Forward hadron production at the LHC

Yoshitaka Itow

STE Lab / Kobayashi-Maskawa Inst.

Nagoya University

"ISVHECRI 2014"

17-23 Aug, 2014, CERN

STEL

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

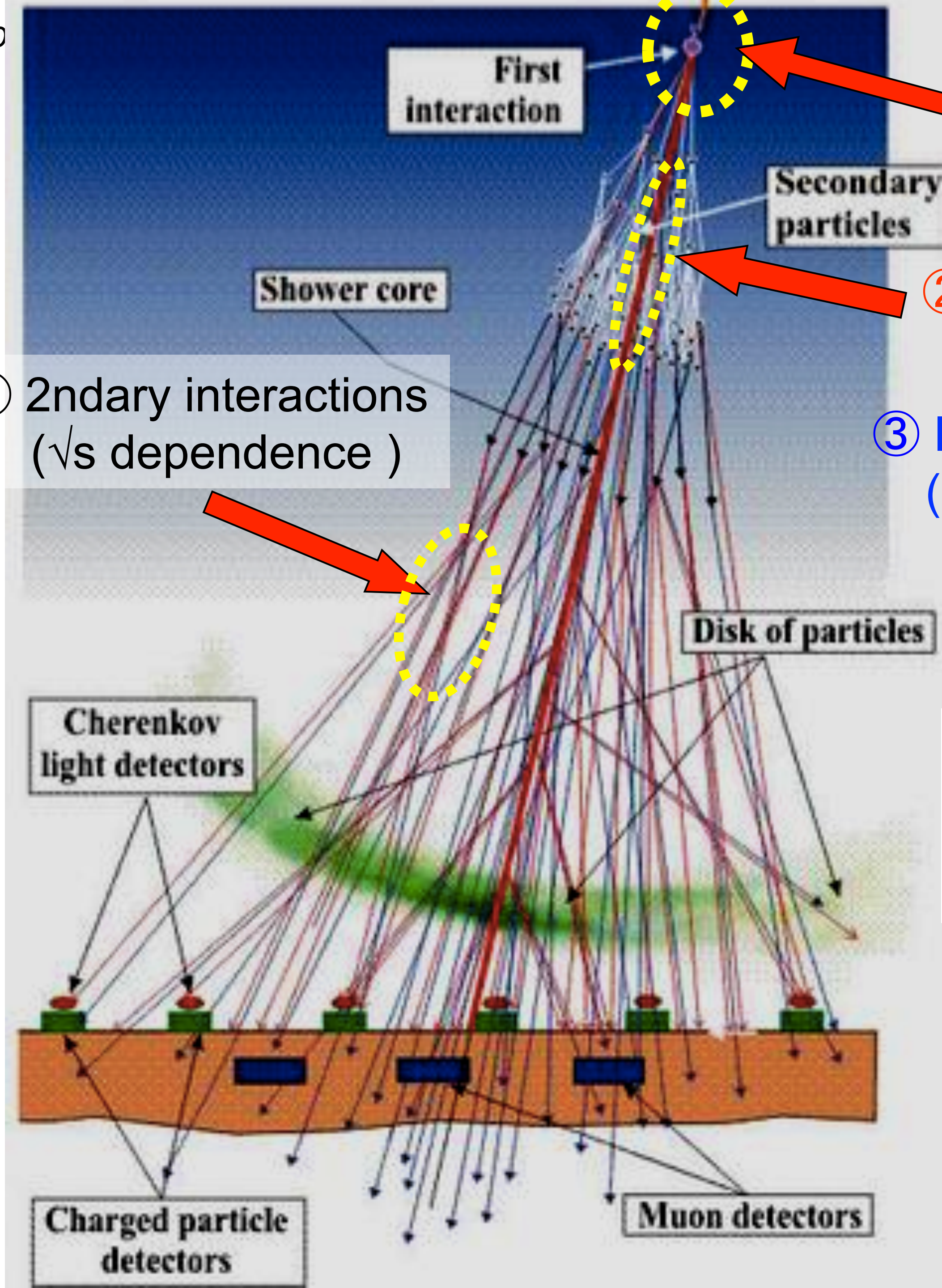
① Inelastic cross section (TOTEM and others)

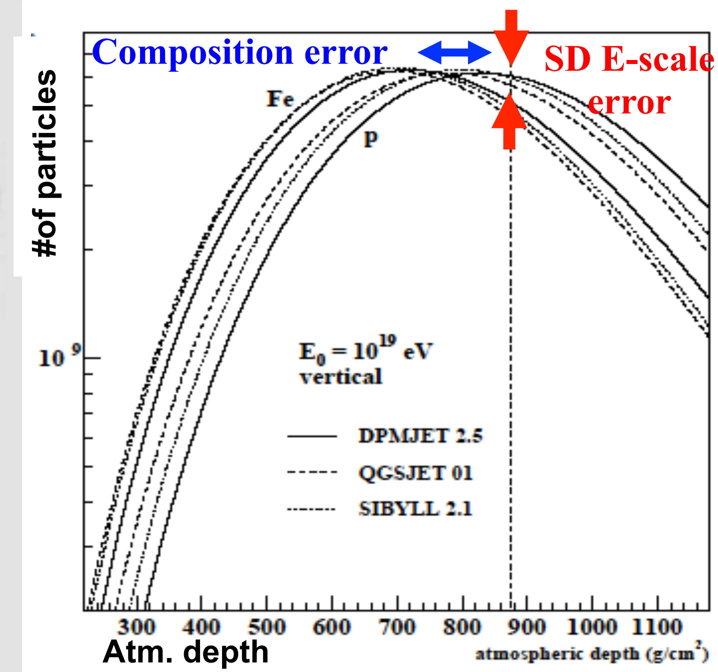
② Forward energy spectrum (γ / π^0 , hadron spectrum)

③ Inelasticity $k = 1 - p_{lead}/p_{beam}$ (leading baryon / γ ratio)

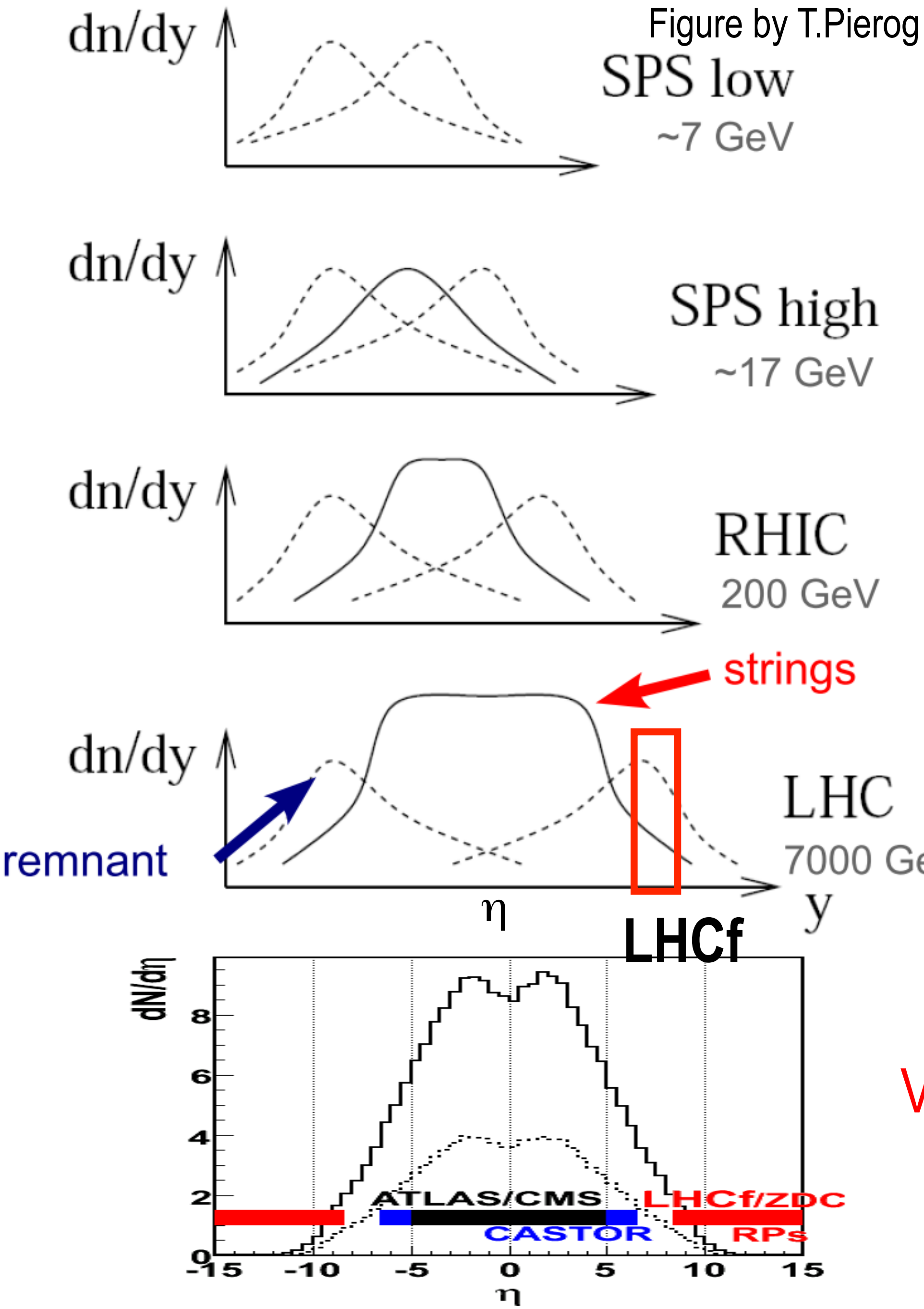
④ Nuclear effect (shadowing, Cronin effect)

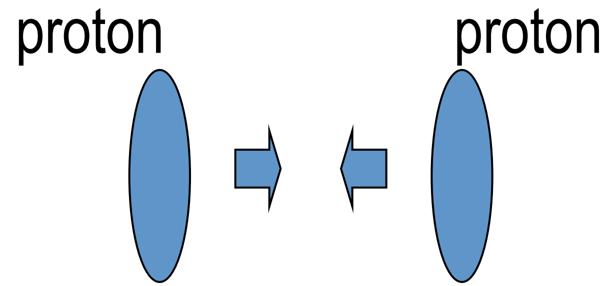
⑤ 2ndary interactions ($\sqrt{s}$ dependence)



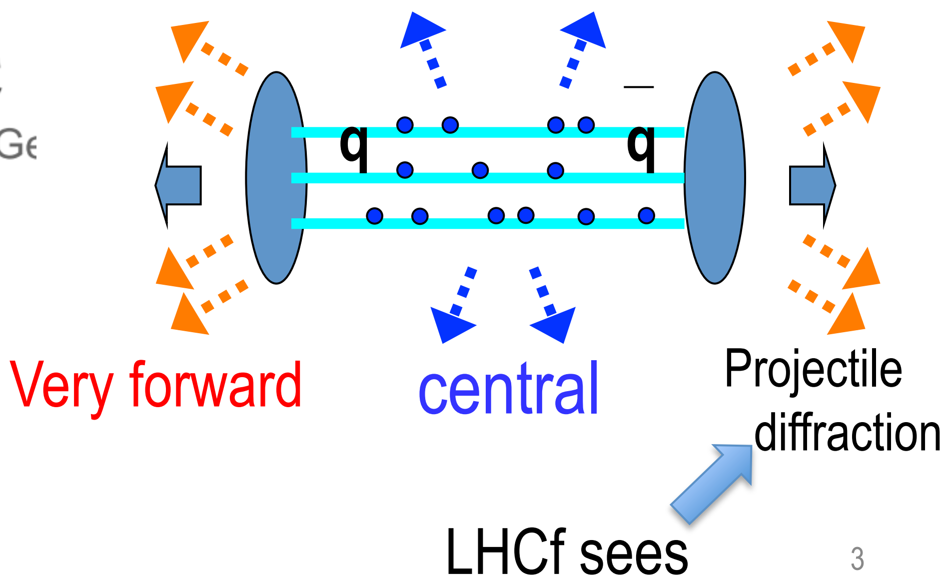


2ndary particle productions

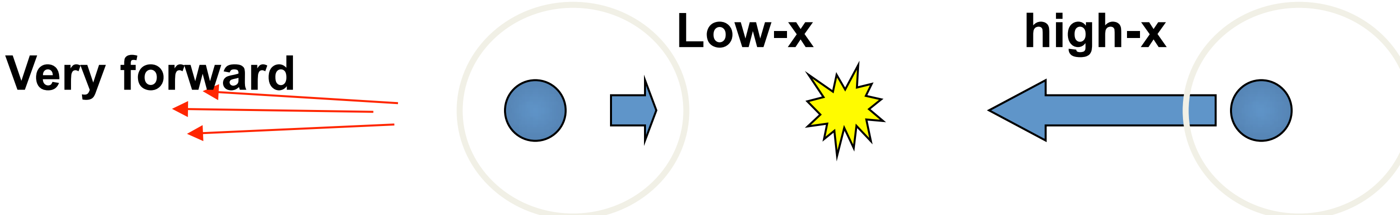




String fragmentation



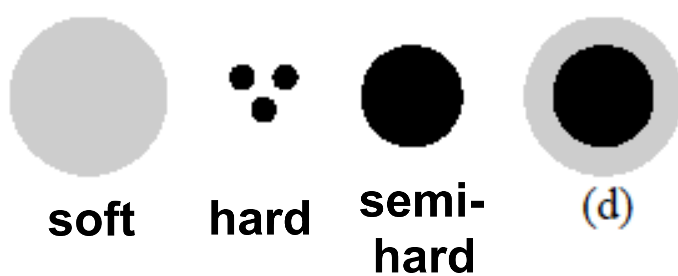
Very forward – connection to low-x physics

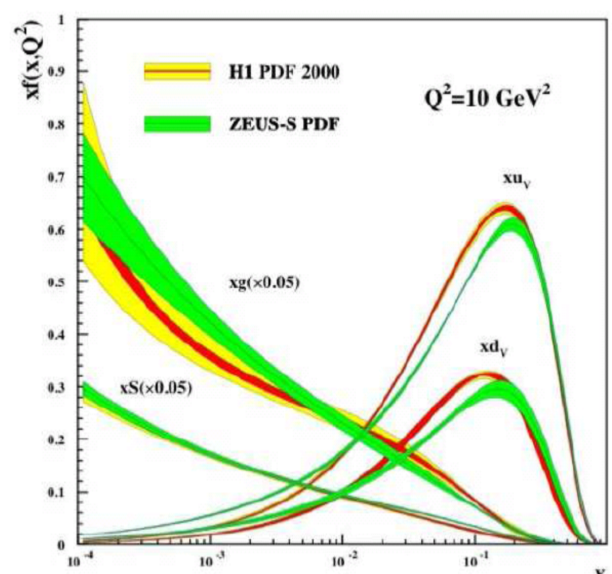


- Very forward region : collision of a low-x parton with a large-x parton
- Small-x gluon become dominating in higher energy collision by self interaction.
- But they may be saturated (Color Glass Condenstation)

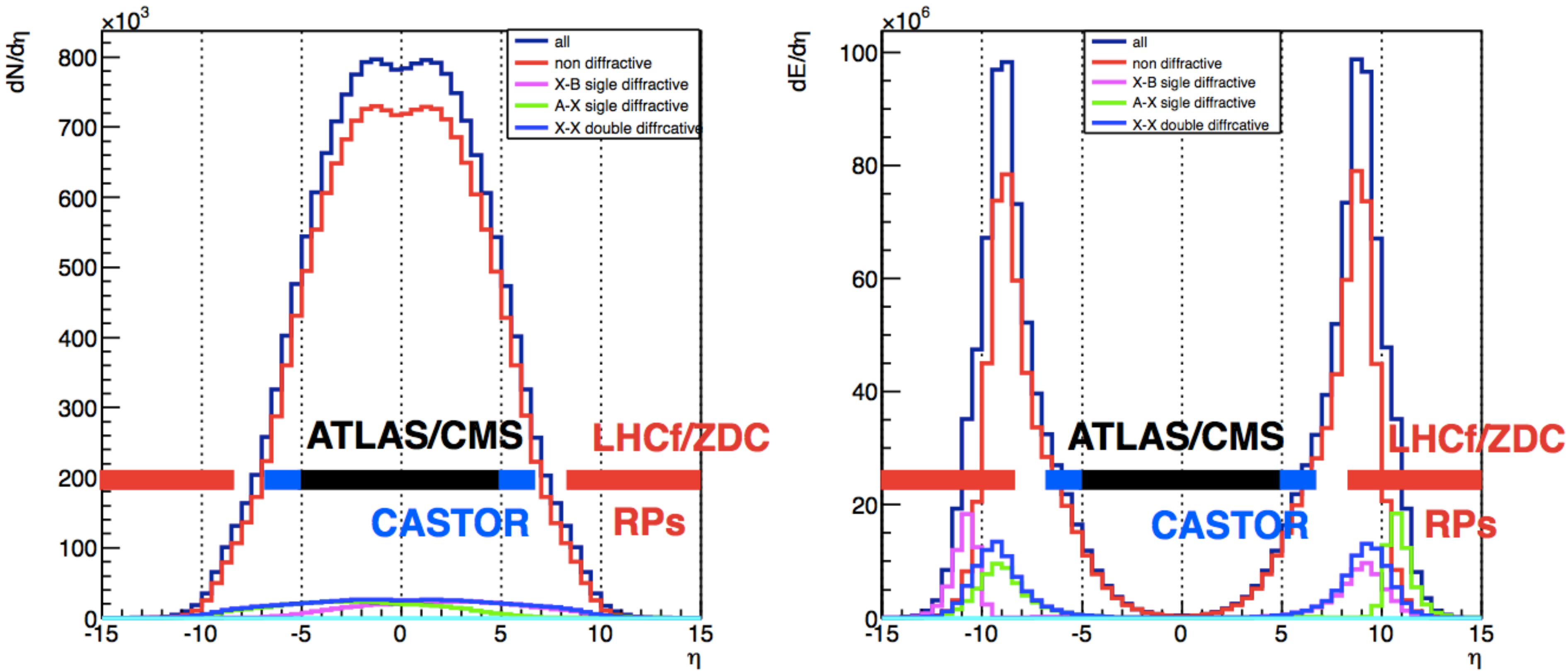
Naively CGC-like suppression may occur in very forward at high energy

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

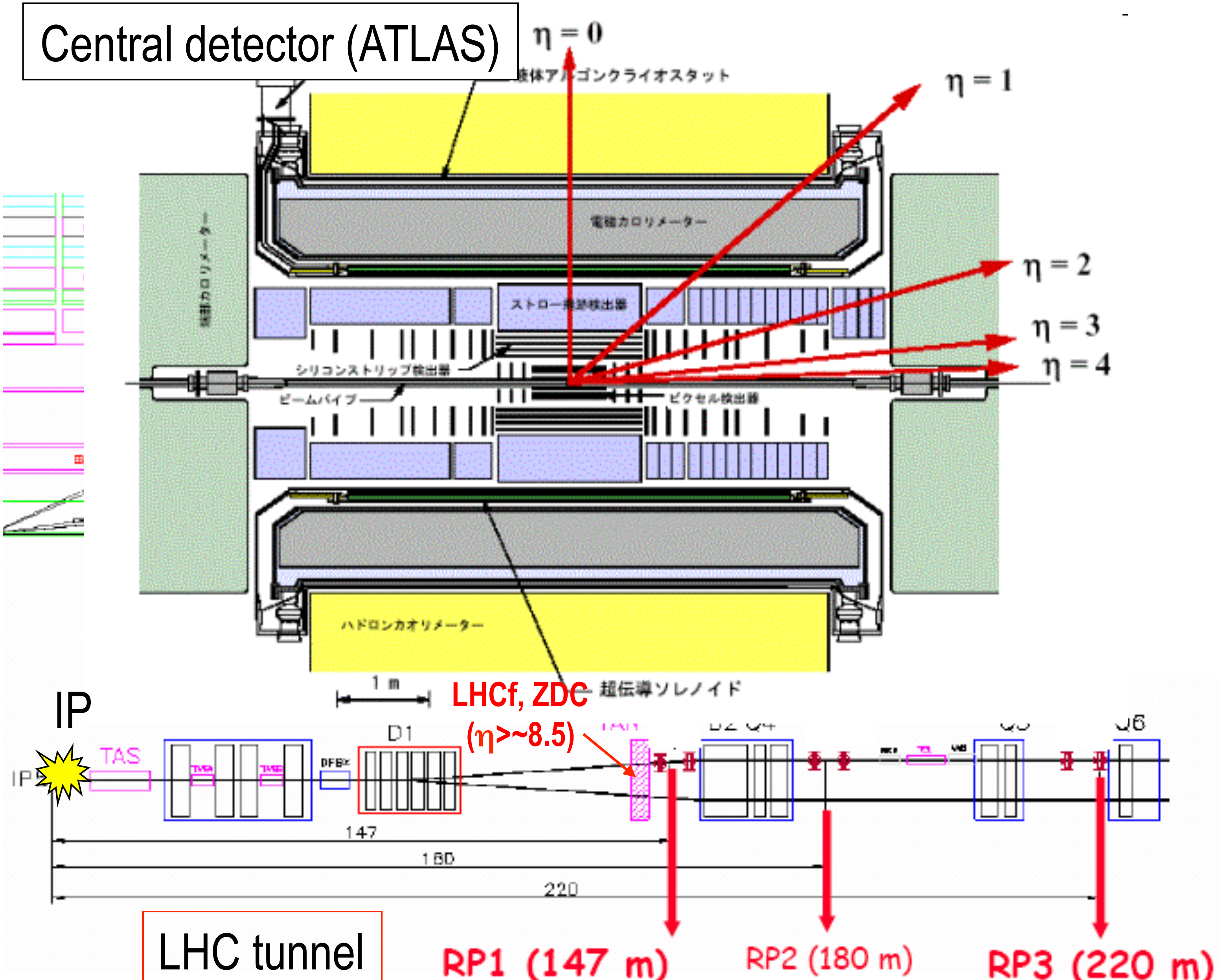




Particle density and energy flow for 7TeV pp



ATLAS and LHCf



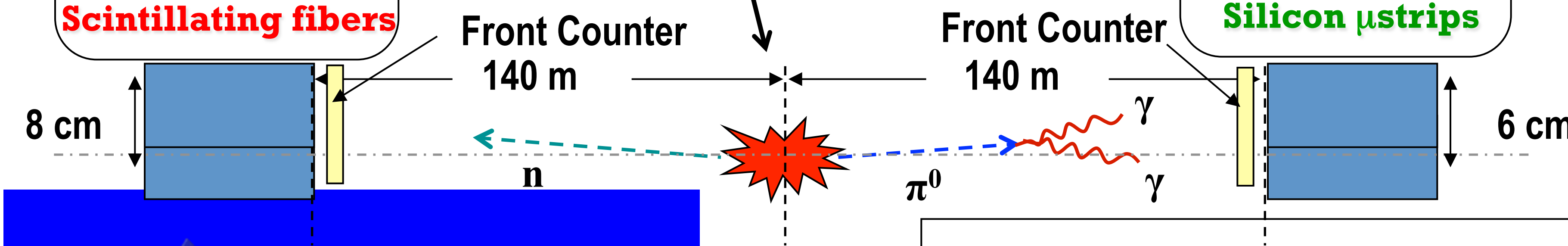
LHCf: location and detector layout

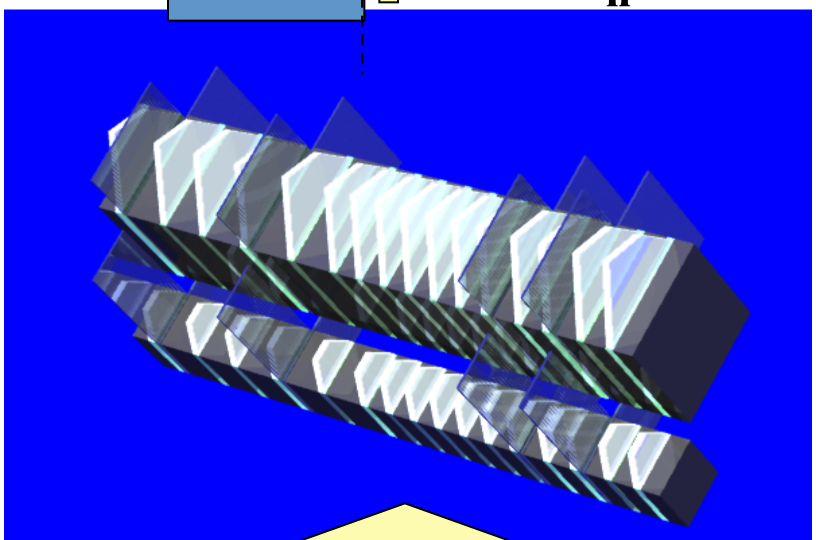
Detector I
Tungsten
Scintillator
Scintillating fibers

INTERACTION POINT

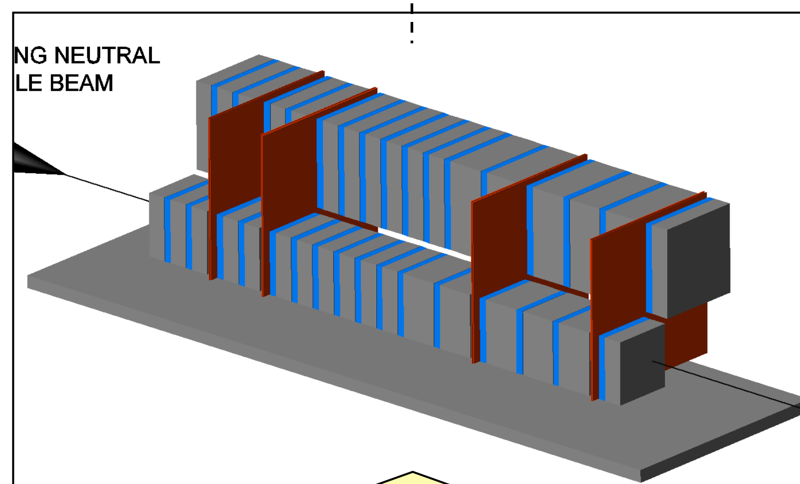
IP1 (ATLAS)

Detector II
Tungsten
Scintillator
Silicon μstrips





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

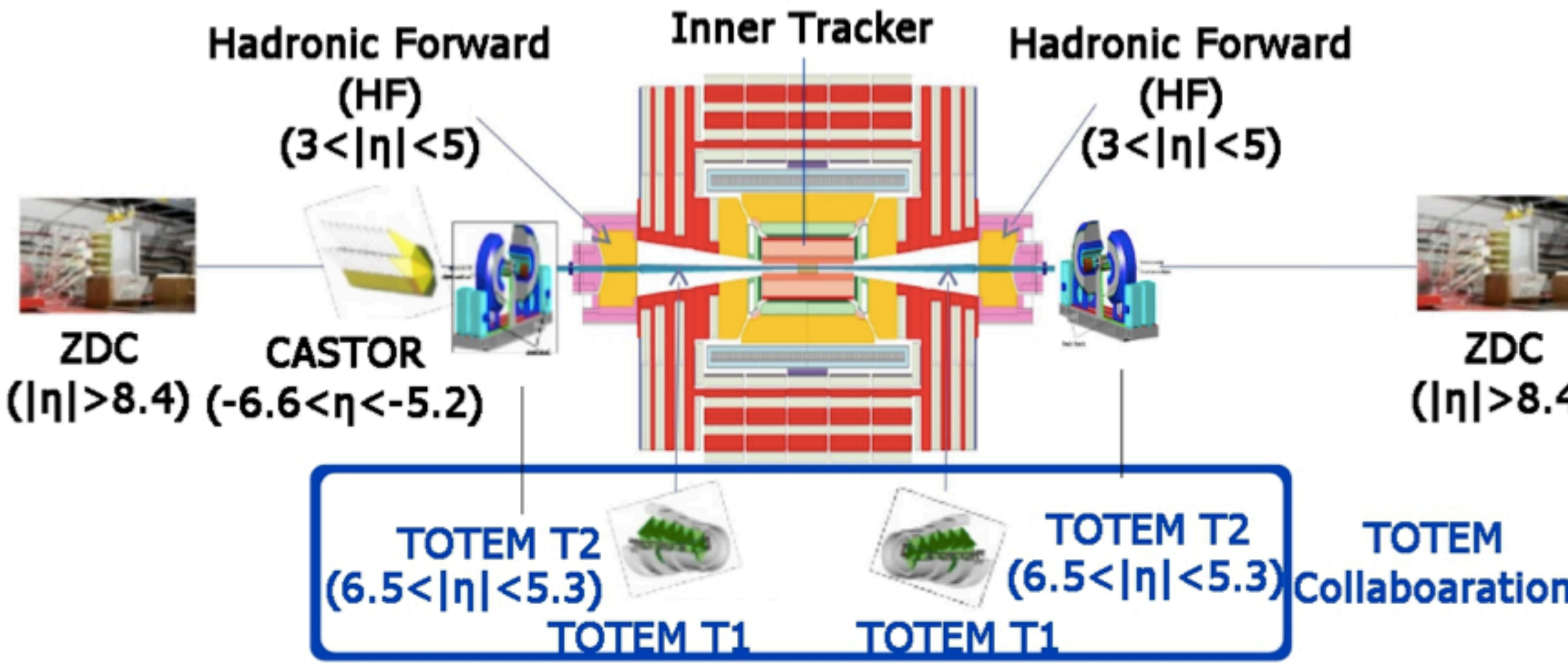


Arm#1 Detector
20mmx20mm+40mmx40mm
4 SciFi tracking layers

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

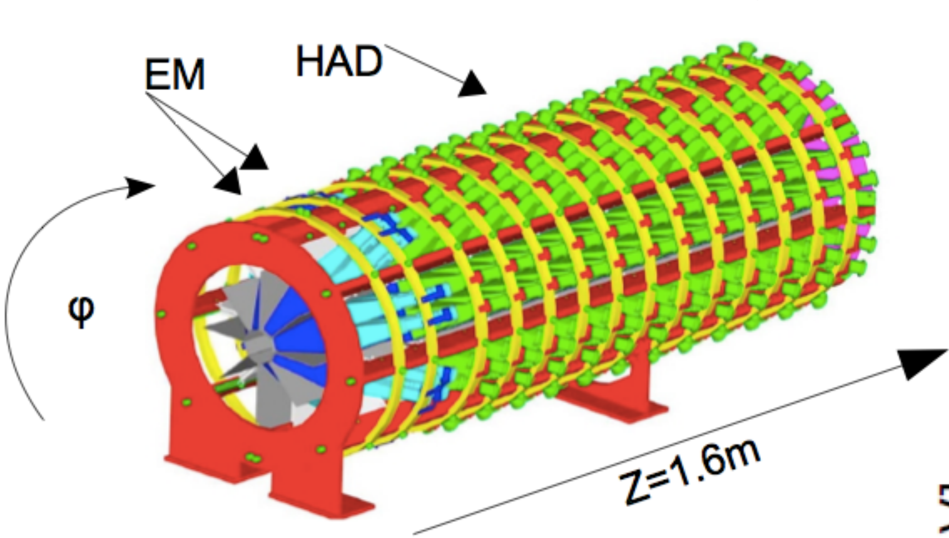
CMS forward and TOTEM

Forward Detectors



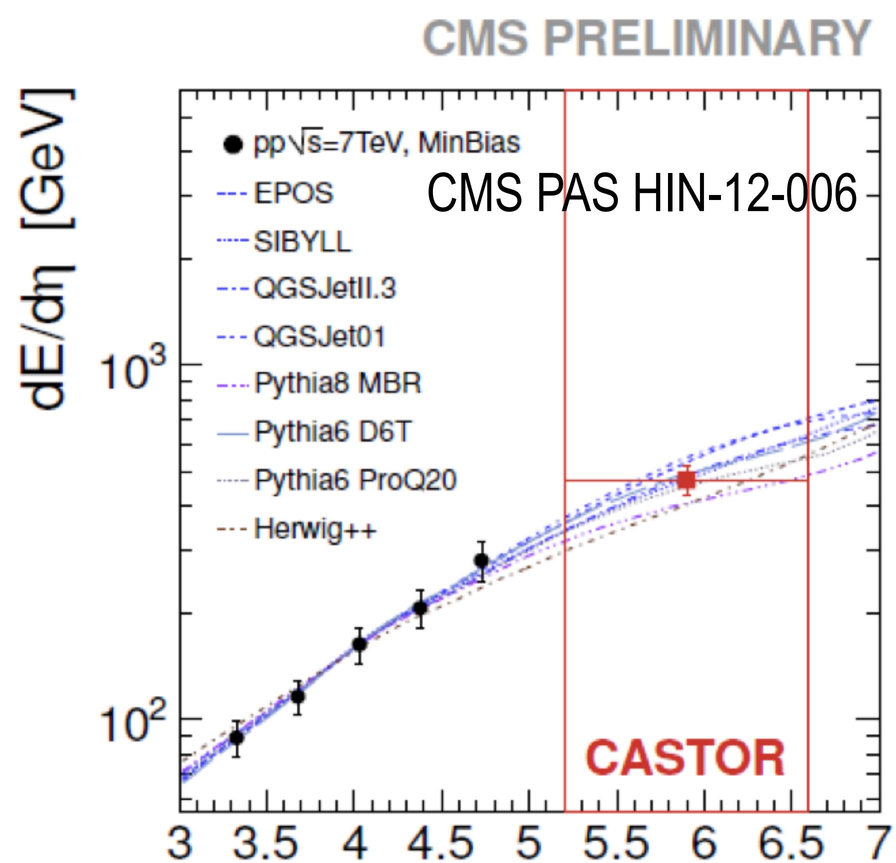
Hadronic Forward (HF)	CASTOR	TOTEM T2
σ_E≈20-40% High granularity Steel absorb. and quartz fibres	σ_E≈5-20% Quartz/tungsten calorimeter	p_T>40MeV Triple-GEM

CMS CASTOR



Covering $-6.6 < \eta < -5.2$
W plate + quartz plates
16 φ seg. , no η seg.
2 EM +10 HAD (10 λ_i total)
So far first 5 Mod. used.

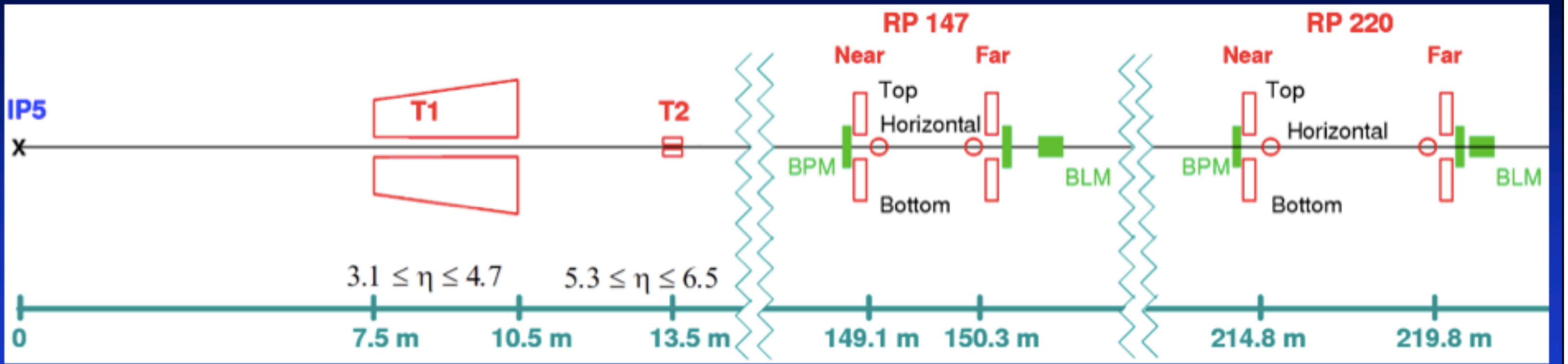
- E calib. is challenging.
- So far calibrate to HF at 7TeV pp by η extrapolation. (PbPb analysis, 20% uncertainty)
- In future, Z->ee or UPC can give precise absolute E scale

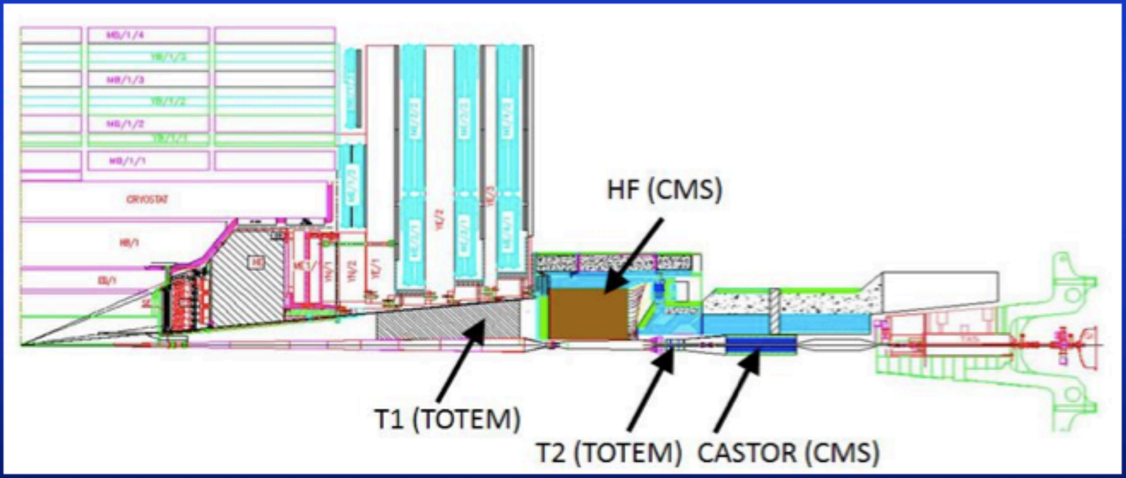


TOTEM

Slide by T.Scorgo (low-x 2014)

TOTEM – Experimental Setup at IP5

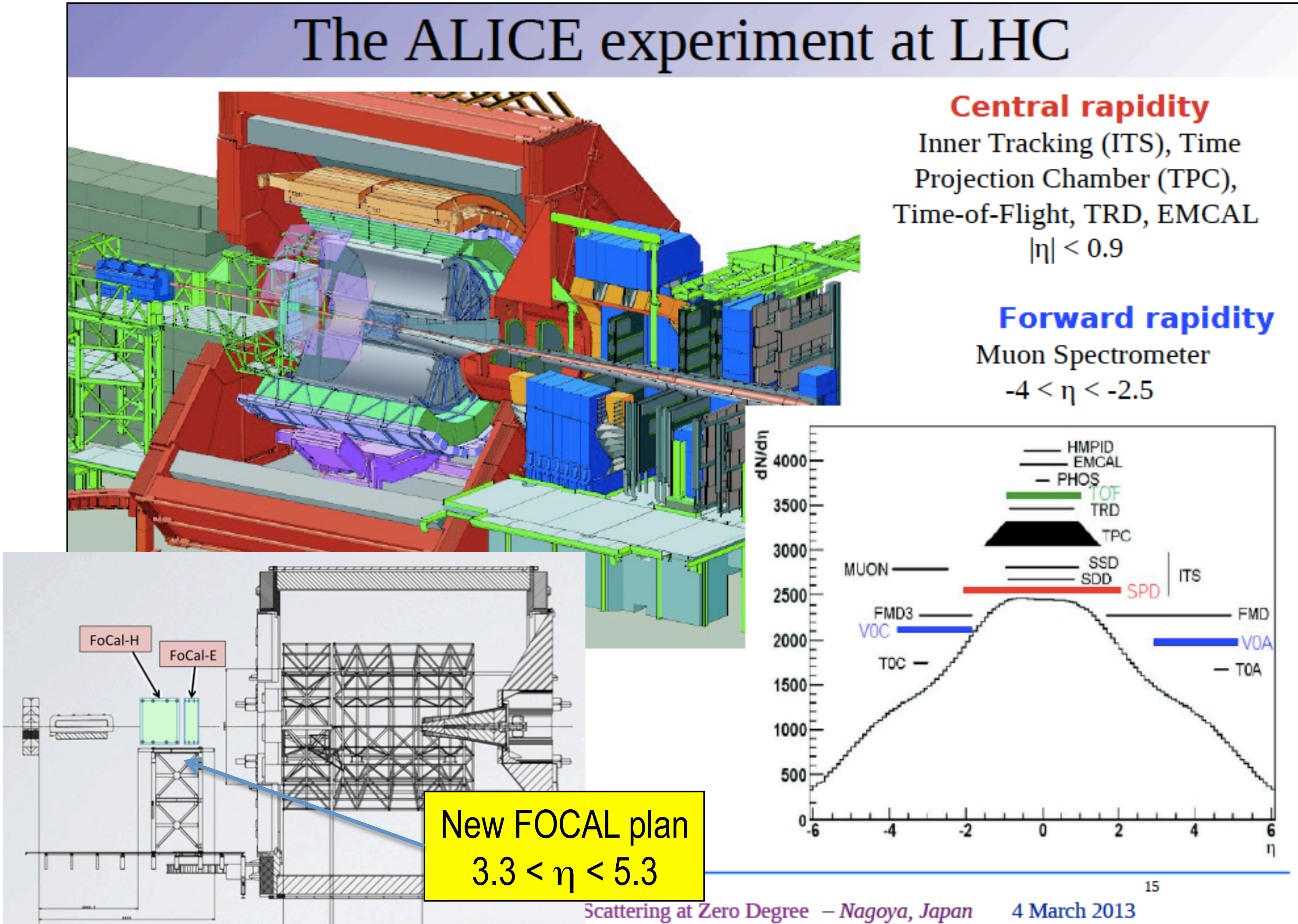




T1, T2: CSC and GEM Inelastic telescopes; RP: Roman Pots
[Details: JINST 3 (2008) S08007 and F. Ferro's talk at this meeting]

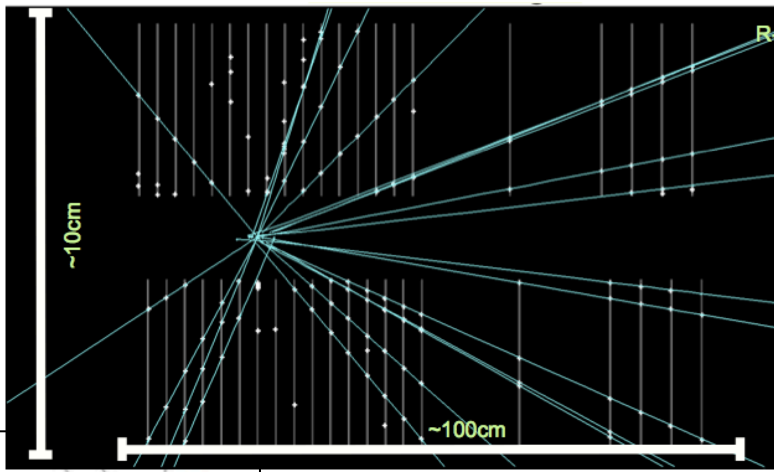
ALICE

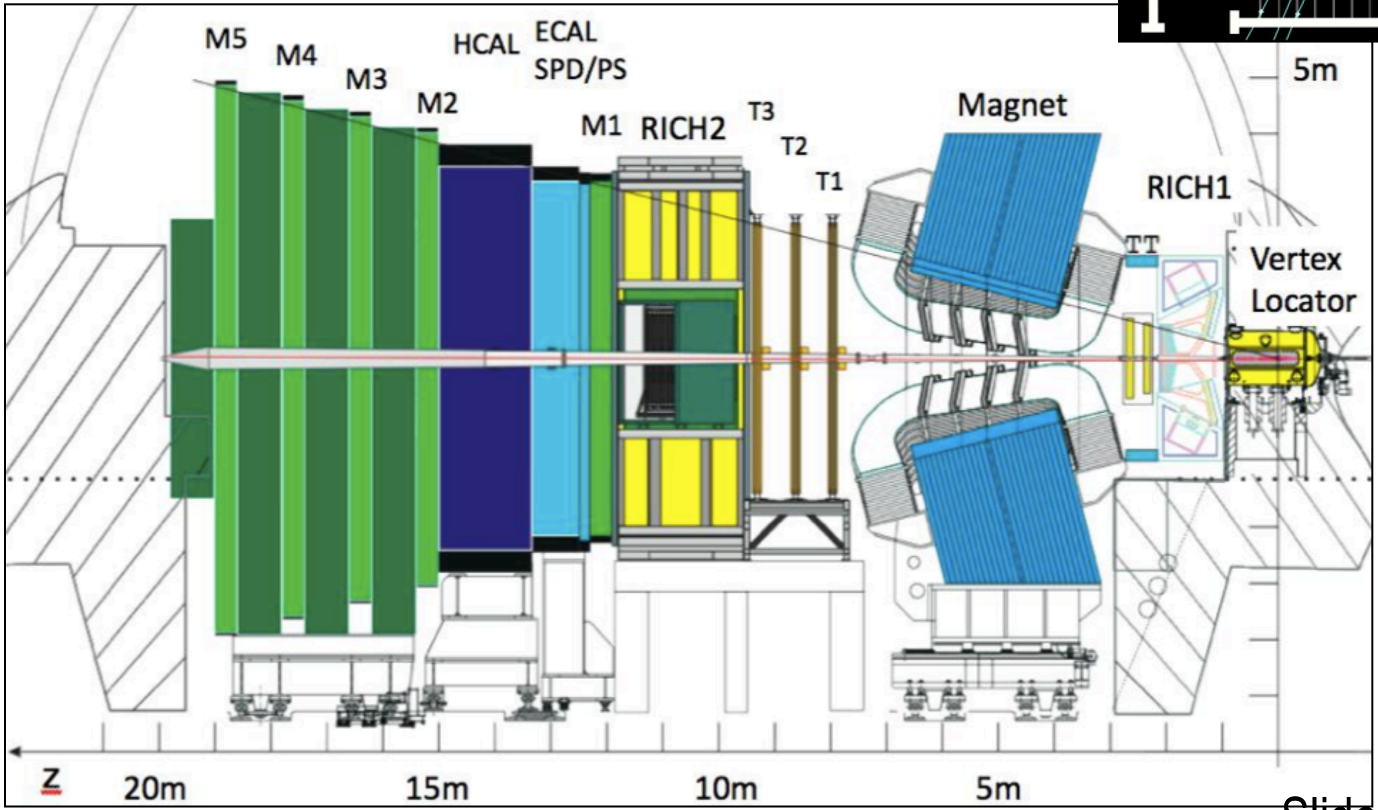
Slide by D.T.Takaki HESZ 2013



LHCb

- Unique forward spectrometer $2 < \eta < 5$
- VELO (vertex locater) 8mm distance to beam





Slides from T.Ruf @ EPS2011

Outline of this talk

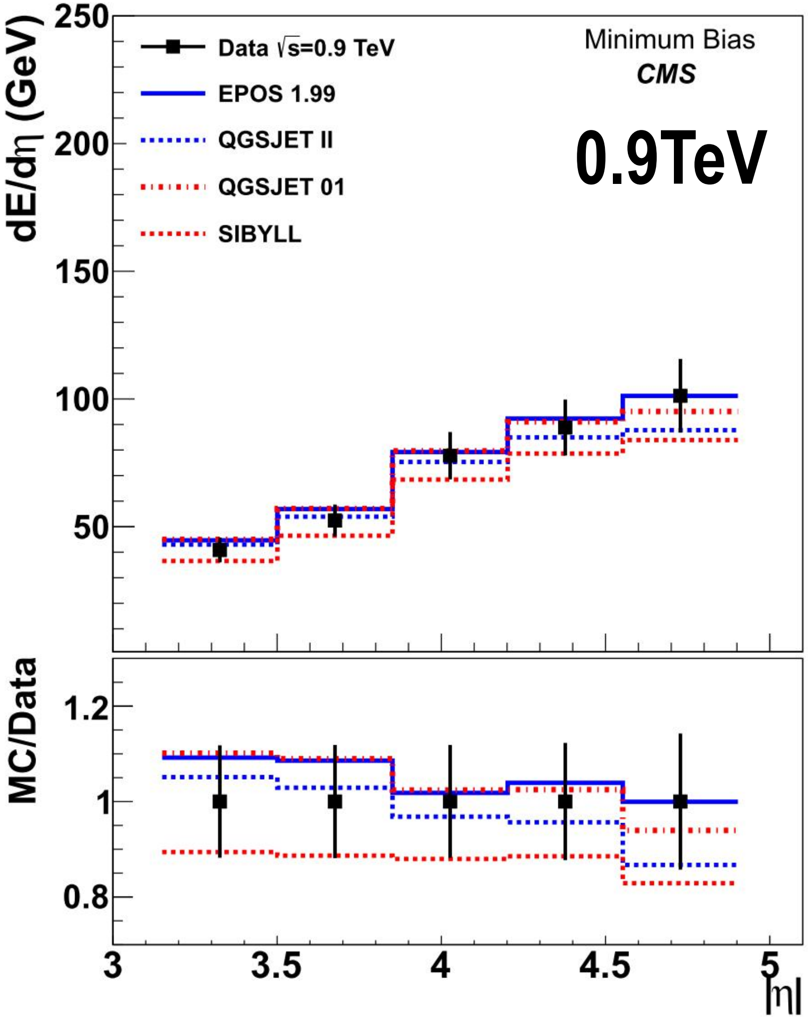
- Energy flow in pp
  - CMS
  - ATLAS
  - LHCf
- Multiplicity in pp
  - CMS+TOTEM
  - LHCb
  - ALICE
- Energy flow in PbPb
  - CMS
- Nuclear modification in pPb
  - ALICE
  - LHCf
- Future

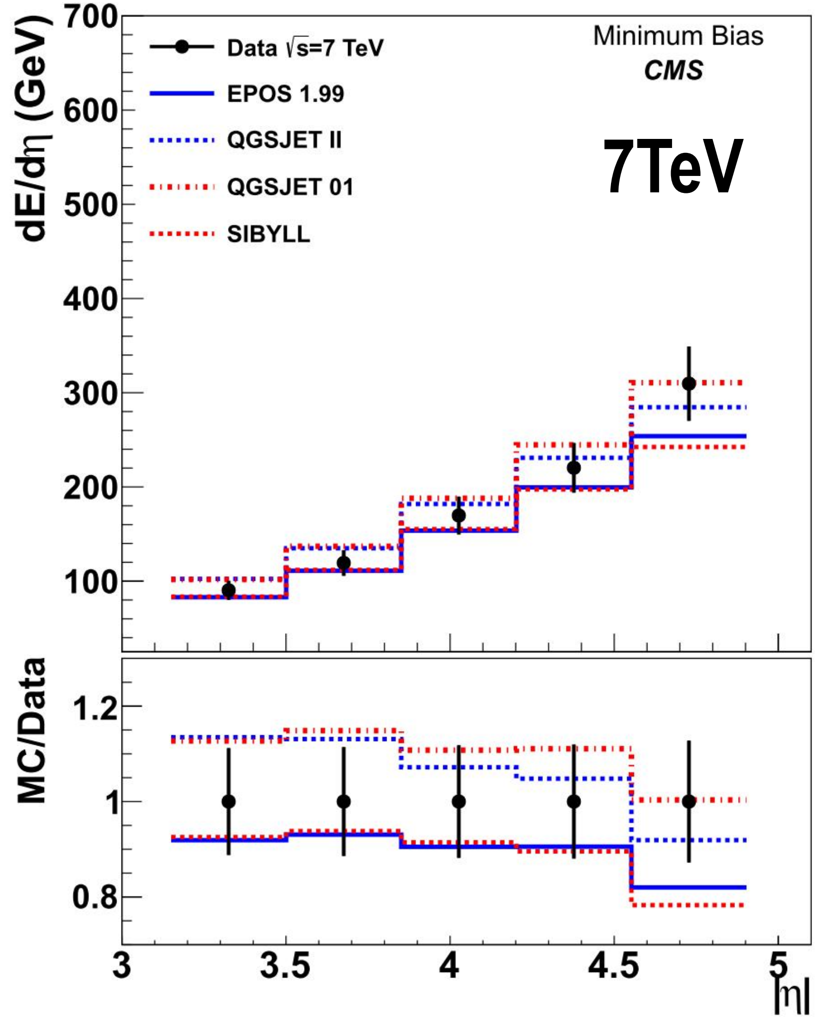
Special thanks to
C.Baus,
R.Ulrich,
S.Ostapchenko,
T.Pierog,
Y.Yamazaki,
N.Sakurai
and more…

Forward energy spectra and energy flow

CMS HF: Forward energy flow

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

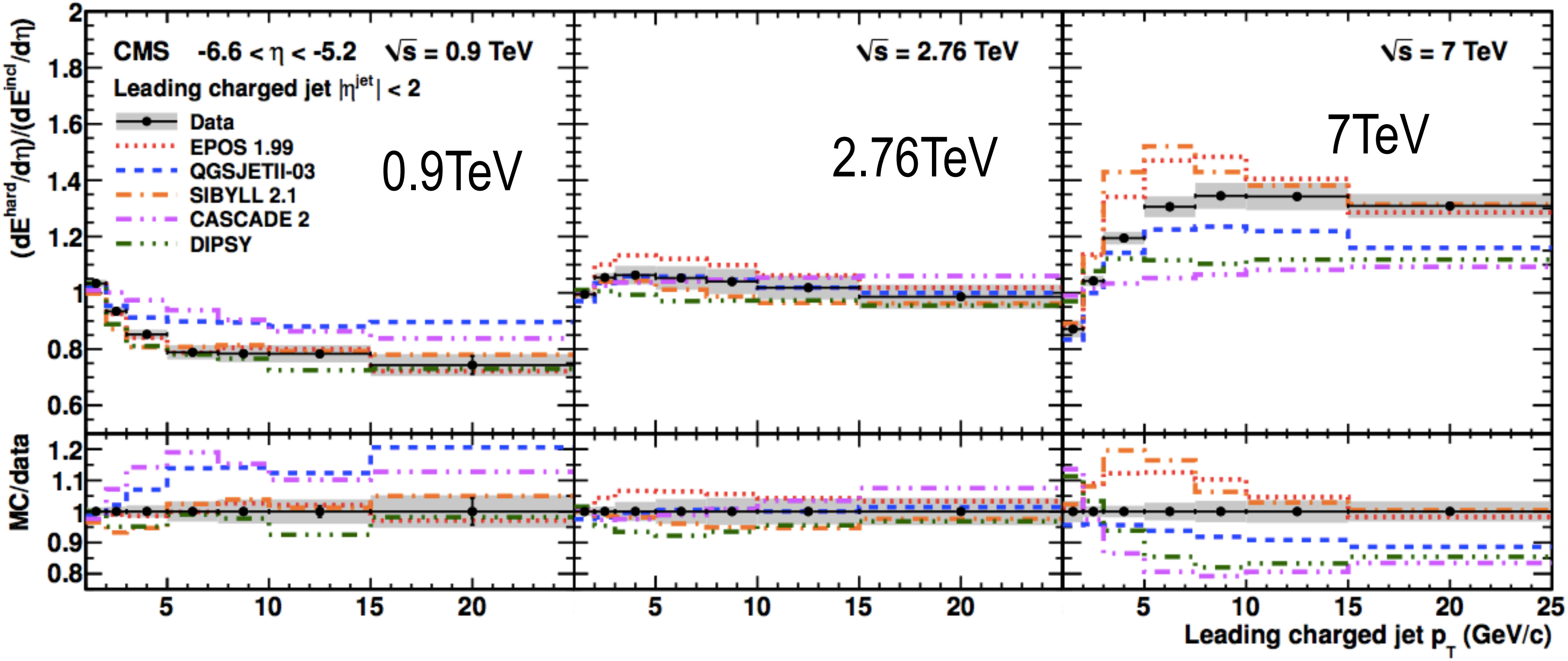




$3.15 < \eta < 4.19$

CMS hard-to-inclusive energy ratios

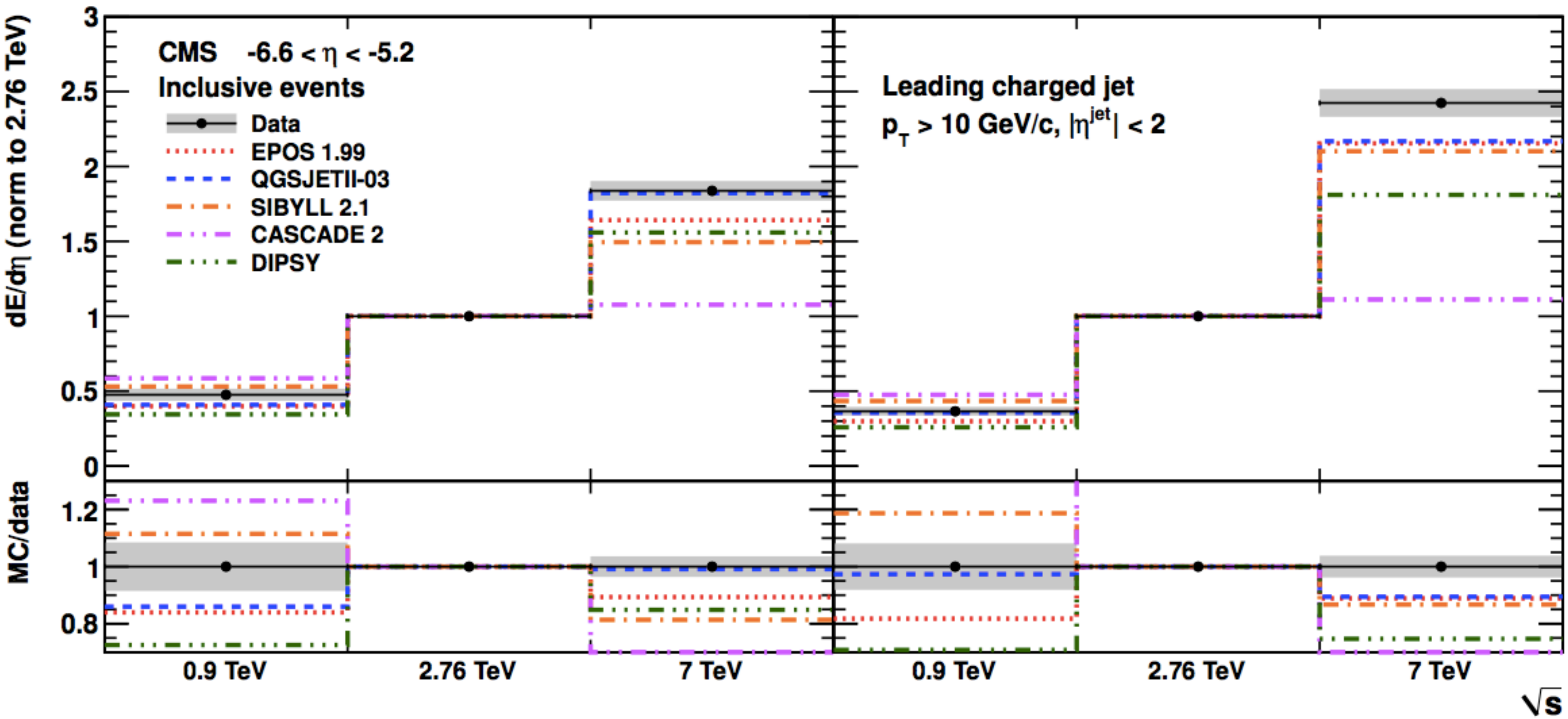
- Ratio of E in $-6.6<\eta<-5.2$ btw two samples JHEP 04 (2013) 072
  - Inclusive and hard samples (leading charged jet in central)
  - Large jet PT -> harder (more central) collisions
- 7 TeV; increase at large PT due to multi parton interactions(MPI)
- 0.9 TeV: decrese at large PT due to less proton remnant energy



Energy dependence of energy flow ratio ($-6.6 < \eta < -5.2$)

JHEP 04 (2013) 072

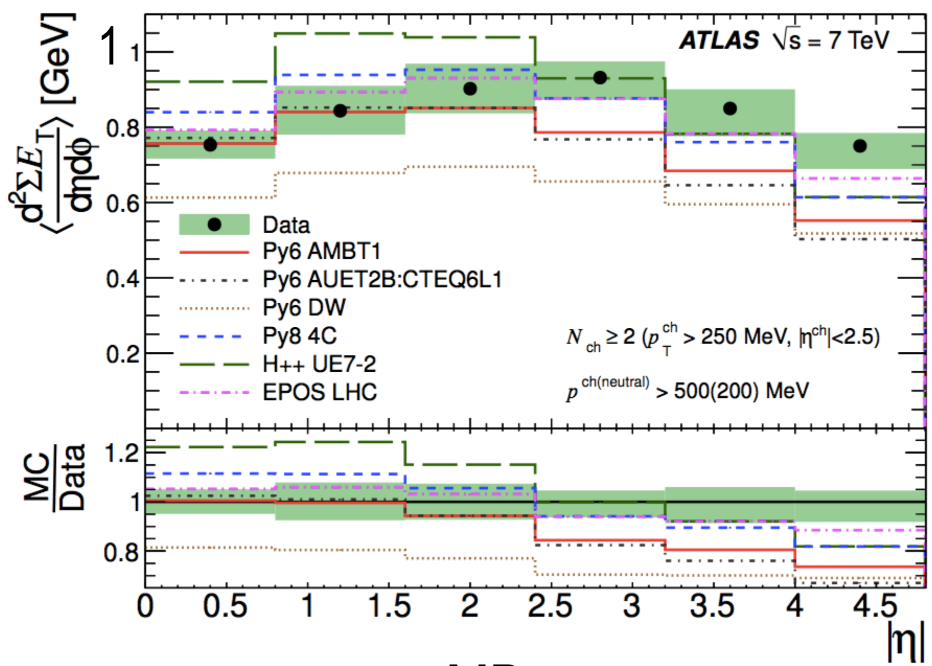
- Relative energy flow ratio to 2.76TeV pp collisions
- Larger slope for hard sample (central jet PT>10GeV/c)
- MPI is important to explain these trend



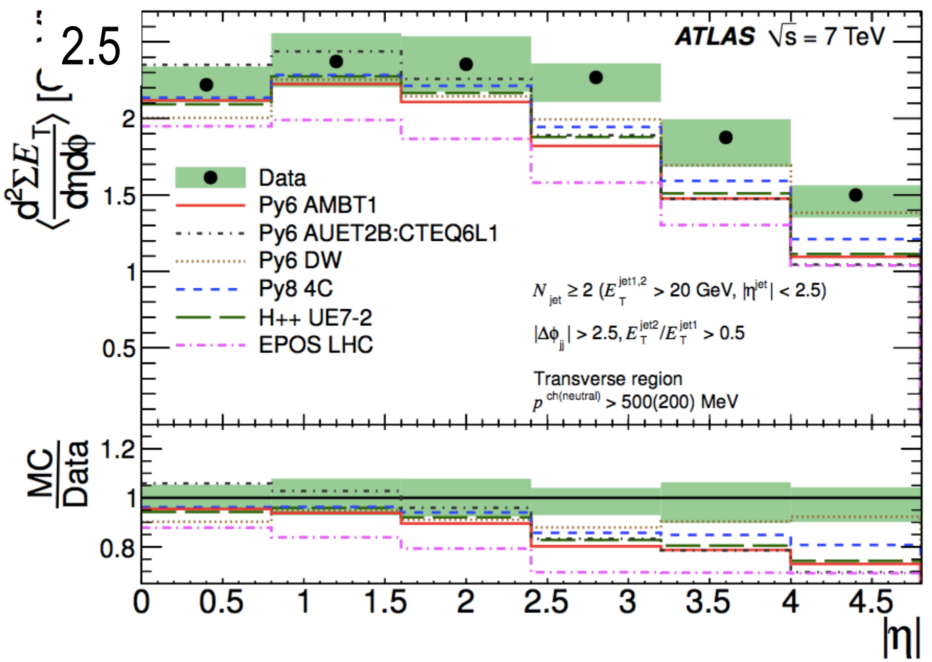
ATLAS ET for MB and hard |η|<4.8

JHEP 11 (2012) 033

- ET sum for charged p>500MeV (neutral >200MeV)
- minimum bias and hard dijet samples
  - MB : 2 PT>150MeV tracks in |η|<2.5
  - DIJET: 2 back-to-back jets w/ ET>20GeV in |η|<2.5



MB

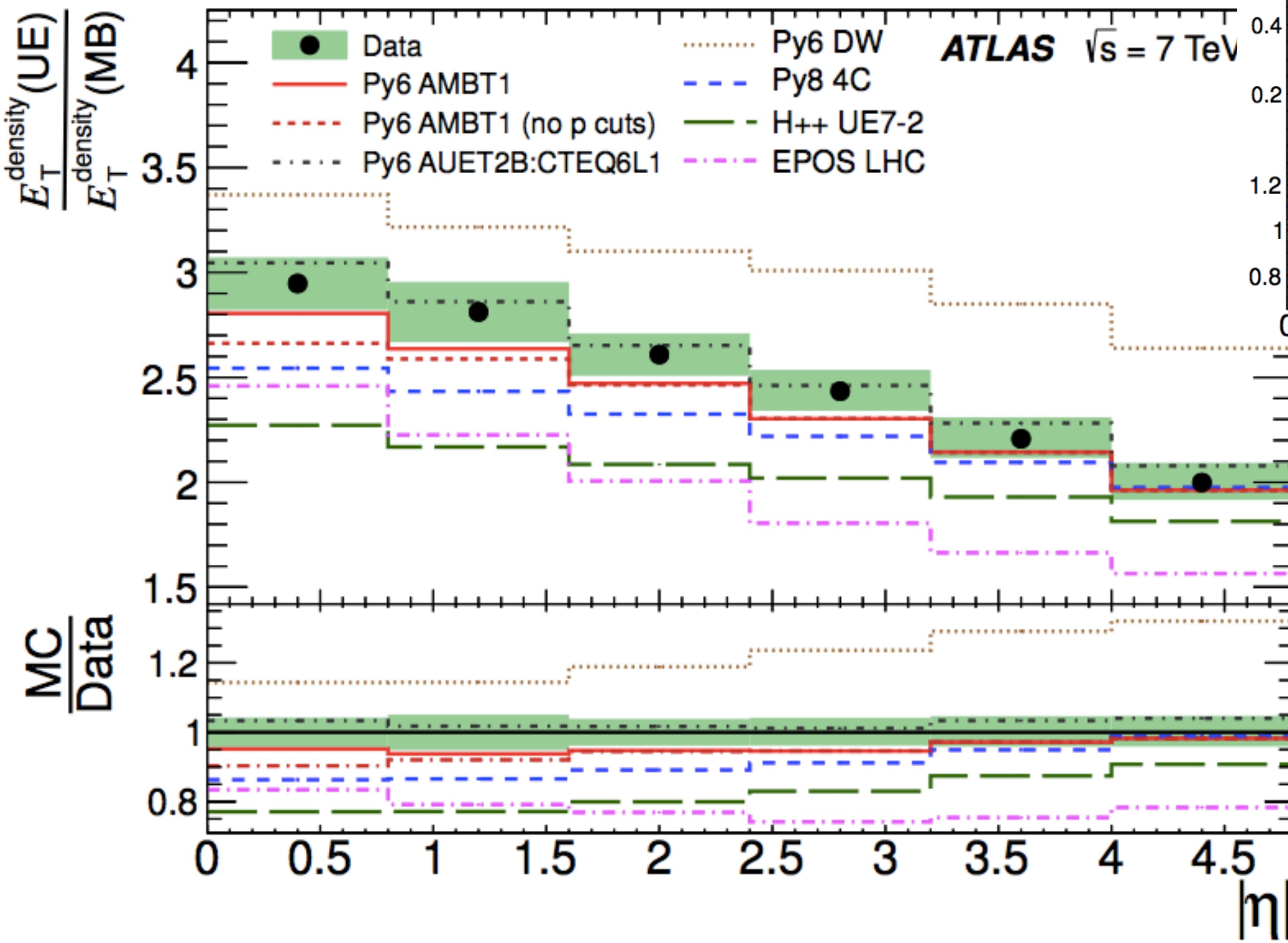


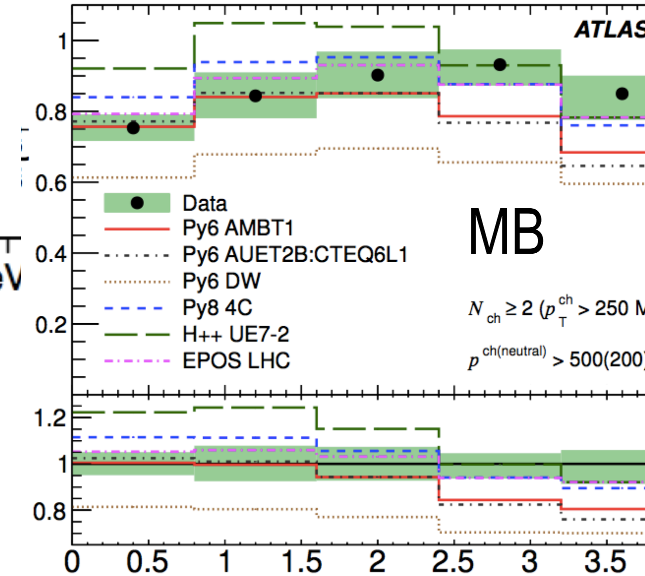
DIJET

ATLAS DIJET/MB ET ratio

JHEP 11 (2012) 033

- EPOS reproduces MB ET, but less in DIJET

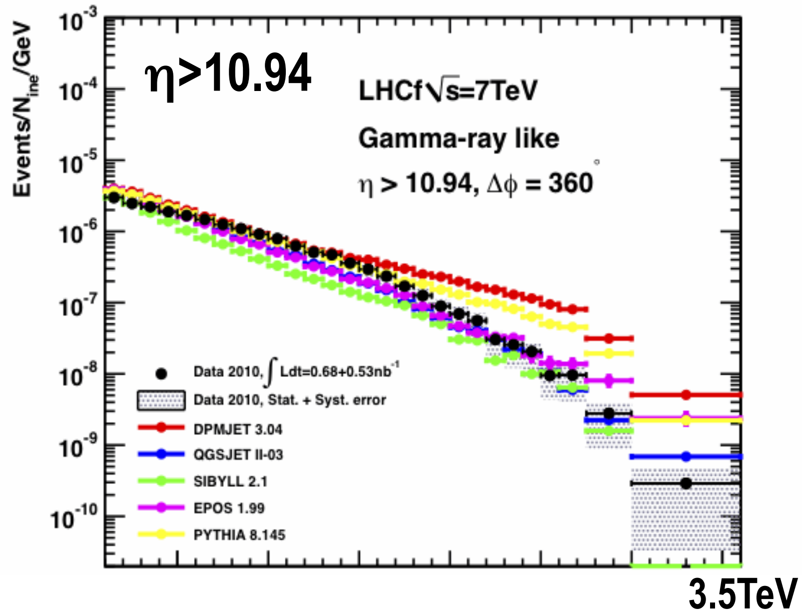


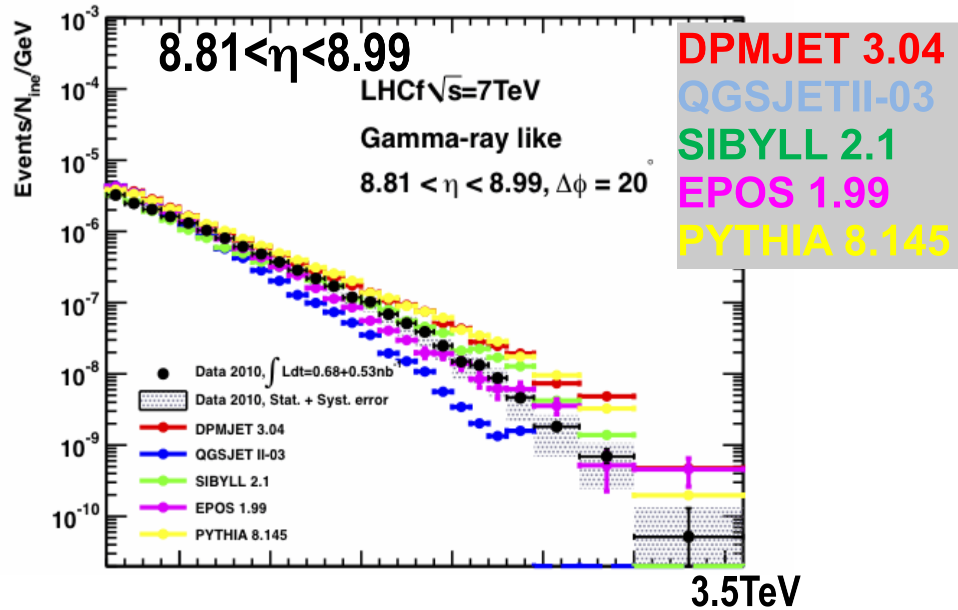


LHCf single Eγ at 7TeV and 0.9 TeV pp

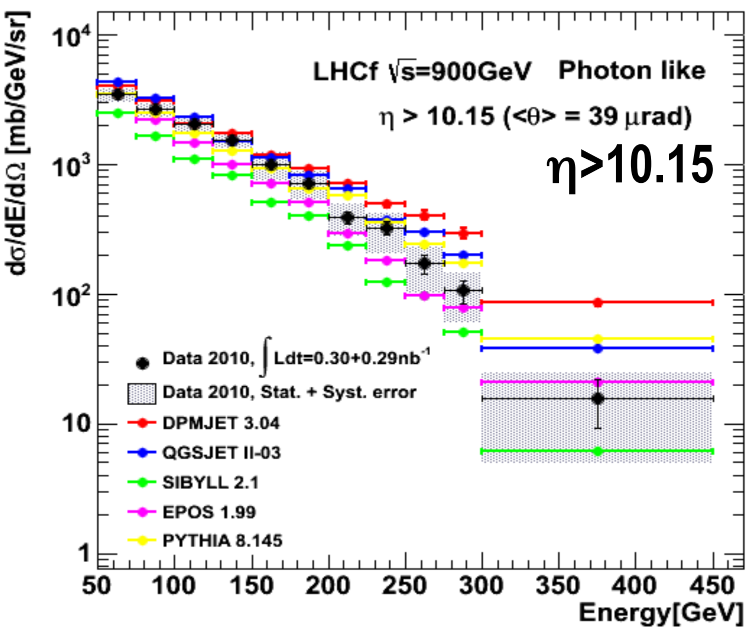
PLB 703 (2011) 128-134
PLB 715 (2012) 298-303

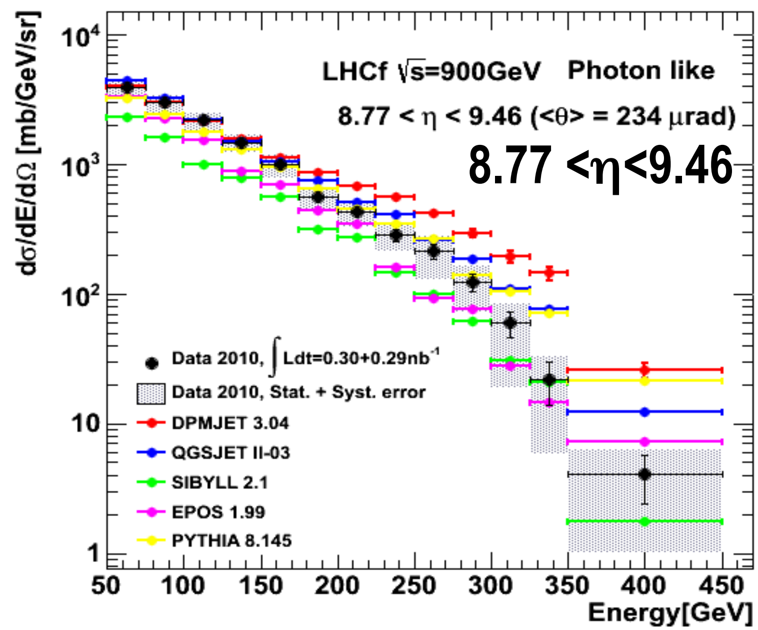
7TeV





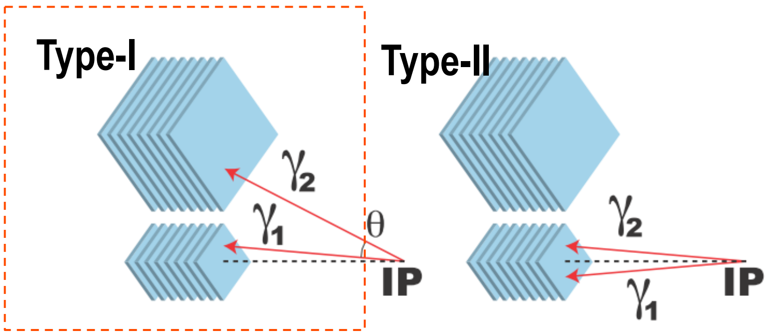
0.9TeV

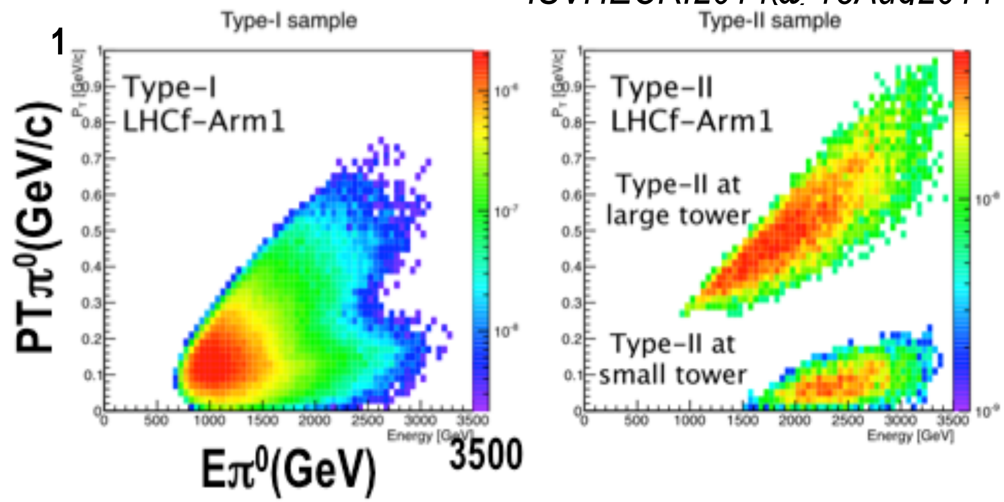


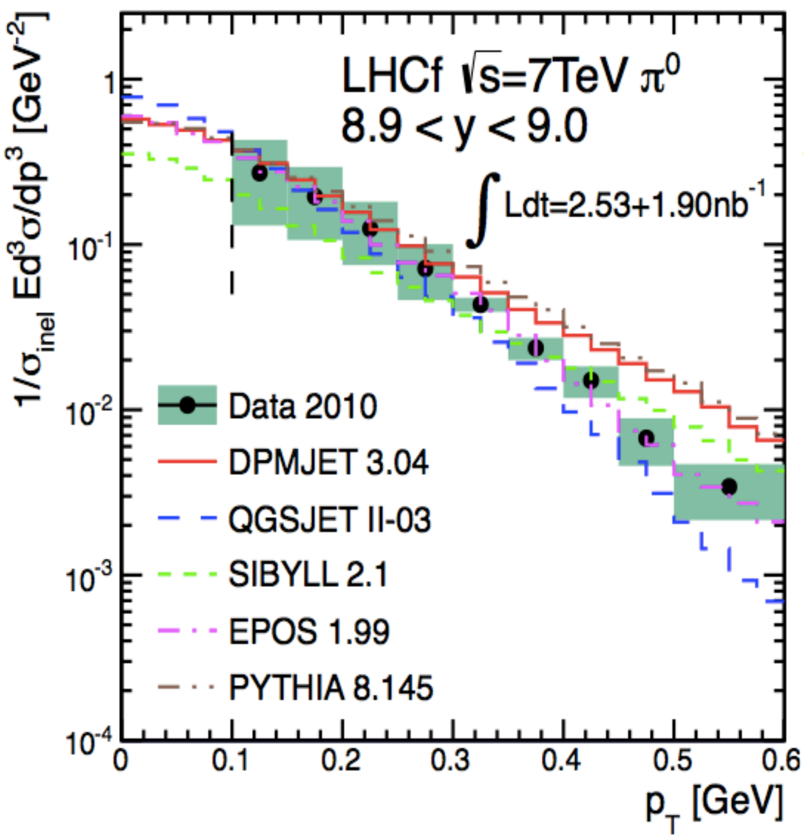


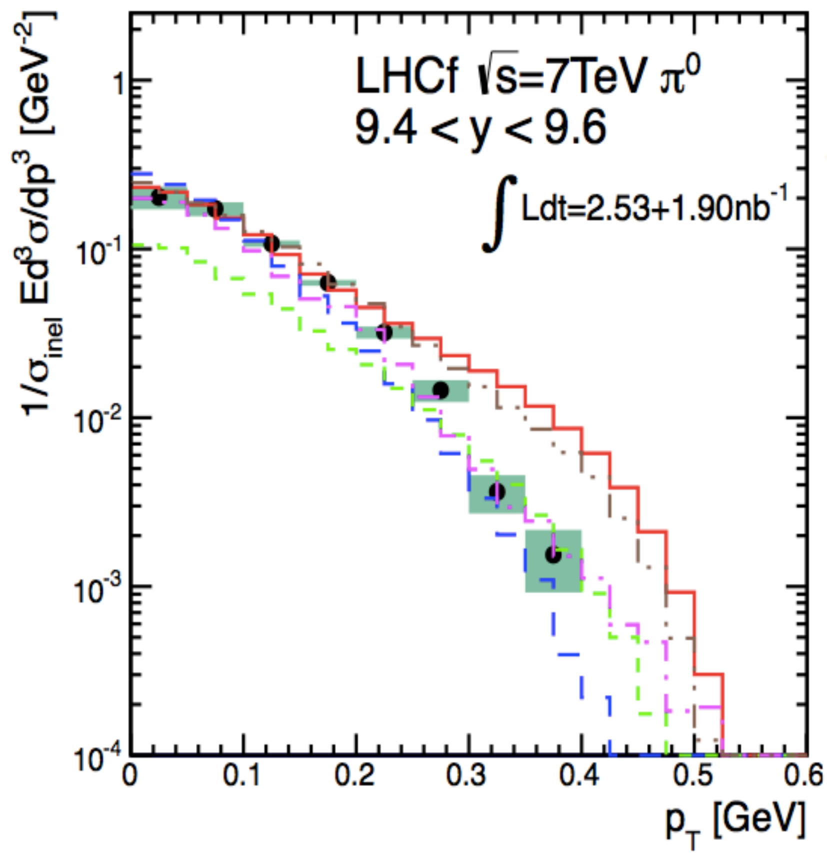
LHCf π^0 P_T at 7TeV pp

PRD 86 (2012) 092001



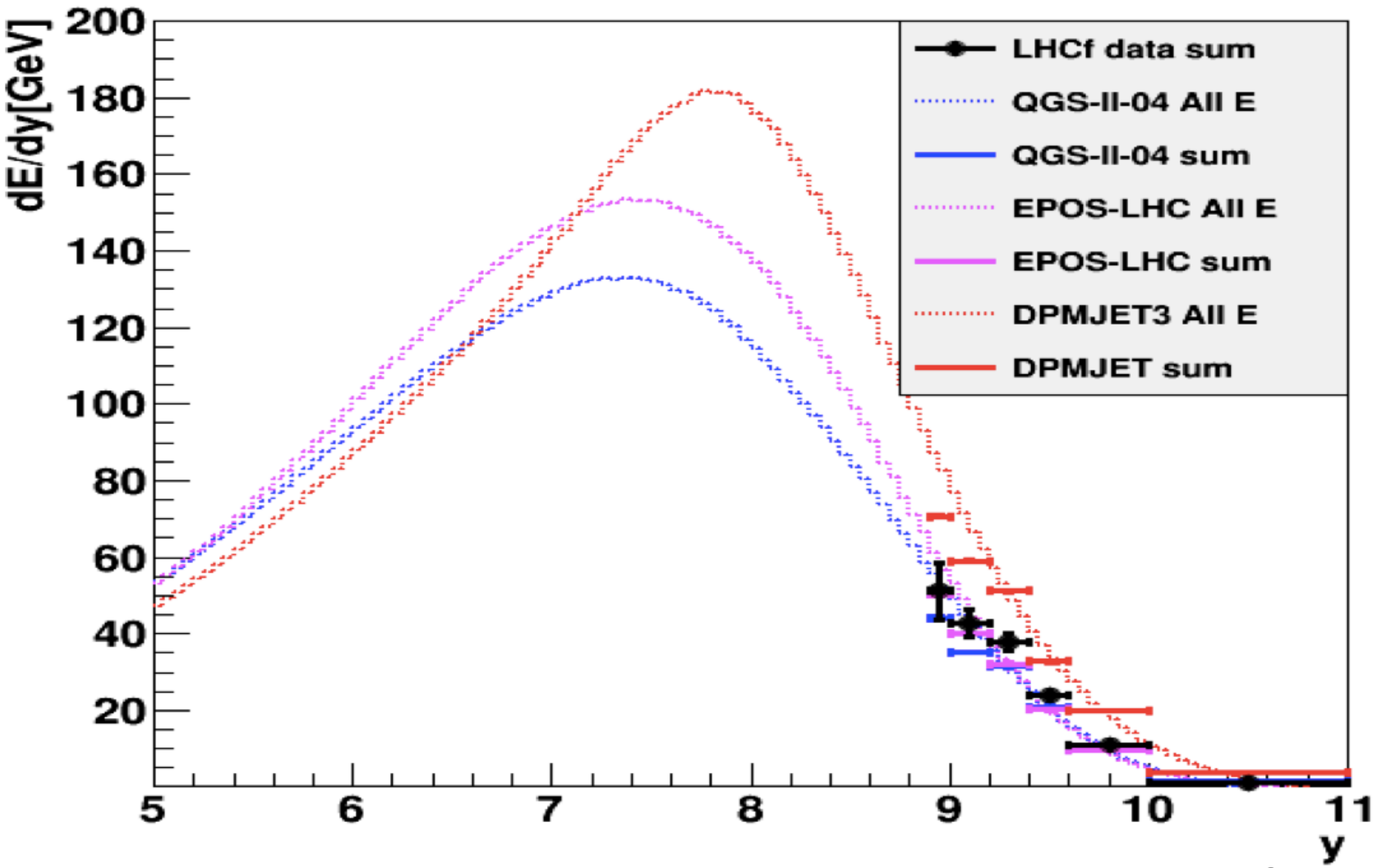






LHCf EM(π^0) energy flows vs rapidity (7TeVpp)

- Integrated p0 energy in LHCf acceptance
- Reasonably reproduced by QGSJET04 and EPOS-LHC
- Only tail covered for 7TeV, but peak covered for 13 TeV

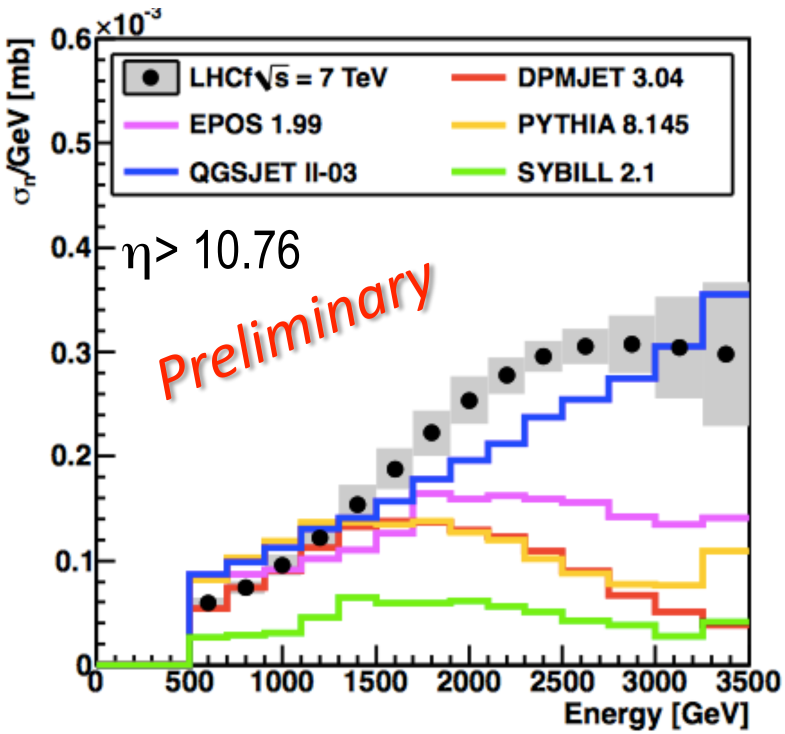


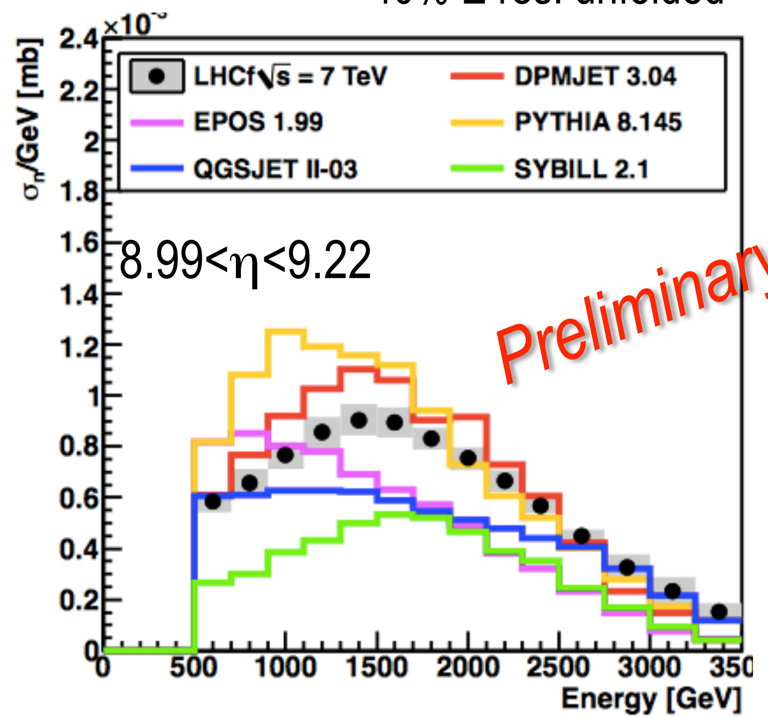
Plot by N.Sakurai

Very forward neutron at 7TeV p-p

- η>10.76 : QGSJET03 good, >h>9.22 DPMJET3 good
- Larger neutron / gamma ratio than expected

40% E res. unfolded





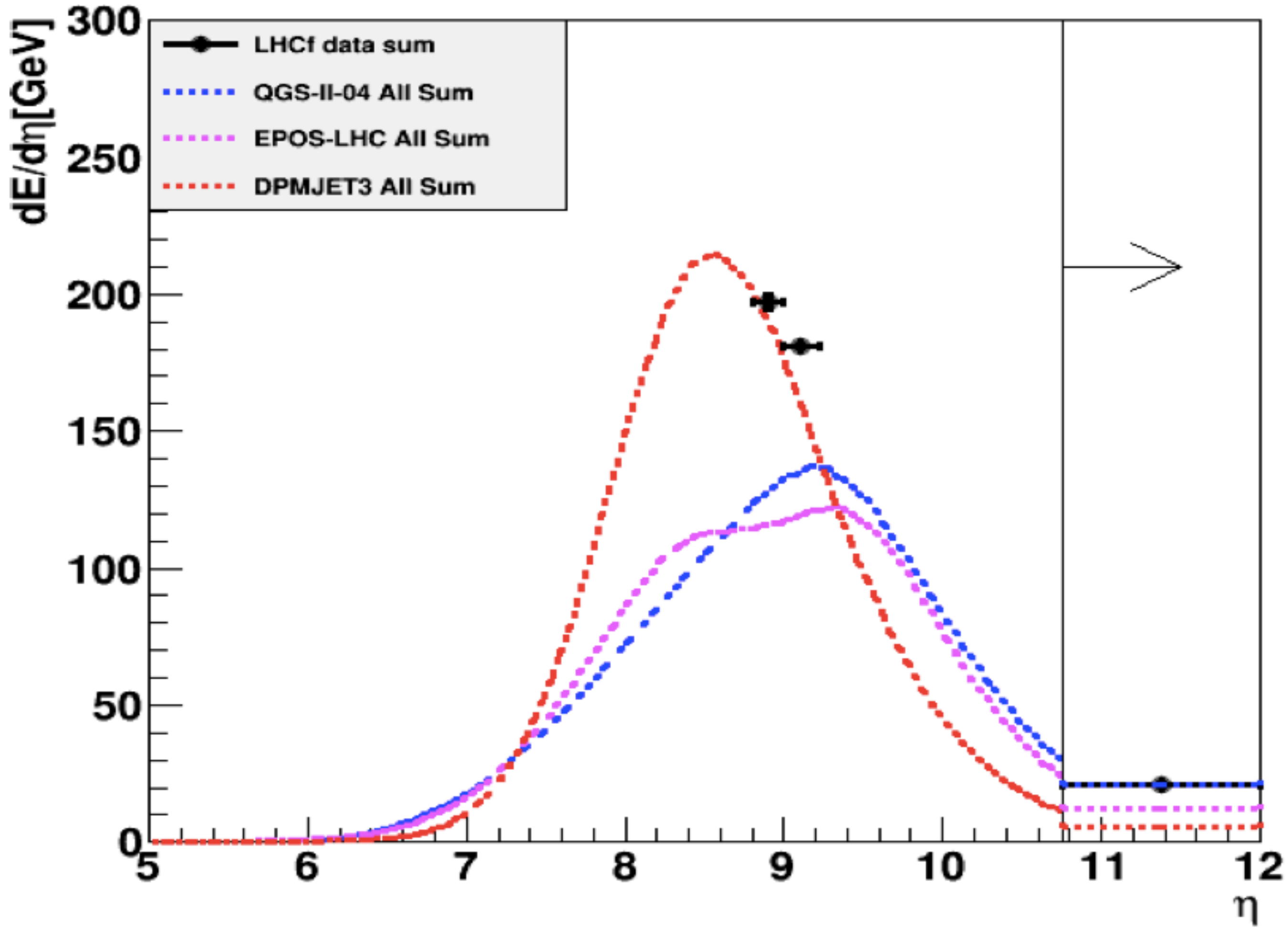
n / γ ratio

Data	3.05±0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

n / γ ratio

Data	1.26±0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

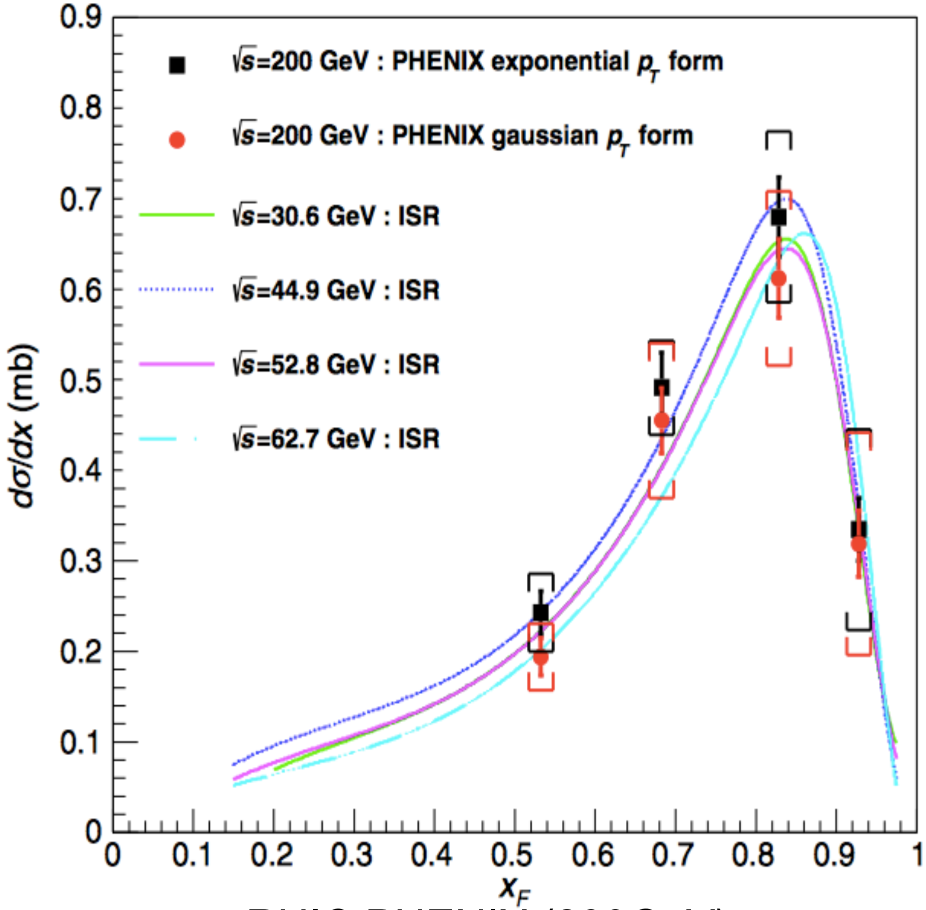
LHCf neutron energy flow vs rapidity



Plot by N.Sakurai

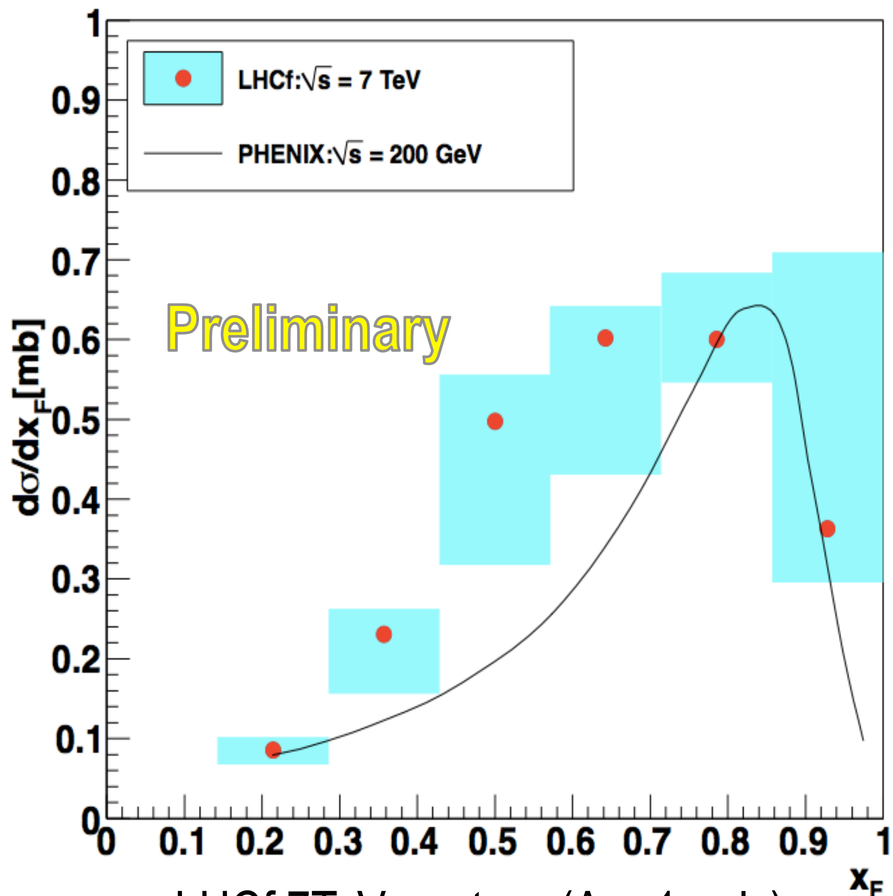
Bump ? at XF=1 for 0 deg neutron

A. Adare, et al., Phys. Rev. D, 88, 032006 (2013)



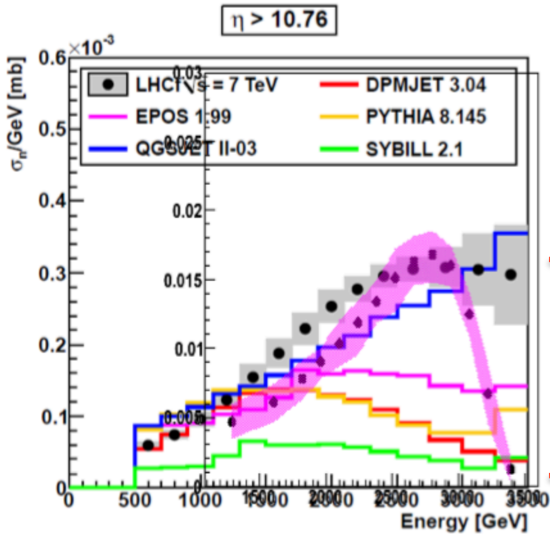
RHIC PHENIX (200GeV), ISR (30.6-62.7 GeV)

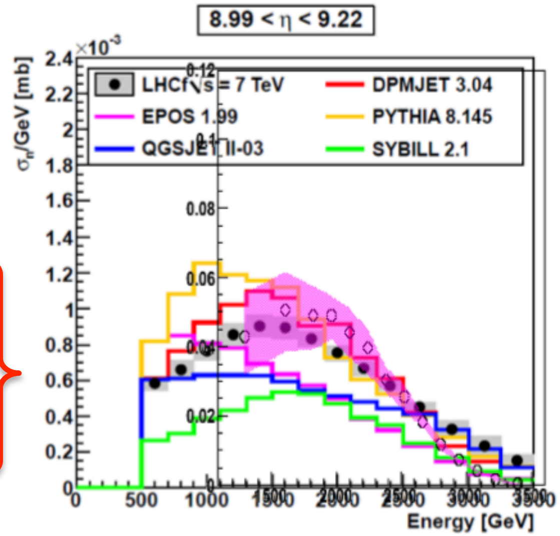
K.Kawade PhD thesis (2014)



LHCf 7TeV neutron (Arm1 only)
$0<P_T<0.11x_F$ GeV/c

Comparyson to HERA 0 deg neutron (Y.Yamazaki @ LOWX2014)

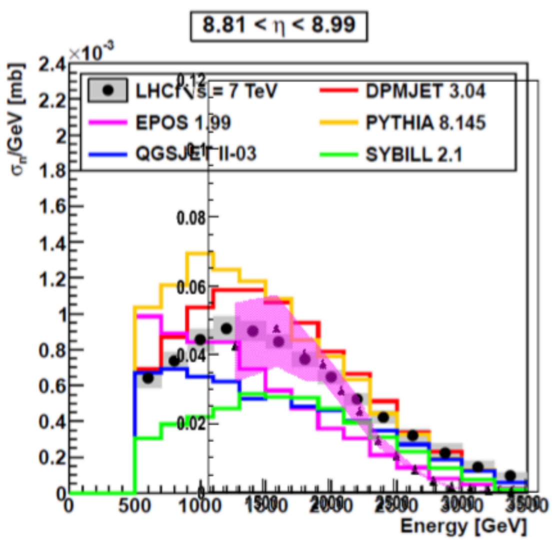




Neutron XF for LHCf kinematical regions calculated based on HERA data (Nuc Phys B 776,(2007) 1) by Y.Yamazaki (Kobe)

Disagree : η>10.76 non zero at Xf=1

Agree : 9.22 > η > 8.81

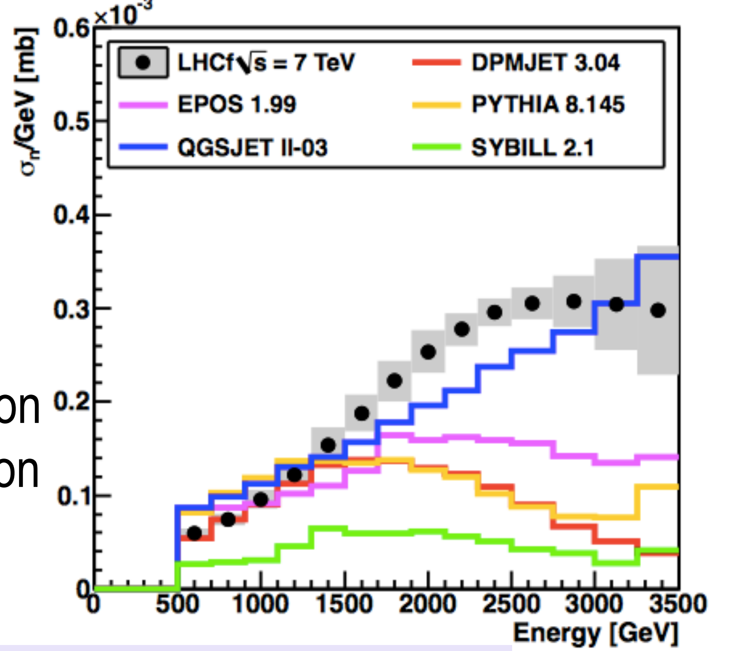


Comparison(2)

- Medium-x_F behaviour: quite well reproduced
  - including the height of peaks, if appropriately normalised by a common factor
- Lack of events for E > 2500 GeV in the HERA parameterisation
- Low-x_F : slight deficit
  - Note that the exponential parameterisation may not be appropriate when the slope is small

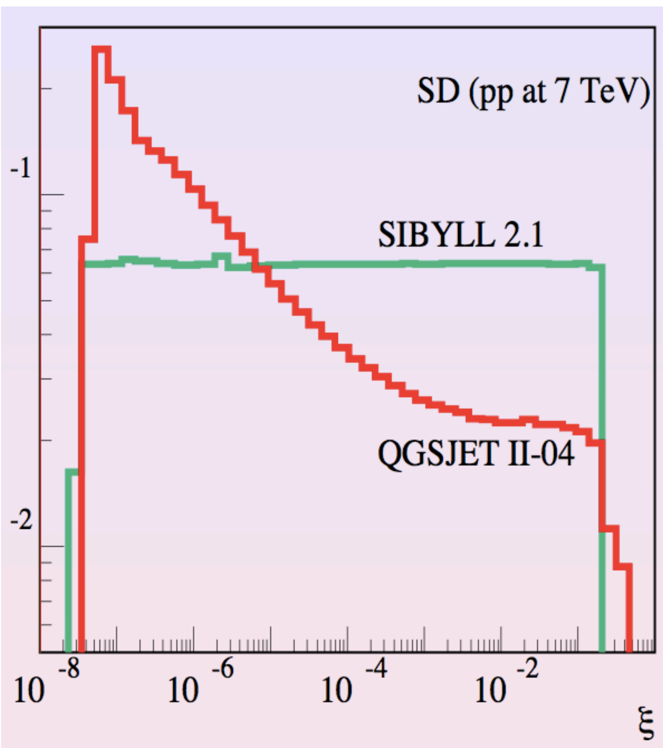
Leading baryon production in ep and hadron-hadron collisions 9

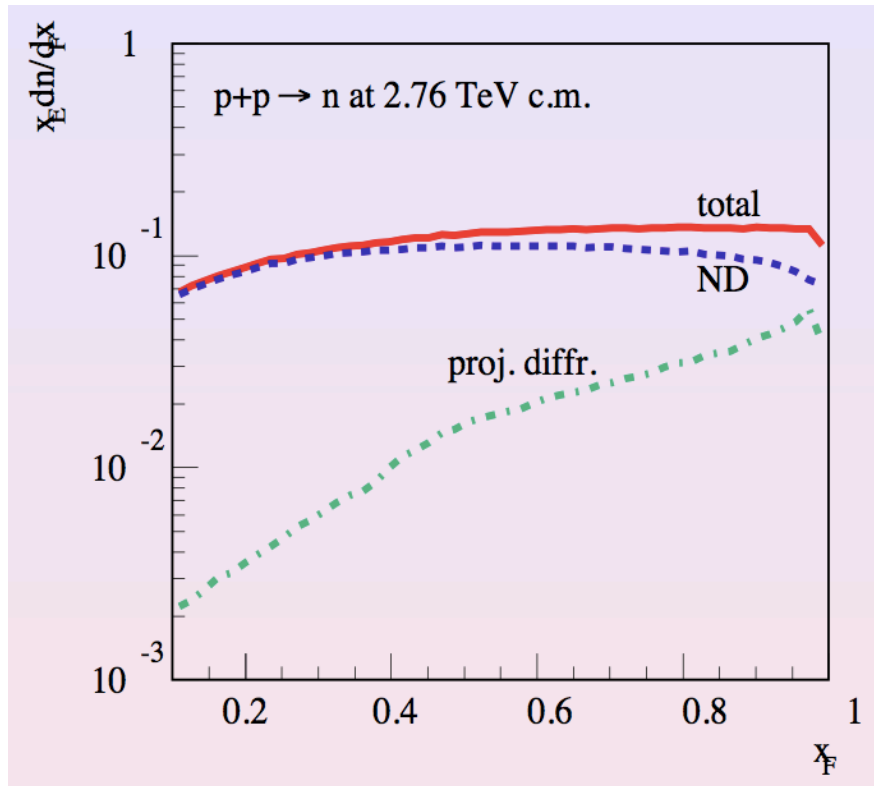
Low mass diffraction plays in XF=1



- QGSJET03(& EPOS also ?) reproduces 0 deg. neutron
- Low ξ bump in low mass diffraction contributes neutron XF bump (c.f. Ostapchenko)

S.Ostapchenko@HESZ2014



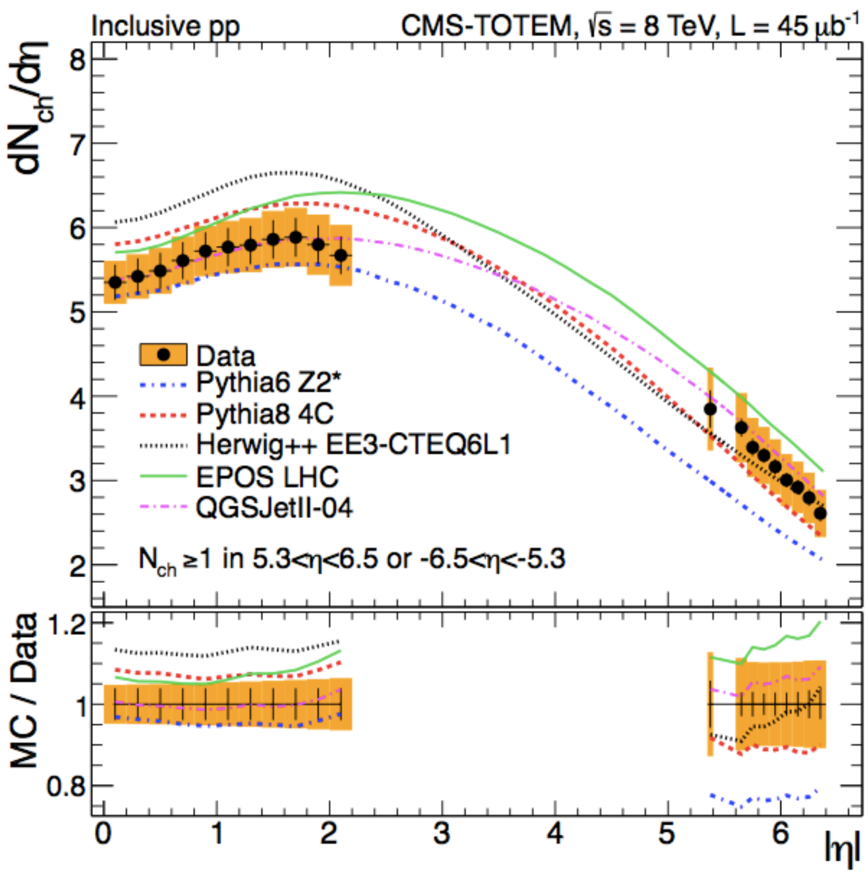


Forward multiplicity

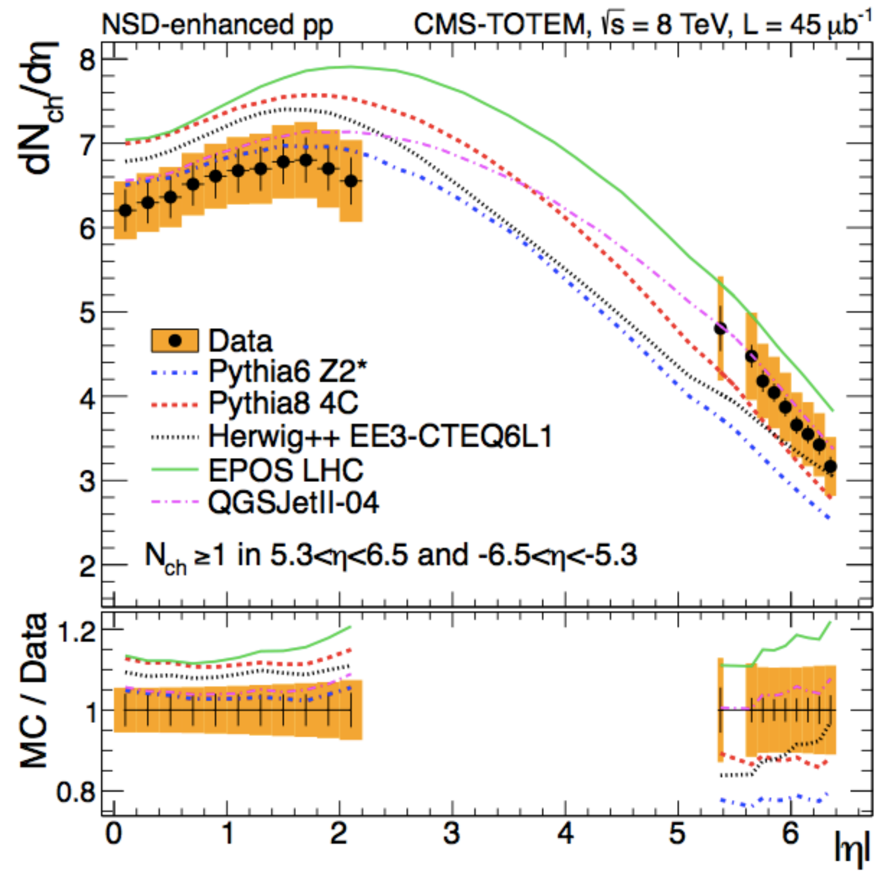
Charged multiplicity in CMS+TOTEM T2

arXiv:1405.0722

- First attempt of CMS+TOTEM common plot
- Reasonable agreement wide η range in 0 ~ 5.3-6.2, while data may prefer less (more) in central (forward)



Inclusive, 8TeV pp

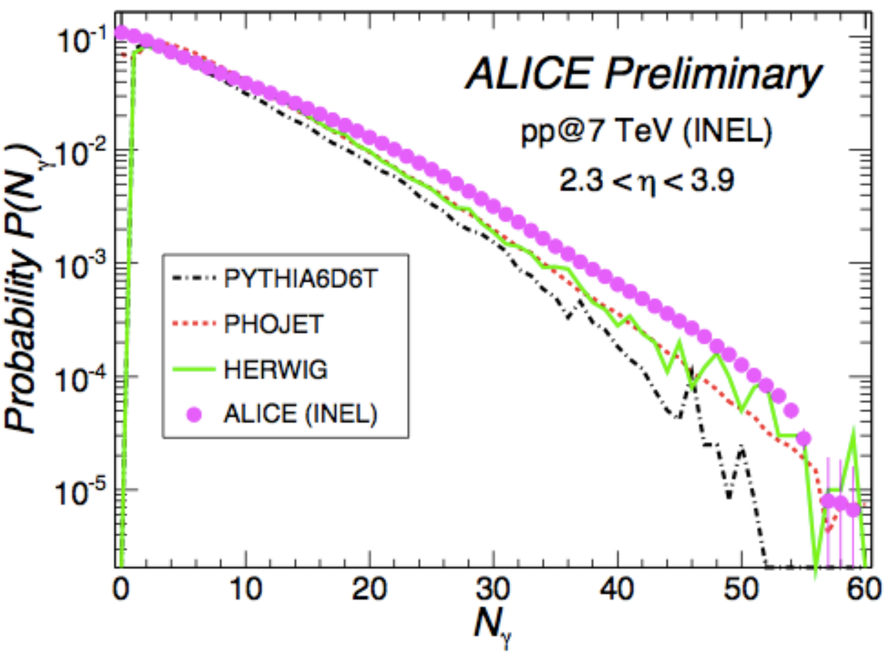


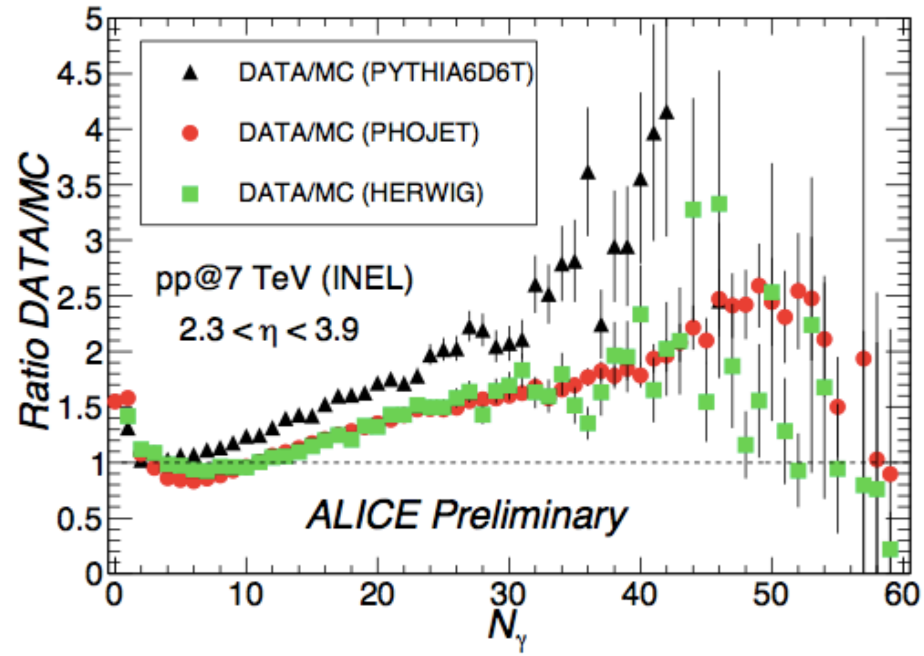
NSD enhanced, 8TeV pp

ALICE photon multiplicity in $2.3<\eta<3.9$

arXiv:1103.1668

- Forward $N\gamma$ by ALICE PMD
- Higher multiplicity than models.



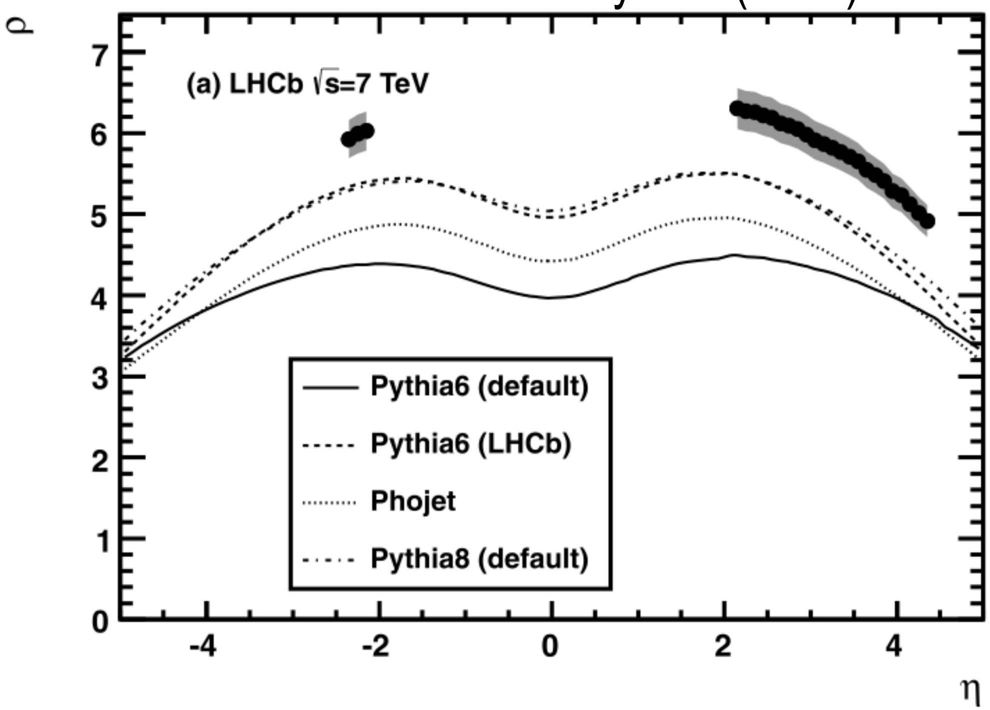


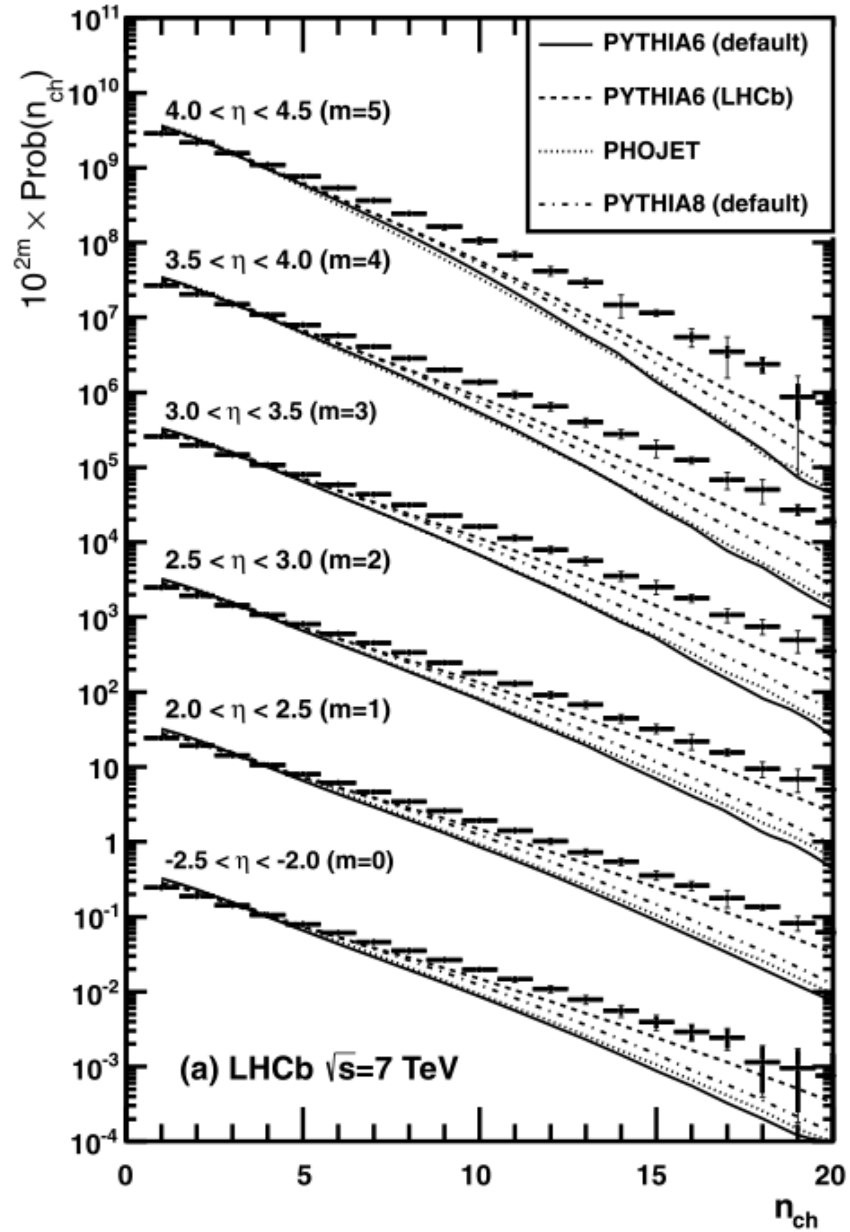
LHCb charged multiplicity

- 2<η<4.5 and -2.5<η<-2
- Data excess substantially
- Forward charm also available ?

(wish for atm prompt ν study)

Eur.Phys.J.C(2012)72:1947



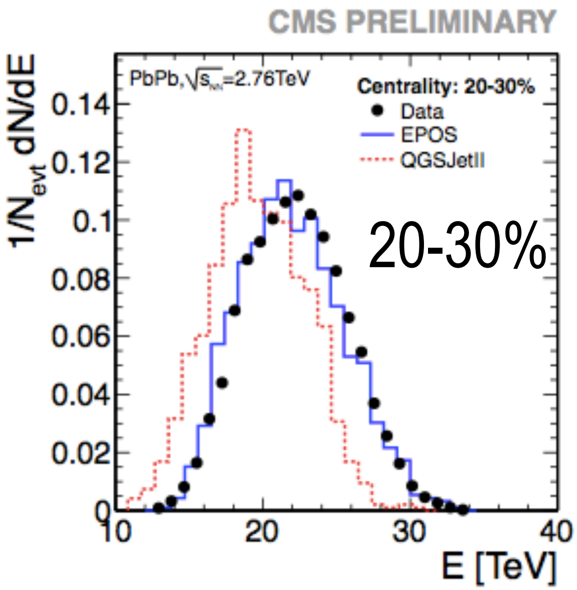


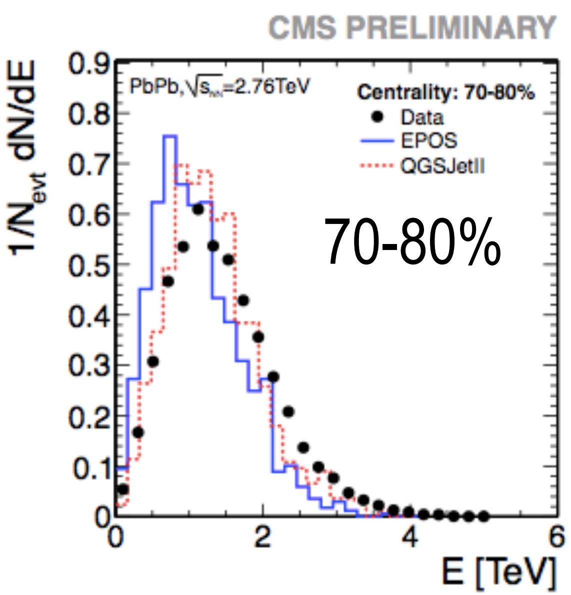
Forward energy flow in PbPb

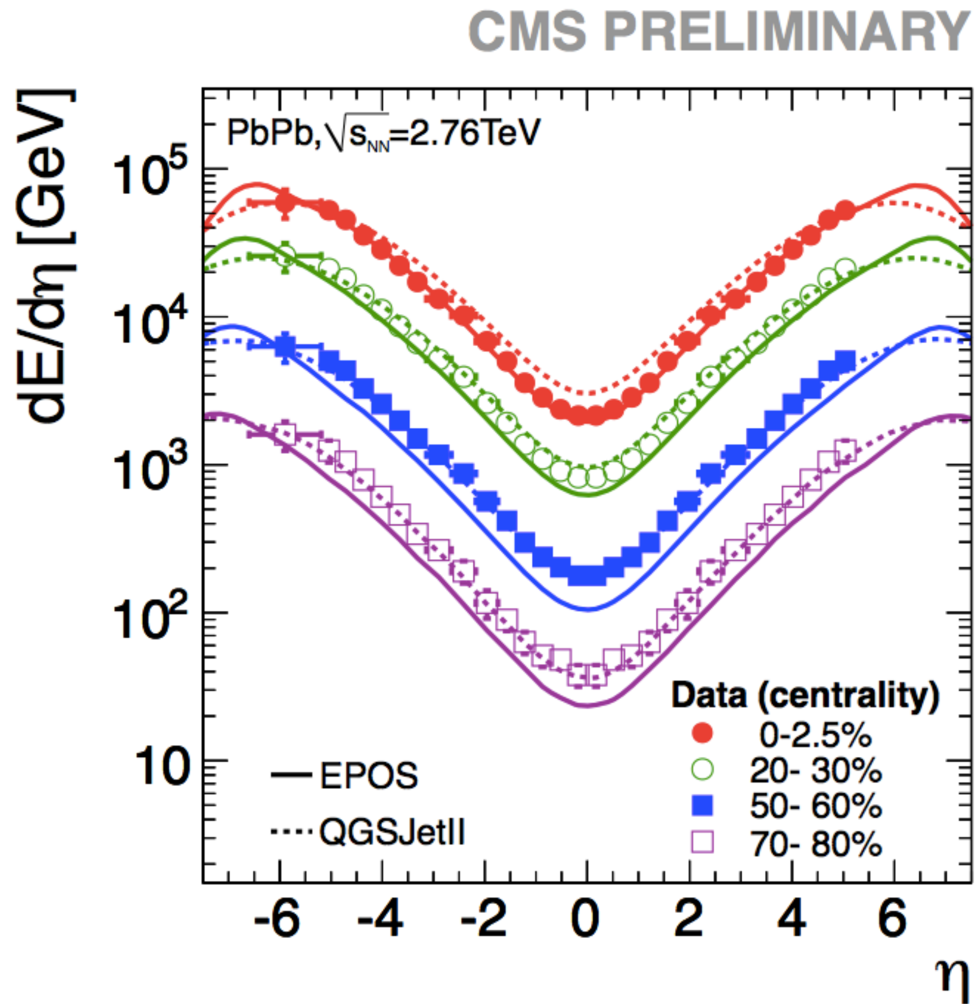
CMS forward energy flow in Pb-Pb

CMS PAS HIN-12-006

- Central : EPOS better
- Peripheral : QGSJET better



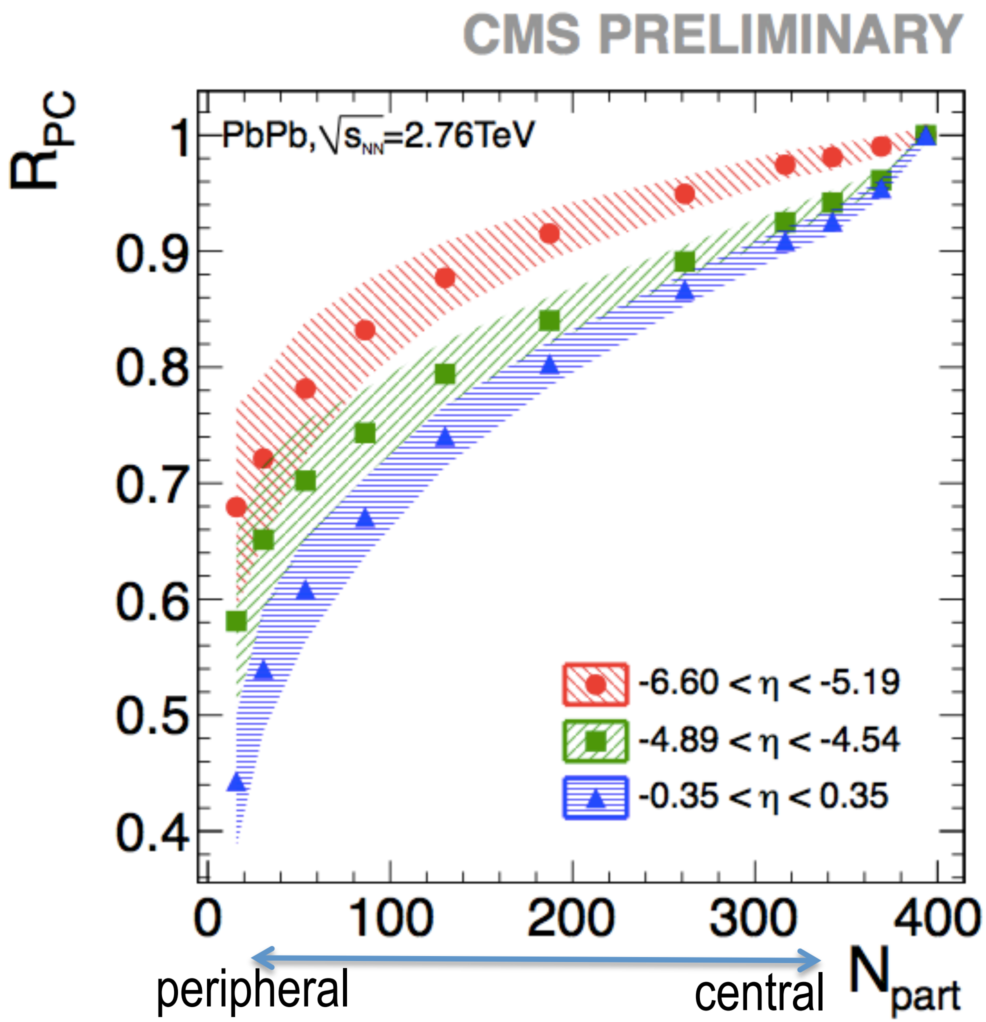


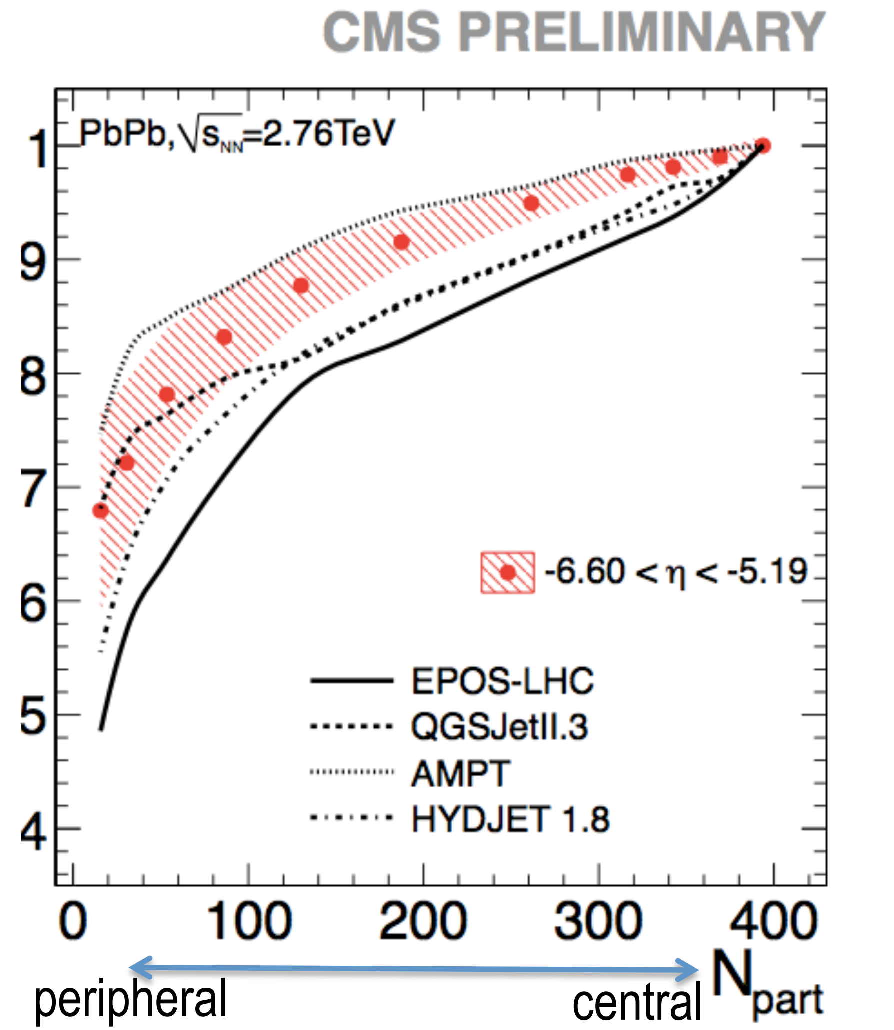


PbPb centrality dependence

$$R_{PC}(\eta, N_{part}) = \frac{\langle E\rangle(\eta, N_{part})}{\langle E\rangle(\eta, N_{part}^{max})} \cdot \frac{N_{part}^{max}}{N_{part}}$$

Forward energy flow
Weaker centrality dependence





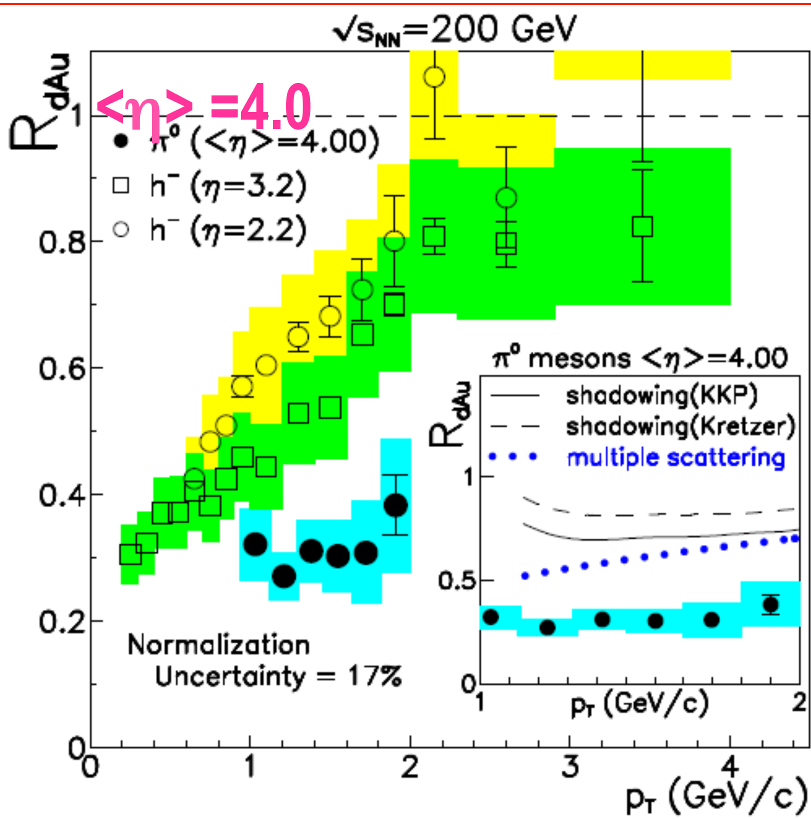
Nuclear modification in pPb

Nuclear shadowing at very forward in p-A ?

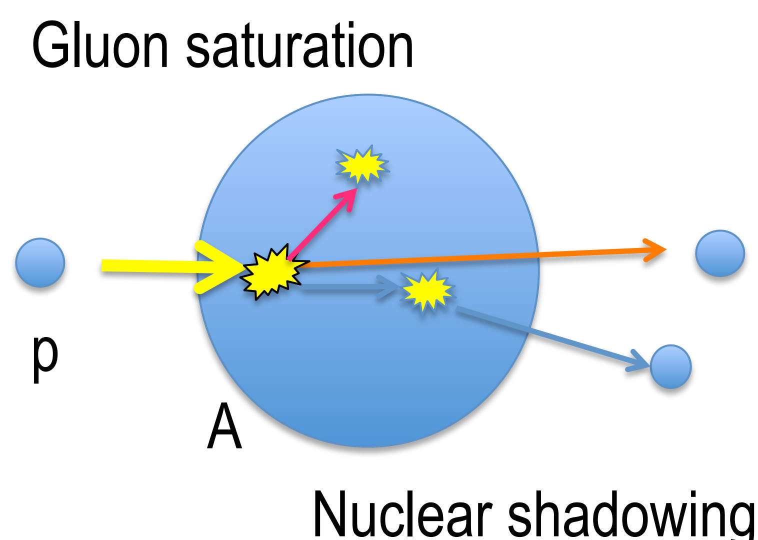
- Suppression and PT broadening due to gluon saturation
- Maybe large at very forward (small-x)

$$R^{Y}_{\mathrm{dAu}} = \frac{\sigma^{pp}_{\mathrm{inel}}}{\langle N_{\mathrm{bin}} \rangle \sigma^{dAu}_{\mathrm{hadr}}} \frac{E\, d^3\sigma/dp^3(d + Au \rightarrow Y + X)}{E\, d^3\sigma/dp^3(p + p \rightarrow Y + X)}$$

$\langle N_{bin} \rangle$:Number of N-N binary collisions (from Glauber model)



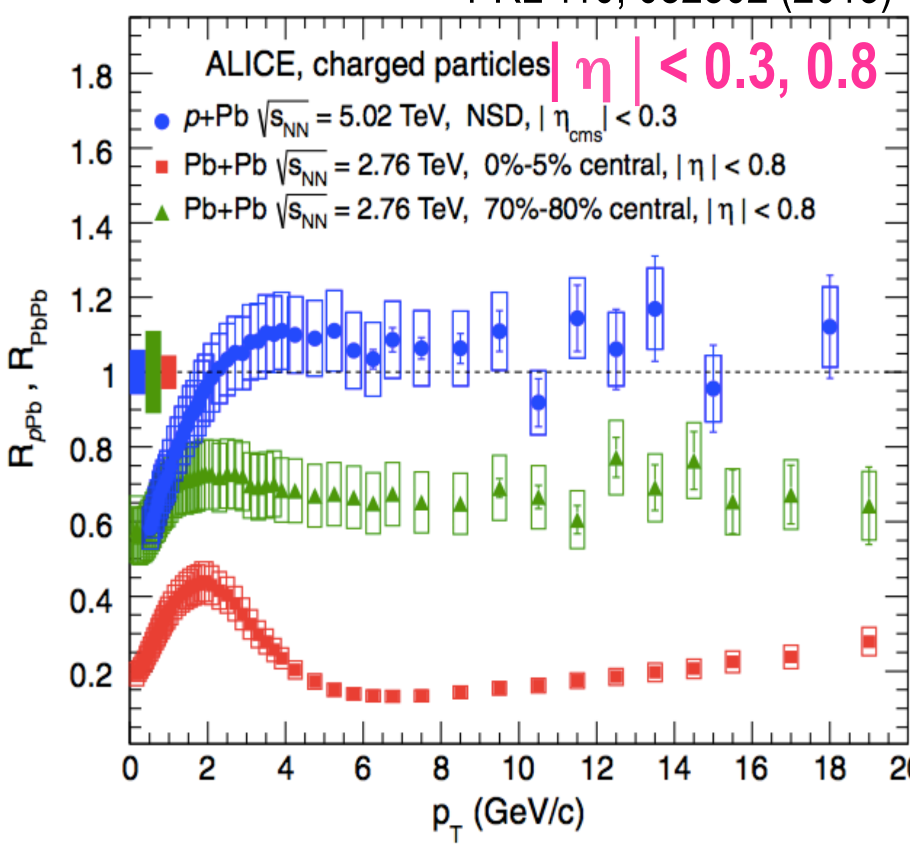
RHIC STAR d-Au, PRL 97, 152302 (2006)



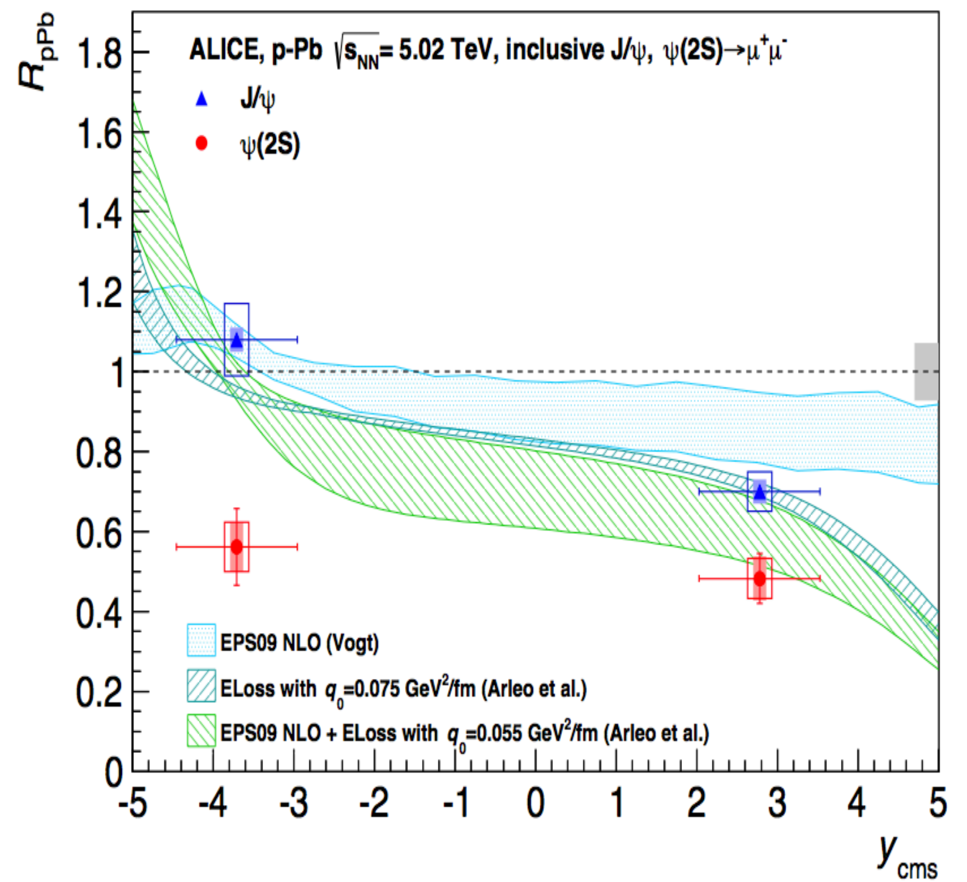
ALICE pPb 5.02TeV R_{pPb}: central and forward

- Large suppression at low PT in pPb in central
- J/φ suppression in forward p side, but no in Pb side
- ψ(2S) suppressed in both side of forward

PRL 110, 082302 (2013)



arXiv:1405.3796

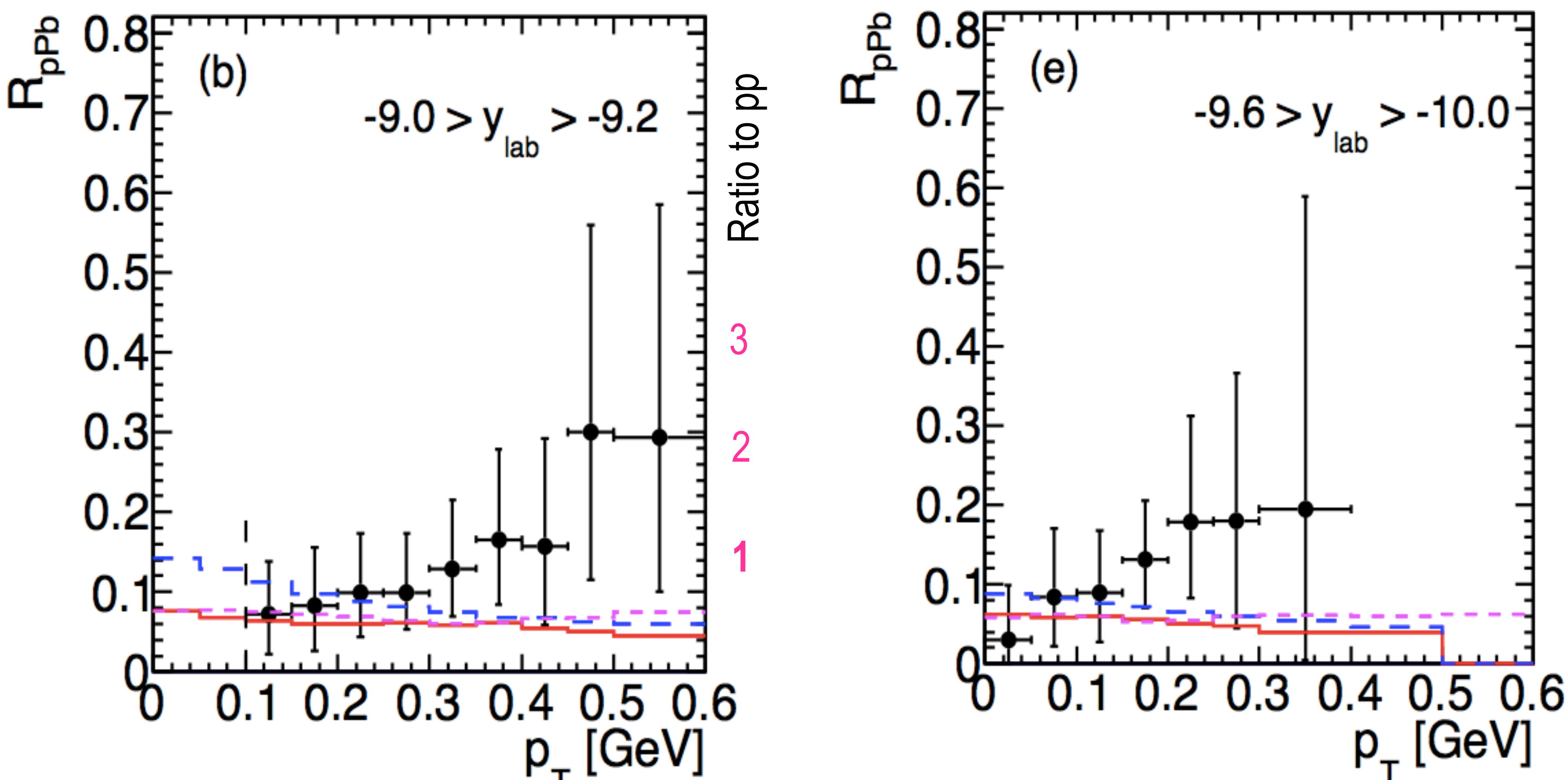


LHCf nuclear modification factor (-11.0>η > -8.9)

- Very large suppression (~ 0.1) at P_T ~ 100MeV region in p-side
- Models also reproduce large suppression, but PT dependence ?

$$R_{\mathrm{pPb}} \equiv \frac{\sigma_{\mathrm{inel}}^{\mathrm{pp}}}{\langle N_{\mathrm{coll}}\rangle \sigma_{\mathrm{inel}}^{\mathrm{pPb}}} \frac{E d^3\sigma^{\mathrm{pPb}}/dp^3}{E d^3\sigma^{\mathrm{pp}}/dp^3}$$

$\langle N\mathrm{coll}\rangle = 6.9 \pm 0.7$

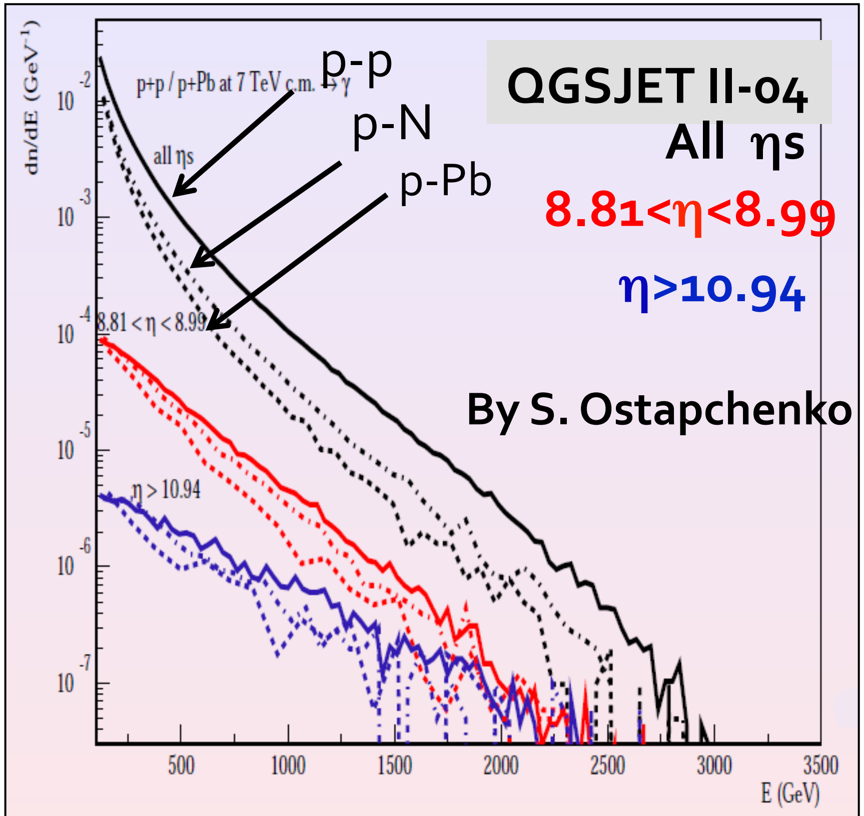


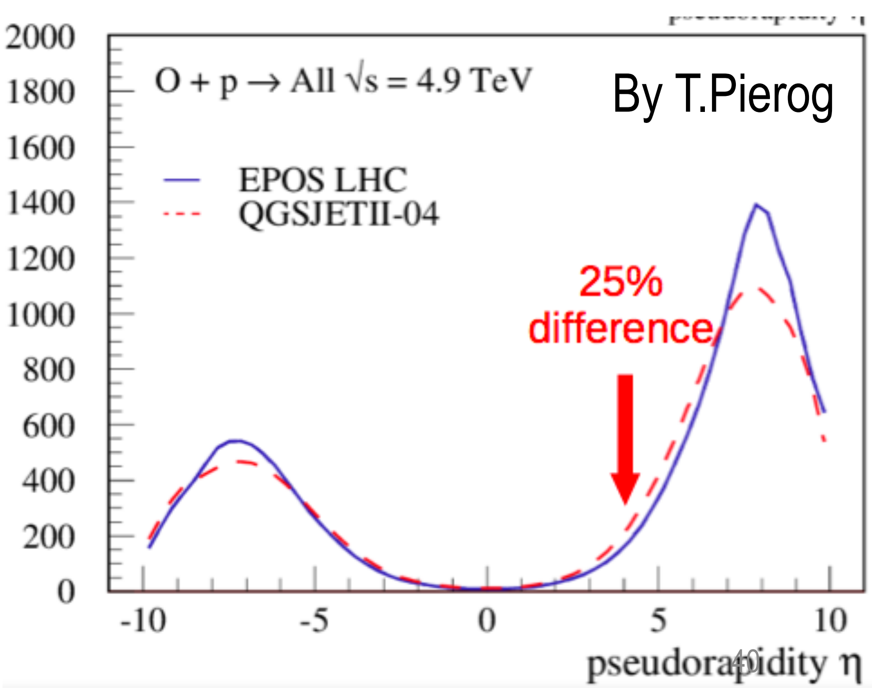
Future

Possible future p-Oxygen run

- Important missing information ; nuclear shadowing
- Large suppression 0.1 for p-Pb for very forward π^0 at low PT
- Less expected for p-Light Ion, but model dependent (~25%)
- Oxygen beam is technically feasible in LHC

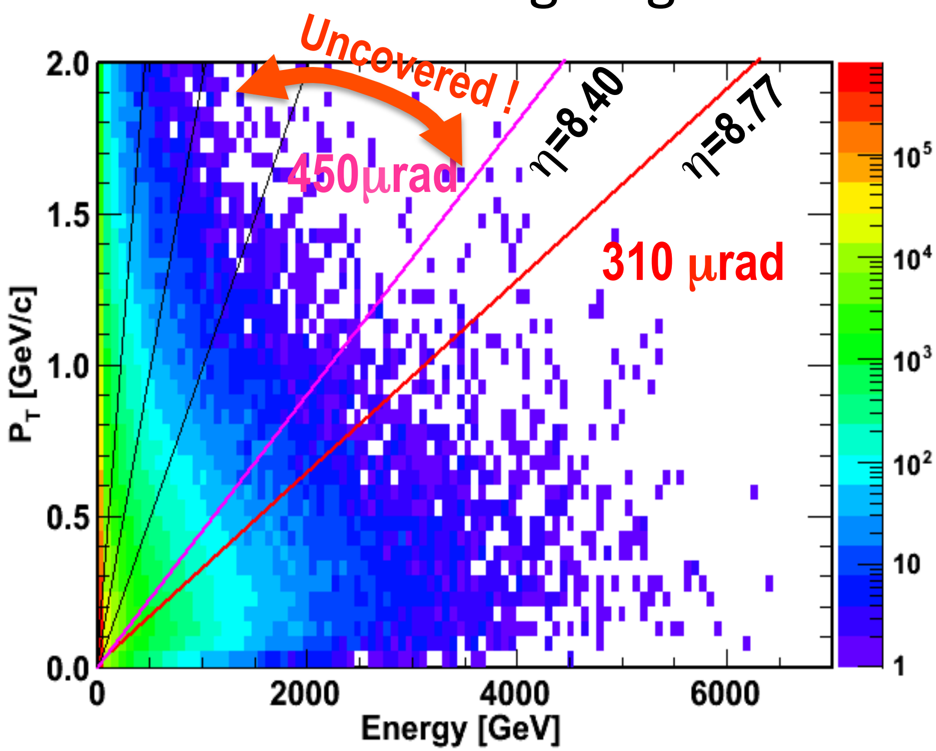
Current largest diff. btw 2 models

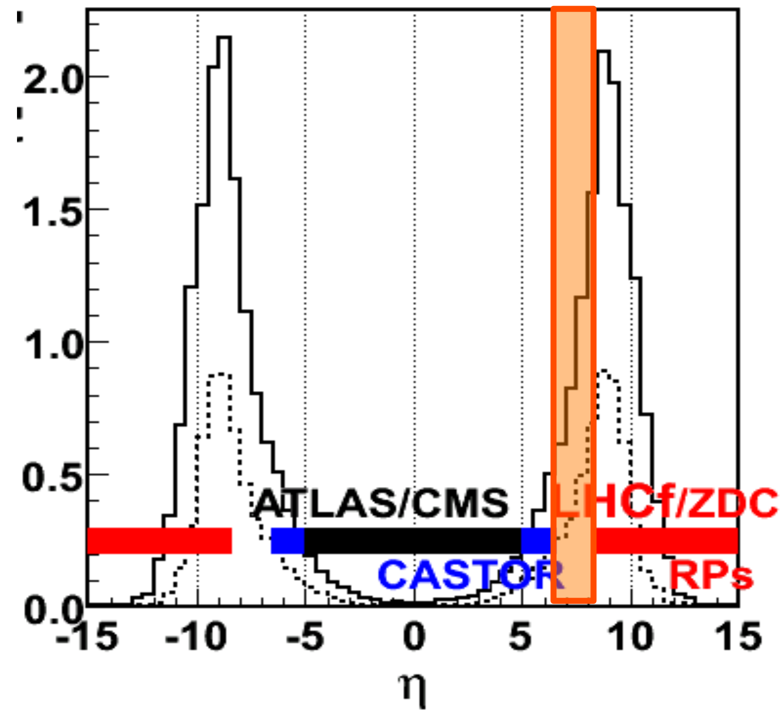


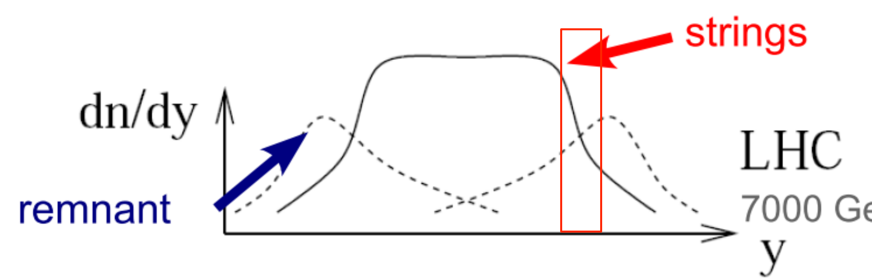


Missing η = 6.6-8.4 coverage, how cover ?

- Current LHCf acceptance limited by beam pipe vertical aperture at D1 exit
- CMS CASTOR Z=14.3m, η = -5.2 - -6.6
- Still large energy flow fraction here
- Interesting transition region from diffraction to string fragmentation.



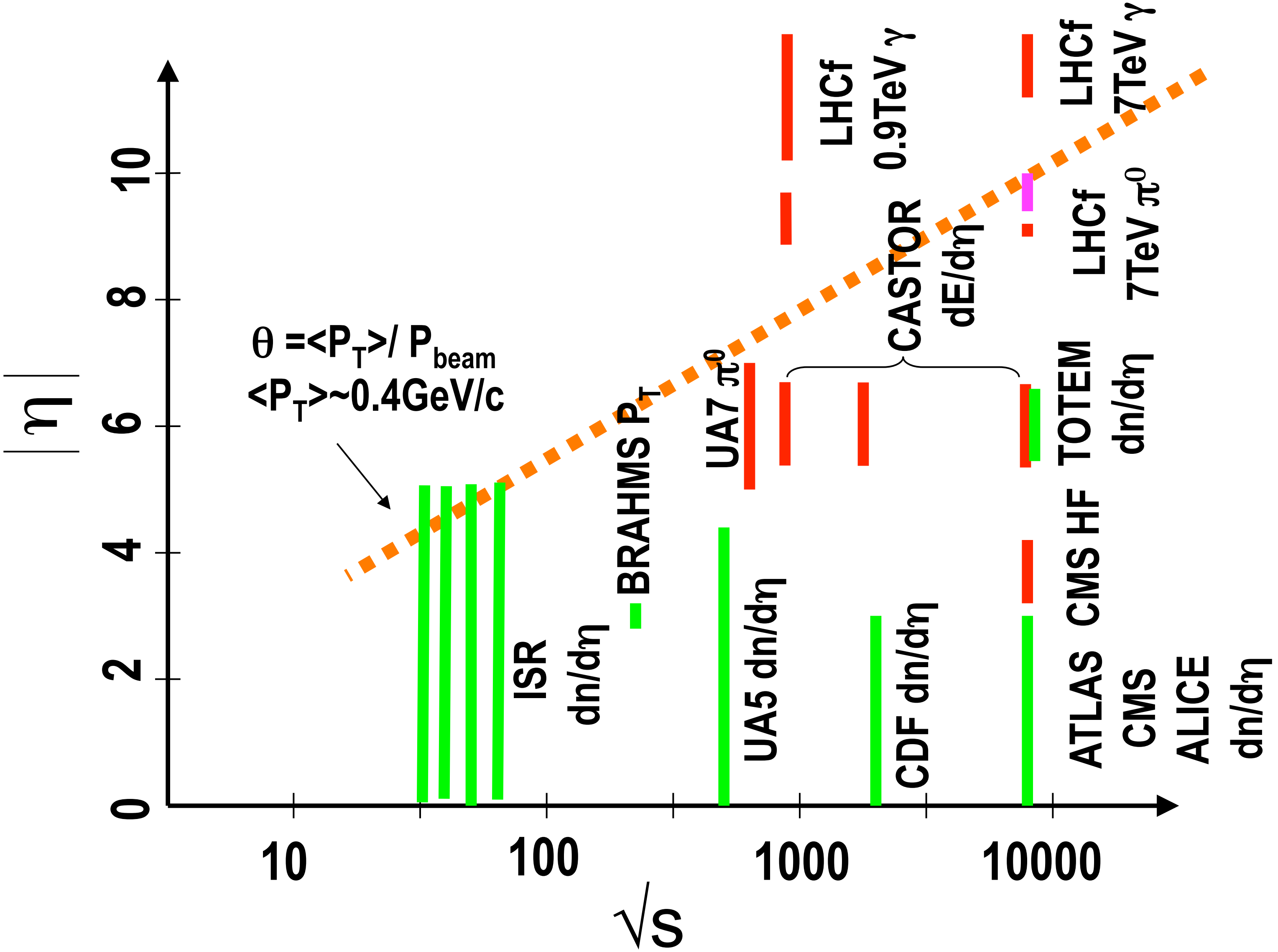




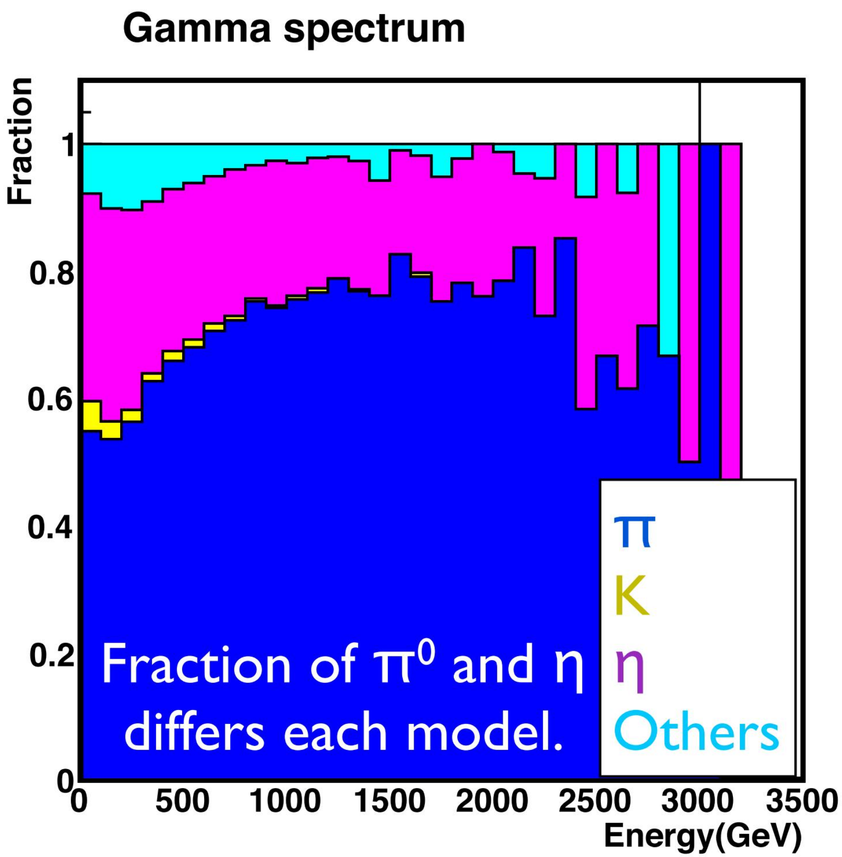
Summary

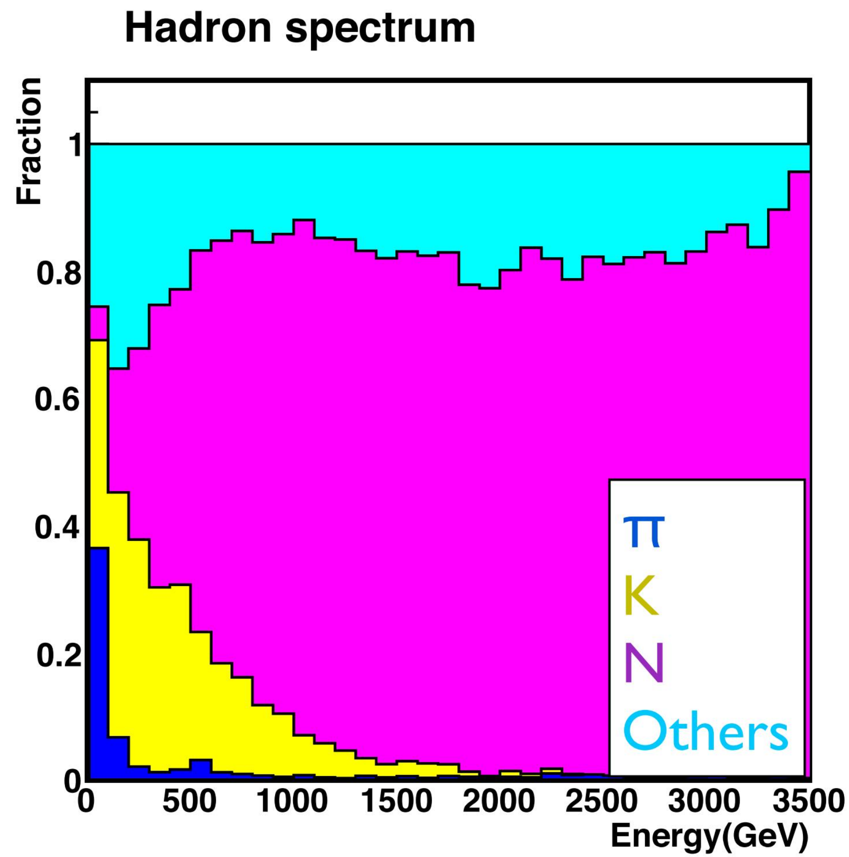
- Now various forward particle production data available at LHC for pp, pPb and PbPb at various energies.
- What we observed is ;
  - None of models can reproduce perfectly
  - But CR models eventually work reasonably well
- We may start to see some trends in forward (personal view)
  - Less energy flow, softer spectrum of $\pi 0$
  - More abundant and larger energy flow of baryon (neutrons)
  - More harder MPI collisions to produce higher multiplicity
  - Larger suppression due to nuclear effect
  - These may suggest some new insight of QCD ?(saturation, etc..?)
- Need more data
  - 13 TeV ! Higher energy density, larger forward collimation
  - Less knowledge for nuclear effect. Future p-O run ?

Summary : forward spectra coverage



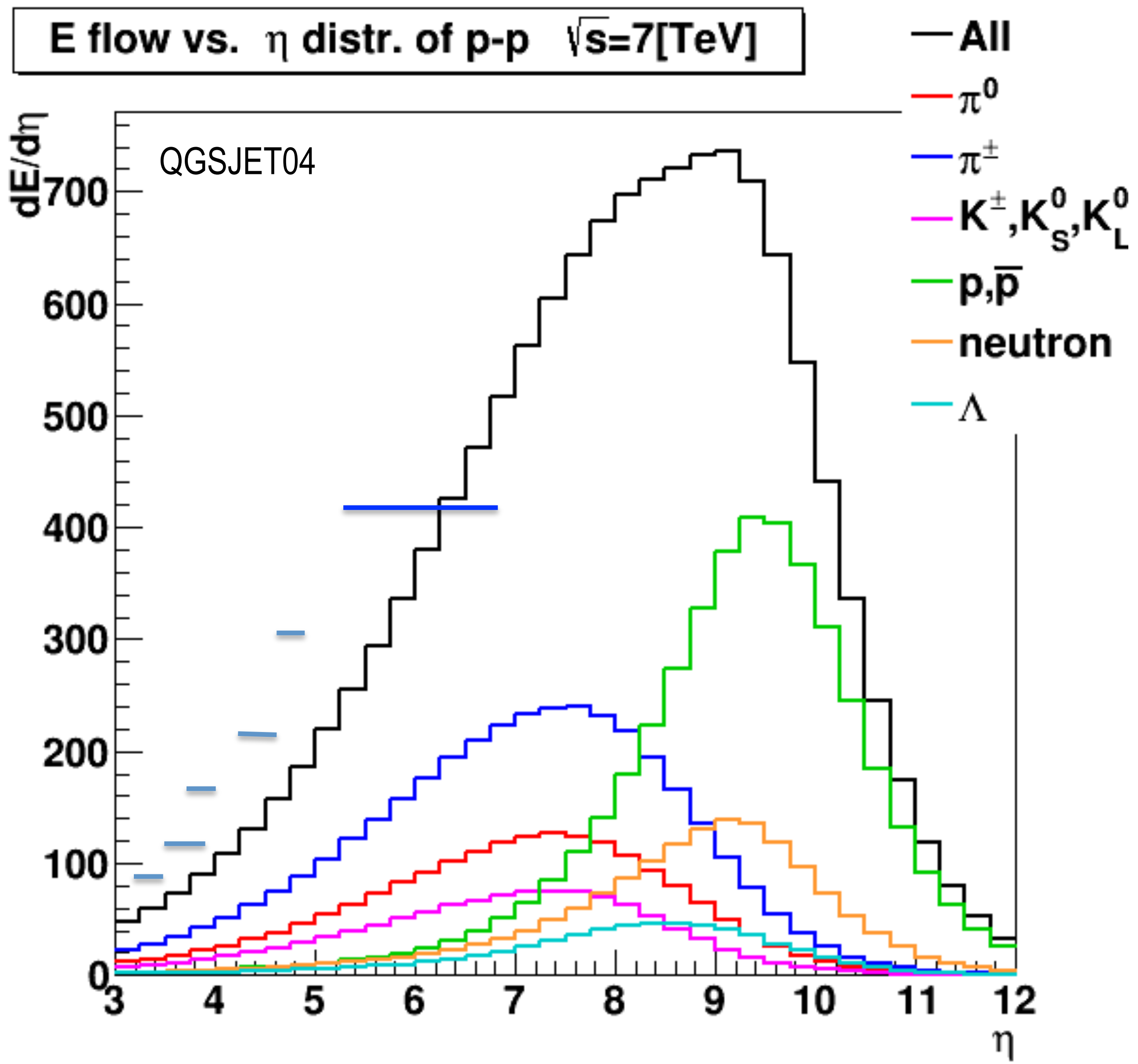
Parent particles relevant for LHCf observations



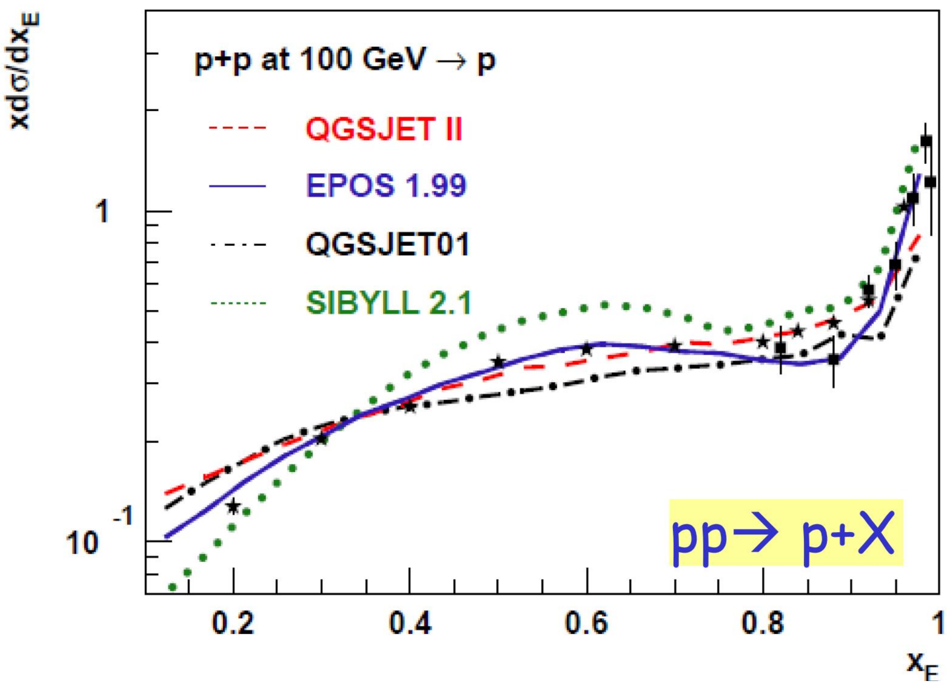


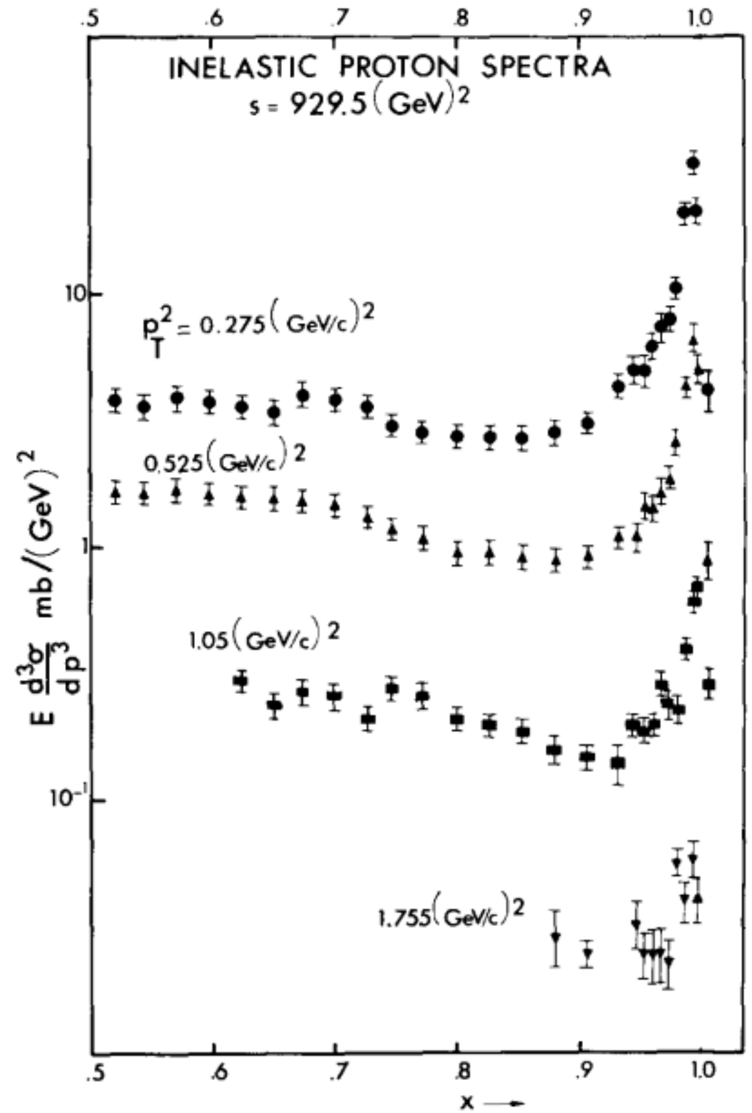
Sybill at 7TeV

7TeV pp energy flow summary



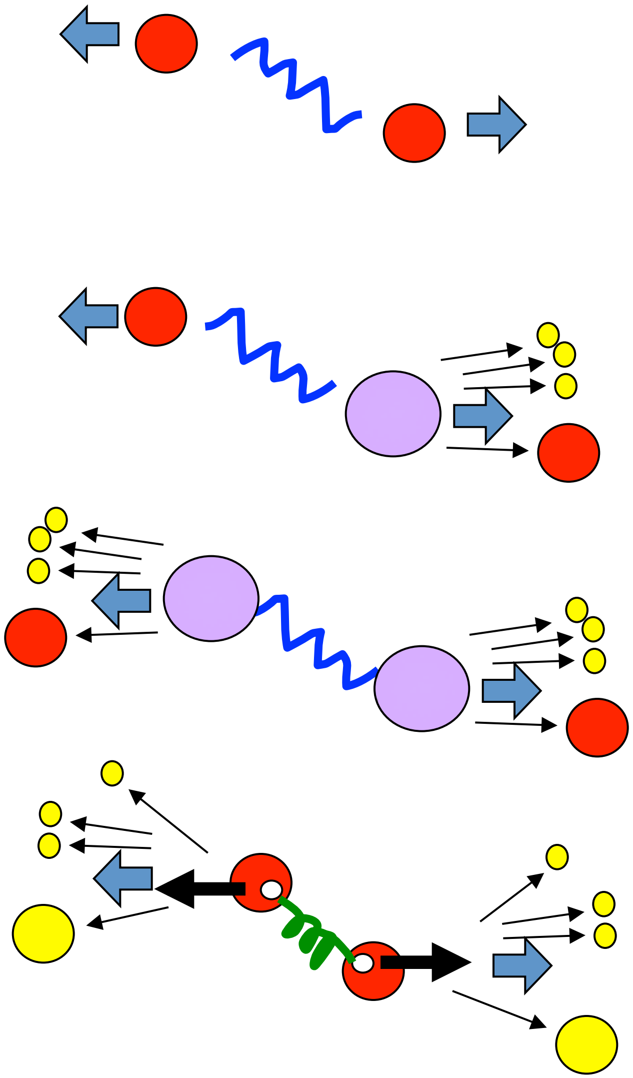
Elasticity (X_F of leading baryon)



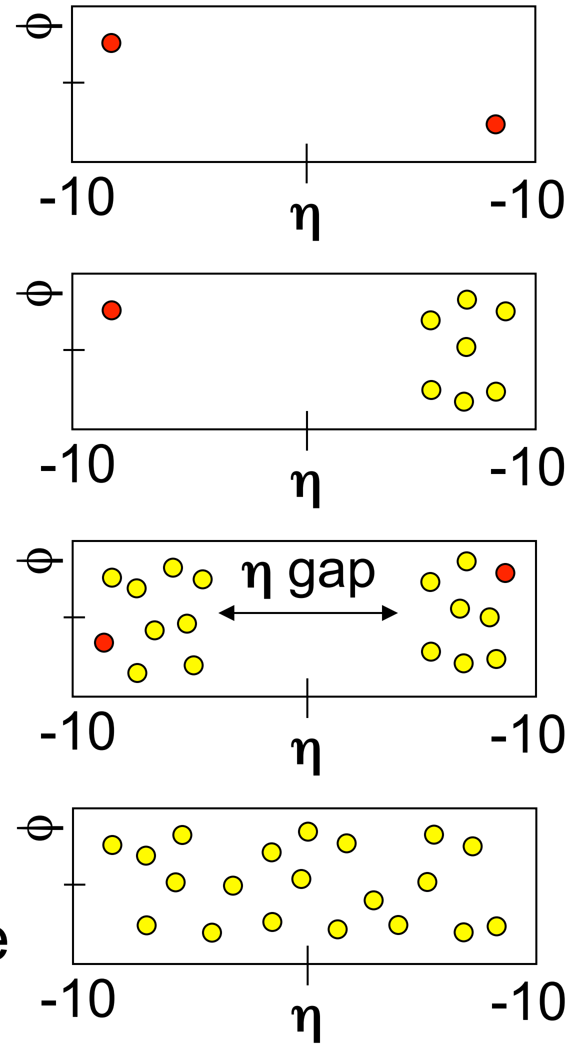


pseudorapidity and interactions

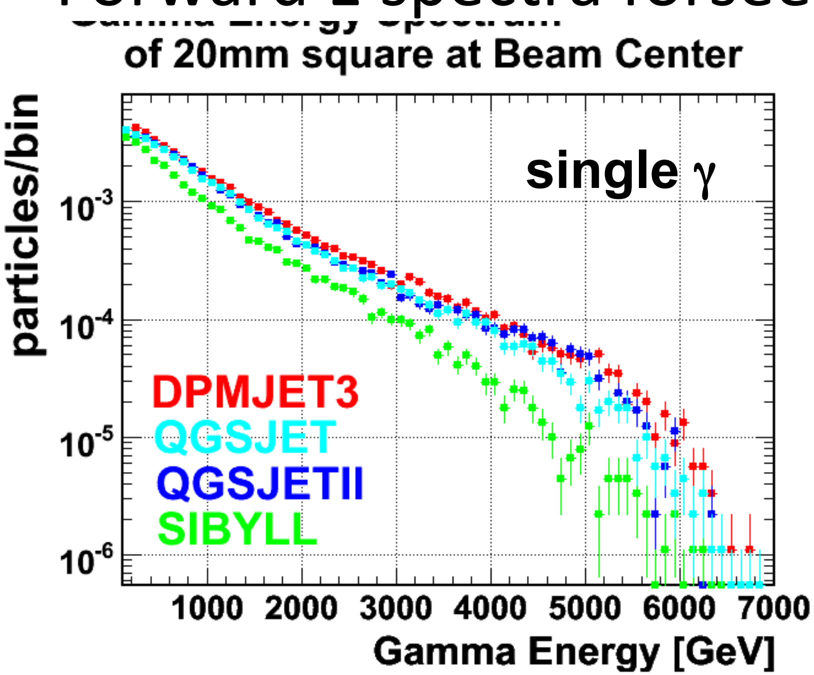
σ @7TeV

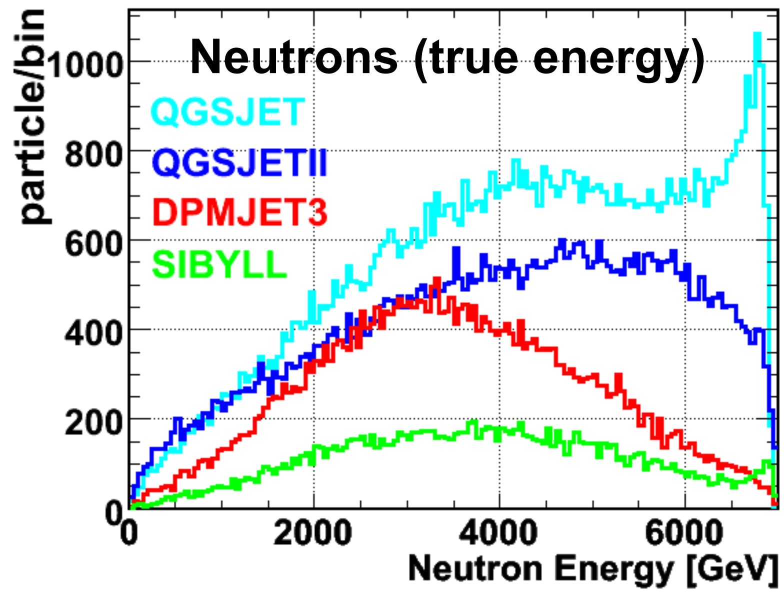


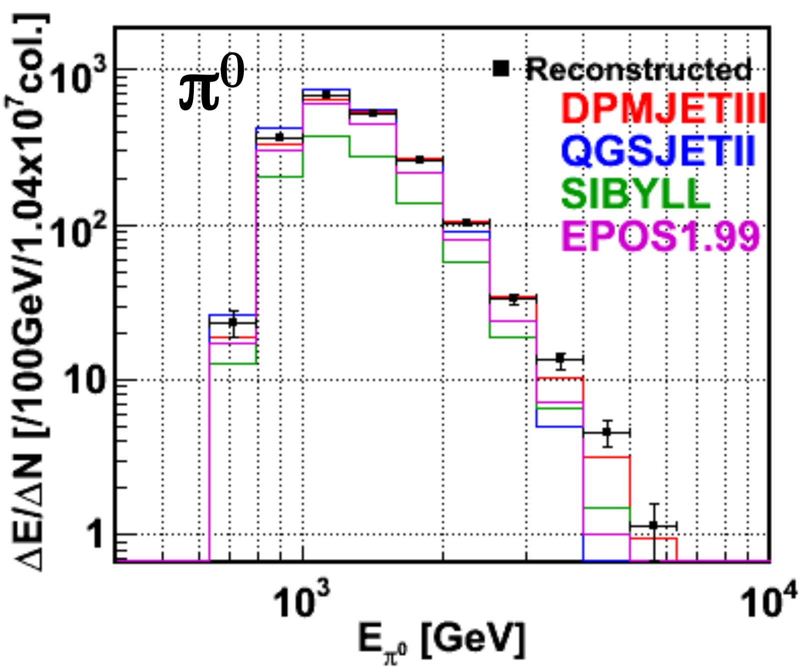
Interaction	σ @7TeV
Elastic	~25mb
Single diffractive	~10mb
Double diffractive	~10mb
Non-diffractive	~50mb

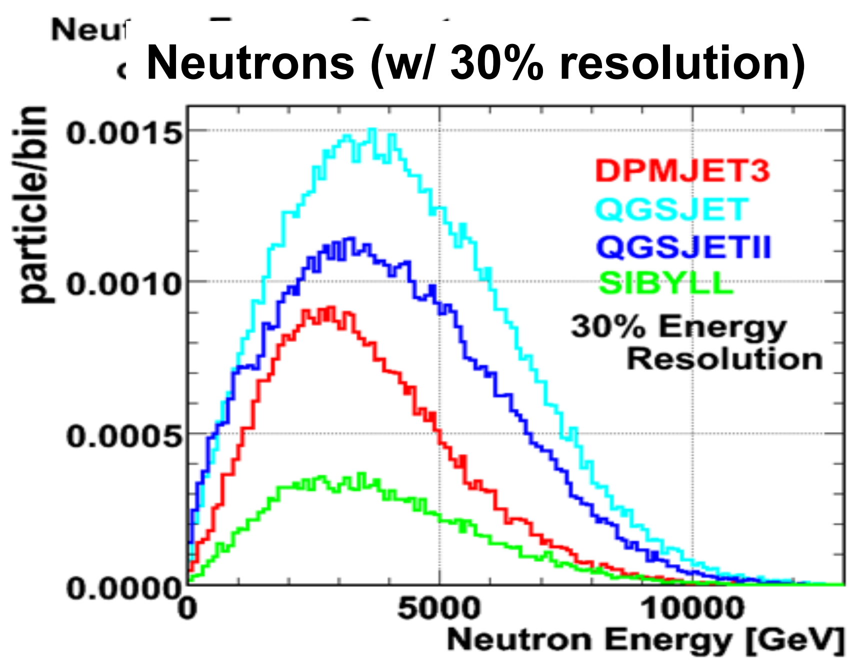


Forward E spectra forseen at 14TeV (MC for ~0.1nb^{-1})

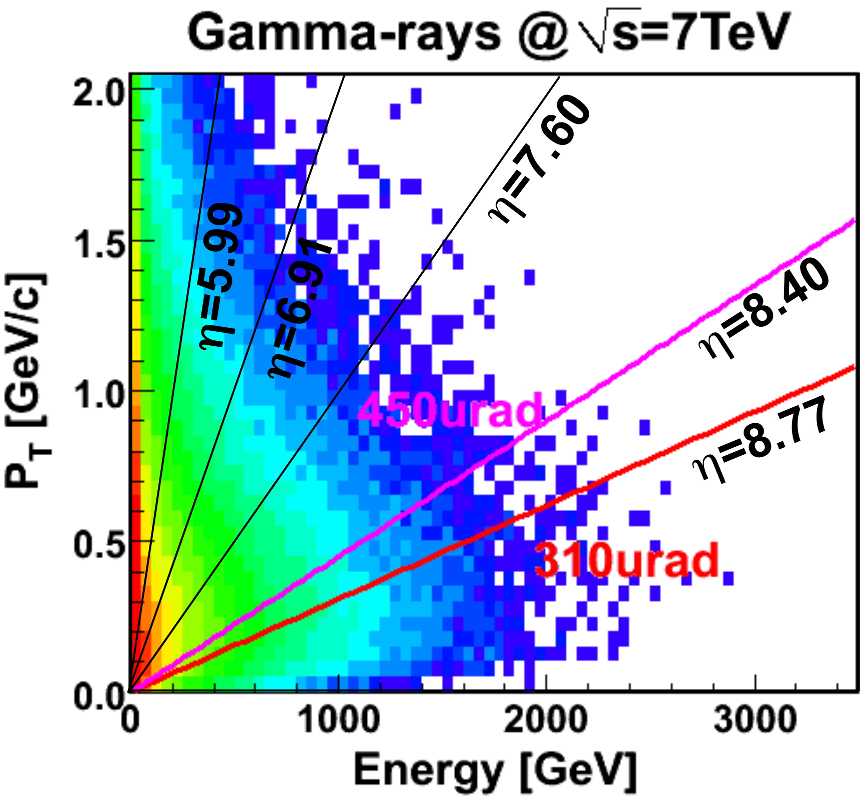


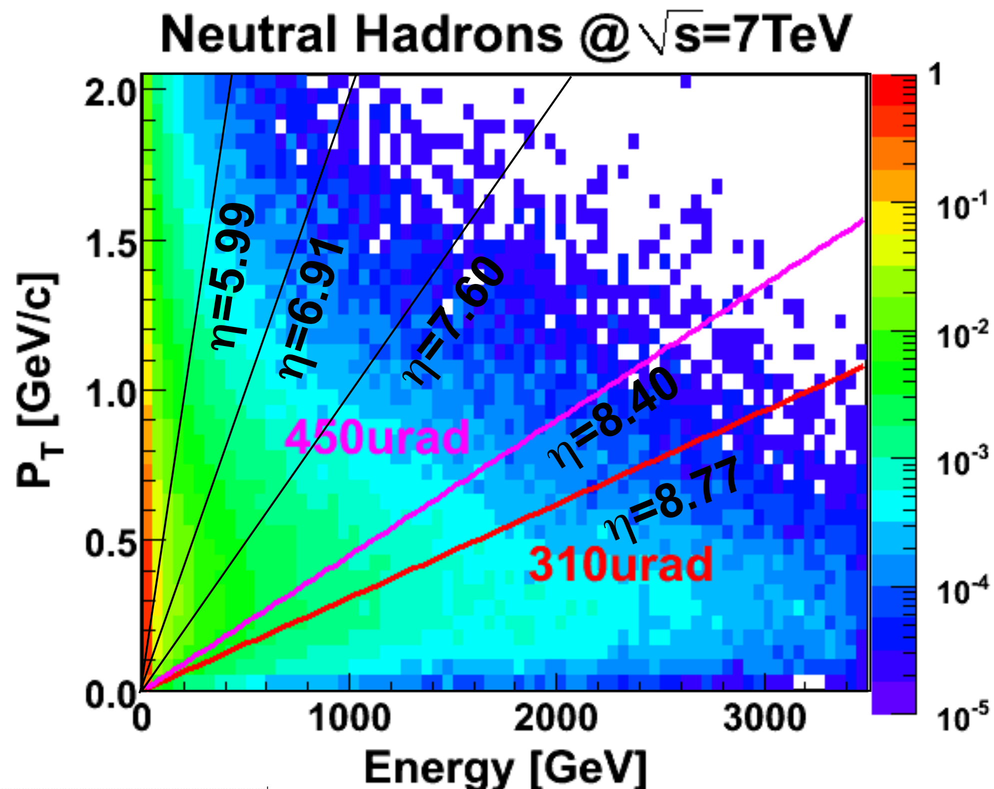


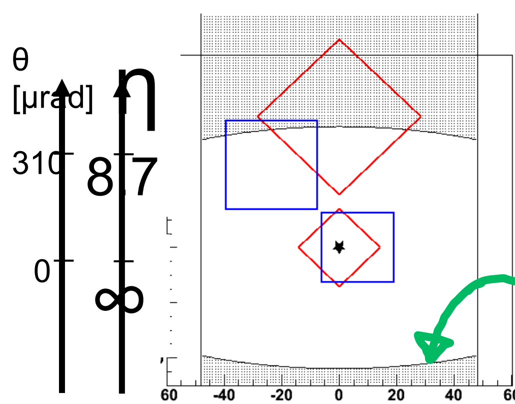




Rapidity vs Forward energy spectra



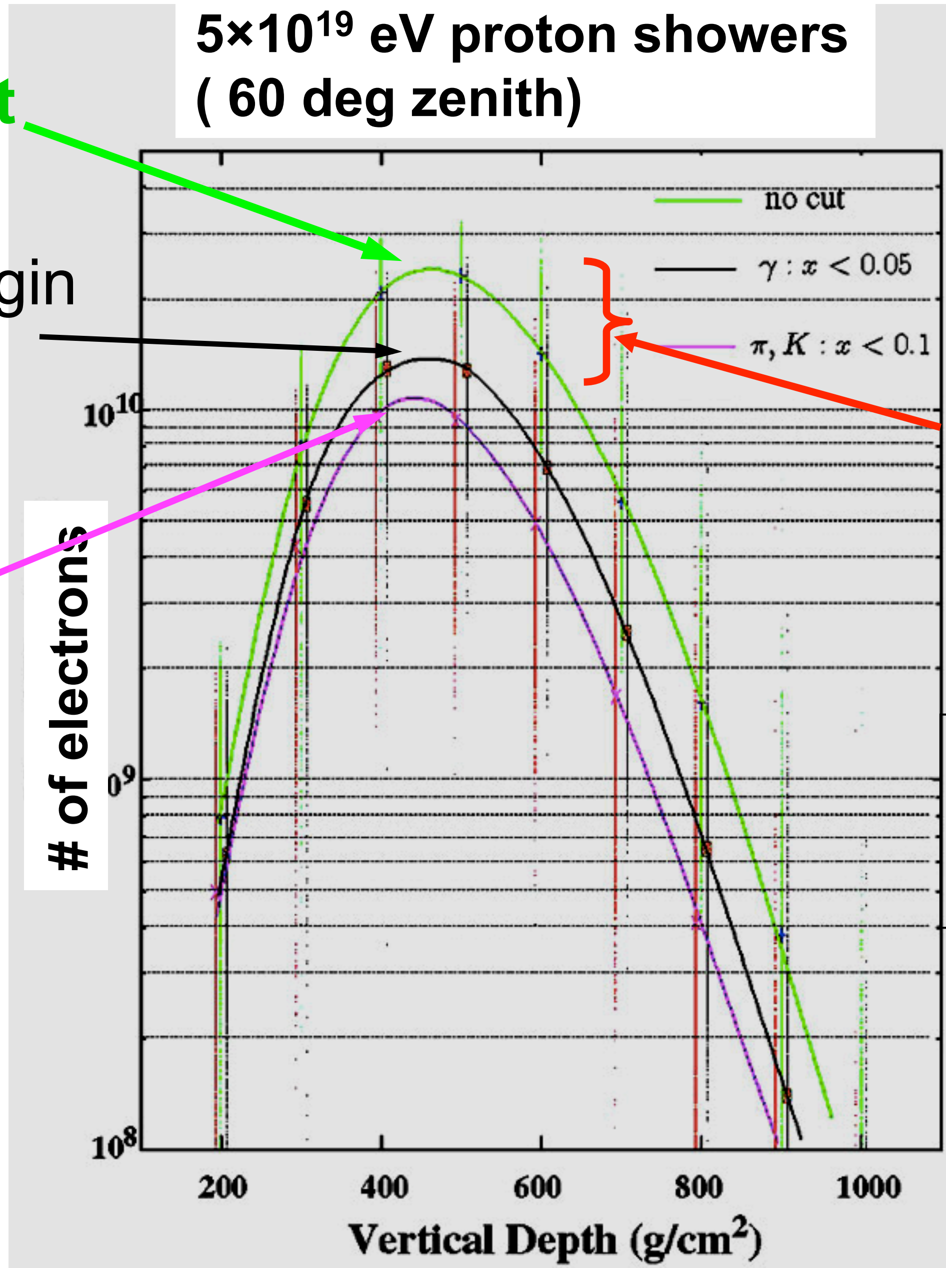




Viewed from IP1 (red:Arm1, blue:Arm2)

Projected edge of beam pipe

Contribution from very forward production



No cut

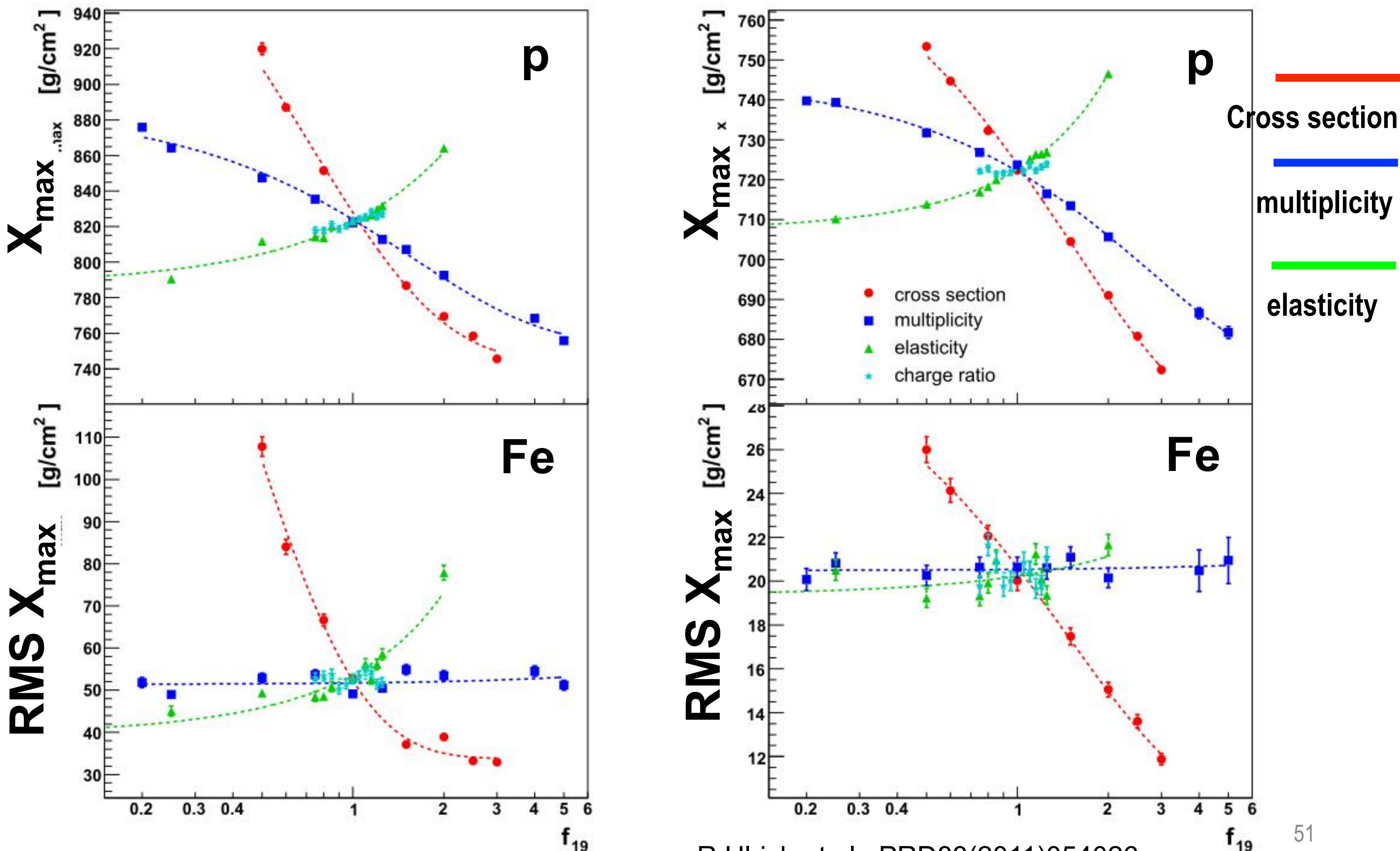
low X_F γ origin ($x_F < 0.05$)

π,K origin ($x_F < 0.1$)

Half of shower particles comes from large X_F γ

Measurement at very forward region is needed

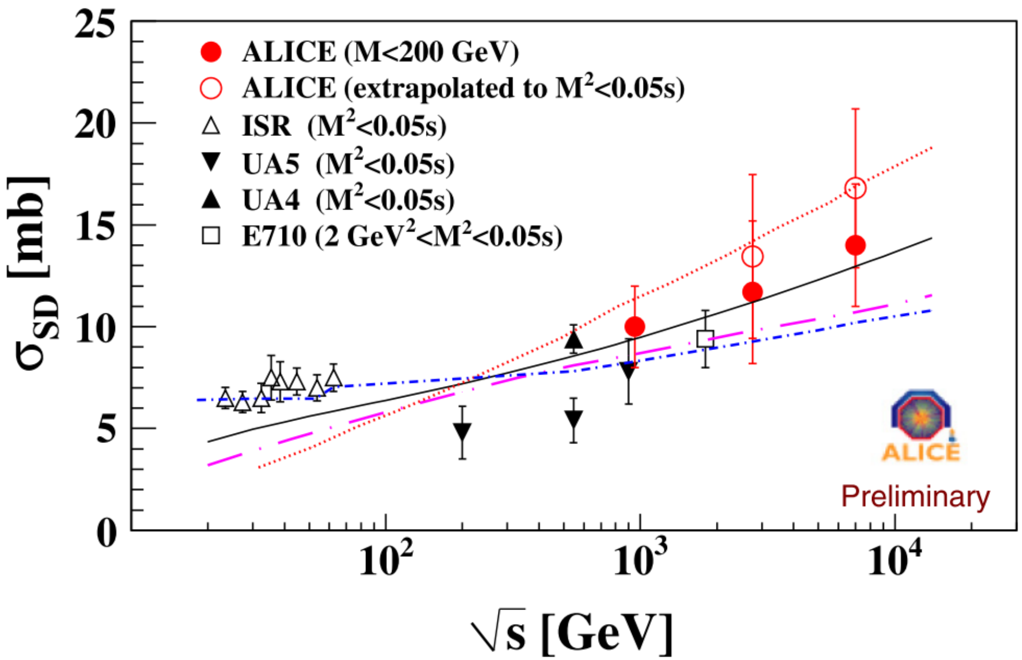
Impact of parameters of interactions

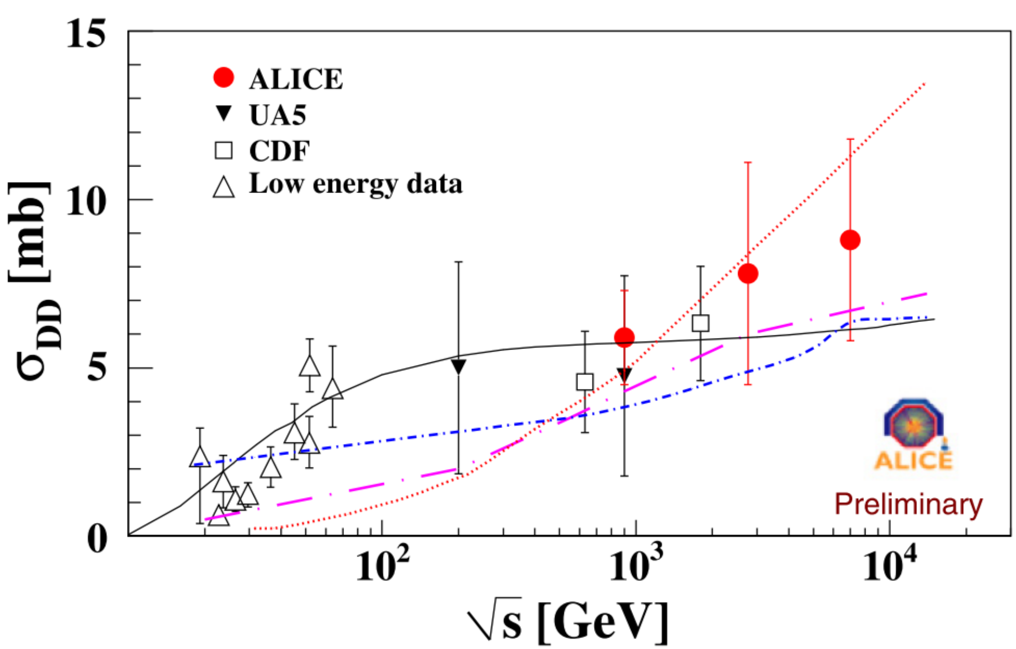


R.Ulrich et al., PRD83(2011)054026

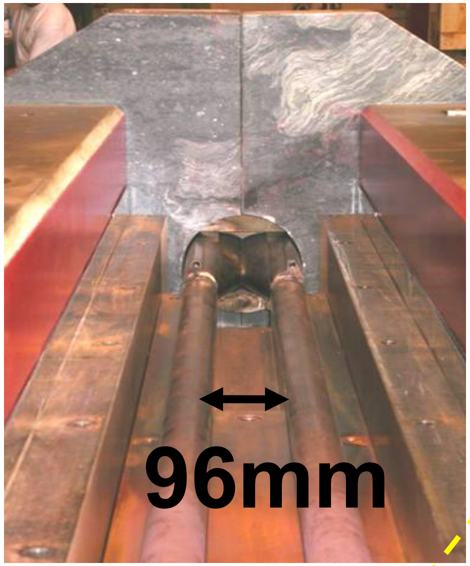
ALICE $\sigma_{diffraction}$

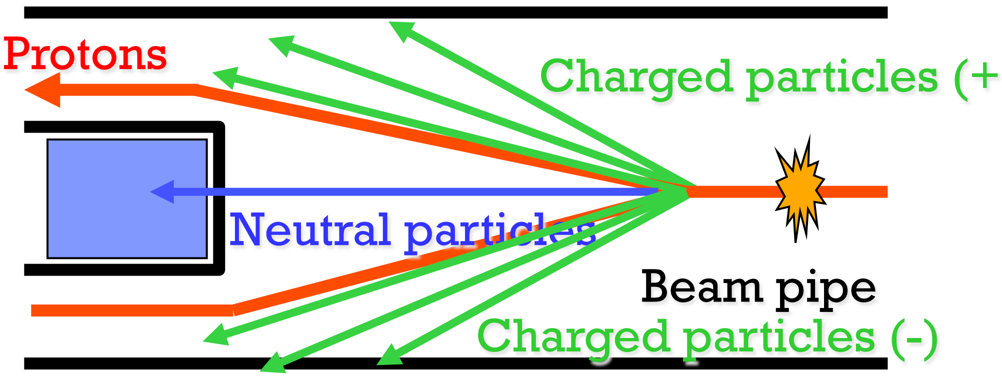
J. Phys. G: Nucl. Part. Phys. 38 (2011) 124044

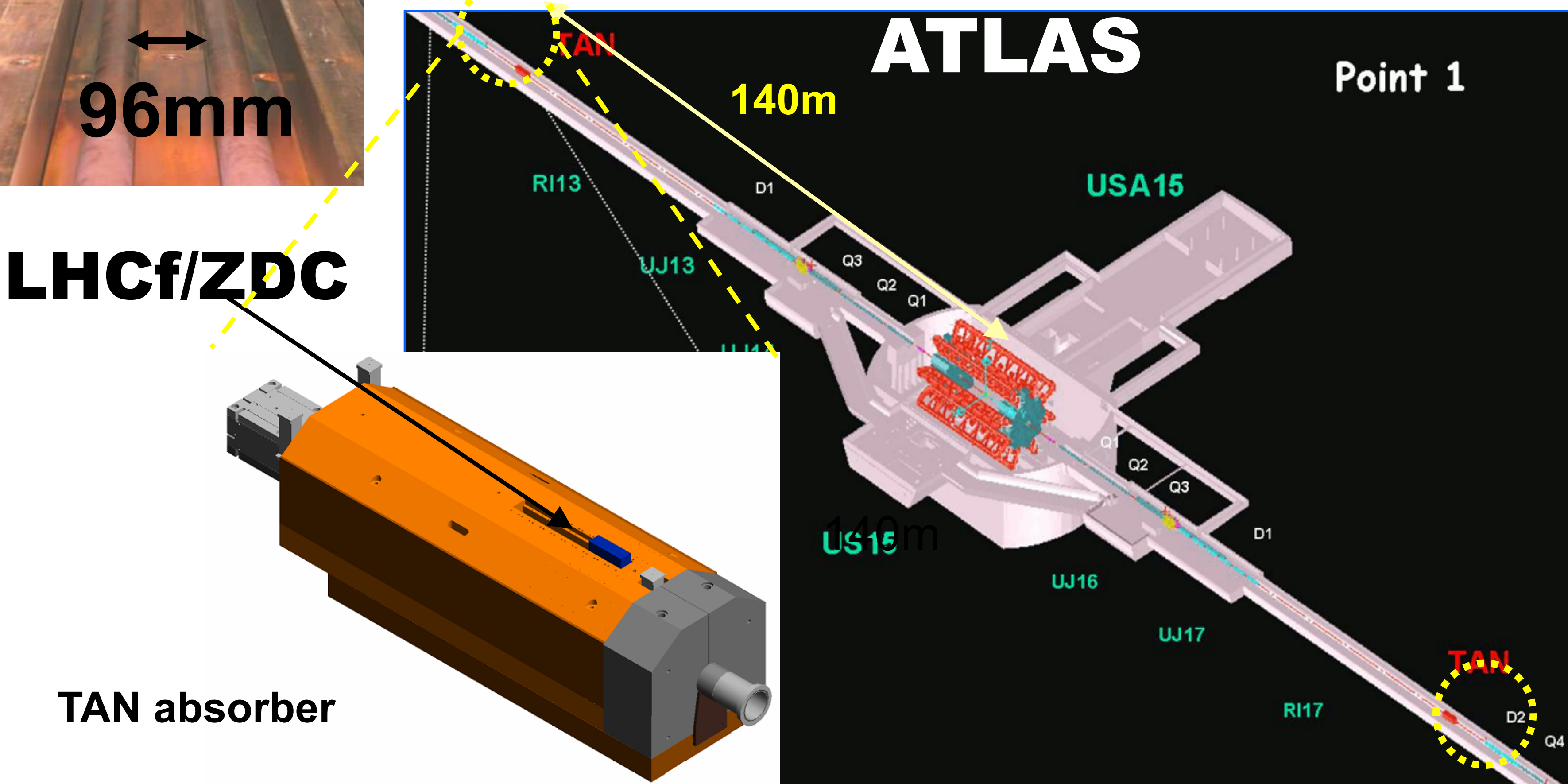




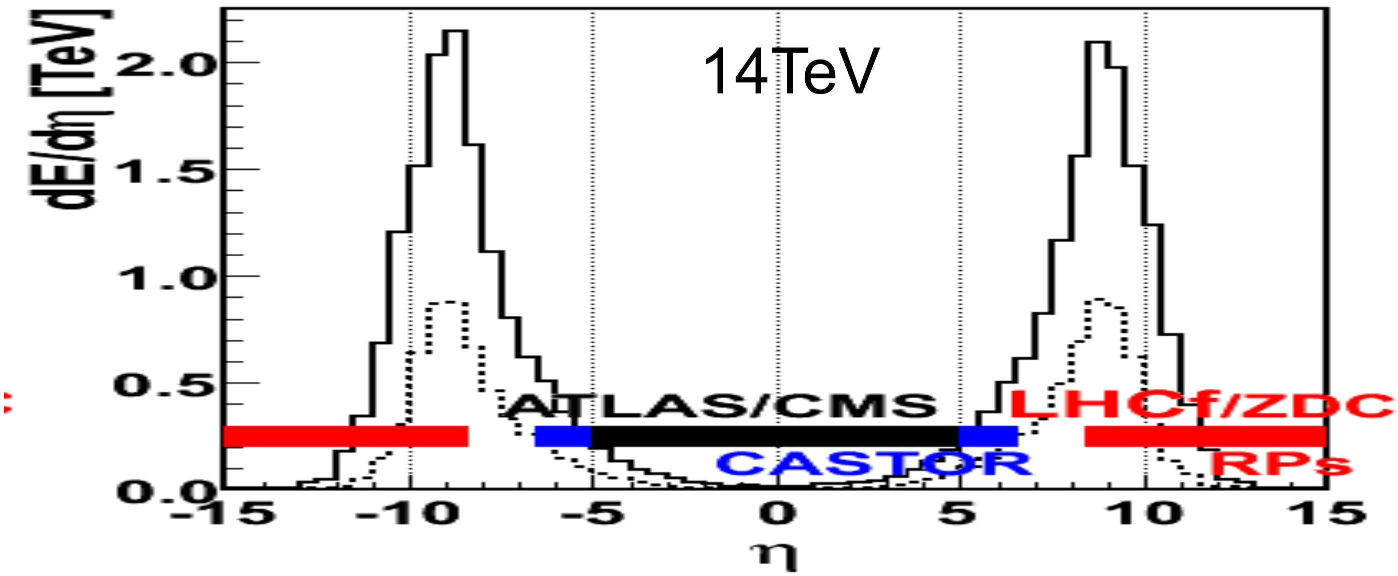
LHC zero degree experimental site

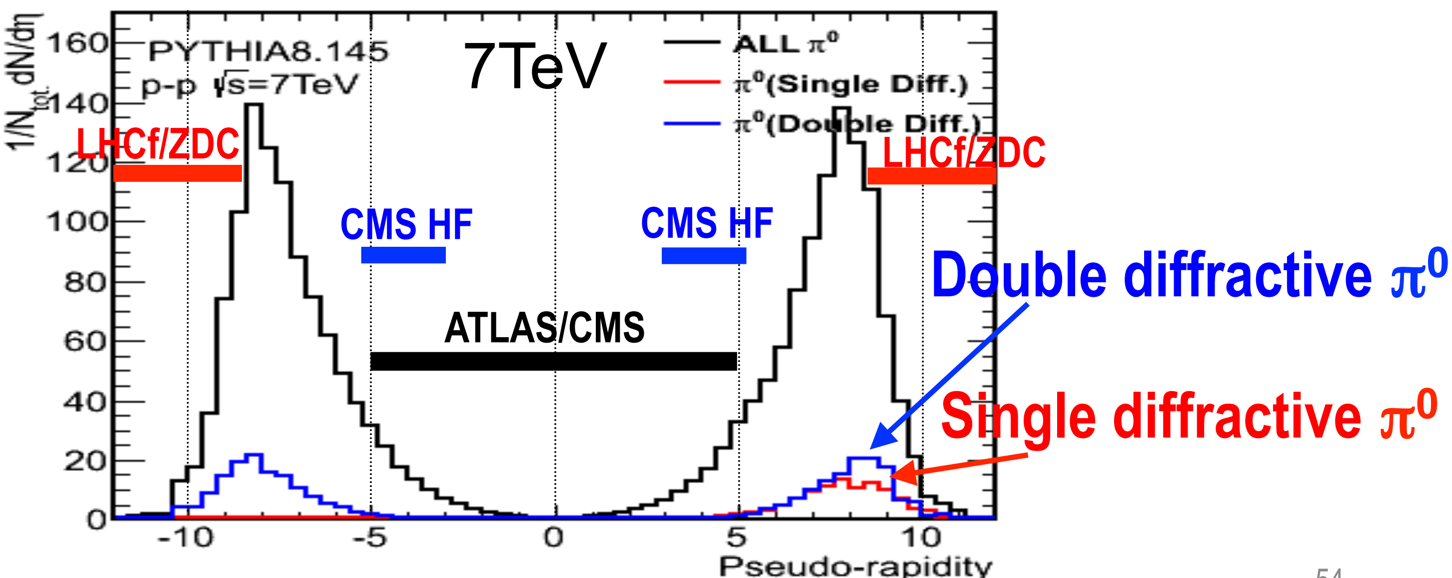






Energy flow for √s=14 and 7TeV





LHCf π^0 p_T for 5.02 TeV pPb (-11.0>η>-8.9)

- Large suppression and PT broadening
- Irrelevant to η region

Phys.Rev.C in press
arXiv:1403.7845