Recent CMS and CMS-TOTEM results on forward physics

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for the CMS and TOTEM Collaborations

Synergies of pp and pA Collisions with an Electron-Ion Collider
RIKEN BNL Research Center Workshop
26–28 June 2017, Brookhaven National Laboratory, NY, USA

Outlook

- Inclusive measurements
  - Soft diffractive cross sections from CMS
  - Soft diffractive cross sections from TOTEM
  - Central and forward energy flow

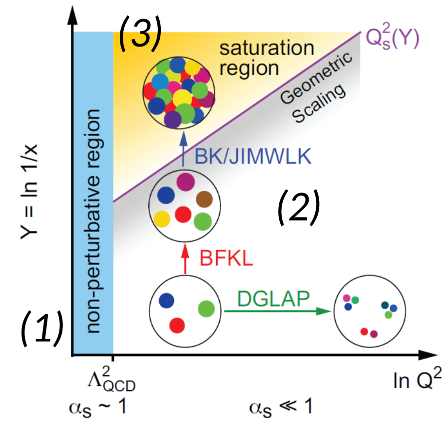
(1) Test QCD in the non-perturbative region (phenomenology). Also a story about detector coverage.

- Measurements with a hard scatter
  - Inclusive forward jets and dijets
  - Diffractive dijets

(2) Test pQCD evolution at low-x, DGLAP vs BFKL, etc.

- Central exclusive (IP-IP, γ-IP, γ-γ) processes
  - Exclusive dihadron production
  - Exclusive Upsilon production in UPC
  - Exclusive WW production

(3) Search for signs of saturation, exotic QCD states (e.g. glueballs), also BSM physics at EW scale.

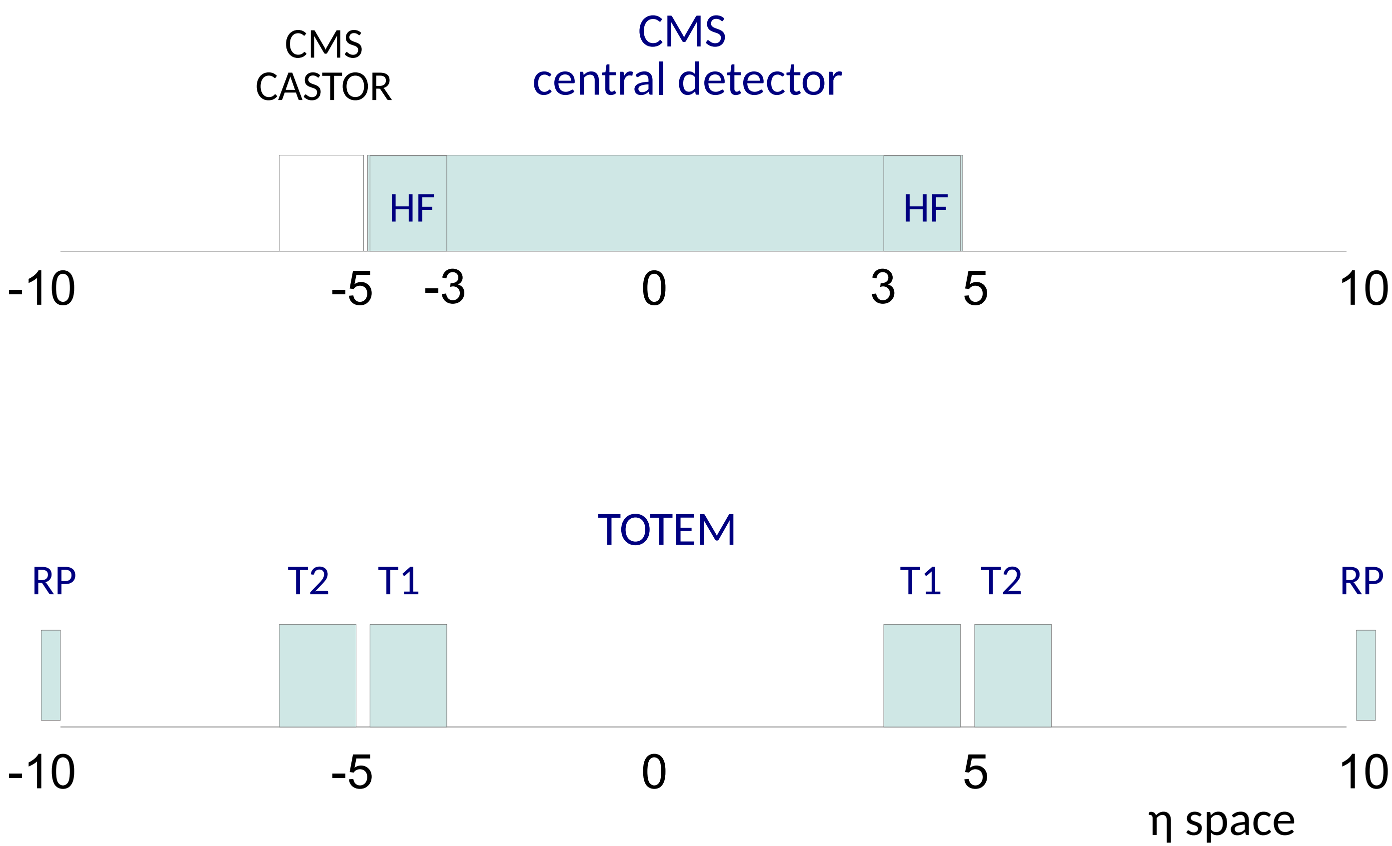


Selected results.
Focus on diffractive and very forward (low-x) QCD phenomena.

Detector coverage

Kinematic limit @7 TeV: $\eta = \pm 0.5 * \log(s/m^2) \approx \pm 10$

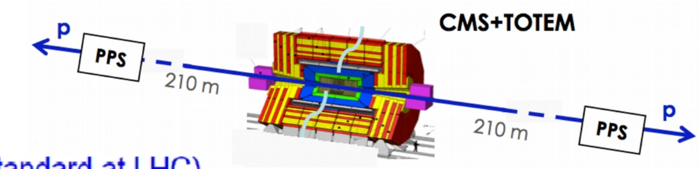
M_X (SD): ~3.4 ~12. ~1100 GeV



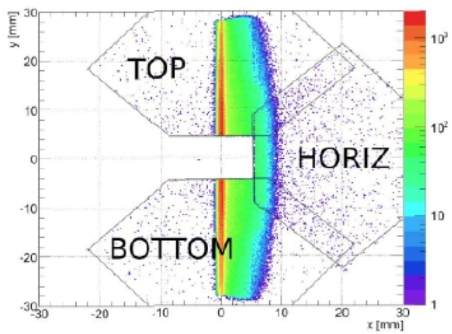
HF – CMS Hadron Forward Calorimeter,
T1/T2 – TOTEM trackers,
RP – TOTEM Roman Pots at ±220m from IP.

Joint CMS-TOTEM runs

Two types of runs with different LHC optics.

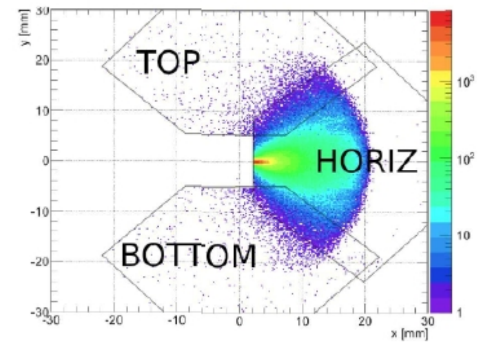


β* = 90 m (developed for σ_{total} measurement)



diffractive protons: mainly in **vertical** RP

β* = 0.55 m (low β* = standard at LHC)



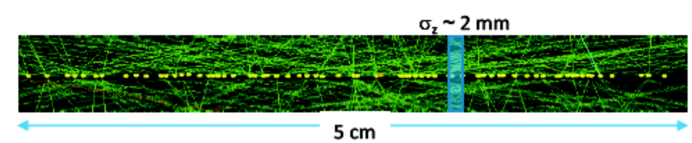
diffractive protons: mainly in **horizontal** RP

Special CMS-TOTEM runs

- High-β*, low-lumi, low-pileup (0.06-0.15) runs.
- ~40/nb of data @8 TeV in 2012,
  ~0.4/pb of data @13 TeV in 2015.
- Separate DAQ systems with trigger communication.
- CMS and TOTEM data reconstructed separately, then merged offline.
- Acceptance: low and moderate Mx , t> 0.01 GeV^2
- Physics examples: Low-mass resonances in central exclusive production, diffraction with proton tag, etc.

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

- Low-β* high-lumi, standard LHC runs.
- ~15/fb (!) of data @13 TeV in 2016,
  full lumi in 2017.
- DAQ, trigger fully integrated with CMS.
- Installed and commissioned in 2016:
  - 2 RP stations for tracking detectors,
  - 1 RP station for fast timing detectors (event vertex).
- Acceptance Mx>400 GeV (CEP, 2 tagged protons).
- Physics: QCD, EWK (LHC as a photon-photon collider), BSM physics.

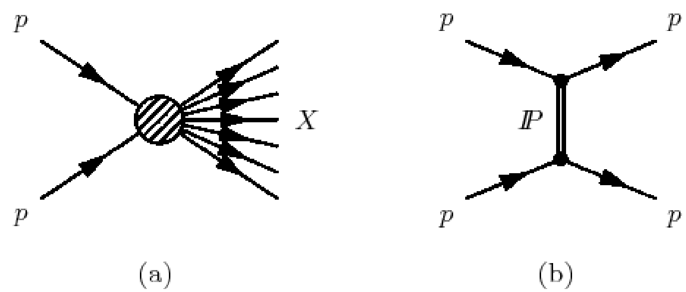


This talk focuses on special CMS-TOTEM runs.

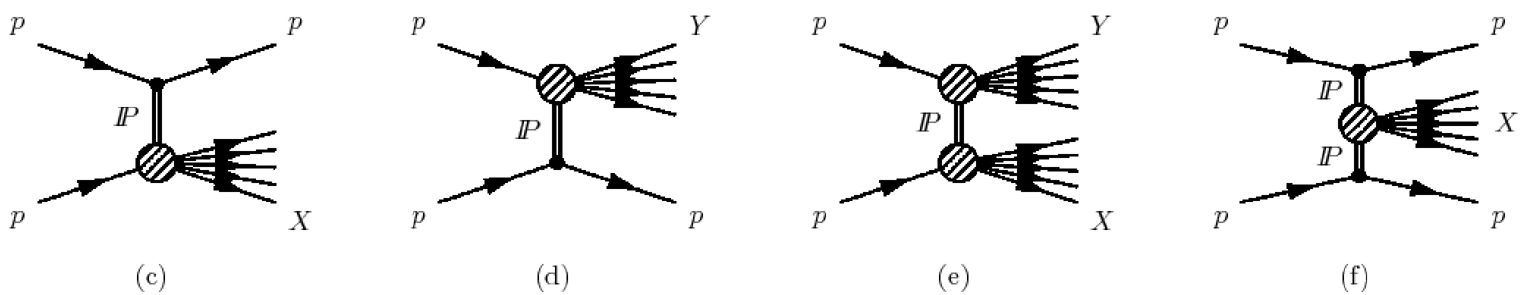
Main processes contributing to the total pp cross section

Non-diffractive
pp → X

(exponentially-suppressed
rapidity gap)



Elastic
pp → pp



Single dissociation (SD)
pp → Xp , pp → pY

Double dissociation (DD),
pp → XY

Central diffraction (CD)
pp → pXp

or **double-Pomeron exchange (DPE)**

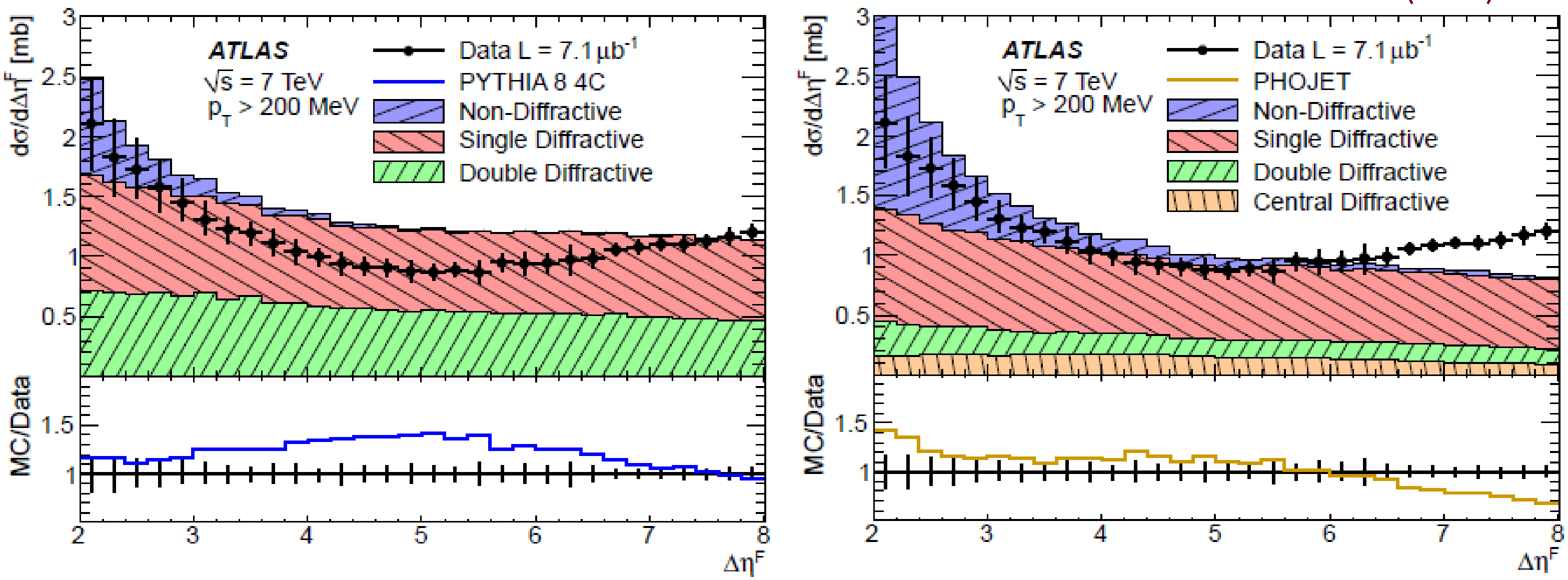
Total – elastic = total inelastic cross section

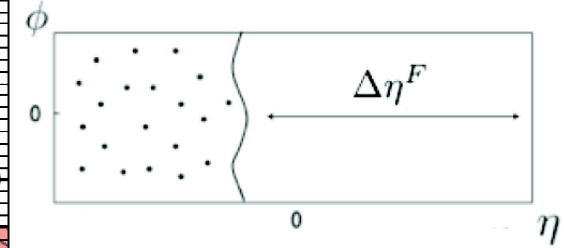
Diffractive processes (SD, DD, CD) - characterized by the presence of a large rapidity gap (LRG) in the final state - about 20-30% of total-inelastic cross section.

Inclusive diffraction with rapidity gaps

Forward rapidity gap cross section from central detector

EPJC 72 (2012) 1926

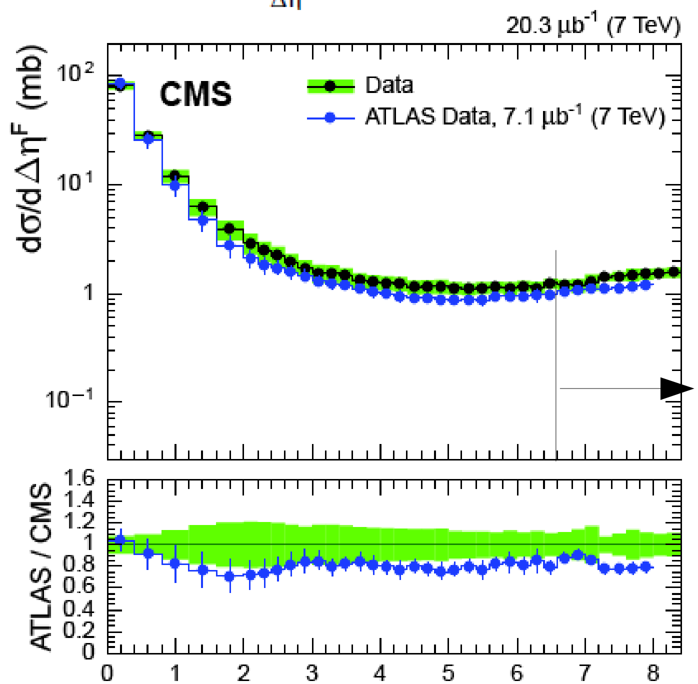




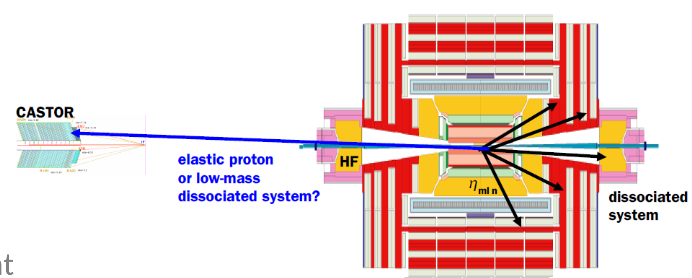
distance to the detector edge

Diffractive events at high values of $\Delta\eta^F$
For $\Delta\eta^F > 3$ measured ~ 1 mb per unit of $\Delta\eta^F$
Test of diffraction models
No SD/DD separation possible

Similar results from CMS.
In addition, CMS uses CASTOR calorimeter ($-6.6<\eta< -5.2$)
to separate SD/DD for events with $\Delta\eta^F > 4$.

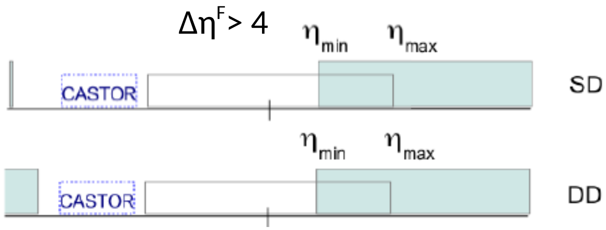


PRD 92 (2015) 012003

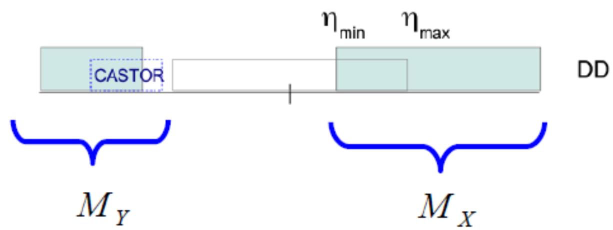


Inclusive SD/DD cross sections @7 TeV

PRD 92 (2015) 012003



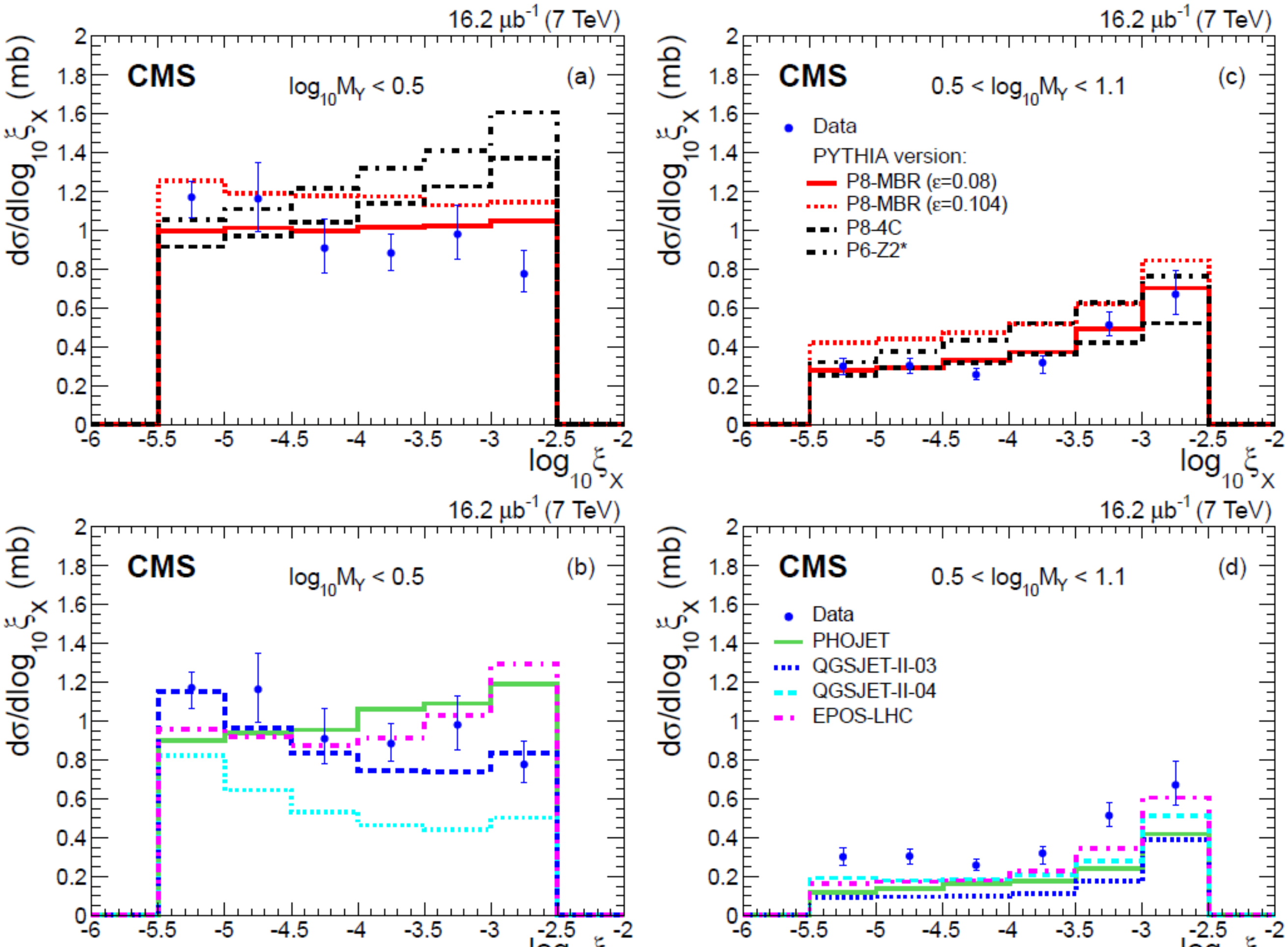
no CASTOR-tag (SD dominated)



CASTOR-tag (DD dominated)

Forward rapidity gap of $\Delta\eta^F > 4$ + SD/DD separation with CASTOR calorimeter ($-6.6<\eta< -5.2$)

$3.2 < M_Y < 12$ GeV



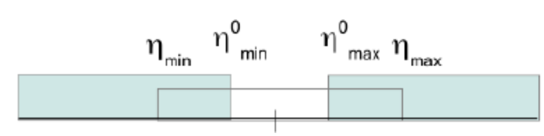
$$\xi_X = \frac{M_X^2}{s}$$

For $12 < M_X < 394$ GeV

Test of diffraction (and hadronization) models

PYTHIA8-MBR describes all aspects of the data

- Also central gap (DD dominated, not shown)



SD cross section from CMS

PRD 92 (2015) 012003

From background-subtracted (with small uncertainties) CASTOR-tag sample:

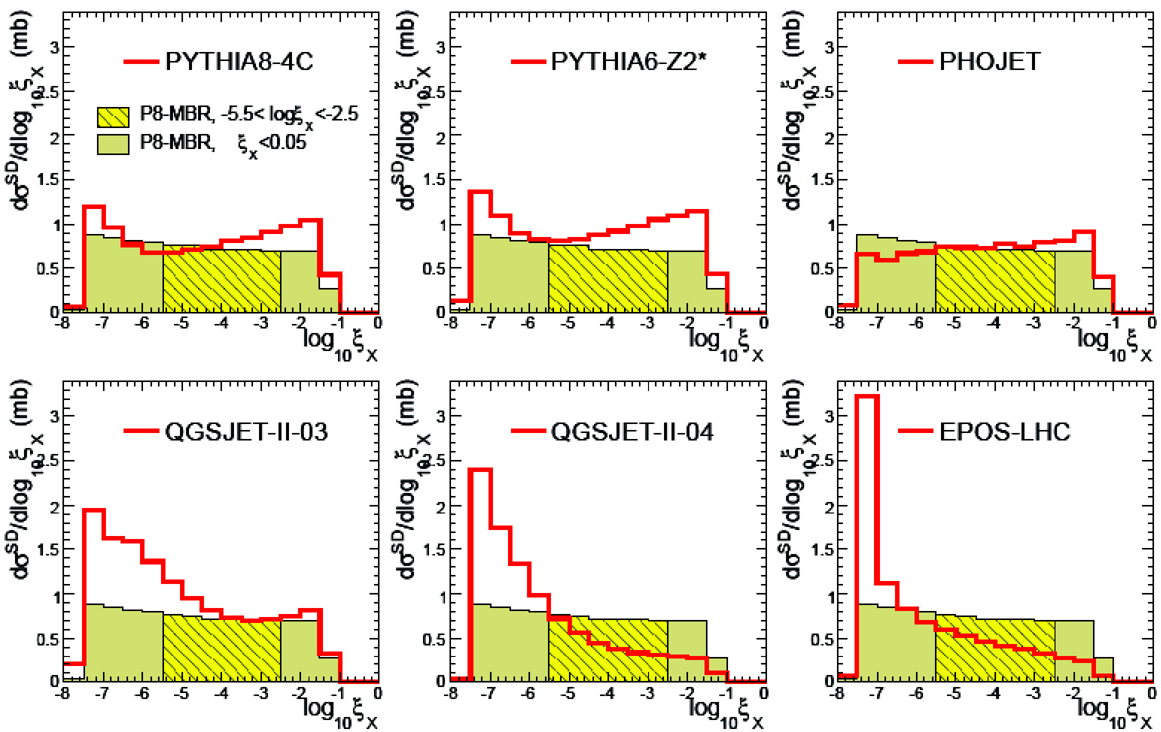
$$\sigma^{SDvis} = 4.06 \pm 0.04\,(stat)^{+0.69}_{-0.63}\,(syst)\,mb \qquad -5.5 < \log_{10}\xi_X < -2.5$$

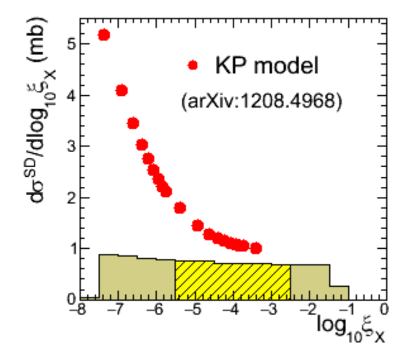
(12 < M_X < 394 GeV)

Extrapolated to the not observed region with PYTHIA8-MBR:
(from yellow to khaki on plots below)

$$\sigma^{SD} = 8.84 \pm 0.08\,(stat)^{+1.49}_{-1.38}\,(syst)^{+1.17}_{-0.37}\,(extr)\,mb \qquad \xi_{X(Y)} < 0.05$$

Large model variations, PYTHIA8-MBR describes the data in the visible region



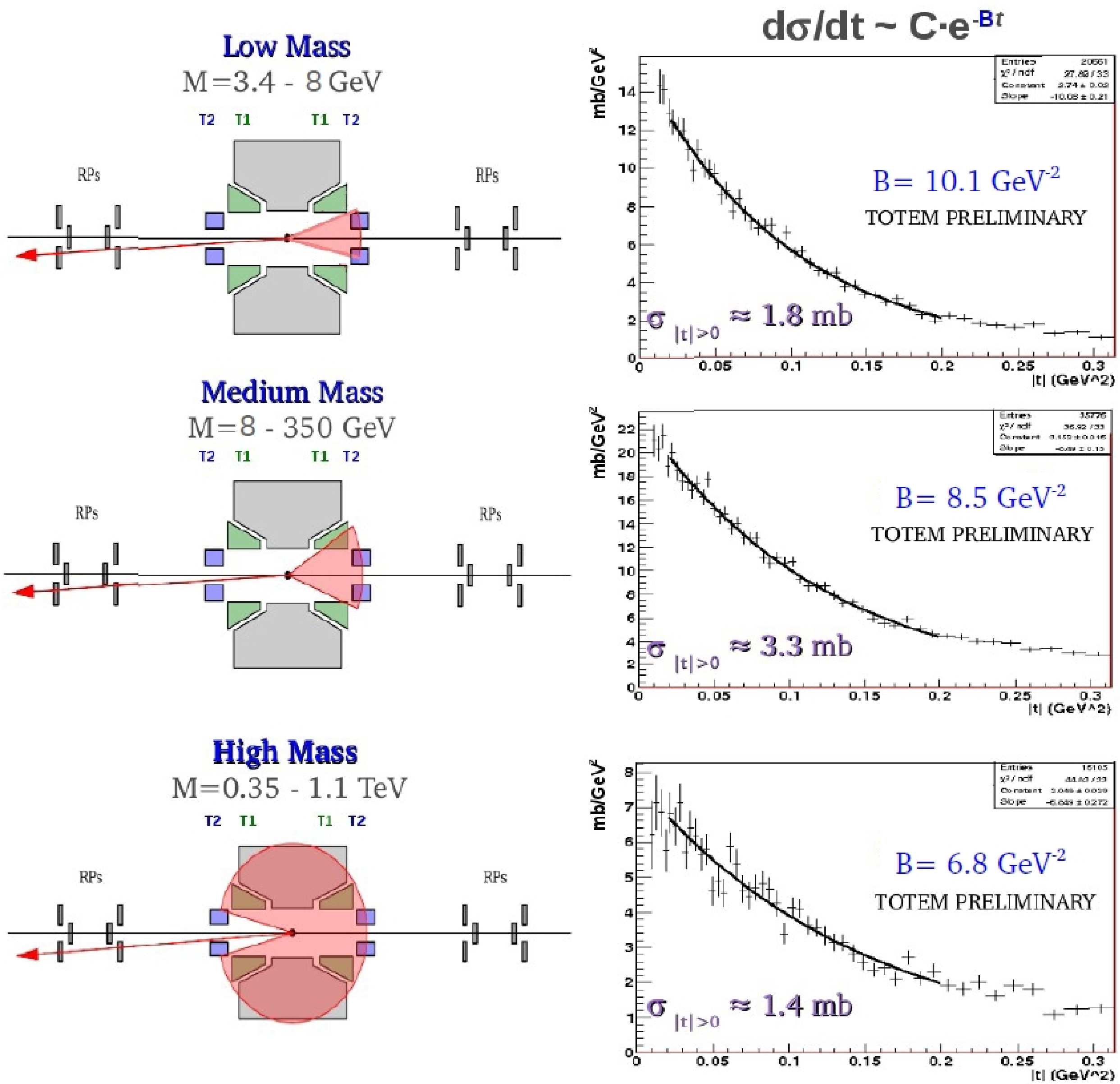


used in EPJC 73 (2013) 2456

Extrapolation uncertainties present also in the measurements of total inelastic cross section by CMS and ATLAS

CMS-PAS-FSQ-15-005, PRL 117 (2016) 182002

SD cross section from TOTEM



Proton tag + combinations of T1 ($3.1<|\eta|<4.7$) T2 ($5.3<|\eta|< 6.5$) detectors to select different Mx bins.

Integrated SD cross section @7 TeV

$$\sigma_{SD} = 6.5 \pm 1.3 \text{ mb}$$
$$(3.4<M_{SD}<1100 \text{ GeV})$$

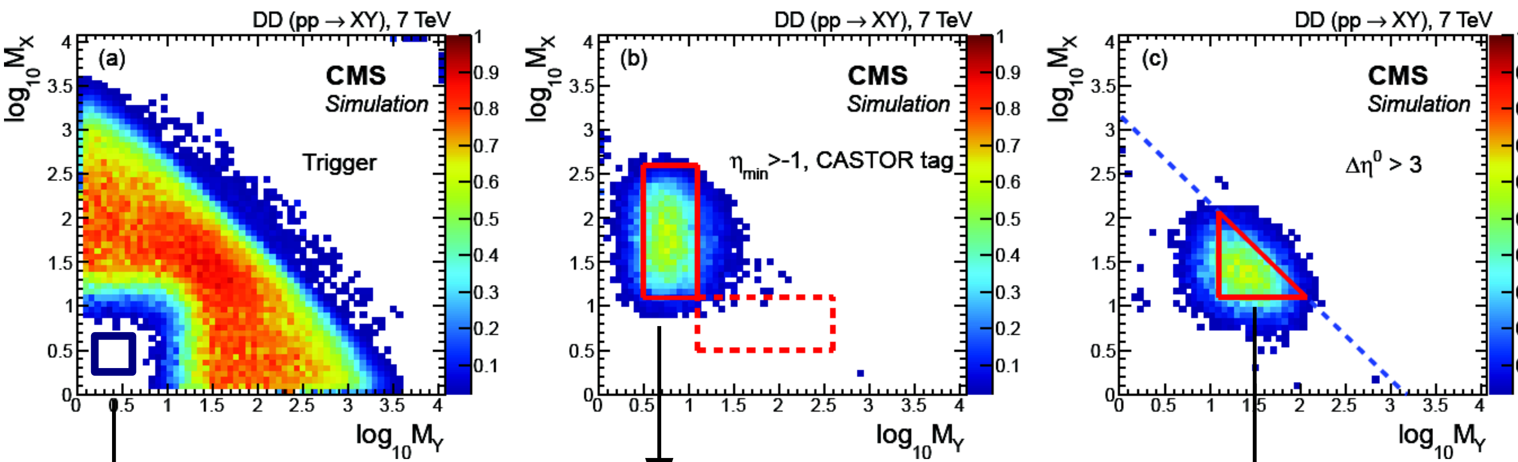
No backgound from DD.

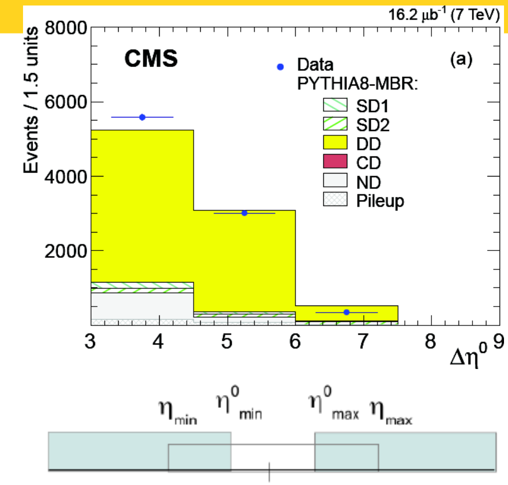
DD cross section from CMS and TOTEM

PRD 92 (2015) 012003

forward gap with CASTOR tag

central gap





$$\sigma^{DDvis}_{CASTOR} = 1.06 \pm 0.02\,(stat) \pm 0.12\,(syst)\,mb$$

for 12 < M_X < 394 GeV, 3.2 < M_Y < 12.6 GeV

$$\sigma^{DDvis}_{CG} = 0.56 \pm 0.01\,(stat)^{+0.15}_{-0.13}\,(syst)\,mb$$

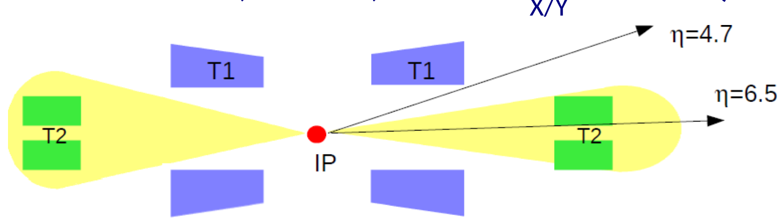
for Δη>3, M_X > 12.6 GeV, M_Y > 12.6 GeV

and extrapolated to Δη>3 with PYTHIA8-MBR:

$$\sigma^{DD} = 5.17 \pm 0.08\,(stat)^{+0.55}_{-0.57}\,(syst)^{+1.62}_{-0.51}\,(extr)\,mb$$

PRL 111 (2013) 262001

TOTEM (T2 on both sides, no T1, 3.4< $M_{X/Y}$ < 8 GeV)

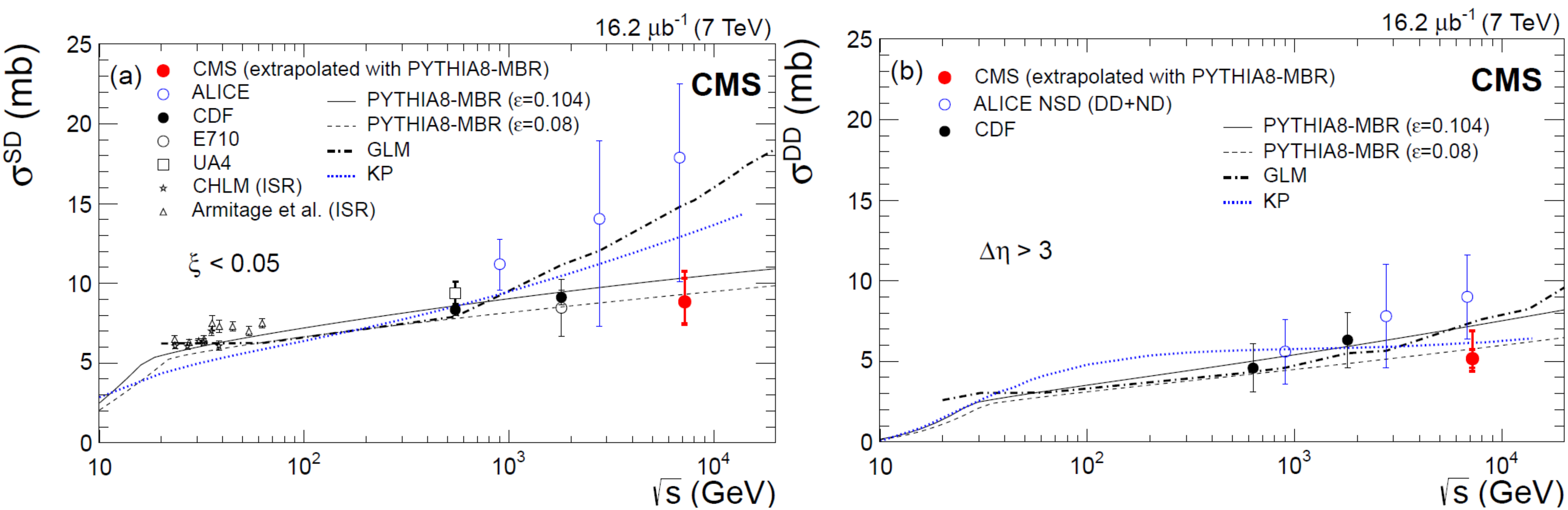


$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 120 \pm 25\mu b$$

SD and DD cross sections

PRD 92 (2015) 012003
ALICE: EPJC 73 (2013) 2456

SD and DD cross section weakly rising with energy



TOTEM SD:

6.5 ± 1.3 mb – SD cross section for $3.4 < M_X < 1.1$ GeV

2.62 ± 2.17 mb - T2-invisible cross section for $M_X < 3.4$ GeV (SD dominated) EPL 101 (2013) 21003

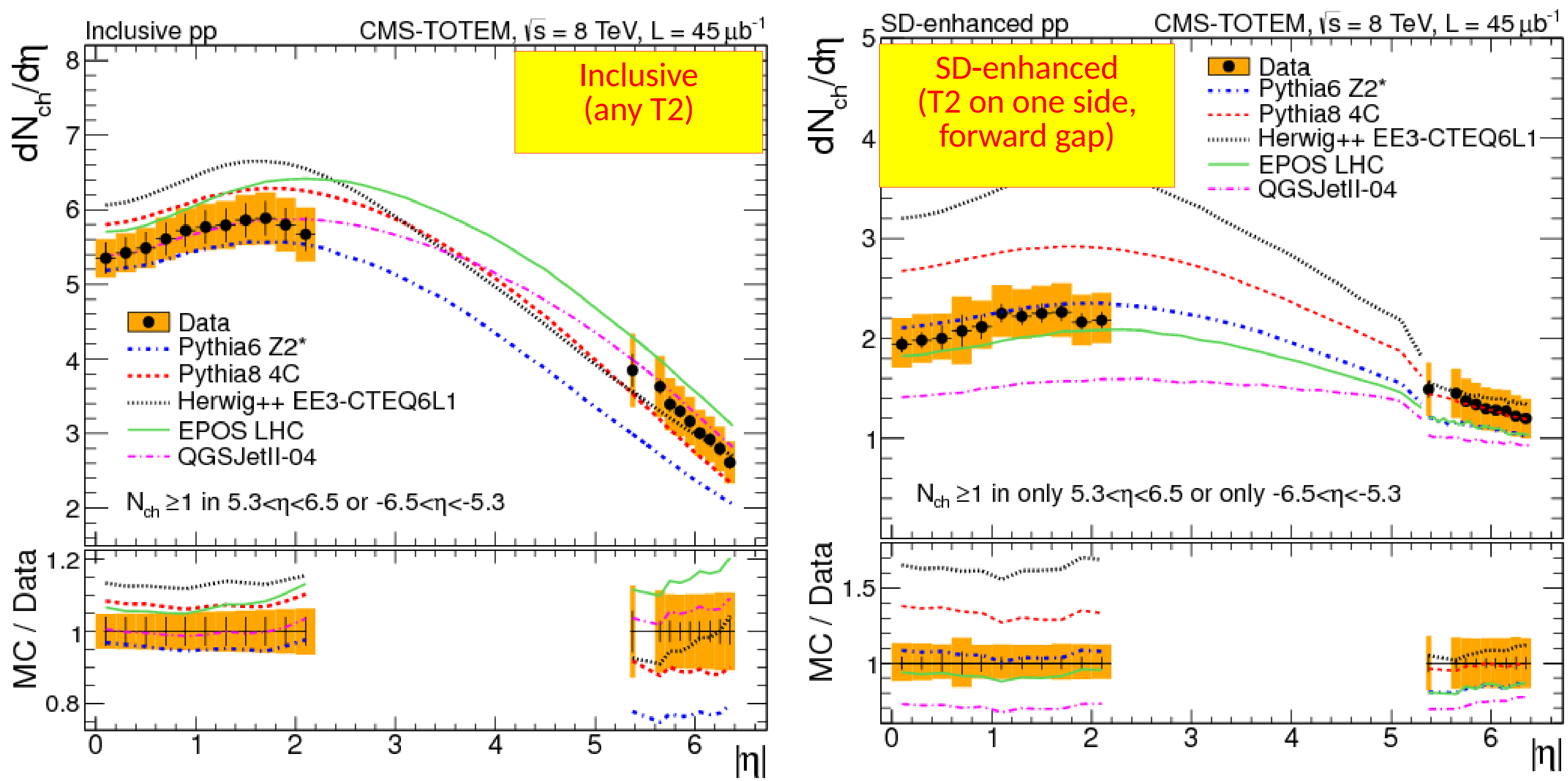
\+ 9.12 ± 2.53 mb for $\xi<0.025$ (extrapolation to $\xi<0.05$ compensated by DD in T2-invisible cross section)

in agreement with extrapolated CMS SD cross section.

Central and forward $dN_{ch}/d\eta$ @8TeV

The first common CMS+TOTEM runs (2012, @8 TeV) and publication
Trigger and event classification based on activity in T2

EPJC 74 (2014) 2053

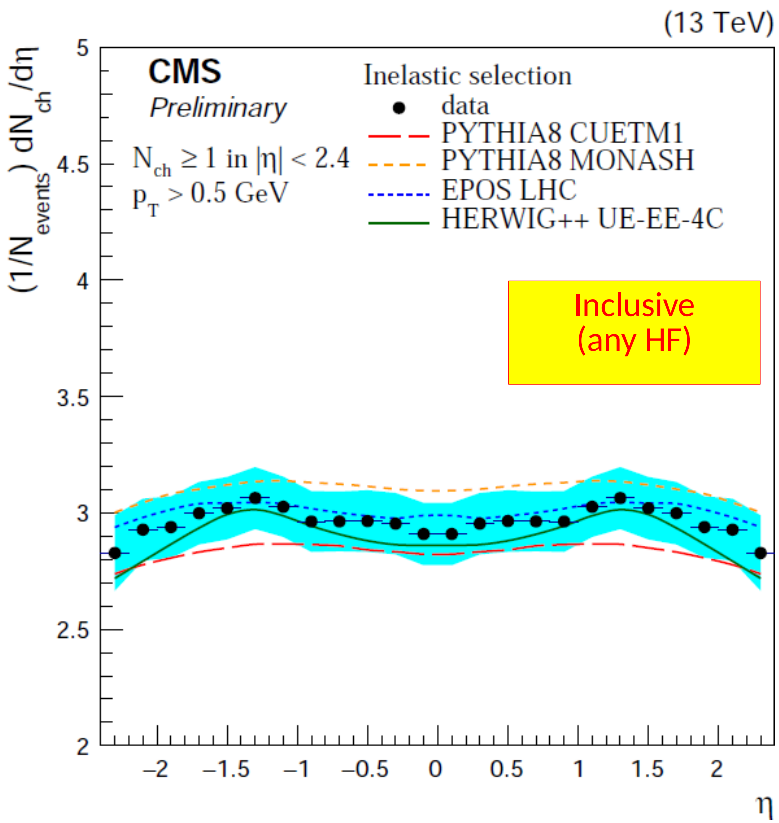


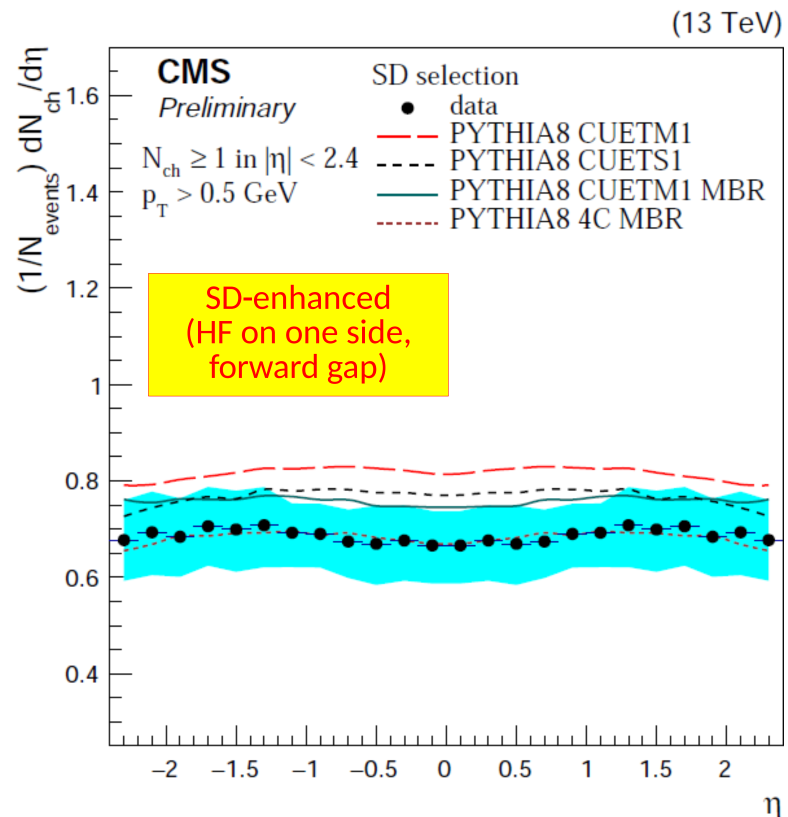
Multiplicity of SD-enhanced events significantly smaller than inclusive ones
No prediction able to describe $dN_{ch}/d\eta$ in the entire η range
Data can help constrain modelling of hadronic final state and diffractive scattering

Central $dN_{ch}/d\eta$ @13TeV

Event classification based on activity in HF ($3<|\eta|<5$)
Inclusive, inelastic, non-SD or SD dominated samples

CMS-PAS-FSQ-15-008





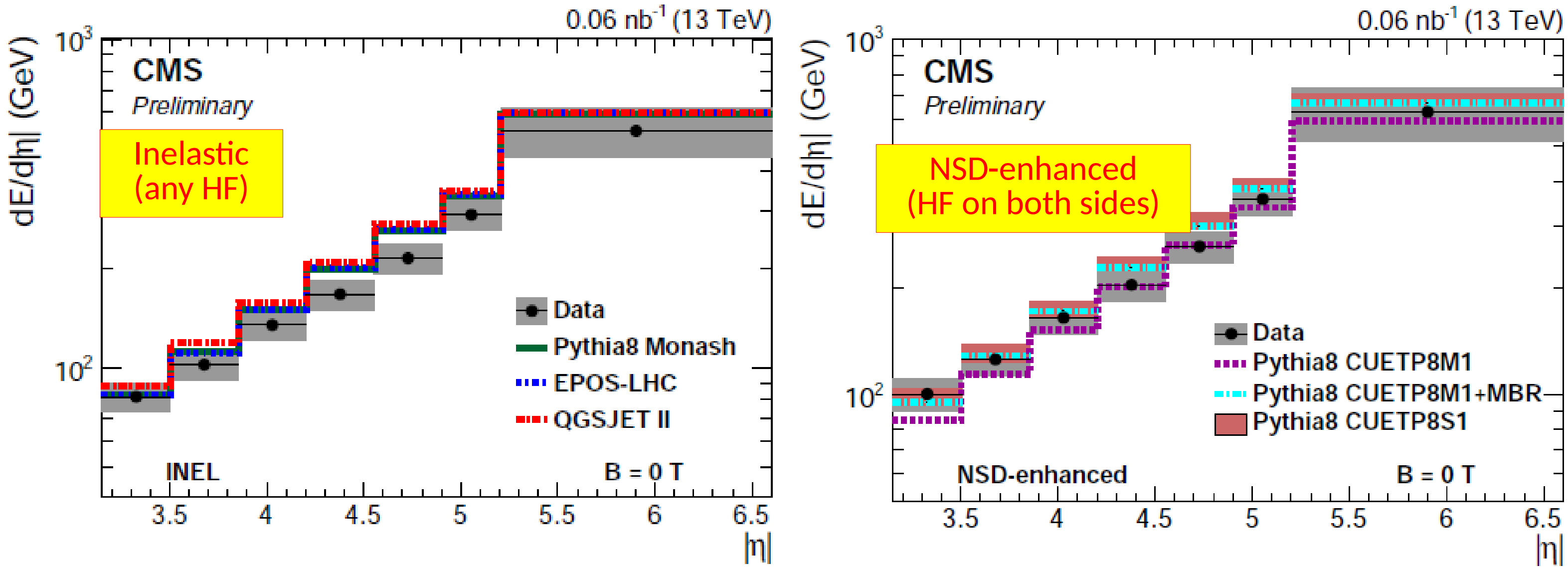
EPOS-LHC gives the best description of the inclusive/non-SD sample
PYTHIA8 4C MBR successfully describes the SD-dominated sample
But no prediction able to simultaneously describe $dN_{ch}/d\eta$ in all event classes

Data @8 TeV and 13 TeV → energy dependence of MC tunes.

Forward energy flow @13TeV

dE/dη and $dE_T/d\eta$ measured for 3.15<|η|<6.6 with HF and CASTOR calorimeters
Event classification based on HF activity

CMS-PAS-FSQ-15-006

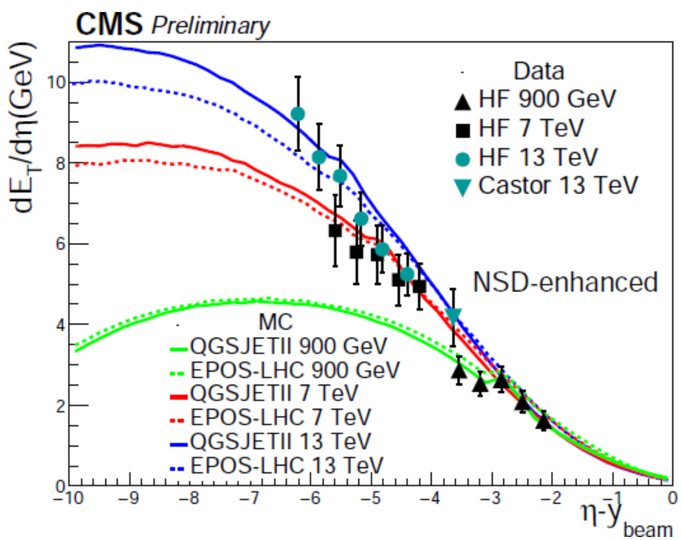


Generally models perform worse in the forward region.

The spread of predictions is large for inelastic sample becomes smaller for NSD-dominated sample.
PYTHIA8 CUETP8M1 gives the best description of the data.

Transverse energy flow as a function of shifted pseudorapidity consistent across wide range of collision energies

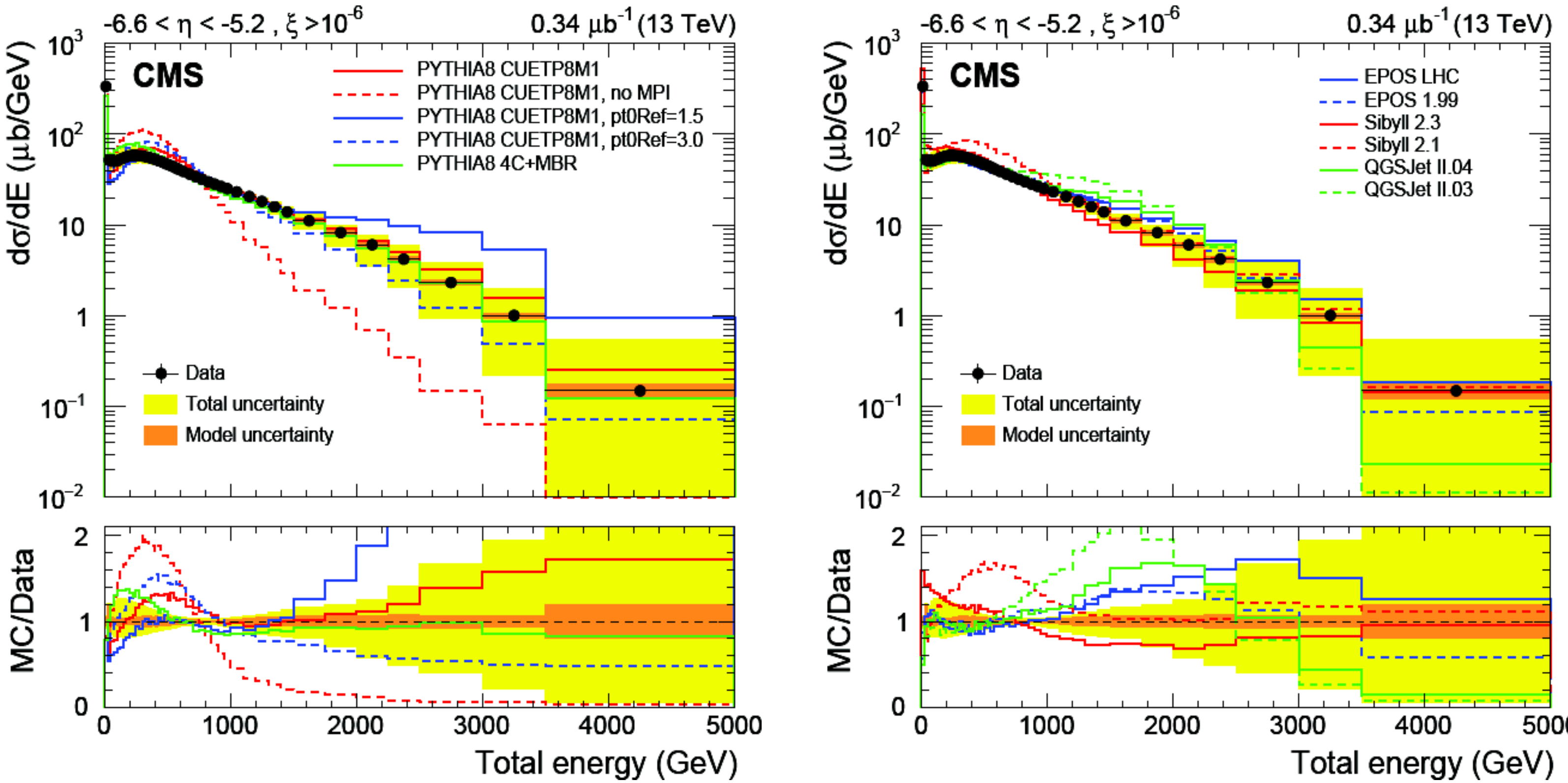
→ limited fragmentation hypothesis



Very forward energy flow @13TeV

Corrected dN/dE spectra measured for -6.6 < η < -5.2 with CASTOR calorimeter
Total energy up to 5 TeV (also its electromagnetic and hadronic components).

CMS-FSQ-16-002
arXiv: 1701.08695
submitted to JHEP



Very good discriminating power between models.

Large sensitivity to MPI and underlying event.
PYTHIA8-CUETP8M1 with MPI off predicts too soft spectra.
Data very sensitive to the tune parameter pT0Ref (MPI pT cut off) .

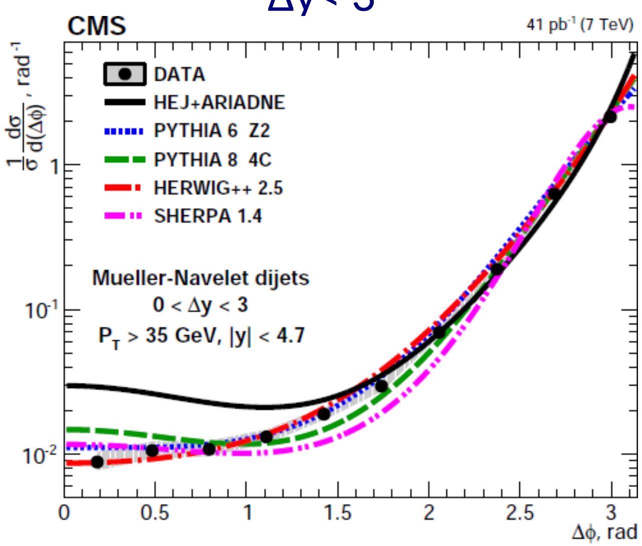
None of the cosmic ray models predicts the entire shape well.

Muller-Navelet di-jet decorrelation

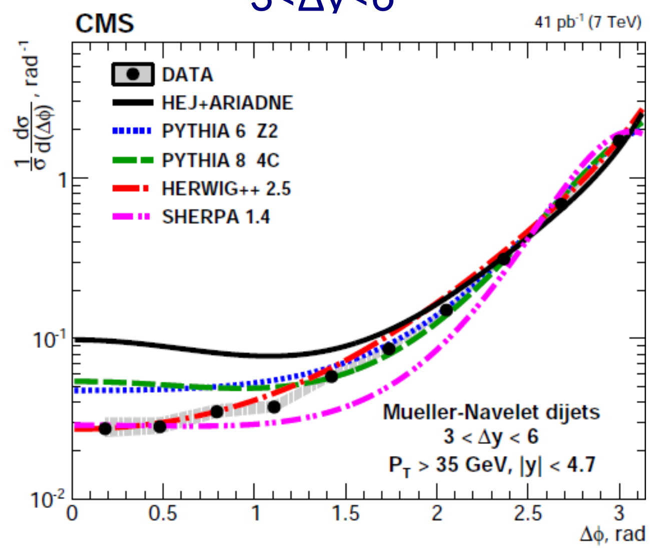
Most forward and backward jets with p_T > 35 GeV, |η| < 4.7
Δφ between jets in bins of Δy

JHEP08(2016)139

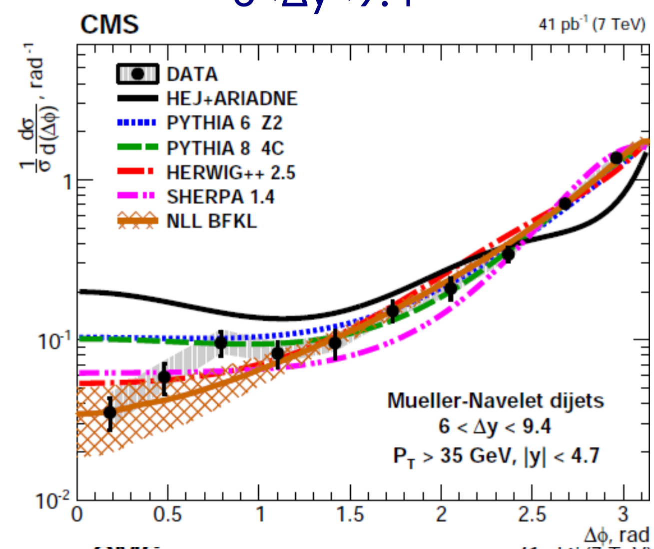
Δy< 3



3<Δy<6



6<Δy<9.4

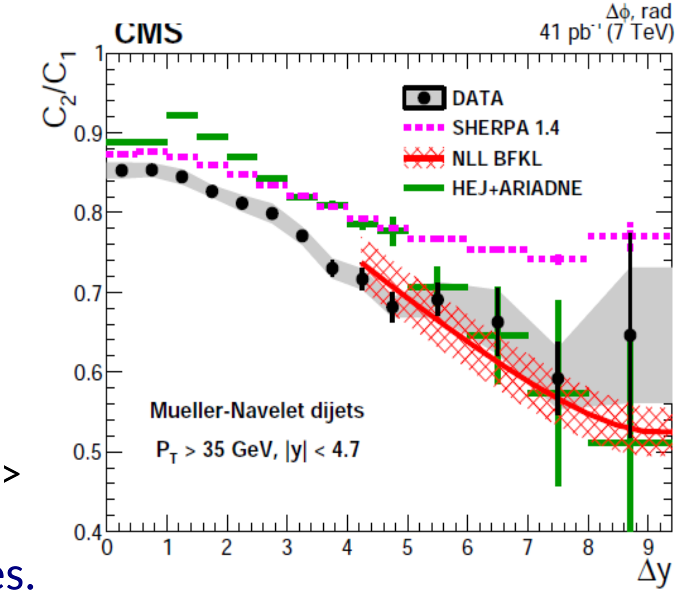


Decorrelation increases with rapidity separation.

DGLAP:
- HERWIG++ 2.5 with LL parton showers and color-coherence effects satisfactorily describes all measured observables.
- PYTHIA6-Z2, PYTHIA8-4C, SHERPA1.4 less accurate description at large Δy.

BFKL:
- HEJ: LL BFKL (ME) + ARIADNE (PS+hadr) predicts too strong decorrelations
- NLL BFKL calculation satisfactorily describes data at large Δy, also average cosine ratios →

$C_n = \langle\cos(n(\pi - \Delta\varphi))\rangle$



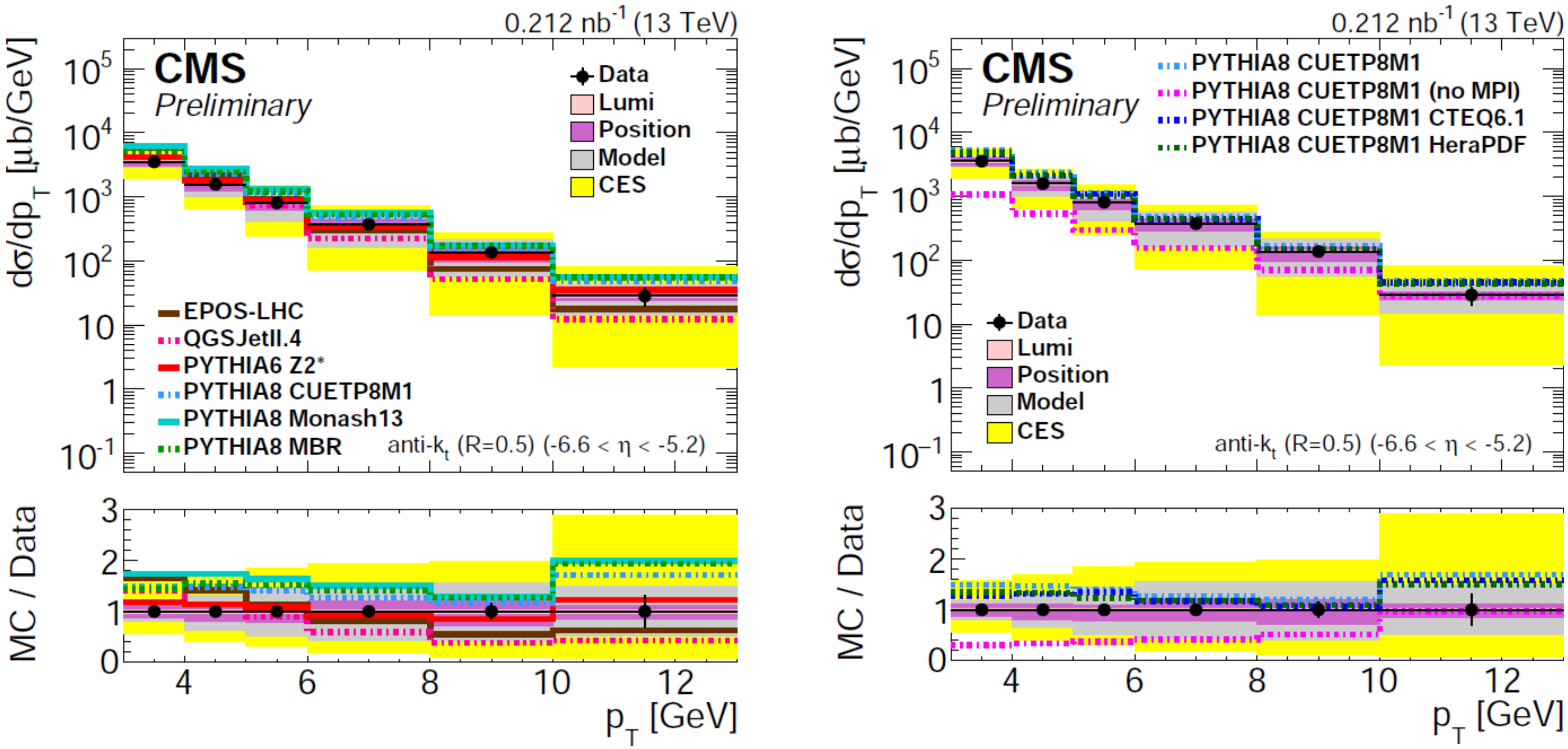
Current kinematical domain:
Transition between regions described by DGLAP and BFKL approaches.
BFKL signatures more pronounced at higher energies?

Very forward inclusive jets in pp@13TeV

Inclusive jets for -6.6 < η < -5.2 and 3< pT<13 GeV with CASTOR calorimeter

CMS-PAS-FSQ-16-003

The measurement demonstrates capability of jet reconstruction with CASTOR.
Most sensitive probes of small-x dynamics when combined with other measured objects.



All models are consistent with the data within uncertainties (energy scale dominant).
In the future, reduce the uncertainty by taking the ratio to the measurements at lower energy (7 TeV).

PYTHIA tunes tend to predict too high cross section, but reproduce the shape.
EPOS-LHC and QGSJet-II-4 tend to predict too low cross section and give too soft shape.
The data has only moderate sensitivity to PDFs used, however is very sensitive to MPI.

Very forward inclusive jets in pPb@5TeV

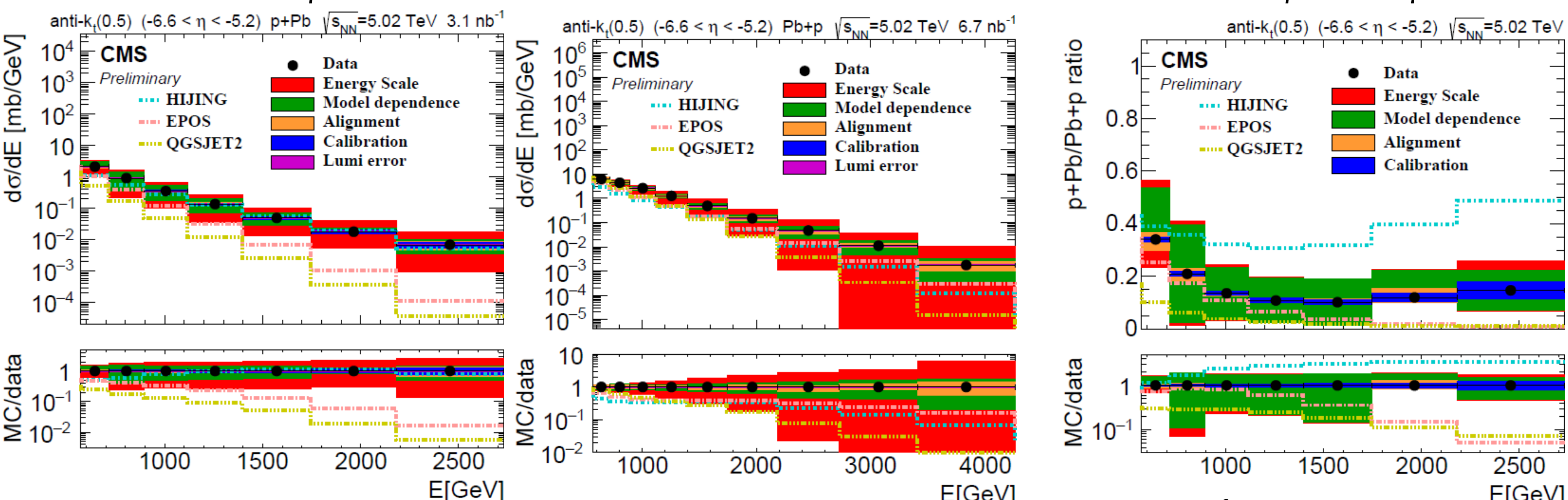
Inclusive jets for -6.6 < η < -5.2 with CASTOR calorimeter. NSD topology.

CMS-PAS-FSQ-17-001

Saturation scale in collisions with heavy ions more perturbative w.r.t. pp collisions.
Signs of non-DGLAP parton evolution, saturation (and/or nuclear) effects?

$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

CASTOR in p direction | *CASTOR in Pb direction* | *Ratio p+Pb/Pb+p*

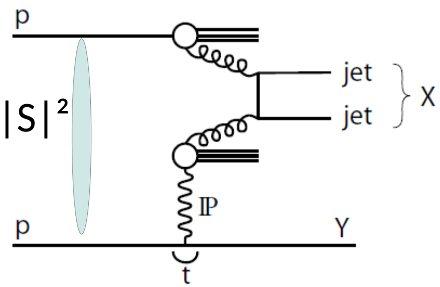


LAB frame

p+Pb: HIJING describes the data well. EPOS and QGSJet2 underestimate the cross section.
Pb+p: models underestimate low-energy tail, but agree within large uncertainty at high energy.

Ratio: Cancellation of energy scale uncertainty allows for better discrimination between the models.
Caveat: asymmetric beams lead to different boost factors and acceptance window for p+Pb and Pb+p.
Saturation expected in p+Pb, but not in Pb+p - a depletion of the ratio at low energy?

Diffractive dijets, gap-jet-jet



Factorization breaking: NLO predictions based on HERA diffractive PDFs overestimate Tevatron diffractive dijet cross sections by ~O(10). Suppression factor $|S|^2$ due to soft rescattering effects (gap survival probability).

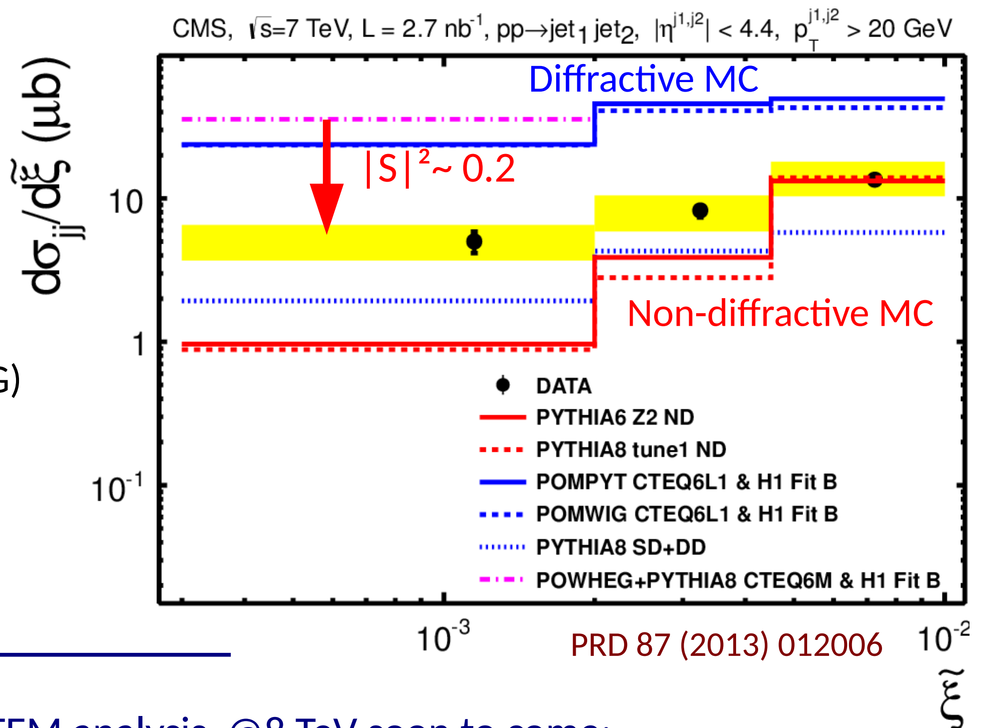
CMS analysis:
Inclusive dijet cross section in 3 bins of ξ @7 TeV

Data/MC in the lowest ξ bin (0.0003< ξ<0.002):

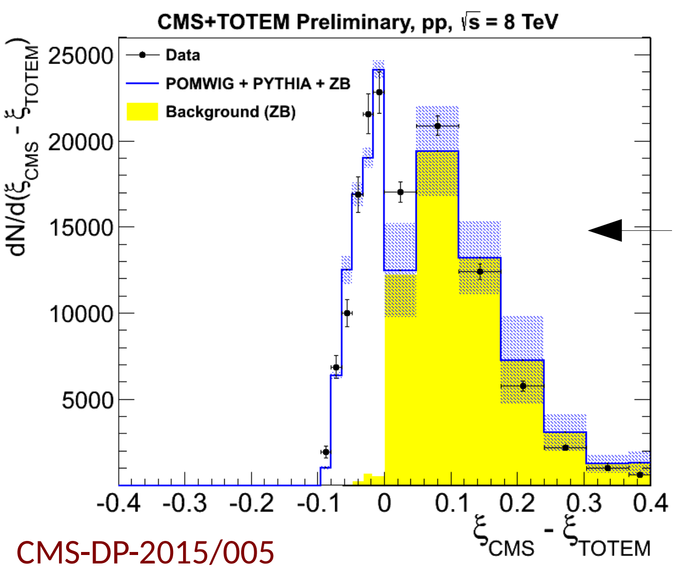
0.21 ±0.07 (LO - POMPYT POMWIG)
0.14 ±0.05 (NLO - POWHEG)

After ND and proton-dissociation correction:

0.12 ±0.05 (LO)
0.08 ±0.04 (NLO).



PRD 87 (2013) 012006



CMS-DP-2015/005

Combined CMS+TOTEM analysis @8 TeV soon to come:

Proton tagging with TOTEM Roman Pots,
No ND and p-diss background,
Demonstrated good control of the background (PU and beam related).

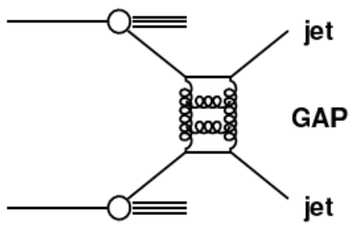
Expect:
Measurement of the t dependence of the cross section,
Improved precision in the gap survival probability estimate,
Comparison to Tevatron results.

Proton tagging greatly improves the analysis!

Diffractive dijets, BFKL with jet-gap-jet

Jets separated by a large rapidity gap, color singlet exchange (CSE)
BFKL dynamics, soft rescattering processes

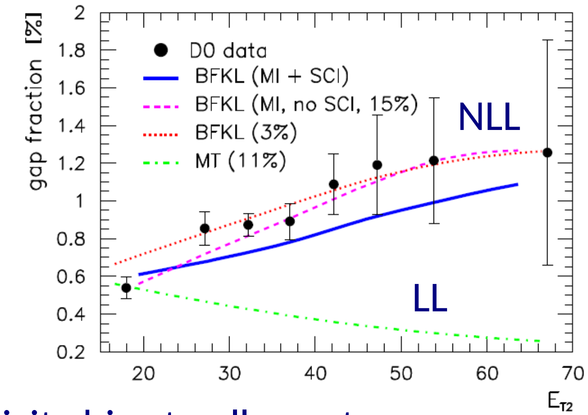
CMS-PAS-FSQ-12-001

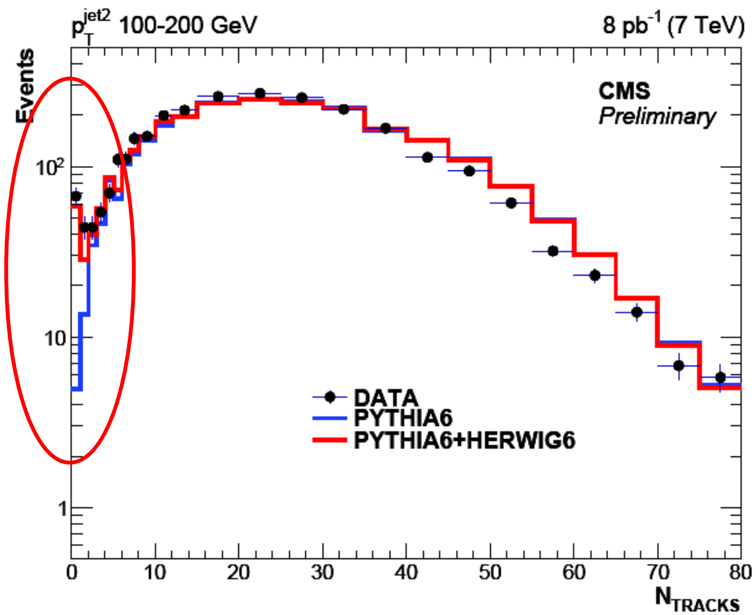


Two leading jets with p_T>40 GeV, |η|>1.5, opposite η signs
No charged tracks in the gap region |η|<1

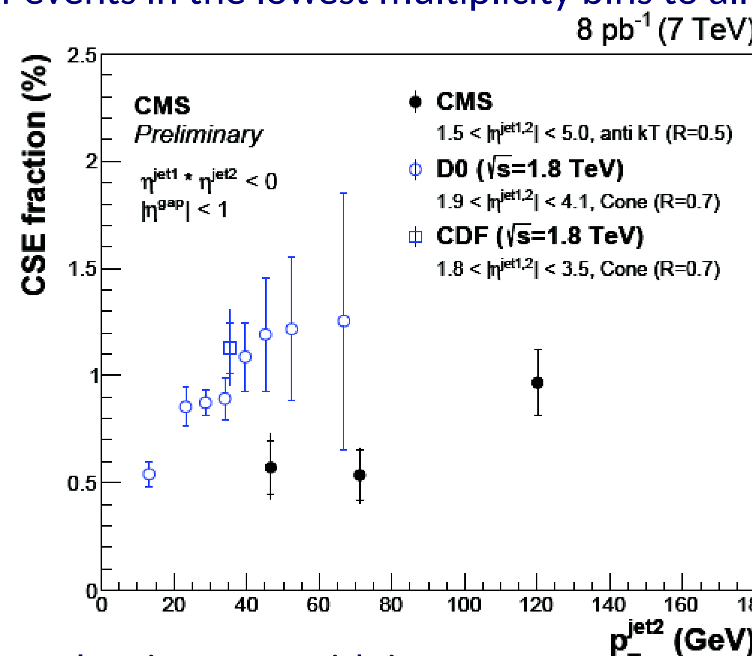
Events with gaps ~1% at Tevatron (CDF, D0)

D0 data, compared to Enberg, Ingelman, Motyka model (NLL BFKL + MPI+SCI) PLB 524 (2002) 273





Gap/CSE fraction :=
ratio of events in the lowest multiplicity bins to all events



Charged multiplicity in the gap region |η|<1:

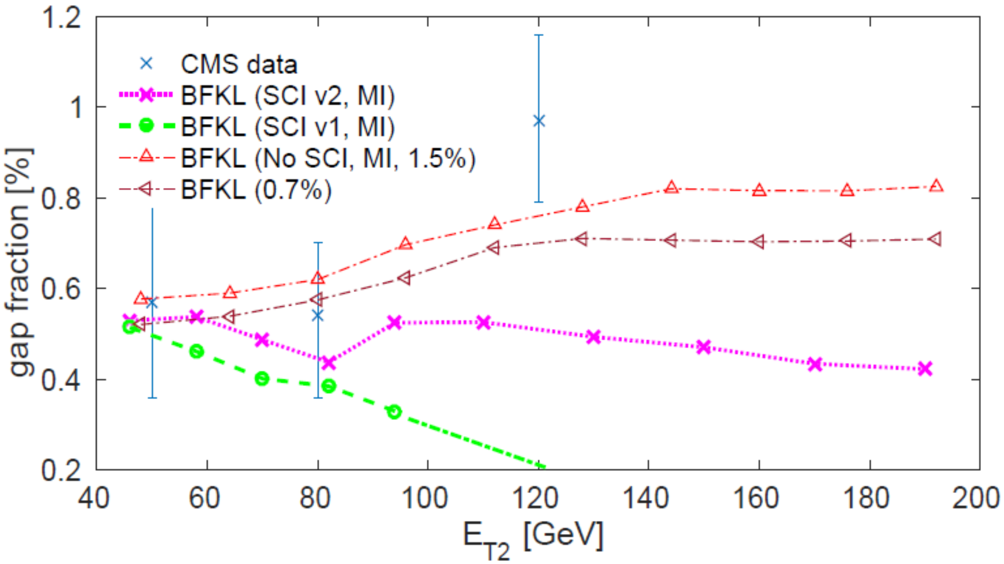
- Clear excess of gap events over PYTHIA6 prediction (LO DGLAP),
- described by HERWIG (LL-BFKL, Mueller-Tang model)

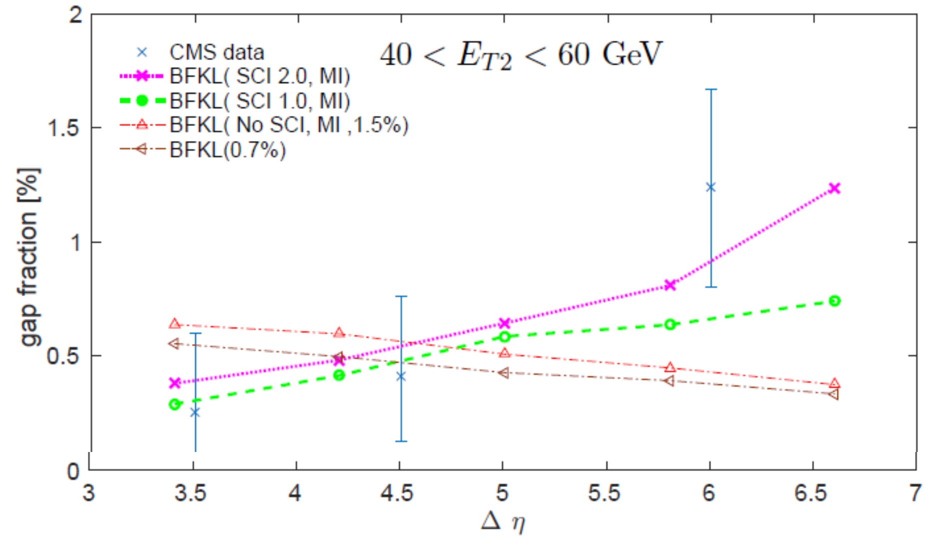
- Modest increase with jet energy
- A factor of ~2 suppression w.r.t. to 1.8 TeV data - larger contribution from rescattering processes

Diffractive dijets, BFKL with jet-gap-jet

Gap/CSE fraction := ratio of dijet events with a rapidity gap to all dijet events

CMS-PAS-FSQ-12-001





Comparison with the NLL BFKL calculations of Ekstedt, Enberg and Ingelman at 7 TeV, with four different approaches for gap survival probability (PYTHIA6 interfaced);

Brown: a scale factor,
Red: MPI (perturbative gluons) + a scale factor (soft gluons)
Green: MPI + soft color interactions (SCI) between partons (good @Tevatron, but kills too many gaps@LHC)
Magenta: MPI+ SCI between group of partons.

arXiv:1703.10919

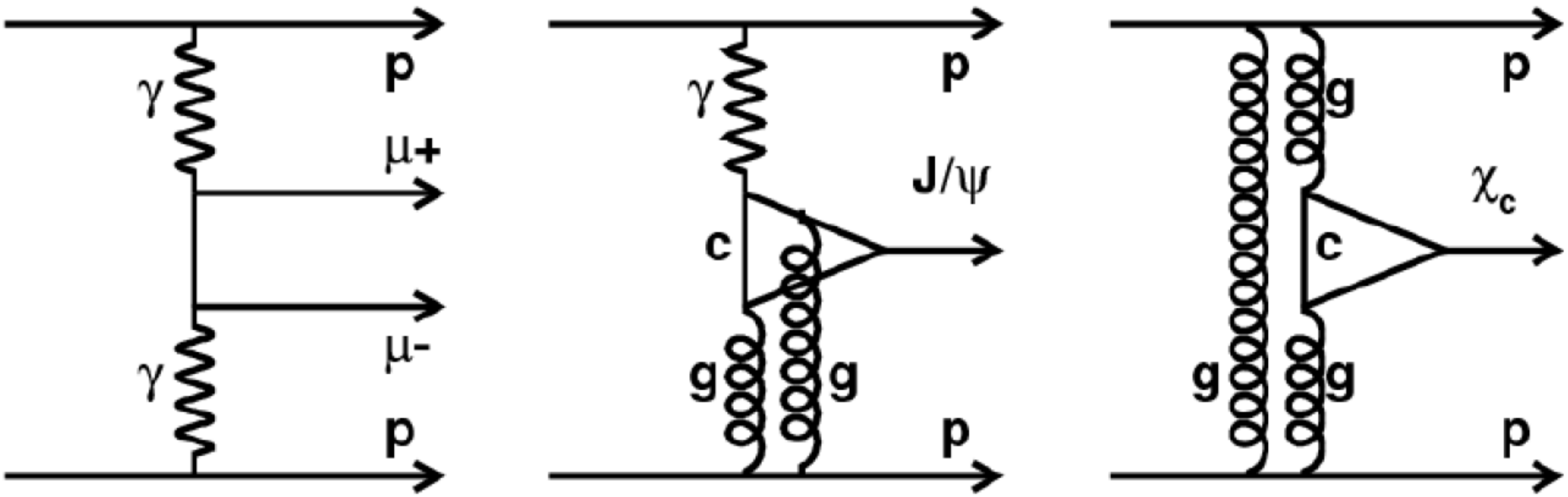
NLL BFKL predictions are able to reproduce the data.
Further improvements in gap survival probability modeling needed.

Similar ongoing CMS-TOTEM analysis @13 TeV, w/o and with proton tag.

Jet-gap-jet events may be still the only experimantal indication of BFKL dynamics at the LHC. They have also been measured at HERA. Perhaps at EIC as well?

PLB 369 (1996) 55, EPJC 24 (2002) 517

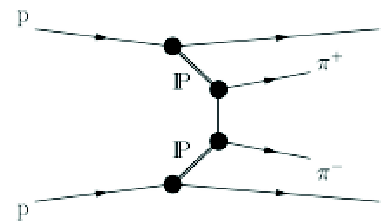
Exclusive Processes



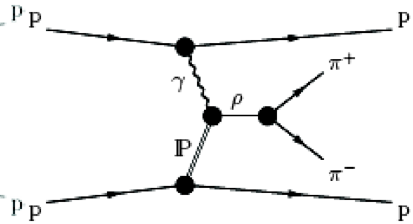
QED | Photo production | Double pomeron exchange

Central Exclusive $\pi^+\pi^-$ production @7 TeV

Spectroscopy of low-mass resonances ($J^{PC} = 0^{++}, 2^{++}, \ldots$)
Gluon-dominated DPE → search for glueball candidates.



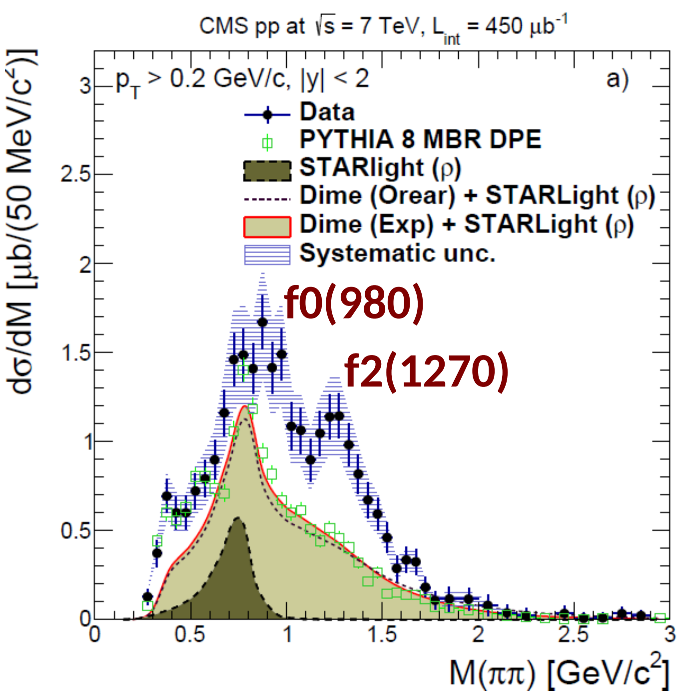
Double-Pomeron Exchange (DPE) - dominant

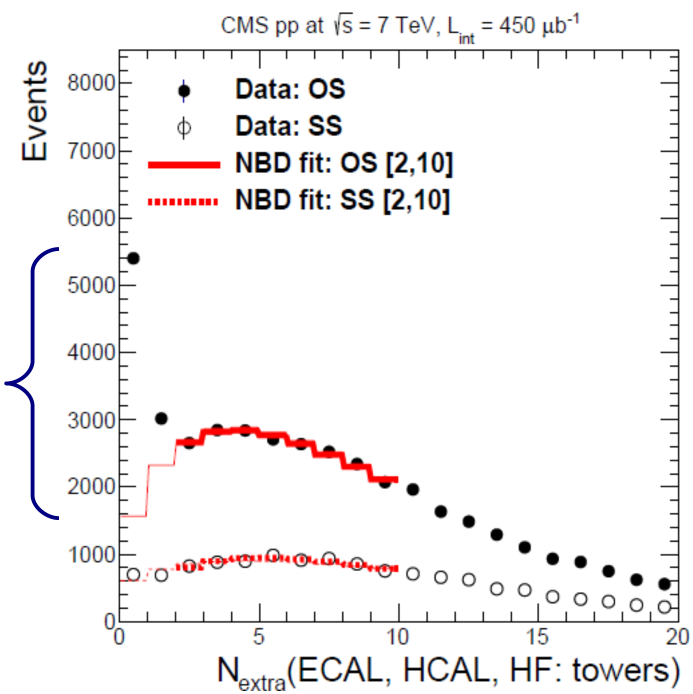


Exclusive ρ photoproduction

Two opposite-sign (OS) pions with $p_T > 0.2$ GeV and $|y| < 2$.
Large background (~50%), estimated from calorimeter multiplicities.

$$\sigma_{\pi^+\pi^-} = 26.5 \pm 0.3\,(\text{stat}) \pm 5.0\,(\text{syst}) \pm 1.1\,(\text{lumi})\ \mu b$$





CMS-FSQ-12-004, submitted to arXiv and PRD

- Excess of data over predictions of STARLIGHT (exclusive ρ) and DIME (non-resonance di-pions) → resonance structure as seen by AFS, CDF, STAR.

Ongoing: - similar CMS analysis @5 TeV and @13 TeV → energy dependence,
- CMS+TOTEM analysis @ 13 TeV with protons tagged in TOTEM Roman Pots → next slide

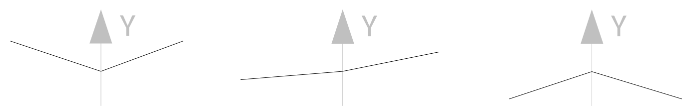
CEP @13 TeV with CMS-TOTEM

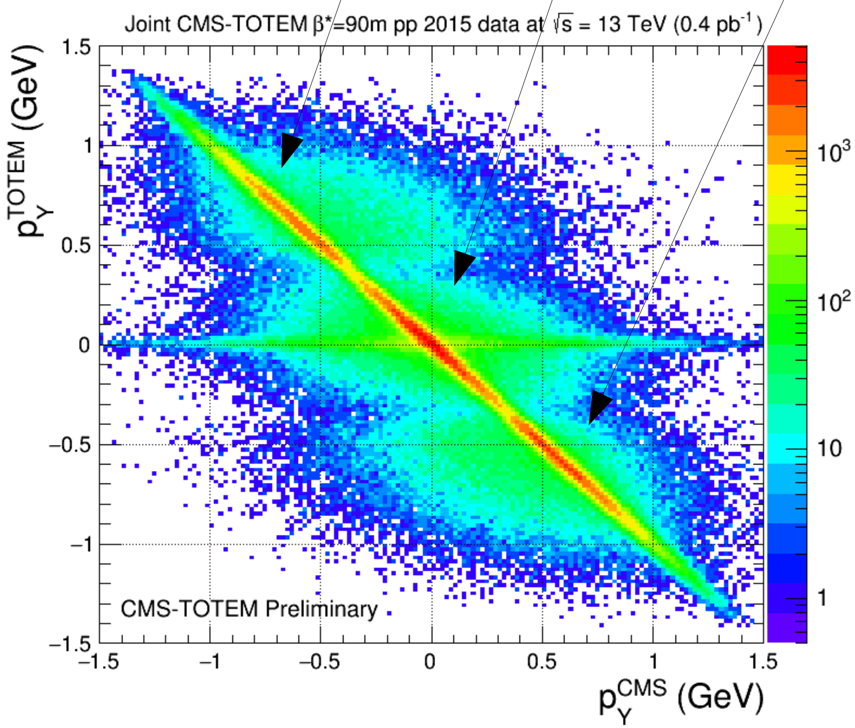
CMS-DP-2017/008

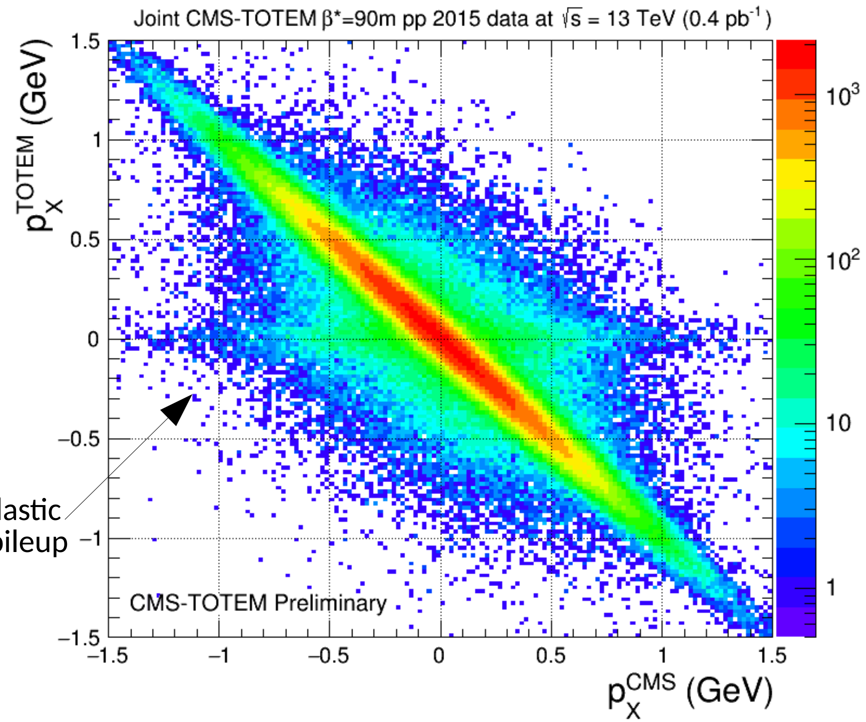
- About 0.4/pb of low-pileup (μ = 0.06-0.15) data.
- Tracks in CMS + diffractive protons in TOTEM Roman Pots (acc. for $t_{1,2}$ > 0.01 GeV^2)

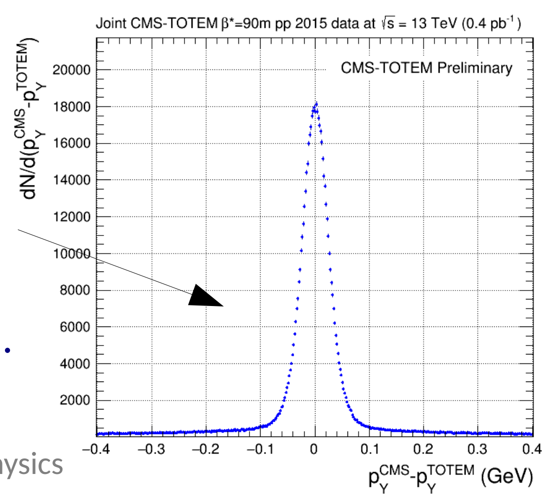
Exclusivity condition: $p_{x,y}^{CMS} = p_{x,y}^{TOTEM}$

Different proton configurations:









Very pure sample of exclusive events selected.

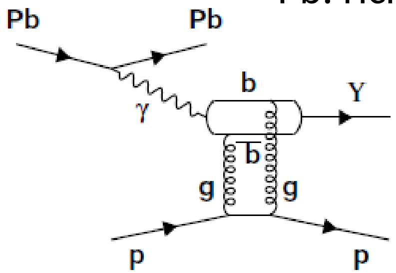
Ongoing analysis:

- Study f0/f2 resonances in the Mx<4 GeV mass range.
- Determine scalar (0^{++}) and tensor (2^{++}) glueball candidates and their decays: $\pi\pi$, KK, $\rho\rho$, ...

Photoproduction of Upsilon in p-Pb

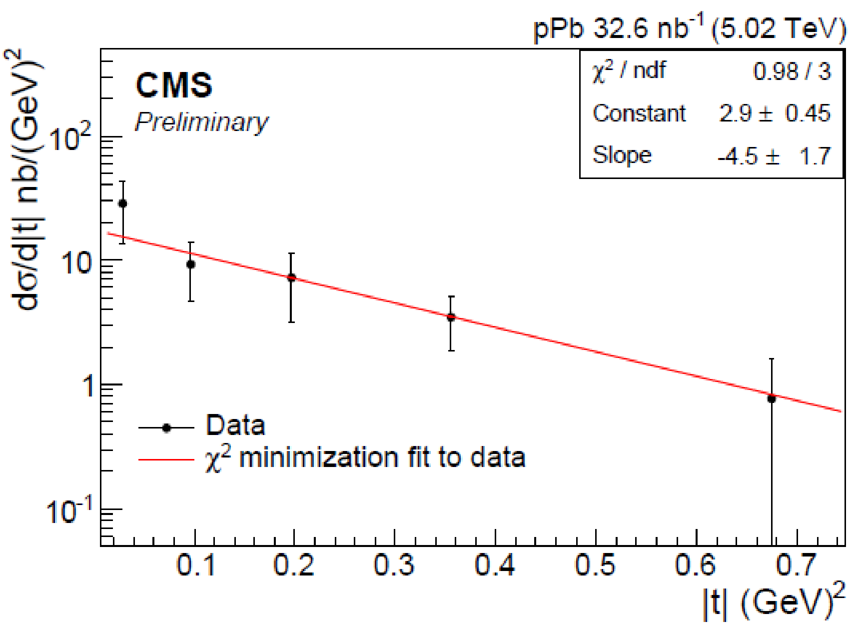
Pb: rich source of photons (flux~Z^2), negligible $X_c \to \gamma Y$ background (DPE)

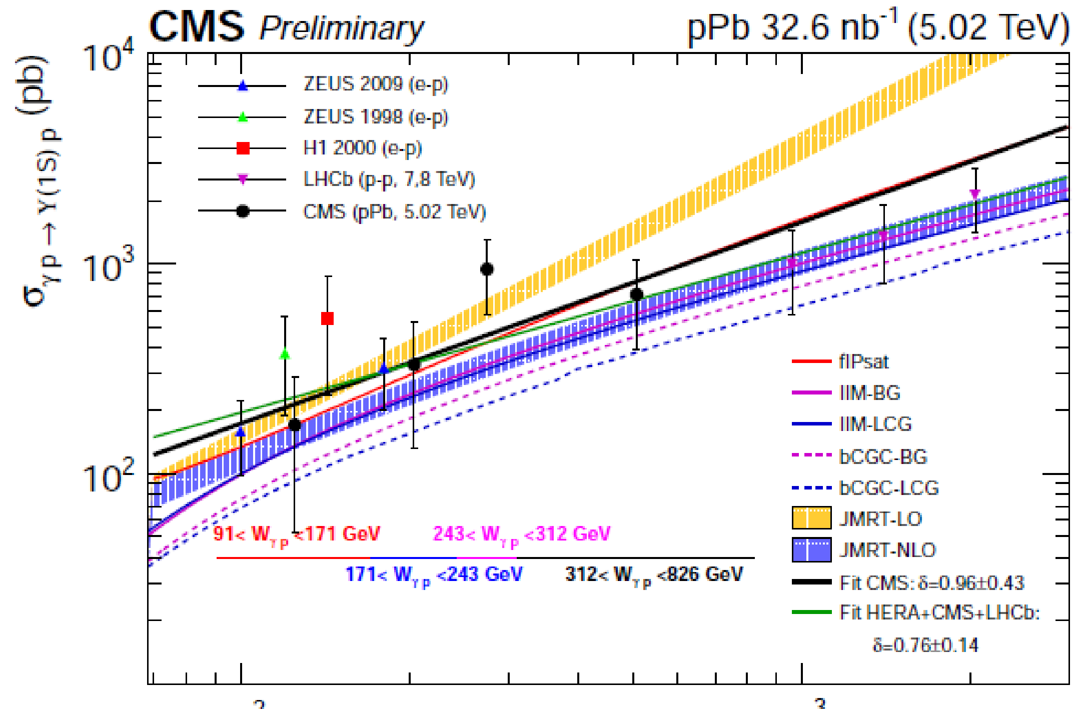
CMS-PAS-FSQ-13-009



Two opposite-sign muons with $p_T > 3.3$ GeV and $|\eta| < 2.2$

Di-muon system with $0.1 < p_T < 1$ GeV and $|\eta| < 2.2$.





$|\eta^\mu| < 2.2$ $\quad$ $2 < \eta^\mu < 4.5$

CMS data fill the gap in the Wγp range between the HERA and LHCb data.

At EIC, forward μ/e detectors could help to reach higher W.

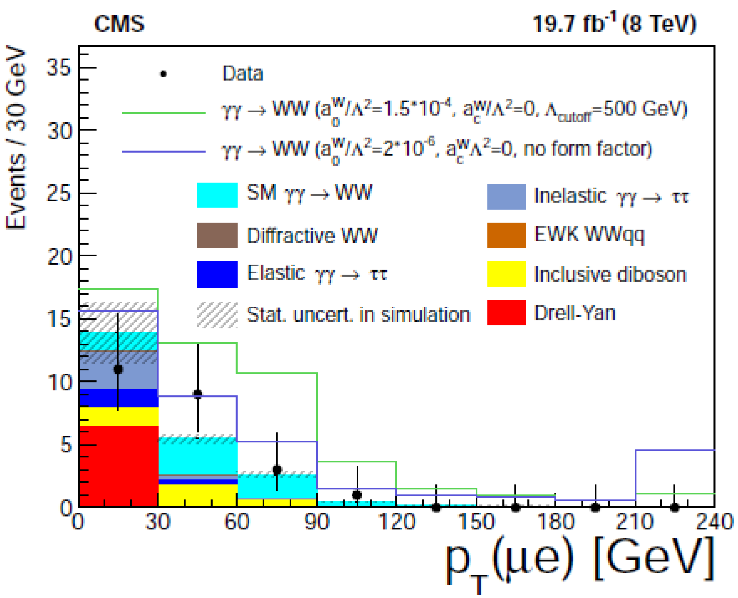
JHEP 09 (2015) 084

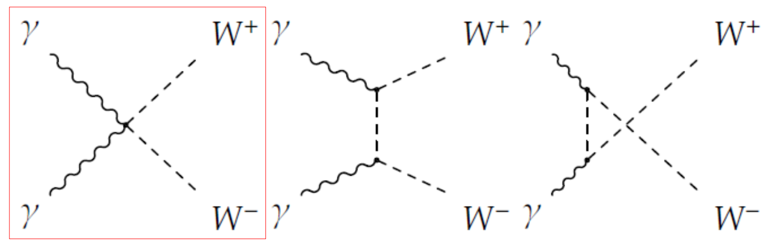
- Cross section sensitive to the square of the gluon density in the proton, and saturation
- Data compared to various theory predictions. LO JMRT disfavoured.

Exclusive γγ →WW production, limits on aQGC

Analysis using L=5 fb^{-1} @7 TeV and L=20 fb^{-1} @8 TeV

JHEP 07 (2013) 116 JHEP 08 (2016) 119





Effective Lagrangian with two additional dimension 6 terms:

$$\mathcal{L}_6^0 = \frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

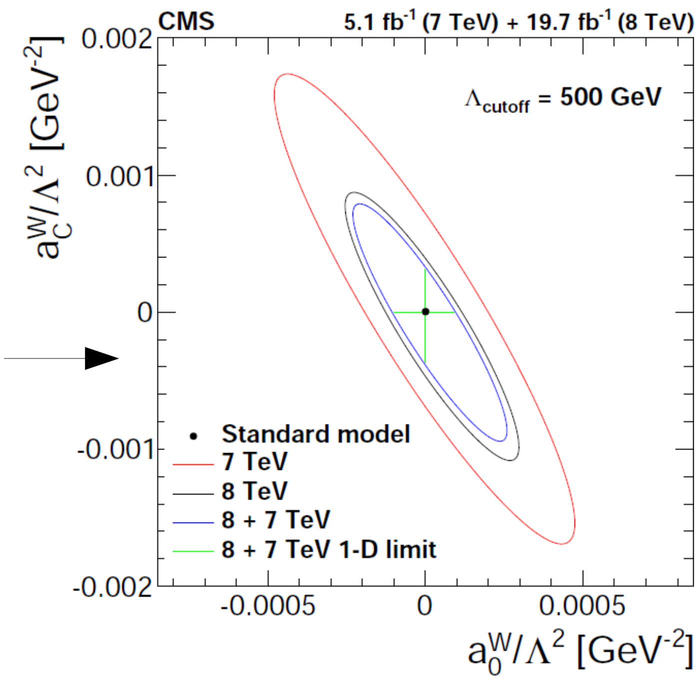
Parameters a_0^W and a_c^W, Λ – scale for new physics

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 10.8^{+5.1}_{-4.1}\ \text{fb}$$

8 TeV data: In eμ channel for pT(eμ)>30 GeV:
13 events observed (SM: 9.2 events)

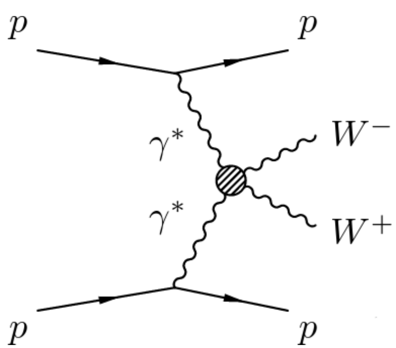
Limits on aQGC @8 TeV are 30% better than @7 TeV.
(limits at @7 TeV are 20 times better than Tevatron and ~O(100) than LEP)

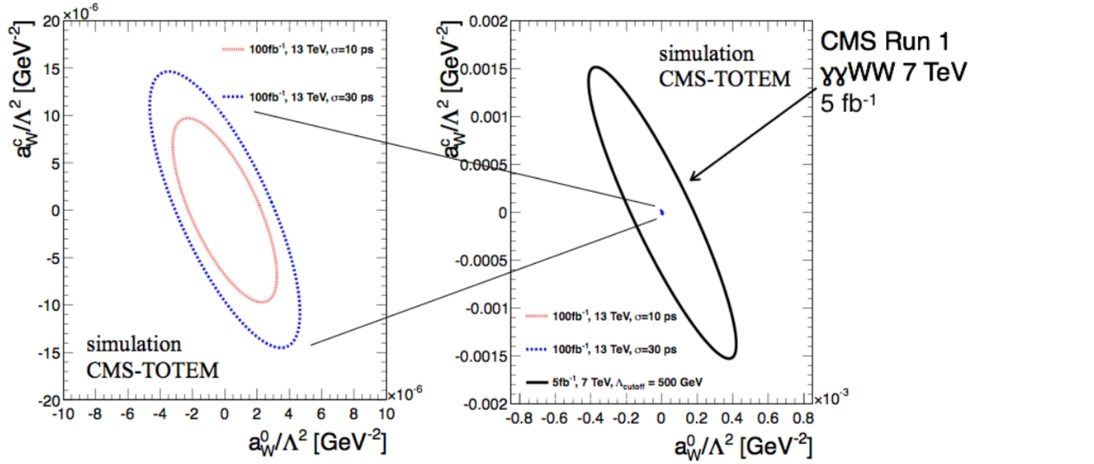
~100x better limits if proton tagging with CT-PPS.
No proton dissociation background!



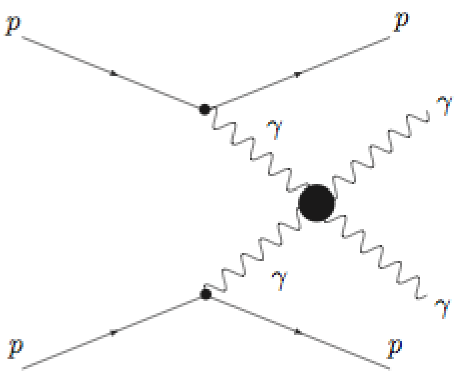
Exclusive γγ →VV production with CT-PPS

With 100/fb collected luminosity (end of 2018?) - two orders of magnitude better limits expected
If only SM background WW events observed.



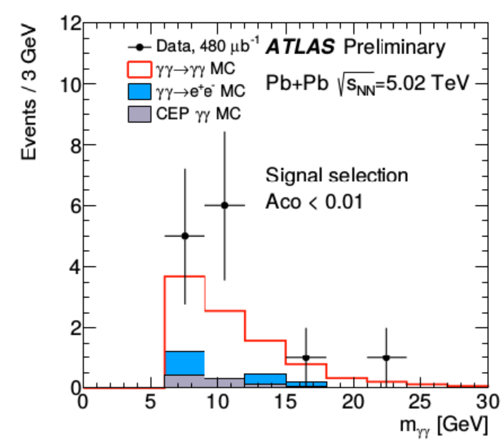


Other ongoing analysis with CT-PPS using 2016 pp data: light by light scattering.



$$\gamma\gamma \to \gamma\gamma$$

Fundamental QED/QCD process unexplored so far.
Loop diagram – sensitive to BSM physics.



ATLAS recently measured this process in PbPb collisions.
(softer photon flux, lower masses). CMS is finishing analysis as well.

Could be an interesting study with high-lumi EIC?

ATLAS-CONF-2016-111

Summary

Many CMS and CMS-TOTEM results on diffraction and forward/low-x QCD physics:

- Diffractive SD and DD cross sections rise slowly with energy
- Particle/energy flow spectra described poorly by models in the forward region - input to MC tunes.
- Forward-backward dijets @7 TeV in transition between regions described by DGLAP and BFKL approaches. Need to expand to higher energy or larger rapidity separation between the jets, e.g. using CASTOR, to access BFKL dynamics.
- Diffractive jet-gap-jet events – a clear experimental indication of BFKL evolution, but compromised by soft rescattering processes.
- Good CMS-TOTEM data sample to study exclusive production of low-mass resonances + glueballs.
- Exclusive Upsilon production in the region sensitive to a possible gluon saturation.
- CT-PPS project - a new window to study EW and BSM physics through high mass gauge boson pair production (WW, ZZ, Zγ, γγ).

Thoughts for EIC:

- Proton tagging rather than diffractive selection based on rapidity gap.
- Heavy VM production: μ/e detection in the forward region could expand accessible W range (low x).
- Can BFKL be studied using jet-gap-jet events at EIC?
- Can γγ -> γγ production (light-by-light scattering) be studied at EIC?
- ...

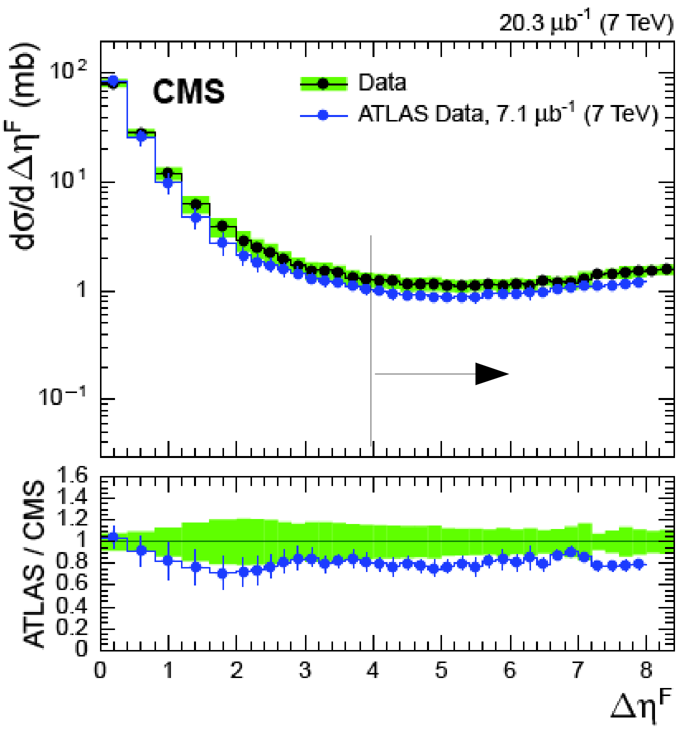
Thank you for your attention!

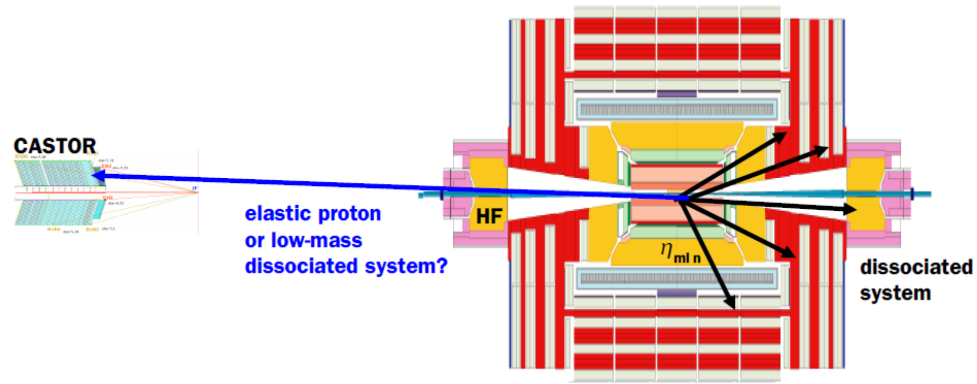
Backup slides

Diffractive results from CMS

PRD 92 (2015) 012003

SD/DD separation with CASTOR ($-6.6<\eta<-5.2$)





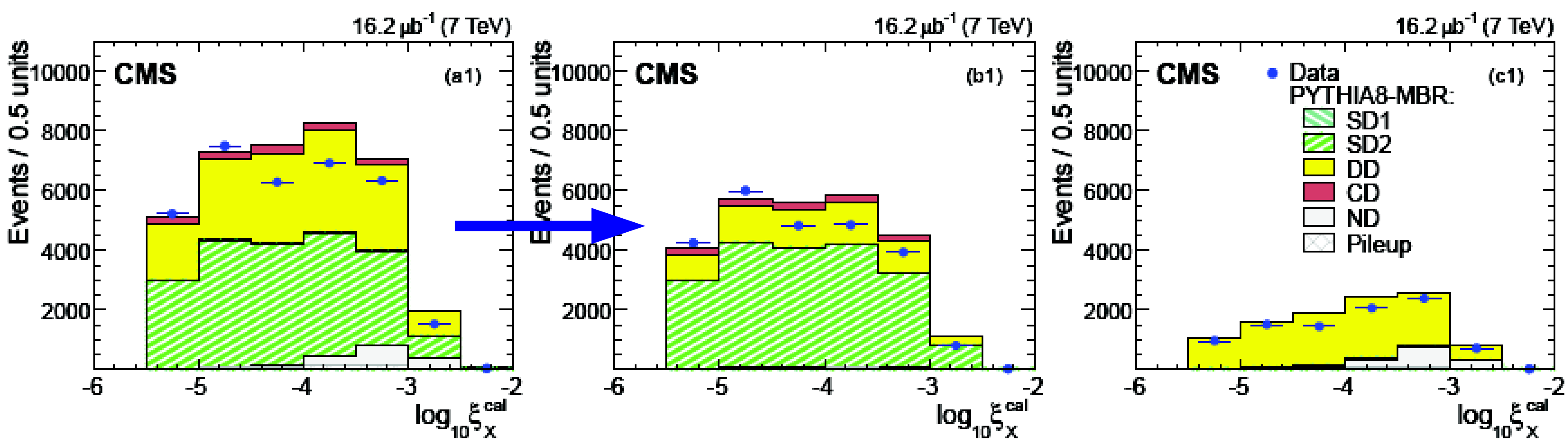
$\Delta\eta^F > 4 \; \approx \; \eta_{min} > -1$

All with $\eta_{min} > -1$

no CASTOR-tag (SD dominated)

CASTOR-tag (DD dominated)

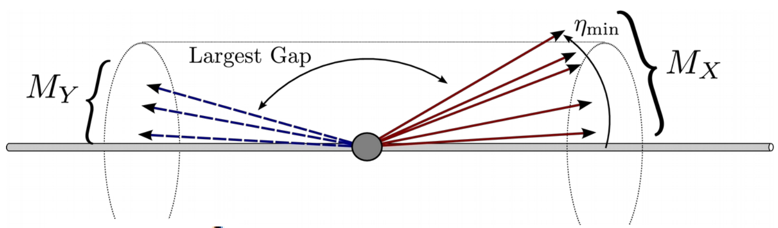
$$\xi_X = \frac{M_X^2}{s}$$



Total inelastic cross section @ 13 TeV

Require an activity in HF or CASTOR calorimeters

CMS-PAS-FSQ-15-005



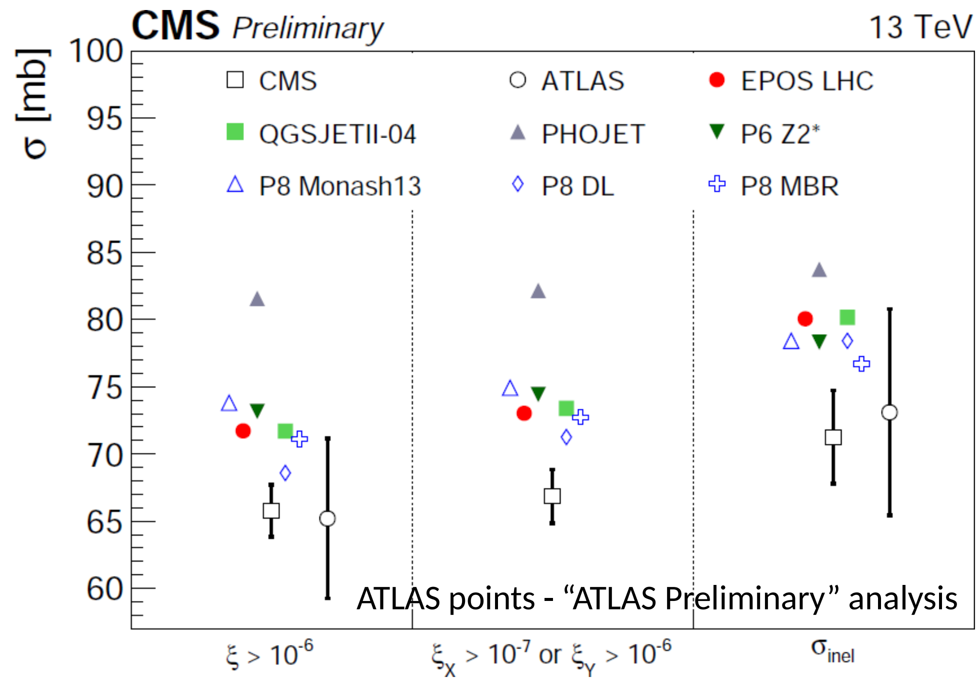
$$\xi_Y = \frac{M_Y^2}{s} \qquad \xi_X = \frac{M_X^2}{s}$$

HF calorimeter
(3.2<|η|<5.2)

CASTOR calorimeter
(-6.6<η<-5.2)

$\xi_Y > 10^{-6}$

$\xi_X > 10^{-7}$



$$\sigma(\xi > 10^{-6}) = 65.77 \pm 0.03\ (\text{stat.}) \pm 0.76\ (\text{sys.}) \pm 1.78\ (\text{lum.})\ \text{mb}$$

ATLAS: 68.1 ±1.4 mb

$$\sigma(\xi_X > 10^{-7}\ \text{or}\ \xi_Y > 10^{-6}) = 66.85 \pm 0.06\ (\text{stat.}) \pm 0.44\ (\text{sys.}) \pm 1.96\ (\text{lum.})\ \text{mb}$$

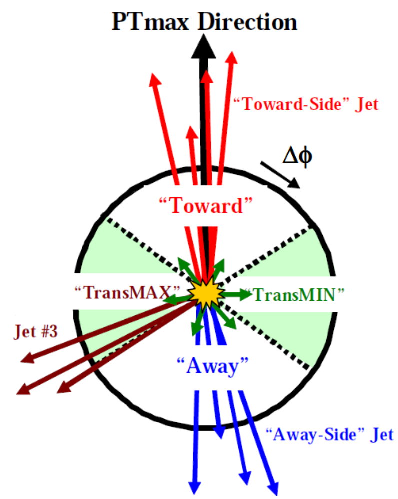
Model	Extrapolation factor
EPOS LHC	1.096
QGSJETII	1.092
PHOJET	1.019
PYTHIA6 Z2*	1.052
PYTHIA8 Monash	1.047
PYTHIA8 DL	1.101
PYTHIA8 MBR	1.054
Average	1.066

$$\sigma_{\text{inel}} = 71.26 \pm 0.06\ (\text{stat.}) \pm 0.47\ (\text{sys.}) \pm 2.09\ (\text{lum.}) \pm 2.72\ (\text{ext.})\ \text{mb}$$

ATLAS:78.1 ± 2.9 mb

PRL 117 (2016) 182002

Underlying Event Activity @13TeV

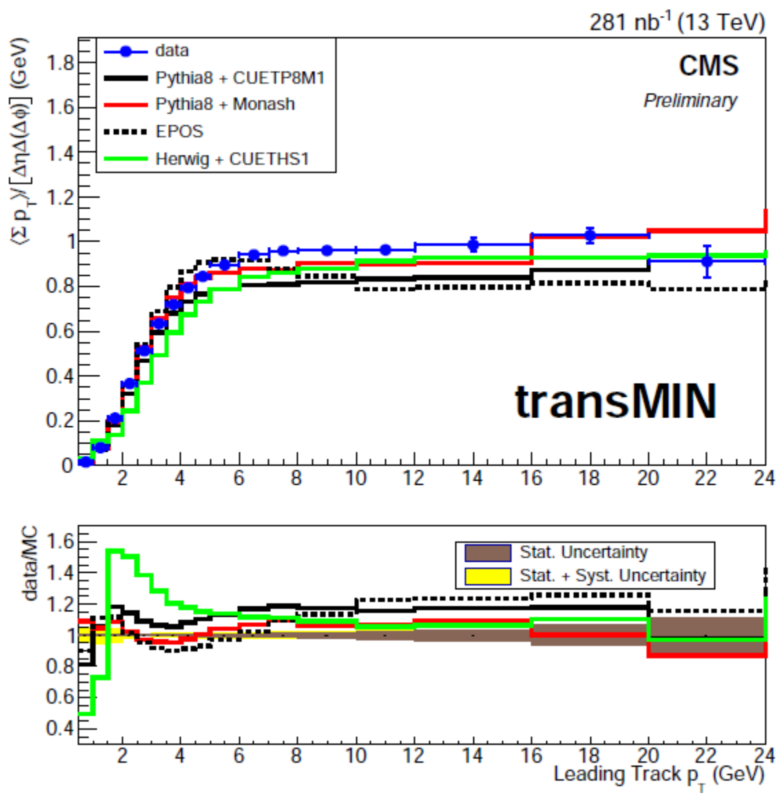


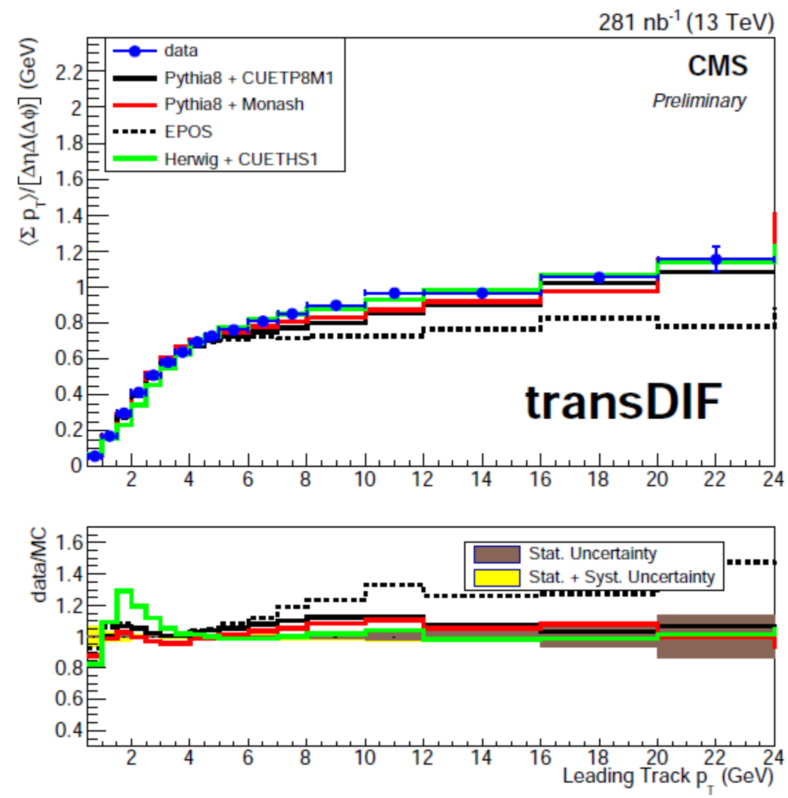
Average particle and energy density for charged particles with p_T > 0.5 GeV, $|\eta| < 2$ measured in the transverse region w.r.t. the leading charged particle/jet.

CMS-PAS-FSQ-15-007

TransMAX – region with higher activity → sensitive to MPI and ISR of hard process
TransMIN - region with lower activity → sensitive to MPI
TransDIFF - TransMAX – TransMIN → sensitive to ISR of hard process

Models tuned to lower energy data (up to 7 TeV).

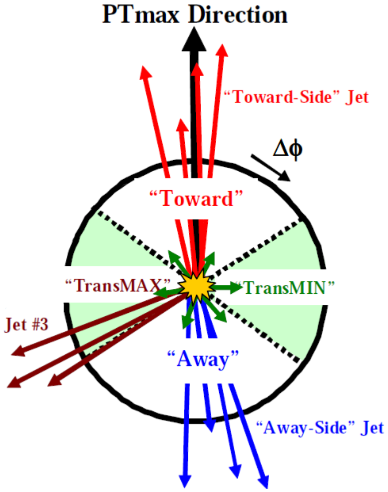




Saturation of MPI at ~5 GeV related to impact parameter

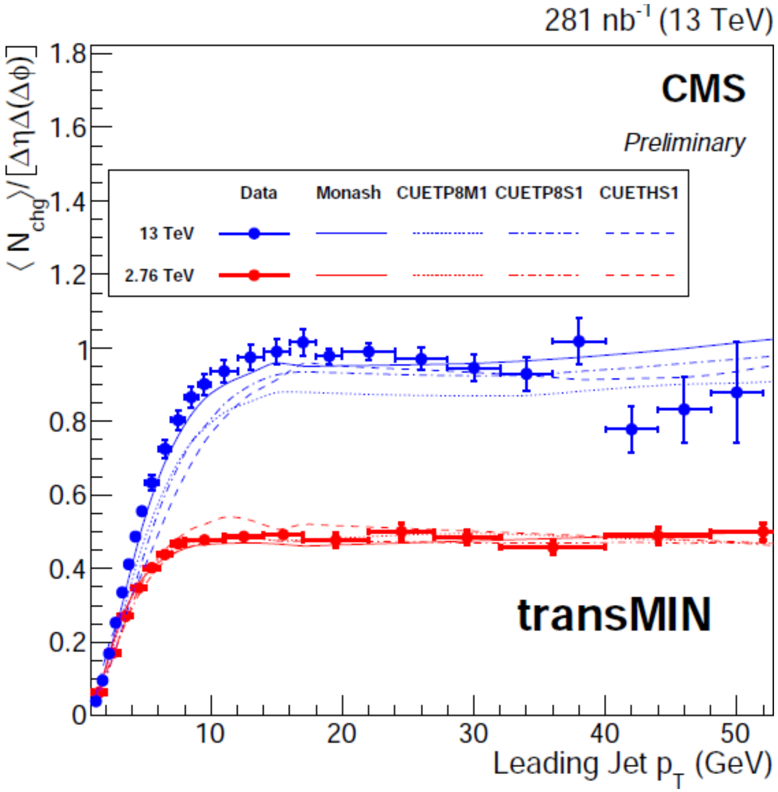
Constant rise after 5 GeV related to increasing ISR activity

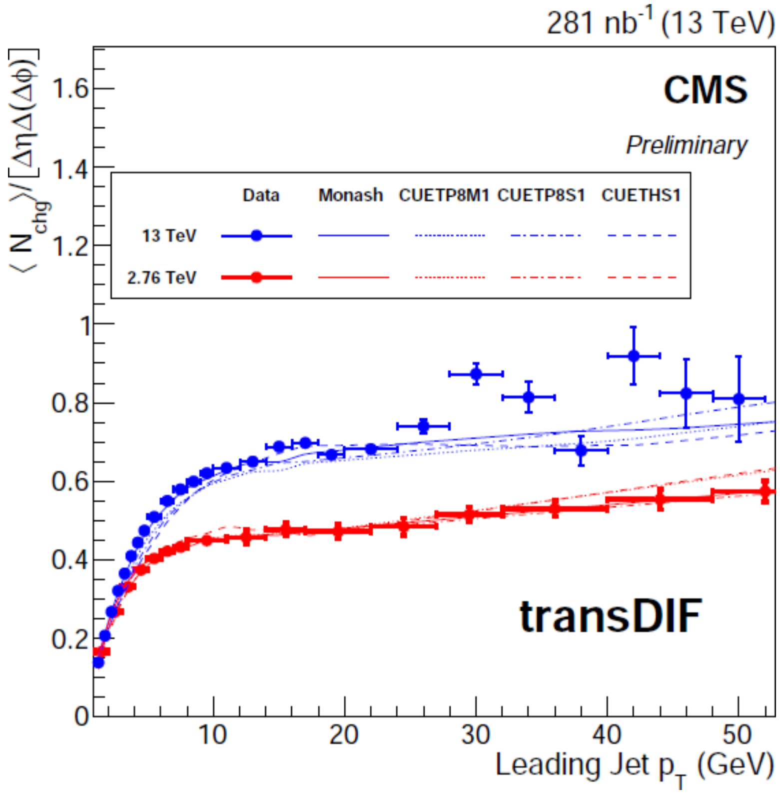
Underlying Event Activity @13TeV



Energy dependence of UE from the comparsion to 2.76 TeV results.

CMS-PAS-FSQ-15-007





MPI activity grows faster with center-of-mass energy than ISR activity.

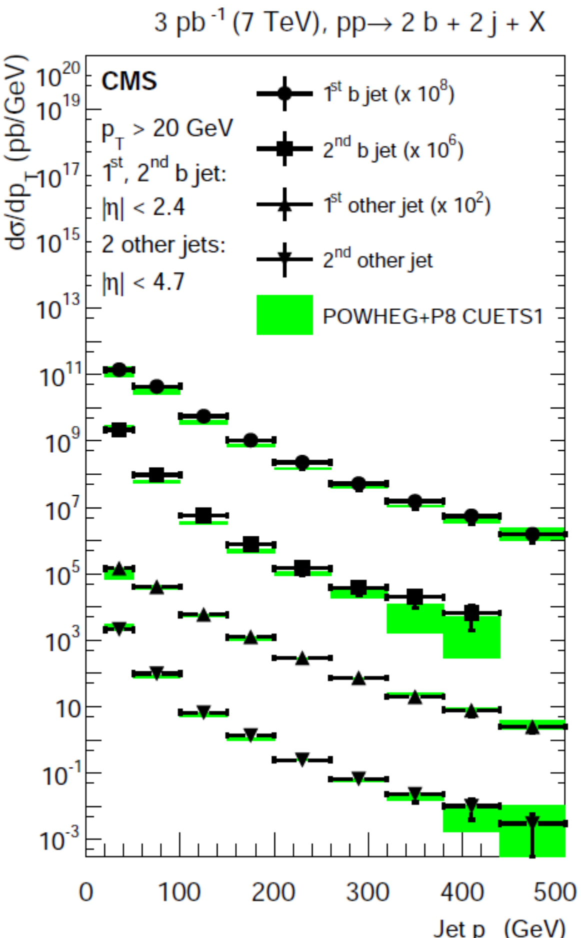
Reasonably good description of ISR by models
13 TeV data can be used to further improve modelling of energy dependence of MPI activity - currently ongoing at CMS, see e.g. Paolo Gunnellini's talk at MPI@LHC 2016.

4-jet production: 2b+2j

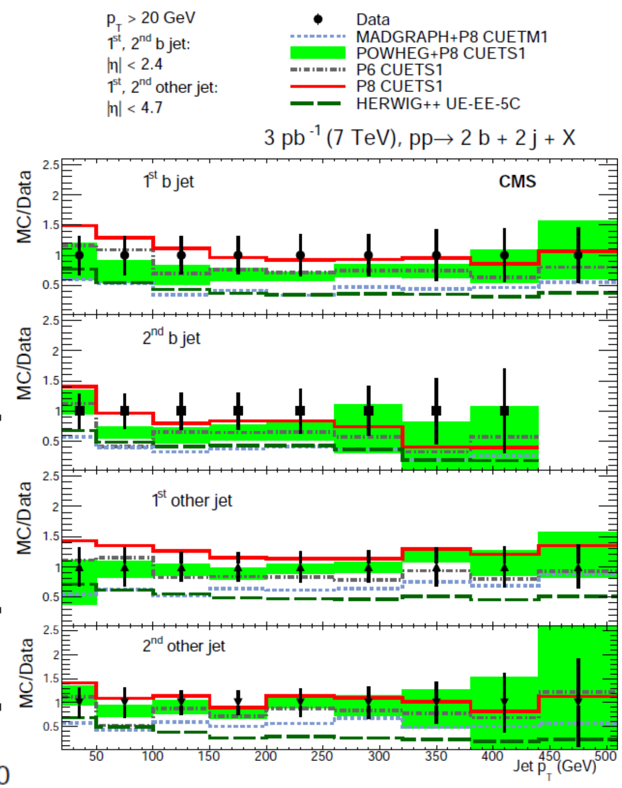
Two b-quark jets with p_T > 20 GeV and |η| < 2.4
Additional two jets with p_T > 20 GeV and |η| < 4.7

CMS-FSQ-13-010, submitted to PRD

arXiv 1609.03489



$$\sigma(pp \to 2b + 2j + X) = 69 \pm 3\,(\mathrm{stat}) \pm 24\,(\mathrm{syst})\,\mathrm{nb}$$



- All predictions describe the data within uncertainties.
- HERWIG++ and MADGRAPH tend to underestimate the data
- POMHEG reproduces the cross sections best

- PYTHIA and HERWIG++ - LO generators with extra jets from PS and MPI
- POMHEG – matrix elements with hard emission @NLO
- MADGRAPH – matrix element with N-jets

CUETP8S1 – CMS UE and DPS tune of PYTHIA8 EPJC 76 (2016) 155
includes CMS 4-jet measurement PRD 89 (2014) 092010

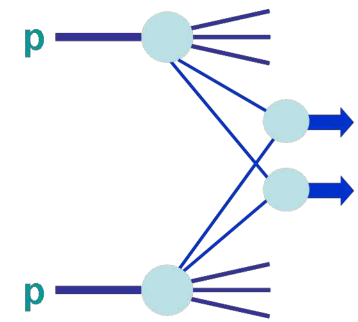
4-jet production: 2b+2j, DPS

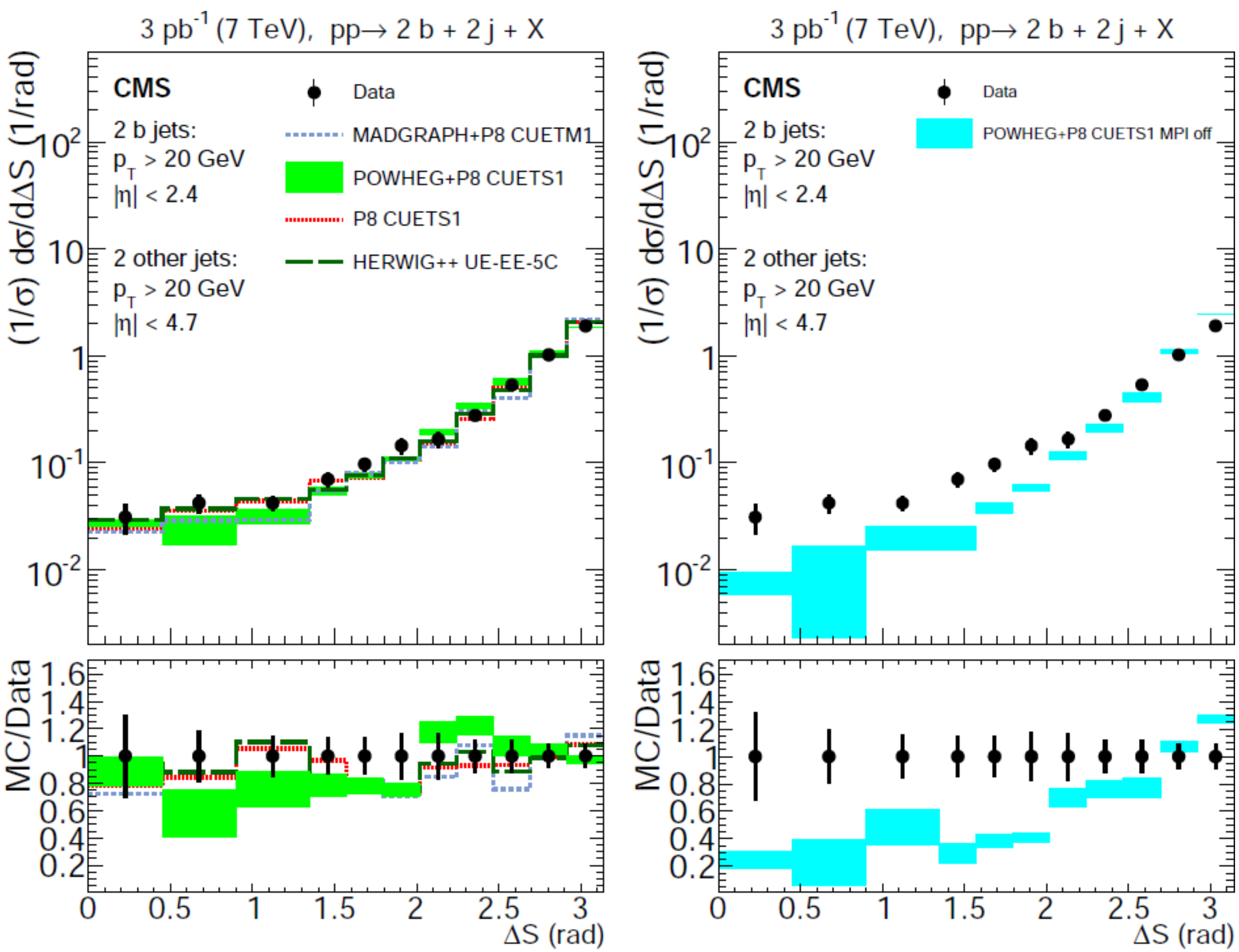
CMS-FSQ-13-010, submitted to PRD

arXiv 1609.03489

2b and 2 light jets may be produced by parton showers or a second hard scattering. Access to DPS! Discriminate between SPS and DPS by studying:

- $\Delta\varphi_{light}$ and $\Delta^{rel}_{light}p_T$ – azimuthal angle and p_T balance of the two light jets (DPS ~= 0)
- ΔS - azimuthal angle between the b-jet and light-jet pairs (DPS flat)





- All MC predictions that include MPI describe the distributions well.
- POWHEG prediction with MPI-off badly fails to describe the data
- Sensitivity to DPS for 2b+2j larger than for 4j. Valuable input to MPI tunes.

Preliminary DPS tune to 2b+2j data gives $\sigma_{eff} = 23.2^{+3.3}_{-2.5}$ mb, in agreement with the result for 4j data.

see e.g. Paolo Gunnellini's talk at MPI@LHC 2016

$$\sigma_{\rm eff} = \frac{1}{m}\frac{\sigma_A \cdot \sigma_B}{\sigma^{DPS}_{A+B}}$$

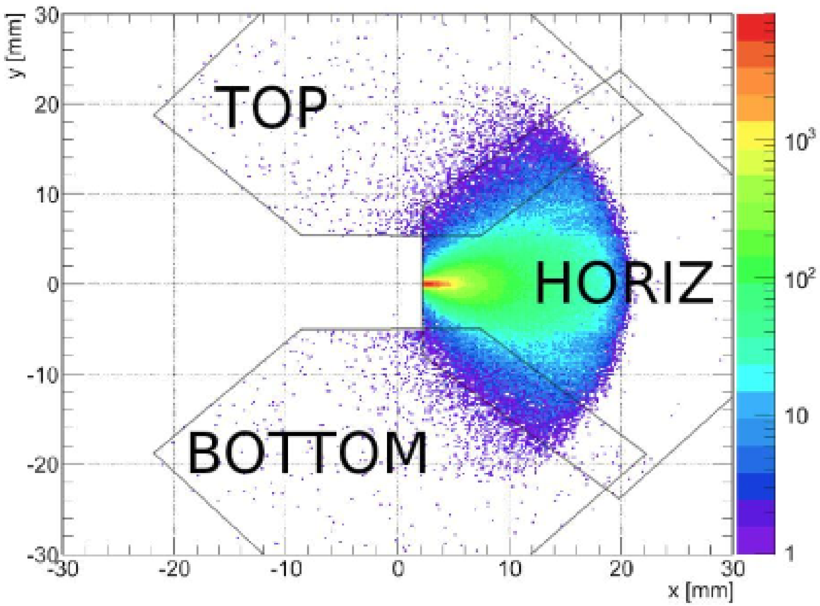
DPS also studied in the same-sign W-pair events @8 TeV. Upper limit of σ_{eff} >5.91 mb.

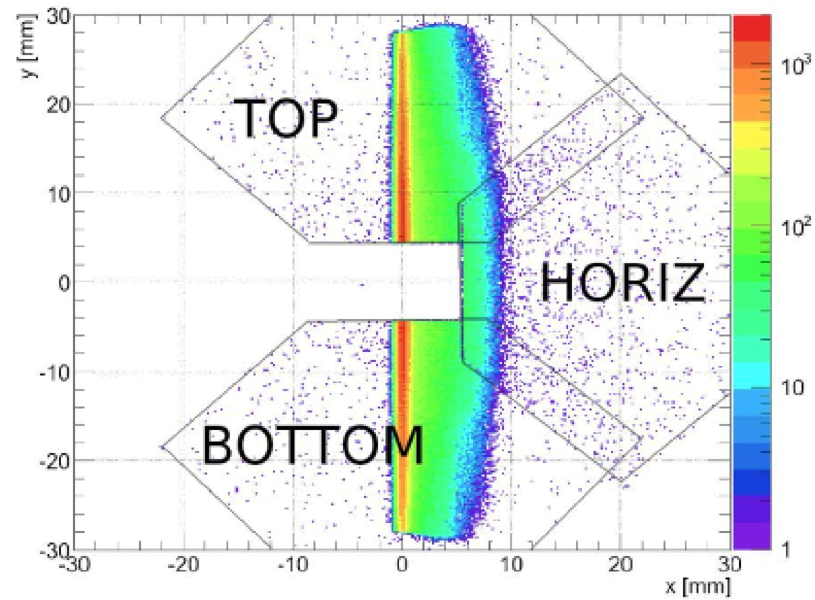
CMS-PAS-FSQ-13-001

Different LHC Optics

Hit maps of simulated diffractive events for 2 optics configurations

β* = 0.55 m (low β* = standard at LHC) | β* = 90 m (developed for σ_{total} measurement)





diffractive protons: mainly in **horizontal** RP
elastic protons: in vertical RP near x ~ 0
sensitivity only for large scattering angles

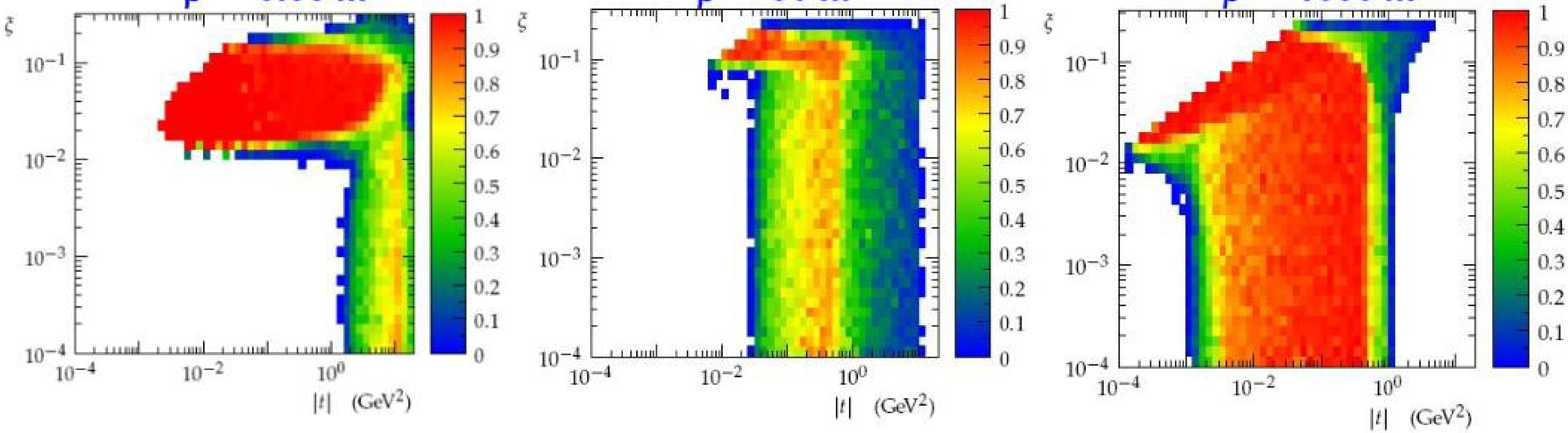
diffractive protons: mainly in **vertical** RP
elastic protons: in narrow band at x ≈ 0,
sensitivity for small vertical scattering angles

	Transverse size of IP	Angular beam divergence	Min. reachable |t|
$\beta^* \sim 0.5$–3.5 m	$\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$ ~ 15-30 μm	$\sigma(\Theta^*_{x,y}) = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$ ~ 10^{-5} μrad	$\|t_{min}\| = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$ ~ 0.3–1 GeV²
$\beta^* = 90$ m	~ 300μm	~10^{-6} μrad	~ 10^{-2} GeV²

LHC Optics & proton acceptance

$t \approx -p^2 \Theta^{*2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

$\beta^* = 0.55$ m | $\beta^* = 90$ m | $\beta^* = 1000$ m



> 10^{33} cm^{-2} s^{-1} ⟵ $\mathcal{L} \propto \frac{1}{\beta^*}$ ⟶ ~10^{27} cm^{-2} s^{-1}

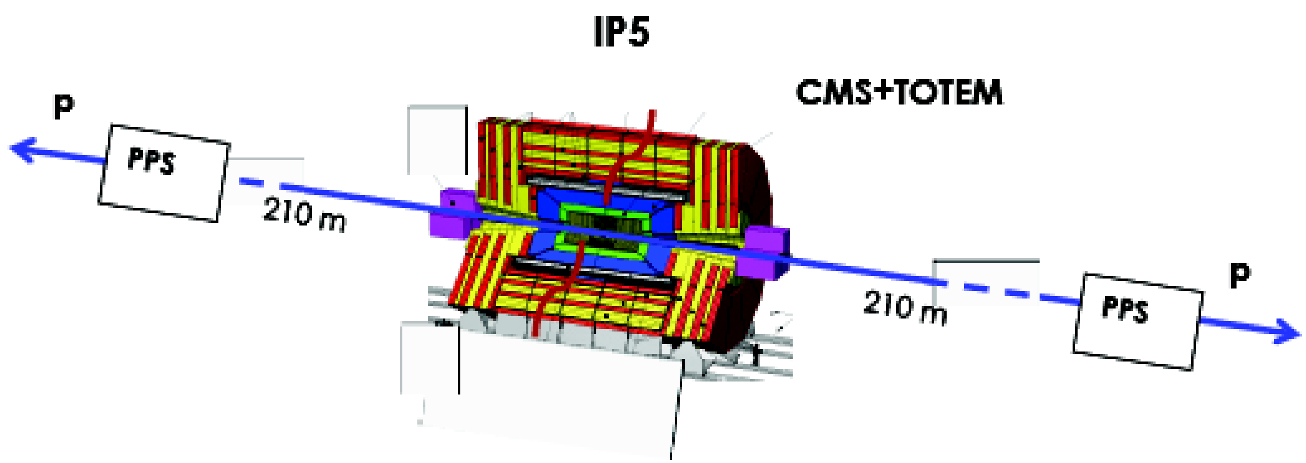
Diffraction:
ξ > ~0.01, low cross-section processes (hard diffraction)
Elastic scattering: large |t|

Diffraction: all ξ if |t| > ~10^{-2} GeV^2, soft & semi-hard diffraction
Elastic scattering: low to mid |t|
Total Cross-Section

Elastic scattering: very low |t|, Coulomb-Nuclear Interference
Total Cross-Section

Forward proton tagging@LHC: CT-PPS

The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS)[1] will allow **precision proton measurements in the very forward regions** on both sides of CMS during **standard LCH running.**



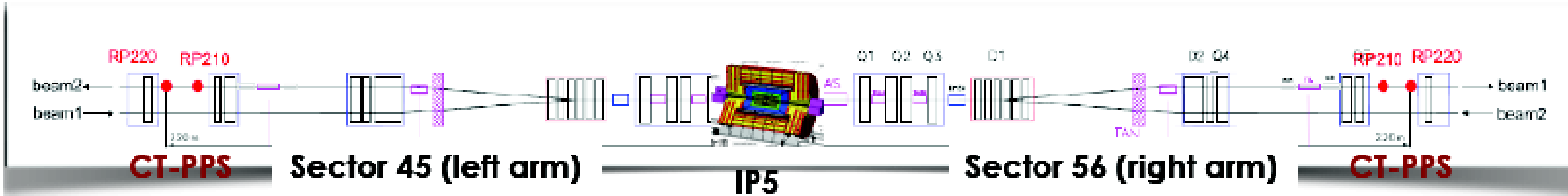
- LHC magnets between IP5 (common CMS-TOTEM interaction point) and the detector stations used to bend out of the beam envelope protons that have lost a small fraction of their initial momentum in the interaction

  → **proton fractional longitudinal momentum loss (ξ) between 2% and 10%**

- Two stations for **tracking detectors** and one station for **timing detectors** installed at ~210 m from IP5 on both sides of the central apparatus

 [1] CT_PPS TDR, CERN-LHCC-2014-021

Experimental Apparatus



Timing detector

Proton timing measurement from both sides of CMS allows to **determine the primary vertex**, correlate it with that of the central detector and **reject pile-up**

- Time resolution ~10 ps

  → **Vertex z-by-timing: ~2 mm**

$$\sigma_{V_z} = \frac{c}{2}\sqrt{2\sigma_{\Delta t}^2}$$

Tracking detectors

Proton position and angle measurements, combined with the beam magnets, allow to **determine the momentum of the scattered protons**

- Position resolution of ~10 μm
- Angular resolution of ~1-2 μrad

  → **$\Delta p/p$ ~ 2 10^{-4}**

  Mass resolution: ~5 GeV/c^2