The Abdus Salam
International Centre for Theoretical Physics

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IAEA
International Atomic Energy Agency

2036-1

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

The LHC & cosmic-rays physics at the highest energies

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The LHC & cosmic-rays physics at the highest energies*

Int. Workshop on QCD from colliders To Super-High-Energy Cosmic Rays

Trieste, May 25 – 29, 2009

David d'Enterria

ICREA, ICCUB – Barcelona

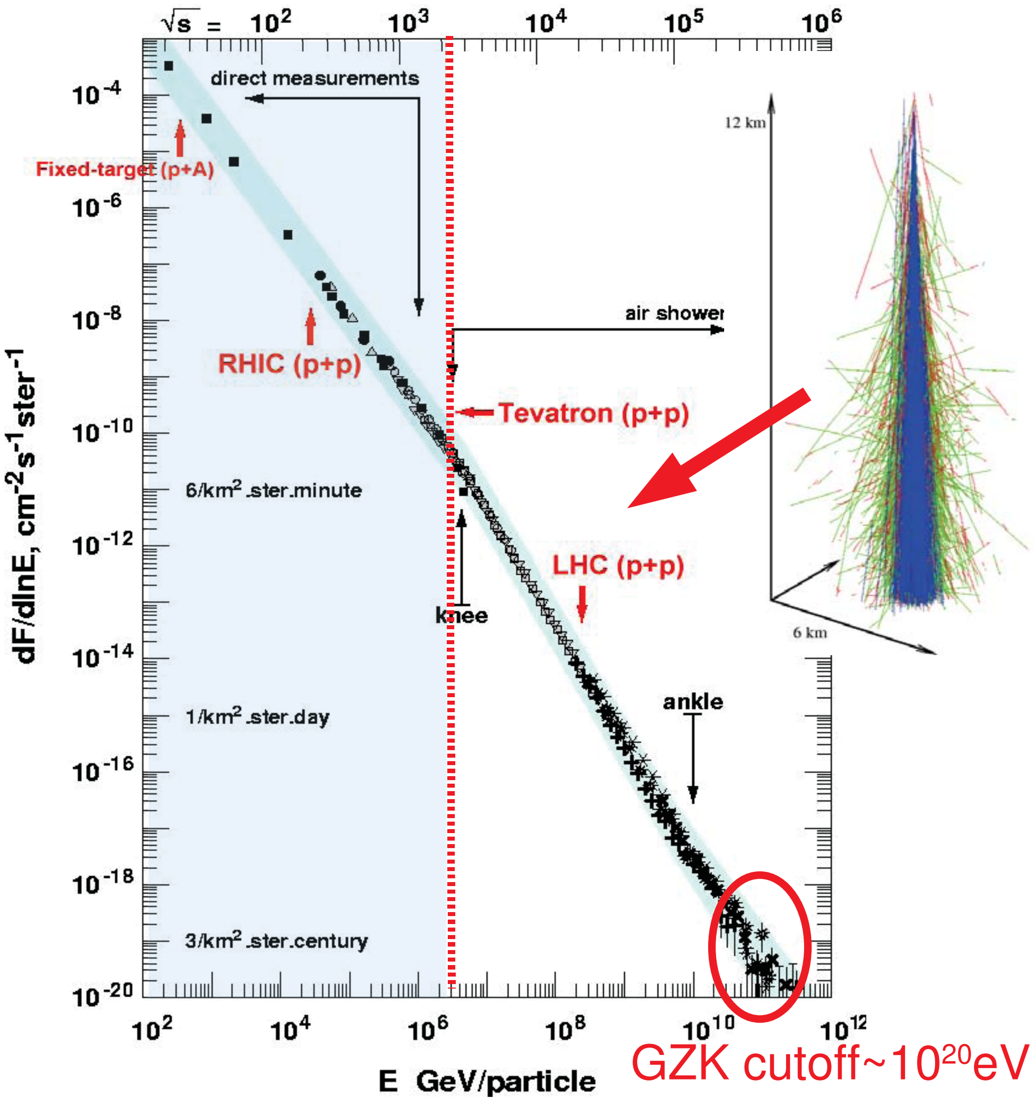
(*) DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Overview

- Ultra-High-Energy (UHE) Cosmic-Rays (CR) via extended air-showers
- Cosmic-Ray MCs uncertainties
- LHC forward detectors
- LHC measurements (I): total p-p cross-section
- LHC measurements (II): high-density QCD effects
- LHC measurements (III): forward particle,energy flow

UHE cosmic-rays via extended air-showers (I)

- Cosmic-ray spectrum:



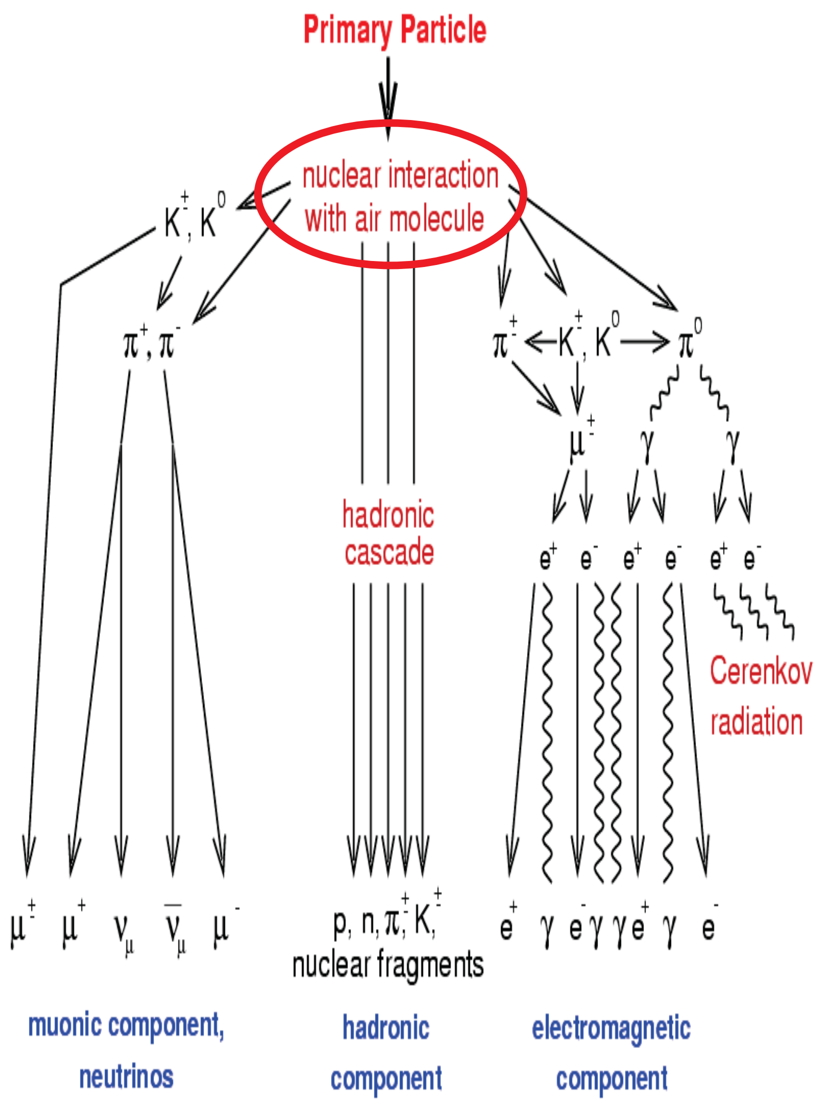
- Only indirect measurements (EAS) above E_{lab} ~100 TeV using the atmosphere as a “calorimeter”

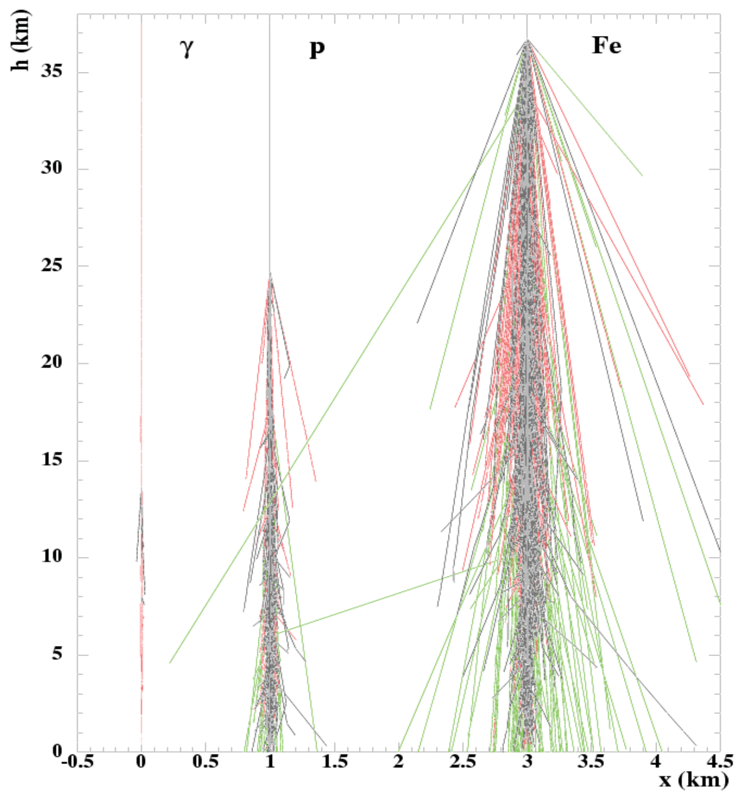
- CR energy & mass determined via hadronic Monte Carlo's:

  Primary interactions dominated by forward & soft QCD interactions.

- MCs tuned with accelerator data: Uncertain $\mathcal{O}(10^6)$ extrapolations from SppS,Tevatron to GZK limit.

UHE cosmic-rays via extended air-showers (II)

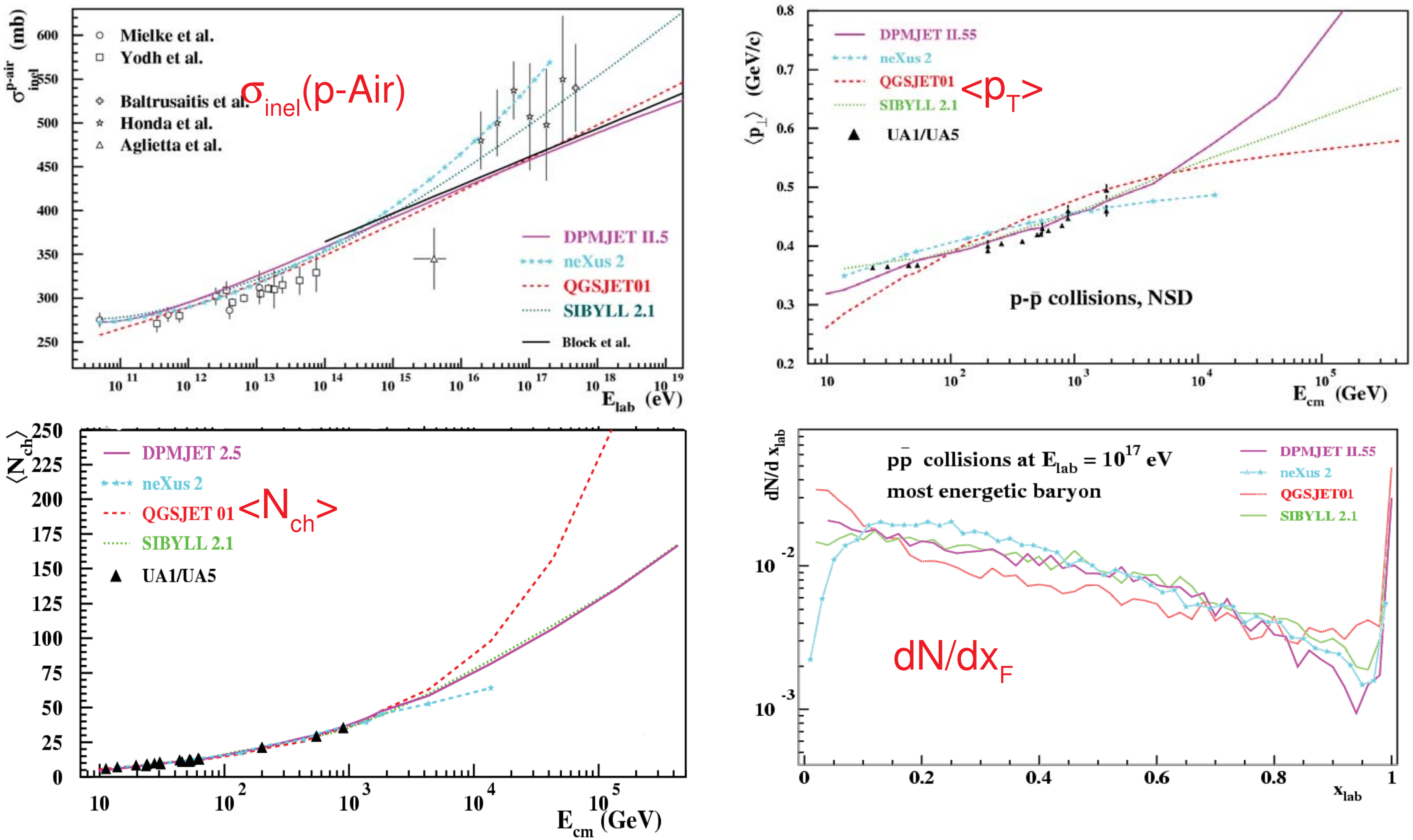




- Determination of E,mass of cosmic rays depends on description of primary UHE QCD (p+N,O Fe+N,O) interactions.
- Hadronic MCs (QGSJET,DPMJet,Sybill, NEXUS/EPOS ...) tuned with accelerator data

Cosmic-ray MCs: model uncertainties

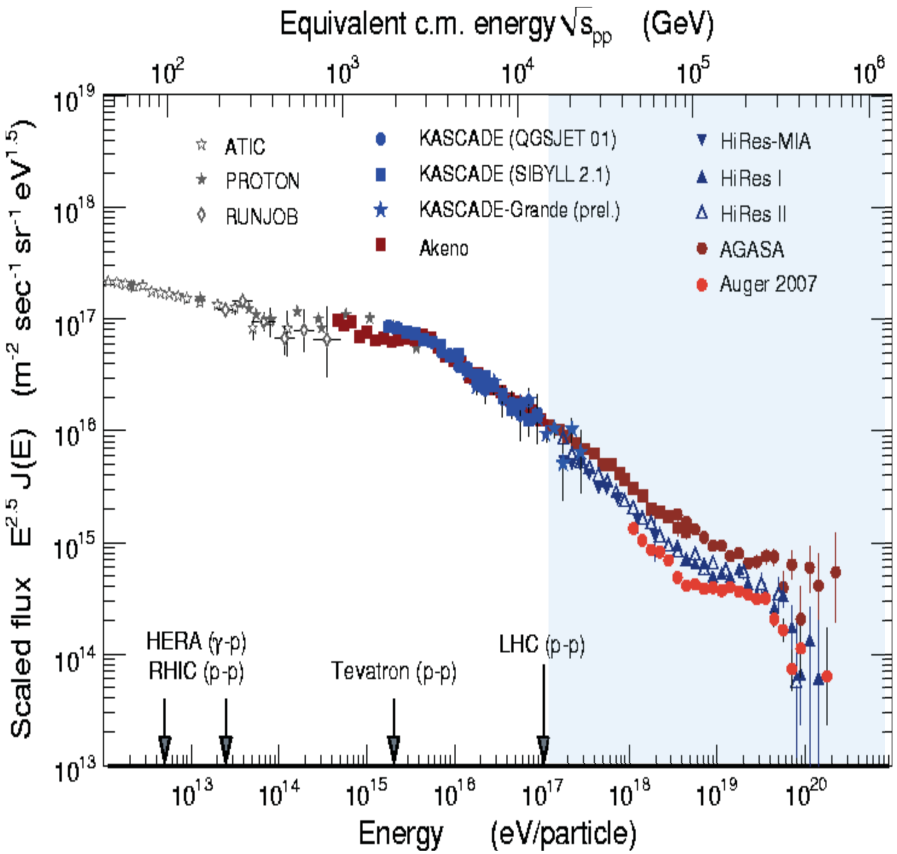
■ Wide range of predictions in basic MC ingredients !



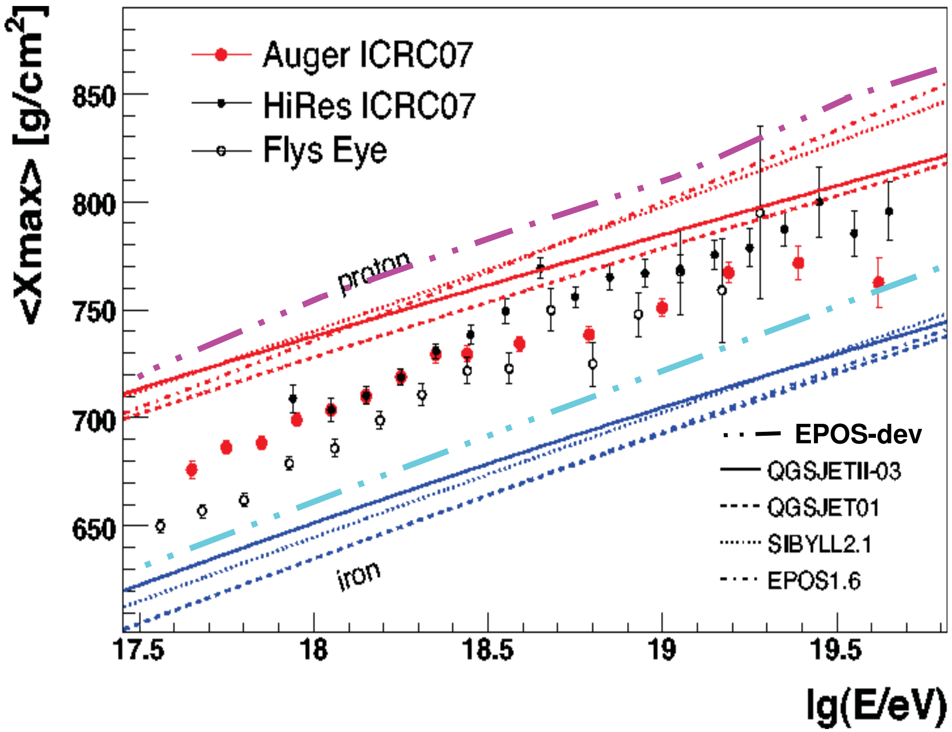
■ Yet, EAS description more robust: x-section & multiplicity partially compensate ...

Cosmic-rays: energy & mass uncertainties

- Beyond 10^{17} eV uncertainties in MCs ⇨ CR identity & energy.



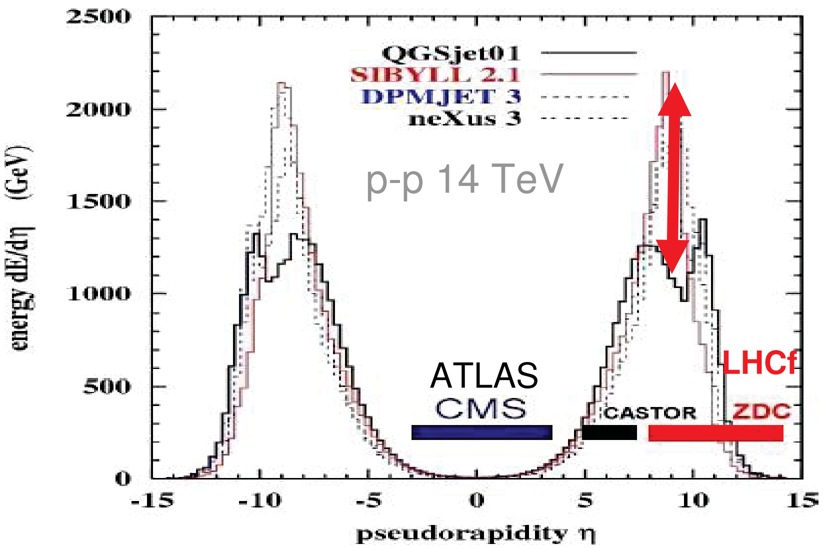
$<X_{max}>$ vs. energy



- QGSJET, SIBYLL: UHECR mass is in between p & Fe
- EPOS-dev: UHECR mass compatible with pure Fe

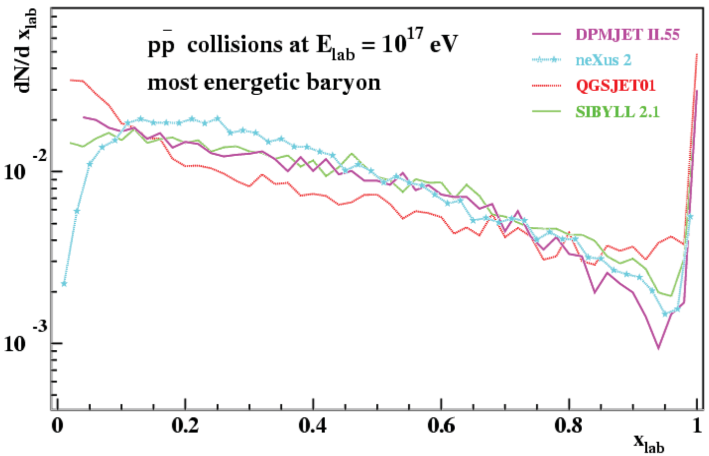
Hadronic MCs: Calibration & tuning at the LHC

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



- Leading baryon (inelasticity):

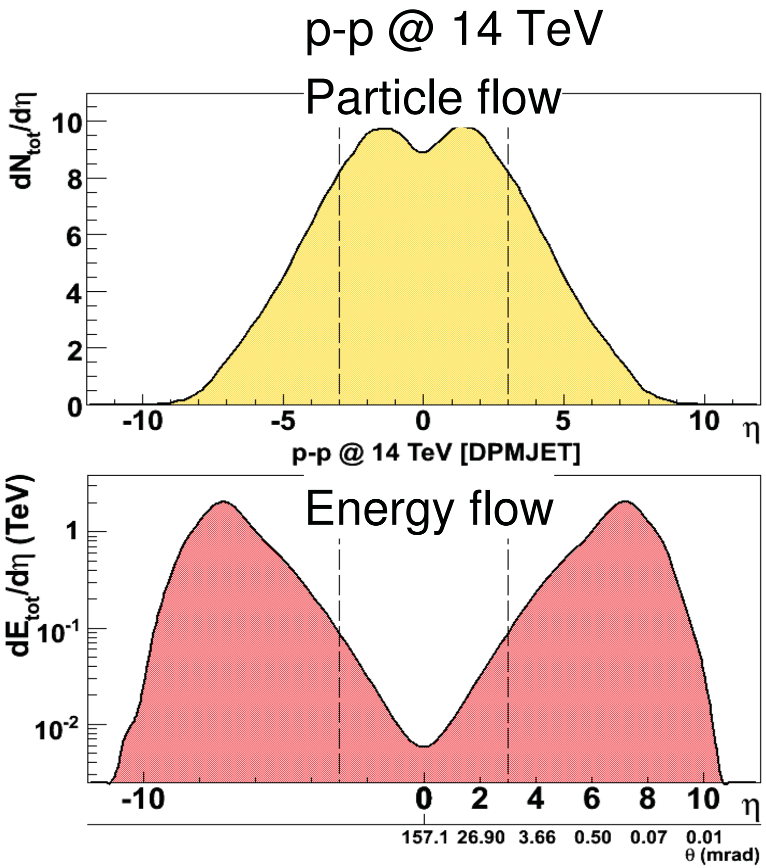
  Neutrals in ZDCs / LHCf:
  neutrons, mesons (π^0,$K^0_s \rightarrow \gamma$)

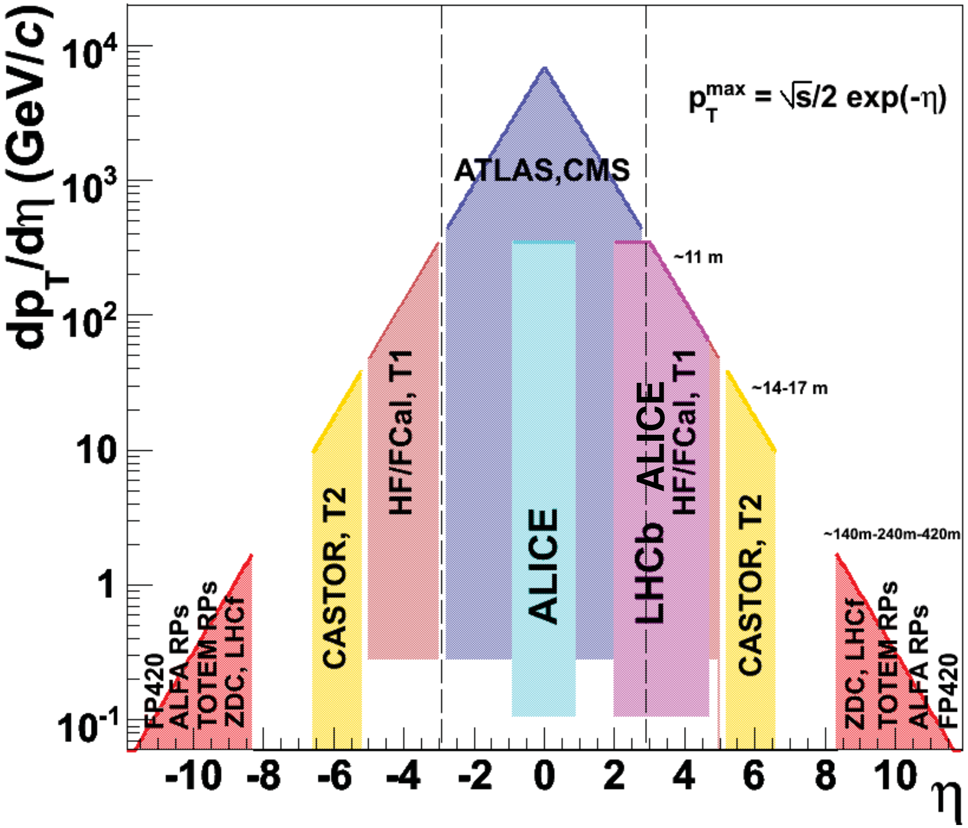


- LHC measurements of forward particle in p-p, p-A, A-A at E_{lab}~100 PeV [CRs: p-Air,α-Air,Fe-Air] will strongly constrain EAS Monte Carlos.

1. LHC forward detectors

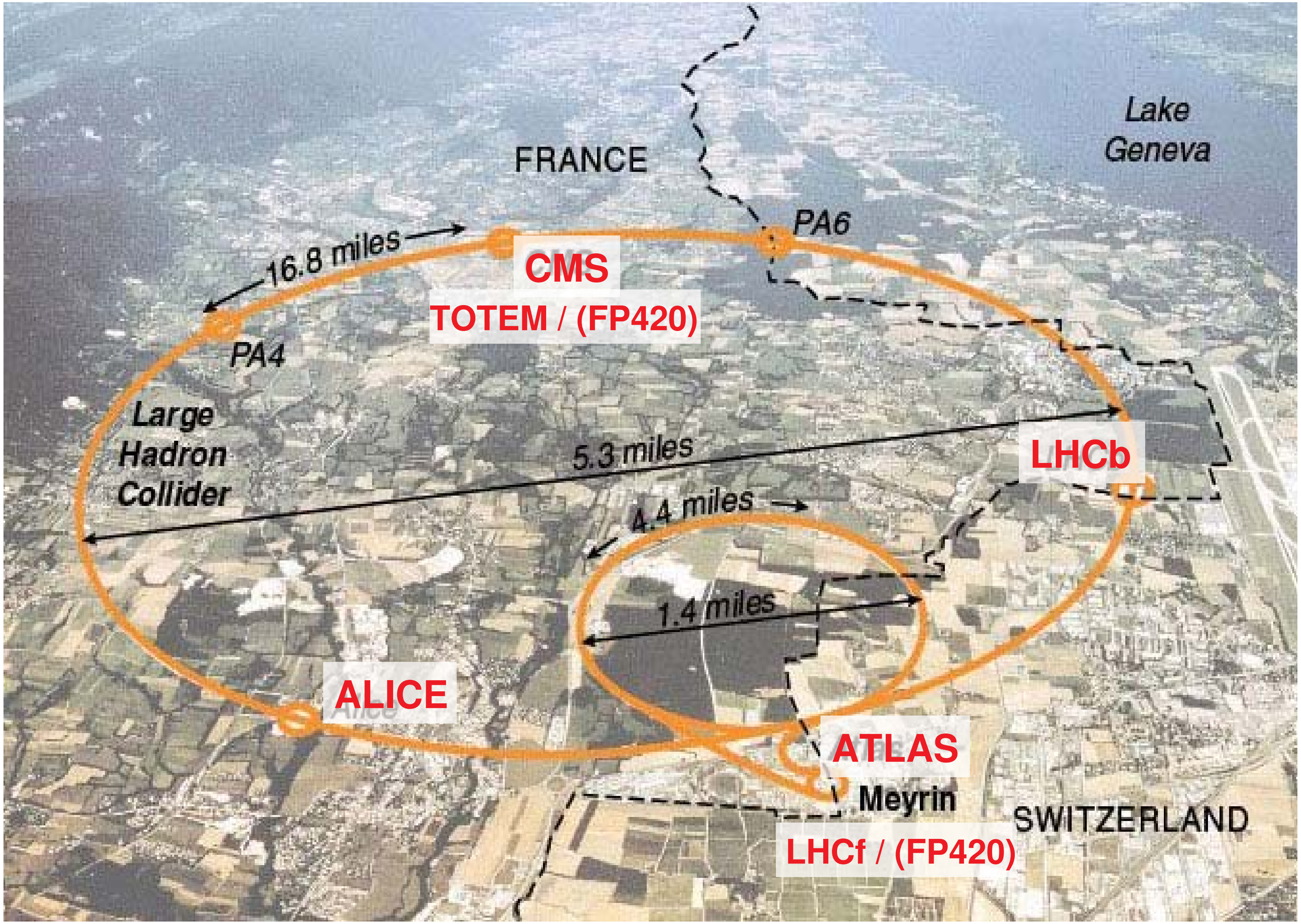
LHC experiments: (p_T,η) acceptance



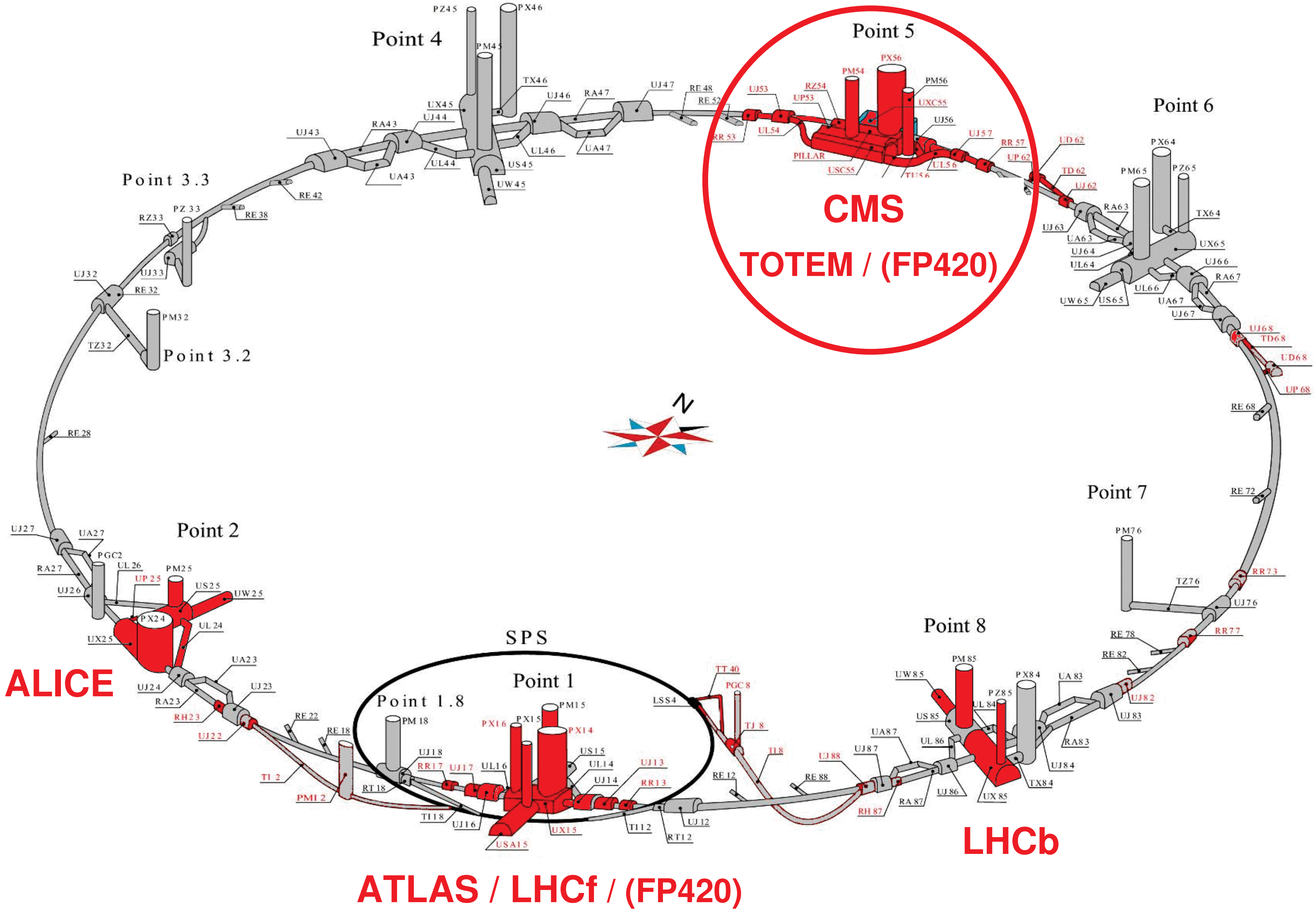


- Particle production at the LHC over $\Delta\eta \sim 2\times\ln(\sqrt{s})/m_p \sim 20$
- All phase-space virtually covered (1st time in a collider) !

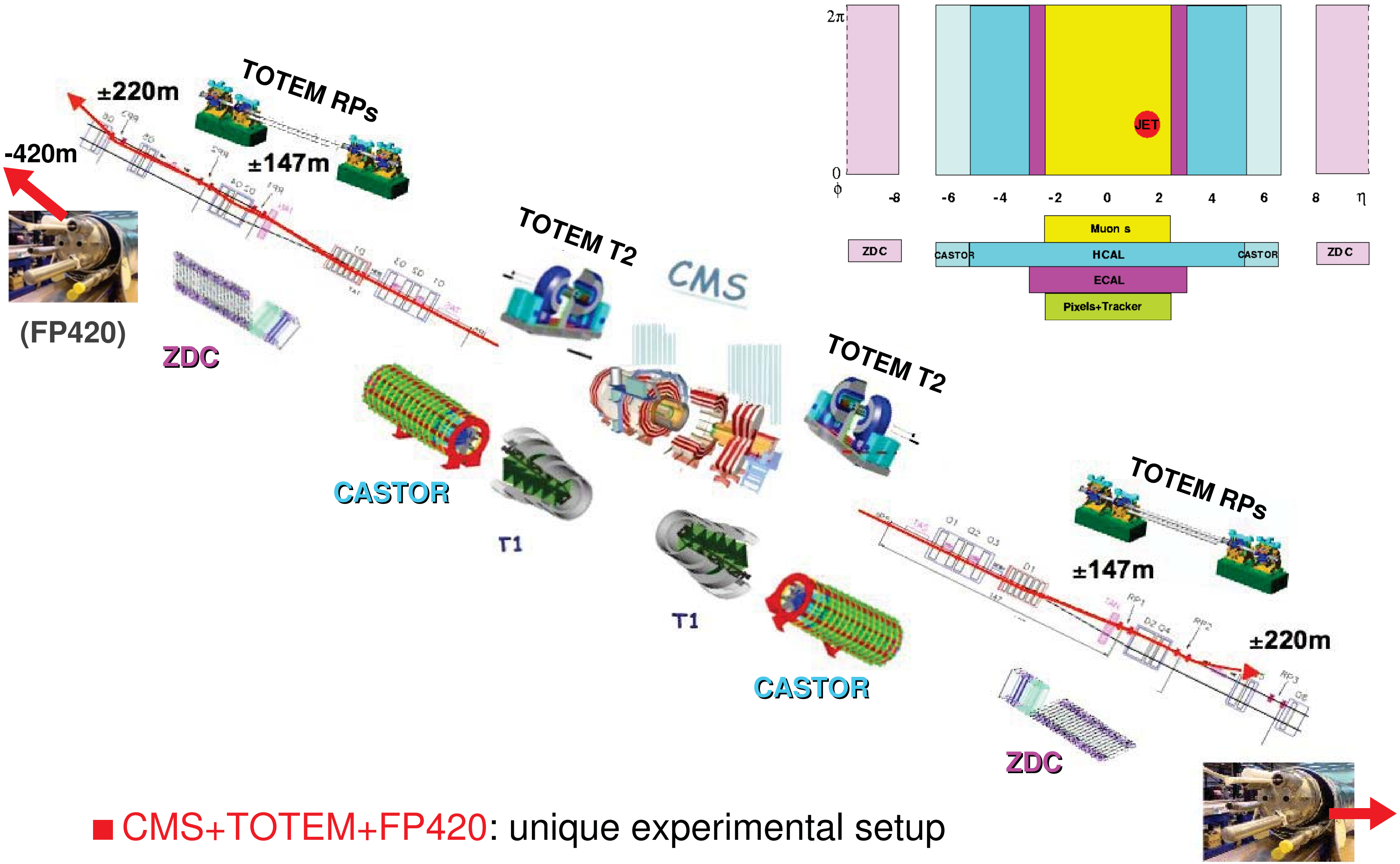
The LHC experiments



The LHC experiments: zoom at IP5

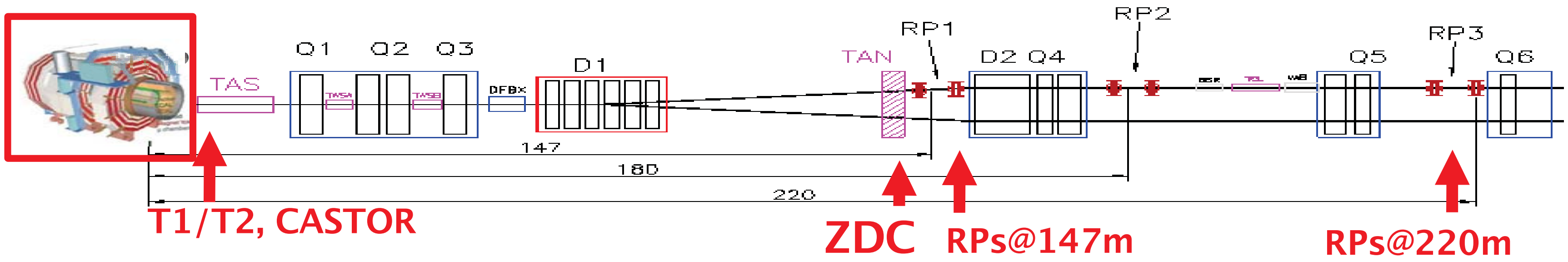


CMS+TOTEM forward detectors



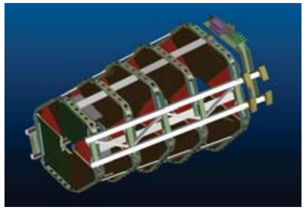
- CMS+TOTEM+FP420: unique experimental setup

CMS+TOTEM forward detectors



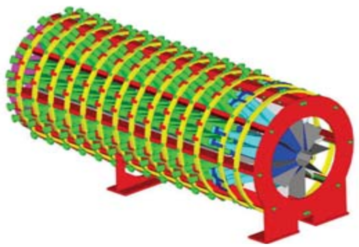
- **TOTEM-T1,T2** (CSC/GEM telescopes):

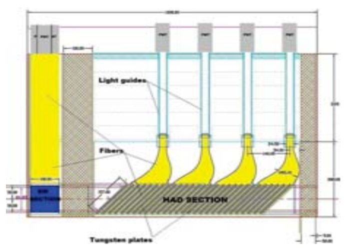
  Tracking over $3.1 < |\eta| < 4.7$, $5.3 < |\eta| < 6.7$



- **CASTOR** (W/Q-fiber calo):

  Calorimetry over $5.1 < |\eta| < 6.6$

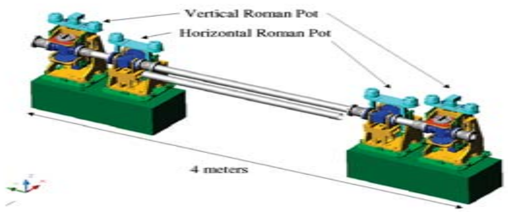


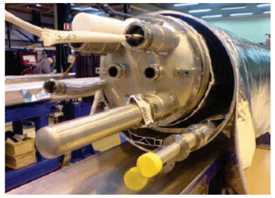


- **ZDC** (W/Q-fiber calo):

  Neutral calorimetry for $|\eta| > 8.3$

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

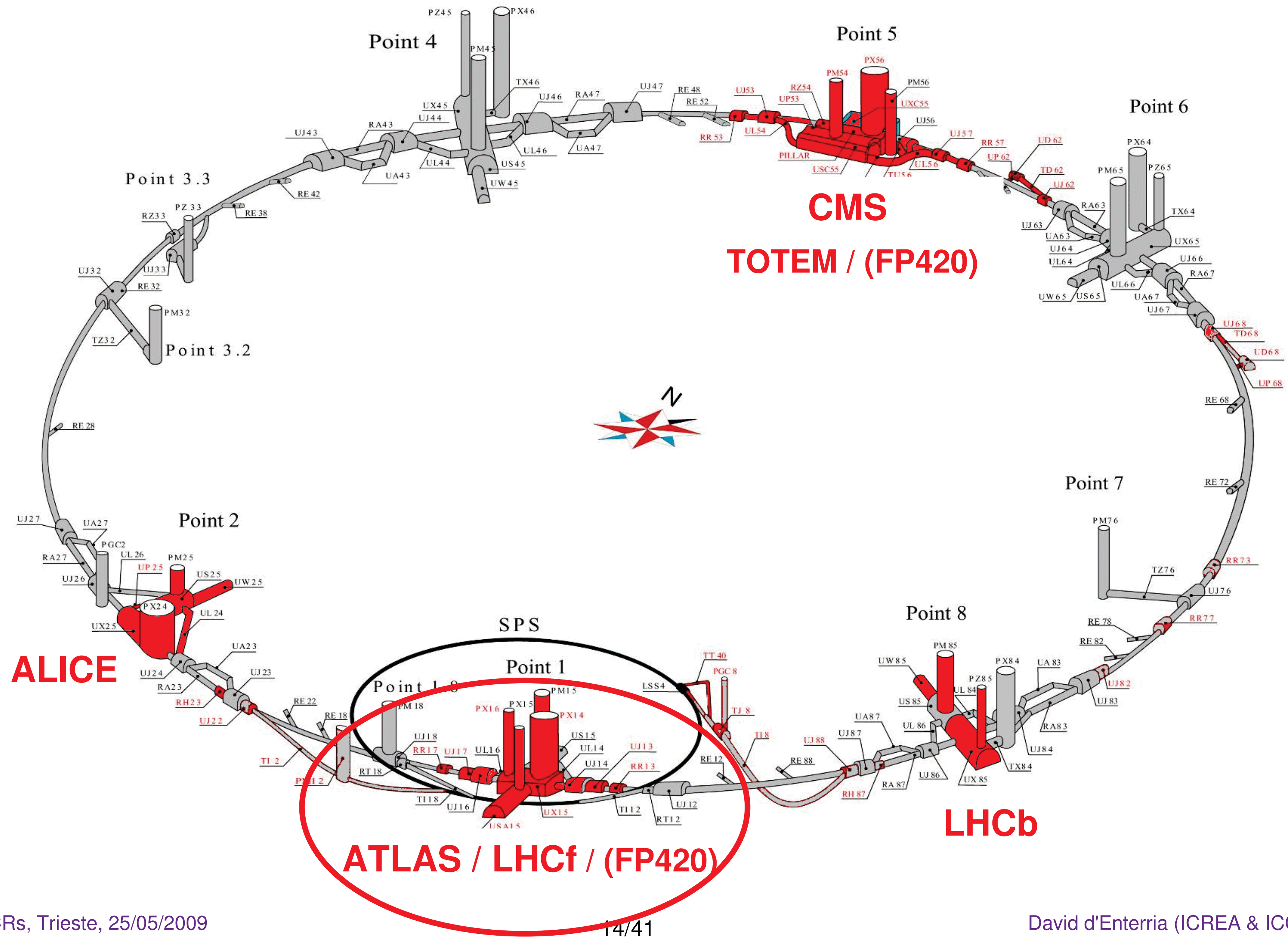




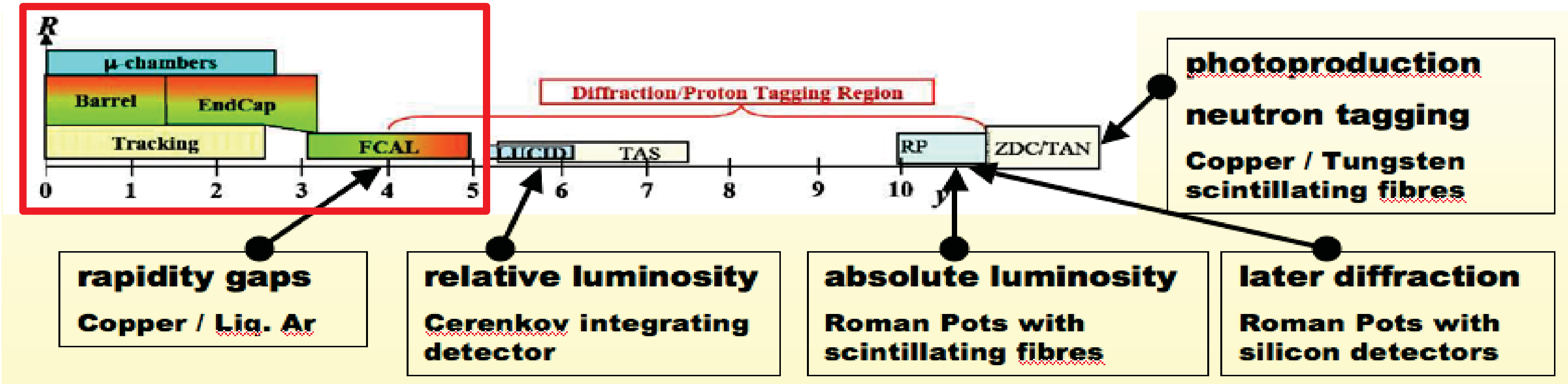
- **FP420** (Si trackers, timing):

  Proton tracking at ±420 m

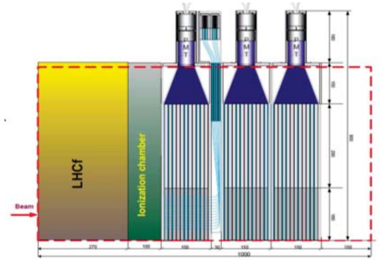
The LHC experiments: zoom at IP1

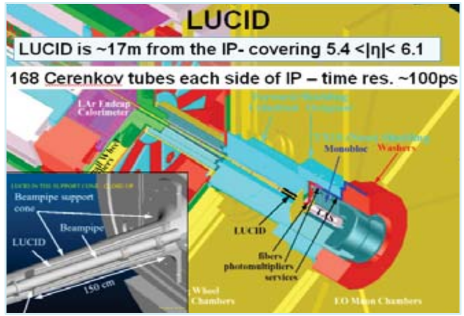


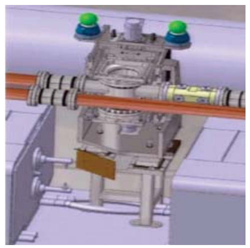
ATLAS forward detectors

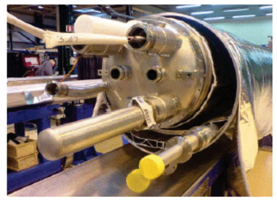


- **LUCID** (Cerenkov Tubes, 17m):
  Cerenkov hits over $5.4 < |\eta| < 6.1$
- **ZDC** (W/Q-fiber calo, 140m):
  Neutral calorimetry over $|\eta| > 8.3$
- **ALPHA** (Sci-Fi RPs):
  Proton taggers at ±240 m
- **FP220,FP420** (Si trackers, timing):
  Proton tracking at ±220, 420 m





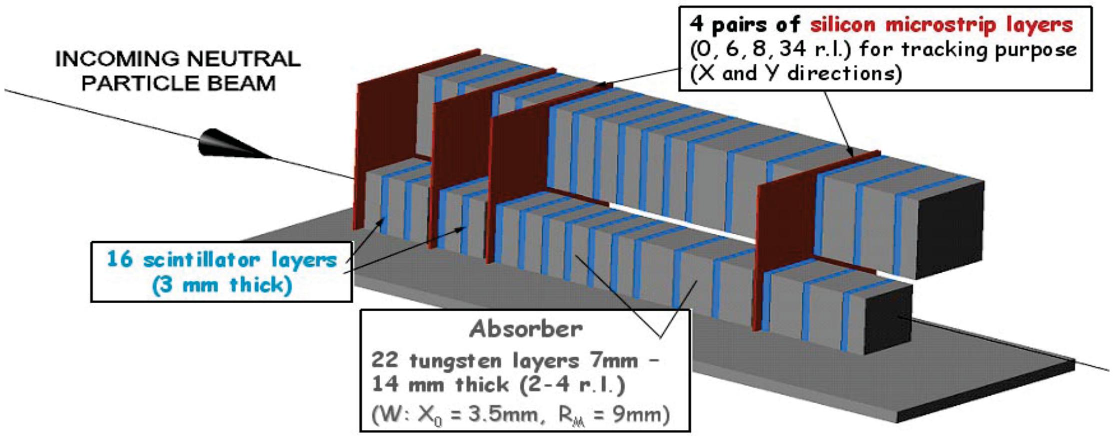




LHC-forward experiment

- **LHC-f** (±140m in ATLAS tunnel): UHECR-oriented detector.

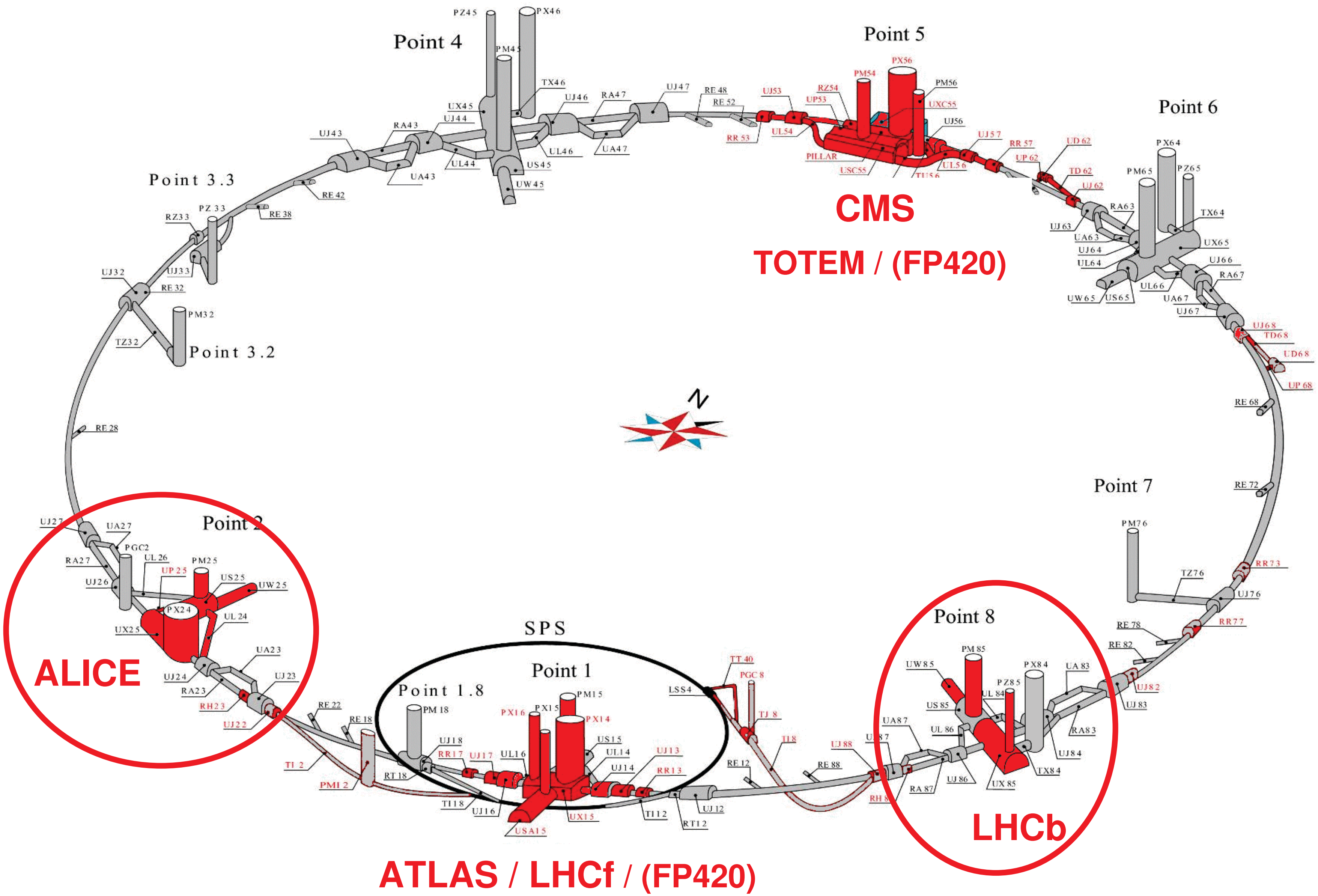
  (smallest LHC experiment: ~20 people)



- Sci-fiber/W calo + Si-strip detector: n,γ detection for |η| > 8.3

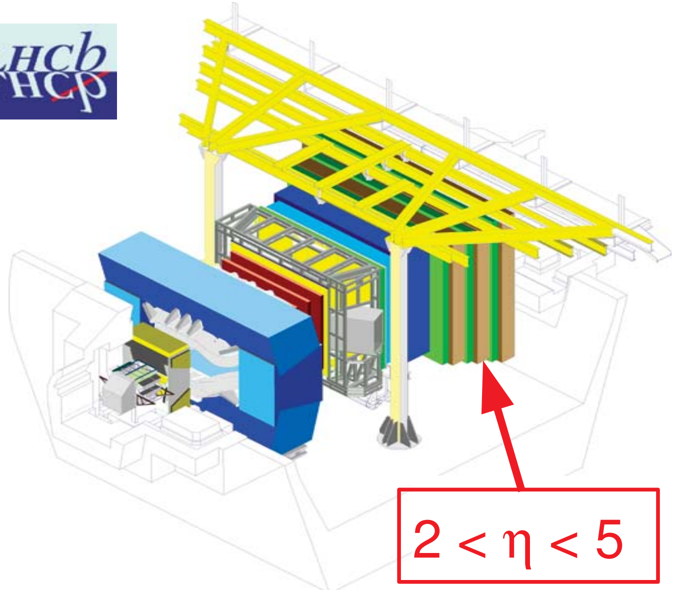
- ATLAS-ZDC will replace LHCf after 1st low-luminosity run.

The LHC experiments: zoom at IP2, IP8

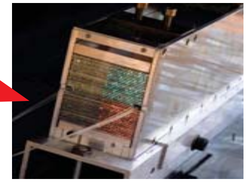


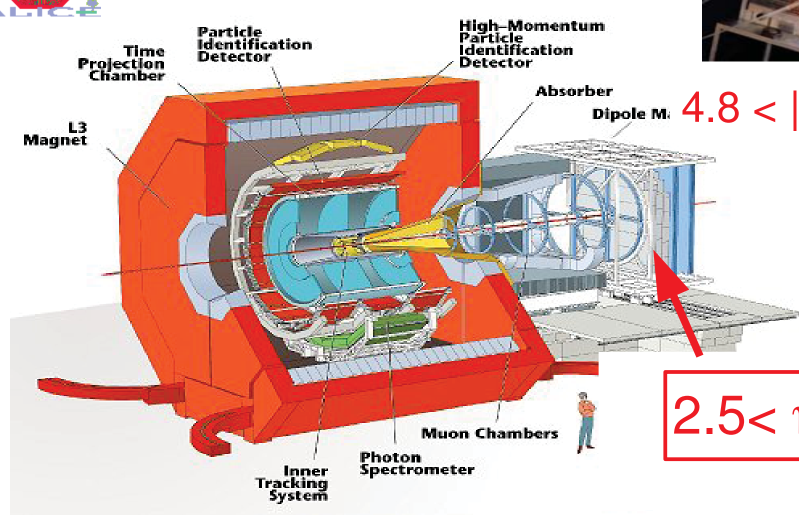
ALICE & LHCb forward detectors

- Forward muon spectrometers:



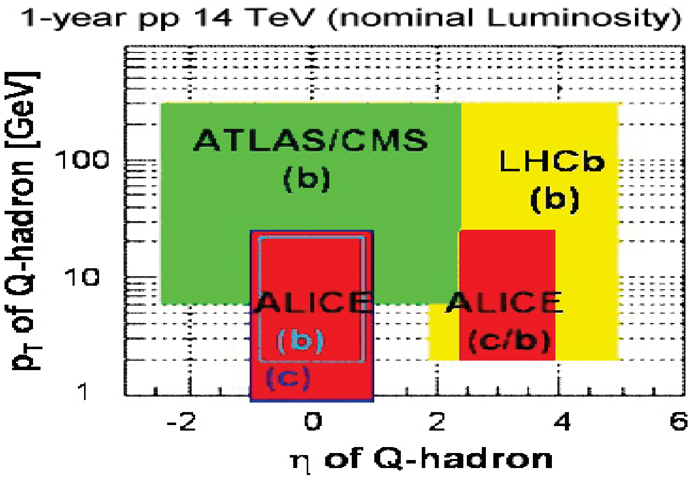
ZDCs also at ±7m,±100m





- Good capabilities for fwd. heavy-Q, $Q\bar{Q}$, gauge bosons measurements:

  (low-x PDFs)



LHC measurements (I): Total p-p cross section

Types of proton-proton collisions

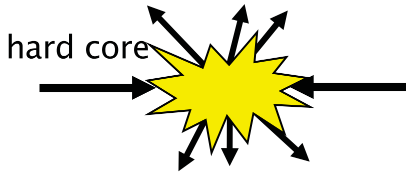
- Total cross-sections at the LHC:

σ_{tot} ~100 mb

$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

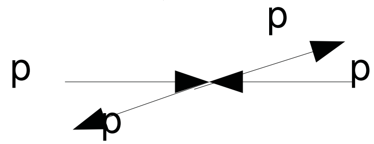
$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$

~60% of the time a **"hard"** collision occurs



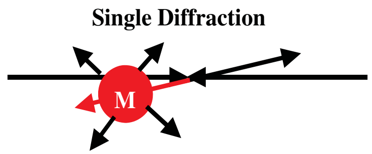
σ_{hc} ~60 mb

~25% of the time the protons **scatter elastically**

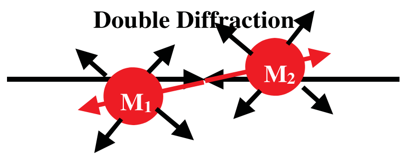


σ_{el} ~25 mb

~10% of the time **single diffraction** occurs

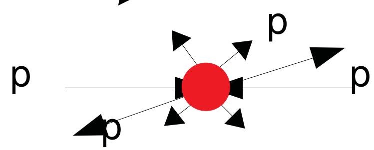


~1% of the time **double diffraction** occurs



σ_{diff} ~15 mb

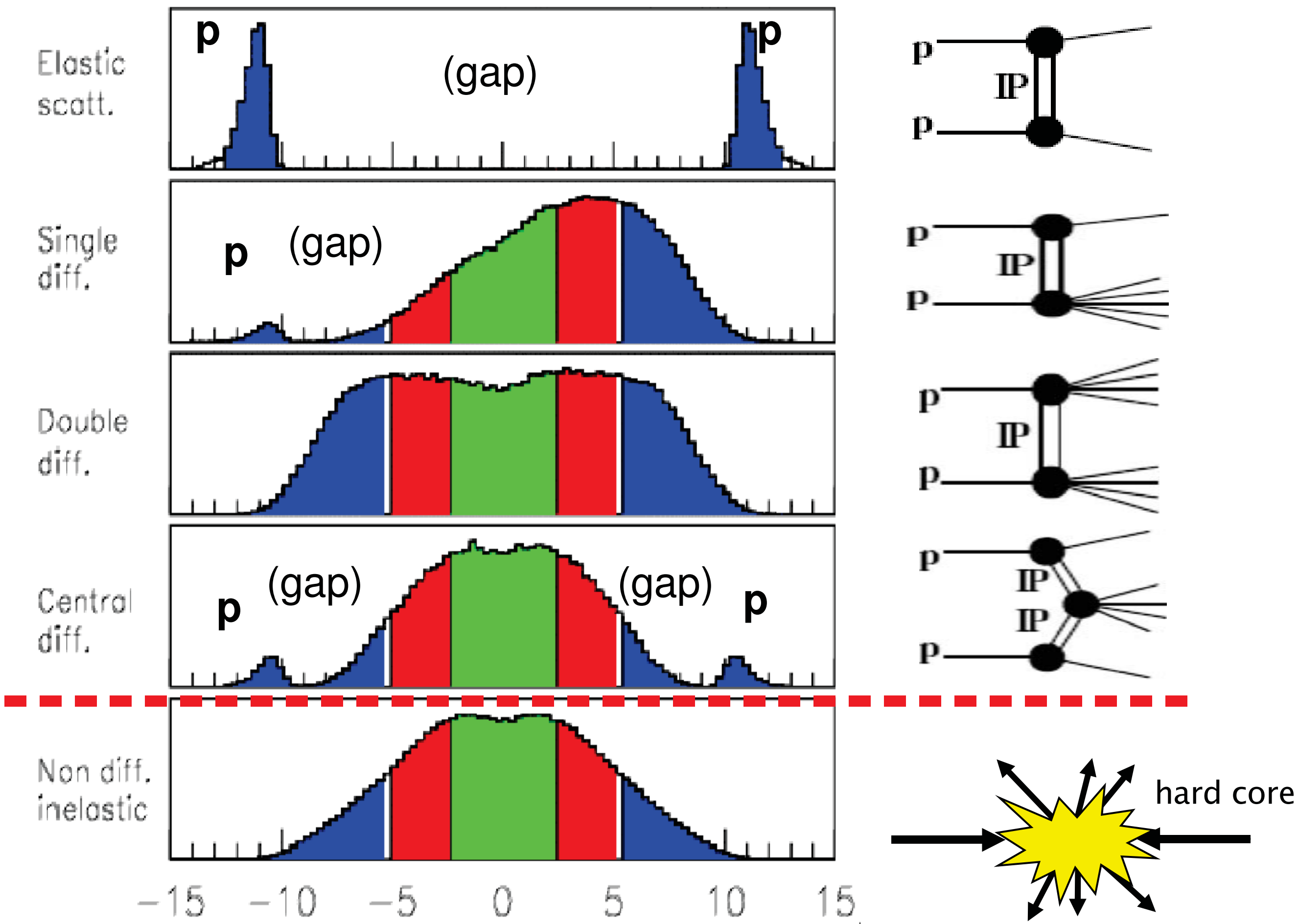
~1% of the time **central (exclusive) diffraction** occurs



Pomeron-induced processes

- Diffractive/Elastic scattering is ~40% p-p σ_{tot} at the LHC !
- Proton(s) intact (scattered at low angles: p taggers), rapidity-gap(s):

- No colour flux !
- Colourless exchange with vacuum quantum-numbers: |Pomeron = 2-gluons in colour singlet state

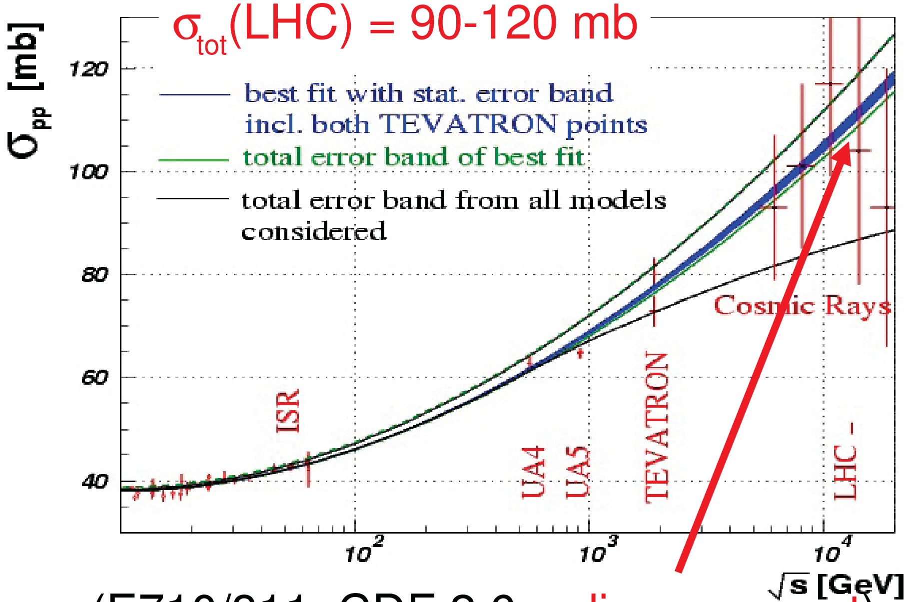


("std" parton-parton colls)

Total p-p cross section, elastic scattering

- Non-computable from 1st-principles QCD, but ...
- Constrained by fundamental QM relations: Froisart bound, optical th., dispersion relations.
- Extrapolations vary by $^{+10}_{-20}$ %.

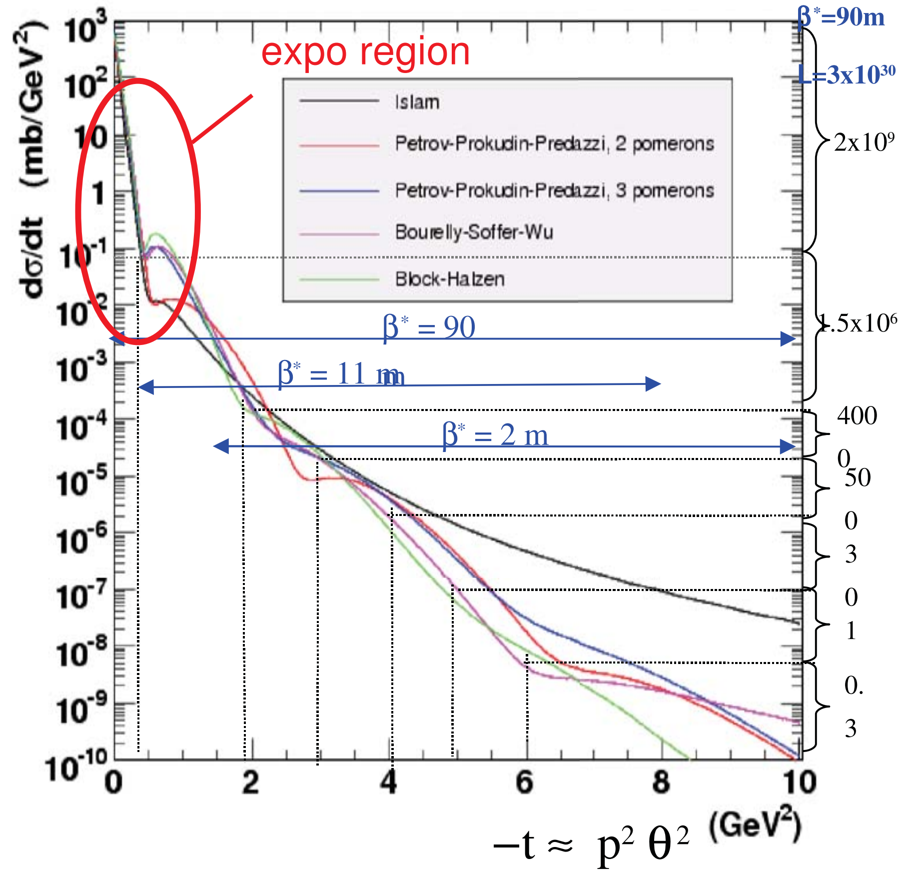
σ_{tot}(LHC) = 90-120 mb



(E710/811–CDF 2.6σ disagreement)

- TOTEM goal: ~1% precision

special run/optics: various β*, low lumi.

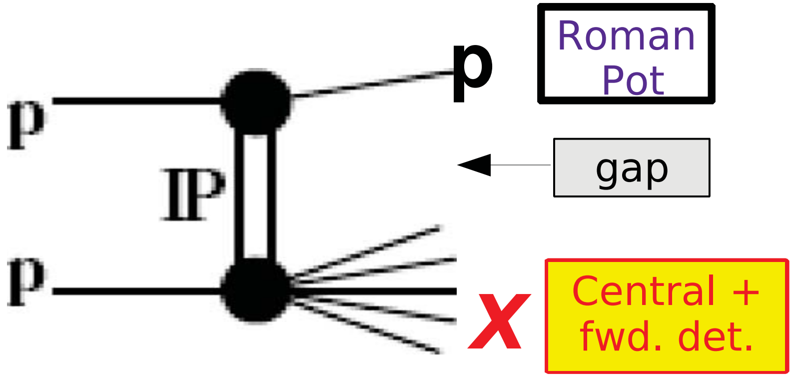


$-t \approx p^2\,\theta^2$

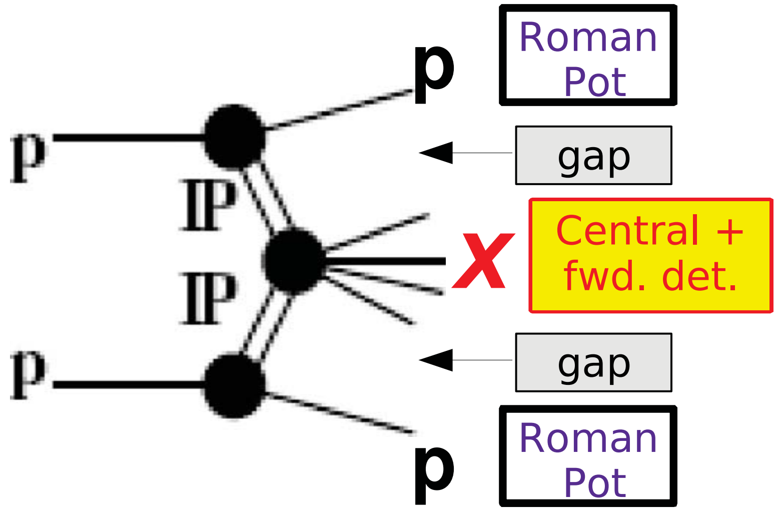
t: 4-mom. transfer squared

Diffractive processes

single/double diffraction:



double-Pomeron exchange:



- **Soft** diffraction (X = anything):
  - npQCD: gap survival probab., multi-parton ints., total σ
- **Hard** diffraction (X = jets, W's, Z's, Higgs, ...):
  - hard processes calculable in pQCD
  - detailed info on proton structure: dPDFs & GPDs
  - discovery physics (!)

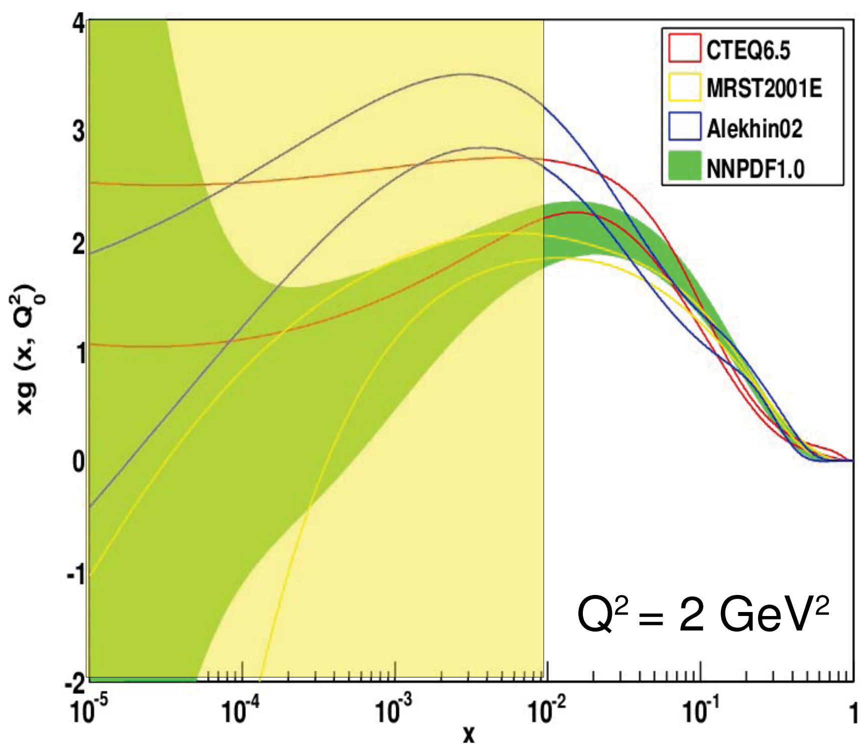
Rich programme accessible with forward detectors & leading proton taggers/trackers

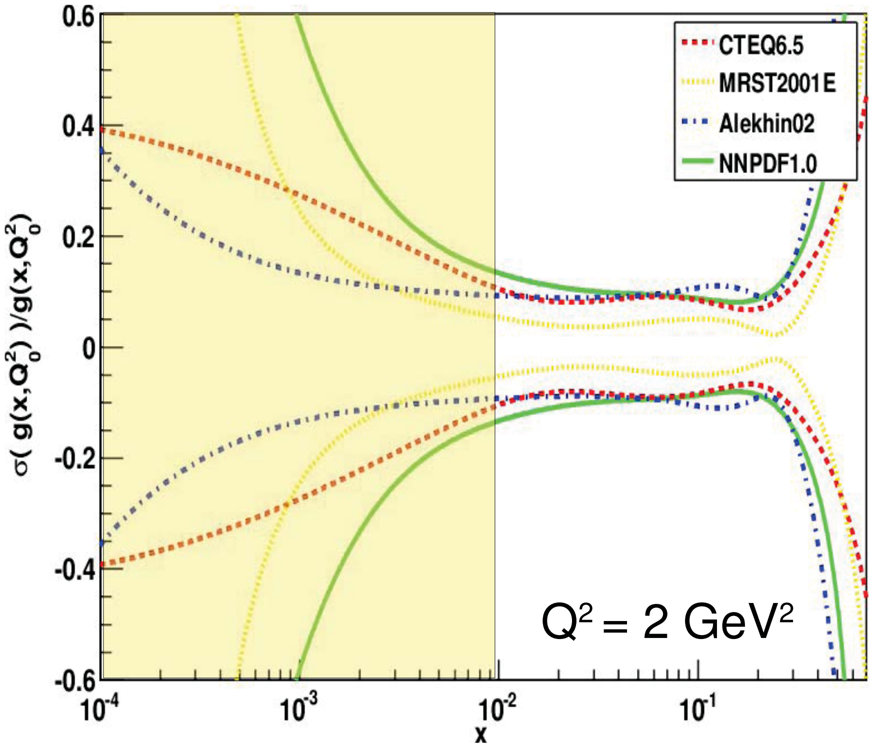
LHC measurements (II): high-density QCD effects

Low-x gluon PDF

- Most of our current knowledge of low-x gluons comes indirectly from F_2 "scaling violations": $\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi} xg(x,Q^2)$
- Large uncertainties below $x{\sim}10^{-2}$ at moderate Q^2 :

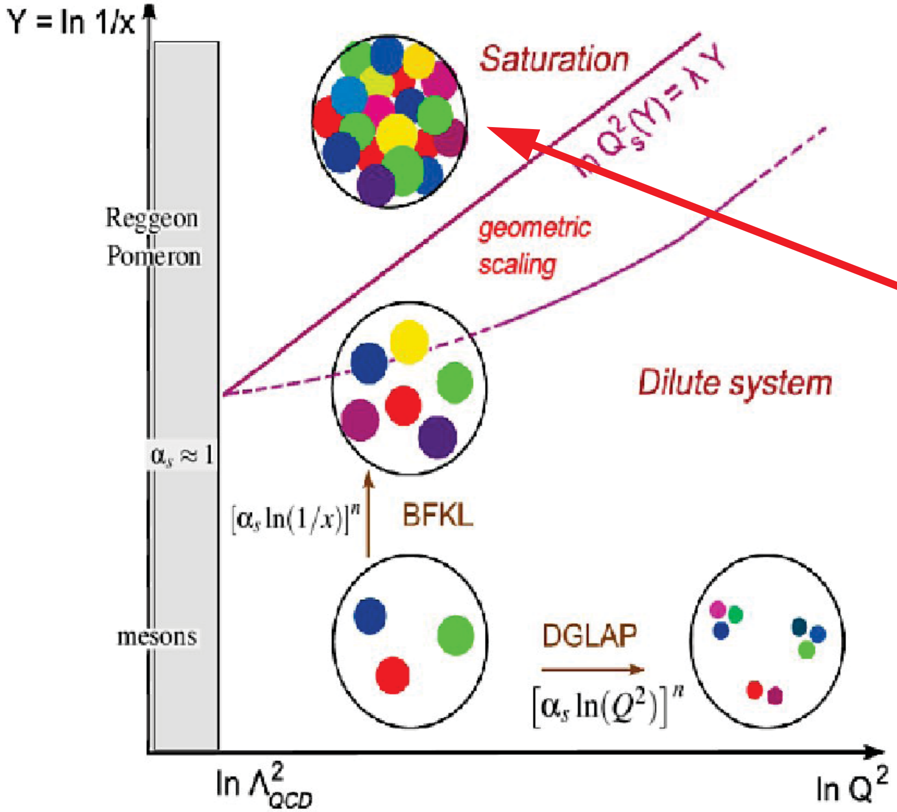
J. Rojo *et al.* arXiv:0808.1231





Low-x PDFs evolution

- **Q² - DGLAP** (k_T-order'd emission): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV² [LT,coll.factoriz.]
- **x - BFKL** (p_L-ordered emission): $F_2(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T-factoriz.]
- Linear equations – single parton radiation/splitting – cannot work at low-x



(i) Too high gluon density: nonlinear gluon-gluon fusion balances branchings

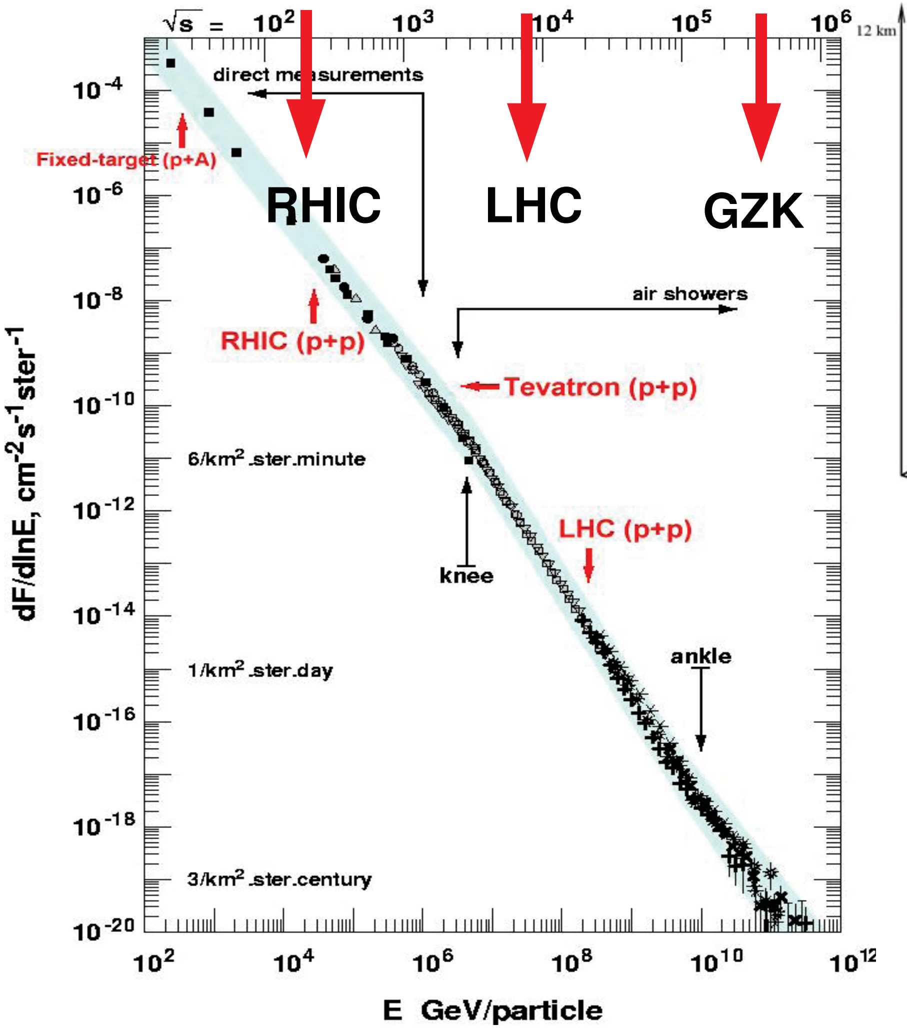
(ii) pQCD (collinear & k_T) factorization assumptions invalid (HT, no incoherent parton scatt.)

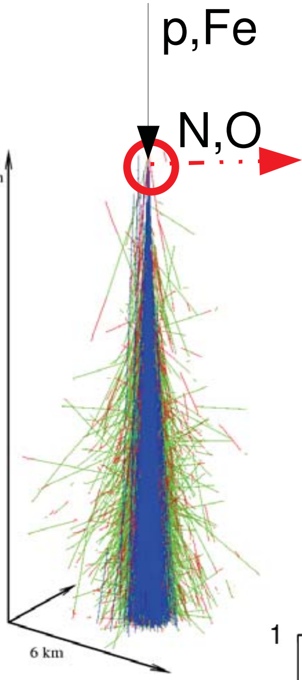
(iii) Violation of unitarity even for $Q^2 >> \Lambda^2$ (too large perturbative cross-sections)

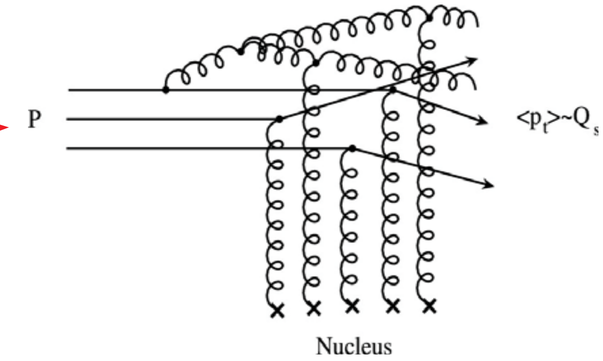
Low-x in UHE cosmic-rays (p-Air, Fe-Air)

log(x)[y=0,y_{max}/2]: [-2,-3] [-3.5,-6] [-5,-8]

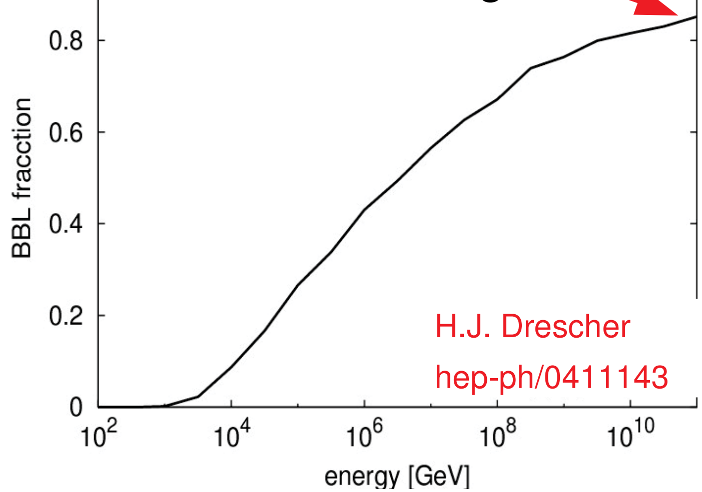
Q_s^2 : ~1.5GeV² ~5GeV² ~20GeV²







- At GZK cut-off energies, ~90% of p-A collisions in the saturation regime



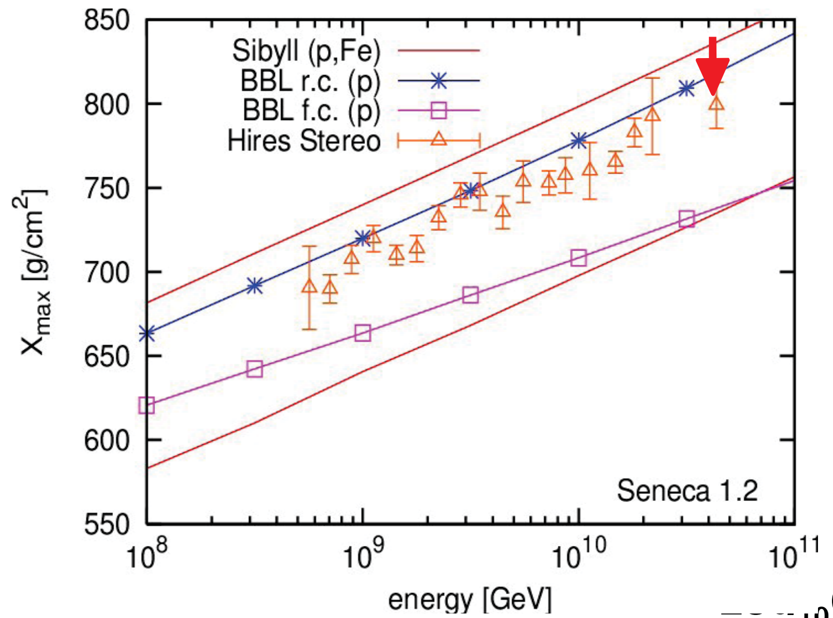
Implications for extended air showers

- Reduced dN/dη (esp. fwd):

  Less penetration:

  lower X_{max} (~ -30 g/cm^2)

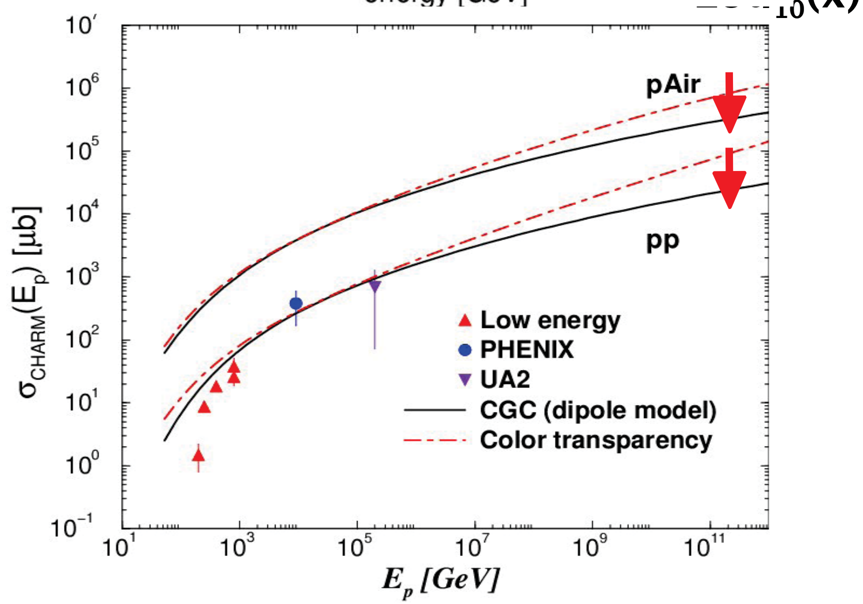
  Drescher, Dumitru, Strikman
  PRL 94 (2005) 231801



- Reduced charm cross sections:

  Less muons !

  Machado&Goncalves
  hep-ph/0607125



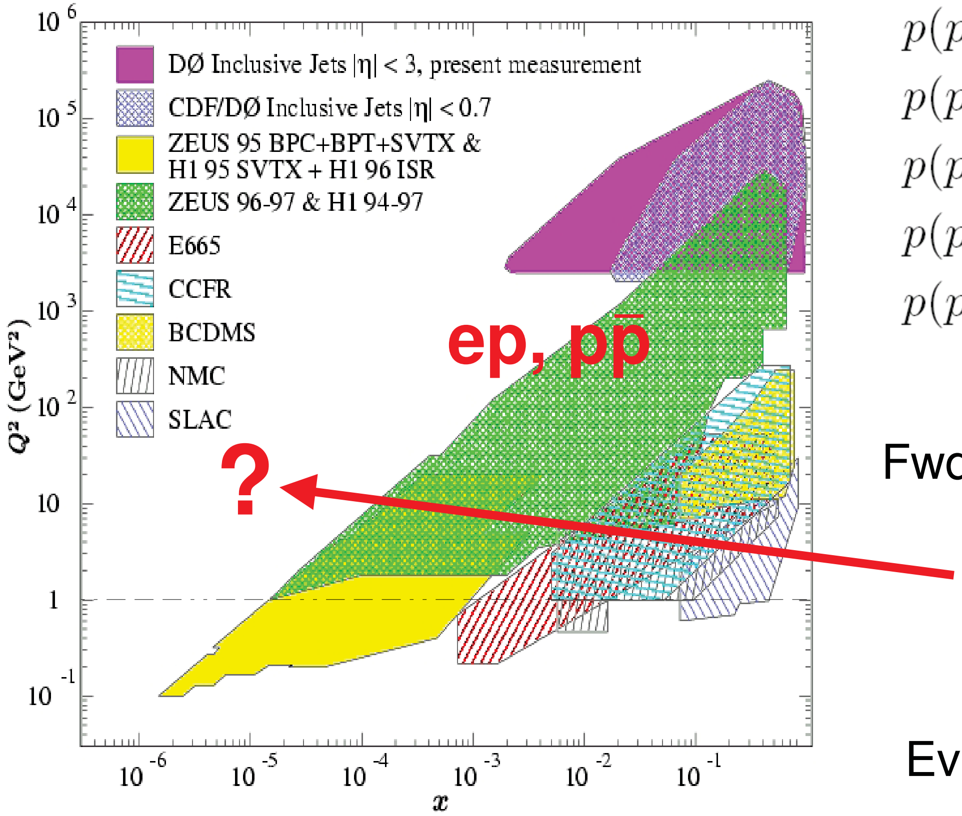
Low-*x* PDF at the LHC (proton)

- p-p @ 14 TeV :

  (i) At y=0, $x=2p_T/\sqrt{s}\sim10^{-3}$ (domain probed at HERA,Tevatron). Go fwd. for $x<10^{-4}$

  (ii) Saturation momentum: $Q_s^2\sim$ 1 GeV² (y=0), 3 GeV² (y=5)

  (iii) Very large perturbative cross-sections:



$$p(p_1)+p(p_2)\rightarrow \text{jet}+\gamma+\ X$$ Prompt γ

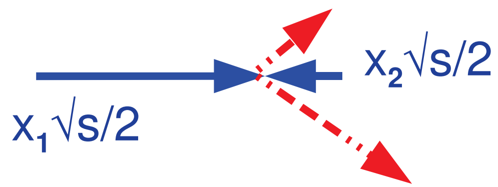
$$p(p_1)+p(p_2)\rightarrow l\bar{l}+\ X$$ Drell-Yan

$$p(p_1)+p(p_2)\rightarrow \text{jet}_1+\text{jet}_2+\ X$$ Jets

$$p(p_1)+p(p_2)\rightarrow Q+\bar{Q}+\ X$$ Heavy flavour

$$p(p_1)+p(p_2)\rightarrow W/Z+\ X$$ W,Z production

Fwd. production:



$$x_2^{min}\sim p_T/\sqrt{s}\cdot e^{-y}=x_T\cdot e^{-y}$$

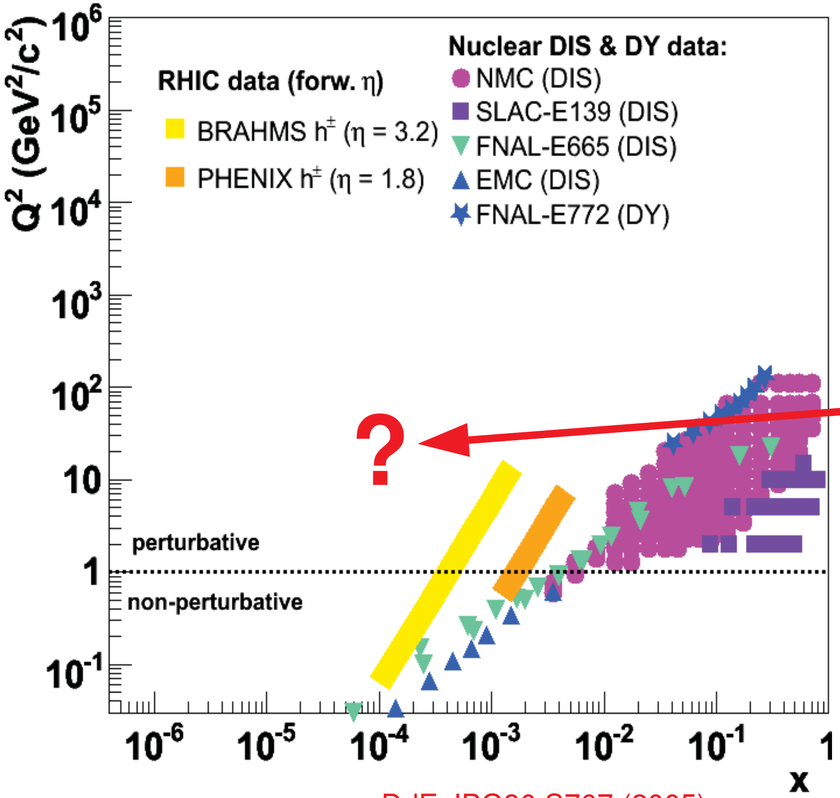
Every 2-units of y, x^{min} decreases by ~10

Low-*x* PDF at the LHC (nucleus)

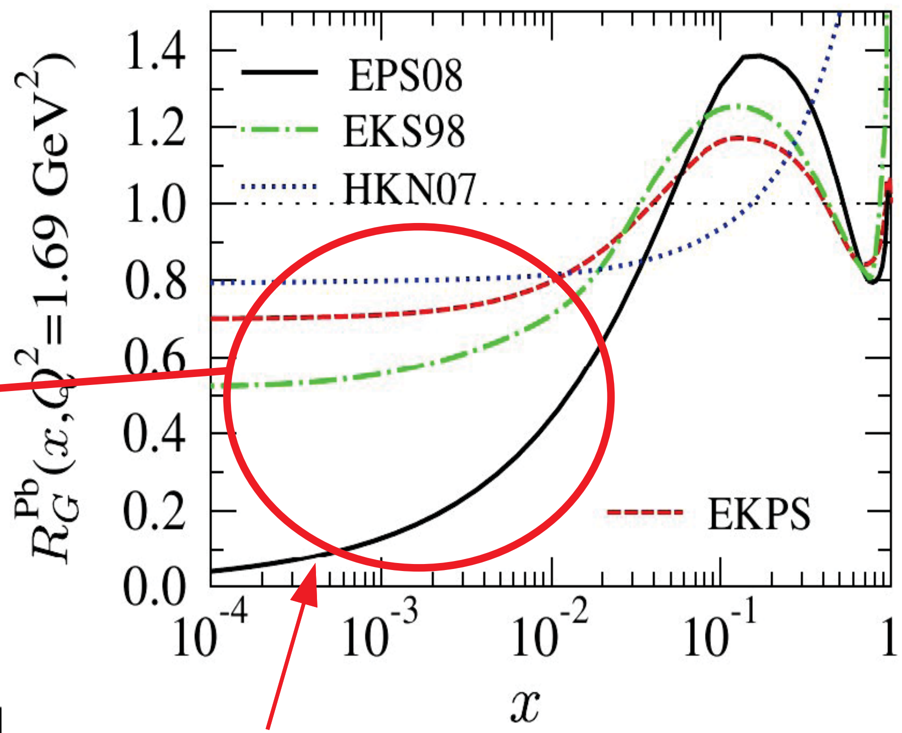
- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:
  - (i) Very high $\sqrt{s}$ $\Rightarrow$ Bjorken $x=2p_T/\sqrt{s}$ ~30-45 times lower than AuAu,dAu @ RHIC !
  - (ii) Saturation momentum enhanced ($A^{1/3}$~6) : $Q_s^2 \sim [5\ GeV^2]e^{(0.3y)}$
  - (iii) Very large perturbative cross-sections.

K.Eskola et al. JHEP 0807 (08)102

Ratio of Pb/p gluon densities:



DdE JPG30:S767 (2005)

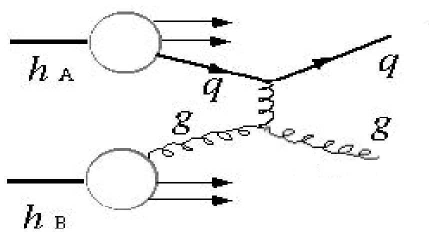


Nuclear $xG(x,Q^2)$ unknown for $x<10^{-2}$!

Example I: Forward jets in CMS ($3 < |\eta| < 6.6$)

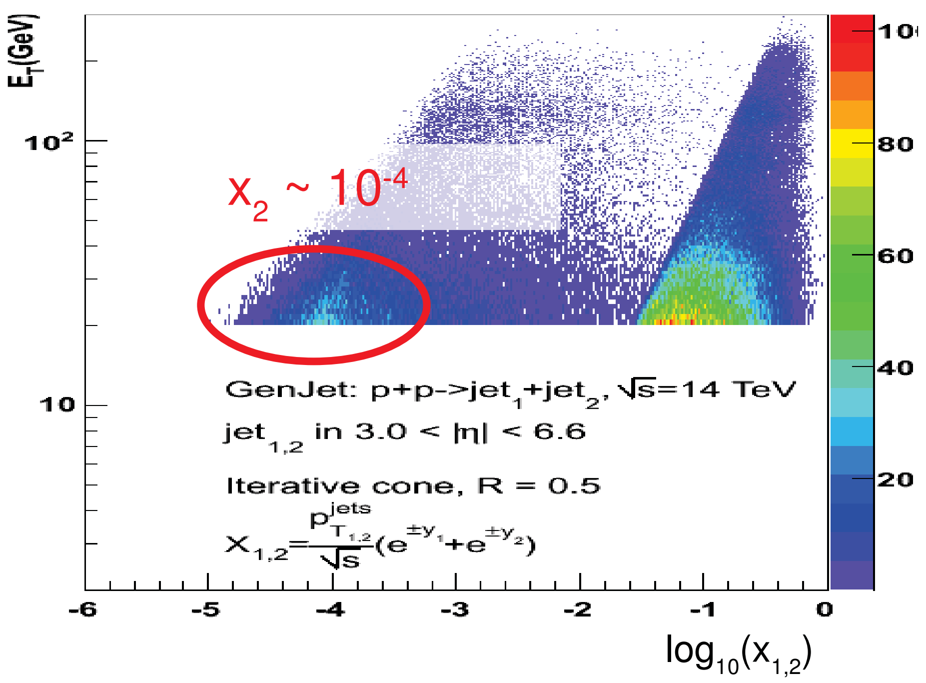
[S.Cerci, DdE arXiv:0812.2665]

- Forward jets (E_T ~20-100 GeV) sensitive to low-x PDFs:

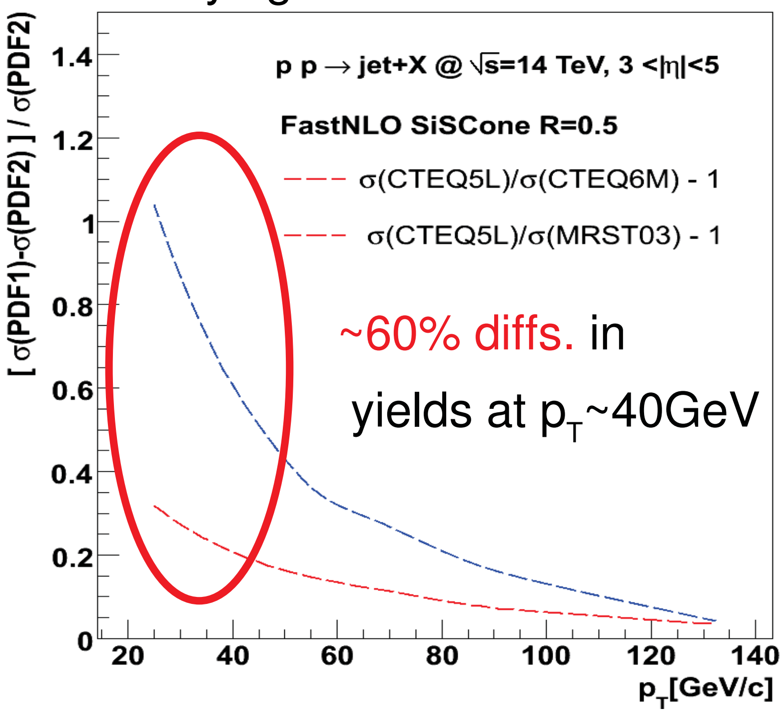


Jets in HF ($3<|\eta|<5$) probe: $x_2 \sim 10^{-4}$

Jets in CASTOR ($5.1<|\eta|< 6.6$): $x_2 \sim 10^{-5}$

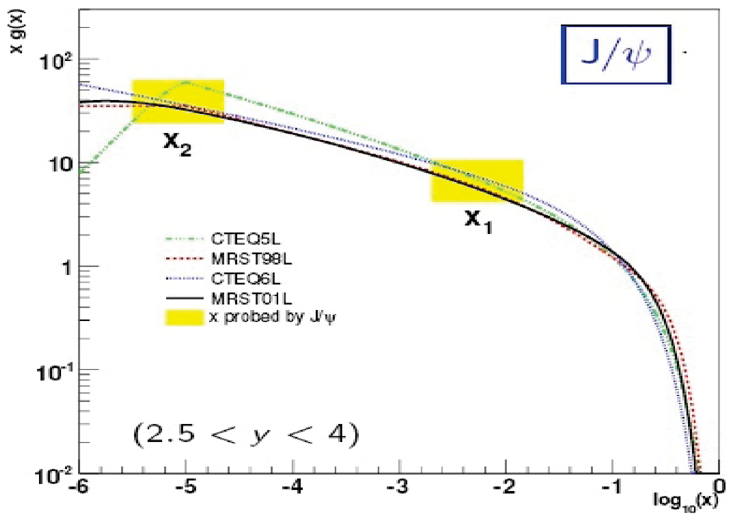


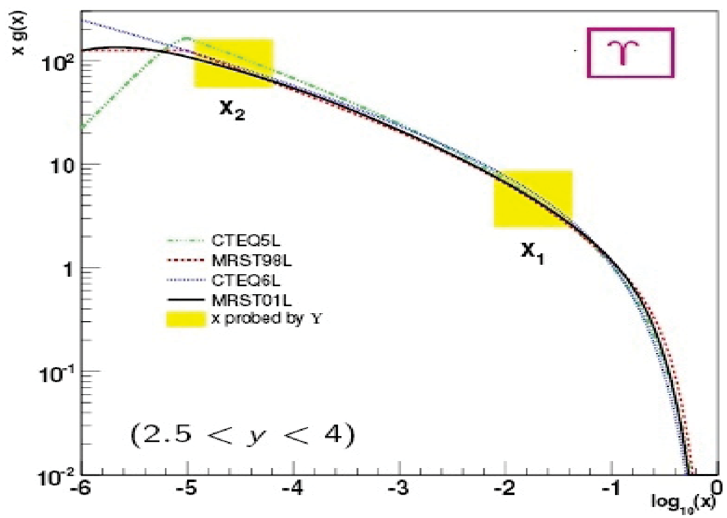
varying PDFs:



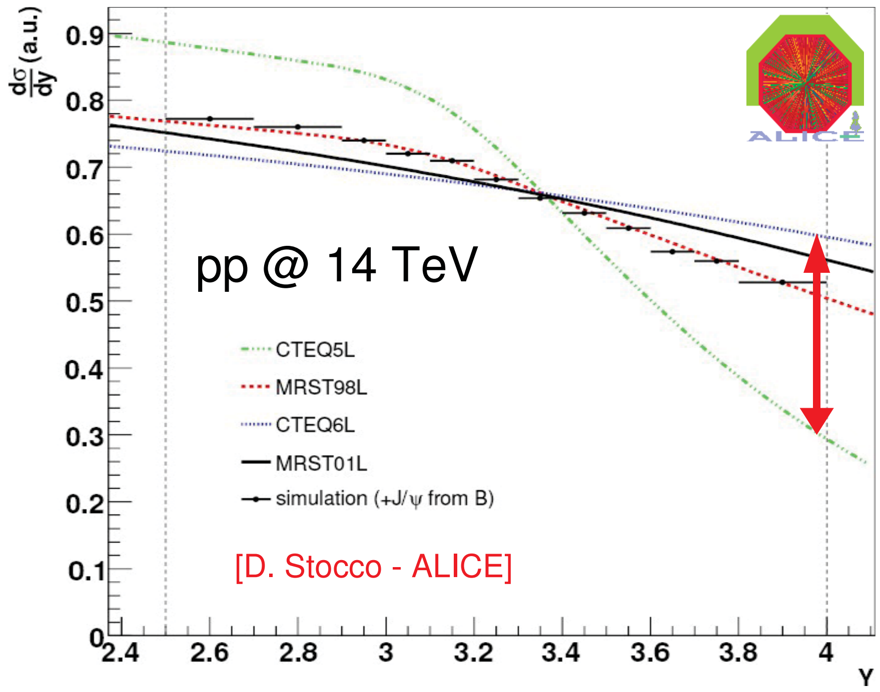
Example II: Forward $Q\bar{Q}$ in ALICE (2.5 <|η| < 4)

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





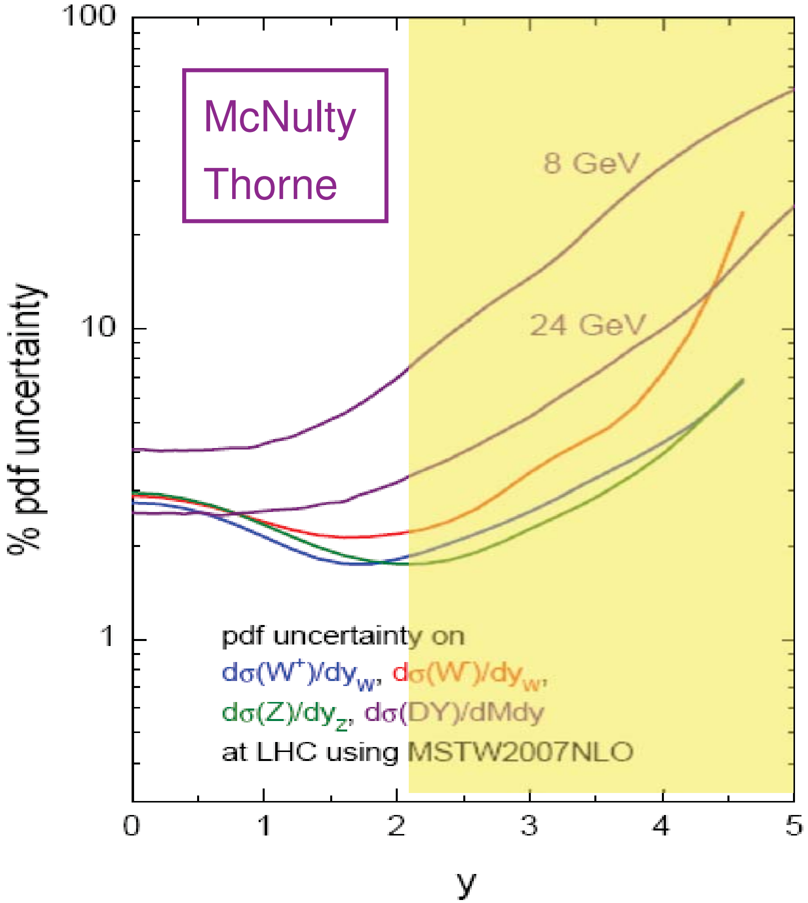
dσ/dy J/ψ: NLO CEM w/ varying PDFs

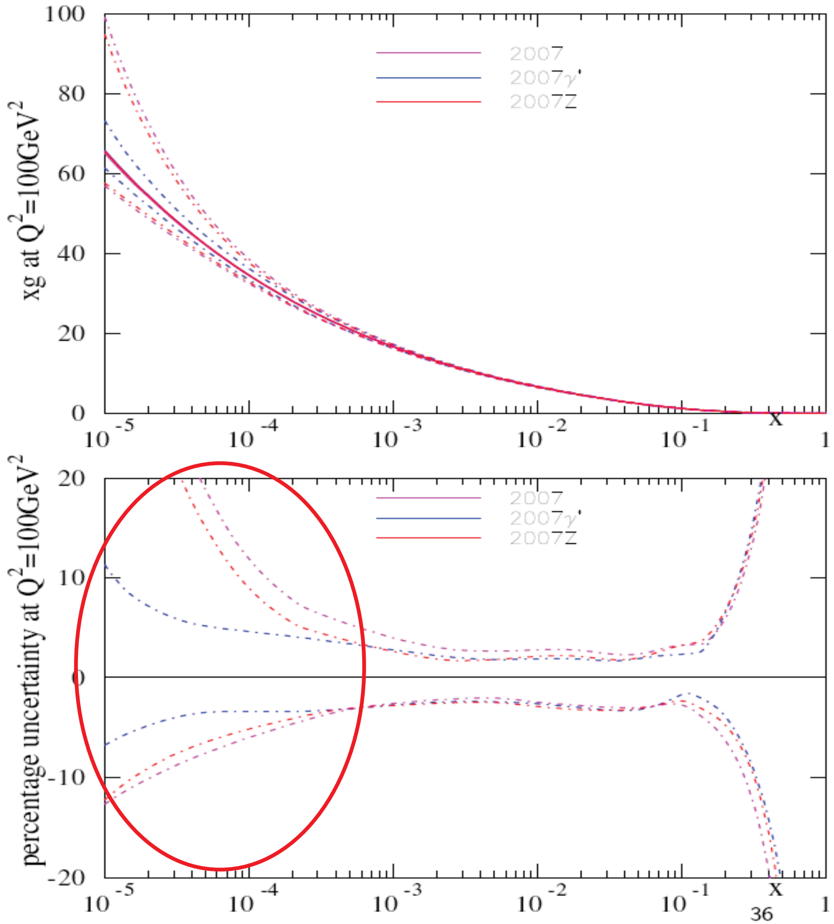


QQbar: Sensitive to different PDFs & to DGLAP versus CGC predictions (Note: $m_{J/\psi}$~Q_s at the LHC)

Example III: γ^*,Z,W in LHCb ($2 < \eta < 5$)

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





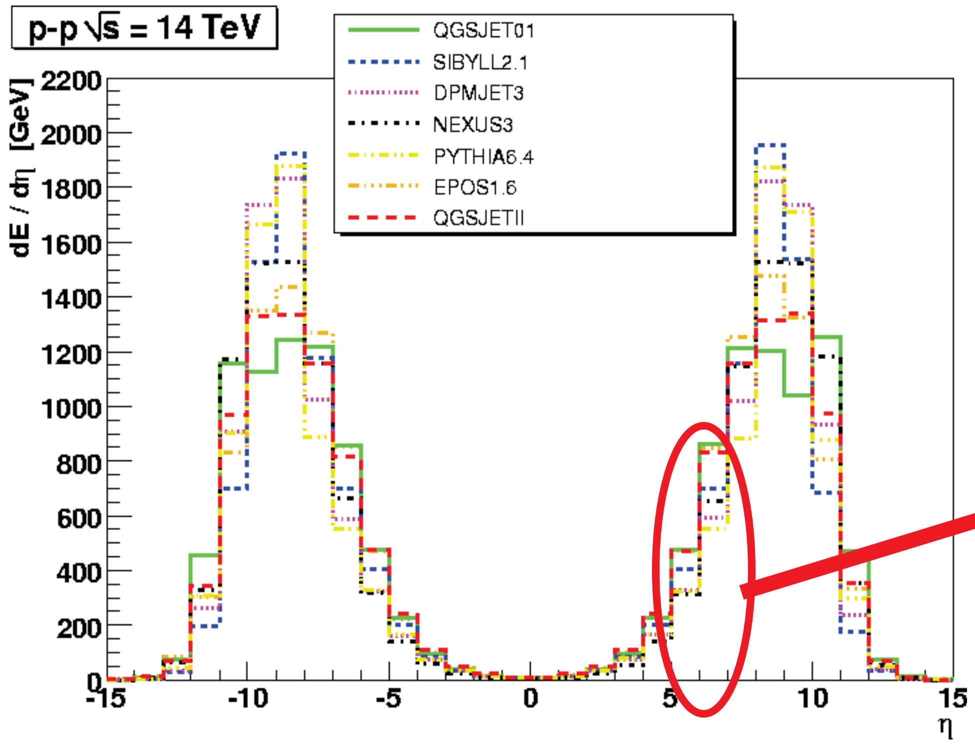
- LHCb: Forward W,Z (lepton) with 1% uncertainty (LHCb note 2007-114)

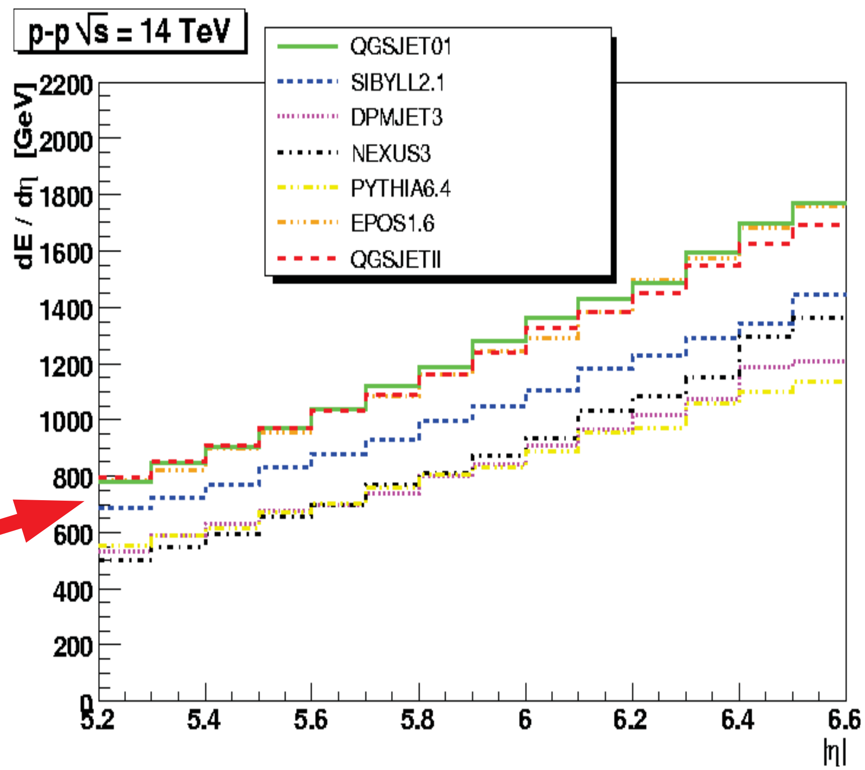
LHC measurements (III): particle, energy flows

proton-proton @ √s = 14 TeV

- Energy rapidity densities (dE/dη), dominated by soft QCD: underlying event, multi-parton interactions, fragmentation, ...

[full η] [CASTOR calorimeter region]

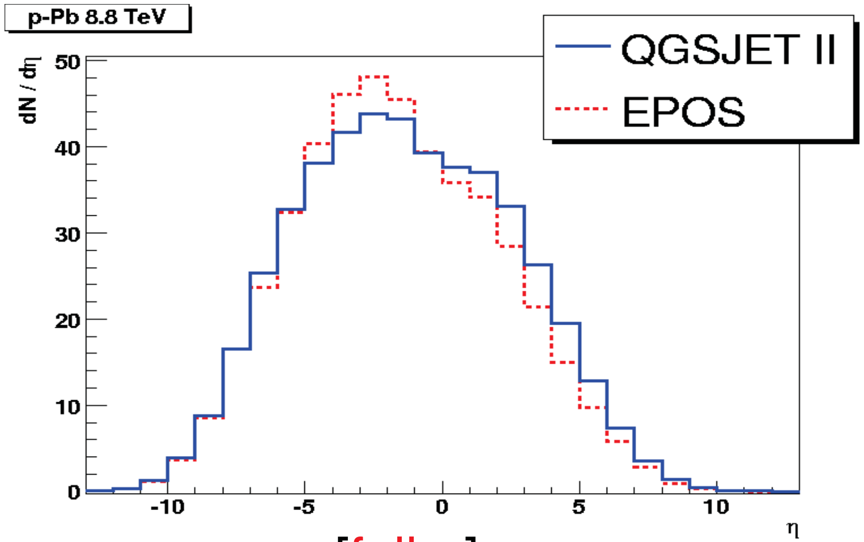




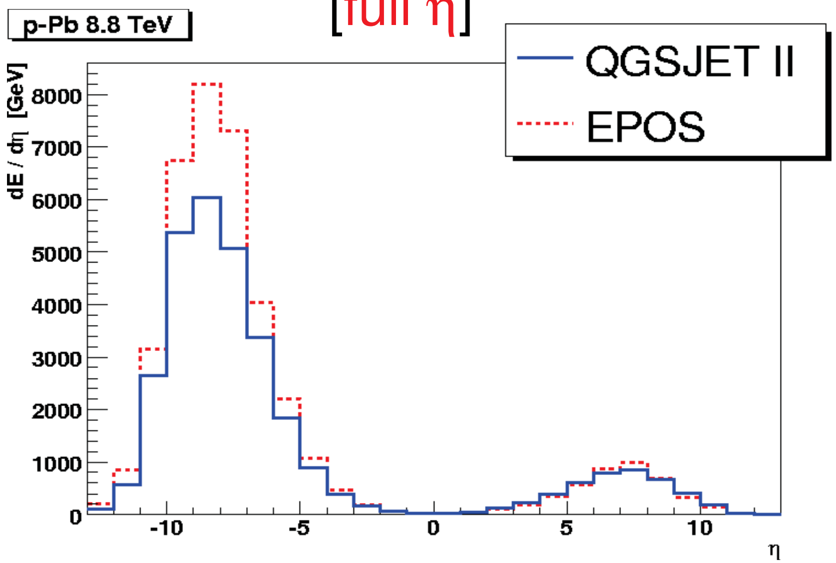
DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

proton-Pb @ √s = 8.8 TeV

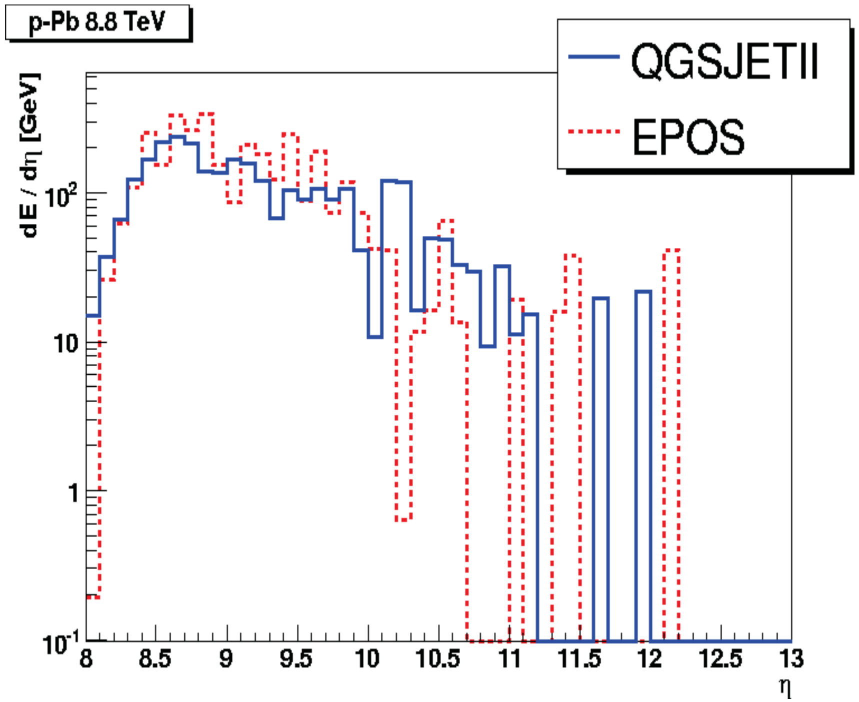
- Particle (dN/dη) & energy (dE/dη) rapidity densities:



[full η]



[ZDCs/LHCf calorimeter region]

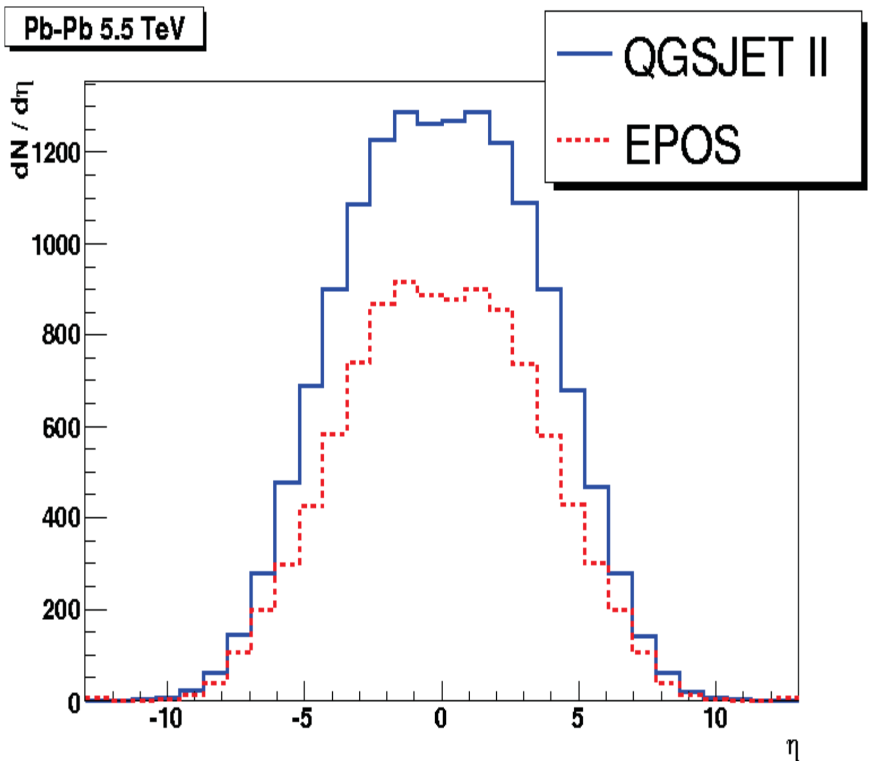


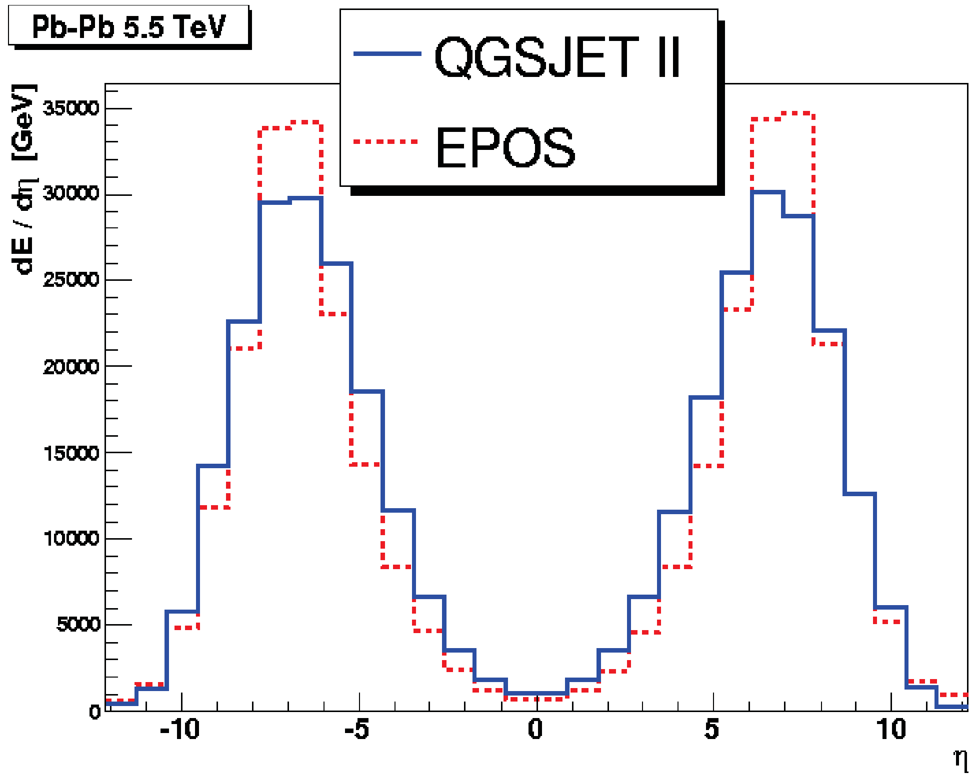
DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Pb-Pb @ √s = 5.5 TeV

- Particle (dN/dη) & energy (dE/dη) rapidity densities:

[full η]



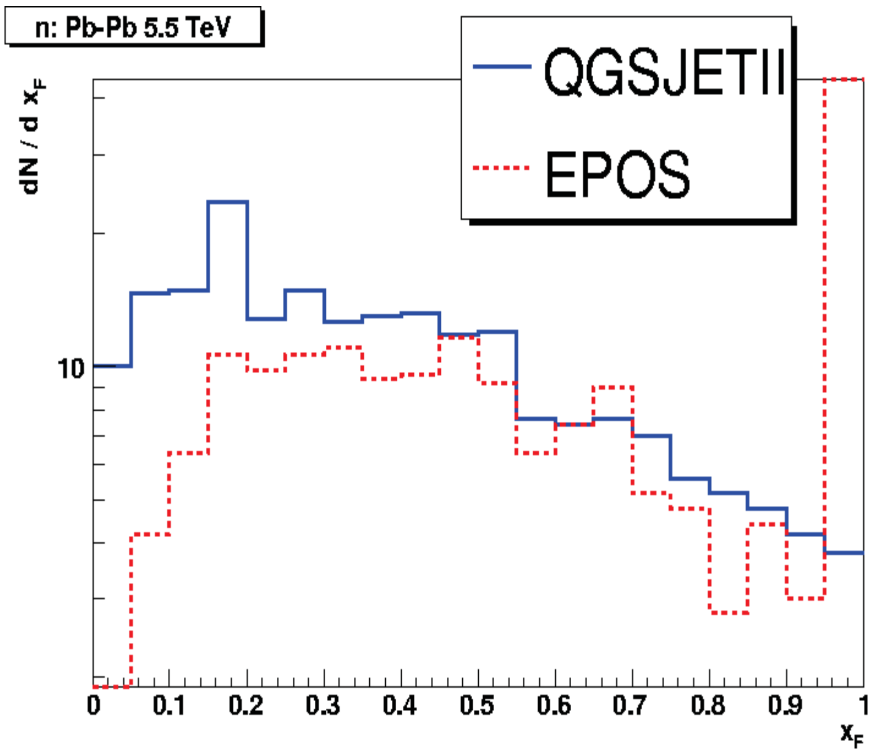


DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

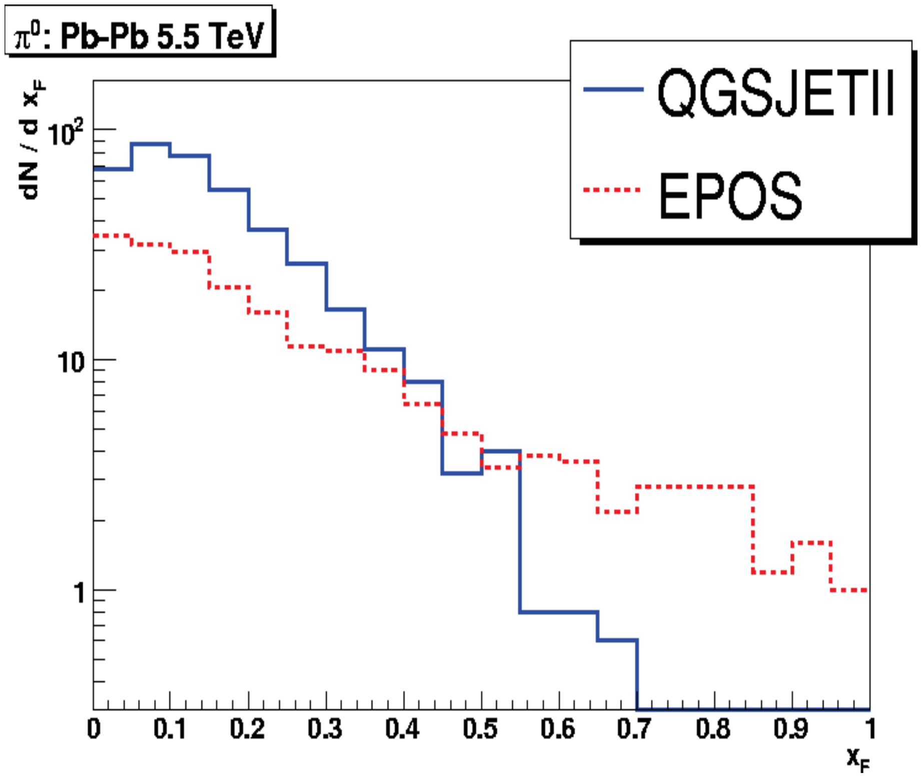
Pb-Pb @ $\sqrt{s}$ = 5.5 TeV

- Leading particle (dN/dxF) in ZDCs/LHCf calorimeter region:

(neutrons)



(neutral pions: γγ)



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

Cosmic-rays "exotic" events

- E~10^{15}-10^{17} eV cosmic-rays "Centauro" events:

(i) anomalous number of (N~0) electromagnetic secondaries
(ii) forward "long-flying" (i.e. non-interacting) component

} "strangelets"? "DCCs"?

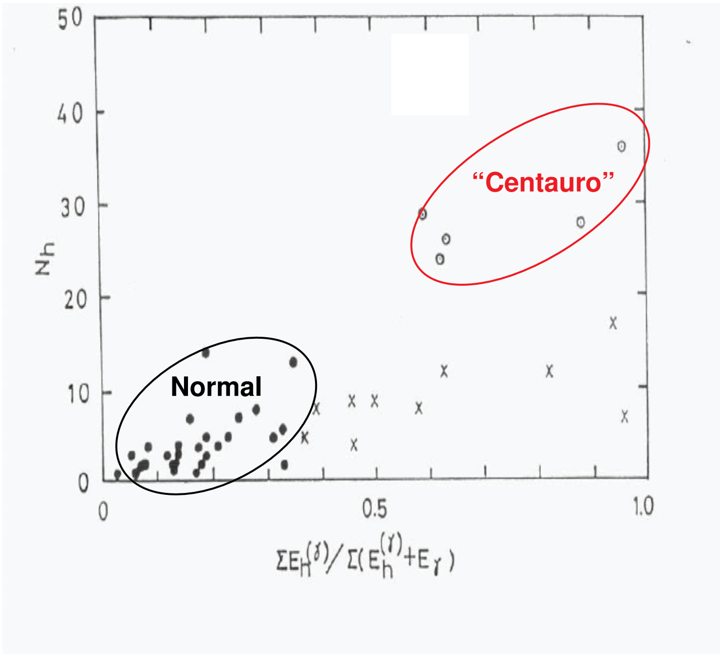
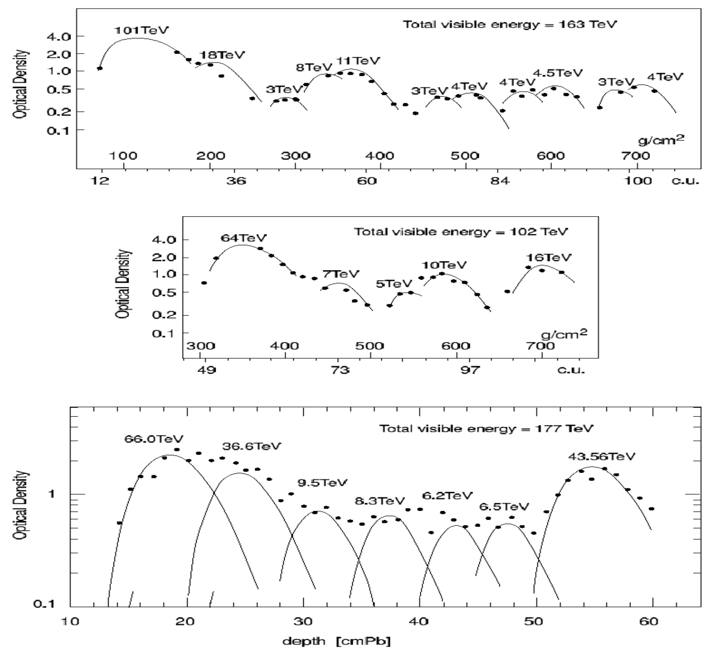


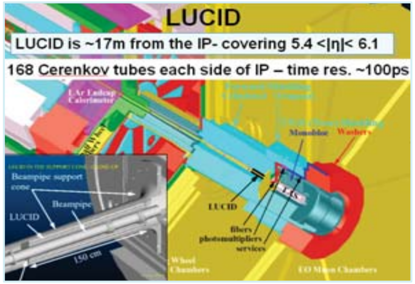
Figure 2.5: Diagram of the number of hadrons and hadronic energy fraction: Chacaltaya events with the total visible energy greater than 100 TeV [38]: (o) Centauro, (×) Mini-Centauro, (•) others; (⋆) C-K [36].



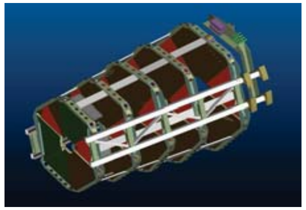
CMS-CASTOR (|η|=5-6.6, longitudinal segmentation) aims at this studies.

Summary: forward instrumentation @ LHC

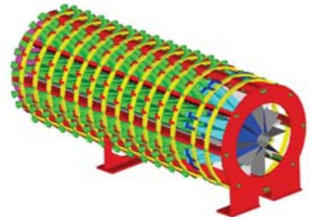
ATLAS LUCID



TOTEM T1

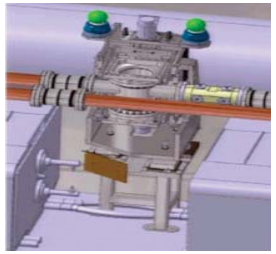


CMS CASTOR

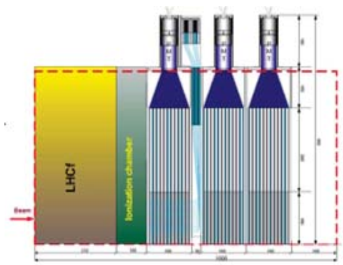


TOTEM T2

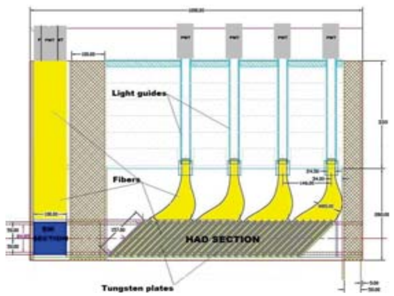
ATLAS ALFA



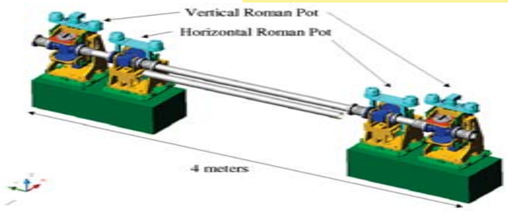
ATLAS ZDCs



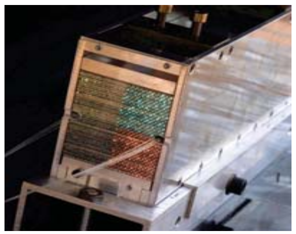
CMS ZDCs



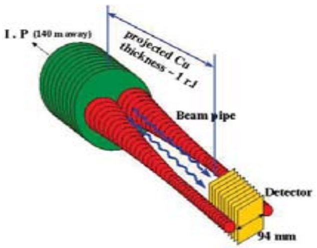
TOTEM RPs



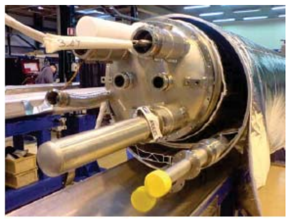
ALICE ZDCs



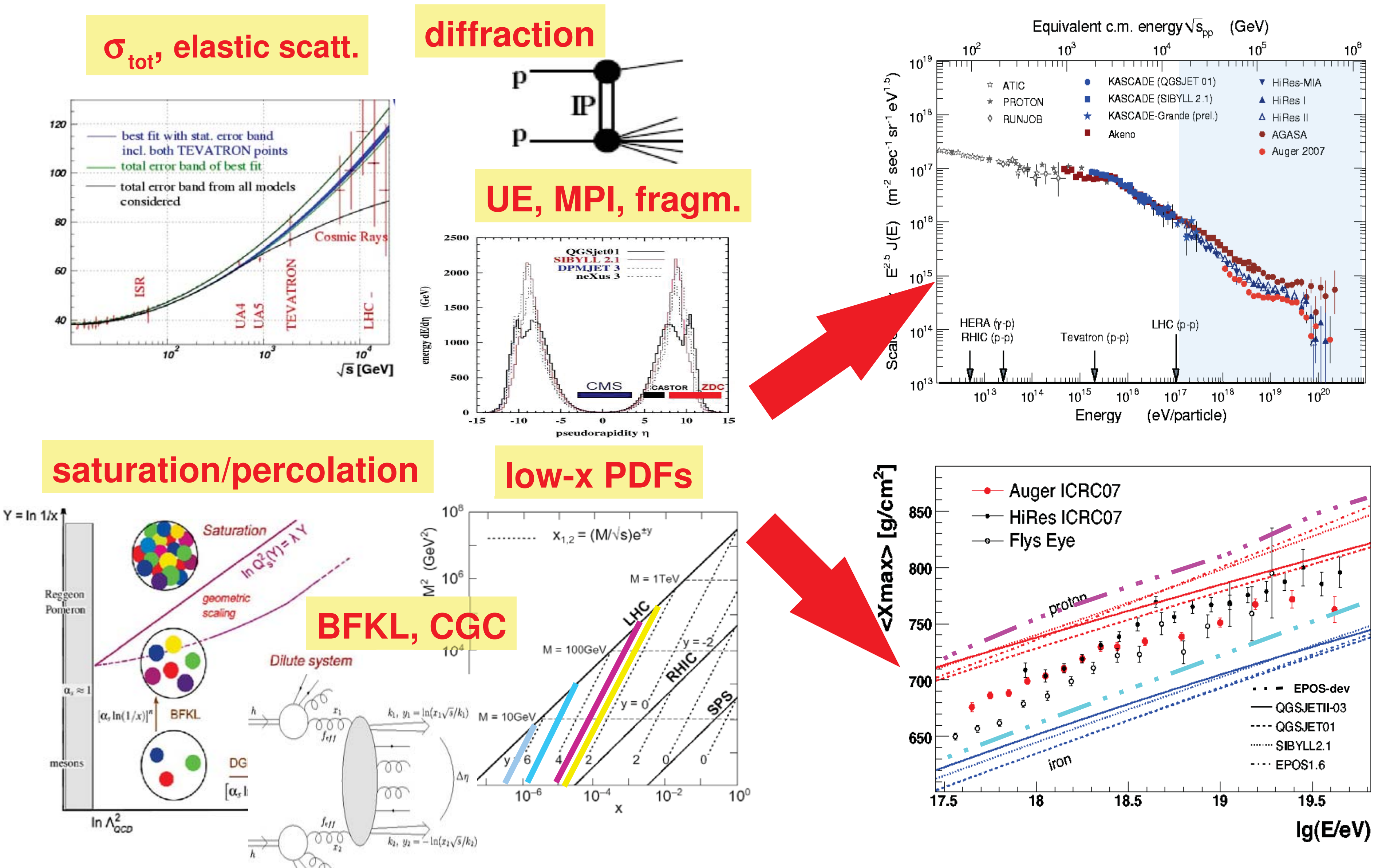
LHCf



FP420

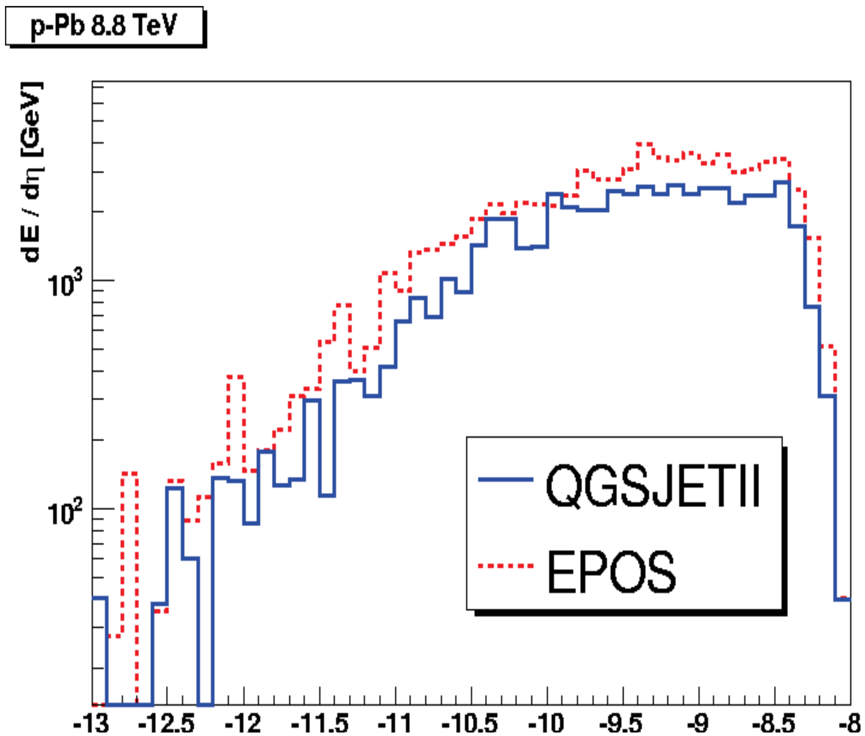


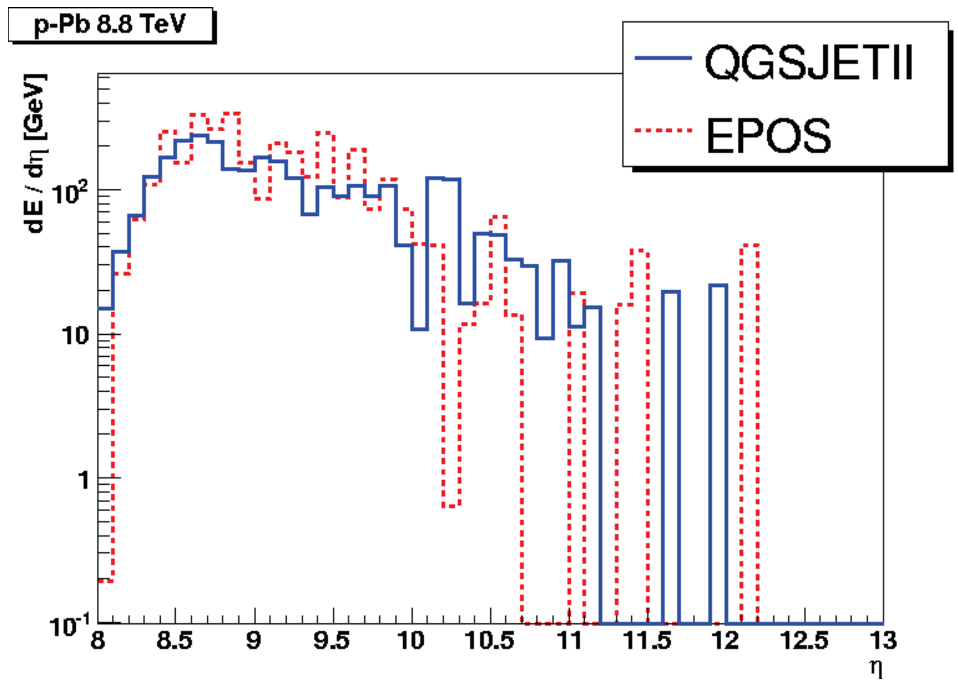
Summary: from LHC-QCD to UHE cosmic-rays



Backup slides

proton-Pb @ √s = 8.8 TeV

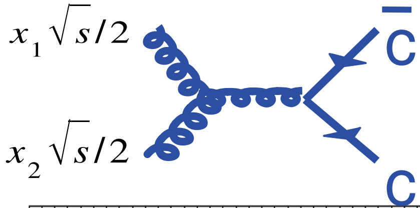


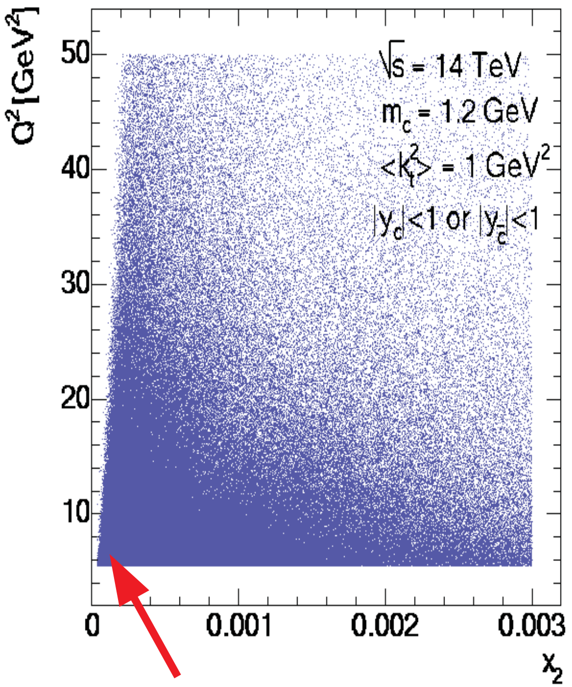


(*) DdE, R.Engel, T.McCauley, T.Pierog: arXiv:0806.0944 [astro-ph]

Example III: Low-p_T charm in ALICE ($|\eta|<1$)

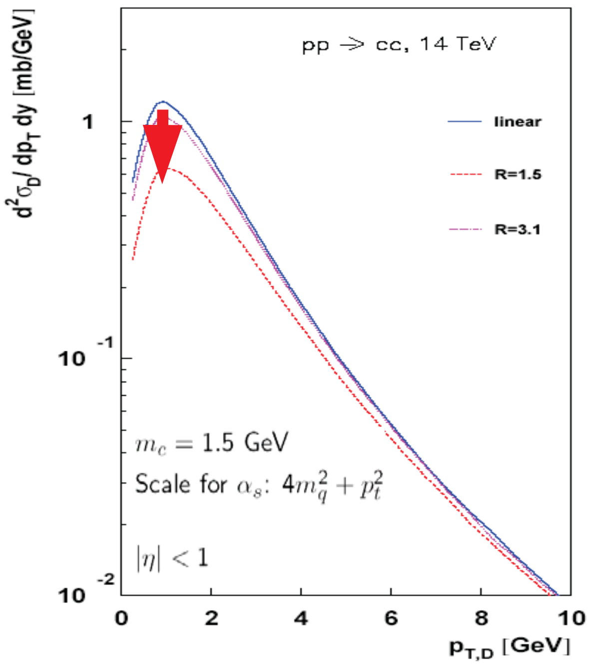
- Open charm measurement in TPC+TRD (y=0):



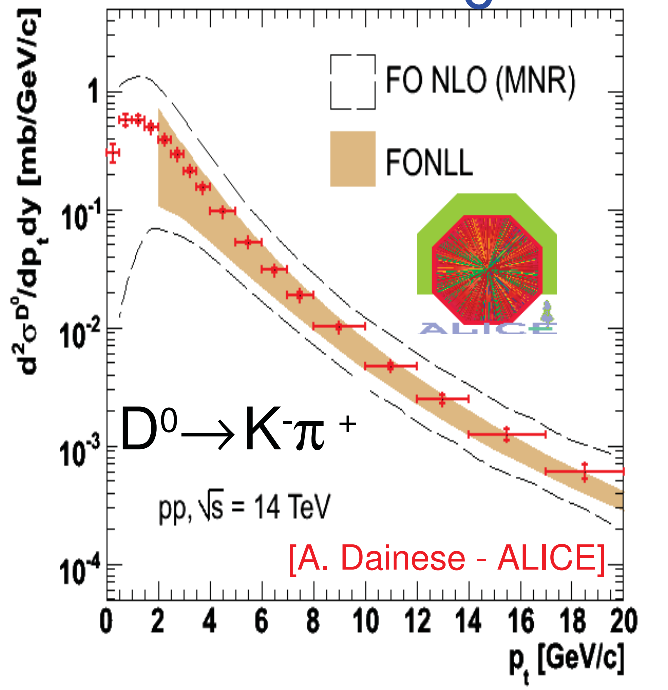


xg(x) in the proton

at $x_1 \sim x_2 \sim m_c/\sqrt{s} \sim 10^{-4}$



Charm suppression
due to non-linear QCD
effects



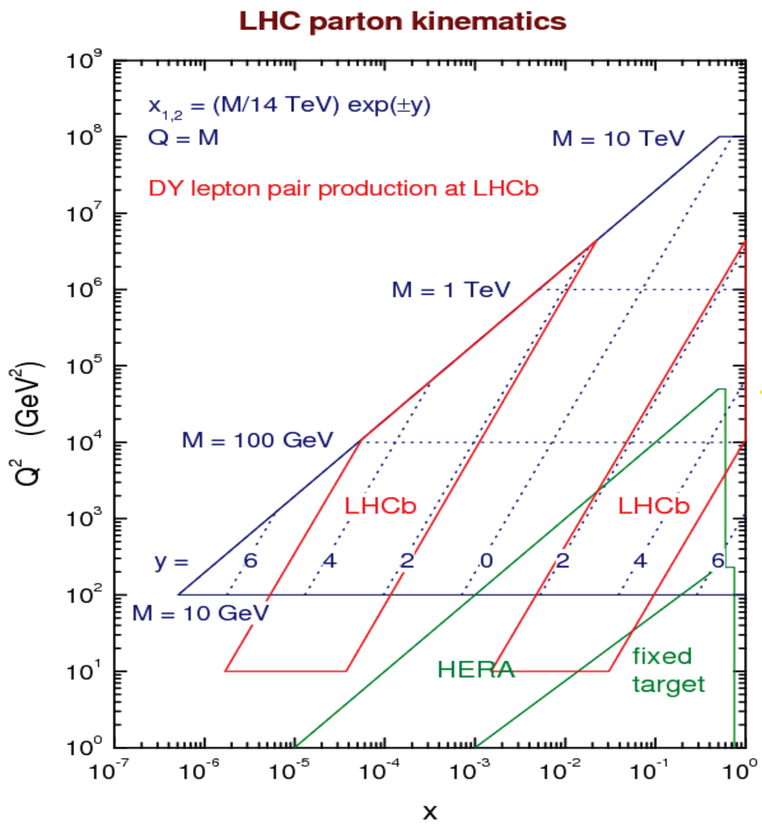
Good reco capabilities
J. Stirling & L. Orr, Del Duca et al.
(displaced vtx.+ $e^{\pm}$ PID)

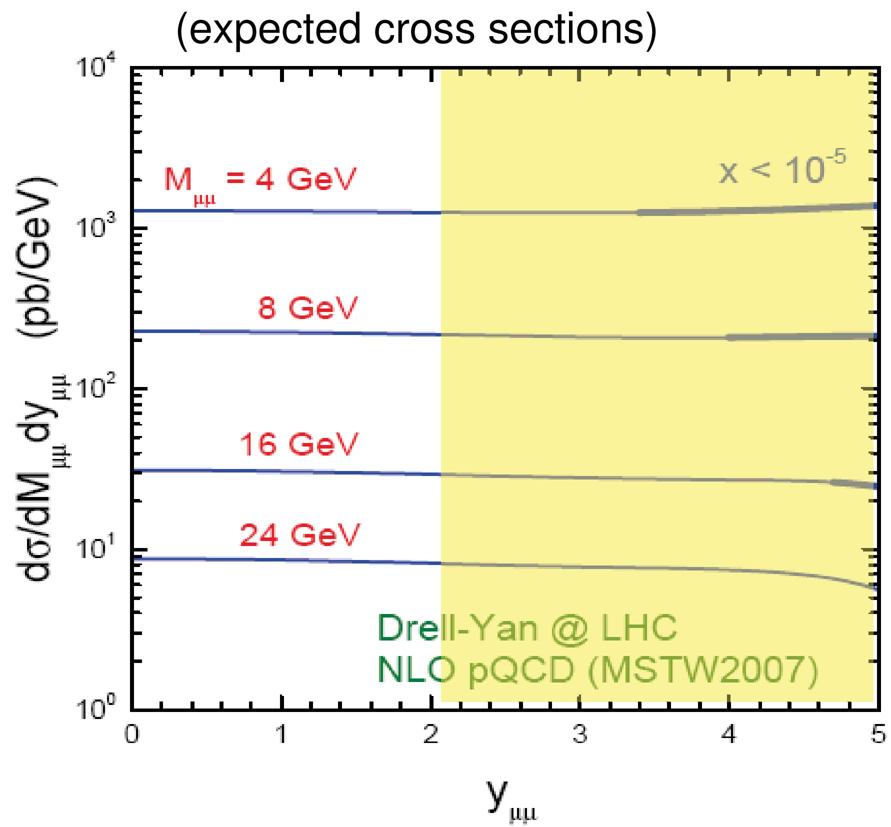
down to p_T = 0 GeV/c

- LHCb: forward open charm/bottom.

Example IV: γ^* in LHCb ($2 < \eta < 5$)

- Drell-Yan forward μ: (trigger on low-p muons: p>8GeV, p_T>1GeV)
- Sensitive to low-x quark densities

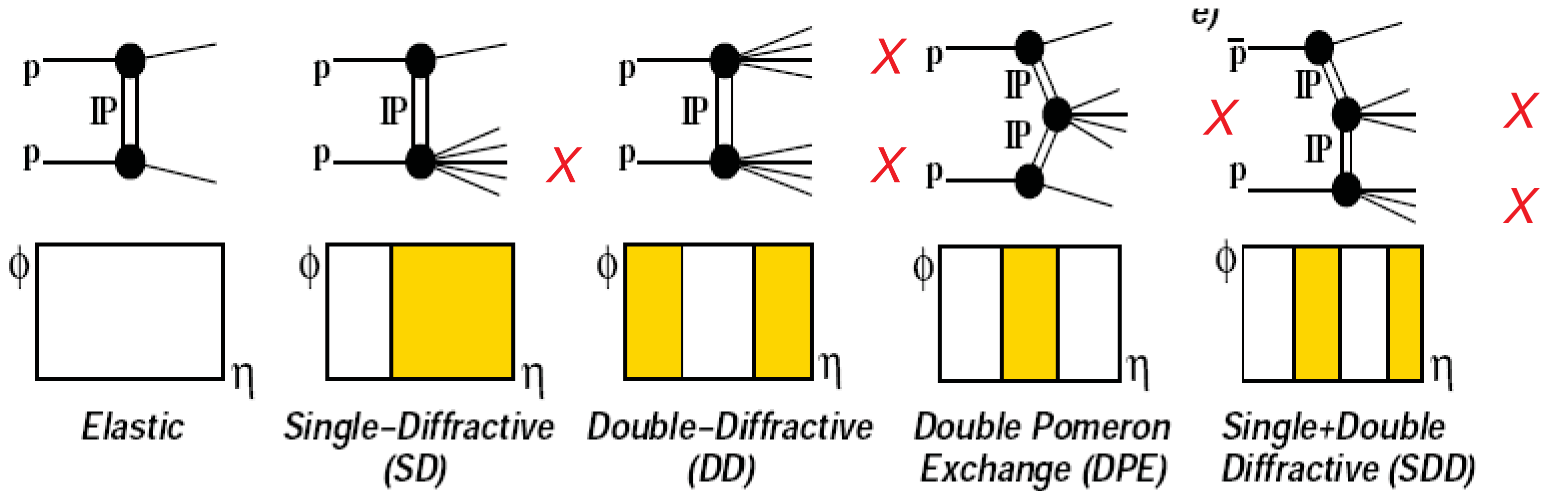




- Need to deal with large QCD (& QED) bckgd.

Pomeron-induced processes

➢ Diffract./Elastic scatt. (~40% p-p σ_{tot}): p intact (Roman Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:



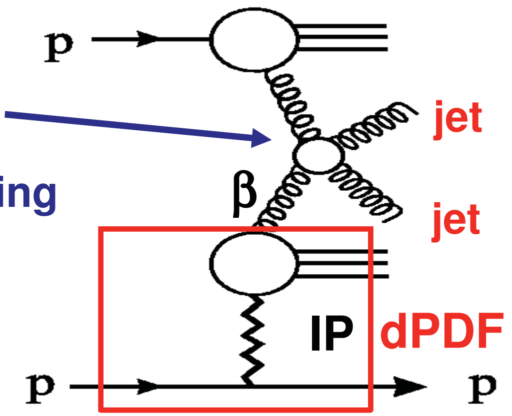
➢ σ_{tot},ρ: Test fundamental QM relations (Froisart bound, optical th., dispersion relat)

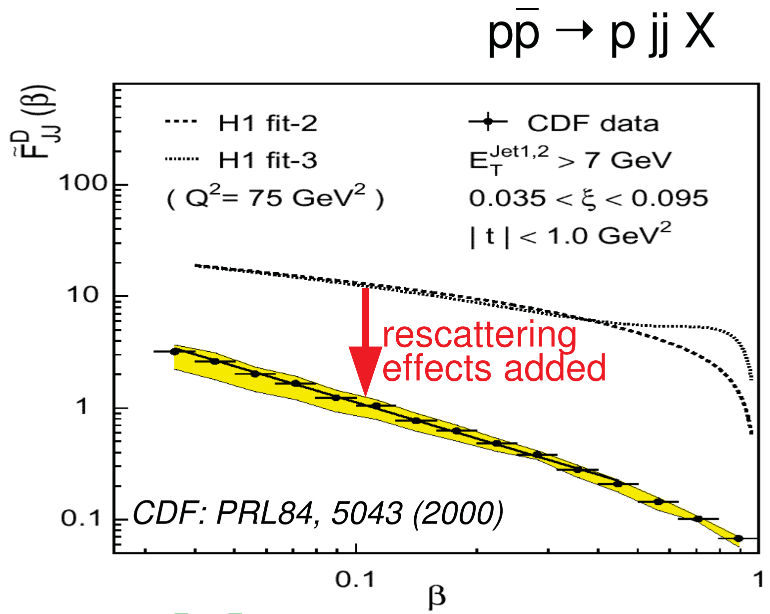
➢ Soft diffraction (*X* = anything): Dominated by soft QCD → SD, DPE vs. s, t, M_X provide valuable info of non-perturb. QCD. Contributions to pile-up p-p events.

➢ Hard diffraction (*X* = jets, W's, Z's ...): Calculable (in principle) in pQCD → Info on proton structure (dPDFs,GPDs), multi-parton interactions, discovery physics (DPE Higgs, beyond SM)

Hard diffraction

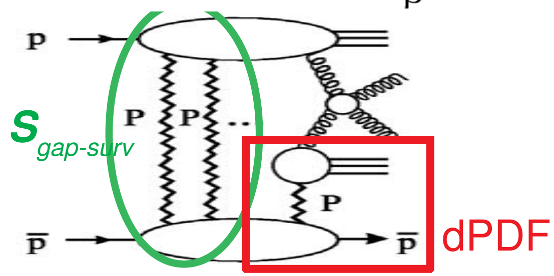
- Hard diffraction calculable using QCD factorization theorem, e.g. ...
- Diffractive dijet cross section = dPDF $\otimes$ $\sigma_{\text{parton-parton}}$ $\otimes$ $S_{\text{gap-survival}}$





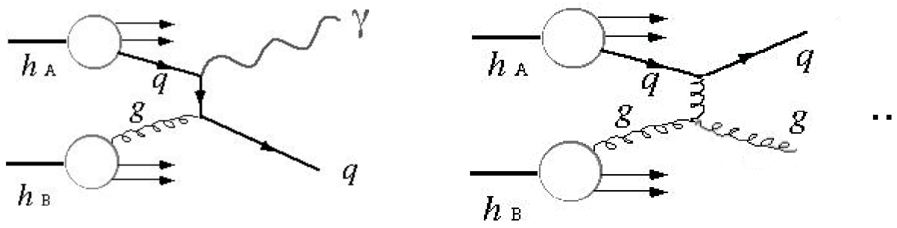
- Diffractive PDFs: probability to find a parton of given *x* under condition that proton stays intact (measured at HERA).

- Gap survival *S*: probability to fill rapidity gap with hadrons from extra rescatterings

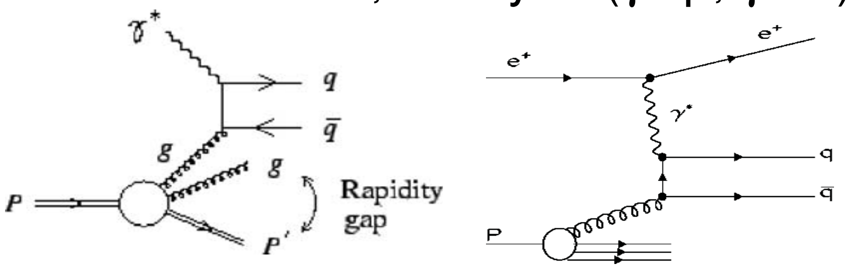


Experimental probes of gluon PDF ($\gamma^{(*)}$p,pp,$\gamma^{(*)}$A,AA)

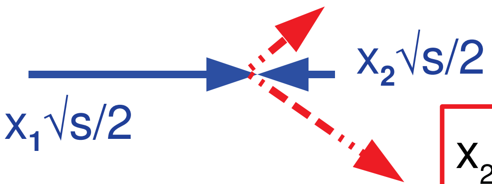
- Perturbative processes:
  - Prompt γ, (di)jets ($\gamma^{(*)}$p, pp, AA):



  - Diffractive $Q\bar{Q}$, heavy-Q ($\gamma^{(*)}$p, $\gamma^{(*)}$A):



- Forward production:



$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$

Every 2-units of y, x^{min} decreases by ~10