Review of accelerator data of relevance to air shower simulations

Yoshitaka Itow
STE Lab / Kobayashi-Maskawa Inst.
Nagoya University

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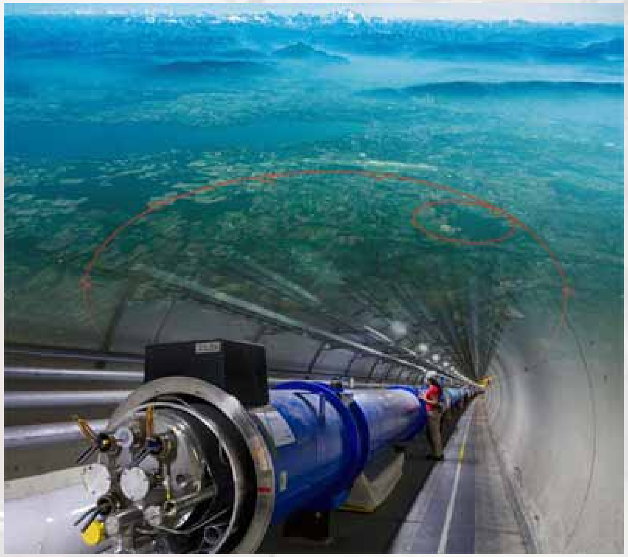
STEL

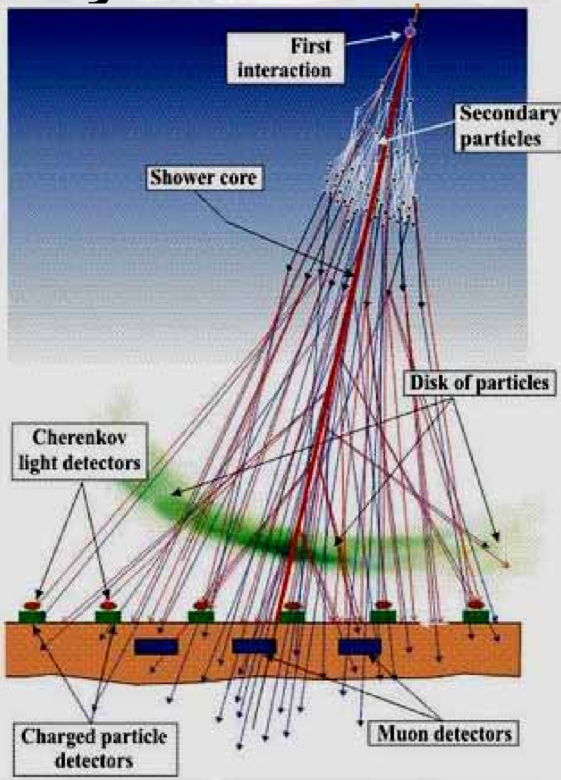
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

Hadron interactions at ultra high energy
Accelerator ↔ Cosmic rays



Precision improvement

Hint for interactions at ultra-ultra high energy

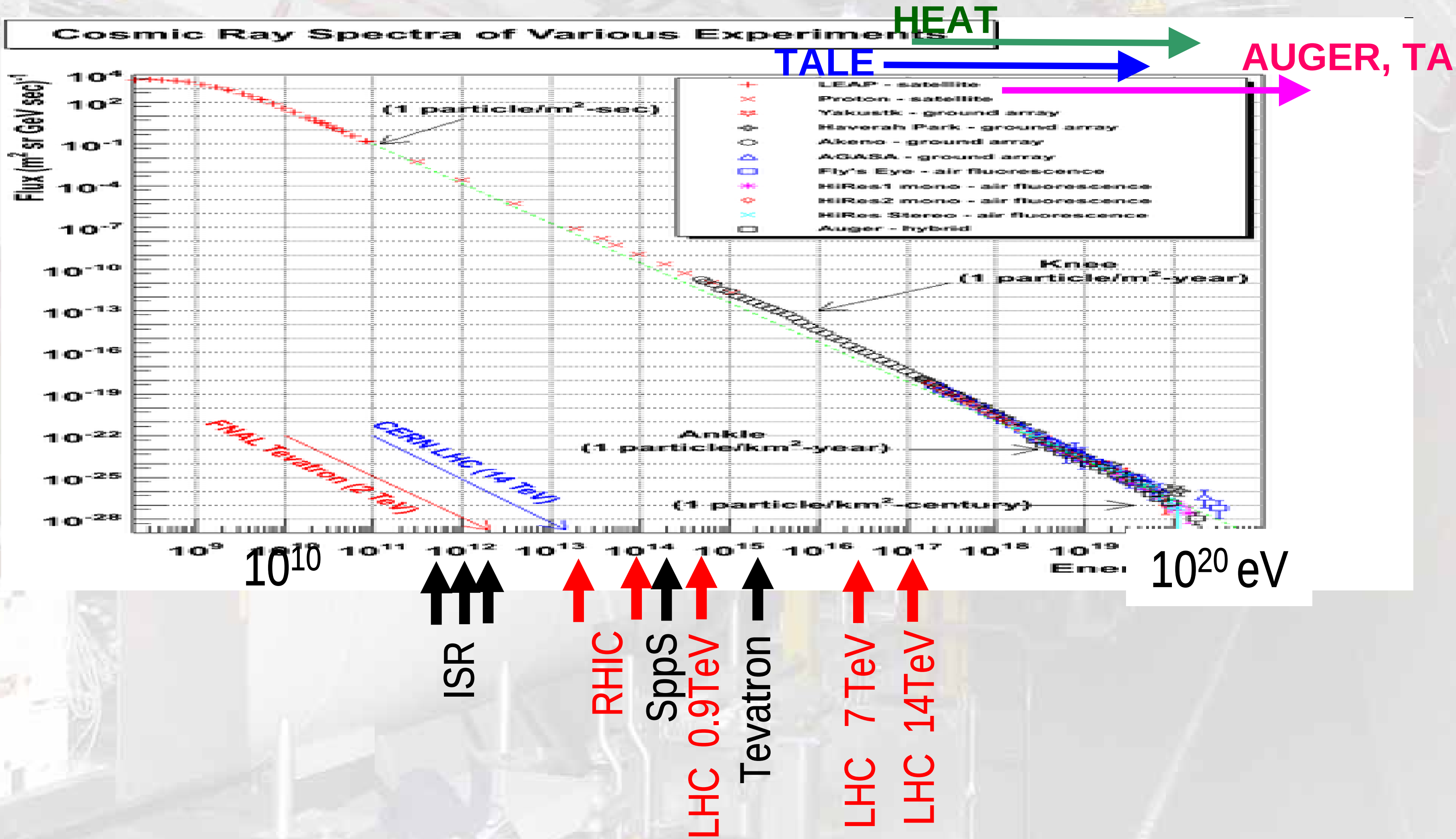


$$E_{CM} \sim (2 \times E_{lab} \times M_p)^{1/2}$$

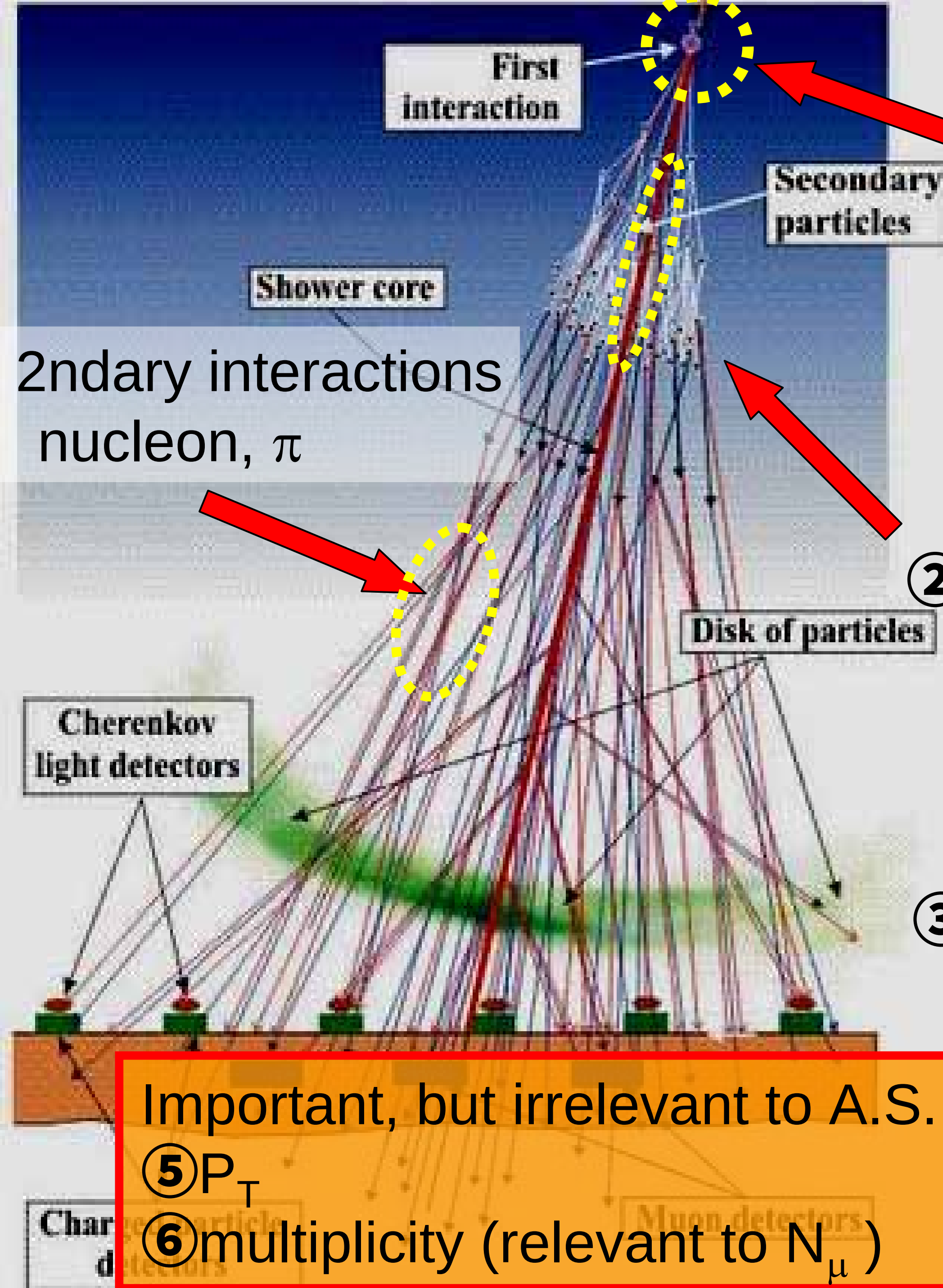
$\sqrt{s}$=14TeV collision at LHC

→10^{17}eV cosmic rays

Cosmic ray spectrum & historical colliders



>40 yrs legacy of wisdom for interactions available !



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
rapid development
If small k
deep penetrating

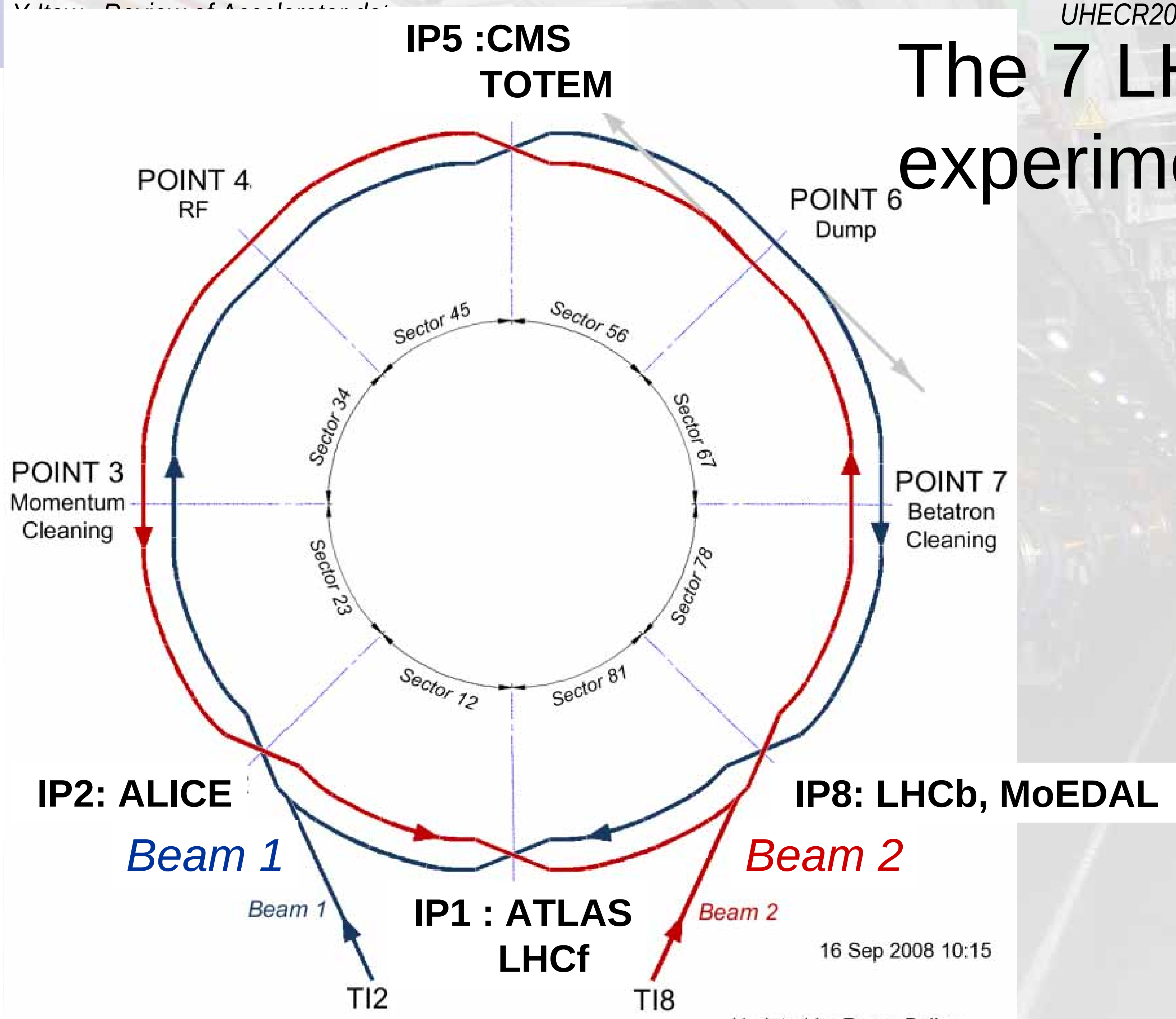
④ 2ndary interactions
nucleon, π

Important, but irrelevant to A.S.
⑤P_T
⑥multiplicity (relevant to N_μ)

Outline of this talk

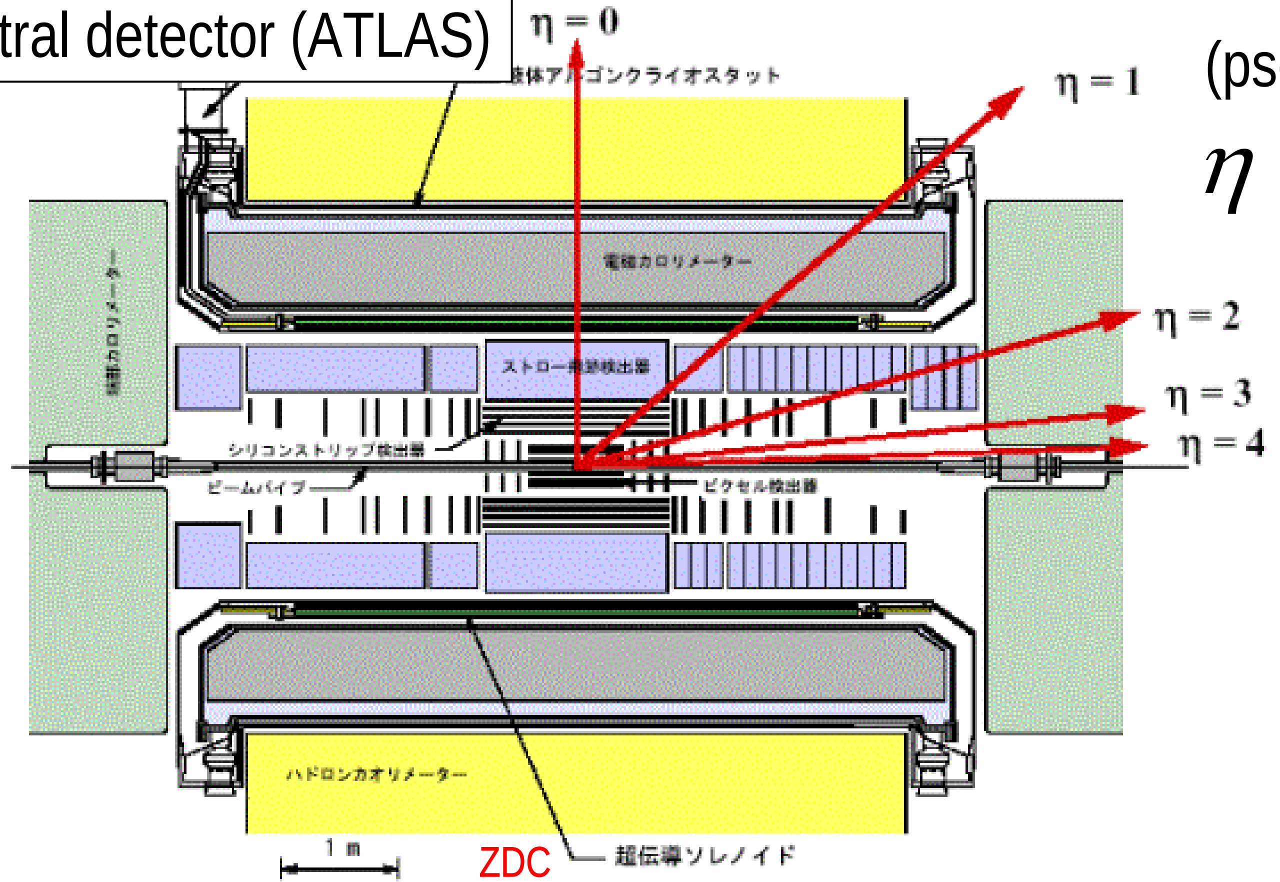
- What type of interactions we concern ?
- Sort out the data regarding as relevance to air showers phenomena, especially focusing on Xmax
  - Inelastic cross section
  - Forward energy spectra
  - Inelasticity
  - low energy data
- Nuclear effect is important, but …
  - This talk focuses just on p-p
  - Comments on possible p-A runs at LHC before long shutdown

The 7 LHC experiments



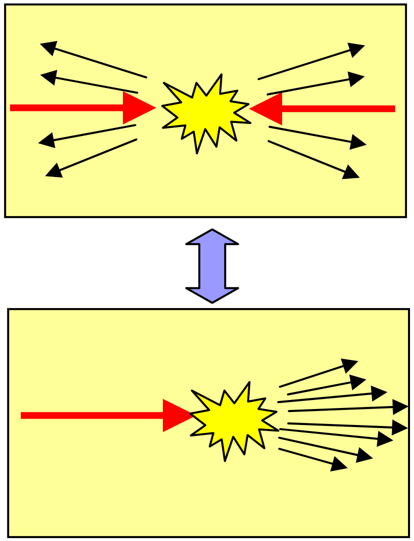
A LHC detector and pseudorapidity

Central detector (ATLAS)

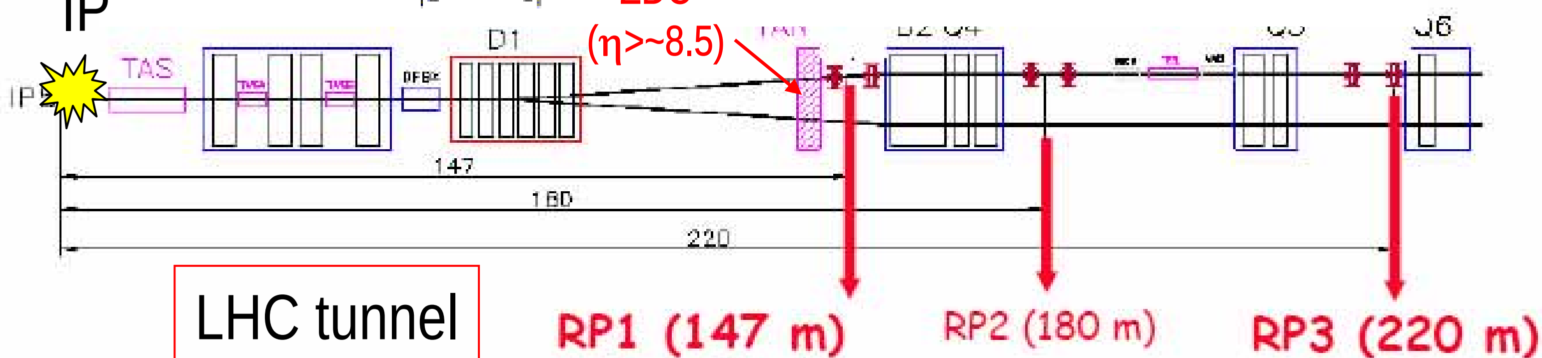


(pseudo)rapidity

$$\eta = -\ln(\tan\frac{\theta}{2})$$

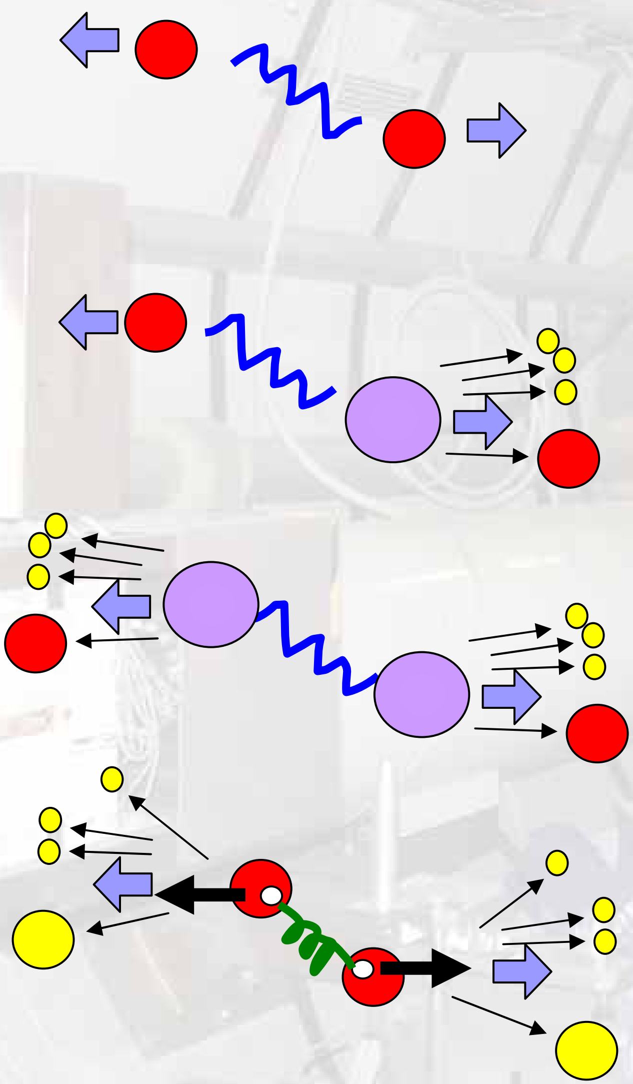


IP

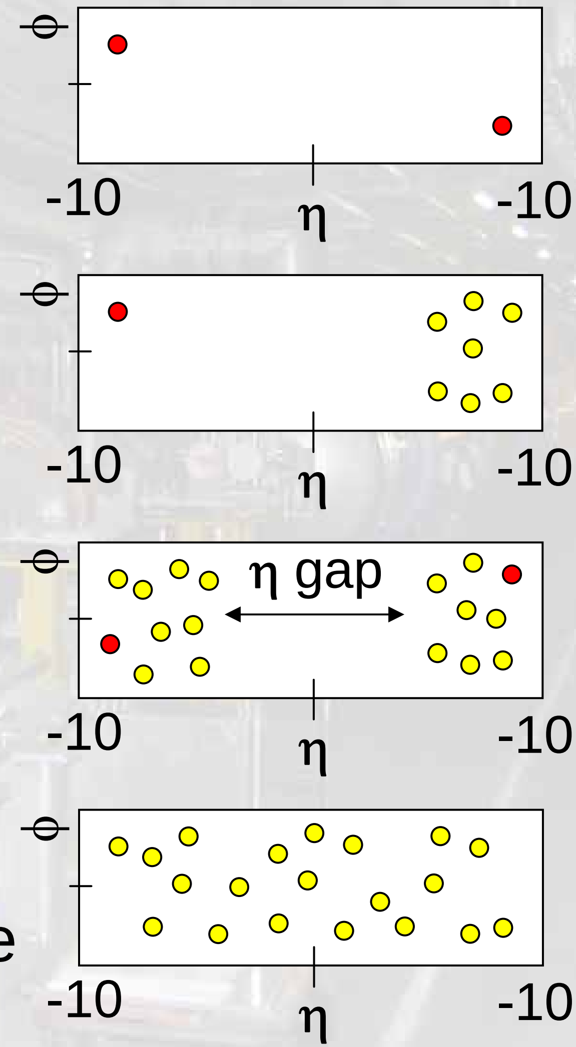


LHC tunnel

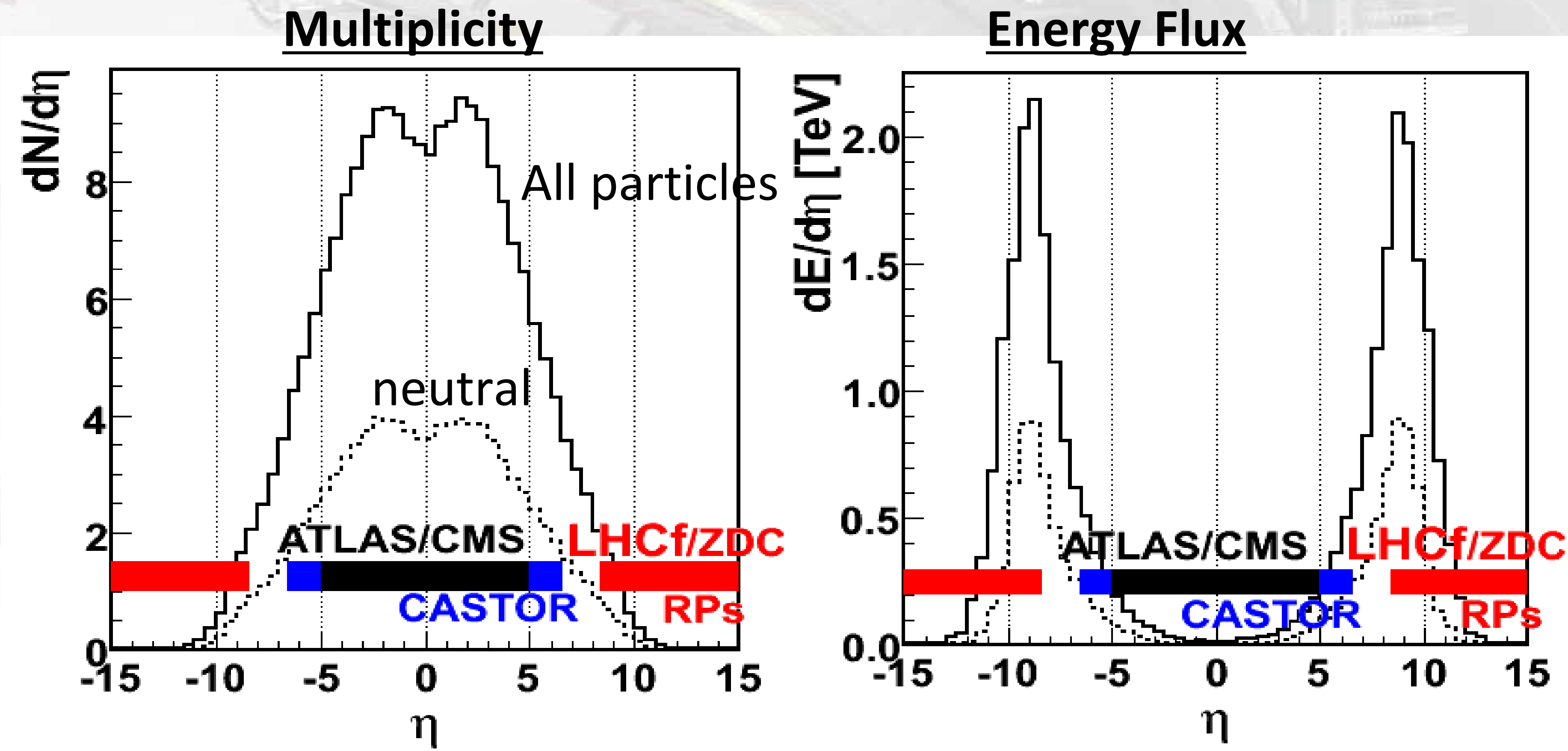
pseudorapidity and interactions



	σ @7TeV
Elastic	~25mb
Single diffractive	~10mb
Double diffractive	~10mb
Non-diffractive	~50mb



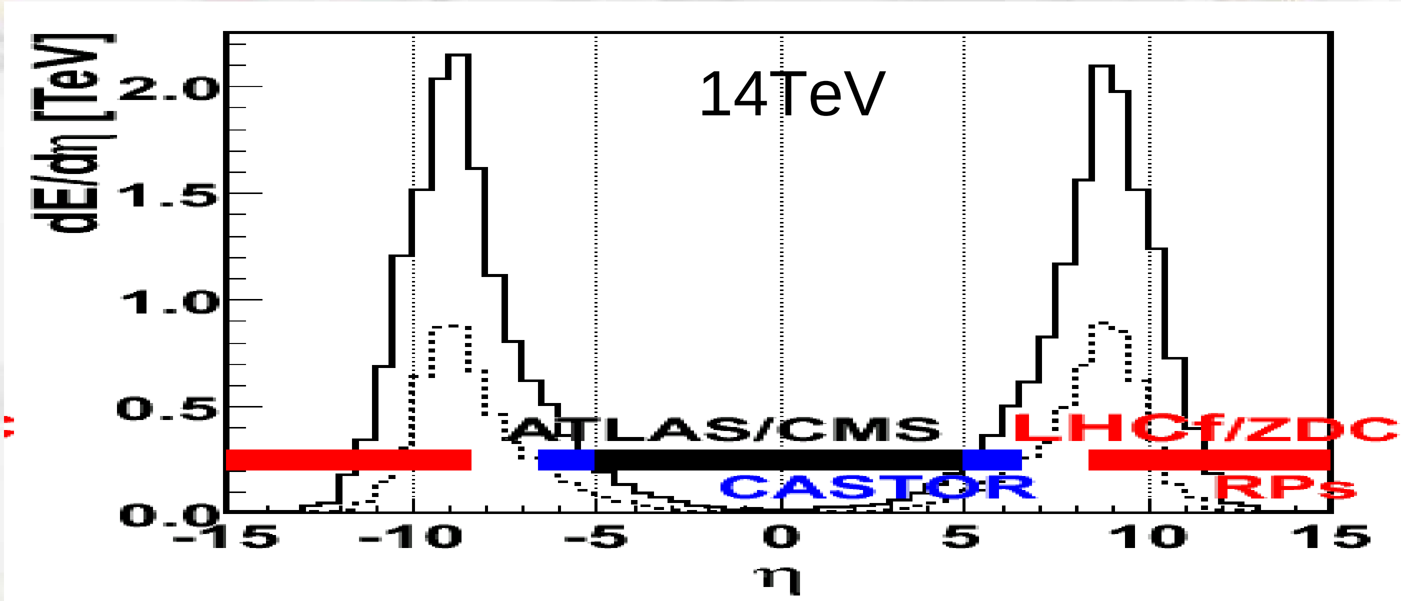
Very forward : Majority of energy flow ($\sqrt{s}$=14TeV)

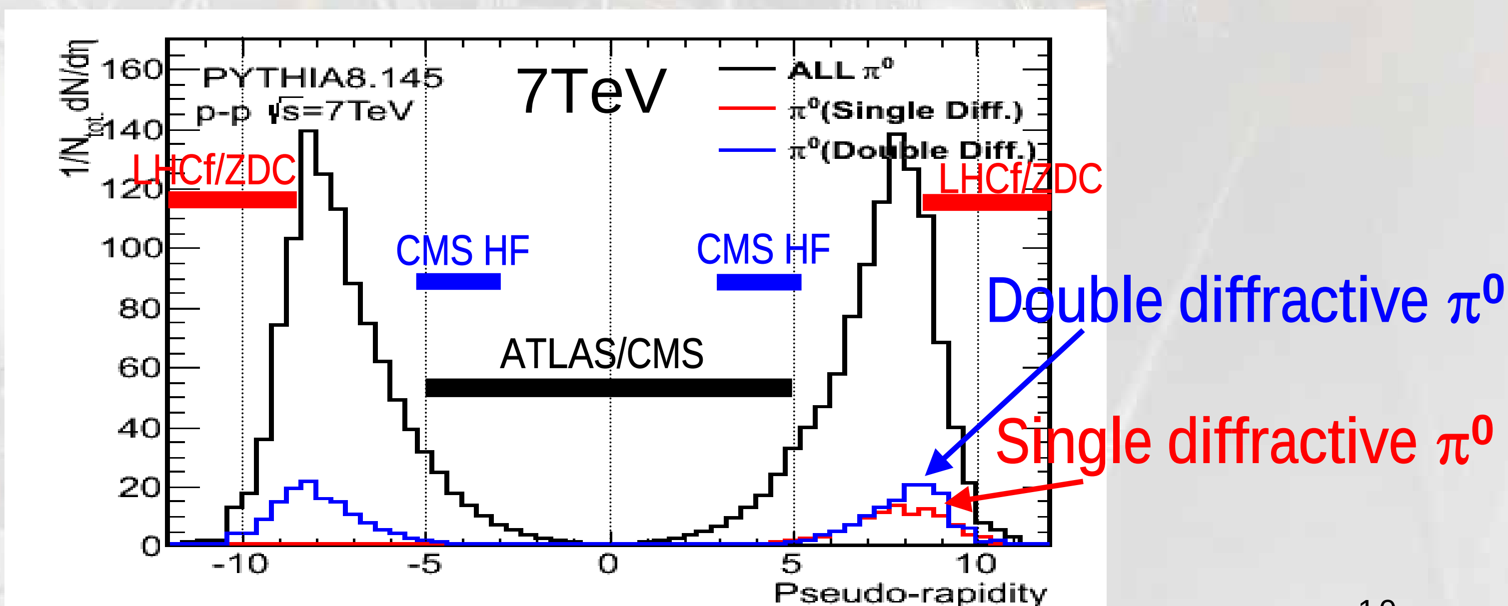


Most of the energy flows into very forward

(Particles of X_F > 0.1 contribute 50% of shower particles)

Energy flow for $\sqrt{s}$=14 and 7TeV





Inelastic cross section

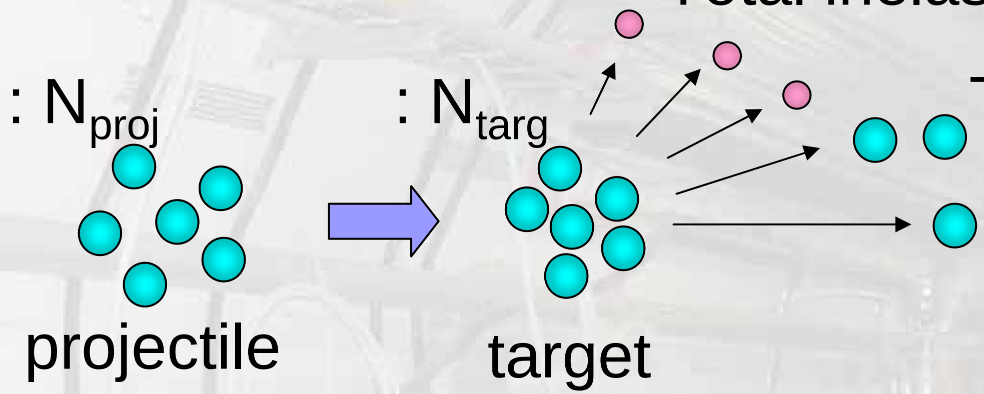
- TOTEM
- ATLAS
- CMS
- ALICE

Measurement of σ_{inel}

Total rate: R_{tot}

Total inelastic rate : R_{inel}

Total elastic rate: R_{el}



$$\left.\frac{dR_{el}}{dt}\right|_{t=0}$$ Elastic rate at 0 degree

Optical theorem

$$\sigma_{tot} = \frac{1}{1+\rho^2}\frac{16\pi}{R_{el}+R_{inel}}\left.\frac{dR_{el}}{dt}\right|_{t=0}$$

$$\rho = \frac{\mathrm{Re}(f_{el}(0))}{\mathrm{Im}(f_{el}(0))}$$

$$t = (p_{in} - p_{out})^2$$

$$\sigma_{tot} L = R_{tot} = R_{el} + R_{inel}$$

VdM scan

$$L = \frac{f_{rev} N_{proj} N_{targ}}{2\pi \Sigma_{proj} \Sigma_{targ}}$$

Simple way

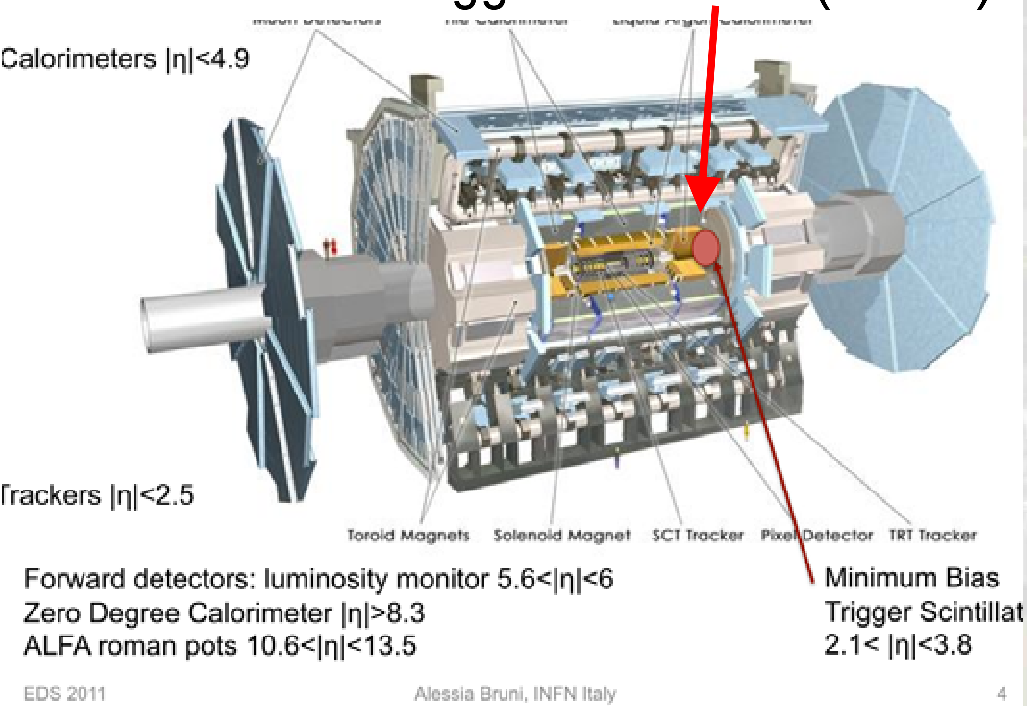
$$\sigma_{inel} = \frac{R_{inel}}{L}, \quad R_{inel} = \frac{R_{obs}}{\varepsilon_{eff}}$$

ATLAS σ_{inela} measurement

Nature Commun. 2 (2011) 463

$$\sigma_{inel}(\xi > 5\times10^{-6}) = \frac{N_{obs} - N_{BG}}{\varepsilon_{trig} \times \int Ldt} \times \frac{1 - f_{\xi<5\times10^{-6}}}{\varepsilon_{sel}}$$

Minimum Bias Trigger Scintillator(MBTS)



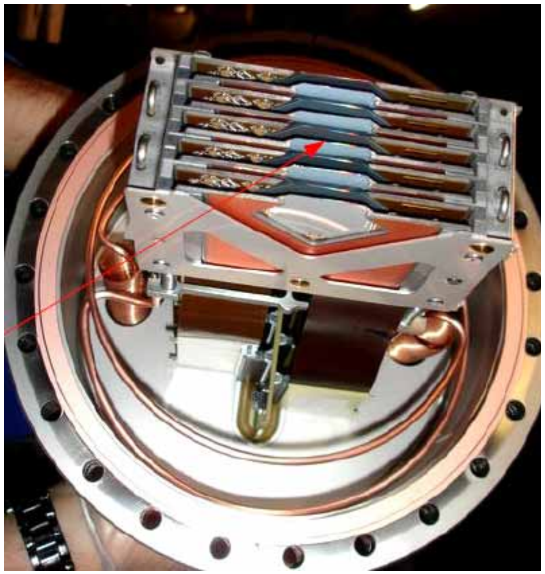
- Use MB events with 20.3 +- 0.7μb^{-1}
- Cut diffractive events (ξ < 5E-6)

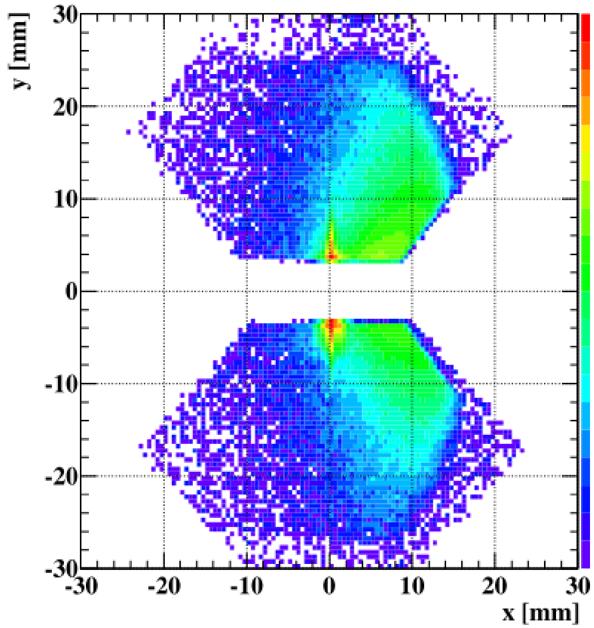
$$\sigma_{inel}(\xi > 5\times10^{-6}) = 60.33 \pm 2.10(\text{exp.})\,mb$$

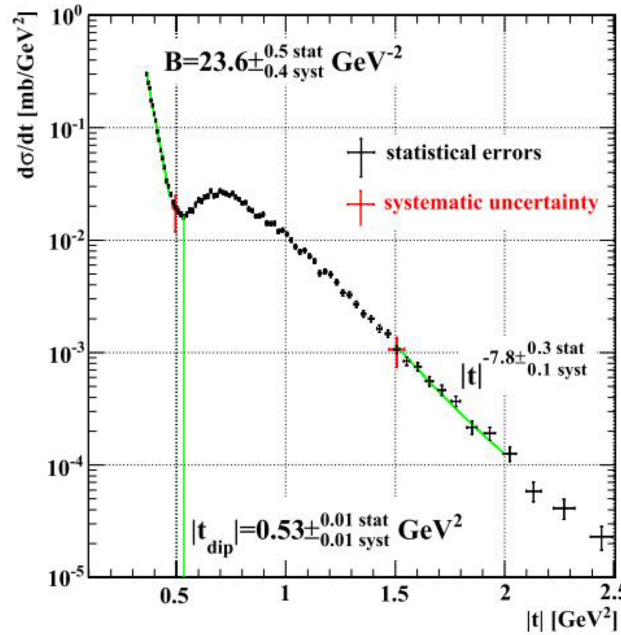
- extrapolate entire ξ

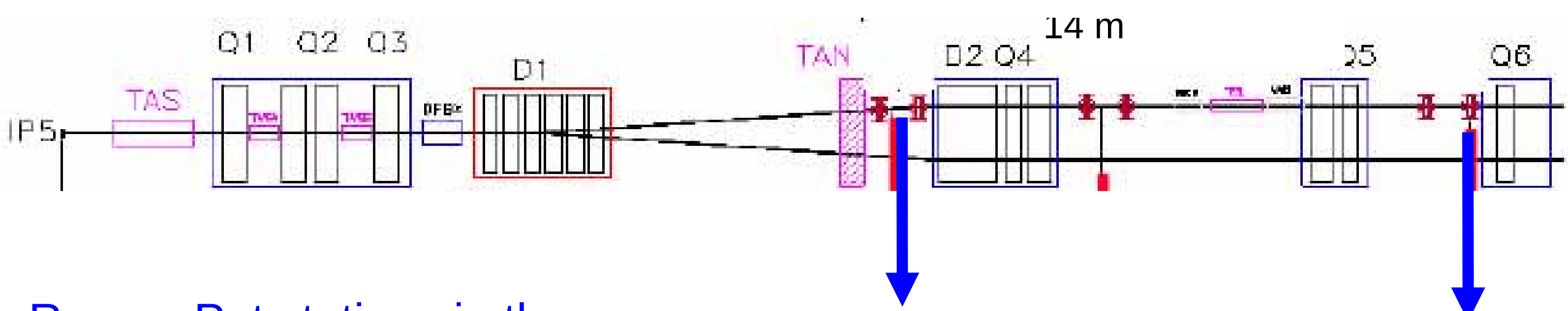
$$\sigma_{inel}(\xi > m^2{}_p / s) = 69.1 \pm 2.4(\text{exp.}) \pm 6.9(extr)\,mb$$

TOTEM "Roman Pod" measurement









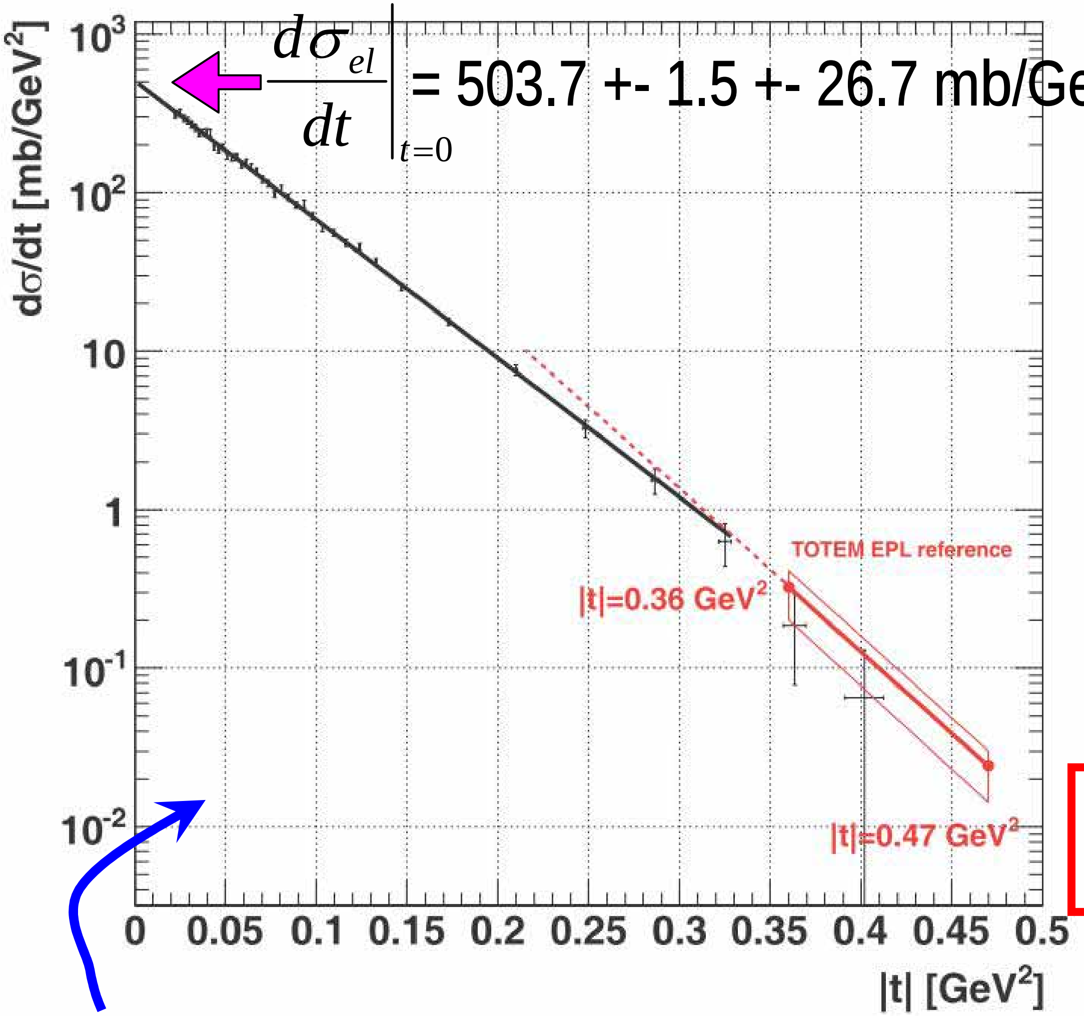
RP (147 m) **RP (220m)**

Roman Pot stations in the LHC tunnel

(F.Ferro, Diffraction 2010)

TOTEM σ_{inel}

EPL, 95 (2011) 41001



$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = 503.7 \pm 1.5 \pm 26.7 \text{ mb/GeV}^2$$

$$\sigma_{tot}^{\ 2} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{dR_{el}}{dt}\right|_{t=0}$$

ρ =0.14 +0.01-0.08
(COMPETE collaboration)

$$\sigma_{tot} = 98.3 \pm 0.2^{+2.8}_{-2.7}\, mb$$

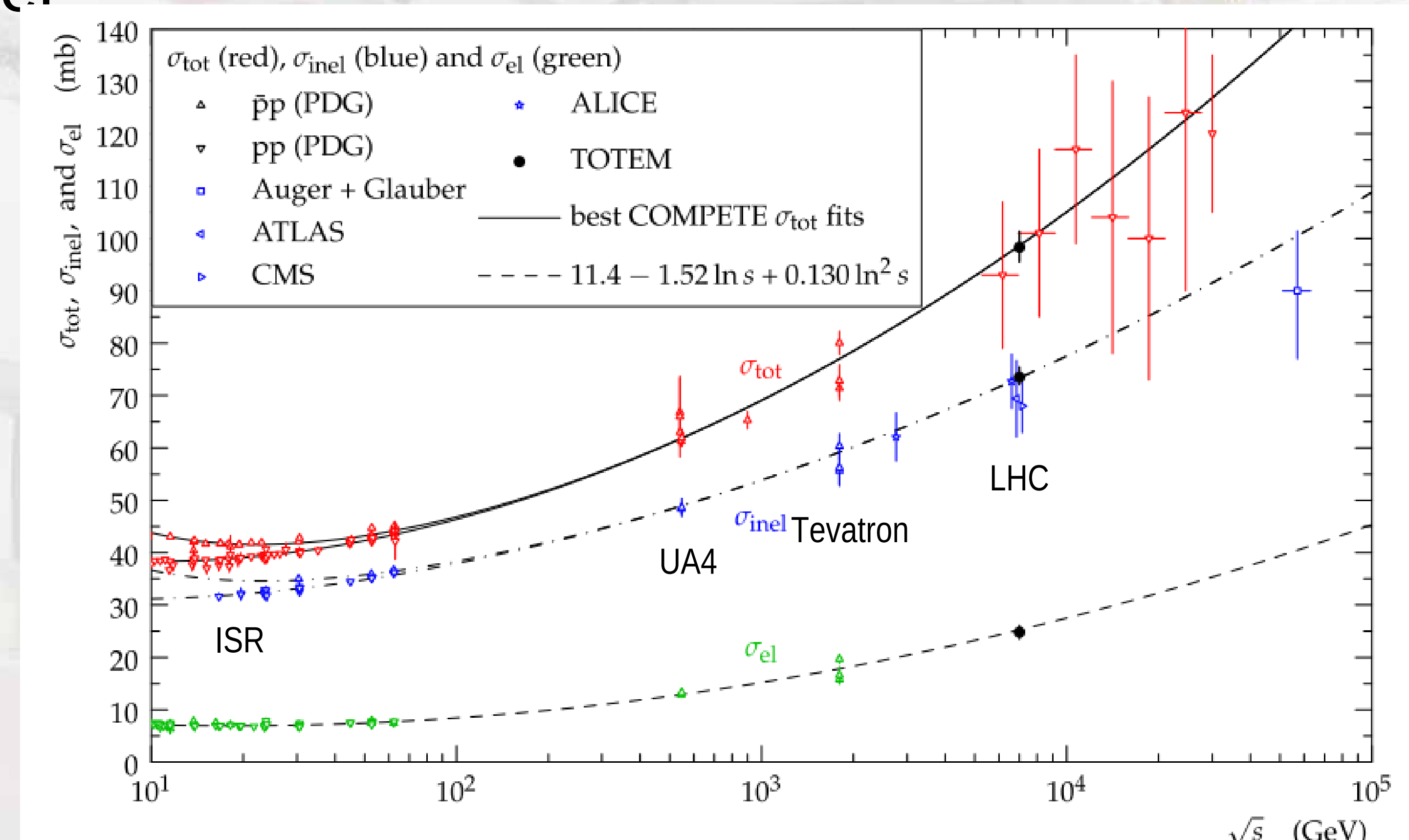
Integrated over entire "t" region

$$\sigma_{el} = \int \frac{d\sigma_{el}}{dt} dt = 24.8 \pm 0.2 \pm 1.2 mb$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$$

$$= 73.5 \pm 0.6^{+1.8}_{-1.3}\, mb$$

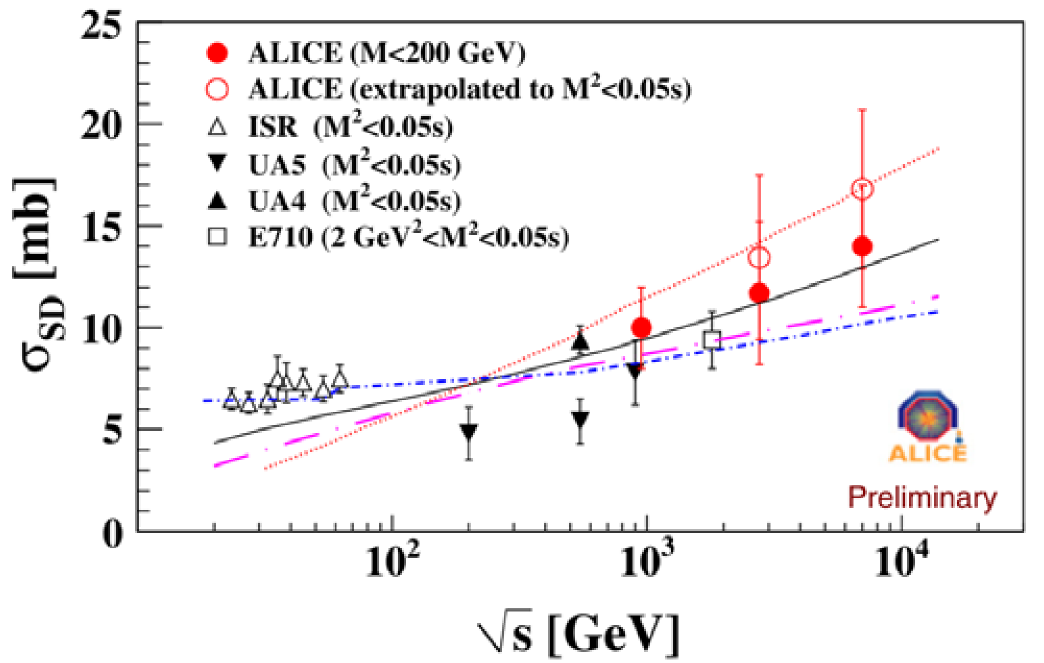
σ_{inel} result @ 7TeV

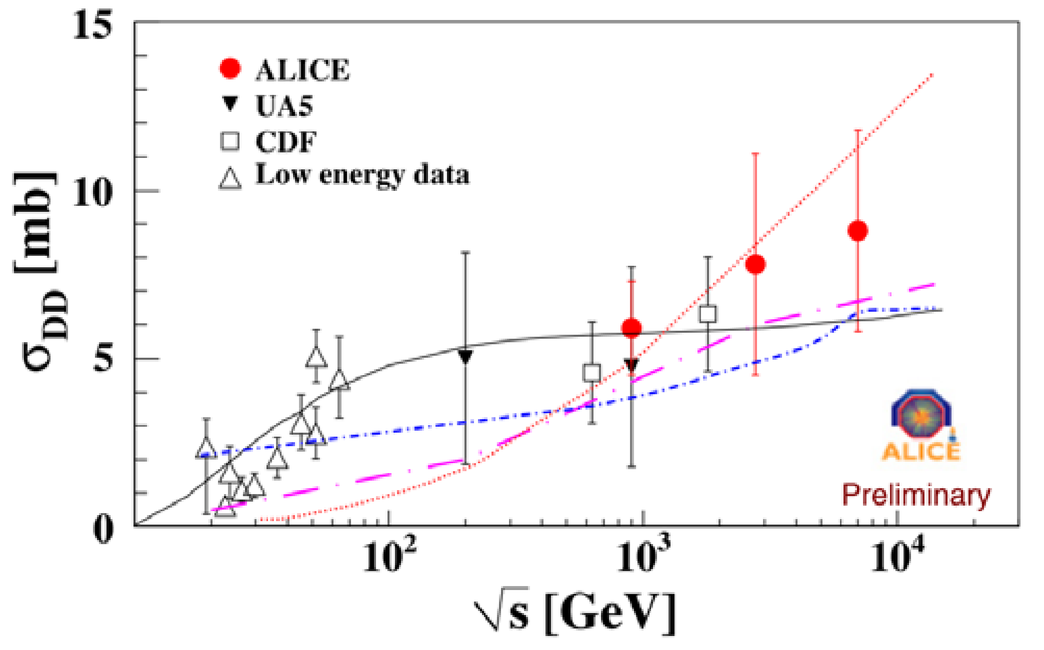


TOTEM	73.5+-0.6+1.8-1.3 mb	dσ/dt(t=0)
ATLAS	69.4+-2.4+-6,9 mb	MBTS sample
CMS	68.0+-2.0+-2.4+-4 mb	Ntrk sample
ALICE	72.7+-1.1+-5.1 mb	VZERO sample

ALICE $\sigma_{diffraction}$

J. Phys. G: Nucl. Part. Phys. 38 (2011) 124044

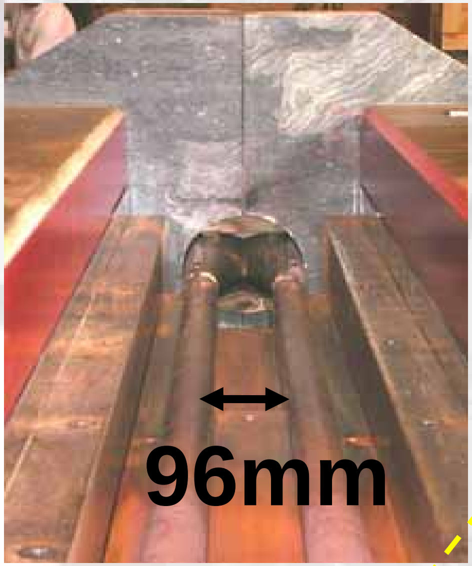


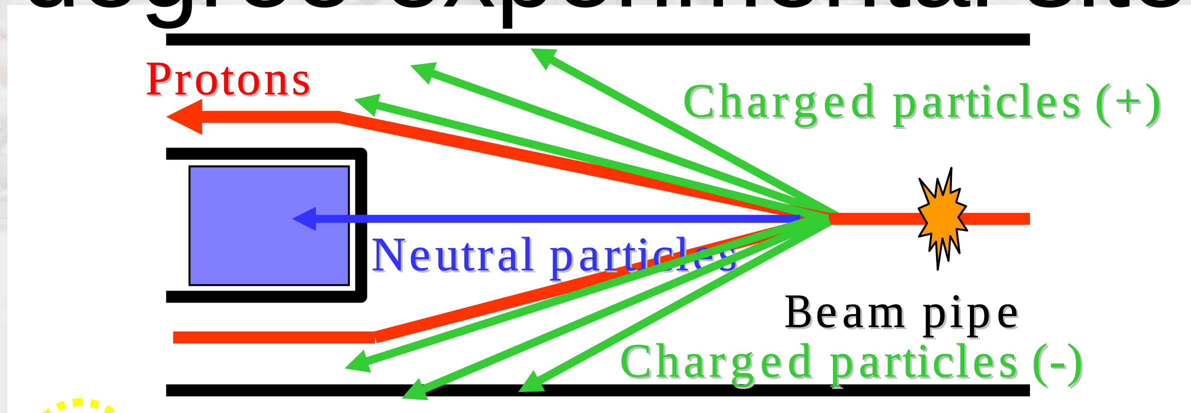


Forward energy spectra / Inelastiscity / P_T

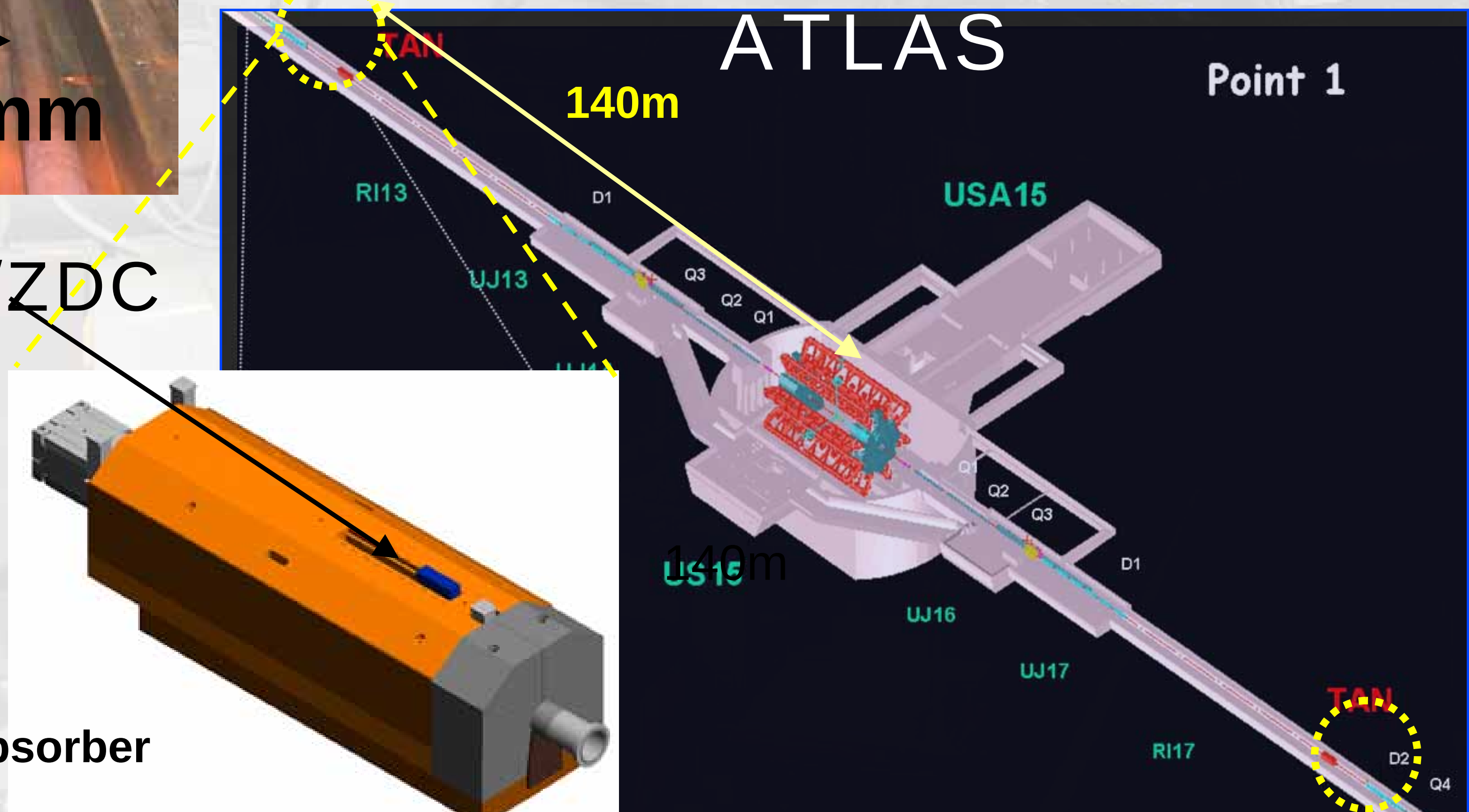
- LHCf
- UA7
- CMS FCAL
- RHIC BRAHMS
- Forward neutron spectra

LHC zero degree experimental site



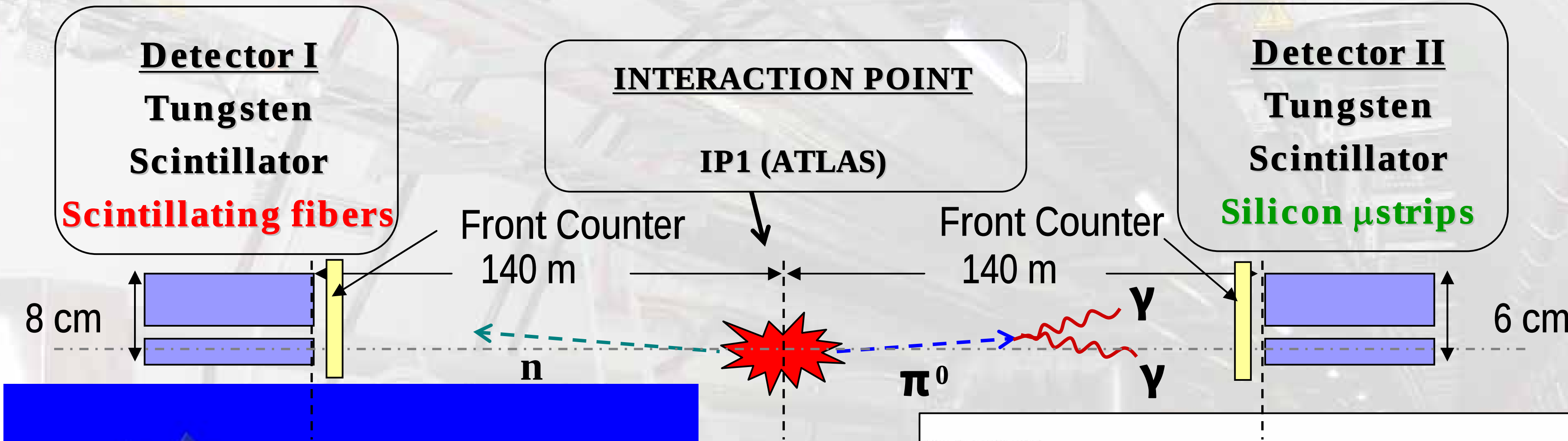


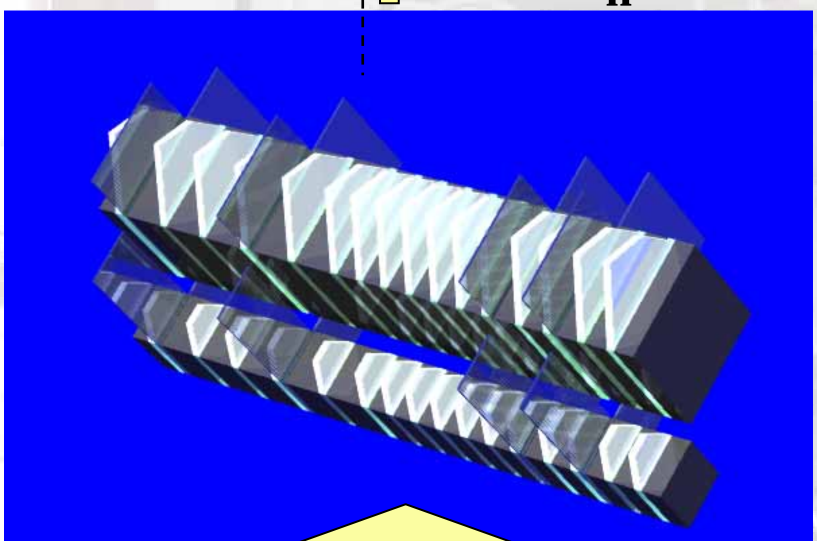
LHCf/ZDC



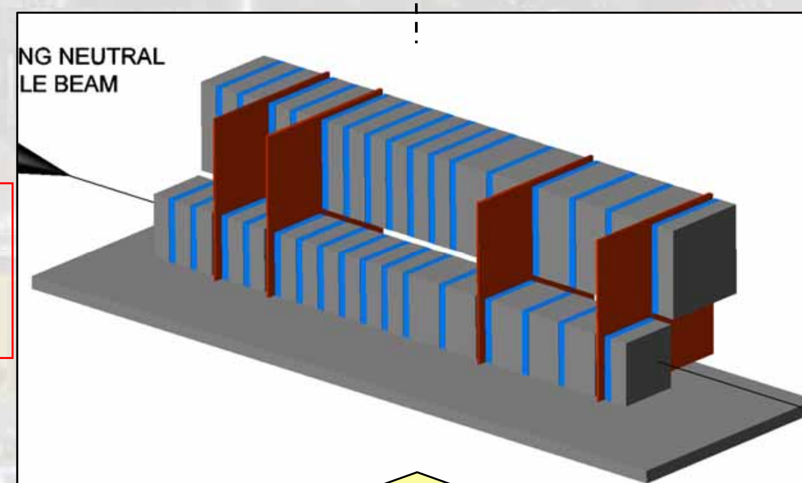
TAN absorber

LHCf: location and detector layout





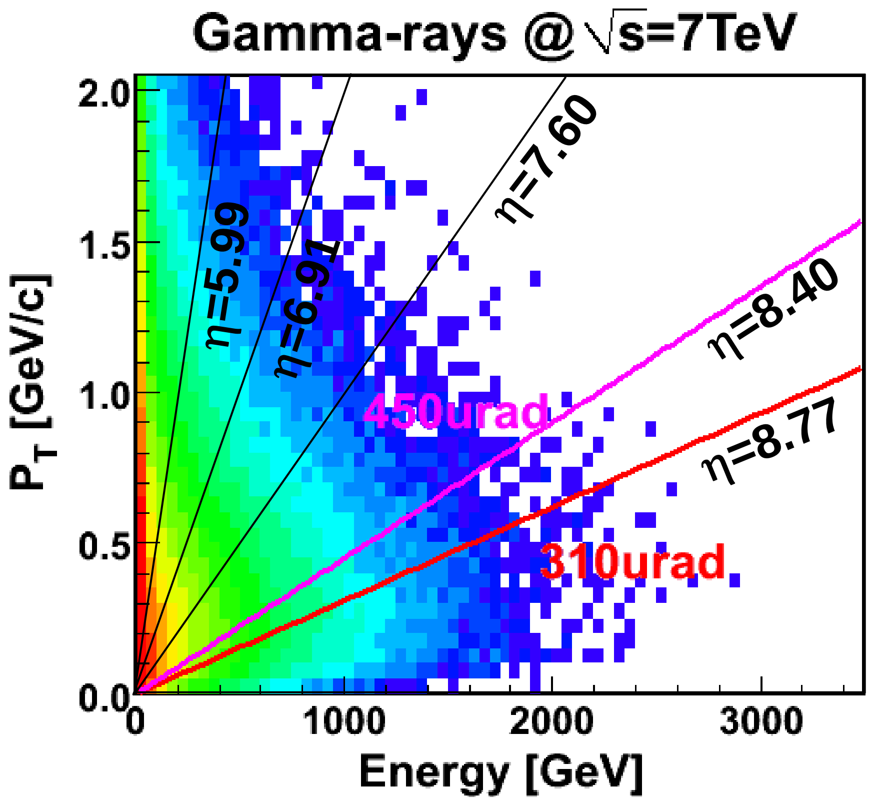
$44X_0$,
$1.6\ \lambda_{int}$

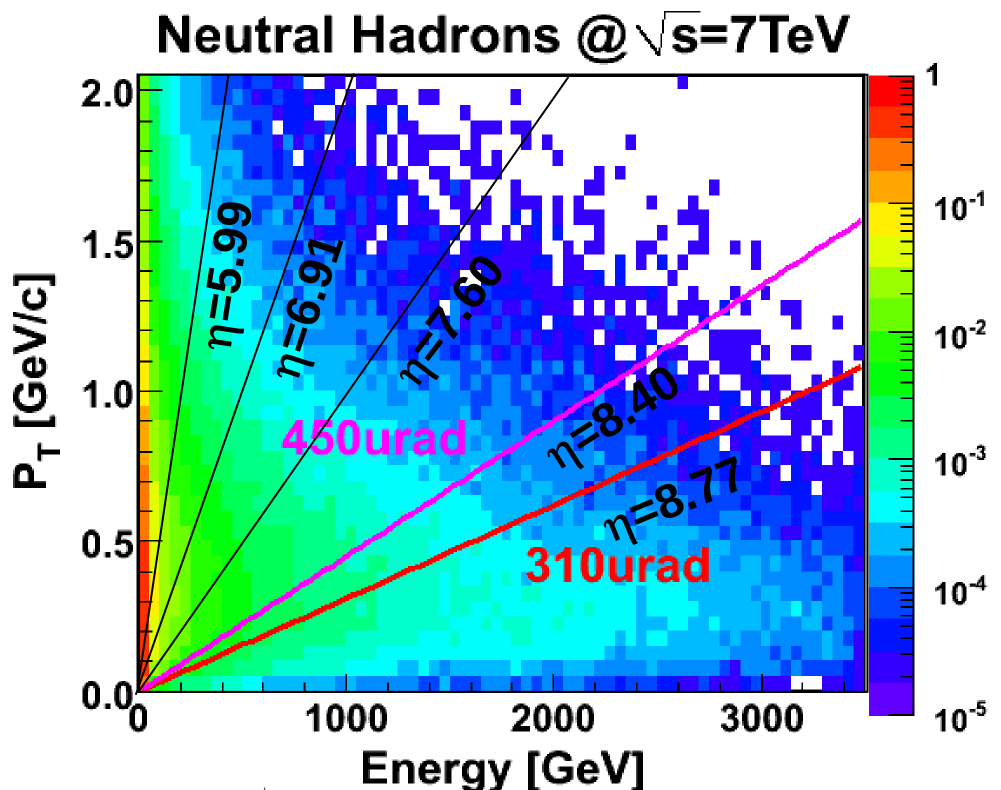


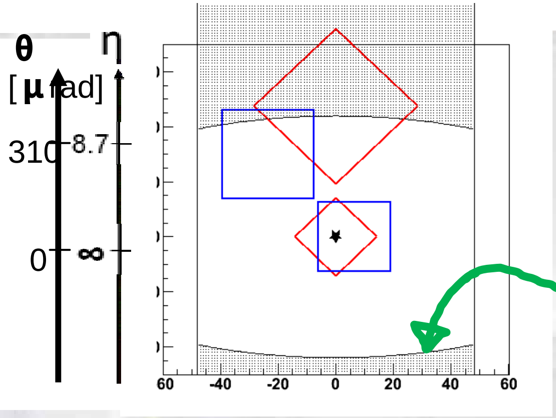
Arm#1 Detector
20mmx20mm+40mmx40mm
4 SciFi tracking layers

Arm#2 Detector
25mmx25mm+32mmx32mm
4 Silicon strip tracking layers

Rapidity vs Forward energy spectra







Viewed from IP1
(red:Arm1, blue:Arm2)

Projected edge of beam pipe

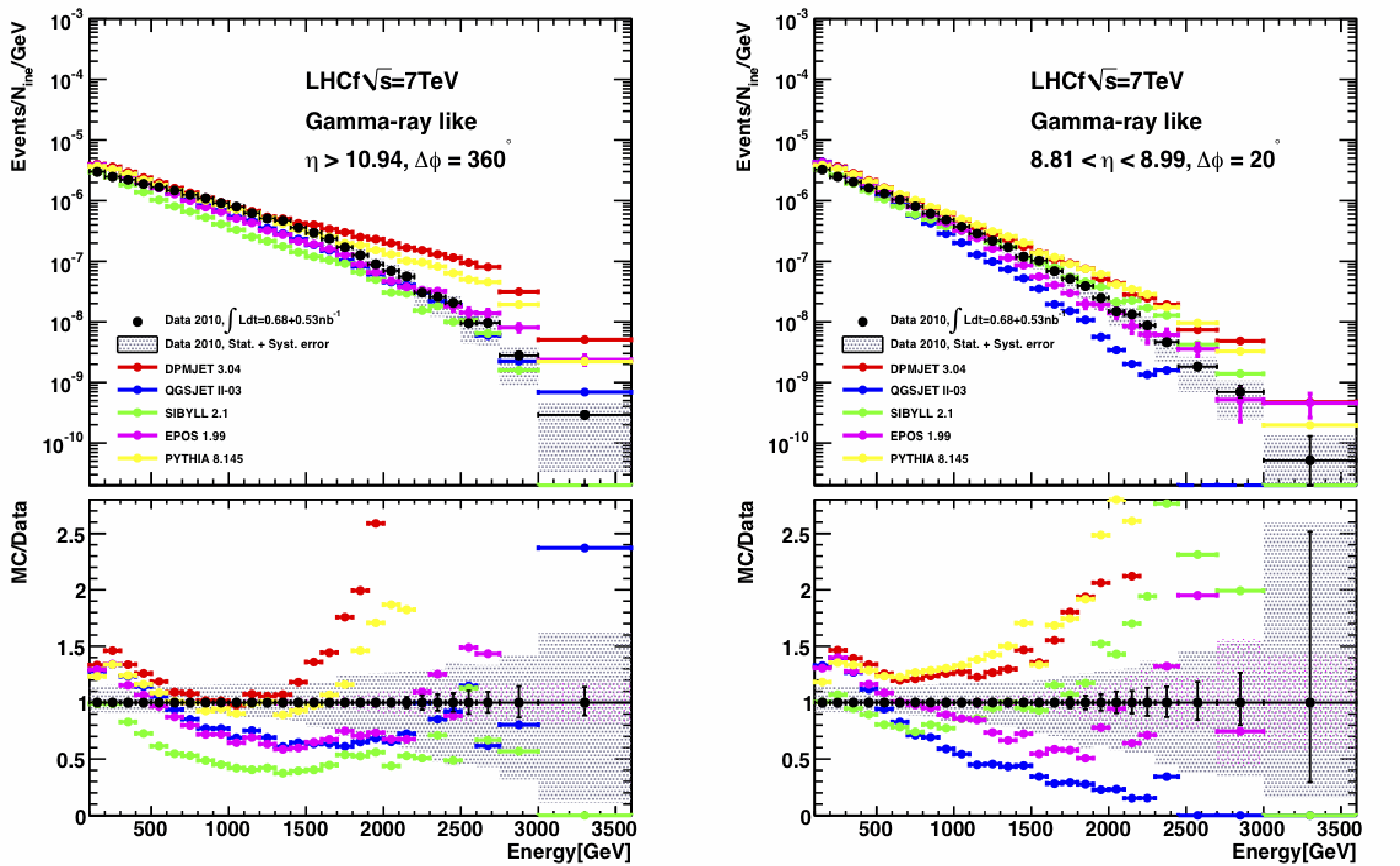
LHCf single γ spectra at 7TeV

Phys.Lett. B703 (2011) 128-134

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

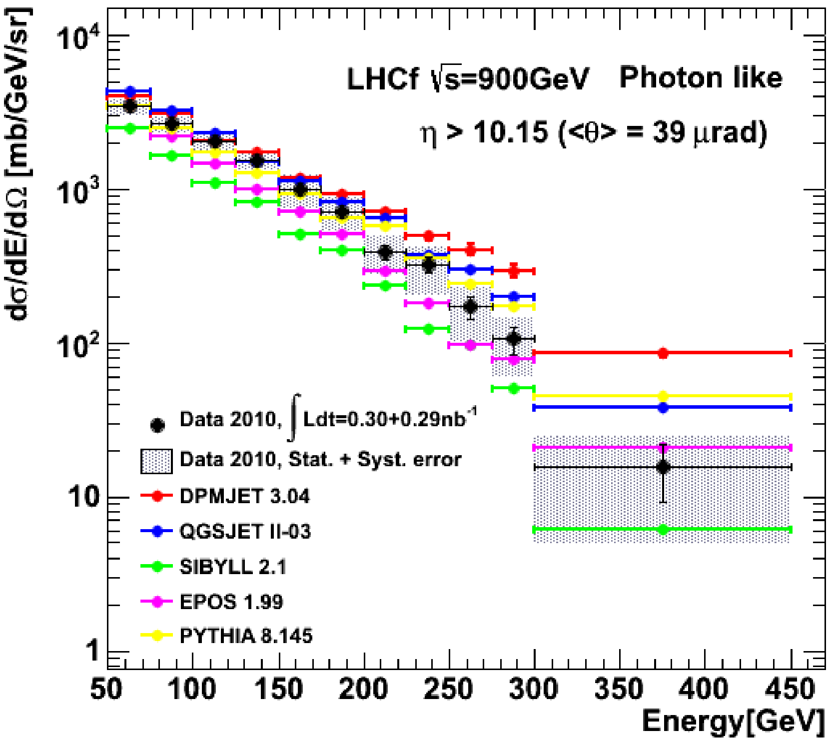
Gray hatch : Systematic Errors

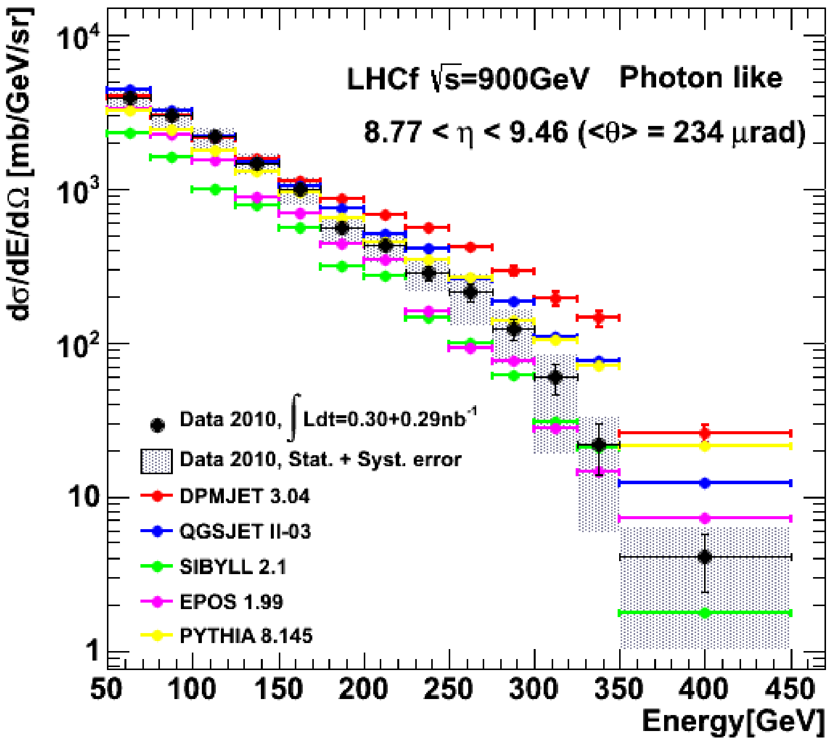
Blue hatch: Statistics errors of MC



New LHCf single γ spectra at 900 GeV

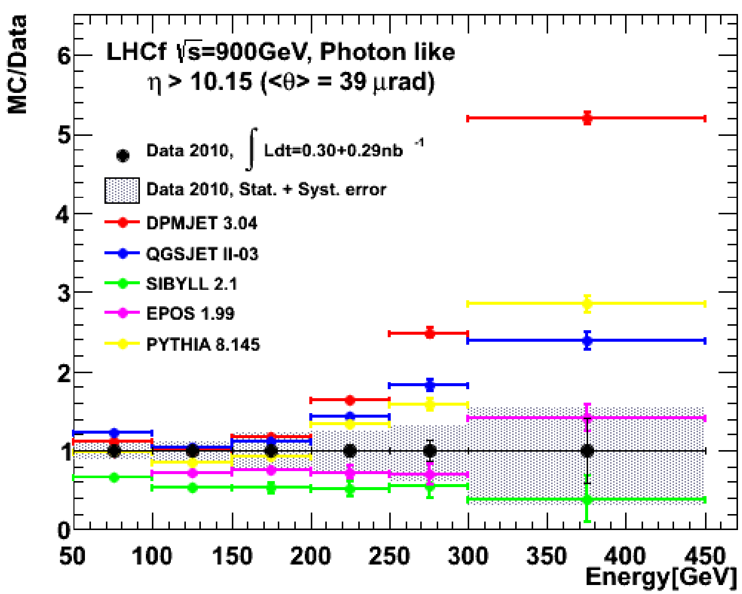
(to be submitted PLB)

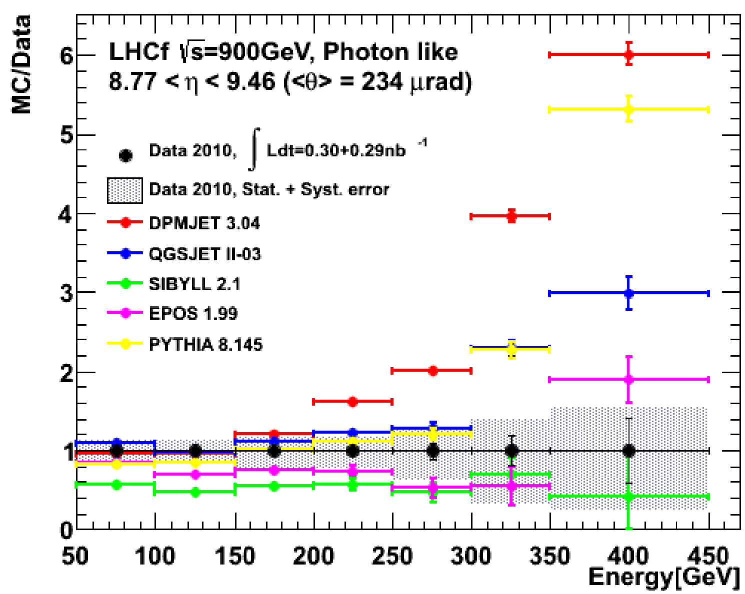




LHCf 900GeV single γ spectra: Data/MC

900GeV

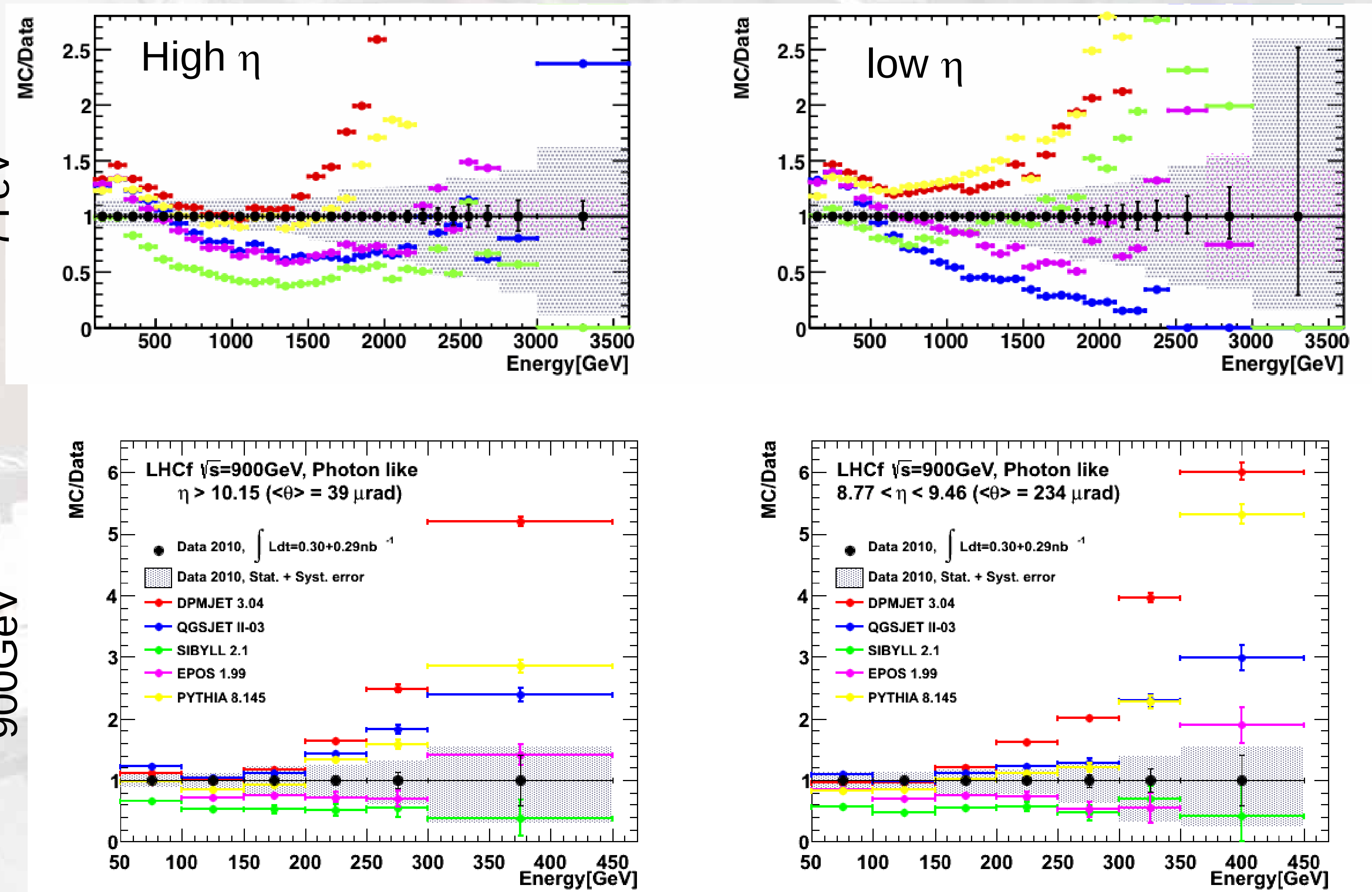




LHCf 900GeV single γ spectra: Data/MC

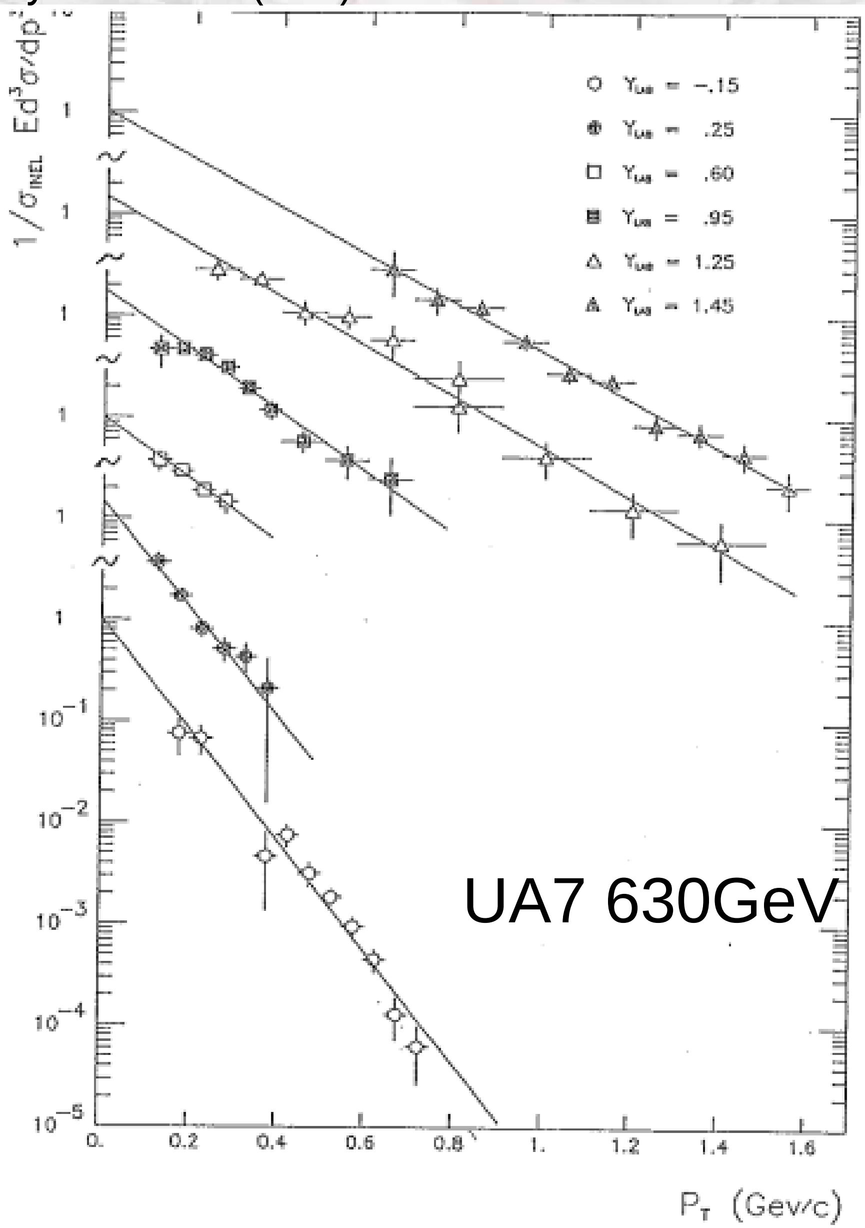
7TeV

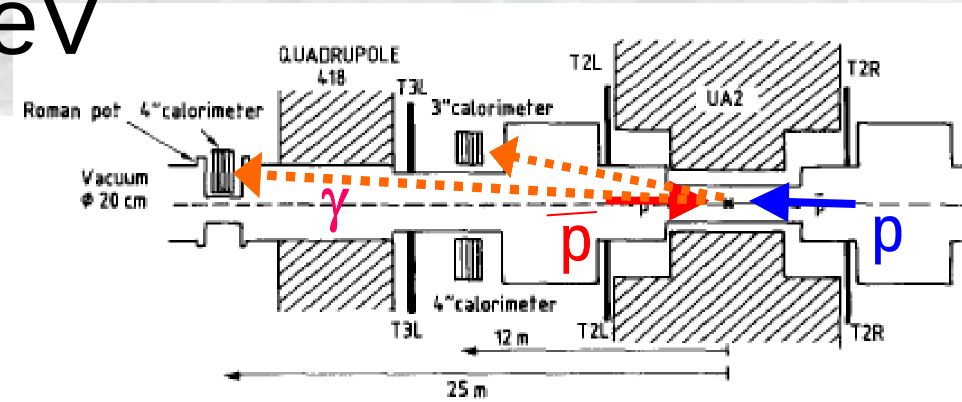
900GeV

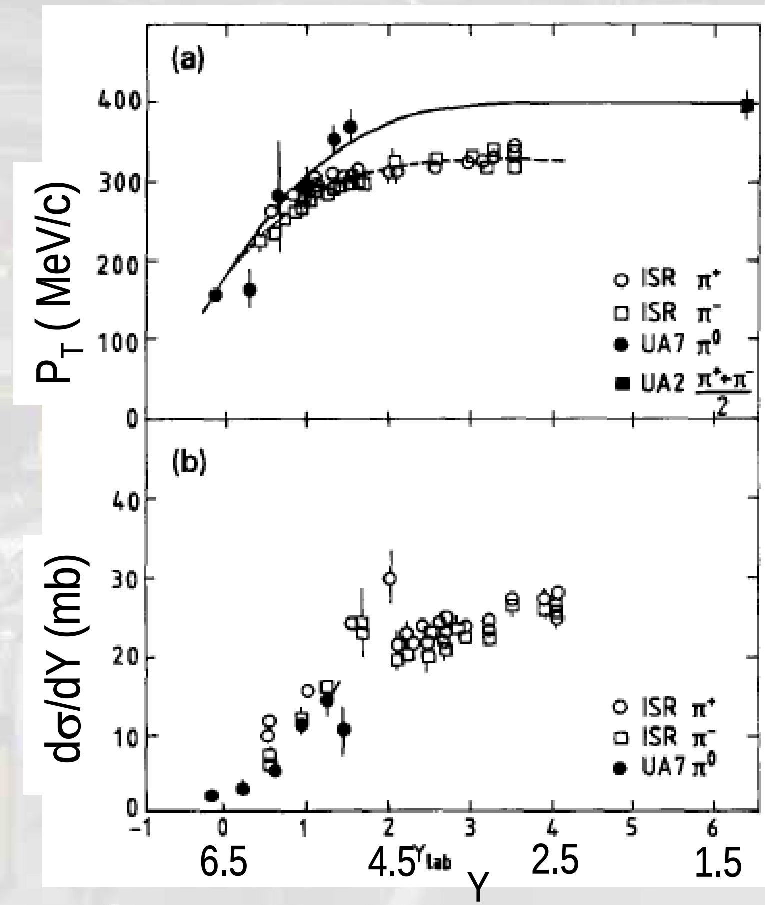


UA7 π^0 P_T at 630GeV

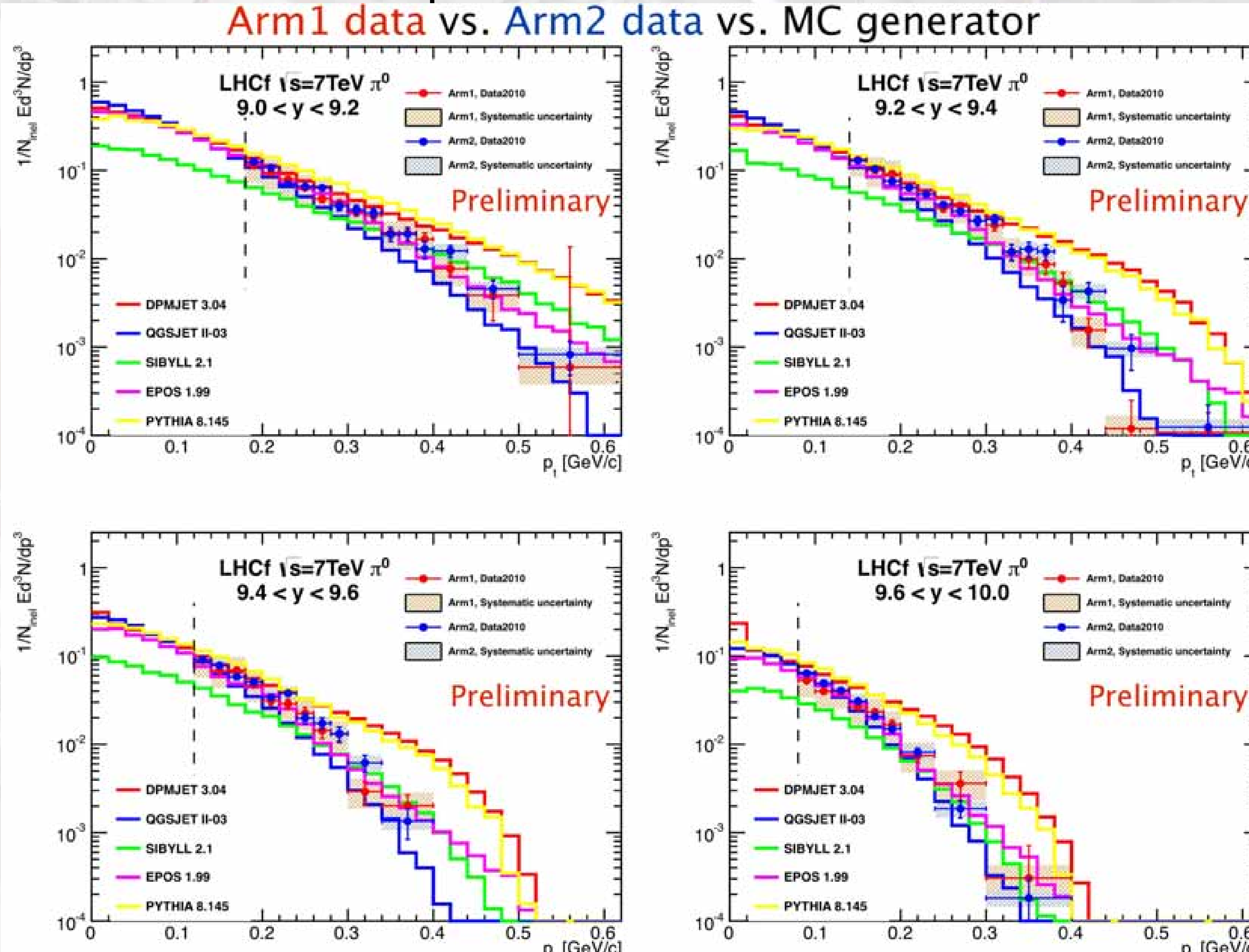
Phys.Lett. B242 (1990) 531-535



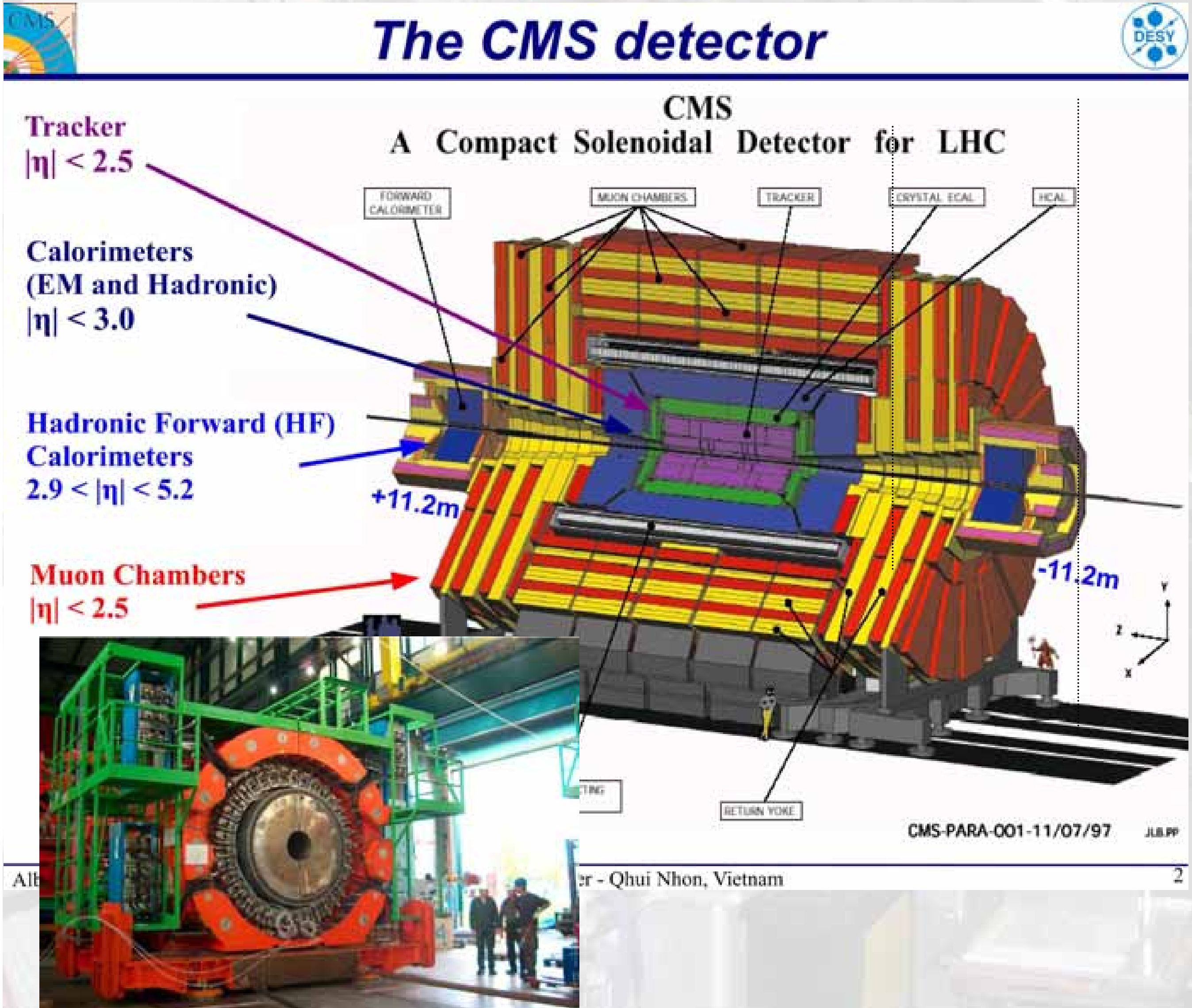


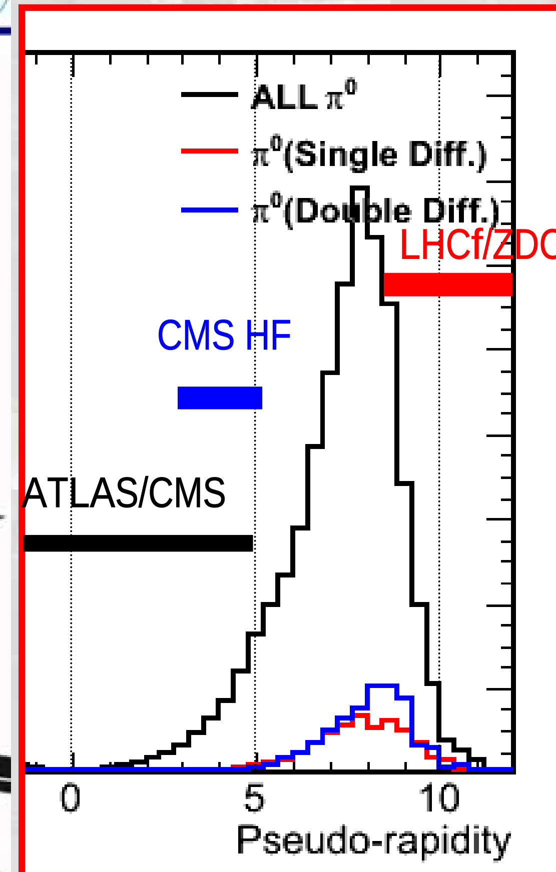


New LHCf π^0 P_T at 7TeV (Preliminary)



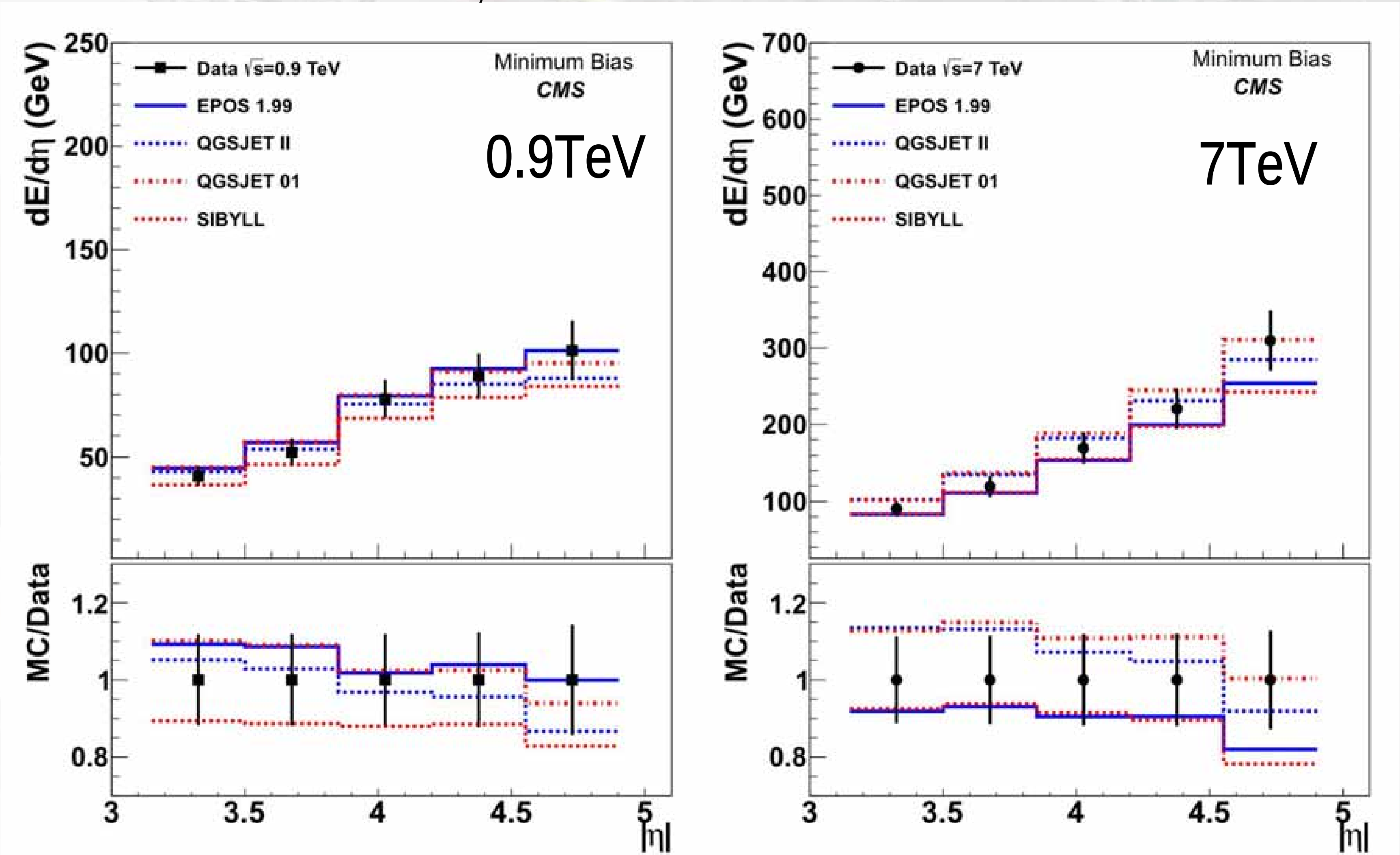
CMS HF : forward energy flow





CMS HF: Forward energy flow

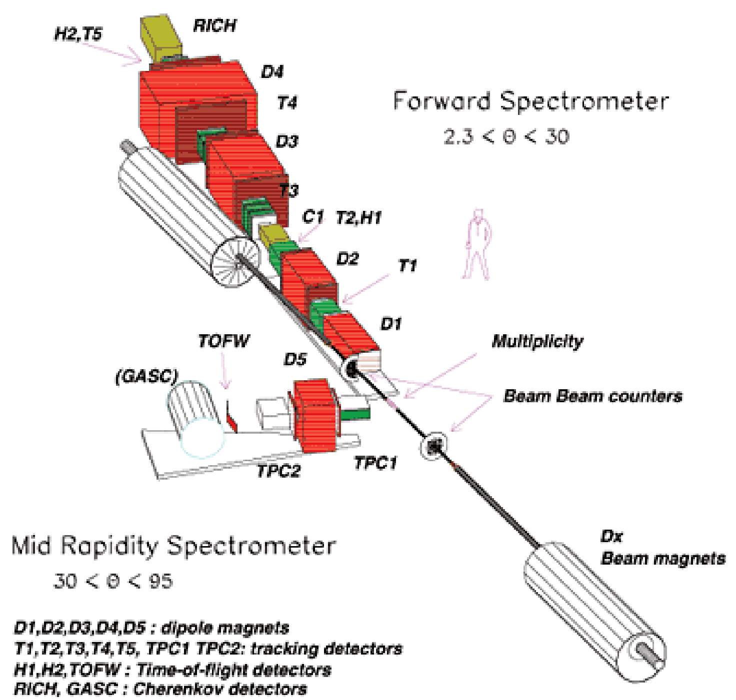
CERN-PH-EP/2011-086, arXiv/0329842

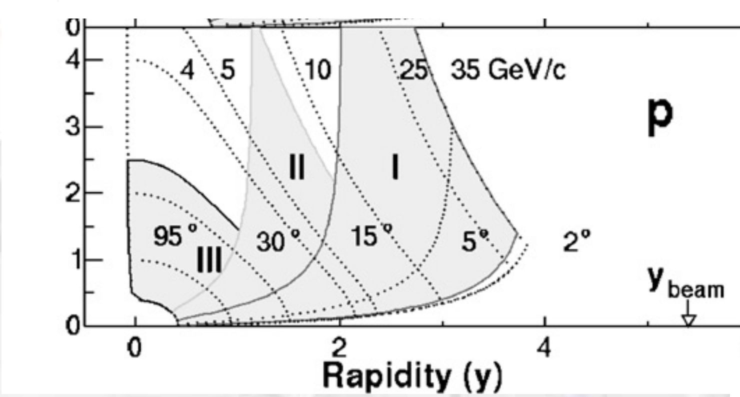


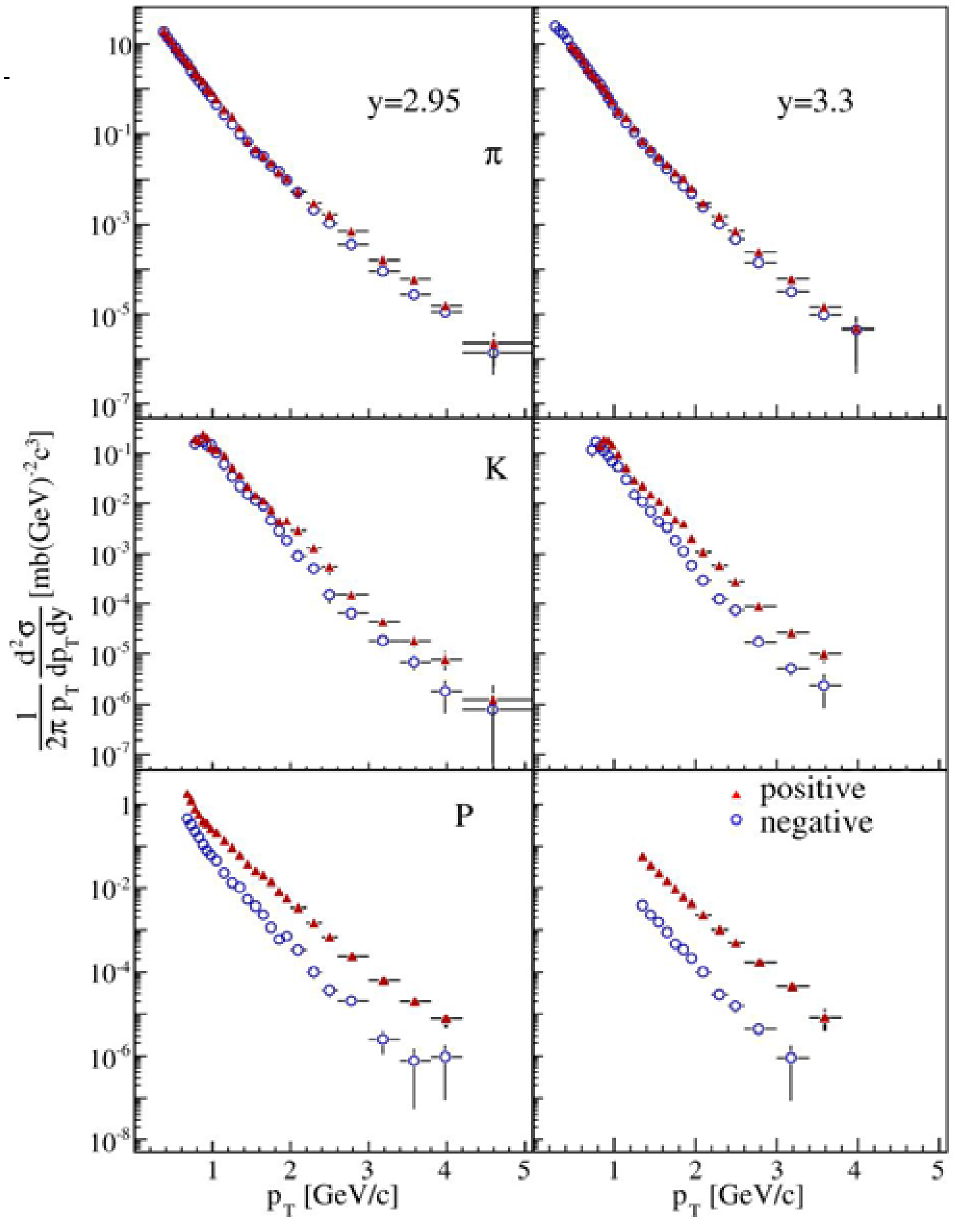
3.15< η <4.19

RHIC BRAHMS : charged spectra at $\sqrt{s}$=200GeV

PRL 98, 252001 (2007)

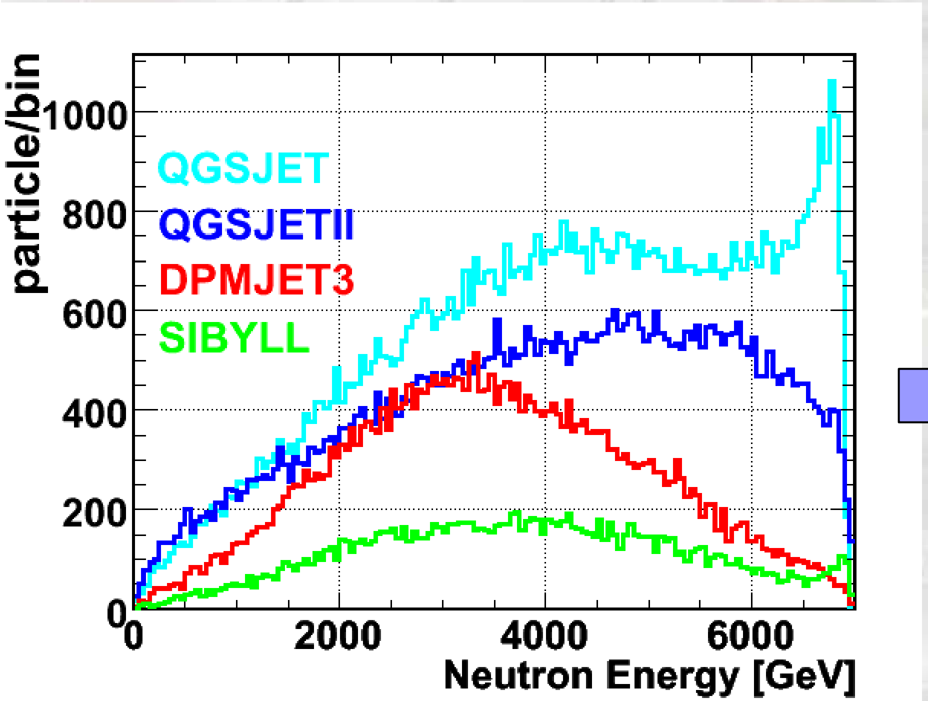




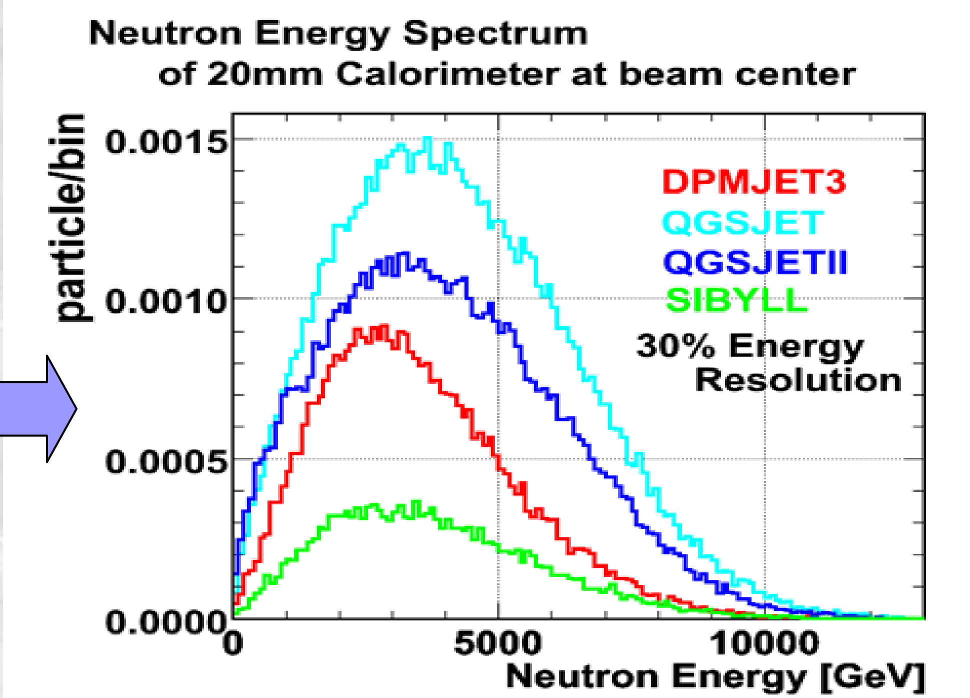


Inelasticity~ 0 degree neutron spectra

- Important for X_{max} and also N_{μ}
- Measurement of inelasticity at LHC energy



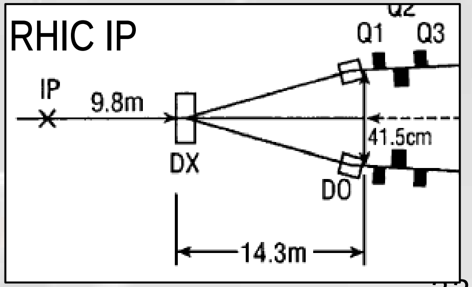
Neutral hadrons at 14 TeV
(LHCf acceptance, no resolution)



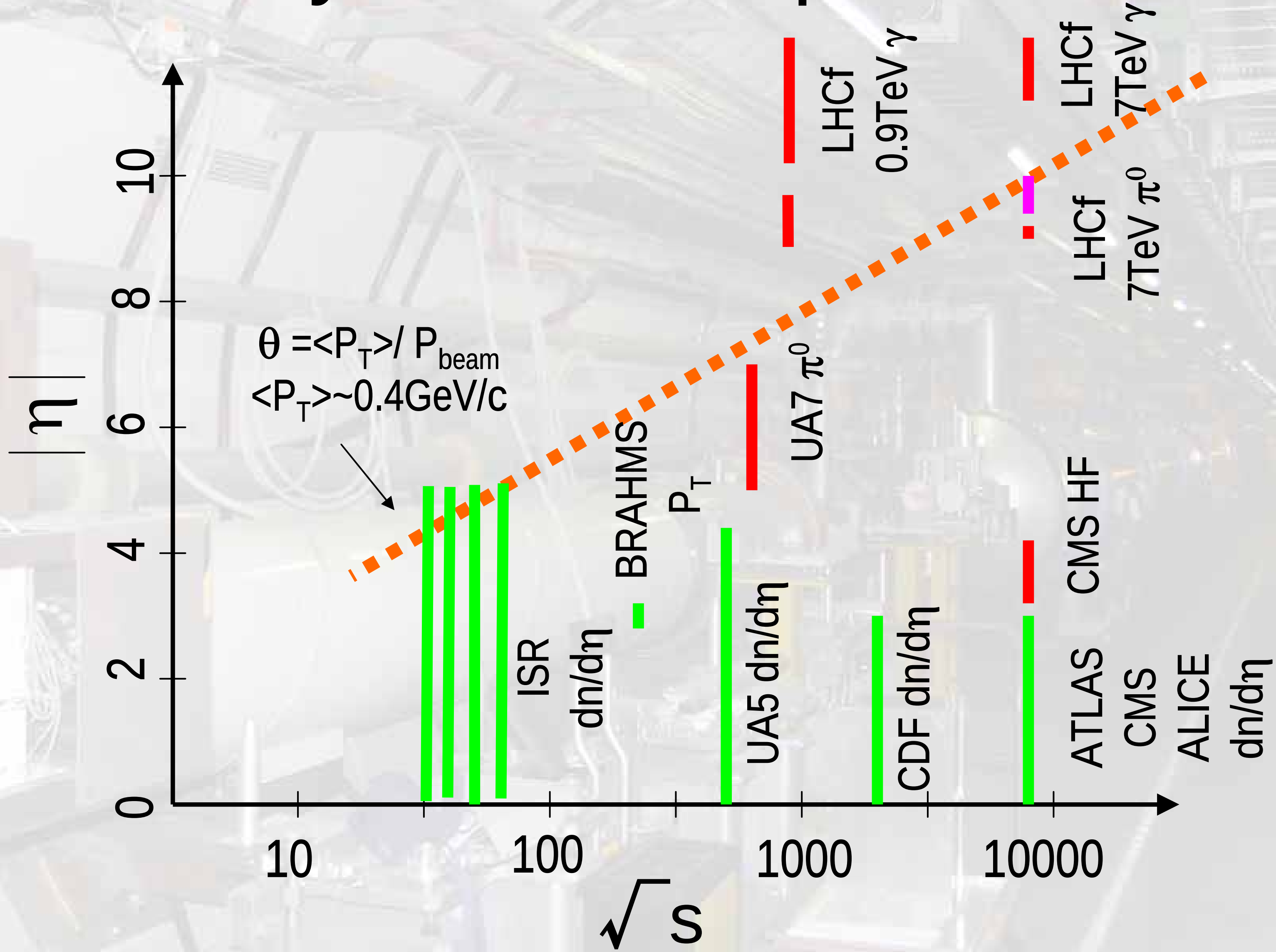
Neutral hadrons at 14 TeV
(LHCf acceptance, 30% resolution)

Future data for forward energy flow

- Forward neutrons by LHC ZDC's
  - So far working well for centrality in HI runs
  - Potentially they can work nicely (PID ?)
  - Combined LHCf+ATLAS ZDC may benefit
- Other LHC forward detectors
  - CMS CASTOR :Only coverage for $\eta \sim 6$
  - TOTEM T1, T2, LHCb VELO($1.6<\eta< 4.9$?)
- New LHC detectors ?
  - CMS Forward Shower Calorimeter (FSC) ?
  - Roman Pod type calorimeter (a la UA7) ?
- RHIC 0dgree measurement ?
  - $\sqrt{s}$= 500GeV with larger P_T acceptance
  - Possible π^0 measurement

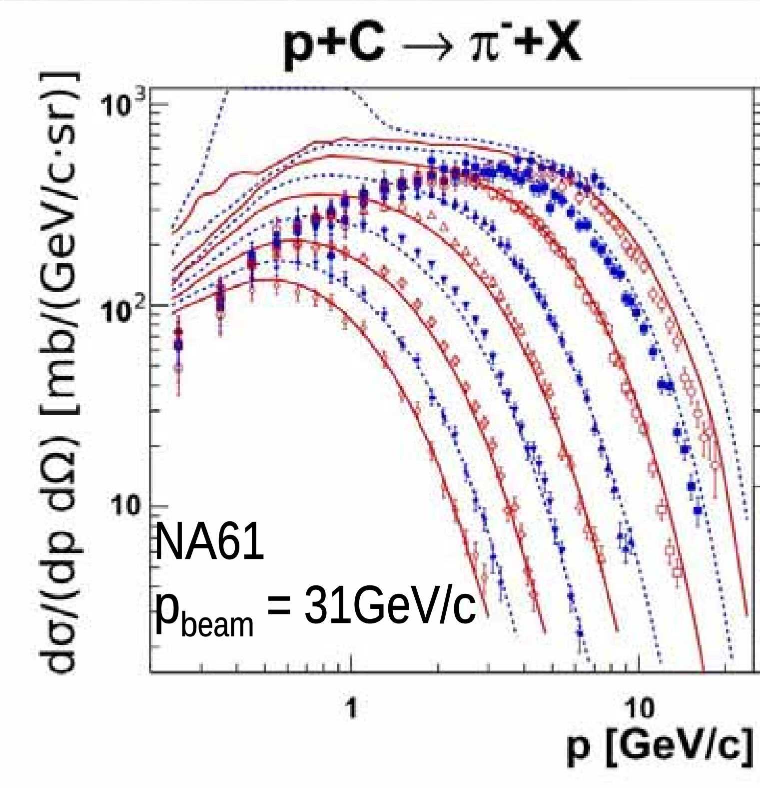


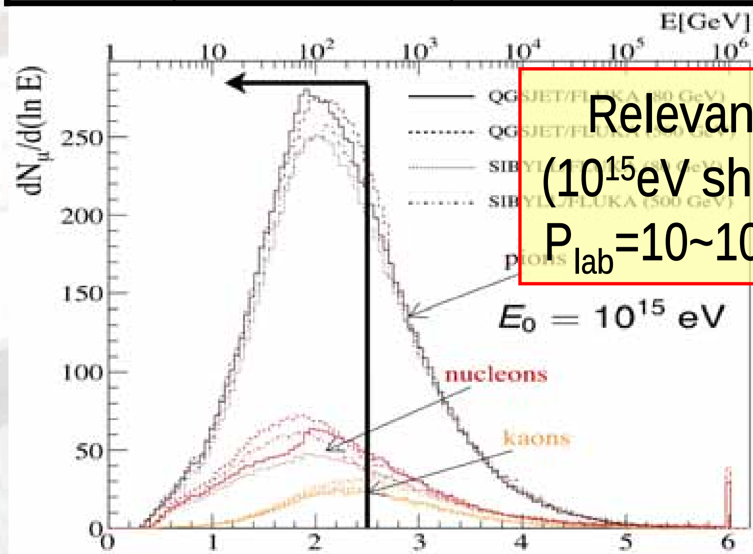
Summary : forward spectra coverage



Low energy data

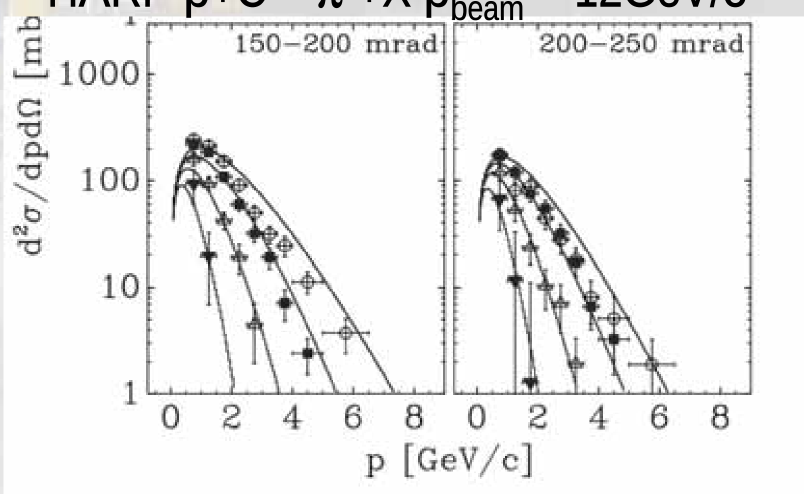
Exp		beam	target
NA49	CERN SPS	128GeV/c p	C, p
NA61	CERN SPS	31GeV/c p, etc π+-	C, Be…
HARP	CERN PS	3,5,8,9,12GeV/c p π+-	C,Be,p..
MIPP	FNAL-MI	58,120GeV/c p	C,Be…



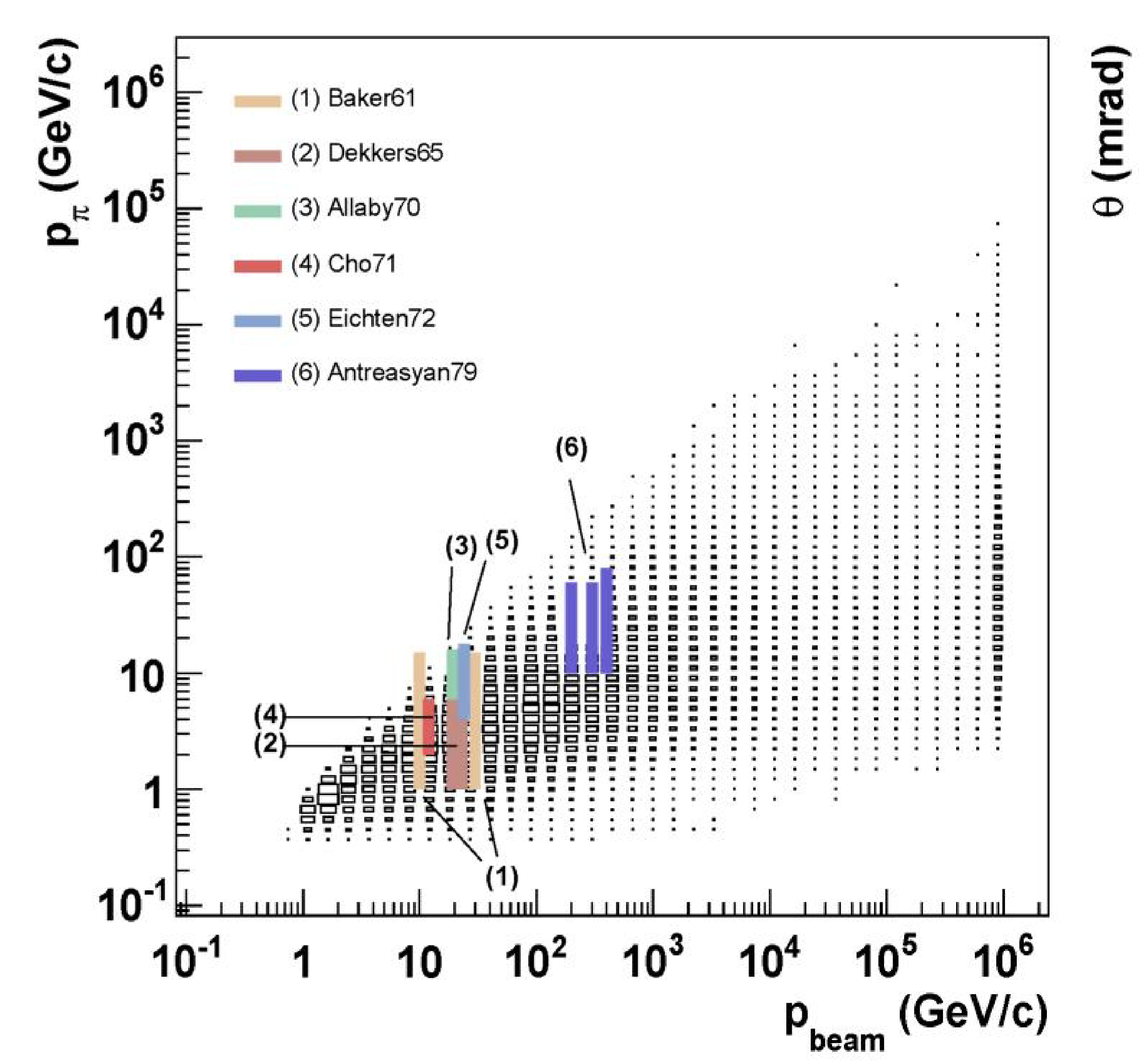


I. C. Maris, ICRC 2009

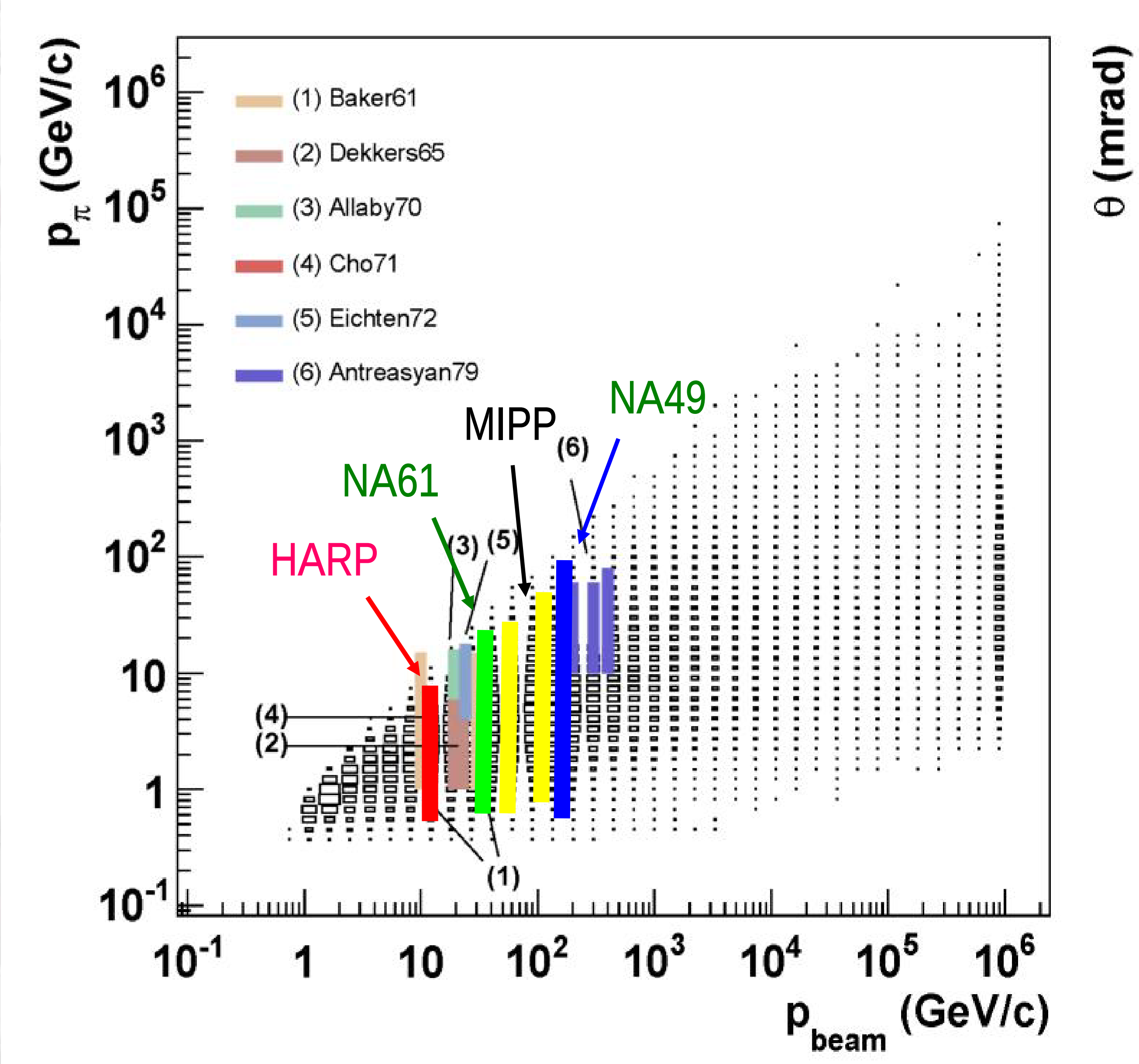
HARP p+C→π +X p_{beam} = 12GeV/c



Available accelerator data summary



Available accelerator data summary



Summary

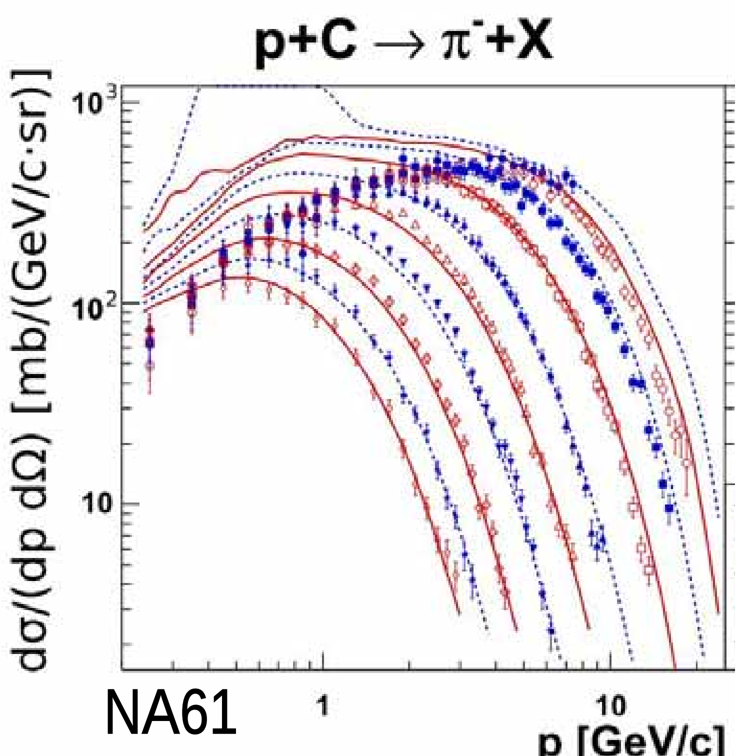
- Synergy btw UHECR and LHC is so important to solve UHECR problems and to explore ultra high E interactions at beyond-LHC.
- Key parameters for understanding air showers, σ_{inel}, forward spectra, inelasticity, multiplicity, P_T should be measured in various energy ranges.
  - First TOTEM σ_{inel}
  - LHCf forward spectra
  - Recent progress in various energy range (i.e. NA61, HARP, etc.)
- Striking impacts on UHECR analysis has been given by recent LHC data as well as legacy data by various accelerator experiments. Stay tuned.
- Nuclear effects (QGP, shadowing, etc.) not address here are also important. LHC A-A, p-A run will be able to address it.

p+C → π X data

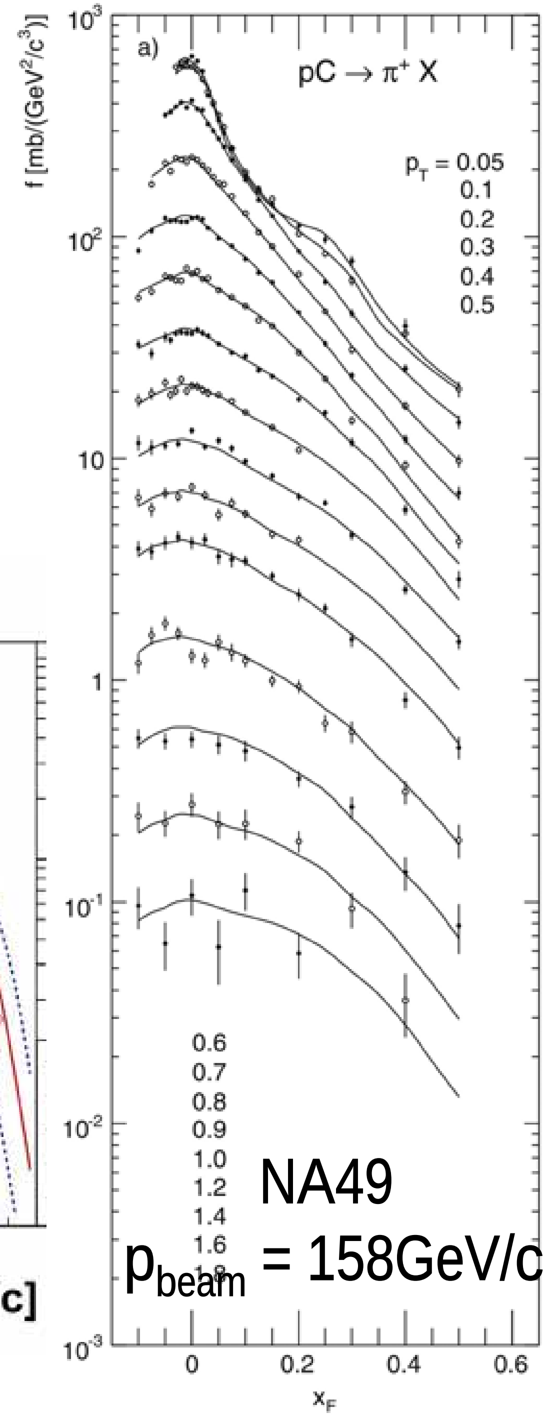
- NA49 (p_{beam}=158GeV/c)
- NA61 (p_{beam}=31GeV/c)

	p	yr	N_{trig} [x10^6]
π⁻C	158	2009	5.5
π⁻C	350	2009	4.6
pC	31	2007	0.7
pC	31	2009	5.4
pp	13	2010	0.7
pp	13	2011	2*
pp	20	2009	2.2
pp	31	2009	3.1
pp	40	2009	5.2
pp	80	2009	4.5
pp	158	2009	3.5
pp	158	2010	44
pp	158	2011	30*

NA61(SHINE) p_{beam} data sets

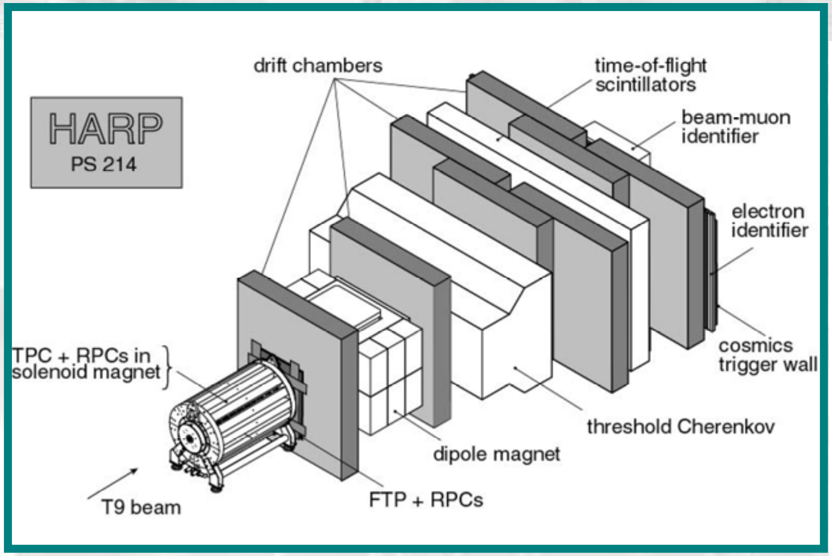


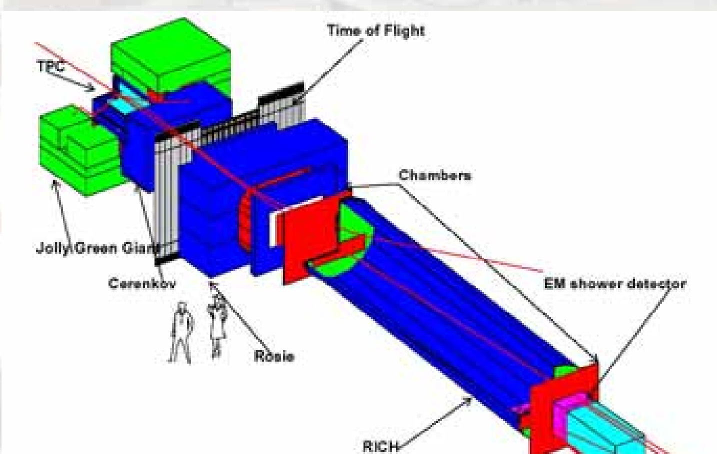
NA61 p_{beam} = 31GeV/c



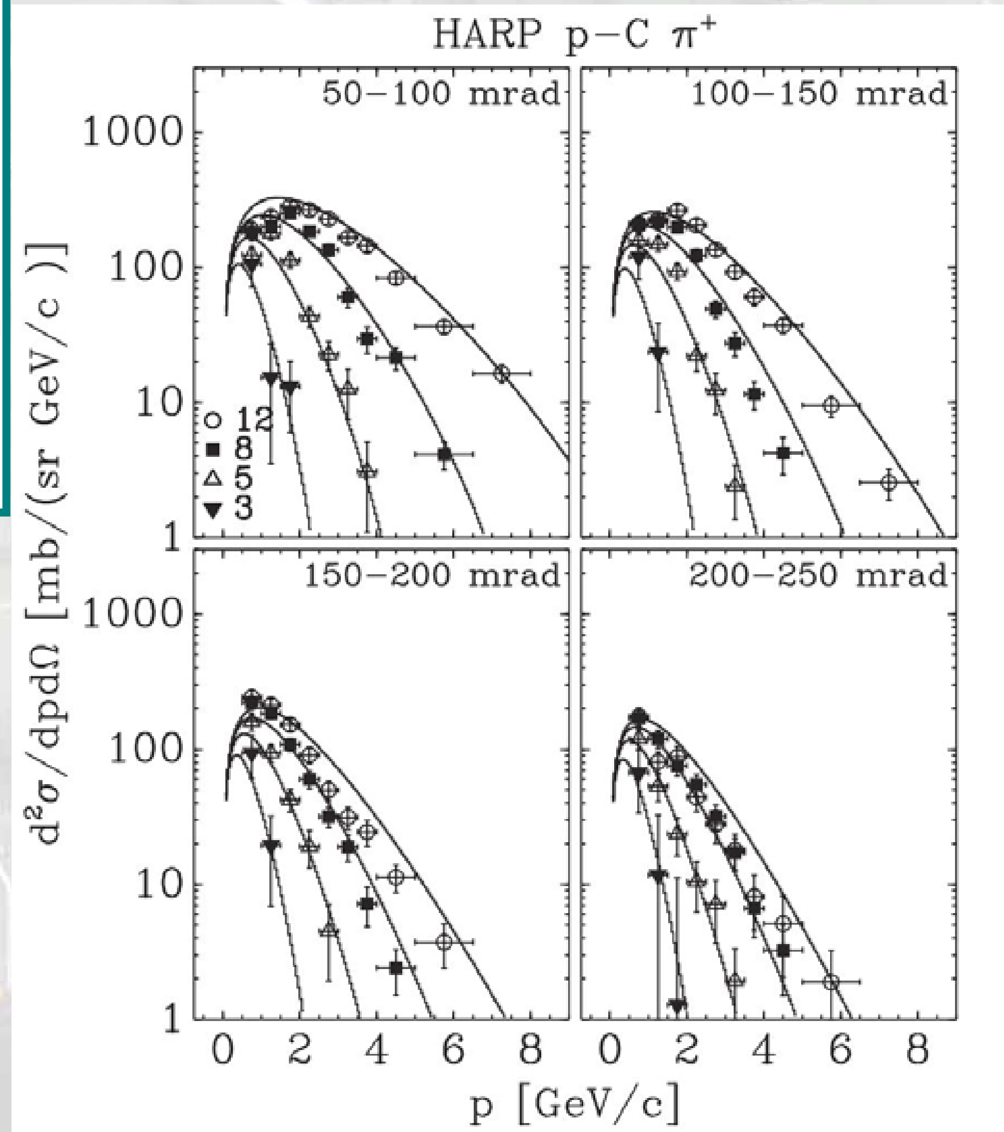
NA49 p_{beam} = 158GeV/c

HARP / MIPP





MIPP detector



Available accelerator data summary

C. Meurer et al.

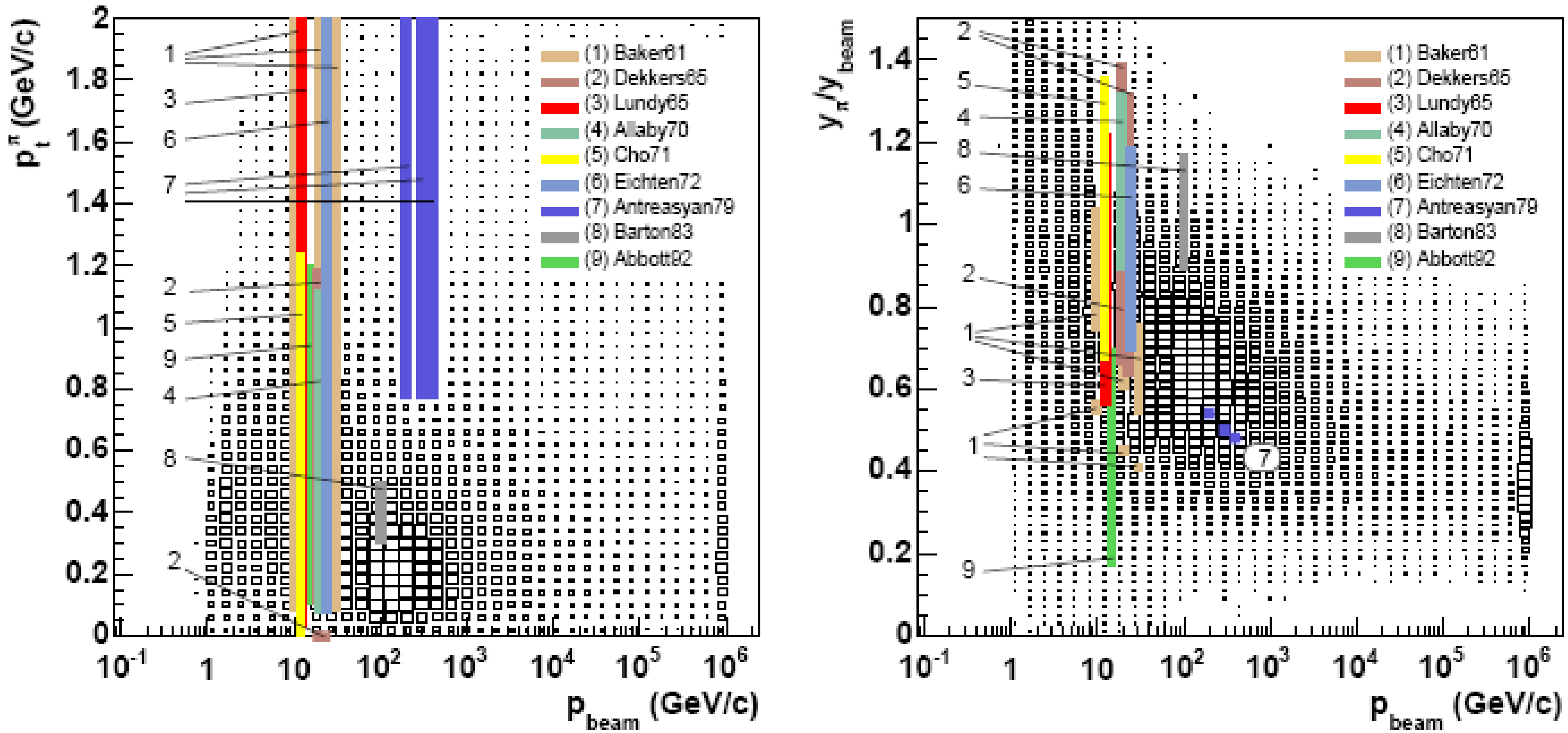
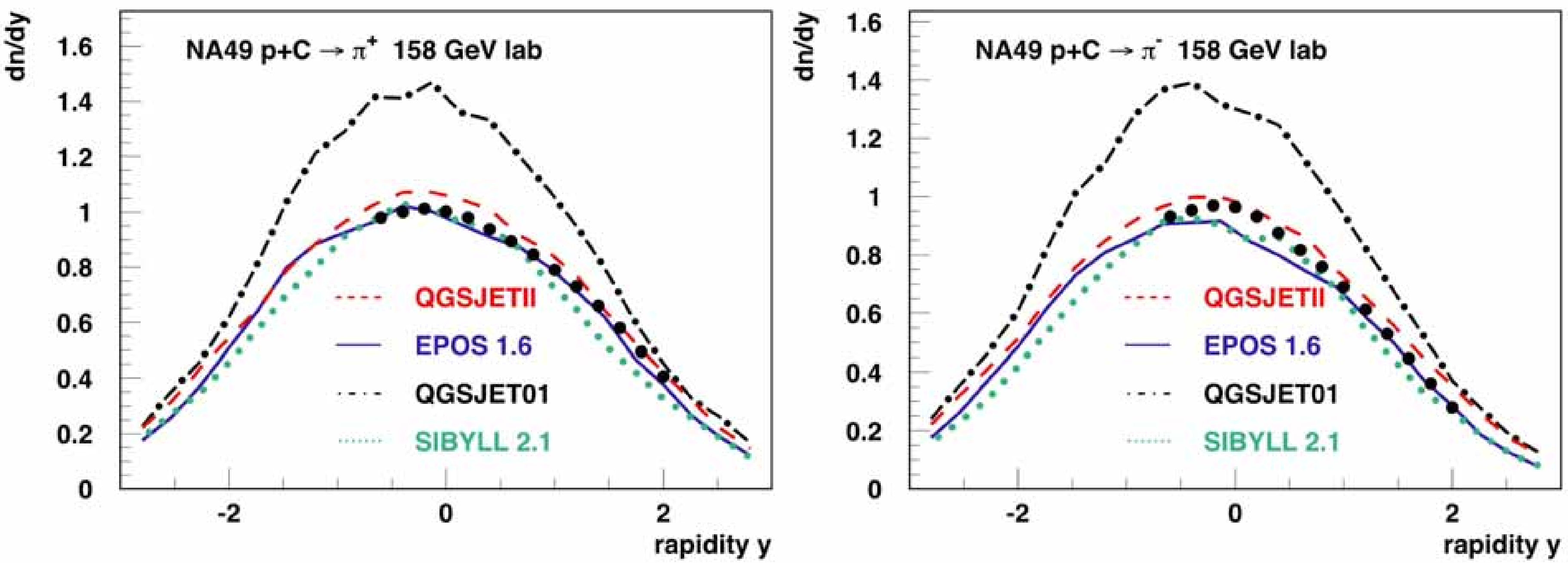
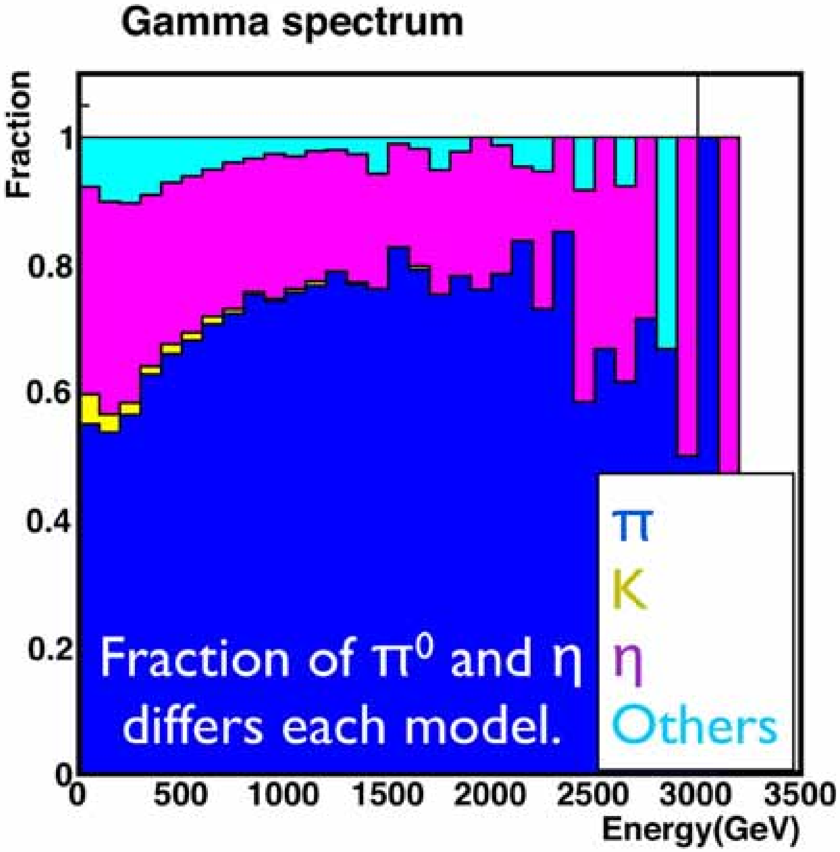


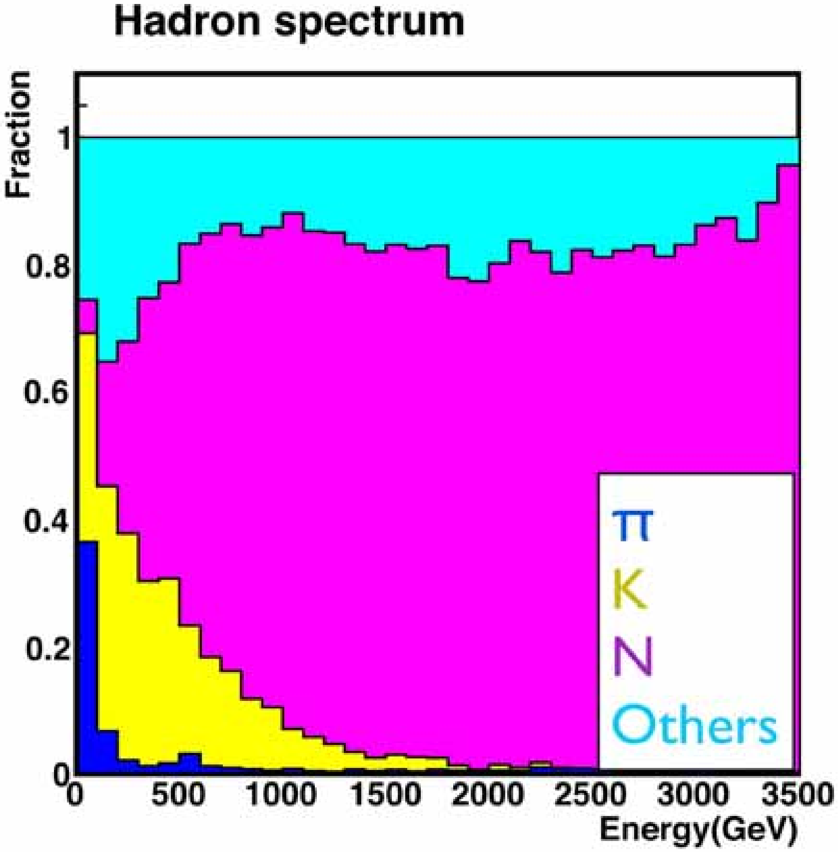
Fig. 9. Compilation of the phase space regions covered by fixed target data given in transverse momentum and rapidity of secondary particles and the phase space regions covered by the $\theta - p_{sec}$



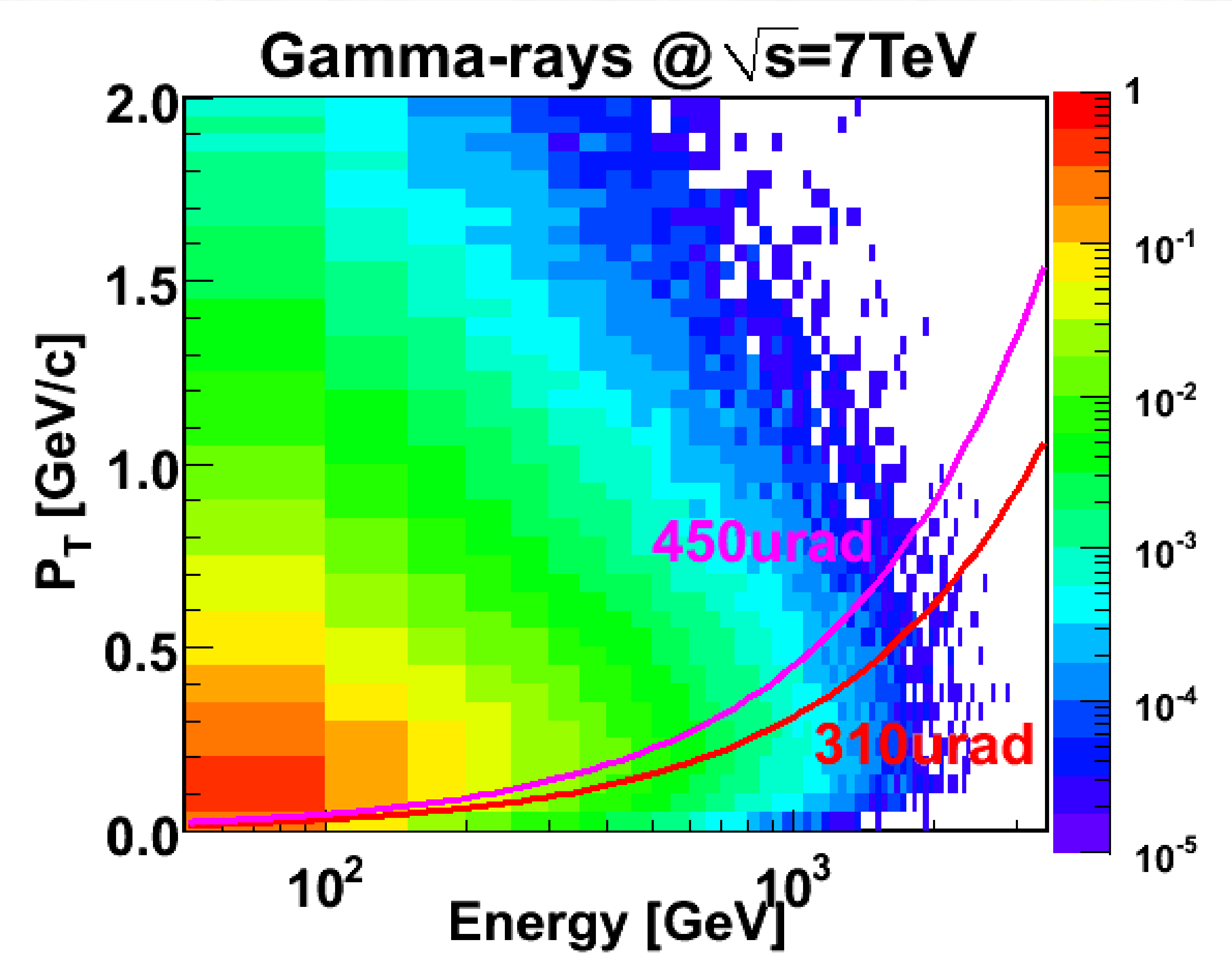
(Tanguy Pierog)

Parent particles relevant for LHCf observations

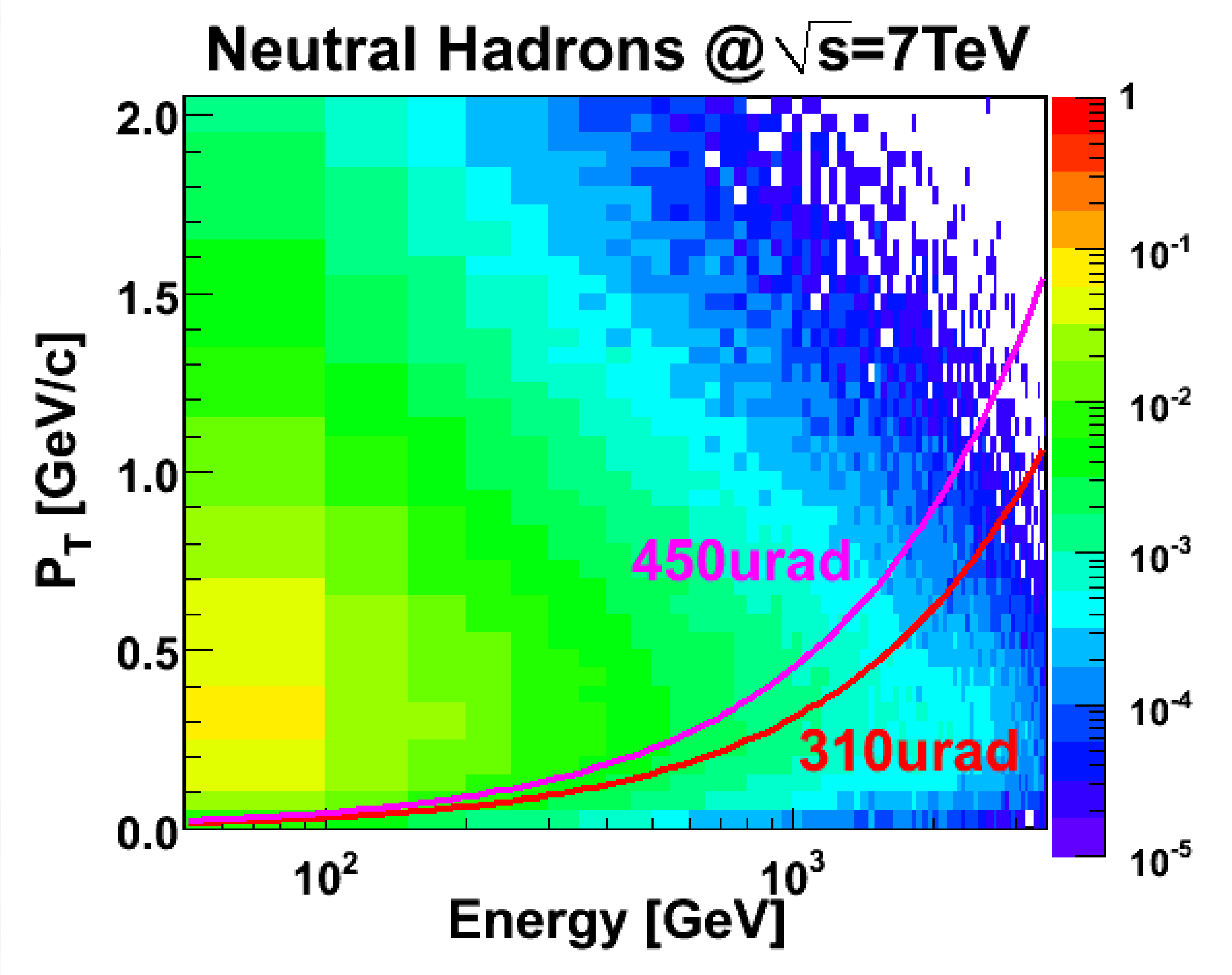




Sybill at 7TeV

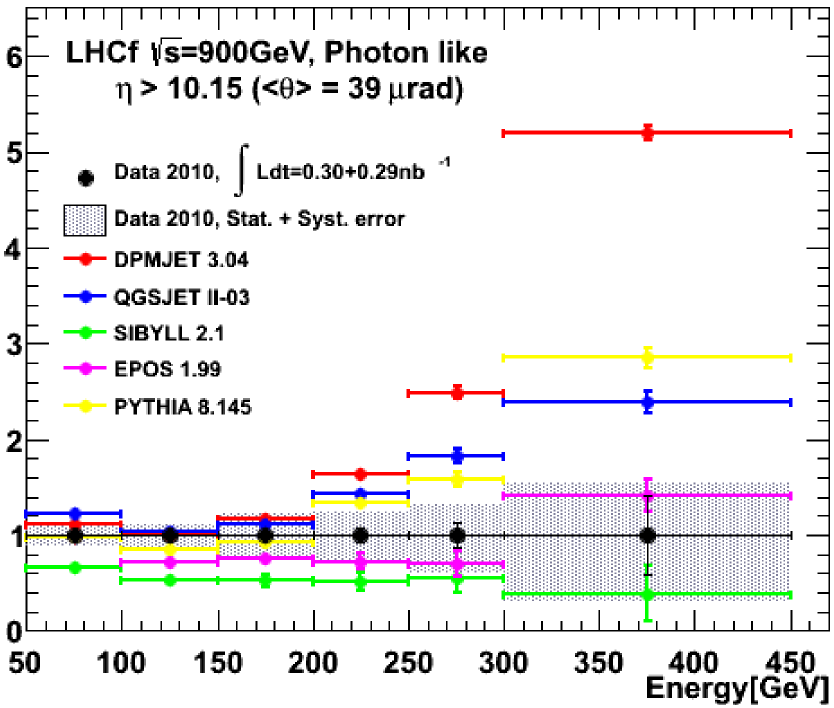

Gamma-rays @ √s=7TeV
P_T [GeV/c]
2.0
1.5
1.0
0.5
0.0
10^2
10^3
Energy [GeV]
450urad
310urad
1
10^-1
10^-2
10^-3
10^-4
10^-5

Inelasticity

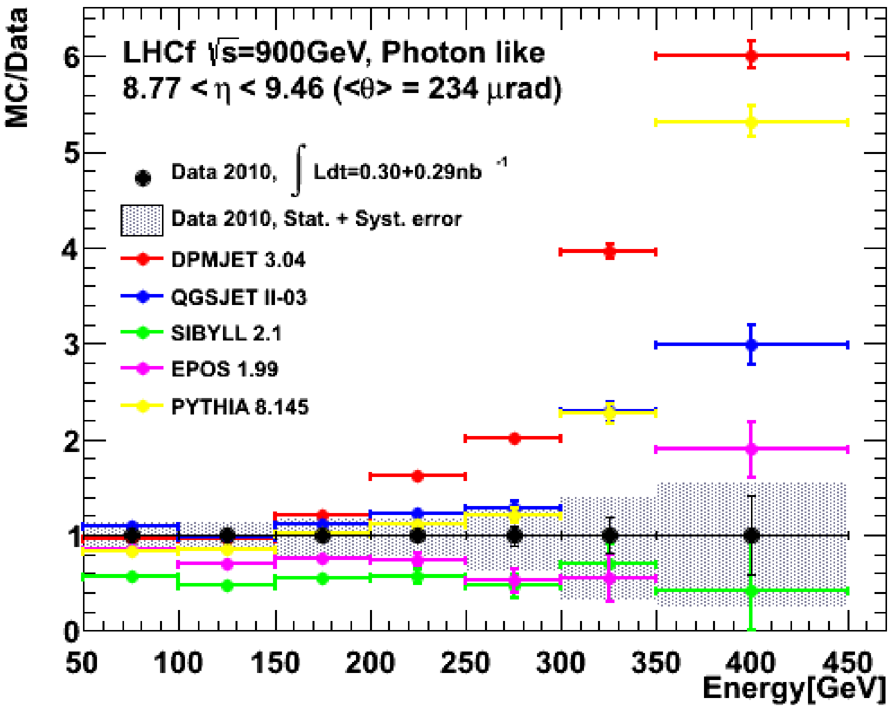


LHCf forward spectra: Data/MC

High η

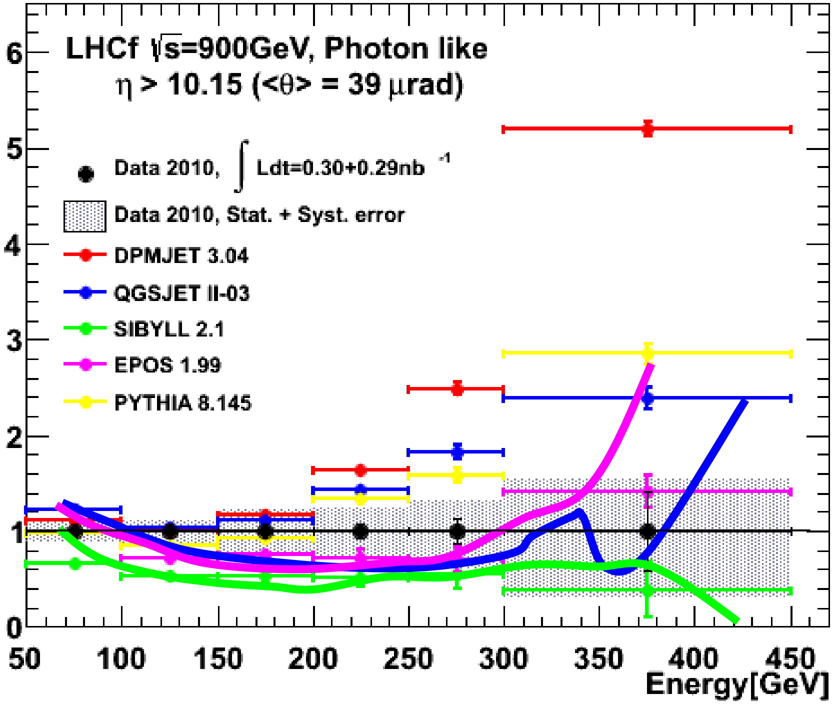


low η

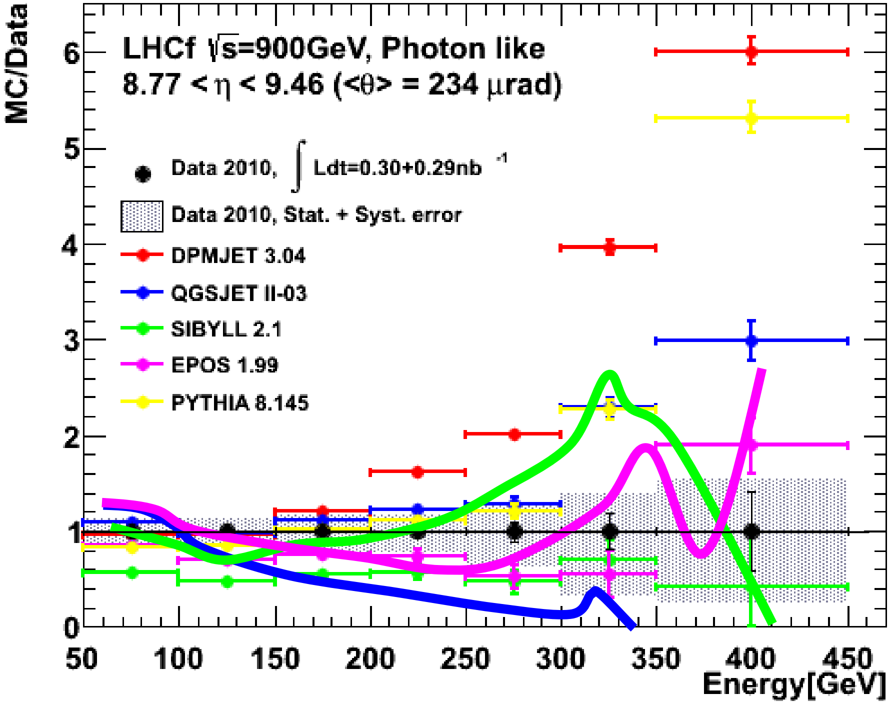


LHCf forward spectra: Data/MC

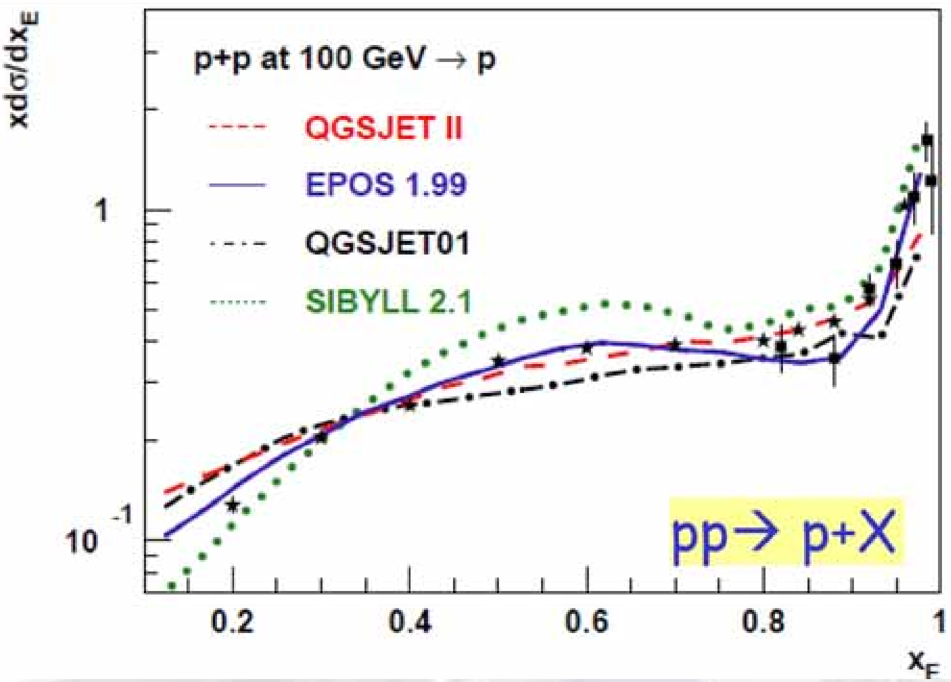
High η

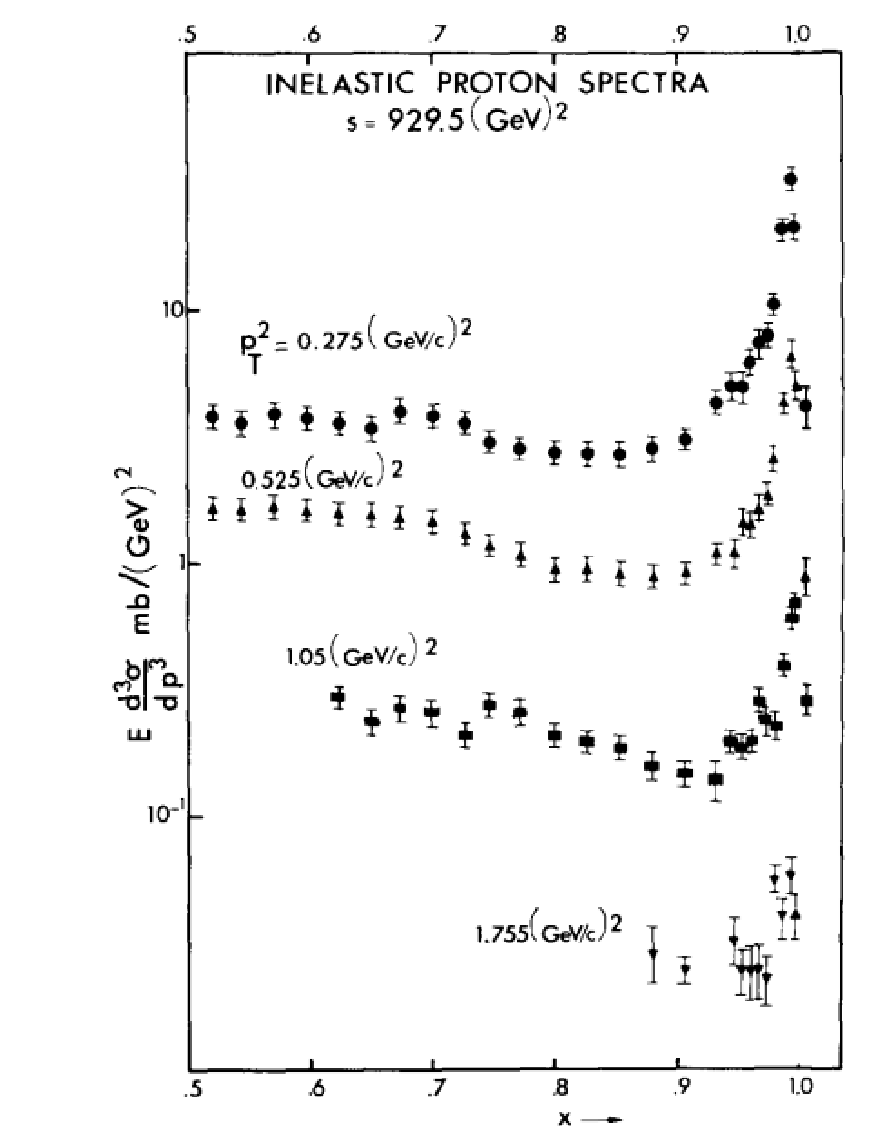


low η

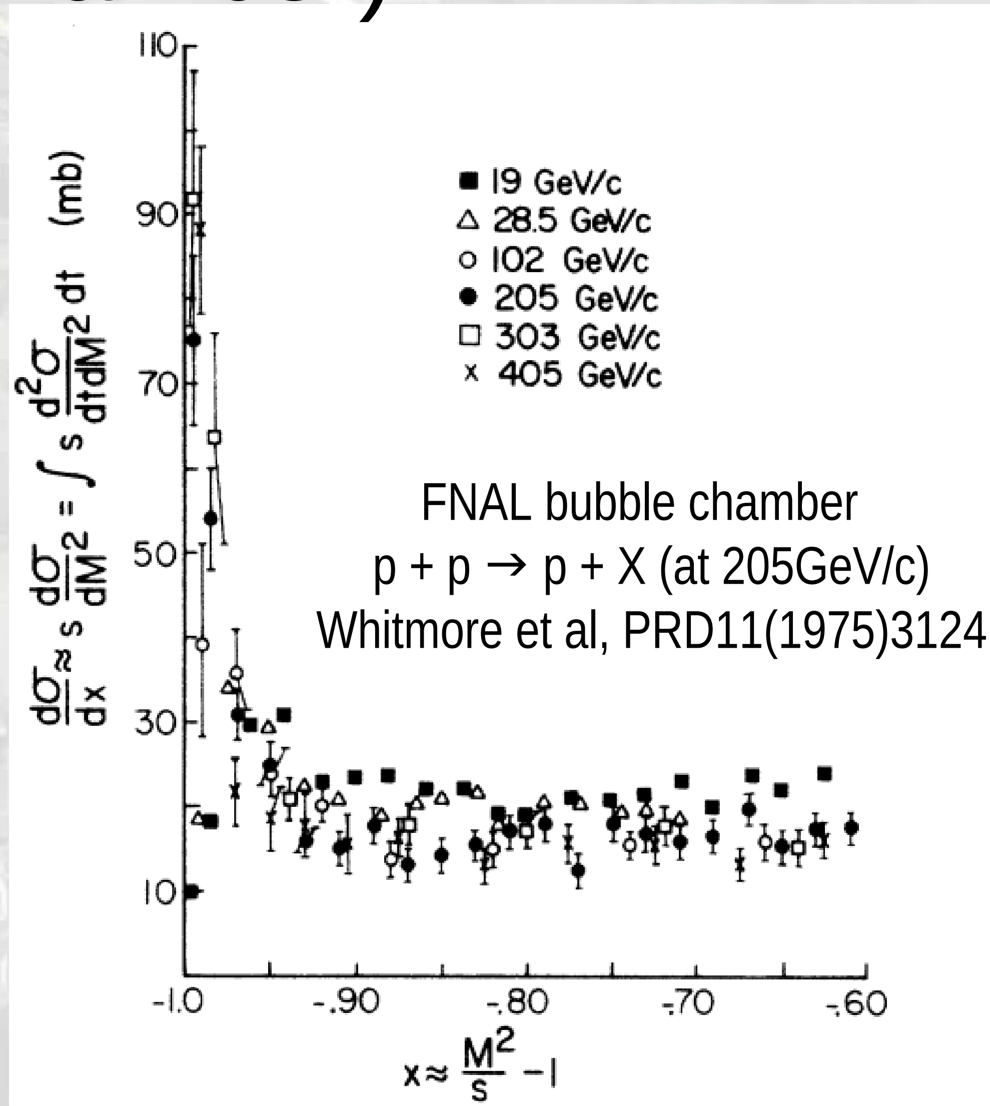


Elasticity (X_F of leading baryon)





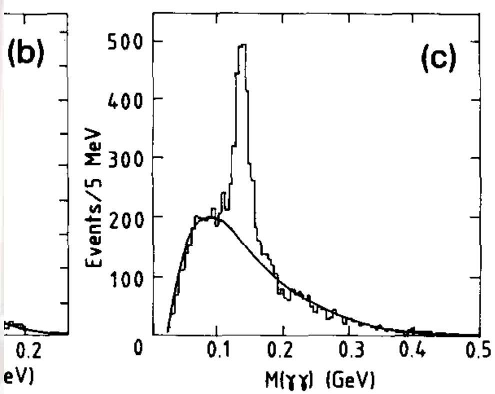
p+p → p+X at P_{beam}= 205GeV (FNAL bubble chamber)



UA7 vs. PYTHIA8

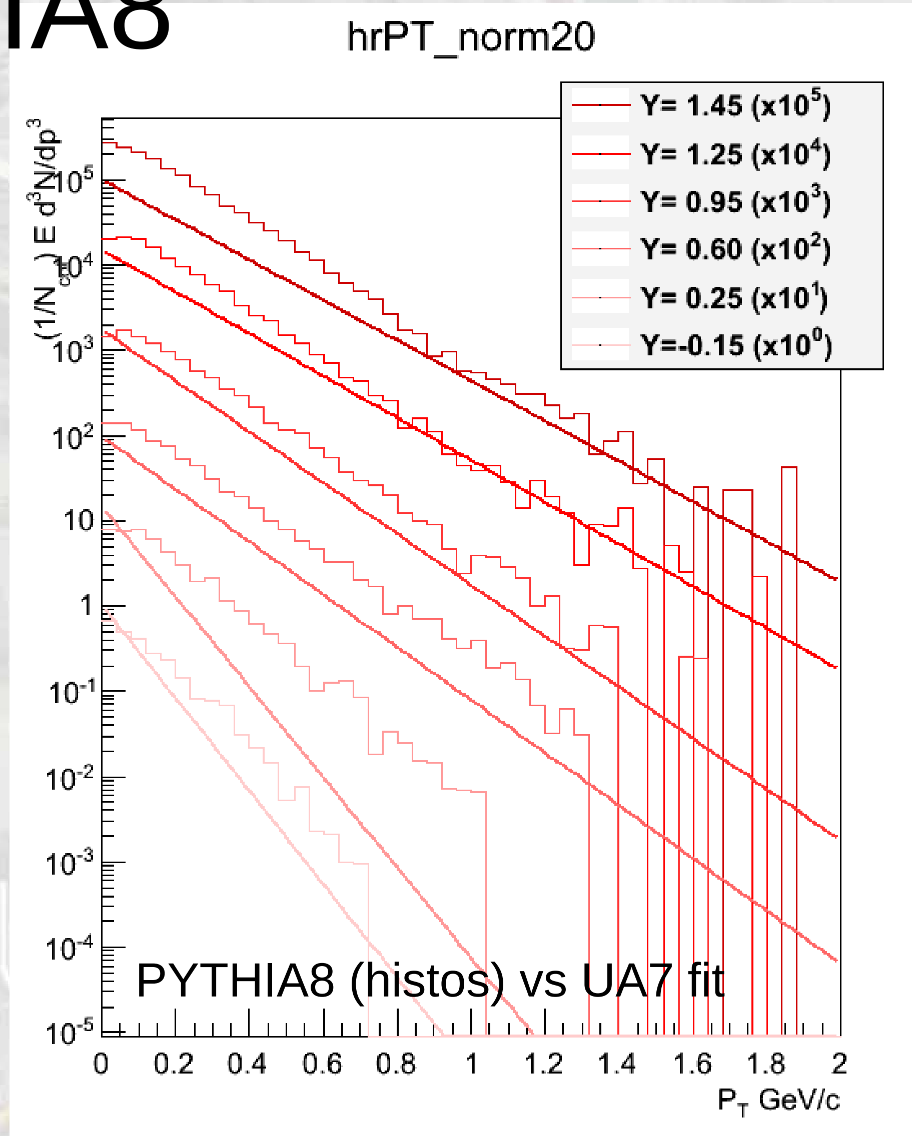
Pare et al.

ETTERS B 14 June 1990



calorimeter no. 1, (b) a pair in the same 4″ calorimeter no. 2, (c) d photon in the 4″ calorimeter no. 2. The lines correspond to the

total cross section measurement [11]. The value $\langle p_t \rangle_0 = 400$ MeV/c has been taken from the UA2 measurement at $Y_{lab} = 6.3$ [2].



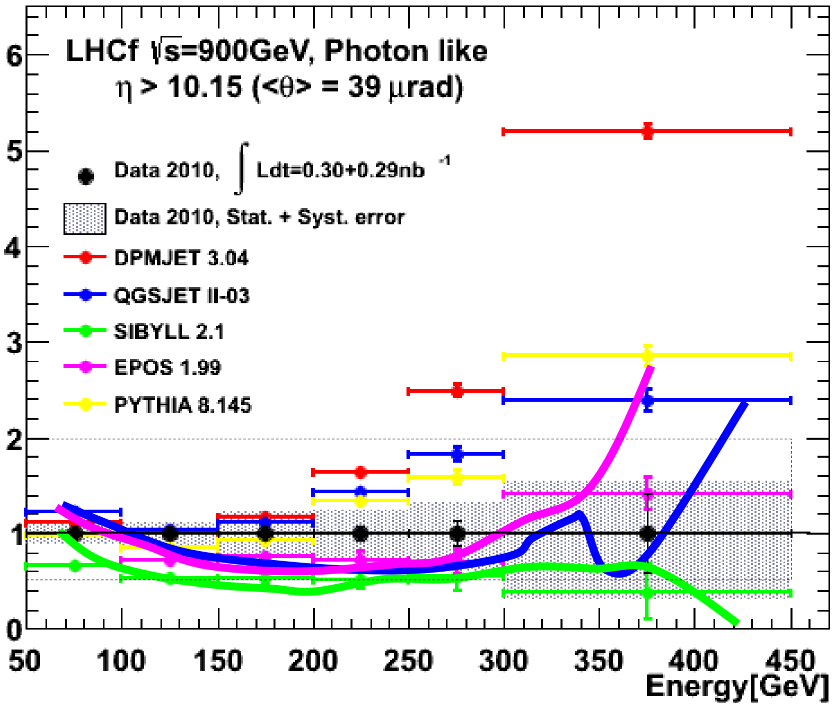
PYTHIA8 does not reproduce UA7

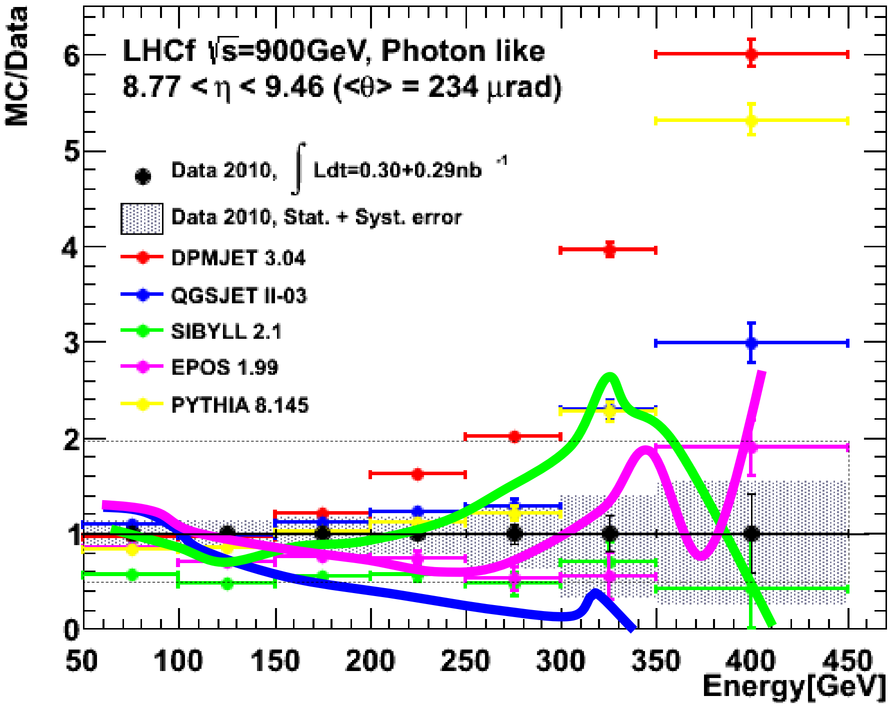
Can we confirm/update/improve UA7?

LHCf forward spectra: Data/MC

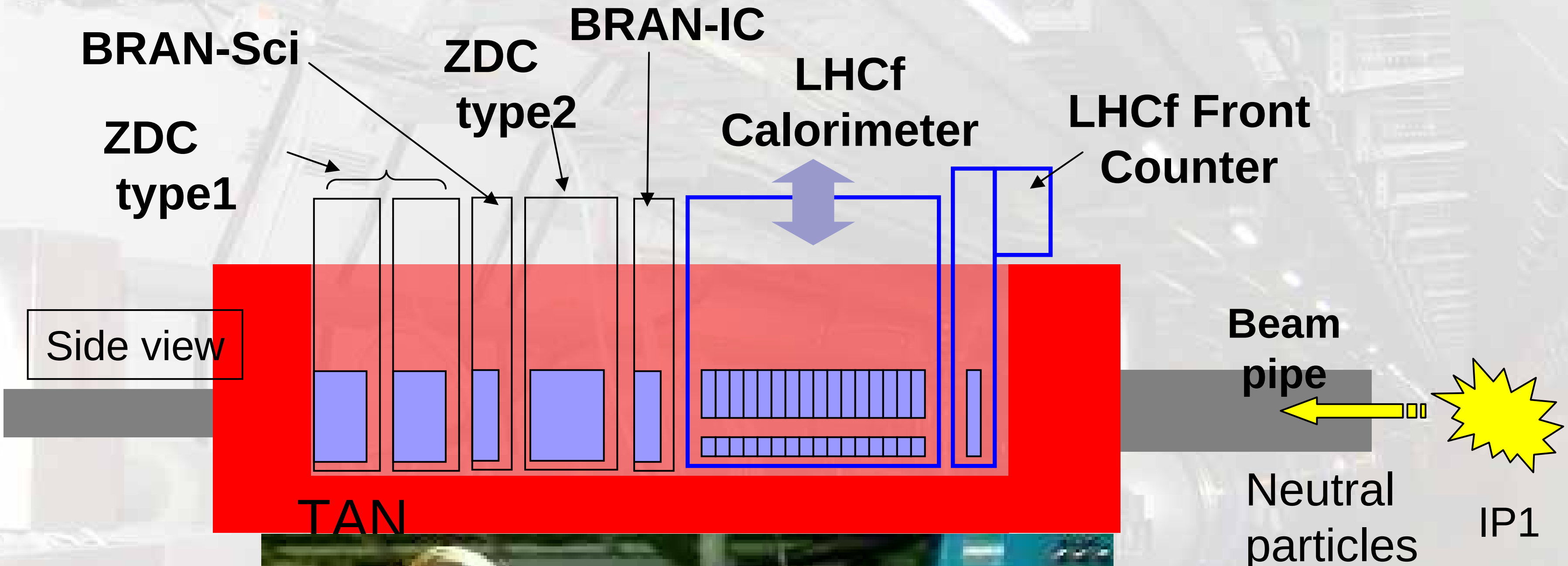
High η

low η

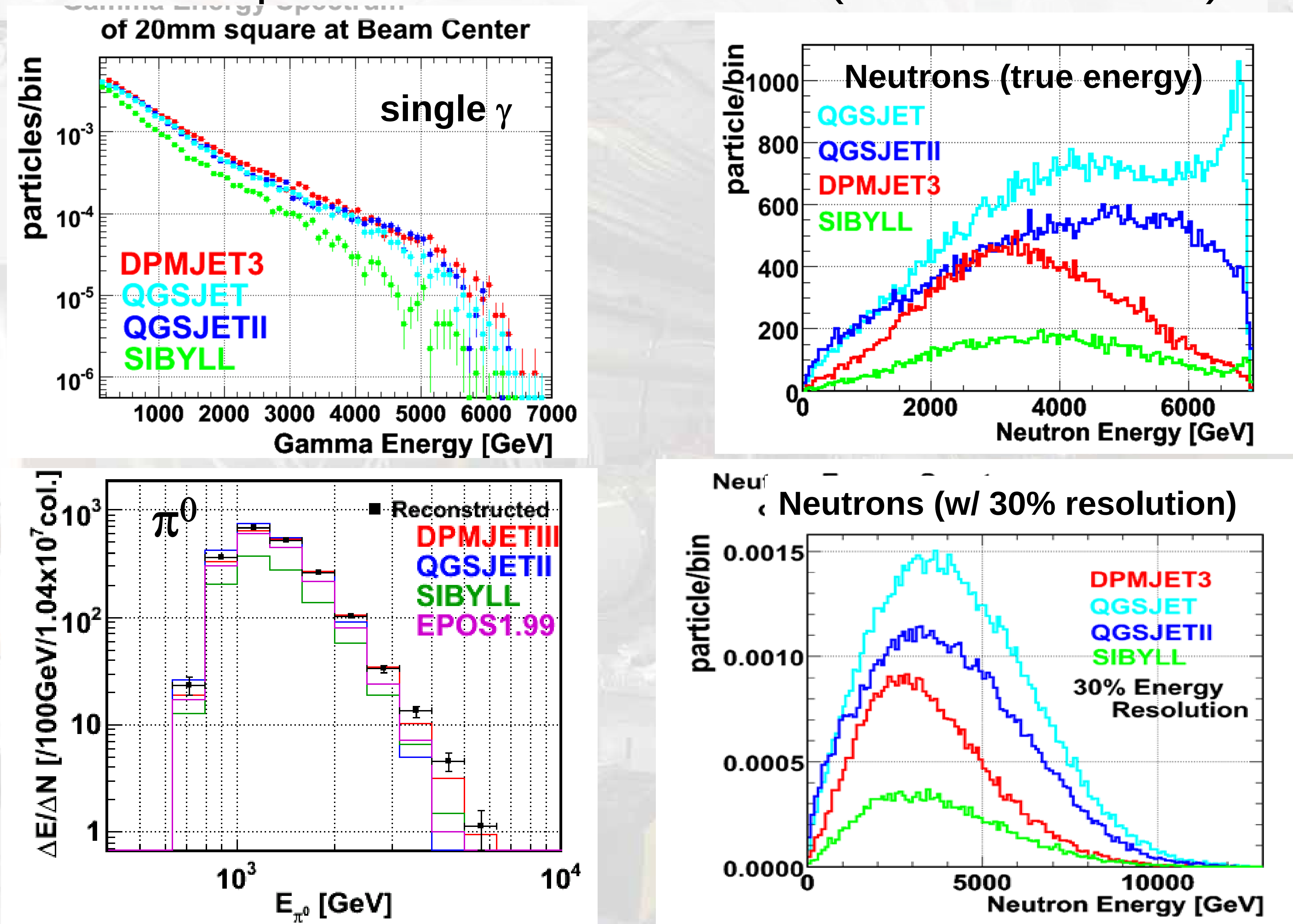




Setup in IP1-TAN (side view)



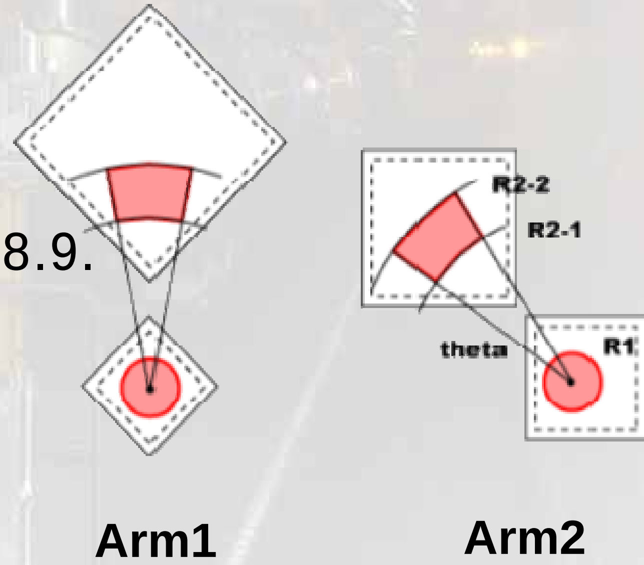
Forward E spectra forseen at 14TeV (MC for ~$0.1 nb^{-1}$)



The single photon energy spectra at 0 degree

(O.Adriani et al., PLB**703 (2011) 128-134**

- DATA
  - 15 May 2010 17:45-21:23, at Low Luminosity $6x10^{28}cm^{-2}s^{-1}$, no beam crossing angle
  - 0.68 nb-1 for Arm1, 0.53nb-1 for Arm2
- MC
  - DPMJET3.04, QGSJETII03, SYBILL2.1, EPOS1.99 PYTHIA 8.145 with the default parameters.
  - 10^7 inelastic p-p collisions by each model.
- Analysis
  - Two pseudo-rapidity, η >10.94 and 8.81< η <8.9.
  - No correction for geometrical acceptance.
  - Combine spectra between Arm1 and Arm2.
  - **Normalized by number of inelastic collisions** with assumption as σ_{inela} = 71.5mb. (c.f. $73.5 \pm 0.6 ^{+1.8}_{-1.3}$ mb by TOTEM)

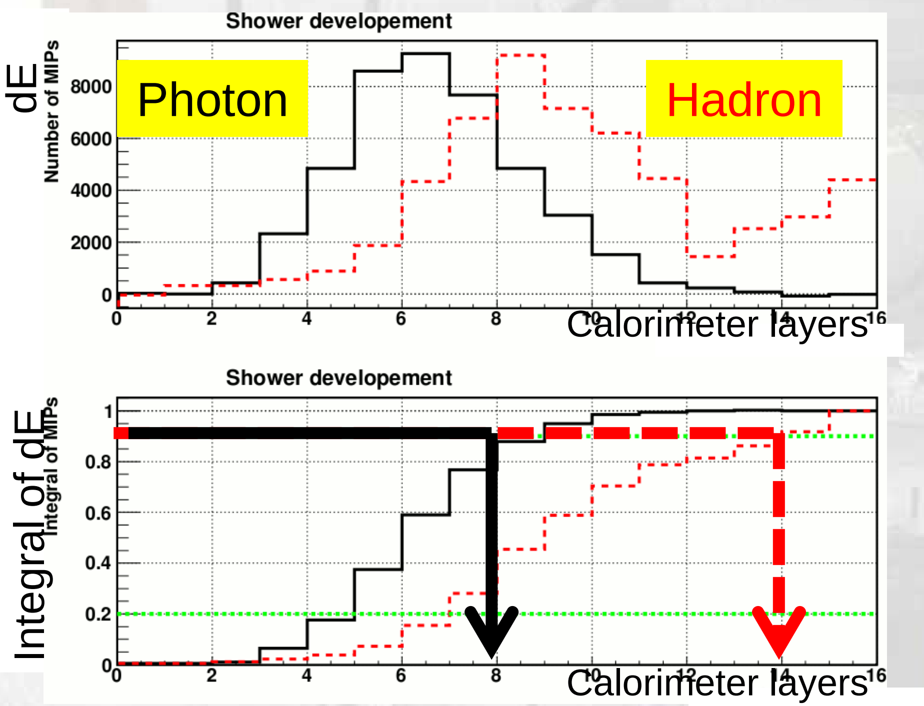


Particle Identification

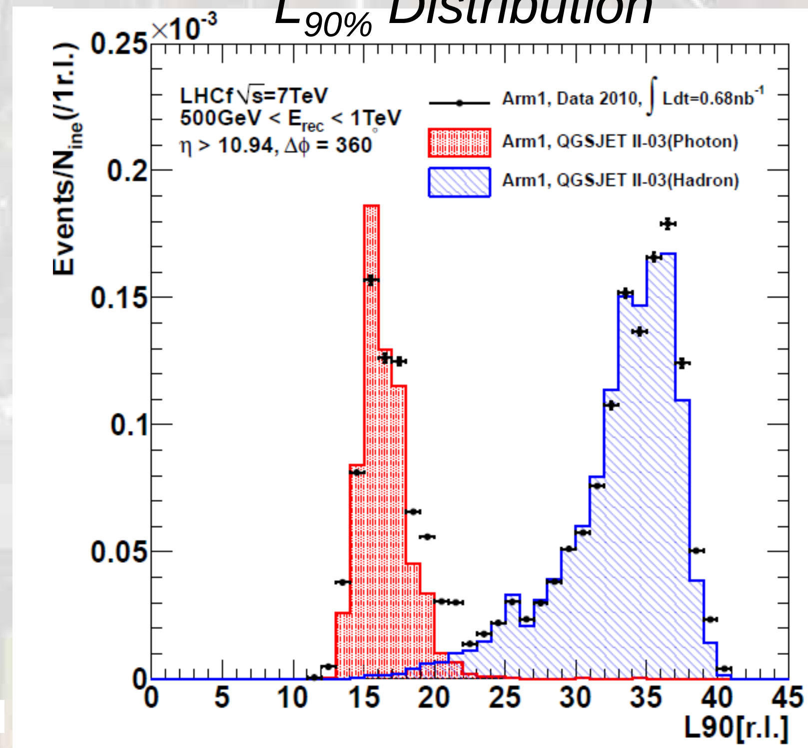
Calorimeter Depth

Elemag: 44r.l.
Hadronic: 1.7 λ

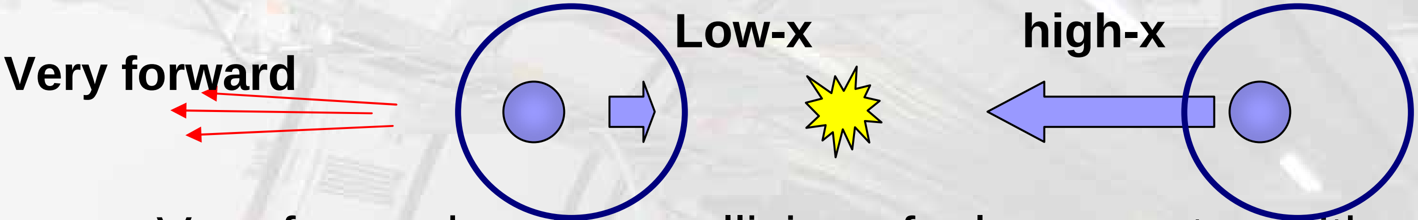
- Event selection and correction
  - Select events <$L_{90\%}$ threshold and multiply P/ **ε**
    ε (photon detection efficiency) and P (photon purity)
  - By normalizing MC template $L_{90\%}$ to data,
    ε and P for certain $L_{90\%}$ threshold are determined.



$L_{90\%}$ Distribution



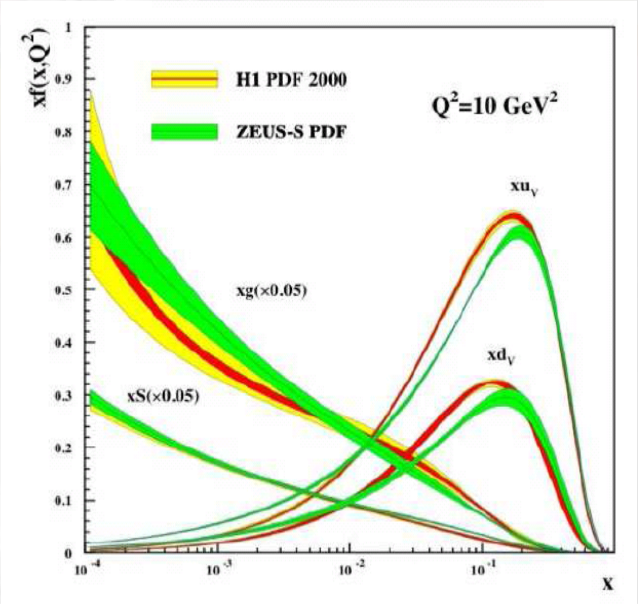
Very forward – connection to low-x physics



- Very forward region : collision of a low-x parton with a large-x parton
- Small-x gluon become dominating in higher energy collision by self interaction.
- But they may be saturated (Color Glass Condenstation)

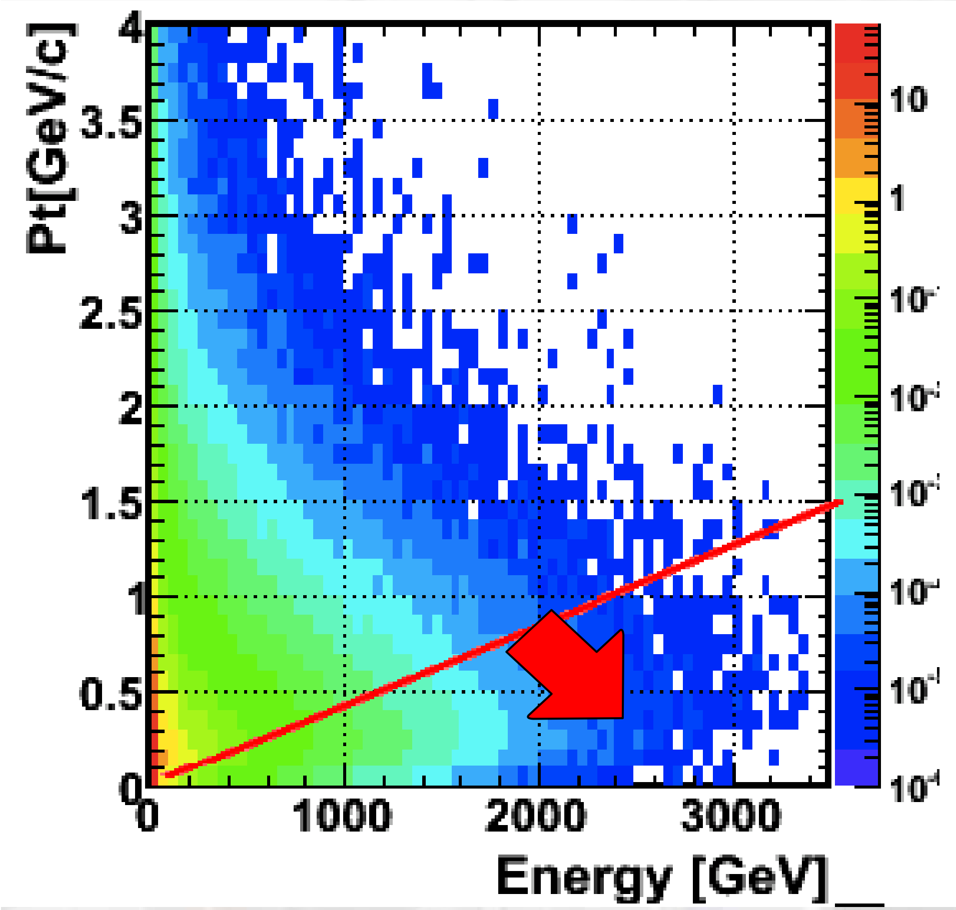
Naively CGC-like suppression may occur in very forward at high energy

→ **However situation is more complex**
(not simple hard parton collsions,
but including soft + semi-hard)

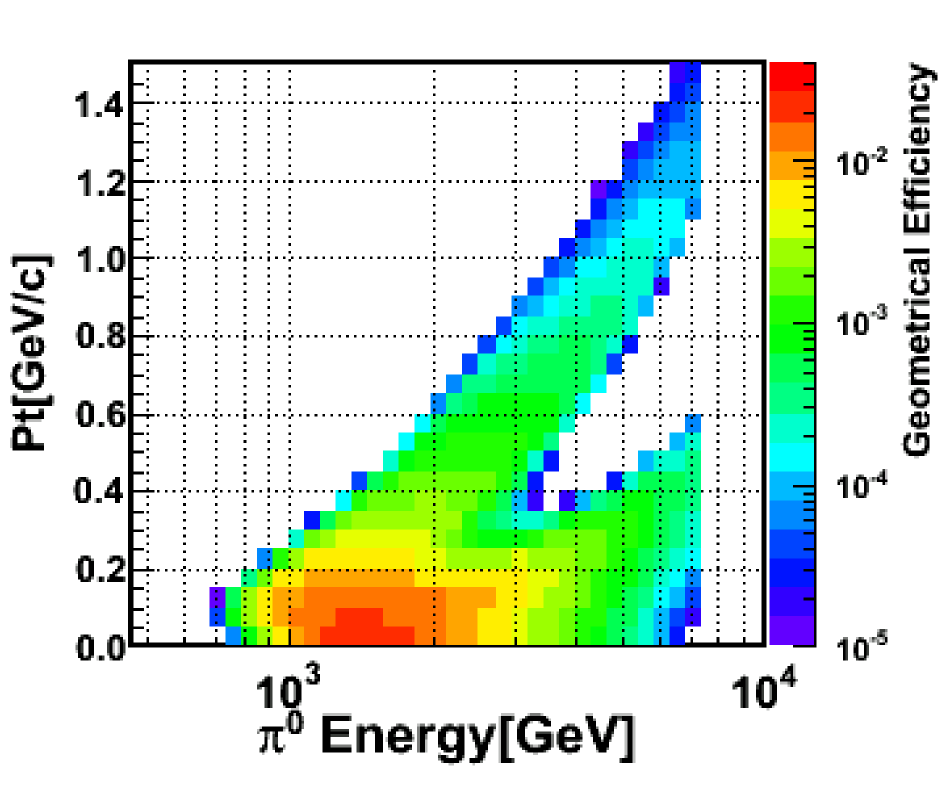


What P_T range LHCf sees ?

γ

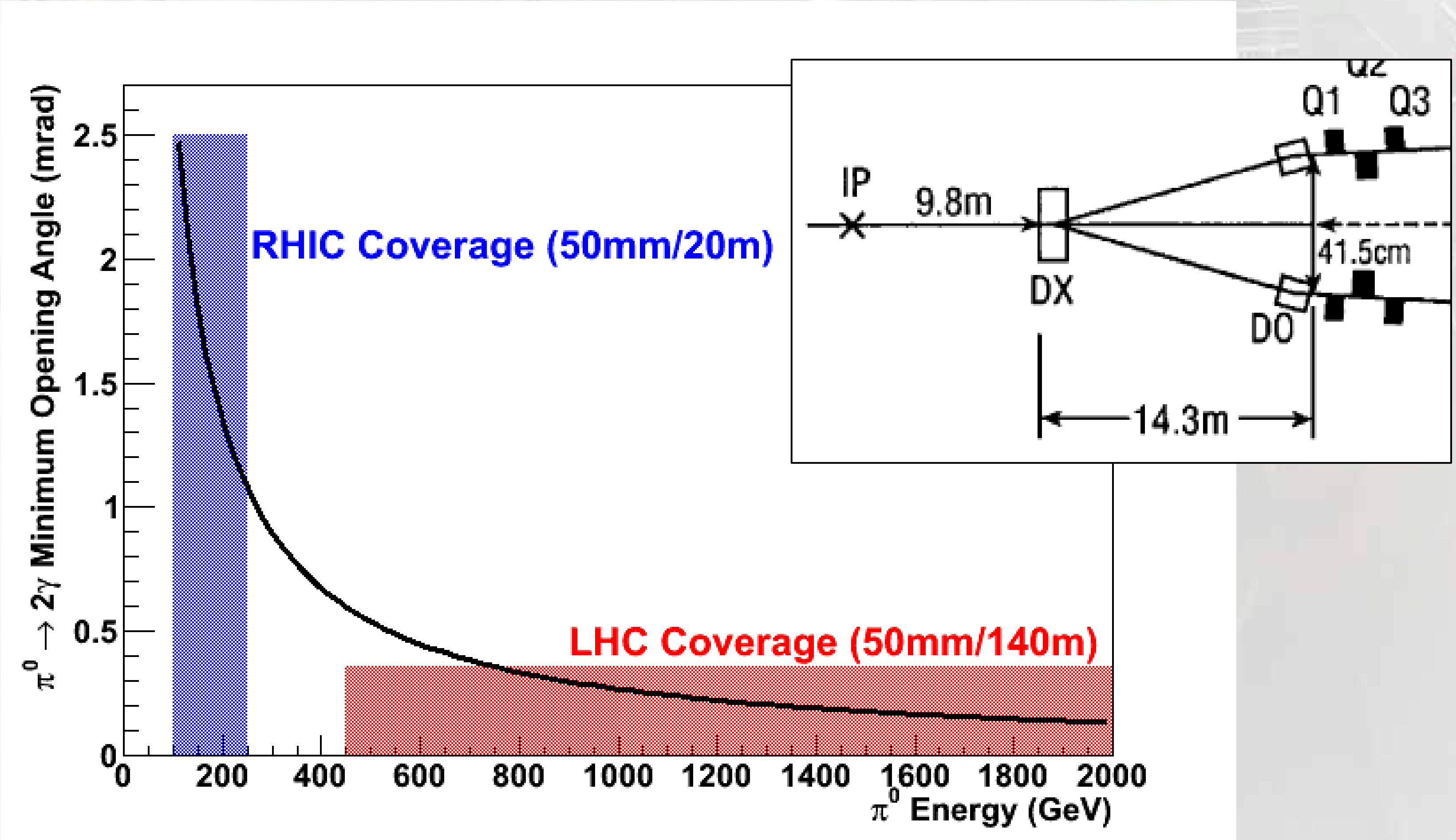


π^0



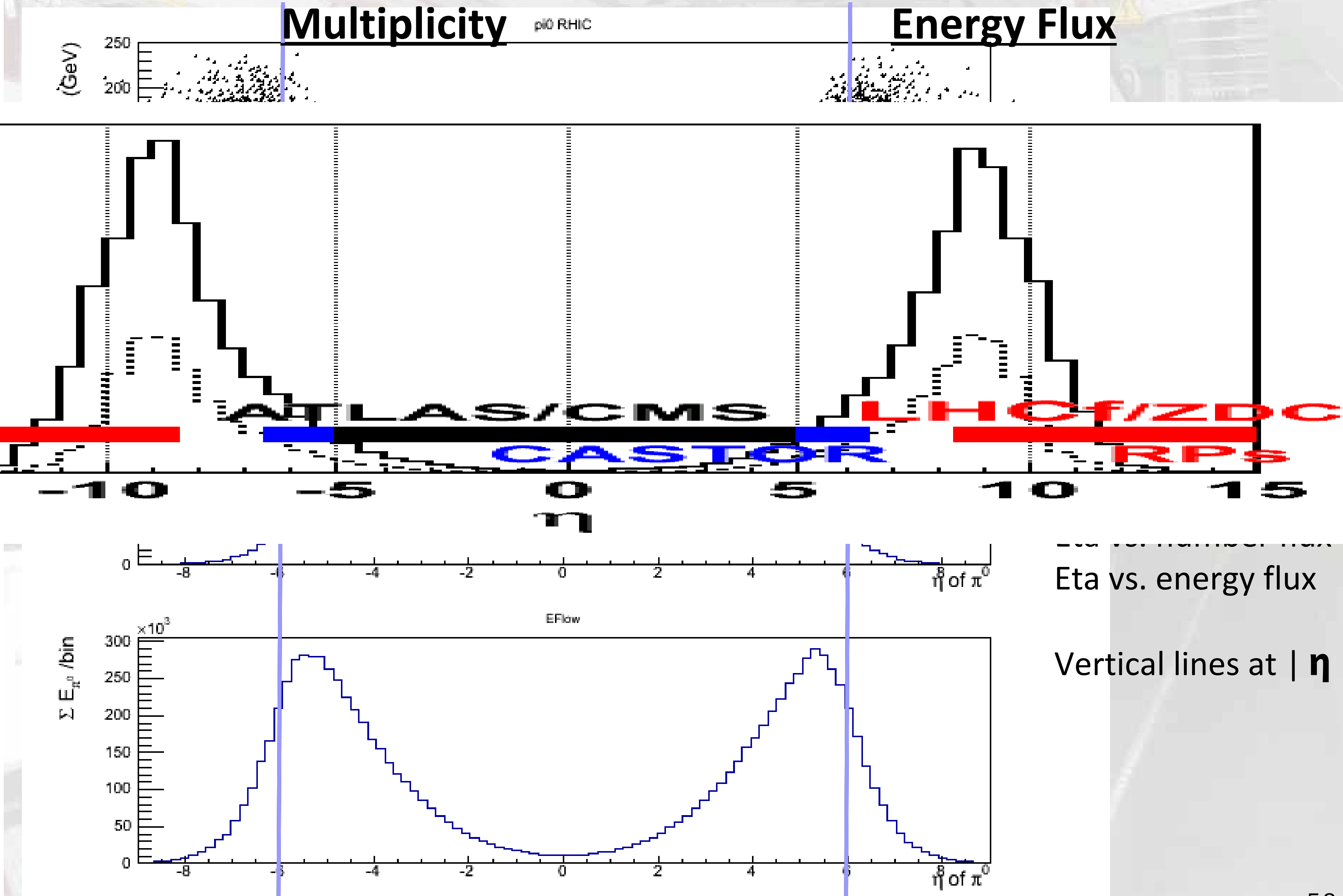
pp 7TeV, EPOS

RHIC: π^0 at $\sqrt{s}$ =500GeV



- ✓ **ZDC space at PHENIX (by Goto-san):**
  10cm radius beam pipe aperture at 18m => η >5.9

Pi0 in 500GeV p-p collisions by PYTHIA8



Eta vs. number flux

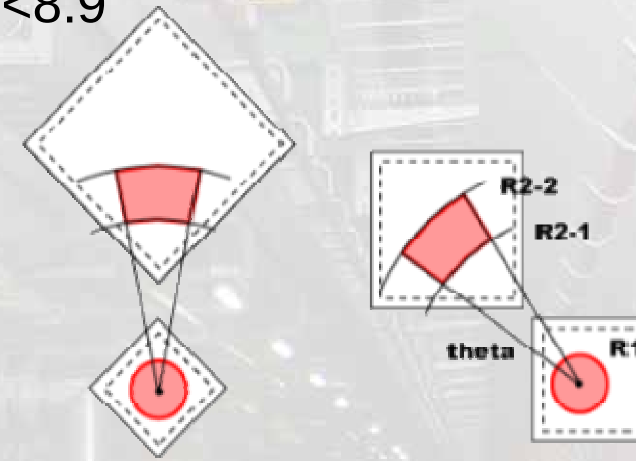
Eta vs. energy flux

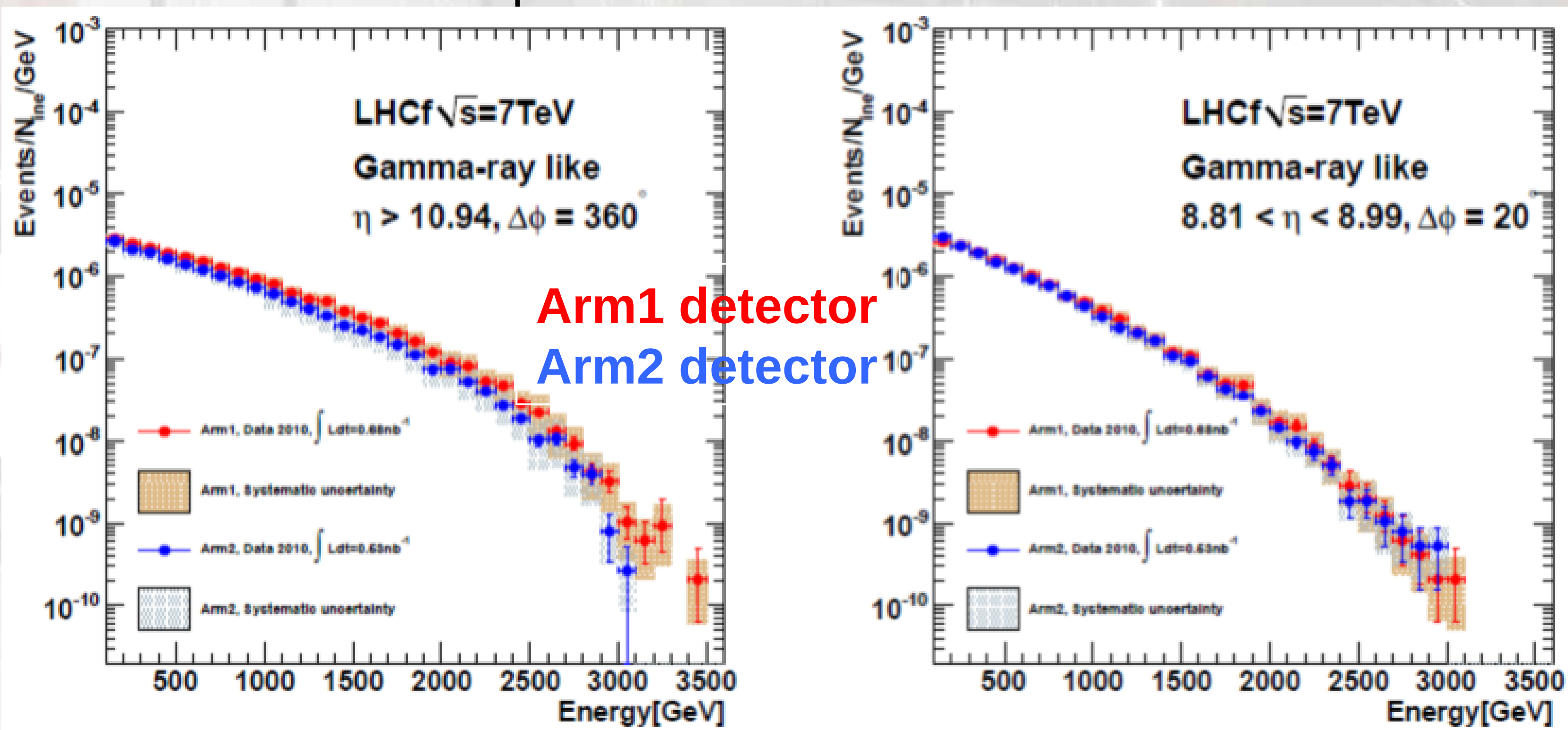
Vertical lines at | **η** |=6

Comparison between the two detector

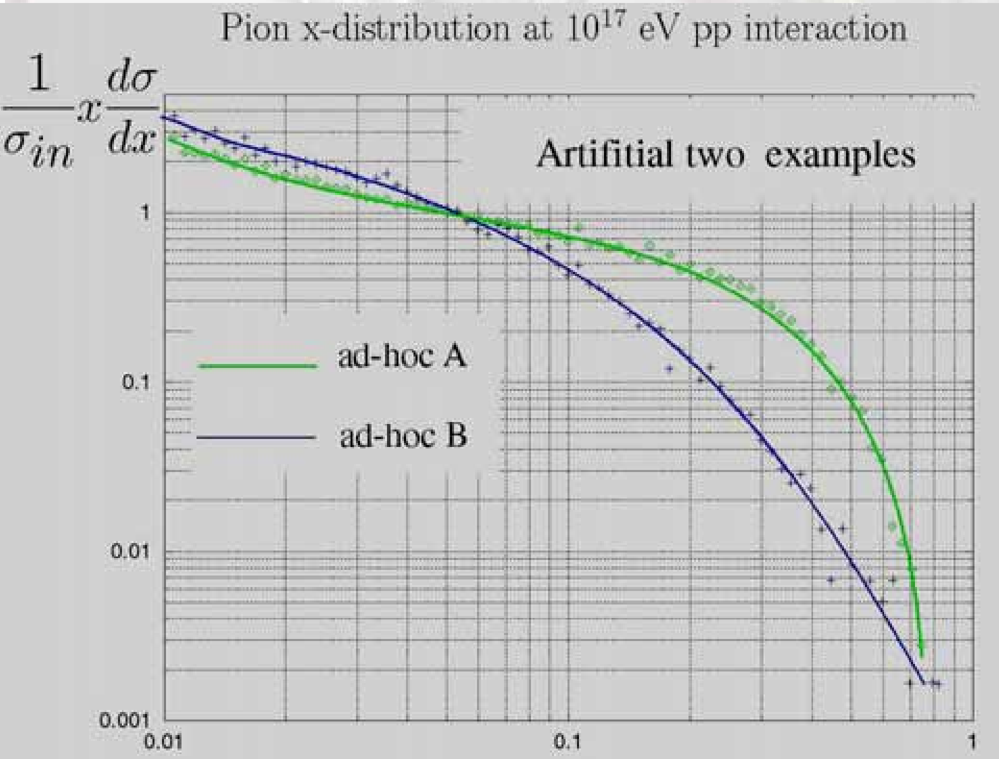
- Pseudo-rapidity selection, η >10.94 and 8.81< η <8.9
- Normalized by number of inelastic collisions with assumption as σ_{inela} = 71.5mb (<->73.5±0.6 $^{+1.8}_{-1.3}$ mb by TOTEM)
- Spectra in the two detectors are consistent within errors.

➔ Combined between spectra of Arm1 and Arm2

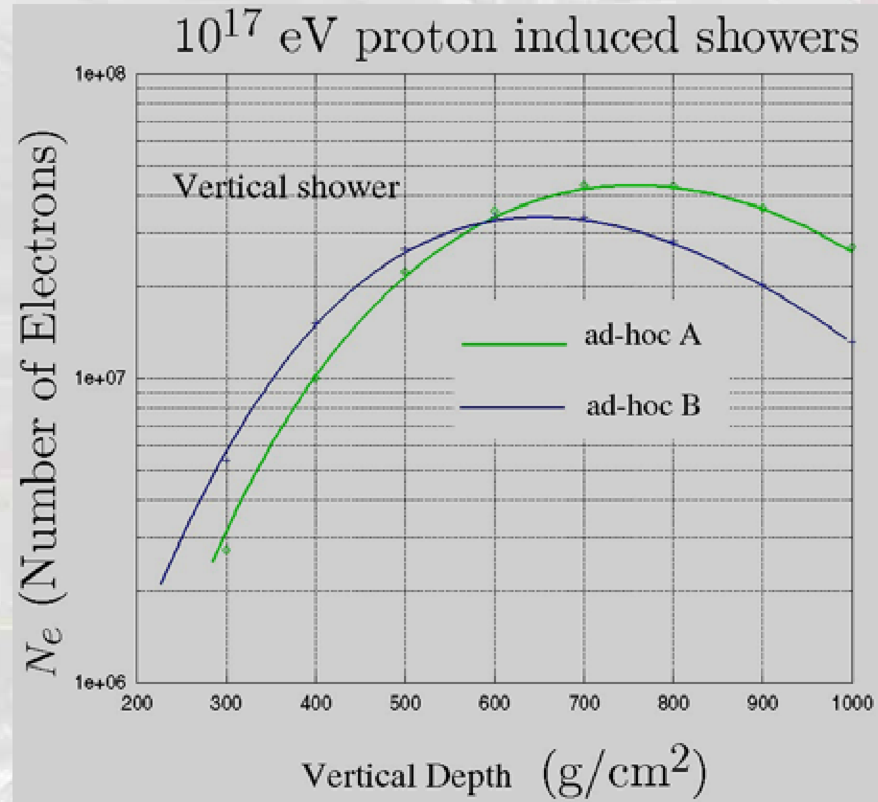




Forward production spectra vs Shower curve



X_F = E/Etot

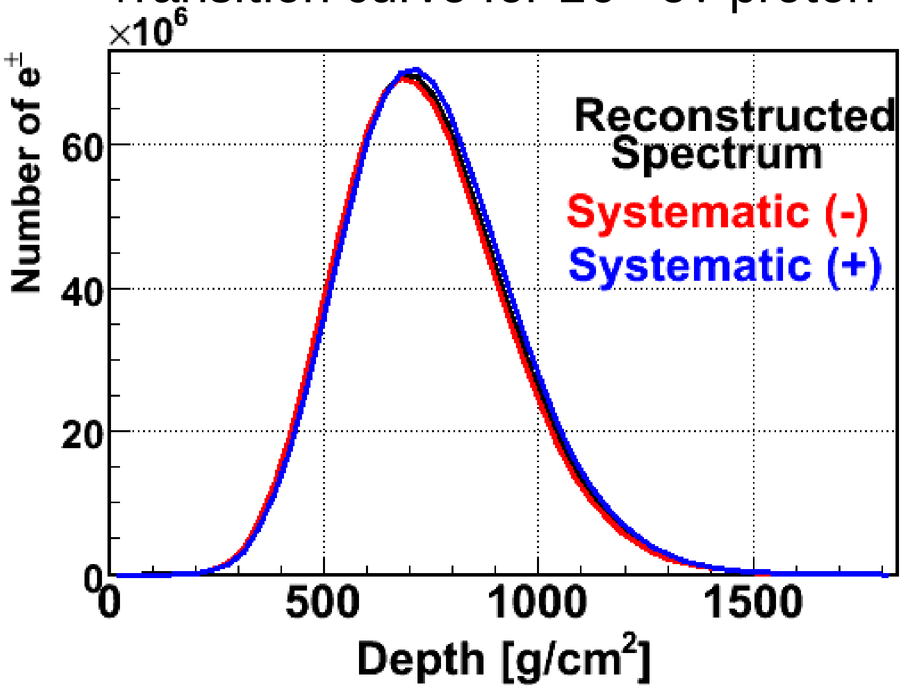


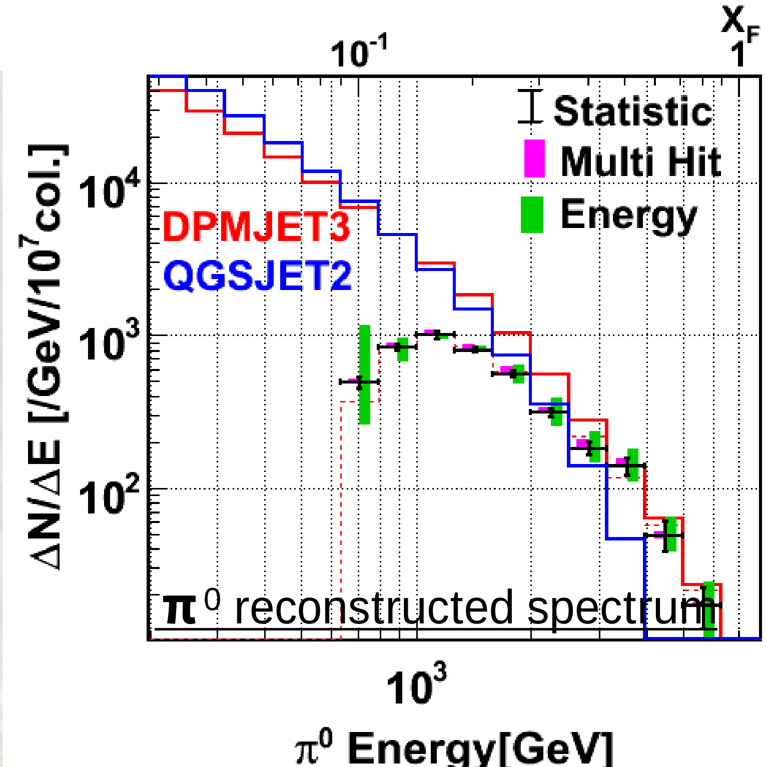
Half of shower particles comes from large X_F γ

Measurement at very forward region is needed

O N C R P H Y

Transition curve for 10^{17}eV proton





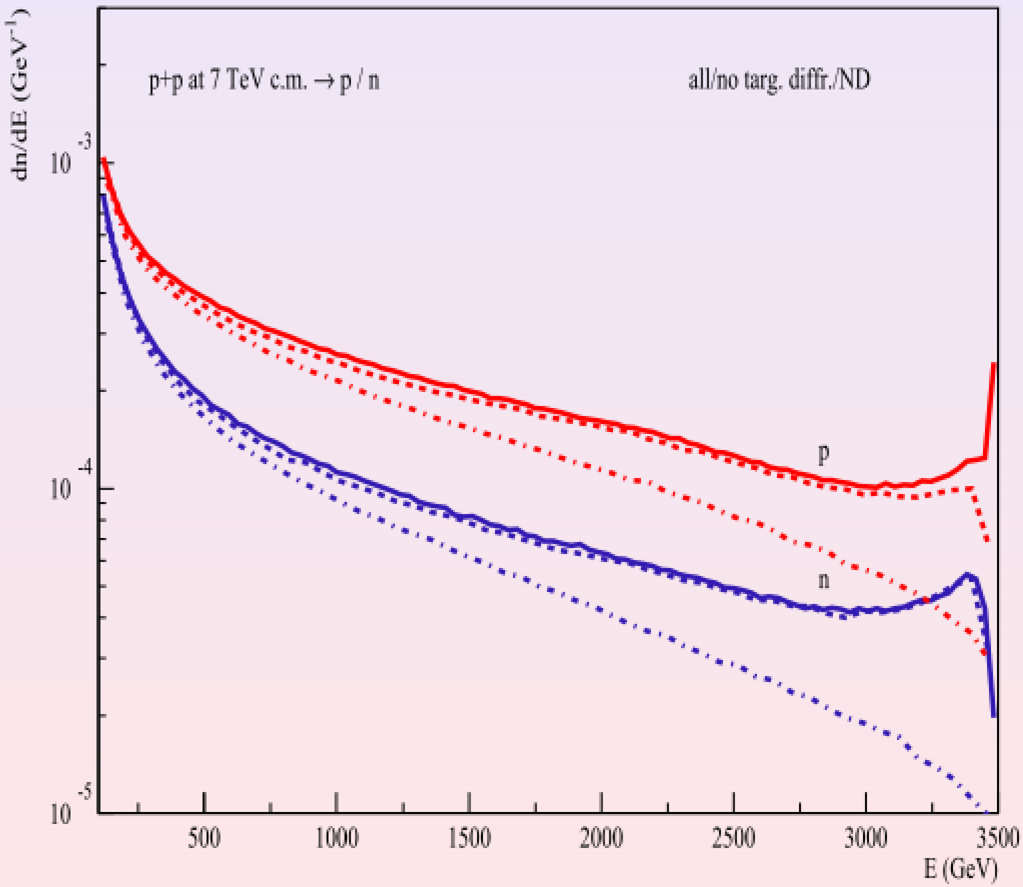
X_{max} = 696.6g/cm^2 ± 2.3 +15.9, -7.8 g/cm^2

statistical systematic

⇔ ΔX_{max} (DPMJET**III**-QGSJET **II**) = 36g/cm^2

Main strength of LHCf – measurements of baryon 'stopping power' ('inelasticity' $K_{\rm inel}$)

- $K_{\rm inel}$ – crucial for studies of UHECR composition: direct impact on air shower $X_{\rm max}$ (along with $\sigma^{\rm inel}_{p-{\rm air}}$)



- or for non-diffractive interactions

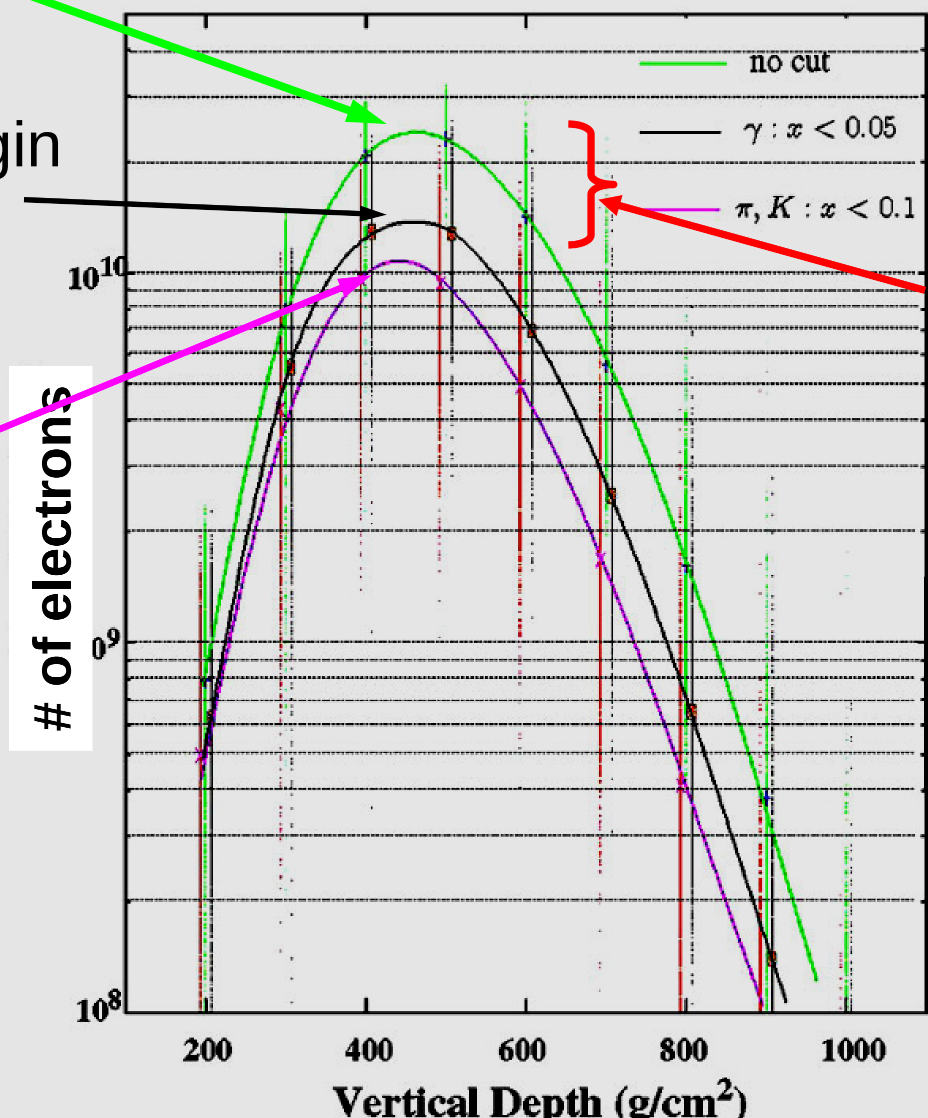
Contribution from very forward production

5×10^{19} eV proton showers
(60 deg zenith)

No cut

low X_F γ origin
(x_F < 0.05)

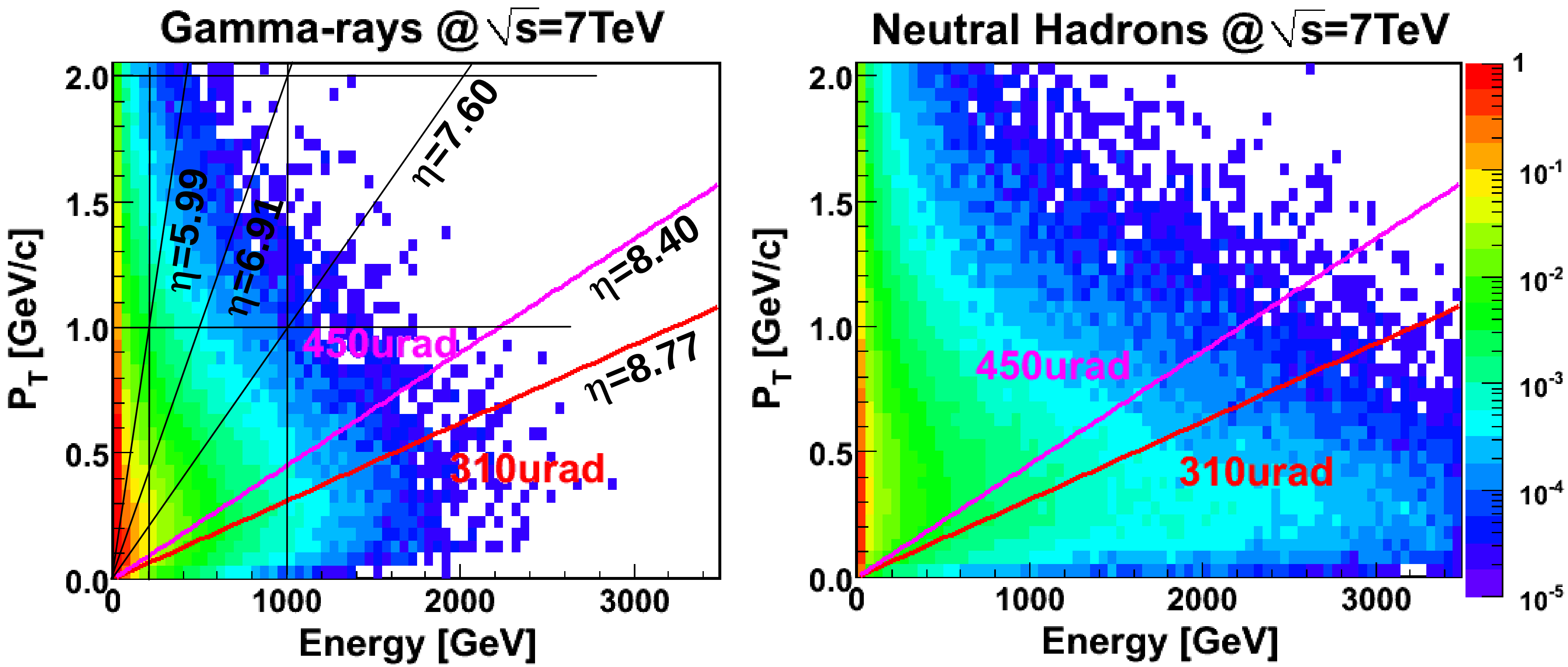
π,K origin
(x_F < 0.1)



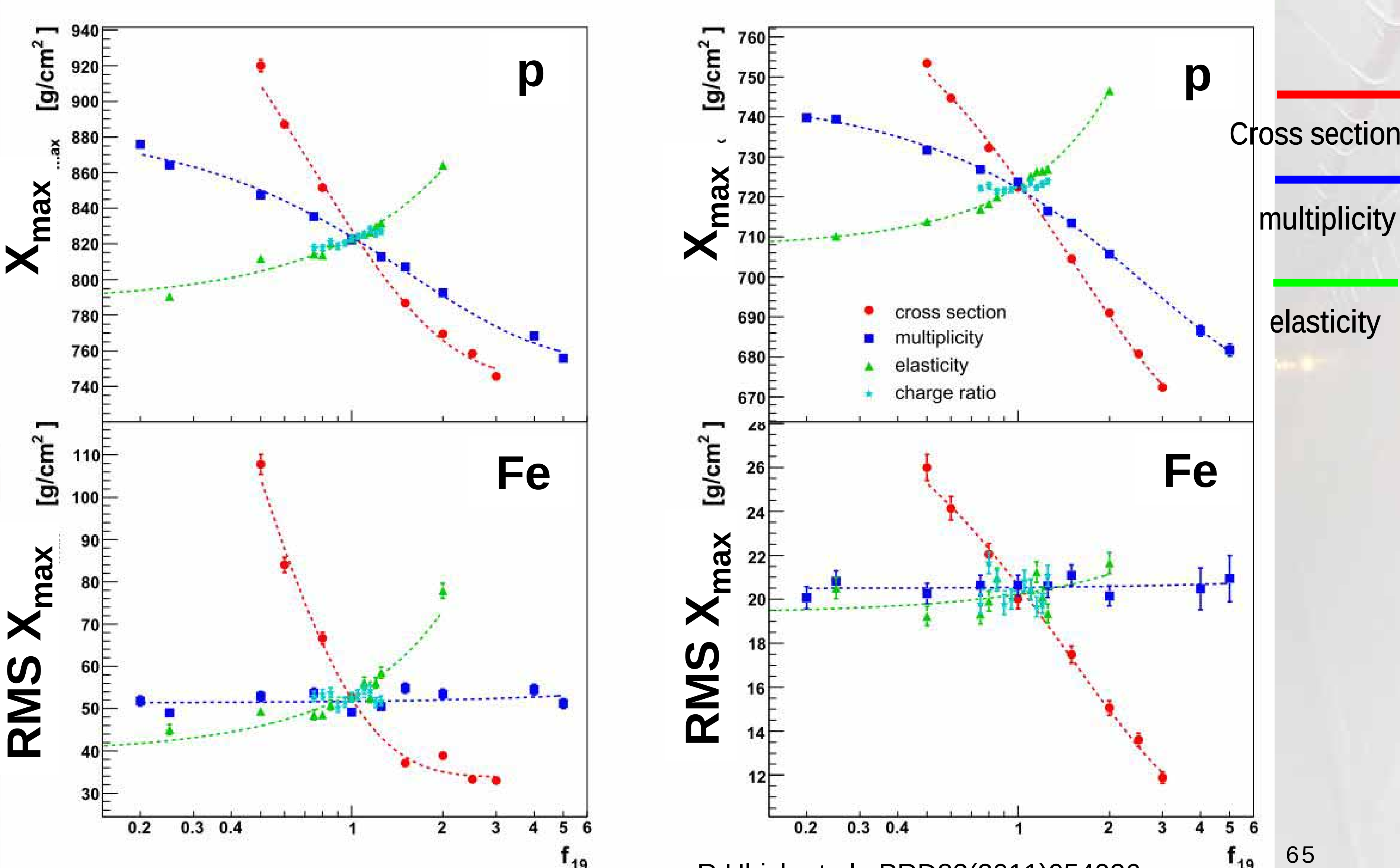
Half of shower particles comes from large X_F γ

Measurement at very forward region is needed

Forward energy spectra



Impact of parameters of interactions



R.Ulrich et al., PRD83(2011)054026

Big LHC detectors