Double parton scattering studies in CMS

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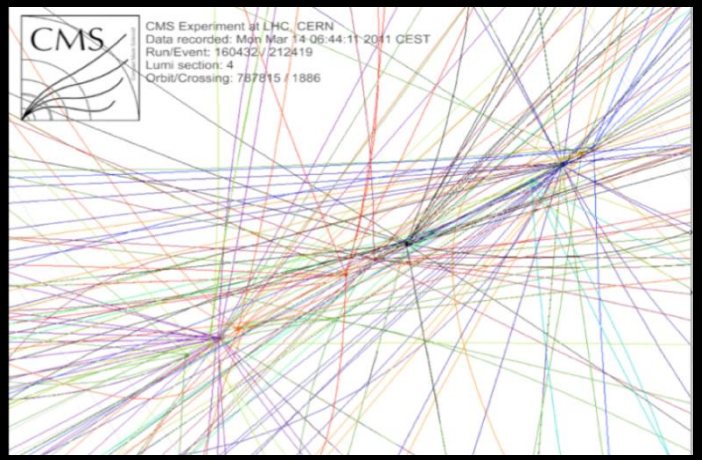
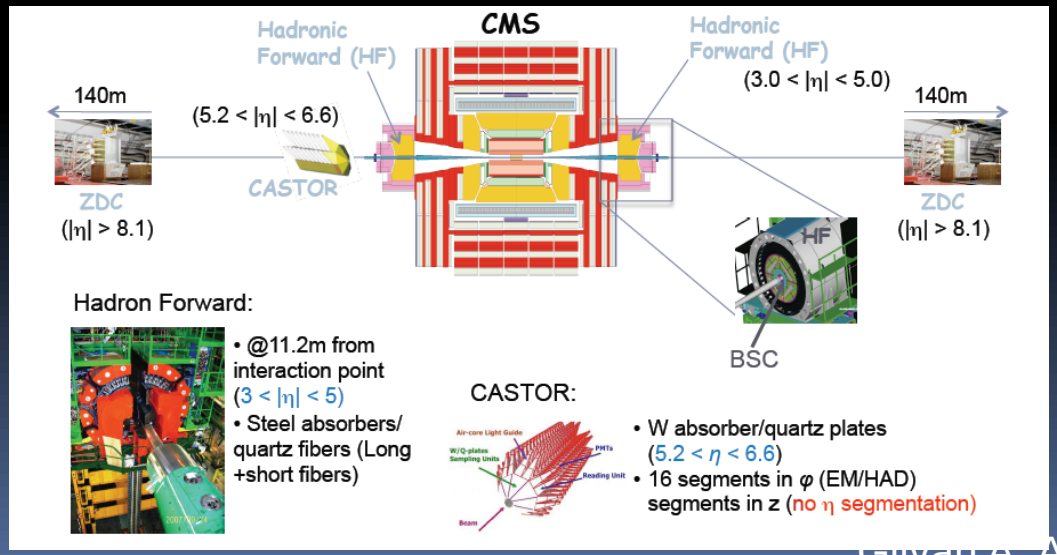
for the CMS collaboration

The setting:CMS@LHC

- High energy and high luminosity
  - Allows high statistics precision measurements, and sensitivity to "rare" processes (hard diffraction, exclusive production)
  - But high luminosity comes with high "pileup" – average 2-8 in 2010/2011, 24 in 2016
  - Low pileup needed for some analysis





- Good detector coverage
  - Tracking to |η| < 2.4
  - Hadronic calorimeter (HF) to |η| < 5
  - Forward calorimeters
  - CASTOR (-6.6< η< -5.2)
  - ZDC (|η| > 8.1)

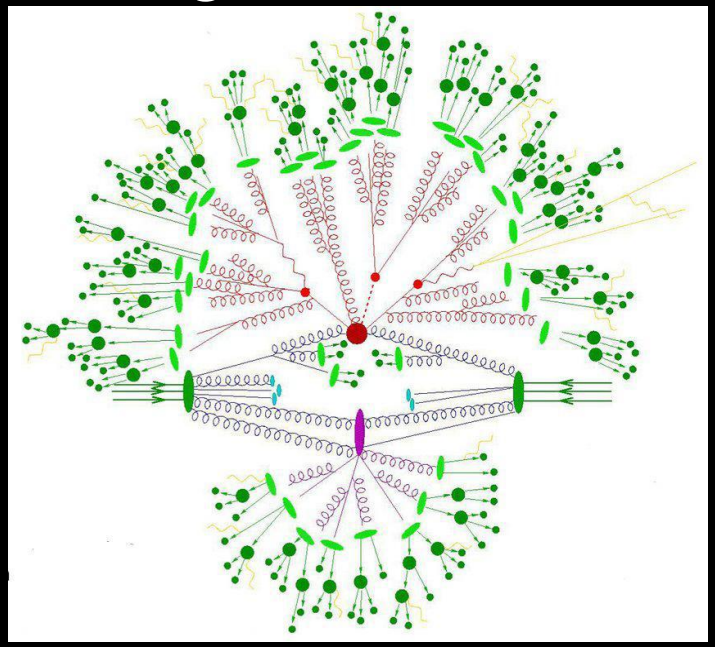
Overview

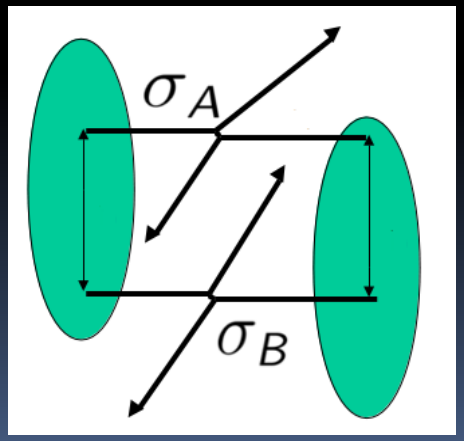
- Studying the Underlying Event and DPS at the LHC
- DPS using
  - Same sign W pair production
  - Events with 2 b jets + 2 light jets
- Many other interesting results not covered here
- http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html

Study of the underlying event and DPS at the LHC

Underlying Event and DPS

- Studying the UE is crucial for understanding background for BSM searches
- UE has several components:
  - Initial and final state radiation
  - Beam - Beam remnants
  - **Multiple Parton Interactions (MPI)**
    - Some MPI can be hard
    - Double Parton Scattering (DPS)





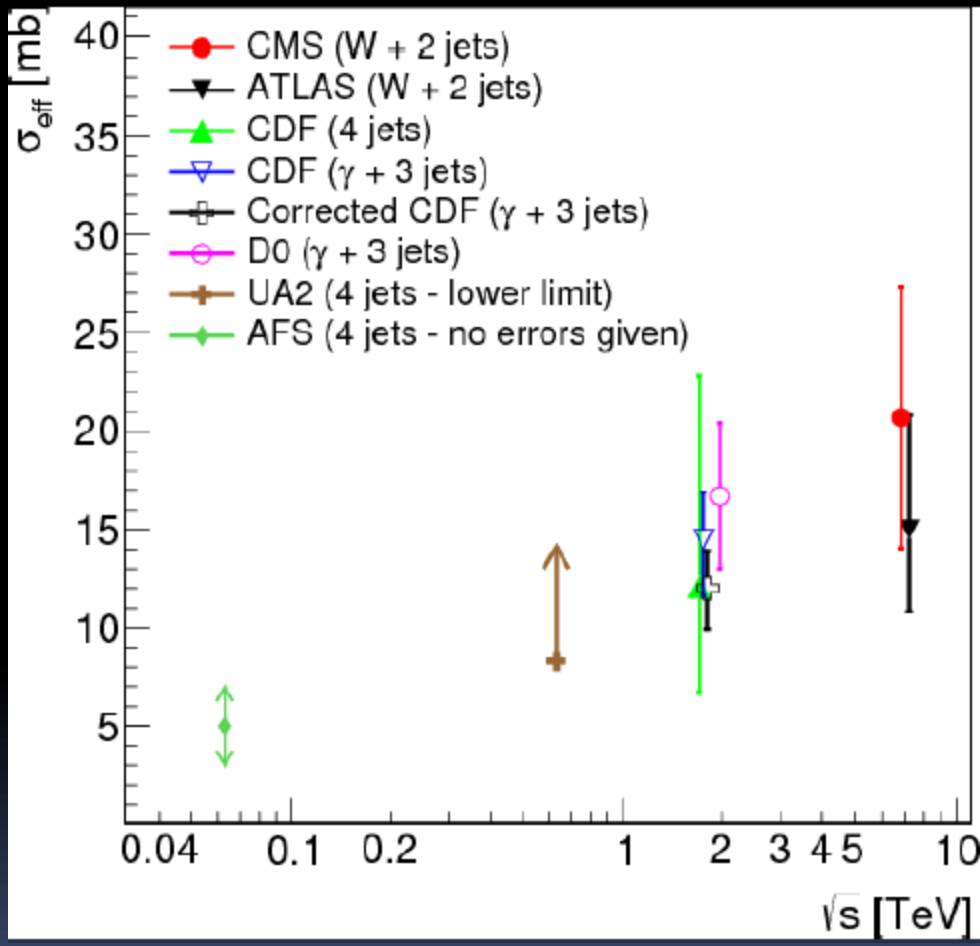
$$\sigma_{AB}^{DPS} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

σ_{eff}- effective area parameter
m = 1 for same type processes
m = 2 otherwise

- More CMS results on Benoit Roland's talk this morning

DPS Measurements

- DPS has been measured at several energies (from 63 GeV up to 7 TeV)
  - Results for σ_{eff} are mostly compatible



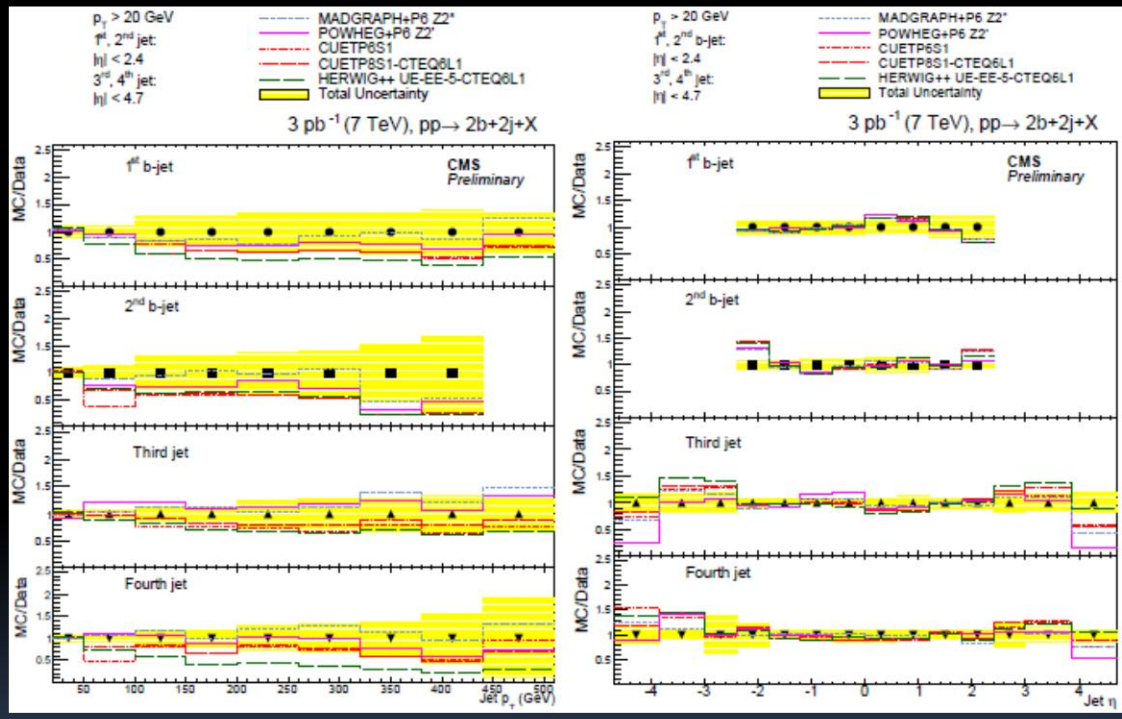
- CMS published results using
  - W+2jet events
  - 4 jet events

- New studies using
  - 2 bjets + 2 light jets
  - Same sign W pair production

DPS in 2b jets + 2 jets

CMS-PAS-FSQ-13-010

- 7T eV Low pileup data (2010) 3.03 pb^{-1}
- *4jets* $p_T > 20$ GeV
  - 2 jets b-tagged (tracker $|\eta| < 2.4$)
  - 2 jets $|\eta| < 4.7$
- Discriminating variables
- $\Delta\phi = \phi_{jet1} - \phi_{jet2}; \phi_{jet3} - \phi_{jet4}$
- $S\phi = \sqrt{(\Delta\phi_{ljets})^2 + (\Delta\phi_{bjets})^2}$
- $\Delta^{rel}_{pT} = p_T$ balance of pairs
- $S'p_T = \sqrt{(\Delta^{rel}_{bottom} p_T)^2 + (\Delta^{rel}_{light} p_T)^2}$
- $\Delta\eta_{ljets}; \Delta\eta_{bjets}$
- ΔS = pair azimuthal angle



- MC samples PYTHIA6.426, PYTHIA8.185, HERWIG++2.5.0 (w and w/o MPI)
  - POWHEG+PYTHIA6Z2*, MADGRAPH5+PYTHIA6Z2*

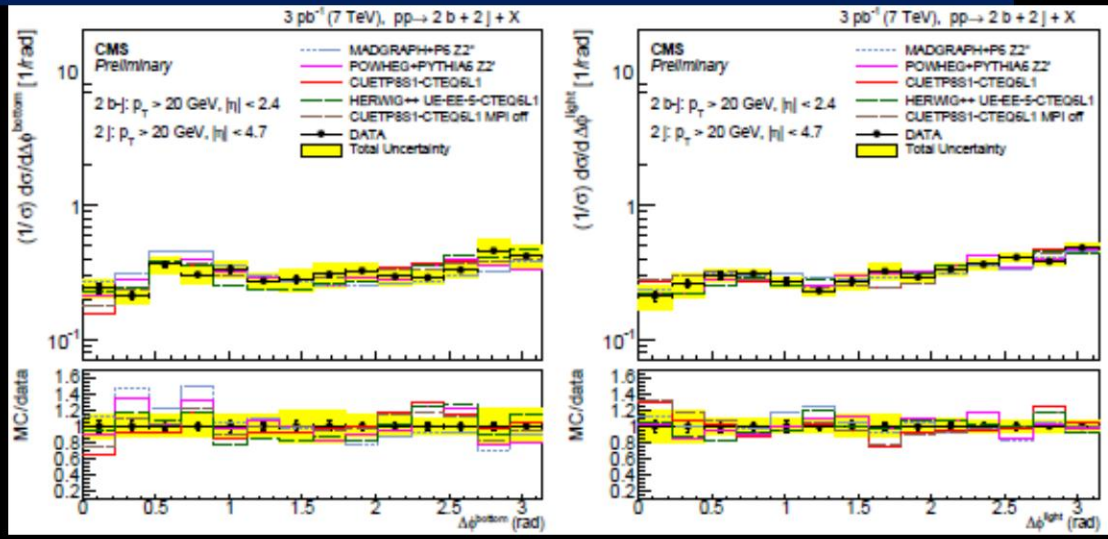
DPS in 2b jets + 2 jets

Sample	PDF	Cross section (nb)
PYTHIA 6 Tune Z2*	CTEQ6L1	76.84
PYTHIA 6 Tune CUETP6S1	CTEQ6L1	76.66
HERWIG ++ Tune UE-EE-3	MRST2008**	43.78
HERWIG ++ Tune UE-EE-5-CTEQ6L1	CTEQ6L1	47.39
PYTHIA 8 Tune CUETP8S1-CTEQ6L1	CTEQ6L1	95.58
POWHEG +PYTHIA 6 Tune Z2*	CT10	77.96
POWHEG +PYTHIA 6 Tune Z2′	CT10	54.91
MADGRAPH +PYTHIA 6 Tune Z2*	CTEQ6L1	39.33
DATA	-	64.6 ± 2.4 (stat.) ± 21.6 (syst.)

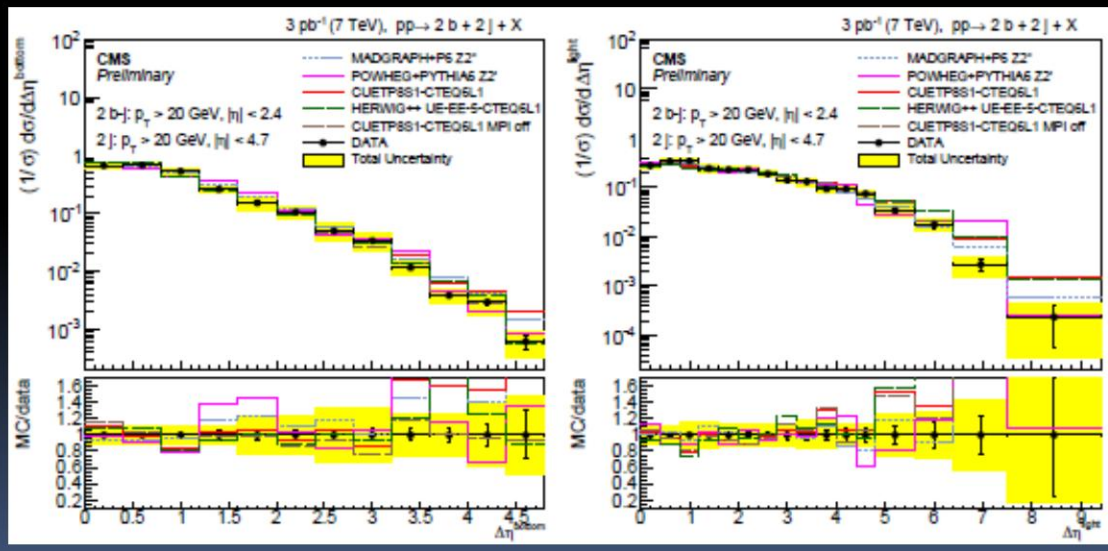
- Cross section predictions vary between models
- *PYTHIA8 overestimate*
- *MADGRAPH & HERWIG++ underestimate*
- *Others do a reasonable job*
- *Data systematics dominated by unfolding and jet energy*

DPS in 2b jets + 2 jets

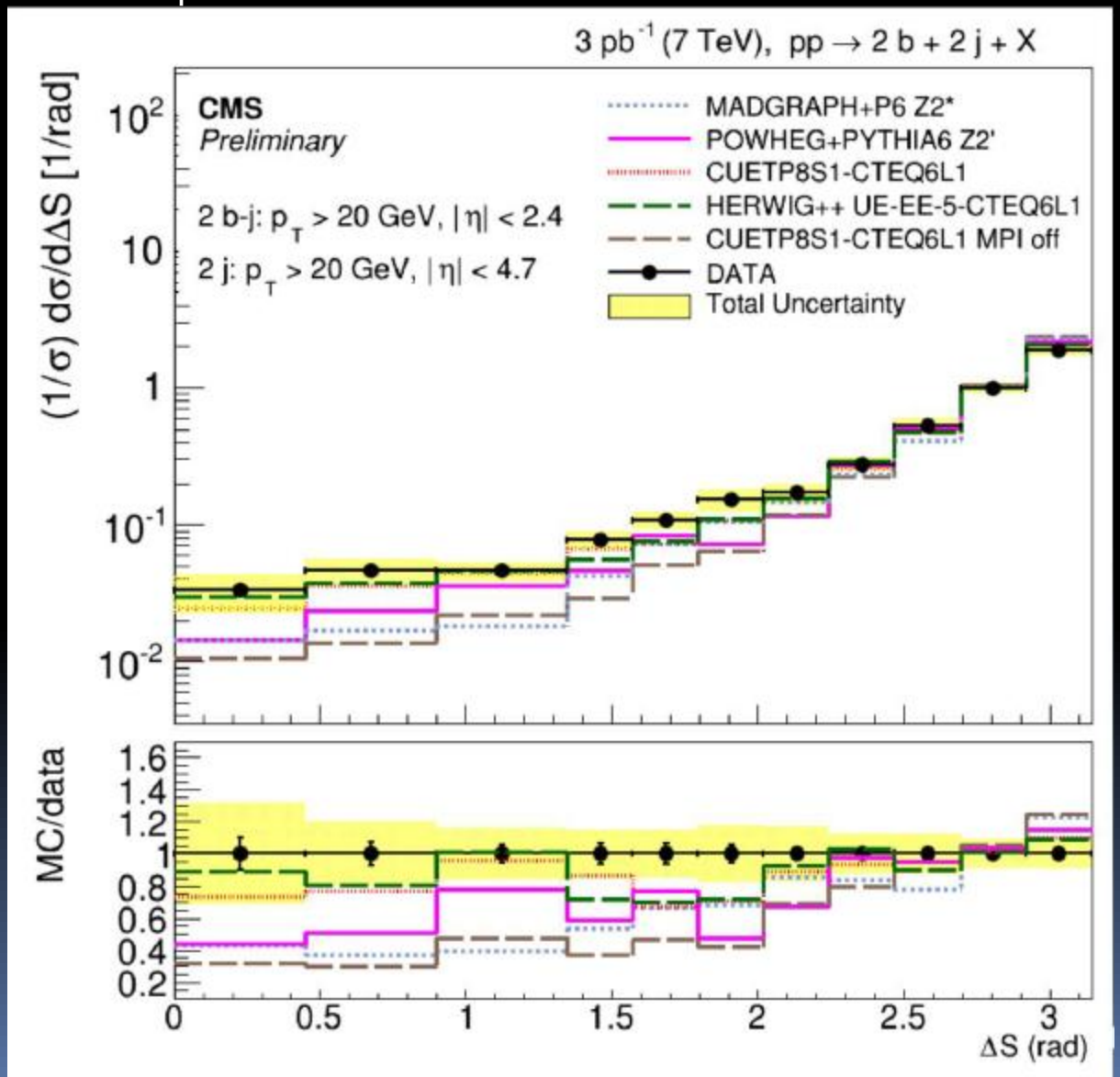
- $\Delta\phi$ well described by all models



- $\Delta\eta_{ljets}$; $\Delta\eta_{bjets}$ not well described at high $\Delta\eta$



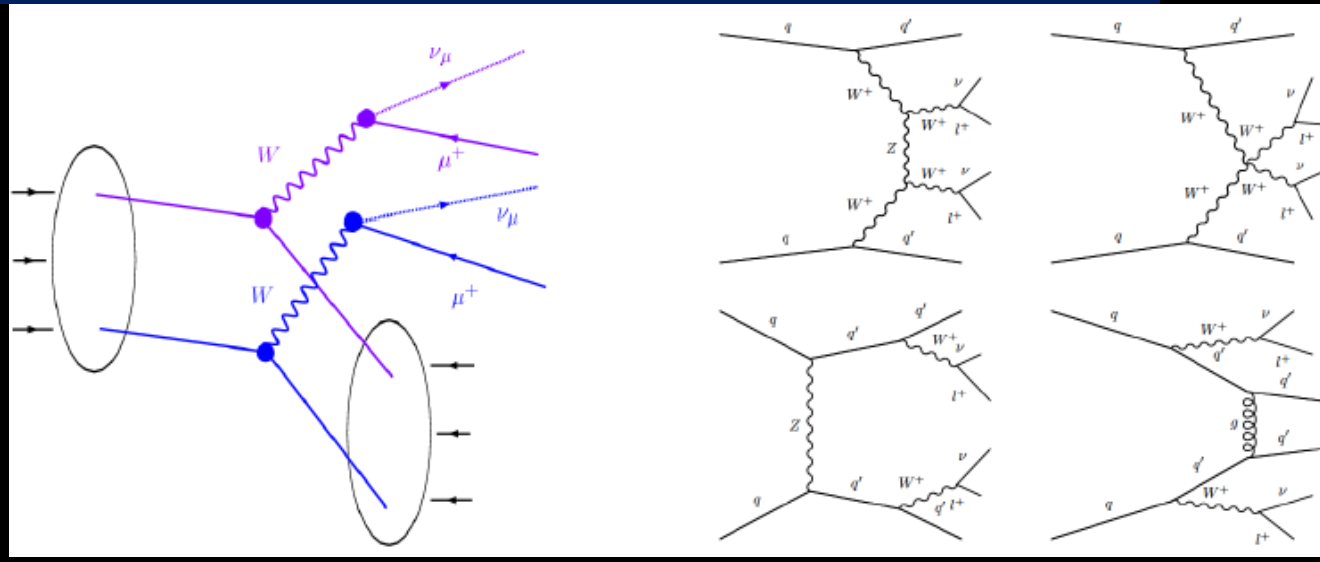
- DPS not well described by all models
- HERWIG++ and PYTHIA8+MPI agree in some regions
- Models w/ MPI-off completely fail at most sensitive region (small ΔS)
- Better DPS implementations are needed

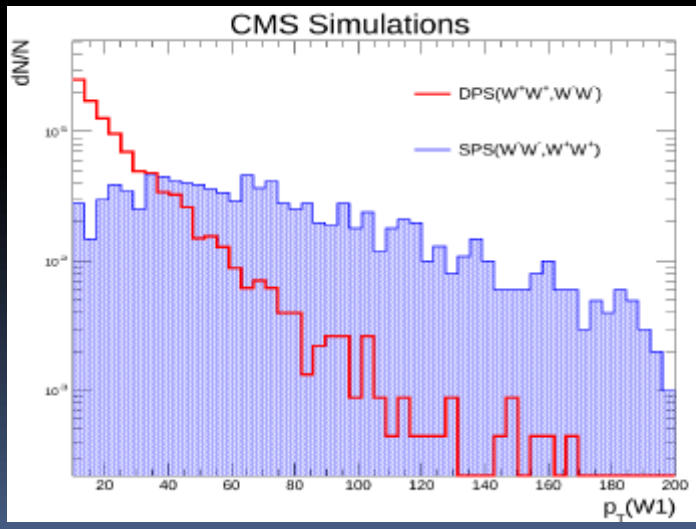


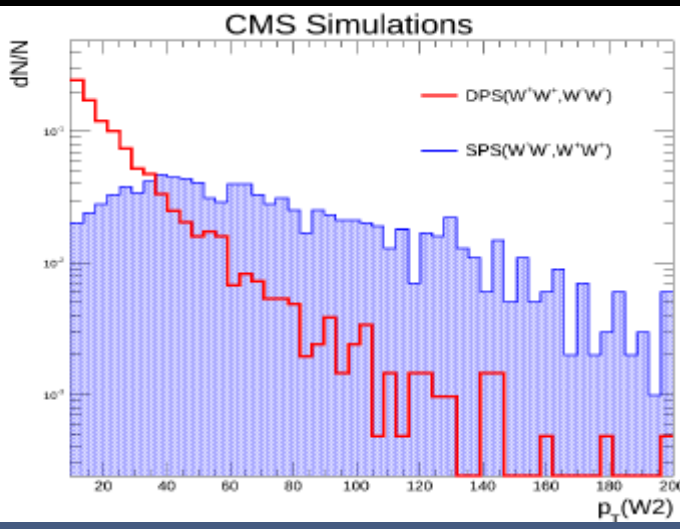
Same sign W pair production

CMS PAS FSQ 16-009

- Pro
  - Clean signature
  - No Jets
  - No lepton correlation
  - W from SPS boosted
  - $\sigma_{DPS} \approx \sigma_{SPS}$
- Con
  - Small σ_{DPS}
- $\sigma_{DPS} \sim 0.2$ pb







Same sign W pair production

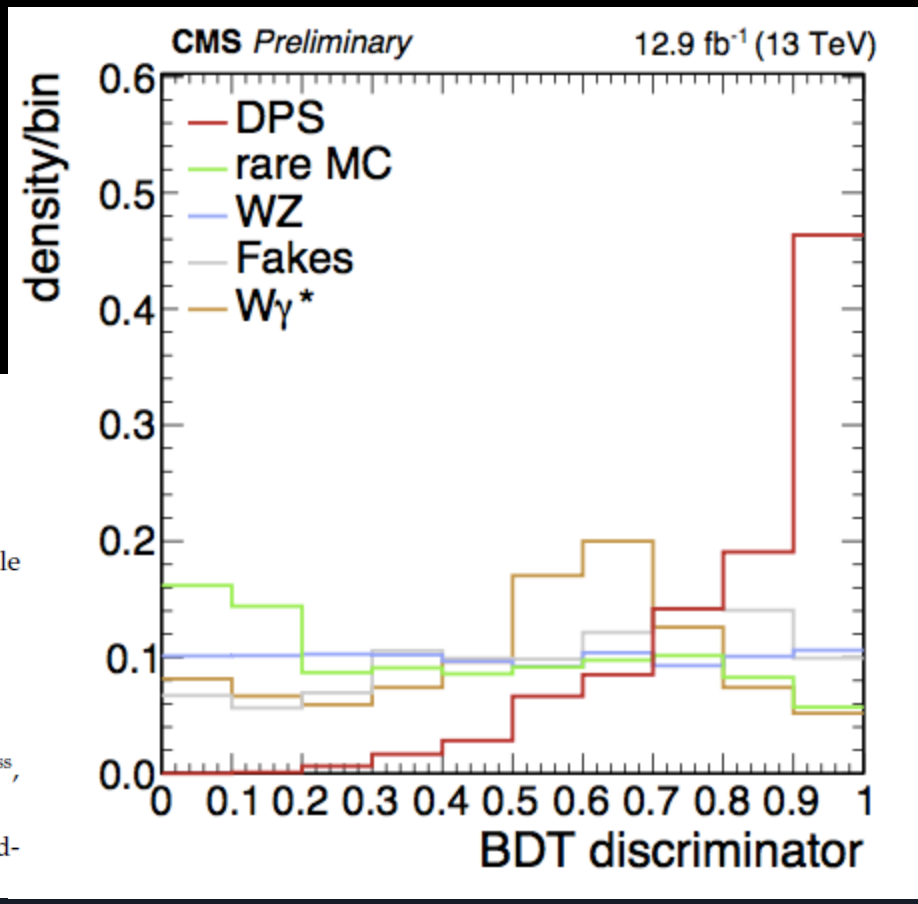
- Data Samples:
  - 13 TeV data (2016) 35.9 fb^{-1} (previous 8 TeV CMS-PAS-FSQ-13-001)
  - Same sign leptons μμ and eμ
  - Trigger on two leptons p_T > 17 GeV (8 GeV subleading)
  - Basic selection:

two leptons $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
$p_T^{\ell 1} > 25$ GeV , $p_T^{\ell 2}$ 20 GeV
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
$E_T^{miss} > 15$ GeV
$N_{jets} < 2$ (30 GeV)
$N_{b\text{-}jets} = 0$ (25 GeV)
veto on additional leptons
veto on hadronic τ leptons

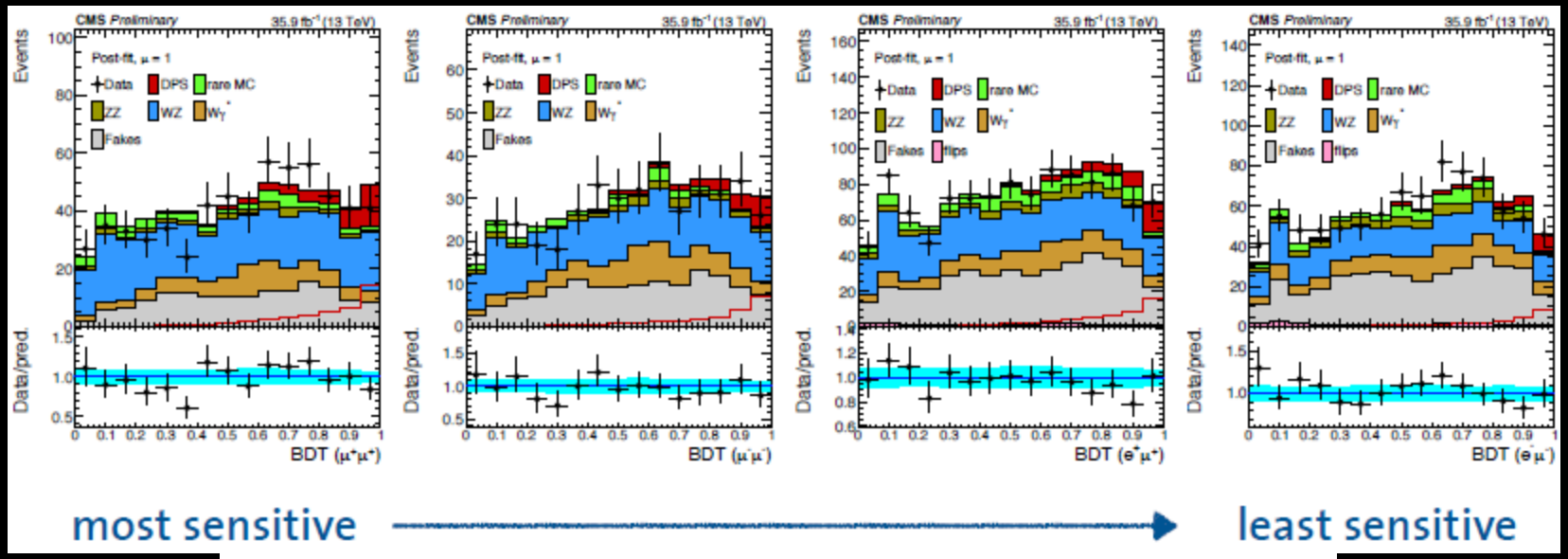
- Backgrounds:
  - Fake leptons (W+jets, tt, QCD) data driven
  - Irreducible backgrounds (WZ, ZZ, WWW, Wγ*) derived from MC
    - MADGRAPH5_aMC@NLO, POWHEGV2 + PYTHIA8-CUETP8M1

- DPS signal kinematics close to irreducible background:
  - Use BDT discriminant
  - WZ mostly flat
  - Training for different flavors and charges
  - Set of 11 variables

- $p_T^{\ell_1}$ and $p_T^{\ell_2}$, the transverse momenta of the leptons,
- E_T^{miss},
- $\eta_1 \times \eta_2$, the product of the two lepton η's,
- $|\eta_1 + \eta_2|$, the absolute sum of the two lepton η's,
- $M_{T2}^{\ell\ell}$, the so-called "s-transverse mass" where the leptons serve as the two visible systems [31, 32], briefly described below,
- $m_{T,(\ell_1,E_T^{miss})}$, the transverse mass between the leading lepton and the E_T^{miss},
- $m_{T,(\ell_1,\ell_2)}$, the transverse mass between the leptons,
- $|\Delta\phi_{(\ell_1,\ell_2)}|$, the azimuthal separation between the leptons,
- $|\Delta\phi_{(\ell_2,E_T^{miss})}|$, the azimuthal separation between the subleading lepton and the E_T^{miss}, and
- $|\Delta\phi_{(\ell\ell,\ell_2)}|$, the azimuthal separation between the di-lepton system and the subleading lepton.



- Fit simultaneously four flavor/charge combinations:
  - Good agreement with BDT classifier



	$\mu^+\mu^+$	$\mu^-\mu^-$	$e^+\mu^+$	$e^-\mu^-$
fakes	151.1 ± 26.6	132.7 ± 23.4	412.7 ± 47.2	341.4 ± 39.0
WZ	277.2 ± 28.1	164.5 ± 16.7	355.9 ± 36.1	228.1 ± 23.2
ZZ	24.8 ± 7.0	18.7 ± 5.3	57.8 ± 16.4	55.8 ± 15.8
$W\gamma*$	85.9 ± 27.5	73.1 ± 23.4	142.8 ± 45.7	127.7 ± 40.9
other rare	39.7 ± 15.0	20.2 ± 7.7	83.7 ± 31.7	49.4 ± 18.8
charge flips	—	—	20.4 ± 0.0	21.5 ± 0.0
background	578.6 ± 50.3	409.2 ± 38.2	1073.3 ± 83.0	824.0 ± 65.8
DPS WW	41.1 ± 1.0	20.6 ± 0.5	48.7 ± 1.2	24.1 ± 0.6
observed	604	411	1091	869

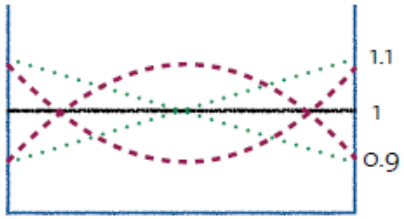
- Systematic uncertainties:
  - WZ and signal shapes from different generators

	normalization	shape
DPS WW	2.6%	alternative
fakes $\mu\mu$	25%	5%
fakes $e\mu$	40%	5%
WZ	16%	alternative
ZZ	30%	5%
other rare	50%	5%
charge-flips $e\mu$	30%	–

  - Shapes

1) alternative shape: the background/signal is allowed to float freely between the central and alternative

2) percentage: shape of the BDT classifier is allowed to float linearly and quadratically by that amount



alternative shapes for signal and WZ

WZ: get alternative shape from different generator

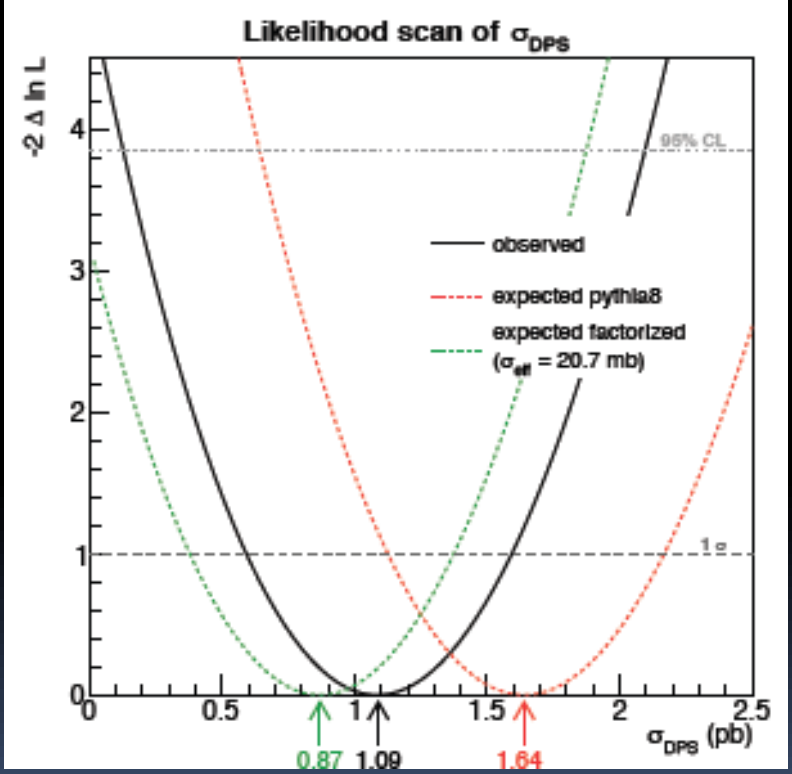
signal: smear MET and re-evaluate BDT

we **tested different pythia tunes**, showing no kinematic dependence

Results

- Constrained fit to four BDT classifiers
- Upper limits on signal strength and cross section
- Expected Significance based on:
  - Pythia 8 CUETP8M1
  - Simplified factorization
- Most precise measurement to date

	expected	observed
$\sigma^{\text{pythia}}_{\text{DPSWW}}$	1.64 pb	$1.09^{+0.50}_{-0.49}$ pb
$\sigma^{\text{factorized}}_{\text{DPSWW}}$	0.87 pb	
significance for $\sigma^{\text{pythia}}_{\text{DPSWW}}$	3.27 σ	2.23 σ
significance for $\sigma^{\text{factorized}}_{\text{DPSWW}}$	1.81 σ	
UL in the absence of signal	< 0.97 pb	< 1.94 pb



Conclusions

- Presented Recent results on DPS at CMS/LHC

- Double Parton Scattering in same sign W pairs
  - Large data sample at 13 TeV
  - Most precise to date

- 2 b jets + 2 light jets
  - Need better model for DPS on MC generators

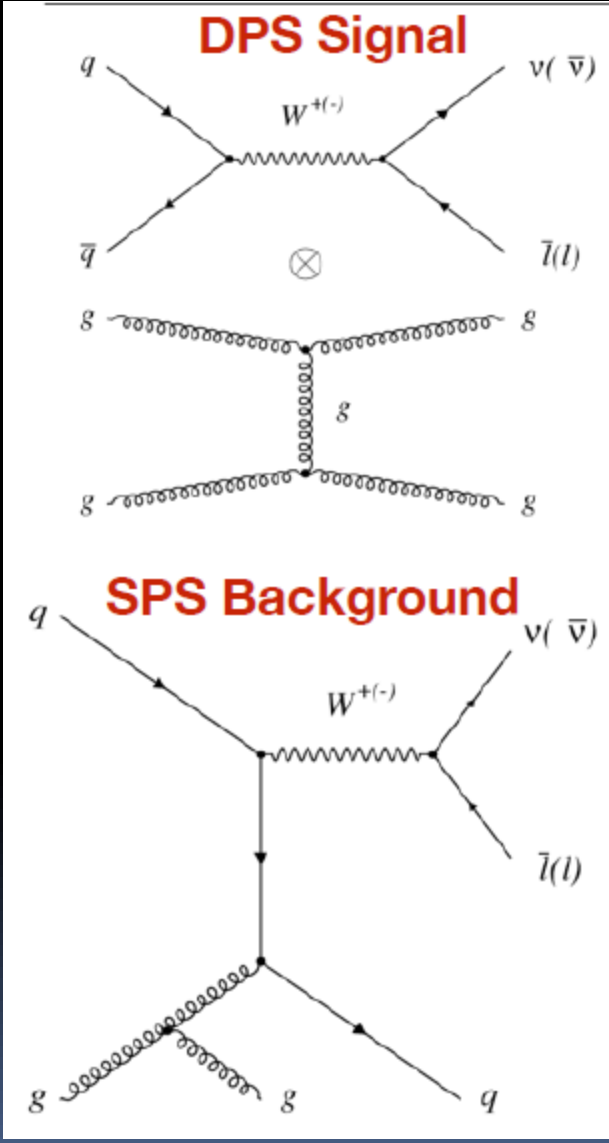
- CMS results provide new constraints for non-perturbative and semi-hard QCD dynamics on MCs

Extra

- Motivation: DPS is important for understanding the partonic correlations and backgrounds for new physics.
- W+2jets advantages
  - Clean tag from W->muon decay
  - Large dijet cross section
- Measurement of σ_{eff}- effective area parameter, input to theoretical models

$$\sigma_{\mathrm{eff}} = \frac{\sigma'_{\mathrm{W+0jet}}}{\sigma'^{\mathrm{DPS}}_{\mathrm{W+2j}}} \cdot \sigma'_{2\mathrm{j}} \longrightarrow \sigma_{\mathrm{eff}} = \frac{R}{f_{\mathrm{DPS}}} \cdot \sigma'_{2\mathrm{j}}$$

- f_{DPS} - fraction of $(W+2j)_{DPS}$ to all (W+2j)
  - From simultaneous fit to discr. variables
- R - fraction of W+0j to W+2j events (from data)
- σ'_{2j}- di-jet cross section at particle level (data)



Luminosity and Pile-up

- The integrated luminosity (*L*) is based on the Van der Meer scans
- The uncertainty of the luminosity is 4%: dominates the systematic uncertainties of this analysis
- Number of collisions per bunch crossing follows Poisson - Average λ *(pile-up)*

$$F_{\text{pileup}} = \frac{\Sigma_{i=1}^{\infty} i P(i,\lambda)}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} \cdot \epsilon_{\text{inel}} = \frac{\epsilon_{\text{inel}}\lambda}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} =$$

$$= 1 + \frac{1}{2}\lambda\epsilon_{\text{inel}} + \frac{1}{12}\lambda^2\epsilon_{\text{inel}}^2 + \mathcal{O}(\lambda^3)$$

- Correction factor – accounts for multiple collisions being counted as one.

LHC as a small x machine

- LHC can access lowest x values
  - for central W/Z production at

7 TeV: $x \sim 0.01$

14 TeV: $x \sim 0.005$

  - at forward rapidities ($\eta \sim 5$):

7 TeV $x \sim 6 \cdot 10^{-5}$

14 TeV $x \sim 3 \cdot 10^{-5}$

  - for central jets with p_t > 20 GeV

7 TeV : $x \sim 0.006$

14 TeV : $x \sim 0.003$

  - at forward rapidities ($\eta \sim 5$):

7 TeV: $x \sim 4 \cdot 10^{-5}$

14 TeV: $x \sim 2 \cdot 10^{-5}$

J. M. Campbell, J. W. Huston, and W. J. Stirling.
Hard Interactions of Quarks and Gluons: A Primer for LHC Physics.
Rept. Prog. Phys., 70:89, 2007.

LHC parton kinematics