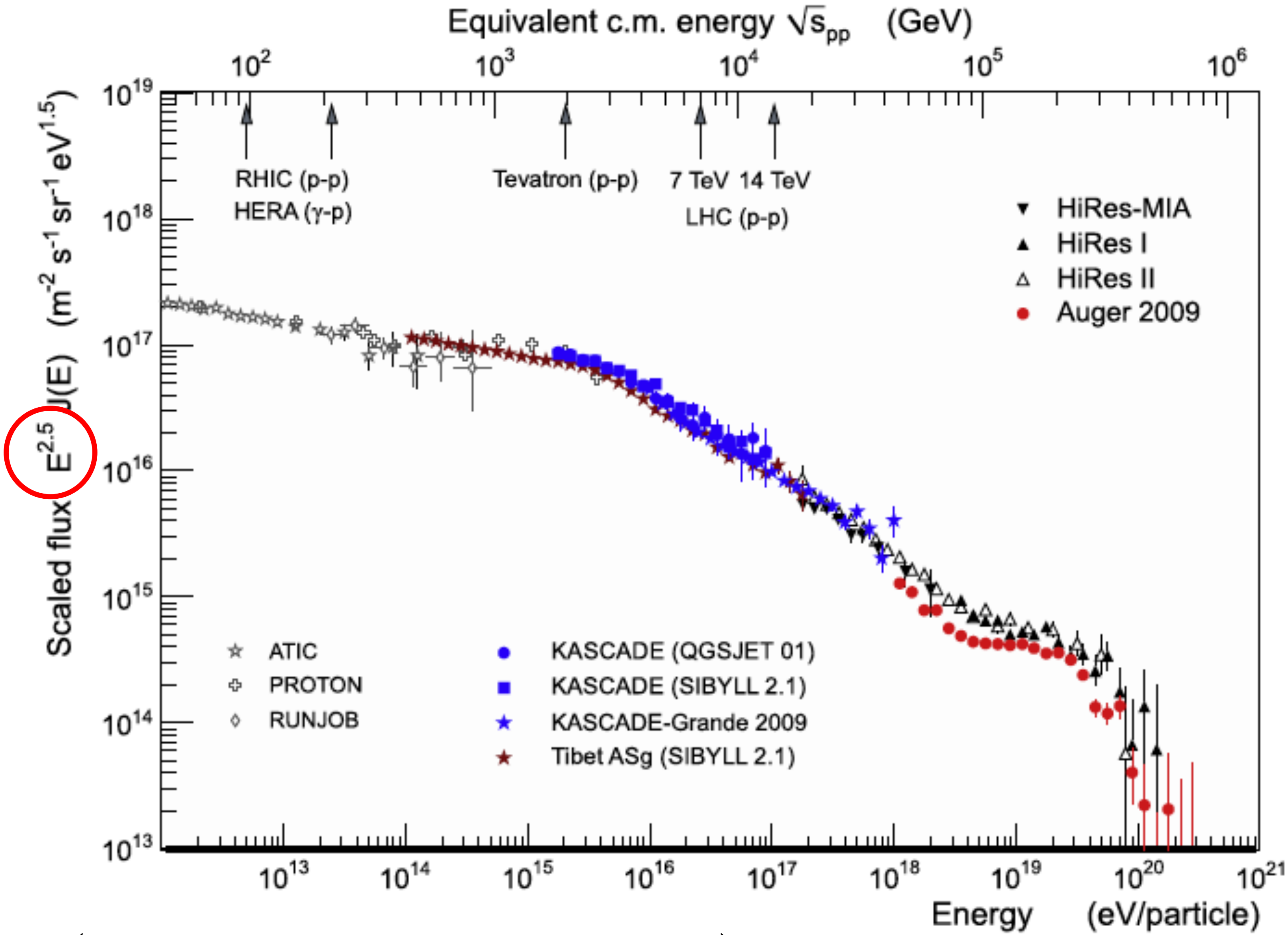
LHCf and RHICf, collider experiments to reveal the nature of high-energy cosmic rays

Takashi Sako

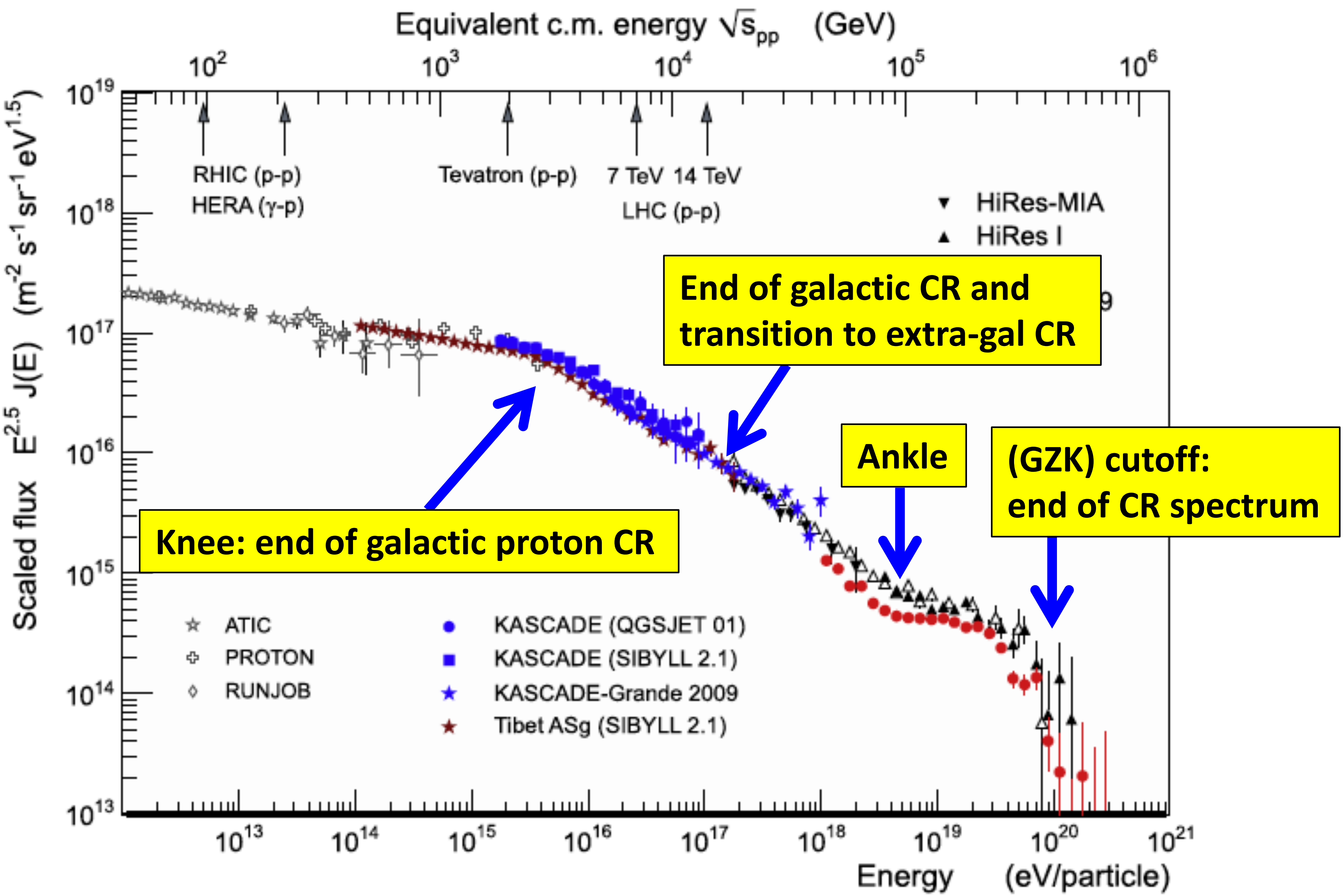
(KMI/ISEE, Nagoya University)

Cosmic rays

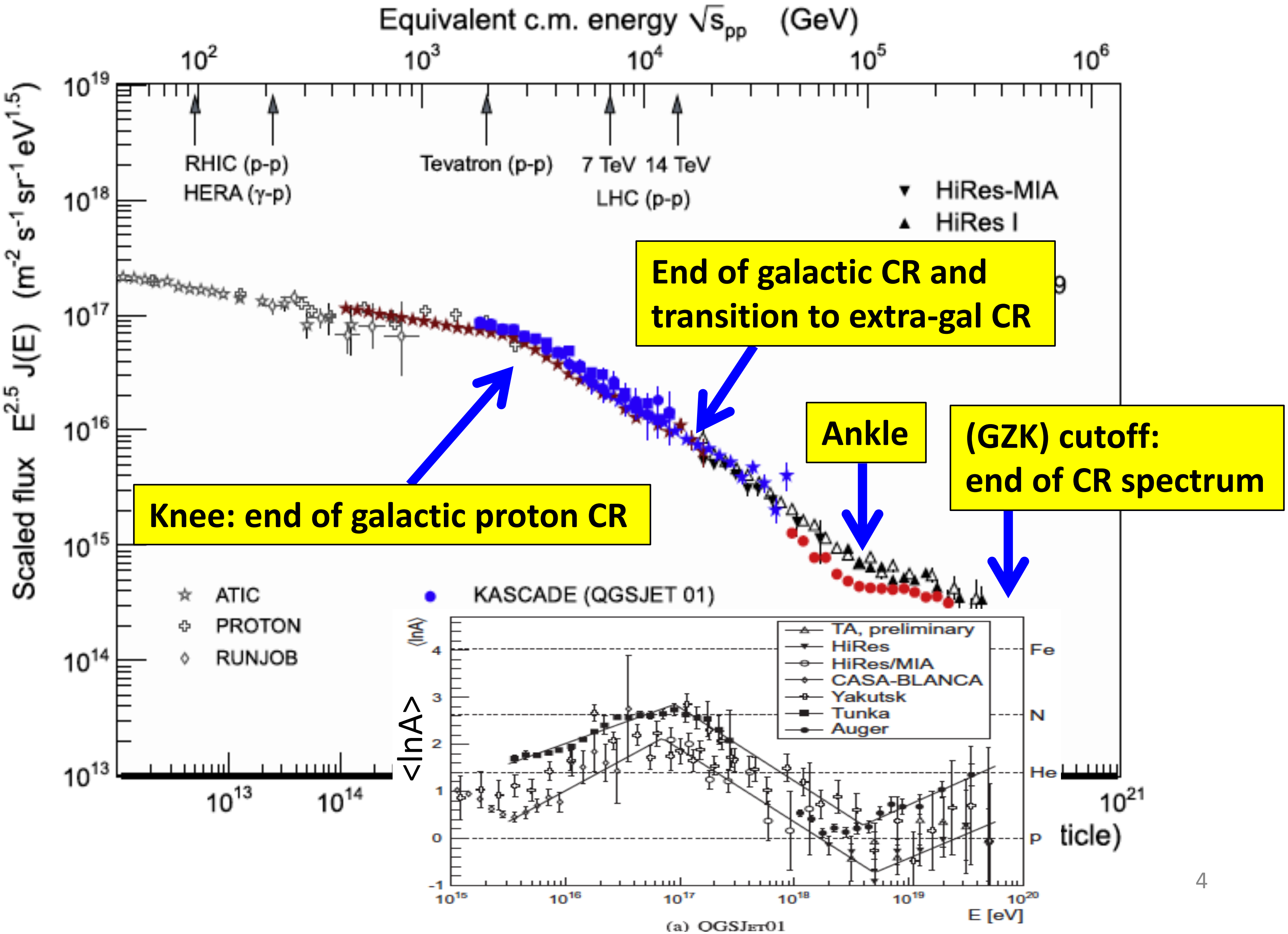


（D’Enterria et al., APP, 35,98-113, 2011 ）

Cosmic rays


Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
10^19
10^18
10^17
10^16
10^15
10^14
10^13
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
End of galactic CR and
transition to extra-gal CR
Ankle
(GZK) cutoff:
end of CR spectrum
Knee: end of galactic proton CR
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Cosmic rays



Equivalent c.m. energy √s_pp (GeV)
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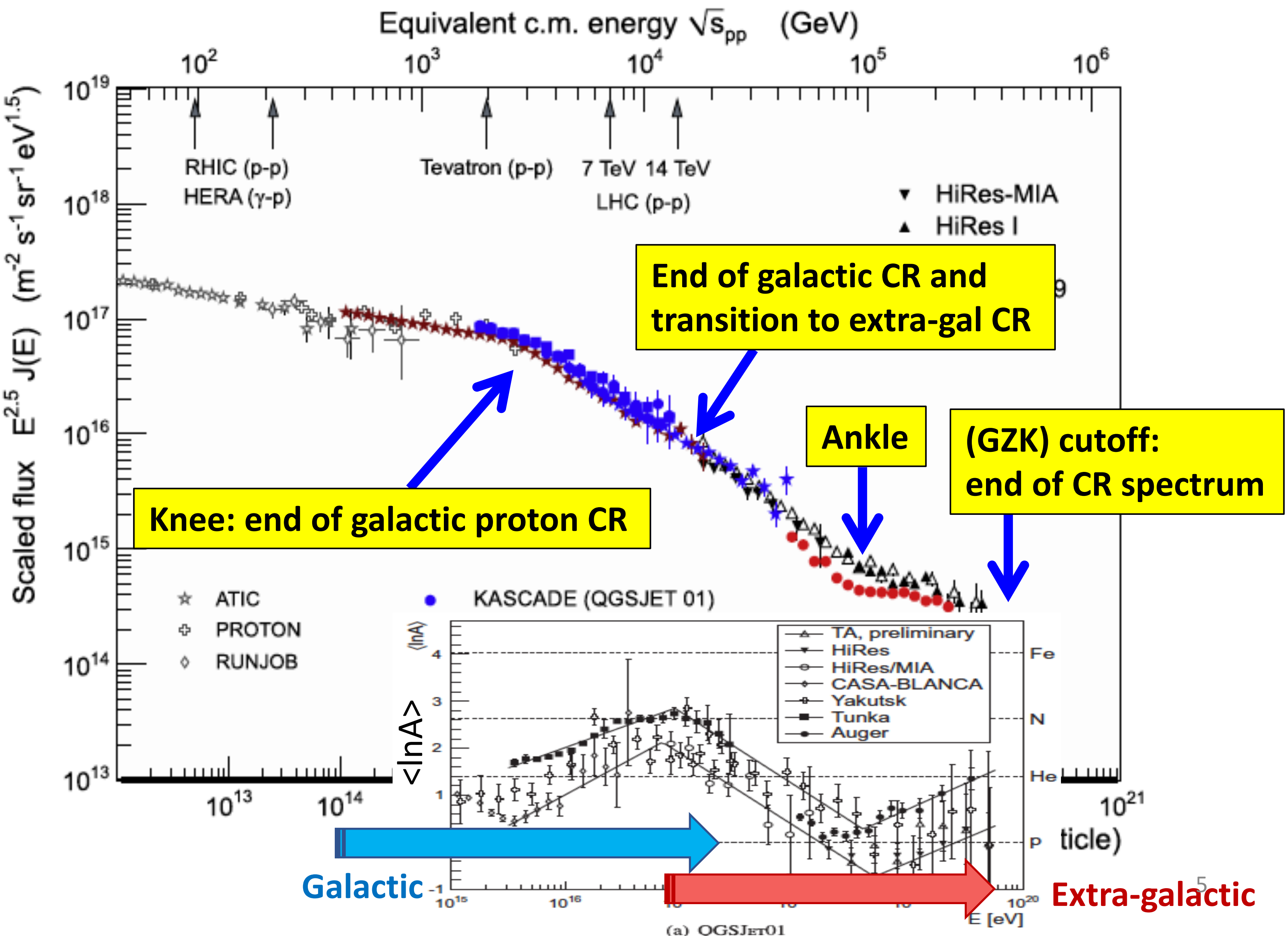
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
TA, preliminary
HiRes
HiRes/MIA
CASA-BLANCA
Yakutsk
Tunka
Auger
<lnA>
Fe
N
He
p
E [eV]
(a) QGSJet01
ticle)

Cosmic rays



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2 10^3 10^4 10^5 10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19} 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13}
End of galactic CR and transition to extra-gal CR
Ankle
(GZK) cutoff: end of CR spectrum
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10^{13} 10^{14} 10^{21}
ticle)
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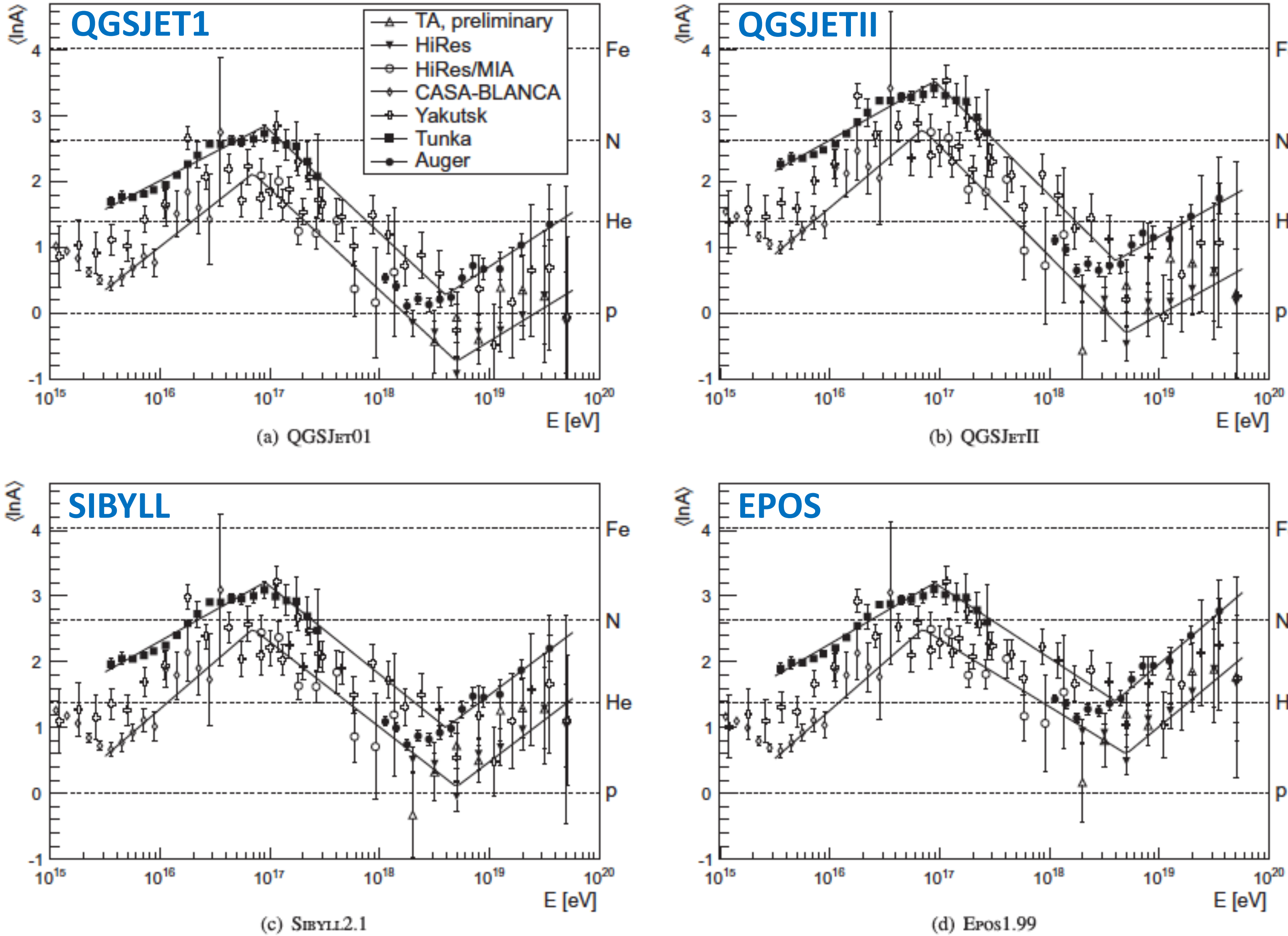
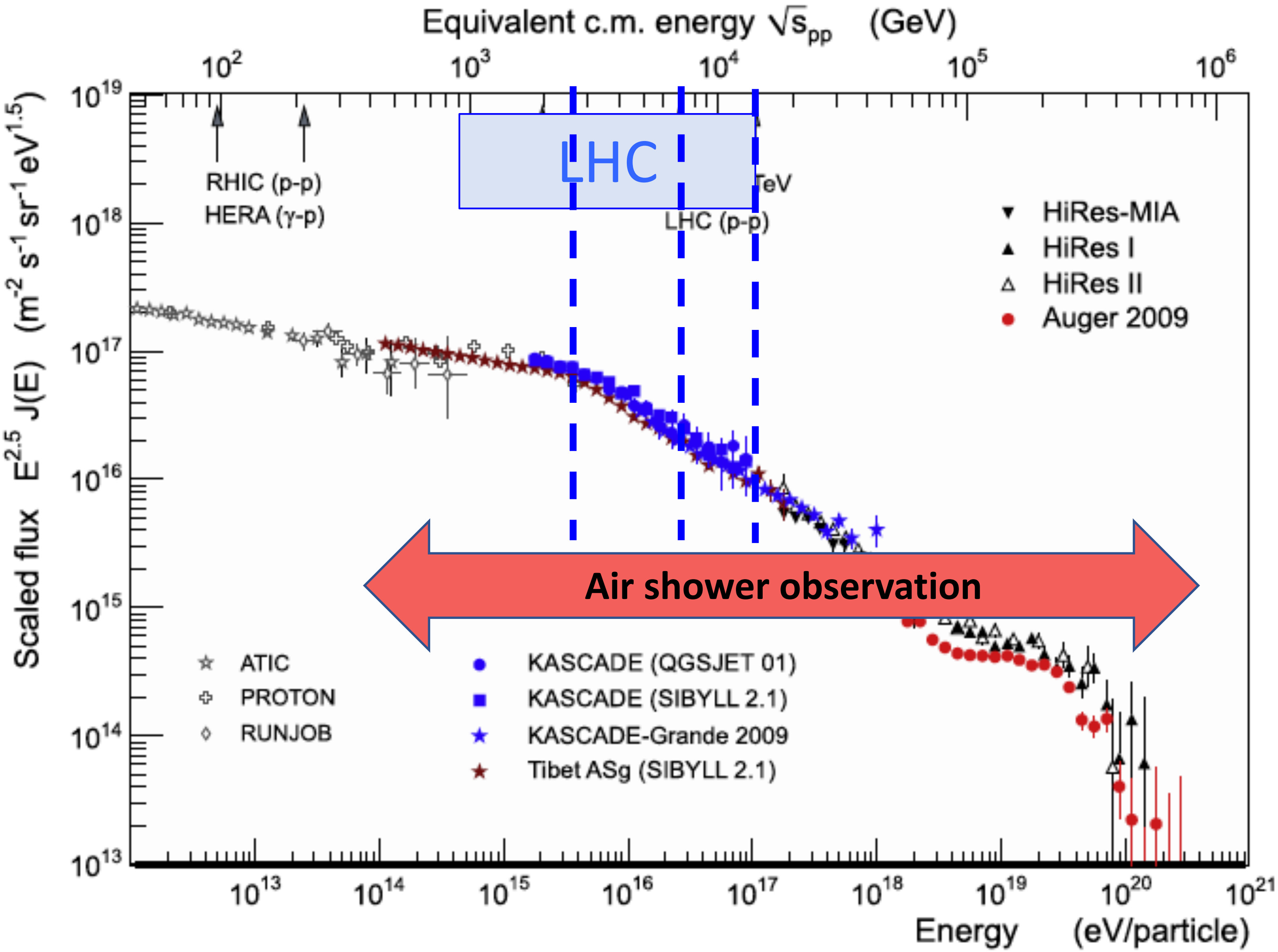
HiRes
HiRes/MIA
CASA-BLANCA
Yakutsk
Tunka
Auger
Fe
N
He
p
E [eV]
(a) QGSJet01
Galactic
Extra-galactic



(Kampert and Unger, Astropart. Phys., 2012)

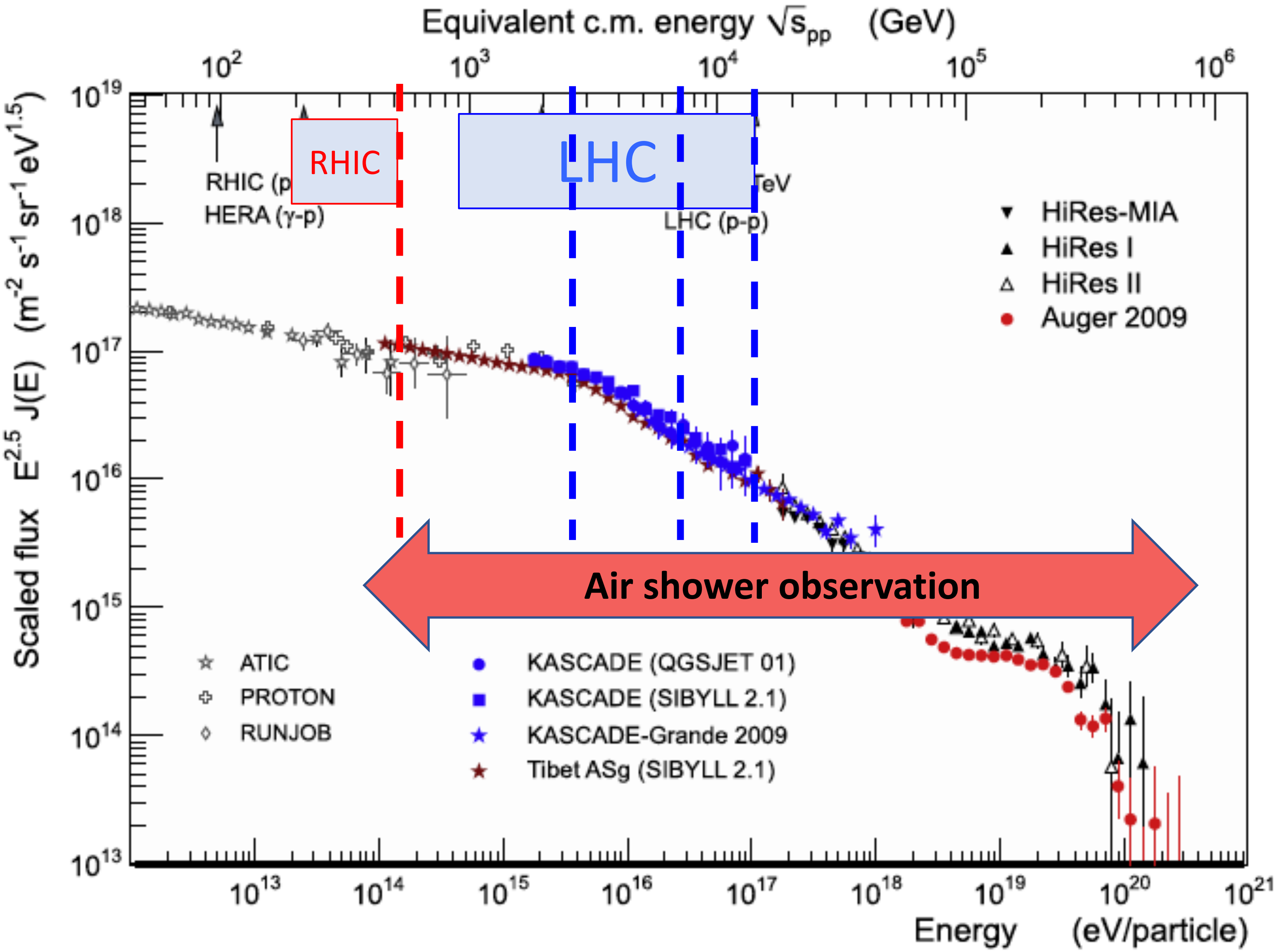
Interpretation depends on the hadronic interaction model
because high-energy CRs are observed through atmospheric air showers

Cosmic rays



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
LHC
RHIC (p-p)
HERA (γ-p)
TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
Scaled flux $E^{2.5}$ J(E) ($m^{-2} s^{-1} sr^{-1} eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
Air shower observation
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

Cosmic rays



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC
LHC
RHIC (p
HERA (γ-p)
TeV
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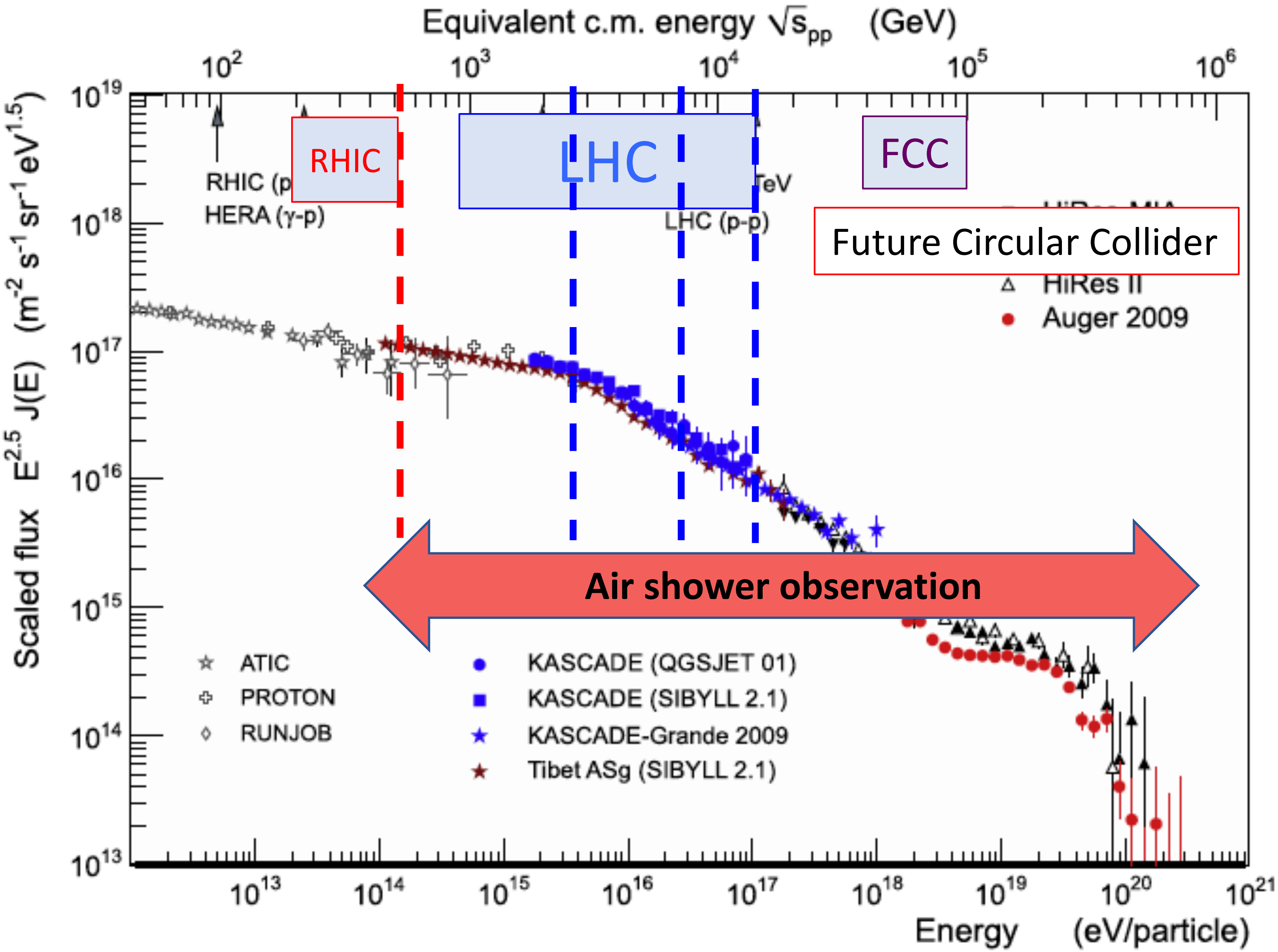
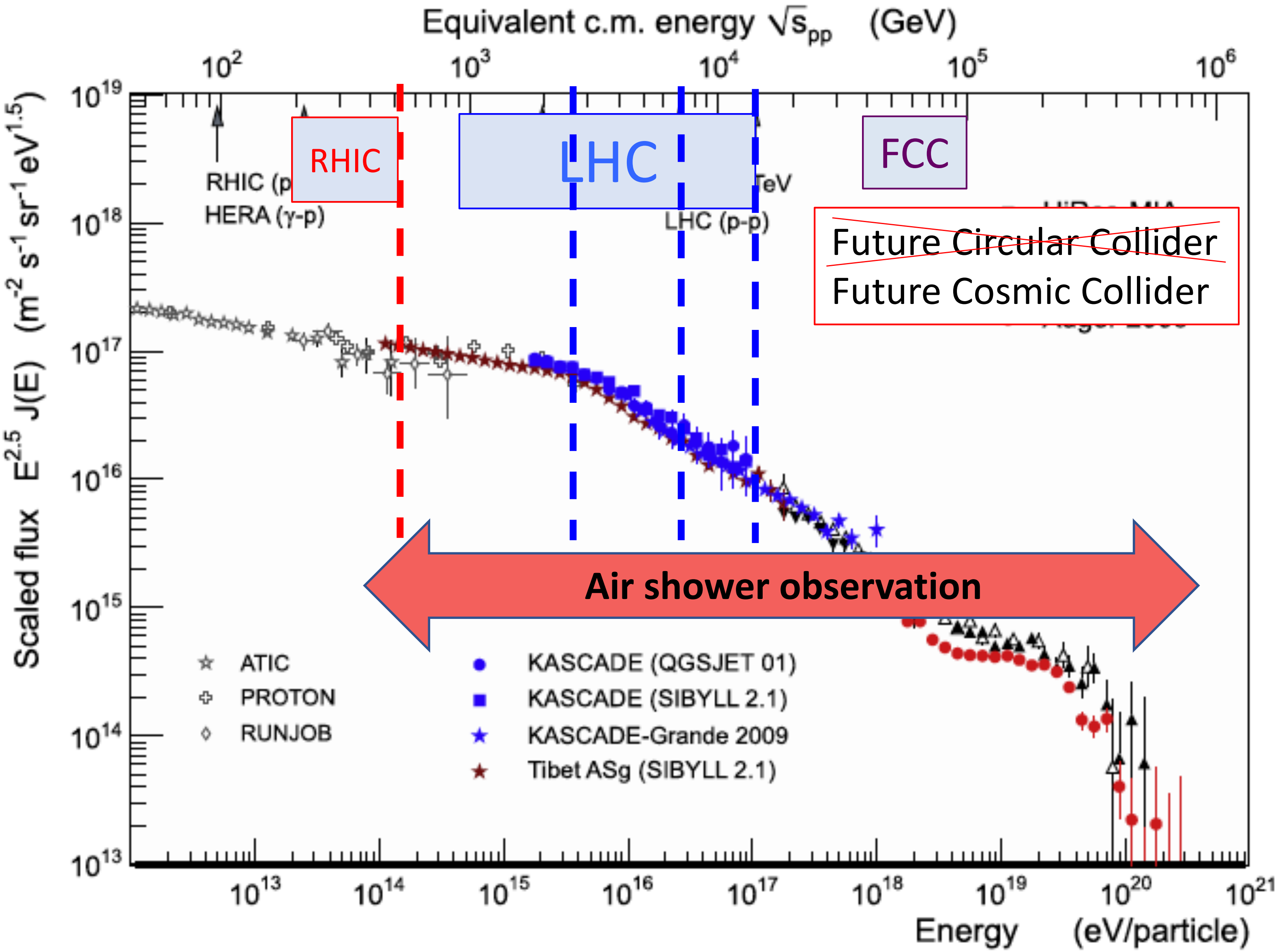
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

Cosmic rays



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC
LHC
FCC
Future Circular Collider
RHIC (p
HERA (γ-p)
TeV
LHC (p-p)
HiRes II
Auger 2009
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Air shower observation
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

Cosmic rays



Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC
LHC
FCC
RHIC (p
HERA (γ-p)
TeV
LHC (p-p)
Future Circular Collider
Future Cosmic Collider
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10^{19}
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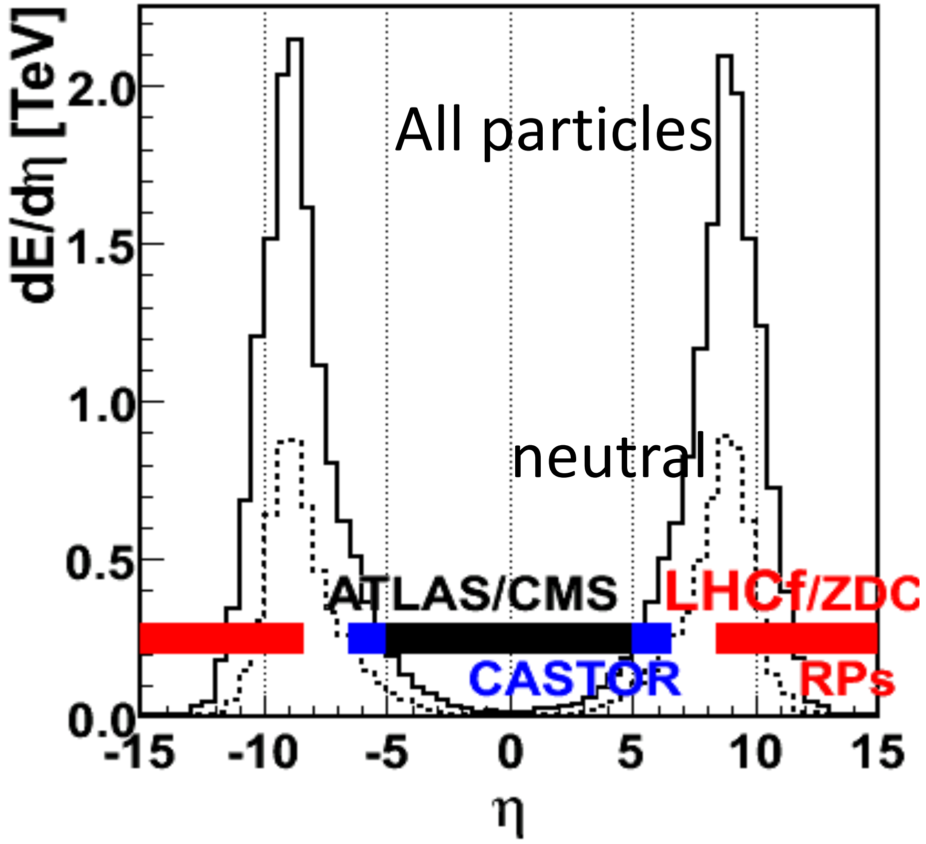
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

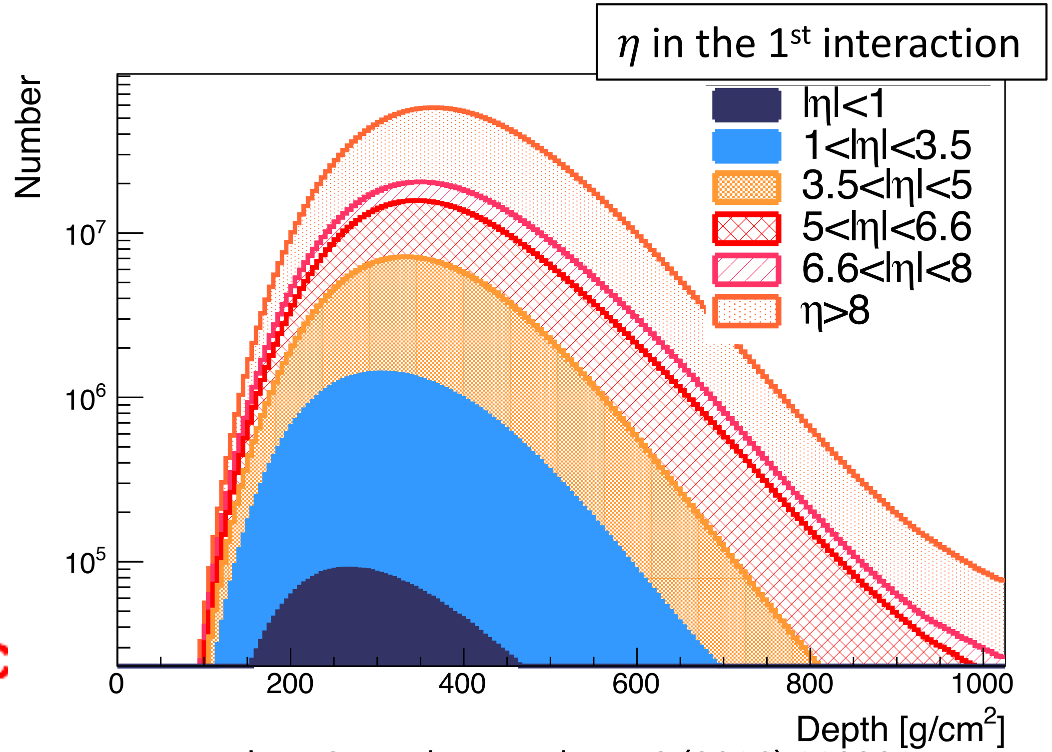
2^{ry} energy flow & air shower

√s=14TeV p-p collision = 10^{17}eV proton hitting a proton at rest

Energy Flux @ √s=14TeV p-p



10^{17}eV proton shower

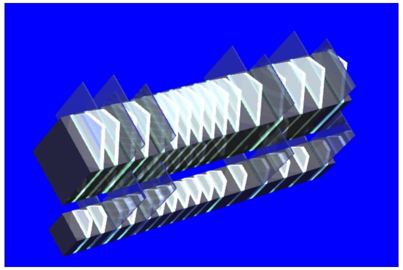


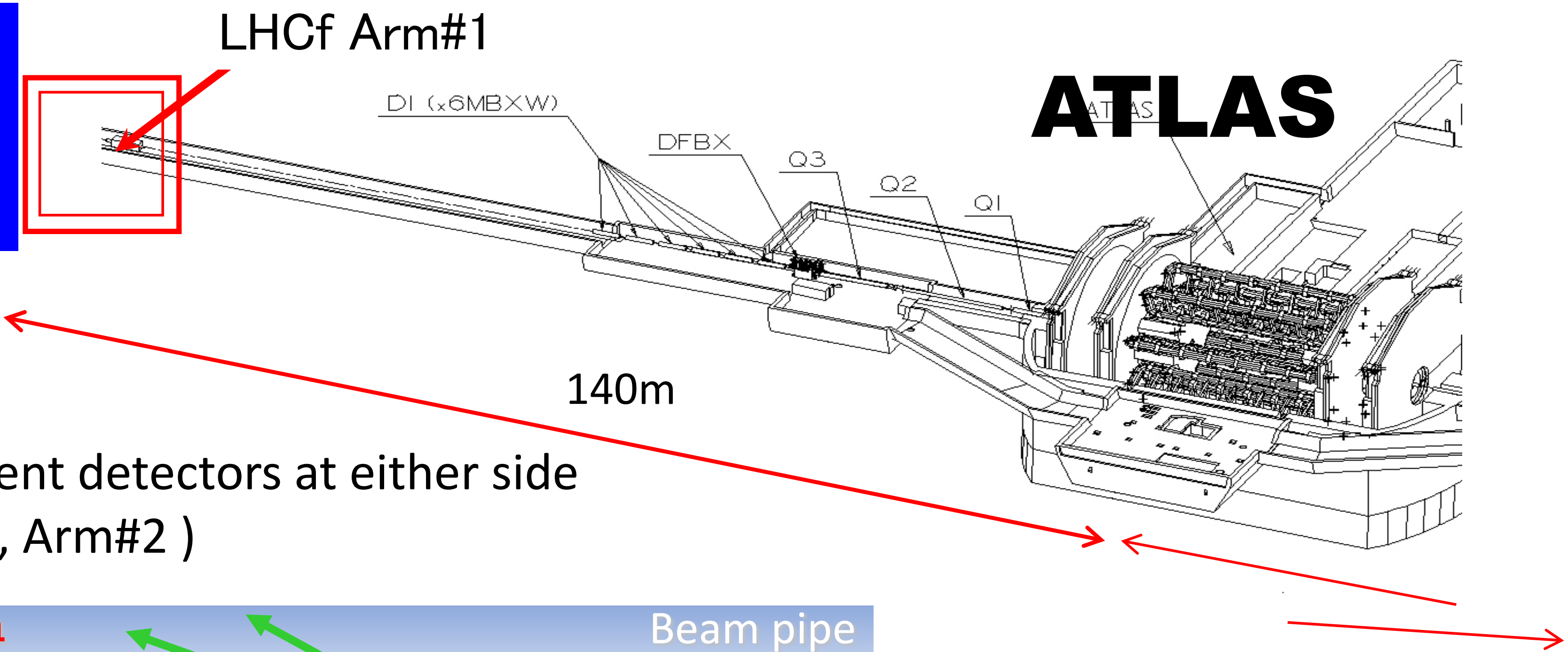
J. Phys. G: Nucl. Part. Phys. 43 (2016) 110201

η=8 => θ~1mrad (CMS)

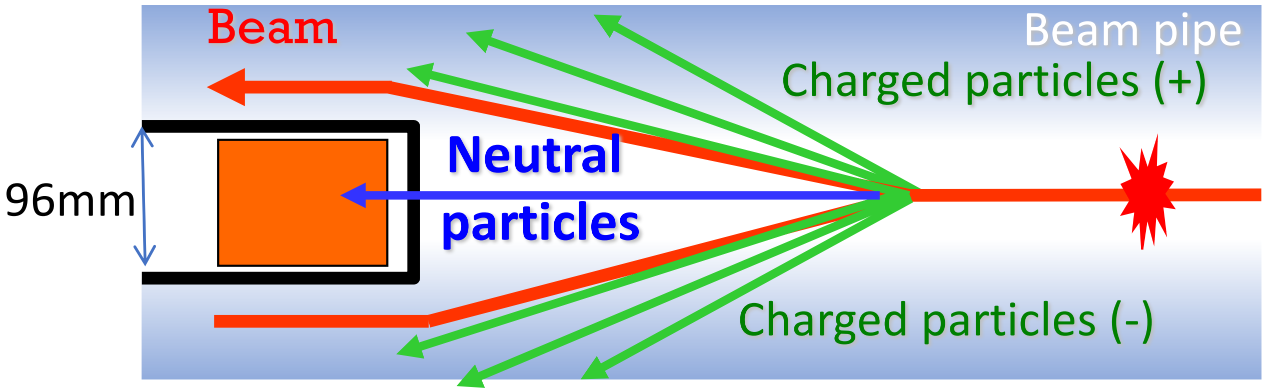
- ✓ Energy flow peaks out of the general purpose central detectors
- ✓ Air shower structure is determined by the forward particles in the first interaction
- ✓ LHCf covers near the peak of energy flow

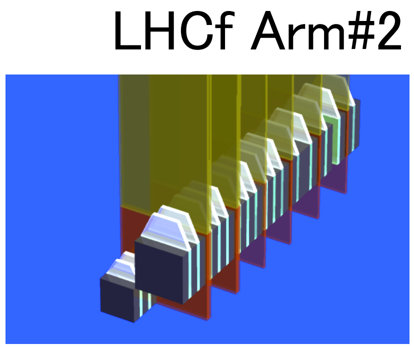
The LHC forward experiment





Two independent detectors at either side of IP1 (Arm#1, Arm#2)

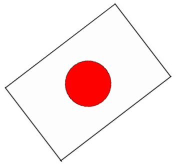




- ✓ All charged particles are swept by dipole magnet
- ✓ Neutral particles (photons and neutrons) arrive at LHCf
- ✓ $\eta>8.4$ (to infinity) is covered

The LHCf Collaboration

[*,]Y.Itow, [*]Y.Makino, [*]K.Masuda, [*]Y.Matsubara, [*]E.Matsubayashi, [***]H.Menjo, [*]Y.Muraki, [*,**]T.Sako, [*]K.Sato, [*] M.Shinoda, [*]M.Ueno, [*]Q.D.Zhou**



[*]Institute for Space-Earth Environmental Research, Nagoya University, Japan
[**]Kobayashi-Maskawa Institute, Nagoya University, Japan
[***]Graduate School of Science, Nagoya University, Japan

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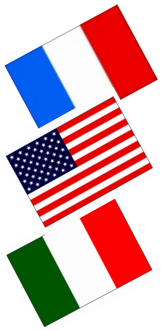
Waseda University, Japan

Y.Shimizu, T.Tamura *Kanagawa University, Japan*

N.Sakurai *Tokushima University, Japan*



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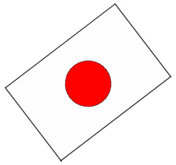
W.C.Turner *LBNL, Berkeley, USA*

O.Adriani, E.Berti, L.Bonechi, M.Bongi, G.Castellini, R.D'Alessandro, P.Papini, S.Ricciarini, A.Tiberio
INFN, Univ. di Firenze, Italy

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

The LHCf Collaboration



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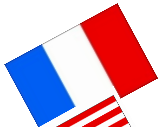
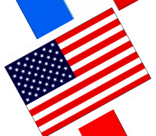
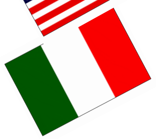
Waseda U

Y.Shimizu, T.Tamura *Kanagawa*

N.Sakurai *Tokushima*







M.Haguenauer *Ecole Polyte*

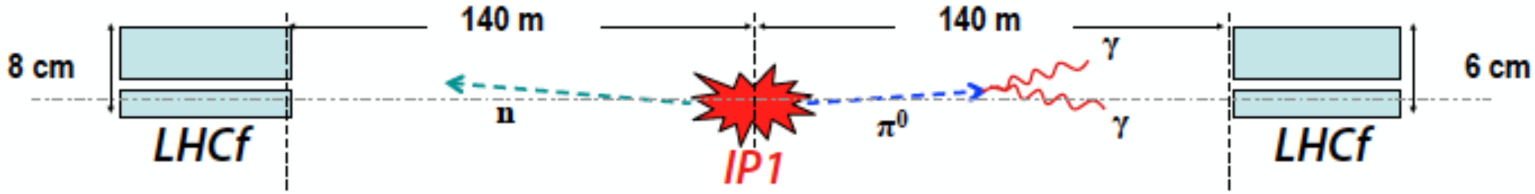
W.C.Turner *LBNL, Berk*

O.Adriani, E.Berti, L.Bonechi,
P.Papini, S.Ricciarini, A.Tiber

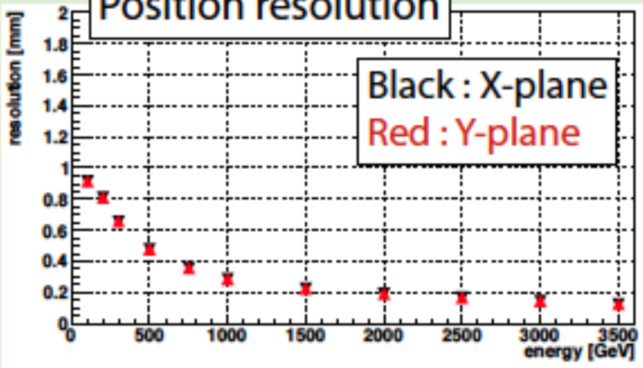
INFN, Univ

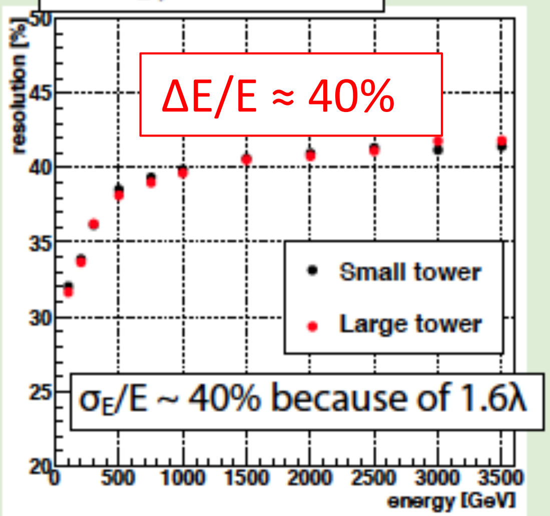
A.Tricomi *INFN, Univ*

Detector performance

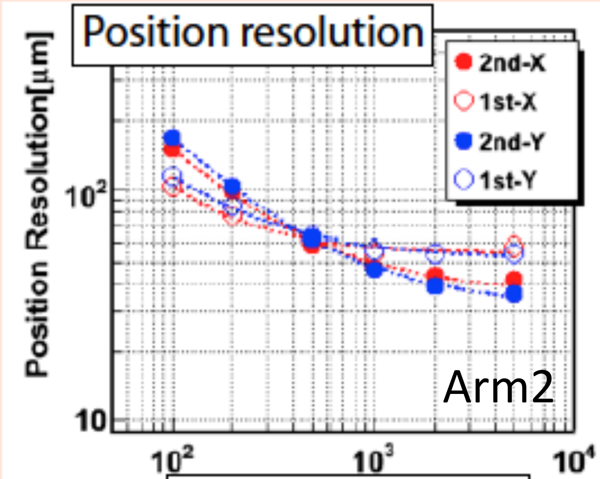


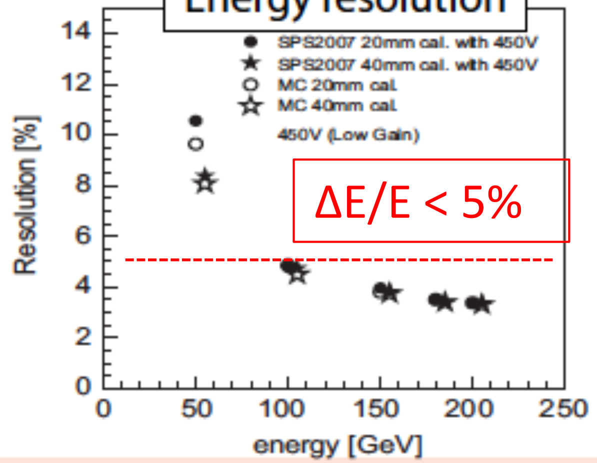
Hadronic shower (MC)





EM shower (MC)





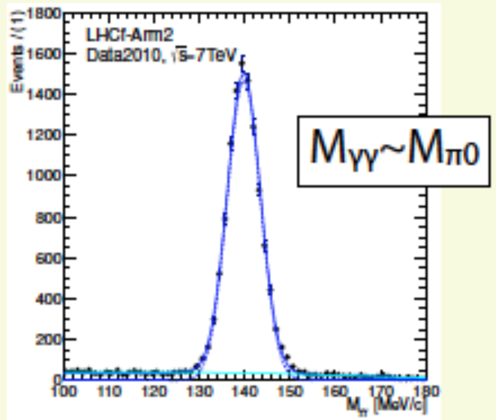
PID technique

400GeV photon

1TeV neutron

Identification of incoming particle by shower shape

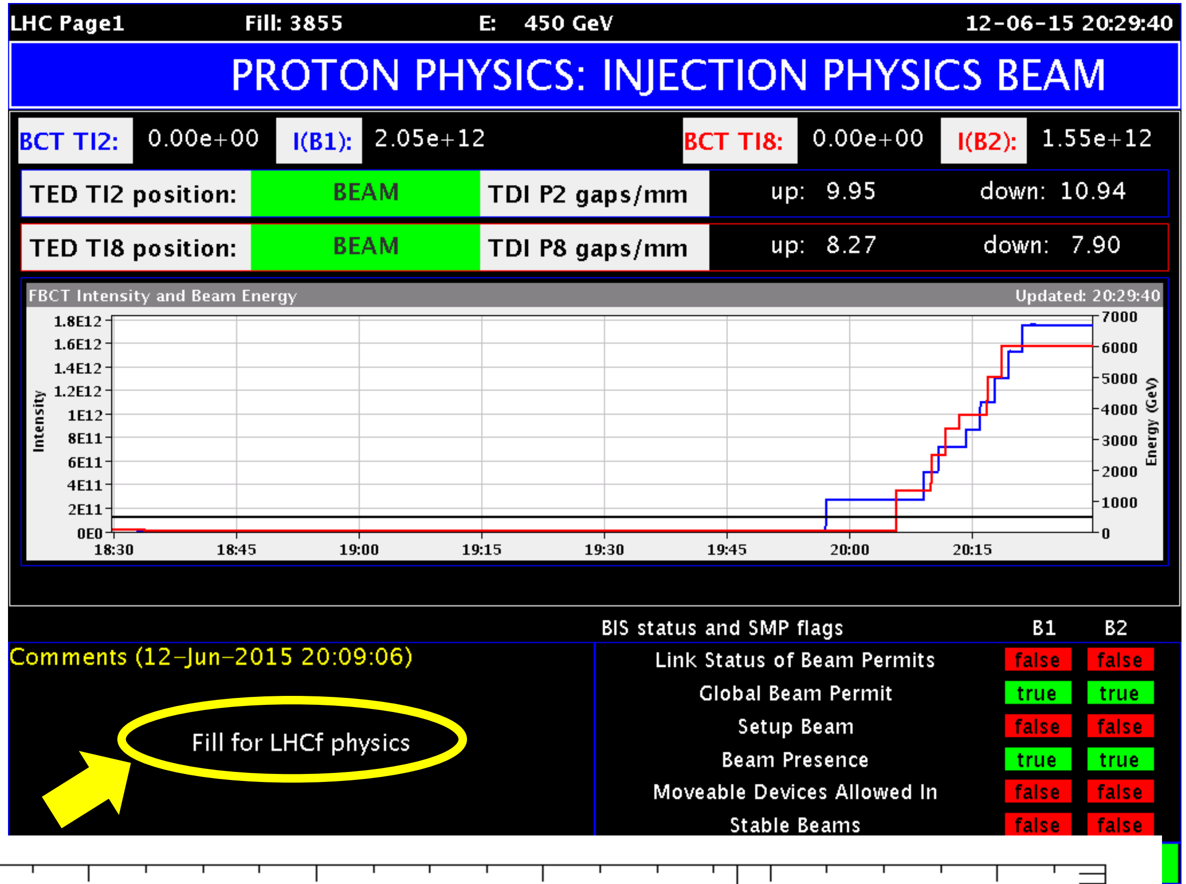
π^0 reconstruction

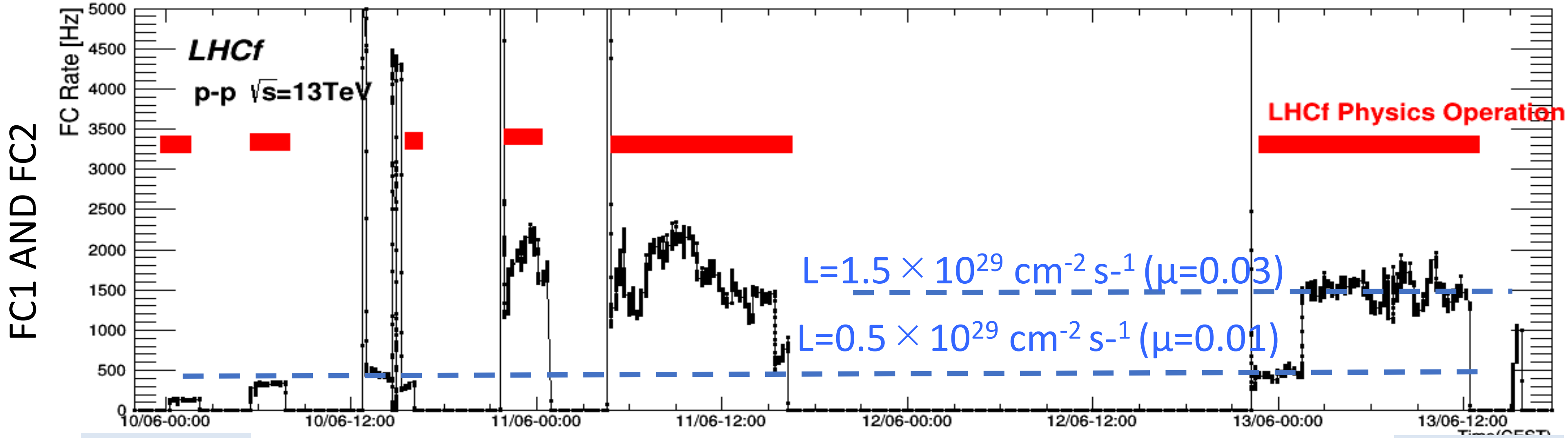


LHCf History

- ✓2004 LOI submitted to CERN
- ✓2006 TDR approved by CERN
- ✓2009 First data taking at $\sqrt{s}$=900GeV p-p collision
- ✓2010 $\sqrt{s}$=7TeV p-p collision
- ✓2013 $\sqrt{s}$=2.76TeV p-p & $\sqrt{s_{NN}}$=5TeV p-Pb collisions
- ✓2015 $\sqrt{s}$=13TeV p-p collision
- ✓2016 $\sqrt{s_{NN}}$=8.1TeV p-Pb collision
- ✓(2017 $\sqrt{s}$=510GeV p-p collision as RHICf)

13TeV operation in June 2015

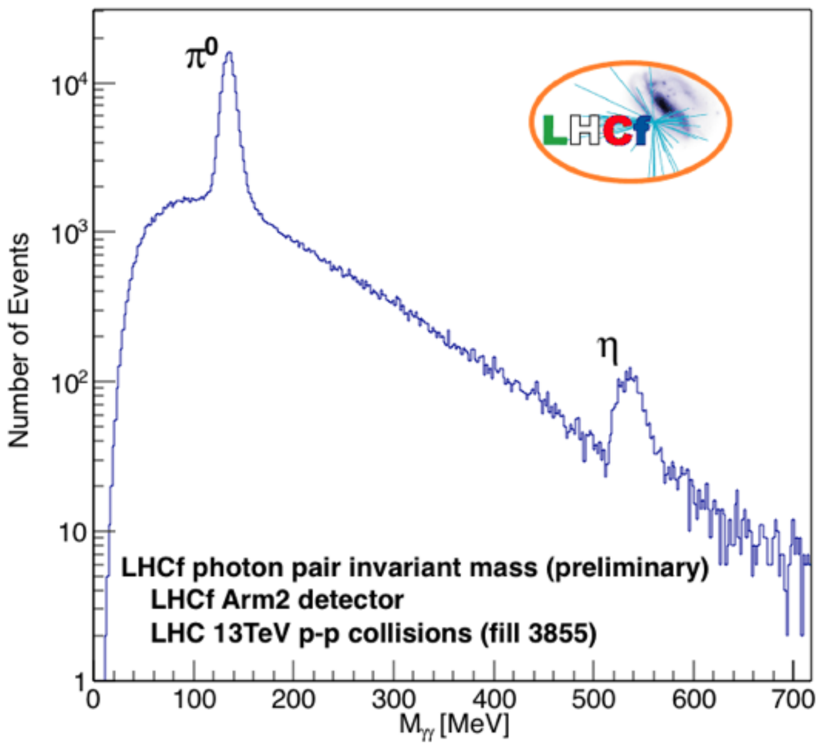


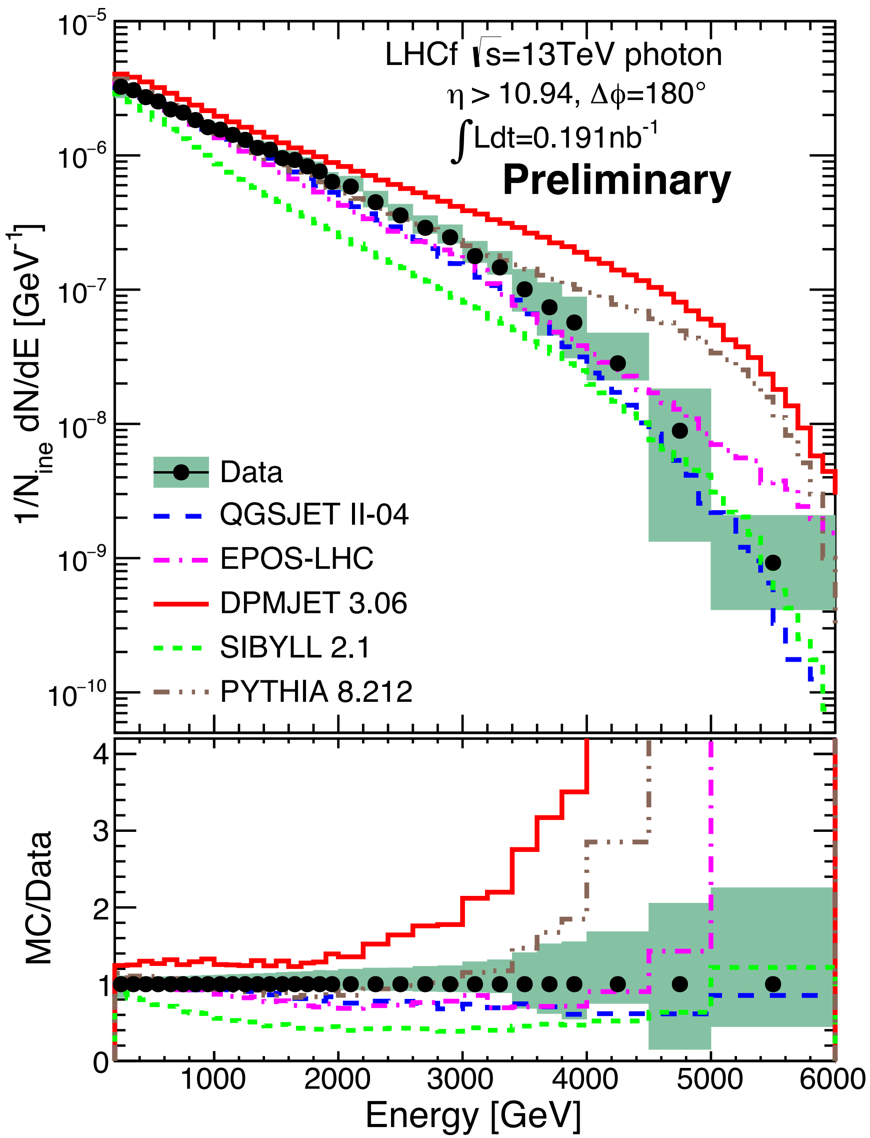


6月10日
0:00

6月13日
12:00

13TeV operation in June 2015





Analyses

Covered today

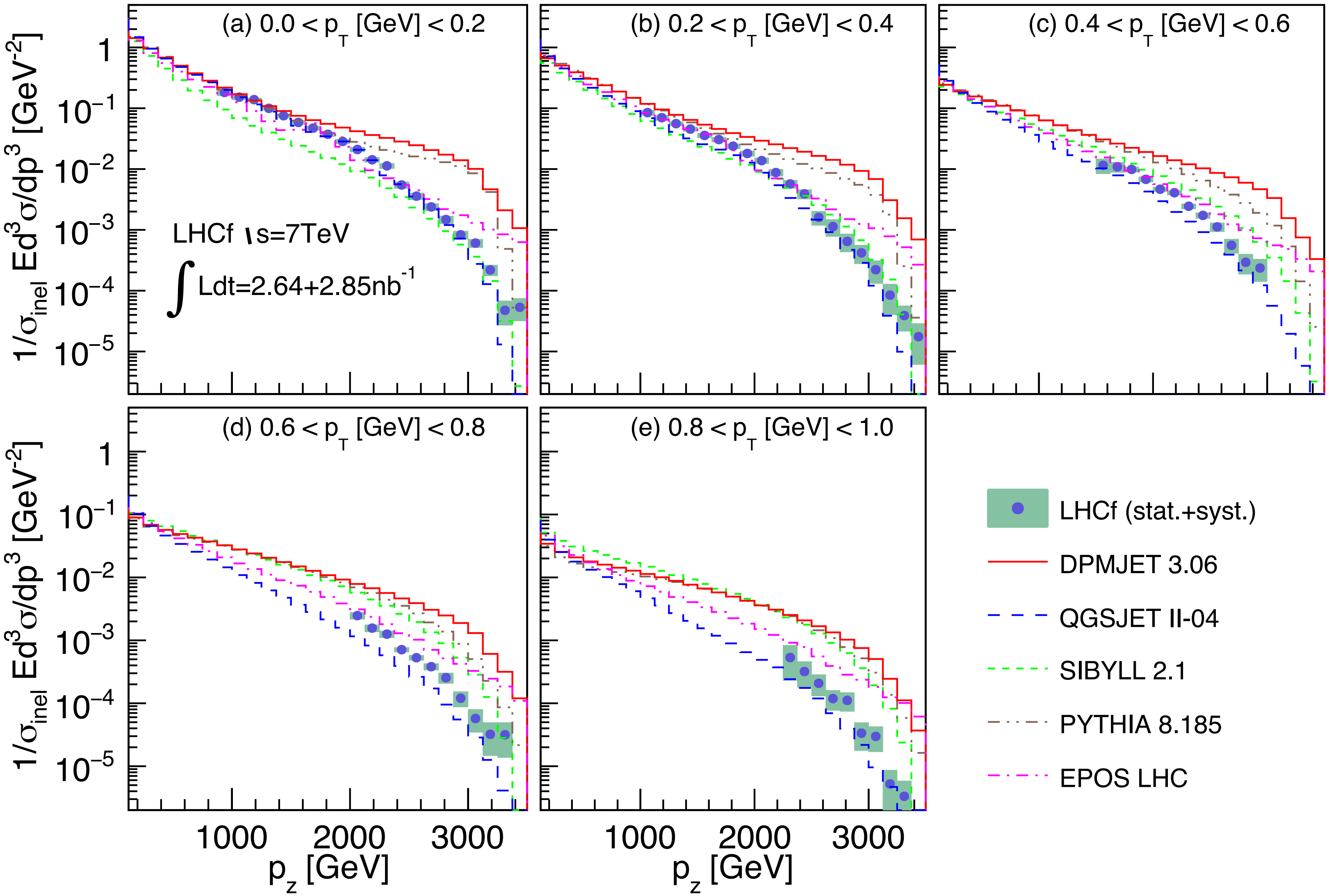
- π^0 cross section at 7TeV, comparison with models
- Neutron cross section at 7TeV, comparison with models
- ATLAS-LHCf joint analysis (MC study)
- √s scaling

Not covered today (see publication list in backup)

- Photon cross sections at 0.9, 7TeV and 13TeV
- π^0 cross section and nuclear effect in 5.02TeV p-Pb collisions

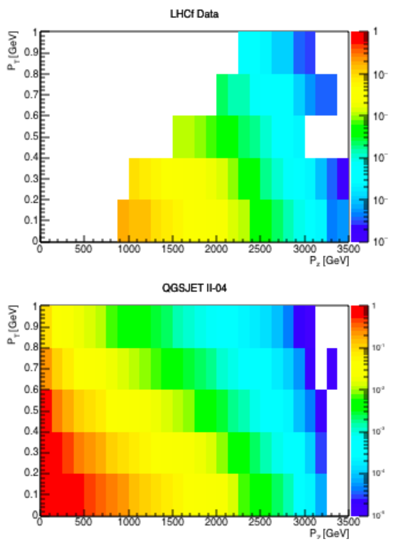
π^0 p_z spectra in 7TeV p-p collisions

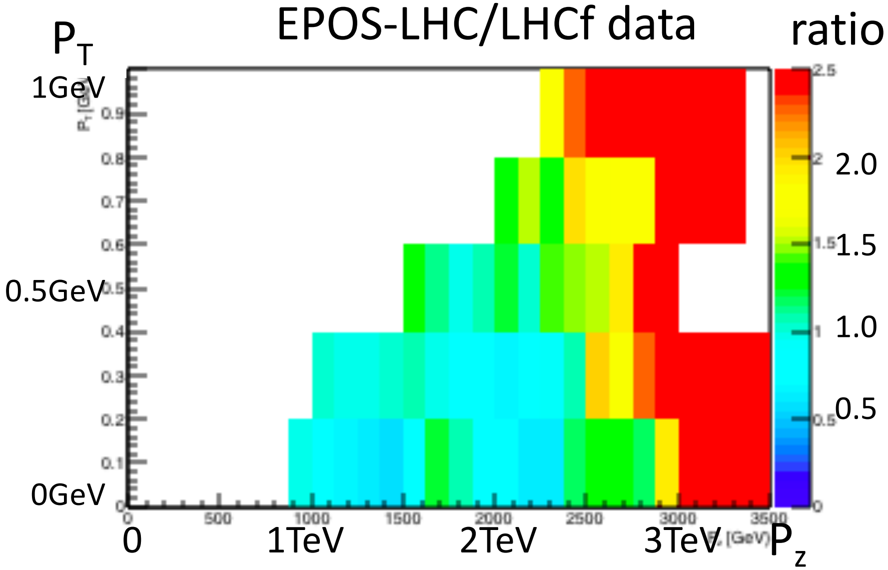
(PRD, 94 (2016) 032007)

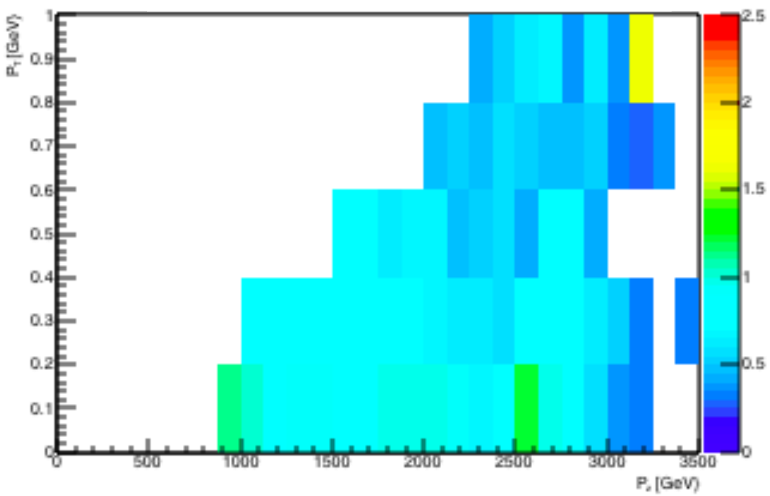


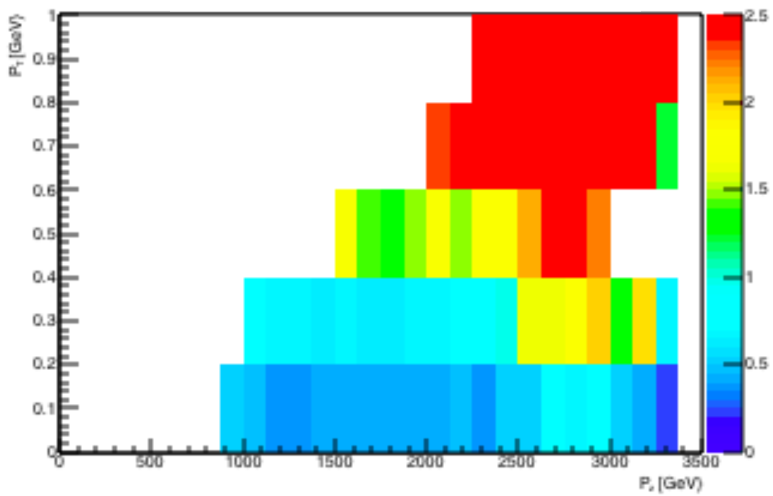
✓ DPMJET3 and PYTHIA8 overestimate over all E-p_T range

π^0 in 7TeV p-p collision
LHCf and models (ratio to data)



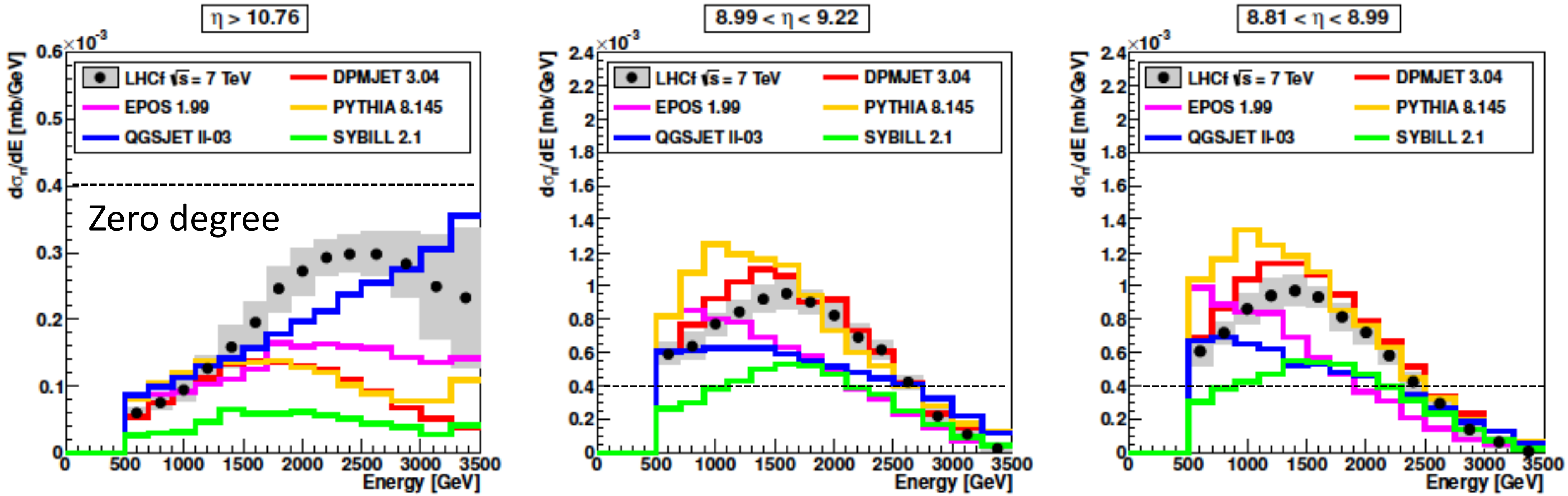






Neutrons in 7TeV p-p collision

(√s=7TeV p-p ; PLB 750 (2015) 360-366)

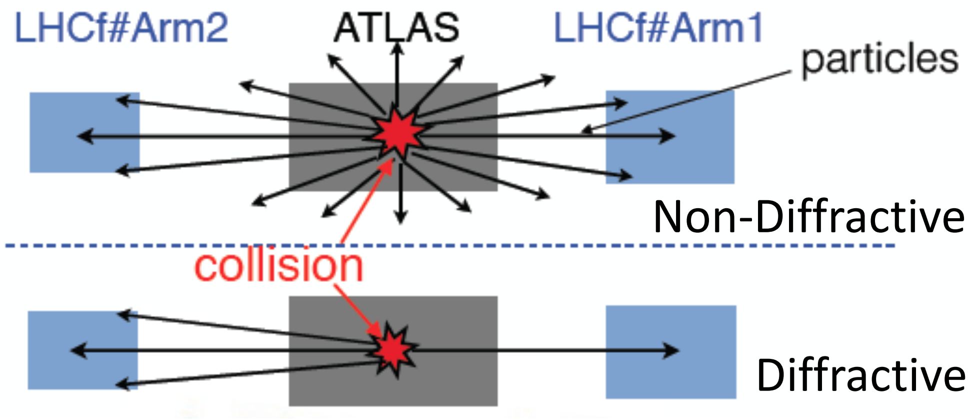


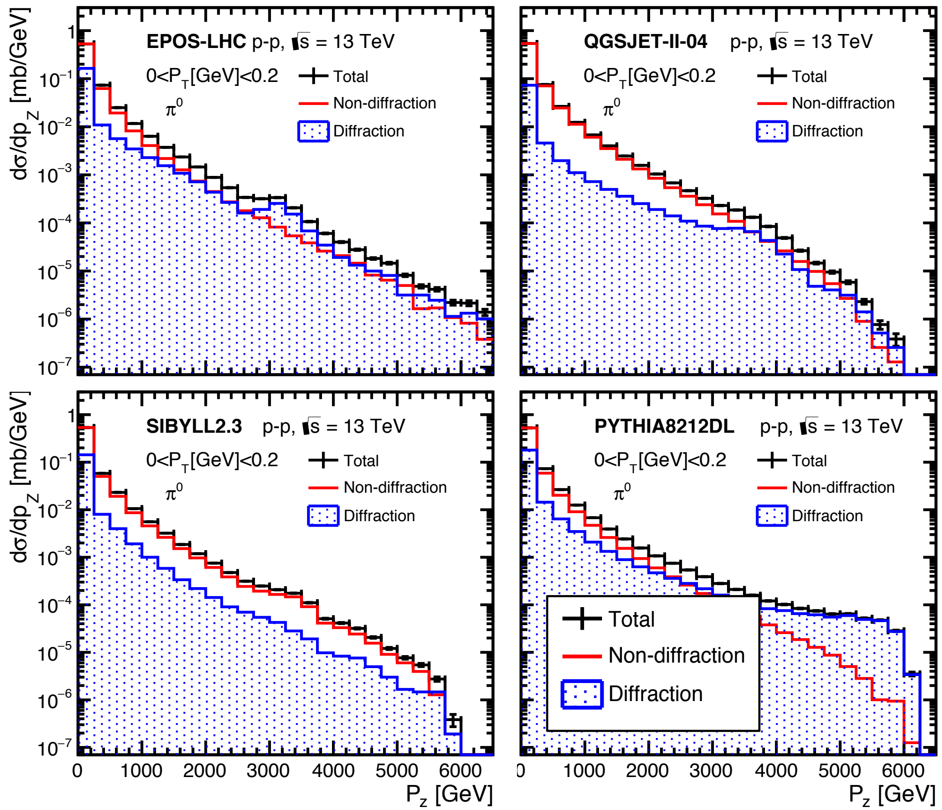
(~10% of other neutral hadrons at 140m are included both in data and MC)

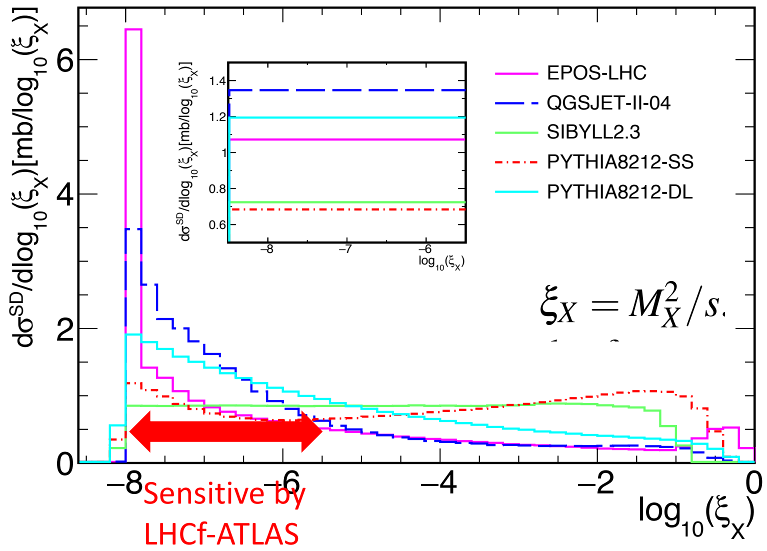
- ✓ Only QGSJET II explains the characteristic peak near zero degree
- ✓ DPM and PYTHIA under production at zero degree
- ✓ DPM and PYTHIA not bad at off-zero degree. DPM is best.

Origin of difference

(Zhou et al., submitted to EPJC, arXiv:1611.07483)





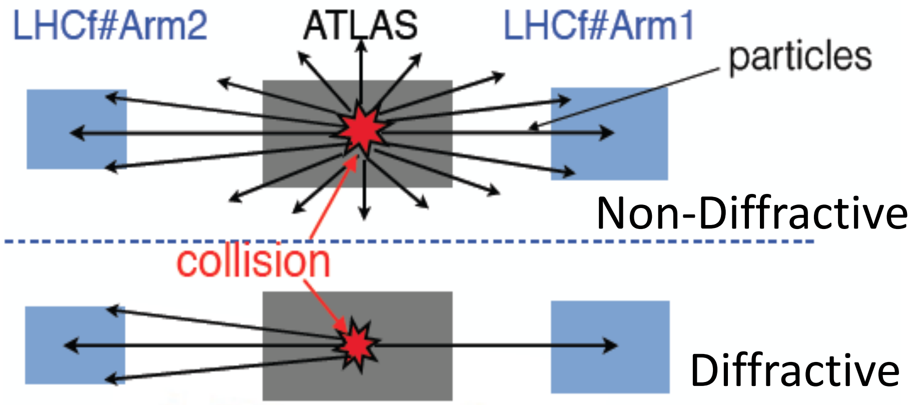


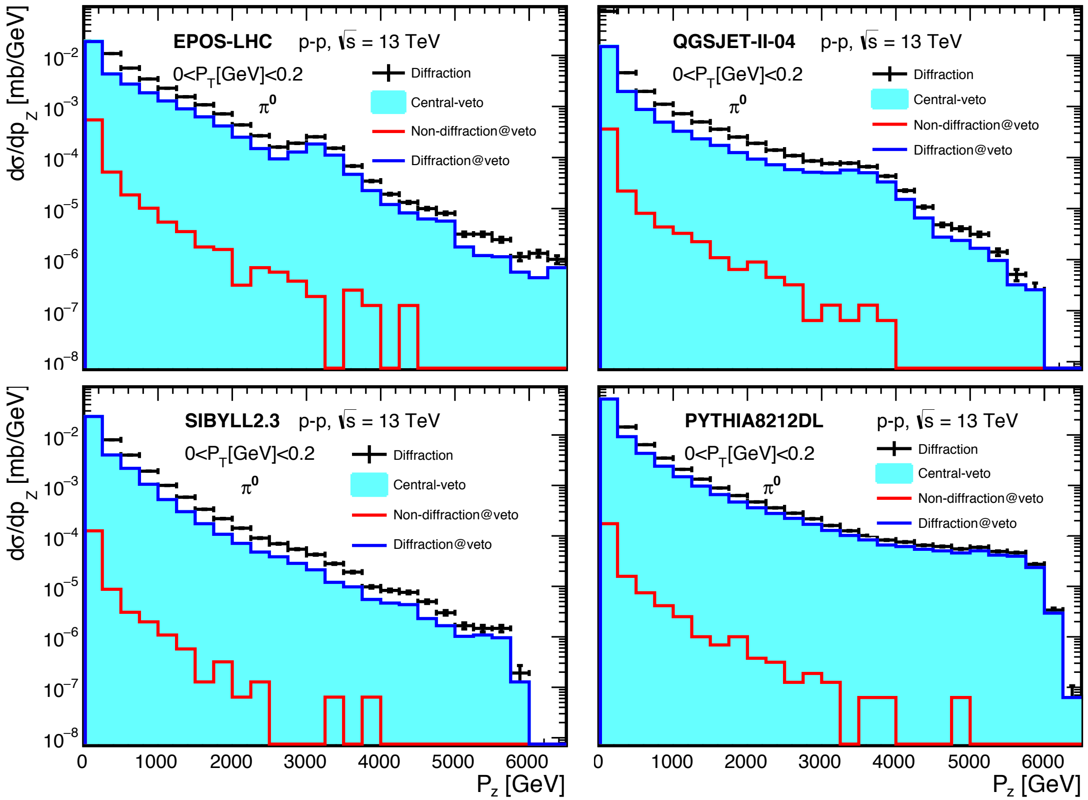
Single diffraction cross sections

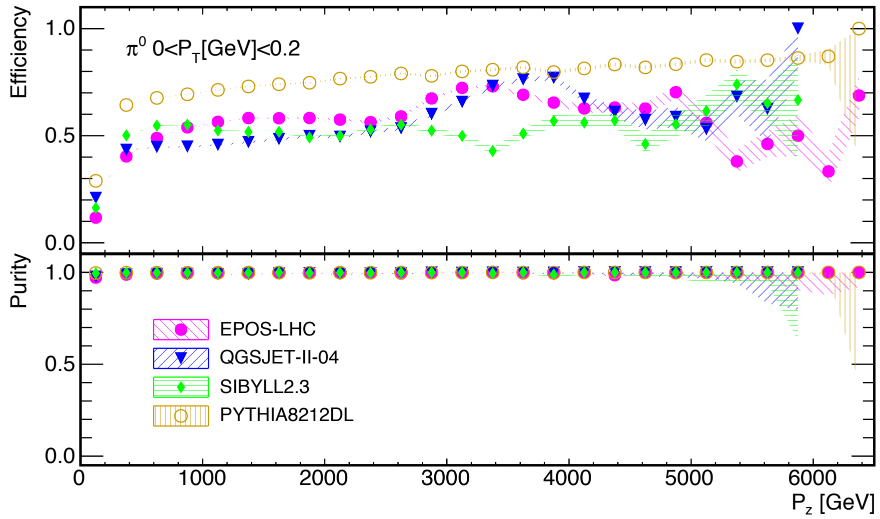
- ✓ ~half of LHCf detected particles are produced in diffractive dissociation
- ✓ Fraction and shape of diffraction/non-diffraction are model dependent
- ✓ By classifying LHCf events with ATLAS track information, LHCf can select pure diffractive samples in never explored mass range (ξ_X)

Tagging by ATLAS

(no track in ATLAS=diffraction-like)







Diffraction selection efficiency and purity

- Diffraction
- Central-veto
- Non-diffraction@veto
- Diffraction@veto

✓ ATLAS track information will be useful to tag diffractive events

✓ Common data taking was done in 13TeV p-p operation

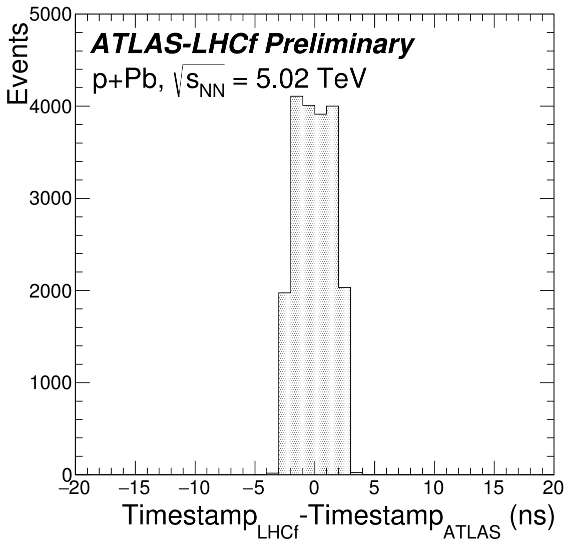
Technical feasibility of ATLAS-LHCf analysis

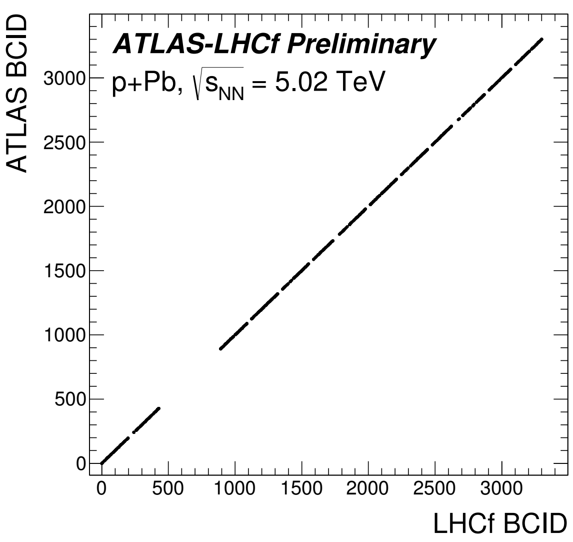
ATLAS LHCf NOTE
August 26, 2015

ATL-PHYS-PUB-2015-038
30 August 2015

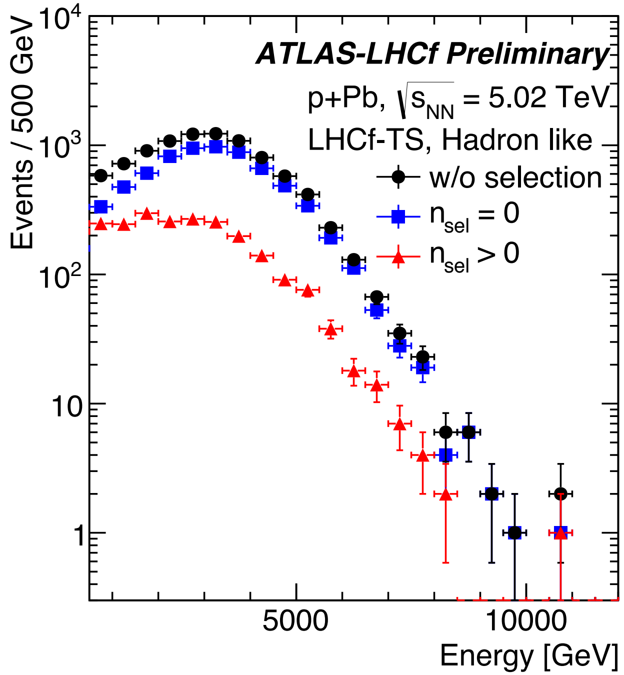
Classification of Events in the Combined ATLAS-LHCf Data Recorded During the *p*+Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

The ATLAS and the LHCf Collaborations





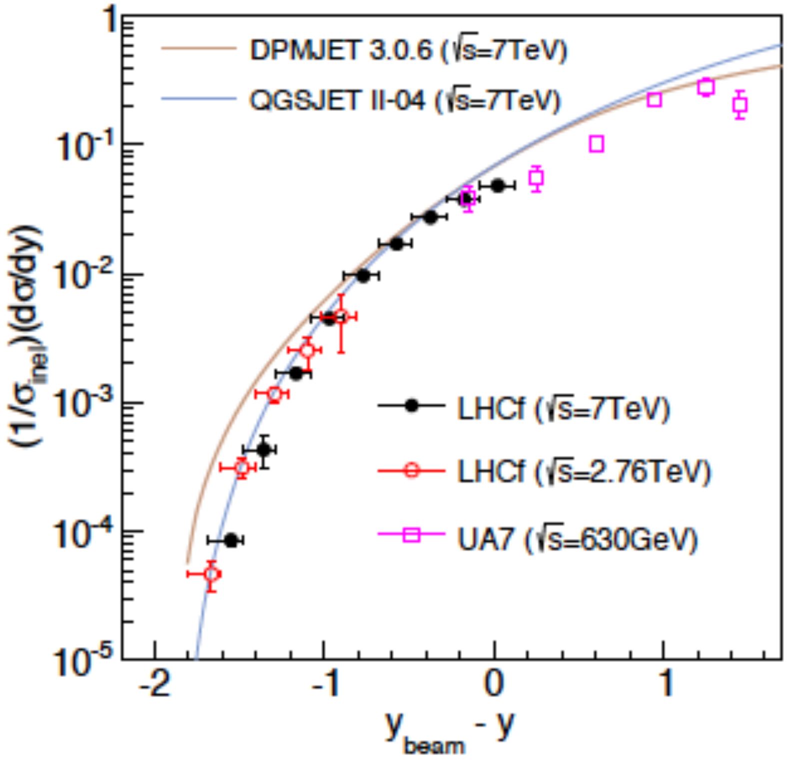
Timing and bunch ID matching



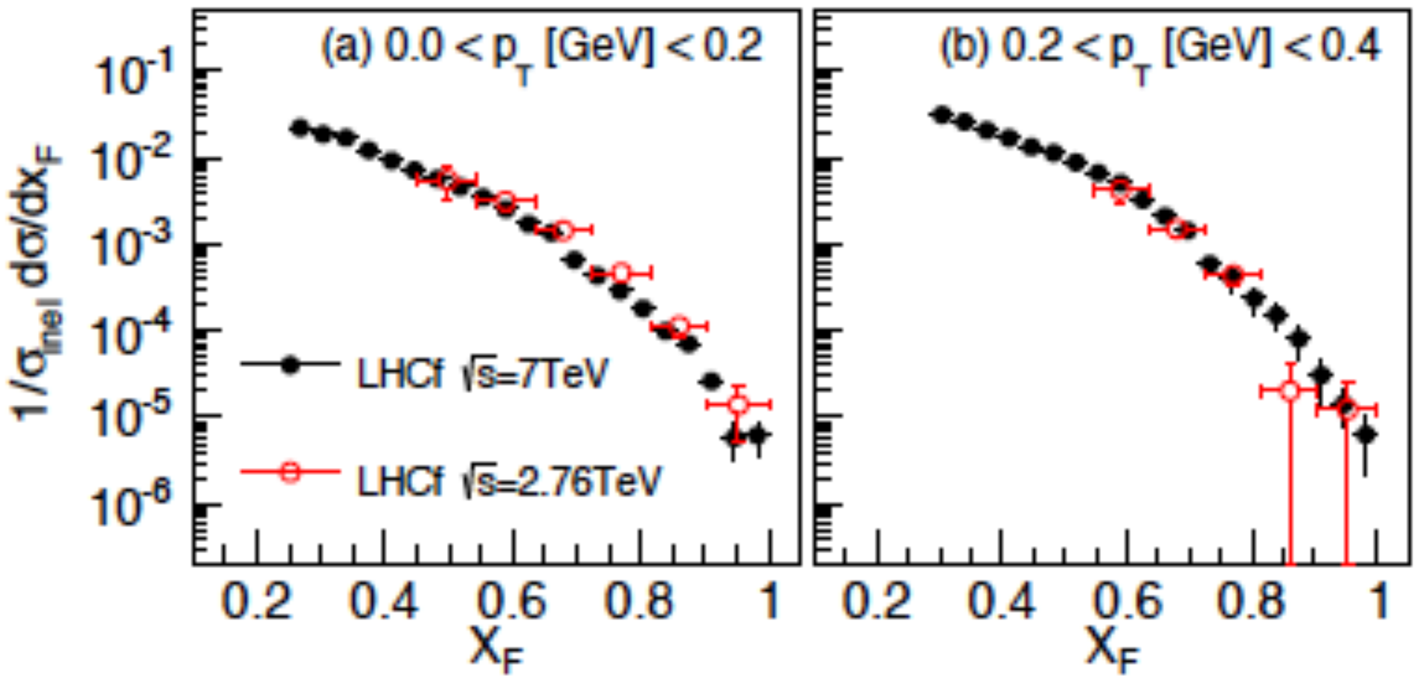
hadron spectrum@ 0 degree
(folded energy)

- ✓ Common Event ID was already tested using 5TeV p-Pb collision data in 2013
- ✓ HE neutrons with n_{sel}=0 are produced in the Ultra-Peripheral Collisions

√s scaling ; π^0

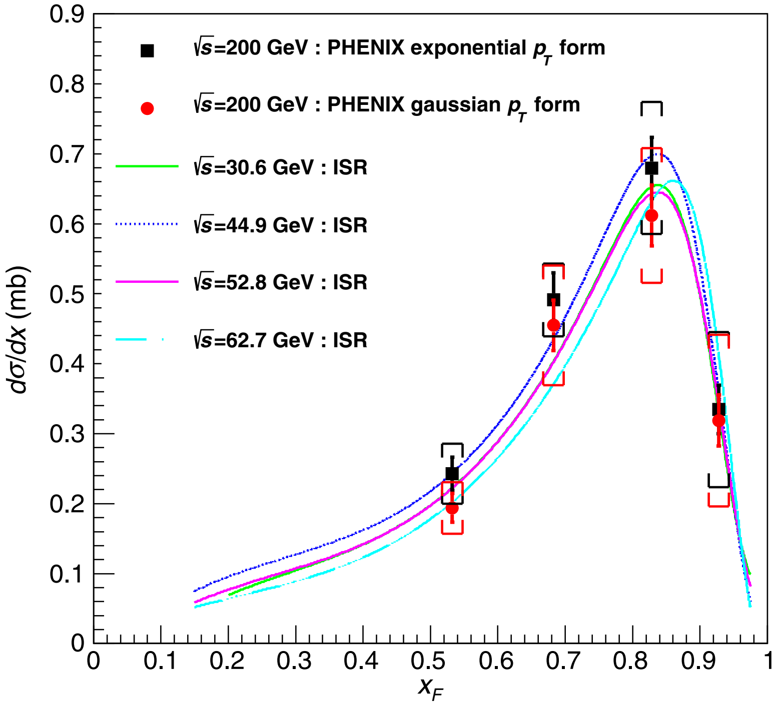


- ✓ Scaling is essential to extrapolate beyond LHC
- ✓ (630GeV –) 2.76TeV – 7TeV
  good scaling within uncertainties
- ✓ Wider coverage in y and p_T with 13TeV data
- ✓ Wider √s coverage with RHICf experiment in 2017 at √s=510GeV



Feynman x;
$x_F = 2p_z/\sqrt{s}$

√s scaling; Neutron @ zero degree

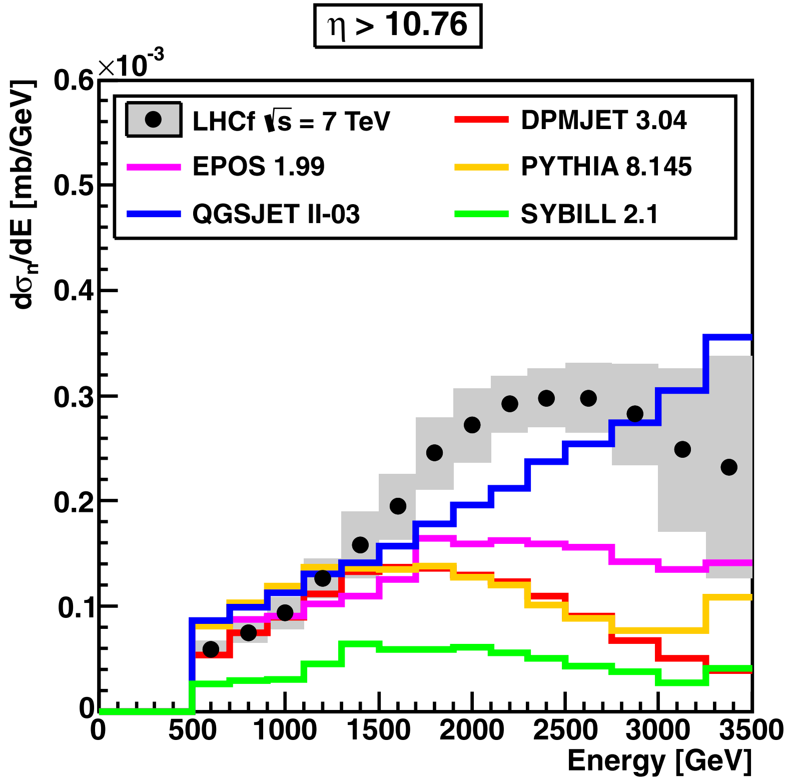


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf

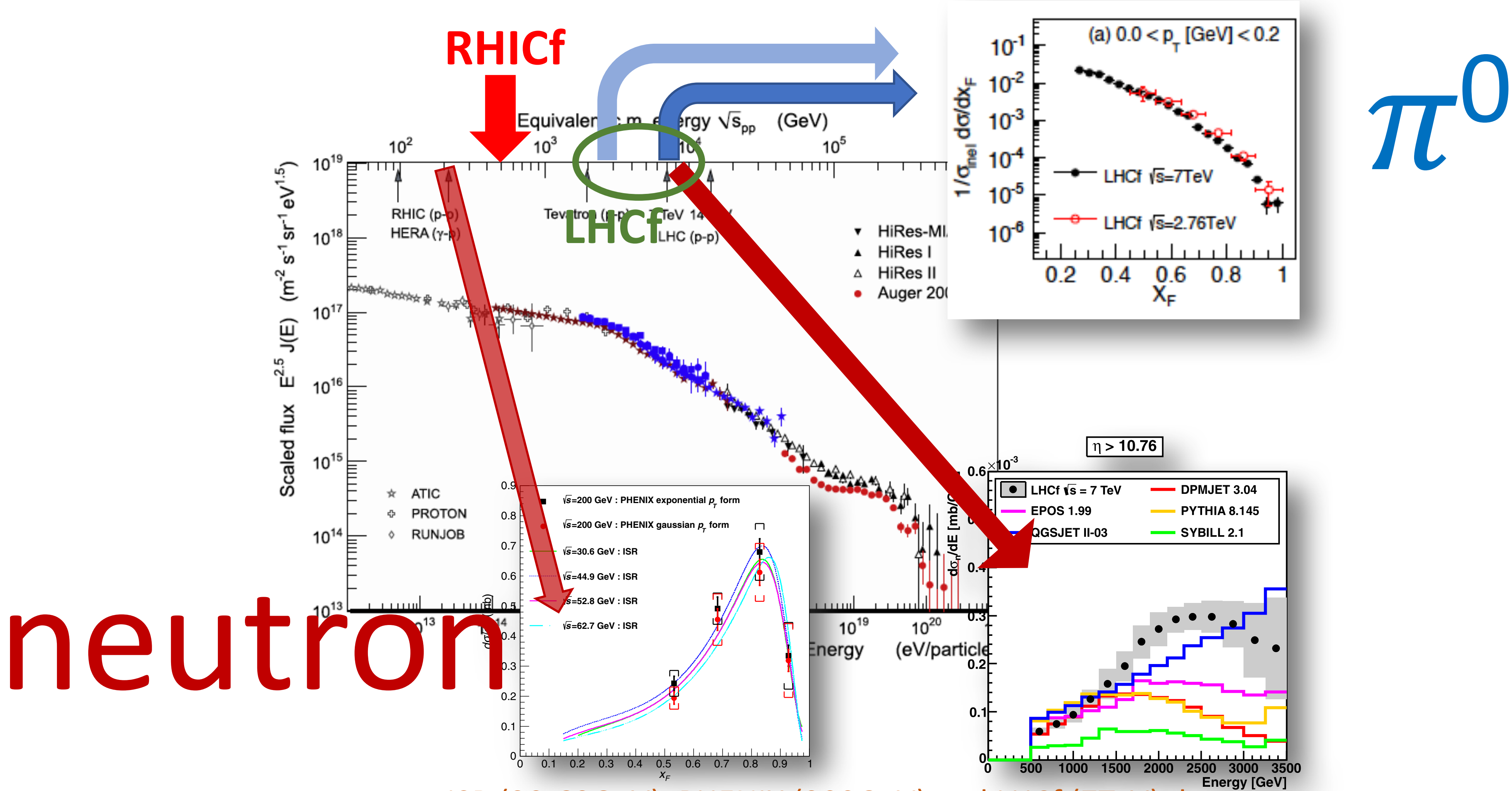
$p_T < 0.15\ x_F$ GeV/c

√s = 7000 GeV @LHC

- ✓ PHENIX explains the result by 1 pion exchange
- ✓ More complicated exchanges at >TeV?
- ✓ LHCf data at 900GeV, 2.76TeV to be analyzed
- ✓ RHICf data at 510GeV will be added in 2017

Feynman scaling, or breaking?

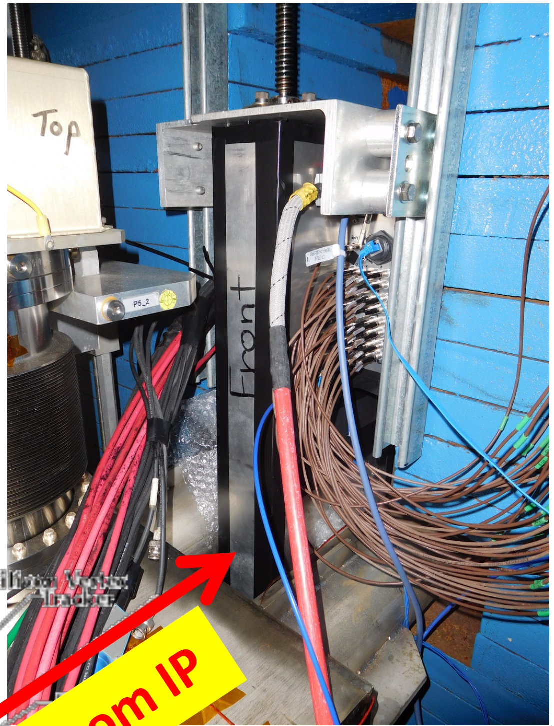
LHCf 2.76TeV and 7TeV data shows
Feynman scaling of forward π^0

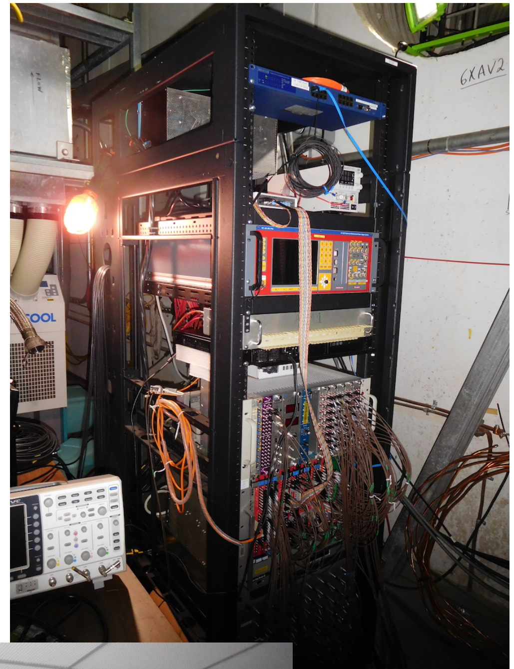


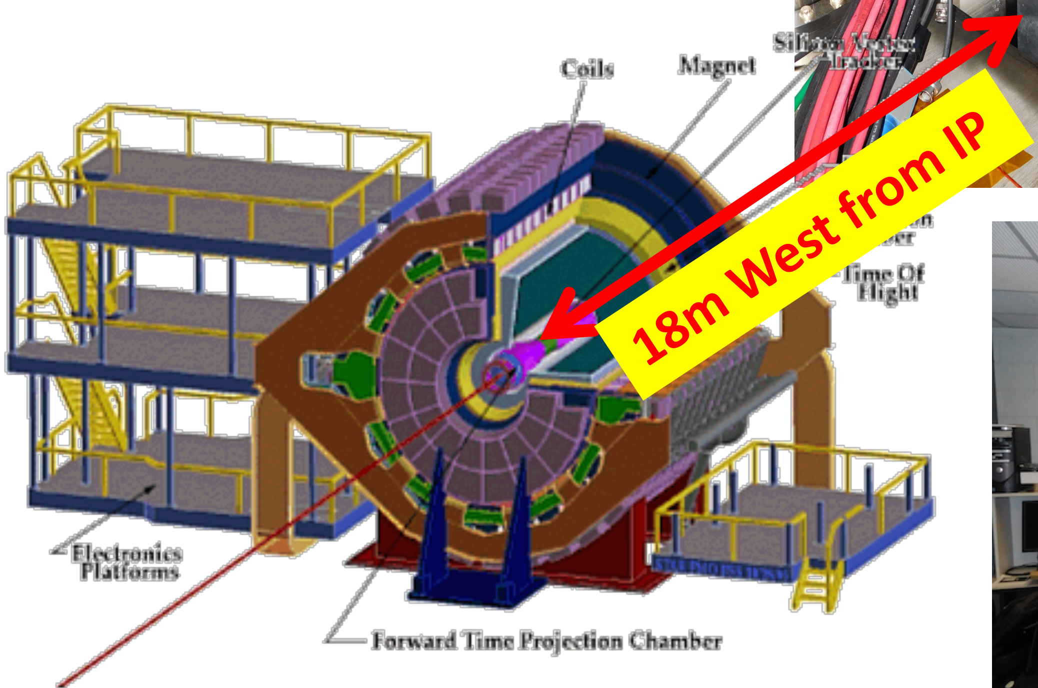
ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data
indicate Feynman scaling ***braking*** of forward neutrons

RHICf Installation @STAR interaction point

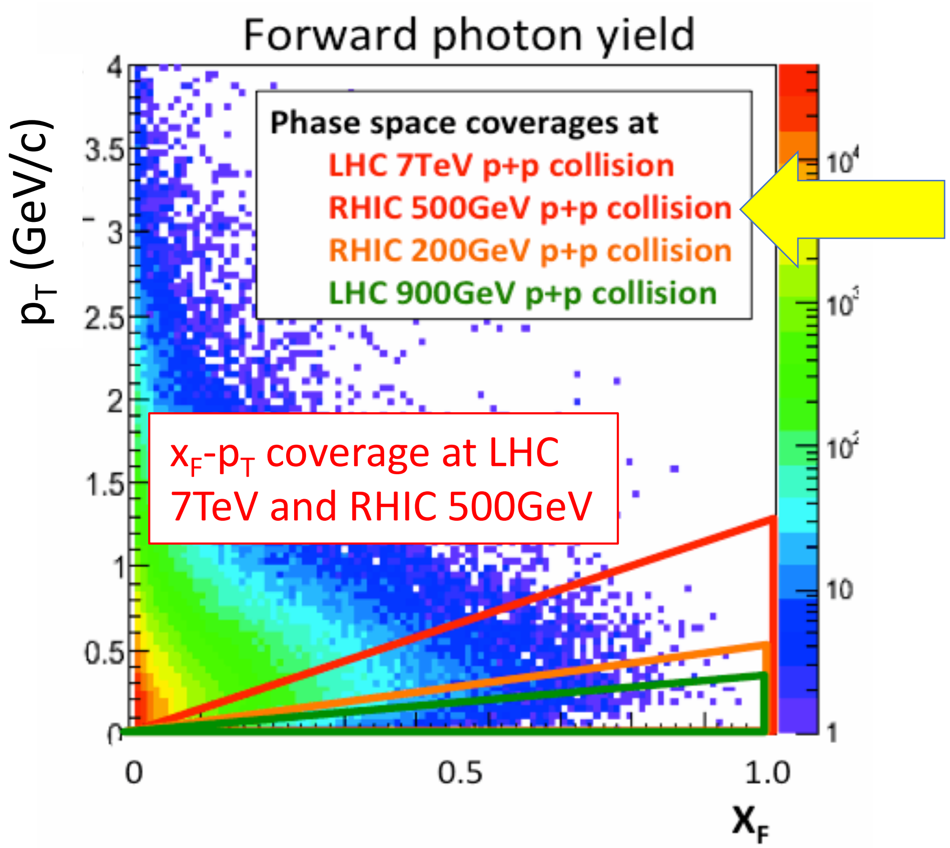
LHCf Arm1 detector, = RHICf, has been transported to BNL in May 2016 and installed in the STAR site in November.







Why not LHC 900GeV?

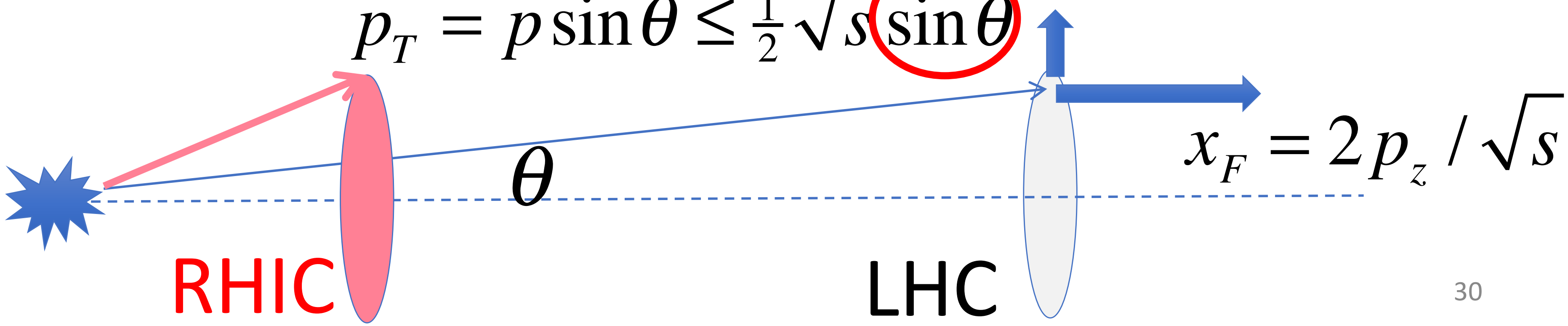


- ✓ Wide x_F-p_T coverage is desired
- ✓ Maximum p_T coverage is proportional to $\theta\sqrt{s}$

⇩

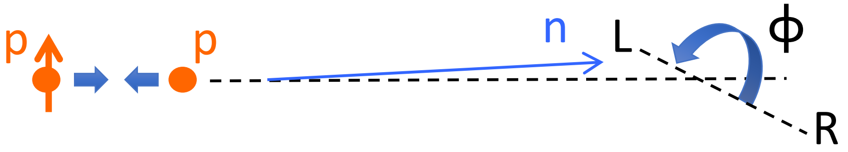
- ✓ RHIC allows larger θ with smaller $\sqrt{s}$
- ✓ x_F-p_T coverage at LHC 7TeV and RHIC 500GeV are almost identical!!

$$p_T = p\sin\theta \le \tfrac{1}{2}\sqrt{s}\sin\theta$$

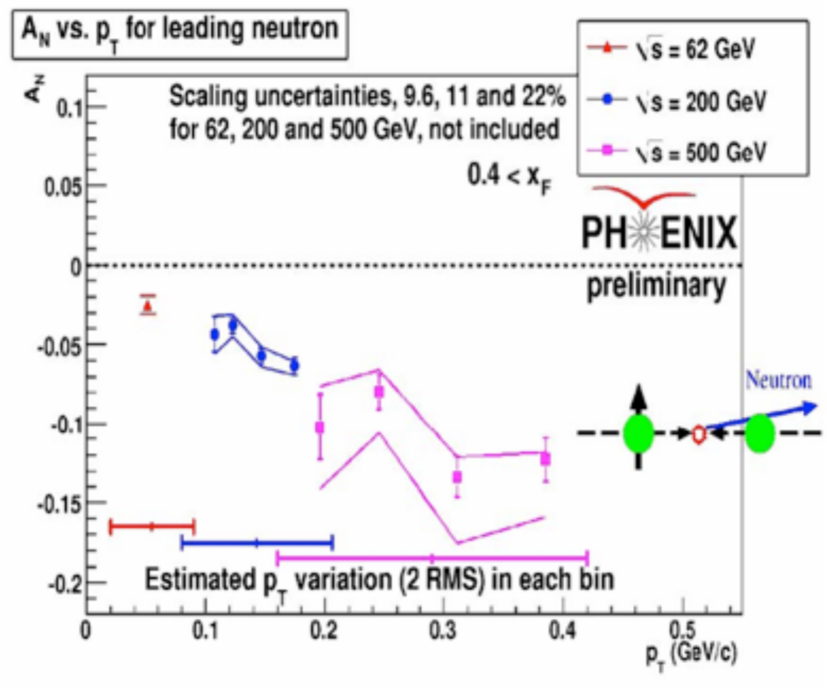


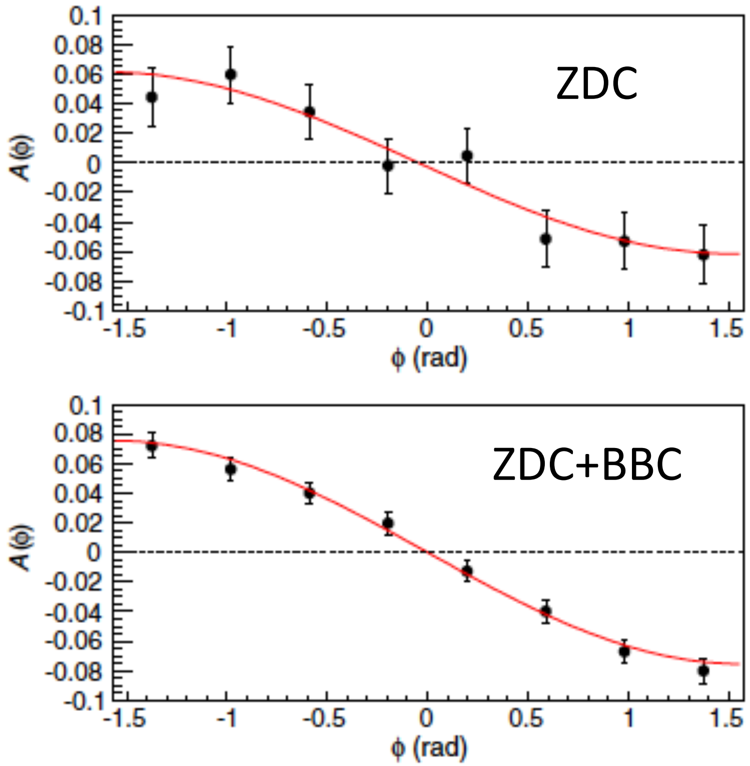
Single-spin asymmetry by PHENIX

(PRD, 88, 032006, 2013)



- ✓ strong asymmetry in forward neutrons was discovered at RHIC
- ✓ scaled with pT at √s = 62, 200, 500 GeV?

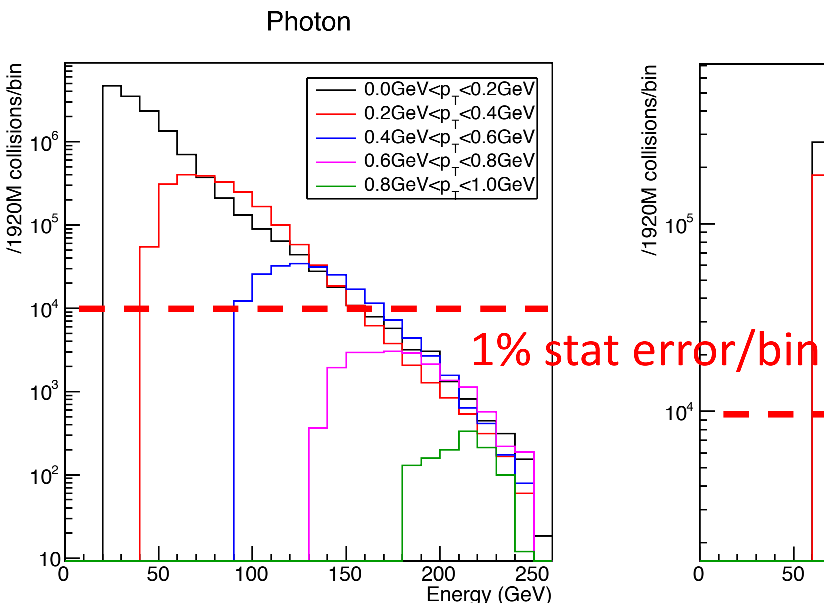


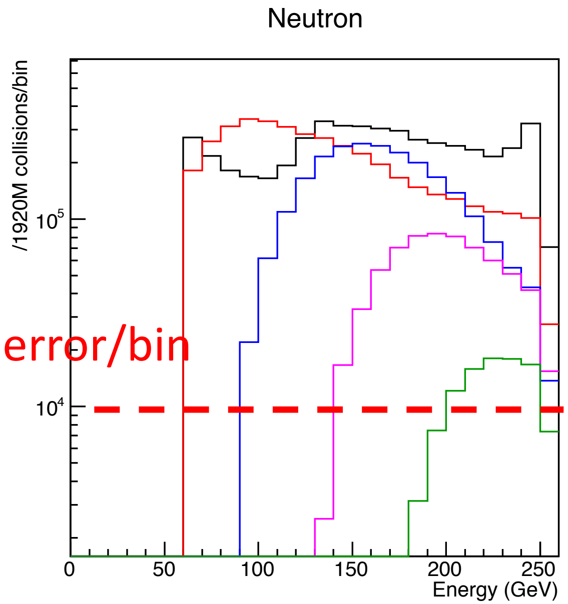


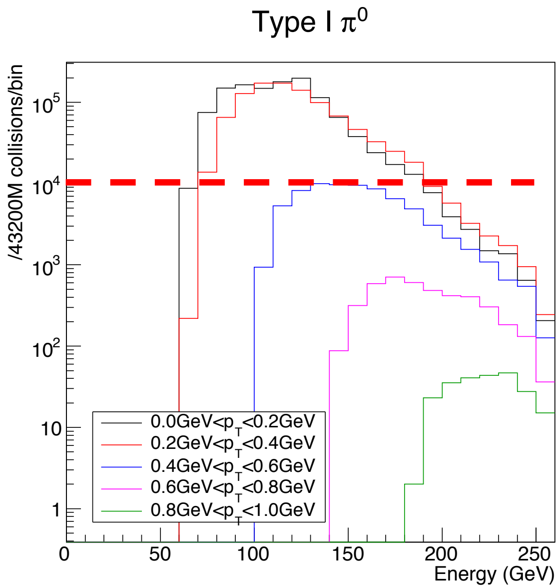
PHENIX results at 200GeV

RHICf can cover pT<1GeV only with √s = 510 GeV operation!

Expected statistics in 12 hours







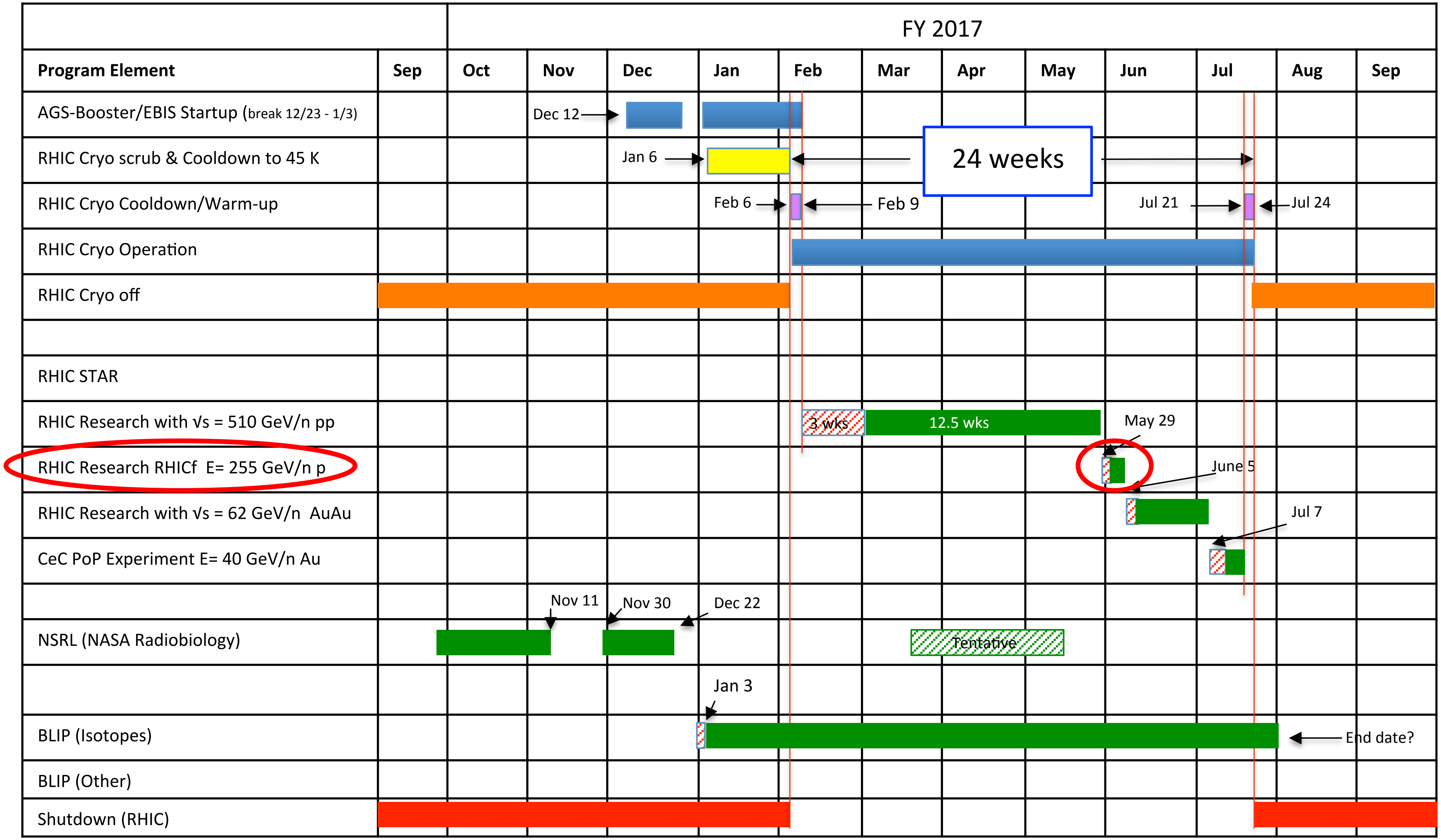
Neutron SSA

$p_T(GeV)$	N $(\times 10^3)$	δA
0.0–0.1	2,310	0.0013
0.1–0.2	2,570	0.0012
0.2–0.3	1,710	0.0015
0.3–0.4	2,190	0.0014
0.4–0.5	1,210	0.0018
0.5–0.6	1,130	0.0019
0.6–0.7	402	0.0032
0.7–0.8	260	0.0039
0.8–1.2	104	0.0062

- ✓ Luminosity error will be about 5%
- ✓ Special trigger for high energy EM shower is under preparation
- ✓ STAR will record events according to the RHICf trigger
  => Fruitful possibilities in joint analyses with central detectors, ZDC, roman pots,…

C-A Operations FY17

December 5, 2016



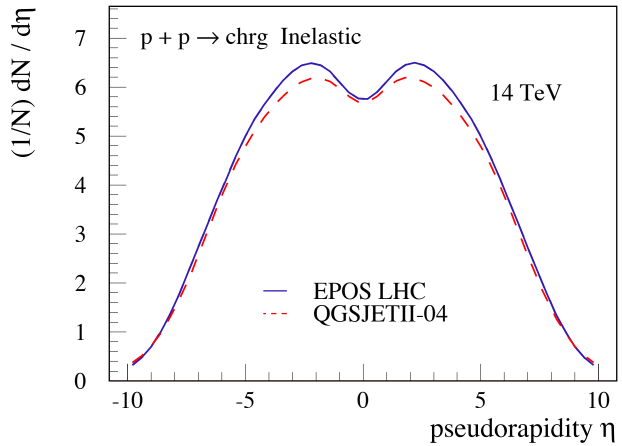
LHC p-O/O-O collisions

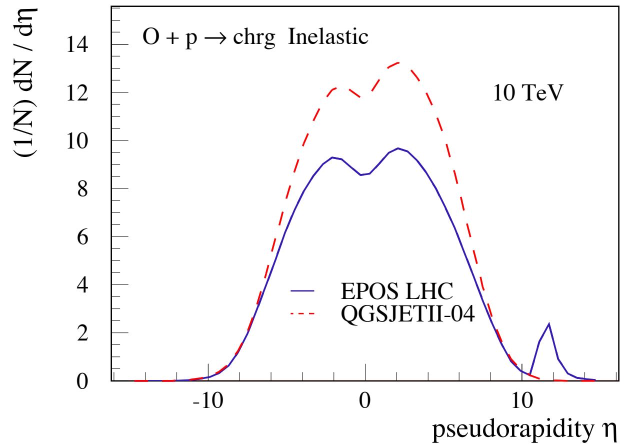
- ✓ LHC is TECHNICALLY able to accelerate and collide Oxygen beams
- ✓ Is nuclear effect in light ion collisions well understood?
- ✓ In A-A collisions, high multiplicity in the very forward region => new detector is required.

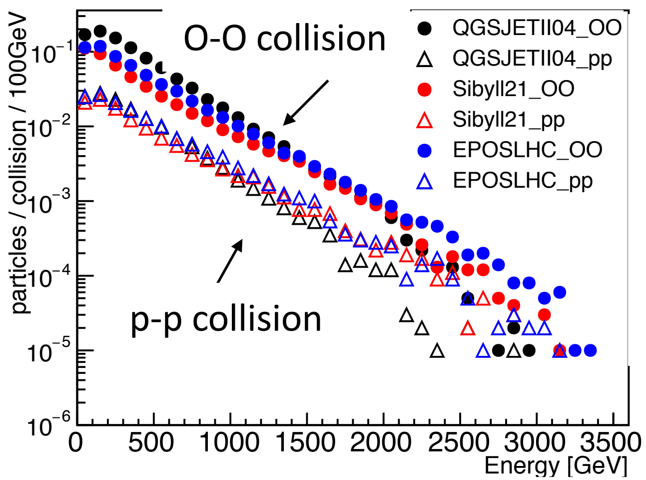
LHC Forward Physics

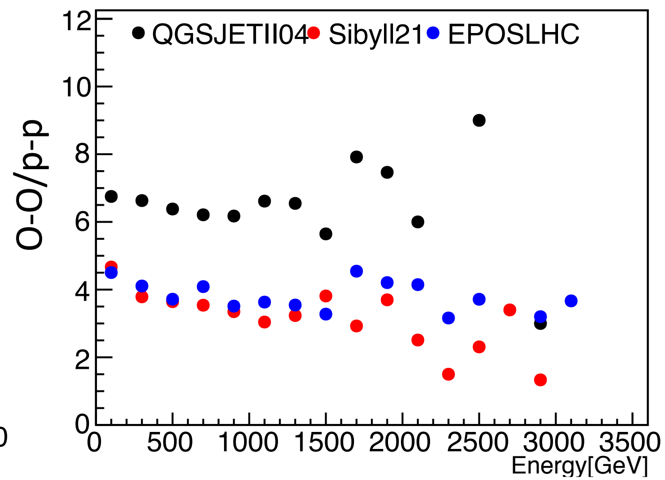
CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167

Multiplicity p-p vs. p-O









Photon spectra p-p vs. O-O

Y. Okuno, Master thesis
Nagoya university (2016)

International workshops lead by the KMI members

Series of zero degree workshop held at KMI

- High-Energy Scattering at Zero Degrees (HESZ), 2013
- Workshop on forward physics and high-energy scattering at zero degrees, 2015
  - Joint workshop with the “LHC forward physics working group meeting”
- Workshop on forward physics and high-energy scattering at zero degrees, 2017
  - Joint workshop with the “LHC forward physics working group meeting”

KMI support for a cosmic-ray conference

- 2016 International Conference on Ultra-High Energy Cosmic Rays, Kyoto (series started in 2010 from Nagoya)

Summary

- ✓ LHCf measured forward particles to improve the air shower simulation at 10^{17}eV
- ✓ Successful operation at various collisions;
  - ✓ 0.9-13TeV p-p, 5-8TeV p-Pb
- ✓ 6 papers for physics analysis are published
- ✓ Construction, operation, analyses are led by the Nagoya members

- ✓ New experiment, RHICf, started to take data in 2017
- ✓ √s scaling (and its break) will be tested in the cosmic-ray equivalent energy range of 10^{14}eV – 10^{17}eV

- ✓ Future plan of LHC p-O, O-O collisions is in investigation
- ✓ Future, future plan to use FCC at 5×10^{18}eV…

Backup

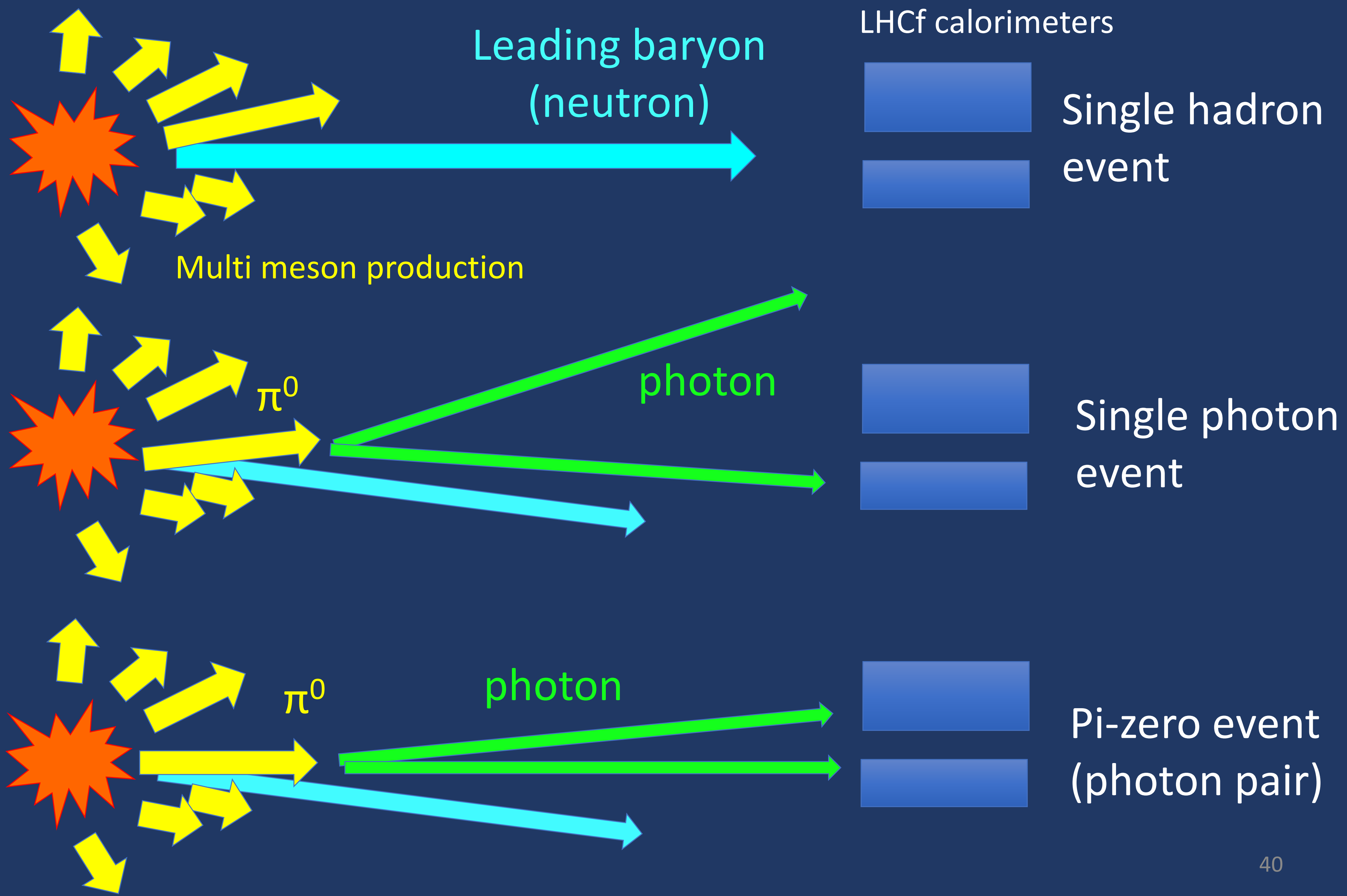
Publications

physics results

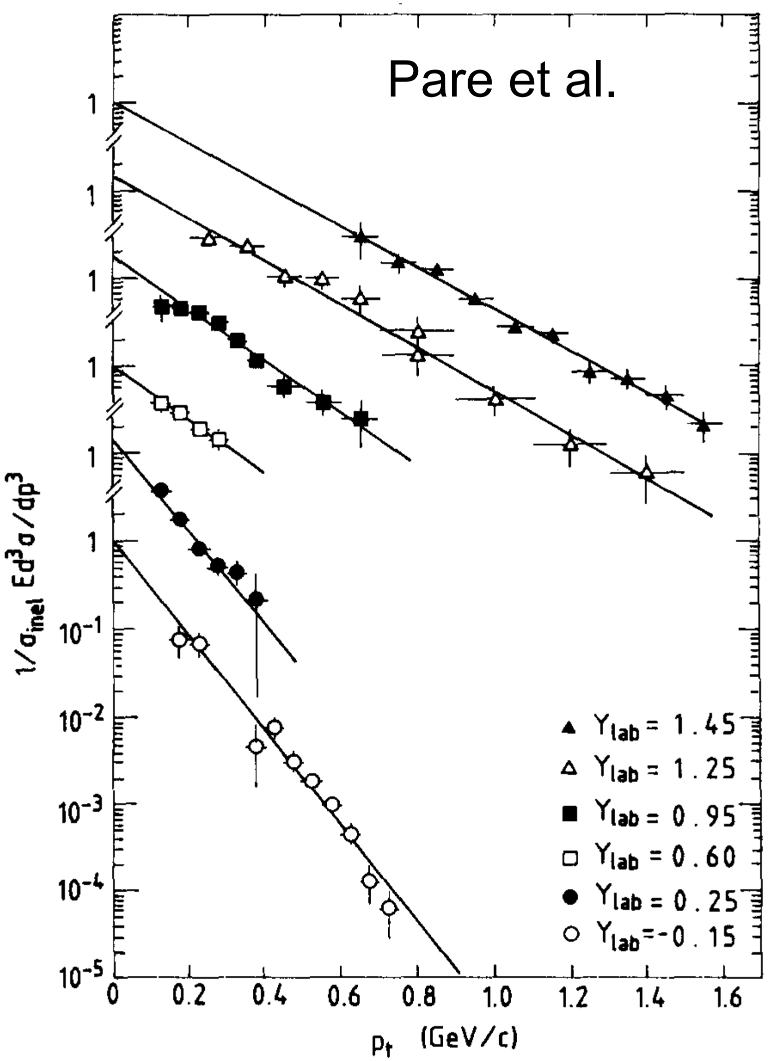
performance results

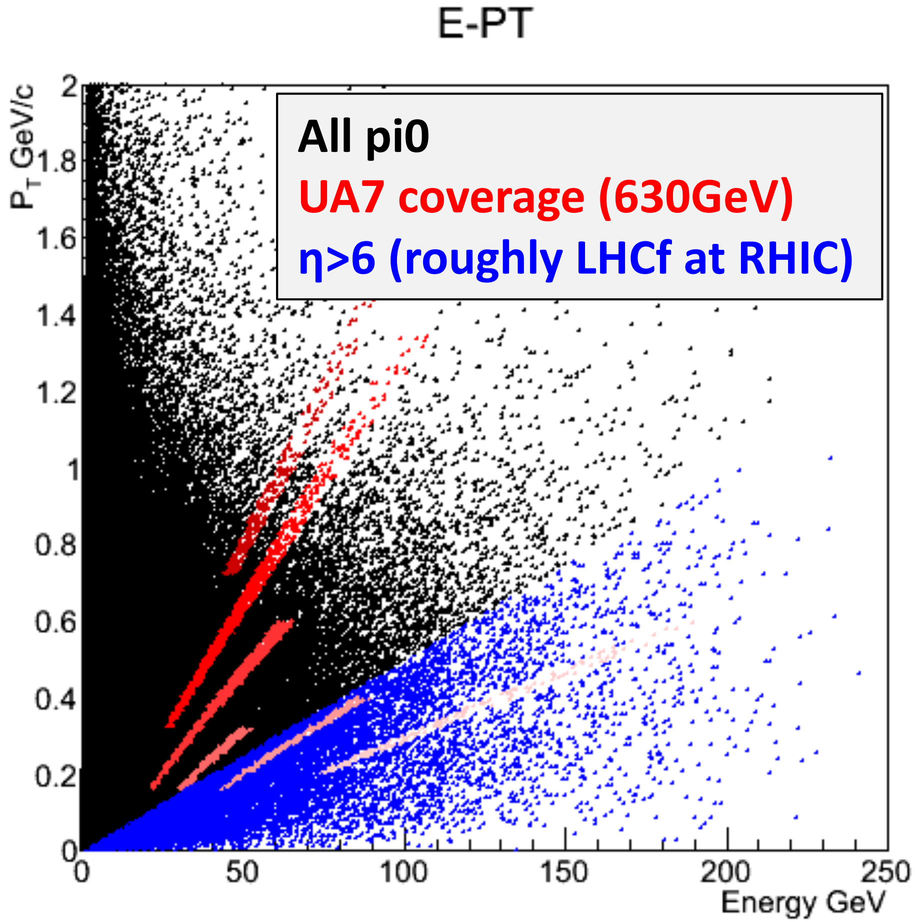
<table>
<tr><th></th><th>Photon
(EM shower)</th><th>Neutron
(hadron shower)</th><th>π^0 (limited acceptance)</th><th>π^0 (full acceptance)</th><th>Performance</th></tr>
<tr><td>Beam test</td><td>NIM, A671 (2012) 129-136
JINST submitted (2017)</td><td>JINST, 9 (2014) P03016</td><td></td><td></td><td></td></tr>
<tr><td>0.9TeV p-p</td><td>PLB, 715 (2012) 298-303</td><td></td><td></td><td></td><td rowspan="2">IJMPA, 28 (2013) 1330036</td></tr>
<tr><td>7TeV p-p</td><td>PLB, 703 (2011) 128-134</td><td>PLB, 750 (2015) 360-366</td><td>PRD, 86 (2012) 092001</td><td rowspan="3">PRD, 94 (2016) 032007</td></tr>
<tr><td>2.76TeV p-p</td><td></td><td></td><td rowspan="2">PRC, 89 (2014) 065209</td><td></td></tr>
<tr><td>5.02TeV p-Pb</td><td></td><td></td><td></td></tr>
<tr><td>13TeV p-p</td><td>In preparation</td><td colspan="3">Analysis in progress</td><td></td></tr>
</table>

Event category of LHCf



π^0 at SppS UA7 (630GeV)
(UA7; Roman Pot calorimeter!!)





Complimentary phase space coverage to UA7

Theoretical explanation

- Pion-a_1 interference: results
  - The data agree well with independence of energy
- The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{|f|^2 + |g|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

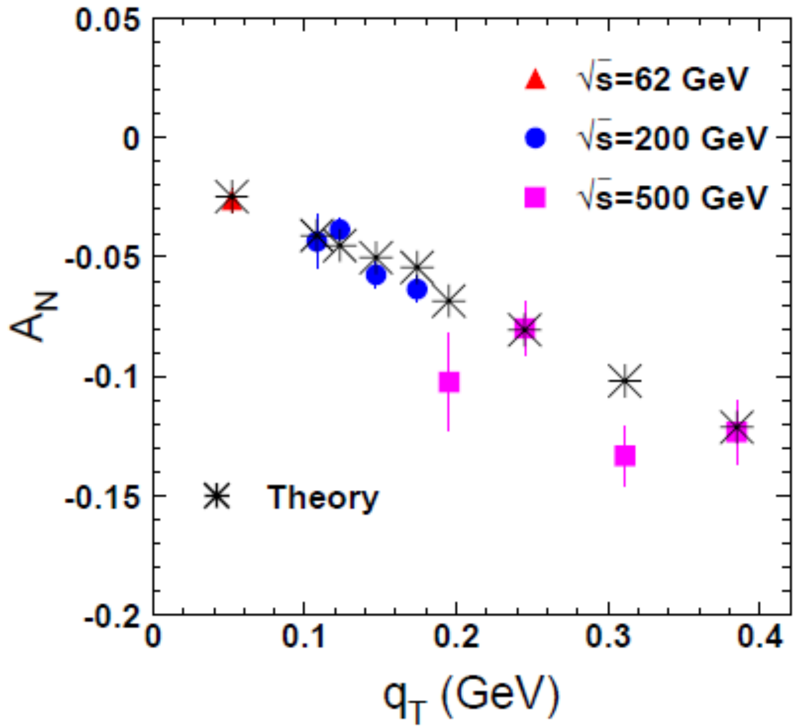


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500\,\mathrm{GeV}$ [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012.

Beam Condition

Parameter	Value
Beam energy (GeV)	255
Beam intensity (protons per bunch)	2×10^{11}
Number of colliding bunch	100
Number of non-colliding bunch	20
Beam emittance (mm mrad)	20
β^* (m)	10
Luminosity ($cm^{-2}s^{-1}$)	1.1×10^{31}
Polarization direction	radial
Polarization amplitude	0.4–0.5
Operation time	1 day

β^* (m) 10 ← to reduce beam divergence

Polarization direction radial ← to measure up-down asymmetry

1day for β^* setup, 1 day for polarization direction, 2 days for physics
=> 1 week near the end of RUN17 including contingency is approved

Light ion collision@LHC

ECR source

- The source can "deliver anything", however...
  - It takes time to commission the whole chain with new species (16 weeks minimum for LEIR/PS/SPS)
  - Switching between two species within one year is difficult (~ 4 weeks to switch ECR for completely different species) -> competition with Pb-Pb and p-Pb in LHC, and primary ions in North Area (Ar, Xe, Pb)
- Oxygen is support gas for Pb
  - One can imagine running O for a short period within Pb year
    - Opens possibility for O-O and p-O
- Other ion mixtures
  - N + O , S + O "Easy"
  - MIVOC (Metal Ions from Volatile Compounds) for Fe...

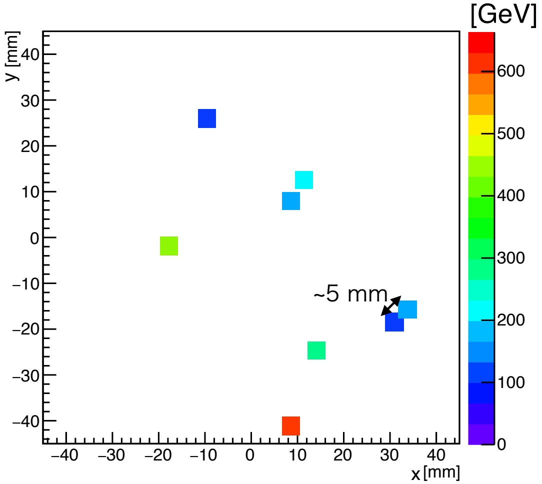
Disclaimer

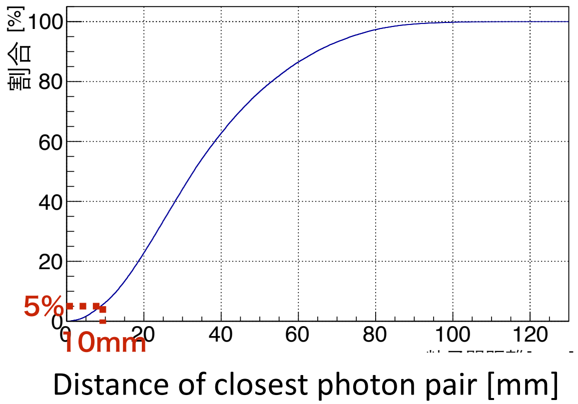
- Very preliminary
- Not endorsed by CERN management
- Only technical feasibility
- Even if feasible, scheduling an actual run would be a hard battle

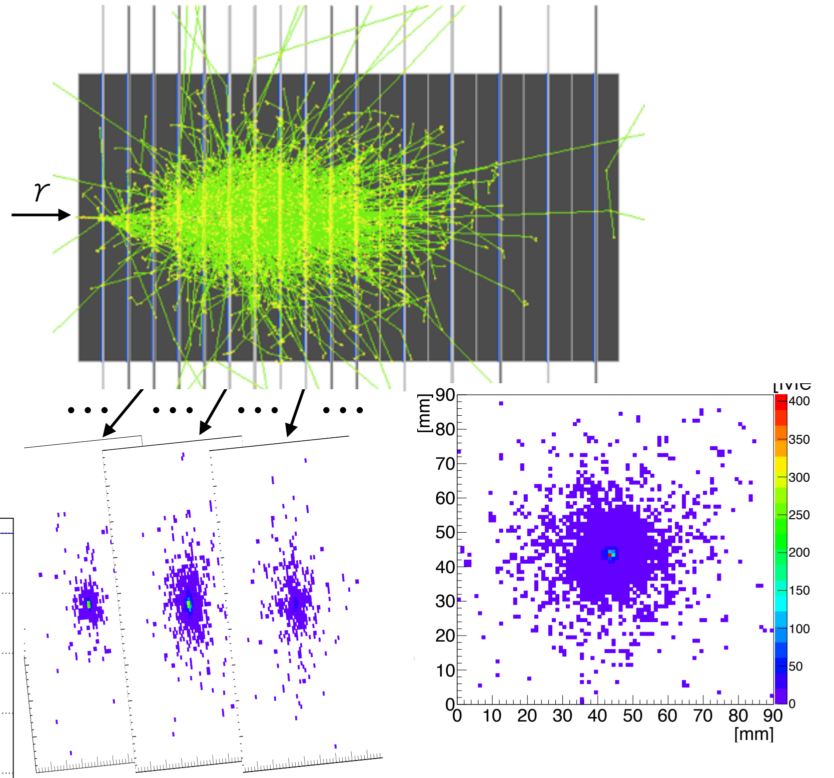
D. Manglunki presented at the workshop: "Results and prospects of forward physics at the LHC: Implications for the study of diffraction, cosmic ray interactions, and more", 11-12 Feb 2013, CERN

All pixelized "Super ZDC"

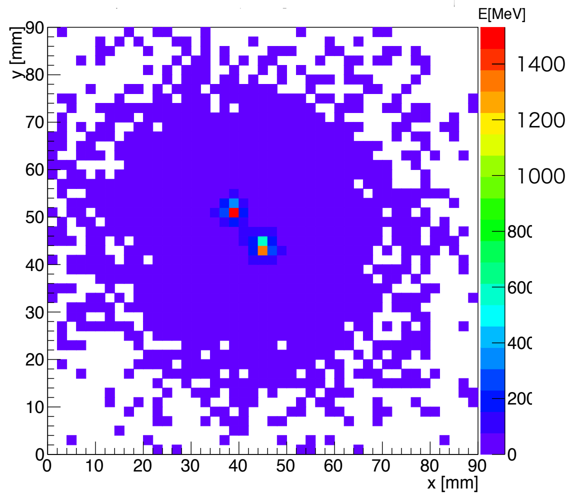
Event sample
Photon hit in 9cmx9cm
(neutron is not yet considered)







2mm pixel size



- ✓ Preliminary study for O-O measurement
- ✓ Multi particle events can be resolved by pixelize the calorimeters
- ✓ 2mm x 2mm pixel calorimeter can separate multi particle events in O-O collisions