Measurement of underlying events and double parton scattering processes at CMS

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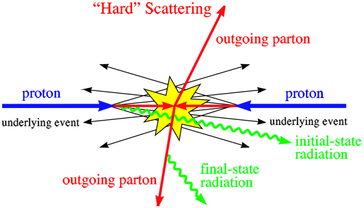
QCD@LHC 2016, Zurich

August 22, 2016

QCD@LHC
22ND–26TH AUGUST 2016
INTERNATIONAL CONFERENCE ZURICH

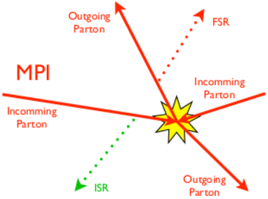
Outline

Hadron-hadron collision: Hard scattering between partons in association with underlying event (UE) activities



UE gets contribution from:

- Beam-Beam Remnants (BBR)
- Multiple Parton Interactions (MPI)
- Soft Initial and final state radiation (ISR & FSR)



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

Why to study UE

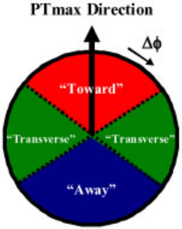
- Important in the study of soft interactions during high luminosity pp collisions
- UE consists of semi-hard and low momentum processes
- UE: Cannot be completely described with pQCD methods
- Any Higgs, SUSY event will contain underlying event
  - **VBF Higgs searches with H $\rightarrow$ WW**
  - No hard jets expected in central region
  - Suppression of QCD radiation in the event: Background Reduction
  - Jet veto efficiency is highly sensitive to the model of UE

  - E_T^{Miss} **+ lepton + Jets: Common signature of BSM searches and top searches**
  - Extra jets can be produced by QCD radiation, MPI, BBR and pileup
- **Experimental study of UE :** Probe to understand interplay of pQCD methods describing the hard processes and phenomenological models of the soft interactions
- **Understanding UE** $\rightarrow$ **Better tuning of MC** $\rightarrow$ **Precise measurements of SM and BSM processes**

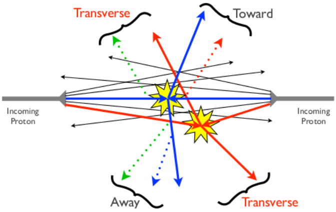
UE Sensitive Observables

Hadronic activity as a function of $\Delta\phi$ between the leading object and any charged track

- $|\Delta\phi| < 60°$: Towards
- $|\Delta\phi| > 120°$: Away
- $60° < |\Delta\phi| < 120°$: Transverse
- Away & towards regions : Dominated by 2-to-2 hard scatter
- Transverse regions : Most sensitive to UE activity



Variables



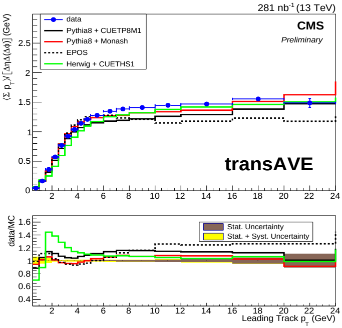
- Average charged particle and $\sum p_T$ density
- TransMAX : density with highest particle/$\sum p_T$ density in transverse region
- TransMIN : density with lowest particle/$\sum p_T$ density in transverse region
- TransDIF : difference of TransMAX and TransMIN
- TransAVE : average density of transverse regions

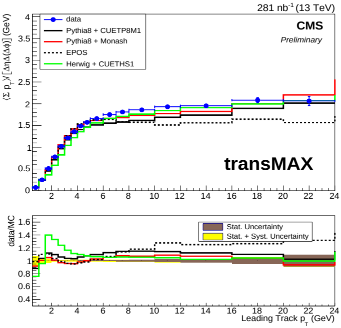
Event selection: 13 TeV UE analysis (CMS-PAS-FSQ-15-007)

- Analyzed Early LHC Run-II Collision data ($\sqrt{s} = 13$ TeV)
- Corresponds to an Integrated Luminosity of 281 nb^{-1}
- Zero-bias, low pile-up data (pile-up = 1.3) triggered using ZeroBias triggers
- Events with exactly one good primary vertex
- High quality tracks ($\sigma_{p_T}/p_T < 0.05$) with $p_T \geqslant 0.5$ GeV/c and $|\eta| < 2.0$
- Cuts on longitudinal and transverse impact parameter significance to remove tracks from secondary decays
- Jets reconstructed with SISCone jet clustering algorithm with cone size of 0.5 built using high purity tracks within $|\eta| < 2.5$
- Jets with $p_T \geqslant 1.0$ GeV/c and $|\eta| < 2.0$
- **Leading track/jet: Highest $p_T \geqslant$ 0.5 ($p_T^{jet} \geqslant$ 1.0) GeV/c and $|\eta| <$ 2.0**
- Compared predictions from different Monte Carlo event generators and tunes with data

Energy density vs Leading Track

- Detector level distributions are corrected to stable particle level using Bayesian unfolding method
- Response matrix constructed using simulated events from PYTHIA8 CUETP8M1 tune
- Corrected distributions are compared with different theory predictions
- Major systematics involve model dependency, pile-up effects, tracking efficiency, impact parameter significance and vertex degree of freedom





- Densities increase sharply with p_T up to 5 GeV and slow rise afterwards
- transDIF : Gives the evolution of radiation with p_T of reference object

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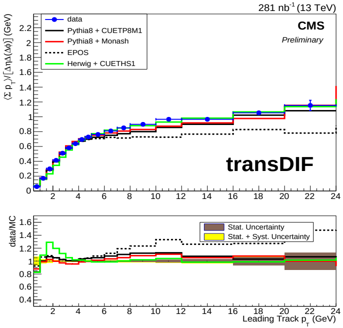

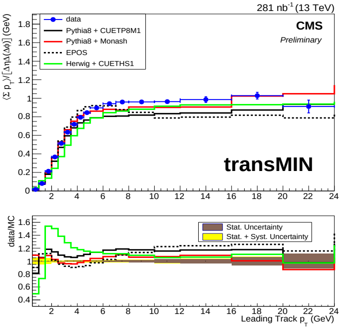

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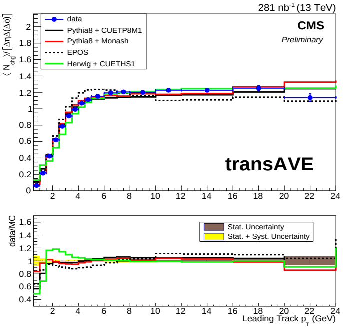
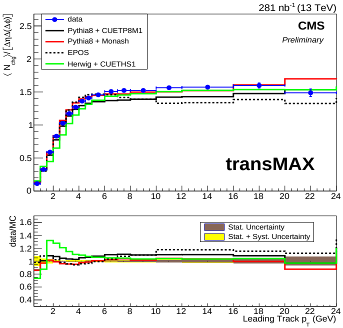
- **Predictions from other simulations deviate from data within 10-30%**





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- transMIN : Captures activity mainly from MPI

- Simulations describe the sharp rise and the flattening of the UE activity nicely
- Systematics uncertainties vary between densities in the different regions with p_T

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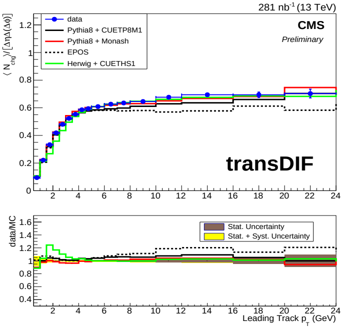

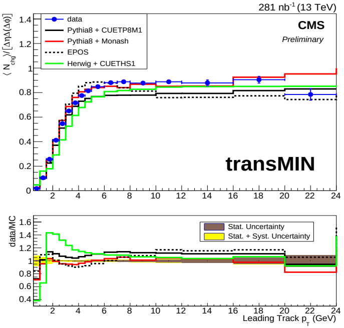

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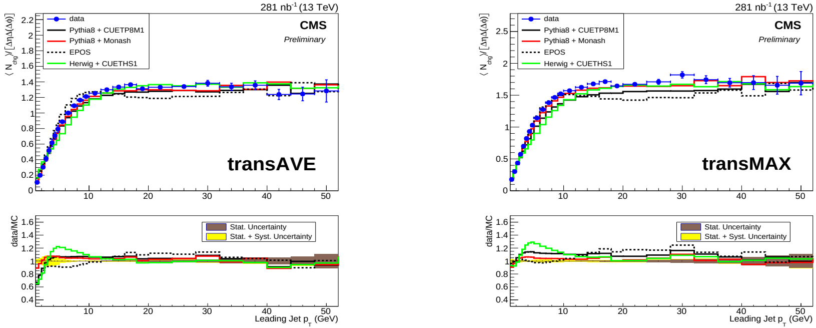
Particle density vs Leading Jet

- Densities increase sharply with p_T^{jet} up to 12-15 GeV and slow rise afterwards
- Sharp rise with p_T is due to an increase in MPI contribution which reaches a plateau in high p_T region



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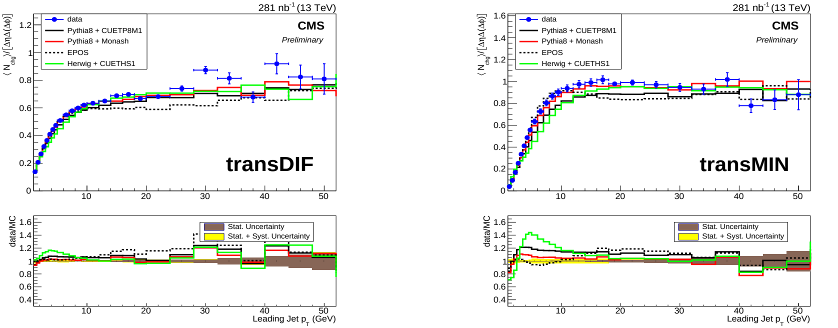

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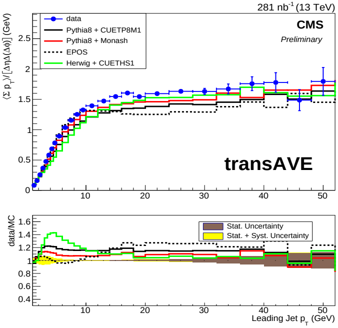

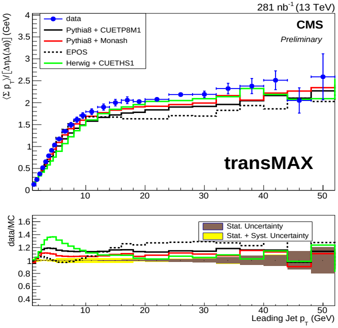

- transMIN densities are flatter as compared to transMAX and transDIF densities
- transMAX and transDIF densities show similar trend in plateau region (larger rise)

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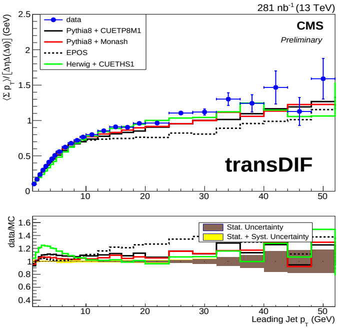

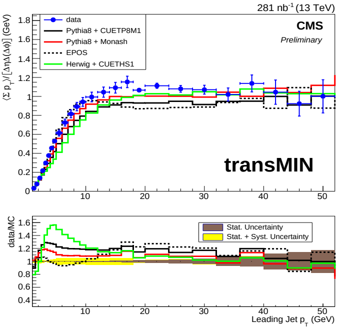

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Cross section for a DPS process can be written as:

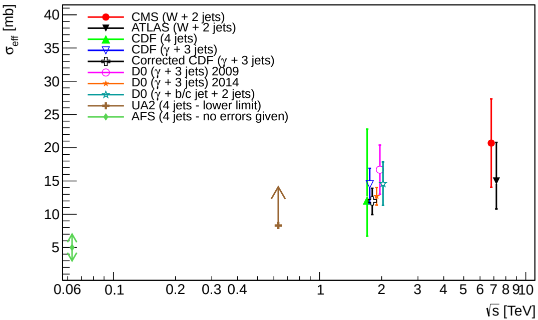
$$\sigma(X+Y) = \frac{m.\sigma(X).\sigma(Y)}{\sigma_{eff}}$$

where $\sigma(X)$ and $\sigma(Y)$ are SPS cross sections for processes X and Y, "m" is the symmetry factor $'m' = \frac{1}{2}$, if processes "X" and "Y" are identical otherwise one.

Measurement of "Effective area parameter for Double Parton Scattering" (σ_{eff}) provides access to information about hadron structure in transverse plane

σ_{eff}

- Measured using processes like 4jets, 2b + 2jets, $W/Z+2-jets, \gamma+3$ jet etc
- Large systematics related to model dependence



Single Parton Scattering (SPS)

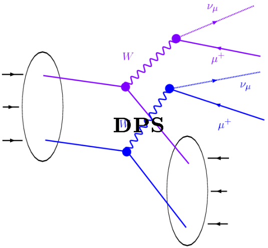
A single pair of partons from colliding hadrons, produce a single hard scattering

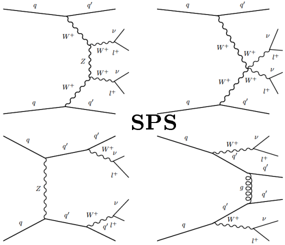
$$pp \rightarrow W^{\pm}W^{\pm}jj + X$$
$$q\bar{q} \rightarrow W^{\pm}W^{\pm}jj \rightarrow l_1 + l_2 + \nu_1 + \nu_2$$

Double Parton Scattering (DPS)

Two independent hard scatterings between two pairs of partons from colliding hadrons

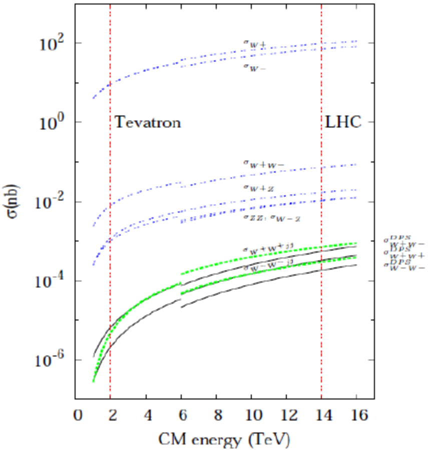
$$pp \rightarrow W^{\pm}W^{\pm} + X$$
$$q\bar{q} \rightarrow W^{\pm} \rightarrow l_1 + \nu_1$$
$$q\bar{q} \rightarrow W^{\pm} \rightarrow l_2 + \nu_2$$





Motivation for Using DPS in Same-Sign WW channel

- W boson production: benchmark process at LHC
- "σ" for same sign WW production is almost same for DPS and SPS processes
- Previous measurements had lower scale of second hard interaction ($\sim$ 40 GeV for W + 2jets, photon + 3jets etc.)
- Current studies involve harder scale for second hard interaction (80 GeV)
- Could be used to check dependency of σ_{eff} on the scale of second hard interaction
- DPS contributes as a background for new Physics searches (SUSY in same-sign lepton final state) and Higgs sector etc.



- Jonathan. R. Gaunt et al. arXiv: 1003.3953v1
- Stirling et al. arXiv: 1003.3953v1

DPS with same-sign WW analysis in dimuon final state: Signal and Background Processes

Signal

- Consists of two same sign leptons with MET produced from decay of W boson pair
- Three final states possible: ee, $e\mu$ or $\mu\mu$
- Analysis focused on $\mu\mu$ in the final state (**charge misidentification : very small** ($\sim 10^{-7}$) **for muons**)

Diboson processes

- Main Processes: WZ, ZZ, Wγ
- Leptons produced from decay of bosons
- One of the leptons escapes detector acceptance

$t\bar{t}$+jets

- Leptons coming from leptonic decay of top in association with jets

QCD and W+Jets

- Originating from jets faking as leptons
- Not described properly by MC simulated samples

SPS

- Two leptons and jets in the final state but originating from single hard scattering

Event selection and Analysis Strategy

Event Selection

- Two same sign muons with leading and sub-leading $\mu(p_T)$ >20 and 10 GeV/c resp.
- MET $>$ 20 GeV, Third muon veto
- Di-lepton invariant mass $>$ 20 GeV/c^2, Z veto
- $|p_T(\mu_1) + p_T(\mu_2)| > 45$ GeV/c

- **Data driven estimate of QCD, W+jets and semi-leptonic decays of top background events**
- Prompt muons: From W or Z decay
- Fake muons: From charged hadrons or semi-leptonic heavy-flavor decays
- **Categories of backgrounds to be estimated: Fake-Fake and Prompt-Fake**

Fakeable Object Method

- Method has been extensively used in Higgs to WW and SUSY searches analyses
- Main idea is to select a control sample of events enriched in the background being estimated
- Extract fake and prompt ratios
- Use an extrapolation factor to relate these events to the background in the signal region

Multi-Variate Analysis (MVA) using Boosted Decision Trees (BDT)

- **Unable to extract signal using cut and count method**
- **MVA based BDT technique has been used to enhance the signal sensitivity**

Training and Testing samples

- **Signal: DPS OS events for training and SS events from MC simulated sample for testing**
- **Background: Three major backgrounds (Fake-Fake, Fake-Prompt and WZ**

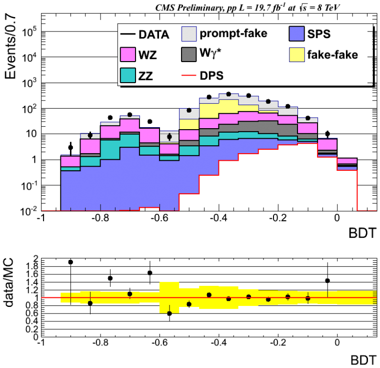
Input Variables

- $\mu_1(p_T)$, $\mu_2(p_T)$
- E_T^{Miss}
- $M_T(\mu_1, \mu_2)$
- $\Delta\phi(\mu_1,\mu_2)$
- $\Delta\phi(\mu_1,E_T^{Miss})$
- $\Delta\phi(\mu_2,E_T^{Miss})$
- $\Delta\phi(\mu_1\mu_2,E_T^{Miss})$
- $M_T(W_{1/2})$

Systematics, Event yields and BDT observable

Source (Effect on Event Yields %)	DPS	SPS	WZ	ZZ	$W\gamma^*$	Fake-Fake	Prompt-Fake
Luminosity	2.5	2.5	2.5	2.5	2.5		
Pile-up	0.5	0.3	0.5	0.1	0.7		
Trigger & Muon id	0.1	0.1	0.1	0.1	0.1		
MET	0.8	1.4	0.4	4.0	2.2		
Fake-Fake normalization						60	
Prompt-Fake normalization							30
MC normalization	4.0	10.0	10.0	4.0	10.0		

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



Limit on DPS Cross section and Effective cross section

- Expected and observed upper limits on the ratio of measured DPS yield w.r.t the yield expected from MC (signal strength, r) at 95% C.L. have been extracted
- CLs method based on the **modified frequentist** approach is used
- Shape of the BDT variable is used to extract the limit
- All systematics have been added in the datacards used for limit extraction

	95 % CLs
BDT : **CMS-PAS-FSQ-13-001**	
Expected	$r < 2.0$
Expected$\pm1\sigma$	[1.4,2.8]
Expected$\pm2\sigma$	[1.1,3.7]
Observed	$r < 1.9$

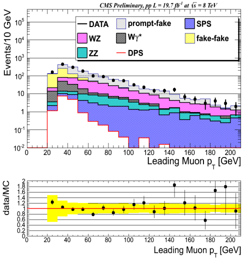
- **Signal strength (ratio of observed to expected signal events), $r < 1.9$**
- **Observed value of r, corresponds to $\sigma_{DPS} < 1.12$ pb**.
- Considering the two scatterings to be independent and no correlation between interacting partons, σ_{DPS} can be used to put a limit on σ_{eff}
- **Limit on σ_{DPS} gives $\sigma_{eff} > 5.91$ mb**

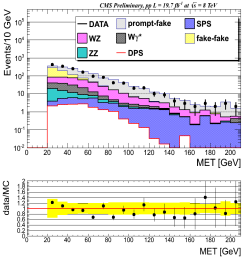
Conclusions

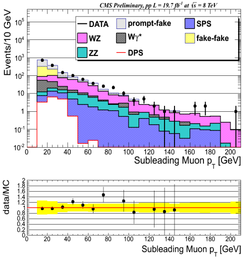
- Rich forward physics programme in CMS
- Measurement of UE activity has been done at $\sqrt{s} = 0.9$, 2.76, 7 and 13 TeV using CMS data
- Results are presented in terms of energy ad particle densities as a function of leading track/jet, fully corrected for detector effects and selection efficiencies
- Measurements are reasonably well described by recent tunes derived from UE activities in fully hadronic final states
- Study of DPS processes has been performed using same sign WW events in dimuon final state
- Shape of the BDT observable is used to set an upper limit on DPS cross section, $\sigma_{WW}^{DPS} < 1.12$ pb at 95 % of confidence level
- Limit on σ_{WW}^{DPS} has been translated to a limit on σ_{eff} using the factorization formula
- $\sigma_{eff} >$ **5.91 mb**

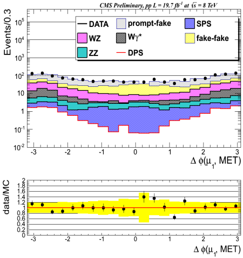
Kinematic Distributions-I

- Nice data-MC agreement observed









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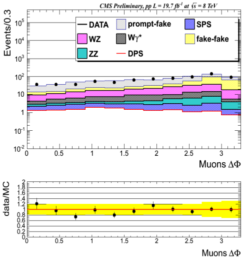
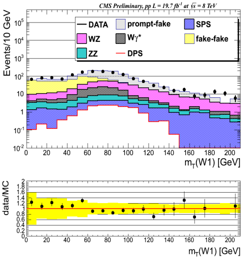
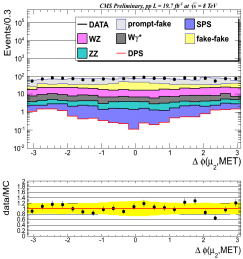
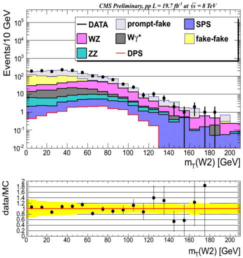








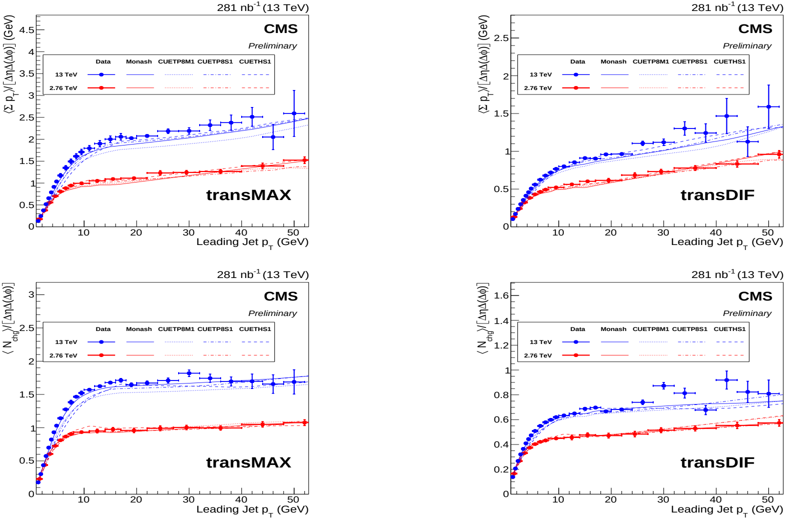
Muon id

Tight muon id

- Normalized $\chi^2 > 10$
- Particle-Flow muon id and Global Muon
- Number of pixel hits > 0
- Muon segments in at least two muon stations
- At least one muon chamber hit included in the global-muon track fit
- $d_{xy} < 2$ mm and $d_z < 5$ mm
- Cut on number of tracker layers with hits > 5

Energy dependence-I

- PYTHIA8 (Monash, CUETP8M1, CUETP8S1), HERWIG++ (CUETHS1) Monash predicts a better centre-of-mass energy dependence



Energy dependence-II

- PYTHIA8 (Monash, CUETP8M1, CUETP8S1), HERWIG++ (CUETHS1) Monash predicts a better centre-of-mass energy dependence