Diffraction at the LHC

Results from TOTEM, CMS and ATLAS

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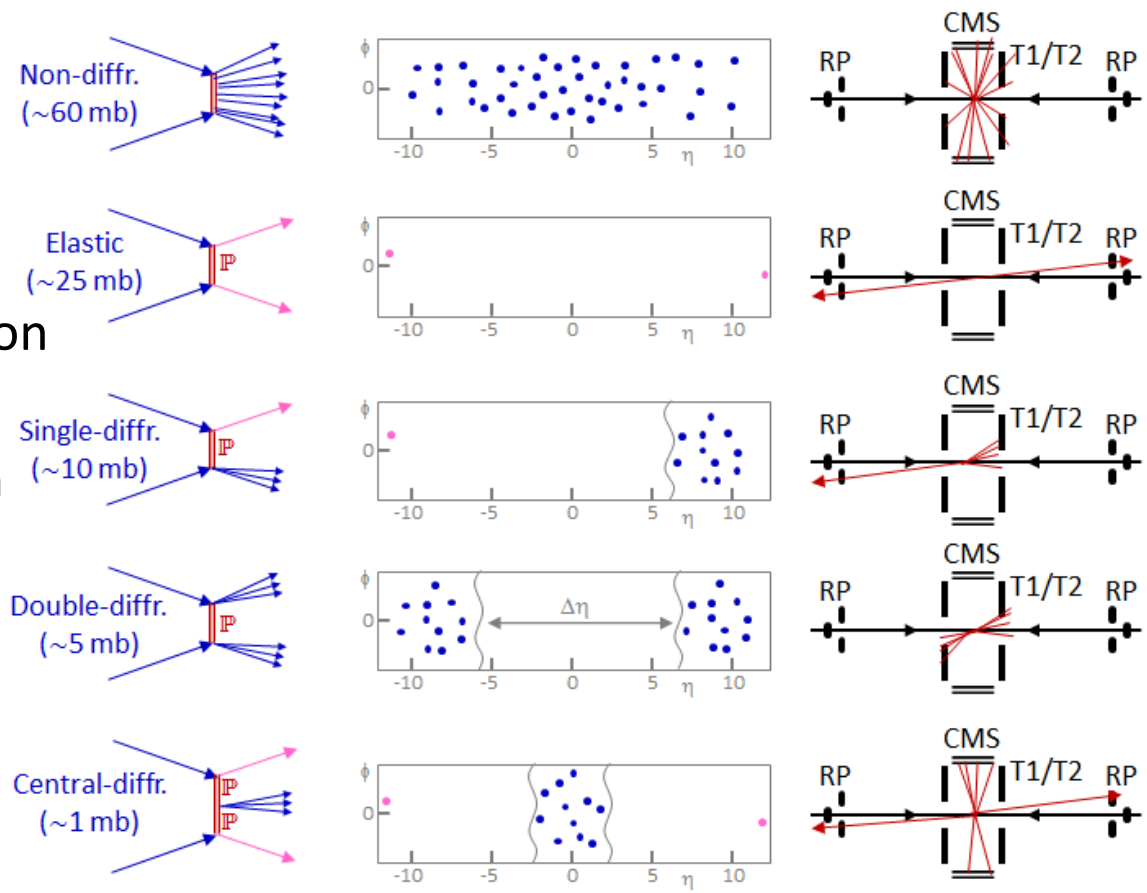
Events in p+p collisions at the LHC

- Elastic + diffractive (colorless interaction) + non-diffractive (color exchange)
- Single diffr.: pp→pX/Xp
- Double diffr.: pp→XY
- Classification: rapidity gap
- Need well-placed detectors
- Also with jets: hard diffraction
- Soft diffraction:
  - Regge theory & the Pomeron
- Kinematic variables:
  - Invariant mass of dissociated particles: M
  - Mom. loss of the proton:

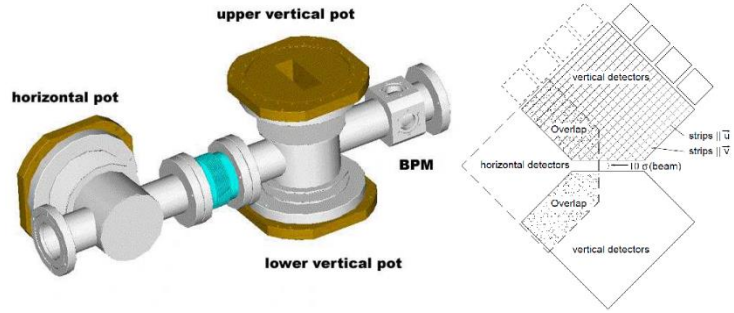
$$\xi = \frac{\Delta p}{p} = \frac{M^2}{s}$$

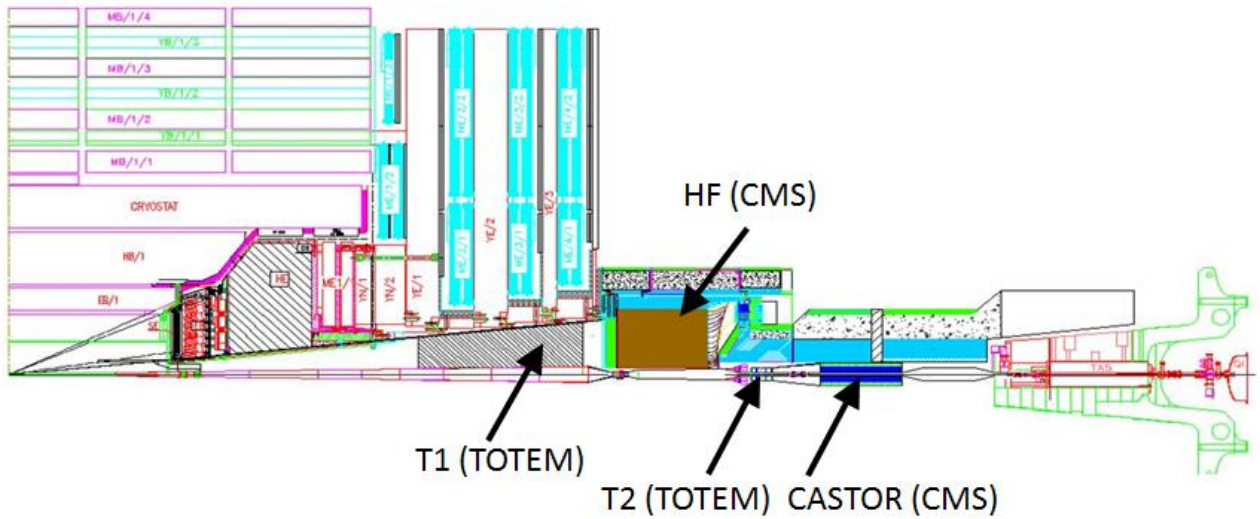
  - Rapidity gap: $\Delta\eta = \ln(\xi)$

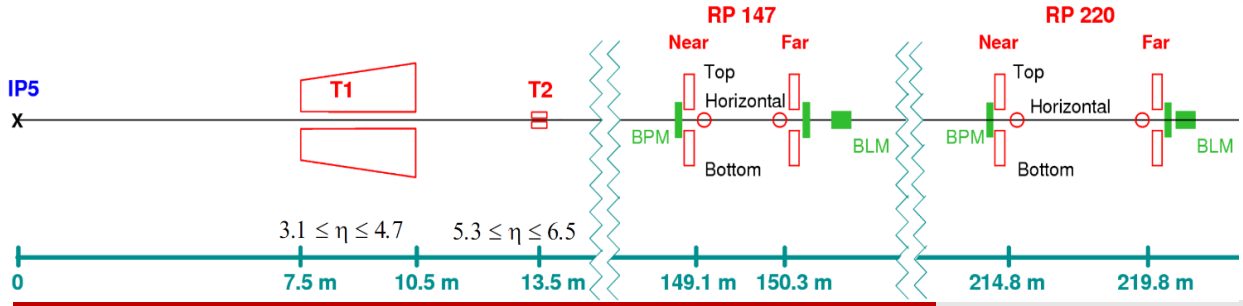


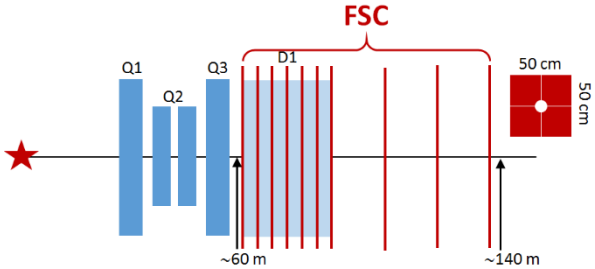
Forward detectors at TOTEM & CMS

- Roman Pot detects deflected protons
  - Edgeless silicon detector
  - Placed 147 and 220 m from IP
  - Few μrad scattering angle ($|\eta|$ around 10)
  - Momentum-transfer: $10^{-4} < |t/\mathrm{GeV}^2| < 10$
- Other forward detectors
  - tracks in SD & DD events
  - HF: $3 < |\eta| < 5$
  - T1: $3.1 < |\eta| < 4.7$
  - T2: $5.3 < |\eta| < 6.5$
  - CASTOR: $5.2 < |\eta| < 6.6$
  - FSC: $6 < |\eta| < 8$



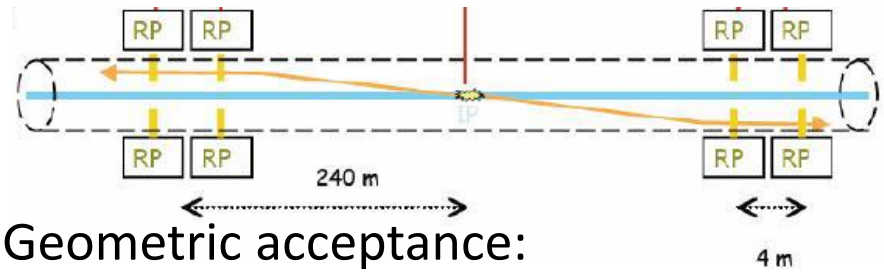




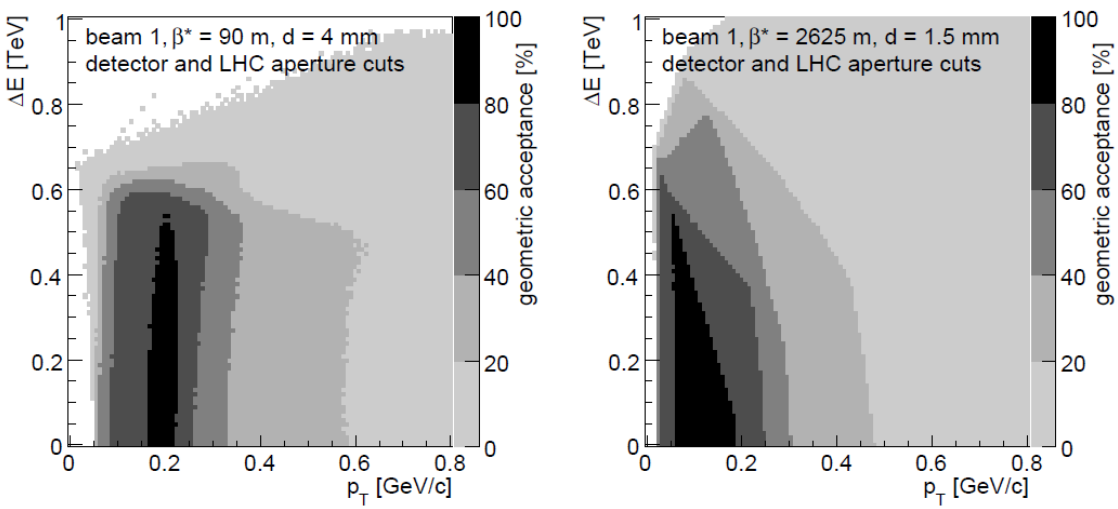


Forward detectors at ATLAS

- LUCID (luminosity): $5.6 < |\eta| < 6$
- ALFA (Roman Pots): $10.6 < |\eta| < 13.5$
  - four RP stations at 237.4 and 241.5 m

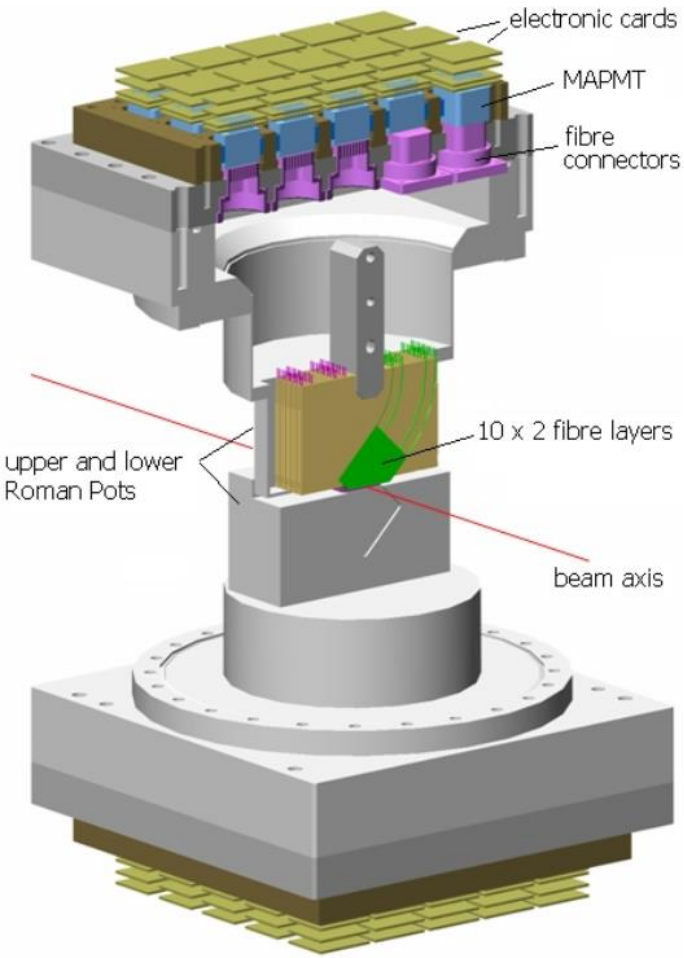


- Geometric acceptance:



- AFP (ATLAS Forward Proton): in approval

Roman Pot station:



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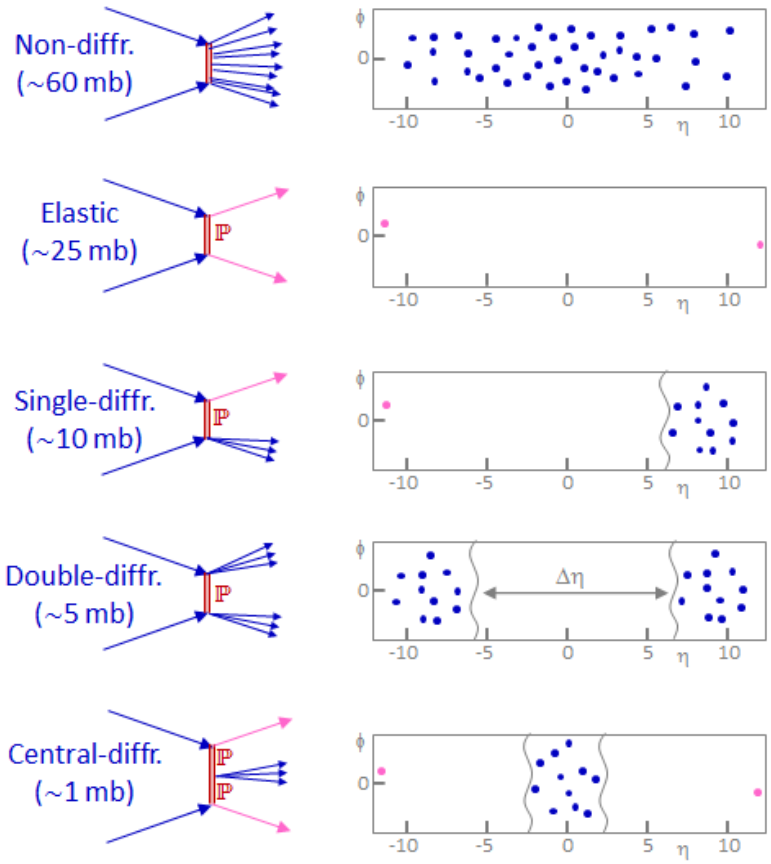
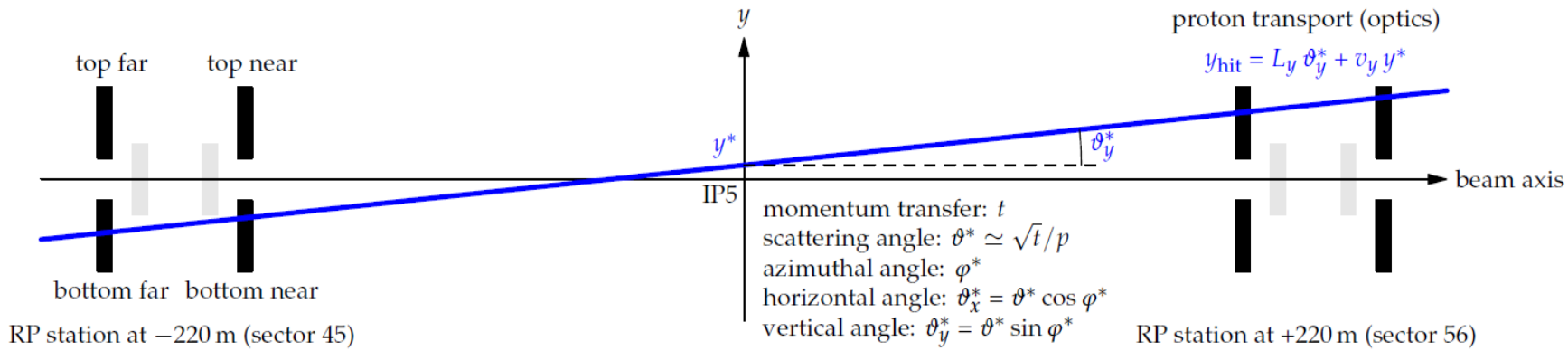
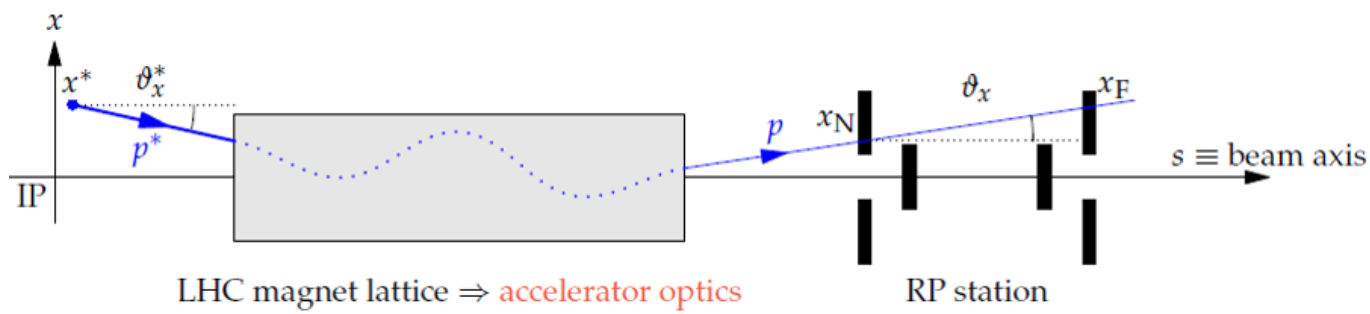


LHC optics for elastic events

- An elastic event at LHC



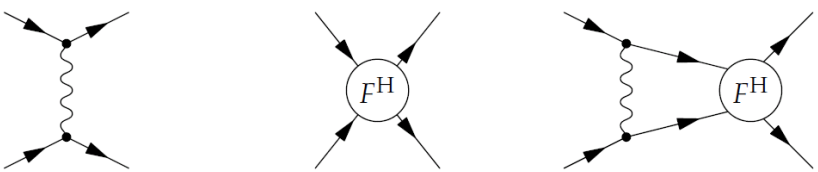
- In reality



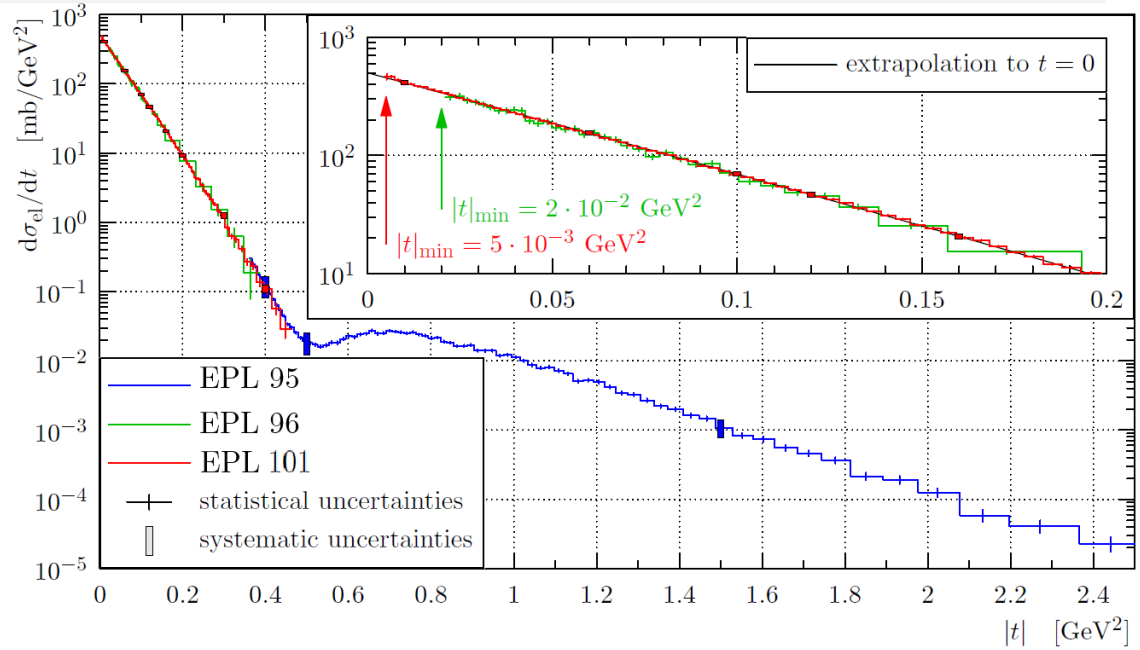
- $\left(x, \Theta_x, y, \Theta_y, \frac{\Delta p}{p}\right)_{RP} \rightarrow \left(x, \Theta_x, y, \Theta_y, \frac{\Delta p}{p}\right)_{IP}$ via the transport matrix, based on betatron amplitude $\beta(s)$; magnification & effective length calculated from it
- Optics errors induced by LHC imperfections need to be under control
- See arXiv:1206.3058 (F. Nemes & H. Niewiadomski) for details

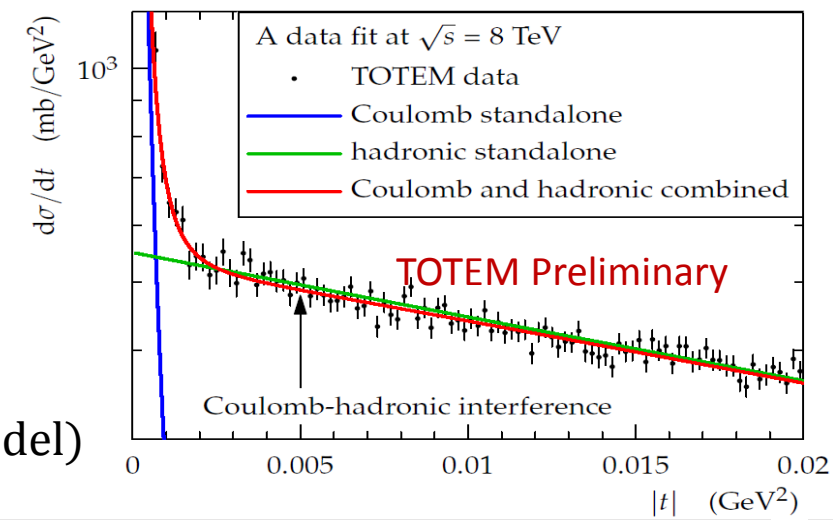
TOTEM: Differential elastic cross-sections

- Based on event numbers & luminosity: $\mathcal{L}\frac{d\sigma}{dt} = \frac{dN}{dt}$
- Measurements at several optics (β^*) setups
- Small $|t|$ (mom. transfer): exponential; diffractive minimum; power-law tail
- Special $\beta^* = 1000$ m run, down to $6 \cdot 10^{-4}$ GeV²
- Sensitive to Coulomb-nuclear interference



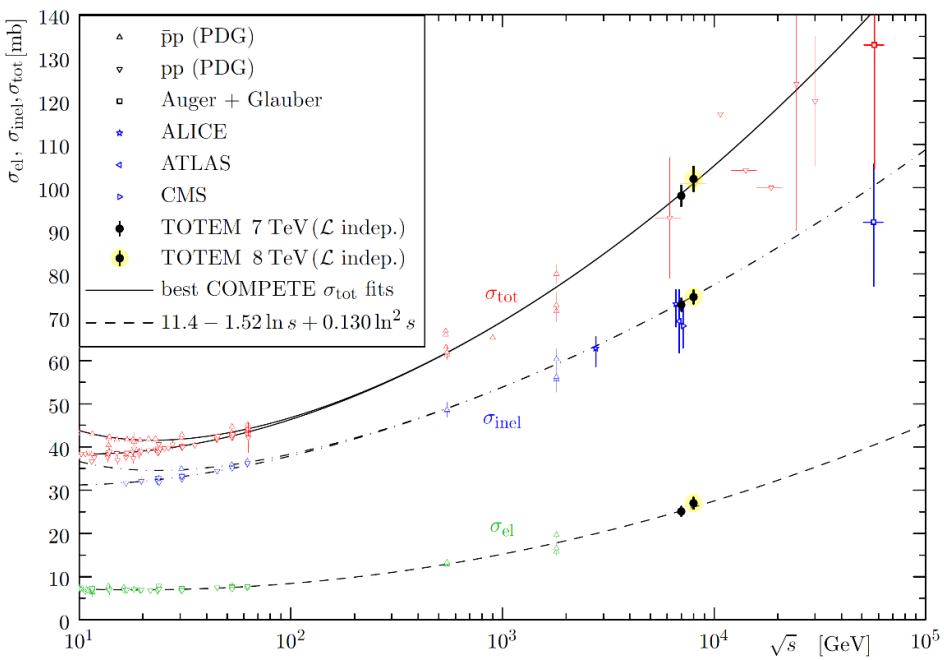
- $\rho = \Re F^H / \Im F^H$ measured:
  $0.110 \pm 0.027(\text{stat}) \pm 0.010(\text{syst})^{+0.013}_{-0.012}(\text{model})$

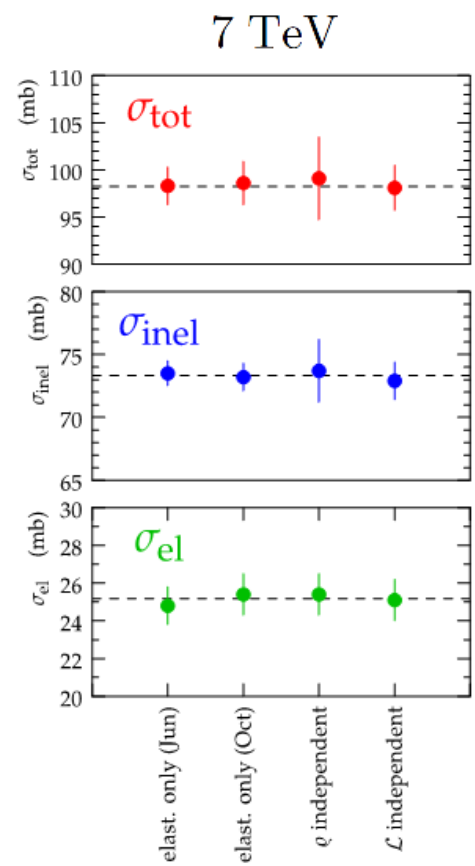




TOTEM: Total cross-section measurements

- „Elastic only" method via optical theorem: $\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\varrho^2}\frac{1}{\mathcal{L}}\frac{dN_{el}}{dt}$
- Luminosity-independent method: $\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\varrho^2}\frac{dN_{el}/dt}{N_{el}+N_{inel}}$
- ϱ-independent method: $\sigma_{tot} = (N_{el} + N_{inel})/\mathcal{L}$
- Total inelastic rate via T2 trigger, corrections from T1 & MC
- Ongoing analyses for 2.76 and 8 TeV with different optics





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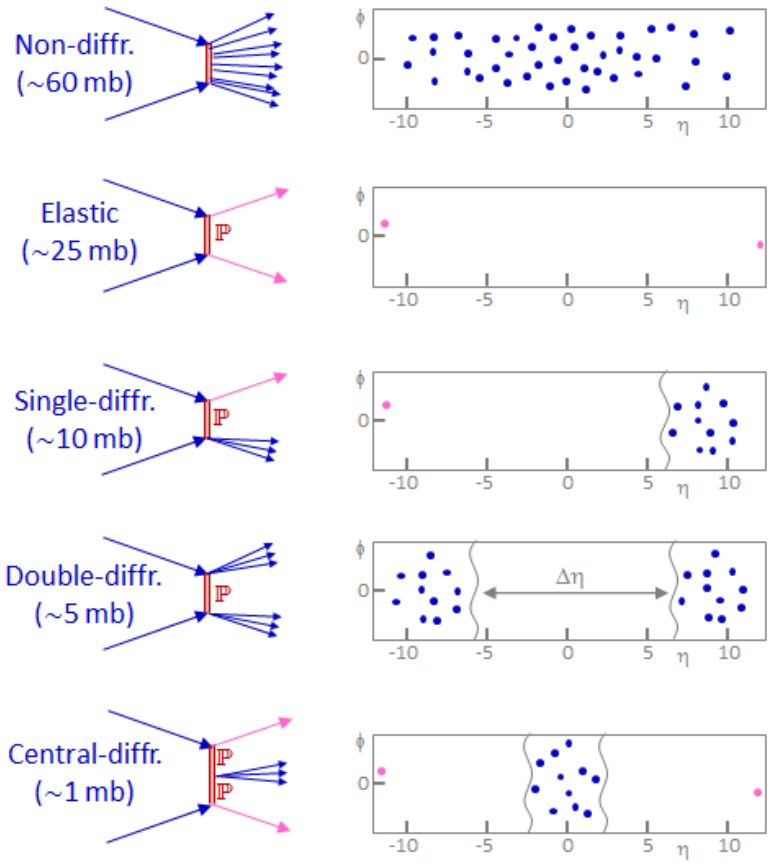
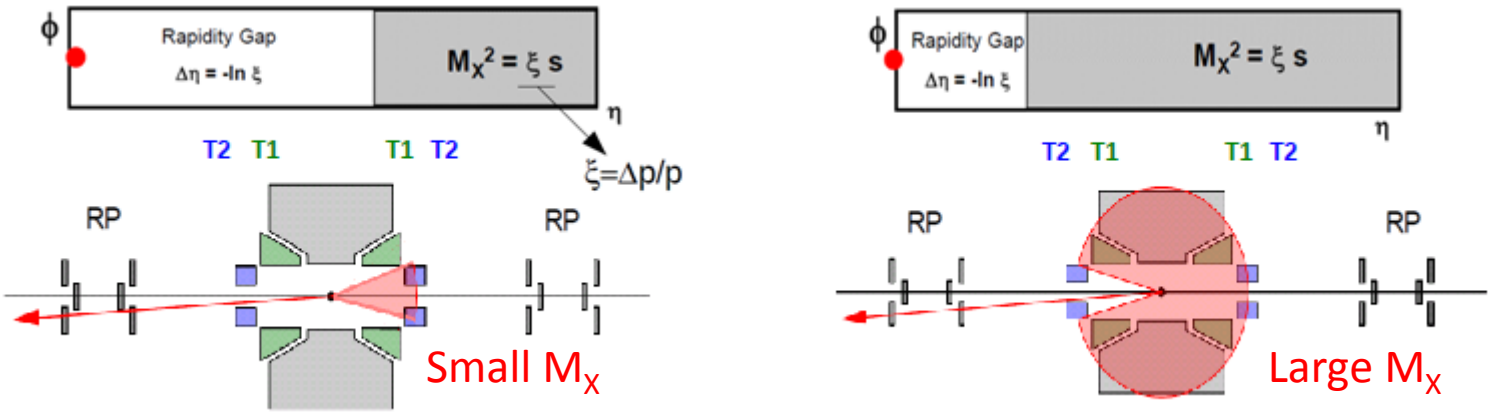


Soft single diffraction at TOTEM

- Rapidity gap ($\Delta\eta = -\ln\xi$) determines diffractive mass ($M_X^2 = \xi s$)



- Event classification based on tracks in T1 & T2, proton in RP

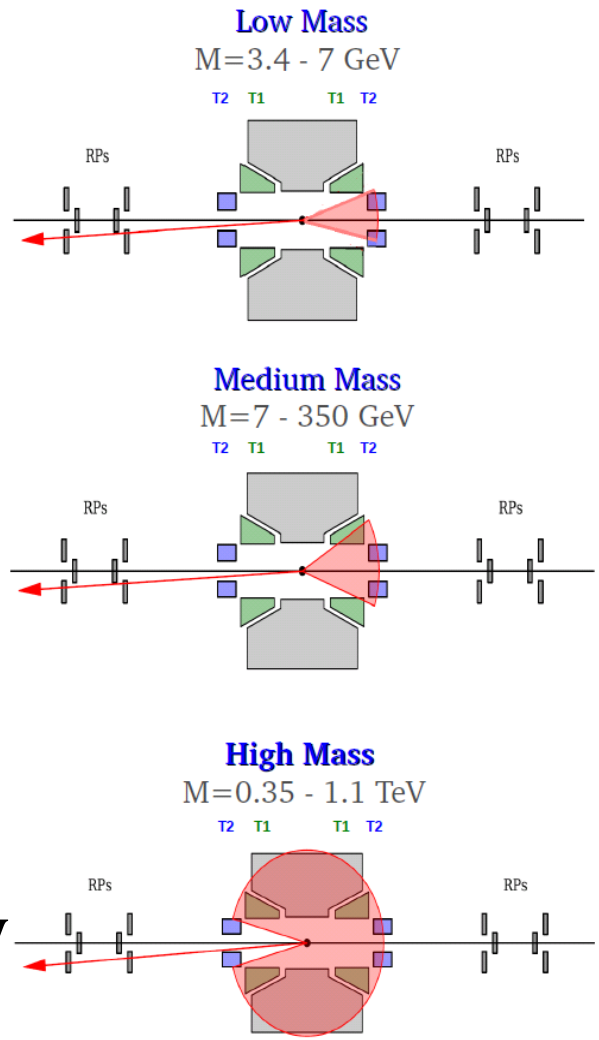
SD class	Configuration	M_X [GeV]	$\xi = \Delta p/p$
Low mass	1 RP + opp. T2	3.4 – 7.0	$2\swarrow 10^{-7} – 10^{-6}$
Medium mass	1 RP + opp. T2 + opp. T1	7.0 – 350	$10^{-6} – 0.0025$
High mass	1 RP + opp. T2 + same T1	350 – 1100	0.0025 – 0.025
Very high mass	1 RP + both T2	1100 – …	0.025 – …

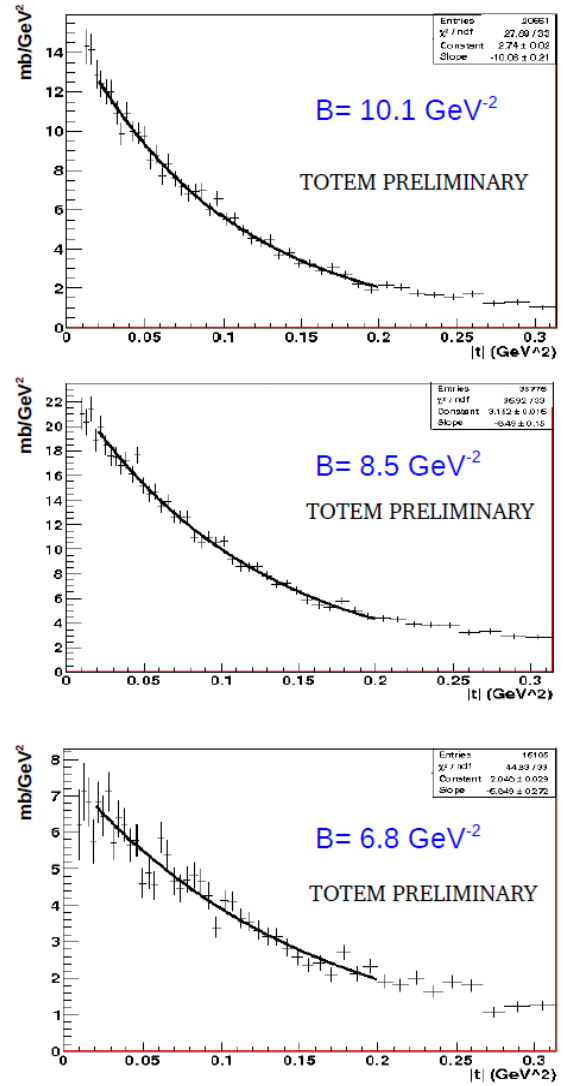
TOTEM results on soft single diffraction

- Exponential shape fitted ($e^{-B|t|}$)
- Corrections:
  - Trigger efficiency
  - Reco. efficiency
  - Proton acceptance
  - Background
  - Extrapolation
- Estimated σ uncertainty: 20%
- Quite preliminary result

  $\sigma_{3.4-1100\ \mathrm{GeV}} = 6.5 \pm 1.3$ mb
  - To be understood!
- Very high mass: ongoing
- ALICE result for $M_X < 200$ GeV

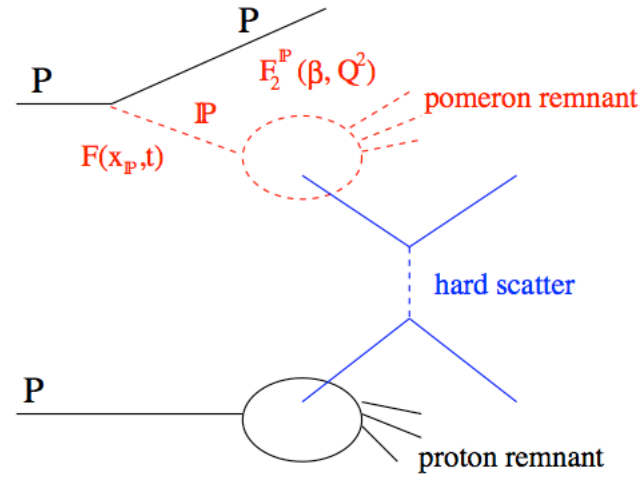
  $\sigma_{<200\ \mathrm{GeV}} = 14.9^{+3.4}_{-5.9}$ mb

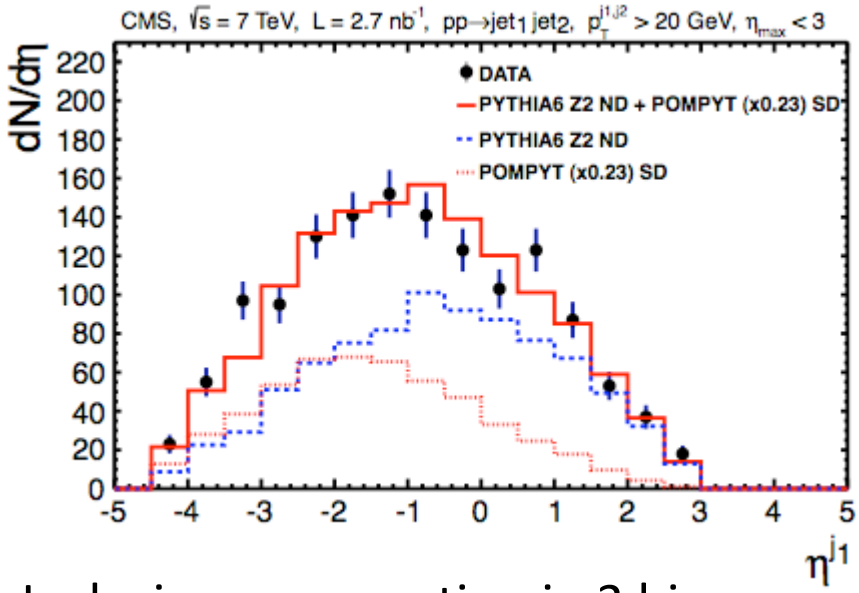




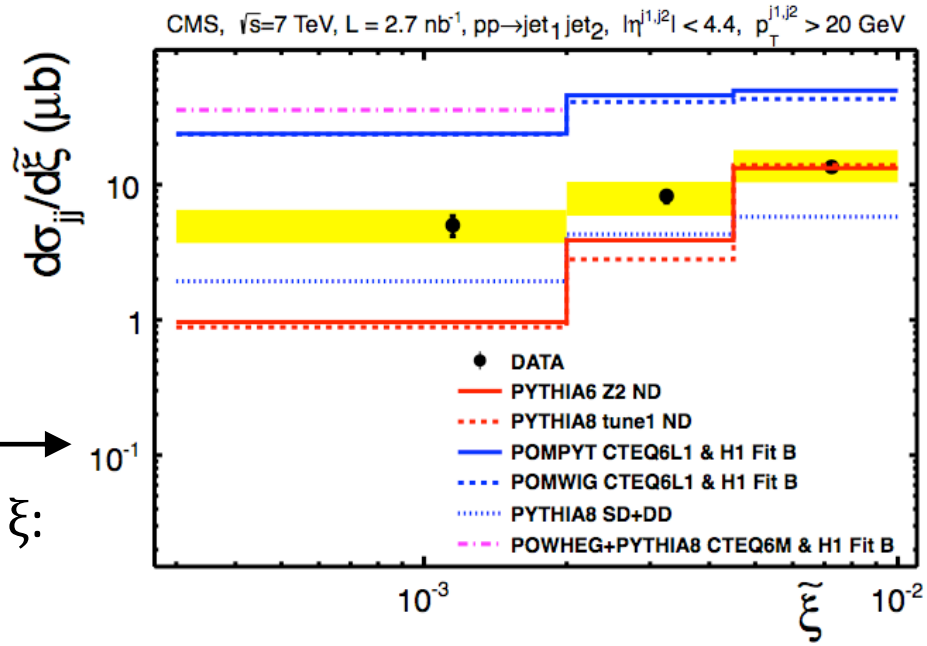
Diffractive dijets at CMS

- Diffraction with a hard scale set by a dijet system
- Described by dPDF ($\mathbb{P}$ flux × PDF) + pQCD σ
- Diffractive selection described by mix of diffr. (POMPYT) & non-diffractive (PYTHIA) samples





- Inclusive cross-section in 3 bins →
- ND MCs underestimate the data at low ξ: evidence for hard diffraction



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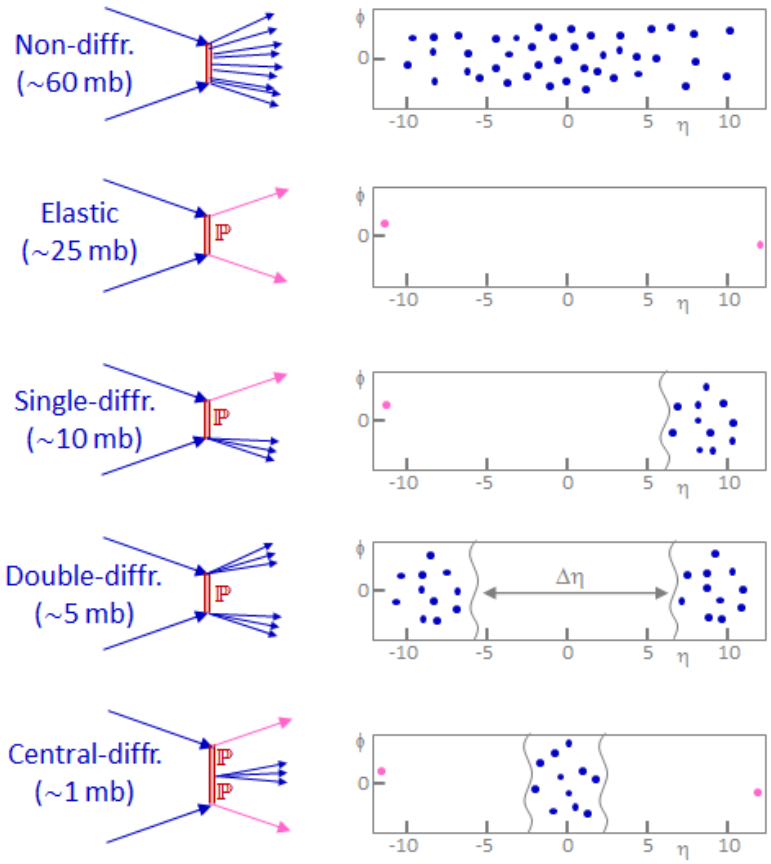
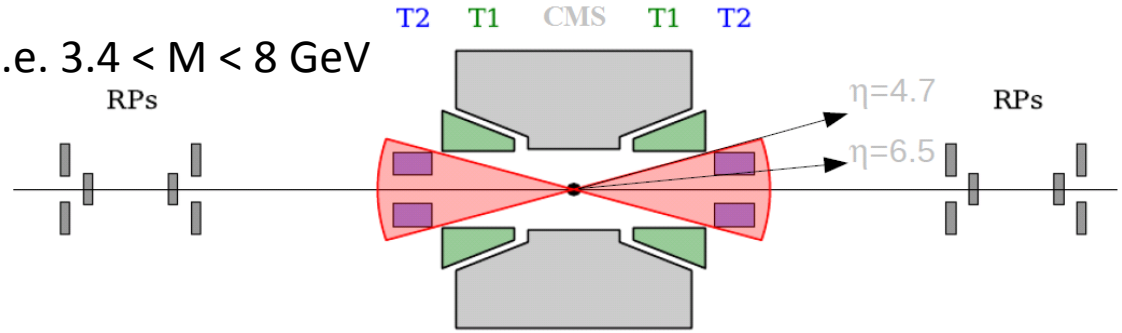
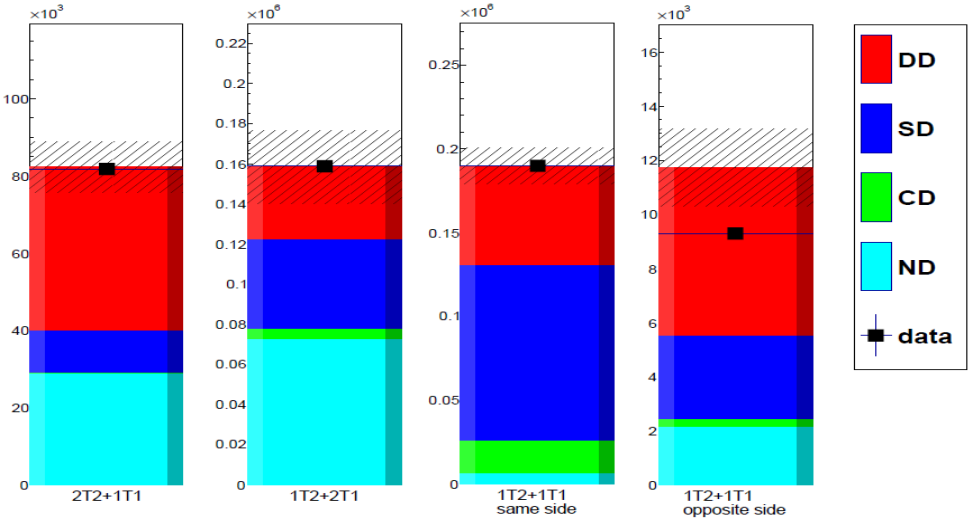


Soft double diffraction at TOTEM

- Particle in both T2 arms, no T1 tracks
  - 0×T1 + 2×T2 topology
  - Pseudorapidity range: 4.7-6.5, i.e. 3.4 < M < 8 GeV



- Background estimation:
  - Single diffractive: 0×T1 + 1×T2 + proton in RP
  - Non-diffractive: MC prediction based on 2×T1 + 2×T2
- Validation of backgr. estimates:



- Ref.: CERN-PH-EP-2013-170

TOTEM results on double diffraction

- Cross-section result: $\sigma_{DD\ (4.7<\eta<6.5)} = 116 \pm 25\ \mu b$
- PYTHIA 8: 159 μb, PHOJET: 101 μb
- Two $\eta_{\min}$ regions: 4.7-5.9 (a) and 5.9-6.5 (b)
- „Differential" result:

	(a|b)+(a|b)	a+a	b+b	a+b	b+a
TOTEM result [μb]	116 ± 25	65 ± 20	12 ± 5	26 ± 5	27 ± 5
PYTHIA [μb]	159	70	17	36	36
PHOJET [μb]	101	44	12	23	23

- PYTHIA total: 8.1 mb, PHOJET total: 3.9 mb
- CERN-PH-EP-2013-170 ; arXiv:1308.6722
- Largest source of uncertainty: tracking, $\eta_{\min}$ reco. to generator transformation
- Improvement expected with 8 TeV data (with CMS)

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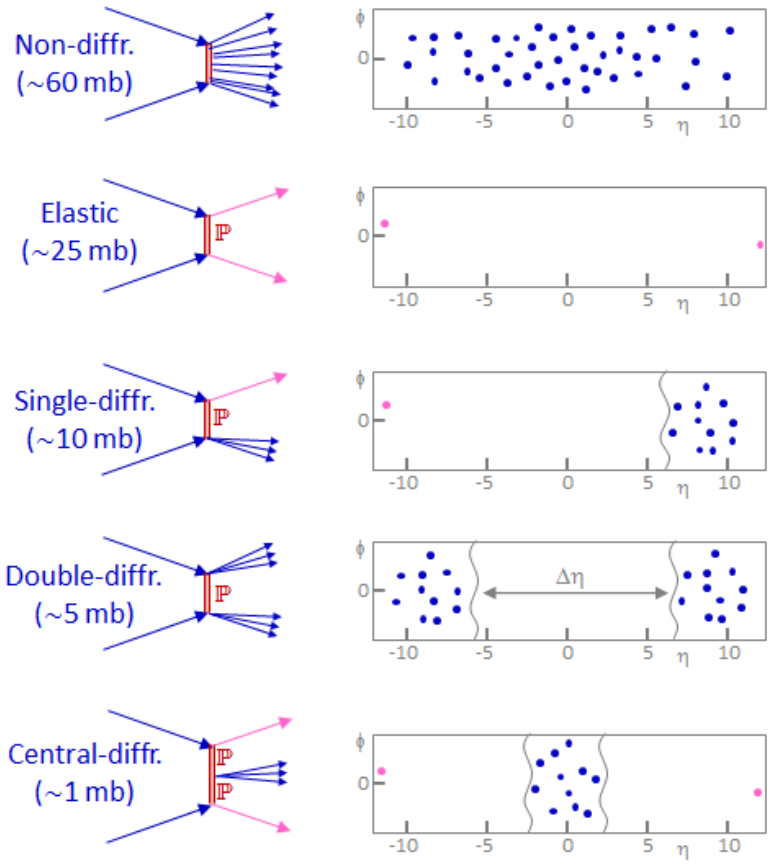
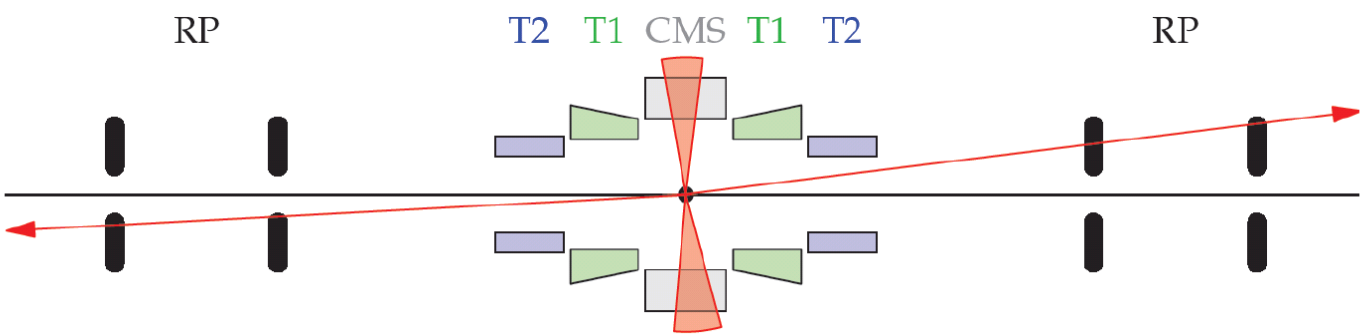
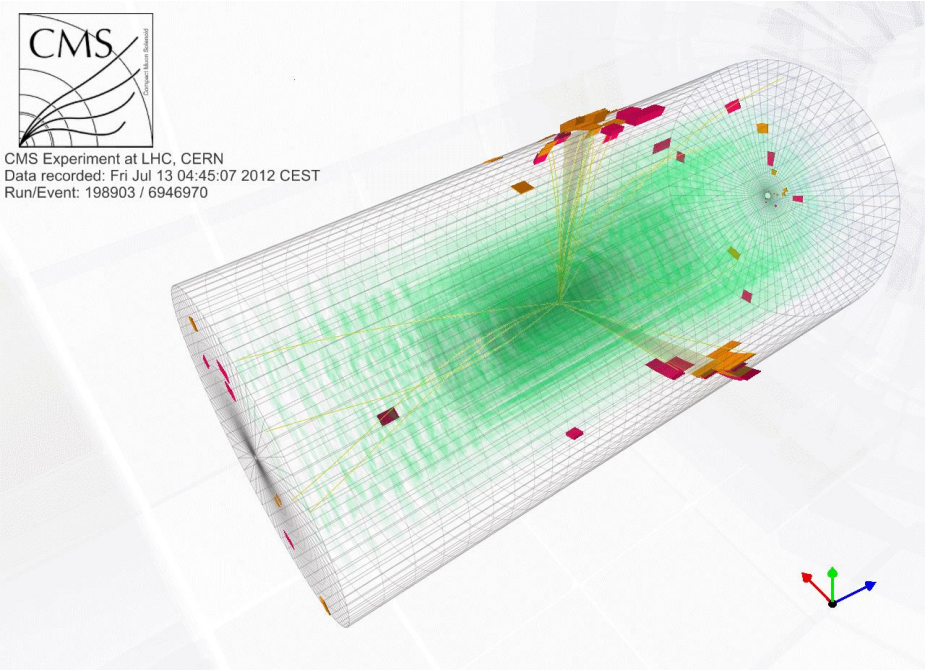


Central diffraction with TOTEM+CMS

- Diffractive mass determined by TOTEM ($M_X = \sqrt{s\xi_1\xi_2}$) & CMS (directly)



- Unprecedented rapidity coverage
- M & p from CMS & TOTEM consistent
- Pile-up removal crucial
  - Elastic + SD or elastic + beam halo
  - Cut on CMS FSC: QCD background
  - CMS and TOTEM masses equal
- High p_t jets with leading protons:
  - Signature: ≥ 2 tracks with $p_t > 20$ GeV
  - Proton in RP
  - FSC & T2 empty



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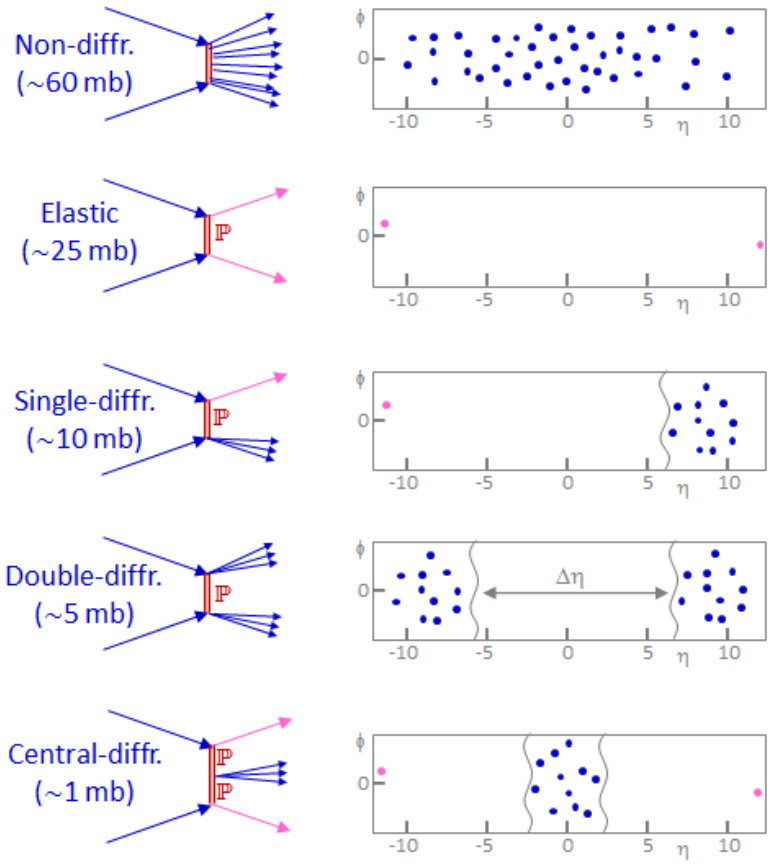
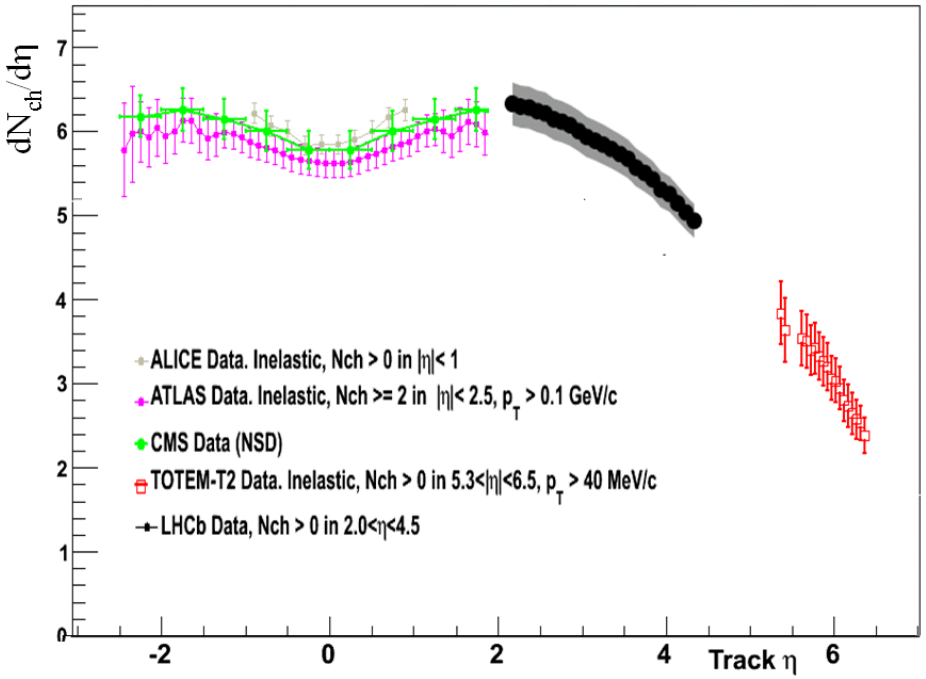
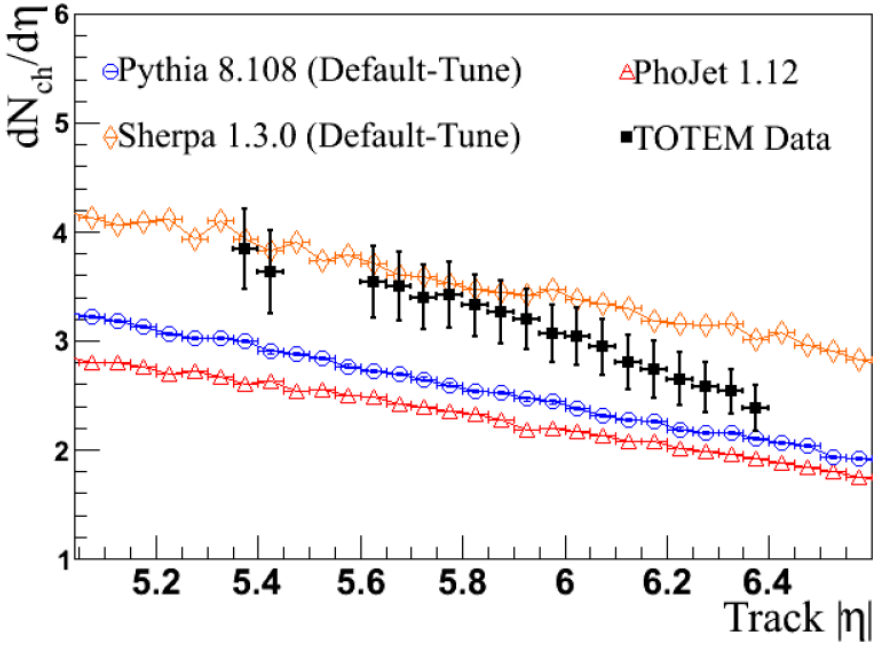


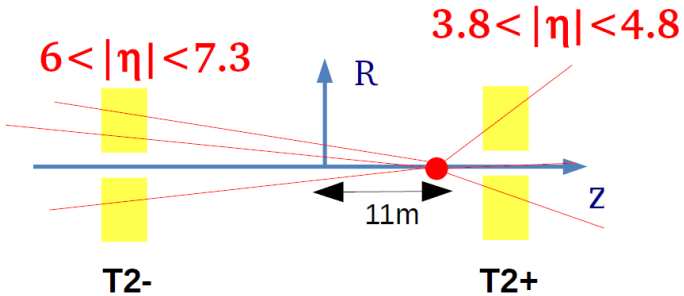
Pseudorapidity distribution results

- TOTEM: based on T2 trigger, at least 1 particle with $p_t > 40\ \mathrm{MeV}/c$
- More than 99% of ND
- Diffractive as well (if $M > 3.4\ \mathrm{GeV}/c^2$)
- LHC dataset compiled



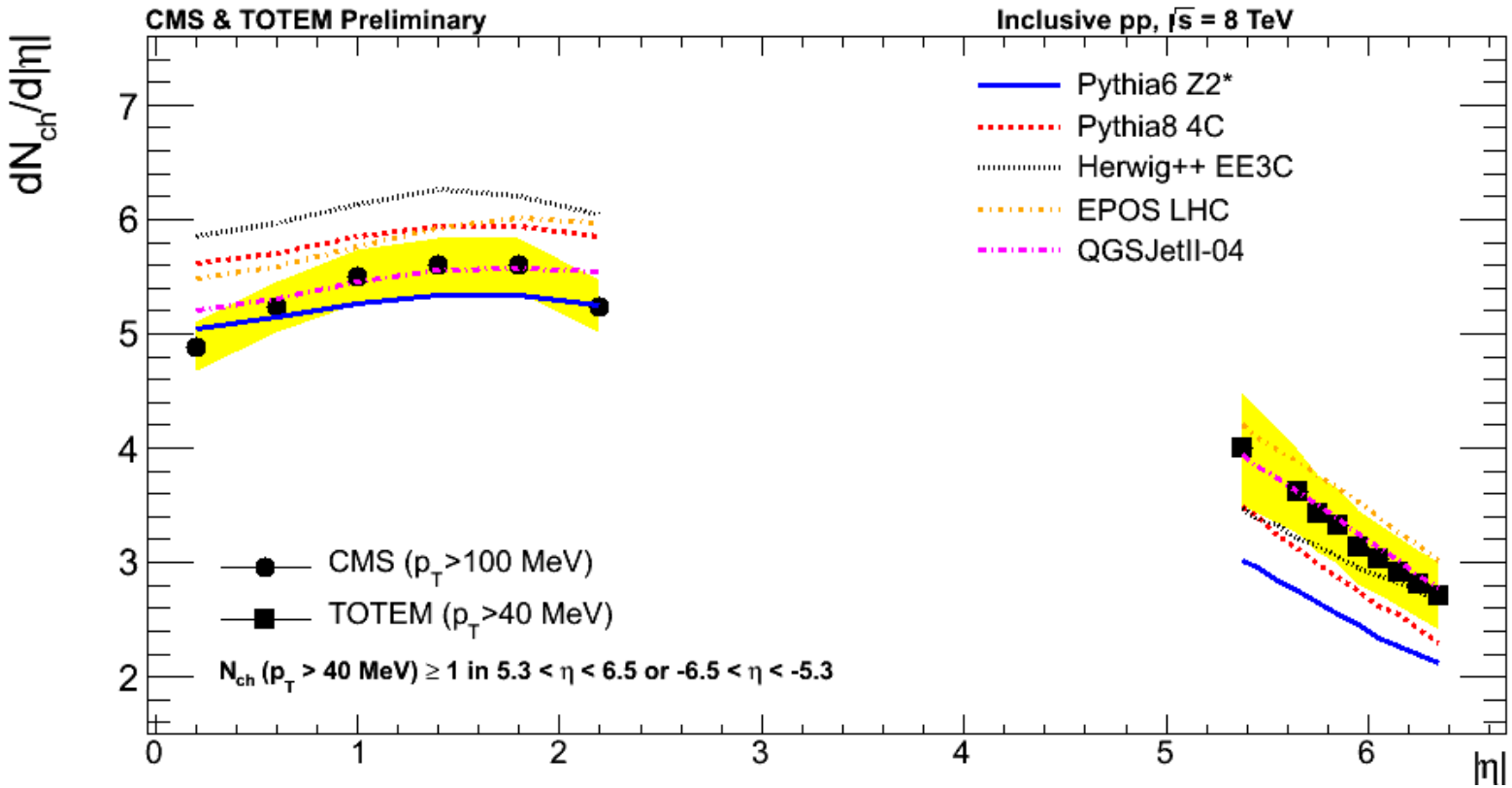


- TOTEM to LHCb: gap covered via displaced vtx. collisions:



Pseudorapidity distributions with TOTEM+CMS

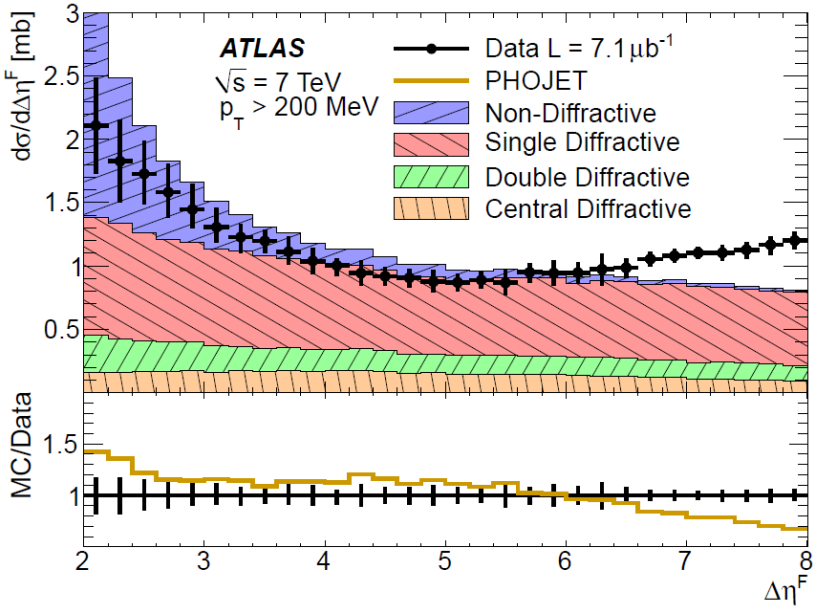
- CMS & TOTEM also triggered with T2, same reconstruction (at least 1 track)
- Corrections and correlated systematics under study

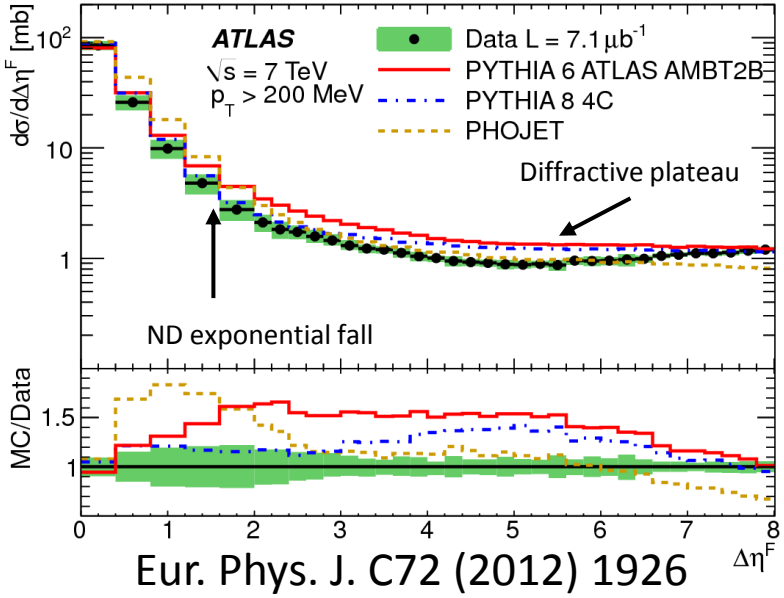


- NSD & SD enhanced measurement also ongoing

Forward rapidity gap cross-sections, ATLAS

- Rapidity gap measured from calorimeter edge ($\eta = \pm 4.9$)
- Systematic uncertainties: ~8% at large gaps, ~20% at small gaps
- Large gaps: contribution of SD and DD
- Small gaps: dominated by hadronization fluctuations in ND
- HERWIG++ (does not contain diffraction): bumps around $\eta \sim 6$, fails
  - Next version handles heavy mass clusters better, fixes rapidity gap modelling
- PYTHIA generally too high; PHOJET works best.





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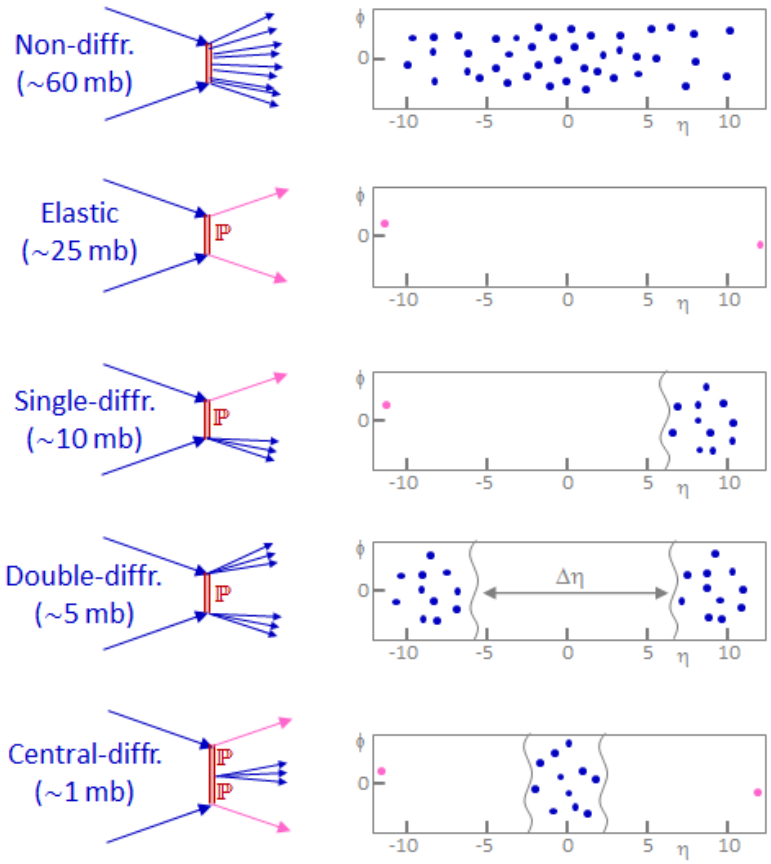


Summary

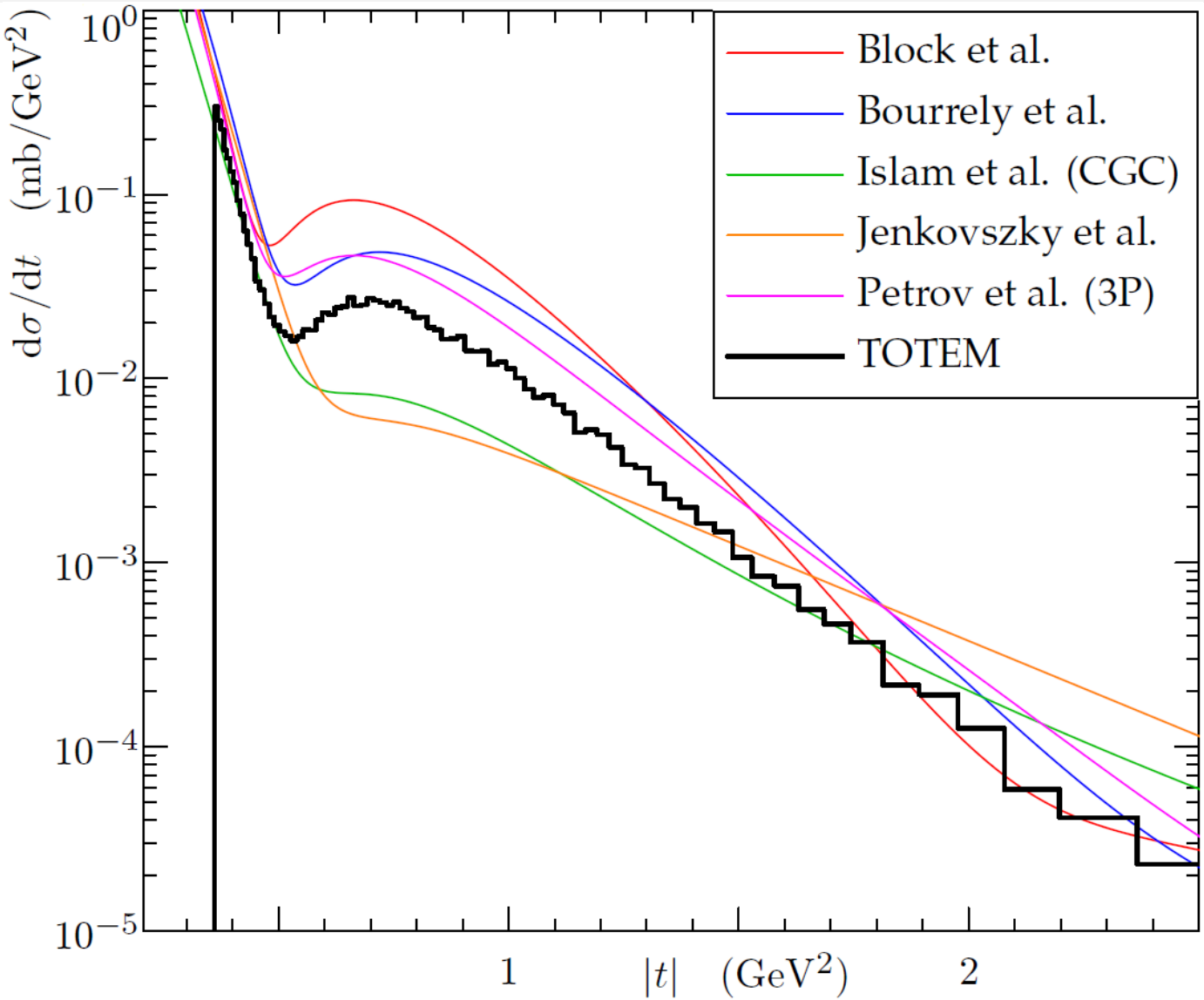
- TOTEM, CMS and ATLAS provide unprecedented measurement possibilities
  - Very forward detectors, especially Roman Pots
- Cross-section measurements
  - Differential cross-section results hardly describable by models
  - Total elastic & inelastic cross-sections measured via independent methods
  - ATLAS measurement: integrated to ξ_{cut}
- Single diffraction
  - TOTEM measurement done in three mass ranges
  - Diffractive dijets measured at CMS
- Double diffraction
  - TOTEM: final result in a limited rapidity region
- Central diffraction
  - Preliminary result at TOTEM & CMS
  - High p_t jets with leading protons seen
- Other results
  - TOTEM+CMS: single diffractive enhanced pseudorapidity distributions
  - Forward rapidity gap cross-section at ATLAS & CMS

Thank you for your attention

Recent talks for further reading:

- ATLAS Results on Soft Diffraction, Simone Monzani, EDS Blois 2013
- Diffraction and rapidity gap measurements with ATLAS, Vlastimil Kus, Photon 2013
- CMS results on soft diffraction, Konstantin Goulianos, EDS Blois 2013
- Diffraction at CMS, Sercan Sen, Forward Physics at the LHC 2013
- CMS results on Hard Diffraction, Christina Mesropian, EDS Blois 2013
- TOTEM Results on Elastic Scattering and Total Cross-Section, Jan Kaspar, EDS Blois 2013
- Review of TOTEM Results, Mario Deile, WE-Heraeus-Summerschool 2013
- Elastic and Inelastic Diffraction at the LHC, Risto Orava, LHCp 2013
- Soft diffraction and forward multiplicity meas. with TOTEM, F. Oljemark, EDS Blois 2013

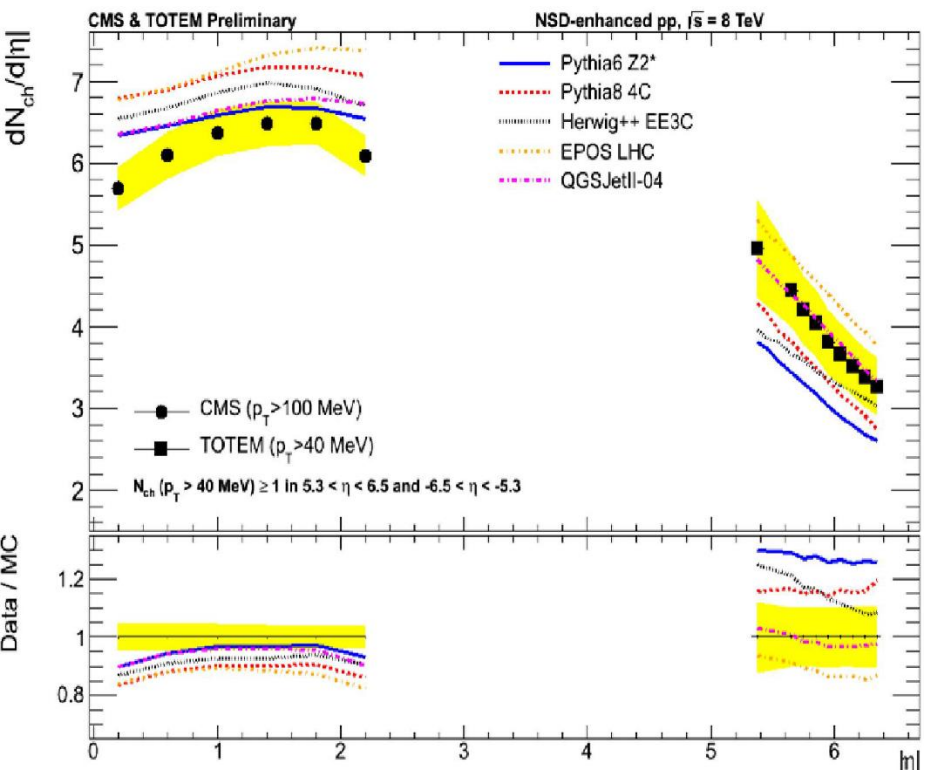
Differential elastic cross-section vs. models



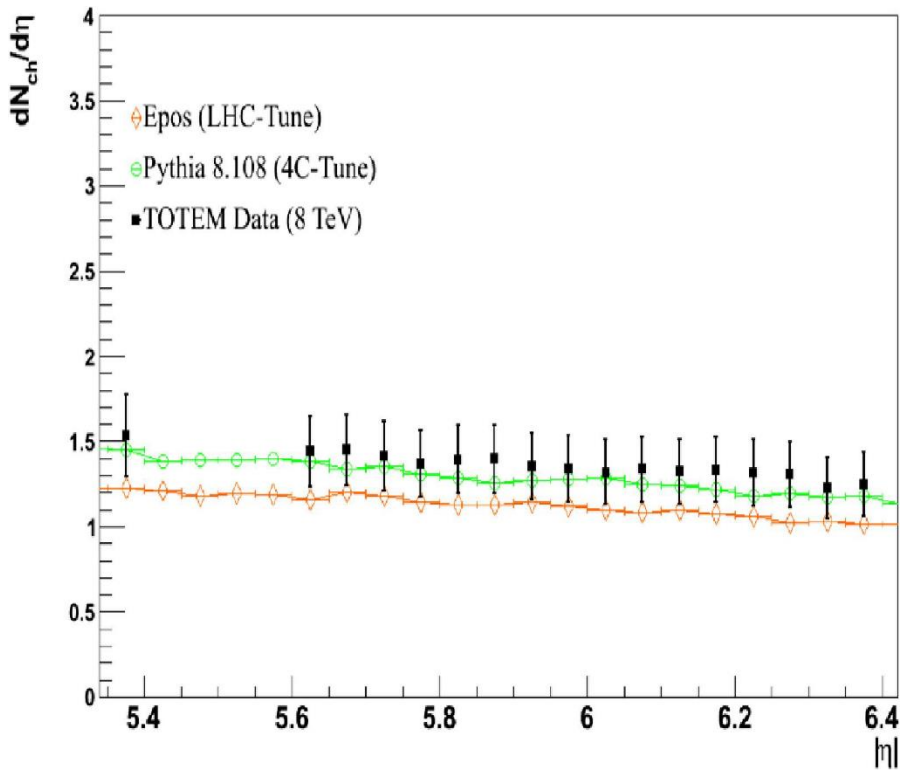
Pseudorapidity distributions: SD/NSD enhanced

- Analysis ongoing in both CMS & TOTEM

NSD-enhanced

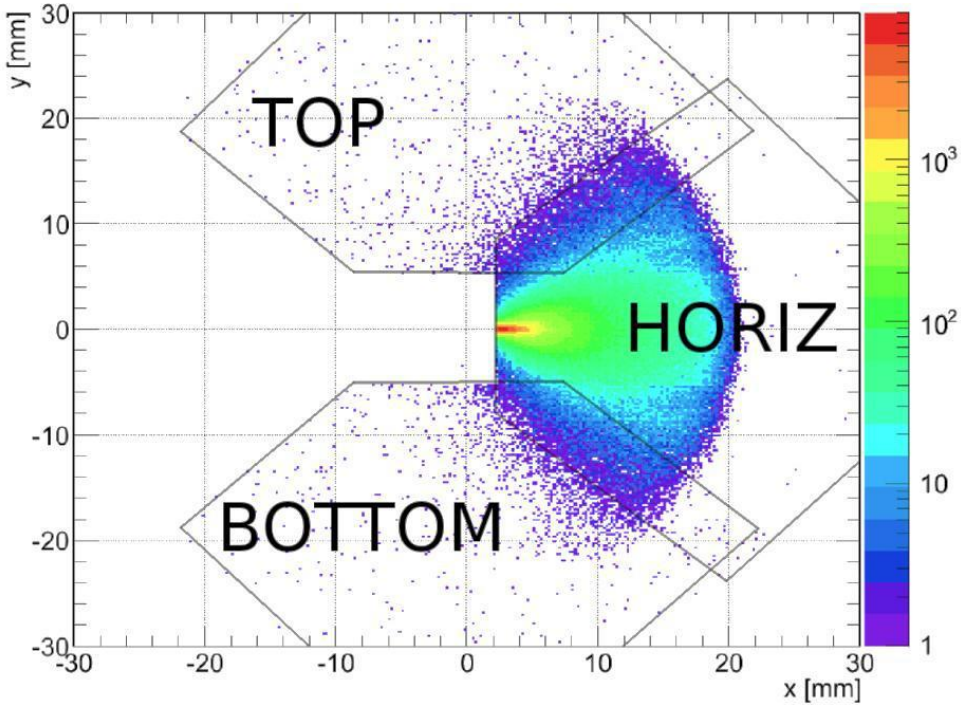


SD-enhanced

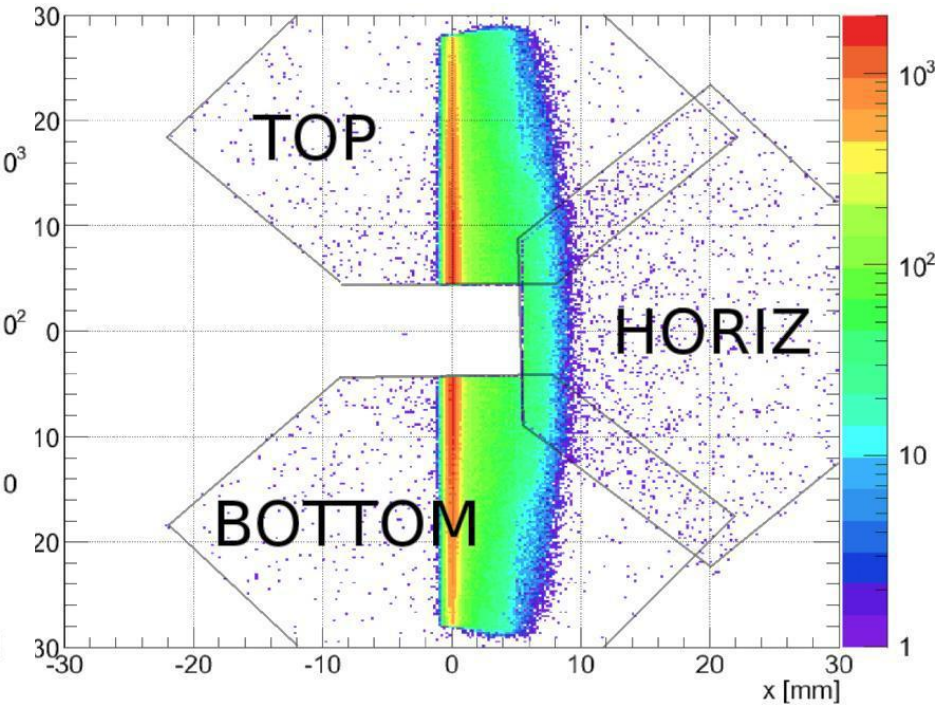


Different optics conditions as seen by TOTEM

Regular $\beta^* = 3.5$ m optics



$\beta^* = 90$ m optics



- RP structure reflects possibilities in various optics conditions
- Low cross-section processes studied with regular optics (continous running)
- High cross-section processes: dedicated short runs with optimized conditions

Cross-section measurements TOTEM

- Elastic dierential cross-section
  - 7 TeV
    - β^* = 90 m and medium |t| at β^* = 3.5 m: published
    - high |t| at β^* = 3.5 m: advanced analysis
  - 8 TeV
    - β^* = 1000 m: publication ongoing
    - β^* = 90 m: advanced analysis
  - 2.76 TeV
    - β^* = 11 m: analysis ongoing
- Total cross-section
  - 7 TeV
    - β^* = 90 m: published
  - 8 TeV
    - β^* = 90 m: published
    - β^* = 1000 m: publication ongoing (+ separation Coulomb/nuclear effects)
  - 2.76 TeV
    - β^* = 11 m: elastic analysis started, inelastic ready
- Coulomb-nuclear interference studies
  - 8 TeV
    - β^* = 1000 m: publication ongoing

TOTEM upgrade plans

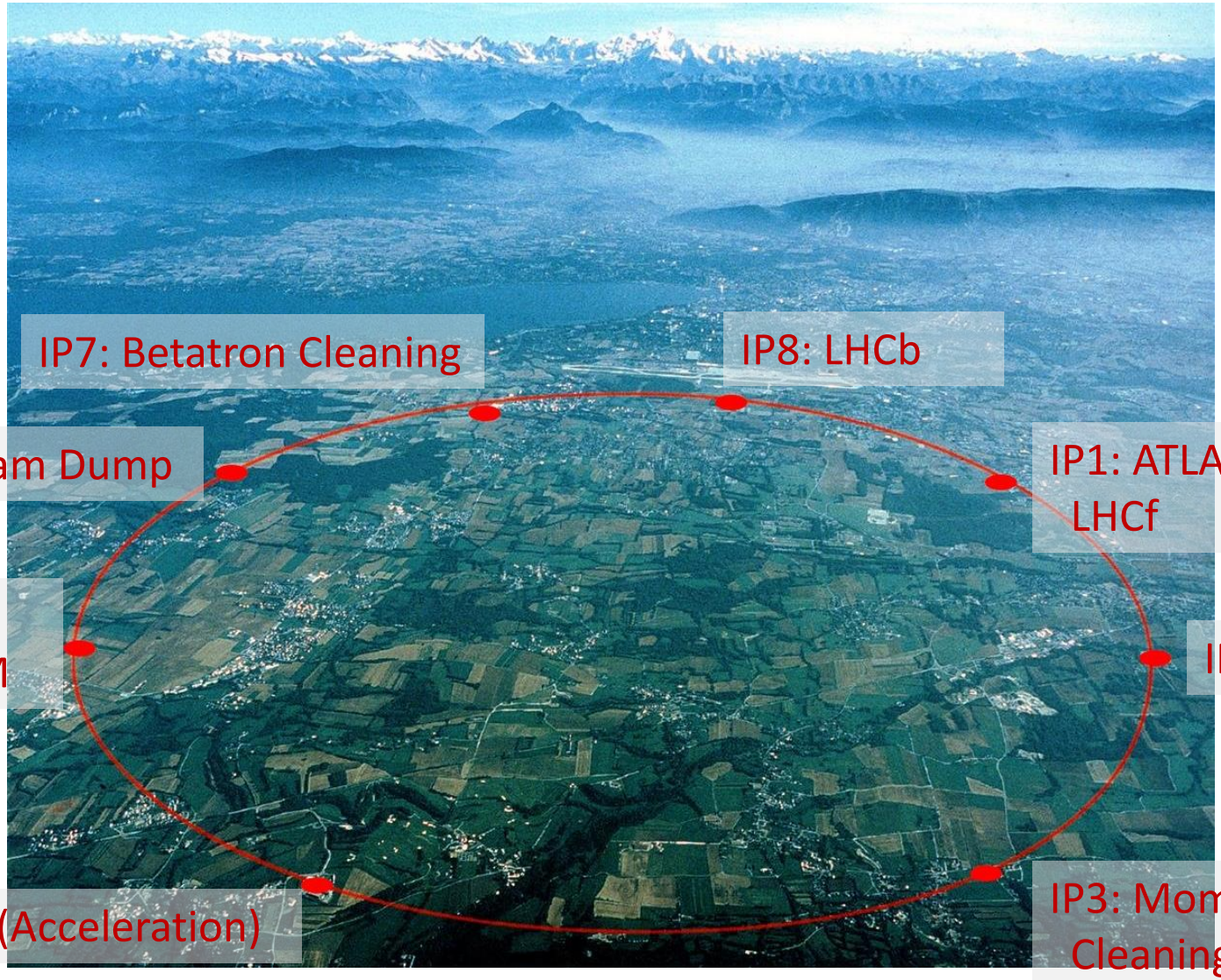
- RP system will consist of 4 RP units/arm, each with 2 vertical + 1 horizontal pots equipped with 10 planes Si-strip detectors, with full trigger capability

- Improving RP multi-track capability
  - Tilt far RP station for ghost track suppression
  - Replace strip detectors with pixel detectors

- Reducing RP-beam coupling
  - Optimized RP impedance (reduce heating & feedback) needed
  - Cylindrical RP with Ferrites shown a reduced beam power-loss
  - For 210m far-horizontal RP a cylindrical copper shield is studied for impedance reduction

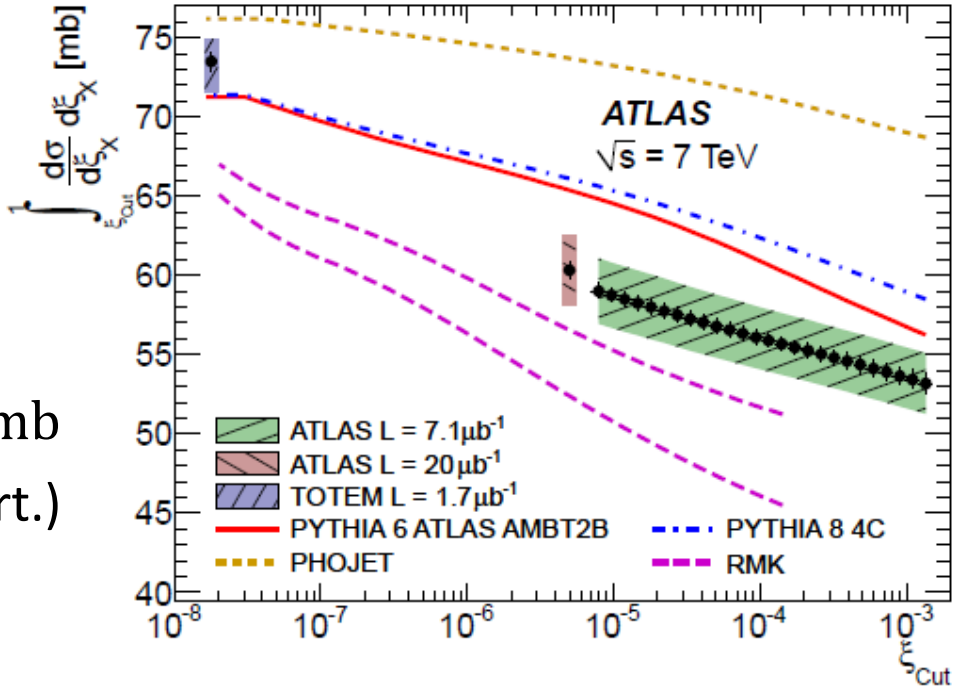
- Improving proton left-right correlation capability
  - Timing sensors with few times 10 ps timing resolution

LHC setup


IP7: Betatron Cleaning
IP8: LHCb
IP6: Beam Dump
IP1: ATLAS, LHCf
IP5: CMS, TOTEM
IP2: ALICE
IP4: RF (Acceleration)
IP3: Momentum Cleaning

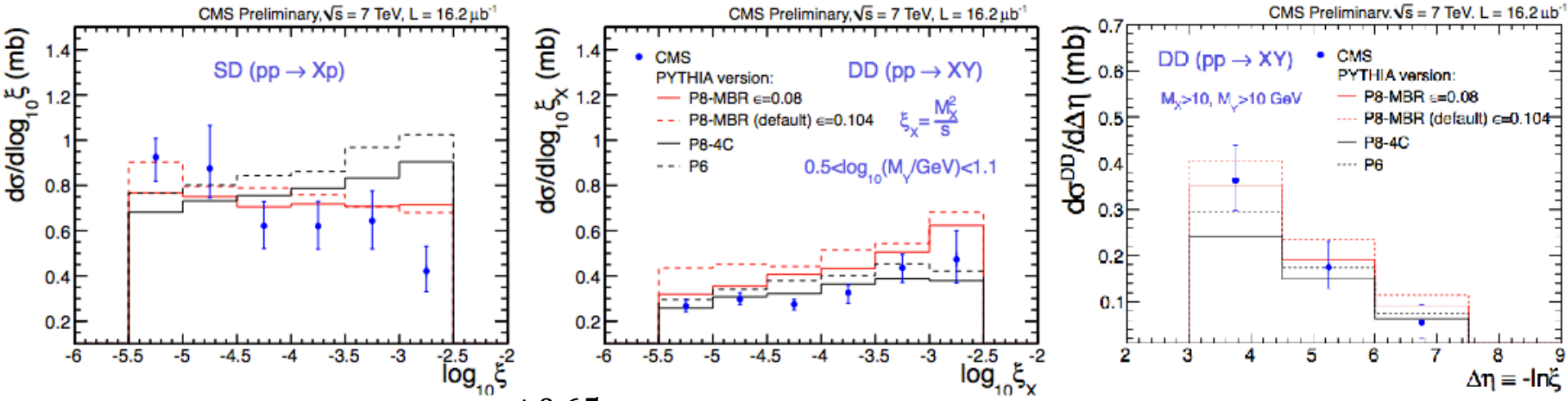
ATLAS: Integrated cross-section for $\xi > \xi_{cut}$

- The inelastic cross-section obtained by integration from ξ_{cut} to 1
- Same as integrating from 0 to $\Delta\eta_f^{max}$
- RMK model (Ryskin, Martin, Khoze), PYTHIA and PHOJET used
- Small ξ region underestimated
- 14.5 mb for $\xi < 8 \cdot 10^{-6}$ compared to 6 mb (3 mb) by PYTHIA (PHOJET)
- RMK model lies below data generally
- Low ξ enhancement in agreement
- Total inelastic cross-section: $\sigma_{\text{inel}} = 69.4 \pm 2.4(\text{exp}) \pm 6.9(\text{extr})$ mb
- In agreement with TOTEM (large uncert.)
- Ref.: Eur. Phys. J. C72 (2012) 1926



SD & DD cross-sections at CMS

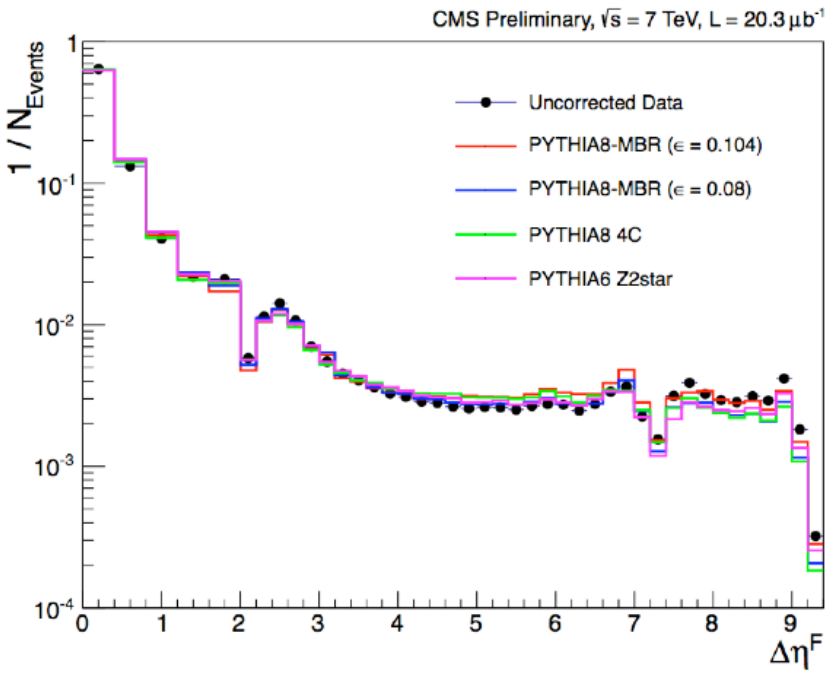
- Measure event counts with gap on + or - side

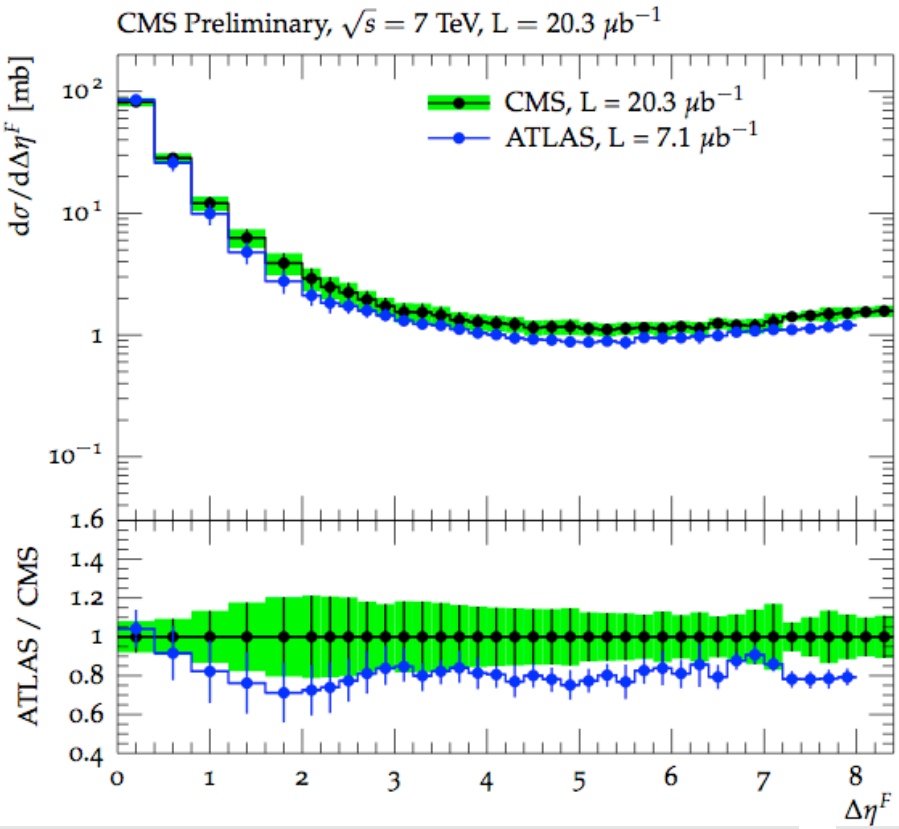


- $\sigma_{SD} = 4.7 \pm 0.04(\text{stat})^{+0.65}_{-0.58}(\text{syst})$ mb, int. over $2.5 < -\log\xi < 5.5$
- Multiplied by 2 to account for both side processes
- $\sigma_{DD} = 0.93 \pm 0.01(\text{stat})^{+0.26}_{-0.22}(\text{syst})$ mb, for $\Delta\eta > 3, M_X, M_Y > 10$ GeV
- Pythia8-MBR: describes SD, DD partially
- Pythia6/8: fails with SD

Forward rapidity gap cross-sections, CMS

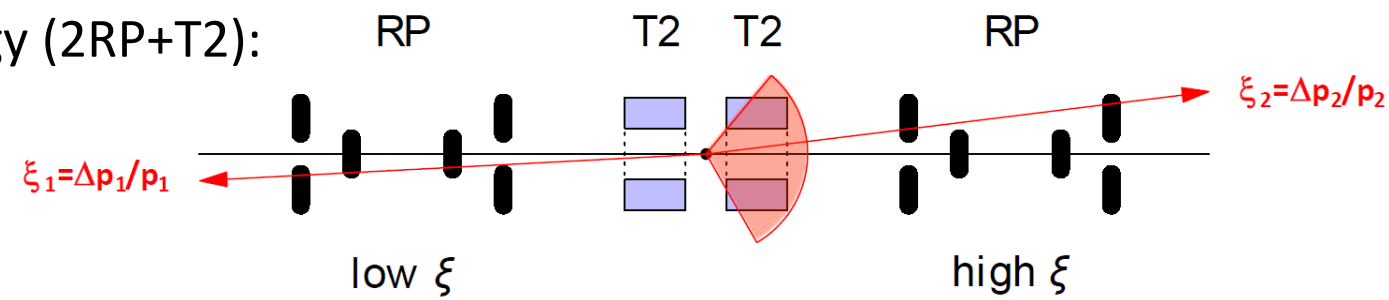
- Exponentially falling non-diffractive contribution at small gap size
- Diffractive plateau and slowly rising cross-section with increasing gap size
- Hard to separate SD and DD events at central region using forward rapidity gap observable
- CMS & ATLAS result compared (slightly different rapidity region)





Central diffraction at TOTEM

- Event topology (2RP+T2):



- Two rapidity gaps $\Delta\eta_1 = \xi_1$ and $\Delta\eta_2 = \xi_2$, thus $M_X^2 = \xi_1\xi_2 s$
- Background: elastic, inelastic with beam-halo (pile-up)
- Beam halo negligible: $y > 11\sigma_{\text{beam}}$
- Elastic rejected via anti-elastic cuts, non-elastic topologies (e.g. top-top)
- Single-arm event rate in RP (corrected):
- Only t distribution is exponential (Jac.)
- MC based fit on t_y distribution
- Cross-section estimate: $\sigma_{CD} \approx 1$ mb