# CMS Diffractive Results

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**On behalf of the CMS Collaboration**
**22nd January 2021**

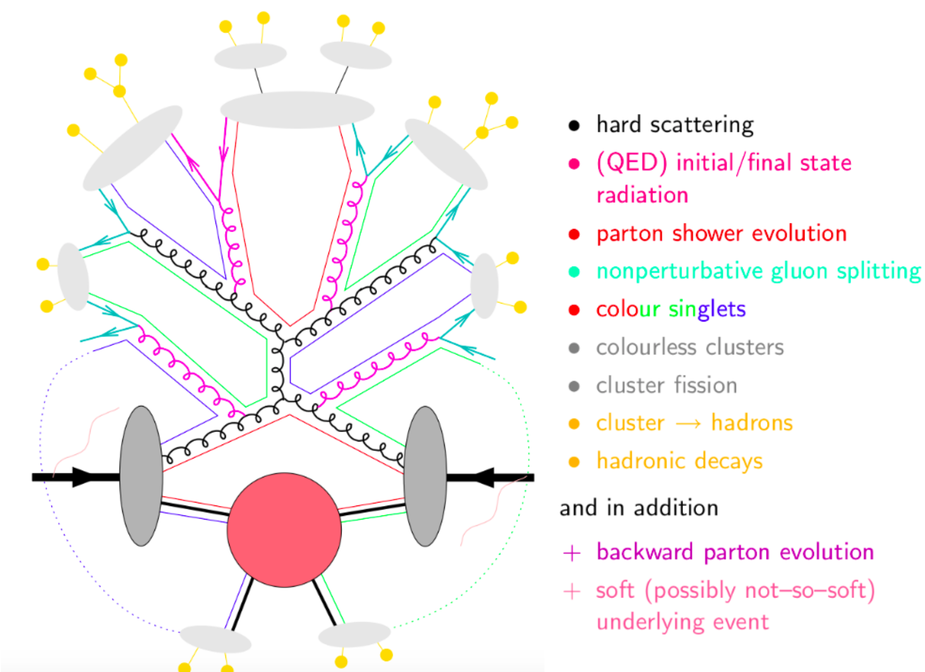

Workshop on forward physics and QCD with LHC, EIC, and cosmic rays

# Outline

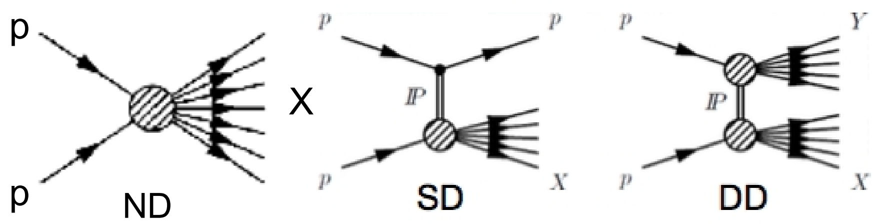
- Introduction
- CMS Detector
- Measurements on the LHC data
    - Diffraction
- Summary

# Introduction

- QCD is the theory of strong interaction describing the interactions between quarks & gluons
  - Hard QCD - high $p_T$: PDFs, strong coupling, perturbation theory, ISR & FSR, parton shower, (subjets)
  - Soft QCD - low $p_T$ : soft interactions with low $p_T$ exchange where perturbative approach is not applicable
    - Minimum bias events, Fragmentation/Hadronization
    - Underlying event
    - Diffraction

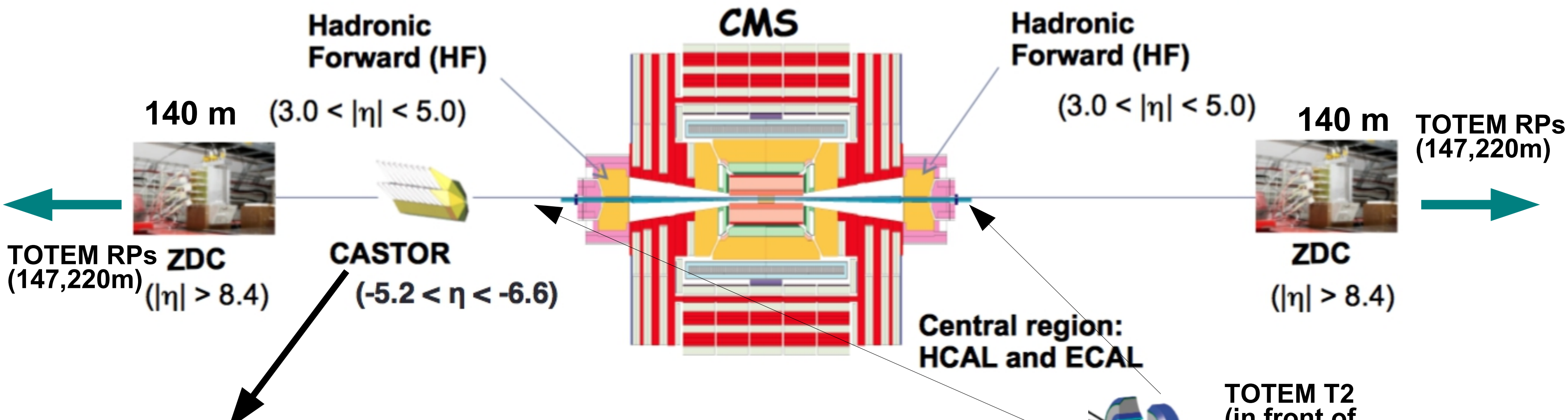


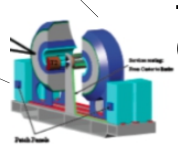

**Elastic/diffractive interactions:**

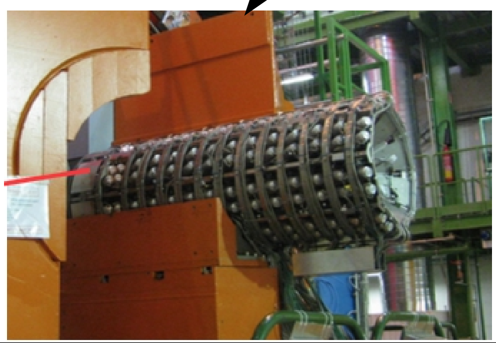



- **Diffractive processes dominate in forward regions**
- Soft diffraction (X=anything):
  - Dominated by soft QCD → SD, DPE vs. s, t, $M_x$
  - Contributions to pile-up p-p events.

# Forward Detectors at CMS

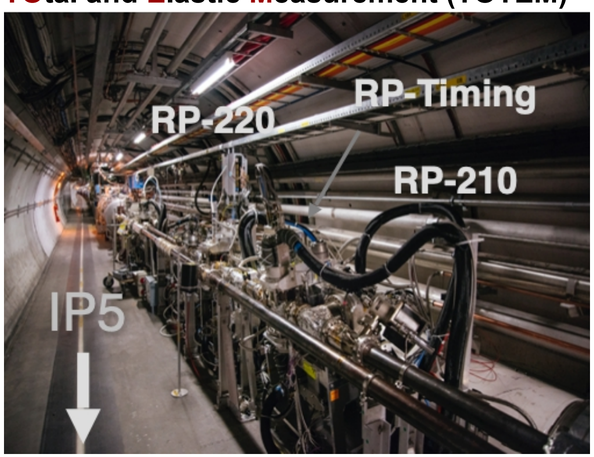


- Tungsten-Quartz-Cherenkov sampling calorimeter
- Segmented in 16 sectors in φ and 14 modules in z
- Separated electromagnetic and hadronic sections
- Located at 14.4 m from IP in CMS

TOtal and Elastic Measurement (TOTEM)




- Leading protons measured at 147 m and 220 m from IP
- Small tracking detectors measure the displacement of protons scattered at small angles w.r.t. the beam
- Proton kinematics reconstruction using simulation of LHC magnets (optics)

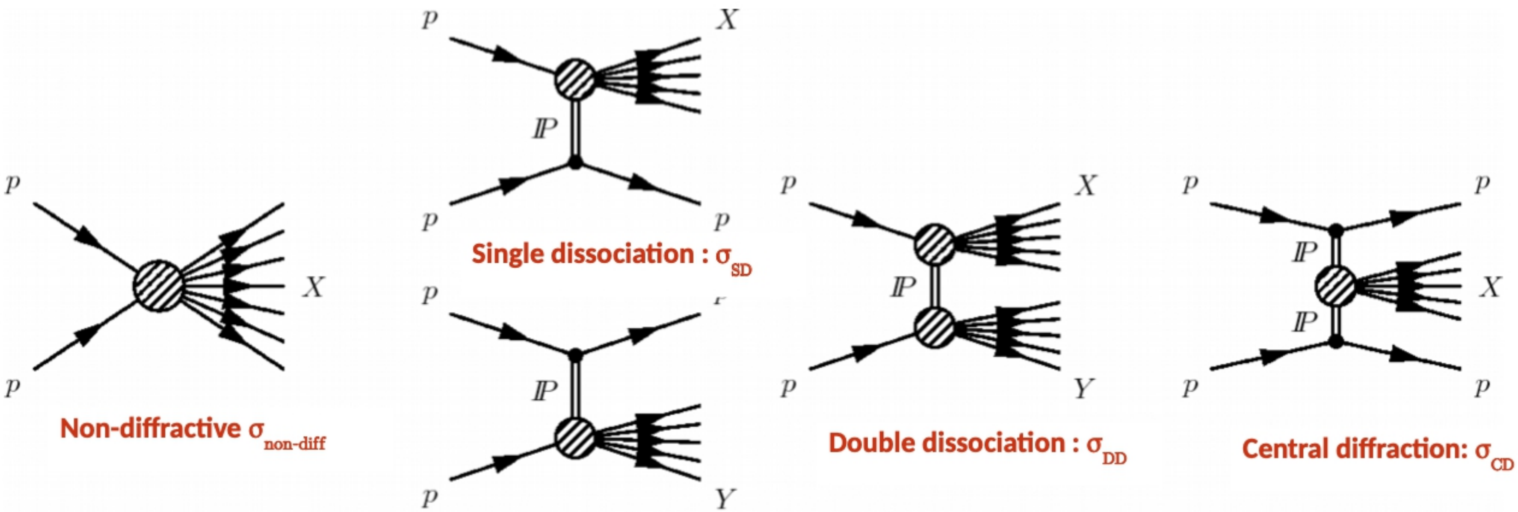
# Inelastic pp cross section @ 13 TeV

JHEP 07 (2018) 161

- **Motivation:**
  - measure the inelastic pp cross section @ 13 TeV in the largest possible phase space that is experimentally accessible
  - the total pp cross section

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s)$$

$$\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).$$




- go more forward and gain information on relative increase
- reduce extrapolation uncertainty
- provide valuable input for phenomenological hadronic interaction models and Monte Carlo (MC) tuning
- Inelastic cross section required for the modelling of pileup.

# Inelastic pp cross section @ 13 TeV

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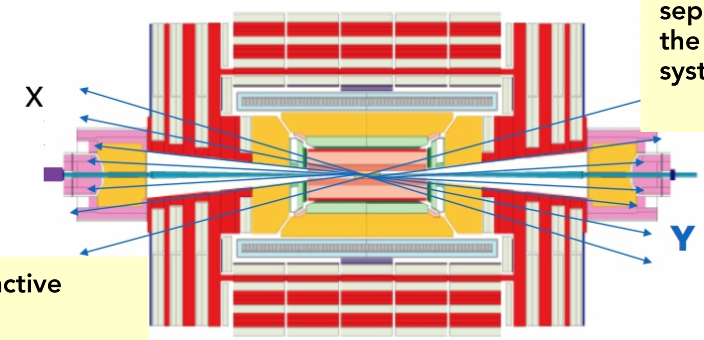
- **Analysis strategy:**
  - Use low pile-up runs from 2015 with B = 0 T and 3.8 T
  - Trigger: both beams present @ IP
  - Count events with an energy deposit above threshold
  - @ least one HF tower above 5 GeV ($\xi > 10^{-6}$)
  - @ least one HF or CASTOR tower above 5 GeV($\xi_X > 10^{-7}$ OR $\xi_Y > 10^{-6}$)

$$\xi_X = \frac{M_X^2}{s} \qquad \xi_Y = \frac{M_Y^2}{s} \qquad \xi = \max(\xi_X, \xi_Y)$$

  - Correction for noise from no-beam events
  - Data driven correction for pile-up events
  - Correction to the particle level–different MC models:

PYTHIA8 (D-L and MBR for diffraction), PYTHIA6, EPOS, QGSJET-II, PHOJET

Diffractive events:
- largest gap separates the dissociation systems




Non-Diffractive events:
- Small largest gap
- randomly located

# Inelastic pp cross section @ 13 TeV (cont'd)

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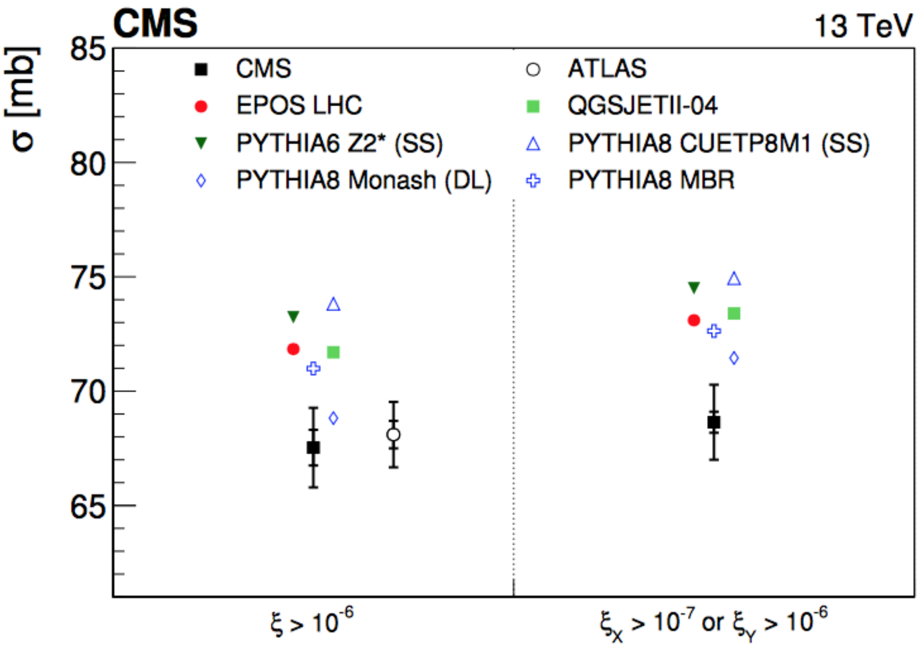



- Most models describe the relative acceptance increase from ($\xi_X > 10^{-6}$, $\xi_Y > 10^{-6}$) to ($\xi_X > 10^{-7}$, $\xi_Y > 10^{-6}$)

| | Relative cross section increase in % |
|---|---|
| Data | 1.64 ± 0.53 |
| EPOS LHC | 1.76 |
| QGSJETII-04 | 2.36 |
| PYTHIA 6 Z2* (SS) | 1.74 |
| PYTHIA 8 CUETP8M1 (SS) | 1.52 |
| PYTHIA 8 Monash (DL) | 3.83 |
| PYTHIA 8 MBR | 2.32 |

HF only: $\sigma(\xi > 10^{-6})$ = 67.5 ± 0.8 (syst) ± 1.6 (lumi) mb

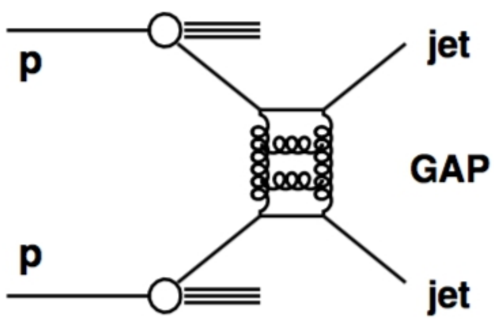
HF or CASTOR: $\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ = 68.6 ± 0.5 (syst) ± 1.6 (lumi) mb

- The measured cross sections are smaller than those predicted by the majority of models for hadron-hadron scattering.

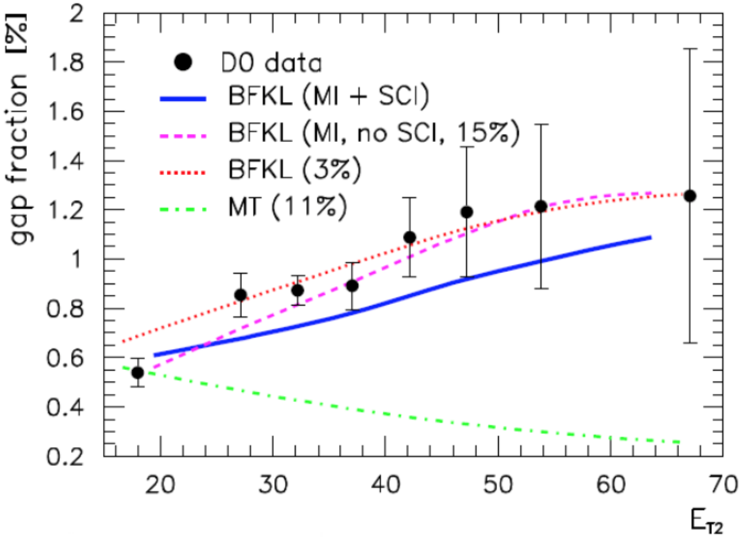
# Dijet events with a large rapidity gap (jet-gap-jet events)

EPJ C 78 (2018) 242

- Jets separated by a large rapidity gap
  - gluon or quark exchange
  - additional particle emissions between jets, DGLAP ($k_T$ ordered)
  - absence of particles produced between the jets (color singlet exchange, CSE),
  - BFKL dynamics (ordering in *x*), rescattering processes
- Events with gaps ~1% observed at Tevatron (CDF, D0) and HERA



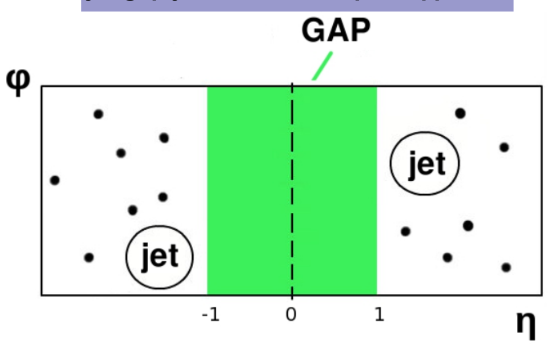

D0 data, compared to Enberg, Ingelman, Motyka model (NLL BFKL + MPI+SCI) [PLB 524 (2002) 273]




**Analysis strategy:**

- Signature: two leading jets with no particles in between
- Jets with $p_T$ > 40 GeV, 1.5 < |y| < 4.5
- Gap particles: |η| < 1, $p_T$ > 0.2 GeV

jet-gap-jet event in the φ vs. η plane.



# Jet-gap-jet events: number of tracks

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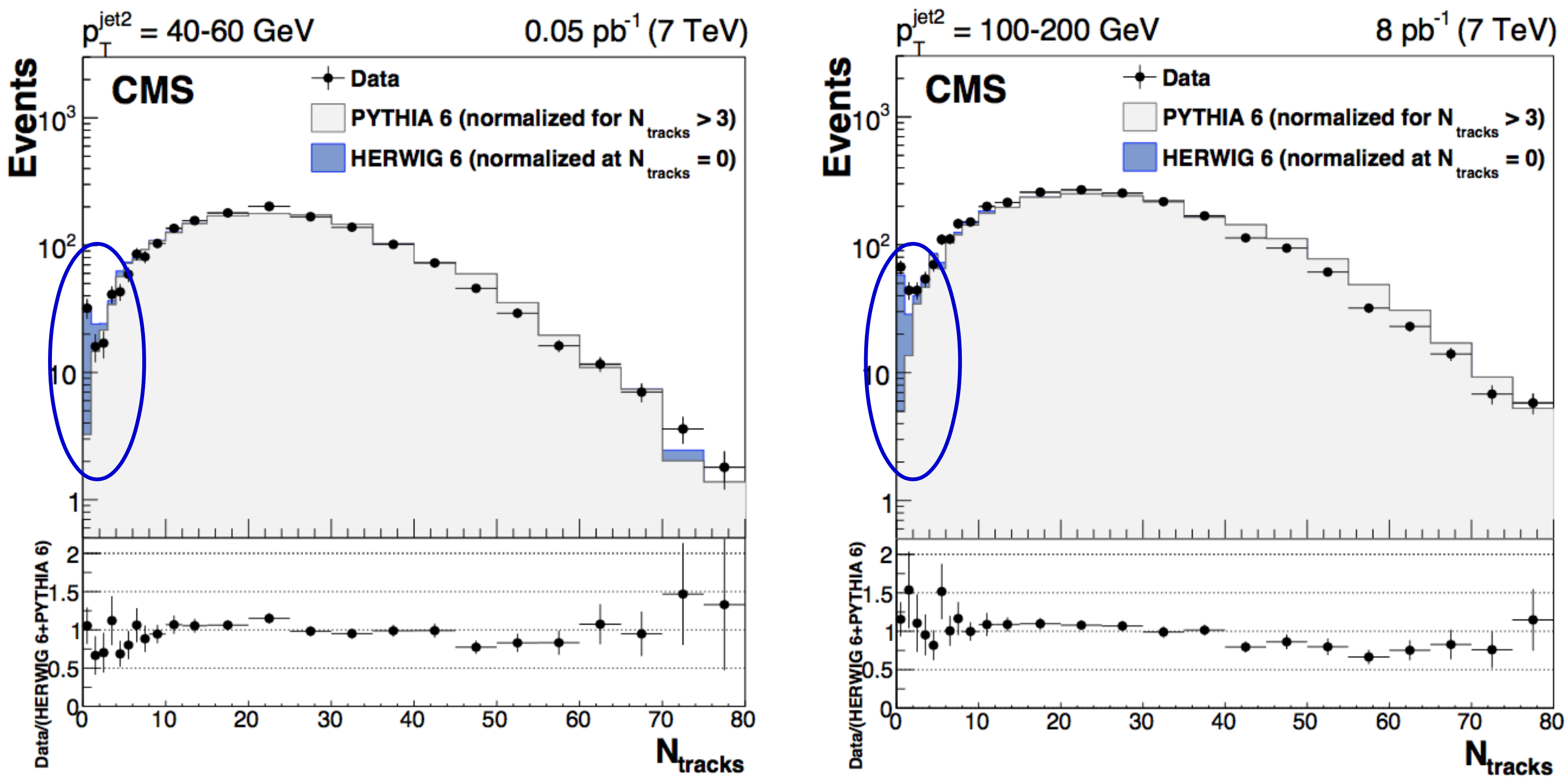
- Number of central tracks between the two leading jets in events with $p_T^{jet2}$ = 40-60 (left) and 100-200 (right)




- Large excess of gap events over PYTHIA6 prediction (LO DGLAP)
  - this excess well described by HERWIG 6 (LL-BFKL, Mueller-Tang model)

# Jet-gap-jet events: pT

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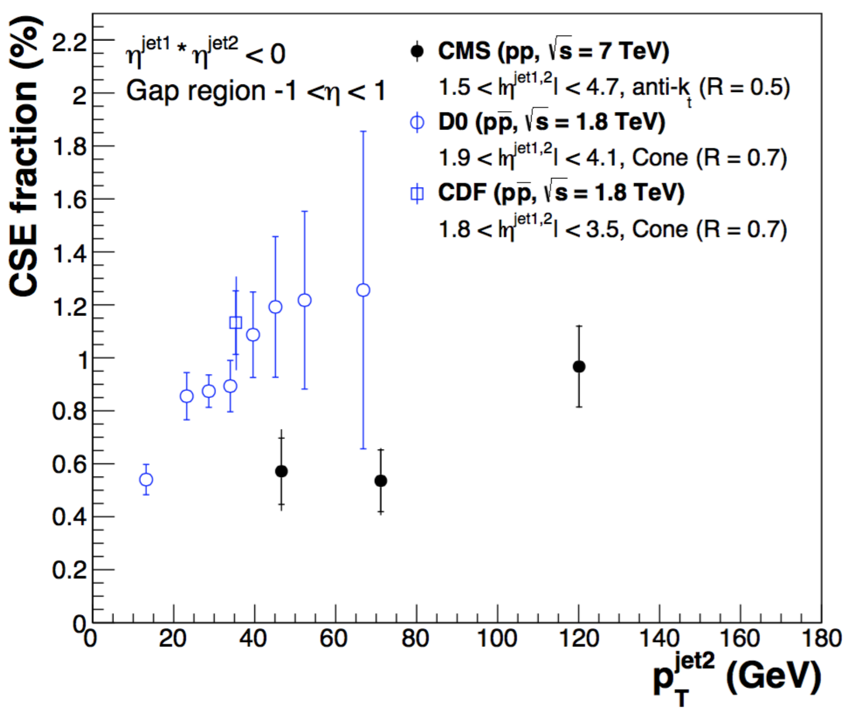
- In order to quantify the contribution from CSE events, CSE fraction

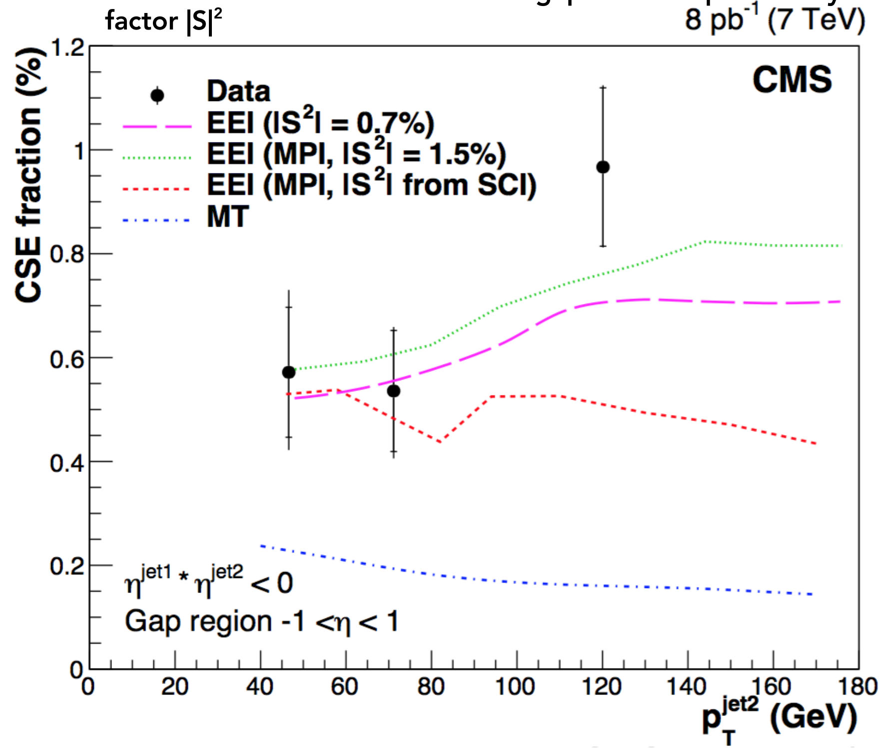
$$f_{CSE} = \frac{N^F_{events} - N^F_{non-CSE}}{N_{events}}$$

  – $N^F_{events}$ : the number of events in the first bins of the multiplicity distribution
  – $N^F_{non-CSE}$: the estimated number of events in these bins originating from non-CSE events
  – $N_{events}$ : the total number of events considered

- $f_{CSE}$ as a function of $p_T^{jet2}$ at √s = 7 TeV, compared to D0 and CDF




- $f_{CSE}$ as a function of $p_T^{jet2}$ at √s = 7 TeV, compared to Mueller and Tang (MT) model
Ekstedt, Enberg, and Ingelman (EEI) model with 3 different treatments of the gap survival probability factor $|S|^2$




- A factor ~2 suppression w.r.t. to D0 and CDF data

observed earlier: 2.5 ± 0.9 (D0) and 3.4 ± 1.2 (CDF) decrease with √s = 0.63 Δ 1.8 TeV

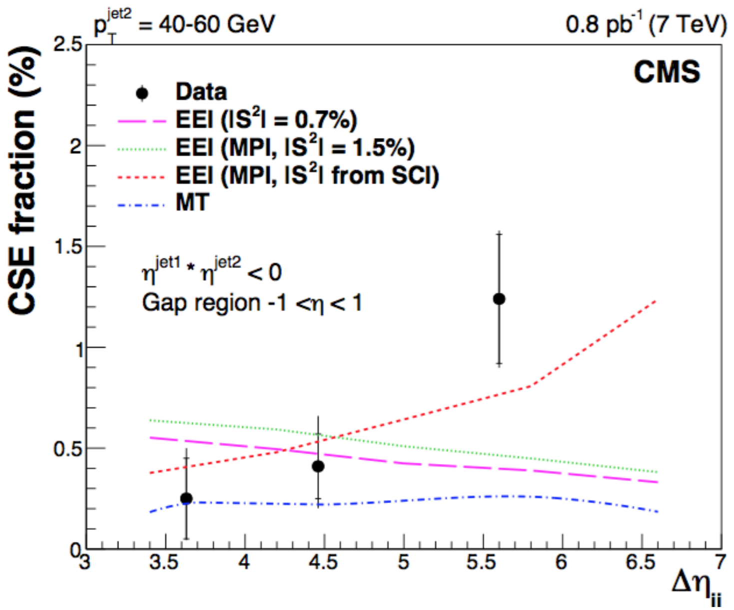
- The MT prediction does not reproduce the increase of $f_{CSE}$

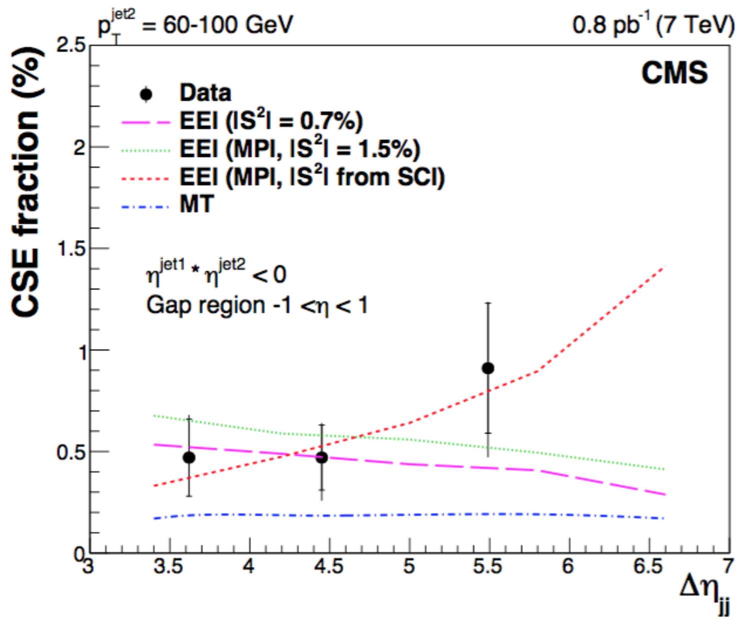
- BFKL cross section is scaled $|S|^2 = 0.7\%$

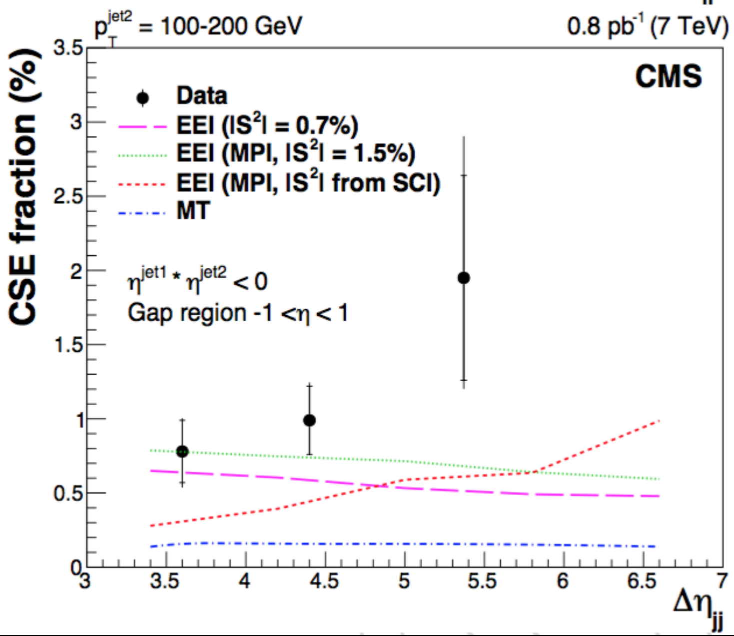
# Jet-gap-jet events: GAP/CSE fraction

EPJ C 78 (2018) 242

- $f_{CSE}$ as a function of eta in 3 $p_T^{jet2}$ ranges



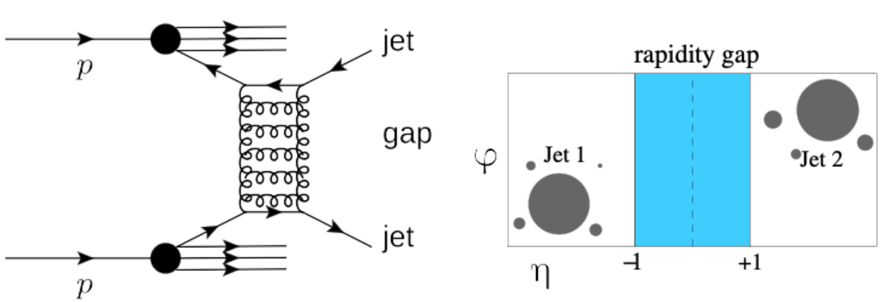

- The NLL BFKL calculations of EEI, with three different implementations of the soft rescattering processes, describe many features of the data,

- But none of the implementations is able to simultaneously describe all the features of the measurement.

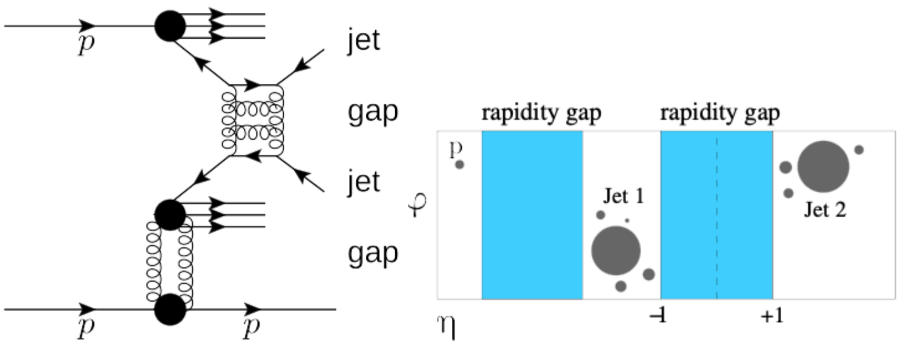
# Hard color-singlet exchange in dijet events @13 TeV

**CMS PAS SMP-19-006**

- Events with two high-$p_T$ jets separated by a large pseudorapidity gap (interval devoid of particle activity).
  - DGLAP dynamics largely suppressed
  - allow to study BFKL pomeron exchange (Color singlet exchange = two-gluon t-channel exchange).




- Central gap signature can be destroyed by soft-parton interactions.
  - Parametrized by means of rapidity gap survival probability ($|S|^2 \approx 10^{-2}$ - $10^{-1}$) at cross section level (NP Correction)




- Analysis strategy:
  - Study jet-gap-jet in inclusive dijet production in pp collisions at 13 TeV with CMS
  - Study jet-gap-jet events with leading protons in pp collisions at 13 TeV (subset of CMS-only dijet sample + forward protons detected with TOTEM roman pots)

**CMS PAS SMP-19-006**

- **Event selection**

* **Dijet Event selection**

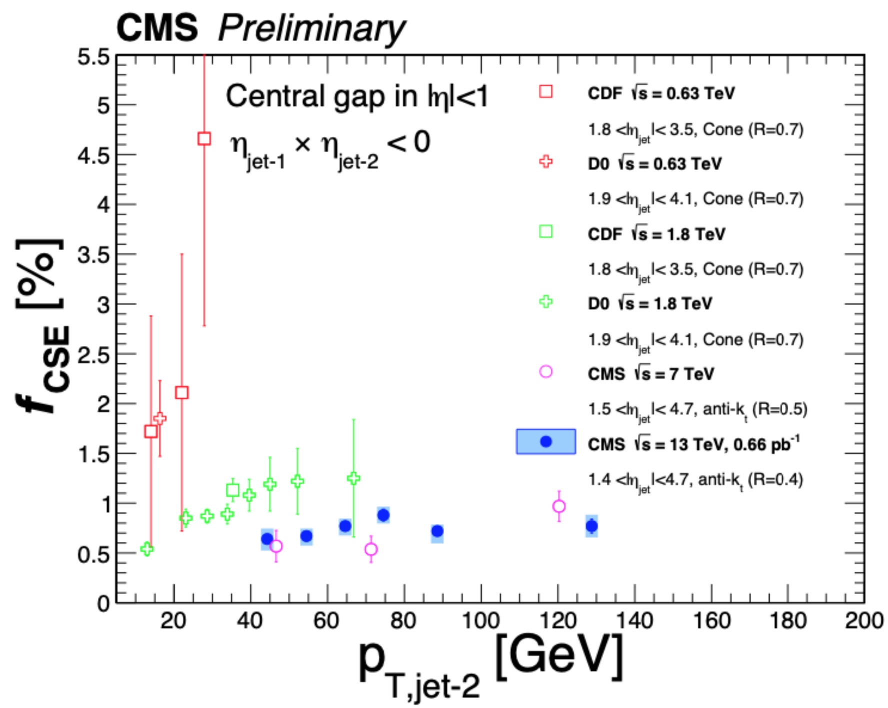
- Jets with $p_{T,\,jet}$ > 40 GeV, 1.4 < $|\eta_{jet}|$ < 4.7
- $\eta_{jet1} \times \eta_{jet2} < 0$ to allow larger rapidity separation

* **Leading proton selection**

- Leading proton must be detected in TOTEM-RPs (sector 45/56)
- Fractional momentum loss $\xi < 0.2$ and the square of the four-momentum transfer at the proton vertex $0.025 < -t < 4$ GeV$^2$

$$f_{\text{CSE}} = \frac{N^{\text{F}} - N^{\text{F}}_{\text{non-CSE}}}{N} \equiv \frac{\text{Number of jet-gap-jet events}}{\text{Number of inclusive dijet events}}$$

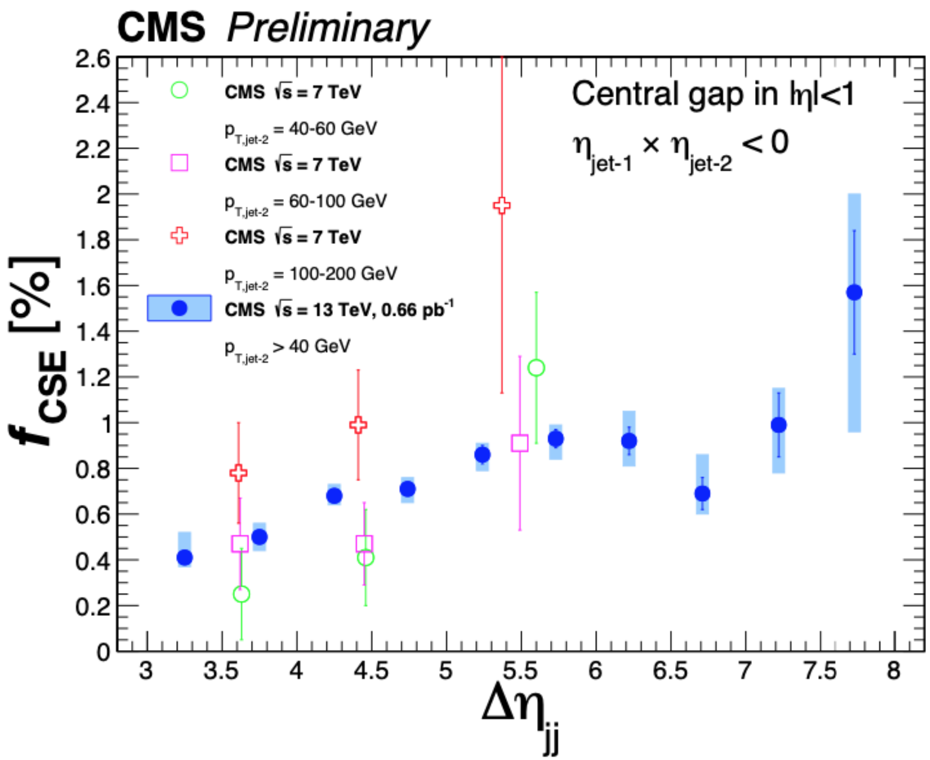
- $N^{\text{F}}$: Number of dijet events with $N_{\text{Tracks}} < 3$ in $|\eta| < 1$ (event counting)
- $N$: Number of dijet events with $N_{\text{Tracks}} \geq 0$ in $|\eta| < 1$ (event counting);
- $N^{\text{F}}_{\text{non-CSE}}$: Non-color-singlet exchange dijet events with $N_{\text{Tracks}} < 3$ in $|\eta| < 1$




- **Comparison with previous measurements**

- **Generally, $|S|^2$ is expected to decrease with increasing $\sqrt{s}$, due to an increase in spectator parton activity with $\sqrt{s}$.**

# Fraction of jet-gap-jet




- $f_{CSE}$ vs. $\Delta\eta_{jj}$ expands the reach in pseudorapidity separations covered in the earlier 7 TeV CMS measurement,
  - trend of increasing $f_{CSE}$ vs. $\Delta\eta_{jj}$ observed @7 TeV is confirmed @13 TeV.
  - extends the range previously explored towards large values of $\Delta\eta_{jj}$.

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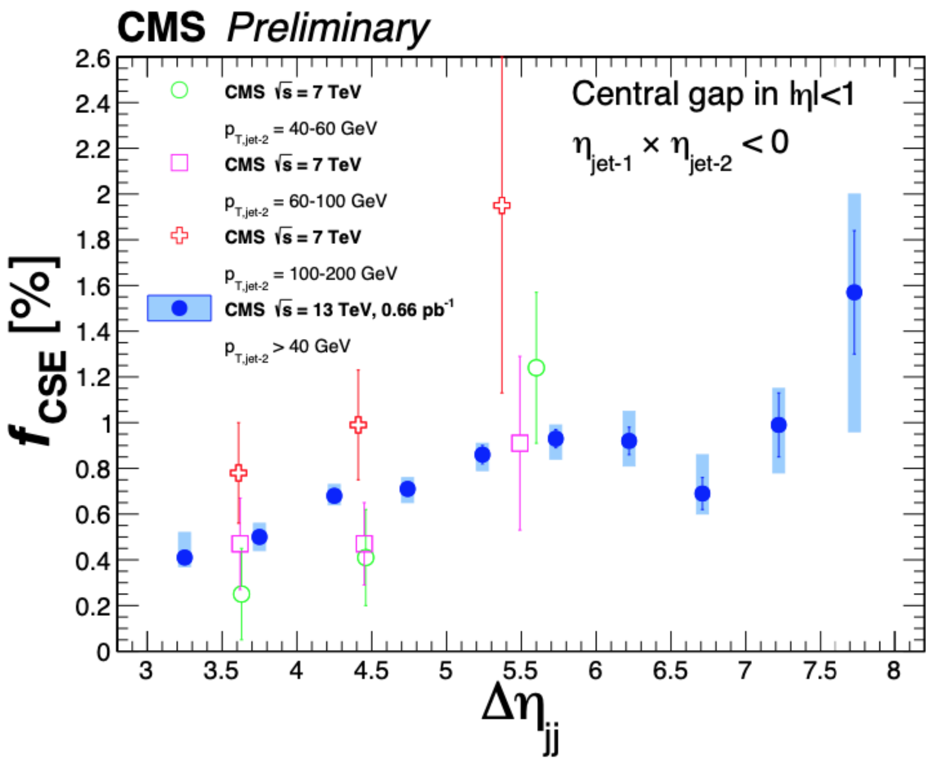


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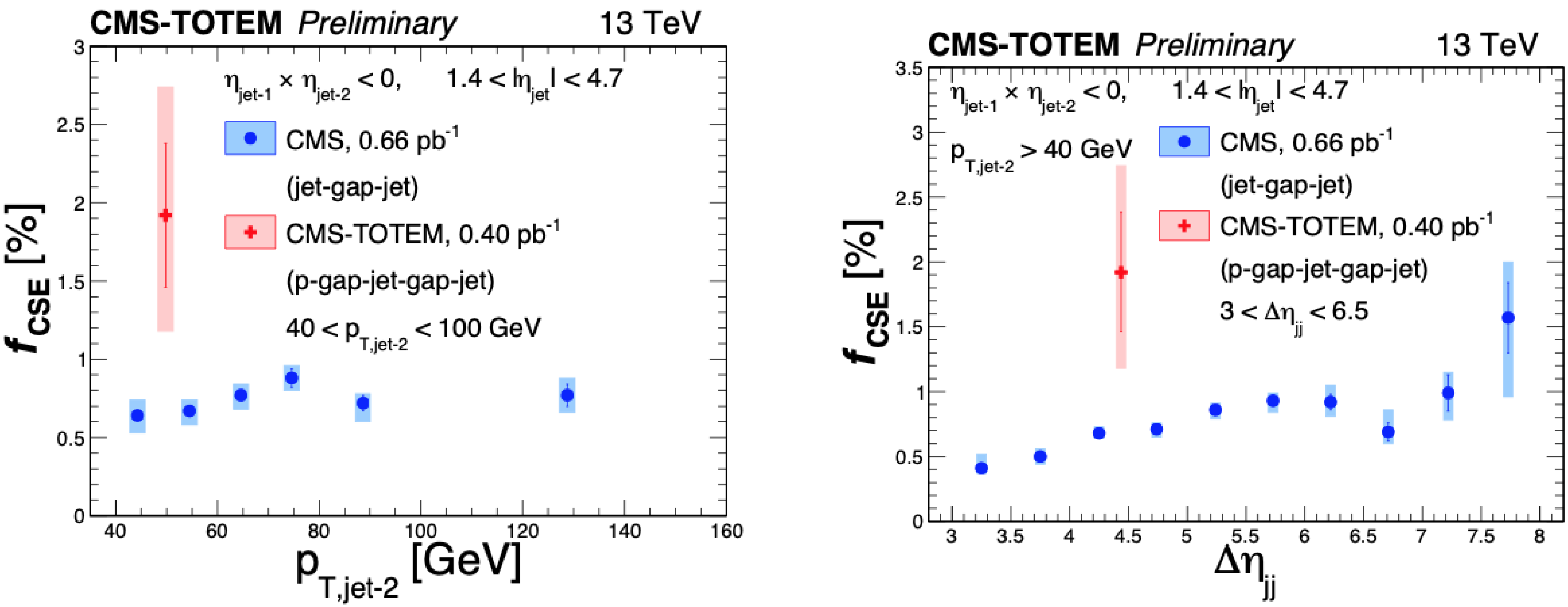
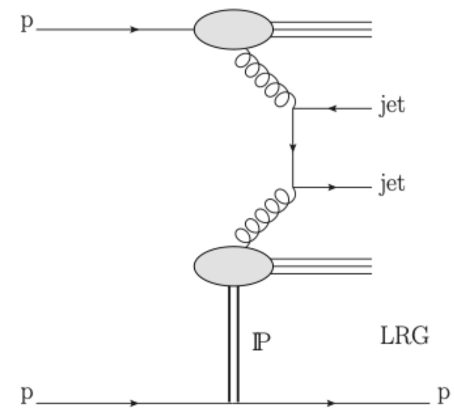



- CMS-TOTEM results, when compared to the CMS results, suggest that the relative abundance of dijet events with a central gap is larger in events with a leading proton
  - Reduced spectator-parton activity in events with leading protons ---> More likely that central gap "survives".
  - The present measurement sets a constraint on the theoretical treatment of rapidity gap survival probability.

# Single-diffractive dijet production @ 8 TeV

arXiv:2002.12146
*Submitted to EPJ C*

- Proton tagging with RP => much more precise studies + large acceptance
- Event selections
  - Low pile up data @ 8 TeV
  - CMS: at least two jets with $p_T$ > 40 GeV and $|\eta|$ < 4.4.
    - At least one reconstructed primary vertex
    - TOTEM measurements important for tuning
  - TOTEM: RP single arm track (acceptance: 0< $\xi$ <0.1, 0.03 < $|t|$ < 0.01 GeV$^2$)



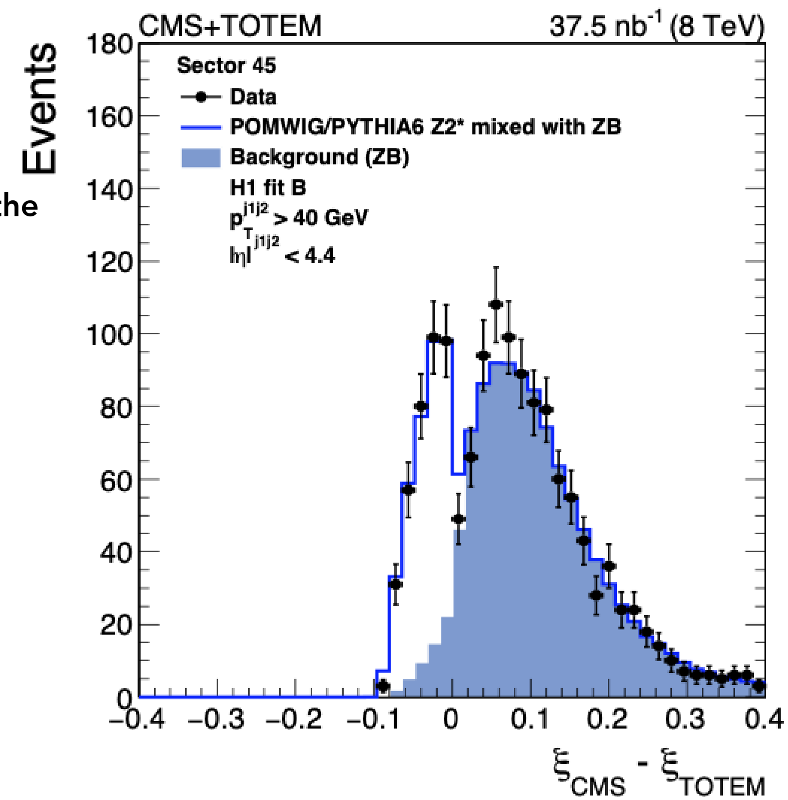

- Observables : $d\sigma/dt$, $d\sigma/d\xi$ where t and $\xi$ are reconstructed from the proton track measured with RP
- **Background:** inclusive dijet with a fake or pile-up single arm RP track rejected comparing $\xi$ and $\xi_{CMS}$:

**Fractional momentum loss:**

$$\xi_{\text{TOTEM}} = 1 - \left|\frac{\mathbf{p}_f}{\mathbf{p}_i}\right| \qquad \xi^{\pm}_{\text{CMS}} = \frac{\sum(E^i \pm p^i_z)}{\sqrt{s}}$$

**Absolute value of the 4-momentum transfer squared**

$$t = (p_f - p_i)^2$$

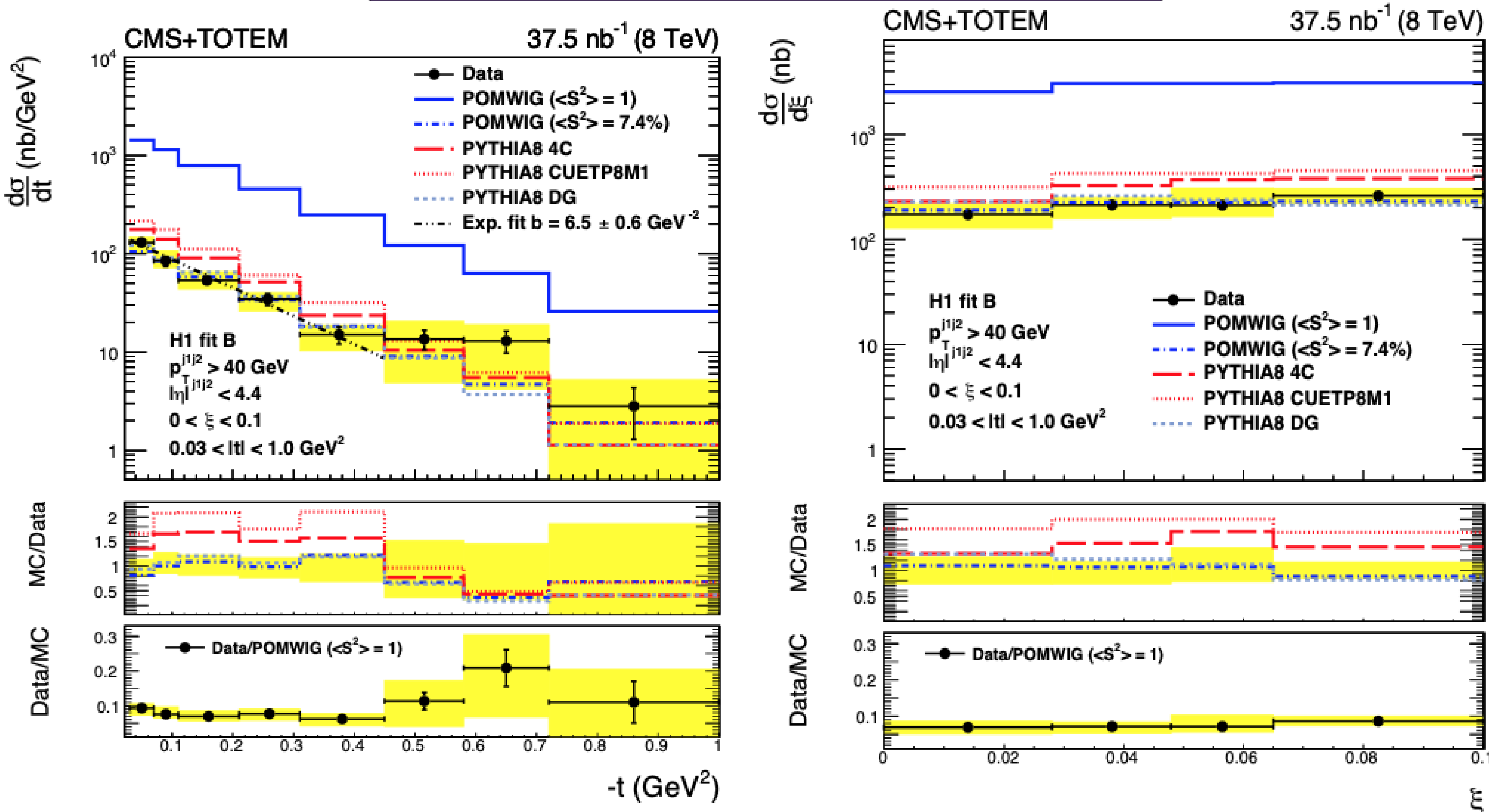


# Extraction of cross section

arXiv:2002.12146

*Submitted to EPJ C*

Differential cross sections as a function of t and ξ

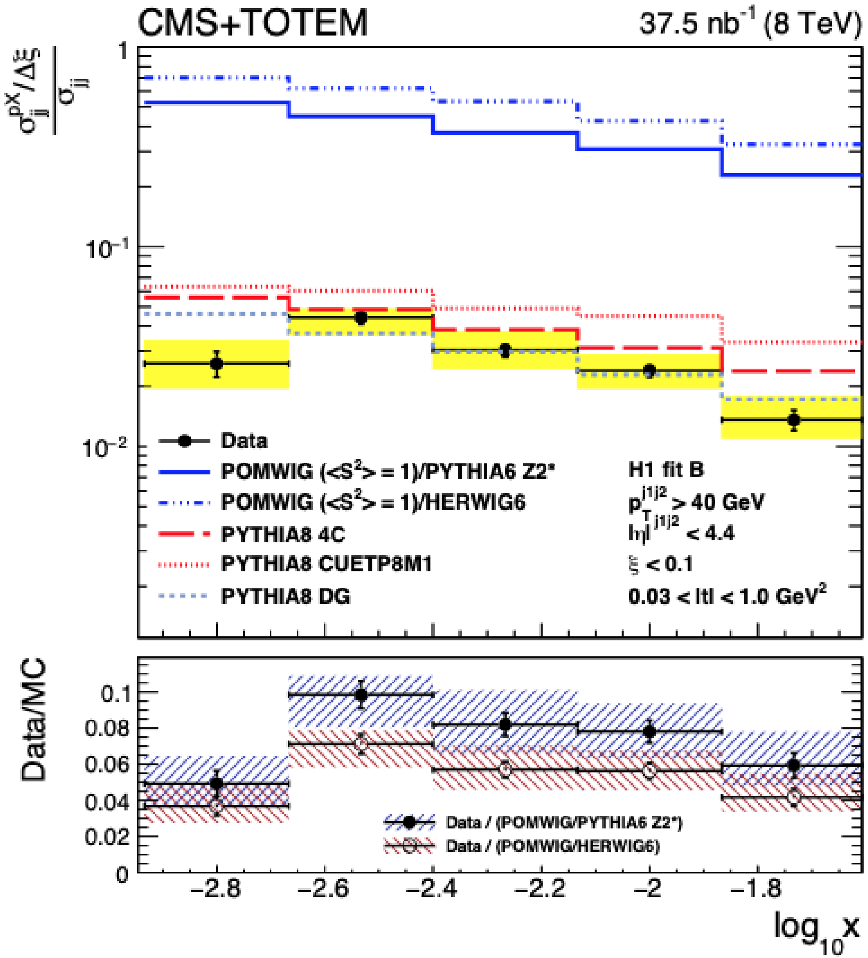


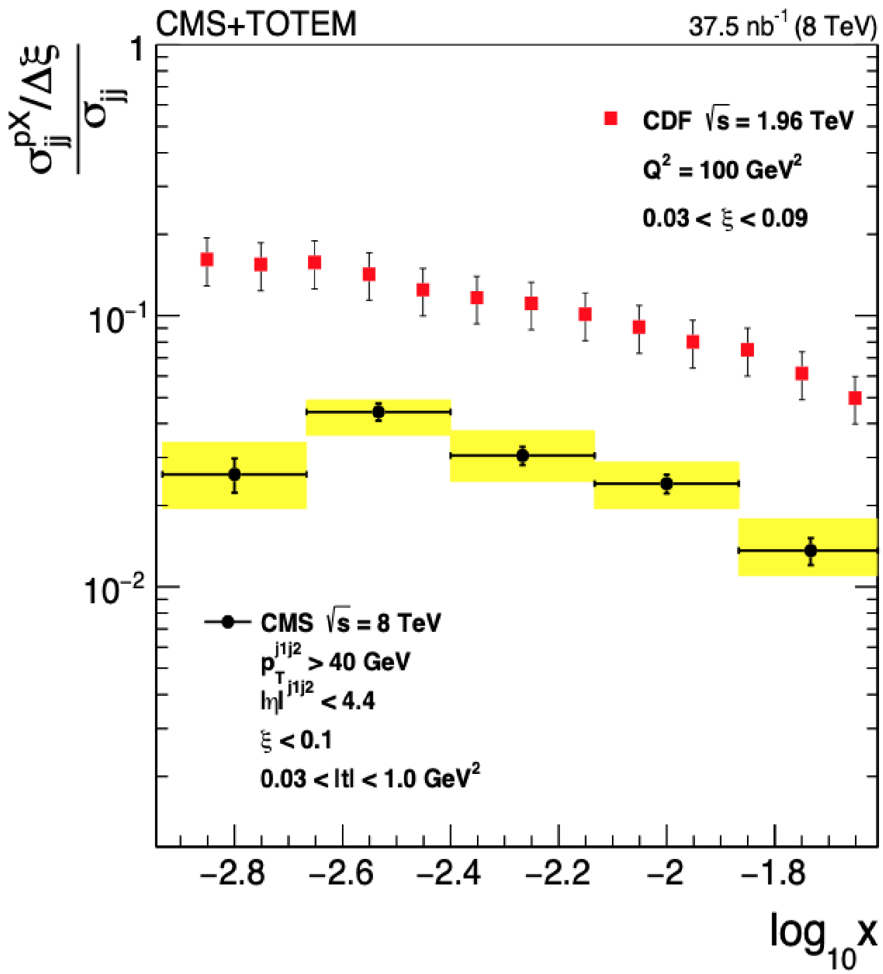

- Events in which the proton is detected on either side of the IP are averaged.
- POMWIG corrected for two values of the suppression of the diffractive cross section (the gap survival probability)
- Pythia8 with Dynamic Gap model (DG) accounts for the MPI and describes the data reasonably well without further corrections

# Extraction of the ratios

arXiv:2002.12146

*Submitted to EPJ C*




- ▶ Compasion of the ratio of the single- diffractive and nondiffractive dijet cross sections from different models
- ▶ SD simulated with POMWIG, PYTHIA8 4C, PYTHIA8 CUETP8M1, and PYTHIA8 DG
- ▶ PYTHIA6 used for simulation of nondiffractive contribution.
- ▶ POMWIG prediction shown with no correction for $\langle S^2 \rangle = 1$
- ▶Ratio as a function of the parton momentum fraction x.
    - ▶ SD to inclusive cross-section ratio decreases with center-of-mass energy as observed at TEVATRON

# Summary

- LHC has provided access to a large phase space fas well as a new energy scale for understanding of various aspects of QCD
- CMS has a rich physics program which is the perfect testing ground for QCD models
  - unique forward detector instrumentation
  - ranging from low to high $p_T$ and from inclusive to exclusive observables
  - improve our picture of hadronic collisions, as well as its universality
- An overview of diffractive measurements has been presented
- Detailed measurements of inelastic cross sections across 11 units of pseudorapidity.
- CSE fraction increases with jet energy and rapidity separation

- Still more measurements and efforts as well as LHC run 3 preparation on-going stay tuned!

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**Thank you for your attention!**

# Summary

- An overview of some representative soft QCD and diffractive measurements has been presented

- LHC has provided access to a large phase space fas well as a new energy scale for understanding of various aspects of QCD

- CMS has a rich physics program which is the perfect testing ground for QCD models
  - improve our picture of hadronic collisions, as well as its universality

- Energy measurements in the very forward rapidity regions indicate some interesting potential to further improve the underlying event model predictions

- Still more measurements and efforts as well as LHC run 3 preparation on-going stay tuned!

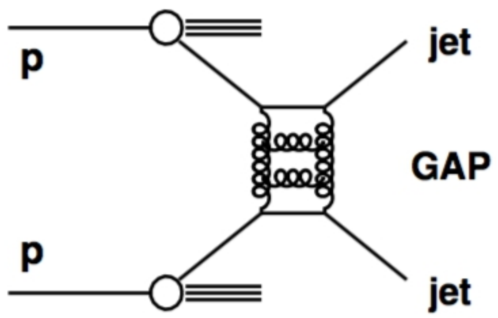
Thank you for your attention!

# BACKUP

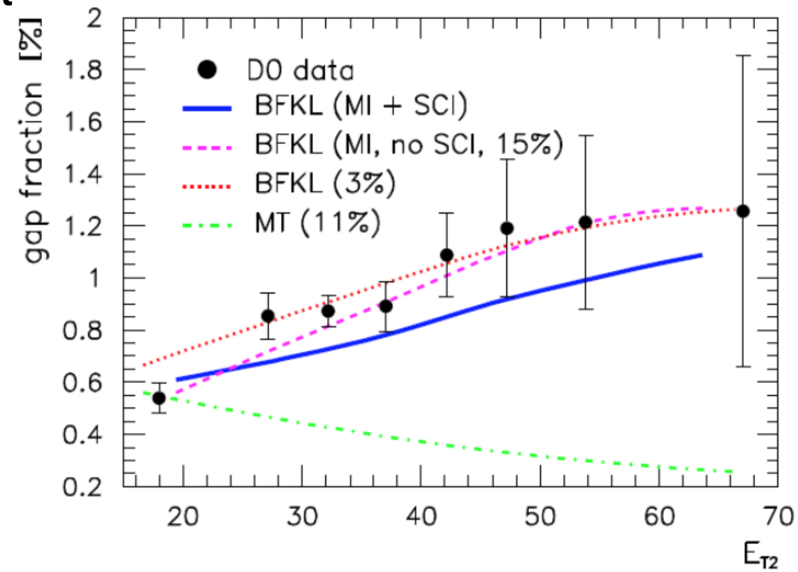
# Dijet events with a large rapidity gap (jet-gap-jet events)

EPJ C 78 (2018) 242

- **Jets separated by a large rapidity gap**
  - **gluon or quark exchange**
  - **additional particle emissions between jets, DGLAP ($k_T$ ordered)**
  - **absence of particles produced between the jets (color singlet exchange, CSE),**
    **BFKL dynamics (ordering in *x*), rescattering processes**
- **Events with gaps ~1% observed at Tevatron (CDF, D0) and HERA**

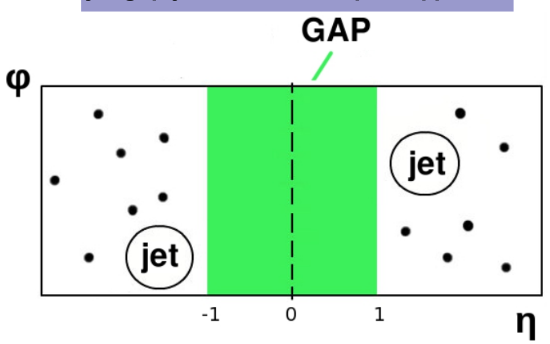



D0 data, compared to Enberg, Ingelman, Motyka model (NLL BFKL + MPI+SCI) [PLB 524 (2002) 273]




- **Analysis strategy:**
  - **Signature: two leading jets with no particles in between**
  - **Jets with $p_T$ > 40 GeV, 1.5 < |y| < 4.5**
  - **Gap particles: |η| < 1, $p_T$ > 0.2 GeV**

jet-gap-jet event in the φ vs. η plane.



# Jet-gap-jet events: number of tracks

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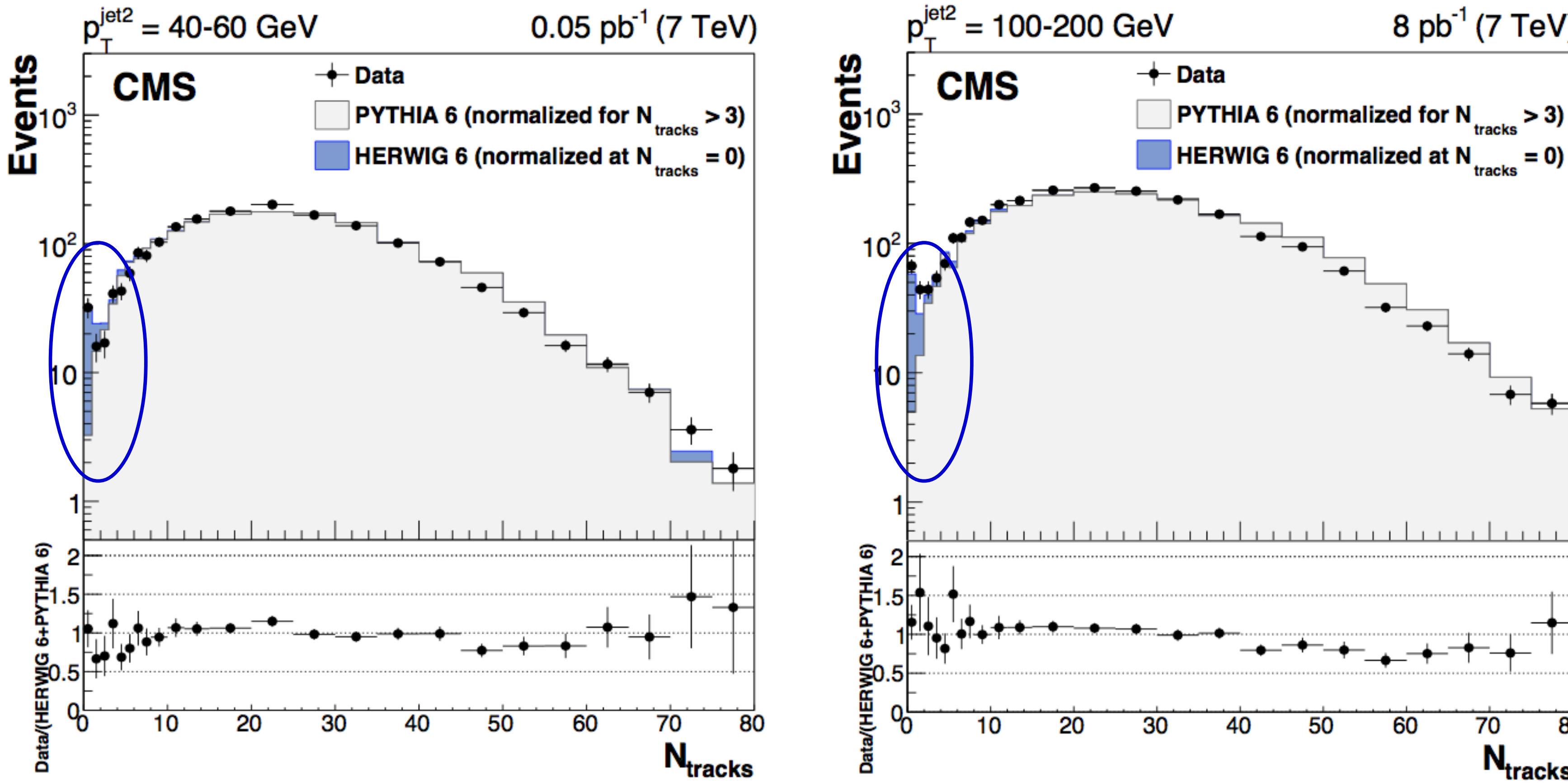
- Number of central tracks between the two leading jets in events with $p_T^{jet2}$ = 40-60 GeV (left) and 100-200 GeV (right)

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  - this excess well described by HERWIG 6 (LL-BFKL, Mueller-Tang model)

# Jet-gap-jet events: $p_T$

EPJ C 78 (2018) 242

- In order to quantify the contribution from CSE events, CSE fraction

$$f_{CSE} = \frac{N^F_{events} - N^F_{non-CSE}}{N_{events}}$$

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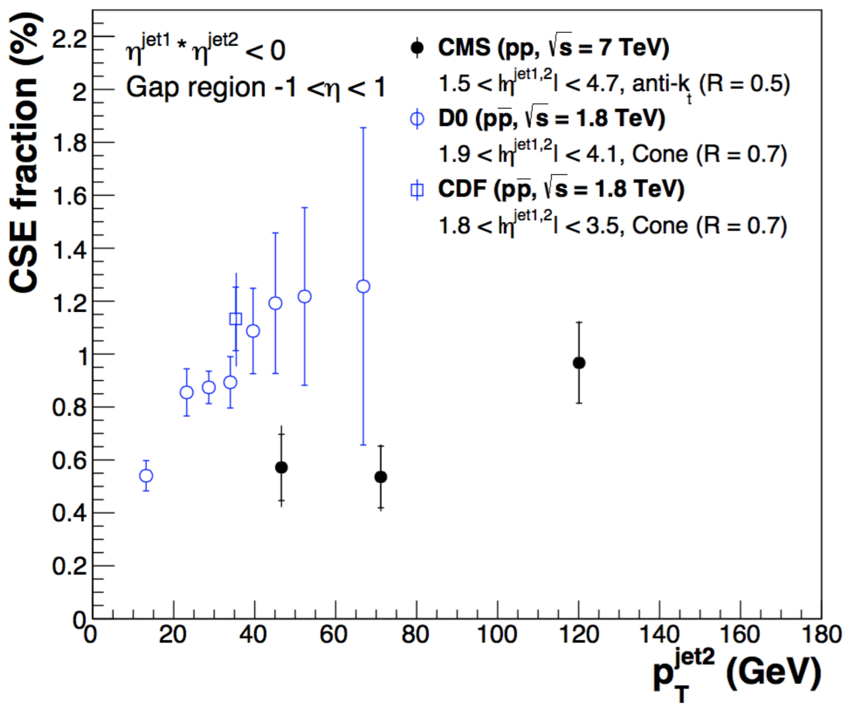
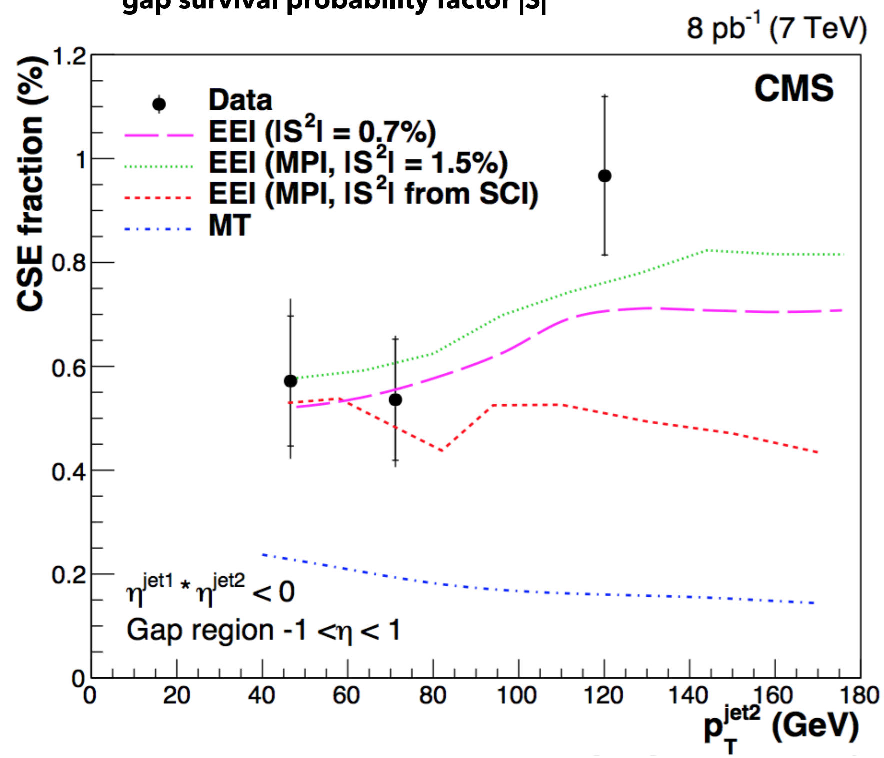
- $f_{CSE}$ as a function of $p_T^{jet2}$ at $\sqrt{s}$ = 7 TeV, compared to D0 and CDF




- $f_{CSE}$ as a function of pjet2 at $\sqrt{s}$ = 7 TeV, compared to Mueller and Tang (MT) model, Ekstedt, Enberg, and Ingelman (EEI) model with 3 different treatments of the gap survival probability factor $|S|^2$




- A factor ~2 suppression w.r.t. to D0 and CDF data observed earlier: 2.5 ± 0.9 (D0) and 3.4 ± 1.2 (CDF) decrease with $\sqrt{s}$ = 0.63 → 1.8 TeV
- The MT prediction does not reproduce the increase of $f_{CSE}$
- BFKL cross section is scaled $|S|^2$ = 0.7%

# Jet-gap-jet events: GAP/CSE fraction

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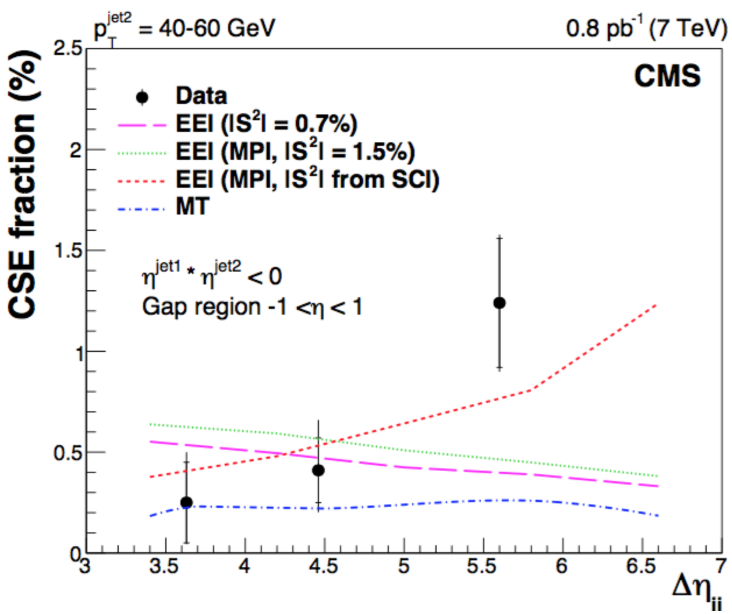
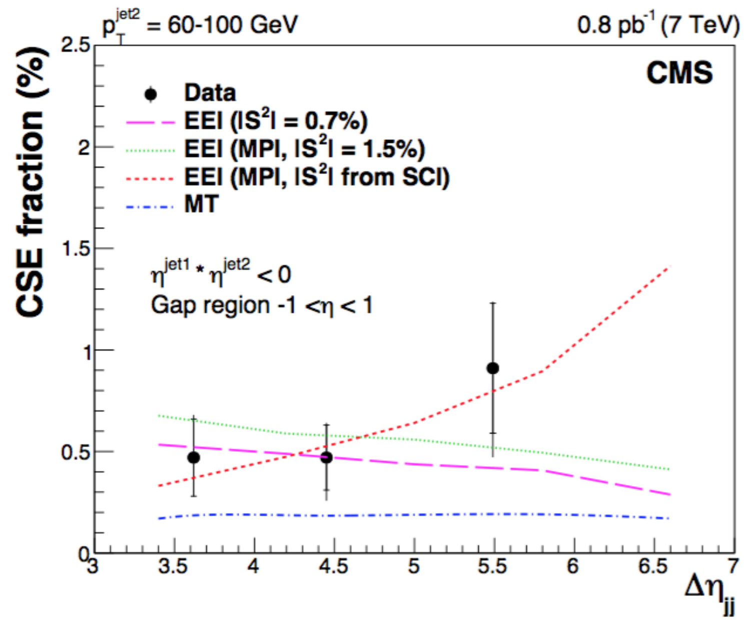
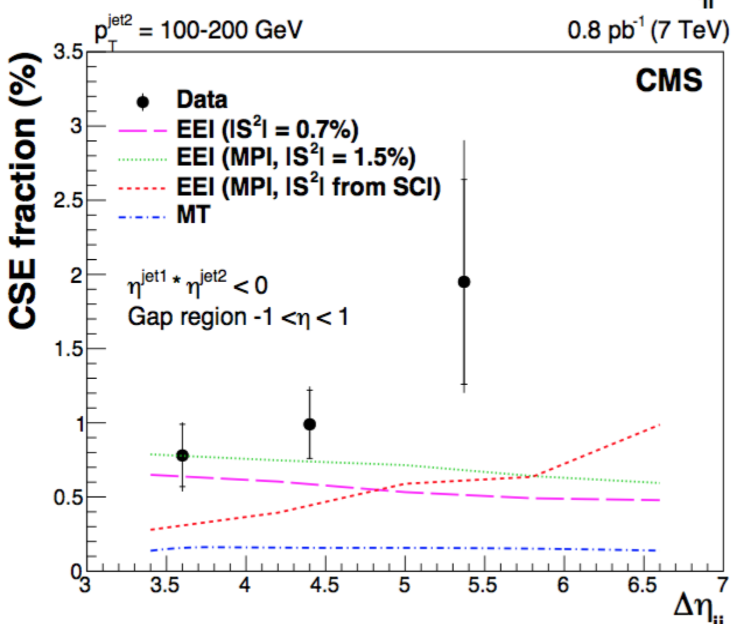
- $f_{CSE}$ as a function of eta in 3 $p_T^{jet2}$ ranges



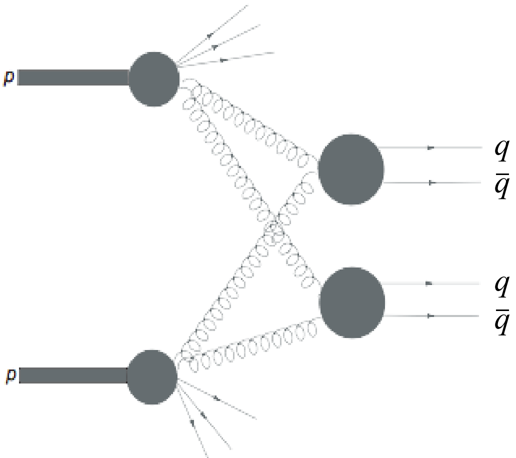




- **The NLL BFKL calculations of EEI, with three different implementations of the soft rescattering processes, describe many features of the data,**
- **But none of the implementations is able to simultaneously describe all the features of the measurement.**

# Double Parton Scattering

- Double Parton Scattering (DPS): two hard scatters within same protons
  - increasingly important at higher s
  - probe transverse profile of proton PDF

$$\sigma^{DPS}_{(hh' \to ab)} = \left(\frac{m}{2}\right) \frac{\sigma^{SPS}_{(hh' \to a)} \cdot \sigma^{SPS}_{(hh' \to b)}}{\sigma_{\text{eff}}}$$




- LO DPS
  $\sigma_{DPS}$ ~ (parton density)$^4$

- m is number of "distinguishable partonic subprocesses"
  - m = 1 when a = b, m = 2 when a ≠ b
- $\sigma_{eff}$, regarded as an important link to transverse profile of partons.
  - assumed to be process & energy independent

# DPS with same-sign WW production @ 13 TeV

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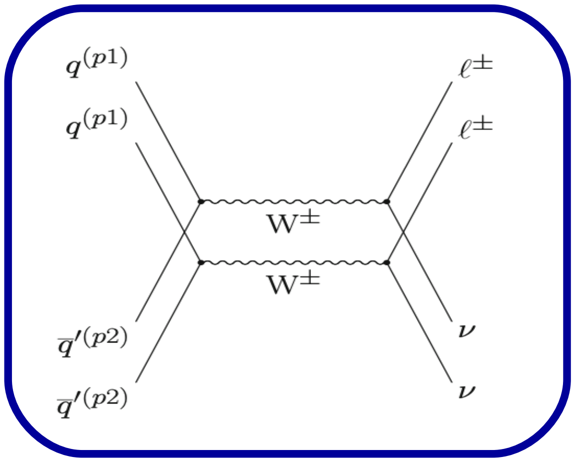
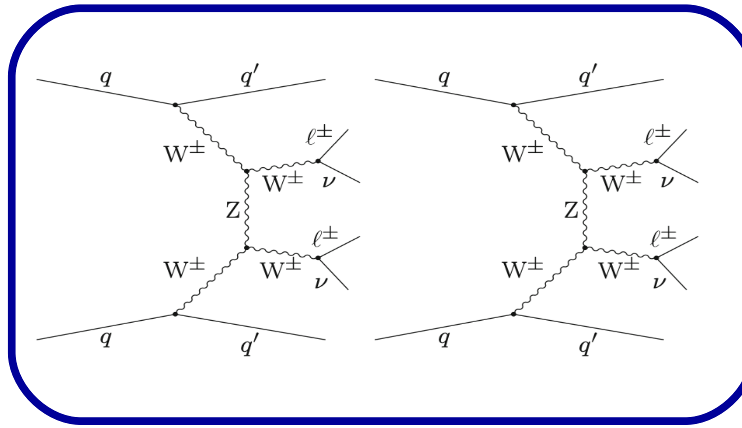
- W Boson Production: a benchmark process at LHC
- Same-sign WW DPS to leptons is very promising theoretically
  - very clean final state: two leptons with some missing $E_T$
  - good process to track down correlations in proton's pdf structure!
  - improved MC models

**DPS**




**SPS**




**Event selection**

Two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$

$p_T^{\ell_1} > 25\,\text{GeV}$ , $p_T^{\ell_2} > 20\,\text{GeV}$

$|\eta_e| < 2.5$, $|\eta_\mu| < 2.4$

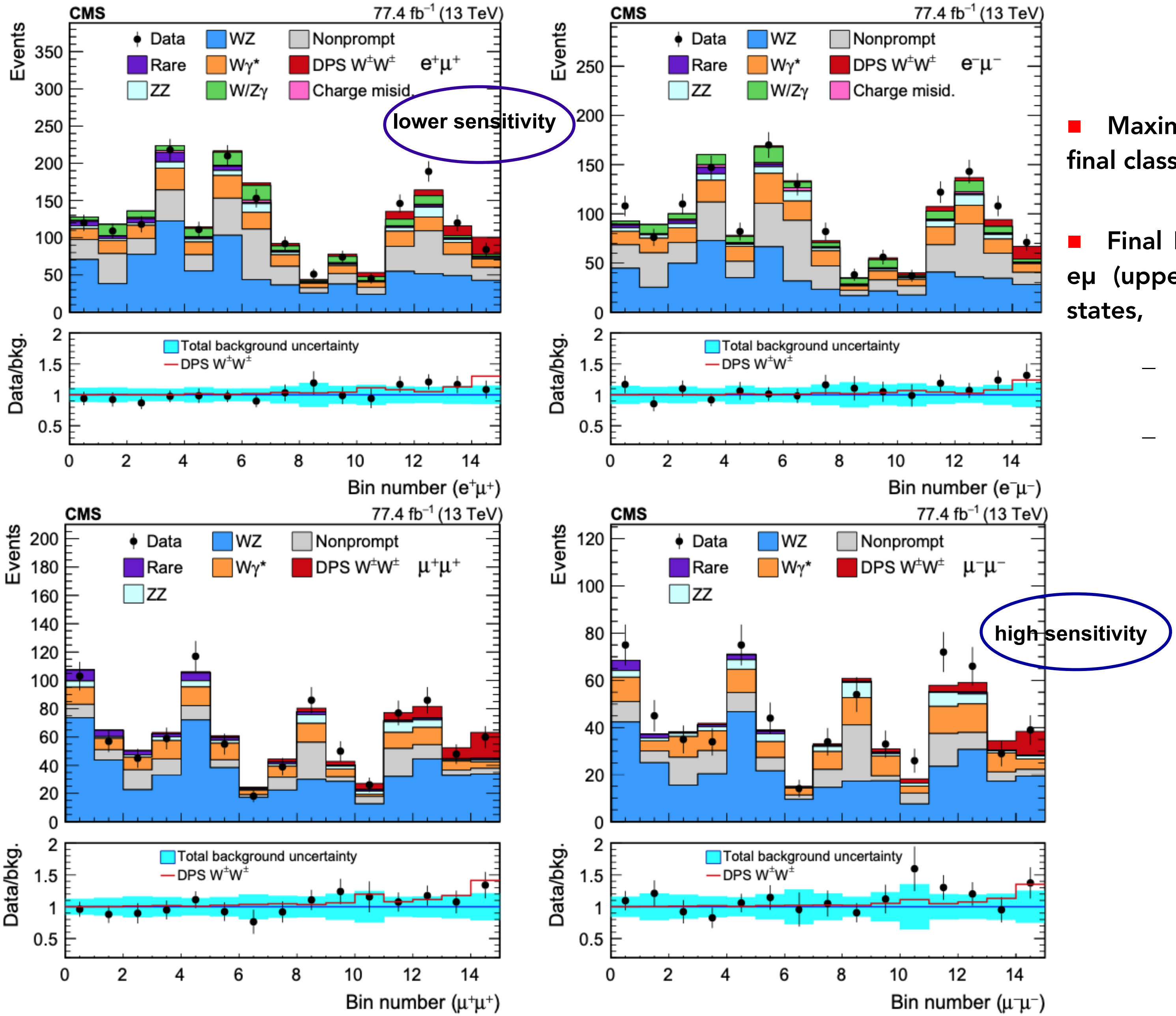
$p_T^{\text{miss}} > 15\,\text{GeV}$

$N_{\text{jets}} < 2$ ($p_T^{\text{jet}} > 30\,\text{GeV}$ and $|\eta_{\text{jet}}| < 2.5$)

$N_{\text{b-tagged jets}} = 0$ ($p_T^{\text{b jet}} > 25\,\text{GeV}$ and $|\eta_{\text{b jet}}| < 2.4$)

Veto on additional e, $\mu$, and $\tau_h$ candidates

# Results: DPS WW @ 13 TeV




- Maximum likelihood fit to the final classifier
- Final BDT classifier output for eμ (upper) and μμ (lower) final states,
  - separate the charge for maximum sensitivity
  - More sensitivity to ++ configuration than --

# Results: DPS WW @ 13 TeV

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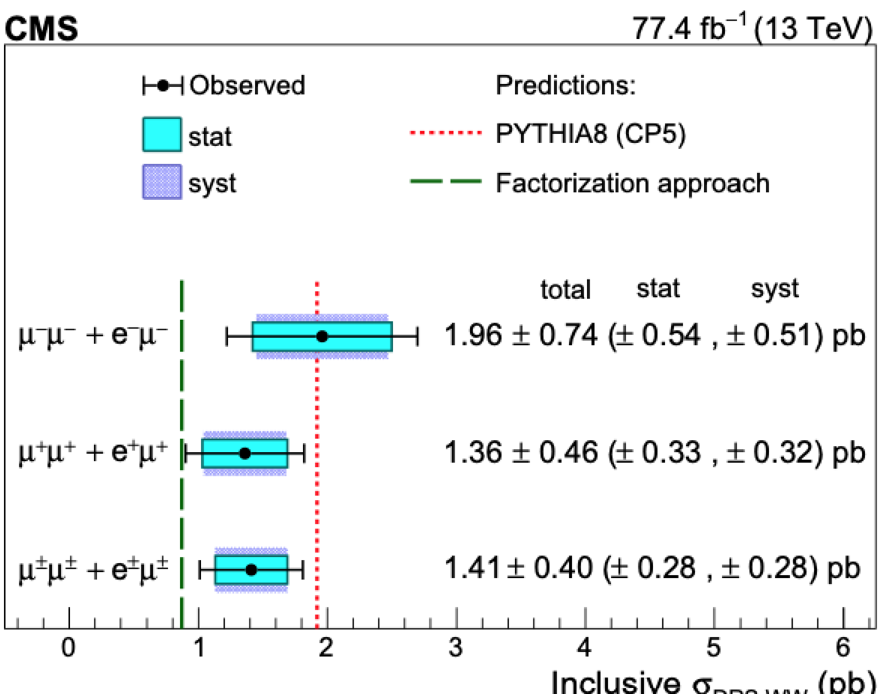
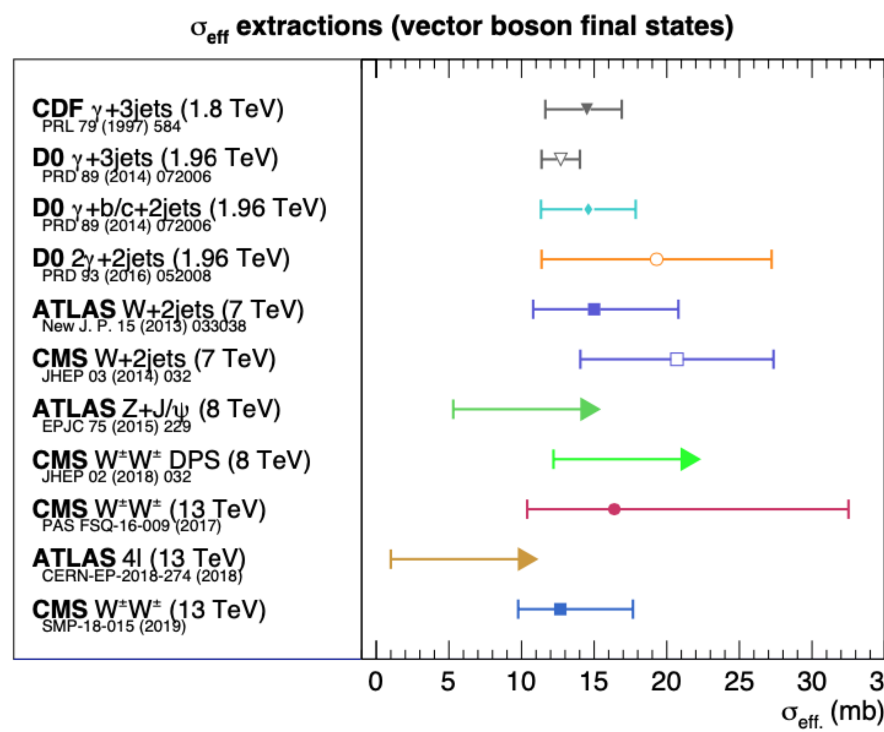
- W Boson Production: a benchmark process at LHC
  - Results obtained from the maximum likelihood fit to the final classifier distribution

| | Value | Significance (standard deviations) |
|---|---|---|
| $\sigma^{\text{PYTHIA}}_{\text{DPS WW, exp}}$ | 1.92 pb | 5.4 |
| $\sigma^{\text{factorized}}_{\text{DPS WW, exp}}$ | 0.87 pb | 2.5 |
| $\sigma_{\text{DPS WW, obs}}$ | $1.41 \pm 0.28$ (stat) $\pm 0.28$ (syst) pb | 3.9 |
| $\sigma_{\text{eff}}$ | $12.7^{+5.0}_{-2.9}$ mb | — |

- Observed cross section values for inclusive DPS WW production



# Average very forward energy @ 13 TeV

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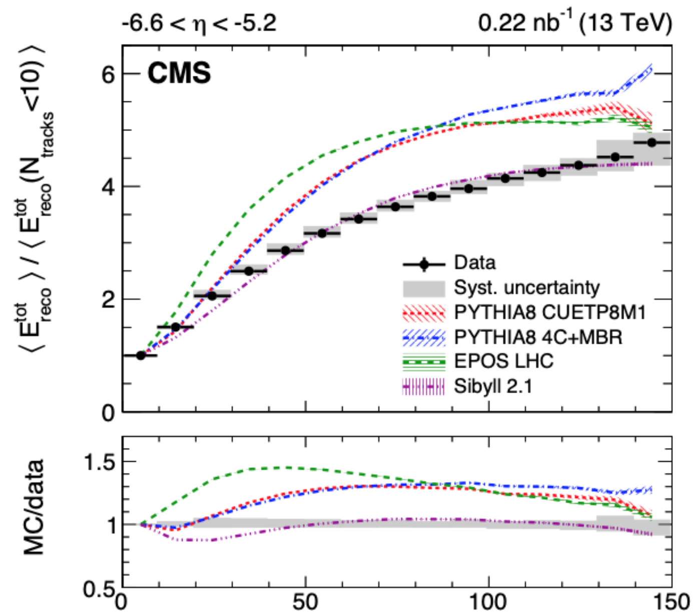
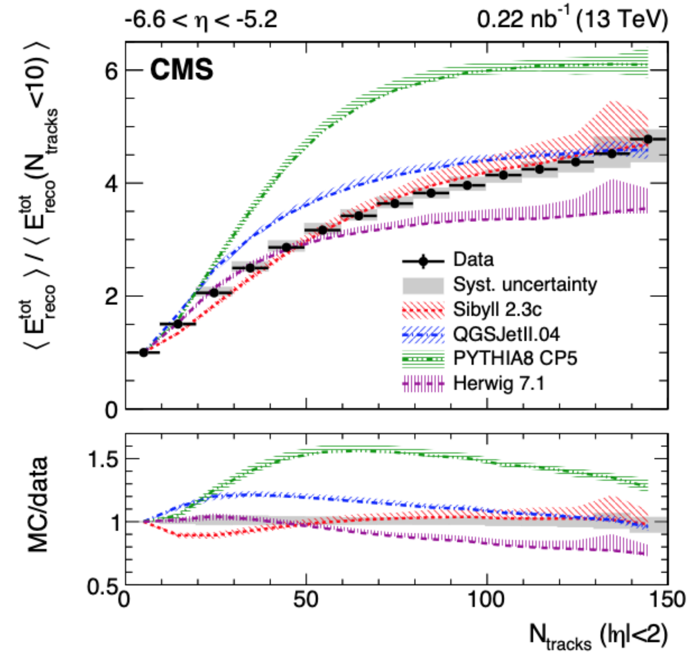
- **Motivation:**
  - Energy carried by particles produced in the very forward region powerful probe
    - to study UE activity
    - to validate MPI models and tuning
  - First correlation study of hadron activity at very forward & central rapidities performed @13 TeV

- **Analysis strategy:**
  - Average energy reconstructed in $-6.6 < \eta < -5.2$ as a function of the track multiplicity
  - Activity in @ least one tower of HF calorimeter
  - At-least one track reconstructed in CMS tracker with $|\eta| < 2$
  - Apply a cut on reco. vertex multiplicity--> reduce PU events




▶ Comparison with models and high energy cosmic ray air showers

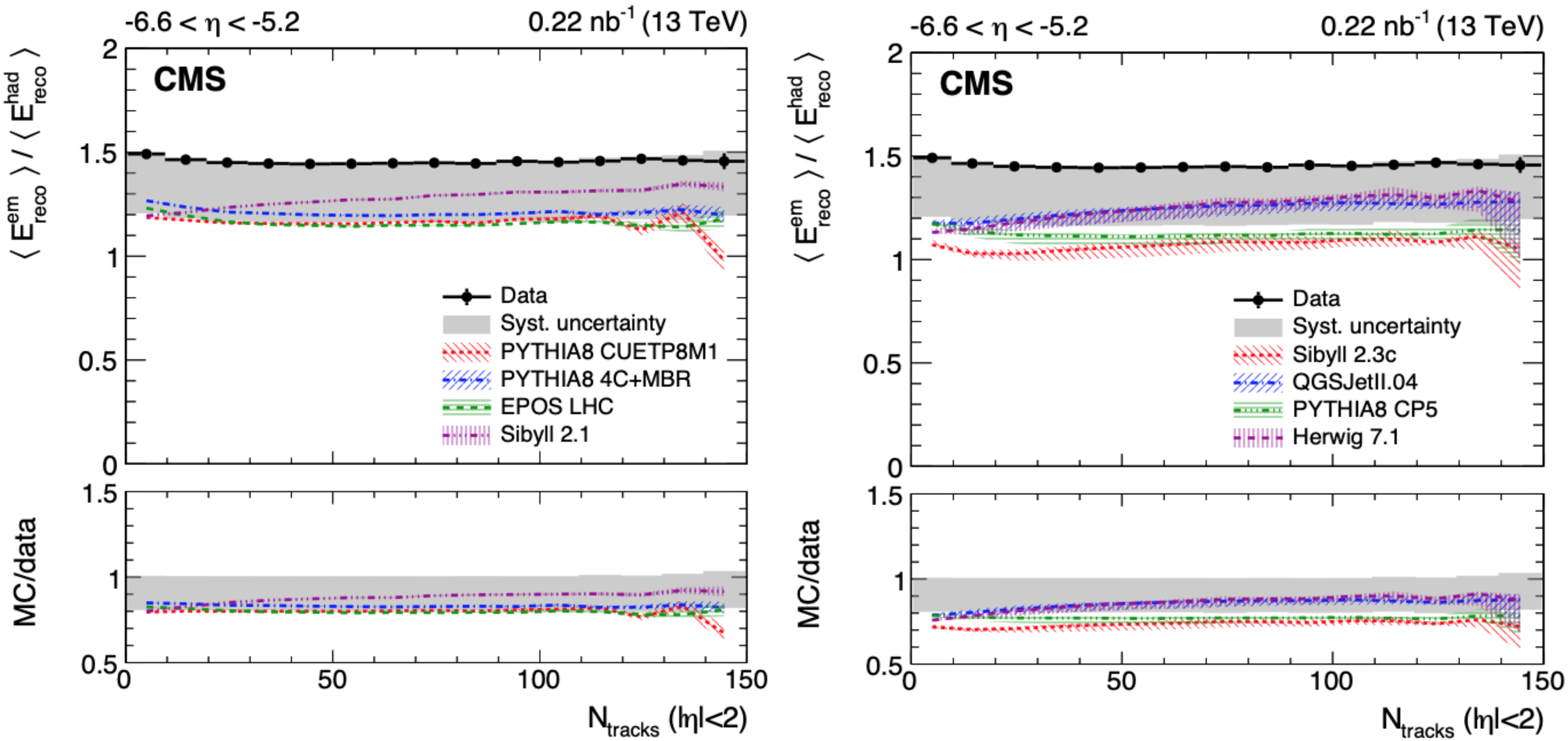
▶ Increase with $N_{tracks}$

▶ UE parameter tunes determined at central rapidity can be safely extrapolated to the very forward region!

▶ SIBYLL 2.1 gives the best description

# Ratio of average EM and hadronic energies

- Ratio is sensitive to the details of hadronisation, and discrepancies between models and data may reflect an inadequate description of the hadron production mechanisms.




- Ratio is approximately constant over the whole multiplicity range.
- No dramatic change of the particle production mechanism is observed at this very forward pseudorapidity.
- All model predictions are lower than the data
  - QGSJETII.04, SIBYLL 2.1, and HERWIG 7.1 provide the best description