Double parton scattering results from CMS

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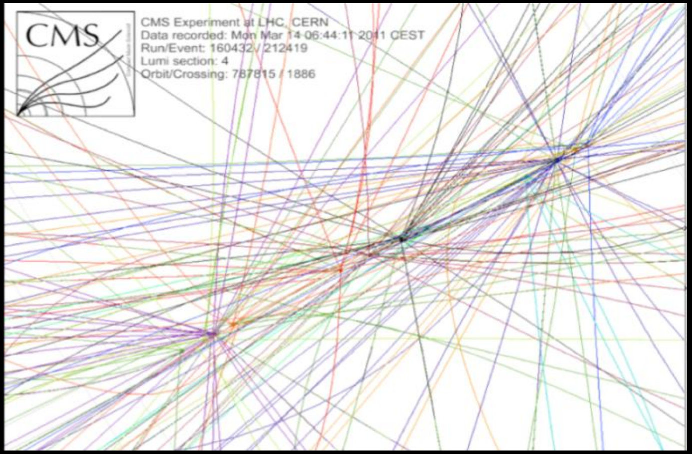
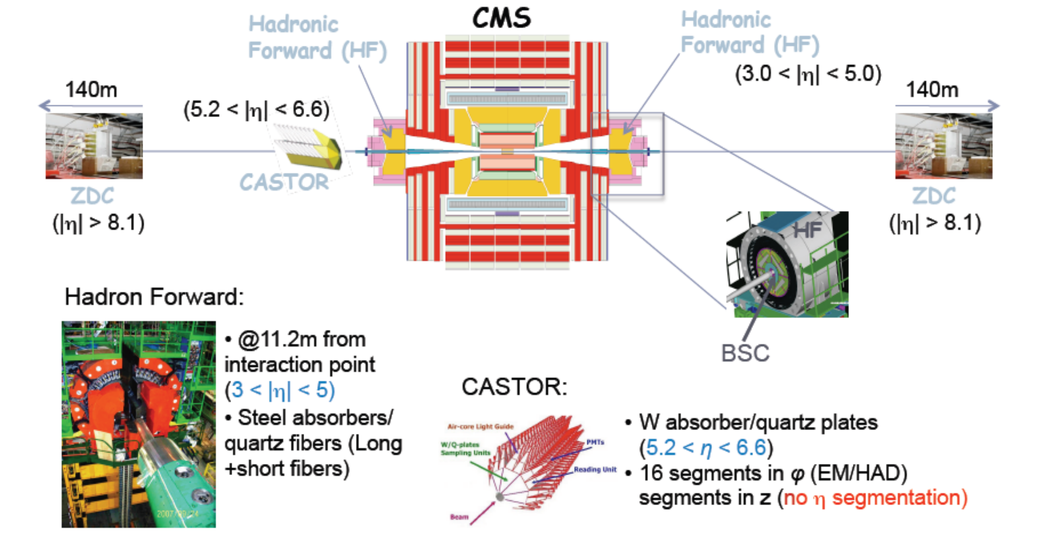
for the CMS collaboration

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, 21 in 2012
  - Low pileup helps in some analysis





- Good detector coverage
  - Tracking to $|\eta| < 2.4$
  - Hadronic calorimeter (HF) to $|\eta| < 5$
  - Forward calorimeters (cover $-6.6 < \eta < -5.2$ (CASTOR) and $|\eta| > 8.1$ (ZDC)

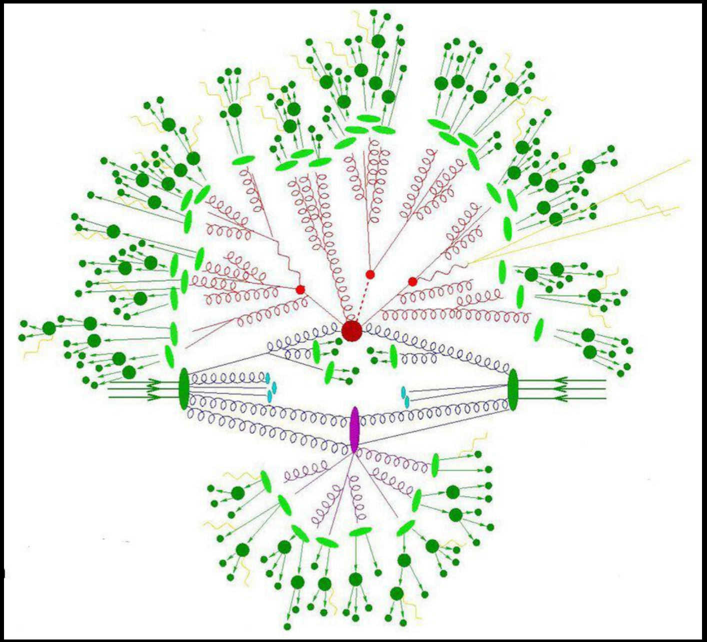
Overview

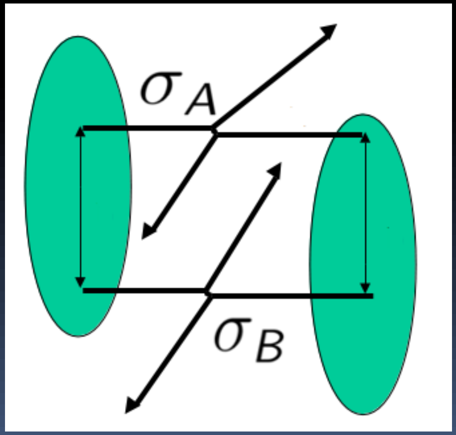
- Studying the Underlying Event and DPS at LHC
- DPS using
  - γ + 3 Jets
  - Same sign W pair production
  - 2b jets + 2 jets events
- Many other interesting results not covered here
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Studying the Underlying Event and DPS at 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)





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

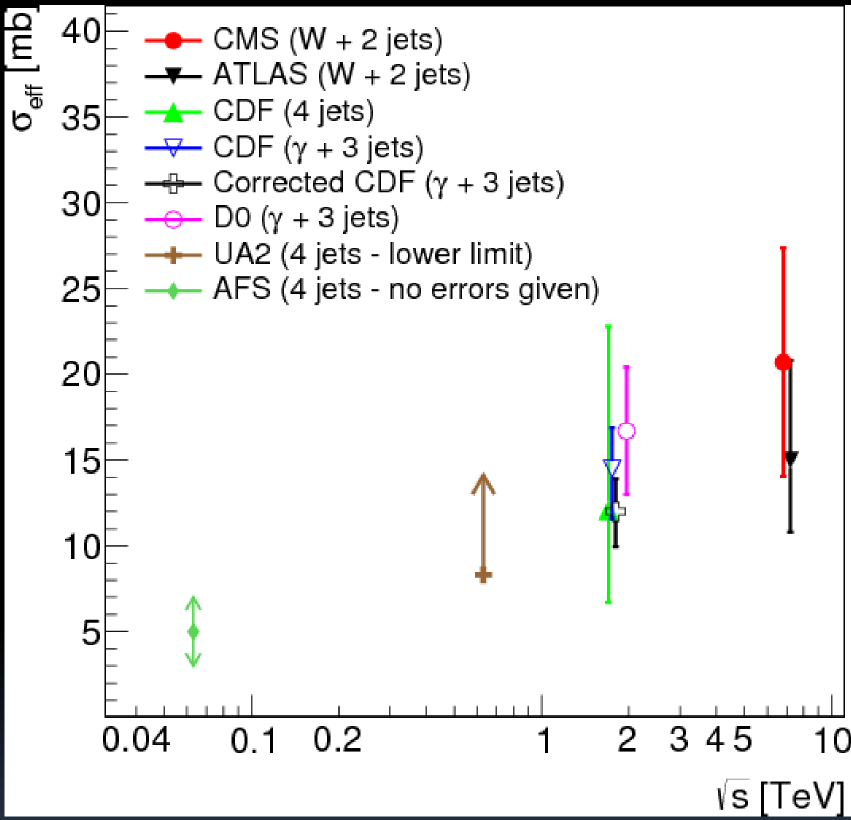
σ_{eff}- effective area parameter
m = 1 for same type processes
m = 2 otherwise

- More CMS results on Ada Solano 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 + 2 jet events JHEP 03 (2014) 032
  - 4 jet events PRD 89 (2014) 092010

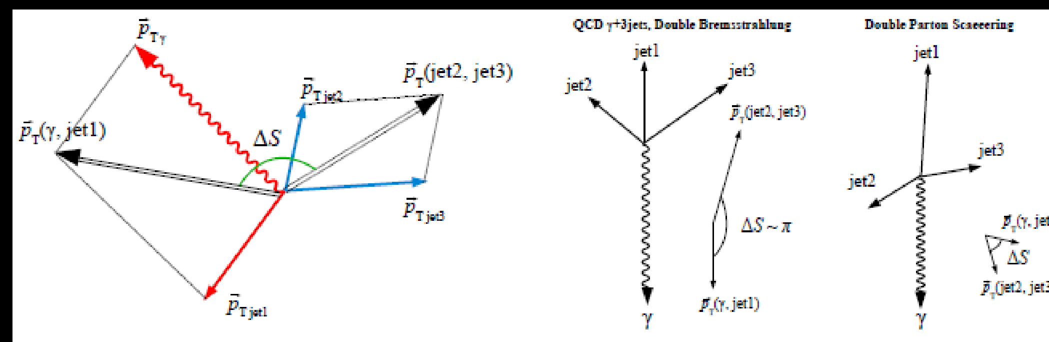
- New studies using:
  - γ + 3 jet events
  - Same sign W pair production events
  - 2b jets + 2 jets events



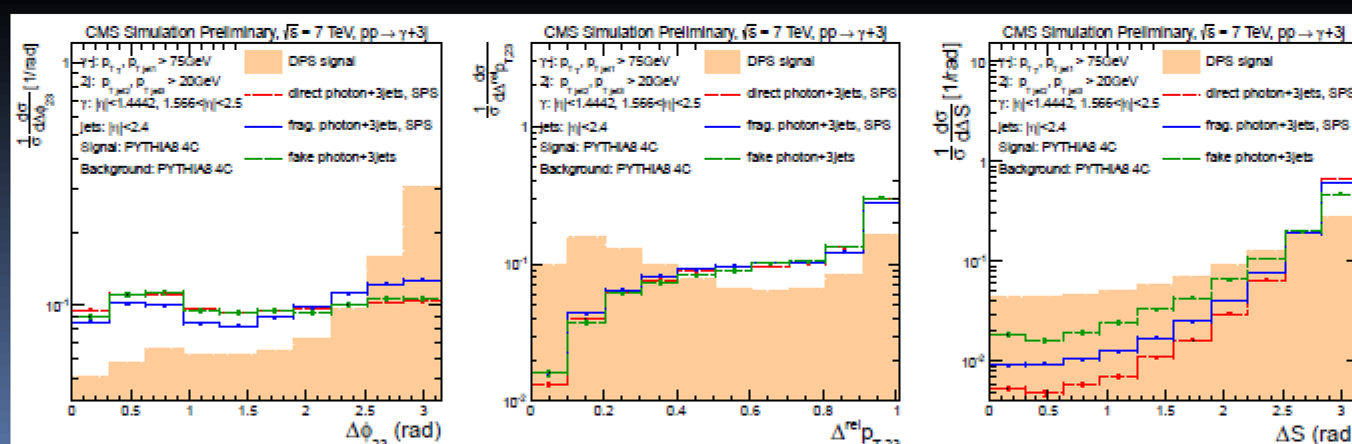
DPS in γ + 3 Jet events

CMS-PAS-FSQ-12-017

- 7 TeV Low pileup data (2010) 36 pb^{-1}
- γ + *leading jet* $p_T > 75$ GeV
  - Other jets $p_T > 20$ GeV
- Discriminating variables
- $\Delta\phi 23 = \phi_{jet2} - \phi_{jet3}$
- $\Delta^{rel}{}_{pT23} = \dfrac{|\vec{p}_{T\ jet2} + \vec{p}_{T\ jet3}|}{|\vec{p}_{T\ jet2}| + |\vec{p}_{T\ jet3}|}$
- ΔS = pair azimuthal angle



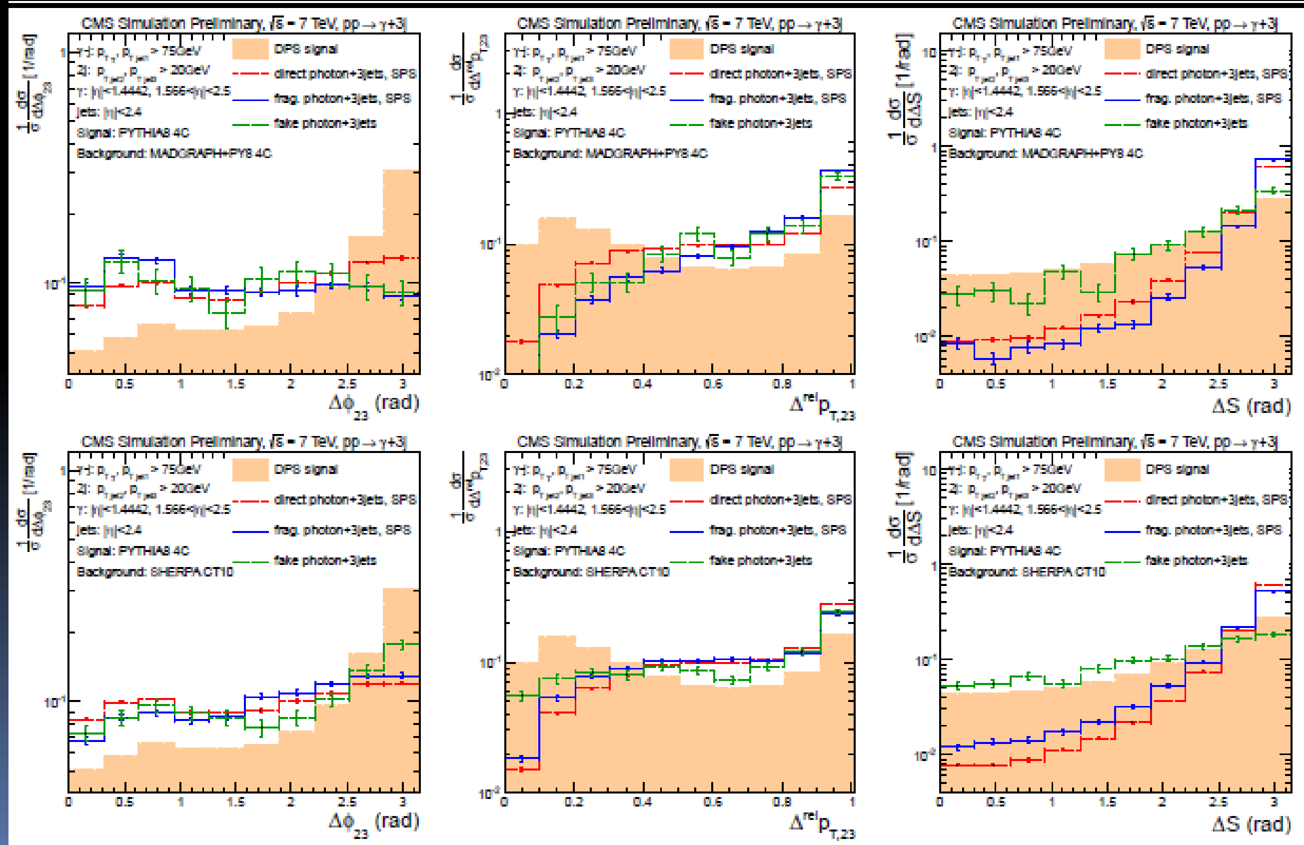
- Distinguishable at gen level (PYTHIA8 4C)



DPS in γ + 3 Jet events

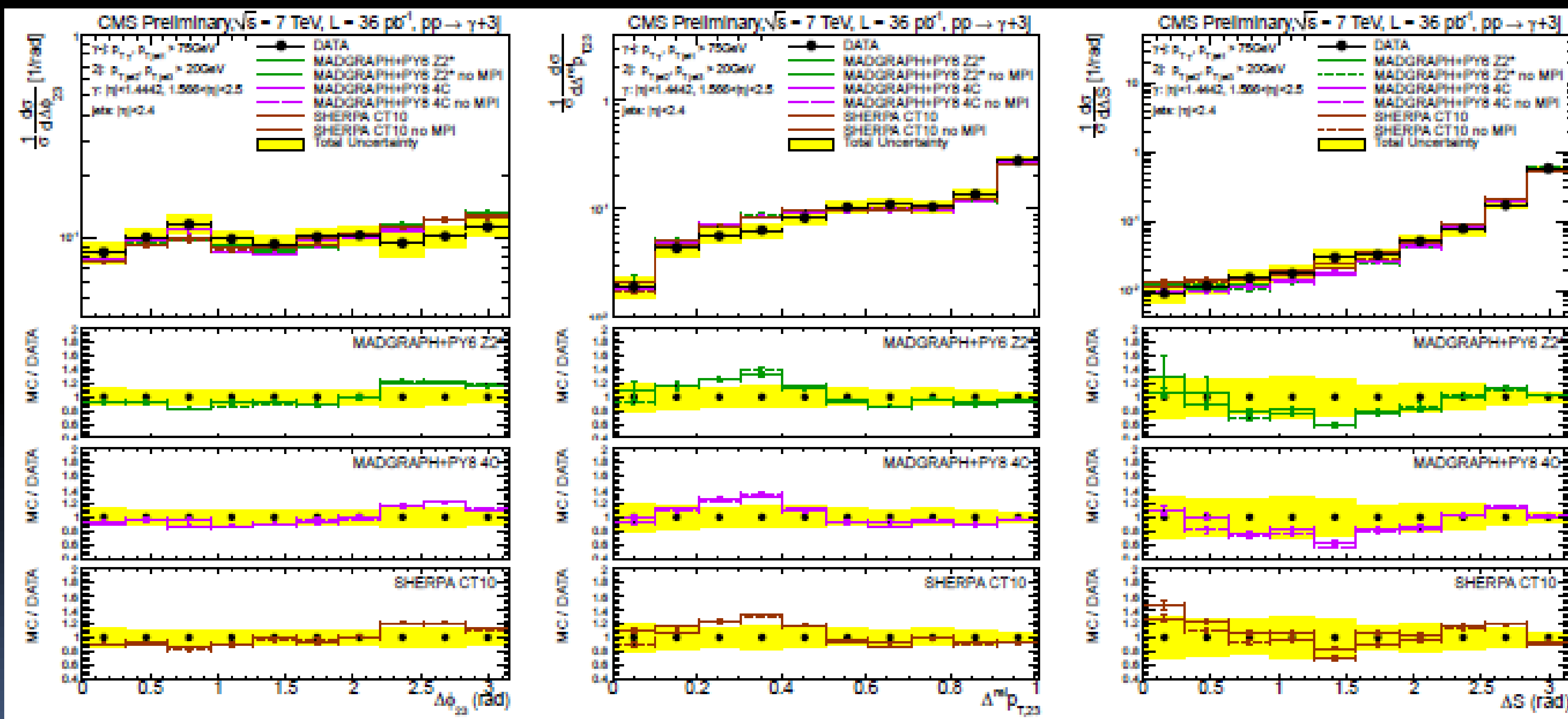
- Matrix element (MADGRAPH5, SHERPA2.1.0) combined with Parton shower (PYTHIA6, PYTHIA8) with several tunes, show sizeable differences

Sample	Tune	direct photon + 3 jets	frag. photon + 3 jets	fake photon + 3 jets
PYTHIA 6	Z2	42.6%	48.2%	9.2%
PYTHIA 8	4C	28.6%	66.1%	5.3%
MADGRAPH + PYTHIA 6	Z2*	92.1%	3.5%	4.4%
	Z2* (NO MPI)	85.0%	9.1%	5.9%
MADGRAPH + PYTHIA 8	4C	83.8%	13.3%	2.9%
	4C (NO MPI)	83.6%	14.0%	2.4%
SHERPA	CT10	52.0%	41.9%	6.0%
	CT10 (NO MPI)	49.2%	45.5%	5.3%



Results γ + 3 Jet events

- Matrix element (MADGRAPH5, SHERPA2.1.0) + PS (PYTHIA6, PYTHIA8) show similar results With/Without MPI
  - Need to improve sensitivity
- Lowering p_T thresholds



Same sign W pair production

CMS-PAS-FSQ-13-001

- Pro

Clean signature

- No jets
- No lepton correlation

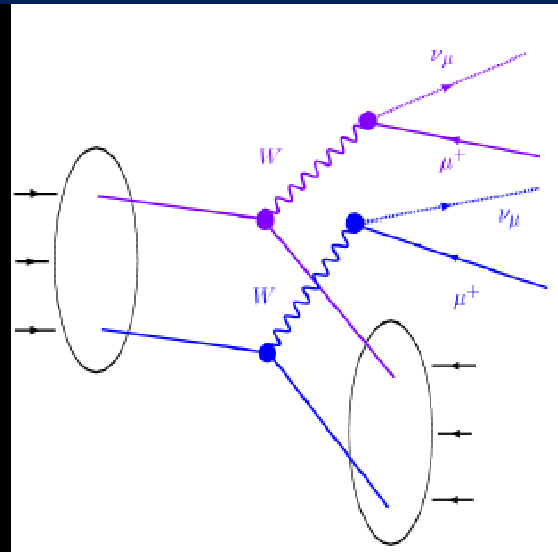
W from SPS boosted

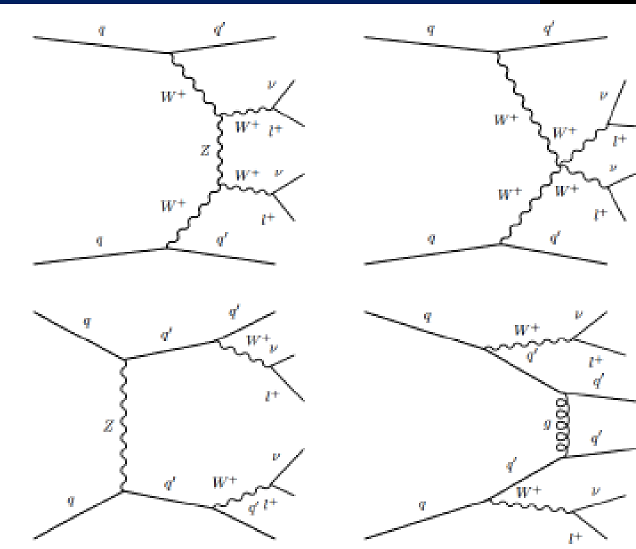
$\sigma_{DPS} \approx \sigma_{SPS}$

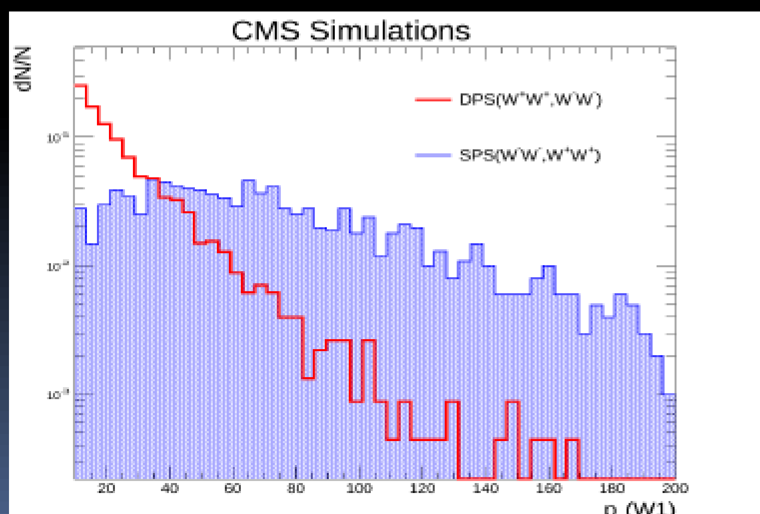
- Con

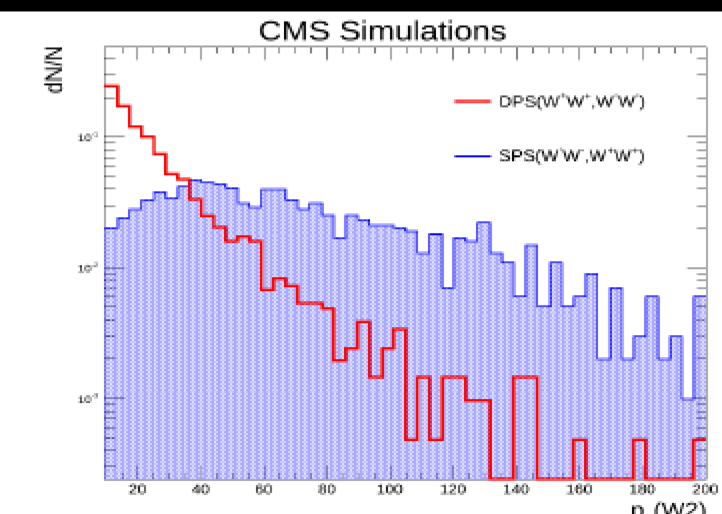
Very small $\sigma_{DPS} \approx 5$ fb

Limits only







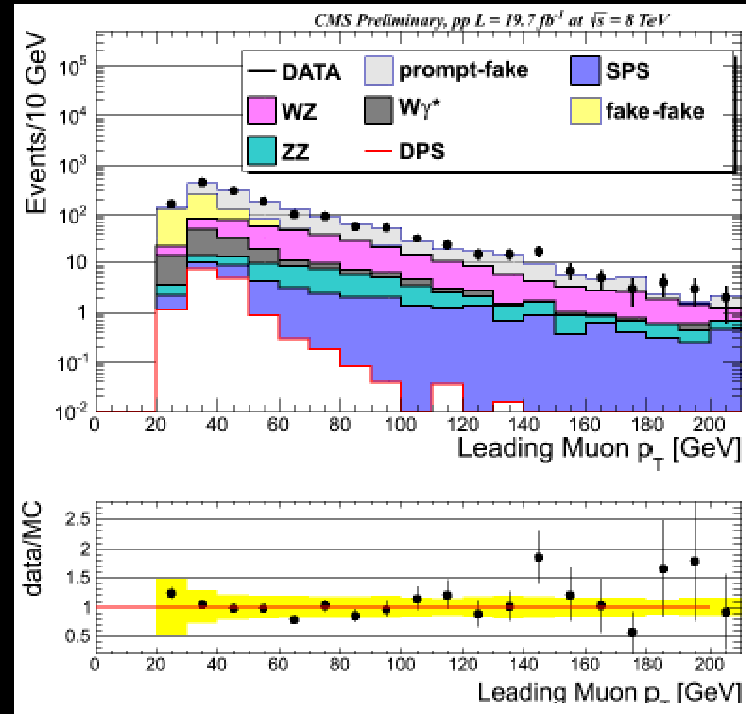


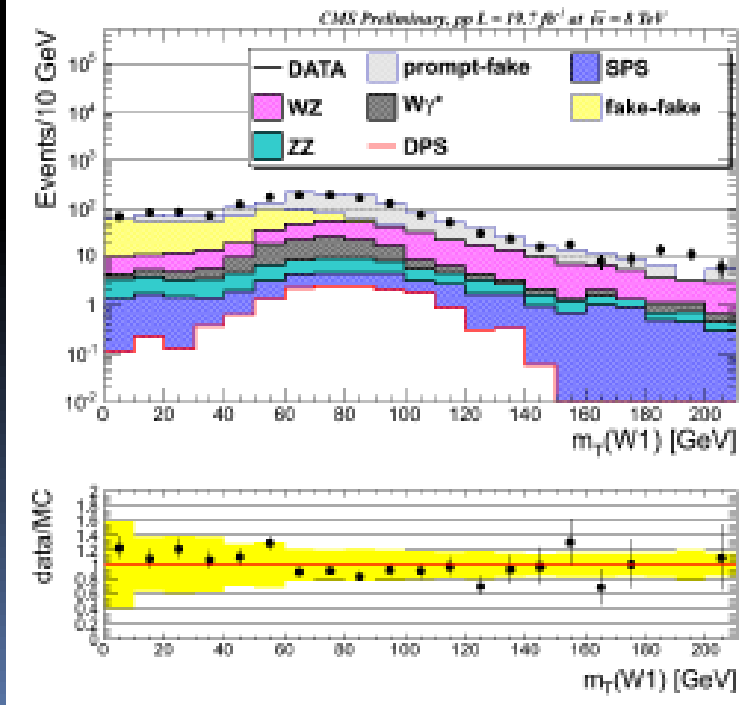
Same sign W pair production

- 8 TeV data (2012) 19.7 fb^{-1}
- *2 same sign μ* $p_T > 20$ GeV ($p_T > 10$ GeV 2nd μ)
  - Veto 3rd μ $p_T > 10$ GeV
- $\Sigma p_{T\mu} > 45$ GeV
- $E_T^{miss} > 20$ GeV – >reduce QCD background
- $20 < M_{\mu\mu} < 75$ GeV or $M_{\mu\mu} > 105$ GeV -> Z mass peak

- PYTHIA8 4C (DPS)
- MADGRAPH5 + PYTHIA6.4.25 Z* (SPS + DY)
- PYTHIA6.4.25 Z* (ZZ+ WZ)
- QCD background -> Data driven (low p_T μ from decays)

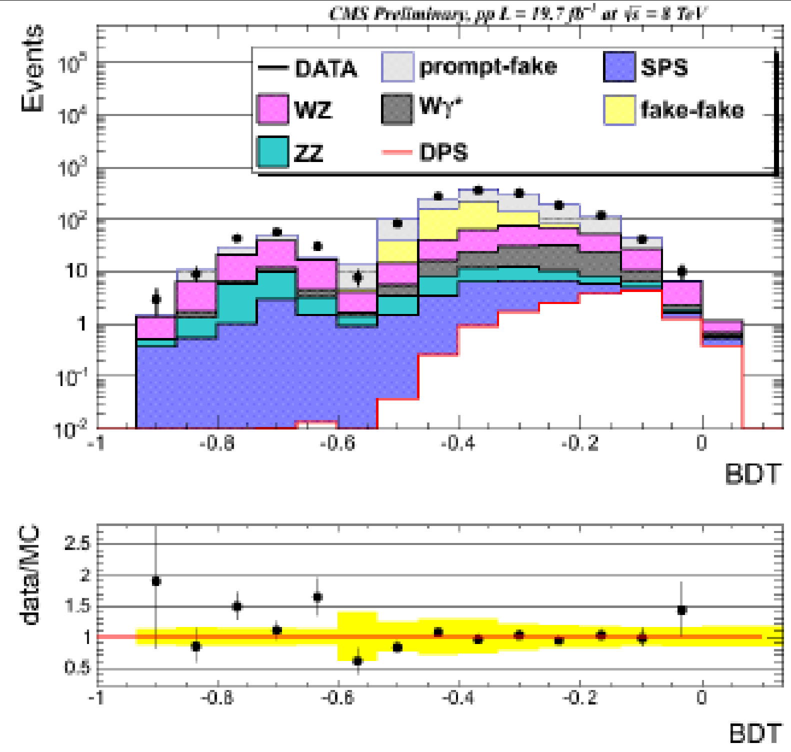
- Use BDT to discriminate DPS
- BDT variables:
  - P_T of both μ
  - E_T^{miss}
  - Dimuon transverse mass
  - $\Delta\phi(\mu,\mu)$
  - $\Delta\phi(\mu,E_T^{miss})$
  - $\Delta\phi(\mu\mu, E_T^{miss})$
  - W transverse mass





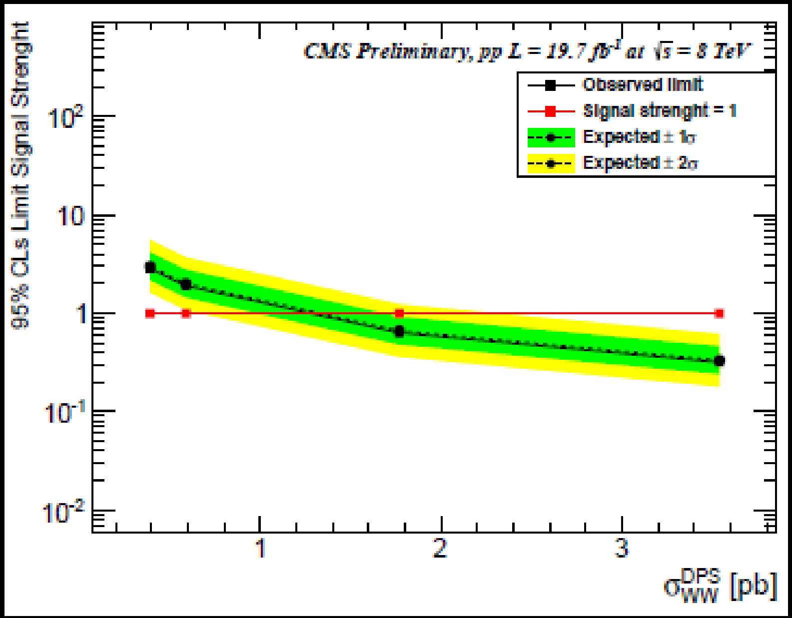
Results Same sign W pair

- BDT discriminant and yields



Sample	Events $\pm$ stat. $\pm$ syst.
DPS	$15.0 \pm 0.5 \pm 0.7$
SPS	$30 \pm 1 \pm 3$
WZ	$263 \pm 3 \pm 30$
ZZ	$40 \pm 1 \pm 2$
$W\gamma*$	$86 \pm 3 \pm 9$
Prompt-Fake	$709 \pm 7 \pm 213$
Fake-Fake	$381 \pm 4 \pm 229$
Total	$1523 \pm 9 \pm 314$
Data	1539

Limit settings W pair



95% CLs	BDT
Expected	$r < 2.001$
Expected $\pm 1\sigma$	[1.443,2.778]
Expected $\pm 2\sigma$	[1.085,3.691]
Observed	$r < 1.897$

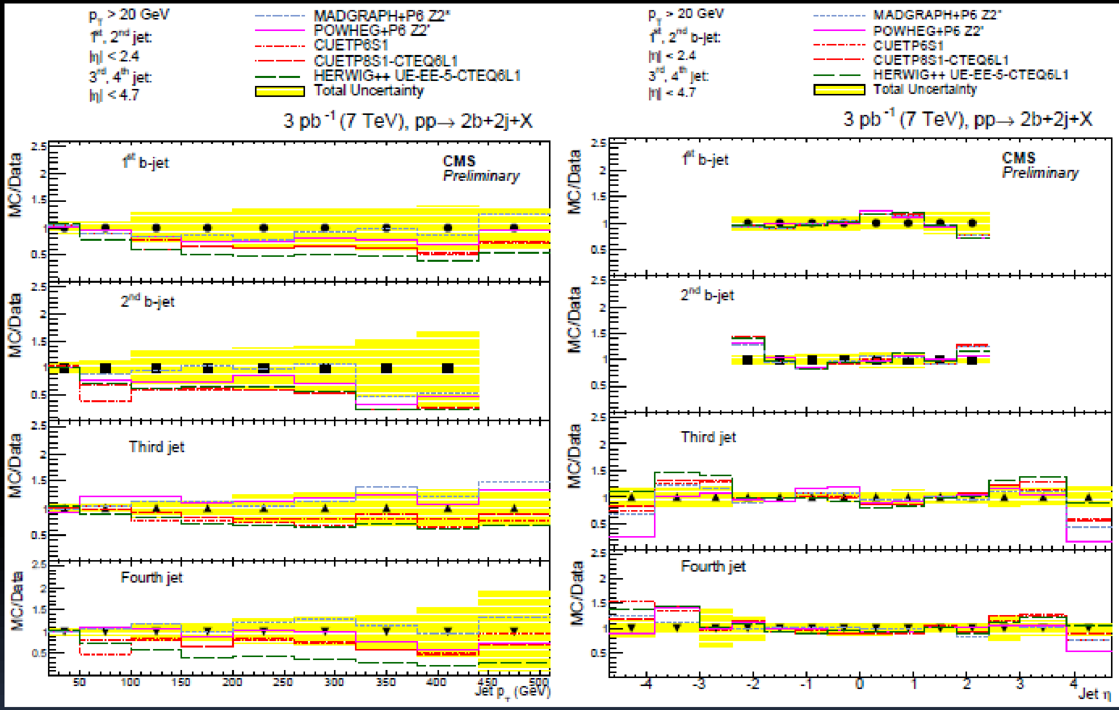
$$\sigma_{WW}^{DPS} < r_{observed} \cdot \sigma_{WW}^{MC} = 1.897 \cdot 0.59\,\mathrm{pb} = 1.12\,\mathrm{pb}$$

$$\sigma_{eff} > \frac{(\sigma_{W\to l\nu})^2}{2 \cdot (BR^2_{W\to l\nu}) \cdot \sigma_{WW}^{DPS}} = 5.91\,\mathrm{mb}$$

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
- $S'p_T = \sqrt{(\Delta^{\rm rel}_{\rm bottom} p_T)^2 + (\Delta^{\rm rel}_{\rm light} p_T)^2}$
- $\Delta\eta_{ljets}; \Delta\eta_{bjets}$
- ΔS = pair azimuthal angle



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

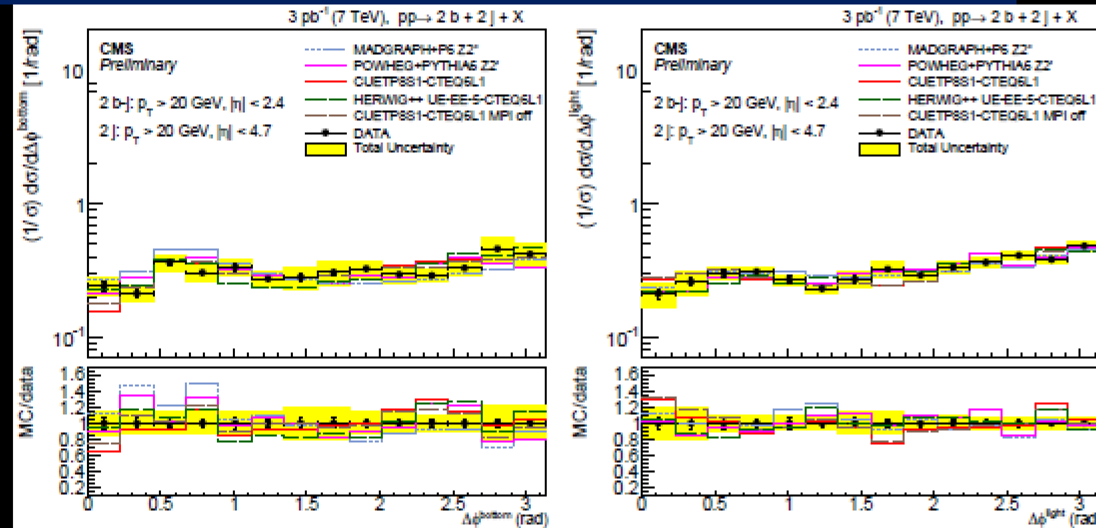
DPS in 2b jets + 2 jets

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.)

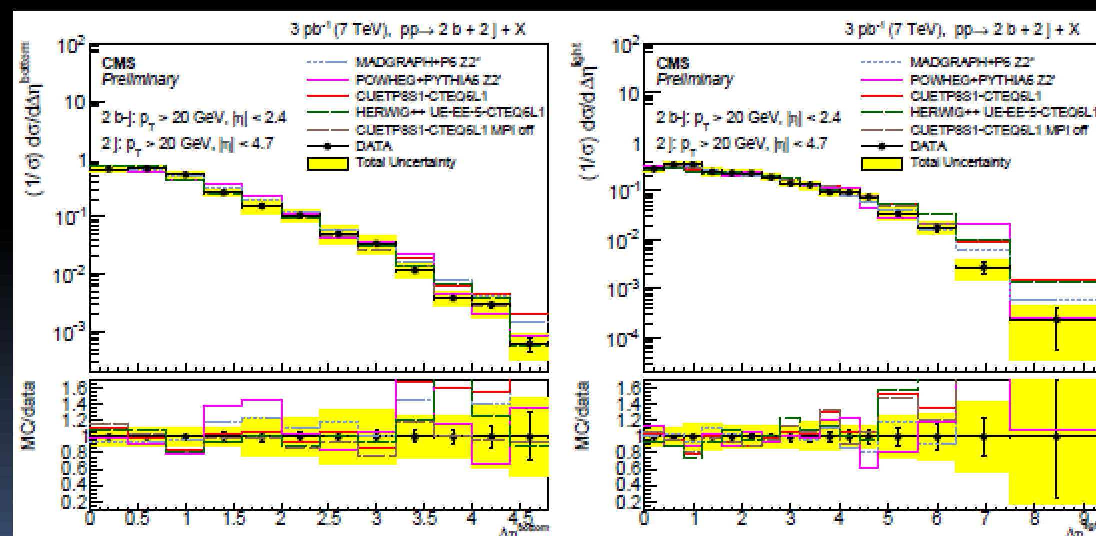
- Cross section predictions vary between models
- *PYTHIA8 overestimate*
- *MADGRAPH & HERWIG++ underestimate*
- *Others do a reasonable job*
- *Data systematics dominated by unfolding and jet energy*

DPS in 2b jets + 2 jets

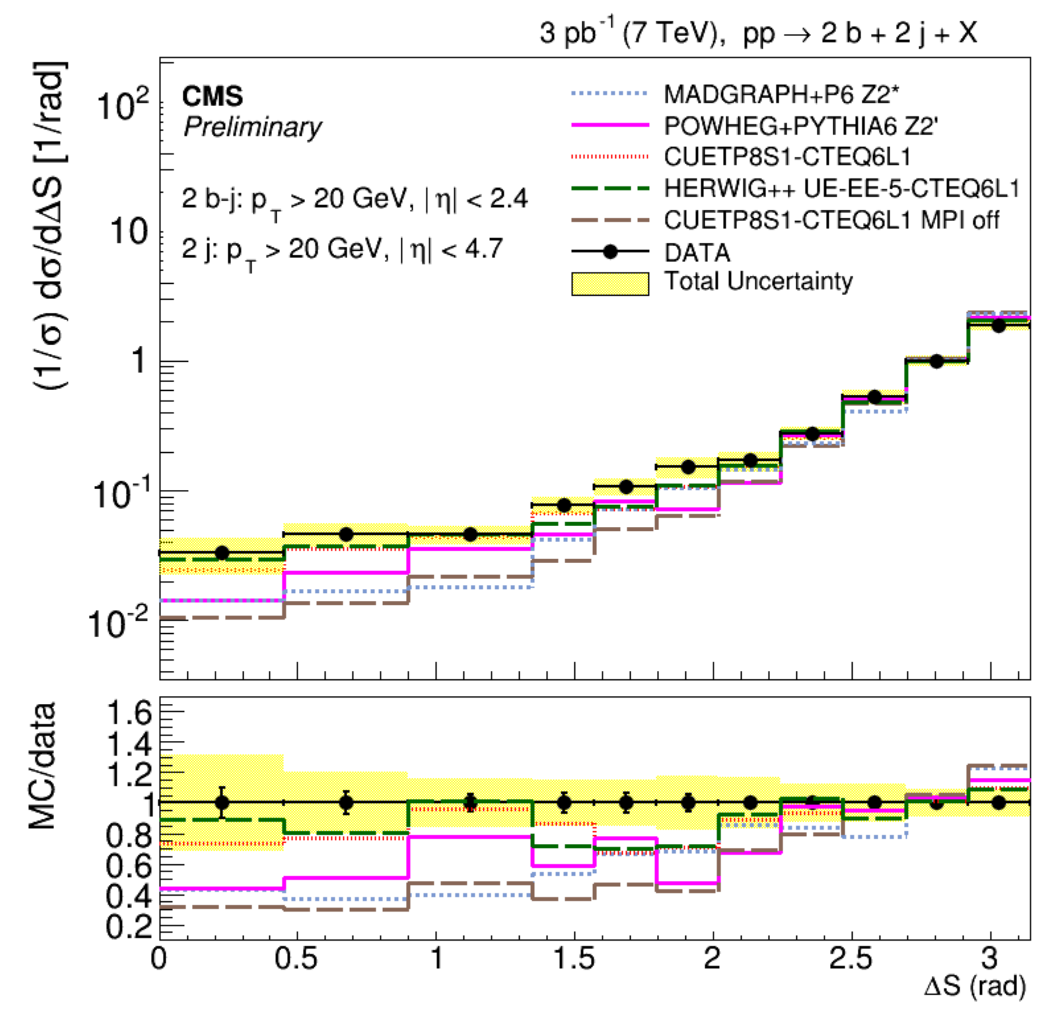
- $\Delta\phi$ well described by all models



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



- ΔS not well described by all models
- HERWIG++ and PYTHIA8+MPI agree in some regions
- Better DPS implementations are needed



Conclusions

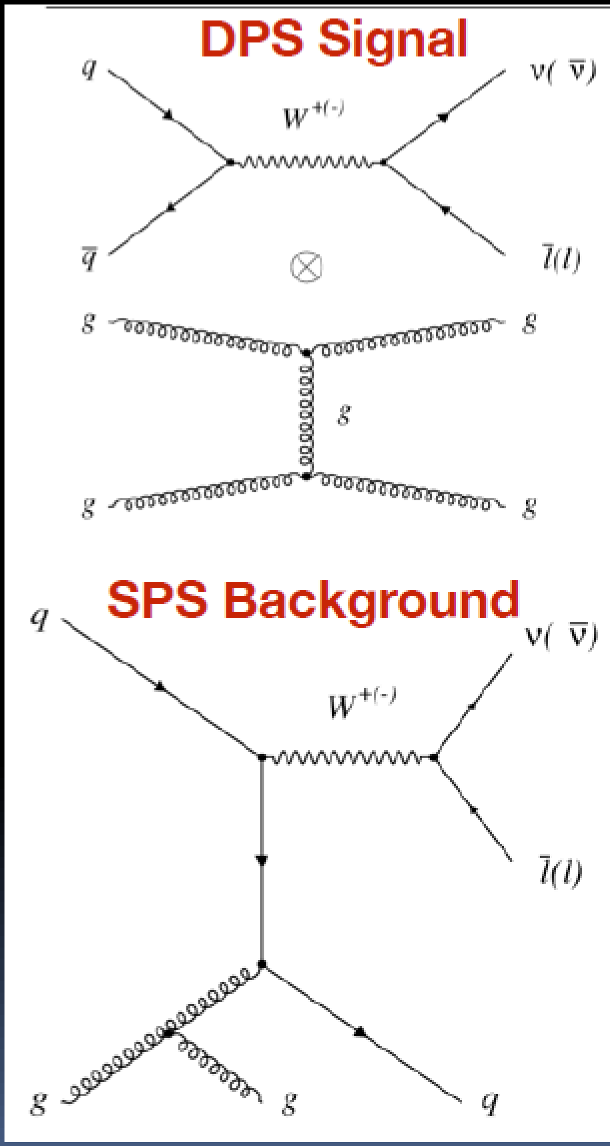
- Presented Recent studies on DPS at CMS/LHC
- Important to study the sensitivity of considered observables
  - Model dependence of predictions for backgrounds to DPS
- Double Parton Scattering needs better understanding for searches
  - Need for better MPI implementation on models
- CMS results provide new constraints for non-perturbative and semi-hard QCD dynamics on MC

Extra

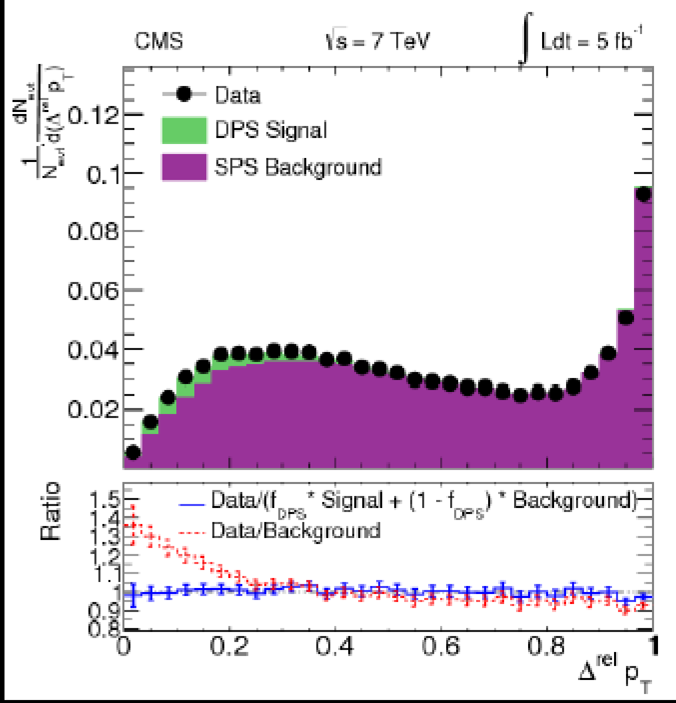
- Motivation: DPS is important for understanding the partonic correlations and backgrounds for new physics.
- W+2jets advantages
  - Clean tag from W->muon decay
  - Large dijet cross section
- Measurement of σ_{eff}- effective area parameter, input to theoretical models

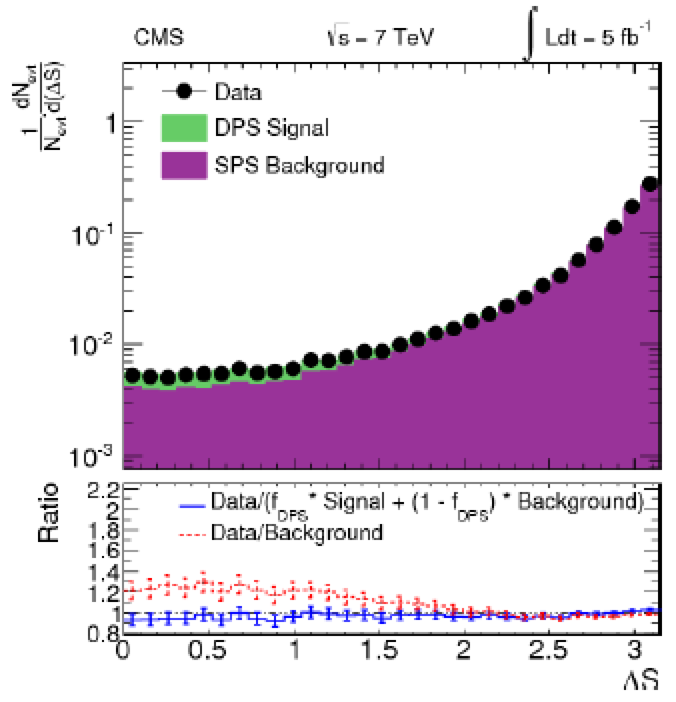
$$\sigma_{\mathrm{eff}} = \frac{\sigma'_{\mathrm{W+0jet}}}{\sigma'^{\mathrm{DPS}}_{\mathrm{W+2j}}} \cdot \sigma'_{2j} \longrightarrow \sigma_{\mathrm{eff}} = \frac{R}{f_{\mathrm{DPS}}} \cdot \sigma'_{2j}$$

- 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)



- Discriminate between SPS and DPS by studying:
  - transverse momentum balance of two jets (DPS around 0) $\Delta_{rel}p_T$
  - azimuthal angle between W and di-jet system ΔS
- Fully-corrected data fitted with DPS and SPS templates (MC based, MADGRAPH5 + PYTHIA8)
- Extract f_{DPS}
- $f_{DPS} = 0.055 \pm 0.002\ (\text{stat}) \pm 0.014\ (\text{syst})$

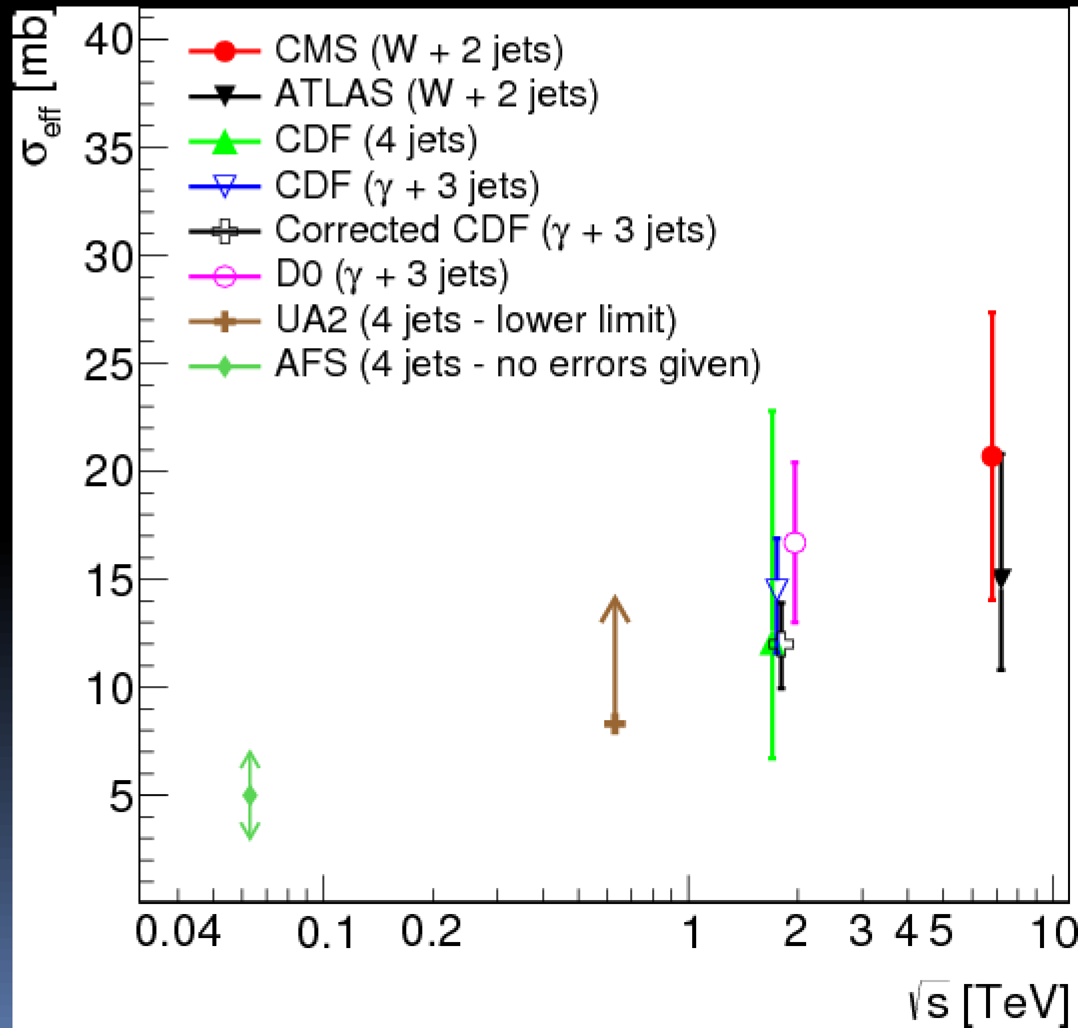




Results

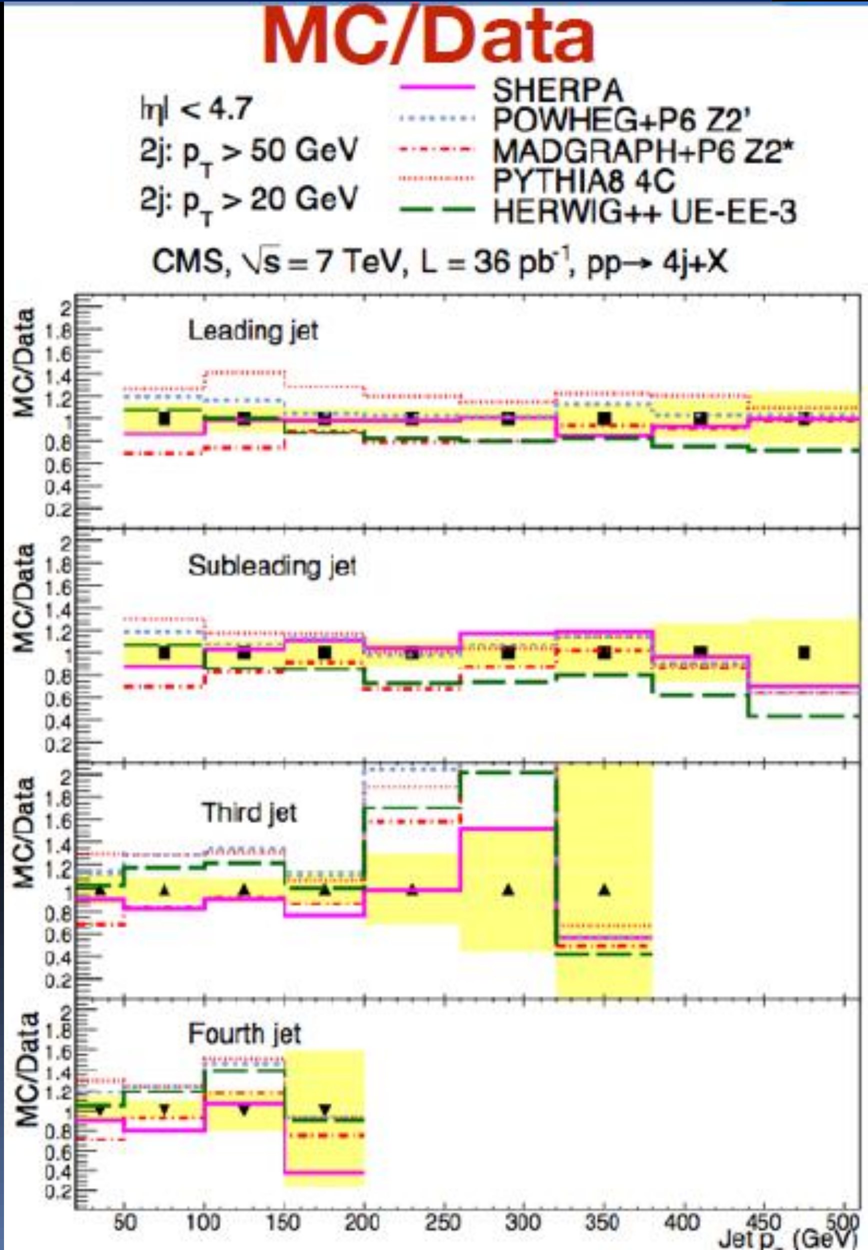
$$\sigma_{\text{eff}} = 20.7 \pm 0.8\,(\text{stat.}) \pm 6.6\,(\text{syst.})\ \text{mb}$$

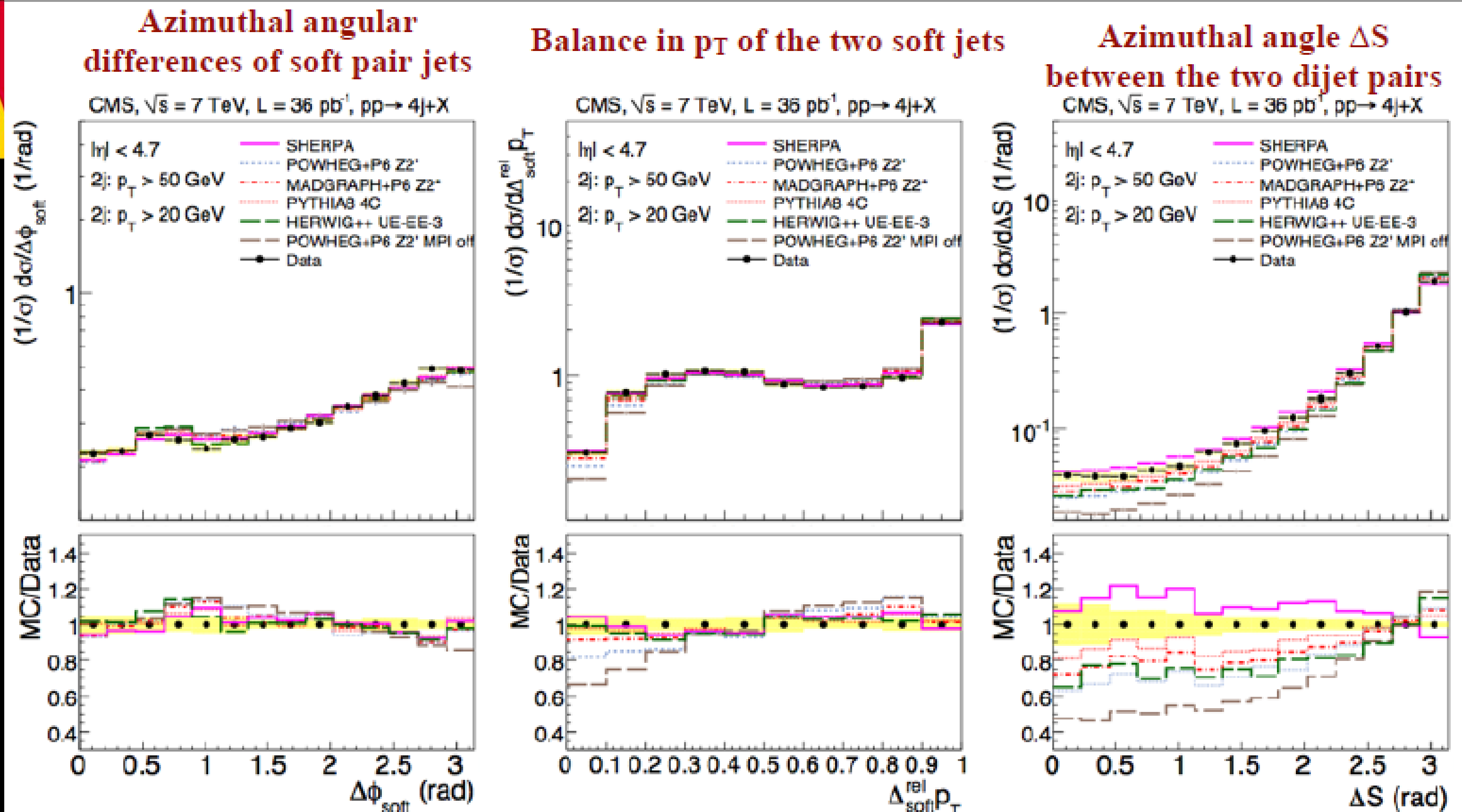
- Measurement consistent with ATLAS, CDF and Do results
- Large uncertainties, difficult to conclude on energy dependence of σ_{eff}
- PYTHIA8: σ_{eff} ~ 20-30 mb, tune dependent



4 Jet events

- 4 Jet events in SPS produced by QCD evolution
  - Good test for higher order QCD calculations and parton shower formalism
- DPS important in the low x region (large parton densities)
- SPS → strongly correlated jets
- DPS → uncorrelated
- Cross section agreement at high p_T
- Significant disagreement at lower p_T values and sub-leading jets





- Discriminating variables similar to W+2Jets
- POWHEG without MPI is far below data at lower discr. values
- SHERPA and PYTHIA8 give the best description
- Recent tune gives $\sigma_{eff} = 21.3^{+1.2}_{-1.6}$ mb   CMS PAS GEN 14-001

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)*

$$
\begin{aligned}
F_{\text{pileup}} &= \frac{\Sigma_{i=1}^{\infty} iP(i,\lambda)}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} \cdot \epsilon_{\text{inel}} = \frac{\epsilon_{\text{inel}}\lambda}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} = \\
&= 1 + \frac{1}{2}\lambda\epsilon_{\text{inel}} + \frac{1}{12}\lambda^2\epsilon_{\text{inel}}^2 + \mathcal{O}(\lambda^3)
\end{aligned}
$$

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