Forward Physics plans at the LHC

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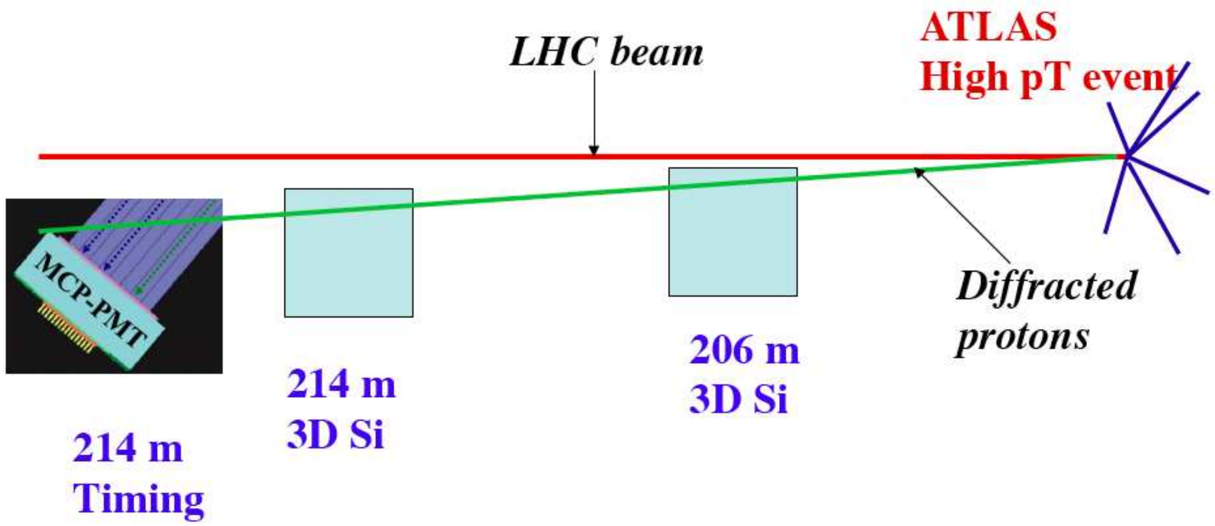
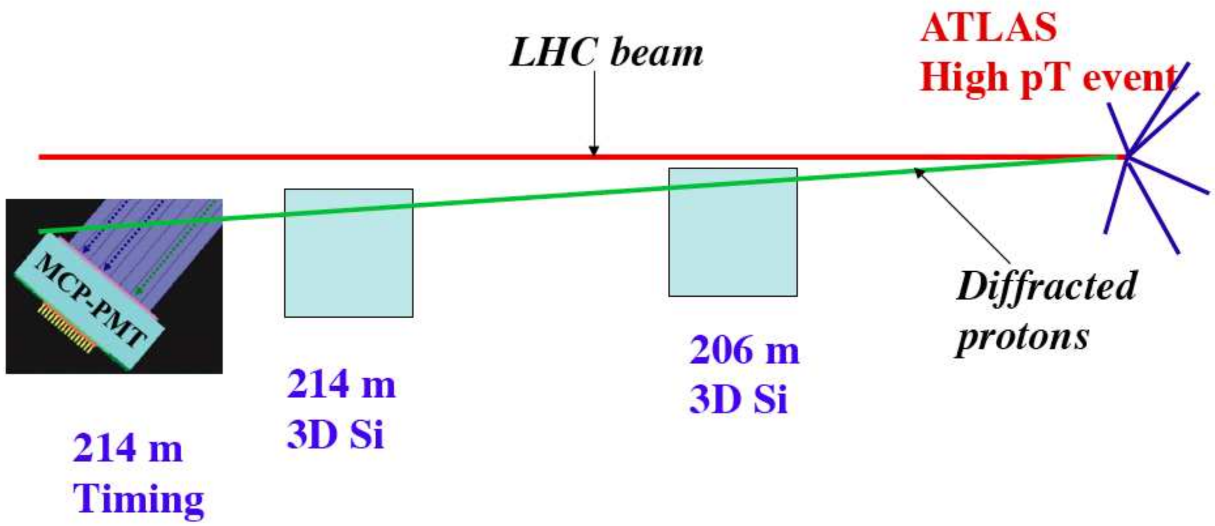
Contents: Forward Physics (QCD and exploratory physics)

- Low luminosity - no pile up
- Medium luminosity - moderate pile up
- High luminosity - high pile up, full luminosity



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

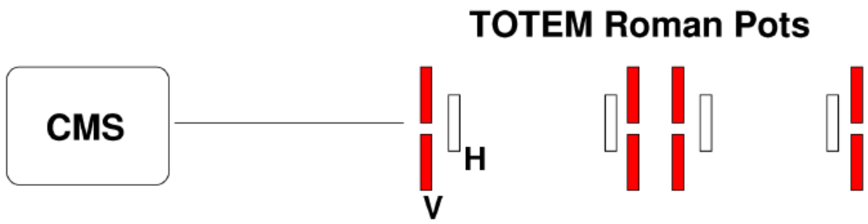


Different kinds of LHC running

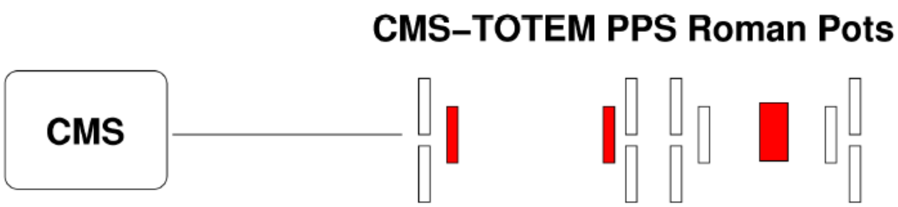
- Low luminosity runs
  - No pile up ($\mu << 1$) (very low luminosity) - dedicated to LHCf measurements (together will all other LHC experiments)
  - No pile up high β^*, ALFA and TOTEM
  - Very low pile up with proton tagged or not: 0.1 to 1 pb^{-1}, a few days are needed
- Medium luminosity runs
  - 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 high β^*, μ ~1, a few days needed to accumulate 1 to 10 pb^{-1}
  - AFP and CMS/TOTEM running at low β^*, low pile up ($\mu = 2, ..., 5$), between one and two weeks of data taking, 10 to 100 pb^{-1}
- High pile up (μ =20,...,100) (high luminosity) with proton tagging; Possibility to collect data with high pile up (50 and above) and also at μ ~25 by restricting to end of store data taking and tails of the vertex distribution: 40% of total luminosity can be collected

Forward detectors

- LHCf close to ATLAS in the very forward region
- New Herschel scintillators in LHCb
- New forward scintillators in Alice
- CASTOR, ZDC in CMS, ZDC, LUCID, ALFA in ATLAS....
- CMS-TOTEM and CT-PPS



CMS-TOTEM
High β*
(special runs)
$\mu = 0.1 - 0.5$
$\mathcal{L}_{int}$ = 1-100 pb^{-1}
vertical RPs



CT-PPS
low β*
(standard runs)
μ = 25 - 50
$\mathcal{L}_{int}$ = ~100 fb^{-1}
horizontal RPs

- AFP: Additional horizontal roman pots in ATLAS at 220 m with respect to ALFA vertical pots

Running conditions

- Low instantaneous luminosity, very low and low pile up
  - Forward energy and multiplicity measurements: LHCf
  - Total cross section measurement: ALFA/TOTEM
  - Low mass resonances and glueballs: CMS/TOTEM, AFP. LHCb
  - Soft QCD with proton tagging: CMS/TOTEM, AFP
  - Single diffractive measurements: TOTEM/CMS, AFP, Alice
- Medium instantaneous luminosity, low pile up
  - Exclusive diffractive measurements: vector mesons, $c\bar{c}$, jets...: LHCb, CMS-TOTEM, AFP
  - DPE/QCD measurements, understanding the structure of diffraction: jets, γ+jet,.CMS/TOTEM, AFP
  - Jet gap jet in diffraction: AFP, CMS/TOTEM
  - Preparing for high lumi measurements: AFP/CT-PPS
- High luminosity: AFP, CT-PPS
  - QCD physics: Exclusive jets....
  - Exploratory physics: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ anomalous couplings
- Detailed planning proposed to the LHCC by next meeting (document to be given before the meeting)

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

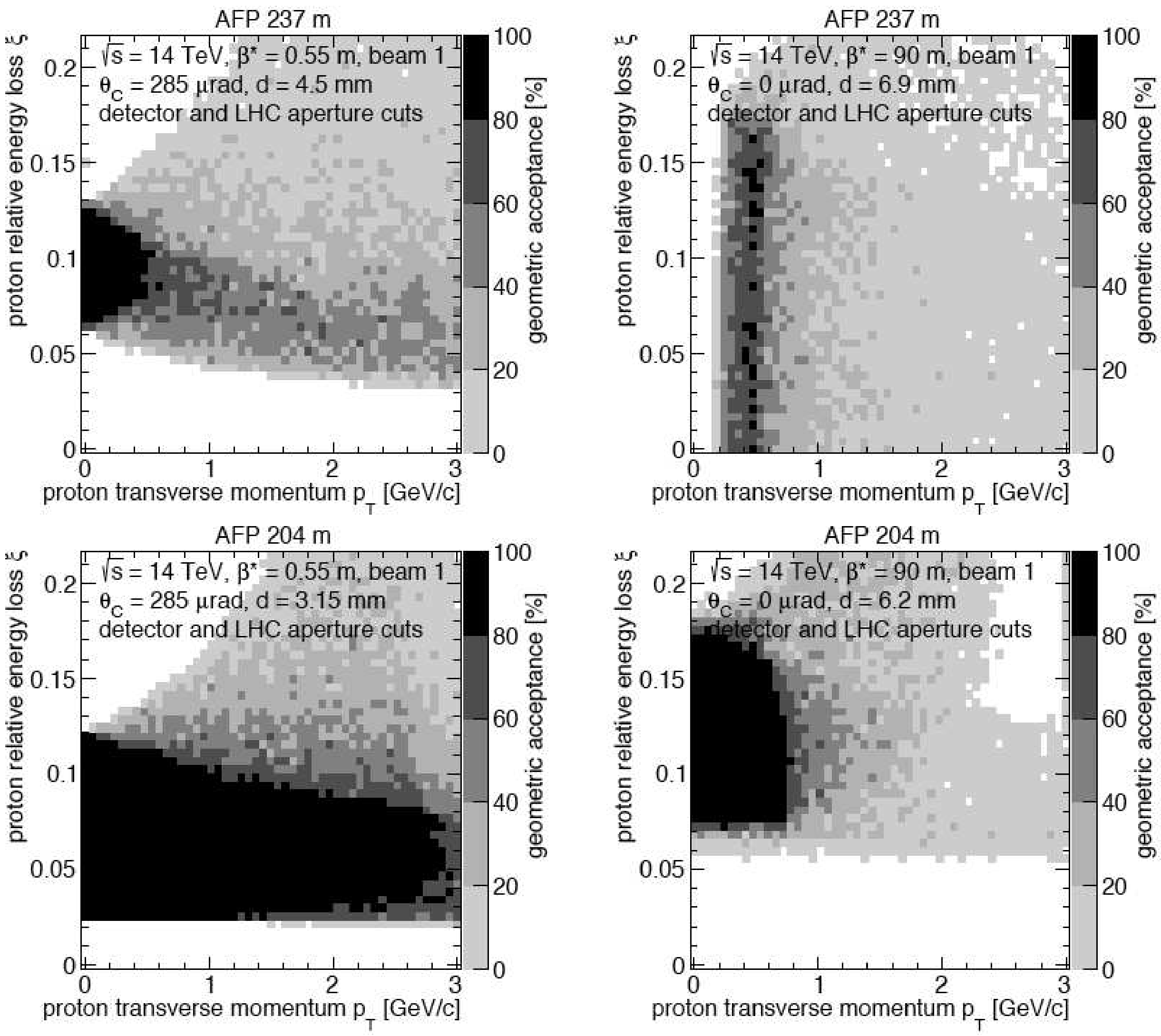
optics

$\beta^* = 0.55$ m nominal (*collision*)

$\beta^* = 90$ m special (*high*-β^*)

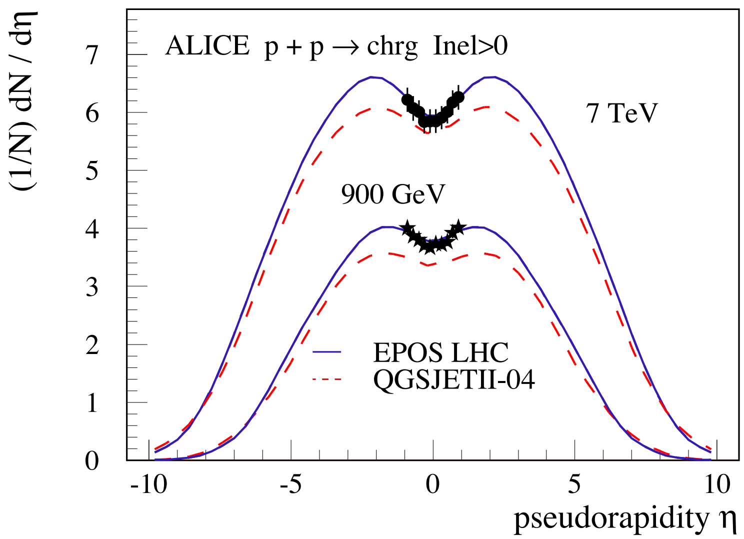
ALFA

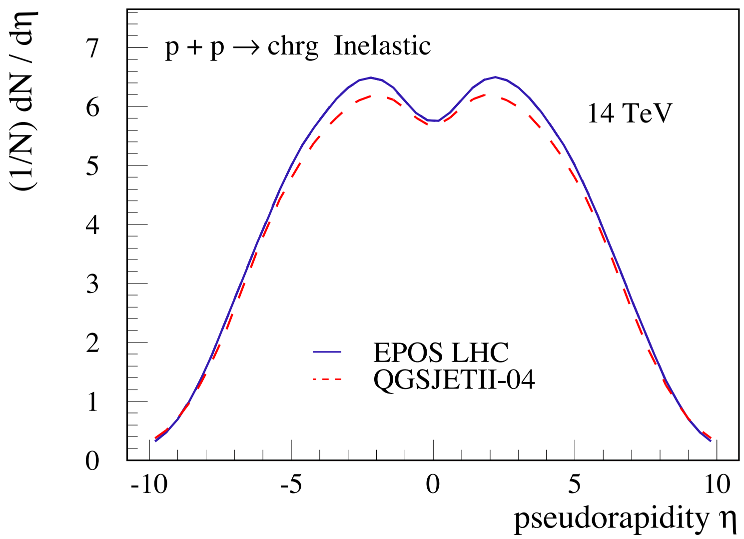
AFP

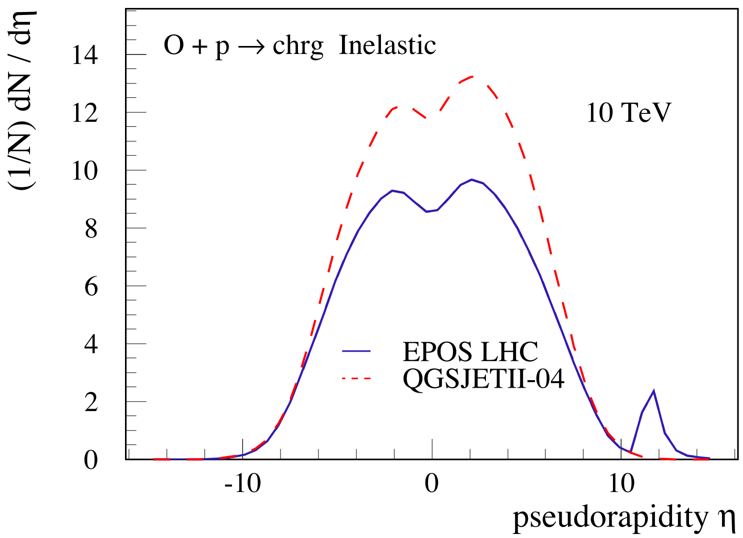


Very low lumi I: Soft interactions

- 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

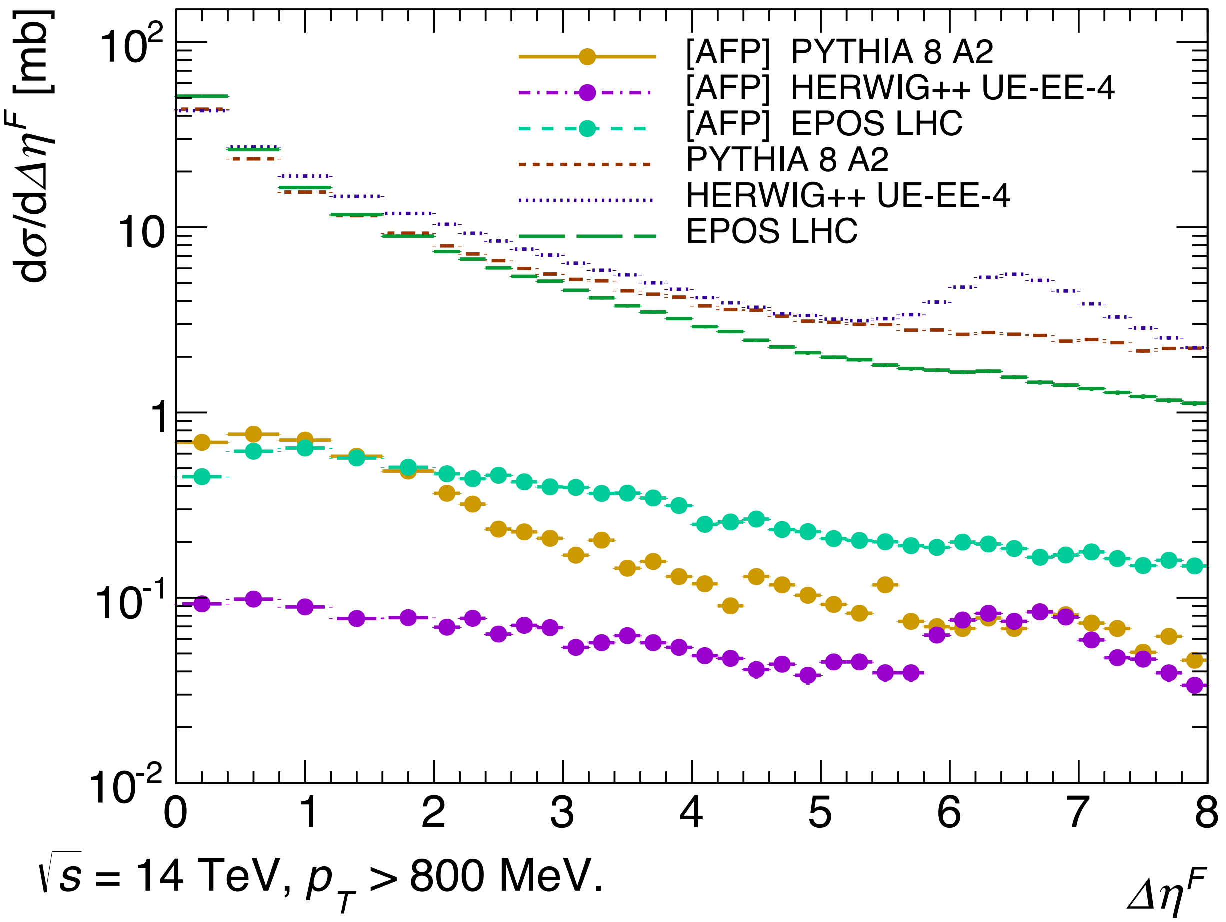






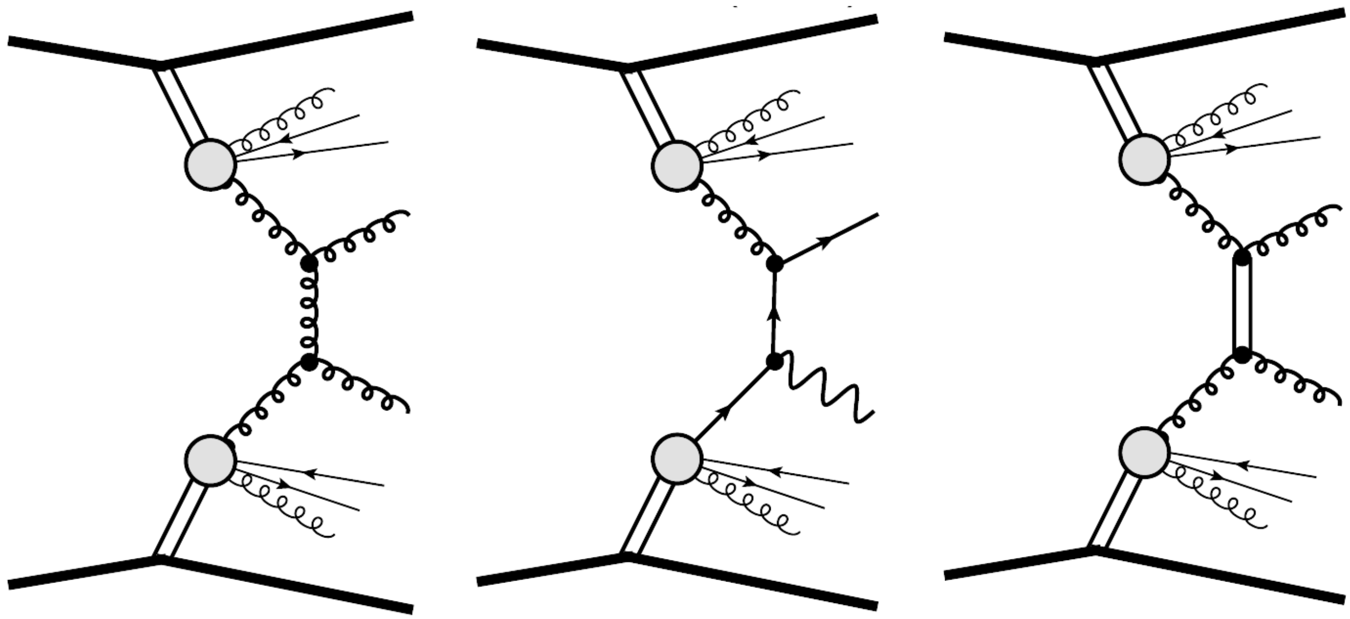
Very low lumi II: Forward gap in soft diffraction

- Measure size of forward gap in diffractive events
- Measurement important to tune models (hadronisation...)
- Larger differences between models when proton is tagged in AFP or CMS/TOTEM



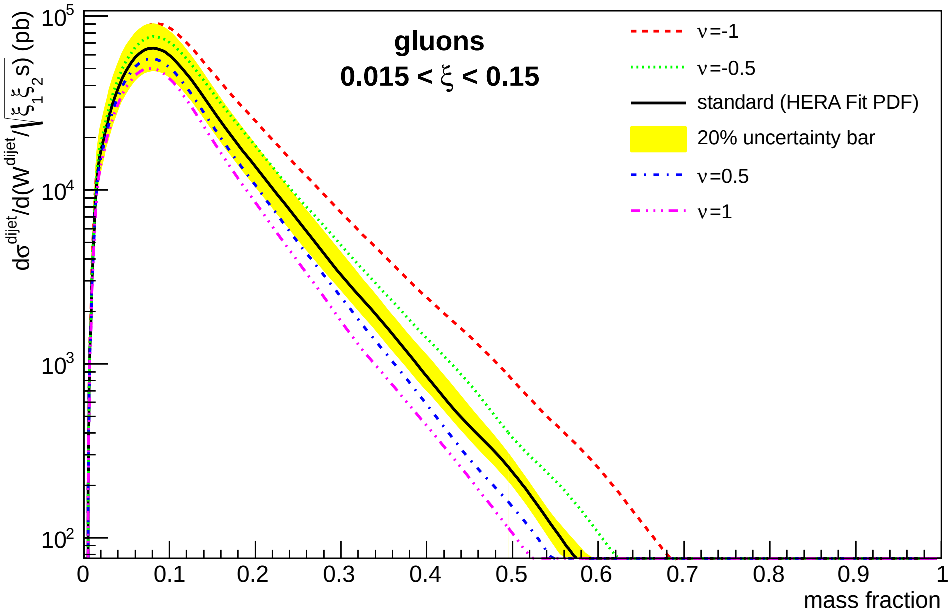
Medium Luminosity I: Inclusive diffraction at the LHC

- 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
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement



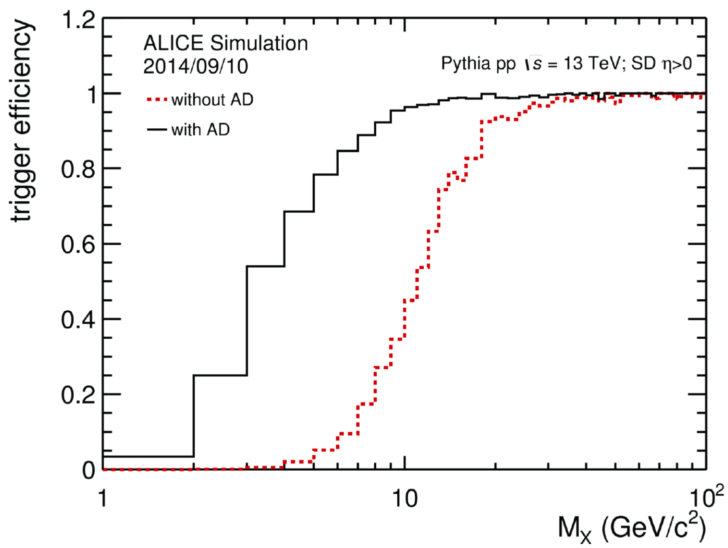
Medium Luminosity II: Inclusive diffraction at the LHC with proton tagging: sensitivity to gluon density

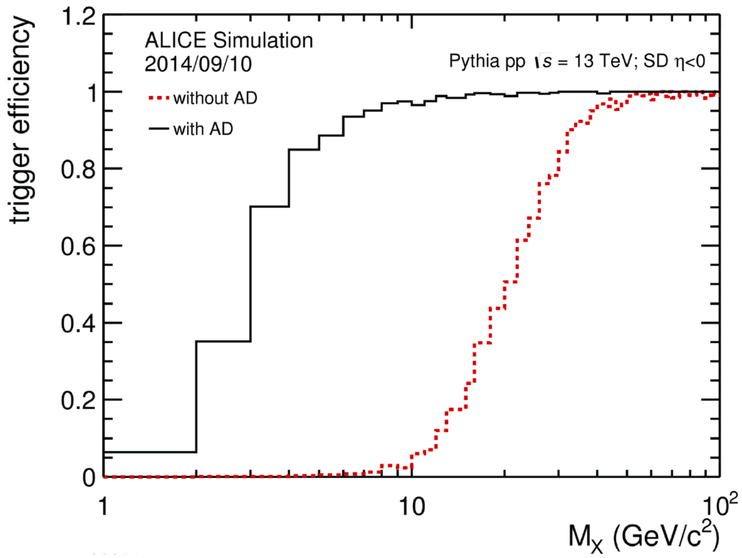
- DPE dijet cross section at the LHC in AFP/CMS-TOTEM acceptance
- Sensitivity to gluon density in Pomeron: in order to illustrate this and show the sensitivity on high β gluon density, multiply the gluon density by $(1-\beta)^{\nu}$ with $\nu = -1, ..., 1$
- Measurements possible at low and high β^*, 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



Medium Lumi III: Forward scintillators in ALICE No proton tagging

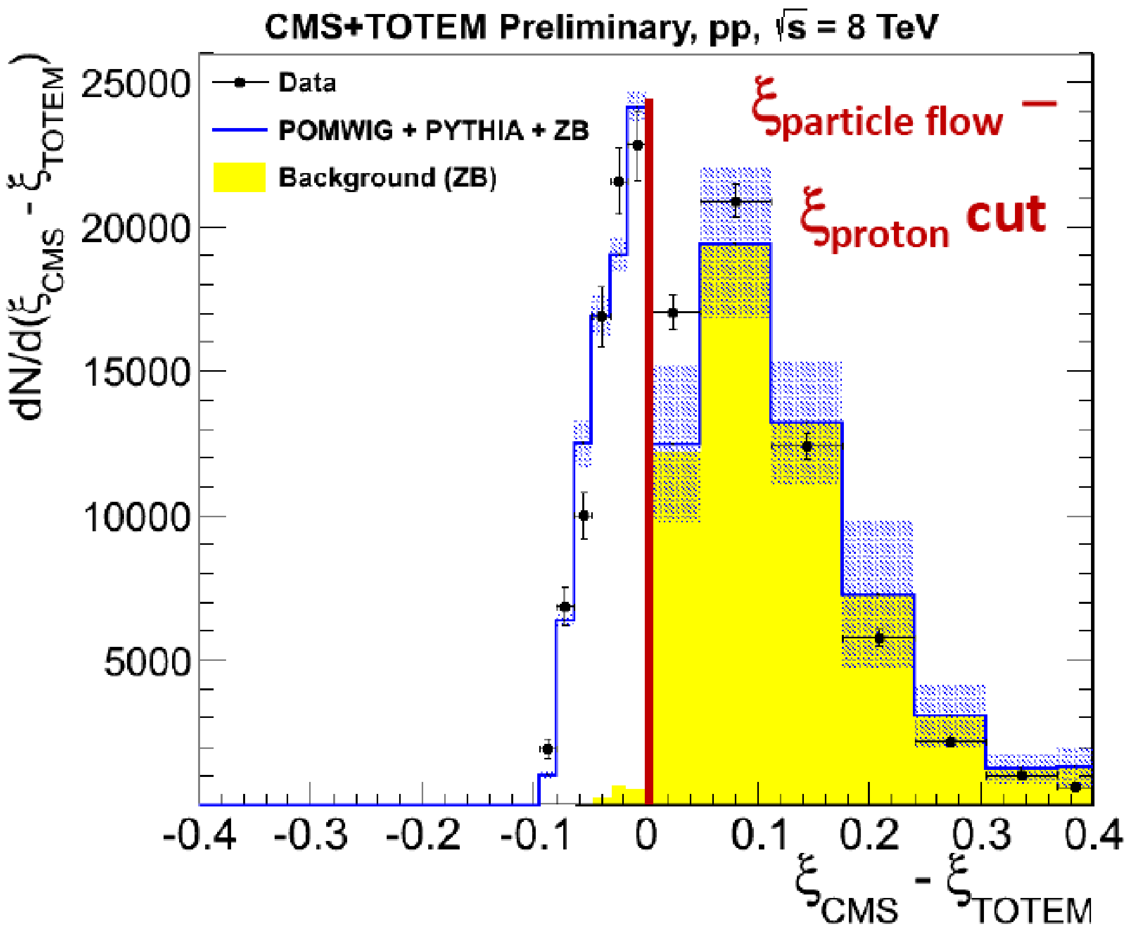
- Two new scintillator hodoscopes placed respectively at $z = -1958$ cm and 1700 cm on each side of the interaction point, covering $-7.0 < \eta < -4.9$ and $4.8 < \eta < 6.3$ and included in trigger.
- Improvement in trigger efficiency of single diffractive events in proton-proton collisions at $\sqrt{S} = 13$ TeV, when using AD detectors





Constraining background from data (CMS/TOTEM)

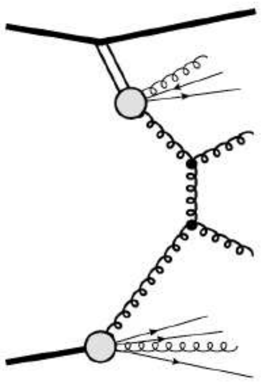
- Experience gained from data taking at the LHC in common CMS-TOTEM runs: determine beam induced background at low pile up, and $\sqrt{S} = 8$ TeV
- CMS/TOTEM has extrapolated the beam induced background from that measurement to $\mu = 50$ to $\sqrt{S}$ =13 TeV
- Physics background computed using POMWIG (SD), PYTHIA (ND and pile up)

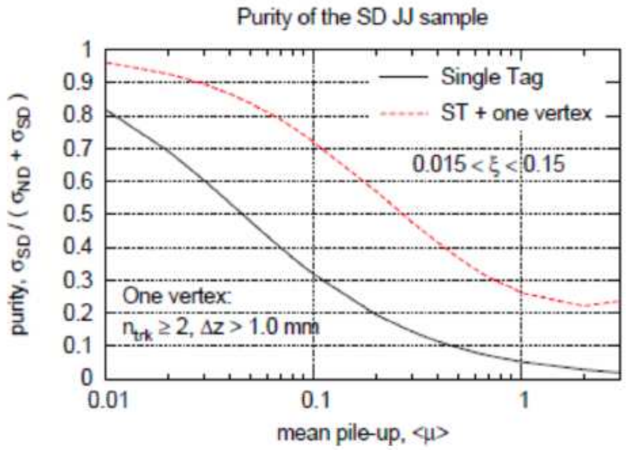


Medium Lumi IV: Single Diffraction and Double Diffractive jets with single/double proton tagging

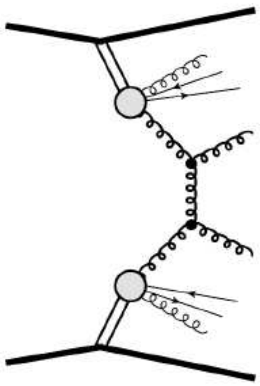
- Study by ATLAS including pile up (CMS-TOTEM at 8 TeV)
- Low Pile up runs (0.1) to get a sample of high purity for SD events
- Moderate pile up for DPE jet measurements (2-3)
- Possibility also to run at high β^* with less pile up

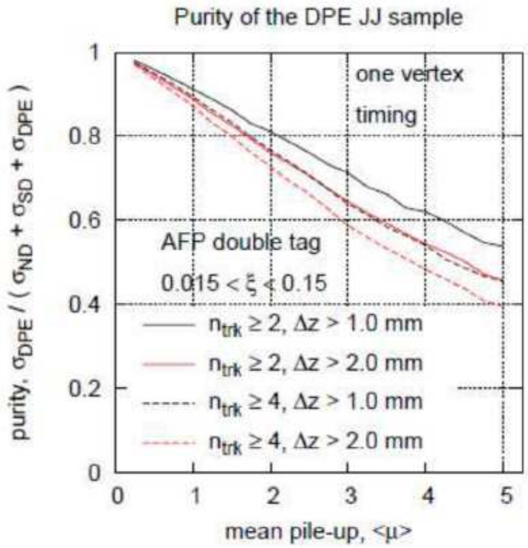
Single diffractive jets





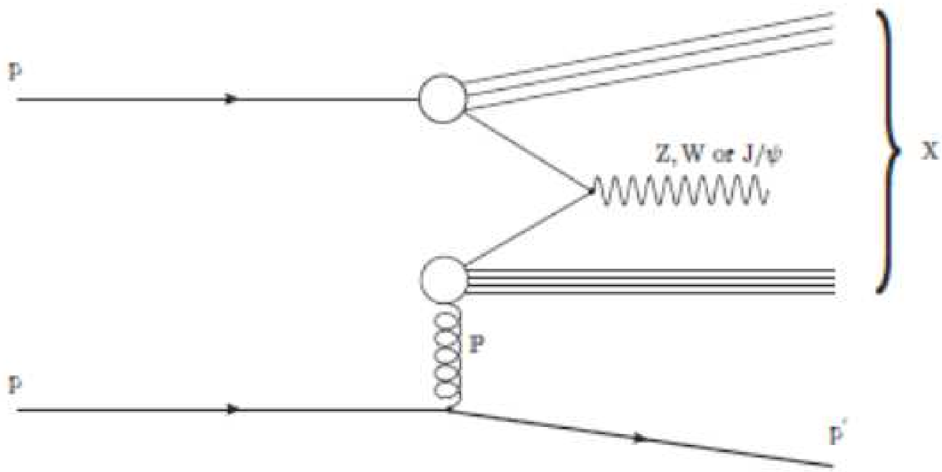
Central diffractive (double Pomeron exchange)





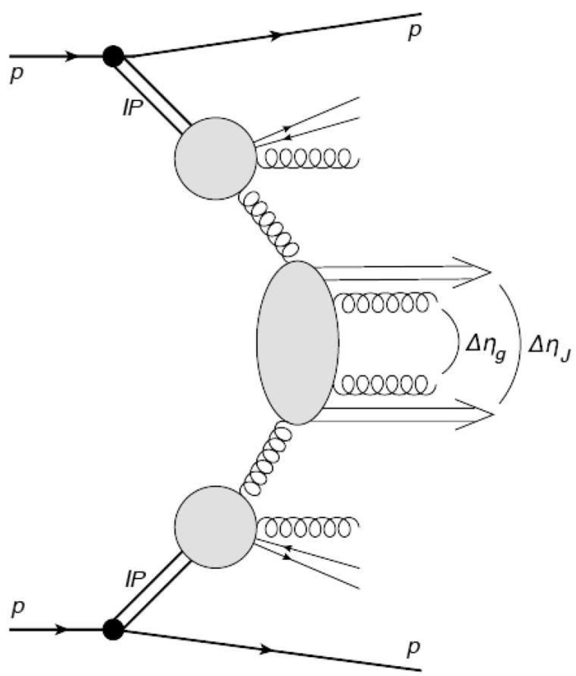
Medium Luminosity V: Single diffraction with proton tagging at high β^*

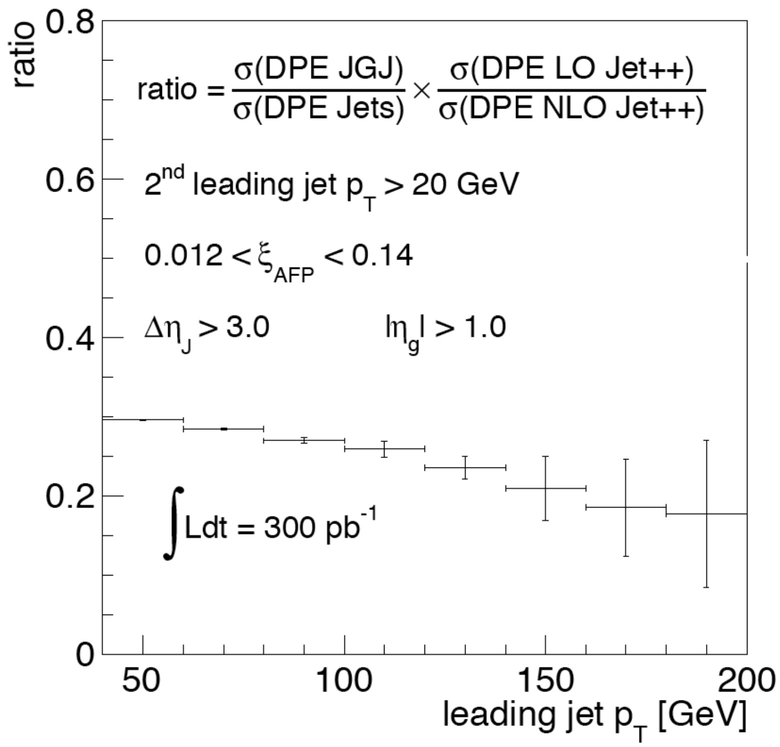
- Run at high β^* (no ξ cut)
- Study different single diffractive processes with low pile up
  - J/Ψ production: Two muons with opposite charge, $3.05 < M_{\mu\mu} < 3.15$ GeV, 3190±155 for 10 pb^{-1}
  - W production: leading lepton p_T >20 GeV, MET >20 GeV, $60 < M_{diff} < 110$, about 337±17 events for 10 pb^{-1}
  - Z production: same cuts, 31±2 events for 10 pb^{-1}
- SD jet production, low mass resonances and glueball states...



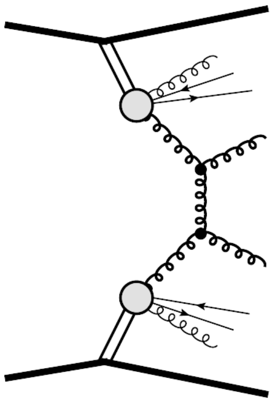
Medium Lumi VI: Jet gap jet events in diffraction with proton tagging

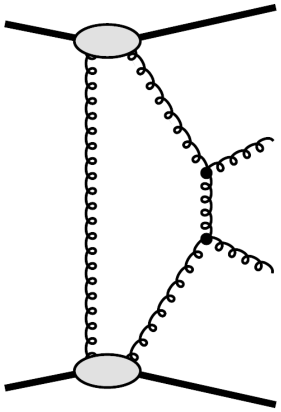
- BFKL (Balitsky Fadin Kuraev Lipatov) allows for QCD prediction (valid at short distances, hard perturbaitive region) for final states with rapidity gaps
- Needs special tests to get clean signals (jet-gap-jet, Mueller Navelet)
- Interest in BFKL also for more fundamental questions, e.g. connection with gravity
- Study BFKL dynamics using jet gap jet events
- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics (advantage of CASTOR in CMS)

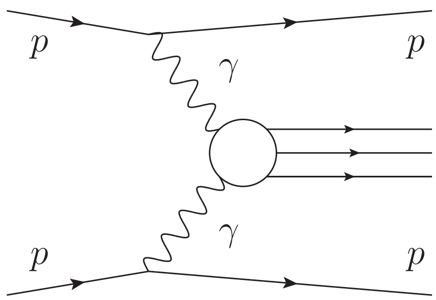


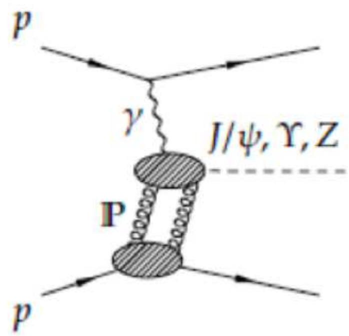


Exclusive diffraction with tagged protons





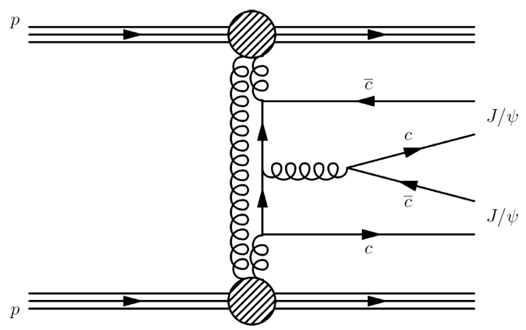


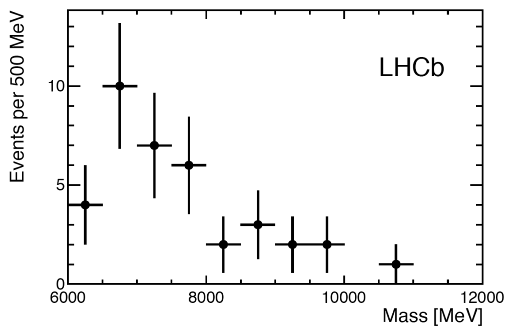


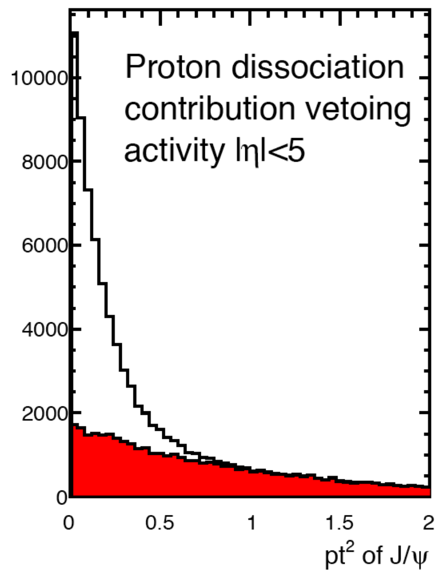
- Many exclusive channels can be studied at medium and high luminosity: jets, χ_C, cahrmonium, J/Ψ....
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Possibility of constraining the 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)

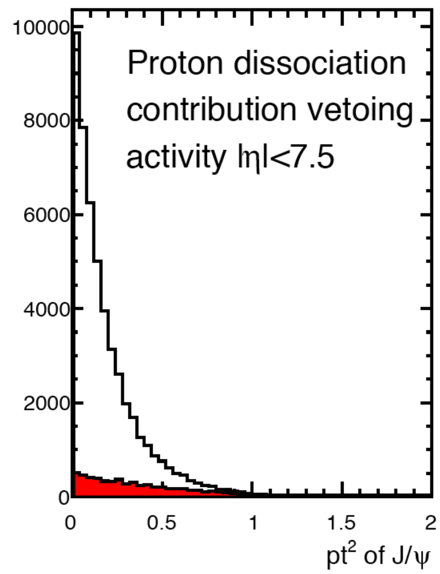
Medium Lumi VII: Exclusive vector mesons - LHCb

- Measurement of vector mesons: very clean sample, example of LHCb, no proton tagging (charmonium with 3 fb^{-1})
- Measurement performed in parallel with theory developments
- Herschel: Scintillators being installed in LHCB in order to get a better control of non exclusive background (some scintillators in the forward region already installed in CMS as well as CASTOR)
- Such channels are sensitive to new physics: if one has a medium mass resonance, (glueball or tetraquark state or exotic), it could lead to a bump in such a spectrum



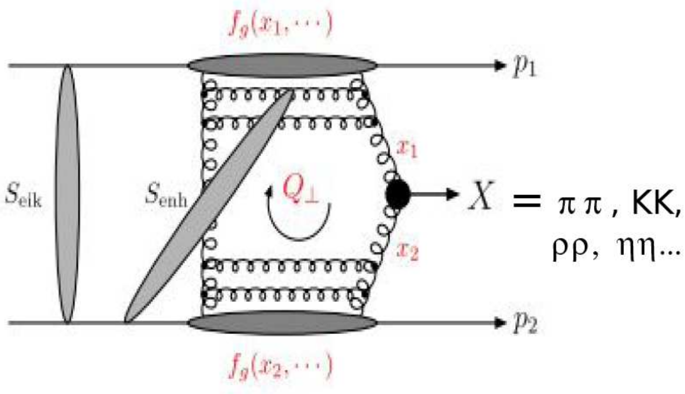


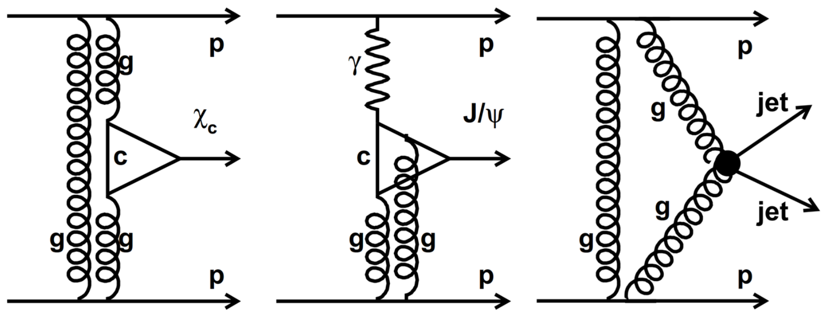




Medium Lumi VIII: Exclusive state measurements

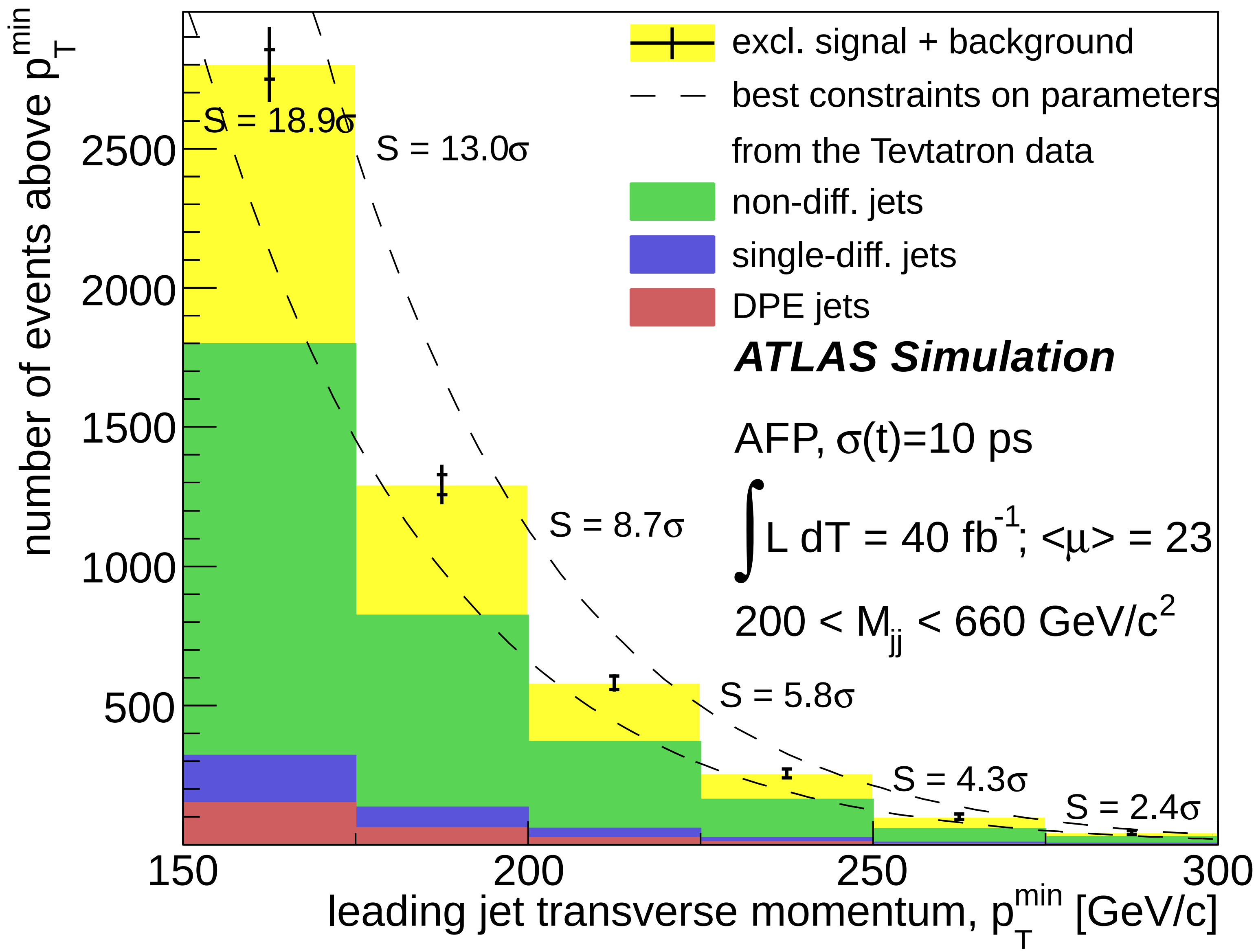
- Many exclusive states can be measured in high β^* runs in CMS/TOTEM, and in standard runs in LHCb
- CMS/TOTEM: Detect both protons, information from central detector, particle Id (pions, kaons with tracker), timing detectors
- Search for glueball states and probing low x gluon down to $x \sim 10^{-4}$
- 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





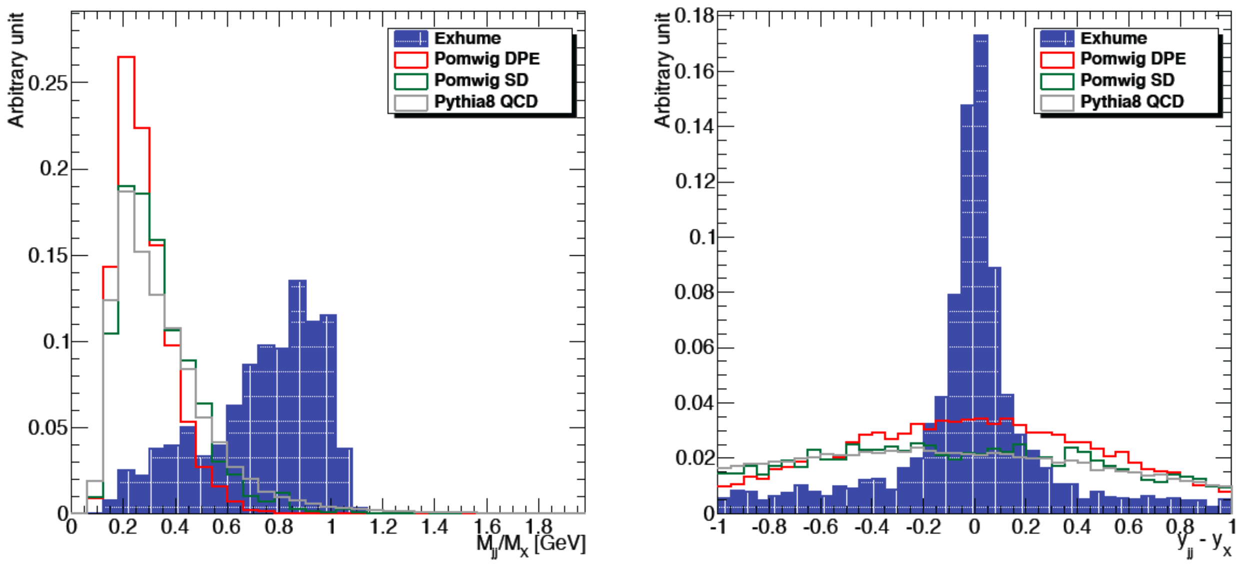
High Lumi I: Exclusive jet production at the LHC with proton tagging (AFP study)

- Jet cross section measurements: up to 18.9 σ for exclusive signal with 40 fb^{-1} ($\mu = 23$): highly significant measurement in high pile up environment, improvement over measurement coming from Tevatron (CDF) studies using $\bar{p}$ forward tagging by about one order of magnitude
- Similar study by CT-PPS

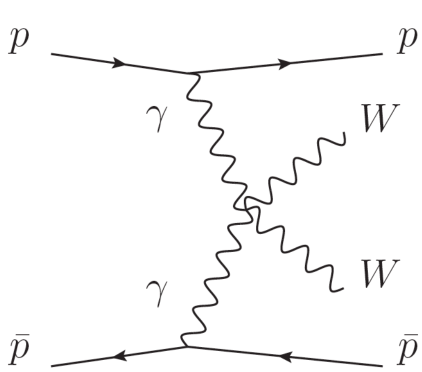


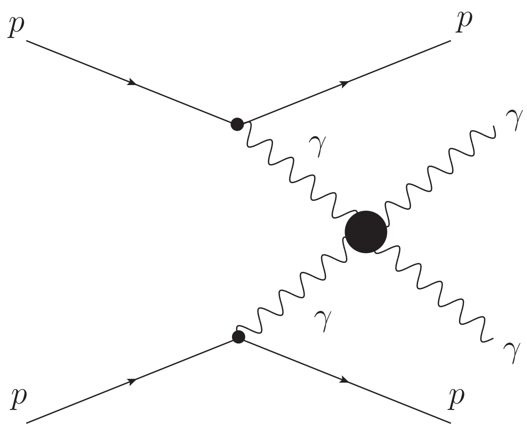
High lumi II: Exclusive jets: Signal and backgrounds with proton tagging (CT-PPS study)

- Signal: exclusive dijet production
- SM background: DPE jet production
- Pile up background: ND and SD + pile up
- Beam induced background estimated by extrapolating TOTEM data
- Importance of exclusivity cut to reject background: before any cuts, ratio of 1 to 10^7 between signal and ND+pile up background, going down to 1 to 3 after cuts for μ =25
- for 1 fb^{-1} of data, 3.5 exclusive dijet events in CT-PPS acceptance after exclusivity cuts for 10 background events

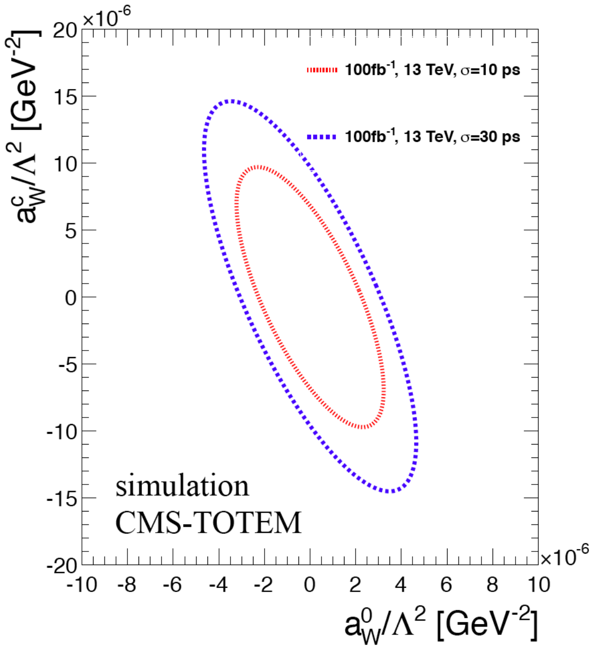


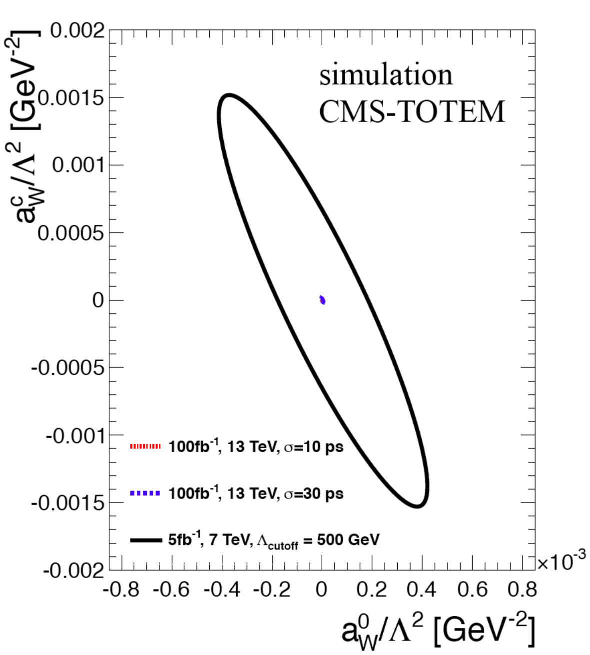
High Lumi IV: Search for quartic anomalous coupling with proton tagging



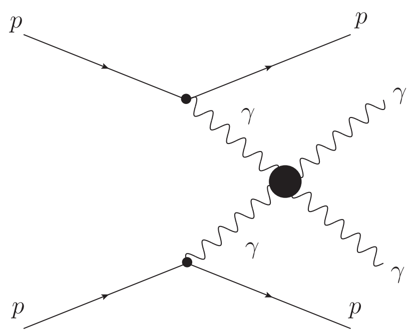


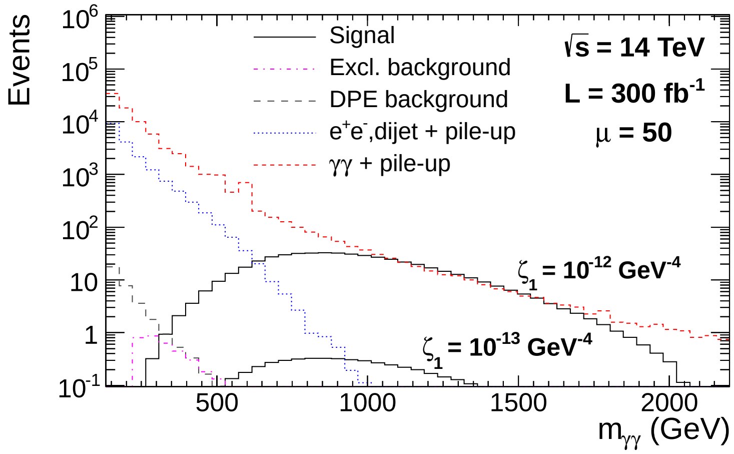
- Study of the processes: $pp \to ppWW$, $pp \to ppZZ$, $pp \to pp\gamma\gamma$
- Process sensitive to anomalous couplings: studying in detail electroweak symmetry breaking, predicted by extradim. models
- Reject pile up by counting the number of track fitted to primary vertex





High lumi VI: Search for quartic $\gamma\gamma$ anomalous couplings with proton tagging

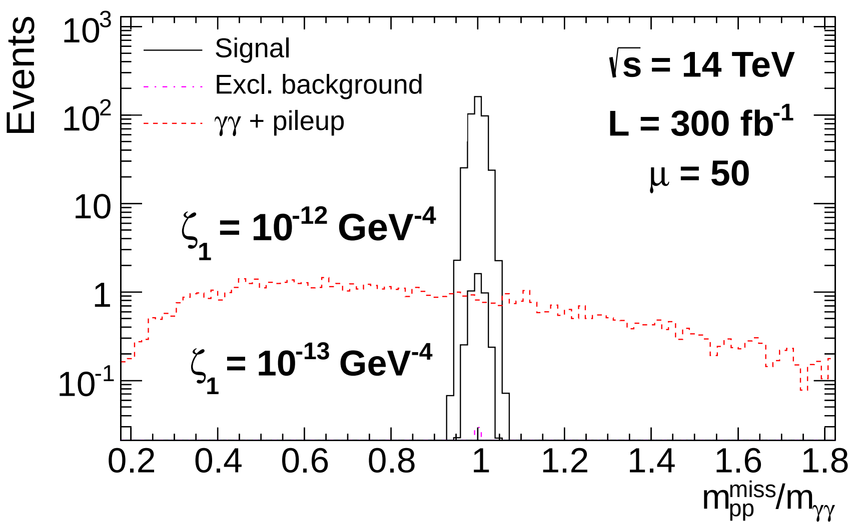


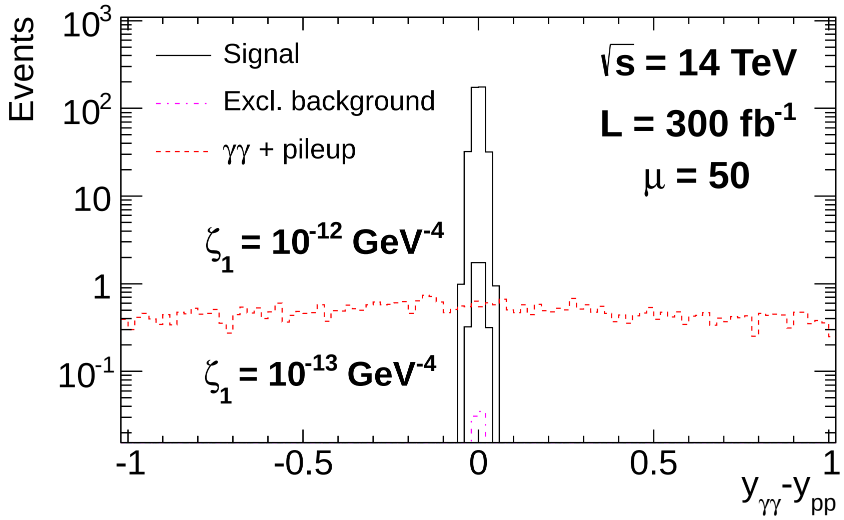


- $\gamma\gamma\gamma\gamma$ couplings predicted by extra-dim, composite Higgs models
- Two effective operators at low energies $\zeta_{1,2} \sim 10^{-14} - 10^{-13}$

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

- Exclusivity cuts suppresses all pile-up backgrounds





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

Cut / Process	Signal	Excl.	DPE	e^+e^-, dijet + pile-up	$\gamma\gamma$ + pile-up
$0.015 < \xi < 0.15$, $p_{T1,2} > 50$ GeV	20.8	3.7	48.2	$2.8\ 10^4$	$1.0\ 10^5$
$p_{T1} > 200$GeV, $p_{T2} > 100$ GeV	17.6	0.2	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	16.6	0.1	0.	0.2	1023
$p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01$	16.2	0.1	0.	0.	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	15.7	0.1	0.	0.	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	15.1	0.1	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 16.2 events ($\zeta_1 = 2\ 10^{-13}$)
  - With exclusivity cuts: 0 background for 15,1 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.	$1 \cdot 10^{-13}$	$9 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$7 \cdot 10^{-15}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$4.5 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$5.5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

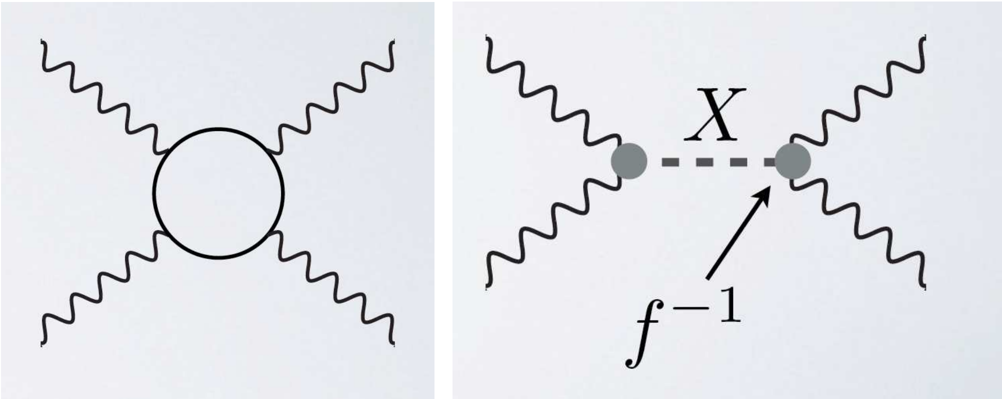
Progress on yellow report

- Introduction: N. Cartiglia, C. Royon
- Monte Carlo: L. Harland-Lang
- Soft Diffraction: V. Avati, T. Martin
- Hard Diffraction: M. Ruspa, M. Trzebinski
- Central Exclusive Production: M. Saimpert, P. Collins, O. Kepka, L. Harland-Lang
- Forward Physics: C. Marquet, J. Bartels
- Cosmic ray: T. Pierog
- Heavy ions: D. Tapia Takaki
- Detectors: J. Baechler, M. Rijssenbeek
- Yellow report well advanced (about 75% complete, to be submitted to the LHCC by Christmas)

Running conditions

- Low instantaneous luminosity, very low and low pile up
  - Forward energy and multiplicity measurements: LHCf
  - Total cross section measurement: ALFA/TOTEM
  - Low mass resonances and glueballs: CMS/TOTEM, AFP. LHCb
  - Soft QCD with proton tagging: CMS/TOTEM, AFP
  - Single diffractive measurements: TOTEM/CMS, AFP, Alice
- Medium instantaneous luminosity, low pile up
  - Exclusive diffractive measurements: vector mesons, $c\bar{c}$, jets...: LHCb, CMS-TOTEM, AFP
  - DPE/QCD measurements, understanding the structure of diffraction: jets, γ+jet,.CMS/TOTEM, AFP
  - Jet gap jet in diffraction: AFP, CMS/TOTEM
  - Preparing for high lumi measurements: AFP/CT-PPS
- High luminosity
  - QCD physics: Exclusive jets....
  - Exploratory physics: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ anomalous couplings
- Detailed planning proposed to the LHCC by next meeting (document to be given before the meeting)

Motivations to look for quartic $\gamma\gamma$ anomalous couplings



- Two effective operators at low energies

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

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle
This leads to ζ_1 of the order of 10^{-14}-10^{-13}

- ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$

High Lumi: Results from full simulation

- Effective anomalous couplings correspond to loops of charged particles, Reaches the values expected for extradim models (C. Grojean, J. Wells)

Cuts	Top	Dibosons	Drell-Yan	W/Z+jet	Diffr.	$a_0^W/\Lambda^2 = 5\cdot 10^{-6}$ GeV^{-2}
timing < 10 ps $p_T^{lep1} > 150$ GeV $p_T^{lep2} > 20$ GeV	5198	601	20093	1820	190	282
M(ll)>300 GeV	1650	176	2512	7.7	176	248
nTracks ≤ 3	2.8	2.1	78	0	51	71
$\Delta\phi < 3.1$	2.5	1.7	29	0	2.5	56
$m_X > 800$ GeV	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300$ GeV	0	0.2	0	0	0.2	35

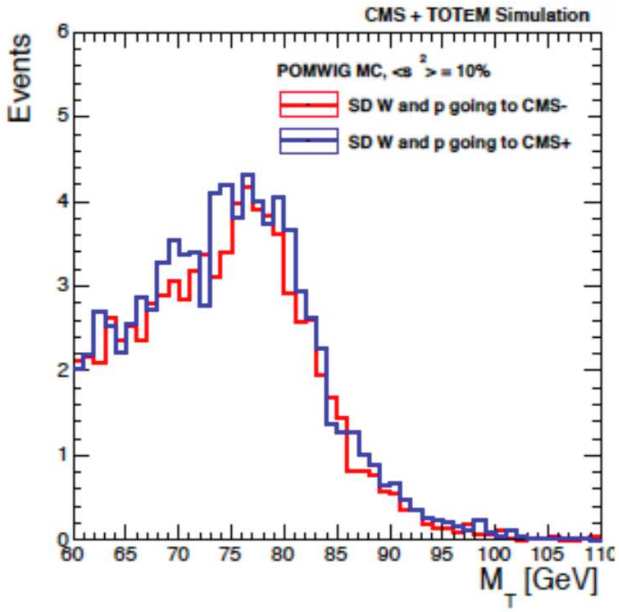
Table 9.5. Number of expected signal and background events for 300 fb^{-1} at pile-up $\mu = 46$. A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

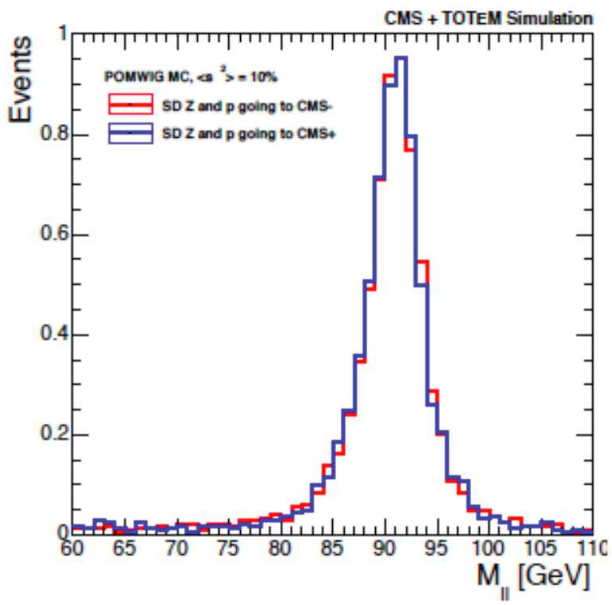
- **Improvement of CMS limits and "standard" LHC methods by studying $pp \to l^\pm \nu\gamma\gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb^{-1} at LHC (CMS mentions that their exclusive analysis will not improve very much at high lumi because of pile-up)**

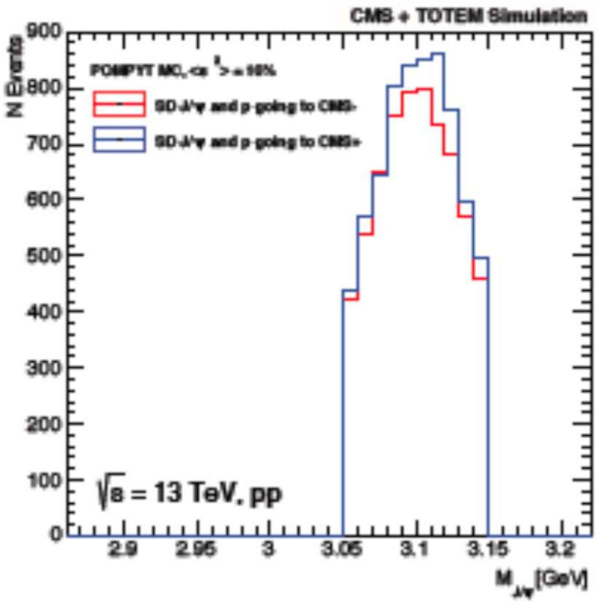
	5σ	95% CL
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	5.5 10^{-6}	2.4 10^{-6}
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	3.2 10^{-6}	1.3 10^{-6}

Medium lumi studies from CMS

Distributions for SD measurements by CMS-TOTEM

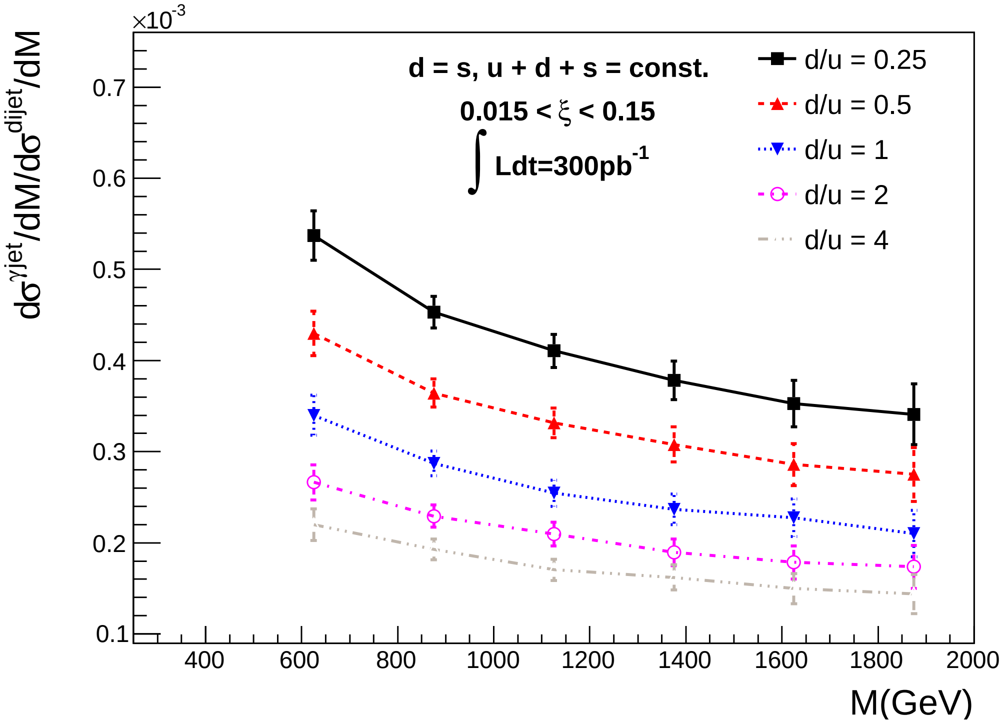






Medium Lumi VI: Inclusive diffraction at the LHC: sensitivity to quark densities

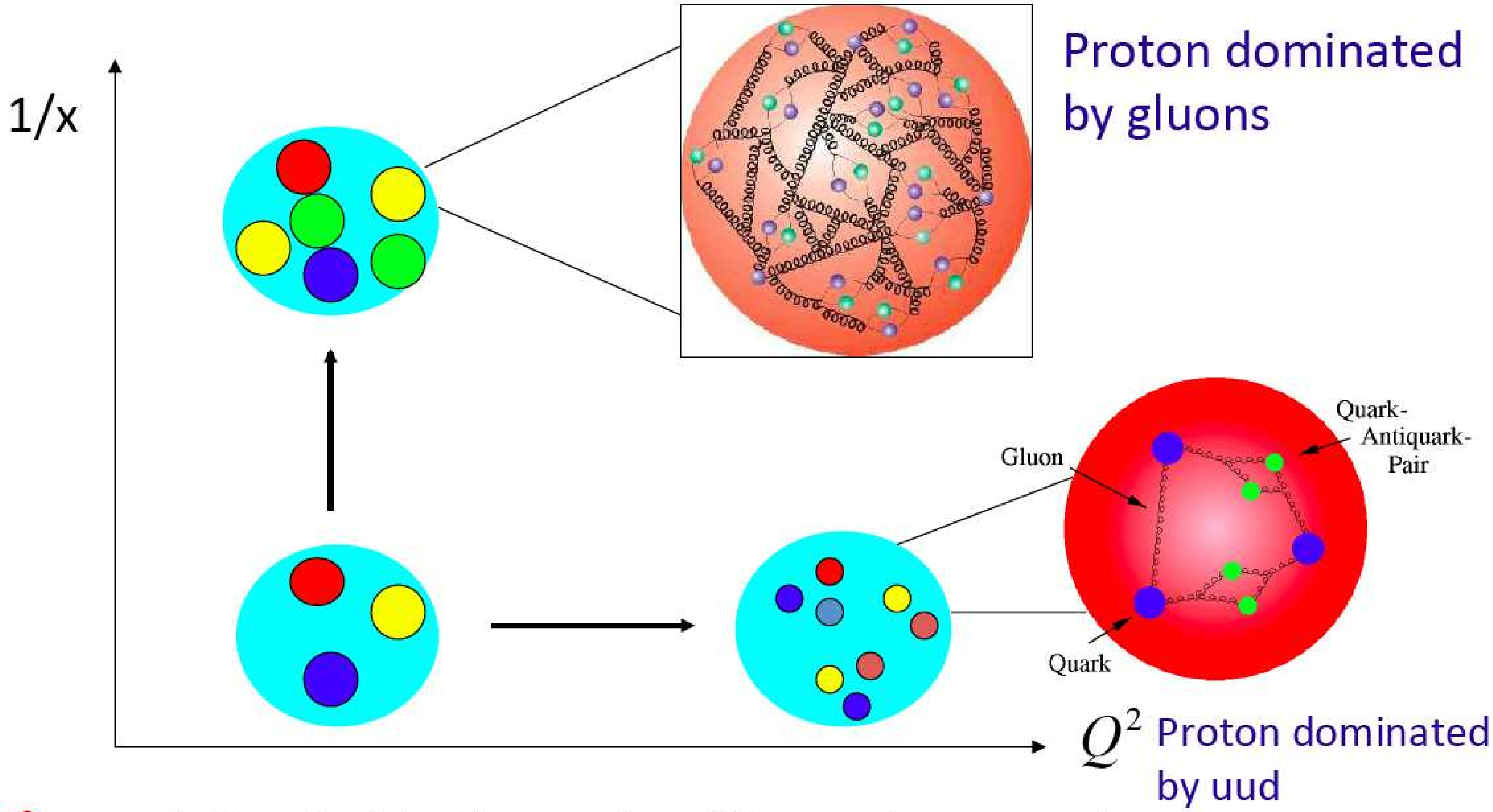
- Predict DPE γ+jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to gluon density in Pomeron, of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA



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

Low and Medium Lumi with proton tagging: Strategy and running

- Many physics topics can be done at low luminosity, low pile up (μ =0.05), also can be done during the "learning" phase to understand background, how close one can go to the beam... needed for the high lumi phase:
  - Total cross section
  - Soft diffraction
  - Low mass resonances and glueball states in central diffraction
  - Pomeron structure: Single diffraction
- Many physics at medium luminosity, moderate pile up (μ <1,2)
  - Pomeron structure (Double Pomeron Exchange): dijets, γ+jets
  - Three jet production (distinguish ggg and $q\bar{q}g$ events)
  - Jet gap jet in diffraction
  - Exclusive $c\bar{c}$ production, χ_C, J/Ψ...
  - Search for missing mass candidates (large diproton mass, nothing in ATLAS/CMS): monopoles, SUSY...