Forward and Diffractive Physics at the LHC

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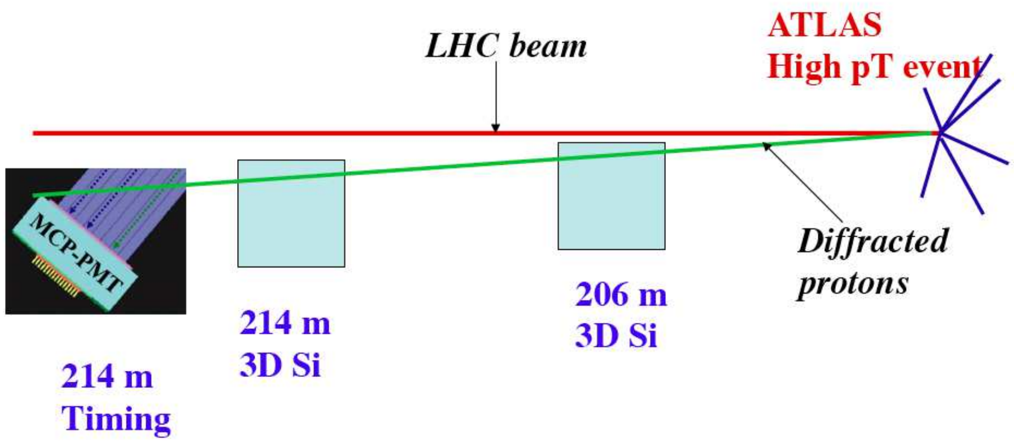
LHCC meeting, 31/10/2016

Contents: Forward Physics (QCD and exploratory physics)

- Yellow report
- Low luminosity - no pile up
- Medium luminosity - moderate pile up
- High luminosity - high pile up, full luminosity
- NB: only a personal selection of topics...



Status of Yellow Report from the LHC Forward Physics WG

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

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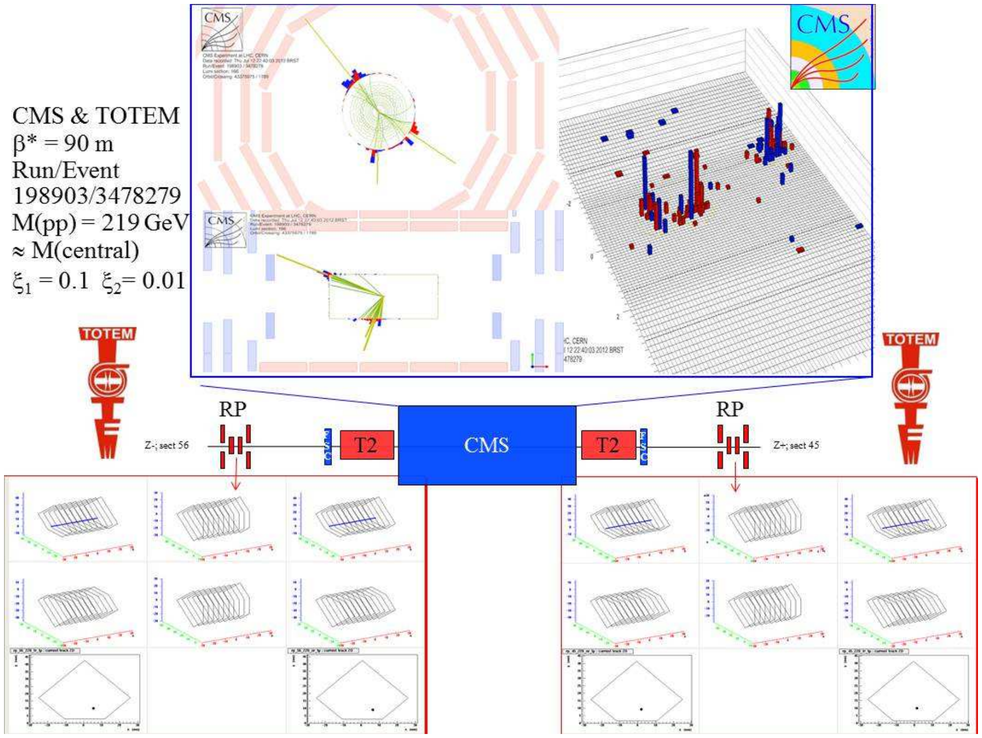
- The LHC Forward Physics "Yellow Report" is now published: K Akiba et al 2016 J. Phys. G: Nucl. Part. Phys. 43 110201
- See: http://iopscience.iop.org/0954-3899/43/11/110201/media for full text
  - Background and run plans: V. Avati, C. Royon
  - Monte Carlo: L. Harland-Lang
  - Soft Diffraction: V. Avati, T. Martin
  - Hard Diffraction: M. Ruspa, M. Trzebinski
  - Central Exclusive Production: M. Saimpert, L. Harland-Lang, V. Khoze
  - BFKL and saturation: C. Marquet, J. Bartels, H. Jung
  - Cosmic ray: T. Pierog
  - Heavy ions: D. Tapia Takaki
  - Detectors: J. Baechler, V. Avati

A few general remarks about Forward Physics

- Forward Physics adresses QCD dynamics at the interface between hard and soft physics
  - Example I: Total pp cross section probes long transverse distances
  - Example II: BFKL (Balitsky Fadin Kuraev Lipatov) Pomeron is valid at short distances
  - Transition: hard diffraction, structure of Pomeron
- Allows in addition searching for physics beyond the standard model
- Important for understanding underlying events, soft QCD: MC tuning, almost all MC designed for hard processes and new physics have difficulties with incorporating diffraction, and need improvement. Measurements of diffraction (rapidity gaps) are vital for testing MC

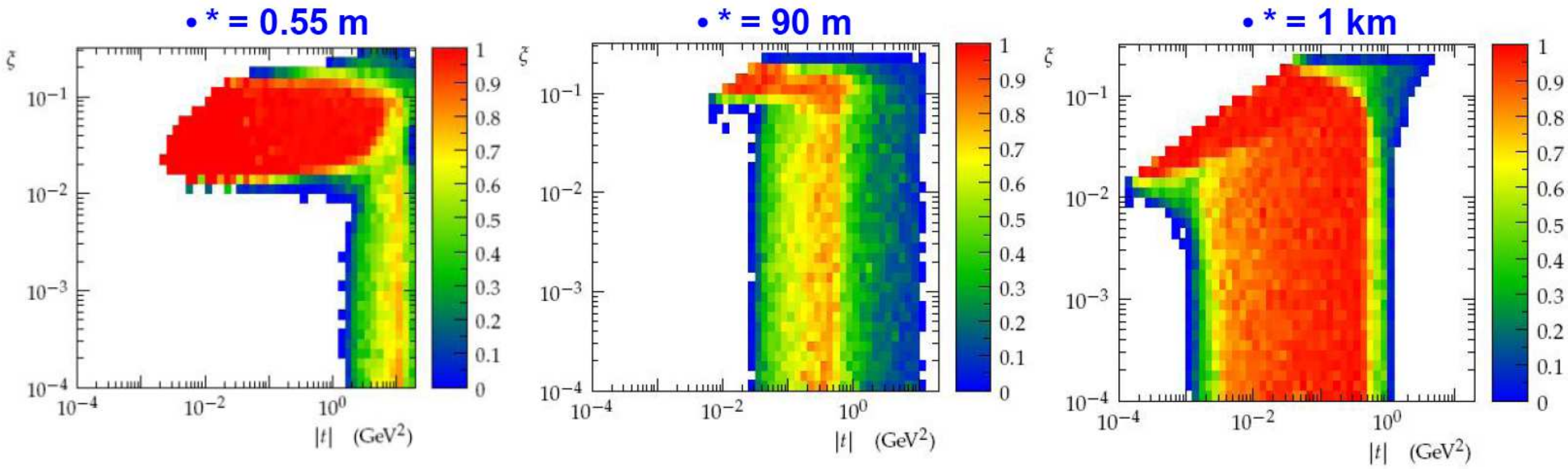


LHC running conditions vs experiments

- Low luminosity runs
  - No pile up ($\mu << 1$) (very low luminosity) - dedicated to LHCf measurements (together will all other LHC experiments): data were taken, proton oxygen data would be of high interest
  - No pile up high β^*, ALFA and TOTEM, dedicated to total cross section measurements
- Medium luminosity runs
  - LHCb runs with little pile up, a few fb^{-1} accumulated
  - Alice, ATLAS, CMS runs at low pile up, rapidity gap measurements
  - CMS-TOTEM and ALFA/AFP special runs at medium β^*, $\mu \sim$2–3, a couple of weeks needed to accumulate 50 to 100 pb^{-1}
  - AFP and CMS/TOTEM running at low β^*, low pile up: not such a good acceptance at low mass, needs beam defocussing
- High pile up ($\mu =$20,...,100) (high luminosity) with proton tagging; Possibility to collect data with high pile up (50 and above)

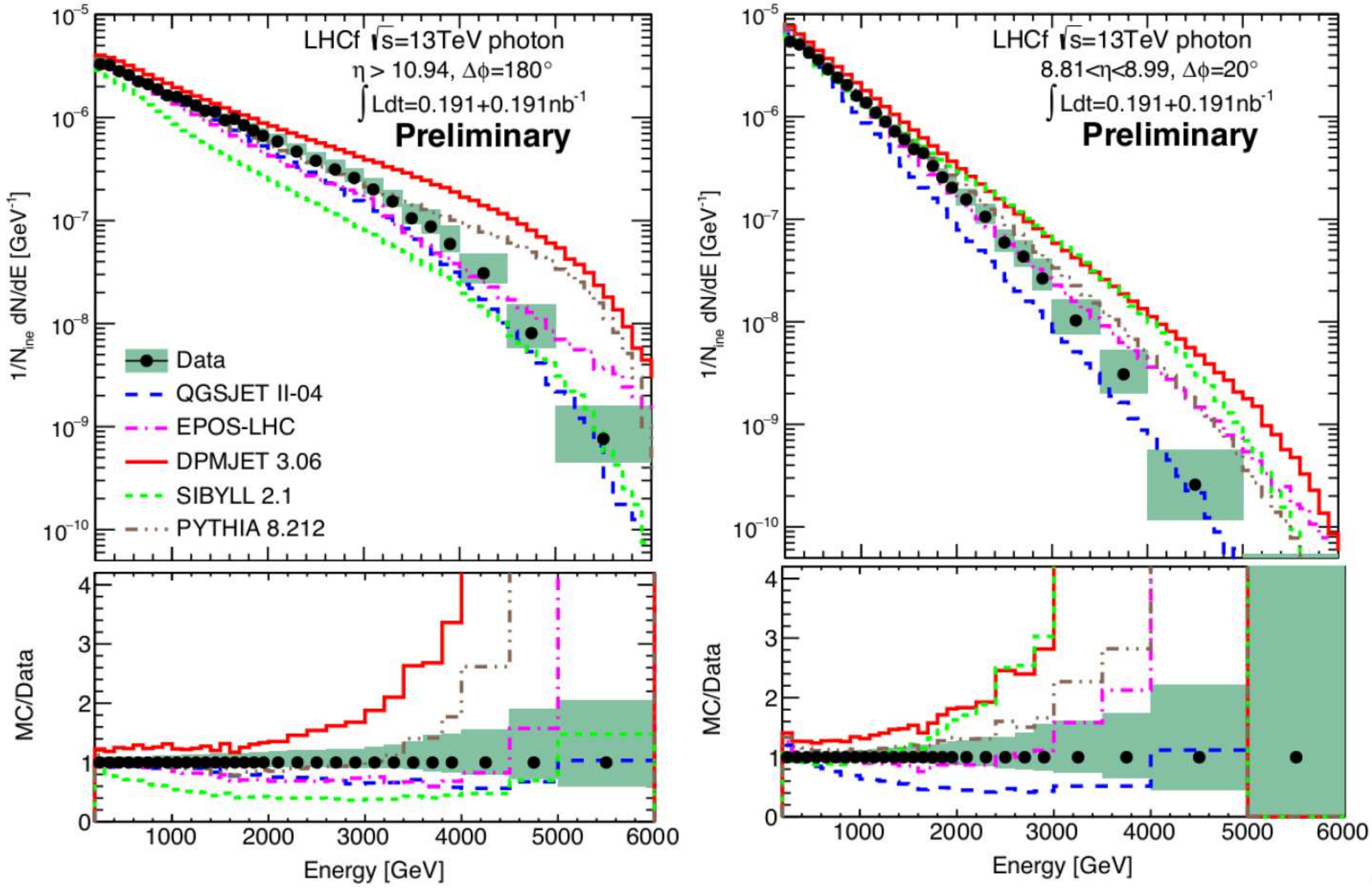
Running conditions: proton tagging

- Possibility to tag intact protons in the final state in CMS-TOTEM and in ATLAS
- High and low β^* runnings: complementarity in kinematical domain, see ξ versus t plots
- High β^* (90 m for instance): good acceptance for all ξ values for $t > 2.10^{-2}$ GeV^2, which means good acceptance for low diffractive masses where cross section is highest, and thus low values of accumulated luminosity enough
- Low β^* for standard high luminosity running: acceptance at high ξ ($\xi > 0.015$), which means high diffractive masses $M > 400$ GeV, low cross section and exploratory physics, high luminosity needed



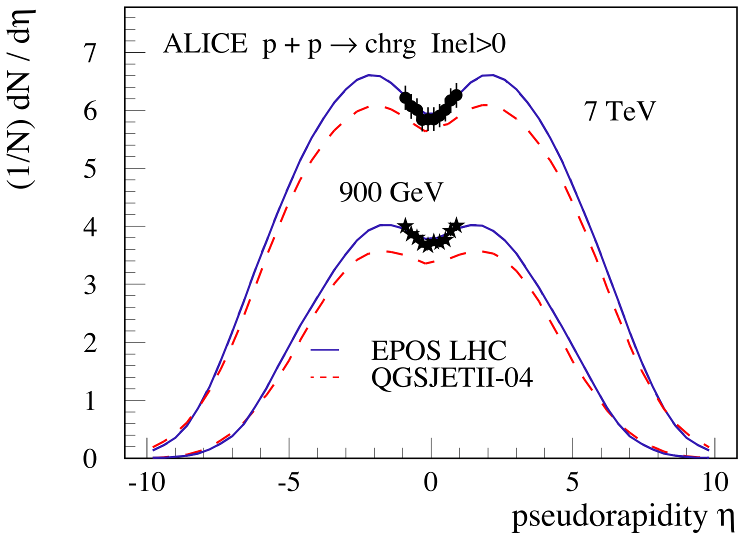
Very Low luminosity: LHCf measurements

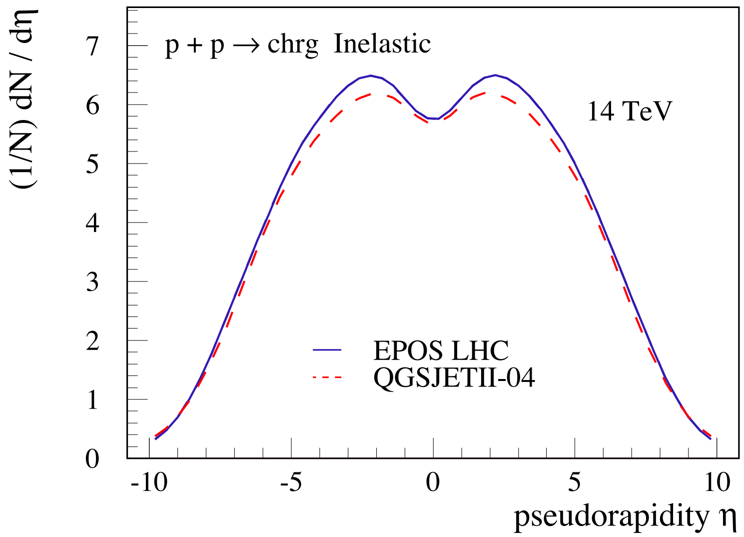
- Measurements of hadron, pion, neutron, γ spectra in the very forward region by LHCf
- Useful to tune models/MC: two kinds of models Pythia/Sybill and EPOS/QGSJET II - different assumptions concerning constituent parton Fock states
- Common data taking between LHCf/ATLAS

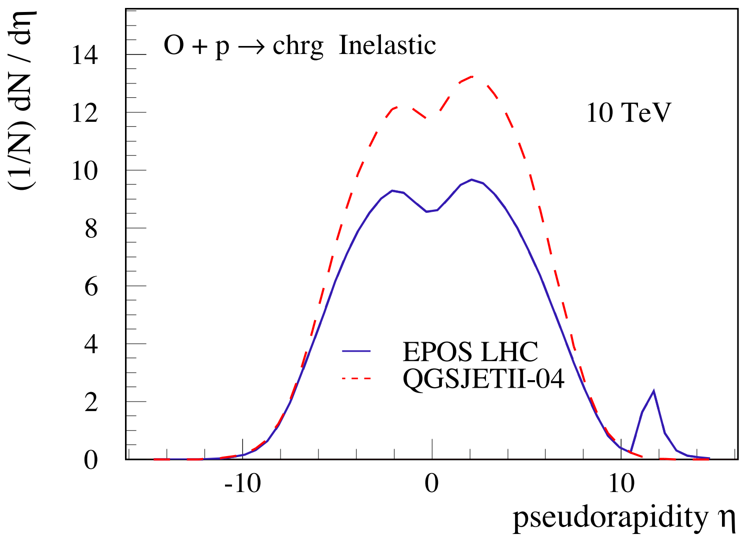


Very low luminosity: Soft interactions

- Measure multiplicity, energy distribution in soft events: complementarity between rapidity reach in LHCf, ATLAS, Alice, CMS...
- Measurement of soft diffraction, total cross section: high β^* measurement in TOTEM, ATLAS-ALFA
- Constrain cosmic ray models
- Importance of measuring p-Oxygen: useful to tune cosmic-ray models

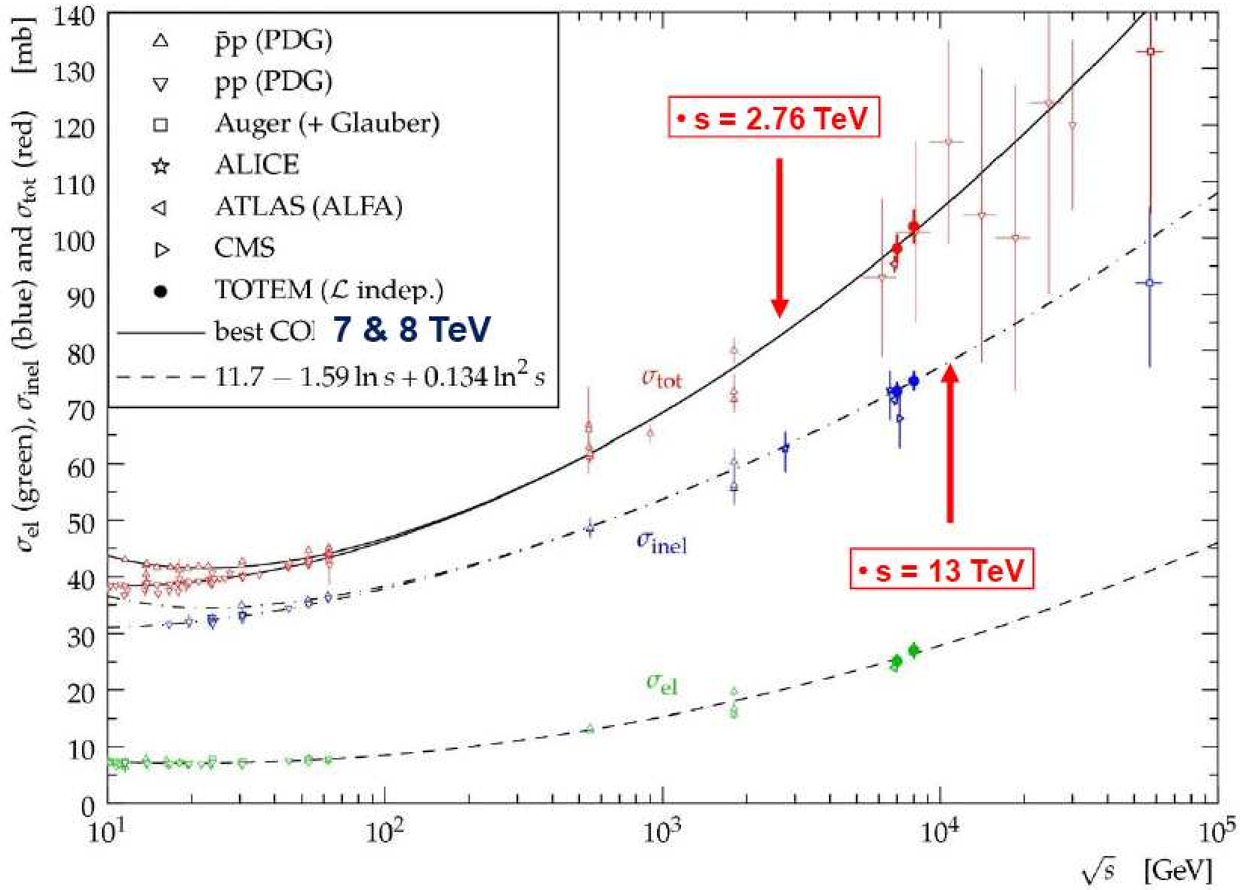






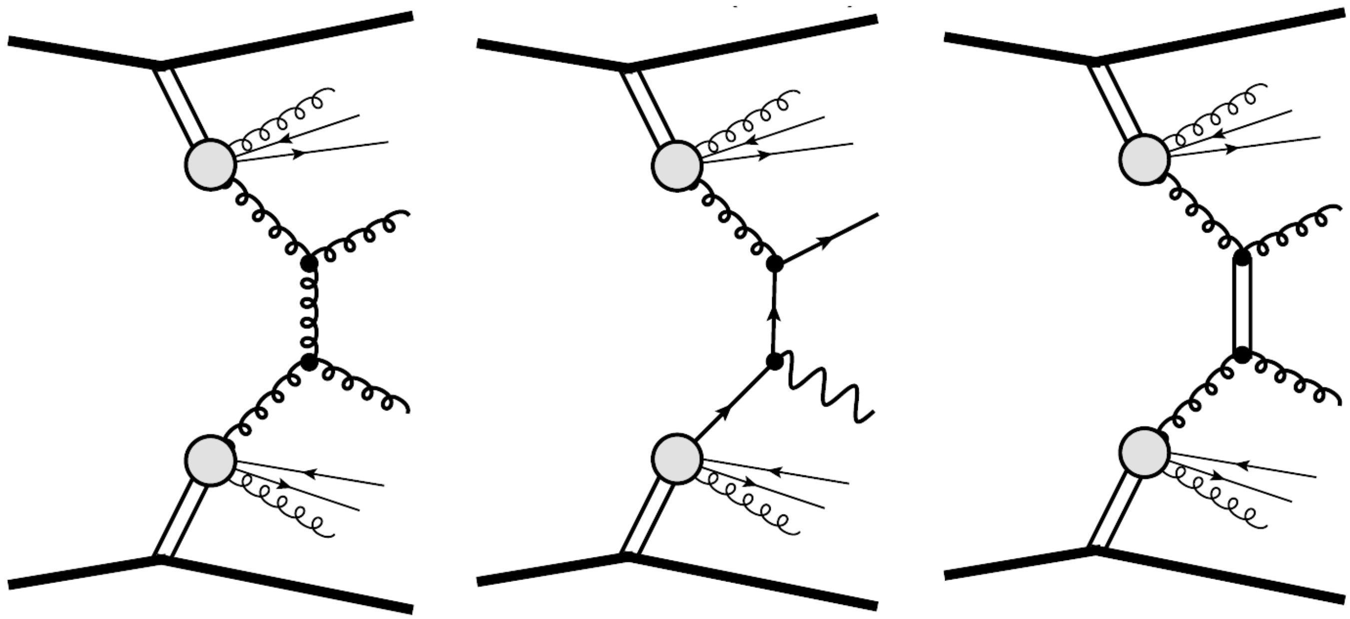
Very low luminosity: total cross section

- Measurements of total, elastic, inelastic cross sections
- Interesting to perform these measurements at 14 TeV (if reached at LHC) and 2 TeV (discrepancy D0/CDF)
- Non exponentiality at low $|t|$ for elastic pp scattering as determined by TOTEM



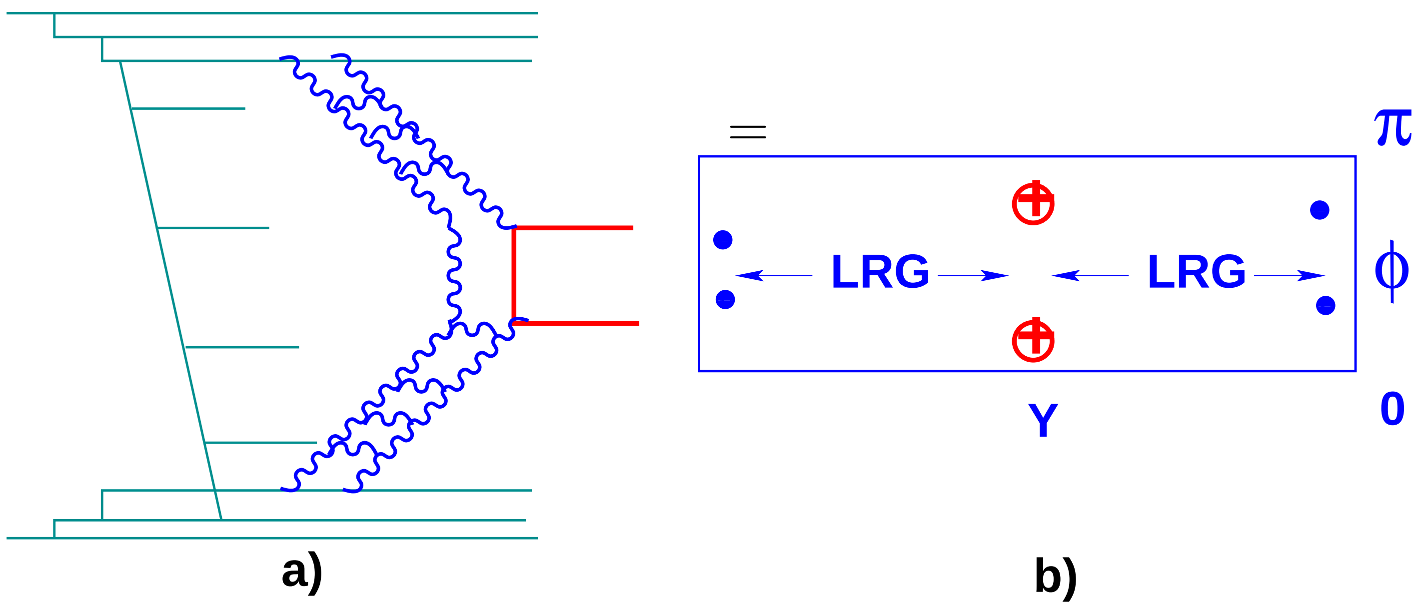
Medium Luminosity: Hard diffraction at the LHC

- Intact protons assumed to be tagged in CMS/TOTEM or AFP
- Constrain the structure of the colorless exchanged object, the Pomeron, and probe evolution equation of QCD
- Dijet production: dominated by gg exchanges
- γ+jet production: dominated by qg exchanges
- Jet gap jet in diffraction: Probe BFKL
- Three aims
  - Is it the same object which explains diffraction in pp and ep?
  - Further constraints on the structure of the Pomeron as was determined at HERA - Reggeon contributions?
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement



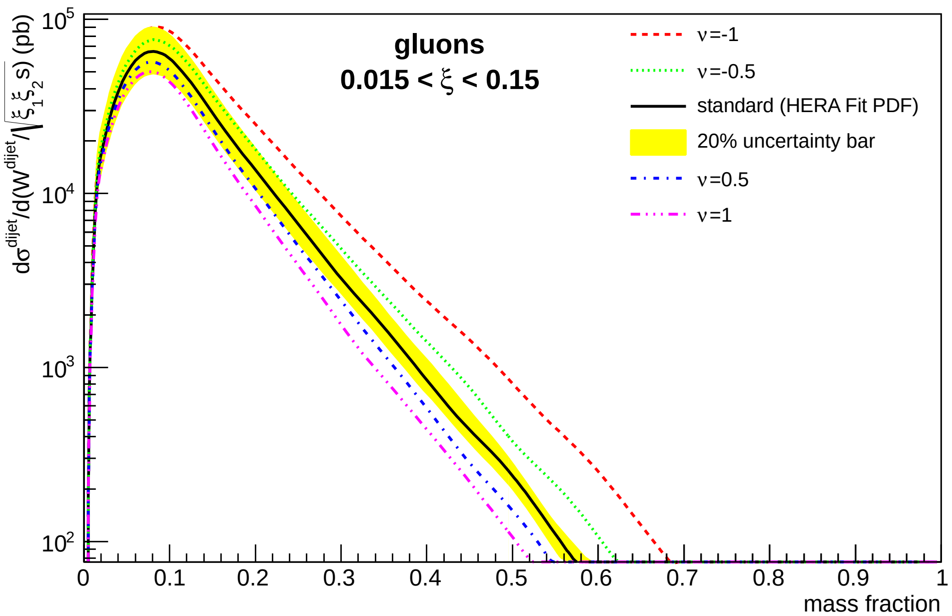
Hard diffraction: A difficulty to go from HERA to LHC: survival probability

- Use parton densities measured at HERA to predict diffractive cross section at the LHC
- Factorisation is not expected to hold: soft gluon exchanges in initial/final states
- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept
- Value of survival probability assumed in these studies: 0.1 at Tevatron (measured), 0.03 at LHC (extrapolated)



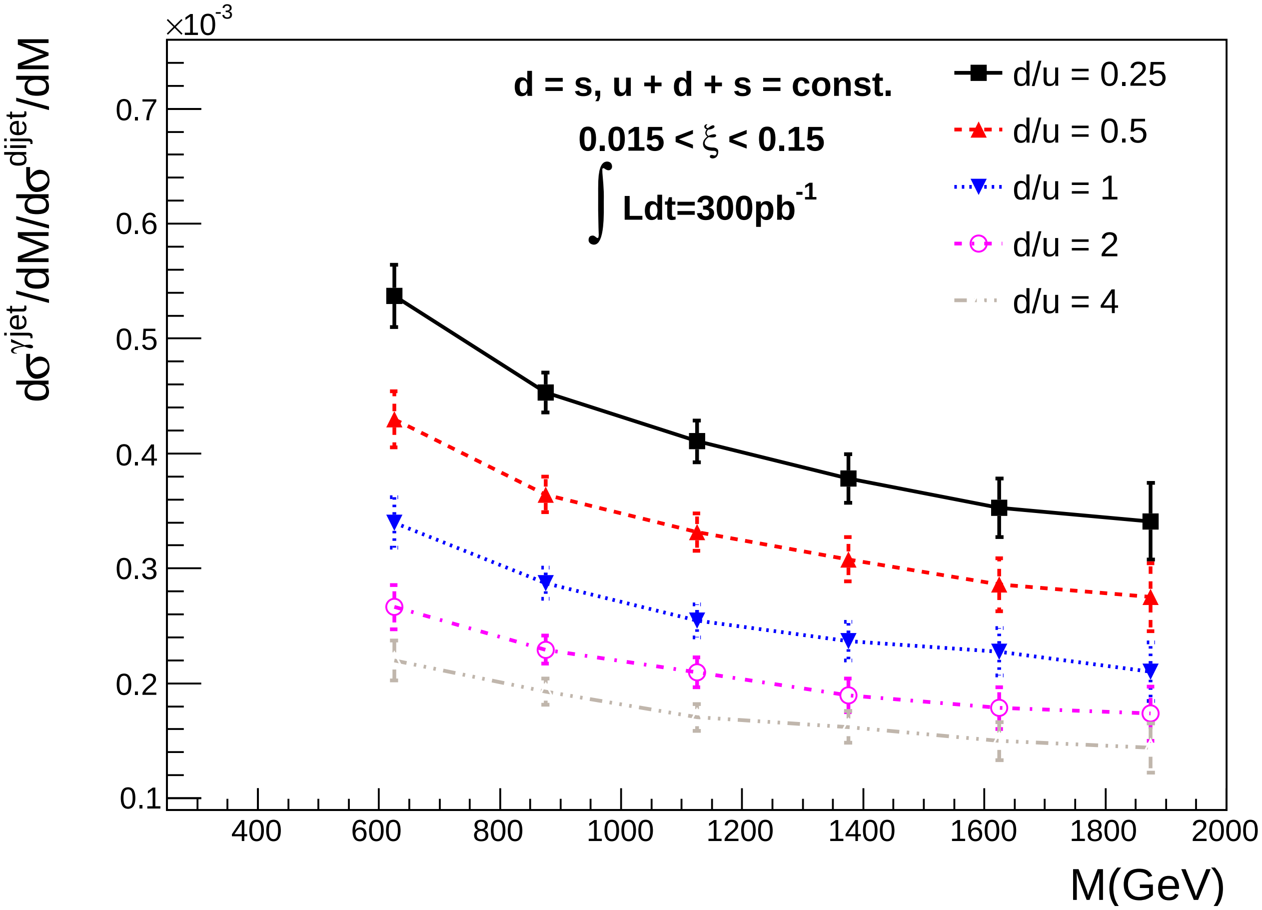
Medium Luminosity: Hard diffraction at the LHC with proton tagging: sensitivity to gluon density

- DPE dijet cross section at the LHC in AFP/CMS-TOTEM acceptance
- Sensitivity to gluon density in Pomeron: in order to illustrate this and show the sensitivity on high β gluon density, multiply the gluon density by $(1-\beta)^\nu$ with $\nu = -1, ..., 1$
- Measurements possible at low and high β^*, allows to test if gluon density is similar between HERA and LHC (universality of Pomeron model)
- Measurement of dijet mass fraction specially interesting M_{JJ}/M_{tot} where $M_{tot} = \sqrt{S \xi_1 \xi_2}$, $\xi_{1,2}$ being the proton momentum carried out by the Pomeron, measured by AFP/CMS-TOTEM
- Possibility to constrain the quark content in the Pomeron using $\gamma +$ jet events



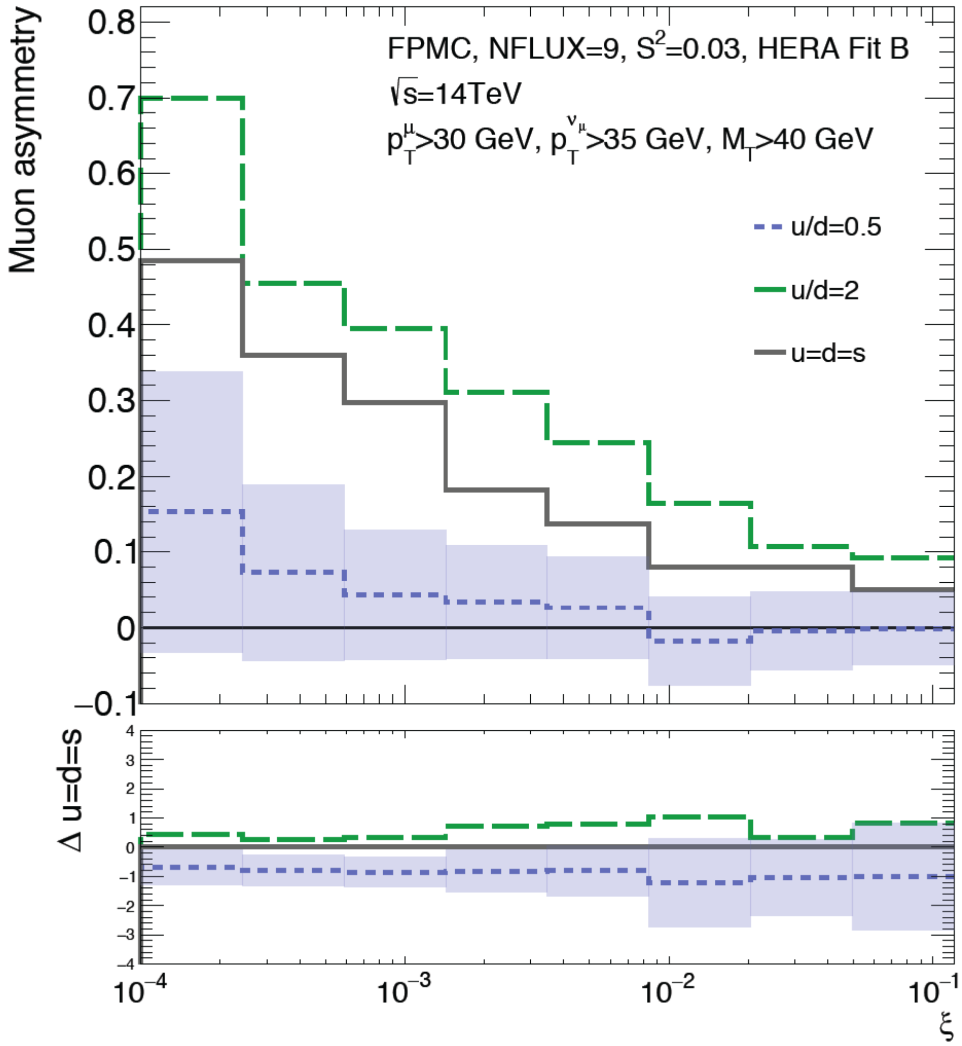
Inclusive diffraction at the LHC: sensitivity to quark densities

- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA



- In addition, constrain Reggeon contributions using dijets, see arXiv:1608.05674

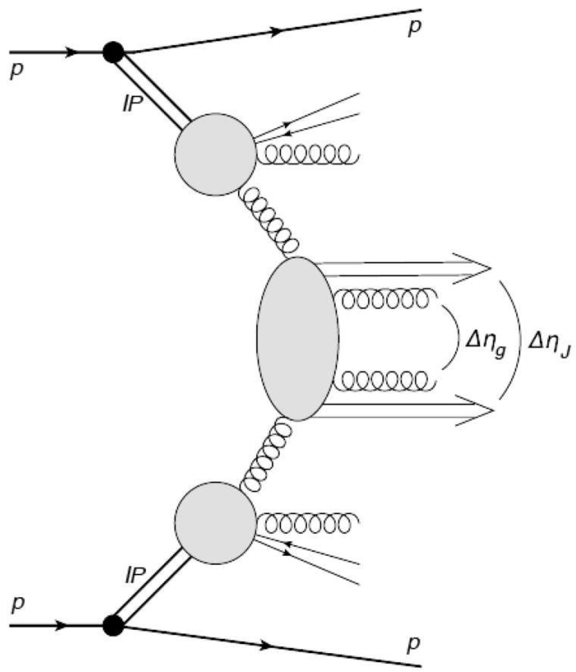
Medium lumi: W charge asymmetry
Sensitivity to quark densities

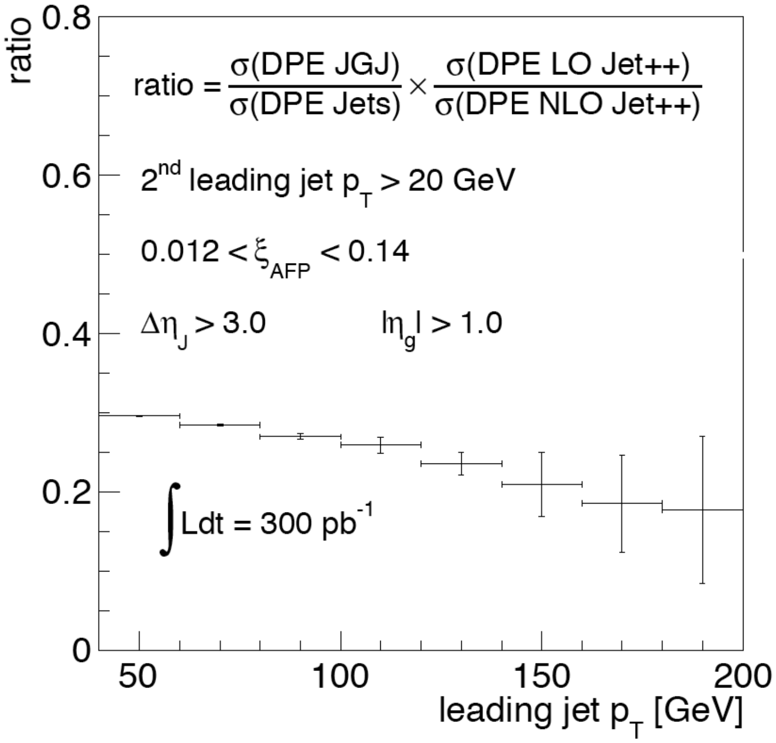


- Measure the average W charge asymmetry in ξ bins to probe the quark content of the proton: $A = (N_{W^+} - N_{W^-})/(N_{W^+} + N_{W^-})$
- Test if u/d is equal to 0.5, 1 or 2 as an example
- A. Chuinard, C. Royon, R. Staszewski, JHEP 1604 (2016) 092

Medium Lumi: Jet gap jet events in diffraction with proton tagging

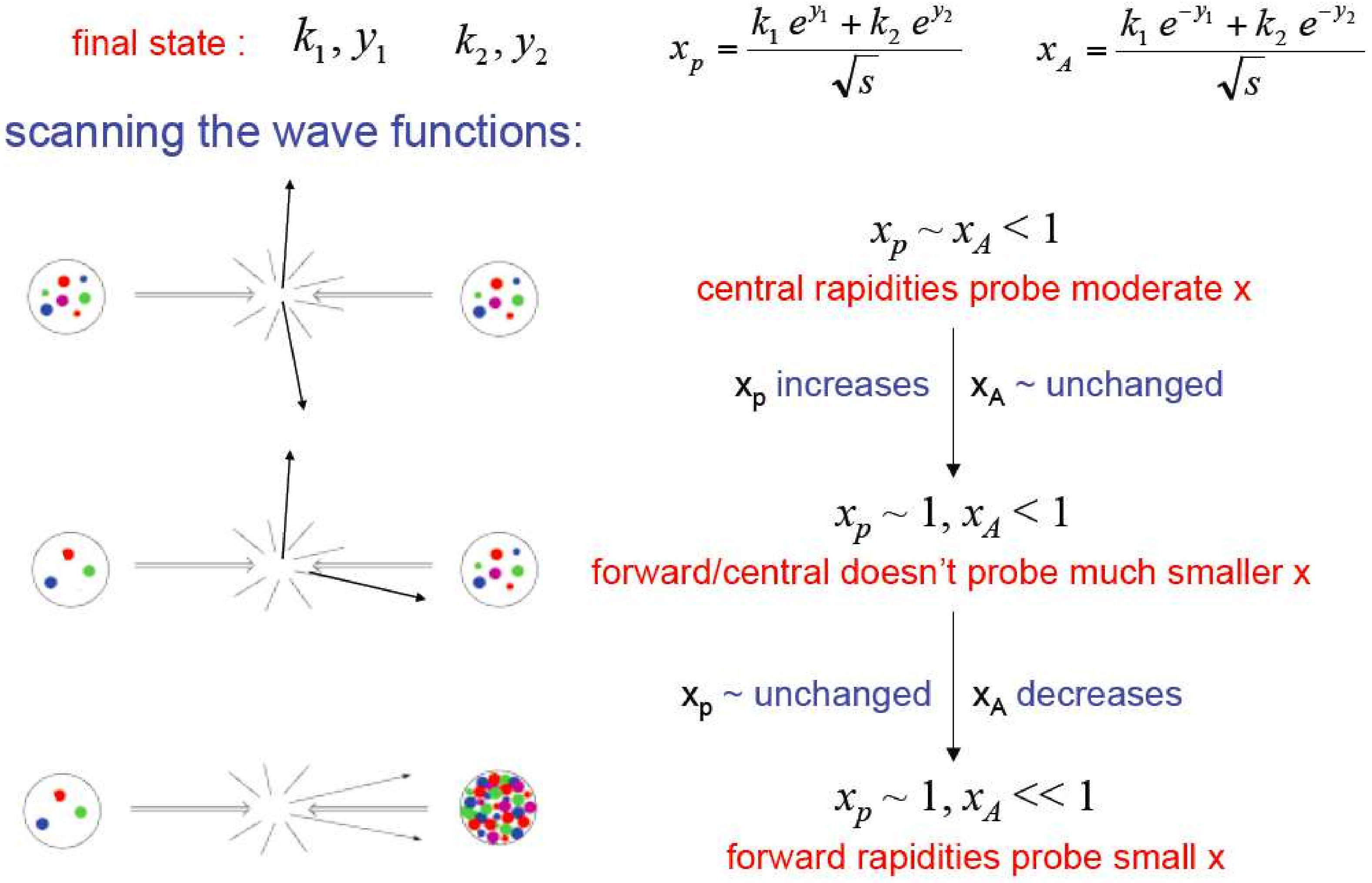
- BFKL (Balitsky Fadin Kuraev Lipatov) allows for QCD prediction (valid at short distances, hard perturbaitive region) for final states with rapidity gaps
- Needs special tests to get clean signals (jet-gap-jet, Mueller Navelet)
- Study BFKL dynamics using jet gap jet events: C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010
- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics (advantage of CASTOR in CMS)





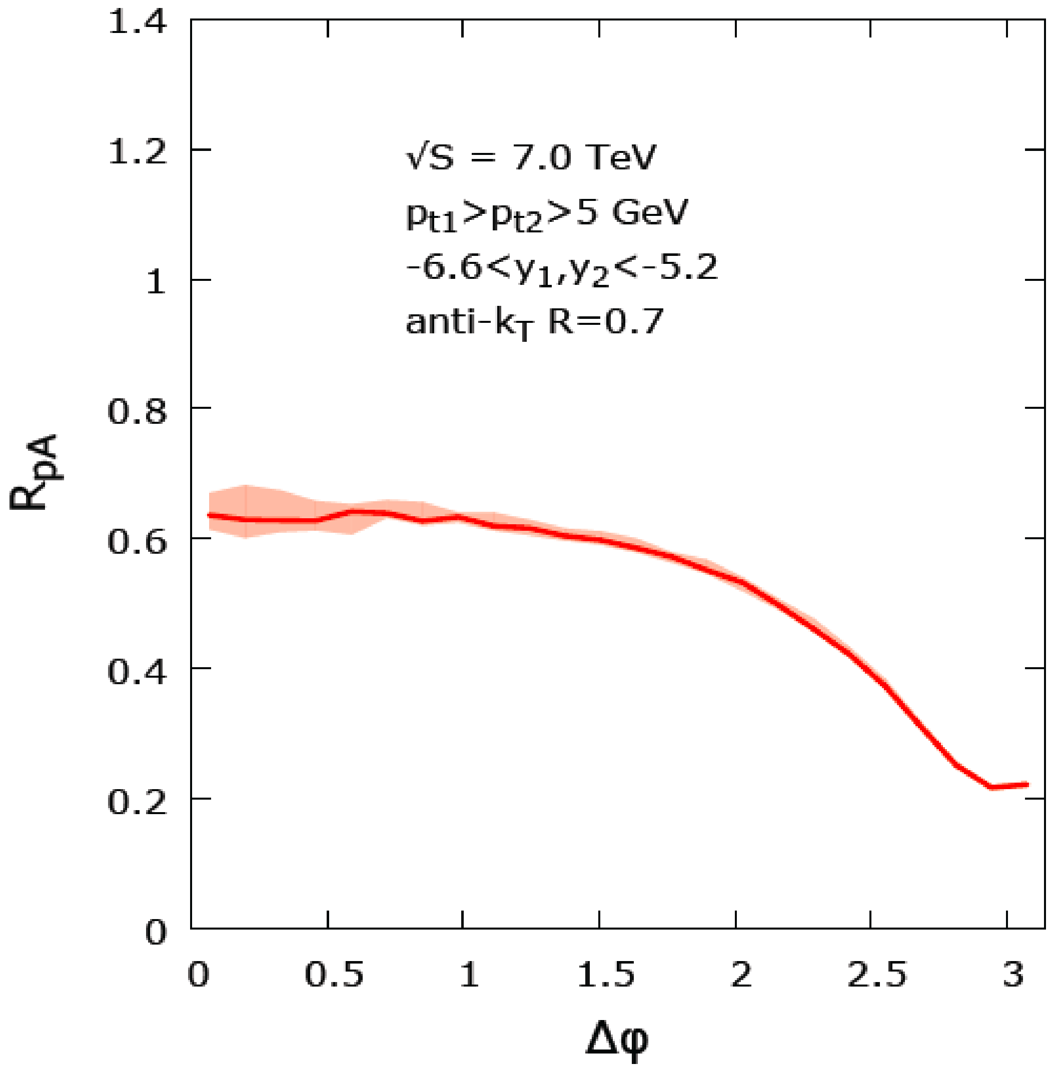
Saturation effects: measuring very forward jets in pA

- Saturation effects: need to go to low x, jets as forward as possible on the same side
- Compare pp and pA runs in order to remove many systematics

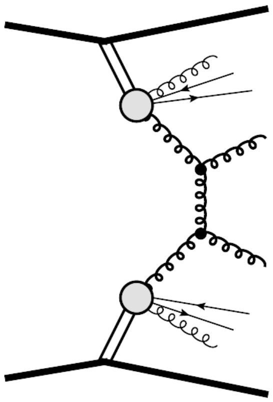


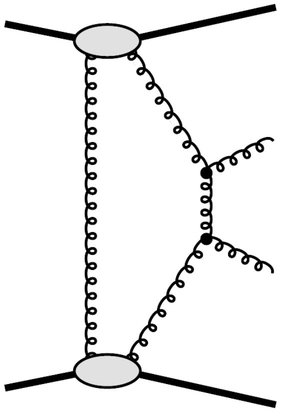
Medium luminosity: Saturation in pA

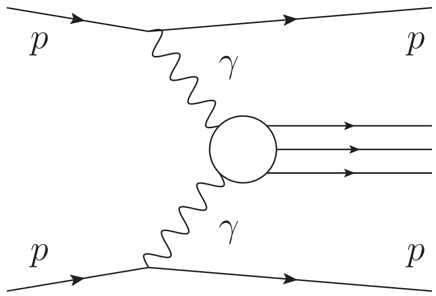
- Suppression factor between pp and pA runs: estimated to be less than 1/2 in CASTOR acceptance
- Important to get CASTOR in pA and low lumi pp data
- Study performed by Cyrille Marquet et al.

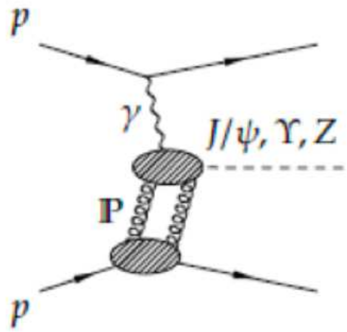


Exclusive diffraction with tagged protons





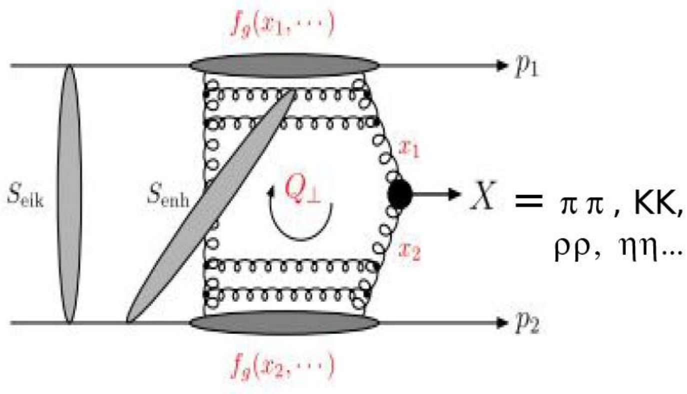


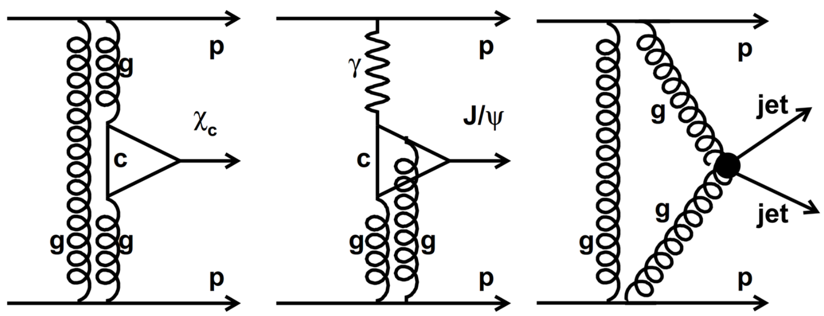


- Many exclusive channels can be studied at medium and high luminosity: jets, χ_C, cahrmonium, J/Ψ....
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Possibility of constraining the background by asking the matching between the information of the two protons and the produced object
- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV (masses above 400 GeV, depending how close one can go to the beam)

Medium Lumi: Exclusive state measurements

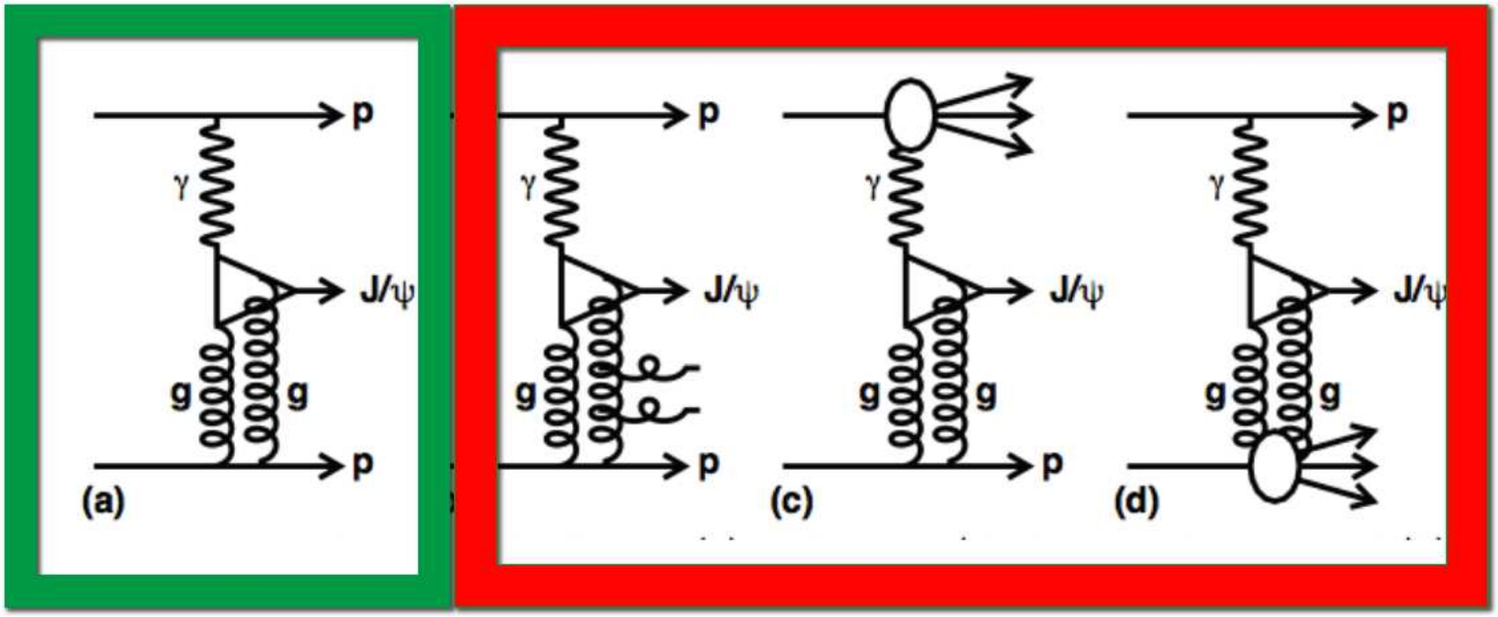
- Many exclusive states can be measured in high β^* runs in CMS/TOTEM, and in standard runs in LHCb
- CMS/TOTEM: Detect both protons, information from central detector, particle Id (pions, kaons with tracker), timing detectors
- Search for glueball states and probing low x gluon down to $x \sim 10^{-4}$
- With 1 pb^{-1}: confirmation of unobserved possible $f_0(1710)$ and $f_0(1500)$ decay modes and first cross-section $\times$ branching ratio estimates for f-states
- With 5-10 pb^{-1}: unambiguous determination of spin and precise measurement of cross-section $\times$ branching ratio for f-states (needed for glueball analysis) and cross-section $\times$ branching ratio estimates for all three $\chi_{C,0,1,2}$ states, comparison with perturbative QCD
- Low mass exclusive dijet production: M_X >60 GeV, cross section of $\sim$ 100 pb





Exclusive channels in LHCb

- Exclusive production of vector mesons: Benefits from the new HERSCHEL detector to reduce inelastic background
- Many analyses in progress: J/Ψ, χ_C, Ψ, Double Charmonia, meson spectroscopy, glueballs, double J/Ψ production...
- Complementarity with CMS/TOTEM-ATLAS: proton tagging, coverage in rapidity

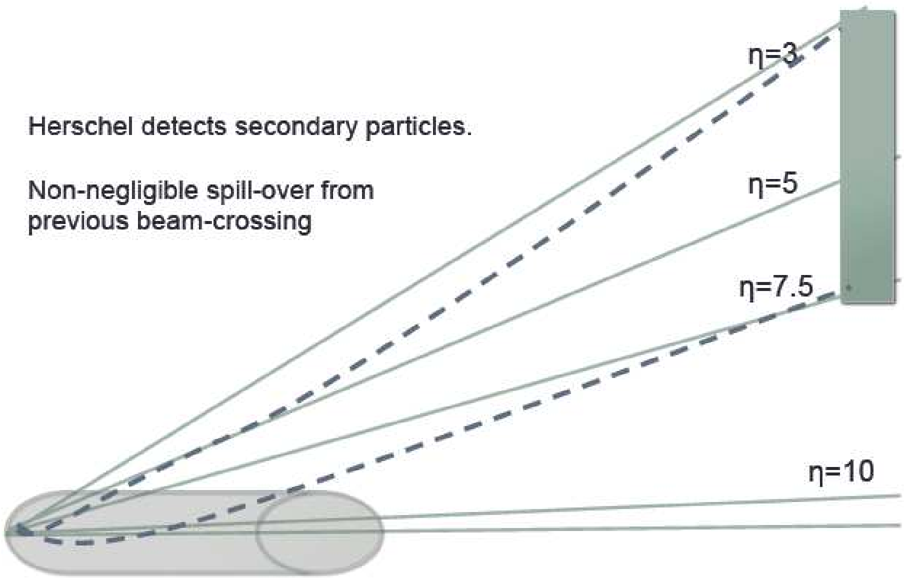


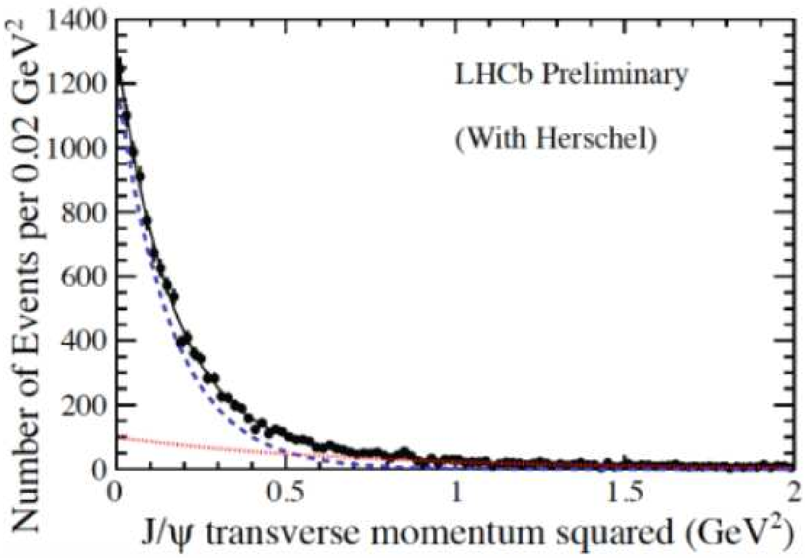
Signal

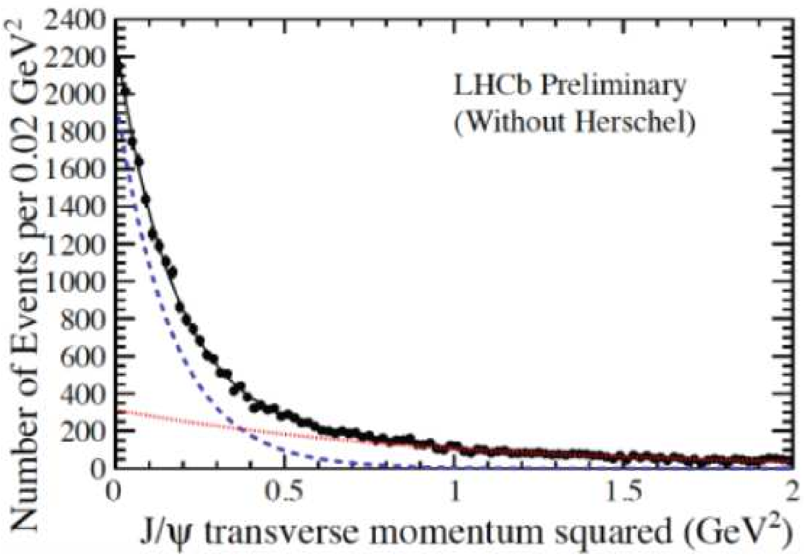
Background

Exclusive channels in LHCb

- Exclusive production of vector mesons
- As an example: J/Ψ production

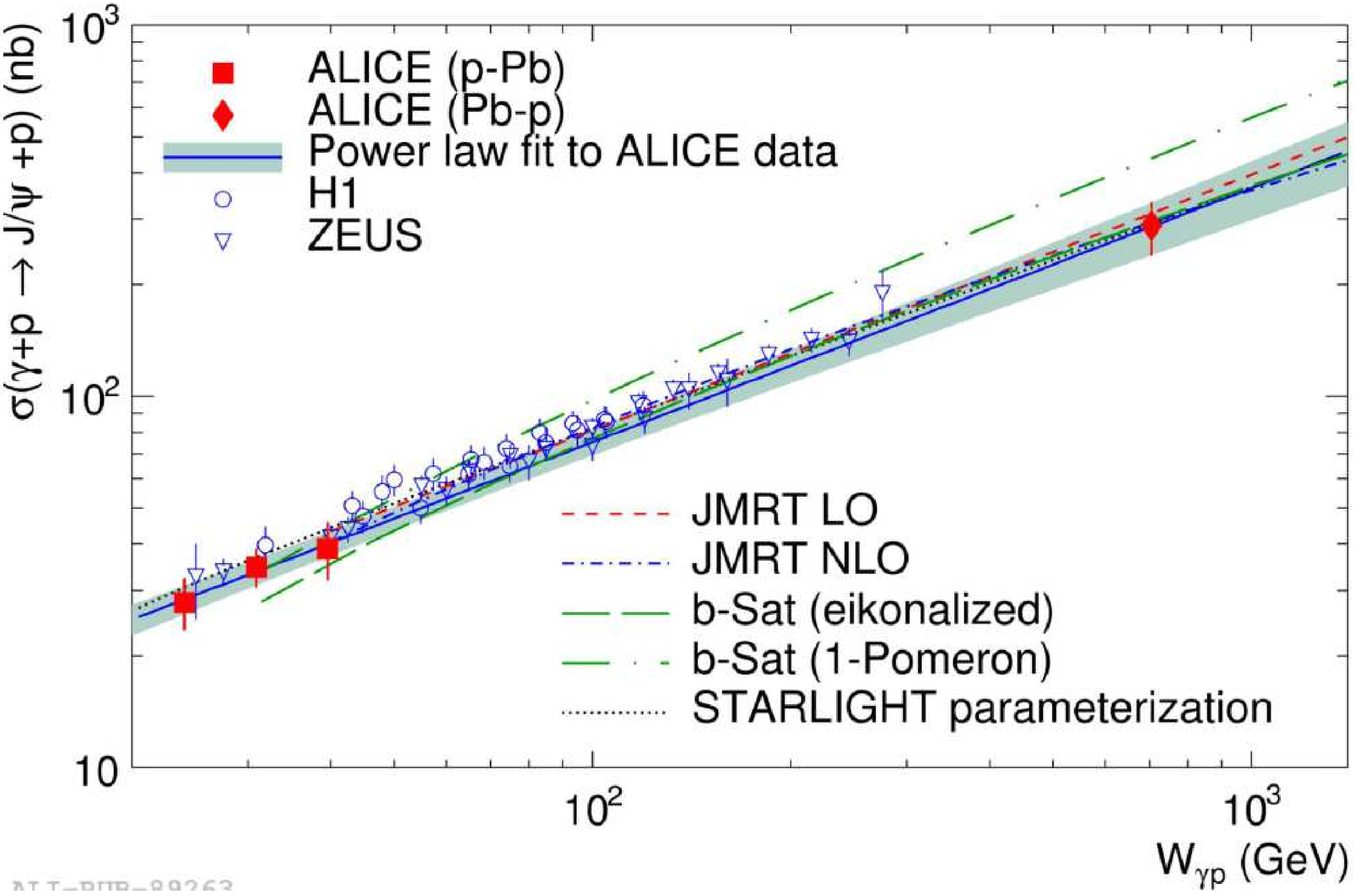




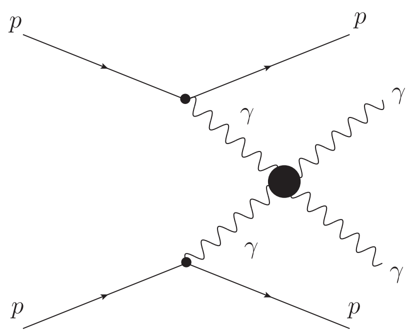


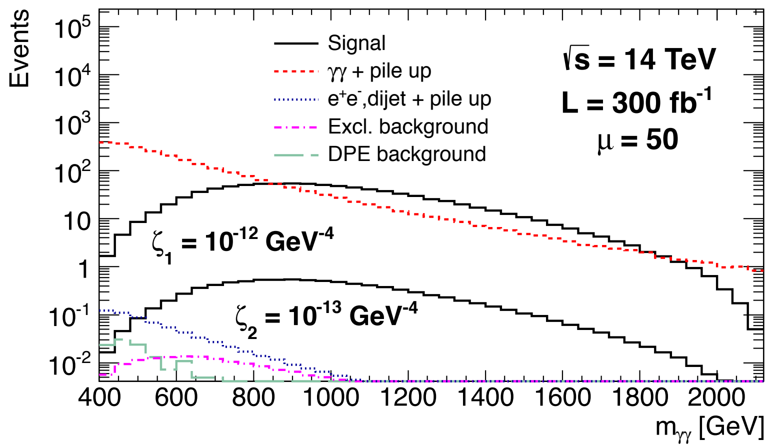
Exclusive channels in ALICE

- Measurements of many exclusive channels in pPb and PbPb collisions
- Example of J/Ψ production cross section: suggests no change in gluon density on proton between HERA and LHC
- Project of installing a very forward calorimeter in ALICE: FoCal, allows to probe gluon at low x in nuclei which is essentially unknown for $x < 10^{-2}$



High lumi: quartic $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ anomalous couplings with proton tagging

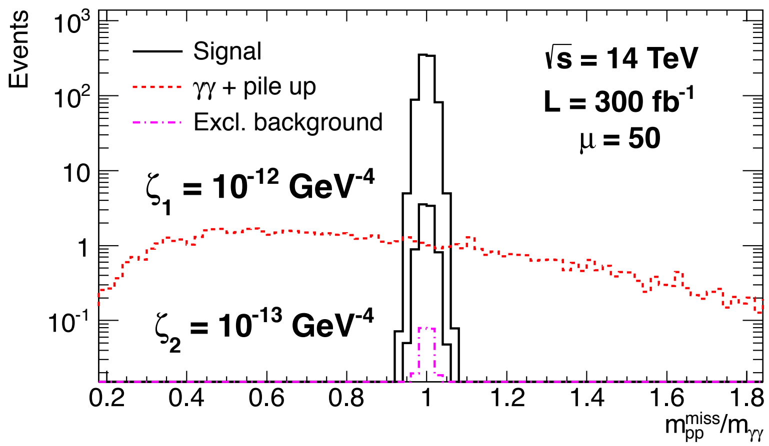


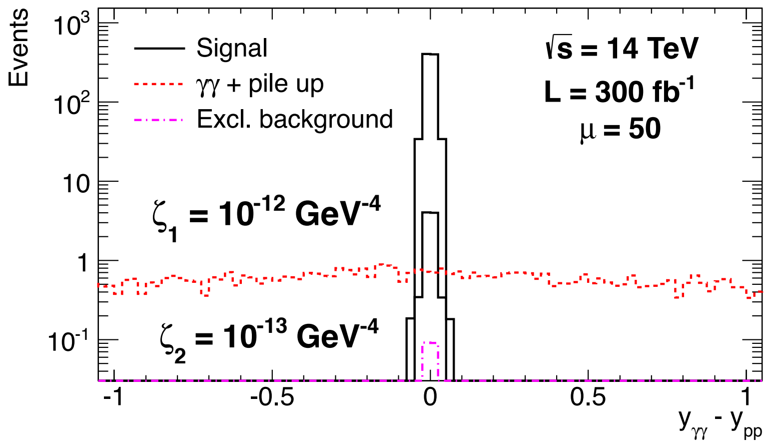


- $\gamma\gamma\gamma\gamma$ couplings predicted by extra-dim, composite Higgs models
- Two effective operators at low energies $\zeta_{1,2} \sim 10^{-14} - 10^{-13}$

$$\mathcal{L}_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- Exclusivity cuts suppresses all pile-up backgrounds





High Lumi: quartic $\gamma\gamma$ anomalous couplings

Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV]	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

- No background after cuts for 300 fb^{-1} **without needing time detector information**
- Exclusivity cuts needed to suppress backgrounds:
  - Without exclusivity cuts using AFP: background of 80.2 for 300 fb^{-1} for a signal of 34.9 events ($\zeta_1 = 2\ 10^{-13}$)
  - With exclusivity cuts: 0 background for 31.8 signal
- String theory/grand unification models predict couplings via radions/heavy charged particles/dilatons for instance up to 10^{-14}-10^{-13}

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile-up (μ)	50	50	50	200
coupling (GeV^{-4})	≥ 1 conv. γ 5 σ	≥ 1 conv. γ 95% CL	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$9 \cdot 10^{-15}$	$7 \cdot 10^{-15}$
ζ_2 f.f.	$2. \cdot 10^{-13}$	$1. \cdot 10^{-13}$	$6 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

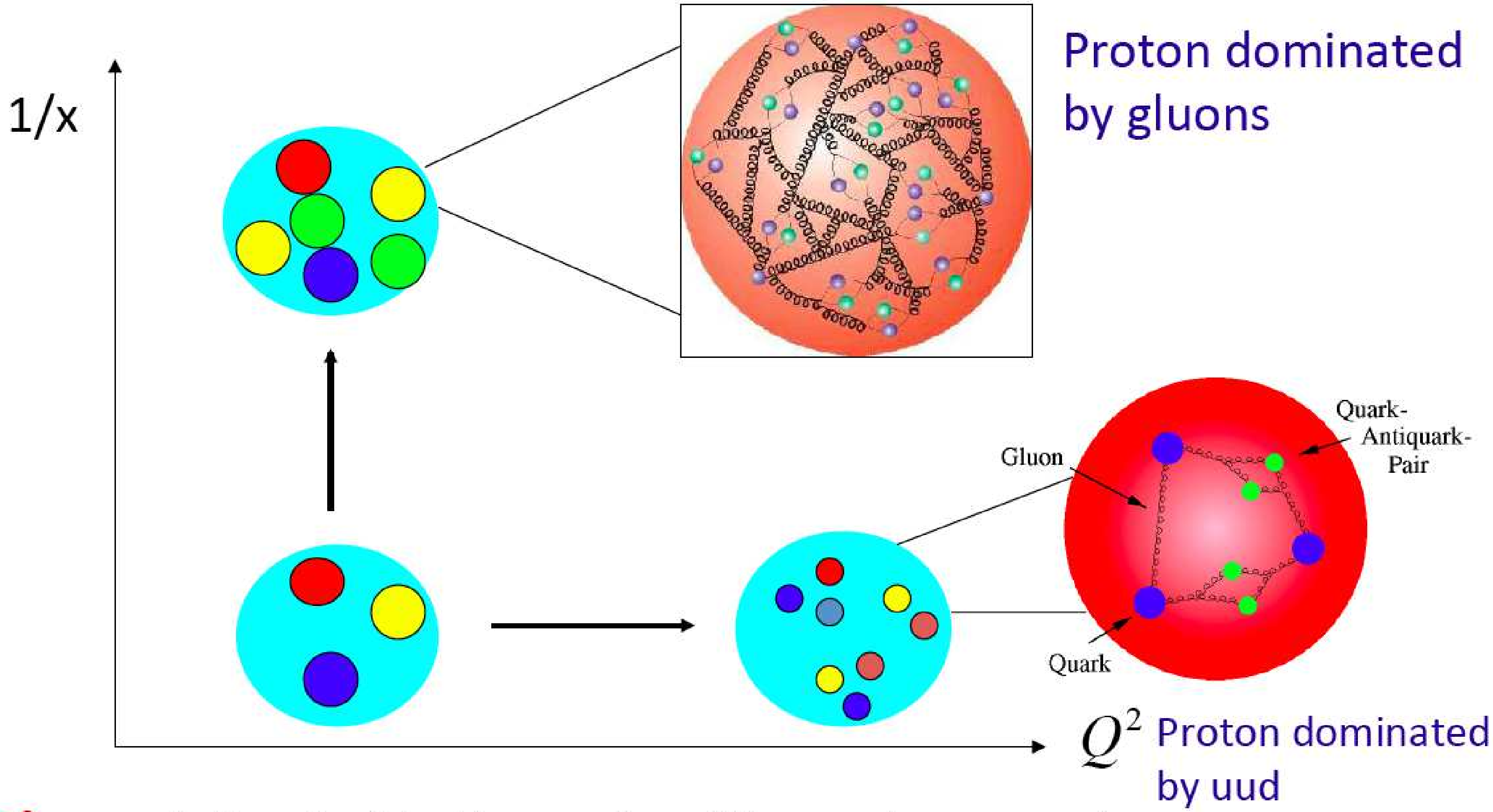
Conclusion: measurements to be performed at the LHC

- Low luminosity: Total. elastic, inelastic cross sections at 2 and 14 TeV; particle production in proton Oxygen collisions (at the end of the LHC, needs LHCf)
- Many measurements to be performed at low/medium diffractive masses: Pomeron structure (quark, gluons), BFKL resummation effects, missing mass studies (Low mass SUSY...), requires proton tagging and moderate pile up, to be done in CMS-TOTEM, CT-PPS and ATLAS/ALFA, ATLAS/AFP
- Exclusive diffraction: Many studies performed already in LHCb, complementarity between ALICE/LHC and CMS-TOTEM/ATLAS (with/without proton tagging)
- Forward detector coverage also fundamental for Pb Pb and p Pb collisions: very forward jets in CMS/CASTOR as an example
- CT-PPS and AFP standard running at high luminosity: accumulates lots of luminosity, beyond standard model physics such as anomalous couplings
- Needs special runs at very low and medium luminosity: for instance, 50 to 100 pb^{-1} of data needed for $\beta \sim$90 m
- Report to the LHCC being written
- Thanks to Nicolo who was leading the LHC Forward Physics WG with me since the beginning, and welcome Ralf!

Looking for BFKL effects

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP): Evolution in Q^2
- Balitski Fadin Kuraev Lipatov (BFKL): Evolution in x

Aim: Understanding the proton structure (quarks, gluons)

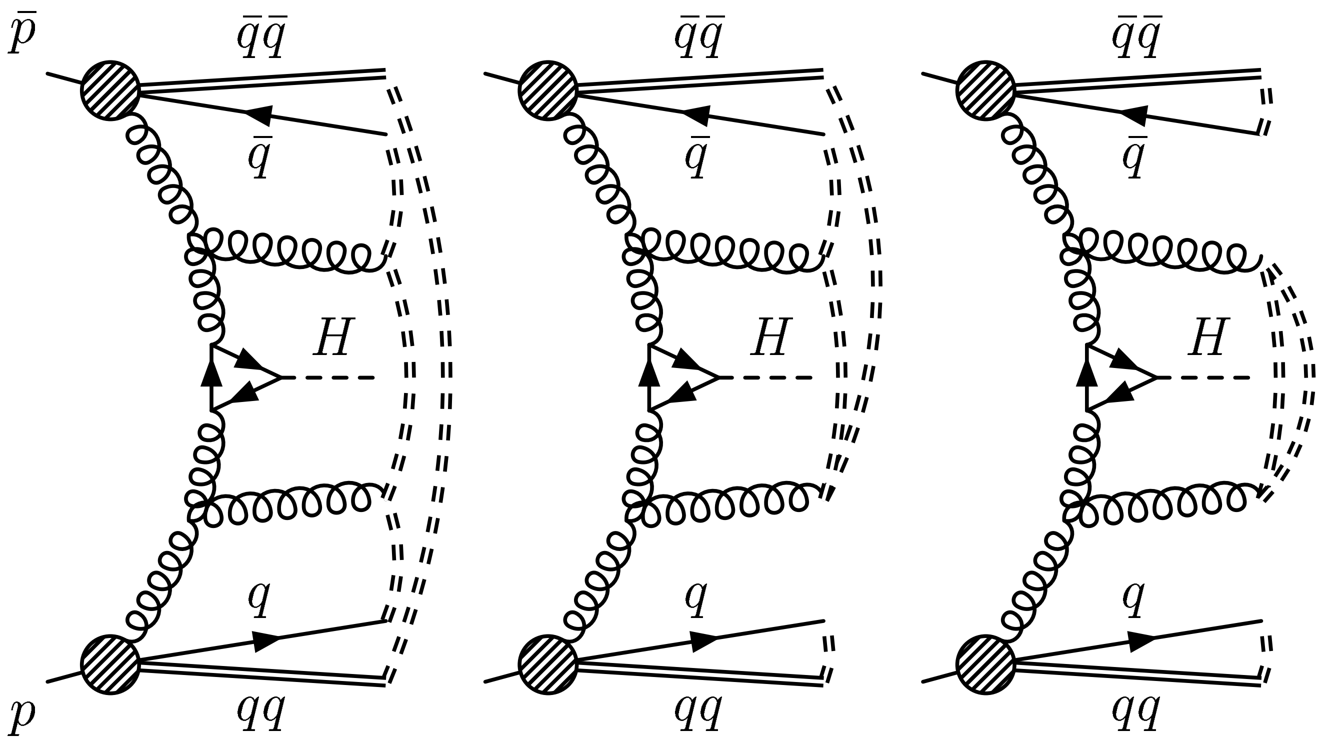


Q^2 : resolution inside the proton (like a microscope)

X :Proton momentum fraction carried away by the interacting quark

Soft Colour Interaction models

- A completely different model to explain diffractive events: Soft Colour Interaction (R.Enberg, G.Ingelman, N.Timneanu, hep-ph/0106246)
- Principle: Variation of colour string topologies, giving a unified description of final states for diffractive and non-diffractive events
- No survival probability for SCI models



Inclusive diffraction at the LHC: sensitivity to soft colour interaction m

- Predict DPE γ+jet divided by dijet cross section at the LHC for pomeron like and SCI models
- In particular, the diffractive mass distribution (the measurement with lowest systematics) allows to distinguish between the two sets of models: flat distribution for SCI