# Very forward particle productions at LHCf and RHICf

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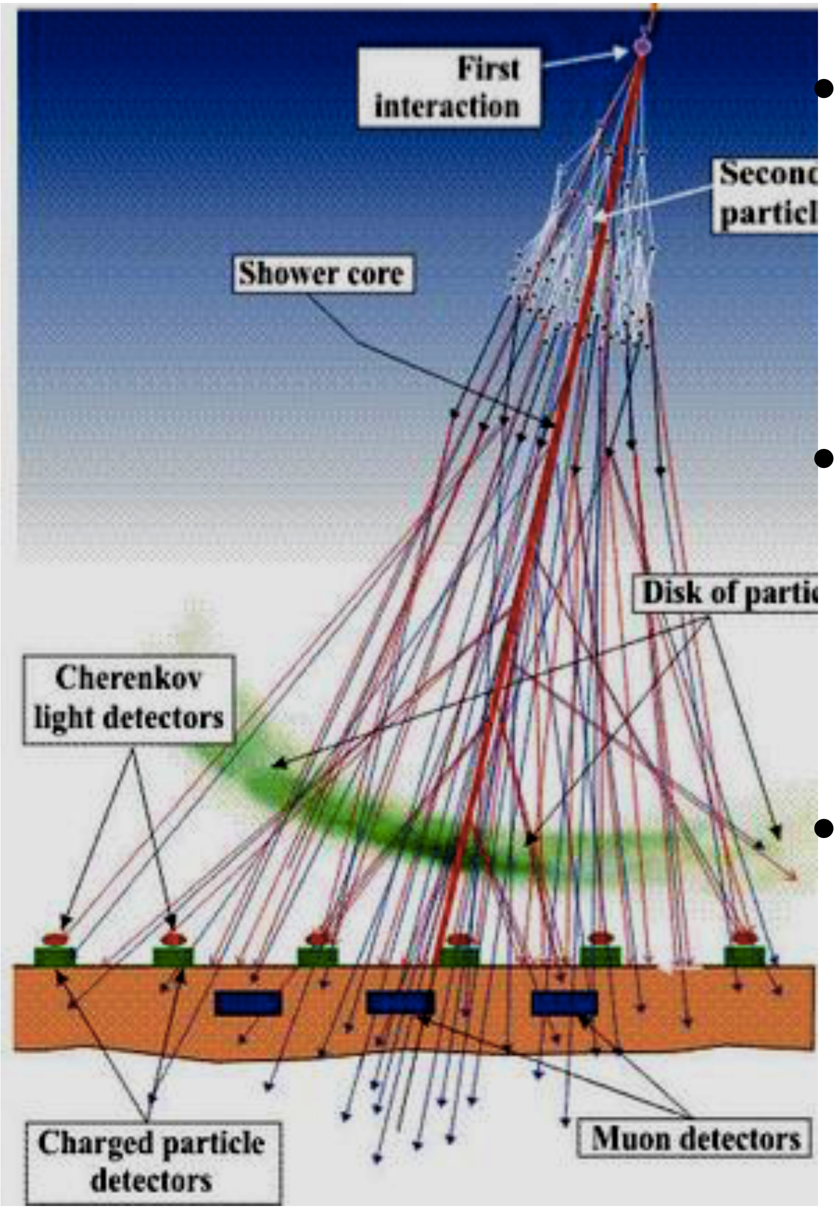
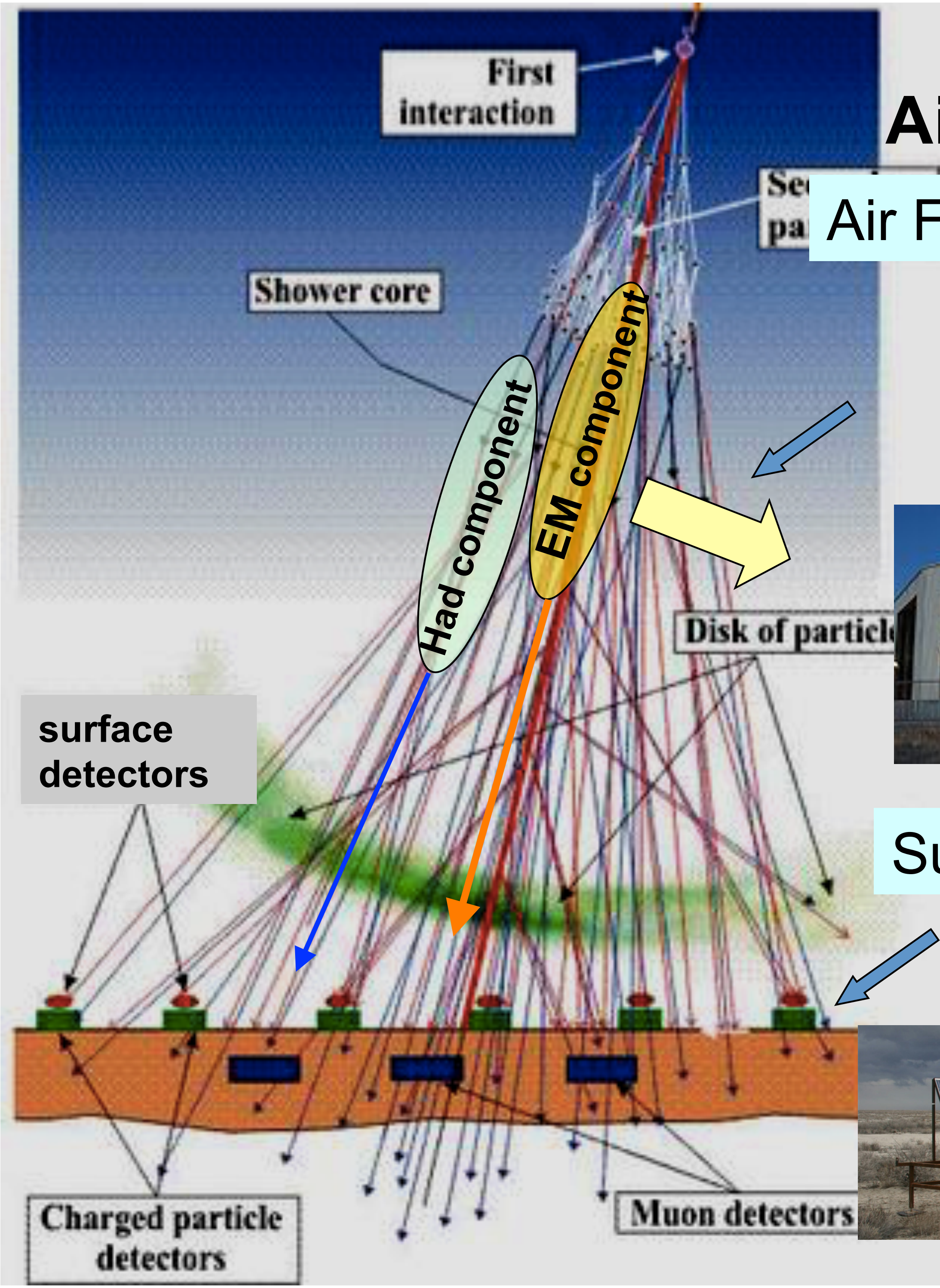
for the LHCf and RHICf Collaboration

11th Circum-Pan-Pacific Symposium on High Energy Spin Physics,
Aug 27 – 30, 2019, ANA Holiday Inn Resort Miyazaki, Japan

# Forward production and cosmic rays




- Air shower measurements of very high cosmic rays rely on hadronic interaction modeling.
- Need precise knowledge on minimum bias interactions, including forward productions
- They are high-energy and non-pQCD regime. Need collider data and a good phenomenological model.




# Air shower observation

## Air Florescence telescope (FD)

EM component
(>90% of collision energy)

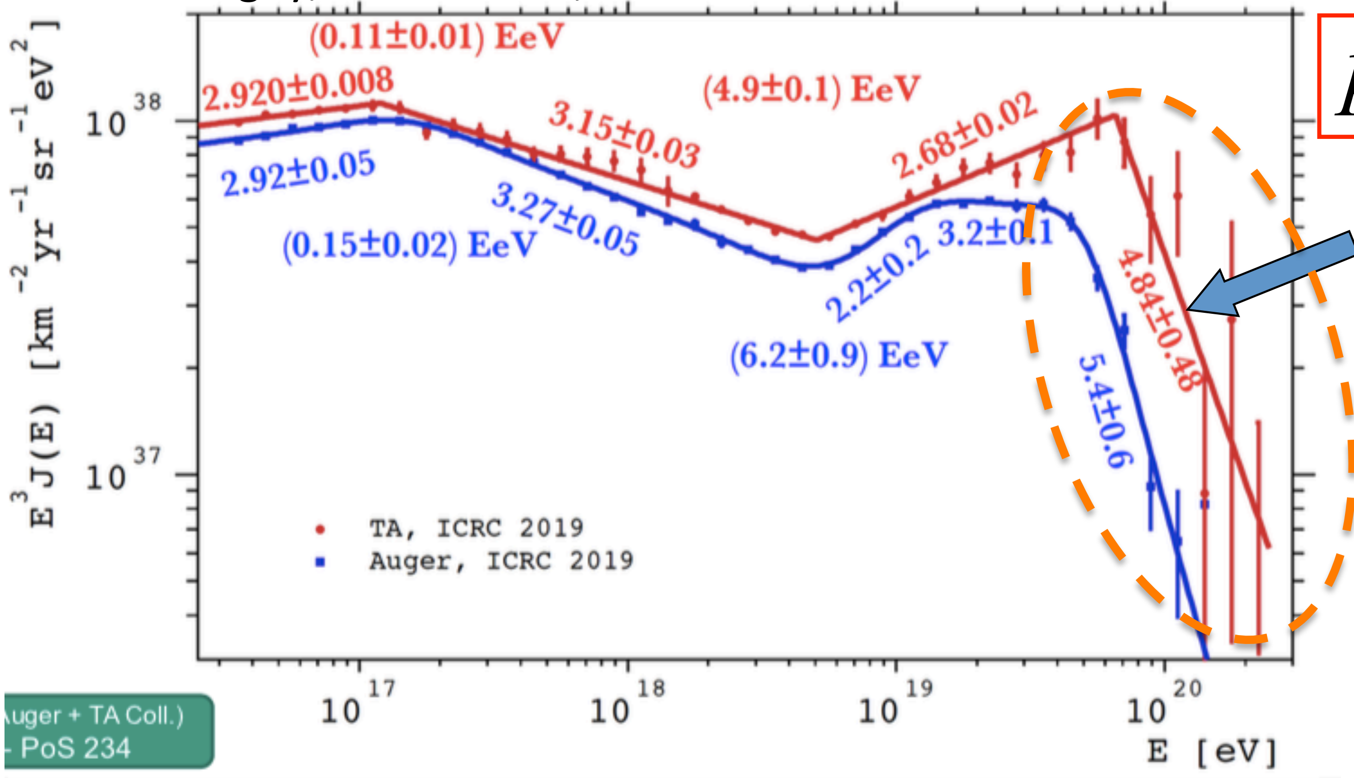
- Total calorimeter
- Shower max altitude

## Surface Detectors (SD)

# of particles at given altitude
(EM or Muon component)

# GZK cut-off confirmed ? But...

O.Deligny, F.Schroeder, ICRC2019




$$\boxed{p + CMB\gamma \rightarrow \Delta}$$

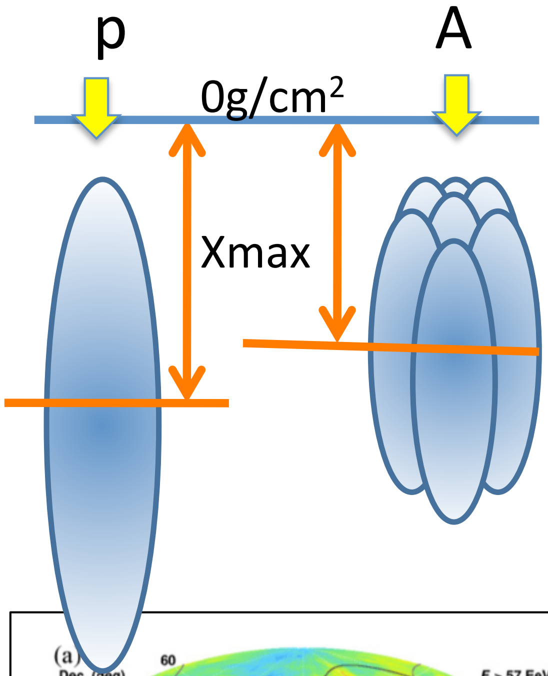
GZK cut off ?

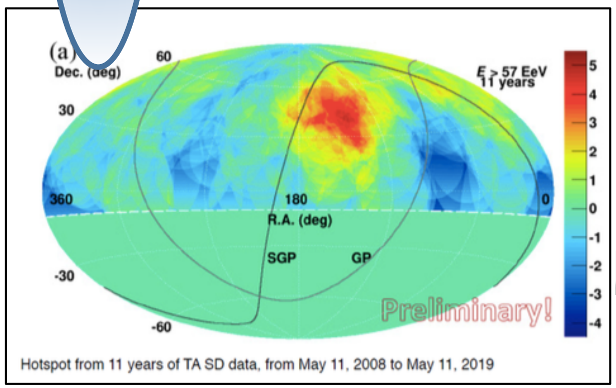
Need to confirm UHECR is p or A ? (photo-dissociation)

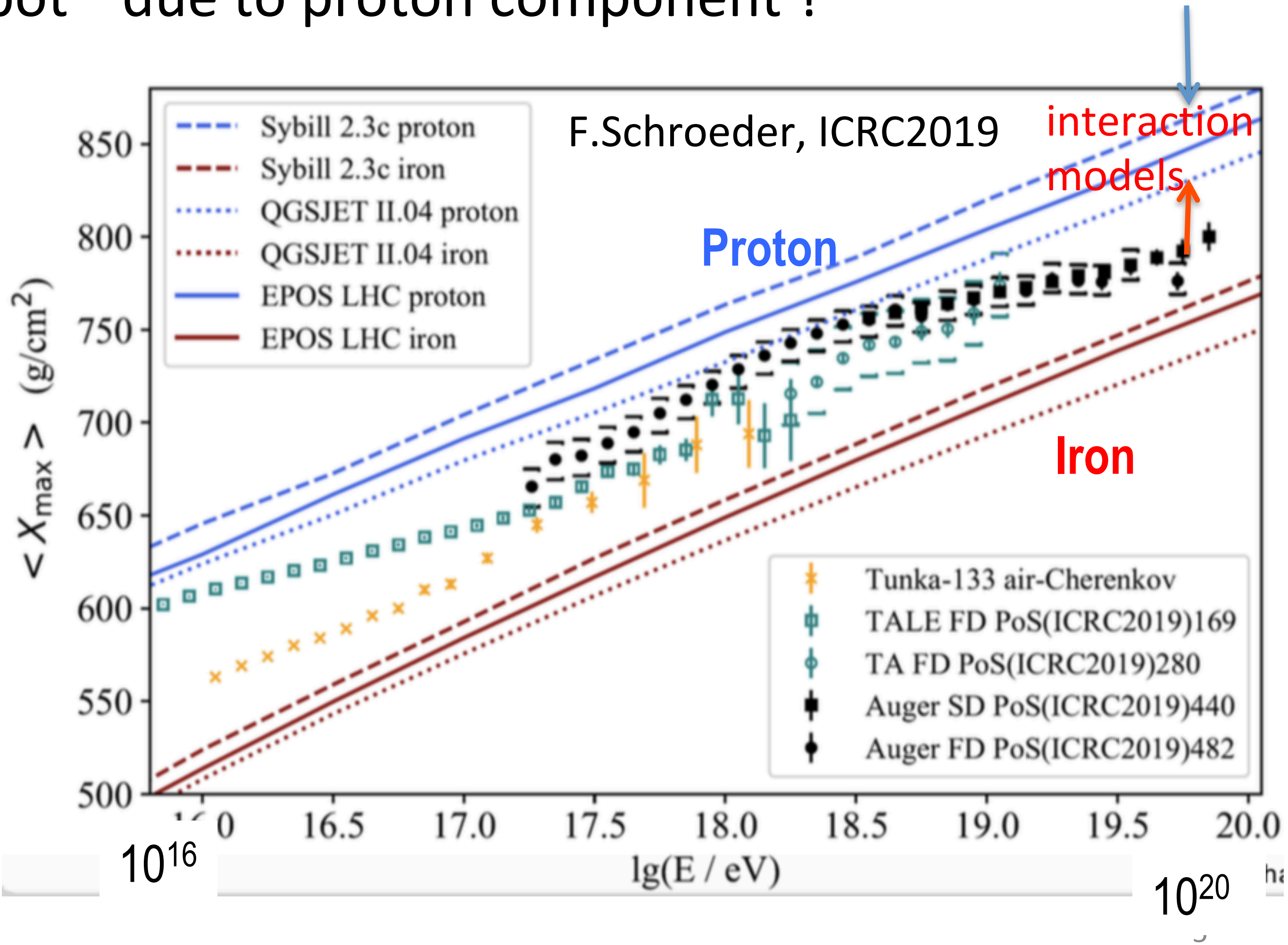
- GZK like cut off observed both by AUGER and by TA, but...
- Chemical composition (p or A) ?, yet controversial
- SD and FD energy scales differ.
- Too much ground muons (>factor 2), if proton (AUGER)

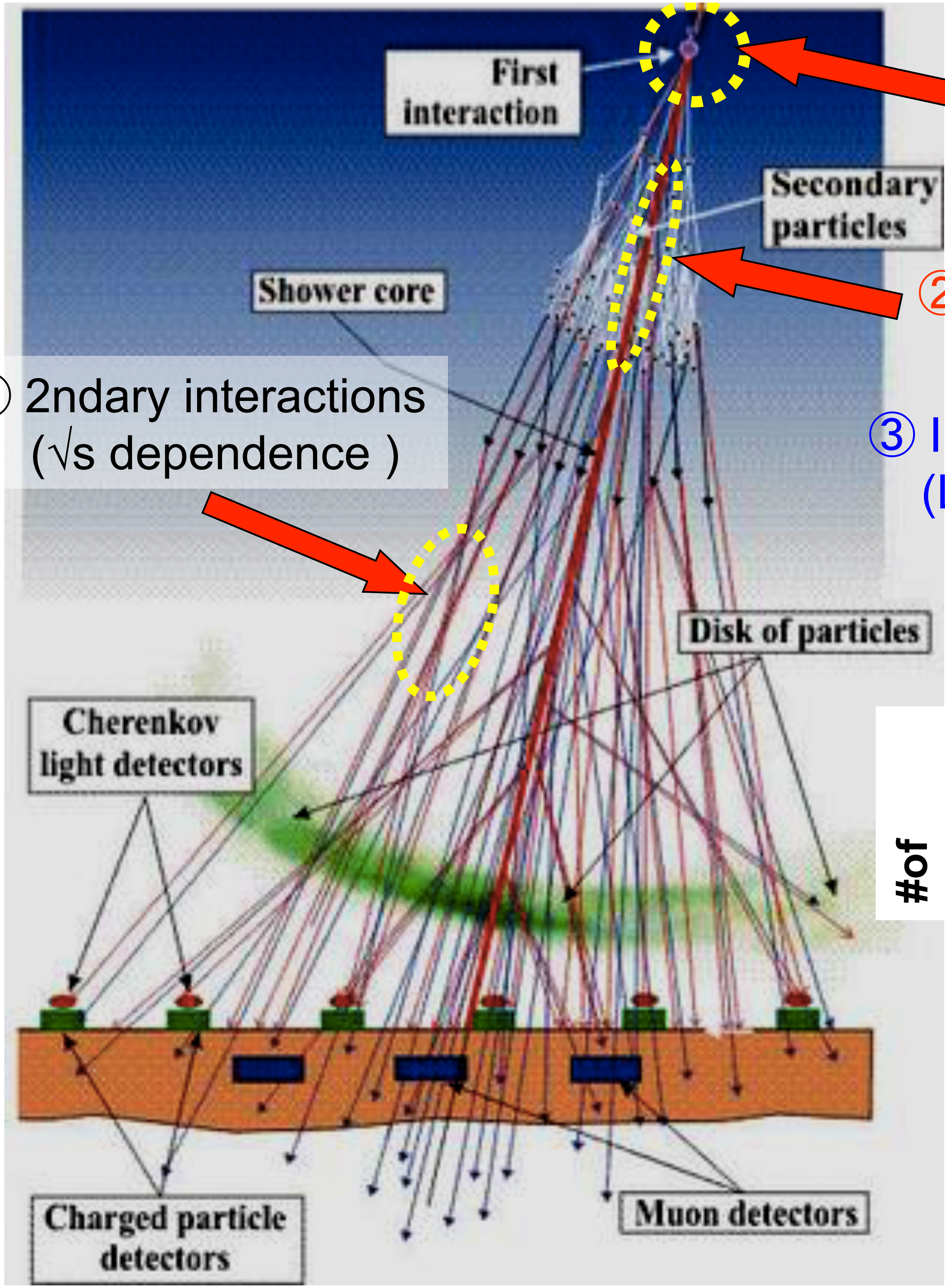
# Chemical composition and shower Xmax

- Proton primaries : deep penetrating shower (large Xmax)
- Nuclear primaries: quick developing showers (small Xmax)
- Data shows transition from light to heavy primary. Pure p or mixed ?
- Indication of "hot spot" due to proton component ?





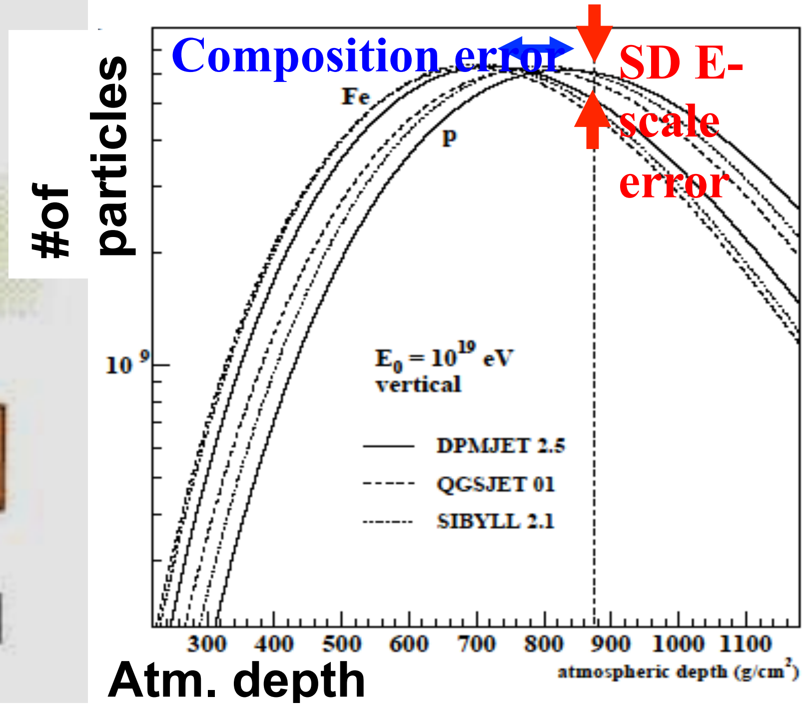

⑤ 2ndary interactions
($\sqrt{s}$ dependence )

① Inelastic cross section
(TOTEM and others)

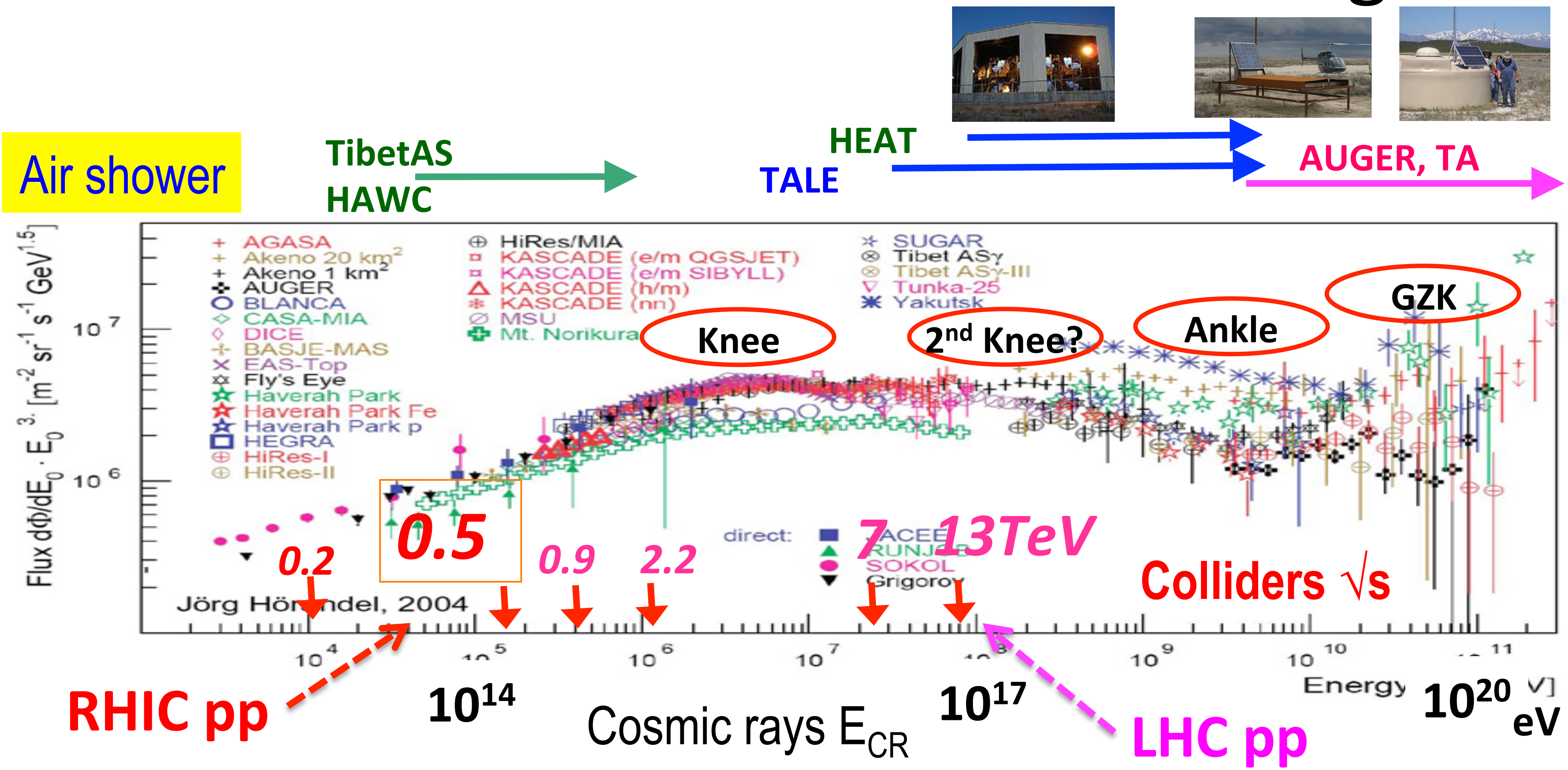
② Forward energy spectrum
( LHCf $\gamma$ / $\pi^0$ spectrum)

③ Inelasticity $k= 1-p_{lead}/p_{beam}$
(LHCf forward neutron, n / $\gamma$ ratio )

④ Nuclear effect
(shadowing, Cronin effect)

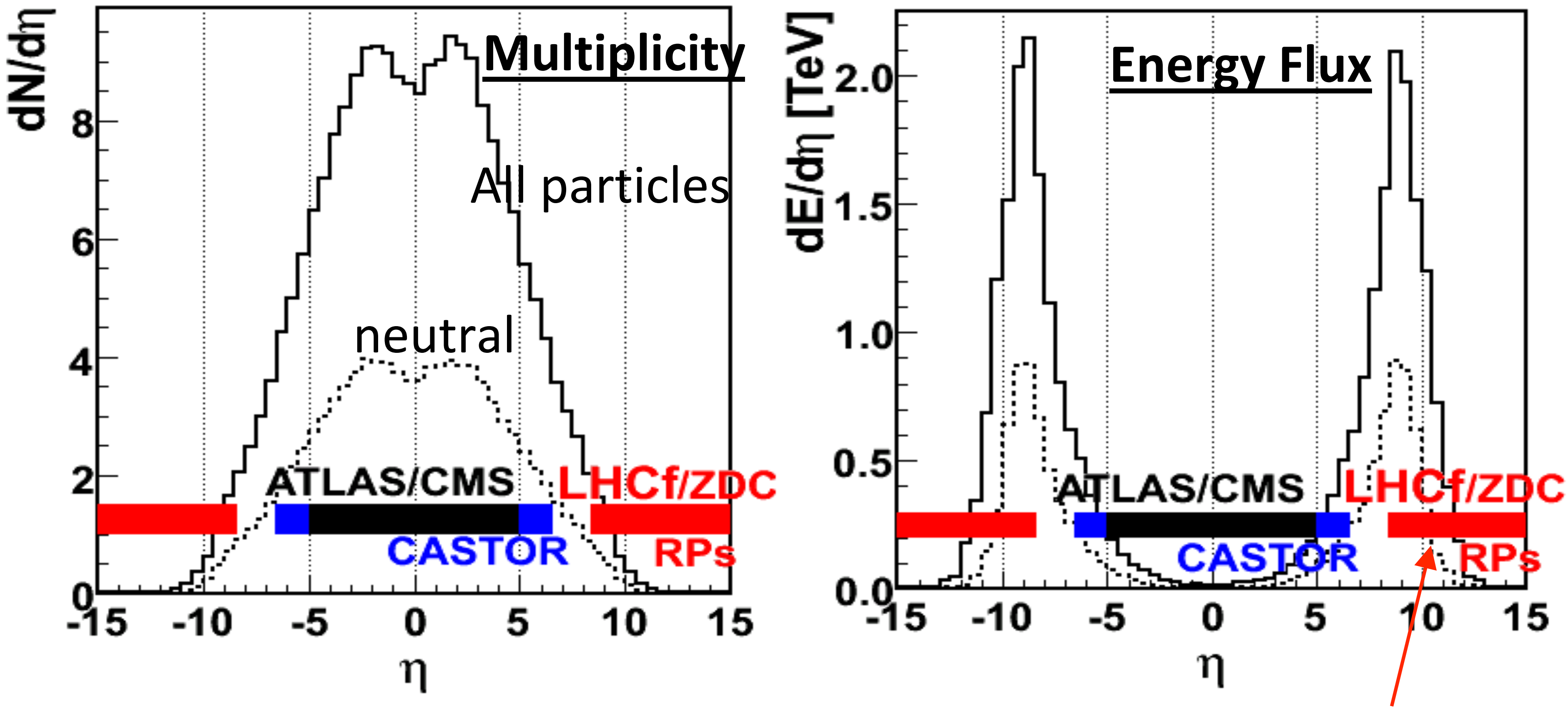


# UHECR Interactions = Collider Energies




- Need dedicated very forward measurement at hadron colliders
- So far LHCf pp (13, 7, 2.76, 0.9 TeV) and p-Pb(5,8 TeV/n) available
- RHIC provies 0.5 TeV pol pp w/ same pT coverage as LHC
- RHIC also provides various p-A or A-A collisions

# Particle productions at LHC ($\sqrt{s}$=14TeV)



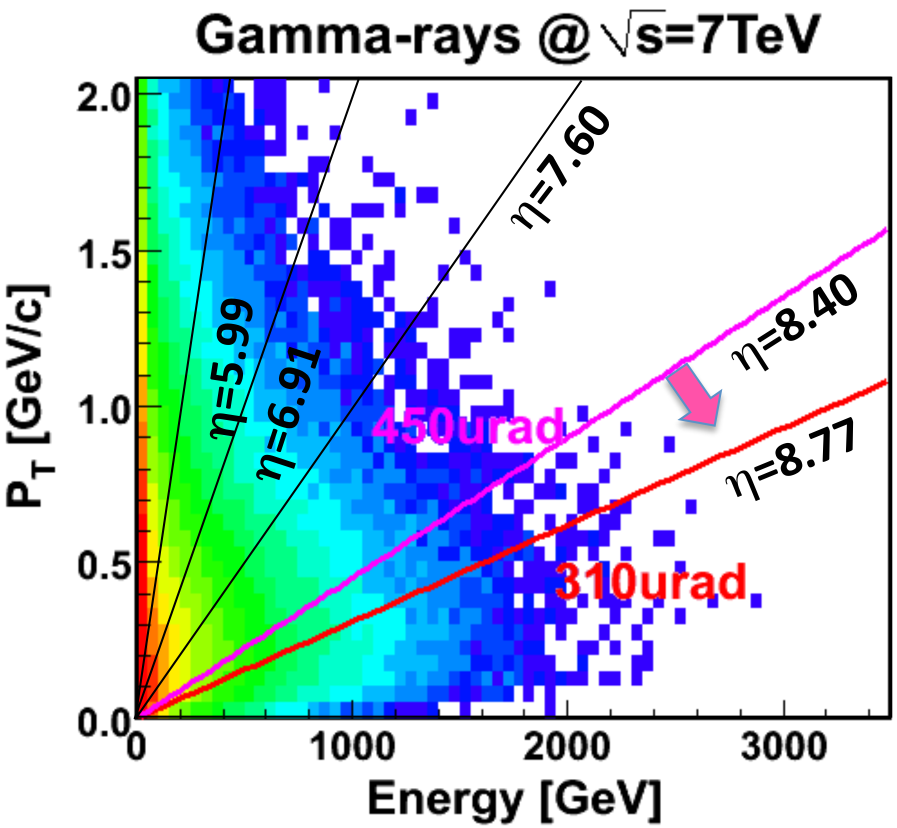

$8.4 < \eta < \infty$

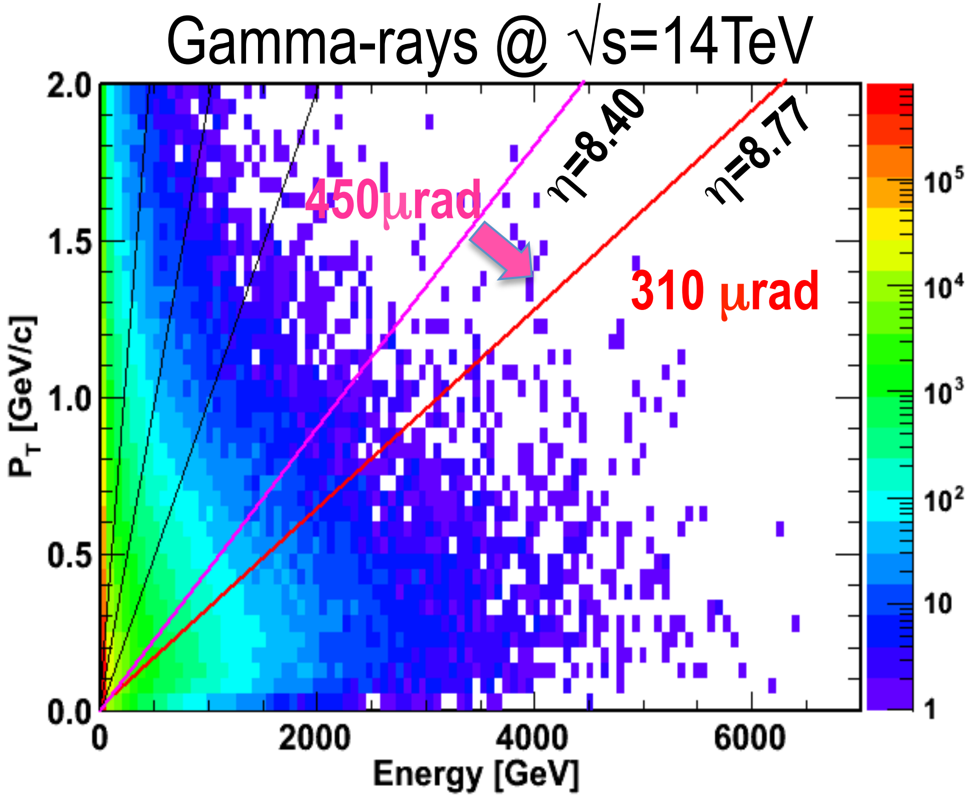
Most of the energy flows into very forward

( Particles of $X_F > 0.1$ contribute 50% of shower particles )

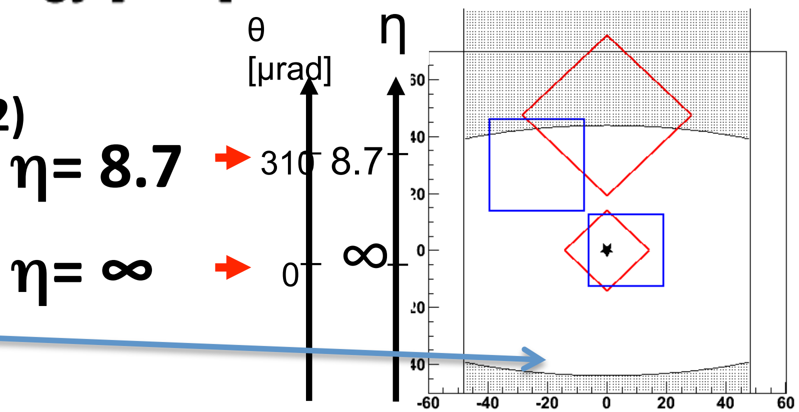
LHCf/ZDC location can access |n| > 8.4

# Rapidity vs Forward energy spectra



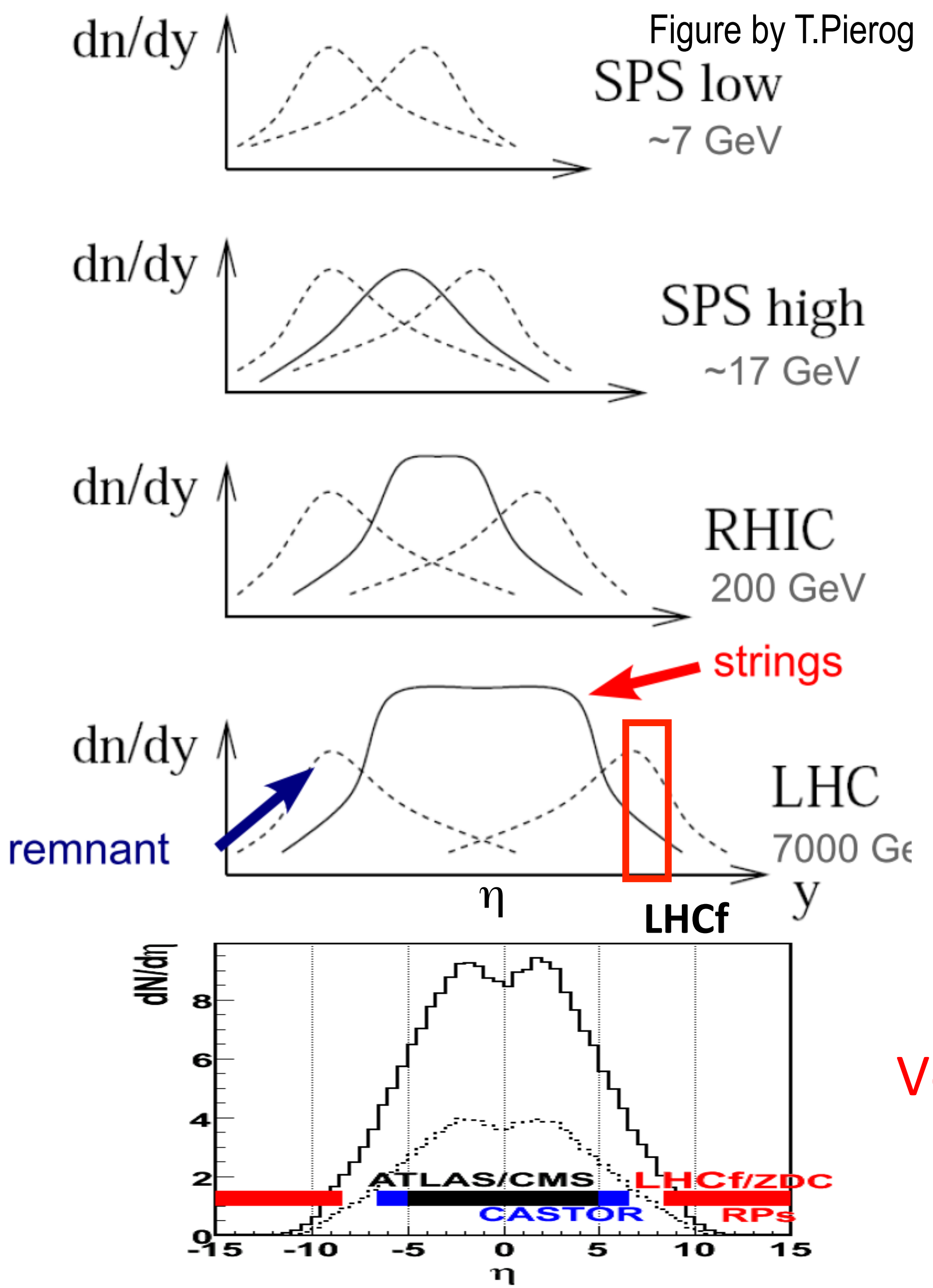

**Viewed from IP1**
**(red:Arm1, blue:Arm2)**

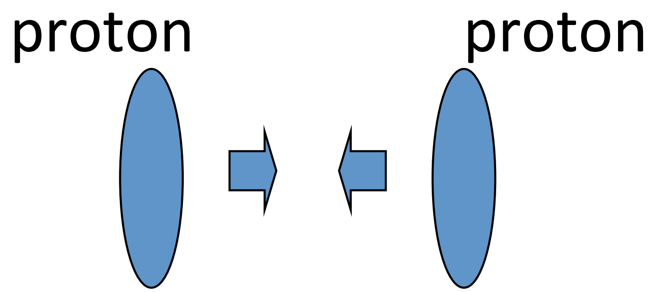


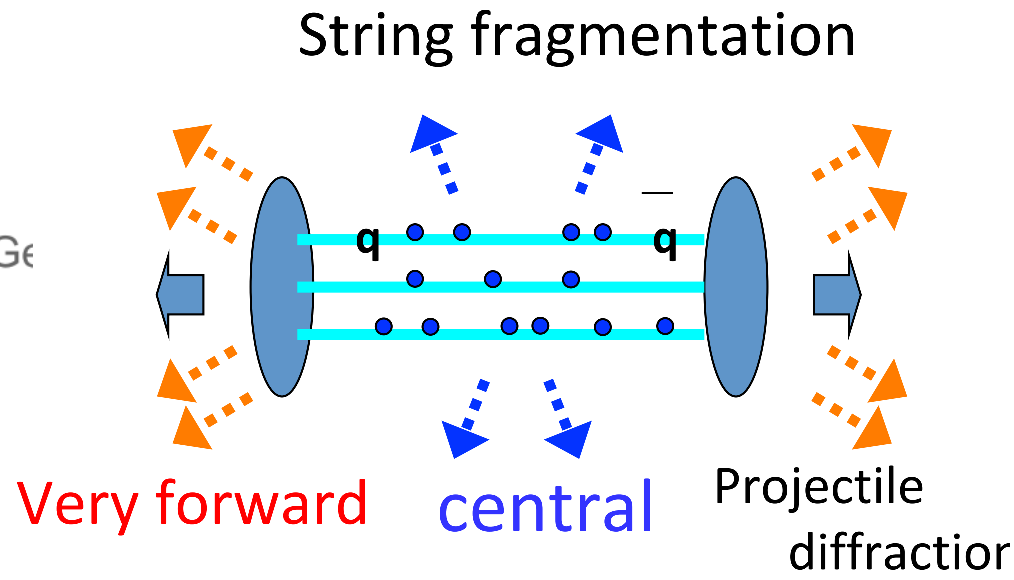

Projected edge of beam pipe

Very Forward
$p_T$ < ~ 1 GeV/c

# 2ndary particle productions

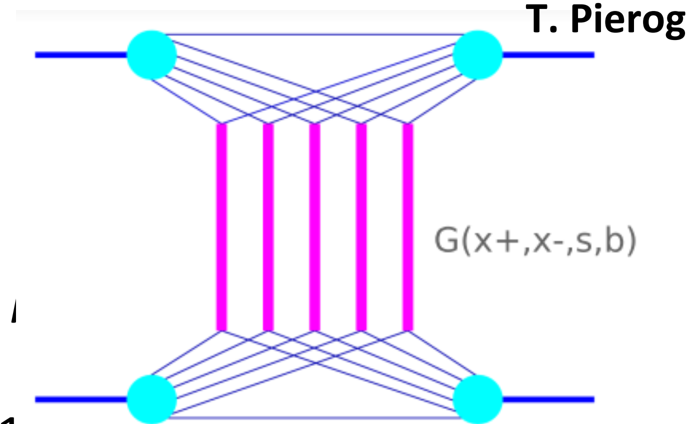


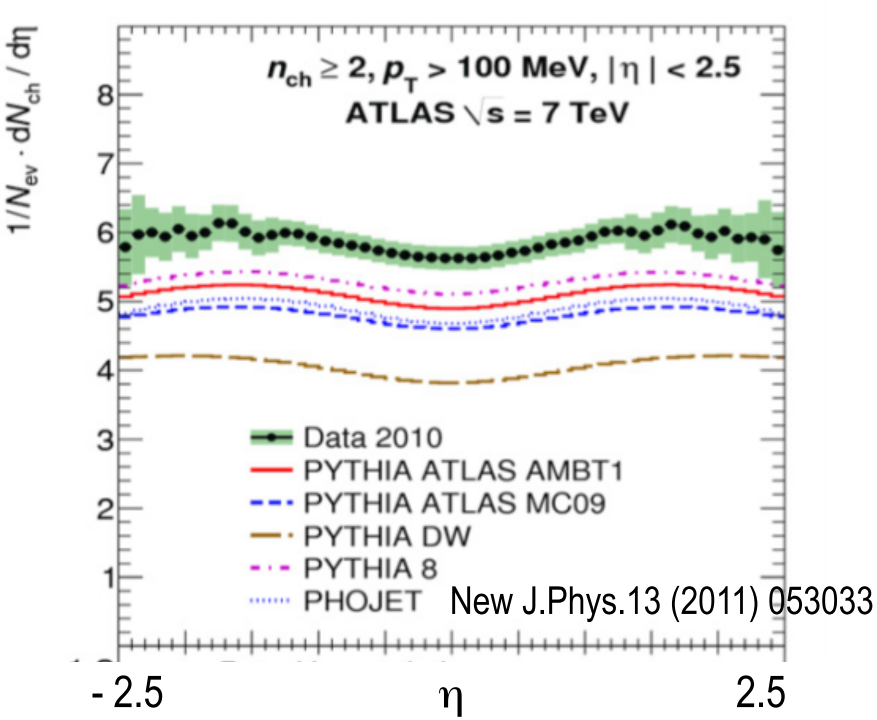



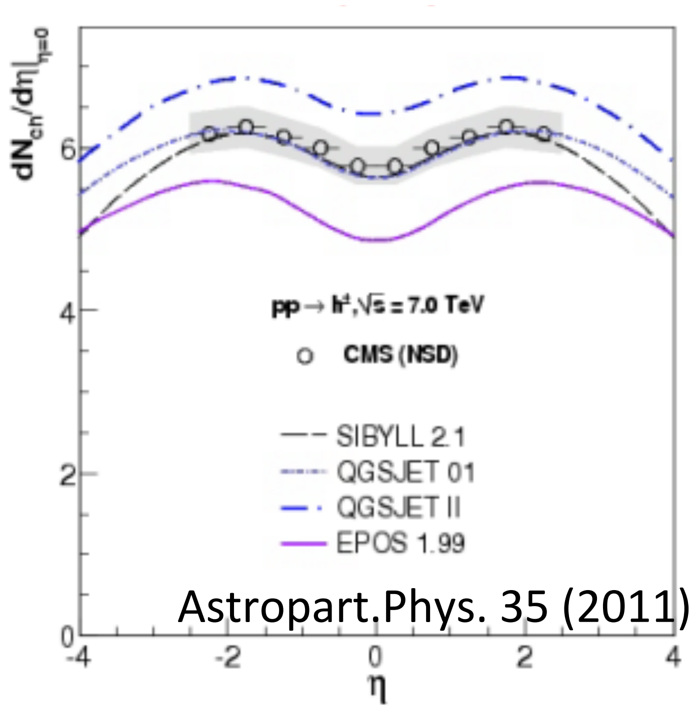
# Gribov-Regge type cosmic ray interaction models

- **SYBILL2.1 → SYBILL2.3c**
  - E.J. Ahn et al., Phys. Rev. **D80**, 094003 (2009).
- **QGSJET II → QGSJETII-4**
  - S. Ostapchenko, Phys. Lett. **636**, 40 (2006).
- **DPMJET3**
  - S. Roesler, R. Engel and J. Ranft, *Proc. of 27th*
- **EPOS1.9 → EPOS-LHC**
  - T. Pierog and K.Werner, Phys. Rev. Lett. **101**, 1




New J.Phys.13 (2011) 053033




Astropart.Phys. 35 (2011) 98-113

# LHCF DETECTORS

# The LHCf Collaboration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**W.C.Turner** *LBNL, Berkeley, USA*

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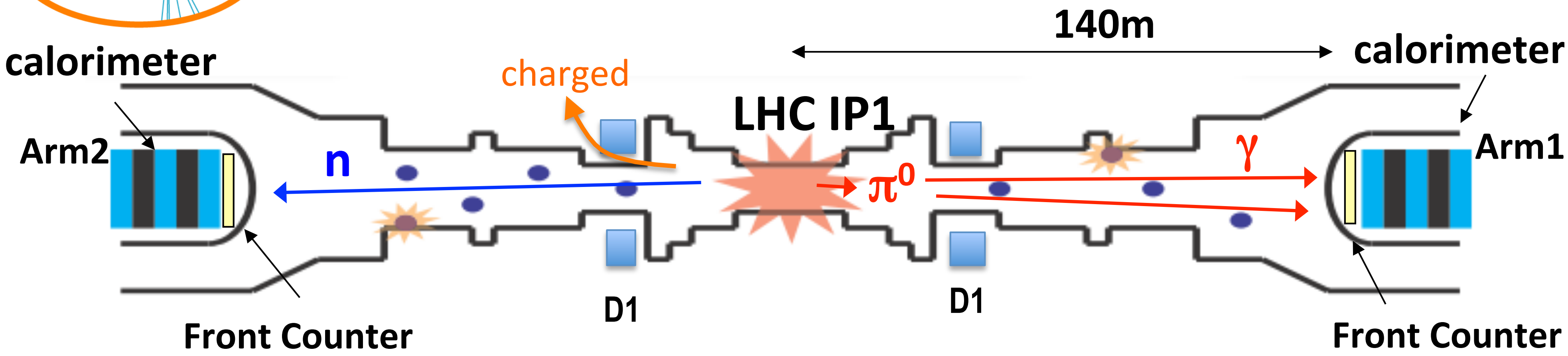
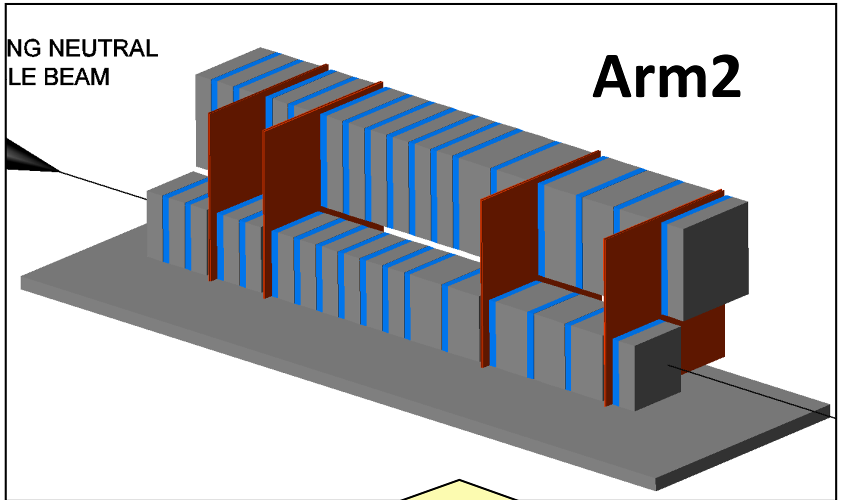
*INFN, Univ. di Firenze, Italy*

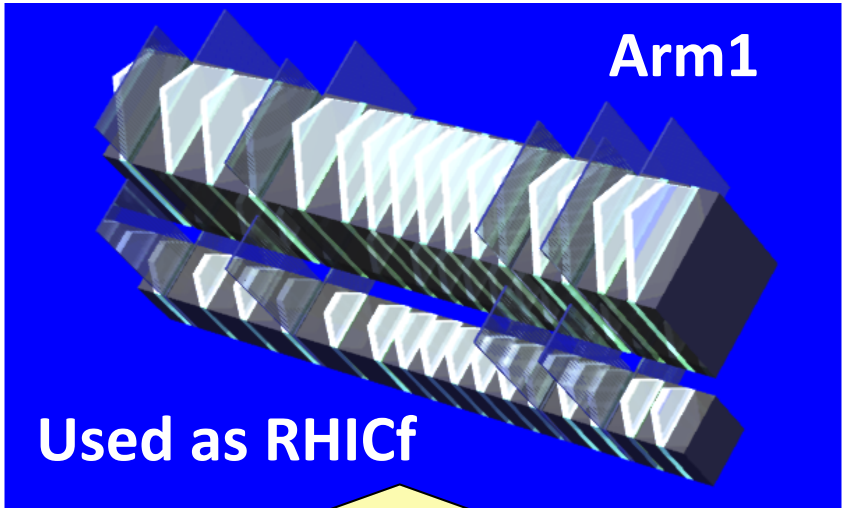
**A.Tricomi** *INFN, Univ. di Catania, Italy*

# The LHCf experiment at LHC



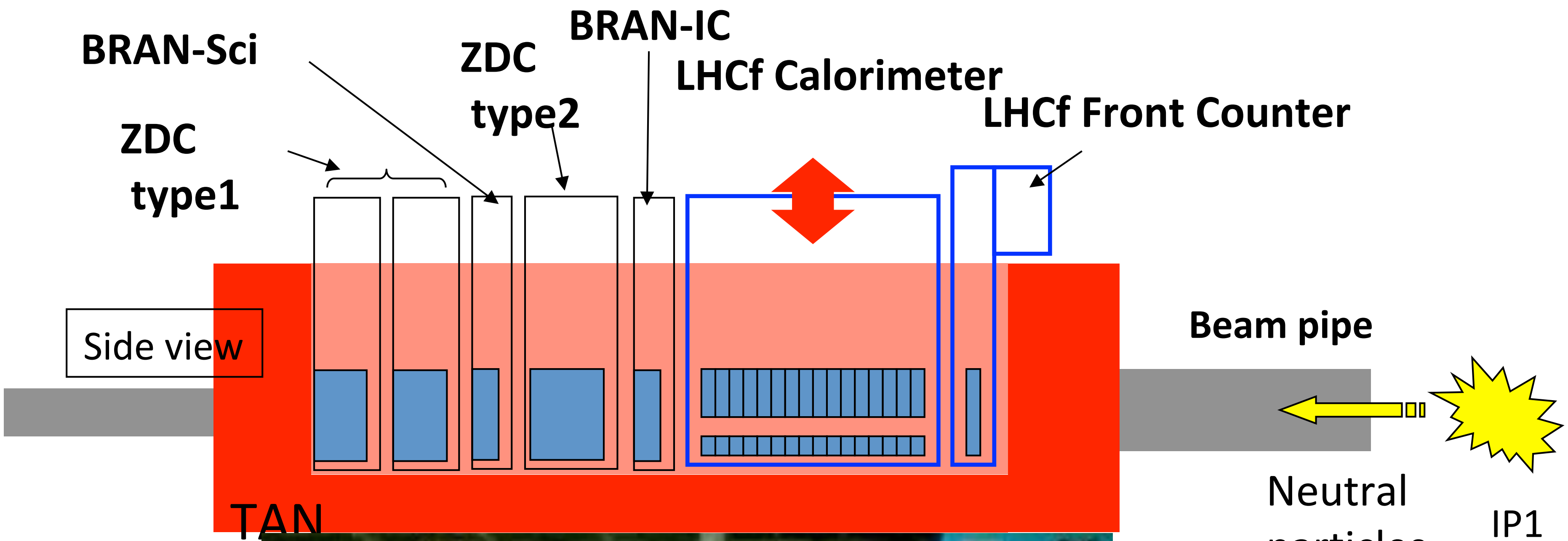

$44X_0$,
$1.6\ \lambda_{int}$

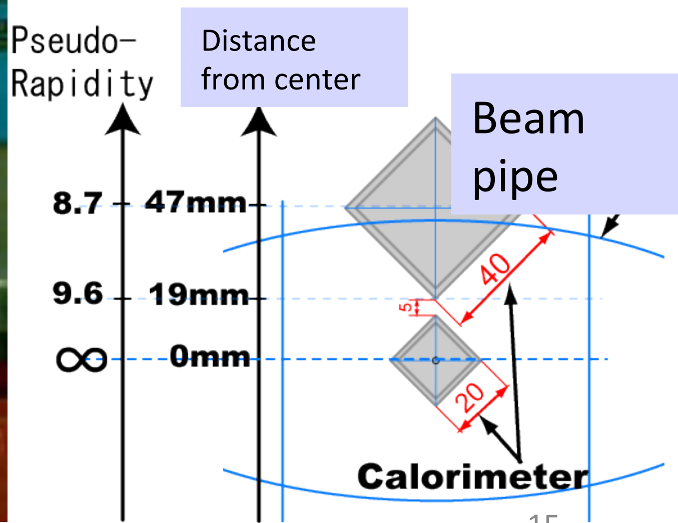



**16 tungsten + GSO scinti. layers**
**25x25mm(TS)+32x32mm (TL)**
**4 Silicon strip tracking layers**

**16 tungsten + GSO scinti. layers**
**20x20mm(TS)+40x40mm (TL)**
**4 GSO-bar tracking layers**

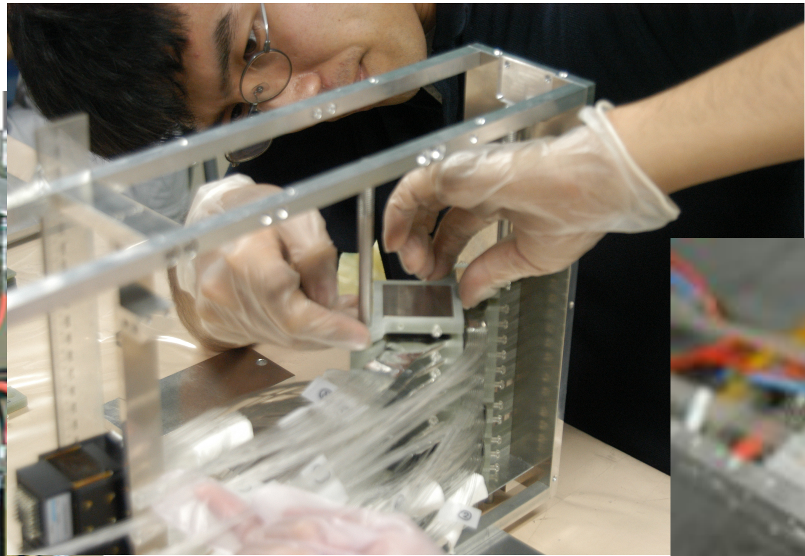
# Setup in IP1-TAN (side view)

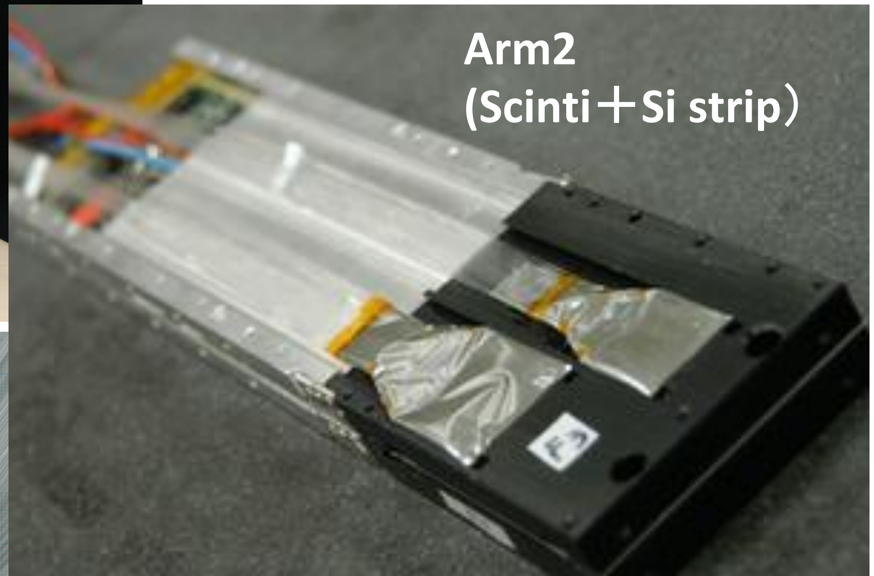


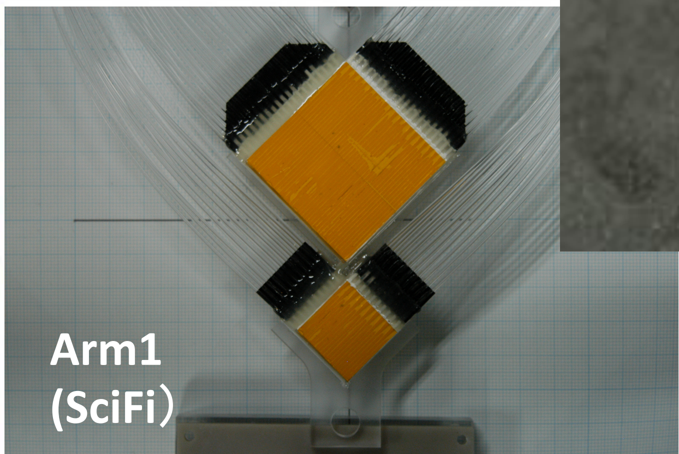



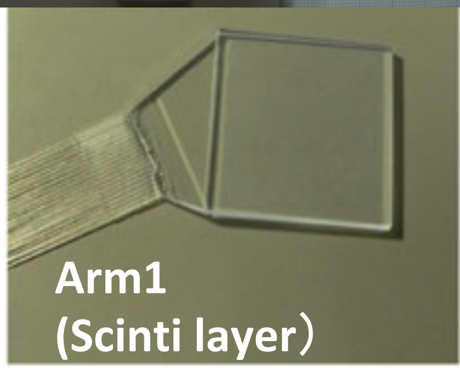
# LHCf calorimeter

Arm1
(during asembling)

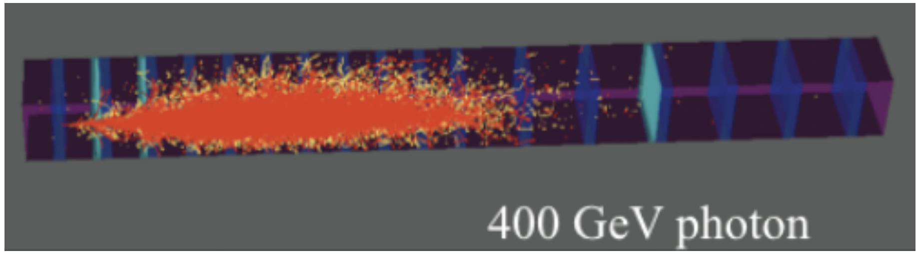


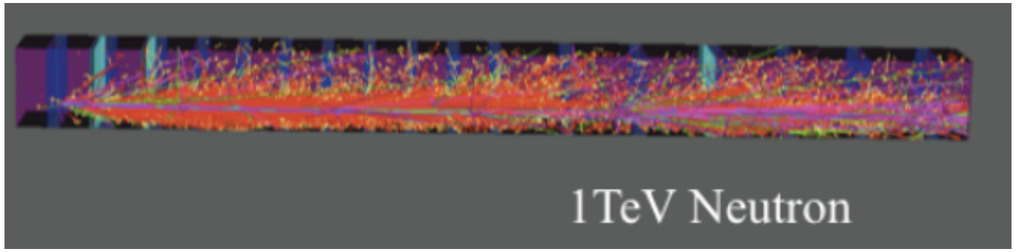


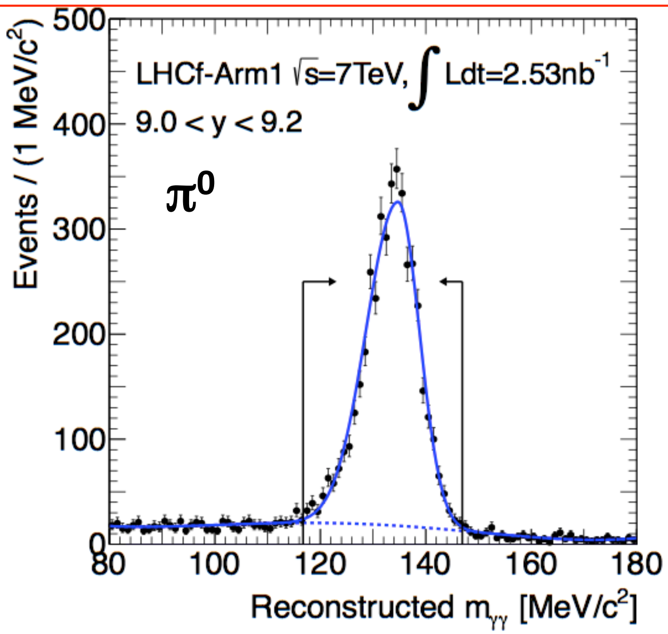



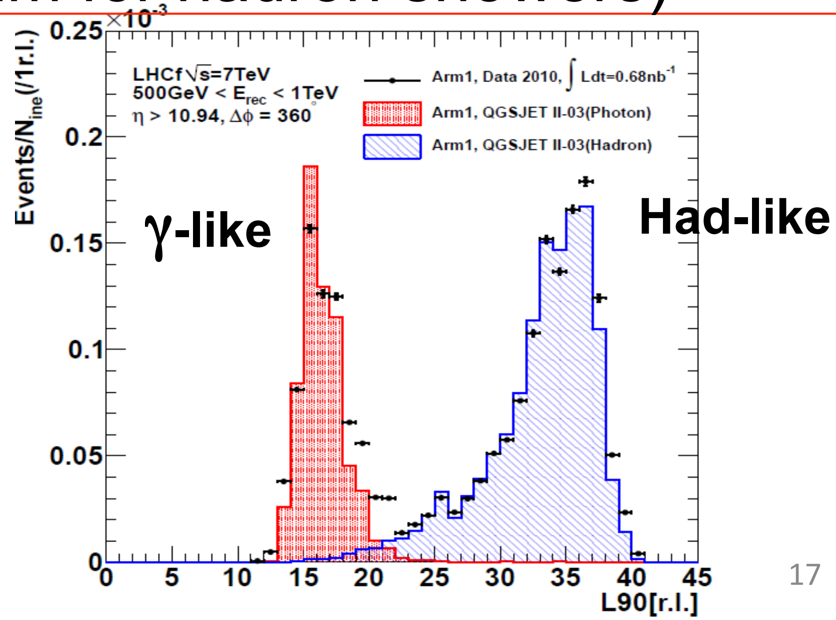

# Calorimeter performance



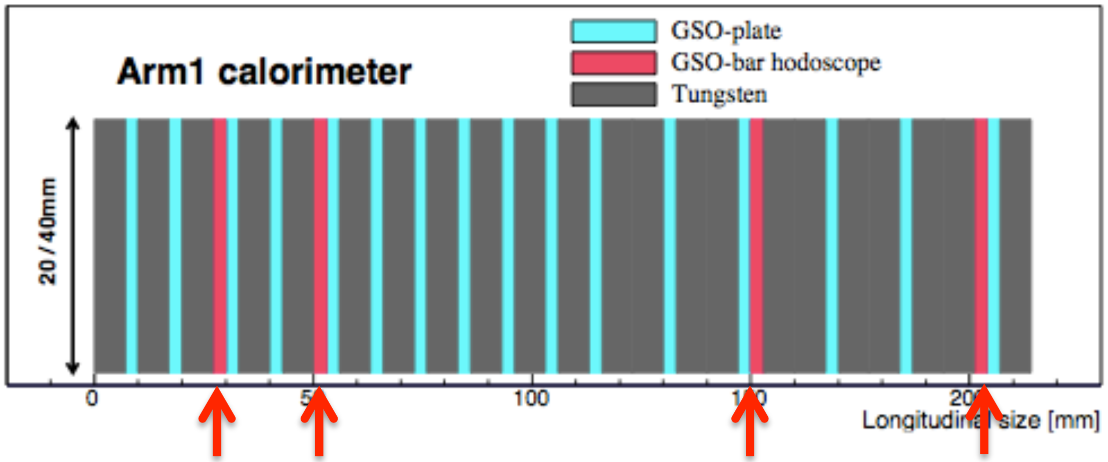



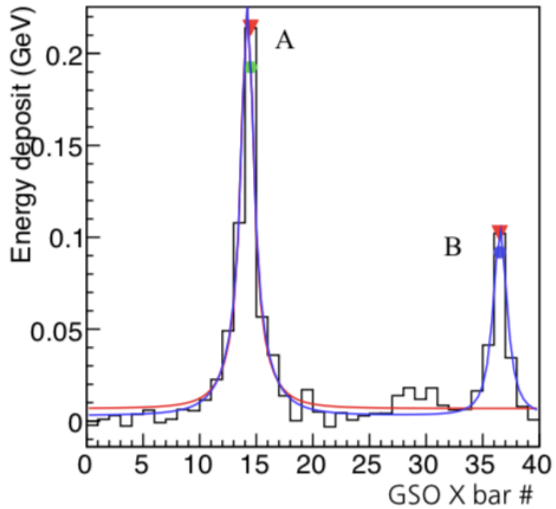

- Gamma-rays (E>100GeV, dE/E<5%)
- Neutral Hadrons (E>a few 100 GeV, dE/E~40%)
- Neutral Pions (E>700GeV, dE/E<3%)
- Shower incident position (170$\mu$m / 40$\mu$m for $\gamma$, Arm1/Arm2)
  ( 1mm for hadron showers)



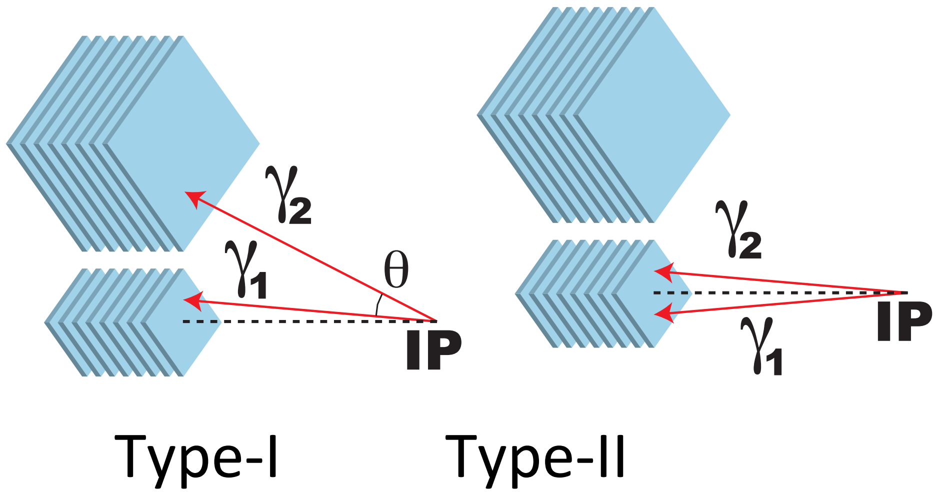



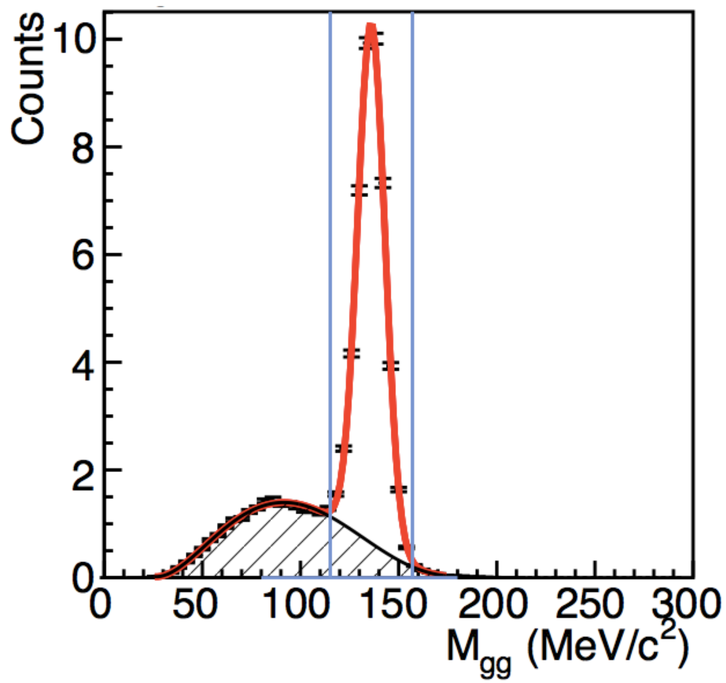
# $\pi^0$ reconstruction capability



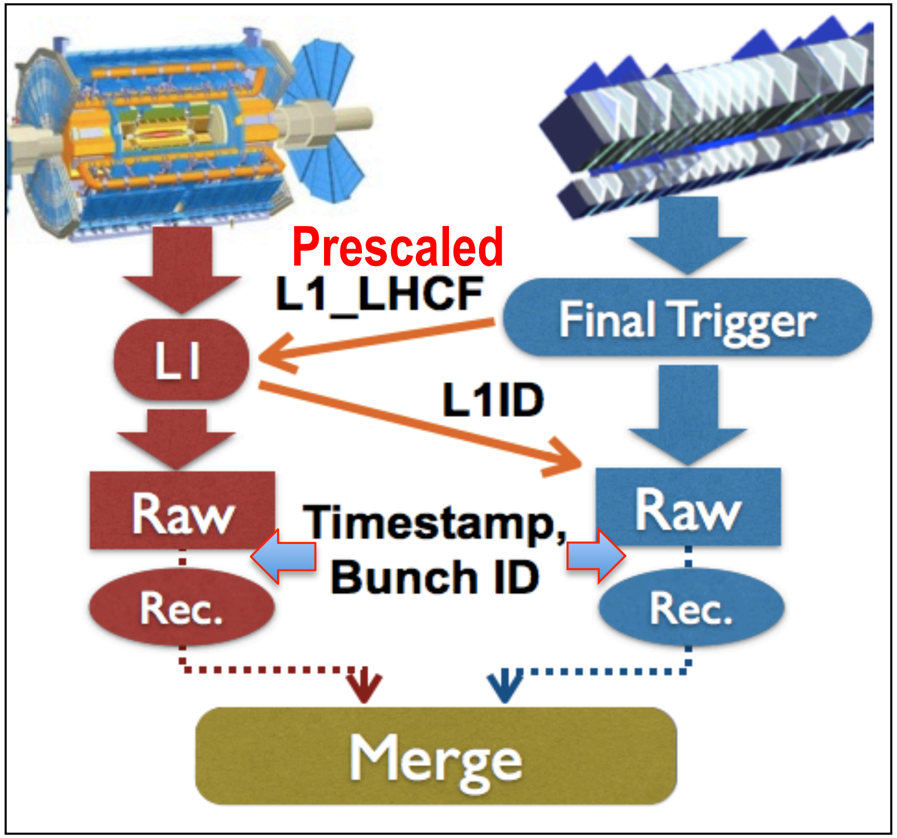



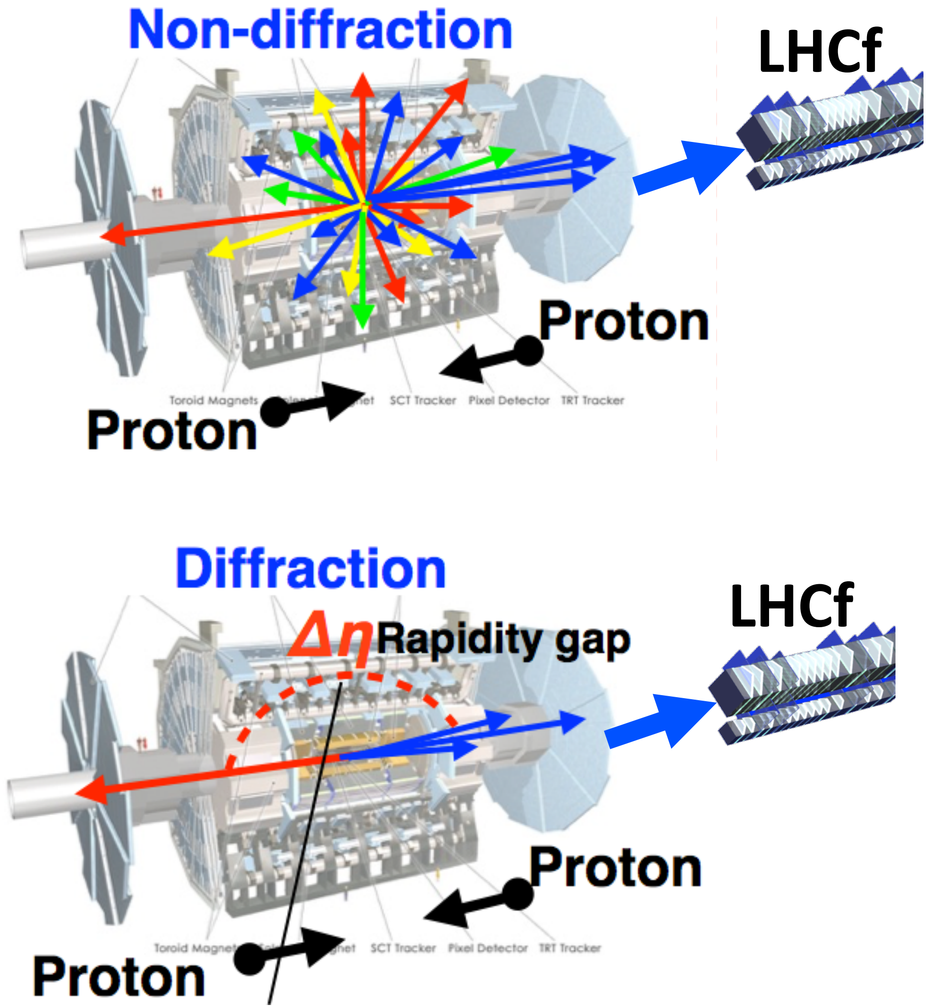

4-layers of 1mm GSO hodoscopes



# ATLAS-LHCf trigger exchange




**Powerful tool to study diffraction/non-diffraction separately**

# LHCF DATA

# Brief history of LHCf

- **May 2004 LOI**
- **Feb 2006 TDR**
- **June 2006 LHCC approved**

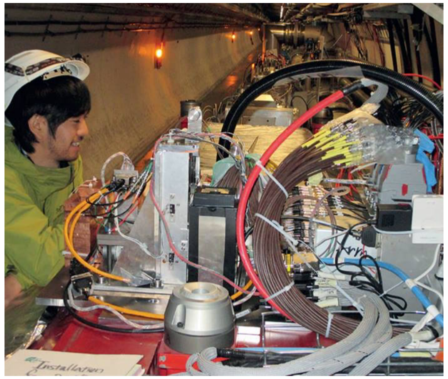
**Jul 2006**
**construction**

**Aug 2007**
**SPS beam test**

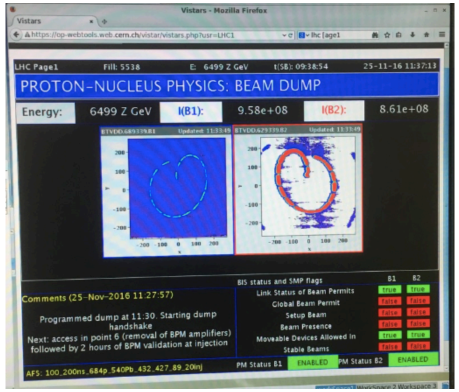
**Jan 2008**
**Installation**
**Sep 2008**
**1st LHC beam**

**Dec- Jul 2010**
**0.9TeV& 7TeV pp**
**Detector removal**

**Dec2012- Feb 2013**
**5TeV/n pPb, 2.76TeVpp**
**(Arm2 only)**
**Detector removal**



**May-June 2015**
**13 TeVpp**
**Detector removal**



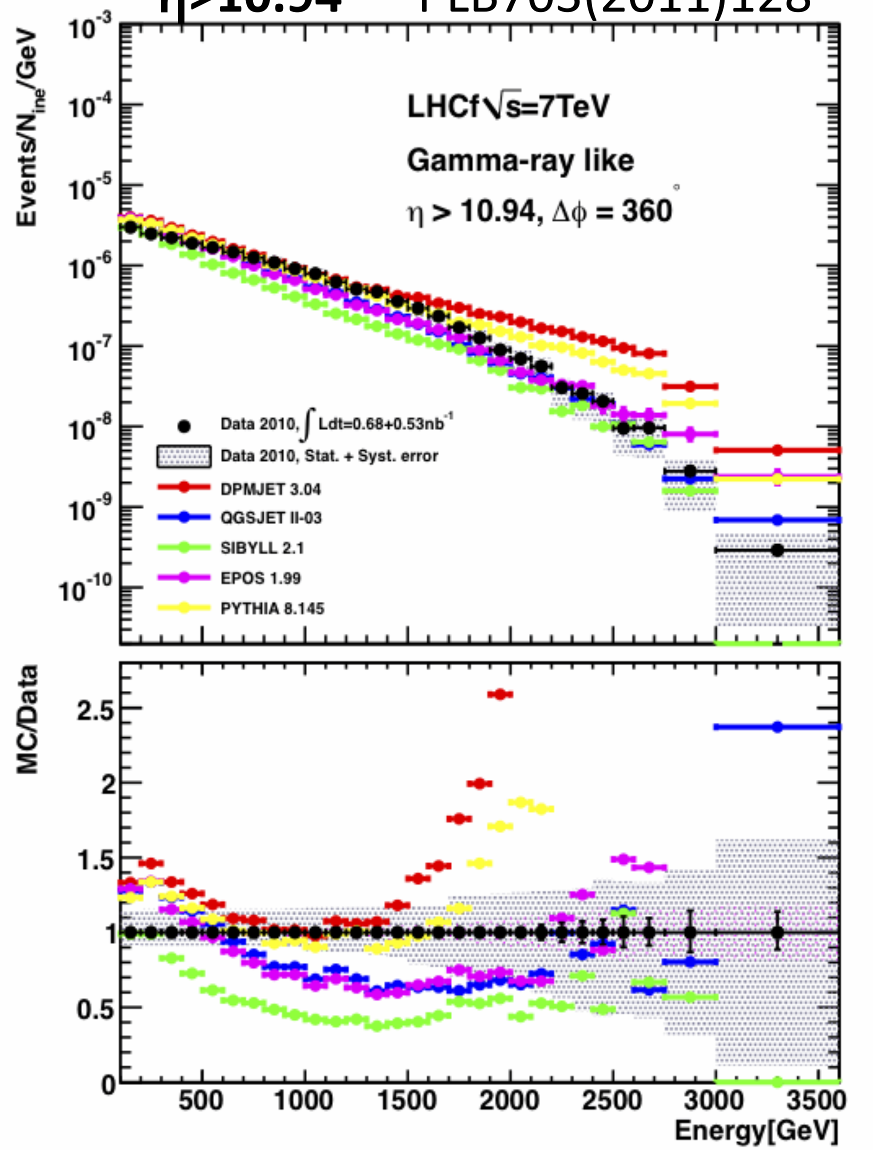

**Nov-Dec 2016**
**8 TeV/n pPb (Arm2)**
**Detector removal**

# LHCf results and publication

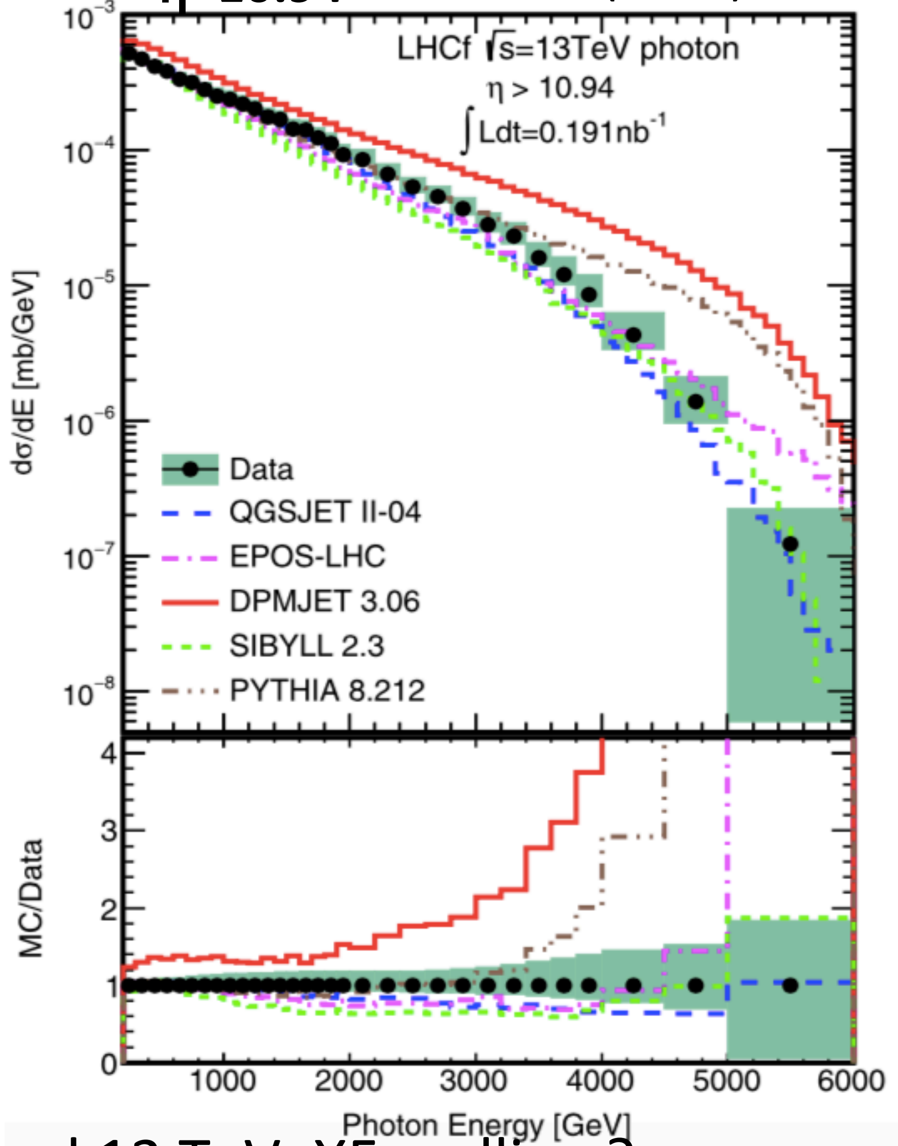
<table>
<tr><th>Run</th><th>$E_{lab}$ (eV)</th><th>Photon</th><th>Neutron</th><th colspan="2">$\pi^0$</th></tr>
<tr><td>p-p $\sqrt{s}$=0.9TeV (2009/2010)</td><td>$4.3\mathrm{x}10^{14}$</td><td>PLB 715, 298 (2012)</td><td></td><td colspan="2">-</td></tr>
<tr><td>p-p $\sqrt{s}$=2.76TeV (2013)</td><td>$4.1\mathrm{x}10^{15}$</td><td></td><td></td><td>PRC 86, 065209 (2014)</td><td rowspan="2">PRD 94 032007 (2016)</td></tr>
<tr><td>p-p $\sqrt{s}$=7TeV (2010)</td><td>$2.6\mathrm{x}10^{16}$</td><td>PLB 703, 128 (2011)</td><td>PLB 750, 360 (2015)</td><td>PRD 86, 092001 (2012)</td></tr>
<tr><td>p-p $\sqrt{s}$=13TeV (2015)</td><td>$9.0\mathrm{x}10^{16}$</td><td>PLB 780, 233 (2018)</td><td>JHEP 1811, 73 (2018)</td><td colspan="2">preliminary</td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)</td><td>$1.4\mathrm{x}10^{16}$</td><td></td><td></td><td>PRC 86, 065209 (2014)</td><td></td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=8TeV (2016)</td><td>$3.6\mathrm{x}10^{16}$</td><td>Preliminary</td><td></td><td colspan="2"></td></tr>
<tr><td>RHICf p-p $\sqrt{s}$=510GeV (2017)</td><td>$1.4\mathrm{x}10^{14}$</td><td colspan="4">on-going</td></tr>
</table>

# Very forward photon spectra at 7/13 TeV pp

η>10.94 PLB703(2011)128




η>10.94 PLB780(2018)233

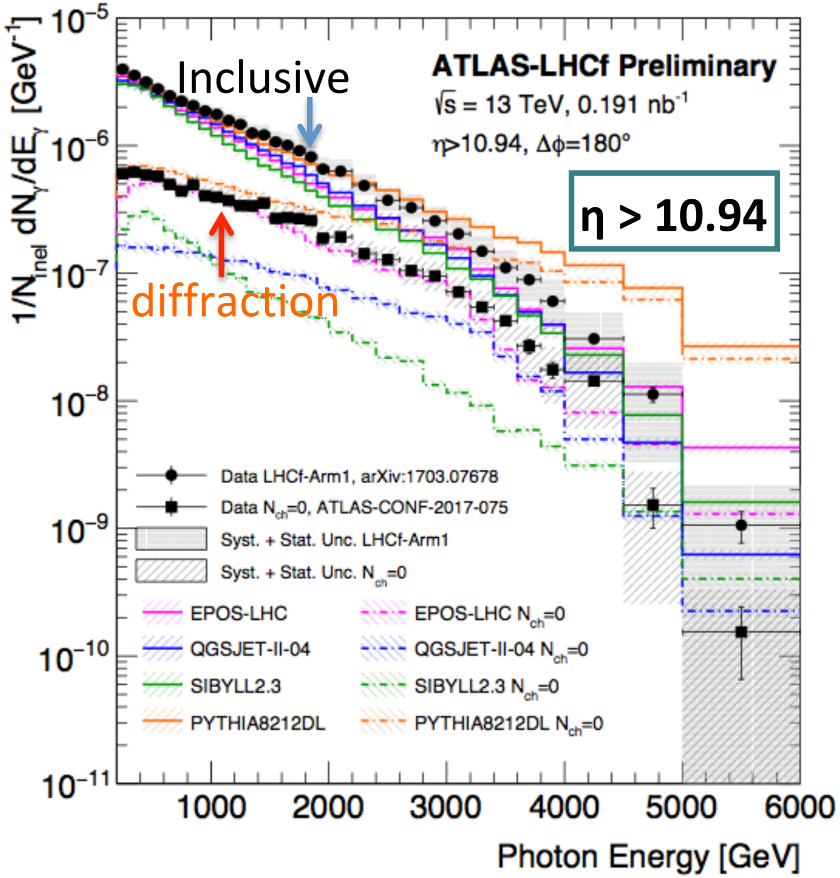


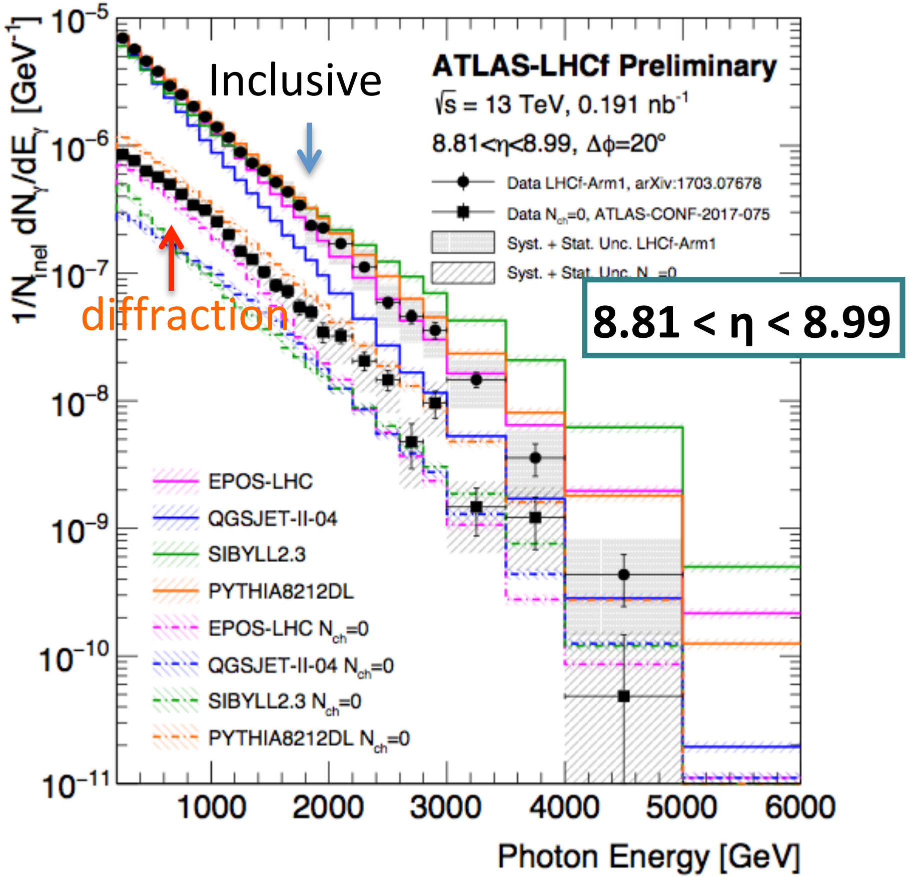

- Basically they look same btw 7 and 13 TeV. XF scalling ?

# Very forward photon from diffraction at 13TeV

ATLAS_CONF_2017_075

- ATLAS-LHCf common data at 13TeV pp
- Rapidity gap events selected as diffraction



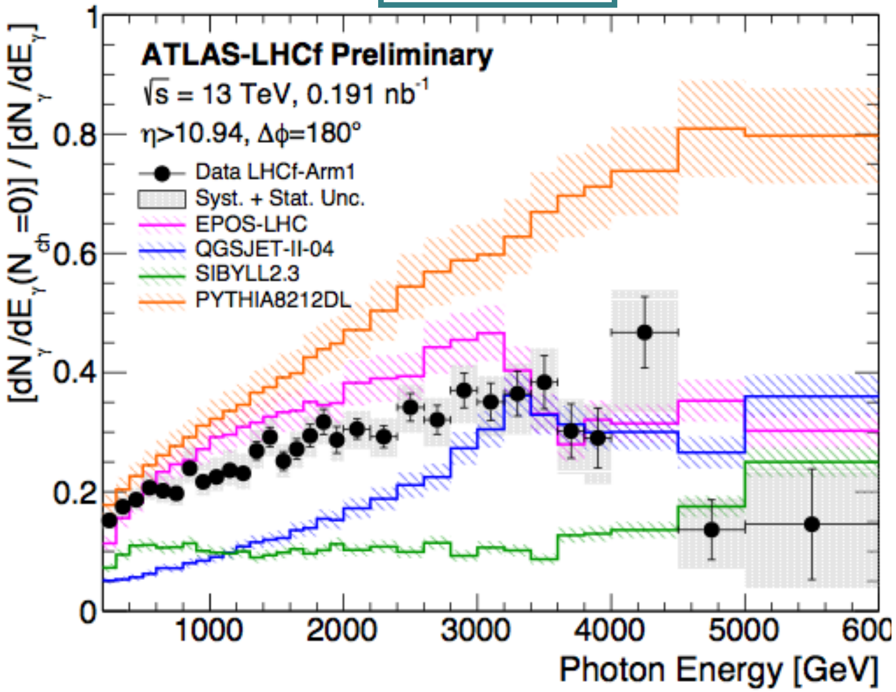

Some of cosmic ray interaction models need large modification
( Both diffraction and non-diffraction)

# Very forward photon: diffraction/total

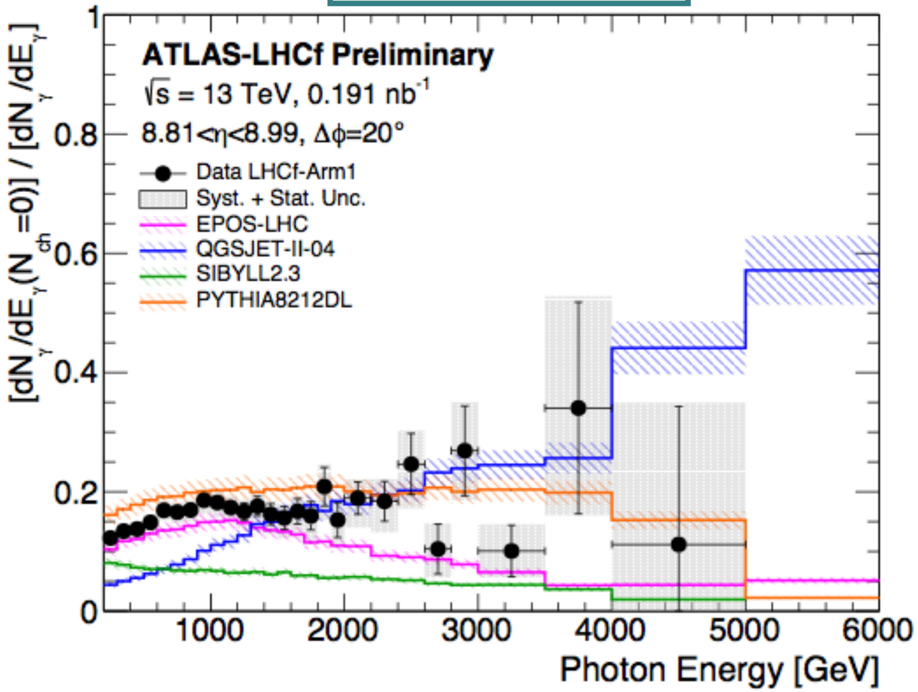
Ratio ($N_{ch=0}$/Inclusive)

ATLAS-CONF-2017-075

**η > 10.94**

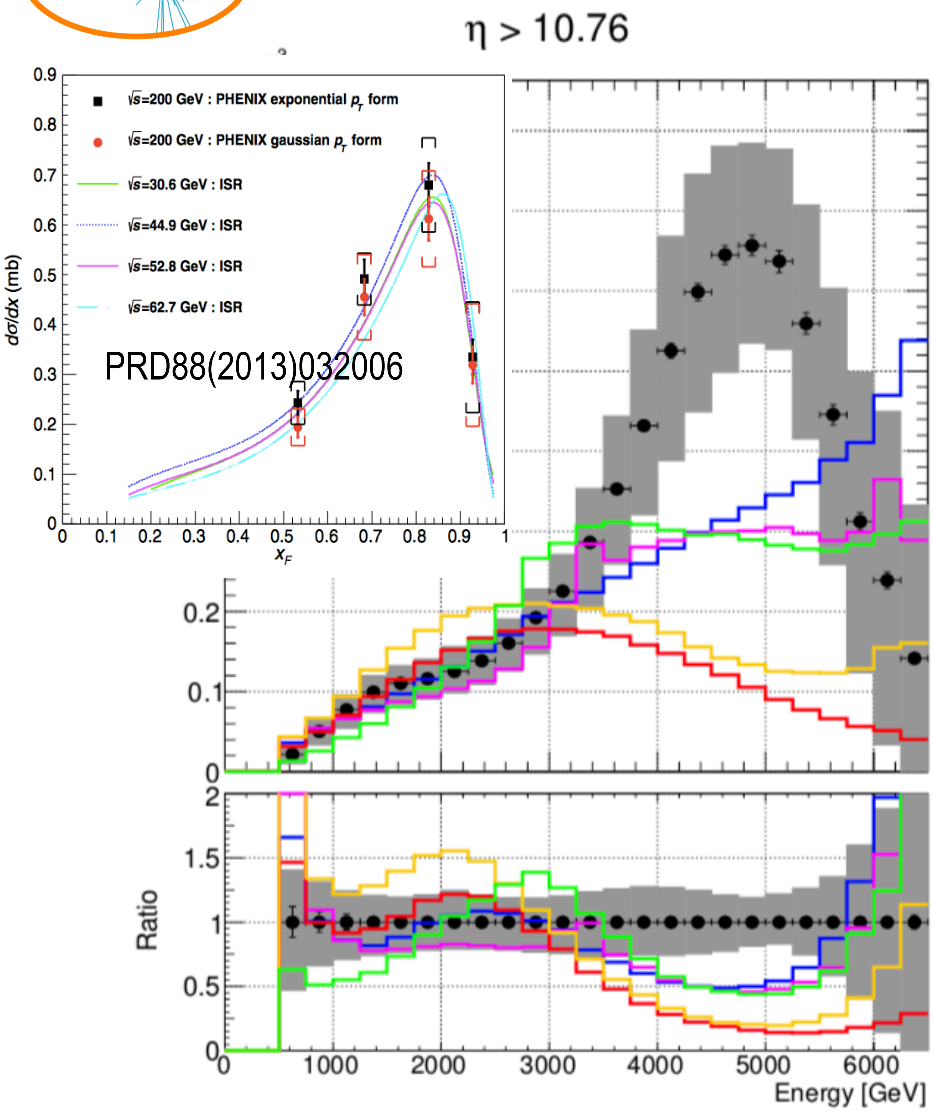


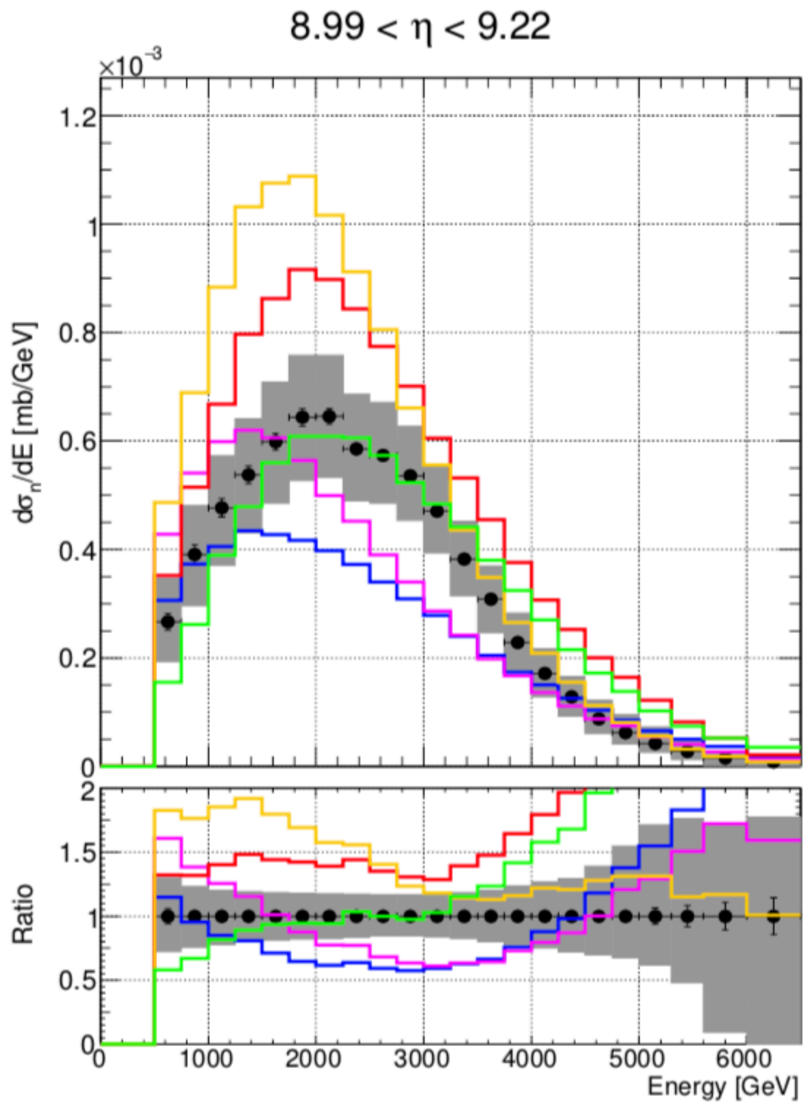

**8.81 < η < 8.99**



# Very forward neutron production at 13 TeV

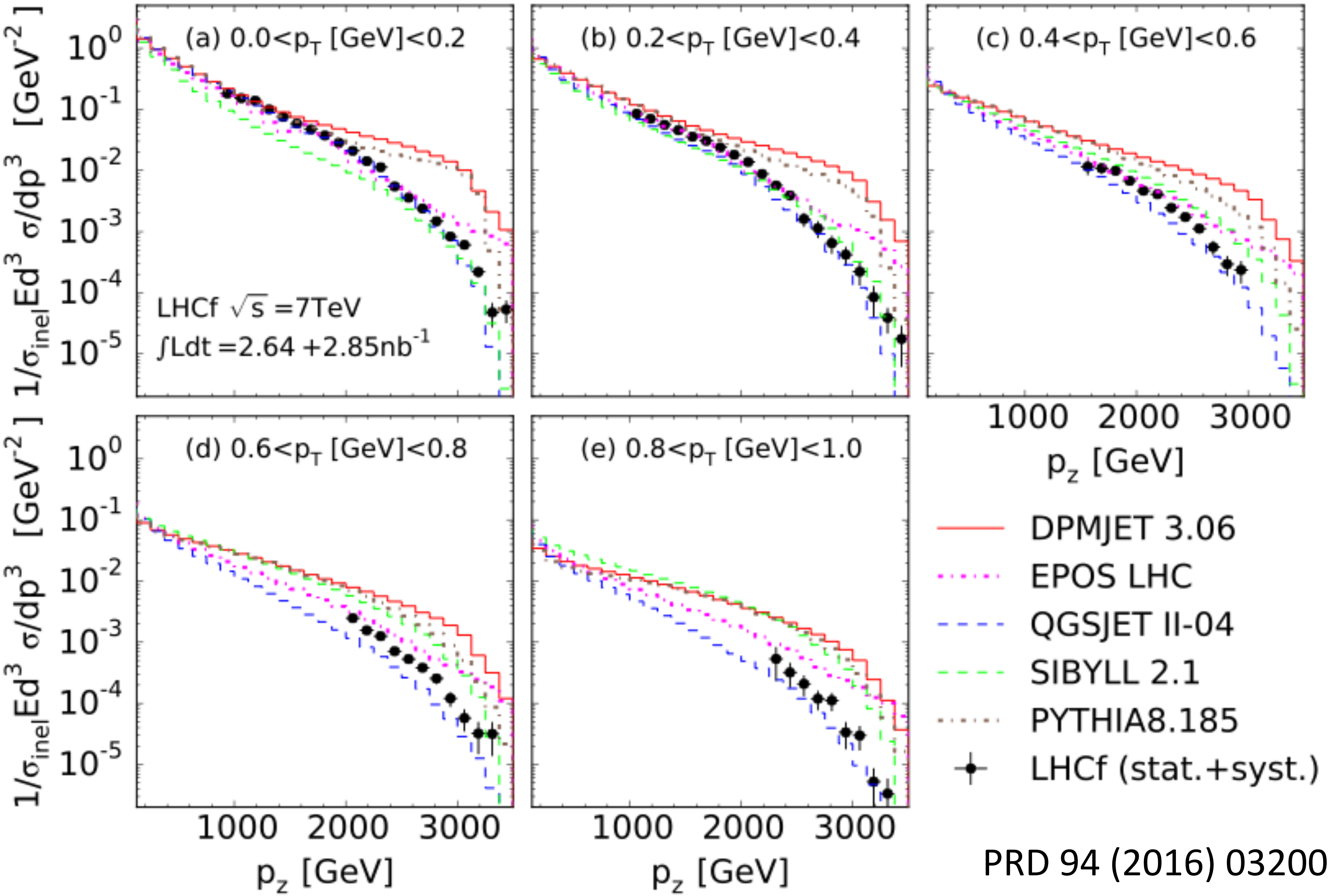
JHEP in press, arXiv:1808.09877, CERN-EP-2018-239




- Large excess in data than any other models at 0-degree ( $\eta$ >10.76)
- XF scaling ? comparison with ISR, PHENIX

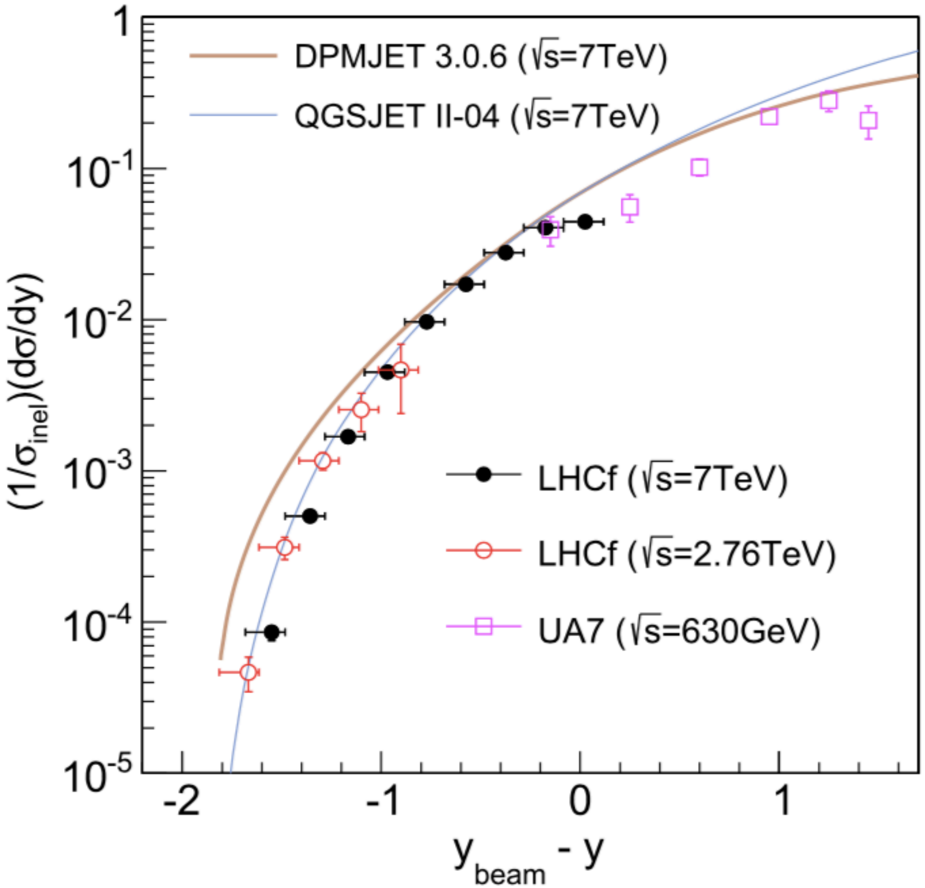
# $\pi^0$ $P_z$ (~ E) at 7 TeV pp

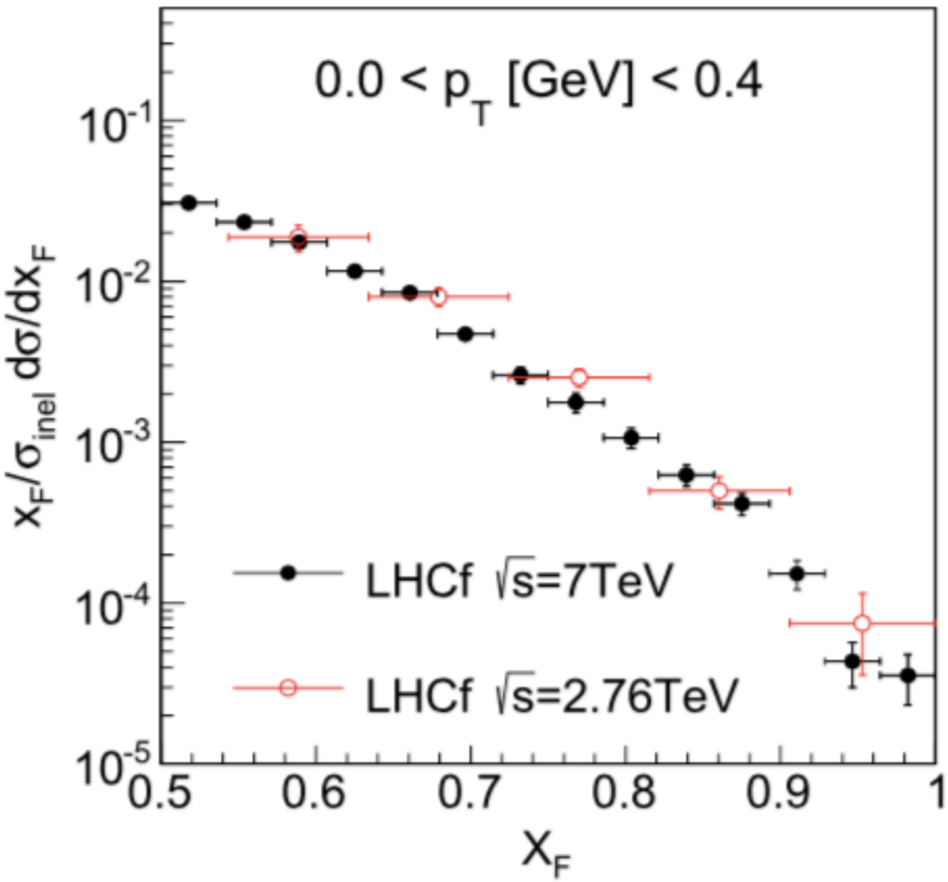



PRD 94 (2016) 032007

# Feynman scaling in $\pi^0$ production

PRD 94 (2016) 032007



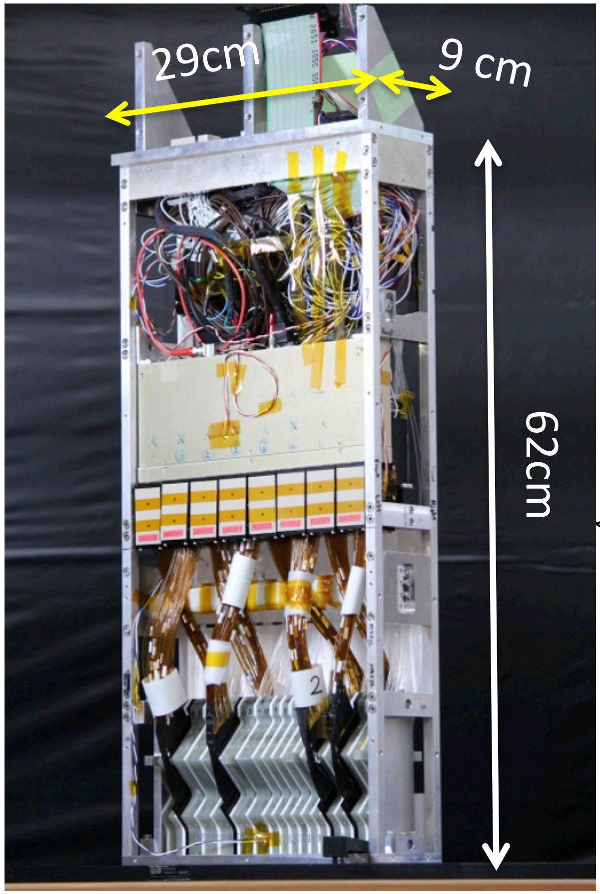

- LHCf $\pi^0$ spectra at $\sqrt{s}$= 2.76 and 7 TeV (preliminary)
- Need same pT coverage in 0.5 TeV → RHICf

# LHCf future in LHC Run-3

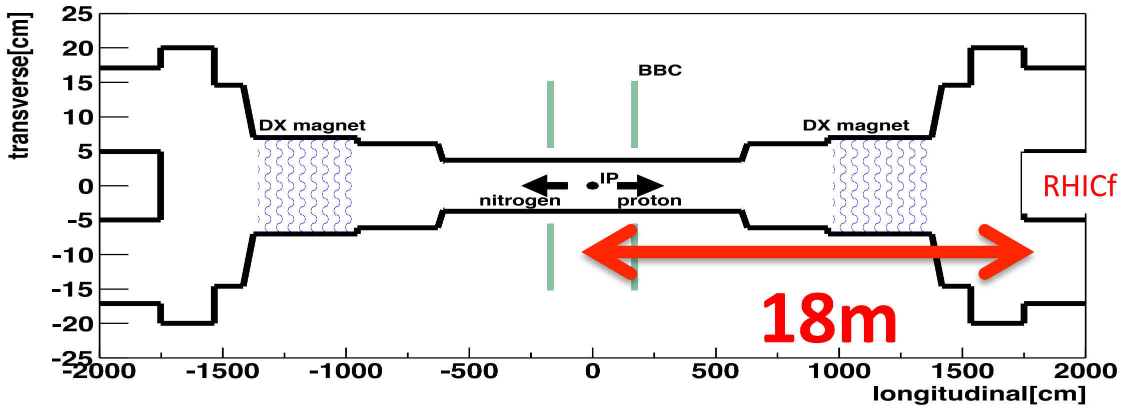
- LHCf will revisit LHC 14 TeV pp in Run-3 in 2021
  - High statistics $\pi^0$ data w/ x10 higher luminosity
  - forward $\eta$n (h → 2$\gamma$ : BR 39.4%)
  - forward $K^0_s$ ($K^0_s \rightarrow \pi^0\pi^0 \rightarrow 4\ \gamma$: BR 30.7%)
- Aiming p-O collisions foreseen in Run-3
  - Worl CR community supports LHC p-O for CR interactions
  - LHCC also supports oxygen beam runs
  - Maybe 2023 ?

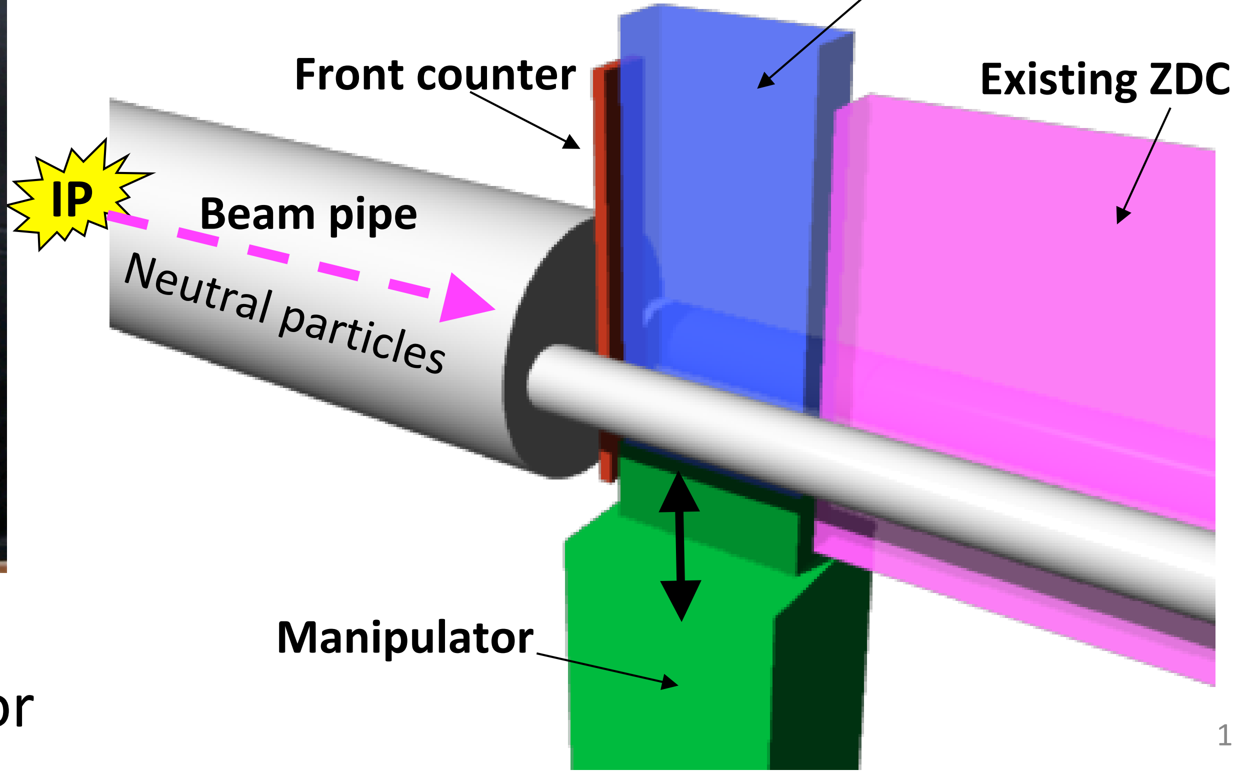
# RHICF

# RHICf: neutral particle measurement at 0-degree of STAR by a small imaging calorimeter




RHICf detector
as LHCf arm1 detector



# Why RHIC (@ lower √s) ?

- ZDC closer to IP, same PT acceptance as LHC
  - RHIC ZDC @ z=18m @500GeVpp,
  - LHC ZDC @ z=140m @ 7, 13 TeVpp

Feynman scaling in forward region; 0.5 TeV ⇔ 7 , 13 TeV

- Rich experience and opportunity for p-A, A-A
  - Understanding nuclear effect in air shower
- Polarized proton collisions
  - Precise spin asymmetry for forward particles
  - Probe for forward productions

# The RHICf collaboration

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# History

- 2011
  First discussion
- 2013
  LOI
- 2014
  Proposal for RUN16 with PHENIX
- 2015
  Proposal for RUN17 with STAR
- 2017 Jun
  Physics run completed

**Proposal; Precise measurements of very forward particle production at RHIC**

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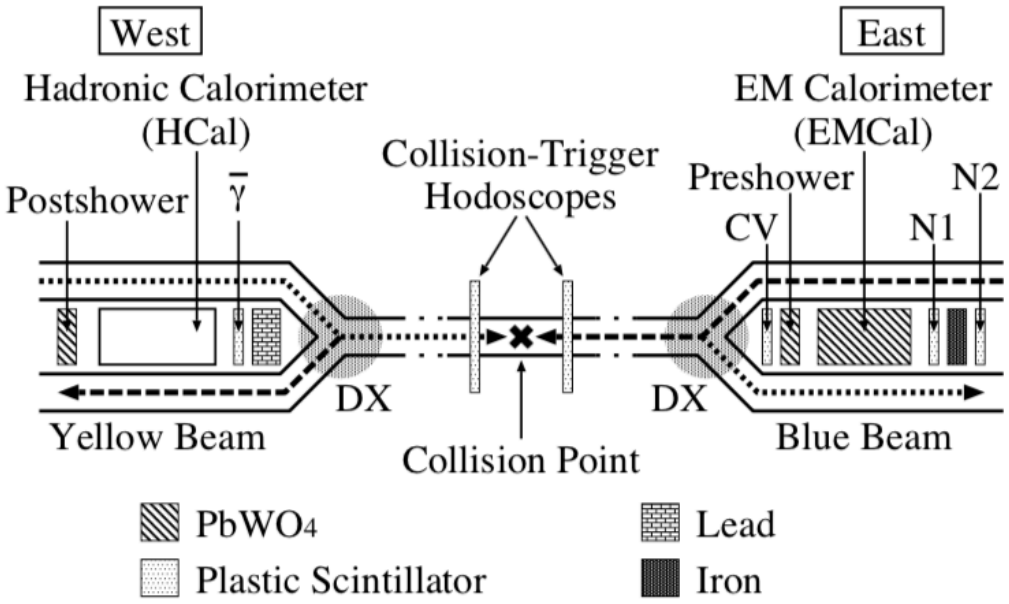
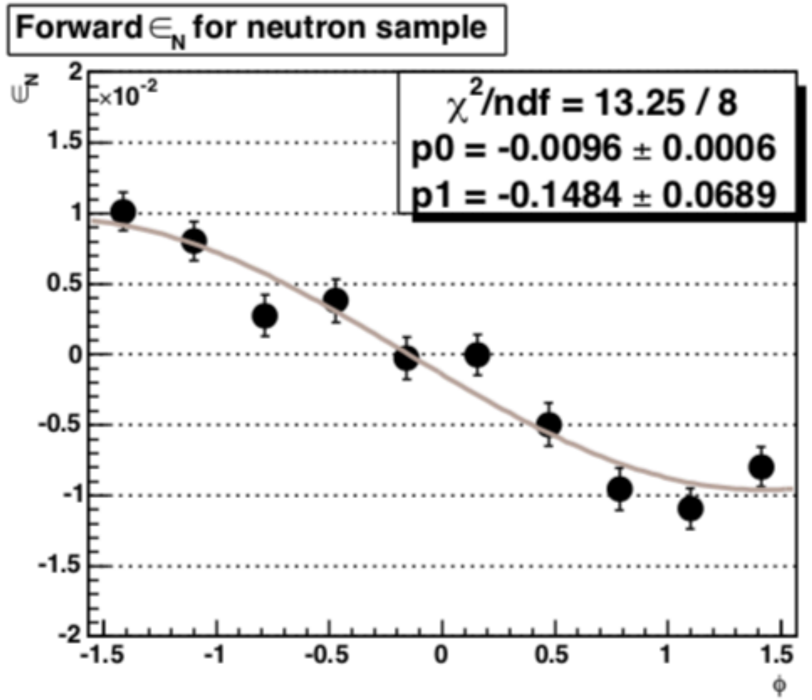
# $A_N$ forward neutron at RHIC-IP12

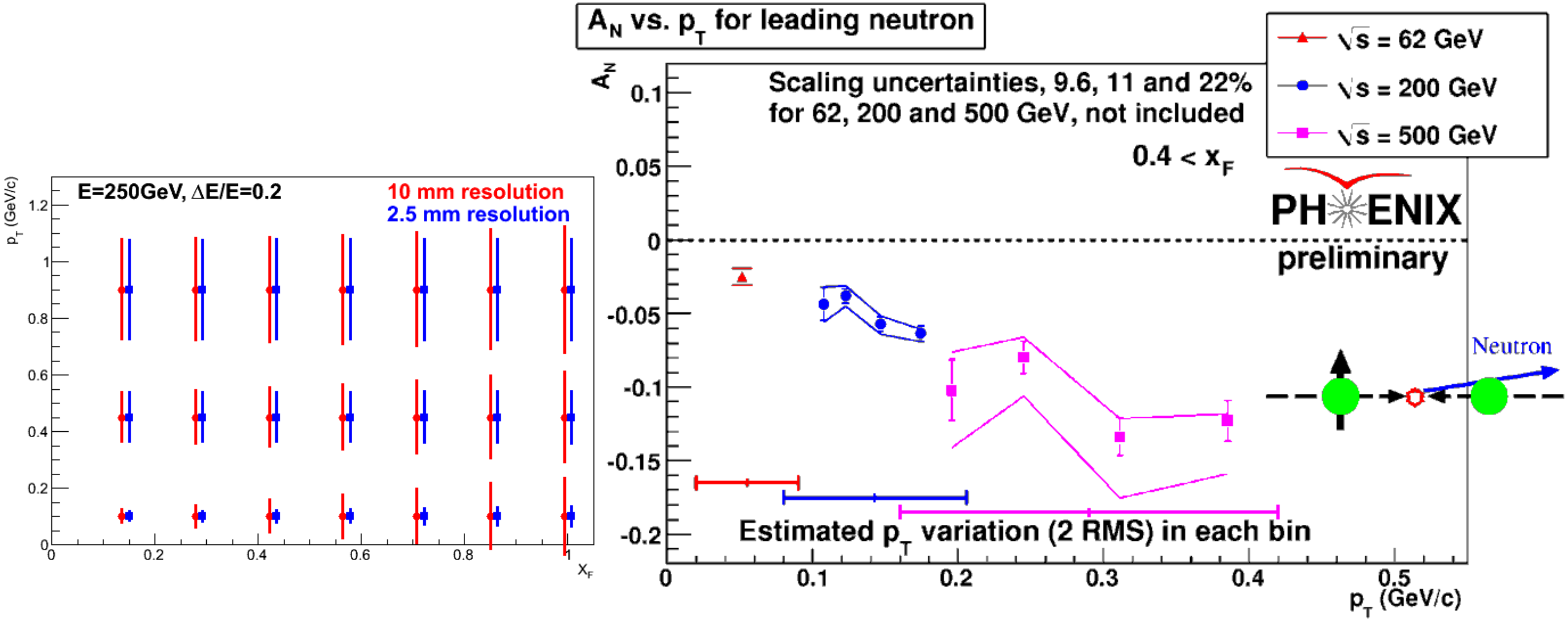
M. Togawa, PhD thesis (2008)




| $A_N$ results from EMCal | | |
|---|---|---|
| | Forward | Backward |
| Neutron | -0.090 ± 0.006 ± 0.009 | 0.003 ± 0.004 ± 0.003 |
| Photon | -0.009 ± 0.015 ± 0.008 | -0.019 ± 0.010 ± 0.004 |
| $\pi^0$ | -0.024 ± 0.031 ± 0.002 | 0.006 ± 0.021 ± 0.001 |
| $A_N$ results from HCal | | |
| Neutron | -0.126 ± 0.017 ± 0.045 | 0.028 ± 0.019 ± 0.010 |

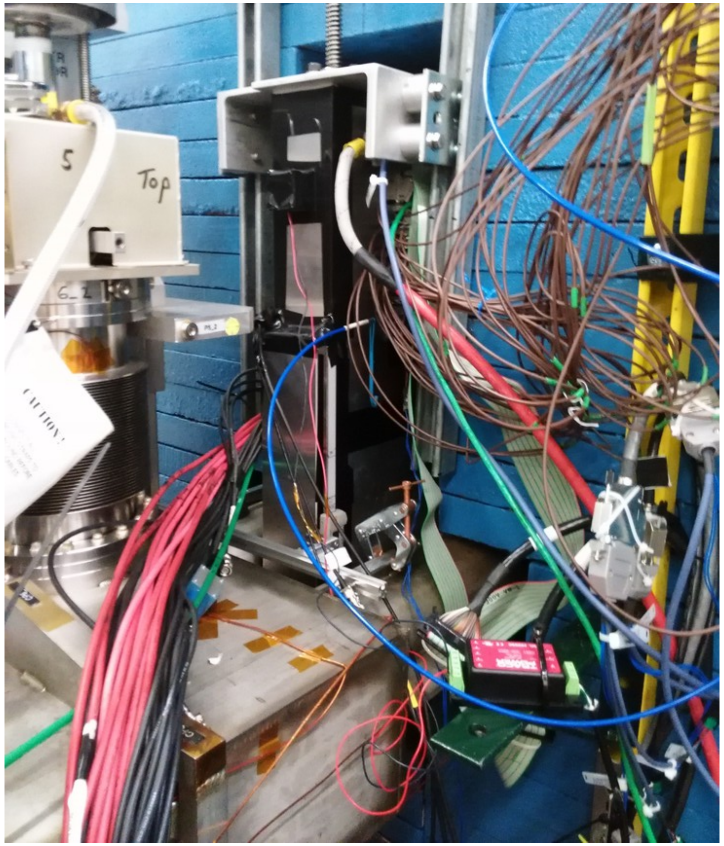
# $A_N$ of forward neutron at RHICf




- Combination of ZDC (good $E_{had}$ resolution) and RHICf detector (good position resolution) provide good $p_T$ resolution in neutron measurements
- With horizontal polarization, covering $p_T$<1GeV/c

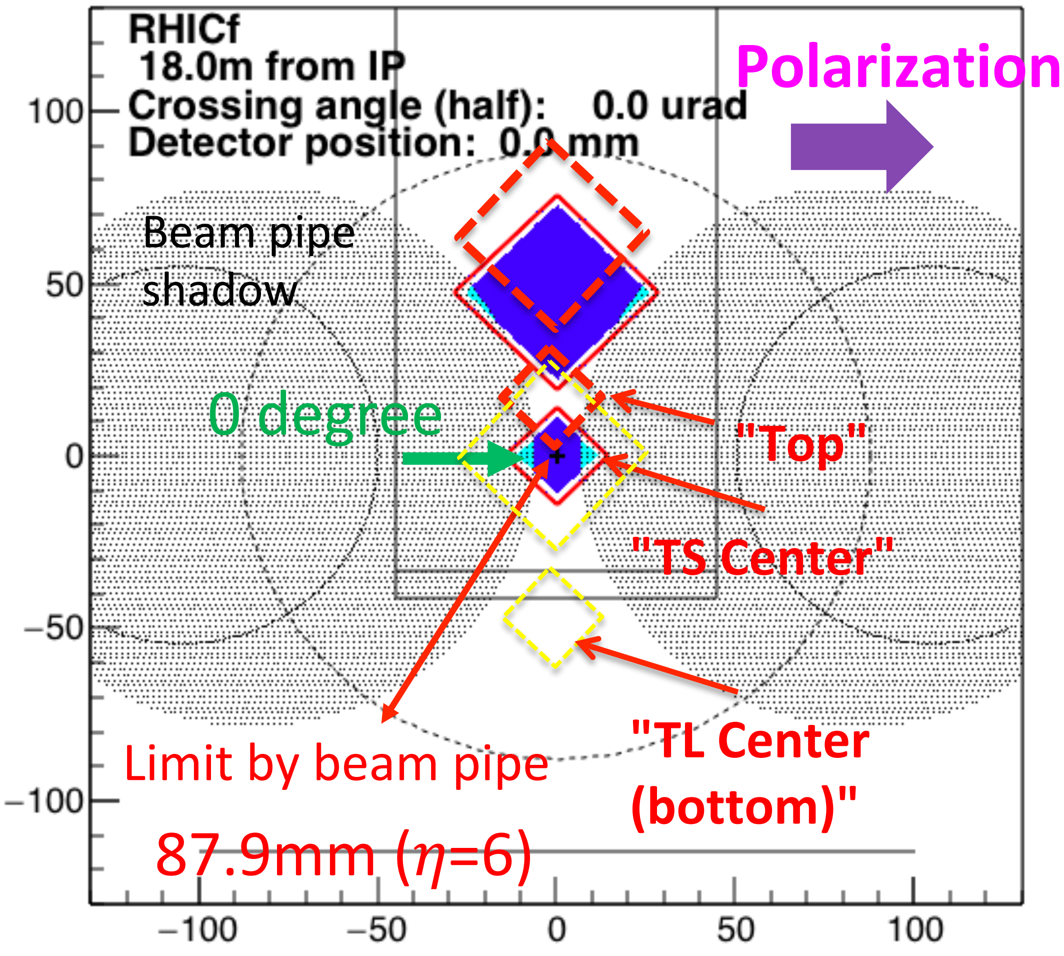
# RHICf physics run (25-27 June, 2017)

- $\sqrt{s}$=510 GeV p+p collisions
- Higher $\beta^*$ (=8m) than usual RHIC operation
- Radial polarization to maximize the single-spin asymmetry in vertical
- Luminosity~$10^{31}$ $cm^{-2}s^{-1}$
- Trig. Thres ~ 10GeV

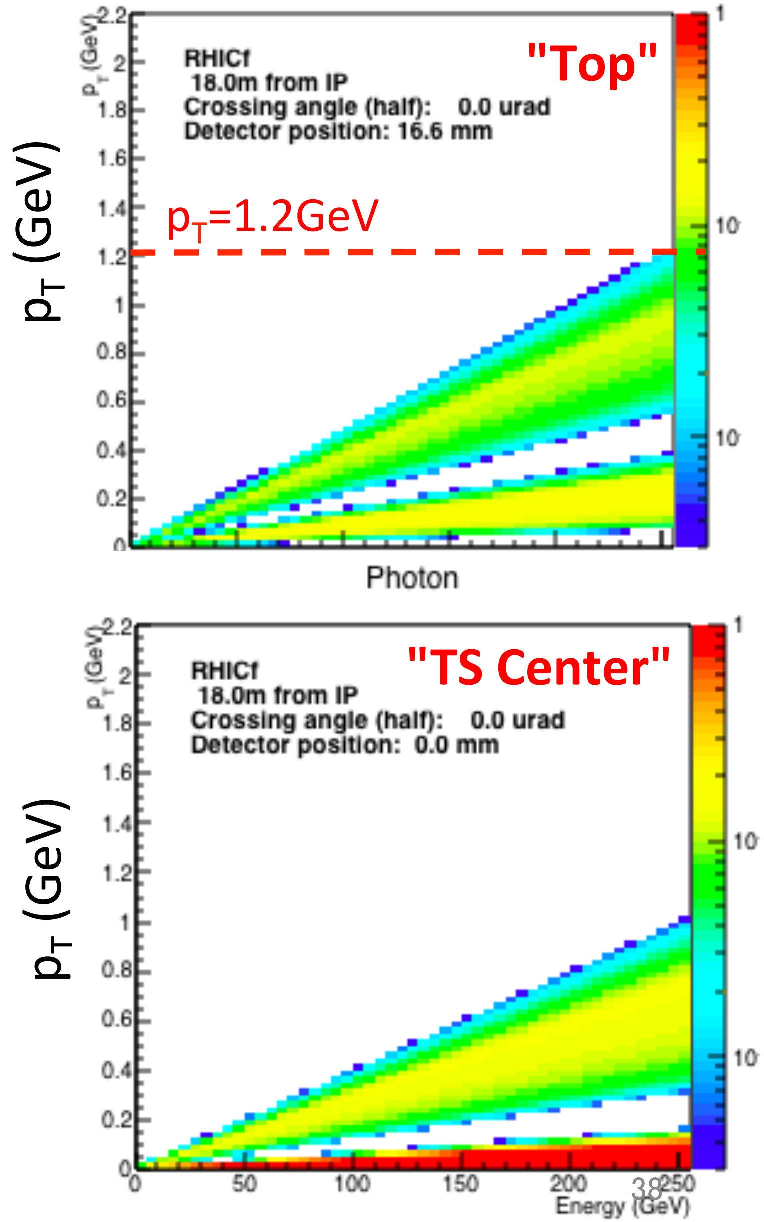



# RHICf detector configuration

Cross section view from IP

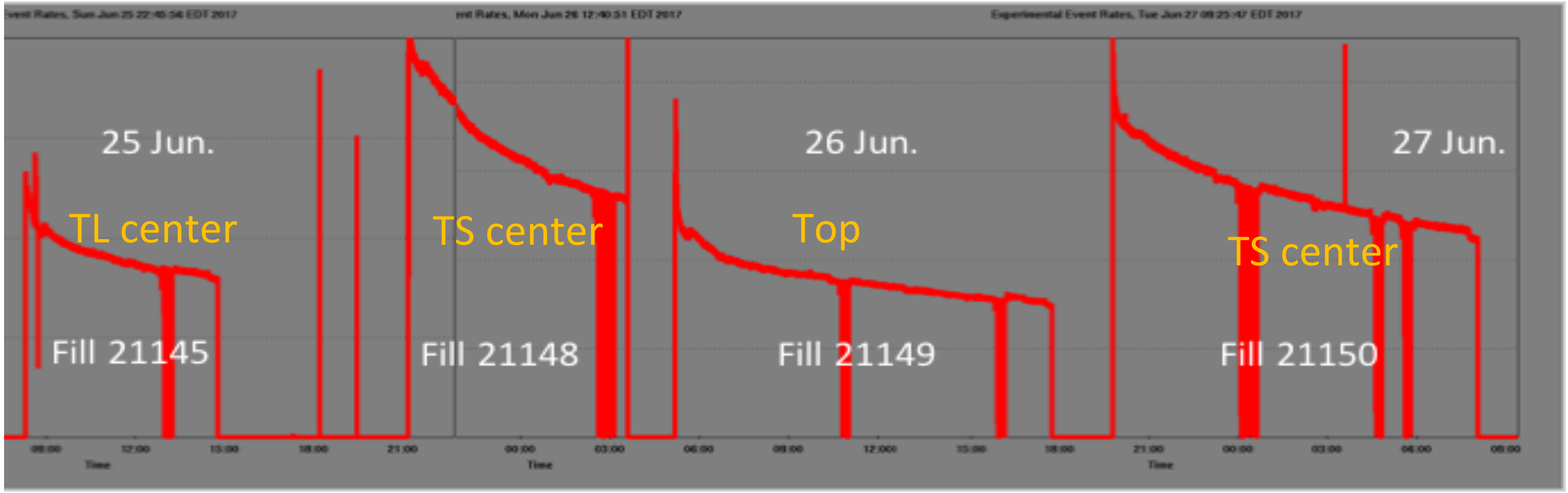


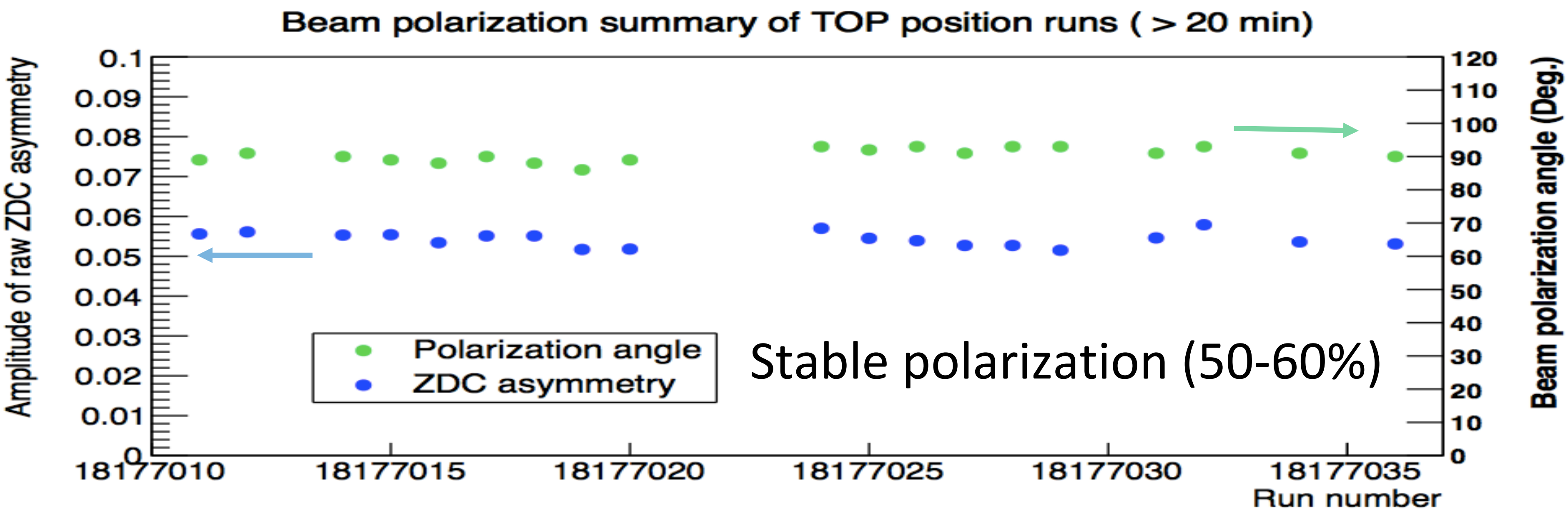

Acceptance in E-$p_T$ phase space



# RHICf beam status

Stable 4 fills for physics w/ 3 detector positions

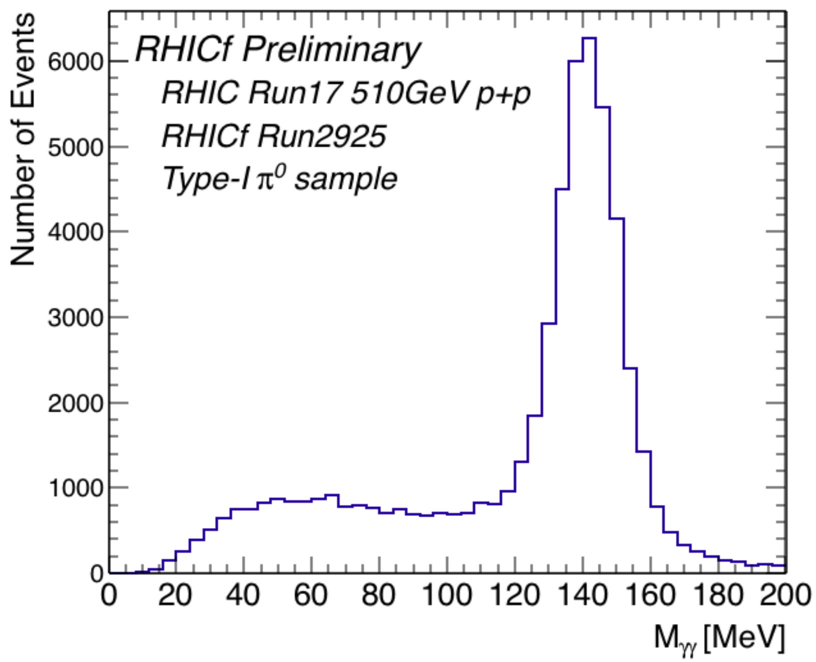


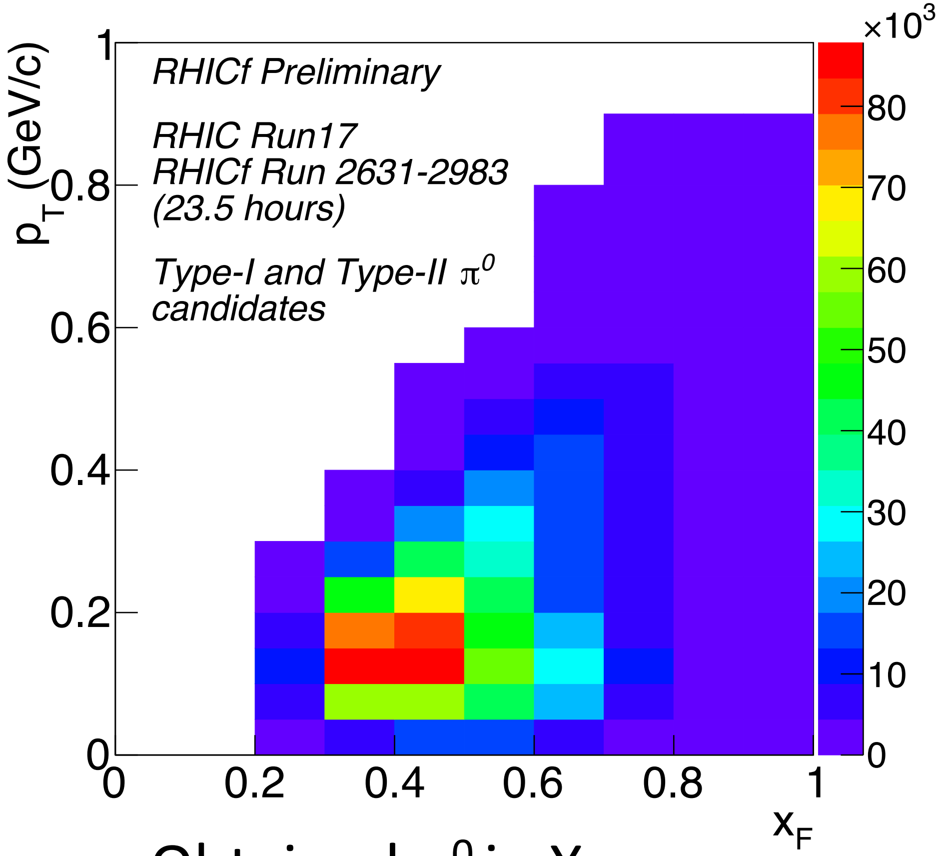

Stable polarization (50-60%)

# On-going analysis

- Calibration, basic performance check being completed
- A clear $\pi^0$ peak confirmed good performance
- Correlation w/ STAR-ZDC, STAR-combined trig. OK
- Photons, neutrons, and $\pi^0$ analysis on-going
- **First $A_N$ results on $\pi^0$**
  **→ next Minho's talk**




Observed $\pi^0$ mass peak




Obtained $\pi^0$ in $X_F$ vs $p_T$

# Summary

- Forward neutral productions have been studied by LHCf and RHICf to verify cosmic ray interactions
  - Covering $E_{CR} = 10^{14}$-$10^{17}$ eV
  - Many new data delivered. No model perfectly reproduces. Benchmark for future modeling works.
  - ATLAS-combined analysis on-going
- RHICf also provides unique AN measurement at very forward (low pT)
  - Very forward w/ same $p_T$ coverage as LHCf but at 0.5 TeV to check Feynman scaling
  - Unexpected is $\pi^0$ $A_N$ discovered → next speaker
  - Precise neutron $A_N$ upto $p_T$ ~ 1 GeV/c
  - Future STAR-combined analysis ?