Forward particle measurements at colliders and air shower development

Takashi Sako

High Energy Cosmic Ray Research Division, ICRR

What I was doing before joining ICRR

Forward particle measurements at colliders and air shower development

What I am studying at ICRR

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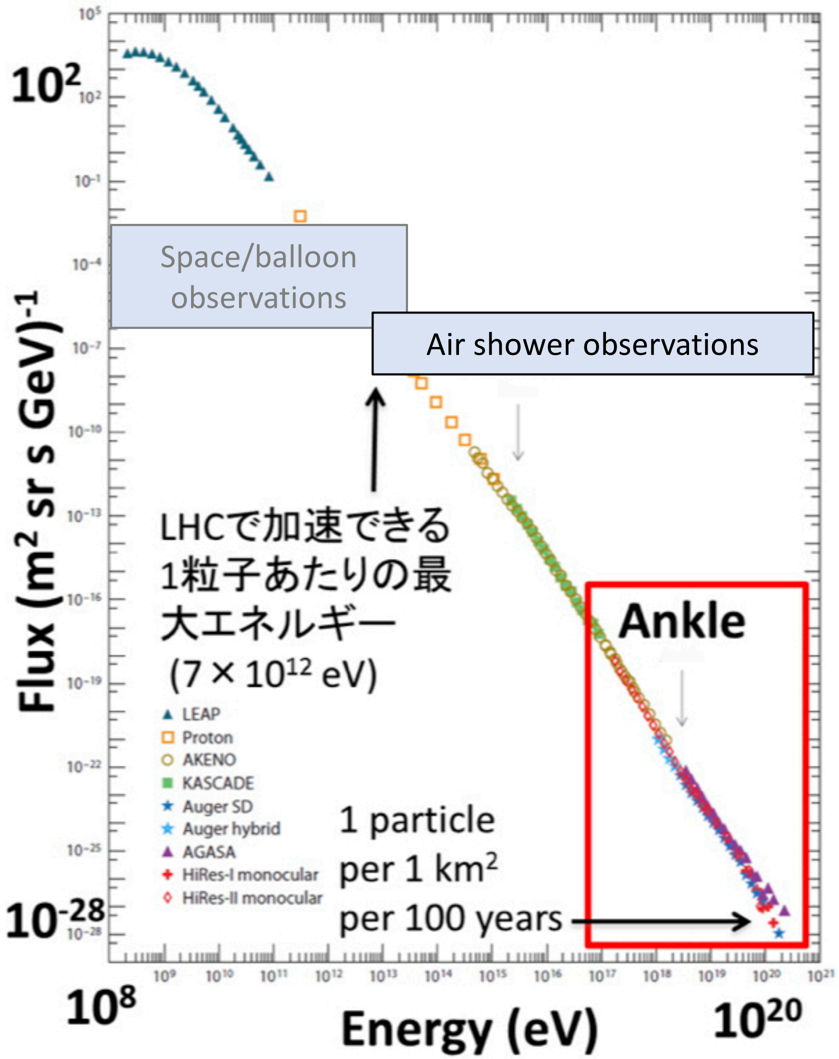
High Energy Cosmic Ray Research Division, ICRR

Outline

- Air shower observation and hadron interaction
- Forward particle measurements at collider
- LHCf and RHICf experiments
  - Introduction to the LHCf experiment
  - Forward π^0 and neutron results
  - √s dependence
  - RHICf
- Model tuning to the LHCf result and impact on air shower simulation
- Summary and future

High-energy cosmic ray observations

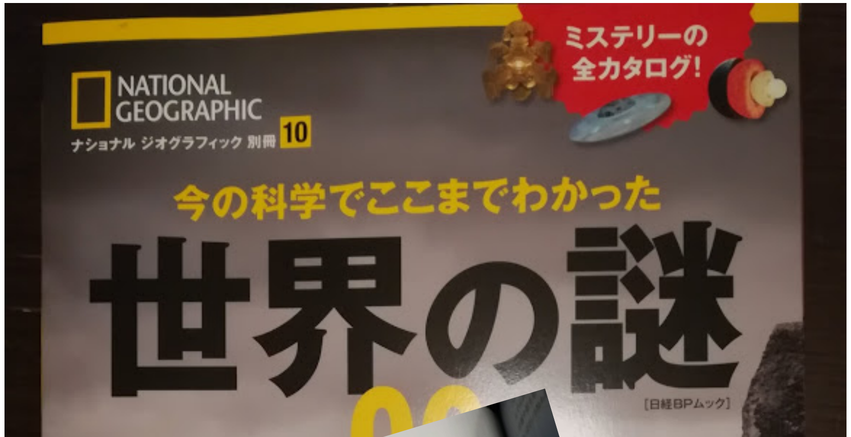


- High-energy particles from outer space, cosmic rays, are observed
- Majority of CRs is fully ionized nuclei including protons
- 10^{20}eV(=16J) CRs are observed
- LHC can accelerate up to 7×10^{12}eV

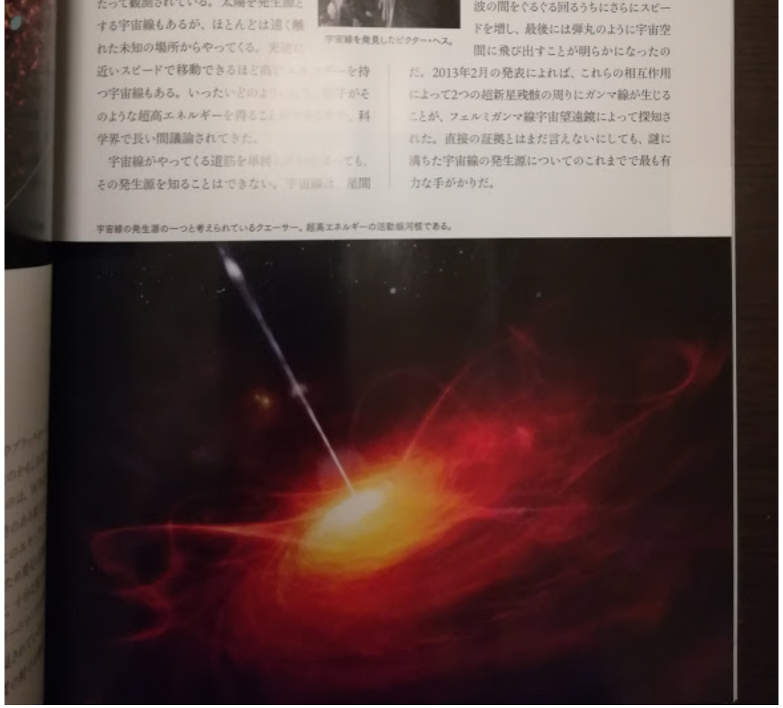
Where is the origin of CRs?
How are they accelerated?

- Very low flux at high energy
  Ex) >10^{20}eV 1 ptcl/1km^2/century
- Direct observation is not available

=> Air shower technique

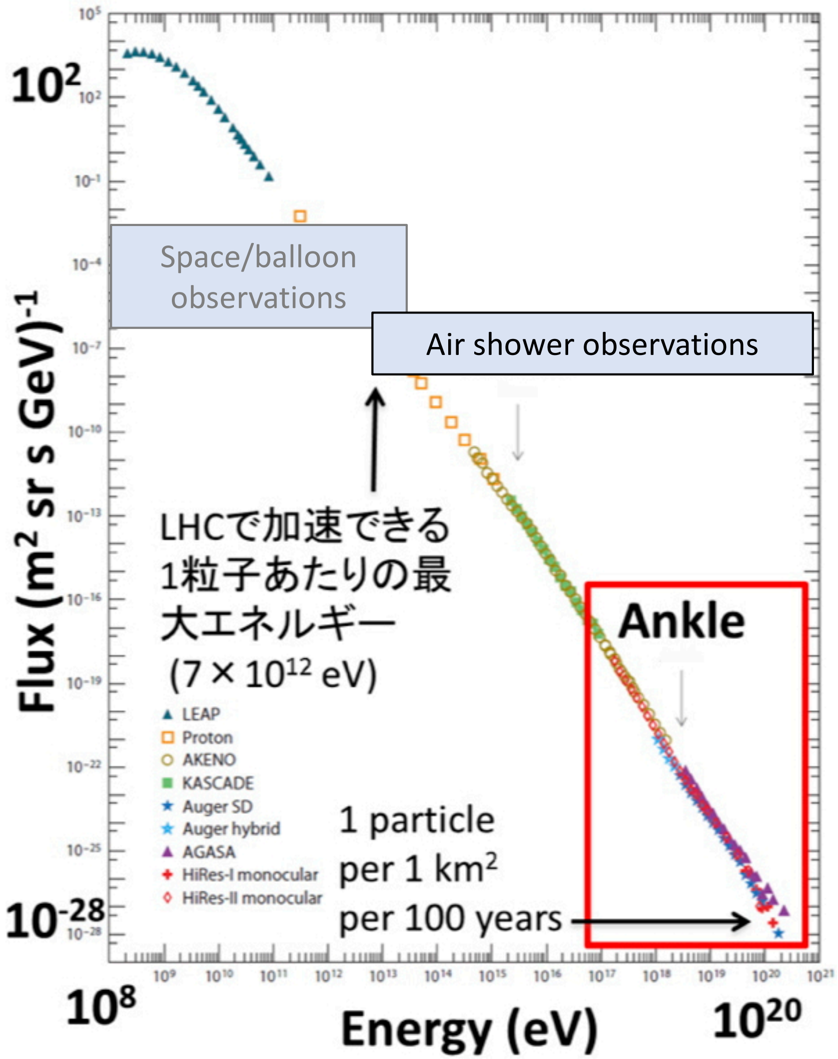

NATIONAL GEOGRAPHIC
ナショナル ジオグラフィック 別冊 10
ミステリーの全カタログ!
今の科学でここまでわかった
世界の謎
[日経BPムック]


39 ロズウエルに隠されている秘密とは?
UFOの目撃情報の中でもとりわけ関心を集めたのは、ロズウエル事件だろう


67 超高エネルギー宇宙線の発生源はどこ?
人は屋外にいるとき、1秒間に約1回は宇宙線を浴びている。それが感じられないのは、「線」とは言っても、その正体はきわめて小さな亜原子粒子、とくにプロトンであるからだ。宇宙線は宇宙のあらゆる方角から高速で地球の大気に降り注いでいることが、ここ100年にわたって観測されている。太陽を発生源とする宇宙線もあるが、ほとんどは遠く離れた未知の場所からやってくる。
磁場に沿って
しかし最近になって、超高
の宇宙線と超新星残骸を取り巻く磁場とを結びつける証拠が見つかった。この磁場に閉じ込められ、エネルギーを帯びた粒子が加速して、超新星の衝撃波の間をぐるぐる回るうちにさらにスピードを増し、最後には弾丸のように宇宙空間に飛び出すことが明らかになったのだ。2013年2月の発表によれば、これらの相互作用によって2つの超新星残骸の周りにガンマ線が生じることが、フェルミガンマ線宇宙望遠鏡によって探知された。直接の証拠とはまだ言えないにしても、謎に満ちた宇宙線の発生源についてのこれまでで最も有力な手がかりだ。
宇宙線を発見したビクター・ヘス。
宇宙線の発生源の一つと考えられているクエーサー。超高エネルギーの活動銀河核である。


89 アトランティスは実在したのか?

High-energy cosmic ray observations



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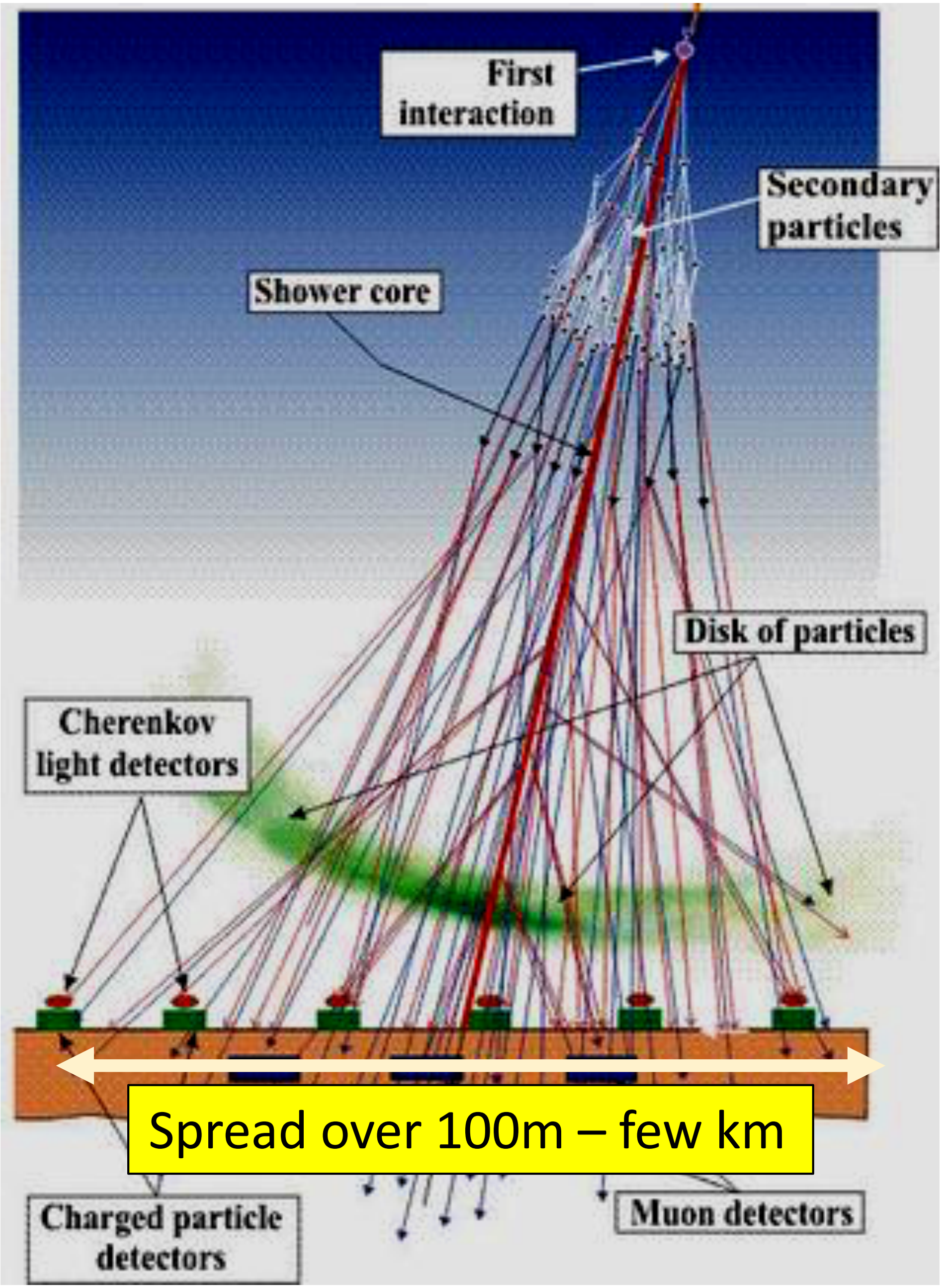
=> Air shower technique

Air shower technique



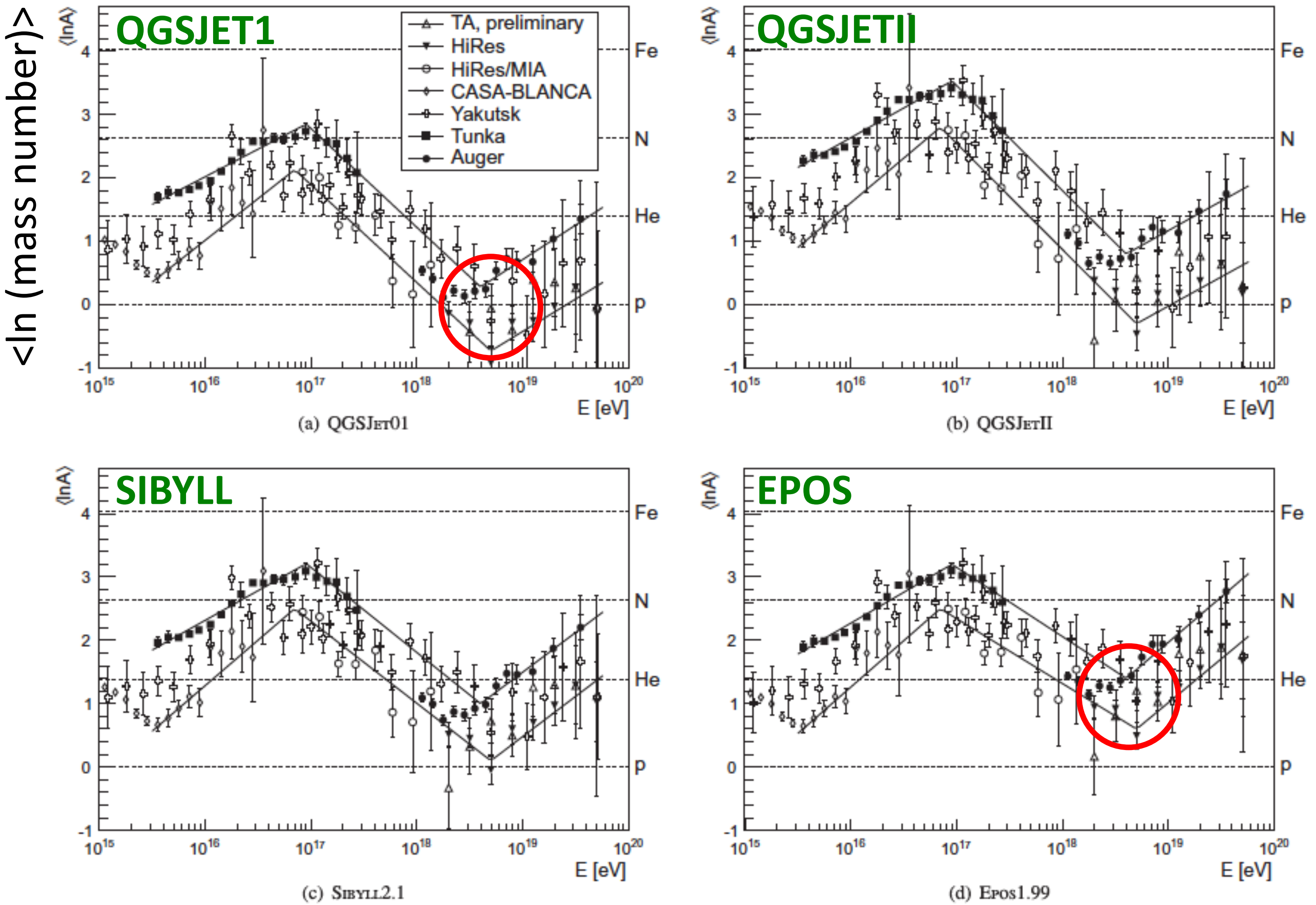
- km^2~$1000km^2$ detection area is achieved using a sparse array of the ground detectors
- Identification of primary particle (nuclei, gamma, etc…) is possible by measuring the difference in the air shower development

- We can (want to) extract
  - Energy
  - Direction
  - Type (mass number, γ, e^-, ν) of the primary particles

=>

Analyses strongly rely on the MC simulation of air shower development, especially fundamental hadronic interaction is essential

Model dependent mass interpretation

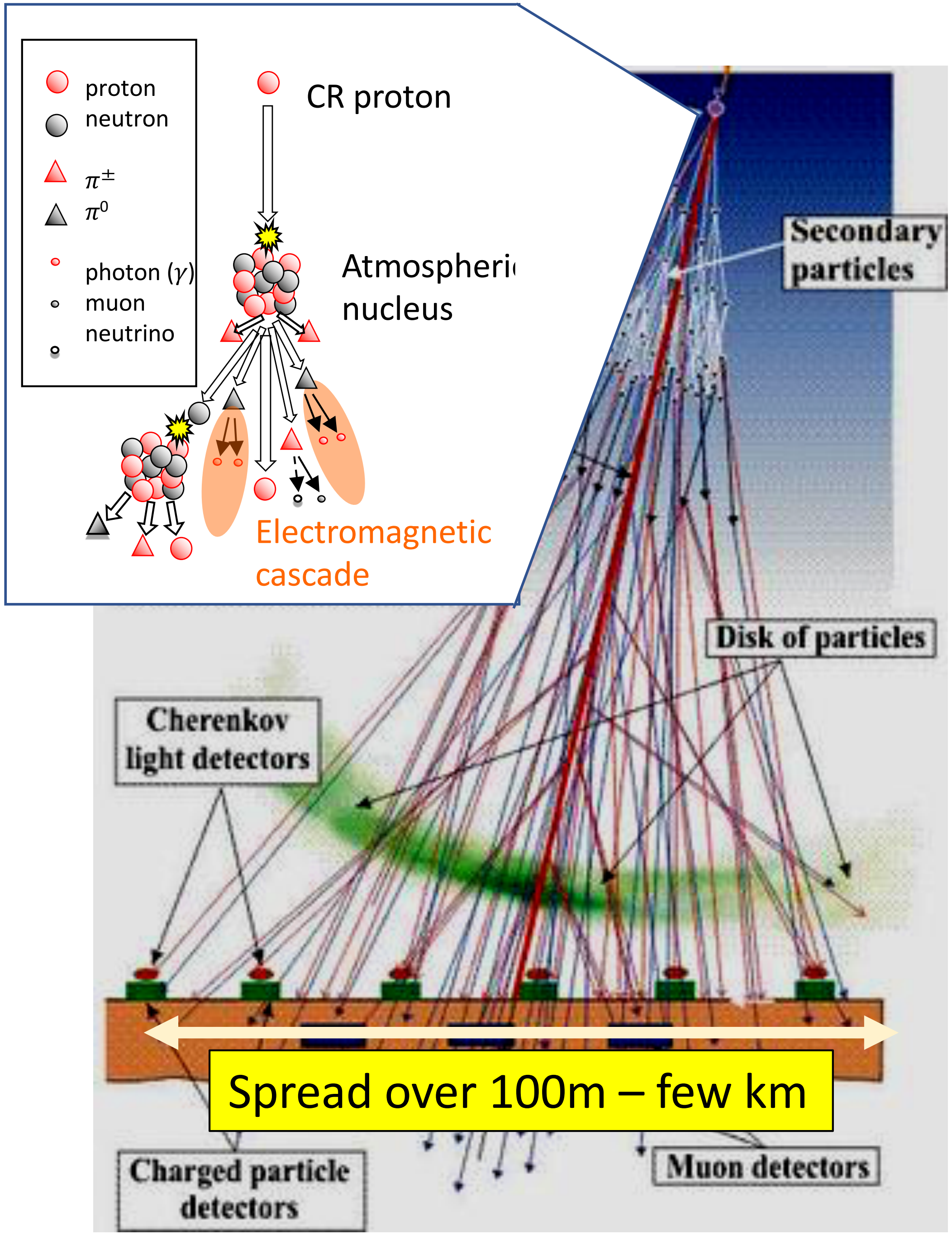


(Kampert and Unger, Astropart. Phys., 2012)

- Is difference between proton and Helium small? => Factor 4 in mass number!!
- Is the truth really between the existing models? => Nobody knows!!

Models must be tested by accelerator data

Hadronic interaction in air shower



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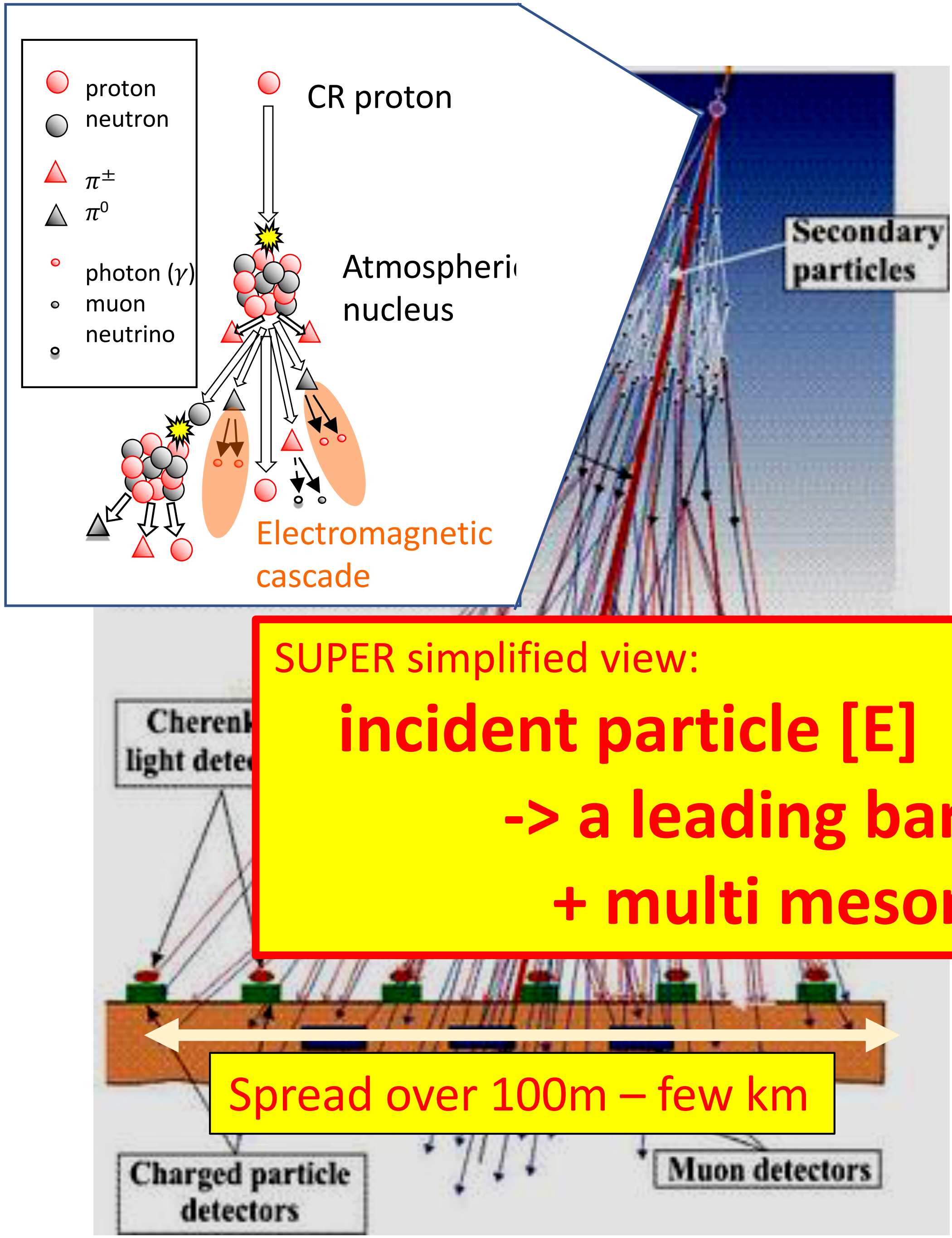

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rticles

=>

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SUPER simplified view:

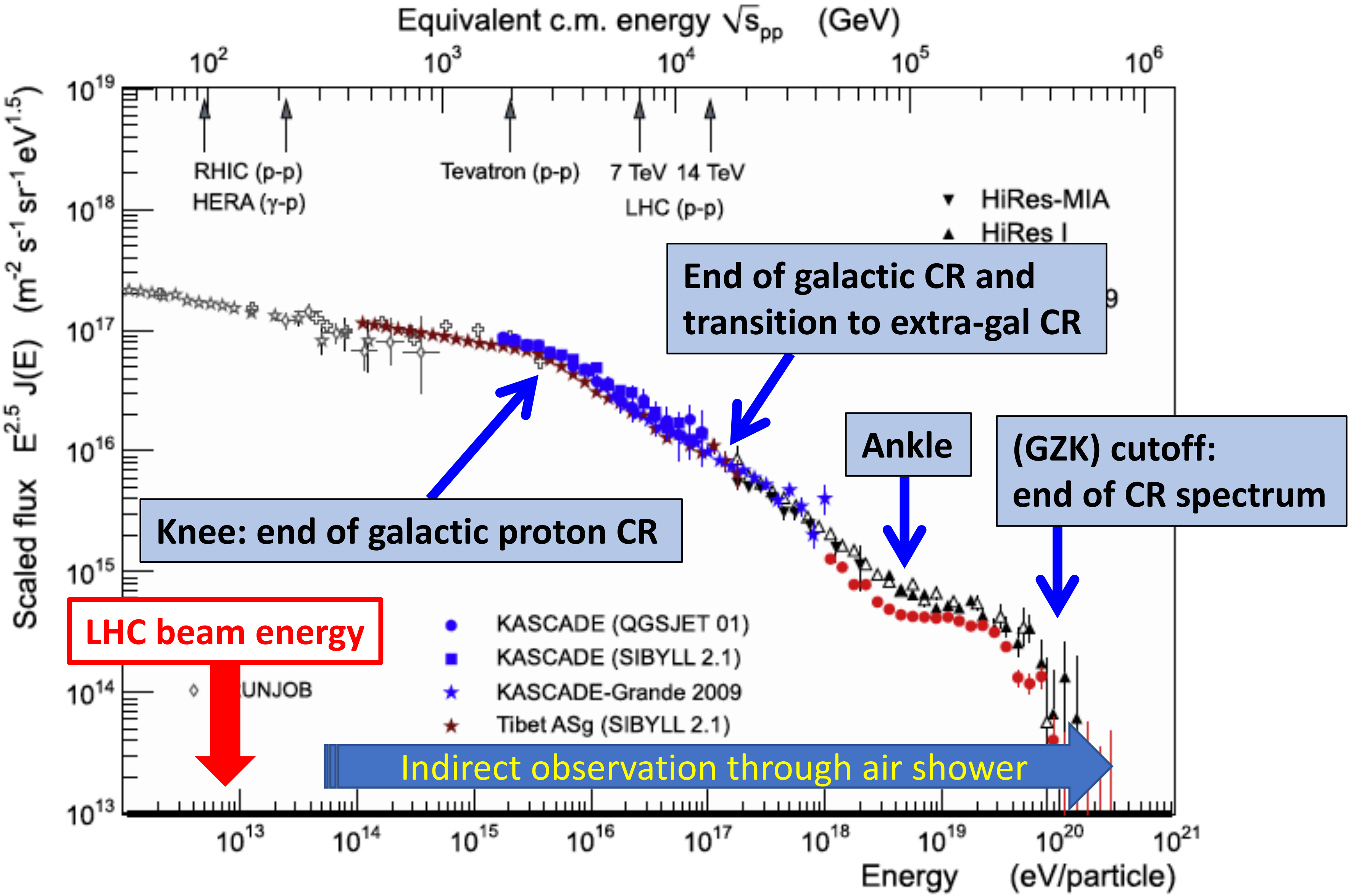
incident particle [E]

-> a leading baryon [k_{ela}E]

+ multi mesons [(1-K_{ela})E/N_{multi}]

Cosmic-ray spectrum and collision energy

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



Cosmic-ray spectrum and collision energy

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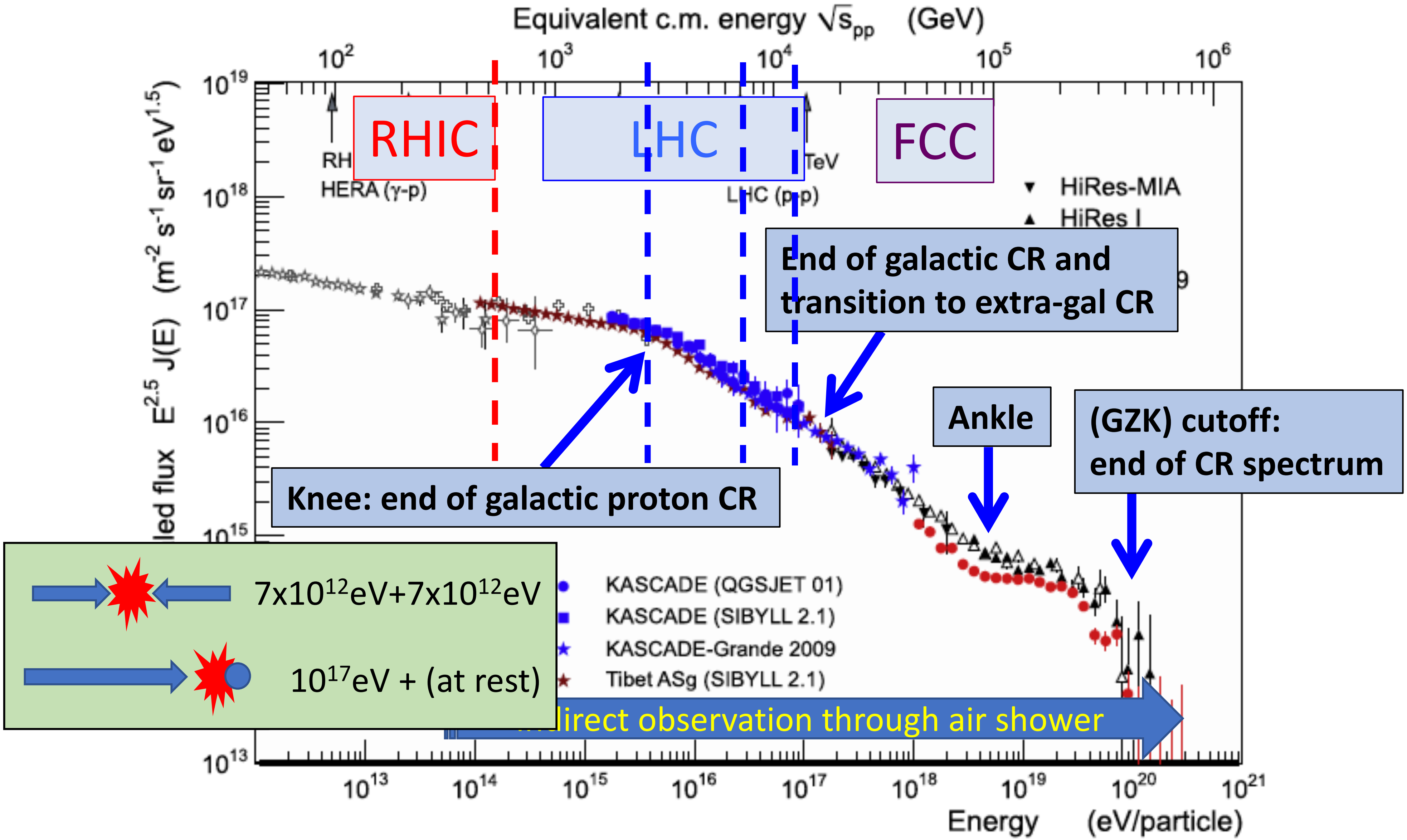
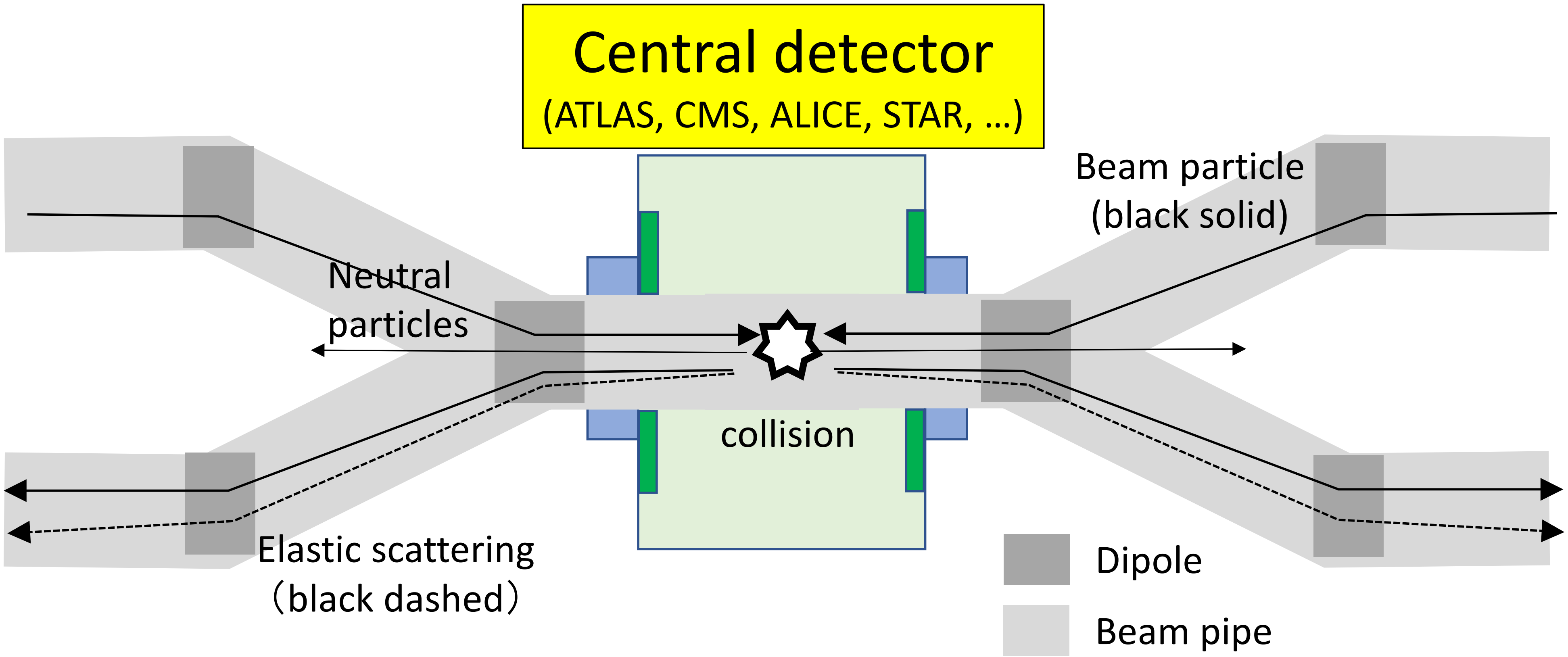


Though the particle energy is 7×10^{12}eV at LHC, the collision energy corresponds to $E_{CR}=10^{17}$eV

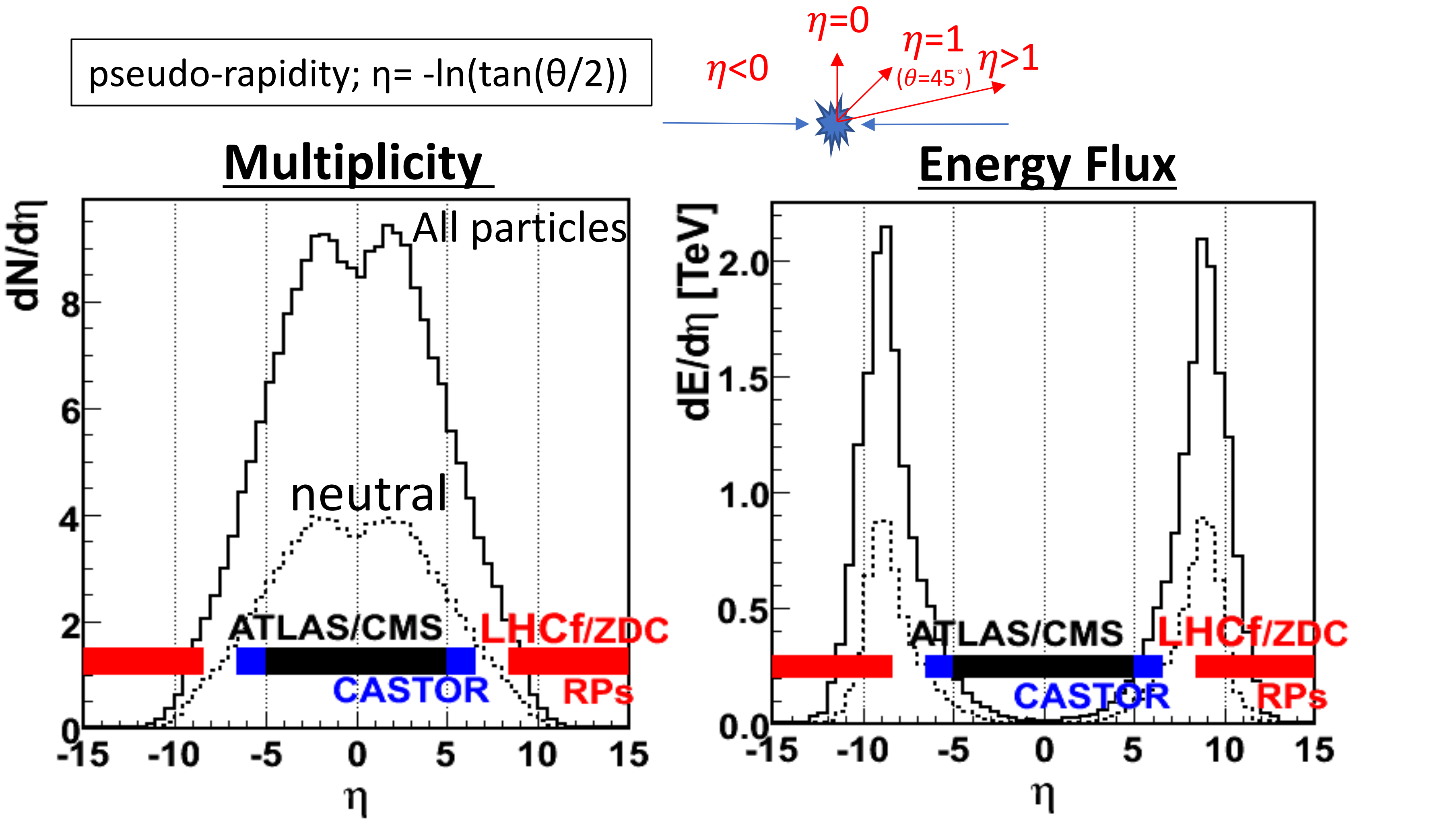
Detectors @ Colliders



- ✓ Main physics at colliders are achieved using the “Central detectors”
- ✓ But...

Angular distribution at colliders

multiplicity and energy flux at LHC 14TeV collisions



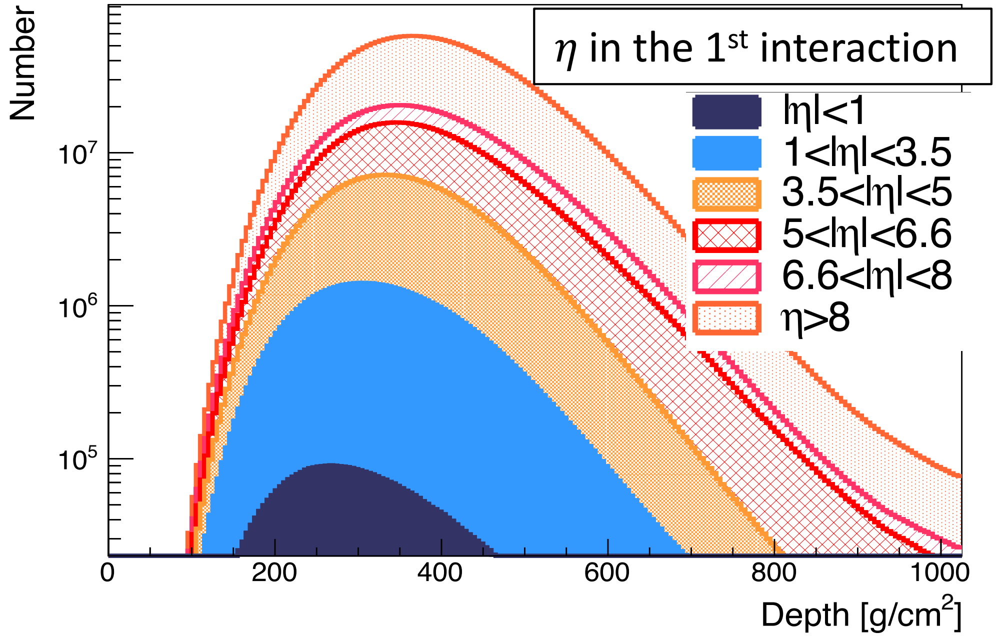
- ✓ Most of the particles are produced in the central region
- ✓ Most of the energy flows into very forward = relevant to CR air shower
  - forward = soft interaction; theoretical difficulty
  - experimental difficulty

Angular distribution at colliders

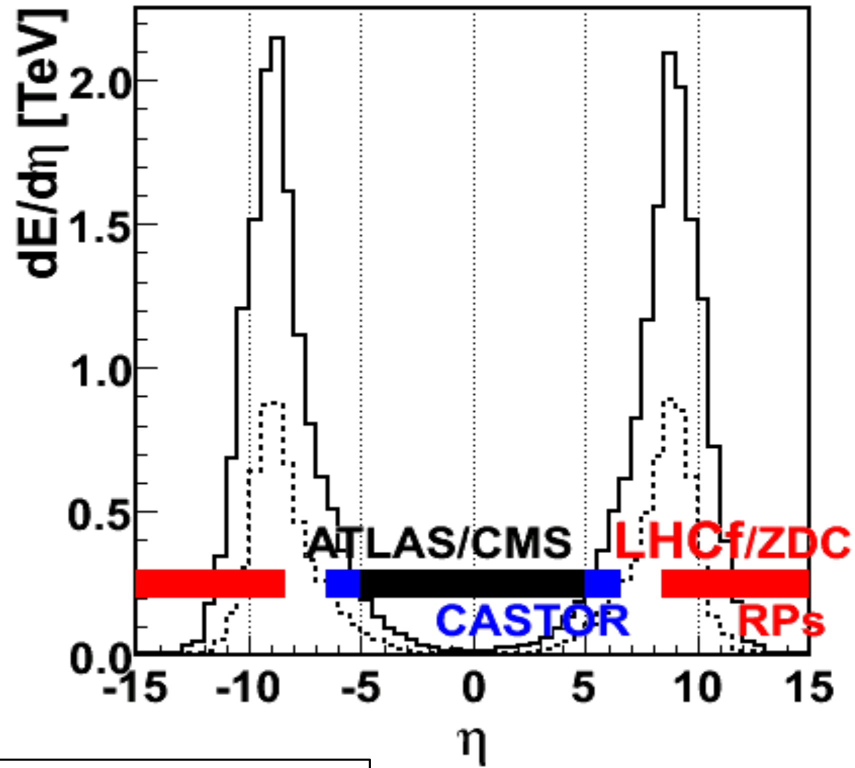
multiplicity and energy flux at LHC 14TeV collisions

pseudo-rapidity; η= -ln(tan(θ/2))

10^{17}eV proton shower



Energy Flux



η=8 => θ~1mrad (CMS)

- ✓ Most of the particles are produced in the central region
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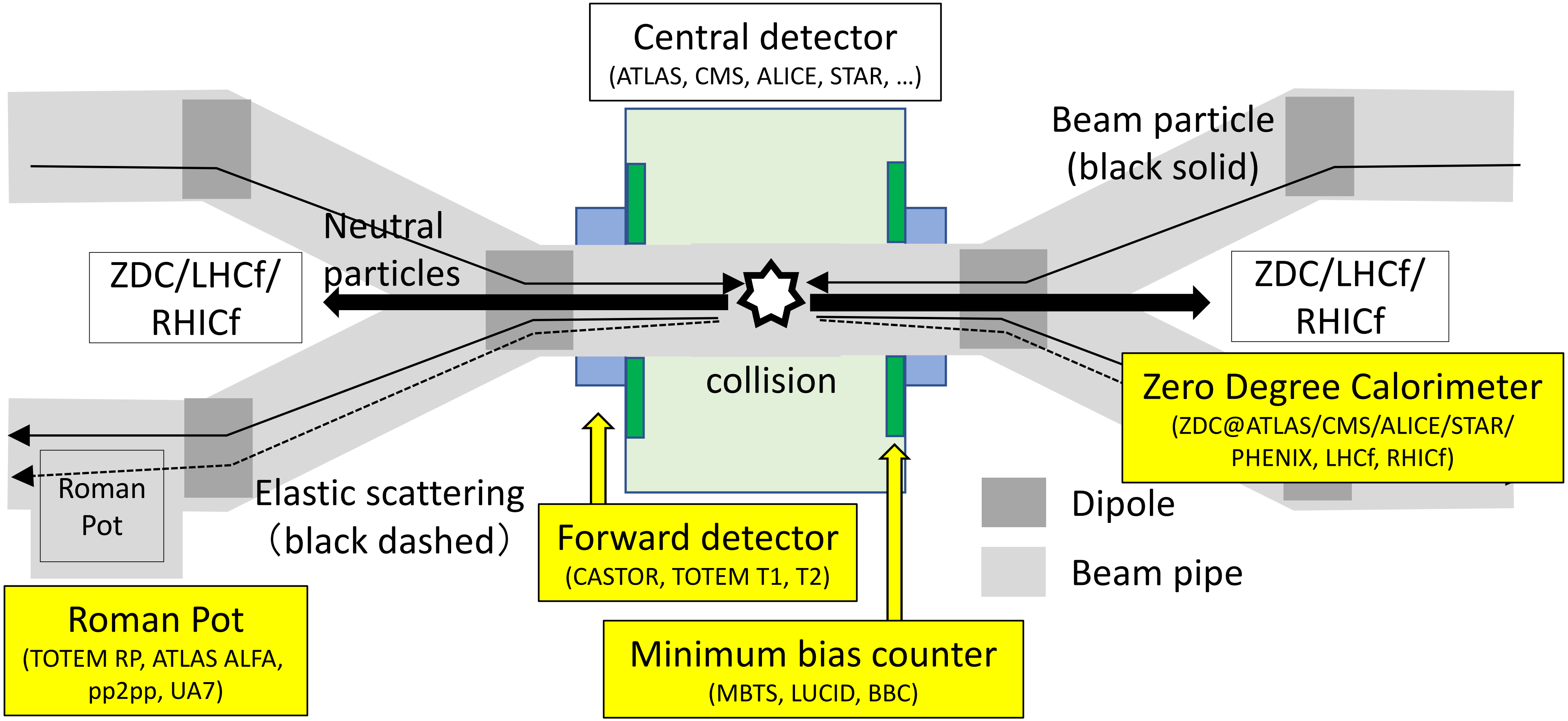
  - experimental difficulty

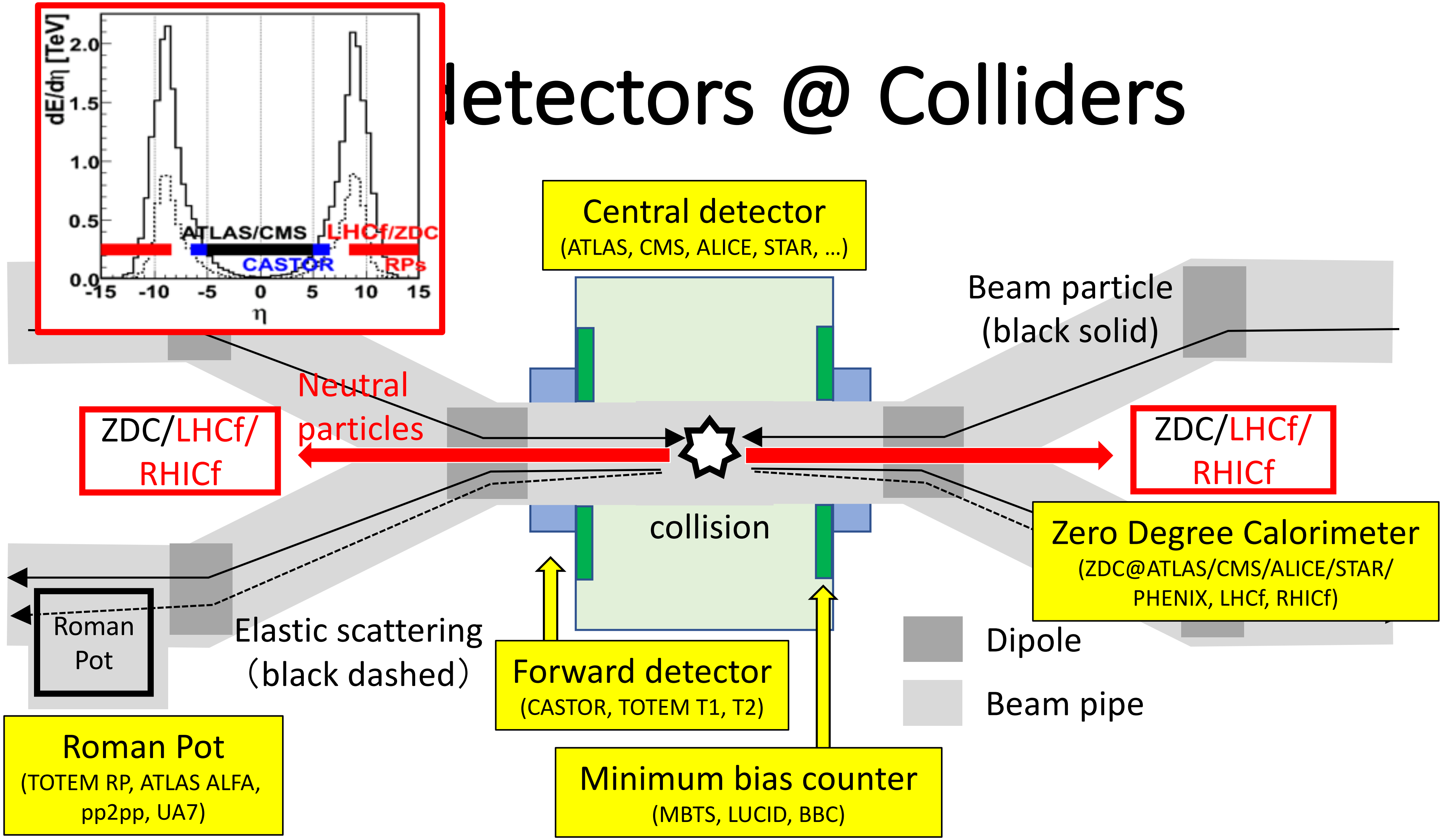
Forward detectors @ Colliders



- ✓ CMS CASTOR and TOTEM T1/T2 cover most forward at CMS
- ✓ TOTEM/ALFA roman pots are powerful for total cross section measurements
- ✓ ZDC/LHCf/RHICf cover neutral particles at zero degree

(zero degree measurement is possible only in p-p, but not in p-pbar)

detectors @ Colliders



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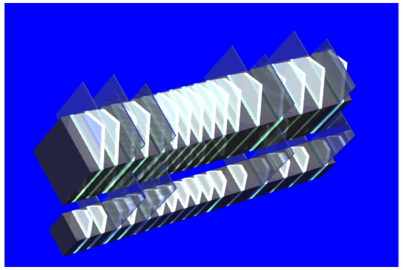
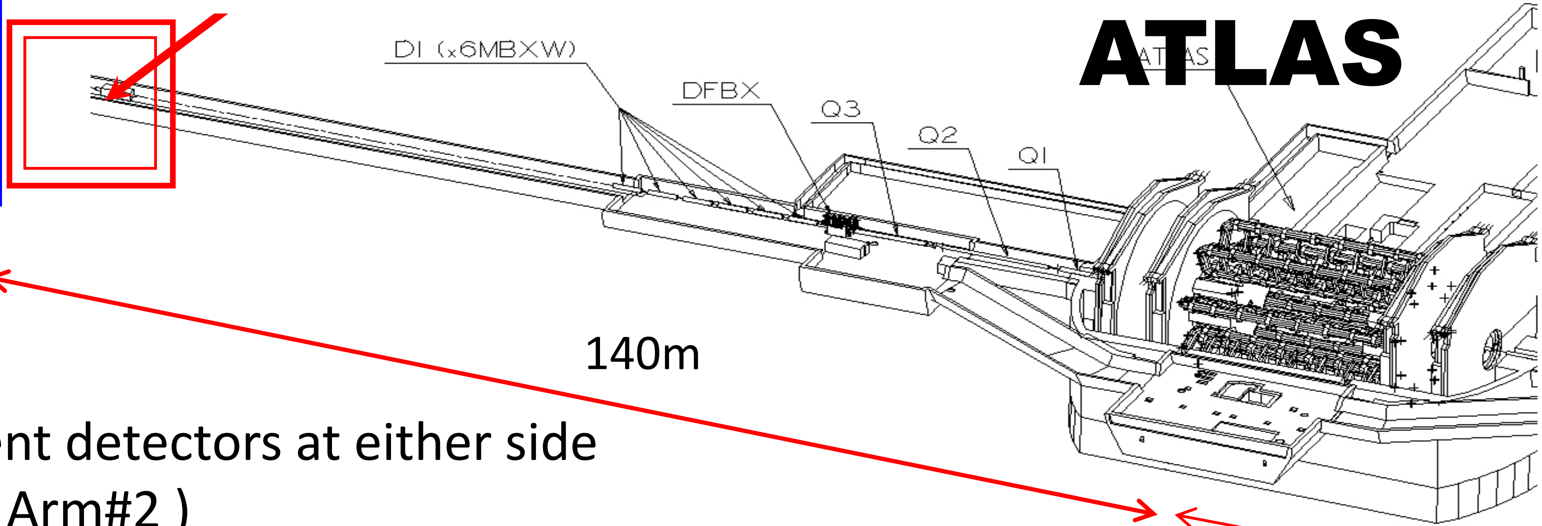
The LHC forward experiment

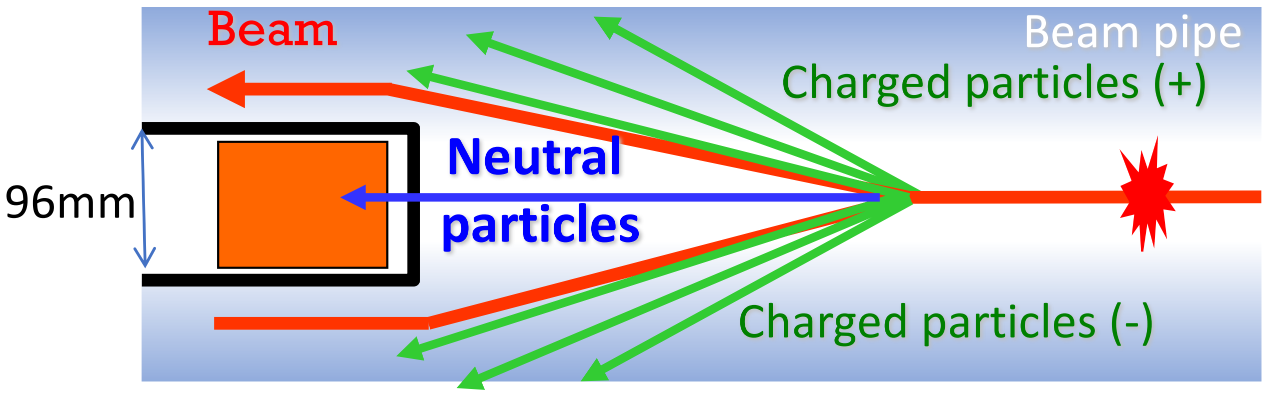


LHCf Arm#1

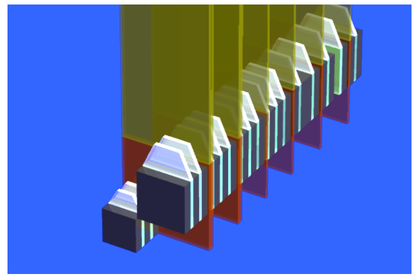


140m

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



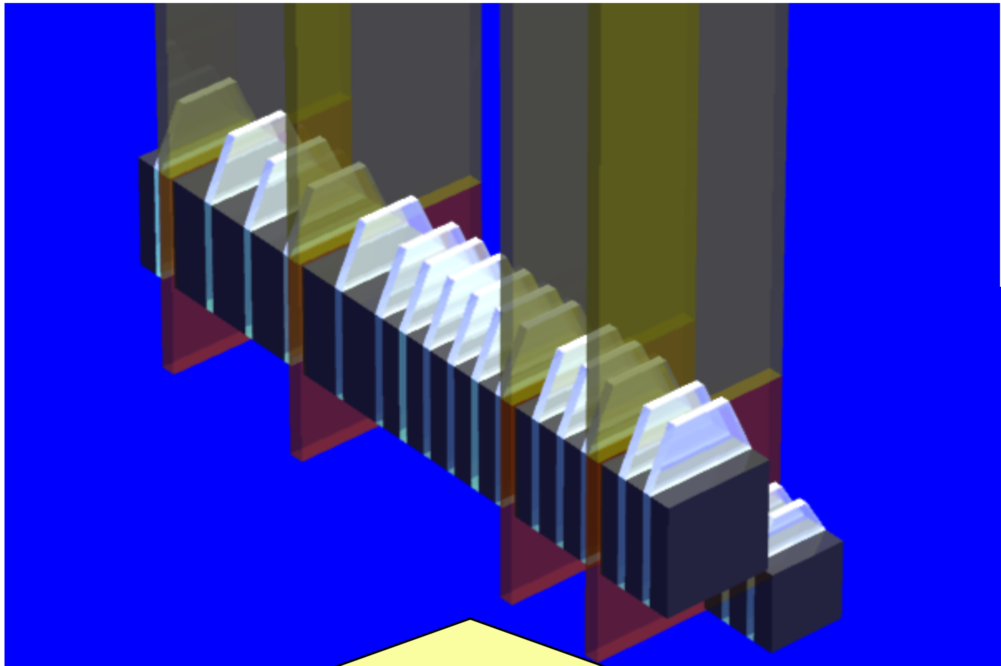
LHCf Arm#2



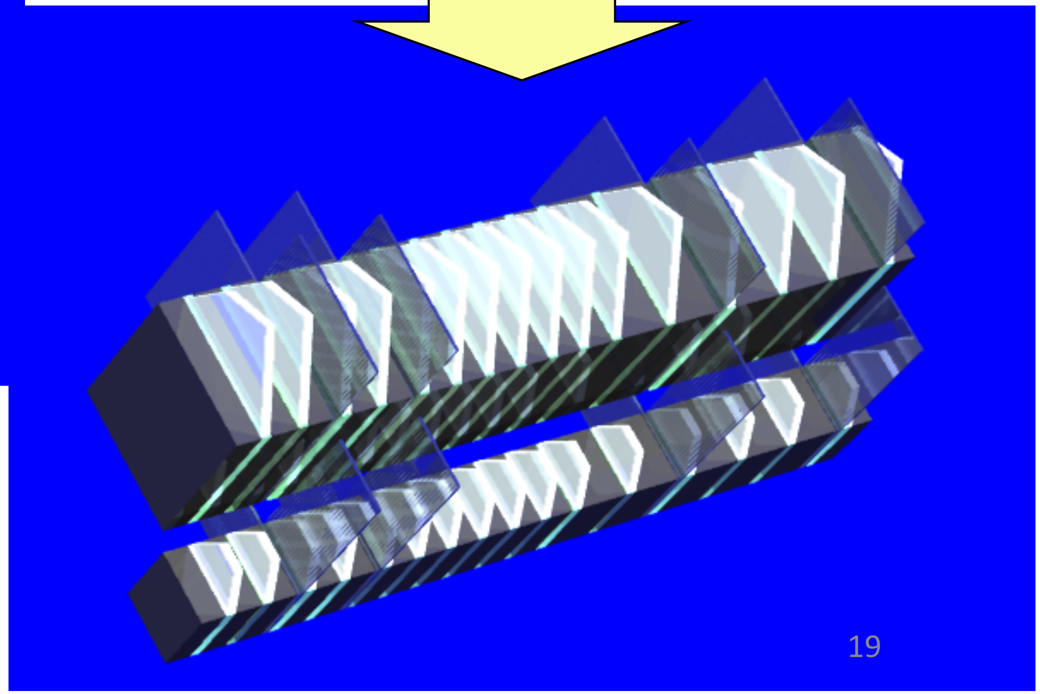
- ✓ All charged particles are swept by dipole magnet
- ✓ Neutral particles (photons and neutrons) arrive at LHCf
- ✓ η>8.4 (to infinity) is covered

LHCf Detectors

- ✓ Imaging sampling shower calorimeters
- ✓ Two calorimeter towers in each of Arm1 and Arm2
- ✓ Each tower has 44 r.l. (1.6λ) of Tungsten,16 sampling scintillator and 4 position sensitive layers
- ✓ Plastic scintillators => GSO scintillators, SciFi => GSO bars in Run2



LHCf Arm#1 Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT



LHCf Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

LHCf Detectors

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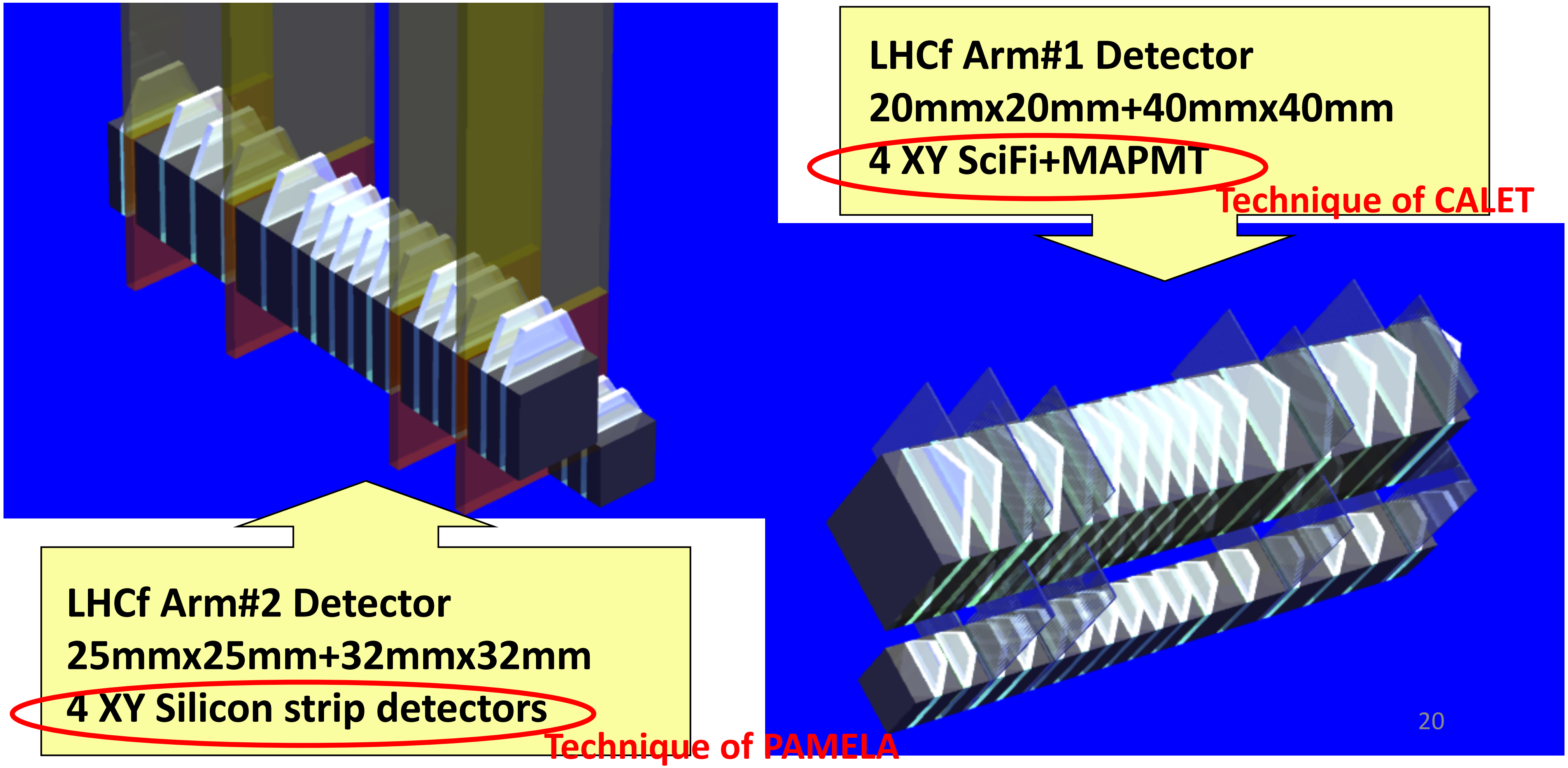
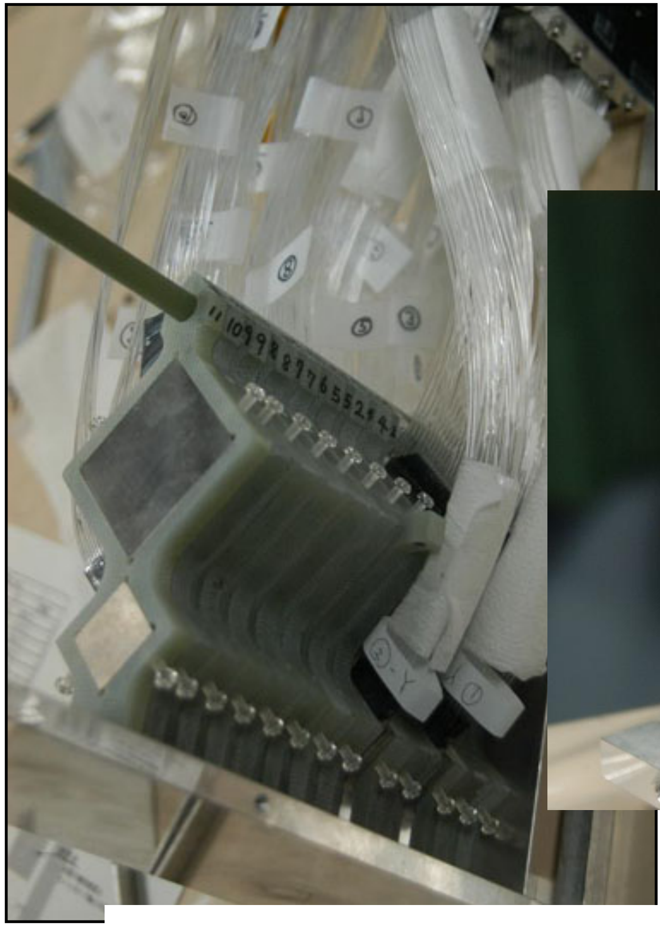
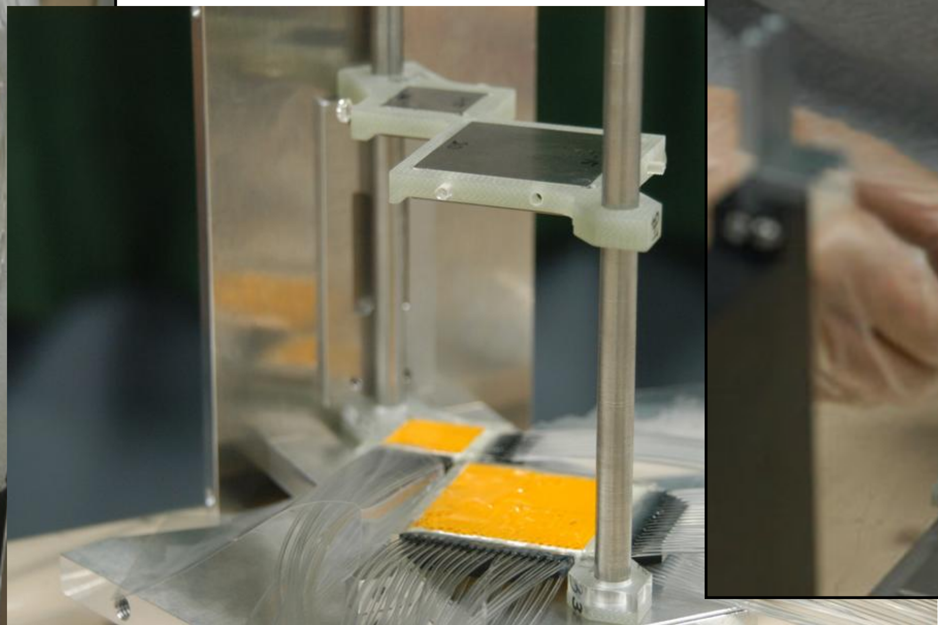
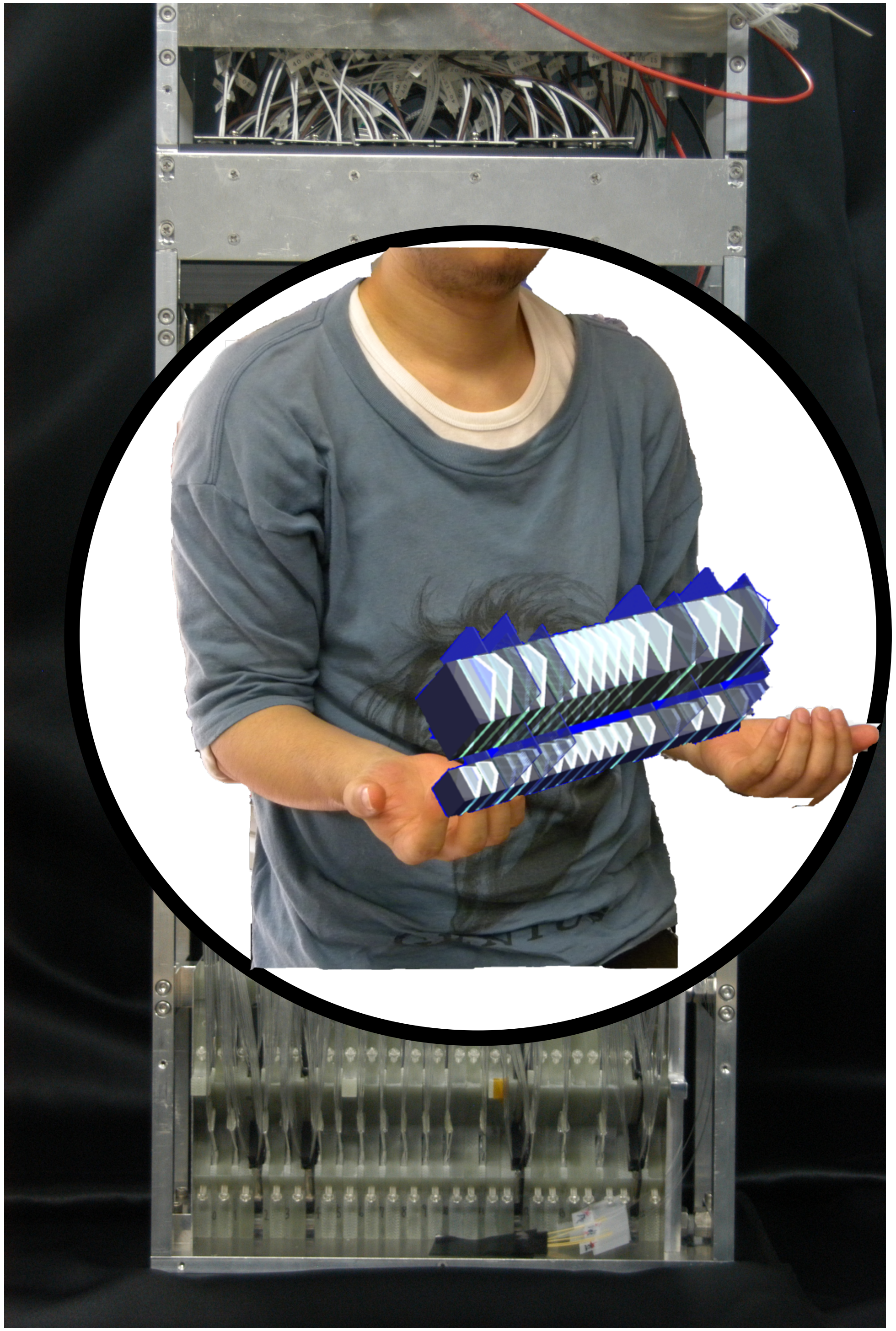


Detector construction in Japan and Italy

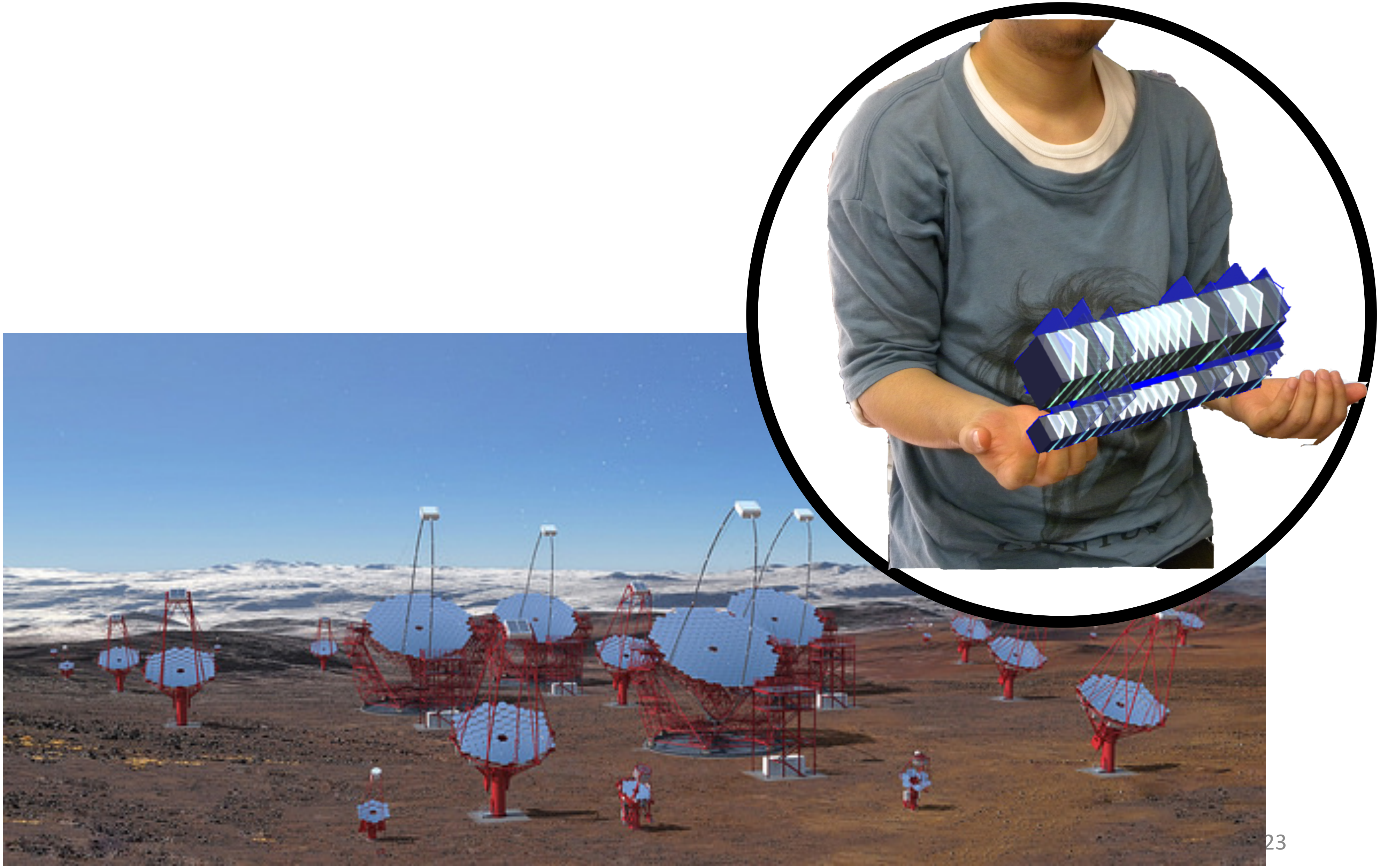




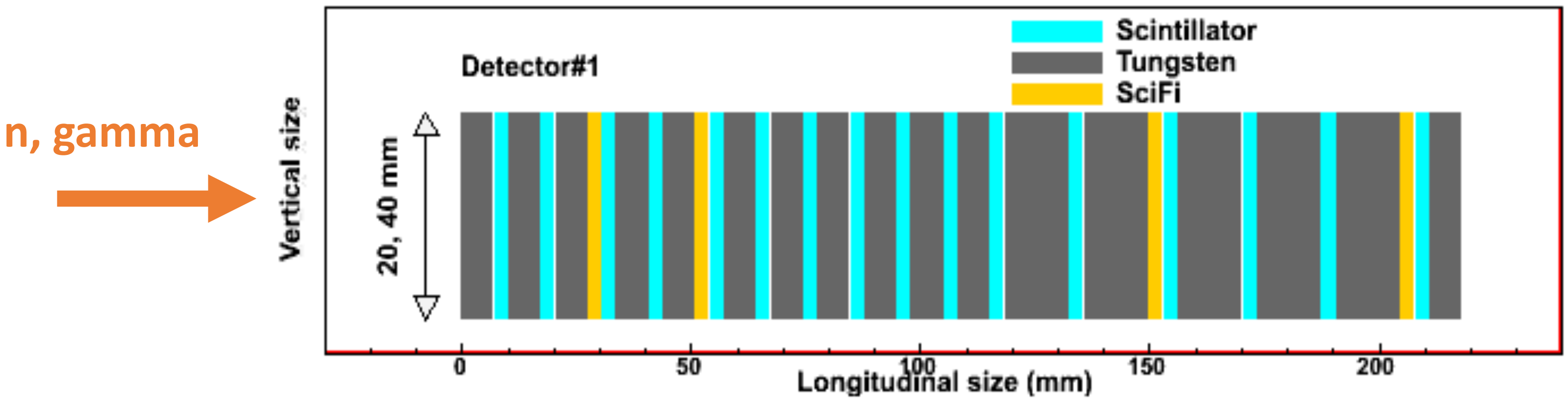
- All of design, construction, calibration of the detectors, data acquisition and analyses are led by the Nagoya U group

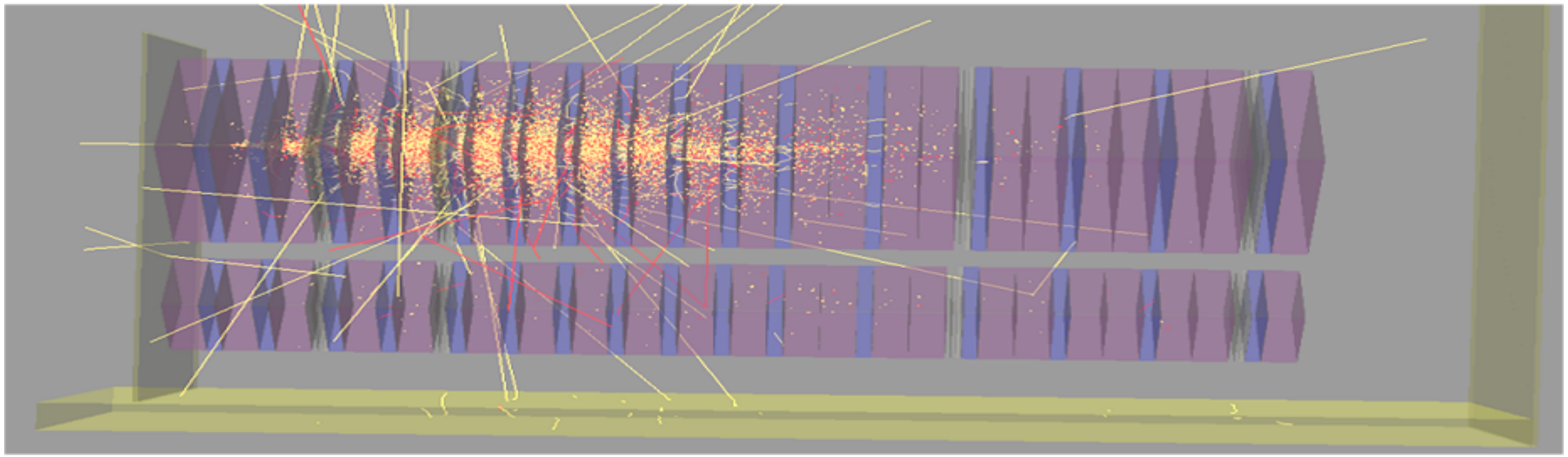

290mm
90mm


Largest and Smallest TeV gamma-ray detectors



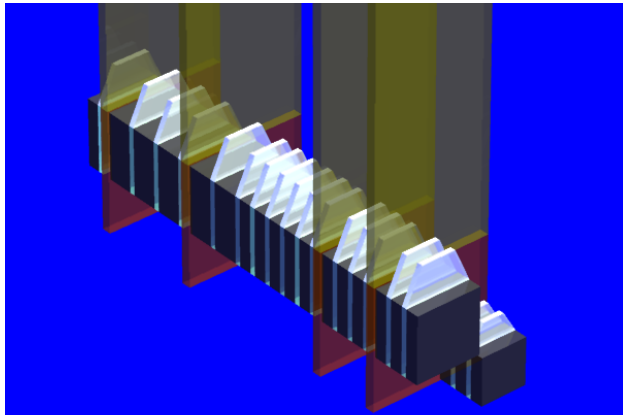
Sampling calorimeter



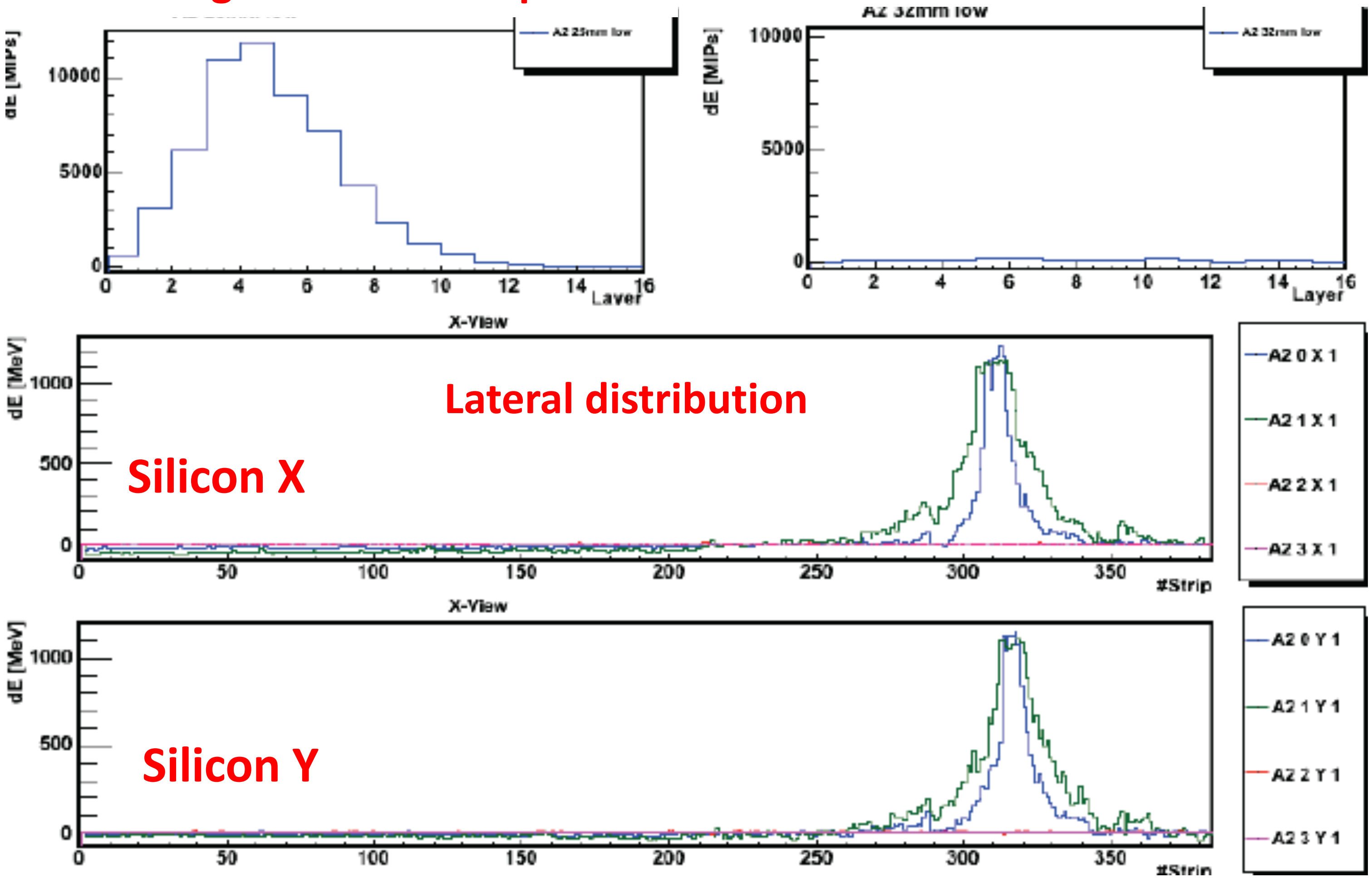


- Incident particles develop showers in Tungsten
- Deposited energy is sampled by scintillators interleaved (3% for EM showers)
- Four strip detector layers record lateral distribution of showers

Event example @ LHC



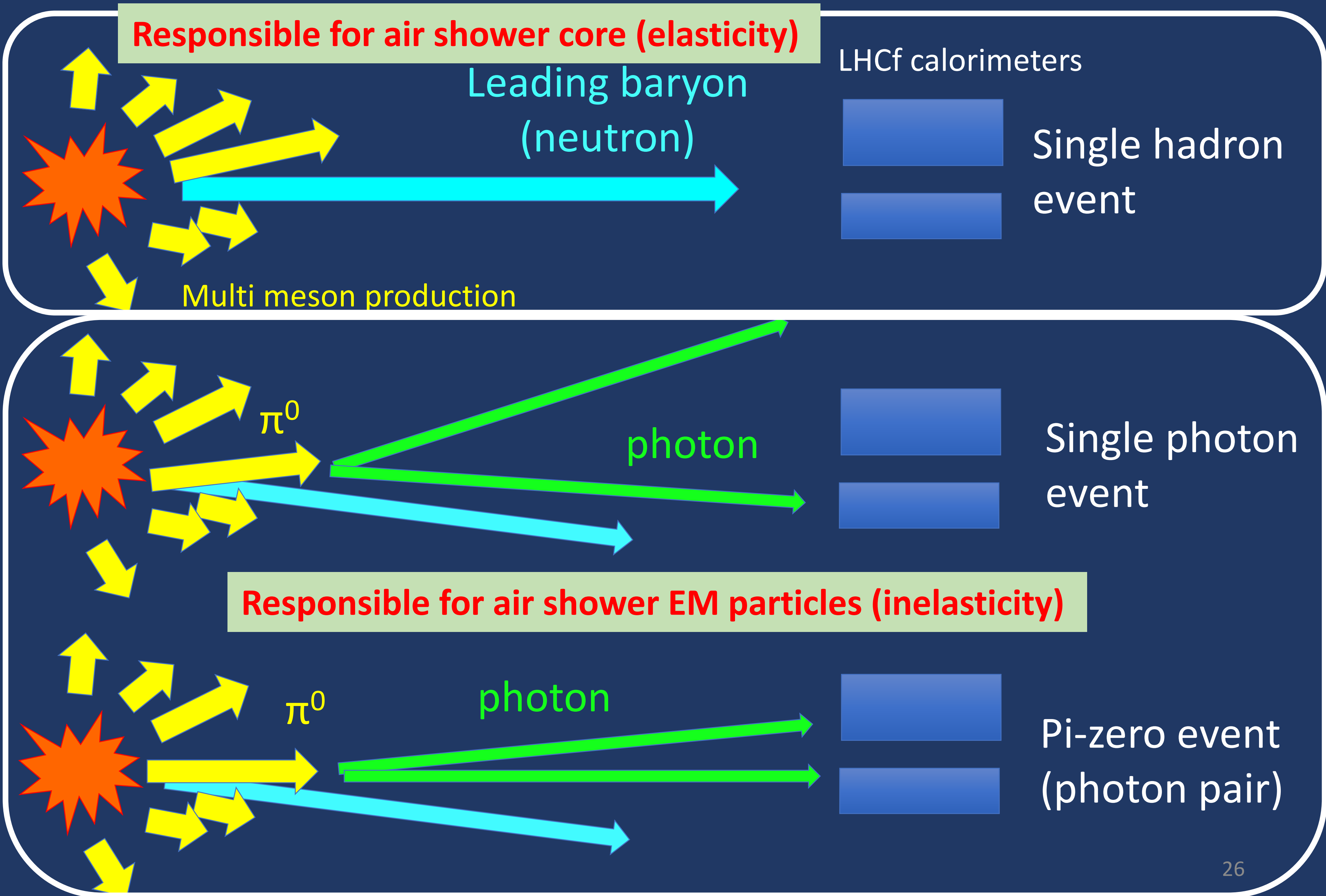
Longitudinal development



Energy
Particle ID

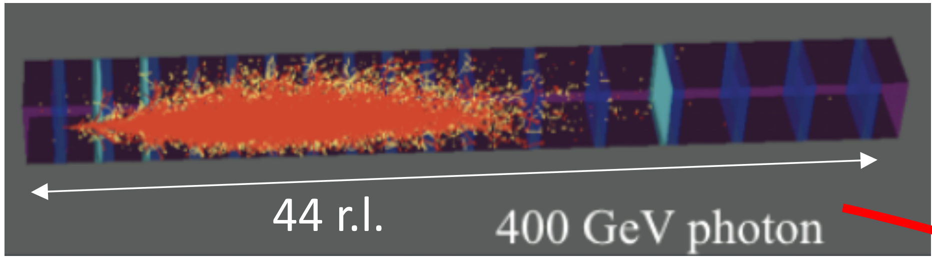
Incident position
Nb. of incident

Event categories of LHCf

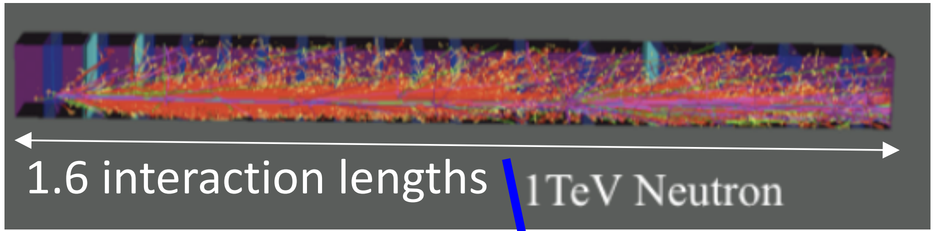


Particle ID (PID)

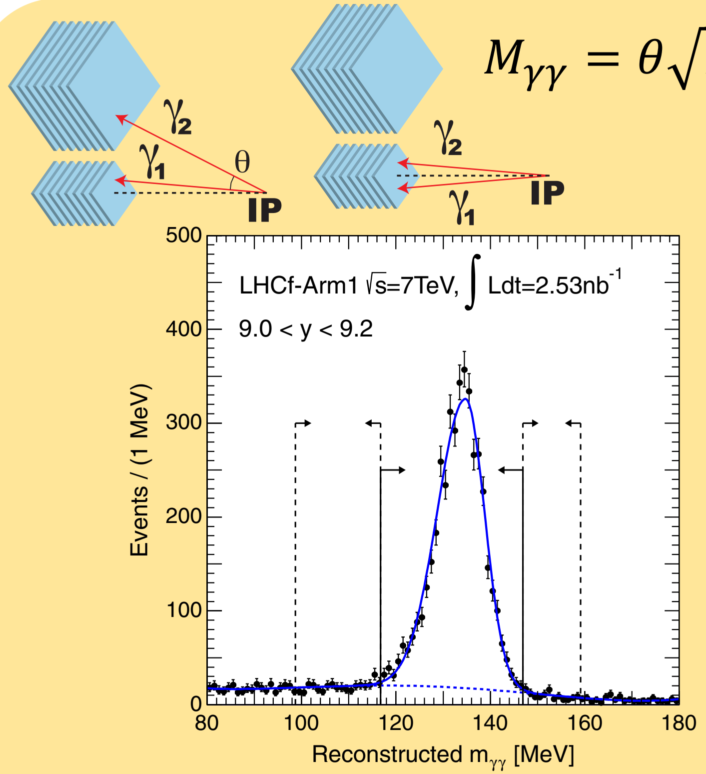
Photon event



Neutron event

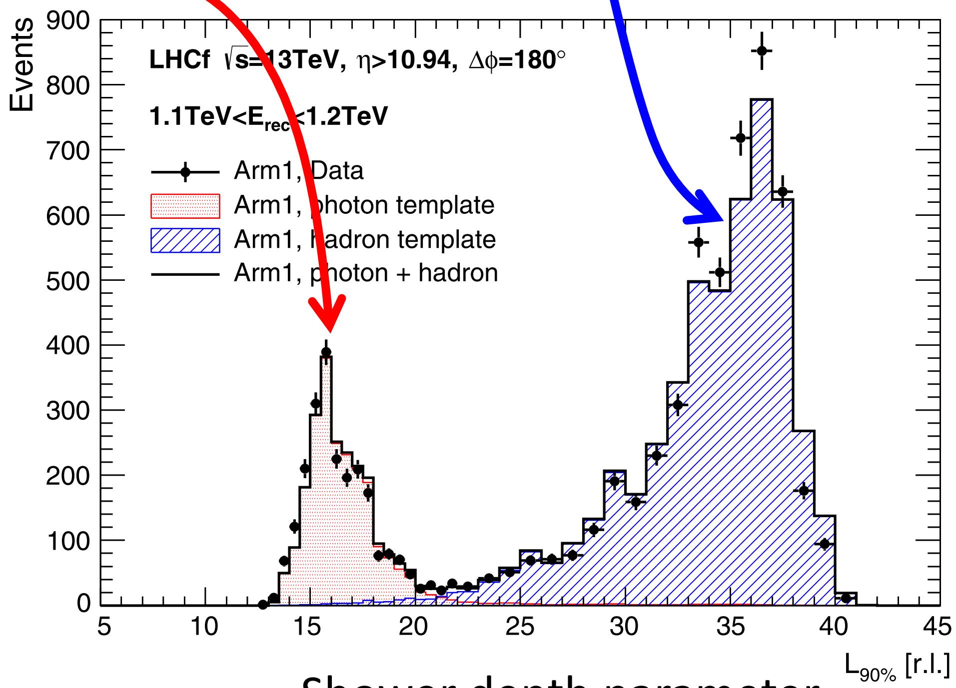


$$M_{\gamma\gamma} = \theta\sqrt{E_1 E_2}$$



Invariant mass of photon pair
Peak @ 135MeV from π^0 decay events

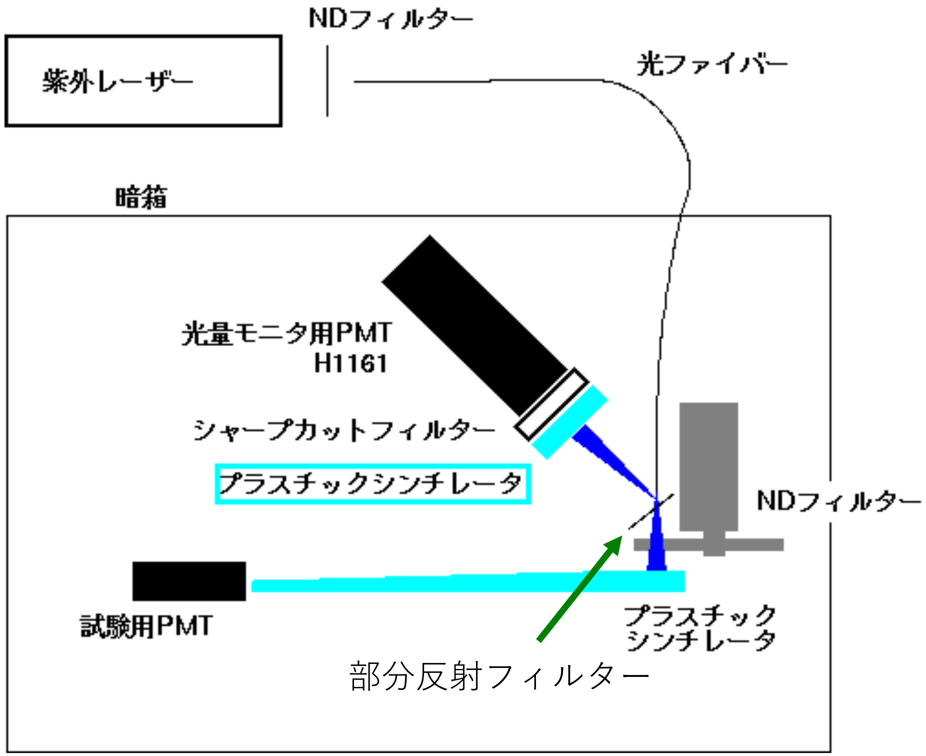
(Adriani et al., PRD, 2012)



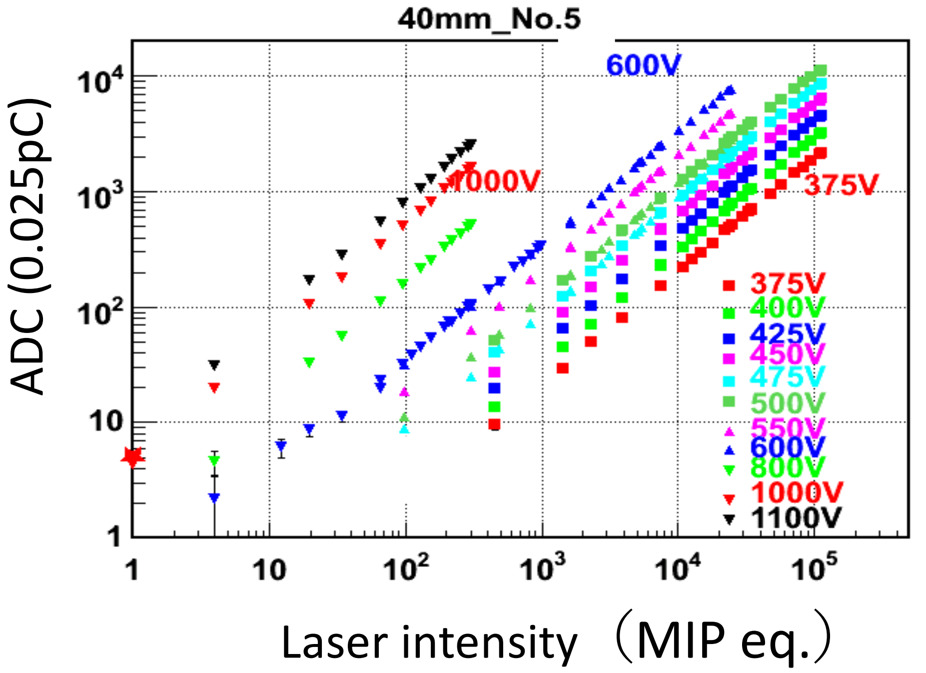
Shower depth parameter

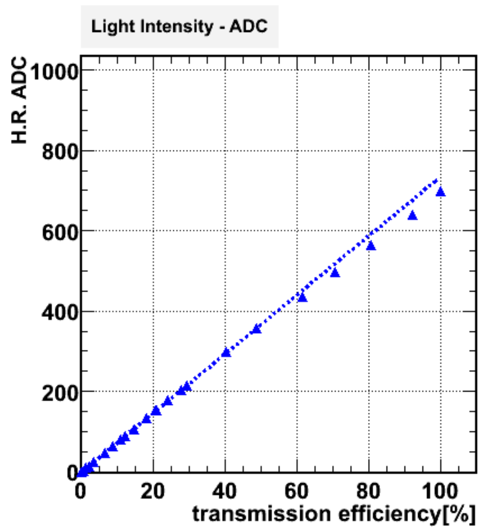
(Adriani et al., PLB, 2018)

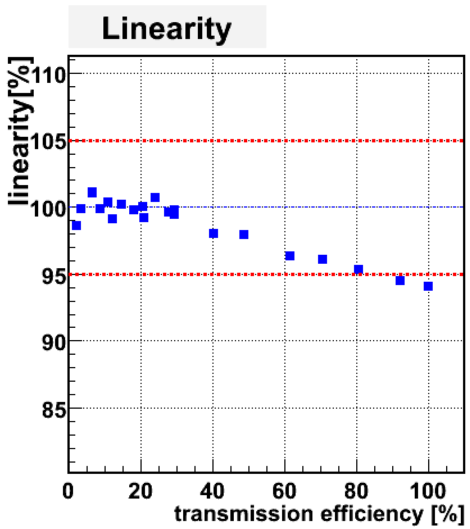
Dynamic range and linearity test using UV pulse laser



結果:各HVにおける光量とADC値の関係



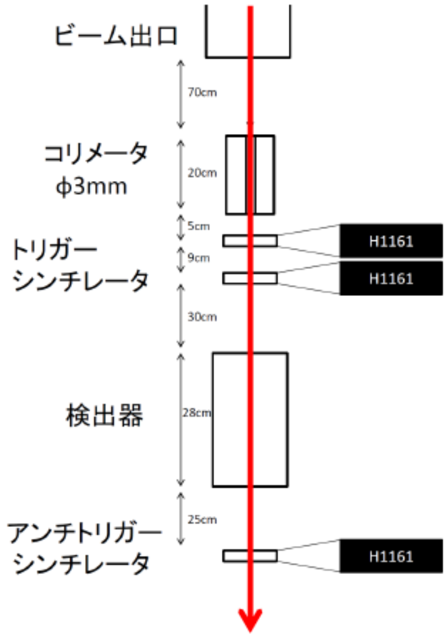


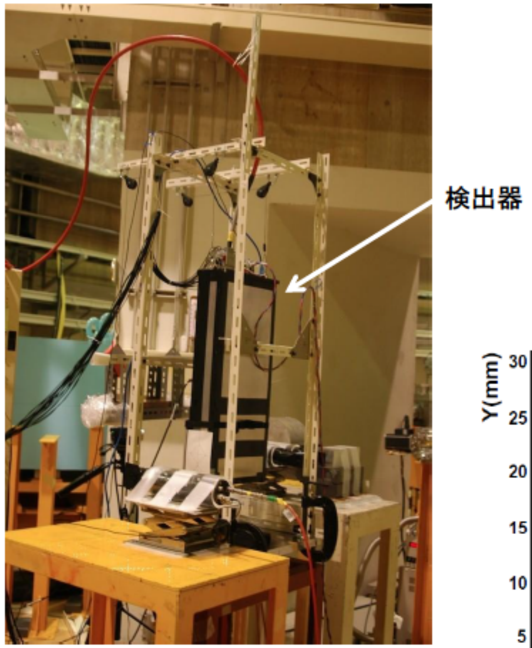


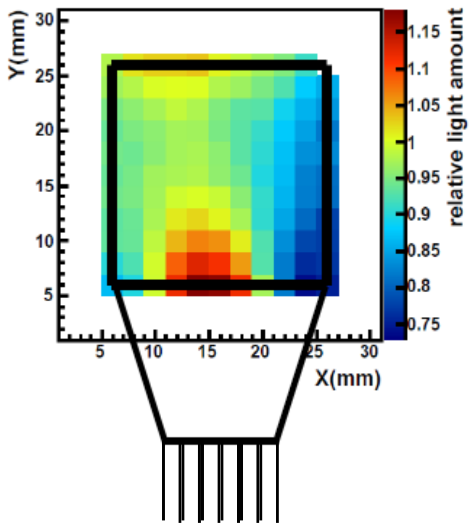
N_2 laser（KEN-1020）
- 337.1nm
- 0.3ns pulse

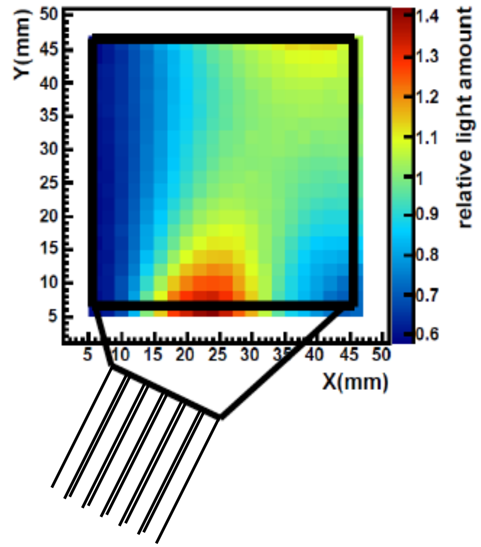
Scintillators with τ=9.6ns (EJ-260) and τ=30ns (GSO) are used to avoid saturation

Non-uniformity calibration at HIMAC





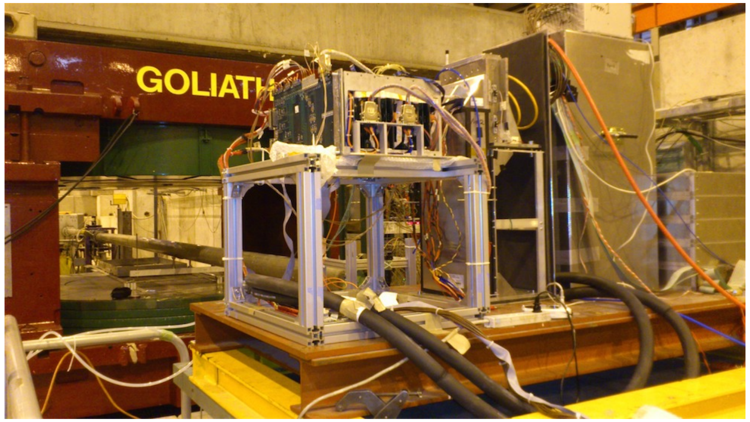


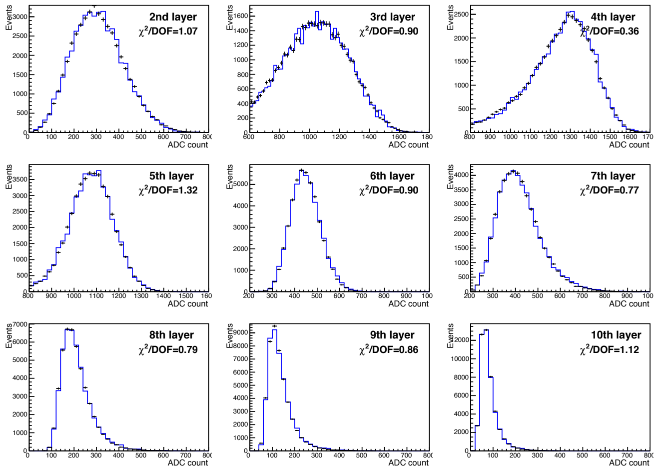


- ➢ Calorimeters WITHOUT tungsten layers were scanned over the ion beam
- ➢ Signal intensity as a function of the position was extracted

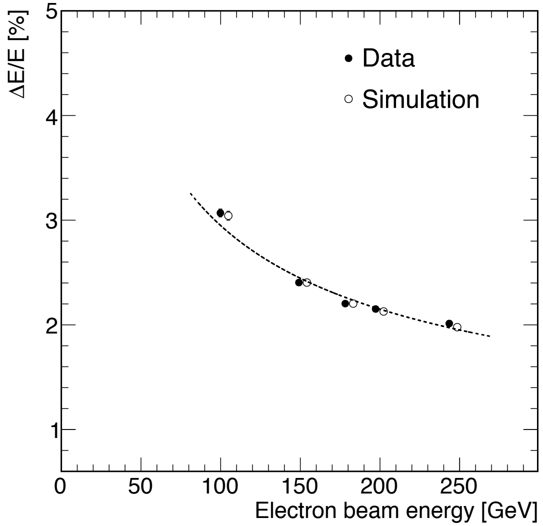
Detector performance @ CERN SPS

Y.Makino et al., JINST 12 P03023 (2017)



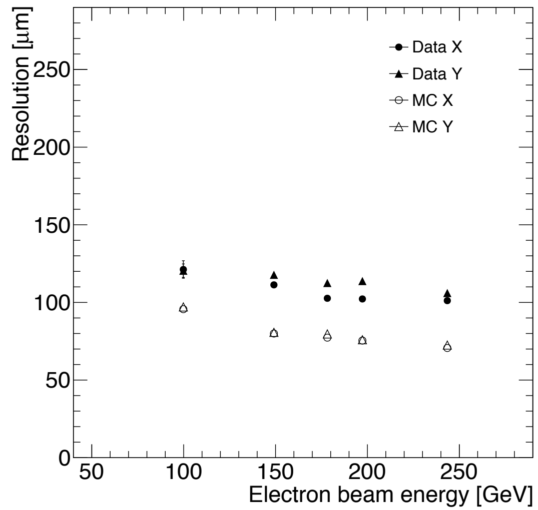


Energy resolution



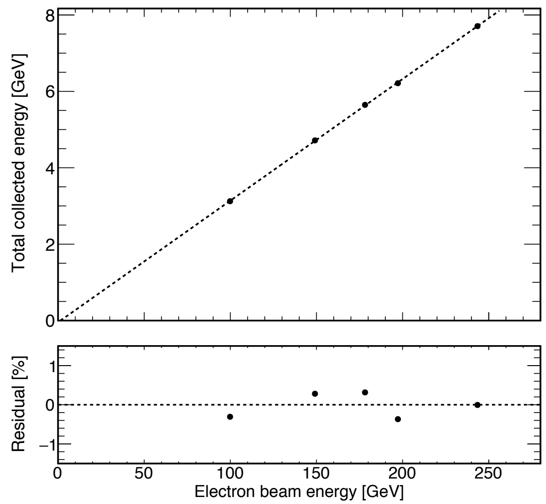
(a) 20 mm

Position resolution



(a) 20 mm 1st layer

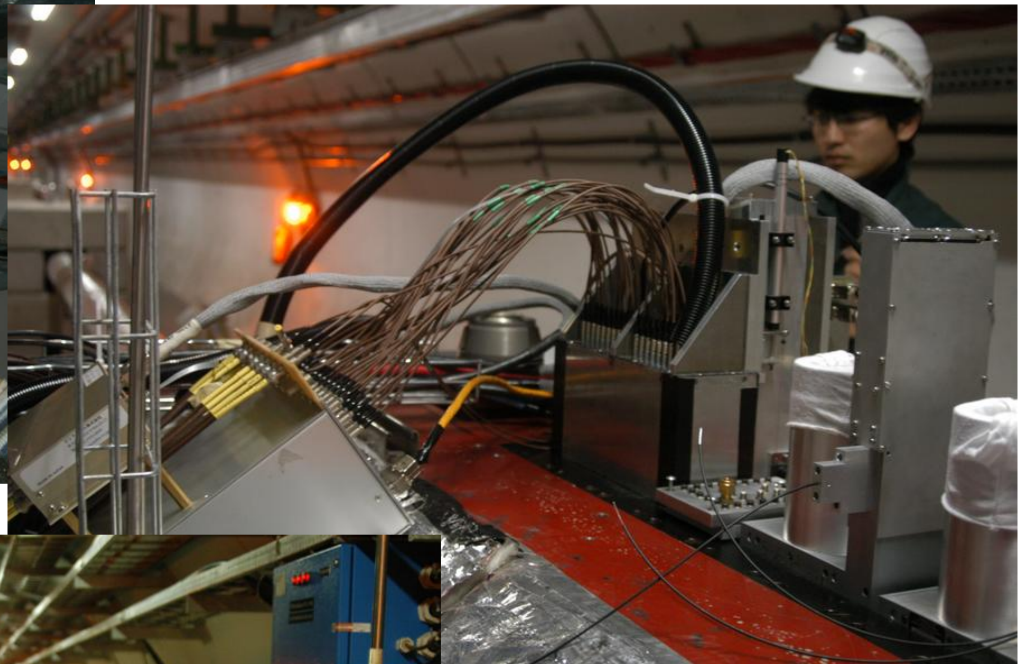
Energy linearity

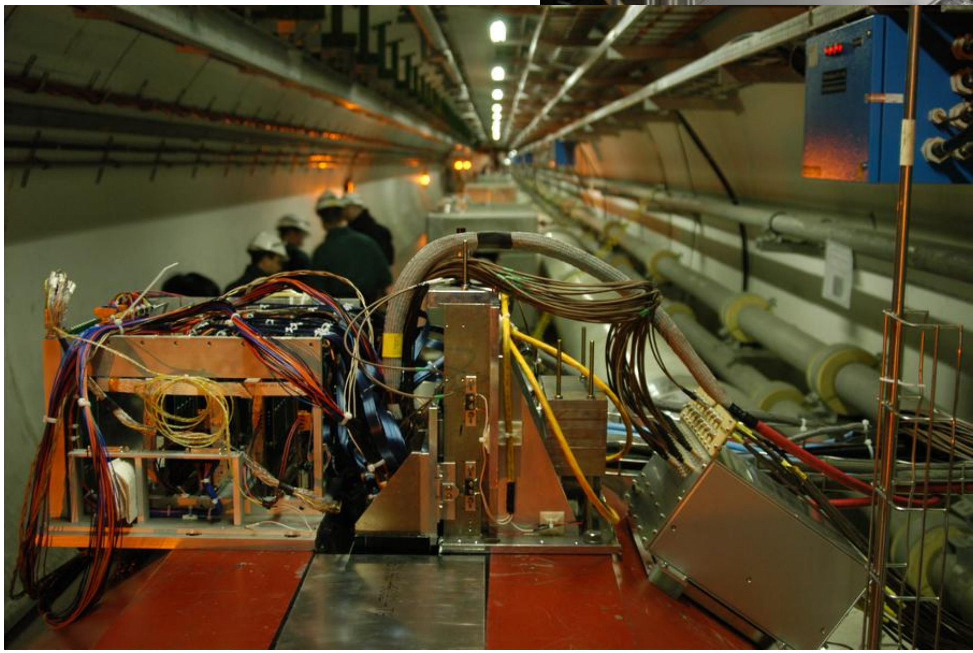


(a) Arm1: 20 mm tower.

- Beam test using 100-250GeV electron and proton beams
- Charge to energy calibration factors
- ∑dE to E function
- Energy resolution, linearity, position resolutions

Installation into the LHC tunnel





LHCf/RHICf 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 polarized p-p collision as RHICf

Publications

physics results

performance results

	Photon (EM shower)	Neutron (hadron shower)	π^0 (limited acceptance)	π^0 (full acceptance)	Performance
Beam test	**NIM, A671 (2012) 129-136**	**JINST, 9 (2014) P03016**			
0.9TeV p-p	**PLB, 715 (2012) 298-303**				**IJMPA, 28 (2013) 1330036**
7TeV p-p	**PLB, 703 (2011) 128-134**	**PLB, 750 (2015) 360-366**	**PRD, 86 (2012) 092001**	**PRD, 94 (2016) 032007**	
2.76TeV p-p			**PRC, 89 (2014) 065209**		
5.02TeV p-Pb					
13TeV p-p	**PLB, 780 (2018) 233-239**	Analysis in progress			

Publications

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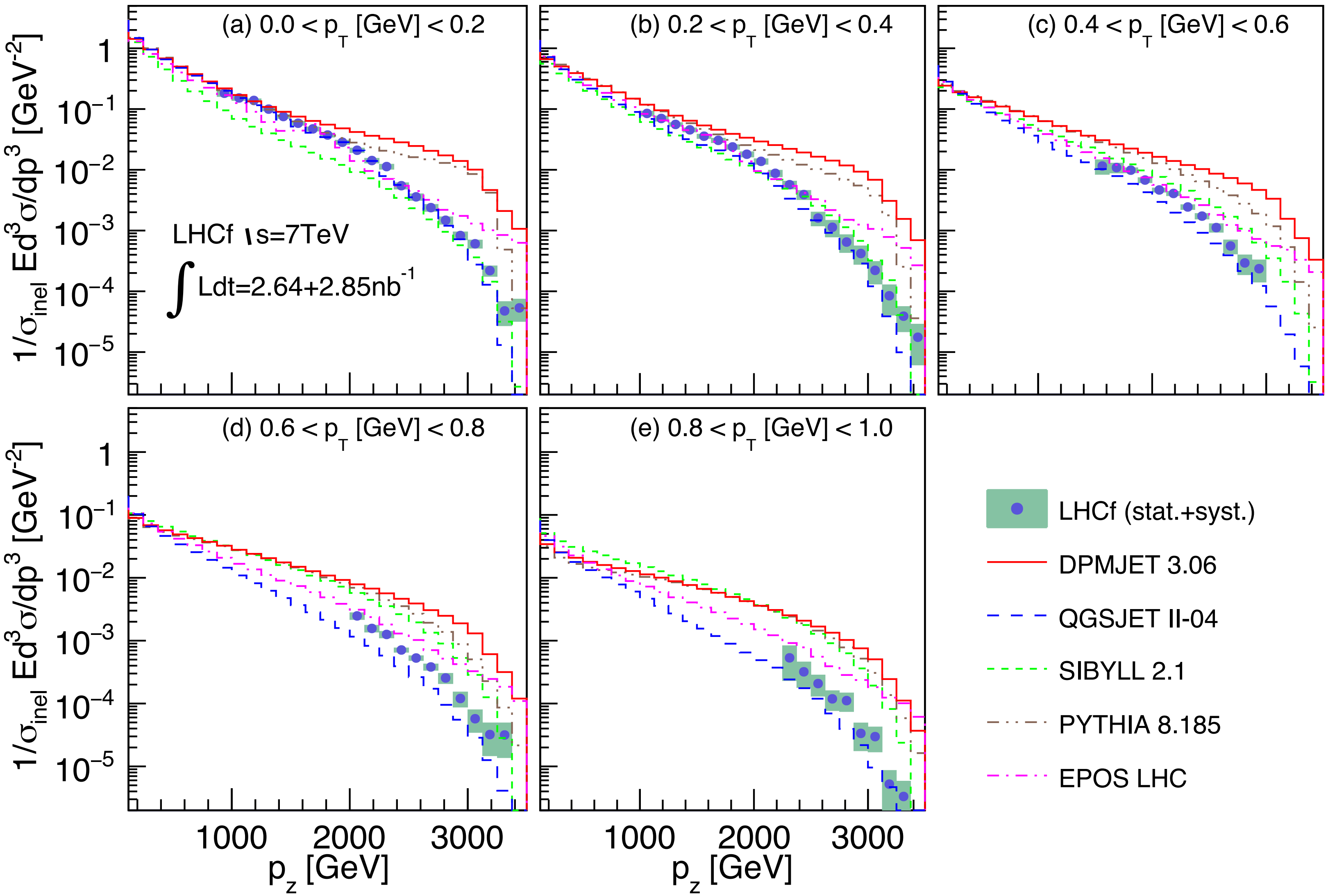
13TeV p-p	**PLB, 780 (2018) 233-239**	Analysis in progress			

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

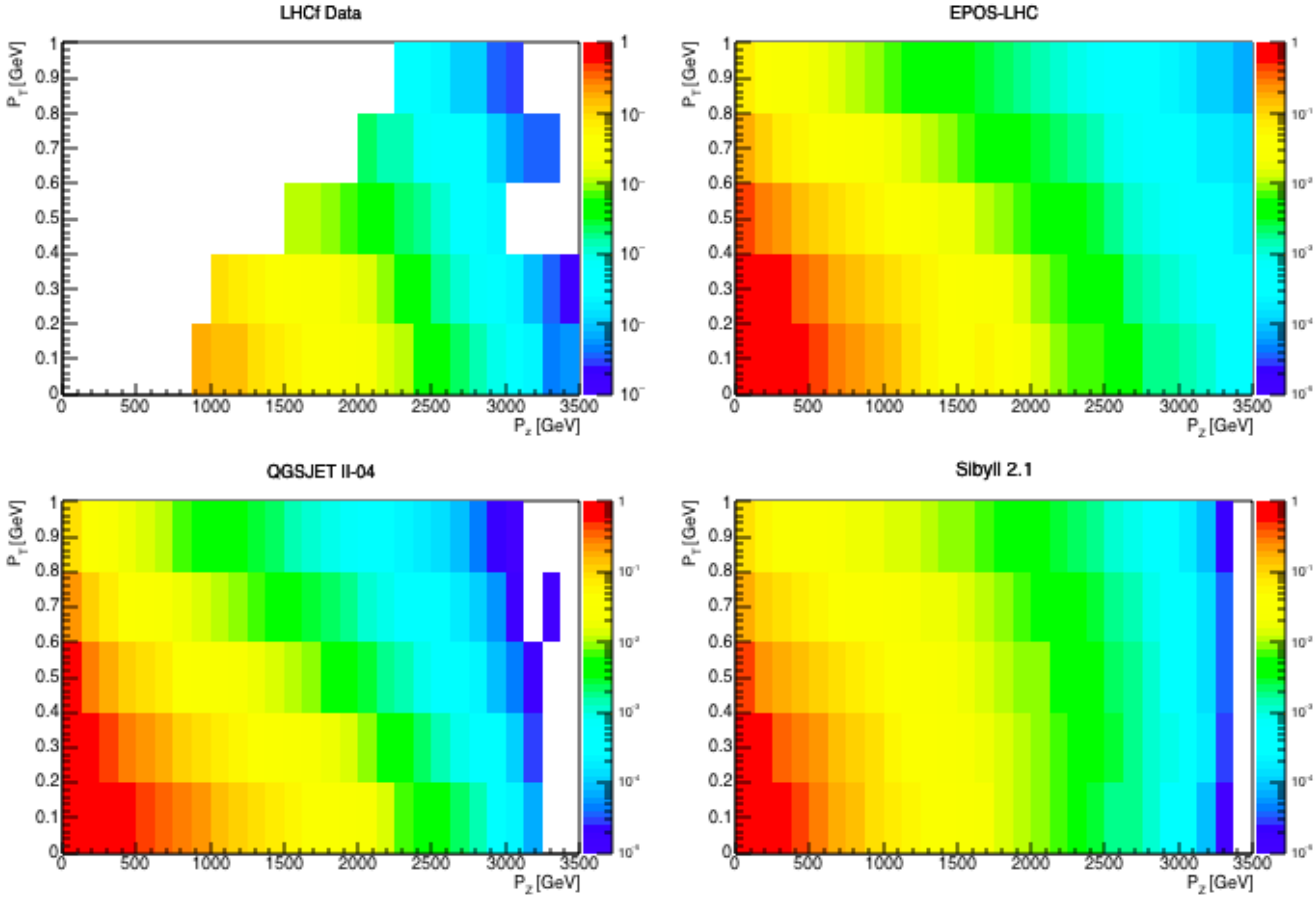
(PRD, 94 (2016) 032007)



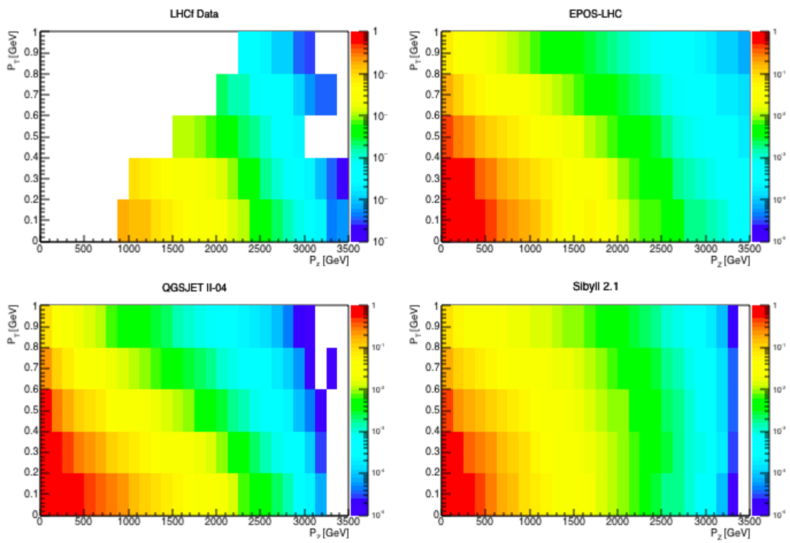
✓ DPMJET3 and PYTHIA8 overestimate over all E-p_T range

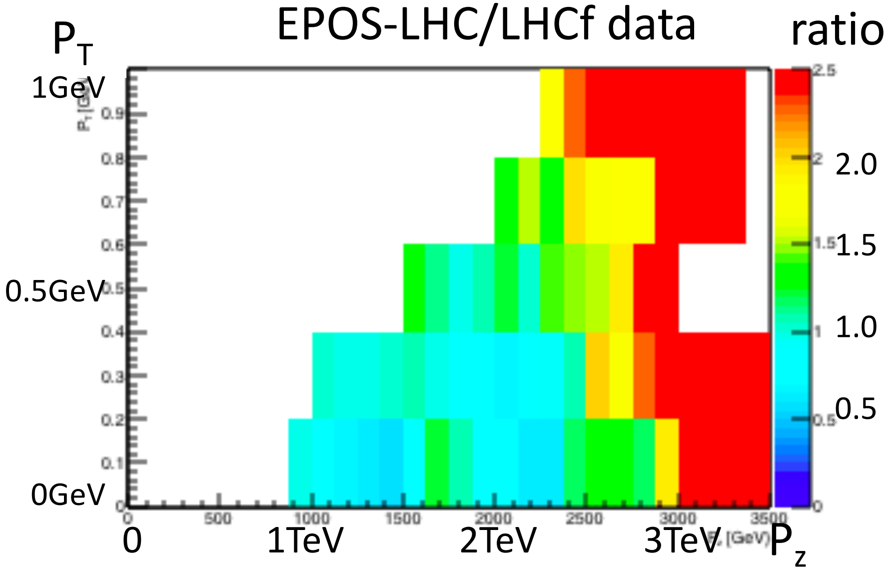
✓ EPOS-LHC and QGSJET II-04, standard in air shower MC, are not bad

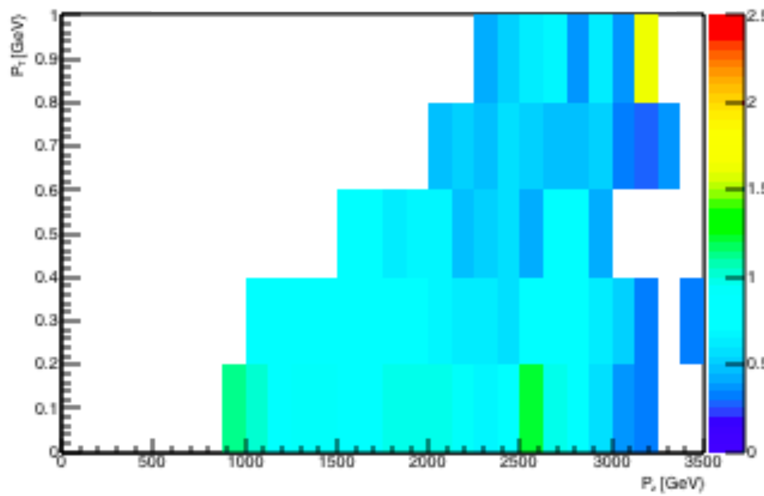
π^0 in 7TeV p-p collision
LHCf and models

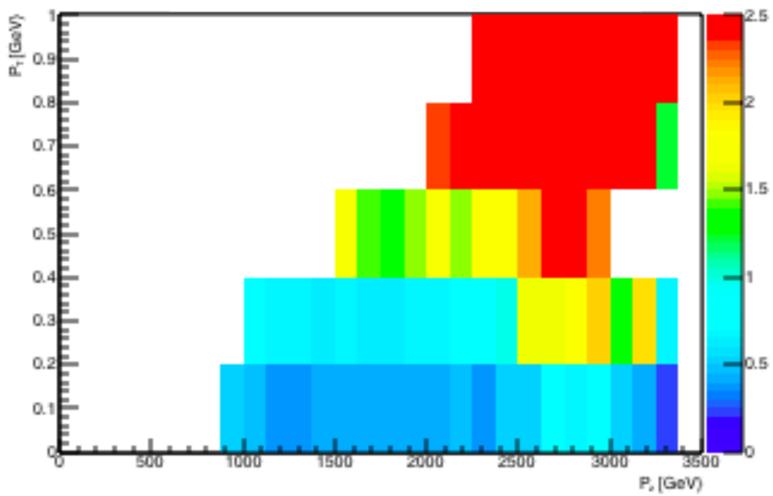


π^0 in 7TeV p-p collision
LHCf and models (ratio to data)



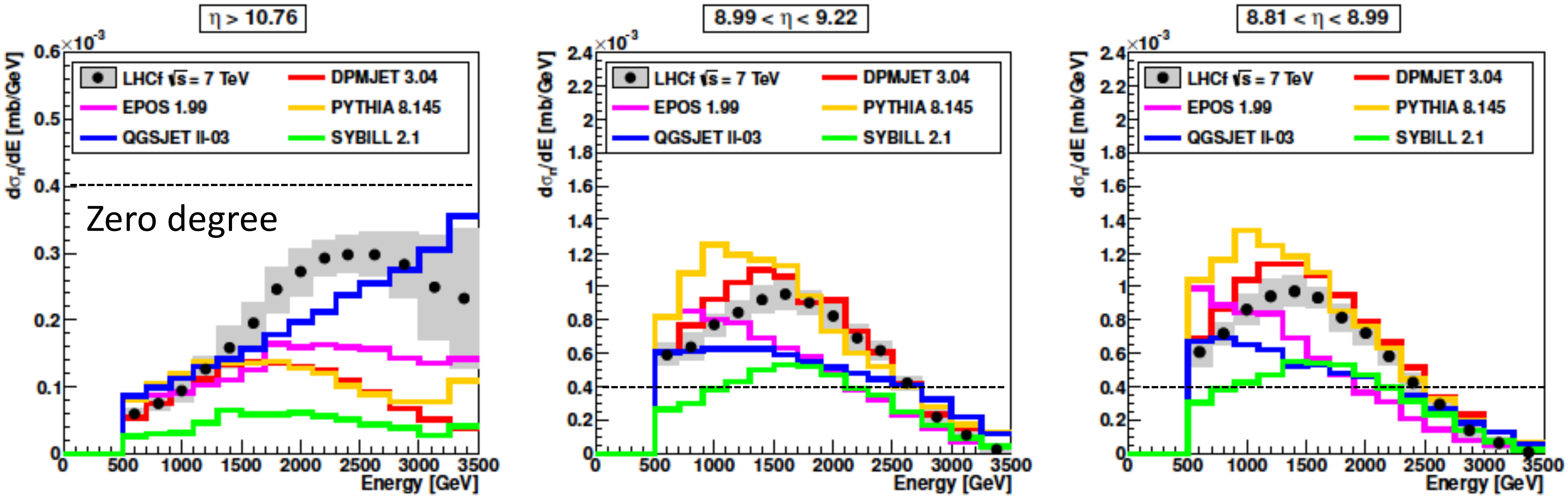






Neutrons in 7TeV p-p collision

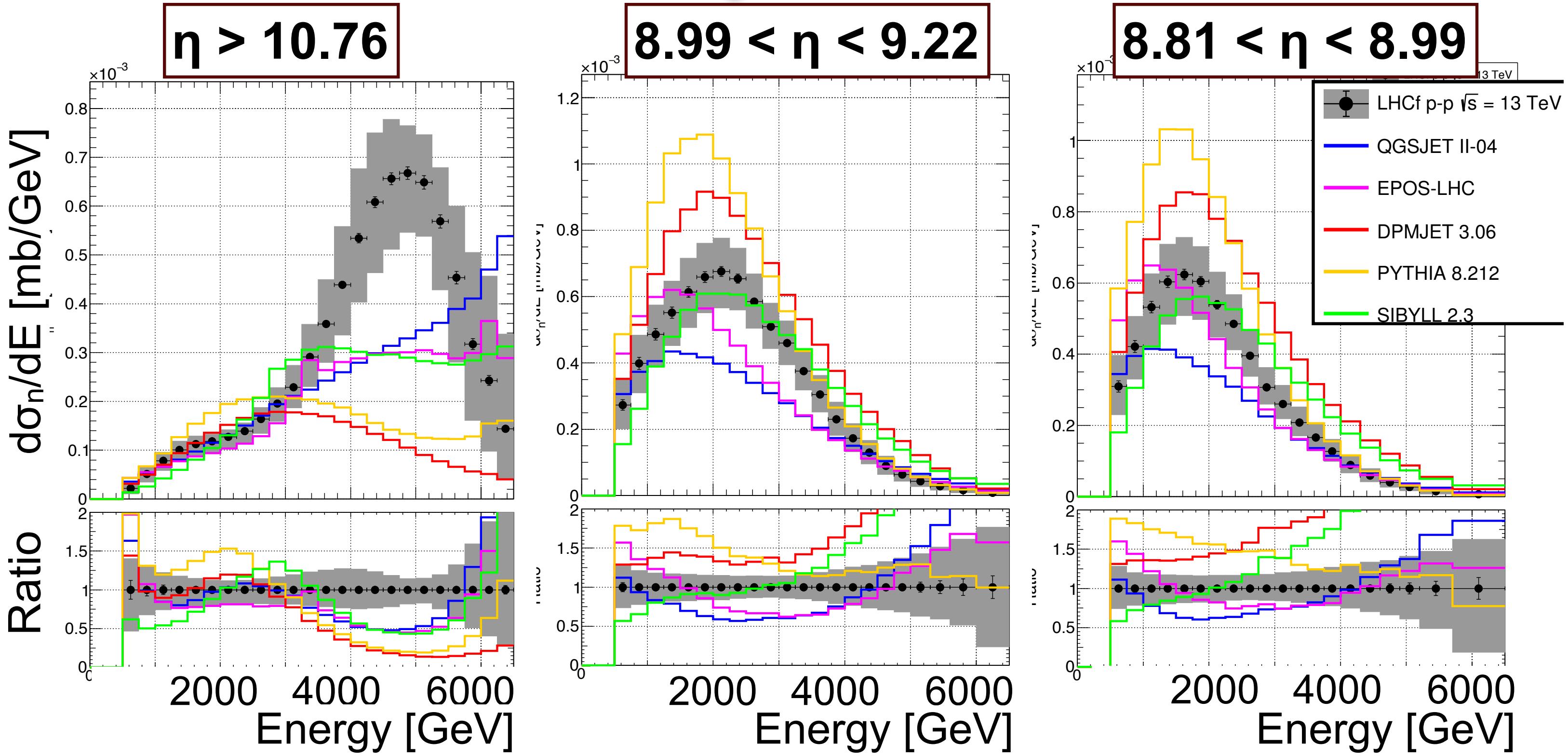
(√s=7TeV p-p ; PLB 750 (2015) 360-366)



(~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.

Neutron, p-p √s=13TeV Unfolded Spectra



- In η > 10.76, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

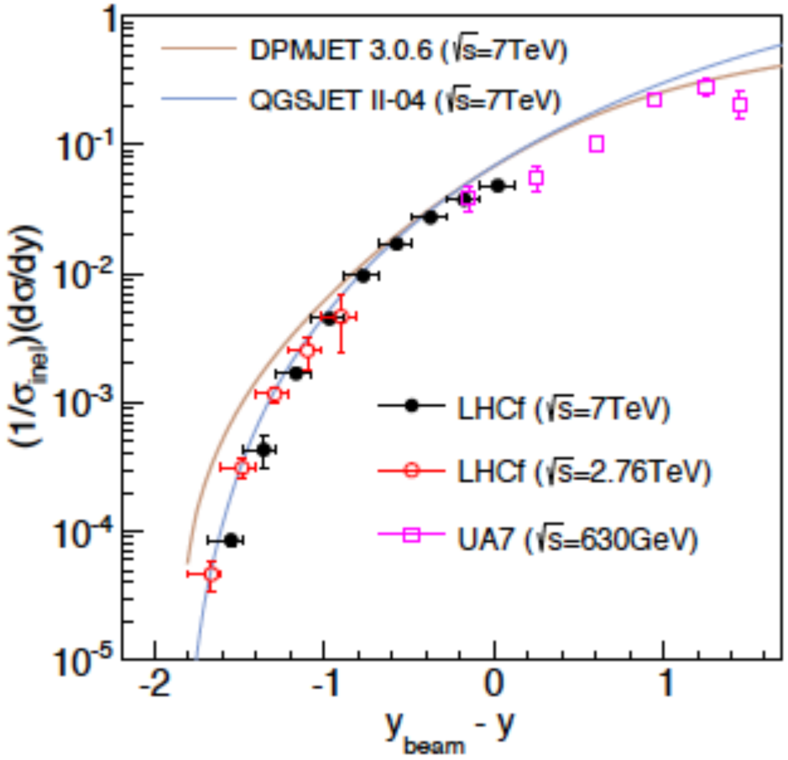
28-Feb.-2018 133rd LHCC Meeting 8

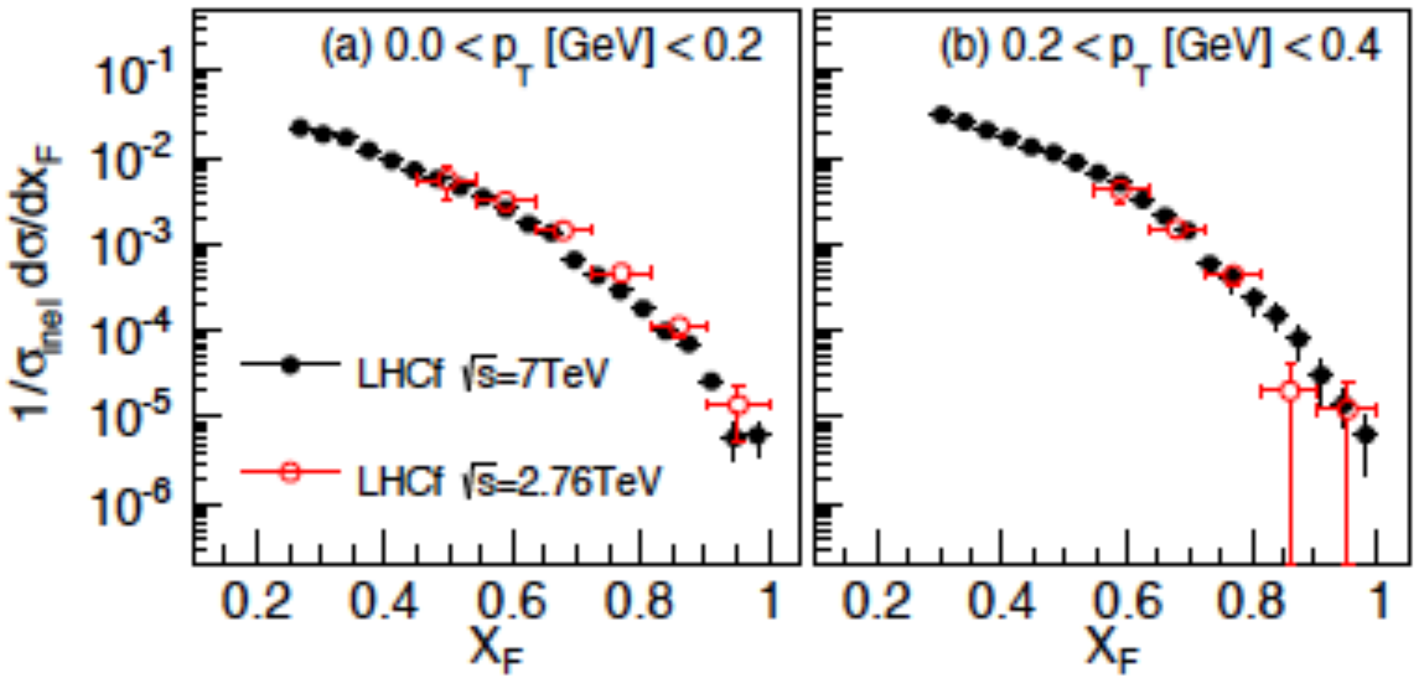
- High-energy peak @ 0 degree is also confirmed with the 13TeV data
- NOTE: p_T coverage is different from the 7TeV analysis

√s scaling ; π^0

collision energy (in)dependence

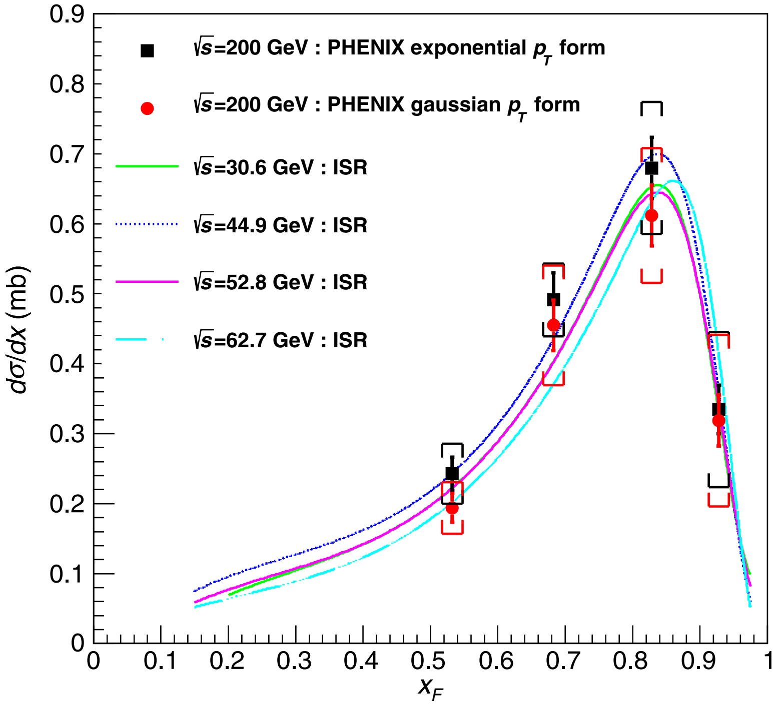
- ✓ Scaling is essential to extrapolate beyond LHC
- ✓ (630GeV –) **2.76TeV – 7TeV**
  good scaling within uncertainties
- ✓ Wider coverage in y and p_T with 13TeV data
- ✓ Wider √s coverage with RHICf experiment in 2017 at √s=510GeV





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

√s scaling; Neutron @ zero degree

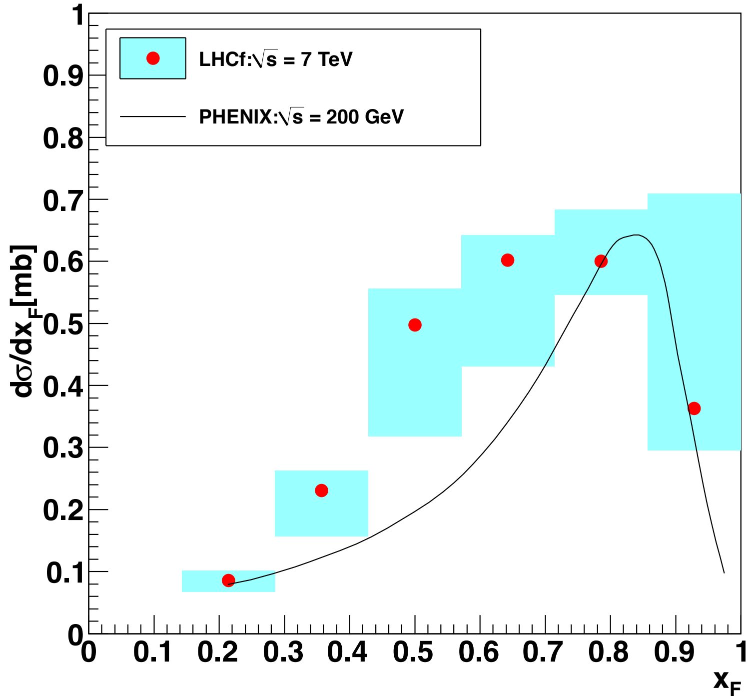


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf, K.Kawade, PhD thesis, CERN-THESIS-2014-315

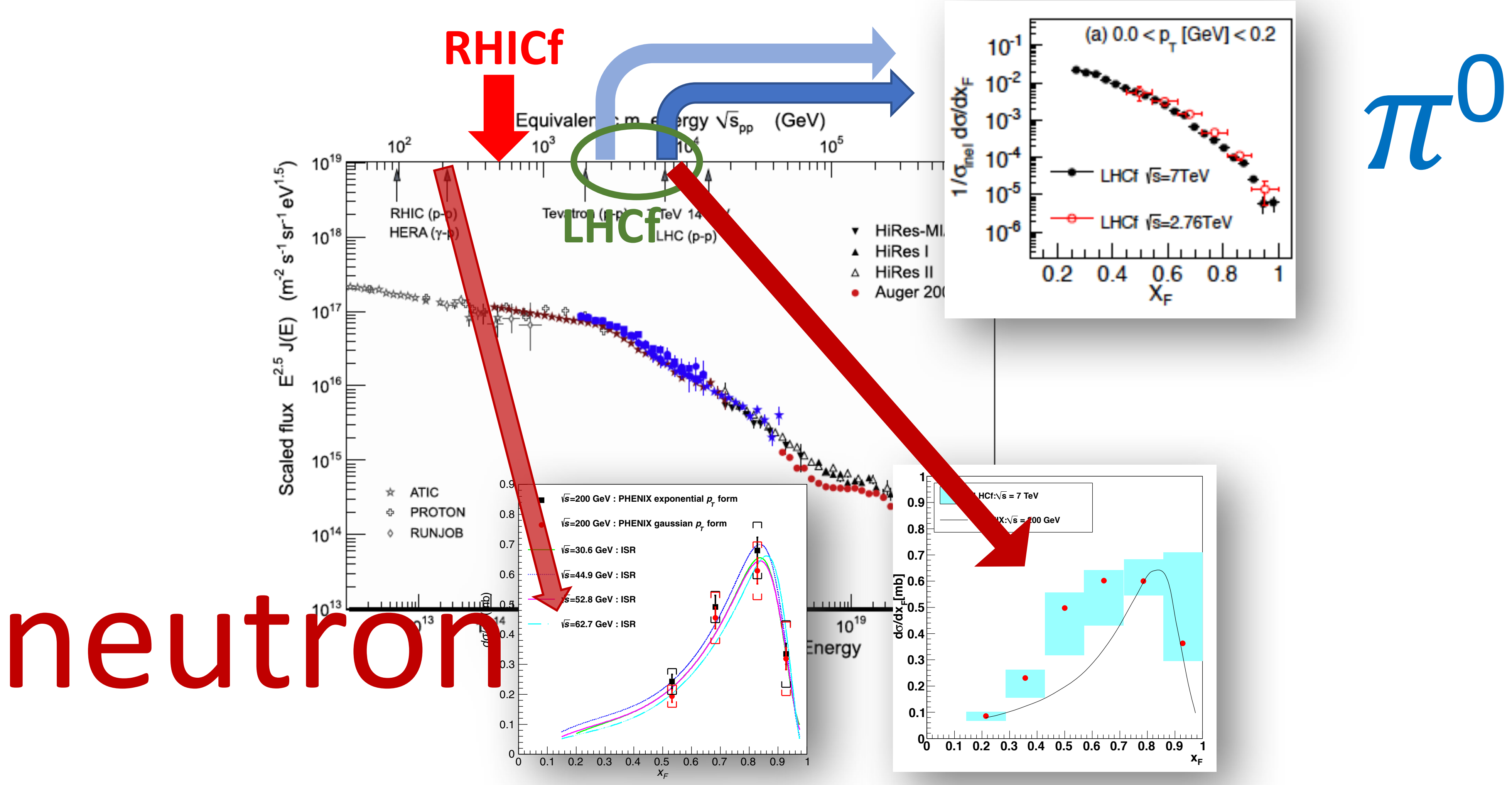
$p_T < 0.11\ x_F$ GeV/c Narrower angle than the published result to compare with the previous works

√s = 7000 GeV @LHC

- ✓ Excellent scaling at √s = 30-200GeV
- ✓ √s = 7TeV result agrees in a peak structure, but slightly soft??
- ✓ LHCf data at 900GeV, 2.76TeV, 13TeV to be analyzed
- ✓ RHICf data at 510GeV becomes available

√s scaling, or breaking?

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

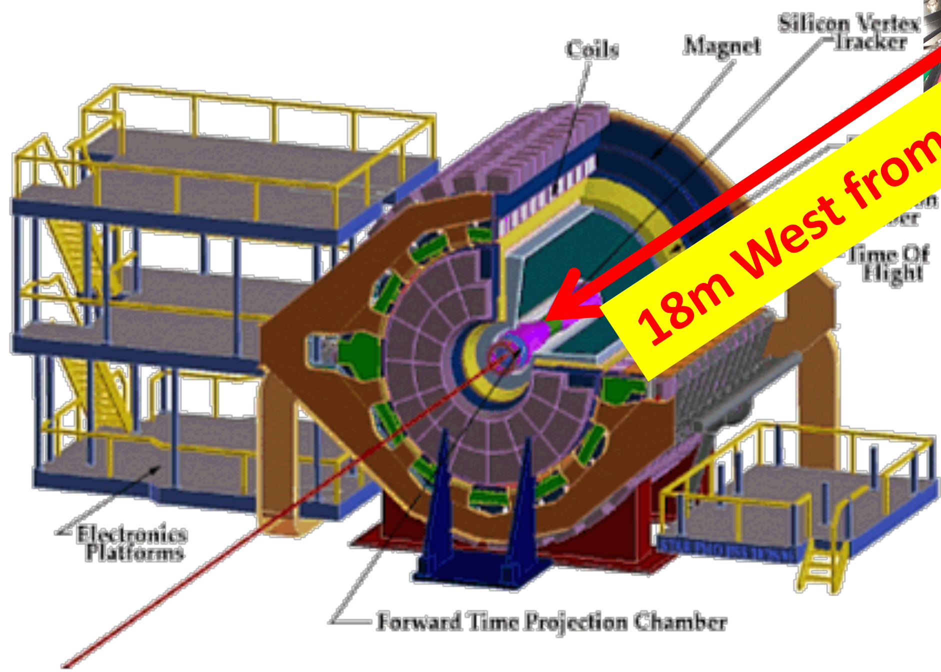


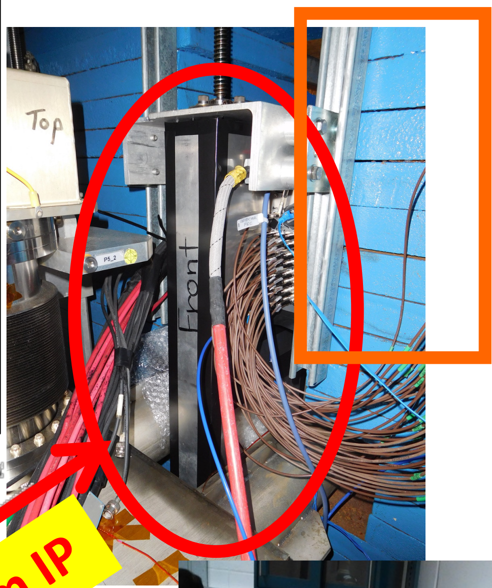
ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data
indicate √s scaling ***braking*** of forward neutrons

RHICf is a kind of Zero degree calorimeters @STAR interaction point

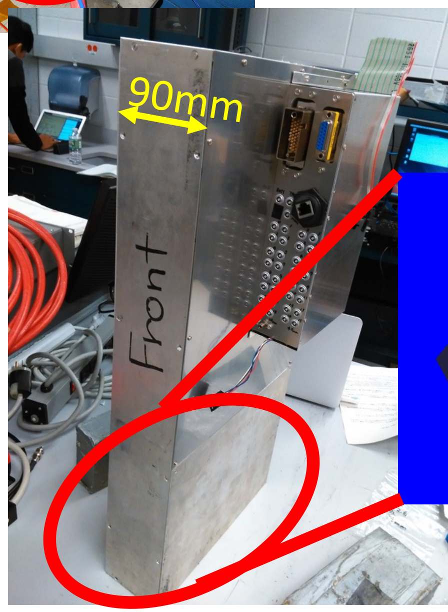
RHICf detector

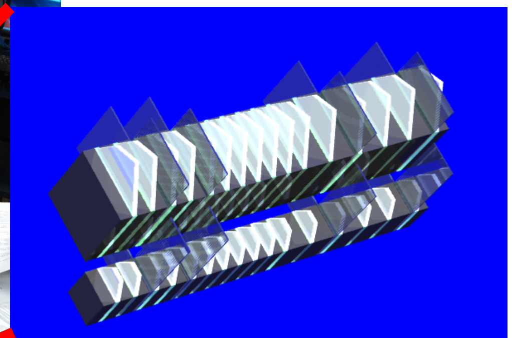
- Former LHCf Arm1 detector used at LHC
- Two compact sampling calorimeters
- 44 r.l. (1.7 hadron interaction lengths)
- <5% and 40% energy resolutions for EM and hadronic showers, respectively
- <0.2mm and <1mm position resolutions for EM and hadronic showers, respectively



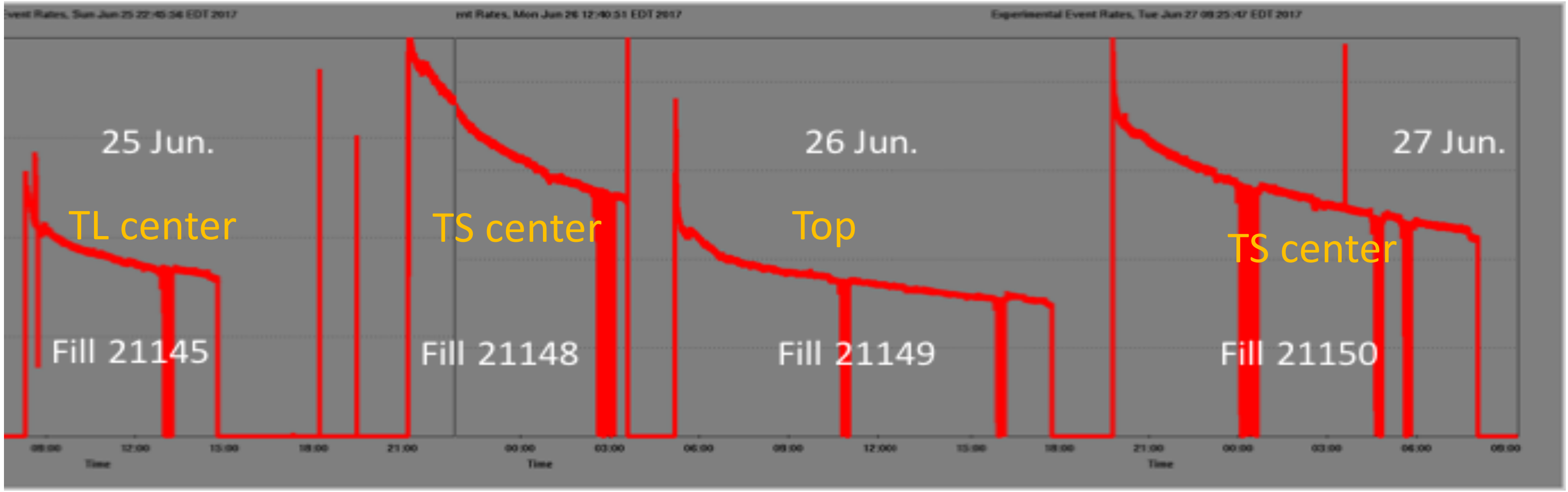


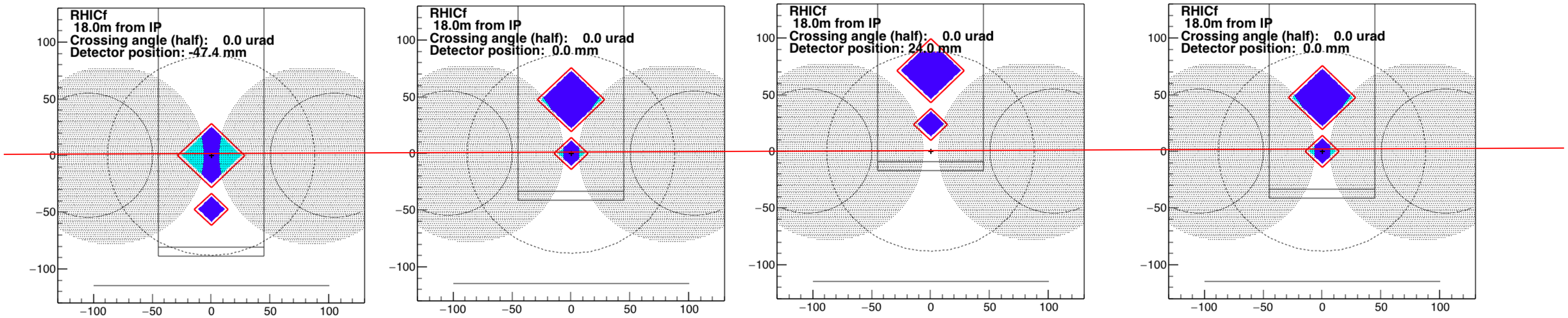
(traditional) Zero Degree Calorimeter behind RHICf





Collision rates in RHICf week



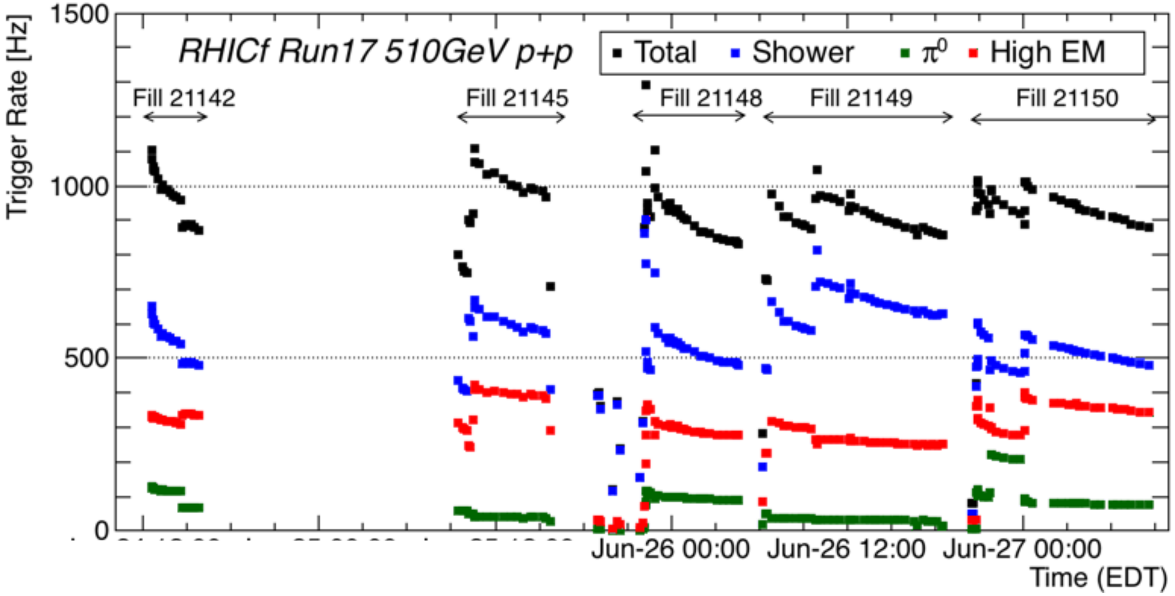


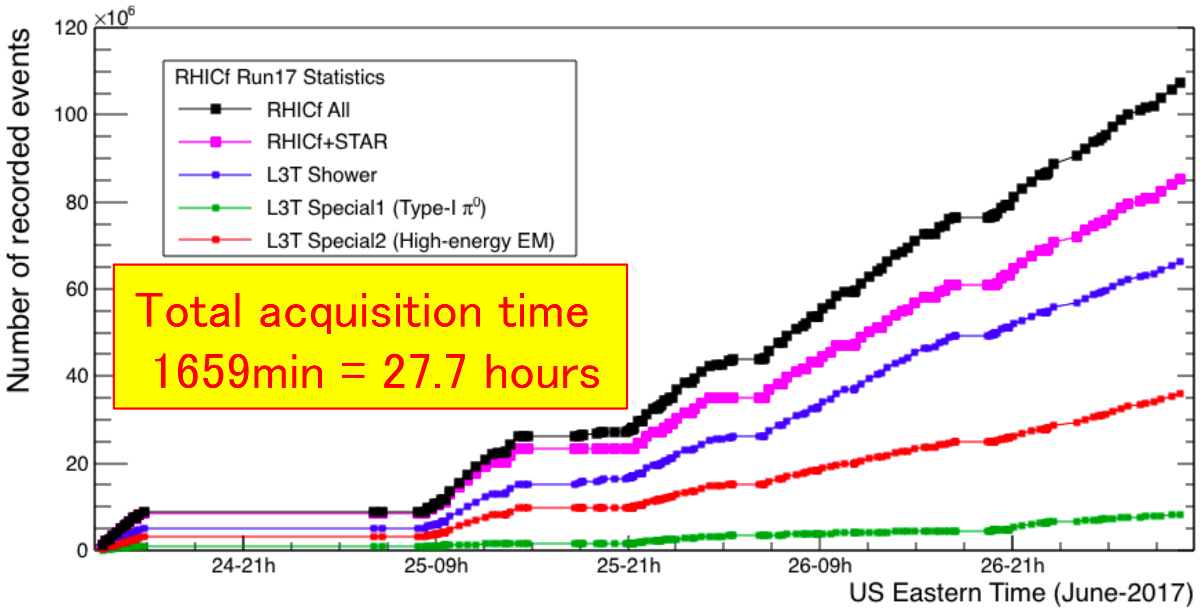
- Higher β^* (=8m) than usual RHIC operation
- Radial polarization (usually vertical) to maximize the single-spin asymmetry in vertical
- Luminosity~10^{31} cm^{-2}s^{-1}

Quick look (statistics)

RHICf DAQ rate

- Max rate was limited ~1kHz
- High rate events were prescaled
- Low rate events were enhanced with special triggers
- Prescale factors were optimized from time to time





Total : 110M events

RHICf+STAR

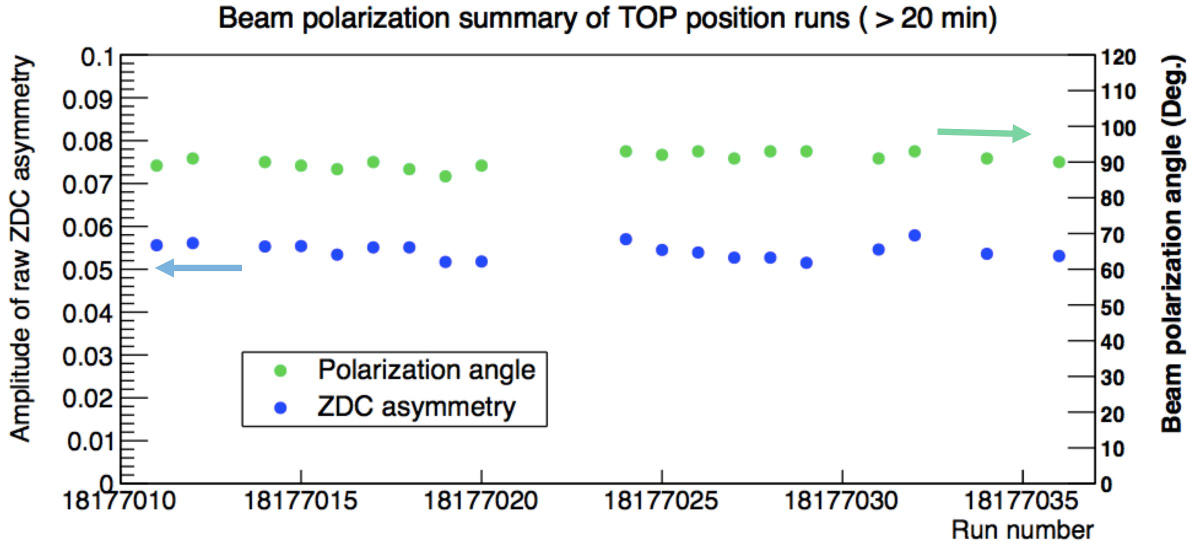
RHICf (shower event)

RHICf (High-energy EM trigger)

RHICf (Type-I π^0 trigger)

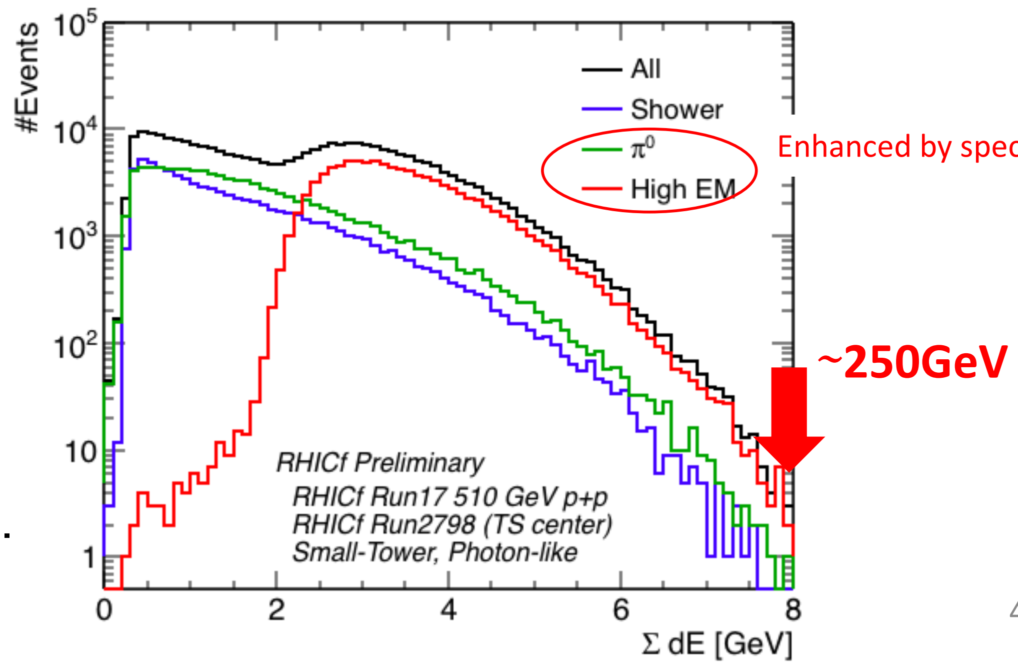
Quick look (polarization & spectrum)

Though physics of polarized beam collision is not covered in this talk…



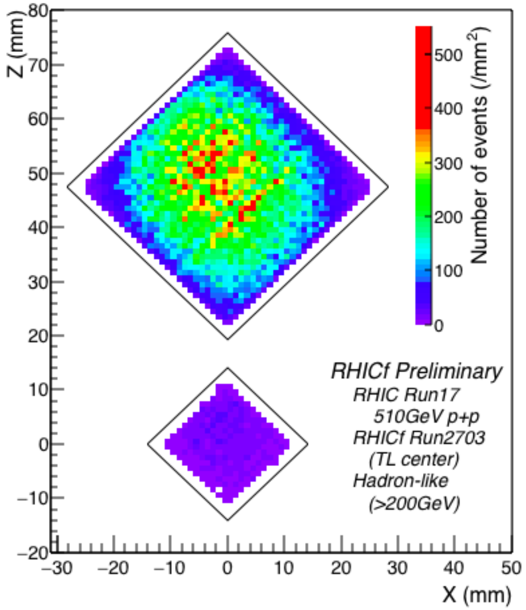
- Polarization angle is 0 in usual RHIC operation (vertical pol)
- Radial polarization (90°) was required for RHICf operation
- Stable radial pol and asymmetry was observed by ZDC

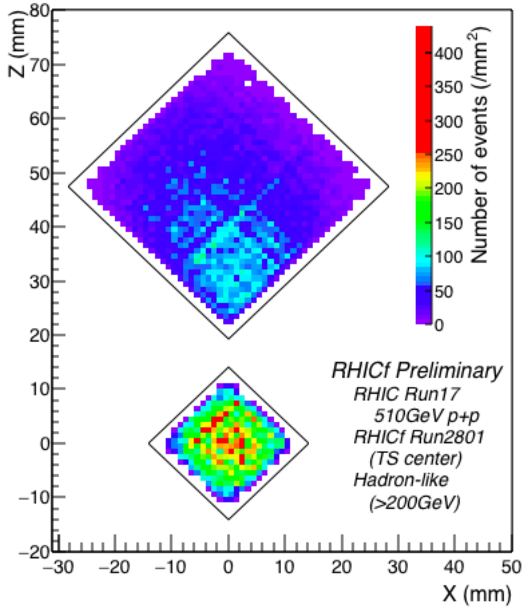
- Energy spectrum of EM-like showers in a 30 minutes run
- High-energy EM showers and π^0 were selectively triggered to compensate the limited DAQ speed.

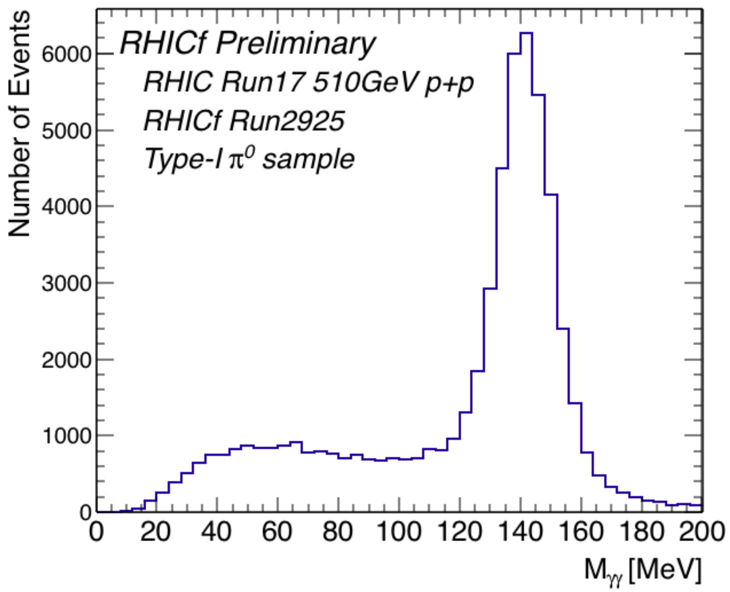


Quick look (basic performance)

Hit maps of >200GeV hadron-like events at different detector positions
=> Determination of "zero degree"



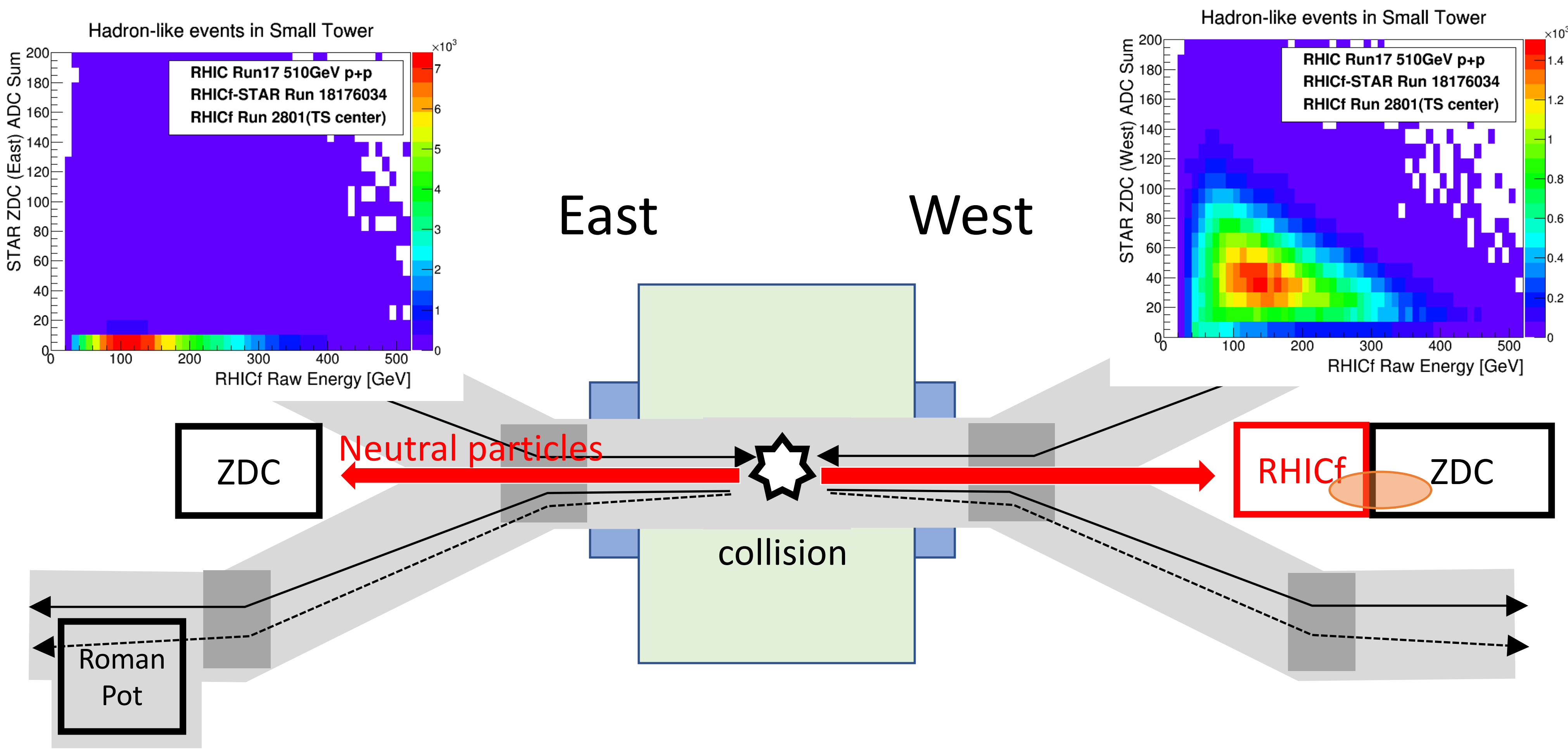




Invariant mass of photon pairs
=> 135MeV peak by π^0

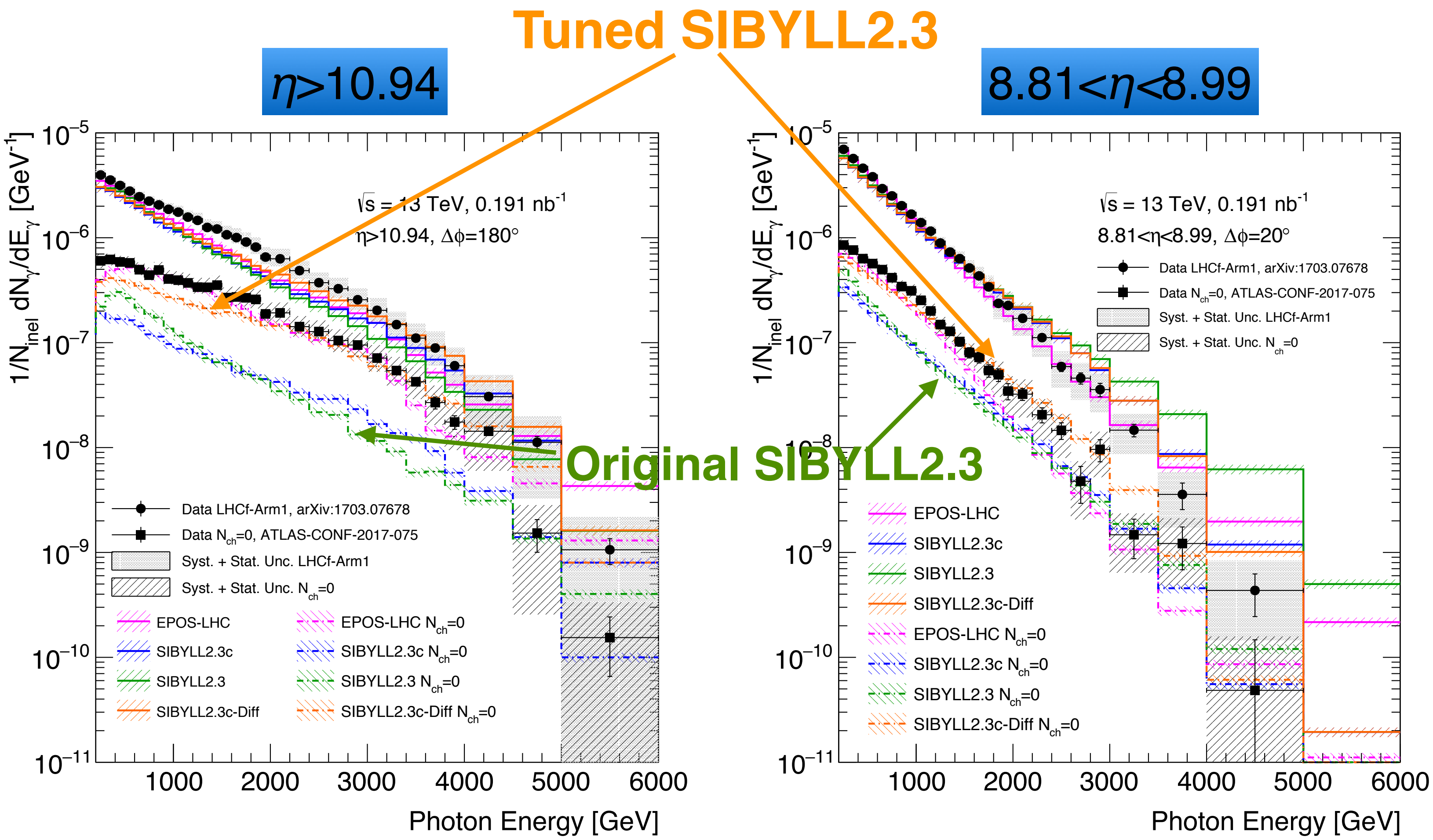
Correction factors considering the final alignment and RHIC energy range are in study.

Quick look(common run with STAR)



- Hadron-like (deep penetrating) showers were selected
- Anticorrelation between the RHICf raw (folded) energy and ZDC measured energy (in ADC unit) is confirmed
- (Anti)correlation only with West ZDC as expected => correct event matching

Model tuning to the LHCf results

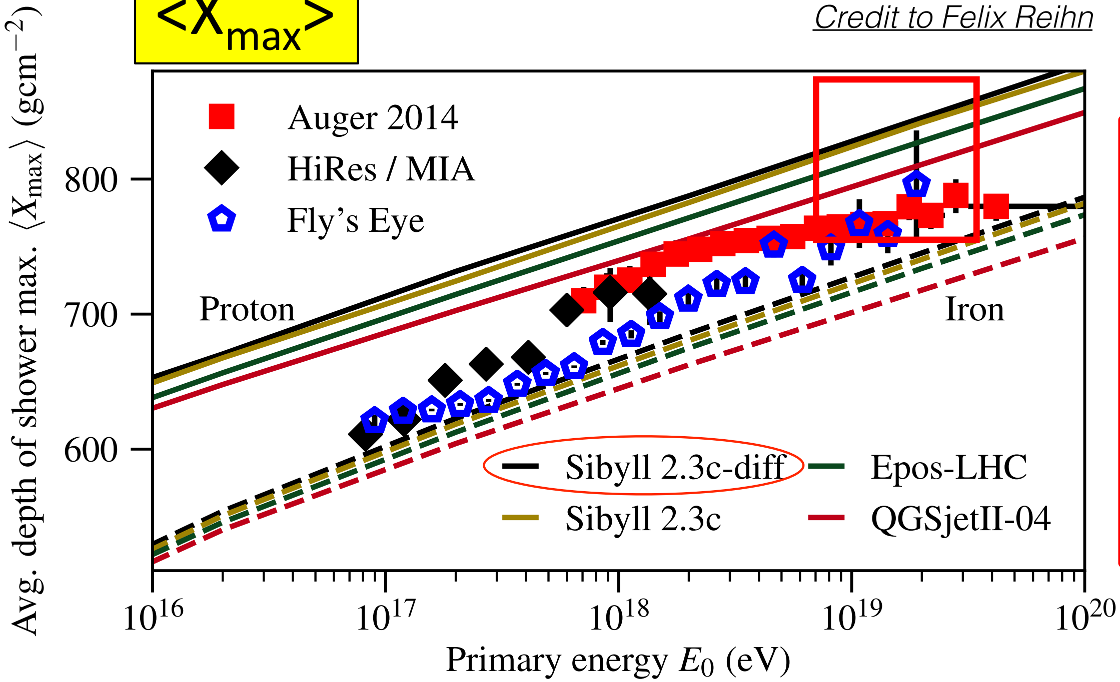


- LHCf photon events are categorized in ‘diffractive’ and ‘non-diffractive’ using the ATLAS information
- SIBYLL2.3c–diff tuned to LHCf diffractive photons

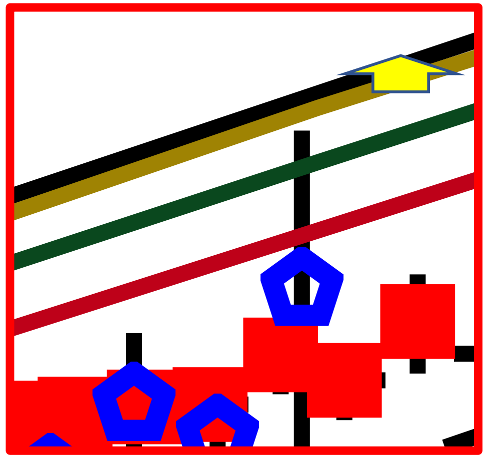
Effect of new tune to air shower

$\langle X_{max} \rangle$

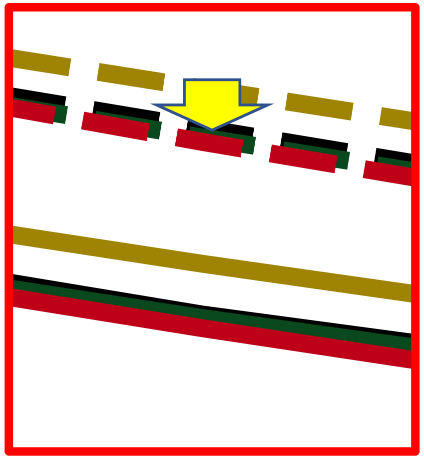
Credit to Felix Reihn



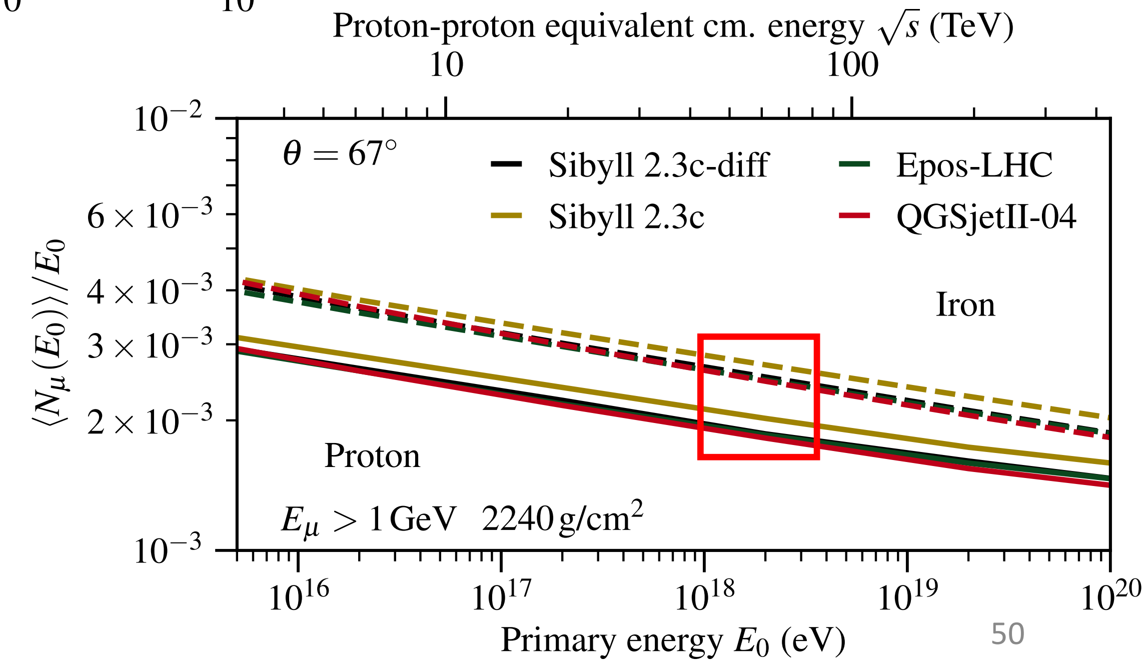
Small but visible impact



N_μ

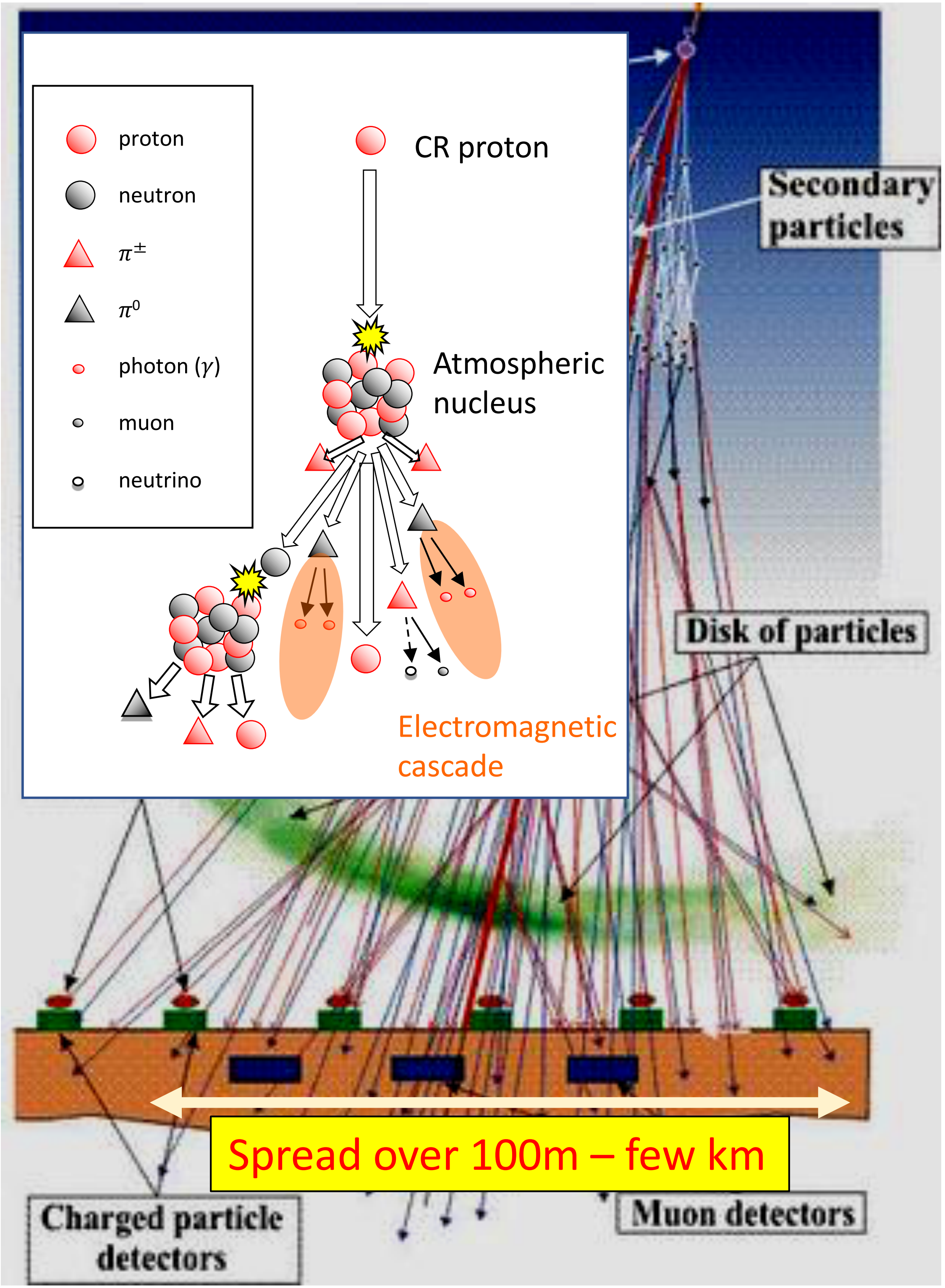


Significant impact



Summary

- Air shower analyses are influenced by the uncertainty of hadronic interaction
- Current and future colliders cover the collision energies appropriate to the air shower observations
- Dedicated forward measurements are important
- LHCf and RHICf observed forward particle production from $E_{CR}=10^{14}$eV to 10^{17}eV
- Current popular models have reasonable agreement with the LHCf results and they are updating
- Next keys are
  - Combined analyses with the central detector (LHCf-ATLAS, RHICf-STAR)
  - Collision energy (in)dependence of particle production (ISR-PHENIX-RHICf-LHCf)
  - Light ion collisions like p-O, O-O at LHC
  - Feedback from the air shower observations

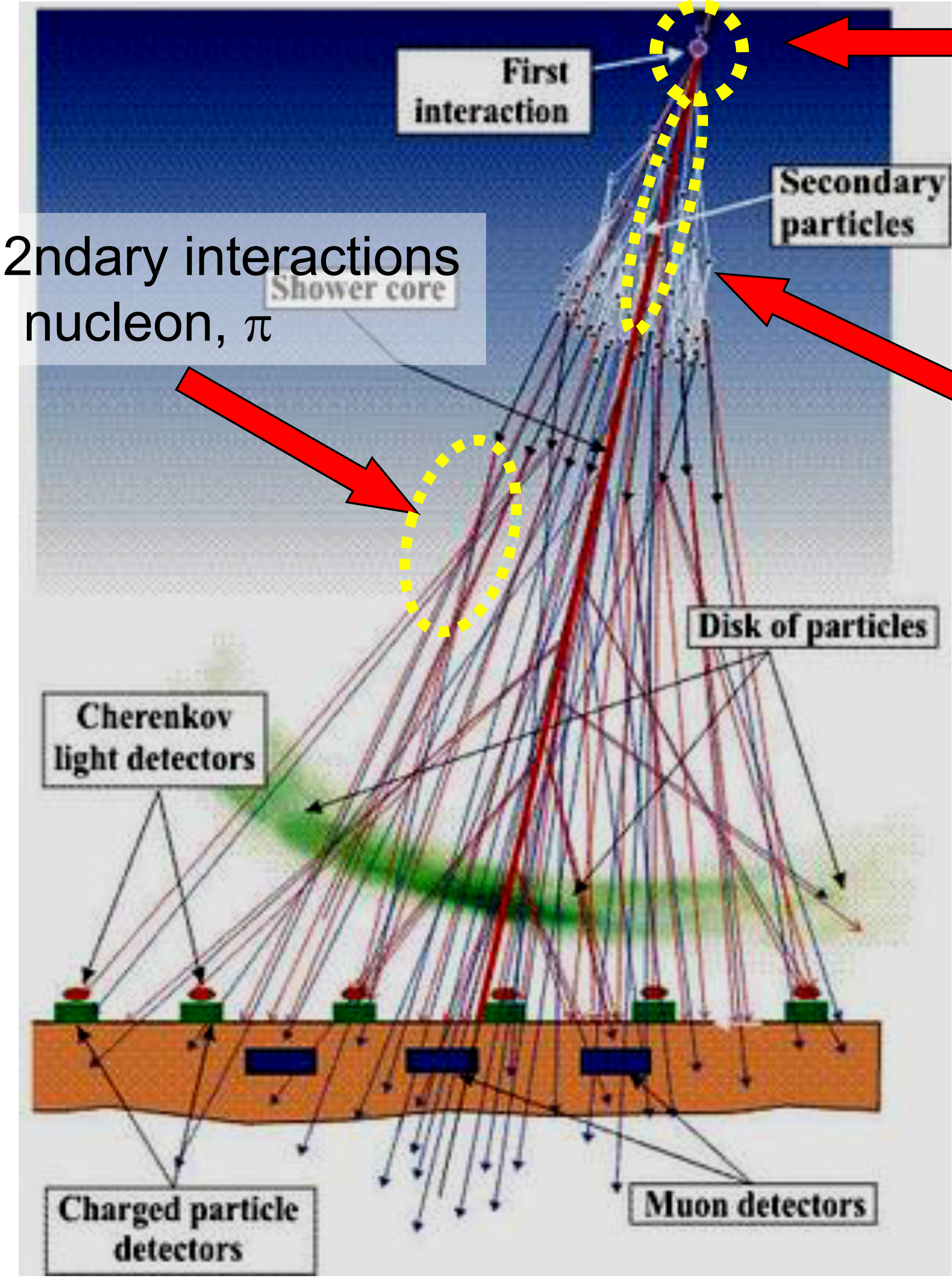


- km^2~1000km^2 detection area is achieved using a sparse array of the ground detectors
- Identification of primary particle (nuclei, gamma, etc...) is possible by measuring the difference in the air shower development

=>

Analyses strongly rely on the MC simulation of air shower development, especially fundamental hadronic interaction is essential

粒子生成素過程と空気シャワー発達



④ 2ndary interactions
nucleon, π

① Inelastic cross section

If large σ
  rapid development
If small σ
  deep penetrating

② Forward energy spectrum

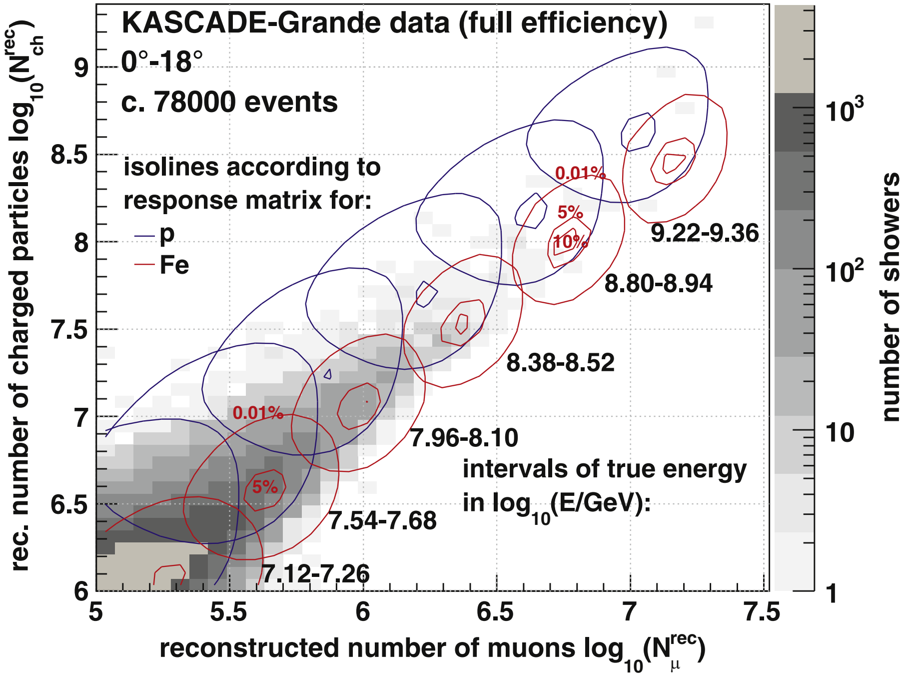
If softer
  shallow development
If harder
  deep penetrating

③ Inelasticity $k = 1 - p_{lead}/p_{beam}$

If large k
  (π^0s carry more energy)
  rapid development
If small k
  (baryons carry more energy)
  deep penetrating

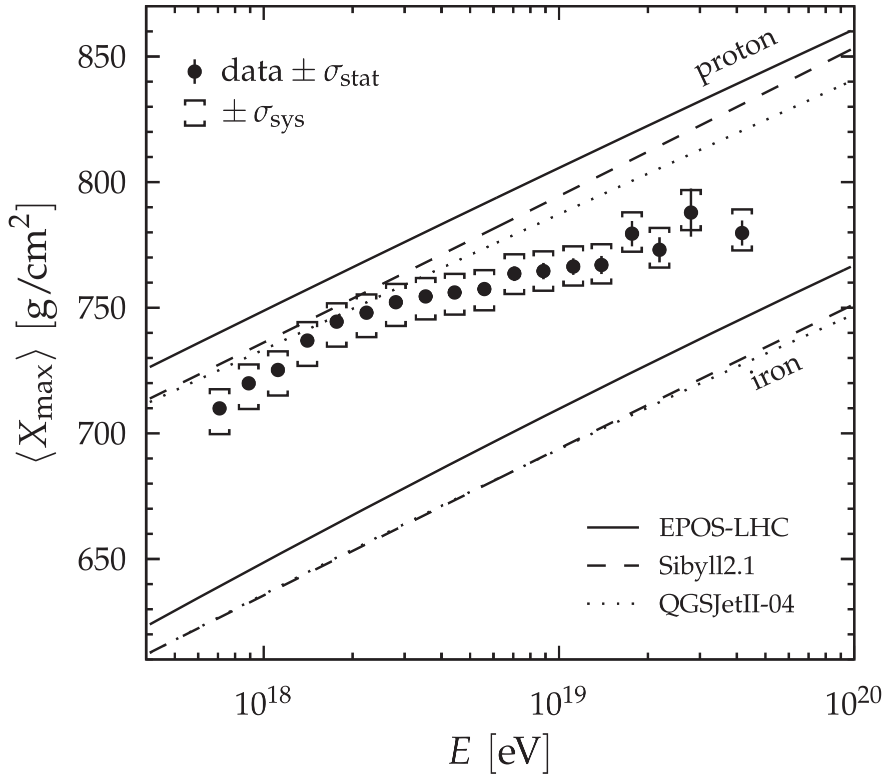
CR mass estimation from air shower

KASCADE Grande, Astropart. Phys., 47 (2013) 54-66



Response (color contours) was calculated using QGSJET II-02 + FLUKA 2002.4

PAO, PRD, 90, 122005 (2014)



✓ Techniques to estimate mass from air shower observations
- Knee to Ankle : $N_e - N_{mu}$
- Ankle to Cutoff : $<X_{max}>$, N_{mu}

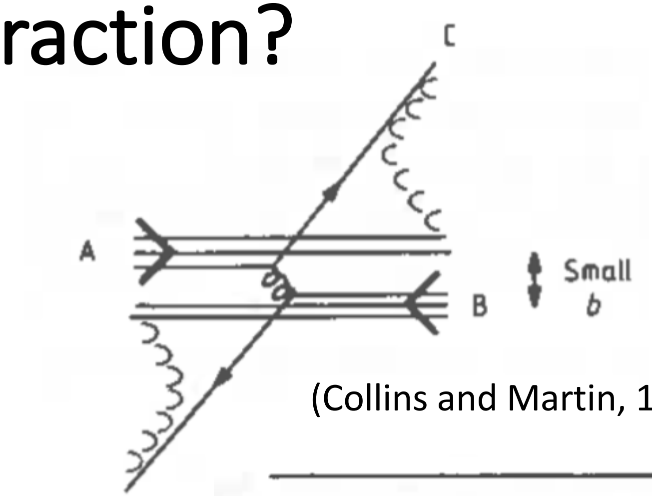
✓ Interpretations rely on the MC predictions with an assumed hadronic interaction model

What is difficulty in hadronic interaction?

- Hard scattering (large Q^2); Perturbative QCD

  2->2 scattering of individual partons (quarks and gluons)
  - Parton-parton cross section
  - Parton distribution function (PDF)
  - Hadronization (fragmentation function)

  are relatively well understood separately



(Collins and Martin, 1984)

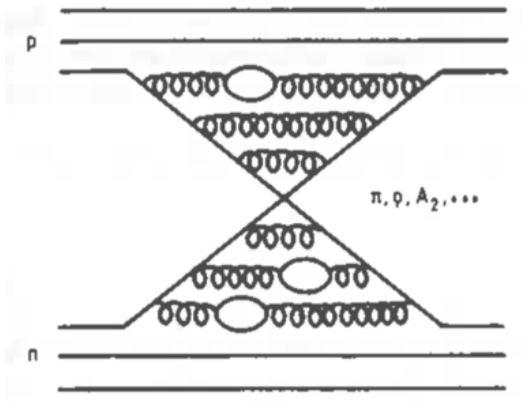
- Soft scattering (small Q^2); non-perturbative

  exchange of group of partons （mesons, Reggeon, Pomeron）

  difficult in first principle calculation of cross sections

  even for the elastic scattering

  phenomenological modeling is necessary

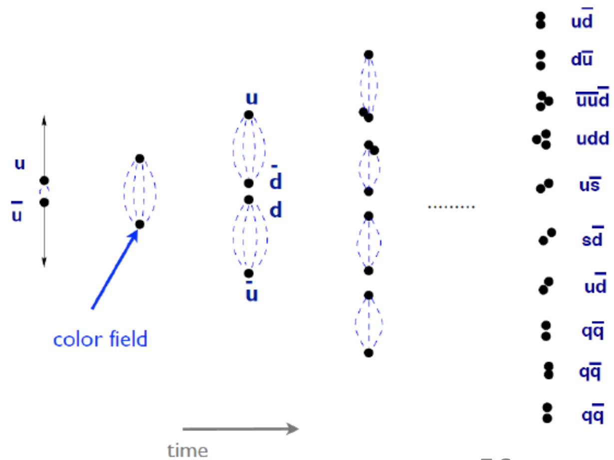


◆ Nature does not have a boarder between soft and hard…

- Nuclear effect ；

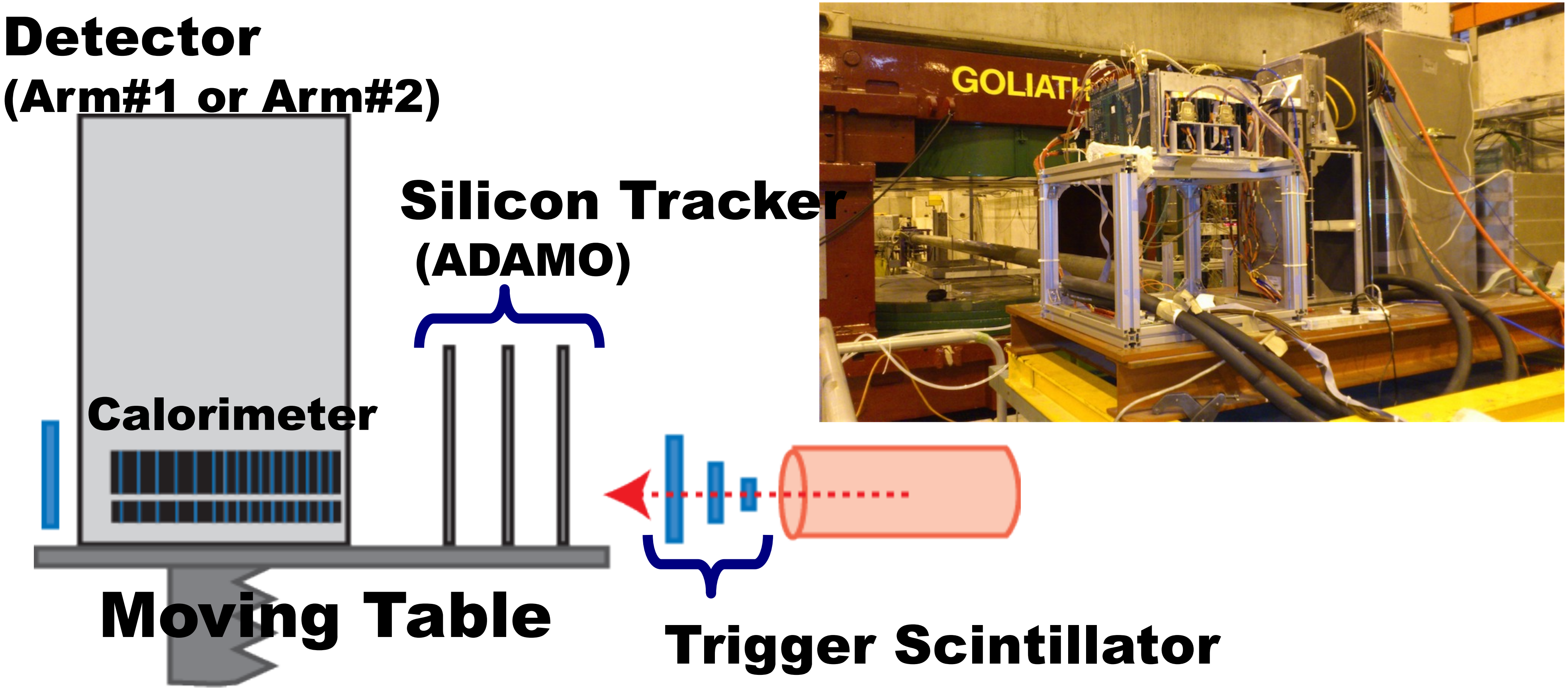
  not so simple like "Glauber effect"

  collective effect in dense matter depends on the impact parameter and issue of modeling



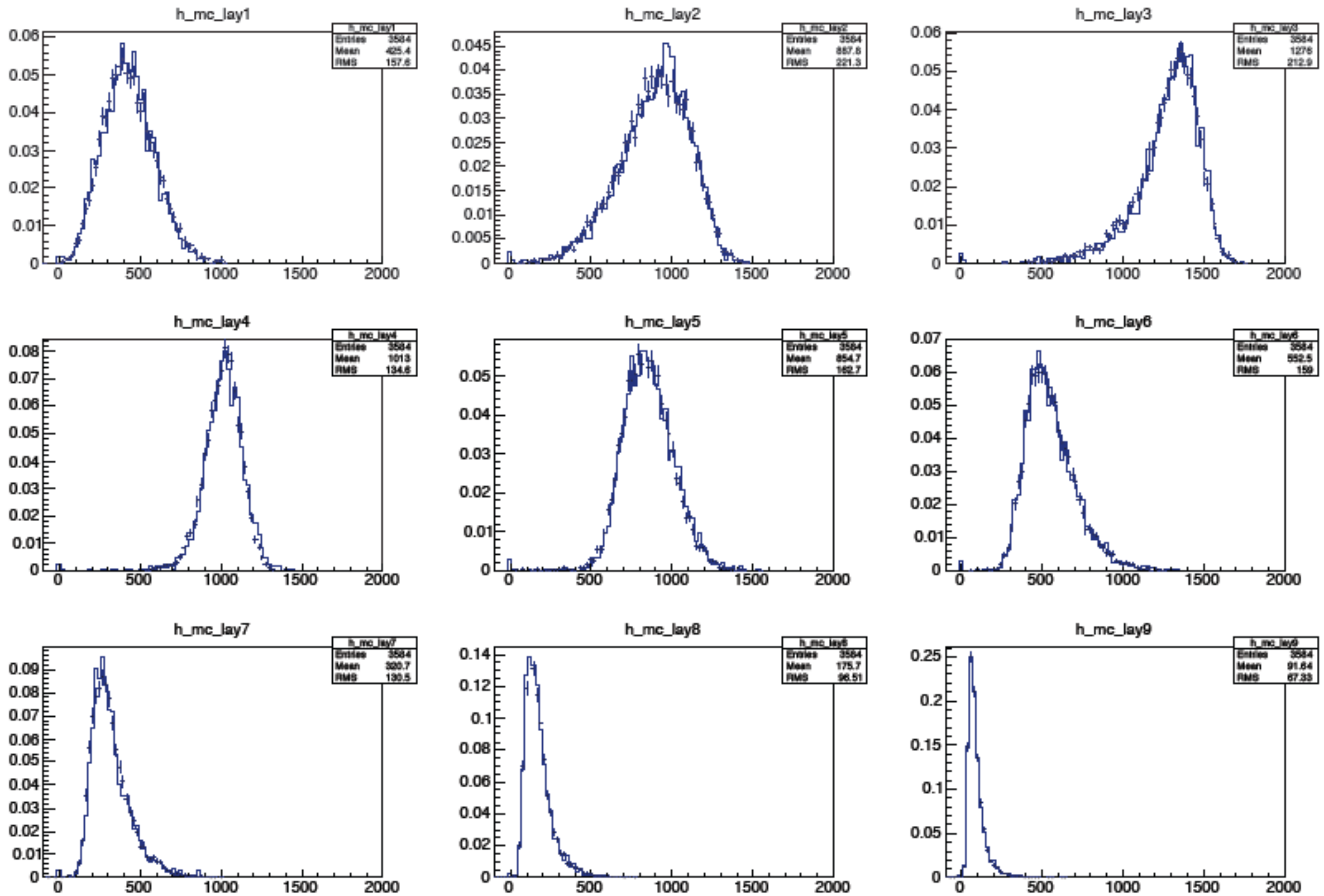
Models must be tested by accelerator data

Setup of SPS beam test



- Calorimeters were exposed to the SPS electron (100-200GeV), proton (350GeV) and muon (150GeV) beams
- Calorimeters were scanned over the beams
- Impact points were measured using a silicon strip tracker

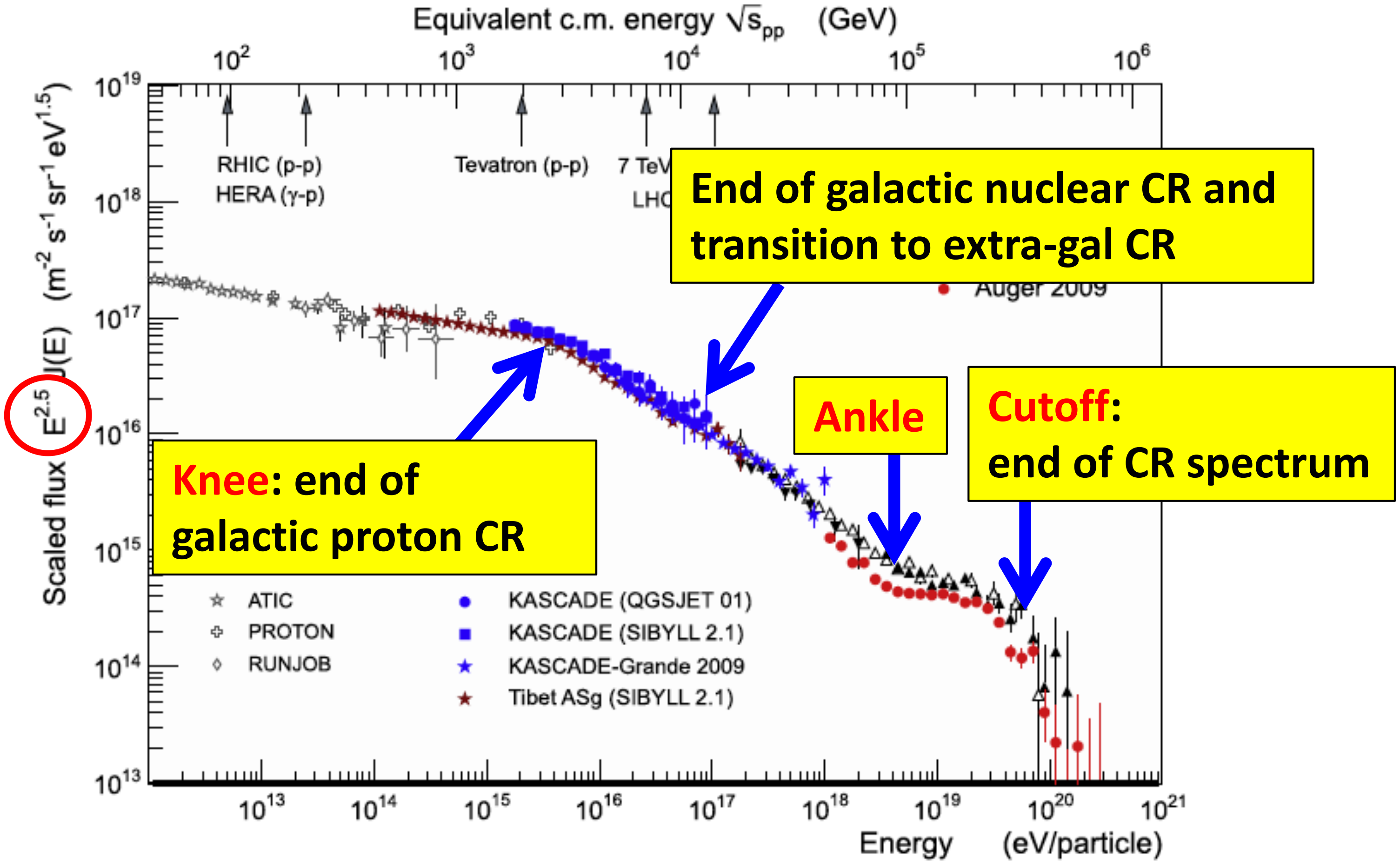
Channel to channel calibration
Beam test results vs. MC simulation



180GeV electron

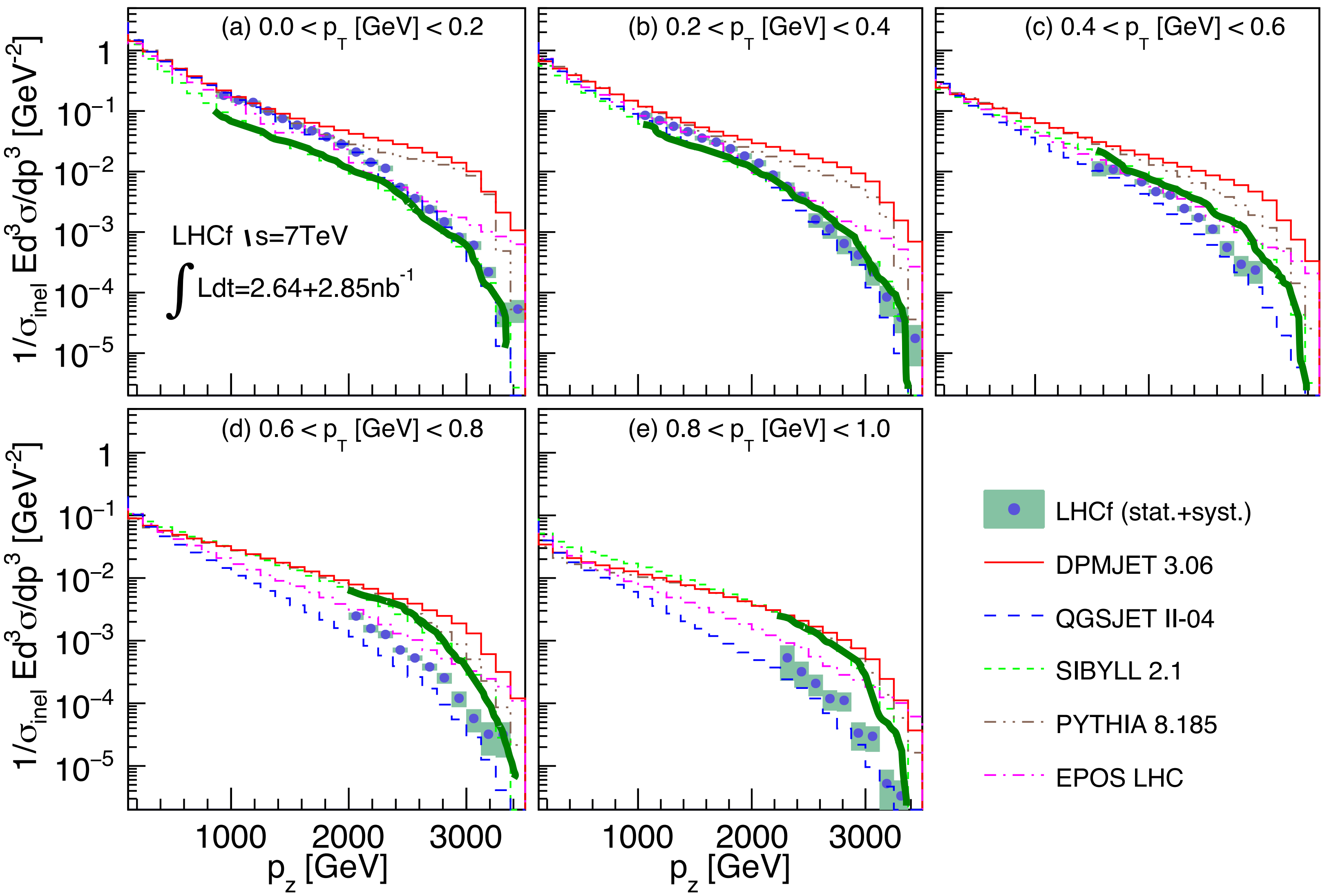
- Charge => energy factors are determined by scaling the MC results to the experimental data

Cosmic-ray flux



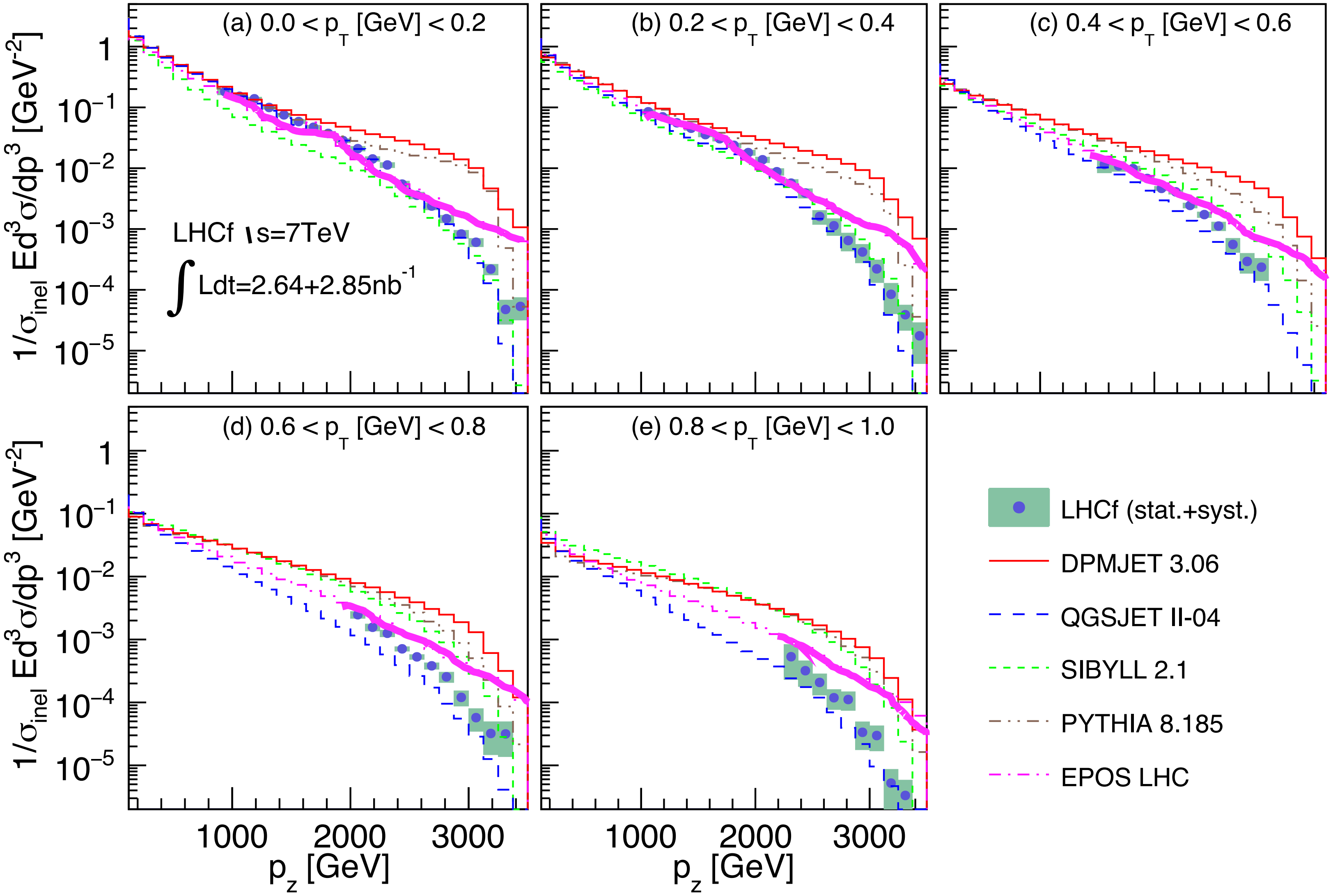
- Maximum energy up to 10^{20} eV (LHC beam energy is $7\text{x}10^{12}$ eV)
- Structures in the energy spectrum suggest their origins
  - Knee @ 10^{15}eV … end of the galactic protons ??
  - Ankle @ 10^{18}eV … transition from galactic to ex-galactic origins ??
  - Cutoff @ 10^{20}eV … end of the ex-galactic origin ??

π^0 SIBYLL 2.1



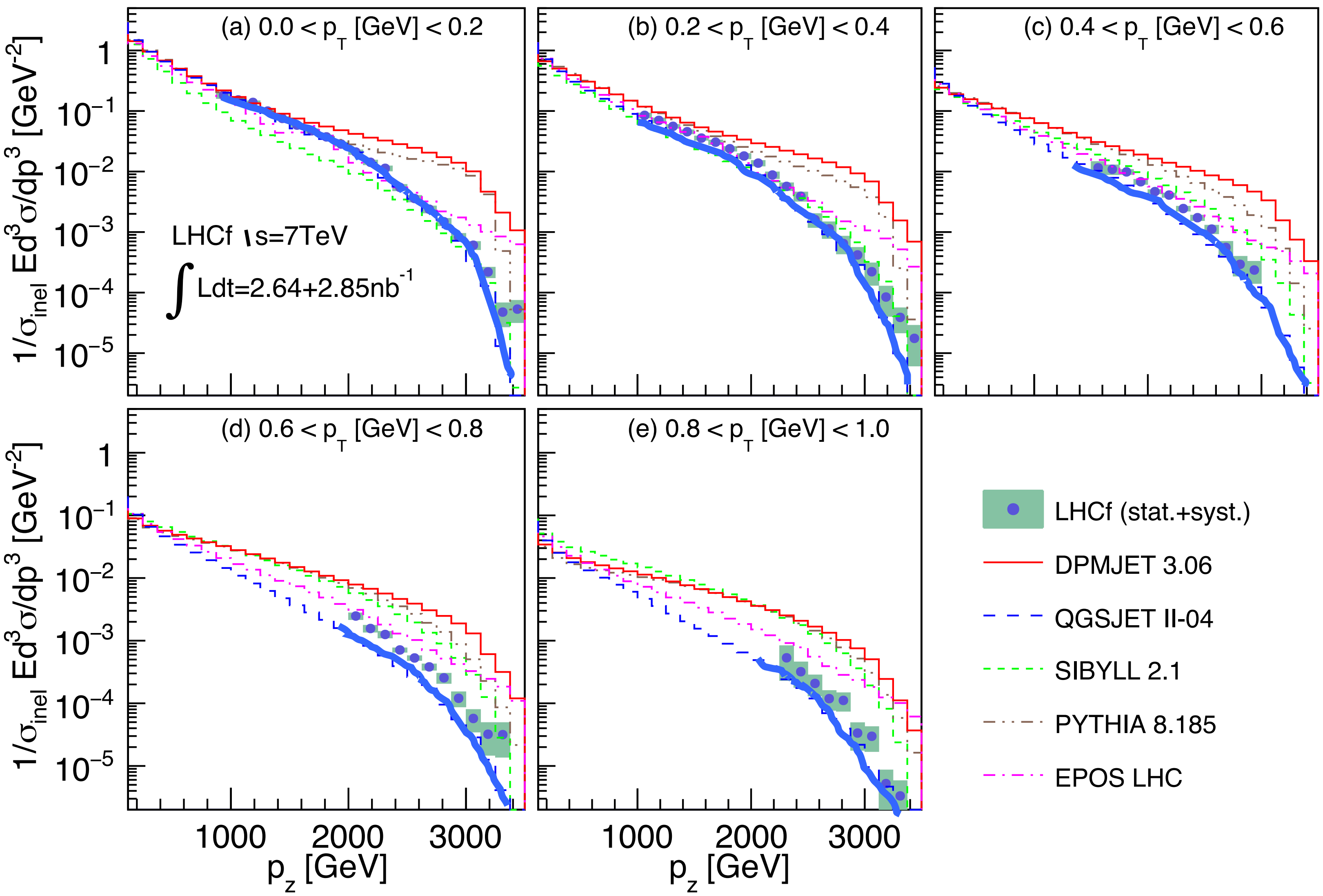
- ✓ Underestimate in low p_T, overestimate in high p_T
- ✓ Totally overestimate because of larger phase space in high p_T

π^0 EPOS-LHC



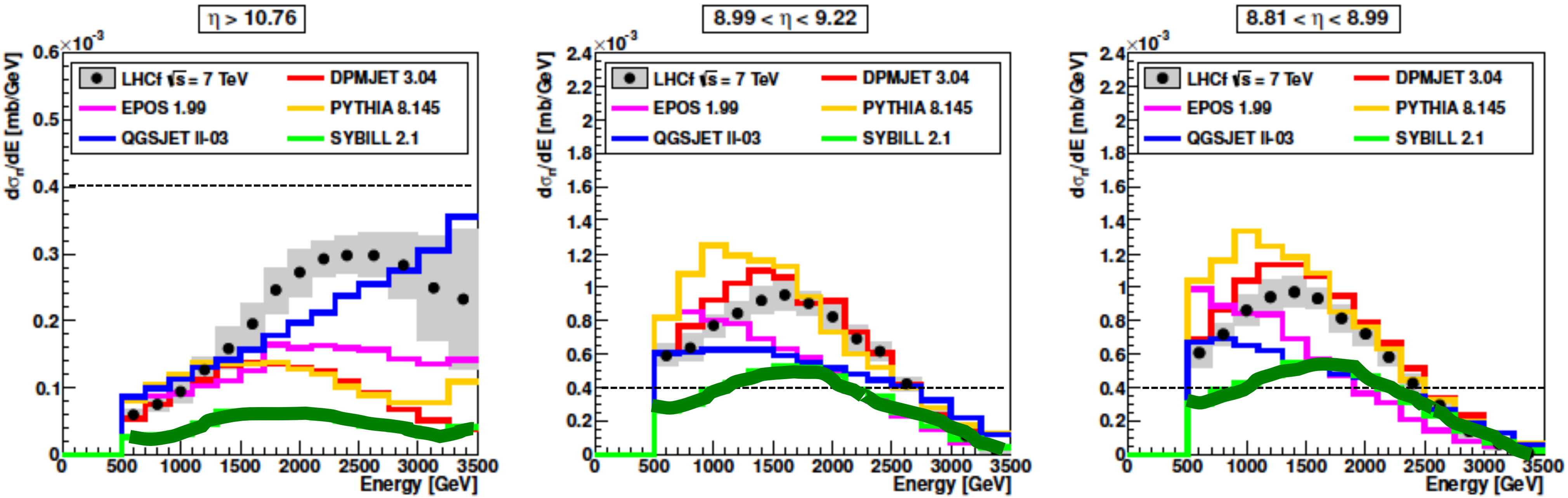
- ✓ Very good agreement at mid-energy (large cross section range)
- ✓ Slightly overestimate in high energy (small cross section range)

π^0 QGSJET II-04



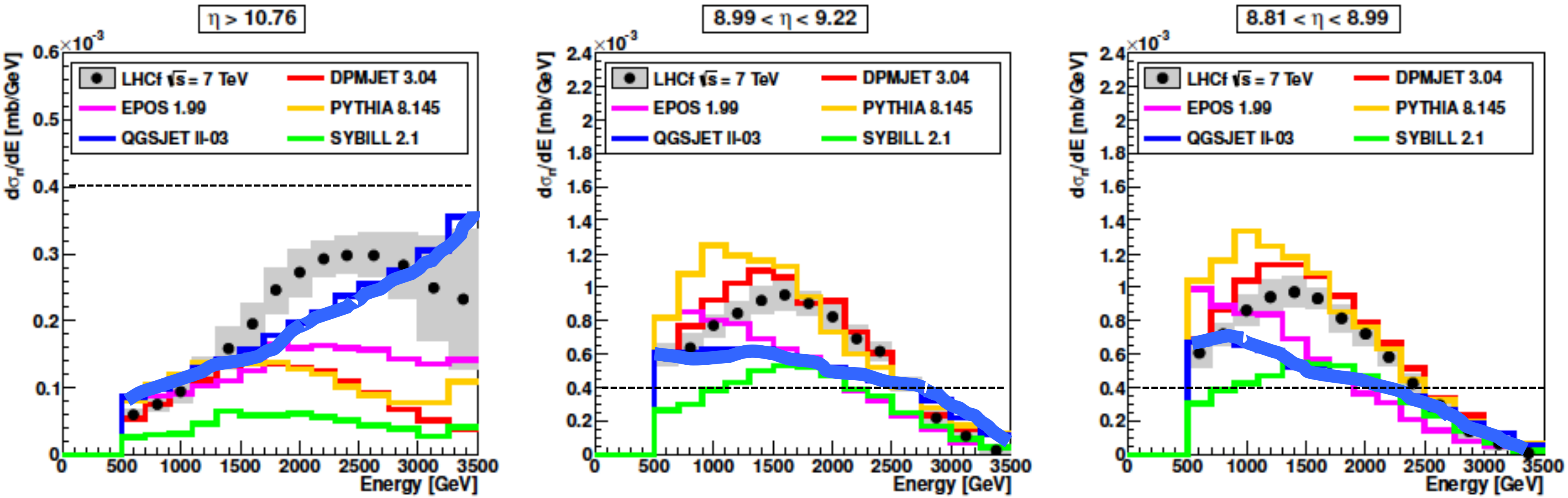
- ✓ Perfect in shape, slightly underestimate in higher p_T
- ✓ Totally slightly underestimate

Neutron SIBYLL 2.1



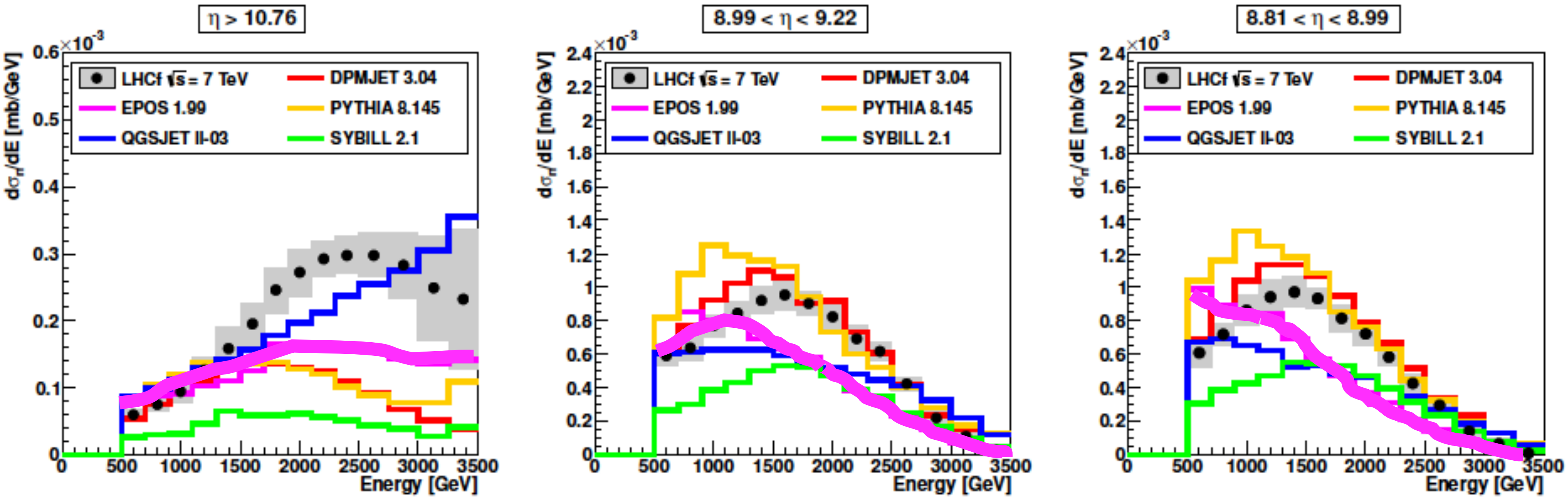
✓ Lowest neutron yield, especially at zero degree

Neutron QGSJET II-03



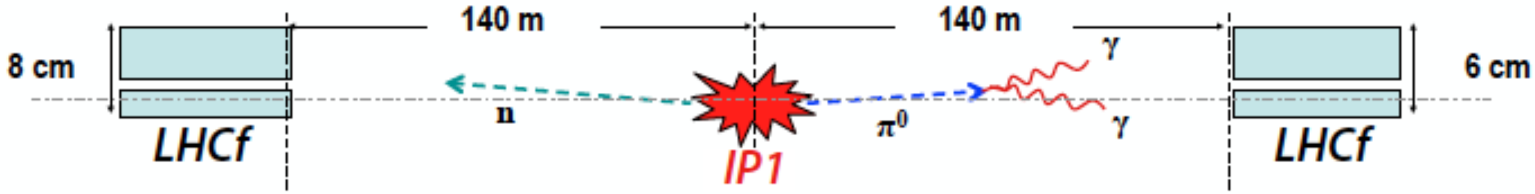
- ✓ Qualitatively nice agreement, only model, at zero degree
- ✓ Lower yield at non-zero angle

Neutron EPOS 1.99

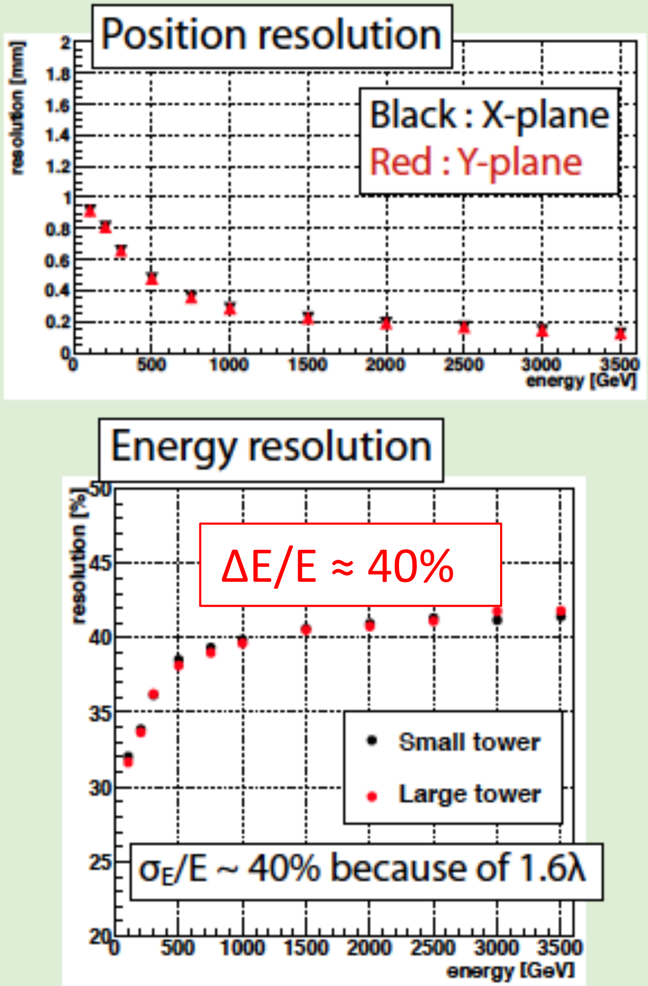


- ✓ Generally low yield

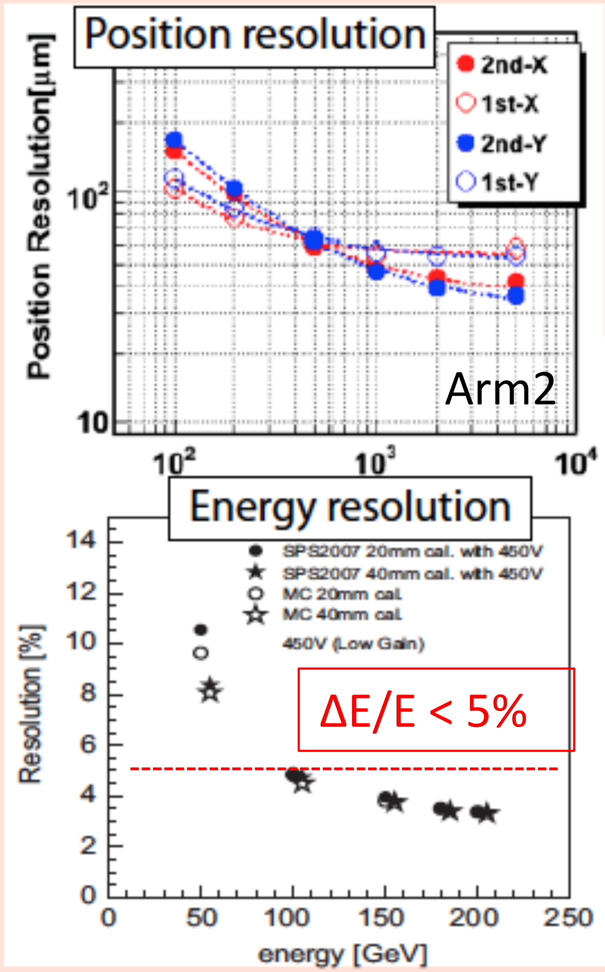
Detector performance



Hadronic shower (MC)



EM shower (MC)



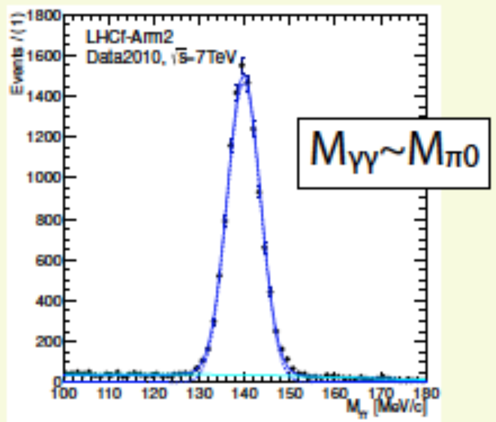
PID technique

400GeV photon

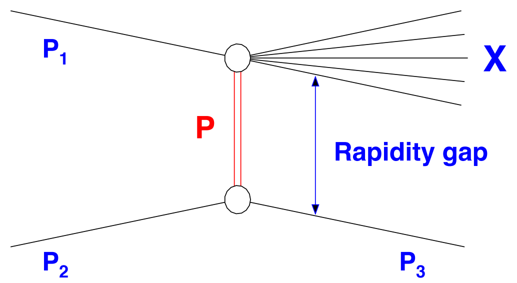
1TeV neutron

Identification of incoming particle by shower shape

π^0 reconstruction



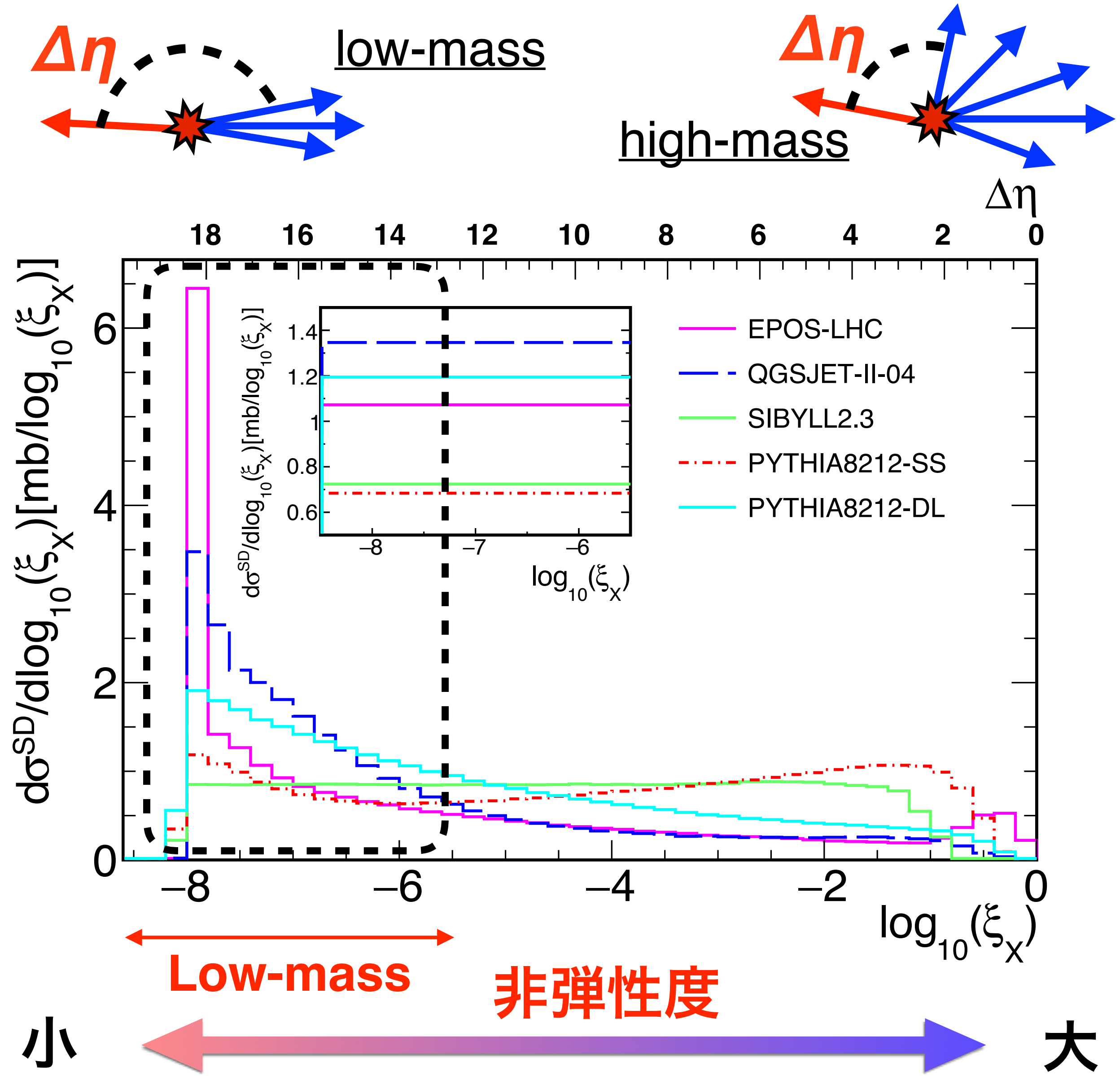
モデルのdiffraction事象の生成質量分布



M_X : Diffractive質量,

X系統の不変質量。

$$\xi_X = \left(\frac{M_X}{\sqrt{s}}\right)^2 \simeq e^{-\Delta\eta}$$



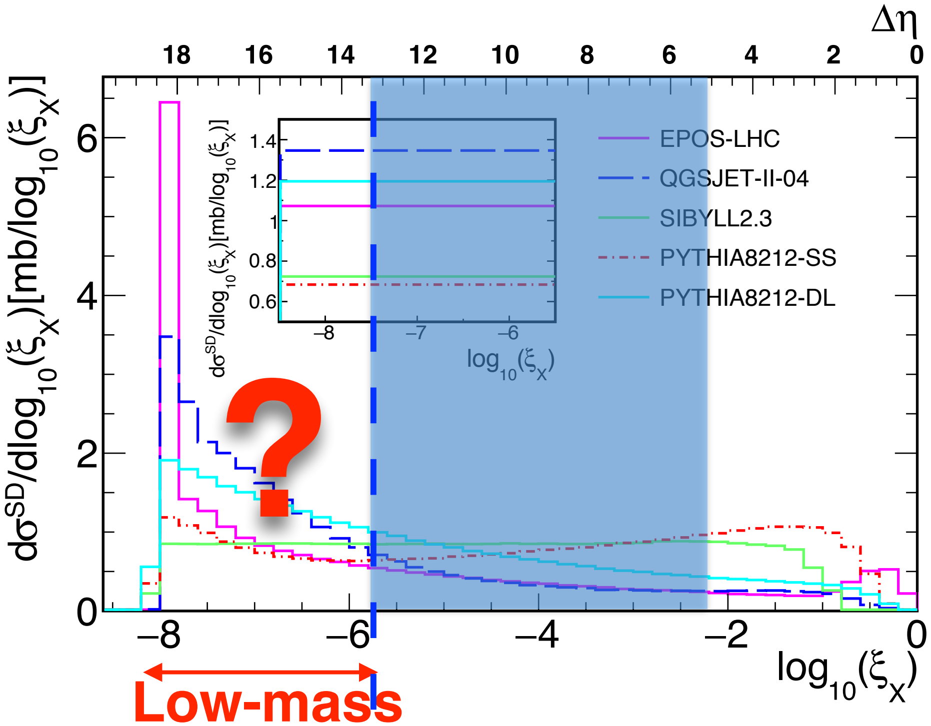
Diffractionの生成質量分布はモデルによって違う、特にlow-mass diffractionの取り扱い。

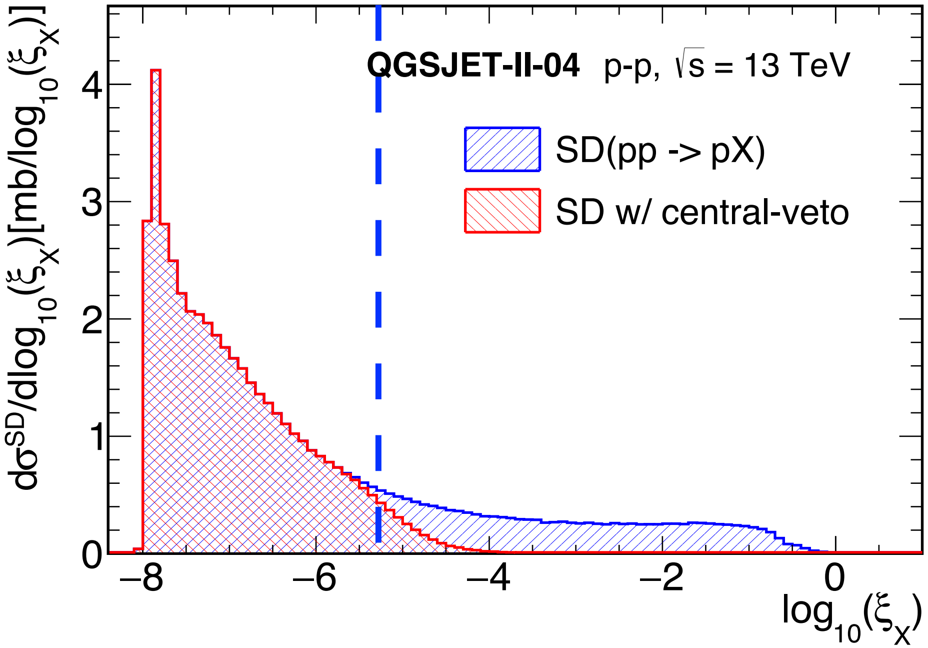
X

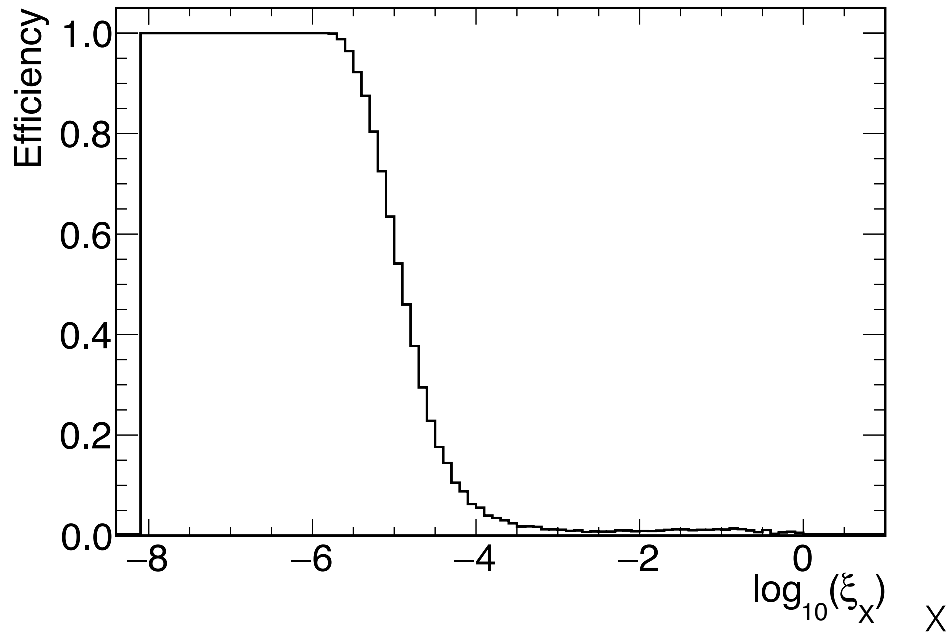
low-mass diffraction事象の感度

❖ Central-veto は low-mass diffraction ($\log_{10}(\xi_x) < -6.0$)に対して約**100%**の検出効率がある。

❖ ATLAS-LHCf連動実験によるこれまで測定例のないlow-mass diffraction事象の選別方法を確立。

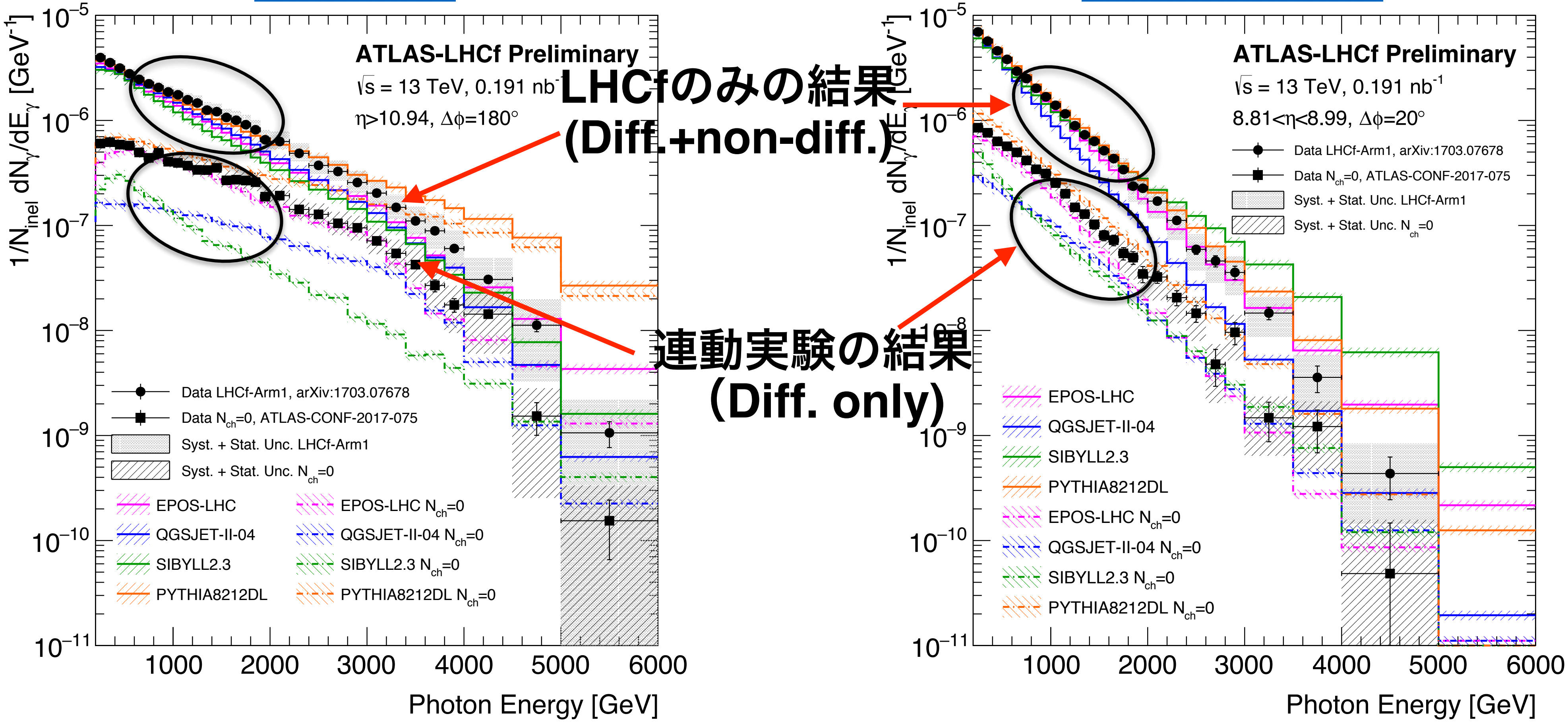






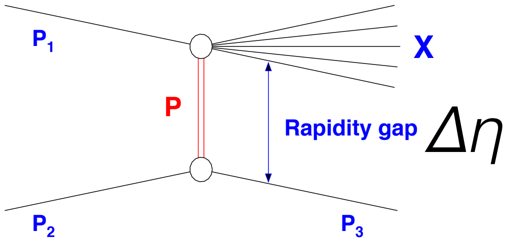
結果１：光子スペクトル

η>10.94　　　　8.81<η<8.99



- $N_{ch} = 0$ の光子スペクトルのデータとモデル予測の比較：
  - $\eta > 10.94$：EPOS-LHCはデータをよく再現した。
  - $8.81 < \eta < 8.99$：PYTHIA8212DLはデータをよく再現した。

Diffractionの生成質量分布の改良



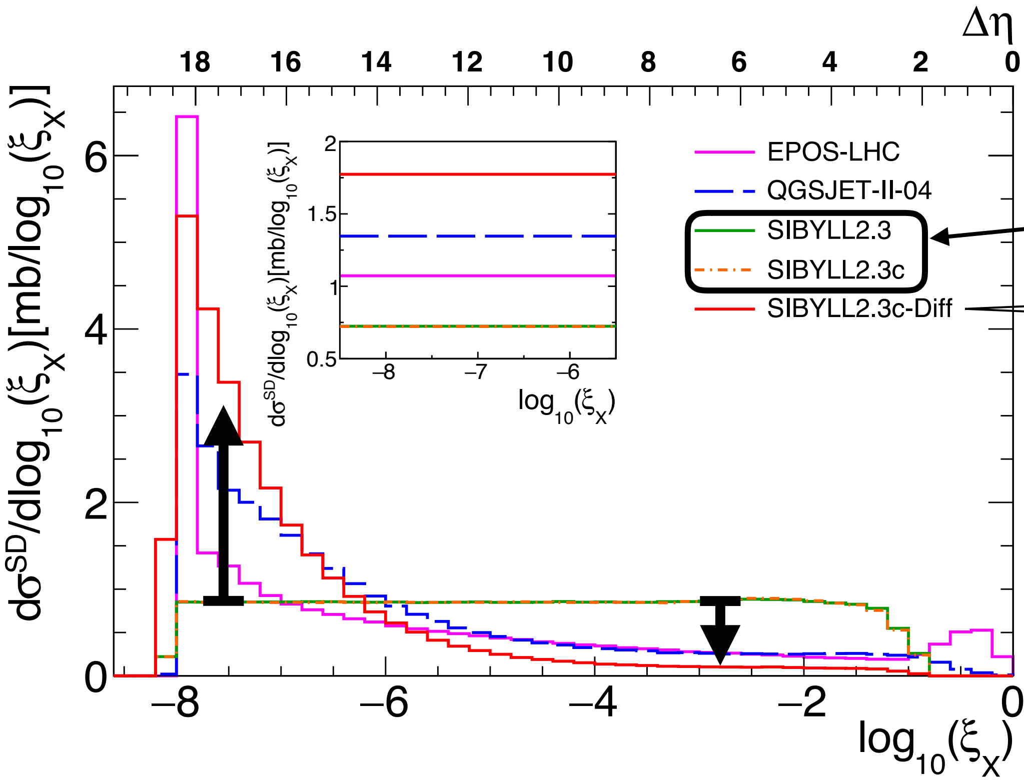
M_X : Diffractive mass, X系統の不変質量

$\xi_X = (\frac{M_X}{\sqrt{s}})^2 \simeq e^{-\Delta\eta}$:陽子が失った運動量の比

$$\frac{d\sigma^{SD}}{d\xi_X dt} = f_P(\xi_X, t)\sigma(M_X^2) \propto \xi_X^{1-2\alpha_P(t)}((M_X^2)^{\alpha_P(0)-1})$$

<u>pomeron flux</u> <u>pomeron cross-section</u>

$\alpha_P(t) = \alpha_P(0) + \alpha'_P t = 1 + \Delta + \alpha' t$: Pomeron 軌道



<u>SIBYLL2.3に実装した</u>

<u>元のpomeron flux</u>

SIBYLL2.3の作者である **Felix Reihn**は連動解析の結果に基づいて、SIBYLL2.3cのdiffractionの生成質量分布を改良した。

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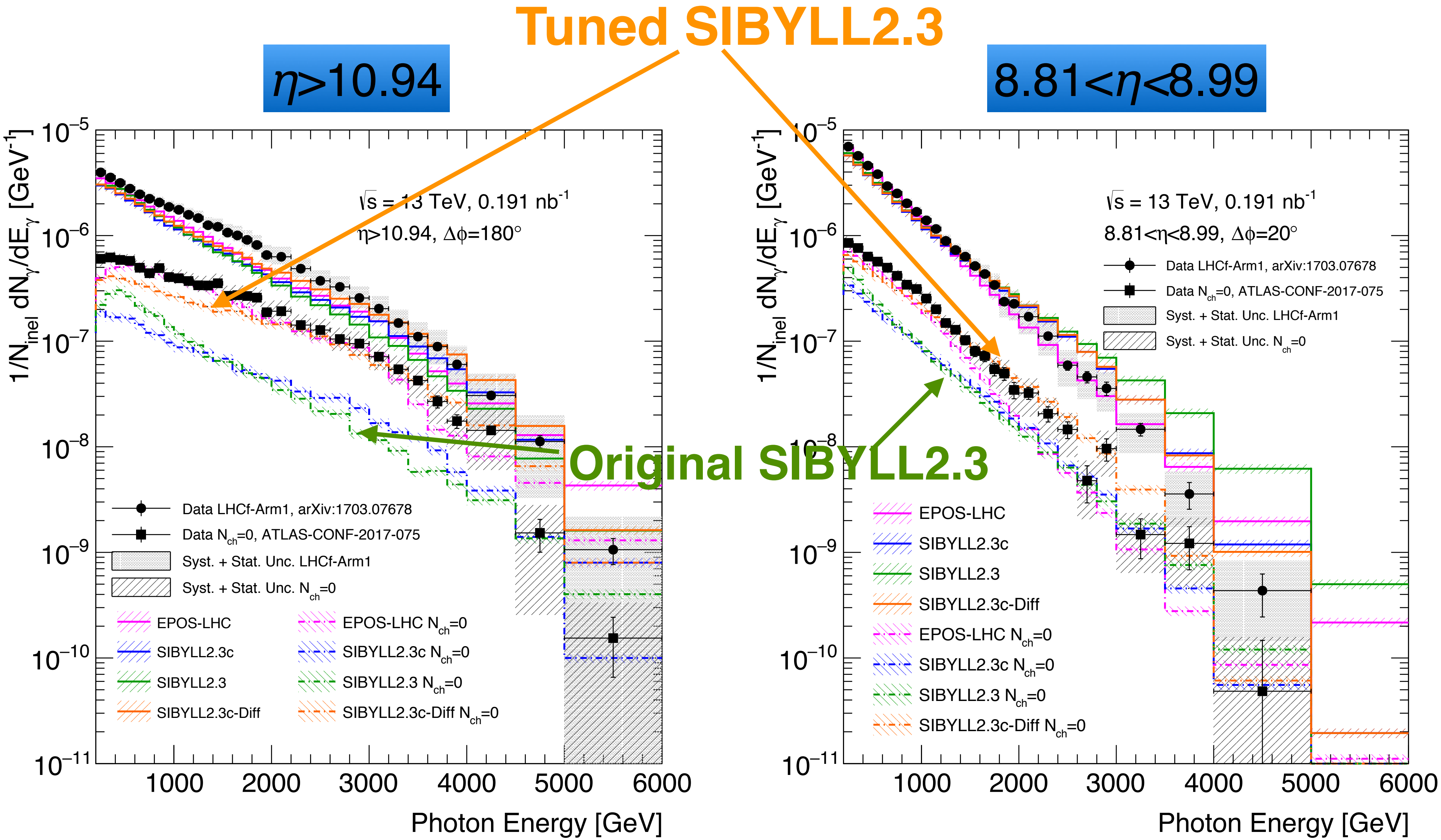
SIBYLL2.3c-Diffの光子スペクトル



SIBYLL2.3c-Diffは連動実験の結果をよく再現できるようになった。

X