Double Parton Scattering Measurements at the CMS Experiment

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Overview

Introduction on double-parton scattering

DPS experiments at CMS

- Study of DPS using W + 2-jet events in proton-proton collisions at √s = 7 TeV
- Measurement of four-jet production in proton-proton collisions at s√ = 7 TeV
- Studies of inclusive four-jet production with two b-tagged jets in proton-proton collisions at 7 TeV
- Evidence for WW production from double-parton interactions in proton-proton collisions at √s = 13 TeV

Conclusion

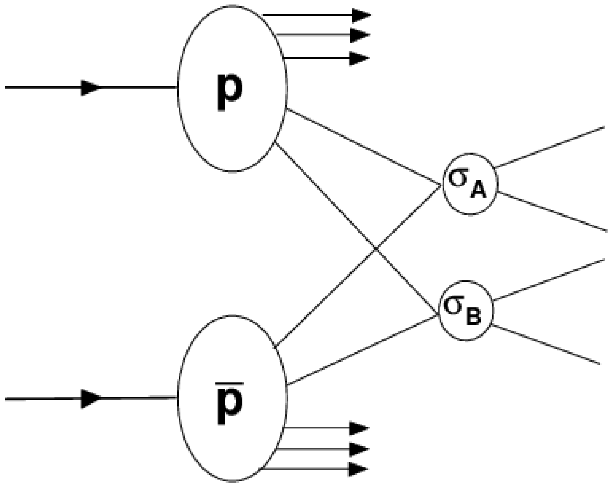
Double Parton Scattering

DPS cross section: factorisation formula

Cross section = parton level cross sections x *double parton distributions*

$$\frac{d\sigma_{DPS}}{dx_A dx_B dx'_A dx'_B} = m\hat{\sigma}_A\hat{\sigma}_B \int d^2\boldsymbol{y}\, F(x_A, x_B, \boldsymbol{y}) F(x'_A, x'_B, \boldsymbol{y})$$

- $\hat{\sigma}_A$ and $\hat{\sigma}_B$ parton level cross sections
- m is a combinatorial factor, ½ if processes are identical
- $F(x_A, x_B, \boldsymbol{y})$ is the double parton distribution function
- $\boldsymbol{y}$ is the transverse distance between the partons or impact parameter



Assume that $F(x_A, x_B, \boldsymbol{y}) = f(x_A) f(x_B) G(\boldsymbol{y})$ and where

- $f(x)$ is the standard single parton distribution func...
- $G(\boldsymbol{y})$ is the transverse part of the double parton distribution and the same for all partons

The differential cross section becomes

$$\frac{d\sigma_{DPS}}{dx_A dx_B dx'_A dx'_B} = m \cdot \hat{\sigma}_A f(x_A) f(x'_A) \cdot \hat{\sigma}_B f(x_B) f(x'_B) \cdot \int d^2\boldsymbol{y}\, G(\boldsymbol{y})$$

Double Parton Scattering

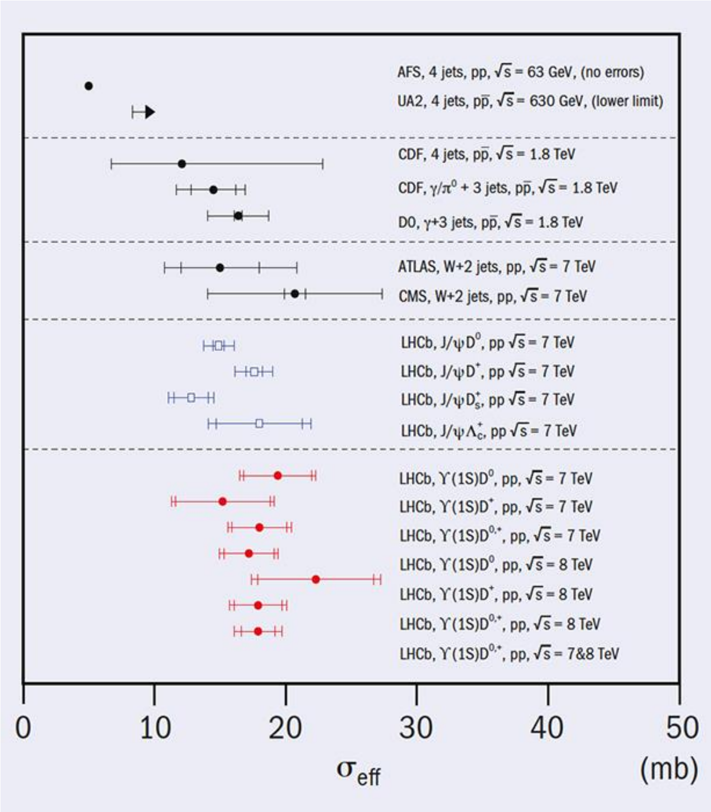
Where $\hat{\sigma} f(x) f(x')$ is the differential cross section for a single parton scattering event, which results in the pocket formula for DPS

$$\frac{d\sigma_{DPS}}{dx_1 dx_2 dx_1' dx_2'} = \frac{m}{\sigma_{eff}} \frac{d\sigma_1}{dx_1 dx_1'} \frac{d\sigma_2}{dx_2 dx_2'}$$

Where $\frac{1}{\sigma_{eff}} = \int d^2\boldsymbol{y} G(\boldsymbol{y})$

In this approach the parameter σ_{eff} is independent of the final state and measurement of effective area parameter σ_{eff} gives insight in hadron structure in the transversal plane!

→ Examine variables that exhibit distinctive behaviour for SPS and DPS processes



Different final states in DPS measurements at CMS

- W + 2 jets
- γ + 3 jets
- Same-sign WW
- 4 jets
- 2b + 2 jets

Study of DPS using W + 2-jet events in proton-proton collisions at √s = 7 TeV

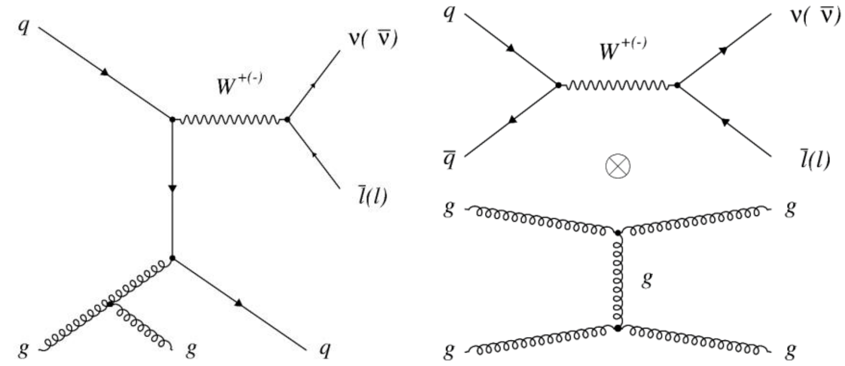
Measure DPS sensitive variable

$$\Delta p_T^{rel} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$$

➡ Jets back-to-back in DPS, variable expected to be small (≈ 0)

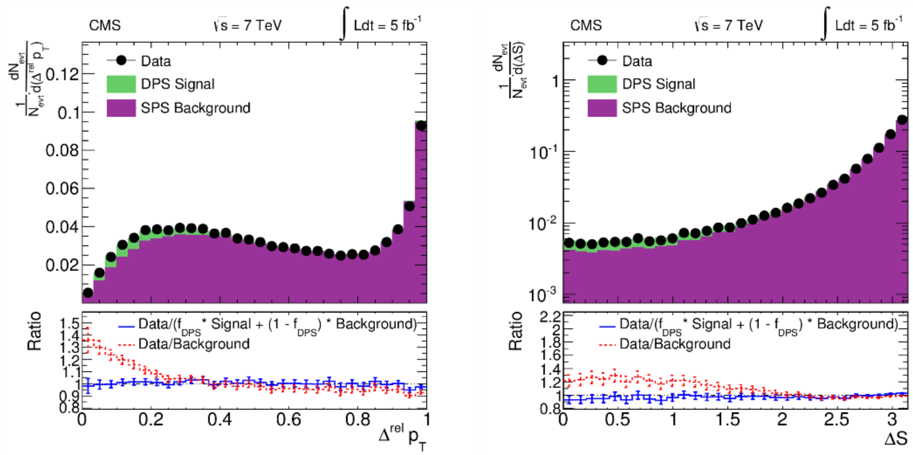
$$\Delta S = \arccos\left(\frac{\vec{p}_T(\mu, E_{T,miss}) \cdot \vec{p}_T(j_1, j_2)}{|\vec{p}_T(\mu, E_{T,miss})| \cdot |\vec{p}_T(j_1, j_2)|}\right)$$

➡ No correlation between particle pairs for DPS, distribution will be flat



Template method used to determine the DPS fraction and σ_{eff}

➡ Fully corrected variables fitted with signal and background template by using a binned likelihood method



Extracted values of DPS faction and σ_{eff}

- $f_{DPS} = 0.055 \pm 0.002\,(\text{stat.}) \pm 0.014\,(\text{syst.})$
- $\sigma_{eff} = 20.7 \pm 0.8\,(\text{stat.}) \pm 6.6\,(\text{syst.})\ \text{mb}$

Measurement of four-jet production in proton-proton collisions at √s = 7 TeV

Measure DPS sensitive variable

$$\Delta p_T^{rel} = \frac{|\vec{p}_T(j_3) + \vec{p}_T(j_4)|}{|\vec{p}_T(j_3)| + |\vec{p}_T(j_4)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j_1,j_2)\cdot\vec{p}_T(j_3,j_4)}{|\vec{p}_T(j_1,j_2)|\cdot|\vec{p}_T(j_3,j_4)|}\right)$$

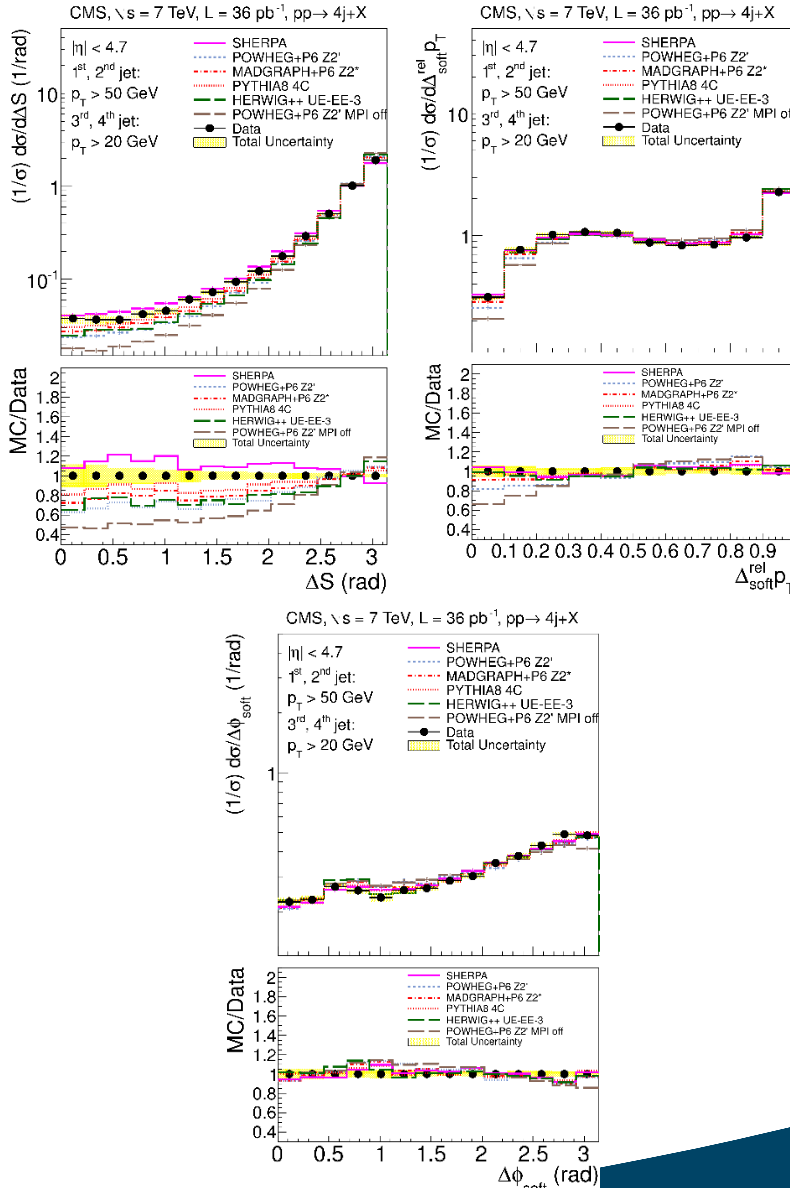
$$\Delta\varphi_{34} = |\varphi(j_3) - \varphi(j_4)|$$

Differential cross section determined

$$\sigma_{4j} = 330 \pm 5\ (\text{stat.}) \pm 45\ (\text{syst.})\ \text{pb}$$

Normalised differential cross section in function of the
variables compared to different MC models with and without MPI

➔ Models only give proper description in some regions of the phase space

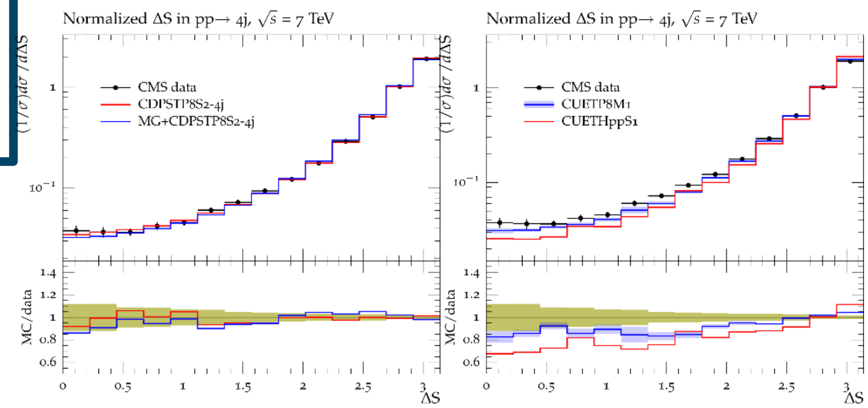


Measurement of four-jet production in proton-proton collisions at √s = 7 TeV

New method for extraction of σ_{eff} applied :

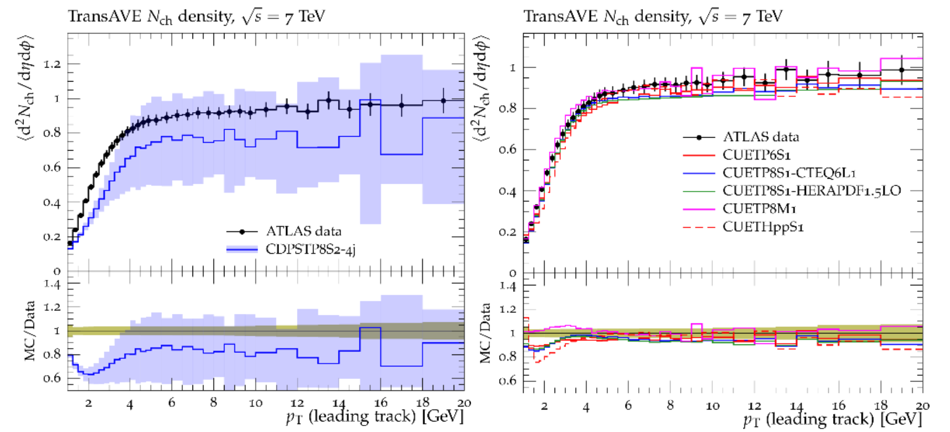
Tuning method (doi:10,1140/epjc/s10052-016-3988-x):
DPS sensitive variables fitted directly and σ_{eff} determined from the models

CMS Tune	σ_{eff}(mb) at 7 TeV	σ_{eff}(mb) at 13 TeV
CUETP8S1-CTEQ6L1	$27.8^{+1.2}_{-1.3}$	$29.9^{+1.6}_{-2.8}$
CUETP8S1-HERAPDF1.5LO	$29.1^{+2.2}_{-2.0}$	$31.0^{+3.8}_{-2.6}$
CUETP8M1	$26.0^{+0.6}_{-0.2}$	$27.9^{+0.7}_{-0.4}$
CUETHppS1	$15.2^{+0.5}_{-0.6}$	$15.2^{+0.5}_{-0.6}$
CDPSTP8S1-4j	$21.3^{+1.2}_{-1.6}$	$21.8^{+1.0}_{-0.7}$
CDPSTP8S2-4j	$19.0^{+4.7}_{-3.0}$	$22.7^{+10.0}_{-5.2}$



2 DPS tunes:

- CDPSTP8S1-4j: only MPI:expPow varied
- CDPSTP8S2-4j: MPI:pT0Ref, MPI:ecmPow and ColourReconnection:range additionally varied



DPS and UE tunes not completely compatible:

➡ DPS sensitive observables not quite as good described by UE tunes

➡ Difficulty of describing soft and hard MPI within the current frameworks

Studies of inclusive four-jet production with two b-tagged jets in proton-proton collisions at √s = 7 TeV

Measure DPS sensitive variable

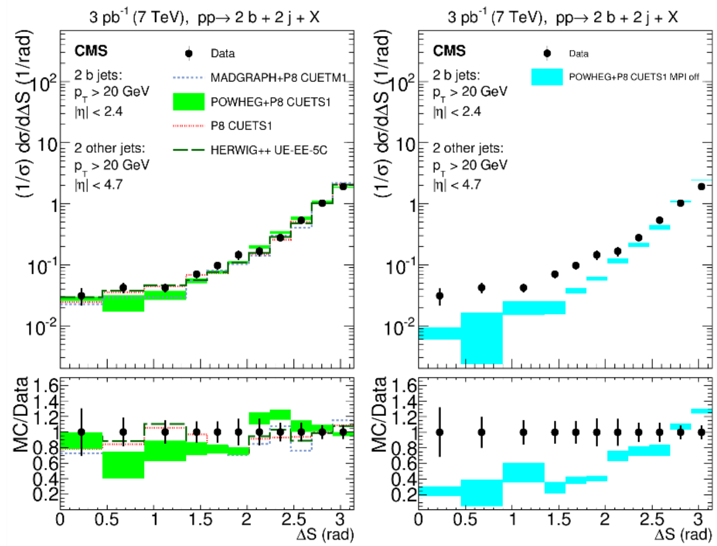
$$\Delta p_T^{rel} = \frac{|\vec{p}_T(light_1) + \vec{p}_T(light_2)|}{|\vec{p}_T(light_1)| + |\vec{p}_T(light_2)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(bottom_1, bottom_2)\cdot\vec{p}_T(light_1, light_2)}{|\vec{p}_T(bottom_1, bottom_2)|\cdot|\vec{p}_T(light_1, light_2)|}\right)$$

$$\Delta\varphi_{light} = |\varphi(light_1) - \varphi(light_2)|$$

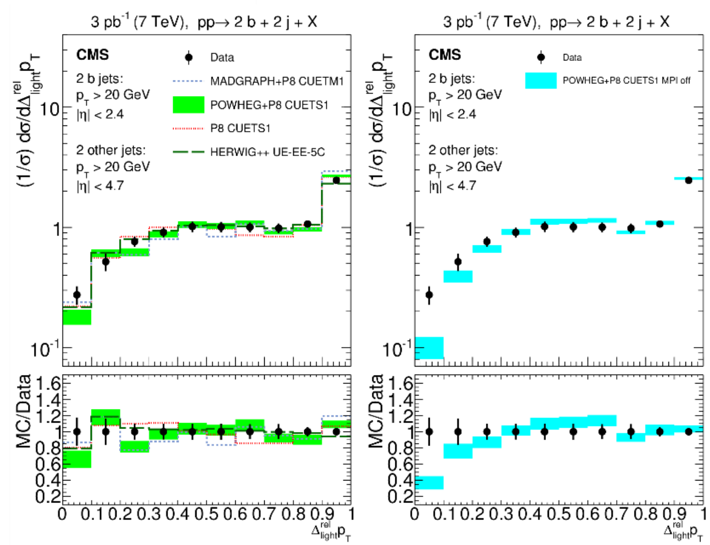
Differential cross section determined

$$\sigma_{2b+2j} = 69 \pm 3\,(\text{stat.}) \pm 24\,(\text{syst.})\text{ pb}$$



Normalised differential cross section will be compared to different MC models

- Good agreement between MC models except Powheg+P8 with no MPI
- Differences in description in DPS sensitive areas
- First sign of DPS sensitivity in multi-jet final state with heavy-quarks



CMS PAS SMP-18-015

Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Motivation

W boson production: benchmark process at LHC and golden channel for DPS production

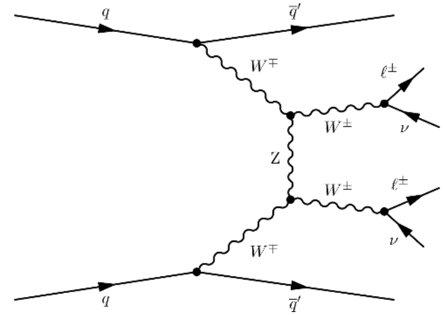
Quark initiated
➡ Sensitive to longitudinal quark polarizations

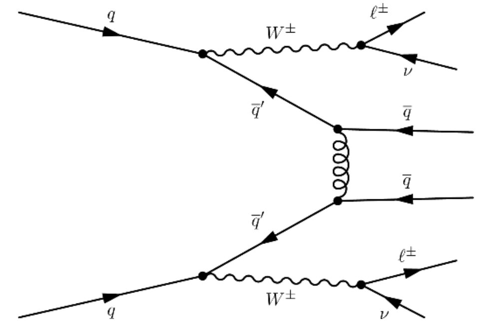
Not sensitive to pileup effects and clean final state

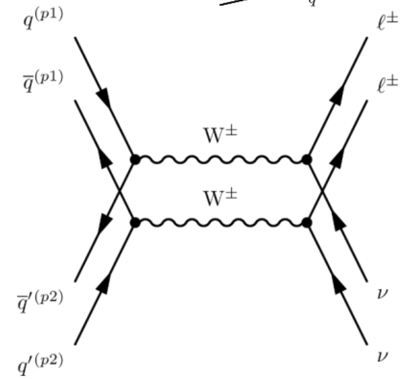
DPS WW process constitutes a background in new physics at LHC

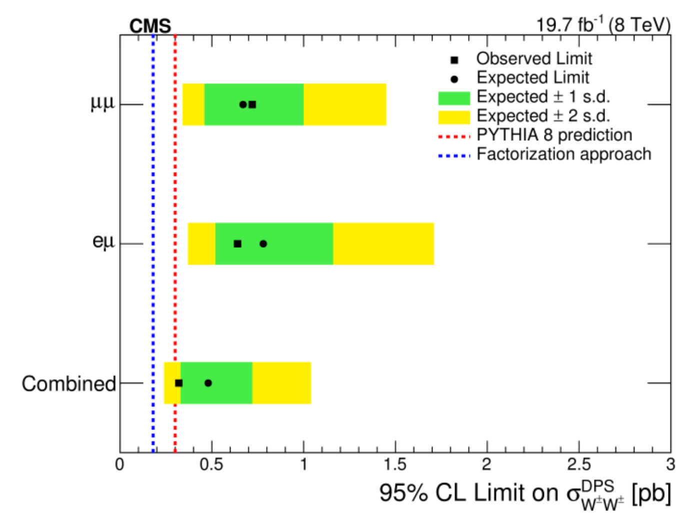
Previous study at √s = 8 TeV (doi:10.1007/JHEP02(2018)032)

- First search for same-sign WW production through DPS
- No significant excess of events observed above the expected SPS yield
- 95% confidence level lower limit of 12.2 mb on σ_{eff} or an upper constraint of 0,32 pb on the cross section









Signal and Background Processes

Signal

- Same-sign lepton pairs (eμ, μμ) coming from W boson pairs
- MET from decay of W bosons

Background

- Diboson processes
  - WZ as dominant background
  - Wγ, Wγ*, Zγ, ZZ and WWW as additional processes
  - One of the leptons escapes detector acceptance
  - Estimation is MC driven
- Electron charge flips
  - Z → ττ with letponic decay τ
  - Data driven estimation
- Production of fake leptons
  - QCD multijet and W+jets: misidentification of jets as leptons
  - Top pair+jets: leptonic decay of top quarks
  - Data driven estimation through fake rate method

Event Selection and Multi-Variate Analysis using a Boosted Decision Tree (BDT) Training

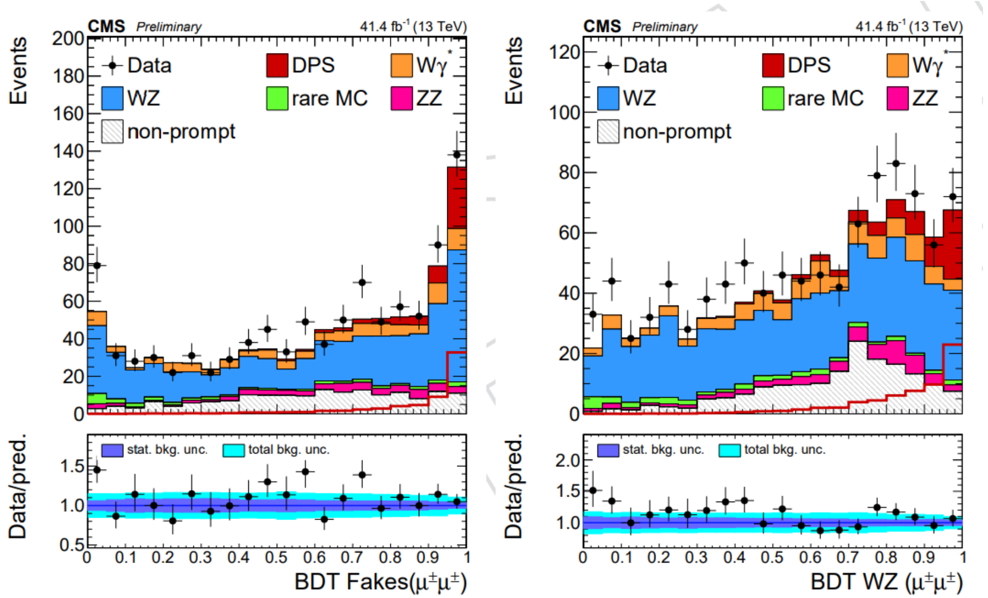
Variables:

- p_T^{l1} and p_T^{l2}
- E_T^{miss}
- M_{T2}^{ll}
- $m_T(l_1, l_2)$
- $m_T\left(l_1, E_T^{miss}\right)$
- $\Delta\varphi(l_1, l_2)$
- $\Delta\varphi(l_1, E_T^{miss})$
- $\Delta\varphi(l_1 l_2, l_2)$
- $\eta_1 \cdot \eta_2$
- $|\eta_1 + \eta_2|$

two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
$p_T^{\ell_1} > 25\,\mathrm{GeV}$, $p_T^{\ell_2} > 20\,\mathrm{GeV}$
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
$p_T^{miss} > 15\,\mathrm{GeV}$
$N_{jets} < 2$ ($p_T > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$)
$N_{b\text{-tagged jets}} = 0$ ($p_T > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$)
veto on additional e, μ, and τ_h

MVA based on BDT technique to enhance signal sensitivity

- 2 BDTs trained
  - WZ background
  - Fake lepton background
- Same variables used in both BDTs
- The BDTs determine a 2D distribution

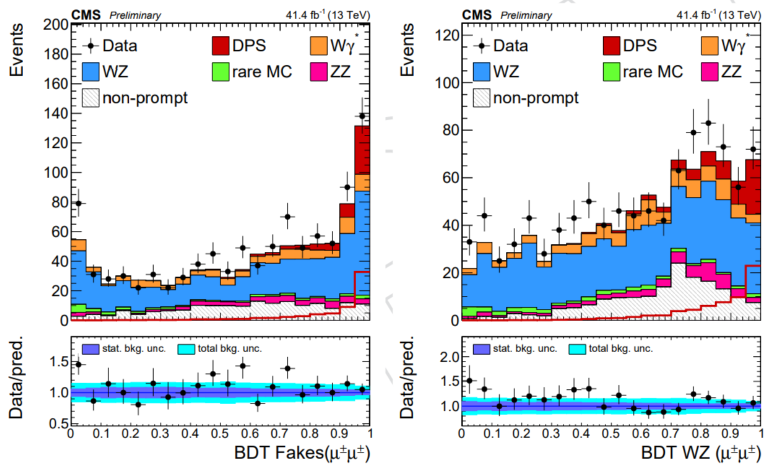


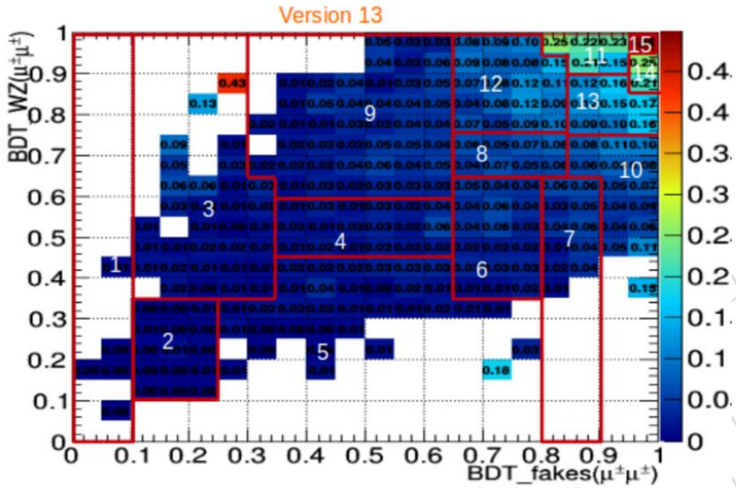
Constructing the Final Classifier

2D BDT distribution mapped into 1D classifier

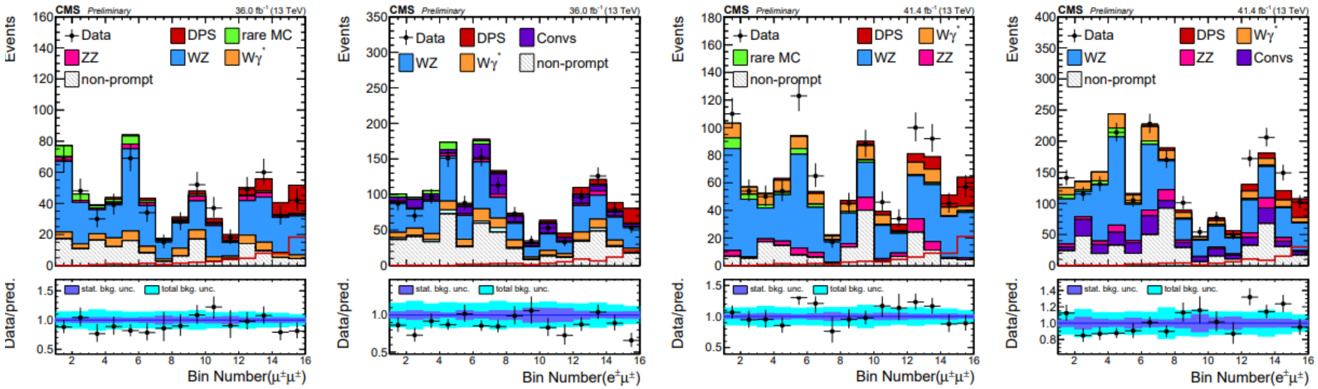
Determination of bins through iterative process

→ Make discrimination between signal and background as large as possible

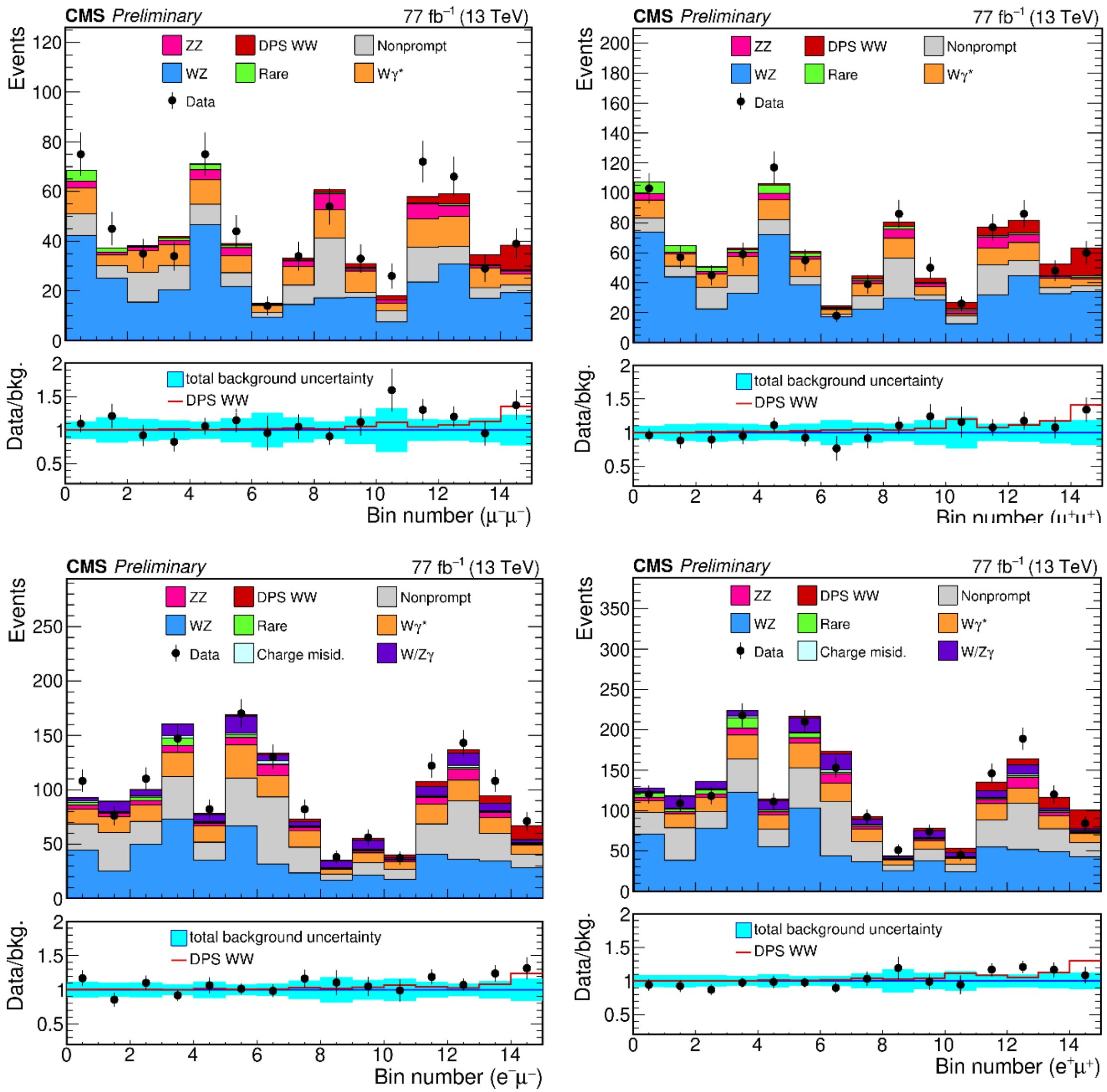




Pre-fit results (2016 left, 2017 right)



Resulting Distributions (post-fit)



Maximum likelihood fit performed to final classifier

Different final states fit separately

→ Better signal sensitivity due to W production asymmetry

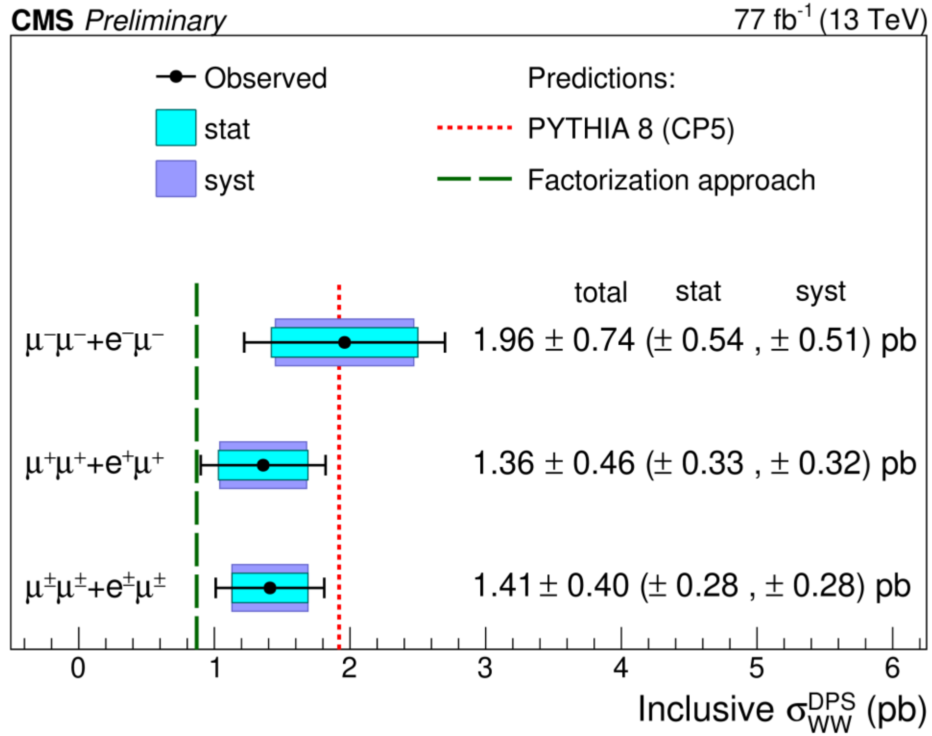
Extraction of σ_{eff}

After training two multivariate classifiers and combining their results a first measurement of DPS same sign WW is achieved

Model predictions:

- Pythia 8 (CP5)
- Factorized approach by using pocket formula with:
  - Inclusive W production cross section
  - σ_{eff} = 20.7 ± 6.6 mb

Cross sections have been deducted for both the lepton pair configurations and their combination



→ The deducted value of σ_{eff} is $12{,}67^{+5{,}01}_{-2{,}92}$ mb

Conclusion

- Multiple studies of different DPS processes have been performed for different final states at the CMS experiment
- Within these final states a proper choice of the many DPS sensitive variables needs to be made
- Proper understanding of the background processes is needed to obtain a value for σ_{eff}, multiple techniques exist
  - Template method
  - Tuning method
  - MVA using BDT