment

Located in the **TI12 tunnel** that connected SPS to LEP, at a distance of 480 m from the interaction point and shielded by 100 m of rock and concrete

SM Background assuming L_{int}~150 fb^{-1} in Run III (estimated by simulation and confirmed by *in situ* measurements):

- $2x10^{9}$ muons above 10 GeV
- 10^{4} interacting neutrinos

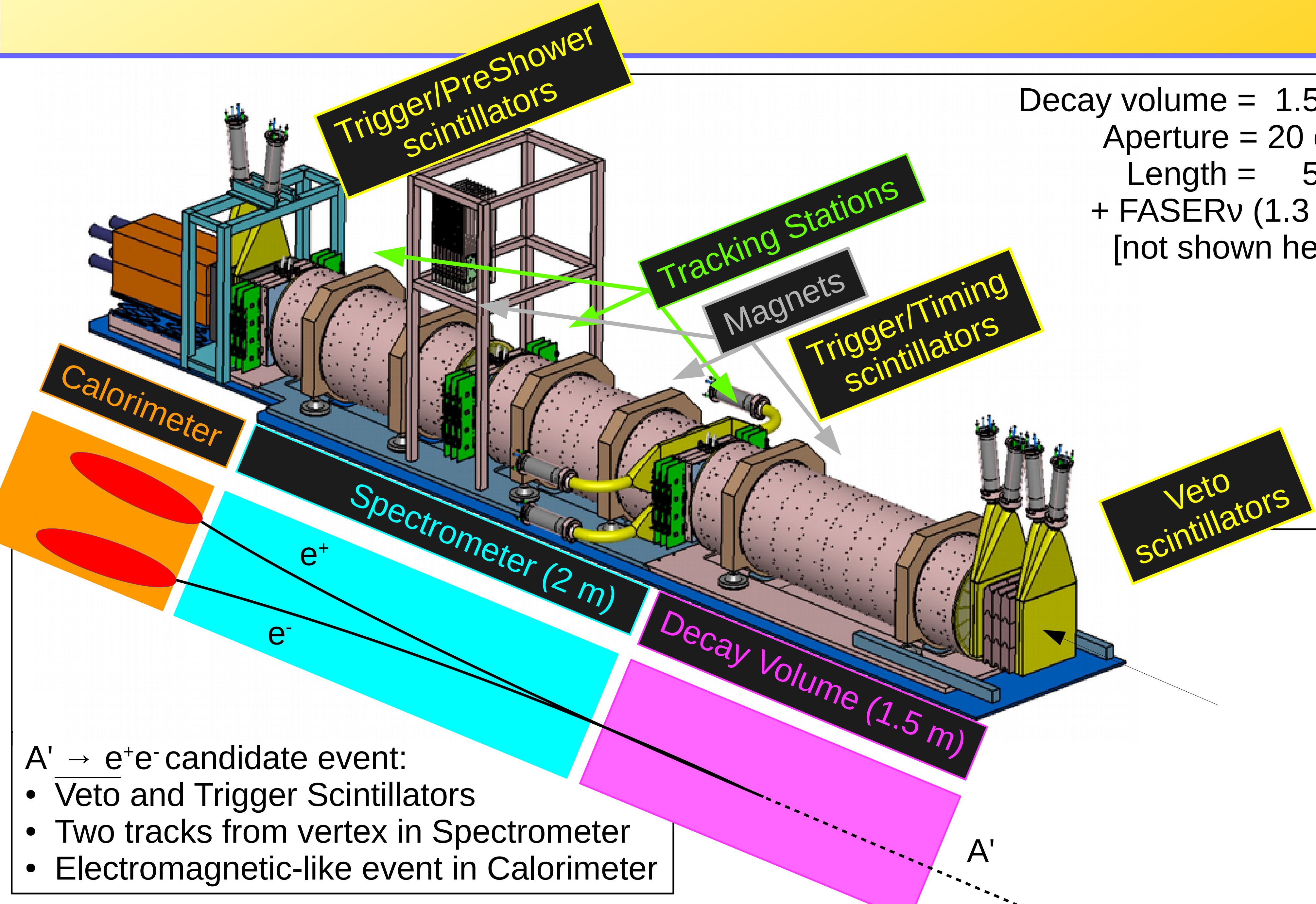
Despite FASER covers $2x10^{-8}$ of the solid angle (**η > 9.1**), 2% of π^{0} above 10 GeV from p-p collisions at 14 TeV are inside its acceptance (for a total of 10^{17} assuming L_{int}~150 fb^{-1} in Run III)



Installation completed in March 2021!

The FASER detector

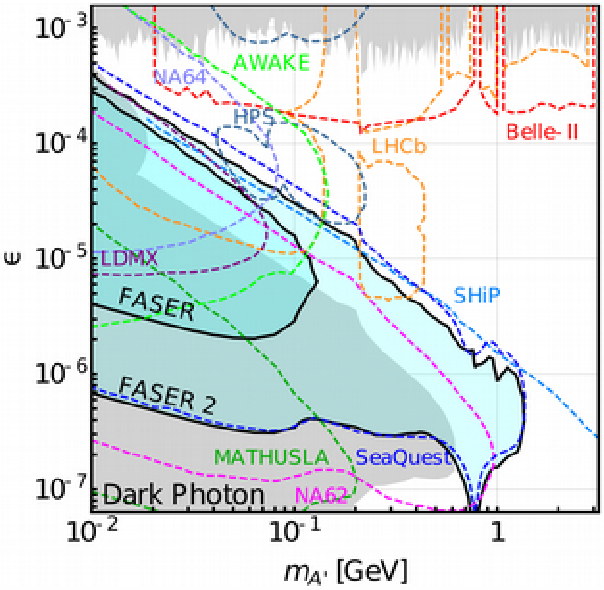
Decay volume = 1.5 m
Aperture = 20 cm
Length = 5 m
+ FASERν (1.3 m)
[not shown here]

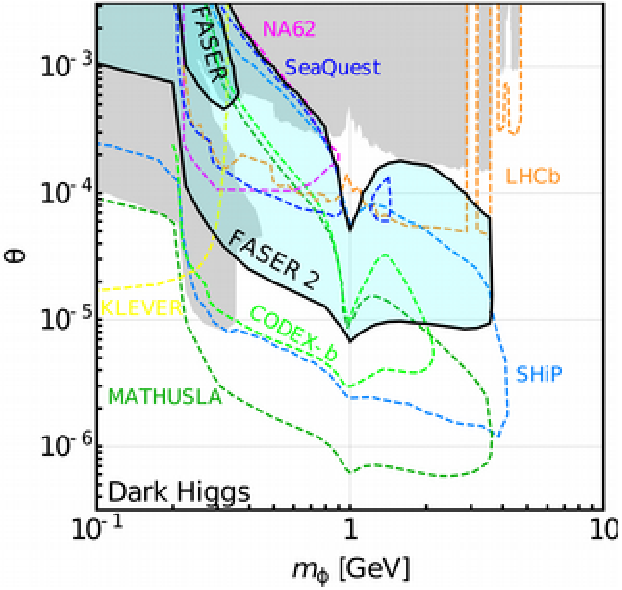


A' → e^+e^- candidate event:

- Veto and Trigger Scintillators
- Two tracks from vertex in Spectrometer
- Electromagnetic-like event in Calorimeter

The FASER experiment





In Run III (L_{int}~150 fb^{-1}), <u>FASER will have a good sensitivity to some BSM particles</u>, like dark photons

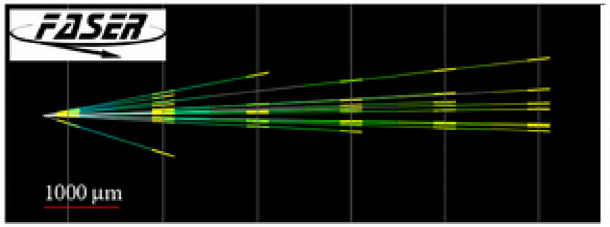
After Run III, a possible upgrade is FASER2, with an increase of the decay volume from 1.5 to 5 m and of the aperture from 20 to 200 cm

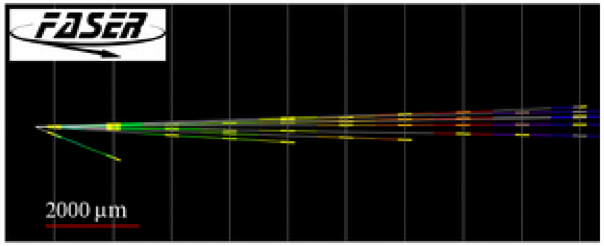
In HL-LHC (L_{int}~ 3 ab^{-1}), <u>FASER2 would have a good sensitivity to a large range of BSM particles</u>

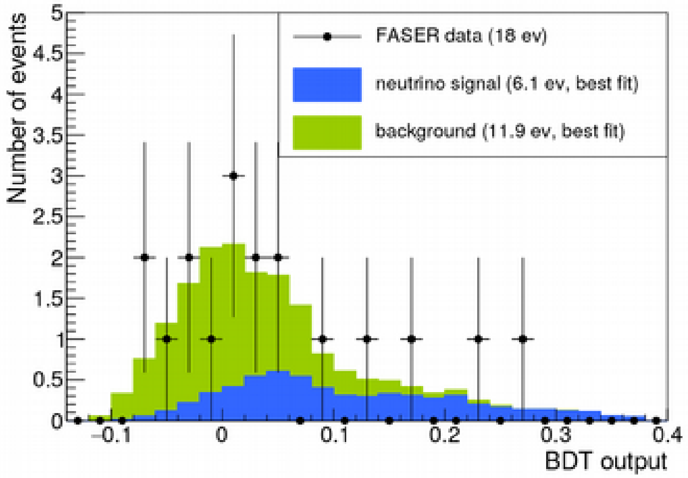
FASERν: emulsion/tungsten detector with a 1t target mass

Thanks to FASERν, FASER will <u>measure neutrino production cross sections at TeV collision energies</u>

<u>First ever detection of neutrinos at a collider</u> using 2018 pilot run: 6 candidates coming from forward region!







arXiv:2105.06197

Summary

LHCf and FASER are both forward experiments but with very different target!

Run III will be the **last Run** for LHCf!

In Run III the LHCf experiment will reach its **main scientific goals**:

- **p-p collisions @ 14 TeV:** Measurements of forward production with large statistics at the highest energy available at a collider
- **p-O collisions @ 9.9 TeV:** Measurements of forward production in a configuration similar to UHECR interaction with atmospheric nucleus

LHCf-ATLAS joint operations will shed new light on different processes responsible for forward production.

Run III will be the **first Run** for FASER!

In Run III (L_{int}~150 fb^{-1}), FASER will search for a limited range of particles from **BSM physics**, like dark photons. **Neutrino production cross sections** will be measured (thanks to *FASERν* detector) at a collider for the first time.

After Run III, a possible upgrade is **FASER2**, which will have good sensitivity to a large range of BSM particles, including dark photons, dark Higgs, heavy neutral leptons and axion-like particles in HL-LHC (L_{int}~3 ab^{-1}).

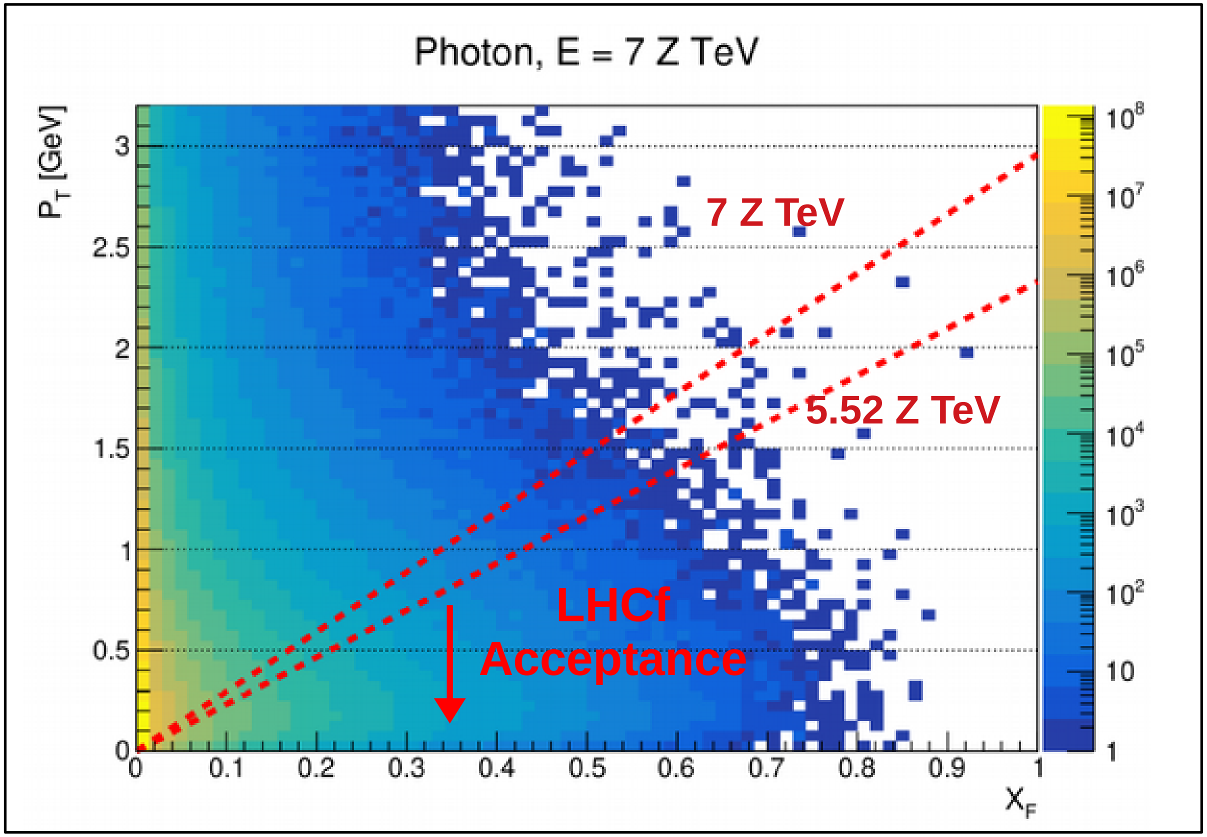
Thank you
for the attention!

In case you have more questions:

https://cern.zoom.us/j/5606239122?pwd=MElpWU9jdHhSOVIxRFJud3pDNFhVdz09

LHCf in Run III

x_F-p_T coverage in p-O collisions



Leading to the maximum coverage in the x_F-p_T plane, Operations @ 7 Z TeV are strongly supported by LHCf

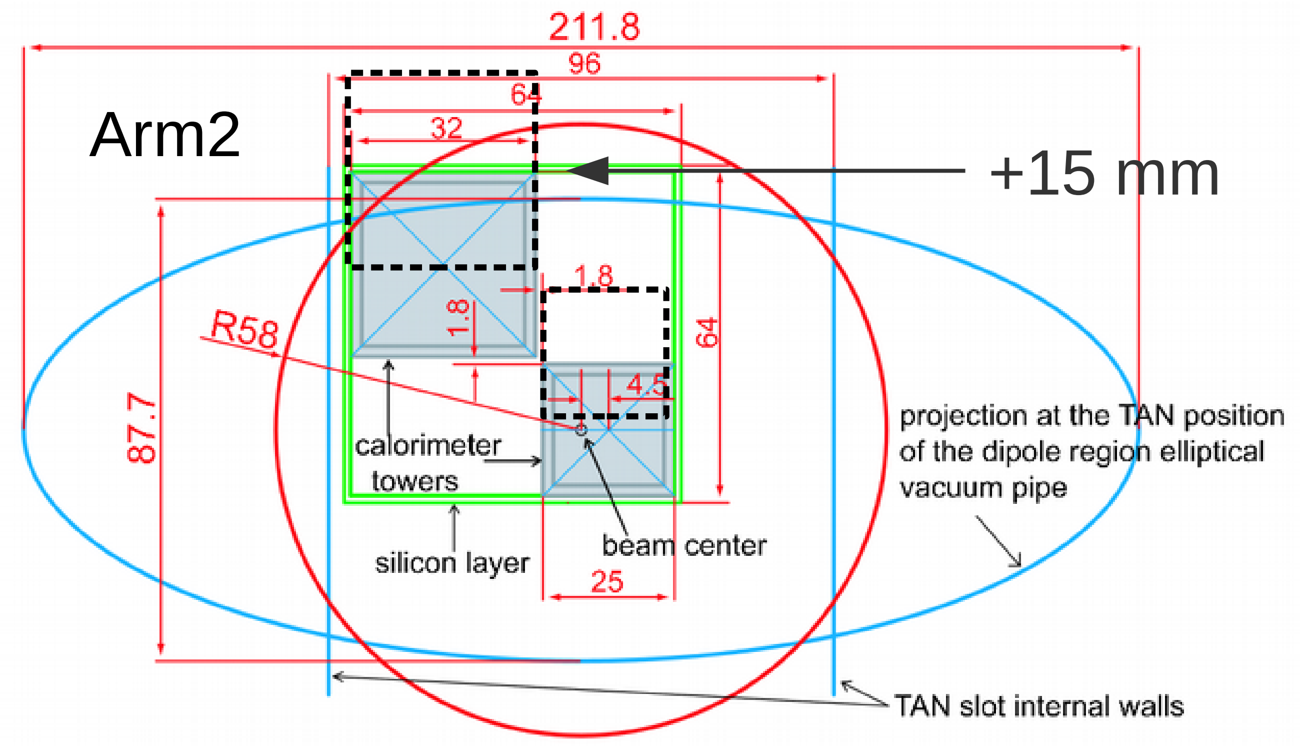
LHCf in Run III

Detector position in p-O and O-O operations

On the **proton remnant** side in p-O collisions, multiplicity is very limited and LHCf can operate at nominal detector position

On the **oxygen remnant** side in p-O or O-O collisions, multiplicity is too high to operate at the nominal position and the detector must be shifted higher by 15 mm

At a price of not covering the most forward region, LHCf can still measure production in $8.4<\eta<11$



LHCf in Run III

Ideal Beam Conditions

Beam conditions are currently under discussion with LPC

Ideal beam condition for **p-p @ 14 TeV**:

- $N_{bunch} = 500$
- $\Delta t_{bunch} = 500$ ns
- $L < 10^{30}$ cm^{-2}s^{-1}
- $\theta_{crossing} = 290$ μrad
- $\mu = 0.01\text{-}0.02$
- $\beta^* = 19$ m

Ideal beam condition for **p-O @ 9.9 TeV**:

- $N_{bunch} = 43$
- $\Delta t_{bunch} = 2$ μs
- $L < 10^{29}$ cm^{-2}s^{-1}
- $\theta_{crossing} = 290$ μrad
- $\mu = 0.01\text{-}0.02$
- $\beta^* = 10$ m

LHCf in Run III

Trigger Scheme

“Shower” trigger

- Prescale factor = 14
- Photons (efficiency ~100% for E > 100 GeV)
- Neutrons (efficiency ~70% for E > 1 TeV)

“Type I” trigger

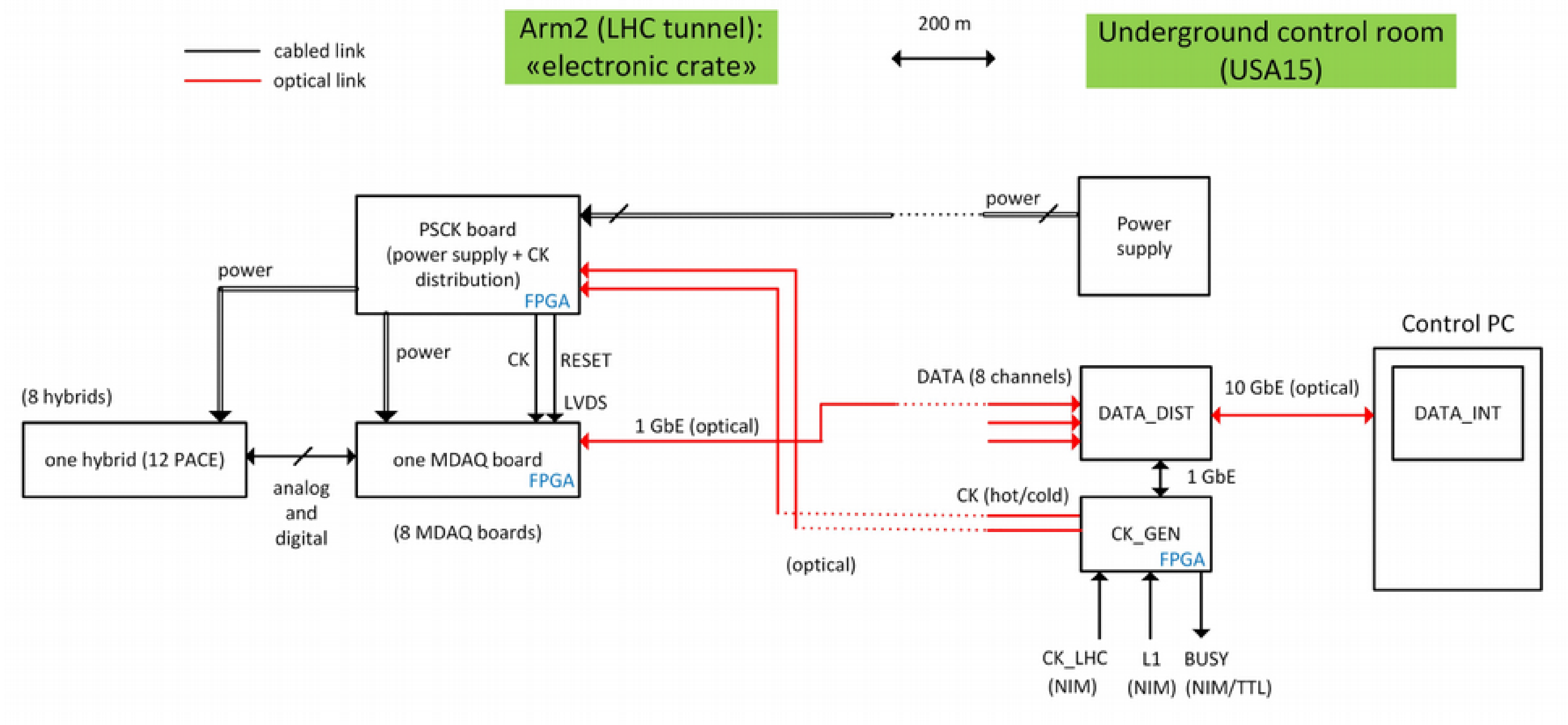
- Prescale factor = 1
- π^0 with one photon in each calorimeter (efficiency ~98%)
- η

“High EM” trigger

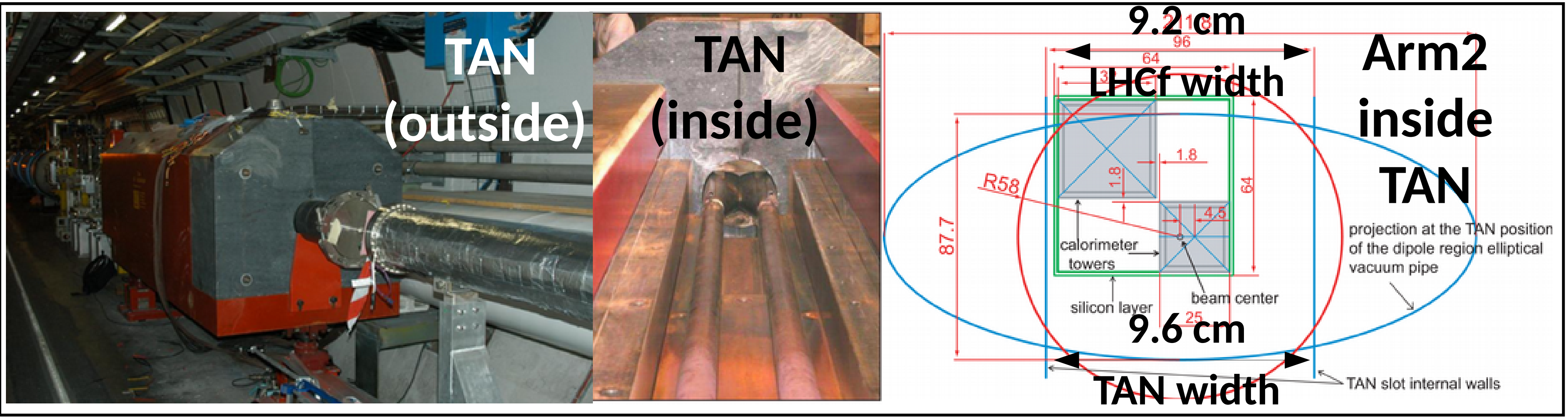
- Prescale factor = 1
- High energy photons (E > 1 TeV)
- π^0 with both photons in the calorimeter (efficiency ~97%)

LHCf in Run III

Arm2 DAQ Upgrade



What happens after Run III



The LHCf detectors are designed to operate in the TAN region, so its size is constrained by the space in TAN internal walls.

After Run III, the distance between the TAN internal walls will be strongly reduced, with this number changing from 9.2 to 5 cm.

The current LHCf detector cannot fit this space, so that it would be necessary to build a new detector to continue operations.

Acquired data and published results

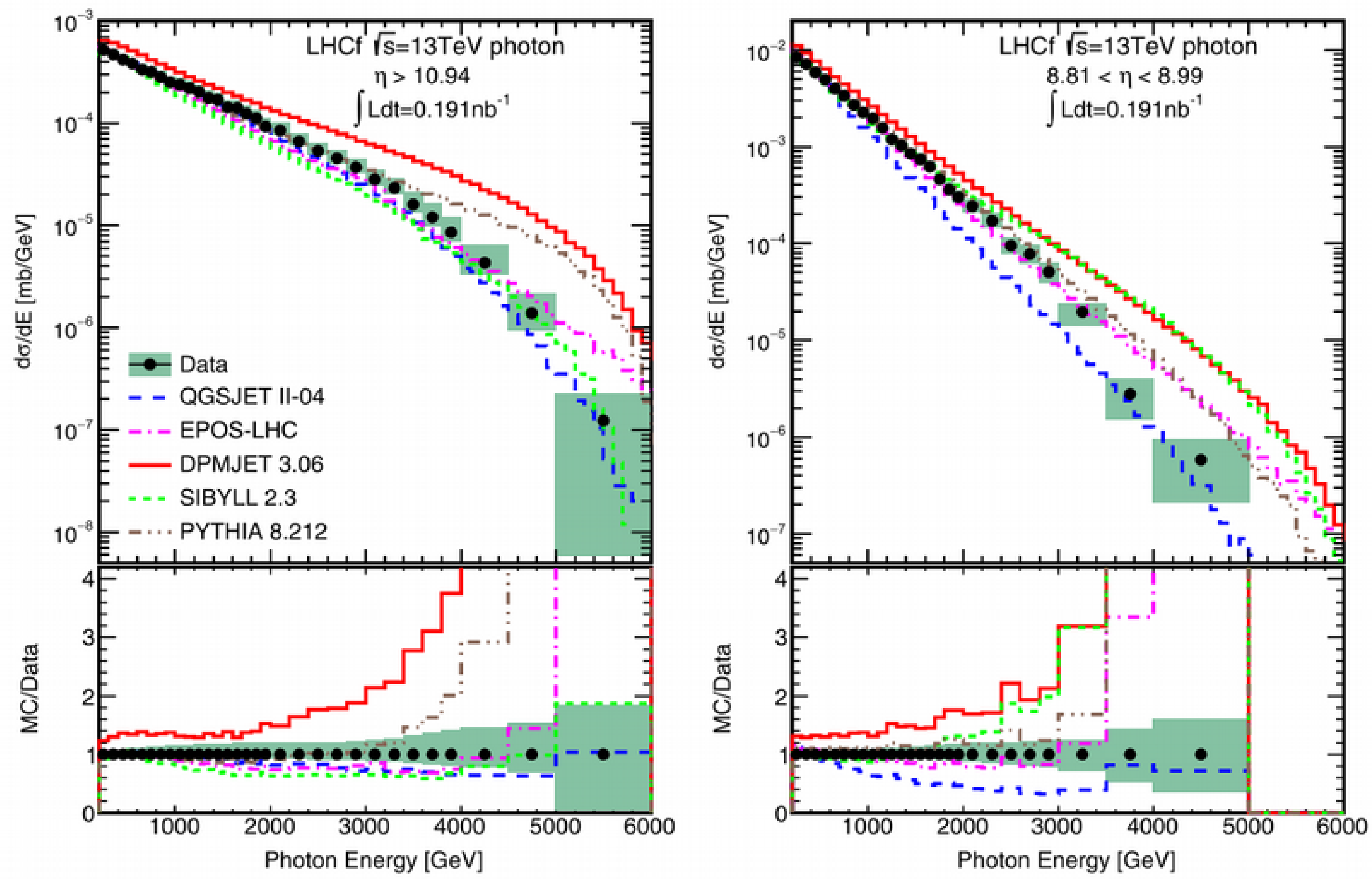
	Proton equivalent energy in LAB (eV)	γ	n	π^0
SPS test beam		NIM A, 671, 129 (2012) JINST 12 P03023 (2017) (upgrade)	JINST 9 P03016 (2014)	
p+p 900 GeV	4.3x10^{14}	Phys. Lett. B 715, 298 (2012)		
p+p 7 TeV	2.6x10^{16}	Phys. Lett. B 703, 128 (2011)	Phys. Lett. B 750 (2015) 360-366	Phys. Rev. D 86, 092001 (2012) + Phys. Rev. D 94 032007 (2016)
p+p 2.76 TeV	4.1x10^{15}			Phys. Rev. C 89, 065209 (2014) + Phys. Rev. D 94 032007 (2016)
p+Pb 5.02 TeV	1.4x10^{16}			
p+p 13 TeV	9.0x10^{16}	PLB 780 (2018) 233-239	JHEP 11 (2018) 073 JHEP 07 (2020) 16	Analysis ongoing
p+Pb 8.1 TeV	3.6x10^{16}	Data taking completed in November 2016		

ATLAS-LHCf common data taking

Thanks to information in the central region it is possible to distinguish between diffractive and non-diffractive events

Photons dσ/dE

p-p √s = 13 TeV

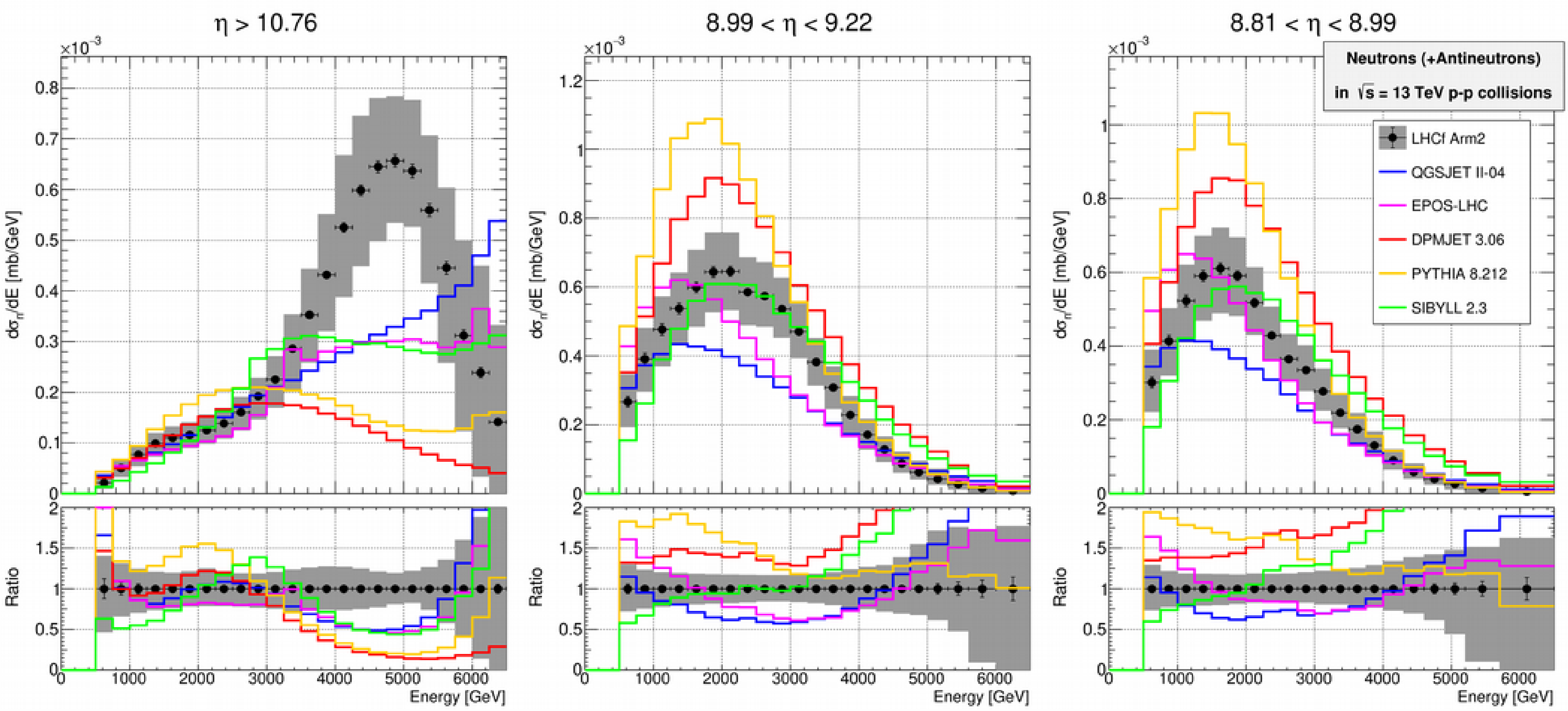


PLB 780 (2018) 233-239

QGSJET II-04 is in good agreement for η>10.94, otherwise softer.
EPOS-LHC is in good agreement below 3-5 TeV, otherwise harder.

Neutrons dσ/dE

p-p √s = 13 TeV



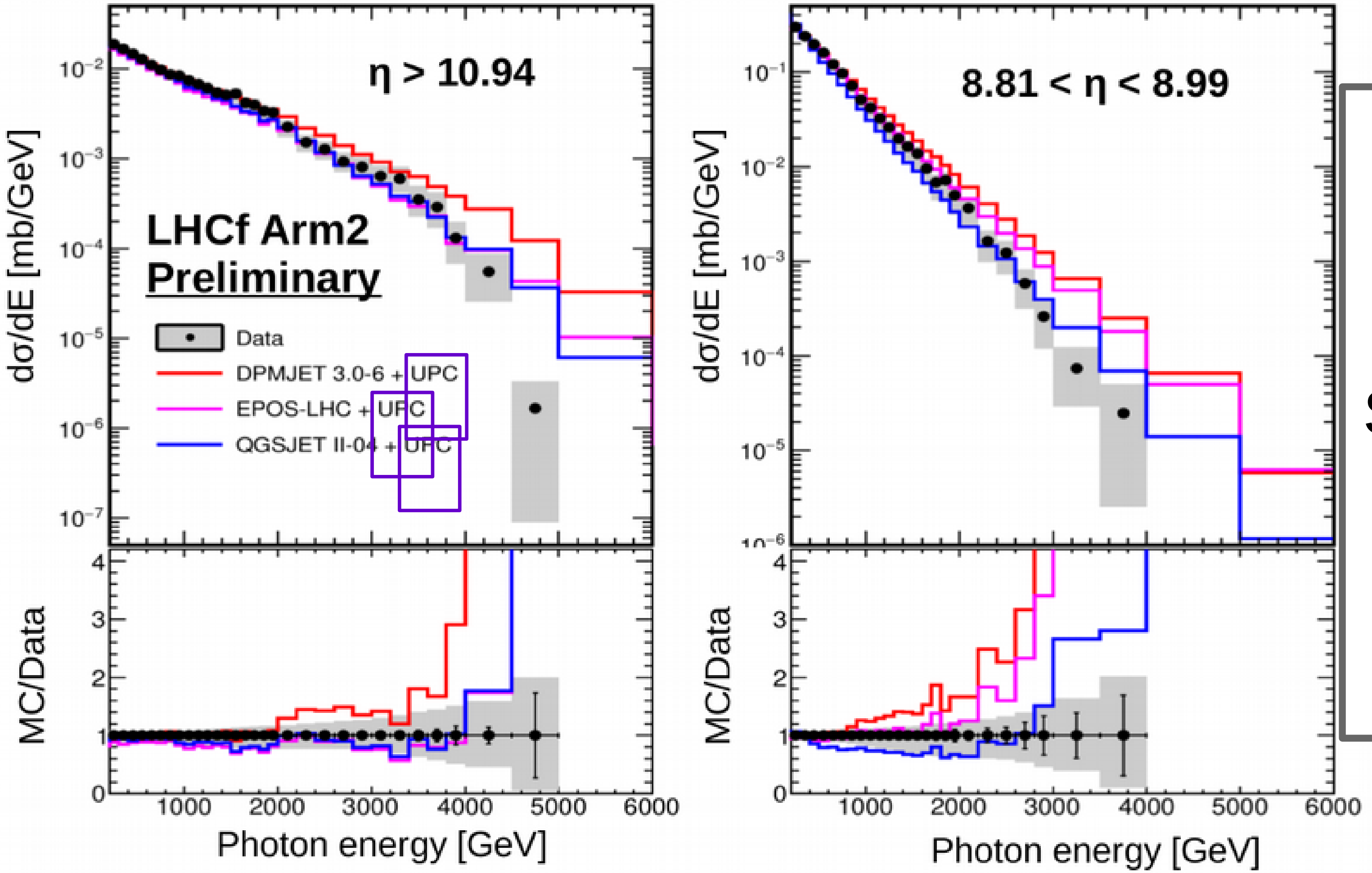
JHEP 11 (2018) 073

In η > 10.76 no model agrees with peak structure and production rate. Among all models, **SIBYLL 2.3** and **EPOS-LHC** have the best overall agreement in 8.99 < η < 9.22 and 8.81 < η < 8.99, respectively.

Analyses for p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Data set
- Fill # 5538
- 25 Nov 9.22-11.28
- $\int \mathcal{L} dt = 8.1\ \mu b^{-1}$
- $\mu = 0.01$

Preliminary

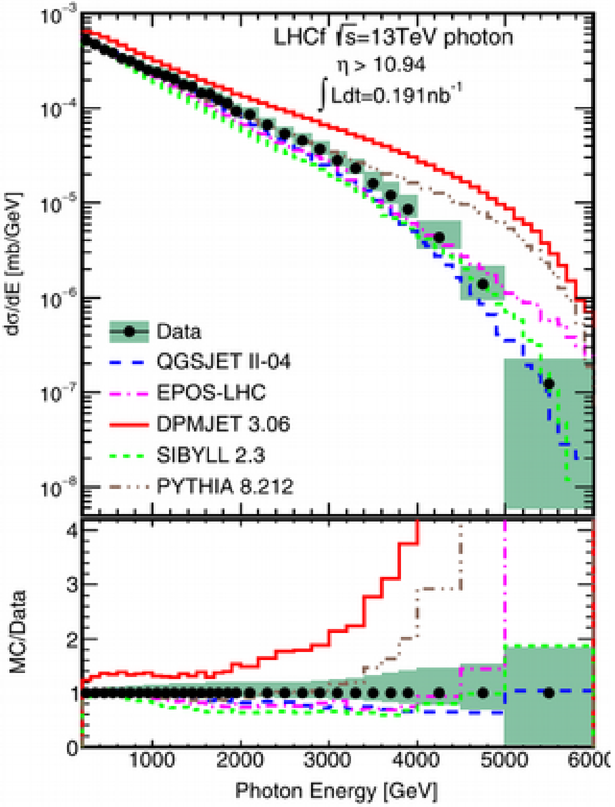


Ultra Peripheral Collisions (**UPC**) simulated using STARLIGHT + SOPHIA/DPMJET and added to hadronic collisions simulations

QGSJET II-04 and **EPOS-LHC** in good agreement for η > 10.94.
No model has good agreement in 8.81 < η < 8.99.

Diffractive and non diffractive events

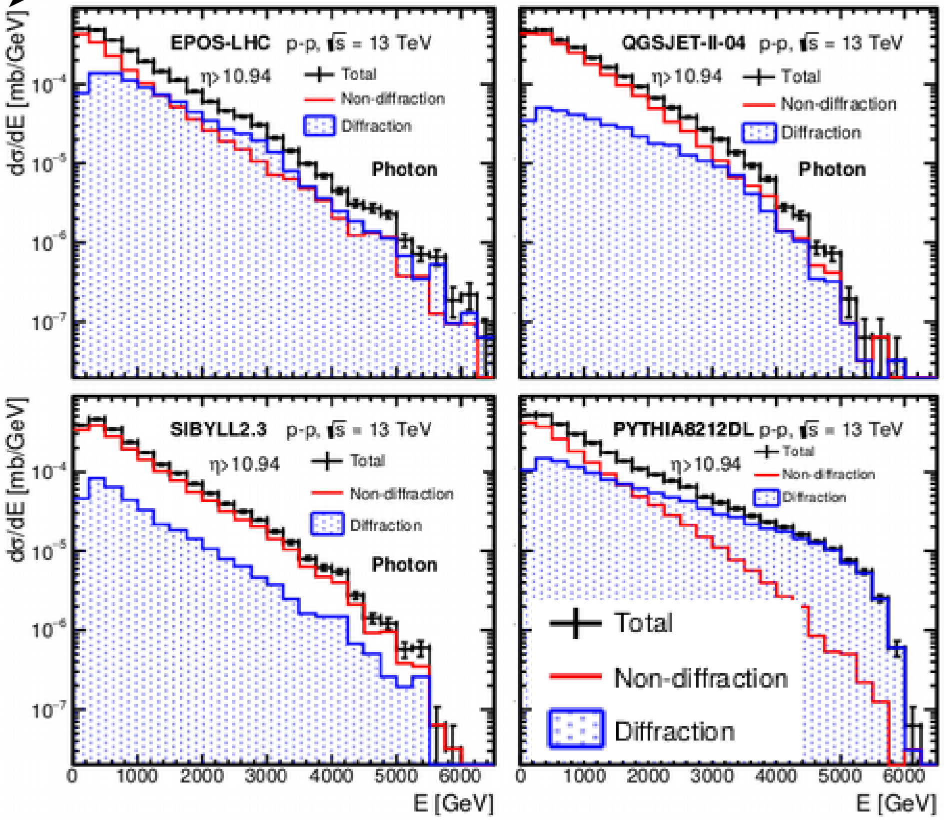
√s = 13 TeV - η > 10.94



LHCf measures the **total production rate** in the forward region

How it is possible to separate diffractive and non-diffractive contributions?

Different models lead to different contributions to **diffractive** and **non-diffractive** events



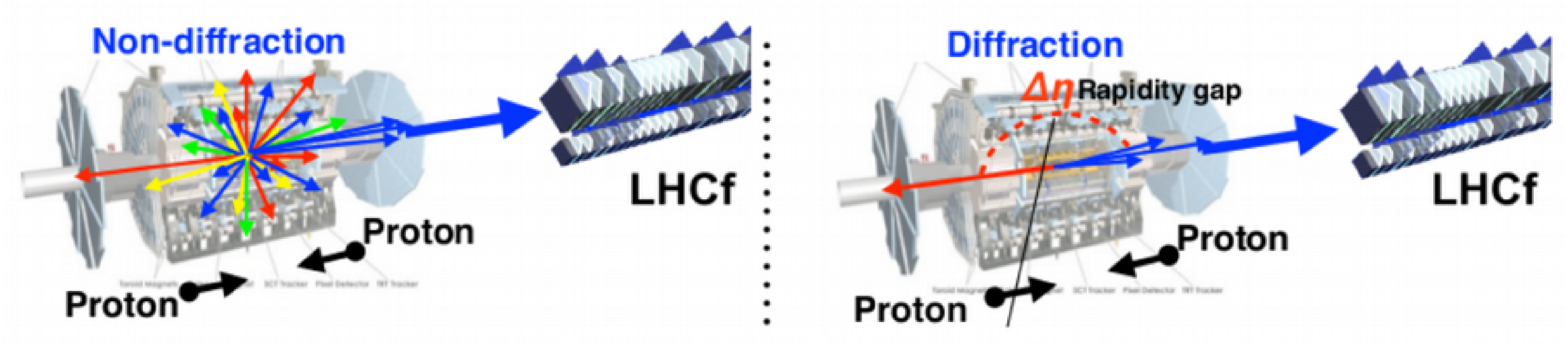
LHCf-ATLAS joint analysis

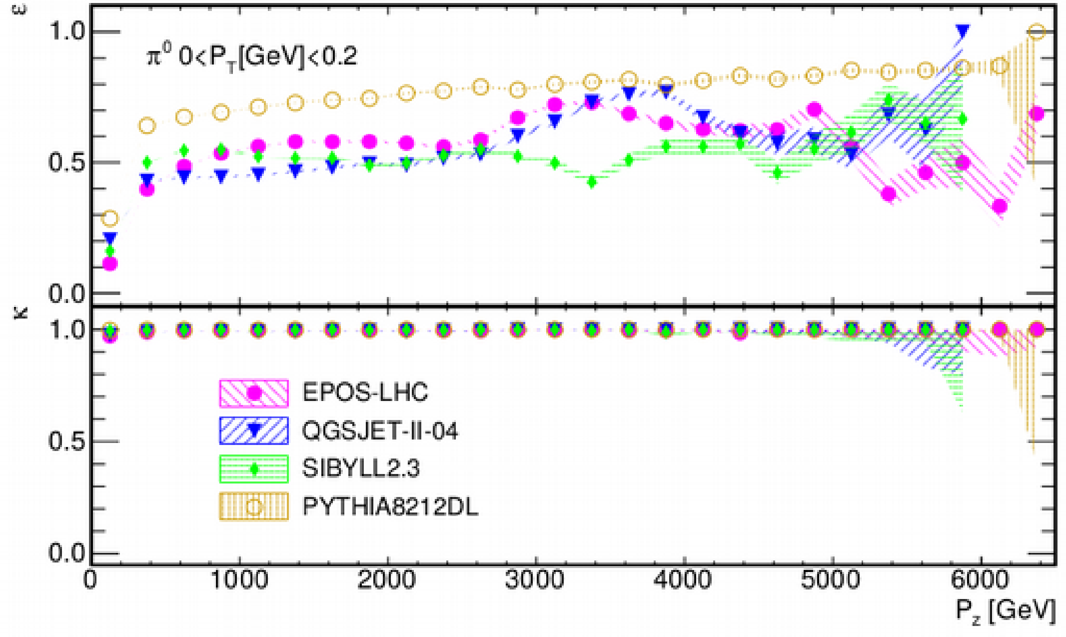
Eur. Phys. J. C (2017) 77:212

LHCf-ATLAS joint analysis

After a preliminary test in 2013, in 2015 and 2016 LHCf and ATLAS had **common operations**.

Diffractive events can be distinguished from non-diffractive events by **ATLAS veto** : tracks=0 at |η|<2.5

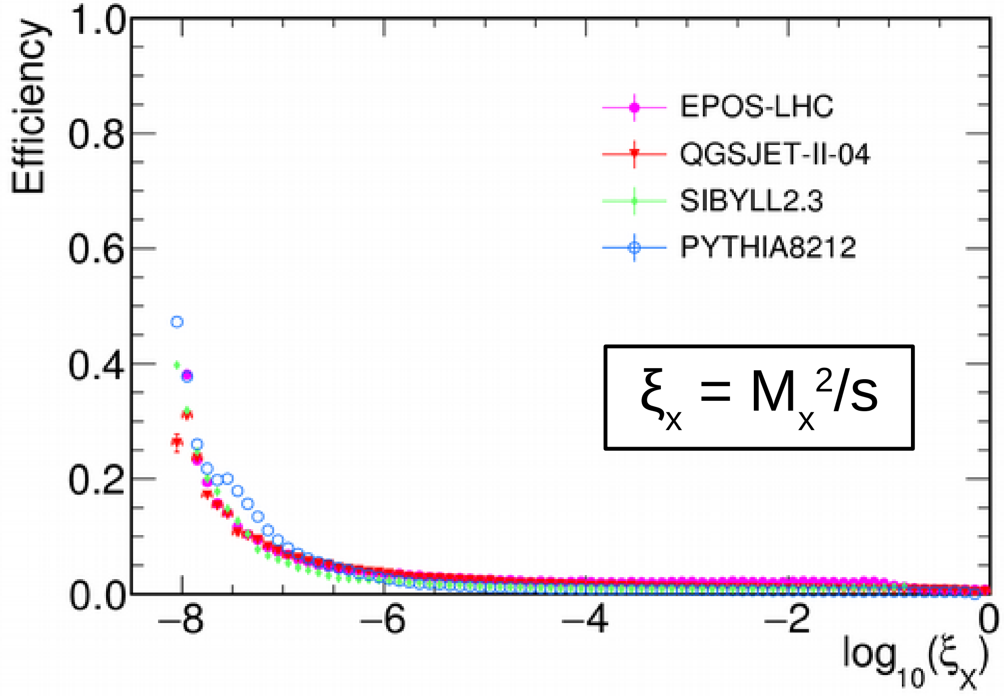




According to simulation studies the ATLAS veto can identify diffractive events with an efficiency of about 50% and a purity of almost 100%

Eur. Phys. J. C (2017) 77:212

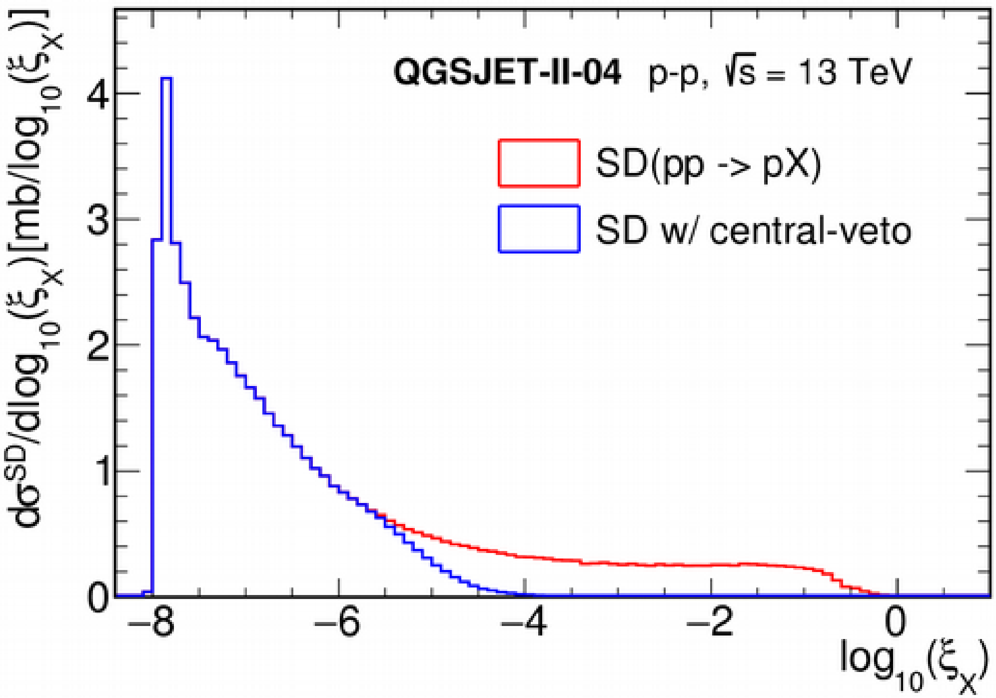
LHCf detection efficiency for single diffraction



$\xi_x = M_x^2/s$

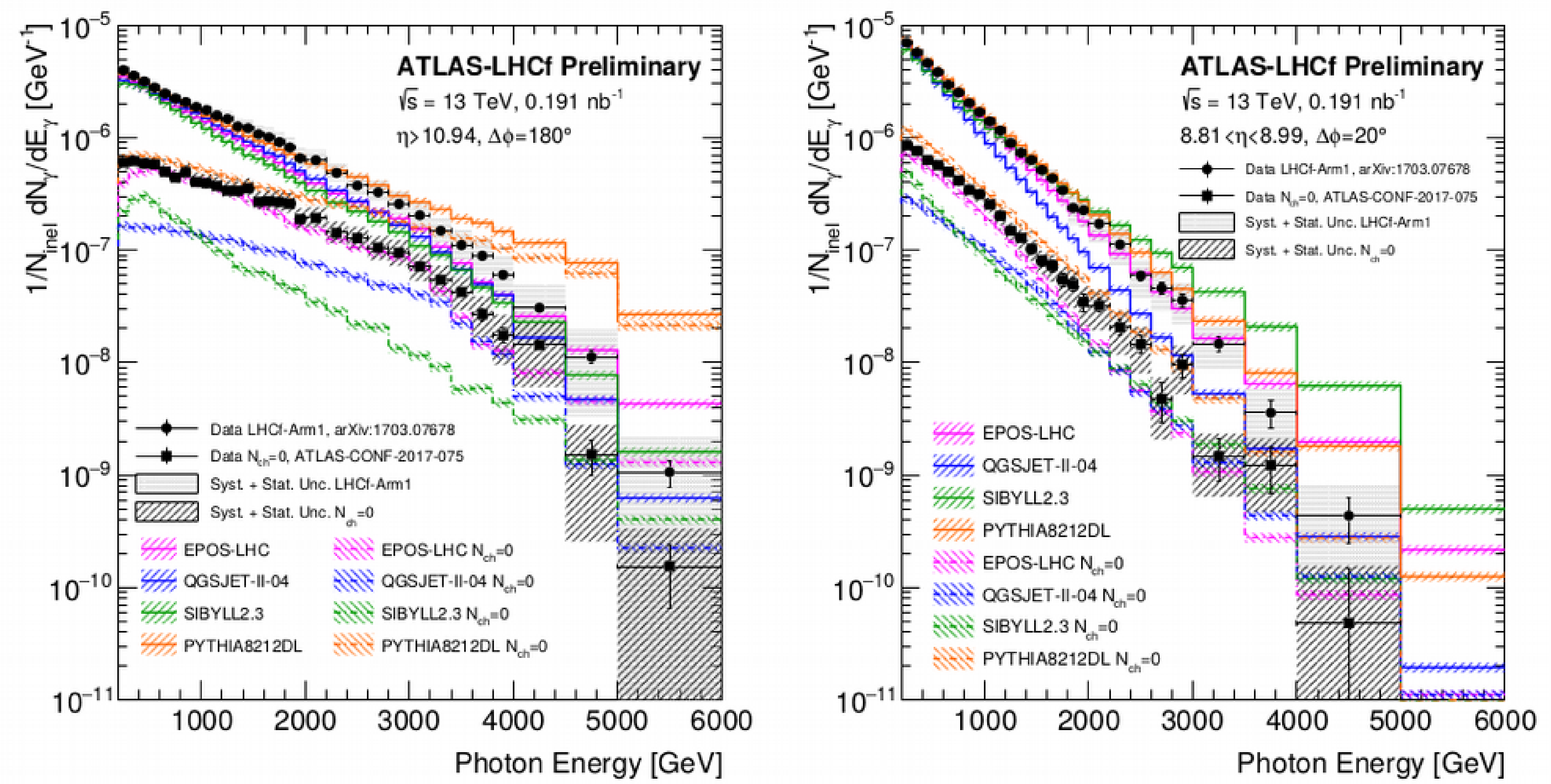
Efficiency
about 5% for $\log_{10} \xi_x \sim -6.5$
about 40% for $\log_{10} \xi_x \sim -8$

Central veto
selection of very low mass diffraction



LHCf-ATLAS combined analysis

Photons production at p-p √s = 13 TeV



ATLAS-CONF-2017-075

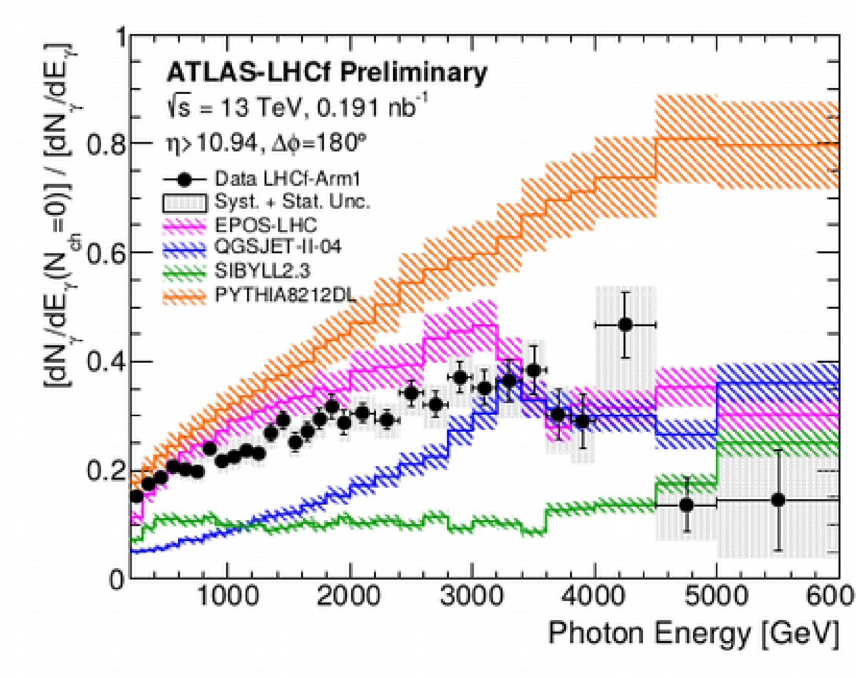
EPOS-LHC is the model in best agreement with data

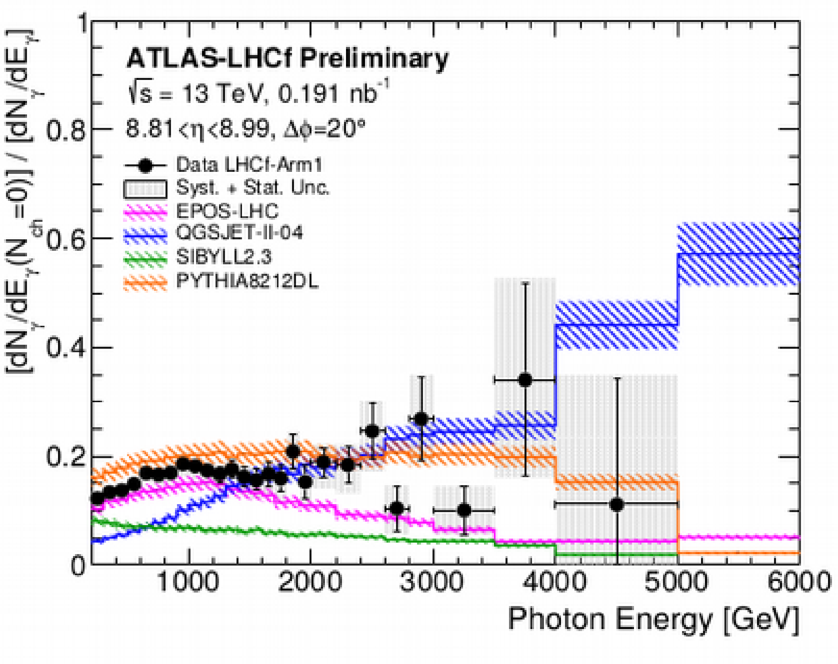
Analysis in progress for publication

LHCf-ATLAS combined analysis

N_{ch}=0/$N_{inclusive}$ photons energy spectra

p-p √s = 13 TeV





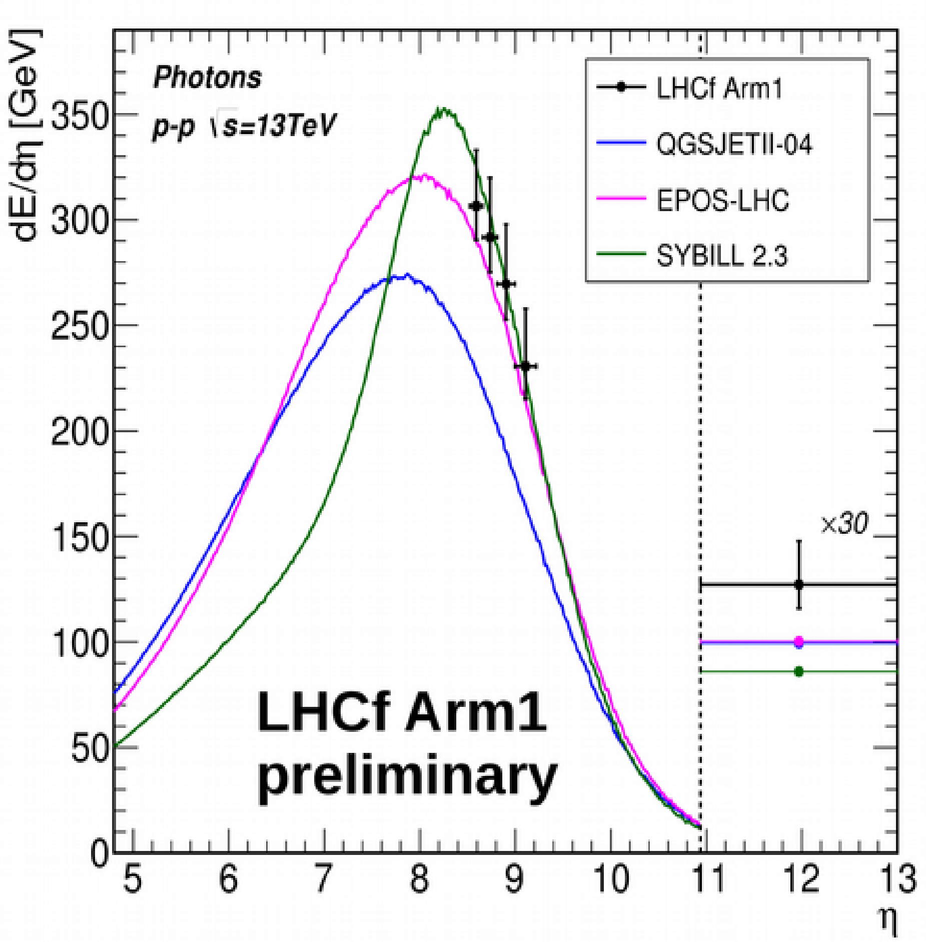
ATLAS-CONF-2017-075

EPOS-LHC is the model in best agreement with data

Preliminary

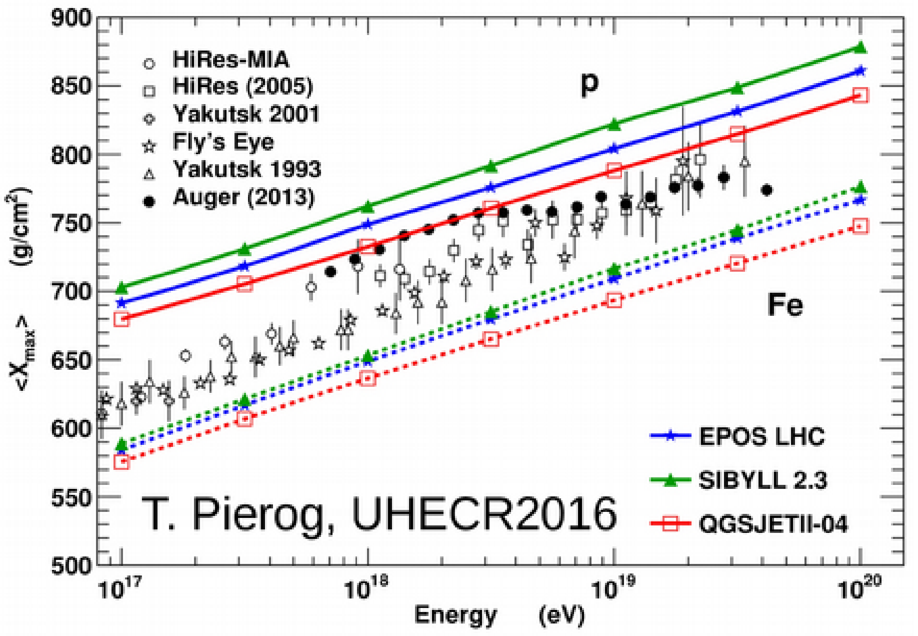
Acceptance extension

Arm1 only



SIBYLL 2.3 and **EPOS-LHC** have the best agreement with data for $\eta < 9.22$

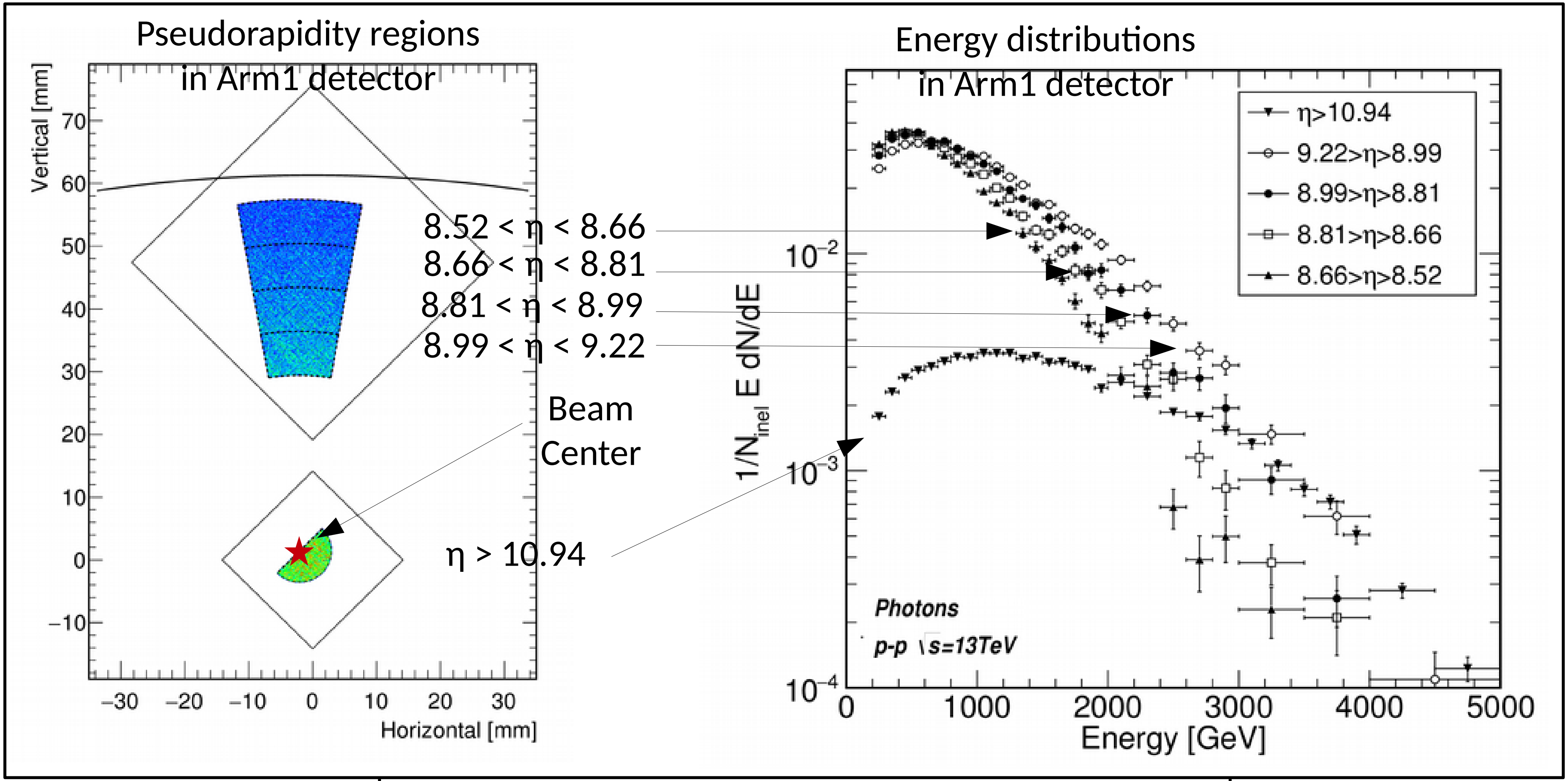
This may suggests that UHECRs have light but not protonic composition



Preliminary

Acceptance extension

Arm1 only



Pseudorapidity regions in Arm1 detector

Energy distributions in Arm1 detector

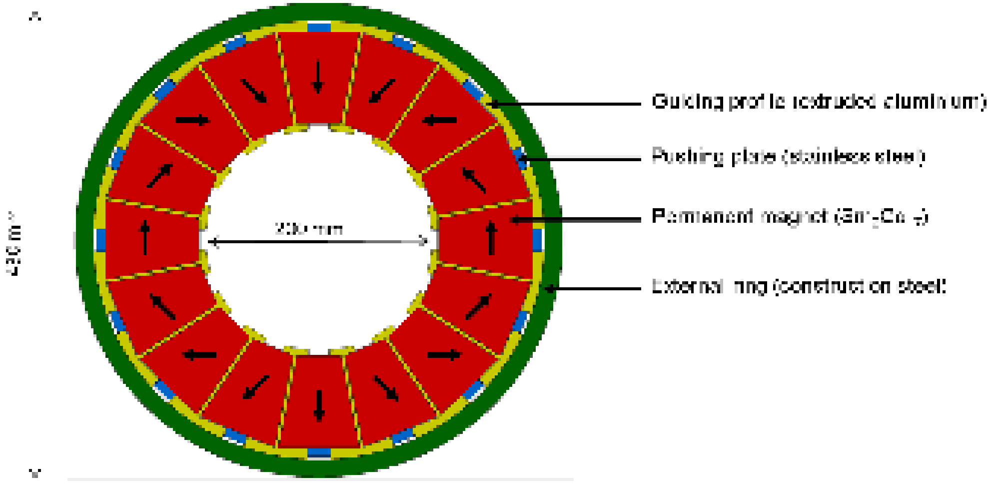
8.52 < η < 8.66
8.66 < η < 8.81
8.81 < η < 8.99
8.99 < η < 9.22

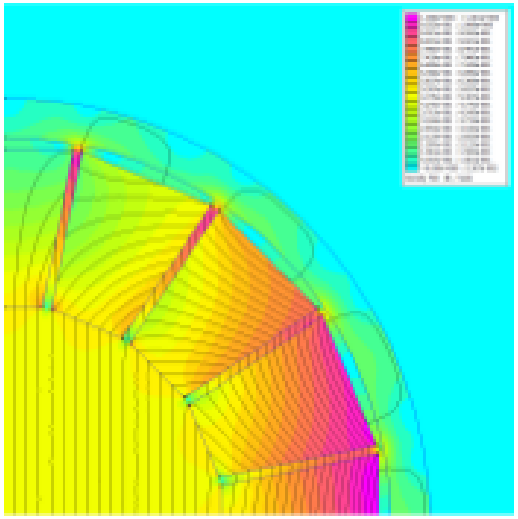
Beam Center

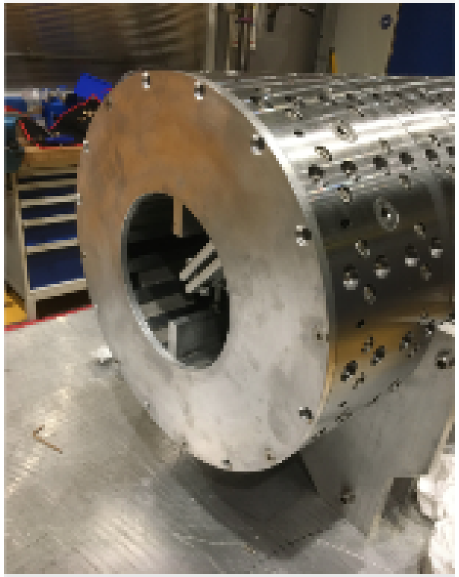
η > 10.94

For η < 9.22 the dominant contribution
is coming from the low energy region

FASER Magnets







- The FASER magnets are 0.55T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet center with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed and to be constructed by TE-MSC group at CERN
  - Main order released in Dec 2019, magnetic blocks for first magnet produced at CERN.

FASER Tracker

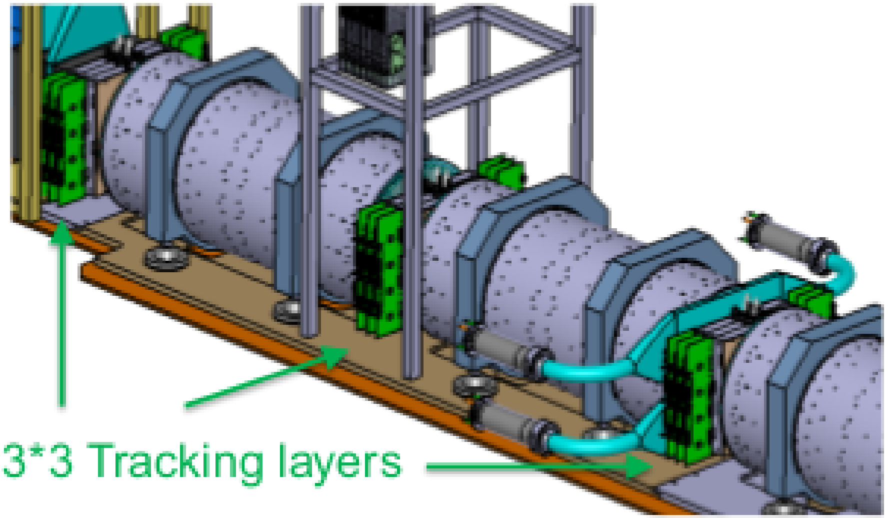
- Made up of semi-conductor strip (SCT) modules
  - ATLAS donated spare SCT modules

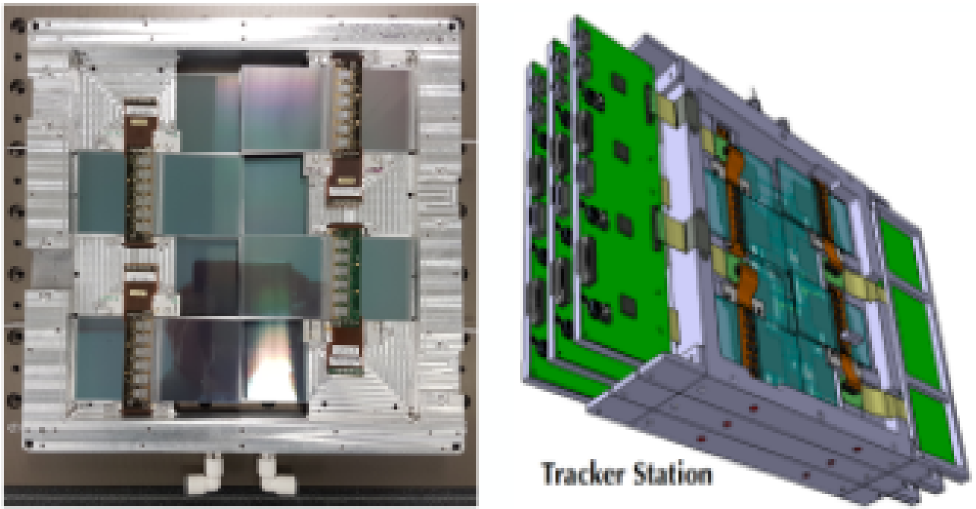
- Each module two pairs of silicon strip detectors glued back-to-back: 768 read-out channels/side
  - Precision measurements in bending plane

- 8 SCT modules give a 24cm x 24cm tracking layer

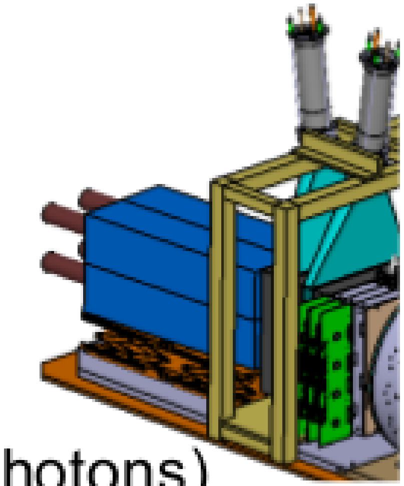
- 3 tracker stations, each with 3 layers
  - 3*3*8=72 SCT modules for the full tracker
  - 10^5 channels in total

- Efficiently separate very closely spaced tracks

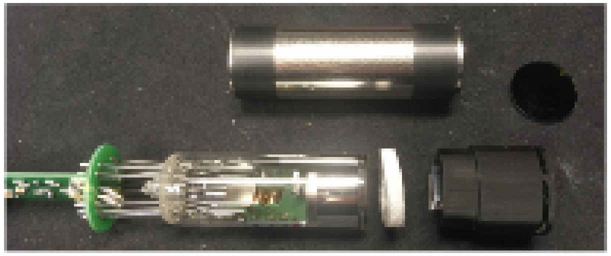

3*3 Tracking layers



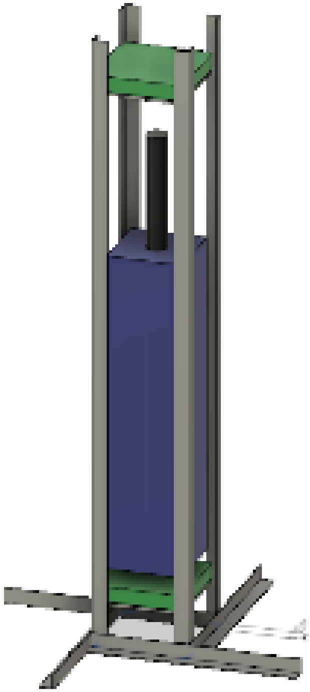
FASER Calorimeter



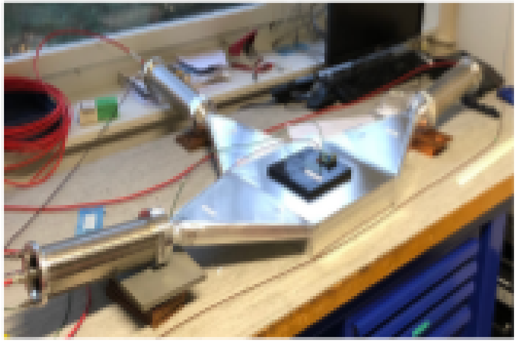
- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- 4 outer ECAL modules donated by LHCb
- 66 layers of lead/scintillator (allows detection of photons)



- Readout by PMT (no longitudinal shower information)
  - Only 4 channels in full calorimeter
- Provides ~1% energy resolution for 1 TeV electrons
- Cosmic ray test stand used for testing calorimeter response and to calibrate PMTs

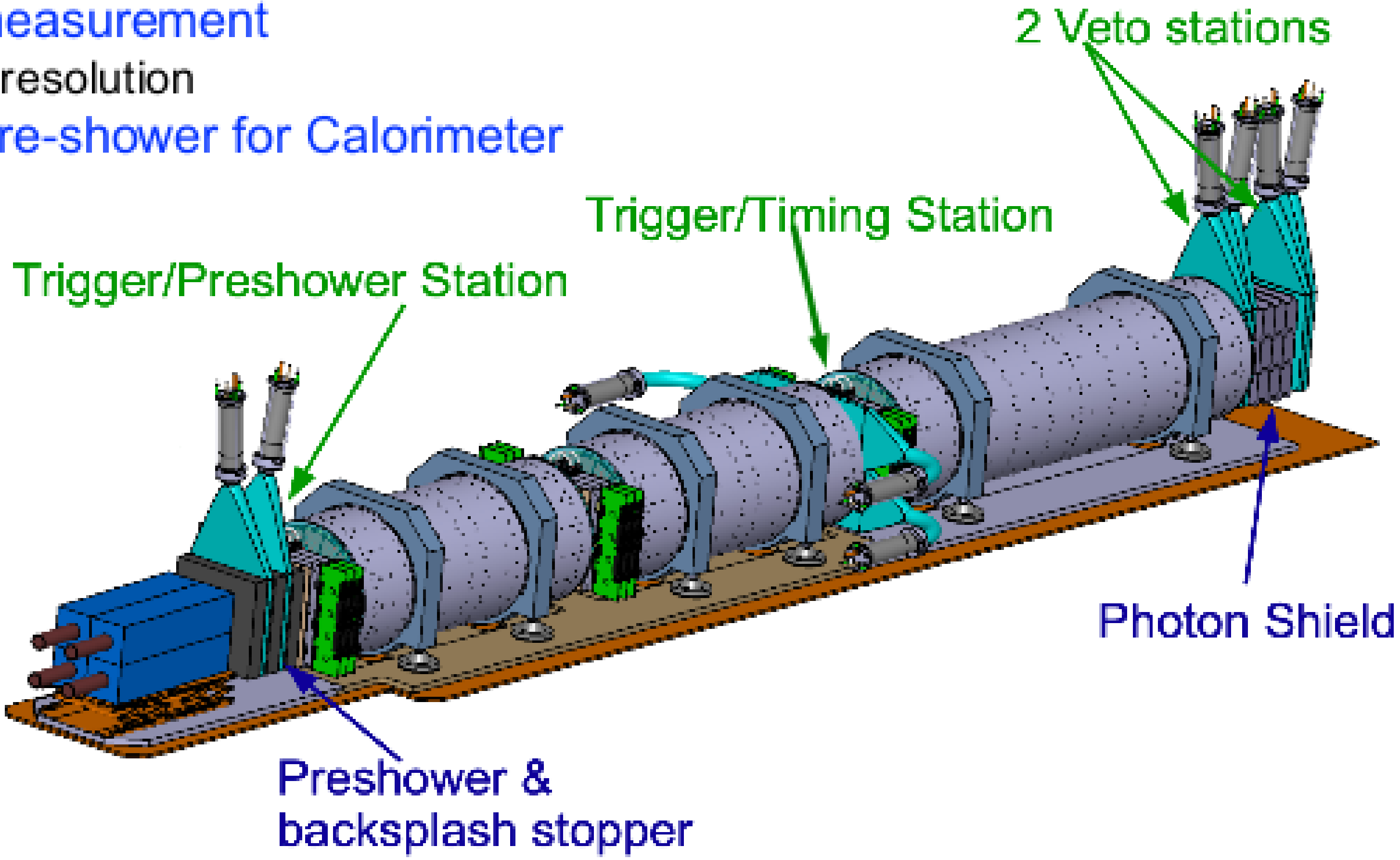


FASER Scintillator



Scintillators used for:

- Vetoing incoming charged particles
    - Very high efficiency needed ($O(10^8)$ incoming muons in 150/fb)
- Triggering
    - Expected trigger rate: ~ 500 Hz (muons)
- Timing measurement
    - ~1ns resolution
- Simple pre-shower for Calorimeter

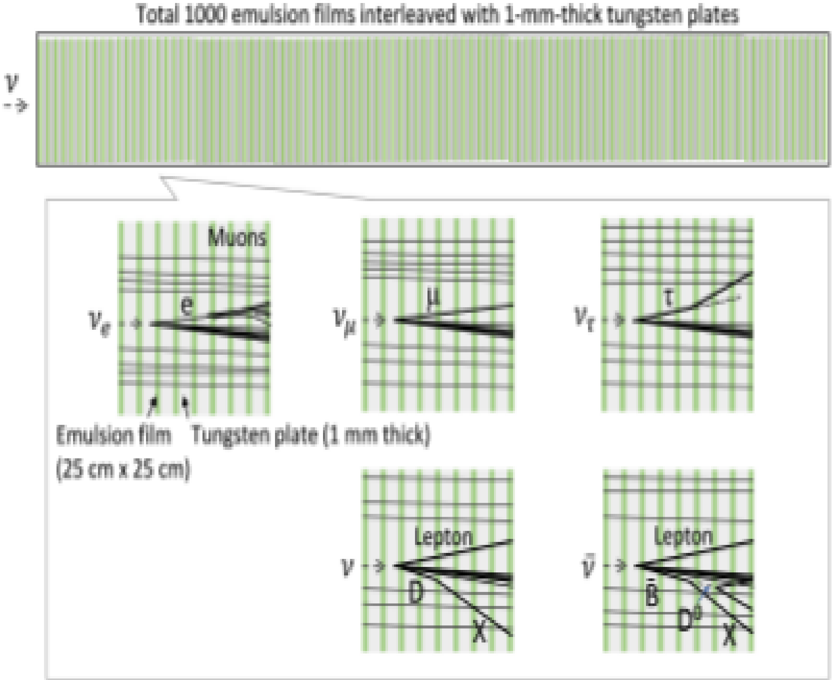


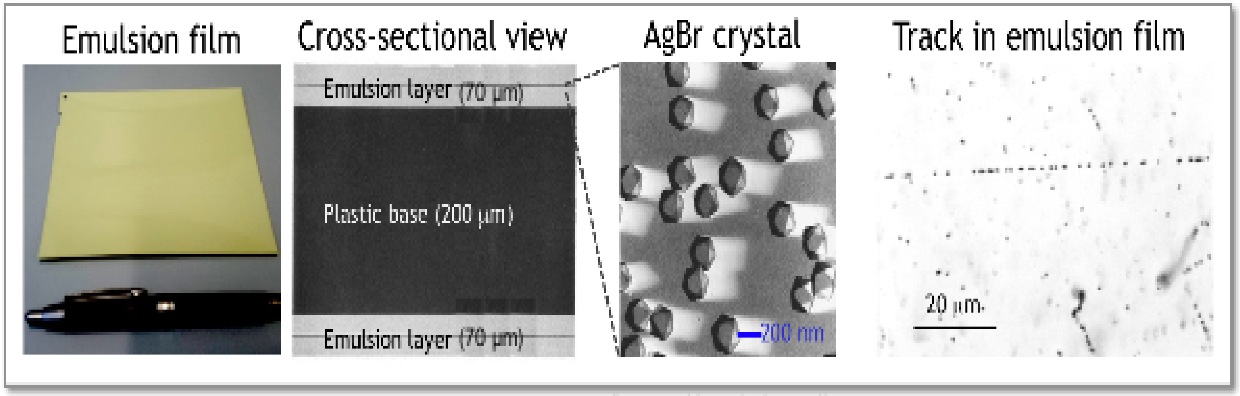
FASERν detector

- FASERν: tungsten emulsion detector in front of FASER
  - 3D tracking detector, 50 nm precision, no timing
  - Total mass 1.2 tons, 285 X_0, 10.1 λ_{int}
- Needs to be exchanged every ~3 months (during technical stops) to control track density $\lesssim 1 \times 10^6$ tracks/cm³
- To be installed before data taking in 2021.
  - 10 emulsion detectors in total needed 2021-2024 data.

	Interactions	Mean energy
$\nu_e + \bar{\nu}_e$	~1300	~830 GeV
$\nu_\mu + \bar{\nu}_\mu$	~20400	~630 GeV
$\nu_\tau + \bar{\nu}_\tau$	21	965 GeV

Assumptions: tungsten emulsion detector (25 cm x 25 cm x 100 cm), 14 TeV, 150 fb⁻¹, E_ν > 100 GeV





dispersed in gelatin media

FASERν detector

- Global reconstruction possible with interface to FASER spectrometer:
  - Muon charge identification → distinguish neutrino/anti-neutrino
  - Momentum of charged tracks → improve neutrino energy reconstruction
  - Timestamp of events and identify additional activity → background rejection
- Interface detector would be installed in 2021-22 YETS.