Recent results from LHCf/RHICf

Takashi Sako
(ICRR, University of Tokyo)
For the LHCf and RHICf collaborations

The LHCf collaboration

Y.Itow, K.Masuda, Y.Matsubara, H.Menjo, Y.Muraki, K.Ohashi, K.Sato, M.Ueno, Q.D.Zhou, T.Sako, K.Yoshida, K.Kasahara, T.Suzuki, S.Torii, Y.Shimizu, T.Tamura, N.Sakurai, M.Haguenauer, W.C.Turner, O.Adriani, E.Berti, L.Bonechi, M.Bongi, G.Castellini, R.D'Alessandro, P.Papini, S.Ricciarini, A.Tiberio, A.Tricomi

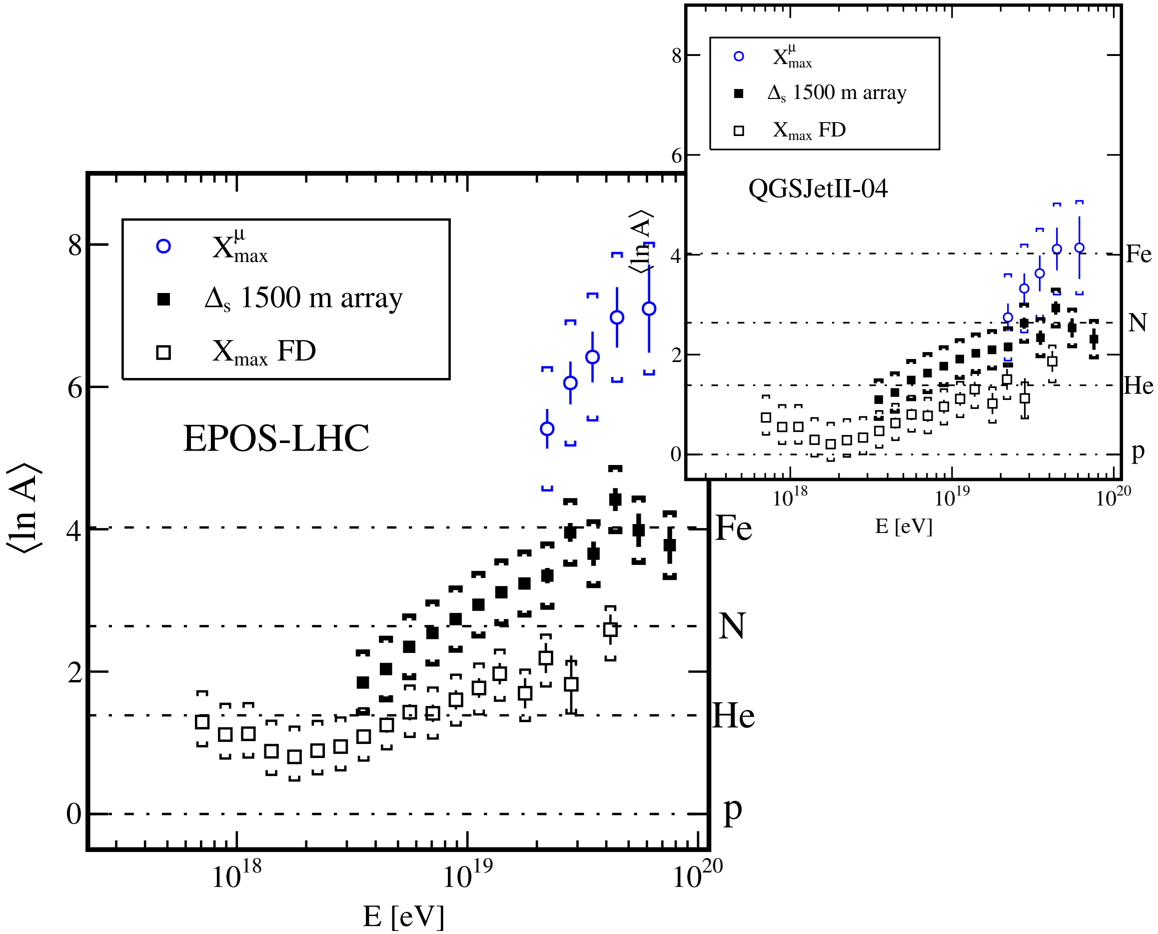
Institute for Space-Earth Environmental Research, Nagoya University, Kobayashi-Maskawa Institute, Nagoya University, Graduate School of Science, Nagoya University, ICRR, University of Tokyo, Shibaura Institute of Technology, Waseda University, Kanagawa University, Japan, Tokushima University, Japan, Ecole Polytechnique, France, LBNL, Berkeley, USA, INFN, Univ. di Firenze, INFN, Univ. di Catania, Italy

The RHICf collaboration

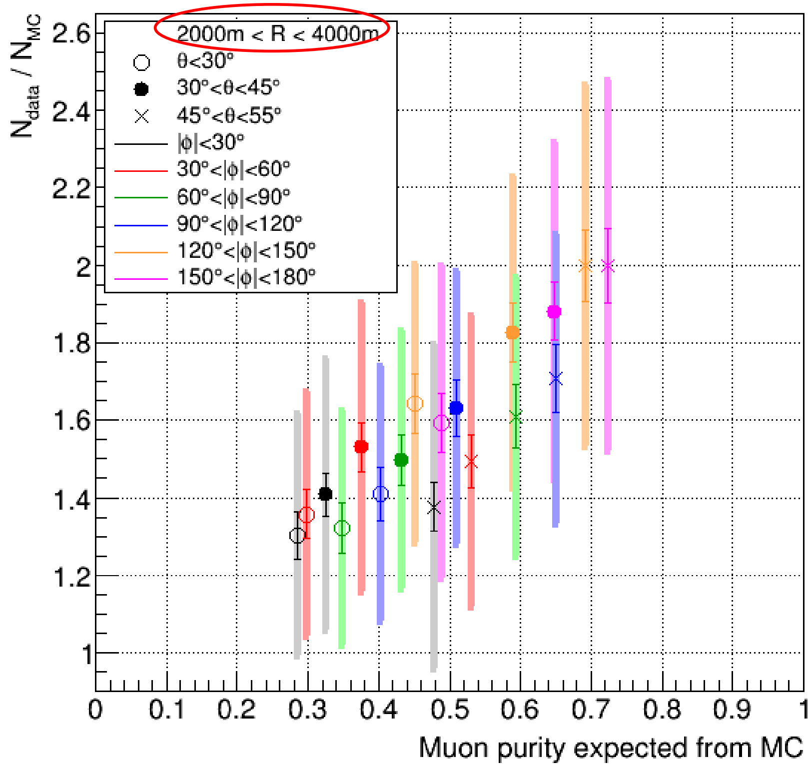
Y.Itow, H.Menjo, K.Sato, M.Ueno, Q.D.Zhou, T.Sako, Y.Goto, I.Nakagawa, R.Saidl, J.S.Park, M.H.Kim, K.Tanida, K.Kasahara, T.Suzuki, S.Torii, N.Sakurai, B.Hong, O.Adriani, E.Berti, L.Bonechi, R.D'Alessandro, A.Tricomi

Institute for Space-Earth Environmental Research, Nagoya University, Kobayashi-Maskawa Institute, Nagoya University, Graduate School of Science, Nagoya University, ICRR, University of Tokyo, Riken/Riken BNL Research Center, JAEA, Waseda University, Tokushima University, Japan, Seoul National University, Korea University, Korea, INFN, Univ. di Firenze, INFN, Univ. di Catania, Italy

Imperfect knowledge in hadronic interaction



18.8< log(E/eV) < 19.2
2000m<R<4000m

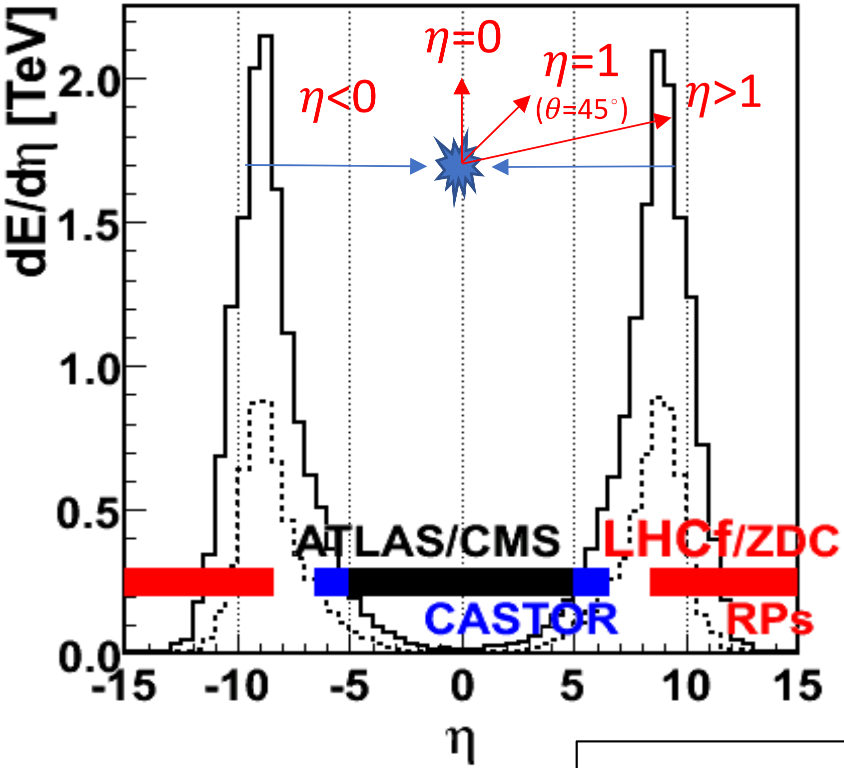


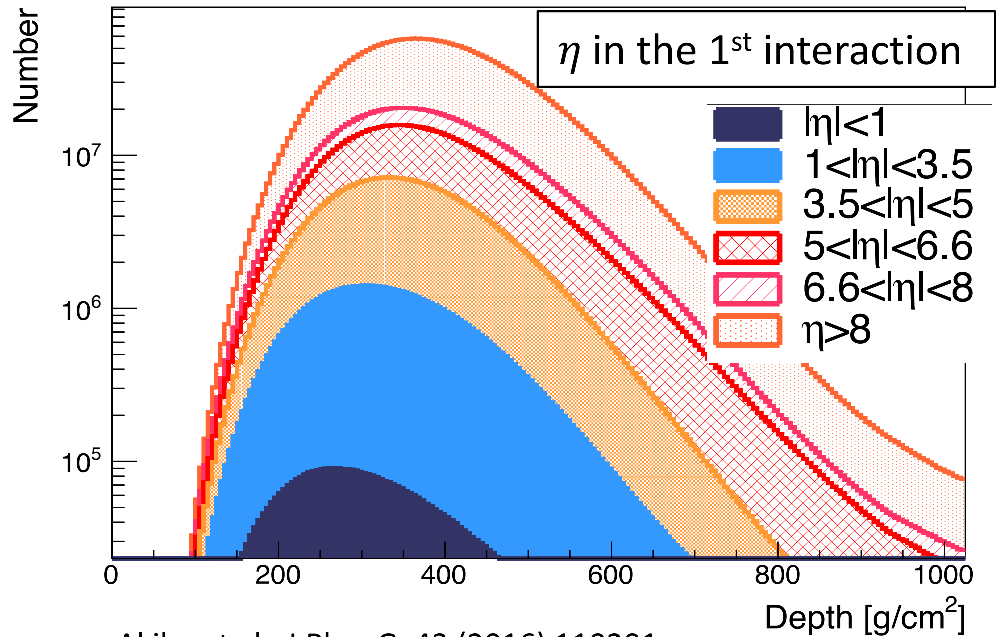
- Auger: different <lnA> with different analysis, different model,…
- Auger talk tomorrow (?)
- PRD 96, 122003 (2017)

- Telescope Array: expected muon purity vs. N_{data}/N_{MC}
- Muon excess as Auger pointed out
- Takeishi-san's talk tomorrow
- PhD thesis of R.Takeishi (2017)

Forward particles in air showers and at colliders

pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$





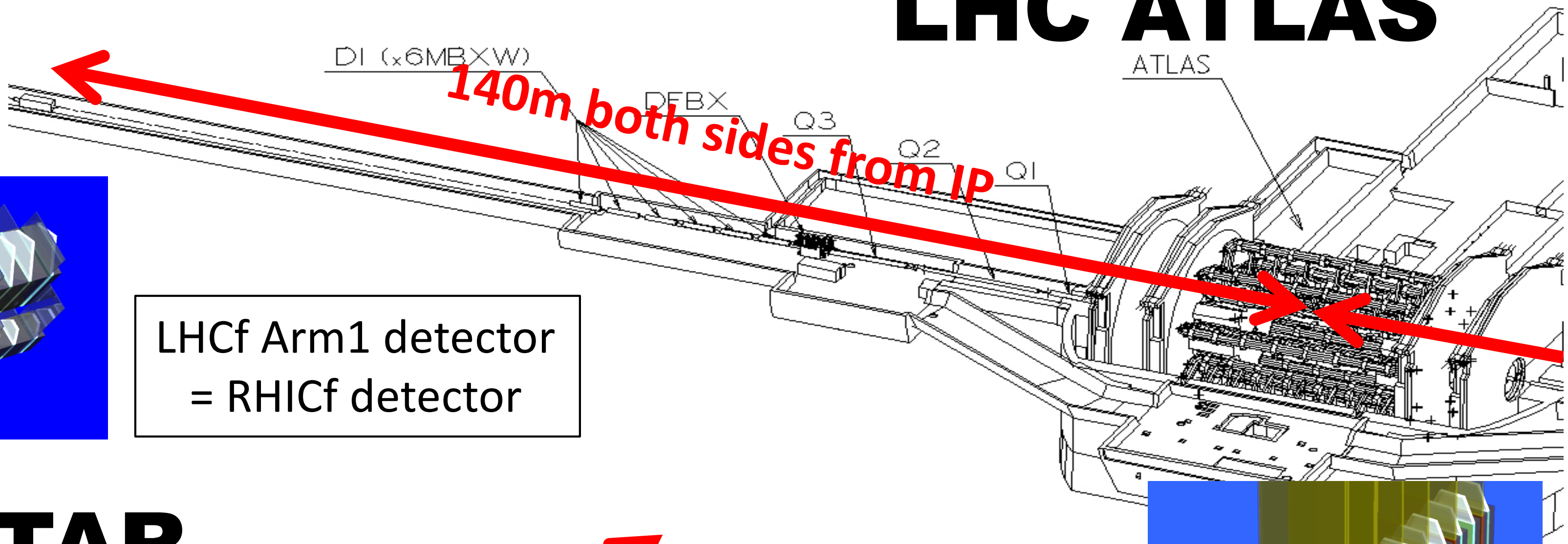
Akiba et al., J.Phys.G, 43 (2016) 110201

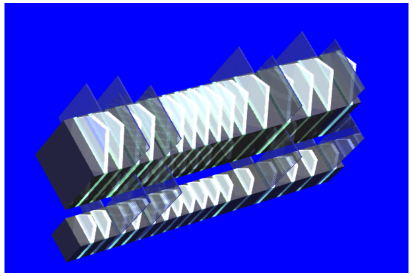
$\eta=8 \;\Rightarrow\; \theta \sim 1\text{mrad (CMS)}$

- ✓ Most of the collision energy flows into very forward region
- ✓ Dedicated experiments are necessary for forward measurement at colliders
- ✓ Most shower particles are daughters of very forward particles in the first interaction

LHC forward and RHIC forward

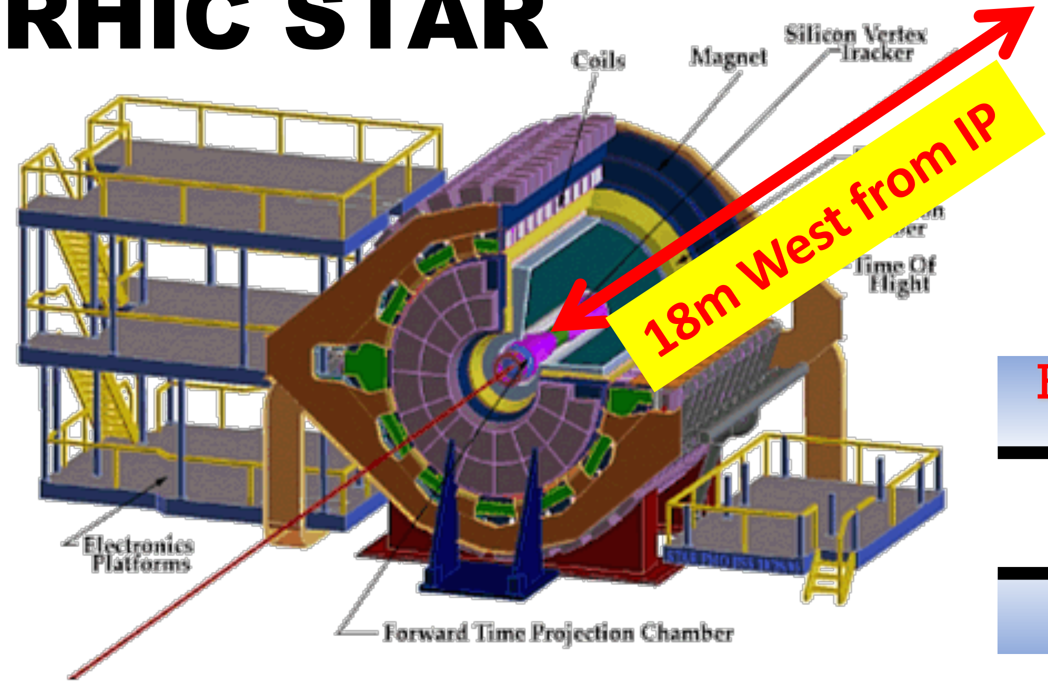
LHC ATLAS

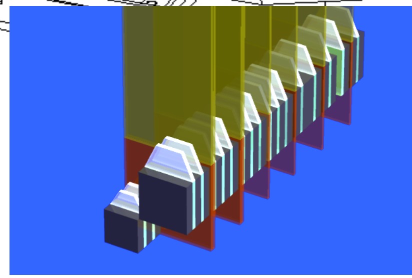




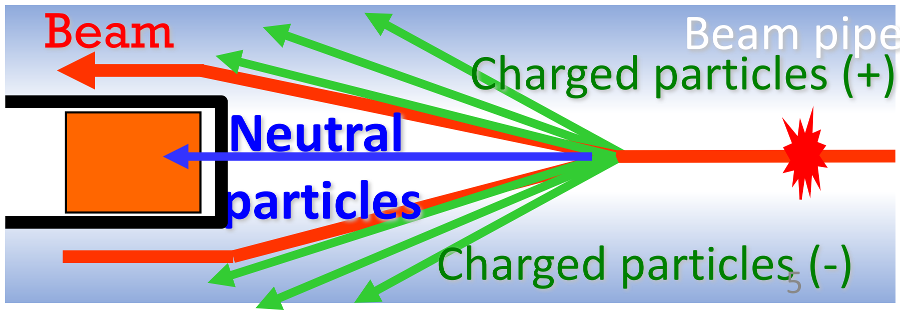
LHCf Arm1 detector
= RHICf detector

RHIC STAR



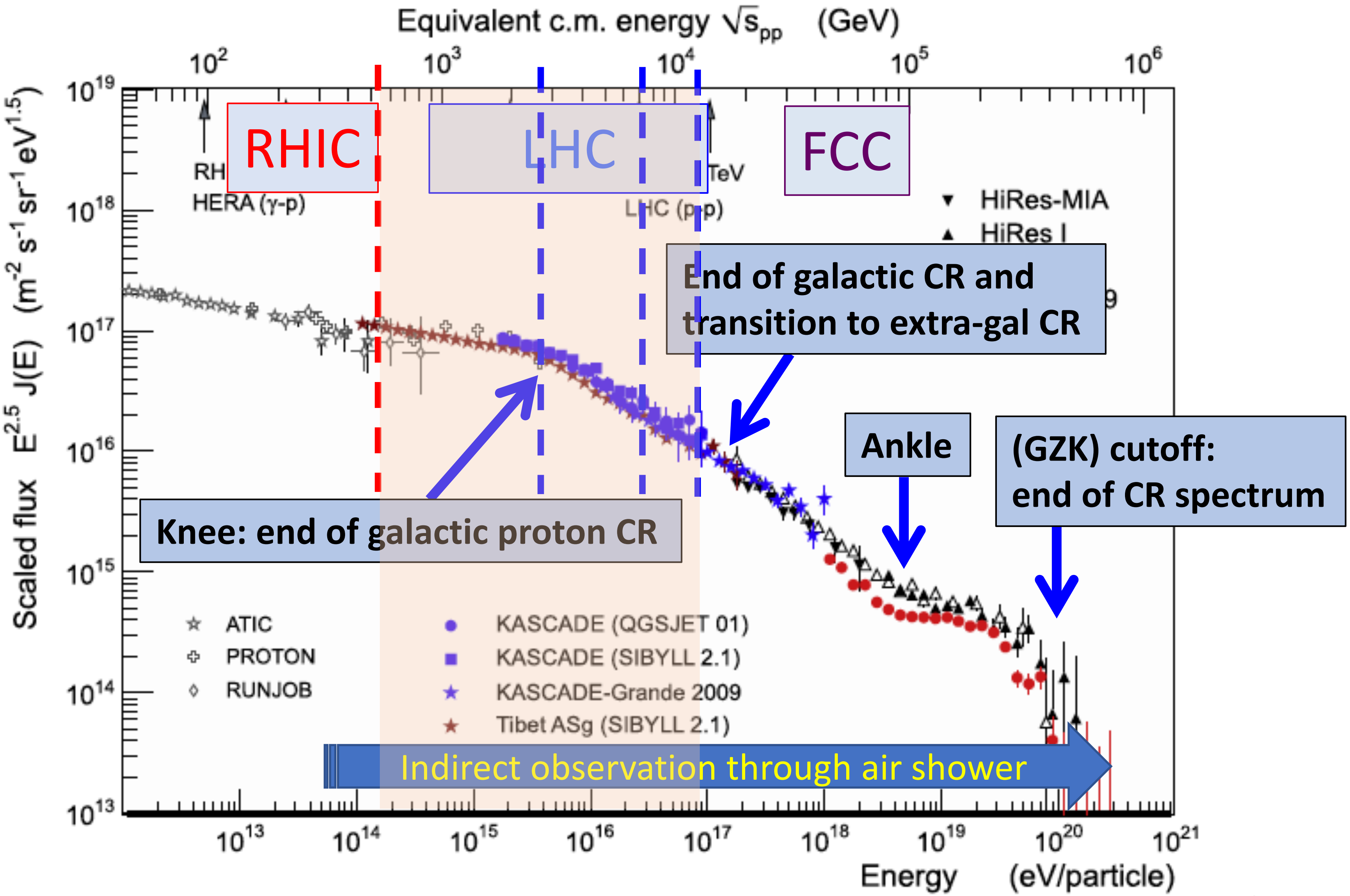


LHCf Arm2 detector



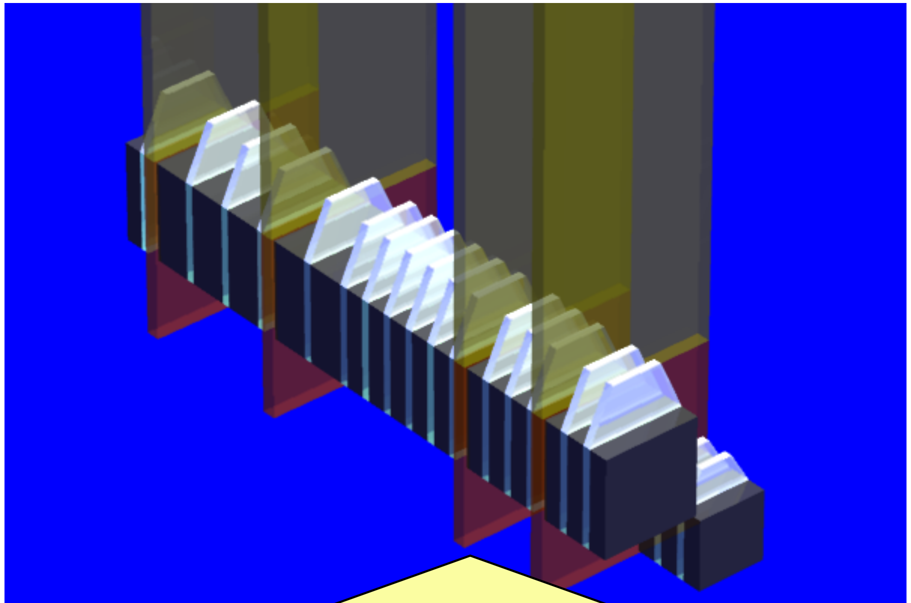
Cosmic-ray spectrum and collision energy

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



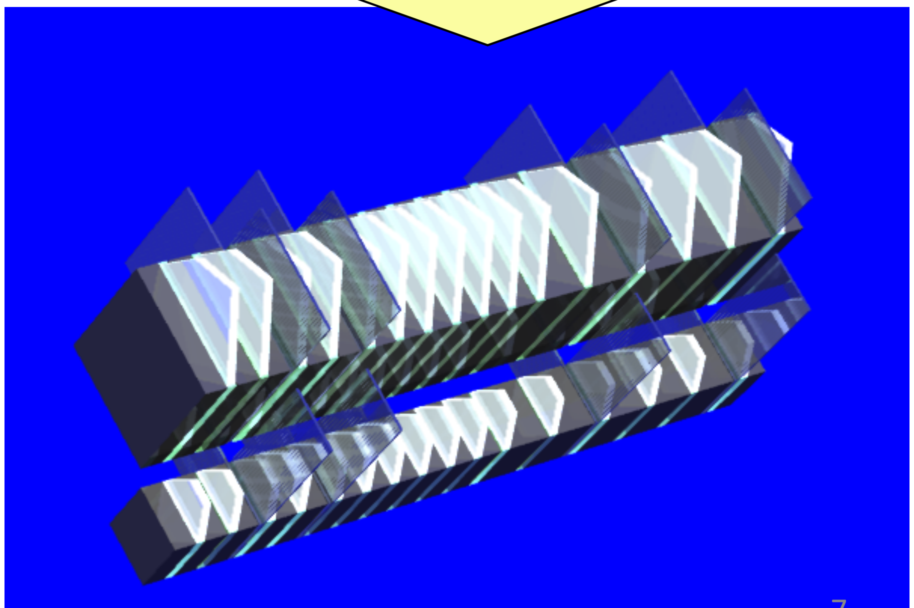
LHCf/RHICf Detectors

- ✓ 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 (13TeV p-p, 8.16TeV p-Pb)

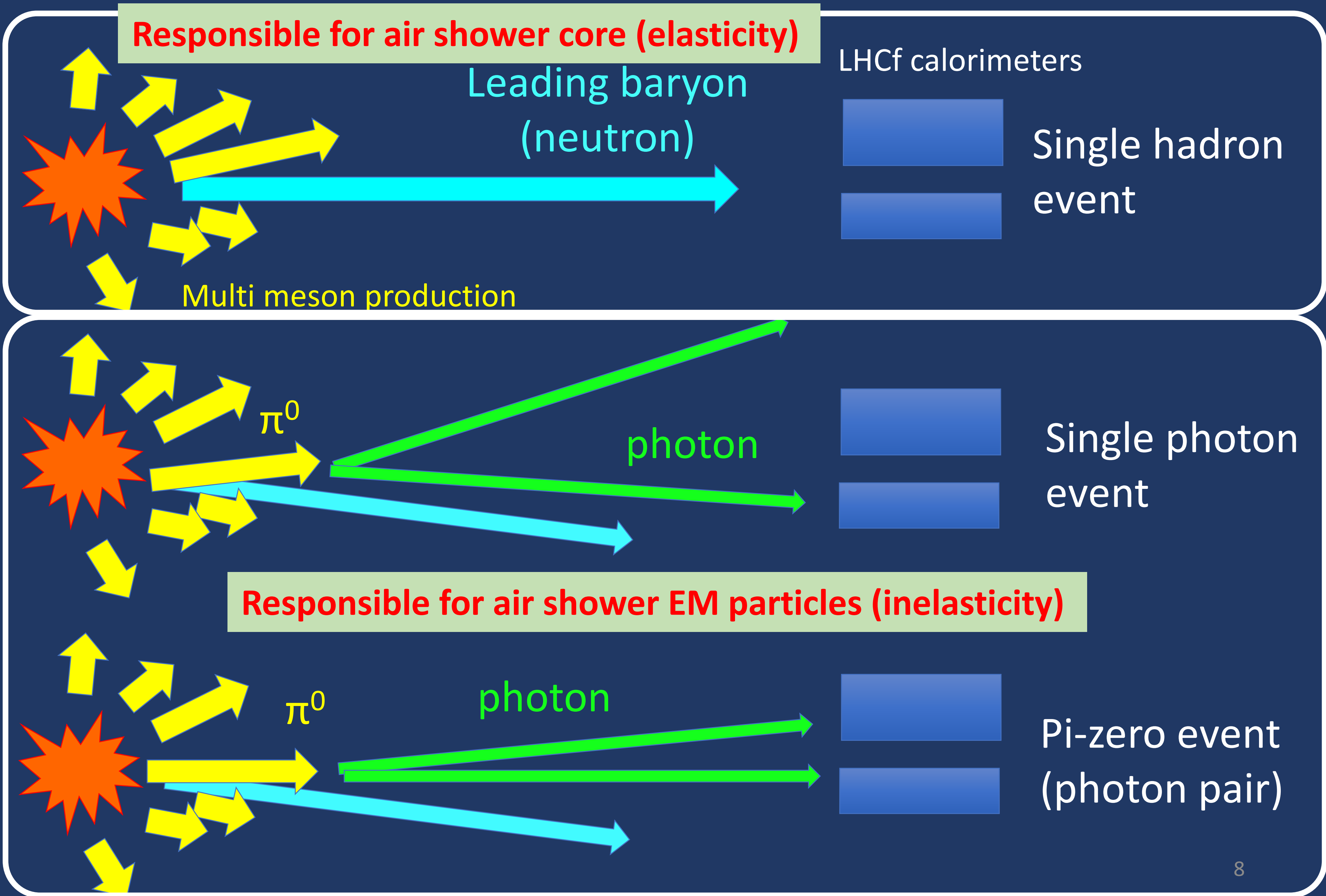


LHCf Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

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

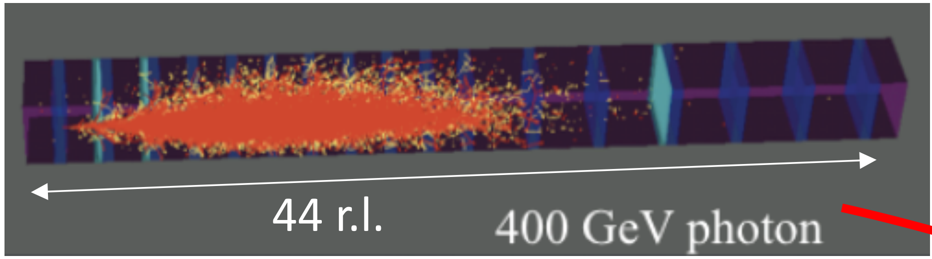


Event categories of LHCf/RHICf

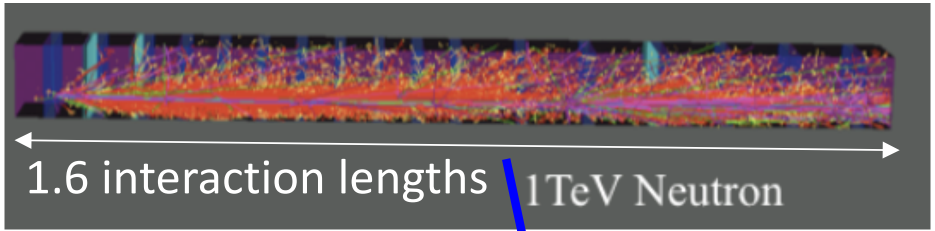


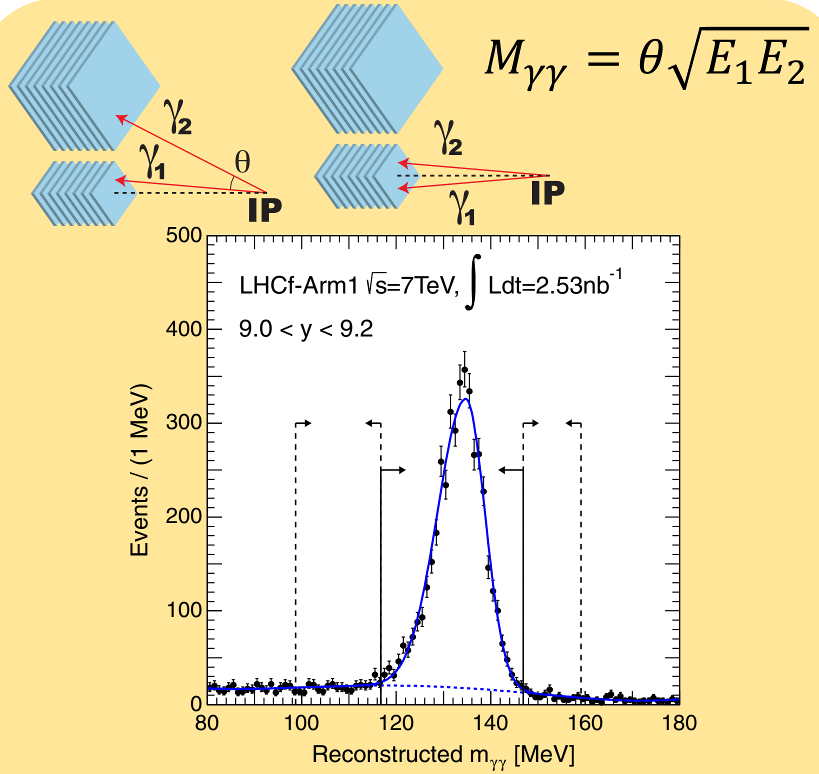
Particle ID (PID)

Photon event



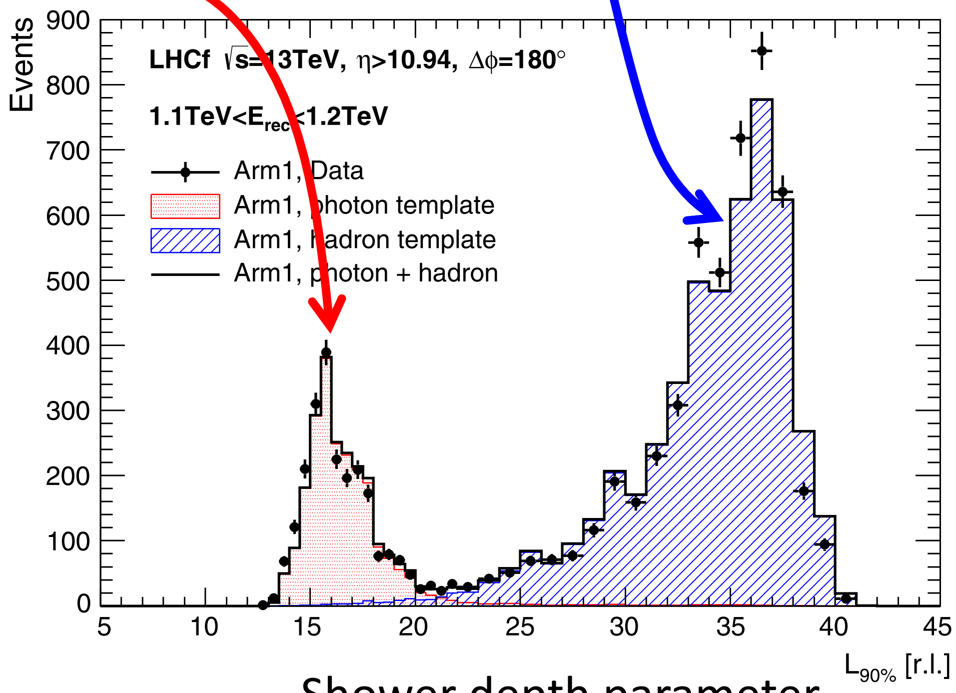
Neutron event





Invariant mass of photon pair

Peak @ 135MeV from π^0 decay events



Shower depth parameter

(Adriani et al., PLB, 2018)

(Adriani et al., PRD, 2012)

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
- ✓2013 LOI submitted to BNL for RHICf
- ✓2015 $\sqrt{s}$=13TeV p-p collision
- ✓2016 $\sqrt{s_{NN}}$=8.16TeV p-Pb collision
- ✓2017 $\sqrt{s}$=510GeV polarized p-p collision as RHICf

LHCf physics results
RHICf physics results
performance results

Analyses and Publications

<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>Single-spin asymmetry</th><th>Performance</th></tr>
<tr><td>Beam test</td><td>NIM, A671 (2012) 129-136</td><td>JINST, 9 (2014) P03016</td><td></td><td></td><td></td><td></td></tr>
<tr><td>0.51TeV polarized p-p @RHIC</td><td>Analysis in progress</td><td></td><td></td><td colspan="2">Analysis in progress</td><td>Analysis in progress</td></tr>
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<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><td></td></tr>
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<tr><td>LHCf+ATLAS</td><td>ATLAS-CONF-2017-075</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Analyses and Publications

Posters in this Workshop

- LHCf physics results
- RHICf physics results
- performance results

	Photon (EM shower)	Neutron (hadron shower)	π^0 (limited acceptance)	π^0 (full acceptance)	Single-spin asymmetry	Performance
Beam test	**NIM, A671 (2012) 129-136**	**JINST, 9 (2014) P03016**				
0.51TeV polarized p-p @RHIC	Analysis in progress			Ana M.H.Kim ess		K.Sato M.Ueno
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						
8.16TeV p-Pb						
13TeV p-p	**PLB, 780 (2018) 233-239**	In preparation				
LHCf+ATLAS	Q.D.Zhou					

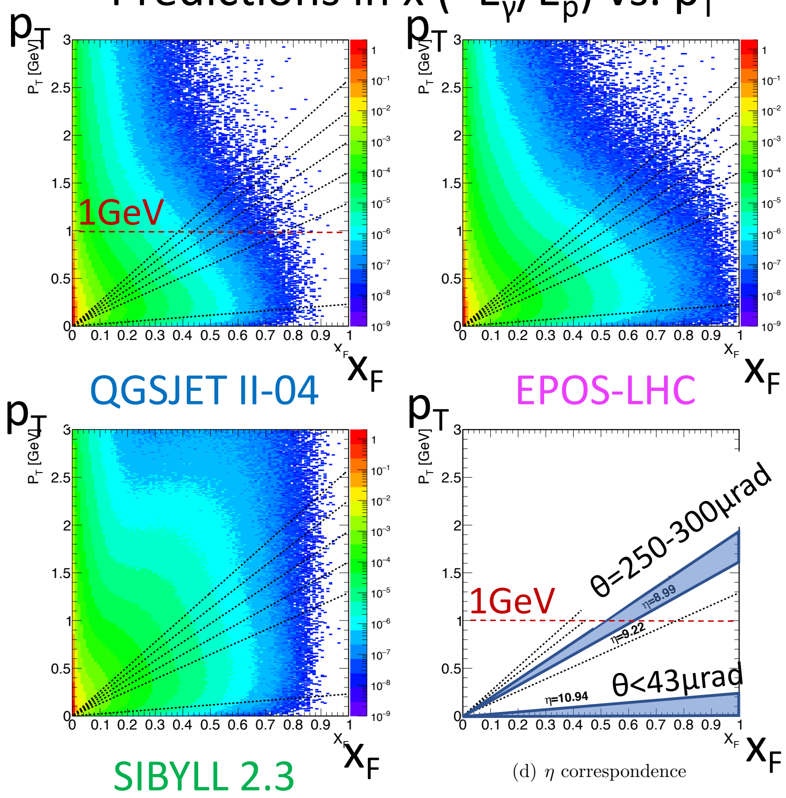
Recent topics in LHCf analysis

- Photon cross section in 13TeV p-p collisions
  - Joint analysis with ATLAS to separate diffractive and non-diffractive origins
- √s dependence
  - π^0 cross section
    - 7TeV p-p collisions
    - Comparison of 2.76TeV and 7TeV data
  - Neutron cross section
    - Preliminary 13TeV results
    - Comparison with data <200GeV collisions (in progress)
  - Comparison with 510GeV p-p collisions

=> RHICf status

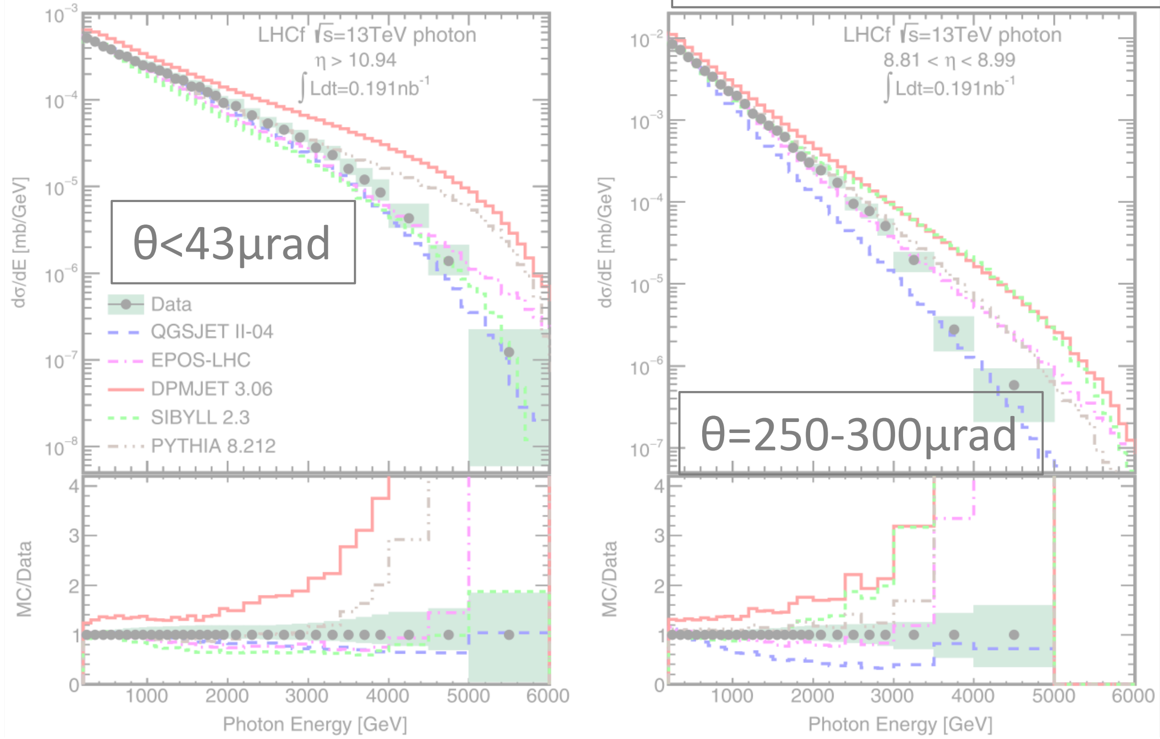
Photon ($\pi^0 \rightarrow 2\gamma$) production cross section in LHC 13TeV p-p collision

Predictions in x (=E_γ/E_p) vs. p_T



Y. Makino, PhD thesis（2017）CERN-THESIS-2017-049

PLB, 780 (2018) 233-239



- PYTHIA8, DPMJET3 overestimate
- SIBYLL2.3 under(over) estimates at small (large) angle
- QGSJET II-04 underestimates
- EPOS-LHC shows best agreement (slight overestimate near maximum energy)

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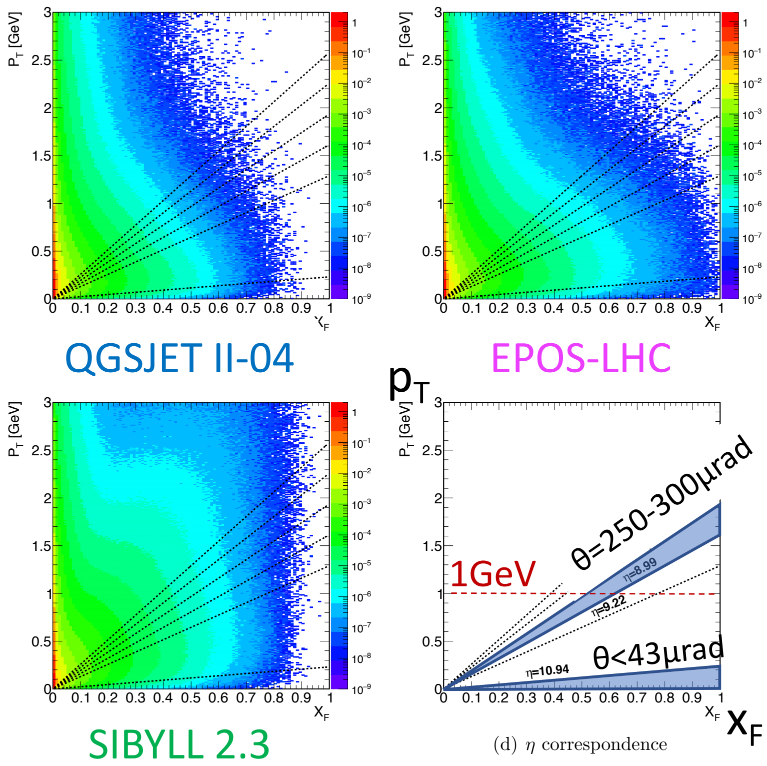

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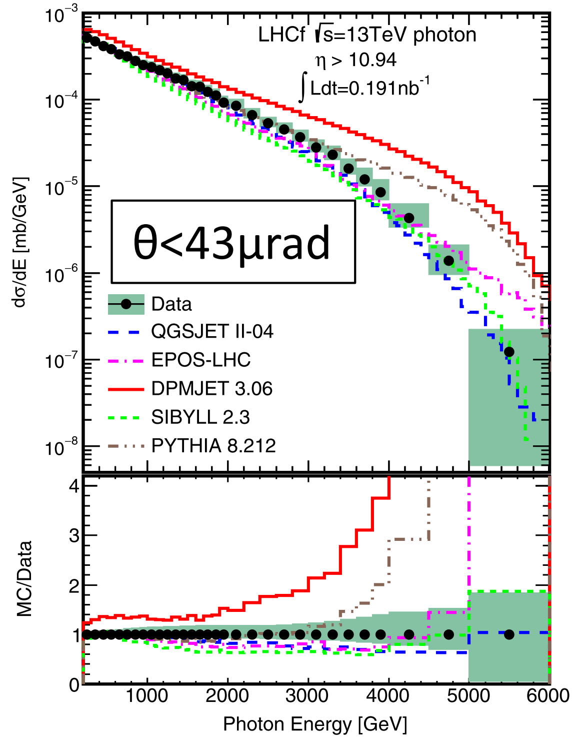

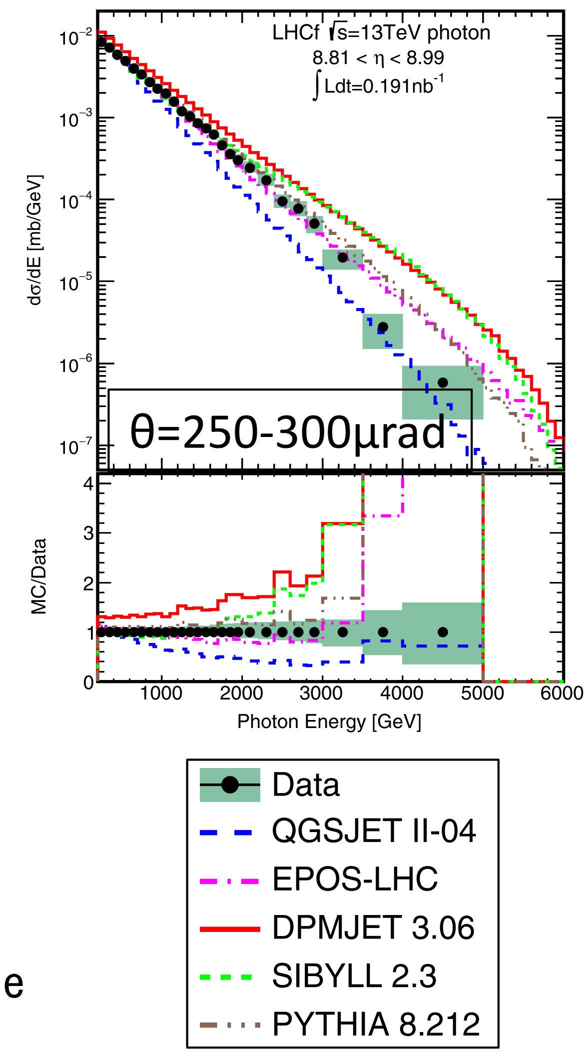

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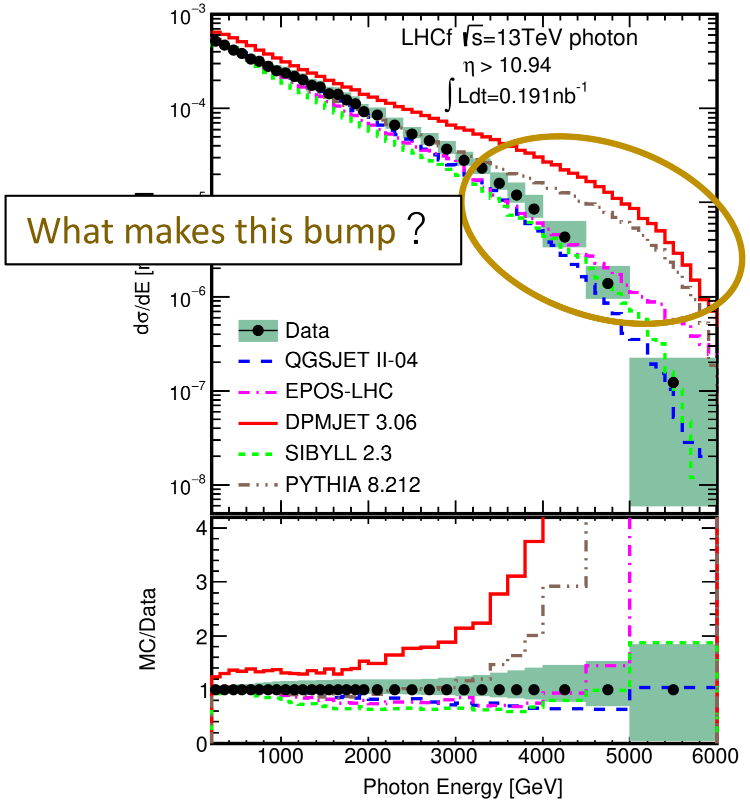
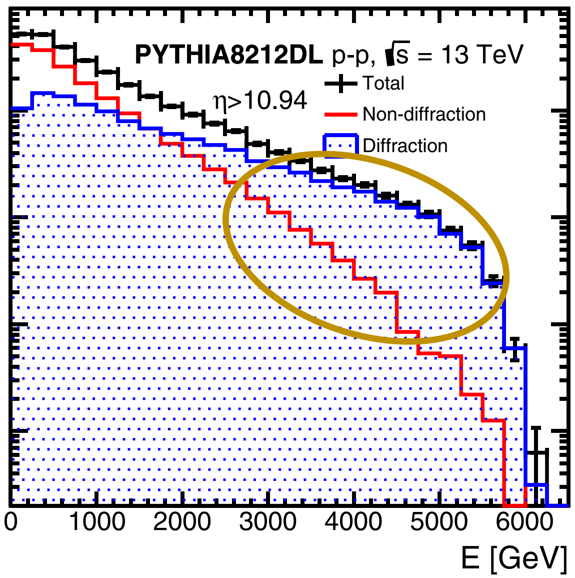
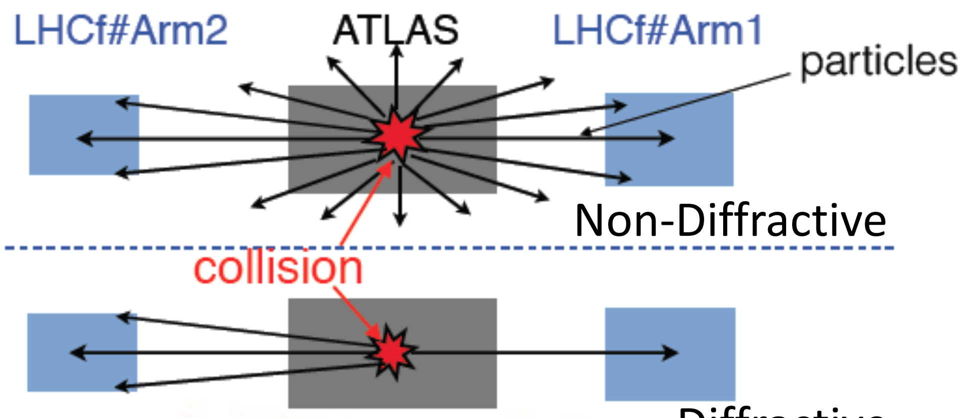
Origin of photons





Zhou, Itow, Menjo and Sako, EPJC (2017) 77:212

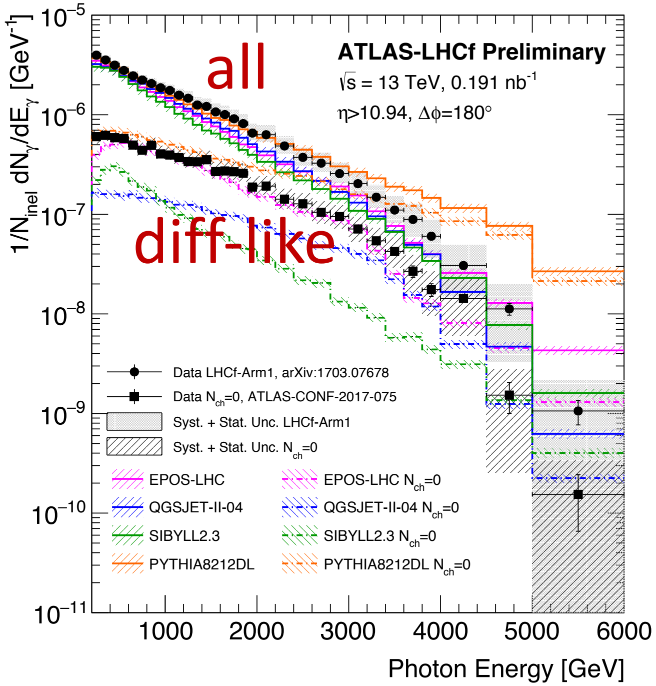
Diffractive
Non-diffractive

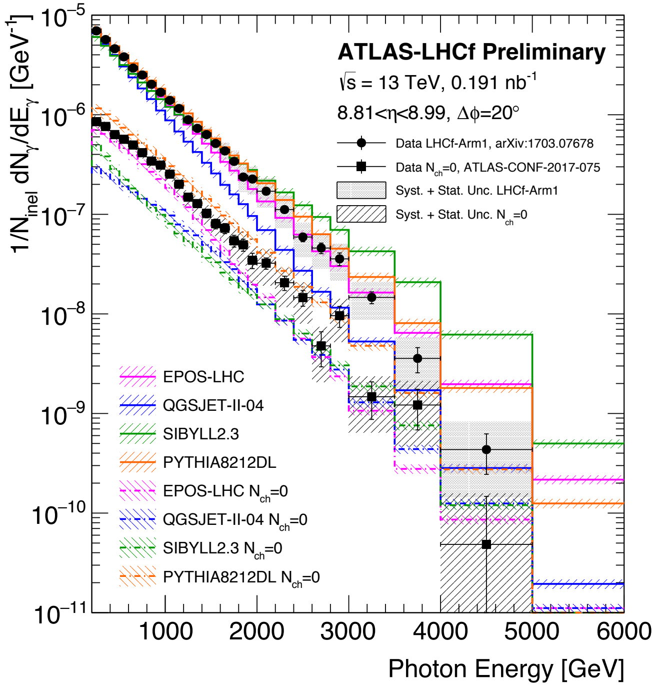


- PYTHIA predicts different spectra between diffractive and non-diffractive interactions
- ATLAS inner tracker enables to categorize events in diffractive-like and non-diffractive-like

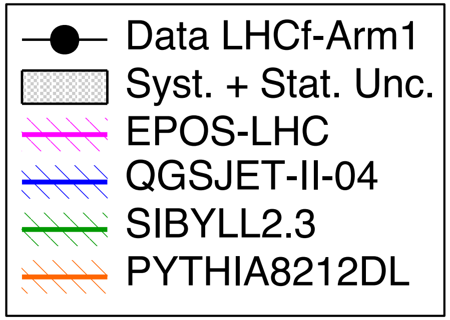
ATLAS-LHCf joint analysis

LHCf (all; ●+solid lines), LHCf diffractive-like (■+dashed lines)

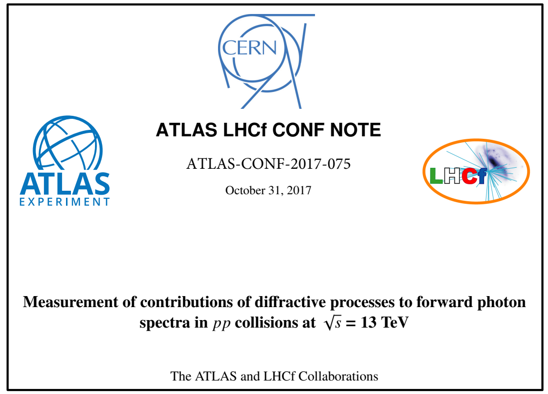




- Use ATLAS N_{ch}=0 to define diffractive-like events
- Applied to LHCf photon cross sections



ATLAS-CONF-2017-075


CERN

ATLAS EXPERIMENT

ATLAS LHCf CONF NOTE

ATLAS-CONF-2017-075

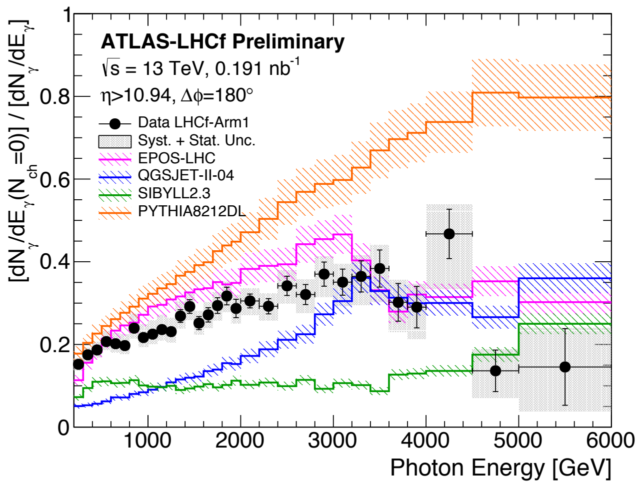
October 31, 2017

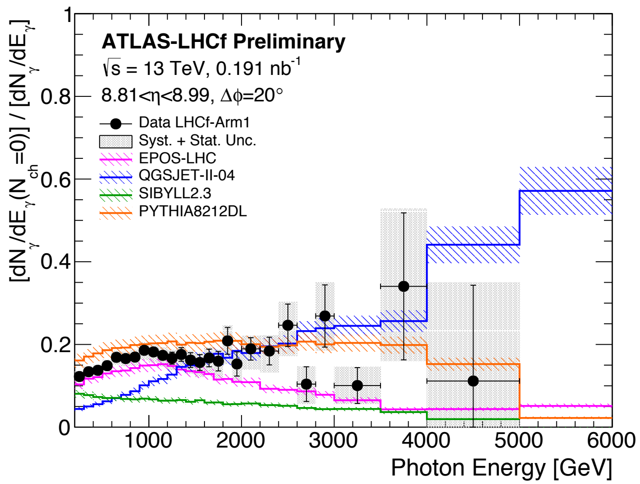
LHCf

Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at $\sqrt{s}$ = 13 TeV

The ATLAS and LHCf Collaborations

diffractive-like/ all

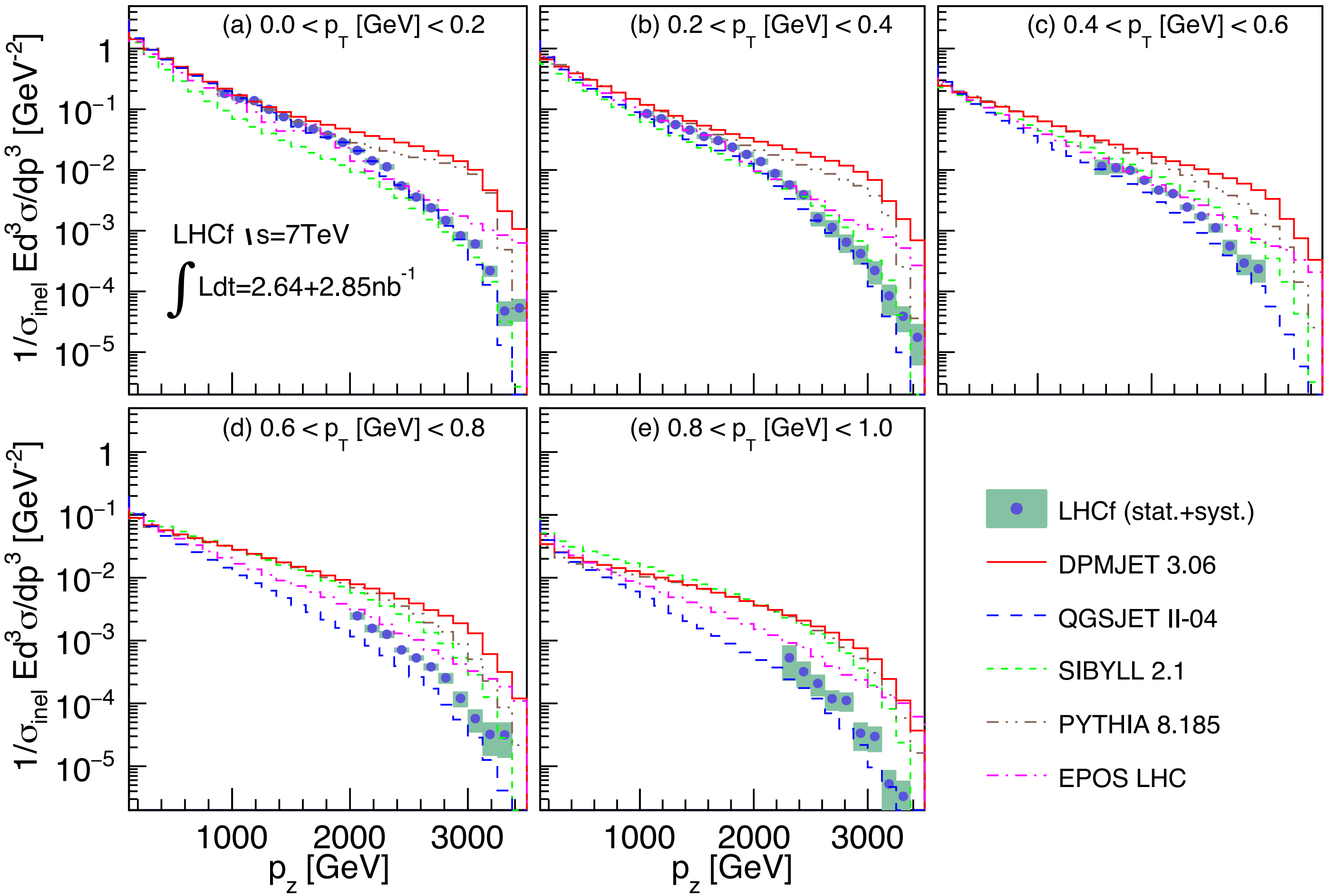




See poster by Q.D.Zhou

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

(PRD, 94 (2016) 032007)

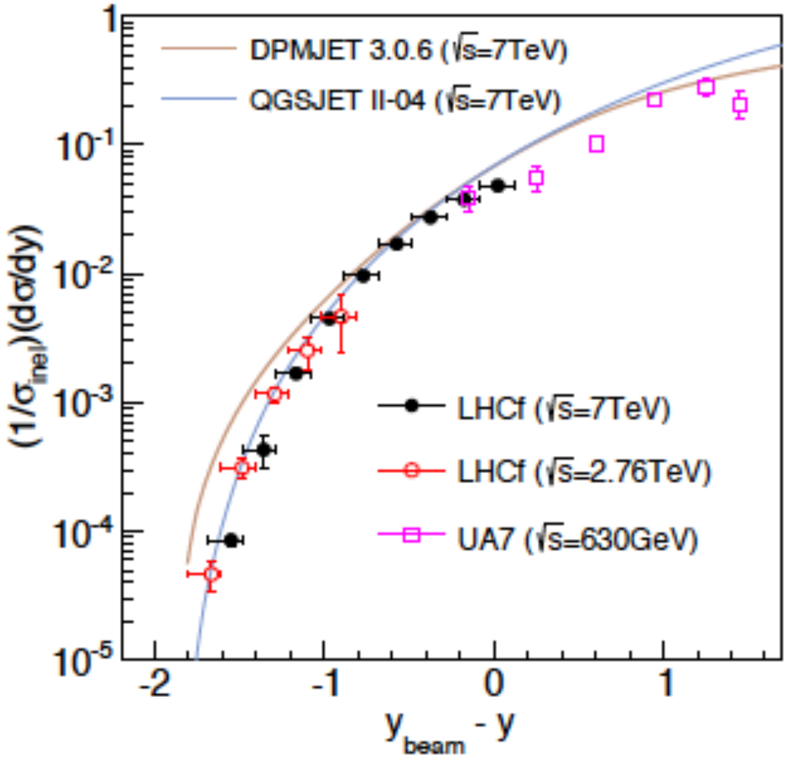


- ✓ Same trend with the photon results (both 7 and 13 TeV)
- ✓ DPMJET3 and PYTHIA8 overestimate over all E-p_T range
- ✓ p_T dependence of SIBYLL2.1 is not compatible with experiment
- ✓ EPOS-LHC and QGSJET II-04, standard in air shower MC, are not bad

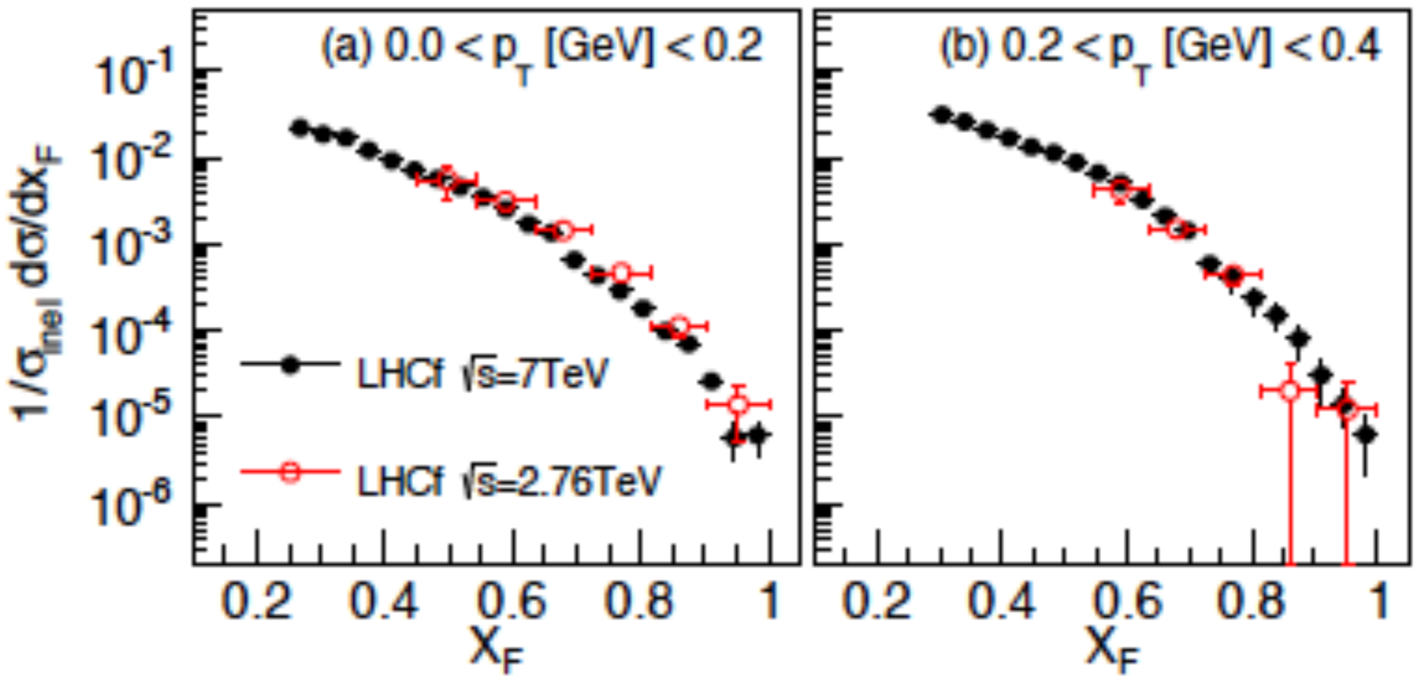
√s scaling ; π^0

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

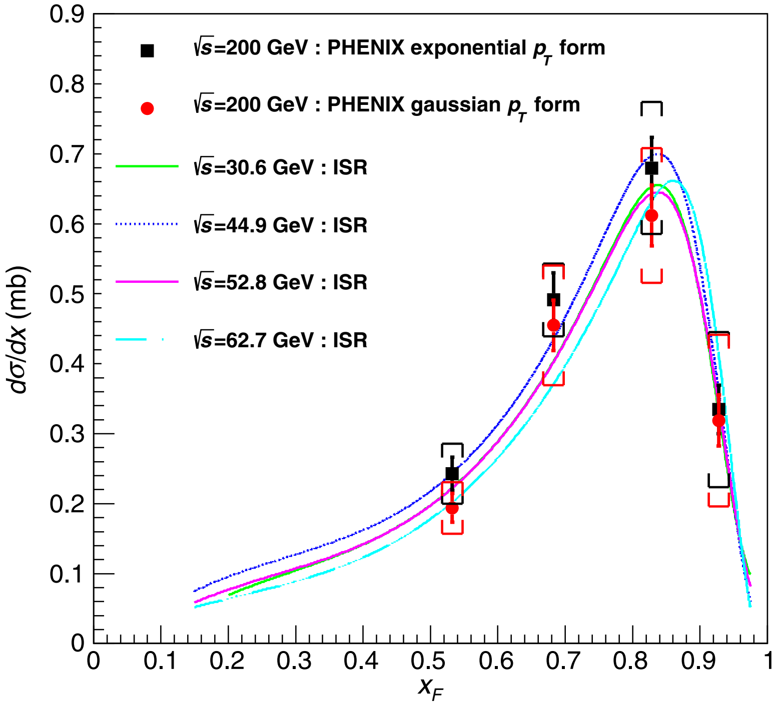


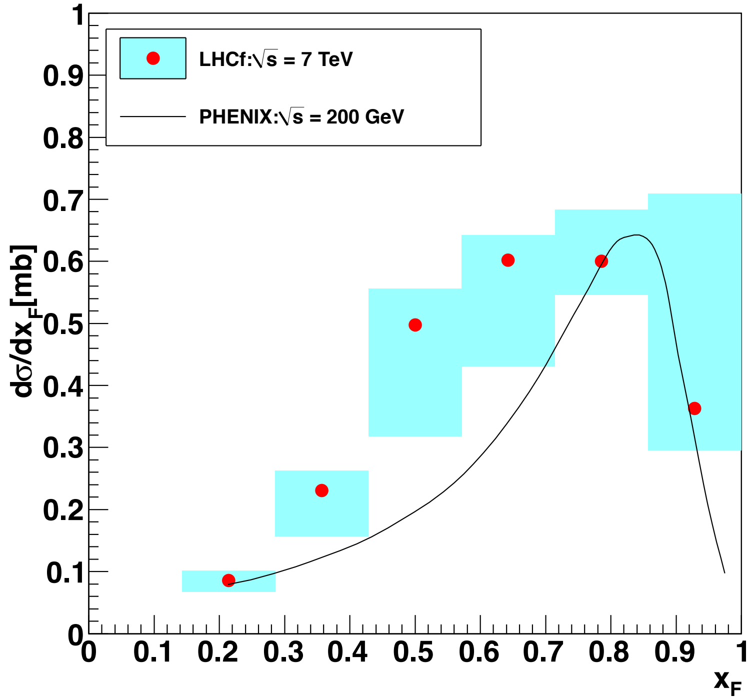
PRD, 94 (2016) 032007



$x_F = 2p_z/\sqrt{s}$

√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

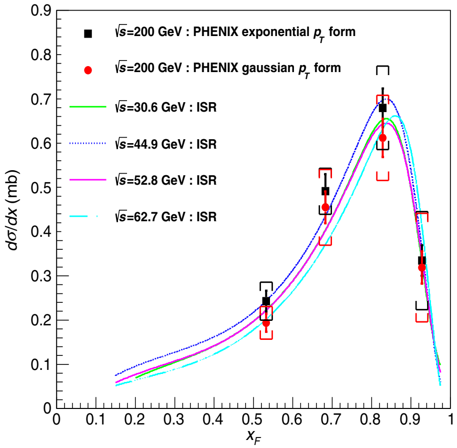
$p_T < 0.11\ x_F$ GeV/c

√s = 7000 GeV @LHC

Narrower angle than the published result to compare with the previous works

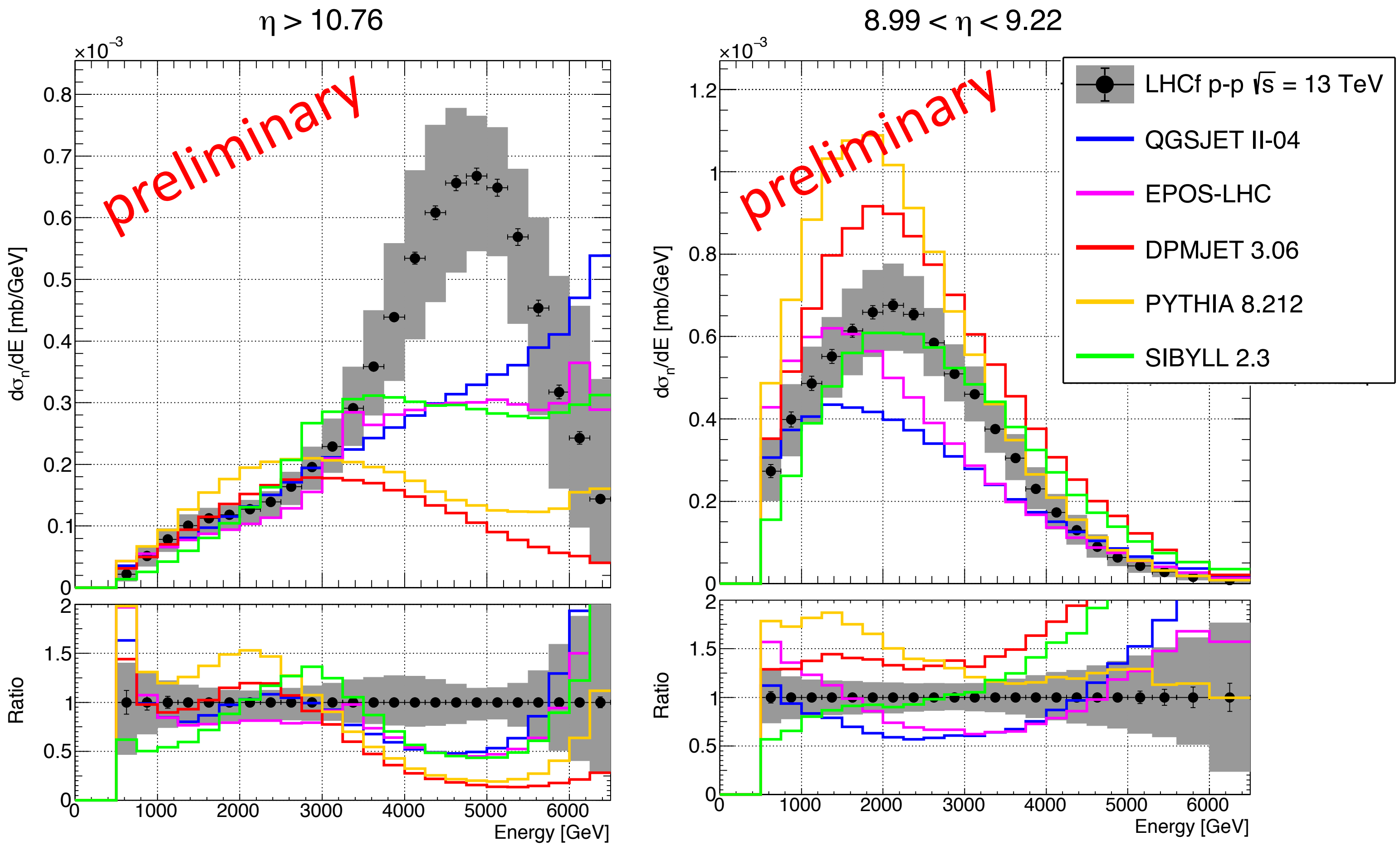
- ✓ Excellent scaling at √s = 30-200GeV
- ✓ √s = 7TeV result agrees in a peak structure, but slightly soft??
- ✓ LHCf data at 900GeV, 2.76TeV, 13TeV to be analyzed
- ✓ RHICf data at 510GeV becomes available

Neutron in 13TeV p-p collisions



ISR+PHENIX

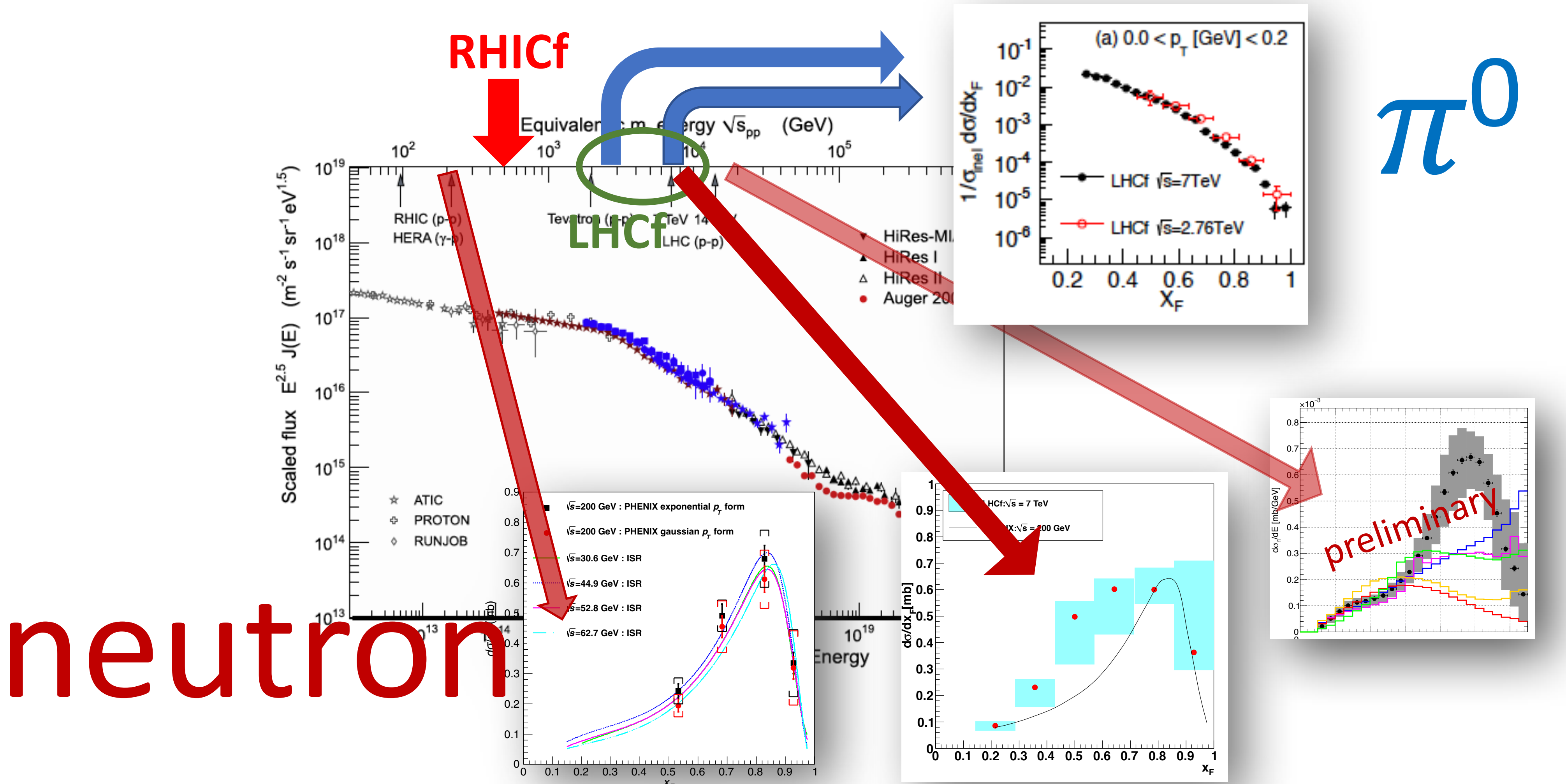
NOTE: p_T range is not same



- Preliminary results (PhD thesis of E.Berti, CERN-THESIS-2017-035 +update)
- Peak structure around 0 degree is similar to the previous results
  (NOTE: p_T range is wider than the previous analyses. Analysis for direct comparison in progress.)
- Effect of unfolding (40% energy resolution) is carefully studied before publication

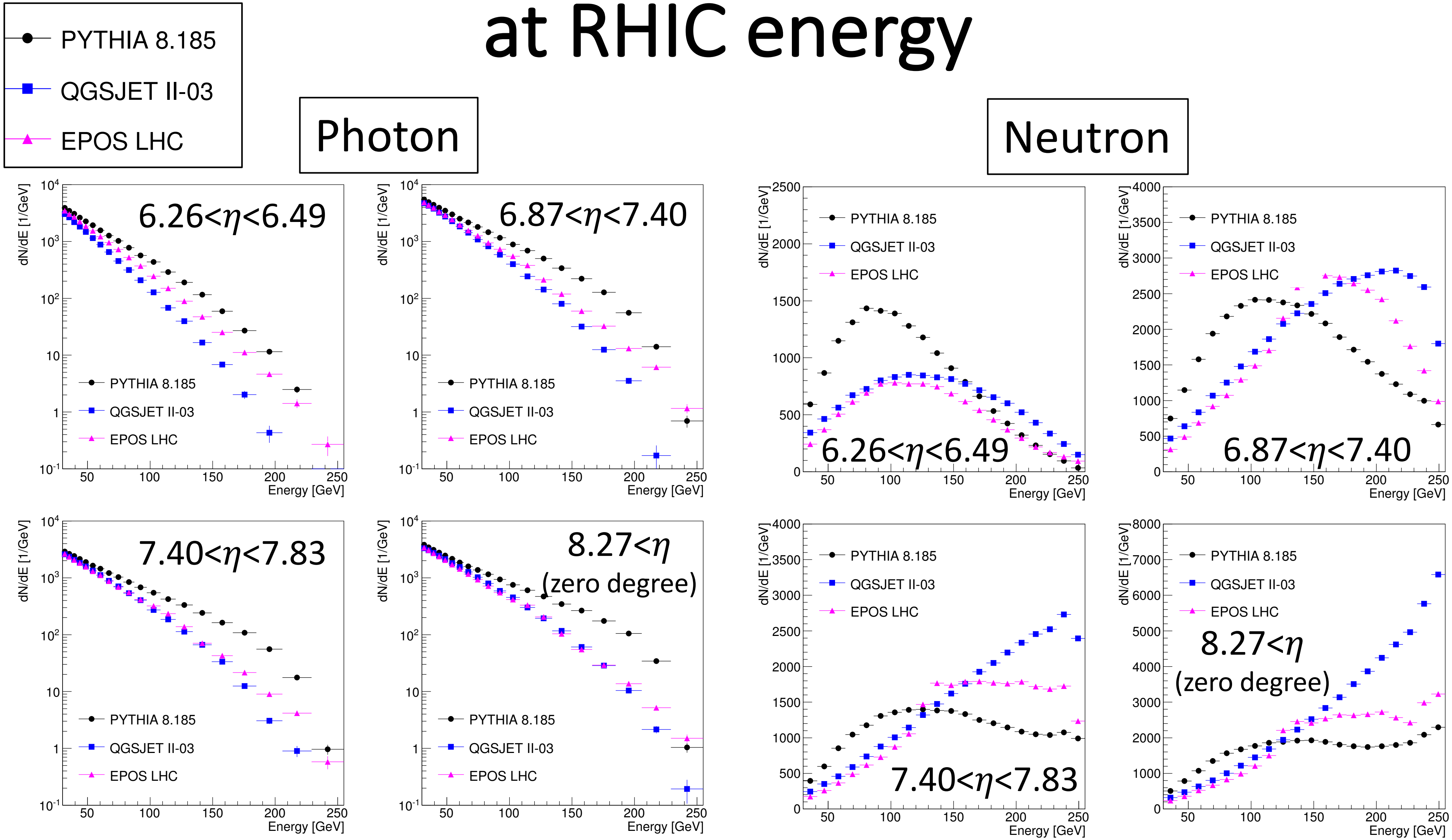
√s scaling, or breaking?

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



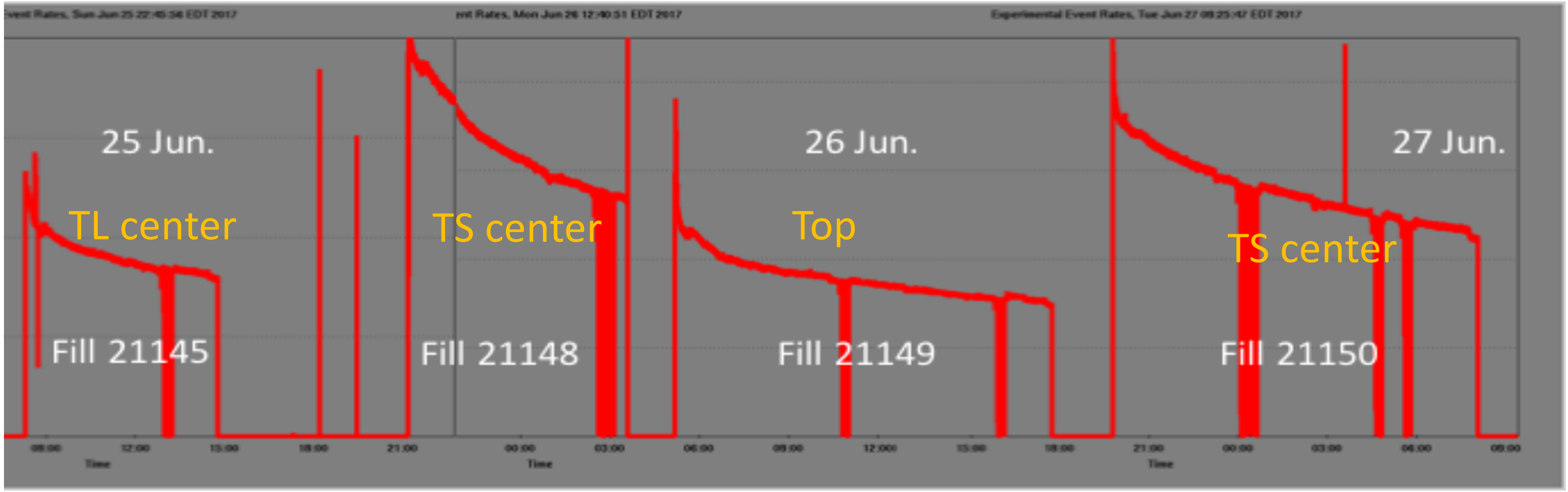
ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data
indicate √s scaling ***braking*** of forward neutrons

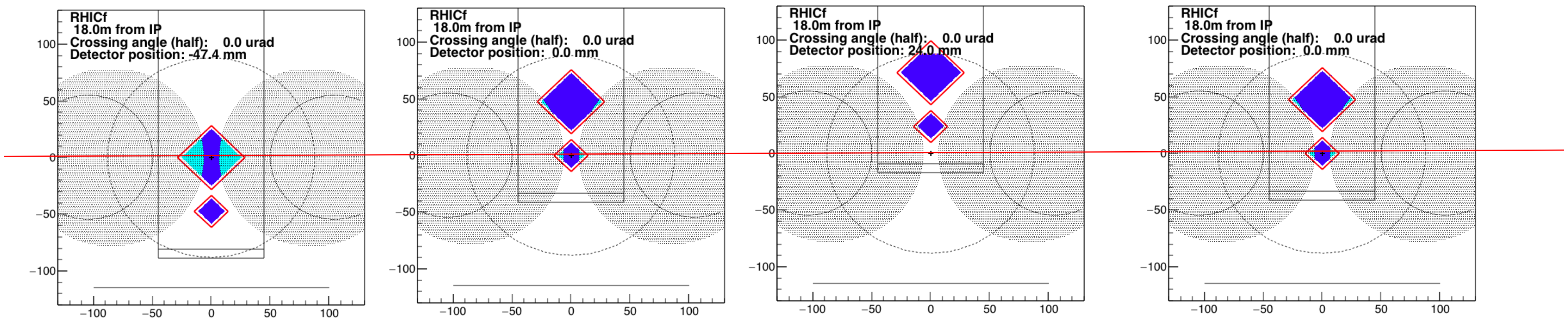
Model to model difference at RHIC energy



✓ Behavior is very similar to the 7TeV, 13TeV cases

Collision rates in 2017 RHICf week



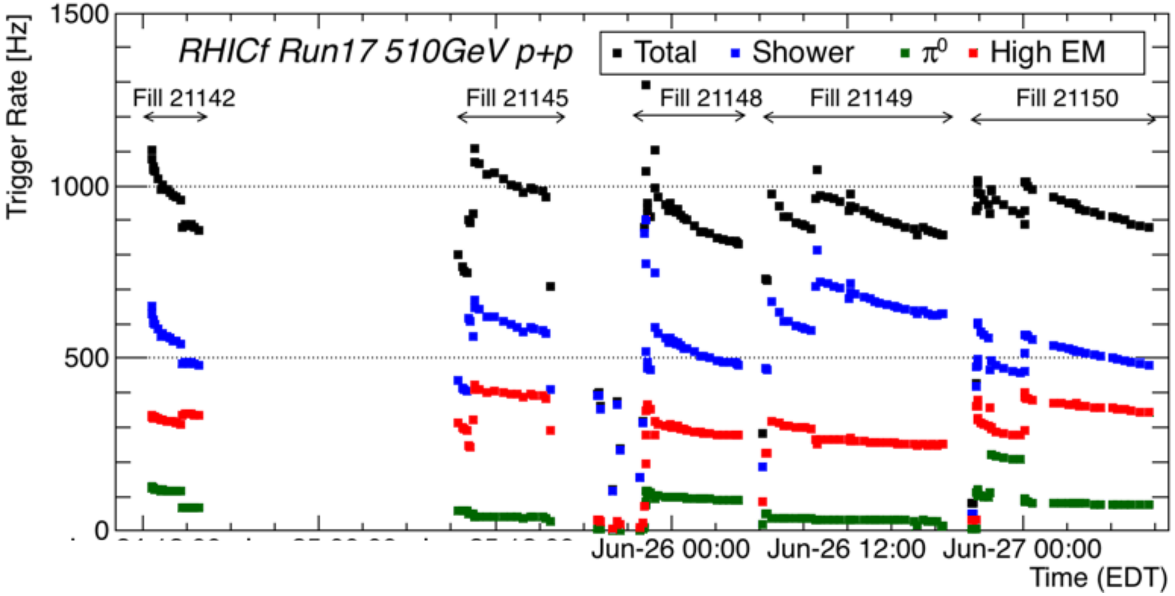


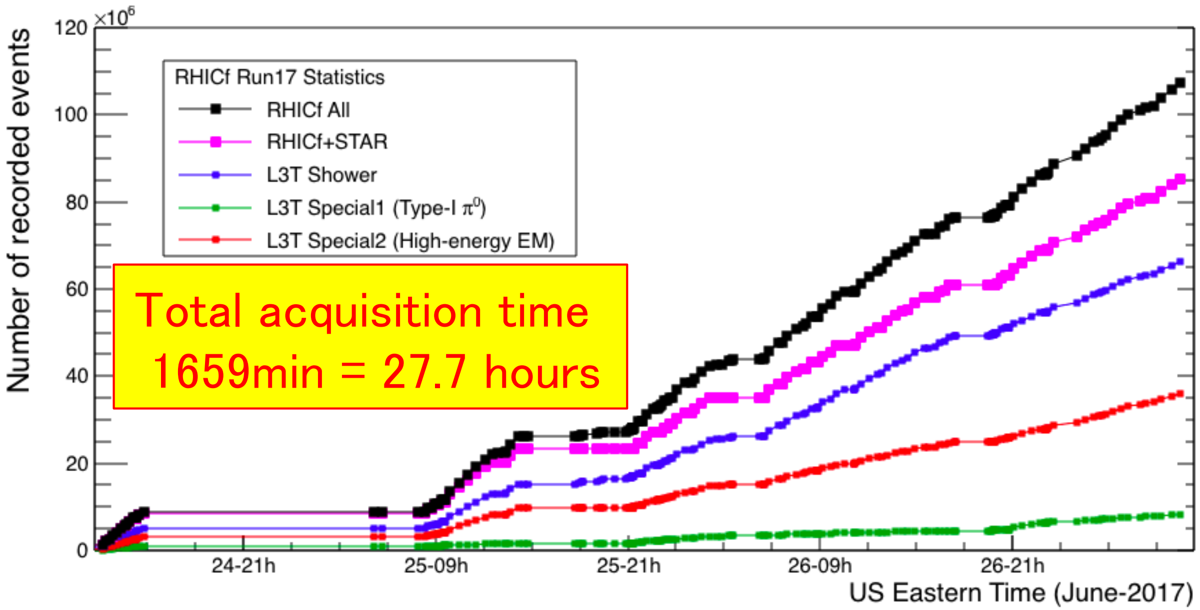
- Higher β^* (=8m) than usual RHIC operation
- Radial polarization (usually vertical) to maximize the single-spin asymmetry in vertical
- Luminosity~10^{31} $cm^{-2}s^{-1}$

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

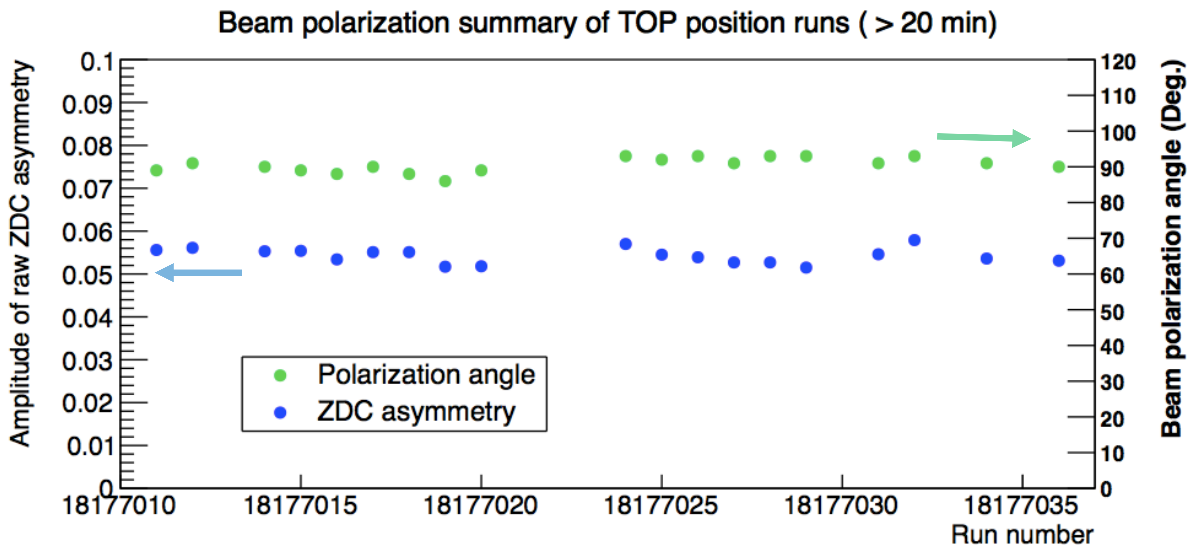
RHICf+STAR

RHICf (shower event)

RHICf (High-energy EM trigger)

RHICf (Type-I π^0 trigger)

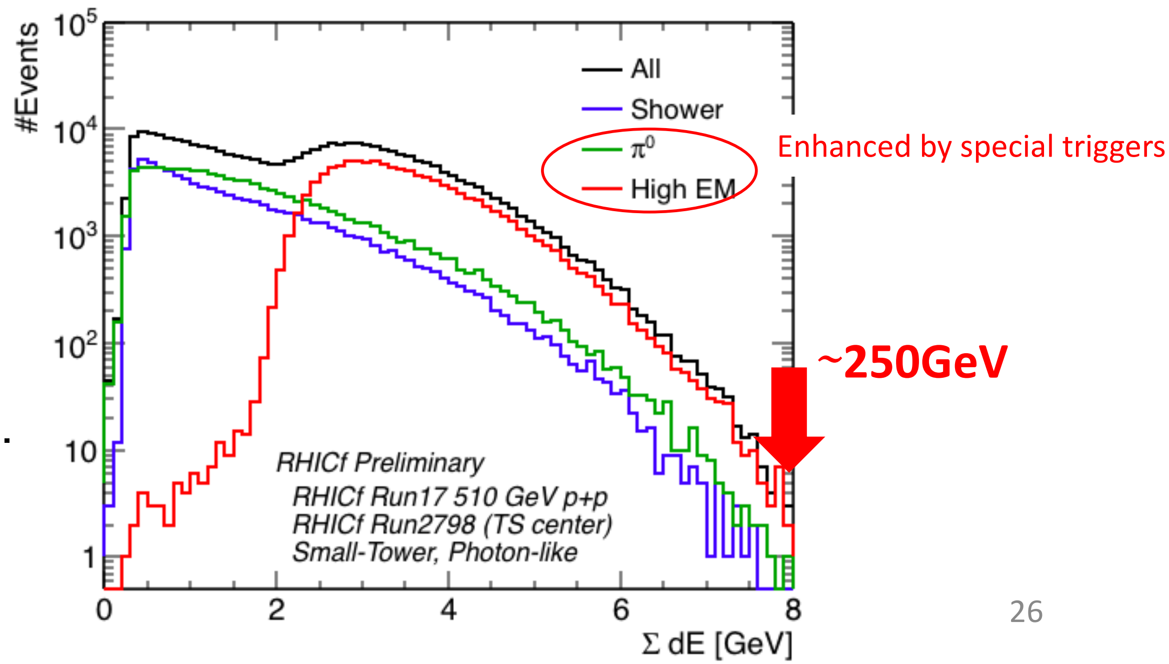
Quick look（polarization & spectrum）



- 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

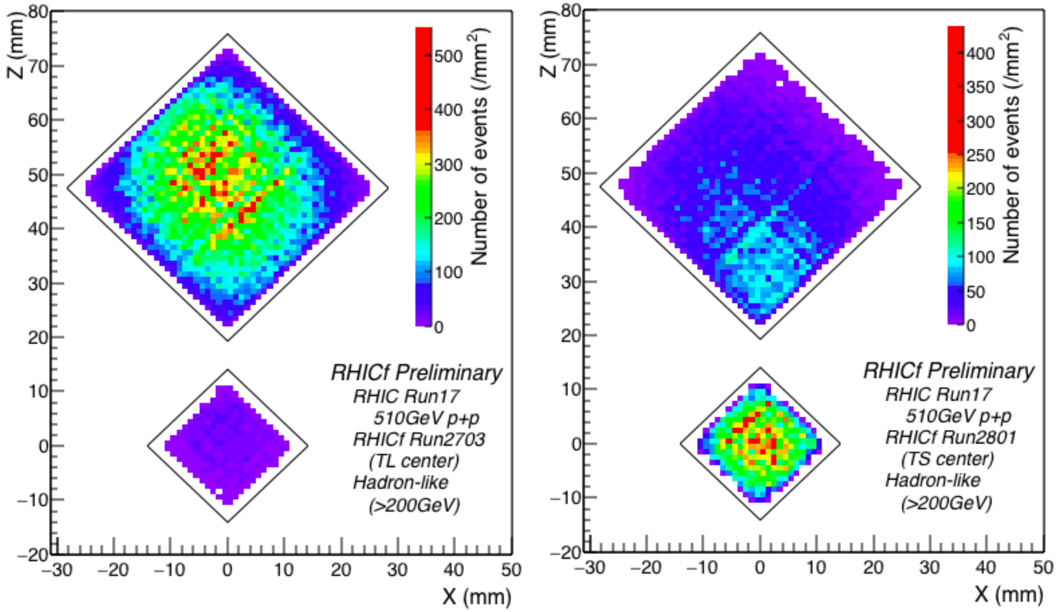
- Energy spectrum of EM-like showers in a 30 minutes run
- High-energy EM showers and π^0 were selectively triggered to compensate the limited DAQ speed.

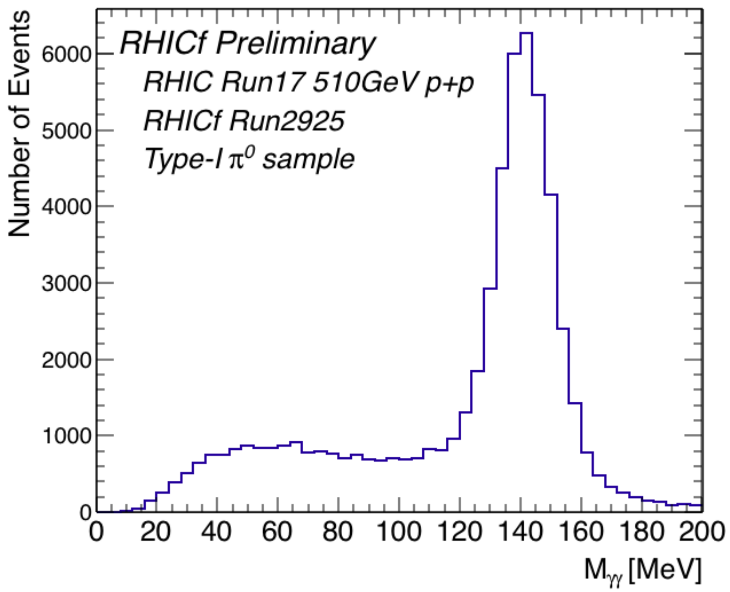
See poster by K.Sato



Quick look (basic performance)

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

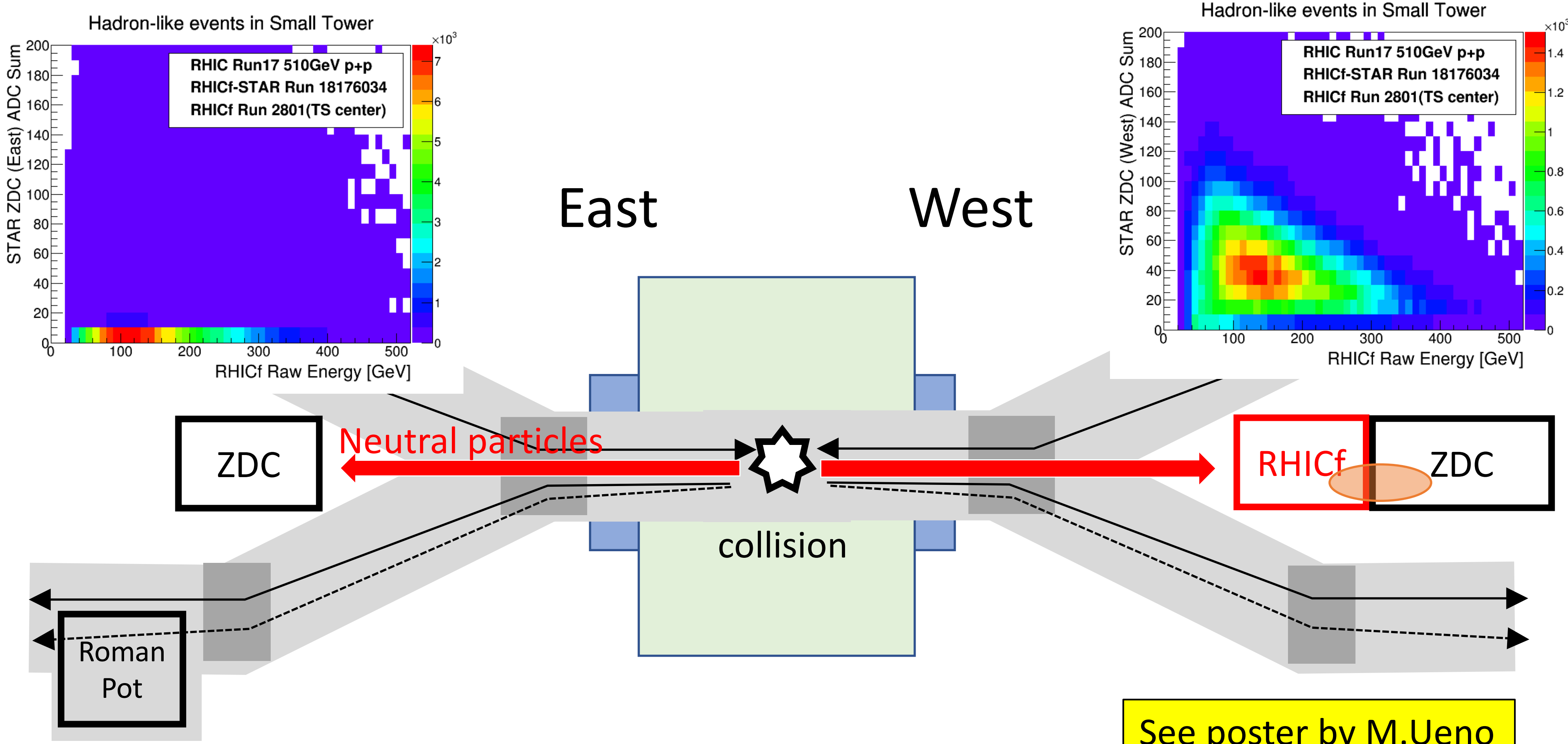




Invariant mass of photon pairs
=> 135MeV peak by π^0

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

Quick look（common run with STAR）

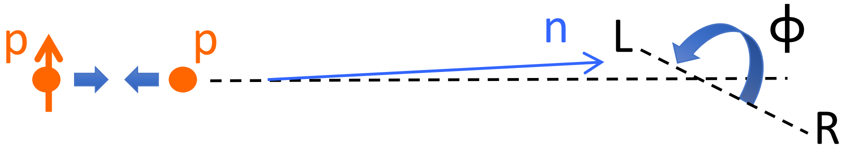


See poster by M.Ueno

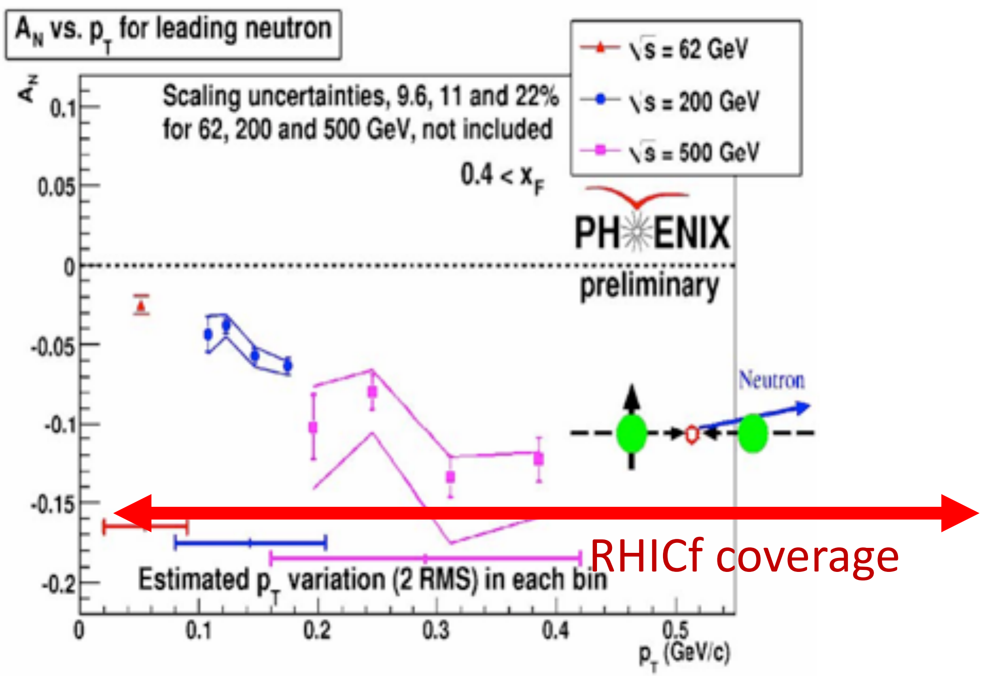
- Hadron-like (deep penetrating) showers were selected
- Anticorrelation between the RHICf raw (folded) energy and ZDC measured energy (in ADC unit) is confirmed
- (Anti)correlation only with West ZDC as expected => correct event matching

Single-spin asymmetry by PHENIX

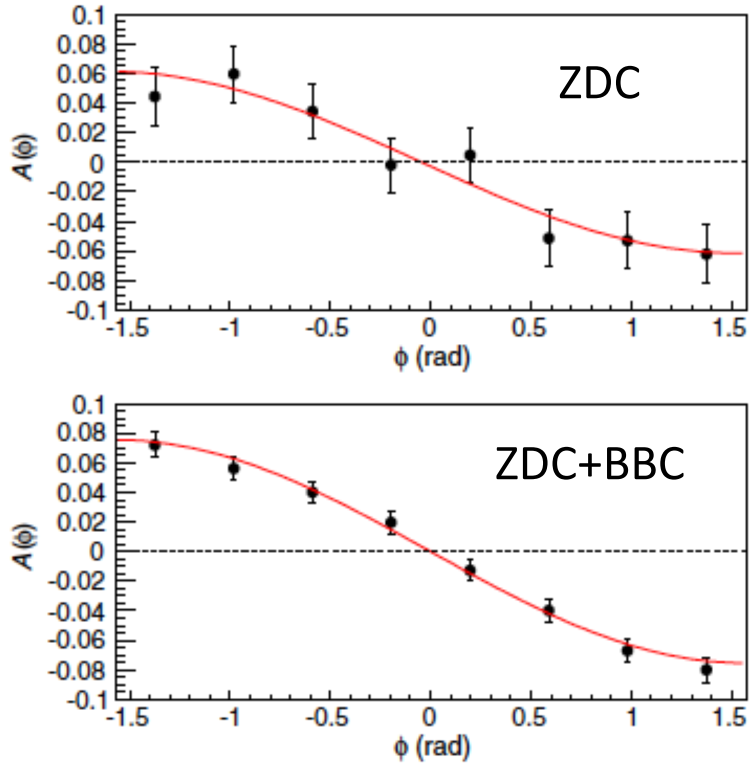
(PRD, 88, 032006, 2013)



- ✓ strong asymmetry in forward neutrons was discovered at RHIC
- ✓ scaled with p_T at $\sqrt{s}$ = 62, 200, 500 GeV?
- ✓ RHICf can cover wide p_T only with $\sqrt{s}$=510GeV



PHENIX neutron results at 200GeV



- ✓ RHICf is capable to discover forward π^0 asymmetry

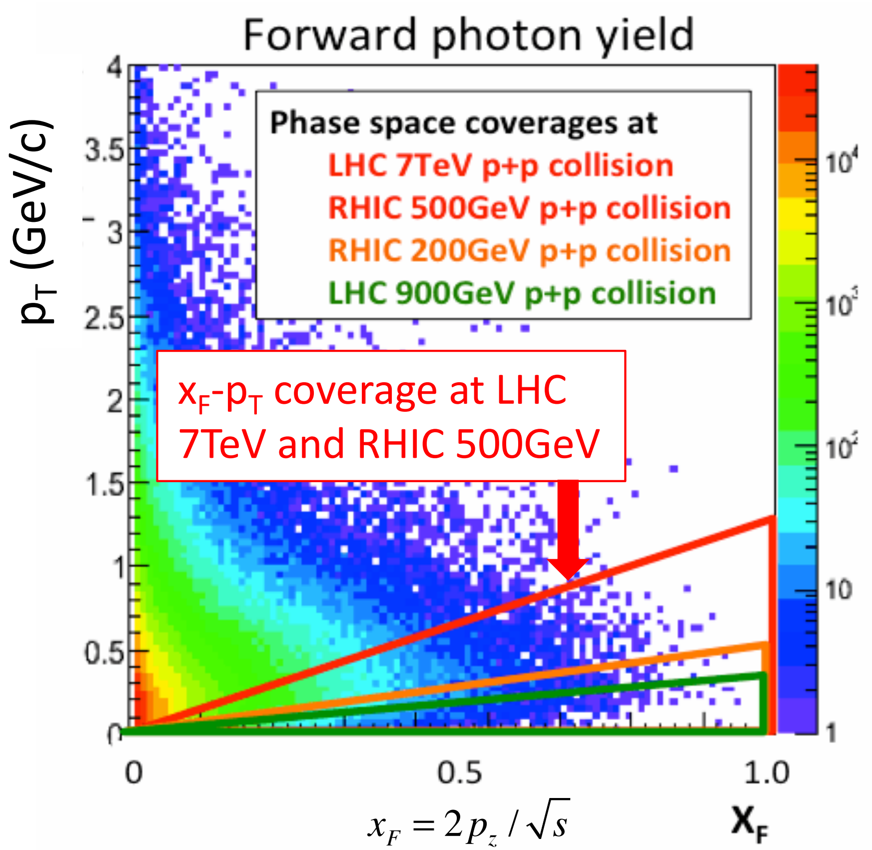
See poster by M.H.Kim

Summary

- Forward particle data are important to improve the air shower modeling
- LHCf and RHICf, dedicated forward experiments, have successful operations from √s=0.51 to 13TeV, corresponding to $E_{CR} = 10^{14}$-10^{17}eV
- LHCf results of photons, neutrons, π^0 cross sections constrain the future model development
- LHCf-ATLAS joint analysis can pin-point the origin of the data-model differences
- Studies of √s dependence help the interpolation and extrapolation of models to unexplored energies
- RHICf shows good data quality and unique analyses with polarized proton collisions are in progress

Backup

Why not LHC 900GeV?



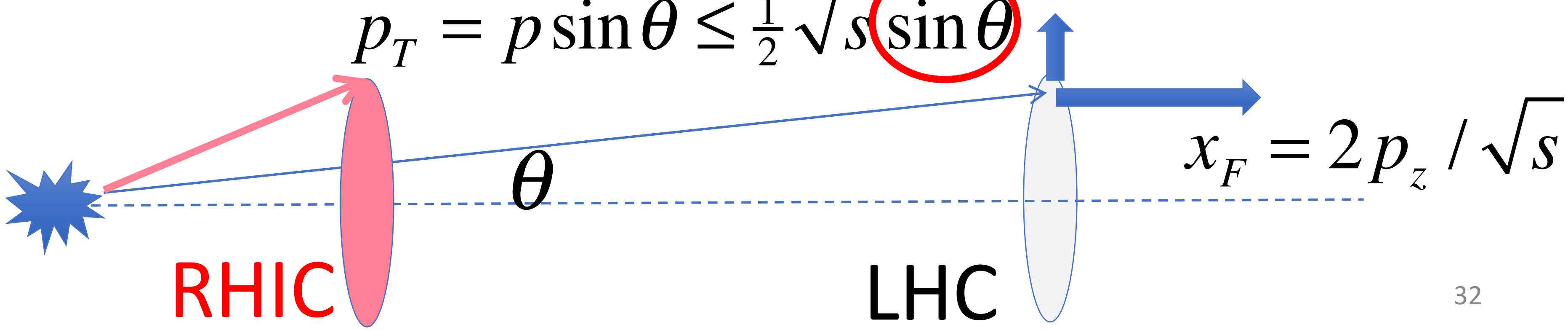
- ✓ Wide x_F-p_T coverage is desired
- ✓ Maximum p_T coverage is proportional to $\theta\sqrt{s}$

⇩

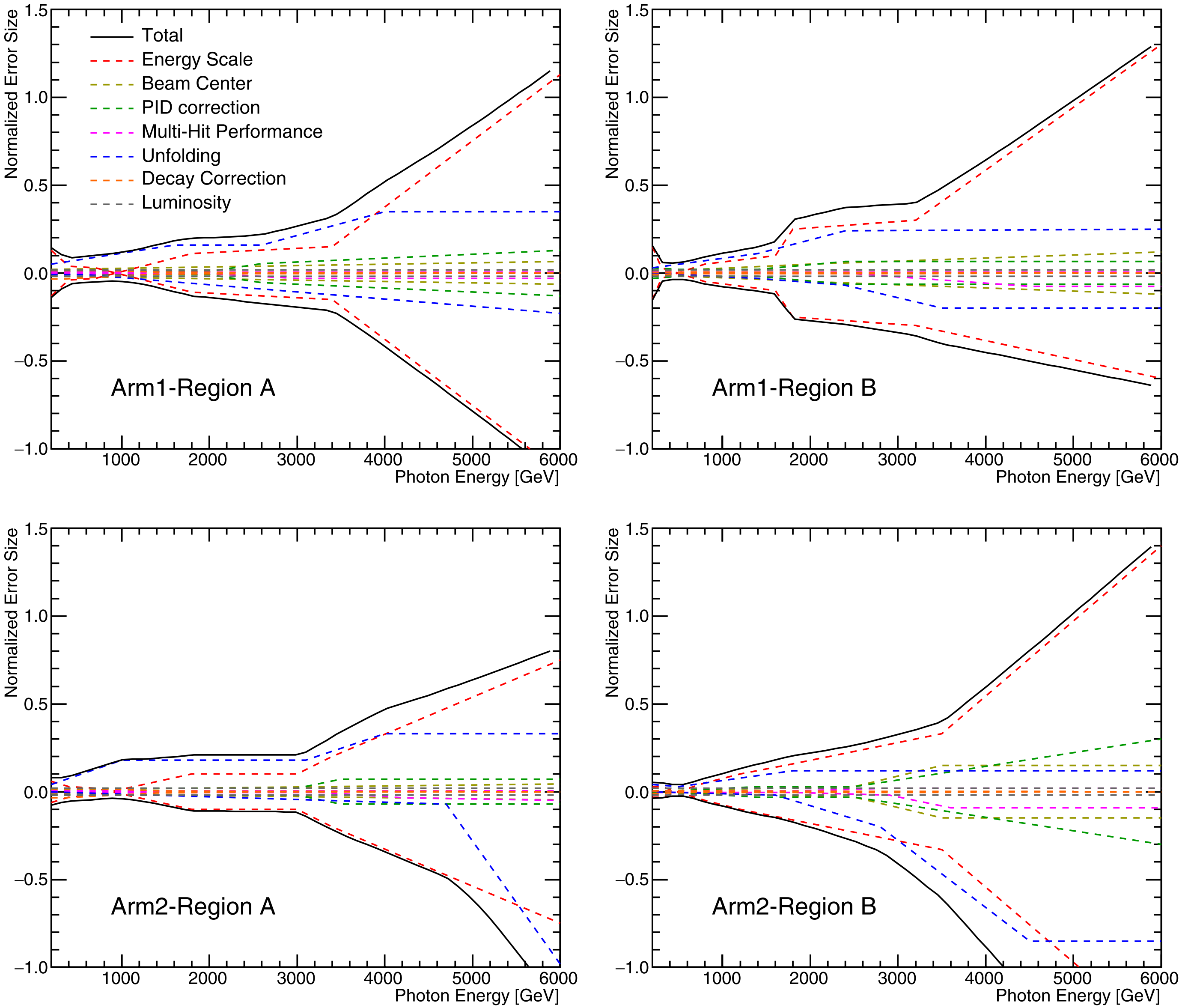
- ✓ RHIC allows larger θ with smaller $\sqrt{s}$
- ✓ x_F-p_T coverage at LHC 7TeV and RHIC 500GeV are almost identical!!

  (beam pipe structure is also taken into account)

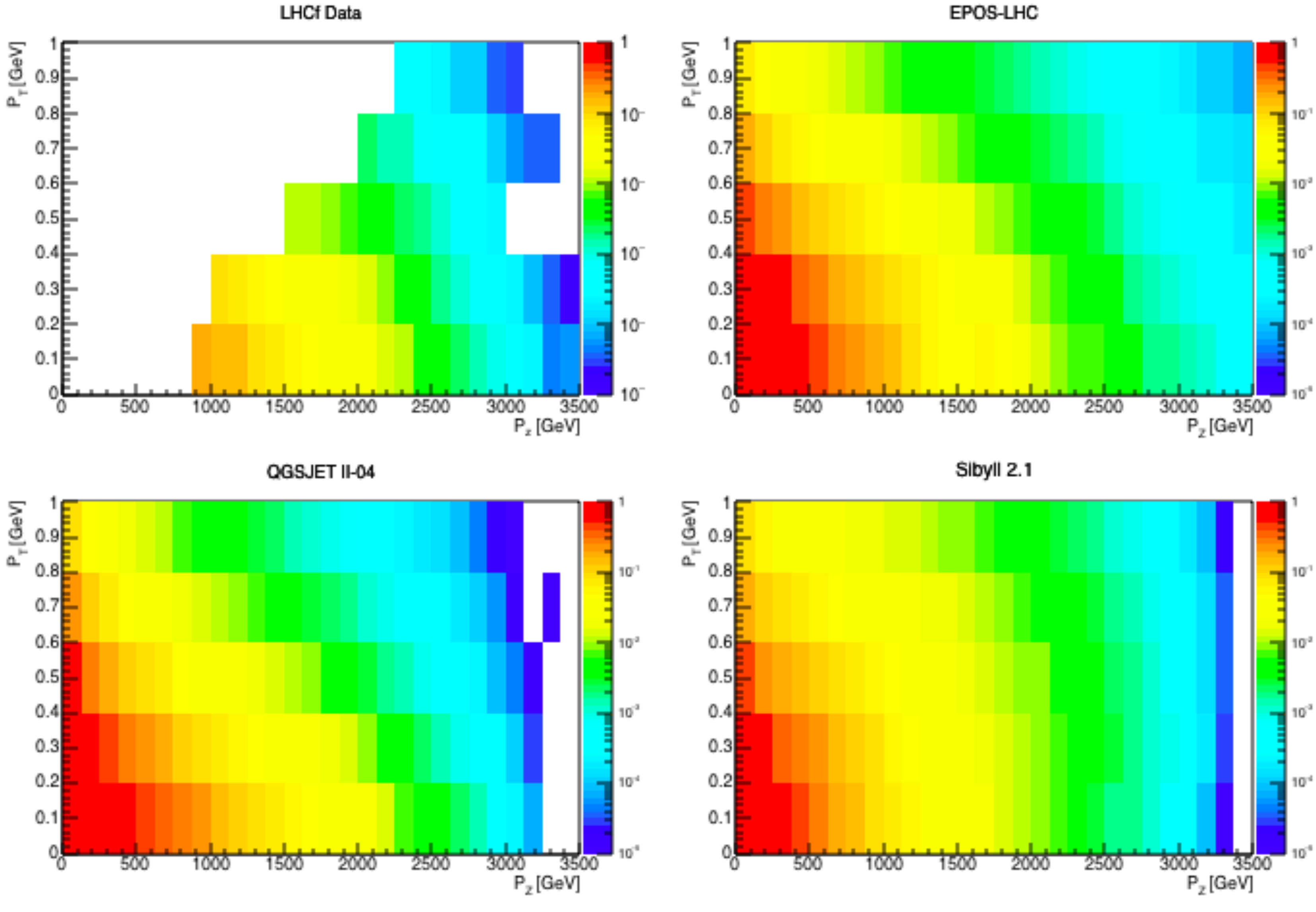
$$p_T = p\sin\theta \leq \tfrac{1}{2}\sqrt{s}\sin\theta$$



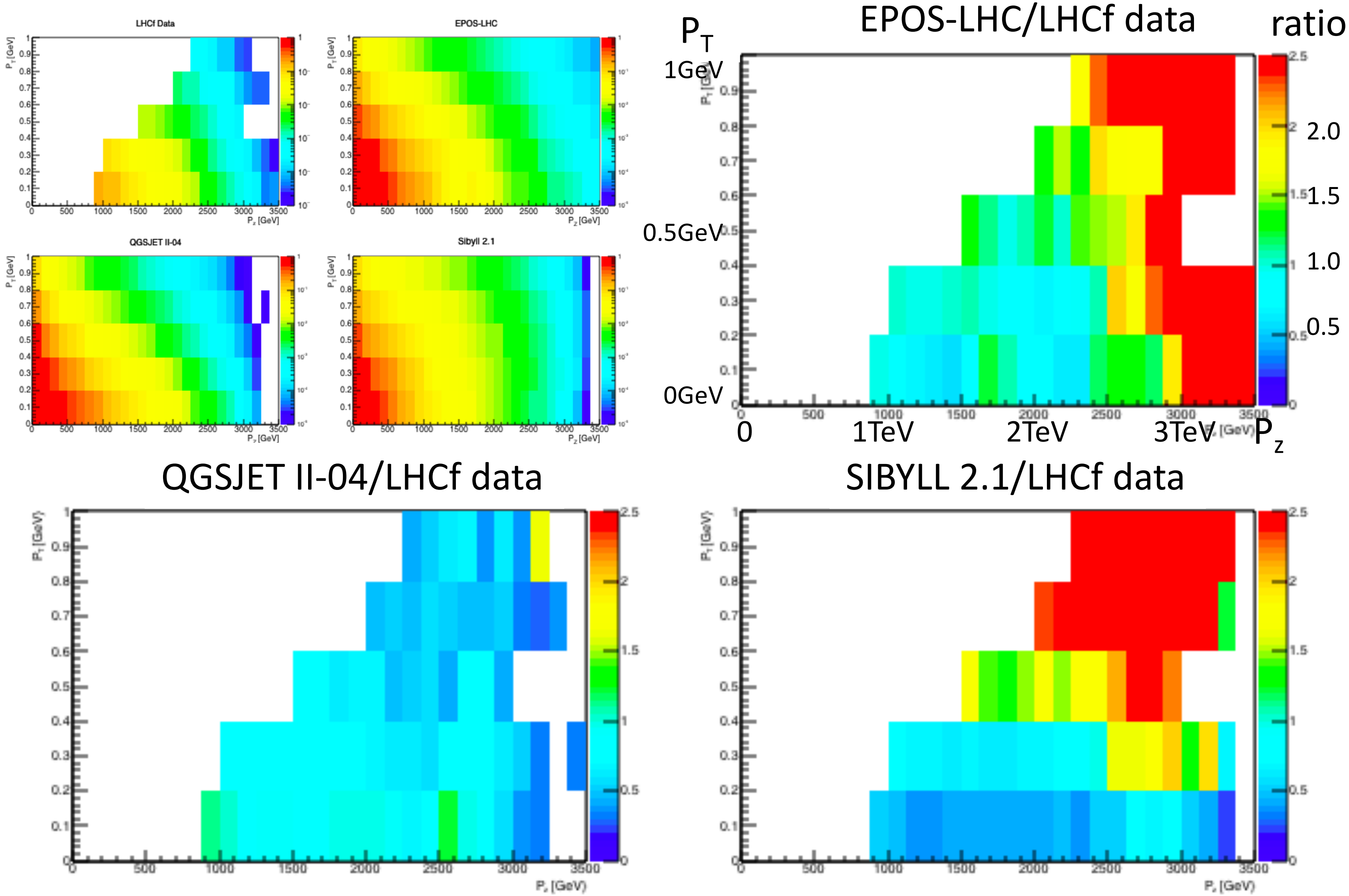
Sys. uncertainty in 13TeV photon analysis



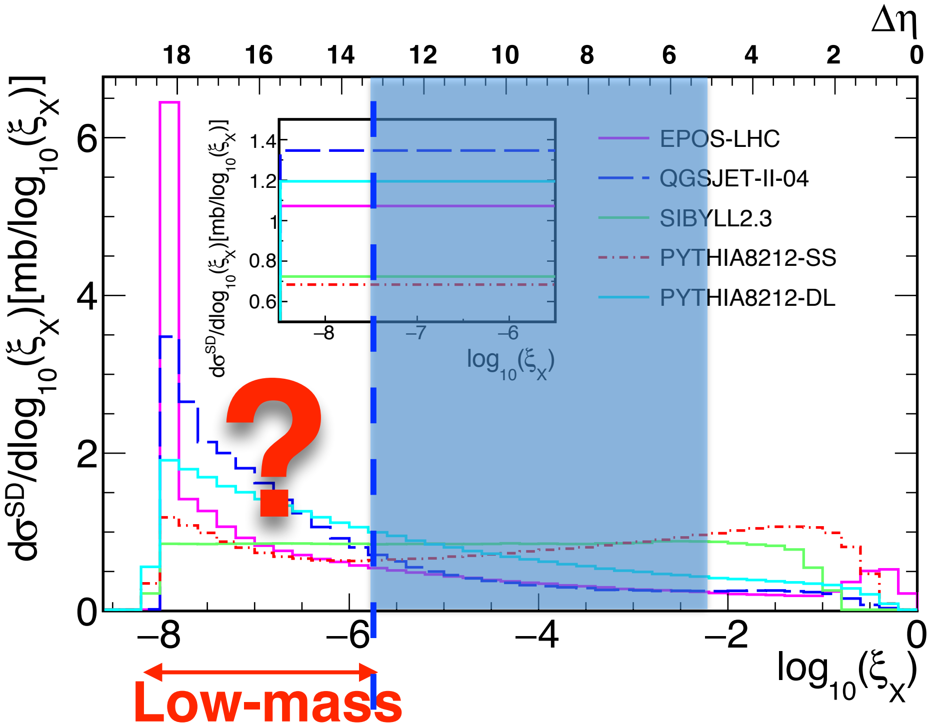
π^0 in 7TeV p-p collision
LHCf and models



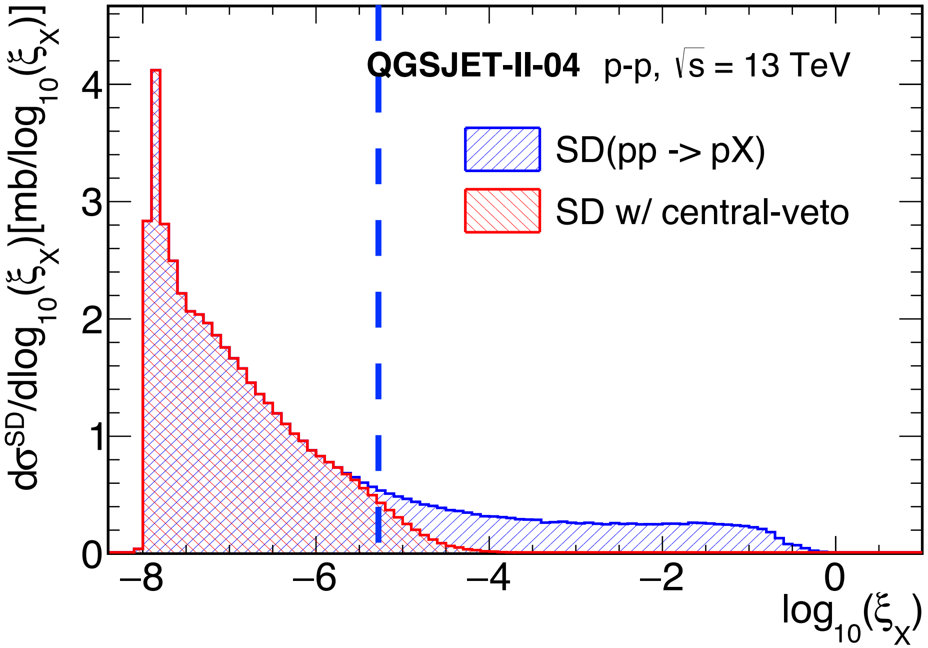
π^0 in 7TeV p-p collision
LHCf and models (ratio to data)

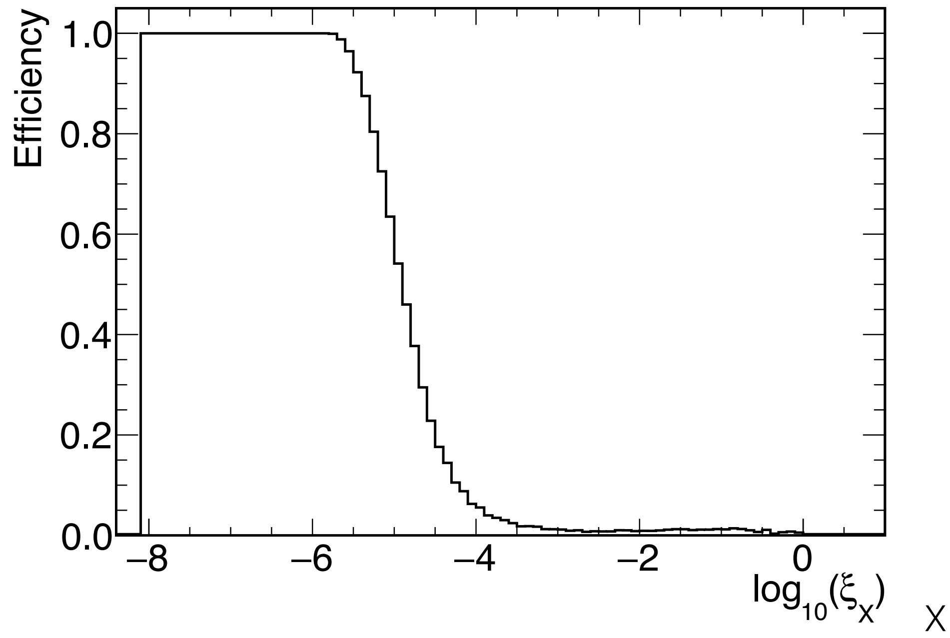


low-mass diffraction事象の感度



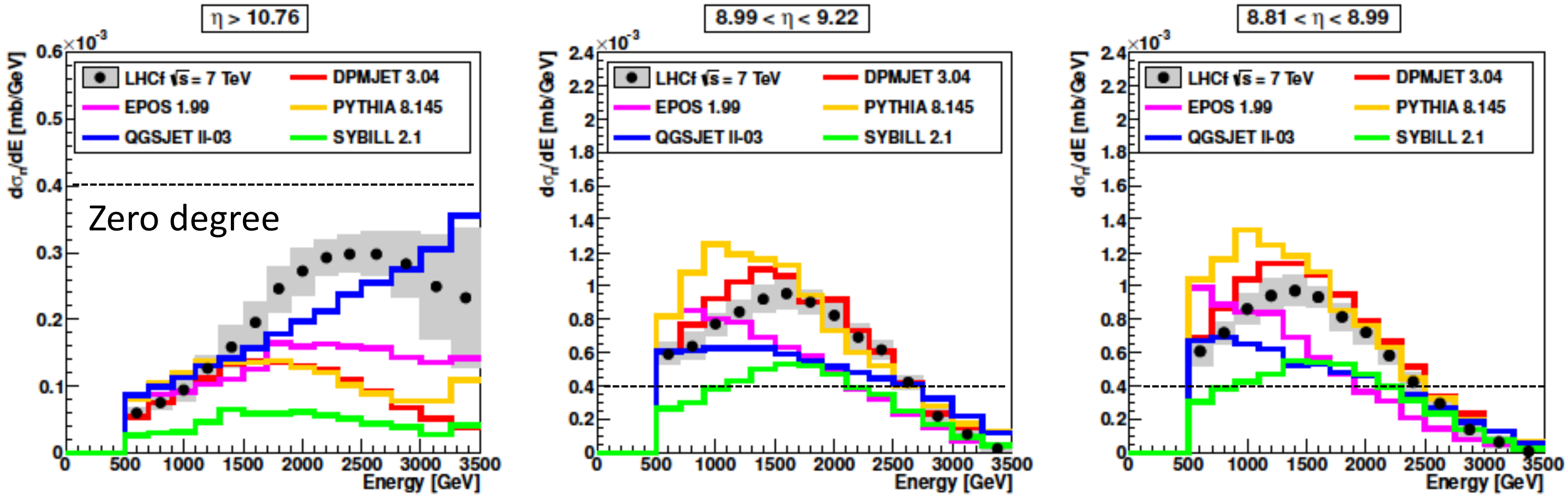
- ❖ Central-veto は low-mass diffraction ($\log_{10}(\xi_x)$ < -6.0)に対して約**100%**の検出効率がある。
- ❖ ATLAS-LHCf連動実験によるこれまで測定例のないlow-mass diffraction事象の選別方法を確立。





Neutrons in 7TeV p-p collision

($\sqrt{s}$=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.

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

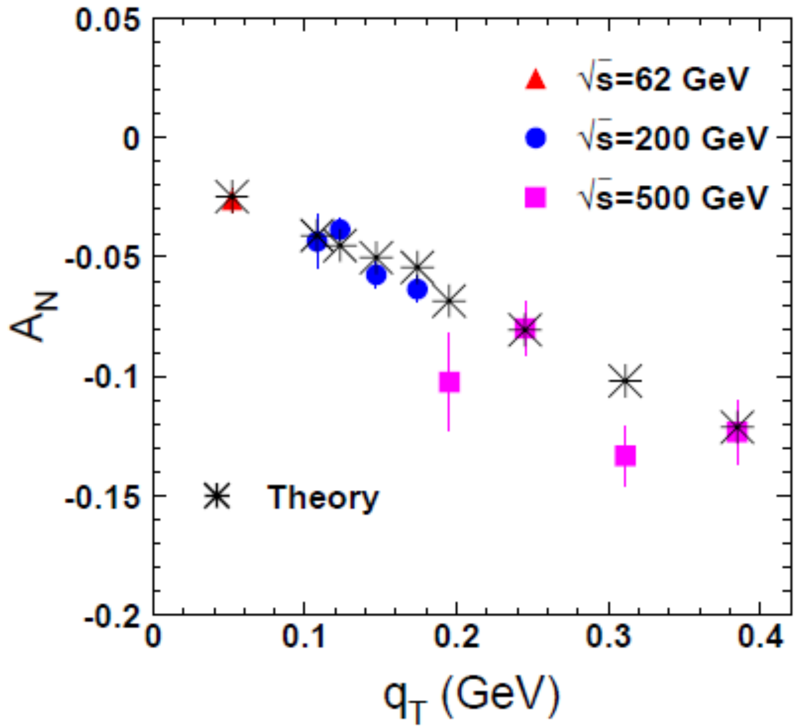
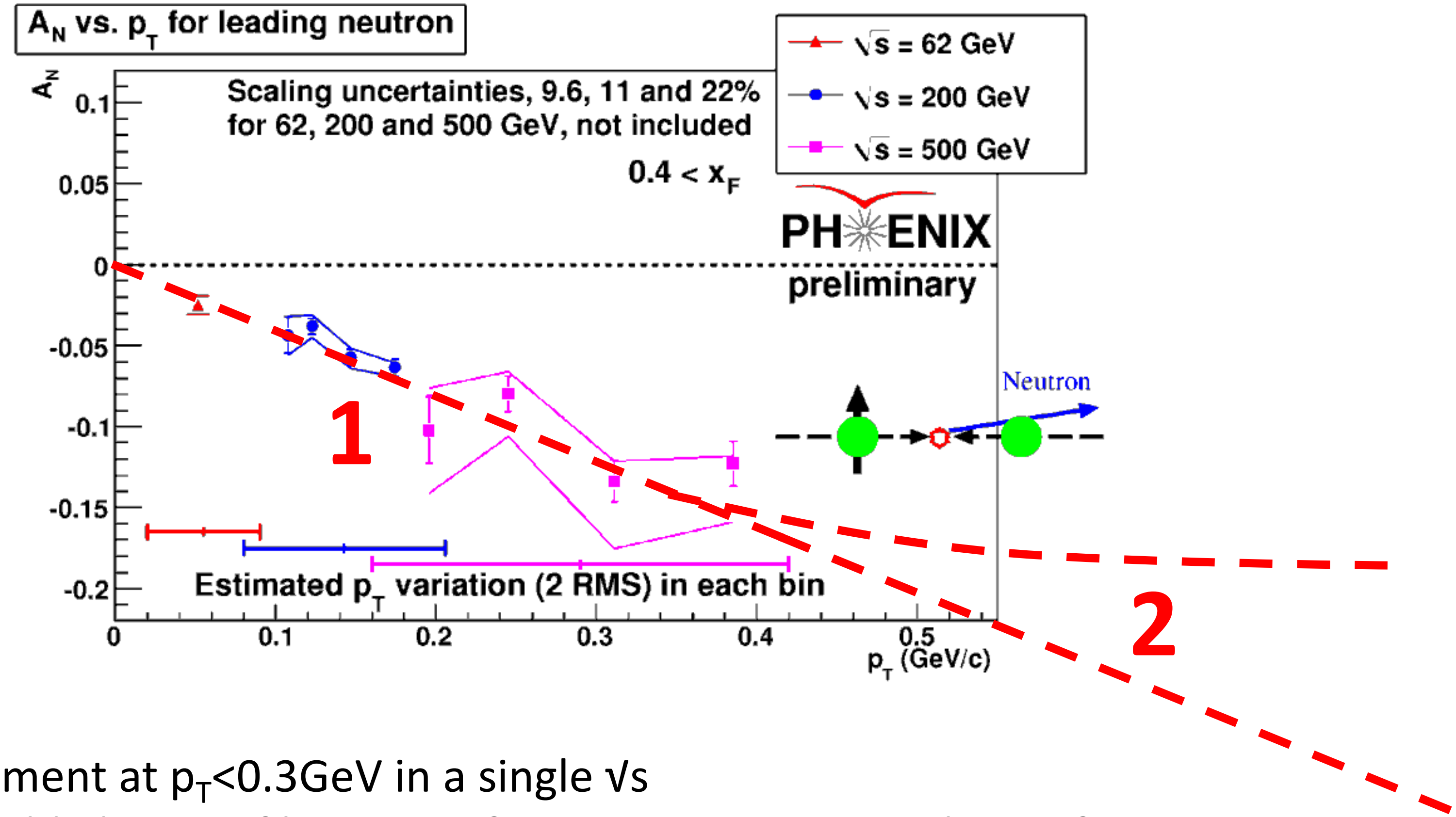


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of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

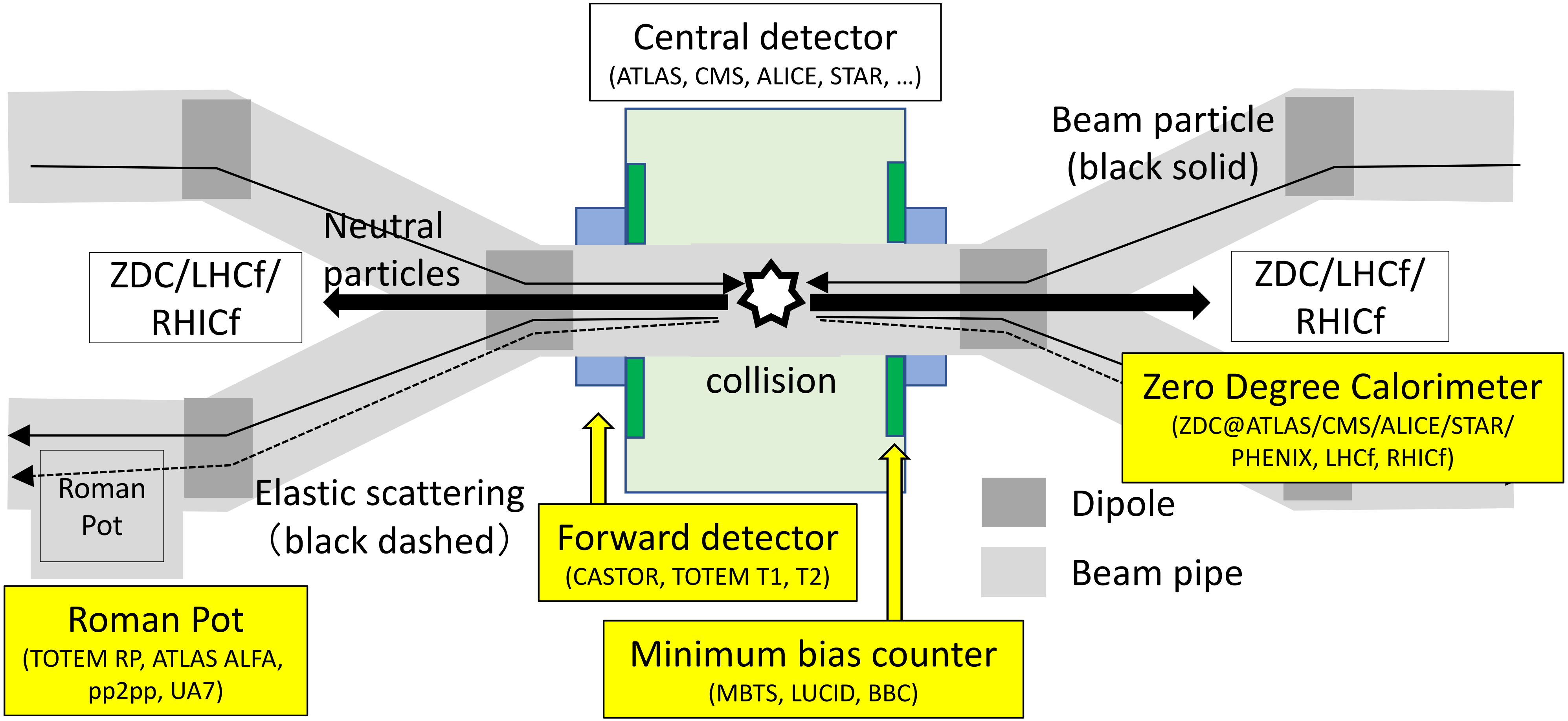
Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012.

SSA of forward neutron production



1. Measurement at p_T<0.3GeV in a single √s
   - possible by RHICf because of its 1mm position resolution for neutrons
2. Measurement at p_T>0.3GeV to know A_N evolution
   - possible by RHICf because of its wide p_T coverage required for cross section measurements

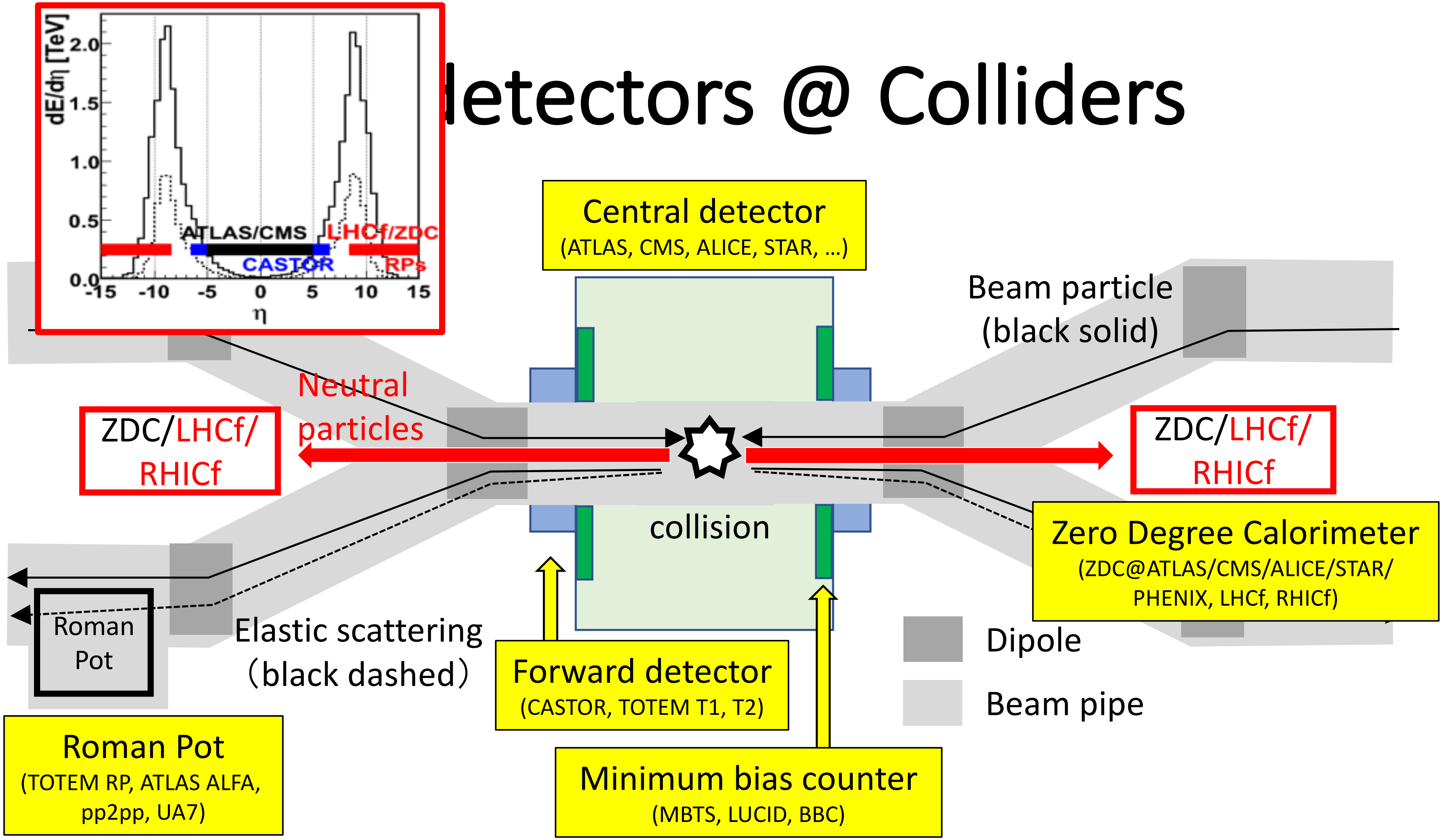
Forward detectors @ Colliders



- ✓ 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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