Recent CMS results on the Soft QCD & Forward Physics

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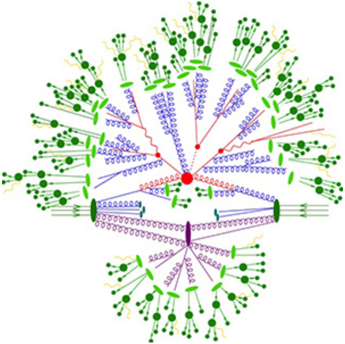
Bird's Eye View

Understanding particle production at the LHC → Important to realize it's physics goals

hard interaction & UE



Diffractive processes dominate in forward regions

Measurements of UE activity in central regions

Beam-beam remnants

Multiple-parton interactions (double-parton scattering)

Initial & final state radiations

- Sensitive to interplay between perturbative & non-perturbative regions
- Non-perturbative phenomenological models → free parameters to tune
- Forward energy drives development of cosmic ray induced air showers

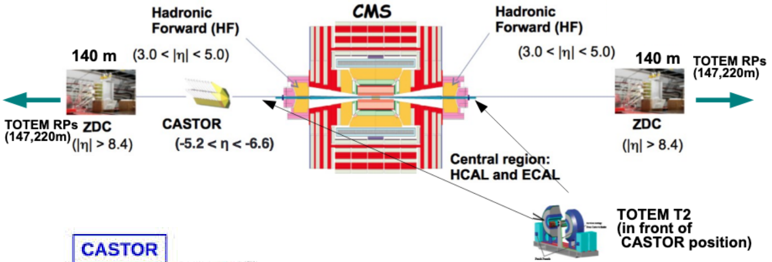
Expt. measurements → MB, UE, total and diffractive cross section & particle correlations

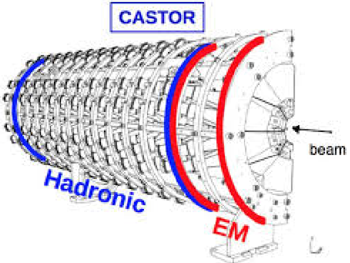
Soft interactions: *Why to study them?*

- Responsible for a very large fraction of the total cross section
- Their modeling impacts all high-p_{T} measurements
- Indispensable ingredients to improve background estimates for SM & BSM processes

Detector Setup

Soft QCD & forward physics at CMS → Facilitated by the forward instrumentation





- CASTOR calorimeter in the very forward region of the CMS ($-6.6 < \eta < -5.2$)
- Cherenkov sampling calorimeter, consisting of quartz and tungsten plates, with an overall depth of 10 interaction lengths

This talk covers results on energy measurements using CASTOR & DPS WW production

Average Very Forward Energy @13 TeV (CMS PAS FSQ-18-001)

- Energy carried by particles produced in the very forward region powerful probe to study UE activity
- Increase of energy with multiplicity is driven by MPI → Model validation & tuning
- Relation between electromagnetic & hadronic energy can constrain muon production in air showers
- First correlation study of hadron activity at very forward & central rapidities performed at 13 TeV
- Results with 0.22 nb^{-1} of low pileup pp data selected using Zerobias triggers at *Zero Tesla*

Rich variety of MC samples compared with data

- PYTHIA8 (CUETP8M1, 4C+MBR, CP5)
- QGSJETII.04
- EPOS LHC
- SIBYLL (2.1,2.3c)
- HERWIG7.1

Analysis Ingredients

- Event selection:
  - Activity in at-least one tower of HF calorimeter
  - At-least one track reconstructed in CMS tracker with $|\eta| < 2.0$
  - Cut on reconstructed vertex multiplicity → reduce pileup contributions
- Pixel-based track reconstruction → straight line tracking & vertexing
- Tracking efficiency ∼76% & misreconstruction probability ∼5% for charged particles with $p_T > 200$ MeV
- Event classification based on number of reconstructed tracks (N_{tracks})
- CASTOR energy scale → Dominating source of uncertainty

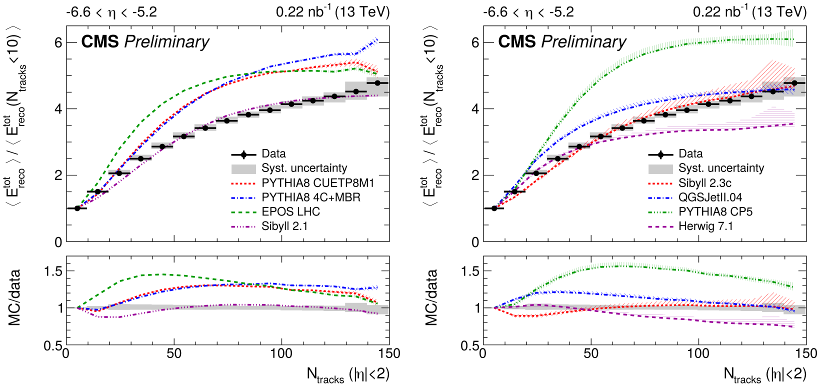
Source	Total energy	Electromagnetic energy	Hadronic energy
CASTOR energy scale	17%	17%	17%
CASTOR intercalibration	2–3%	−8%	+15%
HF energy scale	<0.5%	<0.5%	<0.5%
Tracking efficiency	1–5%	1–5%	1–5%
Pileup rejection	1–8%	1–8%	1–10%
Statistical uncertainty	0.05–1.6%	0.06–1.9%	0.06–1.8%
Total	18–19%	18–20%	20–26%

- **Novel forward folding technique:**
  - Model/theory → Detector level
  - Particle multiplicity and CASTOR energy are smeared

Total Energy

Total energy deposited in CASTOR;

$$E^{tot}_{reco} = \sum_{i=towers} E_i; E_i > \text{Noise threshold}$$

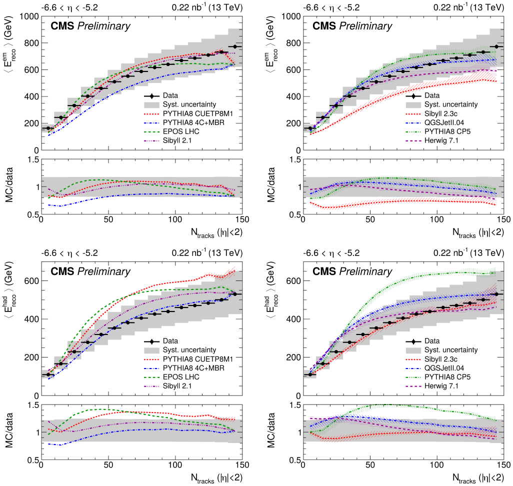


- $\langle E^{tot}_{reco} \rangle$ increases with N$_{tracks}$
- Only Sibyll 2.X & Herwig 7.1 describe the relative increase well
- Mismatch strongest for EPOS LHC & PYTHIA8 CP5

Electromagnetic & Hadronic Energy Components

Relevant for simulation of cosmic ray induced extensive air showers

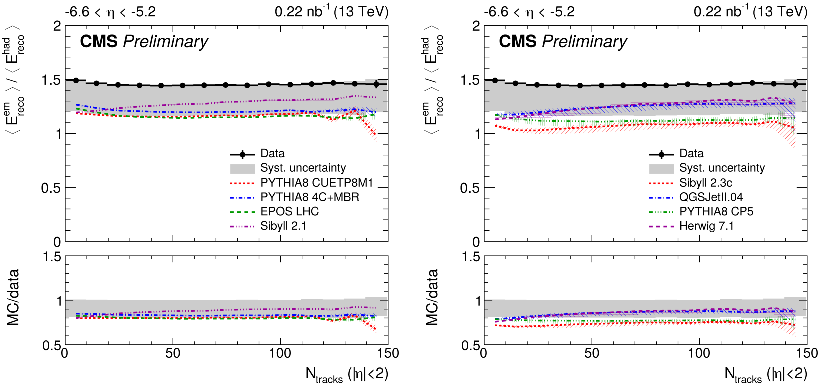
Point towards the modeling accuracy for neutral vs charged pions



- $\langle E^{em}_{reco} \rangle$ described well by all models except SIBYLL2.3c
- PYTHIA8 4C+MBR slightly underestimates $\langle E^{em}_{reco} \rangle$ at low values of N_{tracks}
- $\langle E^{had}_{reco} \rangle \rightarrow$ overestimated by all but SIBYLL2.3c & PYTHIA8 4C+MBR models

Energy Ratio

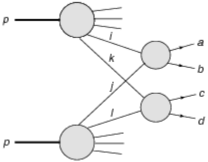
- Sensitive to differences in underlying final state hadron production mechanisms



- Ratio is almost constant over the whole track multiplicity range → No dramatic change of the particle production mechanism in forward regions
- All model predictions are lower than the data
- Energy ratio best described by QGSJETII.04, SIBYLL2.1, & HERWIG7.1

Double-parton Scattering (CMS PAS SMP-18-015)

Double-parton scattering (DPS) $\Rightarrow$ Two separate hard parton-parton interactions in a single pp collision $\rightarrow$ Grows more rapidly as compared to SPS with $\sqrt{s}$



$$\sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{m}{2} \sum_{\mathrm{i,j,k,l}} \int \Gamma_{\mathrm{ij}}(\mathrm{x}_1, \mathrm{x}_2, \mathrm{y}; Q_{\mathrm{A}}, Q_{\mathrm{B}}) \Gamma_{\mathrm{kl}}(\mathrm{x'}_1, \mathrm{x'}_2, \mathrm{y}; Q_{\mathrm{A}}, Q_{\mathrm{B}}) \hat{\sigma}_{\mathrm{ik}}^{\mathrm{A}}(\mathrm{x}_1, \mathrm{x'}_1) \hat{\sigma}_{\mathrm{jl}}^{\mathrm{B}}(\mathrm{x}_2, \mathrm{x'}_2)\, dx_1 dx'_1 dx_2 dx'_2 d^2y$$

m = 2 if A≠B, else 1 | double-parton distribution functions (dPDFs) | parton-level cross sections

Pocket formula: $\sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{\mathrm{m}}{2} \frac{\sigma_{\mathrm{A}} \sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$ $\Rightarrow$ **Used in all phenomenological calculations**

σ_{eff} $\rightarrow$ transverse profile of partons $\rightarrow$ *Assumed to be process & energy independent*

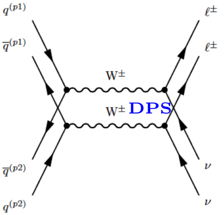
Experimental measurements: $\sigma_{\mathrm{eff.}} \rightarrow$ 15–25 mb with uncertainties $\approx$ 30%

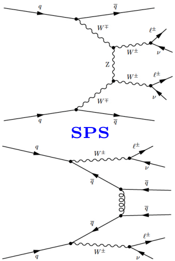
Importance of DPS

- Possible to explore at colliders $\rightarrow$ even using high scale process at the LHC
- Provides information about hadron structure in transverse plane
- Understanding of background contributions to interesting SM & BSM processes

DPS With Same-Sign WW @13TeV

- WW production → Golden channel for DPS production
- Quark initiated → Sensitive to longitudinal quark polarizations
- Non-factorization models predict spin, color, momentum ... interference effects (Phase-2 Upgrade of CMS Muon Detectors)
- SPS $W^{\pm}W^{\pm}$ production suppressed at matrix element level
- Insensitive to pileup effects & clean final state with fully leptonic W decays



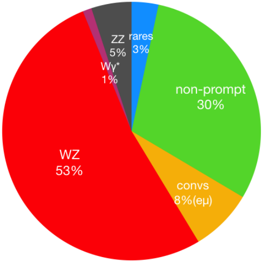


- PYTHIA8 predicts a cross section value of 1.9 pb for inclusive WW production via DPS @13TeV → calculated with $\sigma_{\rm eff} = 28$ mb which is also generator tune dependent!!
- $\sigma_{\rm W}(\rm NNLO) \oplus \sigma_{\rm eff.} = 20.7 \pm 6.6$ mb (CMS)→ $\sigma^{\rm factorized}_{\rm DPSWW} = 0.87$ pb
- Comparison of measured cross section with predictions → Important input for development and testing of existing models of dPDFs → Improved MC models

Analysis Strategy

- 77 fb^{-1} of data from combined 2016 & 2017 at $\sqrt{s} = 13$ TeV
- **Signal ⇒ two same-sign leptons (dimuon or electron-muon pairs)** $\oplus\ p_T^{miss}$
- PYTHIA8 & HERWIG++ signal samples
- Broad spectrum of background processes & few variables to play with!!
- Dominant backgrounds: WZ & non-prompt leptons

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

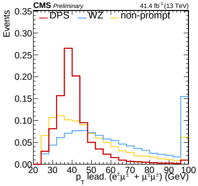


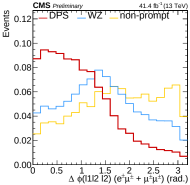
- Signal & background discrimination based on BDT classifiers; trained separately against dominant backgrounds
- Two BDT classifiers → 1D classifier with bins ordered in S/B for statistical analysis

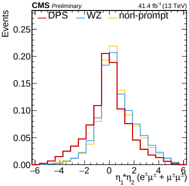
BDT Classifier Training

- Explore topological differences b/w DPS & background processes
- No correlations expected in leptons' kinematic phase space for signal
- Leptons from background processes share the boost $\rightarrow$ correlations in η-ϕ
- Two different BDTs trained, one against WZ & another against fakes

- $\mathrm{pT}_{l_{1,2}}$
- $p_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{M}_{\mathrm{T2}}^{\mathrm{ll}}$
- $\eta_1 \times \eta_2$
- $|\eta_1 + \eta_2|$

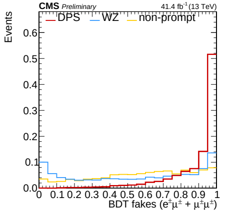


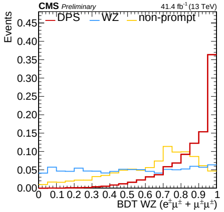




- $\mathrm{m_T}(\mathrm{l}_1, p_{\mathrm{T}}^{\mathrm{miss}})$
- $\mathrm{m_T}(\mathrm{l}_1, \mathrm{l}_2)$
- $\Delta\phi(l_1, l_2)$
- $\Delta\phi(l_2, p_{\mathrm{T}}^{\mathrm{miss}})$
- $\Delta\phi(l_1 l_2, l_2)$

BDT classifier outputs



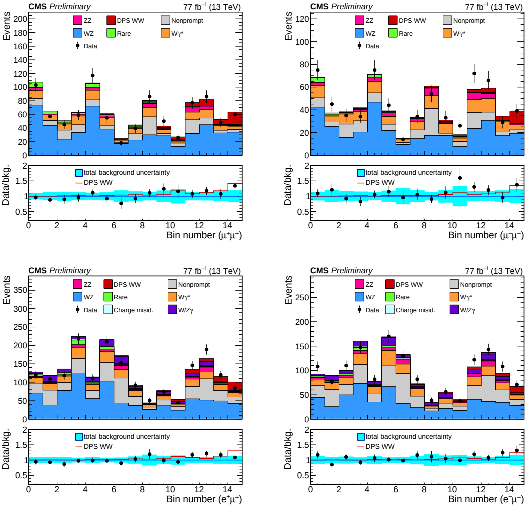


- two BDT classifiers $\rightarrow$ one final discriminant variable
- Bins are defined in a way to have few bins dominated by signal & few by WZ & fakes

Results

- Maximum likelihood fit to the final classifier
- Fitting is performed in 4 different lepton charge & flavor categories → Benefits from asymmetry in W production → better signal sensitivity (by ∼10%)
- Expected to be more sensitive to ++ configuration than --

postfit distributions with 2016 + 2017



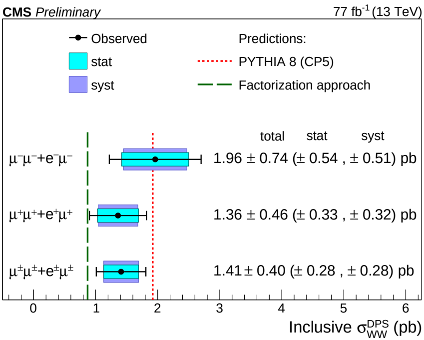
decreasing sensitivity =========>

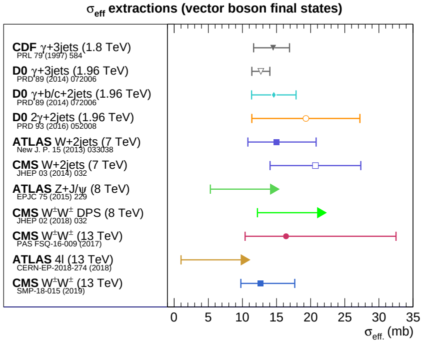
Results

- *First evidence of DPS WW*
- Results from same-sign WW are extrapolated to the inclusive WW phase space

	obtained value	significance (standard deviations)
$\sigma^{\mathrm{PYTHIA8}}_{\mathrm{DPS\,WW,exp}}$	1.92 pb	5.4
$\sigma^{\mathrm{factorized}}_{\mathrm{DPS\,WW,exp}}$	0.87 pb	2.5
$\sigma_{\mathrm{DPS\,WW,obs}}$	1.41 ± 0.28 (stat) ± 0.28 (syst) pb	3.9
σ_{eff}	$12.7^{+5.0}_{-2.9}$ mb	–

Observed cross section is used to extract σ_{eff}





Summary

- Data from the LHC provide a new energy scale for studying soft QCD & forward physics
- Soft QCD processes $\rightarrow$ Test predictions from phenomenological models $\oplus$ input for their improvement
- Still quite a few unresolved problems, but we possess a wealth of data
- Model parameters tuned to UE data at central rapidities are consistent with the very forward data within experimental uncertainties
- Energy measurements in the very forward η regions indicate some interesting potential to further improve the underlying event model predictions
- DPS measurements $\rightarrow$ Important to understand partonic structure of hadrons & for new physics searches @ LHC; very sensitive to non-factorization models
- First evidence for DPS WW production using 2016+2017 CMS data
- Could do some interesting DPS physics with full Run2 data (differential cross sections, correlation studies ....) other than a DPS WW observation

*Soft qcd measurements might not be the discovery channels but important for all future discoveries at the LHC!**

**source: Internet*