

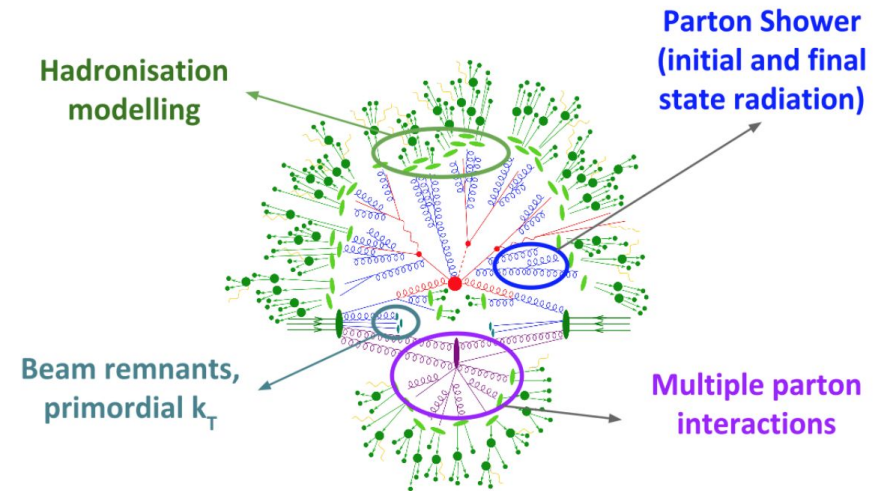
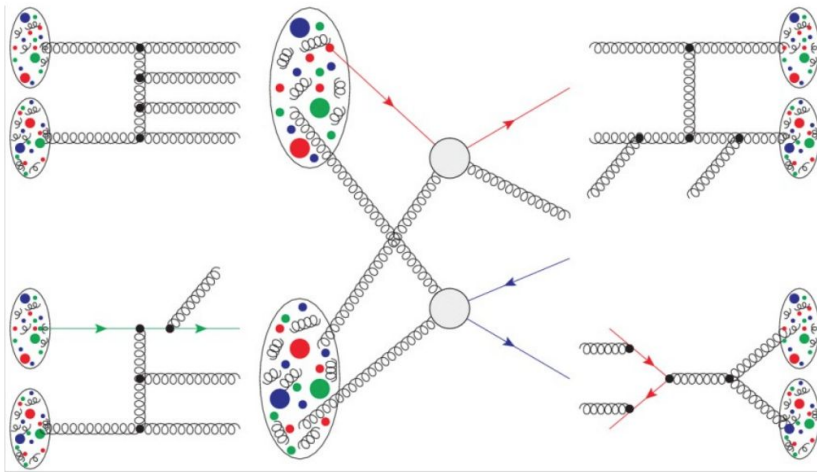
Overview of MPI measurements at LHC

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Panjab University, Chandigarh

PHANC25, 27-30 March 2025
Puri, Odisha

Disclaimer: The presentation includes a (limited) set of personally chosen LHC measurements.

Multiple Parton Interactions



- Mostly produce low Q^2 interactions.
 - Measured collectively with radiations and BBR contribution known as **Underlying Event (UE)**
- Possibility of the production of high Q^2 processes such dijet, Charmonium, $V + \text{jets}$, WW .
 - **Need correlation observables**

Outline

- ❑ Measurement of UE
- ❑ Measurement of hard MPI; **DPS/ TPS**
- ❑ Tuning of MPI models

Underlying Event

- Hadron sub-structure.
- Vertex identification in processes involving neutral particles in final states i.e. $H \rightarrow \gamma\gamma$
- Effect experimental observables such as isolation of leptons and photon, jet energy scale.
- Need proper modeling of UE in Monte-Carlo event generators.

UE dynamics to explore

- Variation with scale of the hard interaction.
- Evolution with collision energy.
- Dependence on the process involved in the hard interaction

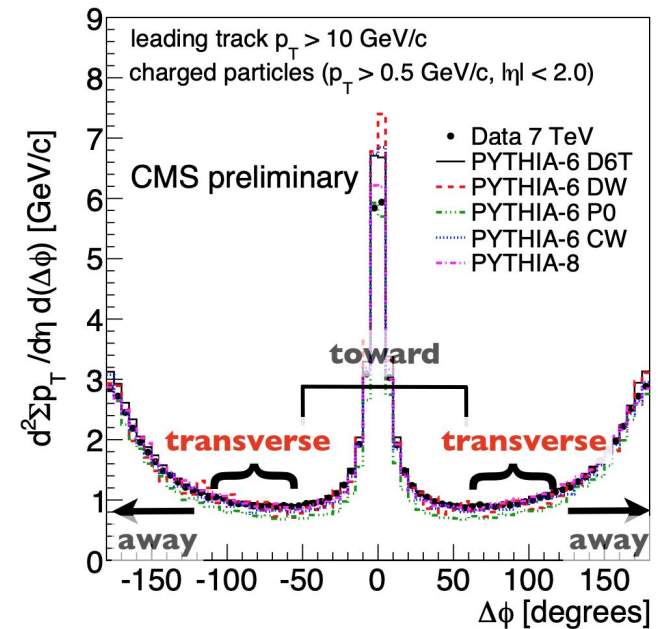
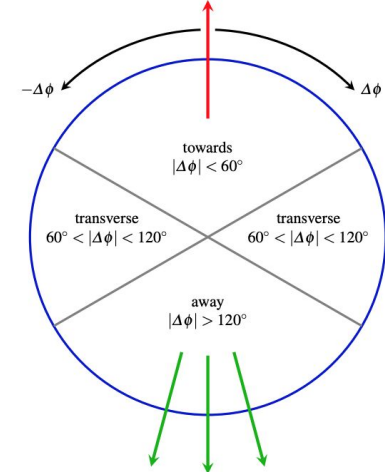
Need range of UE measurements for proper understanding and subsequent modeling.

Underlying Event

Conventional approach;

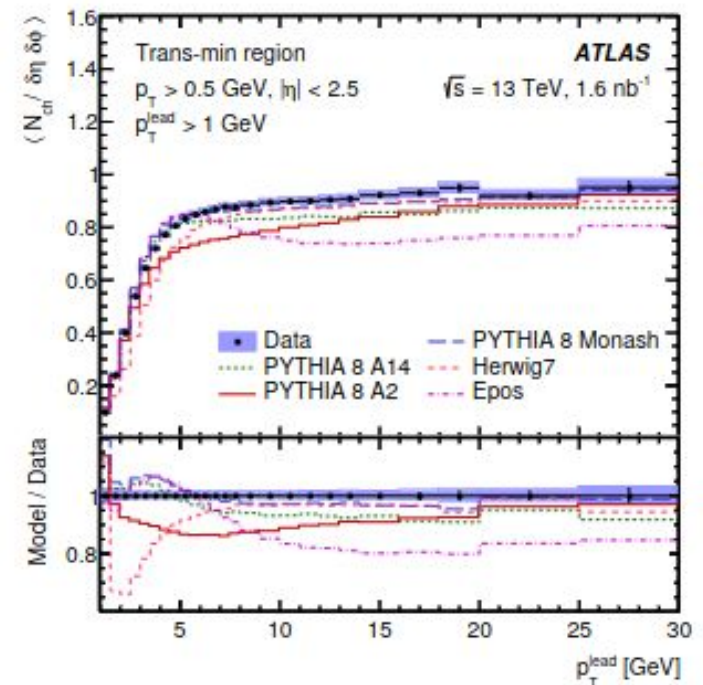
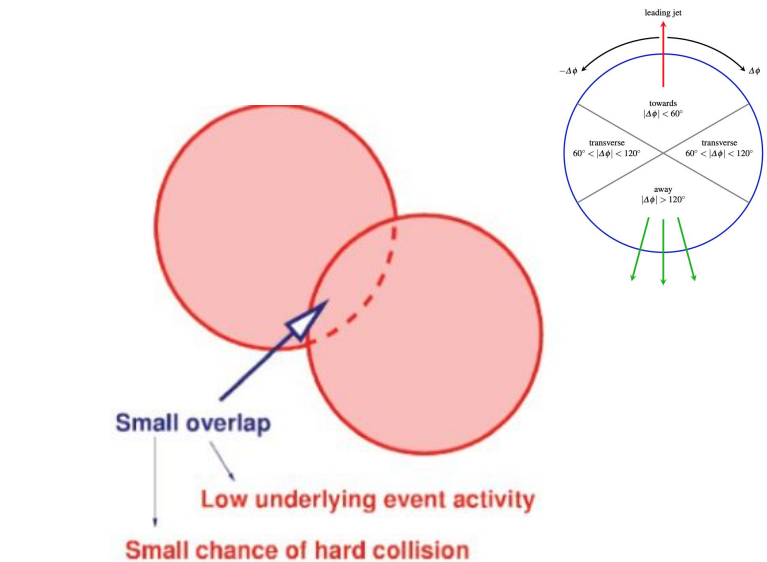
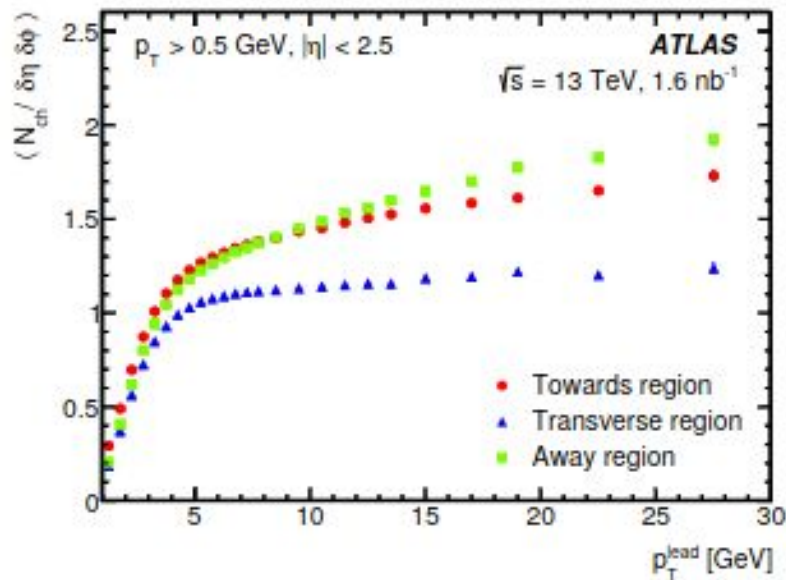
- Identify the hard interaction using an experimentally well defined object i.e. leading track, jet, Drell-Yan, (anti)top-pair
- Investigate particle, charged, activities in different phase-space in the transverse plane.
- Observables;
 $N_{\text{chg}}/\Delta\eta\Delta\phi$, $\Sigma p_T/\Delta\eta\Delta\phi$
 - As a function of p_T of the leading object (defining scale of the interaction)

Leading track/jet/ Drell-Yan/ top pair



UE with leading track/jet

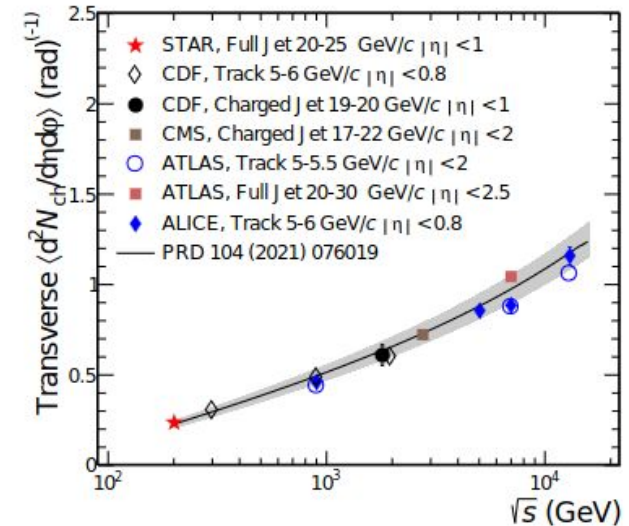
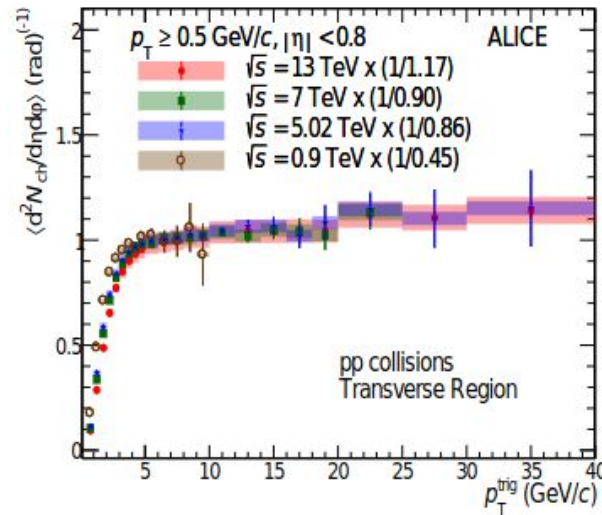
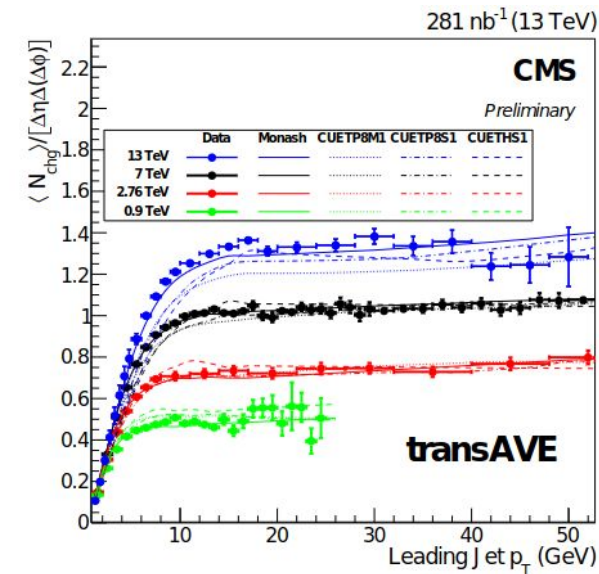
- Faster rise in towards and away region as compared to transverse region.
- Rate of increase changes about 4-5 GeV; production mechanism changes from **MPI** $\rightarrow$ **radiation**
- Can be explained on the basis of overlap model
- Latest tunes such as A14, Monash provides good description of the data



[JHEP03\(2017\)157](#)

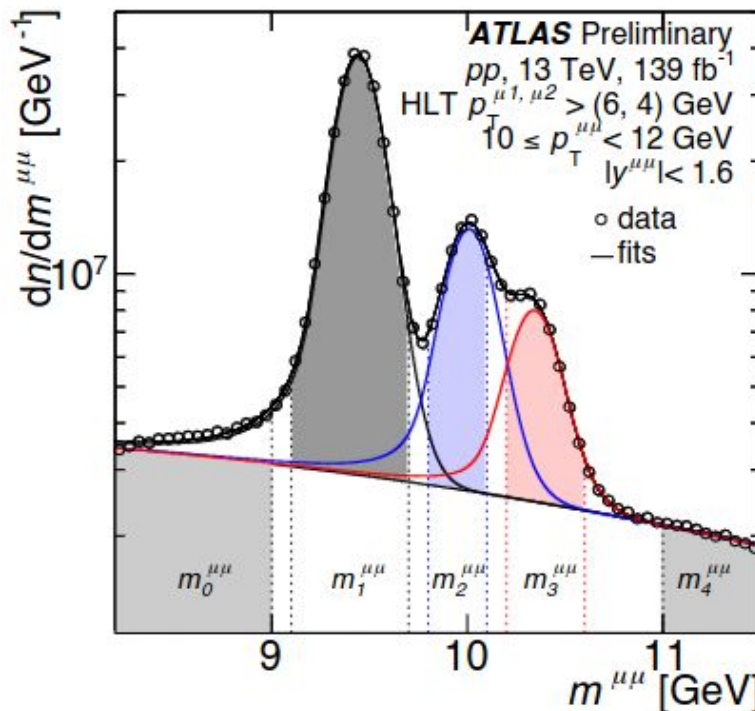
UE with leading track/jet

- An increase of ~ 4 times in particles production as collision energy increases from 0.9 to 13 TeV.
- With collision energy there is minimal effect on the scale dependence and radiation contributions.
- Monash tune doing good job in reproducing collision energy dependence.
- Energy evolution is nicely described by power-law (MPI) + log (radiations)

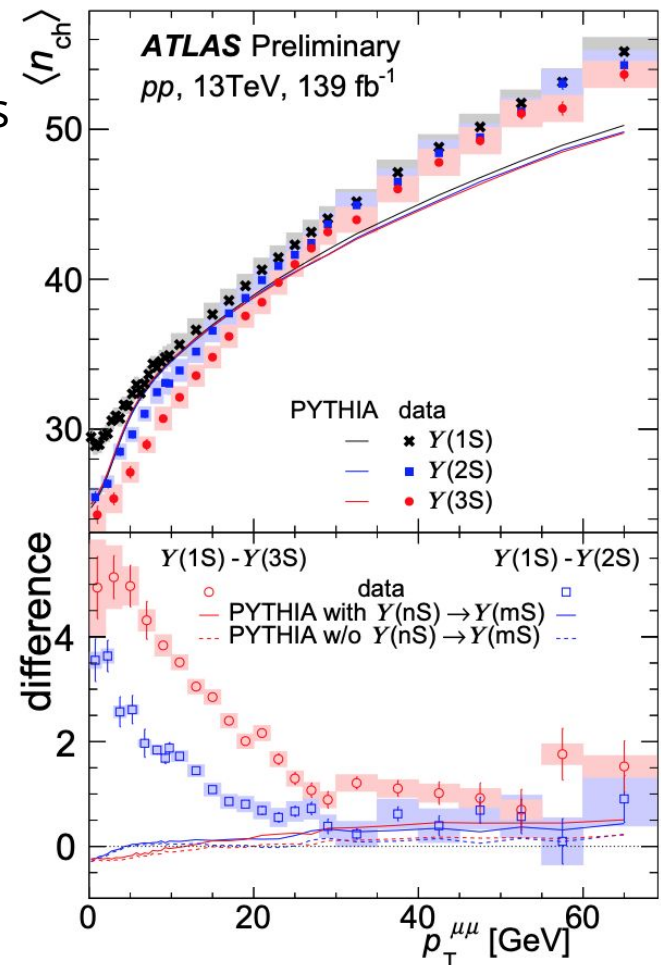


UE with Y (nS)

- Look for modification of underlying event for different Y states; **measure** $\langle n_{ch} \rangle$
- Significant differences observed for different Y states
- The effect is larger at low $p_T^{\mu\mu}$
- Unlike the data, the Pythia 8 prediction shows very similar particle multiplicity



<https://cds.cern.ch/record/2806464>



UE with Drell-Yan

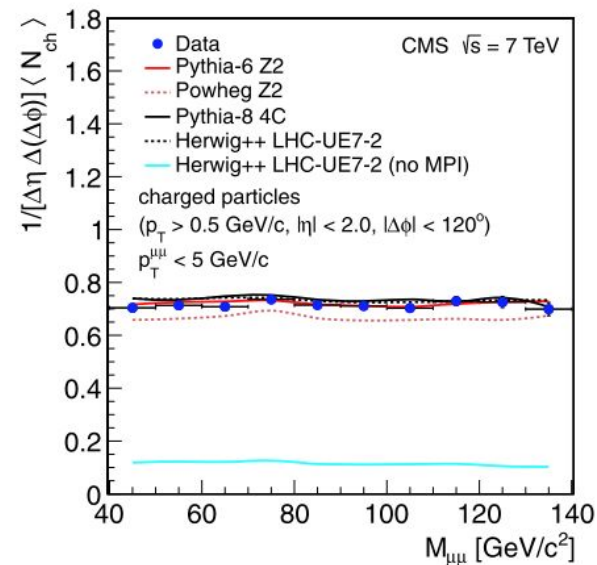
[Eur. Phys. J. C 72, 2080 \(2012\)](#)

[JHEP07\(2018\)032](#)

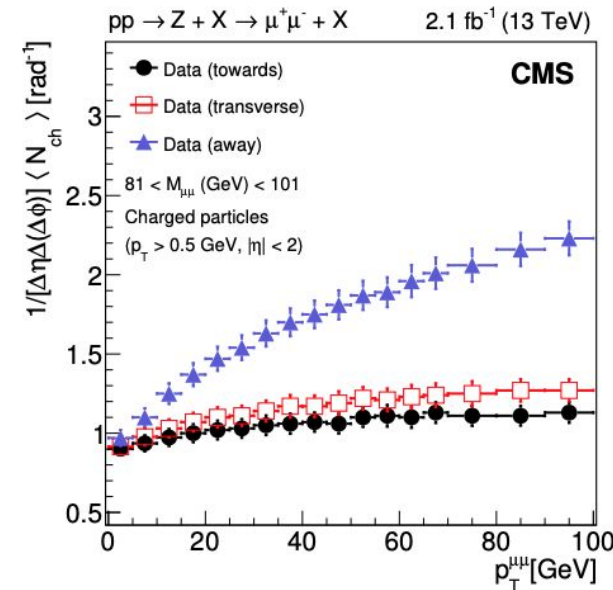
[Eur. Phys. J. C 79, 666 \(2019\)](#)

- Theoretically understood and experimentally clean process.
- No final state radiation.
- Possibility of partial separation of MPI from radiations:

- Unlike leading jet/track, UE do not start from 0: initial scale is set by invariant mass.
- Activity sharply increases with p_T in away region: recoiled hadronic activity.
- Transverse and towards regions sensitive to MPI.
- $p_T \rightarrow 0$, all regions have same activity.



- With $p_T < 5$ GeV, particle production is flat as a function of $M_{\mu\mu}$
- ~80% contribution of MPI.
- Corroborates MPI universality



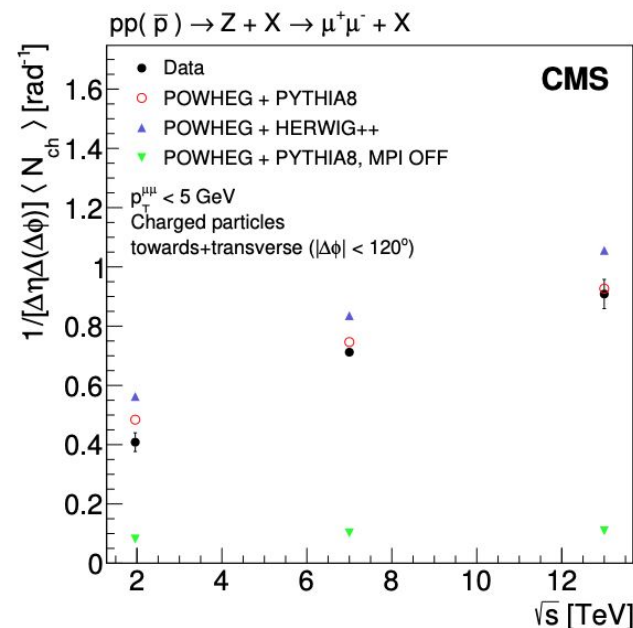
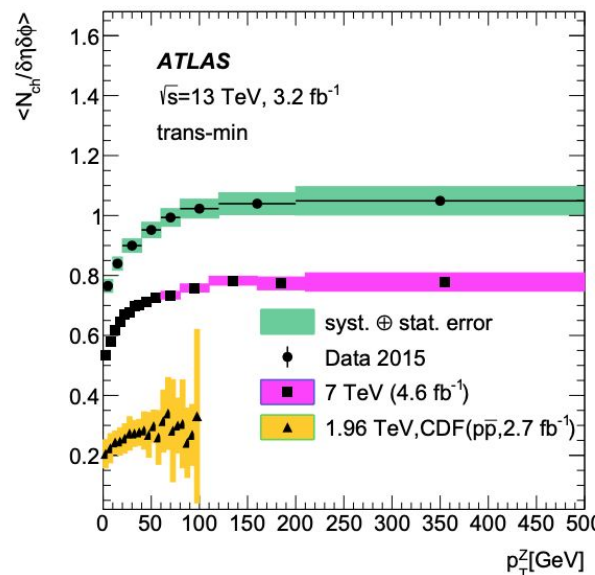
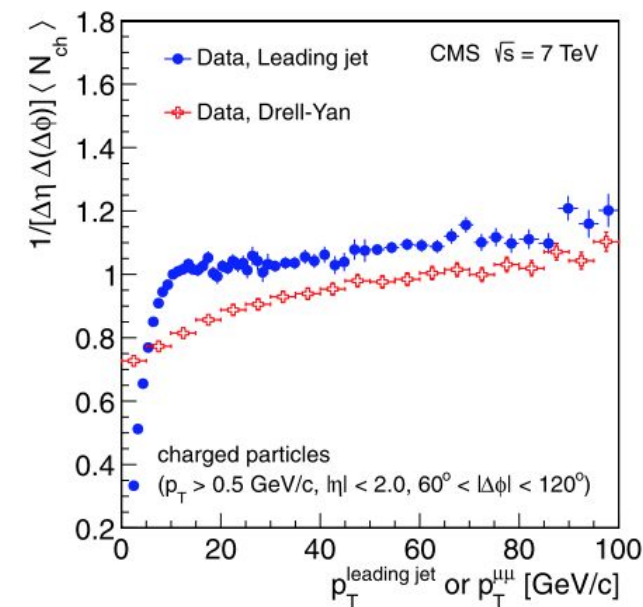
UE with Drell-Yan

[Eur. Phys. J. C 72, 2080 \(2012\)](#)

[JHEP07\(2018\)032](#)

[Eur. Phys. J. C 79, 666 \(2019\)](#)

- For $p_T > 10$ GeV, DY events have a smaller particle density as compared to the hadronic events,
 - Can be attributed to the differences in the nature of radiations



- Increase in activities with collision energy is consistent as observed hadronic events
 - With collision energy, mainly MPI increases and effect on radiation contribution is minimal

Measurement of Hard MPI $\rightarrow$ DPS/TPS

- Unfold correlation observables
- Fit with DPS and SPS templates to extract DPS contribution
- Unfold correlation observables
- Fit data to obtain best MPI model parameters
- Extract DPS contribution using standard x-sec measurement approach : when, (SPS) bkg well defined by MCs and under control

Correlation Observables:

In DPS, two process are independent (unlike SPS production)
 $\rightarrow$ unique features in p_T and ϕ space

$$\sigma_{XY} = \frac{m}{2} \cdot \frac{\sigma_X \cdot \sigma_Y}{\sigma_{eff}} \quad \left\{ \begin{array}{l} m = 1 \text{ when } X = Y \\ m = 2 \text{ when } X \neq Y \end{array} \right.$$

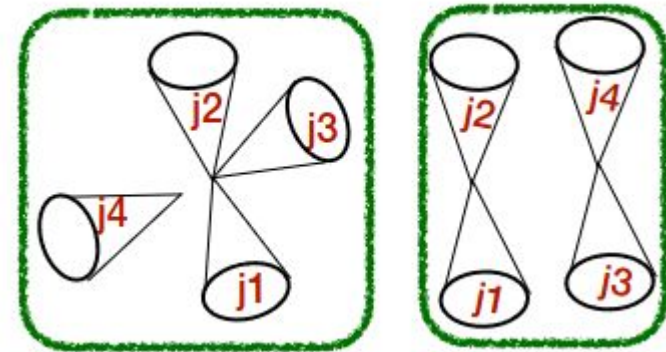
$$\sigma_{eff} = \frac{\sigma_{non-diffractive}}{f} \quad \longrightarrow \quad \begin{array}{l} \text{Impact parameter} \\ \text{enhancement factor;} \\ \text{Dependent on MPI} \\ \text{parameters (tune)} \end{array}$$

Inter-parton transverse separation squared $\rightarrow$ sort of an impact parameter; smaller σ_{eff} implies a larger DPS

DPS with 4 jets

[JHEP01\(2022\)177](#)

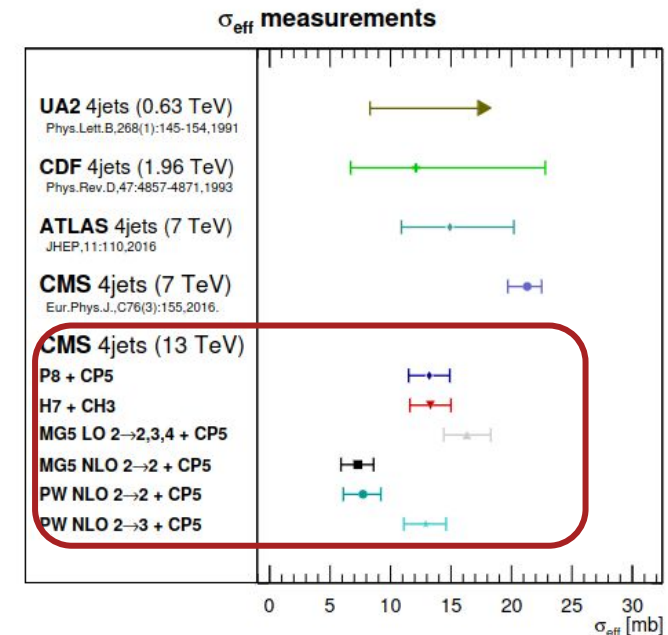
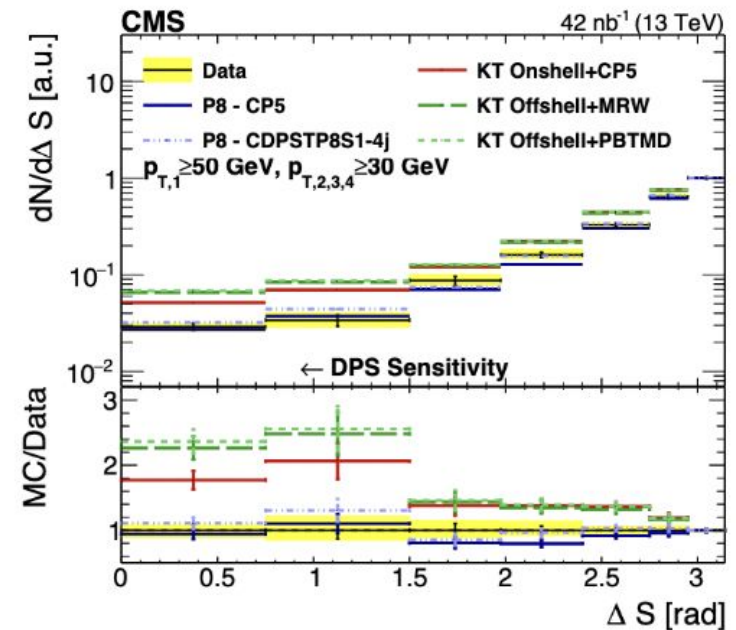
- Jet production is one of the most abundant processes at LHC
 - Low transverse momentum and forward/backward jets allow for the low-x region to be probed → important information for MC tuning
- 42 nb⁻¹ of low-pileup ($\langle \mu \rangle = 1.3$) pp collisions data at 13 TeV selected
 - Exactly one primary vertex
 - 4 jets with asymmetric p_T cuts going down to 20 GeV



$$\Delta S = \arccos \left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}| |\vec{p}_{T,3} + \vec{p}_{T,4}|} \right)$$

DPS with 4 jets

- SPS template from MC, DPS from random mixing of single jet data events
- Jets based measurements have large uncertainty in defining SPS
 - Used wide range of MCs to understand the dependence
- ❑ Py8 with CDPSTP8S1-4j (dedicated DPS tune) describes the data well
- ❑ Excellent sensitivity to different models used to model SPS
- ❑ Extracted σ_{eff} agrees with UA2, CDF, and ATLAS experiments
- ❑ Models using a $2 \rightarrow 2$ ME with older UE tunes $\rightarrow$ need the smallest DPS contribution
- ❑ NLO models yield lowest values of σ_{eff} $\rightarrow$ need even more DPS

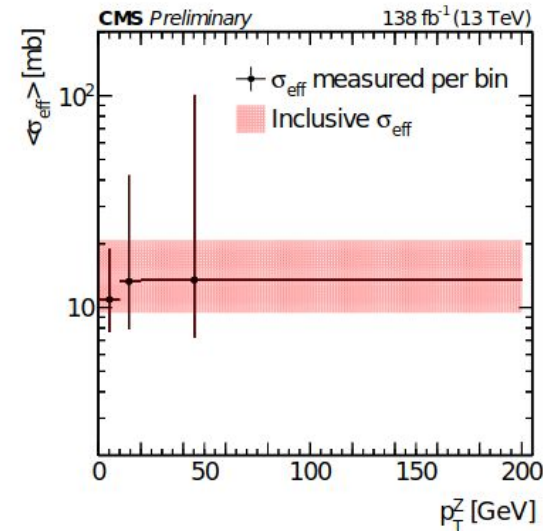
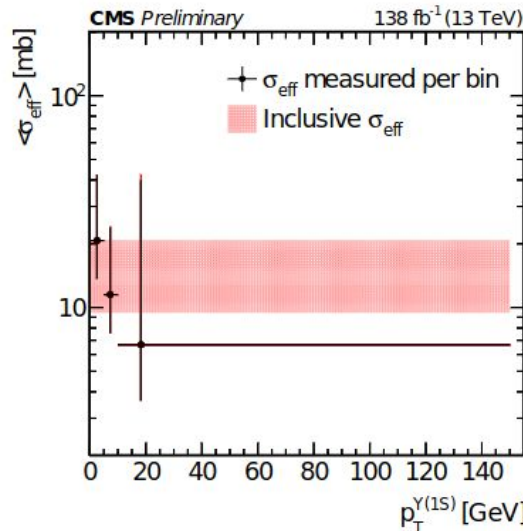
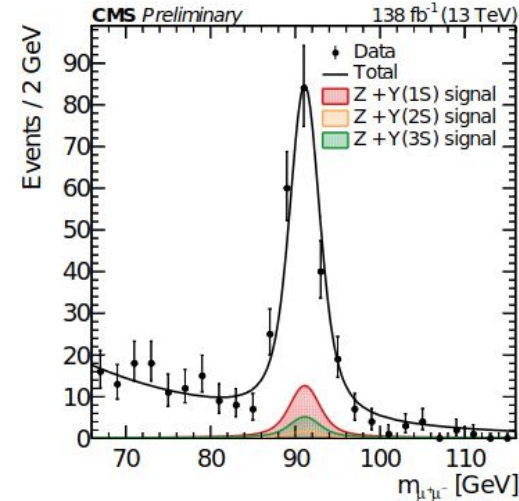
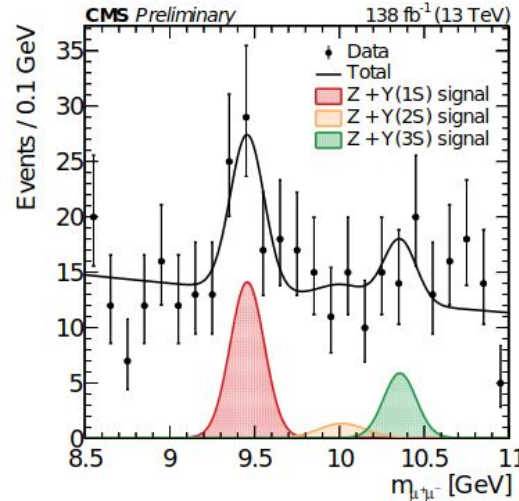


DPS with Z + Y(1S)

CMS-PAS-BPH-23-007

- First Measurement of integrated σ_{eff} and its differential measurement in bins of Y(1S) meson and Z p_{T}
- 2D unbinned maximum likelihood fit in the Z and the Y(nS) candidate mass
- DPS contribution extracted by template fit of rapidity (Δy) and azimuthal ($\Delta\phi$) separations between the Z and the Y(1S) candidates
- Measured σ_{eff} is consistent with the previous measurements

$$\sigma_{\text{eff}} = 13.0^{+7.8}_{-3.5} \text{ mb}$$

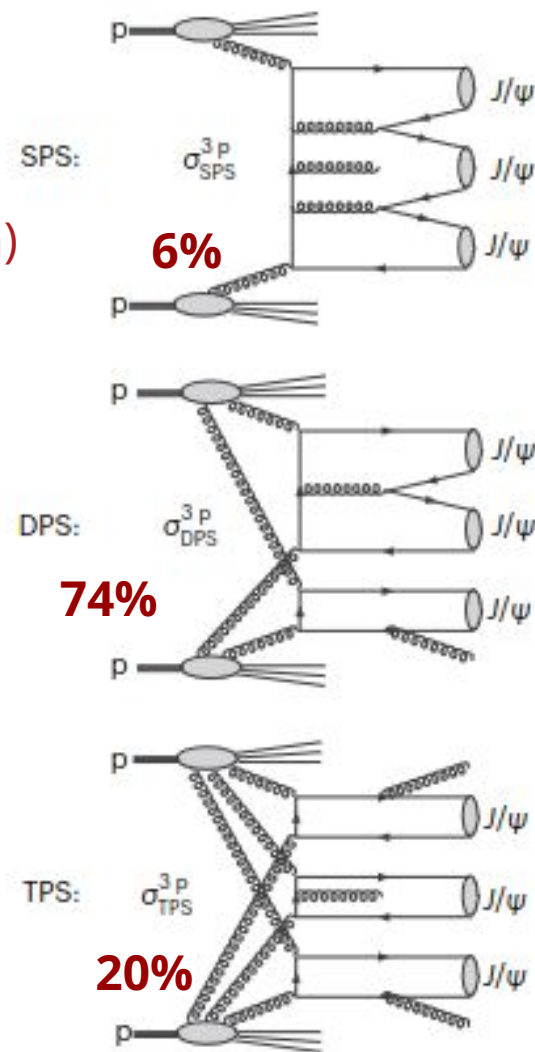


Triple Parton Scattering

- First study of inclusive triple J/ψ production & TPS
→ contributions from DPS (dominated contribution)
+ TPS + SPS (minor contribution)

- Extraction DPS effective cross section

- ❑ Experimentally clean and pure final states with (six) muons
- ❑ J/ψ mesons with $p_T > 6.5$ GeV and $|y| < 2.4$, Invariant mass: 2.6–3.6 GeV
- ❑ Background: semi-leptonic decays of heavy flavour, DY
- ❑ 3D un-binned extended maximum likelihood fit
- ❑ Signal modelled using Gaussian with resolution fixed to MC & mean to PDG J/ψ mass
- ❑ Exponential background



[Nature Physics 19, 338-350 \(2023\)](#)

Triple Parton Scattering

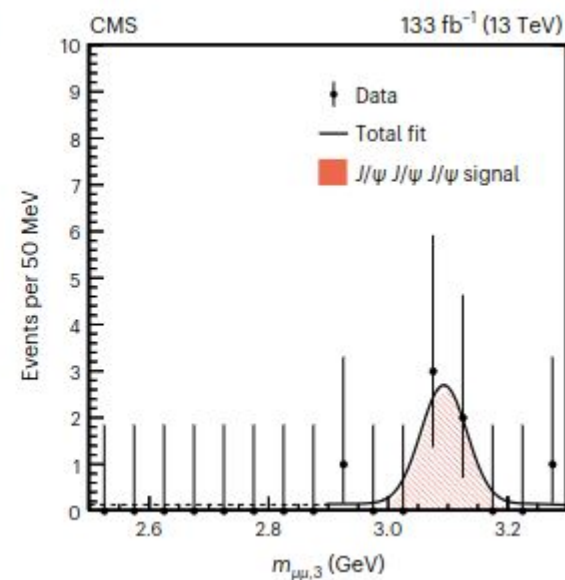
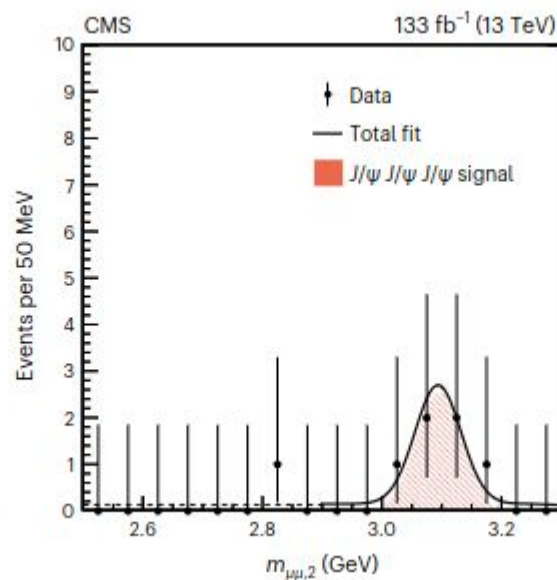
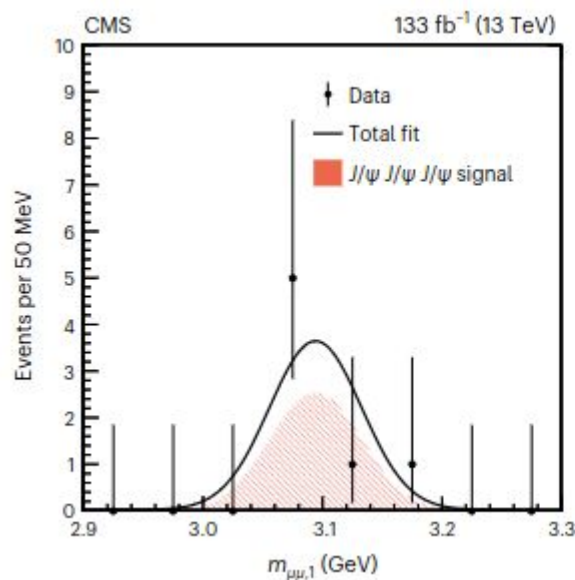
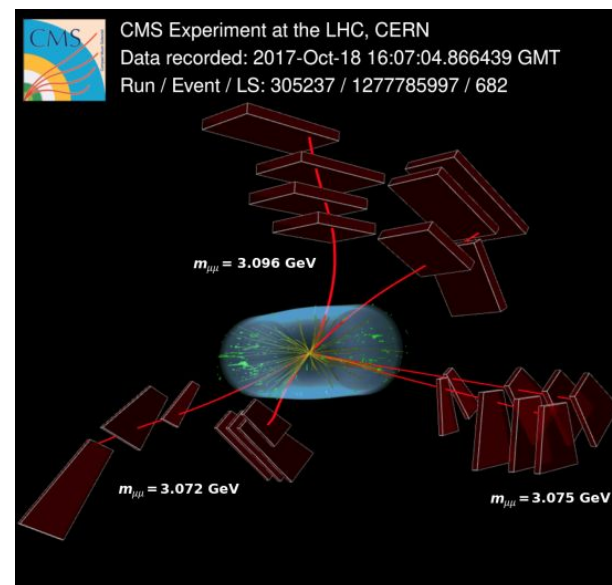
$$N(\text{signal}) = 5.0^{+2.6}_{-1.9}, N(\text{background}) = 1.0^{+1.4}_{-0.8}$$

Signal significance: 6.7 s.d. (obs.) 5.5 s.d. (exp.)

Predictions for SPS cross sections from
HELAC-ONIA & MG

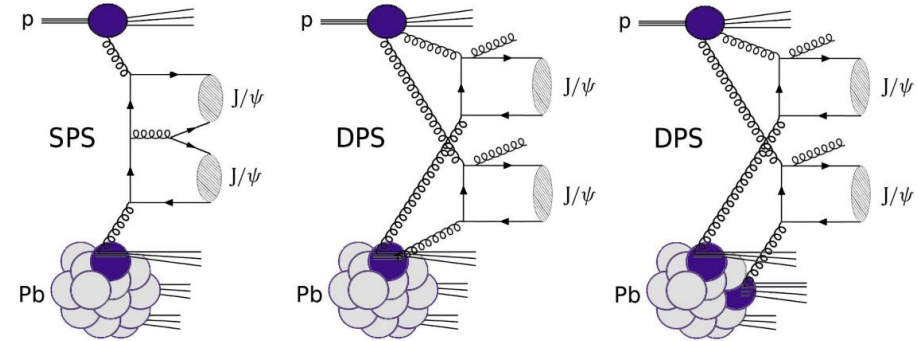
$$\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0} (\text{exp})^{+1.5}_{-1.0} (\text{theo}) \text{ mb}$$

[Nature Physics 19, 338-350 \(2023\)](#)



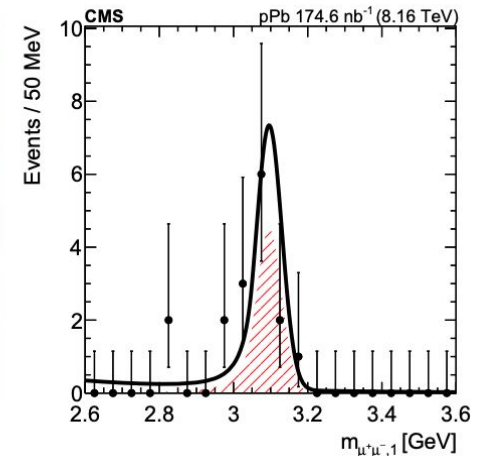
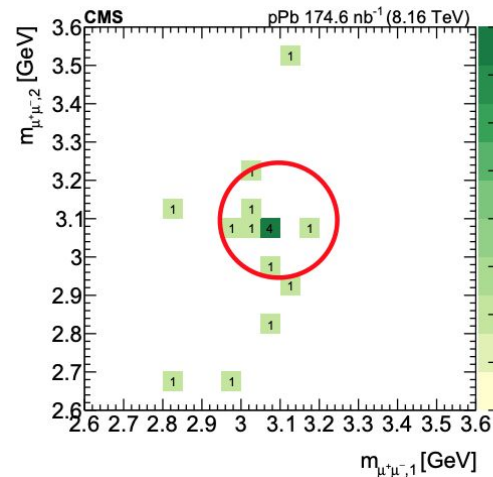
DPS in pPb

- pPb data provide an independent tool to extract σ_{eff}
- DPS is enhanced by a factor of 600 in pPb collisions as compared to pp



- ❑ pPb data sample collected at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ during 2016
- ❑ Integrated luminosity: 174.6 nb^{-1}

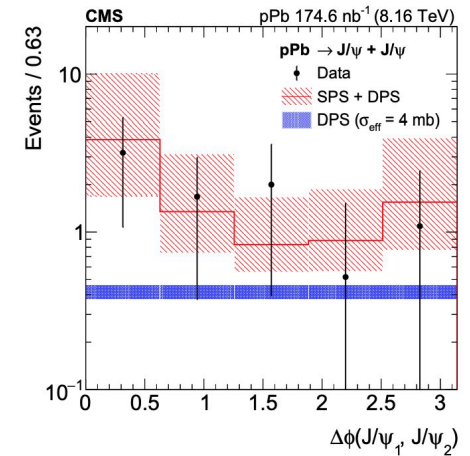
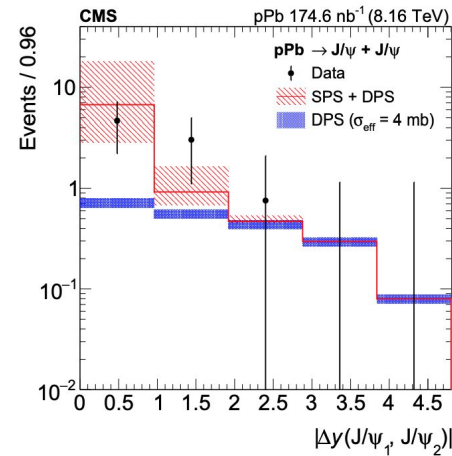
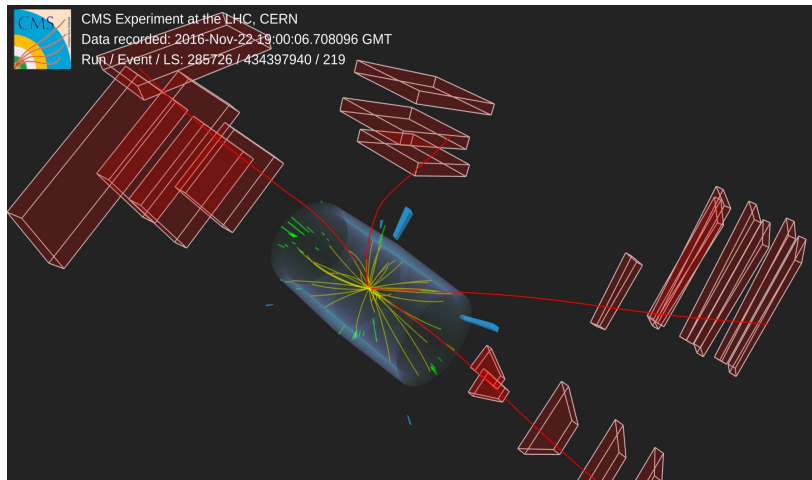
- ❑ Channels considered
 - ❑ $J/\psi(\rightarrow \mu\mu)J/\psi(\rightarrow \mu\mu)$
 - ❑ $J/\psi(\rightarrow \mu\mu)J/\psi(\rightarrow ee)$
- ❑ 4 leptons with common vertex
- ❑ J/ψ mesons with $p_{\text{T}} > 6.5 \text{ GeV}$ and $|y| < 2.4$, decay length $< 0.01 \text{ cm}$ to reduce non-prompt contribution. Invariant mass: 2.6–3.6 GeV



[PRD 110 \(2024\). 092002](#)

DPS in pPb

- ❑ 1D fit of Δy variable in the DPS dominated region $\Delta y > 1.92$
 - ❑ A data driven DPS templated is constructed using two J/ψ from independent events
 - ❑ SPS template derived using simulated events
- ❑ 5.3σ (combination with Fischer Formalism)



$$\sigma(\text{pPb} \rightarrow J/\psi J/\psi + X) = 22.0 \pm 8.9 (\text{stat}) \pm 1.5 (\text{syst}) \text{ nb}$$

$$\sigma_{\text{eff,pA}} = 0.53^{+\infty}_{-0.2} \text{ b}$$

large upper uncertainty indicates the possibility of the absence of DPS contribution

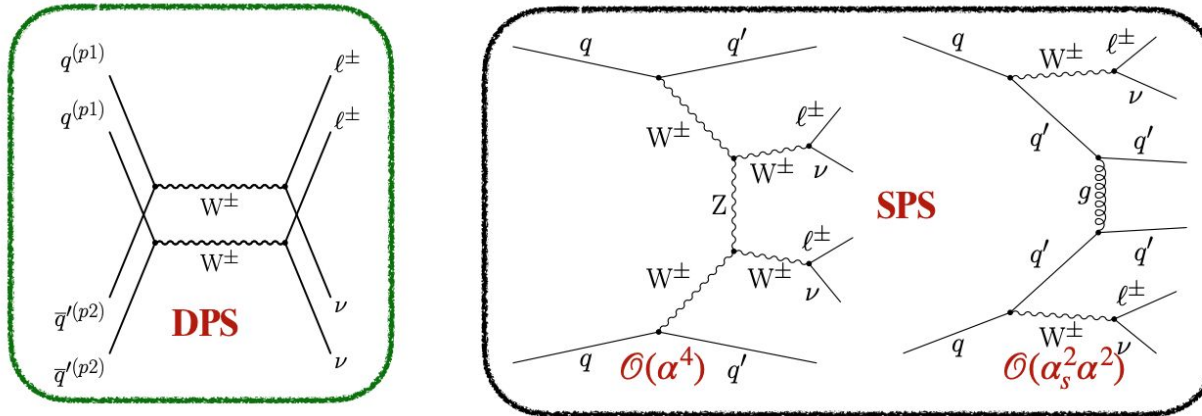
[PRD 110 \(2024\). 092002](#)

$$\sigma_{\text{eff}} = 4.0^{+\infty}_{-1.5} \text{ mb} \rightarrow \sigma_{\text{eff}} > 1.0 \text{ mb at 95\% CL}$$

Same-sign WW

[PRL131, 091803 \(2023\)](#)

- Golden channel for DPS production since SPS production suppressed at matrix element level due to presence of (two) extra jets

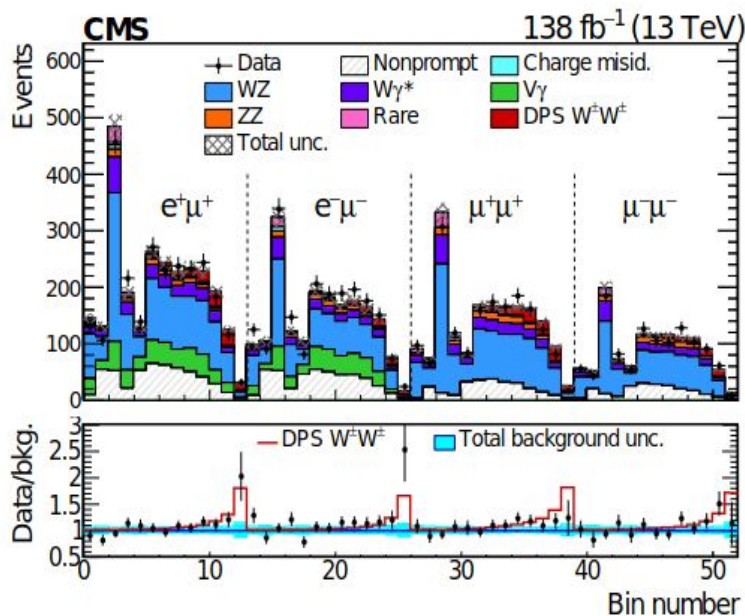


- Experimentally clean final state with leptonic W decays
 - Negligible contributions from leptons from adjacent bunch crossings
 - Background contributions from prompt & nonprompt lepton productions
- Signal extracted using binned maximum likelihood fit to the shape of the BDT classifier

Same-sign WW

[PRL131, 091803 \(2023\)](#)

First observation of $W^\pm W^\pm$ via DPS with 6.2 s.d. (obs.)



CMS Supplementary

CMS $J/\psi+J/\psi+J/\psi$ (13 TeV)
arXiv:2111.05370 (accepted by NatPhys)

ATLAS $J/\psi+J/\psi$ (8 TeV)
Eur. Phys. J. C 77 (2017) 76

D0 $J/\psi+J/\psi$ (1.96 TeV)
Phys. Rev. D 90 (2014) 111101

D0 $J/\psi+Y$ (1.96 TeV)
Phys. Rev. Lett. 116 (2016) 082002

CDF $\gamma+3$ jets (1.8 TeV)
Phys. Rev. Lett. 79 (1997) 584

D0 $\gamma+3$ jets (1.96 TeV)
Phys. Rev. D 89 (2014) 072006

D0 $\gamma+b/c+2$ jets (1.96 TeV)
Phys. Rev. D 89 (2014) 072006

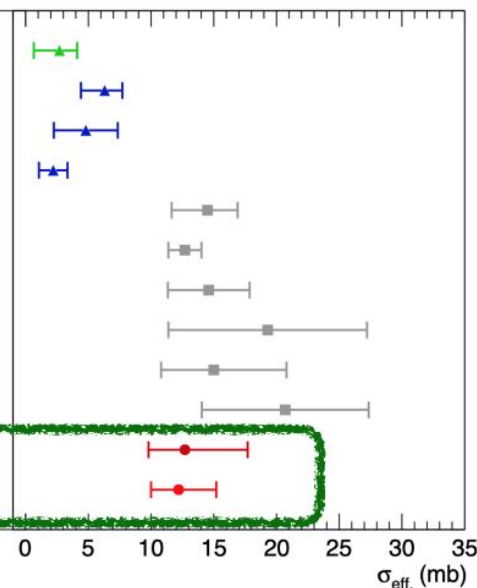
D0 $2\gamma+2$ jets (1.96 TeV)
Phys. Rev. D 93 (2016) 052008

ATLAS $W+2$ jets (7 TeV)
New J. P. 15 (2013) 033038

CMS $W+2$ jets (7 TeV)
JHEP 03 (2014) 032

CMS WW (13 TeV, 77.4 fb⁻¹)
Eur. Phys. J. C 80 (2020) 41

CMS WW (13 TeV, 138.0 fb⁻¹)
arXiv:2206.02681 (submitted to PRL)



Inclusive $W^\pm W^\pm \rightarrow 2l2\nu$ cross section

$$80.7 \pm 11.2 (\text{stat})^{+9.5}_{-8.6} (\text{syst}) \pm 12.1 (\text{model}) \text{ fb}$$

Fiducial cross section

$$6.28 \pm 0.81 (\text{stat}) \pm 0.69 (\text{syst}) \pm 0.37 (\text{model}) \text{ fb}$$

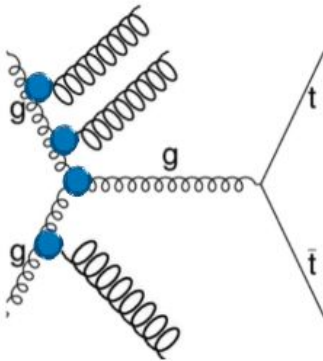
from Herwig: difference in reconstruction Efficiencies for leptons & generator acceptance

Monte Carlo Tuning

- Measurements (often) rely on Monte Carlo
 - Heavily dominated QCD-radiated / jets environment
 - irreducible backgrounds - MC for searches
 - achieve precision (NNLO) for SM measurements
 - need higher accuracy precision on phenom. parameters
- LO and NLO multi-leg generators matched with parton shower
 - MadGraph5 +Pythia8 MLM-merging; LO up to 4 partons
 - MadGraph5_aMC@NLO+Pythia8 FxFx-merging; NLO up to 2 partons
 - Powheg MiNLO +Pythia8; NNLO up to 2 jets
 - Sherpa, Herwig7... NLO

Parameters

- strong coupling and parton density functions appear in many physics stages of pp collisions and can be evaluated at different orders in QCD
- It is important to have tunes at different and PDF orders (they can be very different!) and compare to data to understand their effect



MPI

$$p_T^0 = p_T^{ref} \cdot (E/E_{ref})^\epsilon$$

smooth cut to regularize $p_T \rightarrow 0$ divergences

initial/final state radiation (PS)

strong coupling, regularization
upper scale...

hadronization modelling

length of fragmentation string,
strange baryon suppression...

beam remnants (primordial kT)

width of the gaussian of the primordial
kT in the proton...

Tools/Procedure

PROFESSOR
for tuning MC generators



<https://professor.hepforge.org/>

RIVET
for comparisons



<https://rivet.hepforge.org/>

common strategy, experiment
independent, flexible and reliable

Observables

Generate grid points

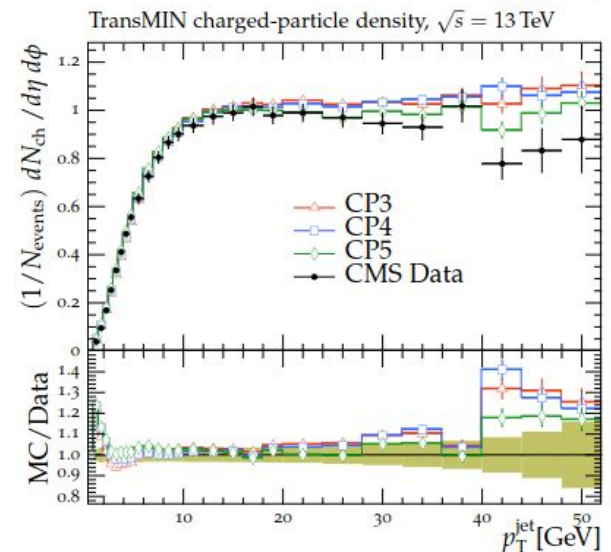
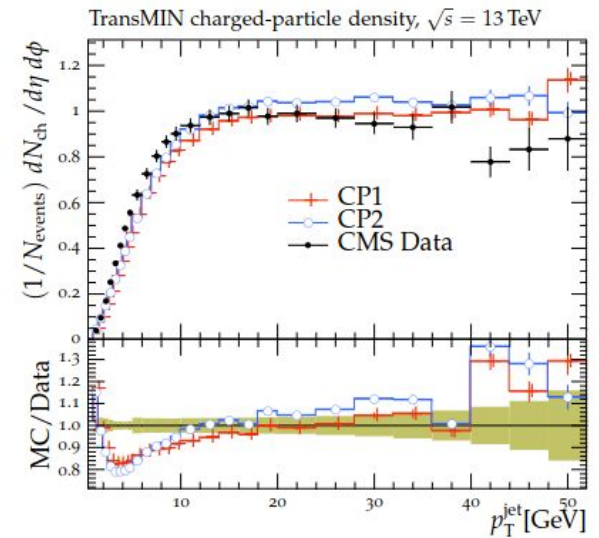
$$\chi^2(p) = \sum w_o \sum \frac{f^b(p) - R(b)^2}{\Delta_b^2}$$

Pythia8 CMS tunes

[Eur. Phys. J. C 80, 4 \(2020\)](#)

PYTHIA8 parameter	CP1	CP2
PDF Set	NNPDF3.1 LO	NNPDF3.1 LO
$\alpha_s(m_Z)$	0.130	0.130
SpaceShower:rapidityOrder	off	off
MultipartonInteractions:EcmRef [GeV]	7000	7000
$\alpha_s^{\text{ISR}}(m_Z)$ value/order	0.1365/LO	0.130/LO
$\alpha_s^{\text{FSR}}(m_Z)$ value/order	0.1365/LO	0.130/LO
$\alpha_s^{\text{MPI}}(m_Z)$ value/order	0.130/LO	0.130/LO
$\alpha_s^{\text{ME}}(m_Z)$ value/order	0.130/LO	0.130/LO
MultipartonInteractions:pT0Ref [GeV]	2.4	2.3
MultipartonInteractions:ecmPow	0.15	0.14
MultipartonInteractions:coreRadius	0.54	0.38
MultipartonInteractions:coreFraction	0.68	0.33
ColorReconnection:range	2.63	2.32
χ^2/dof	0.89	0.54

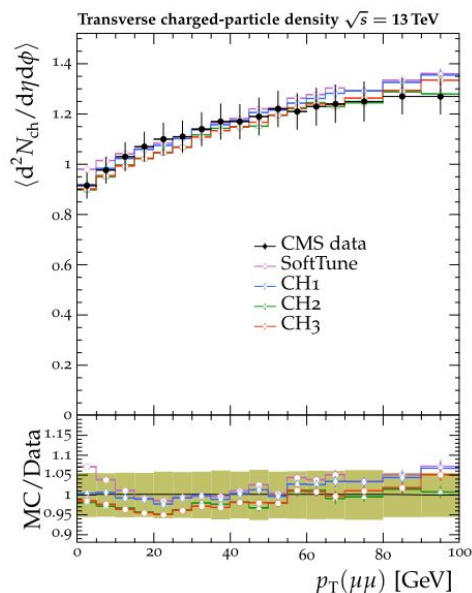
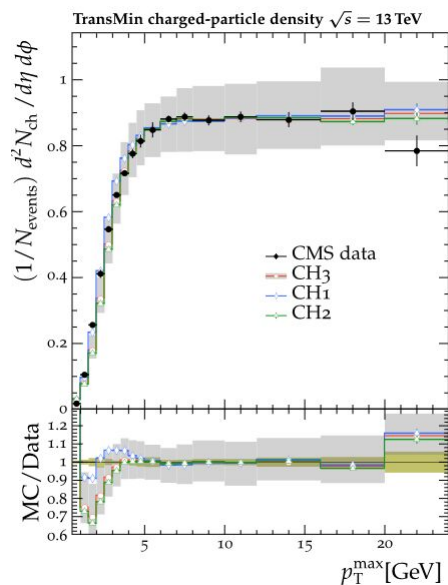
PYTHIA8 parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_s(m_Z)$	0.118	0.118	0.118
SpaceShower:rapidityOrder	off	off	on
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000
$\alpha_s^{\text{ISR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_s^{\text{FSR}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_s^{\text{MPI}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_s^{\text{ME}}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	1.52	1.48	1.41
MultipartonInteractions:ecmPow	0.02	0.02	0.03
MultipartonInteractions:coreRadius	0.54	0.60	0.76
MultipartonInteractions:coreFraction	0.39	0.30	0.63
ColorReconnection:range	4.73	5.61	5.18
χ^2/dof	0.76	0.80	1.04



CMS Herwig(7) tunes

[Eur. Phys. J. C 81, 312 \(2021\)](#)

		SoftTune	CH1	CH2	CH3
$\alpha_S(m_Z)$		0.1262	0.118	0.118	0.118
PS	PDF set	MMHT 2014 LO	NNPDF 3.1 NNLO	NNPDF 3.1 NNLO	NNPDF 3.1 NNLO
	$\alpha_S^{\text{PDF}}(m_Z)$	0.135	0.118	0.118	0.118
MPI & remnants	PDF set	MMHT 2014 LO	NNPDF 3.1 NNLO	NNPDF 3.1 LO	NNPDF 3.1 LO
	$\alpha_S^{\text{PDF}}(m_Z)$	0.135	0.118	0.118	0.130
$p_{\perp,0}^{\text{min}}$ (GeV)		3.502	2.322	3.138	3.040
b		0.416	0.157	0.120	0.136
μ^2 (GeV ⁻²)		1.402	1.532	1.174	1.284
p_{reco}		0.5	0.400	0.479	0.471
χ^2/N_{dof}		12.8	6.75	1.54	1.71

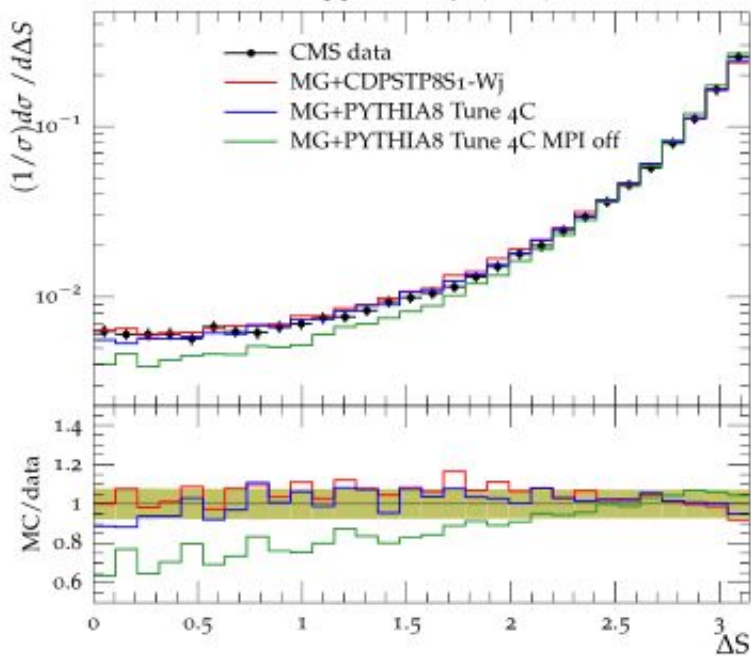


The predictions using the tune CH2 or CH3 provide a better description of the data than those using CH1 or SoftTune.

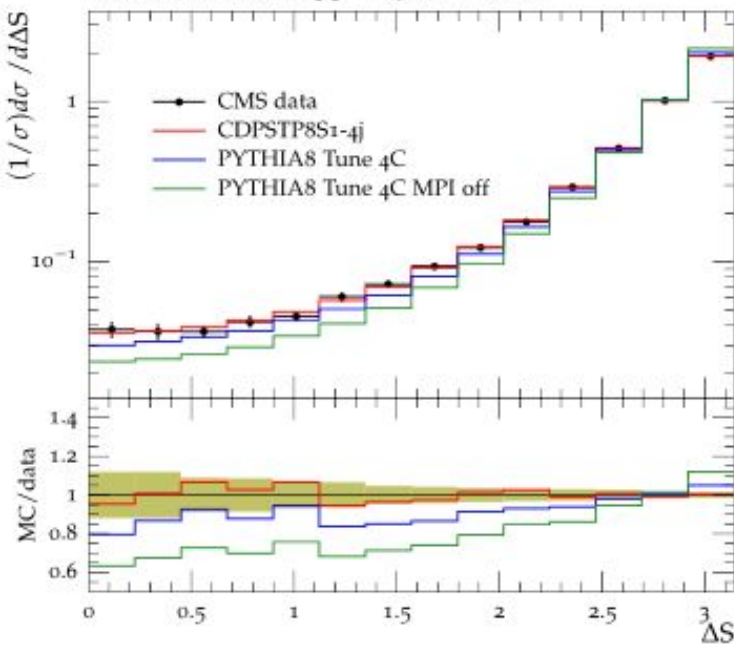
PYTHIA8 parameter	Tuning range	Tune 4C	CDPSTP8S1-Wj	CDPSTP8S2-Wj
PDF		CTEQ6L1	CTEQ6L1	CTEQ6L1
MultipartonInteractions:pT0Ref [GeV]	1.0–3.0	2.085	2.085 ^a	2.501
MultipartonInteractions:ecmPow	0.0–0.4	0.19	0.19 ^a	0.179
MultipartonInteractions:expPow	0.4–10.0	2.0	1.523	1.120
ColourReconnection:range	0.0–9.0	1.5	1.5 ^a	2.586
MultipartonInteractions:ecmRef [GeV]	–	1800	1800 ^a	1800 ^a
χ^2/dof	–	–	0.118	0.09
Predicted σ_{eff} (in mb)	–	30.3	25.9 ^{+2.4} _{-2.9}	25.8 ^{+8.2} _{-4.2}

^a Fixed at Tune 4C value

Normalized ΔS in $pp \rightarrow W+2j$, $\sqrt{s} = 7$ TeV



Normalized ΔS in $pp \rightarrow 4j$, $\sqrt{s} = 7$ TeV



Summary/Outlook

- A range of LHC measurements to understand dynamic of UE
 - Helped in improving the models
 - Is there any surprises in MPI trend at TeV scale?
- DPS is measured in wide spectrum of the final state i.e. $V + \text{jets}$, 4 jets, $V + J/\psi$ (Upsilon), WW
 - Still need a consistent measurement to explore the scale dependence of DPS.
 - Jets processes can be an excellent choice but SPS definition is highly model dependent.
- Dedicate tuning efforts to improve MCs
 - UE + MB, DPS, Color-Reconnection
 - Energy scaling behaviour of intrinsic k_T in DY

Thank you !!