LHCf/RHICfによるトランジション領域における相互作用研究

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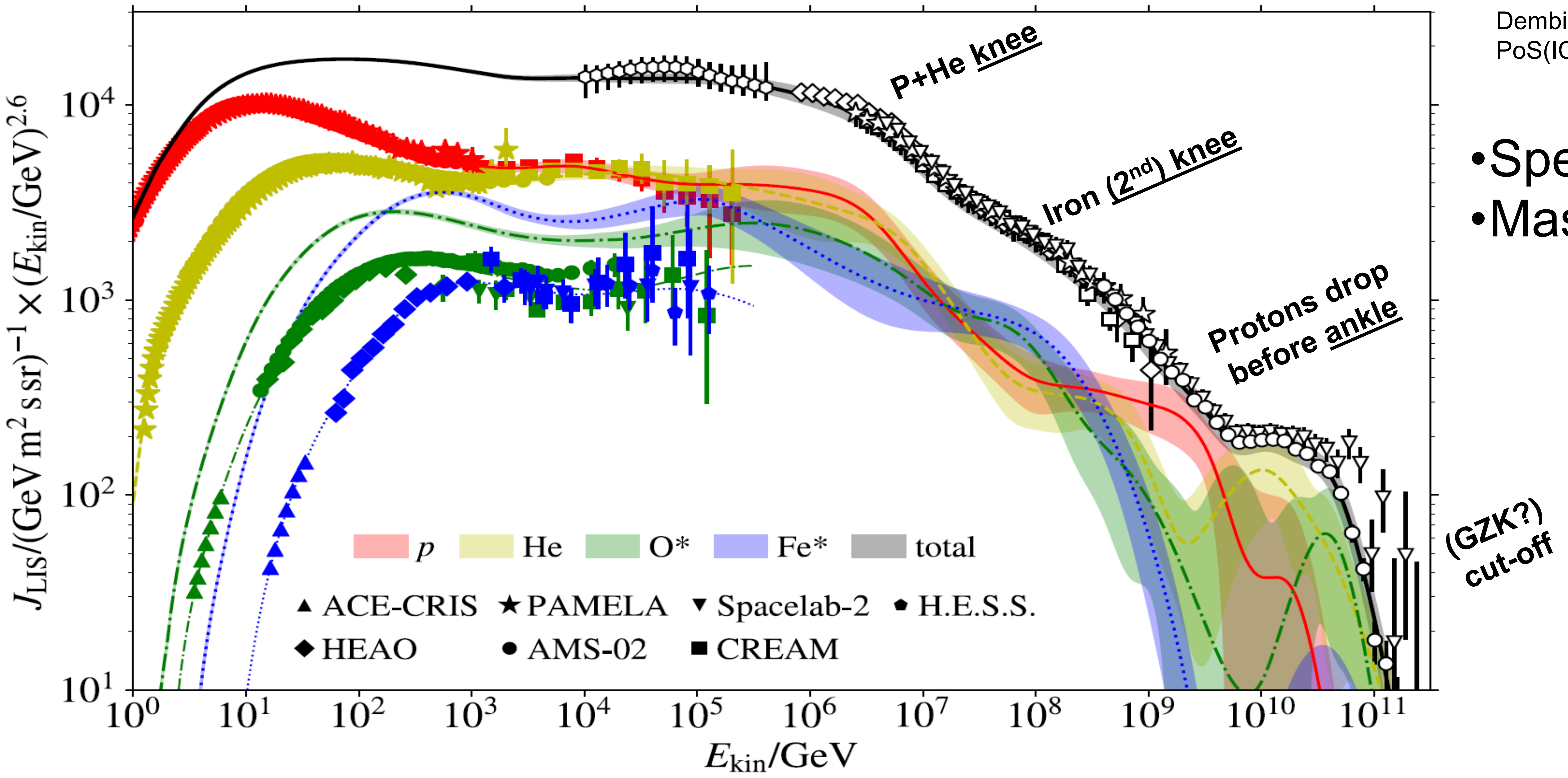
第５回　空気シャワー観測による宇宙線の起源探索勉強会

2022/3/22-23, ハイブリット（ICRR＋オンライン）

Transition: Galactic → Extra Galactic

- Transition region
  - Galactic cosmic-rays: Highest energy
  - Extra galactic cosmic-rays: Low energy tail

Important for both !!



Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.

- Spectrum
- Mass Composition

Estimators of Composition

CR primary energy:
10^{9}-10^{20} eV

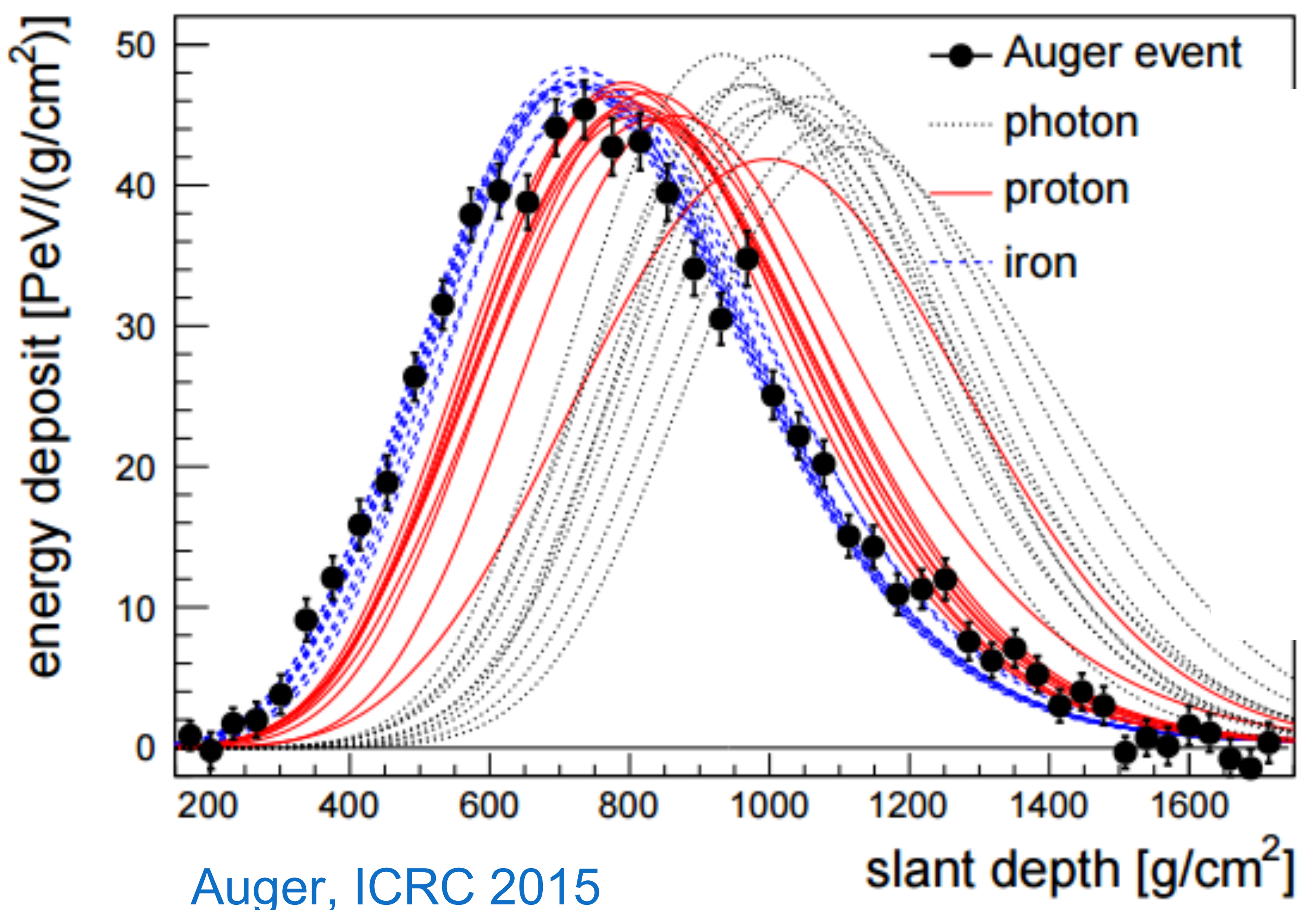
High energy interaction

secondaries' interactions

....

Shower Maximum (X_{Max})

- A-dependency is mainly from difference of σ_{inela}
- High energy interactions are more important.



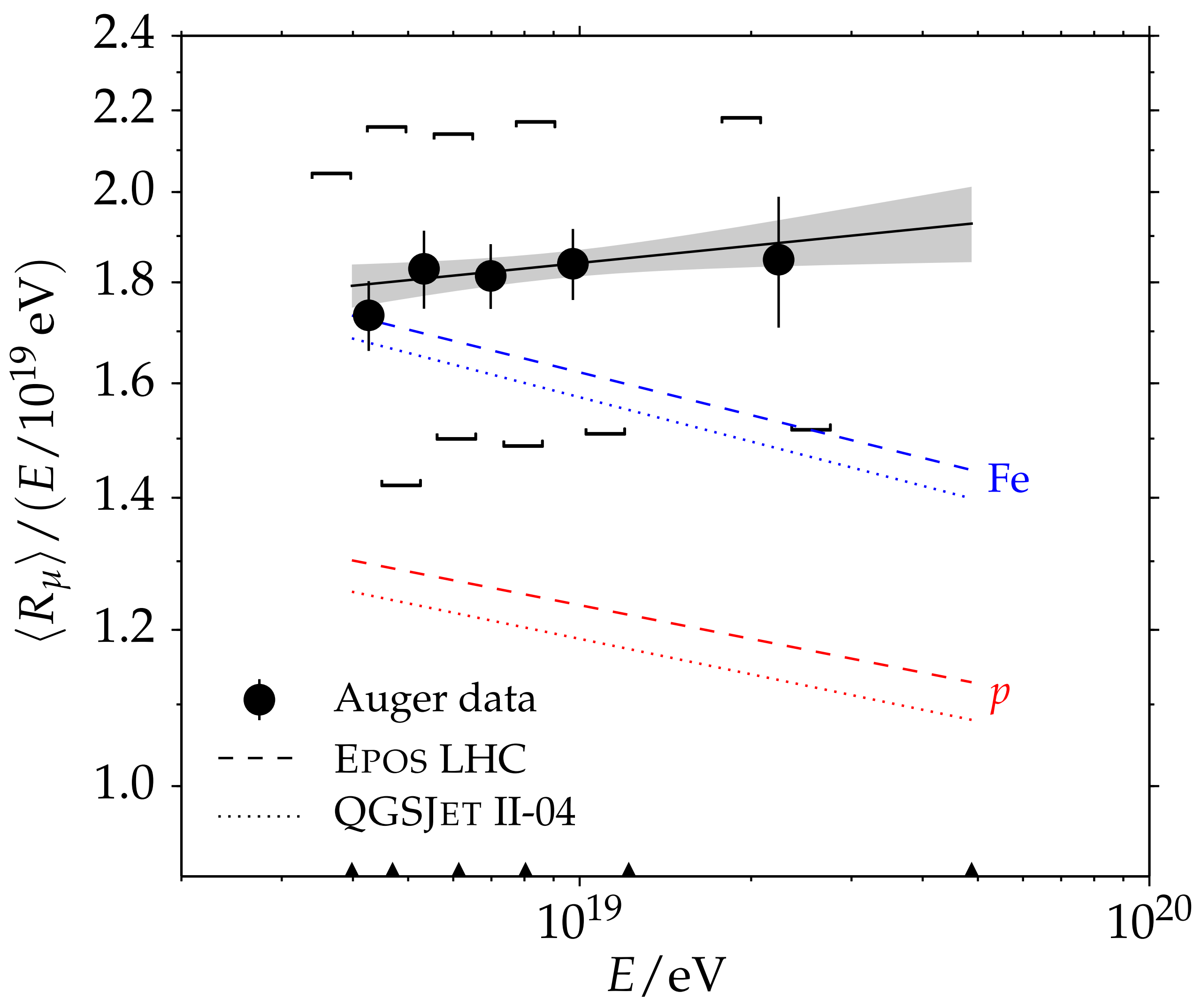
Auger, ICRC 2015

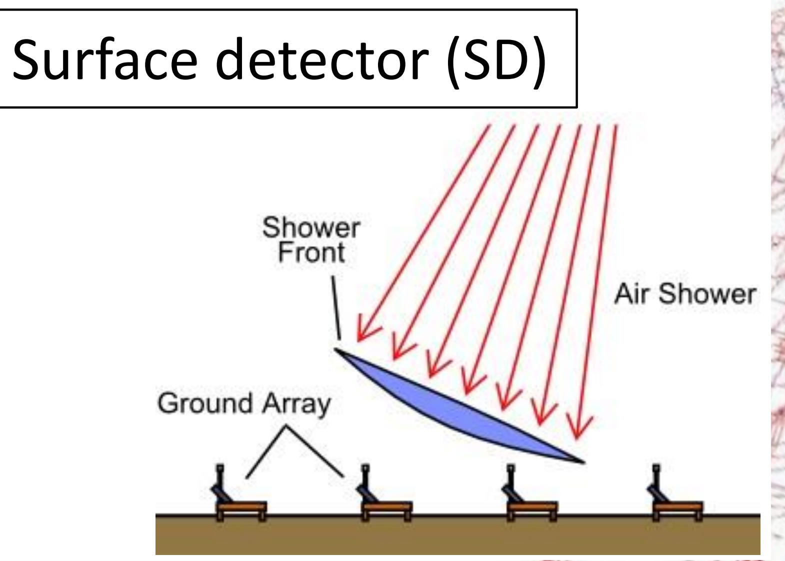
Low energy interactions

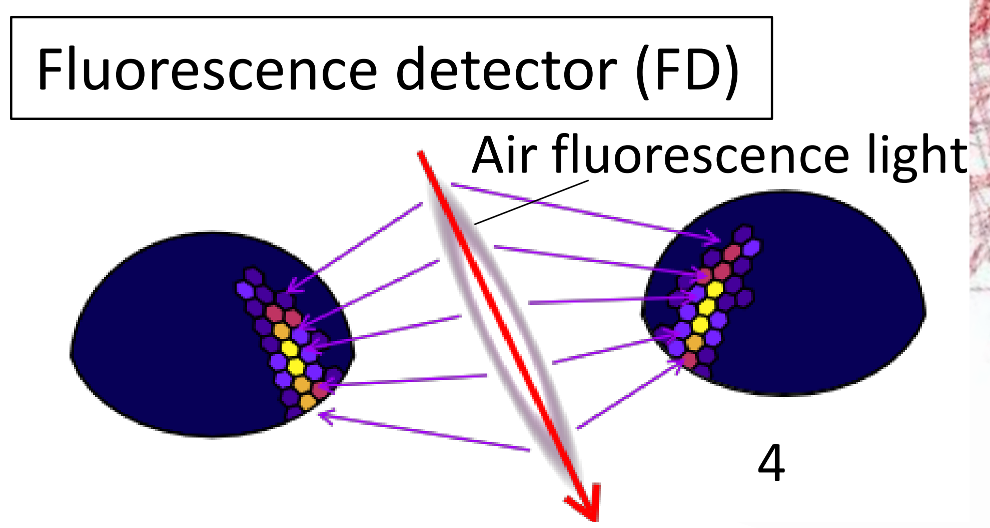
Muon (X^{μ}_{Max}, N_{μ})

- X^{μ}_{Max}: σ_{inela}
  + particle production
- N_{μ} : particle production
  contribution of wide energy ranges

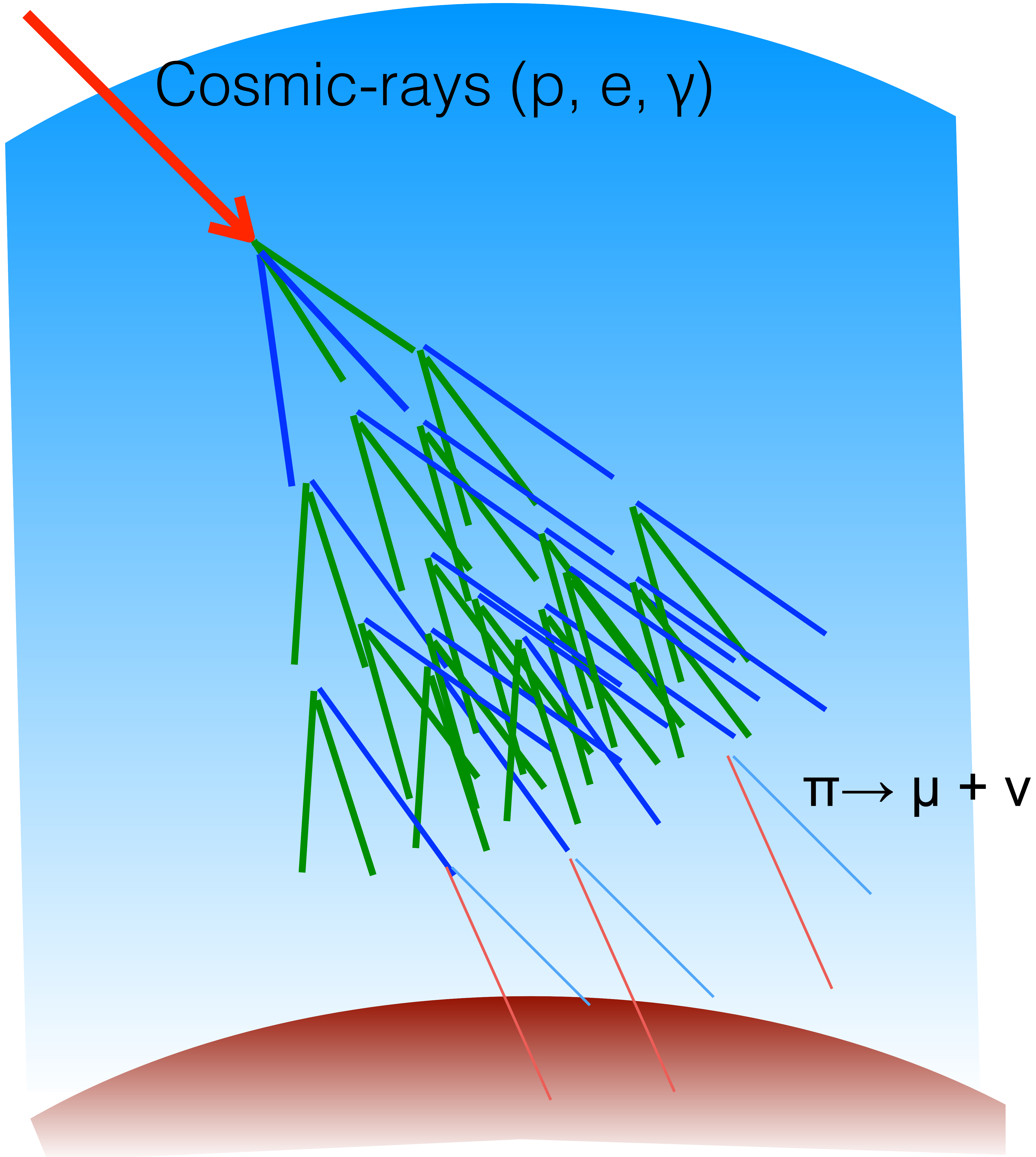
Pierre Auger collab. Phys.Rev.D 91 (2015) 3, 032003

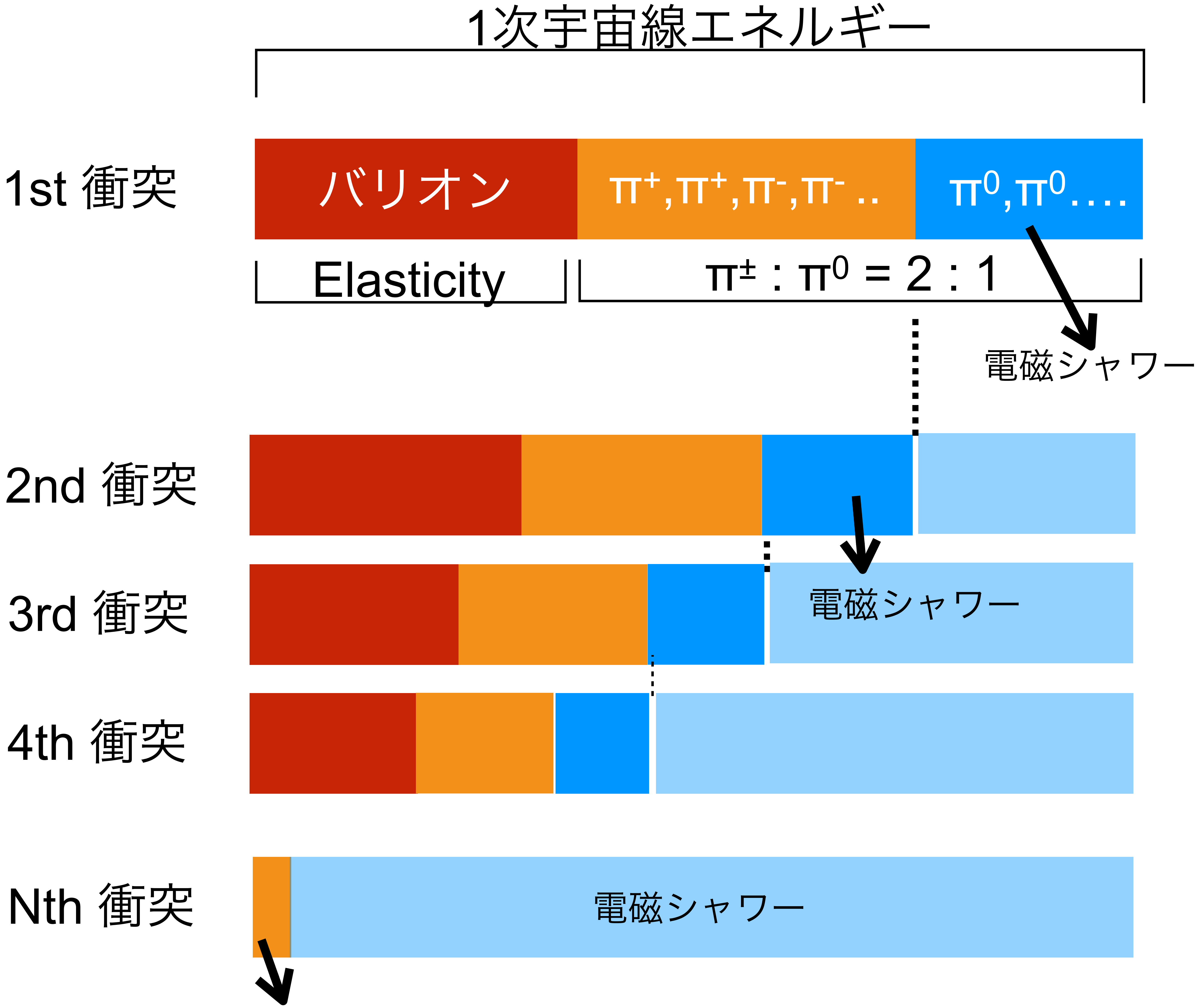






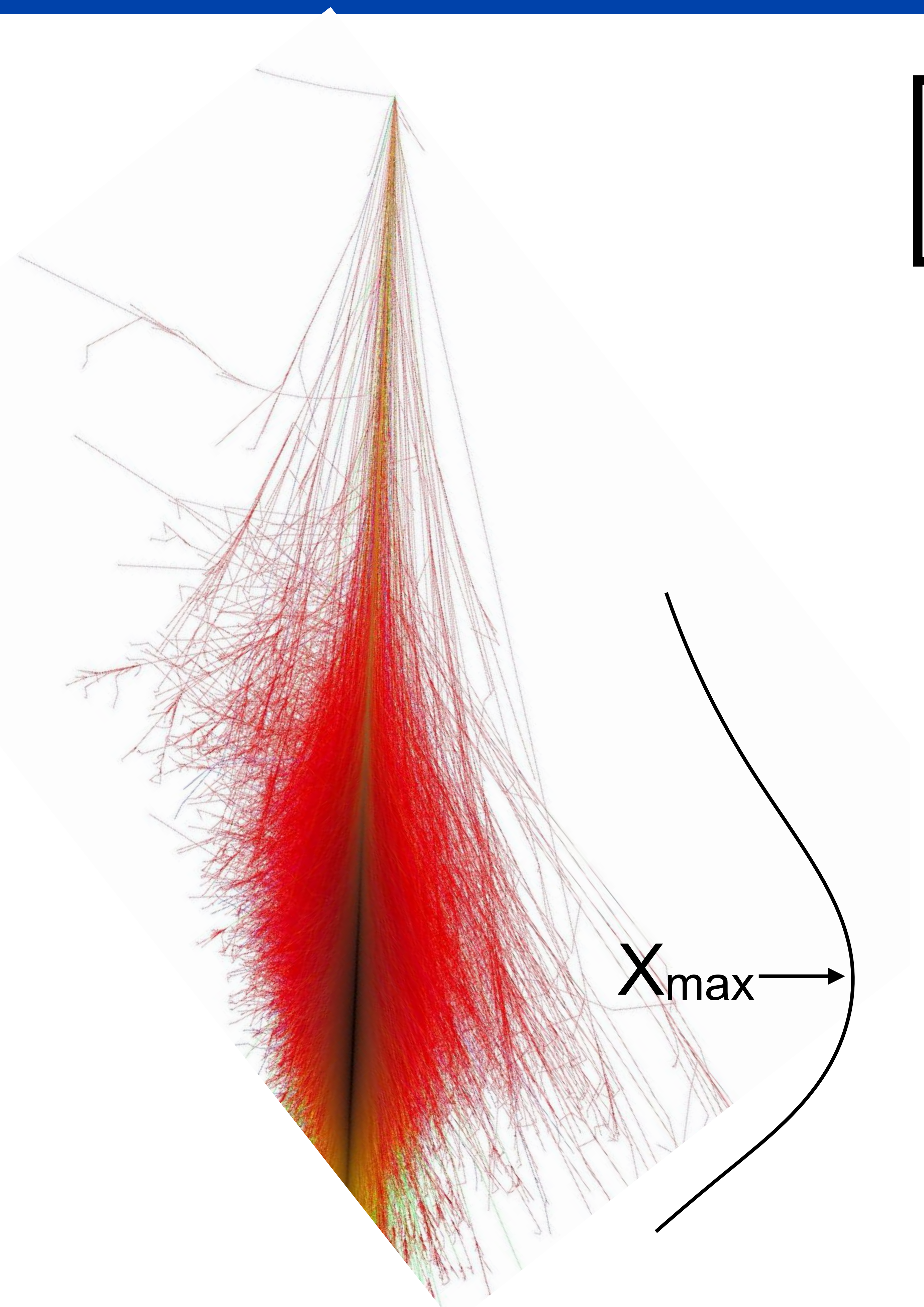
空気シャワー発達とN_μ





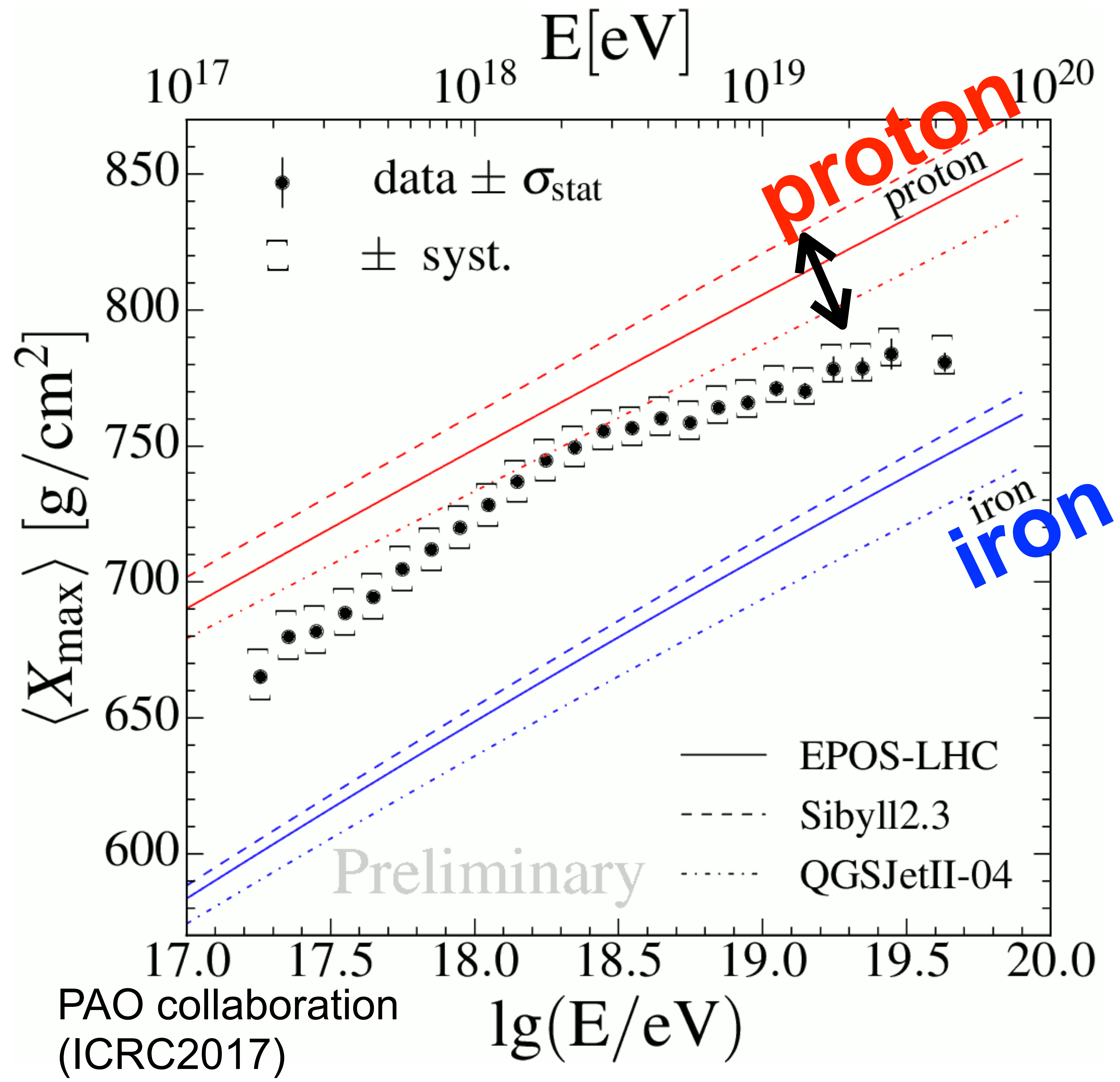
$\pi \rightarrow \mu + \nu$ $N_\mu = E_{HAD} / E_{critical}$

Estimators of Mass Composition



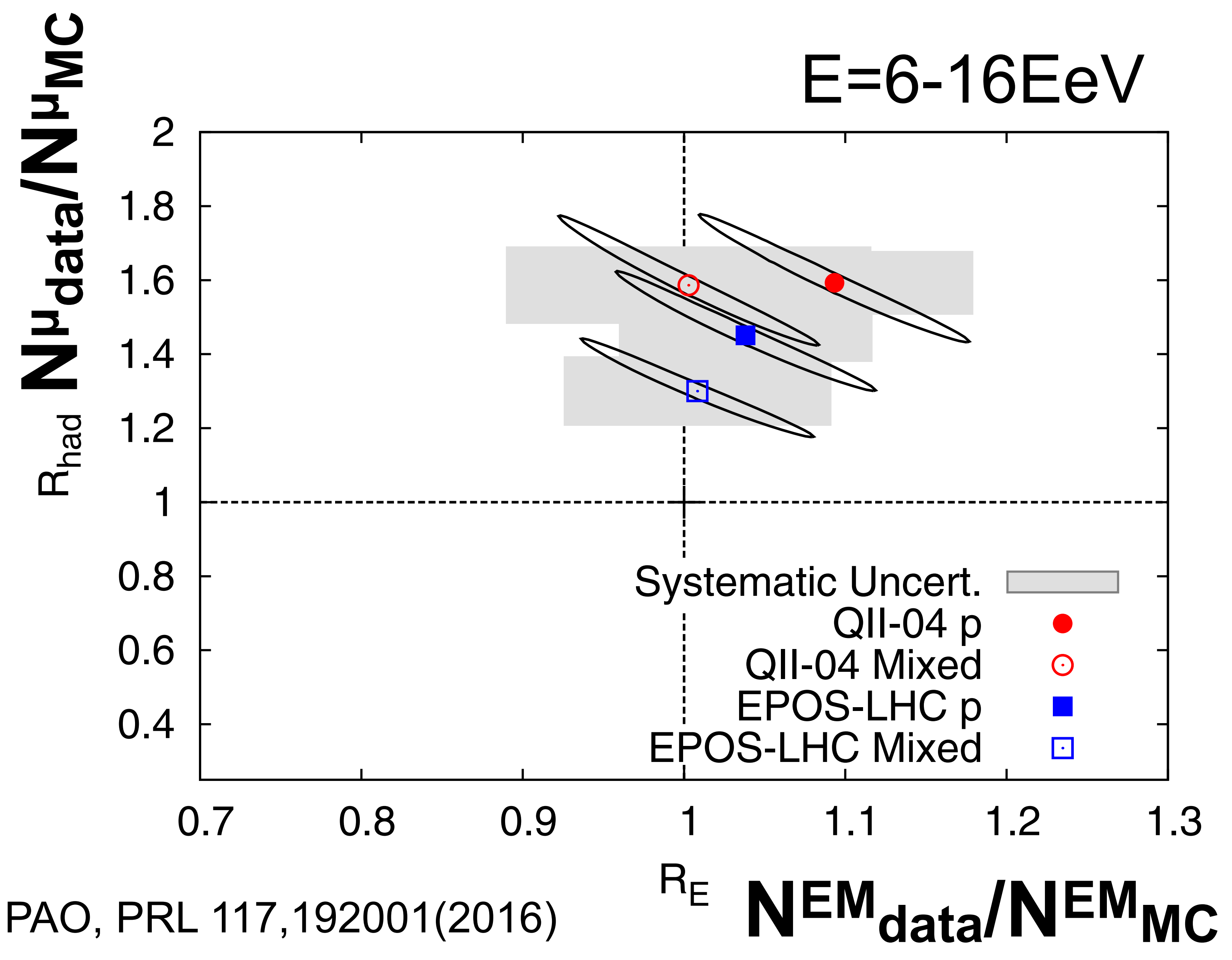
N^{μ}: Number of muons on the ground

Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Muon excess
$N^{\mu}_{data} > N^{\mu}_{MC}$



PAO, PRL 117,192001(2016)

Sensitive $E^{\pi 0}/E^{had}$ for a collision

Several ideas to solve it

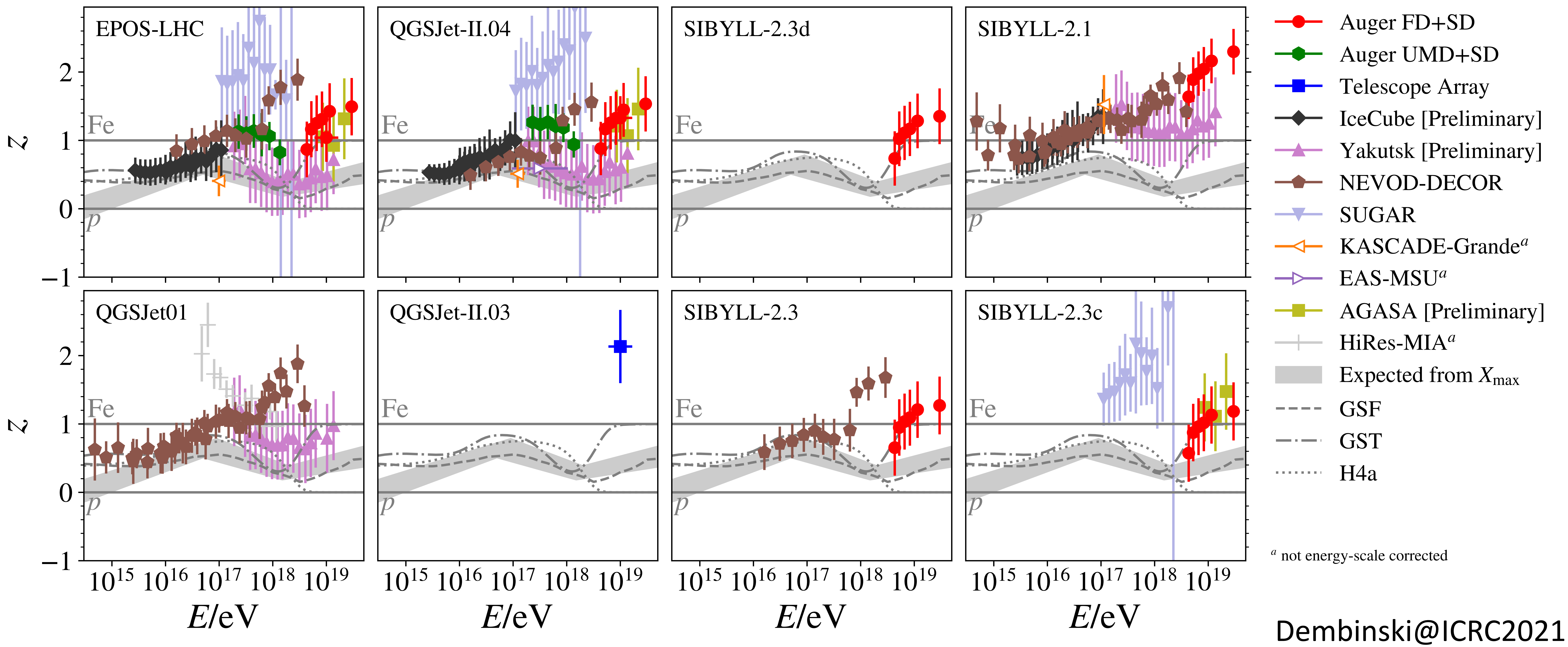
- Strange particles
- Vector meson productions
- QGP

Composition estimated from muon

Abstract muon scale
independent of experiment,
dependent on air shower model

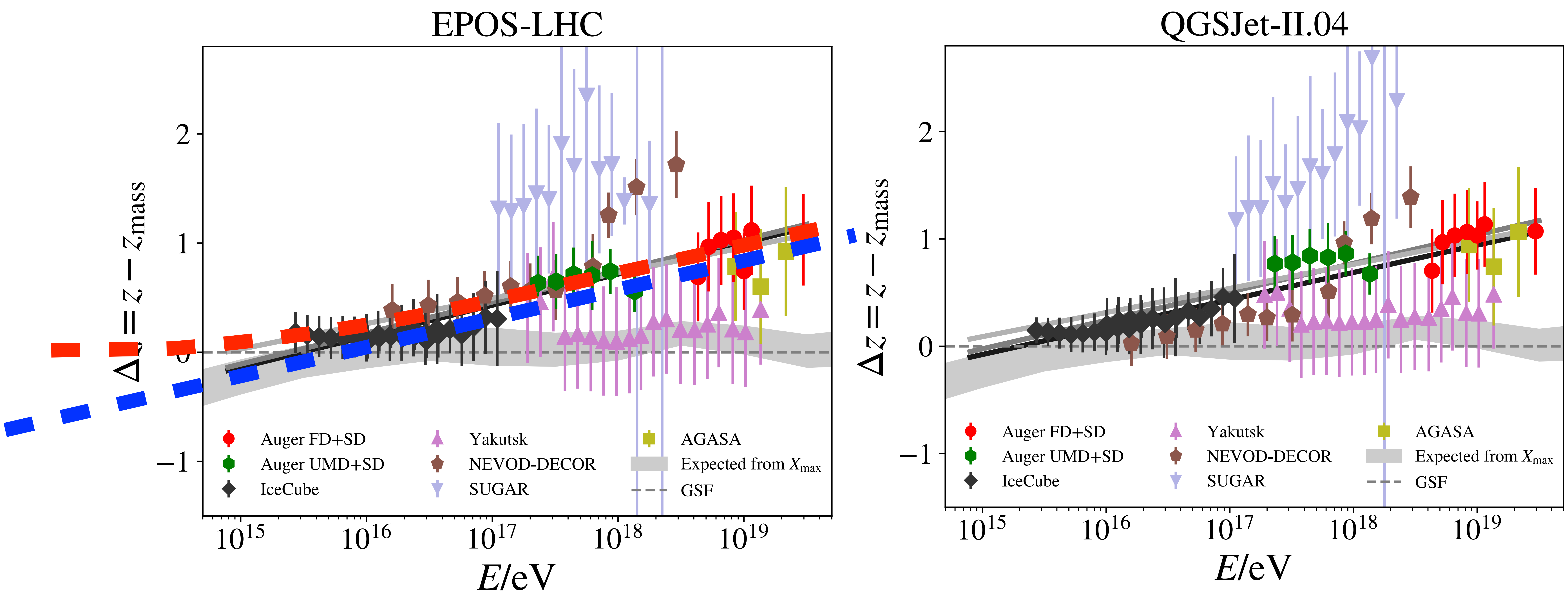
$$z = \frac{\overbrace{\ln(N_\mu^{\text{det}})}^{\text{data}} - \overbrace{\ln(N_{\mu p}^{\text{det}})}^{\text{sim}}}{\underbrace{\ln(N_{\mu\text{Fe}}^{\text{det}})}_{\text{sim}} - \underbrace{\ln(N_{\mu p}^{\text{det}})}_{\text{sim}}}$$

PoS(ICRC2021)349



Energy dependency of muon excess

PoS(ICRC2021)349

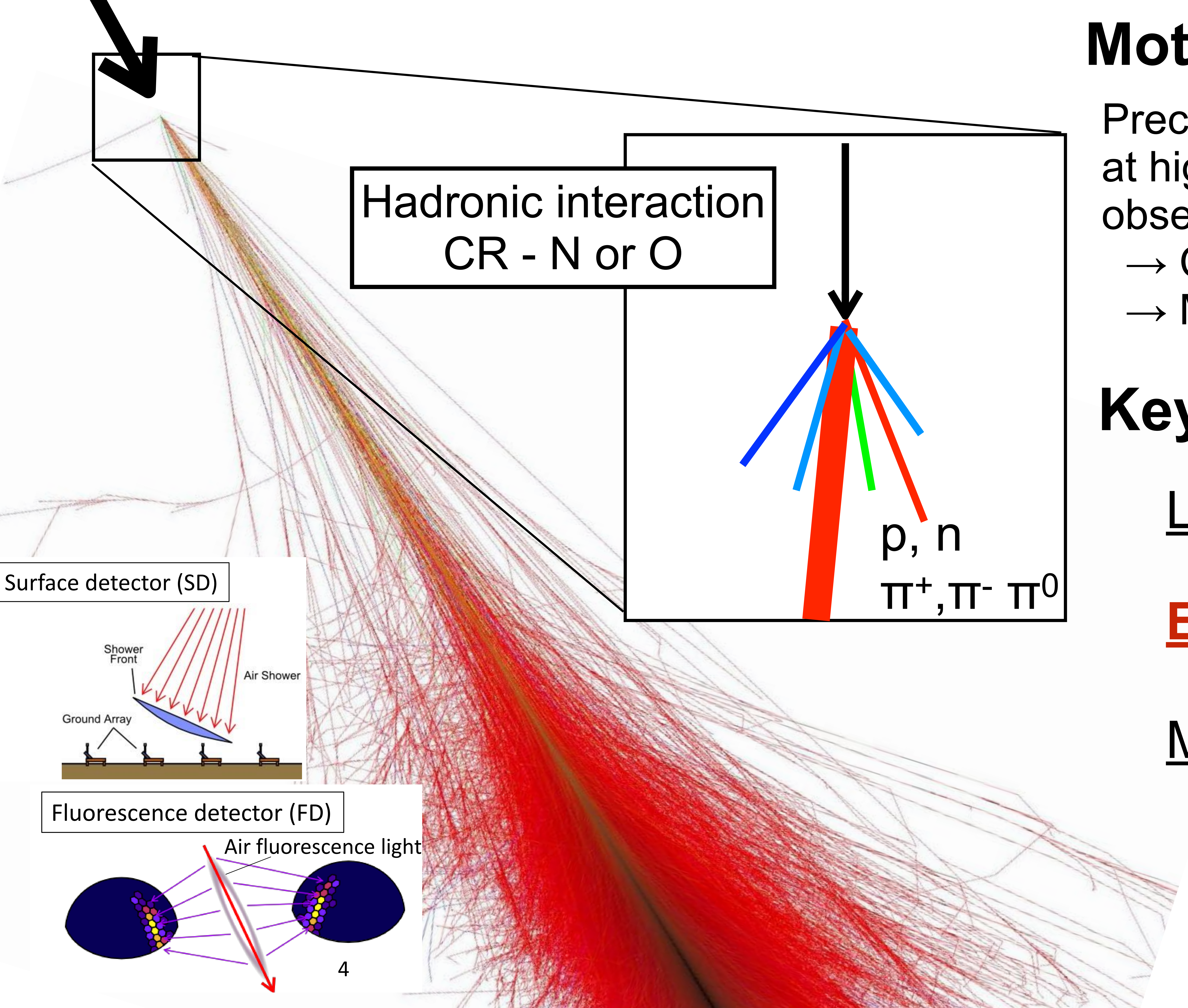


$$z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_{\mu p}^{\mathrm{det}})}{\ln(N_{\mu \mathrm{Fe}}^{\mathrm{det}}) - \ln(N_{\mu p}^{\mathrm{det}})}$$

$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

- Line model with slope fitted to $\Delta z = z - z_{\mathrm{mass}}$
- Correction to $\chi^2/n_{\mathrm{dof}} = 1$ applied to take unexplained spread into account
- Slope is 8σ (10σ) away from zero for EPOS-LHC (QGSJet-II.04)
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; in reach of LHC

Interaction study for cosmic-ray physics



Motivation:

Precise understanding of hadronic interaction at high energy is key to improve the cosmic-ray observation using air-shower technique.

→ CR composition (p, CNO, Fe) measurement

→ Muon deficit problem

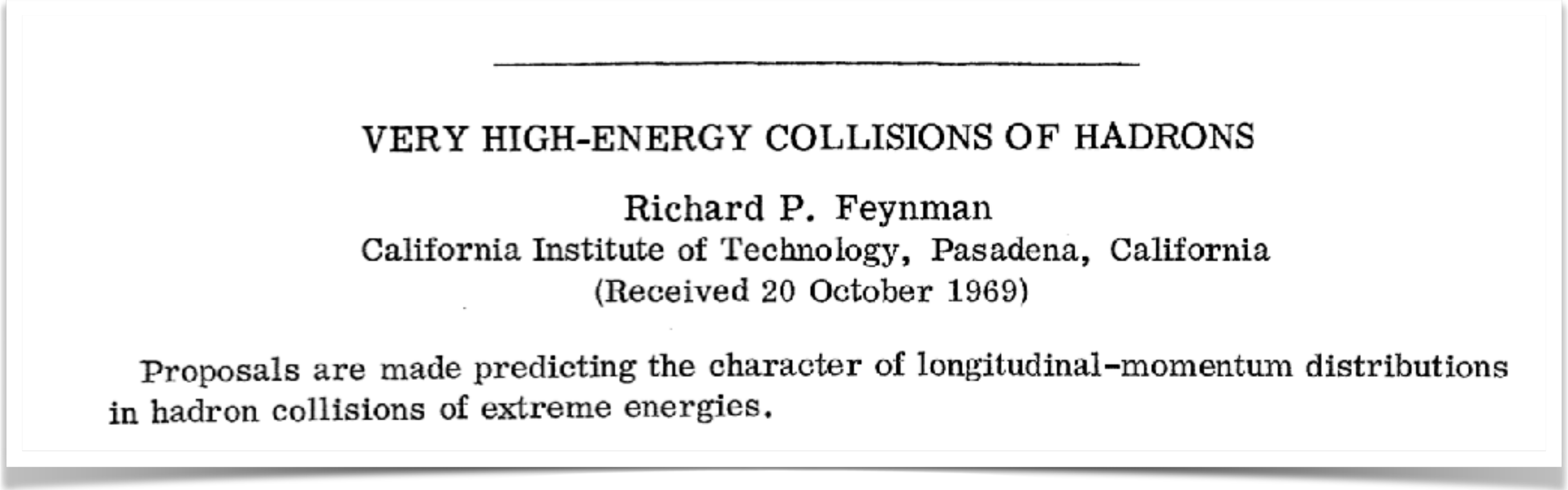
Key items:

<u>Leading particle production</u>

<u>Energy dependency (scaling)</u>

<u>Multiplicity</u>

Collision Energy Scaling (Feynman Scaling)



VERY HIGH-ENERGY COLLISIONS OF HADRONS

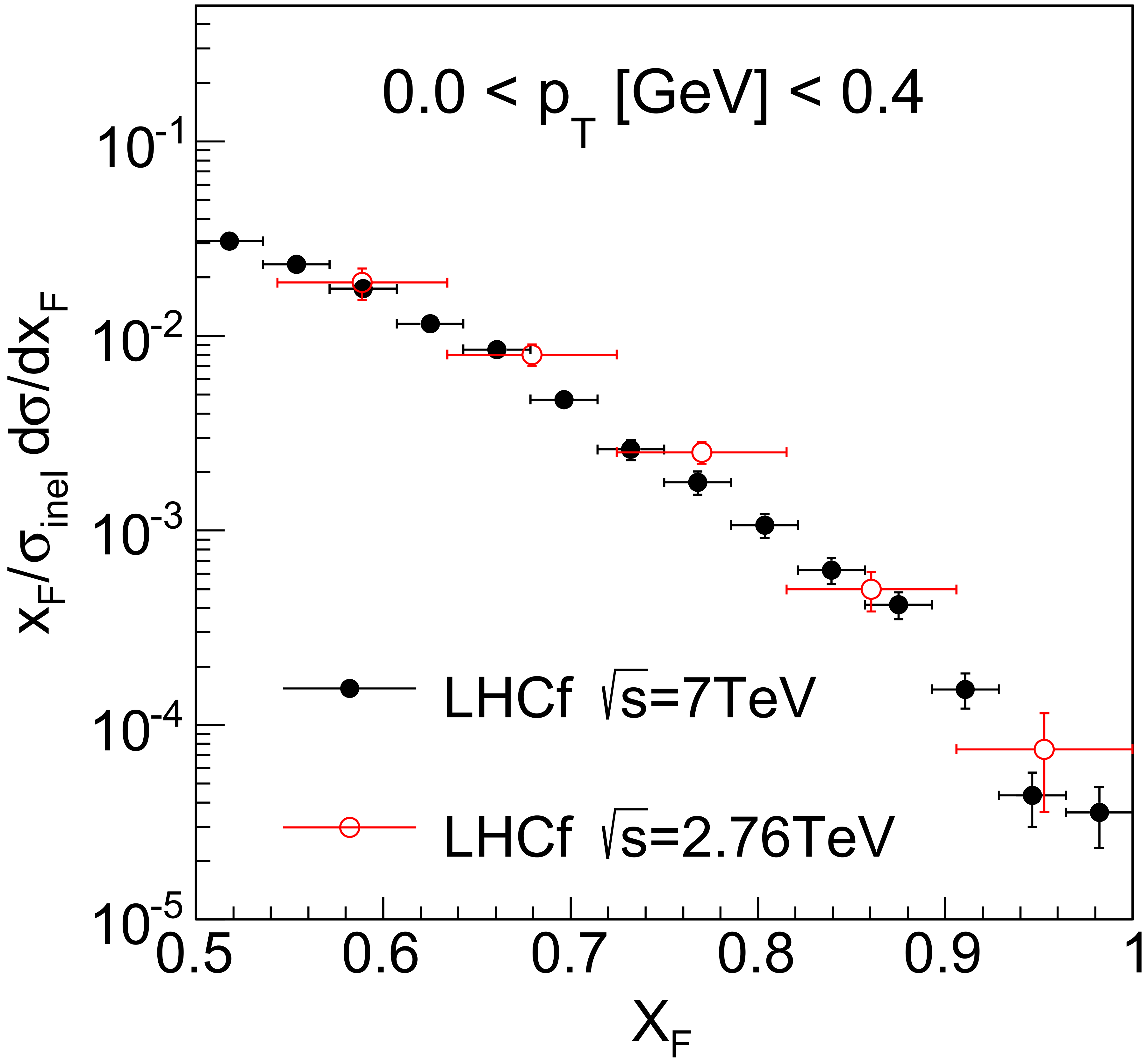
Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

Proposals are made predicting the character of longitudinal-momentum distributions in hadron collisions of extreme energies.

Collision energy scaling of particle production in forward region ($X_F >= 0.2$) was proposed by Feynman.
$X_F = p_L / p_{beam} \sim E / E_{beam}$

Based on the phenomenological model (using reggion)
Not theoretically supported

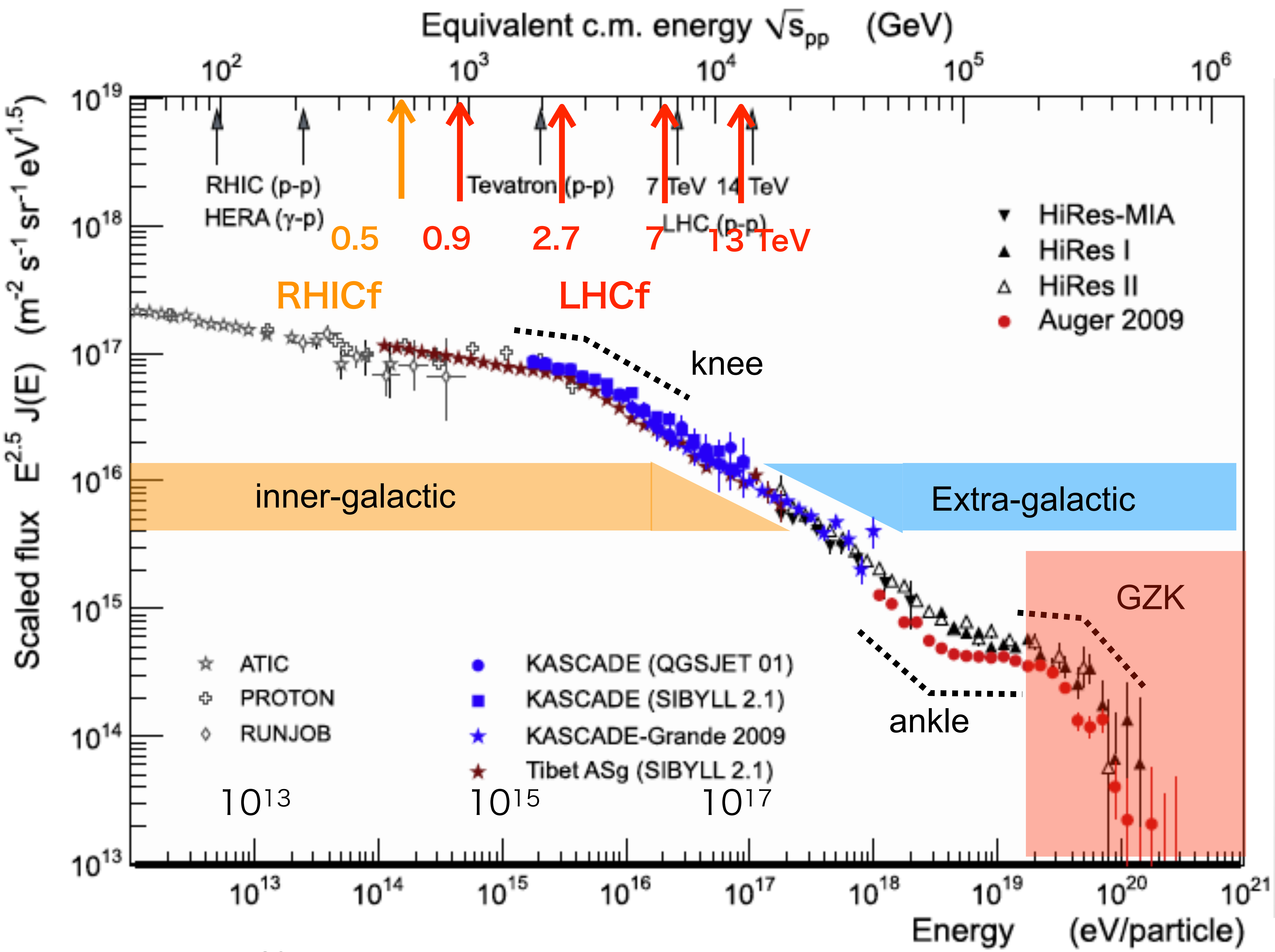
Test of π^0 production by LHCf



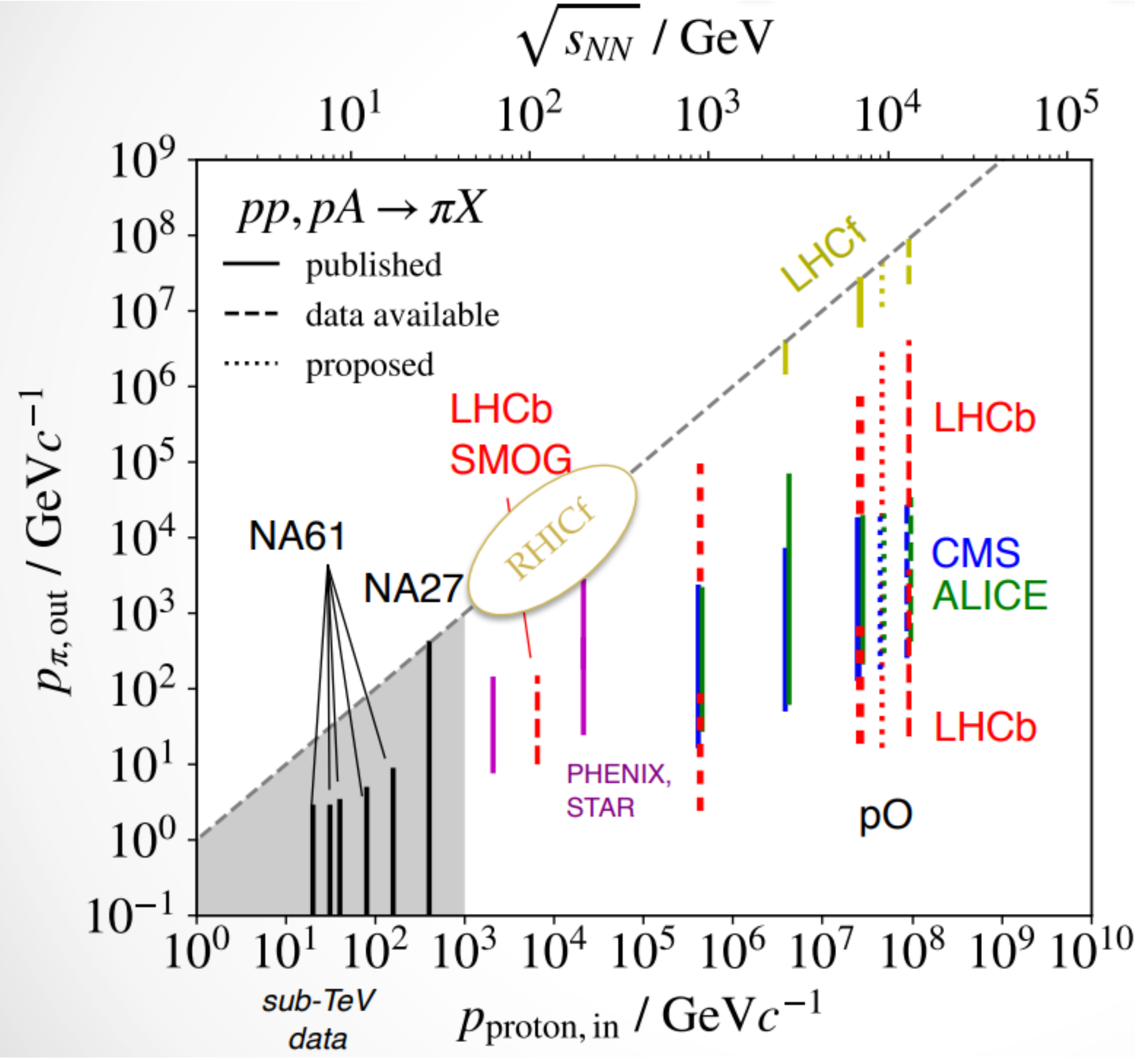
scaling is working
but the energy difference is small (x~3)

CR energies v.s. Collider energies

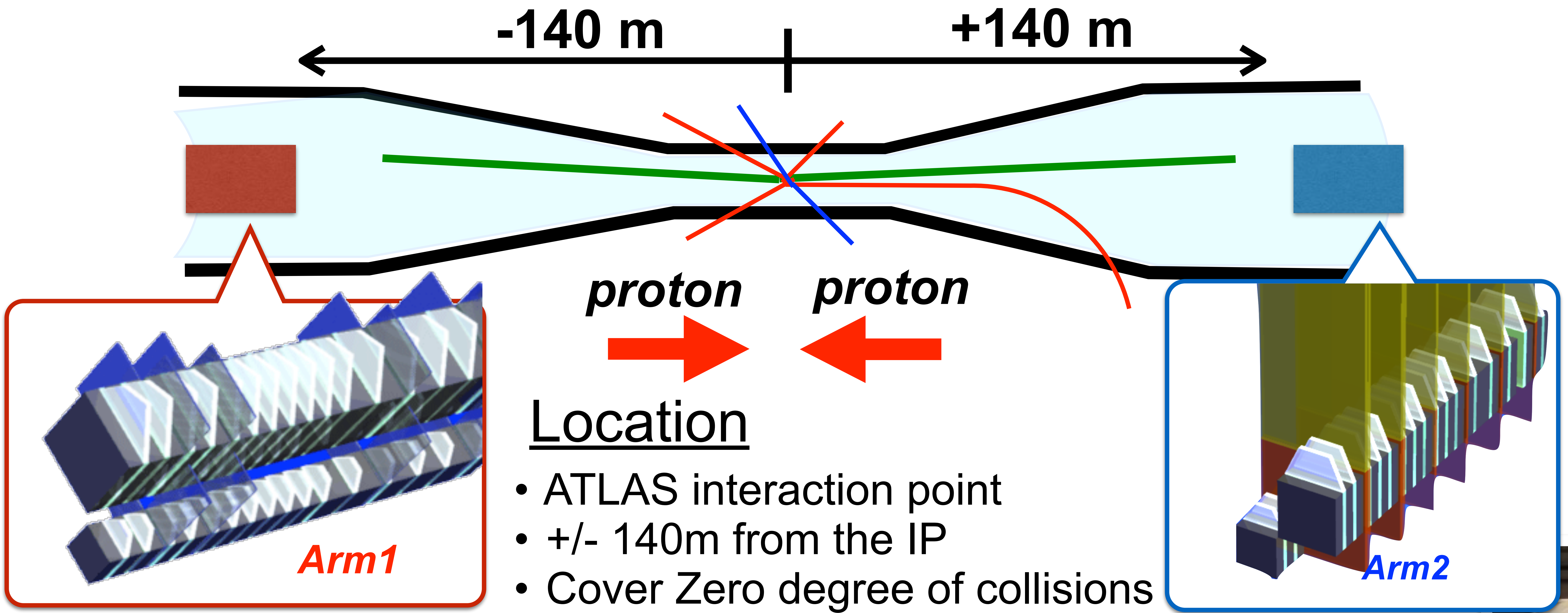
Dembinski@ISVHECRI2018

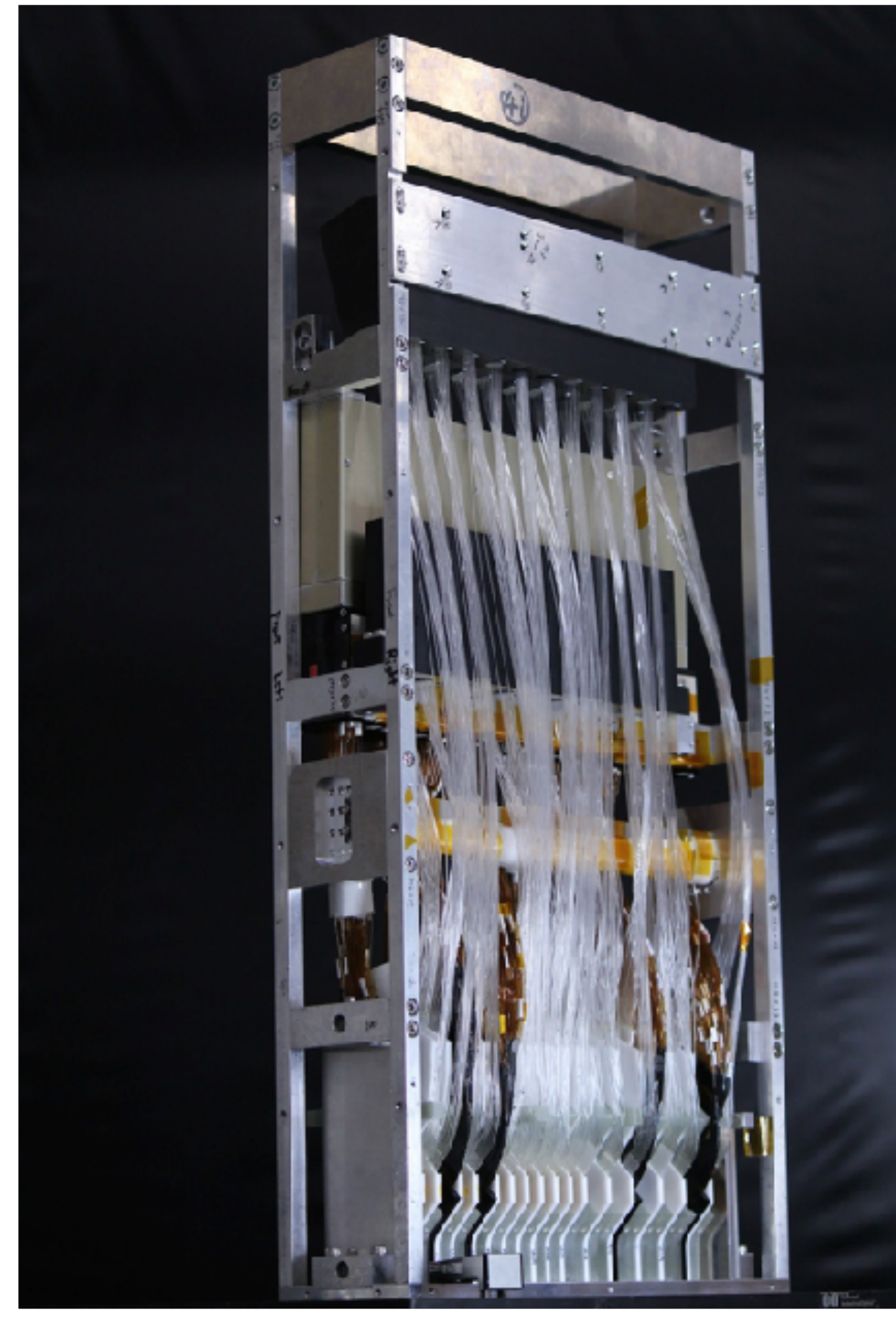


D'Enterria et al., 2011



LHCf experiment





Location

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

LHCf detectors

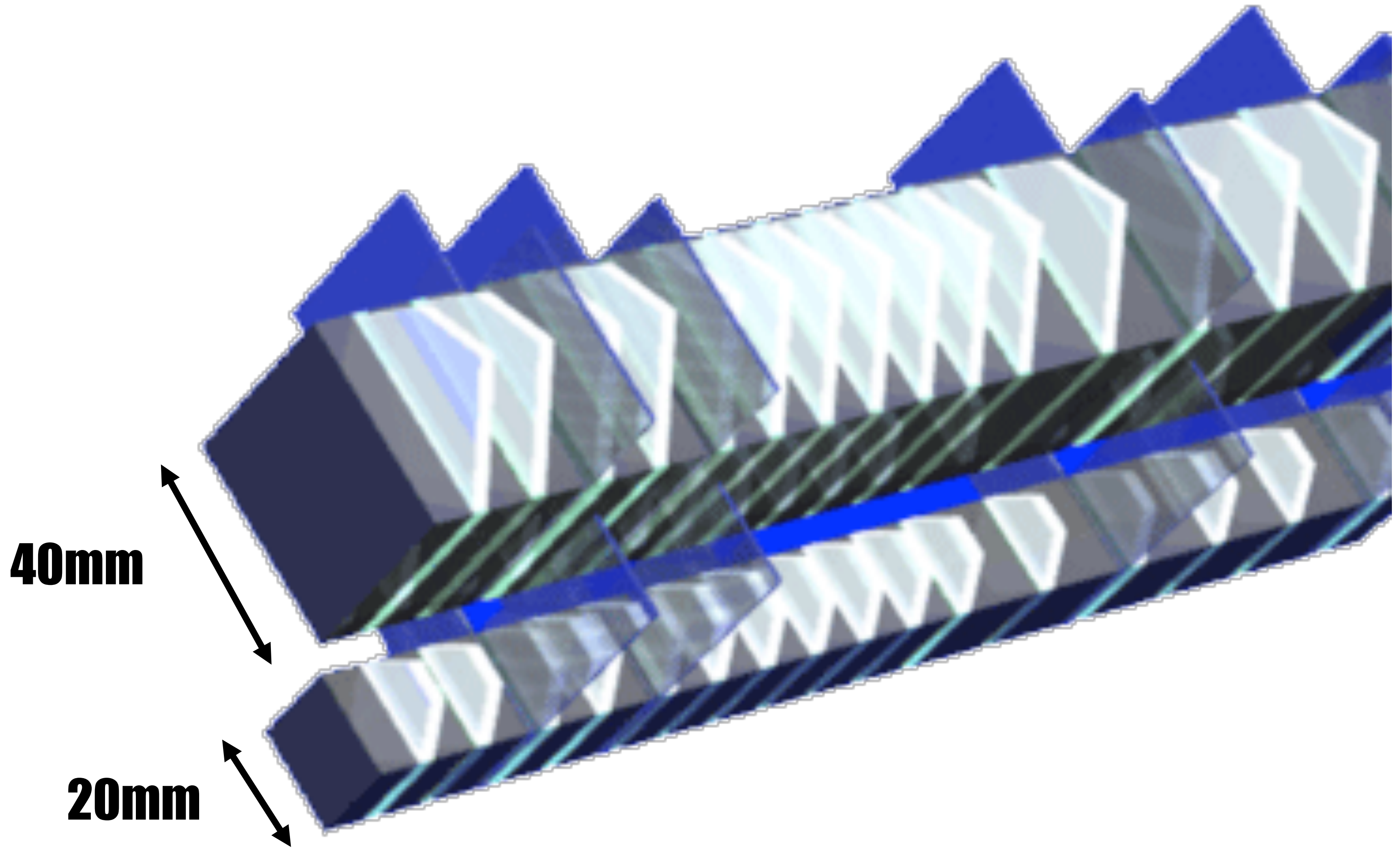
- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

RHICf experiment

Detector

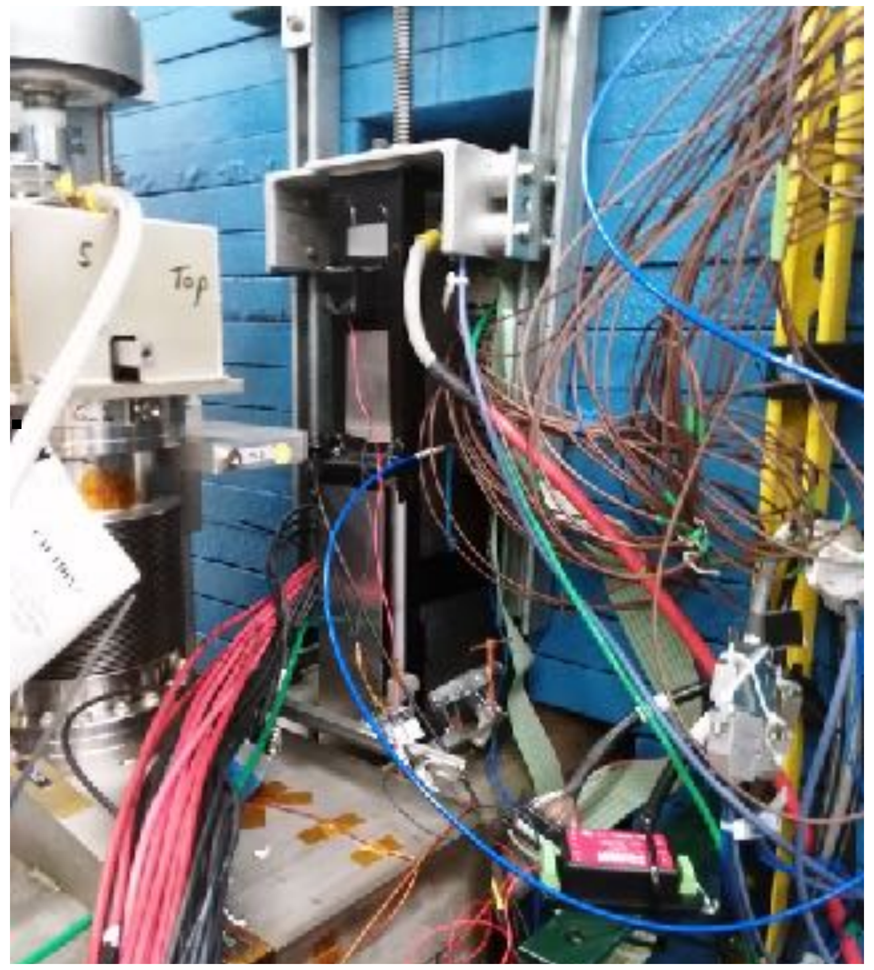
= LHCf Arm1

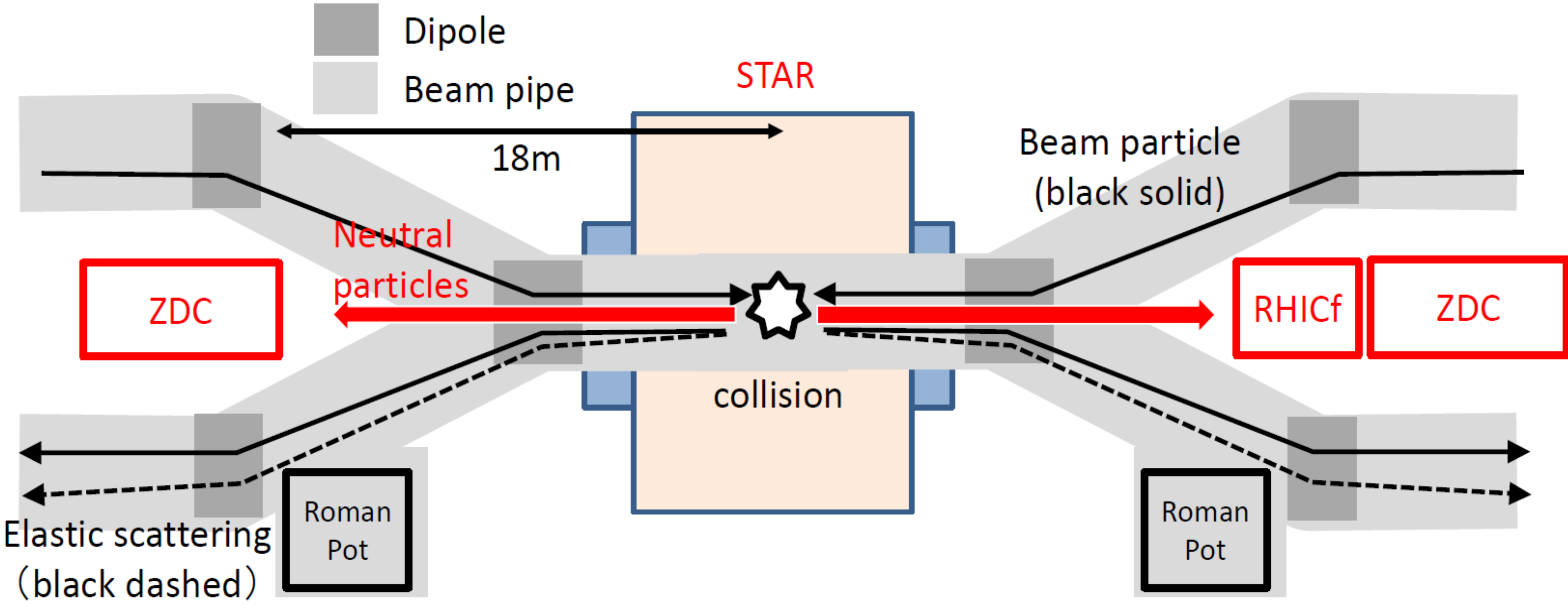
- Sampling and Positioning Calorimeter
- W (44 r.l , $1.7\lambda_I$) and 16 GSO scintillator layers
- Four positioning sensitive layers;
  Arm1: XY-hodoscope of GSO bars (1mm step)
  Arm2: XY-Silicon strip (160 μm step)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**



Operation

- **p+p $\sqrt{s}$ = 510 GeV**
  (radially polarized beam)
- Test of energy scaling with the wide p_T range
- The operation was successfully completed in June 2017
- RHICf covers η >6.1
- Common operation with STAR



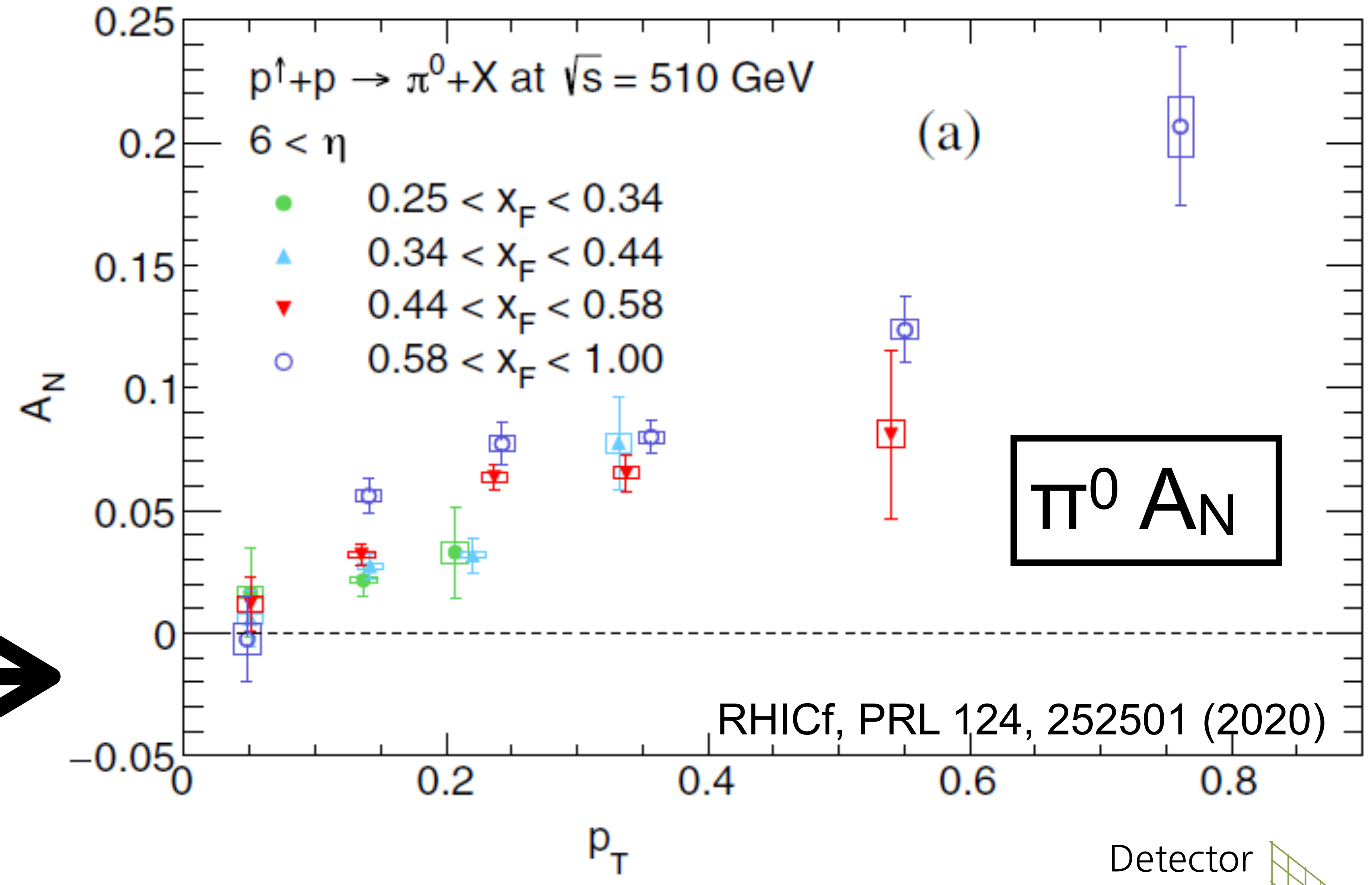


LHCf/RHICf Operations and Analyses

<table>
<tr><th>Run</th><th>E_{lab} (eV)</th><th>Photon</th><th>Neutron</th><th colspan="2">π^0</th><th>LHCf-ATLAS joint analysis</th></tr>
<tr><td>p-p $\sqrt{s}$=0.9TeV (2009/2010)</td><td>4.3×10^{14}</td><td>PLB 715, 298 (2012)</td><td></td><td colspan="2">-</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=2.76TeV (2013)</td><td>4.1×10^{15}</td><td></td><td></td><td>PRC 86, 065209 (2014)</td><td rowspan="2">PRD 94 032007 (2016)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=7TeV (2010)</td><td>2.6×10^{16}</td><td>PLB 703, 128 (2011)</td><td>PLB 750 360 (2015)</td><td>PRD 86, 092001 (2012)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=13TeV (2015)</td><td>9.0×10^{16}</td><td>PLB 780, 233 (2018)</td><td>JHEP 2018, 73 (2018)
JHEP 2020, 016 (2020)</td><td colspan="2">preliminary</td><td>Photon in diffractive coll.
Preliminary: ATLAS-CONF-2017-075
Final: under internal review</td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)</td><td>1.4×10^{16}</td><td></td><td></td><td colspan="2">PRC 86, 065209 (2014)</td><td></td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=8TeV (2016)</td><td>3.6×10^{16}</td><td>Preliminary</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>RHICf p-p $\sqrt{s}$=510GeV (2017)</td><td>1.4×10^{14}</td><td>Submit soon</td><td></td><td colspan="2">Spin Asymmetry
PRL 124 252501 (2021)</td><td>with STAR</td></tr>
</table>

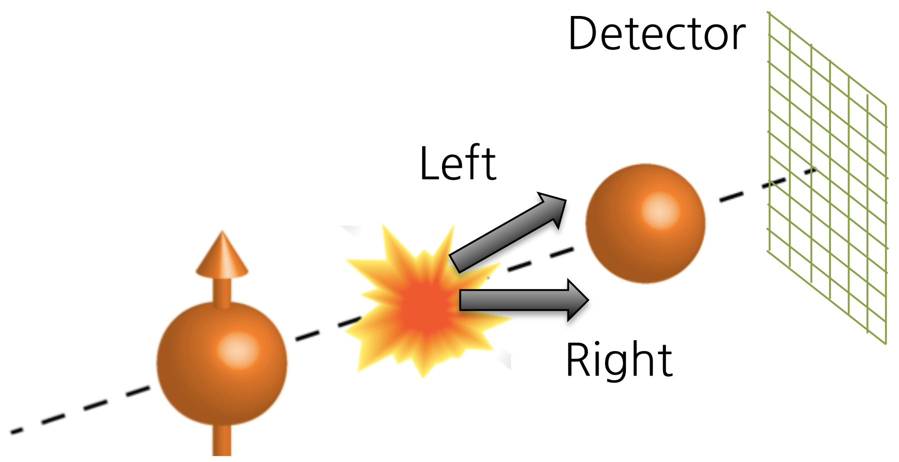
Photon measurement by RHICf

- ## Inclusive production cross-section measurement of forward photons
  - Good performance for photons
    - Energy resolution: 3-5% (~40% for neutrons)
    - Position resolution: 0.1-0.2 mm (~1mm for neutrons)
  - Simpler method than π^0 and neutrons
    - PID selection and background estimation
    - High statistics data
  - Photons are from π^0 dand η decays



- ## Test of collision energy scaling (Feynman scaling law)
  - Comparison with LHCf results ($\sqrt{s}$ = 7, 13 TeV)
    - Test of scaling at zero degree with "π^0" by LHCf (2.76 ⇔ 7 TeV)

      This work can test it in much wider energy range (0.5 ⇔ 13 TeV).



$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}} = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}}$$

Method

- Data set
  - All data obtained in 2017
  - Three detector positions
  - Shower and HighEM trigger samples

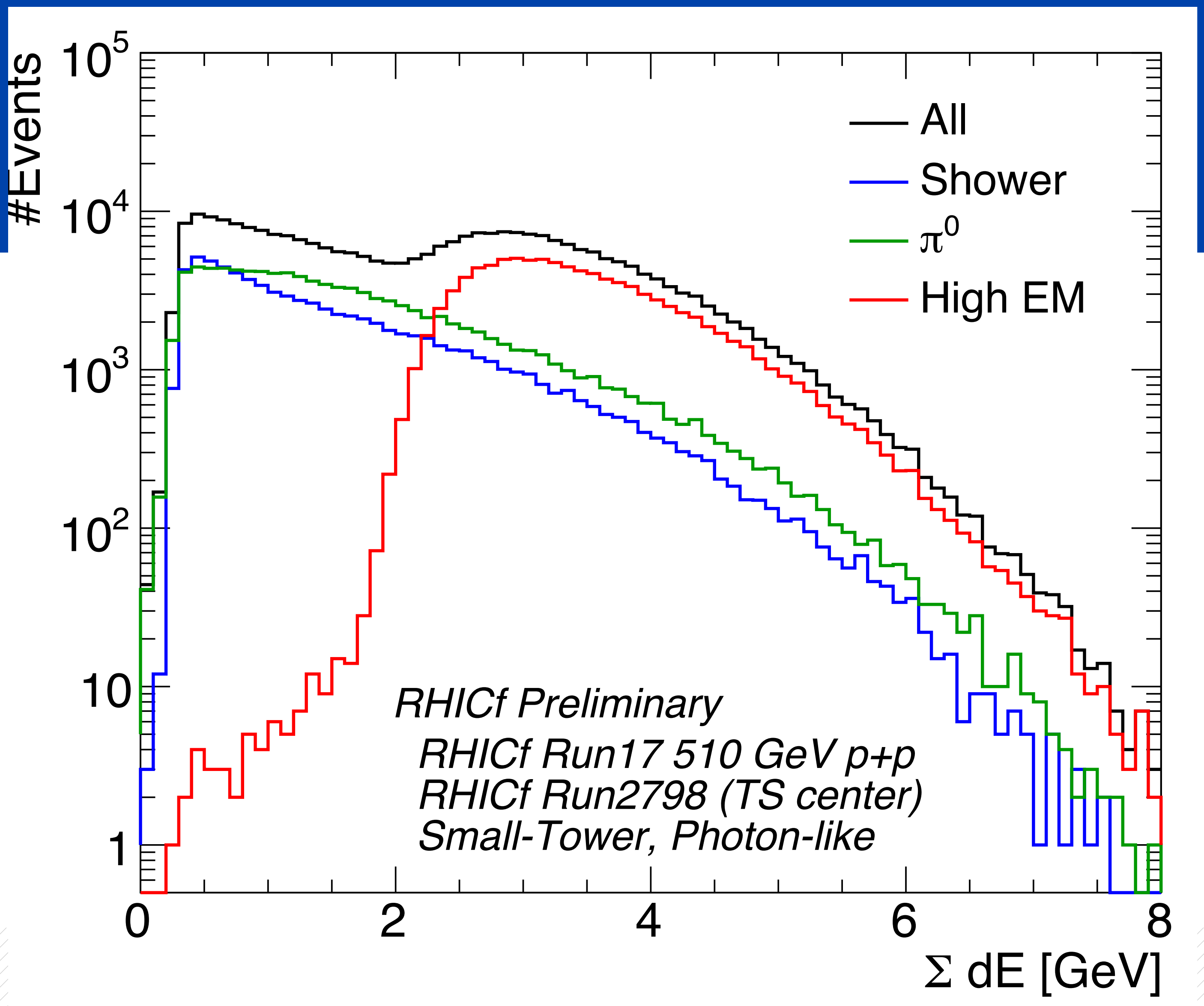
- Event selection
  - PID selection (Photon like)
  - Singe hit selection
  - Fiducial area selection (right figures)

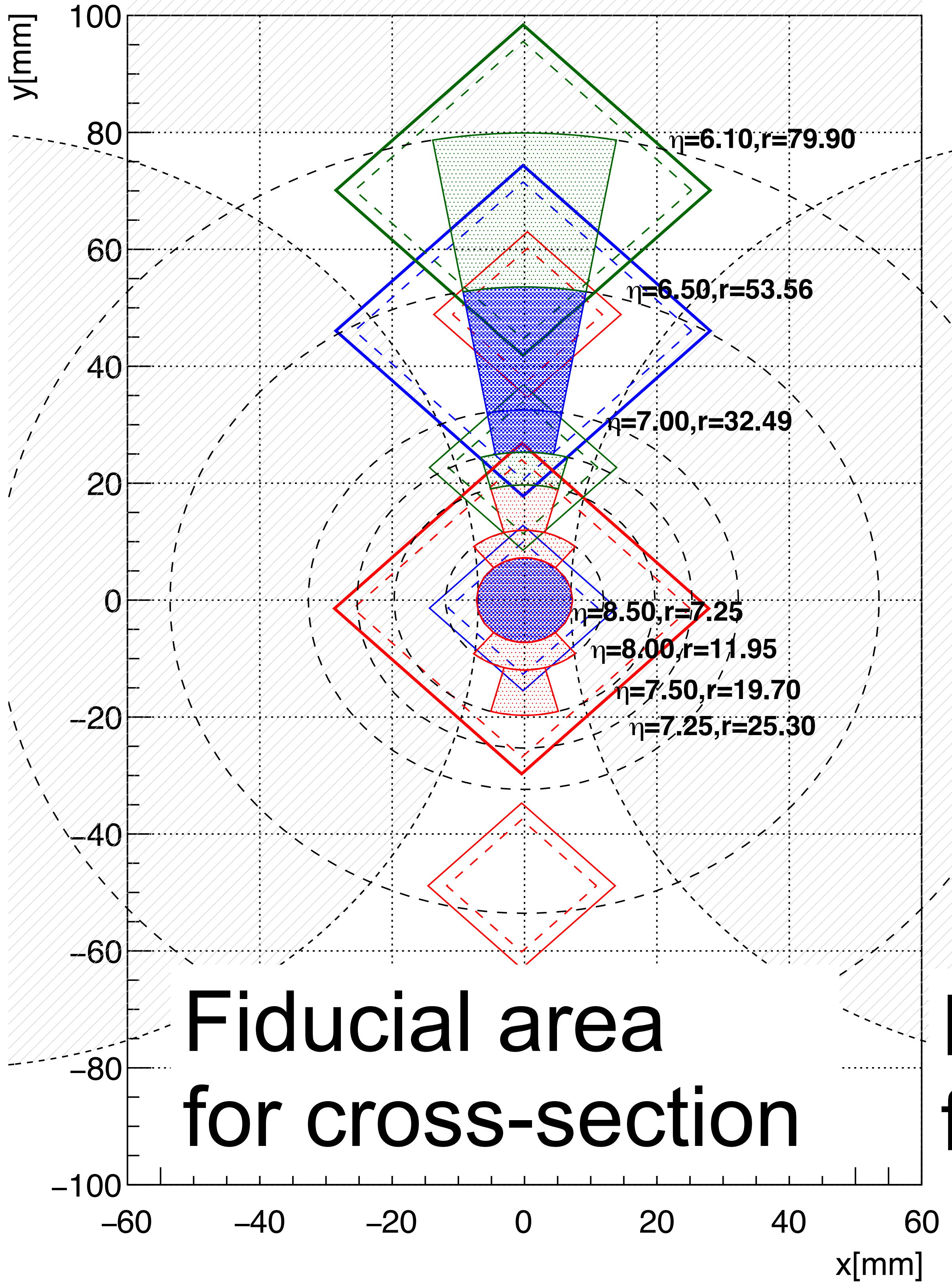
- Analysis method

Efficiency and Multi-hit contribution — Hadron contamination — Beam-gas background

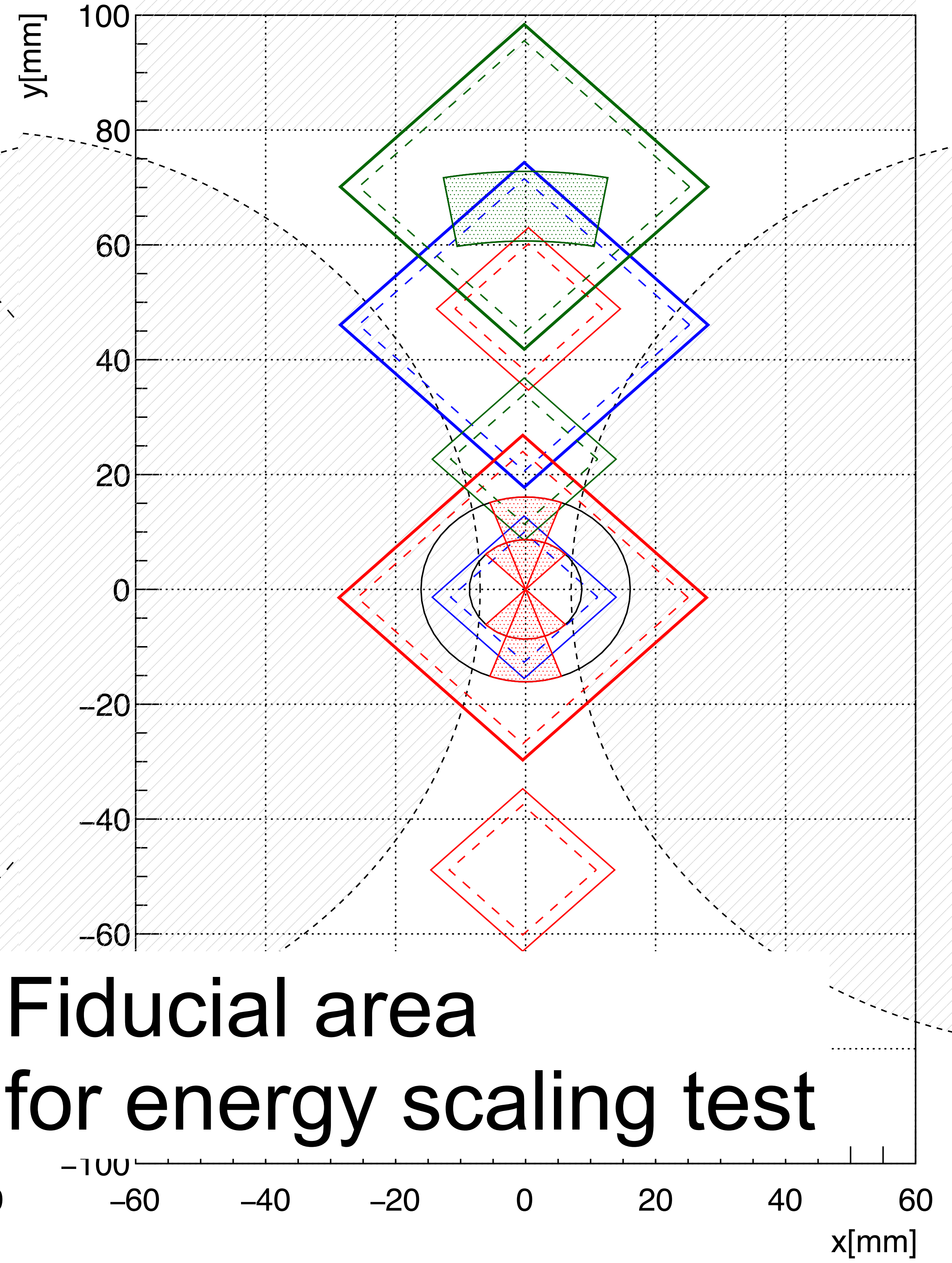
$$\frac{d\sigma}{dX_F} = \frac{C^{c\tau} C^{MC} C^{PID\,purity}(1 - R^{BKG})\, N^{single-\gamma\, like}_{i-trg,spin}}{L^{recode}_{i-trg,spin}\,\Delta X_F}$$

long life-particles' contribution





Fiducial area for cross-section



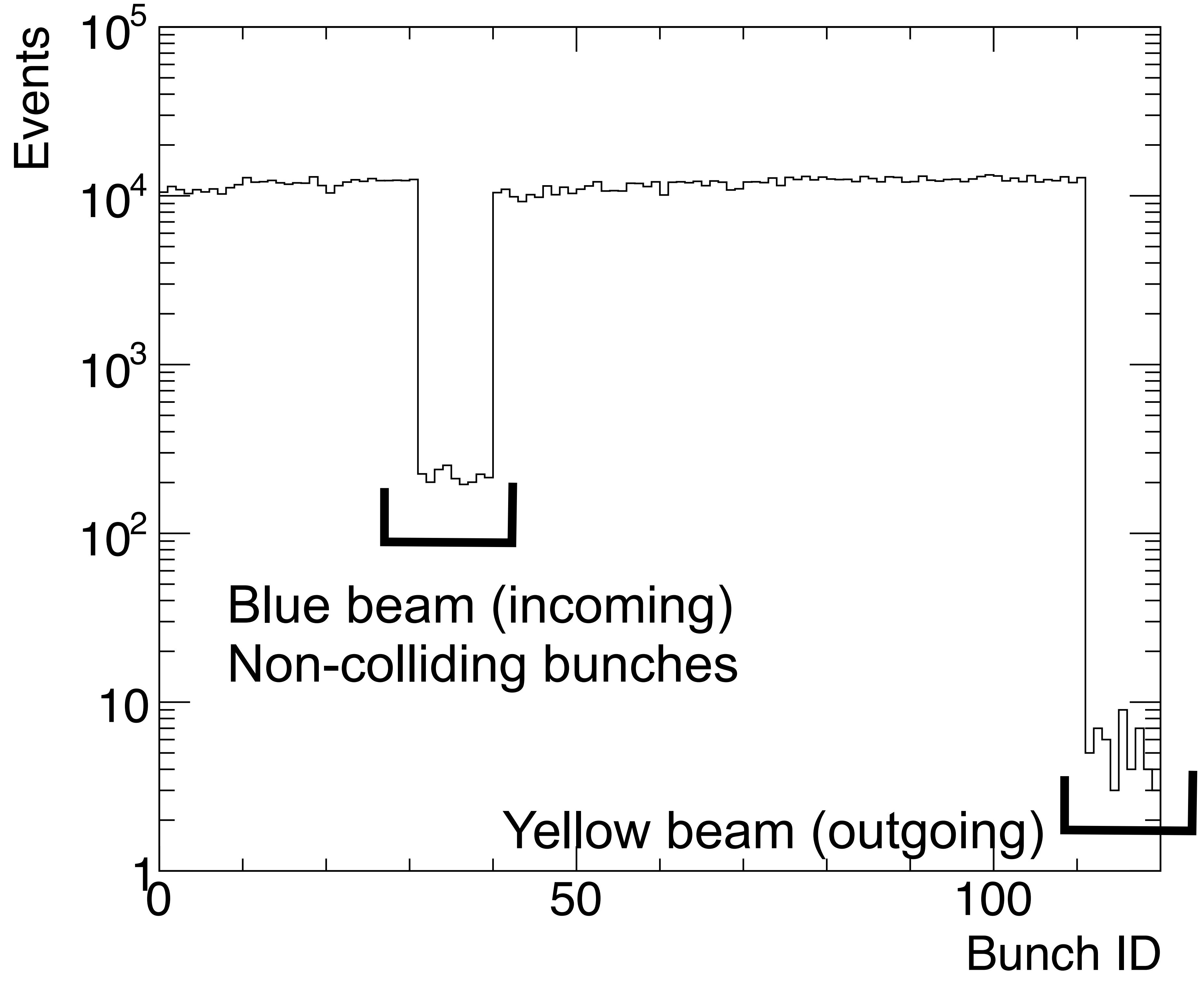
Fiducial area for energy scaling test

Corrections (1)

R^{BKG} : Beam gas background

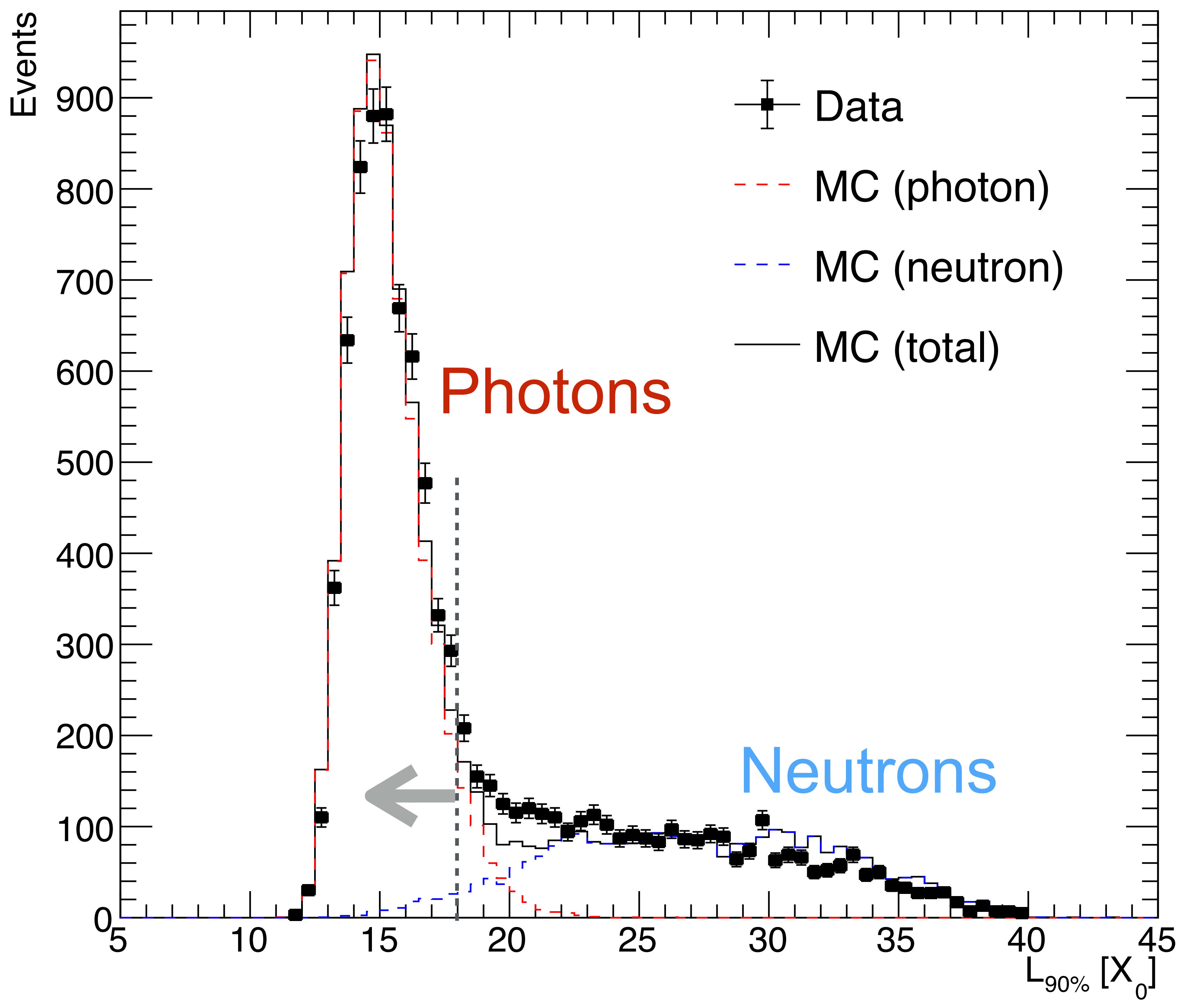
- Collision btw. beam and radical gas
- Estimated using non-colliding bunches
- ~ 2%

#Event in each bunch ID



$C^{PID\ purity}$: Hadron contamination

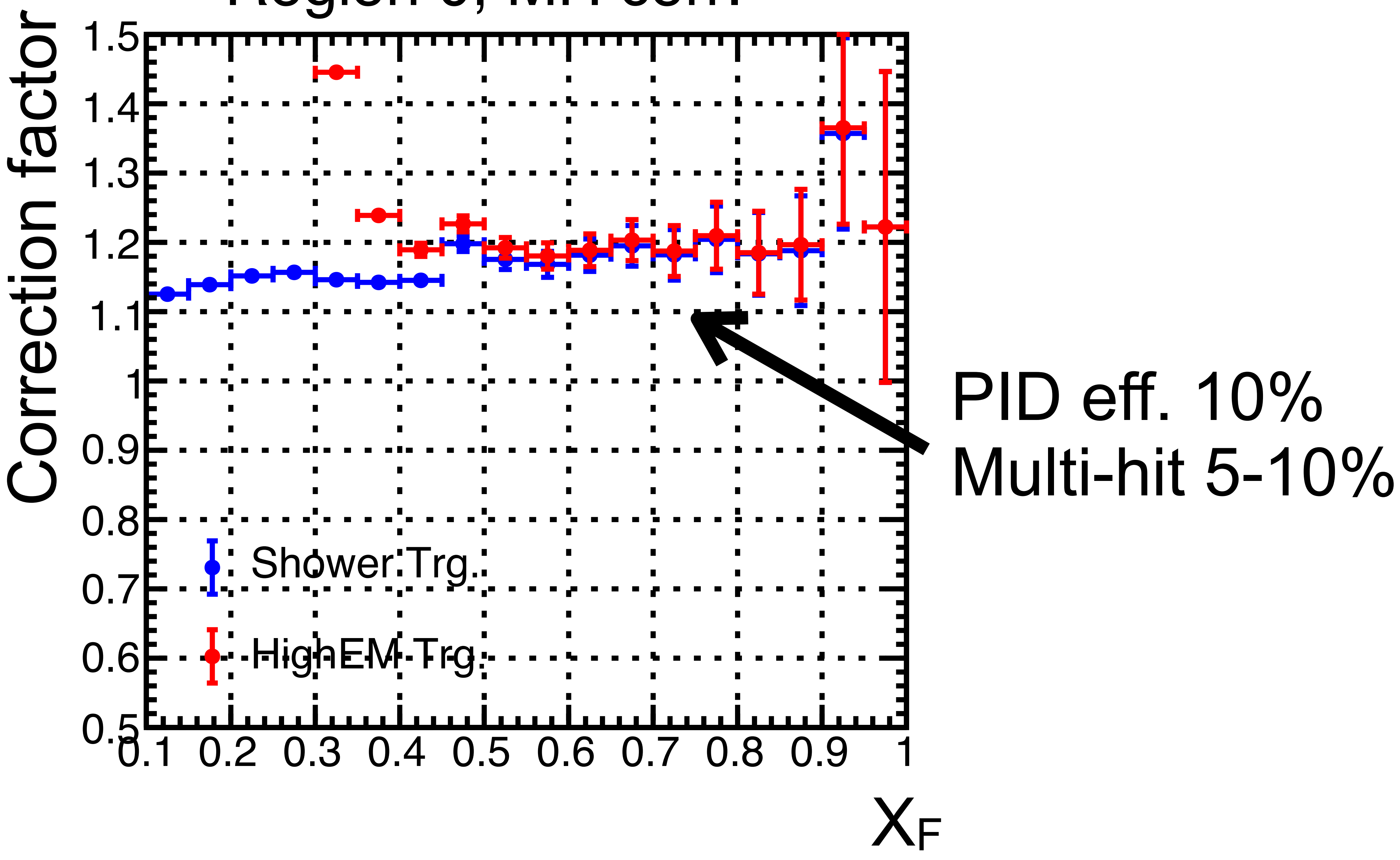
- Contamination of hadrons (neutrons) in the PID selection
- Estimated the purity using template fitting of PID estimator ($L_{90\%}$)



Corrections (2)

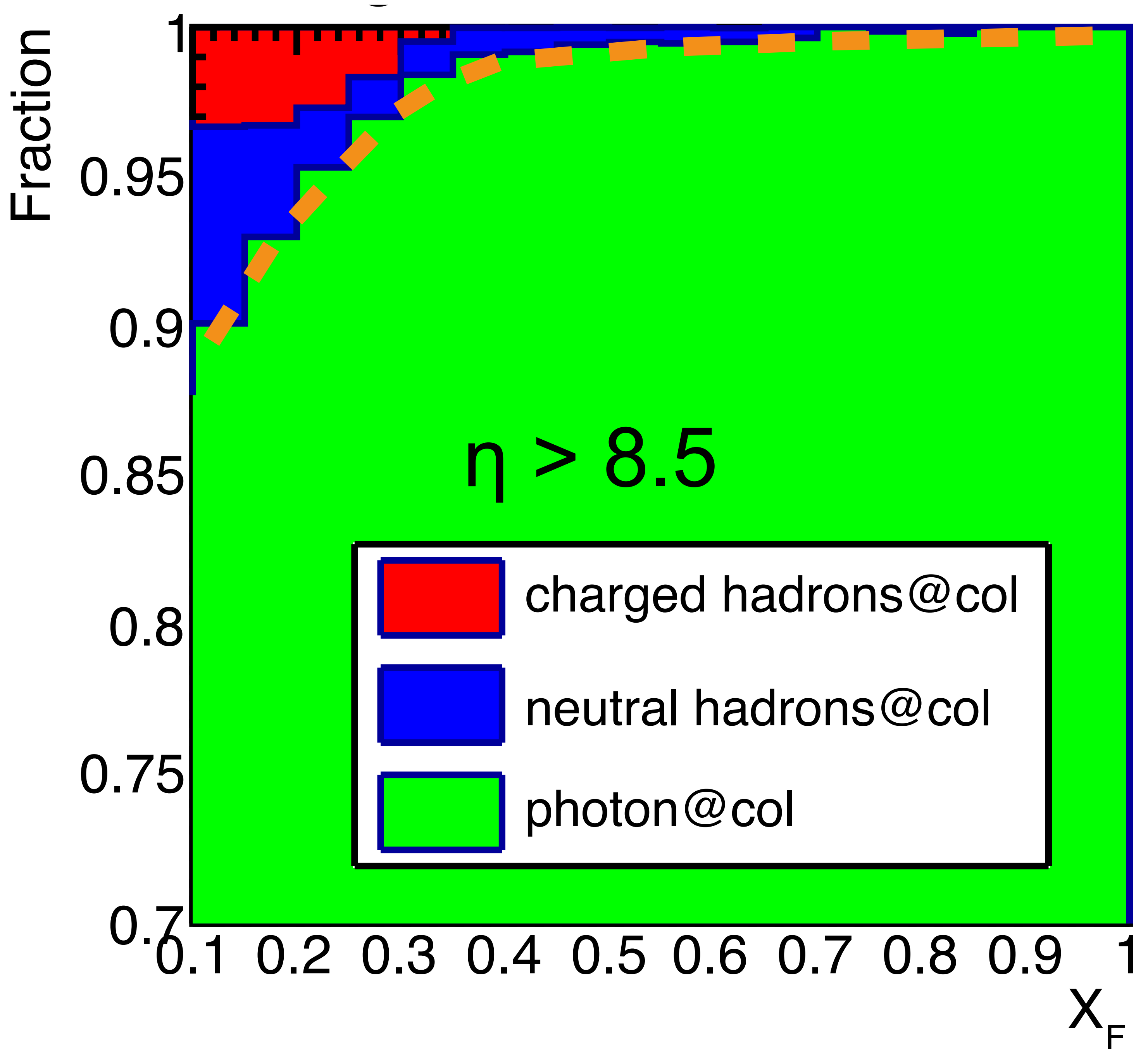
C^{MC} : Efficiency and Multi-hit

- Corrections of
  - Trigger efficiency
  - Selection efficiency in PID, Single-hit
  - Contribution of photons in multi-hit events
- Estimate using full detector simulation



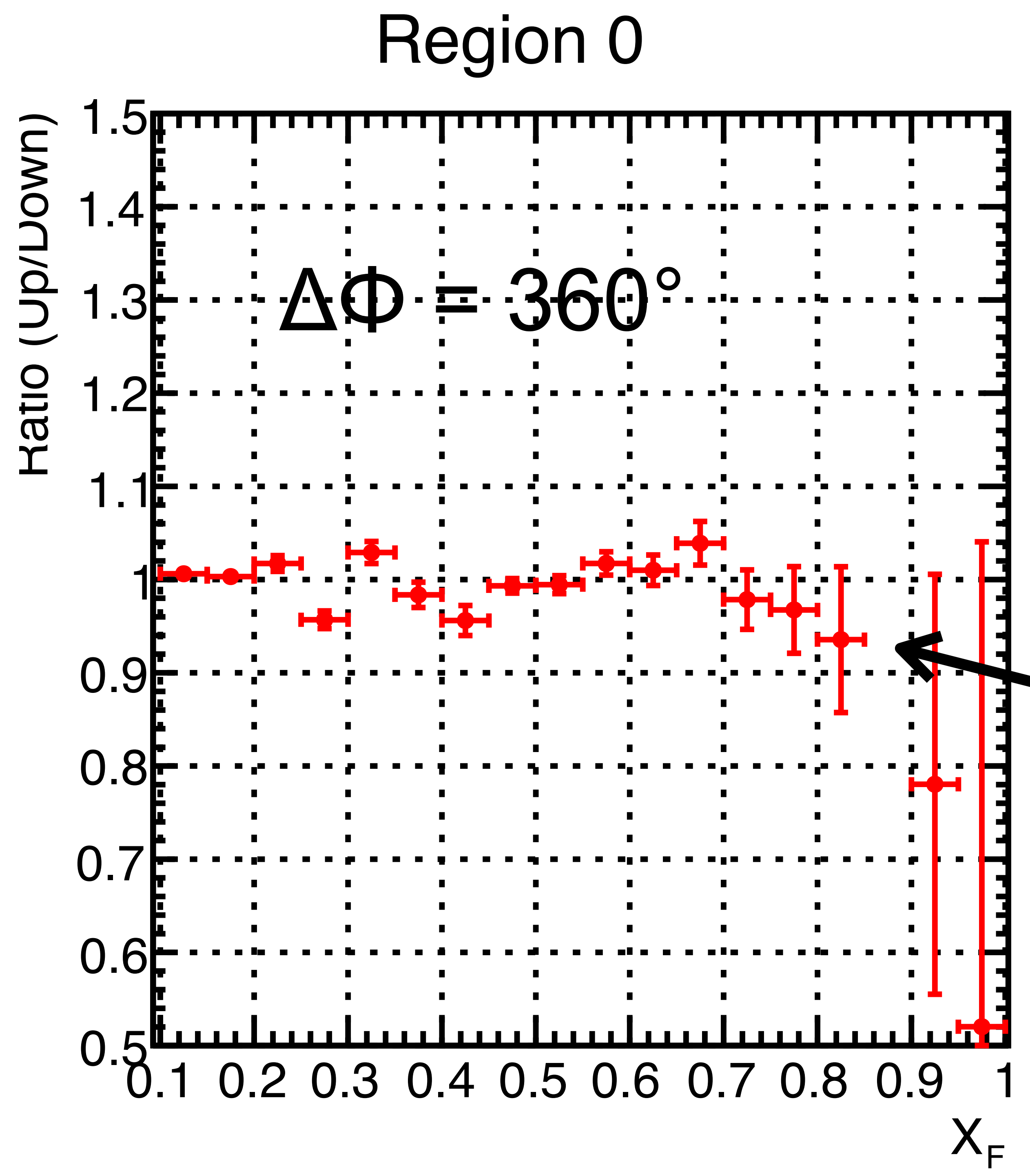
C^{CT} : long-life particle contribution

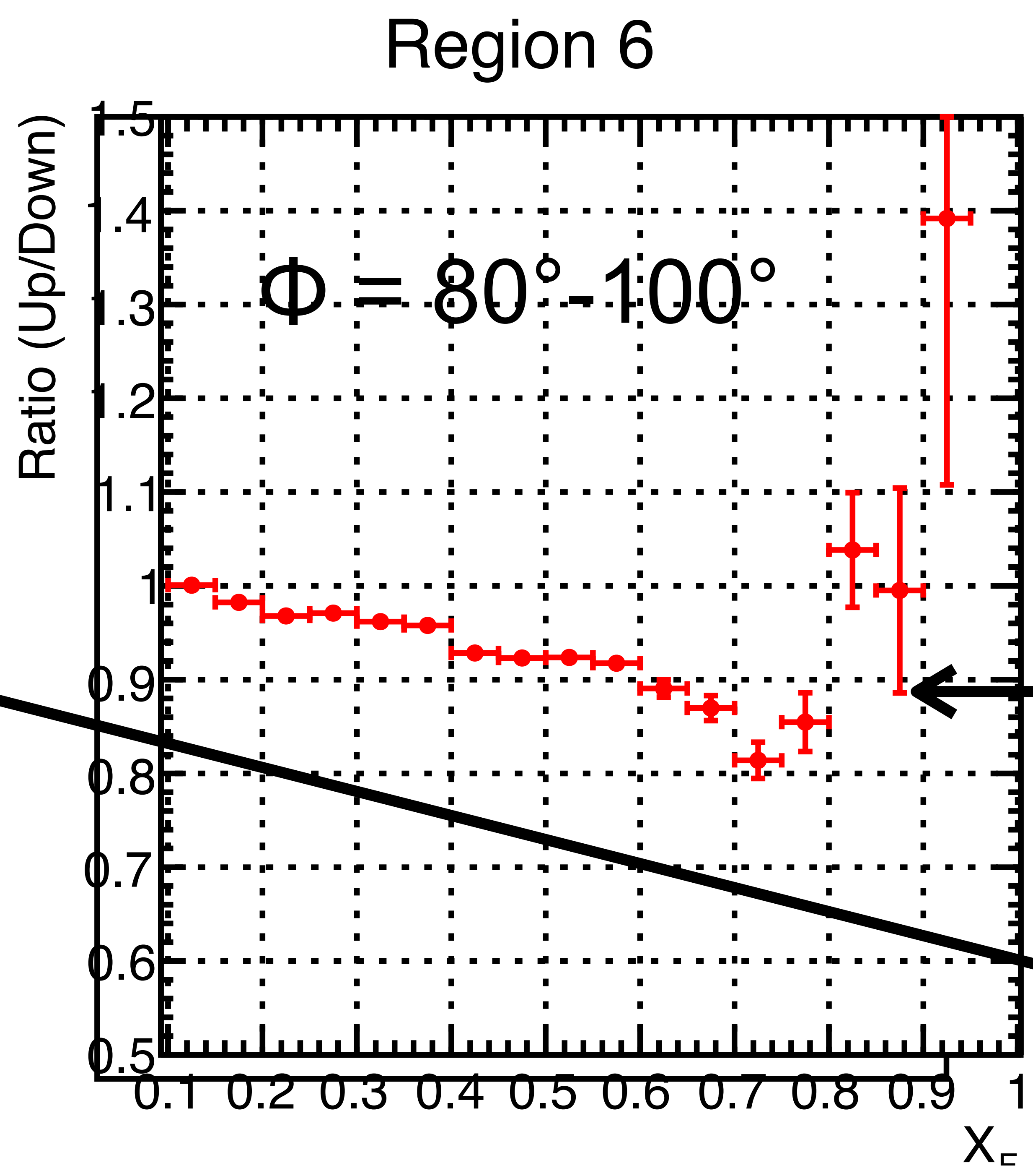
- Photons from K^0, Λ decays
  $K^0 \to 2\pi^0 \to 4\gamma$
  $\Lambda \to n + \pi^0 \to n + 2\gamma$
- Subtract these contributions for easy comparison with models.
- Estimated using MC

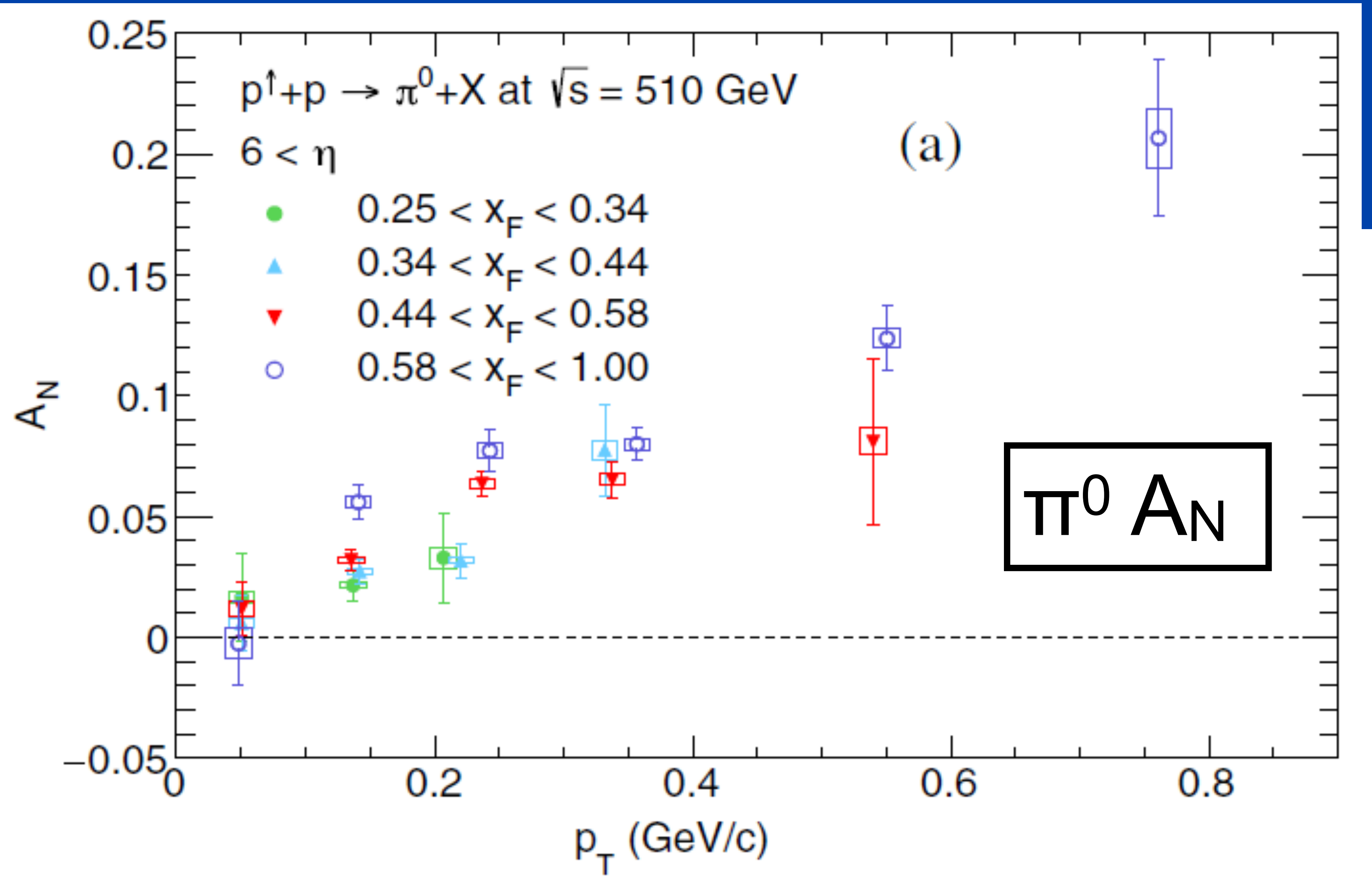


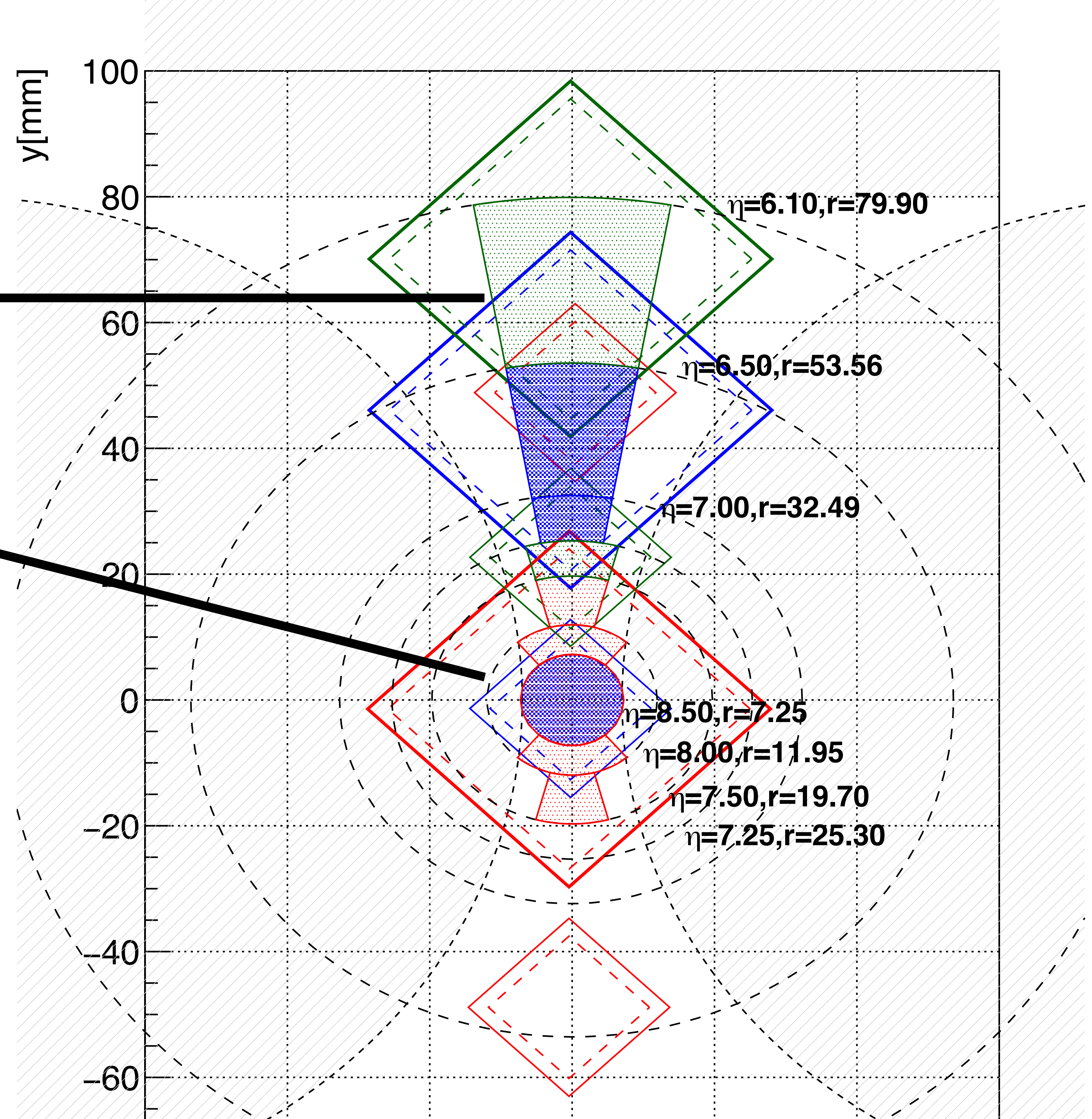
Spin direction dependency

- Large A_N in π^0 induces the spin direction dependency.





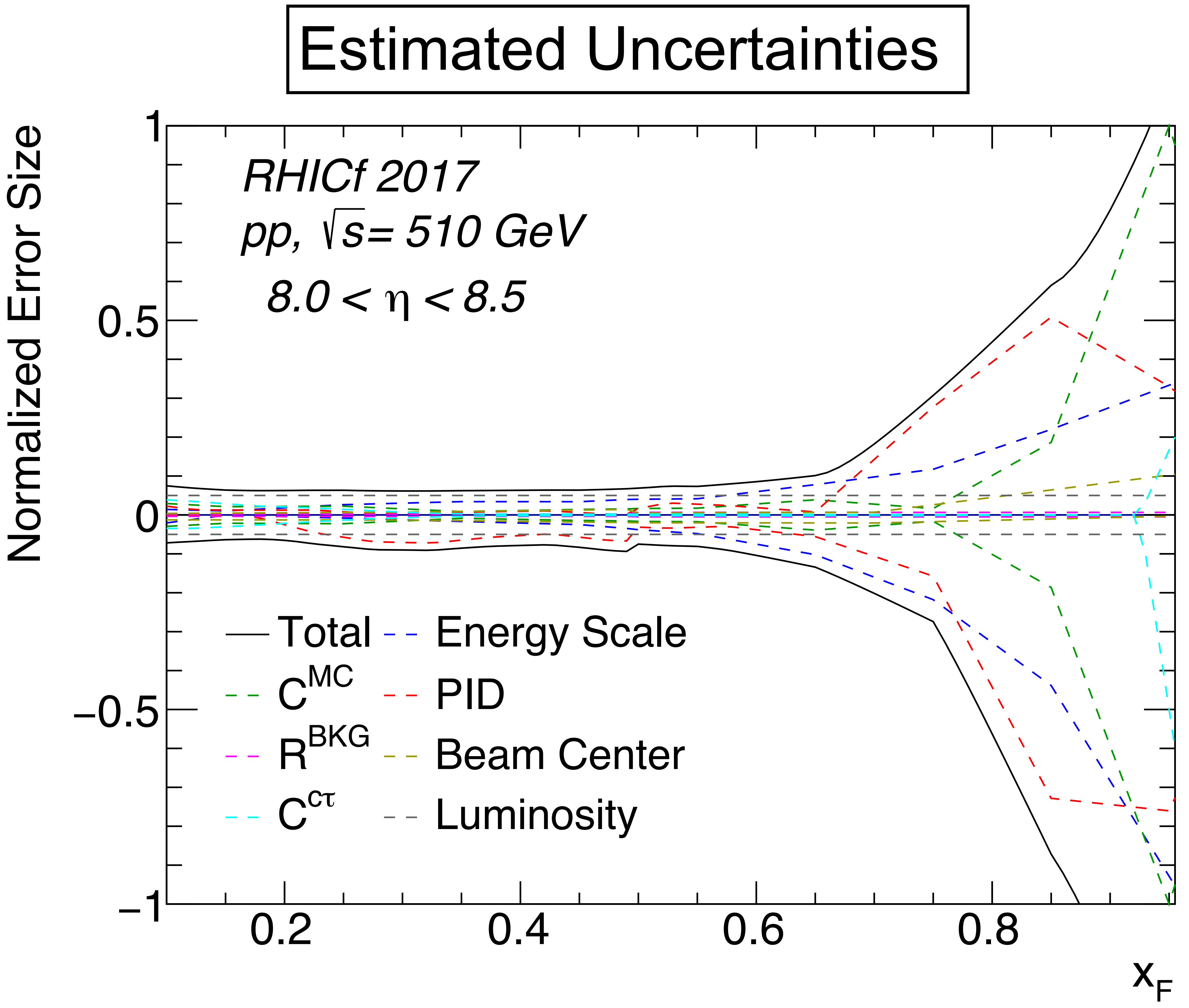




Combining the sample after normalization by Integral luminosity the effect can be cancelled out.

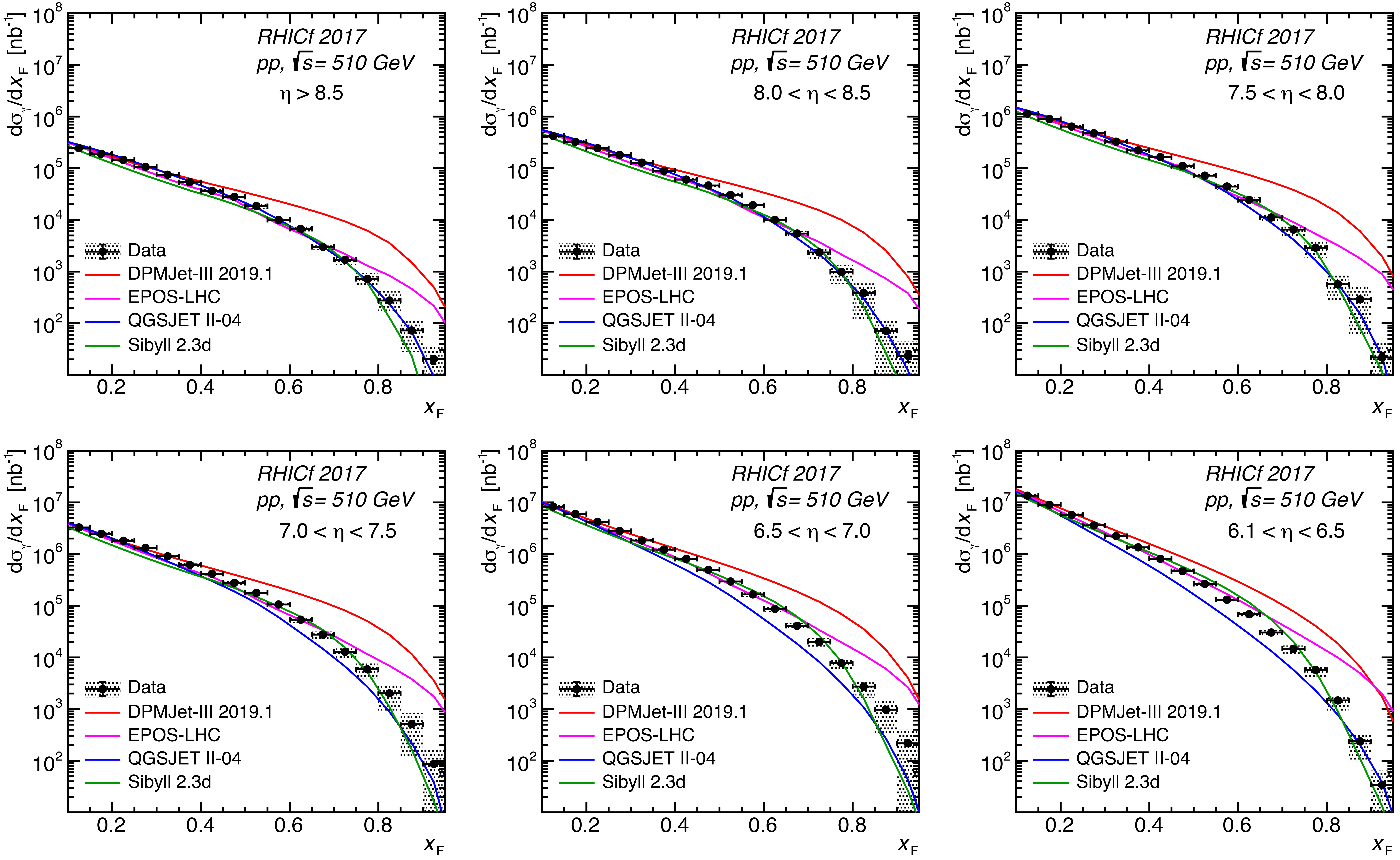
Systematic uncertainties

- Energy Scale
  - Stability, Non-linearity, Non-uniformity
- PID
  - Difference of L90% distribution between data and MC
- Single hit selection ± 1%
  - Estimated by LHCf using beam test data.
- Multi-hit events
  - Model dependency (QGSJET2 and EPOSLHC)
- Beam gas ~±1.5%
  - Consider photon energy dependency
- Beam Center
  - Consider the uncertainty of BC determination.
- C_{ctau} (long life particle contribution)
  - Deviation among models
- Luminosity ~±5%



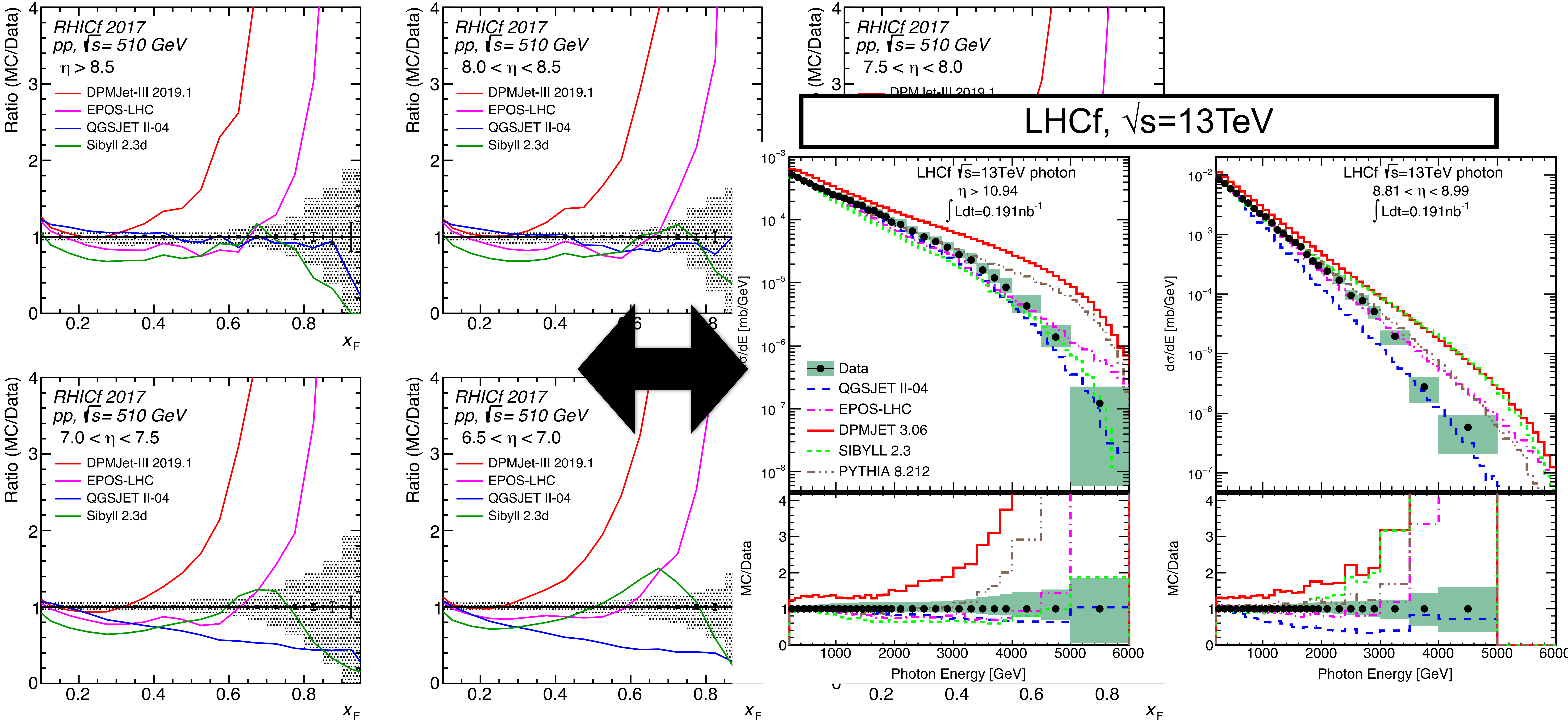
Results

Inclusive production cross-section



Ratio (MC/Data)

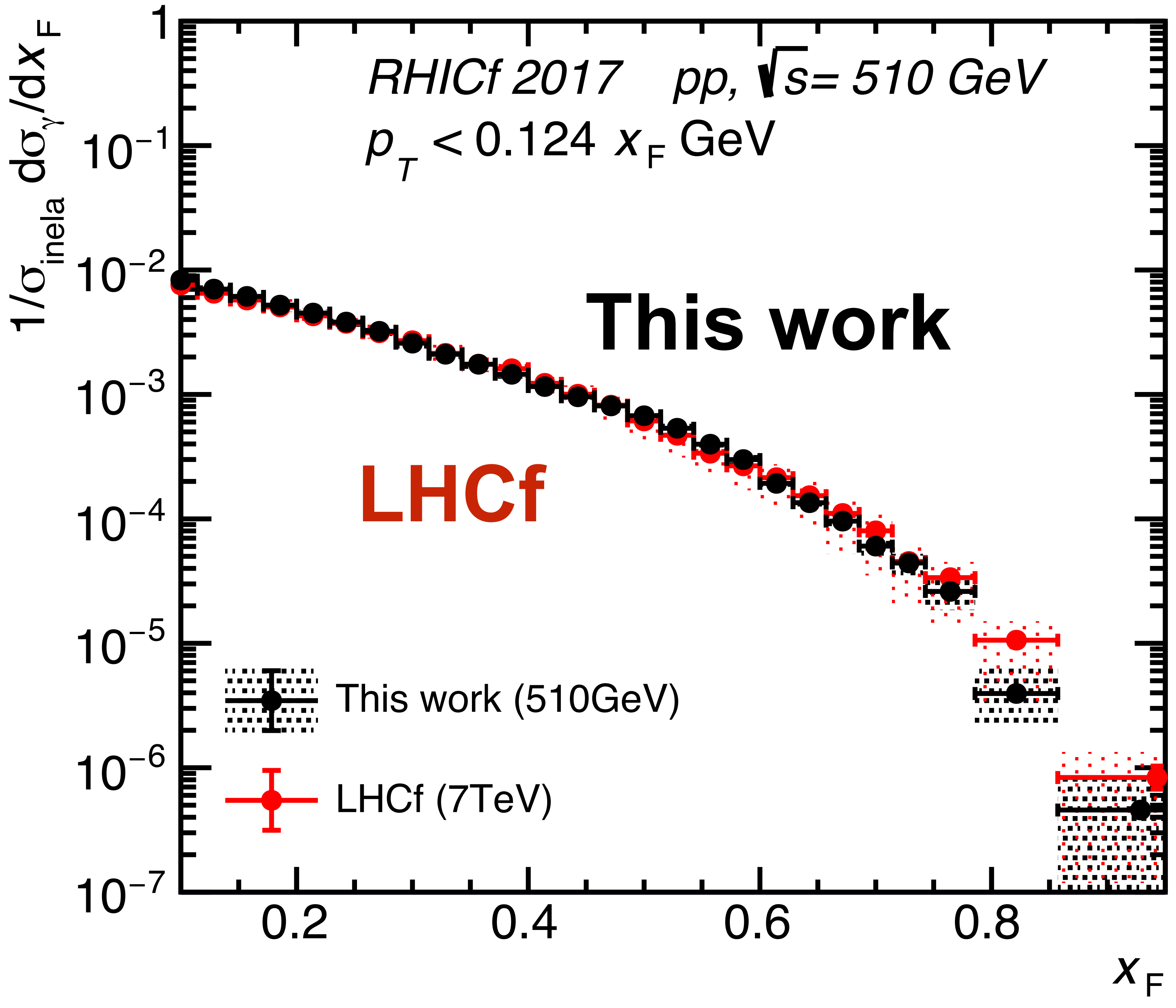
LHCf, √s=13TeV



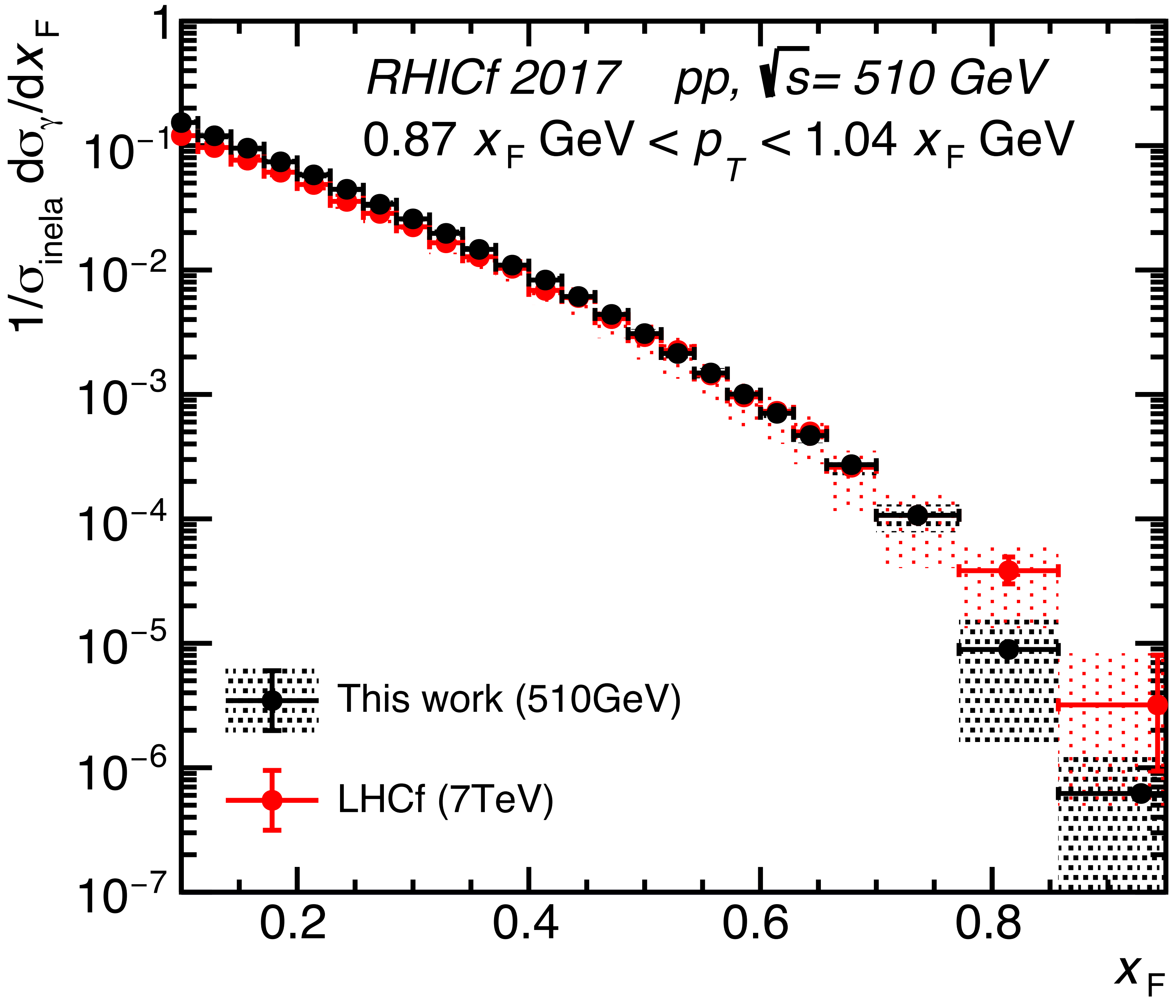
Test of collision energy scaling

- Comparison with LHCf ($\sqrt{s}$ = 7 and 13 TeV) photon results.
- Selected same X_F-p_T phase space coverage as those results
- Normalized by σ_{inela}. (σ_{inela} = 48.3, 72.9, 79.5 mb for 0.5, 7, 13 TeV)

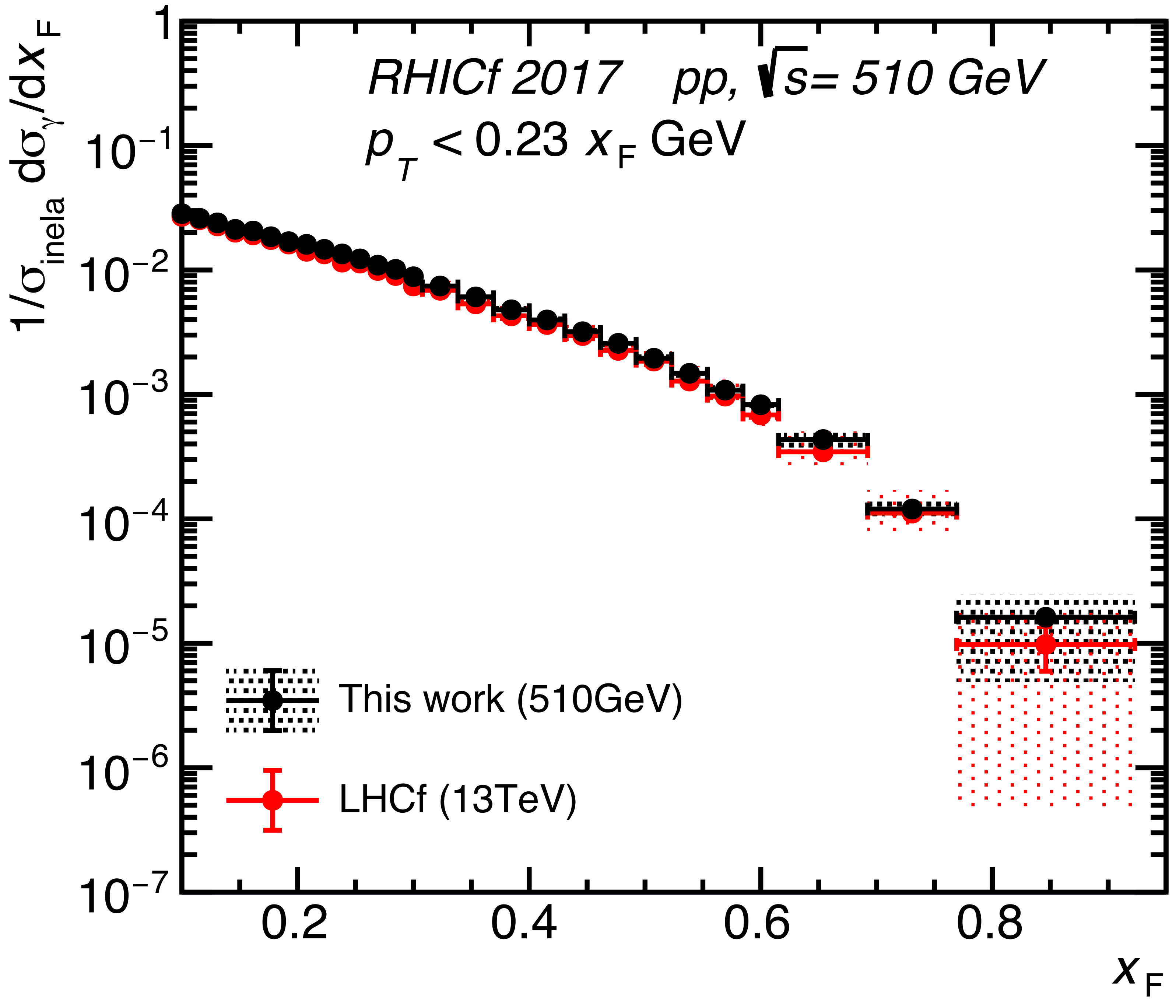
v.s. LHCf 7TeV η > 10.94



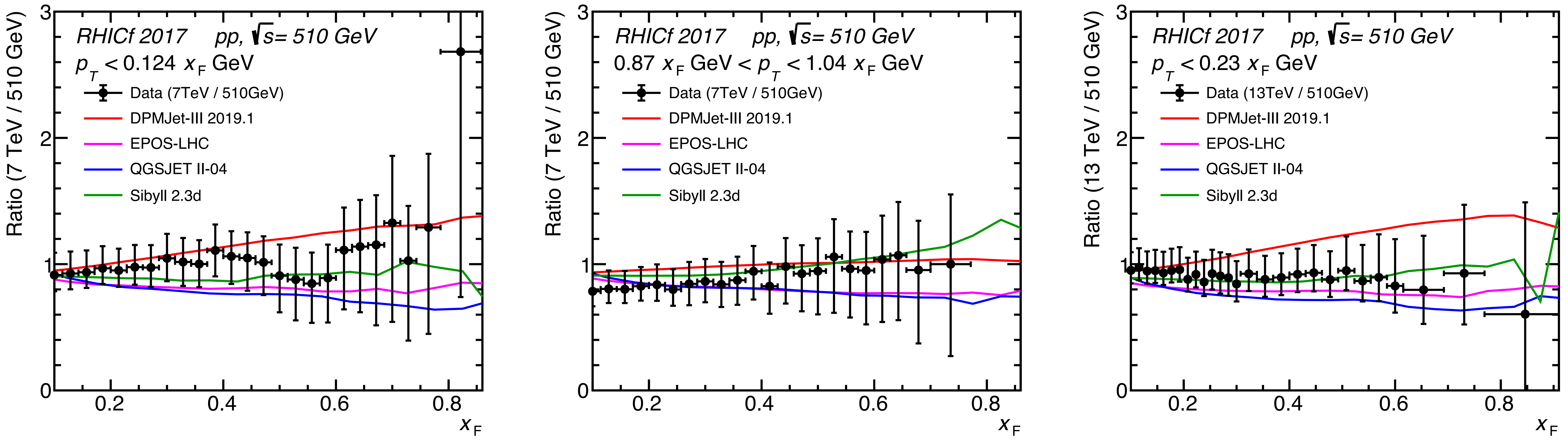
v.s. LHCf 7TeV 8.81 < η < 8.99



v.s. LHCf 13TeV η > 10.94



Ratio (7TeV or 13TeV/ 510GeV)



First confirmation of collision-energy scaling at zero degree photons.

- Consistent with the scaling within the errors

  Lower ratio at X_F<0.4 of the middle plot can be explained by the difference of method with LHCf 7TeV paper.

- No sensitivity to test weak X_F dependency predicted by some models.

  → Need an effort to reduce the errors together with LHCf Collaboration

Summary

- The measurement of inclusive production cross-section of very forward photons at pp collisions, $\sqrt{s}$=510 GeV was performed.

- The result was compared with model predictions
  - EPOSLHC, DPMJETIII (2019): good in $X_F < 0.6$ or 0.3
  - QGSJET II-04, SIBYLL 2.3d: lower or higher yield in lower η regions.
    => This feature is similar as LHCf results at 7 and 13 TeV
    It suggest the common source in the wide energy regions

- Collision energy scaling was confirmed within the errors
  - Wider energy region than LHCf π^0 result (2.76 - 7 TeV)
  - Improvement of error is required to test the weak X_F dependency predicted by models

- Future prospects:
  - Test of scaling with π^0 and neutrons

Advantage of RHICf+STAR

- Higher statistics than LHCf+ATLAS
  - ~100 M events are available (w/ TPC ~ 30%)
    ⇔ 7 M events of LHCf+ATLAS (pp, $\sqrt{s}$=13TeV)
  - Large π^0 samples

- Experience of LHCf-ATLAS joint analysis
  - Developed method can be applied to RHICf + STAR analyses too.

- Availability of ZDC, RPs
  - ZDC was located behind of RHICf
  - RP was installed in one of the 5 Fills