David d'Enterria
CERN, Geneva

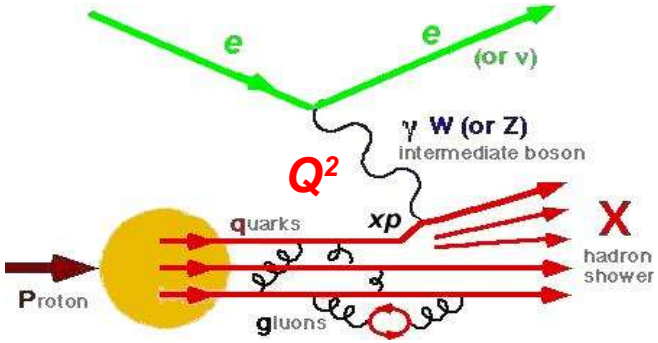
Hot Quarks 2006
Villasimius, Sardegna
May 17th 2006

Low-*x* QCD with CMS at LHC

- Intro: parton saturation & evolution (CGC) at low-*x*
- Experimental signatures
- Results at HERA (proton), RHIC (nucleus)
- LHC perspectives (p,A)
- CMS experimental capabilities

Parton structure at low-*x* (proton)

- DIS *ep* collisions probe partonic distributions in the proton:



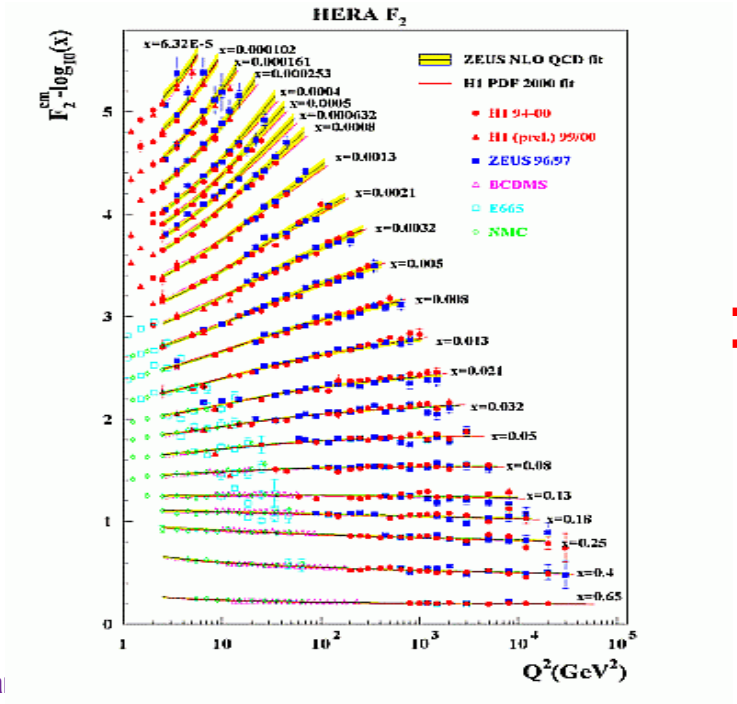
Q^2 = "resolving power"

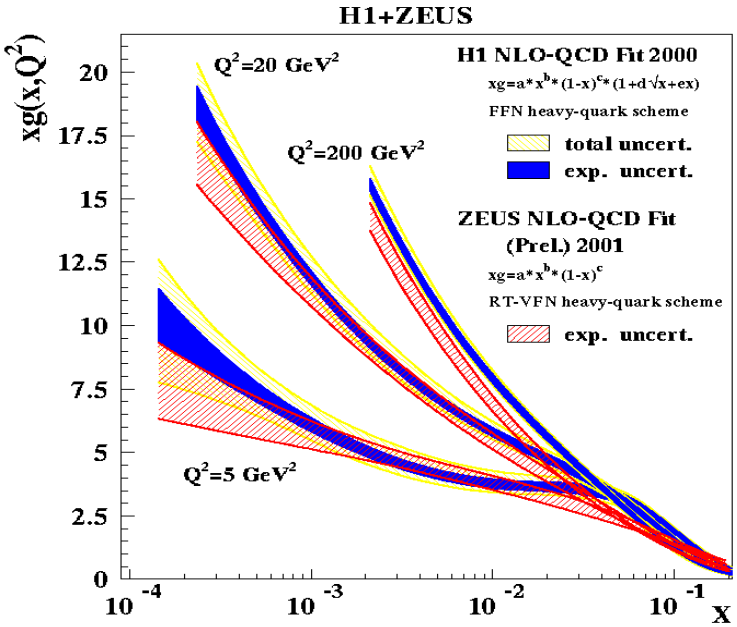
Bjorken x = momentum fraction carried by the parton

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[2xy^2F_1 + 2(1-y)F_2\right]$$

F_1, F_2 = proton structure functions , (y = inelasticity).

- HERA: strong rise at low-x of $F_2(x,Q^2)$ ~ sea-quarks, $\partial \ln F_2/\partial \ln Q^2$ ~ gluons





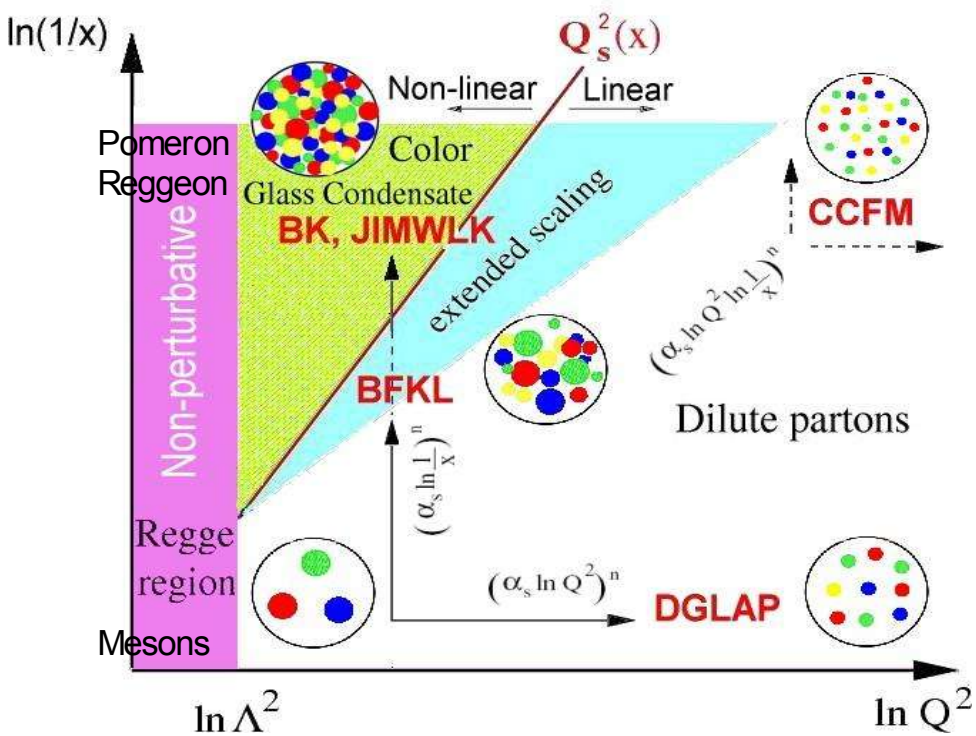
(x,Q^2) parton *quantum evolution* at low-*x*

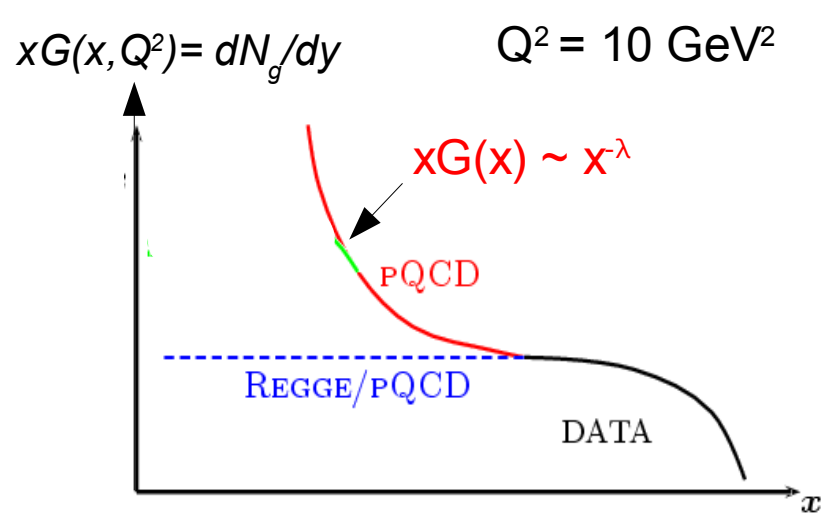
- **DGLAP** (parton branching): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$ start. at $Q_0^2 \sim 1$ GeV^2 ("std" PDFs)
- **BFKL** (parton emission ordered in $p_L \sim x$): $F_2(x) \sim \alpha_s \ln(1/x)^n$ (unintegrated PDFs)
- Linear equations (single parton radiation). Cannot work at low-x !

  (i) Too high gluon density (system not dilute): nonlinear multi-gluon fusion must balance splittings.

  (ii) pQCD (collinear & k_T) factorization should break (invalid assumption of incoherent parton scatt.)

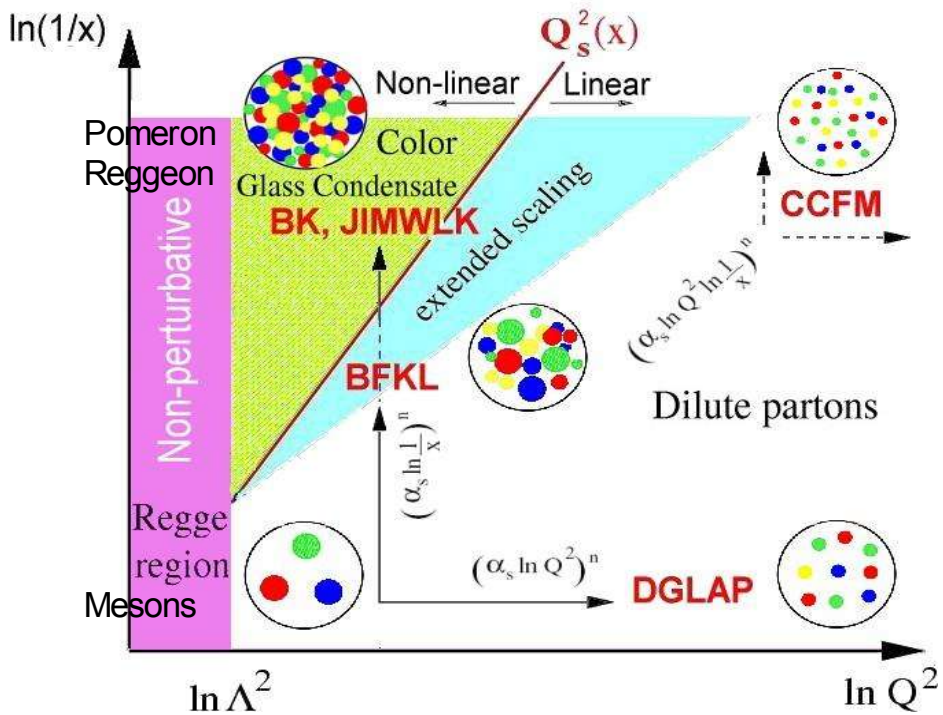
  (iii) Violation of unitarity even for $Q^2 >> \Lambda^2$ (too large perturbative cross-sections).



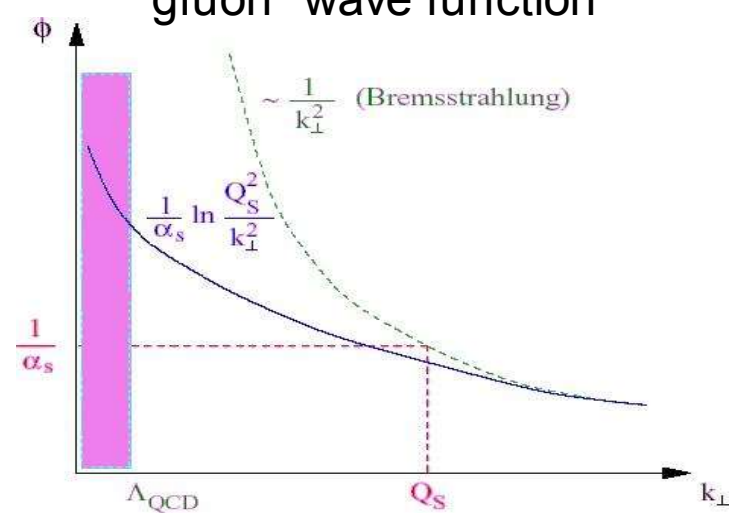


Colour Glass Condensate

- **CGC**: Effective field theory of QCD in high-energy (high density, small-x) limit.
  - hadrons = classical fields (saturated gluon wave-function) below new scale: $Q^2 < Q_s^2$
  - "Sat. momentum": $Q_s^2(x) = \alpha_s N_c \frac{1}{\pi R^2} \frac{dN}{dy}$ *A*-"amplified": $Q_s^2 \sim A^{1/3} \sim 1.5,3$ GeV^2 RHIC,LHC
  - Perturbative calculations (strong $F_{\mu\nu}$ field ⇒ weak coupling $\alpha_s \ll 1$).
  - had.+had: collision (amplitude level) of 1(2) gluon wave function(s): "resums" all mult. scatts.
  - **C**olor **G**lass ("static" color sources = quarks) **C**ondensate (high gluon occupation values).
- Quantum evolution: **BK, JIMWLK**: Non-linear, all-twist eqs. in saturation region

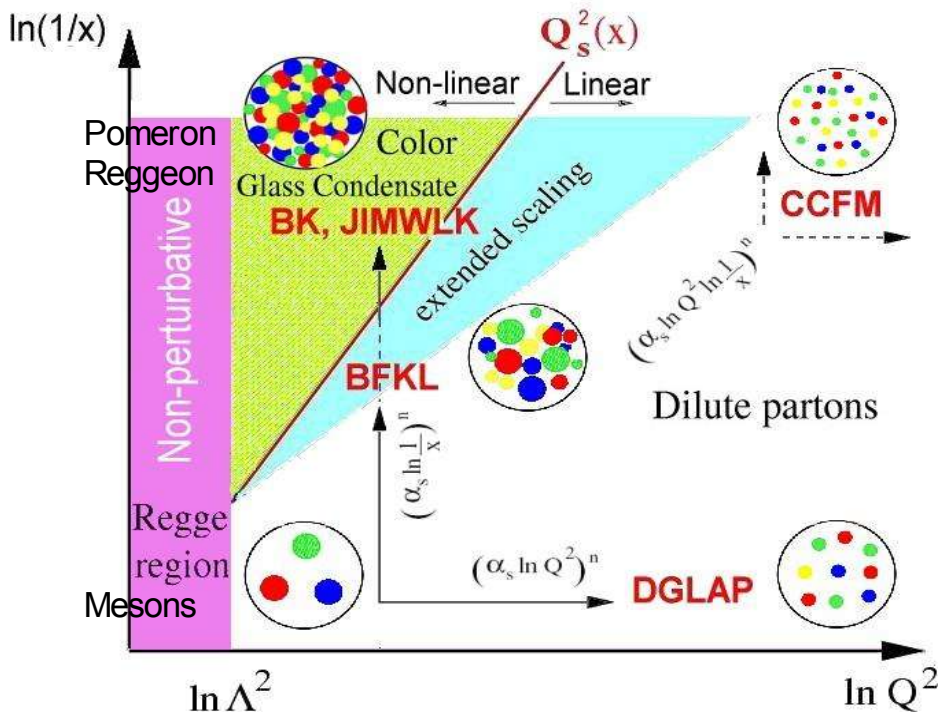


gluon "wave function"



Colour Glass Condensate

- **CGC**: Effective field theory of QCD in high-energy (high density, small-x) limit.
  - hadrons = classical fields (saturated gluon wave-function) below new scale: $Q^2 < Q_s^2$
  - "Sat. momentum": $Q_s^2(x) = \alpha_s N_c \frac{1}{\pi R^2} \frac{dN}{dy}$ *A*-"amplified": $Q_s^2 \sim A^{1/3} \sim 1.5,3$ GeV^2 RHIC,LHC
  - Perturbative calculations (strong $F_{\mu\nu}$ field ⇒ weak coupling $\alpha_s \ll 1$).
  - had.+had: collision (amplitude level) of 1(2) gluon wave function(s): "resums" all mult. scatts.
  - **C**olor **G**lass ("static" color sources = quarks) **C**ondensate (high gluon occupation values).
- Quantum evolution: **BK, JIMWLK**: Non-linear, all-twist eqs. in saturation region



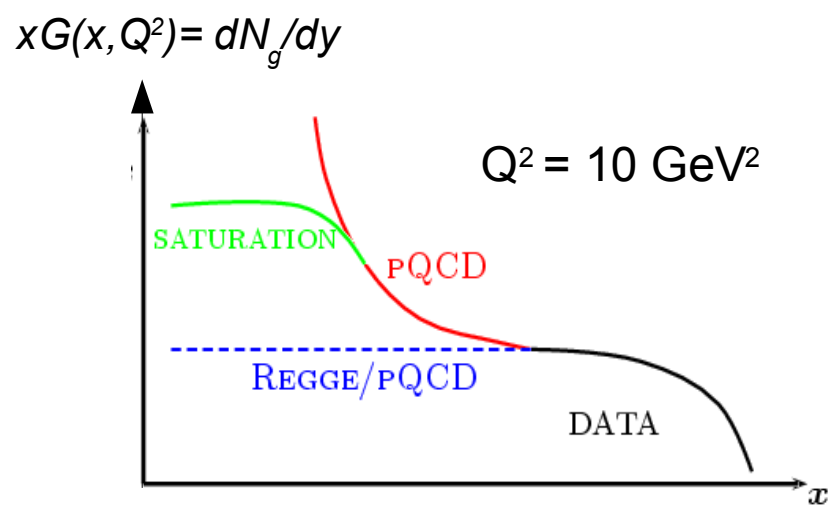
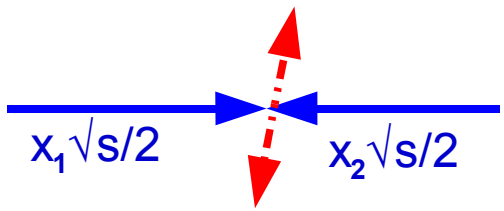


Illustration only. There is no "PDFs" now in the sense of pQCD factorization

Small-*x*: go to forward rapidities

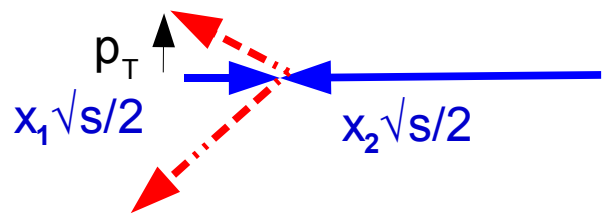
- Parton-parton kinematics:

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



Forward y:

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



Every 2-units of y
x decreases by ~10

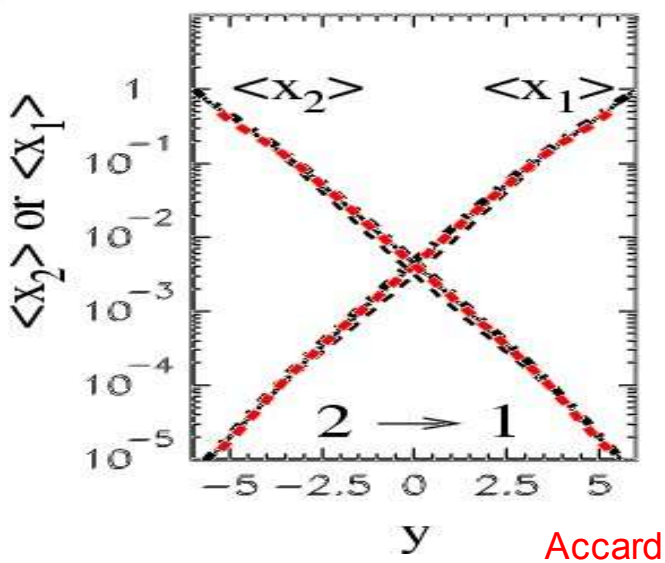
e.g. p_T = 10 GeV/c
$\theta < 10^{-3}$ (η~7- 8)

- In addition: Much lower x values allowed in CGC (2 → 1, "gluon fusion"):

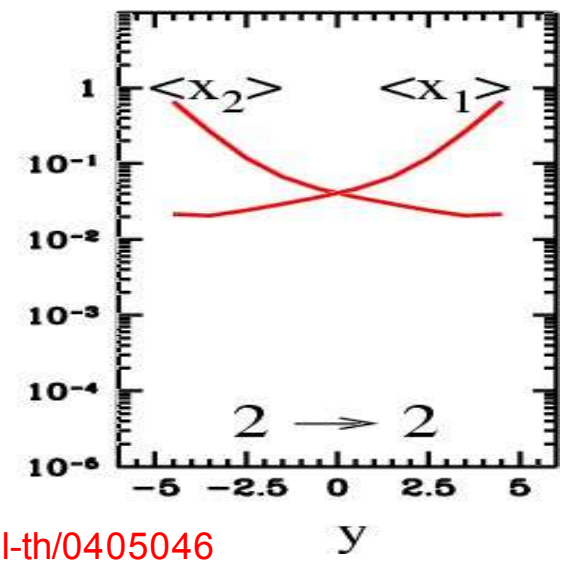
$$x_{1,2}^{2\to 1} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y}\right)$$

Momentum balanced by the "medium" ("gluon ladder")

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



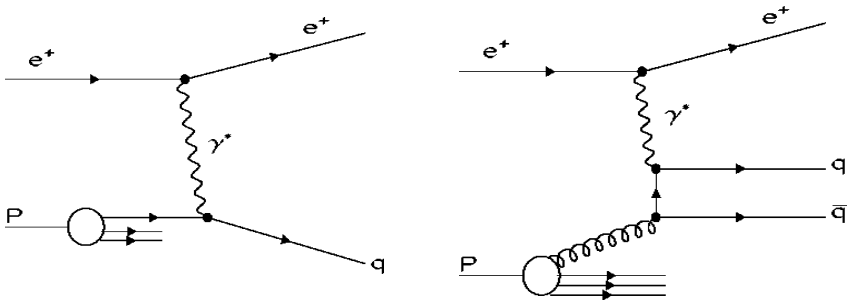
pQCD: x(y=4) ~ 10^{-2}



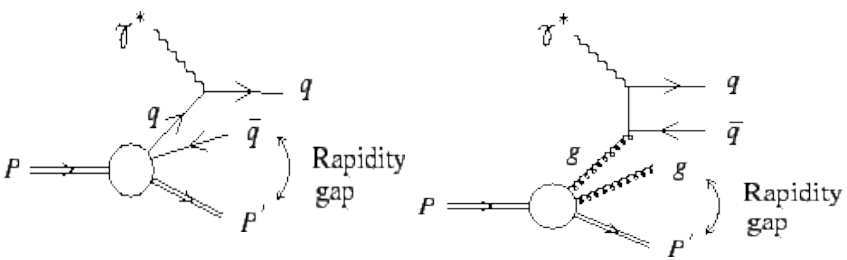
Accardi, nucl-th/0405046

Experimental access to low-*x* parton distrib. (I)

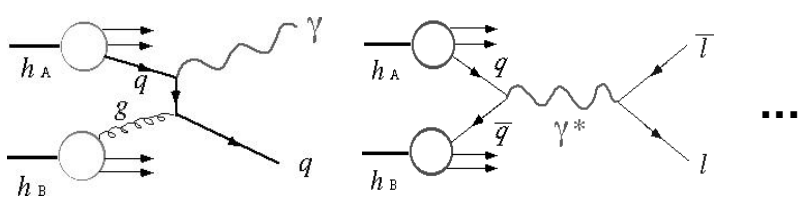
- High-p_T, heavy-Q (ep,eA):

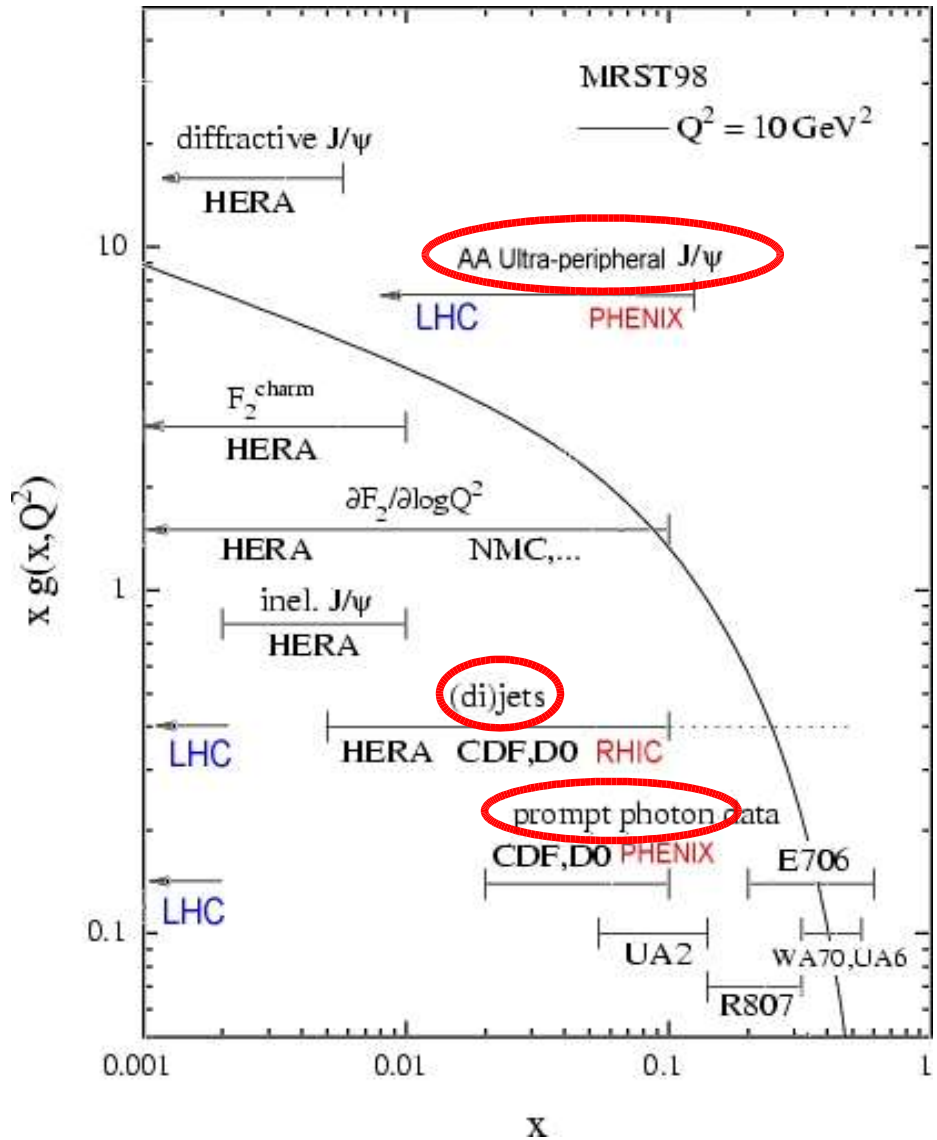


- Diffractive QQbar (ep, γp,A):



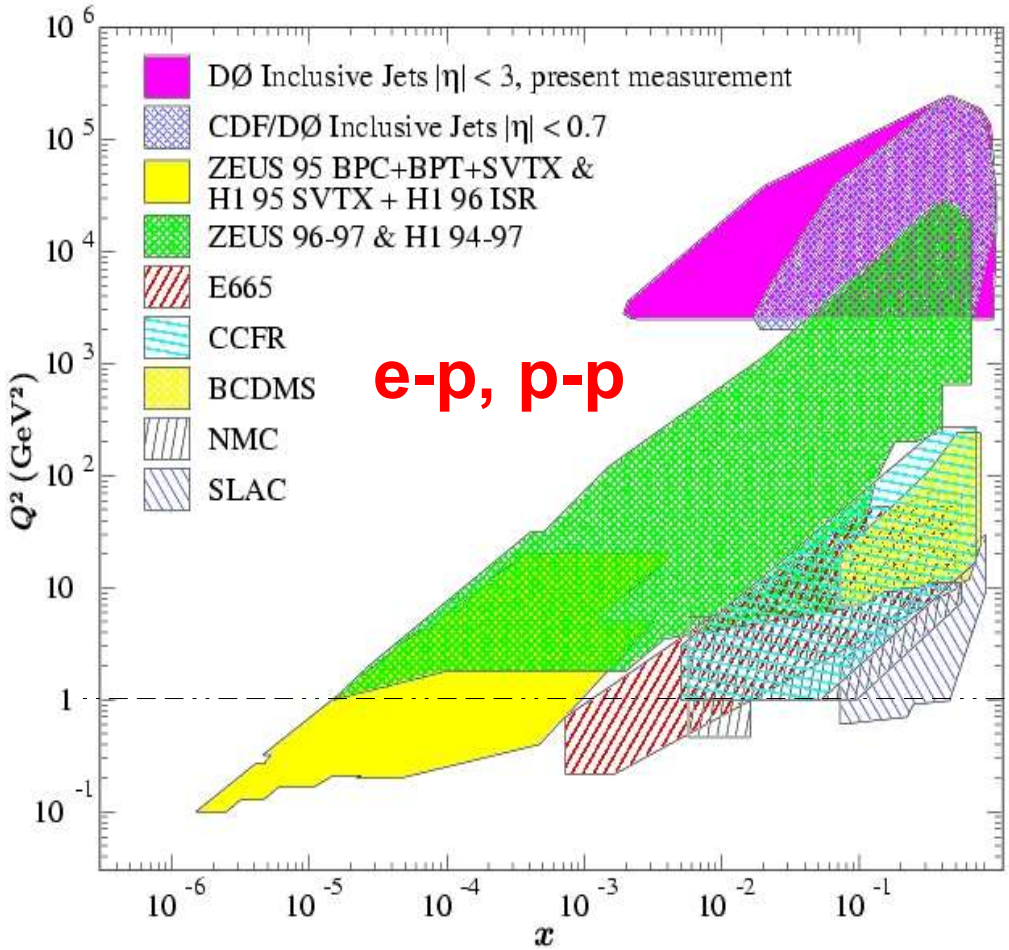
- γ,DY,dijets,heavy-Q (pp,pA,AA):





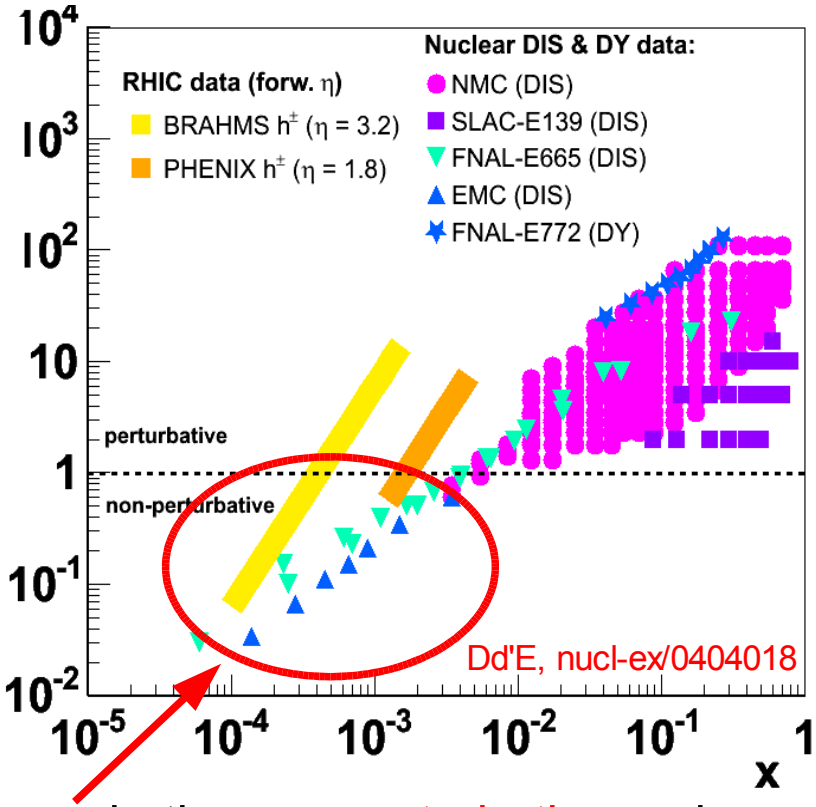
Experimental access to low-*x* parton distrib. (II)

- Kinematical (x,Q^2) domains covered experimentally:



much less nuclear PDF data available:

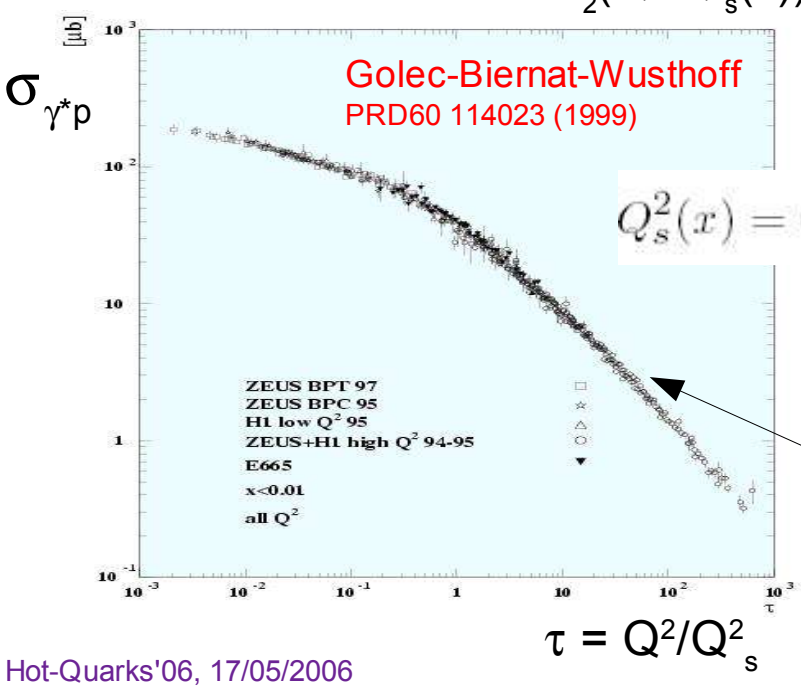
e-A, p-A



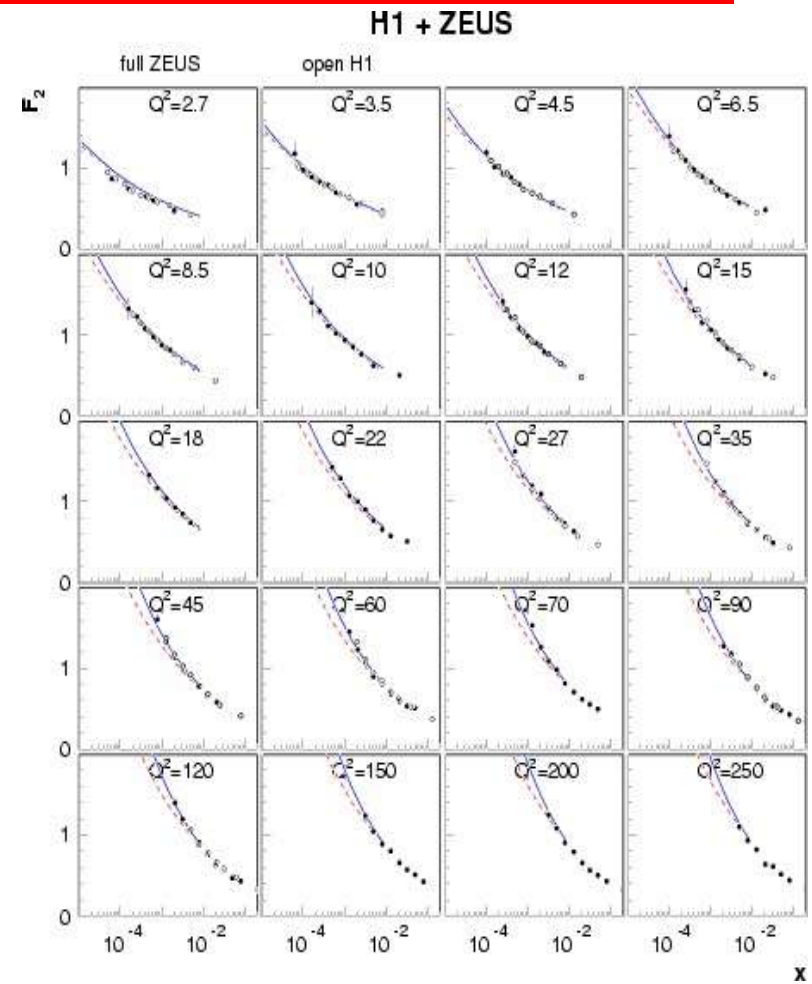
- Most existing low-x nPDFs measurements are in the non-perturbative regime

HERA (ep): indirect evidences for saturation

- Good description of $F_2(x,Q^2)$ in "transition region" (moderate/low Q^2) (limit of DGLAP applicability)
- *[Diffractive PDFs ...]*
- "Geometrical scaling" of $F_2(x,Q^2)$: (x,Q^2)-dependence of structure function only via scaled variable: $F_2(Q^2/Q^2_s(x))$



$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$$



"dipole cross-section" model (derivable within CGC):

$$\sigma_{q\bar{q}p}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-\frac{r_\perp^2 Q_s^2(x)}{4}\right)\right]$$

RHIC (dA,AA): indirect evidences for saturation

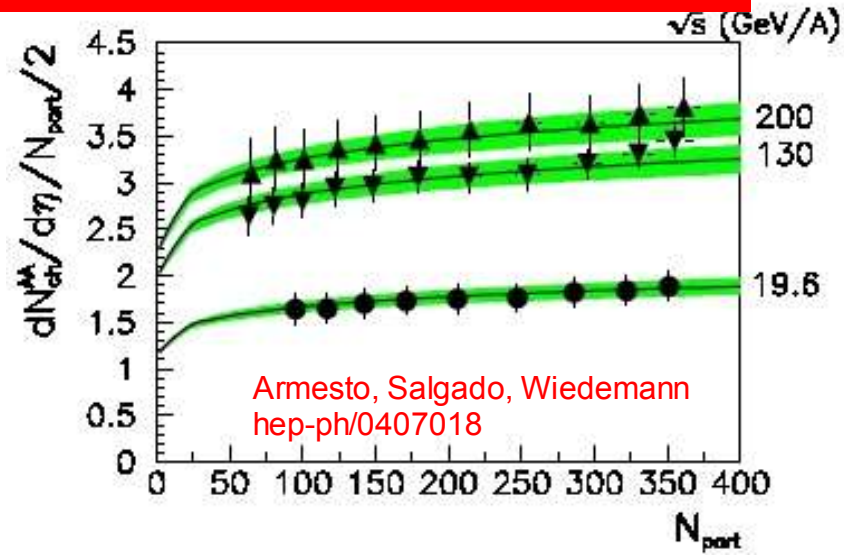
- Total AuAu particle multiplicity (plus its centrality evolution):

Nardi, PLB507(01)121 :

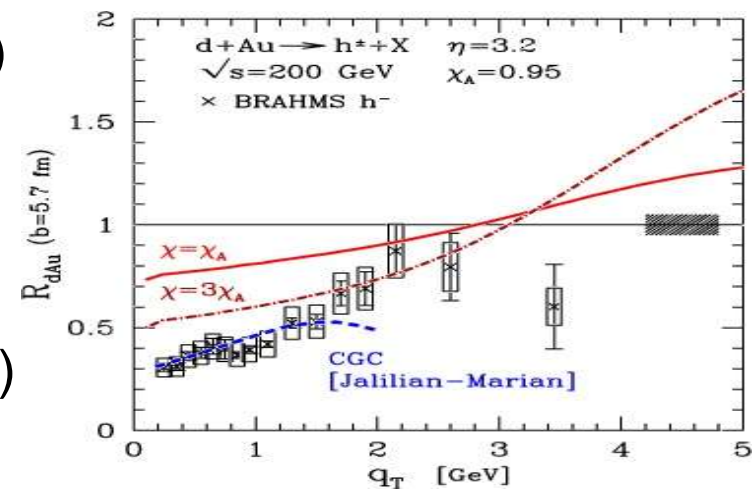
$$\frac{dN}{d^2b d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) A^{1/3}$$

+ assuming "local parton-hadron duality"

1 gluon = 1 final hadron



- d+Au moderate-p_T spectra (& y-evolution) at forward rapidities (suppression):



- CGC "plus": A <u>theory</u> that describes:
  - (leading-twist) "shadowing" (ext. scaling)
  - Cronin-effect (BK quantum evolution)

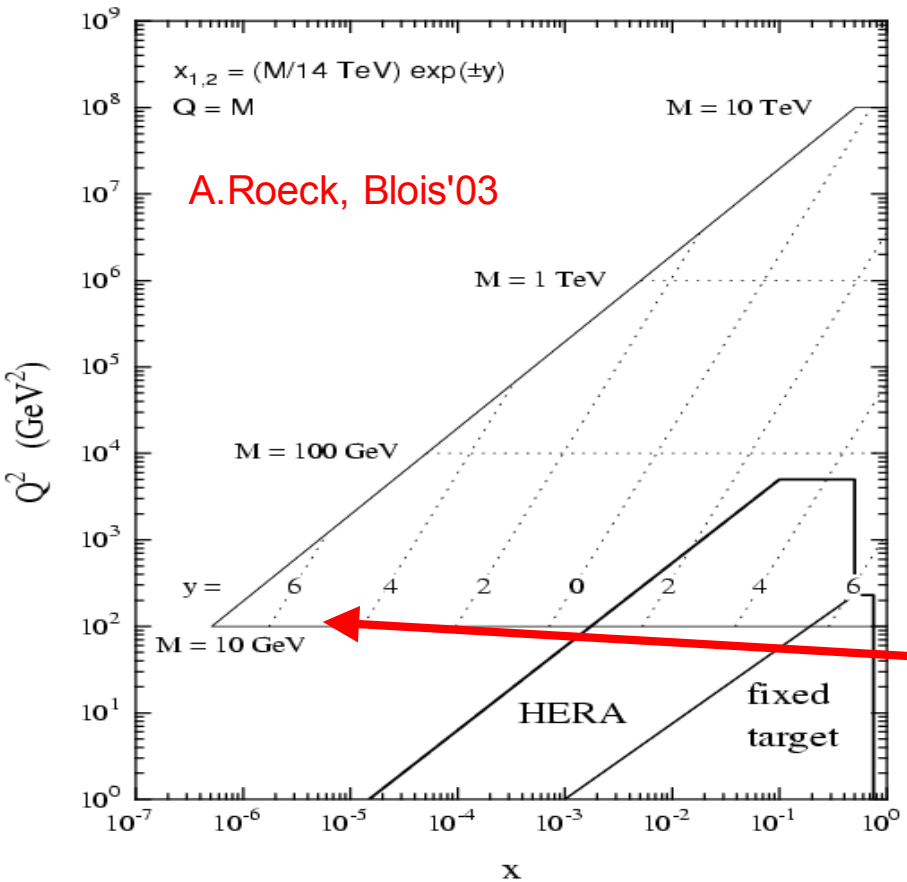
- However: evidences at ~low p_T. Q_s @ RHIC/HERA close to non-perturb. range

Low-*x* at the LHC (proton)

- pp @ 14 TeV :

(i) Very high $\sqrt{s}$ $\Rightarrow$ very small Bjorken $x=2p_T/\sqrt{s}$, ~70 times lower than p+p @ RHIC

(ii) Very large perturbative cross-sections.



Processes:

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

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

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

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

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

For y < 5, M < 10 GeV

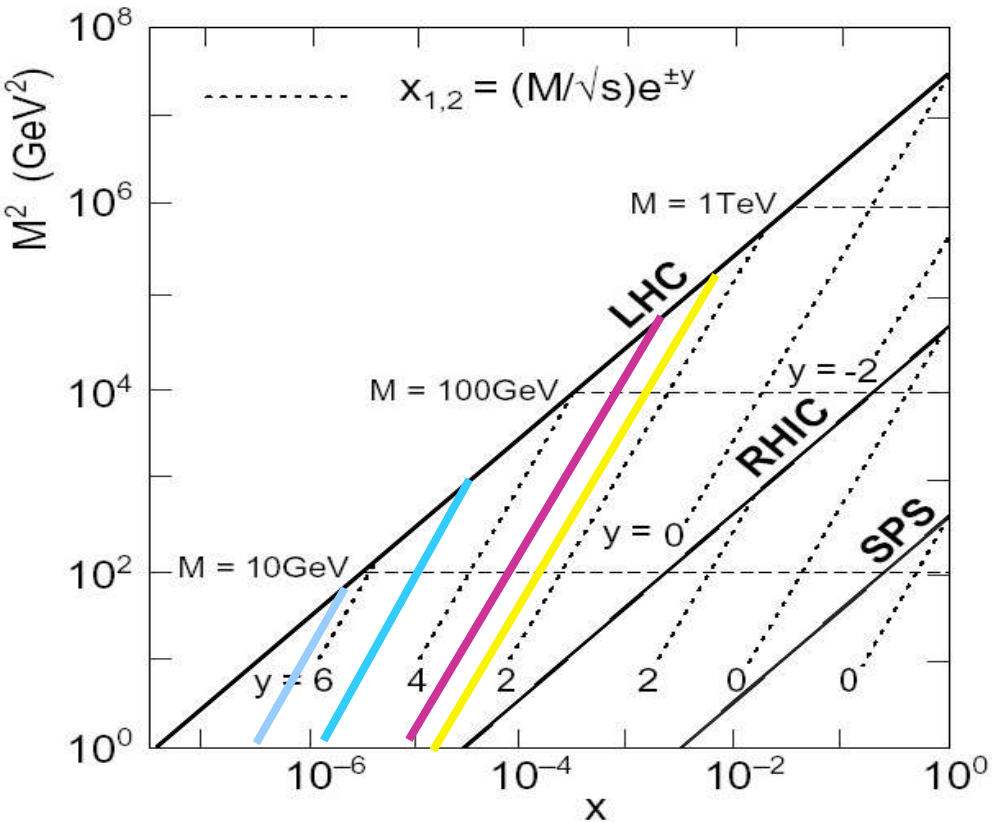
$\Rightarrow$ x down to 10^{-6}-10^{-7} !

Low-*x* at the LHC (nucleus)

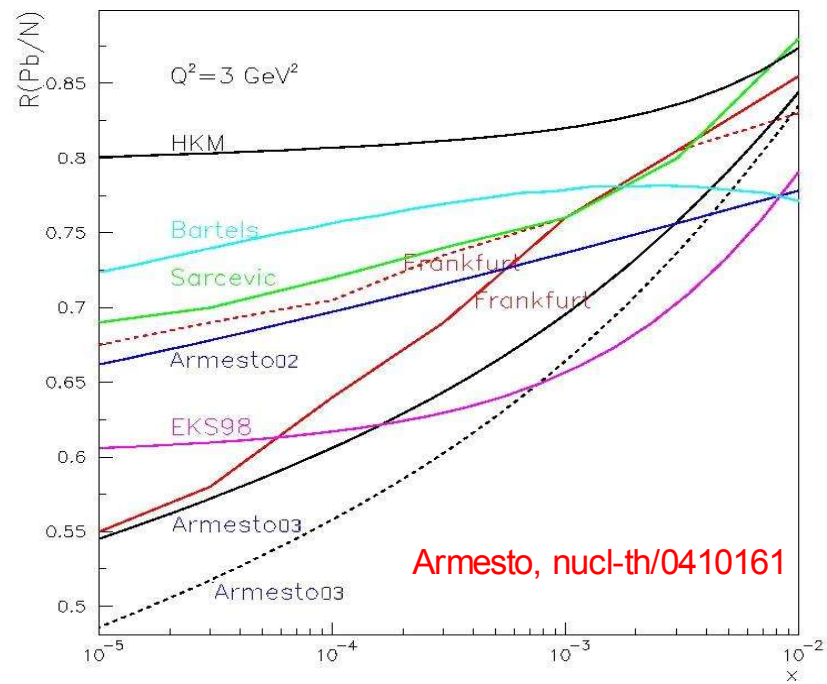
- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:

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

(ii) Very large perturbative cross-sections.

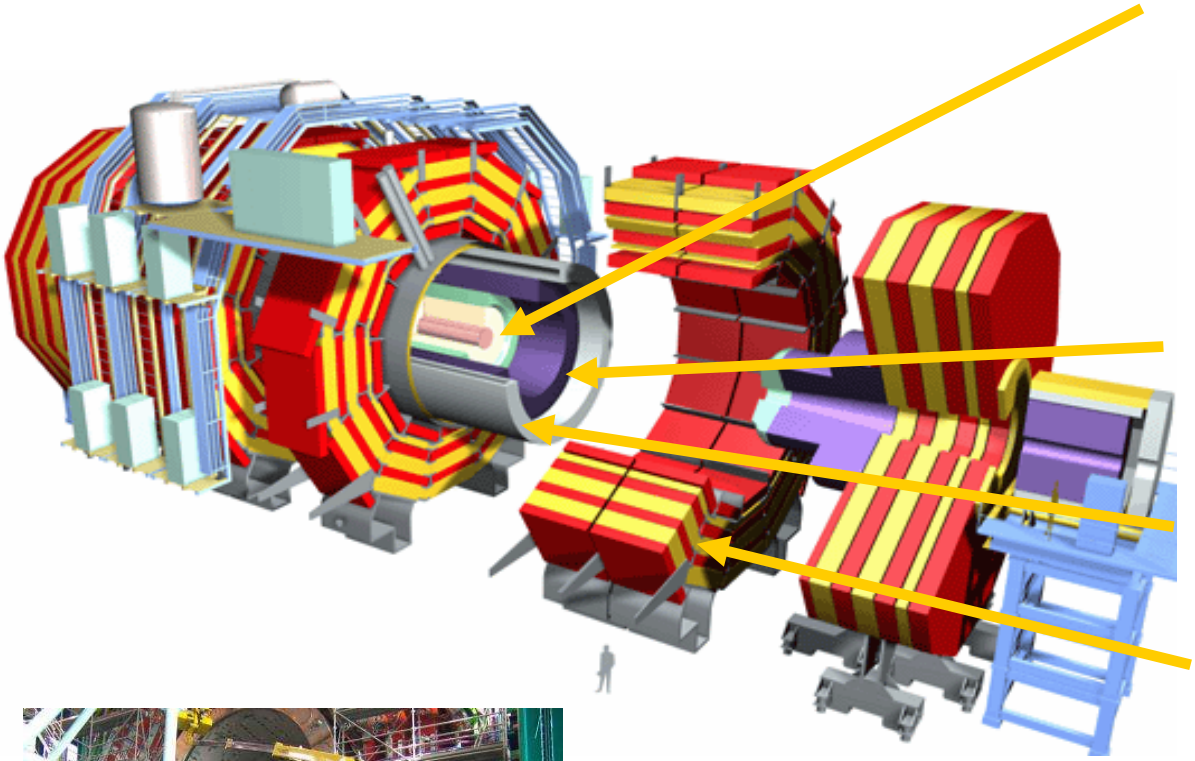


Nuclear $xG(x,Q^2)$ is basically unknown for $x<10^{-3}$!



Armesto, nucl-th/0410161

The CMS experiment (|η|<5)



Silicon Tracker (|η| < 2.5):

- Si pixels, Si strips
- Good eff. & purity for p_T>1 GeV
- Pixel occupancy (PbPb): 1-2%
- $\Delta p/p \approx 2\%$ for p_T<70 GeV

Calorimeters (|η| < 5):

- EM: $PbW0_4$
- HCAL: Scint.+steel

Magnet :

- 4 T solenoid

Muon tracking (|η| < 2.5):

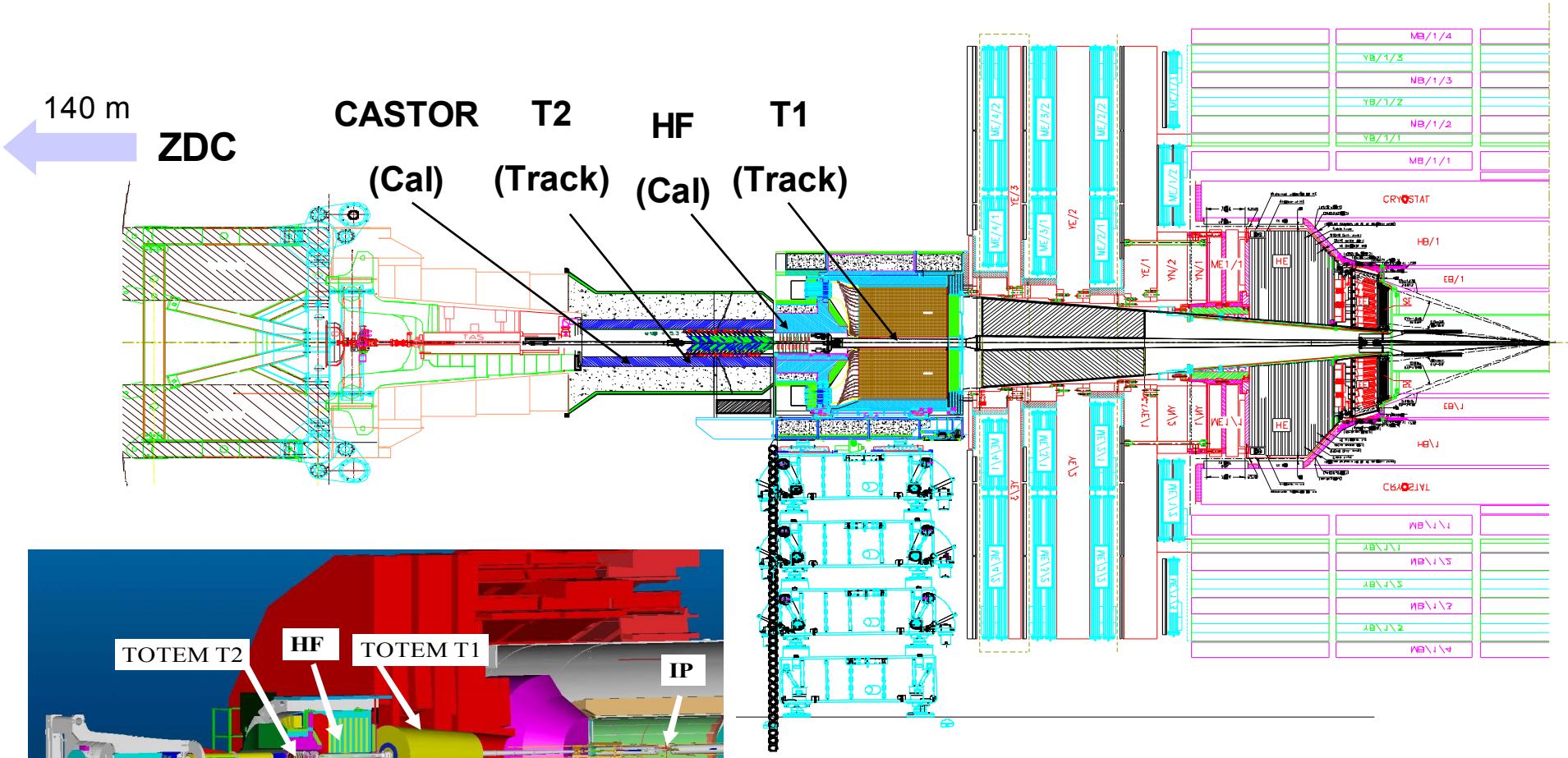
- μ from Z^0, J/ψ , ϒ
- $\sigma_m \approx 50$ MeV at the ϒ mass

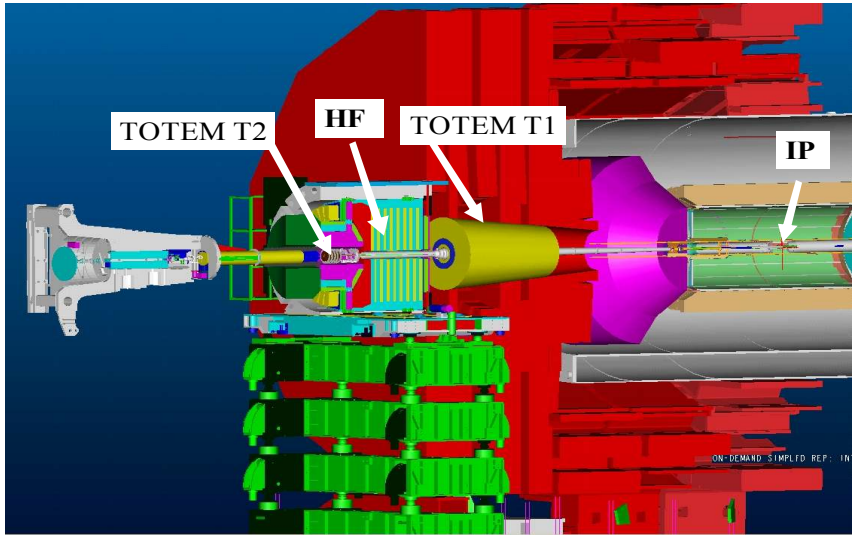
DAQ & Trigger

- High rate capability for A+A, p+A, p+p
- HLT: real time HI event reco

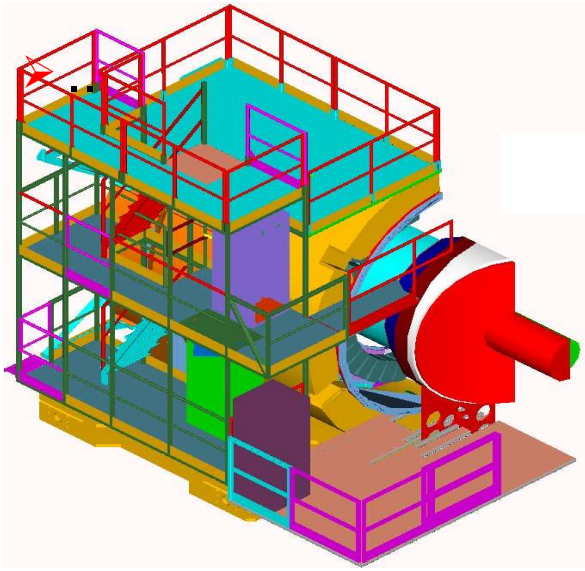
Physics program:
Higgs (EWSB), Beyond SM, Heavy-Ions, low-*x* QCD …

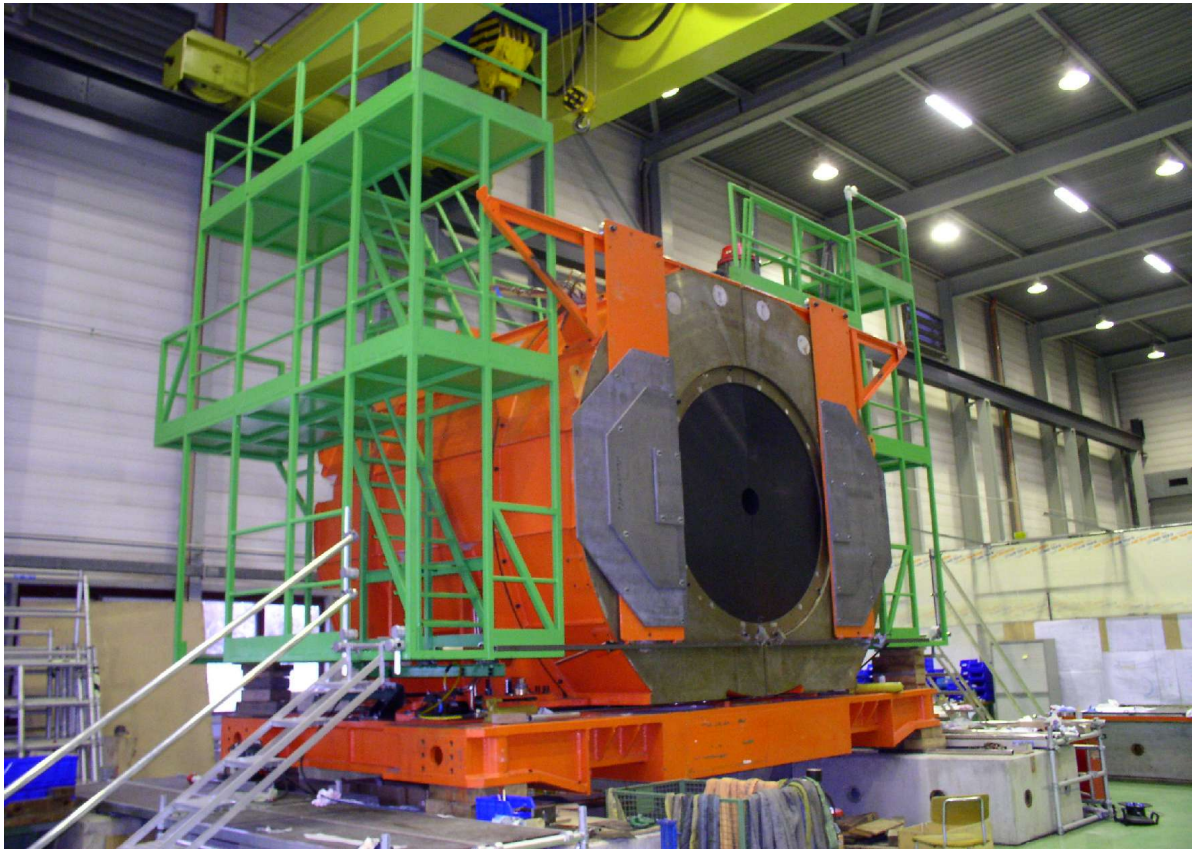
CMS-TOTEM forward detectors (|η|~3-6.7)





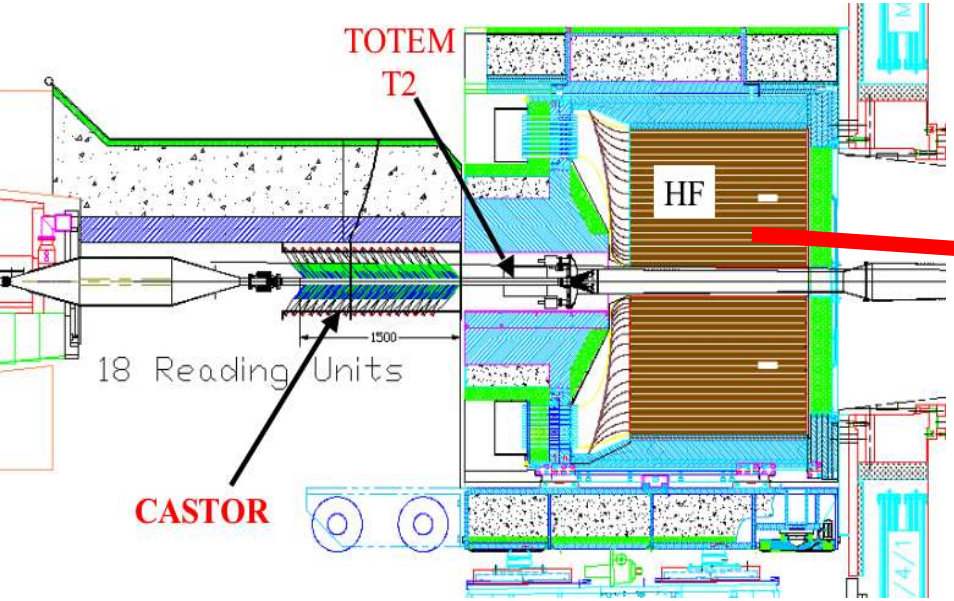
HF, TOTEM (T1,T2), CASTOR

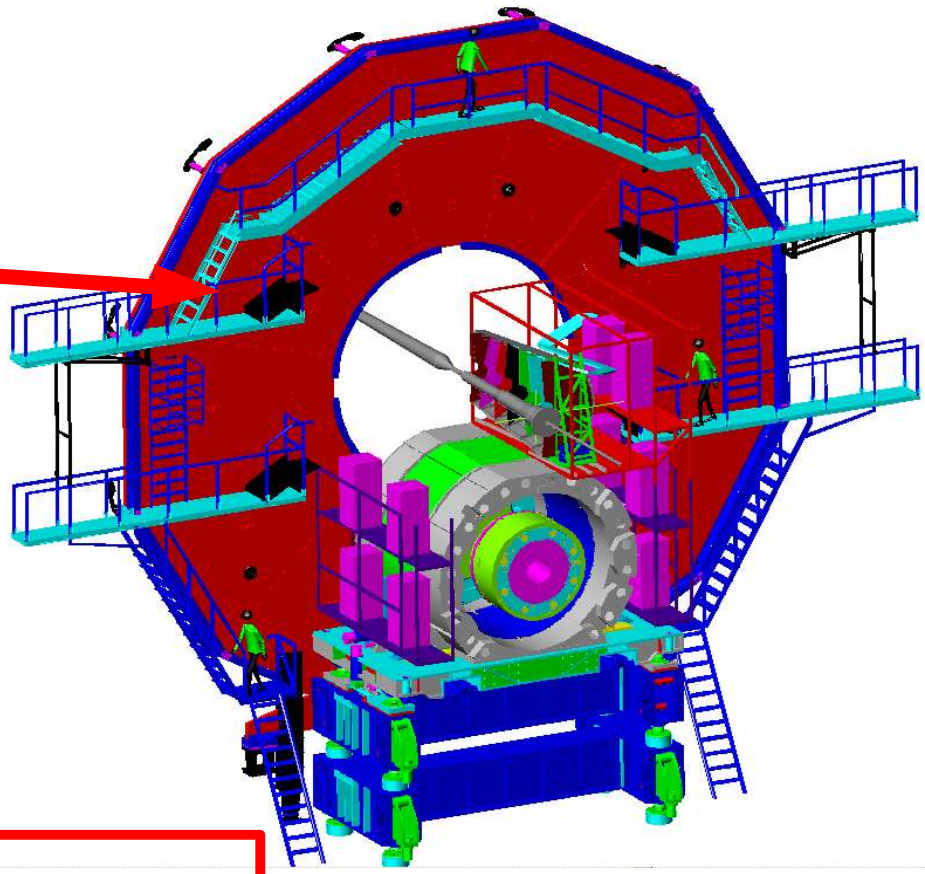




Hadronic Forward Calorimeter (2.5 <η< 5)

➢ ..



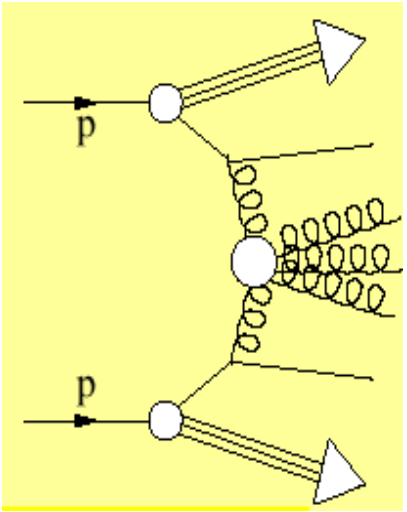


- 11.2 m from IP5.
- Steel+quartz-fibre Cherenkov (EM+HAD) calorimeter
- 1.65 m absorber depth
- 900 towers (1200 channels): $\Delta\eta \times \Delta\Phi \sim 0.18 \times 0.18$
- Hamamatsu R7525 rad-hard PMTs

Low-*x* measurements with HF

- Forward jet production ("Mueller-Navelet" BFKL jets):

hadron-hadron



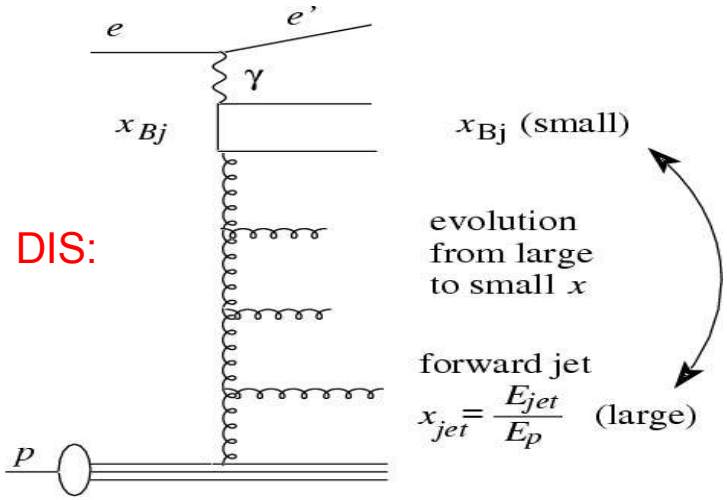
jet

$\Delta\eta$

jet

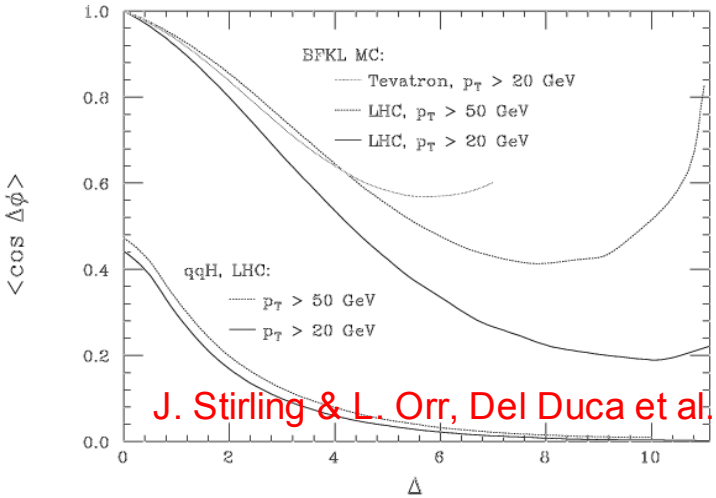
A.Roeck, Blois'03

DIS:



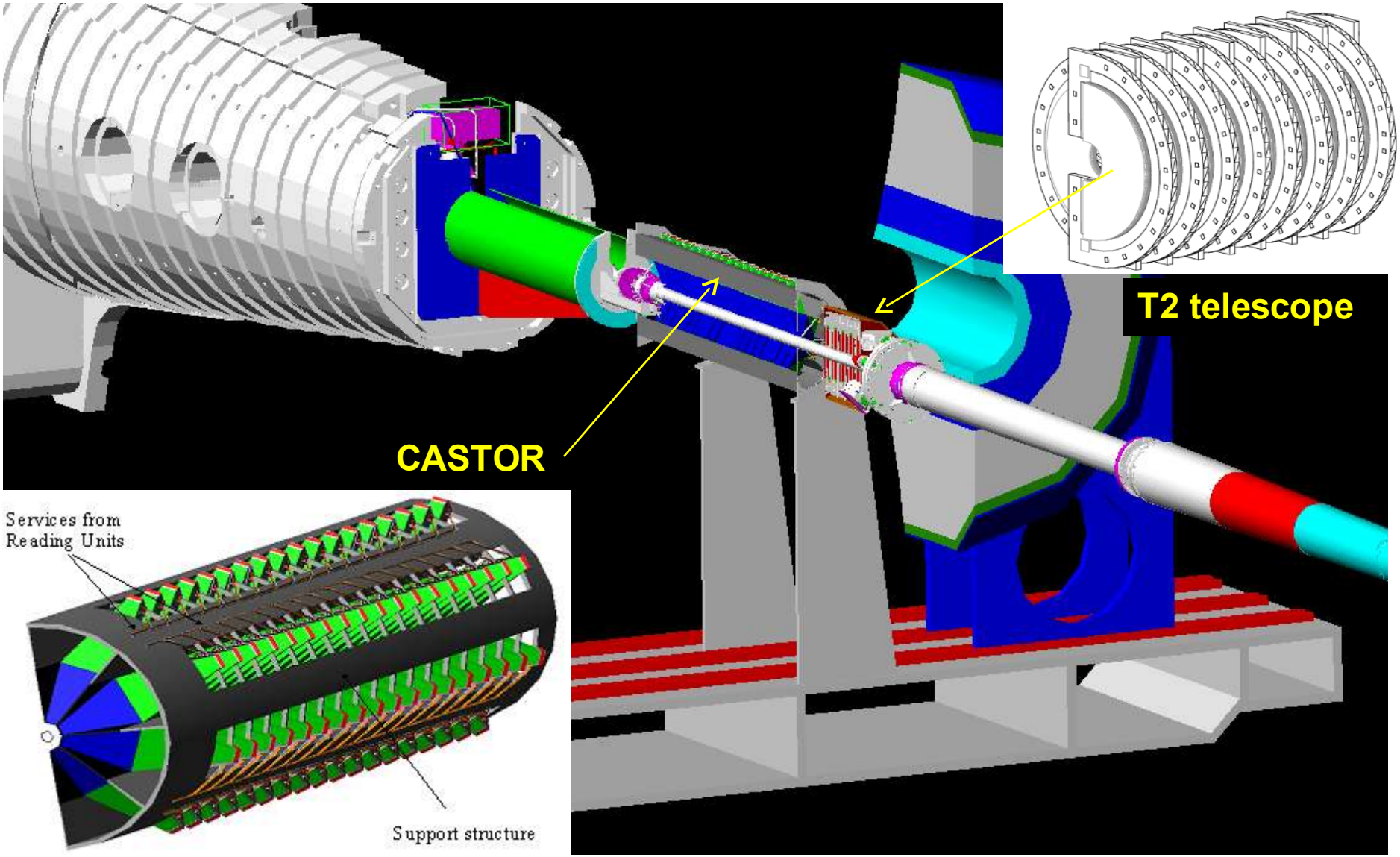
Azimuthal decorrelation between the 2 jets versus rapidity distance between the 2 jets:

Large $\Delta\eta$ range required

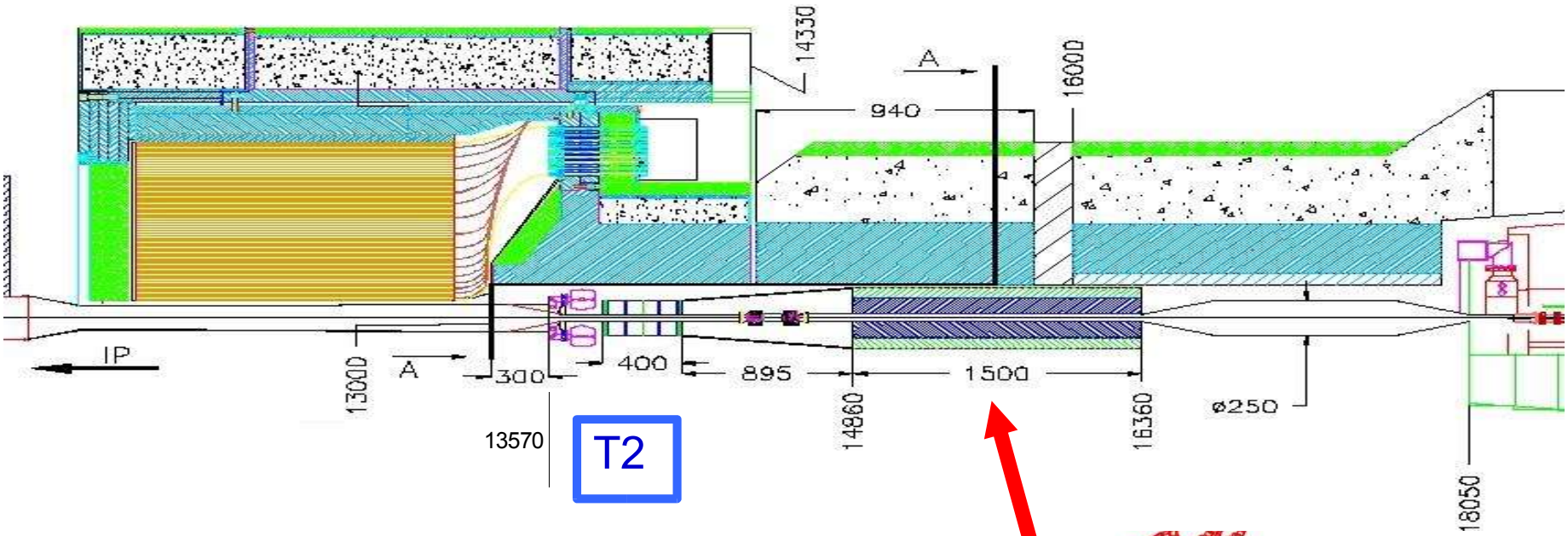


J. Stirling & L. Orr, Del Duca et al.

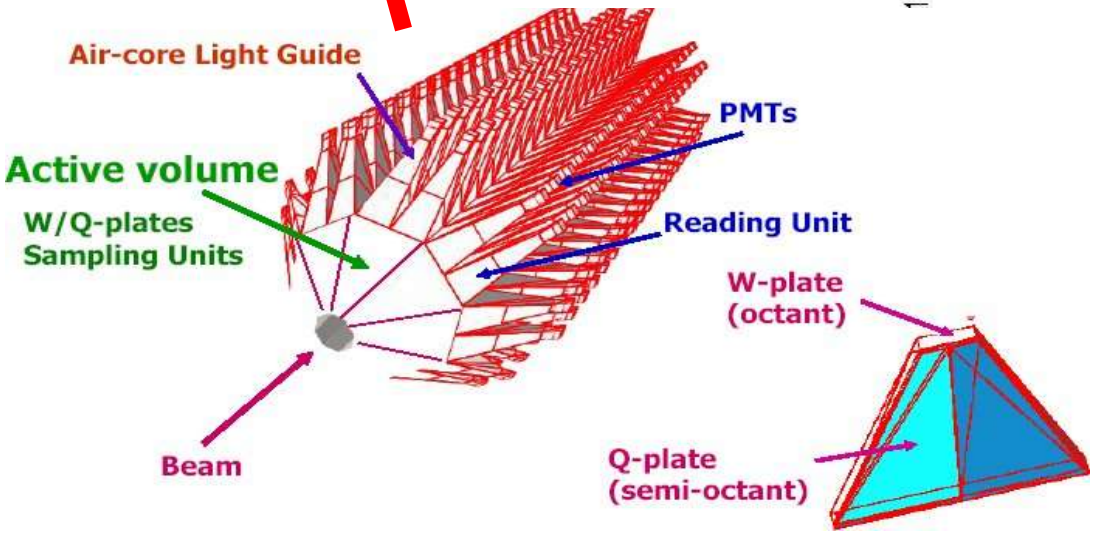
T2 and CASTOR (5.1 <η < 6.7)



CASTOR forward calorimeter (5.1 <η < 6.6)

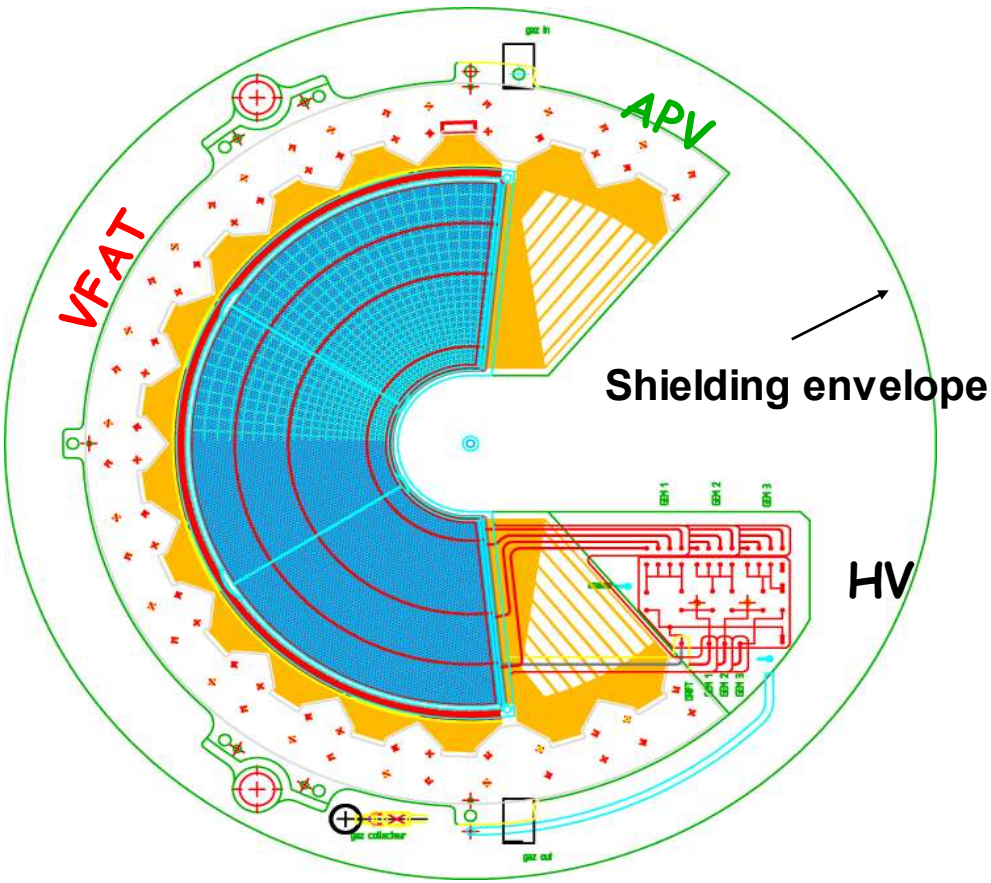


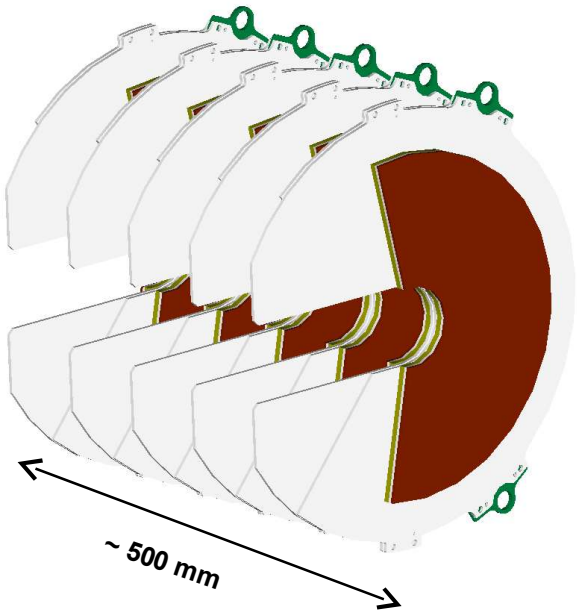
- Tungsten plates + quartz fibres
- Cherenkov sampling calorimeter
- Light-guides + APDs readout
- Azimuth segmented (8 octants)
- EM section: 11.2 cm ~ 19 X_0
- HAD+EM sections: 136 cm~ 10λ_I
- 192 channels



TOTEM T2 Tracker (5.3 <η< 6.7)

- TOTEM GEM ("Gas Electron Multiplier") charged particle telescope detector:

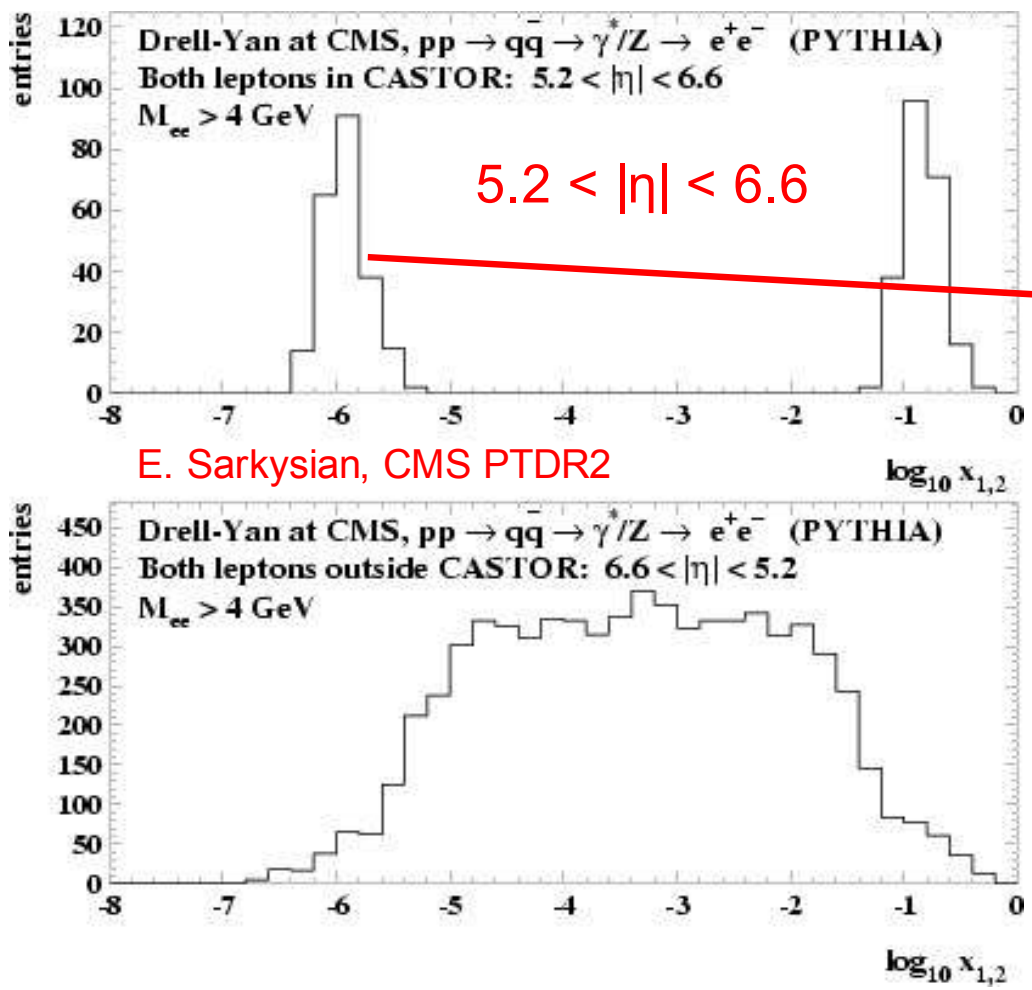




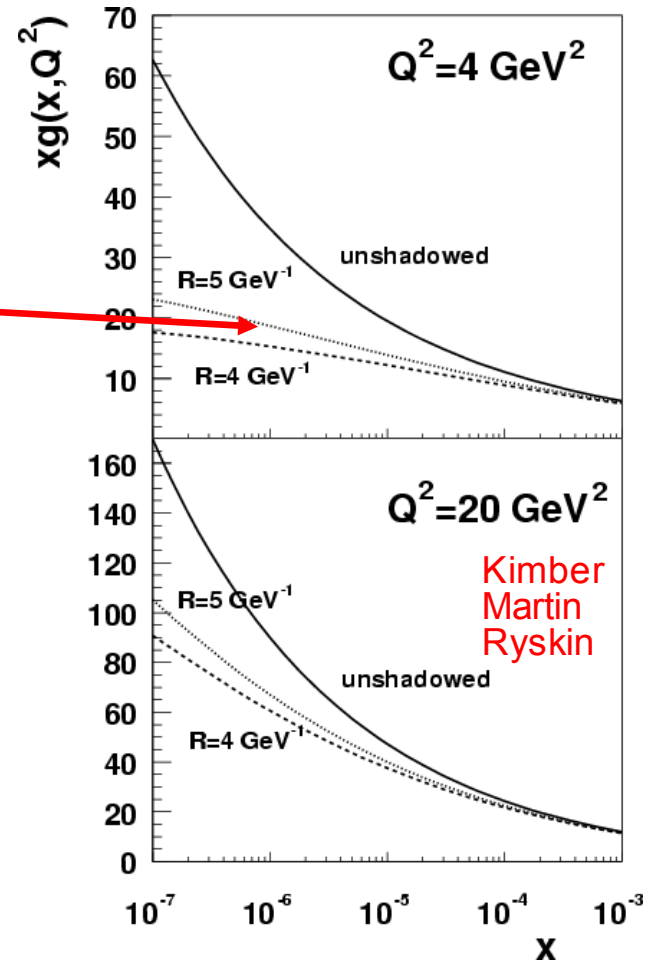
GEM half telescope

Low-*x* measurements with T2 + CASTOR

- Drell-Yan:



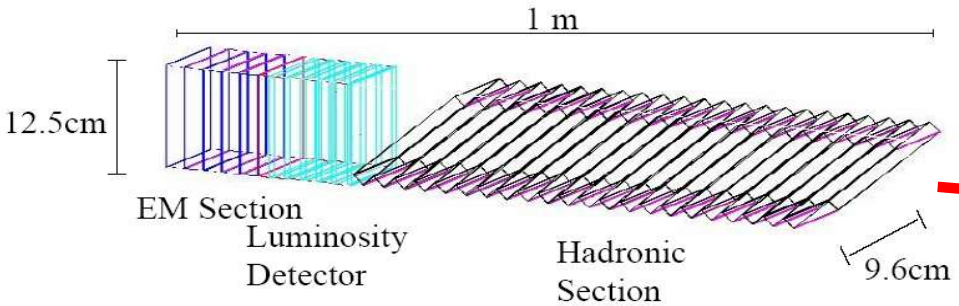
E. Sarkysian, CMS PTDR2

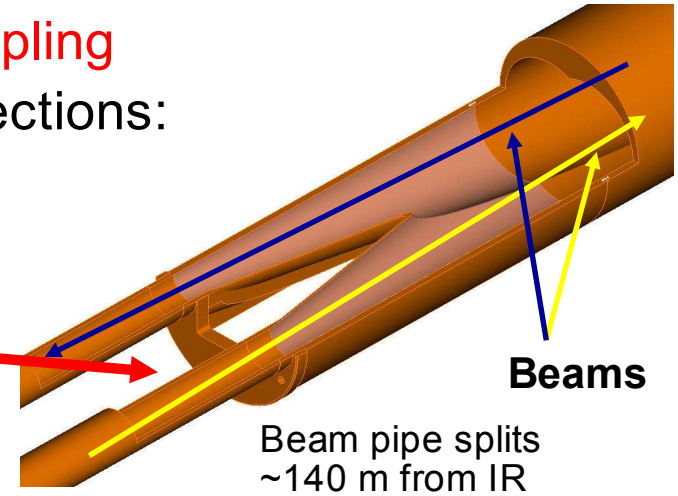


- Inclusive high-p_T hadrons likely possible too (under study ...).

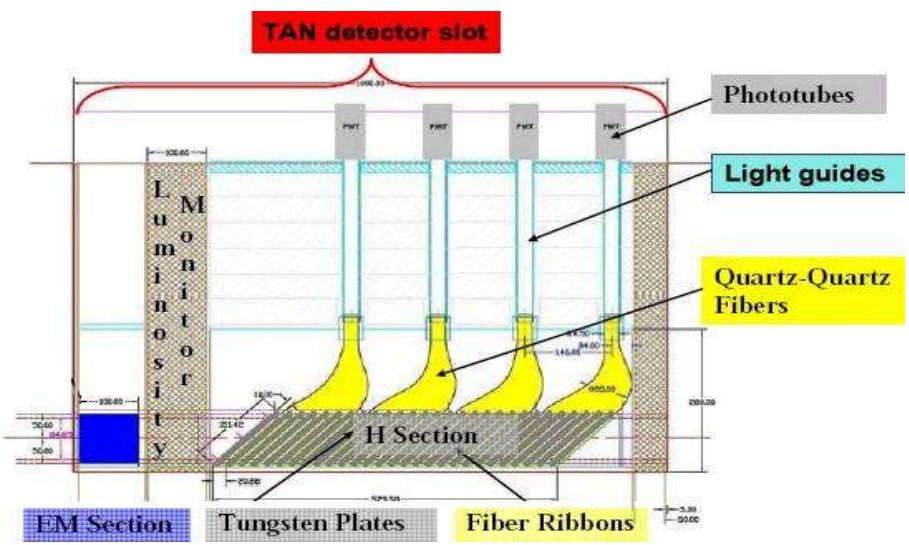
Zero Degree Calorimeter (|η|> 8.1 neutral)

- ZDC = Tungsten-plates+Quartz-fibres sampling Cerenkov calorimeter with HAD and EM sections:



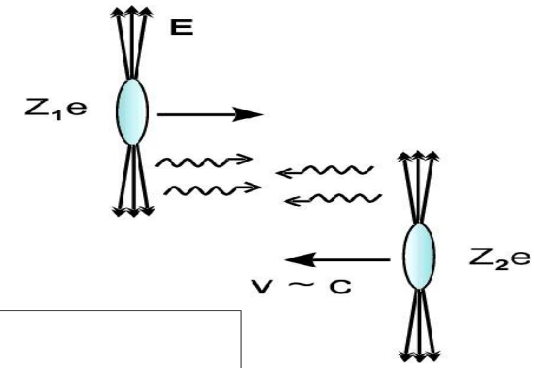


- ZDC: forward neutral energy (n,γ) detection:



- *(Follows closely RHIC experience).*
- EM section: x33 2mm-W cells (~$19X_0$)
- HAD sect: x24 15mm-W cells (~$5.6\lambda_0$)
- PMTs: R7525 (as HF)
- Rad hard to ~20 Grad (AA, pp low lum.)
- Energy resolution (n,γ): σ/E~10%
- Position resolution: ~2 mm (EM sect.)
- Signals available for L1

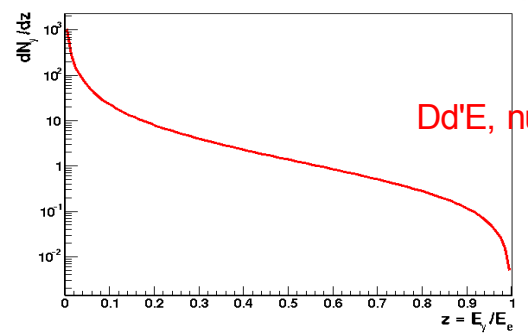
γA : LHC as a photon collider



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

$$\frac{dN_\gamma}{dE}(b > b_{min}) \propto \frac{\alpha_{em} Z^2}{\pi} \frac{1}{E}$$

(soft bremsstrahlung γ spectrum)



Dd'E, nucl-ex/0601001

- 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: $\sqrt{s_{\gamma A}} \approx$ 0.7 – 2. TeV ≈ (3 – 10) × $\sqrt{s_{\gamma p}}$(HERA)
  - Bjorken x range: (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}
- Very large pQCD cross-sections:

QQbar: σ (LHC) ~ (40–100)×σ(RHIC) J/ψ: 32 Hz (30M/year), Υ(1S): 170000 (1st UPC meas.)

γA : ZDC-tagged hard photoproduction

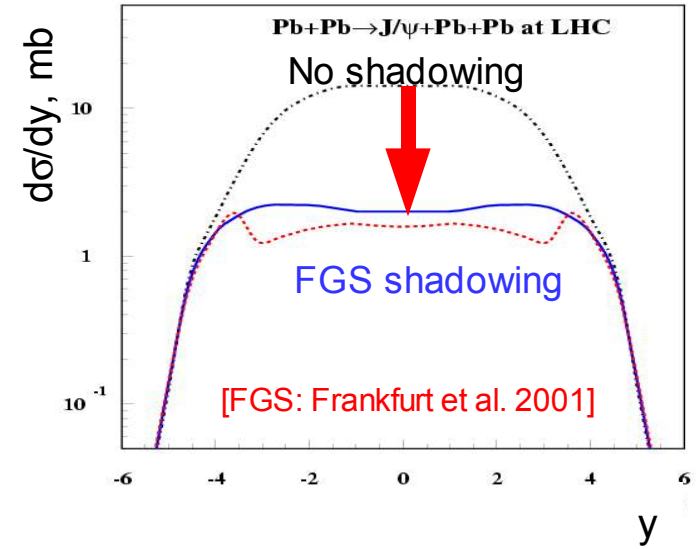
- Quarkonia: $\gamma + A \rightarrow J/\Psi, \Upsilon + A$ very sensitive to nuclear gluon density at small-x:

  Perturbative process:

  $\sigma(J/\Psi, \Upsilon) \sim | xG(x,Q^2)|^2$

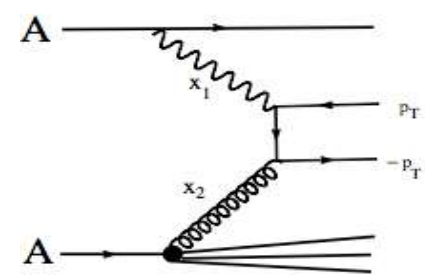
  ~30% reduction of $G(x,Q^2) \Rightarrow 0.5 \cdot \sigma_{J/\Psi,\Upsilon}$

  Even stronger suppression expected if gluon saturation (CGC).



- Dijet: via gluon exchange (well described in QCD & tested @ HERA)

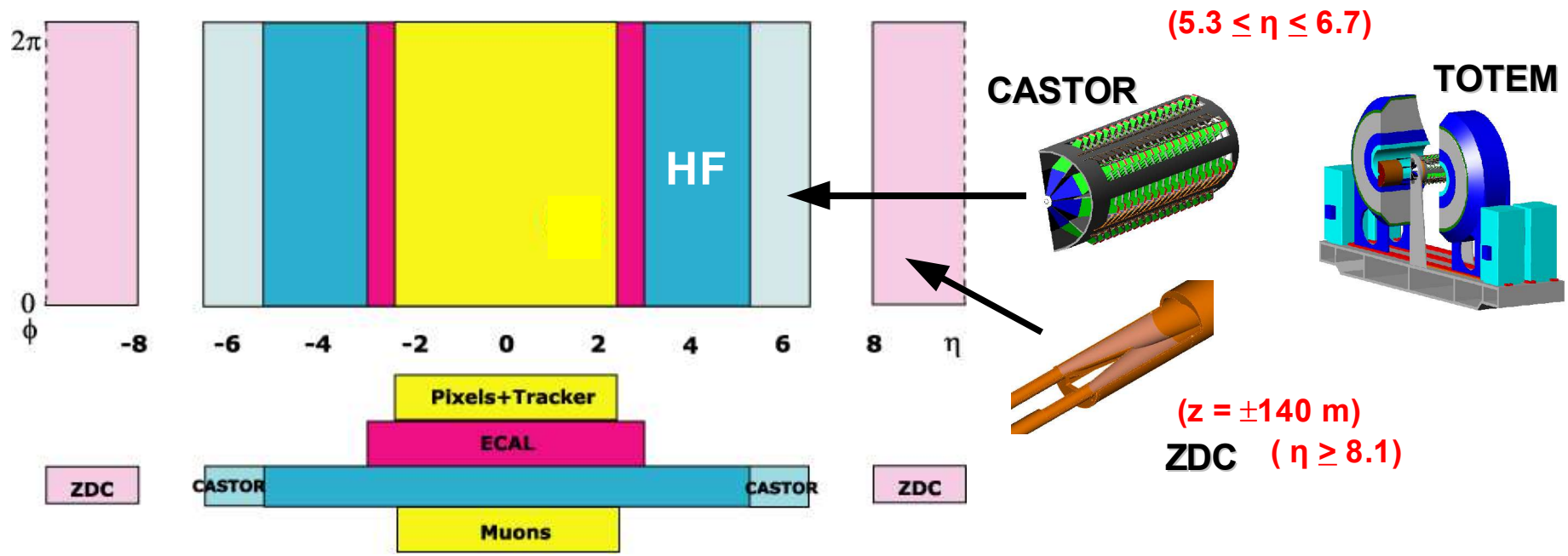
  Wider range of Q^2 than QQbar.
  Photon-jet (~1% of dijet rate) has clear signature
  ttbar possible in pA collisions (measure charge of top quark)



- Bottom line: all UPC processes only possible w/ ZDC neutron-tagging

Summary: CMS = low-*x* QCD experiment at LHC

- HF,CASTOR,ZDC + TOTEM: Unparalleled forward coverage at LHC



- Unique low-x QCD capabilities in pp, pA, AA at LHC.
- Hard scattering measurements (jets, high-p_T, DY) down to $x \sim 10^{-6}$
- Studies of gluon saturation,CGC, non-linear QCD fully accessible.

Backup slides

...

- ..

100 cm of space available
(9.6 x 12.5 x 100 cm)

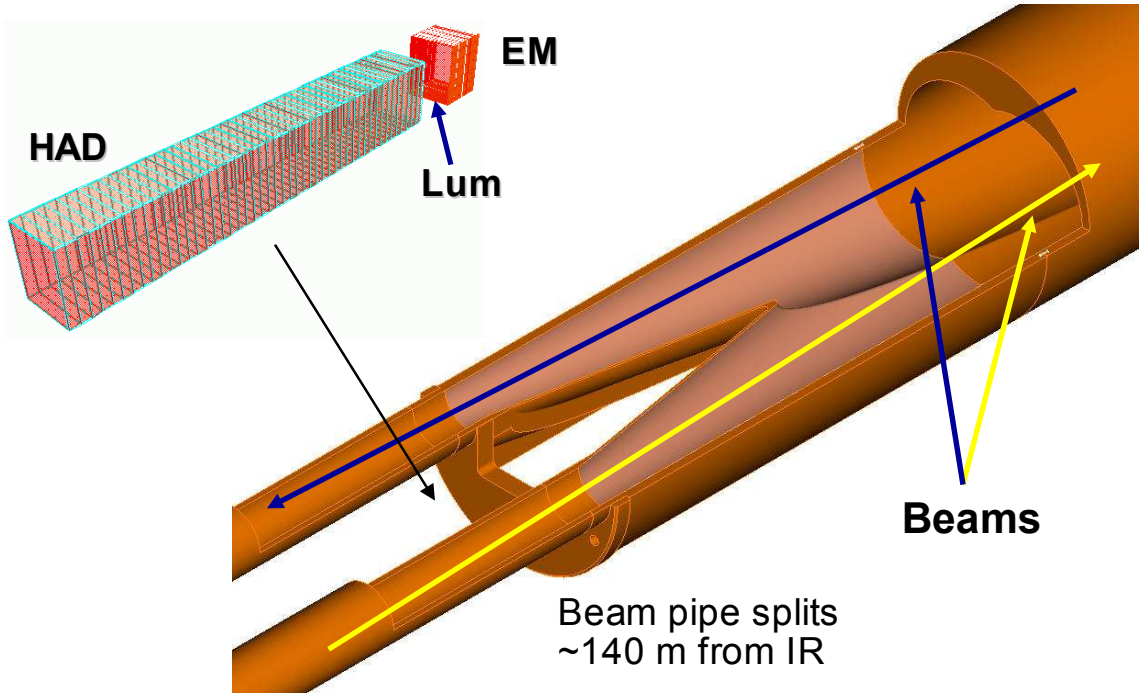
Quartz fiber/tungsten plates

EM section segmented horizontally,
HAD section longitudinally

Luminosity detector in 2nd 10 cm

Improves resolution at large b

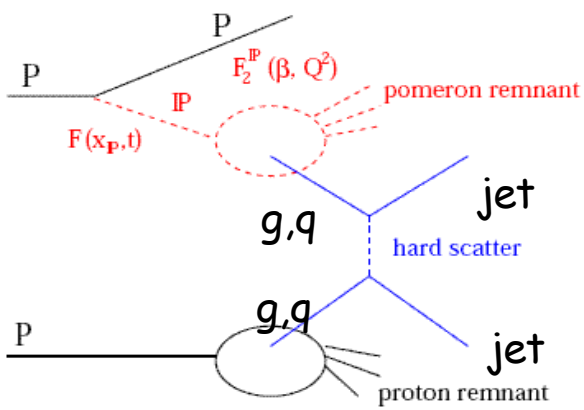
Readout through HF electronics –
signals available for L1 trigger

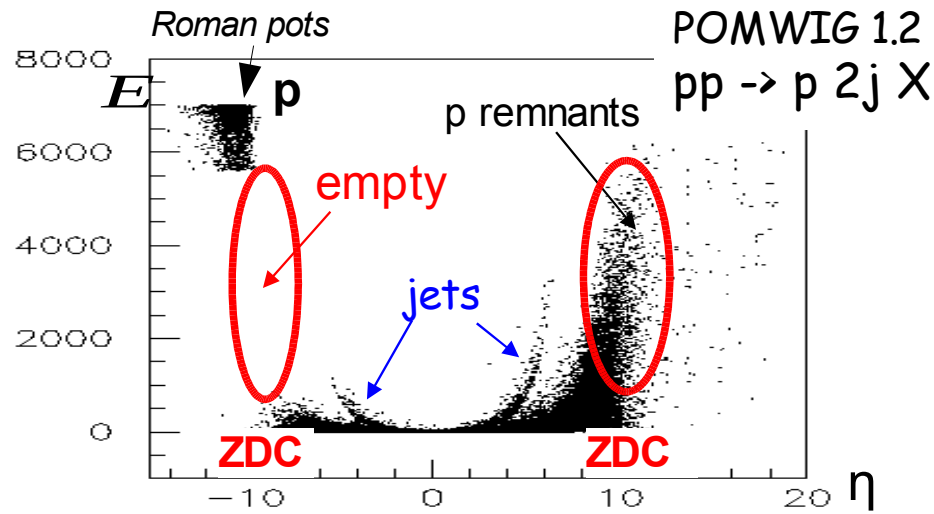


Diffractive pp collisions

- No ZDC activity = large rapidity gap. Complements (trigger & offline) leading proton detectors e.g. in dijet single diffraction:

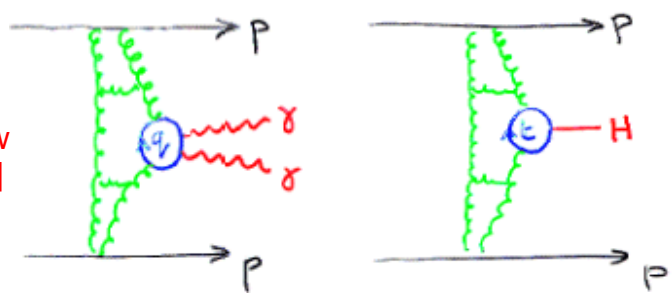
[from A.Sobol CMS, Feb'06]





- ZDC (even w/o leading p detection) can help "calibrate" DPE Higgs prod.:

[from M.Albrow CMS, Feb'06]



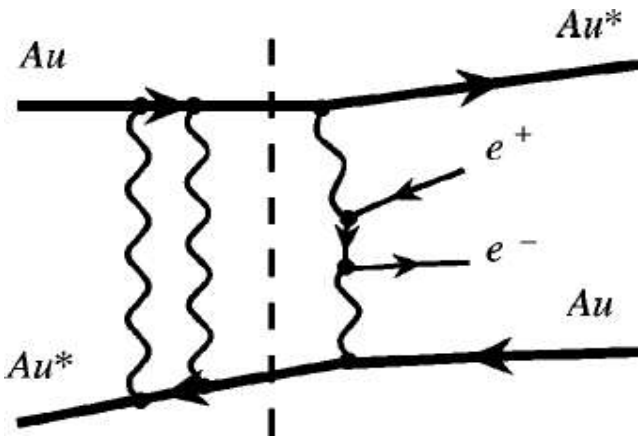
1st process measurable w/ ZDC.
Both closely related (QCD part identical).
Measurement of one constrains the other.

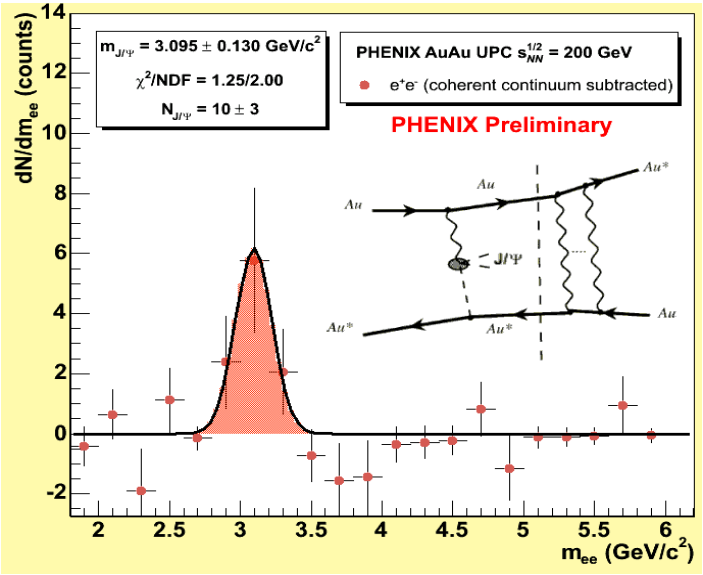
- Bottom line: ZDC reduces to "zero" holes & cracks in CMS (full 4π). Helps all diffractive ($\mathbb{P}$-, γ-mediated) analysis in pp,pA,AA.

$\gamma\gamma$, γA : physics topics

- Typical diagrams for $\gamma\gamma$ and γA collisions:

Dd'E, nucl-ex/0601001





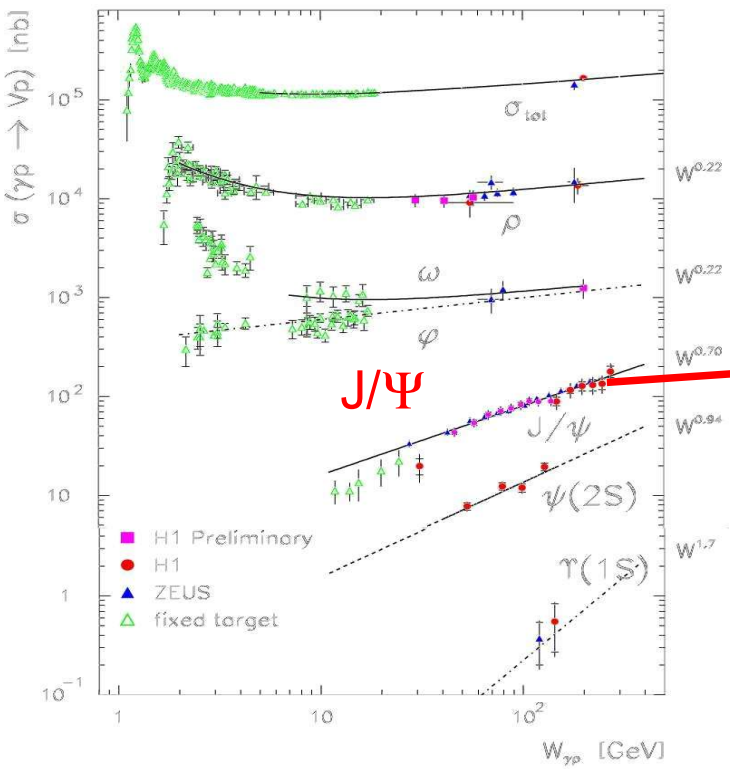
- Physics: QED, precision QCD — Precision QCD *(low bckgd, simpler initial state than p,A+A)*
- Measurements: $\ell^+\ell^-$, C-even $c\bar{c}$ $b\bar{b}$, W^+W^-... — Quarkonia, heavy-Q, jets ...
- Topics: QED in strong regime ($Z\alpha_{em}$~1), heavy-Q spectroscopy, [quartic GC ($WW\gamma\gamma$), ...] — Nuclear $G_A(x,Q^2)$, low-x physics, QQbar in cold nuclear matter

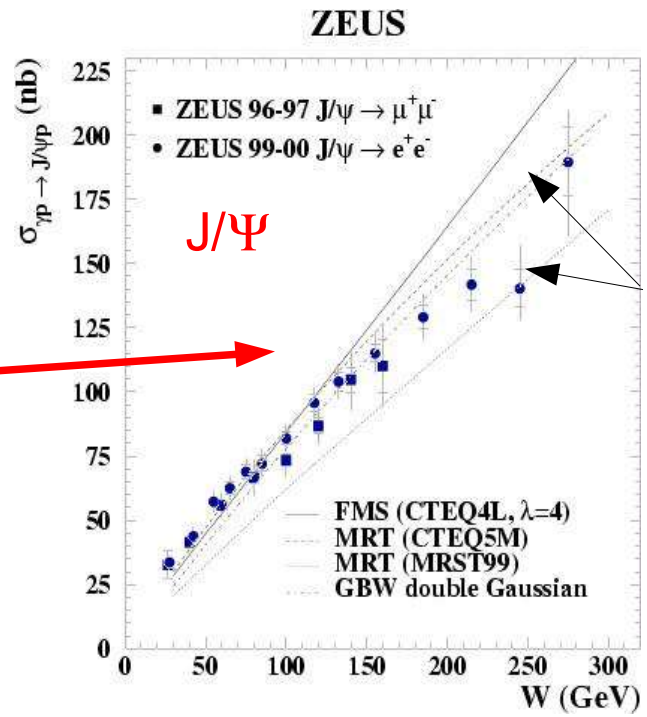
- All UPC measurements at RHIC: ZDC-triggered (neutron tagging) !

Example: Quarkonia γ-production @ HERA

- HERA: $\gamma p \to Vp$ ($V=J/\Psi,\Upsilon$) very sensitive to gluon distrib. at small-x:

Perturbative process: $$\left.\frac{d\sigma(\gamma p \to V p)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG(x,Q^2)\right]^2, \text{ with } Q^2 = M_V^2/4, \quad x = M_V^2/W_{\gamma p}^2$$

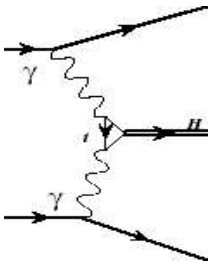




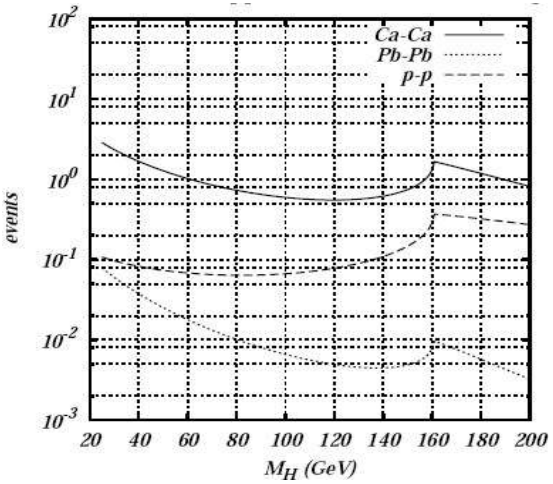
Ryskin et al.
ZPC 76 (1997)231

Discriminates diff. Ansätze & evolutions of $G(x,Q^2)$

$\gamma\gamma$: Discovery physics & others



- $\gamma\gamma \rightarrow$ Higgs ($\rightarrow b\bar{b}$)
  - Rate is very low (better w/ lighter ions, pA or pp)
  - Establishes the nature of Higgs (J^{PC}, SM vs. MSSM)



- $\gamma\gamma \rightarrow W^+W^-$ & photoproduction of W^+W^-:
  - Study quartic/triple $\gamma\gamma WW$, γWW vertices
  - Anomalous coupling sensitive to new physics
- Other "discovery" channels:

  $\gamma\gamma$ production of magnetic monopoles, SUSY, ...
- Others:
  - e^+e^- pair production

    Tests QED in very strong fields (grazing b=2R colls ~ 5 e^+e^- pairs produced). Huge rates: σ~13,000 b in ALICE inner Si
  - Quantum correlations in multiple Vector Meson Production
  - QQbar spectroscopy: $\gamma+\gamma \rightarrow 0^{+-}2^{++}$ states (η_b, χ_{b0}, χ_{b2},...).

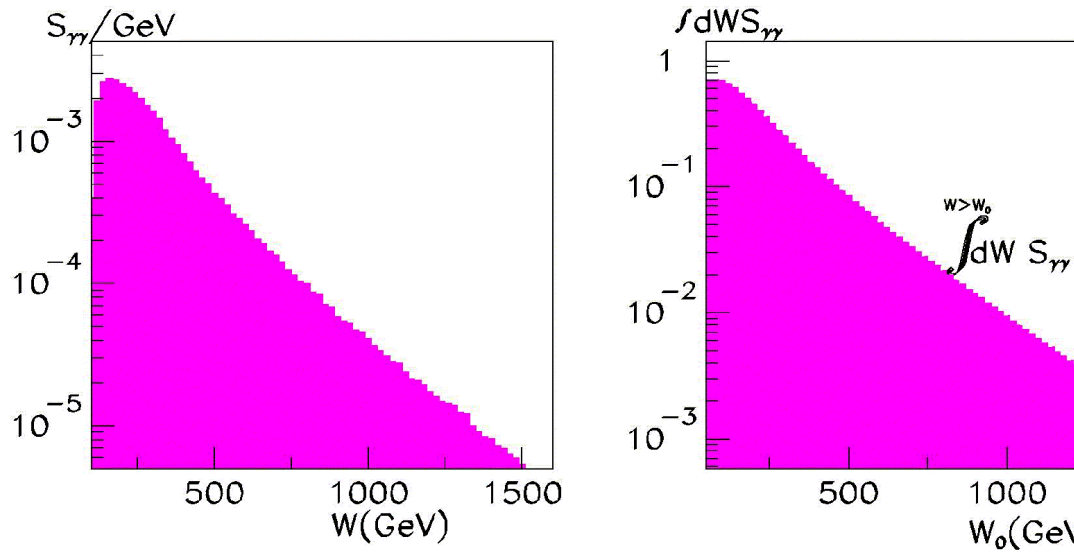
γp interactions at the LHC

➢ ..

- 0.01 < x < 0.1, γ tagging range
- 0.005 < x < 0.3, Bjorken-x range

γ g luminosity spectra

K Piotrzkowski

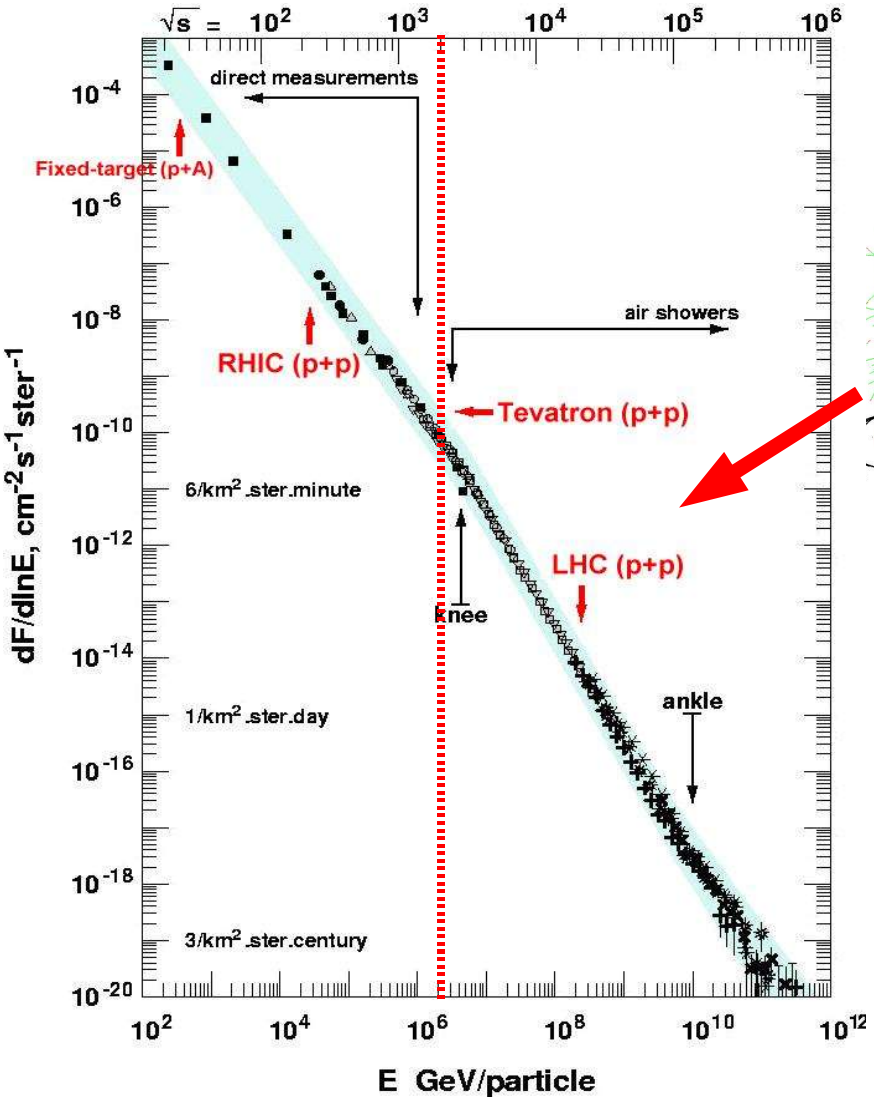


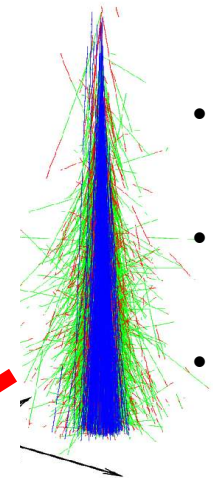
γp Physics Menu:

- anomalous W and Z production at $W_{\gamma q} \geq$ 1 TeV
- top pair production – top charge + threshold scanning?
- single top production and anomalous Wtb vertex
- SM BEH – for example, γ b → H b, γ q → H W q
- SUSY studies (complementary to the nominal ones) - $H^+ t$ production (and H^{++}), b and t spairs, $\tilde{t}\chi$ pair, ...
- Exotics: compositness, excited quarks, .

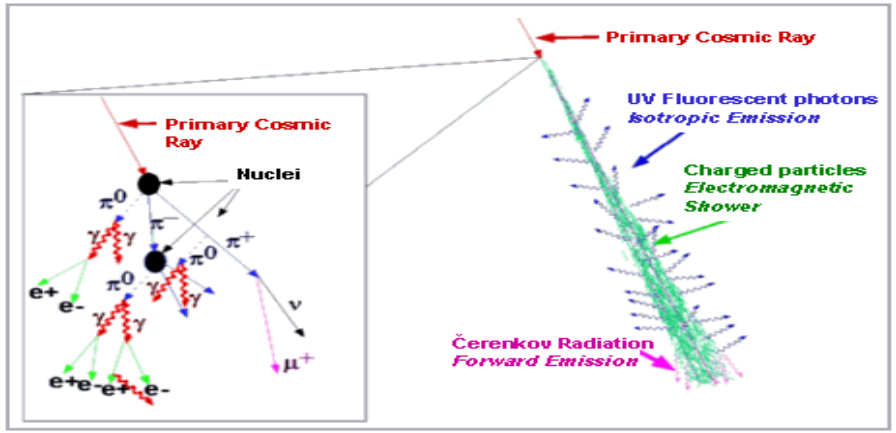
UHE cosmic-rays via extended air-showers

- Cosmic-ray energy spectrum:



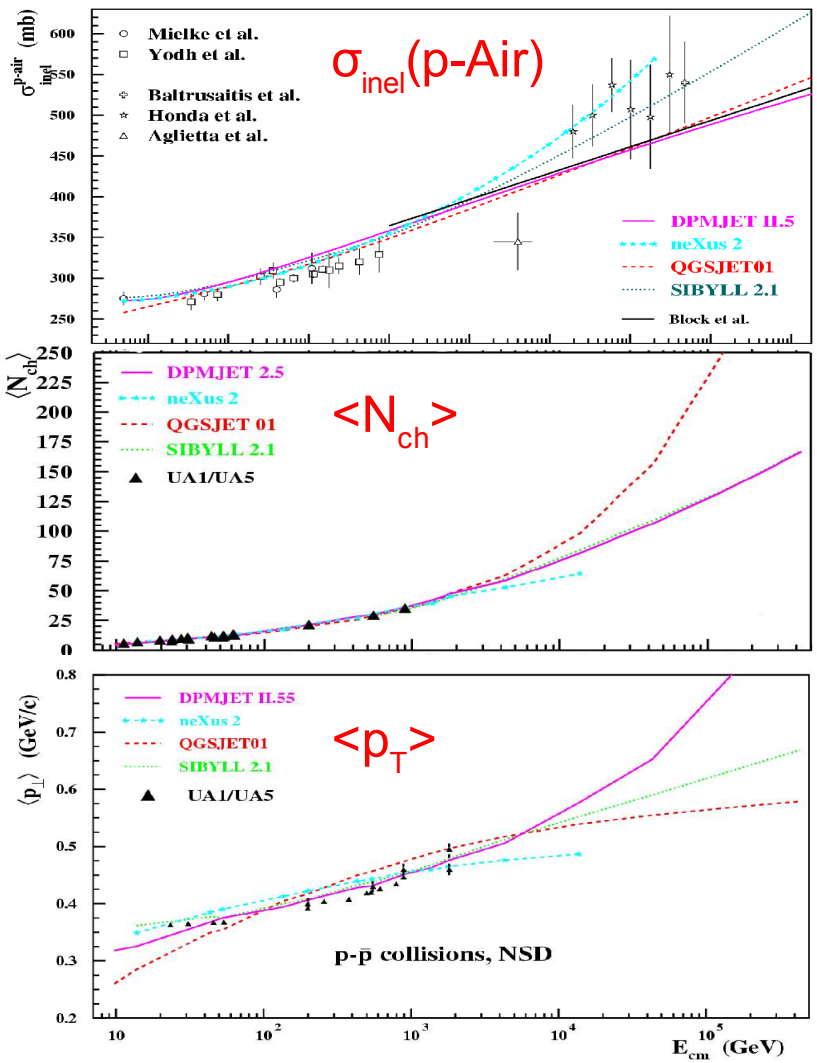


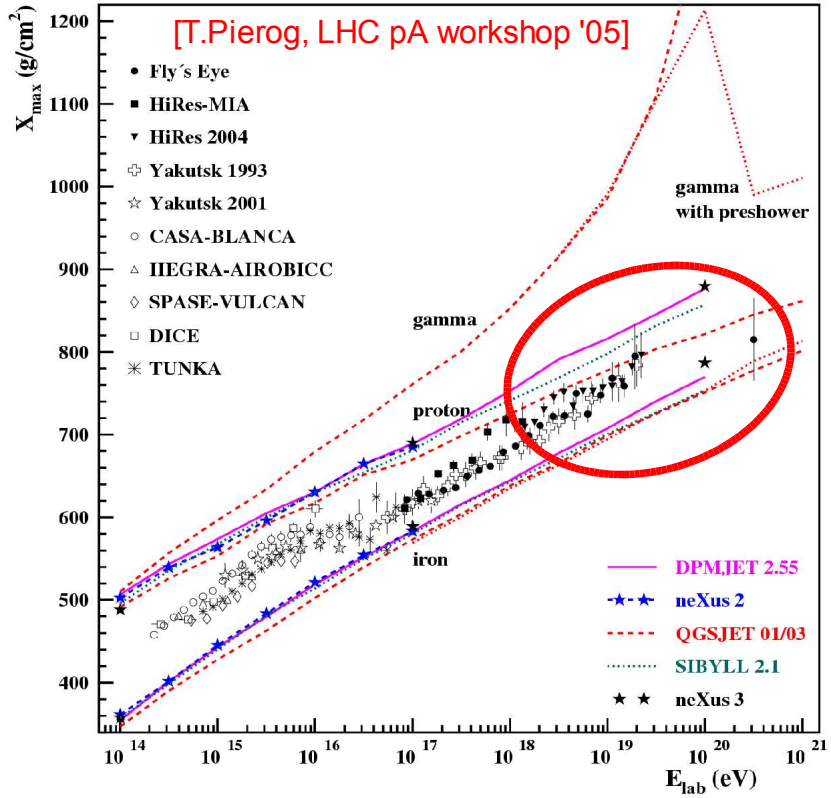
- Low stat. for E_{lab} > 100 TeV (10^{-14} eV) : only "indirect" measurements (EAS) exist
- Cosmic-ray energy & mass determined via Monte Carlo codes.
- Shower development dominated by forward, soft QCD interactions.
- Primary interactions extrapolated from SppS,Tevatron data (E_{lab} <100 TeV) up to a factor x10^6



Current uncertainties of hadronic models

- Key (Regge-Gribov) QCD models predictions in PeV-range:

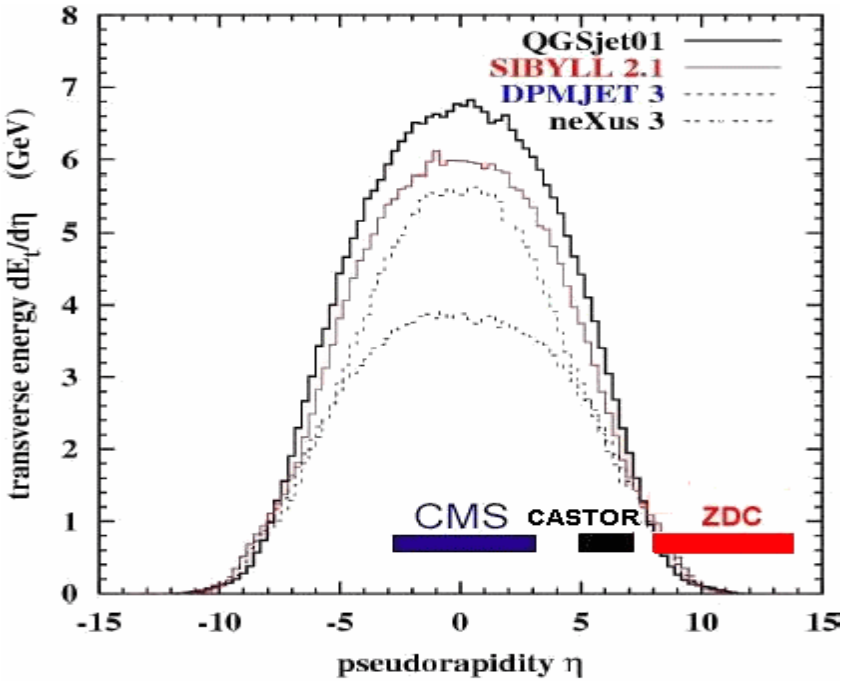


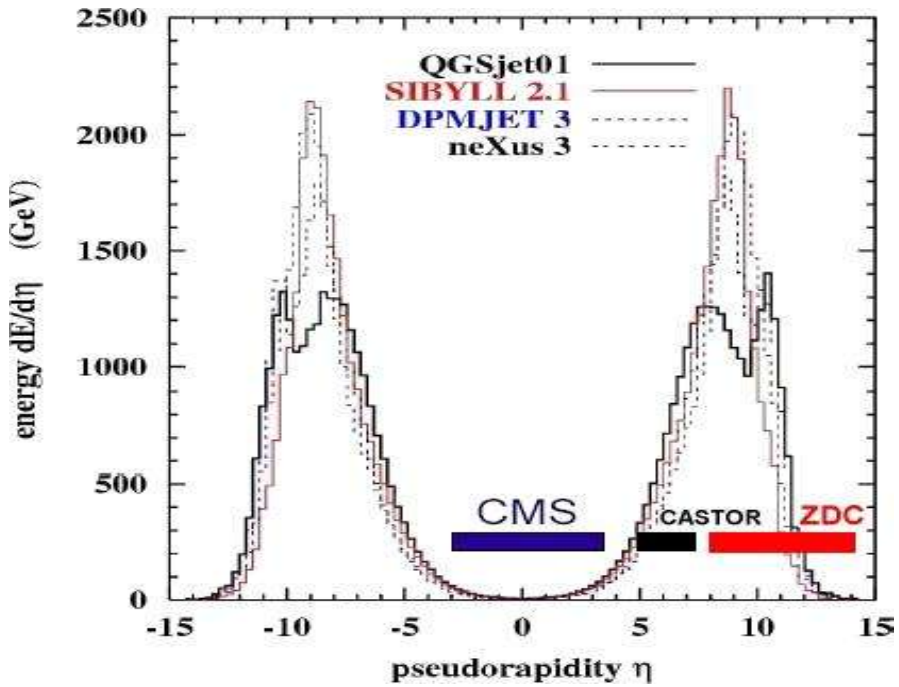


- Wide range of predictions !
- Air showers rather insensitive (correlated cross-section & multiplicity: partial compensation).
- Yet ... ~20% energy & composition uncertainties esp. at high-end of spectrum (E >10^{18} eV)

Calibration and tuning of hadronic models

- Model predictions of particle multiplicity & energy flow at LHC:





- ZDC: Direct measurement of forward leading baryon (neutron) and π^0 cross-sections & energy in pp,pA,AA at E_{lab} ~ 100 PeV ! (strong model constraint)