EDS'09: 13th International Conference on Elastic & Diffractive Scattering
CERN, 29 June – 3 July 2009

Forward Experiments at LHC:
how LHC can contribute to Cosmic Ray Physics

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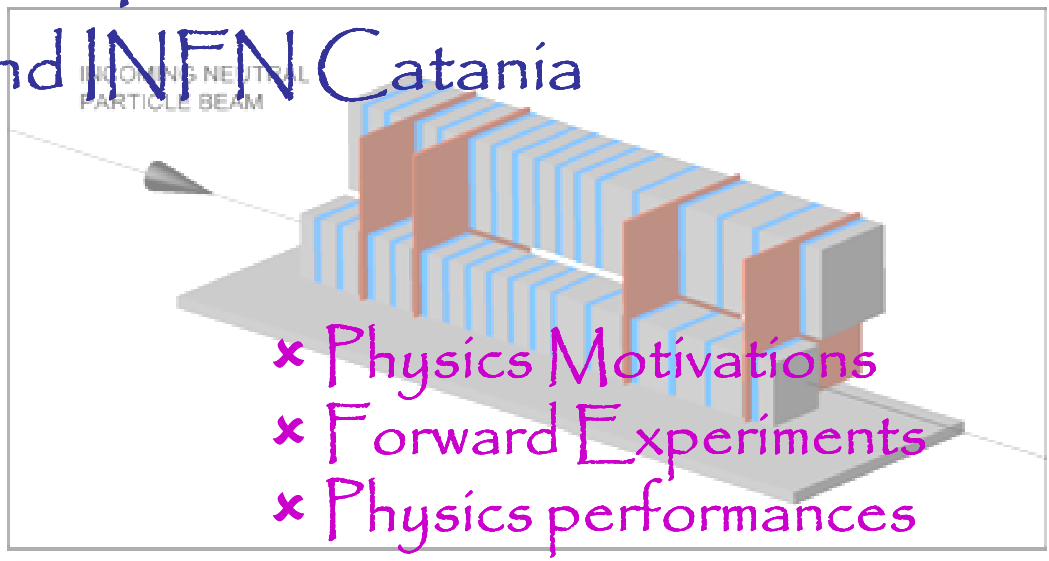
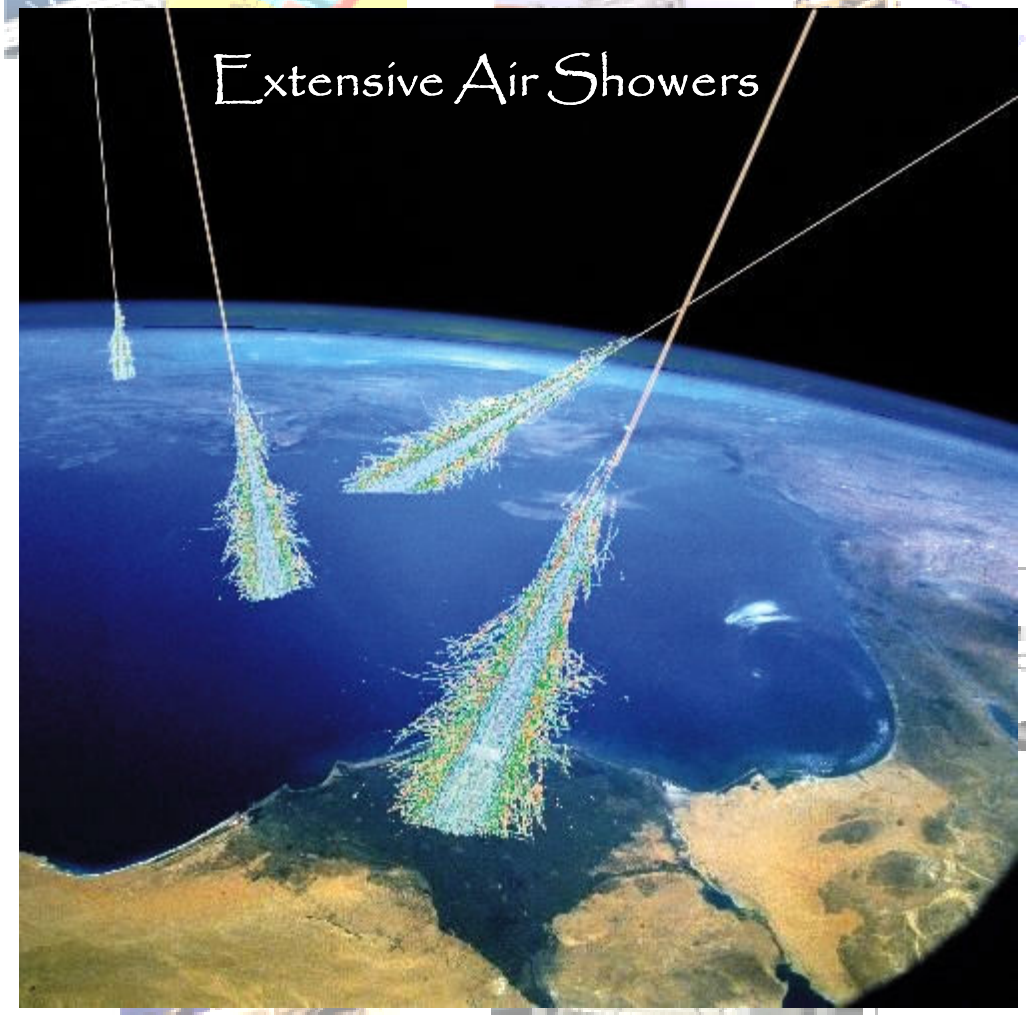


- Physics Motivations
- Forward Experiments
- Physics performances

Ultra High Energy Cosmic Rays



Experimental observations: at E>100 TeV only EAS
(shower of secondary particles)

- lateral distribution
- longitudinal distribution
- particle type
- arrival direction

Air shower development (particle interaction in the atmosphere)

Astrophysical parameters:
(primary particles)

- spectrum
- composition
- source distribution
- origin and propagation

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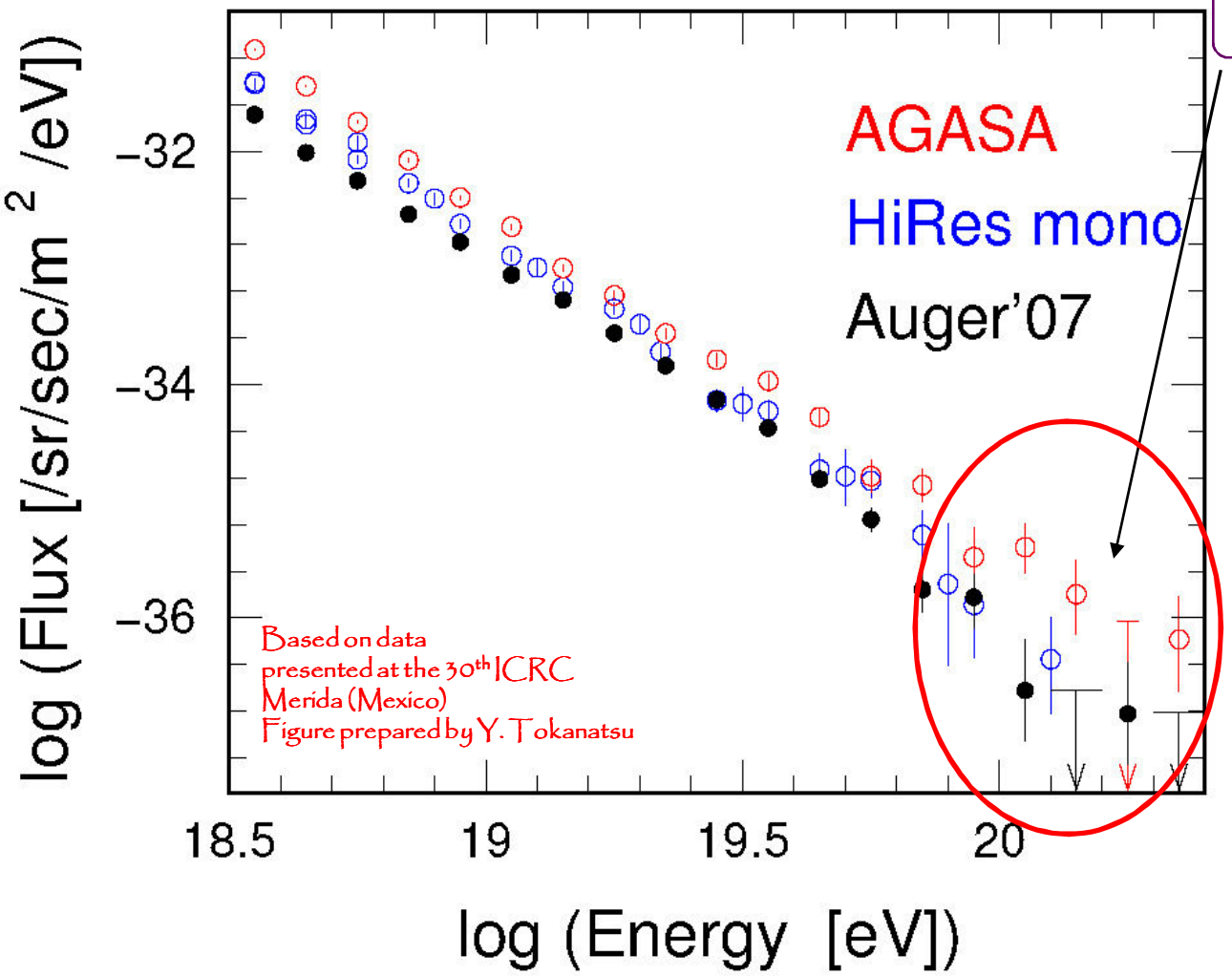
The Cosmic Ray Spectra



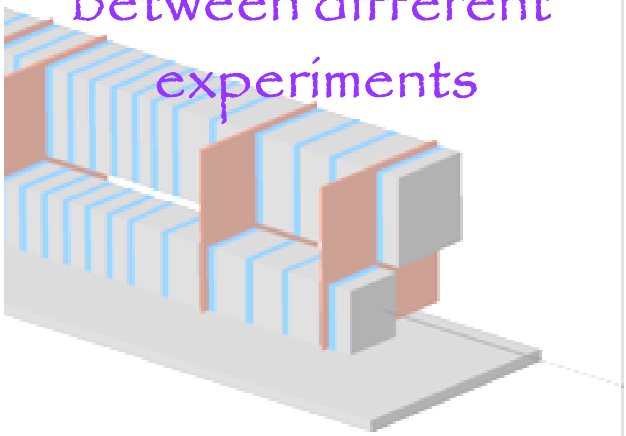
GZK cutoff: 10^{20} eV

GZK cutoff would limit energy to 10^{20} eV (for protons, due to Cosmic Microwave Background

$p\gamma(2.7K) \rightarrow \Delta \rightarrow N\pi$

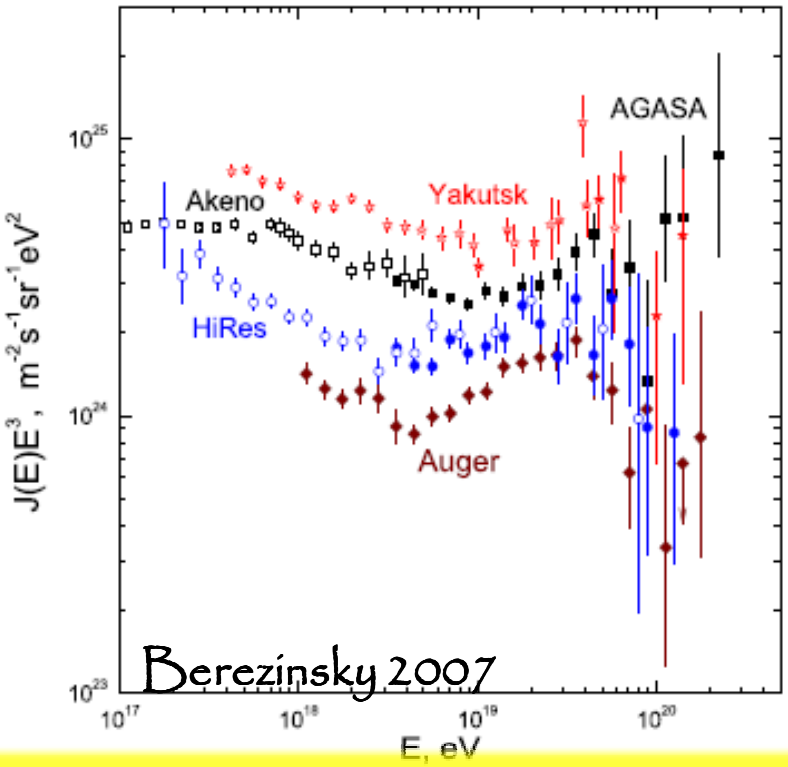
super GZK events?!?

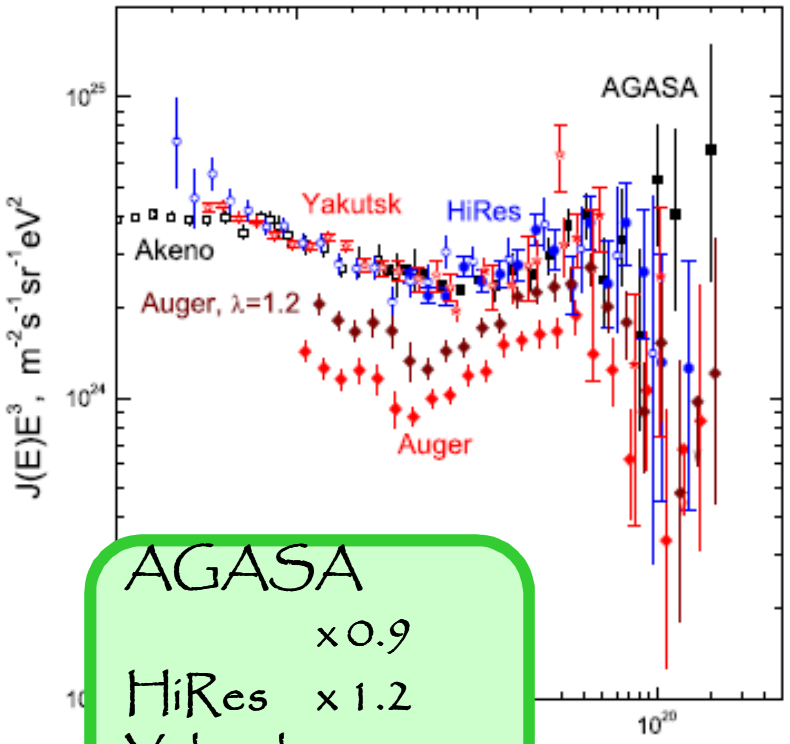
Different results between different experiments



The Cosmic Ray Spectra

Difference in the energy scale between different experiments???





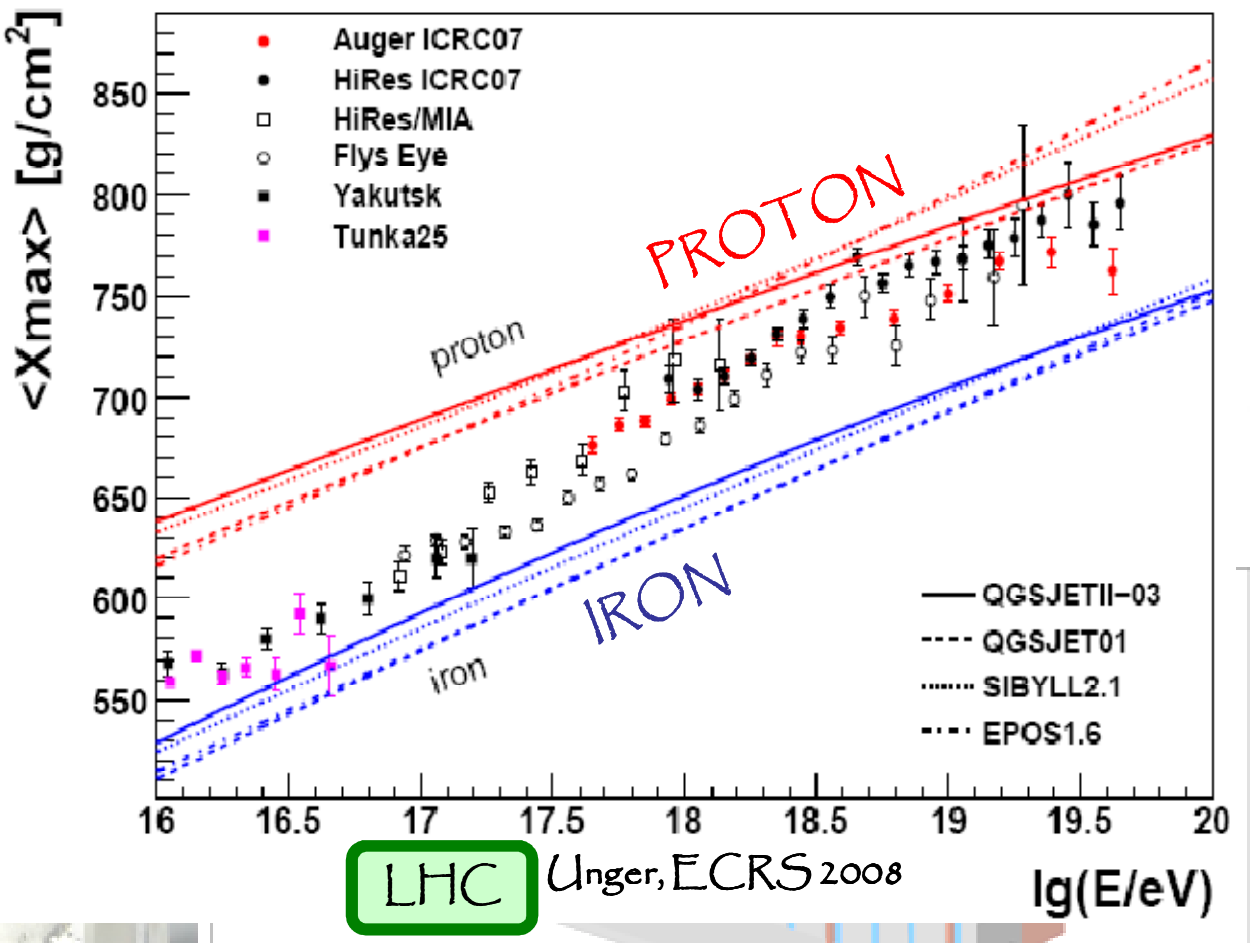
AGASA ×0.9
HiRes ×1.2
Yakutsk ×0.75
Auger ×1.2

AGASA Systematics
Total ±18%
Hadron interaction
(QGSJET, SIBYLL) ~10%
(Takeda et al., 2003)

HECR composition

The depth of the maximum of the shower X_{max} in the atmosphere depends on energy and type of the primary particle.

Different hadronic interaction models give different answers about the composition of HECR.

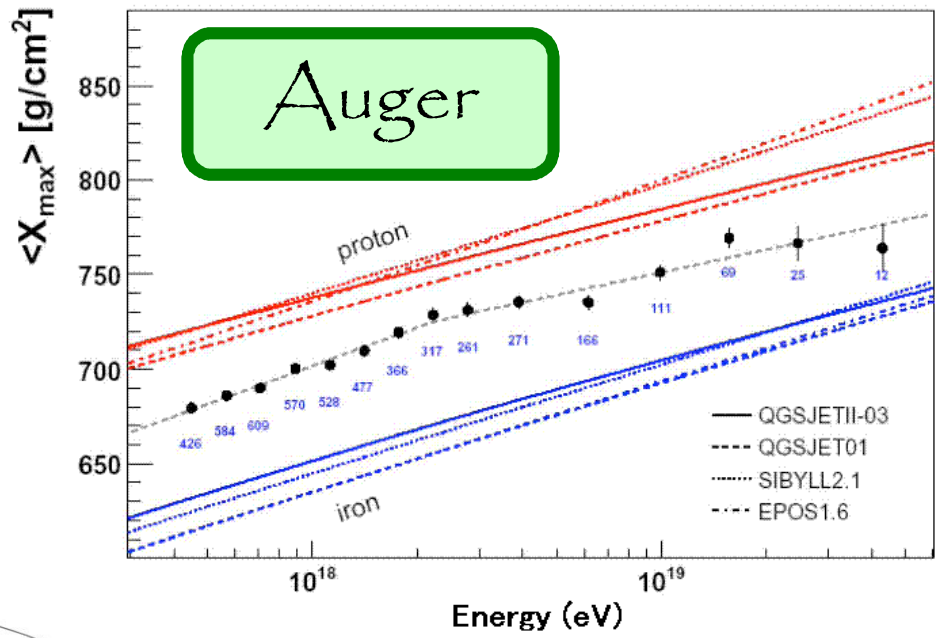


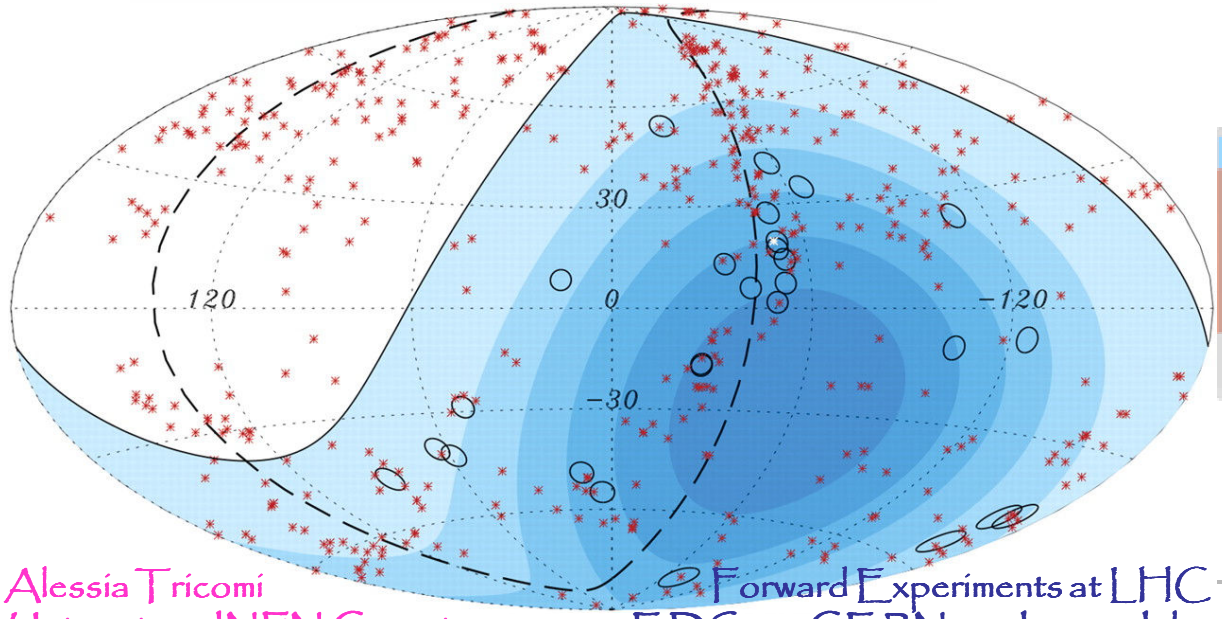
LHC

Unger, ECRS 2008

HECR composition

X_{max} measurements favors heavier composition as the energy increases





Anisotropy would favor proton primaries (AGN correlation)

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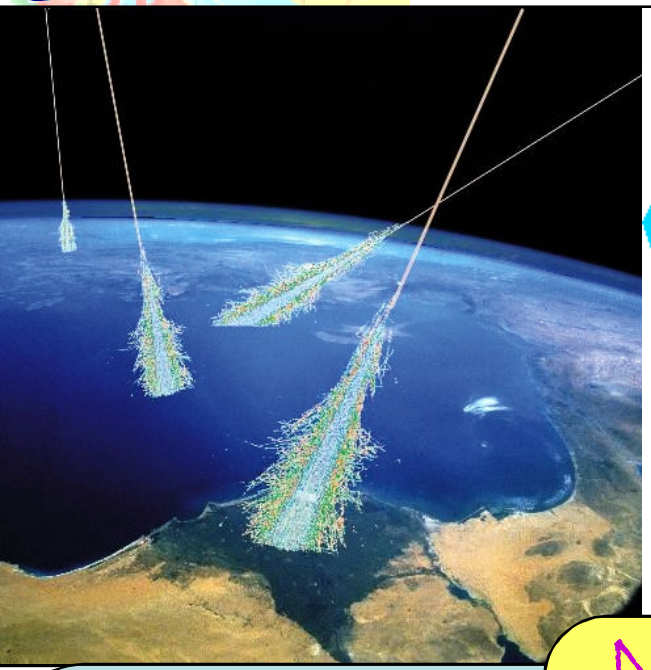
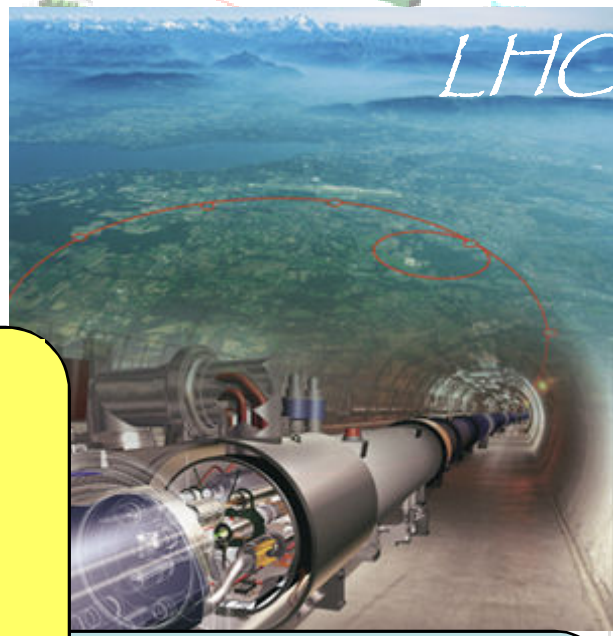
Modelling Cosmic Rays at LHC





Astrophysical pa

- source type
- source distribut
- source spectru
- source composition
- propagation

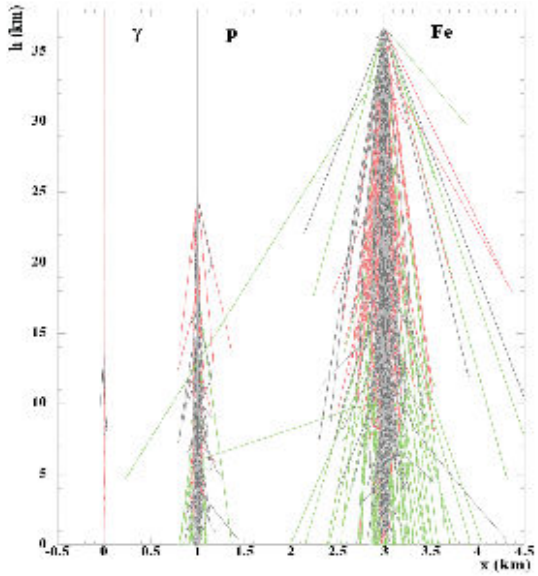
Nuclear Interaction

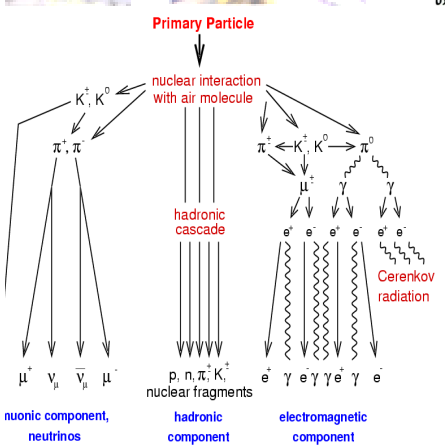
- calibration with data of Monte Carlo used in Cosmic Ray Physics

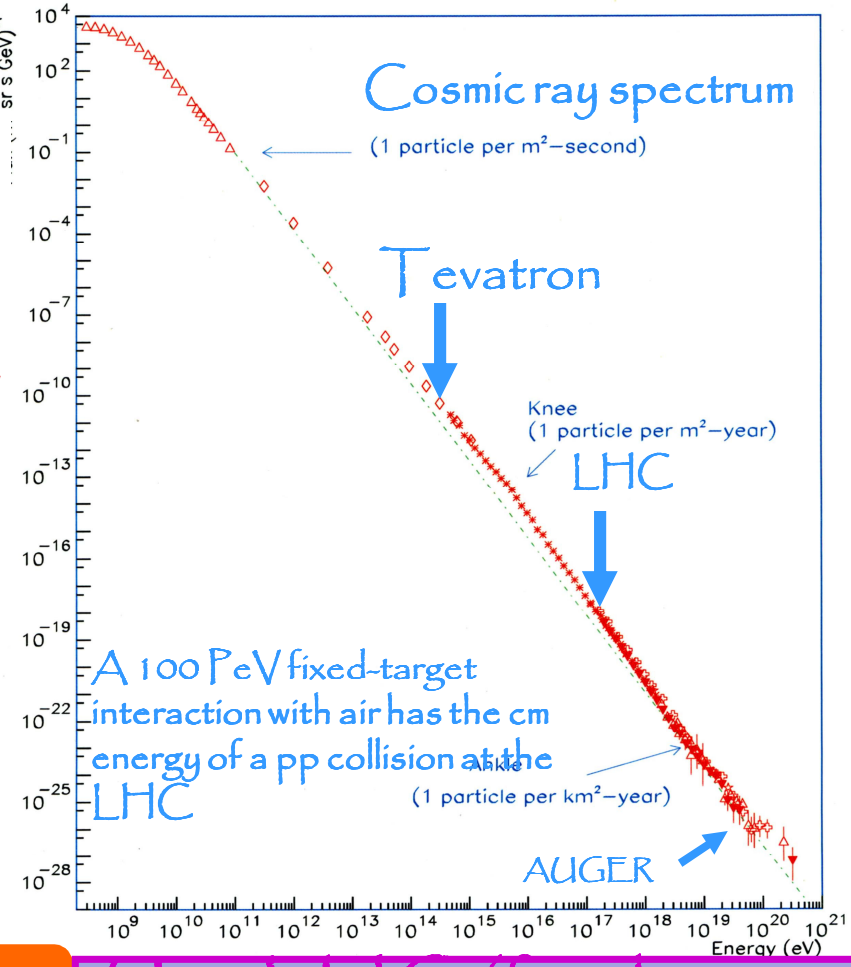
rd Physics

- cross section
- particle spectra (E, P_T, θ, η, X_F)

Development of atmospheric showers







Determination of E and mass of cosmic rays depends on description of primary UHE QCD (p+N,O Fe+N,O) interaction

Hadronic MC's need tuning with data

The dominant contribution to the energy flux is in the very forward region ($\theta \approx 0$)

In this forward region the highest energy avail… measurements of π^0 cross section done by U…

($E = 10^{14}$ eV, $y = 5 \div 7$)

Use LHC (firstly proposed by LHCf)

$\sqrt{s} = 14$ TeV $\Rightarrow E_{lab} = 10^{17}$ eV

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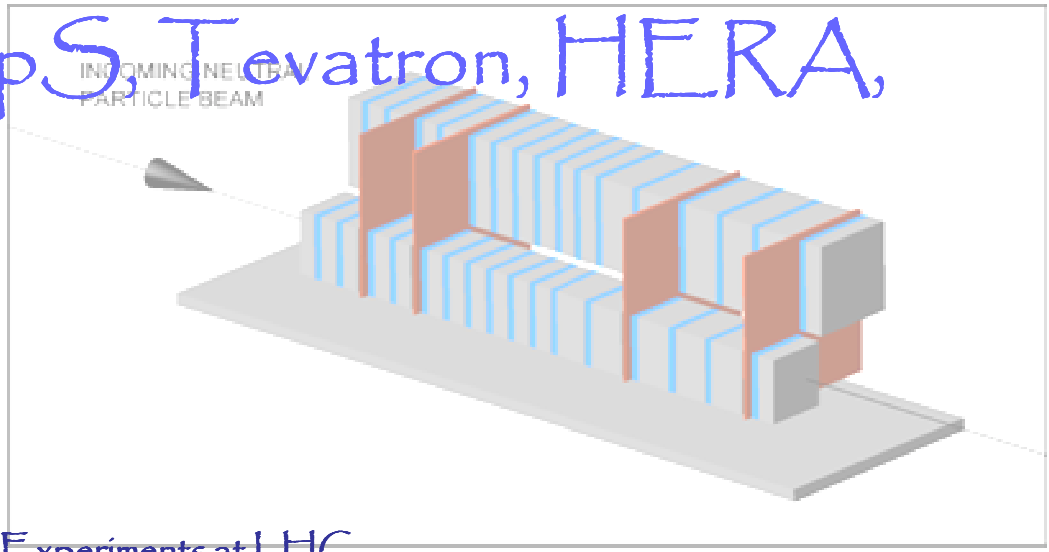
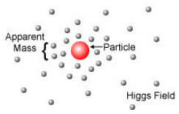
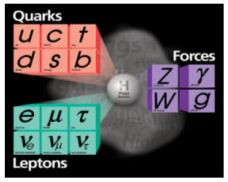
What accelerator experiment can do?

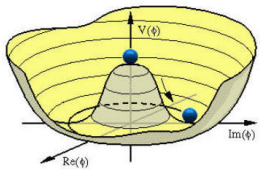
- Key parameters
  - Total (inelastic) cross section
  - Elasticity / Inelasticity
  - Secondary distribution (E, P_T, θ, η, X_F)
- Technique of the forward measurements
- Existing data (SppS, Tevatron, HERA, RHIC)
- LHC experiments

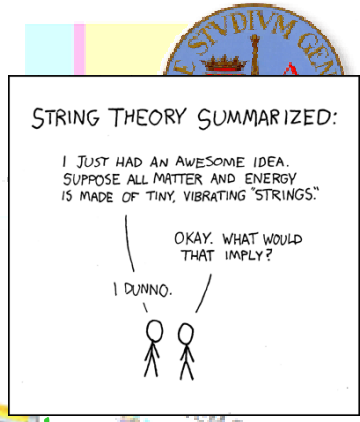


But...

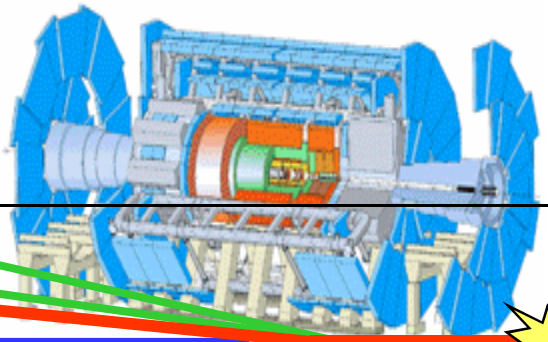




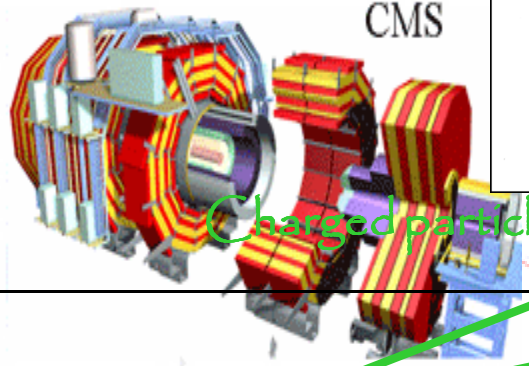




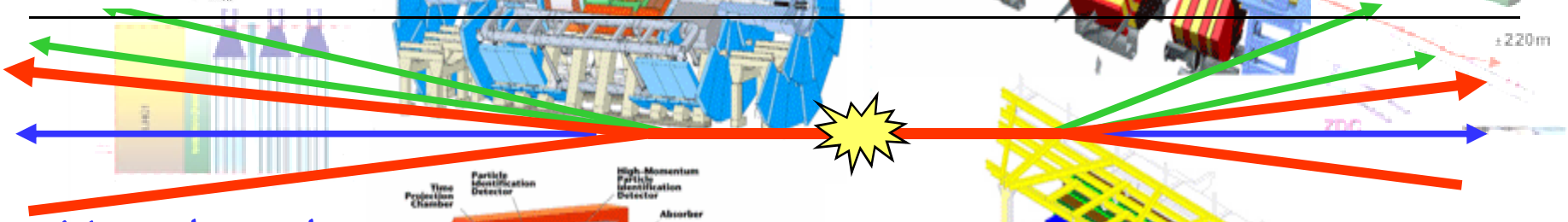
ATLAS



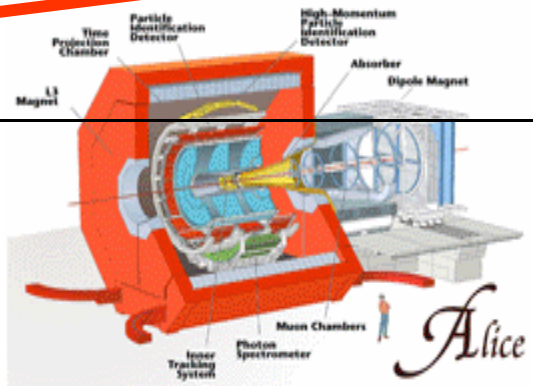
CMS

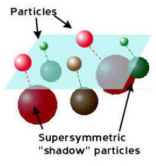


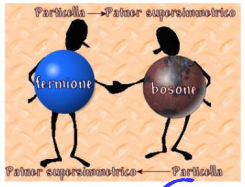
Charged particles



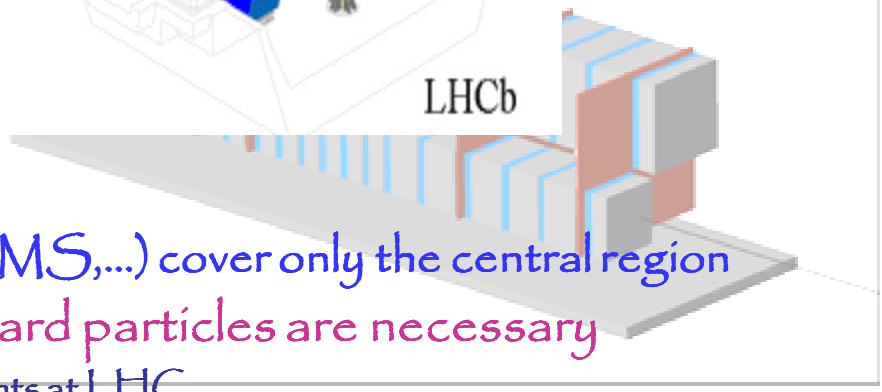
Neutral particles







Beam pipe



General purpose detectors (ATLAS, CMS,...) cover only the central region

Special detectors to access forward particles are necessary

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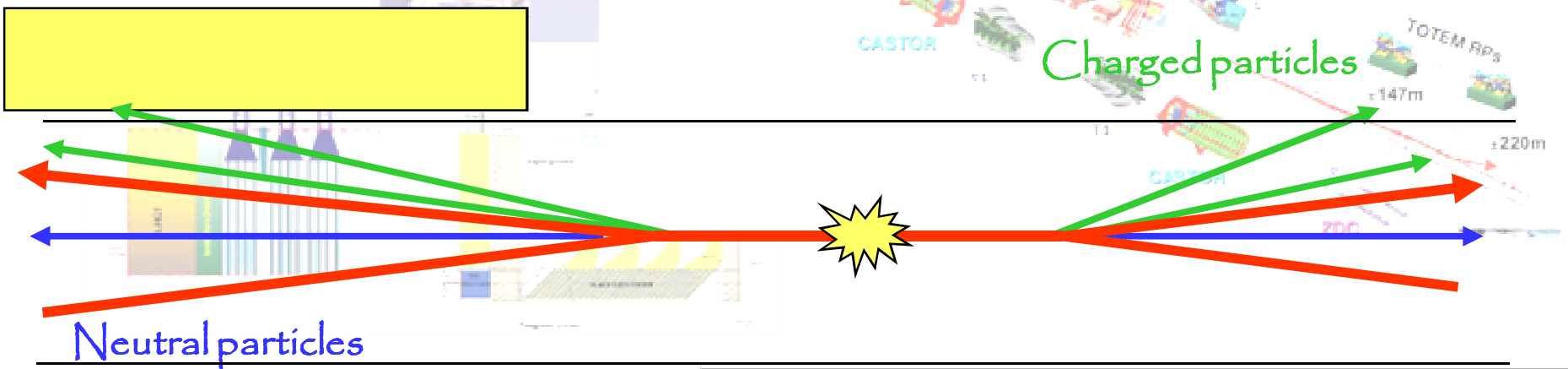
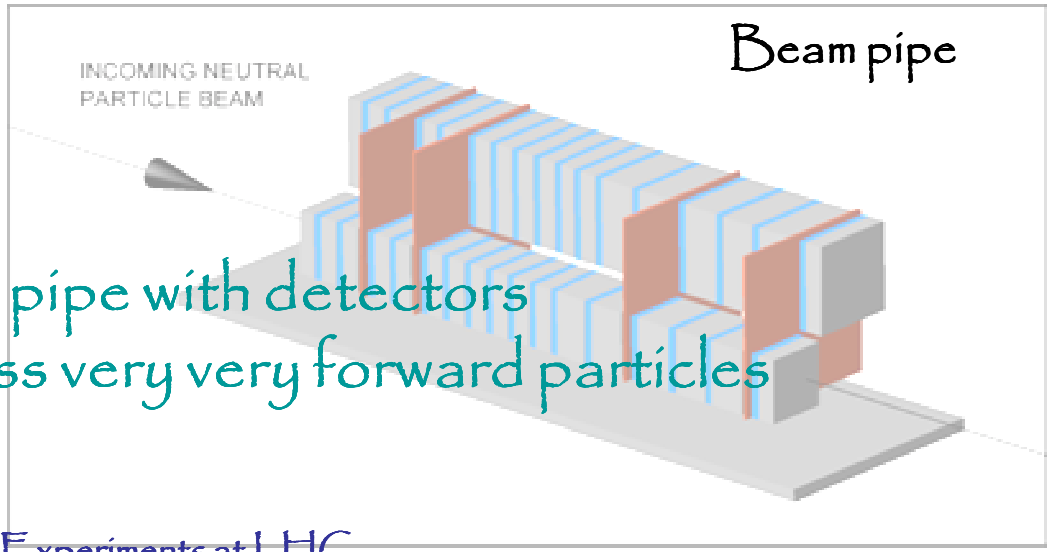
Forward Experiments at LHC

EDS'09, CERN 29 Jun - 3 July 2009

How to access Very Forward Physics at LHC?





Surrounding the beam pipe with detectors
Simple way, but still miss very very forward particles

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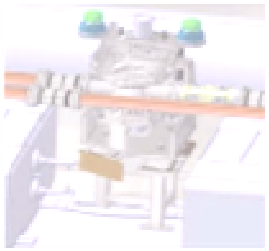
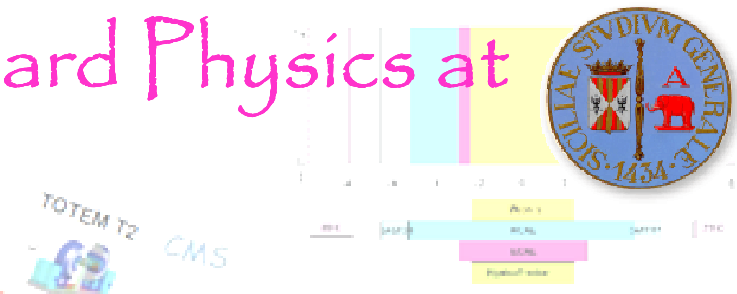
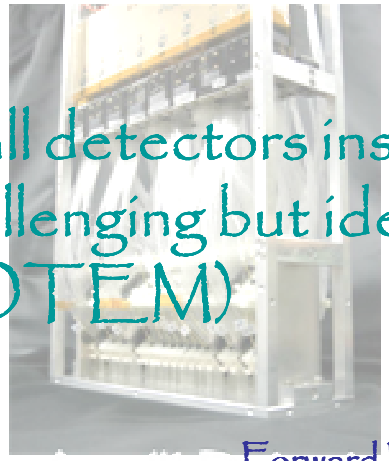
How to access Very Forward Physics at LHC?

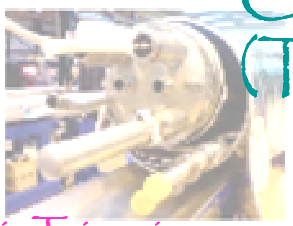




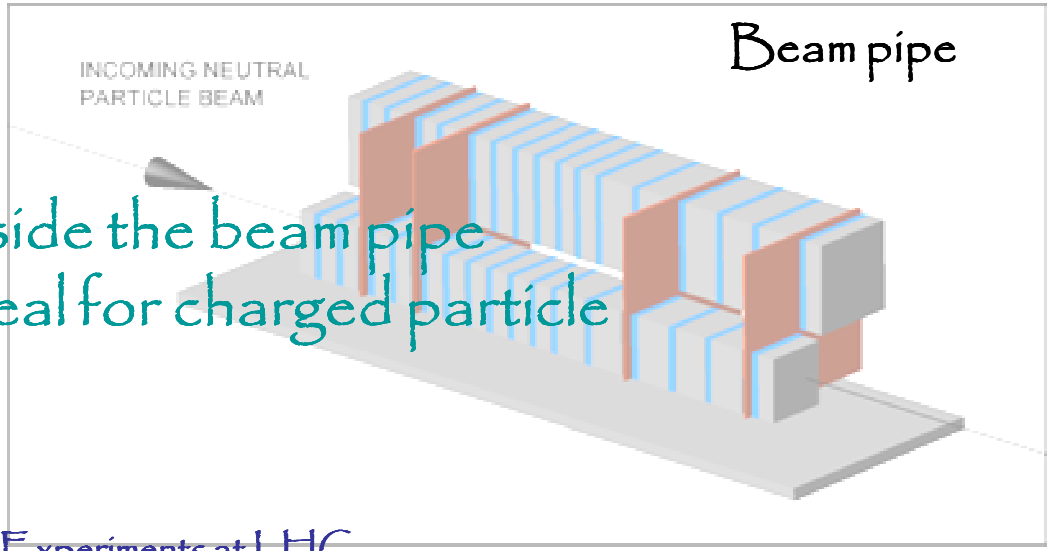
Charged particles

Neutral particles





Install detectors inside the beam pipe
Challenging but ideal for charged particle (TOTEM)



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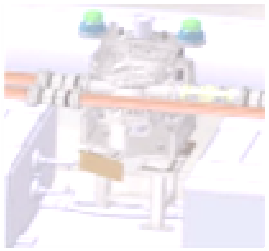
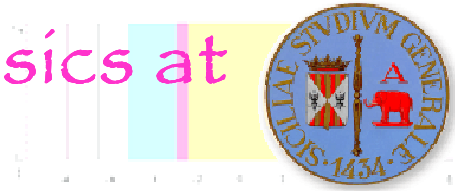
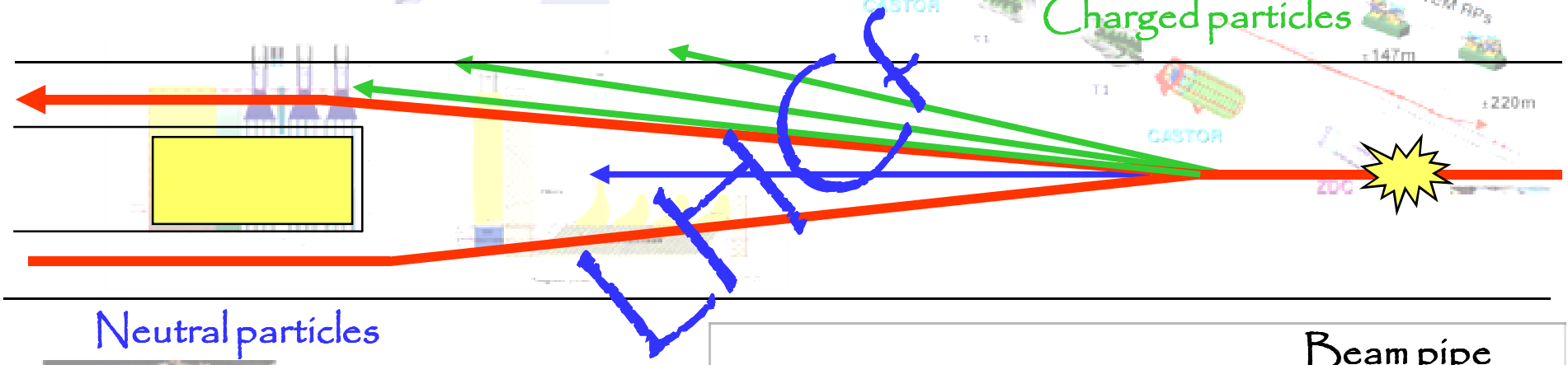
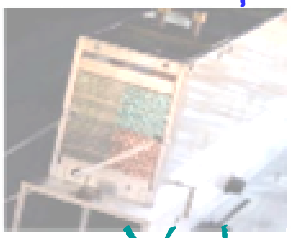
How to access Very Forward Physics at LHC?

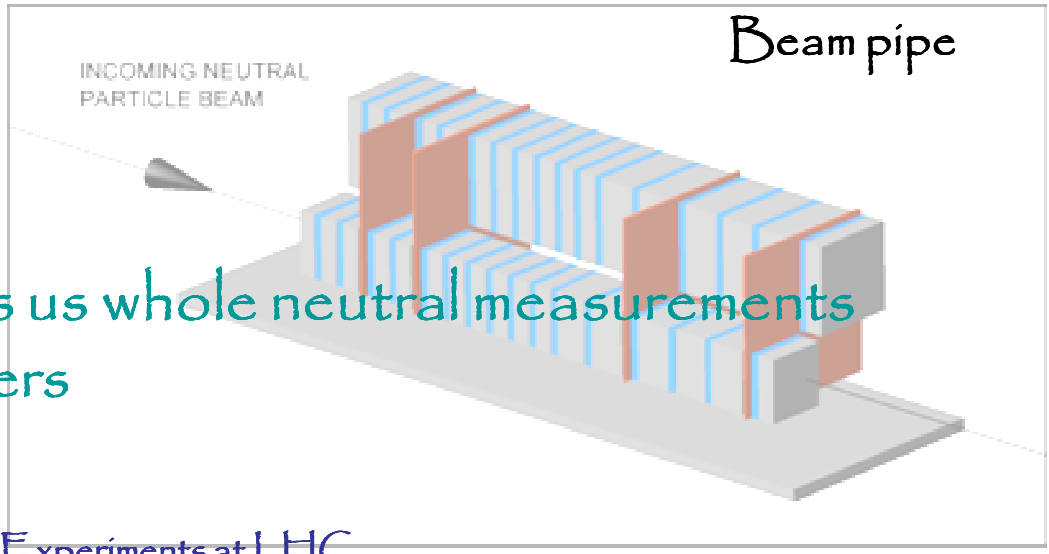






Neutral particles





Y shape chamber enables us whole neutral measurements

Zero Degree Calorimeters

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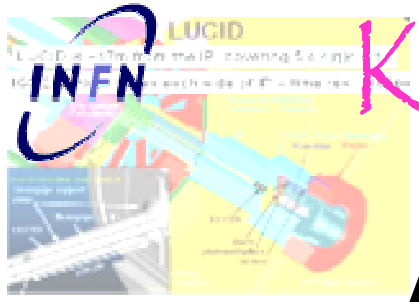
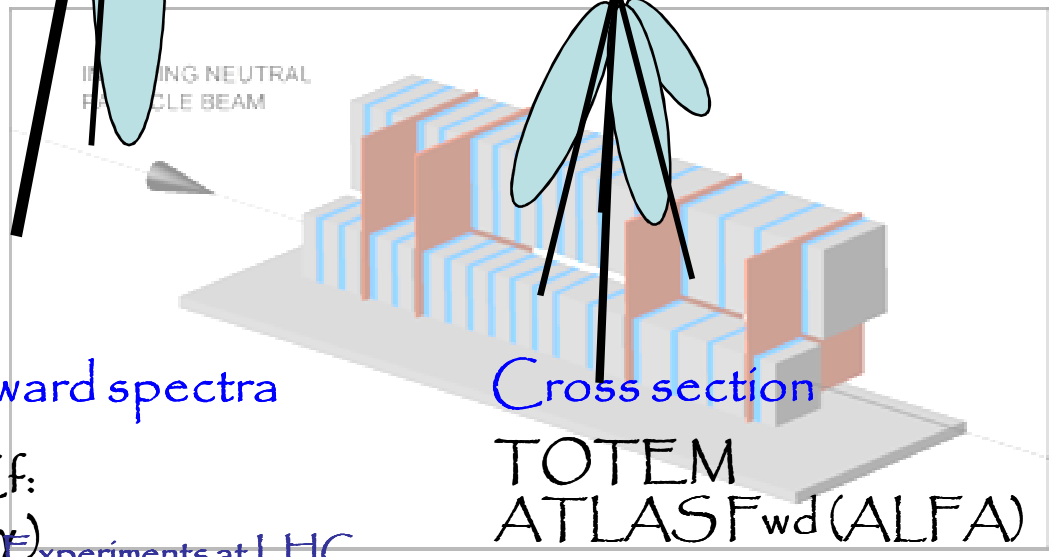
Key Measurements at LHC



E_0

EM shower

$E_{leading\ hadron}$



Elasticity / inelasticity

Forward spectra

Cross section

Neutrals in ZDCs / LHCf:
neutrons, mesons ($\pi^0, K^0 \rightarrow \gamma$)

TOTEM
ATLAS Fwd (ALFA)

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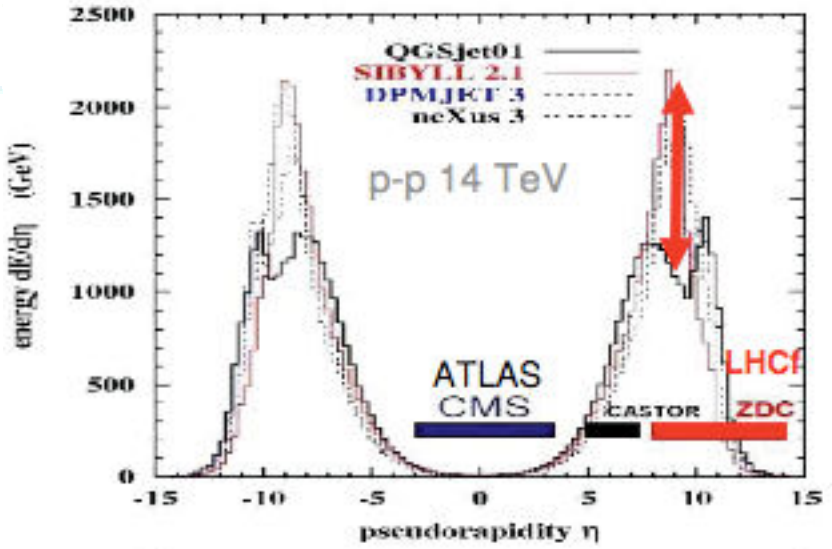
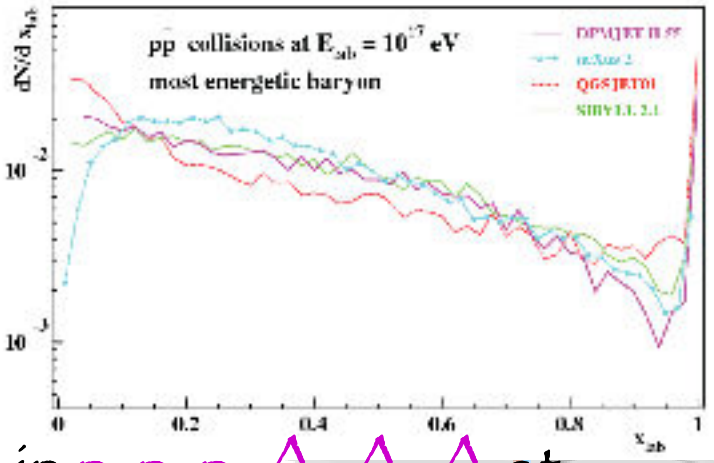
MC tuning at LHC

MC predictions for forward multiplicity & energy flow accessible over large η range



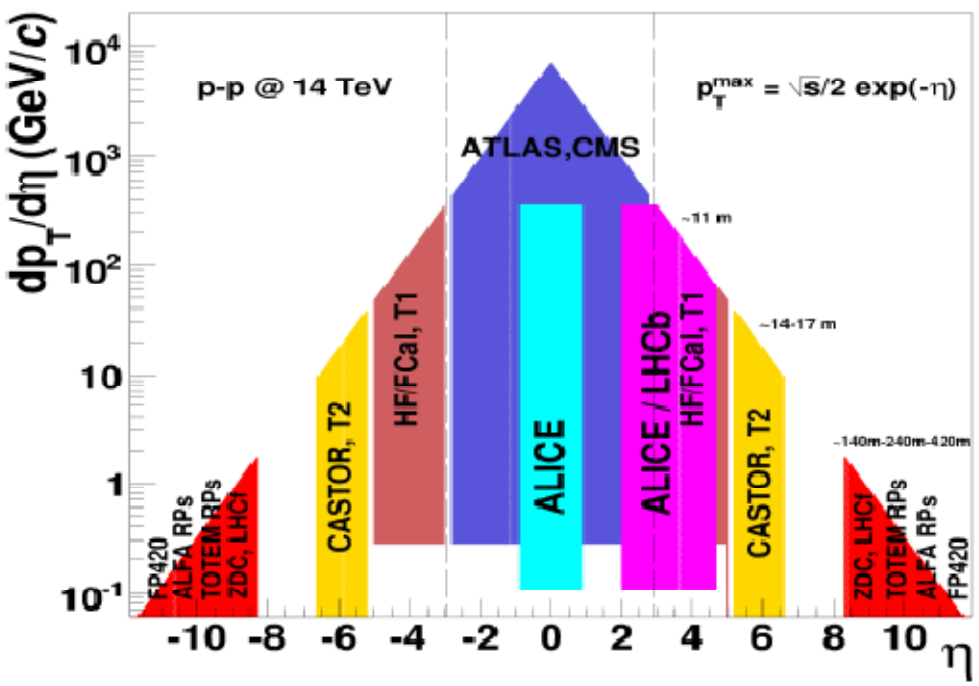
Leading baryon (inelasticity): Neutrals in ZDCs / LHCf: neutrons, mesons ($\pi^0, K^0_s \rightarrow \gamma\gamma$)

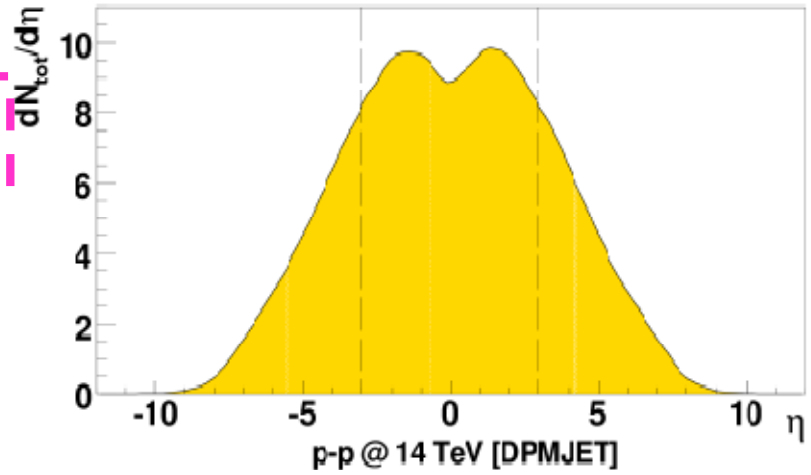


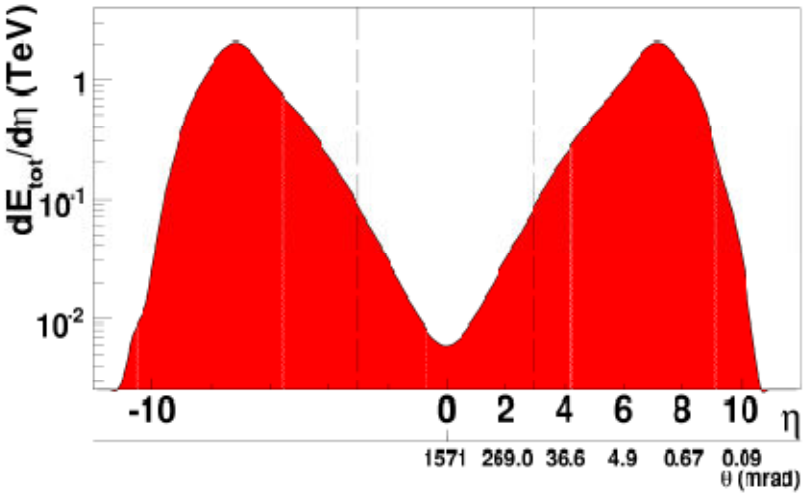
LHC measurements of forward particle in p-p, p-A, A-A at Elab≅100 PeV able to strongly constrain EAS Monte Carlos.

Pseudo rapidity coverage at LHC

pseudorapidity: $\eta = -\ln(\tan\theta/2)$







Particle production at LHC over $\Delta\eta E\pm 10$

All phase space covered thanks to dedicated forward detectors!

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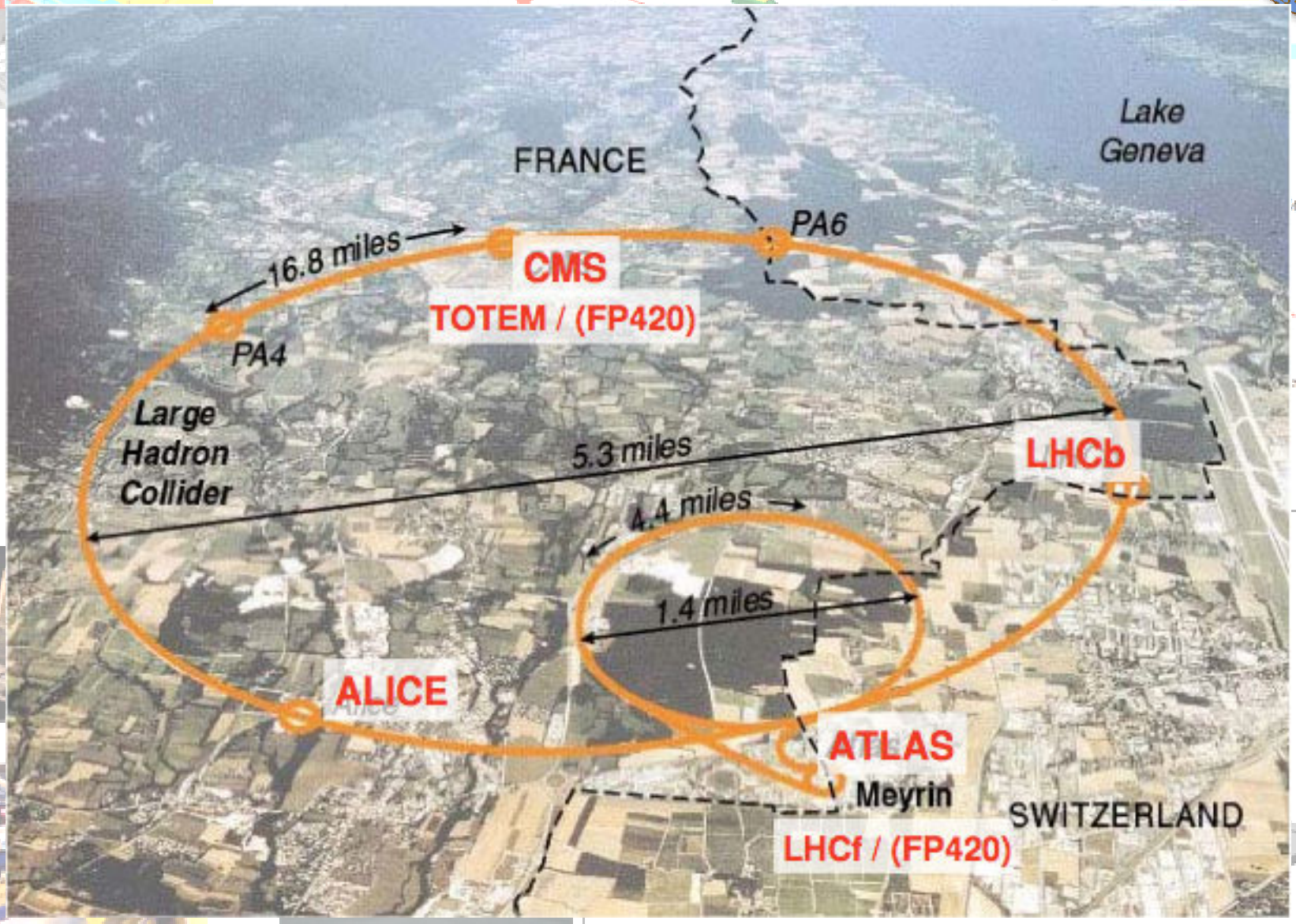
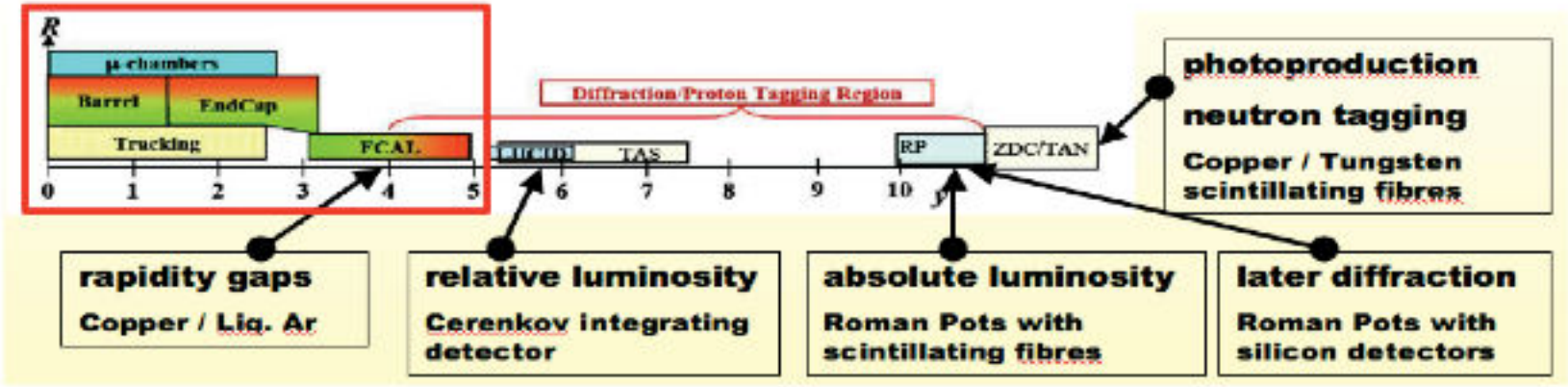
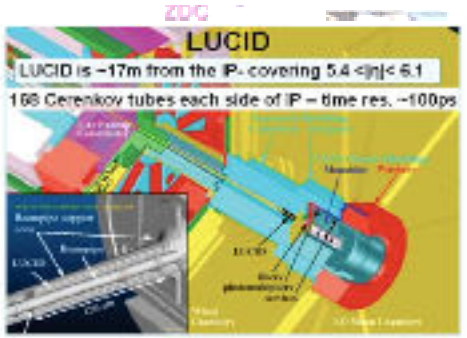
LHC experiments



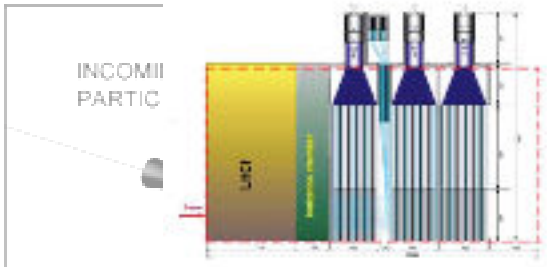
IP1: ATLAS forward detector



LUCID (Cerenkov Tubes, 17m):
Cerenkov hits over $5.4 < |\eta| < 6.1$



ZDC (W/Q-fiber calo, 140m):
Neutral calorimetry over $|\eta| > 8.3$



ALPHA (Sci-Fi RPs):
Proton taggers at ± 240 m

FP220, FP420 (Si trackers, timing):
Proton tracking at ±220, 420 m

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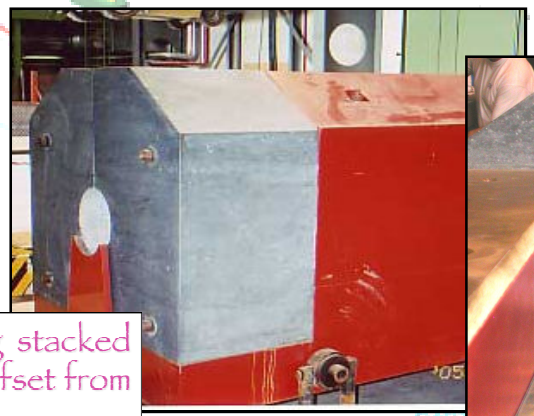
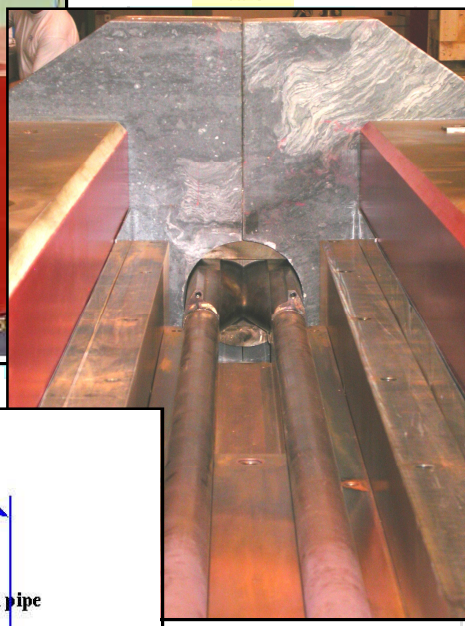
IP1: LHCf detector

UHECR-oriented experiment
(~30 Japan-European Collaborators)
Installed at ±140 m on both side of IP1
in TAN region





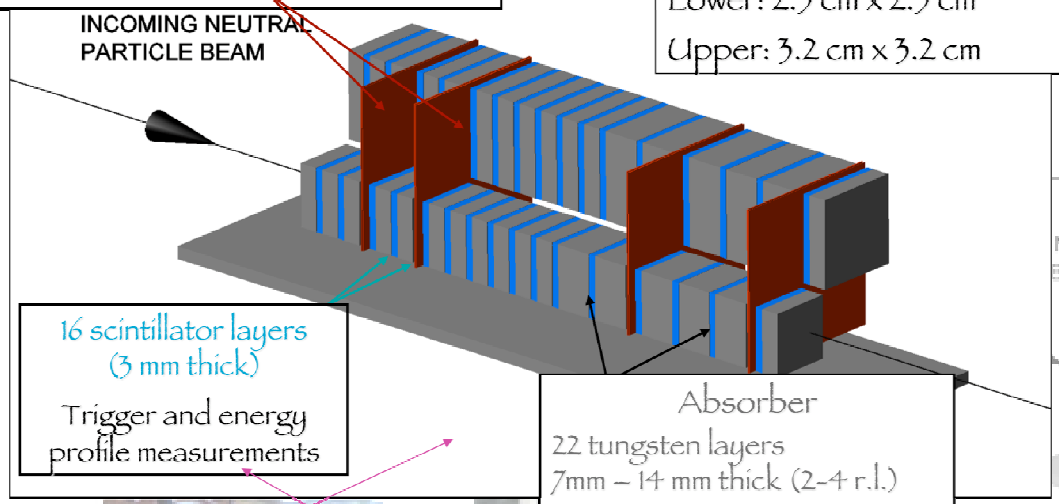
Impact point (η)

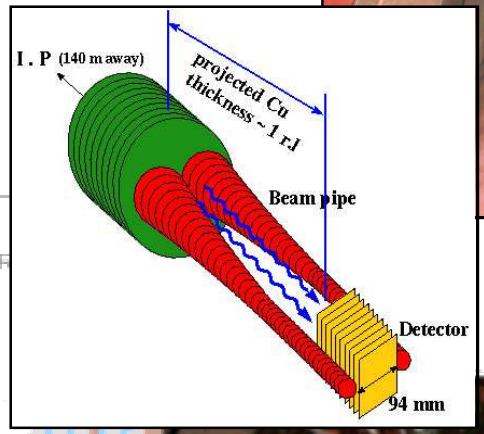
4 pairs of silicon microstrip layers
(6, 12, 30, 42 r.l.) for tracking purpose
(X and Y directions)

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm





16 scintillator layers
(3 mm thick)

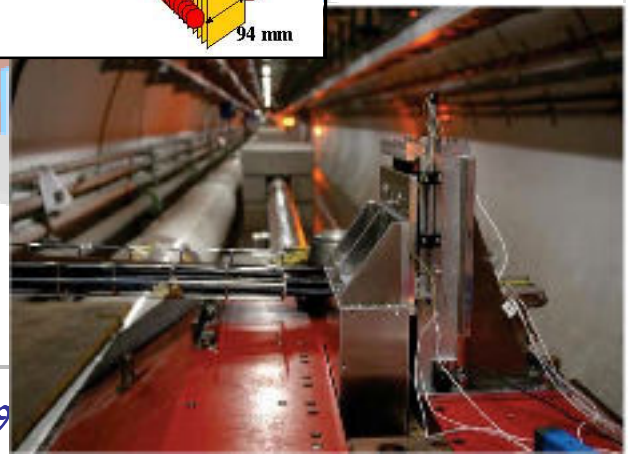
Trigger and energy
profile measurements

Absorber

22 tungsten layers
7mm – 14 mm thick (2-4 r.l.)
(W: X_0 = 3.5mm, R_M = 9mm)

Energy

Double ARM detector:
ARM1: Sci/W + 4 XY Sci Fiber Layers
ARM2: Sci/W + 4 XY Si μ-strip Layers



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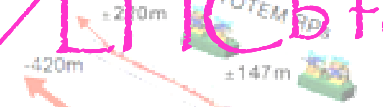
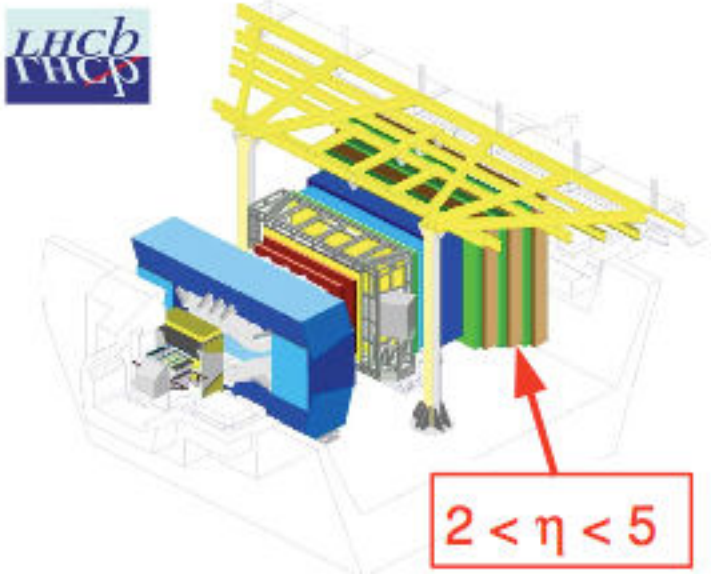
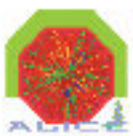
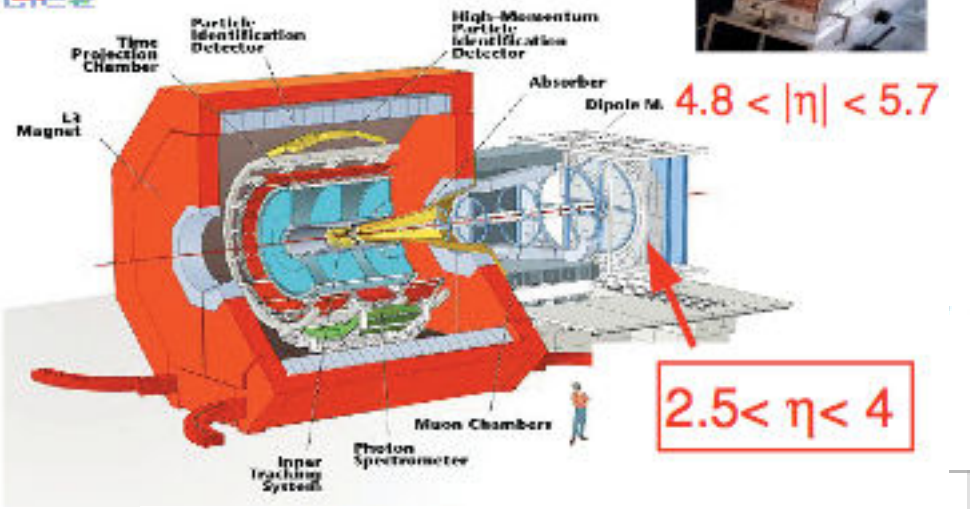
IP2-IP8: ALICE/LHCb forward detectors



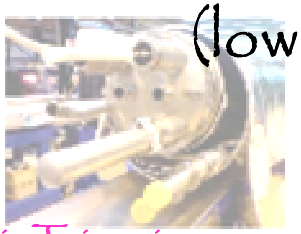


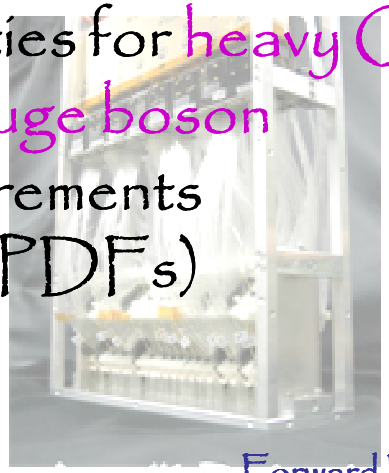


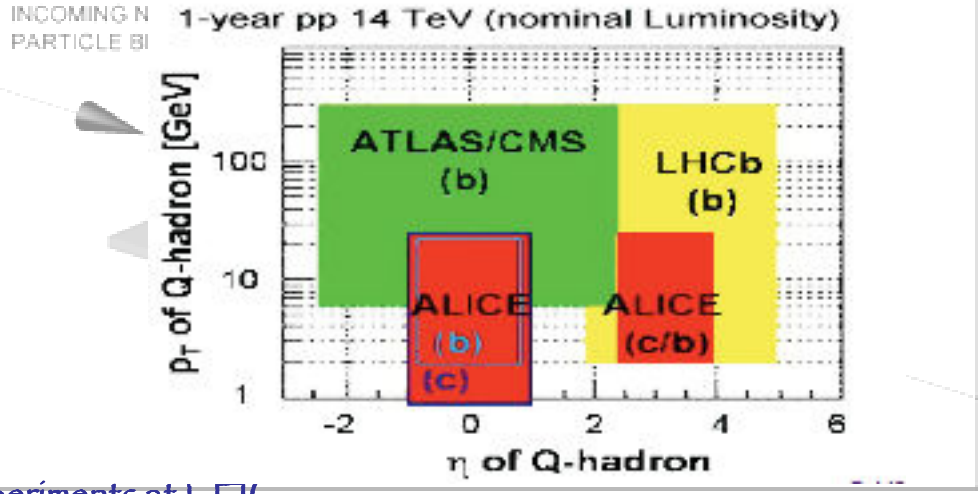
ZDCs also at ±7m, ±100 m



Good capabilities for heavy Q, QQ, gauge boson measurements (low x-PDFs)







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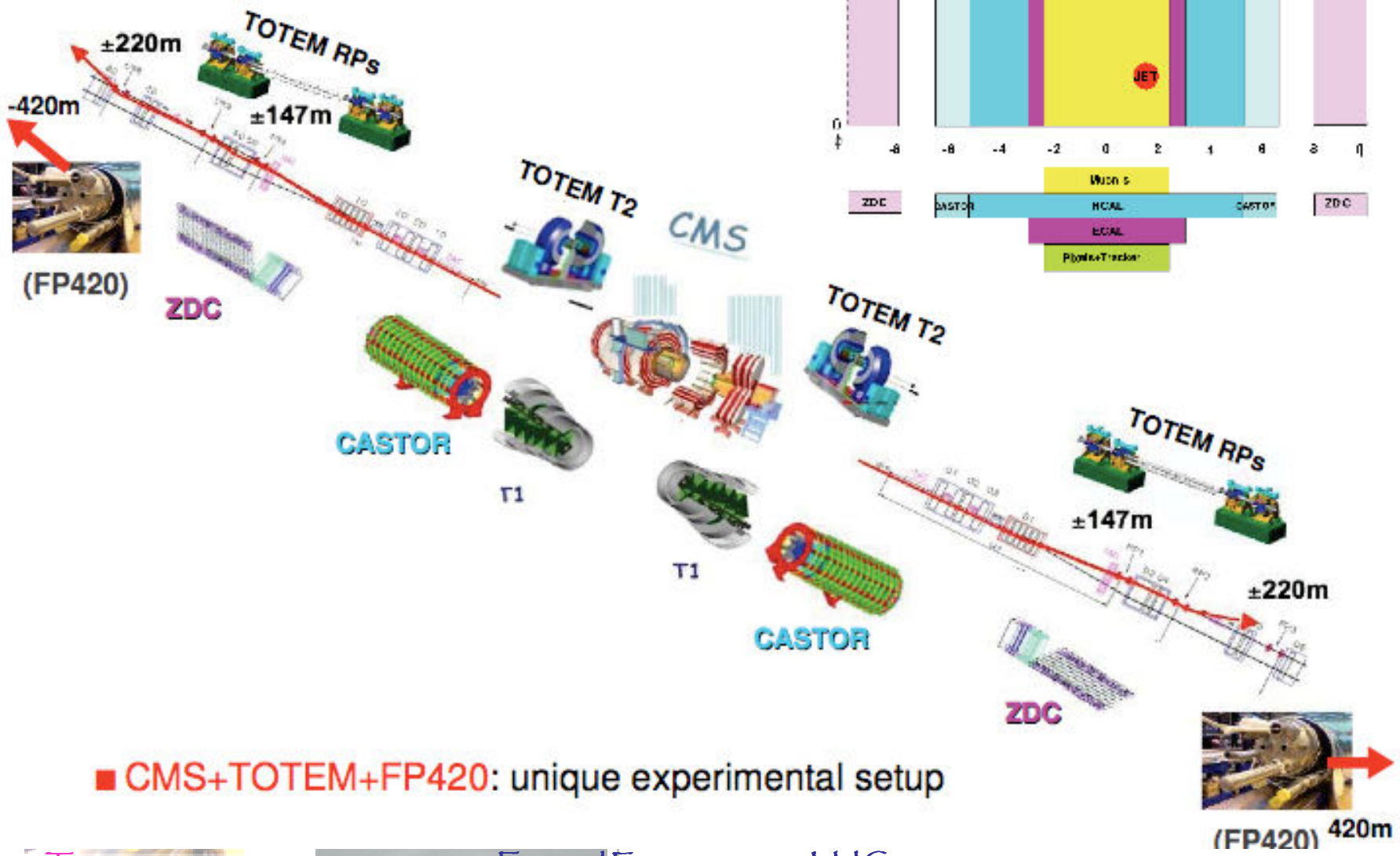
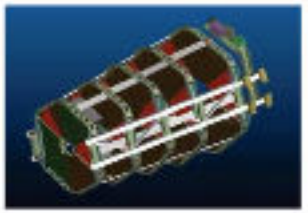
IP5: CMS forward+TOTEM detectors



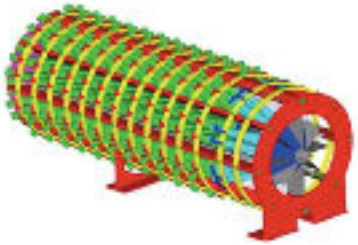
■ CMS+TOTEM+FP420: unique experimental setup

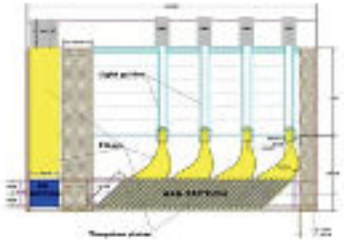
IP5: CMS forward+TOTEM detectors

TOTEM-T1,T2 (CSC/GEM telescopes):
Tracking over $3.1 < |\eta| < 4.7, 5.3 < |\eta| < 6.7$



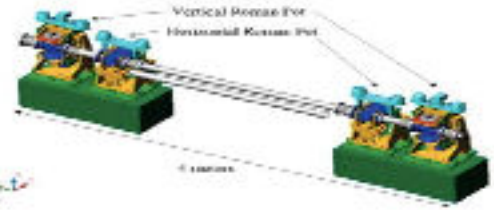
CASTOR (W/Q-fiber calo):
Calorimetry over $5.1 < |\eta| < 6.6$





ZDC (W/Q-fiber calo):
Neutral calorimetry for $|\eta| > 8.3$

TOTEM (Si Roman Pots):
Proton taggers at ±147, ±220 m



FP420 (Si trackers, timing):
Proton tracking at ±420 m

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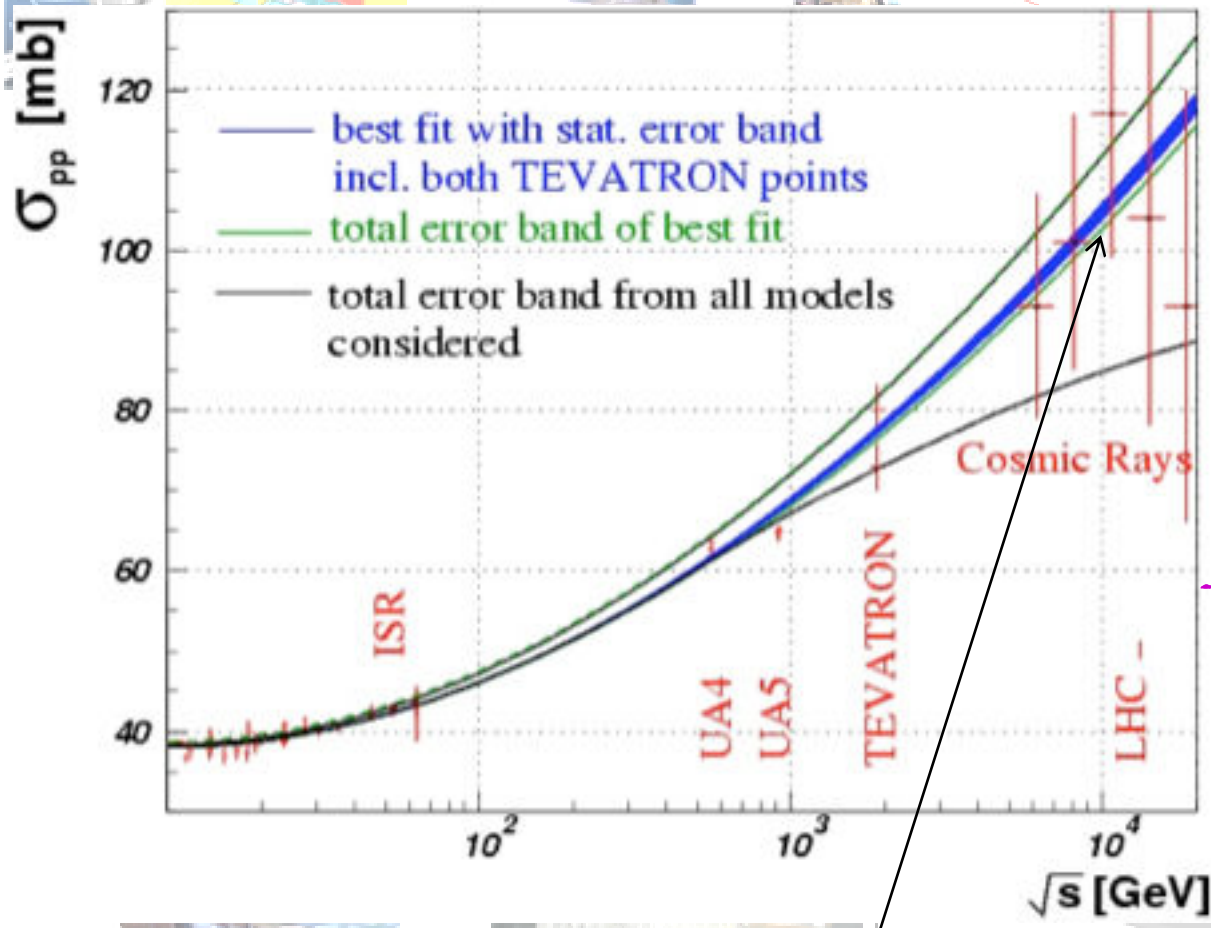
TOTEM: p-p total cross section

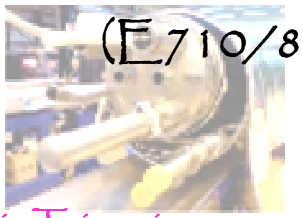


~ ln 2 s

Extrapolations vary by
σ(LHC) = 90-130 mb

TOTEM goal: ≅1% precisi

special run/optics: various β*, low lumi



(E710/811~CDF 2.6σ disagreement)

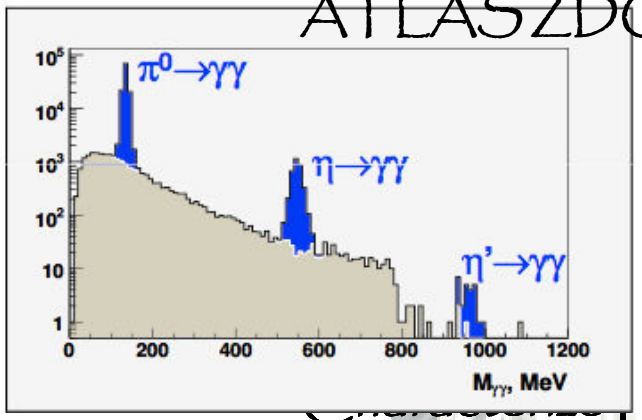
ZDC: Zero Degree Calorimeters

- ✓ ALICE, ATLAS & CMS ZDC (complemented by CASTOR)
  - ~ Total energy flow, wide aperture, high energy resolution for hadrons, (proton measurement only by ALICE ZDC)

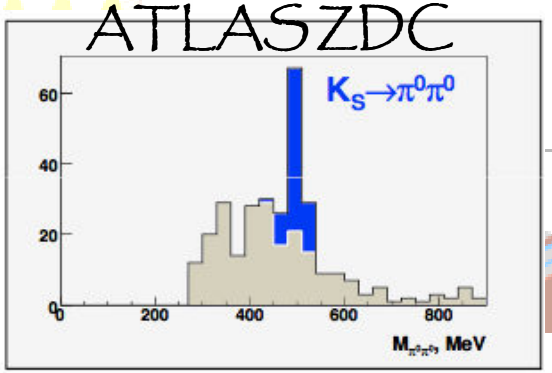
PP Physics

- » enhance acceptance of central detectors for diffractive Physics
- » kinematics and production spectra of forward particles

ATLAS ZDC

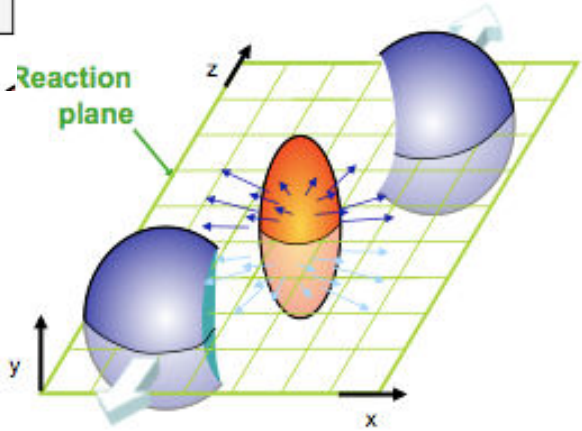


ATLAS ZDC



HI Physics

- » Count spectator neutrons
- » Measure centrality (magnitude and direction of impact parameter)

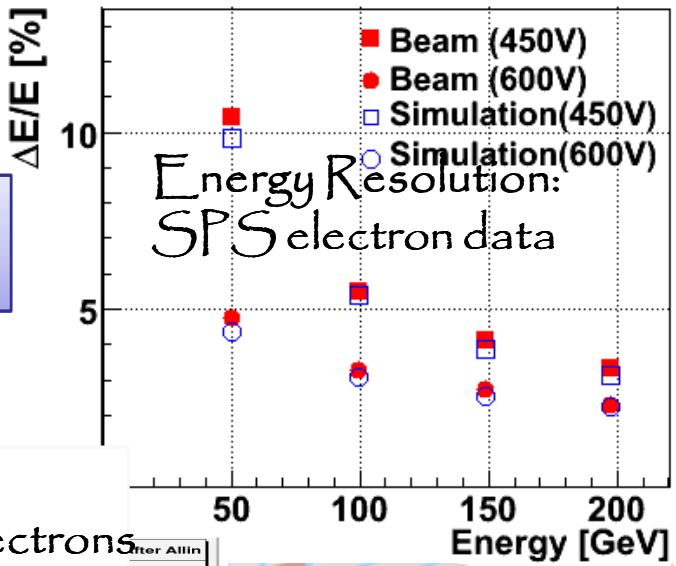


Zero Degree Calorimeters: LHCf

LHCf: same η coverage as other ZDCs but fully dedicated experiment to HECR Physics

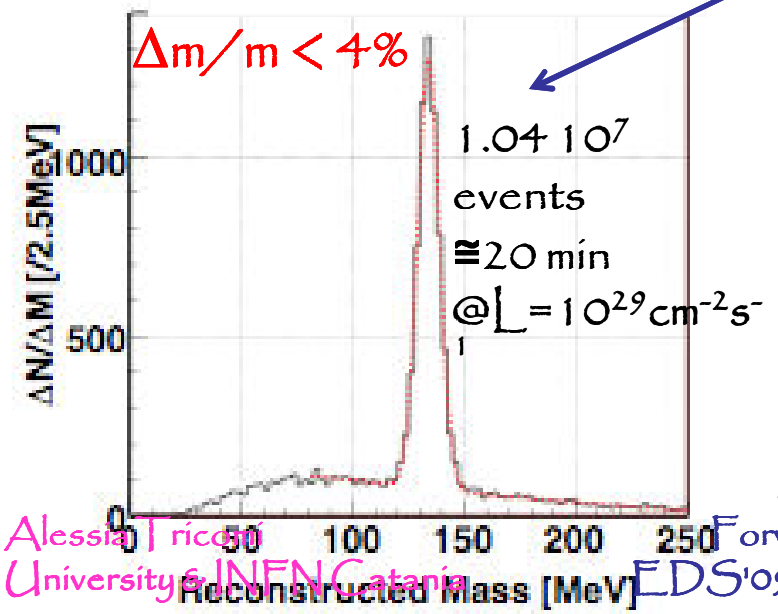
- Double ARM calorimeters with imaging and PID capabilities
- Excellent energy resolution (<5%) for γ and π^0, π^0 mass resolution (< 5%) and Spatial resolution (40-200 μm)
- Good neutron energy resolution (<30%)

Very important tool to calibrate energy scale

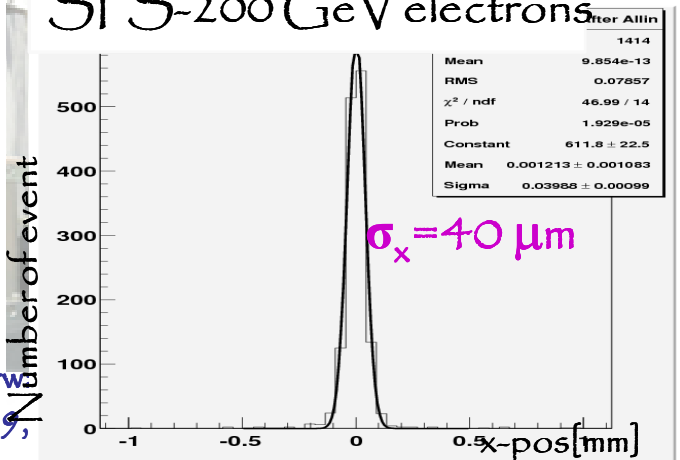


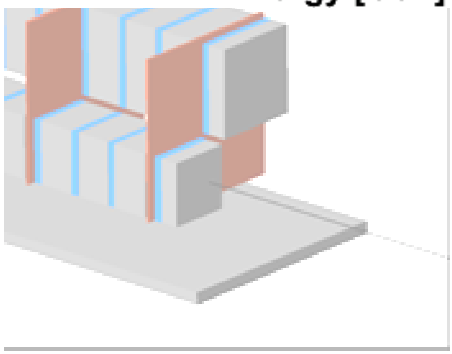
Energy Resolution: SPS electron data

Spatial Resolution: SPS-200 GeV electrons



Spatial Resolution: SPS-200 GeV electrons





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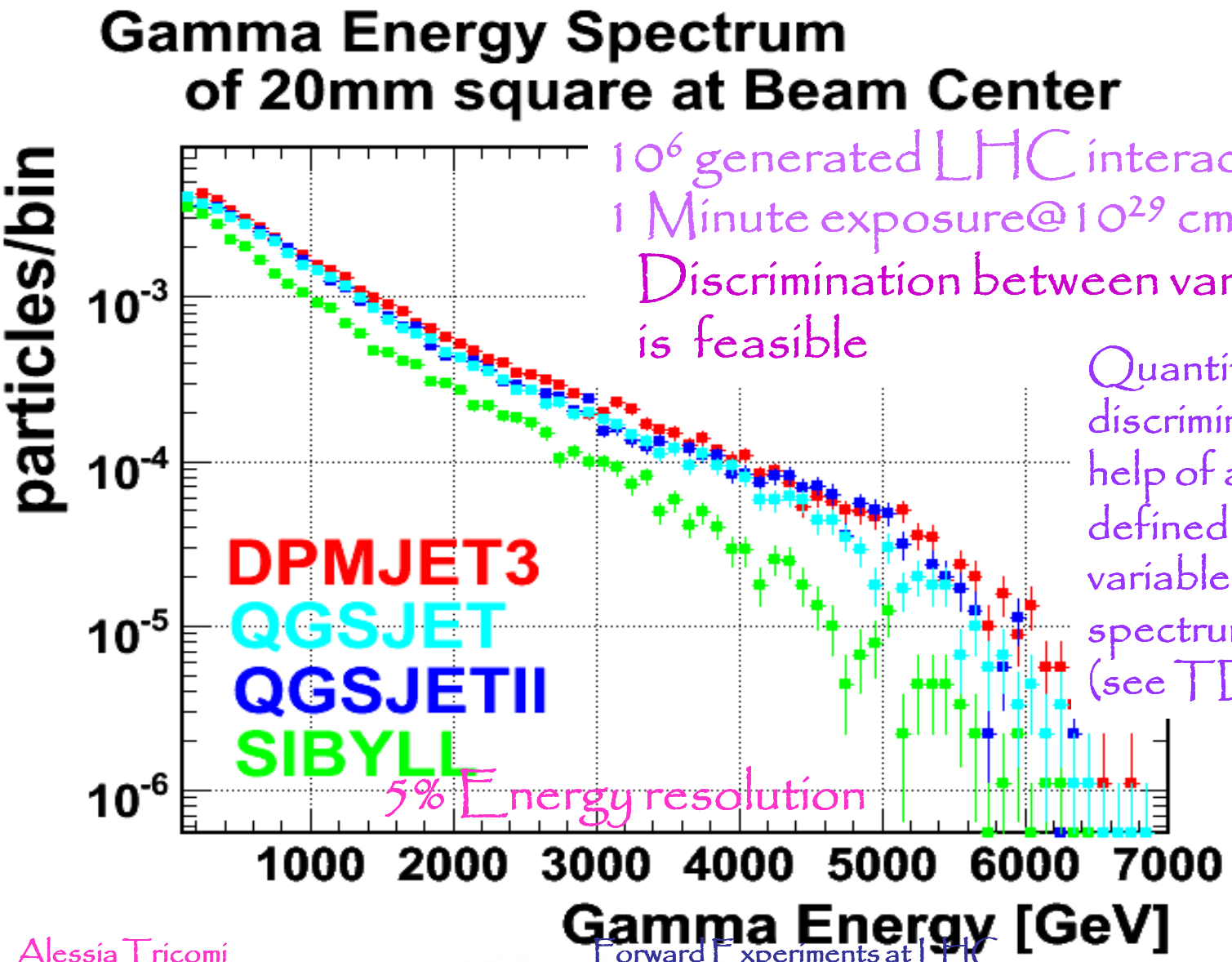
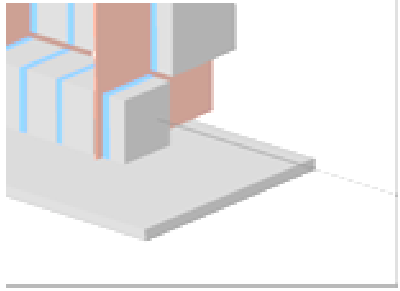
Forward Physics and EDS'09, Otranto, June 2009

LHCf : Monte Carlo discrimination



10^6 generated LHC interactions →
1 Minute exposure@10^{29} $cm^{-2}s^{-1}$ luminosity
Discrimination between various models is feasible

Quantitative discrimination with the help of a properly defined χ^2 discriminating variable based on the spectrum shape (see TDR for details)



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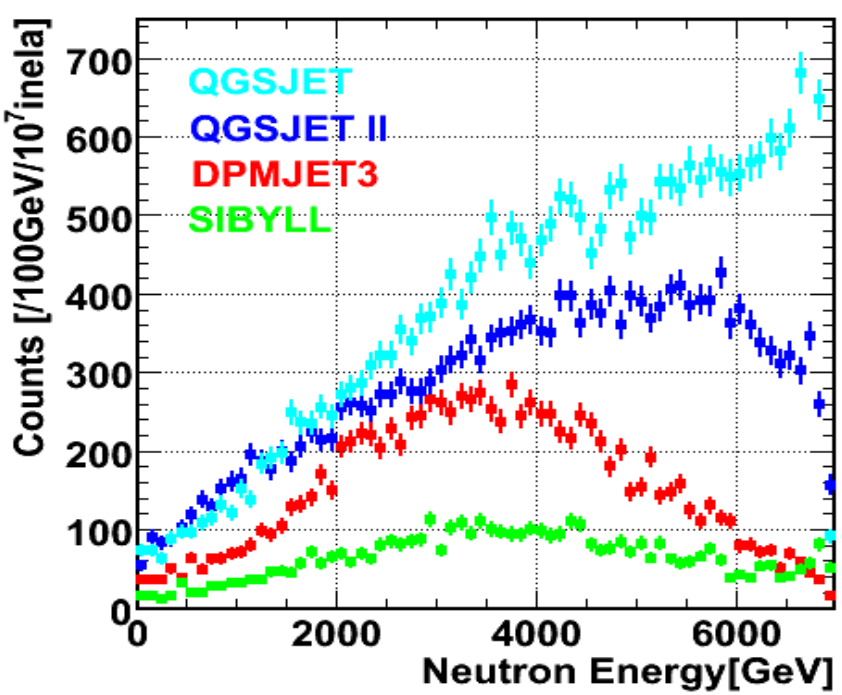
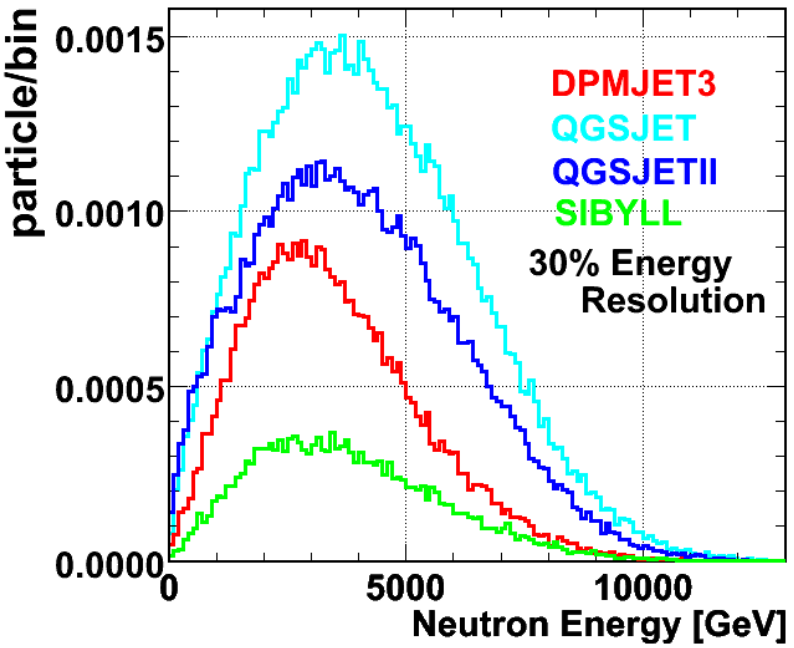
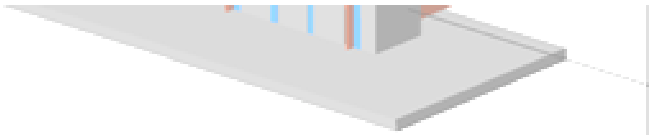
LHCf: model dependence of neutron energy distribution

Original n energy

30% energy resolution



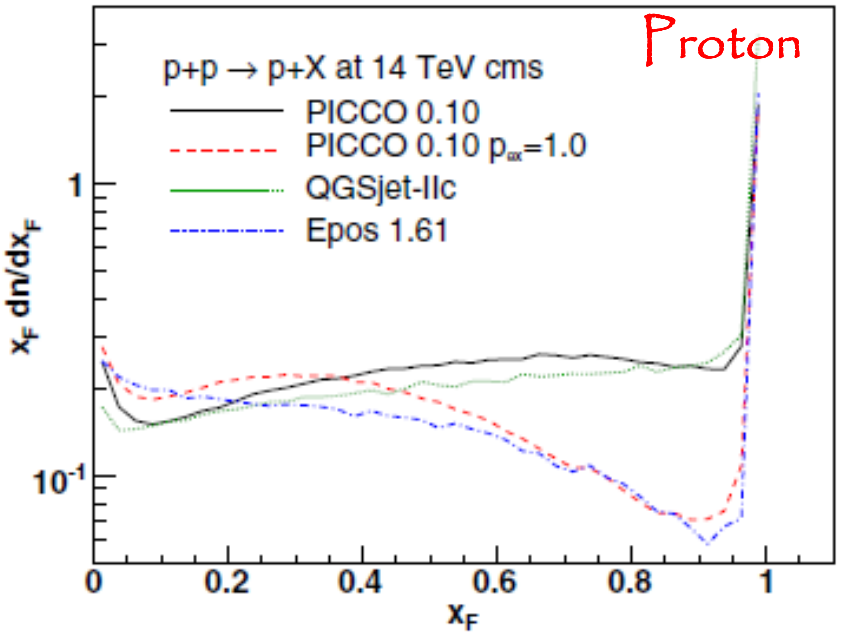


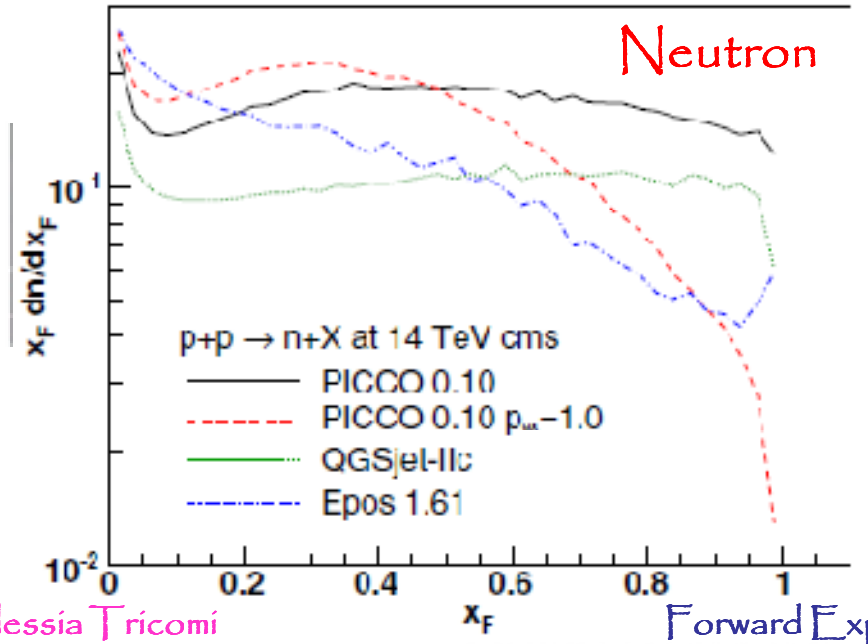


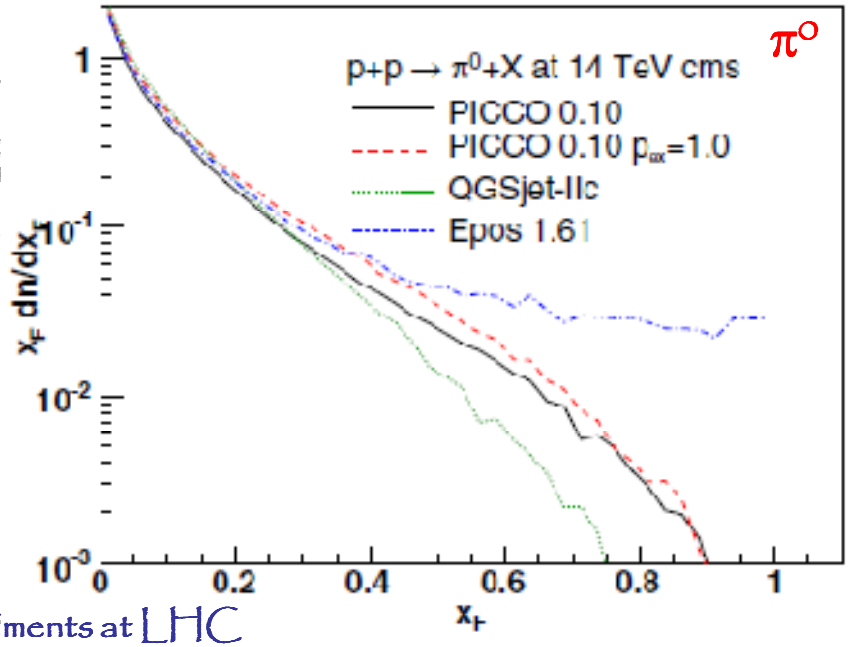
New Models

PICCO
EPOS

Drescher, Physical Review D77, 056003 (2008)

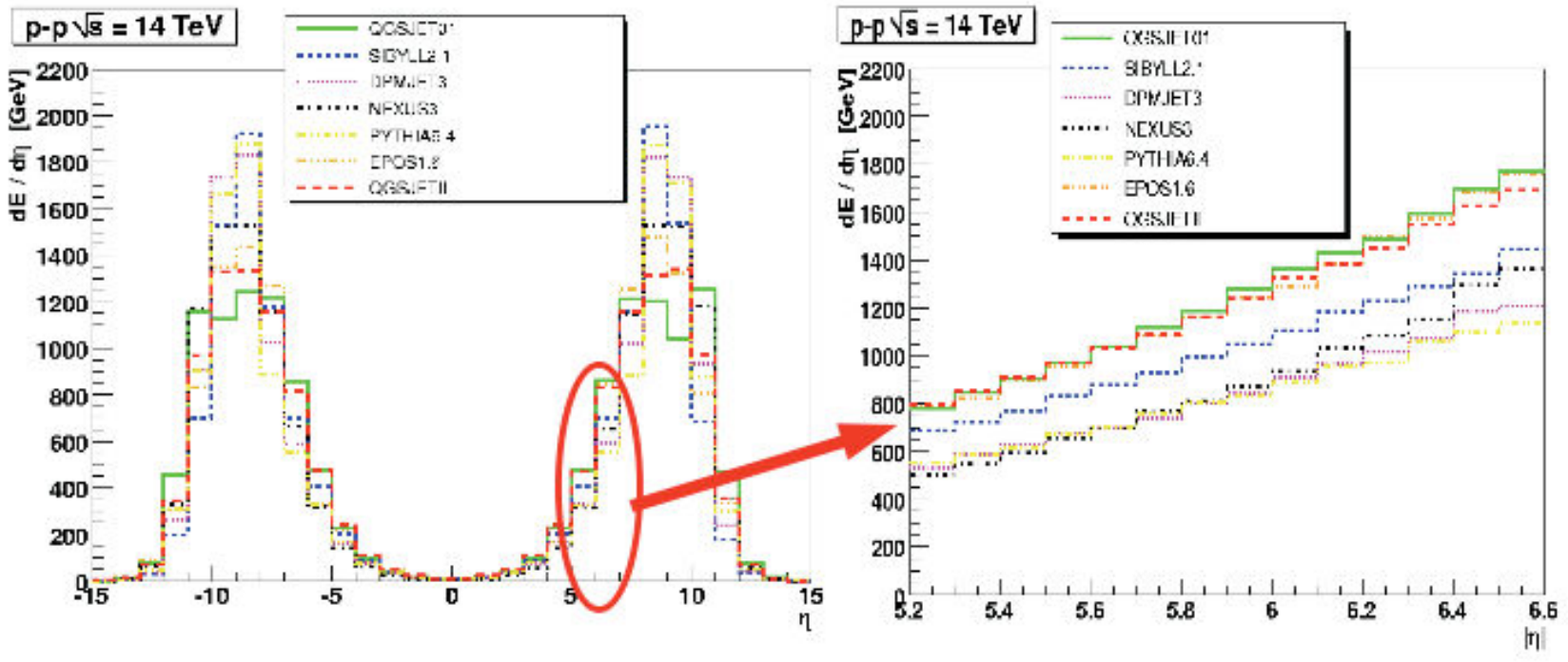






MC model tuning: pp @ √s = 14 TeV

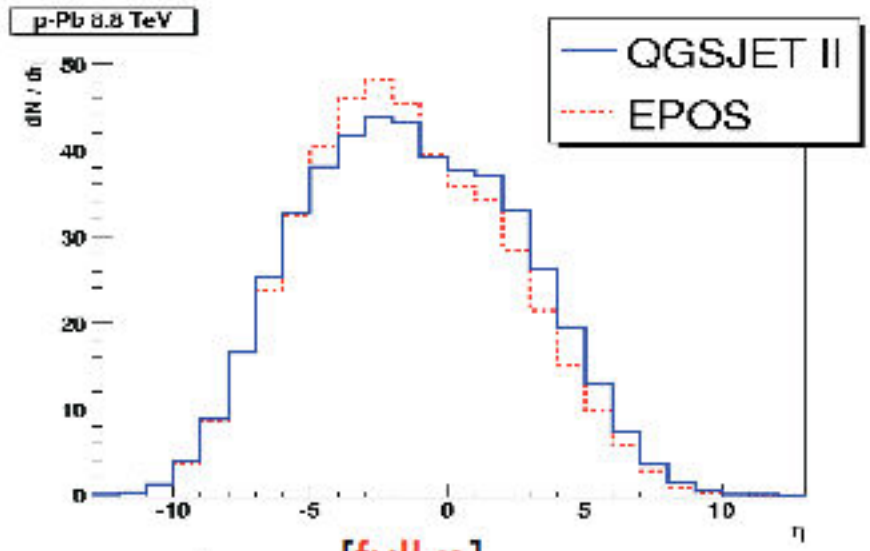
[full η] [CASTOR calorimeter region]



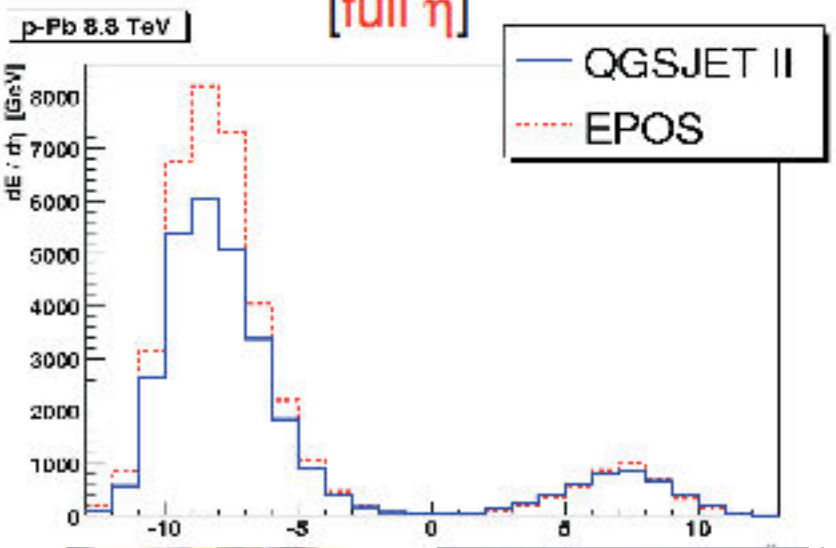
DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Dominated by Soft QCD: underlying events, multiparton interactions, fragmentations

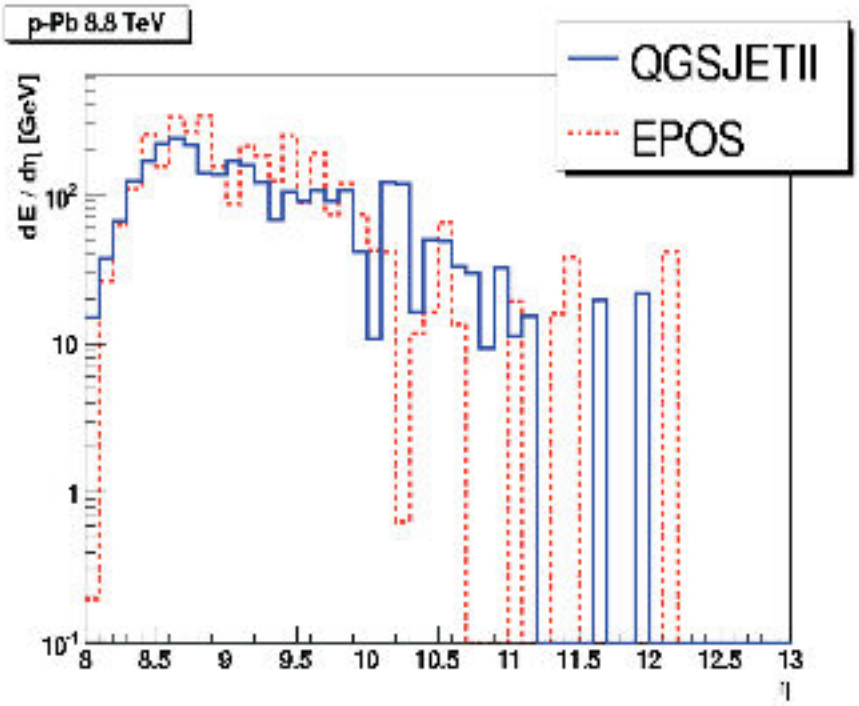
MC Model tuning: p+A @ √s= 8.8 TeV



[full η]



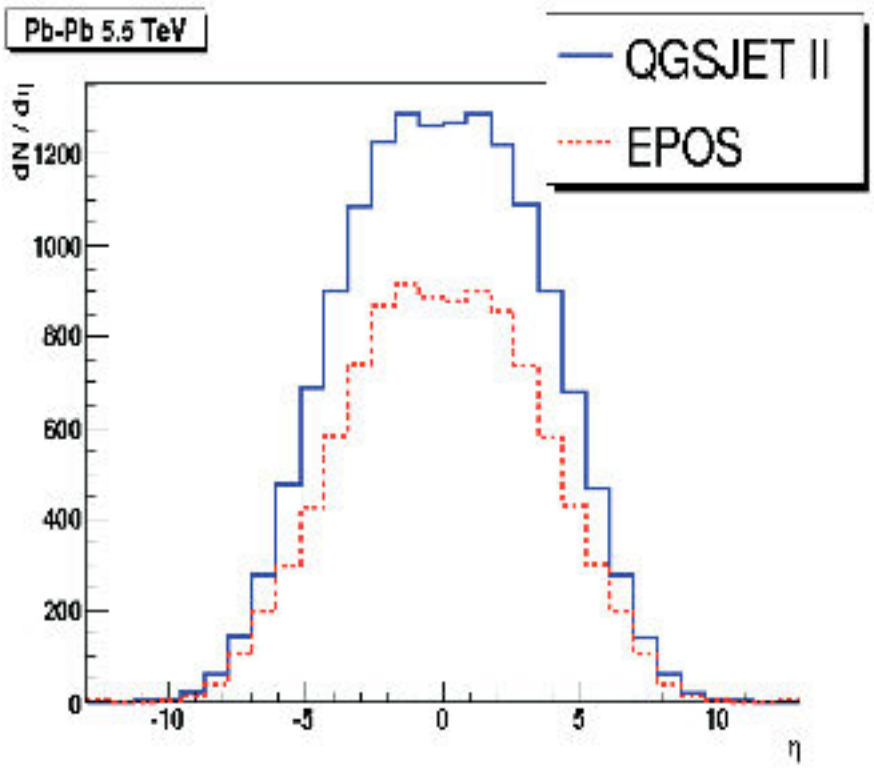
[ZDCs/LHCf calorimeter region]

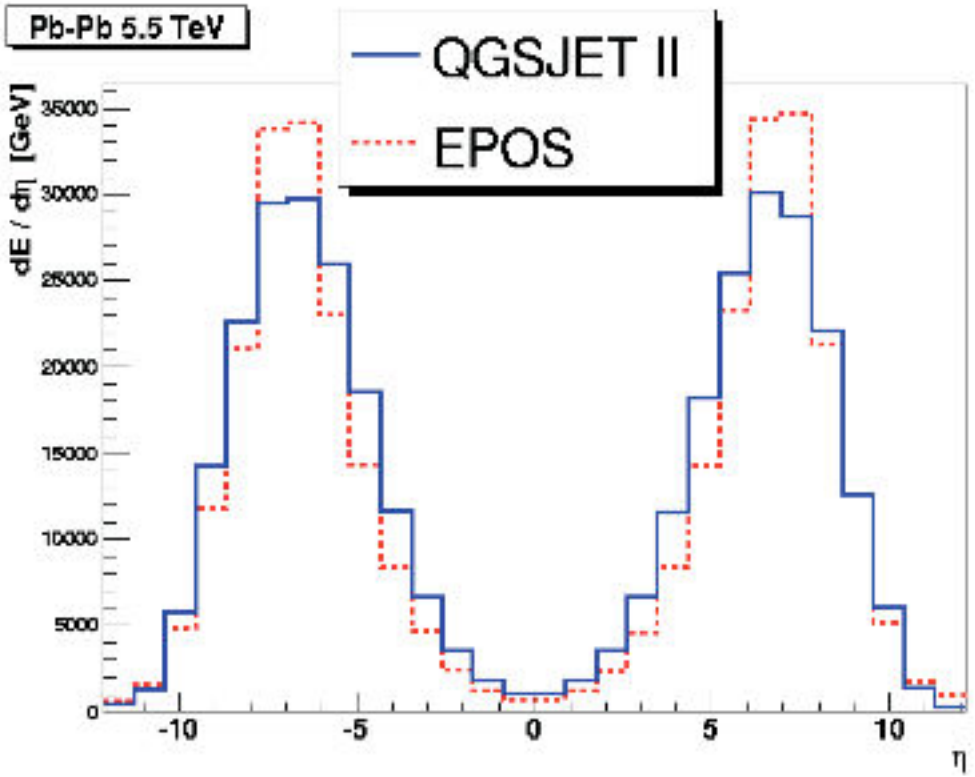


DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

MC Model tuning: A+A @ √s=5.5 TeV

[full η]



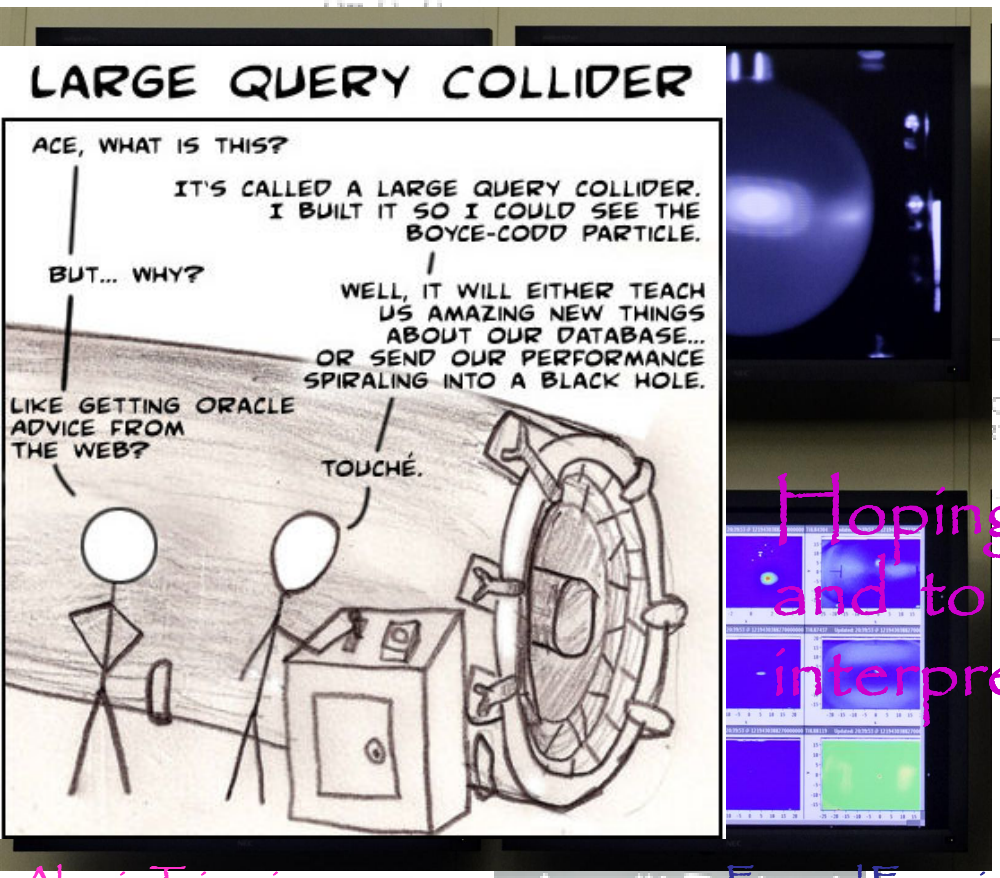


DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Conclusions and plans

Compilation of EAS data is affected by the uncertanties of hadron interaction models.

LHC fwd experiments will provide crucial data of hadron interaction for CR study covering the whole phase space



Several detectors already installed

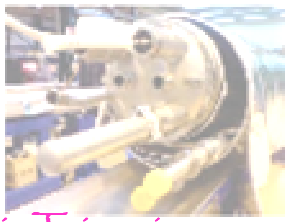
LHCf ready for data taking already during LHC commissioning

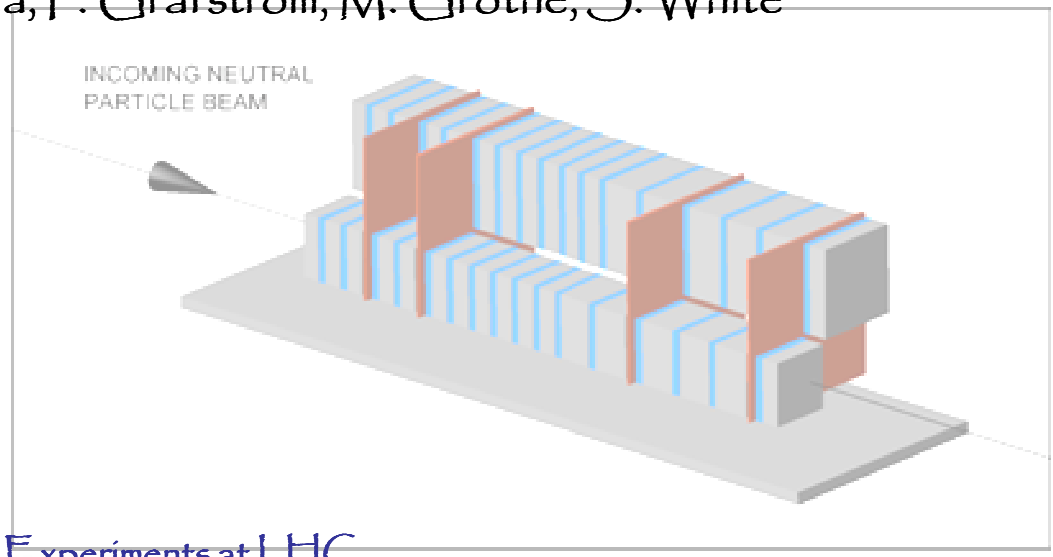
We need only to wait LHC restart!

Hoping to answer all our questions and to help EAS experiments to interpret their data

Aknowledgement

Thanks to ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM Collaborations for useful material
In particular, I wish to thank
O. Adriani, K. Eggert, D. D'Enterria, P. Grafstrom, M. Grothe, S. White





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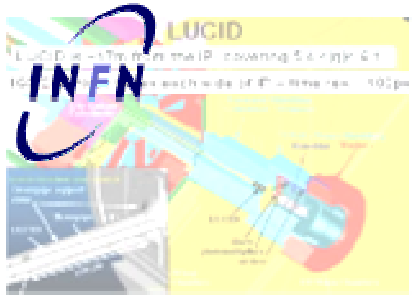
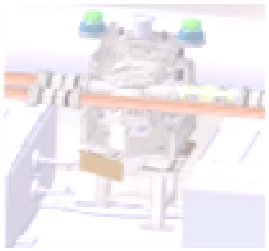
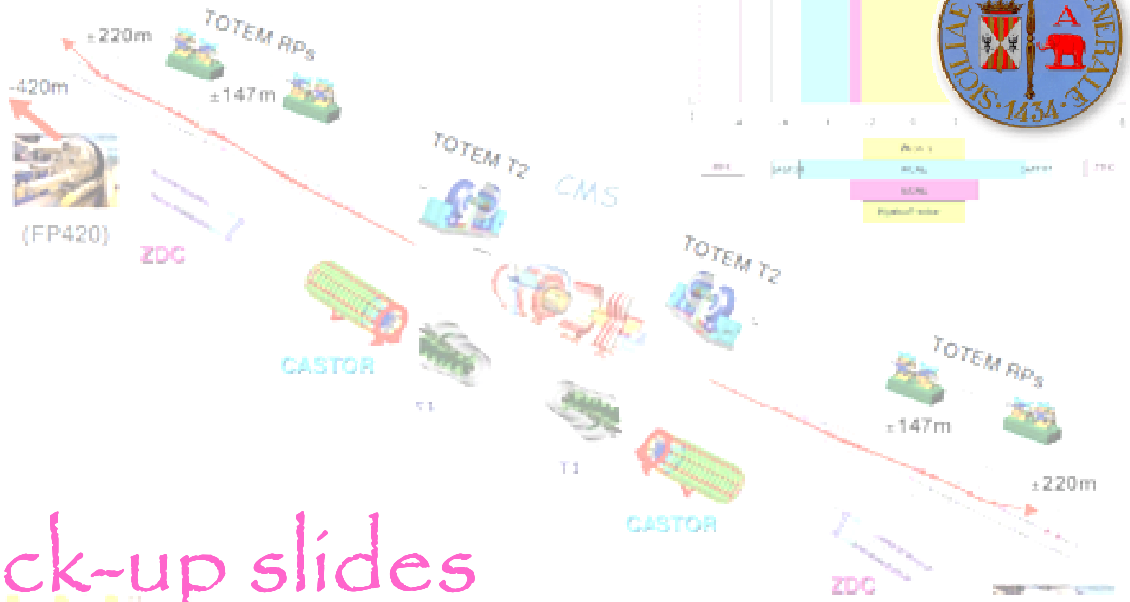
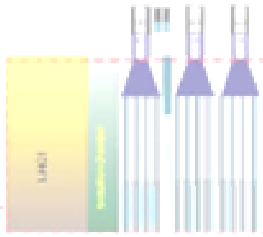
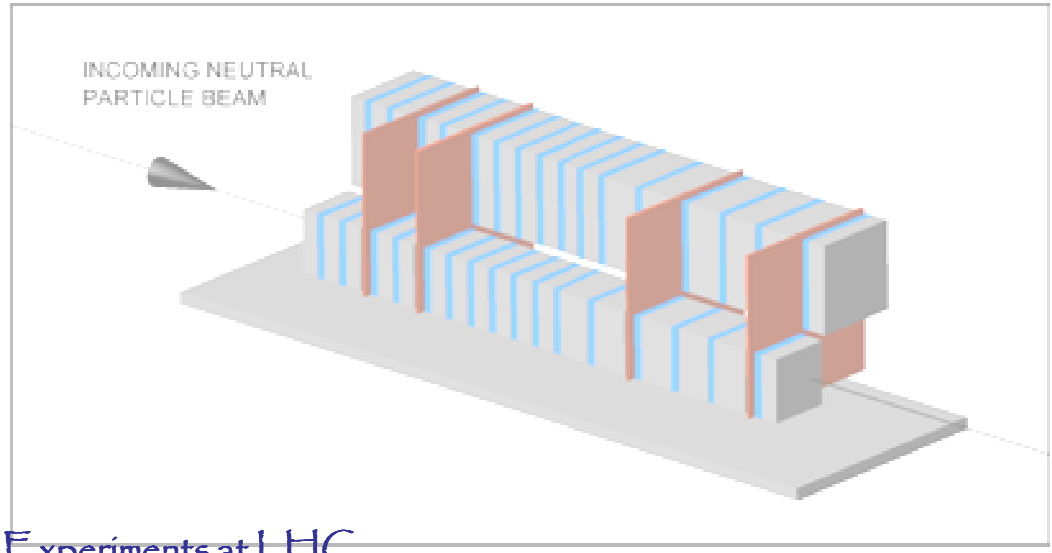








Back-up slides



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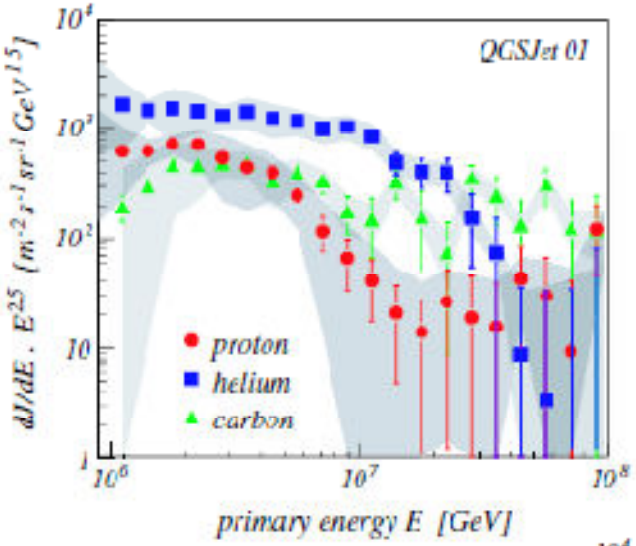
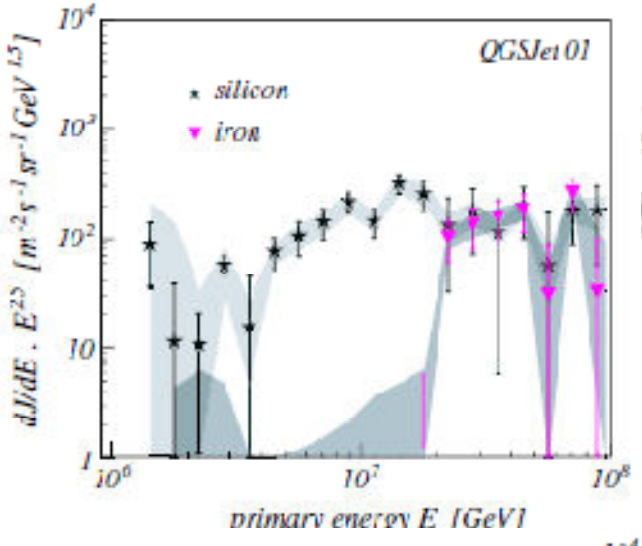
Cosmic Ray Composition

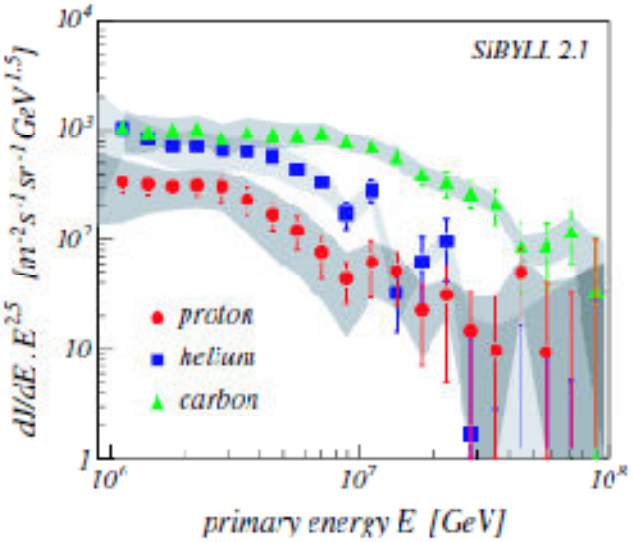
Kascade Results

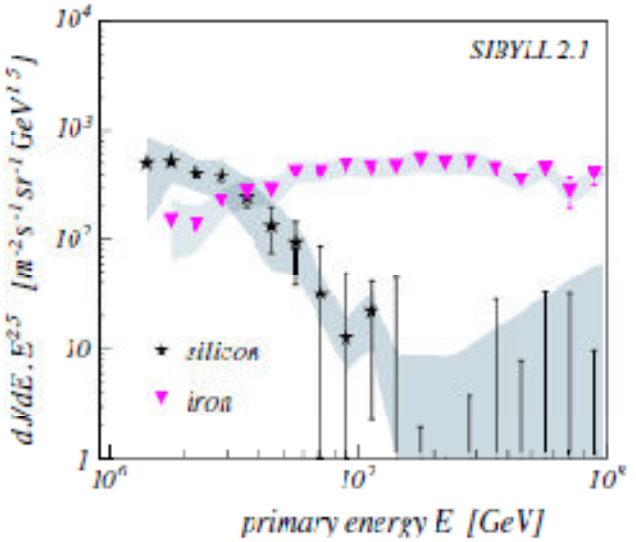




QGSJET01

SIBYLL 2.1





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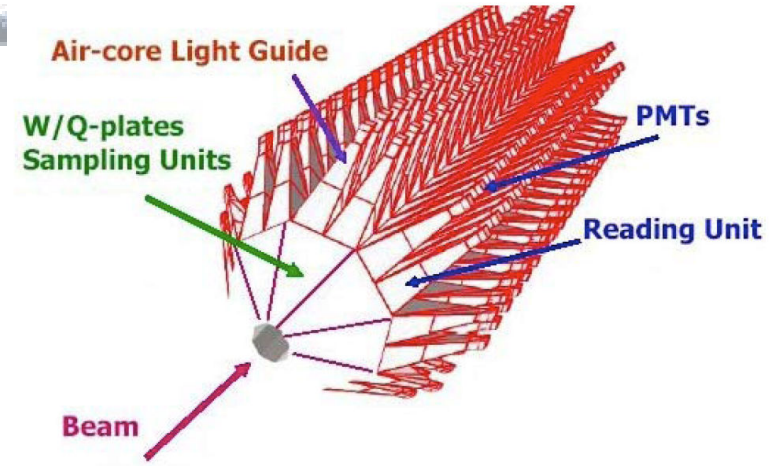
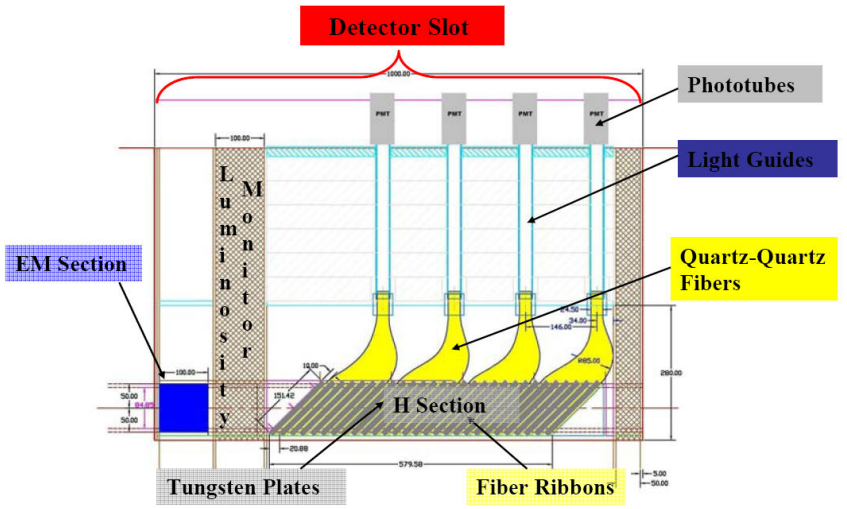
CMS CASTOR & ZDC calorimeters

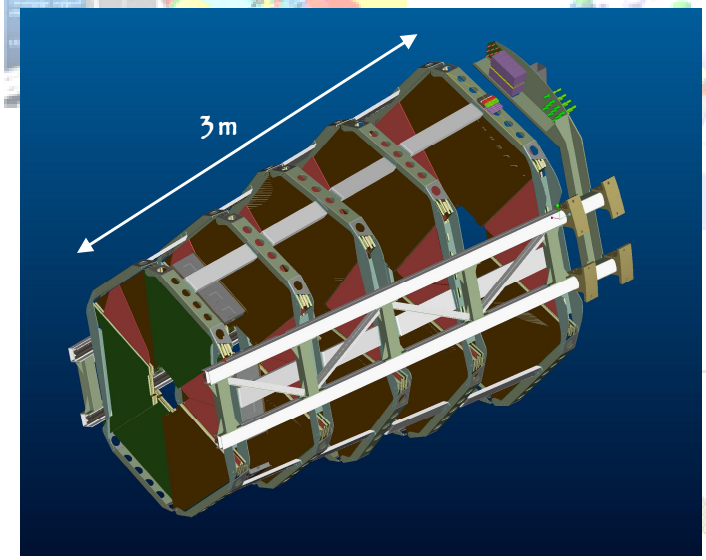


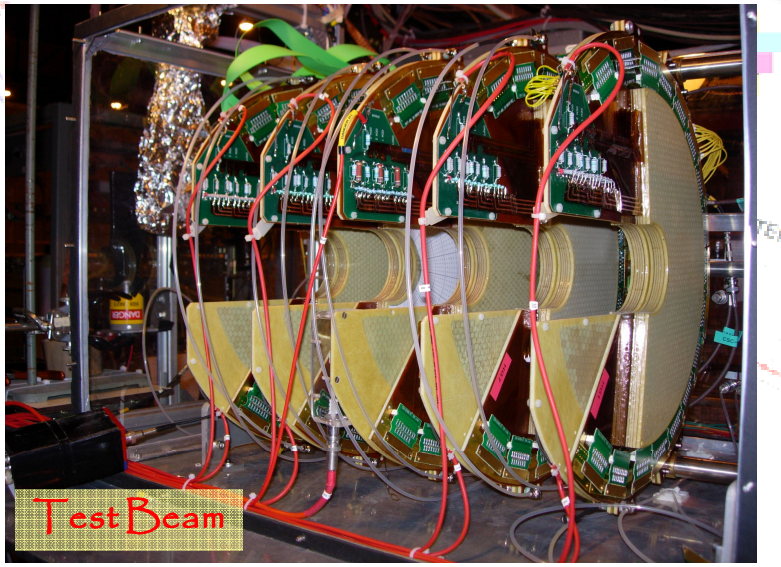


- **extends calorimetric coverage of CMS to $5.2 < \eta < 6.6$**
- **signal collection through Čerenkov photons transmitted to PMTs through aircore lightguides**
- **W absorber & quartz plates sandwich,**
- **electromagnetic and hadronic sections**
- **16 seg. in φ, 14 seg in z, none in η**

- **140 m from interaction point in TAN absorber**
  - **Tungsten/quartz Čerenkov calorimeter with separate e.m. and had. Sections**
  - **Acceptance for neutrals (γ, π^0, n) from $\eta > 8.1$, 100% for $\eta > 8.4$**

TOTEM T1 & T2 tracking detectors





- Cathode Strip Chambers (CSC)
- Mounted in front of HadronForward calorimeter of CMS
- $3.1 < |\eta| < 4.7$
- 5 planes with 3 coordinates/plane
- 6 trapezoidal CSC detectors/plane
- Resolution $\sigma \sim 0.8$ mm

- Gas Electron Multiplier (GEM)
- Mounted in front of CASTOR
- $5.3 < |\eta| < 6.5$
- 10 planes formed by 20 GEM semi-circular modules
- Radial position from strips, η,ϕ from pads
- Resolution $\sigma_{strip} \sim 70\mu m$

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Detector #1

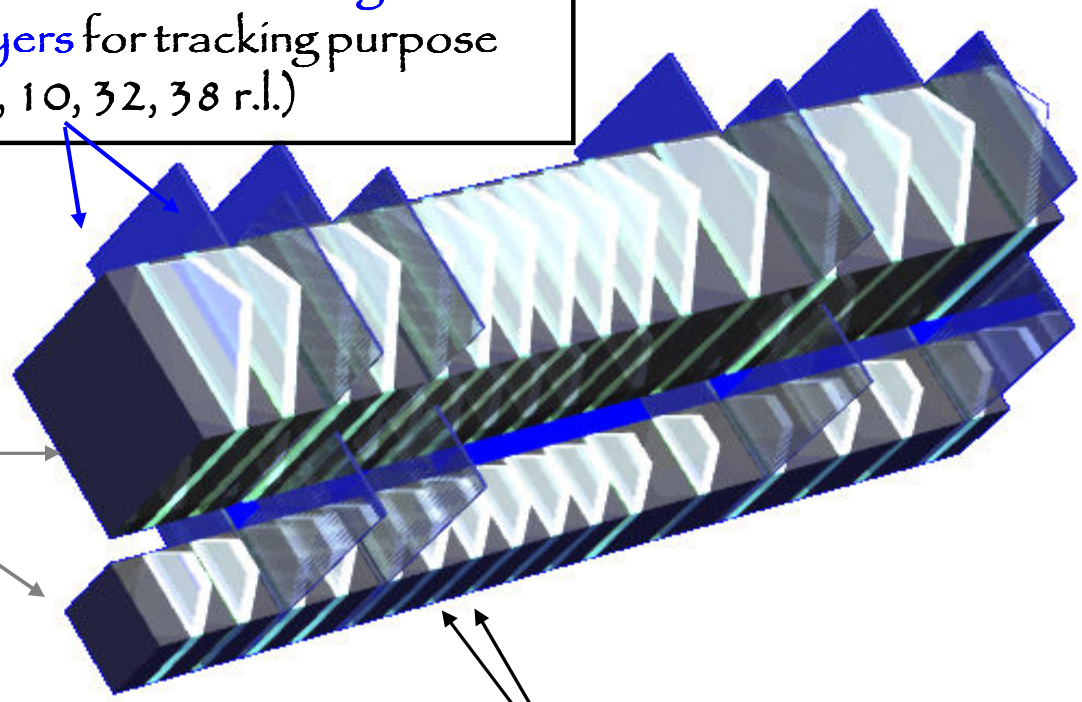
2 towers 24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area

Upper: 4 cm x 4 cm area

Impact point (η)

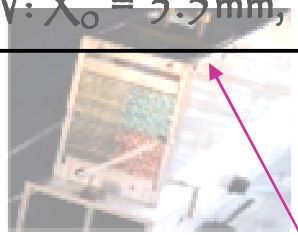
4 pairs of scintillating fiber layers for tracking purpose (6, 10, 32, 38 r.l.)

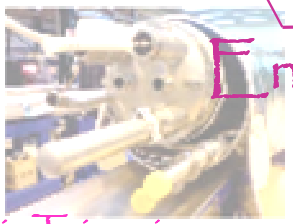


Absorber

22 tungsten layers
7mm – 14 mm thick

(W: X_0 = 3.5mm, R_M = 9mm)





Energy

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Detector # 2

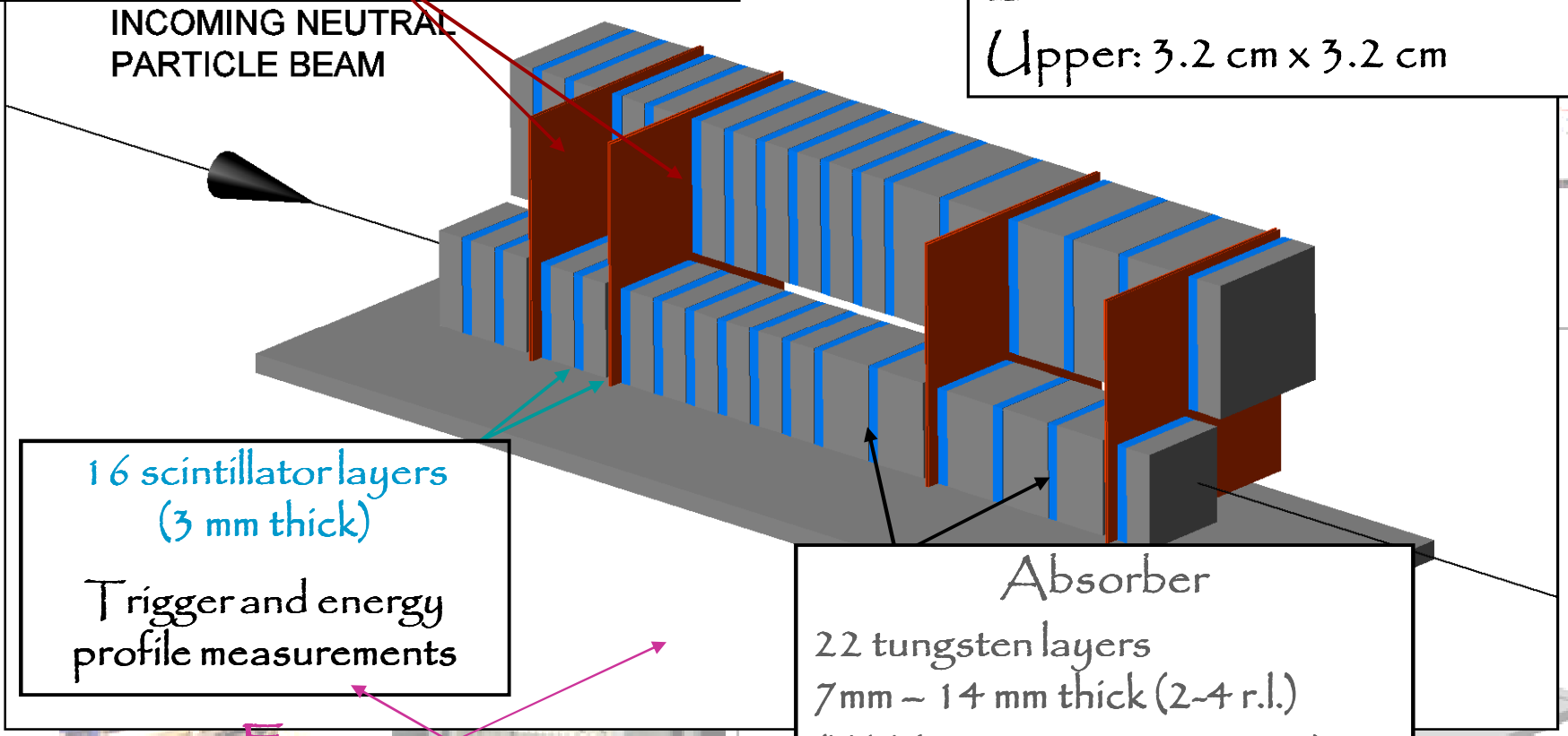
Impact point (η)

4 pairs of silicon microstrip layers
(6, 12, 30, 42 r.l.) for tracking purpose
(X and Y directions)

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm



16 scintillator layers
(3 mm thick)

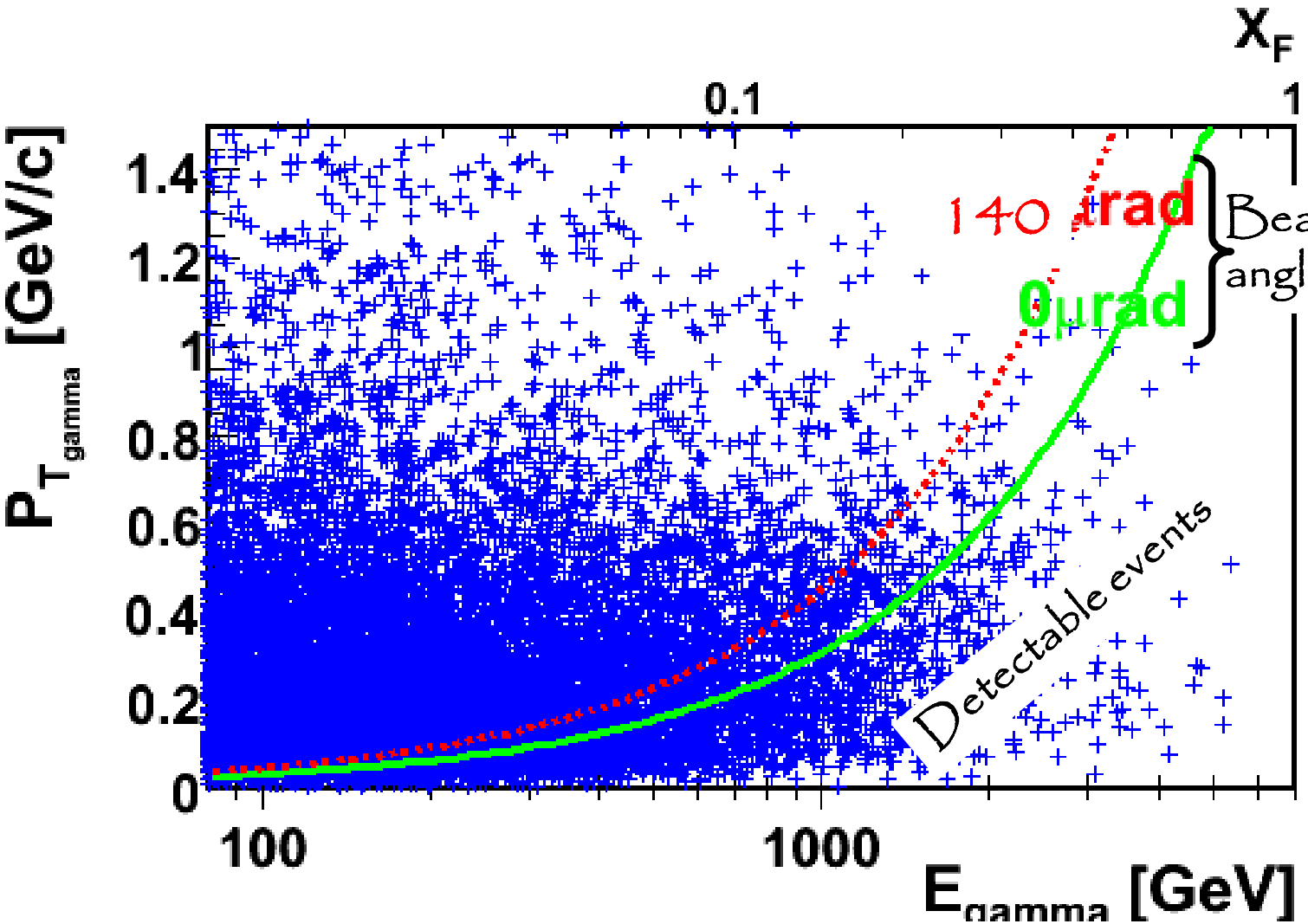
Trigger and energy profile measurements

Absorber

22 tungsten layers
7mm – 14 mm thick (2-4 r.l.)
(W: X_0 = 3.5mm, R_M = 9mm)

Energy

LHCf: acceptance on $P_T\gamma$-E_γ plane



A vertical beam crossing angle > 0 increases the acceptance of LHCf

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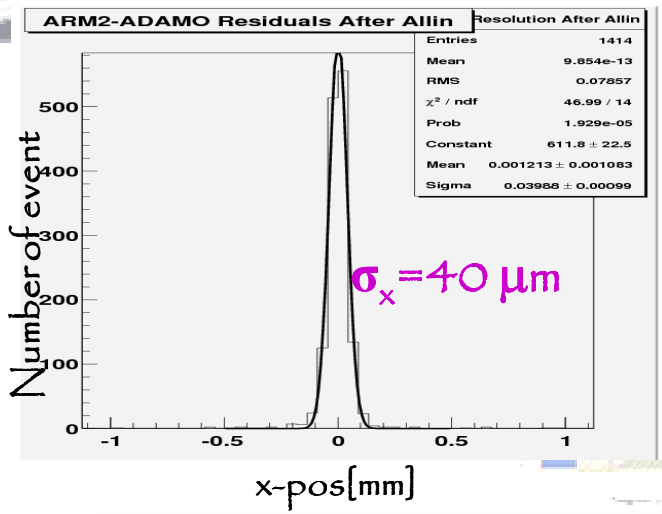
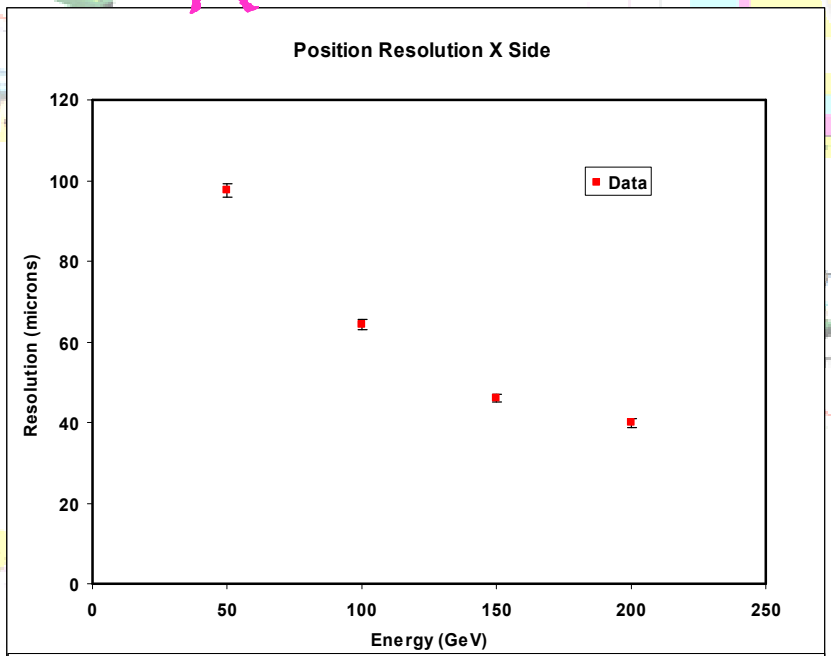
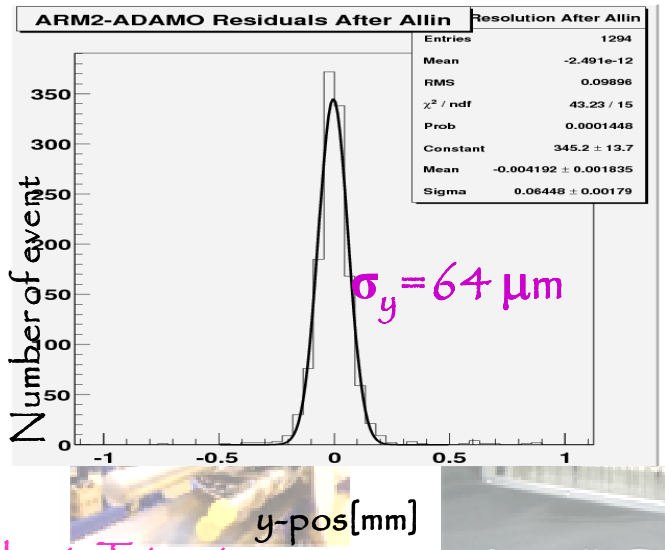
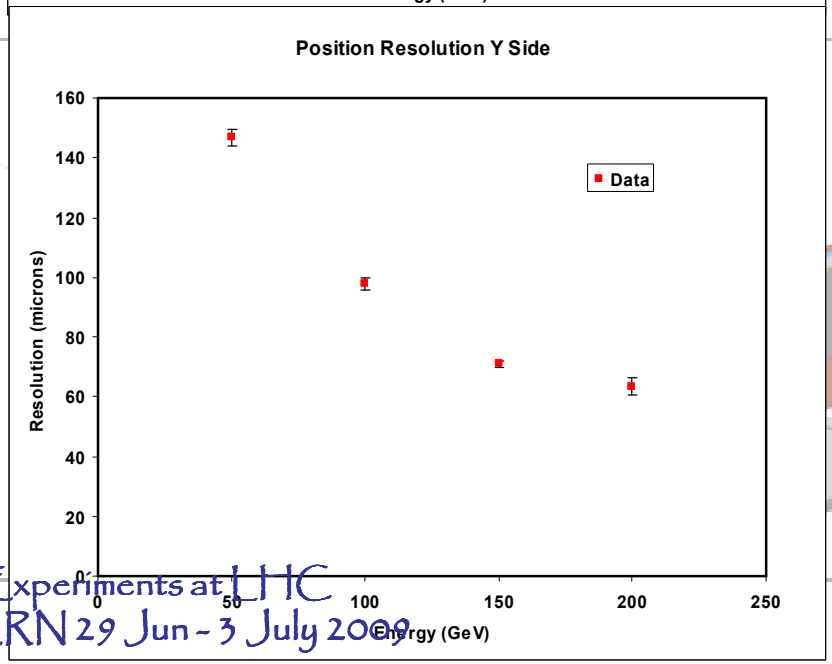
ARM2 Position Resolution

200 GeV electrons









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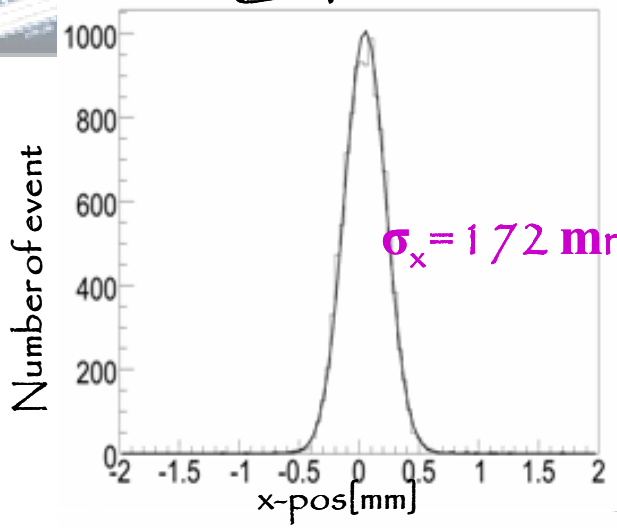
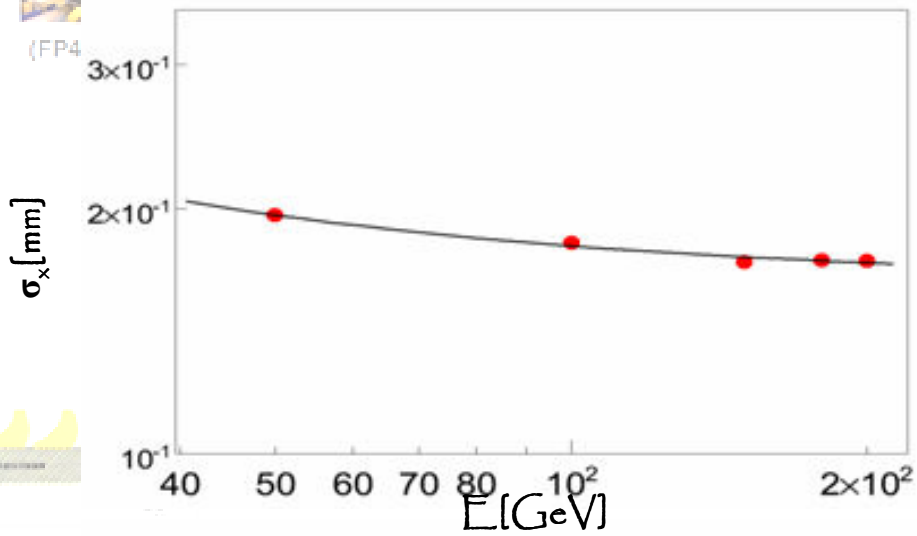
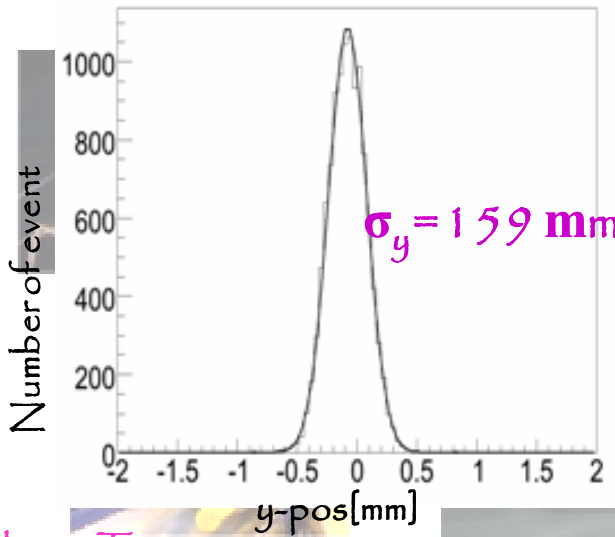
ARM1 Position resolution

200 GeV electrons

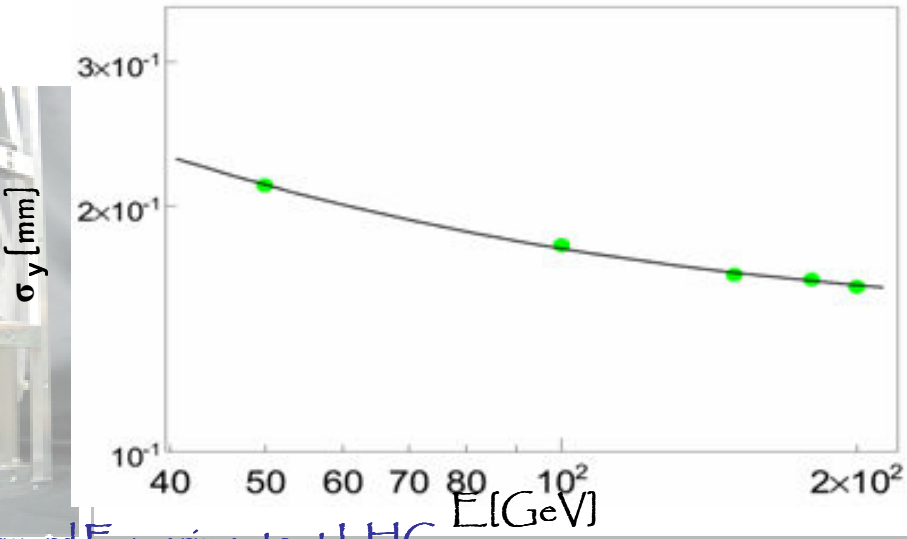


$\sigma_x = 172$ mm

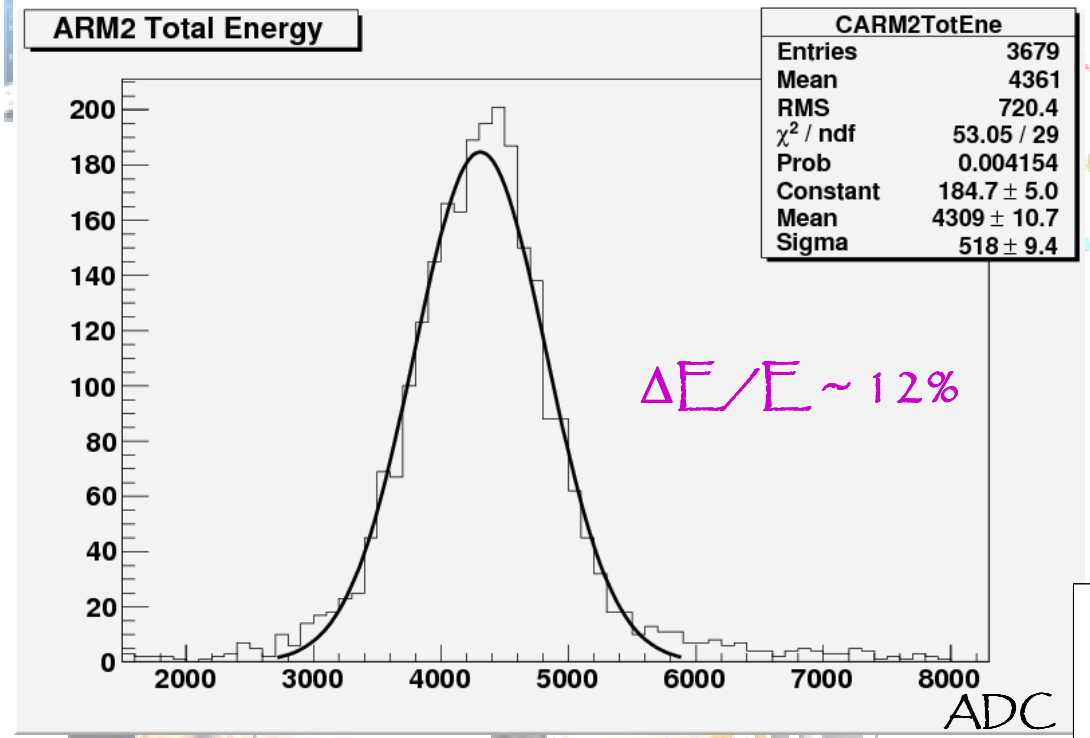




$\sigma_y = 159$ mm



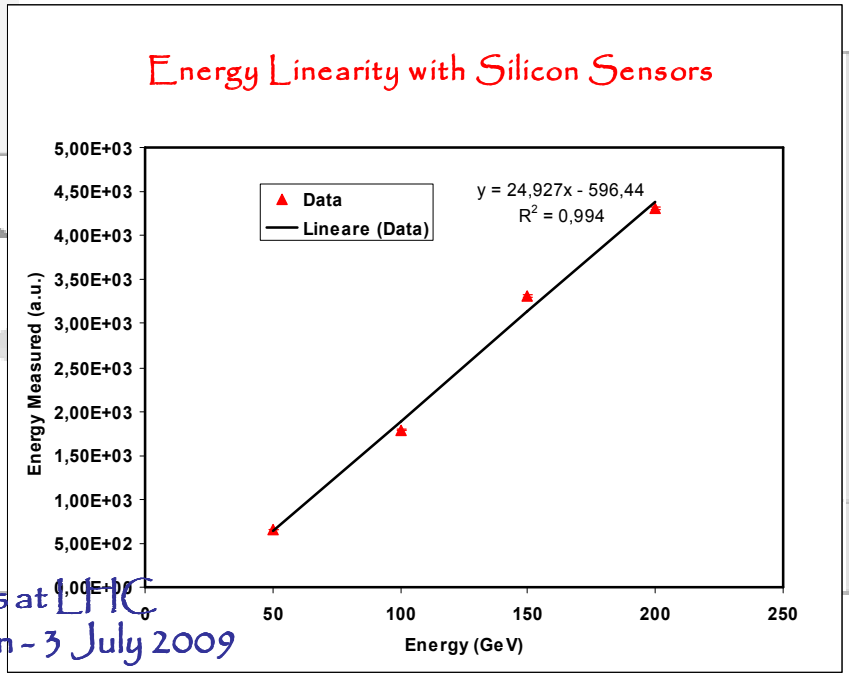
ARM2-Silicon Energy Resolution



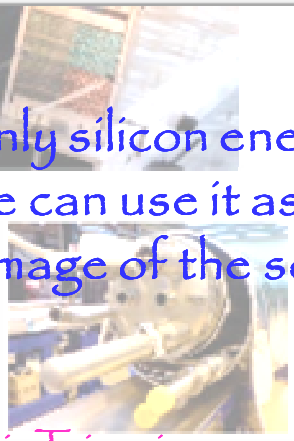
ΔE/E ~ 12%

200 GeV electrons
SPS beam test data

No correction/calibration applied



Only silicon energy resolution ~ 10%!!!!!
We can use it as a check for the radiation damage of the scintillators



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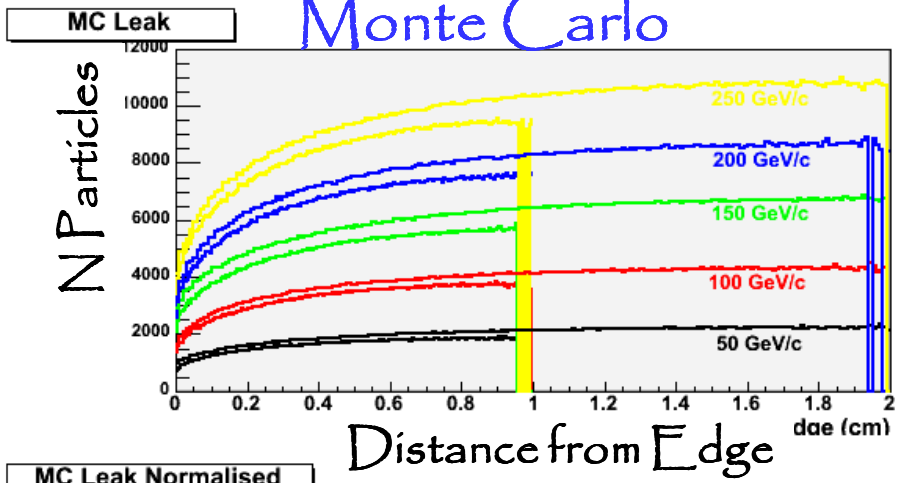
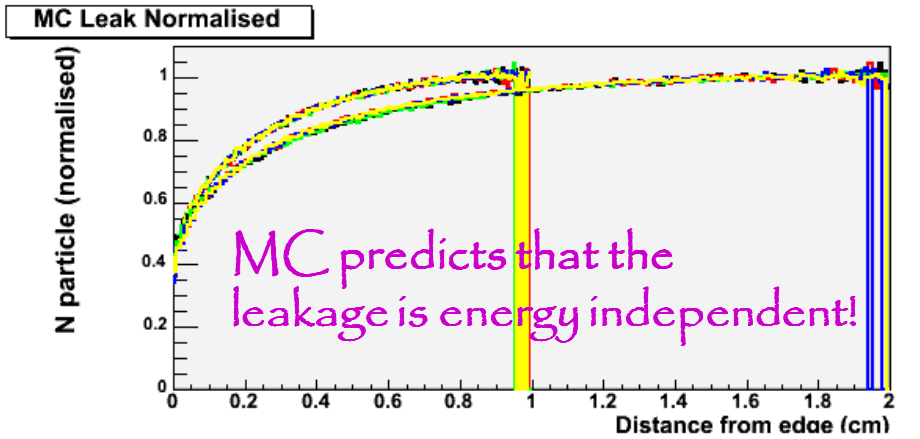
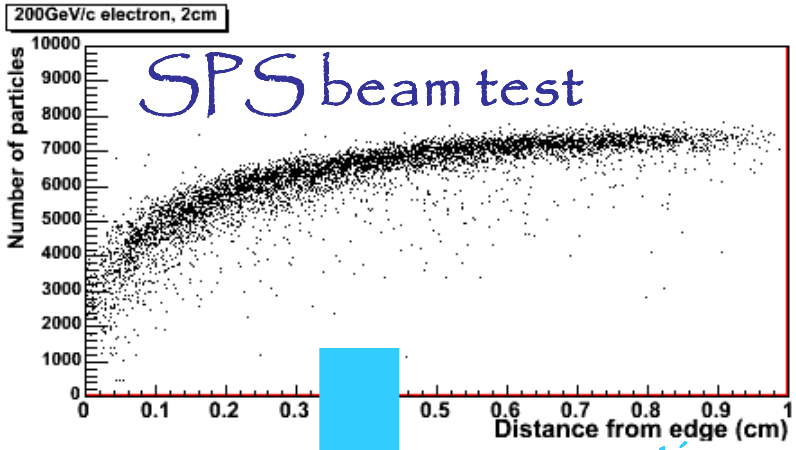
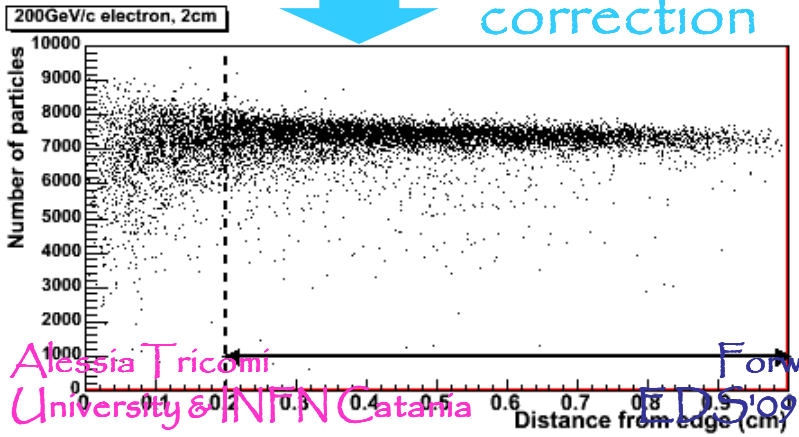
Energy Resolution

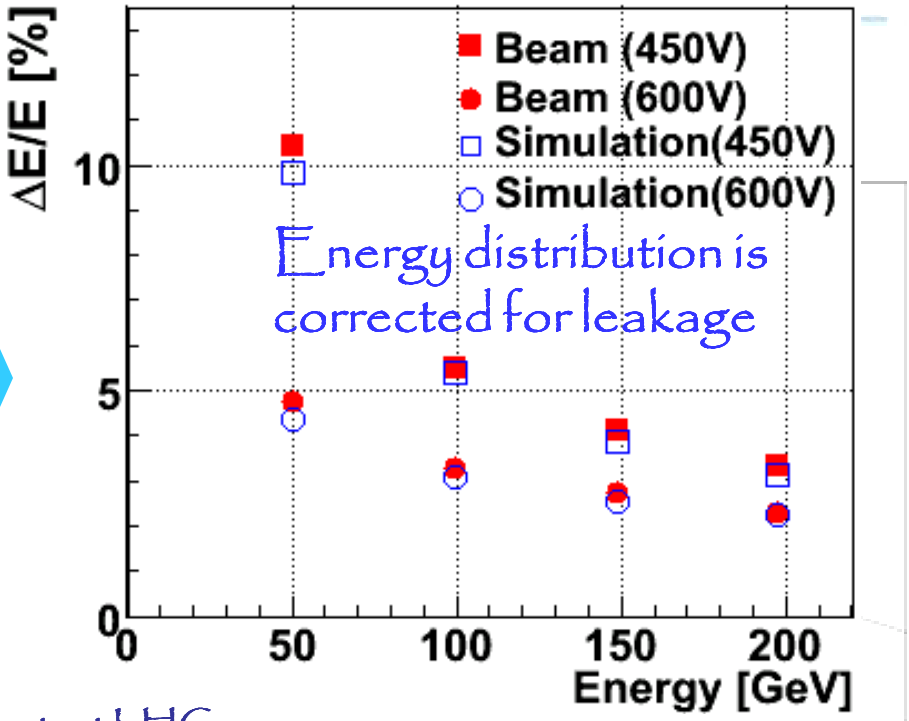




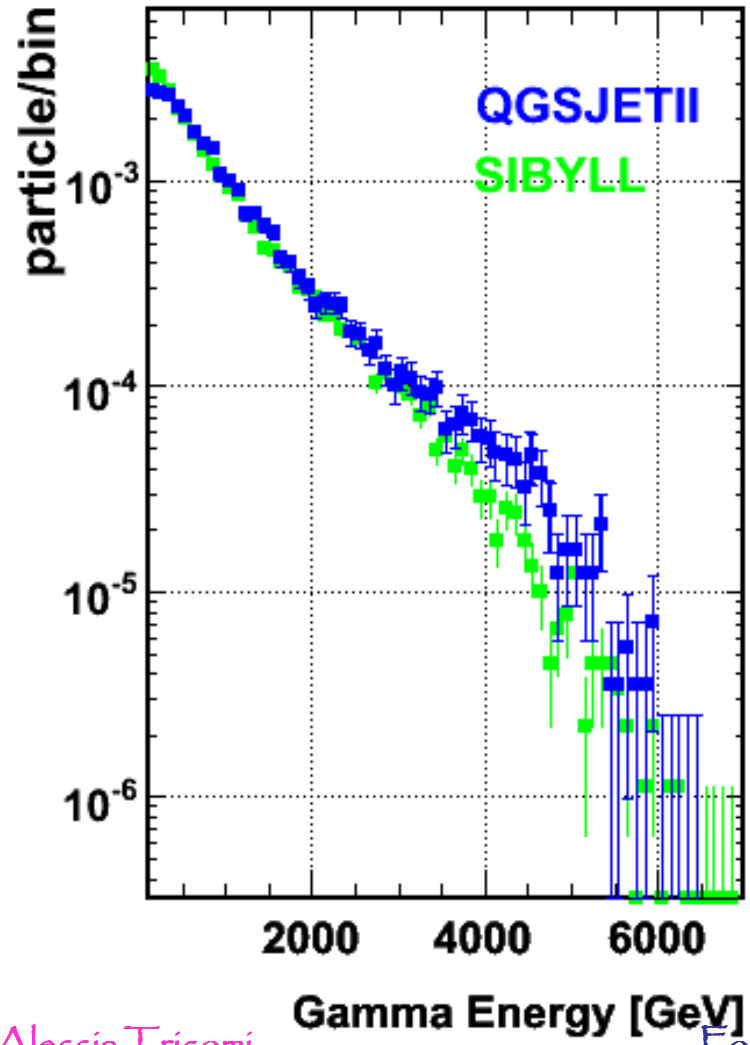


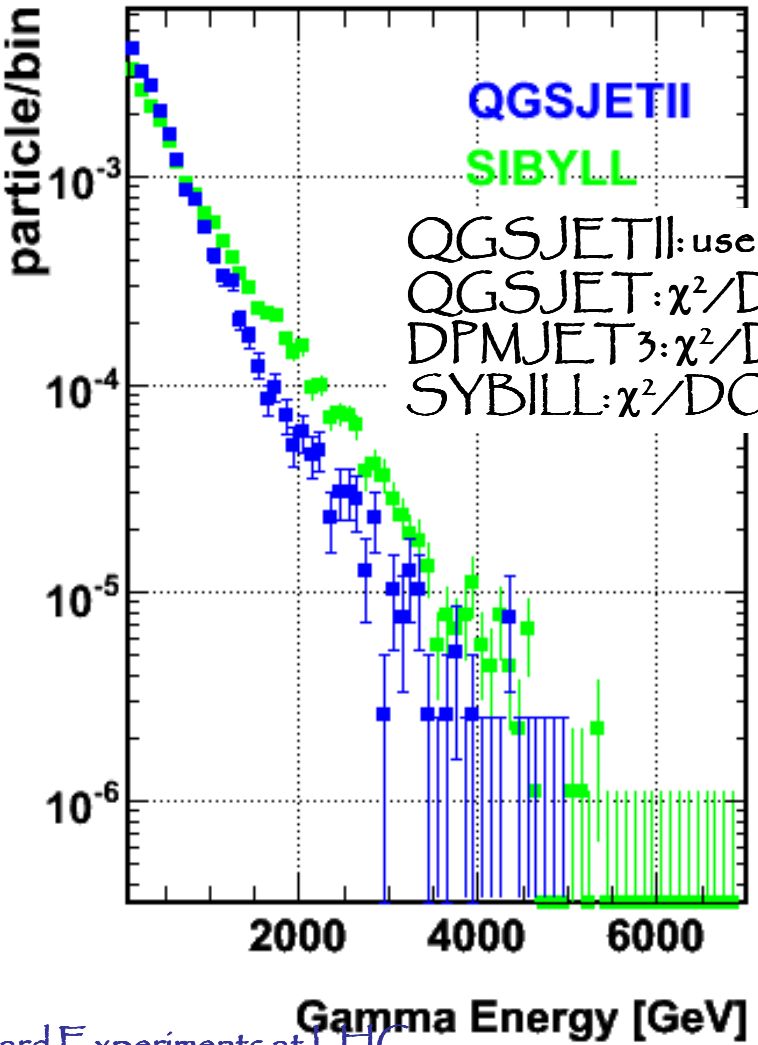
correction



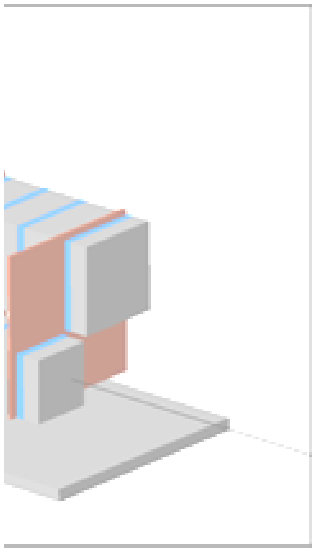


γ ray energy spectrum for different positions





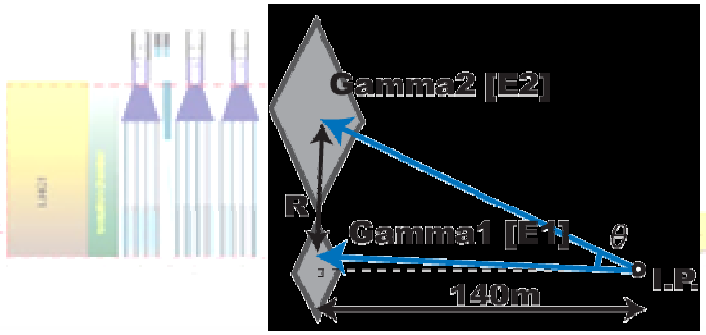
QGSJETII: used model
QGSJET: χ^2/DOF=107/125
DPMJET3: χ^2/DOF=224/125
SYBILL: χ^2/DOF=816/125

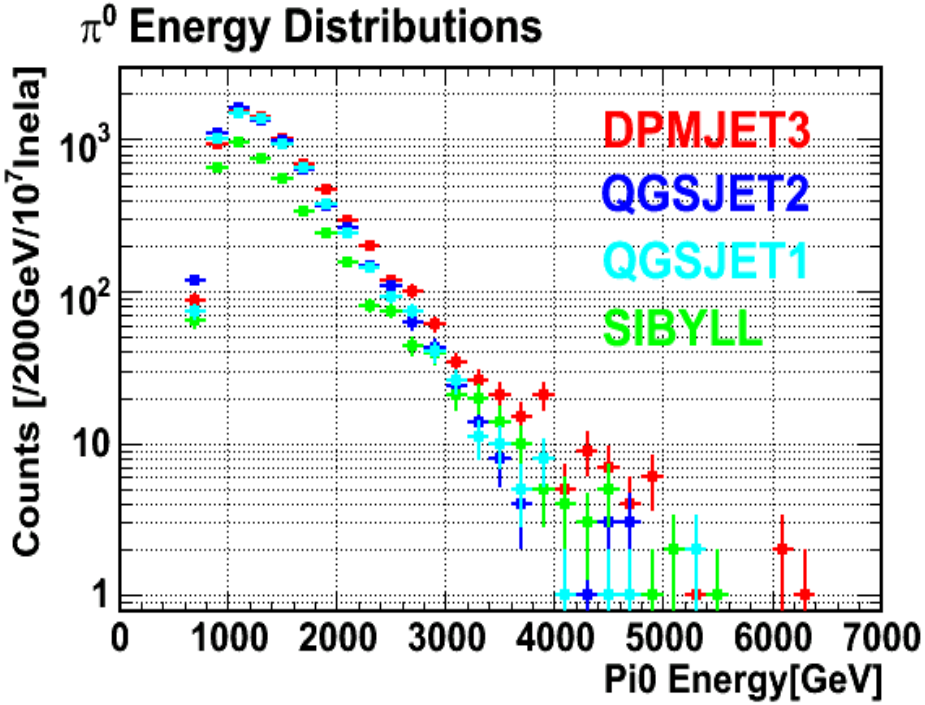


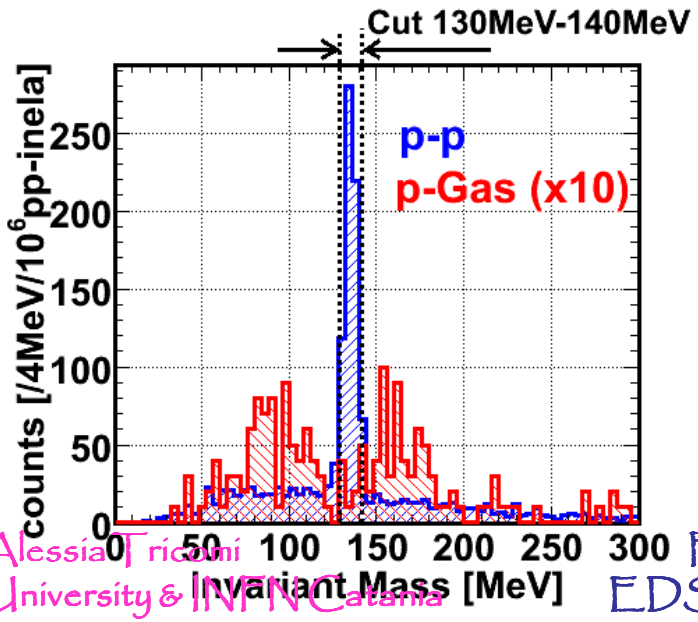
π^0 spectra

p^0 produced at collision can be extracted by using gamma pair events

Powerful tool to calibrate the energy scale and also to eliminate beam-gas BG

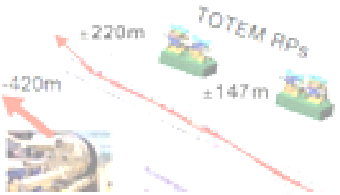


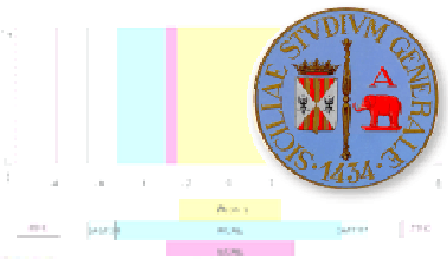


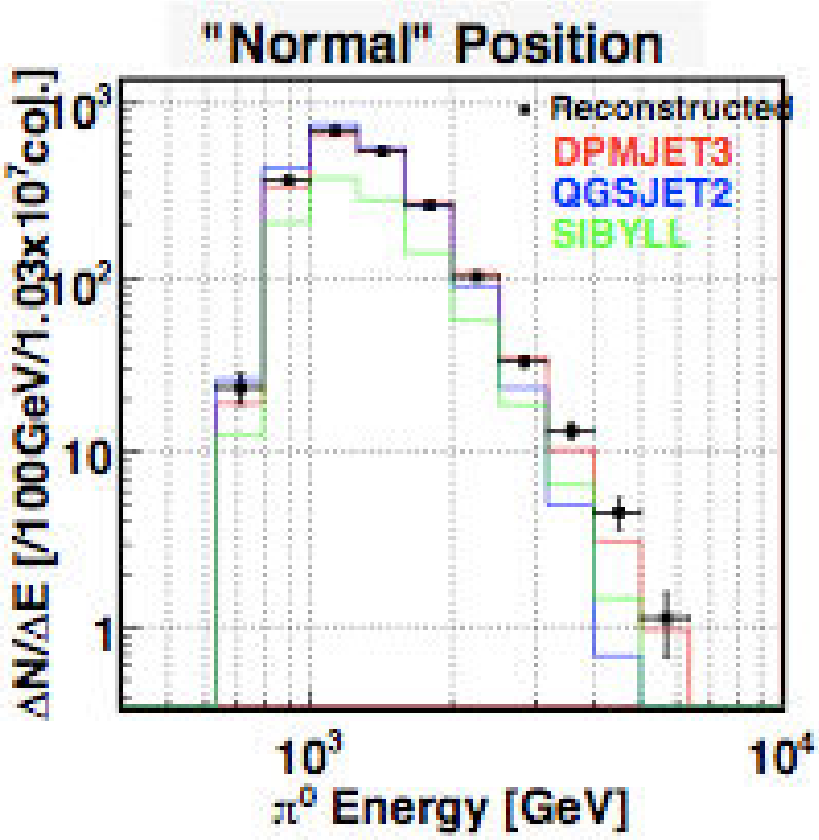


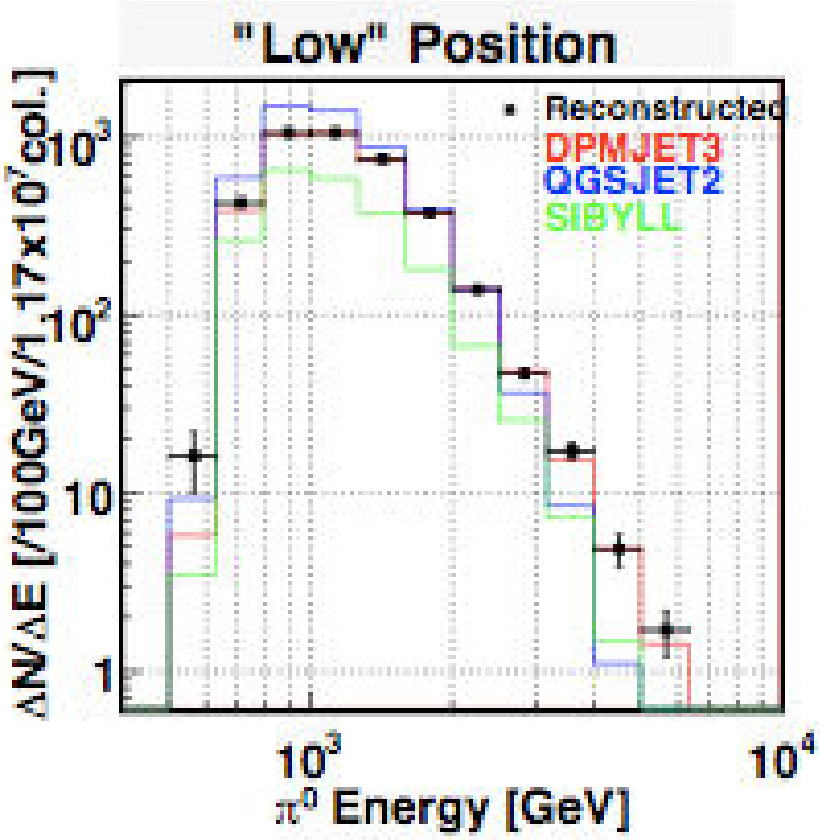
QGSJETII
⇔ DPMJET3 χ^2= 106 (C.L.<10^{-6})
⇔ SIBYLL χ^2= 83 (C.L.<10^{-6})
DPMJET3
⇔ SIBYLL χ^2= 28 (C.L.= 0.024)
10^7 events DOF = 17-2=15

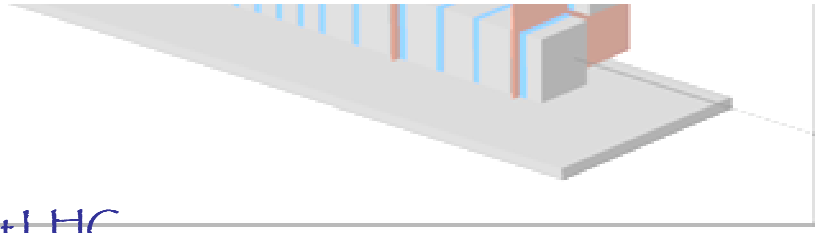

LUCID


±220m
TOTEM RPs
±147m
-420m
TOTEM T2

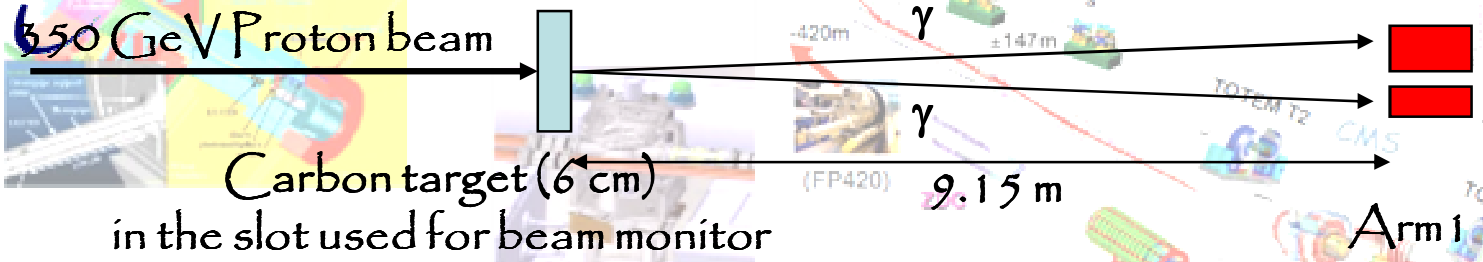



"Normal" Position
Reconstructed
DPMJET3
QGSJET2
SIBYLL
ΔN/ΔE [/100GeV/1.03x10^7col.]
10^3
10^2
10
1
10^3
10^4
π^0 Energy [GeV]


"Low" Position
Reconstructed
DPMJET3
QGSJET2
SIBYLL
ΔN/ΔE [/100GeV/1.17x10^7col.]
10^3
10^2
10
1
10^3
10^4
π^0 Energy [GeV]



π^0 reconstruction



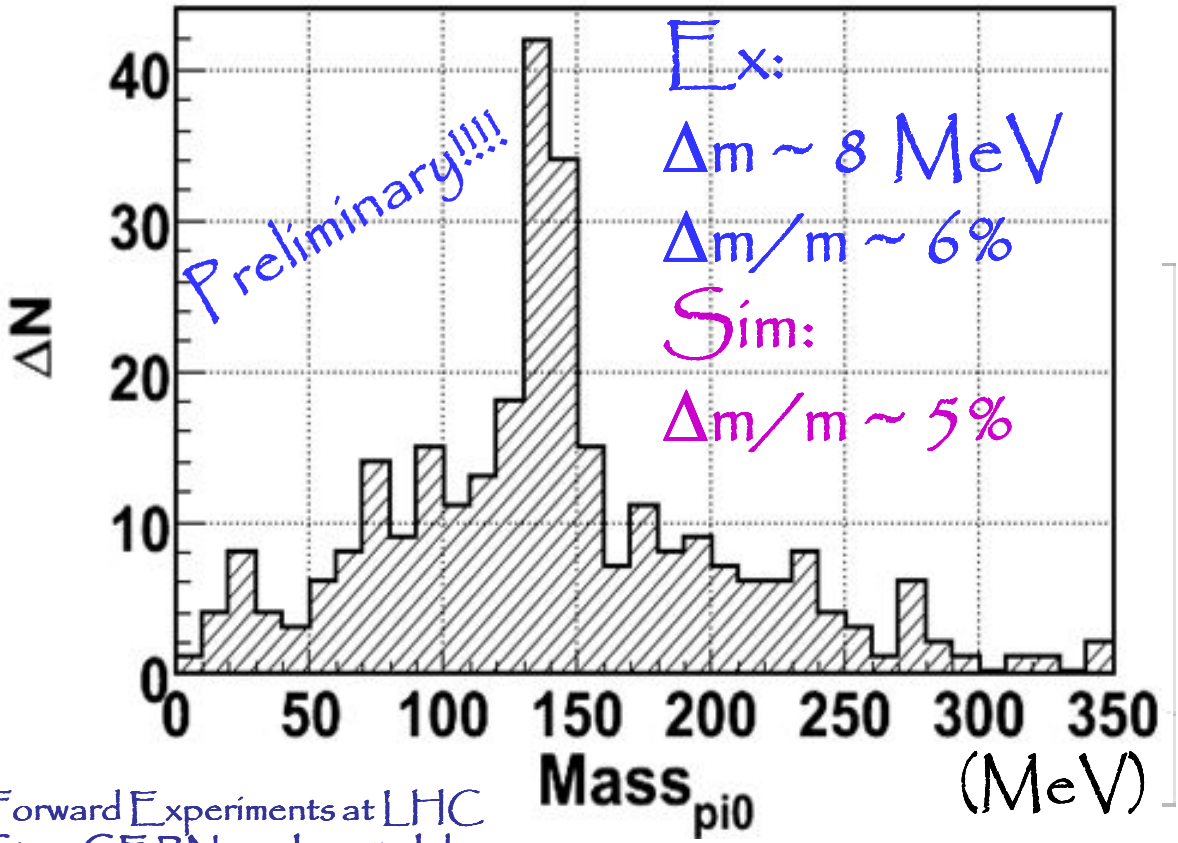
$>10^7$ proton on target (special setting from the SPS people)

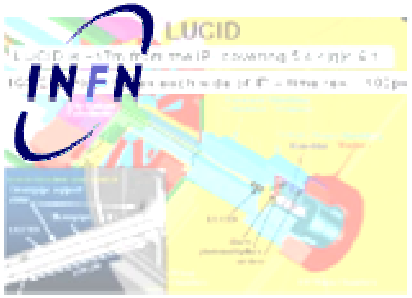
Dedicated trigger on both towers of the calorimeter has been used

≈ 250 π^0 events triggered (in a quite huge background) and on disk

Main problems:

- ✓ low photon energy (≥ 20 GeV)
- ✓ Direct protons in the towers
- ✓ Multi hits in the same tower

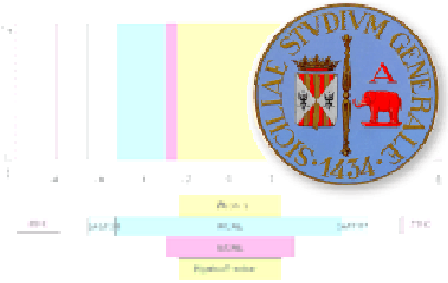


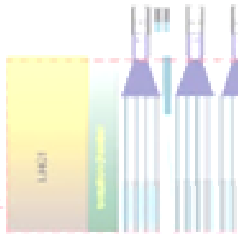


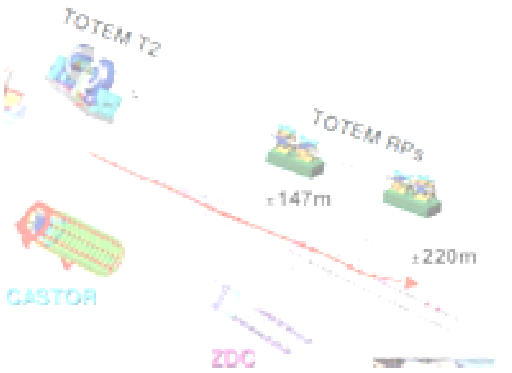
π^0 rate

1. One Particle Incident on each Calorimeter	0.0040
2. Gamma Incident on each Calorimeter	0.0032
3. Invariant mass cut (125 MeV < $M_{\gamma\gamma}$ < 145MeV)	0.0007

Table 6: Event rate of π^0 production per inelastic collision for Detector #1. Here the 2cm×2cm calorimeter is at the center of beam-pipe and the beam crossing angle is zero.

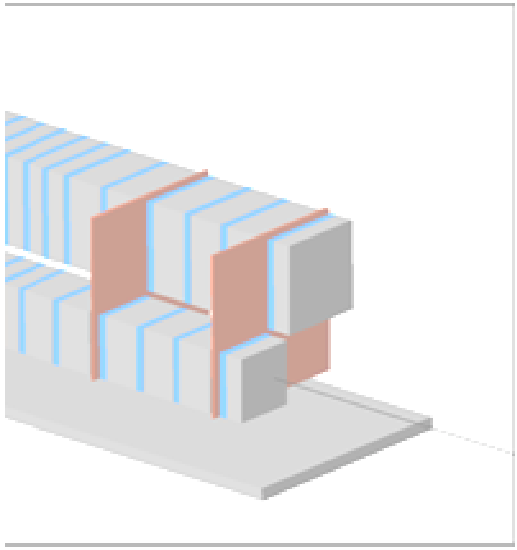






1. One Particle Incident on each Calorimeter	0.0066
2. Gamma Incident on each Calorimeter	0.0052
3. Invariant mass cut (125 MeV < $M_{\gamma\gamma}$ < 145MeV)	0.0011

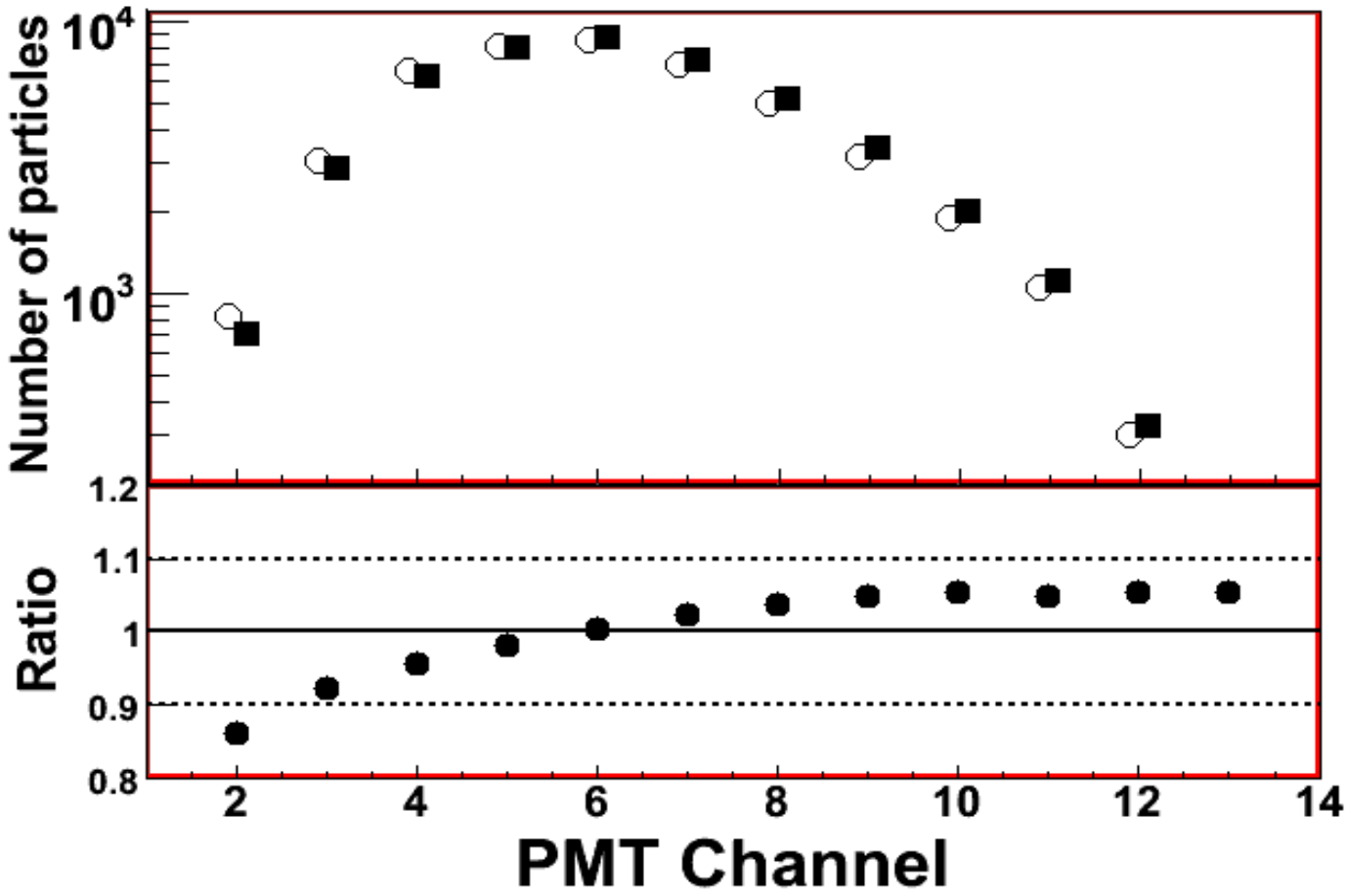
Table 7: Event rate of π^0 production per inelastic collision for Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and te beam crossing angle is 140μrad.



1. One Particle Incident on each Calorimeter	0.0080
2. Gamma Incident on each Calorimeter	0.0063
3. Invariant mass cut (125 MeV < $M_{\gamma\gamma}$ < 145MeV)	0.0015

Table 8: Event rate of π^0 production per inelastic collision for Detector #2. Here the 2.5cm×2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0μrad.

The LPM effect



Transition curve of a 1 TeV photon w/ and w/o LPM to be measured by LHCf

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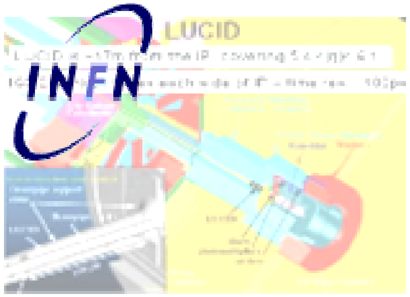
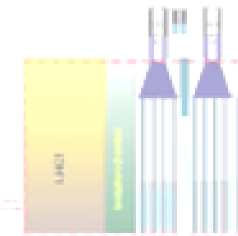
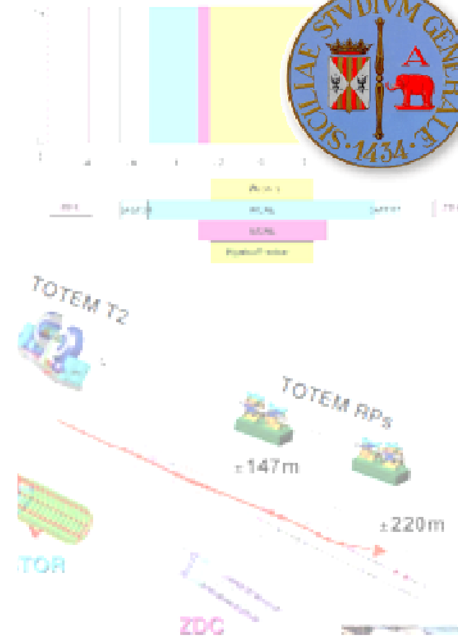
γ rate





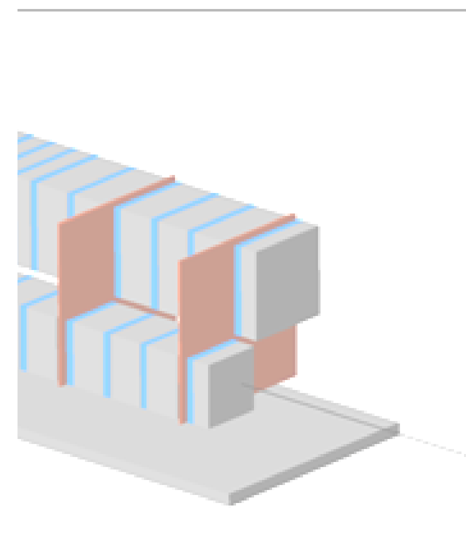
	20mm x 20mm	40mm x 40mm
1. Sum E > 100GeV	0.0674	0.0465
2. One Gamma Incident	0.0478	0.0353
3. One Hadron Incident	0.0146	0.0052
4. One Gamma in fiducial	0.0297	0.0272
5. One Neutron in fiducial	0.0006	0.0001

Table 3: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of beam-pipe and without beam crossing angle..



	20mm × 20mm	40mm × 40mm
1. Sum E > 100GeV	0.0674	0.0869
2. One Gamma Incident	0.0478	0.0623
3. One Hadron Incident	0.0145	0.0081
4. One Gamma in fiducial	0.0297	0.0511
5. One Neutron in fiducial	0.0006	0.0002

Table 4: Event rate of single γ's and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and with beam crossing angle of 140μrad.



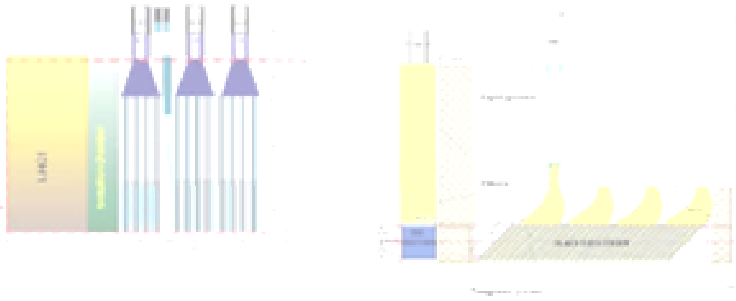
	20mm × 20mm	40mm × 40mm
1. Sum E > 100GeV	0.0949	0.0721
2. One Gamma Incident	0.0654	0.0528
3. One Hadron Incident	0.0198	0.0078
4. One Gamma in fiducial	0.0445	0.0427
5. One Neutron in fiducial	0.0009	0.0002

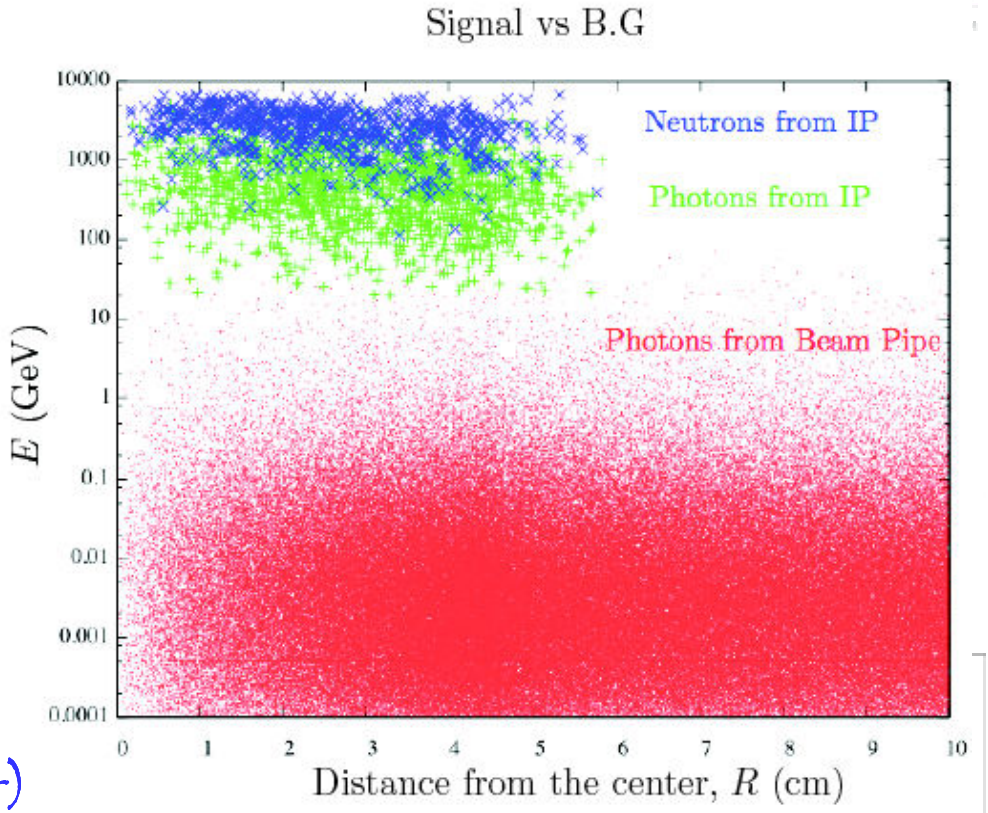
Table 5: Event rate of single γ's and hadrons per inelastic collision for the Detector #2. Here the detector is in default position and without beam crossing angle.

Estimate of the background

✓ beam-beam pipe

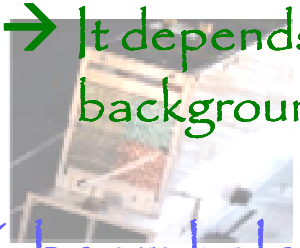
→ E_γ(signal) > 200 GeV, OK
background < 1 %

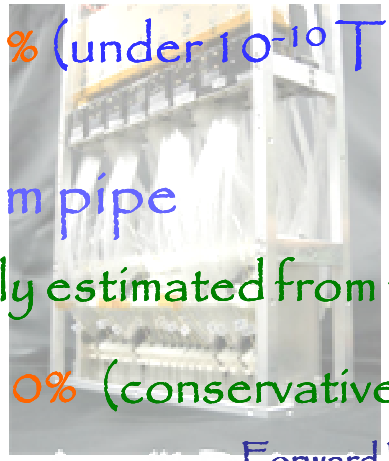




✓ beam-gas

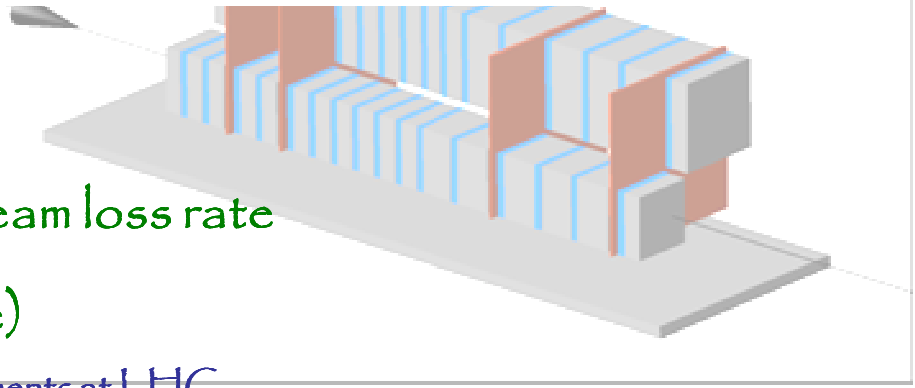
→ It depends on the beam condition
background < 1 % (under 10^{-10} Torr)





✓ beam halo-beam pipe

→ It has been newly estimated from the beam loss rate
background < 10% (conservative value)



'Analysis' of Beam Gas events

We got 116 FC triggers in 8.275.034 BPTX: $N_t = 116$

2.10^9 protons/bunch

Total # of protons: $N_p = 1.7 \times 10^{16}$

We try to estimate the gas density ρ from this rate:

$$N_t = N_p * L * \sigma * \rho$$

L = effective lenght ~ 100 m

σ = Cross section ~ 80 mbarn = 80×10^{-31} m²

We find: $\rho = 8.5 \times 10^{12}$ H/m³ = 4.2×10^{12} H_2/m³

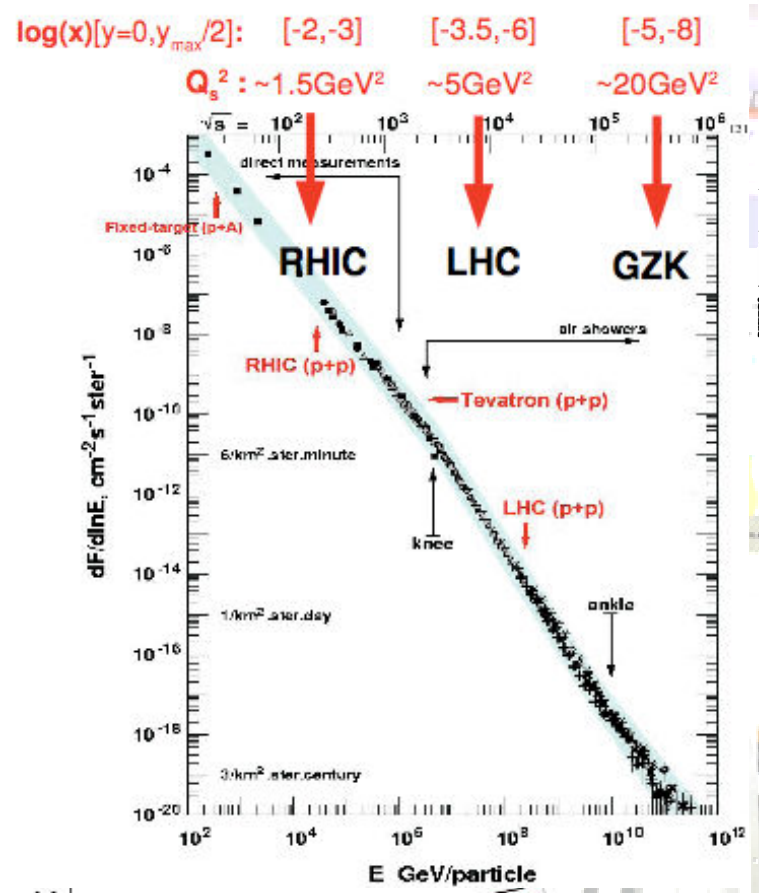
From the LHC Project Report #783: $\rho = 10^{12}$ H_2/m³

From the pressure measurement in April 2008: $\rho \sim 10^{12}$ H_2/m³

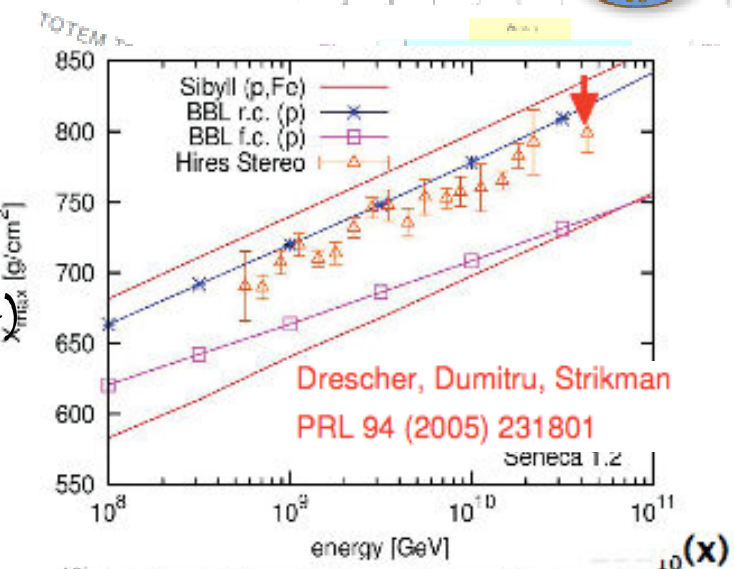
~CONSISTENT!!!!!!!!!!!!

Alessia Tricomi
University & INFN Catania

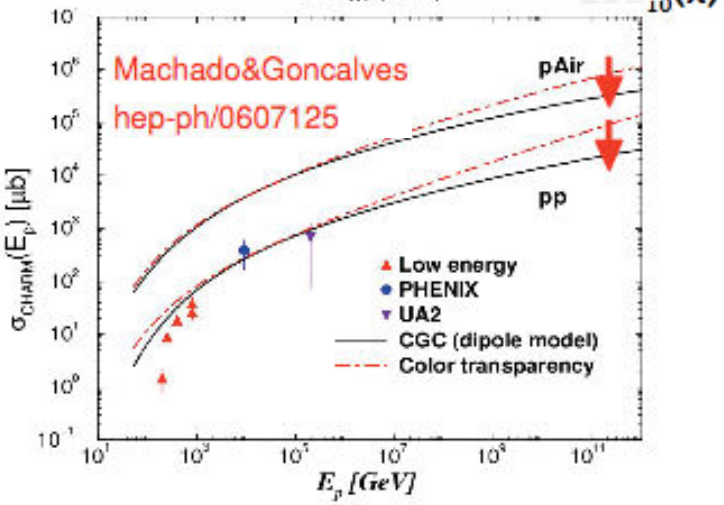
Low-x Physycs and UHECR

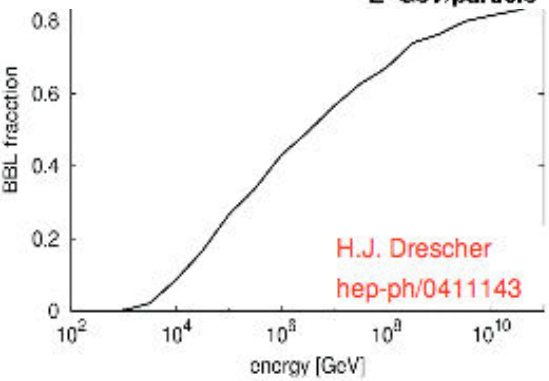


Reduced dN/dη :
Less penetration:
lower X (~ -30 g/cm²)



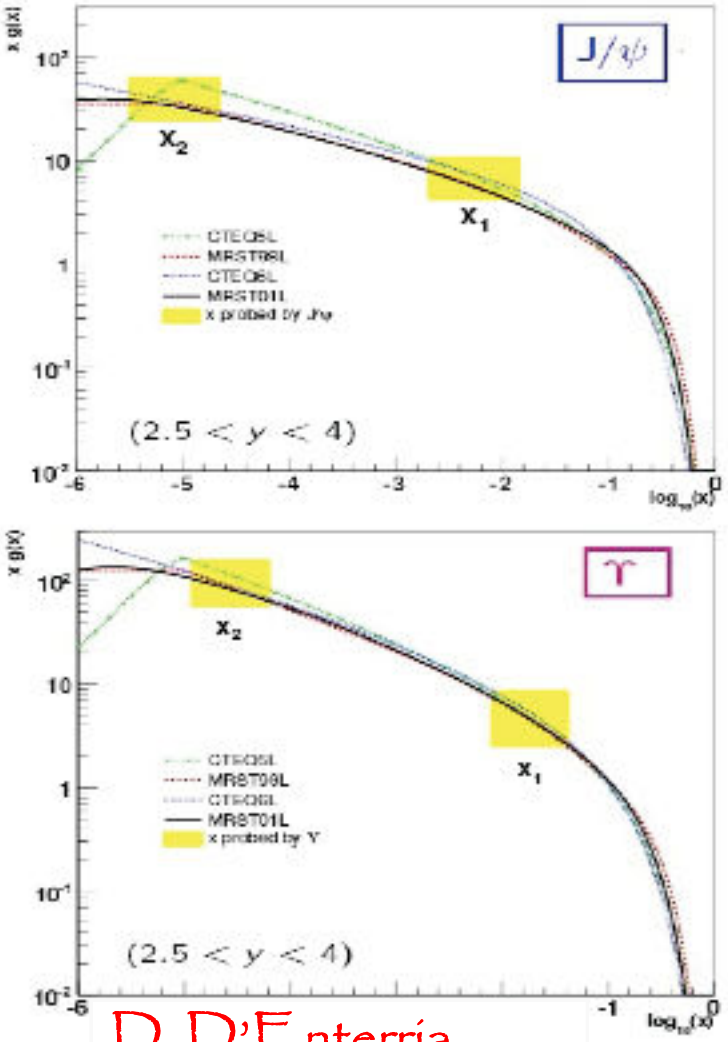
Reduced charm cross sections:
Less muons !



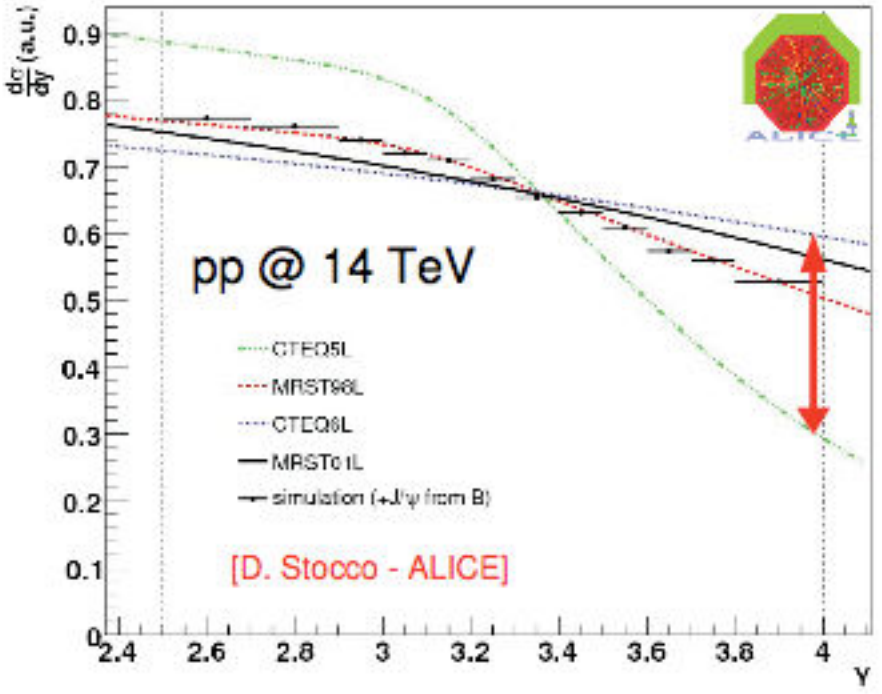


Forward QQ in ALICE

- J/ψ measurement in μ-spectrometer: xg(x) in the proton at $x_2 \sim 10^{-5}$:



dσ/dy J/ψ: NLO CEM w/ varying PDFs

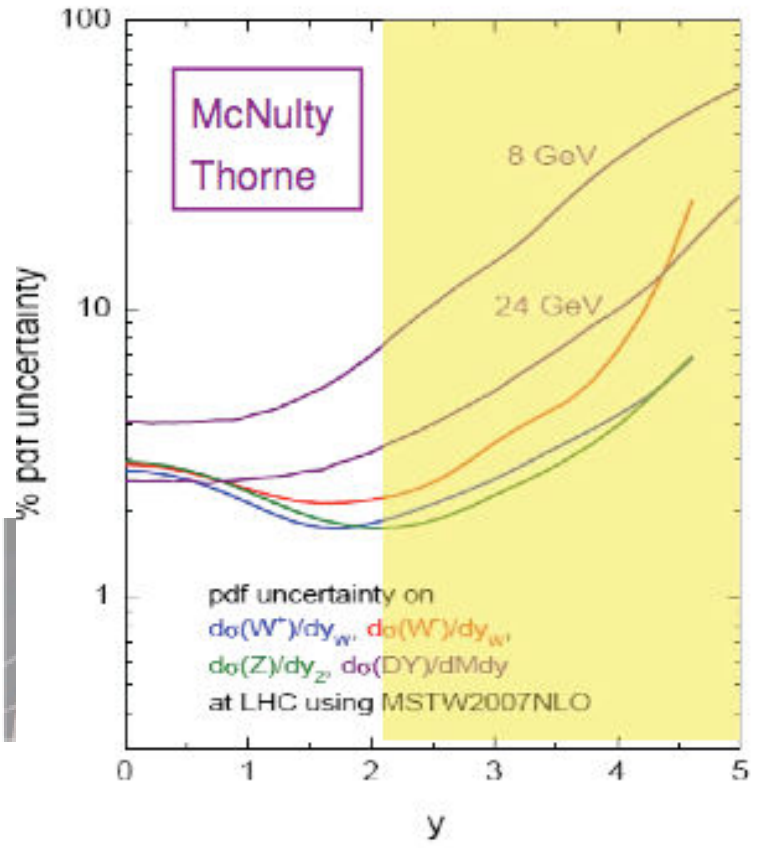


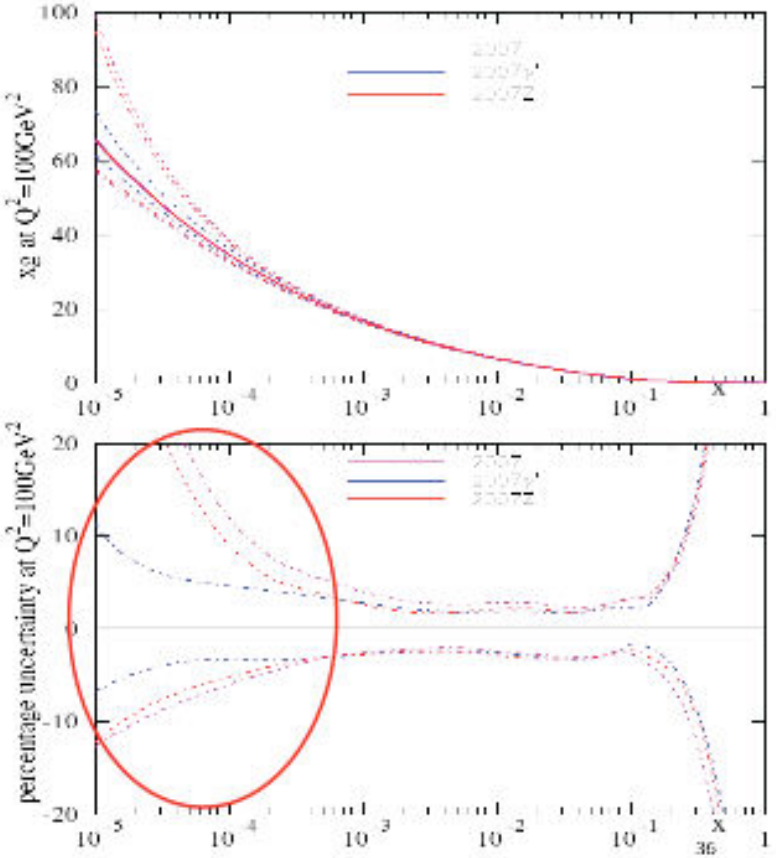
QQbar: Sensitive to different PDFs & to DGLAP versus CGC predictions

(Note: $m_{J/\psi} \sim Q_s$ at the LHC)

γ*, Z, W in LHCb (2<η<5

- Impact of 1 fb^{-1} LHCb data for forward γ*(M = 14 GeV), W,Z production on the gluon distribution uncertainty:





- LHCb: Forward W,Z (lepton) with 1% uncertainty (LHCb note 2007-114)