Forward physics at the LHC

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Forward physics programme at the LHC

1. Diffractive physics (soft & hard):
   - Total cross-section, elastic scatt., single/double diffraction
   - Gap survival dynamics, p-p underlying event, ...
   - Hard diffraction: dijets, vector-bosons, heavy-Q, QQbar, direct-γ
2. Higgs and new physics:
   - Central exclusive (SM, MSSM) Higgs production
3. Low-x QCD:
   - Parton saturation, non-linear QCD evolution, multi-parton scatt. … via: (i) forward DY, jets (p-p, p-A), (ii) photoproduction (γ-p, γ-A interactions)
4. Cosmic-rays physics:
   - Forward energy & particle flows / min. bias events (p-p,p-A,A-A)
   - Exotica: “Centauro” events (DCCs, strangelets)
5. EWK (two-photon, γ–W) interacions:
   - Absolute luminosity (~3% QED precision) via: pp $\to \gamma\gamma \to$ ppee,pp$\mu\mu$
   - Triple (quartic) gauge boson couplings via: pp $\to \gamma$p $\to$ pnW ($\gamma\gamma \to$ZZ,WW)

Forward physics plans at the LHC

1. **CMS** (fwd. EOI submitted Jan.'04, CMS+TOTEM LOI LHCC-2006-039):
   - CASTOR, ZDCs, TAS (under consideration), +TOTEM
   - Soft&hard diffraction (w/ TOTEM or rapgaps), low-x QCD, cosmic-rays, γ–p, γ–A, γ–γ

2. **ATLAS** (fwd. LOI submitted Mar.'04):
   - ALPHA RPs (LOI R&D), LUCID, ZDC (approved 2007), TAS (under consideration)
   - Total p-p cross-section, photo-production (UPC Pb-Pb)

3. **ALICE**:
   - ZDCs, fwd. muon spectrometer
   - Diffraction, low-x QCD

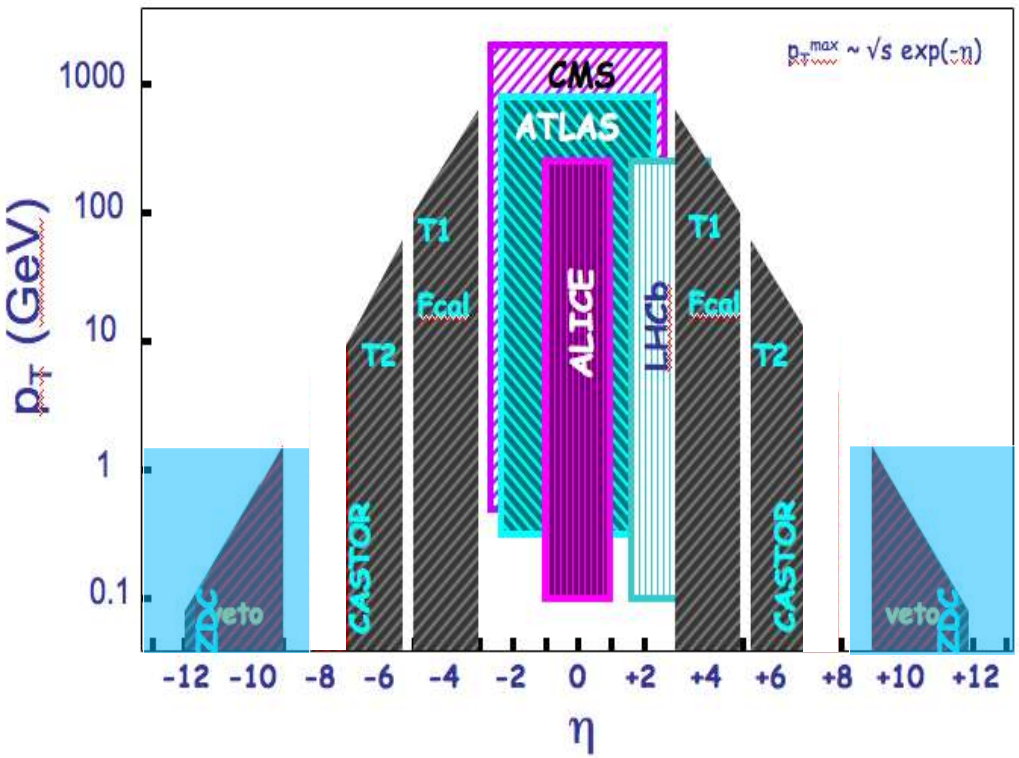
4. **LHCb**:
   - Forward muon spectrometer
   - Low-x PDFs

5. **TOTEM** (approved LHCC July'04):
   - Roman pots (220 m), trackers (T1, T2)
   - Elastic scattering, total p-p cross section, soft diffraction

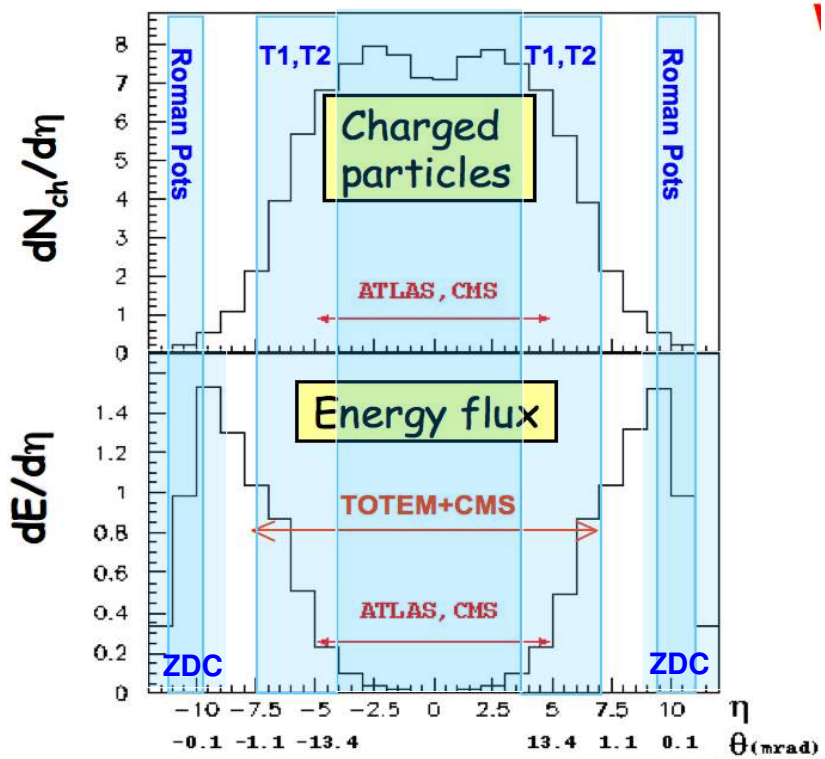
6. **LHCf** (approved LHCC 2006):
   - EM Calo (ATLAS-TAN, 140 m)
   - Cosmic-rays (forward γ,π^0)

7. **FP420** (R&D collab. LHCC-2005-025):
   - Feasibility studies for near-beam dets. at 420m
   - QCD, exclusive Higgs, new physics

LHC forward detectors (p_T,η) acceptance



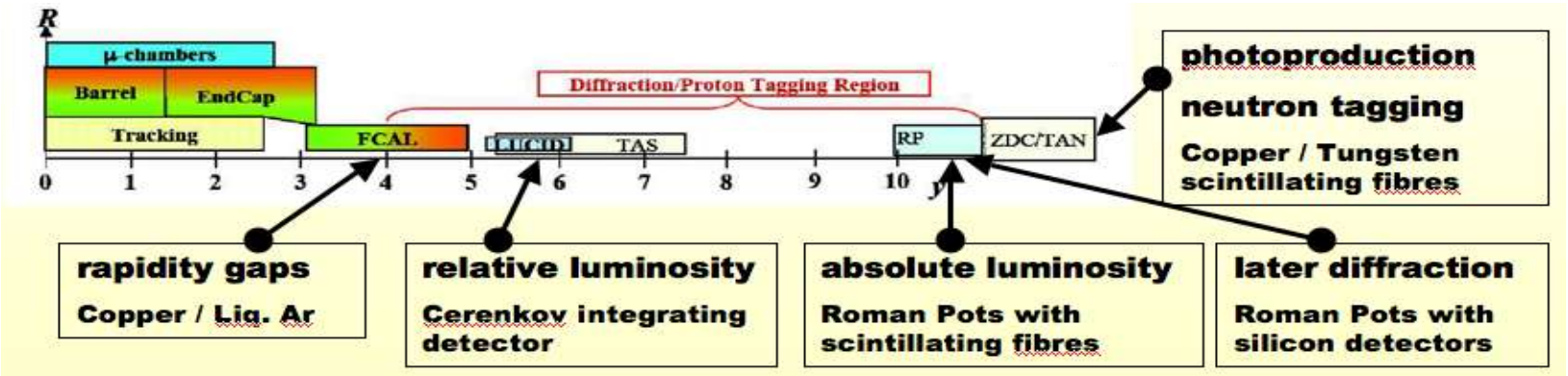
p-p @ 14 TeV

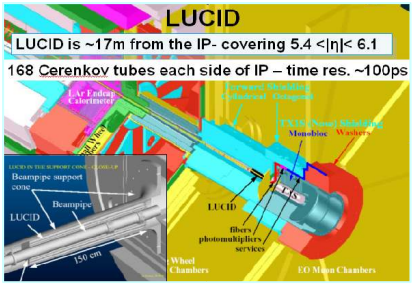


- All phase-space virtually covered at the LHC (first time in a collider)
- Ongoing plans to instrument the only current "hole": TAS (6.6<|η|<8.3) [20 cm slot with quartz-fibers]

ATLAS forward detectors

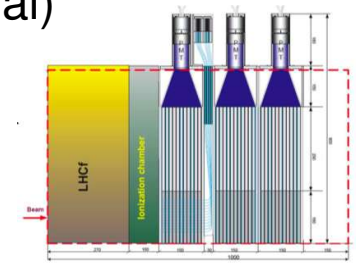
[cf. S.Ask talk]



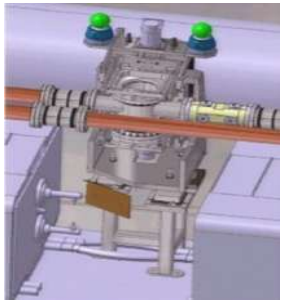


- LUCID (Cerenkov Tubes): 17 m, 5.4 < |η| < 6.1
  Relative luminosity

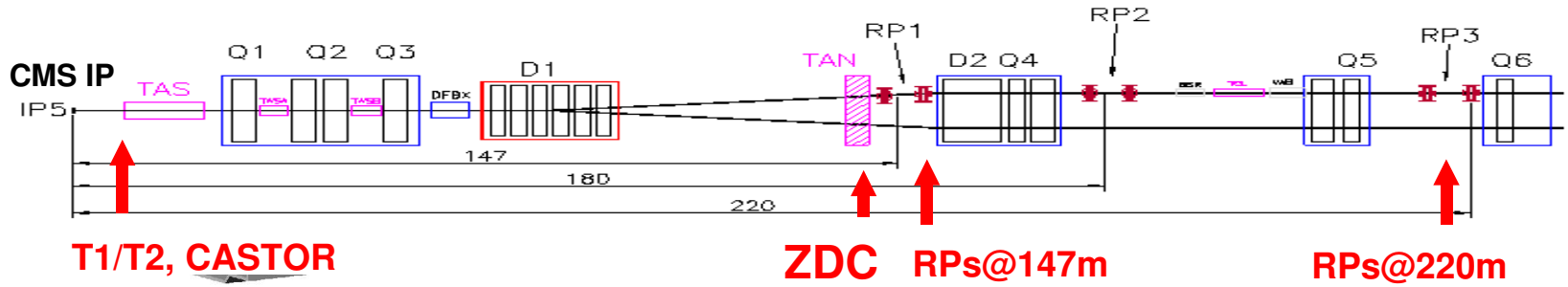
- ZDC (W/Q-fiber calo): 140m, |η| > 8.3 (neutral)
  n,γ detection: relative lumi, CRs, heavy-ions
  (L1 trigger, centrality, photoprod, ...)



- ALPHA (Sci-Fi in RPs): 240 m.
  Abs. lumi (elastic scatt. in Coulomb interf. region)

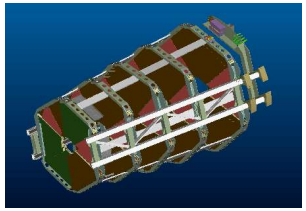


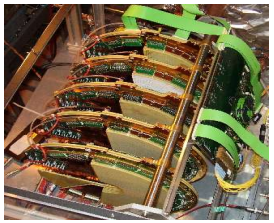
CMS+TOTEM forward detectors



- TOTEM-T1 (CSC telescope): $3.1 < |\eta| < 4.7$
- TOTEM-T2 (GEM telescope): $5.3 < |\eta| < 6.7$

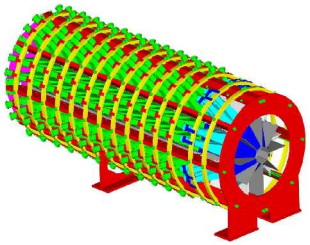
  Soft diffraction (SD,DPE), MB/UE/MPI

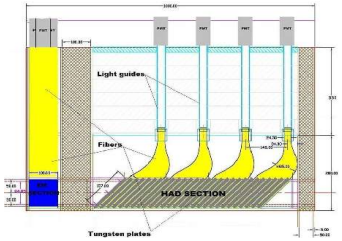




- CASTOR (W/-Q-fiber calo): $5.3 < |\eta| < 6.5$

  Miss.-E_T, diffract., low-x QCD, MB/UE/MPI, heavy-ions (L1 trigger, centrality, ...), CRs



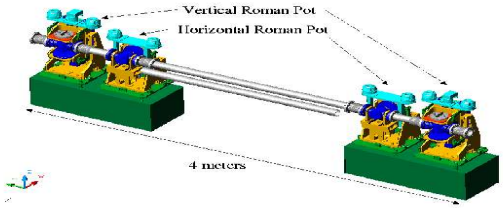


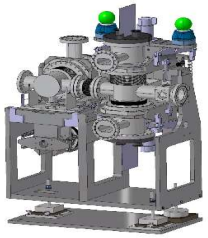
- ZDC (W/Q-fiber calo): $|\eta| > 8.3$ (neutral)

  CRs, heavy-ions (L1 trigger, centrality, γ-A, ..

- TOTEM Roman pots: 147, 220 m

  Leading p: σ_{tot}, elastic scatt., diffraction

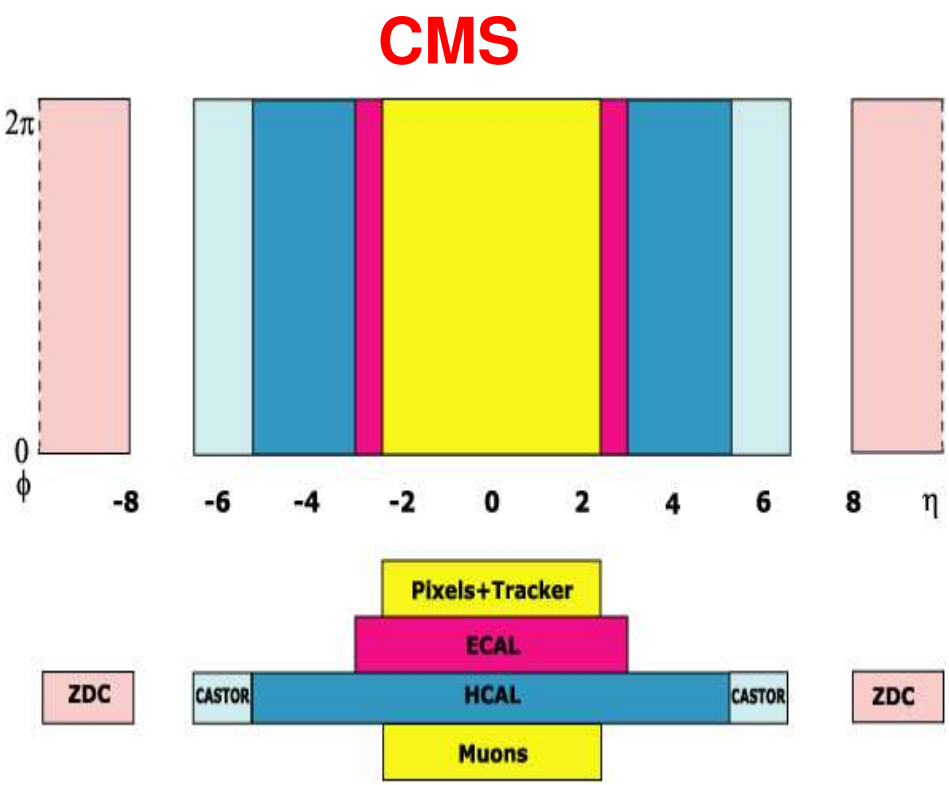


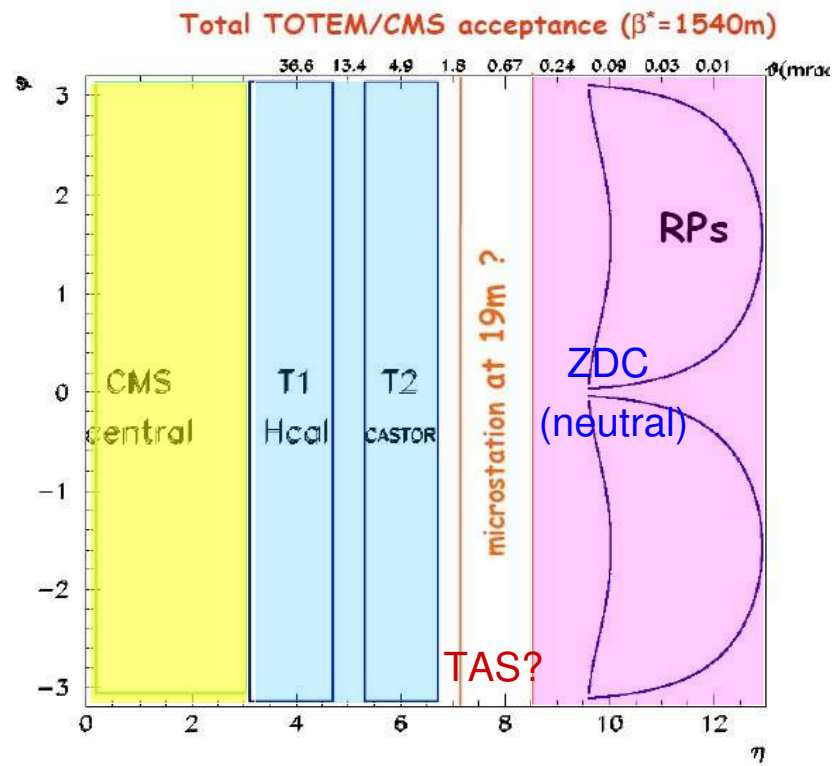


CMS+TOTEM forward detectors

[cf. K.Borras talk]

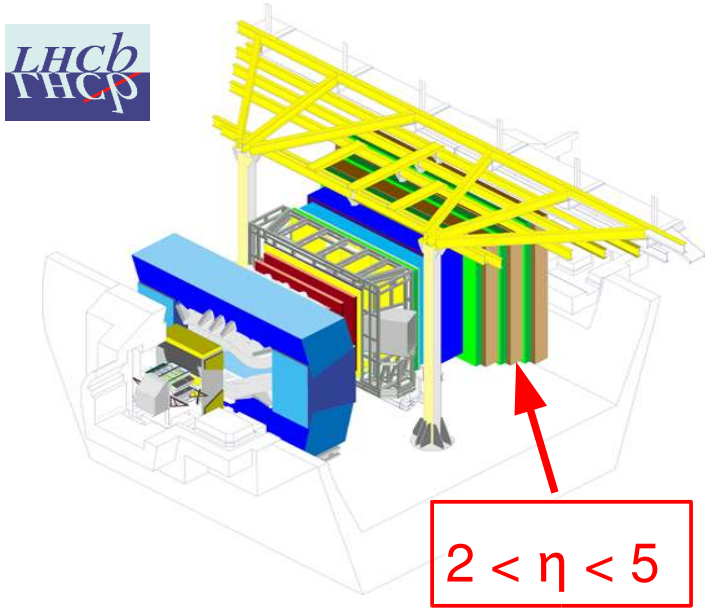
- CMS (central,CASTOR,ZDC)+TOTEM: largest acceptance ever at a collider



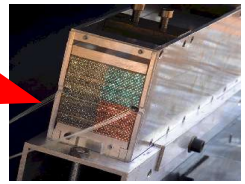


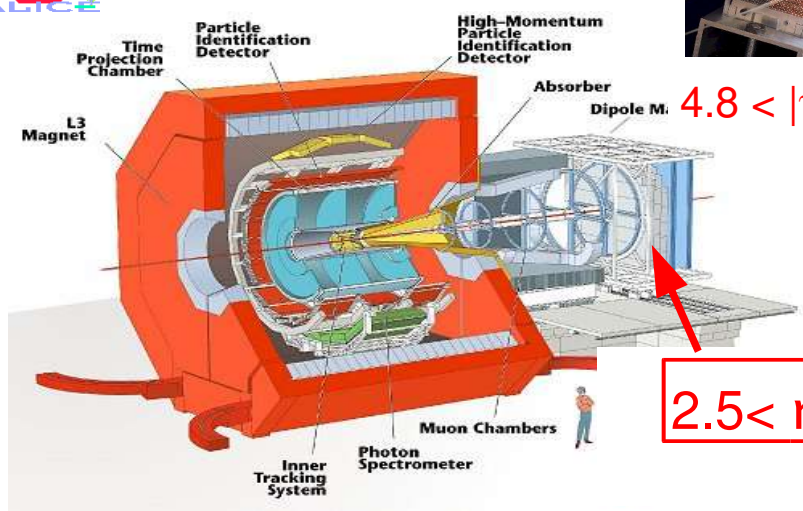
ALICE & LHCb forward detectors

- Forward muon spectrometers:



ZDCs also at 7m,100m

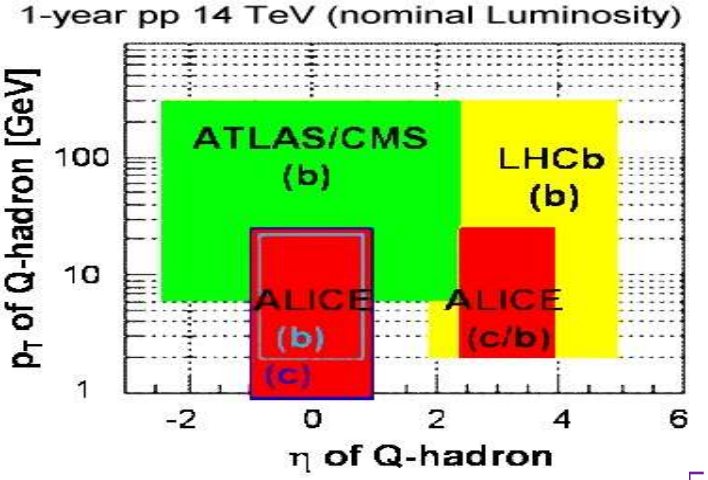




4.8 < |η| < 5.7

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

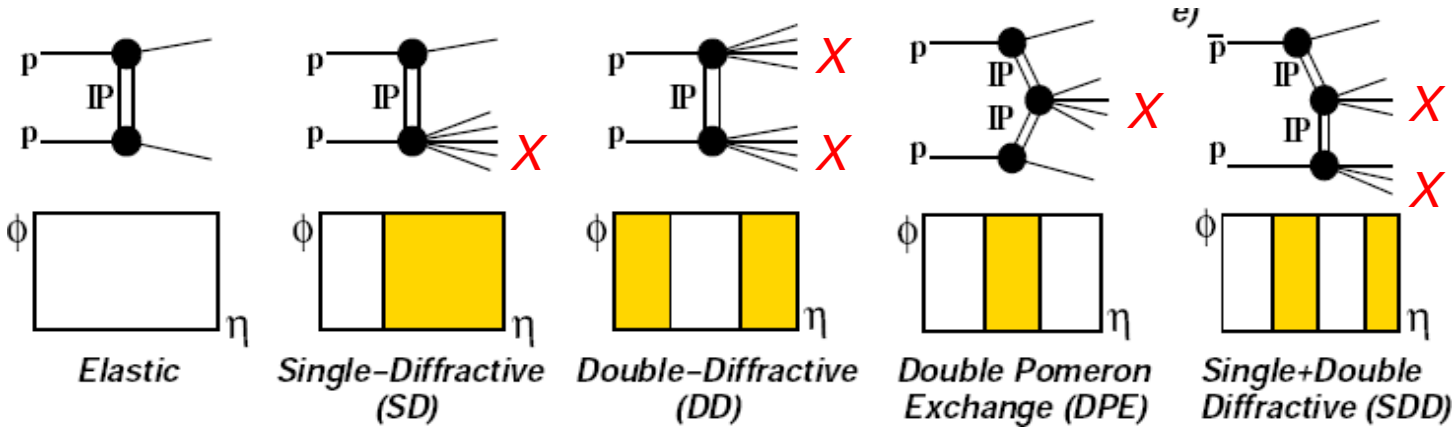
(low-x PDFs)



Diffractive physics

Pomeron-induced processes

- Diffractive scattering (~25% p-p σ_{tot}): p intact (Roman Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:



- Soft diffraction:

  X = anything : dominated by soft QCD → SD, DPE vs. s, t, M_X provide valuable info of non-perturbative QCD. Min. bias p-p. Contributions to pile-up p-p events

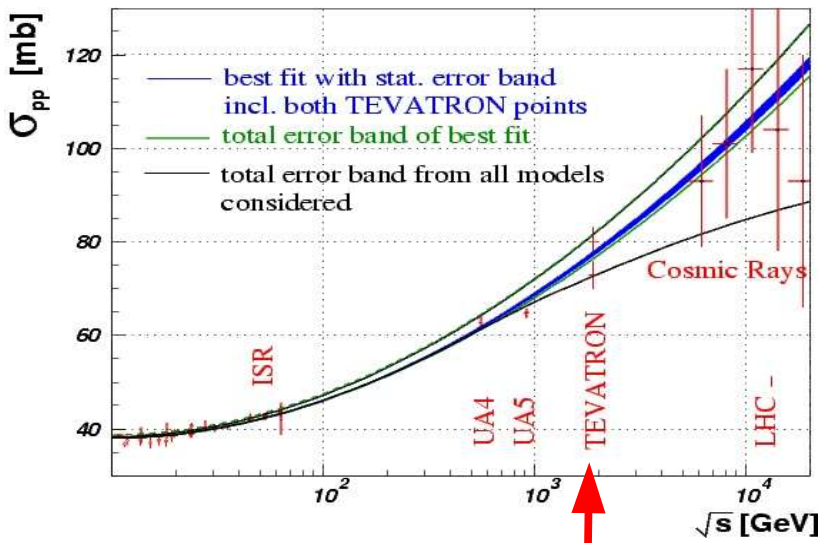
- Hard diffraction:

  X = jets, W's, Z's ... calculable in pQCD → Info on proton structure (dPDFs and GPDs), multi-parton interactions, discovery physics (DPE Higgs, beyond SM)

Total p-p cross section, elastic scattering

[cf. K.Eggert talk]

- σ_{tot} predictions for LHC vary by $^{+10}_{-20}$ %.



E710/811–CDF 2.6σ disagreement

COMPETE extrapolation for LHC:

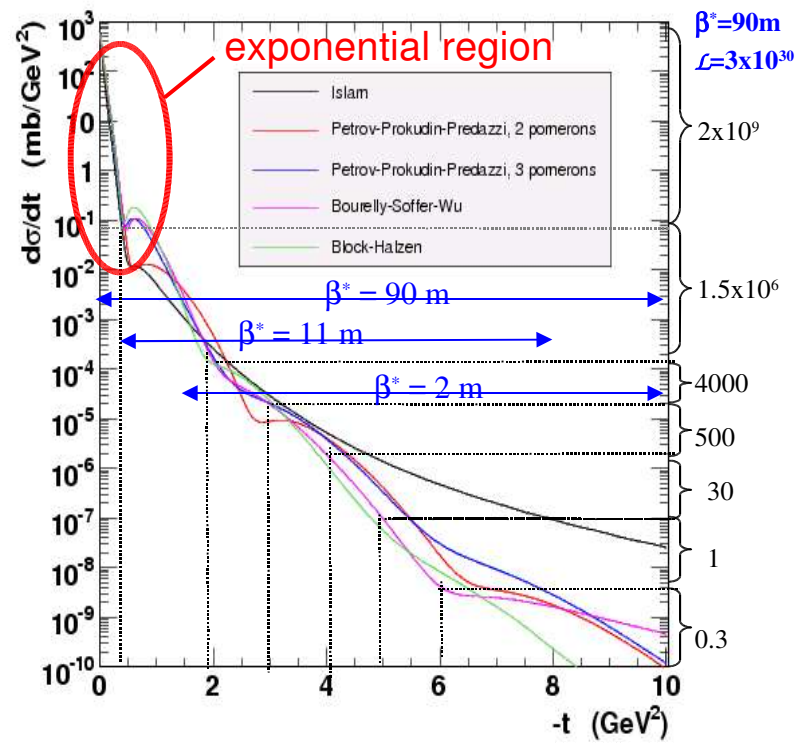
$$\sigma_{tot} = 111.5 \pm 1.2 \; ^{+4.1}_{-2.1} \; \text{mb}$$

- TOTEM goal: ~1% precision

(for β* = 1500m)

- Luminosity measurement via optical theorem:

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el} + N_{inel}}$$



β* = 90m optics needed (acceptance at low |t|)

Higgs (and new) physics

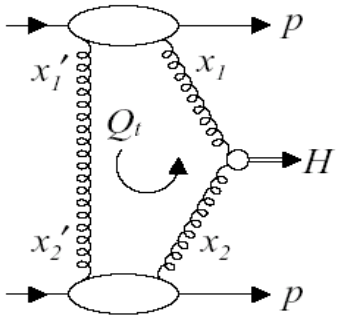
Exclusive DPE Higgs: FP-420 project

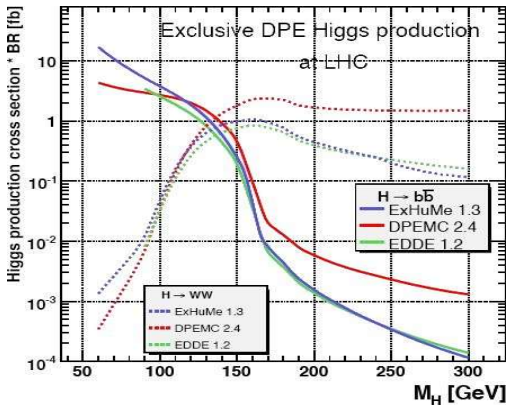
[cf. C.Royon & A.Pilkington talks]

- Exclusive central Higgs production: $pp \to p\,H\,p$

σ_H = 3-10 fb (SM), x10(0) in MSSM

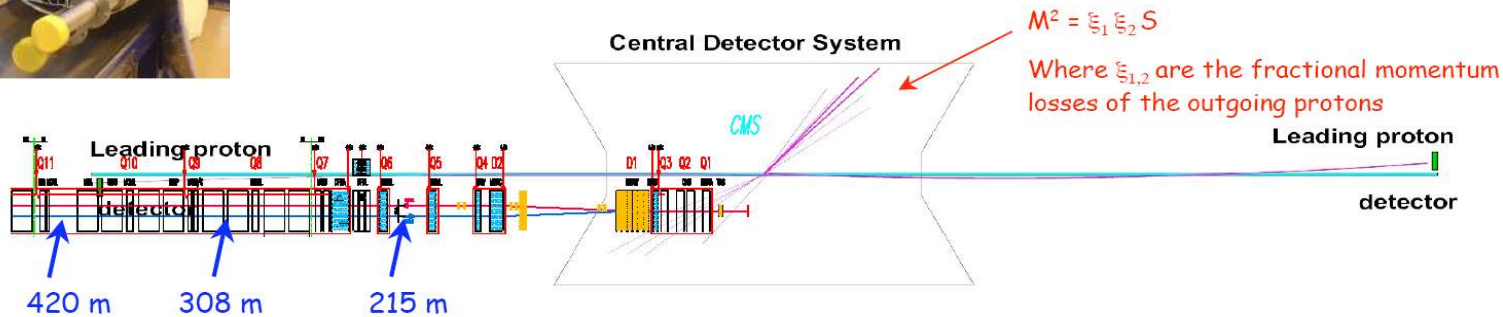
- High precision m_H (p time diff.)
- Quantum numbers ($J^{PC} = 0^{++}$ rule)





- For m_H<200 GeV, need acceptance for proton tagging at 420 m
- FP420 R&D collaboration (report 1st-half '07, ATLAS/CMS to decide):

Novel technologies: (i) moving beampipe, (2) Fast (τ ~10 ps) Cerenkov dets.: GASTOF (gas), Quartic (Quartz)



Low-x QCD physics

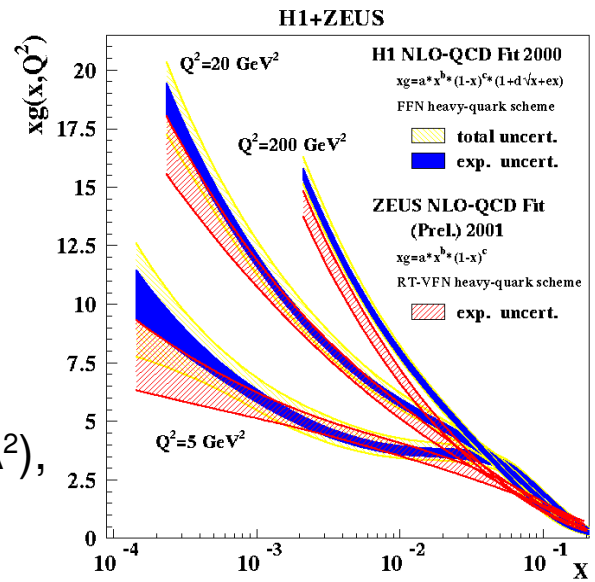
Parton saturation & evolution at low-x

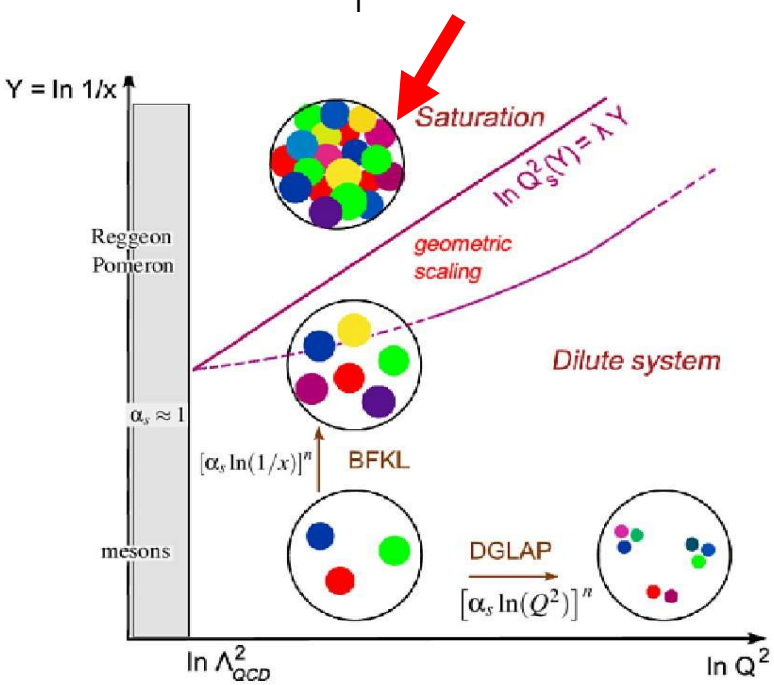
- Strong rise at low-x of gluons (HERA):
- Radiation controlled by QCD evolution eqs.:

Q^2 - DGLAP: $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV^2

x - BFKL: $F_2(x) \sim \alpha_s \ln(1/x)^n$

Linear equations (single parton radiation/splitting) cannot work at low-x: Unitarity violated (even for $Q^2 >> \Lambda^2$), collinear & k_T factorization invalid





- Gluon-gluon fusion balances parton branchings below "saturation scale": $Q_s^2 \sim [1\text{GeV}]^2 \cdot e^y$ (LHC)
- Enhanced in nuclei ($A^{1/3} \sim 6$) : $Q_s^2 \sim [5\ \text{GeV}^2] e^{(0.3y)}$
- CGC = effective-field theory describes hadrons as classical fields below Q_s
- Non-linear JIMWLK/BK evolution eqs.

[cf. R. Venugopalan talk]

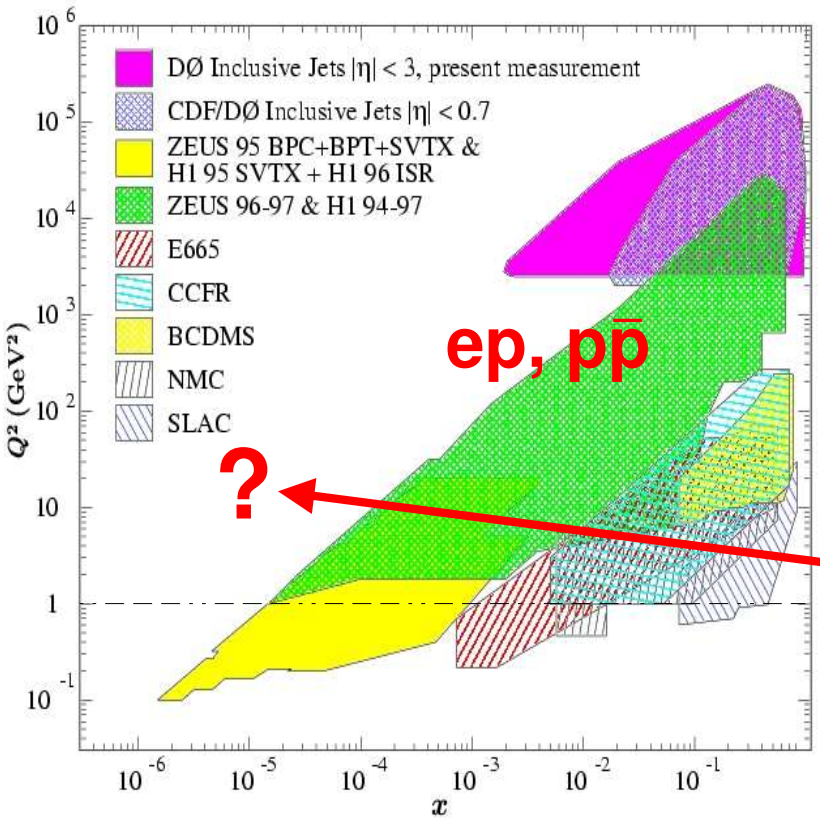
Low-*x* proton PDF studies

- pp @ 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 GeV^2 (y=0), 3 GeV^2 (y=5)

(iii) Very large perturbative cross-sections:



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

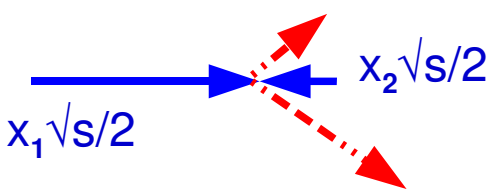
$p(p_1)+p(p_2)\to l\bar{l}+X$ Drell-Yan

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

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

$p(p_1)+p(p_2)\to W/Z+X$ 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

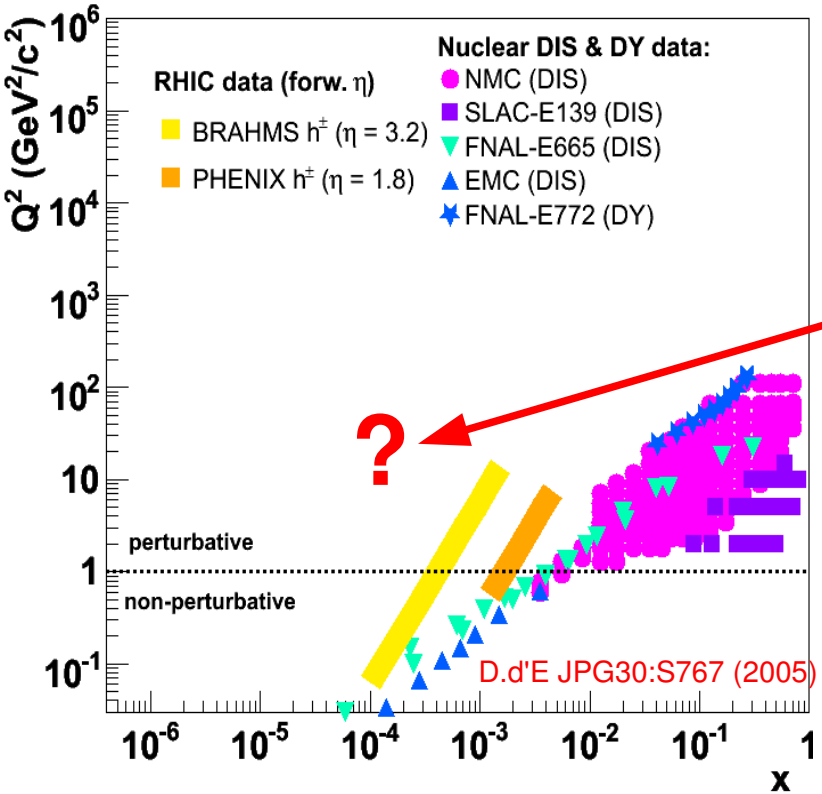
Low-*x* nuclear PDF studies

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:

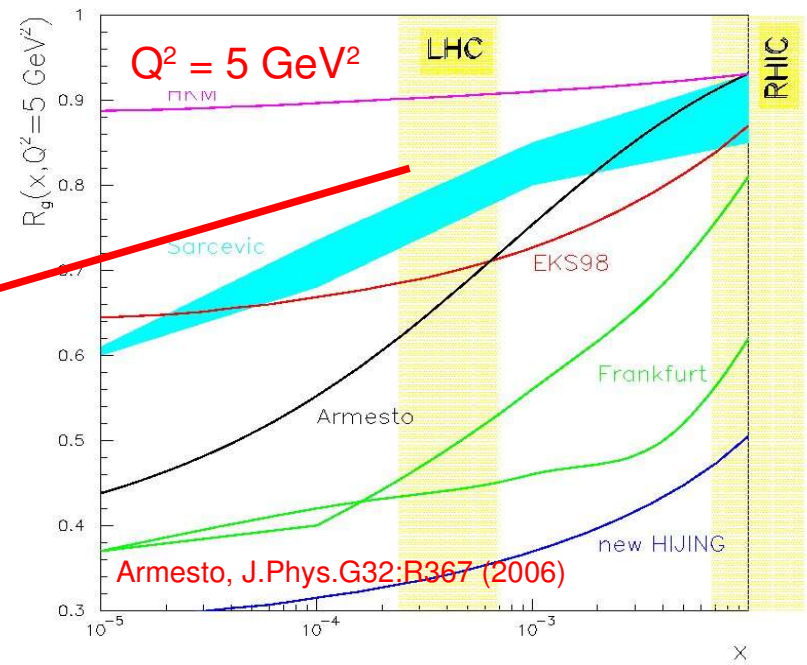
  (i) Very high $\sqrt{s}$ $\Rightarrow$ Bjorken $x=2p_T/\sqrt{s}$~30-45 times lower than AuAu,dAu @ RHIC !

  (ii) Saturation momentum ($A^{1/3}$~6) : $Q_s^2 \sim [5\ \mathrm{GeV}^2]e^{(0.3y)}$

  (iii) Very large perturbative cross-sections.



Ratio of Pb/p gluon densities:



Nuclear $xG(x,Q^2)$ basically unknown for $x<10^{-3}$!

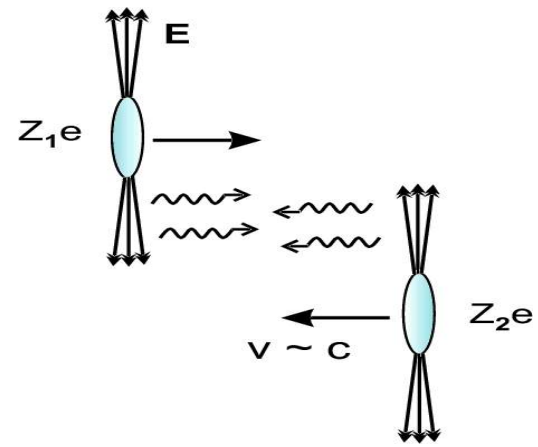
Case-study I: ϒ photoproduction in CMS (Pb-Pb)

[Dd'E, hep-ex/0703024]

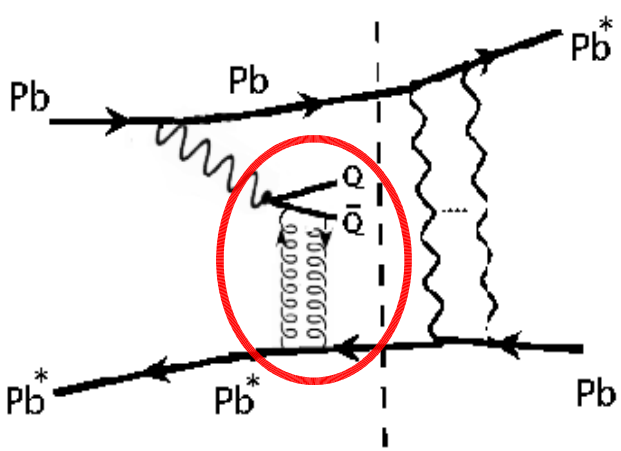
- High energy heavy-ions produce strong electromagnetic fields due to the coherent action of Z_{Pb} = 82 protons:
- Equivalent flux of photons in EM (aka. Ultra-Peripheral, $b_{min} \sim 2R_A \sim 20$ fm) AA colls.:

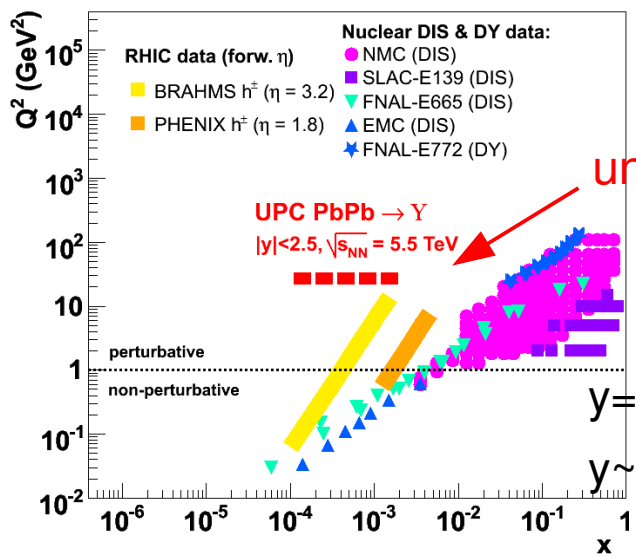
  Max. γ energy: $E_{\gamma max} \sim 80$ GeV (PbPb-LHC)

  γ Pb: max. $\sqrt{s_{\gamma Pb}} \approx 1.$ TeV $\approx$ 3. - 4. × $\sqrt{s_{\gamma p}}$(HERA)



- $Q\bar{Q}$ diffractive photoprod. (ZDC n-tagging) sensitive to $|xG|^2$





[cf. T.Teubner talk]

unexplored $xG_A(x,Q^2)$

y=0: $x(\Upsilon) = 2 \cdot 10^{-3}$

y~2: $x(\Upsilon) \sim x(y=0) \cdot e^{-y} \sim 10^{-4}$

Case-study I: ϒ photoproduction in CMS (Pb-Pb)

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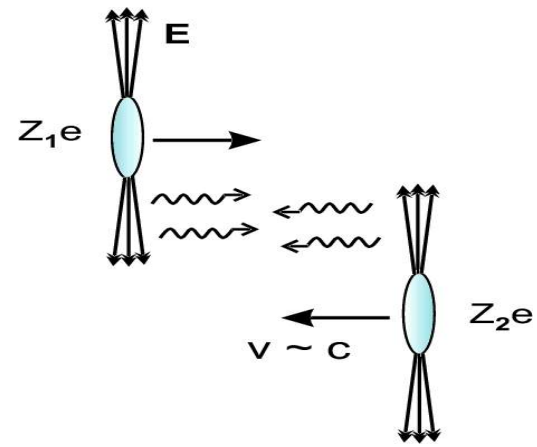

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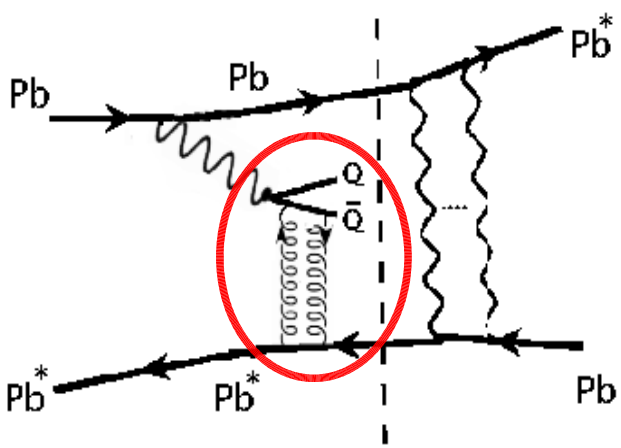
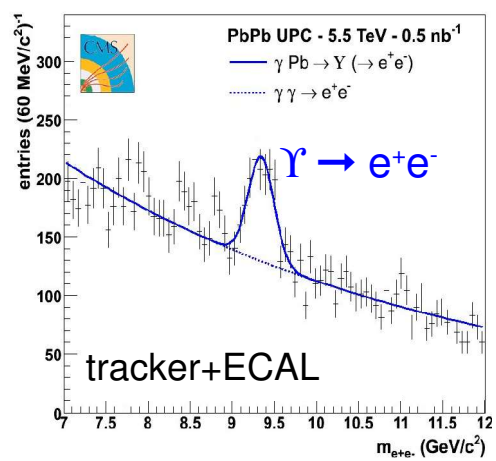
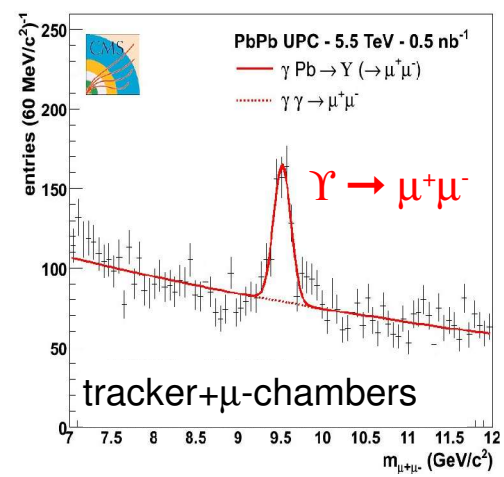


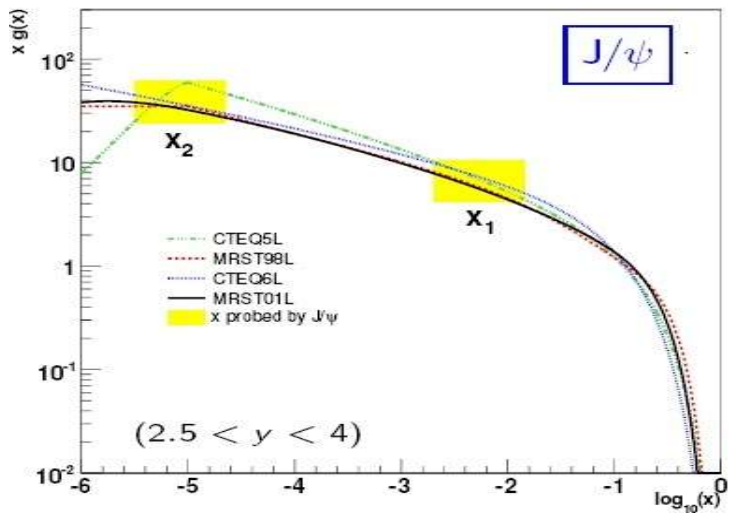


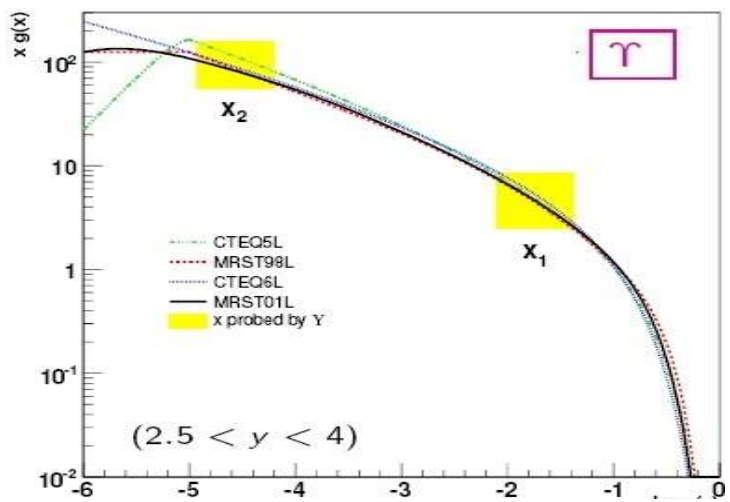


~500 ϒ/0.5 nb^{-1} expected in CMS

Case-study II: Forward $Q\bar{Q}$ in ALICE (p-p)

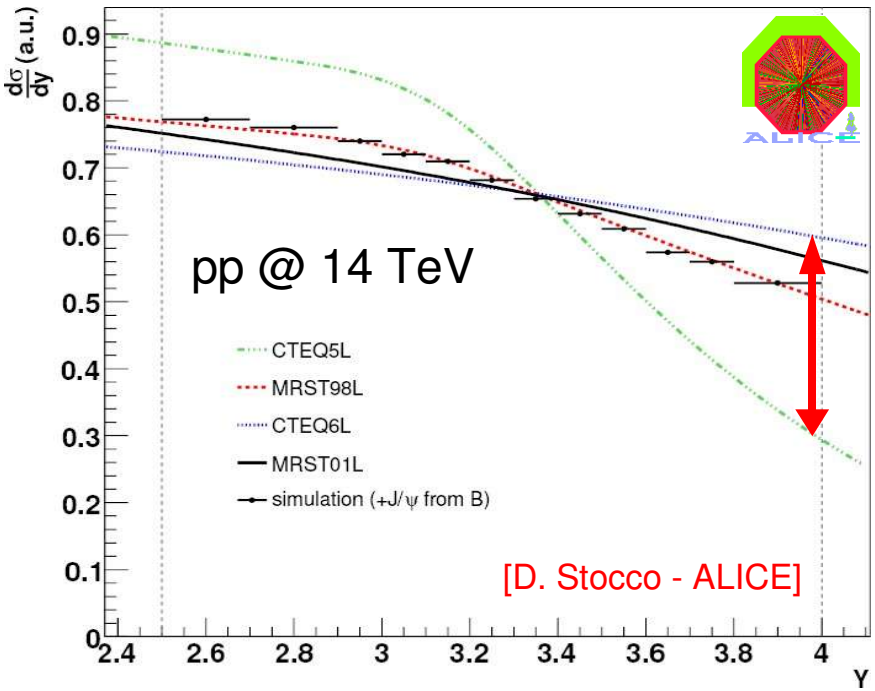
- J/ψ measurement in μ-spectrometer (2.5 <|η|< 4): xg(x) at $x_2 \sim 10^{-5}$





$\log_{10}(x)$

dσ/dy J/ψ: NLO CEM w/ varying PDFs



QQbar: Sensitive to diff. PDFs

and DGLAP vs non-linear evolutions

Case-study III: Forward (di)jets in CMS (p-p)

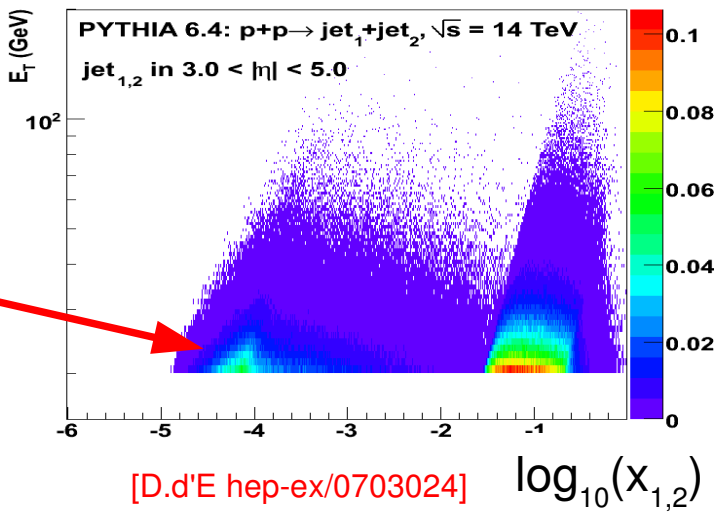
- Forward "soft" jets (E_T ~20-100 GeV):

  $p + p \rightarrow jet1 + jet2 + X$ (VBF-Higgs trigger)

  Jets in HFs sensitive to : $x_2 \sim 10^{-4}$

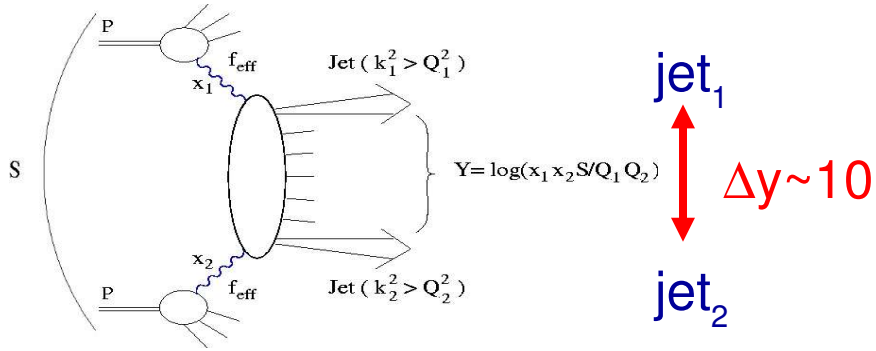
  Jets in CASTOR (5.3 <|η|< 6.6): $x_2 \sim 10^{-6}$!

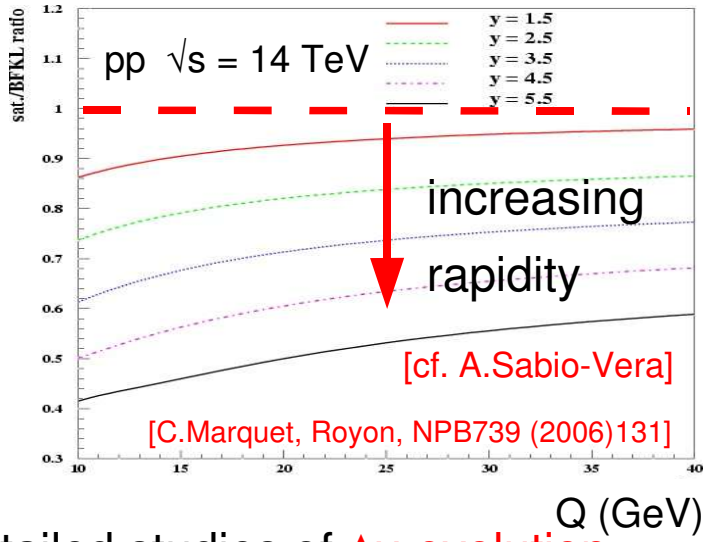
  Stats. ~10^7/1 pb^{-1}, large? jet reco systematics



[D.d'E hep-ex/0703024]

- Mueller-Navelet dijets separated by large Δy: very sensitive to non-DGLAP evolution



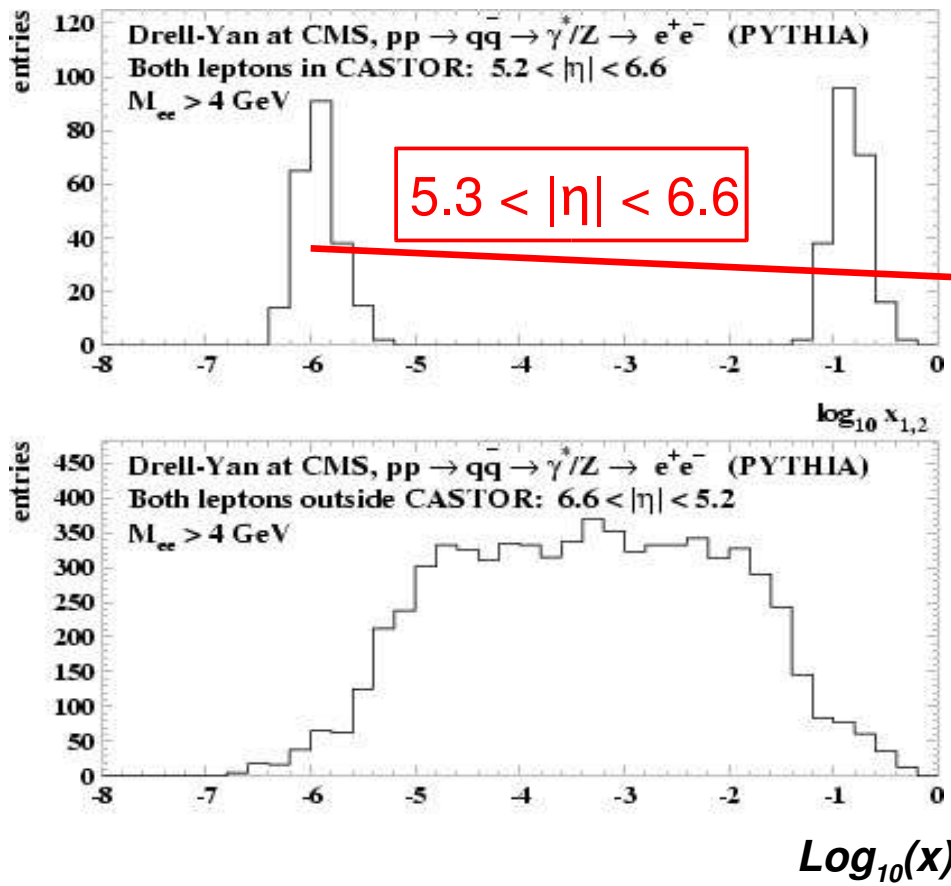


~10^4 dijets ($HF^{\pm}$,E_T>30 GeV): enough stats. for detailed studies of Δy-evolution

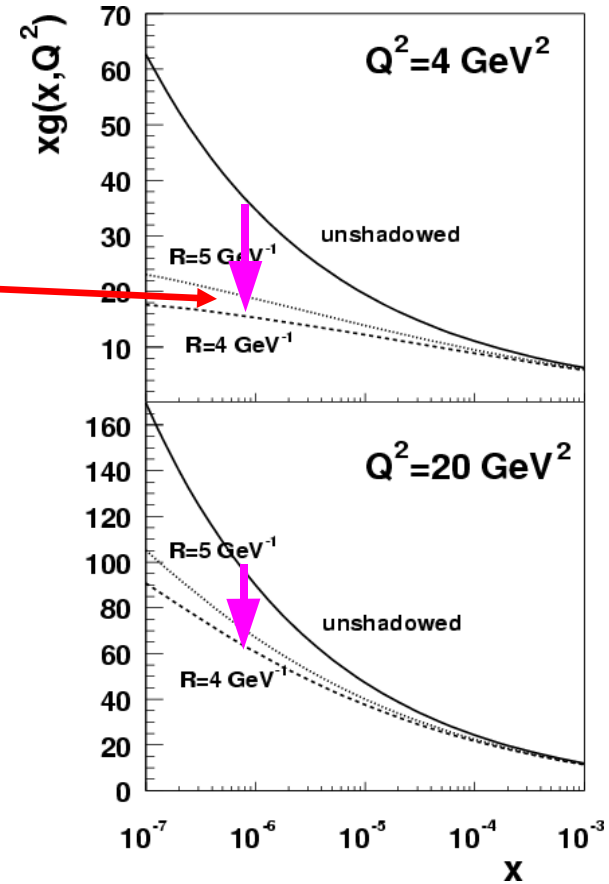
Case-study IV: Forward DY in CMS (p-p)

[cf. K.Borras talk]

- Drell-Yan feasibility studies with CMS (CASTOR) + TOTEM (T2):
- Sensitive to low-x quark densities



PDF parametrizations

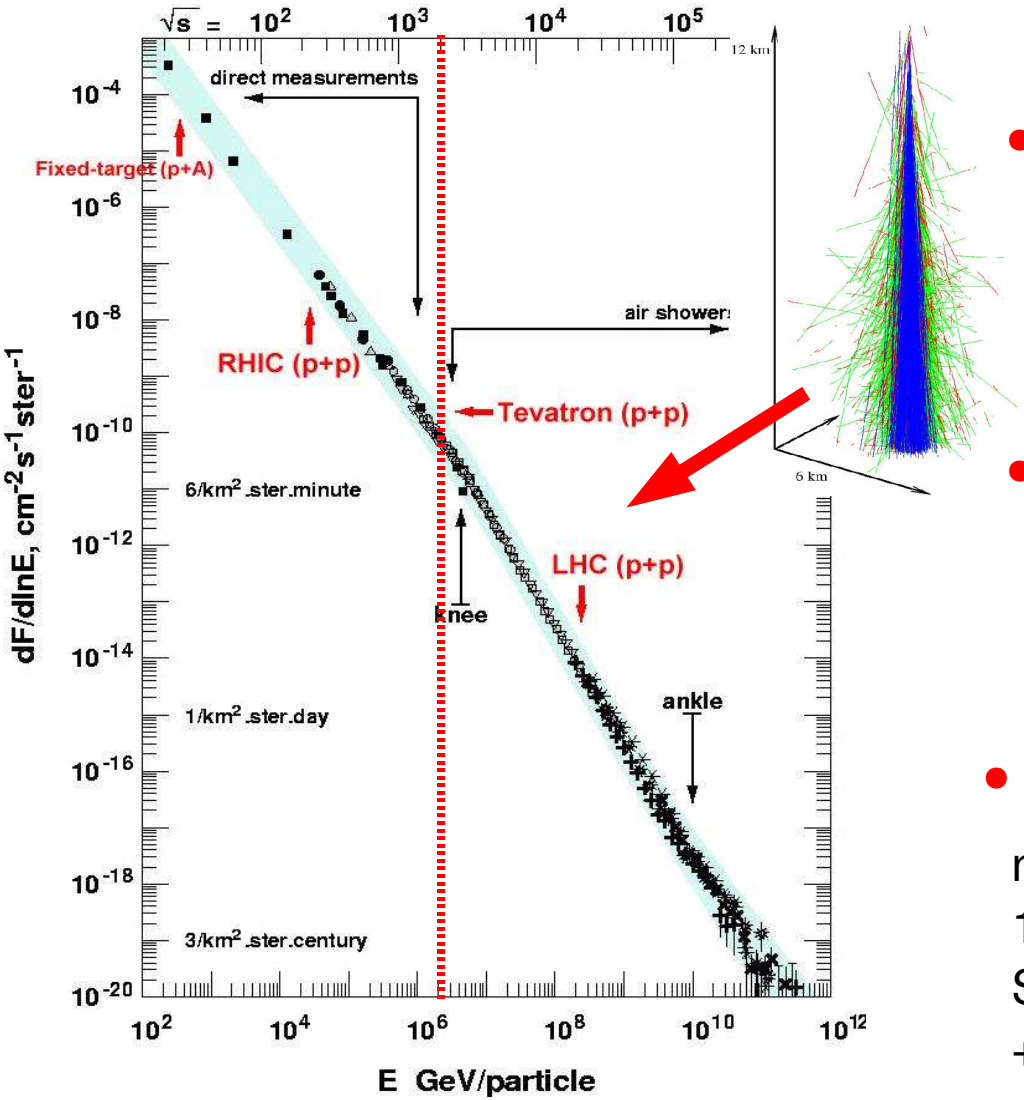


TOTEM T2 tracker+ CASTOR needed to deal w/ large QCD (& QED) bckgd

Cosmic-rays physics

UHE cosmic-rays via extended air-showers

- Cosmic-ray energy spectrum:

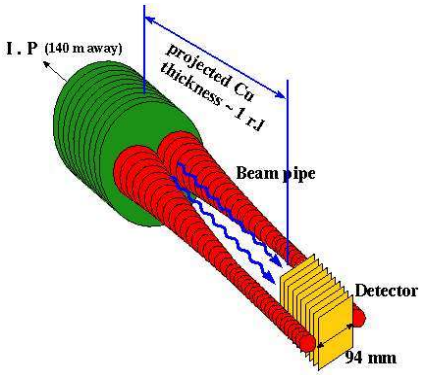


- Only "indirect" measurements (EAS) above E_{lab} ~100 TeV
- CR energy & mass determined via hadronic MC simulations: Shower development dominated by fwd, soft QCD interactions.
- Uncertain x10^6 extrapolations from SppS,Tevatron to GZK limit.

LHC: $\sqrt{s}$ = 14 TeV $\Leftrightarrow$ $E_{lab} = 10^{17}$ eV

- LHCf experiment:

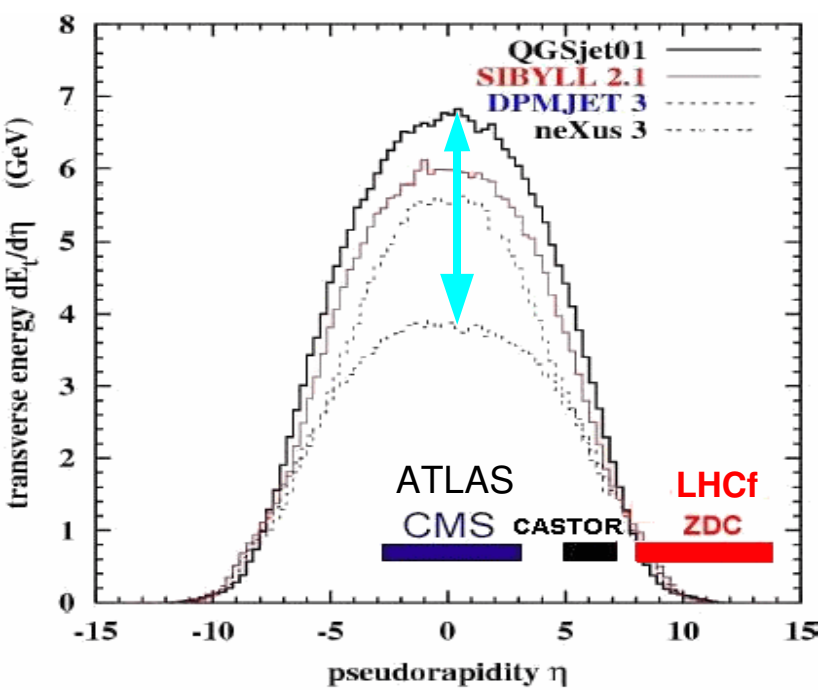
n,γ detection
140 m from IP2
Sci-fiber/W calo
+Silicon strip det.

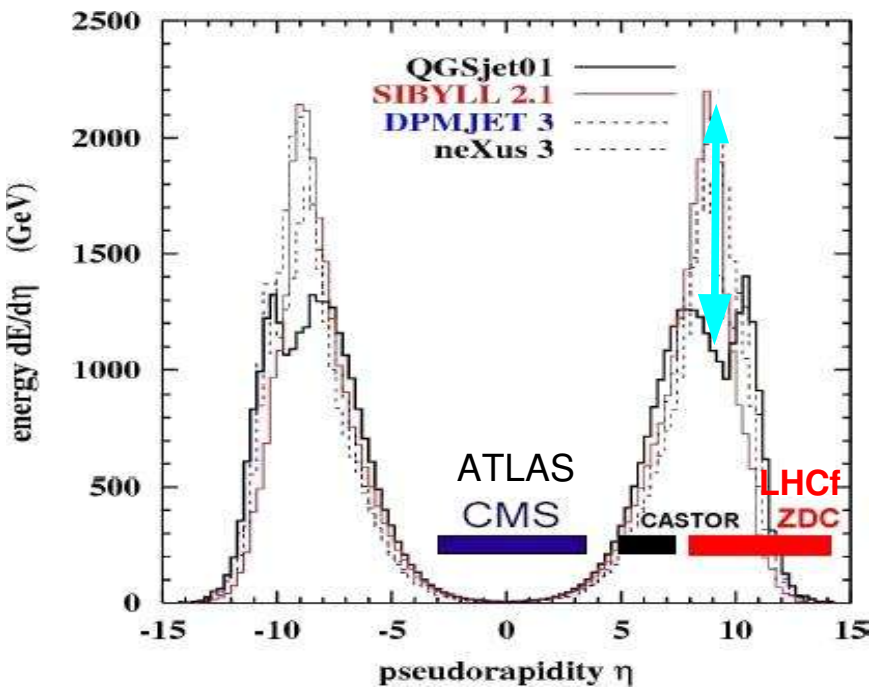


Calibration & tuning of hadronic models

- Model predictions of particle multiplicity & energy flow at LHC differ by up to a factor ~2:

[R.Engel]





- ZDCs,LHCf: Measurement of fwd dN/dη,dE/dη leading baryon (n), neutral meson (π^0,K^0_s) in pp, pA, AA at E_{lab}~100 PeV: Strong EAS model constraint

[CRs collisions: p-Air, α-Air, Fe-Air]

Cosmic-rays "exotica"

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

  (i) anomalous number of (N~0) electromagnetic secondaries } "strangelets"?

  (ii) forward "long-flying" (i.e. non-interacting) component } "DCCs"?

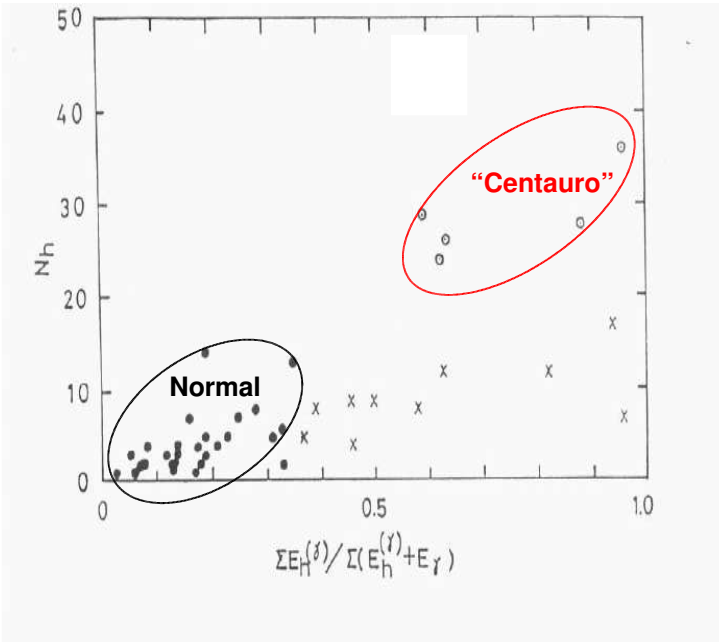
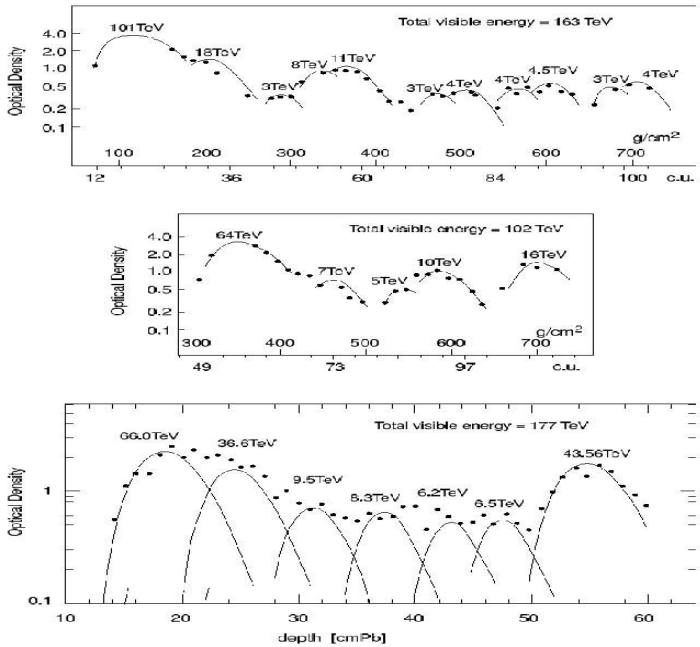


Figure 2.5: Diagram of the number of hadrons and hadronic energy fraction: Chacaltaya events with the total visible energy greater than 100 TeV [38]: (o) Centauro, (×) Mini-Centauro, (•) others; (⋆) C-K [36].



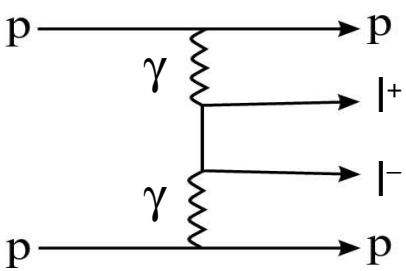
CMS-CASTOR (longitud. segmentation) can access this research programme.

EWK (γ-γ,γ-W,....) physics

Two-photon, γ-W interactions

[K.Piotrzkowski, CMS]

- Exclusive l^+l^- (e^+e^-,$\mu^+\mu^-$) production



(e^+e^- in T2/CASTOR)

($\mu^+\mu^-$ in muon-chambers)

(fwd. proton in RPs)

QED process: σ known precisely (LPAIR)

Signature: back-to-back leptons

RPs: reco of proton ξ w/ resol. of 10^{-4}

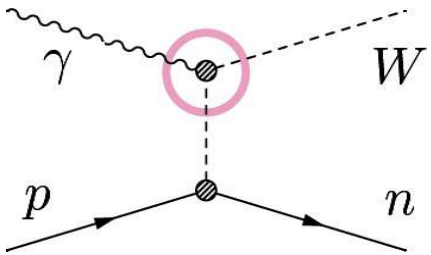
~300 evts./100 pb^{-1} after CMS μ trigger

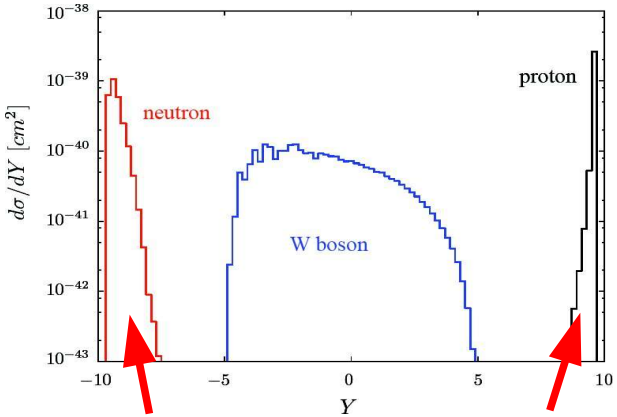
- Absolute p-p luminosity within ~3% (theo)
- Cross-calibration of near-beam dets.

[U.Dreyer, ECT*-UPC-Workshop]

- W-photoproduction:

Triple (anomalous?) gauge couplings





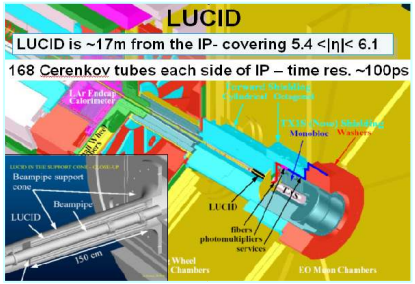
n,p tagging in ZDC/RPs

~50 evts./100 pb^{-1} in p-p 14 TeV

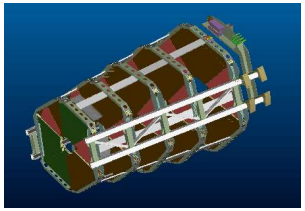
[Also quartic couplings via $\gamma\gamma \to WW,ZZ$]

Summary: forward instrumentation @ LHC

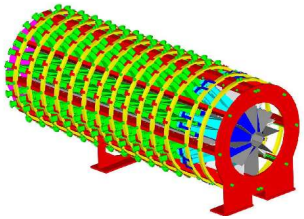
LUCID



TOTEM T1

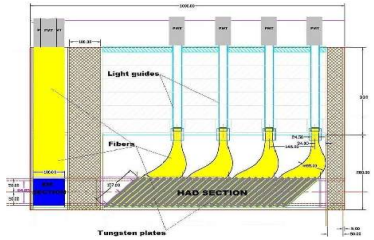


CASTOR

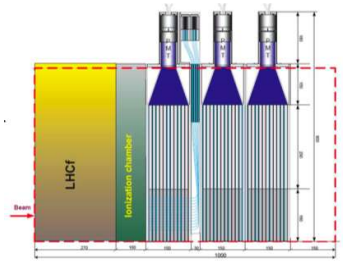


TOTEM T2

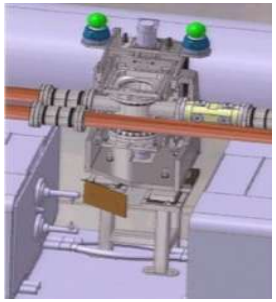
CMS ZDCs



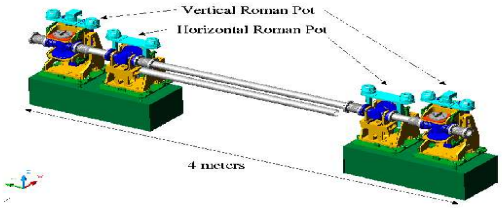
ATLAS ZDCs

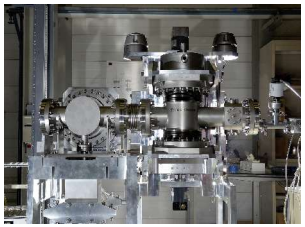


ALFA

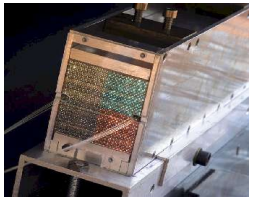


TOTEM RPs

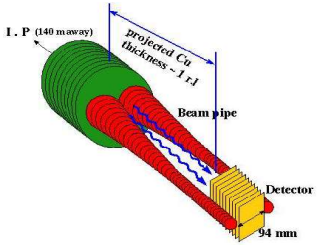




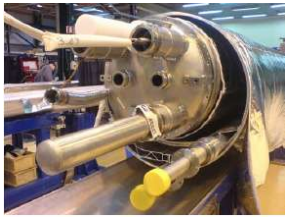
ALICE ZDCs



LHCf

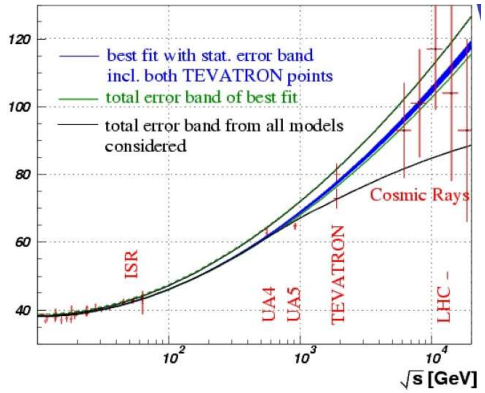


FP420

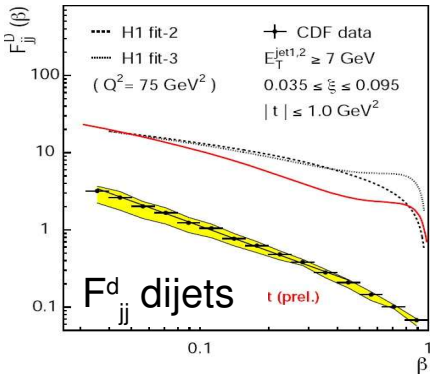


Summary: forward physics @ LHC

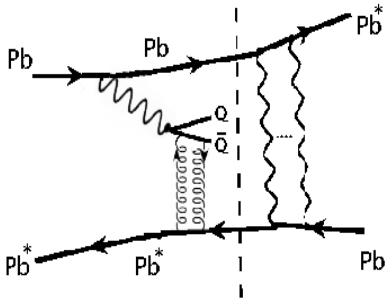
p-p σ_{tot}, elastic scatt.



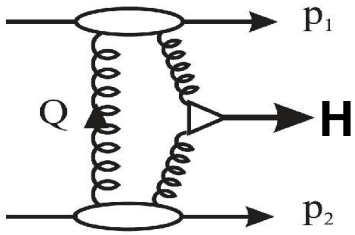
hard diffraction



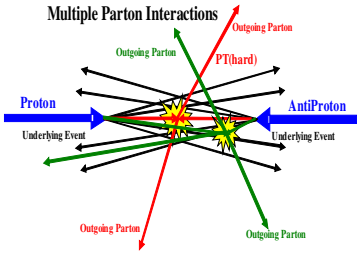
VM photoprod.



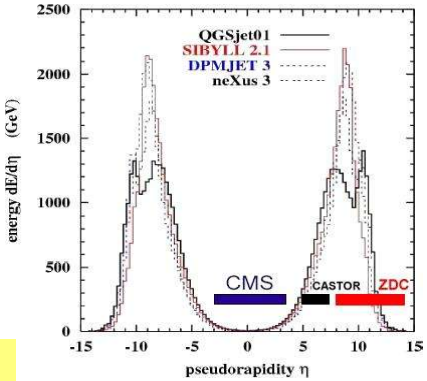
exclusive Higgs



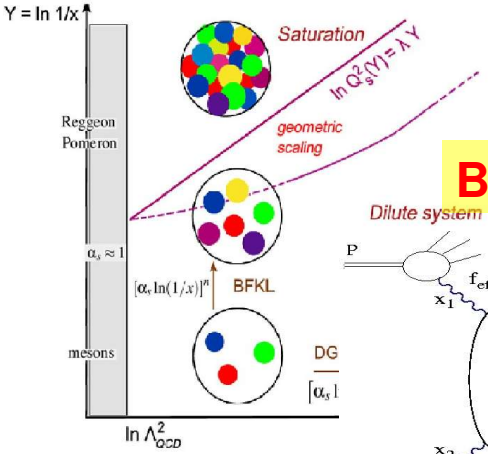
MB/UE/MPI



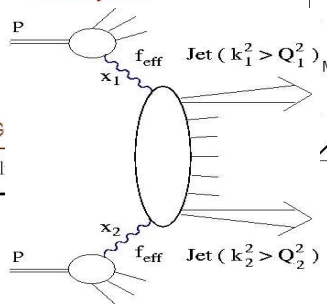
cosmic-rays



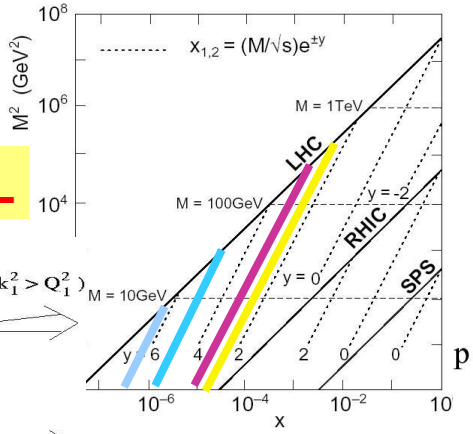
gluon saturation, CGC



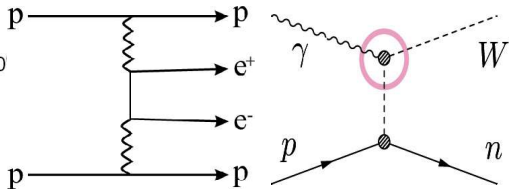
BFKL

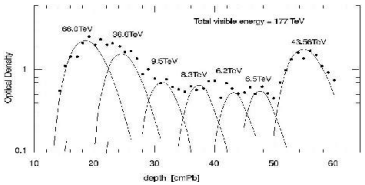


low-x PDFs



QED (γ-γ,γ-W,...)

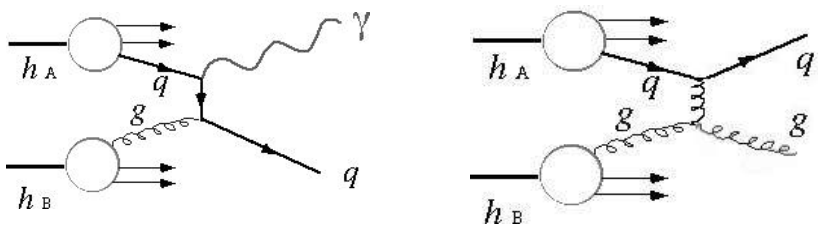




Backup slides

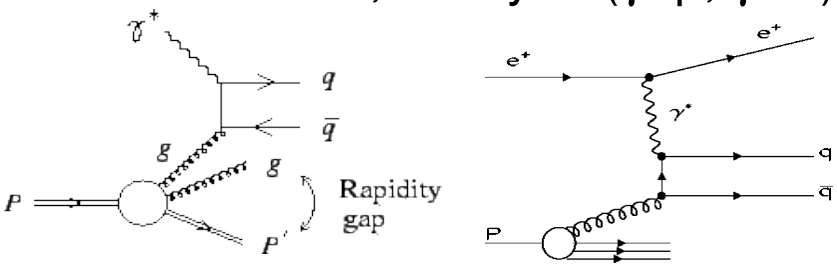
Experimental probes of gluon PDF ($\gamma^{(*)}$p,pp,$\gamma^{(*)}$A,AA)

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

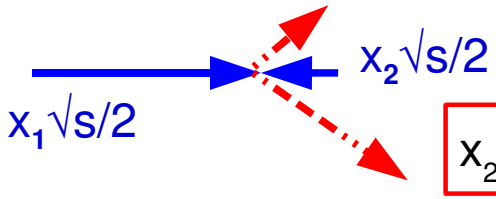


..

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

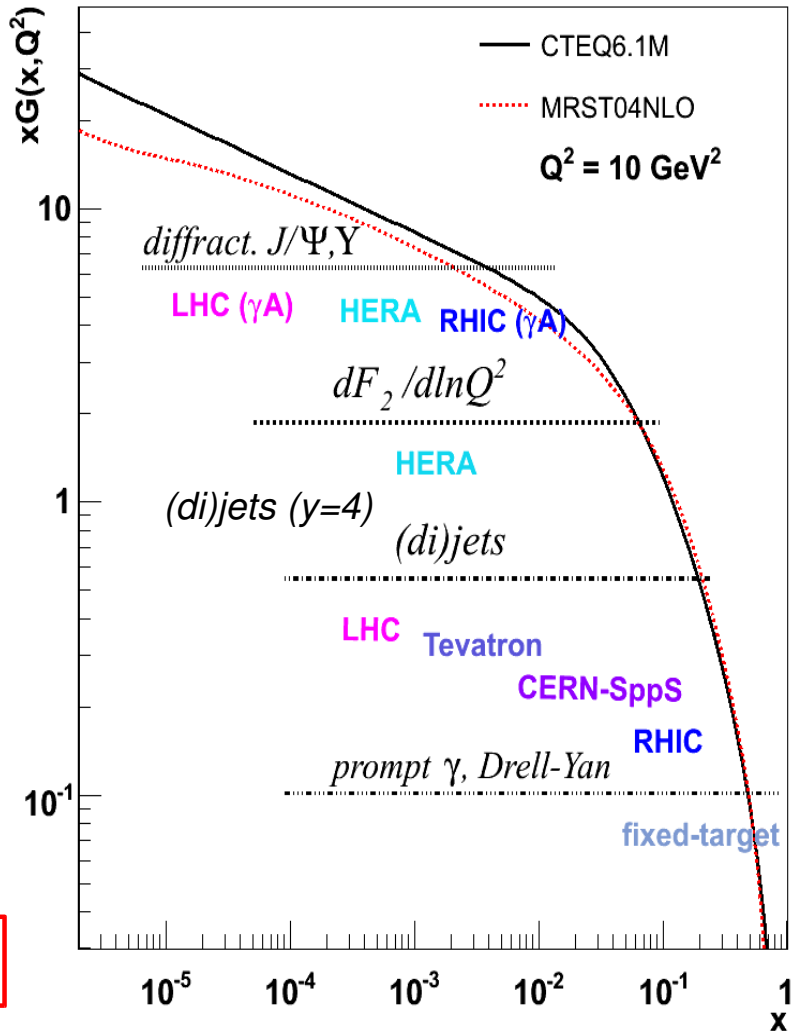


- Forward production:



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

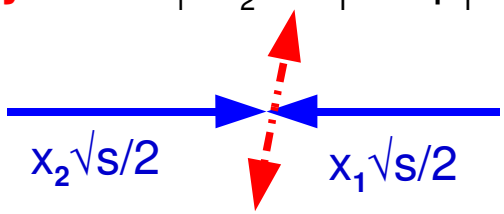
Every 2-units of y, x^{min} decreases by ~10



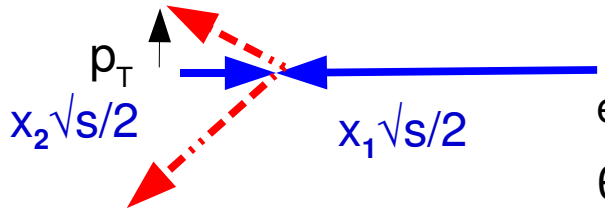
Small-*x* → Forward rapidities

- 2 → 2 parton kinematics:

  y = 0: $x_1 \sim x_2 \sim x_T = 2p_T/\sqrt{s}$



$$x_{1,2}^{2\to 2} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y} + e^{\pm y'}\right) \Rightarrow x_2^{min} = \frac{x_T\, e^{-\eta}}{2 - x_T\, e^{\eta}}$$



e.g. LHC, p_T = 10 GeV/c

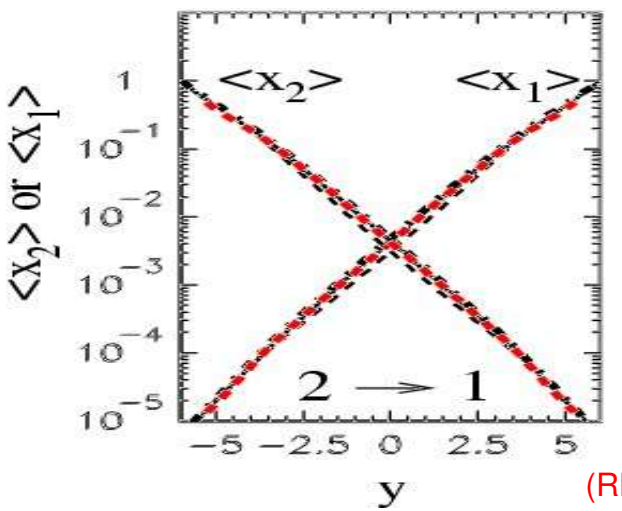
$\theta \sim 10^{-3}$ ($\eta \sim 7$): $x_{min} \sim 10^{-6}$

- 2 → 1 (gluon fusion) CGC kinematics: much lower *x* allowed ($x_2 \sim x_2^{min}$)

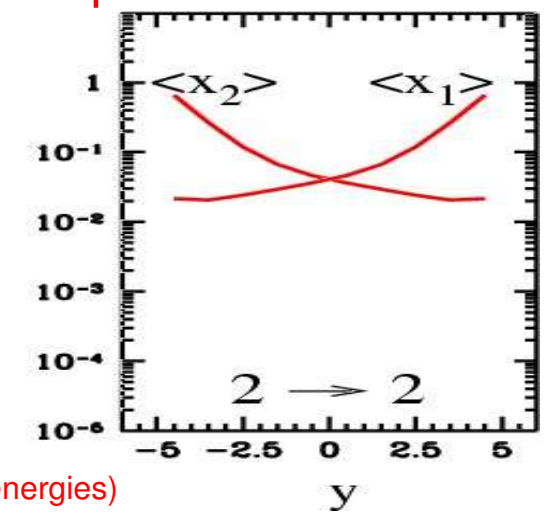
$$x_{1,2}^{2\to 1} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y}\right)$$

Every 2-units of y, x_2 decreases by ~10

CGC: x(y=4) ~ 10^{-4}



pQCD: x(y=4) ~ 10^{-2}



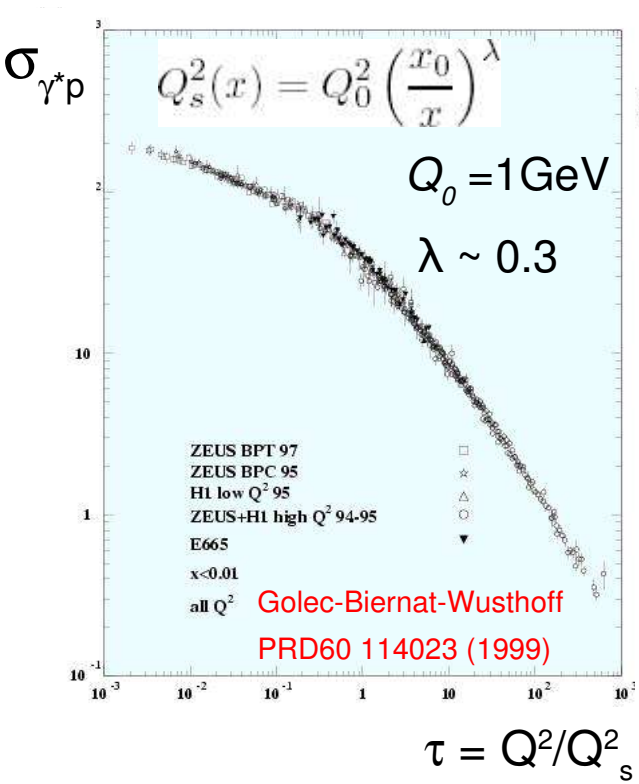
(RHIC energies)

[Accardi,nucl-th/0405046]

Saturation hints at HERA ?

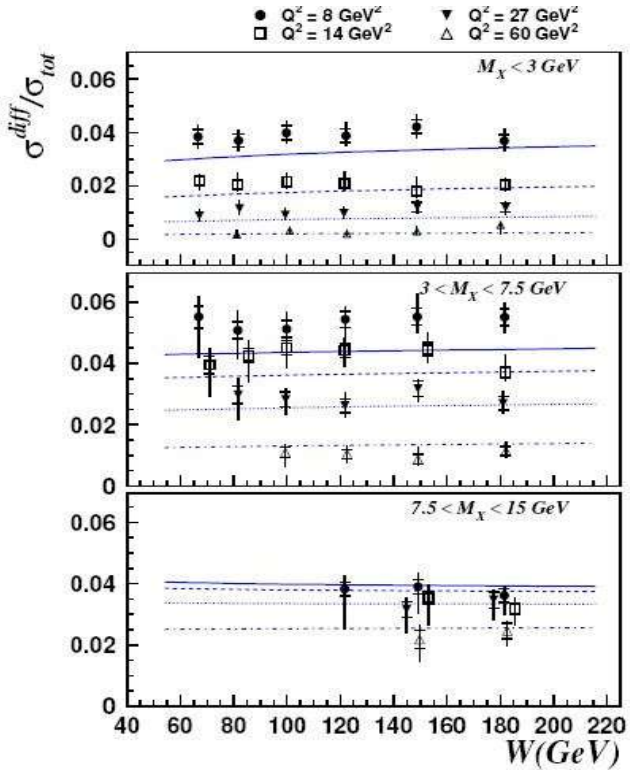
- DGLAP fits most of ep data ... Saturation models explain better a few cases:

"Geometric scaling"



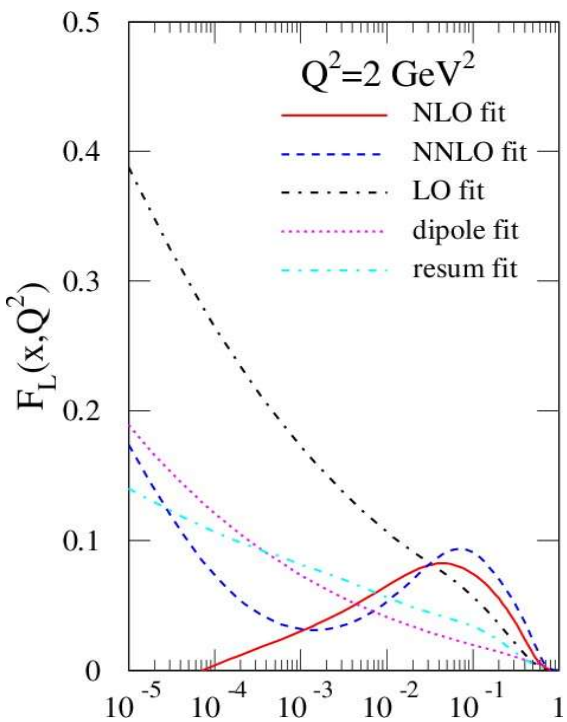
Inclusive DIS x-section depends on single scale Q^2/Q_s^2 for $x < 0.01$

flat $\sigma_{diffract}/\sigma_{tot}$ vs energy



Diffract. & total x-sections similar W dependence ≠ pQCD: $\sigma_{tot} \sim W^{2\lambda} \neq \sigma_{diff} \sim W^{4\lambda}$

Longitudinal struc. funct.



Gluon (F_L) at NLO becomes negative for Q^2~2 GeV^2 at low-x

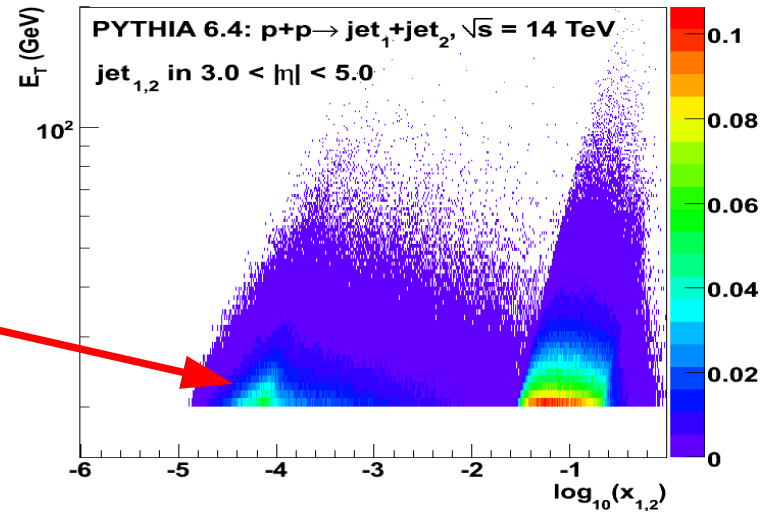
Case-study III: Forward jets in CMS (3 <|η|< 5)

- Forward "soft" jets (E_T ~20-100 GeV):

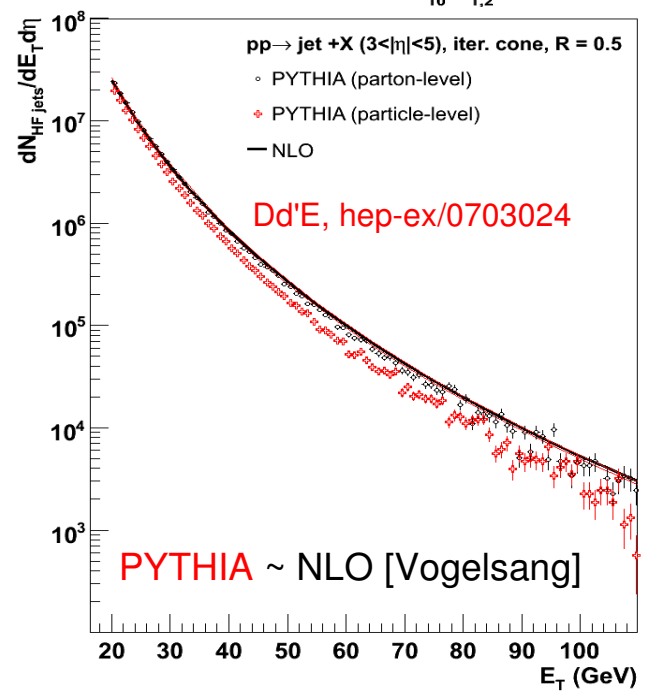
  $p + p \rightarrow jet1 + jet2 + X$ (VBF-Higgs trigger)

  Sensitive to partons with: $x_2 \sim 10^{-4}$

  Jets in CASTOR (5.3 <|η|< 6.6): $x_2 \sim 10^{-6}$



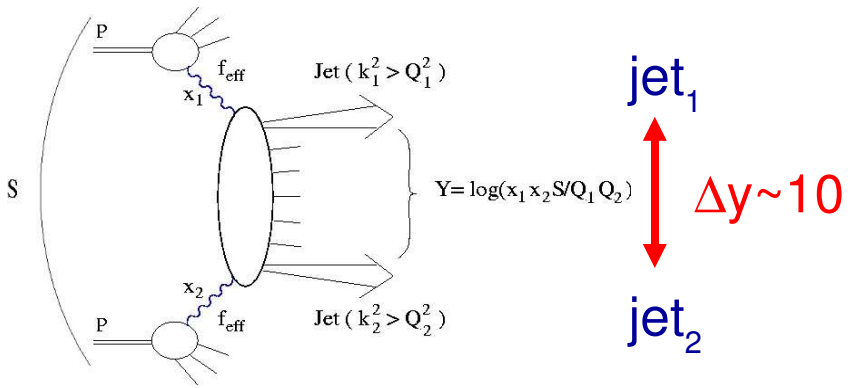
- Inclusive fwd. jet reconstruction (HF):
  - PYTHIA 6.4. min-bias (hard&soft QCD)
  - MC-level proof-of-principle only
  - HF grid: $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$
  - Iterative cone, R=0.5, E_{thresh}=10 GeV, E_{seed}=3 GeV
  - Missing important corrections: underlying-evt. (PYTHIA CMS-Tune), hadronization (cluster vs. Lund)
  - Large yields. Low-E_T uncertainties to be determined.



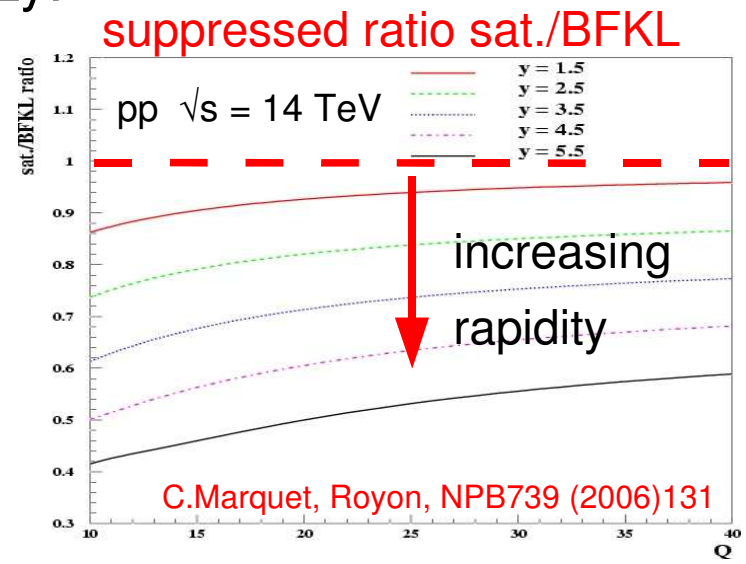
Case-study V: Mueller-Navelet dijets in CMS-HF

- Mueller-Navelet dijets separated by large Δy:

  very sensitive to non-DGLAP evolution



A.H.Mueller, H.Navelet, NPB282 (1987)727



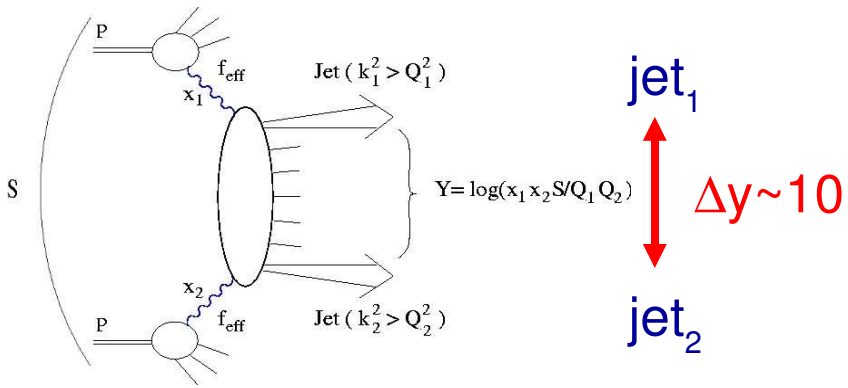
- Proof-of-principle study in CMS: MC-level dijet reconstruction applying MN kinematics cuts to PYTHIA pp-14 TeV:
  - $E_{T,i} > 20\,\mathrm{GeV}$
  - $|E_{T,1} - E_{T,2}| < 2.5\,\mathrm{GeV}$ (similar virtuality, to minimise DGLAP-evolution)
  - $3 < |\eta_{1,2}| < 5$ (both jets in HF)
  - $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF)
  - $|\eta_1| - |\eta_2| < 0.25$ (almost back-to-back in pseudo-rapidity)

$$\frac{d^2\sigma}{d\eta dQ} = \frac{N_{jets}}{\Delta\eta\Delta Q}\frac{1}{\int \mathcal{L}dt}$$

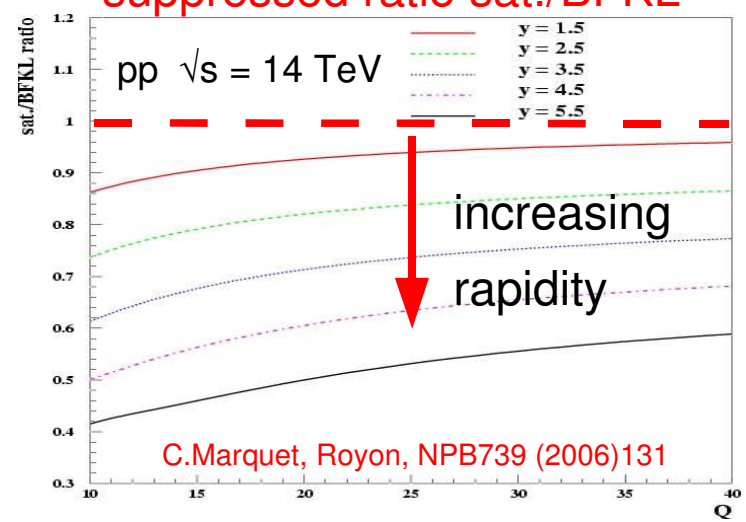
$$Q \equiv \sqrt{E_{T,1} \cdot E_{T,2}}$$

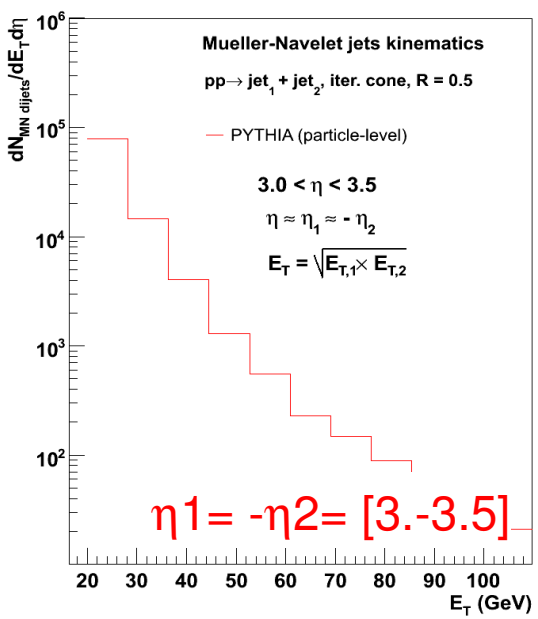
Case-study V: Mueller-Navelet dijets in CMS-HF

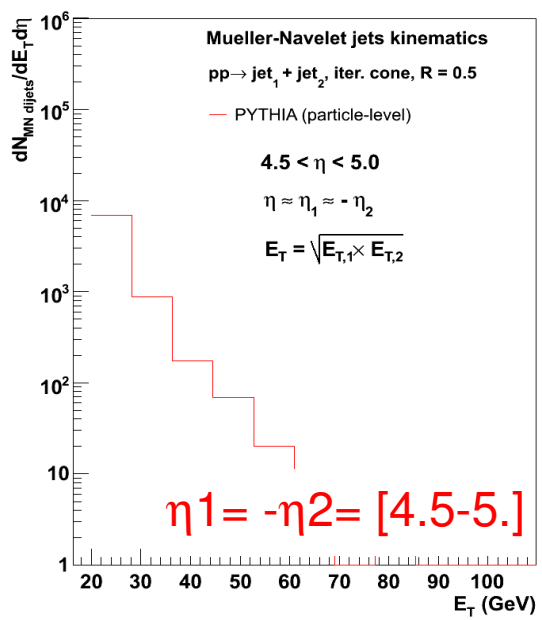
- Mueller-Navelet dijets separated by large Δy: very sensitive to non-DGLAP evolution



suppressed ratio sat./BFKL





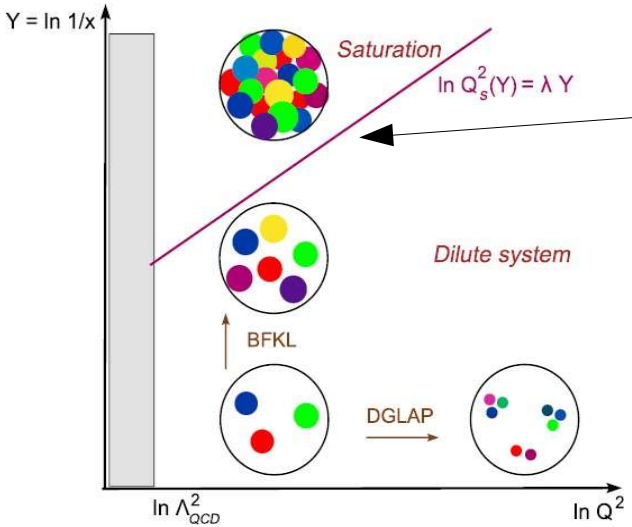


PYTHIA rates with M-N kin. cuts: ~10^4 dijets [E_T~30 GeV] in $\mathcal{L}$ ~ 1 pb^{-1} (low luminosity run): enough stats. for detailed studies of Δy-evolution.

Dd'E, hep-ex/0703024

"Saturation scale" (Q_s)

- Onset of non-linear QCD when gluons are numerous enough (low-x) & "large" enough (low-Q^2) to overlap:



$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$

$$\sim A^{1/3} x^{-\lambda} \sim A^{1/3} (\sqrt{s})^{\lambda} \sim A^{1/3} e^{\lambda y} \qquad \lambda \sim 0.3$$

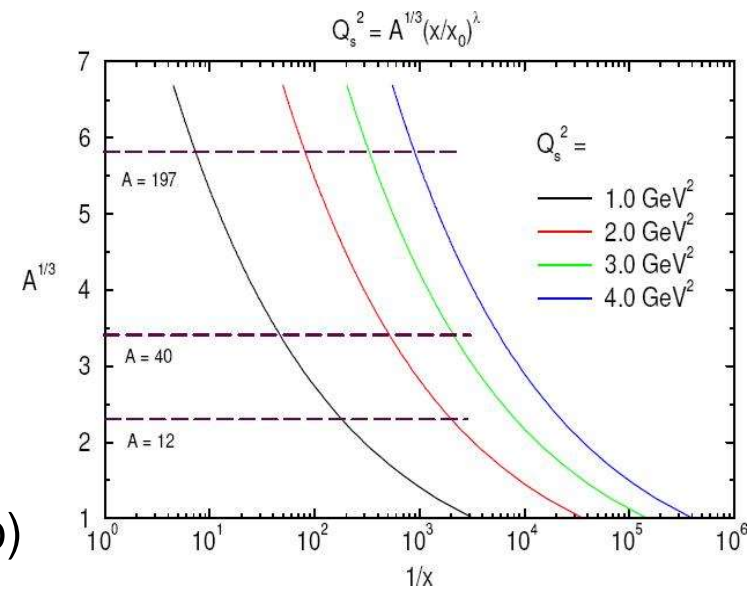
Saturation for: low x, large s, large y, large A

- Nucleus (larger parton tranverse density) amplifies saturation effects:

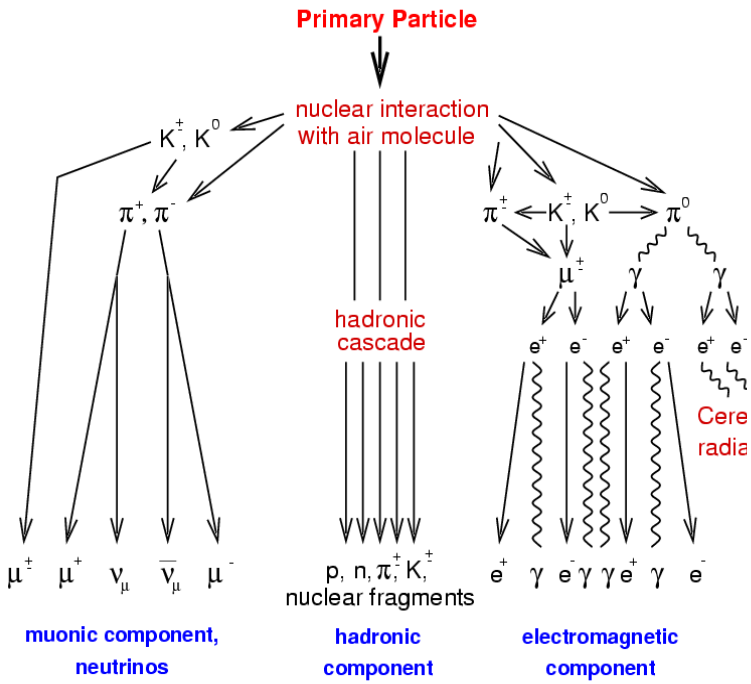
$$Q_s^2 \sim A^{1/3} \sim 6$$

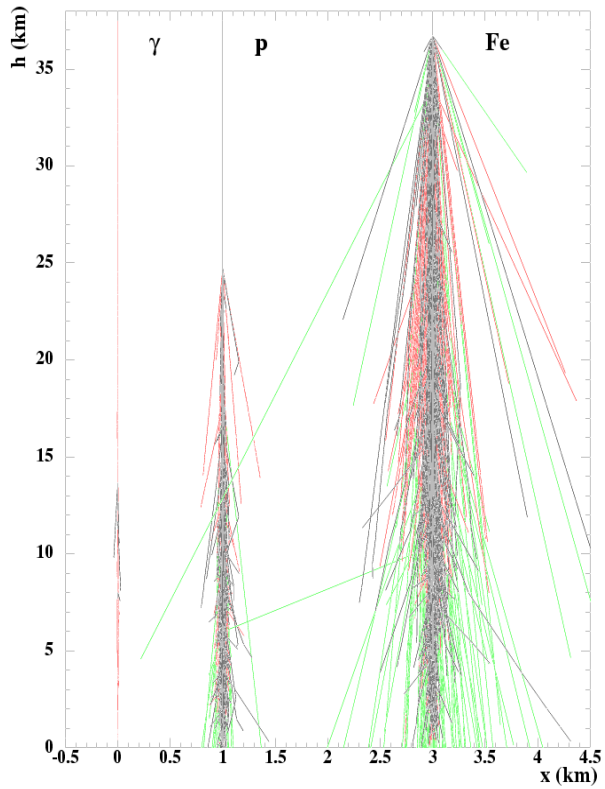
Q_s^2~1 GeV^2 (HERA,p)

Q_s^2~2 GeV^2 (e)RHIC (Au),5 GeV^2 (LHC,Pb)

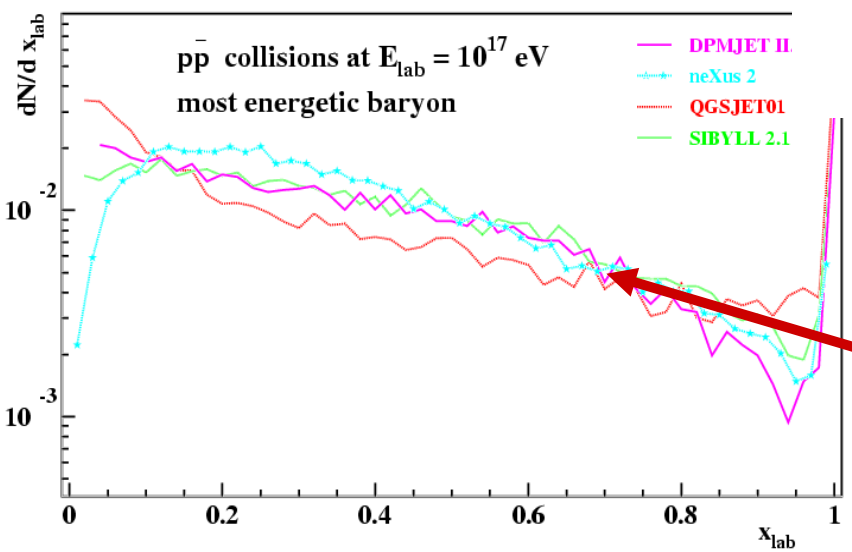


UHE cosmic-rays via extended air-showers





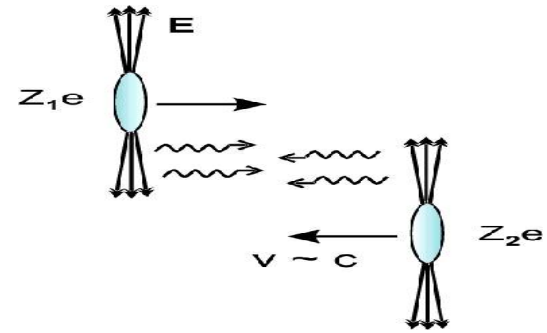
Knowledge of the energy and particle flow in high-energy p+N,O, Fe+N,O collisions is crucial for cosmic ray showers >100 PeV:



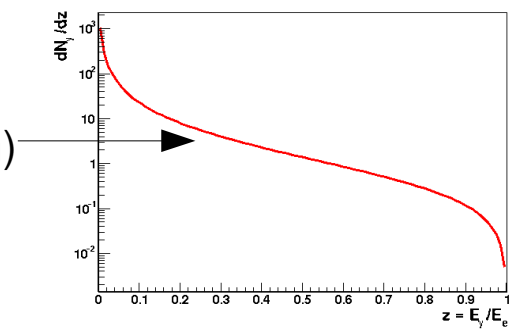
Determination of E,mass of cosmic rays depends on hadronic MC. Forward region poorly known. Models differ by factor 2 or more. Need forward particle/energy measurements: dN/d_h, $dE_{(T)}/d\eta$, particle ID …

Photoproduction (γ A) in UPC AA collisions

- Heavy-ions (charge Z) produce strong EM fields (coherent action of all protons):
- Equivalent flux of photons in electromagnetic (aka. Ultra-Peripheral, $b_{min} \sim 2R_A$) A+A :



$$\frac{dN_\gamma}{d_E}(b > b_{min}) \propto \frac{\alpha_{em} Z^2}{\pi} \frac{1}{E}$$ (soft bremsstrahlung γ spectrum)

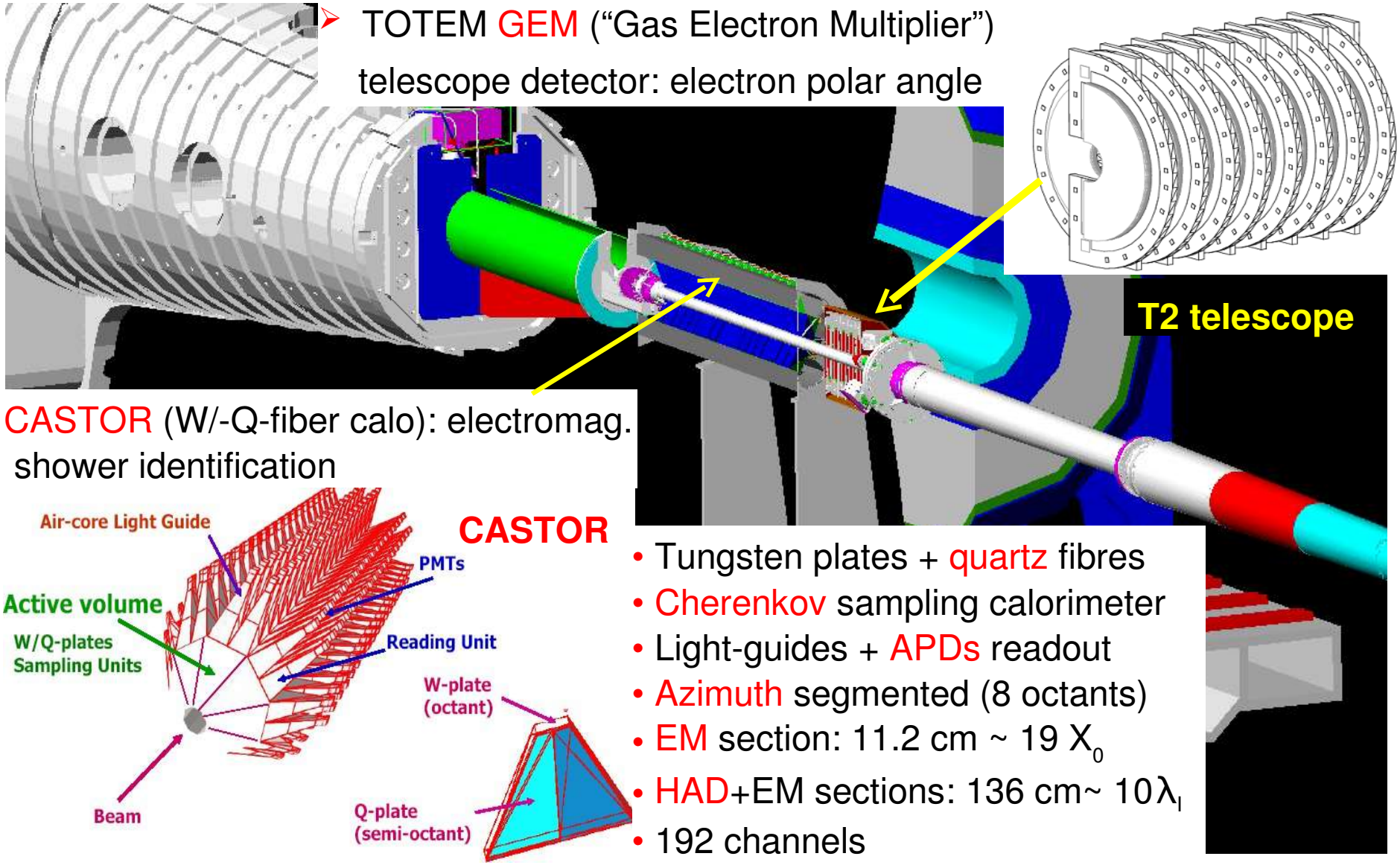


- Photon beams:
  - **Flux ~ Z^2** (~$7 \cdot 10^3$ for Pb).
  - "Coherence condition" : γ wavelength > nucleus size

    Maximum γ energy: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 – 160 GeV (Pb,Ca)
  - Center of mass-energies (LHC): $\sqrt{s_{\gamma A}} \approx$ **0.7 – 2. TeV** $\approx$ **(3 – 10) × $\sqrt{s_{\gamma p}}$(HERA)**
  - Bjorken x range in nucleus: (y=0): x(J/Ψ) ~$3 \cdot 10^{-3}$, x(ϒ)~10^{-2}

    (y=3): x(J/Ψ) ~ $2 \cdot 10^{-5}$, x(ϒ)~10^{-4}
- Forward neutron-tagging (ZDC): ~50% UPC colls. lead to nuclear breakup.

CMS: TOTEM-2 and CASTOR (5.2 <|η|< 6.6)



- TOTEM GEM ("Gas Electron Multiplier") telescope detector: electron polar angle

CASTOR (W/-Q-fiber calo): electromag. shower identification

- Tungsten plates + quartz fibres
- Cherenkov sampling calorimeter
- Light-guides + APDs readout
- Azimuth segmented (8 octants)
- EM section: 11.2 cm ~ 19 X_0
- HAD+EM sections: 136 cm~ 10λ_I
- 192 channels