The DPS measurements and tunes at CMS

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on behlaf of the CMS Collaboration

Monday, August 26
Low-x 2019, Nicosia

The MC event picture

aka Divide and Conquer

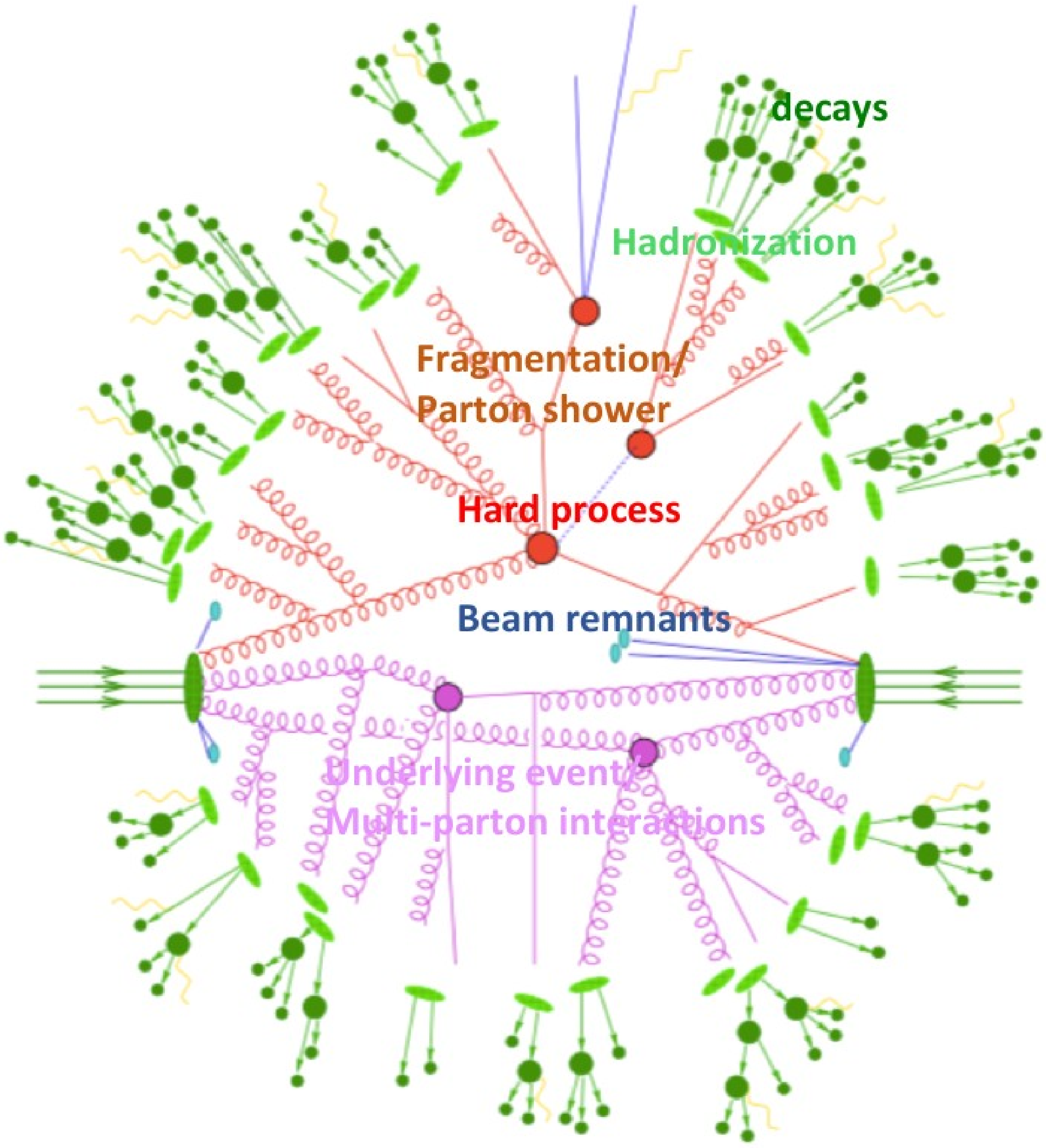
#pars ↓ — QCD scale ↑

1) Hard sub-process
   - Initial-state shower
   - Final-state shower
   - Multi parton interaction
2) Proton remnant
3) Hadronization
4) Particle decays

+ PDF choice

More parameters → more freedom in their choice

The Higgs production involves ~10 additional MPIs



Geissberger at all JHEP02 (2004) 056

Perturbative order of PDFs in the MC generators

Nowadays, many MC predictions based on

- NLO + PS, e.g. MC@NLO or POWHEG
- NNLO + PS, e.g. NNLOPS

(N)NLO PDFS

However:

- The MPI ME included only at LO
- The PS uses LO splitting functions

LO PDFS

Pythia8
The LO PDFs are recommended (low-x & low-scale behavior better under control)

Herwig7
NLO PDFs for ME+PS
LO PDFs for MPI

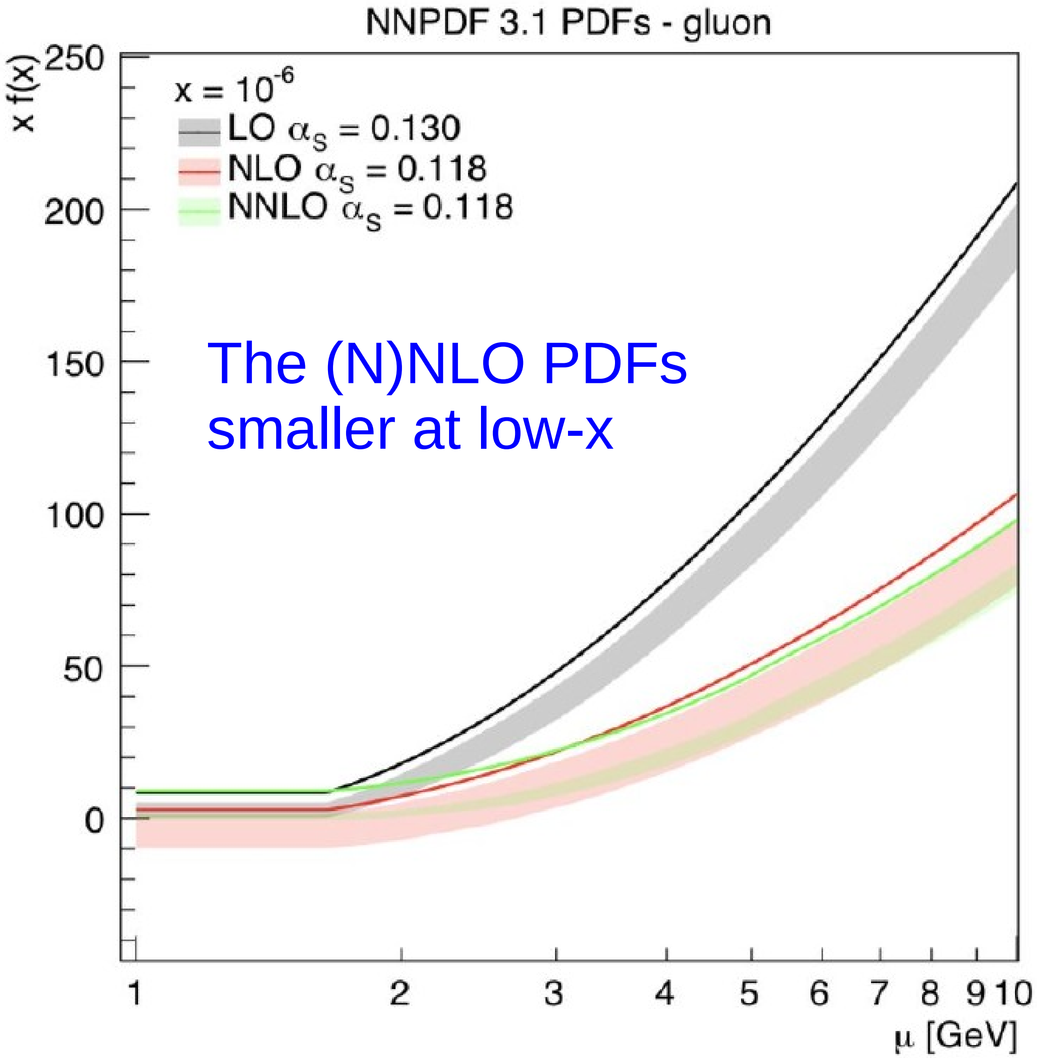
Sherpa
Uses the NNLO PDFs in the default tune

LO or (N)NLO PDFs for Pythia8 tune?

- The CMS 7TeV tunes (like CUETP8M1) based on NNPDF2.3 LO (`Tune::pp = 18`)
- In 2018 with 13 TeV data available the LO, NLO & NNLO NNPDF 3.1 tested for tuning (arXiv:1903.12179)

CP1-2: LO PDF, α_s(LO) = 0.130
CP3: NLO PDF, α_s(NLO) = 0.118
CP4-5: NNLO PDF, α_s(NLO) = 0.118

In the NNPDF 3.1 no constraint on PDF positivity
→ Even LO PDF is sometimes negative



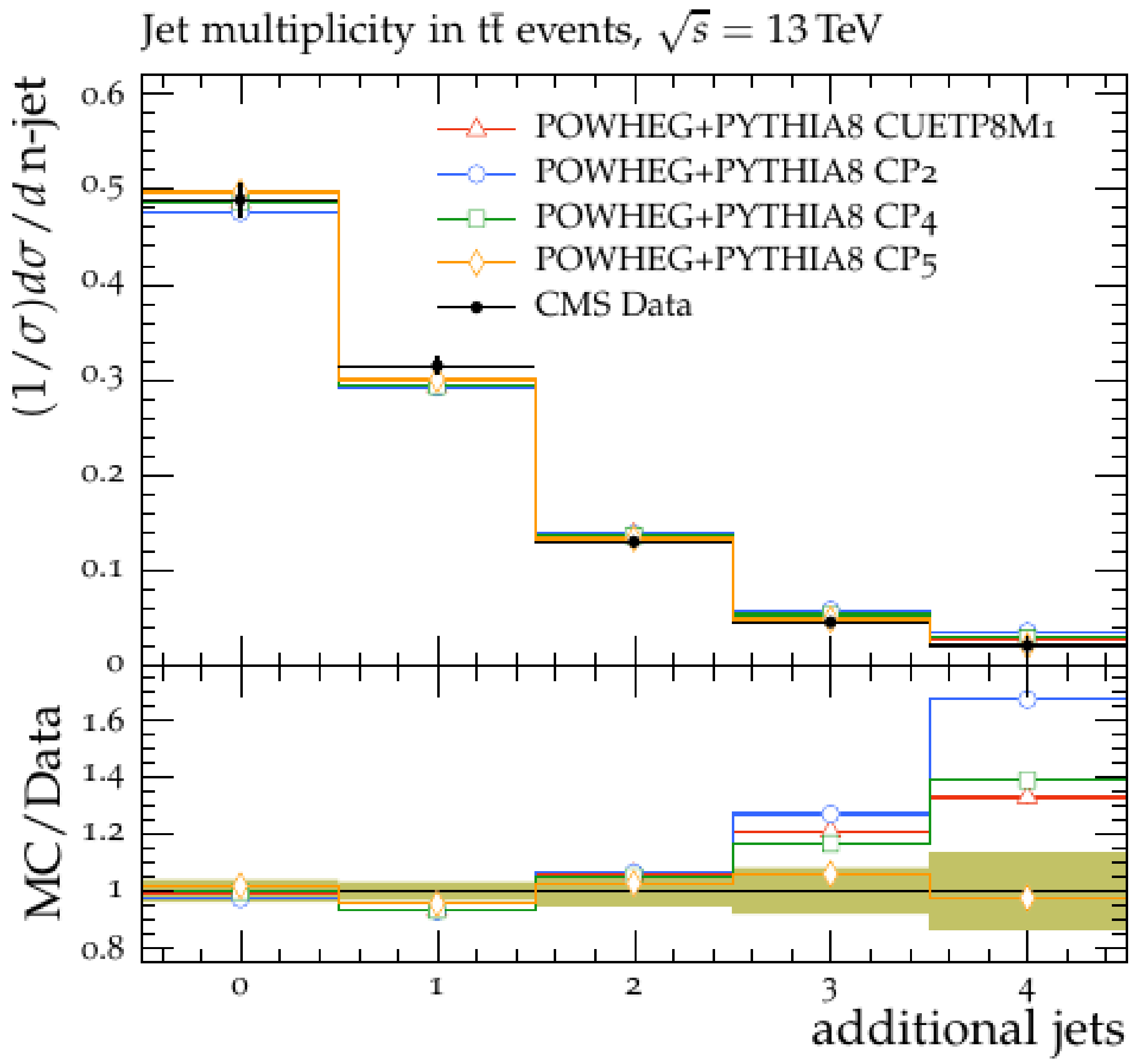
NNPDF3.1sx NNLO+NLLx should give stable low-x behavior, JHEP 1901 (2019) 217

The UE tune dependence in $t\bar{t}$

Phys.Rev. D95 (2017) no.9, 092001

Higher jet multiplicities strongly affected by the PS & MPI parameters

UE Measurements to constrain these parameters

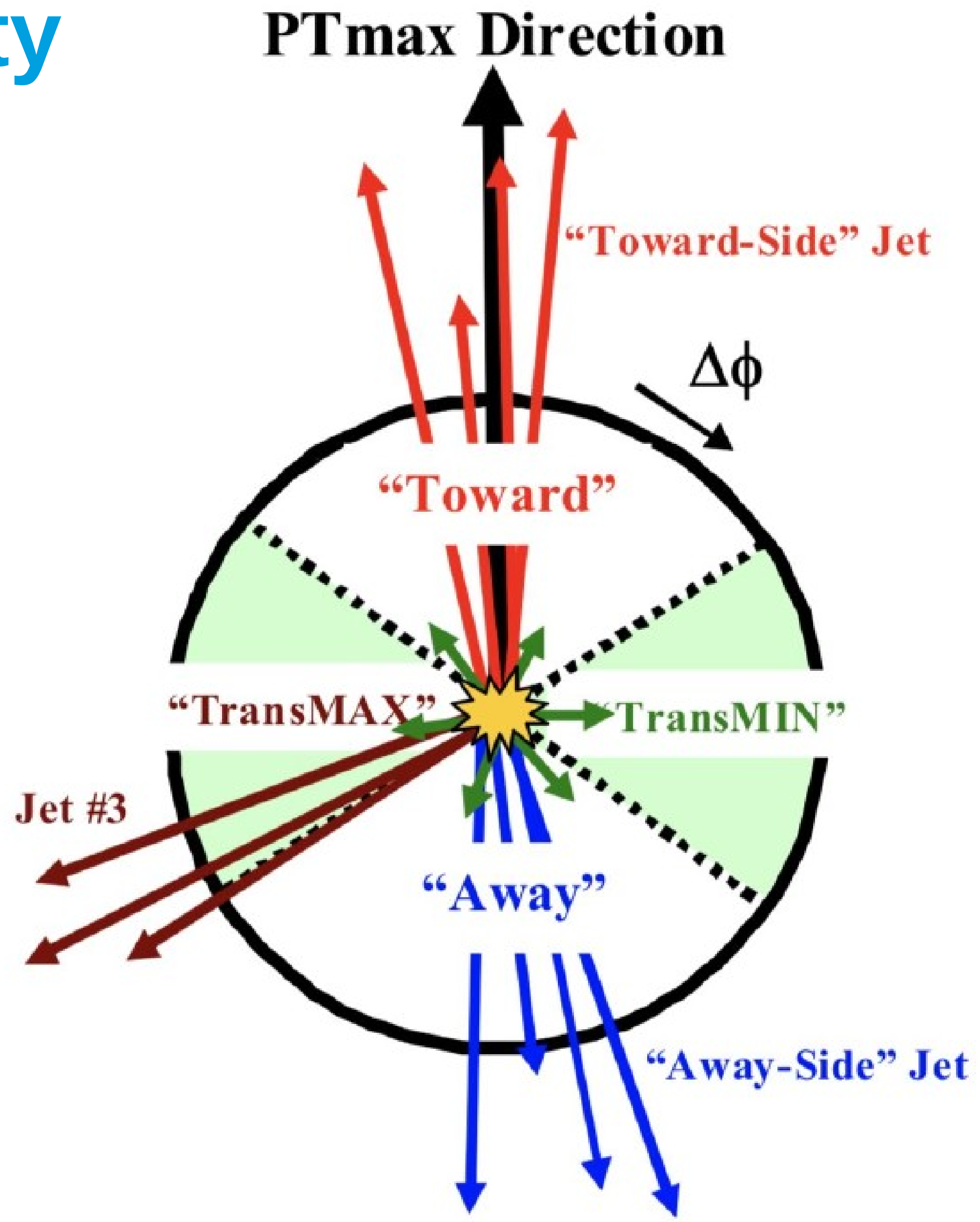


Measurement of the UE activity

- UE activity studied as a function of p_T of the leading particle
- 4 regions in the ΔΦ variable:
  → Toward: ΔΦ < 60°
  → Transverse: 60° < ΔΦ < 120°
  (divided into TransMIN & TransMAX according the activity)
  → Away: ΔΦ > 120°

Observables

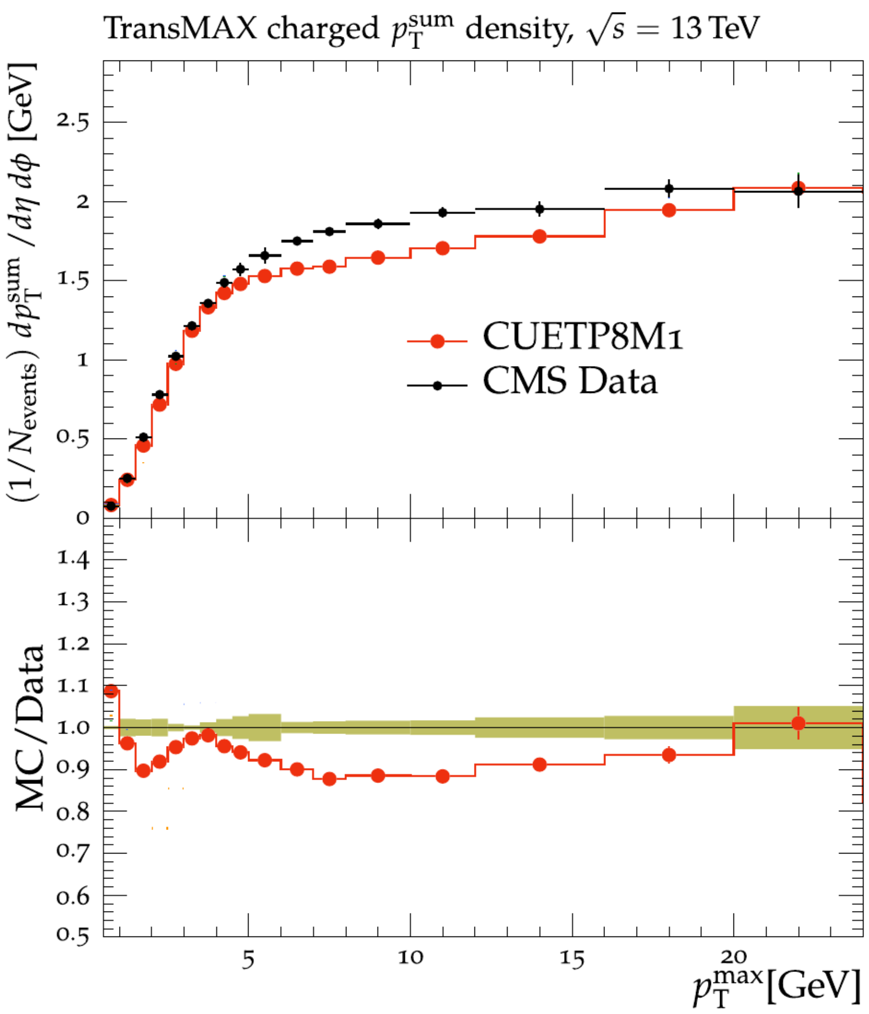
- Average Charged Particle Multiplicity per event and per unit of η, Φ
- Average p_T sum per event and per unit of η, Φ

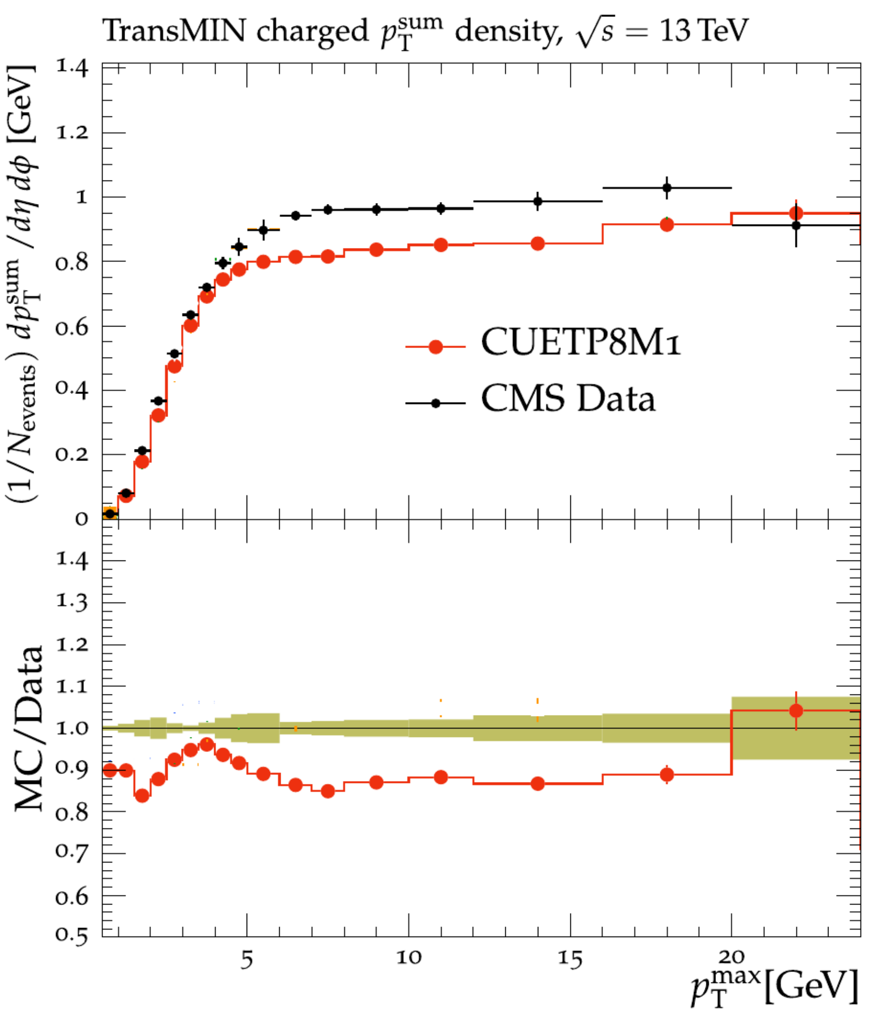


The older 7 TeV tunes vs 13 TeV data

The older CMS tune CUETP8M1
(Eur. Phys. J. C (2016) 76 :155)
tends to underestimate the energy flow in the transverse region

Need for new UE tunes with 13 TeV data





The new 13TeV tunes: What is fixed?

- The 13 TeV tunes based on the Monash Pythia8 tune (Eur.Phys.J. C74 (2014) no.8, 3024)
- The tunes differ in:
  - → The PDF order
  - → The α_s order & value for ISR, FSR, MPI, ME
  - → The ISR rapidity ordering

arXiv:1903.12179

PYTHIA8 parameter	CP1	CP2	CP3	CP4	CP5
PDF Set	NNPDF3.1 LO	NNPDF3.1 LO	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.130	0.130	0.118	0.118	0.118
SpaceShower:rapidityOrder	off	off	off	off	on
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.1365/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.1365/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO

Effort to have consistent α_s value and order (CP3, CP4, CP5)

The new 13TeV tunes: What is tuned?

Parameter description	Name in PYTHIA8	Range considered
MPI threshold [GeV], pT0Ref, at $\sqrt{s} = \sqrt{s_0}$	`MultipartonInteractions:pT0Ref`	1.0–3.0
Exponent of $\sqrt{s}$ dependence, ϵ	`MultipartonInteractions:ecmPow`	0.0–0.3
Matter fraction contained in the core	`MultipartonInteractions:coreFraction`	0.1–0.95
Radius of the core	`MultipartonInteractions:coreRadius`	0.1–0.8
Range of color reconnection probability	`ColorReconnection:range`	1.0–9.0

Inclusive parton-parton cross section > σ_{inel}

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \sim \frac{\alpha_S^2(p_T^2)}{p_T^4} \Rightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \sim \frac{\alpha_S^2(p_T^2 + p_{T0}^2)}{(p_T^2 + p_{T0}^2)^2}$$

$$p_{T0}^2 = p_{T0}^{\mathrm{ref}} \left(\frac{E_{\mathrm{cms}}}{7000\ \mathrm{GeV}} \right)^{E_{\mathrm{cm}}^{\mathrm{pow}}}$$

Lower p_{T0} → More MPI interactions

The new 13TeV tunes: What is tuned?

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Exponent of $\sqrt{s}$ dependence, ϵ	`MultipartonInteractions:ecmPow`	0.0–0.3
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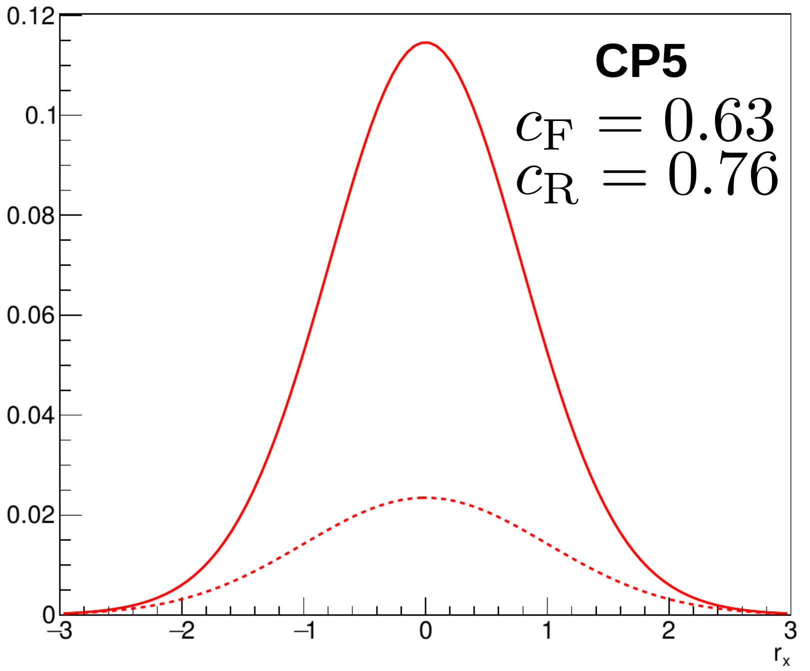
The double Gaussian matter distribution
→ Fraction of the inner Gaussian
→ Inner / outer width

$$\rho(r) \propto (1 - c_{\mathrm{F}})\, \mathrm{e}^{-\frac{r^2}{2}} + \frac{c_{\mathrm{F}}}{c_{\mathrm{R}}^3} \mathrm{e}^{-\frac{r^2}{2c_{\mathrm{R}}^2}}$$

Overlap function:

$$\mathcal{O}(b) \propto \int \mathrm{d}t \int \mathrm{d}^3x\, \rho(x, y, z)\, \rho(x + b, y, z + t)$$



Double Gaussian enhances the event by event fluctuations in the particle multiplicity

The new 13TeV tunes: What is tuned?

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The probability to reconnect the color lines of two MPI 2→2 interactions

$$p \sim \frac{(p_{T0}^{\text{rec}})^2}{p_T^2 + (p_{T0}^{\text{rec}})^2}$$

$$p_{T0}^{\text{rec}} = p_{T0} \times \boxed{\text{range}}$$

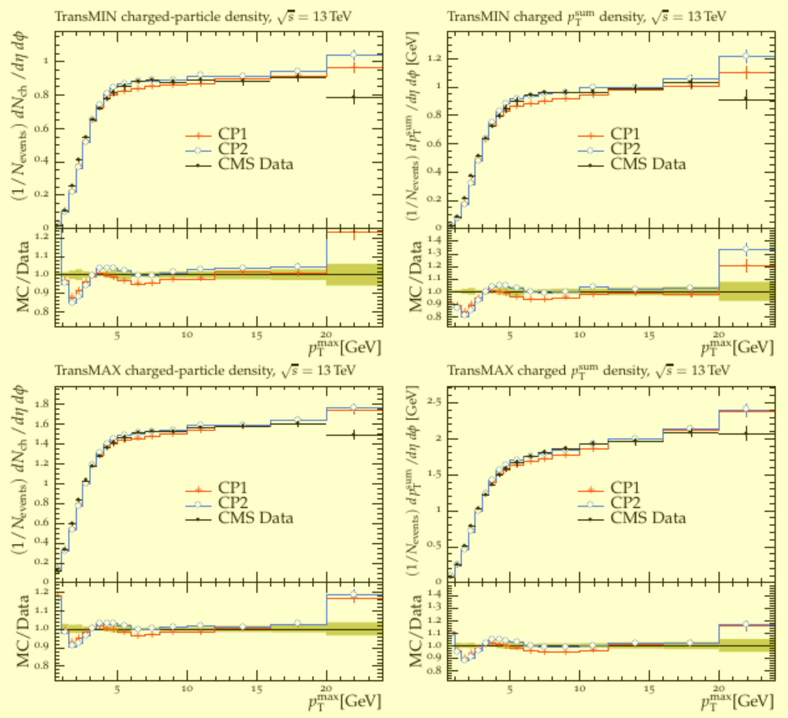
Smaller range
→ lower reconnection probability

The new 13TeV tunes: On which data?

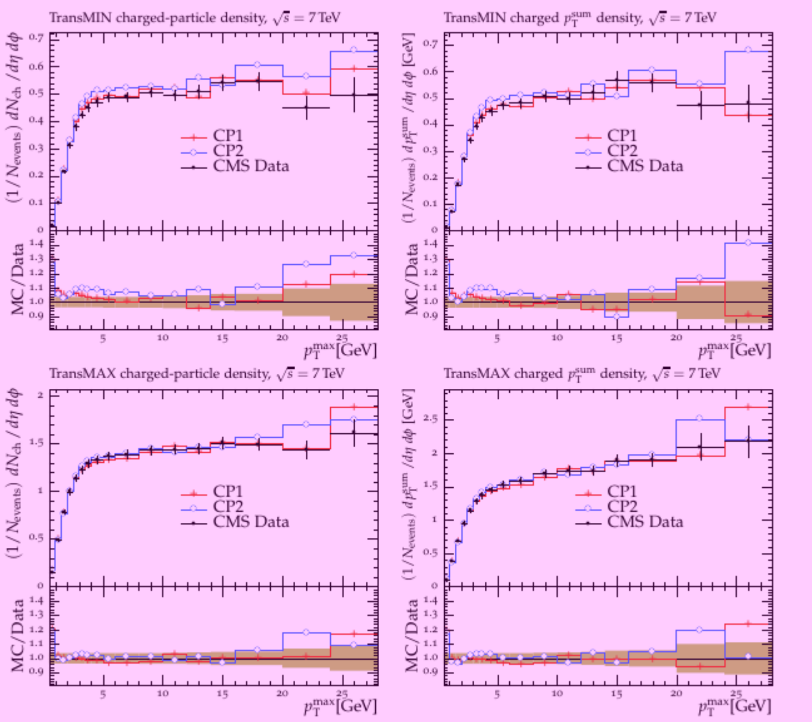
TransMIN-N_{ch}	TransMIN-p_T^{Sum}
TransMAX-N_{ch}	TransMAX-p_T^{Sum}

for 1.96 TeV, 7 TeV, 13 TeV
(12 distributions)

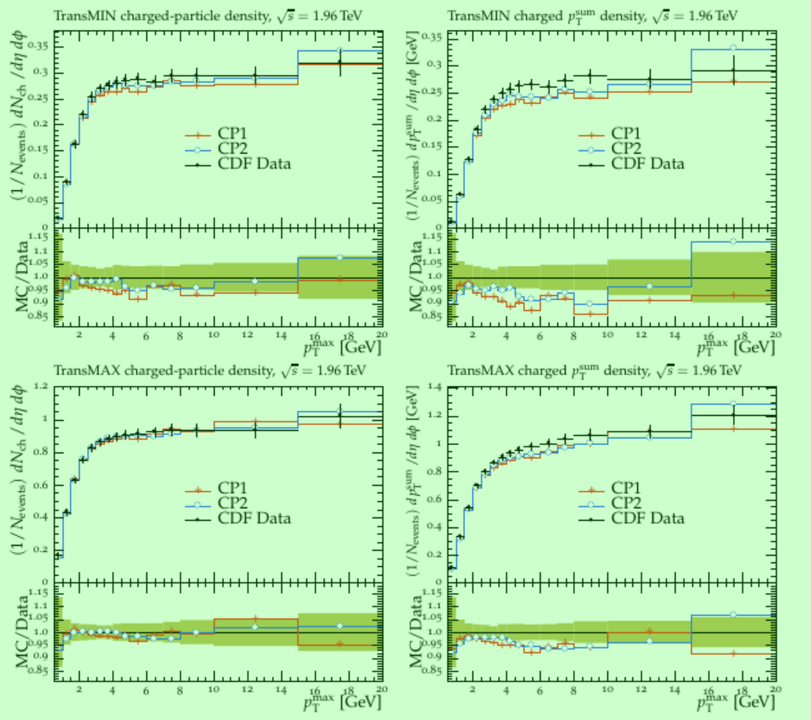
13 TeV



7 TeV



1.96 TeV



The new 13TeV tunes: Result of tuning

- All tune variants have reasonable χ^2/dof
- The (N)NLO tunes tend to have lower p_{T0}^{Ref} (to balance lower PDFs)

Professor based tuning

1) Randomly select ~100 points in the parameter space and generate corresponding MC samples
2) Calculate chi2 for each sample and interpolate by parabolic function
   → **minimum**

Eur.Phys.J. C65 (2010) 331-357

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PDF Set	NNPDF3.1 LO	NNPDF3.1 LO	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
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SpaceShower:rapidityOrder	off	off	off	off	on
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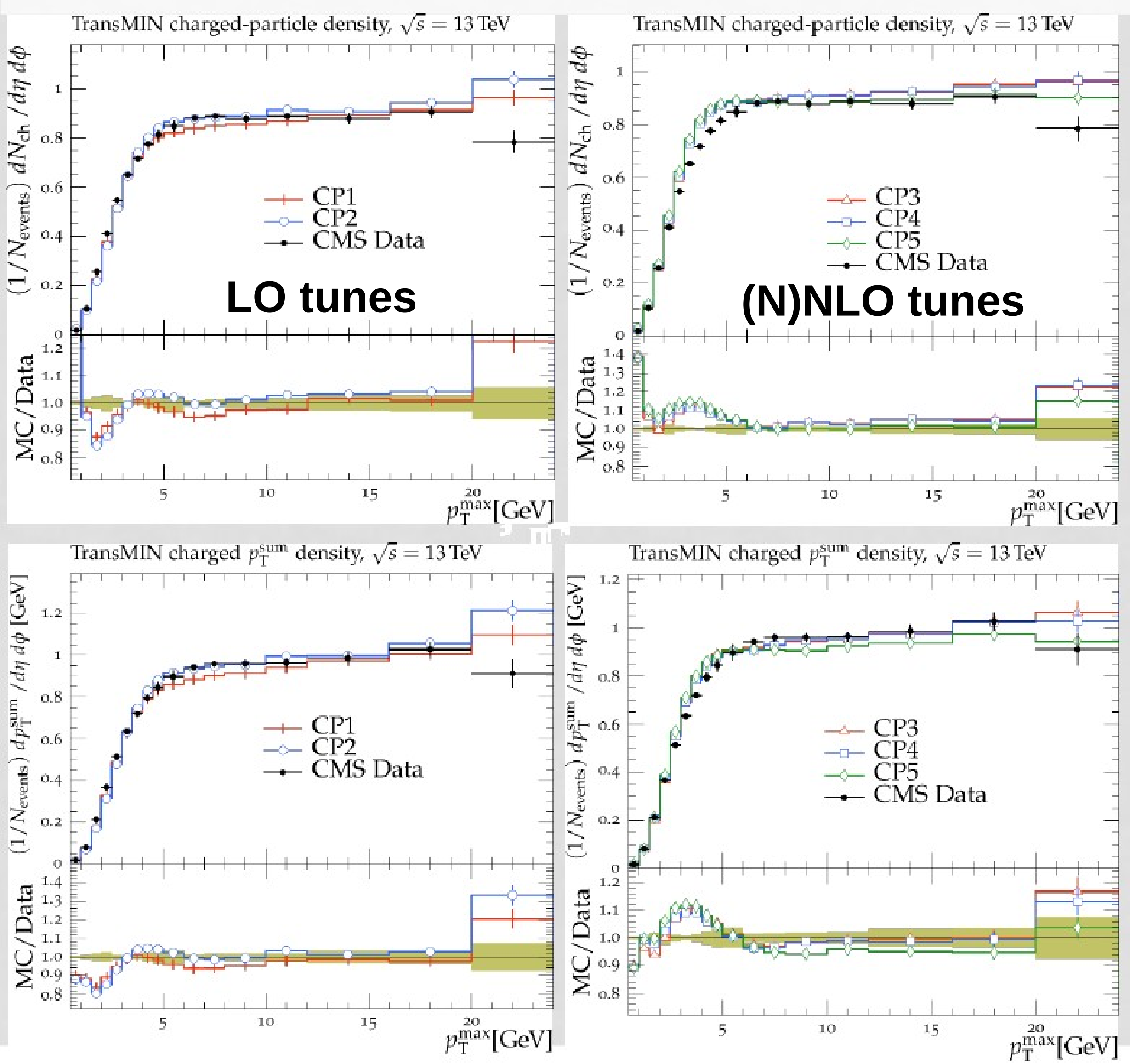
$\alpha_S^{FSR}(m_Z)$ value/order	0.1365/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.130/LO	0.130/LO	0.118/NLO	0.118/NLO	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	2.4	2.3	1.52	1.48	1.41
MultipartonInteractions:ecmPow	0.15	0.14	0.02	0.02	0.03
MultipartonInteractions:coreRadius	0.54	0.38	0.54	0.60	0.76
MultipartonInteractions:coreFraction	0.68	0.33	0.39	0.30	0.63
ColorReconnection:range	2.63	2.32	4.73	5.61	5.18
χ^2/dof	0.89	0.54	0.76	0.80	1.04

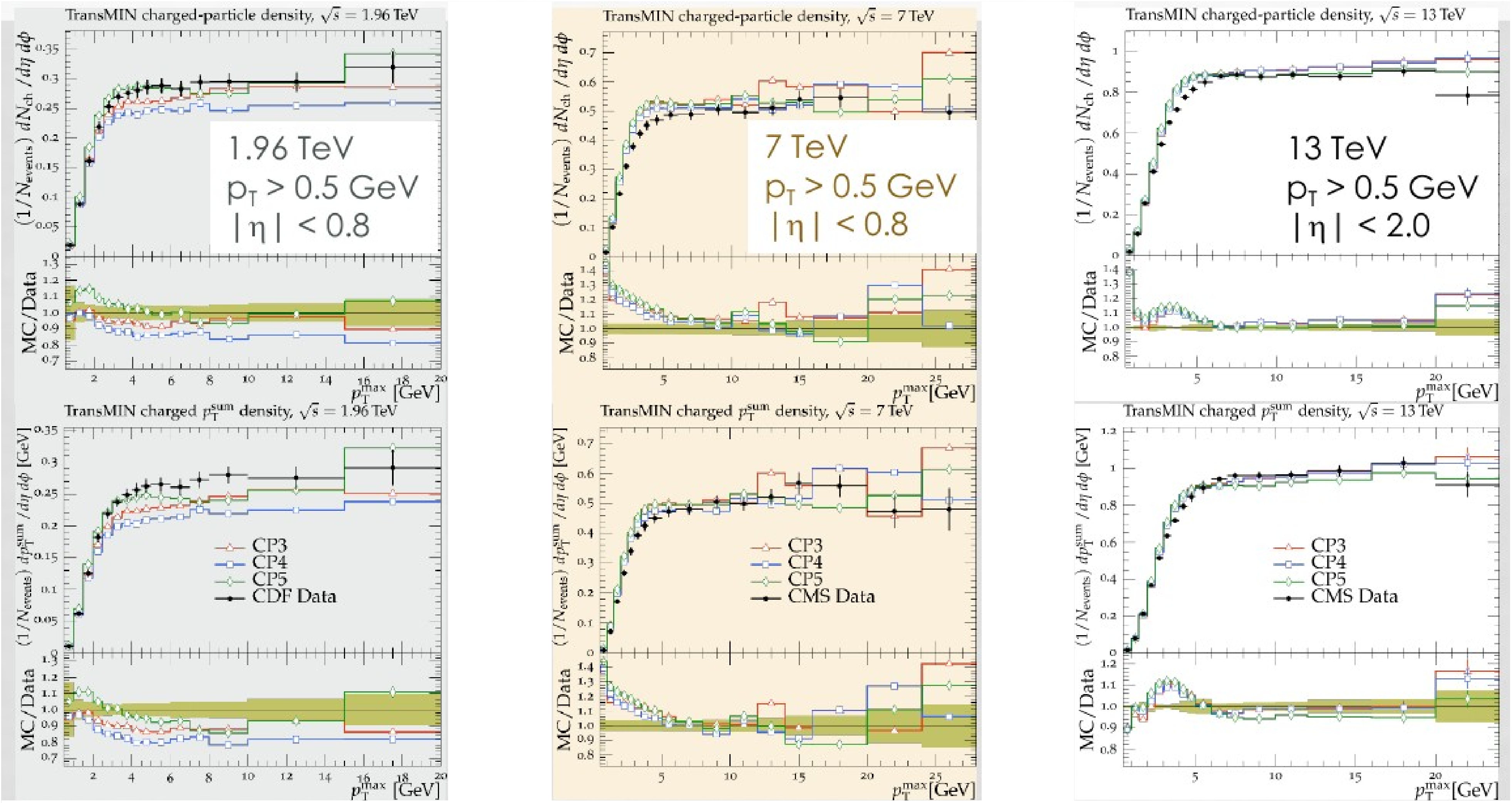
Performance of the new tunes – LO vs (N)NLO



- The behavior of the LO and (N)NLO tunes differs in the low p_T^{max} region, where MC/Data is up to 15% off
- Nevertheless, both the LO and (N)NLO tunes provide similar performance

$$p_T > 0.5\,\mathrm{GeV}$$
$$|\eta| < 2$$

Performance of the new tunes – Energy dependence



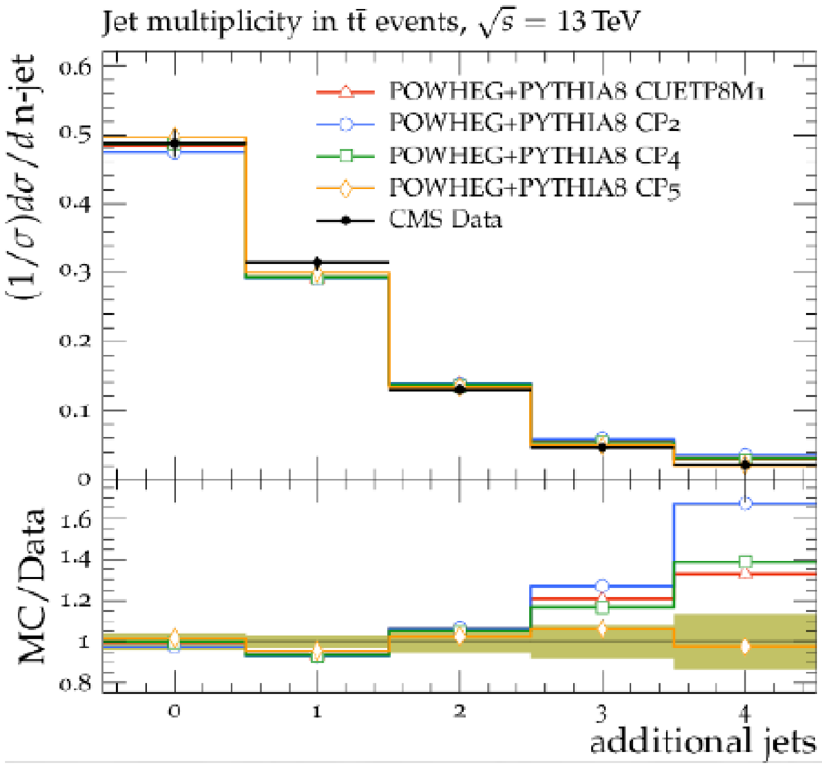
The NNLO based CP5 tune with rapidity ordering most stable over beam energy

Performance of the new tunes – jet multiplicities in $t\bar{t}$

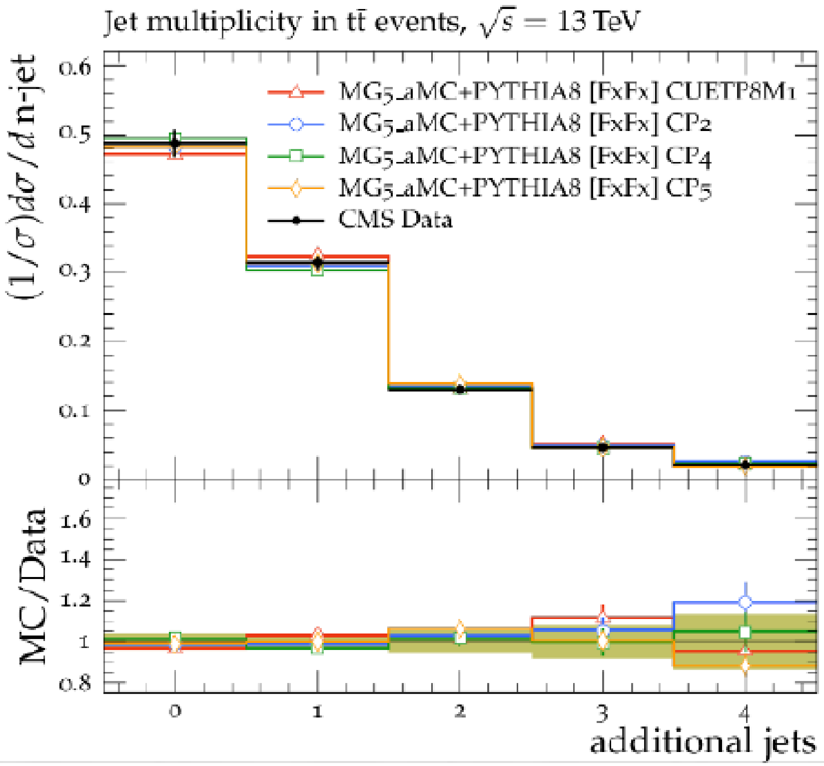
For **POWHEG** predictions the higher jet multiplicities mostly overestimated, only CP5 with rap-ordering gives correct rate

For **MC@NLO** predictions all tunes give similar performance

POWHEG (0-jets NLO)

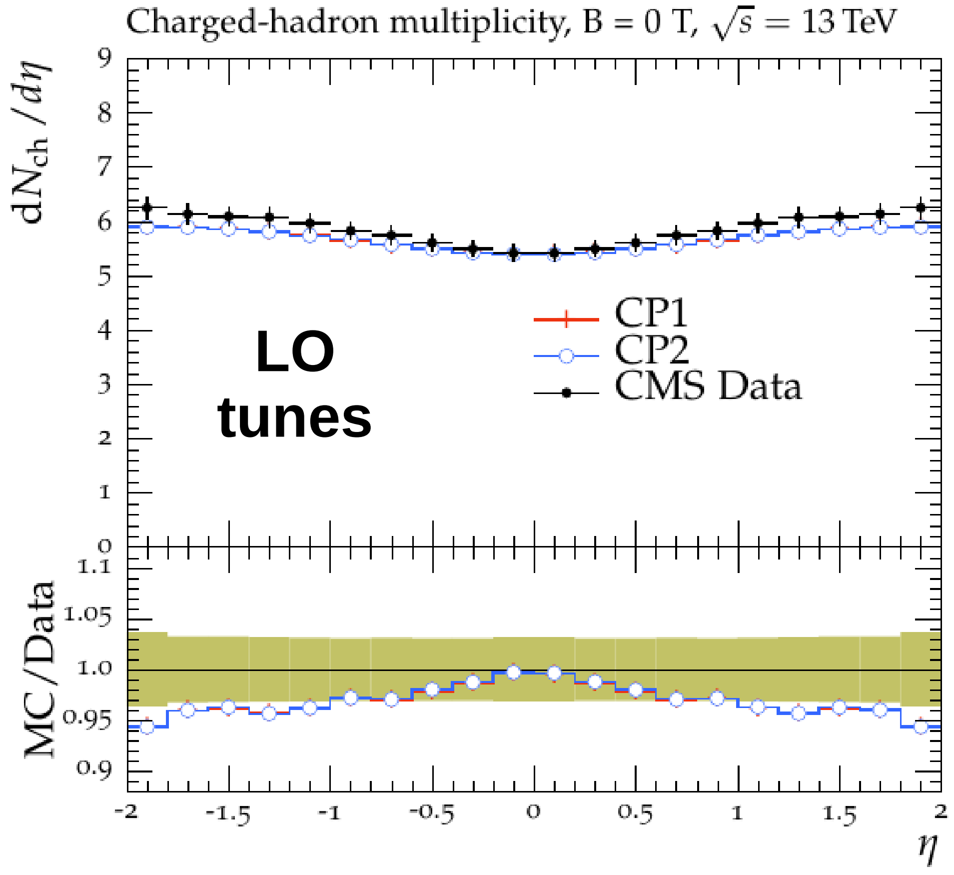


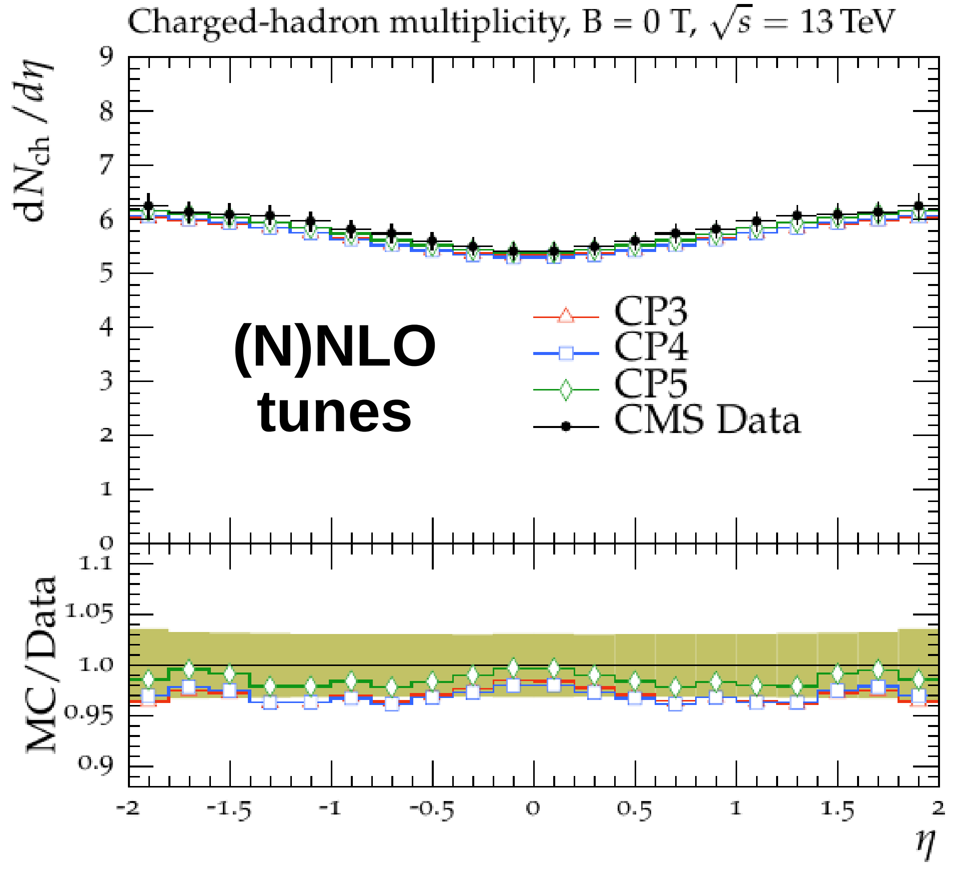
MC@NLO (2-jets NLO)



Performance of the new tunes – MB

- Charged hadron multiplicity for 0T data
- The data description similar for LO & (N)NLO tunes, the **CP5** performs slightly better



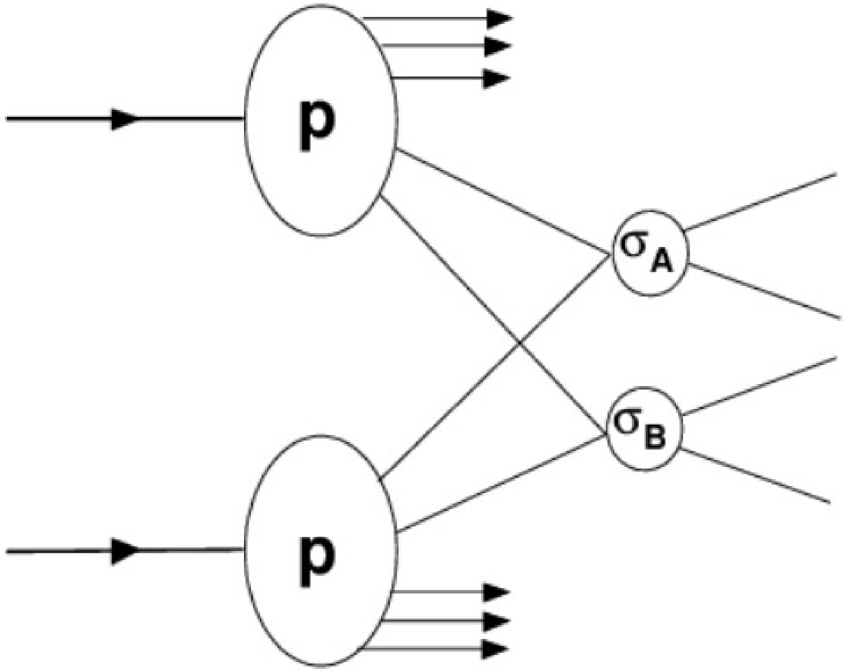


Double Parton Scattering

- Two partonic interactions at the comparable scales
- $\sigma_{\rm eff}$ defined as:

$$\sigma^{\rm DPS}_{AB} \stackrel{\rm def}{=} m \frac{\sigma_A \sigma_B}{\sigma_{\rm eff}}$$

$$A = B \Rightarrow m = 1/2$$
$$A \neq B \Rightarrow m = 1$$



DPS factorization formula:

double-parton PDF

$$\frac{{\rm d}\sigma_{\rm DPS}}{{\rm d}x_A {\rm d}x_B {\rm d}x'_A {\rm d}x'_B} = m\, \hat{\sigma}_A\, \hat{\sigma}_B \int {\rm d}\mathbf{y} F(x_A, x_B, \mathbf{y})\, F(x'_A, x'_B, \mathbf{y})$$

PDF

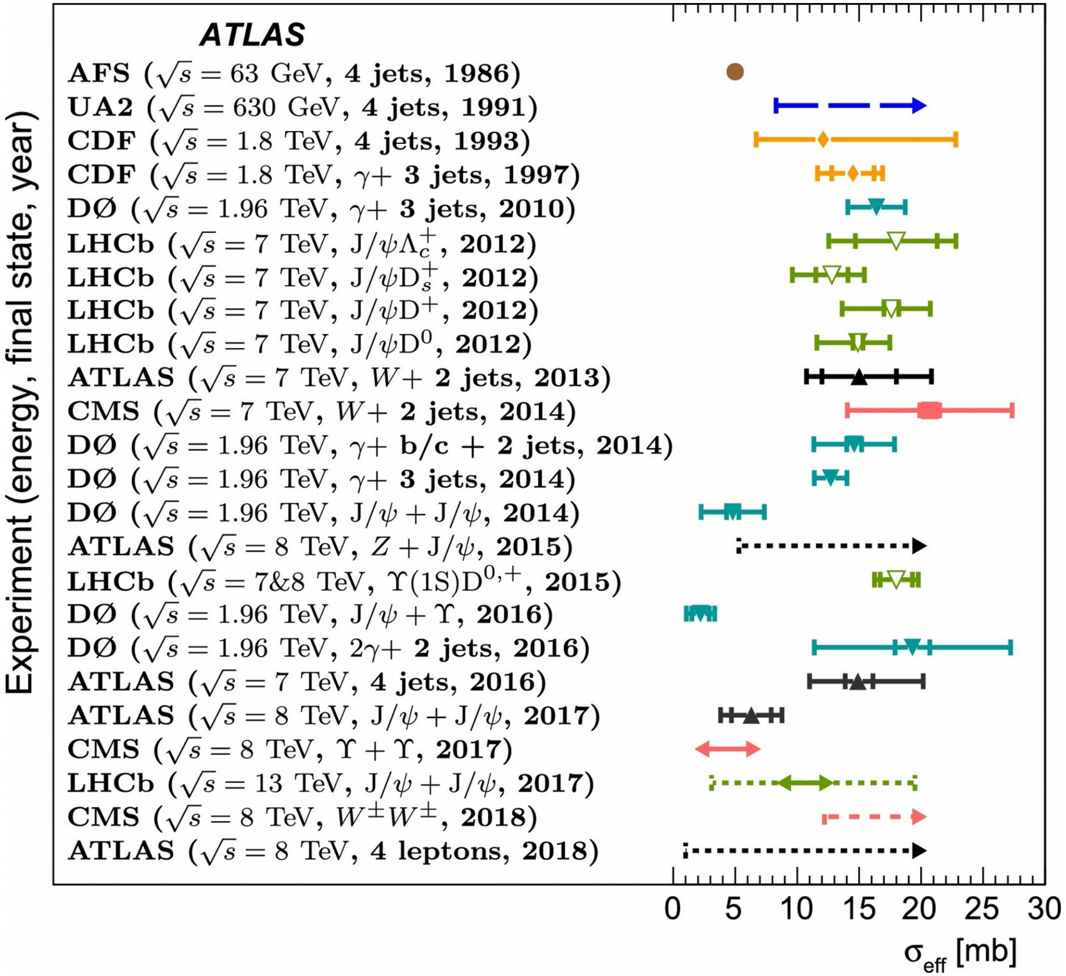
If $F(x_A, x_B, \mathbf{y}) = f(x_A) f(x_B) G(\mathbf{y}) \Rightarrow 1/\sigma_{\rm eff} = \int {\rm d}^2\mathbf{y} G(\mathbf{y})$

Double Parton Scatering at CMS

- At CMS, the DPS studied in several final states
- The 4j, 2j2b & same sign W discussed

Energy	Process1	Process2
7 TeV	j + j	j + j
7 TeV	b + b	j + j
7 TeV	W	j + j
7 TeV	γ + j	j + j
8 TeV	ϒ	ϒ
13 TeV	W	W

Phys.Lett. B790 (2019) 595-614



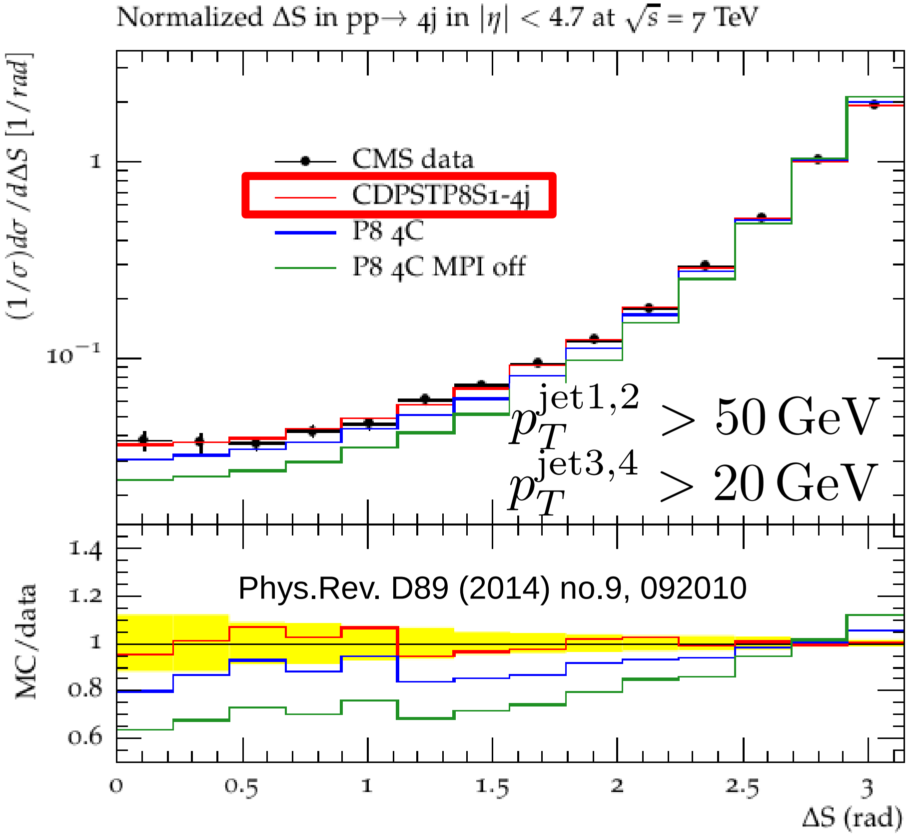
DPS in jet production (7 TeV)

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

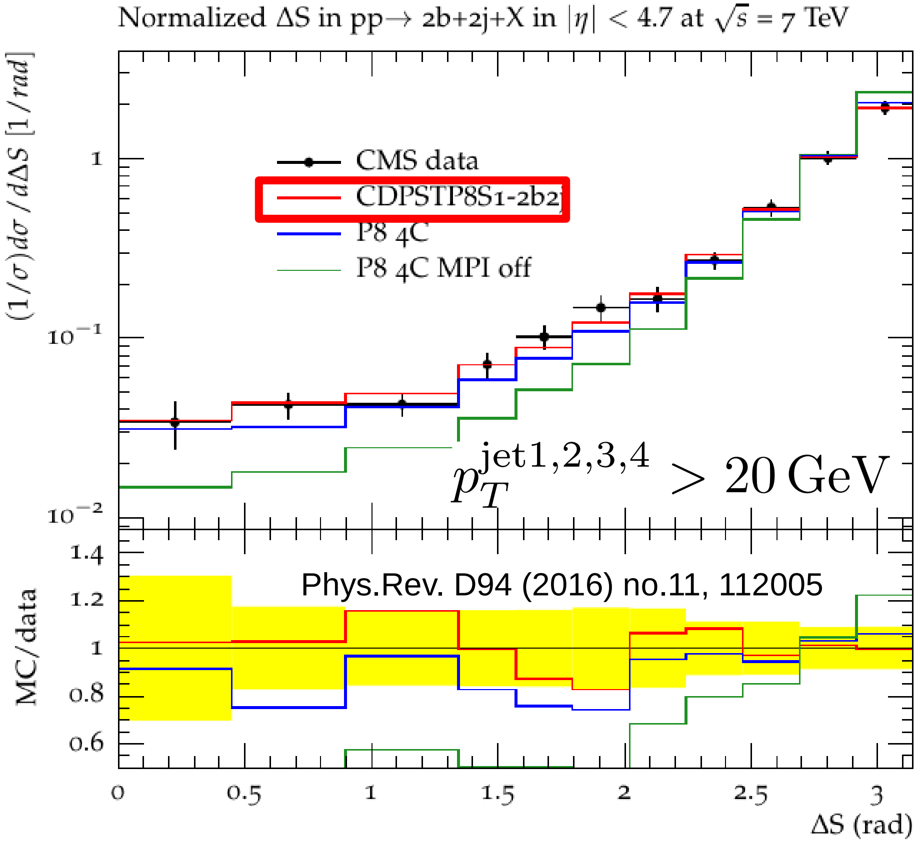
- The amount of DPS measured by the **tuning method** (MPI-sensitive parameters tuned for each process independently)
- The f_{EH} related to the matter profile and p_{T0}

$$\sigma_{\text{eff}} = \frac{\sigma_{\text{inel}}}{f_{\text{EH}}}$$

2j (2j) $\sigma_{\text{eff}}^{4j} = 21.3^{+1.2}_{-1.6}$



2j (2b) $\sigma_{\text{eff}}^{2j2b} = 25.2^{+4.1}_{-2.9}$



Gunnellini, Paolo, DOI: 10.1007/978-3-319-22213-4

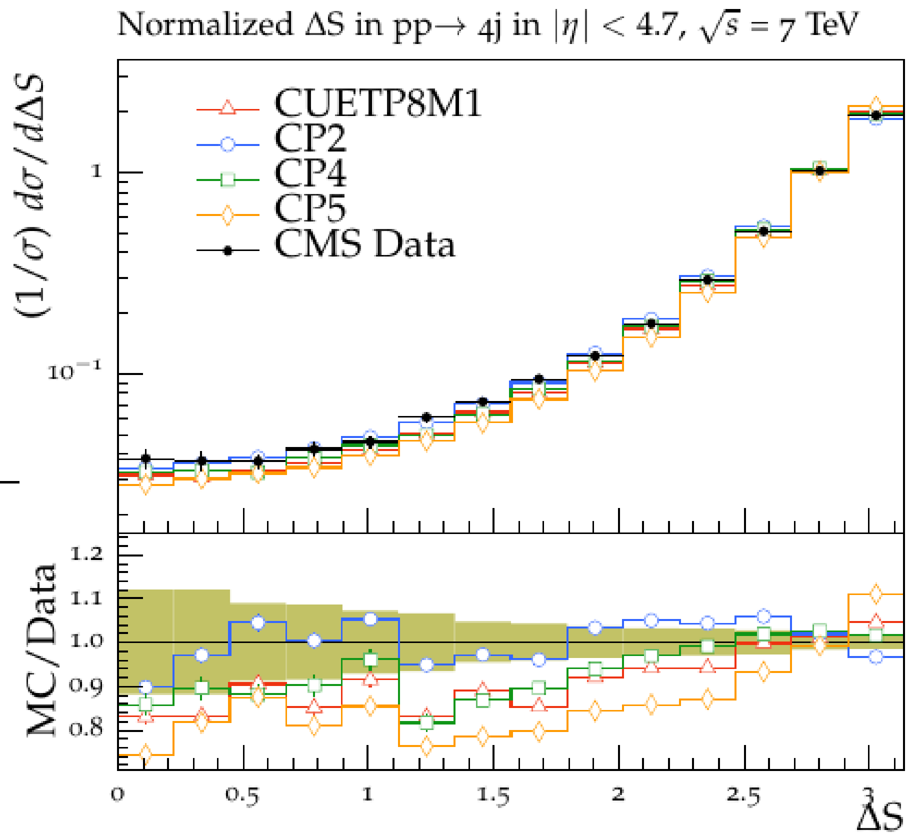
DPS in jet production (7 TeV)

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

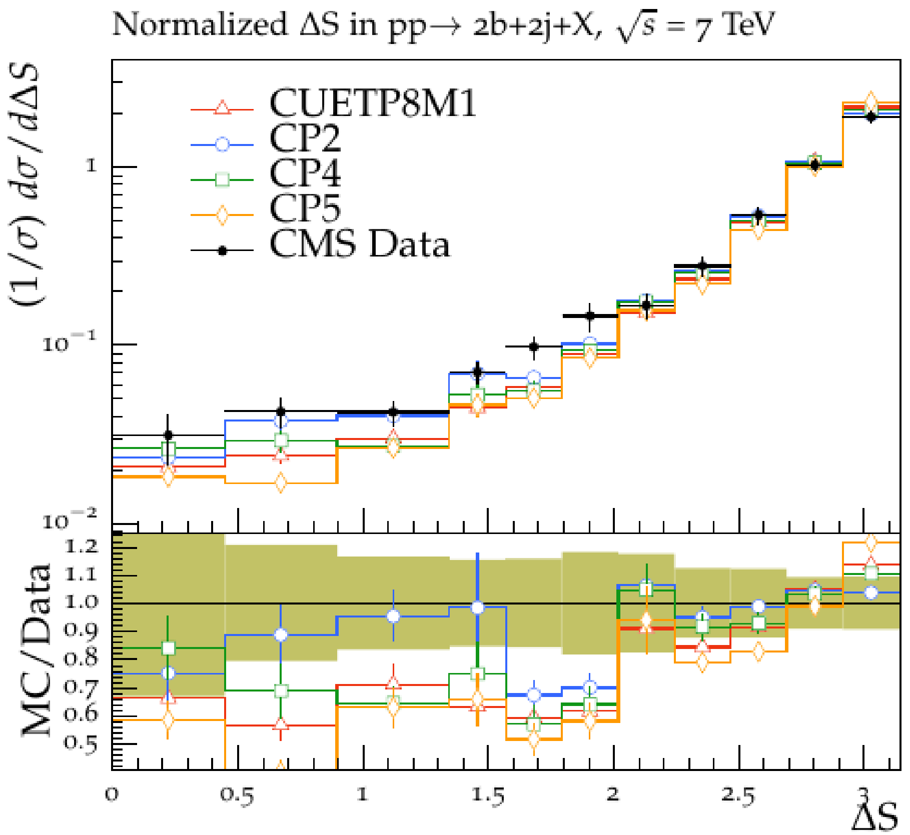
- New CMS tunes provide slightly worse description of the ΔS
- σ_{eff} consistent within unc.

	$\sqrt{s} = 7$ TeV σ_{eff} [mb]	$\sqrt{s} = 13$ TeV σ_{eff} [mb]
CP1	$26.3^{+1.0}_{-1.7}$	$27.8^{+1.1}_{-1.4}$
CP2	$24.7^{+1.0}_{-1.6}$	$26.0^{+1.0}_{-1.3}$
CP3	$24.1^{+1.0}_{-1.5}$	$25.2^{+1.0}_{-1.3}$
CP4	$23.9^{+1.0}_{-1.5}$	$25.3^{+1.1}_{-1.4}$
CP5	$24.0^{+1.0}_{-1.6}$	$25.3^{+1.0}_{-1.3}$

2j (2j) $\sigma_{eff}^{4j} = 21.3^{+1.2}_{-1.6}$



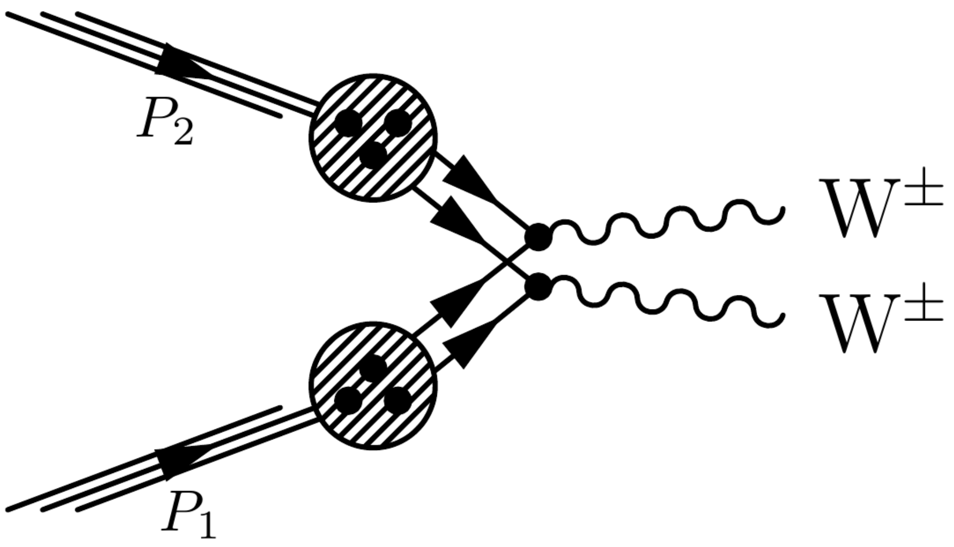
2j (2b) $\sigma_{eff}^{2j2b} = 25.2^{+4.1}_{-2.9}$



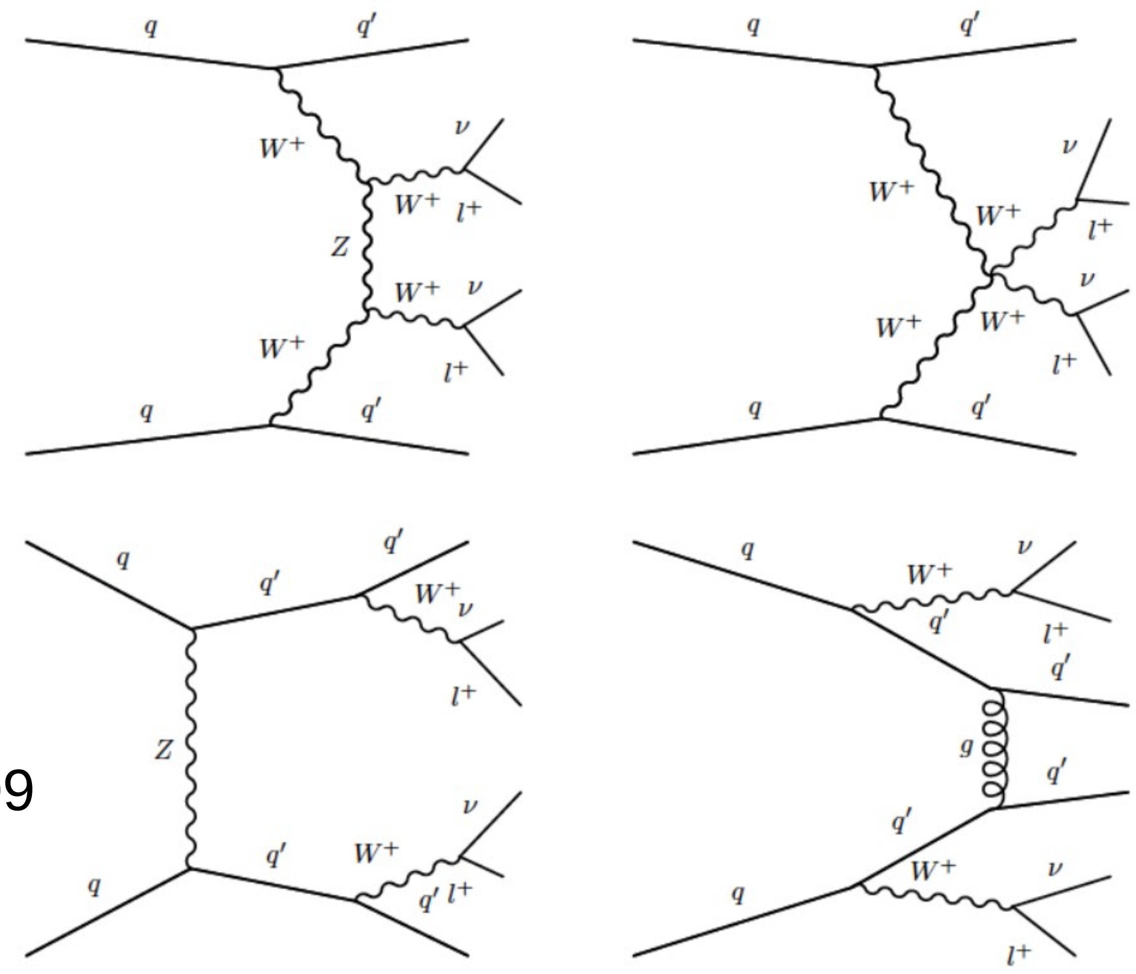
arXiv:1903.12179

DPS in same sign WW production (13 TeV)

DPS Production (signal)



SPS Production (BG)



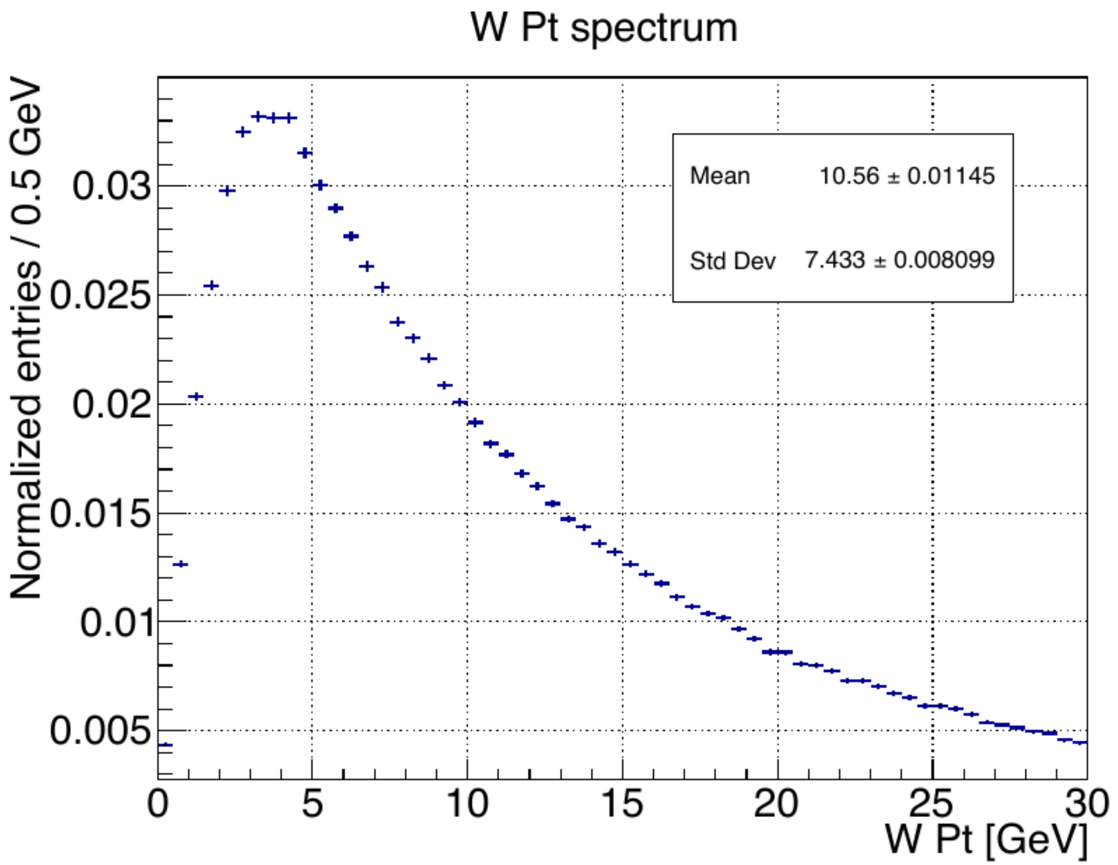
CMS-PAS-FSQ-16-009

DPS WW – Event selection

- Selection
  → veto on jets
  → tighter veto on b-jets (typically from ME)

- Inclusively produced W tends to have small p_T (=small jet recoil)

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)
$N_{\text{b-jets}} = 0$ ($p_{\mathrm{T}} > 25$ GeV)
veto on additional leptons
veto on hadronic τ lepton decays

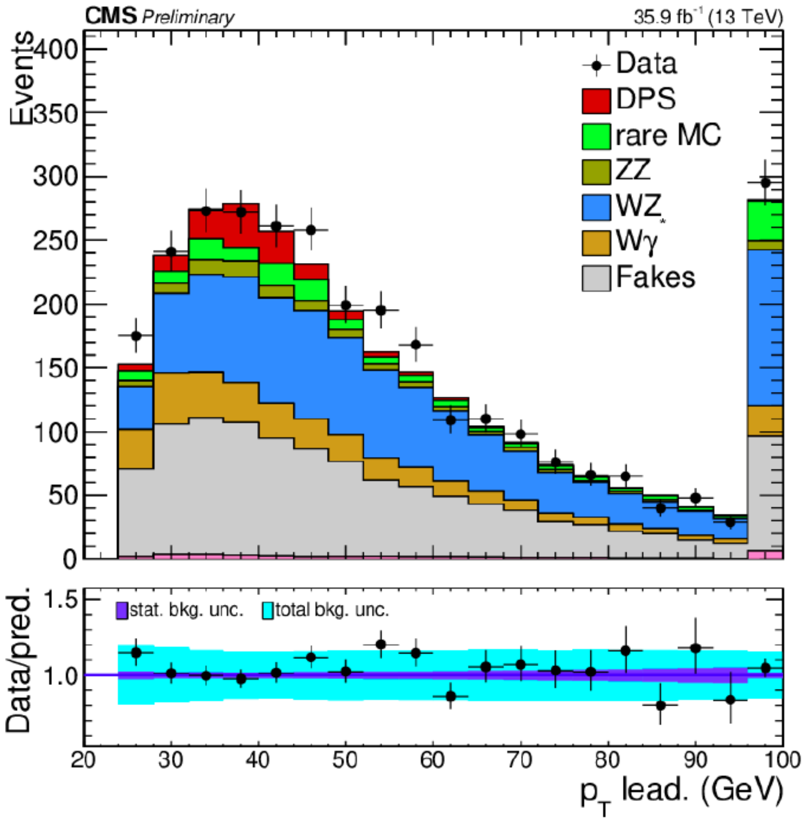


https://www2.physics.ox.ac.uk/sites/default/files/2012-03-27/w_mass_oxford_pdf_81806.pdf

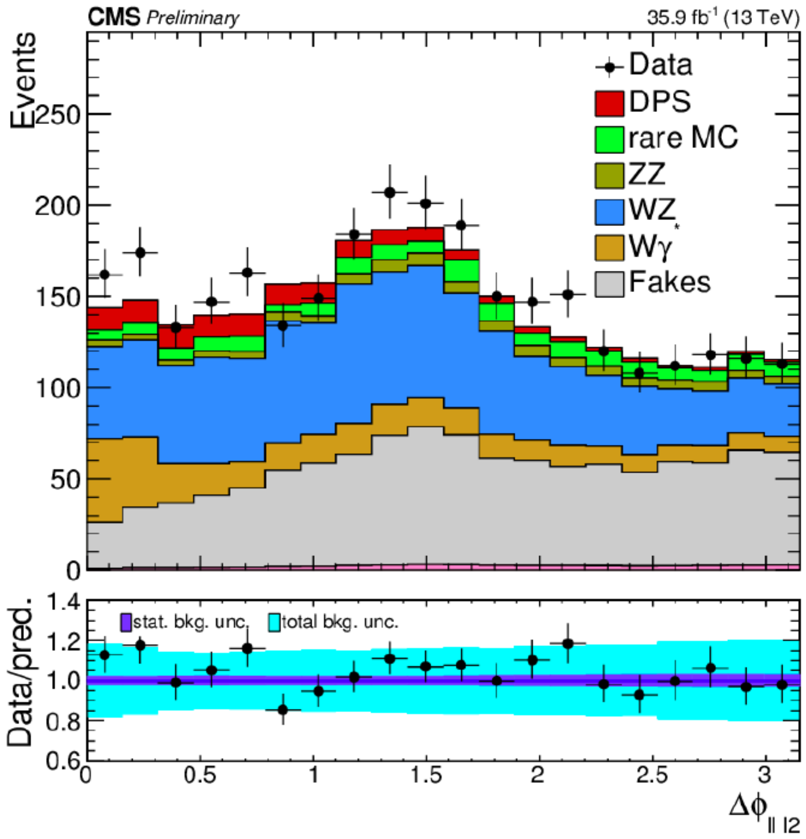
DPS WW – Event classification

- BDT constructed from 11 kinematic variables
- Crucial is the BG from W+Z production
- Fakes = missidentified leptons, mostly multi-jet + W+jet

p_T of the leading lepton



Azimuthal angle between ll & l2



DPS WW – Event classification

- The expected and observed event yields for 2016 data (35.9 fb^{-1})
- The DPS cross section for leptons with positive charge enhanced since $\sigma_{pp\to W^+}/\sigma_{pp\to W^-} \sim 1.4$

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

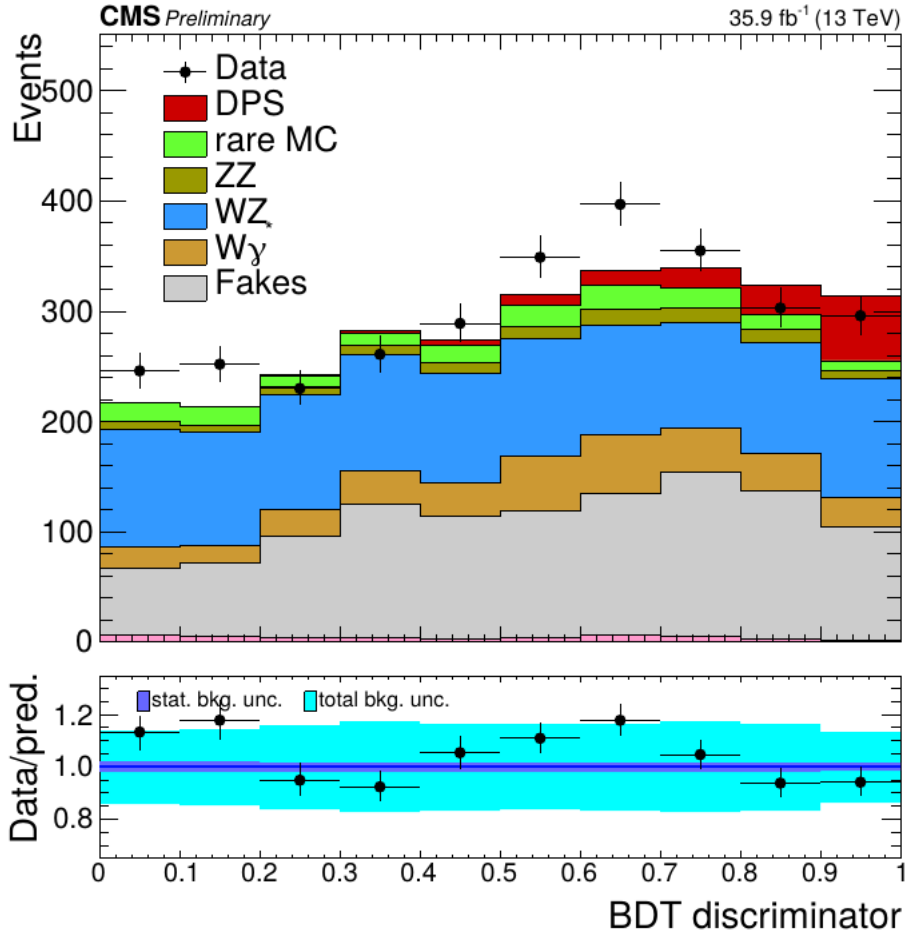
DPS WW – The DPS cross section

- Discriminator fitted by signal and BG MC templates
- The observed DPS x-section consistent with expectations

SecondHard:SingleW = on

Using σ_{eff} 20.7 mb (from W +2jet)

	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

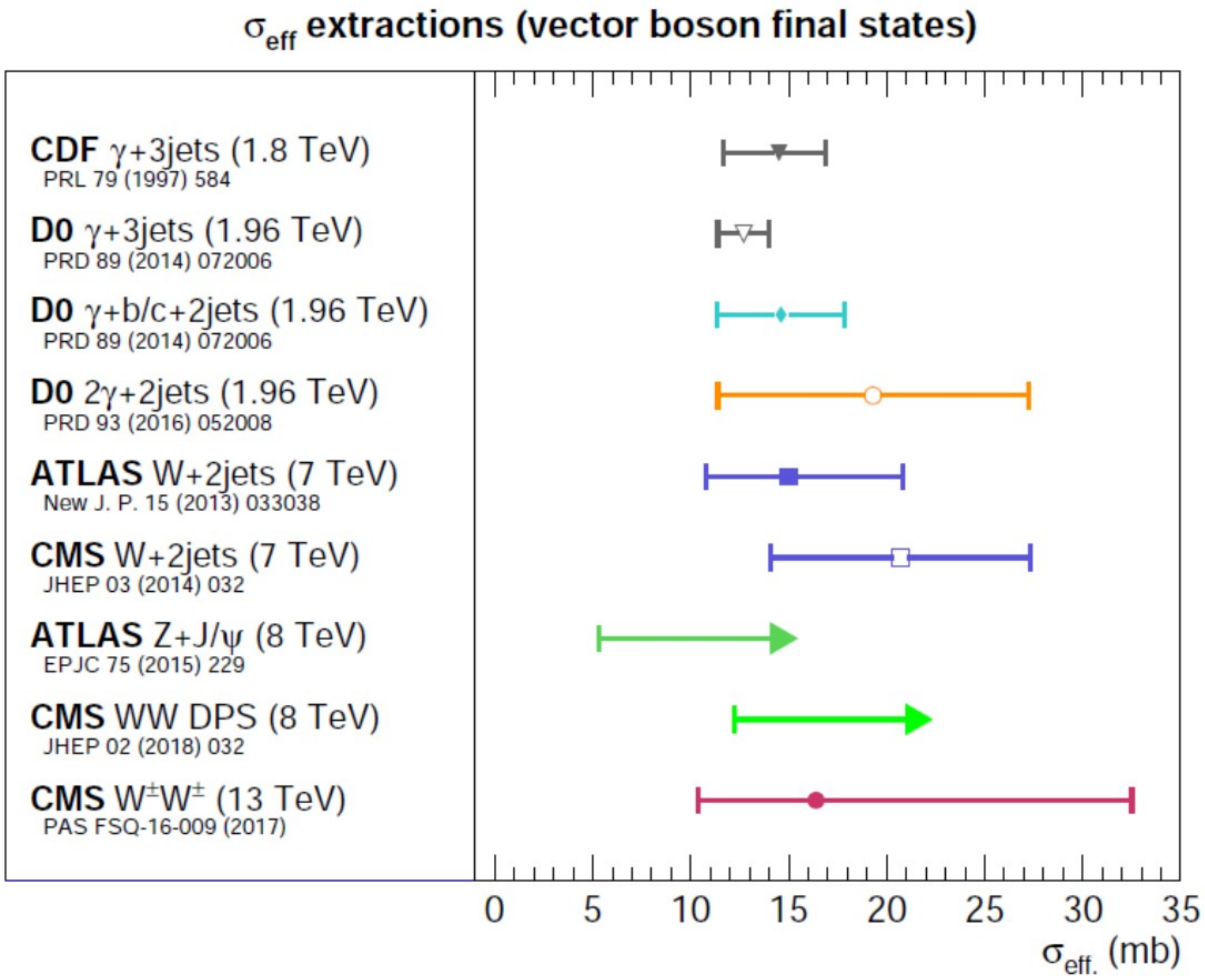


Effective DPS cross sections with V-boson

- On average σ_{eff} ~ 15mb
- No significant energy/process dependence observed

1.09 pb

$$\sigma^{DPS}_{W^\pm W^\pm} = \frac{1}{2}\frac{\sigma^2_{W^+} + \sigma^2_{W^-}}{\sigma_{\text{eff}}}$$



Conclusions

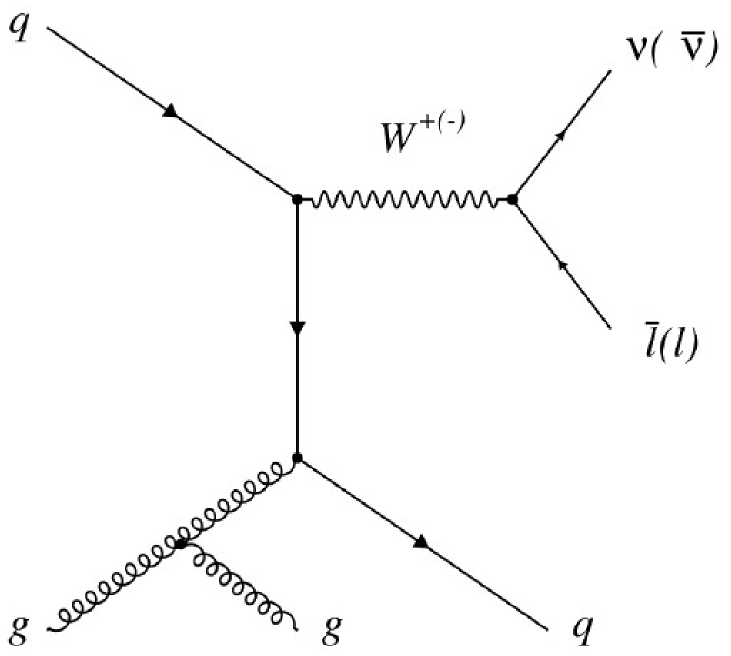
- New CMS 13 TeV tunes CP1-CP5 introduced
- At CMS the CP5 tune base on NNPDF 3.1 NNLO used as default since:
  → the (N)NLO PDFs better suited for matched NLO+PS MCs
  → gives best beam-energy stability for UE measurements
  → reasonably describes high jet multiplicities in ttbar

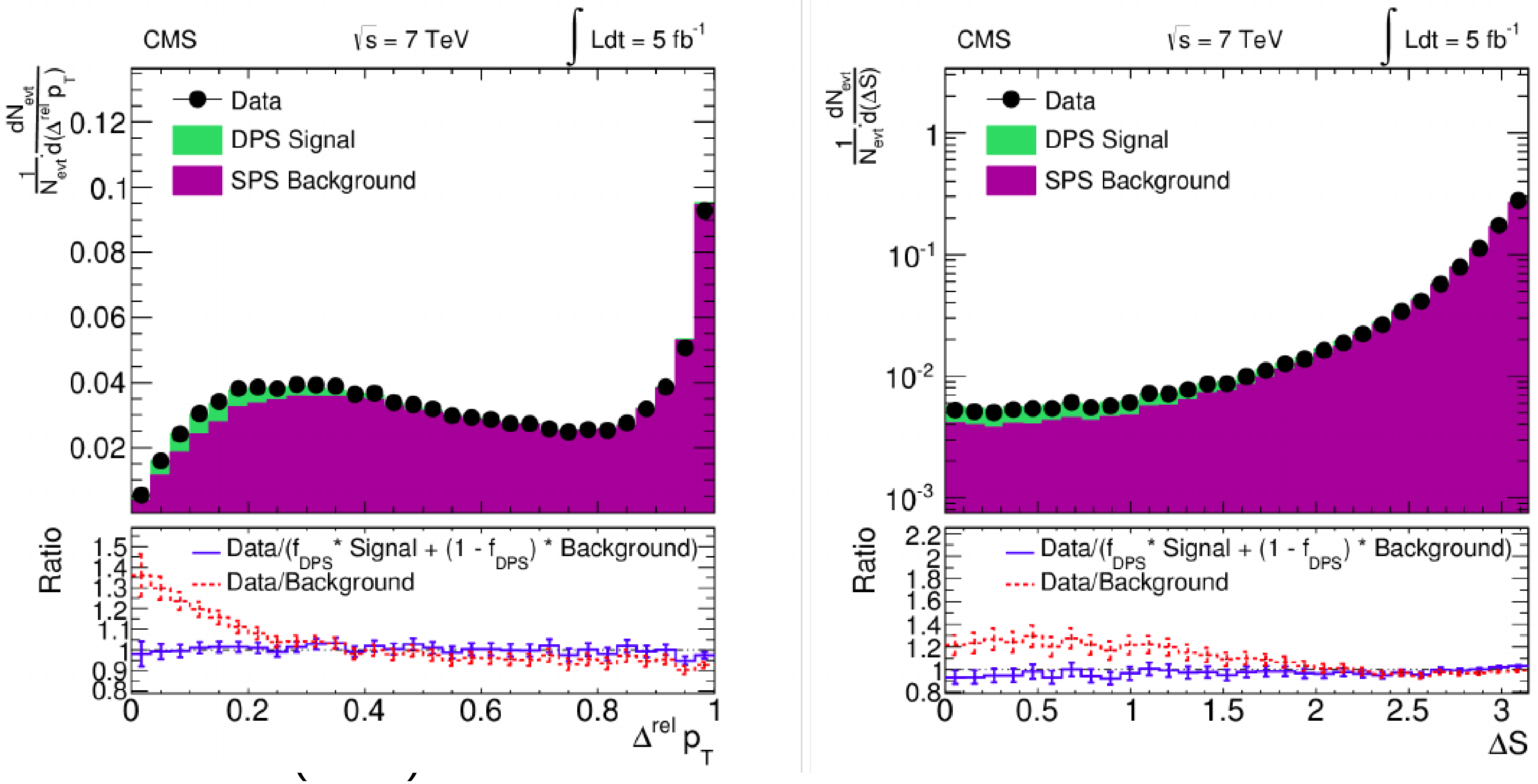
- The σ_{eff} measured in various final states, most recently in the same sign WW production at 13 TeV
- After selecting DPS-sensitive observables, the σ_{eff} can be extracted by:
  → template method
  → tuning method

Backup

W + jj DPS at 7 TeV

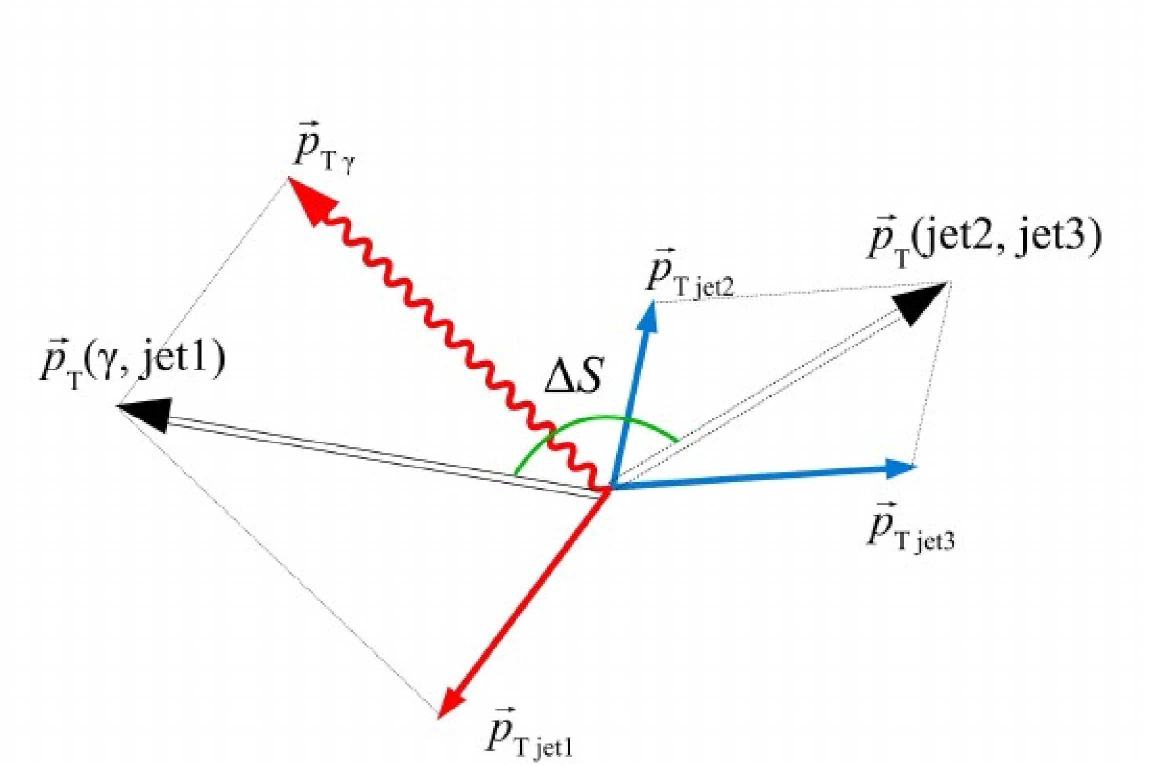
- W→ μν + 2 jets
- DPS fraction 5.5% ± 1.4%
- σ_{eff} = 20.7±0.8 (stat) 6.6 (syst) mb

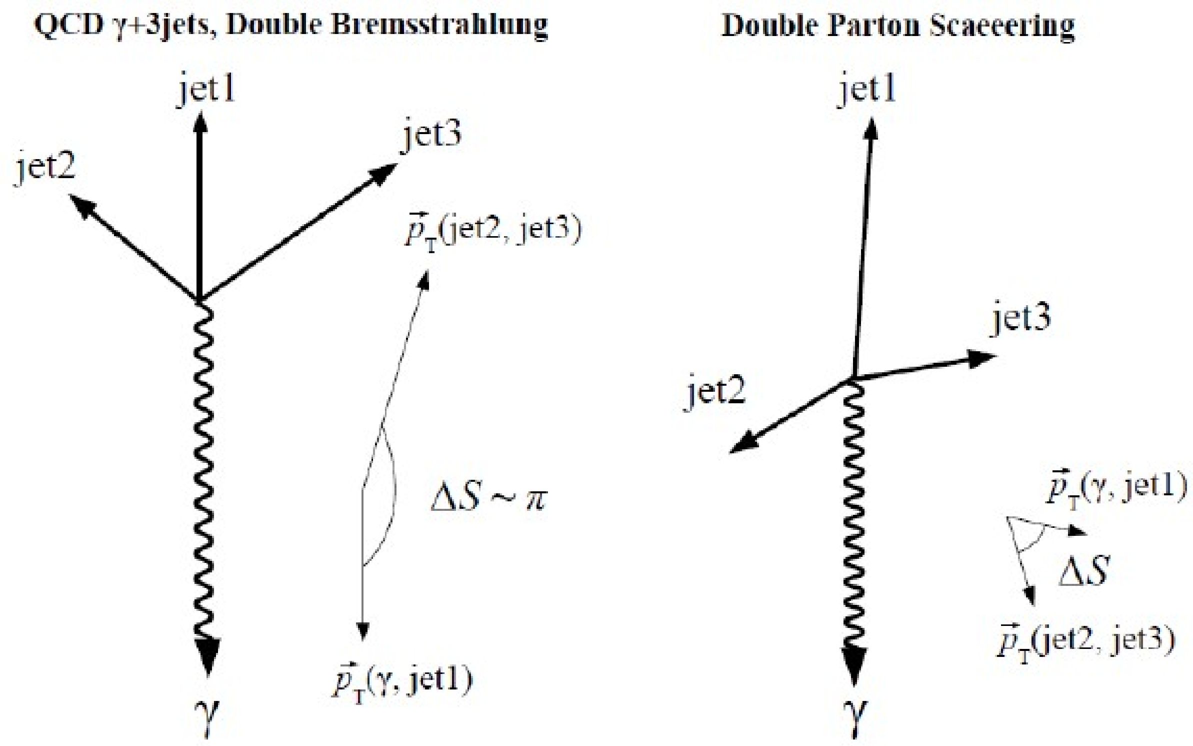




gamma + 3j DPS at 7 TeV

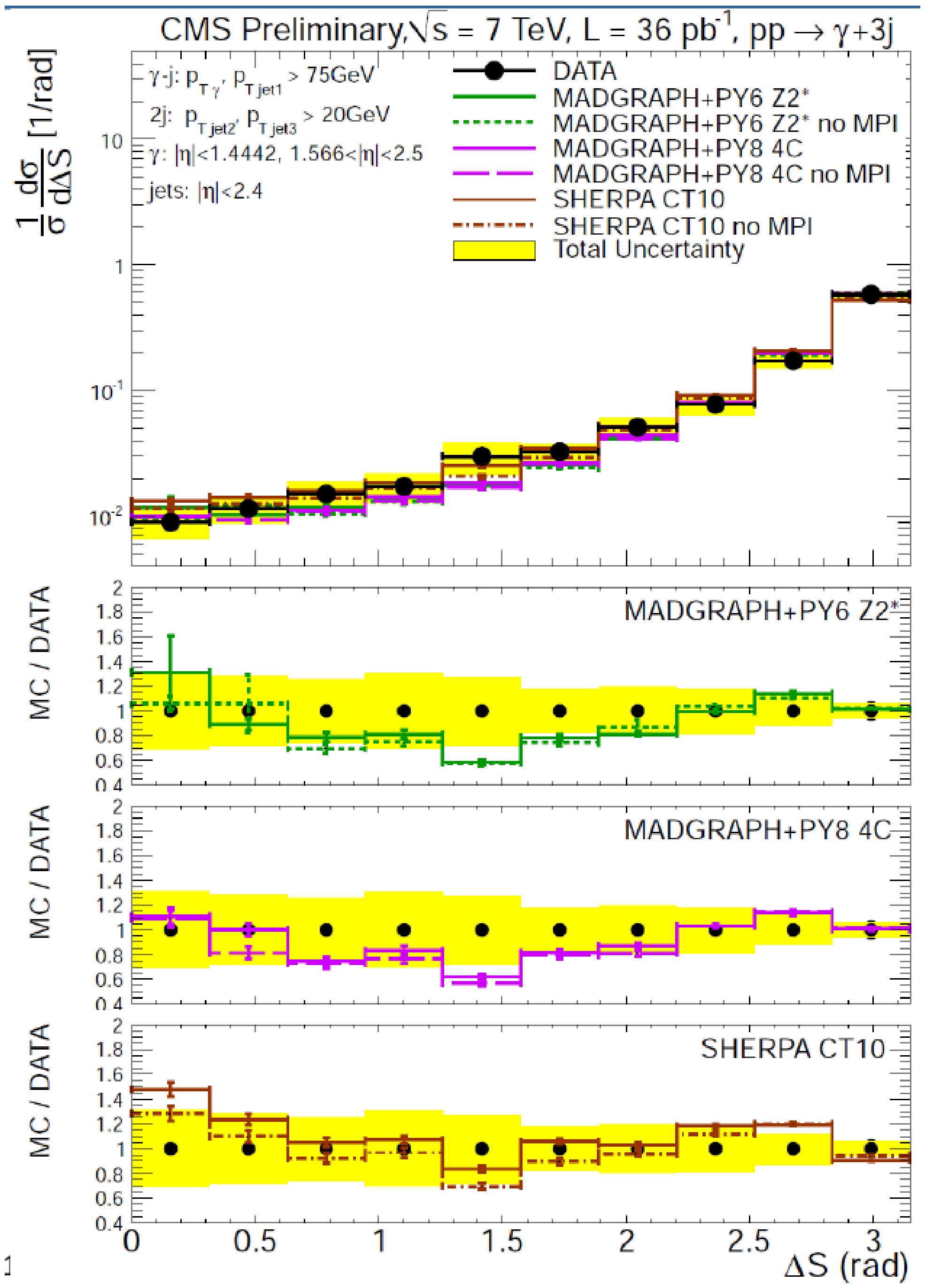
- Gamma + leading jet (p_T > 75 GeV)
- Two other jets (p_T > 20 GeV)
- 36 pb^{-1}



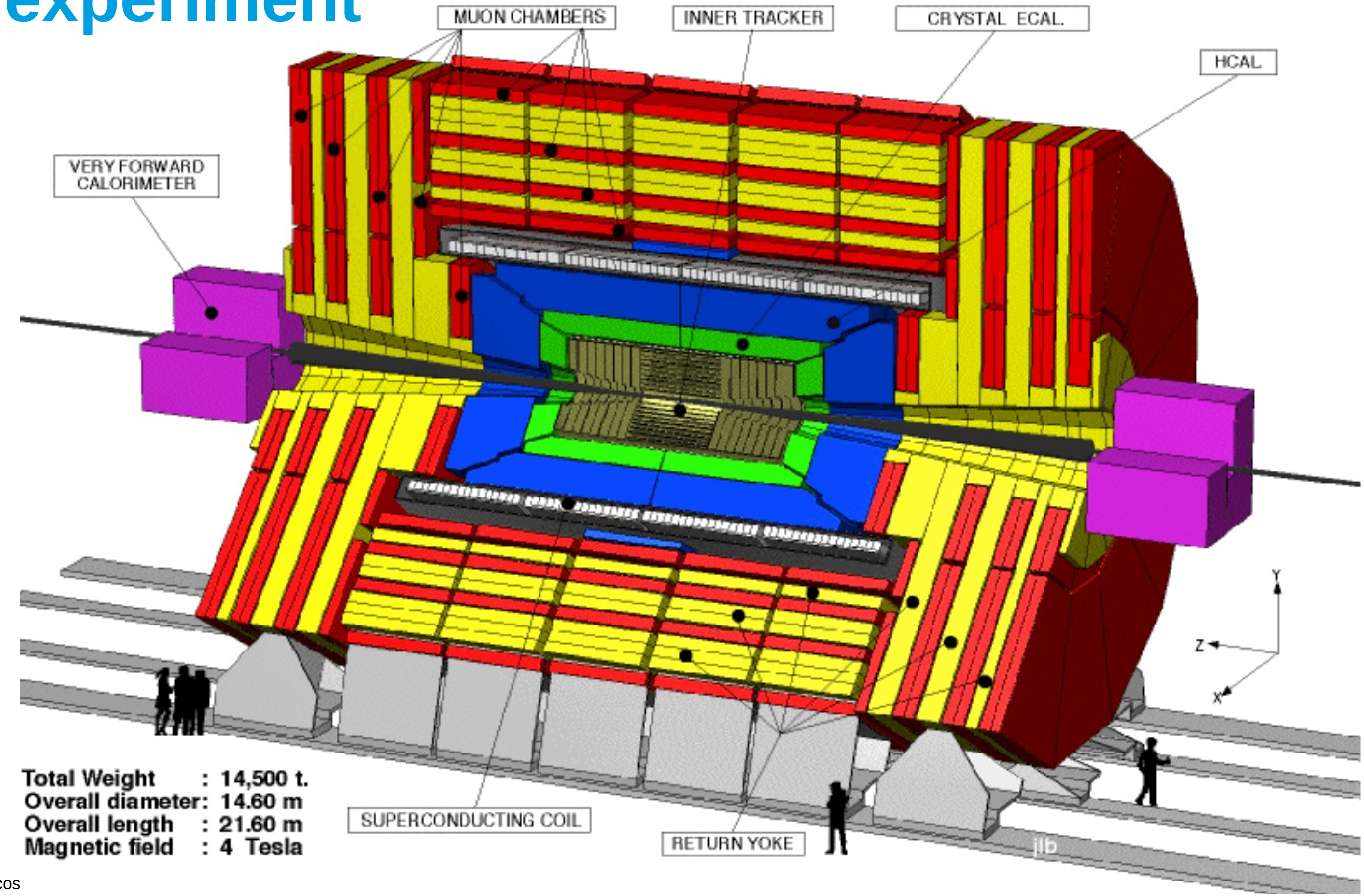


gamma + 3j DPS at 7 TeV

- Even the ΔS variable not very sensitive to DPS
- The no-MPI MC provides by chance slightly better data description
  → other effects more important than MPI for this process
- Conclusion on DPS not possible within given precision



CMS experiment



CMS experiment