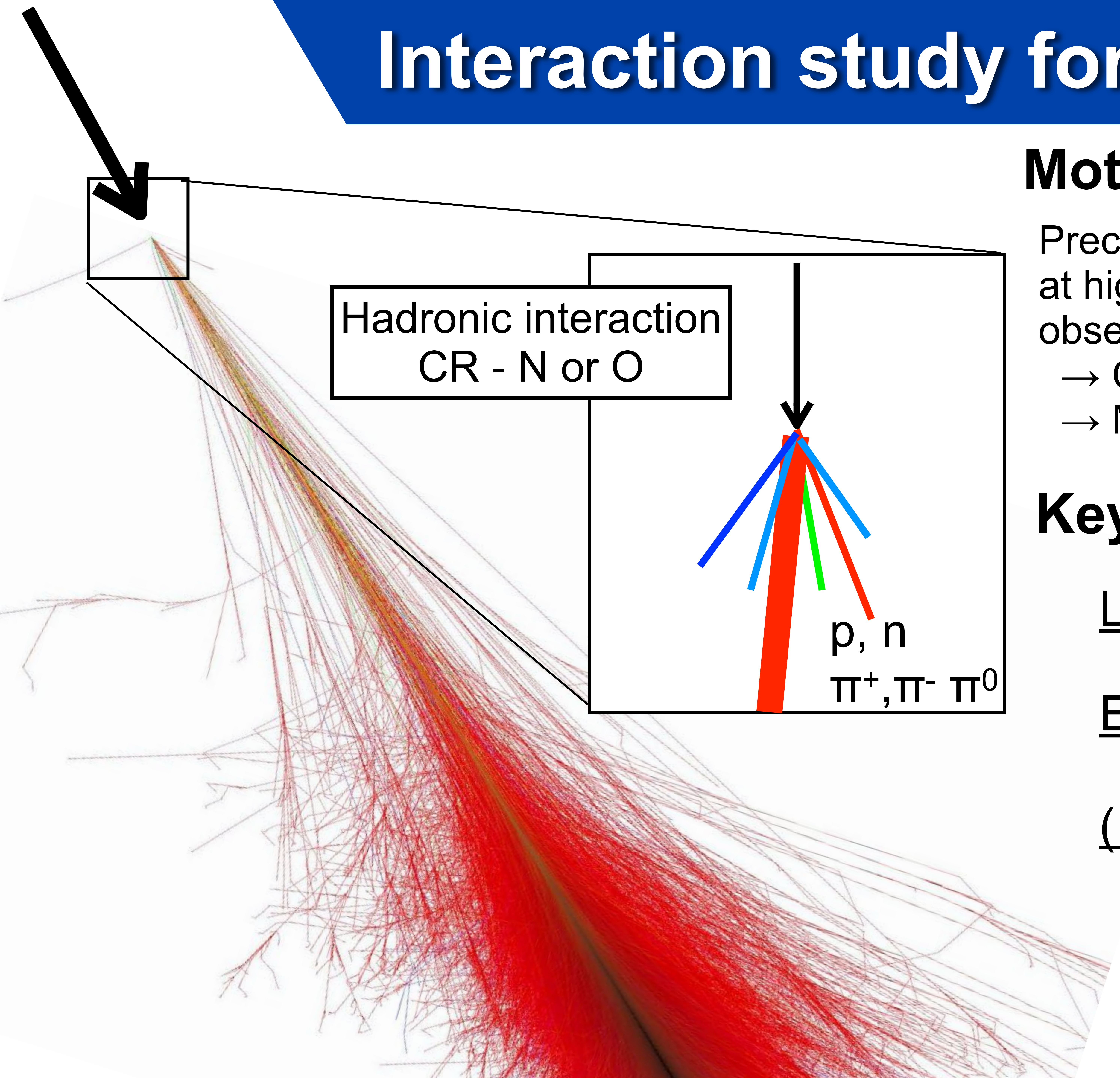
Cross-section measurement Status of RHICf analysis and prospects of RHICf II

H. Menjo, *Nagoya Univ*

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

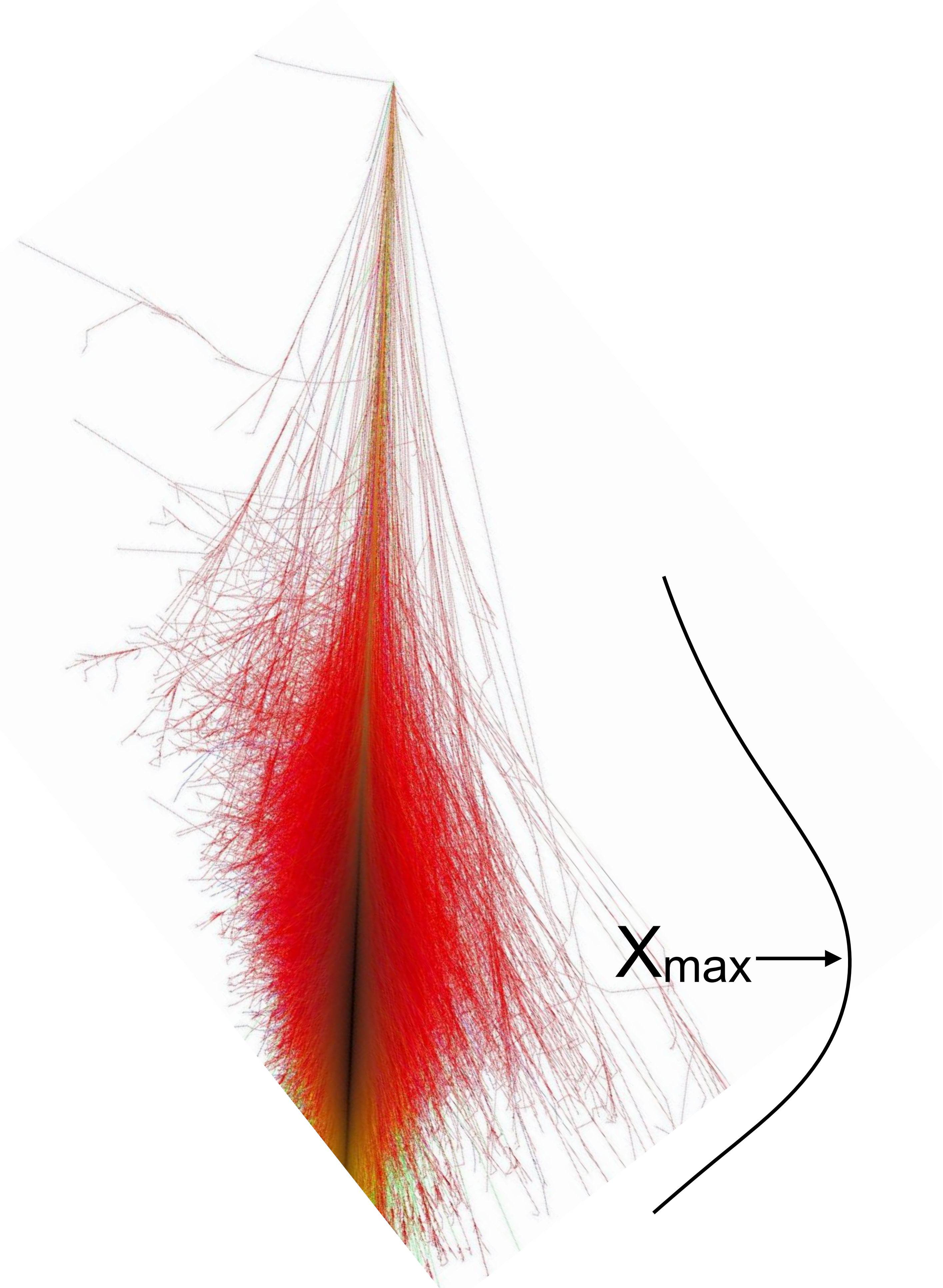
Key items:

Leading particle production

Energy dependency (scaling)

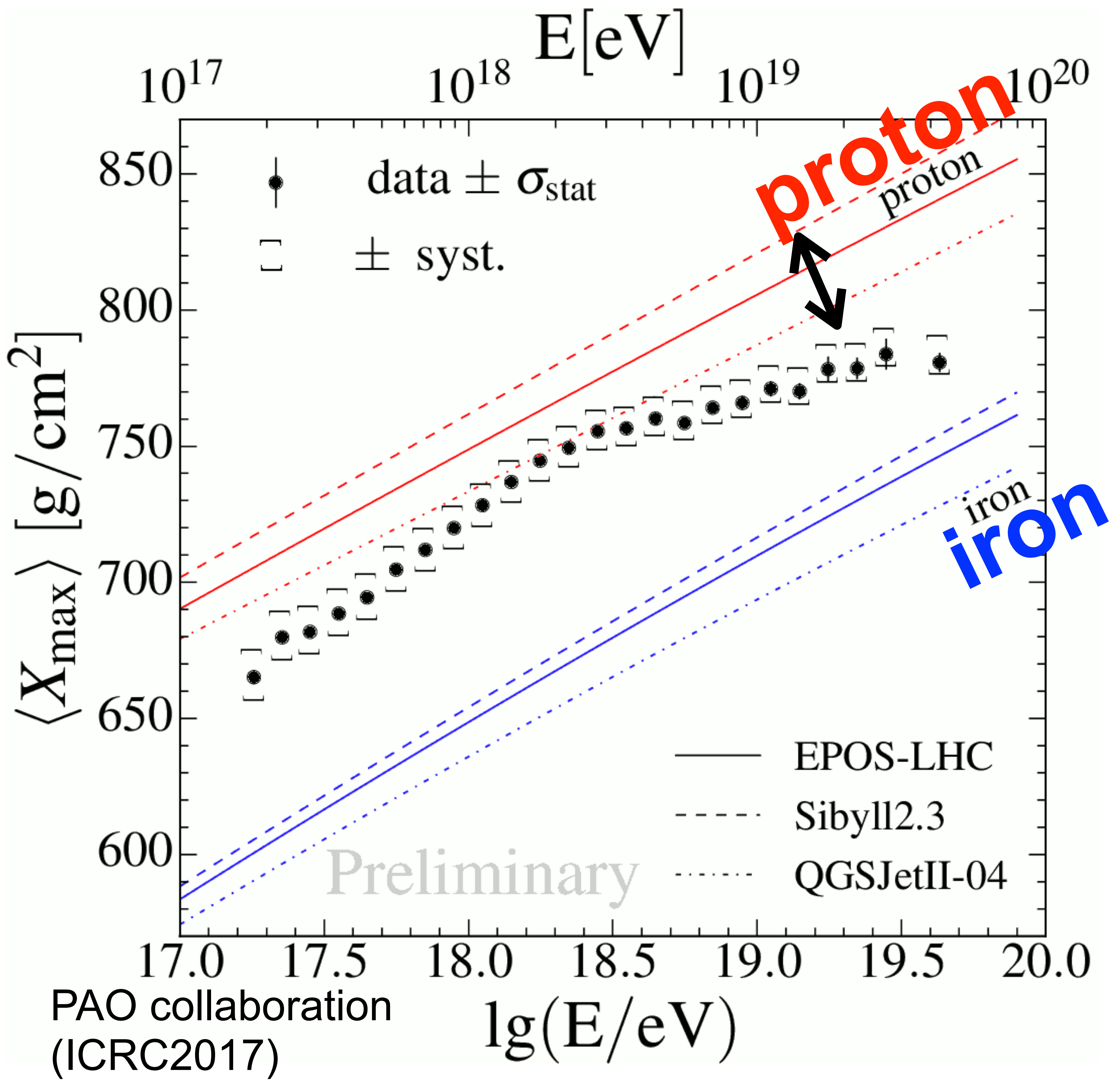
(p-π interaction)

Issues on UHECR observations



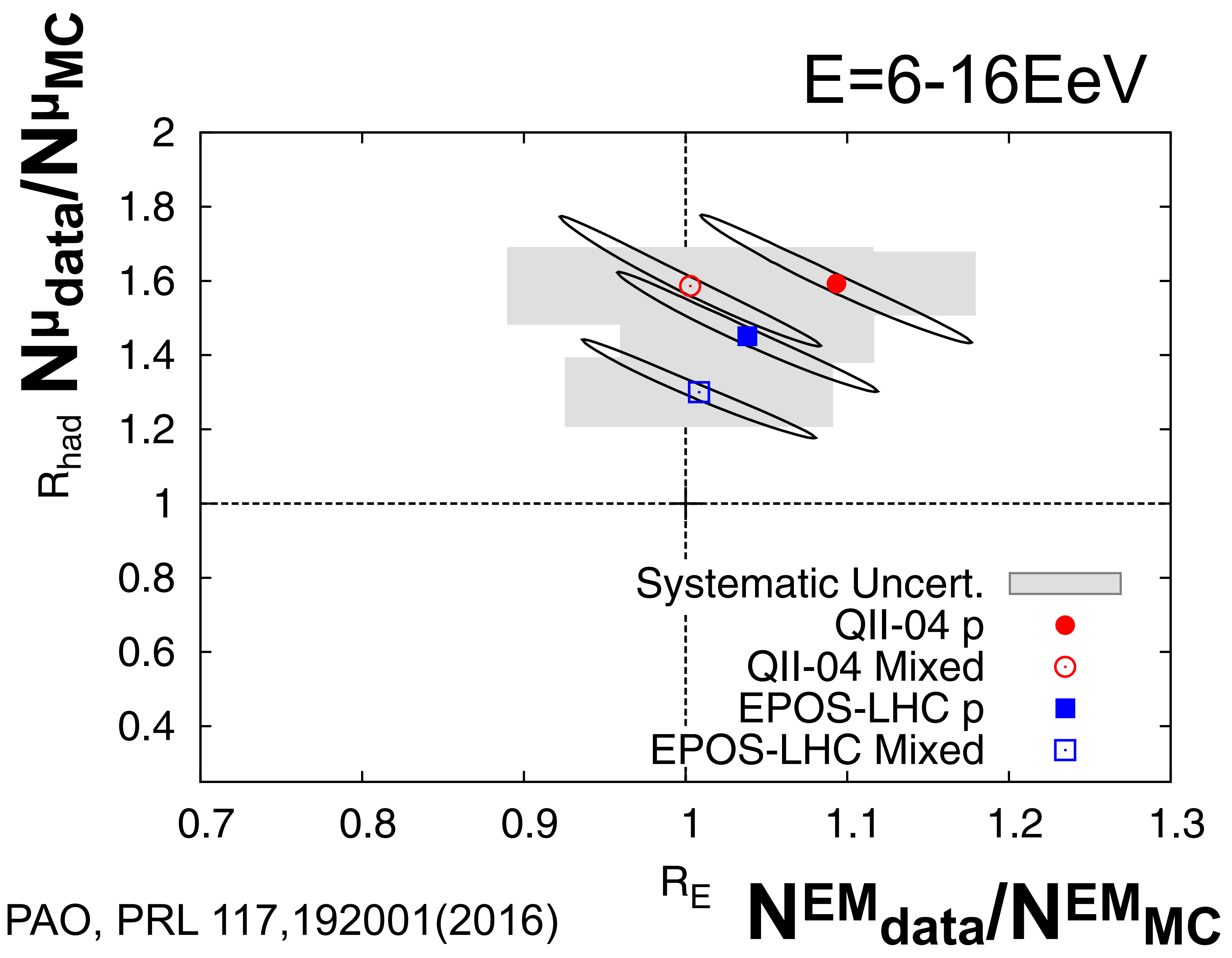
N^{μ}: Number of muons
on the ground

Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

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



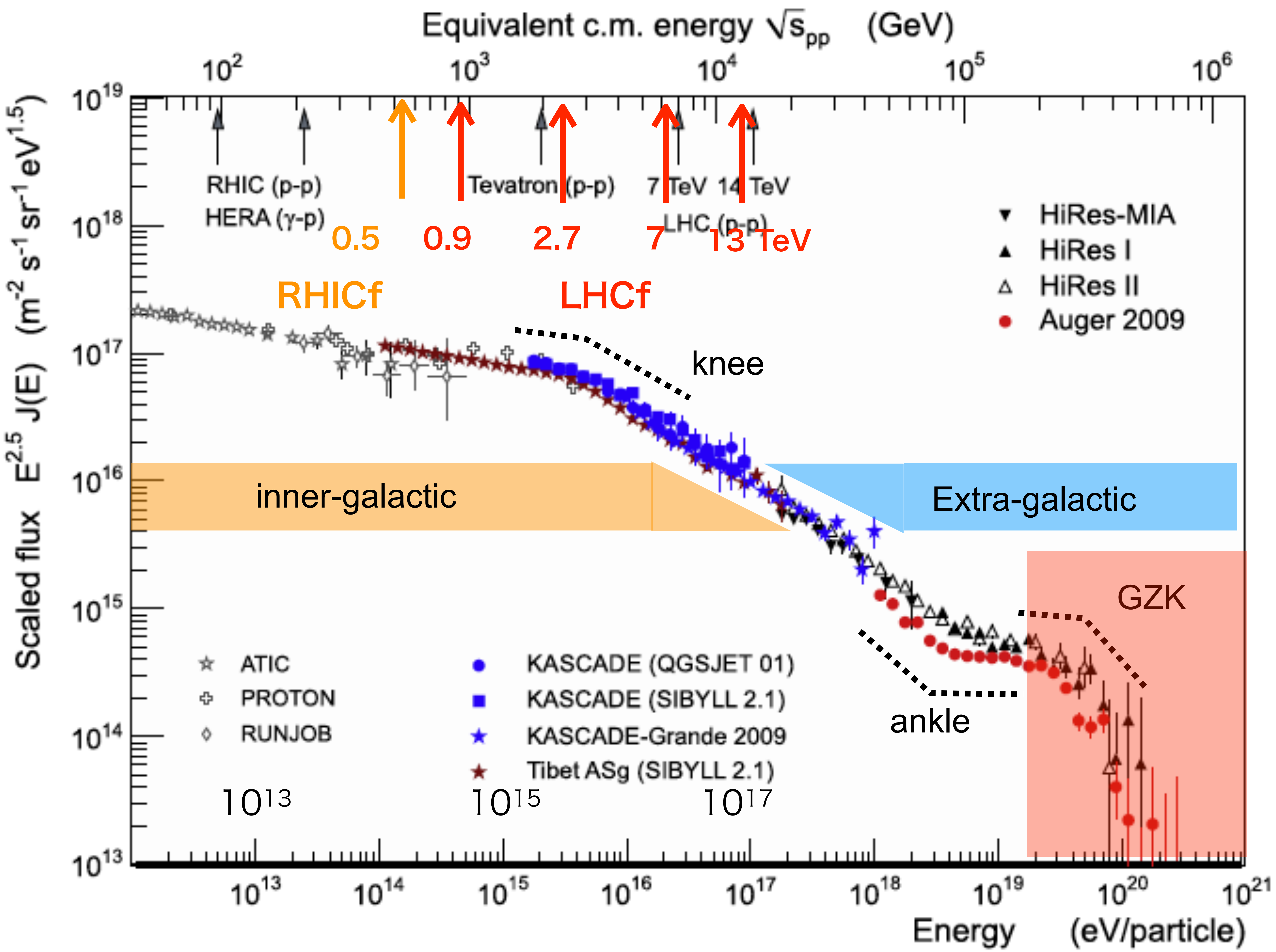
PAO, PRL 117,192001(2016)

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

Several ideas to solve it

- Strange particles
- Vector meson productions
- QGP

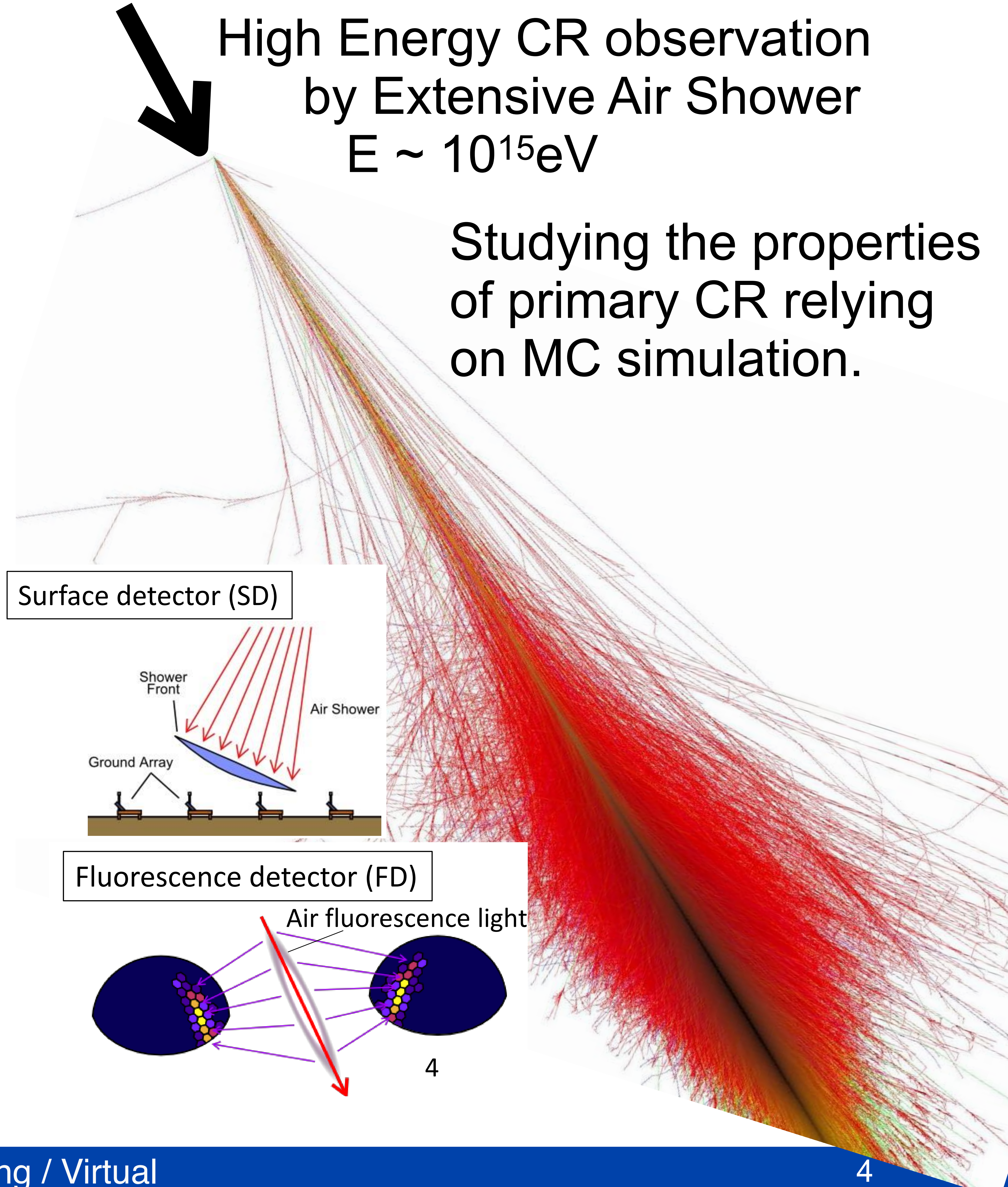
CR energies v.s. Collider energies



D'Enterria et al., 2011

High Energy CR observation
by Extensive Air Shower
$E \sim 10^{15}$eV

Studying the properties of primary CR relying on MC simulation.

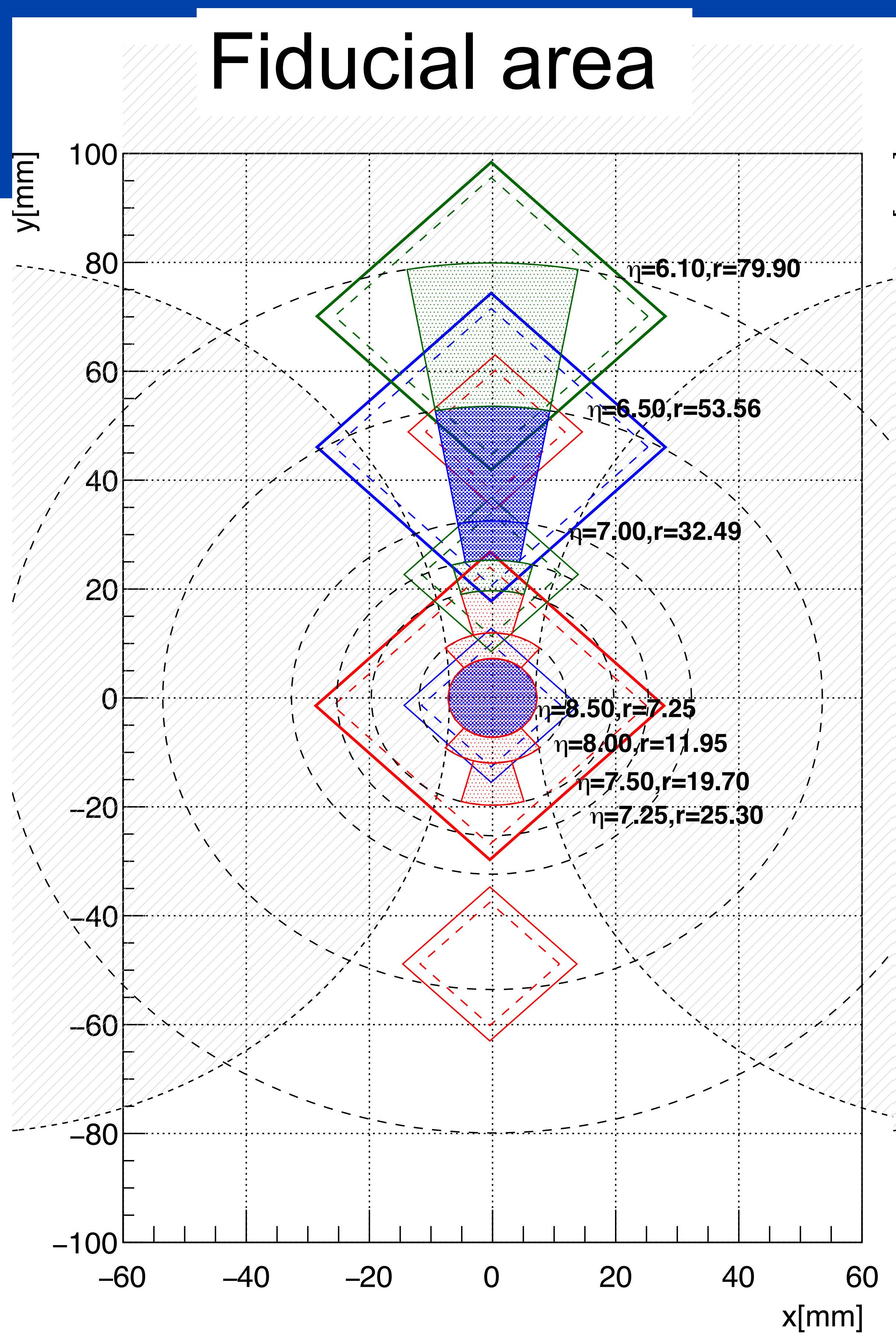


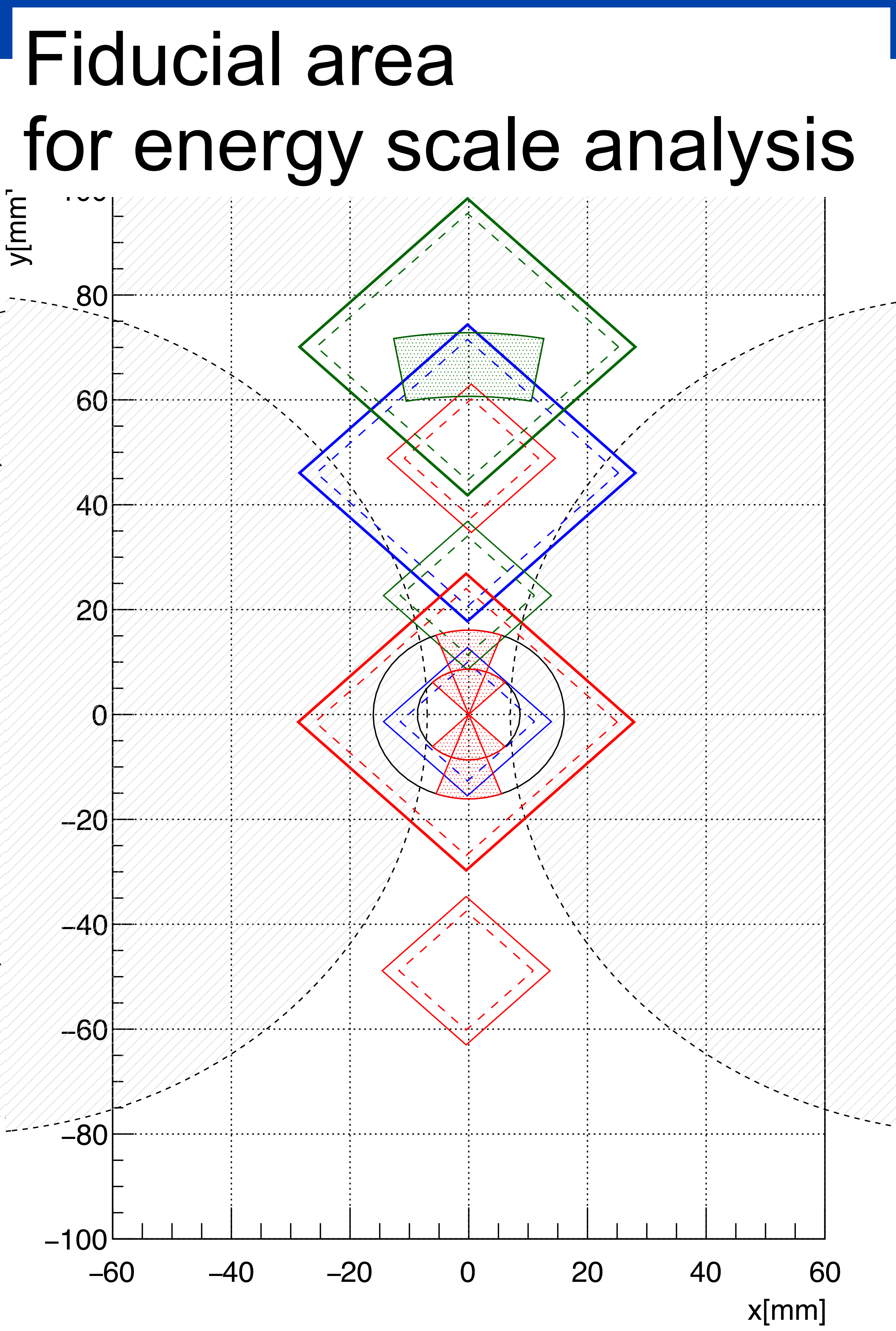
Status of RHICf standalone analysis

- Three main targets
  - Photon incisive
    → Analysis was completed. Writing the draft of paper.
  - π^0 inclusive
    → π^0 reconstruction method was well established by Minho’s analysis. For cross-section measurement, careful check of efficiency must be performed (which is canceled out in A_N measurement)
  - Neutron inclusive
    → Minho’s analysis may work for cross-section measurement with minimal check and studies.

Photon analysis

- Data set
  - Same as Minho's π⁰ AN analysis except removing low-threshold runs.
- Event selection
  - Single-photon like
  - Fiducial area selection (right figures)
- Analysis method


Fiducial area


Fiducial area
for energy scale analysis

Using full simulation

Template fit of L90% distribution

Estimate using non-colliding bunch events

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

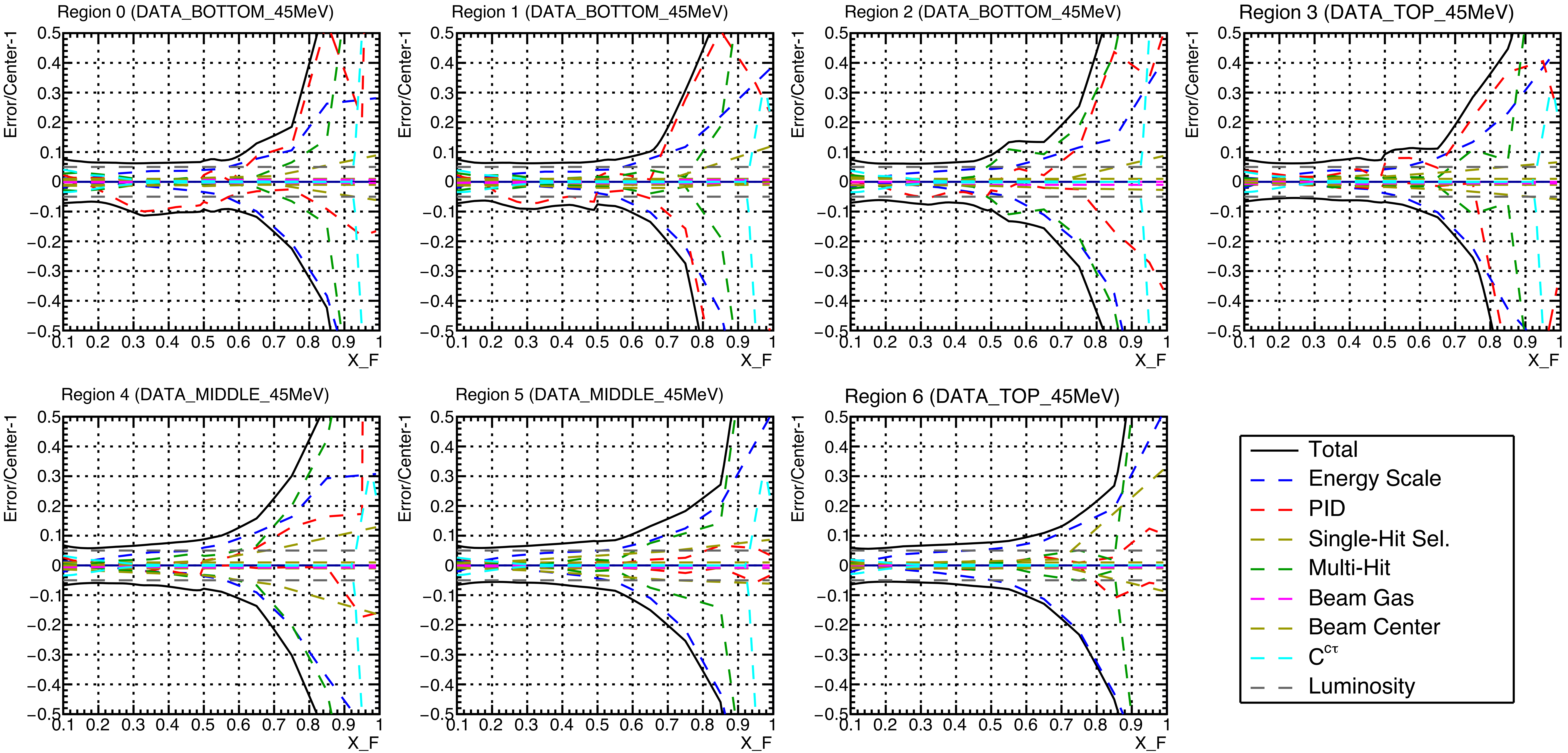
$\uparrow$

Dedicated simulation

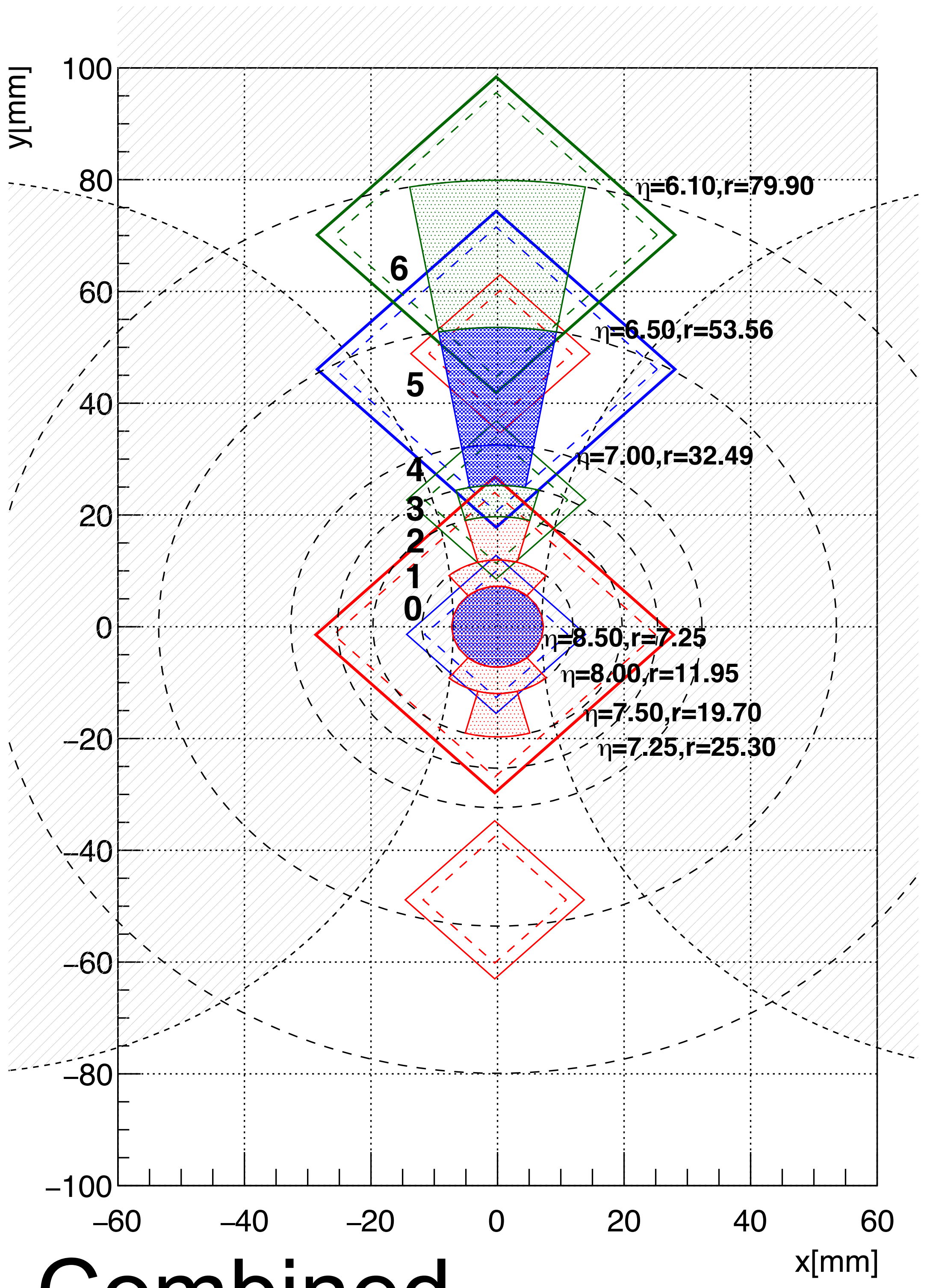
List of systematic uncertainties

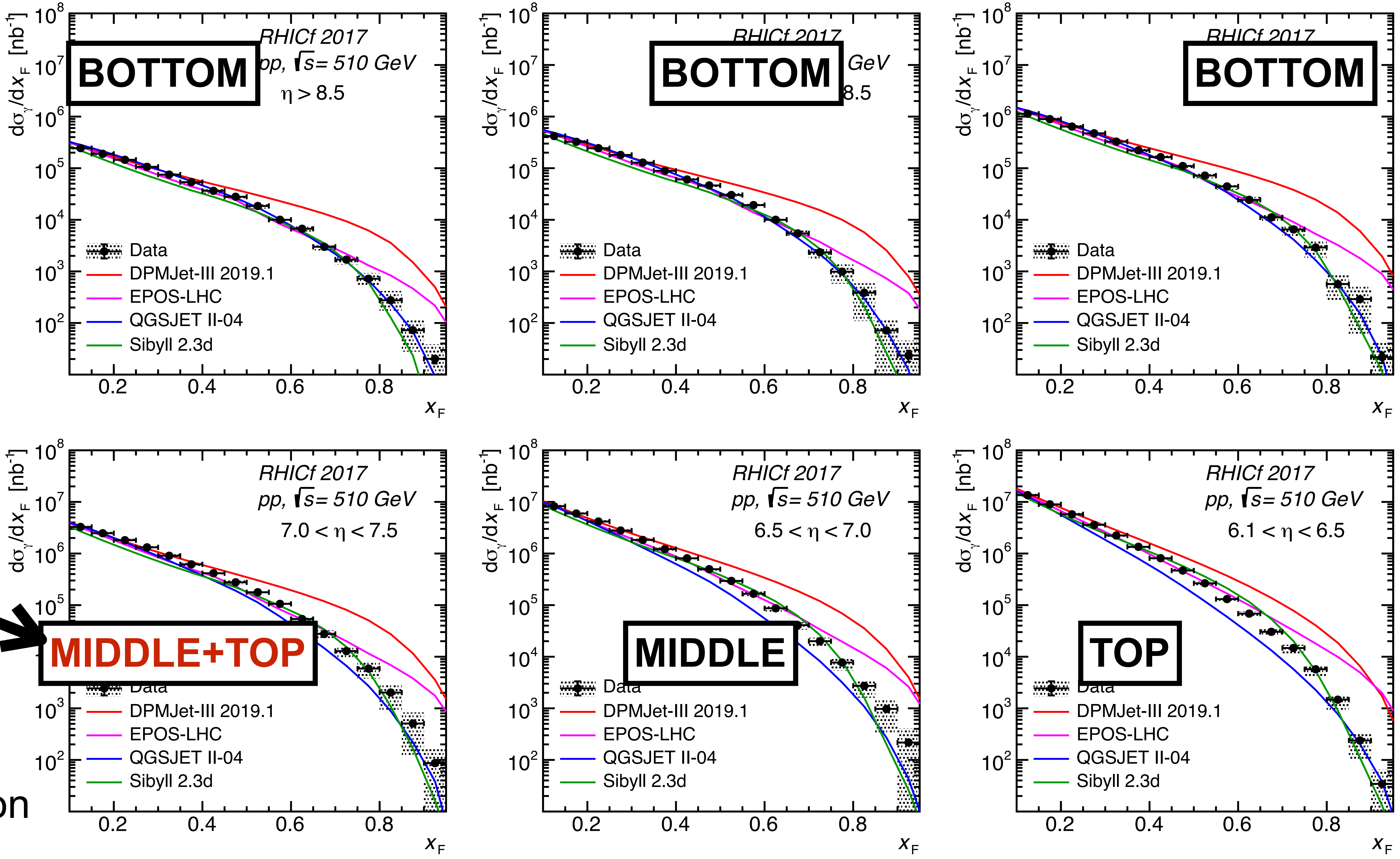
- Energy Scale
  - Stability, Non-linearity, Non-uniformity
- PID
  - Difference of L90% distribution between data and MC
- Single hit selection ± 1%
  - Estimated by LHCf using beam test data.
- Multi-hit events
  - Model dependency (QGSJET2 and EPOSLHC)
- Beam gas ~±1.5%
  - Consider photon energy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

Estimated uncertainties



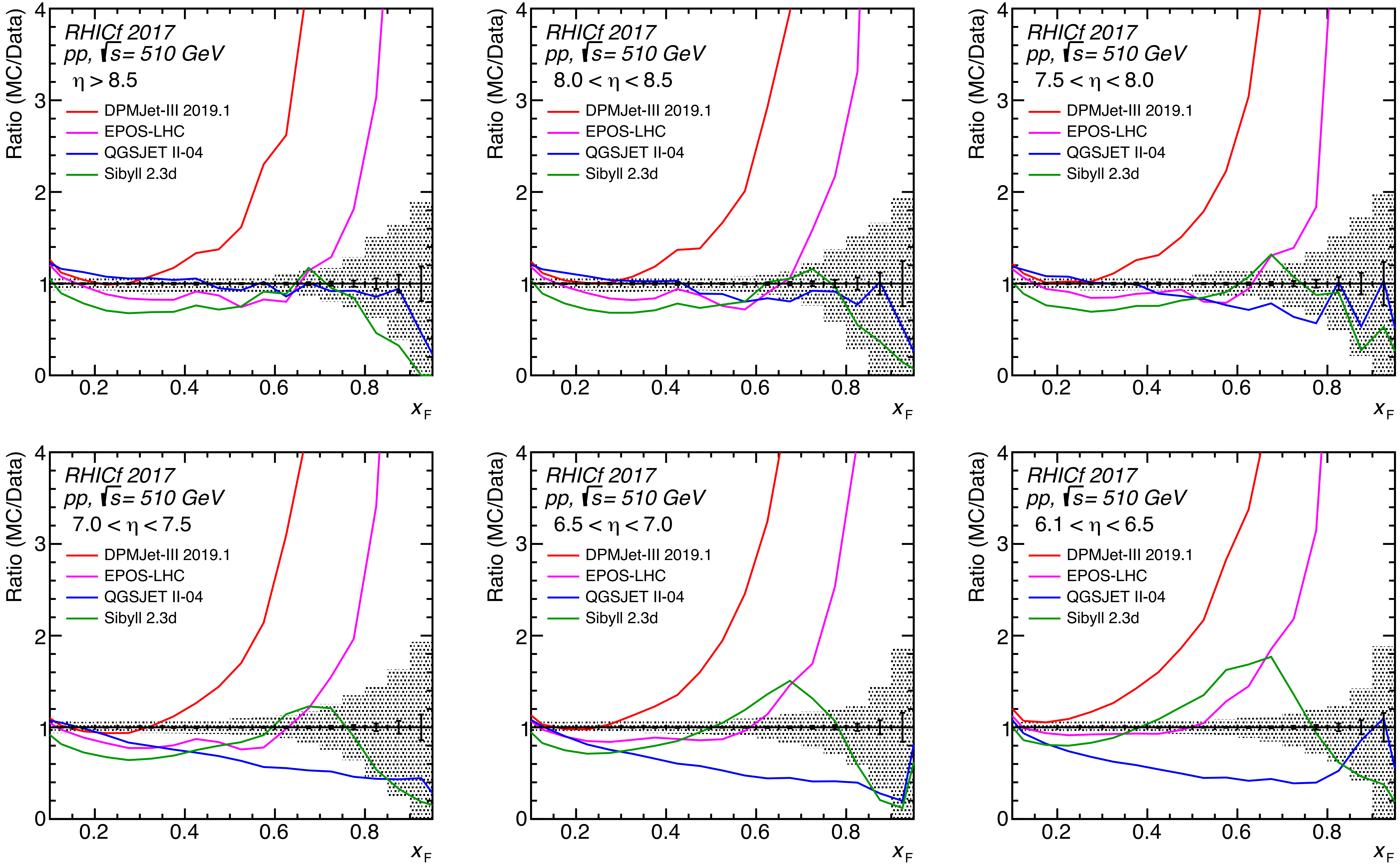
Spectra for each η bin





Combined
Two position data
(region 3 + 4)
stat. → quadratic sum
syst. → simple sum
considering correlation

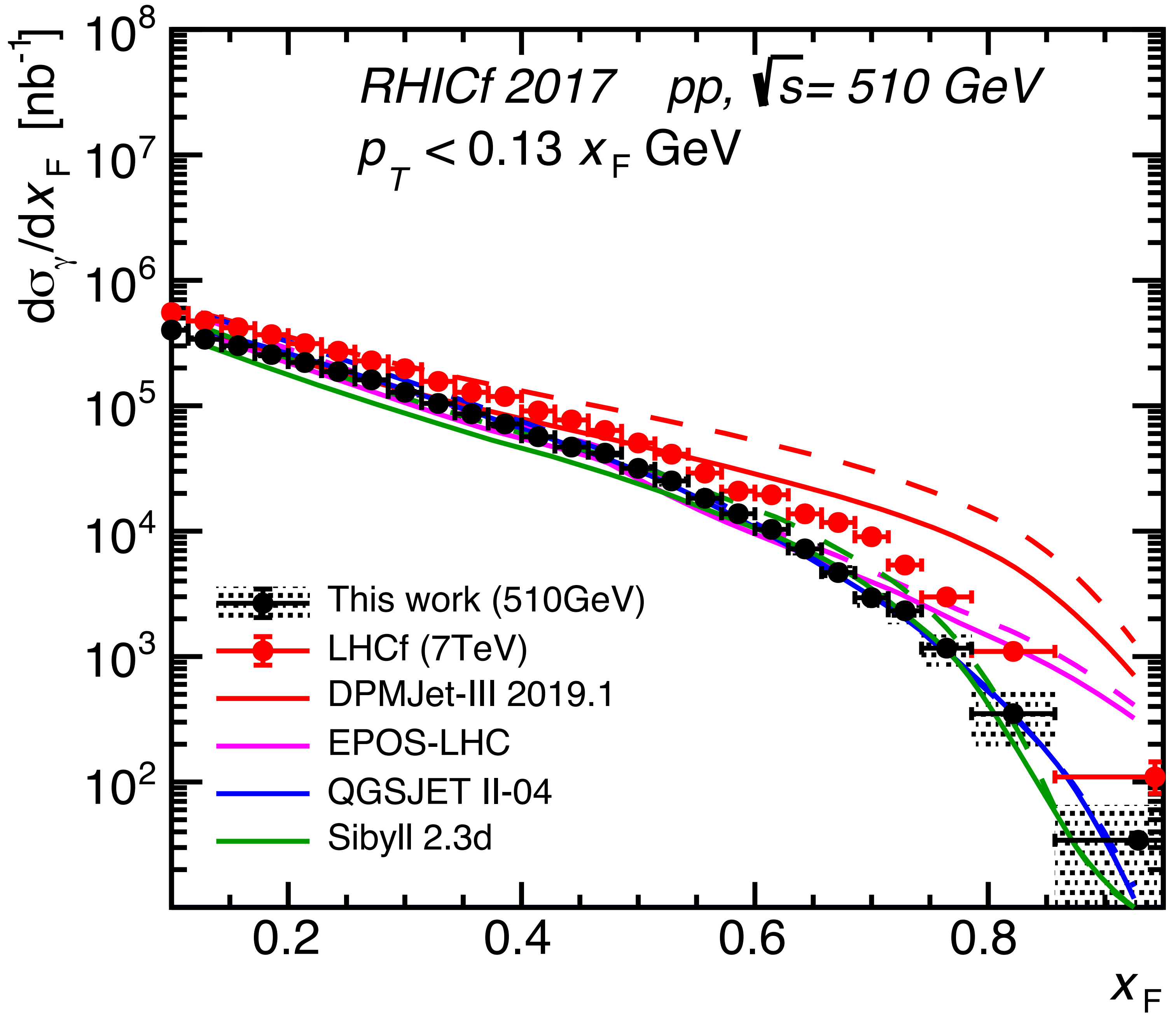
Ratio (MC/Data)



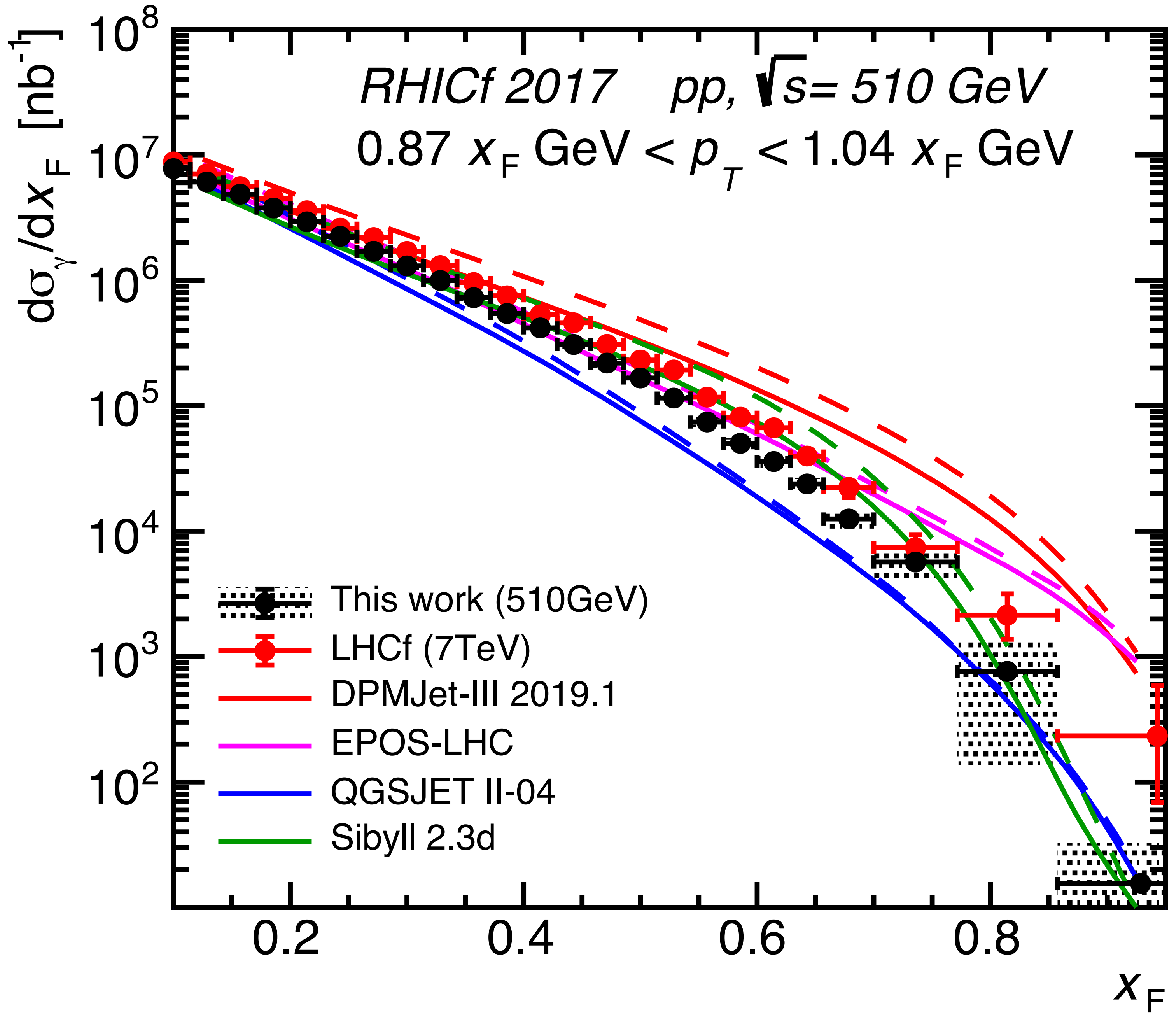
Test of collision-energy dependency

- Comparison with LHCf (7TeV and 13 TeV) photon results.
- Same X_F-p_T phase space coverage.

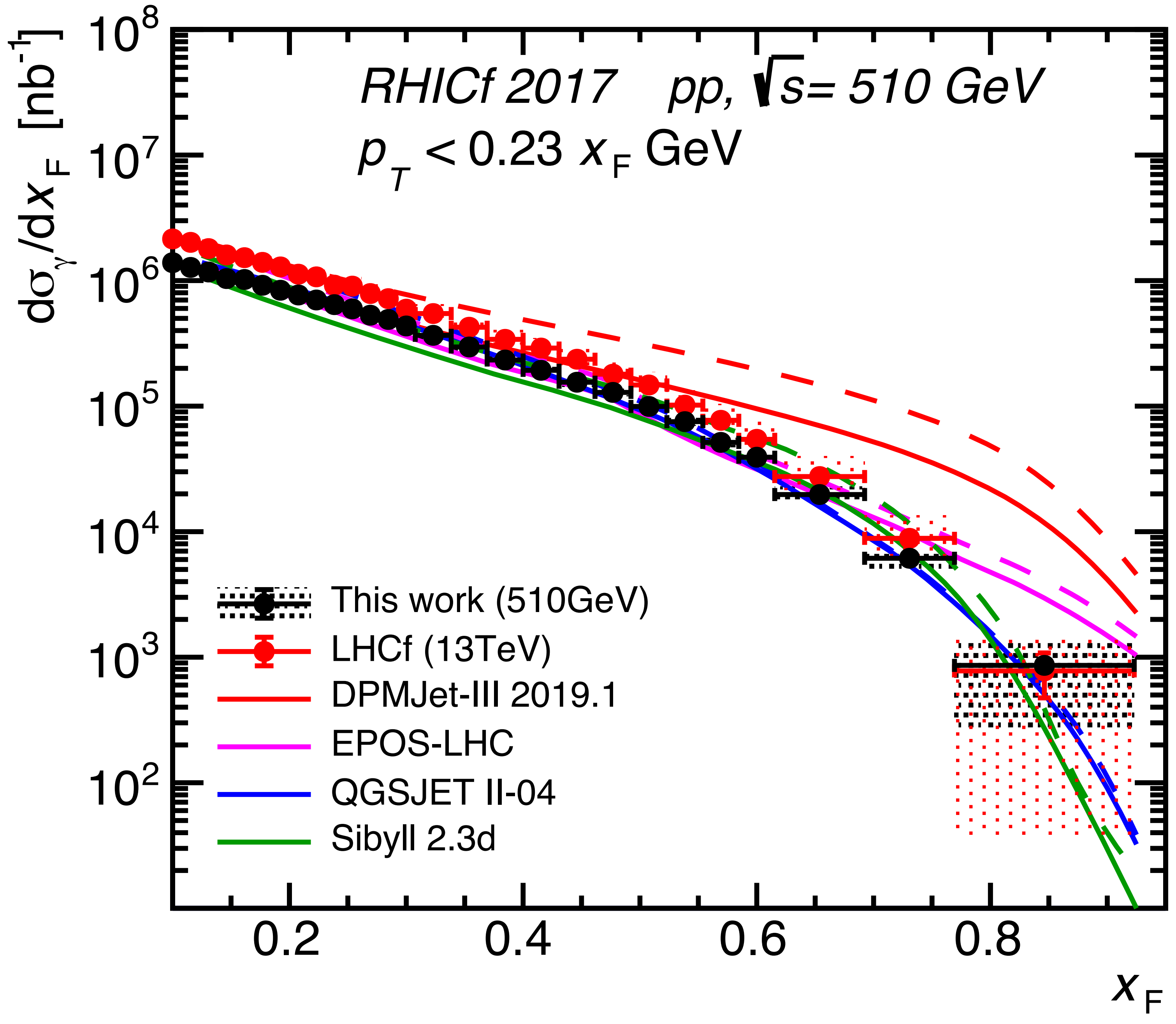
v.s. LHCf 7TeV η > 10.94



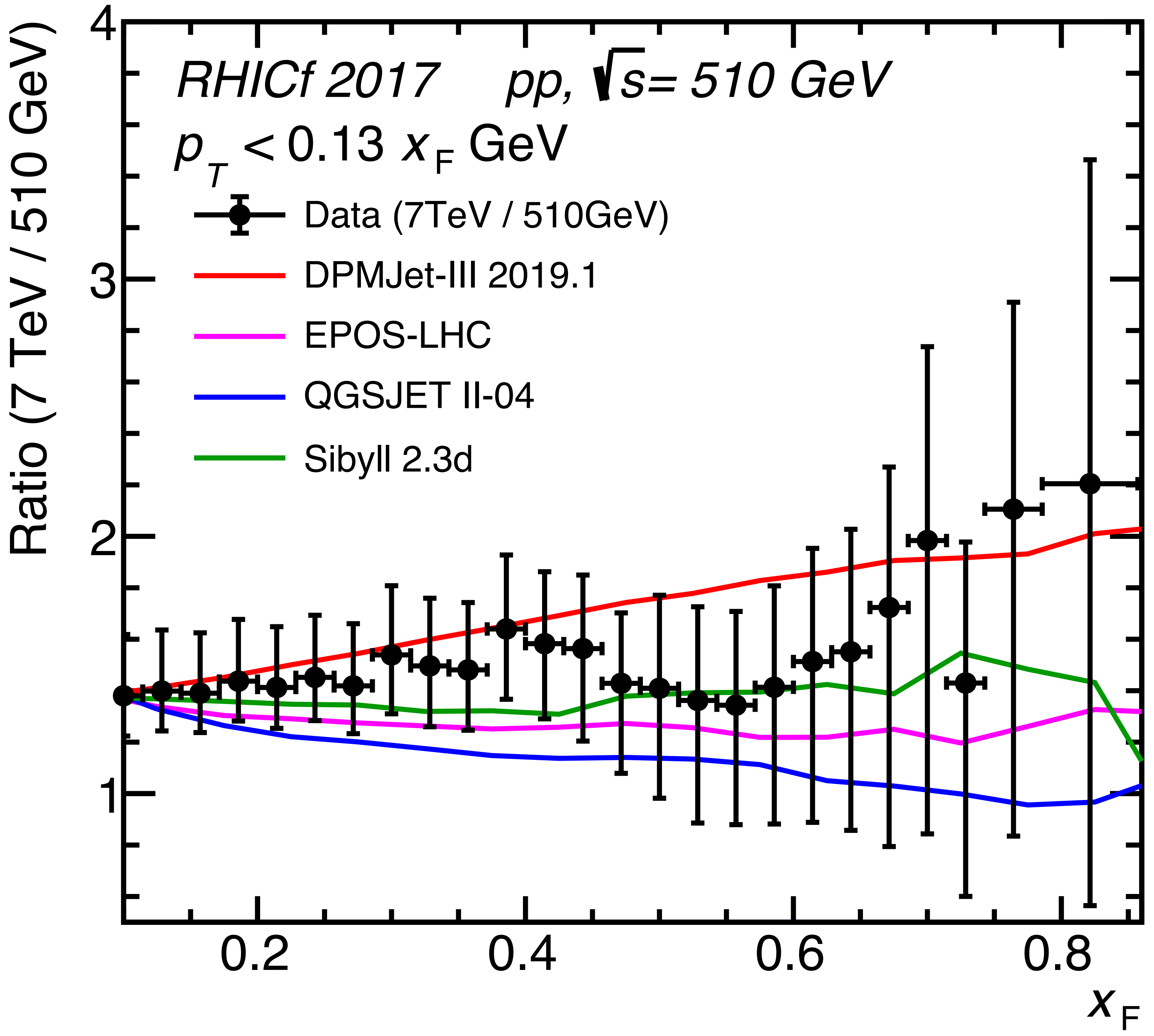
v.s. LHCf 7TeV 8.81 < η < 8.99

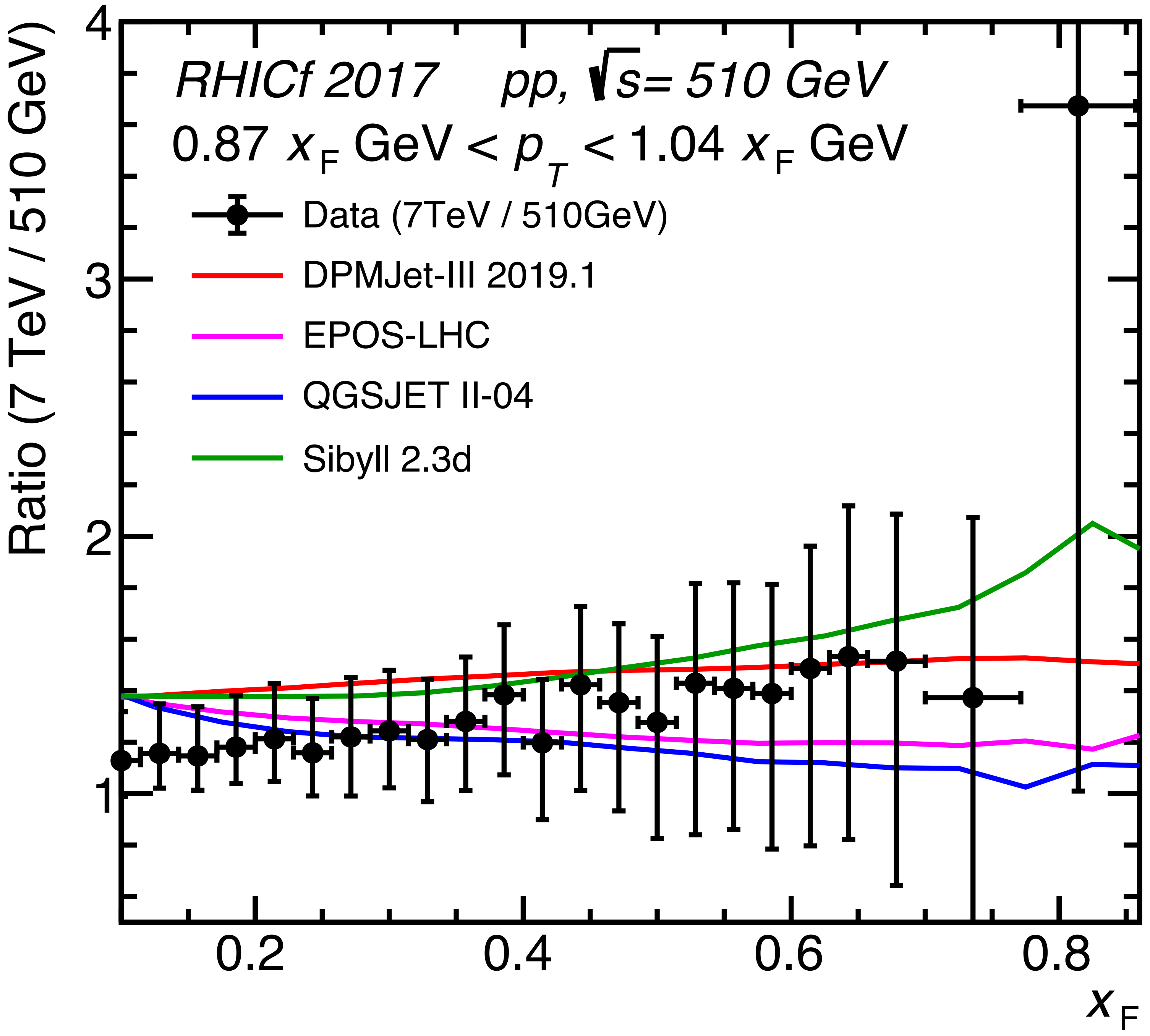


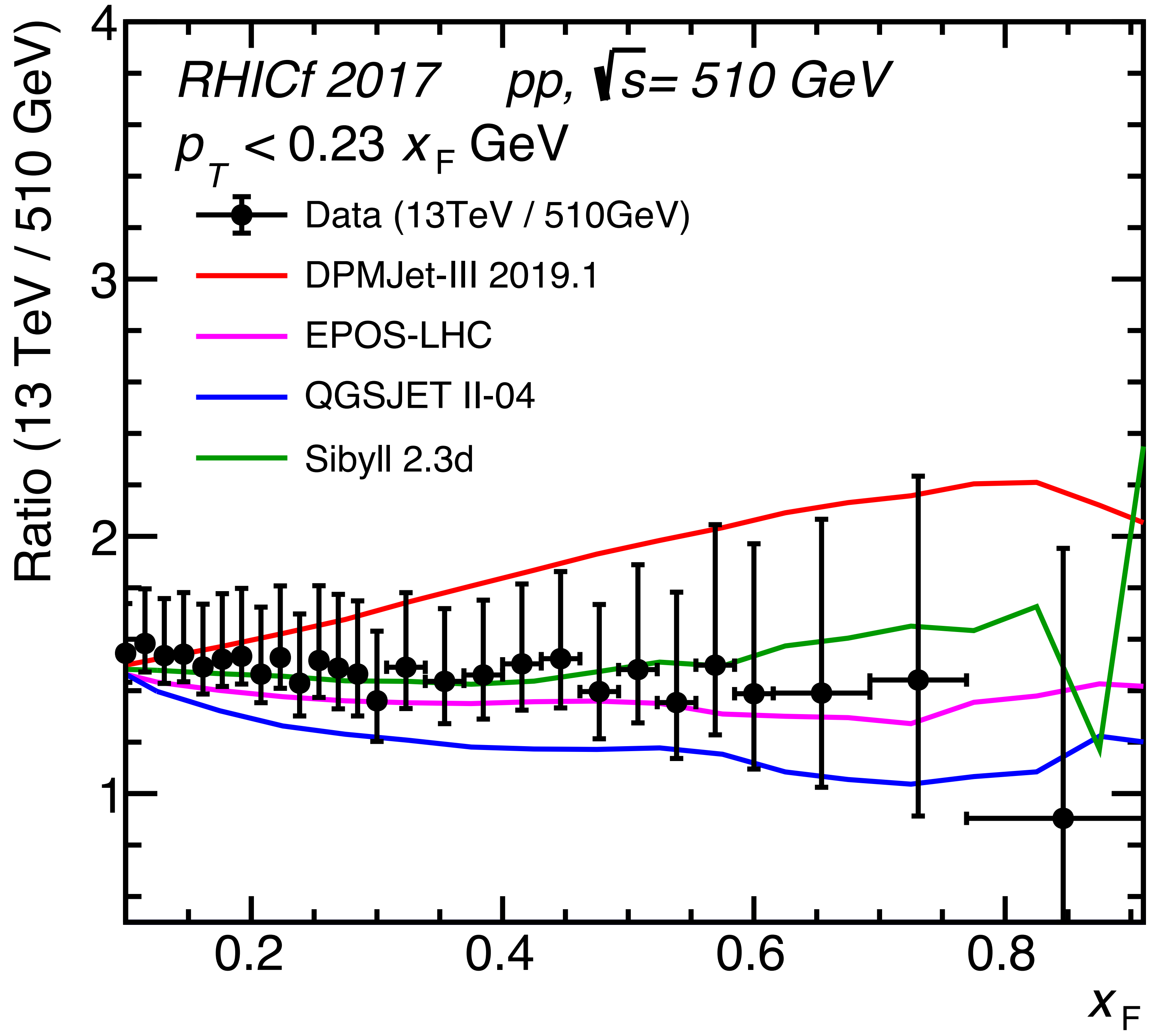
v.s. LHCf 13TeV η > 10.94



Ratio (7TeV or 13TeV/ 510GeV)







Quadratic sum of LHCf and RHICf errors
LHCf syst error dominant except high energy bins.

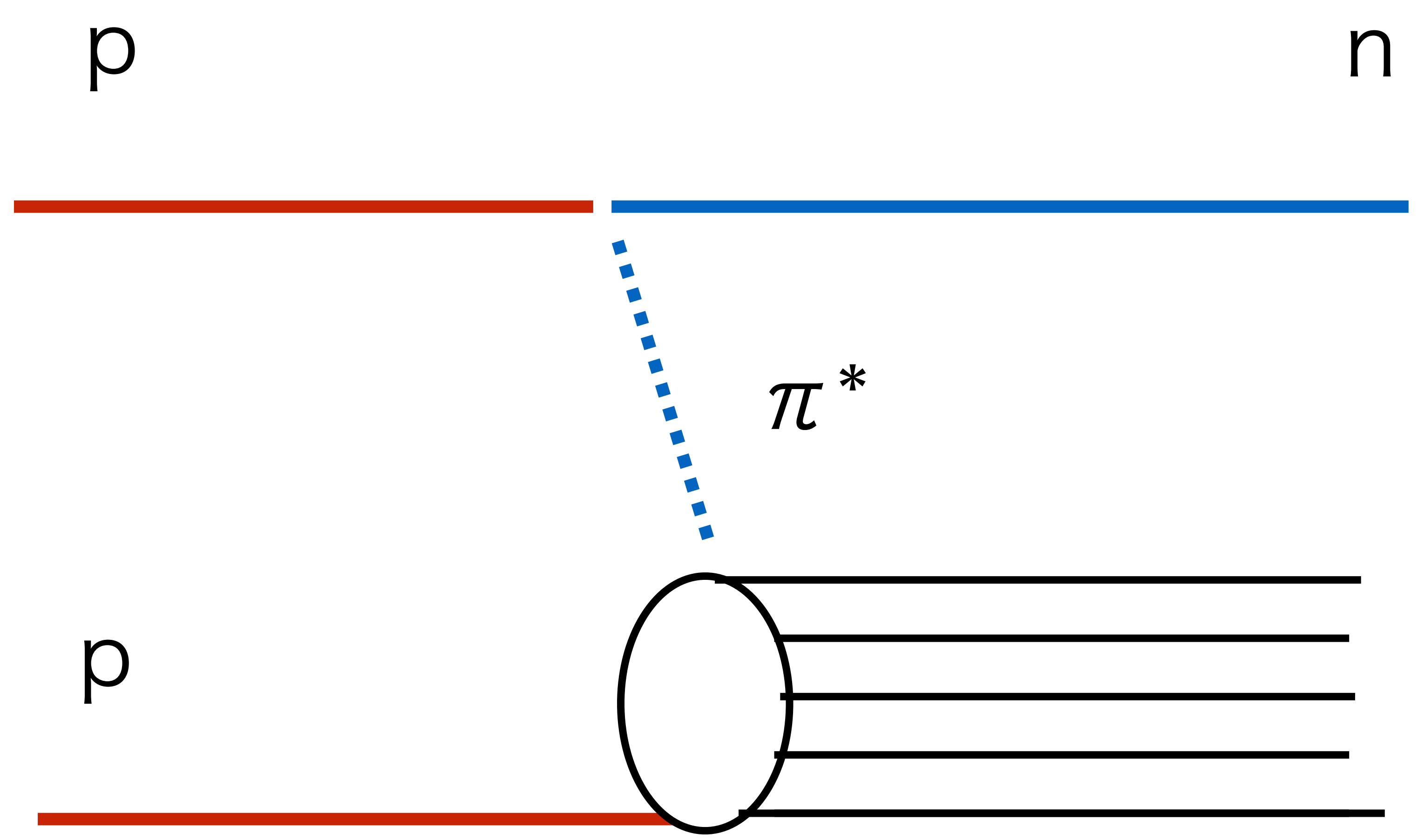
First confirmation of collision-energy dependency at zero degree photons.
No sensitivity to test the hadronic interaction model due to large error.

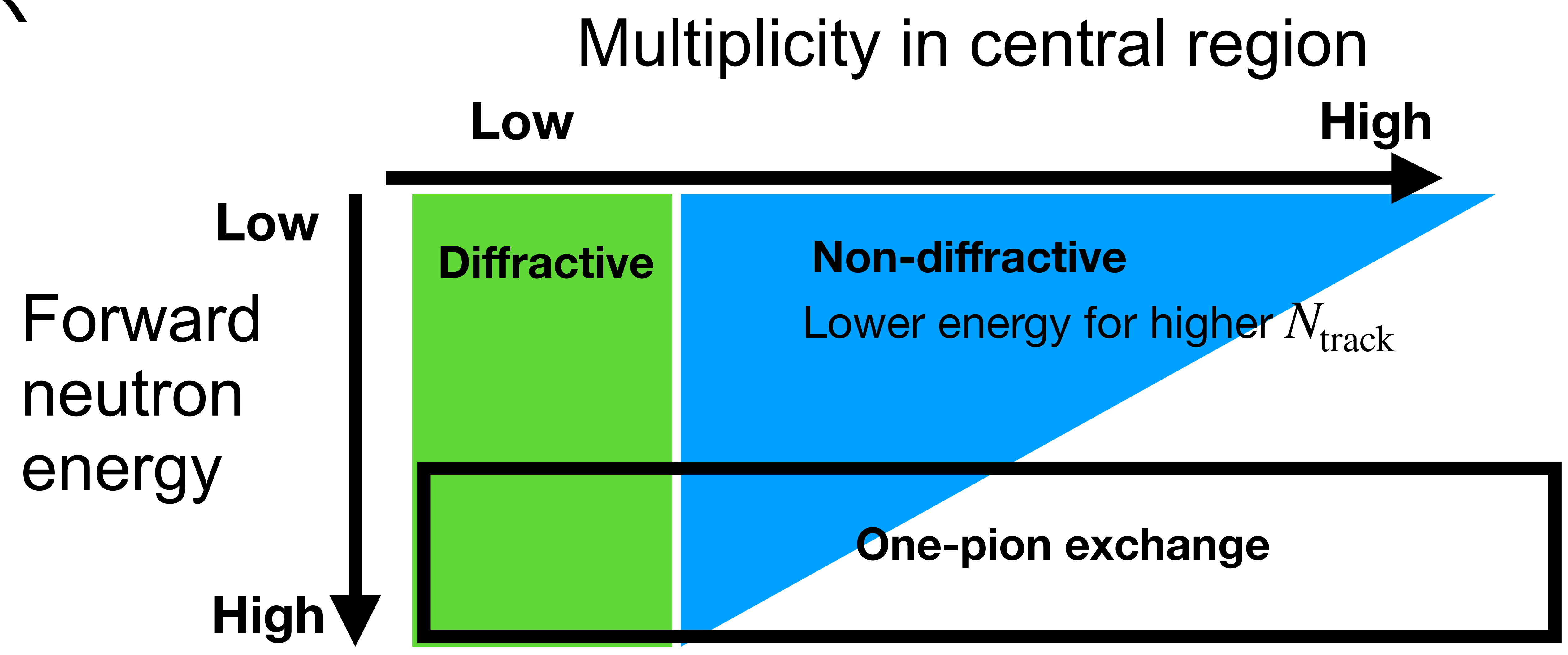
Prospects

- Joint analysis with STAR
- RHICf2 operation

Physics cases

- Central (STAR) - Forward (RHICf) correlation
  - Studies of diffractive collisions
    - → Require no-track or large rapidity gap in STAR
    - → Measure particles in RHICf for studying very-low mass diffractive
  - Study of MPI modeling
    - → Estimate number of MPIs from STAR tracks
    - → Measurement of beam remnant (high energy neutron) in RHICf
  - p-π collision via One-Pion exchange
    - → Event selection with high energy neutrons in RHICf
    - → Measure the multiplicity in STAR




Multiplicity in central region

Low → High

Forward neutron energy

Low ↓ High

Diffractive

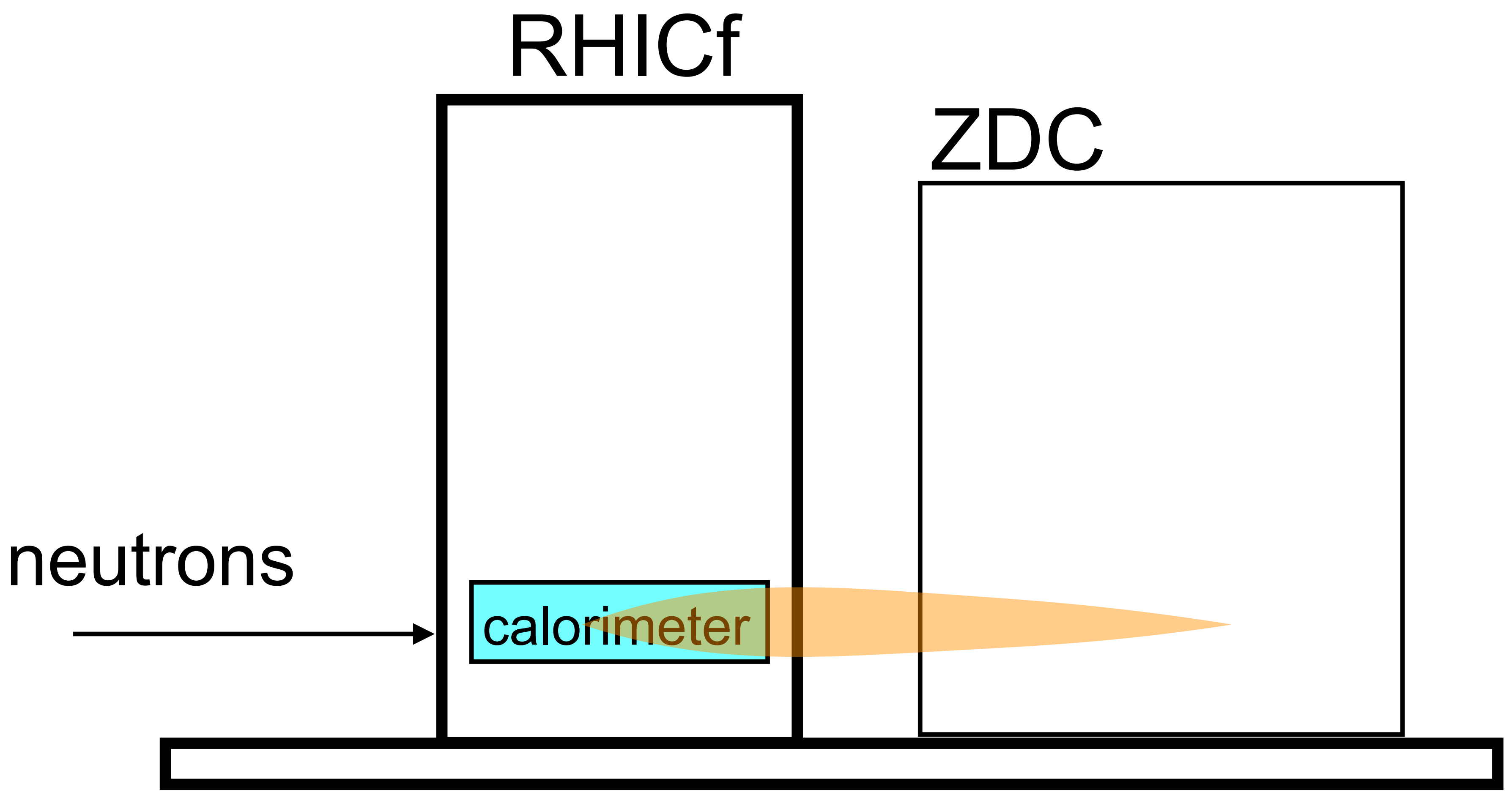
Non-diffractive

Lower energy for higher N_{track}

One-pion exchange

Physics cases

- Forward (STAR-ZDC) - Forward (RHICf)
  - Improvement of neutron measurement
    - Good energy resolution: 20% (⇔ RHICf only 40%)
    - Good position resolution: < 1mm (⇔ ZDC only 1cm)



- Forward (STAR-RomanPot) - Forward (RHICf)
  - Detail study of single diffractive interaction
    - Measurement of ξ by RP
    - Measurement of dissociation in RHICf
  - Measurement of resonances
    - Δ resonance → p in RP + π^0 in RHICf

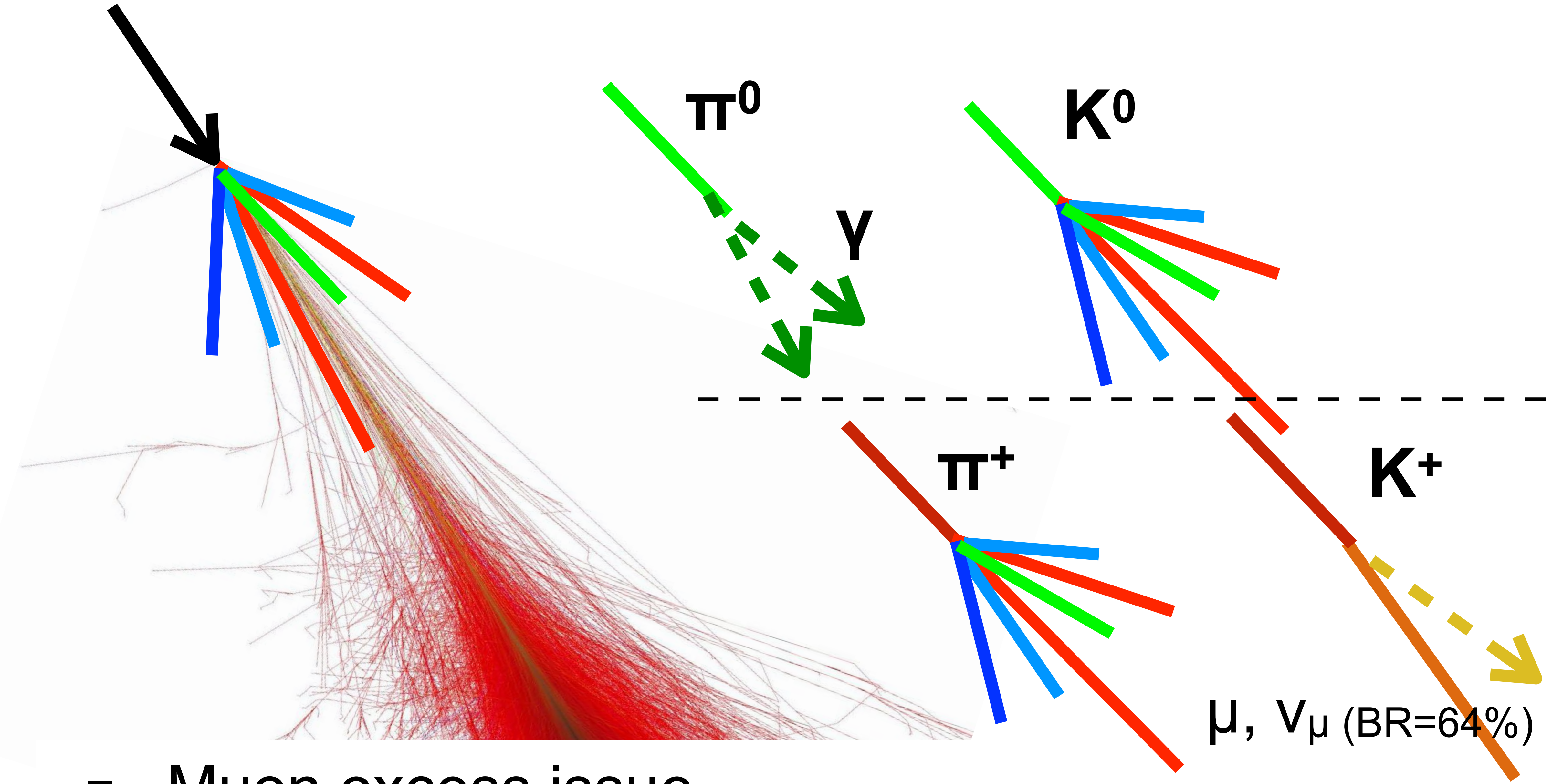
Target of RHICf II

- Increase statistics of high-X_F π^0
- Measurement of strange hadrons at 0 degree
  - $K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$ (B.R. 30.7%)
  - $\Lambda \rightarrow n+\pi^0 \rightarrow n+2\gamma$ (B.R. 35.9%)

- p + A collisions
  - A-dependence of A_N
    - Strong A-dependence of Neutron by PHENIX (Pays. Rev. Lett 120, 022001 (2018))
    - A-depedence of very forward π^0
  - p + light ion collisions for Cosmic-rays
    - Ideal condition for CR-Air interaction studies

Motivation of K0s, Λ measurement

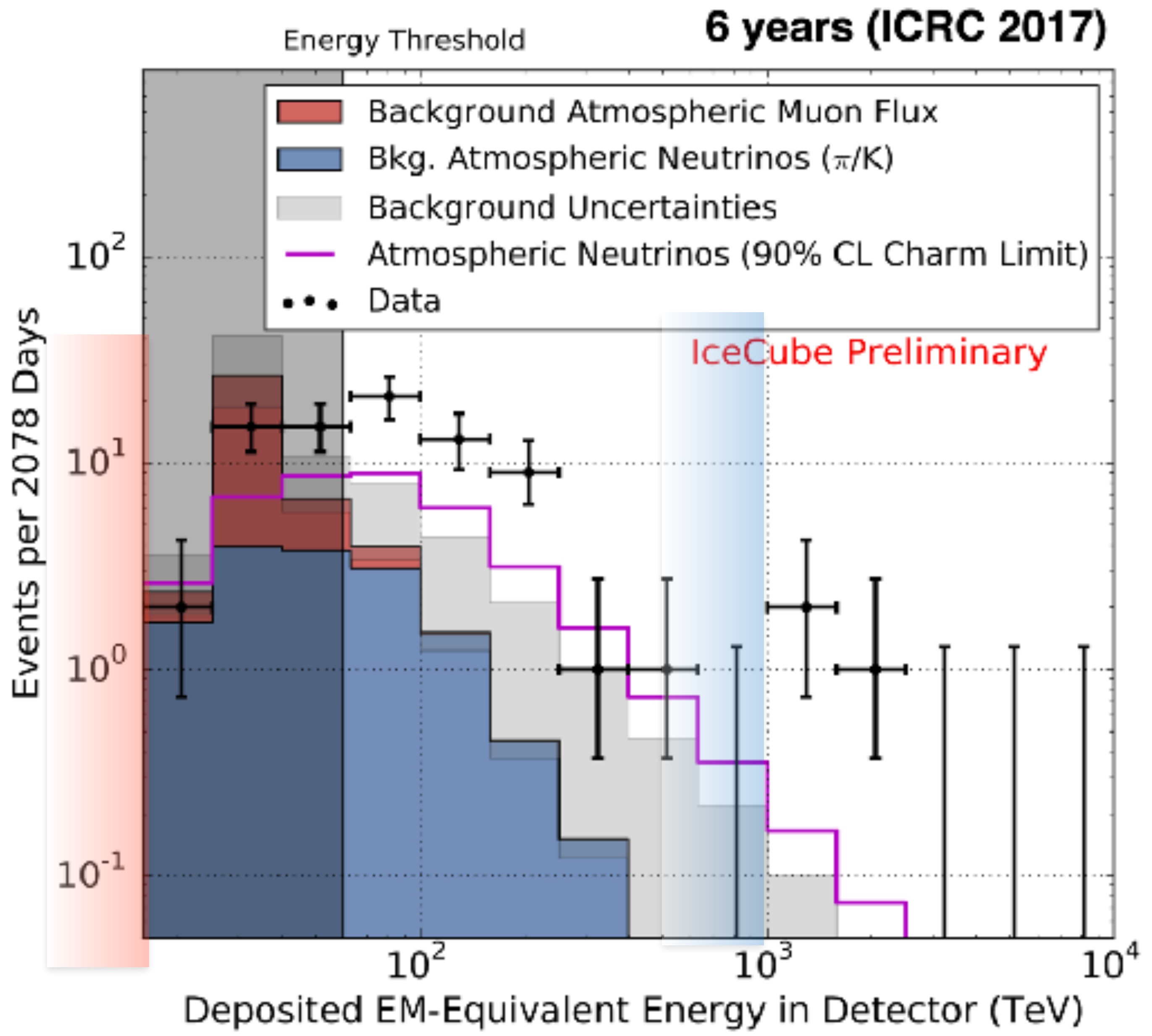
Impact on air shower development



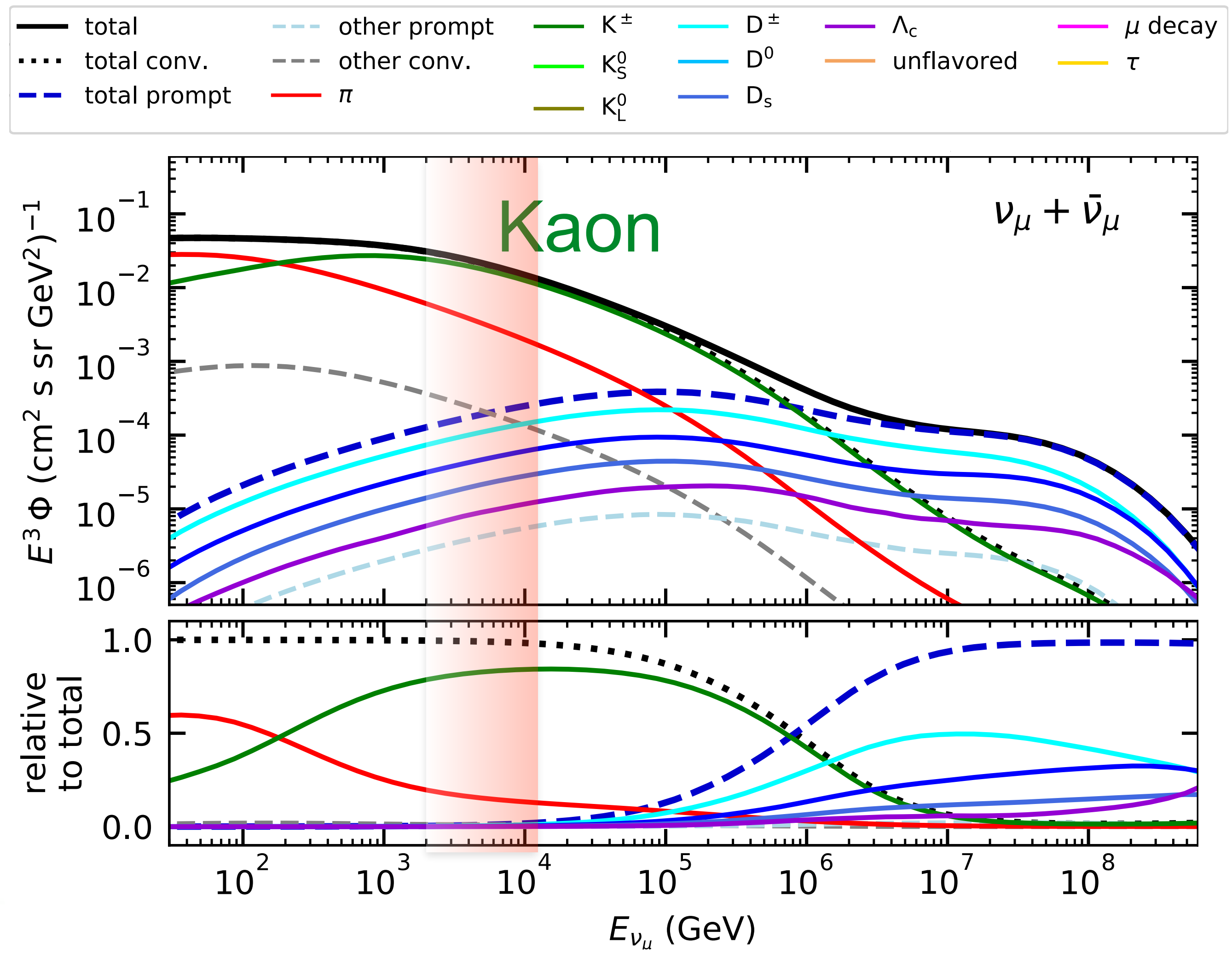
- Muon excess issue
  - ☐ If higher Kaon production in high energy → increase the muon number on the ground.
    A high energy π^0 decays immediately
    →EM component,
    A high energy K^0 collides air before its decay
    → Hadronic component
  - ☐ Large K/π ratio in QGP
- Impact on atmospheric ν flux (next page)

For neutrino physics

- ☐ Hot topics: Astro-neutrino detection by IceCube
- ☐ large uncertainty on background estimation of Atm. ν
- ☐ Kaons are dominant source of ν_μ in E_ν <~ 10^{15}eV



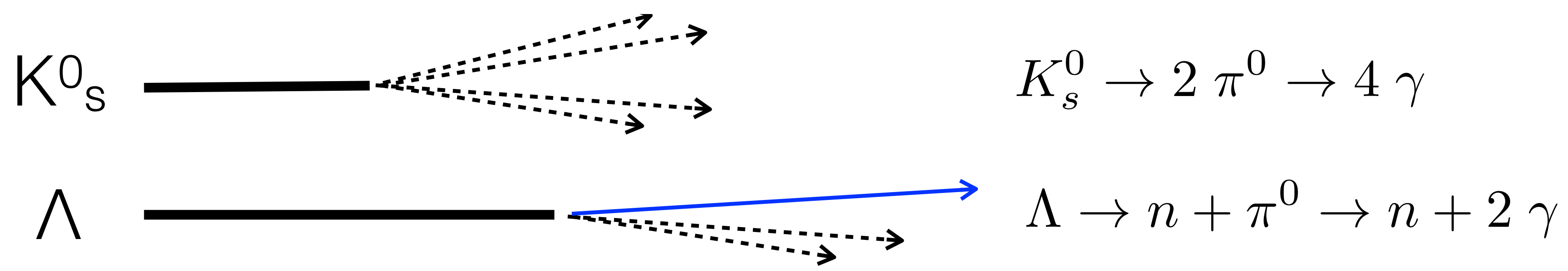
Atmospheric ν_μ flux



Not only for astro-neutrino but also for accelerator neutrino physics (FASER, SND)

Sensitivity of K0s, Λ measurement by RHICf II

- 4 γ for K^0_s and n+2γ for Λ detection simultaneously



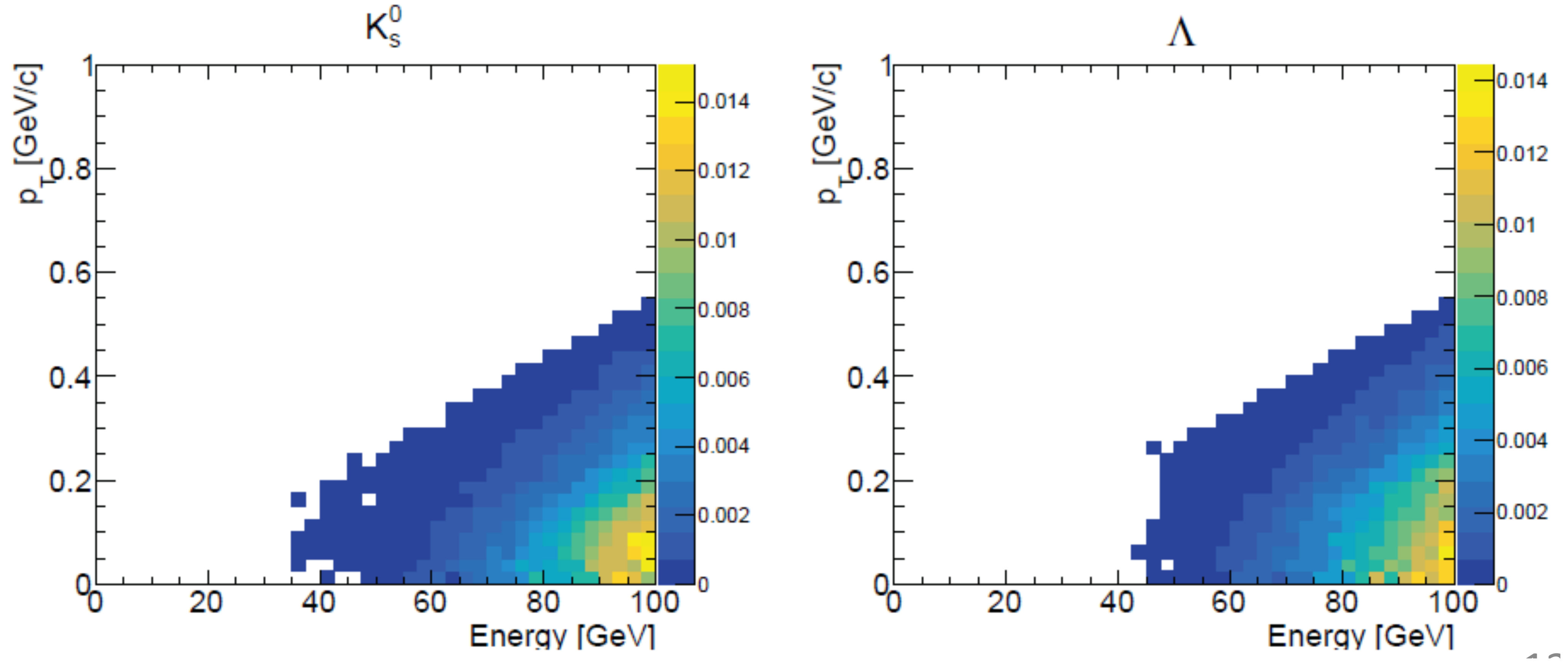
$K_s^0 \to 2\,\pi^0 \to 4\,\gamma$

$\Lambda \to n + \pi^0 \to n + 2\,\gamma$

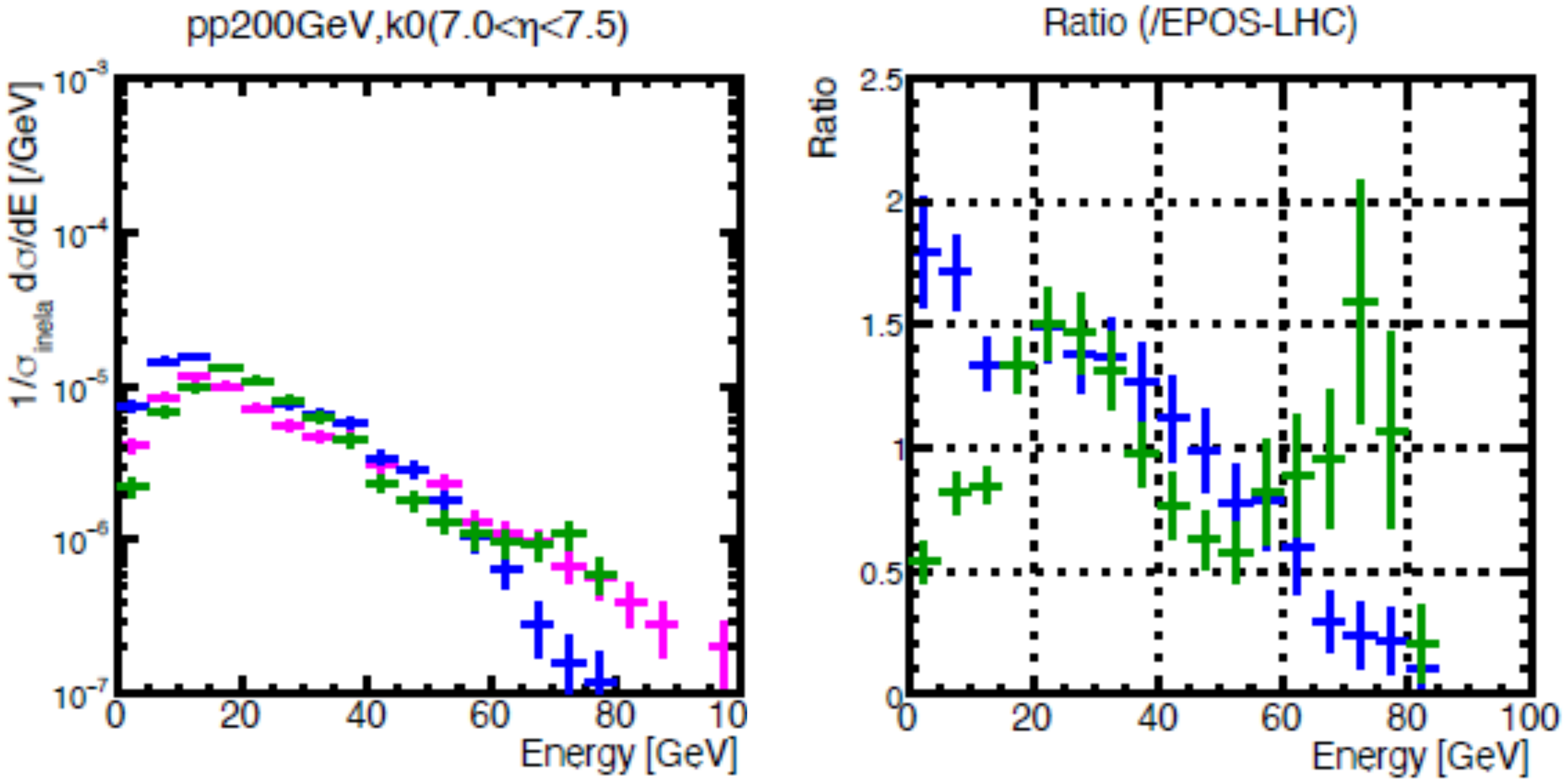
- Wide acceptance
- Fine segmentation

RHICf 👍

- Geometrical accettante



Model predictions



- To-Do
  - Study using pp collision MC
    - estimation of expected background (combinatorial background)
  - Trigger development

Backup

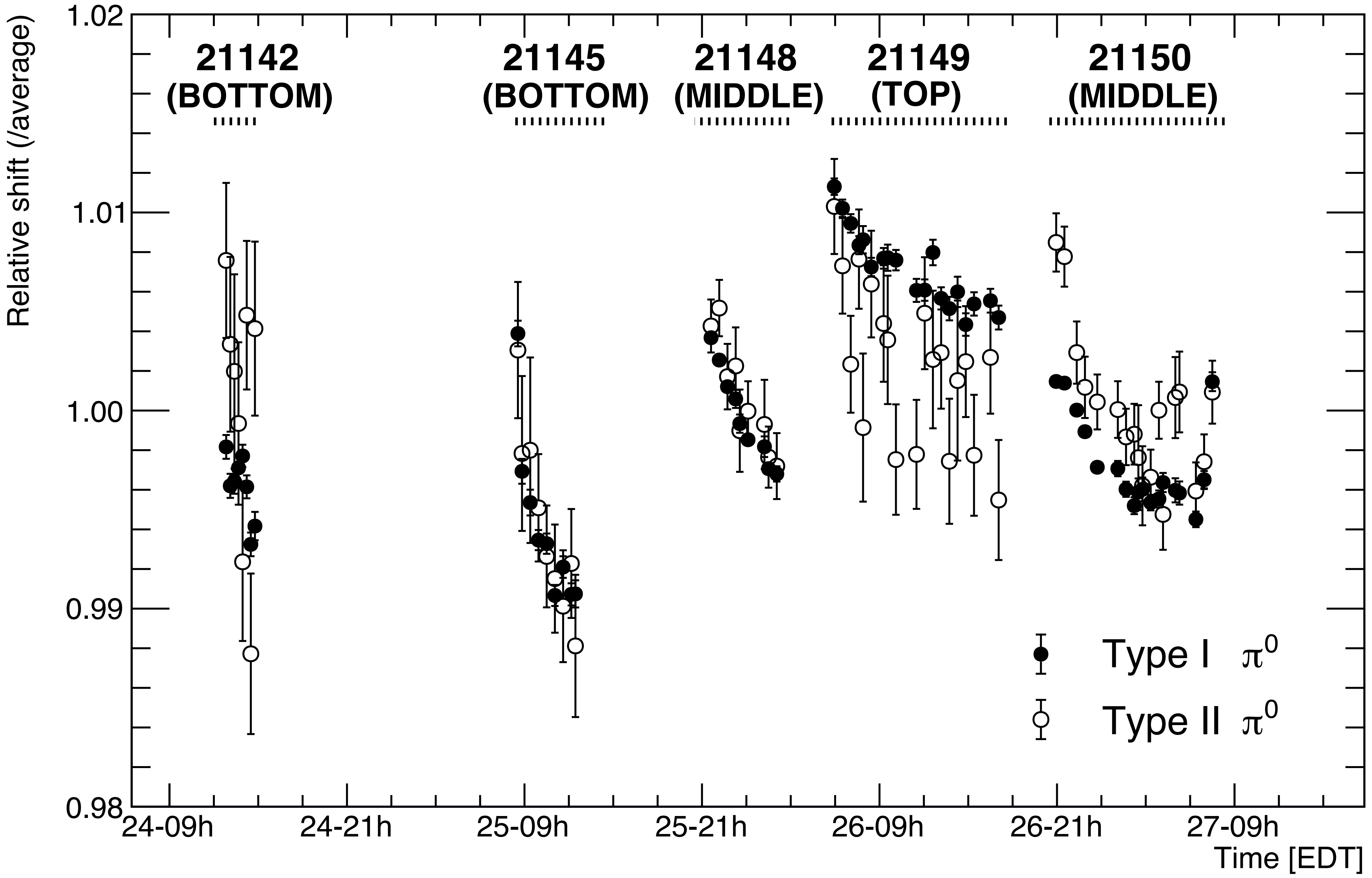
Systematic Uncertainties of photon results

List of 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%

1. Energy Scale

- Sources of energy scale errors
  - ☐ Overall energy scale calibration by pi0 mass peak
    → Negligible
  - ☐ Stabilities of energy scale during the operation
    → Estimated by Pi0 mass peak: ΔE/E = ± 1%
    (see performance paper)



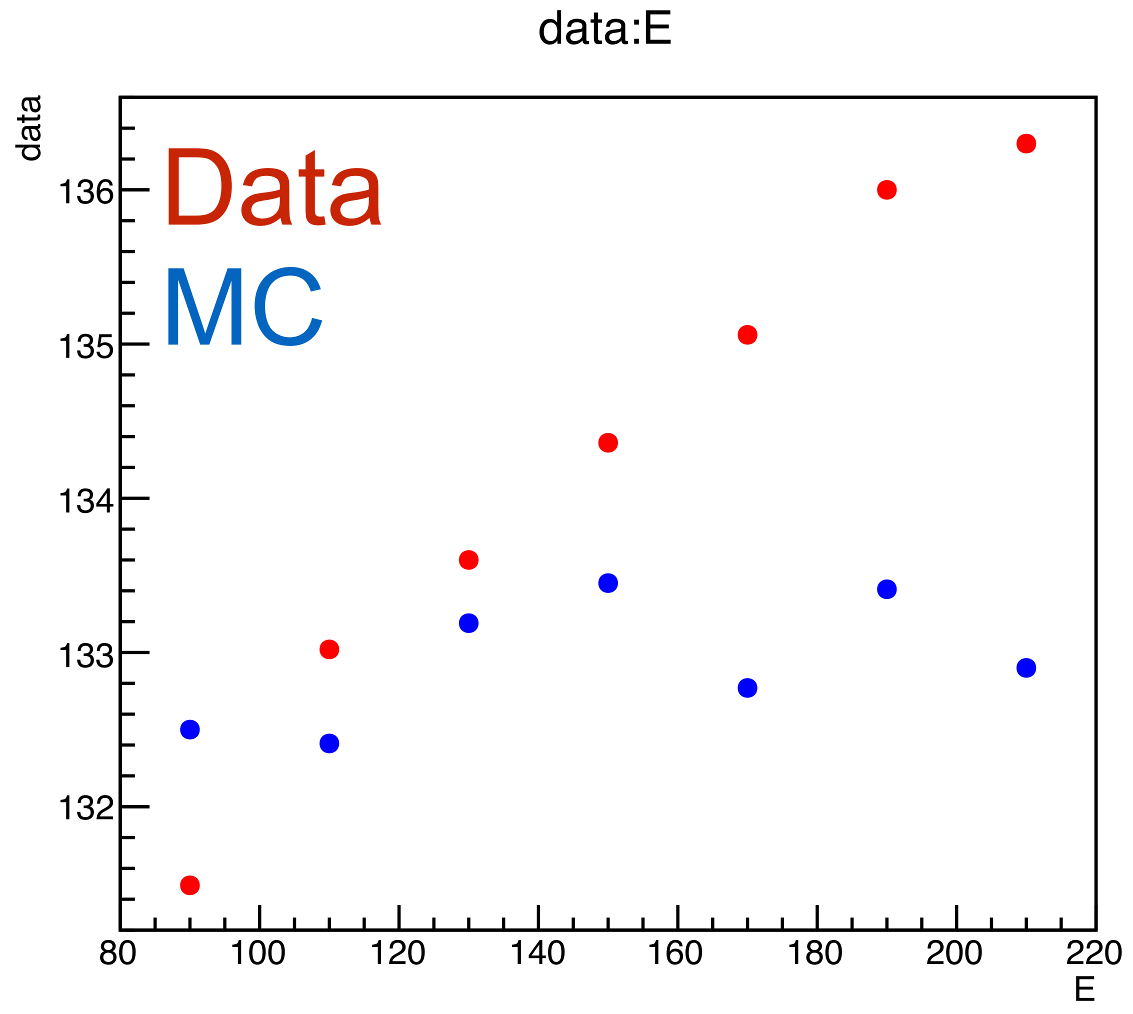
  - ☐ Non-linearity
    → Pi0 mass peak shift as a function of energy (discuss in the next slide)
  - ☐ Non-uniformity
    → found in the consistency check (discuss in the next next slide)

1. Energy Scale: Non-linearity

- Pi0 mass peak shift

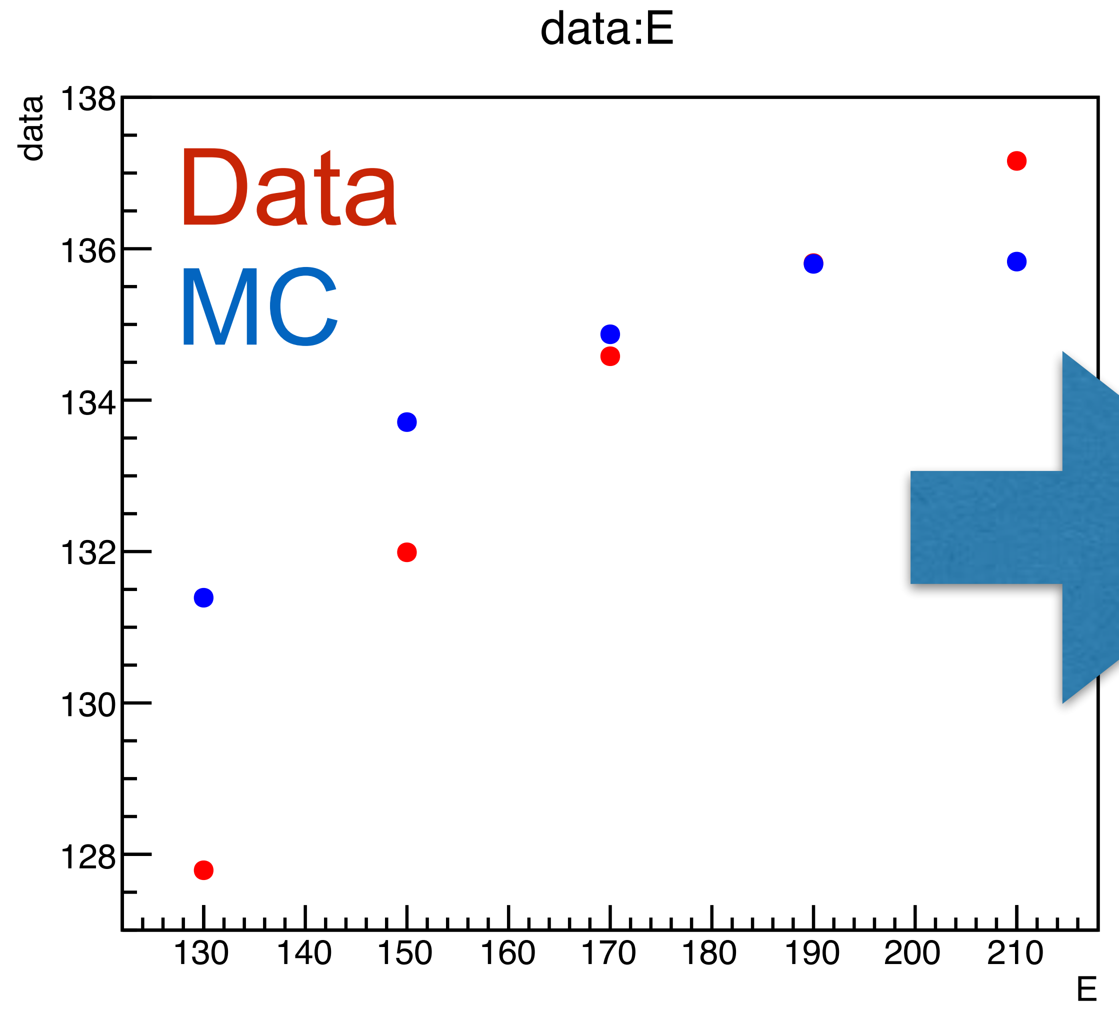
Peak Mass [MeV]

Type1 Pi0



Pi0 Energy

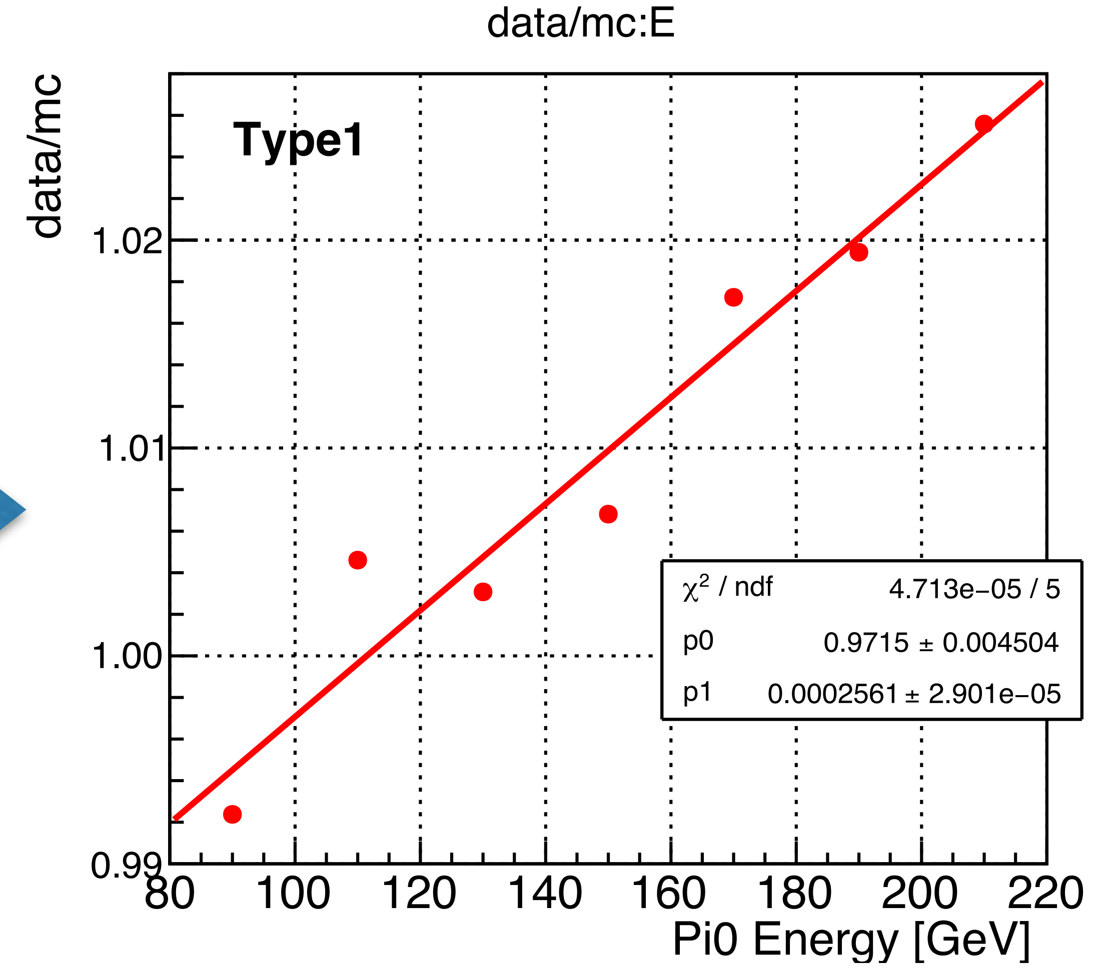
Type2-TL Pi0



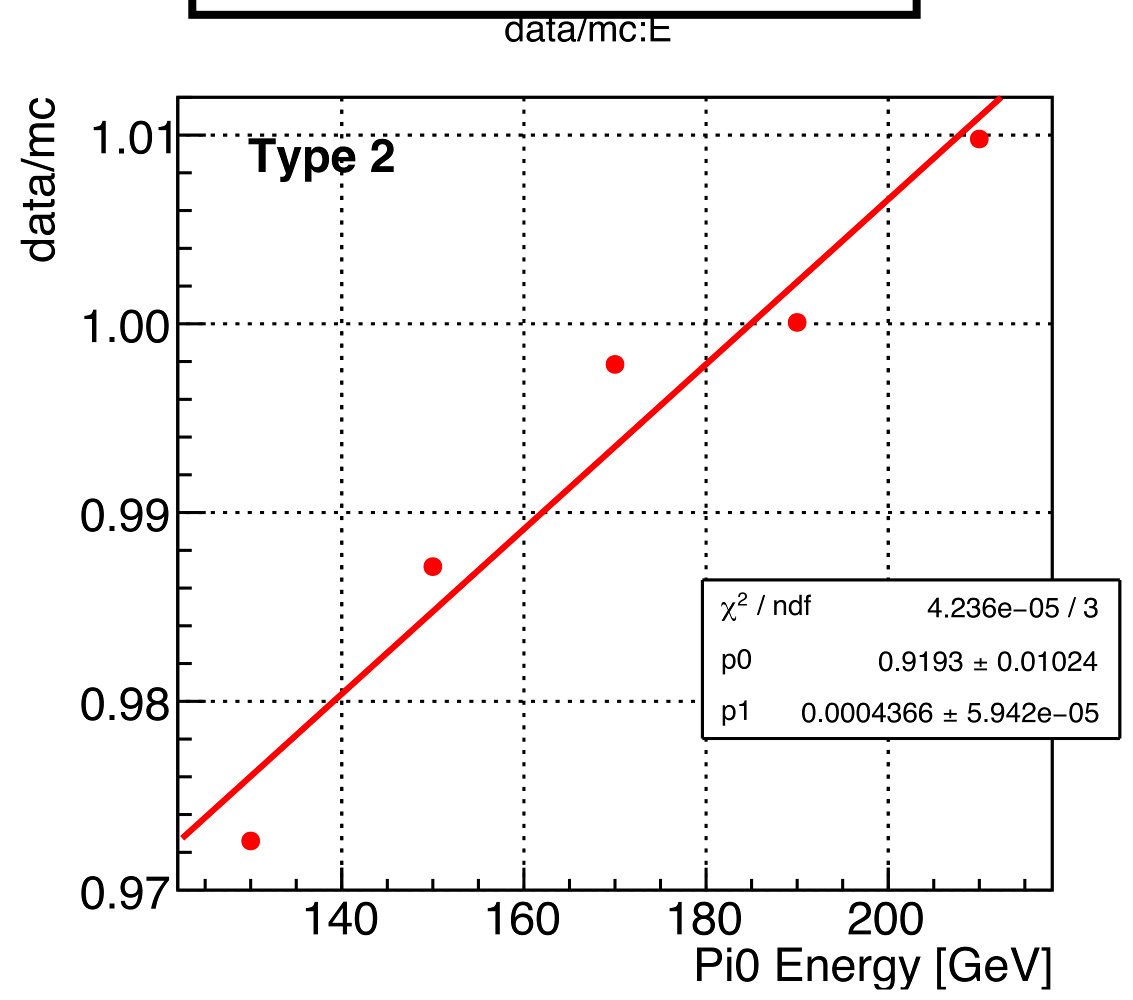
Pi0 Energy

Data/MC

Type1 Pi0



Type2-TL Pi0

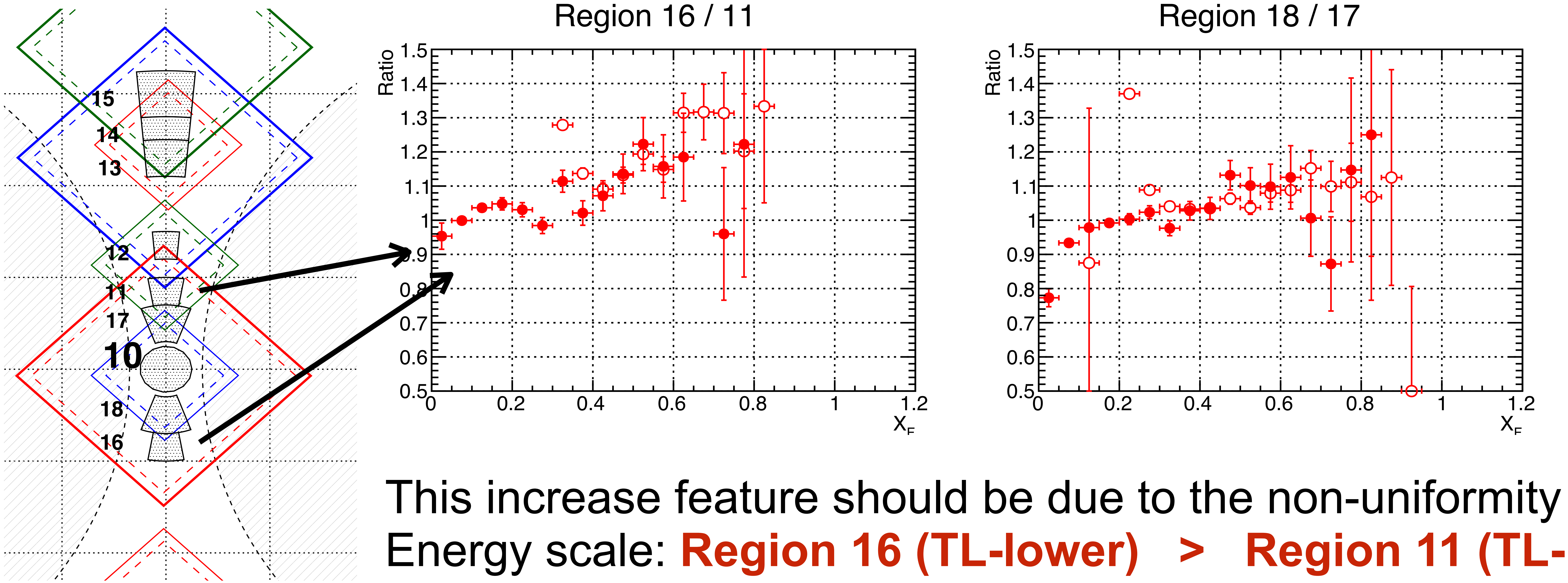


- Data/MC represent the non-linearity of the data
  → Fit by a linear function to make the model.
  Type 1: 0.97 + 2.6% E/100GeV
  Type 2: 0.92 + 4.4% E/100GeV

Too much !! It is not compatible with Type1.
Light attenuation in GSO bar may affect it.
Take only the model of Type1 for syst. study

1. Energy Scale: Non-Uniformity (1)

- Non-linearity found in comparison of spectra

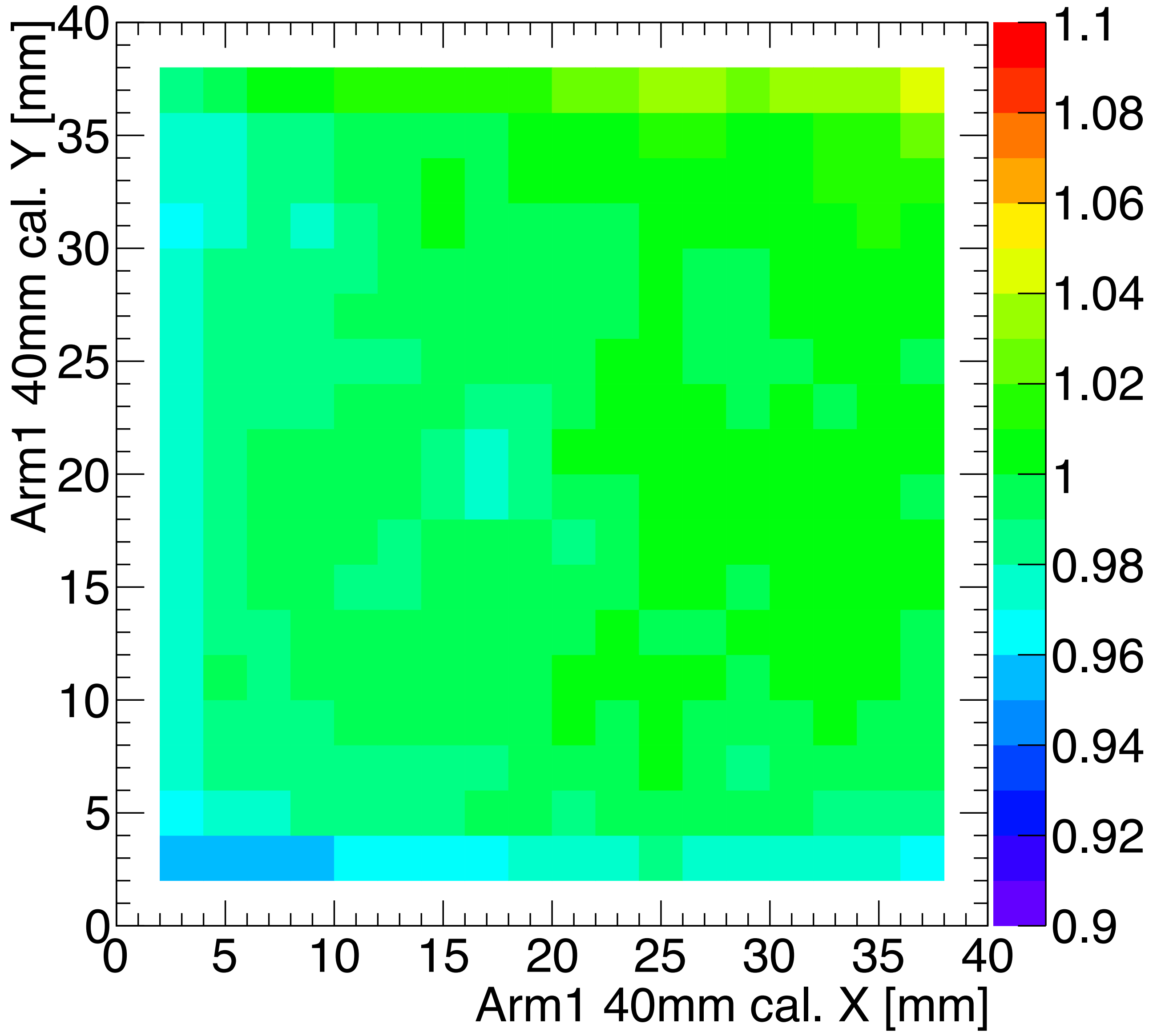


This increase feature should be due to the non-uniformity of energy scale

Energy scale: **Region 16 (TL-lower) > Region 11 (TL-upper)**

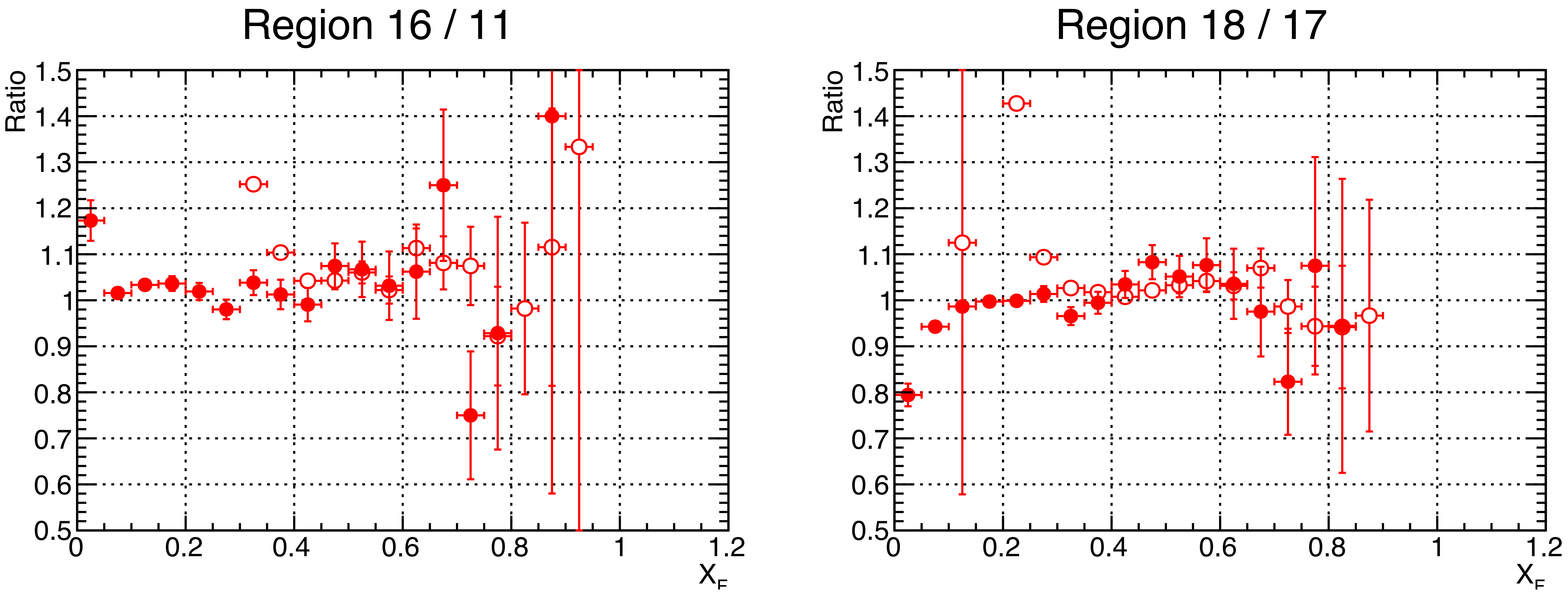
1. Energy Scale: Non-Uniformity (2)

- Detector uniformity has been tested using beam test data (Makio et al. *JINST* **12** P03023)



Uniformity map tested with 150GeV electron beam
=> **TL-lower < TL-upper**
Opposite direction to the expected by RHICf data.

However if apply the inverse of map: +3% → -3% to RHICf data, the Region 16/11 became flat !! But **why ??**

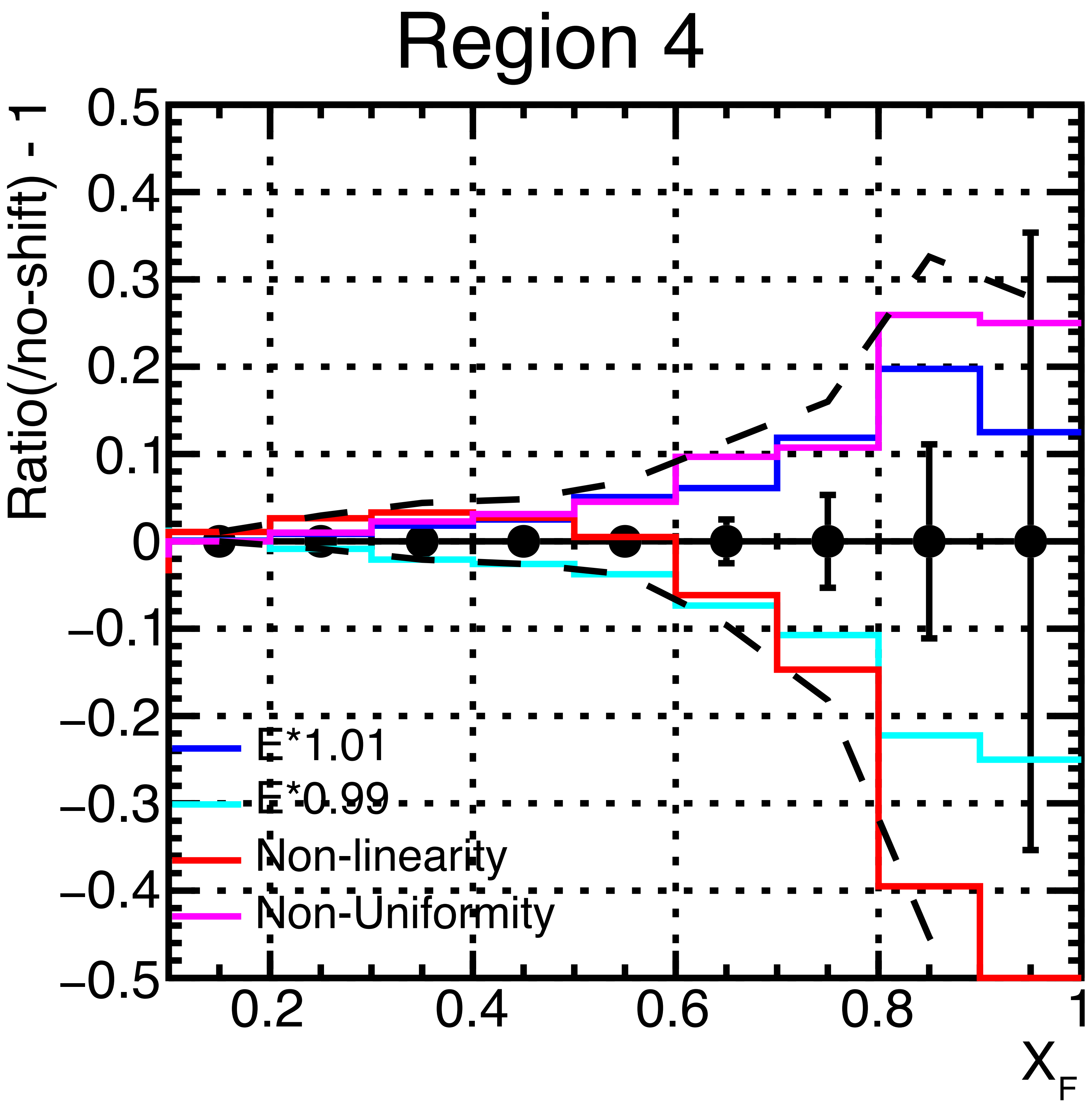


It is not understood why the inverse works.
However it is a good model to estimate the systematic error due to uniformity.

1. Energy scale systematic error.

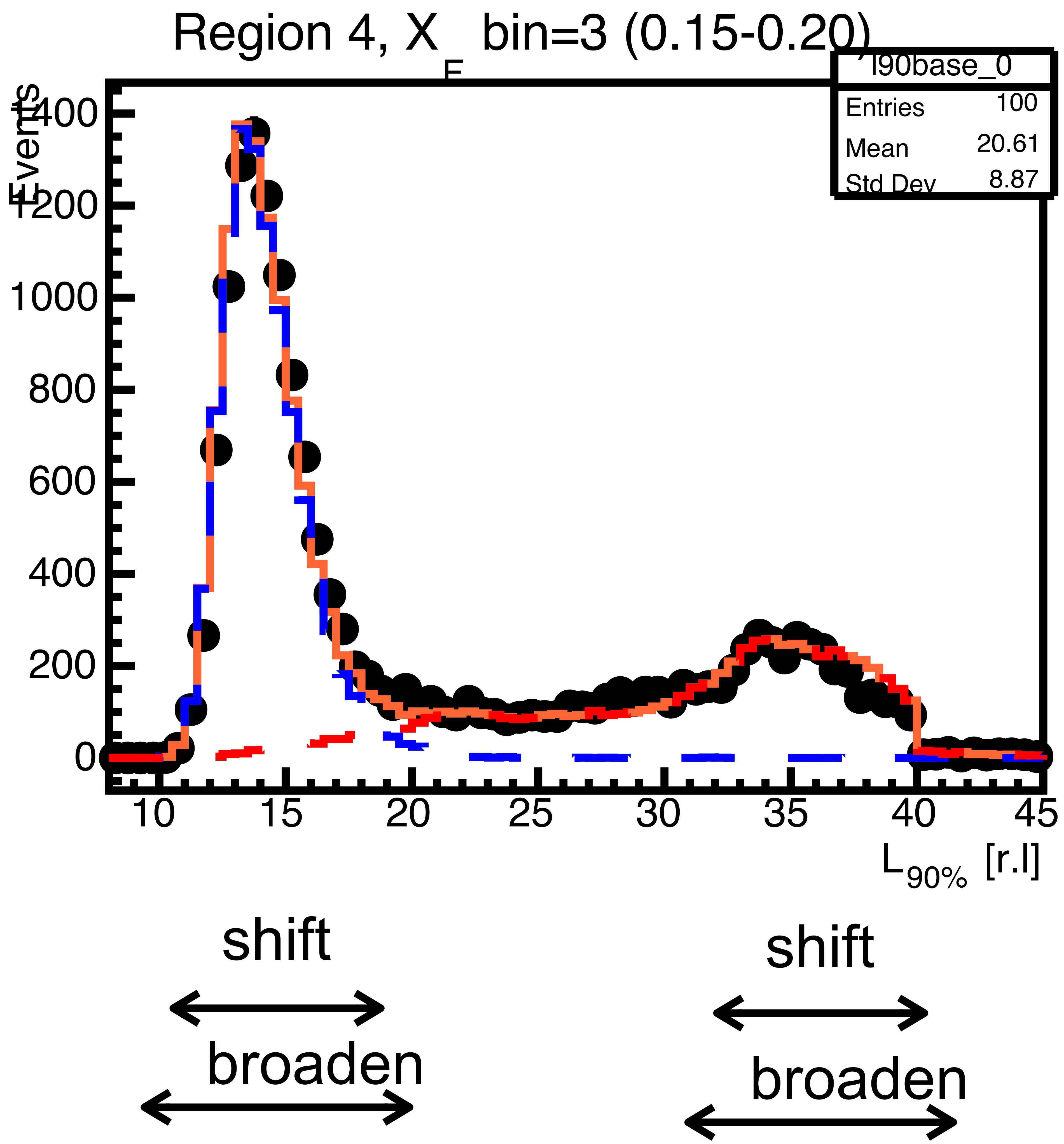
- Estimate the systematic uncertainty of energy by applying the model, energy shift +1%, -1%, Non-linearity, and non-uniformity.

Example) MIDDLE, Shower trigger



········· Quadratic sum in upper or lower side
→ Energy Scale Systematic uncertainty

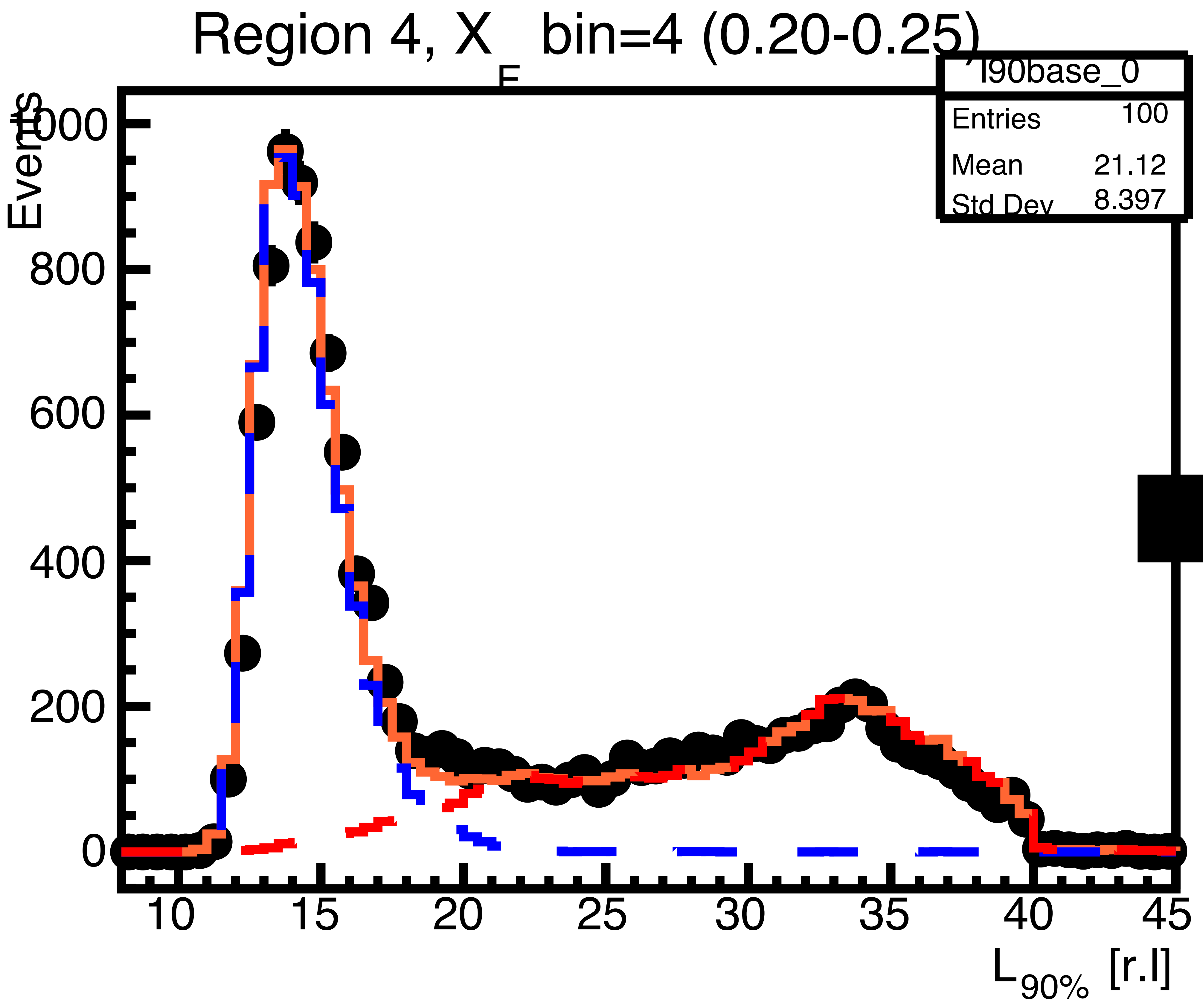
2. PID Systematic uncertainty



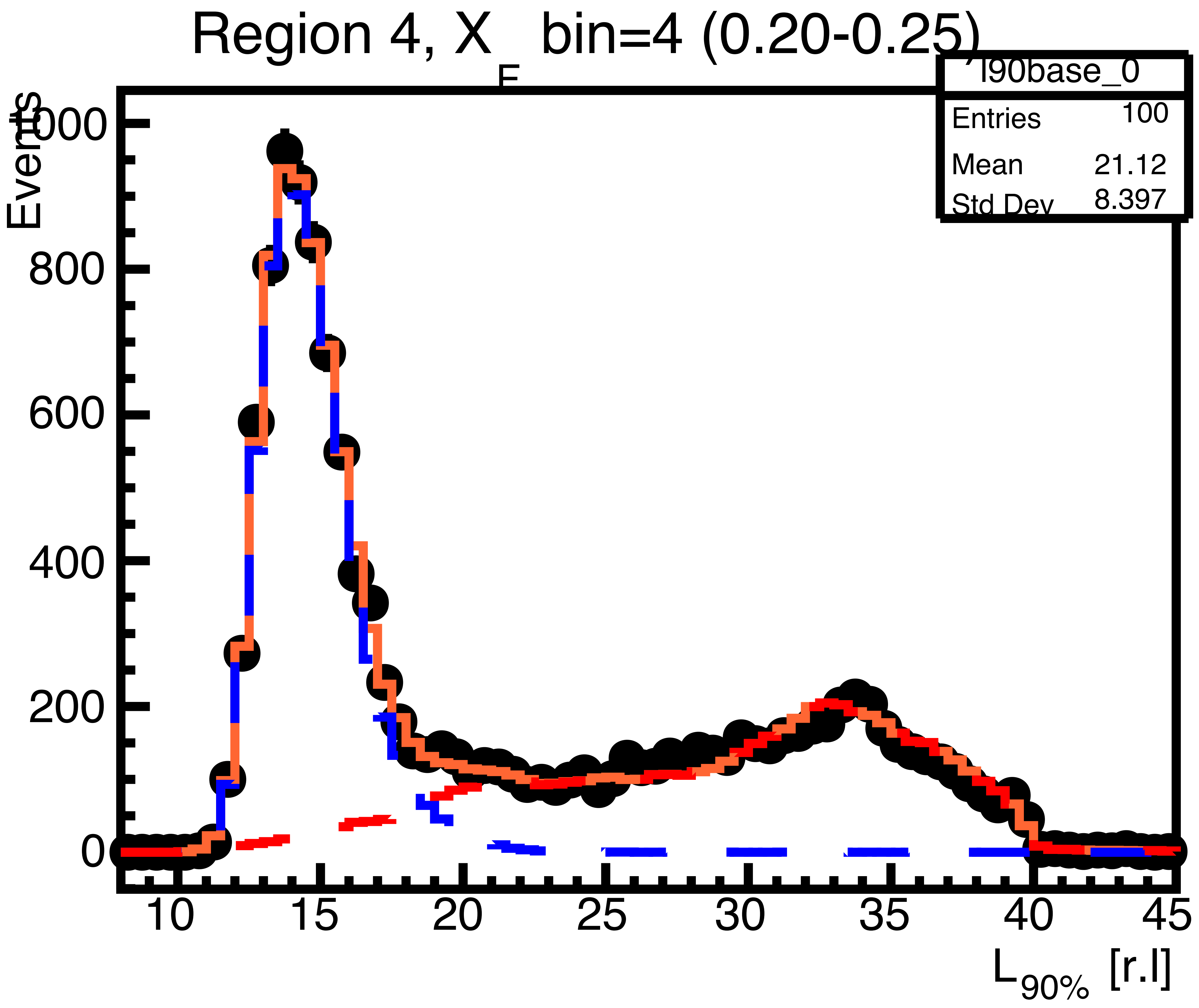
- Difference of L90% distribution affect estimation of both efficiency and purity.
- How we can model the difference ?
  - Take the method used in LHCf.
    Perform the template fitting with accepting shift and broaden the MC original templates for photons and neutrons.
    Free parameters: 2 (scalex2) → 6
  - Implementation (detail):
    1. make template distribution with x10 finer binning
    2. smear with gaussian function (σ=0.25 r.l.)
    3. make the function by linear interpolation of distribution.
    4. fit the data distribution by the function (6 free parameters)
  - Finally compare the results of default method with the modified method

2. PID Systematic uncertainty

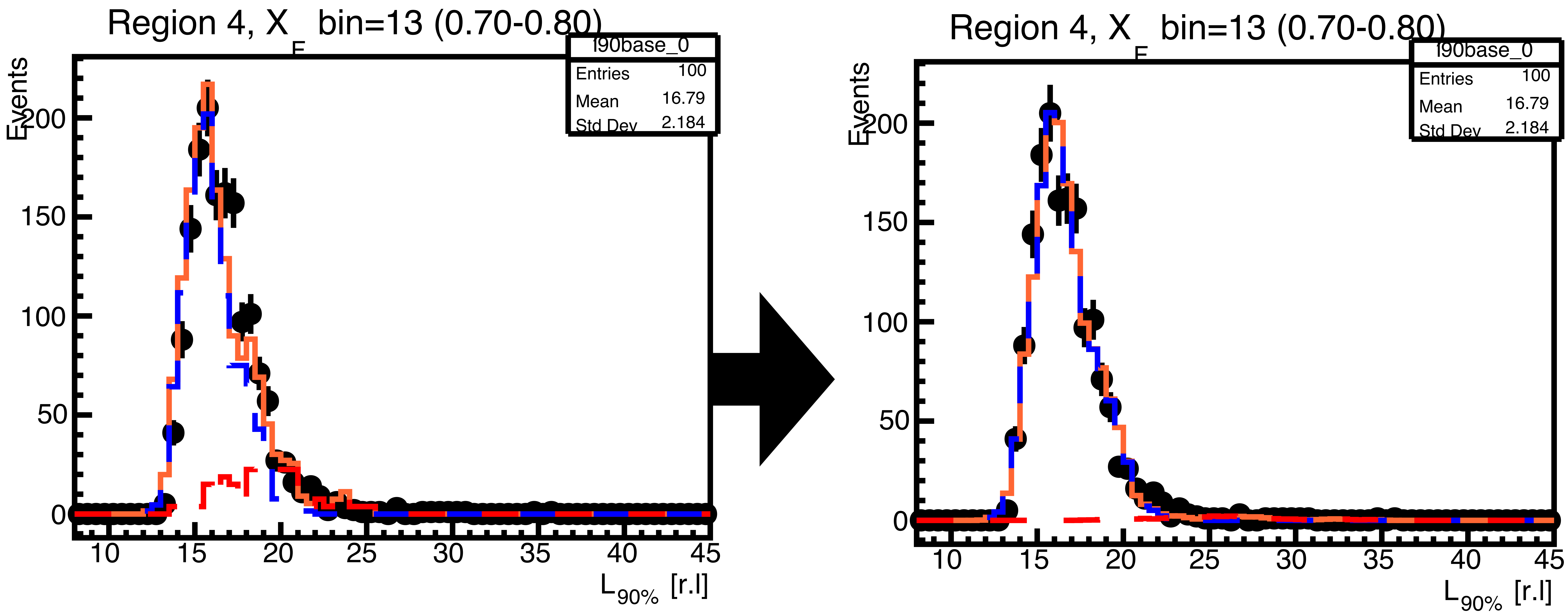
Fit1 (Default method)



Fit2 (modified method)



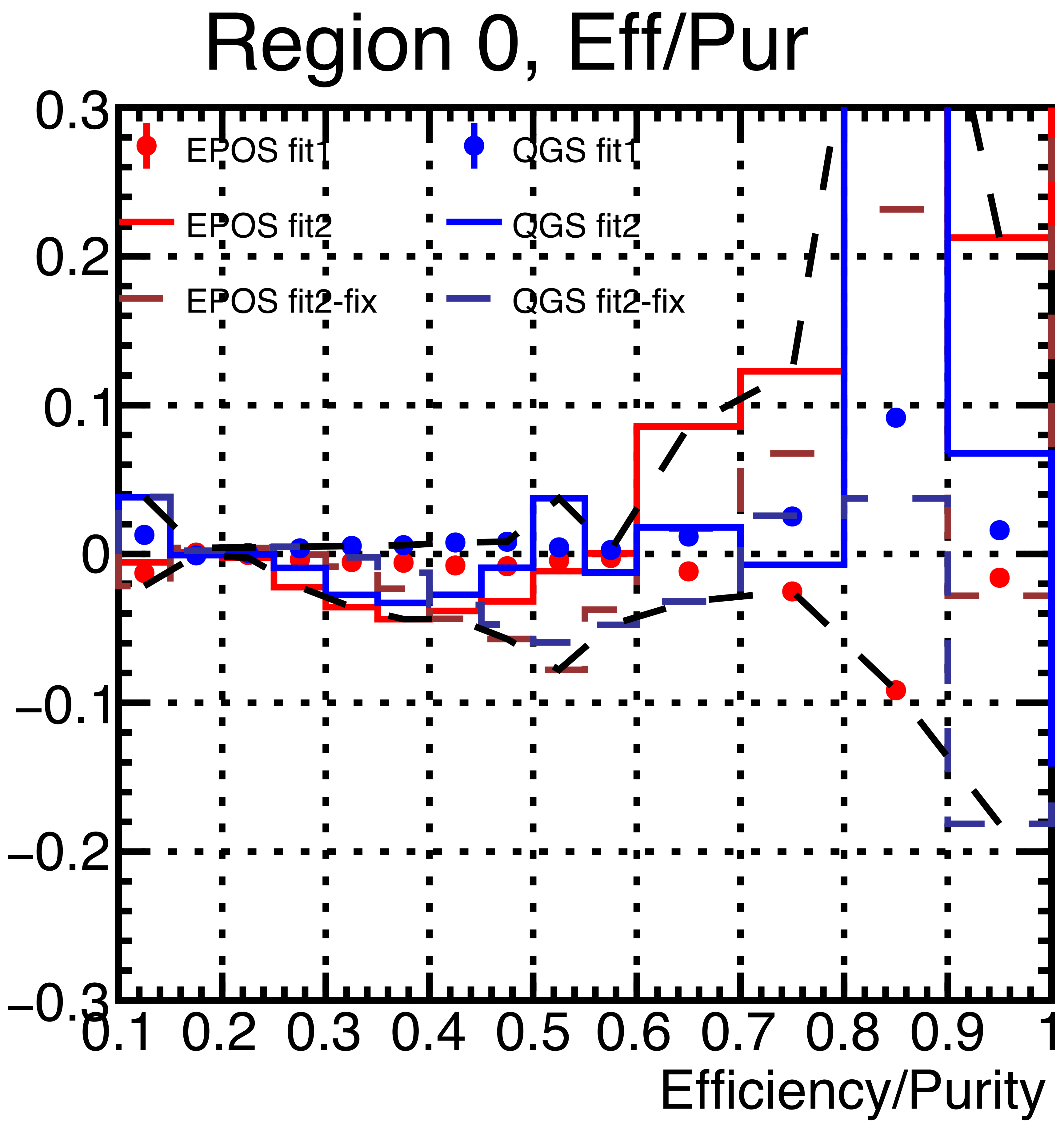
2. PID Systematic uncertainty



- In high energy (highEM trigger sample), few event in large $L_{90\%}$ region.
  → It is difficult to get the stable result in modified method.

2. PID Systematic uncertainty

Example) BOTTOM, Shower Tag



- Fit1: Default method
- Fit2: Modified method (shift+broaden)
- Fit2-fix: Modified method but fixed shift and broaden parameters to 0.

→ Difference of results between the Fit1 and Fit2-fix is also not negligible.

Center value of PID correction factor:
Average of Fit1-QGS and Fit1-EPOS

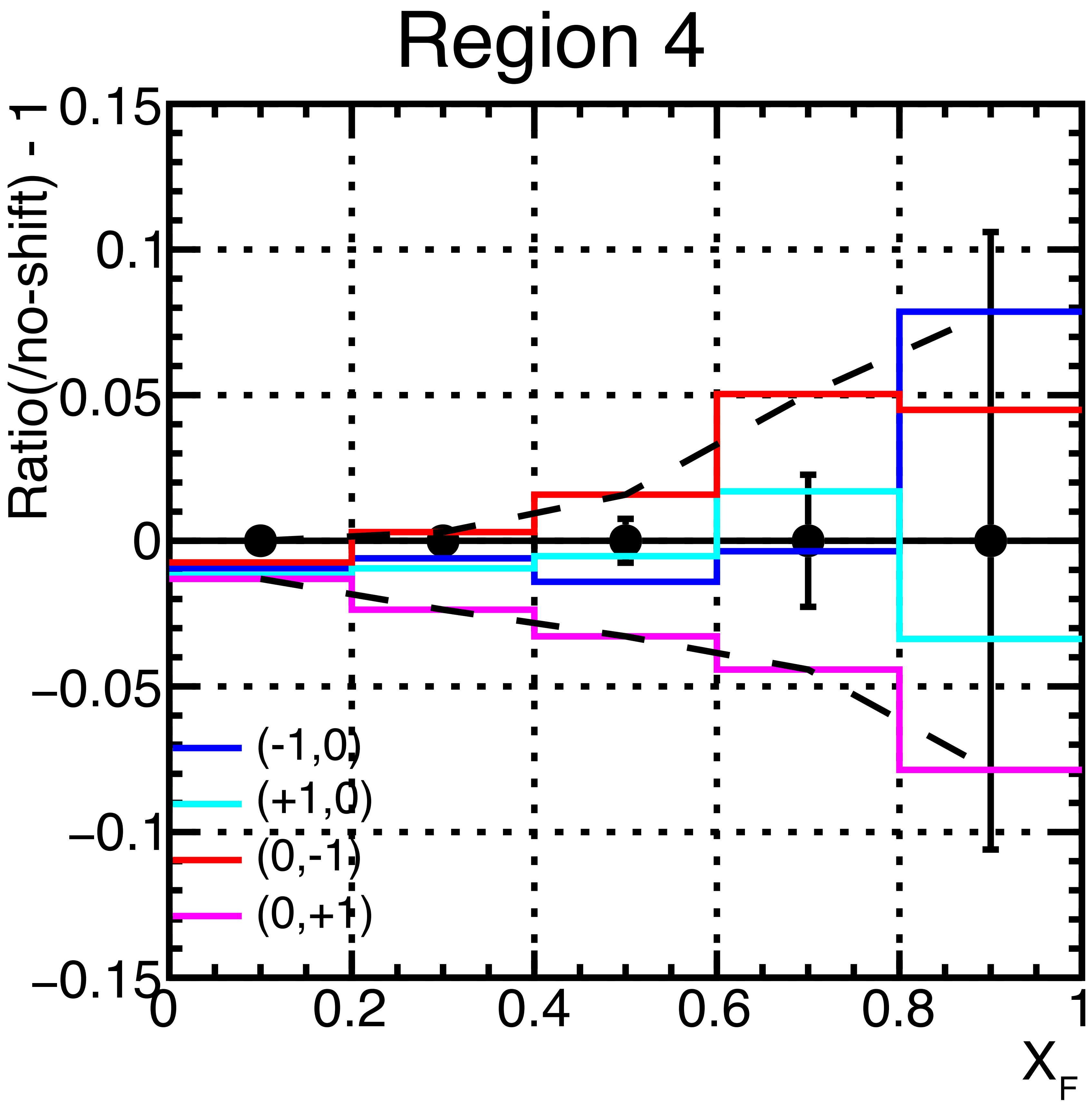
Systematic error:
Maximum deviation of the six results

3. Beam Center Position

- Uncertainty of Beam Center Position
  - The difference of estimated beam center position between hit and A_N method is < 1mm (refer Minho's analysis note.)
  - The BC at TOP is estimated by using only our on-site measurement.

➡ Δ = 1.0 mm (conservatively)

- The estimation of systematic error on the spectra.
  - Repeat all procedure with the beam center offset of
    (Δx,Δy) = (+1mm, 0), (-1mm,0),
    (0, +1mm), (0, -1mm)
  - Take maximum deviation from the nominal value at (Δx,Δy) = (0,0) as systematic uncertainty



C^{MC} : MC-based correction

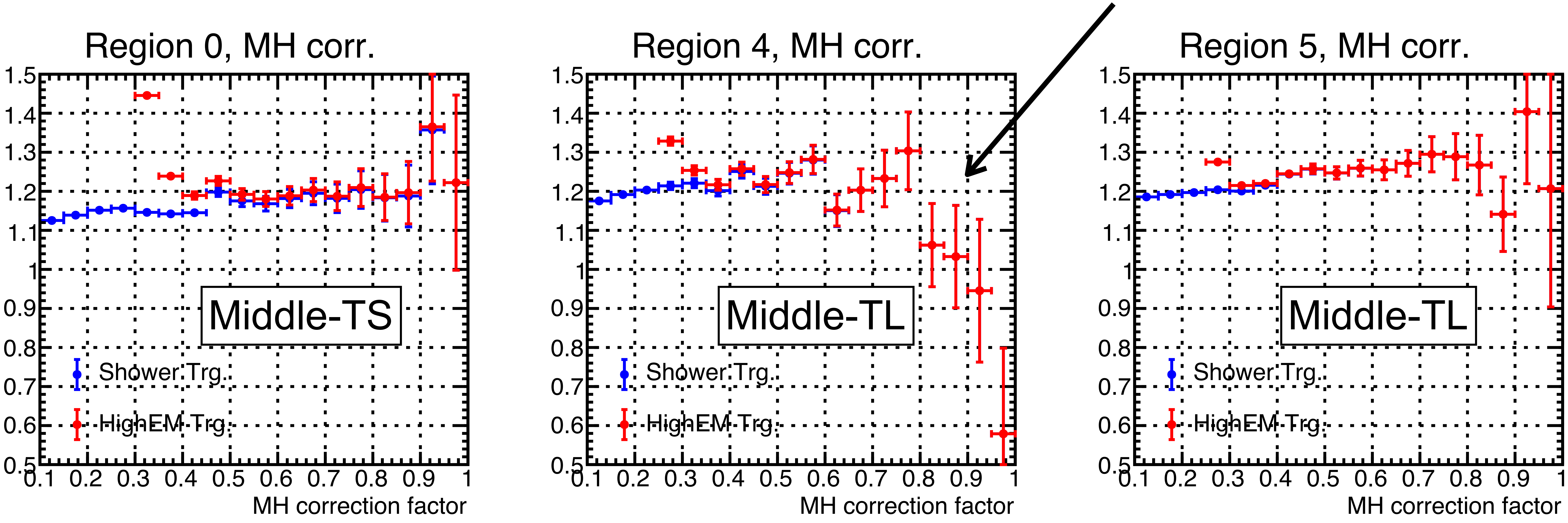
- Overall correction for
  - Trigger efficiency
  - Reconstruction efficiency (PID and single hit selection) and
  - Contamination of MH event as single hit
  - Recover the photon in MH events (for single photon → inclusive photon)

- Estimation method
  - Use MC data sets (EPOS-LHC, QGSJET II-04)
  - $C^{MC} = \dfrac{N^{MC}_{true,all-photon}}{N^{MC}_{rec,single-photon}}$ ← The true-single hadron events are excluded because the contamination should be corrected by PID correction

MC-base correction

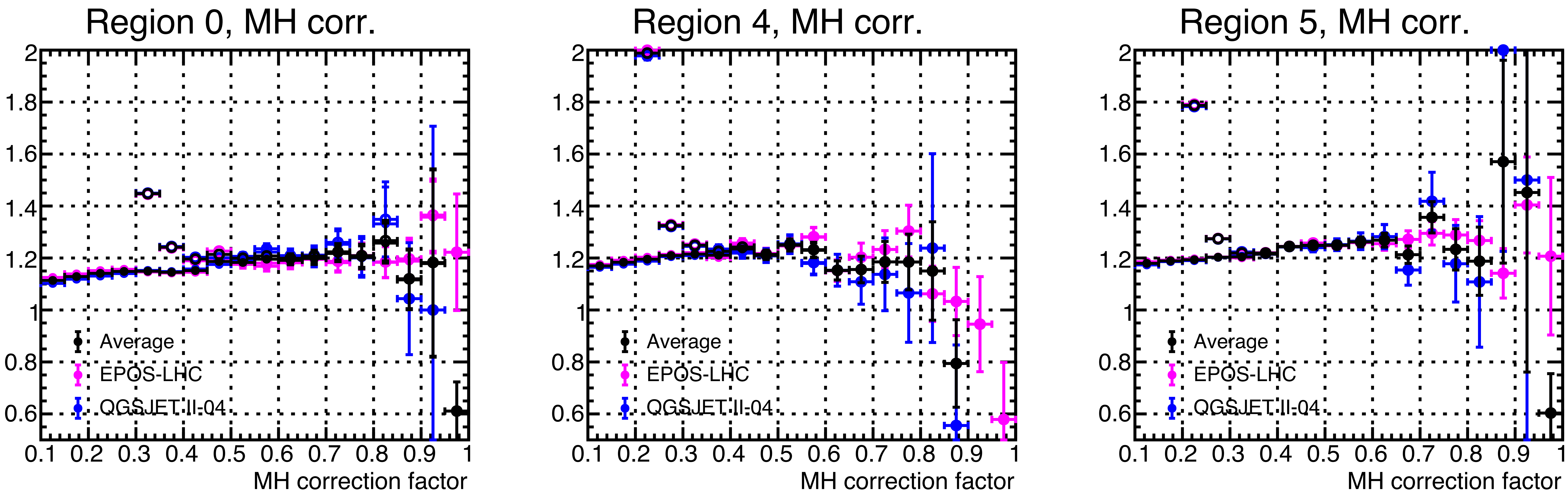
Estimated correction factor for MIDDLE by EPOS-LHC

Binning will change to avoid the statistical fluctuation



- Correction of 10-30%
- ~ 10% for PID efficiency (L90% threshold is defined as 90% efficiency criteria)
- No impact of DAQ trigger (100% for shower trig, 95% for HighEM trigger)
  - Considering photon like event selection by $L_{90\%}$, 100% trigger efficiency for High EM too.
- The remaining 10-20% is a contribution of MH
  - Larger correction in TL than TS

C^{MC} : Comparison between models



Take the average of two models as the correction factor and the deviation as the systematic uncertainty

Found a bug for BOTTOM and TOP results. Recalculation is on-going now

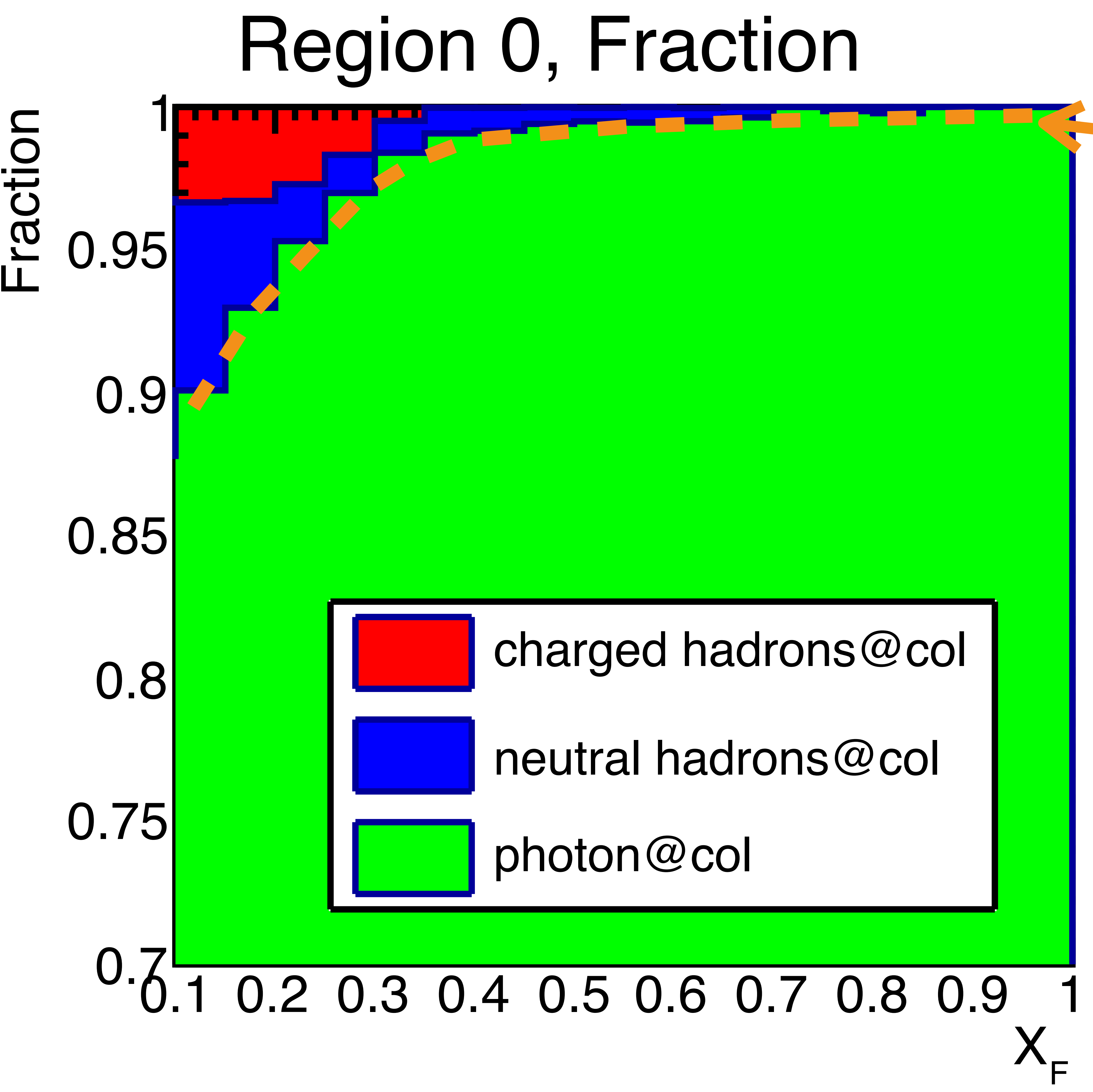
C^{CT}: Long life particle correction

- Estimate the contribution of decay products of long life particle particles like K^0
- Set up a dedicated MC
  - Full Geant4 simulation takes too much time to be computed.
  - Simple event generator + transportation simulation
    - CRMC v1.8.0 for event generation
      EPOS-LHC, QGSJET2-4, Sibyll 2.3d, DPMJET3-2019
    - EPICS v9.165 for transportation
      Simple sphere geometry as a decay volume (r=1781.30 cm)
      No magnetic field
  - Output the photon distributions
    - at collision (CRMC output + 1cm sphere)
    - at r=1781.26 cm (RHICf detector location)

$>$ The ratio ⇒ Correction factor

C^{CT}: Long life particle correction

$\eta > 8.5$

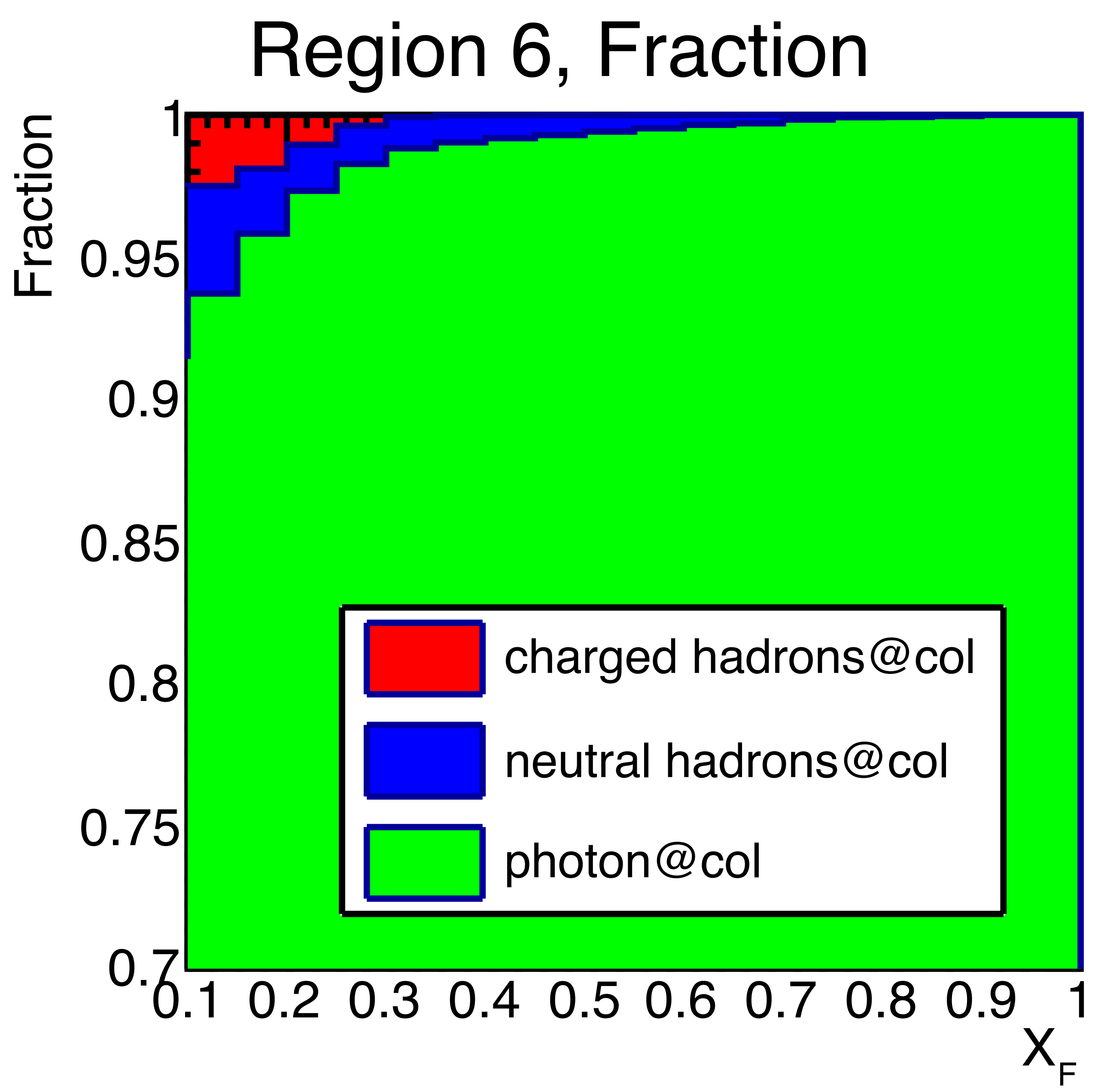


Correction factor

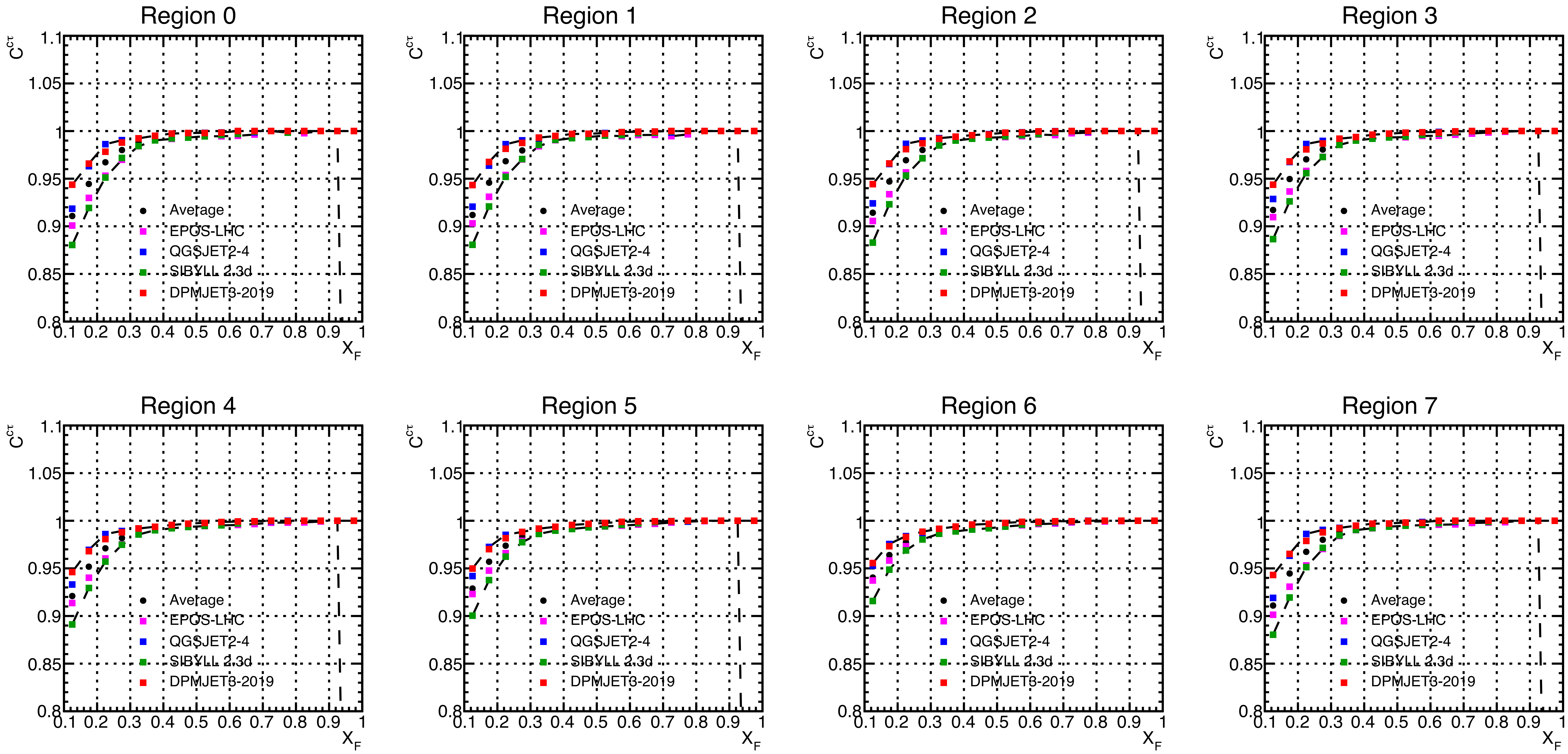
- Max. 10% at lowest X_F bin
- In the long-life particle contribution
  - neutral hadron dominant
  - charged hadron a few %

→ In the real situation (with D1 magnet) the charged-hadrons contribution is suppressed a bit. This should be a systematic uncertainty but smaller than model dependency (next page)

$6.1 < \eta < 6.5$



C^{CT}: Comparison between models

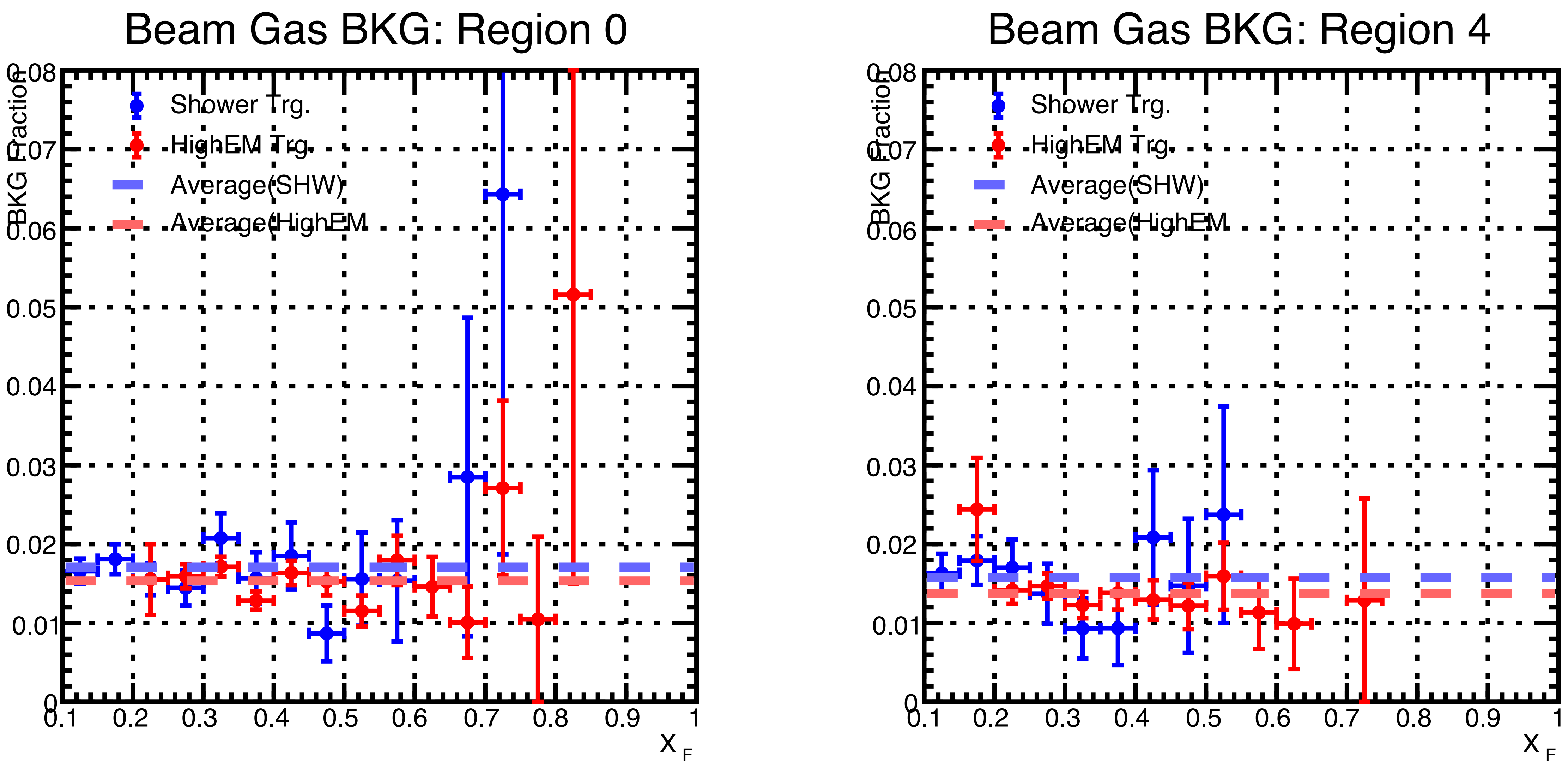


Take the average of four models as the correction factor and the deviation as the systematic uncertainty

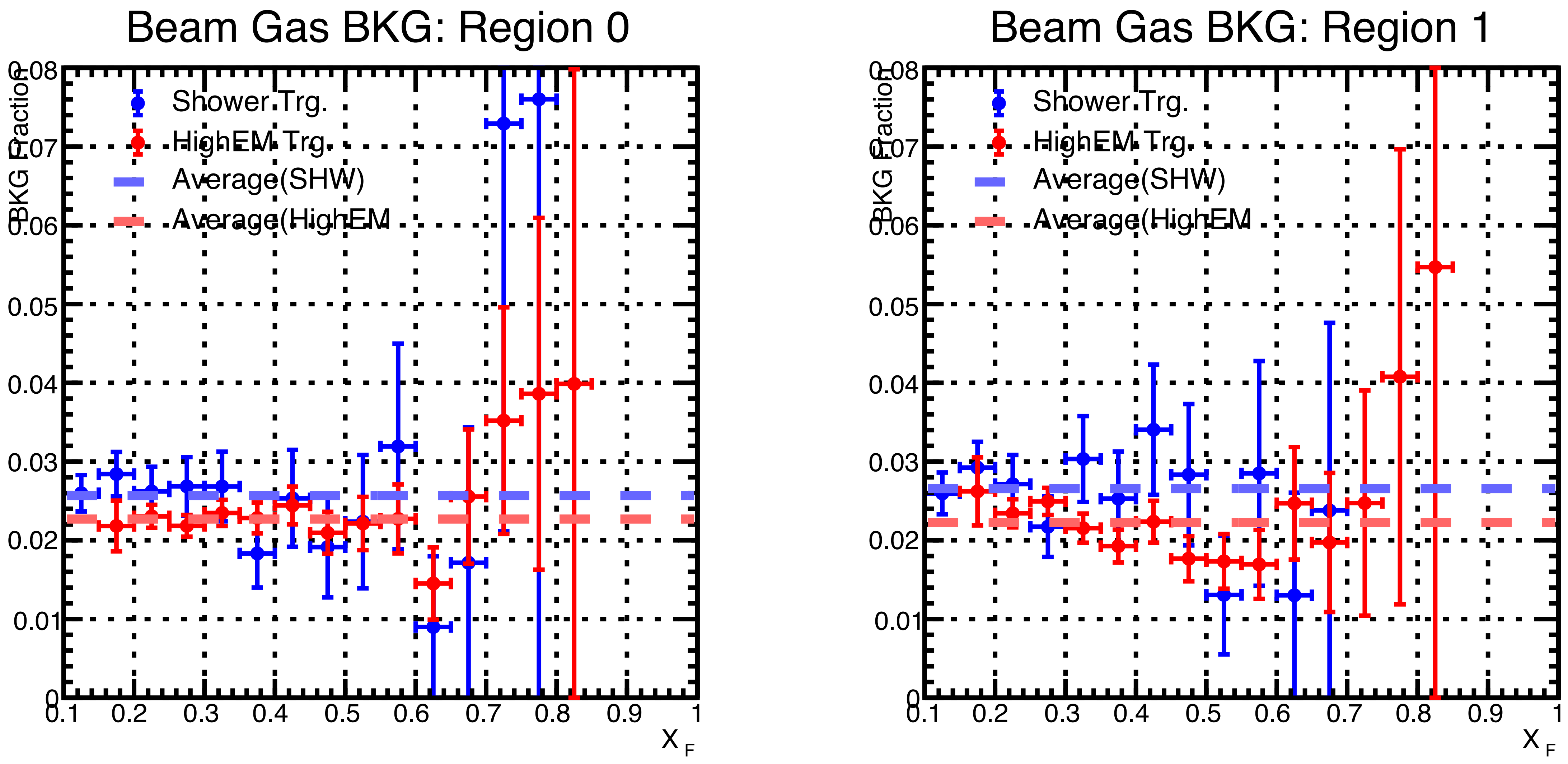
R^{BKG}: Beam-gas background

- Beam gas background can be estimated using the non-colliding bunches and the beam intensities of each bunches
- Little region dependency and photon energy
  → R^{BKG} is estimated as a photon-energy independent value
  to avoid the statistical fluctuation.
- R^{BKG} = 1.5 - 2.5 % (depend on the fill)

Fill 21148 (MIDDLE)

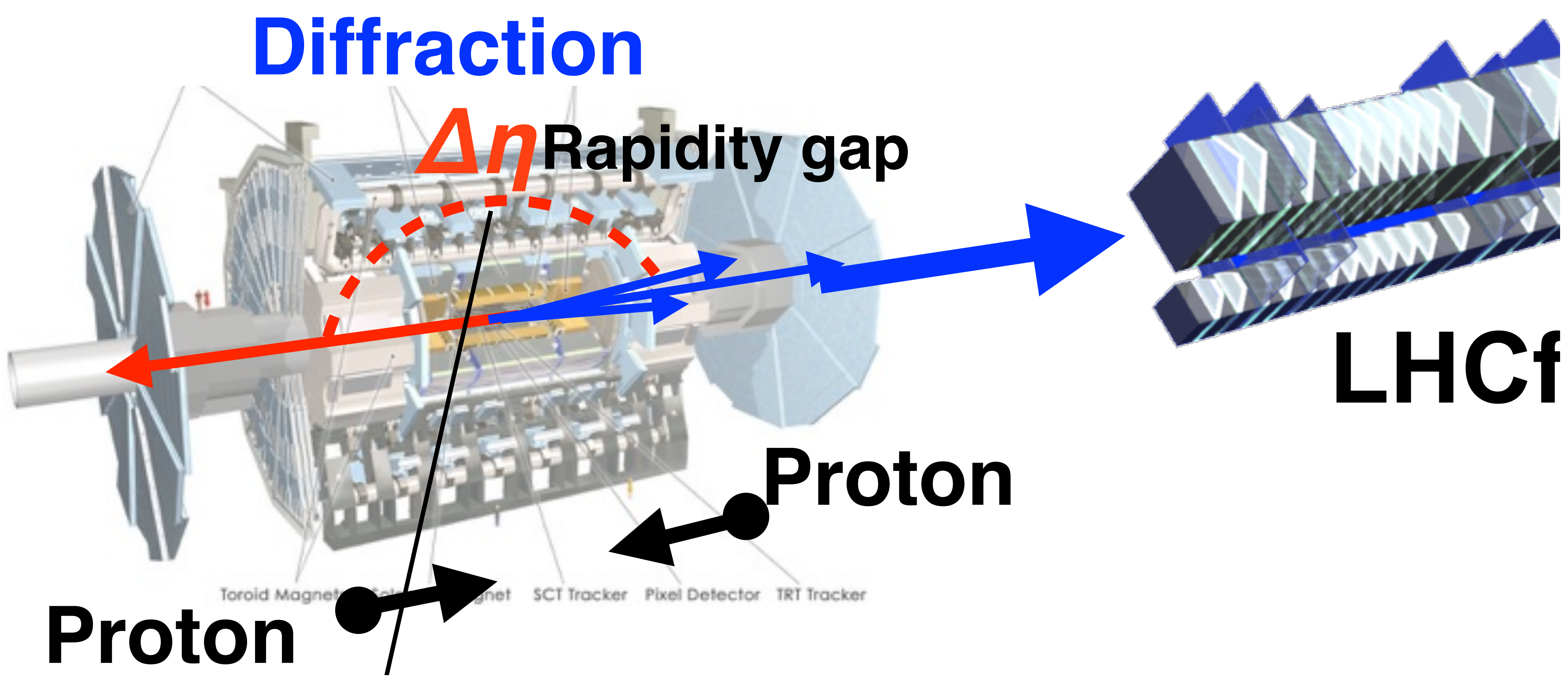


Fill 21145 (BOTTOM)

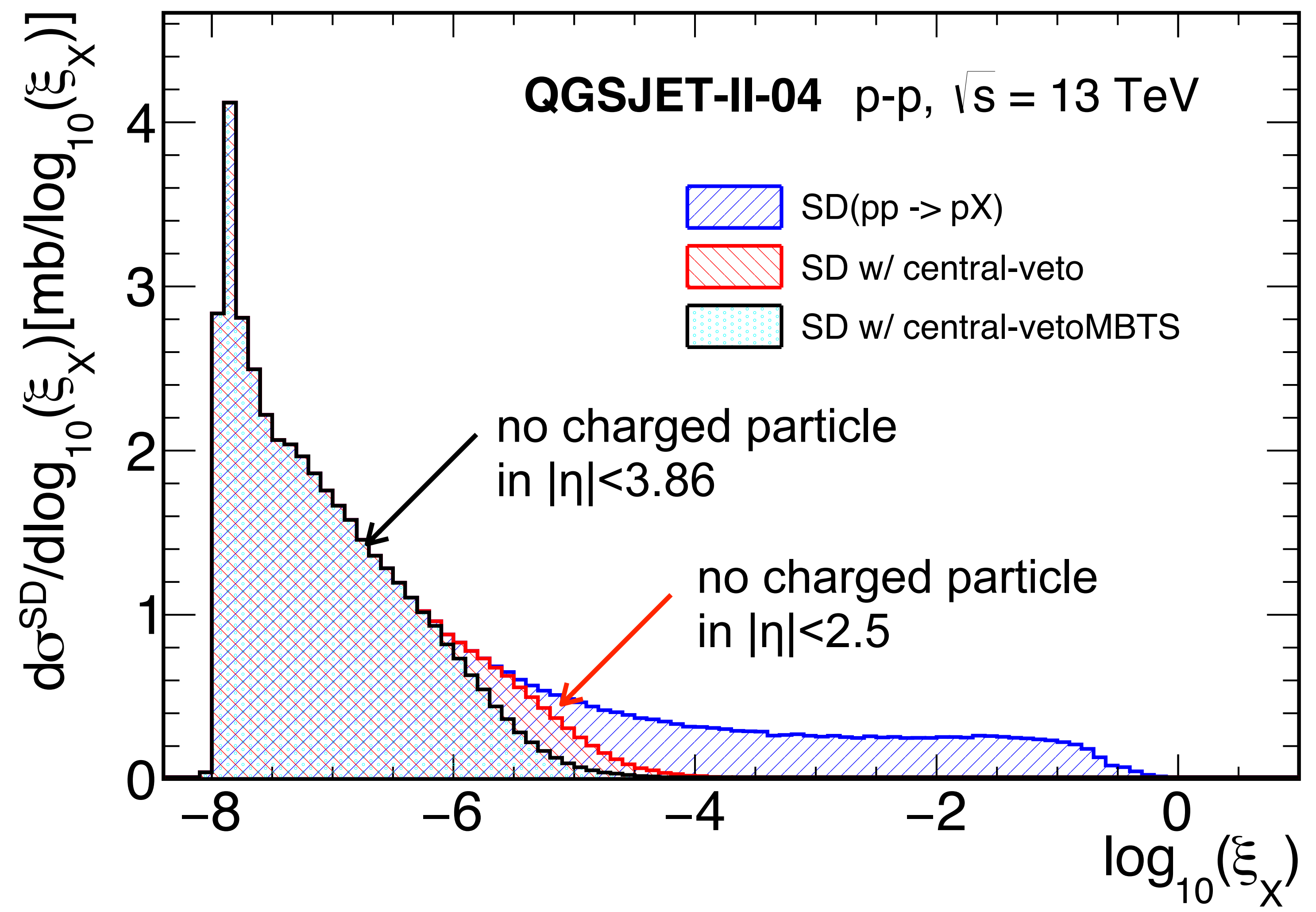


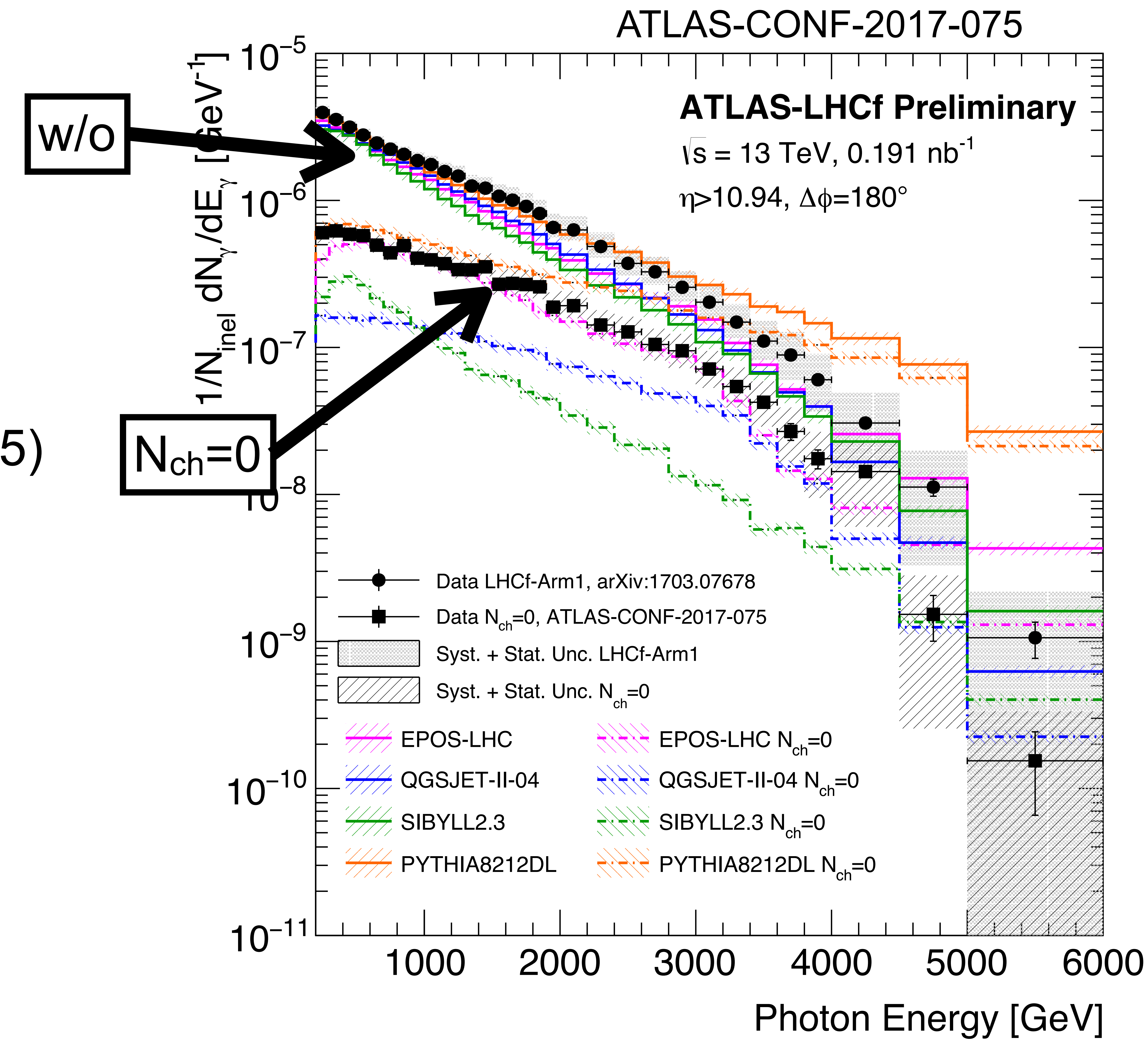
Example: LHCf-ATLAS joint analysis

Measurement of very low-mass diffractive interaction



- require no particle in ATLAS tracker (|η| < 2.5)
  → pure low-mass diff. sample ($\log_{10}\xi < -5.5$)





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