Forward detectors & forward physics at the LHC

Joint Meeting HLPW08, March 2008

Spa, Belgium

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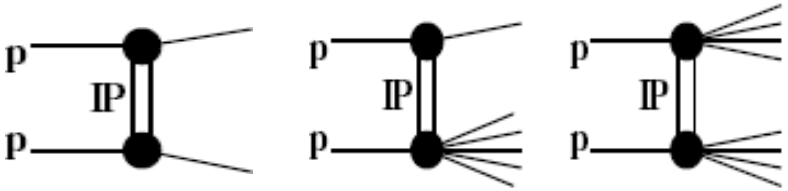
CERN

(*) arXiv:0708.0551 [hep-ex]

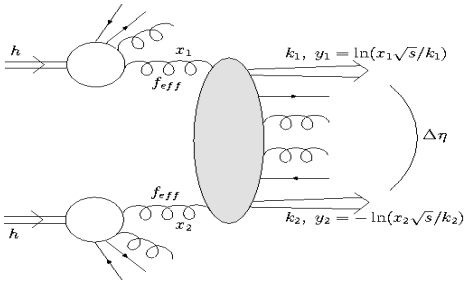
Why forward physics ?

- Many interesting (mostly color-singlet exchange) scattering processes at the LHC are characterized by forward particle production:

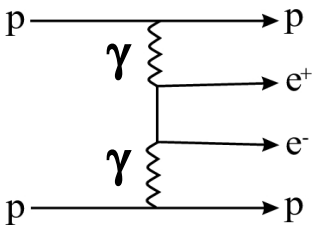
QCD: elastic, diffractive interactions

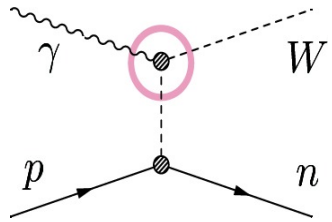


QCD: low-x

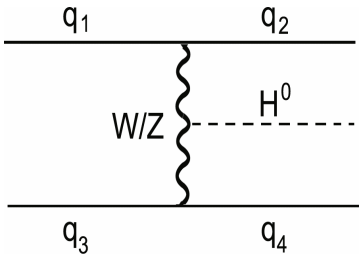


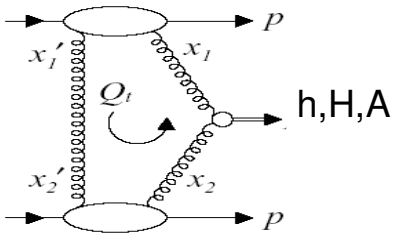
EWK: two-photon, photon-proton colls.





Higgs: VBF, central exclusive





Beyond SM: MSSM Higgs, ...

Forward measurements ("selected menu")

1. Diffractive & elastic p-p collisions:
   - Total cross-sections, elastic scattering.
   - Soft & hard diffraction. [Cf. also Alice Dechambre]

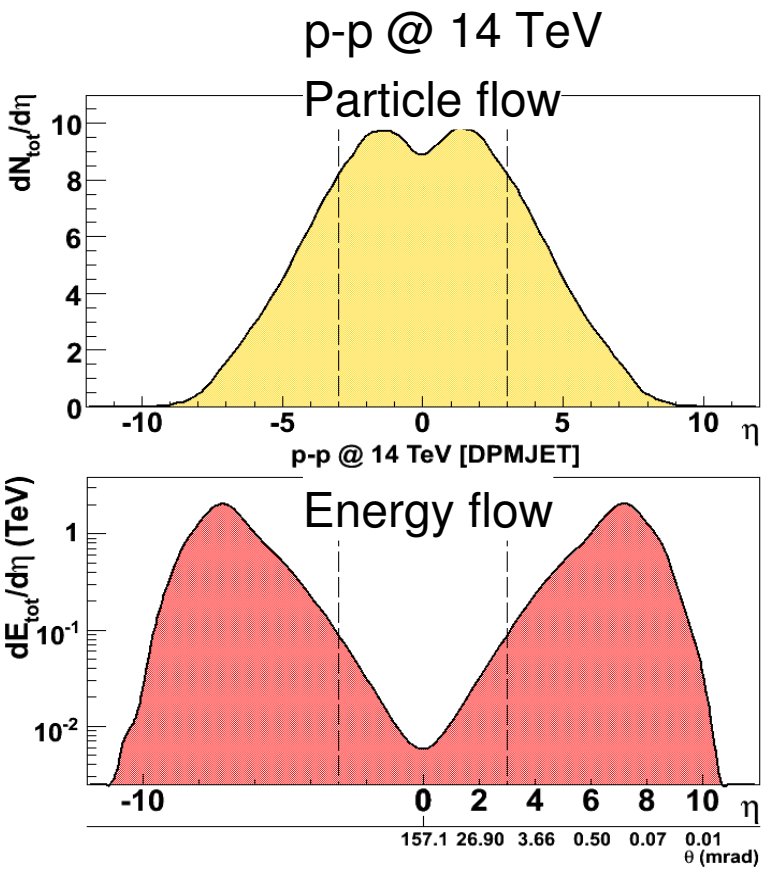
2. Low-x QCD:
   - Parton saturation, non-linear QCD evolution via:
     (i) forward jets, $Q\bar{Q}$ (p-p, p-A), (ii) $Q\bar{Q}$ photoprod. (γ-p, γ-A interactions)

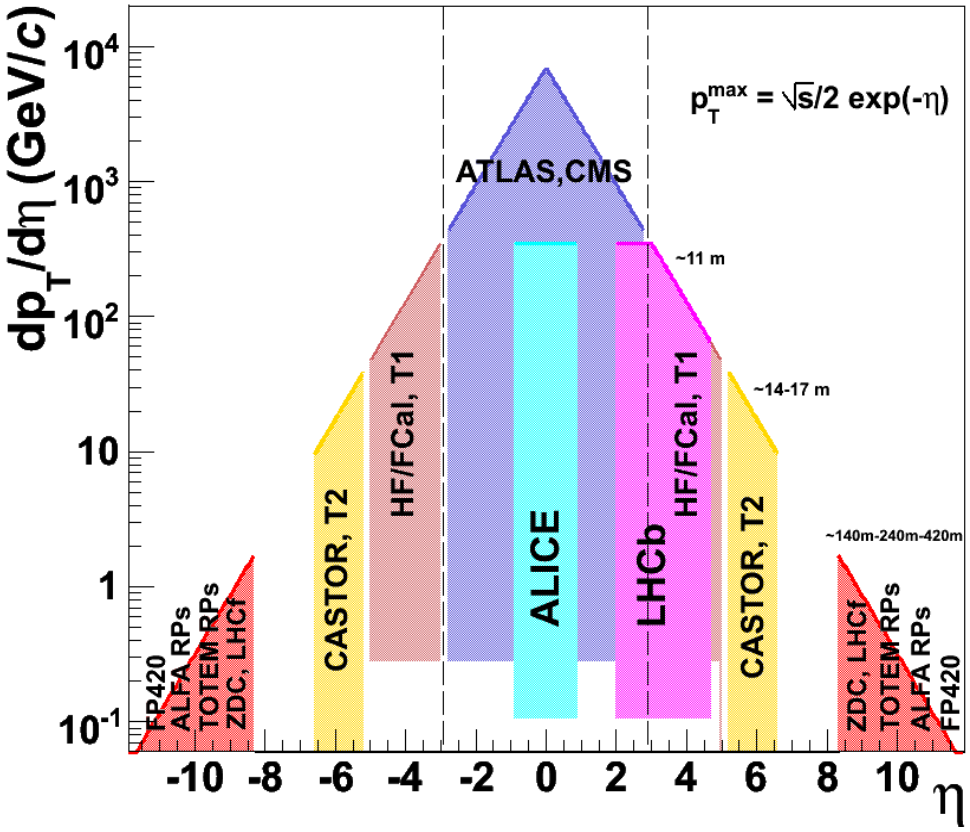
3. UHE Cosmic-rays physics:
   - Forward energy & particle flows (p-p, p-A, A-A).

4. EWK: two-photon, γ–proton interactions: [Cf. also Séverine Ovyn]
   - Absolute luminosity (~3% QED precision) via: $pp \to \gamma\gamma \to p\, \ell^+\ell^- p$
   - Triple/Quartic gauge boson couplings via: $pp \to \gamma p \to pnW$, $\gamma\gamma \to WW,ZZ$

5. Higgs & beyond SM:
   - Vector-Boson-Fusion Higgs tagging
   - Central exclusive (SM, MSSM) Higgs

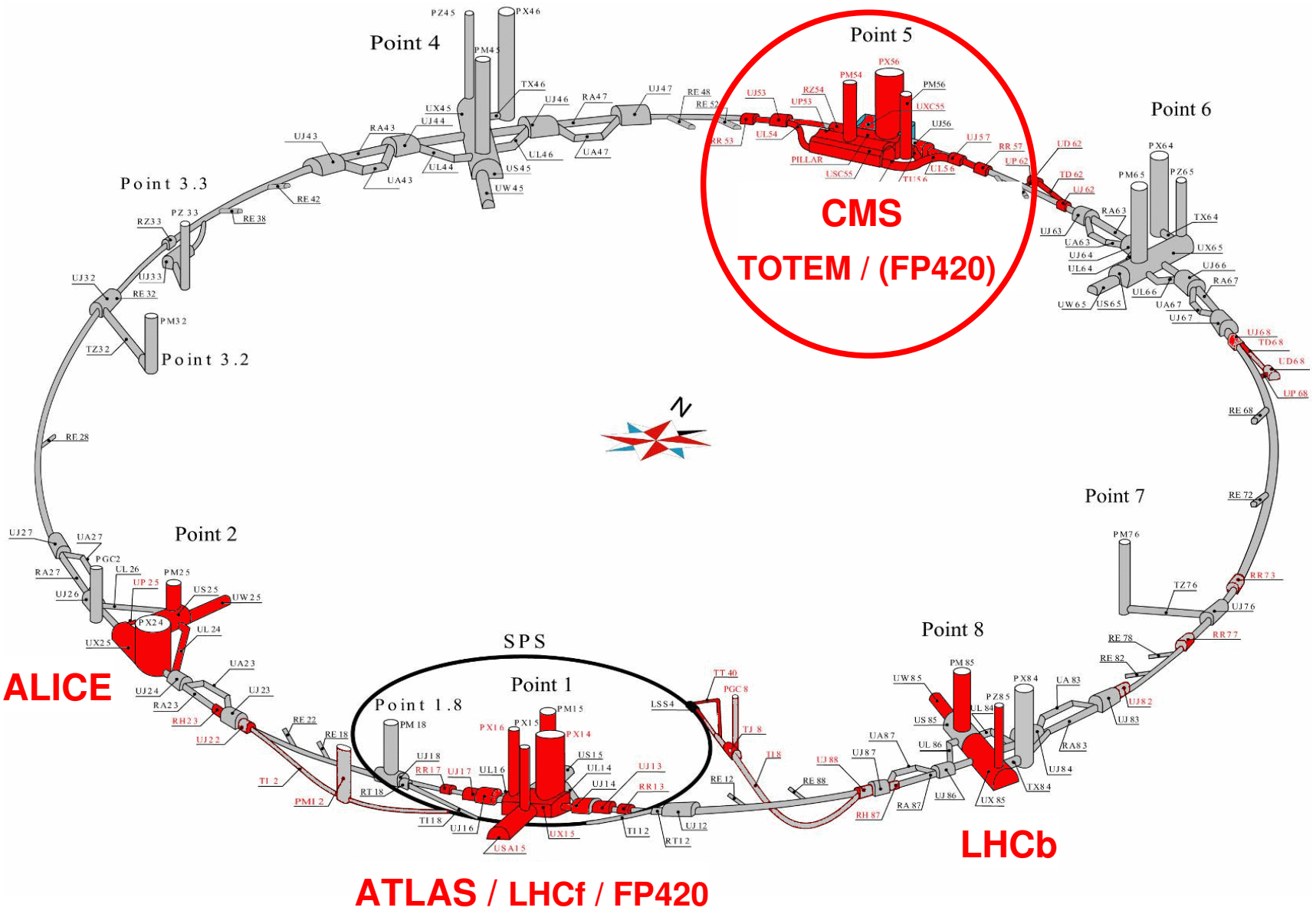
The LHC experiments: (p_T,η) acceptance



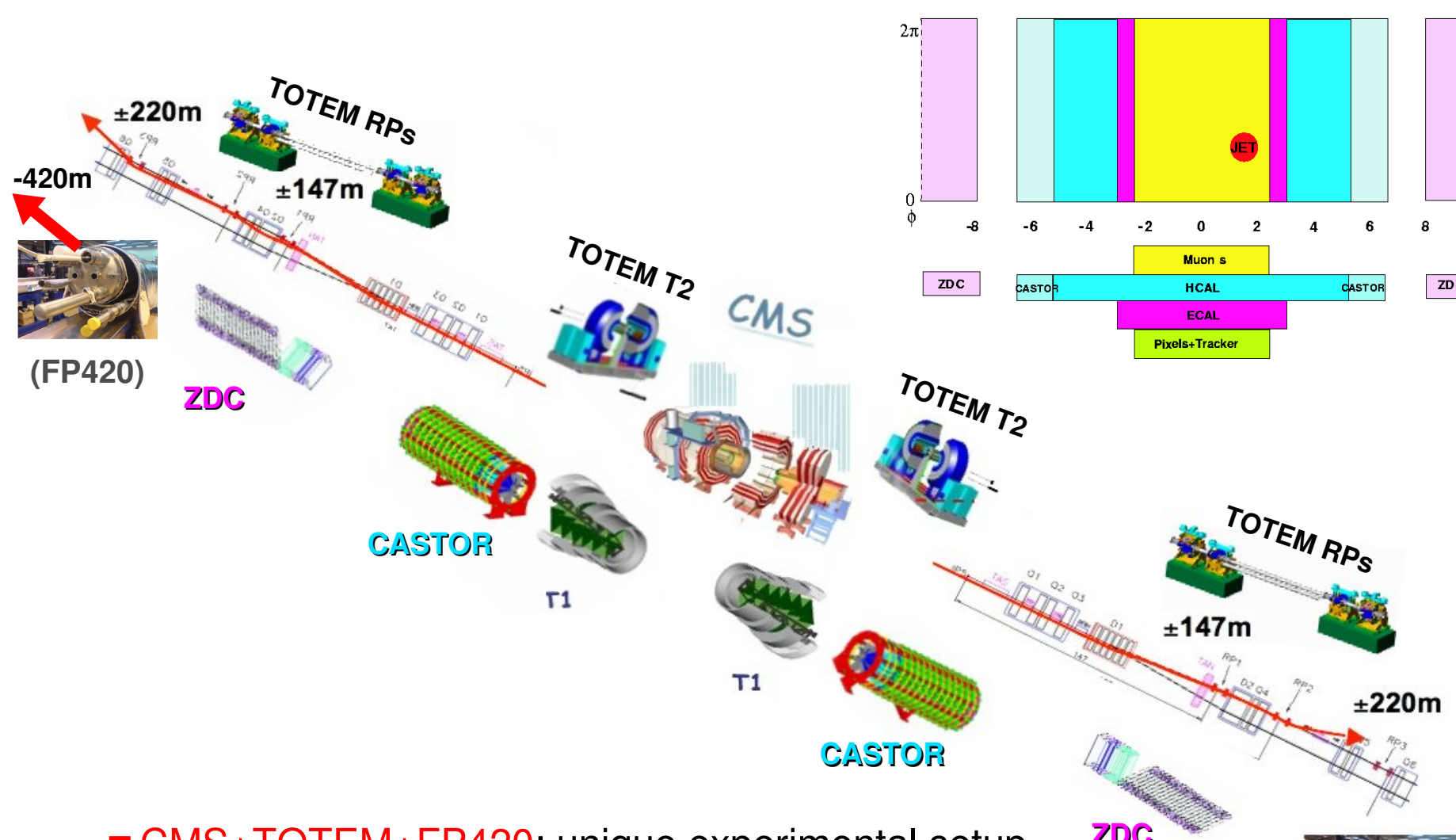


- Particle production at the LHC over $\Delta\eta \sim 2\times\ln(\sqrt{s})/m_p \sim 20$
- All phase-space virtually covered (1st time in a collider)

The LHC experiments: zoom at IP5

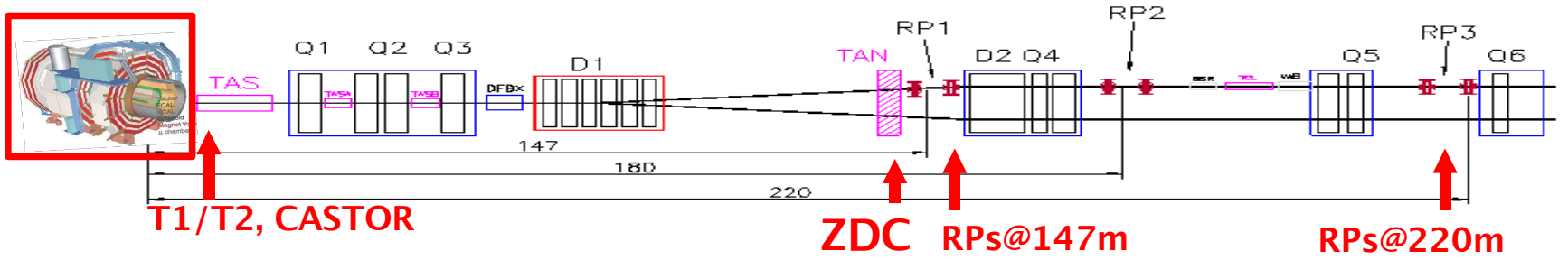


CMS+TOTEM forward detectors



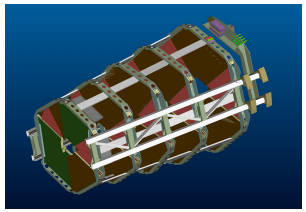
- CMS+TOTEM+FP420: unique experimental setup
- All phase-space virtually covered (1st time in a collider)

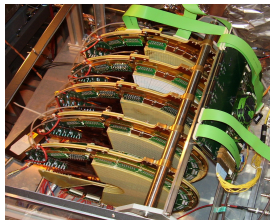
CMS+TOTEM forward detectors



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

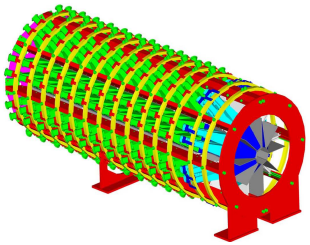
  fwd. particles: soft diffraction (SD,DPE), MB/UE/MPI

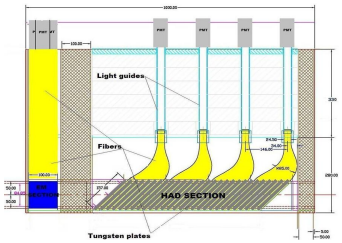




- **CASTOR** (W/Q-fiber calo): $5.1 < |\eta| < 6.6$

  fwd. particles: jets, ME_T, diffract., low-x QCD, MB/UE/MPI, heavy-ions (L1, centrality, ...), CRs



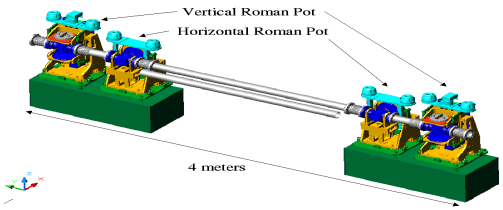


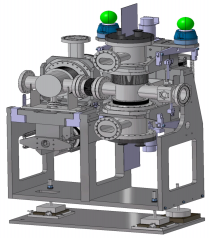
- **ZDC** (W/Q-fiber calo): $|\eta| > 8.3$ (neutral)

  zero-degree n,γ: CRs, HI (L1, centrality, γ-A,...)

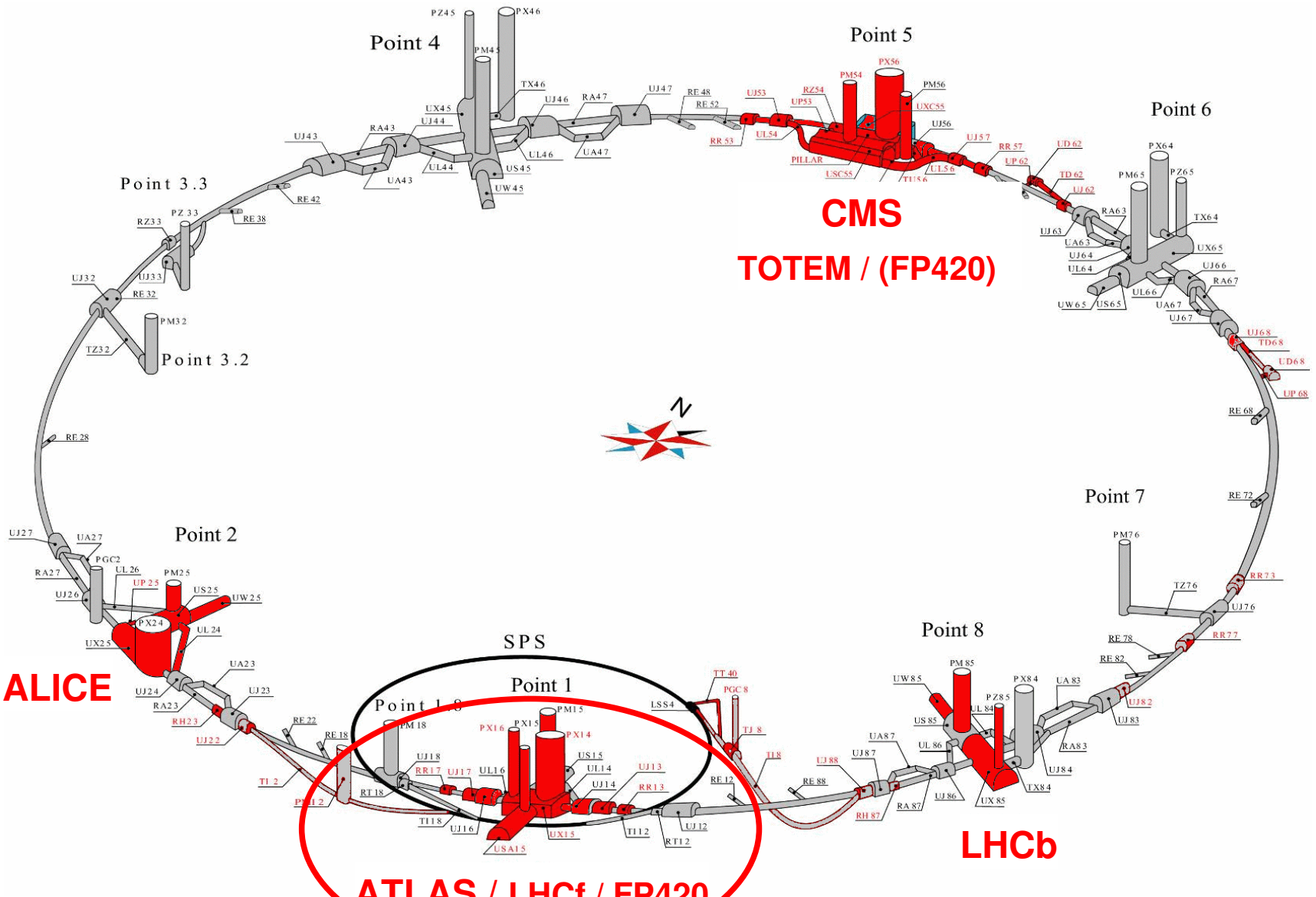
- **TOTEM Roman Pots** (Si): ±147, ±220 m

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

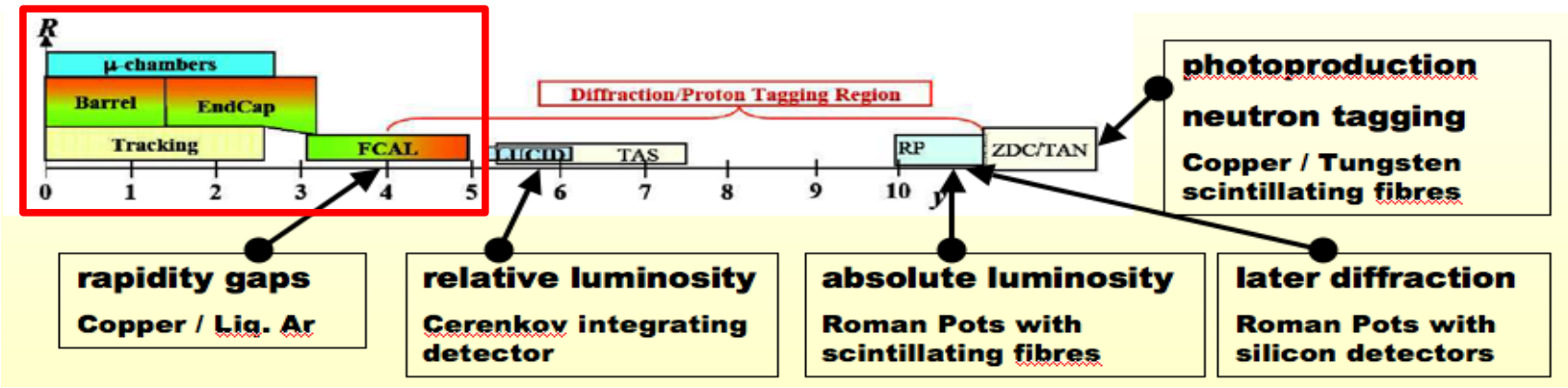


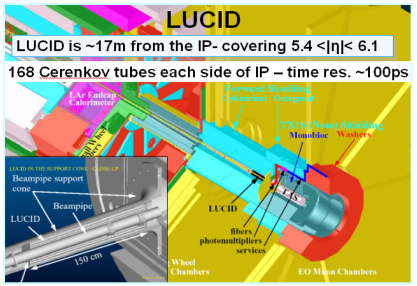


The LHC experiments: zoom at IP1



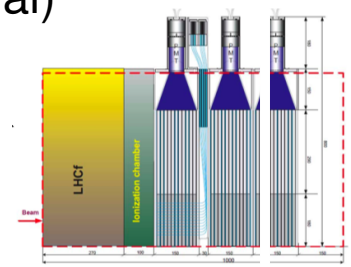
ATLAS forward detectors



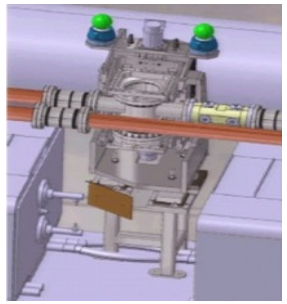


- **LUCID** (Cerenkov Tubes): 17 m, 5.4 < |η| < 6.1
  rap. gaps: relative luminosity, diffraction

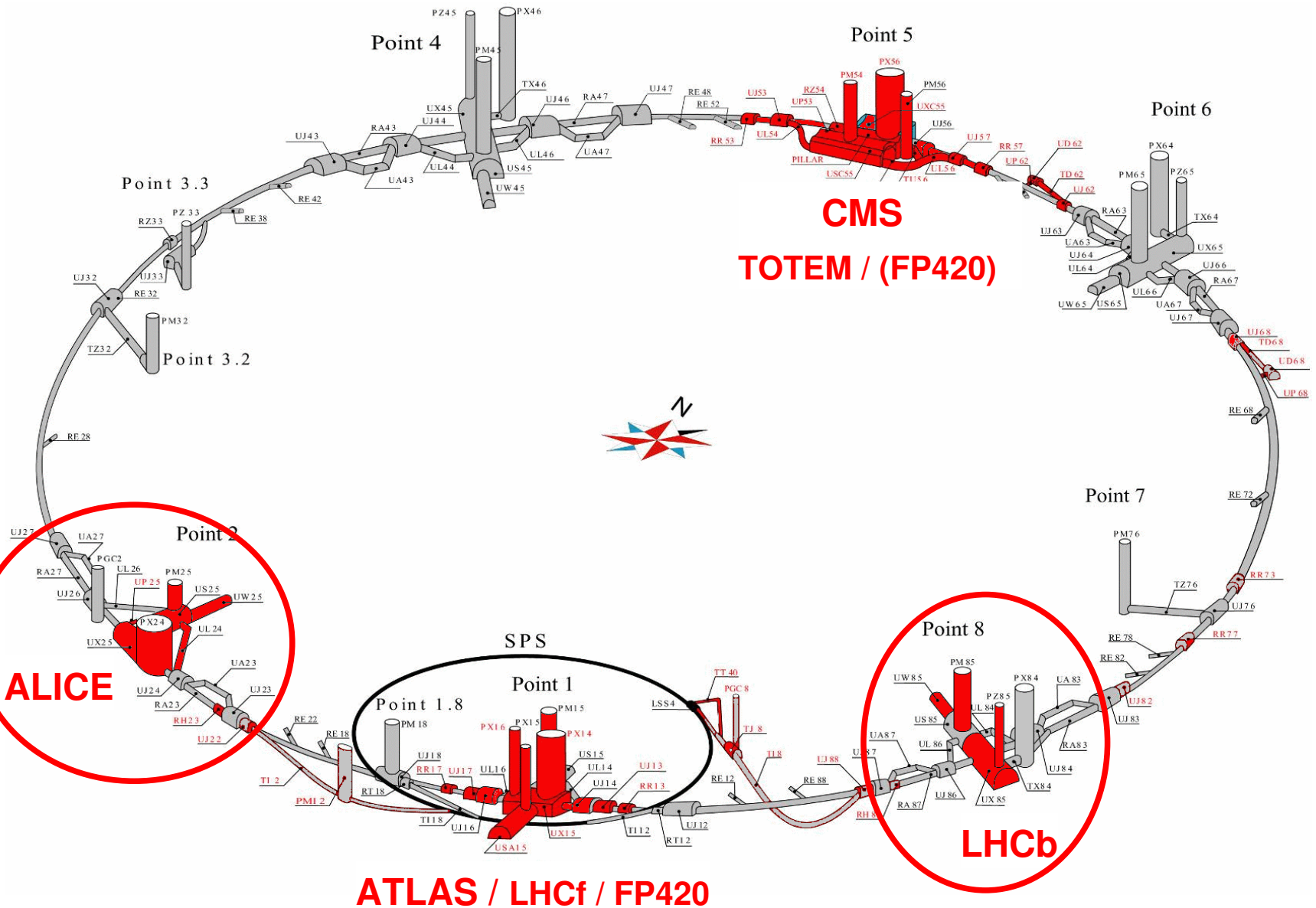
- **ZDC** (W/Q-fiber calo): 140m, |η| > 8.3 (neutral)
  zero-degree n,γ : relative lumi, CRs, heavy-ions
  (L1 trigger, centrality, photoprod, ...)



- **ALPHA** (Sci-Fi in RPs): ±240 m.
  leading p: abs. lumi (elastic scatt. in Coulomb interf. region)

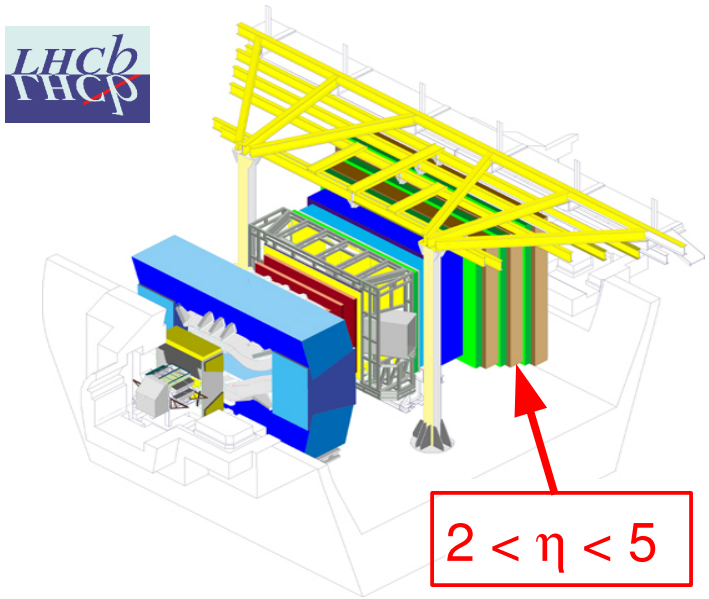


The LHC experiments: zoom at IP2, IP8

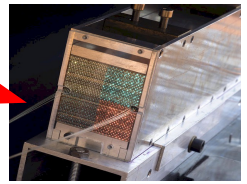


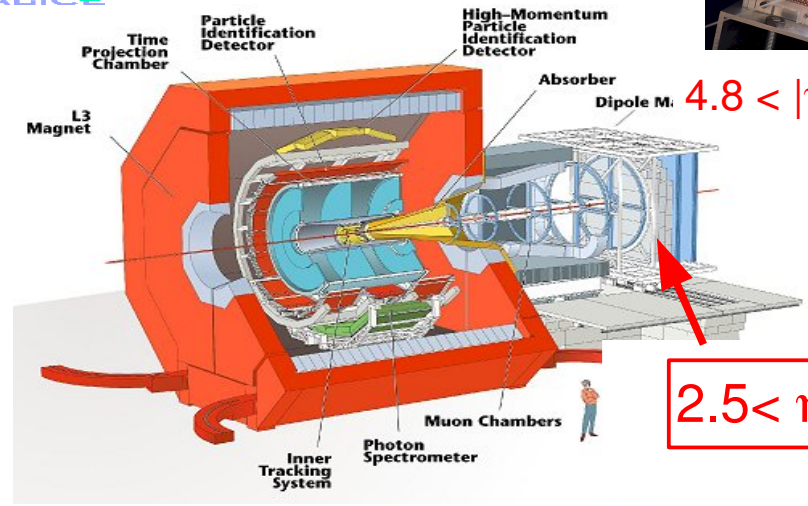
ALICE & LHCb forward detectors

- Forward muon spectrometers:



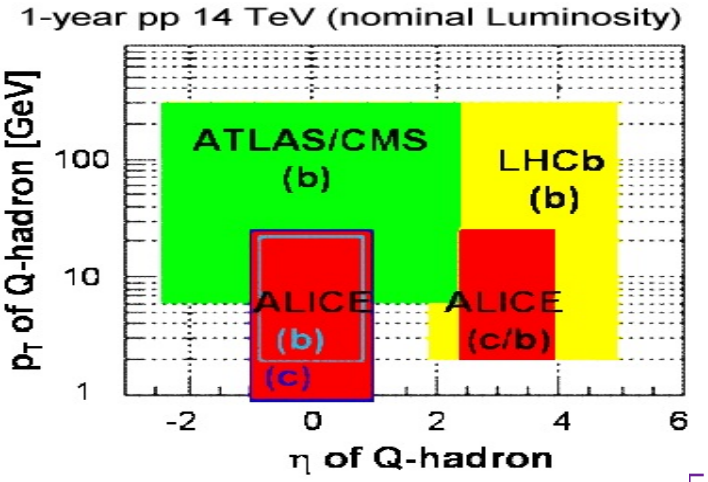
ZDCs also at ±7m,±100m





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

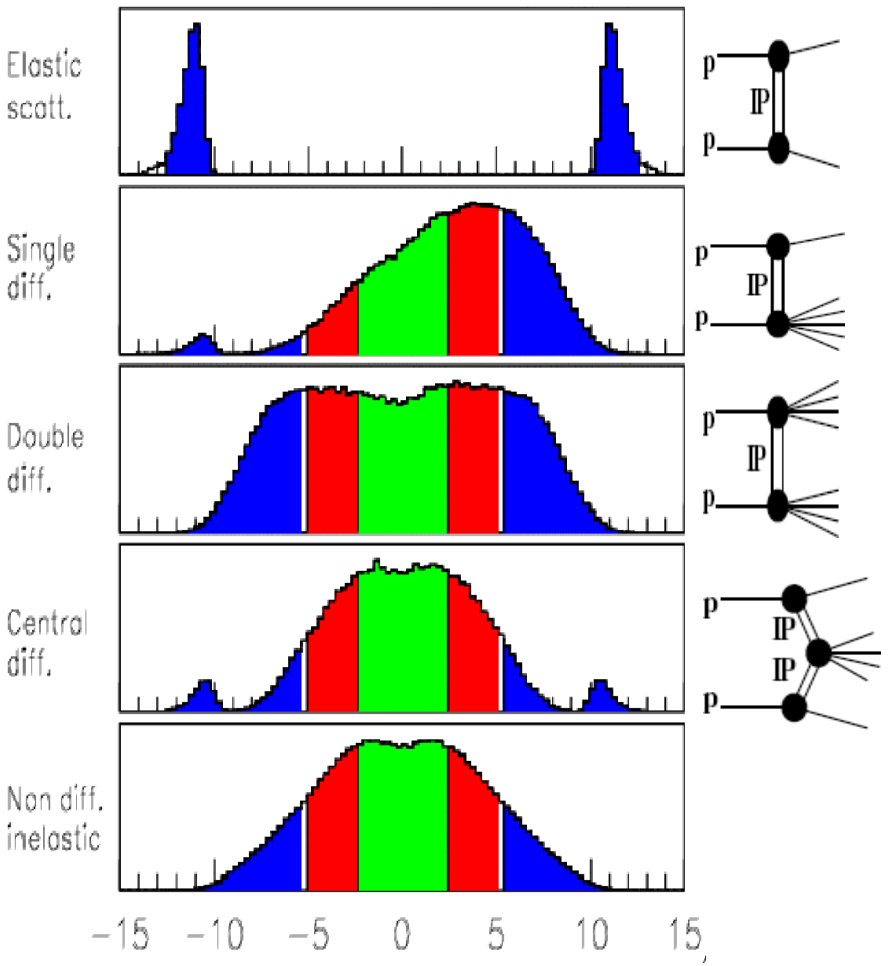
(low-x PDFs)



1. Diffractive physics

Pomeron-induced processes

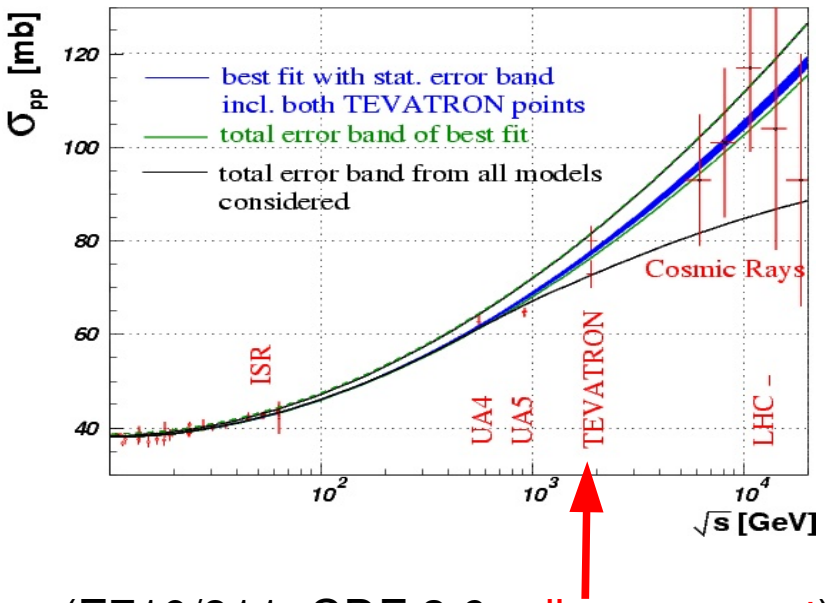
- Diffractive/Elastic scatt. (~40% p-p σ_{tot}): p intact (Roman-Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:



- 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:
  - valuable info on npQCD
  - contributions to pile-up p-p events
- Hard diffraction (*X* = jets, W's, Z's ...): Calculable in pQCD:
  - proton structure info: dPDFs,GPDs
  - discovery physics: CEP (SM,MSSM) Higgs

Total p-p cross section, elastic scattering

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



(E710/811–CDF 2.6σ disagreement)

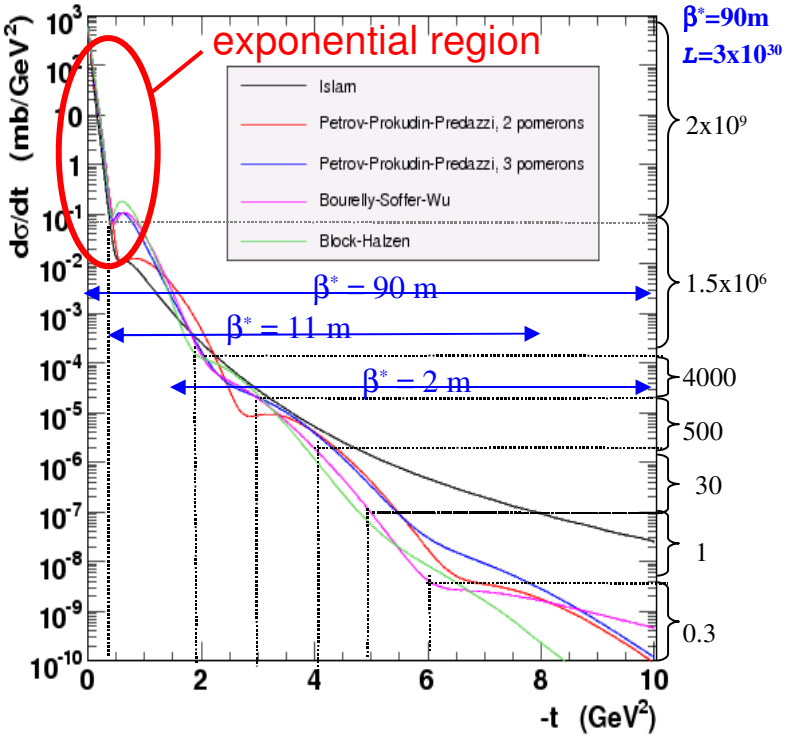
COMPETE extrapolation for LHC:

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

- TOTEM goal: ~1% precision (for β* = 1500m)

- Luminosity measurement via optical theorem:

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



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

2. Low-x QCD physics

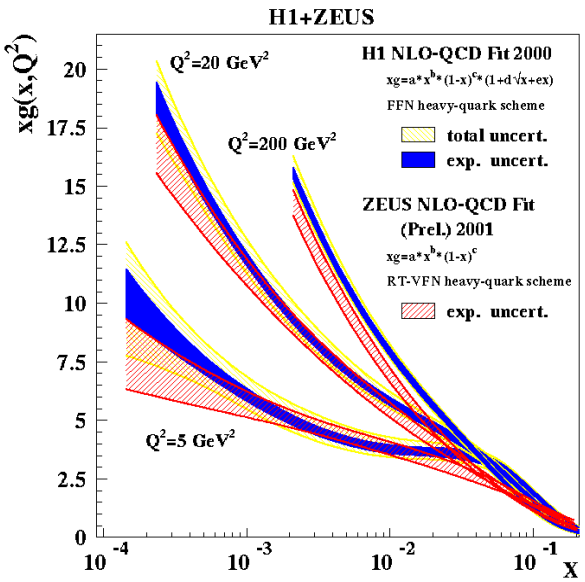
Parton saturation & evolution at low-x

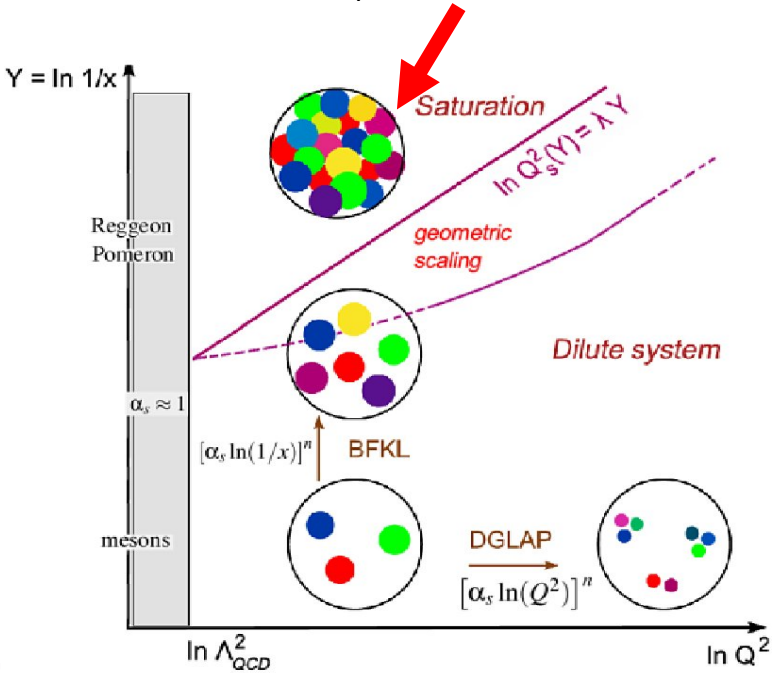
- Strong rise at low-x of gluons (HERA):
- Radiation controlled by QCD evolution eqs.:

  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 (for $Q^2 >> \Lambda^2$), collinear & k_T factorization invalid





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

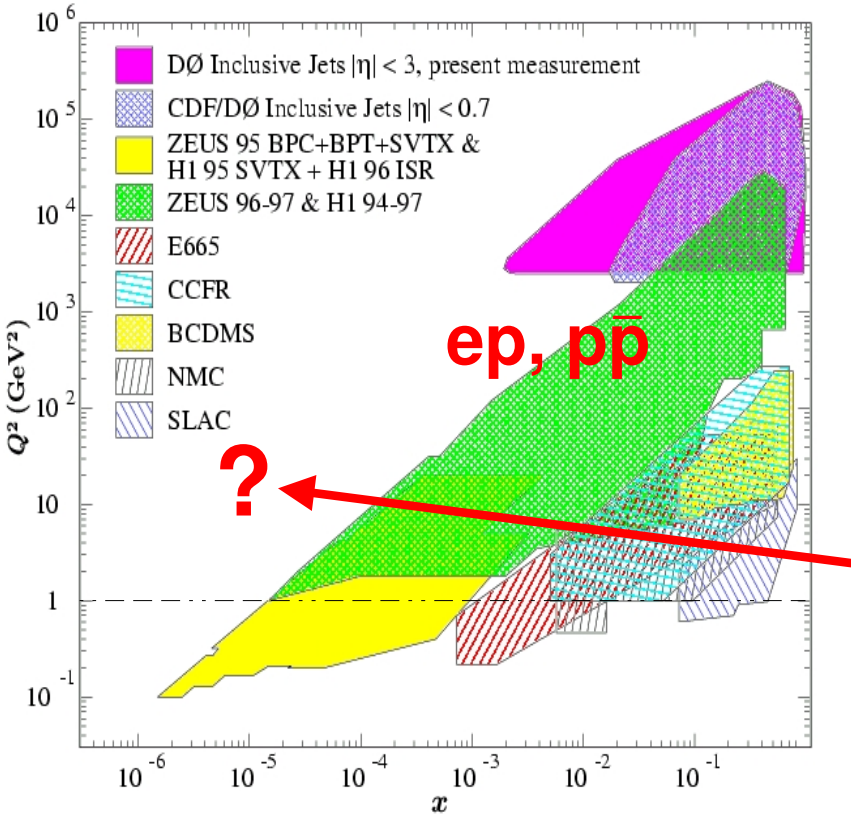
Low-*x* proton PDF studies

- 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 GeV² (y=0), 3 GeV² (y=5)

(iii) Very large perturbative cross-sections:



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

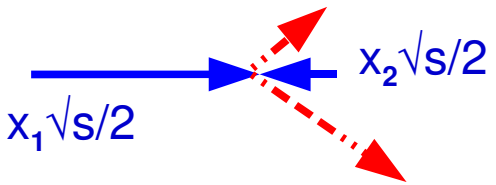
$p(p_1)+p(p_2)\rightarrow l\bar{l}+\text{X}$ Drell-Yan

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

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

$p(p_1)+p(p_2)\rightarrow W/Z+\text{X}$ 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 QCD via forward (di)jets in CMS

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

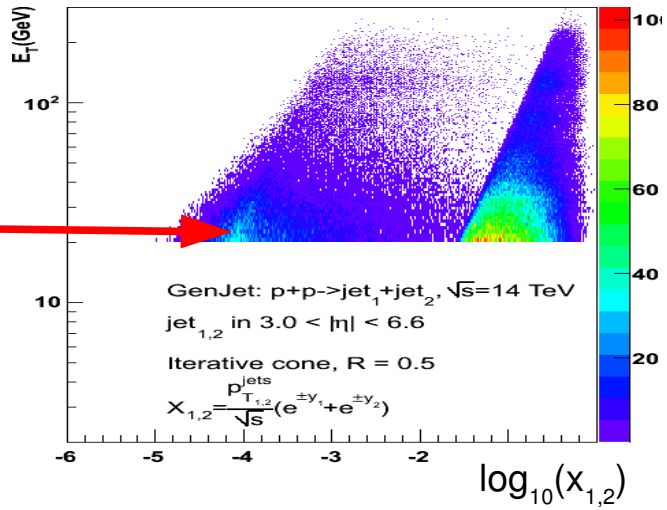
■ Forward "soft" jets (E_T ~20-100 GeV):

p + p → jet1 + jet2 + X

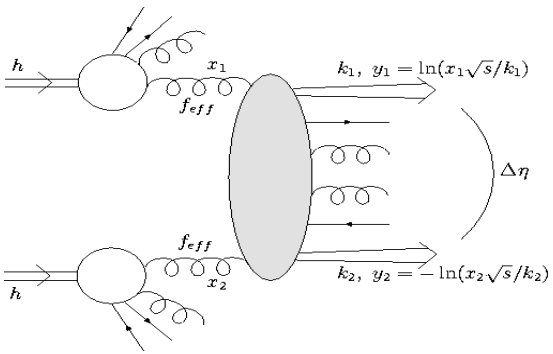
Jets in HF (3<|η|<5) sensitive to : $x_2 \sim 10^{-4}$

Jets in CASTOR (5.1 <|η|< 6.6): $x_2 \sim 10^{-6}$!

Stats. ~10^7/1 pb^{-1} (ongoing full jet reco studies)



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



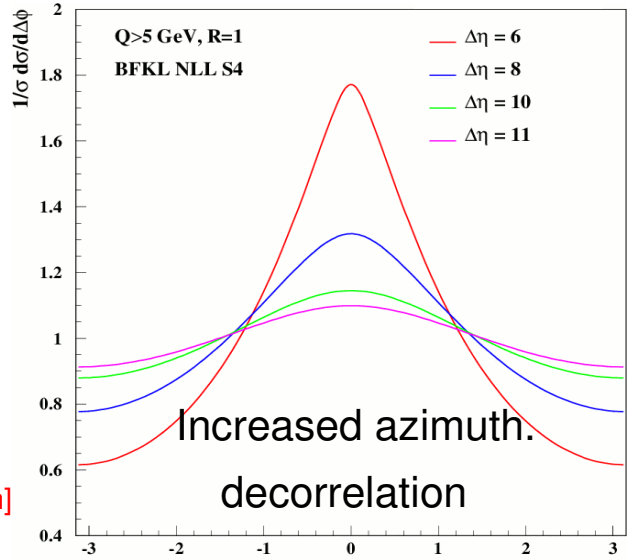
jet$_1$

Δy~10

jet$_2$

[A.Sabio-Vera]

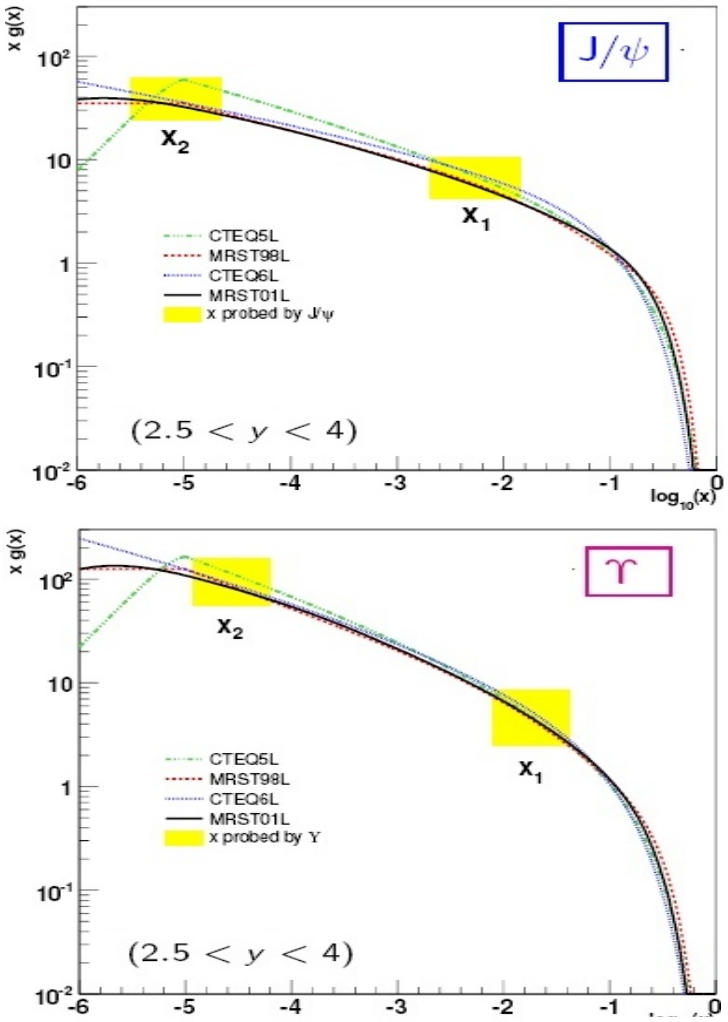
[C.Marquet, Royon]



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

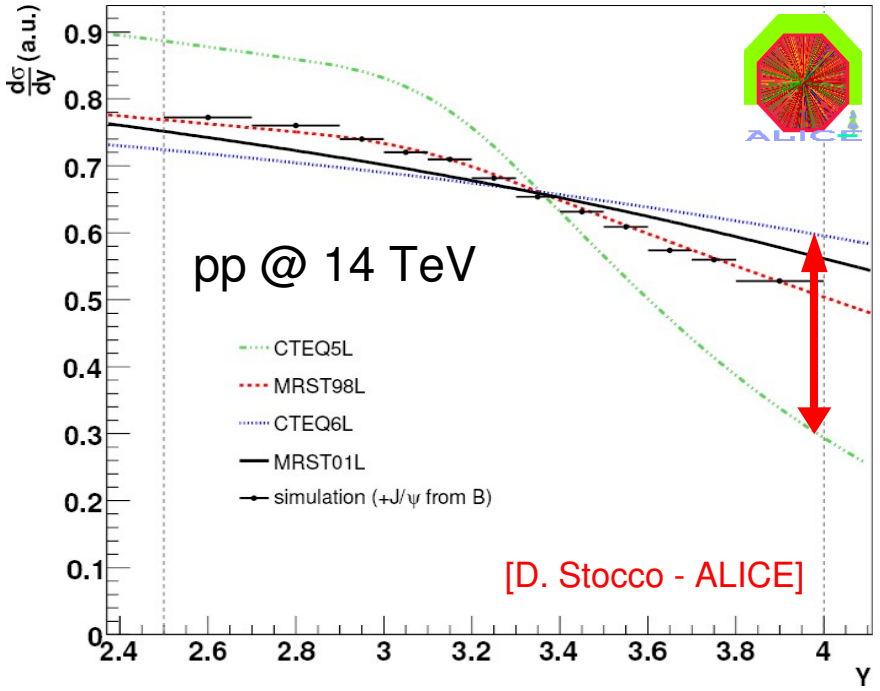
Low-x via forward QQ̄ in ALICE

- J/ψ measurement in μ-spectrometer ($2.5 < \eta < 4$): $xg(x)$ 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

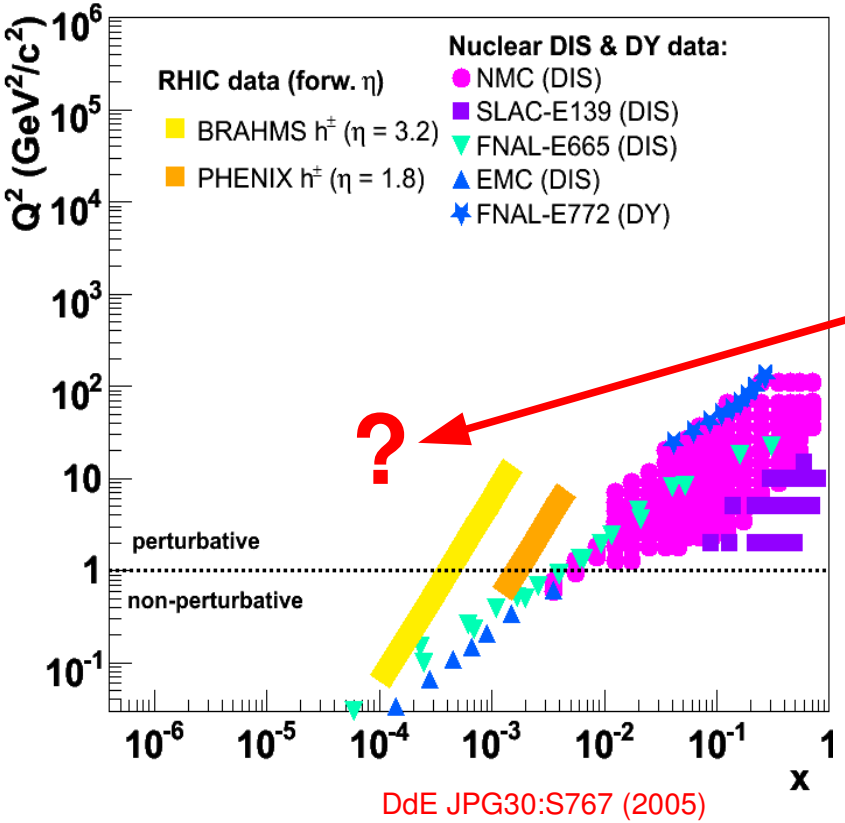
Low-*x* nuclear PDF studies

- 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 !

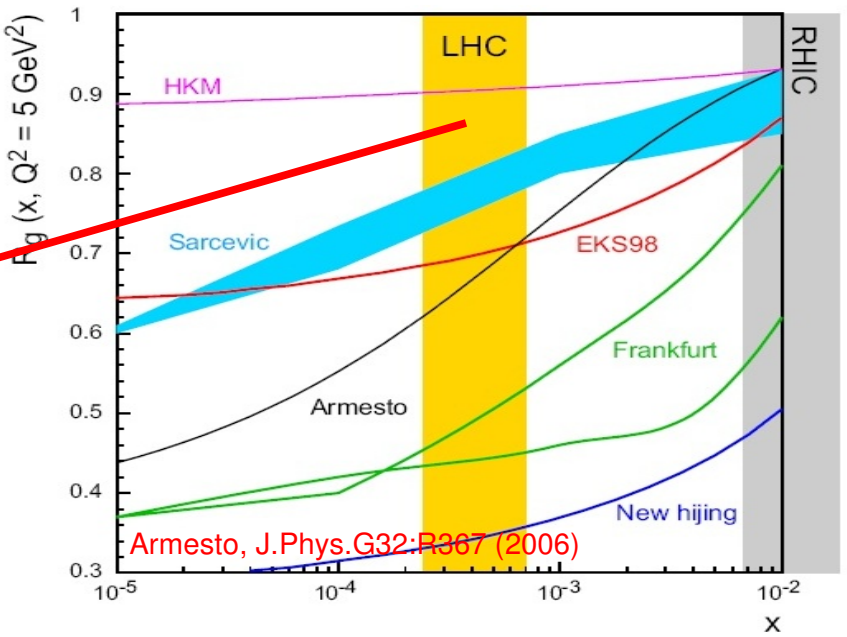
(ii) Saturation momentum enhanced ($A^{1/3}$~6) : $Q_s^2 \sim [5\ \mathrm{GeV}^2]e^{(0.3y)}$

(iii) Very large perturbative cross-sections.



DdE JPG30:S767 (2005)

Ratio of Pb/p gluon densities:



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

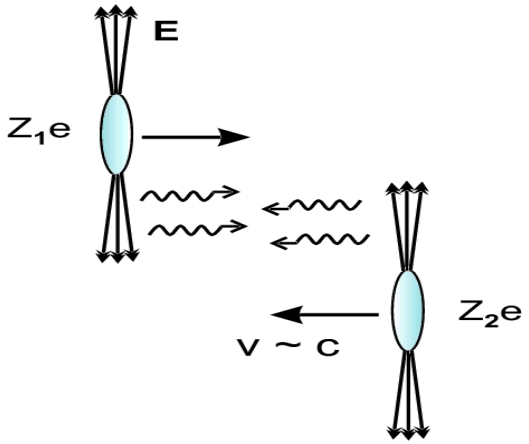
Low-x via Υ photoproduction in CMS (Pb-Pb)

[Dd'E, hep-ex/0703024]

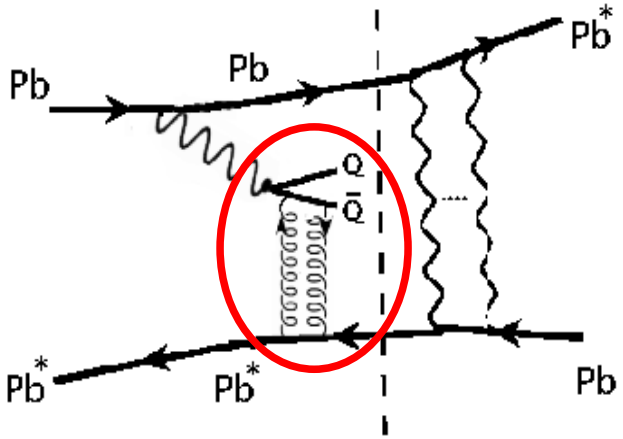
- High energy heavy-ions produce strong electromagnetic fields due to the coherent action of $Z_{Pb} = 82$ protons:
- Equivalent photon flux in Ultra-Peripheral Collisions:

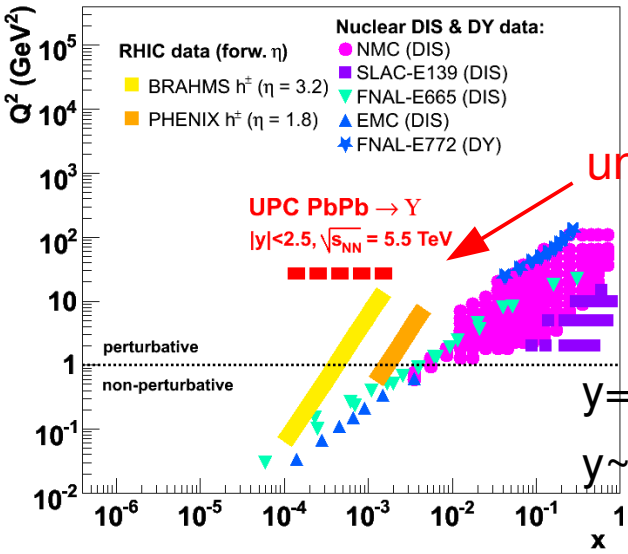
  ($b_{min} \sim 2R_A \sim 20$ fm): $E_\gamma^{max} \sim 80$ GeV (PbPb-LHC)

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



- $Q\bar{Q}$ diffractive photoproduction (ZDC neutron-tagging) sensitive to $|xG|^2$





unexplored $xG_A(x,Q^2)$

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

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

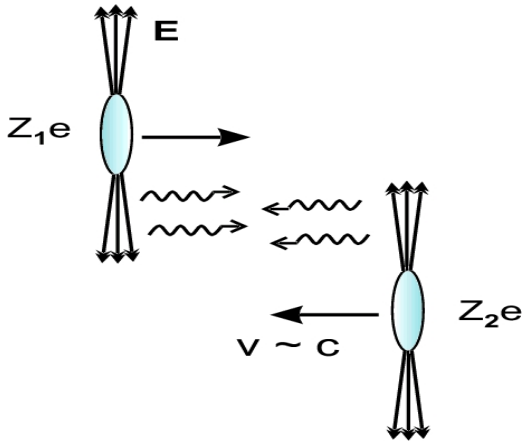
Low-x via Υ photoproduction in CMS (Pb-Pb)

[Dd'E, hep-ex/0703024]

- High energy heavy-ions produce strong electromagnetic fields due to the coherent action of $Z_{Pb} = 82$ protons:
- Equivalent photon flux in Ultra-Peripheral Collisions:

  ($b_{min} \sim 2R_A \sim 20$ fm): $E_\gamma^{max} \sim 80$ GeV (PbPb-LHC)

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



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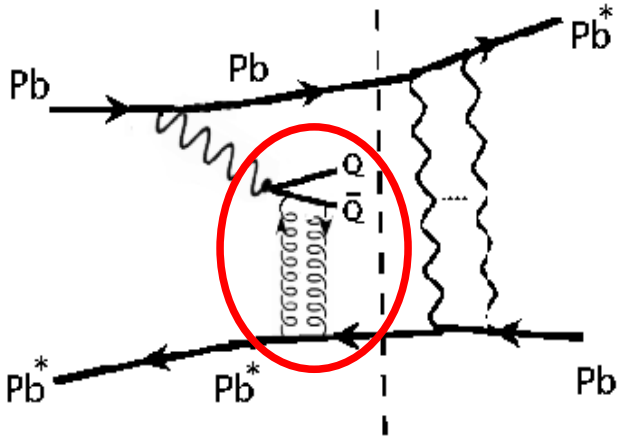
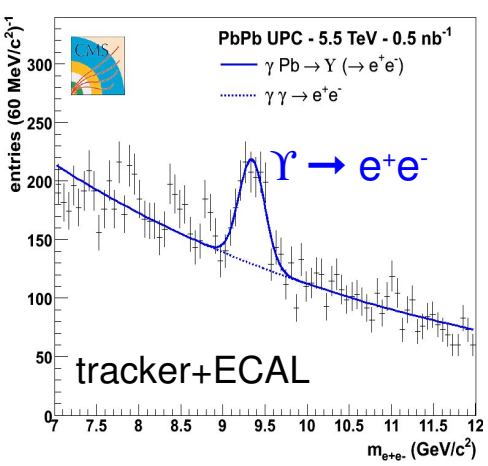
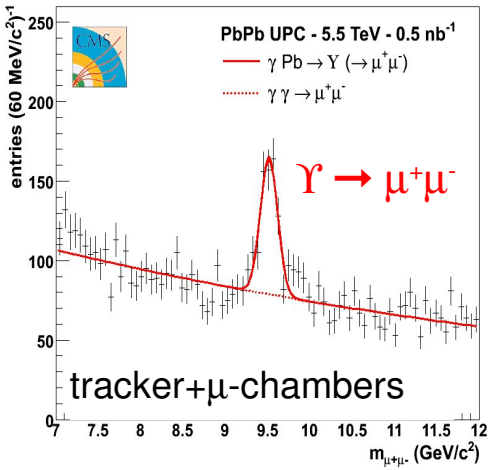




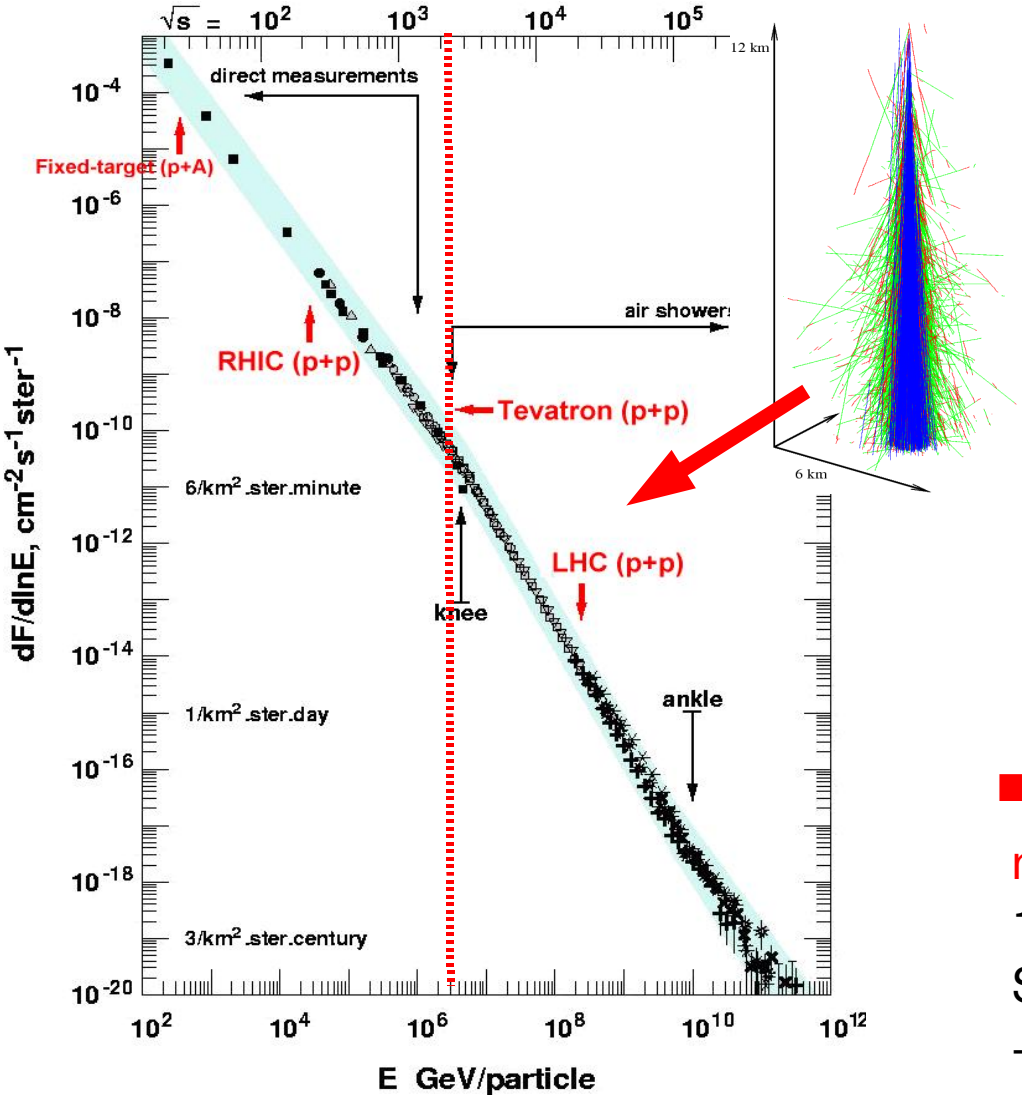


~500 Υ/0.5 nb^{-1} expected in CMS

3. Cosmic-rays physics

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

- Cosmic-ray energy spectrum:

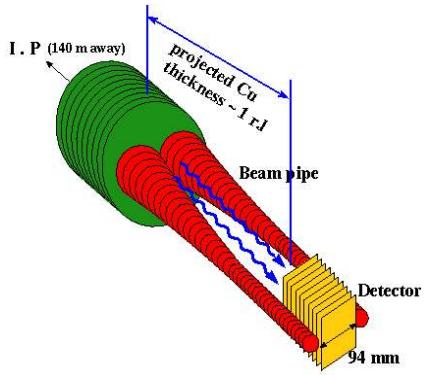


- Only "indirect" measurements (EAS) above E_{lab} ~100 TeV
- CR energy & mass determined via hadronic MC simulations: Shower development dominated by fwd, soft QCD interactions.
- Uncertain x10^6 extrapolations from SppS,Tevatron to GZK limit.

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

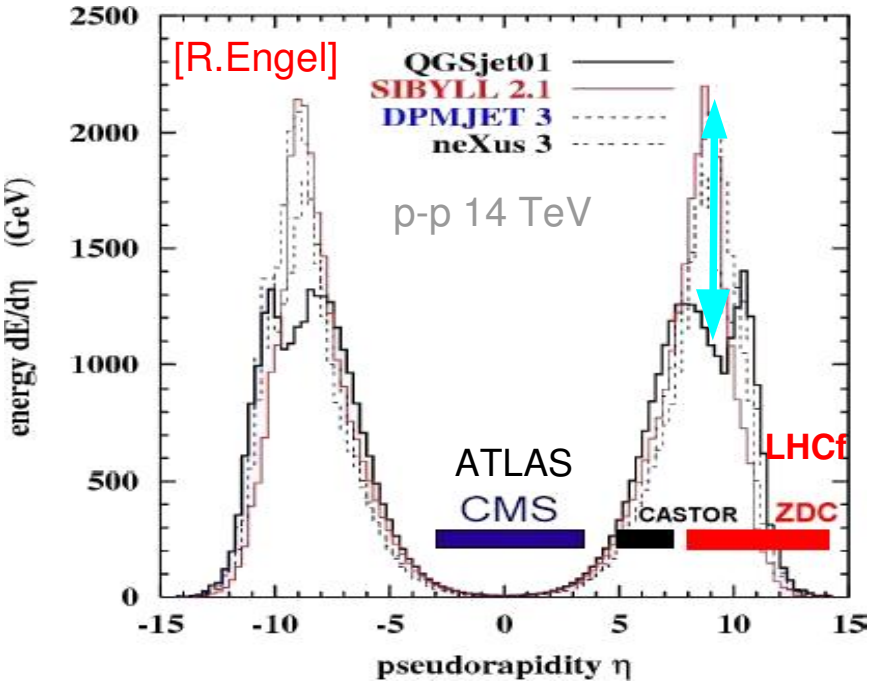
- LHCf experiment:

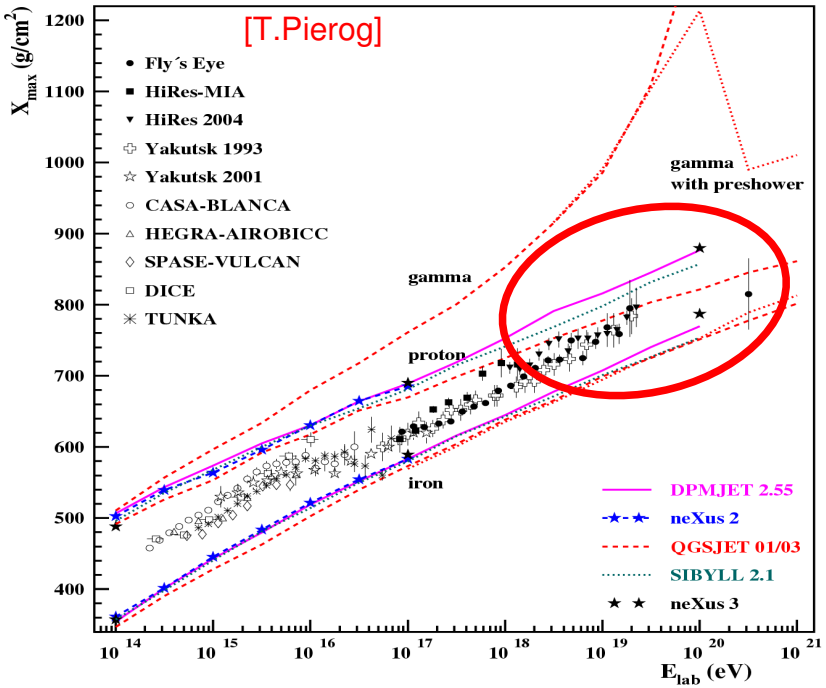
n,γ detection
140 m from IP2
Sci-fiber/W calo
+Si strip detector



Calibration & tuning of hadronic MCs

- Model predictions of particle multiplicity, energy flow, sigma-tot, ... differ by large factors:





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

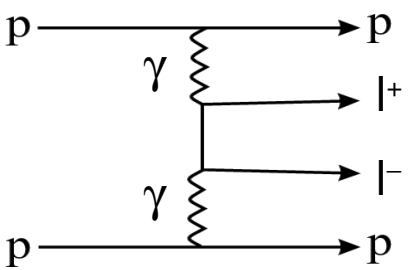
[CRs collisions: p-Air, α-Air, Fe-Air]

4. EWK (γ-γ,γ-p) physics

γ–γ , γ–W interactions

[Cf. also Séverine Ovyn]

- 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

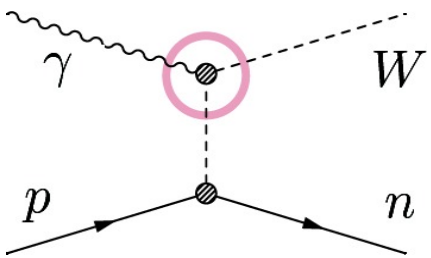
RPs: reco of proton ξ w/ resol. of 10^{-4}

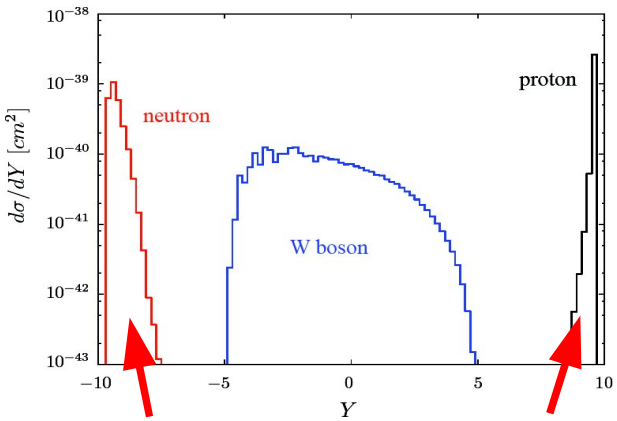
~300 evts./100 pb^{-1} after CMS μ trigger

- Absolute p-p luminosity within ~3% (theo)
- Cross-calibration of FP420,TOTEM dets.

➢ 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: γγ→WW,ZZ]

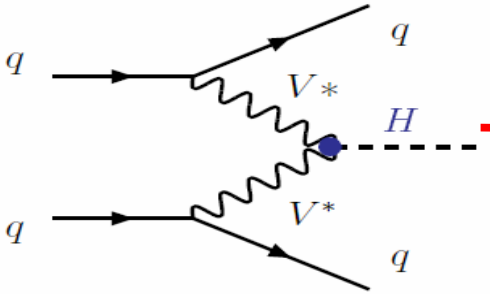
5. Higgs (SM, MSSM)

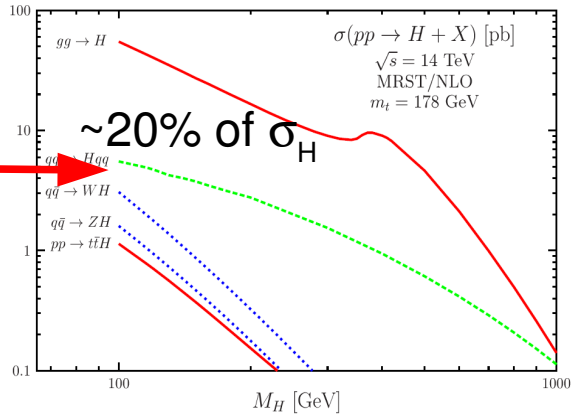
Vector-Boson-Fusion Higgs tagging

- qq→ qqH accompanied by forward jets:

2 jets (p_T~20-60 GeV)

w/ large Δη~5 separation

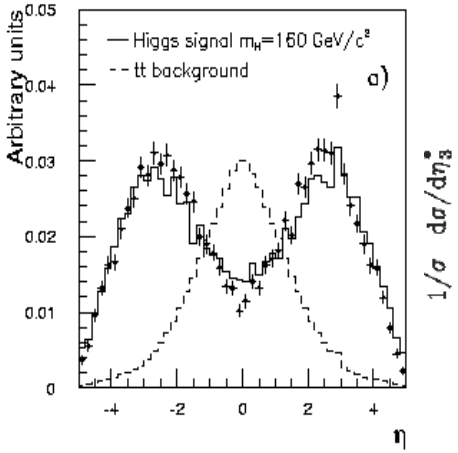


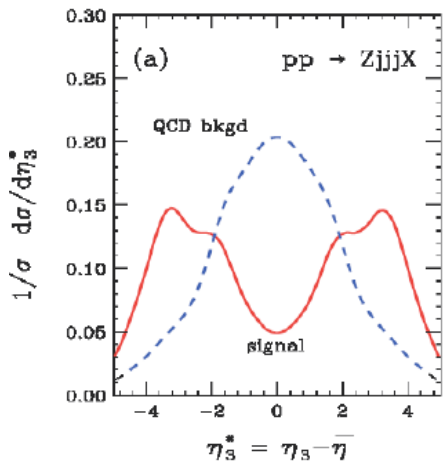


- Good QCD background rejection :

H→WW(→l±jj ν) vs. ttbar,WW

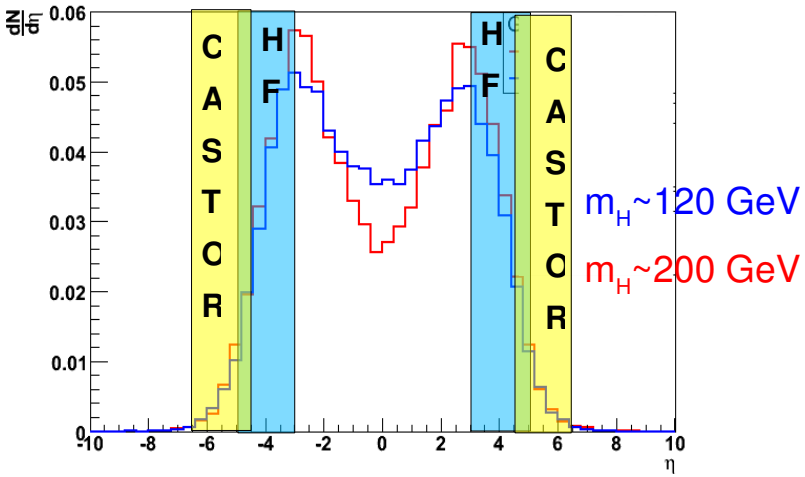
H→ττ vs. Z+nj, W+nj, ttbar





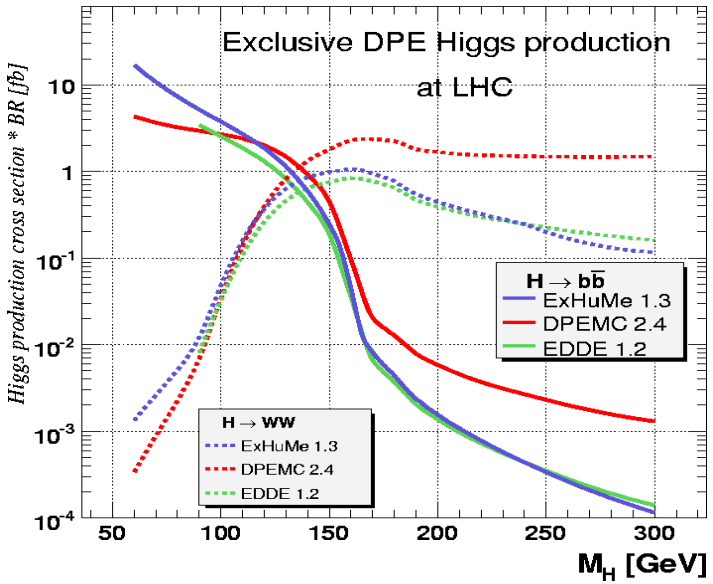
background jets at central rapidities

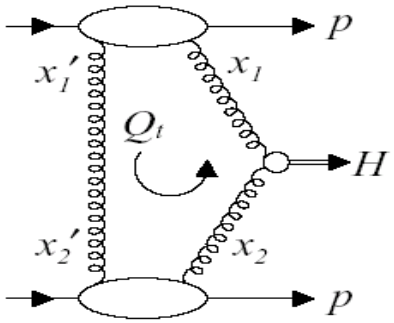
CMS: Combined HF+CASTOR extends VBF jet tagging efficiency



Central exclusive Higgs

- Central exclusive Higgs production: pp → p H p





(leading proton)

H decay in central det

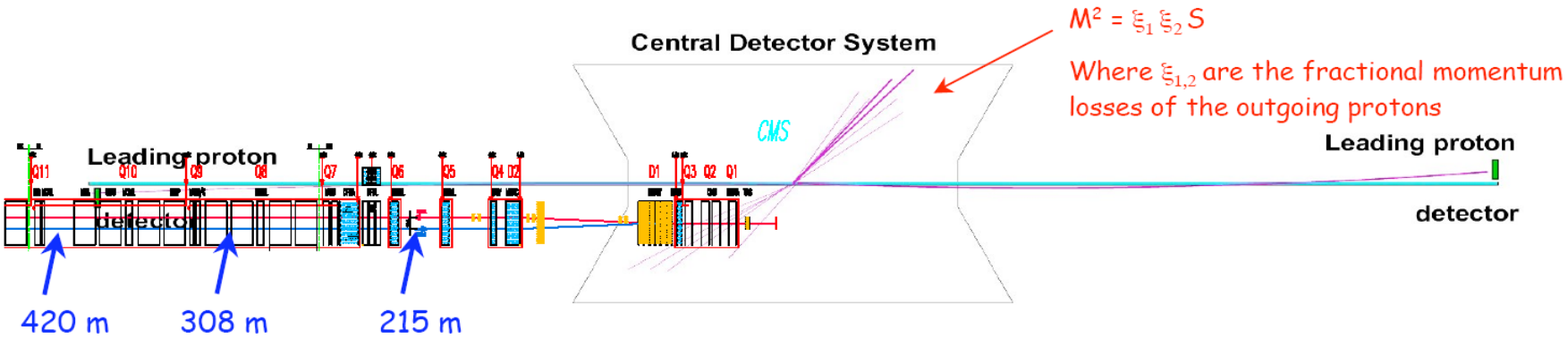
(leading proton)

σ_H = 3-10 fb (SM), x10(0) in MSSM

- Motivations:
  - Quantum numbers: central system is approx. $J^{PC} = 0^{++}$ (selection rule)
  - Excellent mass resolution: from protons, indep. of central decay products.
  - Enhanced S/B: Reduced QCD background. H→ bbar channel accessible
  - CP violation in Higgs sector: directly measurable from protons azimuthal asymm.
  - Discovery channel: in certain regions in MSSM

Central exclusive Higgs: FP-420 project

- For m_H< 200 GeV, proton tagging acceptance needed at ±420 m
- FP420 R&D collaboration (ATLAS/CMS under discussion)

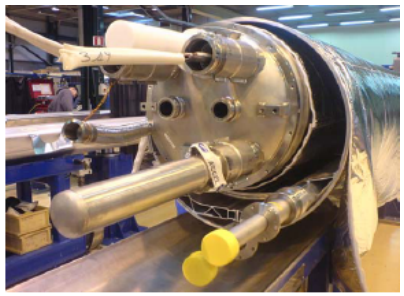


- Novel technologies:

(i) Moving beampipe in cold LHC area

(ii) Very fast (τ ~10 ps) Cerenkov detectors:

GASTOF (gas), Quartic (Quartz)

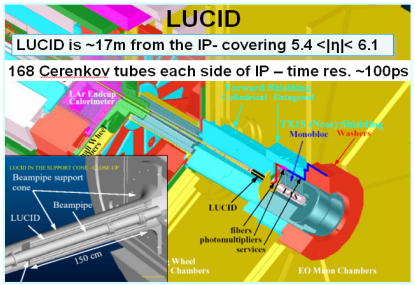


Precise leading protons time-difference to

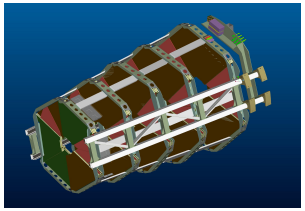
isolate pp → p H p vertex in high luminosity (~25 p-p colls.) conditions

Summary: forward instrumentation @ LHC

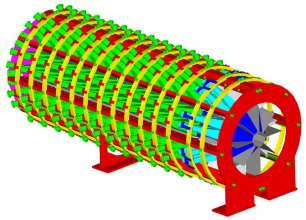
ATLAS LUCID



TOTEM T1



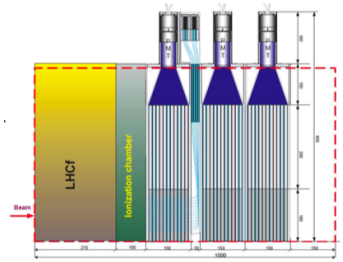
CMS CASTOR



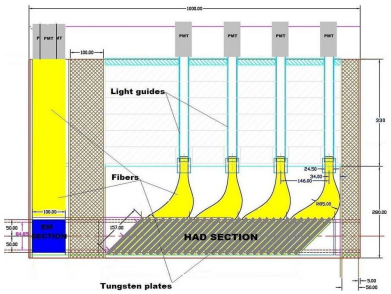
TOTEM T2

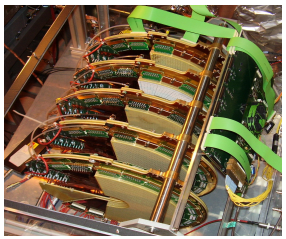
ATLAS ALFA

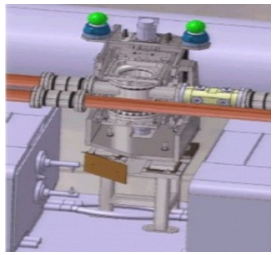
ATLAS ZDCs



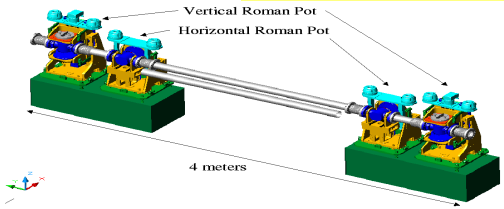
CMS ZDCs

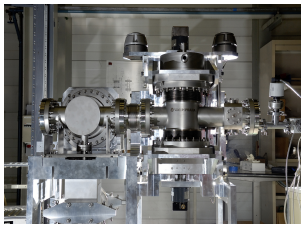




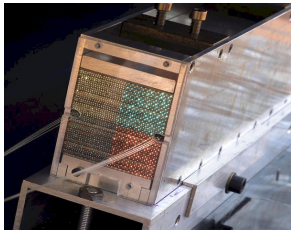


TOTEM RPs

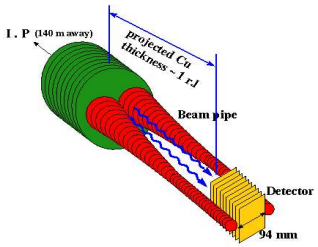




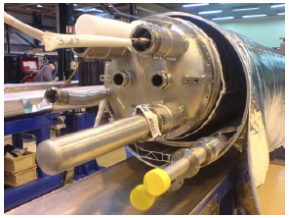
ALICE ZDCs



LHCf

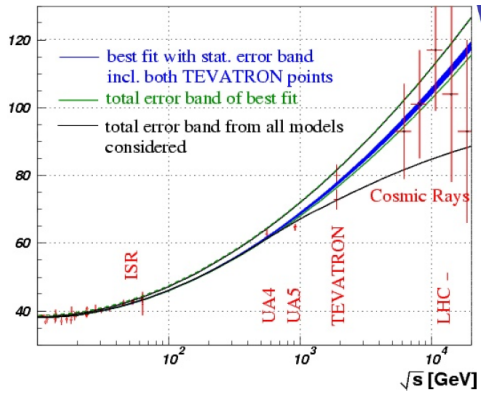


FP420

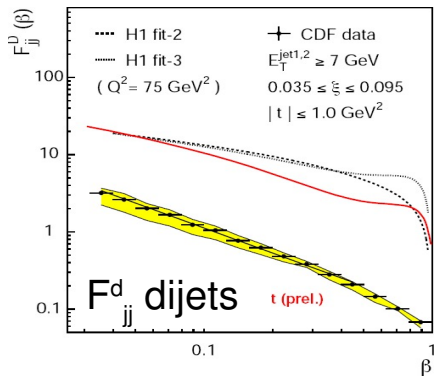


Summary: forward physics @ LHC

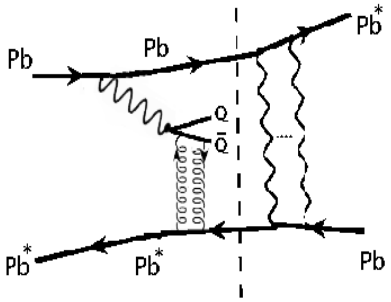
p-p σ_{tot}, elastic scatt.



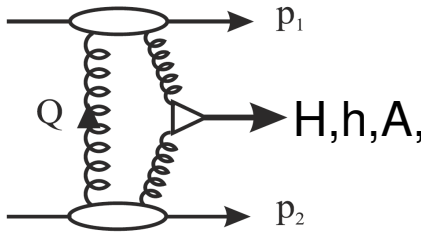
hard diffraction



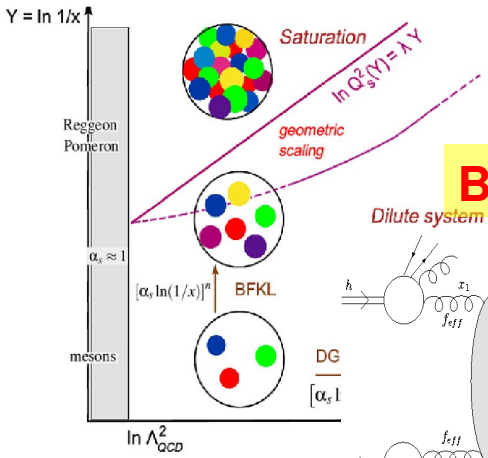
VM photoprod.



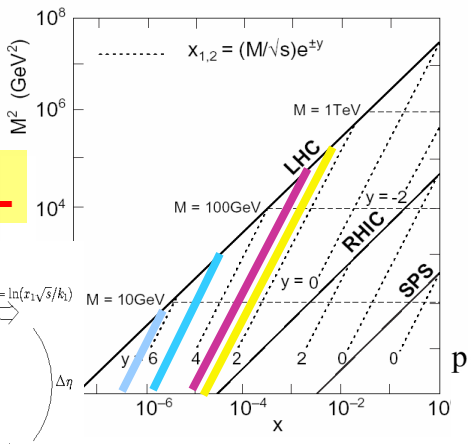
(B)SM Higgs



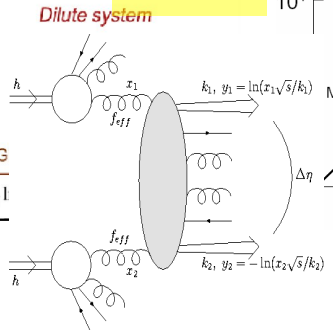
gluon saturation, CGC



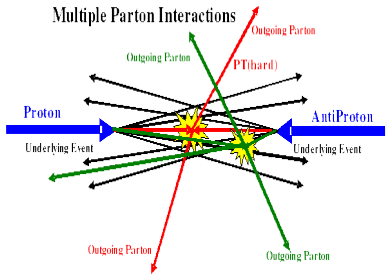
low-x PDFs



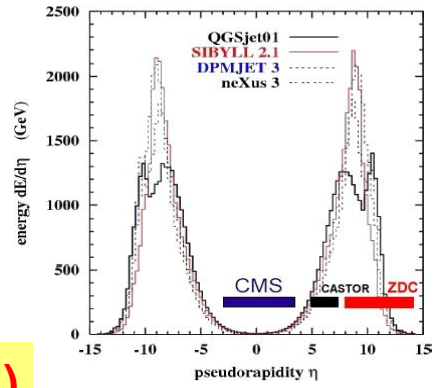
BFKL



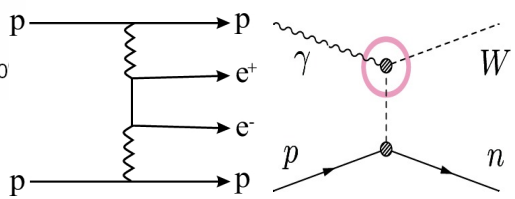
MB/UE/MPI

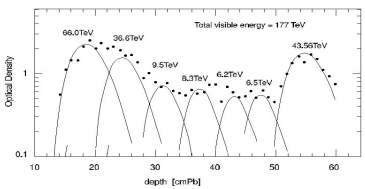


UHE cosmic-rays



EWK (γ-γ,γ-W,...)

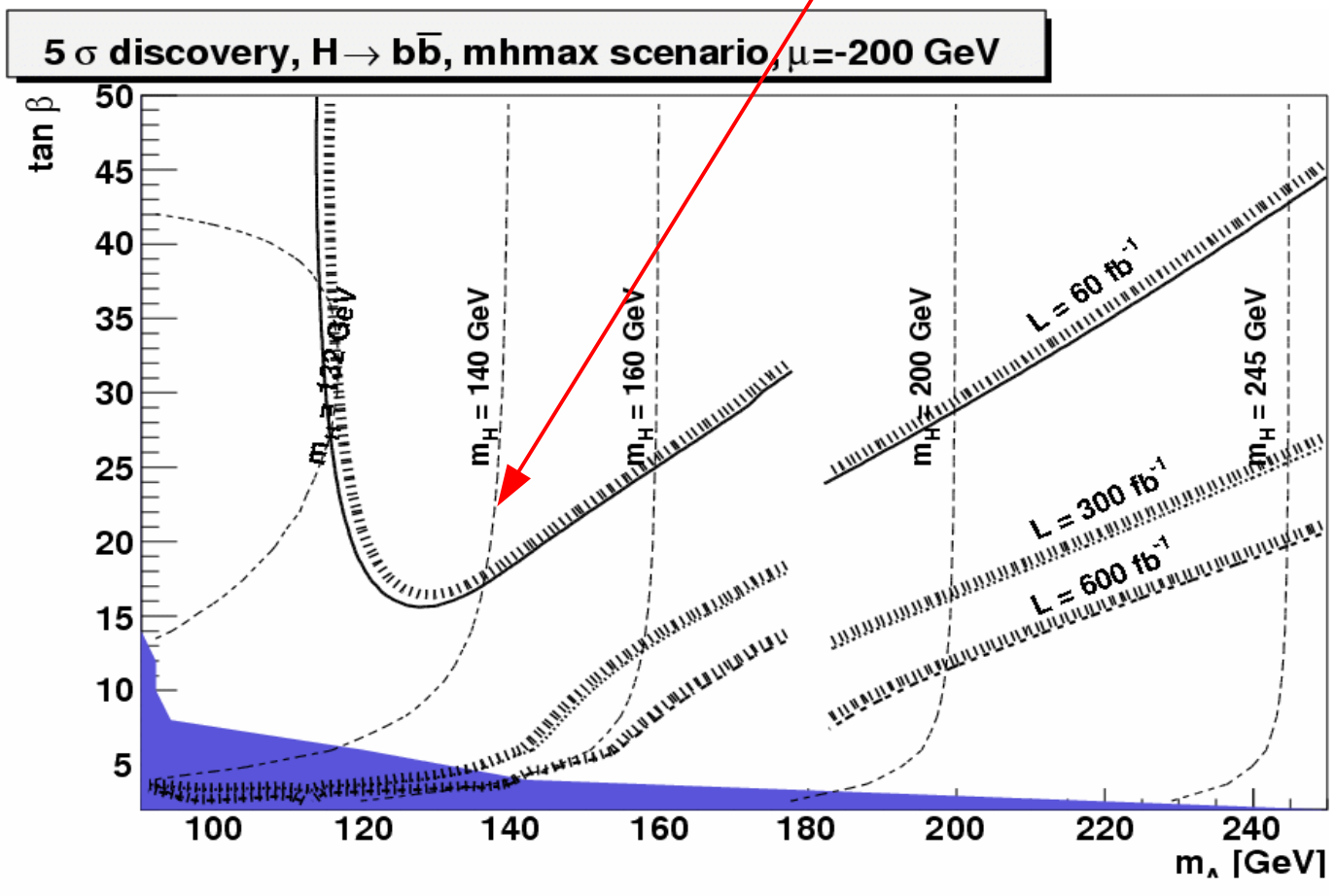




Backup slides

Central exclusive MSSM Higgs

- MSSM h^0, H^0, A^0, H^+, H^-: Tagged proton channel can be the discovery channel in various MSSM scenarios (for similar masses of the 3 neutral Higgs & large tanβ)



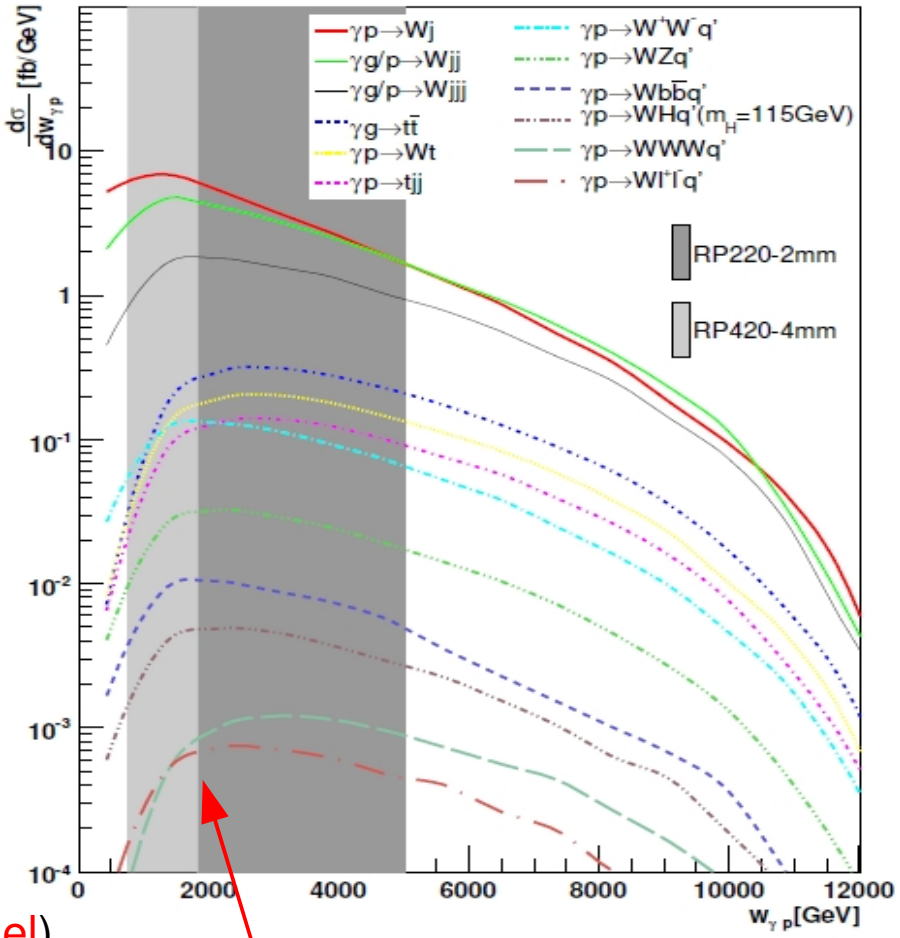
[Heinemann et al. arXiv:0708.3052]

γ proton interactions

[Cf. Séverine Ovyn & UCL CMS group]

- Large variety of processes.
- Significant cross-sections up to ~2 TeV.
- Alternative ("cleaner", better S/B than p-p) access to:

- top physics (e.g. $|V_{tb}|$ via Wt channel)
- Associated WH production
- Anomalous single top production



(assoc. WH-channel)

via Wt-channel)

220 & 420 m proton detectors essential for tagging photon interactions at the LHC