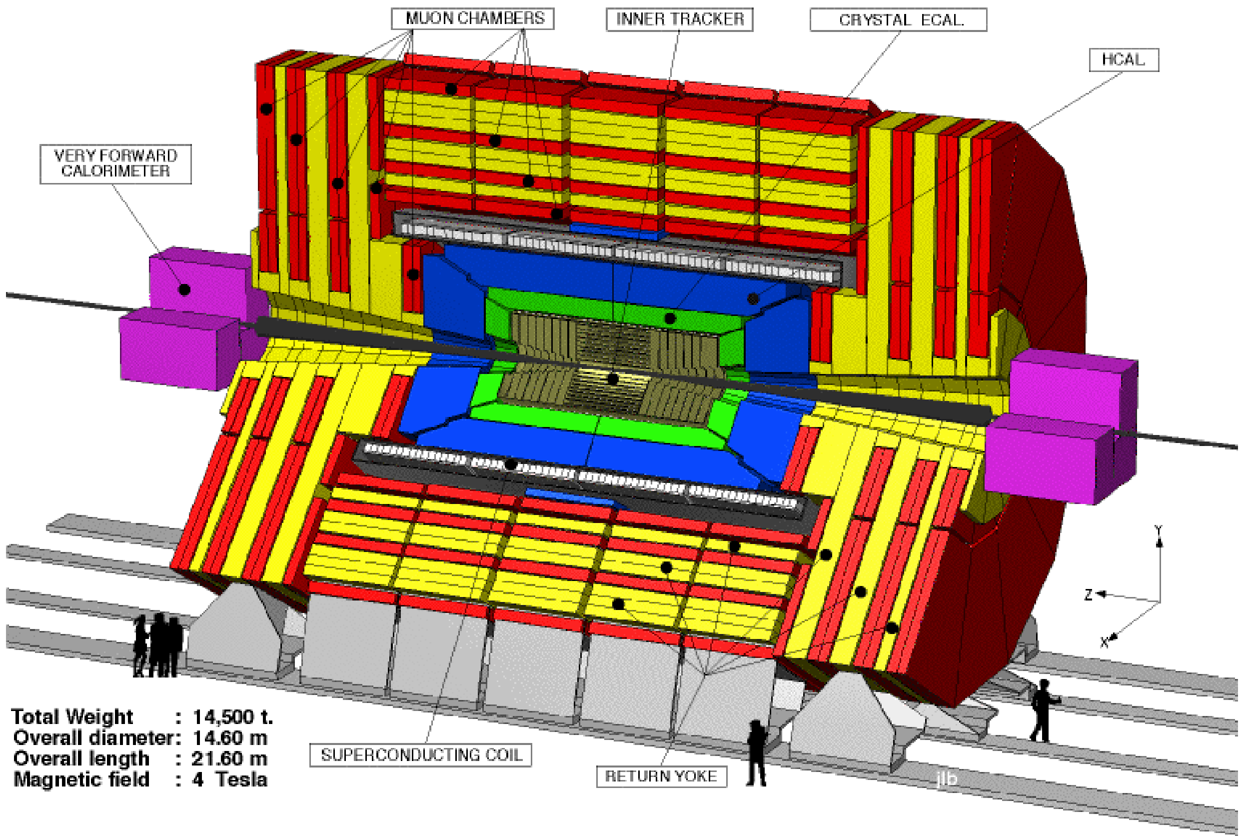
Double parton scattering, minimum bias and underlying event measurements at CMS

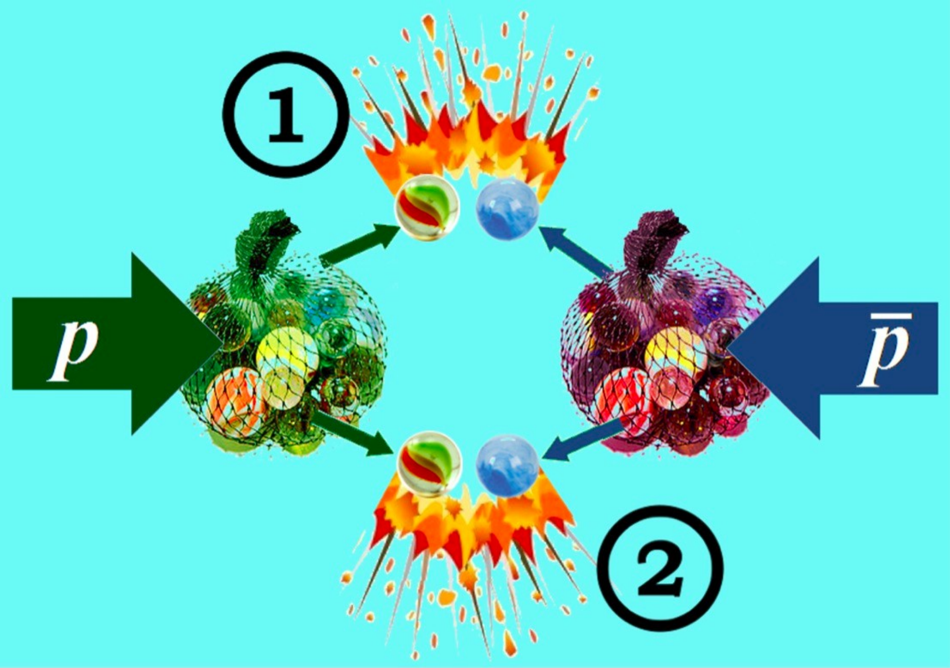


Veres Gábor

CMS magyar megbeszélés, Budapest, 4th June, 2018

Eötvös Loránd University Budapest
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group

Double parton scattering measurements at CMS



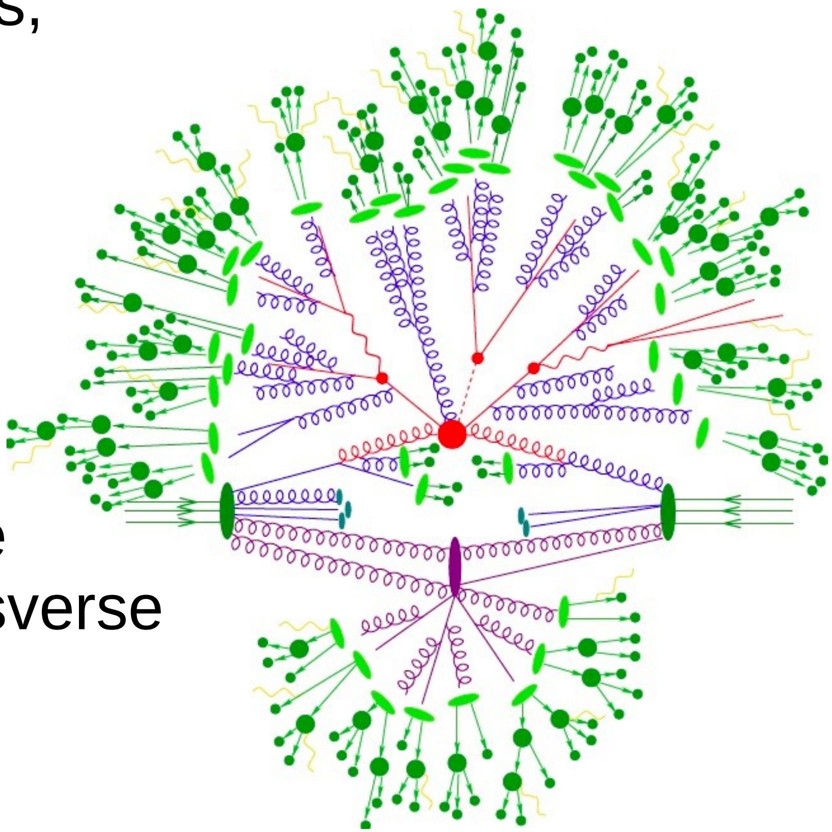
Gábor Veres

DIS 2018 Kobe, Japan, 17th April, 2018

Eötvös Loránd University Budapest
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group

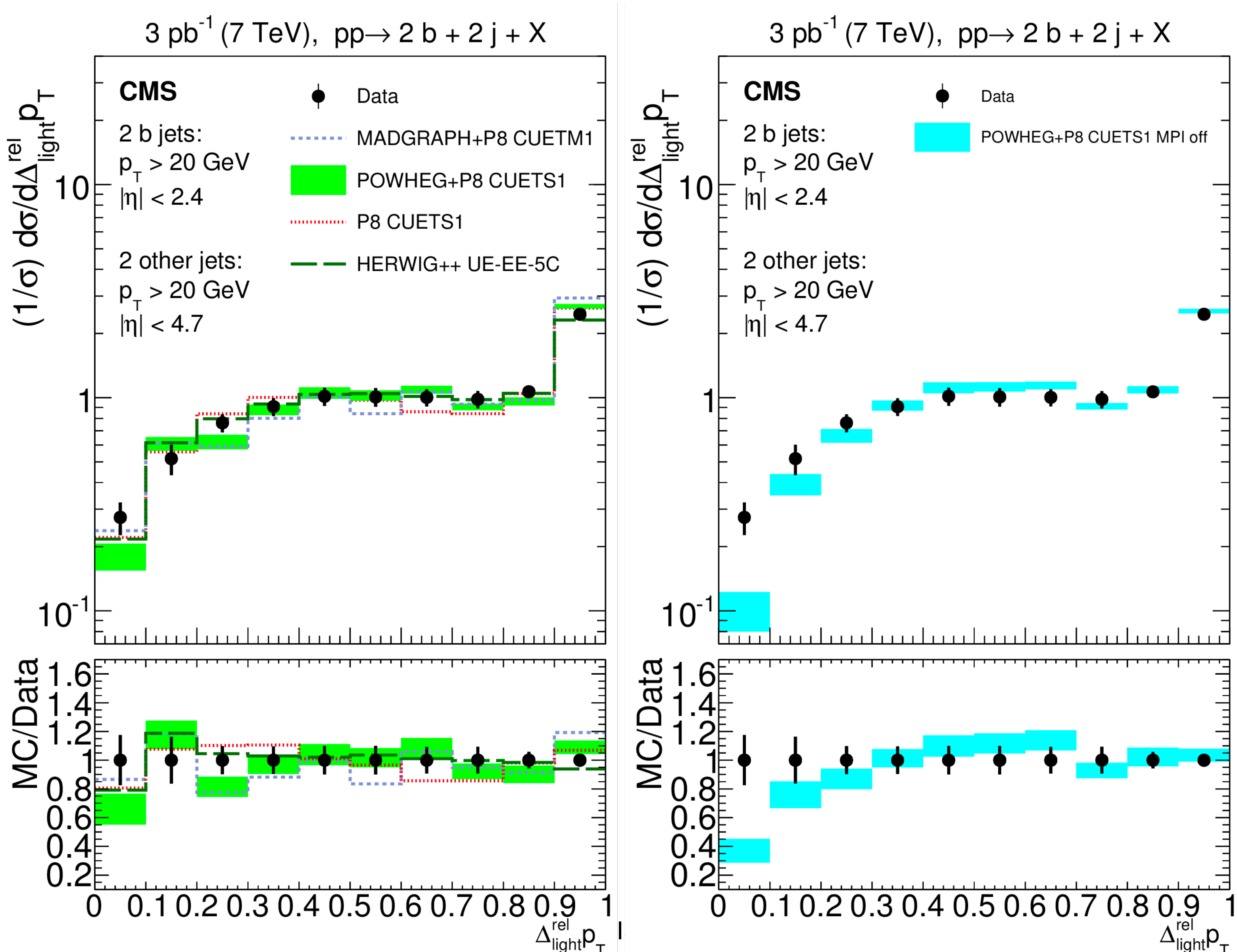
Multiple parton interactions

- Theoretical idea dates back to the parton model
- Double parton scattering signatures: 4 jets, 2 jets and W, 3 jets and photon, etc...
- LHC is especially abundant in MPI
  - high energy final states
- Complicated correlation effects are still unexplored
- The effective cross section: overlap of the spatial distributions of partons in the transverse plane
- Experimental challenges:
  - DPS final states can also be produced by SPS
  - Sometimes complicated multivariate analyses



2 jets + 2 b-jets in pp collisions at 7 TeV

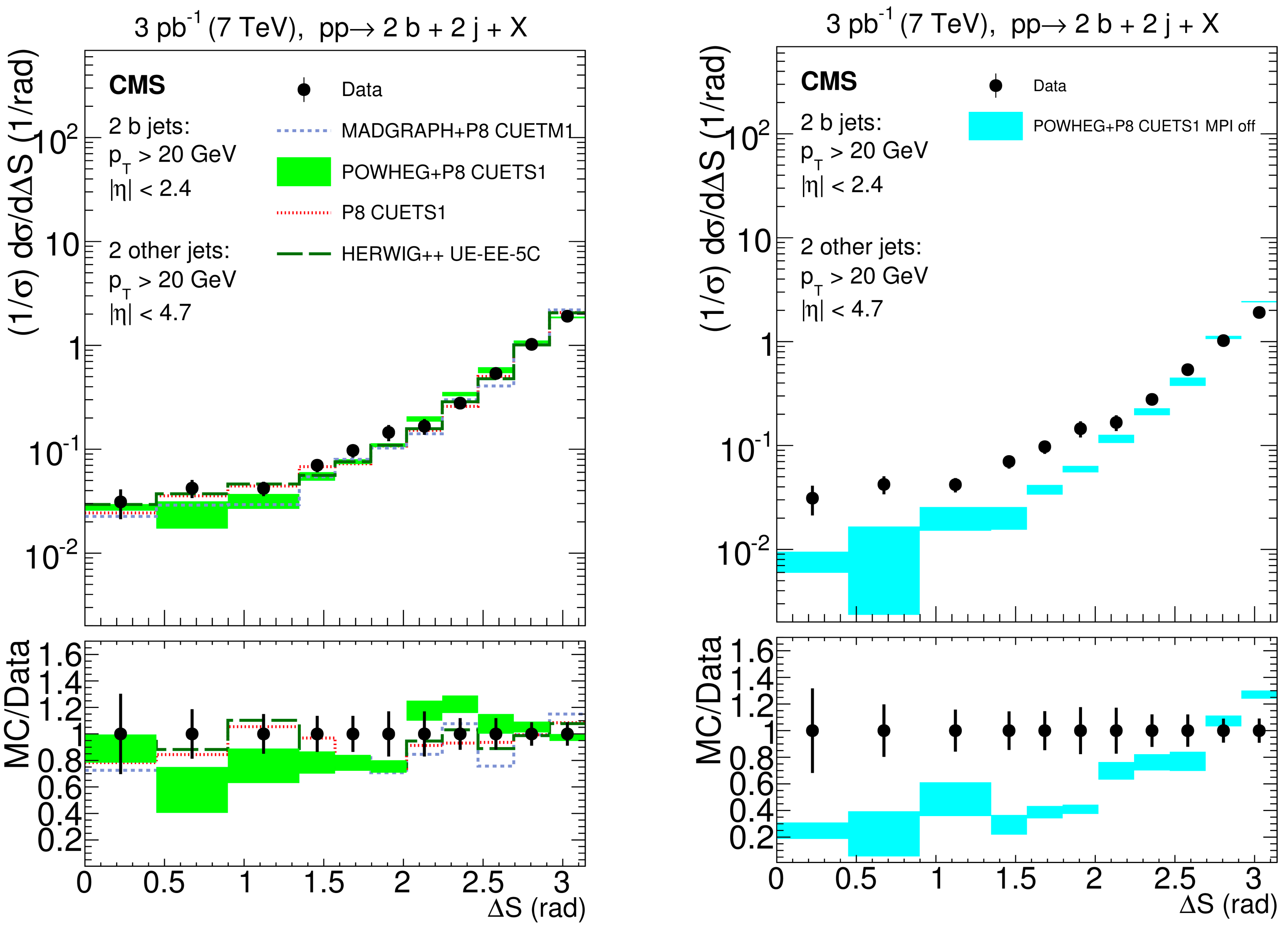
- Kinematical distributions between 2 b-jets and 2 light jets
- Data well described by pQCD @NLO with PS and MPI
- Jet correlations do not agree with no-MPI models



PRD 94 (2016) 112005
CMS-FSQ-13-010

2 jets + 2 b-jets in pp collisions at 7 TeV

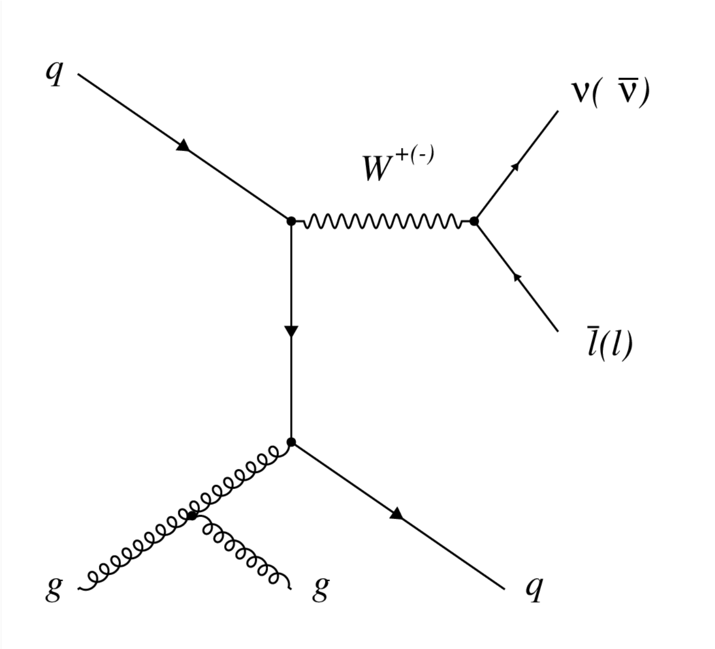
- $\sigma(pp\rightarrow bb+jj+X)=69\pm3(st)\pm24(sy)$nb for $p_T>20$ GeV and $|\eta_{b(j)}|<2.4(4.7)$
- ΔS: azimuthal angle between two dijet pairs

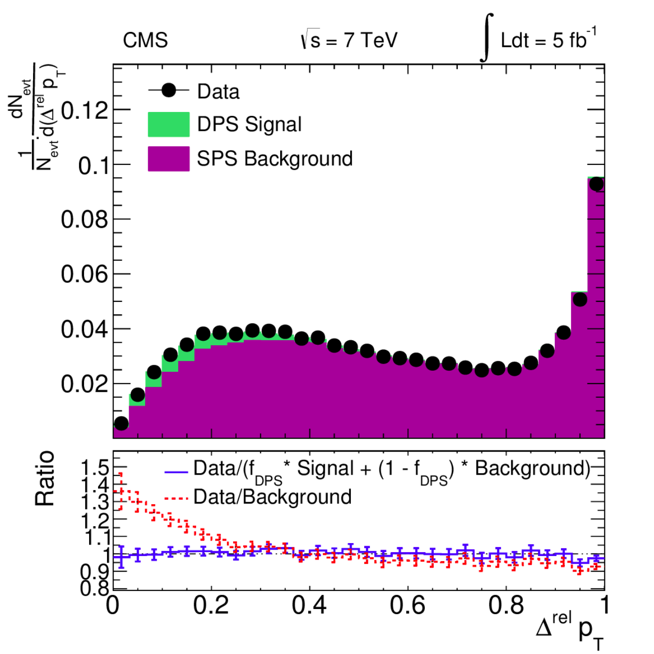


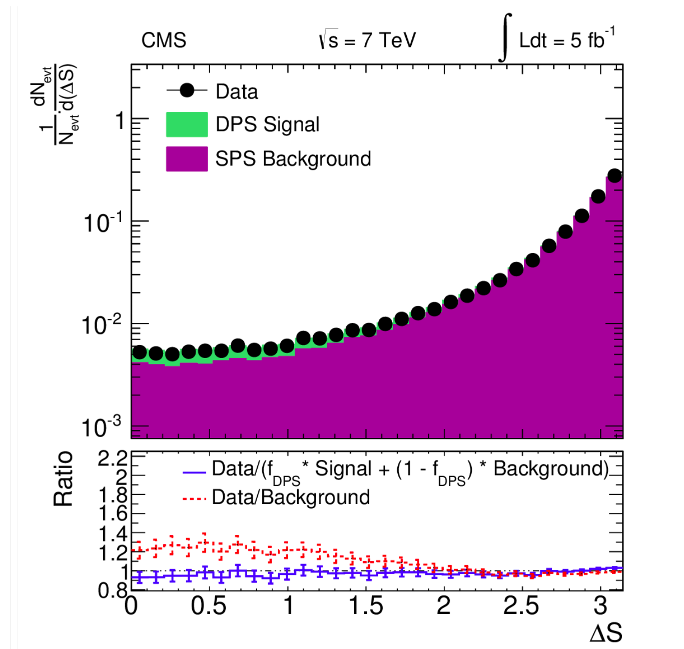
PRD 94 (2016) 112005
CMS-FSQ-13-010

DPS in W+2jets in pp collisions at 7 TeV

- $W \to \mu\nu$ deay with two associated jets, 5 fb^{-1} data, template fit
- Fraction of W from DPS: 0.055 ± 0.002 (stat) ± 0.014 (syst)
- MadGraph5+PYTHIA8 and POWHEG2 + PYTHIA6: MPI is needed
- From that, σ_{eff} = 20.7 ± 0.8 (stat) ± 6.6 (syst) mb

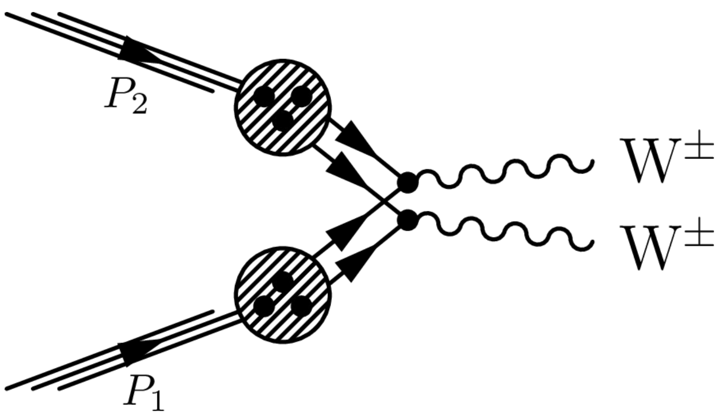




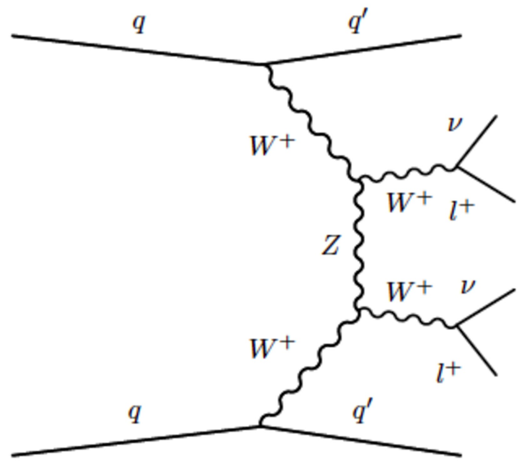


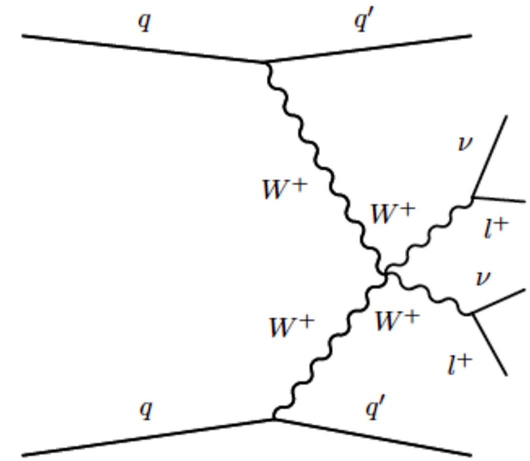
DPS in same-sign WW events at 13 TeV

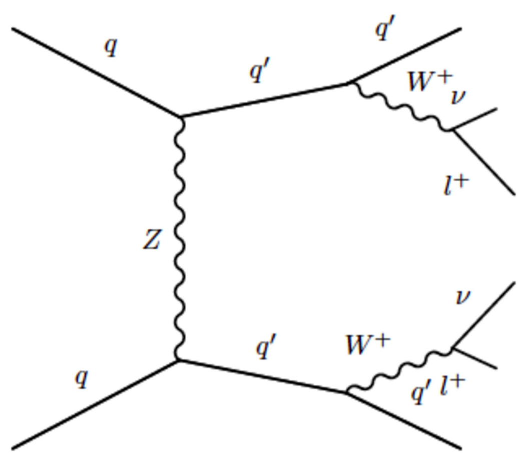
- $W^{\pm}W^{\pm}$ studied in the $\mu^{\pm}\mu^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states. 2016 data
- Single parton scattering (SPS): 2 jets in the final state!

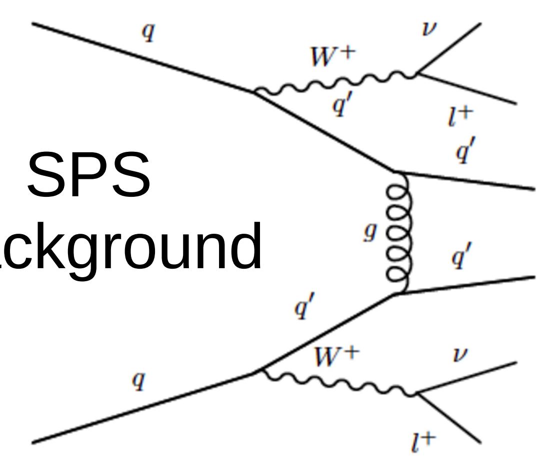


DPS signal









SPS background

CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

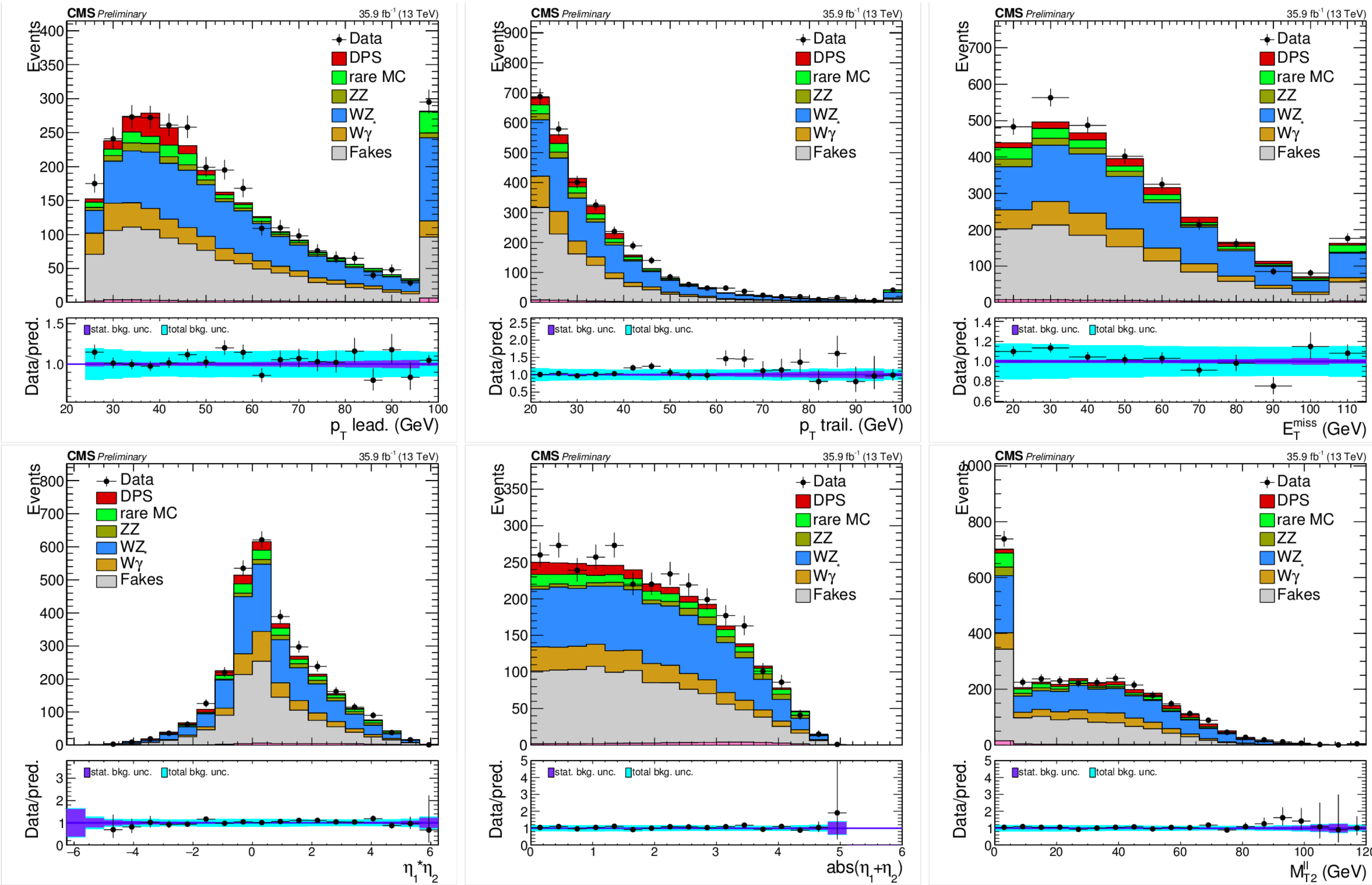
- $W^{\pm}W^{\pm}$ studied in the $\mu^{\pm}\mu^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states. 2016 data
- Single parton scattering (SPS): 2 jets in the final state!
- Therefore, the event selection uses a jet veto:

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

CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

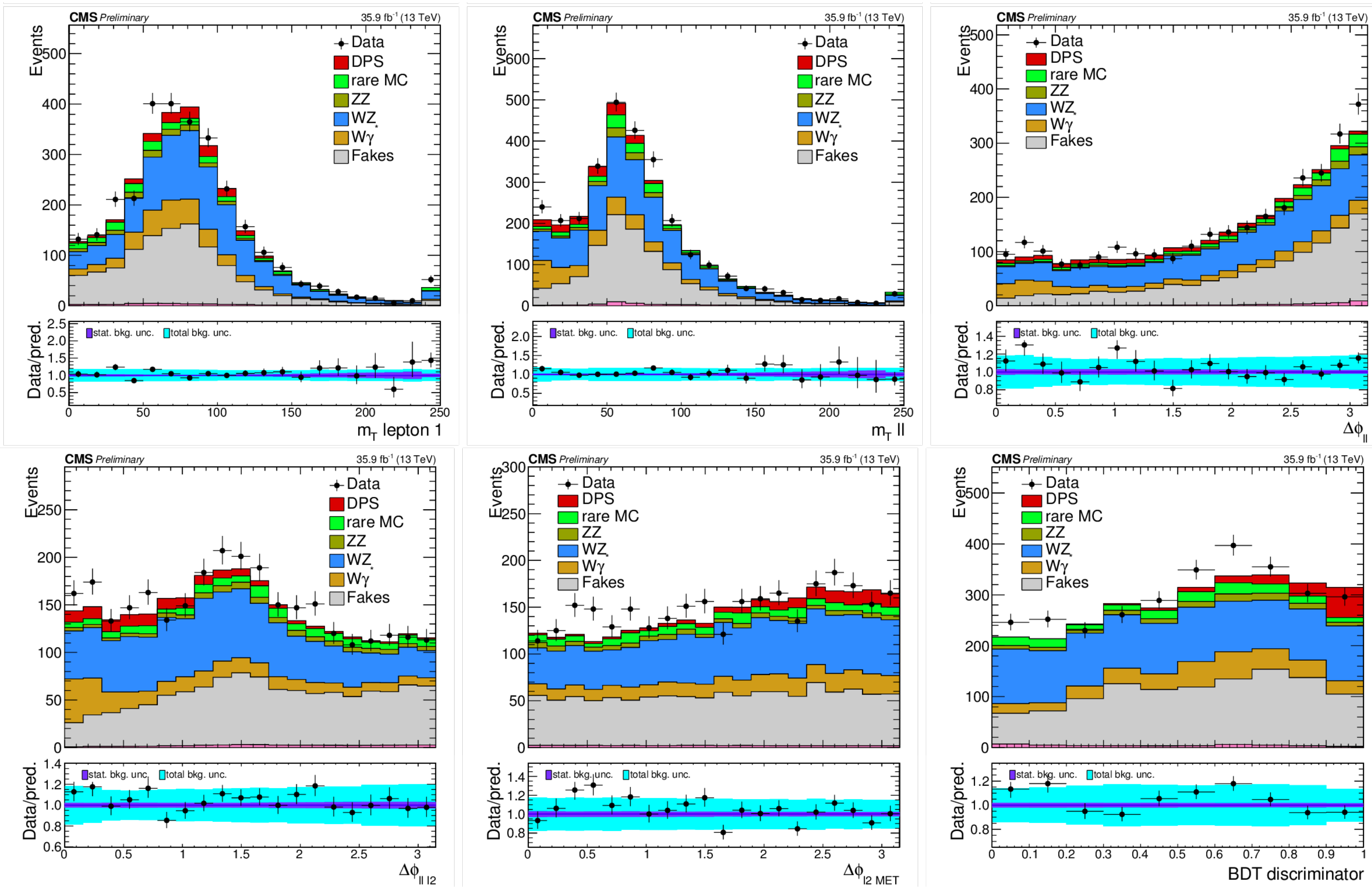
- A multivariate classifier is used to distinguish signal and bkgd



CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

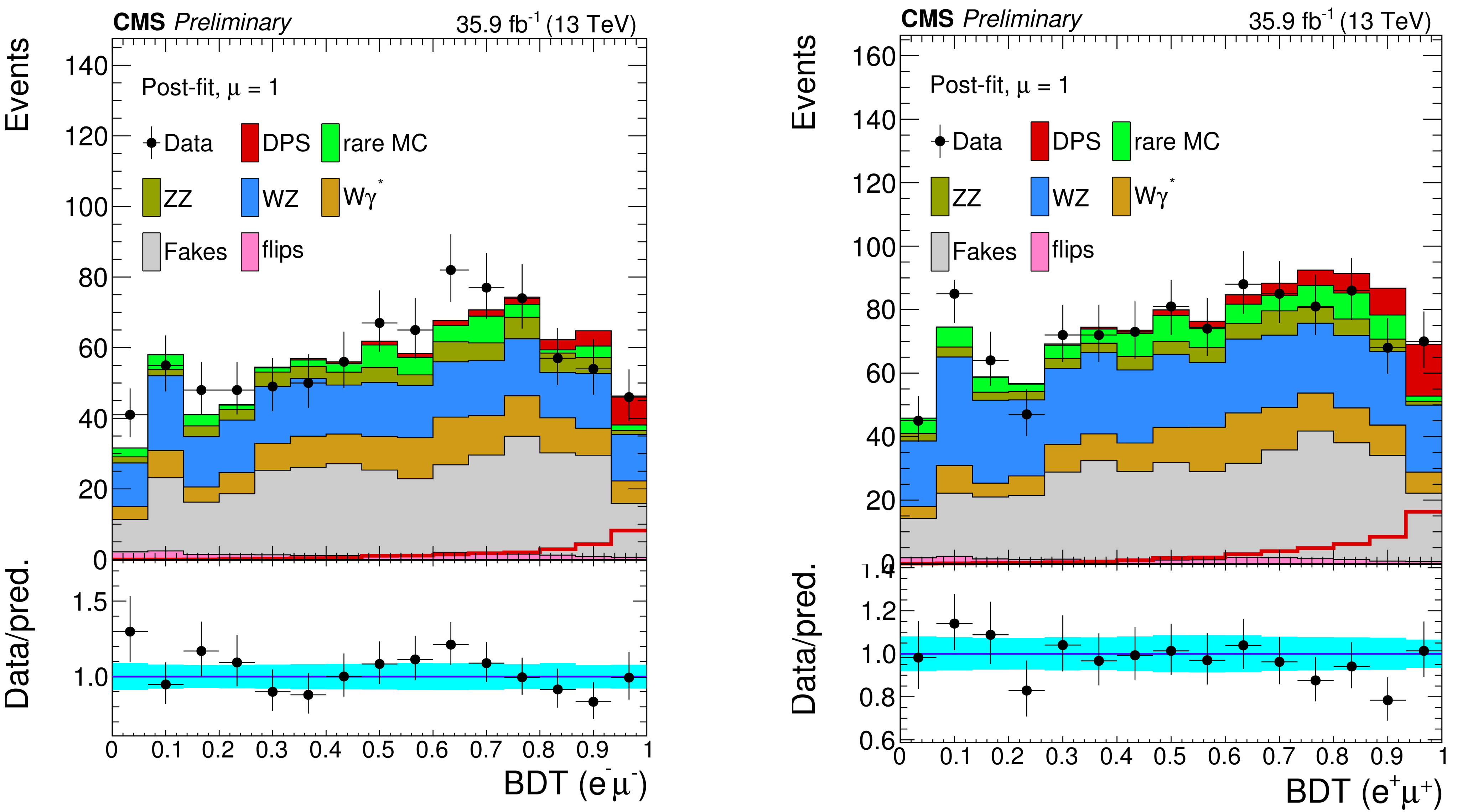
- A multivariate classifier is used to distinguish signal and bkgd



CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

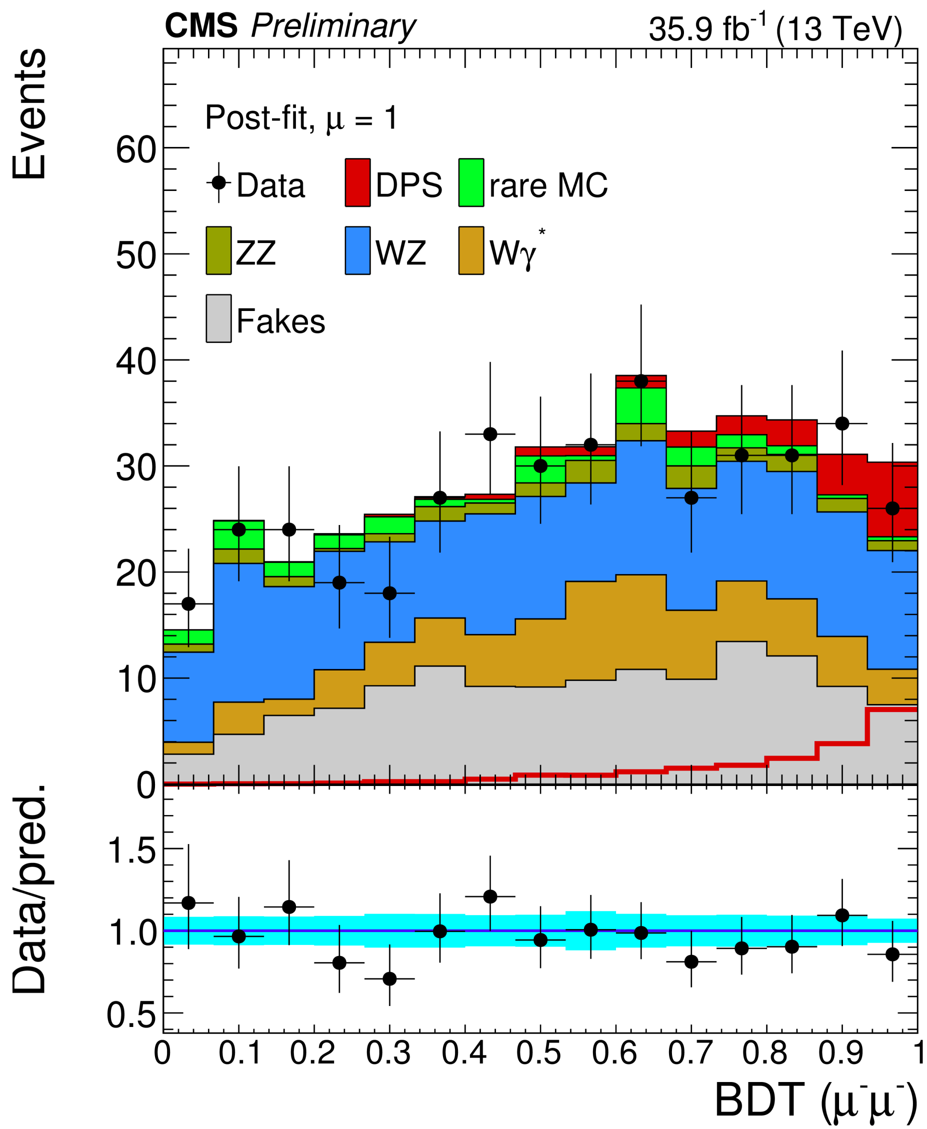
- BDT classifier output for $e^-\mu^-$ and $e^+\mu^+$

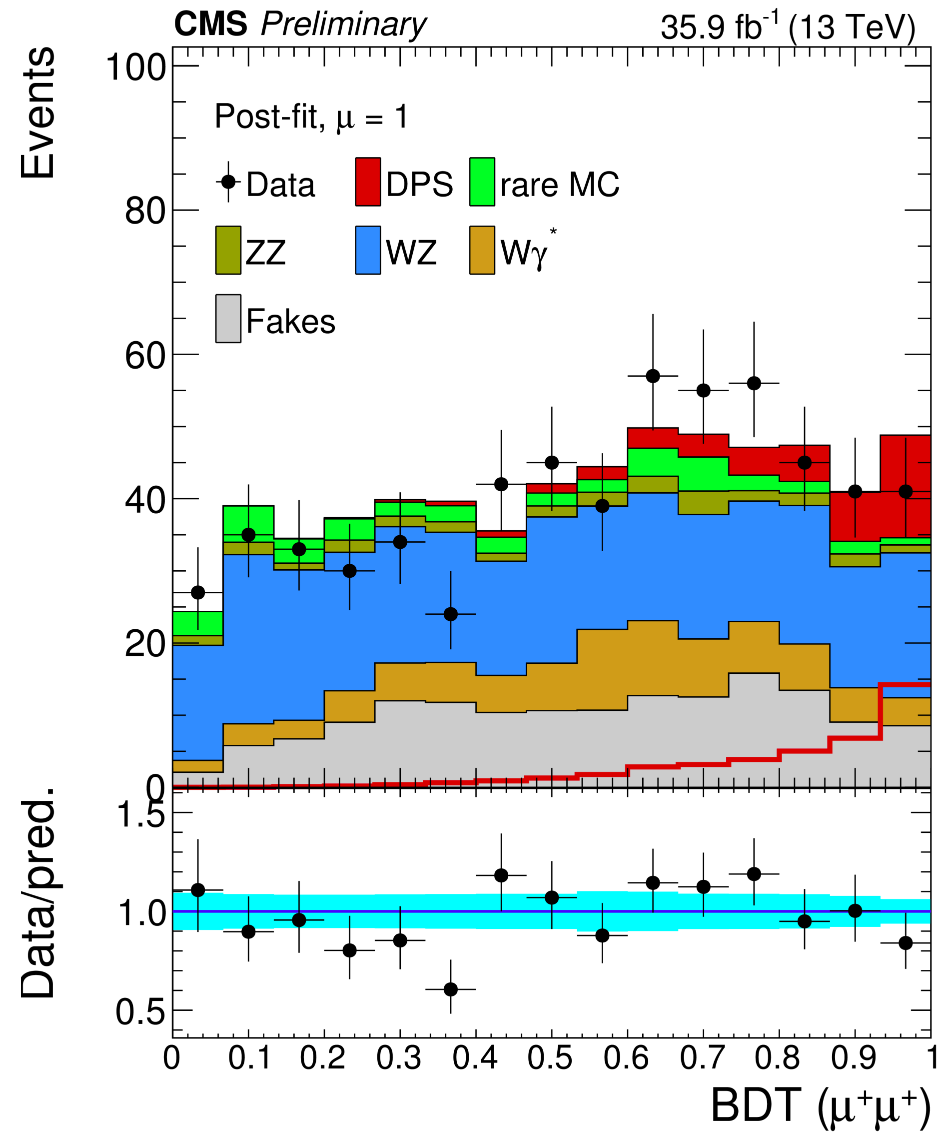


CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

- BDT classifier output for $\mu^-\mu^-$ and $\mu^+\mu^+$





CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 13 TeV

- Expected background and signal yields, and observed number of data events in 35.9 fb^{-1}:

	$\mu^+\mu^+$	$\mu^-\mu^-$	$e^+\mu^+$	$e^-\mu^-$
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

DPS in same-sign WW events at 13 TeV

- Fit to the constrained BDT classifier
- Result: $1.09^{+0.50}_{-0.49}$ pb (2.23σ), PYTHIA 8 prediction: 1.64 pb

	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

CMS-PAS-FSQ-16-009

DPS in same-sign WW events at 8 TeV

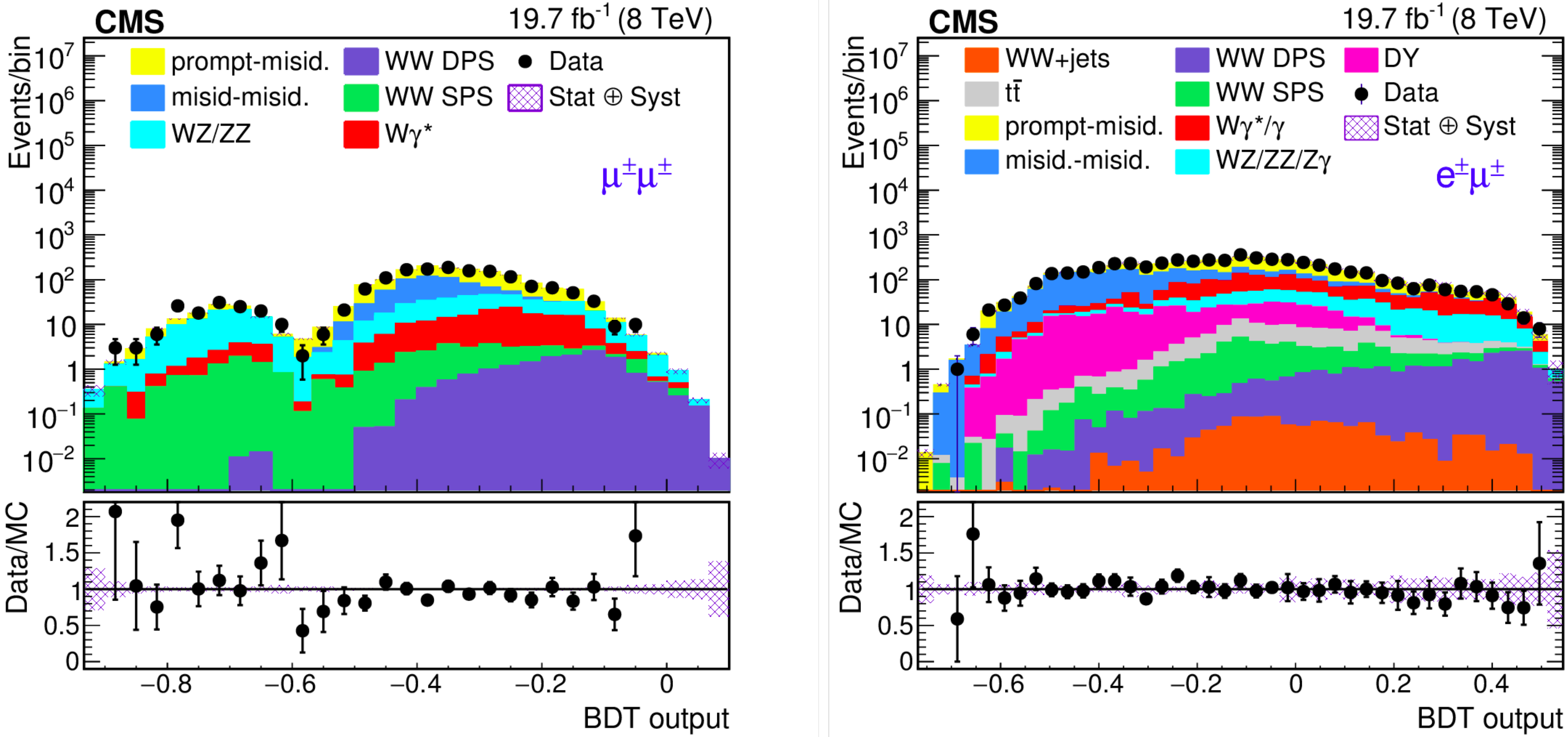
- $W^{\pm}W^{\pm}$ events in 19.7 fb^{-1} of data at 8 TeV
- Our first search for same-sign WW production via DPS
- Event selection:

Dimuon channel	Electron-muon channel
Pair of same-sign leptons	
Leading lepton $p_T > 20\,GeV$	
Subleading lepton $p_T > 10\,GeV$	
No third isolated and identified lepton with $p_T > 10\,GeV$	
$p_T^{miss} > 20\,GeV$	
$m_{\ell\ell} > 20\,GeV$	
$m_{\ell\ell} \notin [75, 105]\,GeV$	—
$\|p_{T_{\mu_1}}\| + \|p_{T_{\mu_2}}\| > 45\,GeV$	—
—	No b-tagged jet with $p_T > 30\,GeV$ and $\|\eta\| < 2.1$

JHEP 1802 (2018) 032
CMS-PAS-FSQ-16-005

DPS in same-sign WW events at 8 TeV

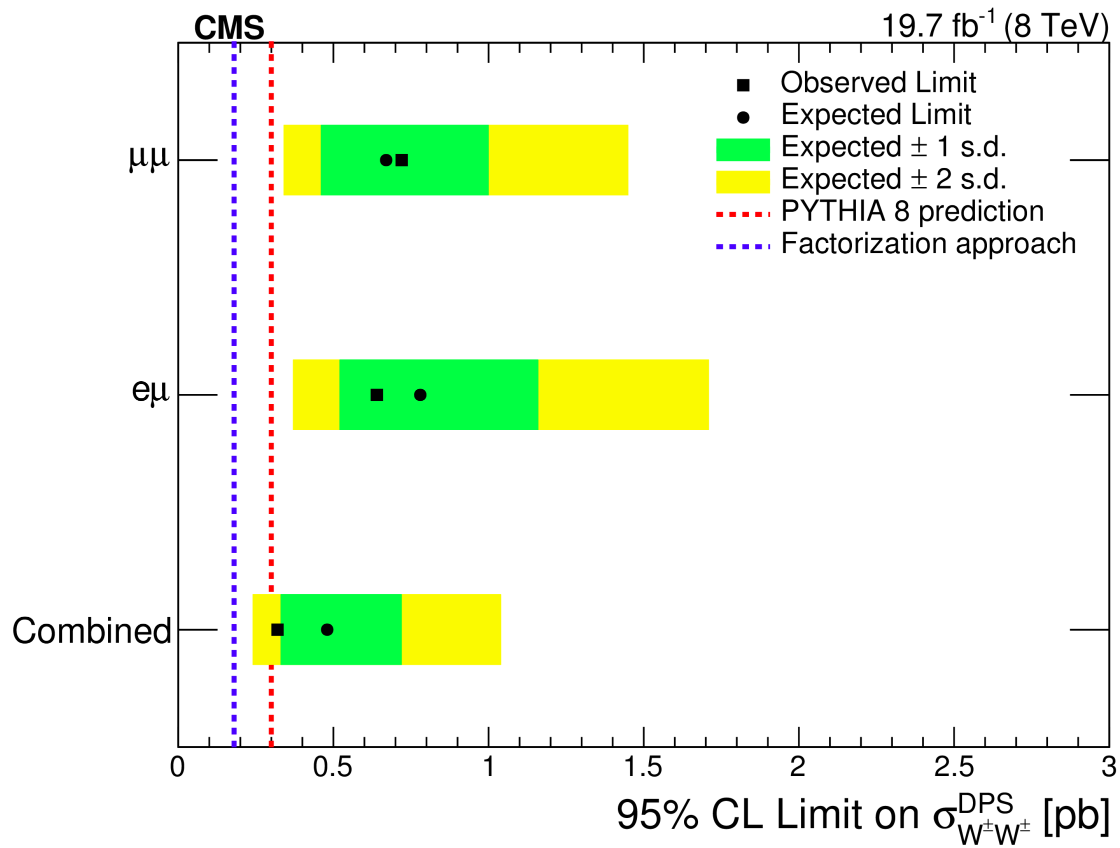
- Distribution of the BDT discriminant in the $\mu^{\pm}\mu^{\pm}$ and $e^{\pm}e^{\pm}$ events



JHEP 1802 (2018) 032
CMS-PAS-FSQ-16-005

DPS in same-sign WW events at 8 TeV

- No significant excess observed above the SPS process
- 0.32 pb is the upper limit (95% CL) for DPS
- Therefore a **lower limit of 12.2 mb** is set for the effective DPS cross section parameter (95% CL)

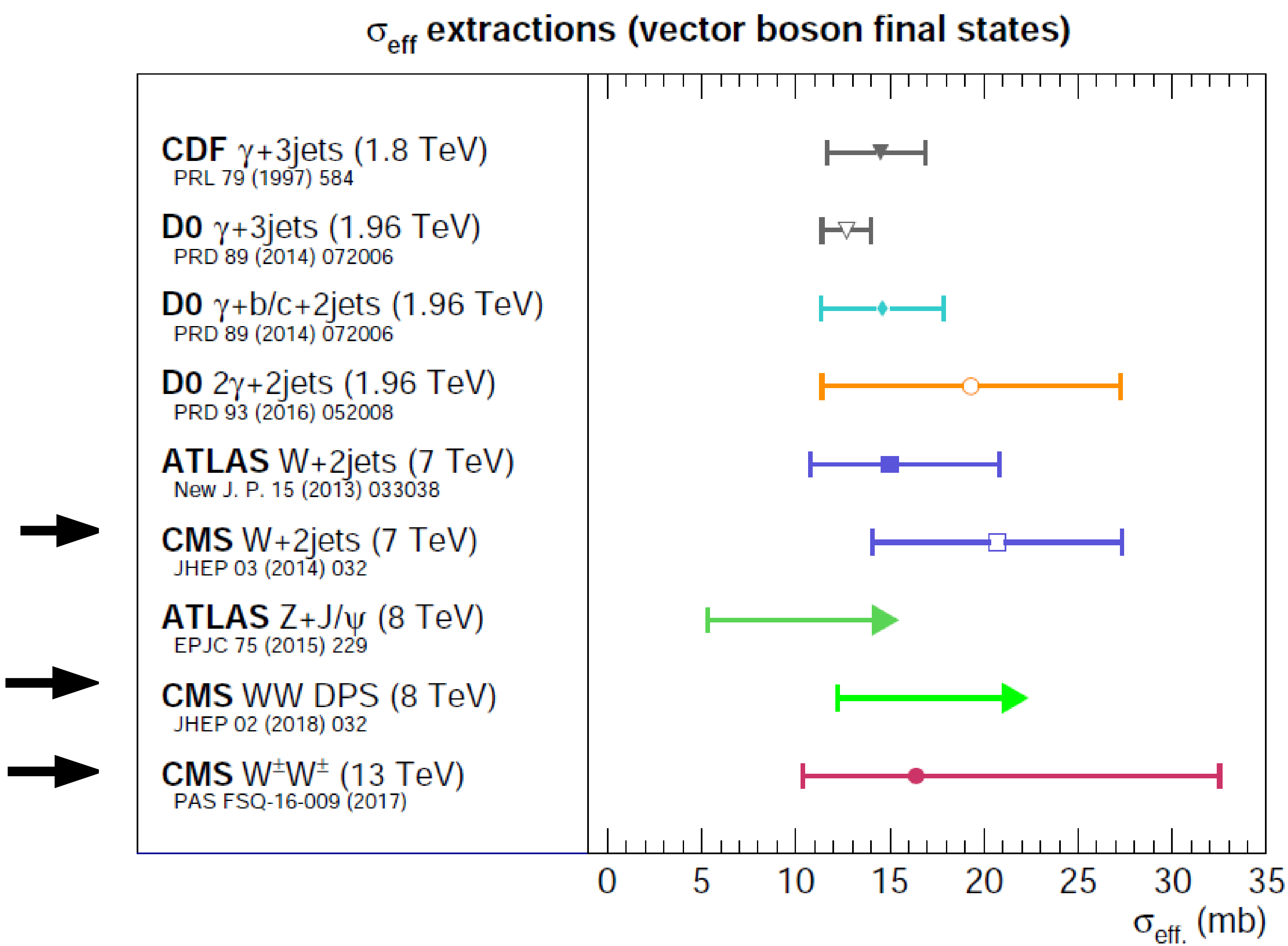


JHEP 1802 (2018) 032

CMS-PAS-FSQ-16-005

Effective cross section compilation

- Summary of the effective DPS cross section measurements



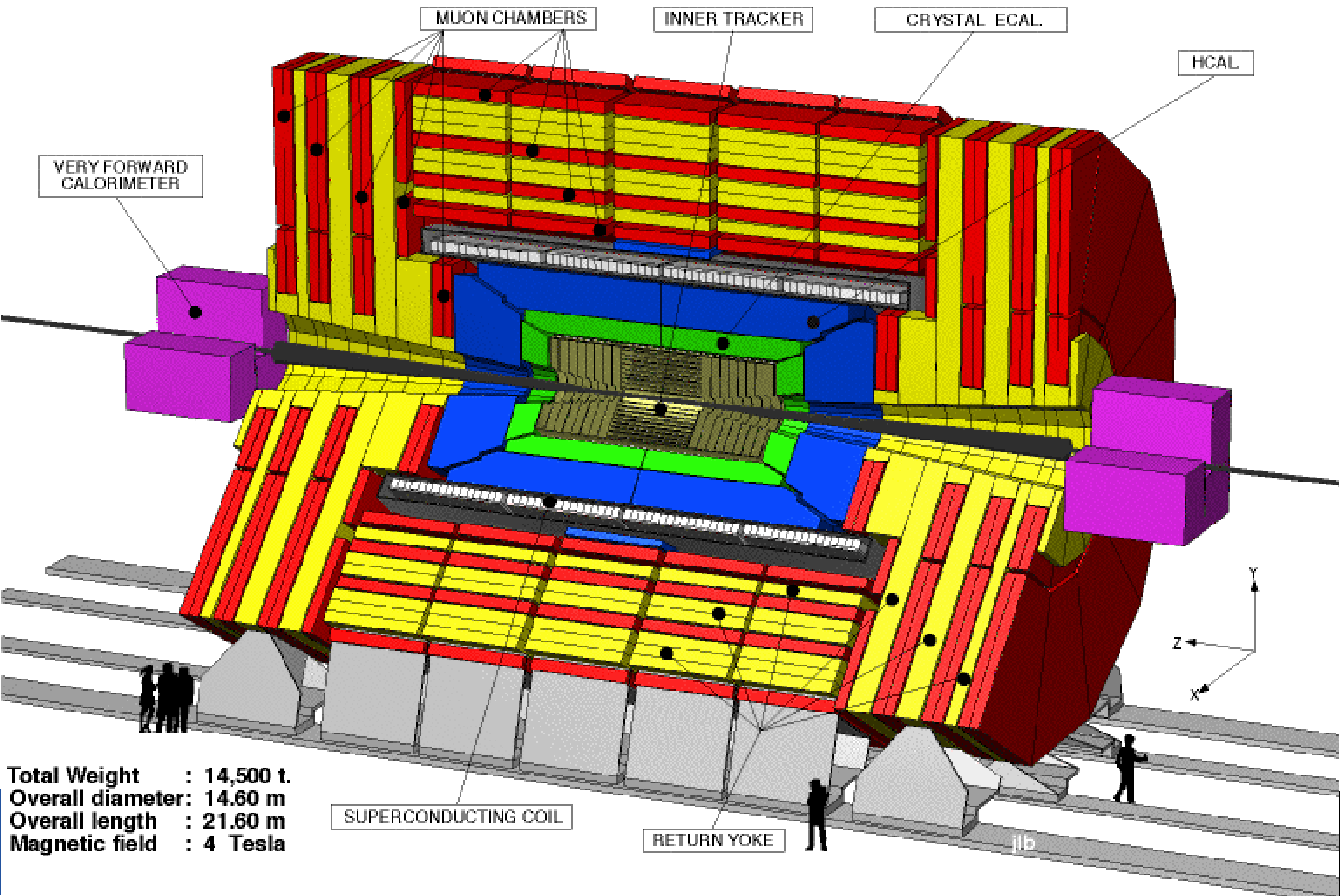
Summary

- Multi Parton Interactions can be studied in many ways, in various channels
  - Multiple jets
  - Vector bosons and multijets
  - vector boson pairs...
- Challenges:
  - Complicated **multivariate** analysis methods
  - Finding appropriate and sensitive **observables** is nontrivial
  - High **luminosity** is often essential
- Very active field and important new observations:
  - Tiny cross sections, extreme **tests** of the Standard Model,...

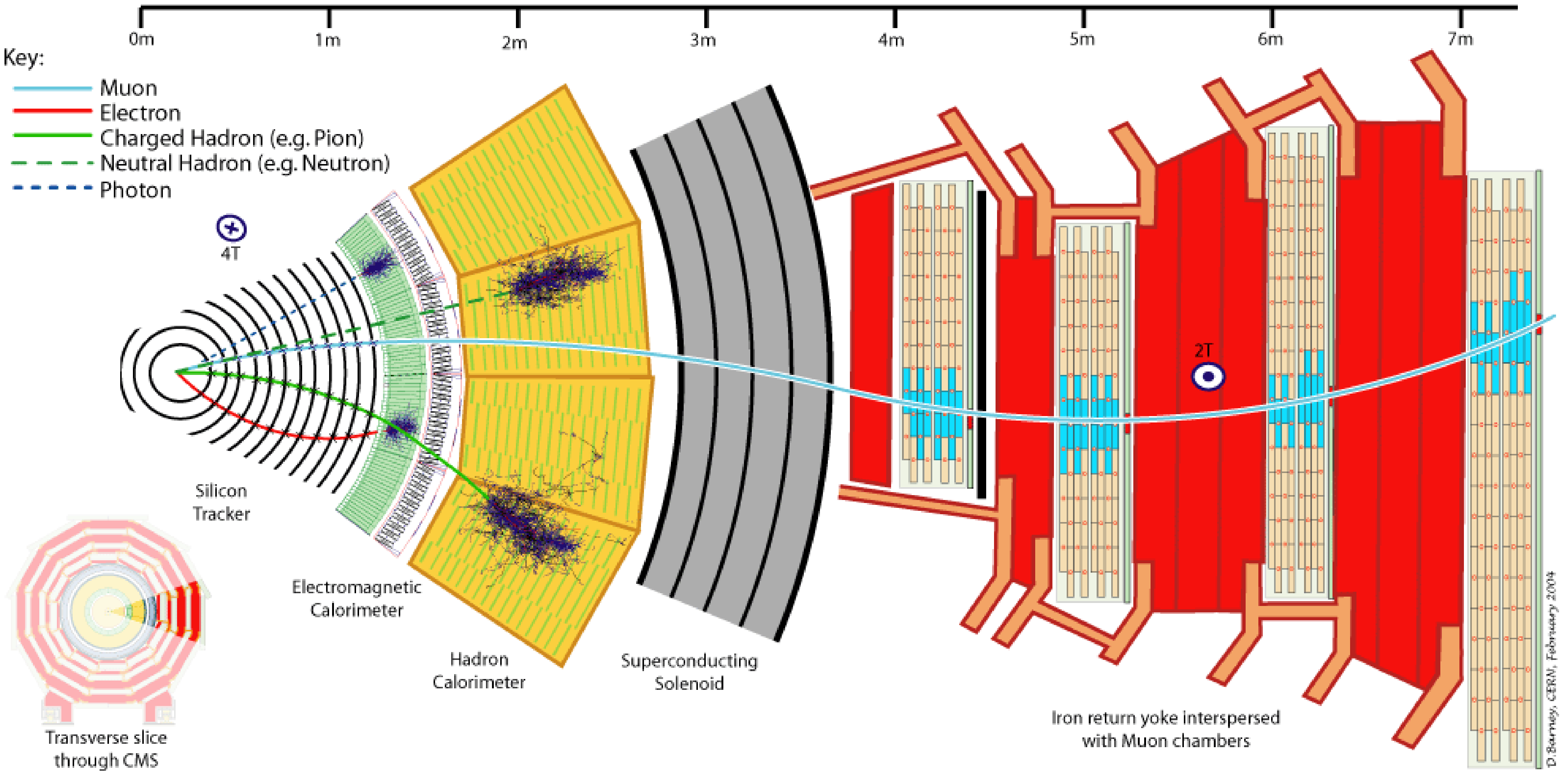
With more date collected, new opportunities!

BACKUP

The CMS experiment

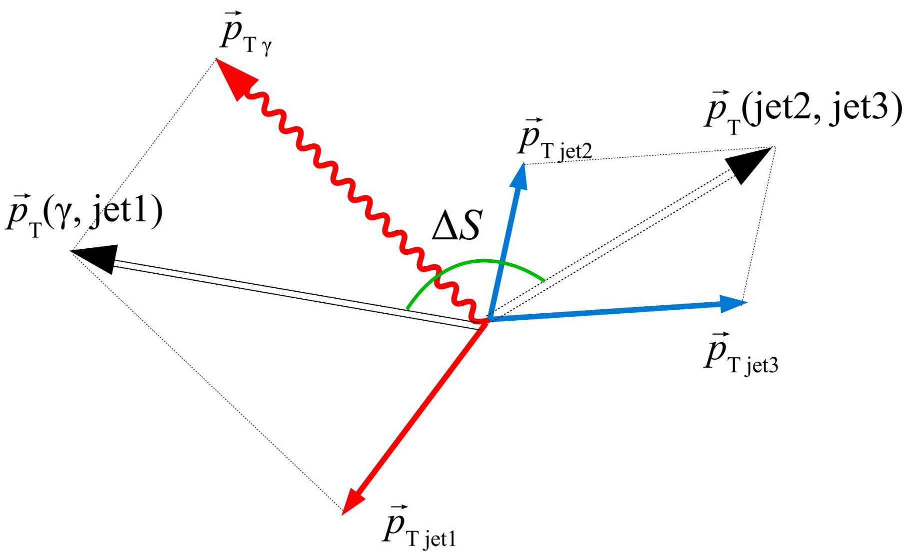


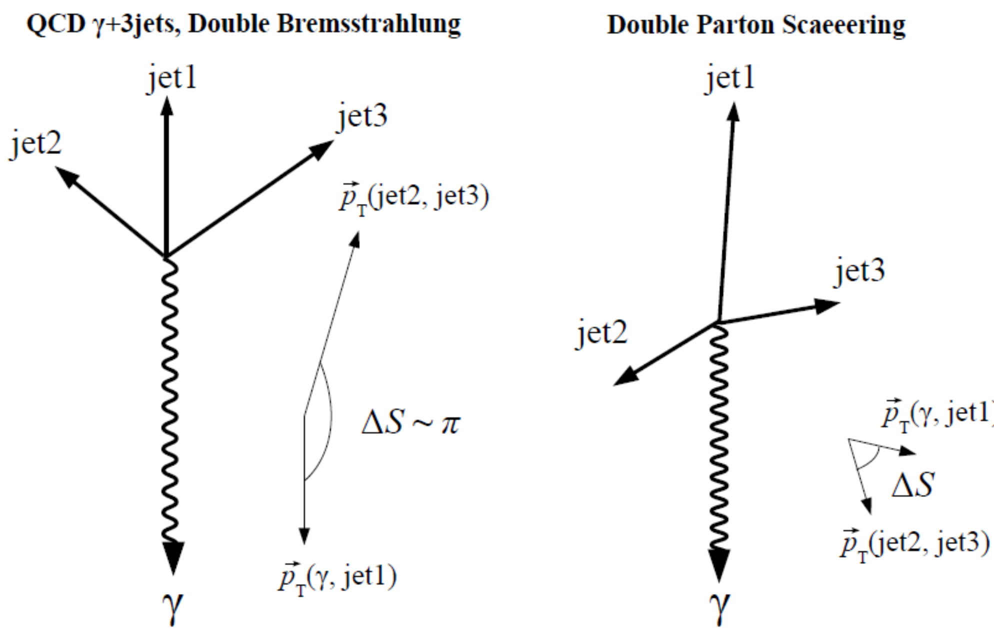
The CMS Experiment



DPS in γ+3 jets in pp collisions at 7 TeV

- 36 pb^{-1} of data in 2010
- The photon and the leading jet are required to have p_T>75 GeV
- Two other jets are in the p_T>20 GeV range



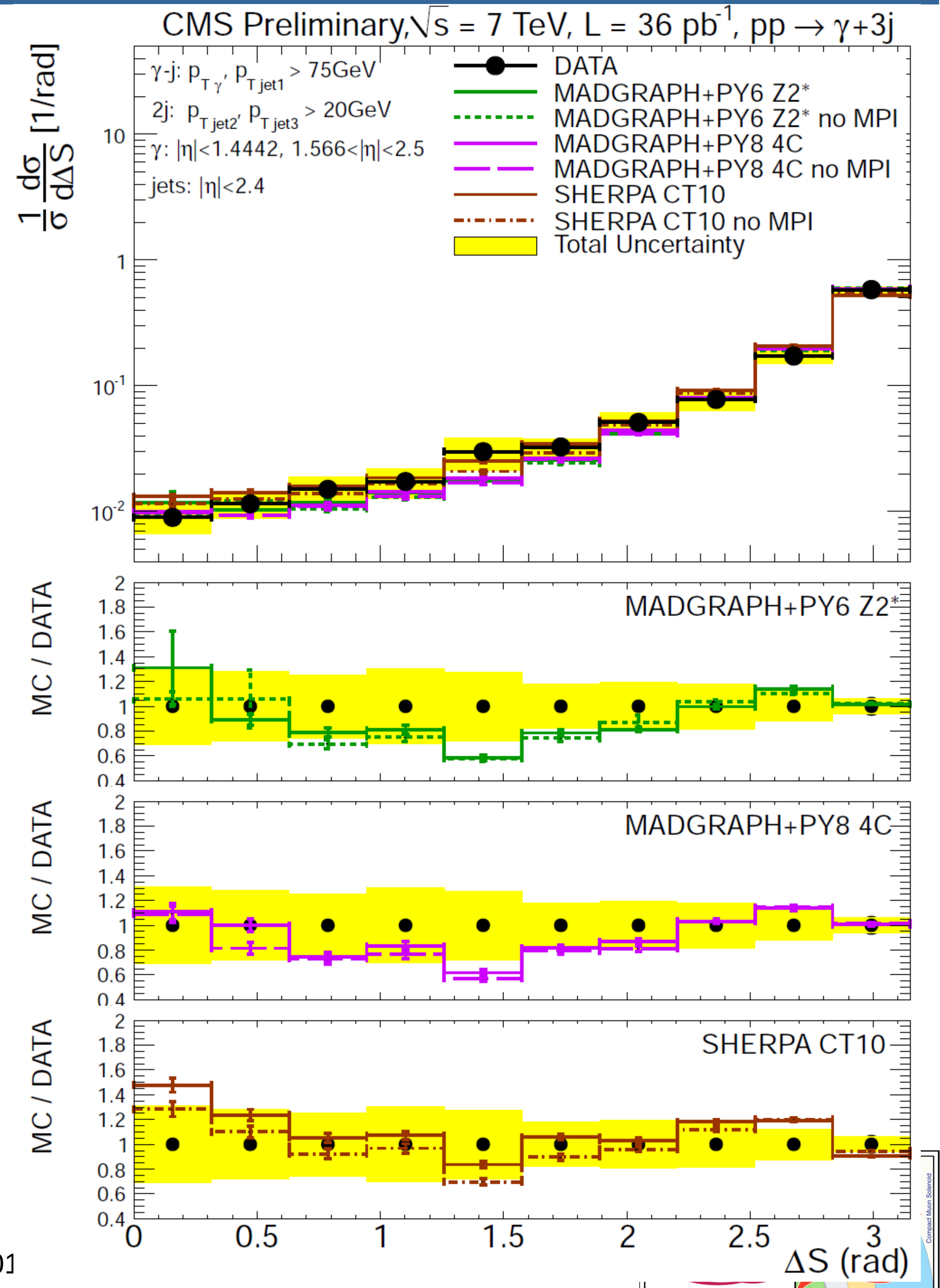


CMS-FSQ-12-017

DPS in γ+3 jets in pp collisions at 7 TeV

- Many kinematical distributions are compared to MC predictions
- For example, ΔS distributions are sensitive to DPS in the low ΔS region
- Higher order, parton showers affect the SPS contributions
- MC with and without MPI do not differ significantly
- Conclusion on DPS component is not possible within this given precision

- Let us look at other observables!



CMS-FSQ-12-017

Outline

Minimum bias and underlying event activity are the most basic quantities in **QCD**, yet hard to measure and extremely hard to predict precisely. It has been an active research field at the LHC with several related topics:

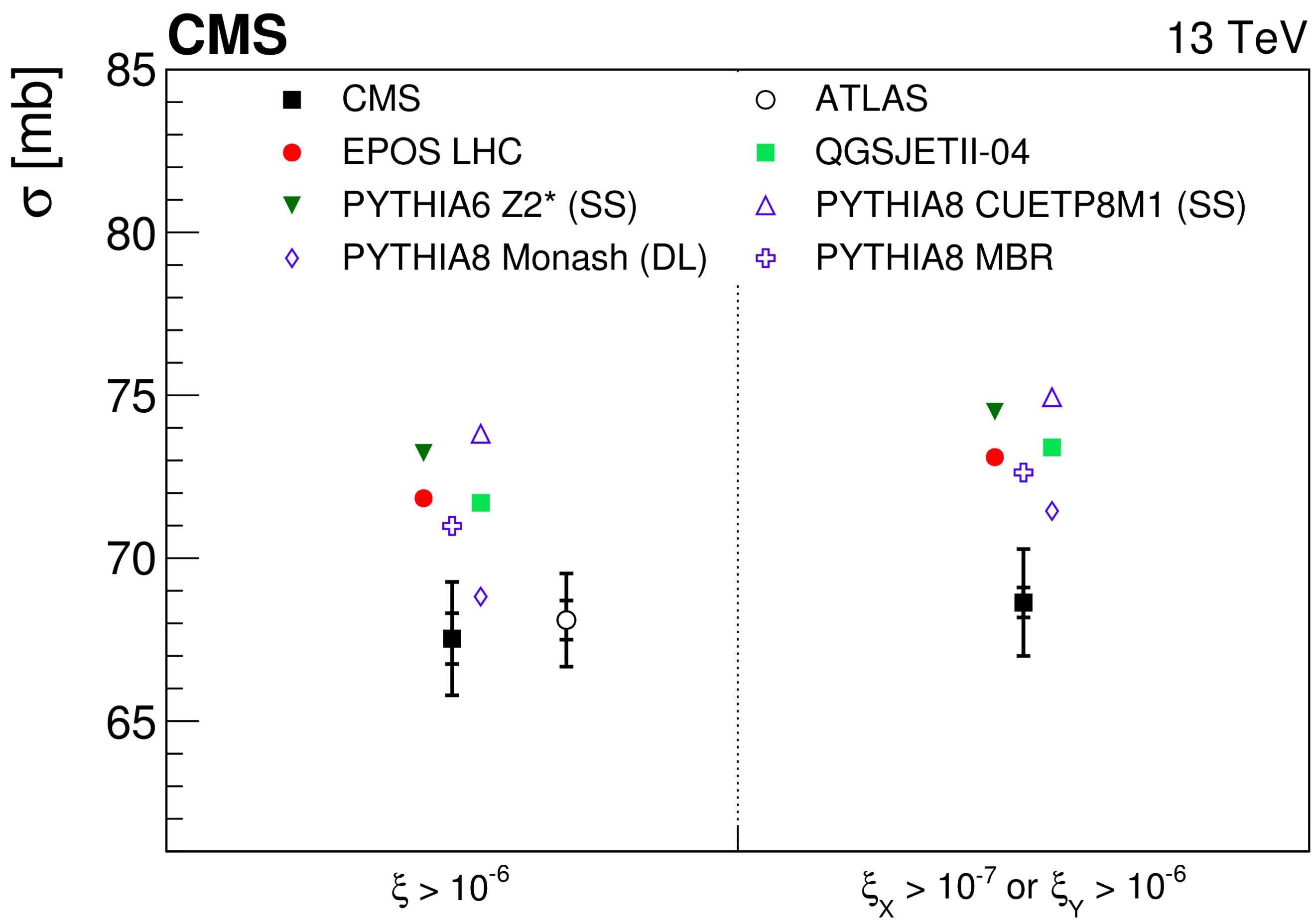
- Cross sections (total, inelastic, elastic)
- Soft particle distributions (global particle production)
- Identified particles, scaling features (hadronization)
- Energy flow and charged particles at high rapidities, forward physics (high density of soft gluons)
- Underlying event (correlation between soft and hard processes)

Minimum bias measurements

- Low momentum-transfer, non-perturbative QCD, effective models
- Large majority of final state particles originate from soft processes
- Connections to cosmic ray physics (particle shower shapes)
- Also important for understanding high-pileup collisions a the LHC
- Sensitive to the number of interactions between quarks and gluons
- Identified low-p_T particles characterize the expansion of QCD matter
- Soft particle multiplicity is a scaling parameter between systems

Inelastic cross section at 13 TeV

- Events counted by forward calorimeter deposits (HF, CASTOR)
- σ_{inel} = 68.6±0.5±(syst)±1.6(lumi)mb for M_X>4.1 and/or M_Y>13 GeV

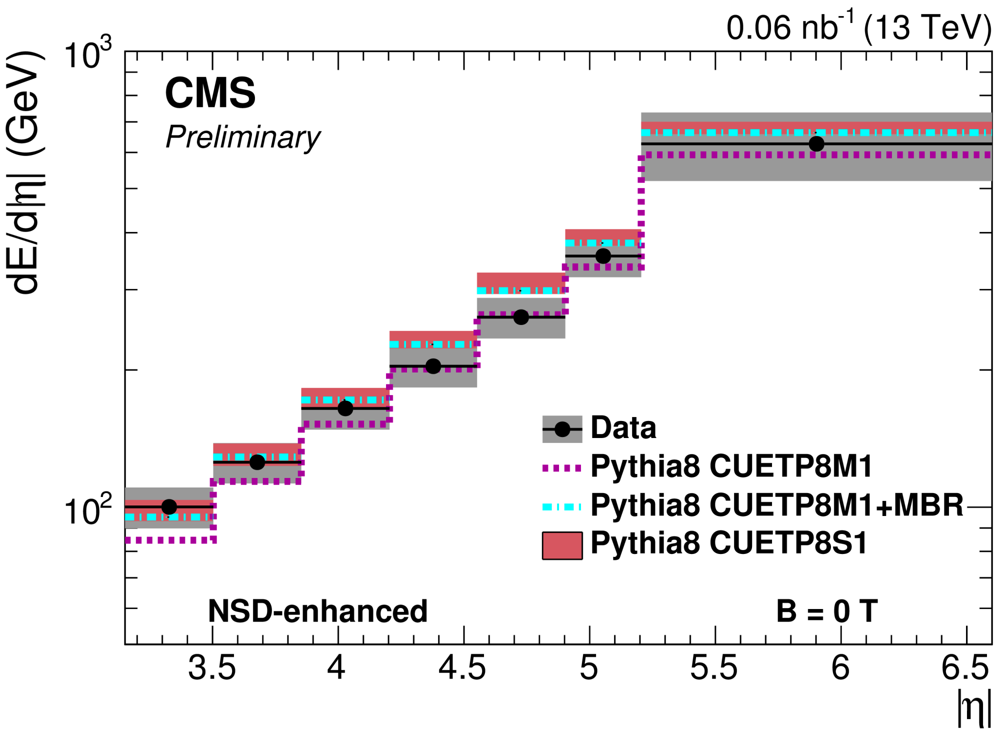


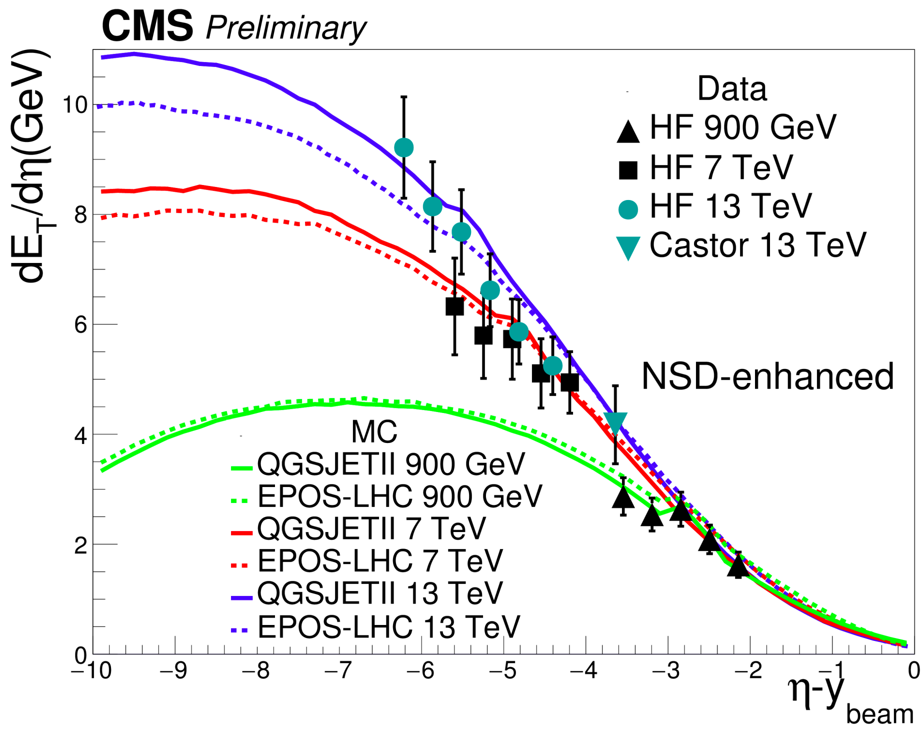
arXiv:1802.02613, submitted to JHEP
CMS-PAS-FSQ-15-005

Underestimated low-mass diffraction in models?

$dE_{(T)}/d\eta$ at 13 TeV

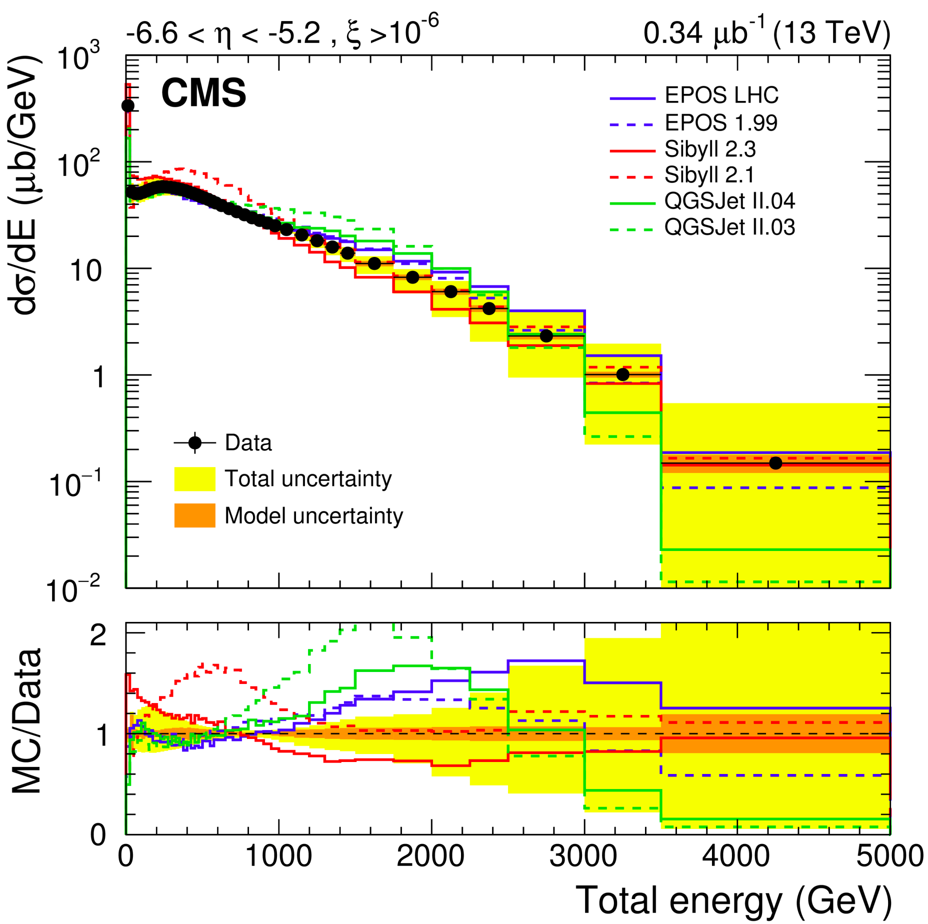
- (Transverse) energy flow measured with calorimeters (HF)
- Inelastic and non-single-diffractive event selection
- NSD: at least two particles on each side in $3.9<|\eta|<4.4$
- PYTHIA8, EPOS, QGSJET gives a reasonable description for NSD (but larger deviations for inelastic events!)

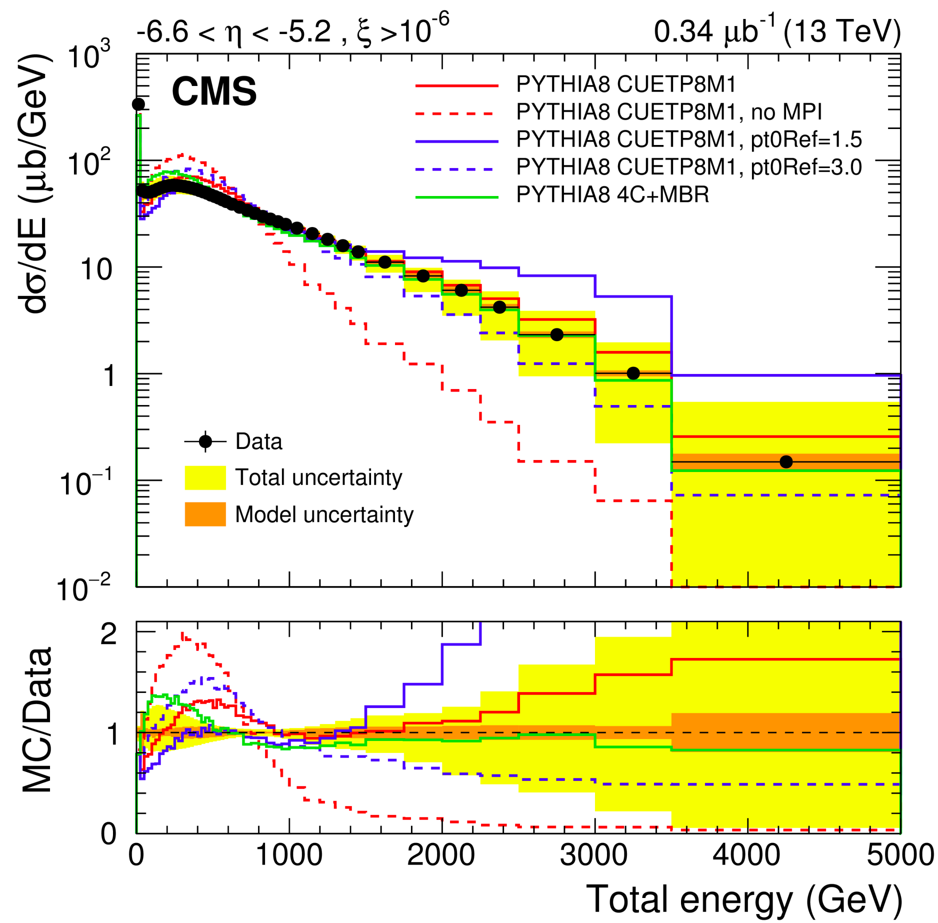




Very forward energy spectrum @13 TeV

- CASTOR calorimeter in CMS, $-6.6 < \eta < -5.2$. Events with $\xi > 10^{-6}$
- EM and HAD energy components. Relevance to MPI and CR
- None of the generators describe all data. PYTHIA w/o MPI excluded
- CR models adjusted to low energy LHC data perform better

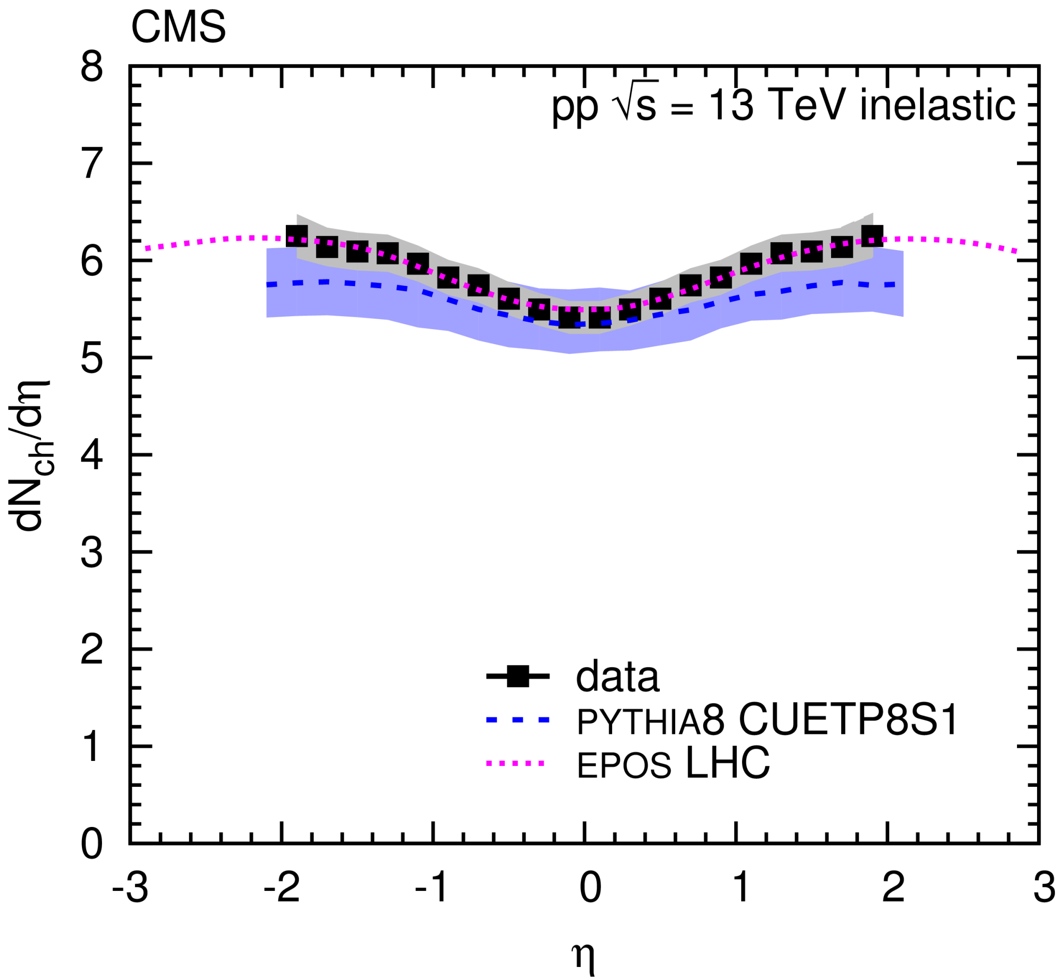


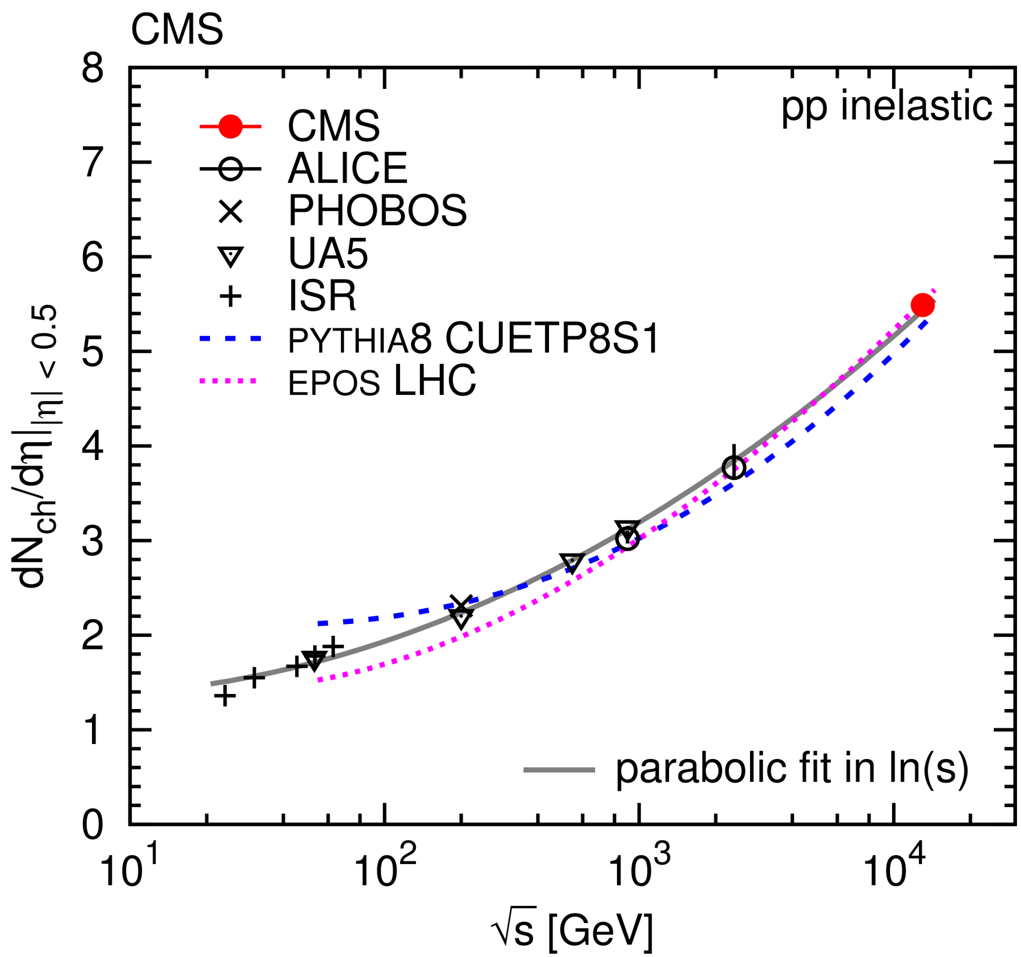


JHEP 08 (2017) 046
CMS-FSQ-16-002

Charged particle dN/dη at 13 TeV

- Measurement done with zero magnetic field, straight tracks
- First CMS measurement at 13 TeV
- EPOS agrees with the data best, but PYTHIA8 is consistent too

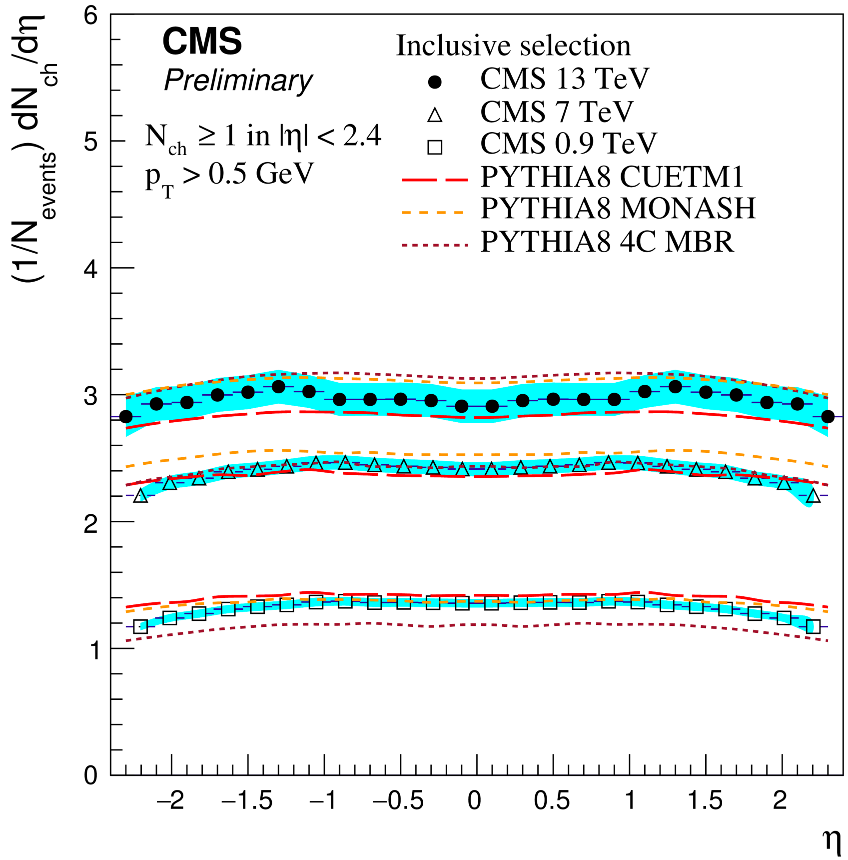


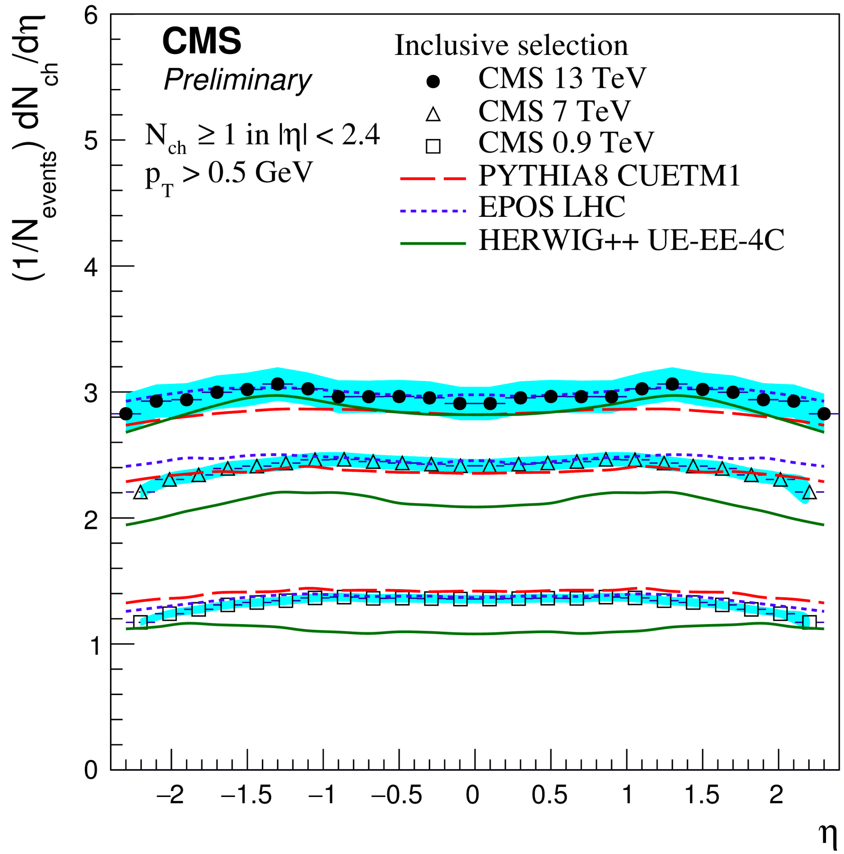


Phys. Lett. B 751 (2015) 143
CMS-PAS-FSQ-15-001

Charged particle dN/dη at 13 TeV

- $|\eta| < 2.4$ and $p_T > 0.5$ GeV
- 4 event sets: inclusive; inel.-enhanced; SD-enhanced, NSD-enhanced
- A large variety of MC models tested, and none of them agree with all aspects of the data

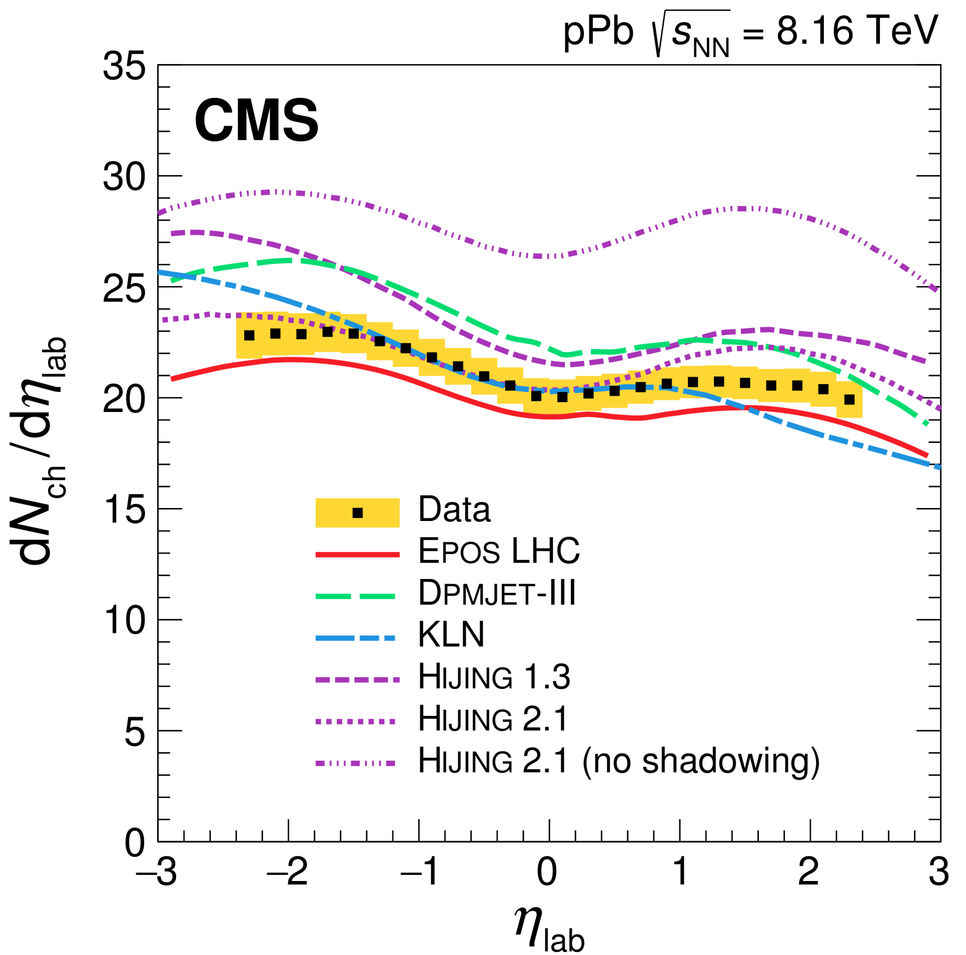


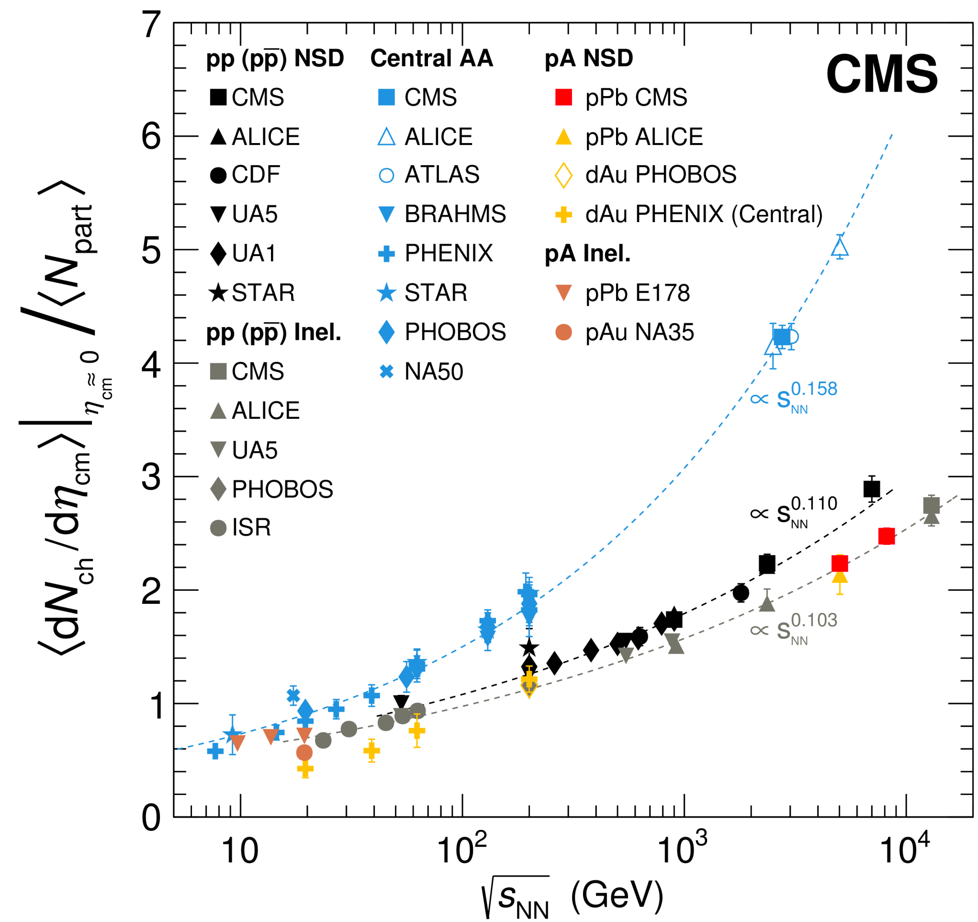


CMS-PAS-FSQ-15-008

dN/dη in pPb at 5 and 8.16 TeV

- Charged hadrons reconstructed from hit pairs (tracklets)
- Non-single diffractive event selection, first measurement at top √s
- Results at 8 TeV higher than EPOS and lower than HIJING 1.3

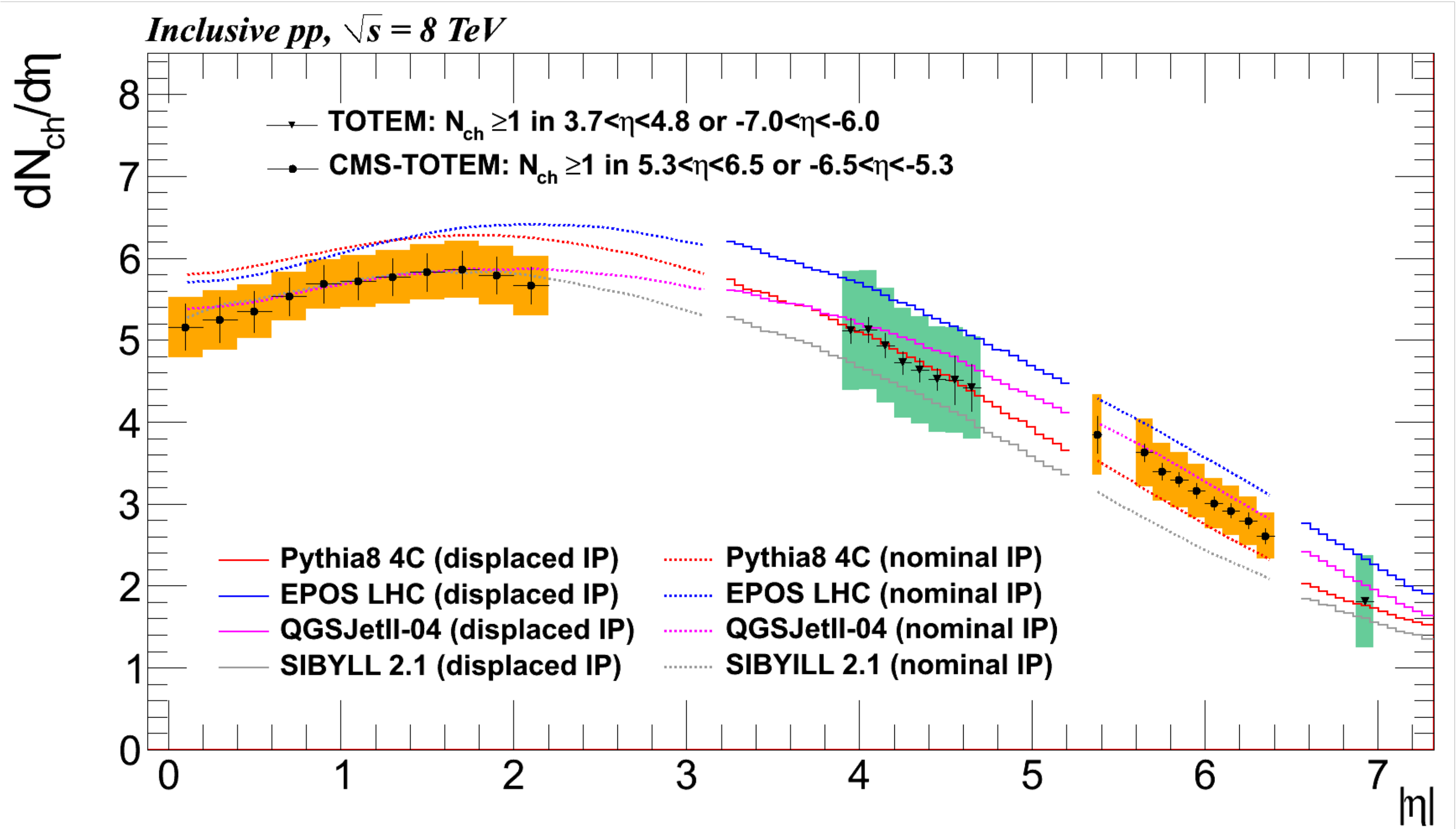




JHEP 1801 (2018) 045
CMS-PAS-HIN-16-021

Forward dN/dη at 8 TeV

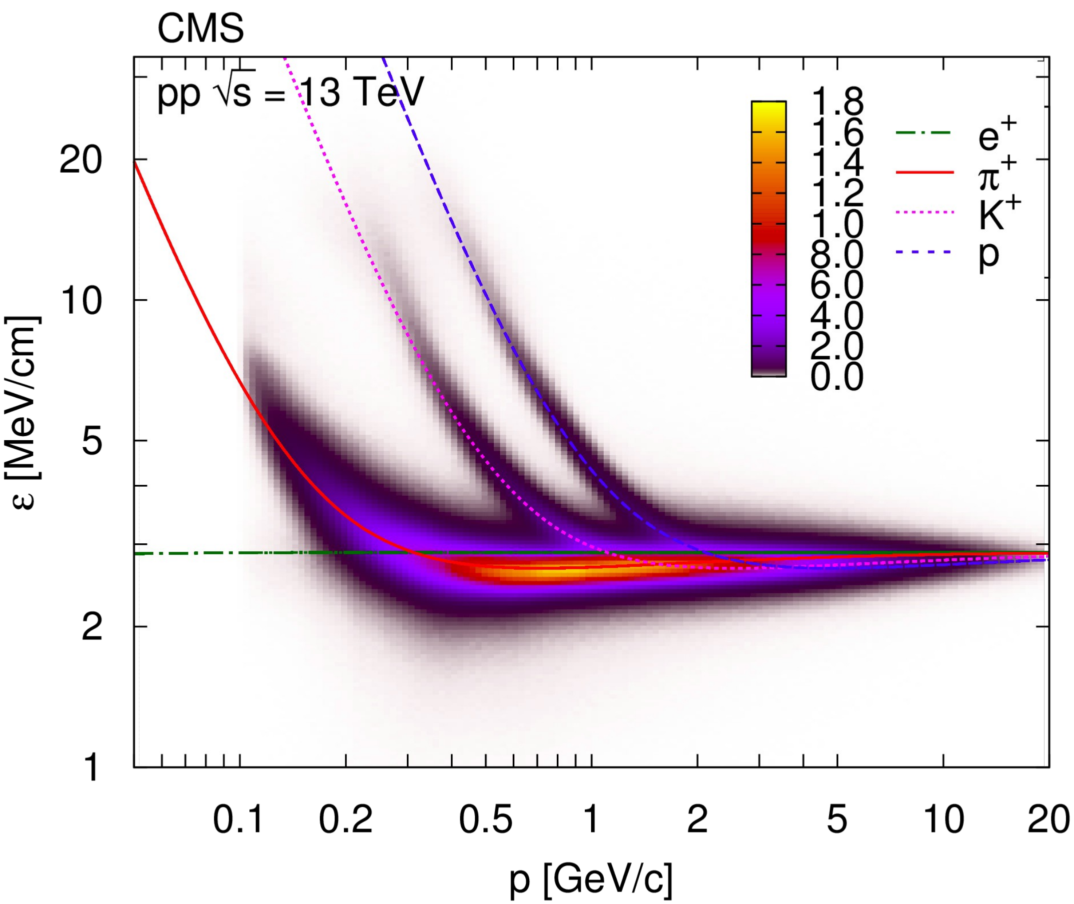
- Using a displaced interaction point at 11.25 m, using TOTEM T2±
- Dedicated non-standard run at β*=90 m
- 3.9 < η < 4.7 and -6.95 < η < -6.90
- Models consistent with the measurements within uncertainties

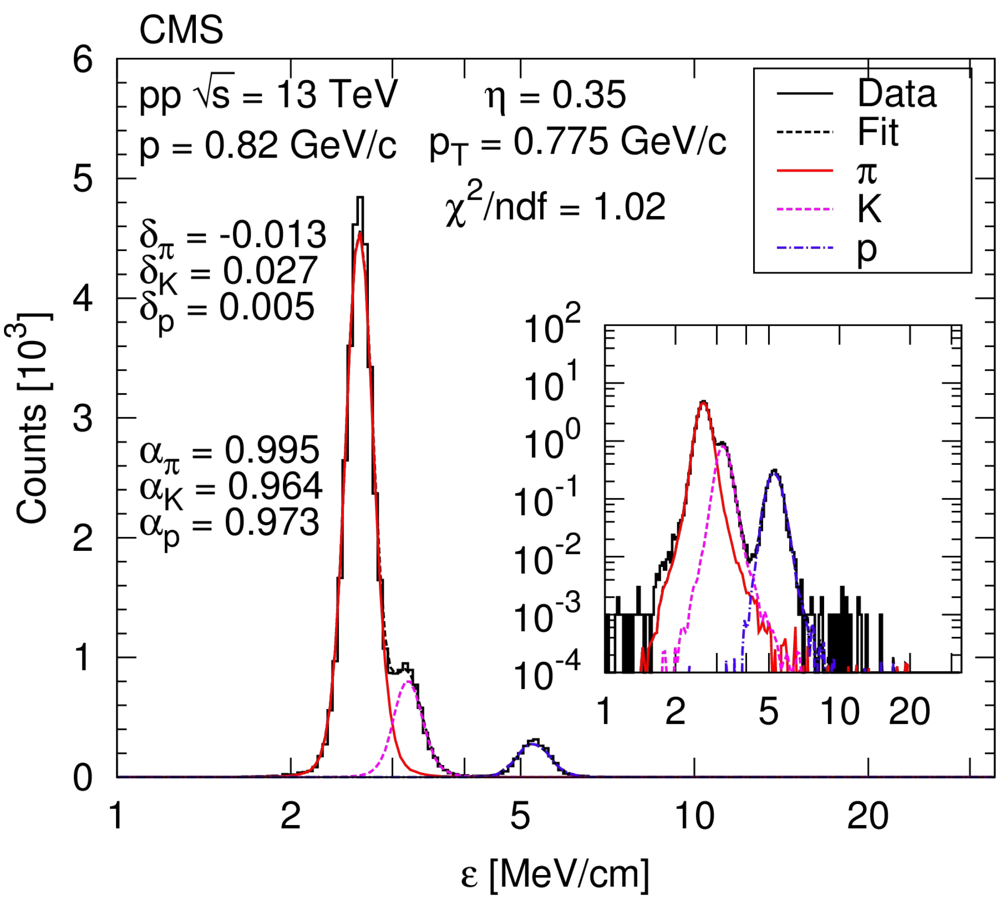


EPJC 75 (2015) 126
EPJC 74 (2014) 3053

Identified hadrons at 13 TeV

- Charged pion, kaon, and proton production in pp at 13 TeV
- Identification: dE/dx energy loss in the silicon tracker

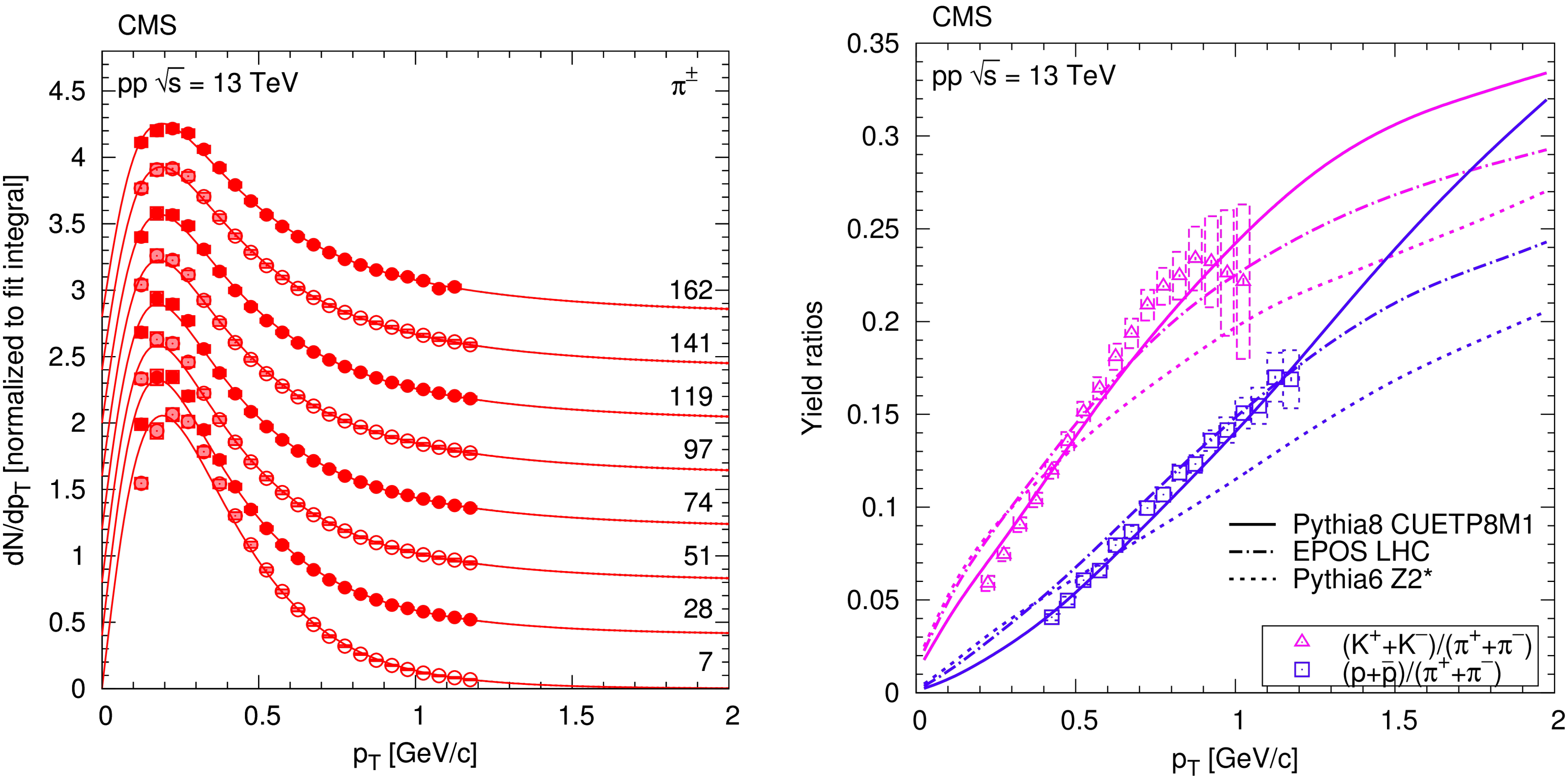




Phys.Rev. D96 (2017) no.11, 11200
CMS-FSQ-16-004

Identified hadrons at 13 TeV

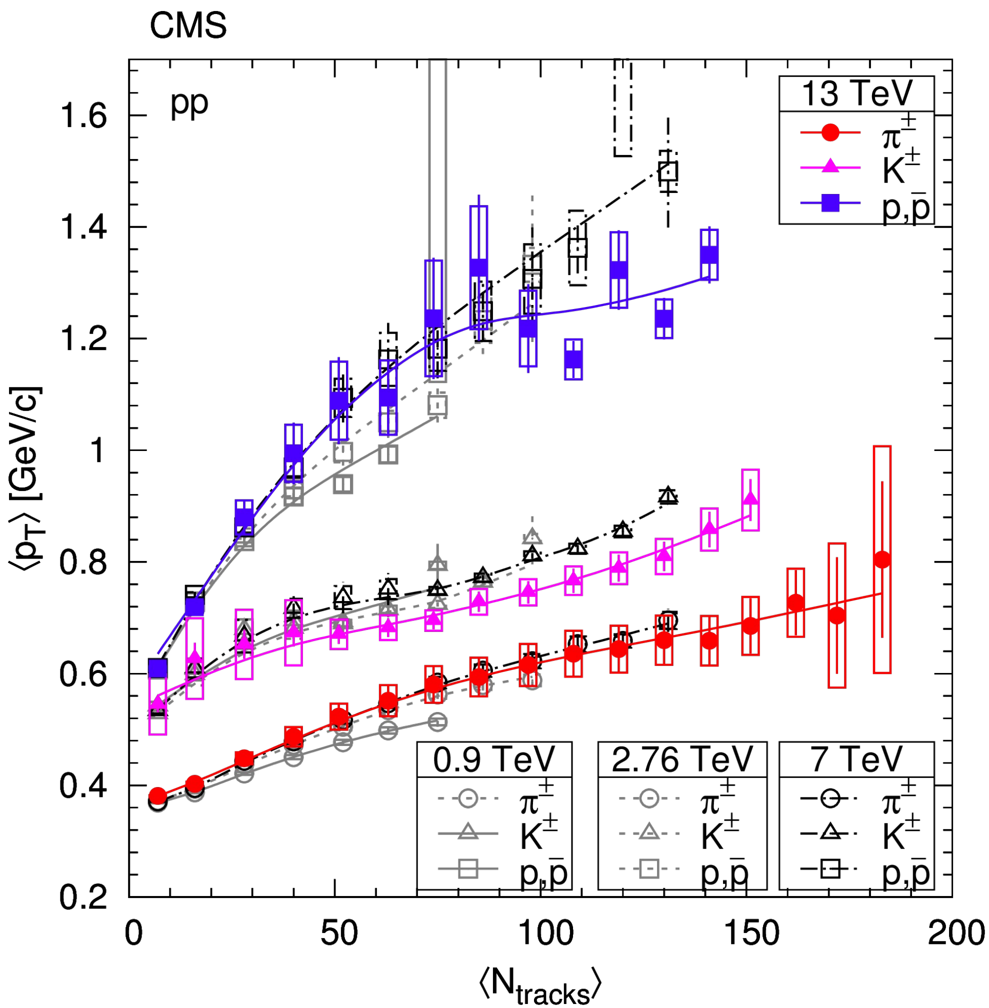
- Yields measured as a function of p_T, η, N_{ch}
- Particle ratios strongly increase with p_T, PYTHIA8 agrees well

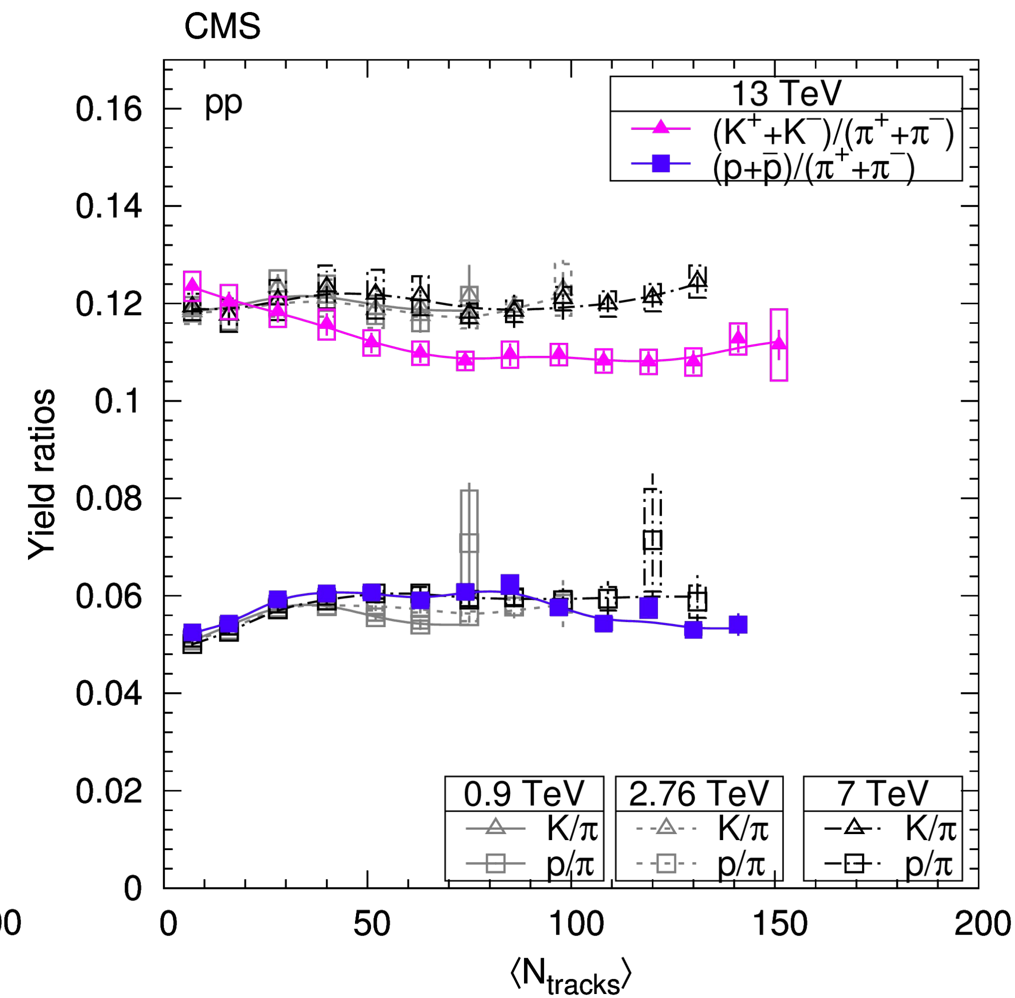


Phys.Rev. D96 (2017) no.11, 11200
CMS-FSQ-16-004

Identified hadrons at 13 TeV

- Mean p_T increases with mass and N_{ch}
- Mean p_T and hadron yield ratios depend on N_{ch}, but not on $\sqrt{s}$

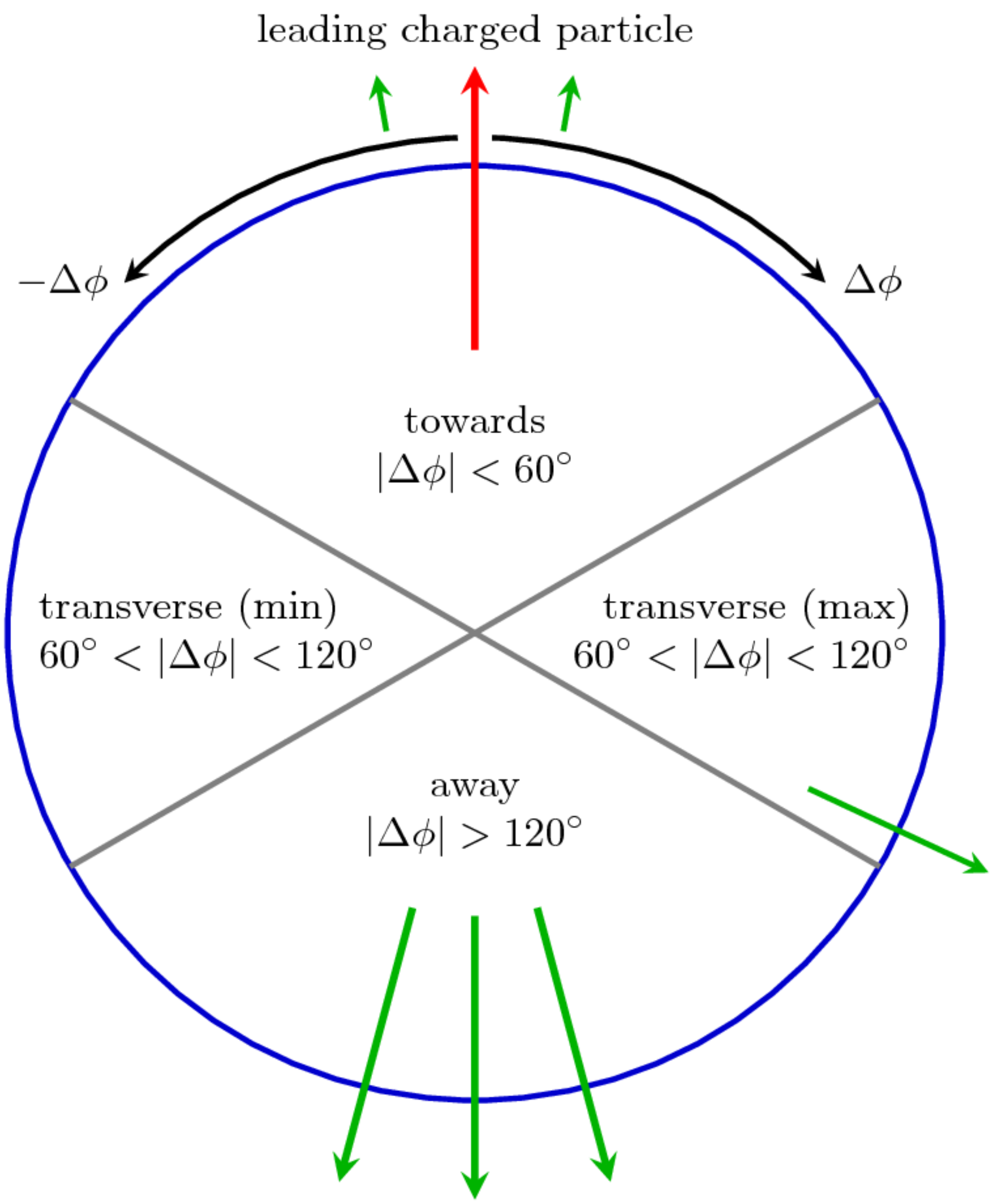




Phys.Rev. D96 (2017) no.11, 11200
CMS-FSQ-16-004

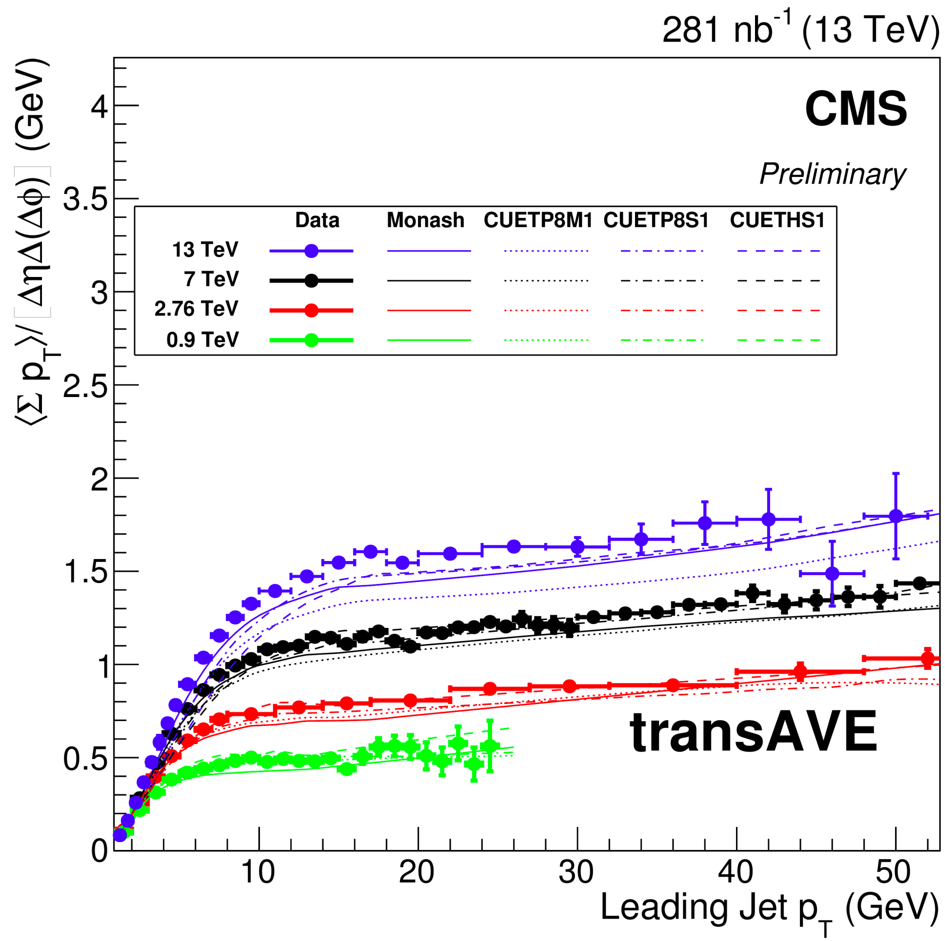
Underlying Event

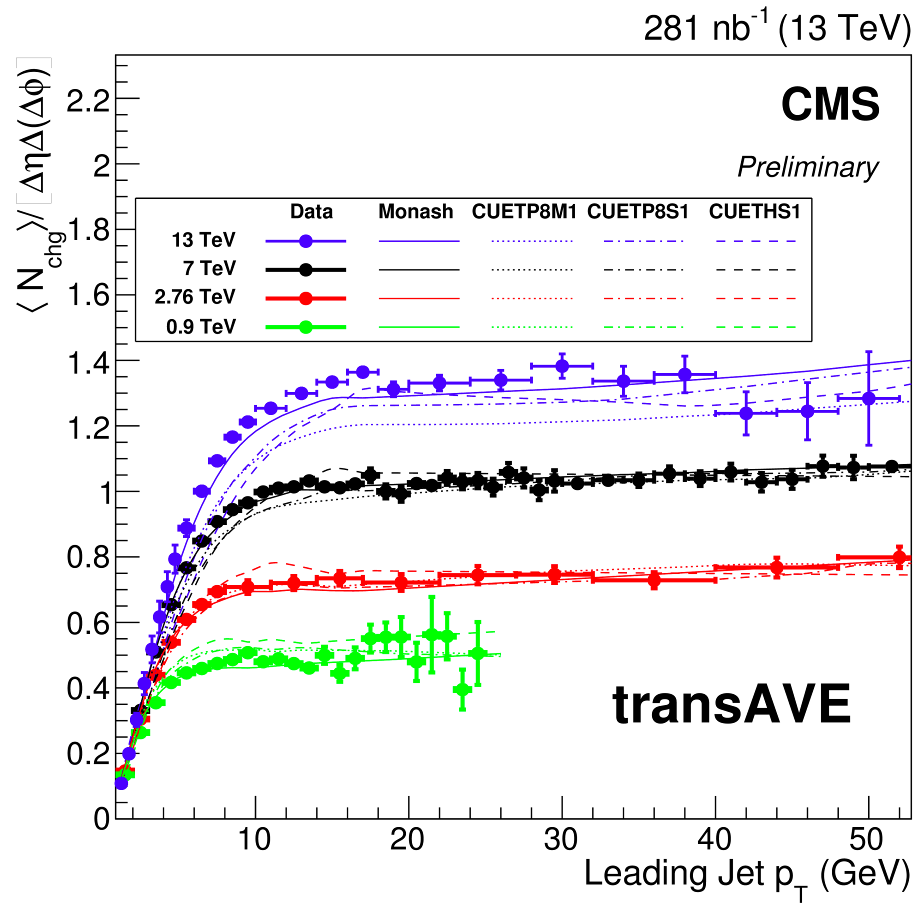
- Soft interactions accompanying a hard scattering
- Important for searches for new physics, lepton and photon isolation, $H \rightarrow \gamma\gamma$ vertex reconstruction, ...
- In models: initial and final state radiation, color connections, MPI
- Empirical tuning of MC event generators



Underlying event activity at 13 TeV

- Leading charged particle (jets) as reference objects
- Sum-p_T and average multiplicity, in the transverse region
- PYTHIA8-Monash has the best agreement with data
- UE activity grows with collision energy

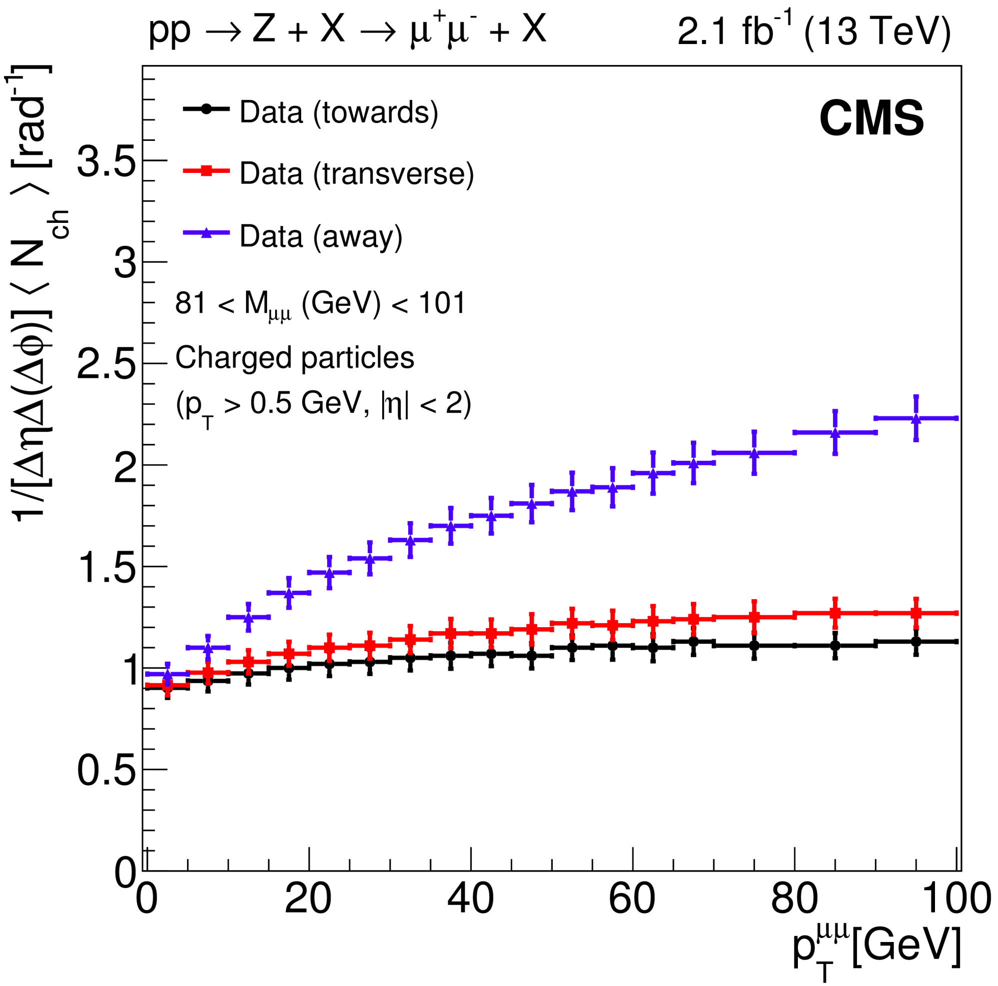


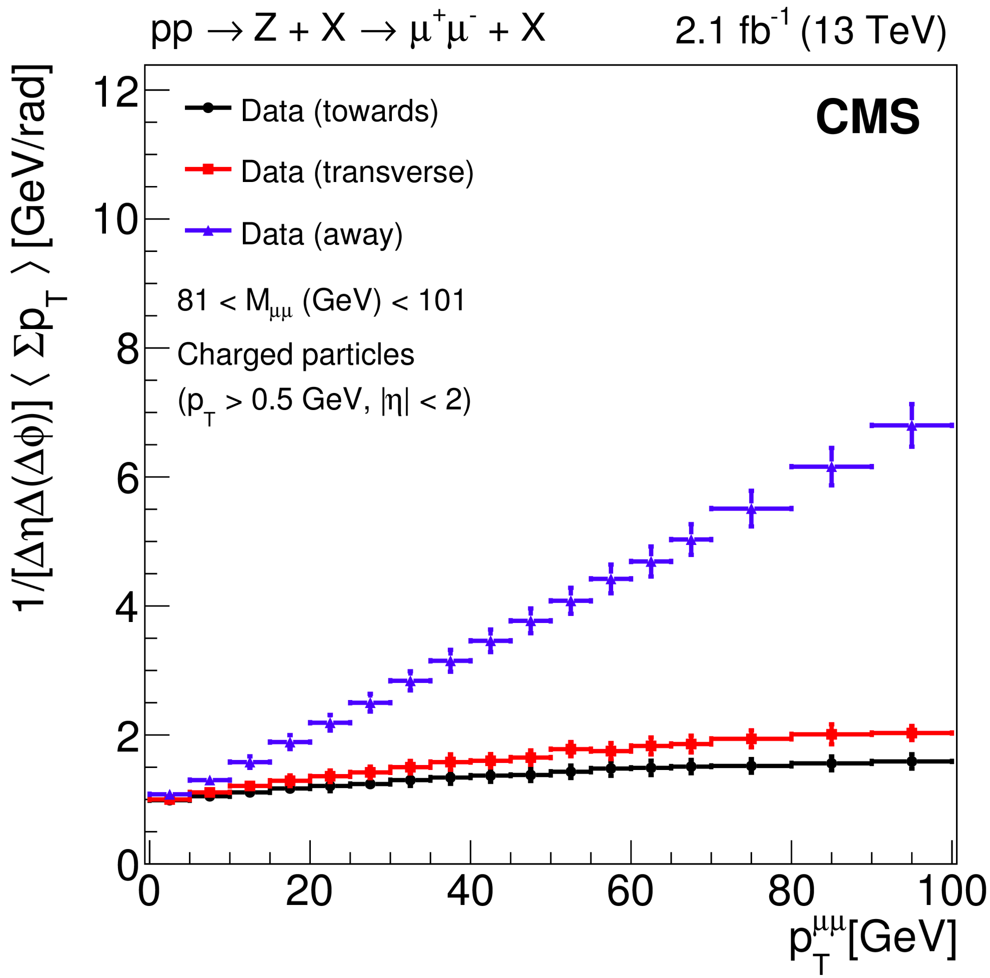


CMS-PAS-FSQ-15-007

UE using Z bosons at 13 TeV

- Underlying event in the presence of a $Z \to \mu\mu$, 2.1 fb^{-1} of data
- Charged particle multiplicity and scalar p_T sum vs. $p_T(\mu\mu)$

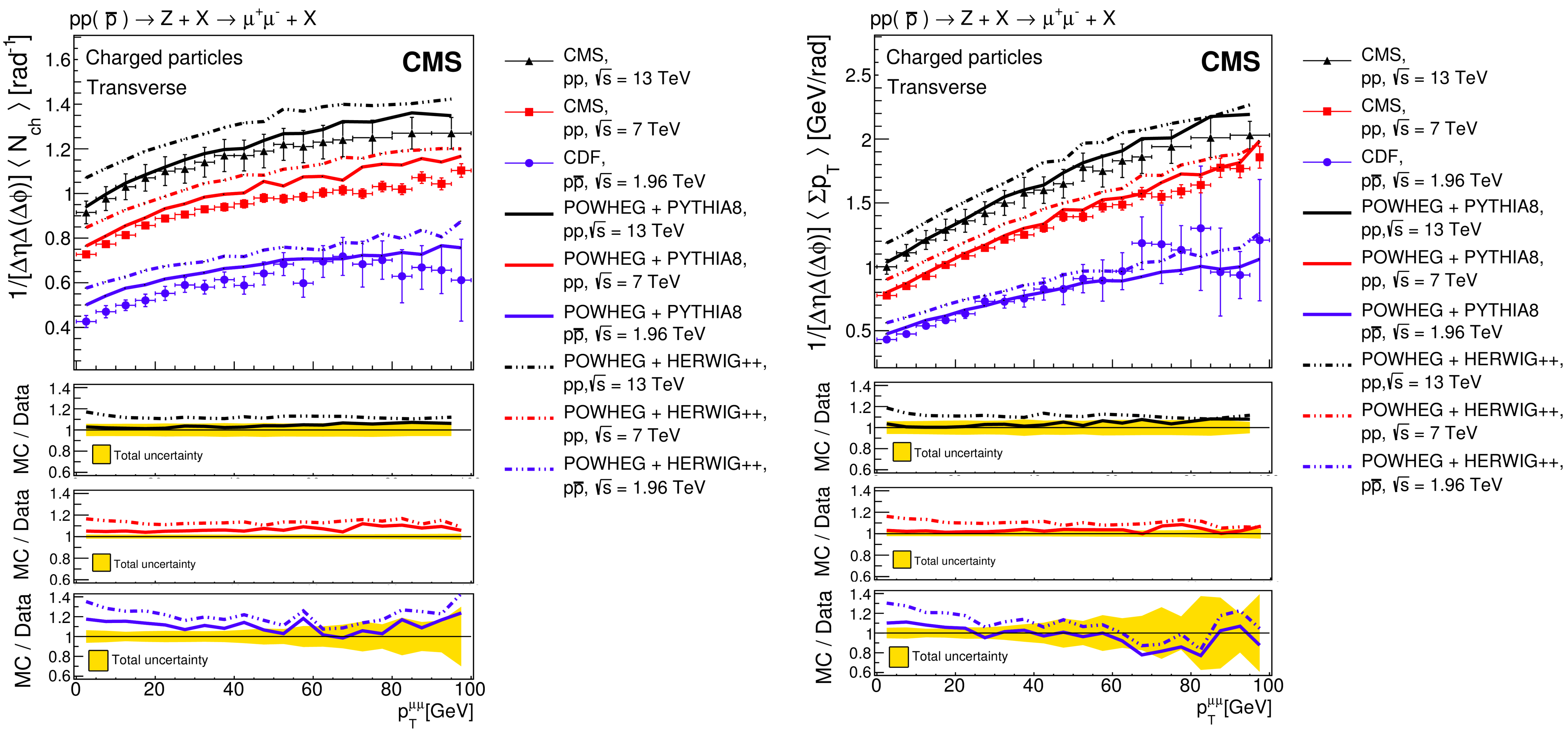




Submitted to JHEP, arXiv:1711.04299, *CMS-PAS-FSQ-16-008*

UE using Z bosons at 13 TeV

- Madgraph and powheg agree with the data, the combination of powheg and herwig++ overestimates them by 10-15%.
- UE increases logarithmically with √s, models not very precise



Submitted to JHEP, arXiv:1711.04299, *CMS-PAS-FSQ-16-008*

Summary

- Soft QCD is important for many different aspects of LHC physics:
  - **Non-perturbative** and **global** features of the collisions
  - **High pileup** simulations, **searches** for new physics
  - **Cosmic rays**
- Challenges:
  - Special LHC **runs**
  - Unique **instrumentation**
  - Unique analysis **techniques**
- Active field that provides important fundamental information
  - Soft-hard transition, MPI, model tuning...

Challenges for experiment and phenomenology!