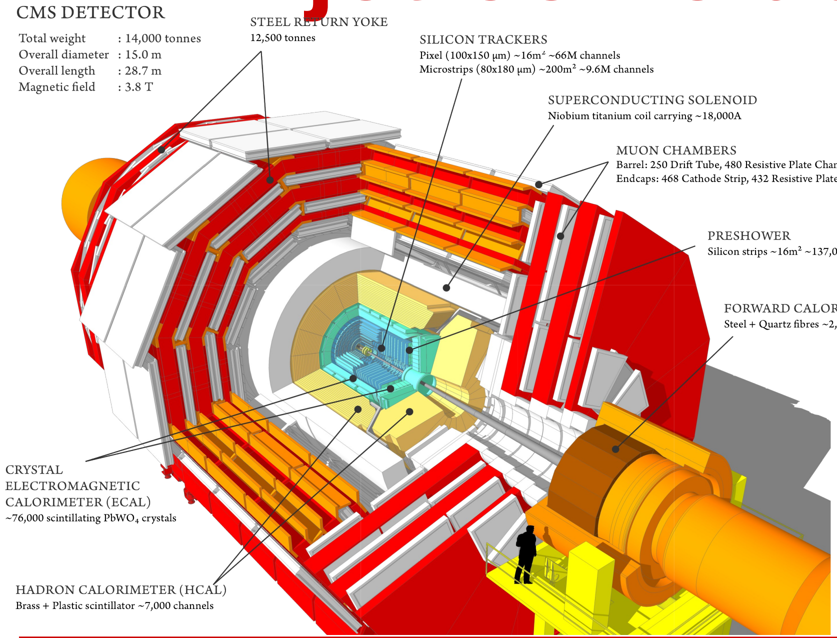
# Multi-jet production and jet correlations at CMS

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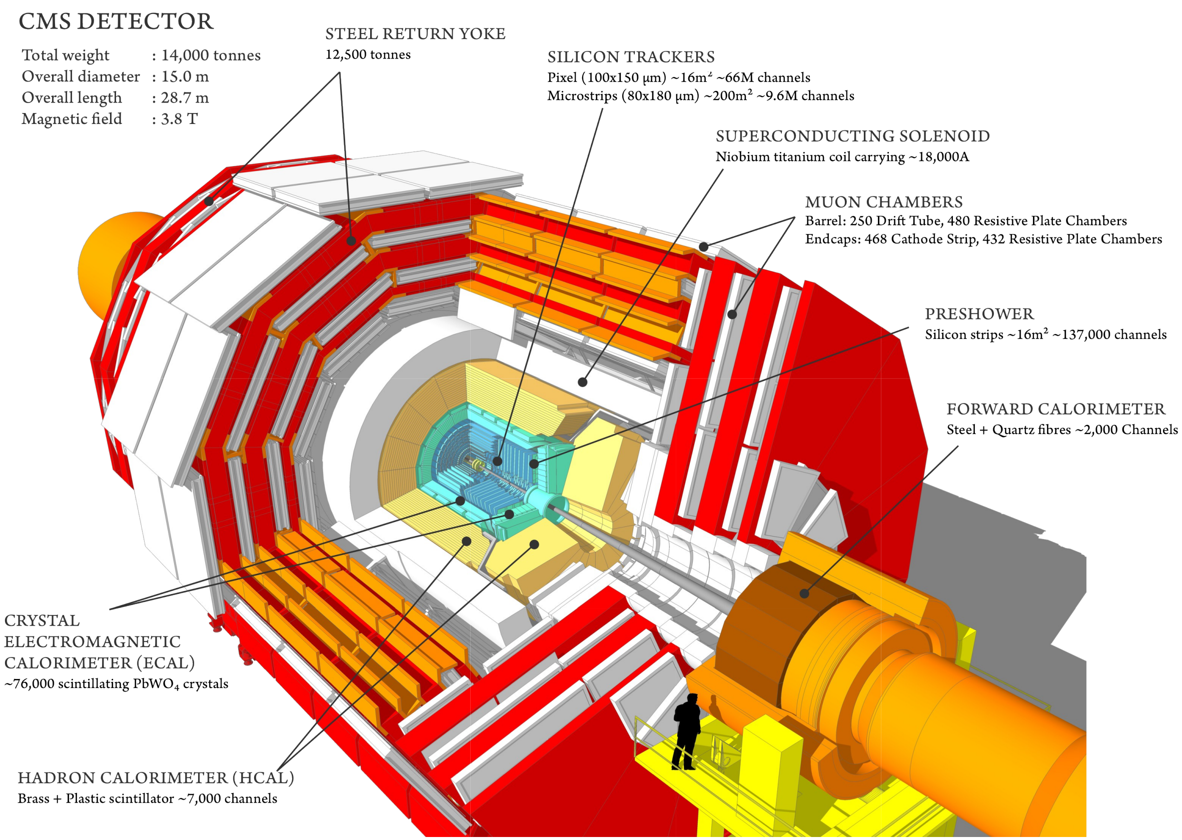
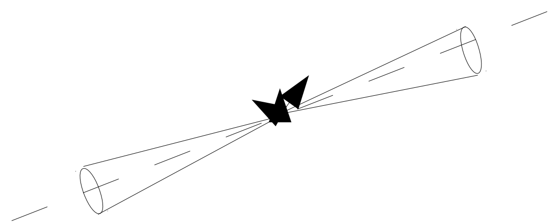
# Outline

- **Mueller-Navelet** dijets at 7 TeV: decorrelation (DGLAP vs. BFKL)
- Dijets with rapidity gap at 7 TeV: **color-singlet exchange**



# MN dijet decorrelations, 7 TeV

- Azimuthal angle correlations between most forward and backward jets (Mueller-Navelet configuartion).

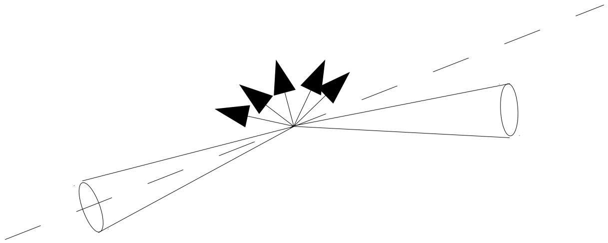


- Anti-$k_T$ jets, R=0.5, $p_T$>35 GeV, |y|<4.7, separation $\Delta y \approx 9.4$
- pQCD calculations with collinear factorisation using the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (**DGLAP**) parton evolution scheme are very successful
- At low $p_T$ and large $\Delta y$, Balitsky–Fadin–Kuraev–Lipatov (**BFKL**) evolution equations are more appropriate.
  - LL at infinite energy, NLL at finite energy
  - Prediction: dijet xsec increasing with $\Delta y$

**ArXiv:1601.06713**
**Submitted to JHEP**

# MN dijet decorrelations, 7 TeV

- Jets: back-to-back ($\Delta\phi=\pi$) on tree level; any decorrelation is due to higher order processes, semi-hard parton interactions



- D0 did not find significant BFKL indications ($\Delta y<6$). Decorrelations are predicted to be sensitive to BFKL.
- 
- Trigger: x100 gain: forward-backward dijet trigger with $|y|>3$ GeV, $p_T>35$ GeV
- Average pileup = 2.2, but only single-vertex events used
- Unfolding for detector resolution, bin migrations < 20%.

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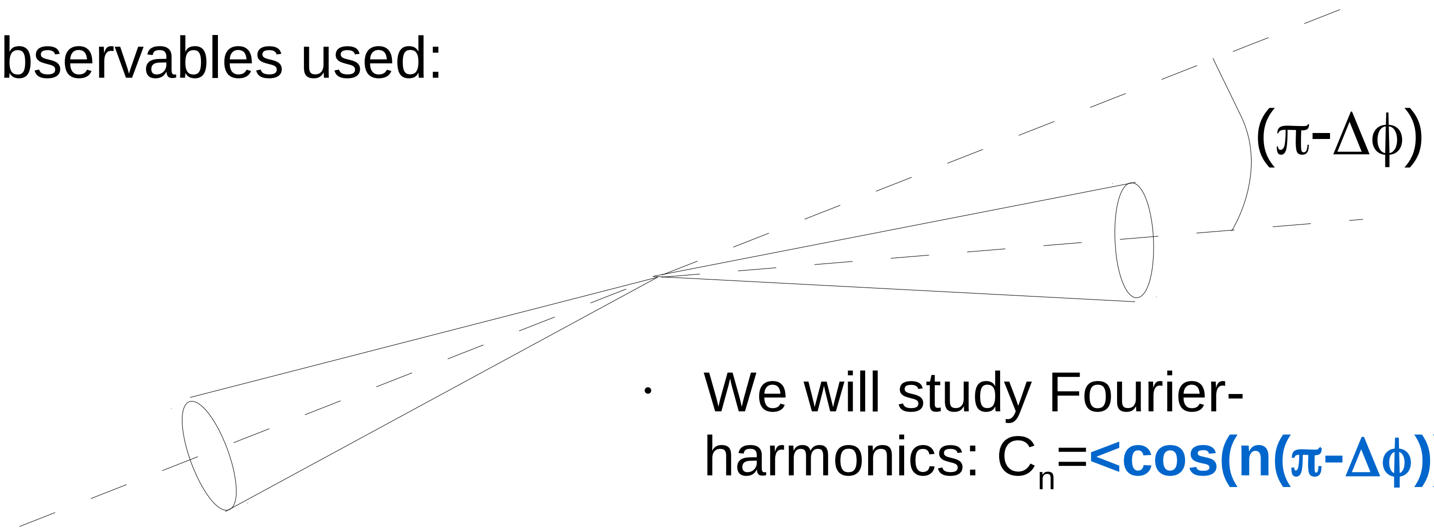
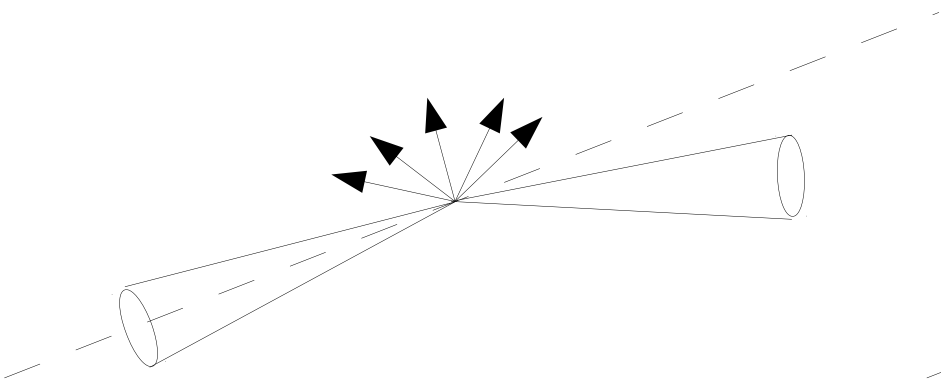
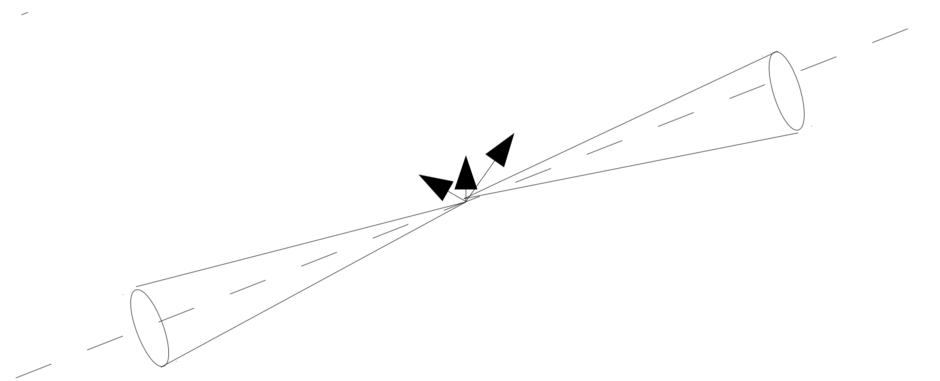
# Observables

- The observables used:




- We will study Fourier-harmonics: $C_n$=**<cos(n(π-Δφ))>**





**BFKL**: large jet Δη:
parton emissions, decorrelation

**DGLAP**: low $p_T$ emissions,
independent of jet Δη: no decorrelation

# Monte Carlo models

- DGLAP+LL soft and collinear radiation, tuned to LHC data:
  - **PYTHIA6** Z2, **PYTHIA8** 4C, **HERWIG++**
- DGLAP with three-level matrix elements + LL parton showers
  - **SHERPA**
- NLO terms:
  - **POWHEG**, interfaced with PYTHIA
- NLL **BFKL analytical** predictions
  - Phys. Rev. Lett. 112 (2013) 082003
- LL **BFKL matrix elements**
  - HEJ+ARIADNE (for hadronisation and PS)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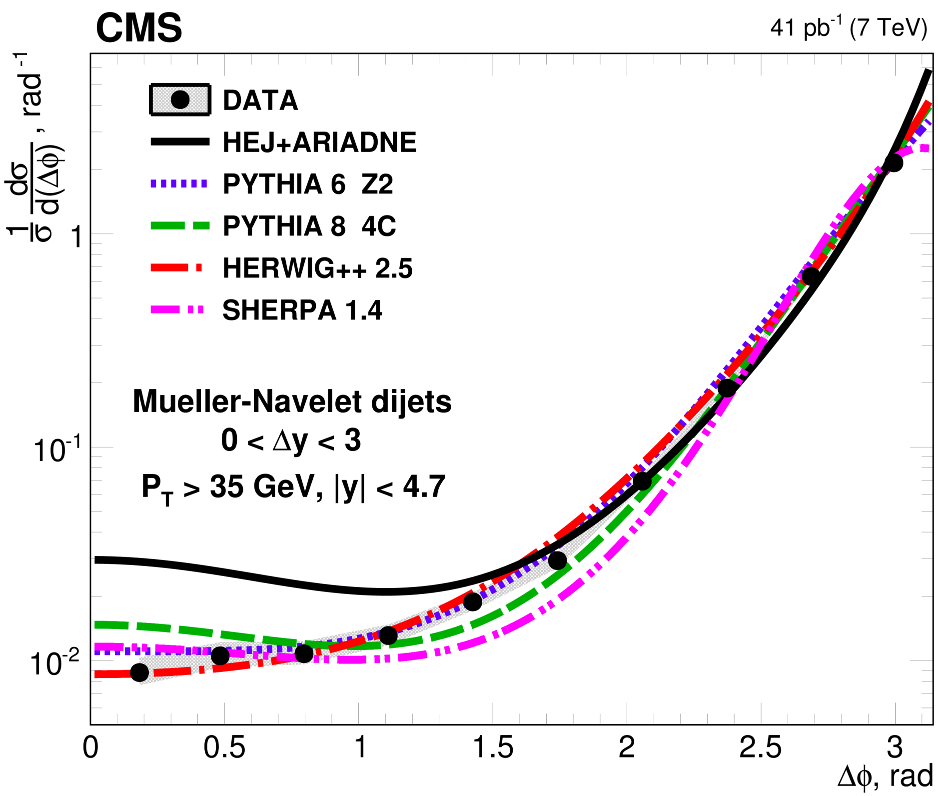
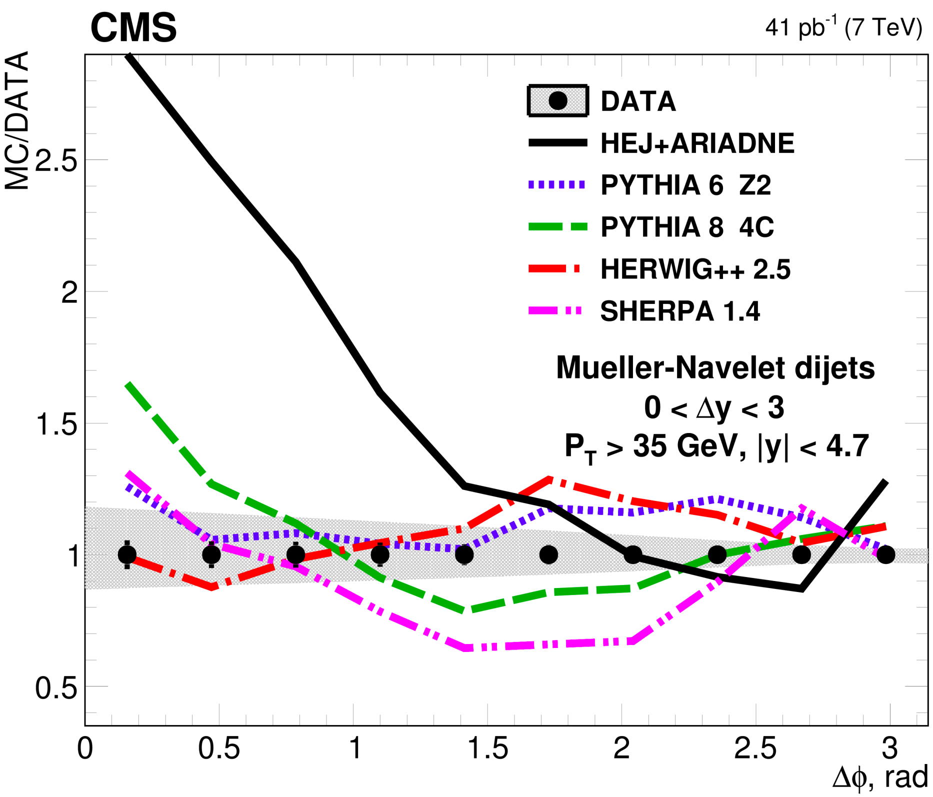
# Azimuthal angle difference, Δy<3

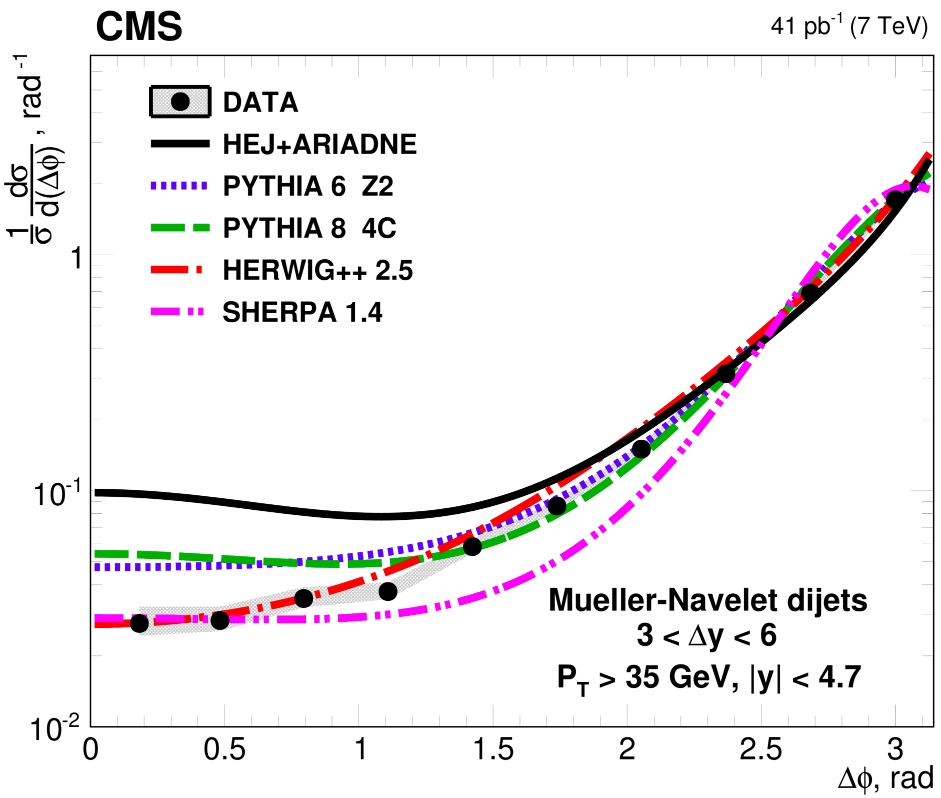
- Sharp **correlation** between jets
- **DGLAP** models PYTHIA6 and HERWIG++ agree well with data
- **PYTHIA8** and **SHERPA**: significant deviations
- **HEJ** overestimates decorrelations

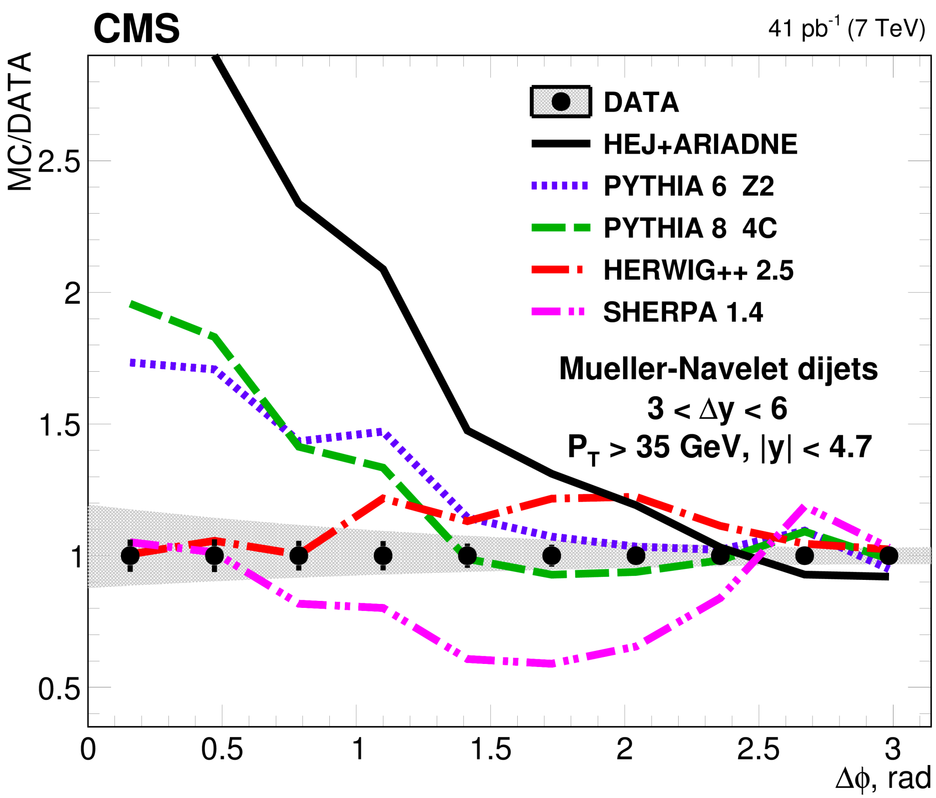


# Azimuthal angle difference, 3<Δy<6

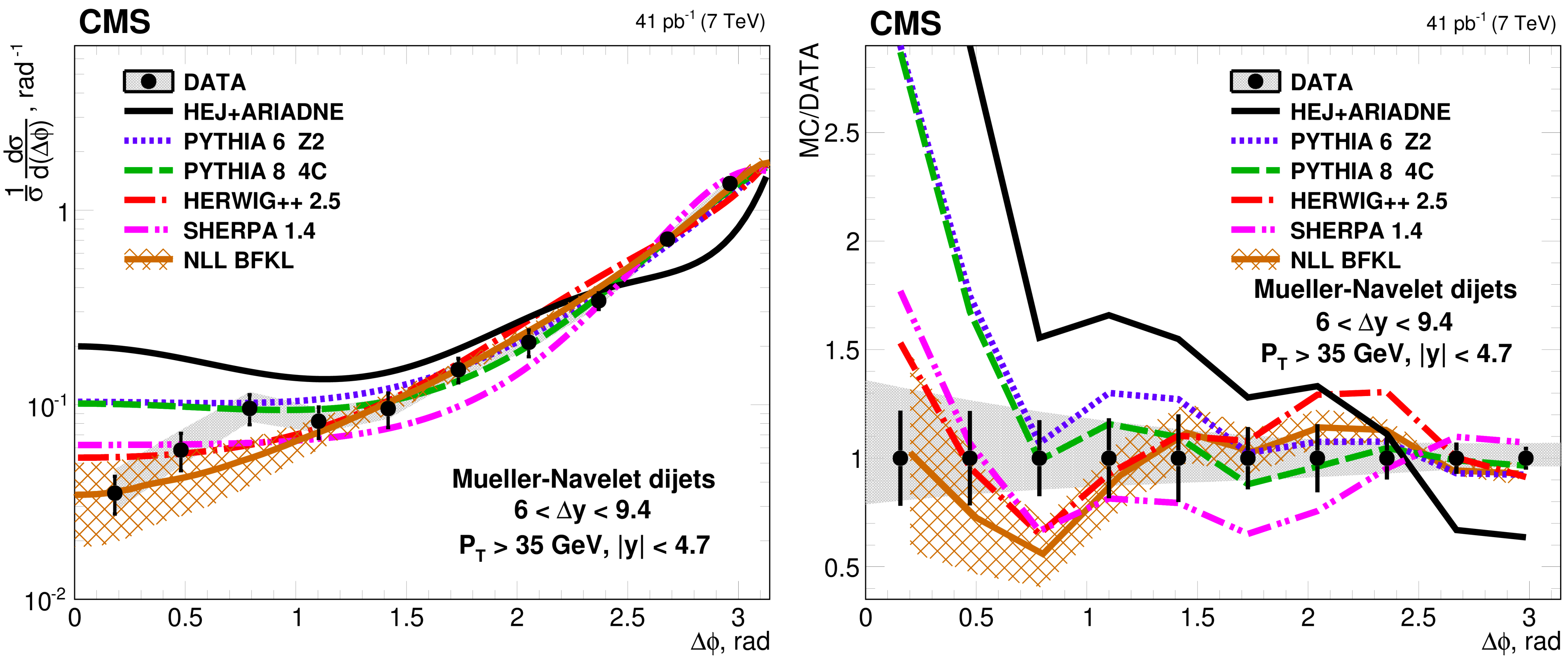
- **PYTHIA** deviates from data at small $\Delta\phi$, where **HERWIG** and **SHERPA** are successful



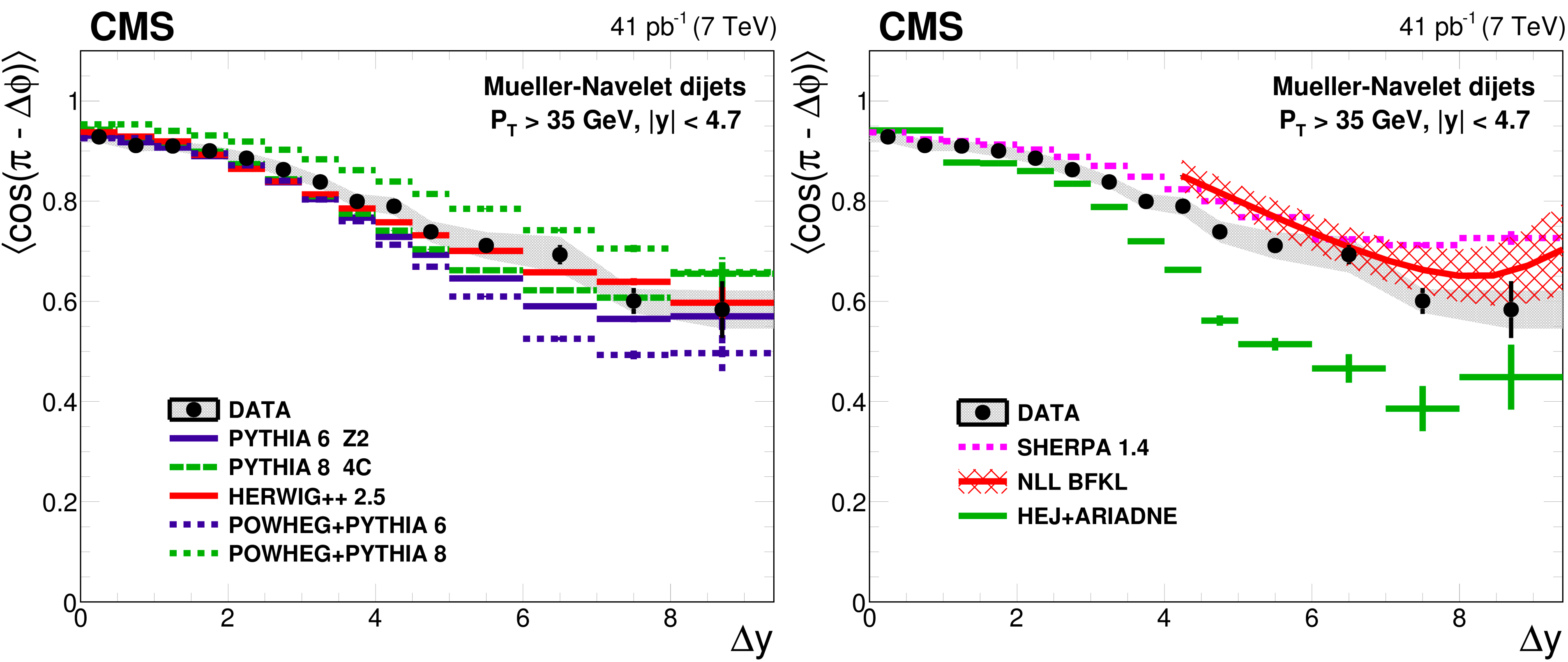
# Azimuthal angle difference, $6<\Delta y<9.4$

- Correlation diluted at very high $\Delta y$
- **PYTHIA** deviates from data at small $\Delta\phi$
- We will study Fourier-harmonics: $C_n=\langle\cos(n(\pi-\Delta\phi))\rangle$



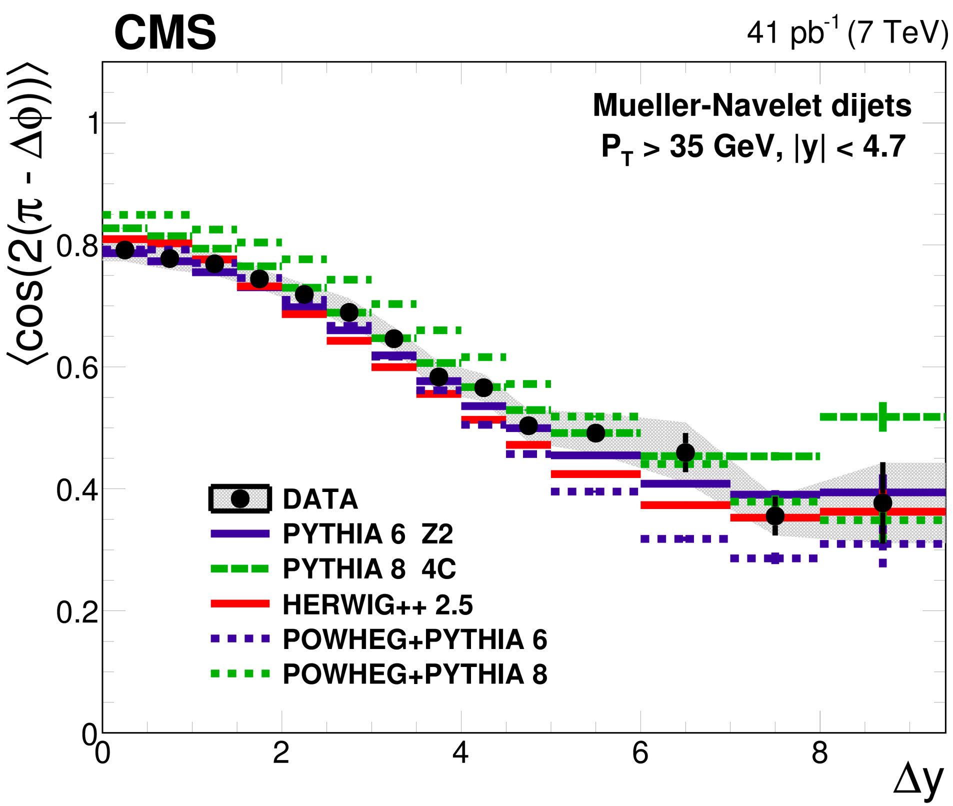
# $C_1 \equiv \langle\cos(\pi-\Delta\phi)\rangle$ distributions

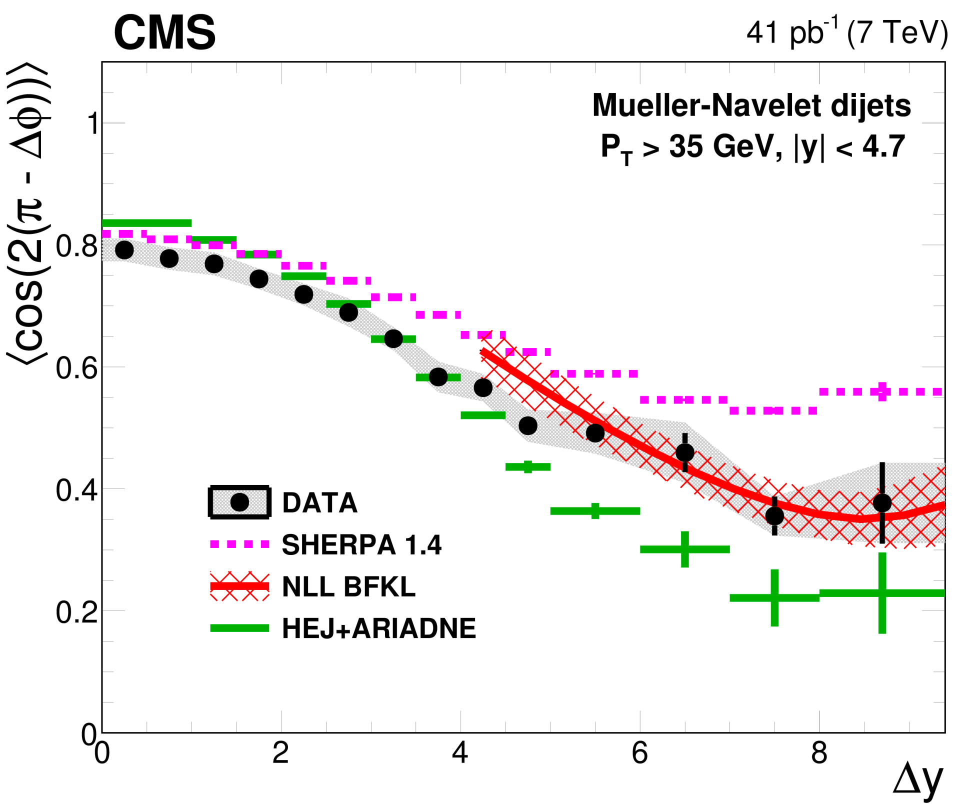
- <cos> can be expressed using conformal symmetries in **BFKL**
- **HERWIG++**: fair agreement
- **POWHEG** shows no improvement
- **SHERPA**: not enough decorrelation, HEJ: too much decorrelation



# $C_2 \equiv \langle\cos(2(\pi-\Delta\phi))\rangle$ distributions

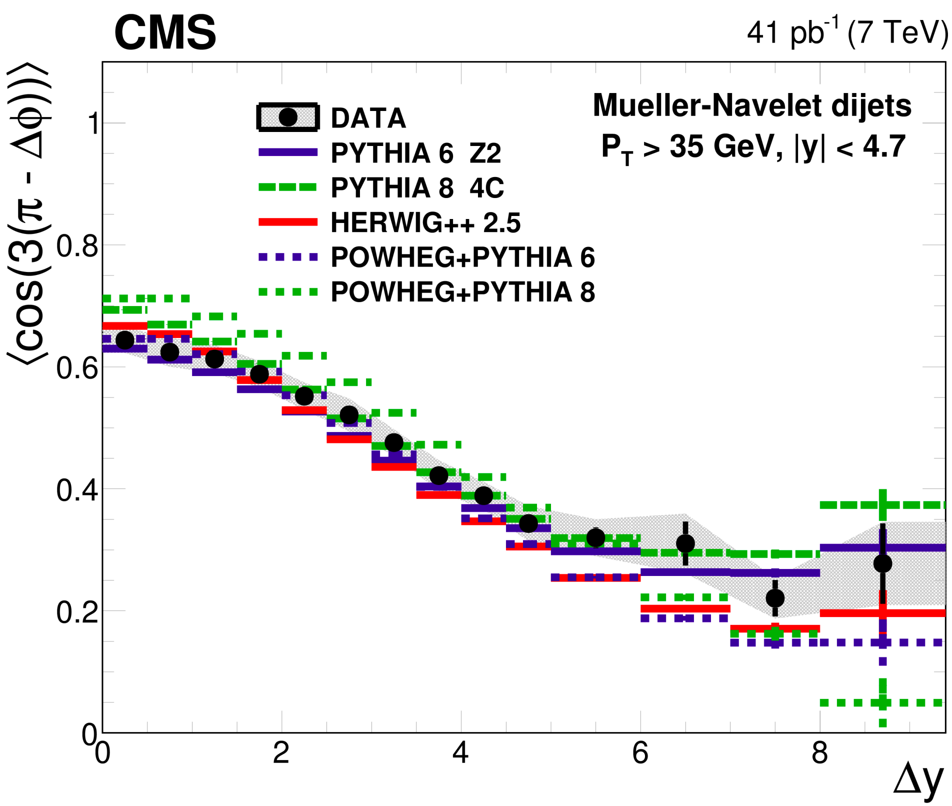
- **PYTHIA** 6 and 8: fair agreement with data
- **SHERPA**: not enough decorrelation
- **HEJ**: too much decorrelation

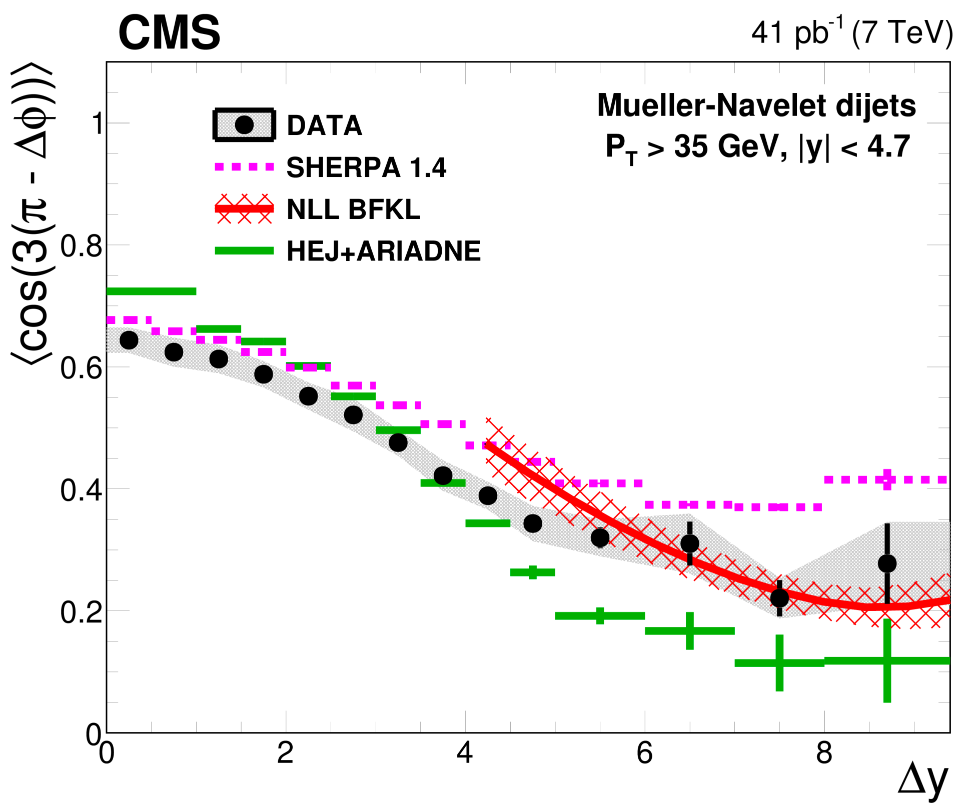


# $C_3 \equiv \langle\cos(3(\pi-\Delta\phi))\rangle$ distributions

- **PYTHIA** 6 and 8: fair agreement with data
- **SHERPA**: not enough decorrelation
- **HEJ**: too much decorrelation

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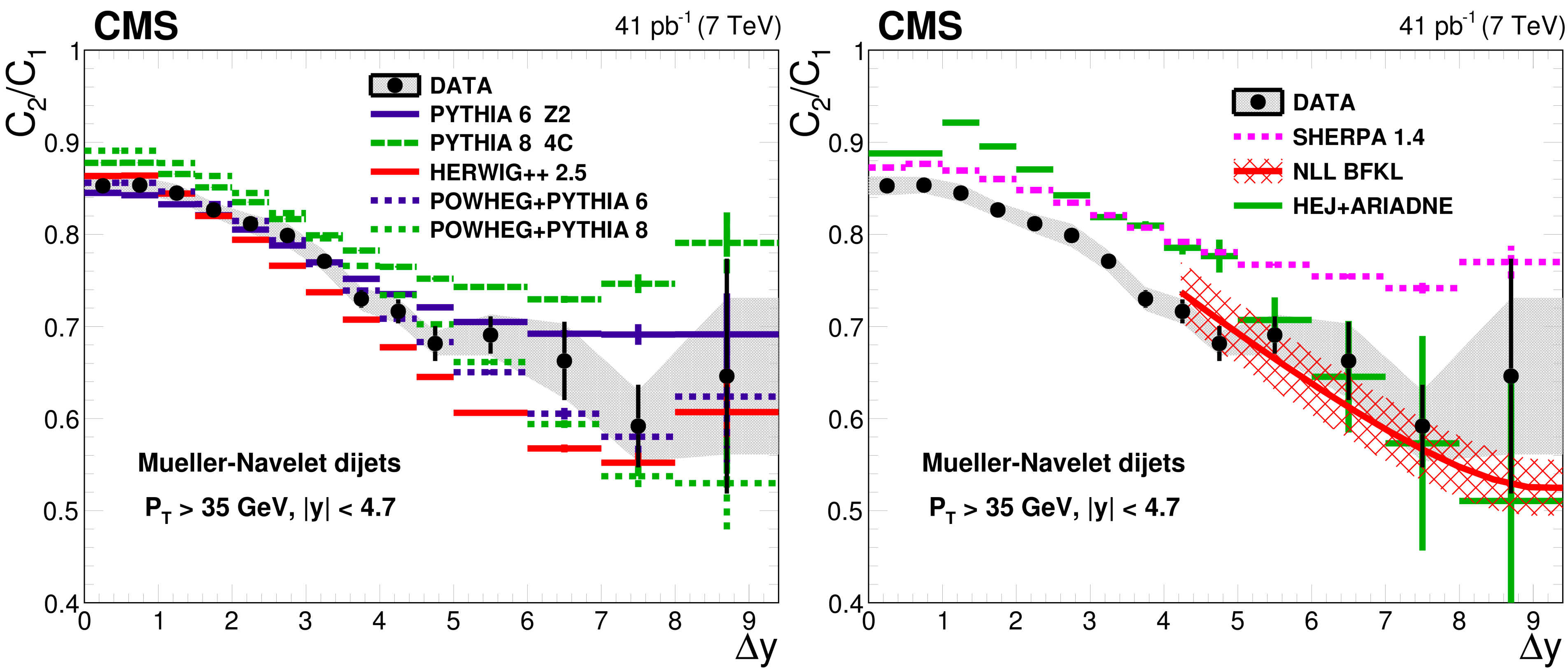
# $C_2/C_1$ ratios

- Ratios suppress **DGLAP** contributions and uncertainties of factorization and renormalization scales
- **PYTHIA** and **SHERPA** underestimates decorrelation, **HERWIG** overestimates
- NLL **BFKL**: good agreement with data



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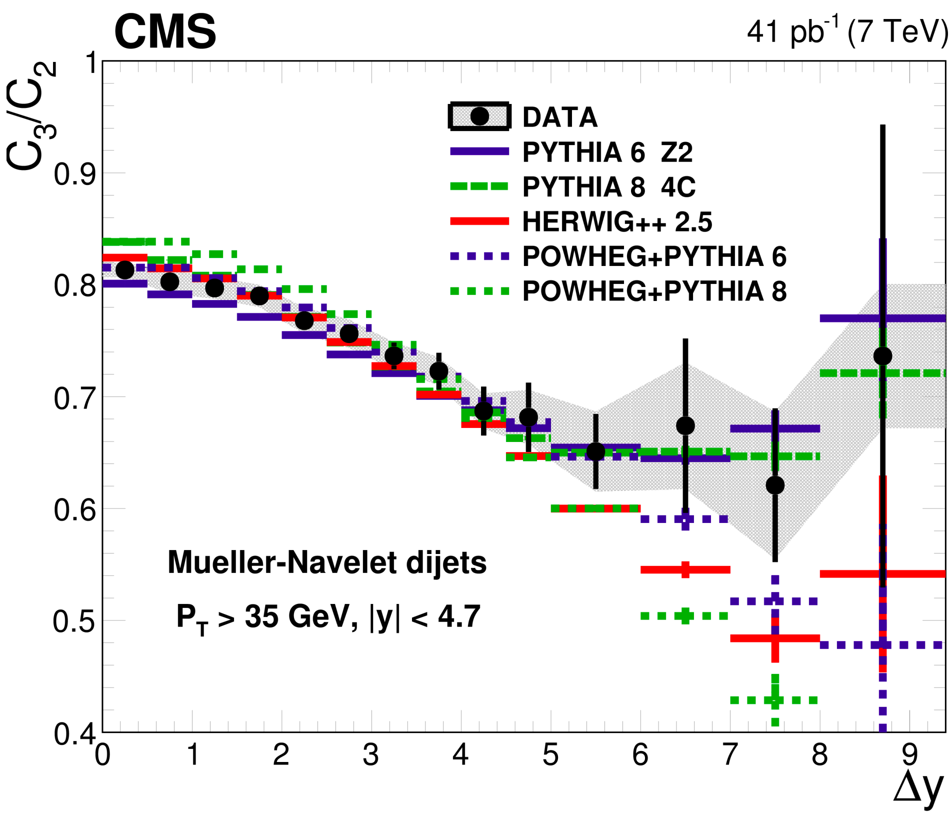
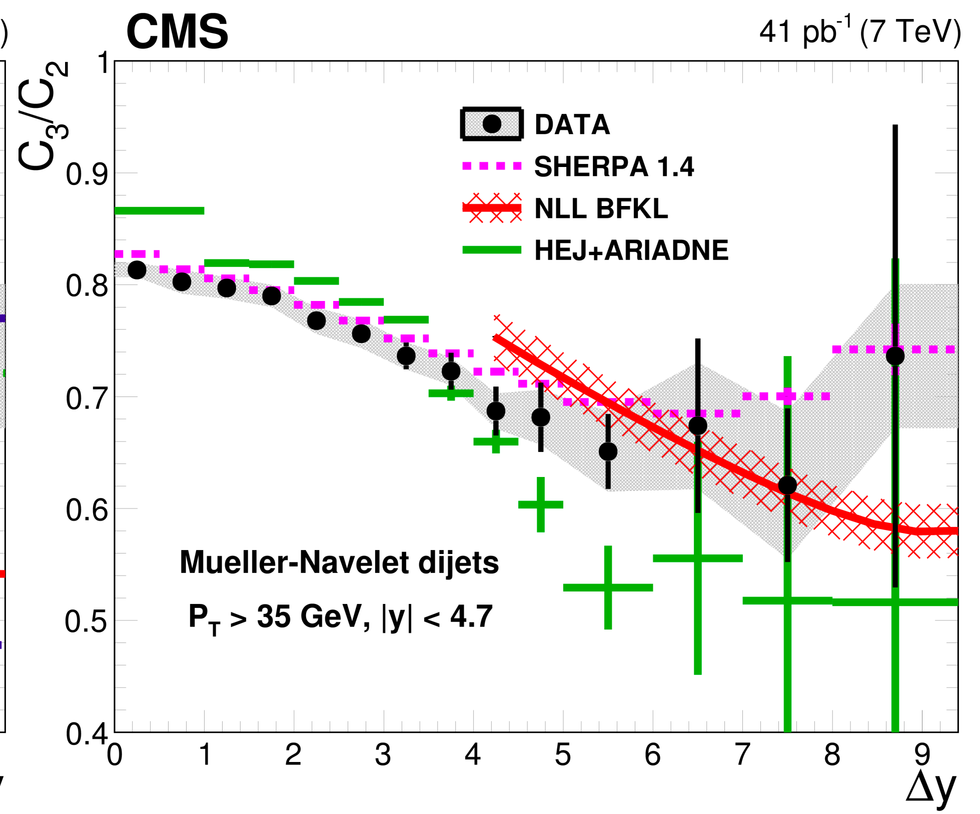
# $C_3/C_2$ ratios

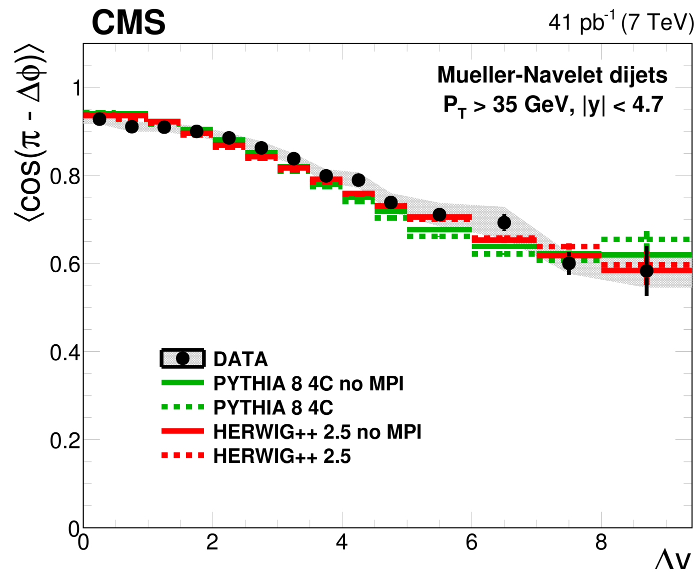
- **PYTHIA** consistent with data, **HERWIG** and **HEJ** overestimates
- **SHERPA** consistent with data
- NLL **BFKL**: good agreement with data

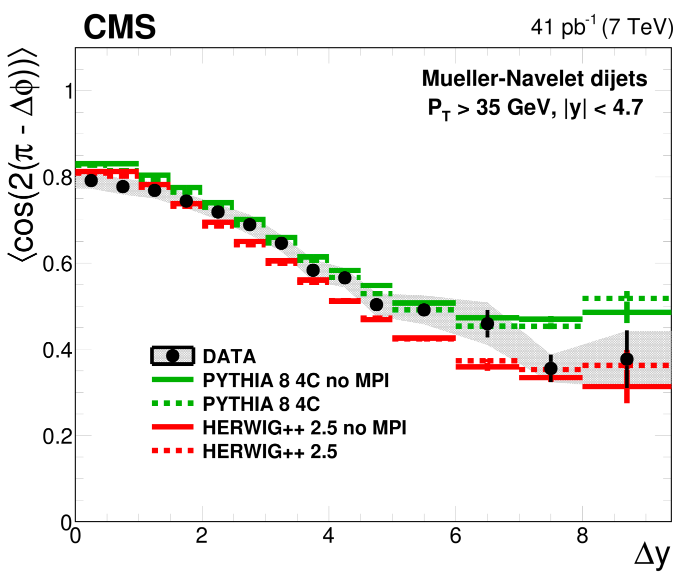


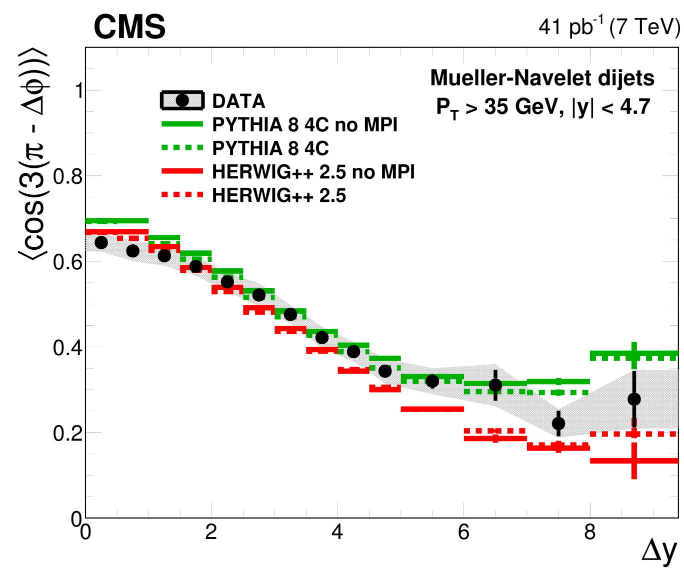



# <cos(n(π-Δϕ))> distributions: MPI?

- Multi-parton interactions are another source of decorrelation
- Turning **MPI** on (dashed lines) or off (solid lines) in **PYTHIA8** and **HERWIG++** **does not change** the average cosine distributions!



# $C_2/C_1$ ratios: MPI?

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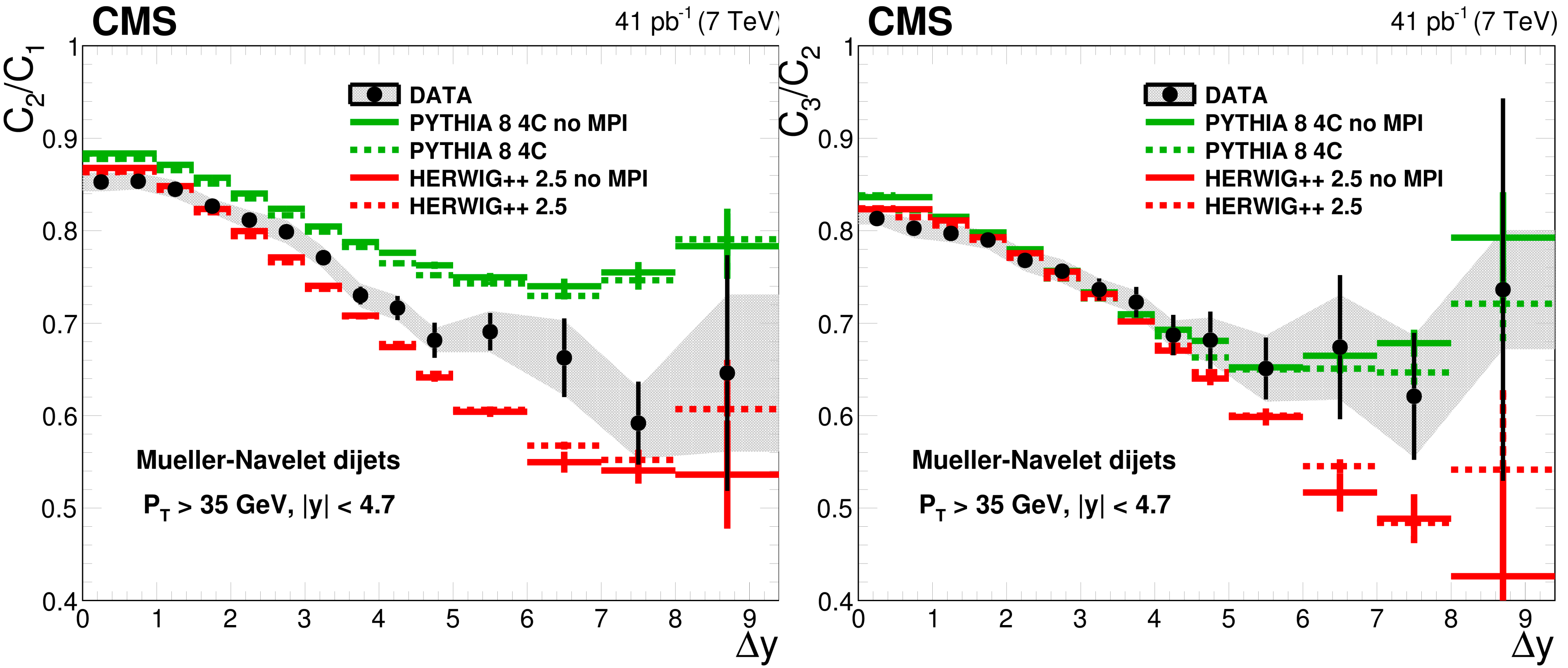


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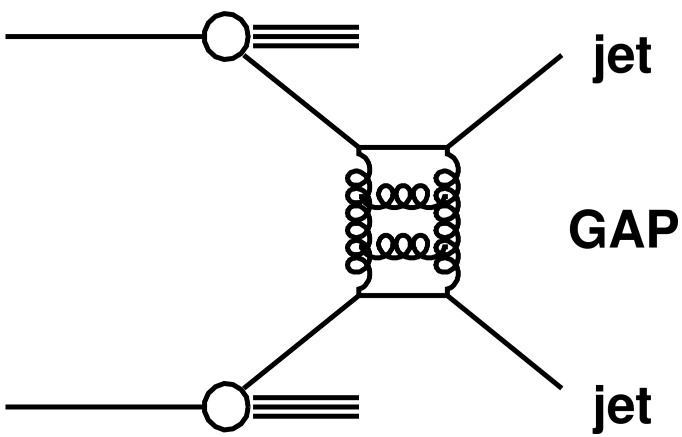
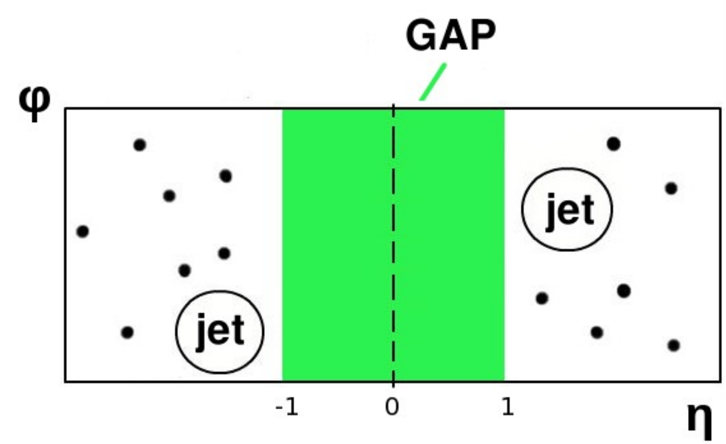
# Dijets with rapidity gap, 7 TeV

- Signature: **two** leading **jets** with no particles in between
- Jets with $p_T$>40 GeV, 1.5<|y|<4.5
- Dijets: **normally** gluon or quark exchange; color field; additional particle emissions between jets, **DGLAP** ($k_T$ ordered)
- No activity between jets: **BFKL** (ordering in x)
- Absence of particles: consistent with diffraction, color singlet exchange (CSE) – here a gluon ladder?
- Jet-gap-jet observed at D0, CDF, Tevatron, HERA
- Gap particles: $|\eta|<1$, $p_T$>0.2 GeV



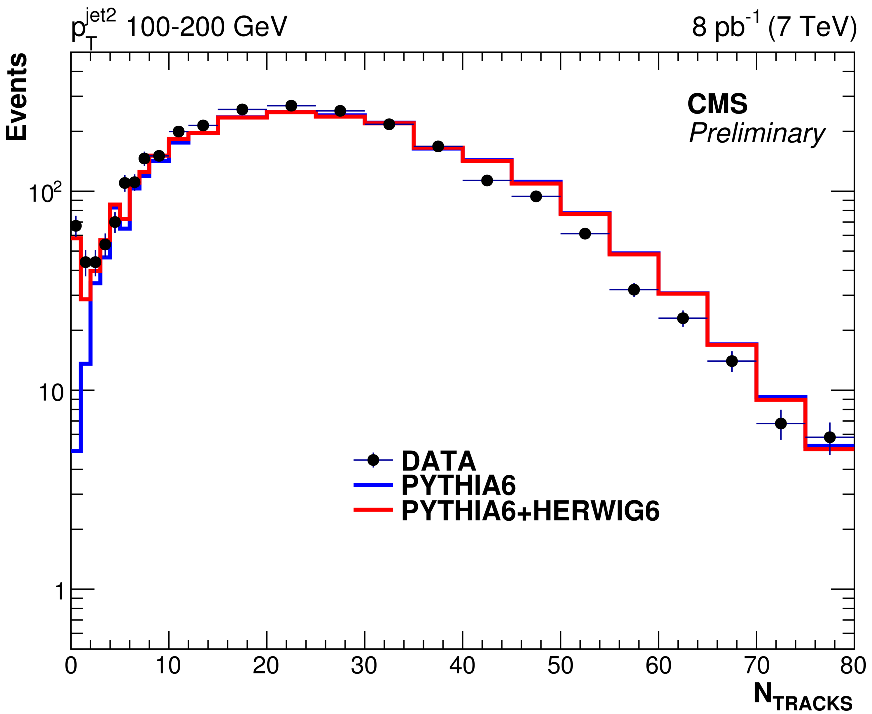

CMS PAS FSQ-12-001

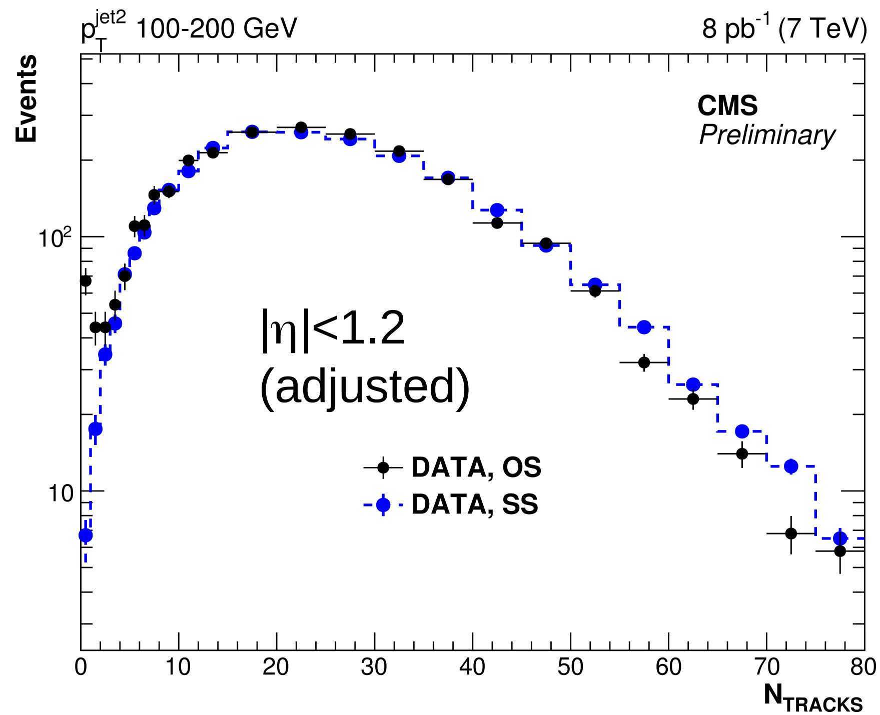
# Number of tracks between the jets

- Track multipicity distribution well described by **DGLAP**...
- ...Except at zero (jet-gap-get events!), which is described by **BFKL** (CSE)

Comparison with MC models

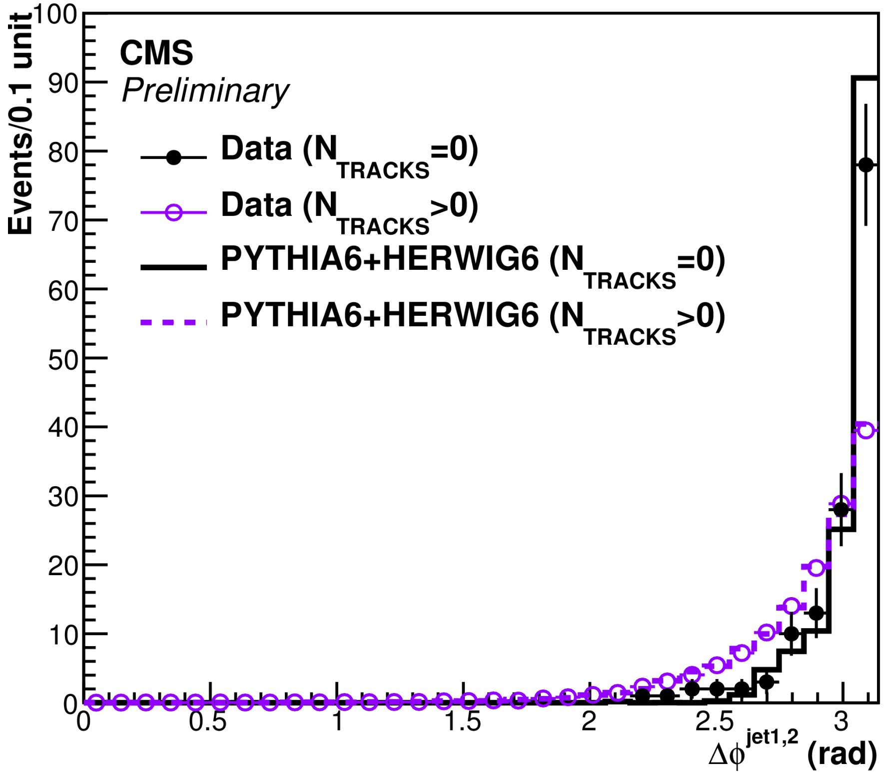
SS: the two leading jets are on the same side. Used to estimate background for the CSE peak.

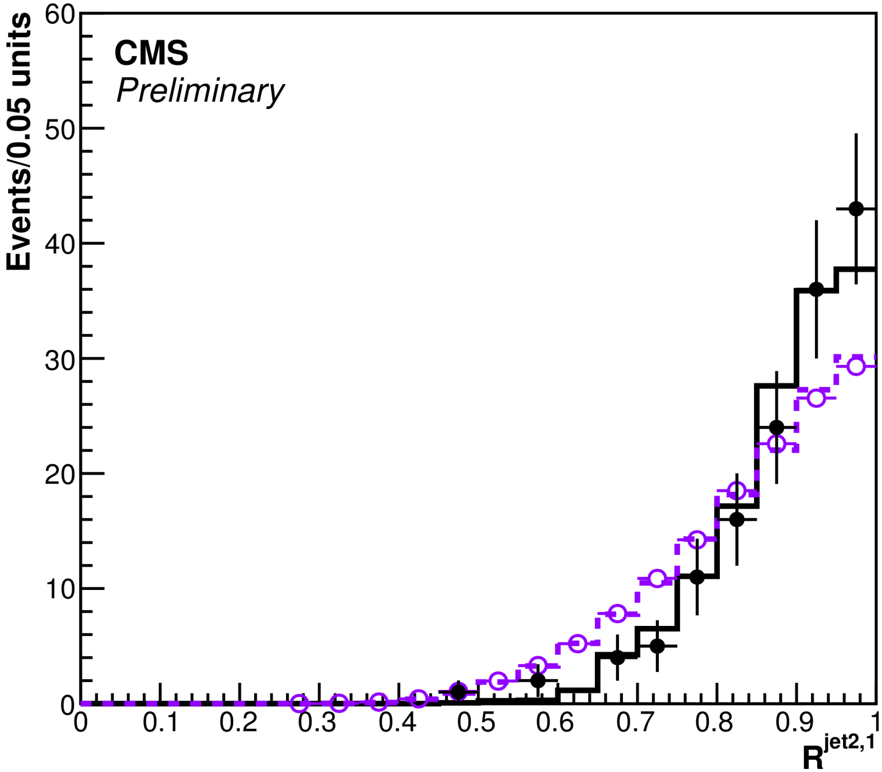


# Dijet $\Delta\phi$ and $p_T$ ratio distributions

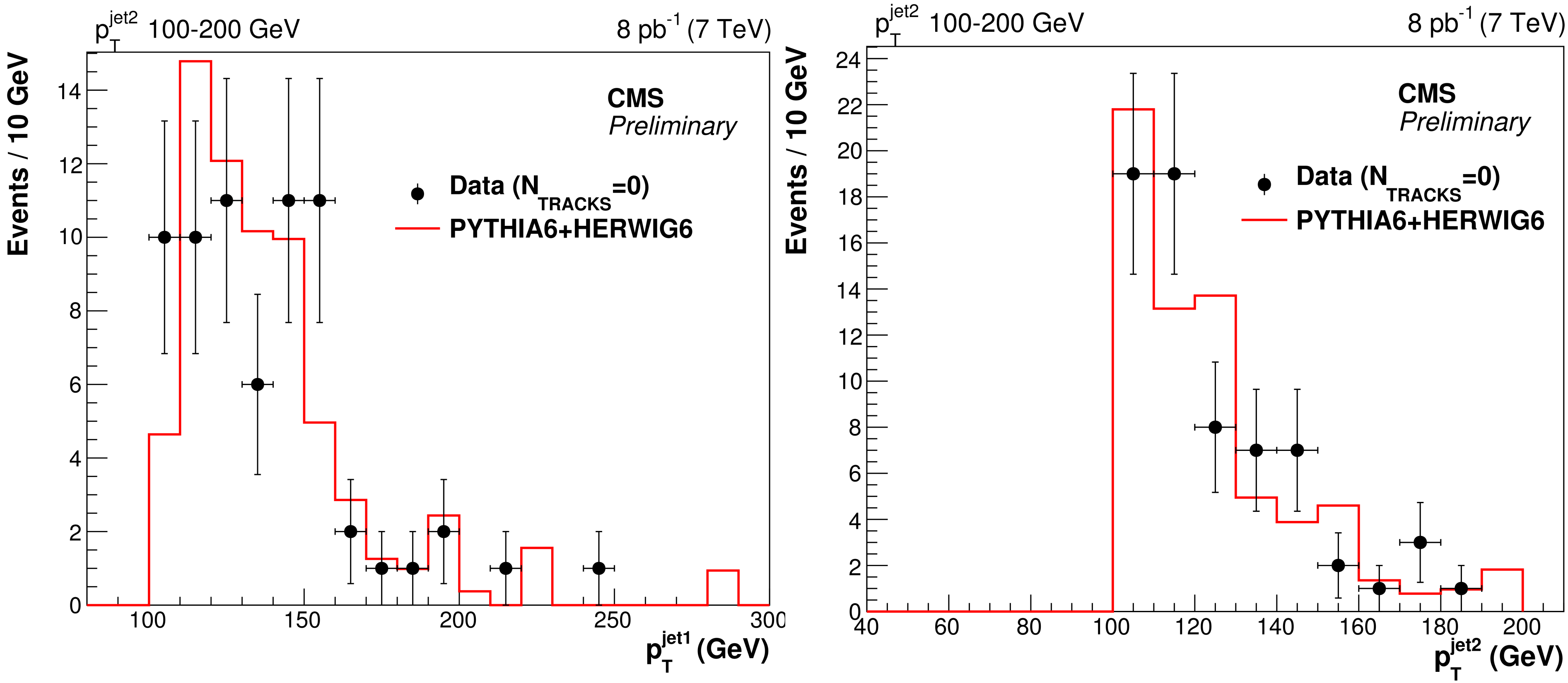
- The azimuthal angle difference and $R=p_{T2}/p_{T1}$ ratio distributions are well described by MC (CSE and non-CSE)
- For CSE ($N_{tracks}=0$), jets are more back-to-back and balanced



# Jet $p_T$ distributions

- In the zero-multiplicity bin (jet-gap-jet), the **BFKL**-based MC describes the $p_T$ distributions of the leading and subleading jet.

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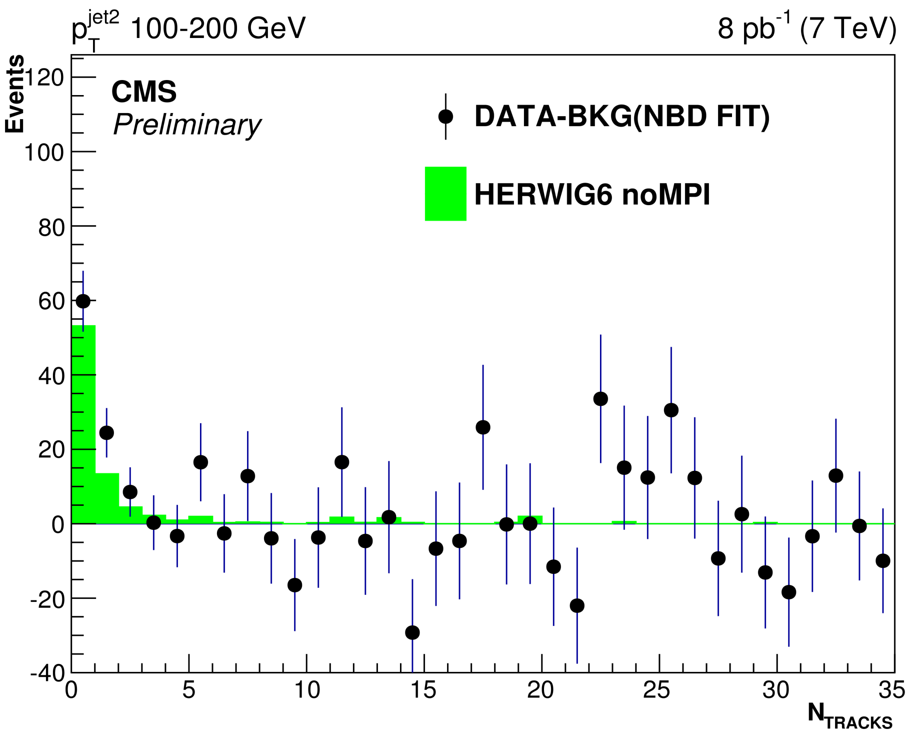
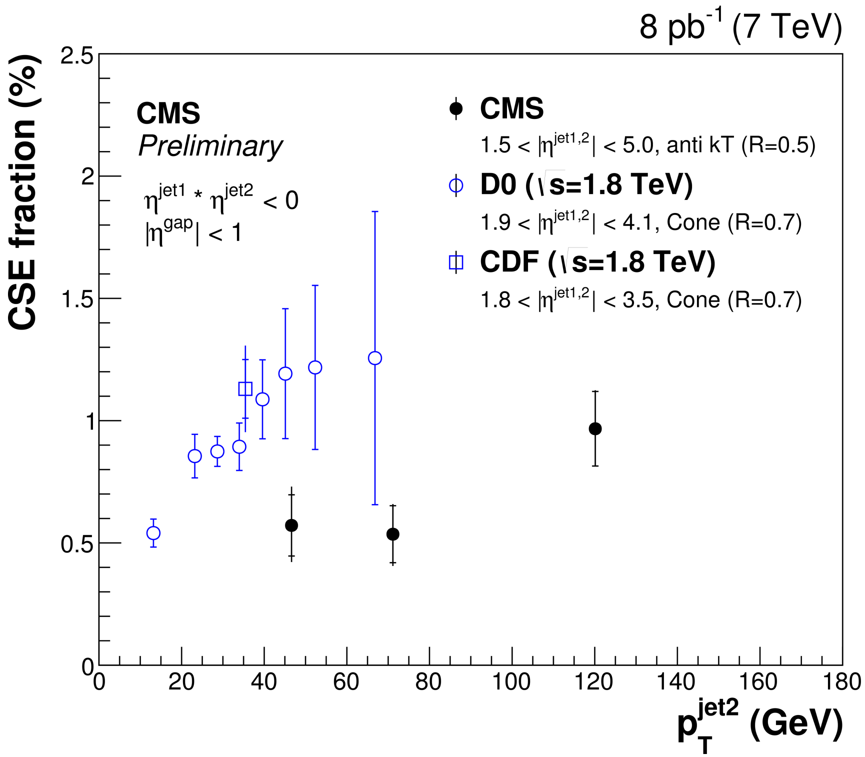
# After background subtraction

- The non-CSE background is subtracted
- The CSE peak at low multiplicity is described by **HERWIG6**
- The fraction of these CSE dijets is 0.5-1%, increasing with $p_T$
- Decrease with increasing energy: more rescattering (gap destruction)

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# Summary

Mueller-Navelet dijet decorrelations (7 TeV):

- **DGLAP** MC with LL PS and color coherence effects (HERWIG++) describes the data well
- POWHEG witn NLO + PYTHIA is not better than PYTHIA alone
- HEJ(LL **BFKL**) overestimates decorrelations
- Analytical NLL **BFKL** calculation agrees with data
- Higher collision energies may be more decisive

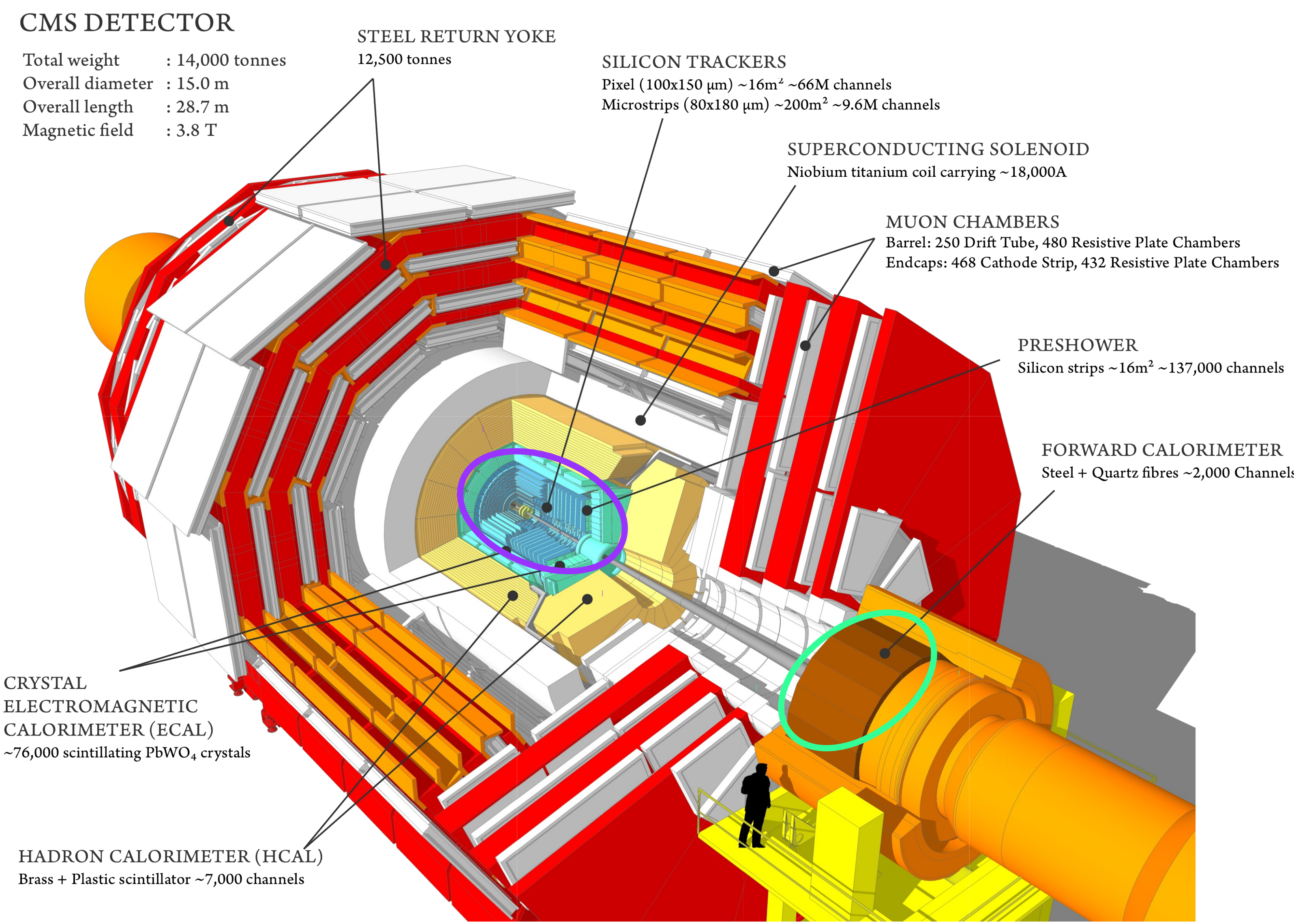
Jet-gap-jet events (7 TeV):

- LO **DGLAP** does not reproduce dijet events with no particles between them
- The CSE fraction (0.5-1%) rises with $p_T$
- ...and decreases with collision energy

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

# BACKUP

# The CMS Experiment



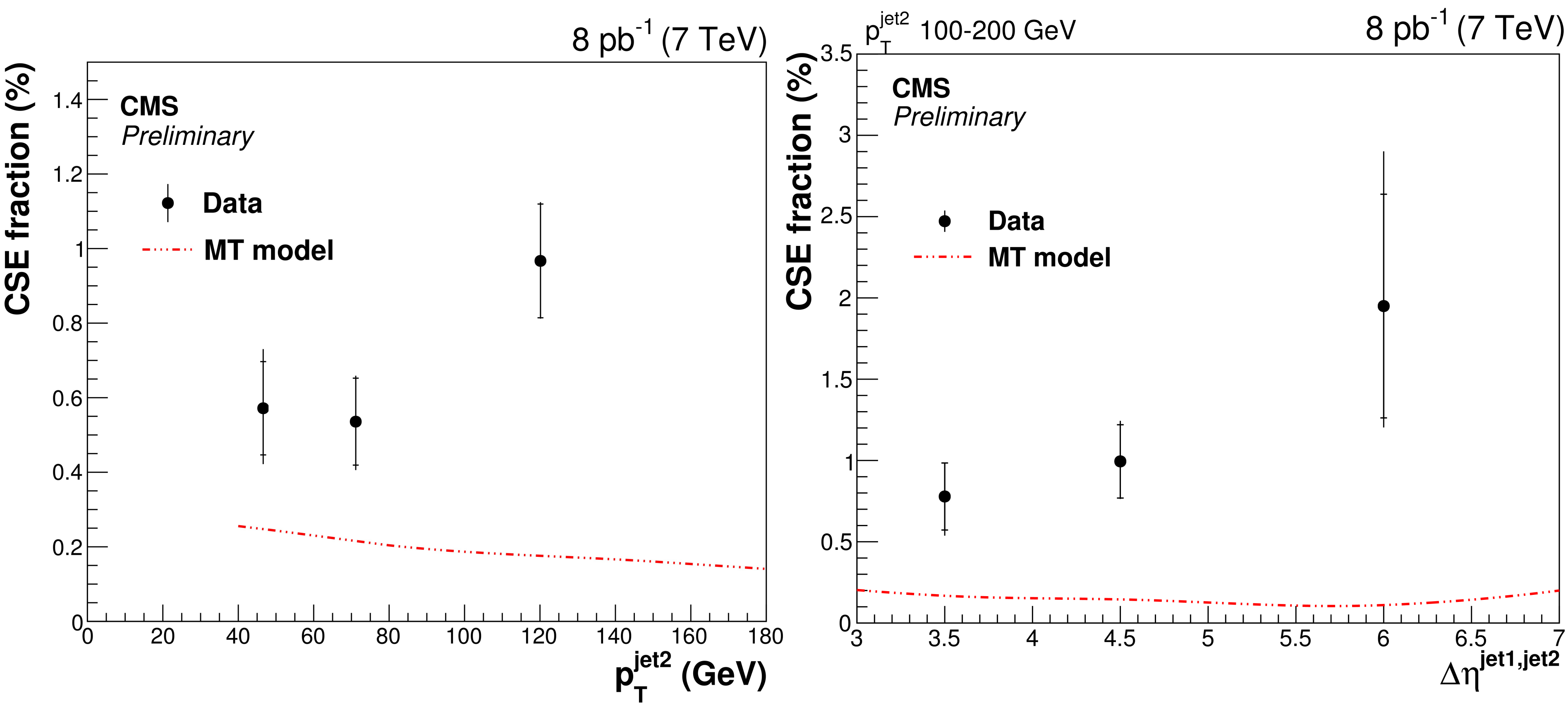
# Systematic uncertainties: MN decorr.

- Systematic undcertainties of the MN dijet decorrelation measurement:

| Observable | JES | JER | Corrections | Total systematic | Statistical |
|---|---|---|---|---|---|
| $\Delta\phi(\|\Delta y\| < 3.0)$ | $+(2.3-13.7)$ $-(3.0-10.2)$ | $+(0.1-10.6)$ $-(0.4-7.6)$ | 0.1–2.0 | $+(2.3-17.4)$ $-(3.0-12.7)$ | 0.3–5.1 |
| $\Delta\phi(3.0 < \|\Delta y\| < 6.0)$ | $+(2.5-16.4)$ $-(2.9-10.8)$ | $+(0.7-6.2)$ $-(0.8-3.4)$ | 0.4–2.3 | $+(3.0-17.5)$ $-(3.1-11.3)$ | 0.9–6.2 |
| $\Delta\phi(6.0 < \|\Delta y\| < 9.4)$ | $+(2.1-31.5)$ $-(1.9-17.3)$ | $+(5.8-17.4)$ $-(2.1-9.7)$ | 0.4–4.5 | $+(6.8-32.6)$ $-(3.6-19.5)$ | 5.3–22.0 |
| $C_1$ | 1.0–5.5 | 0.6–4.6 | 0.1–3.2 | 1.1–6.5 | 0.2–9.7 |
| $C_2$ | 1.8–16.9 | 1.0–4.0 | 0.1–4.9 | 2.3–17.4 | 0.5–17.7 |
| $C_3$ | 2.7–23.8 | 1.5–15.1 | 0.1–6.4 | 3.2–24.6 | 0.7–23.7 |
| $C_2/C_1$ | 0.8–12.5 | 0.4–5.6 | 0.1–2.6 | 1.0–13.1 | 0.5–19.7 |
| $C_3/C_2$ | 0.7–7.1 | 0.2–7.0 | 0.03–4.3 | 0.7–10.6 | 0.8–28.1 |

# Color Singlet Exchange fraction

- The CSE fraction is plotted as a function of $p_{T2}$ and $\Delta\eta$
- Mueller-Tang model underestimates CSE fraction and does not reproduce rising trend



# Monte Carlo models and data (jet-gap-jet)

- PYTHIA6 Z2*:
  - LO **DGLAP**
  - Lund string fragmentation
  - MPI, ISR, FSR
  - tuned to LHC UE data

- HERWIG6:
  - hard CSE via elastic parton scattering (Mueller-Tang model)
  - based on LL **BFKL**
  - cluster fragmentation
  - no MPI (for that, JIMMY)

- Event selection in data:
  - At least 2 jets
  - 0 or 1 vertex
  - The two leading jets in different hemisphere, and $|\eta|>1.5$