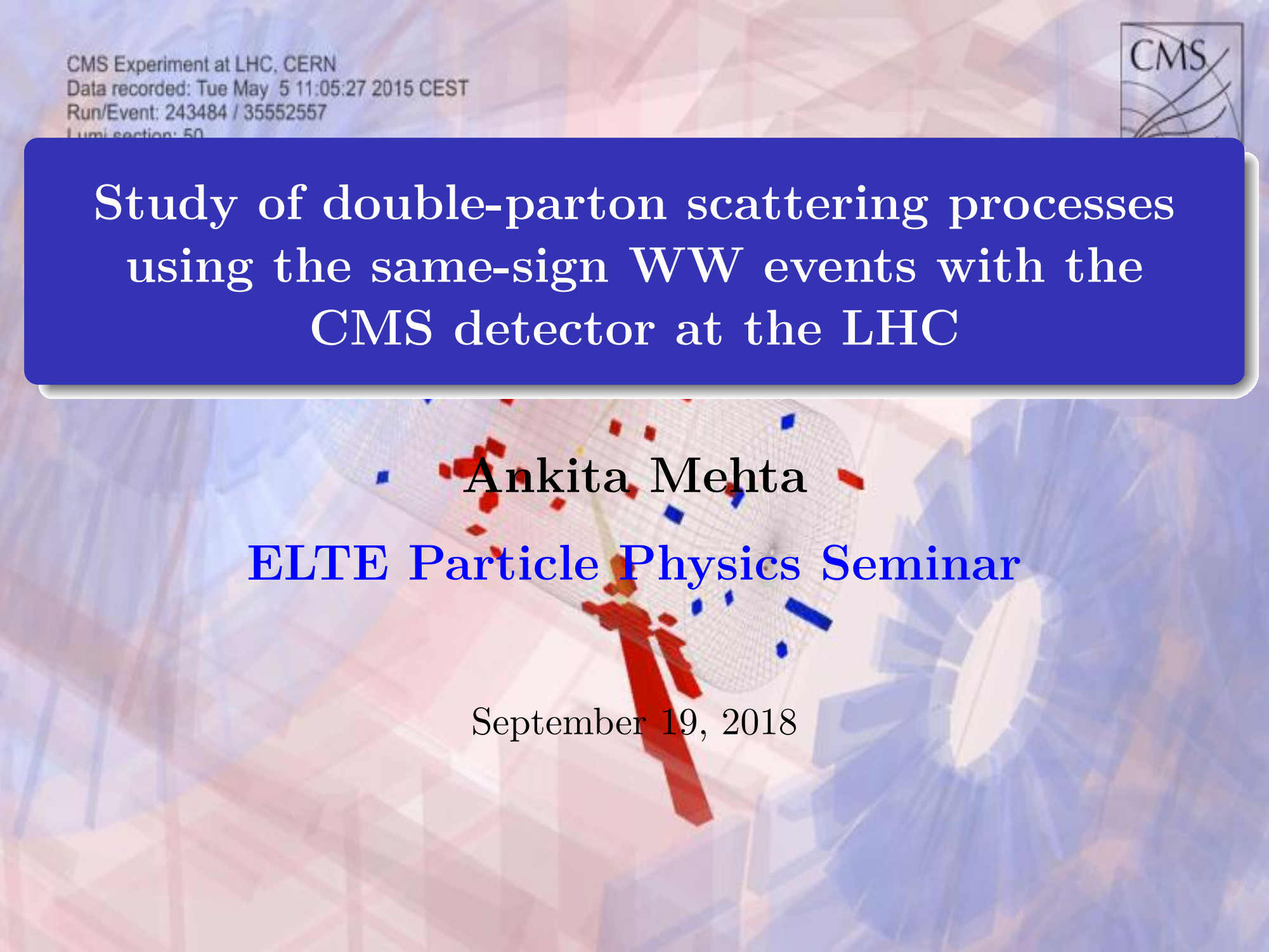

Study of double-parton scattering processes using the same-sign WW events with the CMS detector at the LHC

Ankita Mehta

ELTE Particle Physics Seminar

September 19, 2018

Outline

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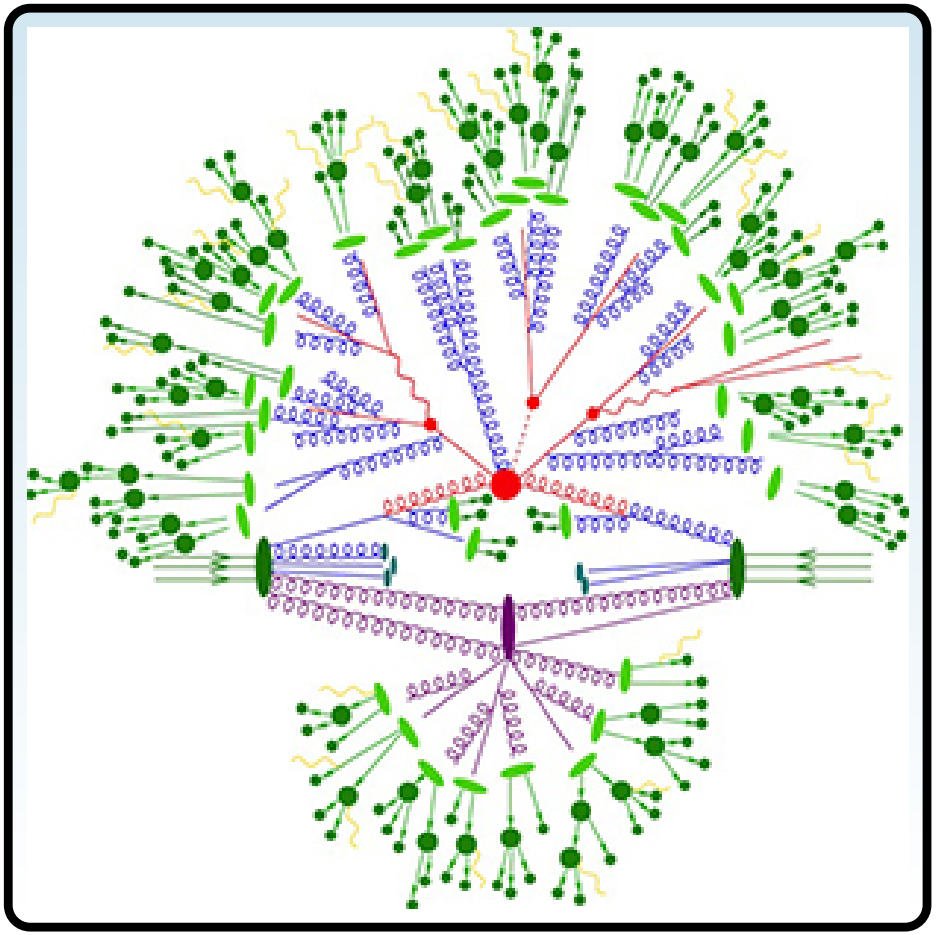
1. Double-Parton Scattering Processes
2. Motivation to Perform DPS Studies using Same-Sign WW Events
3. DPS studies using same-sign WW events @ 8 TeV
4. Systematics Uncertainties
5. Multivariate Analysis
6. Results
7. Current status @ 13 TeV
8. Summary & Future Outlook
9. Backup

Multi-Parton Interactions

Hadron-hadron collision: Hard scattering between partons $\oplus$ underlying event (UE) activity



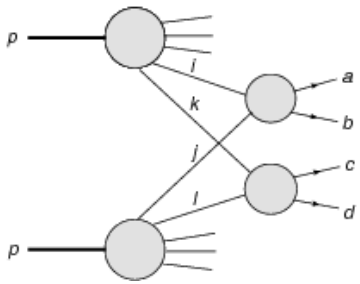
UE gets contribution from:

- **Beam-Beam Remnants**
- **Multiple-Parton Interactions (MPI)**
- **Initial State & Final State Radiations**

Generally UE is a softer contribution, but some MPI can be hard → Double-Parton Scattering

Double-Parton Scattering

Simultaneous occurrence of 2 hard parton scatters → **Double-Parton Scattering (DPS)**



$$\sigma^{D}_{(A,B)} = \frac{m}{2}\sum_{i,j,k,l}\int \Gamma_{ij}(x_1,x_2,b;t_1,t_2)\hat{\sigma}^{A}_{ik}(x_1,x'_1)\hat{\sigma}^{B}_{jl}(x_2,x'_2) \times \Gamma_{kl}(x'_1,x'_2,b;t_1,t_2)dx_1dx_2dx'_1dx'_2d^2b$$

partonic cross sections

pdf terms

transverse distance between partons

Assume complete factorization of DPDFs

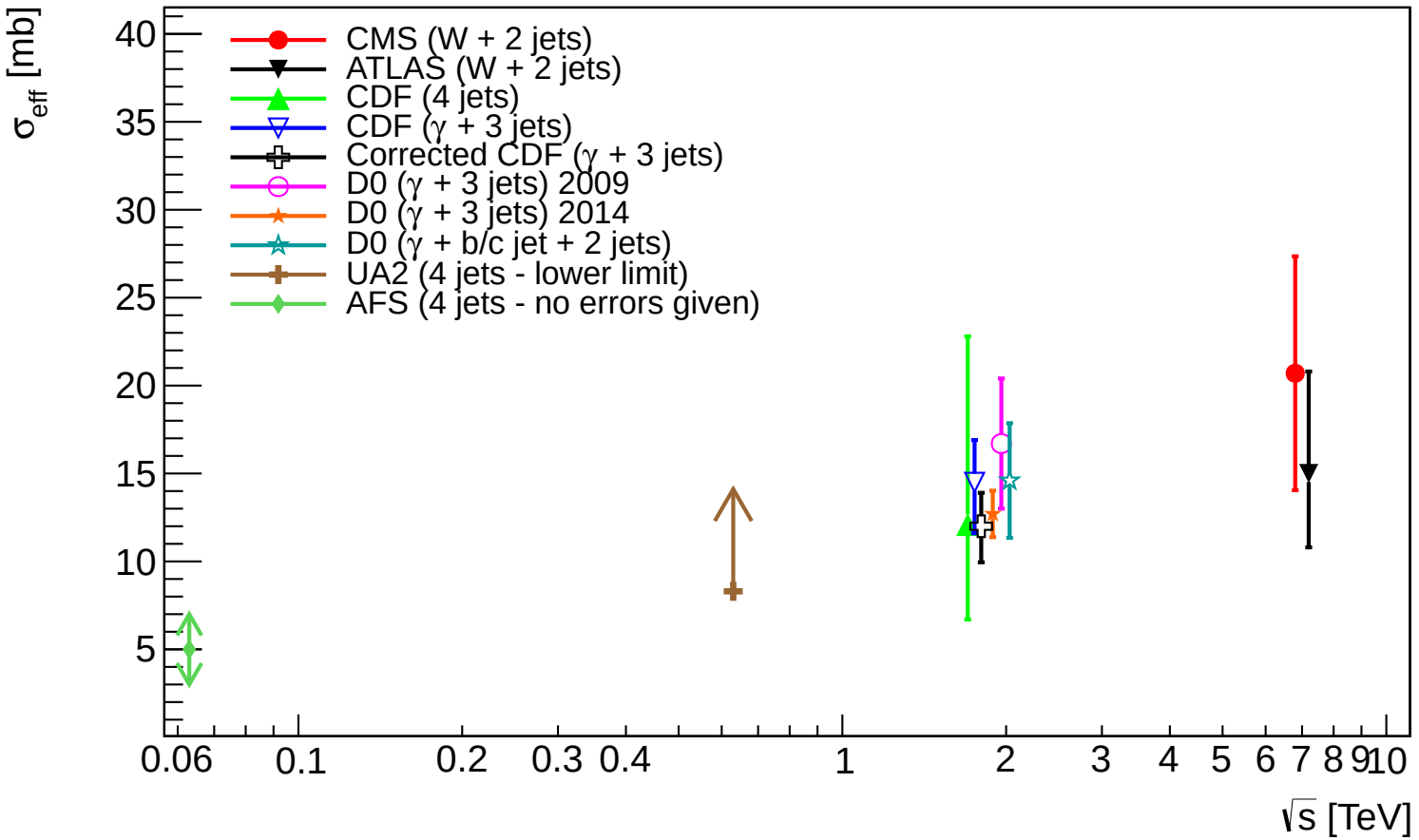
- $\sigma^{\mathrm{DPS}}_{\mathrm{AB}} = \frac{\mathrm{m}\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{2\sigma_{\mathrm{eff}}}$ (m = 1 if A==B, else 2)
- σ_{eff} ⇒ Extent of overlap in the transverse direction
- σ_{eff} ⇒ Predicted to be independent of process type & collision energy → Needs an experimental verification

Importance of DPS Processes

- Grow with energy/gluon density
- **Test the validity of factorization approach → Expected to breakdown at some point**
- Information about hadron structure in transverse plane
- Background estimation for interesting physics processes

Existing Measurements

- Different measurements at different collisionenergies & using multiple final states

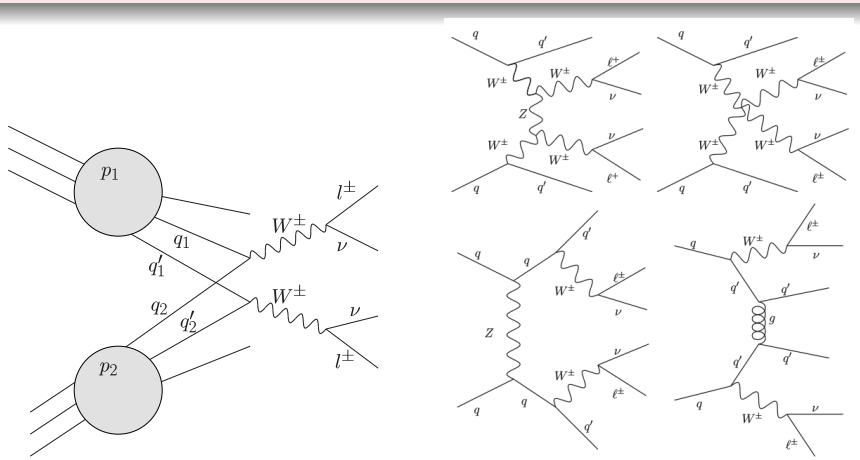


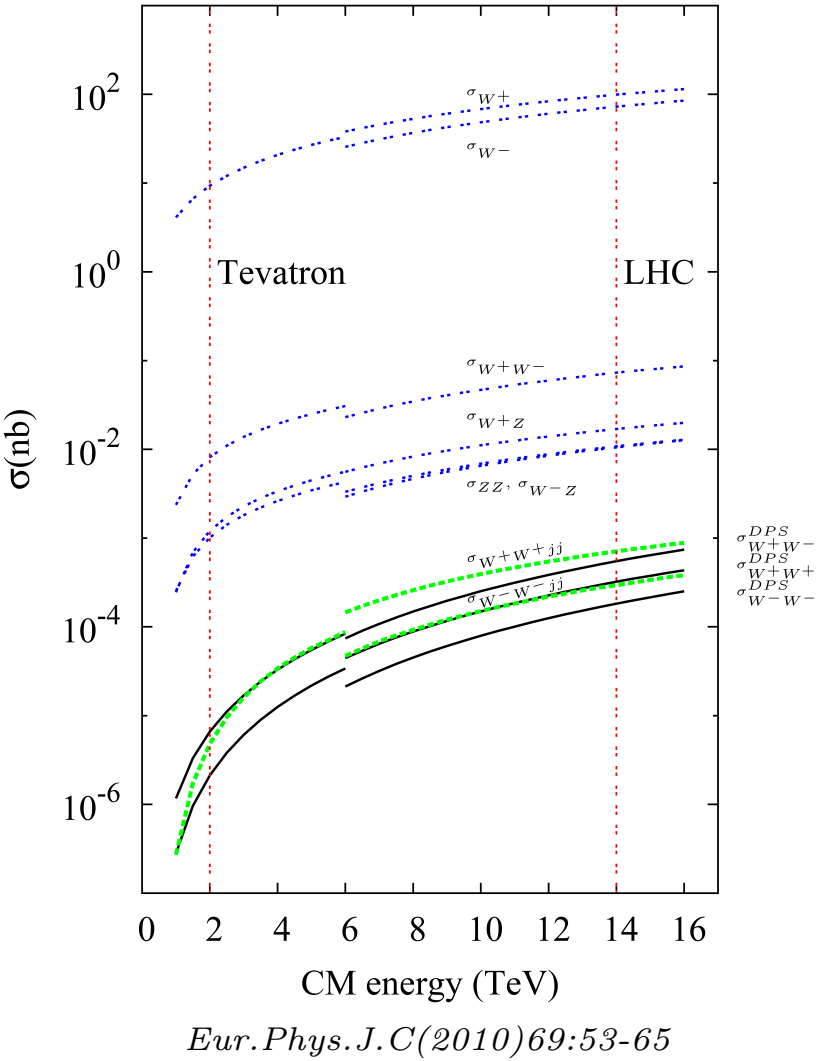
- Measurements agree within large systematics uncertainties → No clear conclusion about the dynamics of σ_{eff}.

Same-sign WW (JHEP02(2018)032)

Why Same-Sign WW ?

- Production cross section of diboson processes → Sensitive to new particle productions
- W boson production → benchmark process to study at the LHC
- $\sigma^{\mathrm{DPS}}_{\mathrm{W}^{\pm}\mathrm{W}^{\pm}} \approx \sigma^{\mathrm{SPS}}_{\mathrm{W}^{\pm}\mathrm{W}^{\pm}}$
- Clean final state with leptonically decaying W bosons

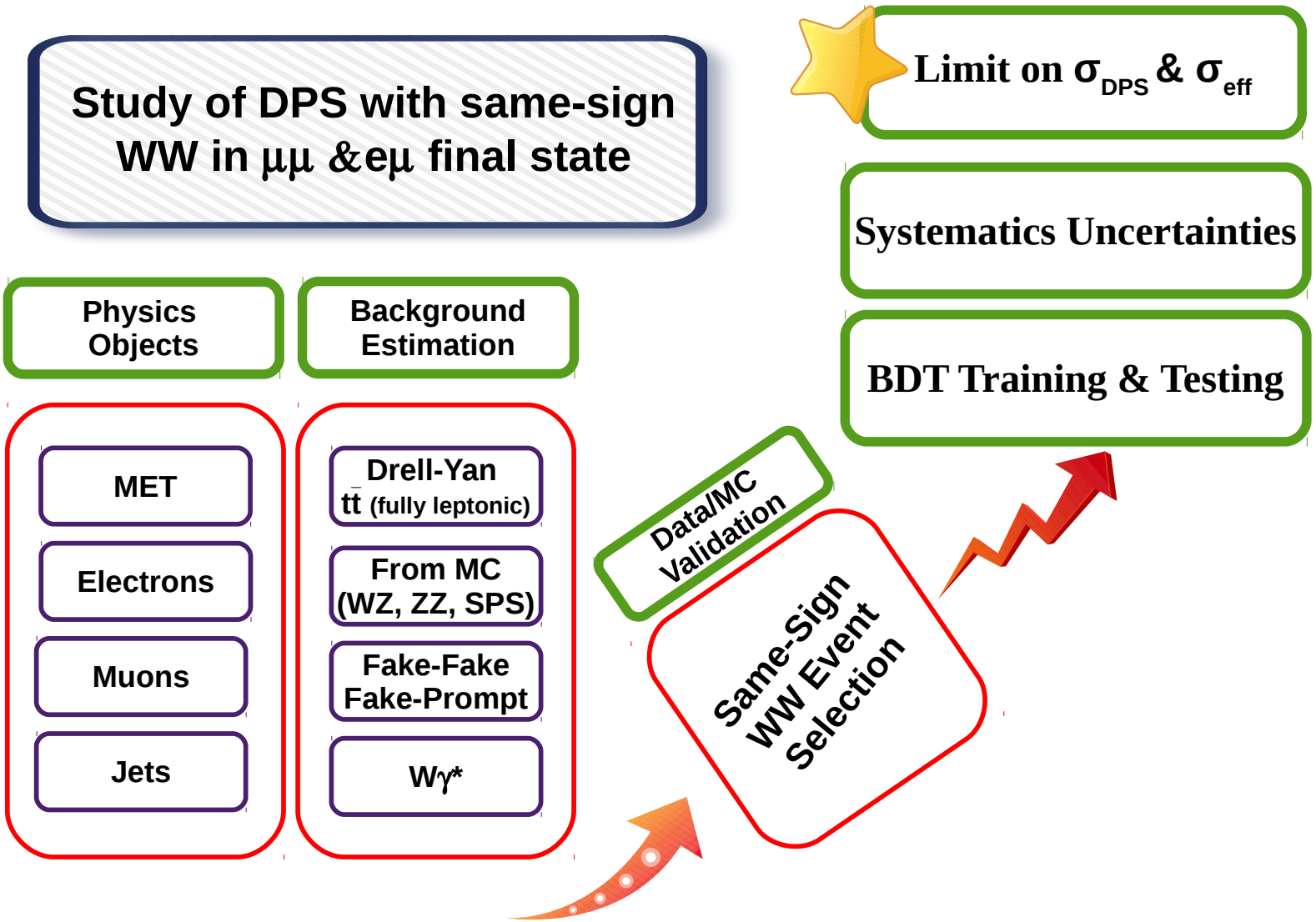




Eur.Phys.J.C(2010)69:53-65

DPS with same-sign WW → Hardest momentum scale explored for DPS, so-far

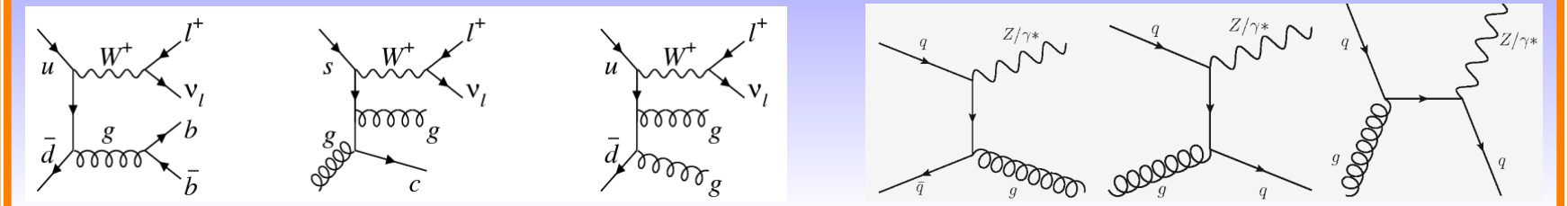
Analysis Strategy



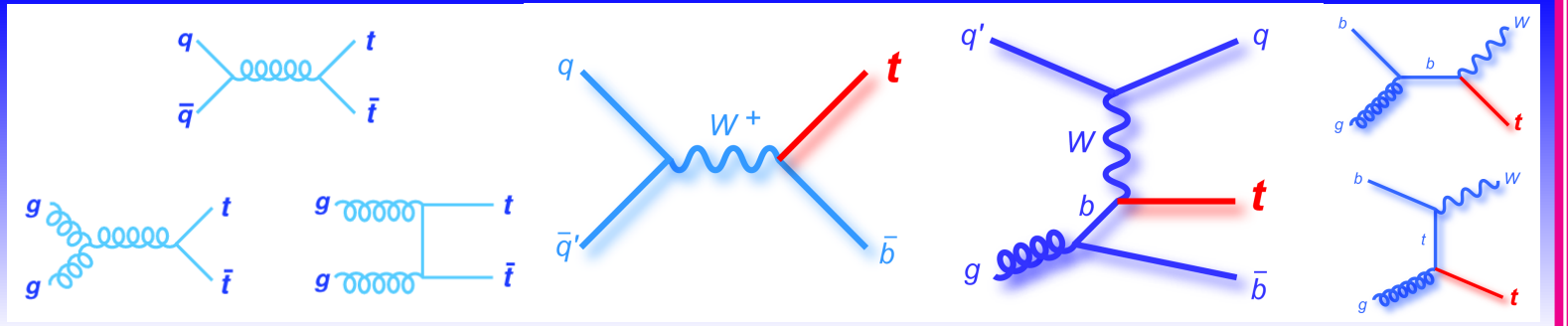
Background Menu

Jet induced processes (estimated from the data)

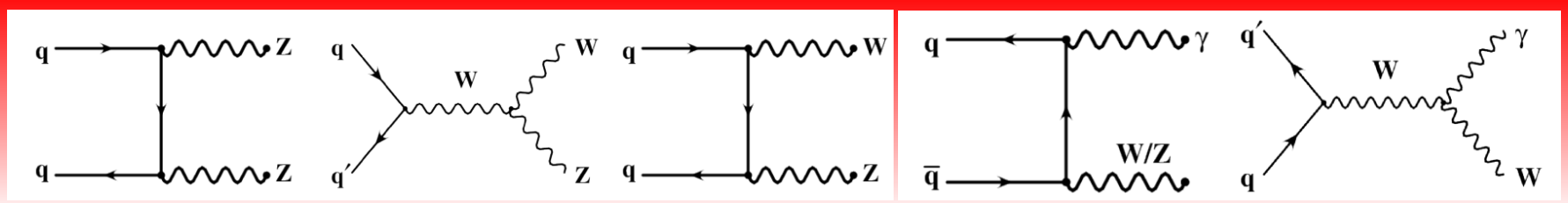
DY processes (estimated from the MC)



Top quark processes (estimated from the data & MC)

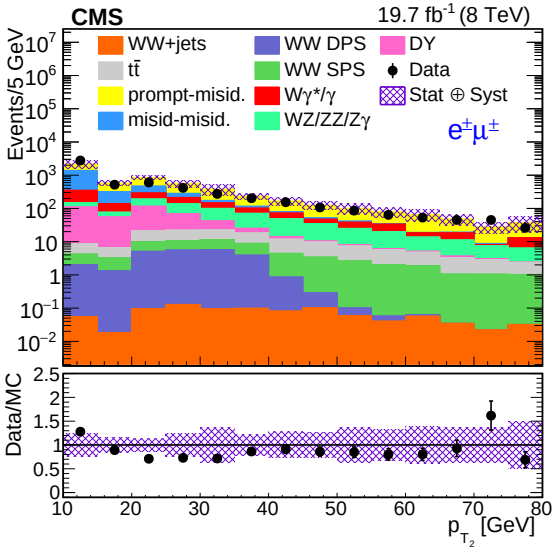


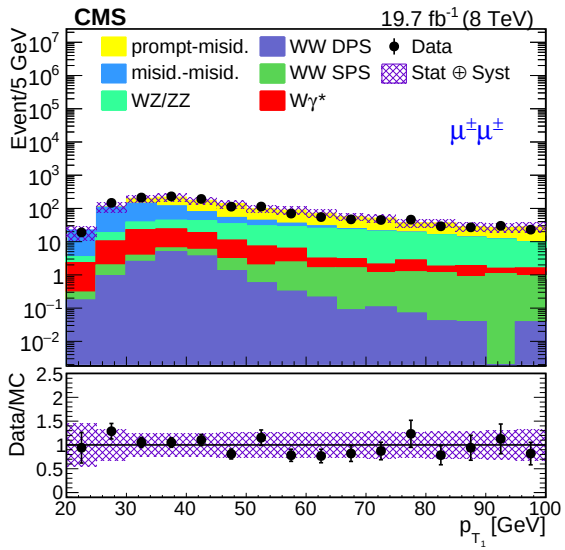
Diboson processes (estimated from the MC)



Baseline Event Selection

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





Data-MC agreement within systematic uncertainties

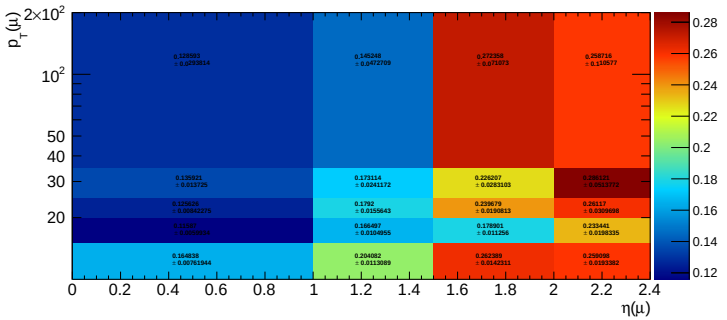
Estimation of Jet Induced Processes

- Different background enriched (fake control) regions for the two final states
- Probability of a loose lepton like object to be misidentified as a lepton → Fake Rate
- Probability for a loose prompt lepton to also pass the tight selection → Prompt Rate
- Contamination from W/Z decays is subtracted while calculating fake rates
- Extrapolation factor relates background misidentified with this criteria, to the background events in the signal phase space

Fake Control Regions:

Region 1 ($\mu\mu$ channel)	Region 2 (eμ channel)
Only one loose lepton with $p_{\mathrm{T}} > 10$ GeV	Only one loose lepton with $p_{\mathrm{T}} > 10$ GeV
$m_{\mathrm{T}}(\ell, p_{\mathrm{T}}^{\mathrm{miss}}) < 20$ GeV	$m_{\mathrm{T}}(\ell, p_{\mathrm{T}}^{\mathrm{miss}}) < 20$ GeV
$p_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV	$p_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV
–	At least one b-tagged jet with $p_{\mathrm{T}} > 30$ GeV & $\lvert\eta\rvert < 2.1$

Muon (electron) fake ratios → 10–30% (10–40%)
Muon (electron) prompt ratios → 70-95% (65–90%)



Systematic Uncertainties

	DPS	Diboson	Top	DY	Fakes
Effect on event yields in %					
Luminosity calibration	2.5				
Pileup reweighting	4.5				
Lepton reconstruction & trigger efficiency	1-5				
$p_{\mathrm{T}}^{\mathrm{miss}}$	1.0	3.0-8.0	0.9	17.5	
btagging	2.7	1-4	4.1	0.7	
Cross section	10	10 (30% for Wγ/γ^*)	10	10	
Estimation method					40 for misid.misid. 3 $\oplus$ shape for prompt-misid.

Multivariate Analysis: Boosted Decision Trees (BDT)

Input Variables: $\mu\mu$ final state

- p_{T_1}, p_{T_2}, p_T^{miss},$\Delta\phi(\vec{p}_{T_1}, \vec{p}_T^{miss})$
- $\Delta\phi(\vec{p}_{T_2}, \vec{p}_T^{miss})$, $\Delta\phi(\vec{p}_{T_1}, \vec{p}_{T_2})$
- $m_T(\mu_{1/2}, \vec{p}_T^{miss})$, $m_T(\mu_1, \mu_2)$

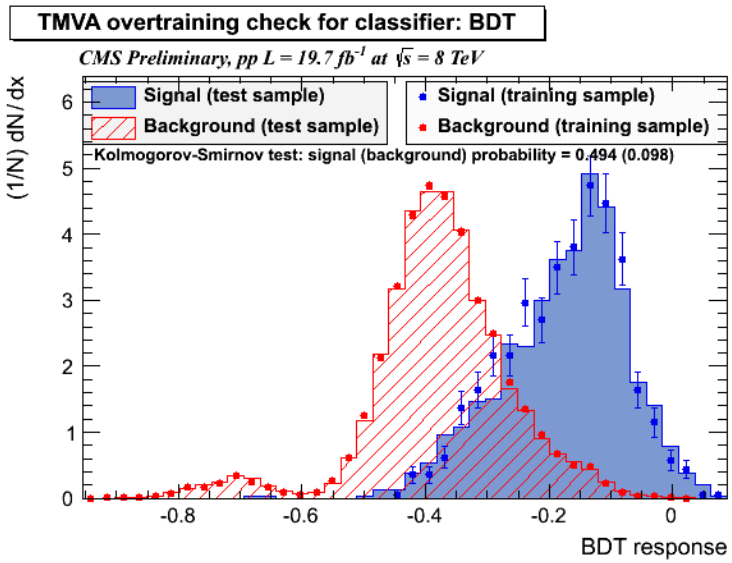
Input Variables: eμ final state

- $p_{T_{1,2}}$, p_T^{miss}
- $\Delta\eta(l_1, l_2)$, $\Delta\phi(\vec{p}_{T_2}, \vec{p}_T^{miss})$
- $\Delta\phi(\vec{p}_{T_1}, \vec{p}_{T_2})$, $\Delta\phi(\vec{p}_{T_1}\vec{p}_{T_2}, \vec{p}_T^{miss})$.

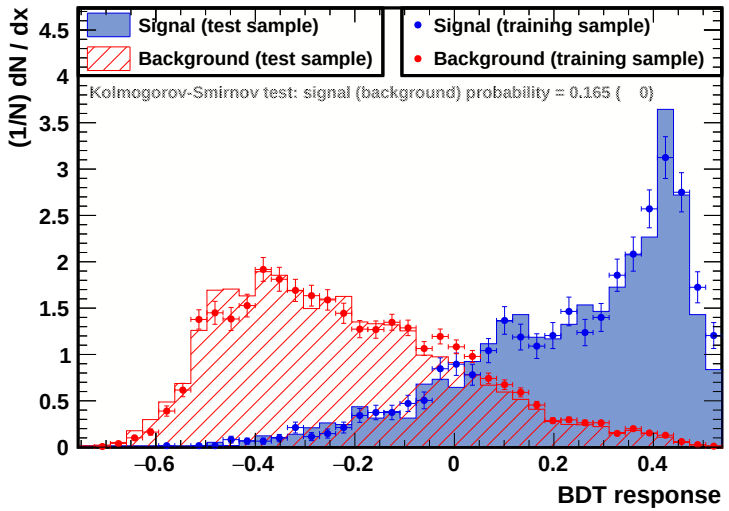
Training & Testing Samples

- Signal: DPS OS events for training & SS events from MC sample for testing
- Background: WZ, misid.-misid. & prompt-misid. events (both OS & SS)

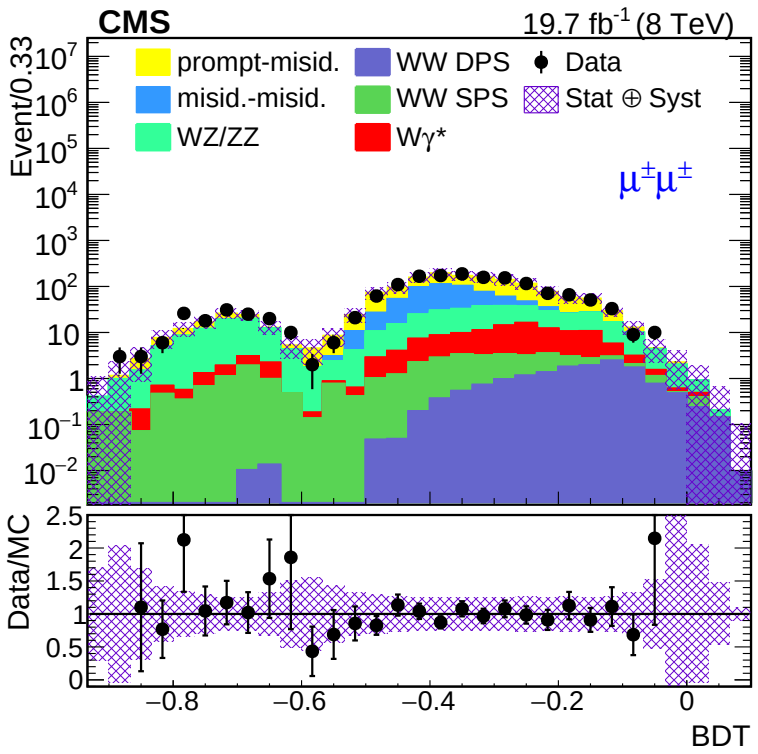
$\mu\mu$ channel

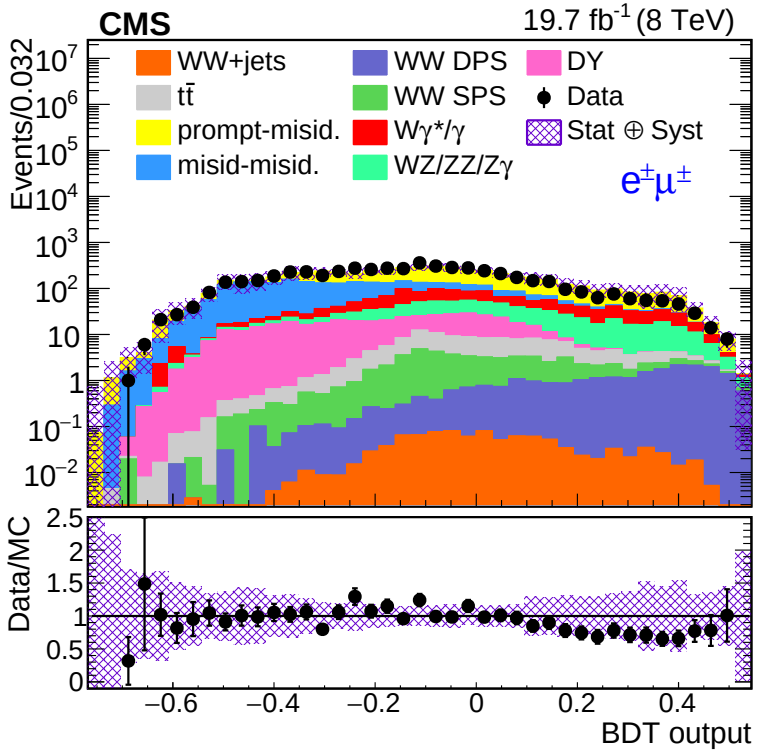


eμ channel



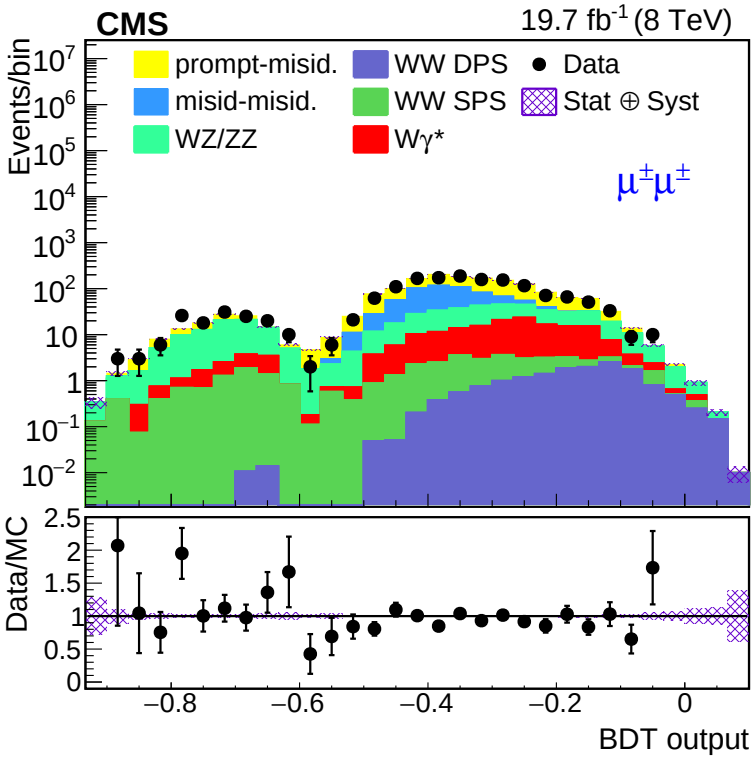
BDT Discriminant

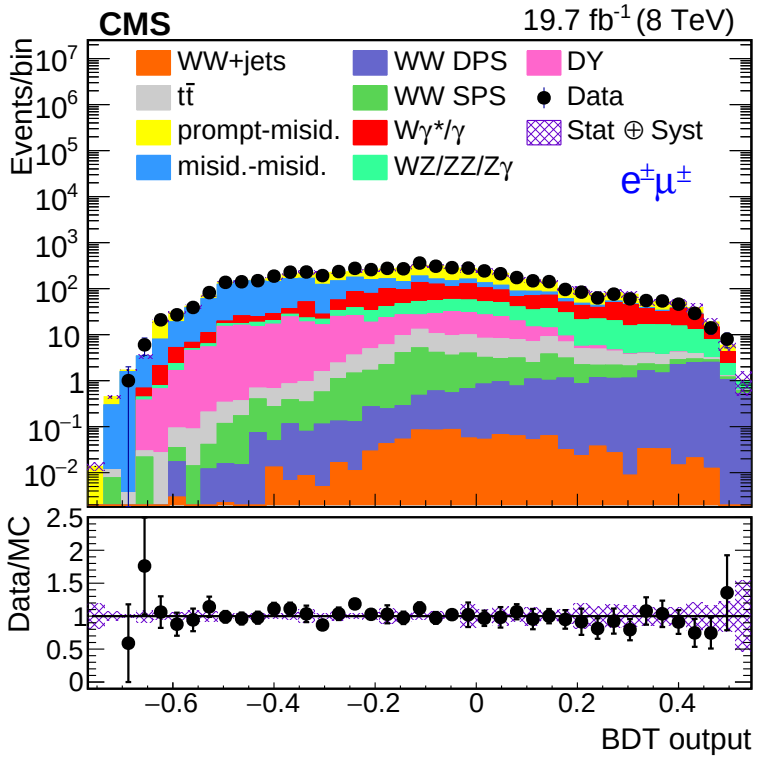




- Shapes of the BDT discriminant from two final states are used to perform the statistical analysis
- A binned maximum likelihood fit is performed simultaneously on two channels
- Systematic uncertainties are properly correlated while performing the combination

Post-fit BDT Distributions

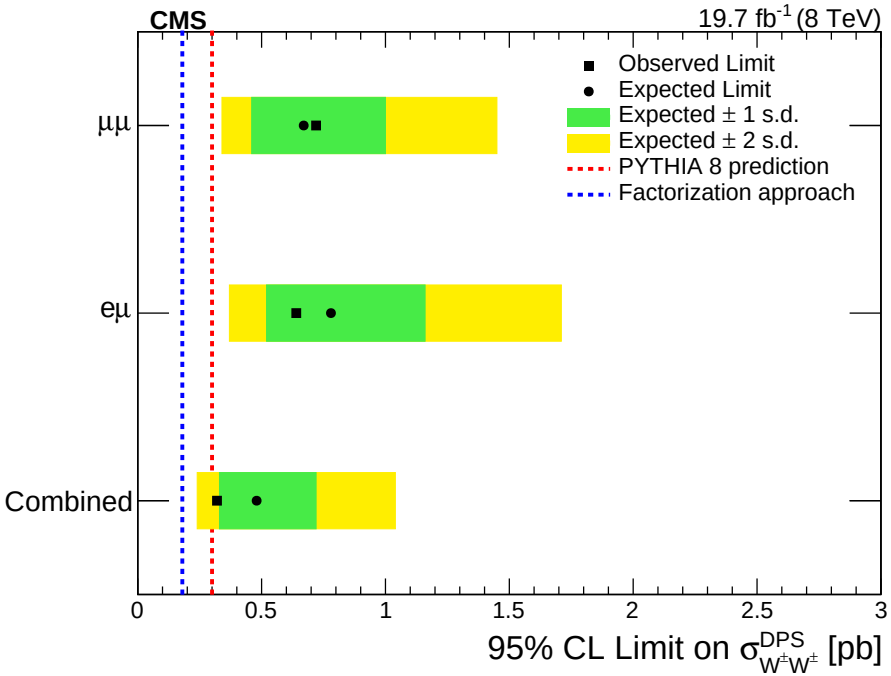


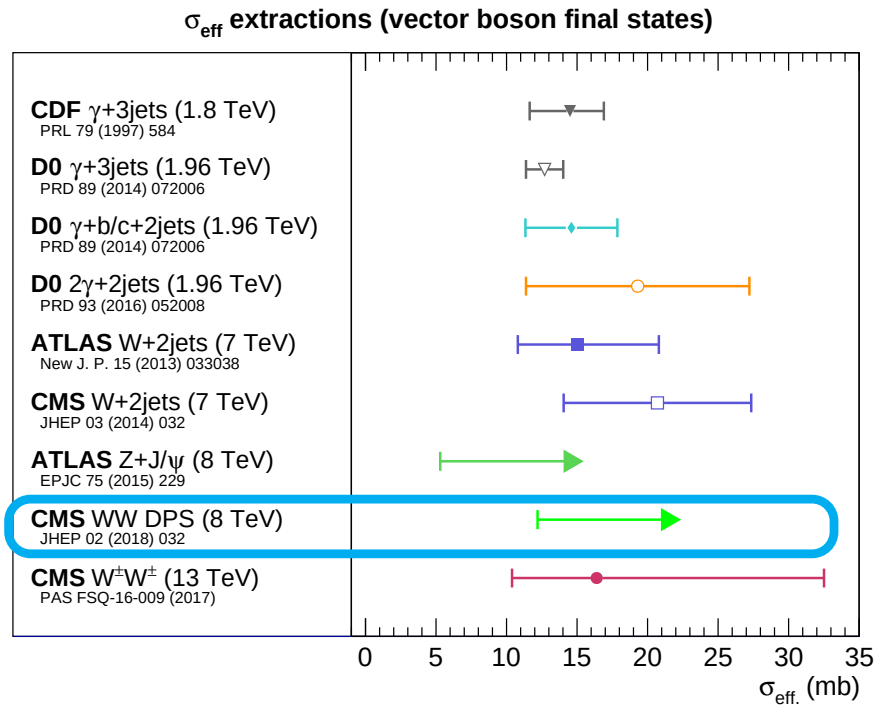


- Systematic uncertainties are considerably constrained by the fit
- No excess is observed over background yields

Results

Limits on $\sigma^{\mathrm{DPS}}_{W^{\pm}W^{\pm}}$ & σ_{eff}





- Combination of two final states → Stringent Limits
- Results consistent with previous measurements & predictions from simulations within uncertainties

DPS Studies using same-sign WW events @ 13 TeV (CDS Record 2257583)

Event Selection

- 2 same-sign leptons ($\mu\mu$ or eμ): $\mathrm{p_T}(l_{1/2}) > 25/20$ GeV
- $p_{\mathrm{T}}^{\mathrm{miss}} > 15$ GeV
- $\mathrm{N_{jets}} < 2$ ($\mathrm{p_T} > 30$ GeV)
- $\mathrm{N_{bjets}} = 0$ ($\mathrm{p_T} > 25$ GeV)
- Veto on additional leptons & τ_{had}

Signal & Background Processes

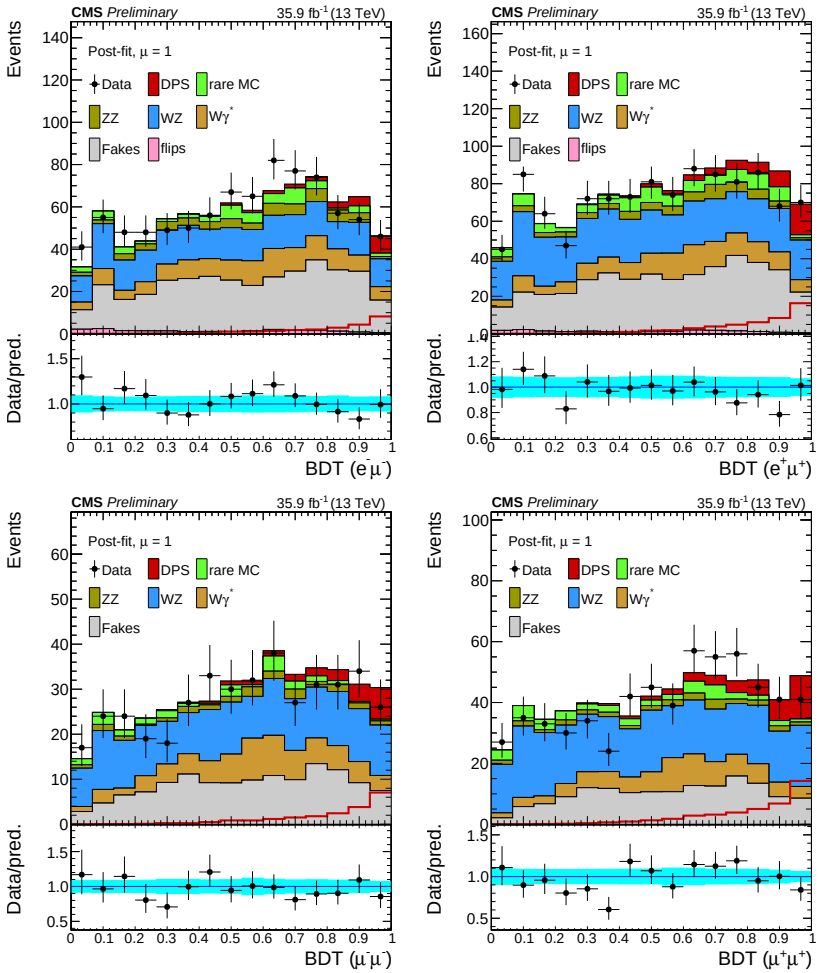
- PYTHIA8 (CUETP8M1 TUNE) Signal sample
- Backgrounds: WZ, Jet induced backgrounds, Diboson, Triboson & $\mathrm{Z} \to \tau\tau$

BDTs trained against the WZ background process using 11 input variables

- $p_{\mathrm{T}} l_{1,2}$, $p_{\mathrm{T}}^{\mathrm{miss}}$, $\eta_1 \times \eta_2$, $|\eta_1 + \eta_2|$
- $\mathrm{M_{T2}^{ll}}$, $\mathrm{m_T(l_1, } p_{\mathrm{T}}^{\mathrm{miss}}\mathrm{)}$, $\mathrm{m_T(l_1, l_2)}$
- $\Delta\phi(l_1, l_2)$, $\Delta\phi(l_2, p_{\mathrm{T}}^{\mathrm{miss}})$, $\Delta\phi(l_1 l_2, l_2)$

Results

- Shapes of BDT $\rightarrow$ Fitted using a likelihood fit for e^+e^+,e^-e^-,$\mu^+\mu^+$,$\mu^-\mu^-$



	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

2σ sensitivity $\rightarrow$ I$^{\text{st}}$ time in WW DPS

Summary

- DPS measurements → Important to understand partonic structure of hadrons & for new physics searches @ LHC
- DPS analysis has been performed using same-sign WW events in dimuon & electron-muon final state at $\sqrt{s} = 8$ TeV
- MVA based on BDTs used to enhance signal sensitivity
- Upper limit of 0.32 pb on $\sigma^{\mathrm{DPS}}_{W^{\pm}W^{\pm}}$ & lower limit of 12.2 mb on σ_{eff}
- Results consistent with previous measurements & predictions from simulations within uncertainties

Future Outlook

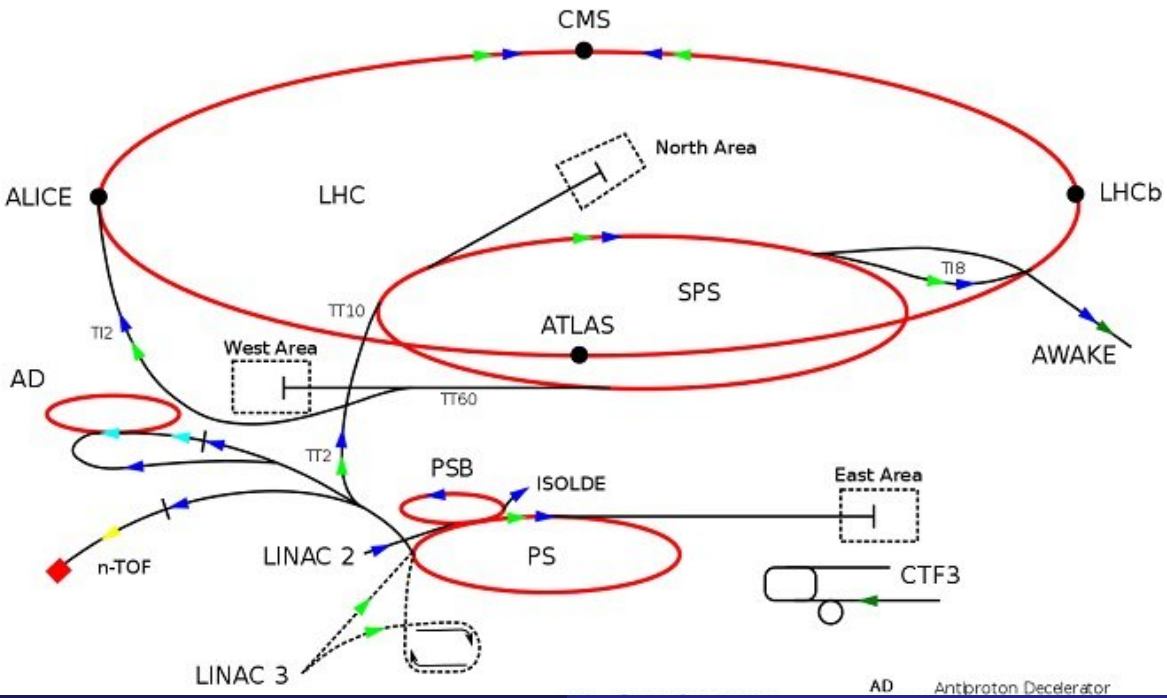
- Same-sign WW final state → Golden channel to look for DPS signal
- 2σ sensitivity observed from 13 TeV analysis → Observed cross section lies in between the MC predictions and the one calculated using the factorization approach
- **With more data @ 13 Tev data → Possible to see DPS signal in same-sign WW events**
- MVA techniques could be used to enhance sensitivity of DPS signals in various final states

thank you!!

Backup

Large Hadron Collider - World's Most Powerful & the Largest Microscope

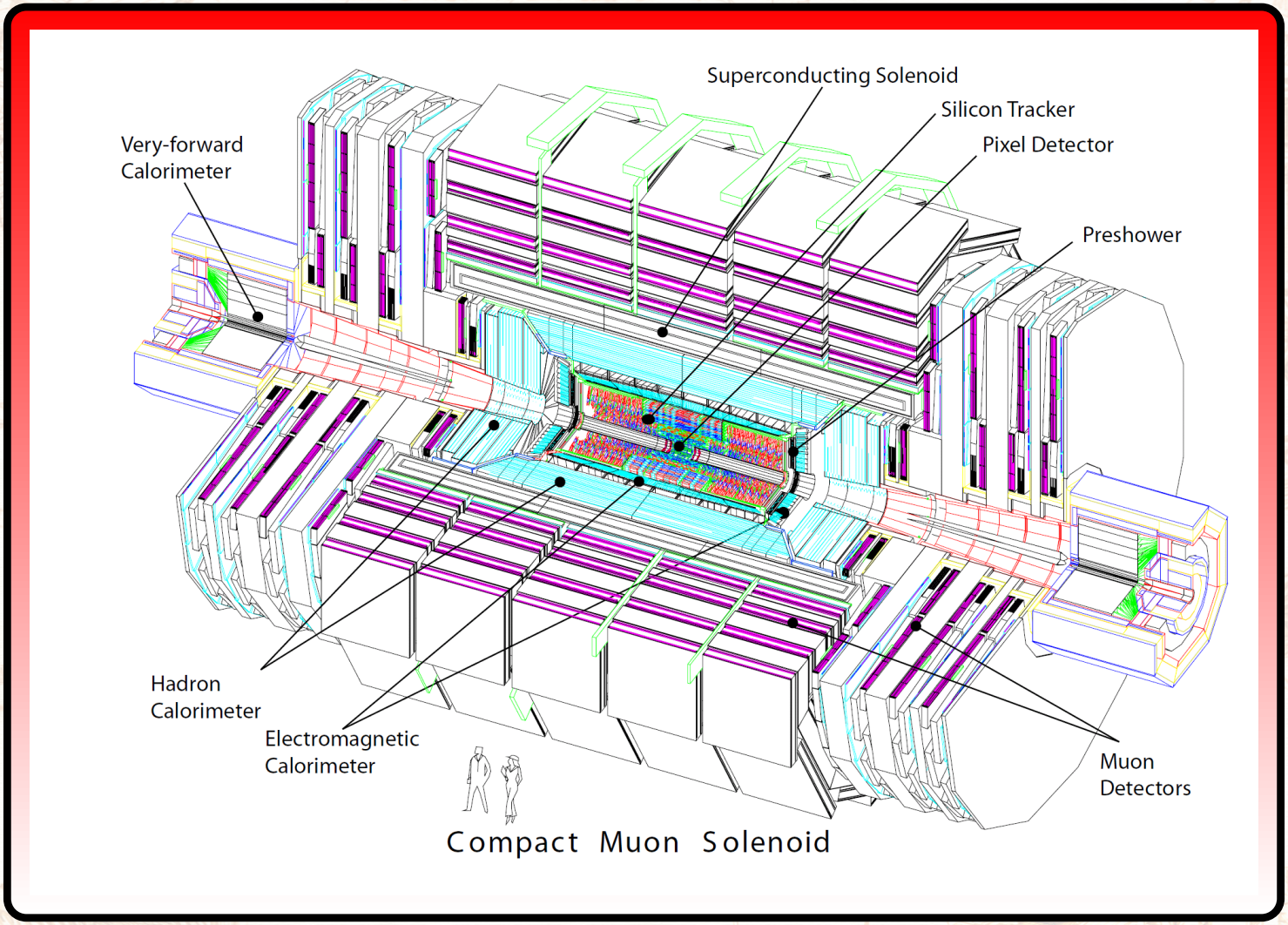
- 27 km ring buried 50-175 m underground near Geneva
- Superconducting accelerator → A variety of magnets to guide & focus particle beams
- High-energy protons traveling in two counter-rotating beams are smashed together to search for signatures of supersymmetry, dark matter, the origins of mass, etc.→ 40 million times per second
- Currently operating at $\sqrt{s} = 13$ TeV with peak luminosity $\sim \mathcal{L} = 2.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



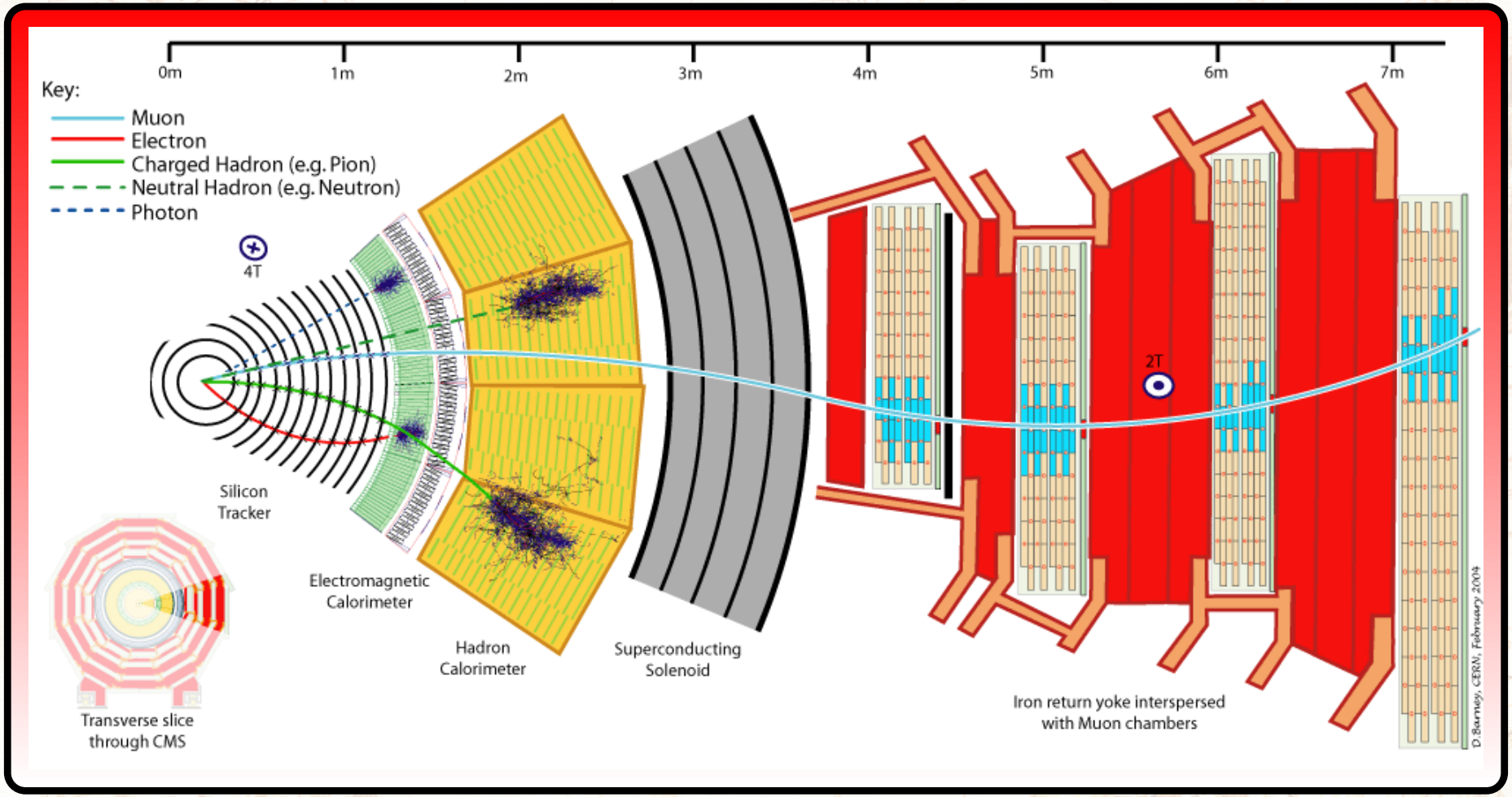
Interaction points

- **ALICE**
- **ATLAS**
- **CMS**
- **LHCb**

Compact Muon Solenoid (CMS) Detector



Compact Muon Solenoid (CMS) Detector



Estimation of Fully Leptonic Top and DY Backgrounds

- Fully leptonic decays of $t\bar{t}$ & DY processes mimic the electron-muon final state when charge of one of the lepton is misreconstructed or hadronically decaying tau lepton is misidentified as a lepton
- Electron charge misidentification probability for electron in data & simulation is compatible $\rightarrow$ Backgrounds could be estimated from simulated samples
- Limited size of the simulated samples $\rightarrow$ Larger statistical fluctuations in final obervables
- Shapes of the kinematic observables for these backgrounds $\rightarrow$ Taken from opposite-sign dilepton events
- Resulting yields of these background processes are then normalized to the corresponding predicted same-sign yields
- Shapes of the kinematic observables for these backgrounds are compared under the same-sign and opposite-sign selection criteria, and are found to be compatible

DDT Method: Loose object Defn

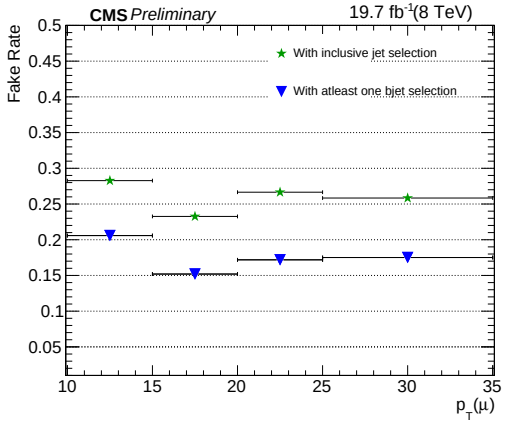
Loose Electron

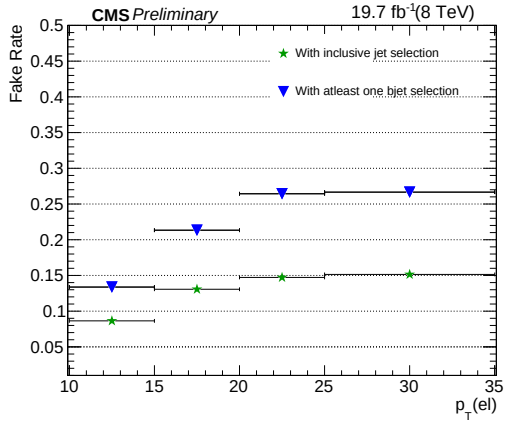
- $p_T > 10$ GeV/c, $|\eta| < 2.5$
- $\sigma_{i\eta i\eta} < 0.01/0.03$ (barrel/endcap)
- $|\Delta\phi_{in}| < 0.15/0.10$, $|\Delta\eta_{in}| < 0.007/0.009$
- $H/E < 0.12/0.10$, $\frac{\Sigma_{ECAL} E_T}{p_T^{el}} < 0.2$
- $\frac{[\Sigma_{HCAL} E_T]-1}{p_T^{el}} < 0.2$, $\frac{\Sigma_{trk} E_T}{p_T^{el}} < 0.2$

Loose Muon

- $|d_0| < 0.02$ cm, Iso < 0.4

Fake ratios from two different control regions

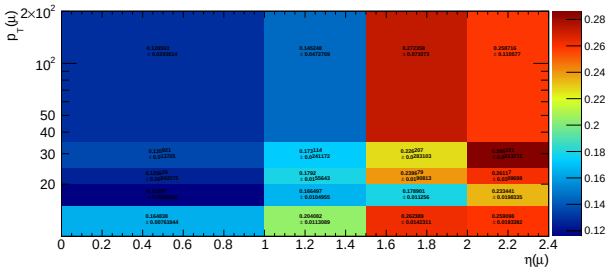


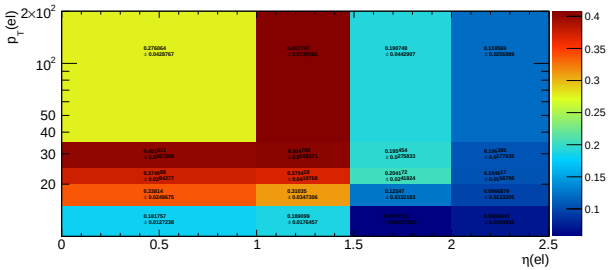


We are dominated by events with FP events (one fake electron and prompt muon, 2000 events out of 2500 total fake prompt events)

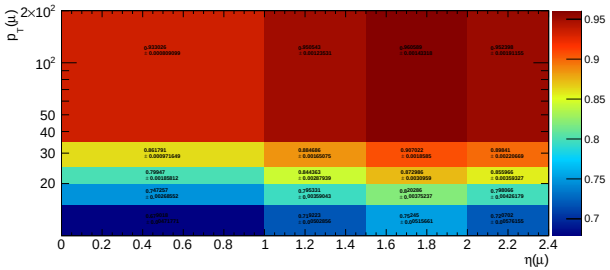
Fake Ratios & Prompt Ratios

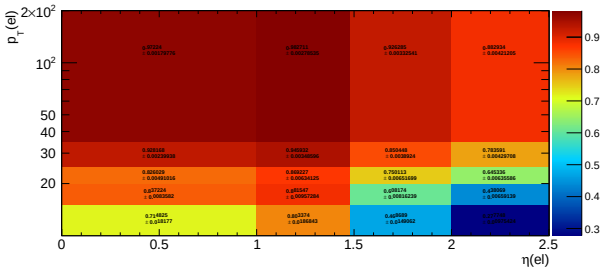
Fake Ratios:





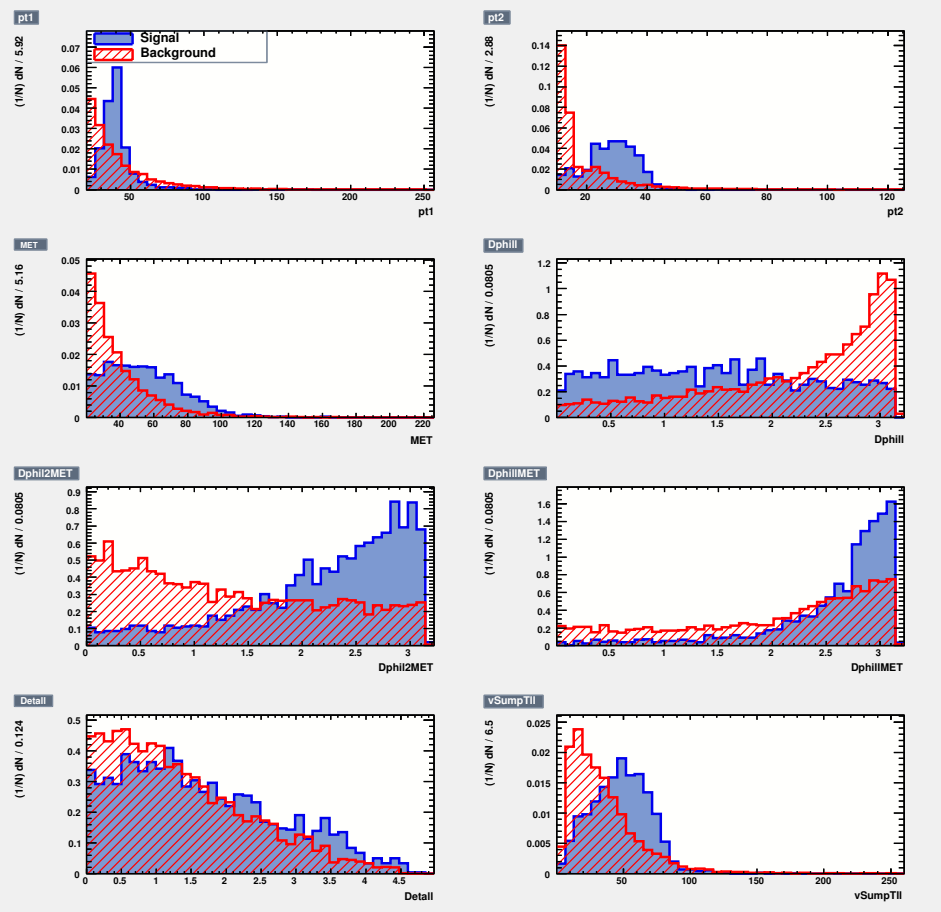
Prompt Ratios:



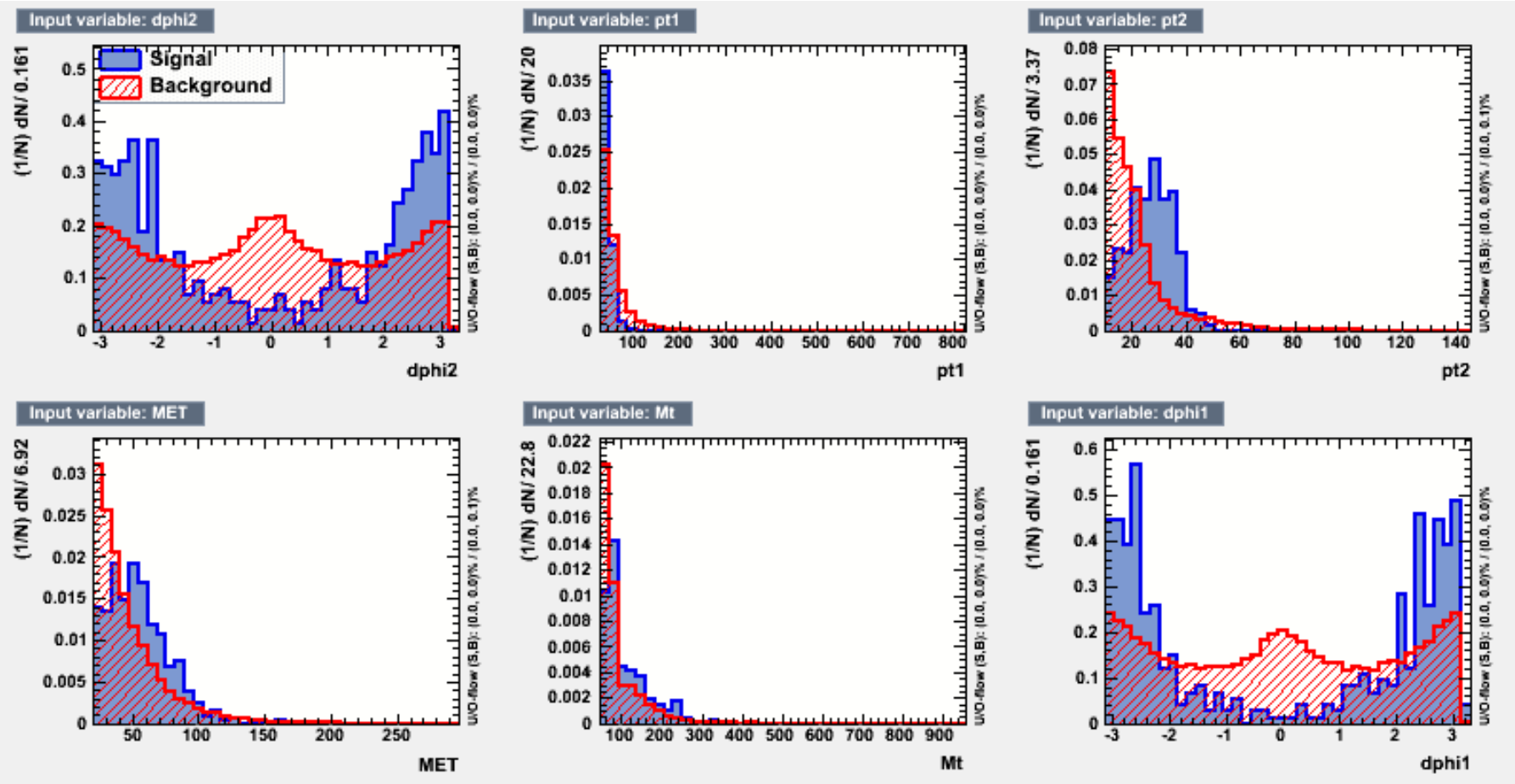


- For electrons fake ratios ∼10–40%; for muons fake ratio ∼10–30%
- For electrons Prompt ratio ∼65–90%; for muons Prompt ratio ∼70-95%

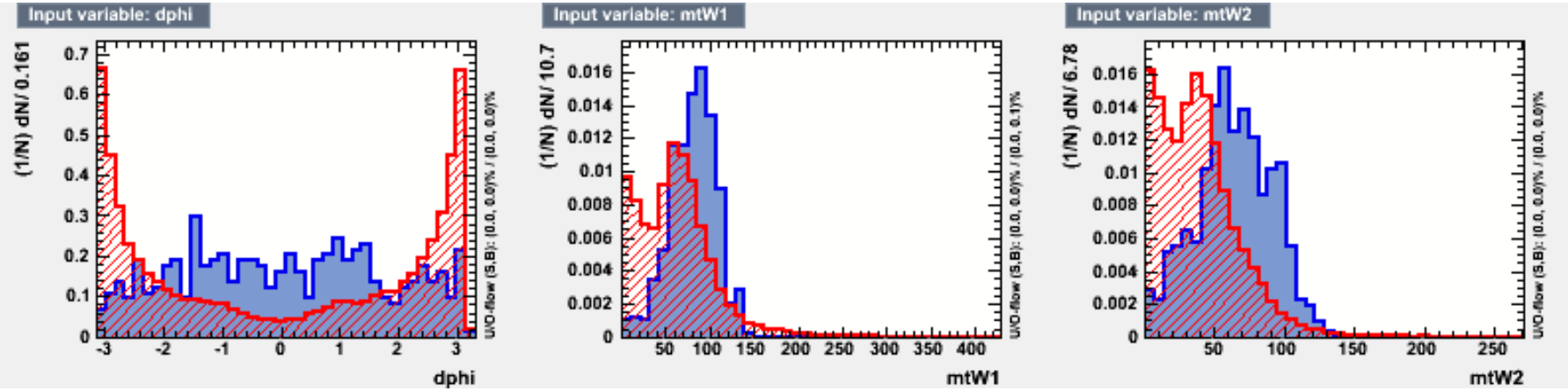
Input Variables (emu) -I



Input Variables (dimu) -I

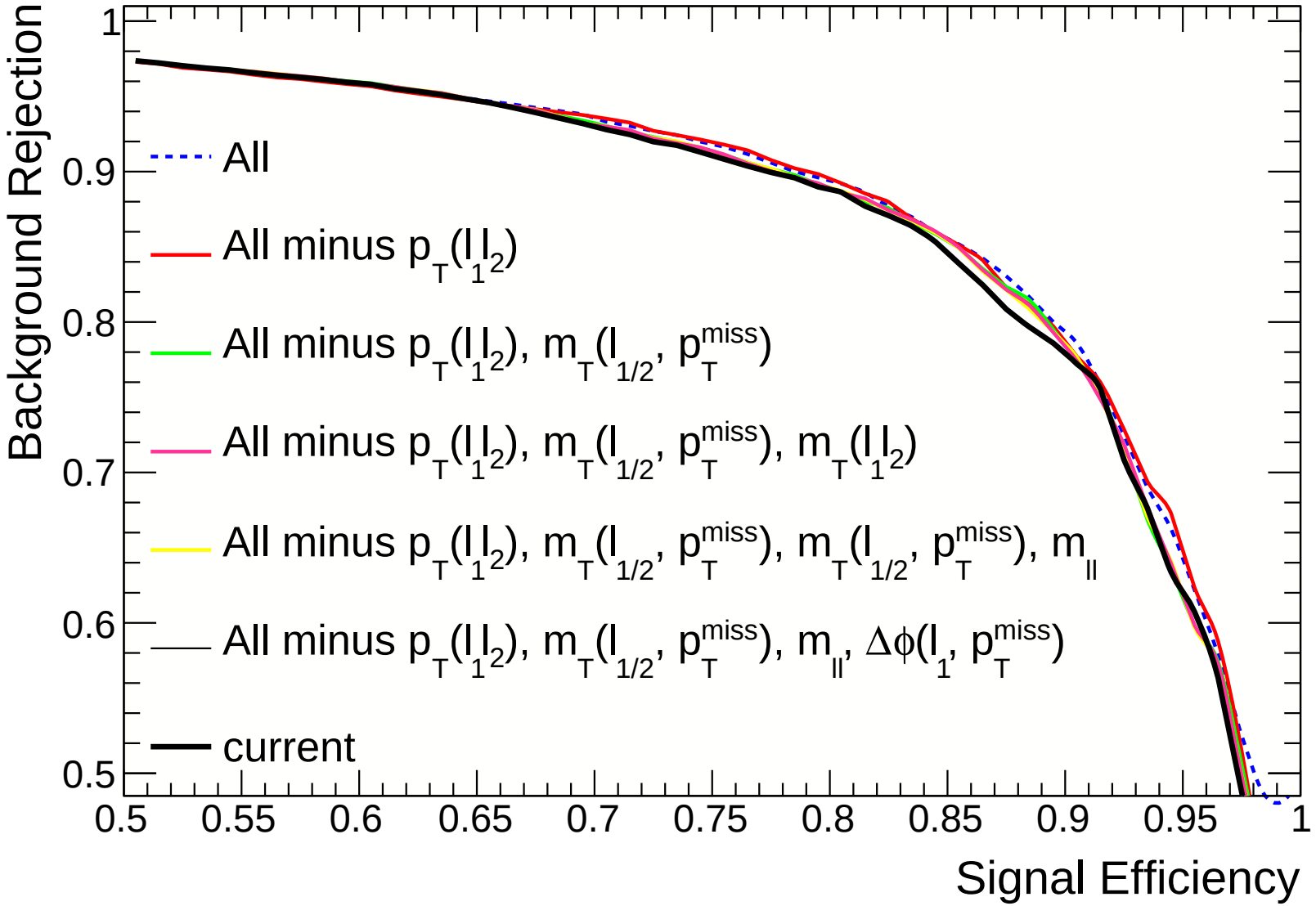


Input Variables (dimu) -II



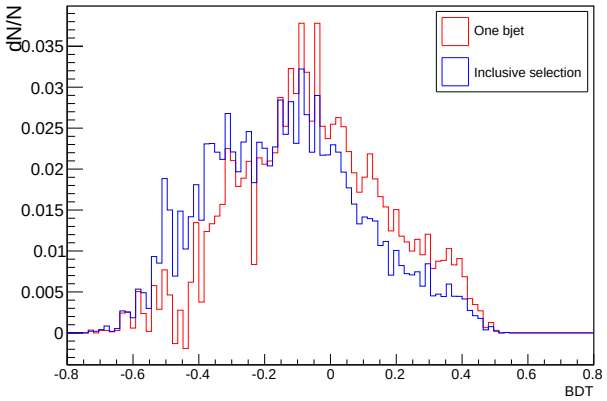
Input variable Optimization

MVA_BDT



Shape Syst on DDT

Prompt-Misid.



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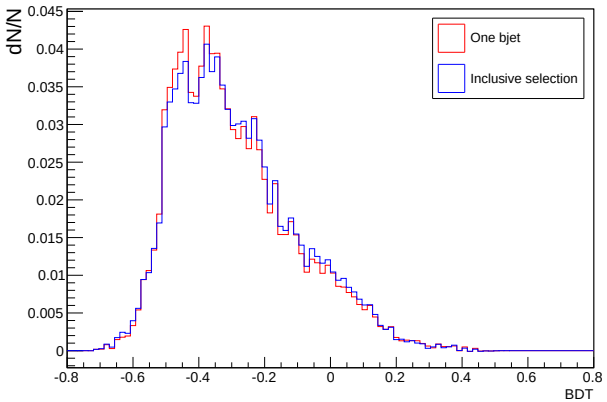
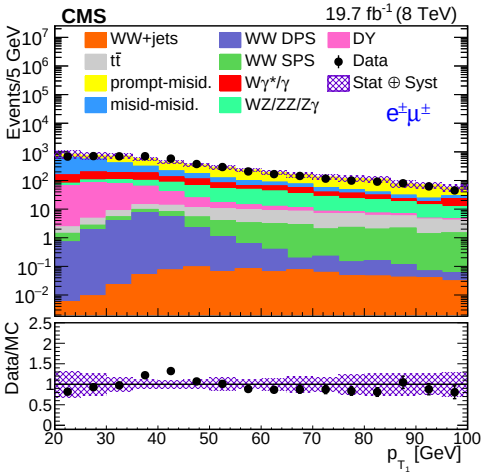
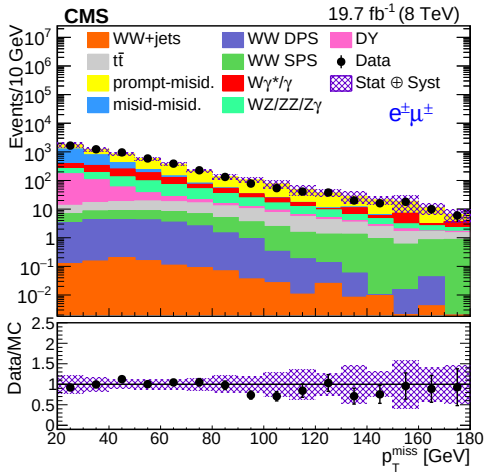
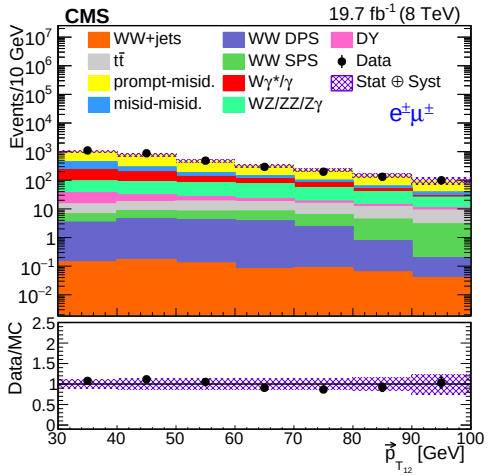


BDT Input Variables-I

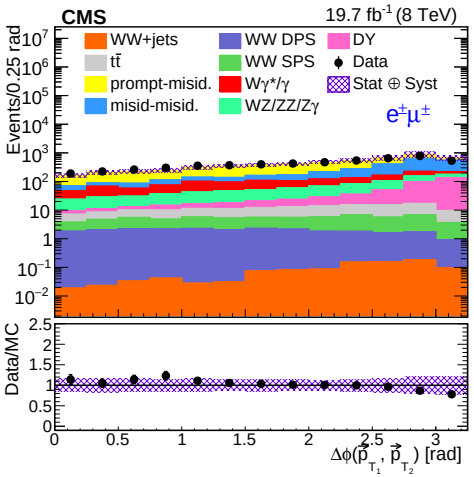


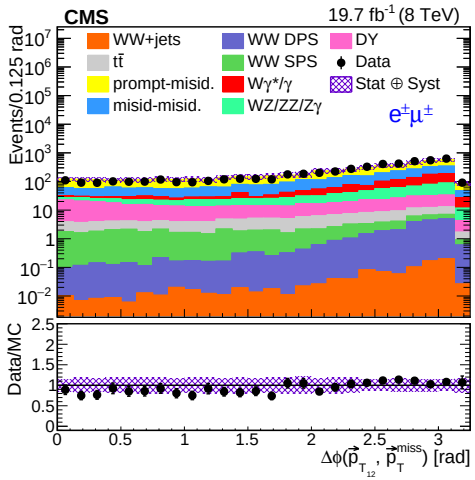


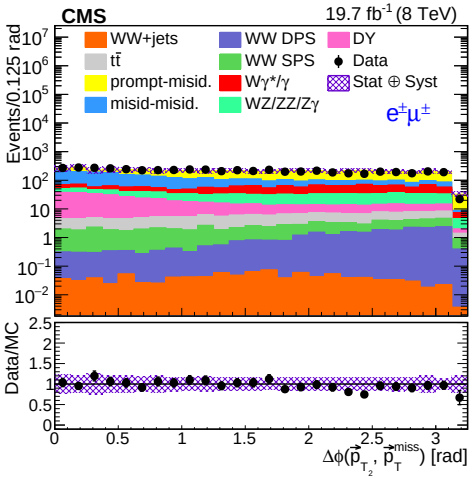


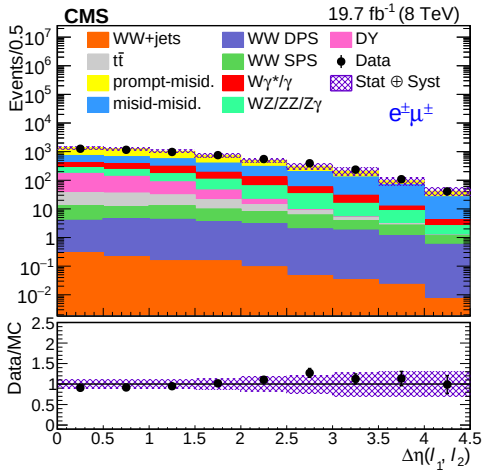
- **Data-MC agreement within uncertainties**
- **Major background contribution from fake-prompt background**

BDT Input Variables-II



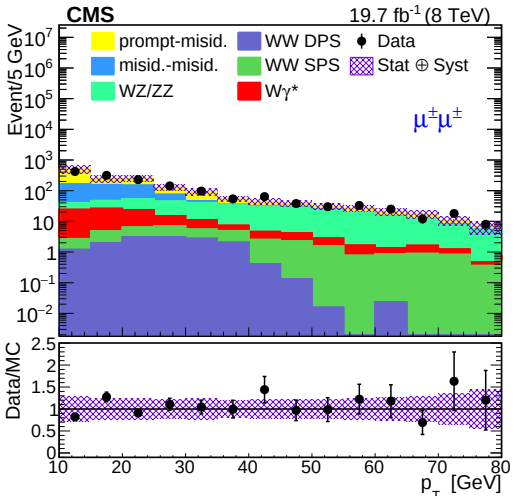


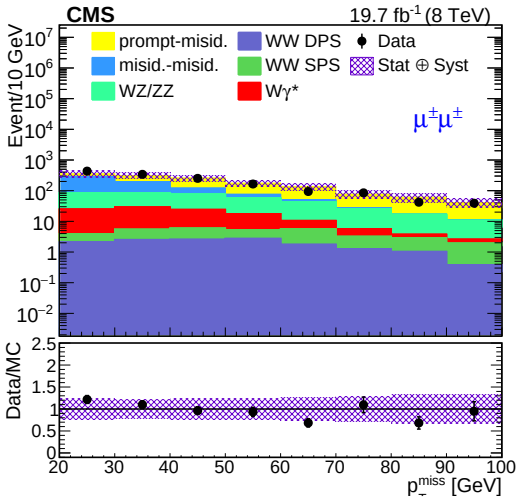


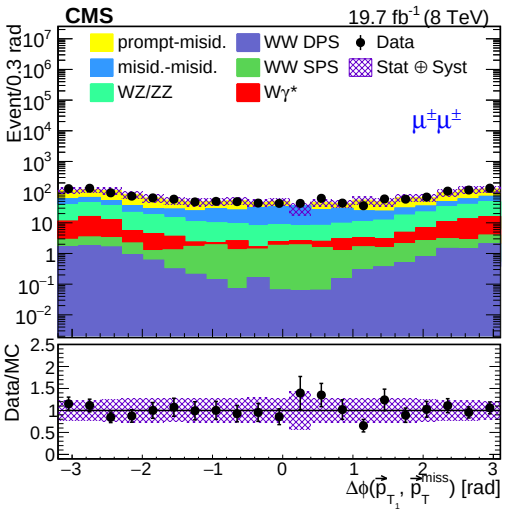


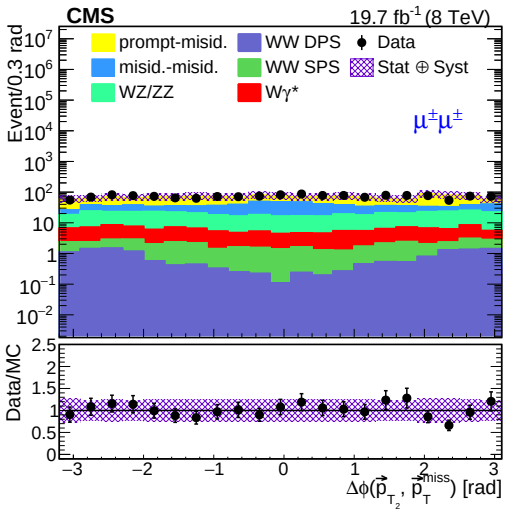
- **Data-MC agreement within uncertainties**
- **Major background contribution from fake-prompt background**

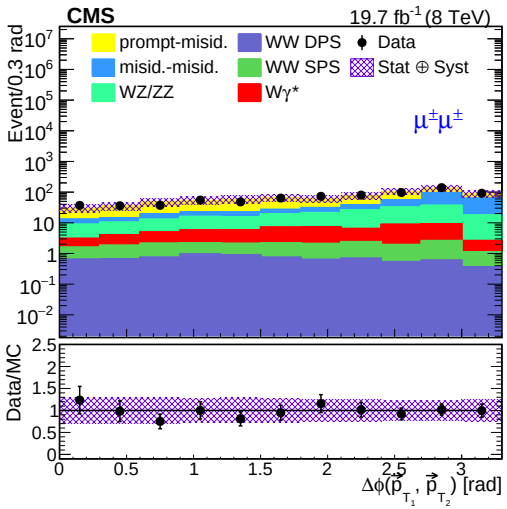
Dimuon Final state: BDT input variables-I





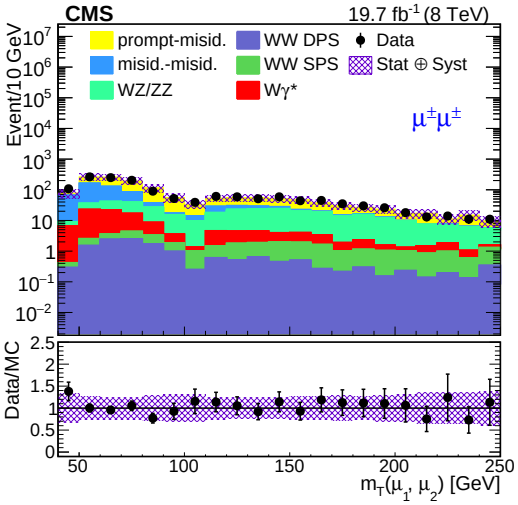


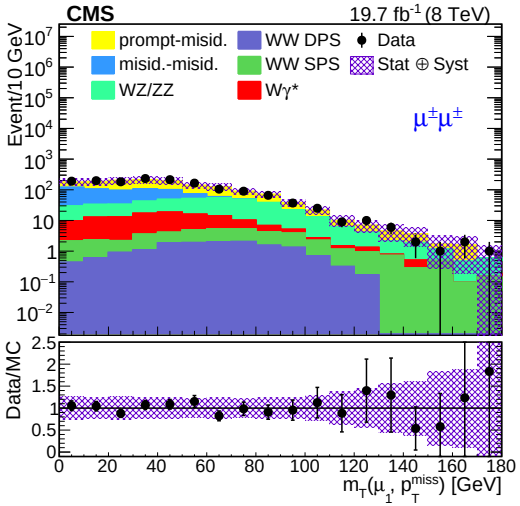


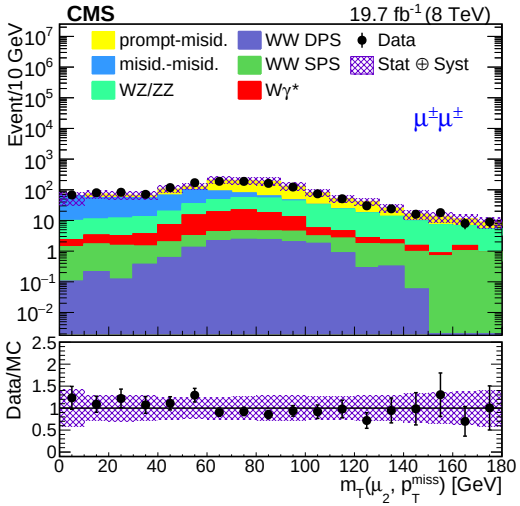


- **Data-MC agreement within uncertainties**
- **Major background contribution from fake-prompt background**

Dimuon Final state: BDT input variables-II







- **Data-MC agreement within uncertainties**
- **Major background contribution from fake-prompt background**