Modelling the data at the LHC

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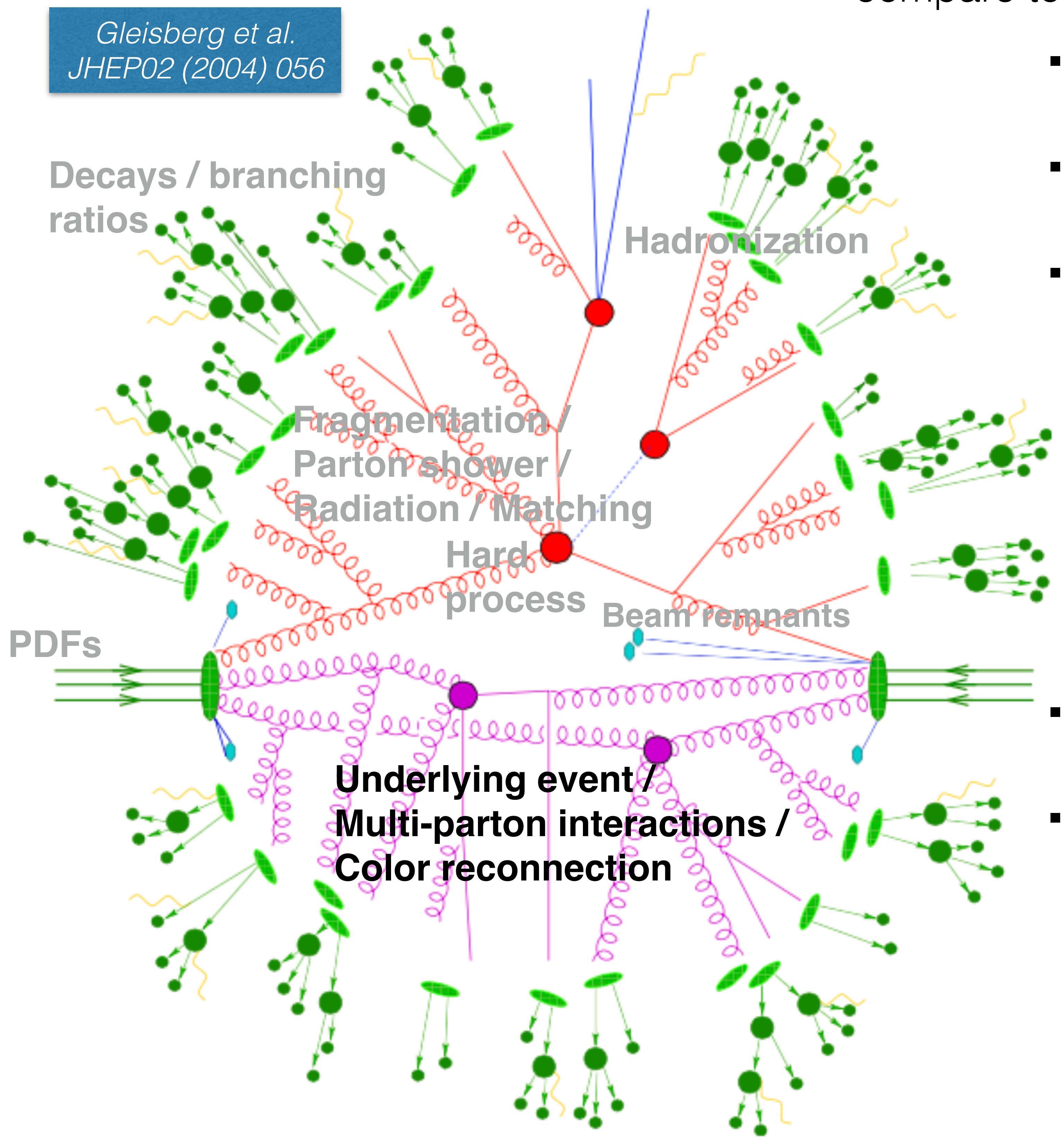
for the ATLAS and CMS Collaborations

Event Modelling at the LHC

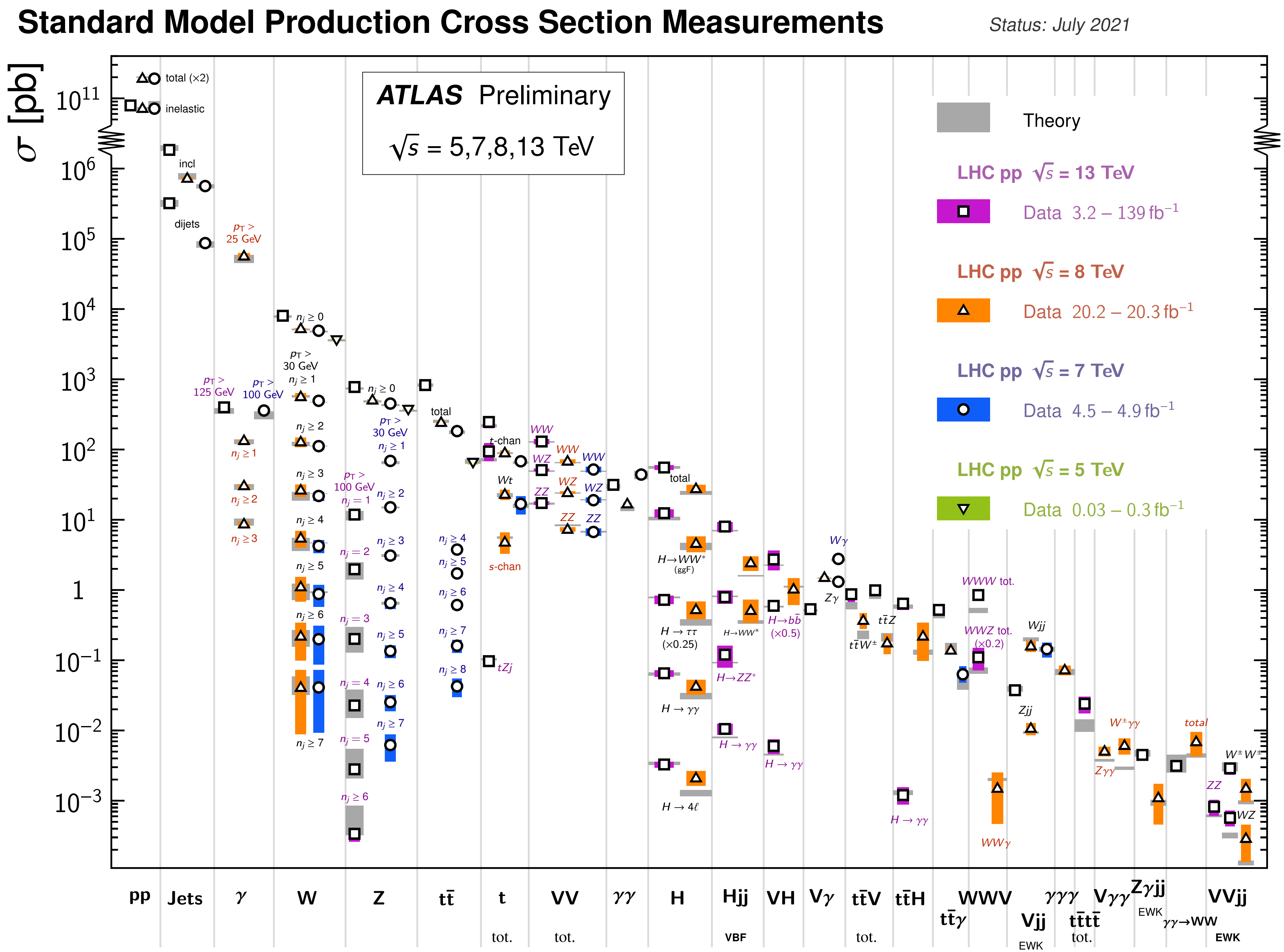
- Measurements at hadron colliders rely on large scale Monte Carlo production.
  - Interpretation of data — test SM with more accurate and precise calculations to understand perturbative and non-perturbative QCD as well as electroweak effects.
    - Soft QCD measurements
    - Precision measurements (e.g. top quark mass) dominated by theory uncertainties
    - Dedicated measurements to better understand and constrain each source of modelling uncertainty —> Underlying event in ttbar, Z+jets, …
  - Many cases in which irreducible backgrounds extrapolated to signal phase-space regions for new physics searches or rare SM process measurements through predictions using MC simulations.
    - Dedicated measurements in specific or extreme phase-space regions in new physics searches

Event Modelling at the LHC

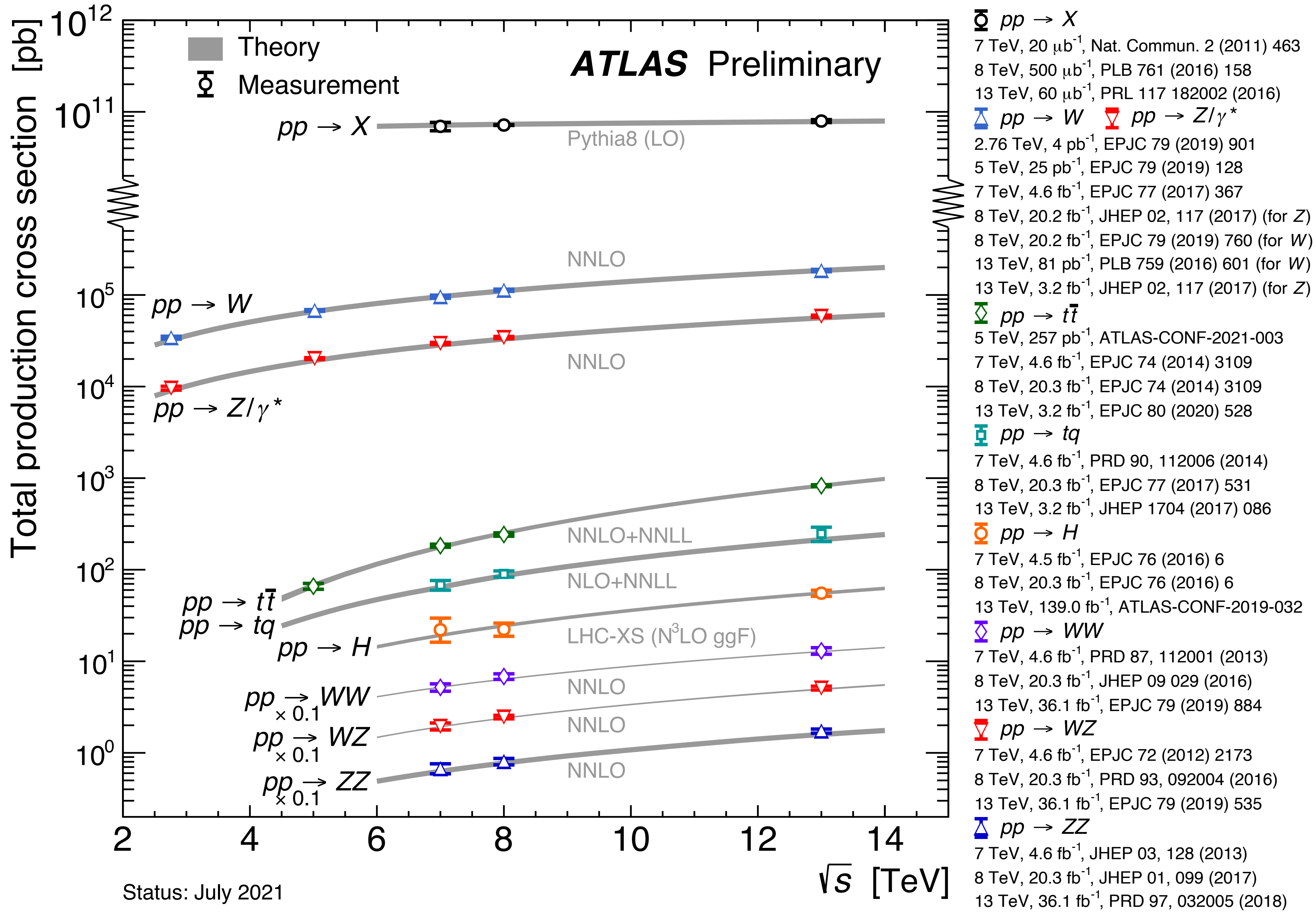


- Many pieces, approximations, parameters, settings to compare to data and tune.
  - Matrix element (ME) generation: Sherpa, MG5_aMC, POWHEG BOX, Pythia, Herwig, Alpgen, …
  - Hadronization and parton shower (PS): Pythia, Herwig, Ariadne, … and tunes.
  - Depending on the process/generator Multi-leg LO and (N)NLO consistently matched to the PS with N number of extra jets
    - Matching/merging prescriptions: MC@NLO, POWHEG, KrkNLO, CKKW(-L), MLM, MEPS@NLO, MONLO, FxFx, UNLOPS, Herwig7, Matchbox, …
    - e.g. DY MG5_aMC@NLO+Pythia8 with MLM — complex process up to 4 additional jets
  - Particle decays and QED corrections: EvtGen, Tauola, Photos, …
  - Other essential tools with diverse scopes: Rivet, Professor/Apprentice, HepMC, FastJet,…

A recent review and for references: Valassi, Yazgan, McFayden et al. CSBS 5 (2021) 12



- Cross sections measured at the LHC (both by ATLAS and CMS) for > 14 orders of magnitude.
- SM inclusive cross section predictions in very good agreement with data.



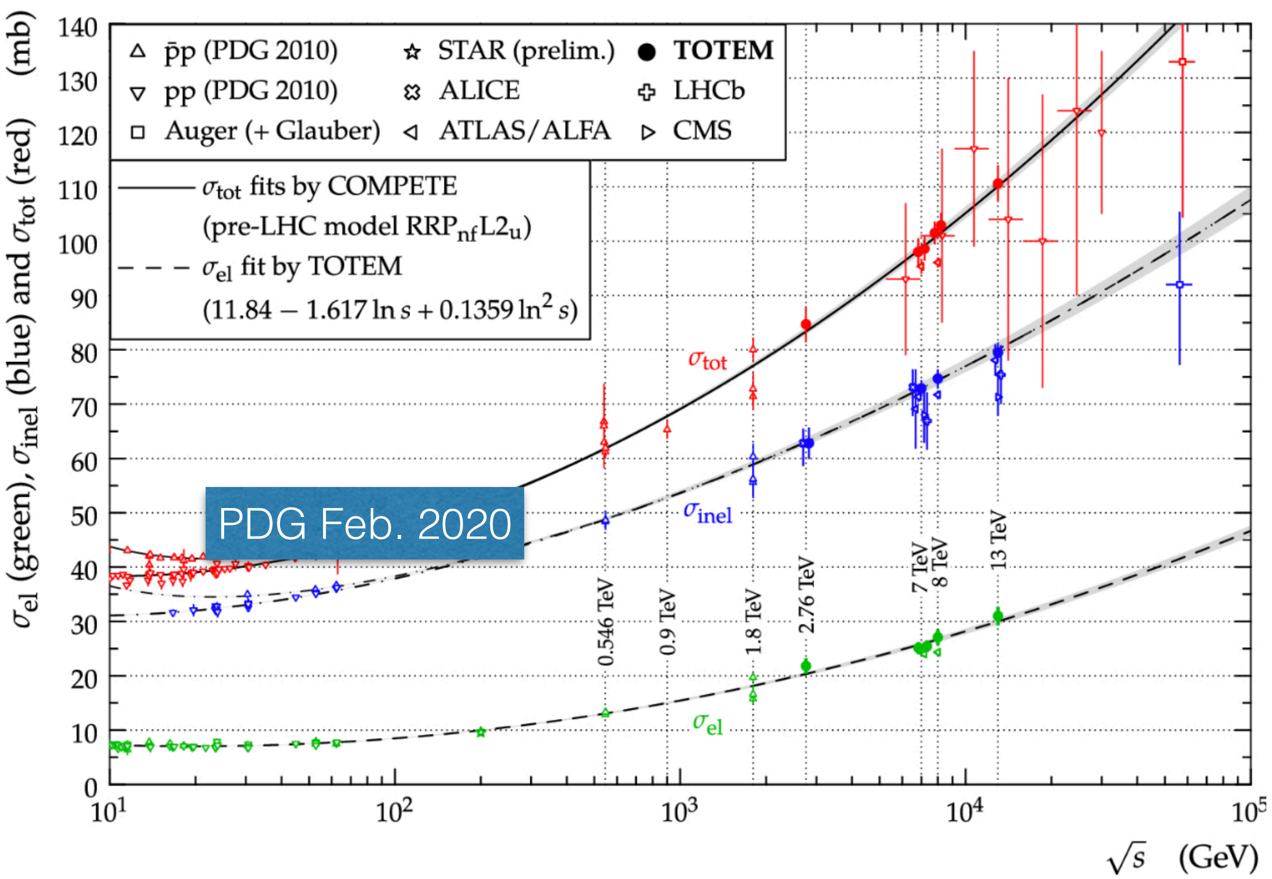
- At different $\sqrt{s}$ and up to NNLO for many processes (and recently up to N^{3}LO for some of them).
- No sign of new physics —> the effects may be subtle and may require precision measurements.
- Each process and piece deserves a full presentation. I'll very briefly show only a few in ~17 min.

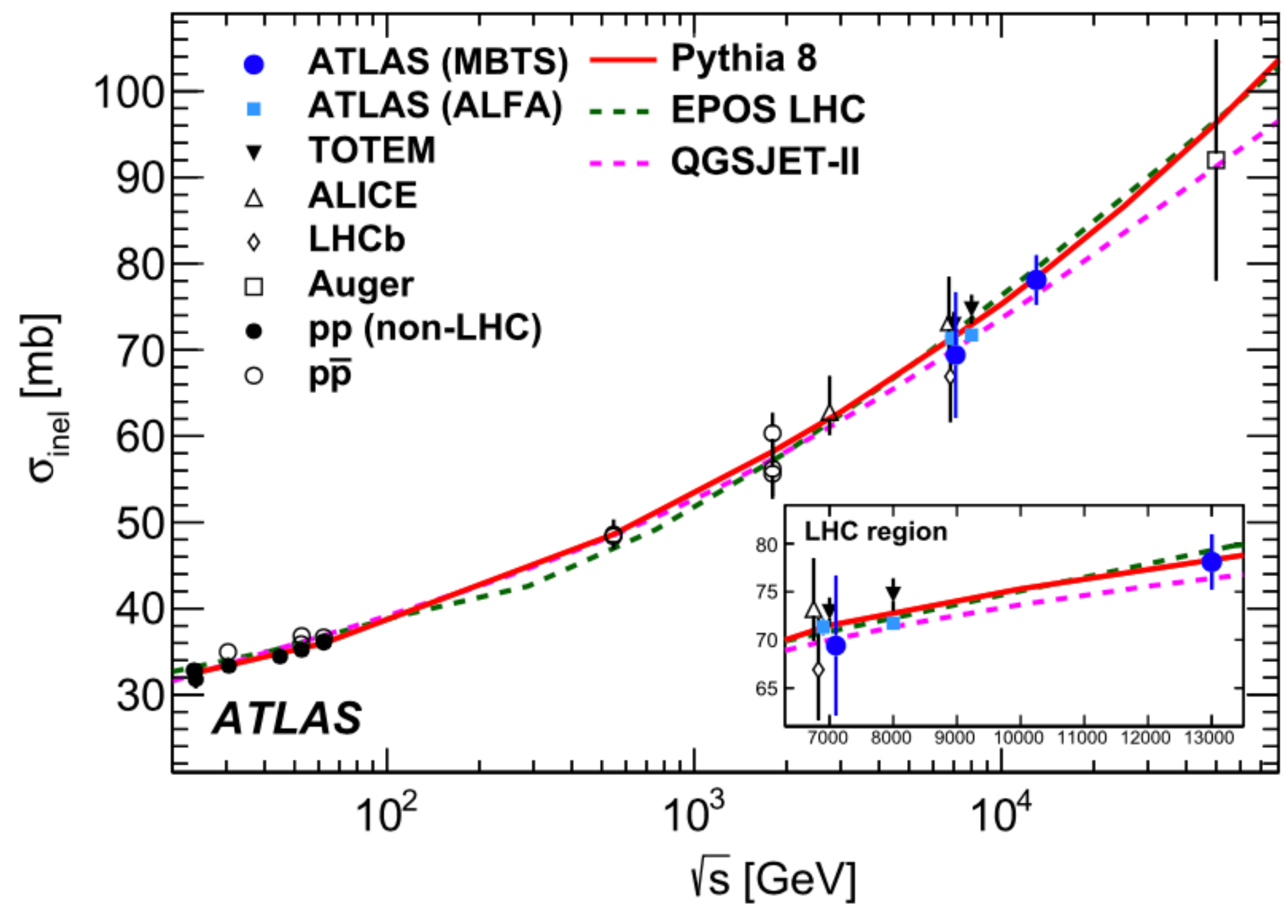
Total cross-sections

PRL 117(2016)182002

- Rise of pp cross-sections with √s predicted by Heisenberg (1952) and observed at the CERN ISR (1973).
- Probes non-perturbative QCD.
- Unitarity, analyticity, and factorization arguments—> upper bound on total hadronic cross sections that prevents a rise more rapid than $\ln^2(s)$.
- Collider (up to 13 TeV) and cosmic rays (up to ~60 TeV) data show cross sections rise logarithmically with center of mass energy.

- ATLAS 13 TeV measurement of inelastic pp cross section using 60 μb^{-1}.
- Inelastic events are selected with rings of plastic scintillators in the forward region ($2.07<|\eta|<3.86$).
- σ_{inel}(fiducial $M^2_X/s > 10^{-6}$) = 68.1+/-0.6(exp)+/-1.3(lum) mb. M^2_X=larger invariant mass of the two hadronic systems separated by the largest rapidity gap in the event.
- σ_{inel}(extrapolation to full phase space using 7 TeV measurements) = 78.1+/-0.6(exp)+/-1.3(lum)+/-2.6 mb.





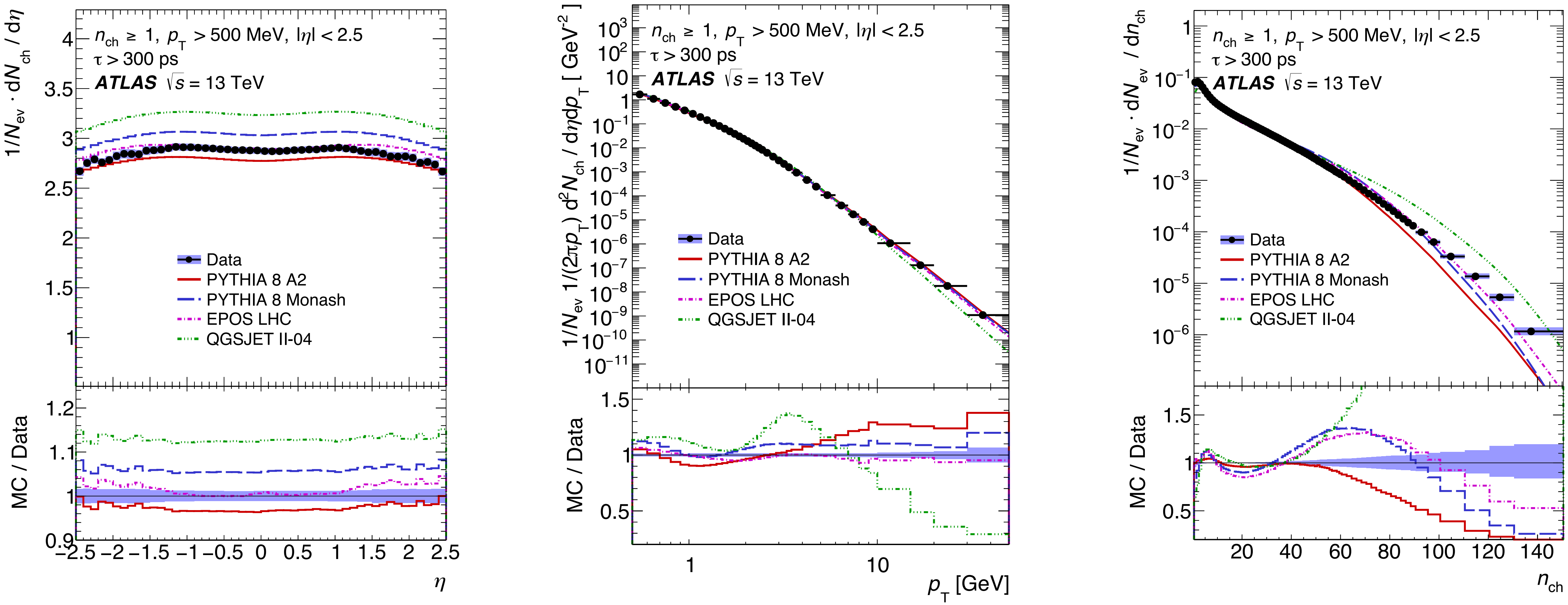
For the recent LHC measurements see, e.g.:

- Inelastic cross sections at 13 TeV [ATLAS]
- Elastic differential cross section at 13 TeV [TOTEM]
- Inelastic pp cross section at 13 TeV [CMS]

Measurement in good agreement with PYTHIA8 and EPOS in the LHC region and is consistent w/ the inelastic cross section increasing with center of mass energy.

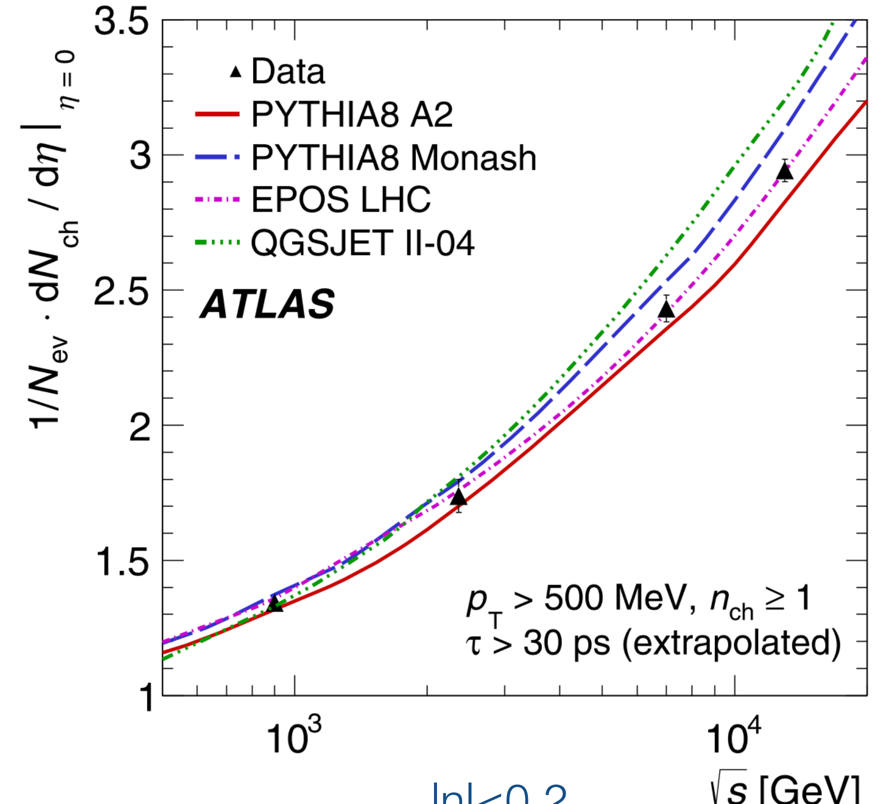
Minimum Bias at 13 TeV with ATLAS with 170 μb^{-1}

PLB 758 (2016) 67



Generator	Version	Tune	PDF
PYTHIA 8	8.185	A2	MSTW2008LO [21]
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [22]
EPOS	LHCv3400	LHC	N/A
QGSJET-II	II-04	default	N/A

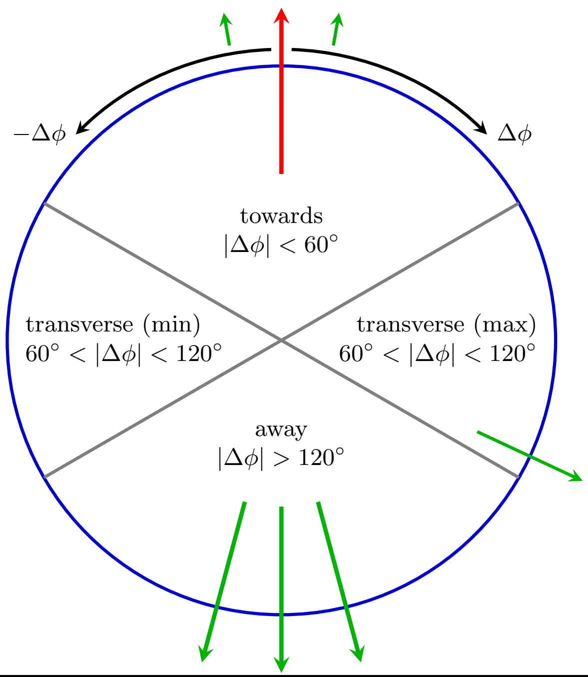
- Dominant systematic uncertainty: track reconstruction efficiency
- Agreement of predictions and data not perfect.
- EPOS: best description of the data (also vs √s).
- Pythia8 with A2 and Monash tunes provide reasonable descriptions.
- QGSJET-II worst description of the data.

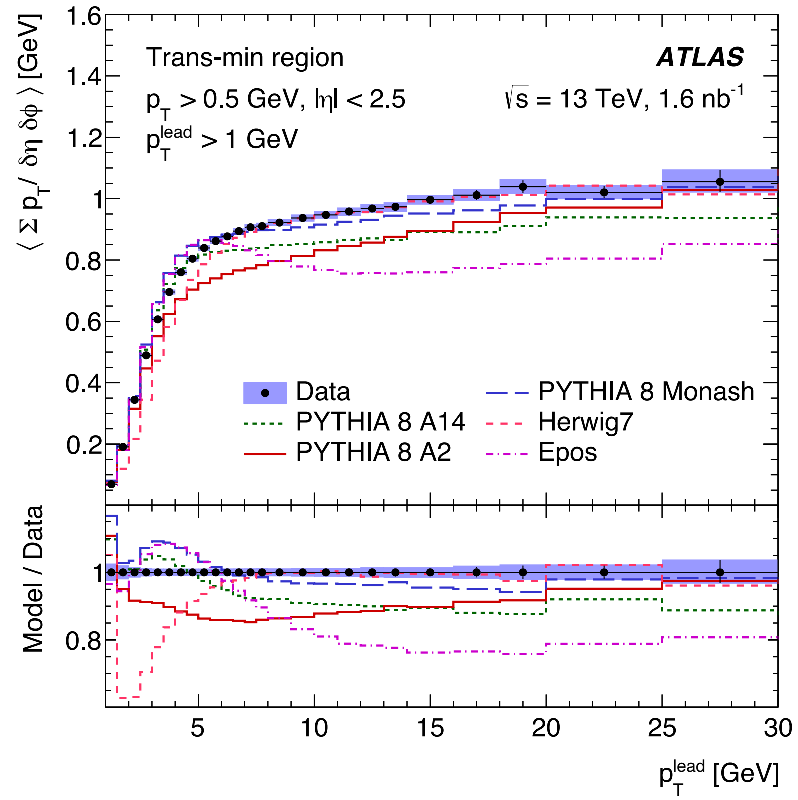


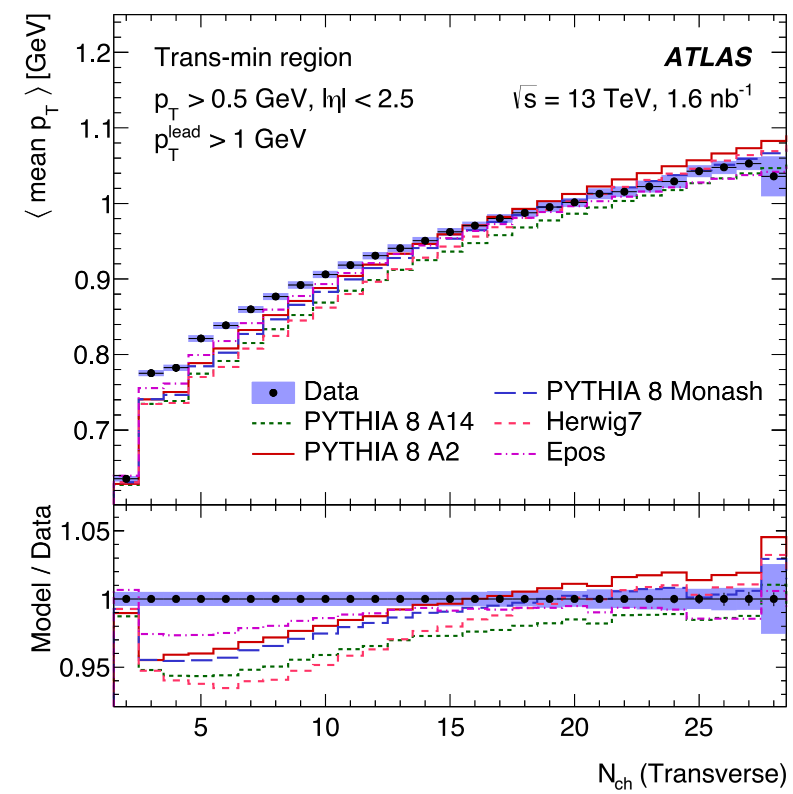
|η|<0.2

Underlying event in ATLAS at 13 TeV

JHEP03(2017)157







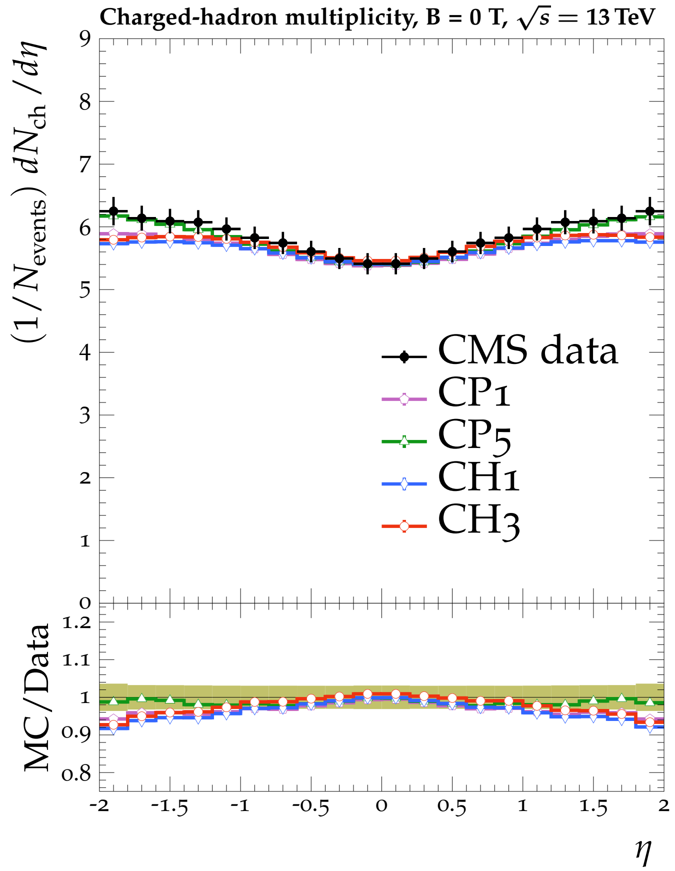
Symbol	Description
Binned variables	
p_T^{lead}	Transverse momentum of the leading charged particle
N_{ch}(transverse)	Number of charged particles in the transverse region
$\lvert\Delta\phi\rvert$	Absolute difference in particle azimuthal angle from the leading charged particle
Averaged variables	
$\langle N_{ch}/\delta\eta\delta\phi\rangle$	Mean number of charged particles per unit η–ϕ (in radians)
$\langle\sum p_T/\delta\eta\delta\phi\rangle$	Mean scalar p_T sum of charged particles per unit η–ϕ (in radians)
$\langle$mean $p_T\rangle$	Mean per-event average p_T of charged particles ($\geq$ 1 charged particle required)

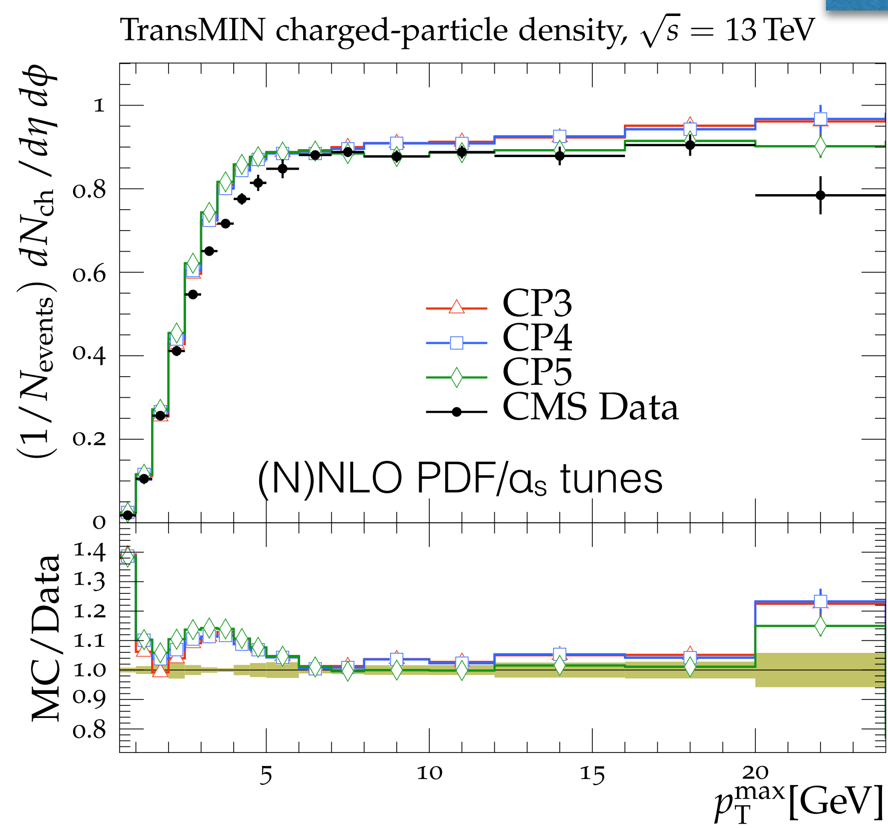
Generator	Version	Tune	PDF	Focus	From
Pythia 8	8.185	A2	MSTW2008 LO	MB	ATLAS
Pythia 8	8.185	A14	NNPDF2.3 LO	UE	ATLAS
Pythia 8	8.186	Monash	NNPDF2.3 LO	MB/UE	Authors
Herwig 7	7.0.1	UE-MMHT	MMHT2014 LO	UE/DPS	Authors
Epos	3.4	LHC	—	MB	Authors

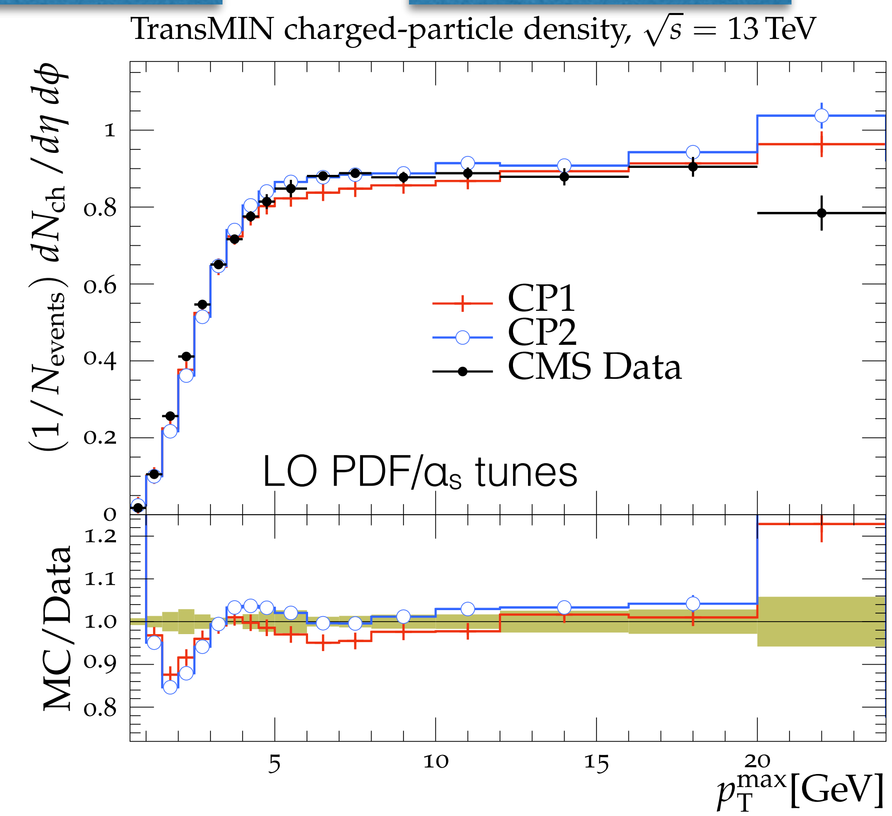
- Dominant uncertainties are due to track reconstruction and unfolding.
- Current models/settings for UE modelling describe the data to ~5% accuracy >> data uncertainties ~ 1%.
- Evidence in systematic mismodelling in various observables. —> Improved MC tunes would be beneficial for the interpretation of LHC data.
- There is no obvious best model for all observables but EPOS MC specialised for the simulation of inclusive soft QCD processes show particular discrepancies as p_T scale increases —> May not be adequate for modelling MPI at LHC (although it provides the best description of minimum-bias data).

New CMS Underlying tunes for Pythia8 and Herwig7

EPJC 80 (2020) 4 EPJC 81 (2021) 312







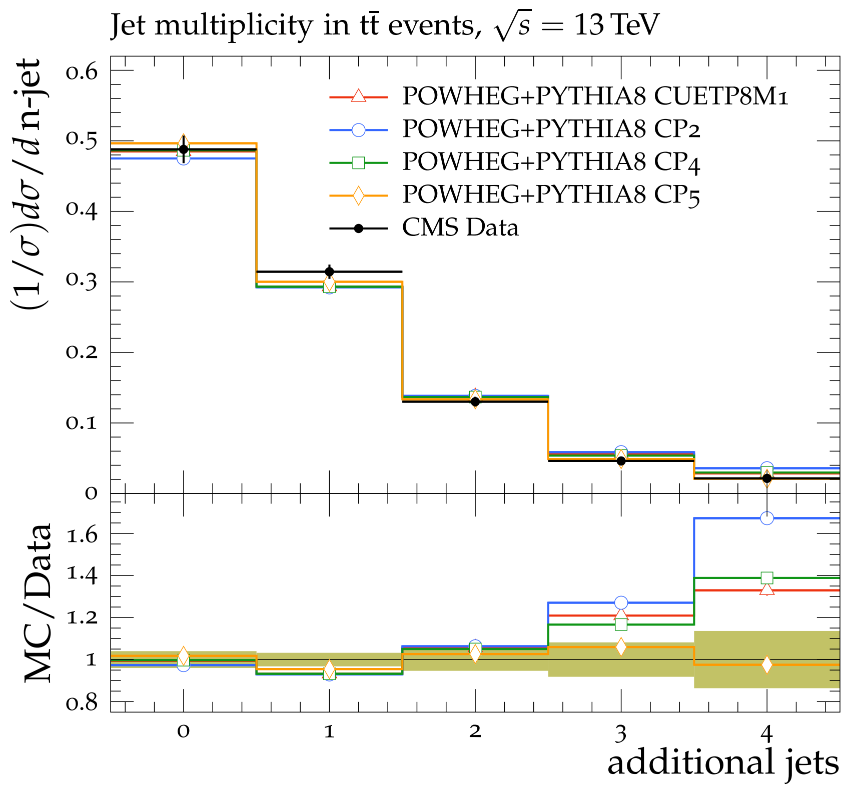
- New tunes use 1.96-13 TeV UE and minbias data.
- And PDF order and $\alpha_s(M_Z)$ consistent in various components of the PS and ME (and in Herwig possible to set MPI at a different order).

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
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO

		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
	$\alpha_S^{PDF}(m_Z)$	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
	$\alpha_S^{PDF}(m_Z)$	0.135	0.118	0.118	0.130

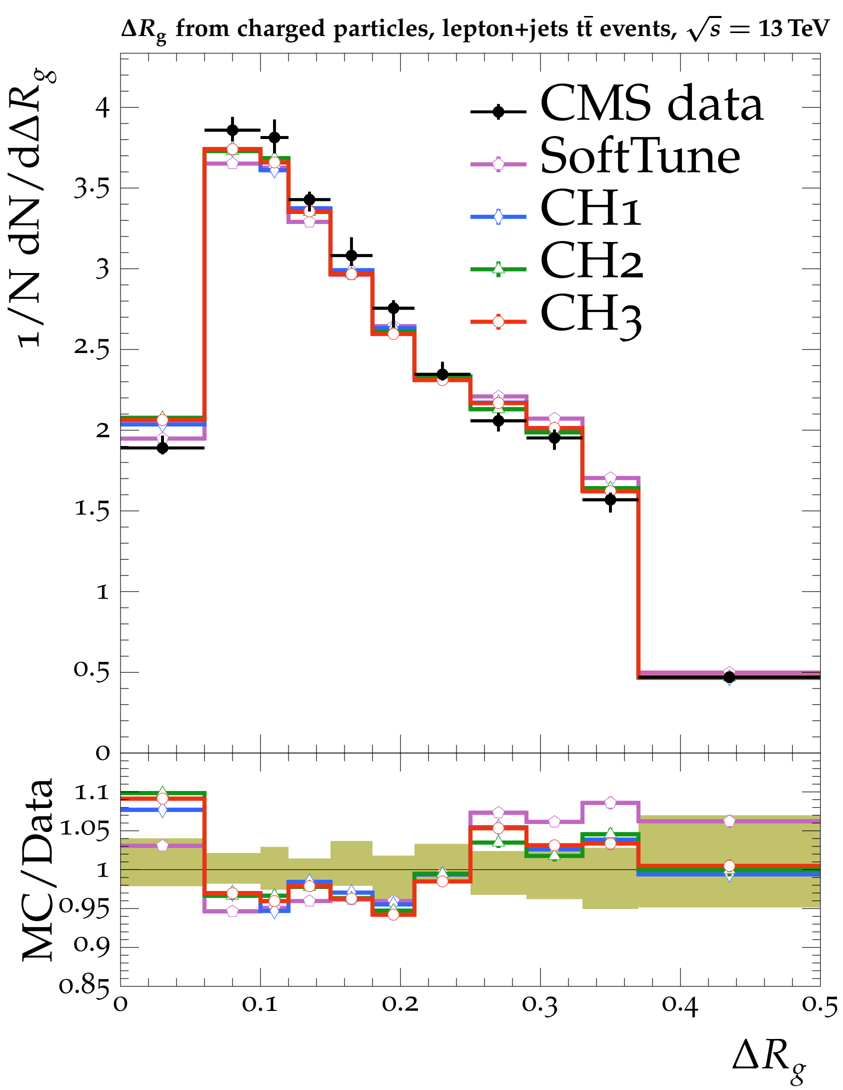
- Predictions from PYTHIA8 and HERWIG7 with (N)NLO-PDF-based tunes reliably describe the central values of min-bias and UE data with similar or better than the predictions form LO-PDF tunes *(new LO and (N)NNLO tunes and significantly better than old tunes extracted using data at lower collision energies).*
- DPS is described worse by (N)NLO CPX tunes.
- CPX tunes simultaneously describe the N_{ch} in diffractive and inelastic collisions.
- CPX tunes describe the min-bias data up to |η|<4.7.
- No tune describes the very forward region (-6.6 < η < -5.2) better than ~10%.
- New tunes are tested also against ttbar, DY, dijet, V+jets and also inclusive jet and event shape observables from LEP for the HERWIG7 tune.

New CMS Underlying tunes for Pythia8 and Herwig7



- CP5 —> *RapidityOrdering for ISR* makes a big difference in POWHEG+PYTHIA8.
- All predictions equivalently good for MG5_aMC+PYTHIA8 [FxFx].
- Azimuthal dijet correlations are also better described when $\alpha_S^{ISR}(M_Z)=0.118$ is used (i.e. CP3-CP5 tunes)

EPJC 80 (2020) 4

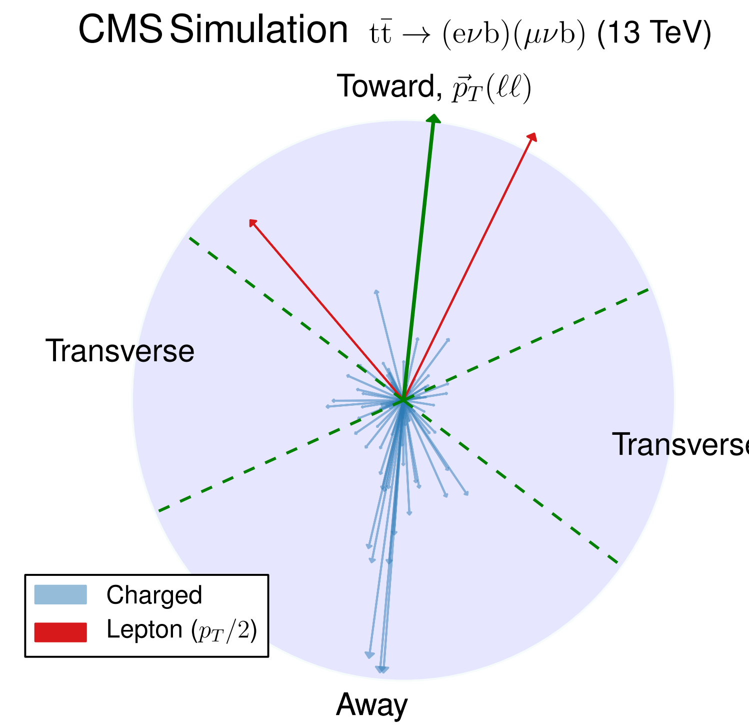


EPJC 81 (2021) 312

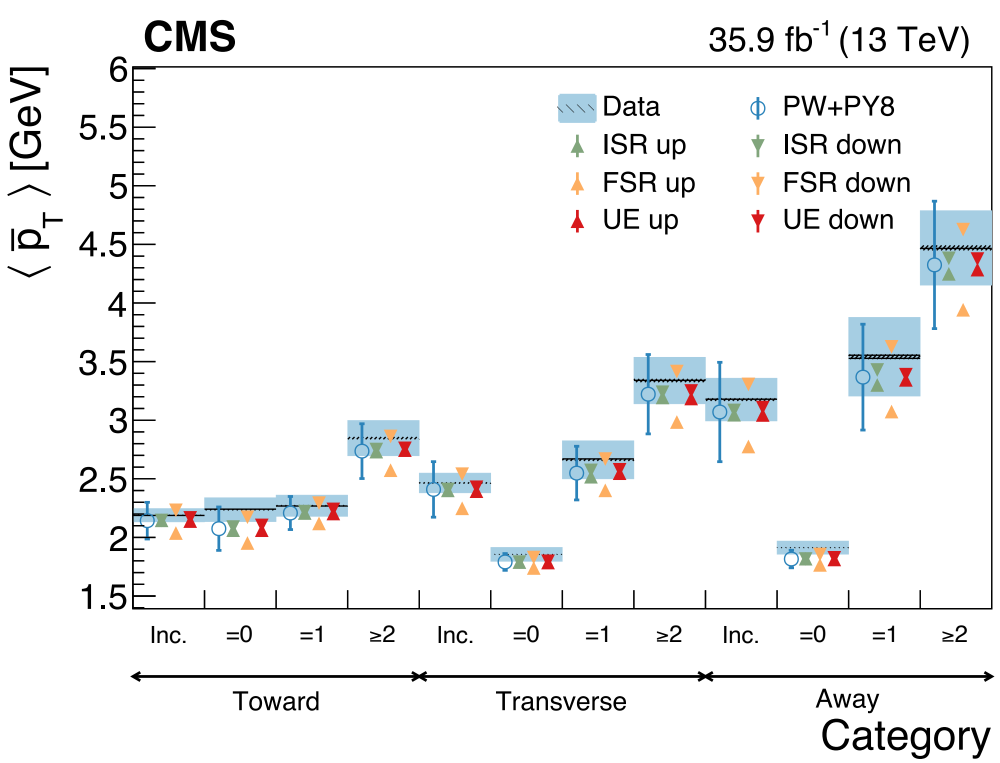
- Jet substructure angle between the groomed subjets in lepton+jets events in ttbar.
- Worse description by CHX at low values and the opposite for high values.
- ΔR_g strongly dependent on the amount of FSR, the difference between CHX and SoftTune comes from the choice of $\alpha_s(M_Z)$ and CH tunes are preferred by the data.

Underlying Event in ttbar events

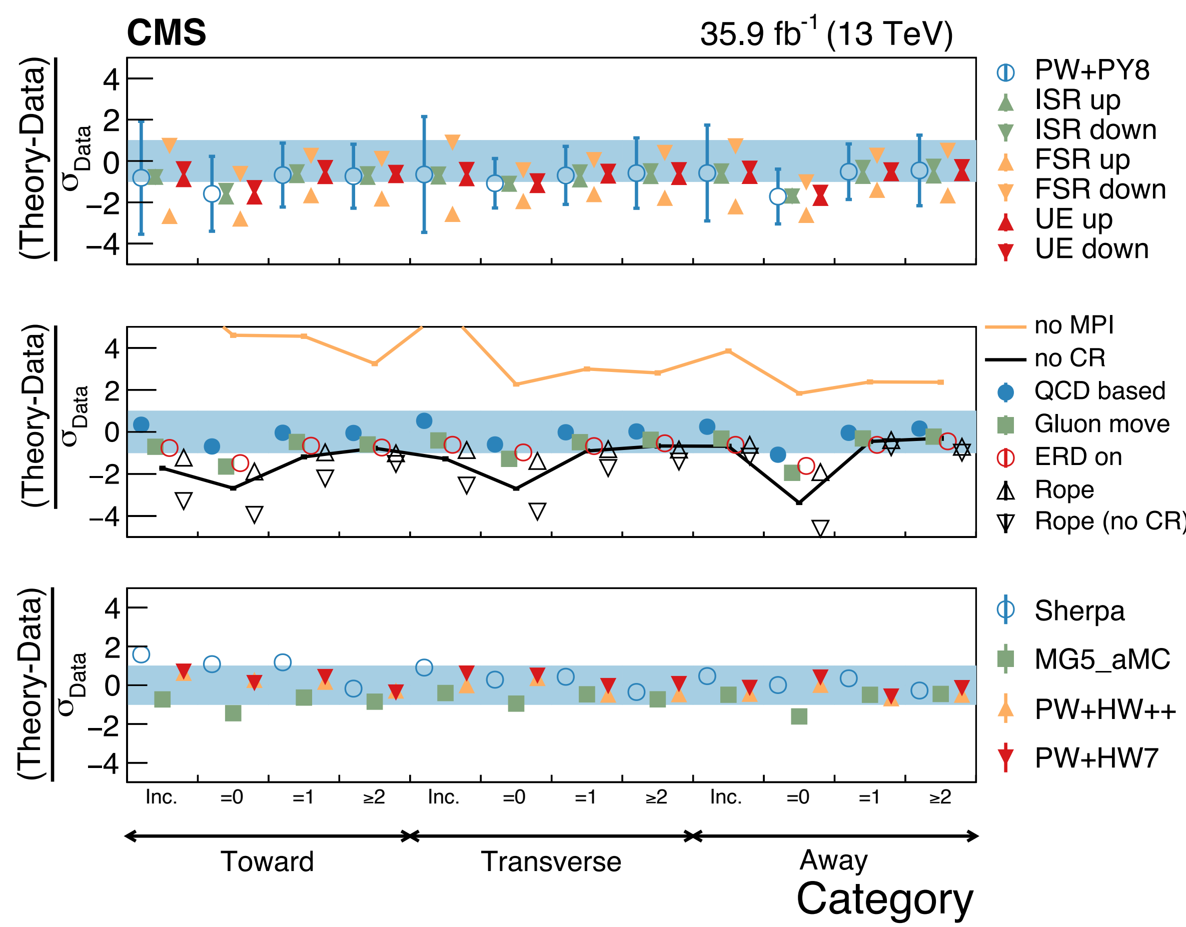
- Measurement to characterise, for the first time, UE properties in ttbar production at a scale larger than $2m_t$. —> universality of UE tested.
- > 200 distributions unfolded to particle level in different categories to enhance sensitivity to the modelling of MPI, color reconnection, $\alpha_s^{FSR}(M_Z)$ in Pythia8.
- Dominant uncertainties: tracking efficiency, $\alpha_s^{ISR/FSR}(M_Z)$, top p_T.
- Good agreement of POWHEG+PYTHIA8 with CUETP8M2T4 tune in UE event regions.
- Data disfavor default settings in SHERPA, HERWIG++, and HERWIG7.
- $\alpha_s^{FSR}(M_Z)$=0.120+/-0.006 extracted using average p_T.
  - Uncertainties correspond to a ~√2 variation of μ_R (instead of a ~2 variation).
- *UE, jet substructure in ttbar events prefer significantly lower $\alpha_s^{FSR}(M_Z)$ and jet multiplicity in ttbar lower $\alpha_s^{ISR}(M_Z)$ than assumed in Monash.*



EPJC 79 (2019) 123



Error bars and band: stat. uncertainty except PW+PY8 total uncertainty.



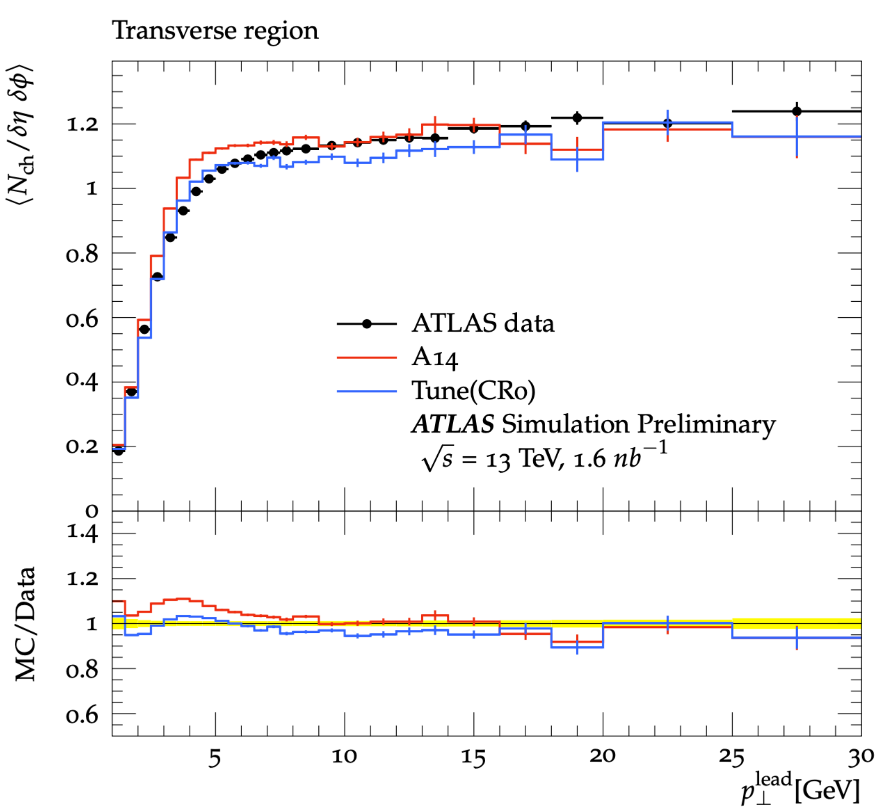
CR effects subtle but more pronounced for n_j=0.

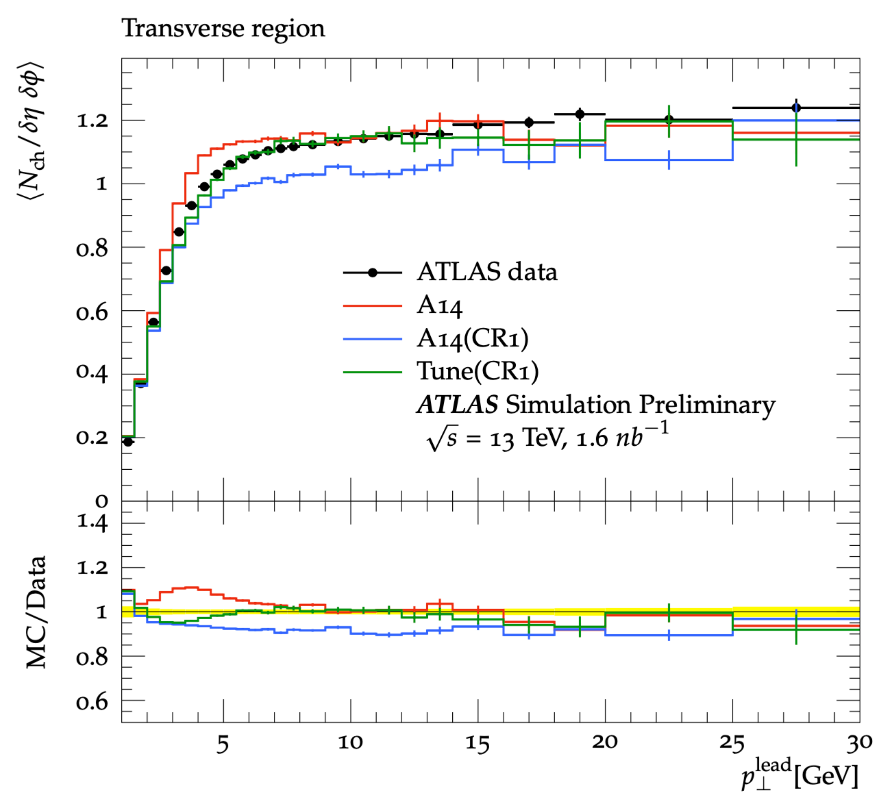
Different Color Reconnection Models for PYTHIA8 in UE

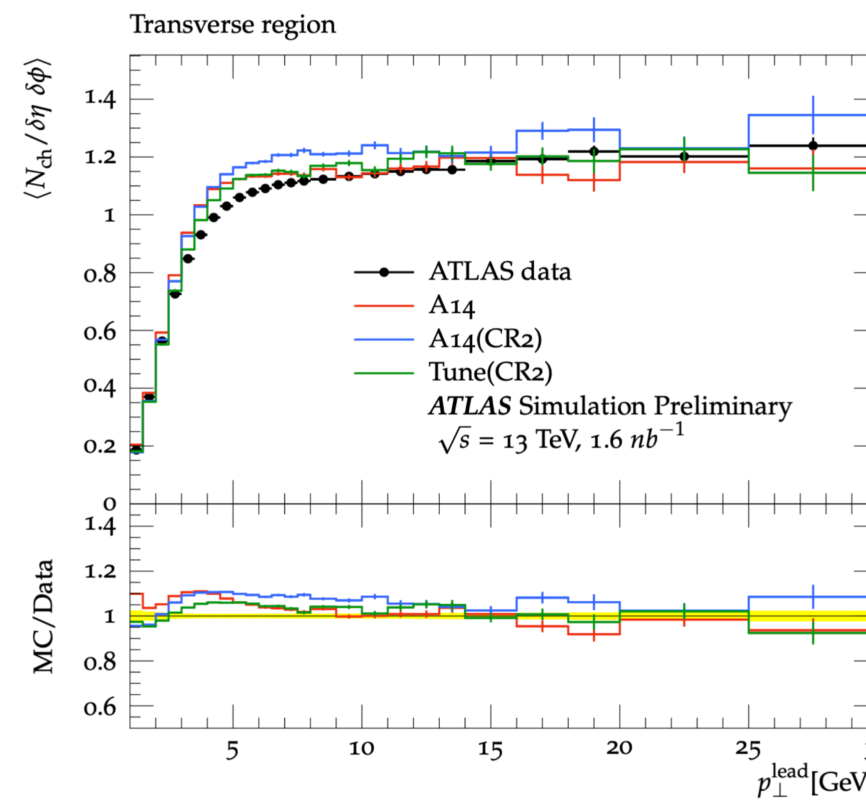
Parameter	Definition
MPI Parameters	
`MultipartonInteractions:pT0Ref`	p_T regularisation parameter
`MultipartonInteractions:expPow`	Exponent of matter overlap function
MPI based CR model (CR0)	
`ColourReconnection:range`	CR strength
QCD-based model (CR1)	
`ColourReconnection:m0`	Mass parameter of order λ_{QCD} used in the string length measure
`ColourReconnection:junctionCorrection`	Multiplicative correction to string length above
Gluon-move scheme (CR2)	
`ColourReconnection:m2Lambda`	Equivalent to m0 for QCD-based model
`ColourReconnection:fracGluon`	Average fraction of gluons that undergo a colour reconnection
`ColourReconnection:dLambdaCut`	Minimal value for decrease in string length

ATL-PHYS-PUB-2017-008

Parameter	A14/ Default (range)	Tune CR0	CR1	CR2
`MultipartonInteractions:pT0Ref`	2.09	2.15	1.89	2.21
`MultipartonInteractions:expPow`	1.85	1.81	2.10	1.63
`ColourReconnection:range`	1.71	2.92	–	–
`ColourReconnection:m0`	0.3 (0.1 - 5)	–	2.17	–
`ColourReconnection:junctionCorrection`	1.20 (0.01 - 10)	–	9.33	–
`ColourReconnection:m2Lambda`	1.0 (0.25-16)	–	–	6.73
`ColourReconnection:fracGluon`	1.0 (0-1)	–	–	0.93
`ColourReconnection:dLambdaCut`	0 (0-10)	–	–	*0.0*
χ^2, $Ndof$		17706, 2929	18597, 2928	113814, 2928
		6.1	6.4	38.9





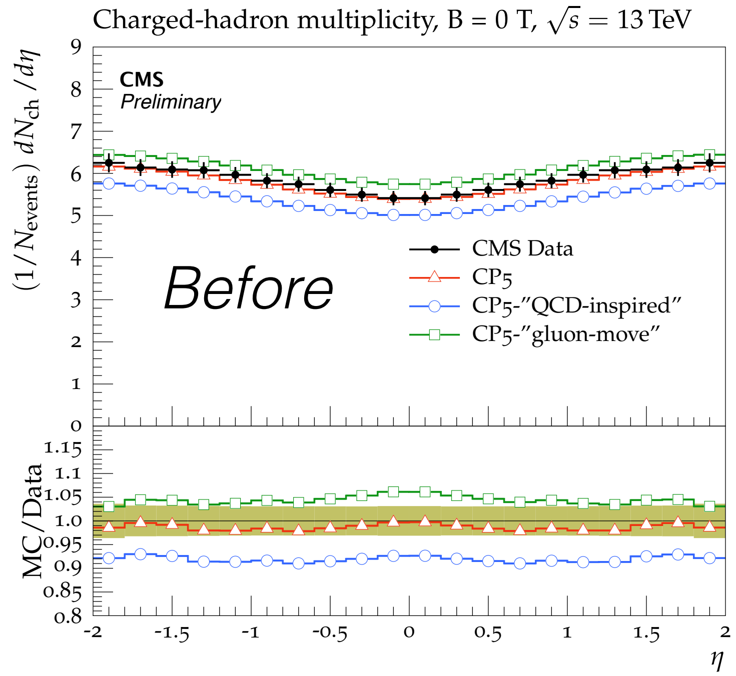


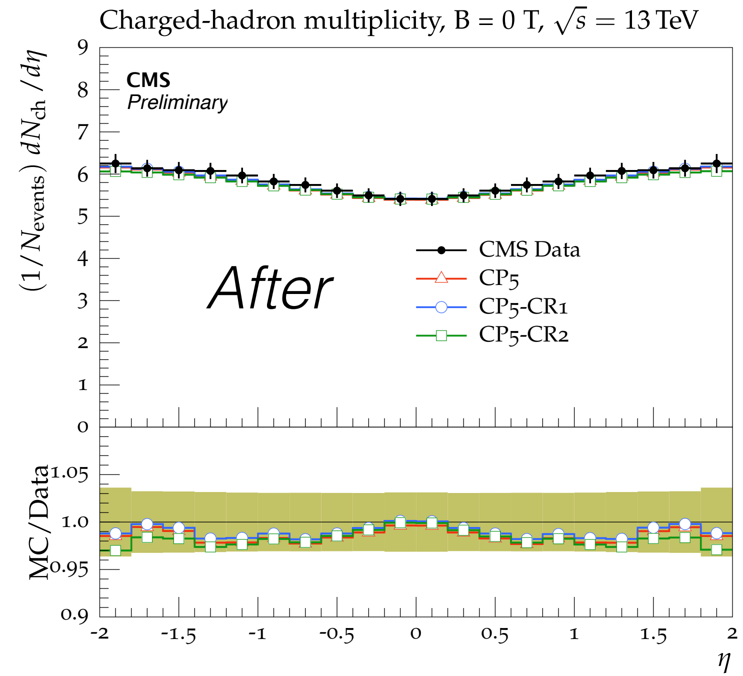
- Reference Run I and II data from ATLAS at $\sqrt{s}$ = 900 GeV, 7 TeV, 13 TeV
- Overall all CR models can be tuned to describe most observables within 20%.
- None of the models individually describe all observables perfectly but it is shown that each could be tuned to describe the data reasonably well.
- CR0 and CR1 models perform significantly better than CR2.
- Further studies are needed to understand the effect of tunes in UE observables.

New PYTHIA8 color reconnection tunes in CMS based on CP5

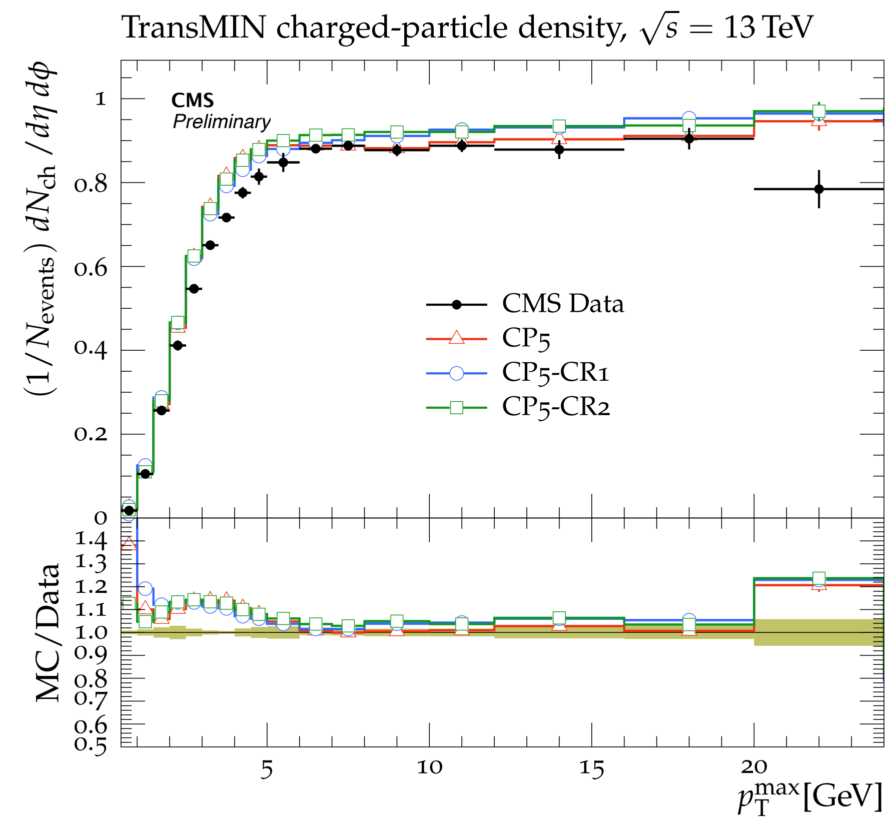
CMS-PAS-GEN-17-002
Made public last night

- 1.96, 7, and 13 TeV data to constrain the parameters for the CR and MPI simultaneously starting from the CP5 tune.
- Tested with LEP, 1.96, 7, 8, and 13 TeV data with MB, UE, forward energy flow, strange particle production, p/π, jet shapes and colour flow in ttbar, …
- Checked top quark mass uncertainty using new CR tunes.





PYTHIA8 Parameter	CP5 [18]	CP5-CR1	CP5-CR2[1]
PDF set	NNPDF3.1 NNLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
SpaceShower:rapidityOrder	on	on	on
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
StringZ:aLund	–	0.38	–
StringZ:bLund	–	0.64	–
StringFlav:probQQtoQ	–	0.078	–
StringFlav:probStoUD	–	0.2	–
SigmaTotal:zeroAXB	off	off	off
BeamRemnants:remnantMode	–	1	–
ColourReconnection:mode	–	1	2
MultipartonInteractions:pT0Ref [GeV]	1.410	1.375	1.454
MultipartonInteractions:ecmPow	0.033	0.033	0.054
MultipartonInteractions:coreRadius	0.763	0.605	0.649
MultipartonInteractions:coreFraction	0.630	0.445	0.489
ColourReconnection:range	5.176	–	–
ColourReconnection:junctionCorrection	–	0.238	–
ColourReconnection:timeDilationPar	–	8.580	–
ColourReconnection:m0	–	1.721	–
ColourReconnection:m2lambda	–	–	4.917
ColourReconnection:fracGluon	–	–	0.993
N_{dof}	183[2]	157	158
χ^{*2}/N_{dof}	1.04	2.37	0.89



- Predictions of the new CR tunes for MinBias and UE significantly better than the CR models with the default parameters before tuning (also in the forward region).
- In general agreement between data/MC is similar to that of CP5.

Top quark mass predicted by different tunes

- The shift in 13 TeV measurement using CUETP8M2T4 CR tunes is 0.31 GeV.
- The largest source of systematic uncertainty. EPJC 78 (2018) 891

CMS-PAS-GEN-17-002

Table 4: The top quark mass, m_t, and W mass, m_W, extracted by a fit to the predictions of the different PYTHIA8 tunes. The uncertainties in the m_t and m_W values correspond to the uncertainty in the fitted m_t and m_W.

Tune	m_t [GeV]	Δm_t [GeV]	m_W [GeV]	Δm_W [GeV]	$\Delta m_t - 0.5 \times \Delta m_W$ [GeV]
CP5	171.93 ± 0.02	0	79.76 ± 0.02	0	0
CP5 erdOn	172.18 ± 0.03	0.25	80.15 ± 0.02	0.40	0.13
CP5-CR1	171.97 ± 0.02	0.04	79.74 ± 0.02	-0.02	0.05
CP5-CR1 erdOn	172.01 ± 0.03	0.08	79.98 ± 0.02	0.23	-0.04
CP5-CR2	171.91 ± 0.02	-0.02	79.85 ± 0.02	0.10	-0.07
CP5-CR2 erdOn	172.32 ± 0.03	0.39	79.90 ± 0.02	0.14	0.32

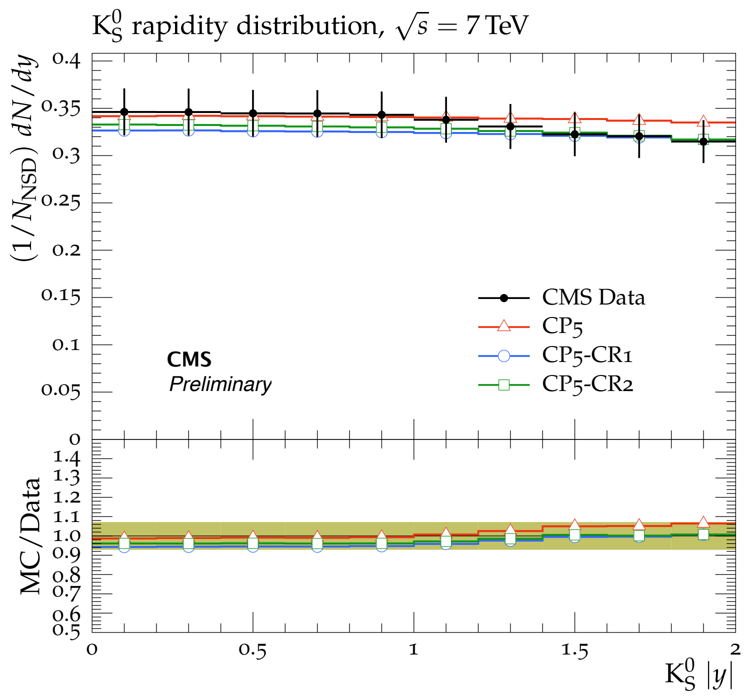
- Top/W mass values obtained by fitting a Gaussian with an 8 GeV mass window around the peak.
- Largest deviation 0.32 from CP5: CP5-CR2erdOn similar to the 13 TeV measurement using CUETP82T4.
  - CP5 with its CR tunes does't improve or degrade the precision of the top quark mass measurements.
  - We need more detailed studies with UE, jet shapes, and others (or we will need to learn to live with it).

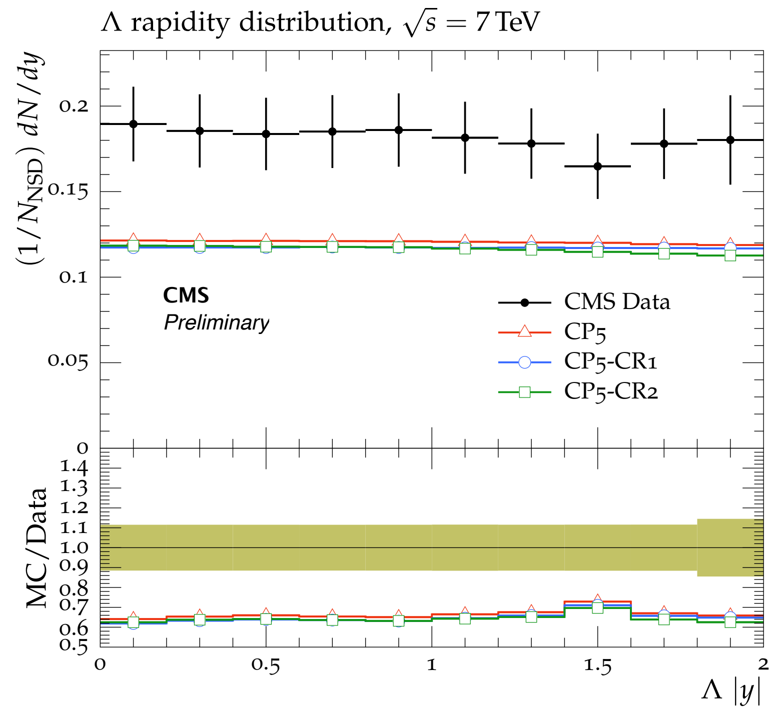
- Semi-leptonic top pair events.
- Top candidates constructed from a RIVET routine from combining 3 jets with pT > 30 GeV.
  - One jet from the decay of a b-quark. The other 2 required to be light jets to reconstruct W boson in 75-85 GeV.
  - All possible 3-jet combinations satisfying these requirements considered.

0.5: used in the original measurement taking into account the shift in W mass but giving it a weight optimised for each measurement. *Not re-optimized for this estimation.*

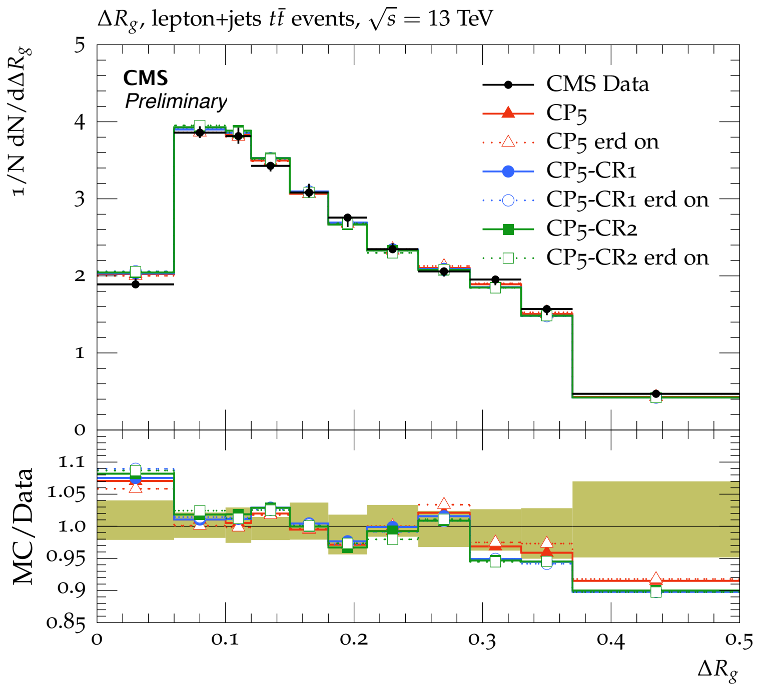
New PYTHIA8 color reconnection tunes in CMS based on CP5

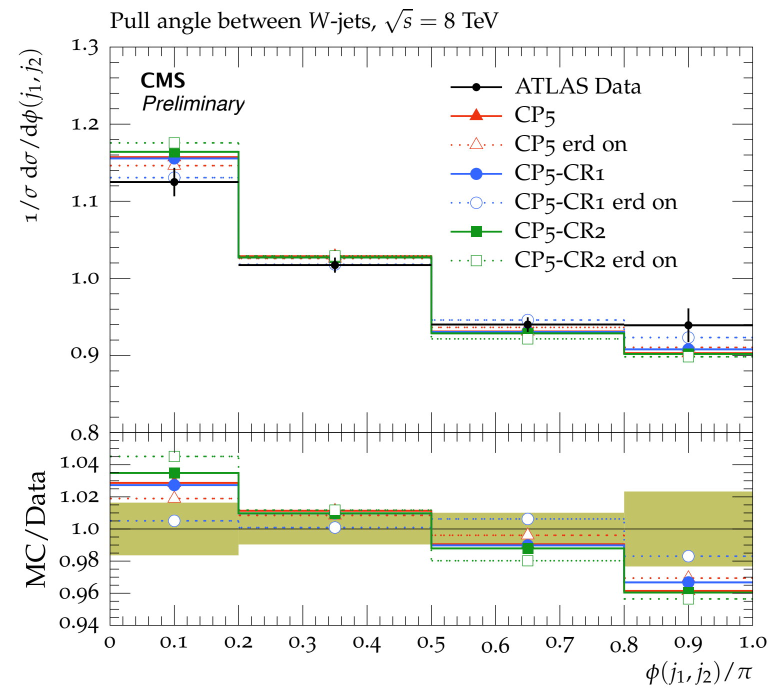
CMS-PAS-GEN-17-002





- New CR tunes alone don't improve the description of strange particle production vs |y| of Λ baryons. —> Need to use improved hadronization models?





- None of the tunes describe jet shapes and all tunes have similar predictions (except CP5 provides good description for non-top-quark events).
- Some differences w.r.t. color flow data which is particularly sensitive to the ERD option in the CR models.

- Baryon/meson ratios described well from 10 GeV, 90 GeV, and 13 TeV but not true differentially for p/π in the range p_T=0.4-1.2 GeV in MB events at 13 TeV.

- *Drell-Yan: impact of CR models negligible and higher order corrections are needed to fully describe the Z p_T.*

Z+Jets Production

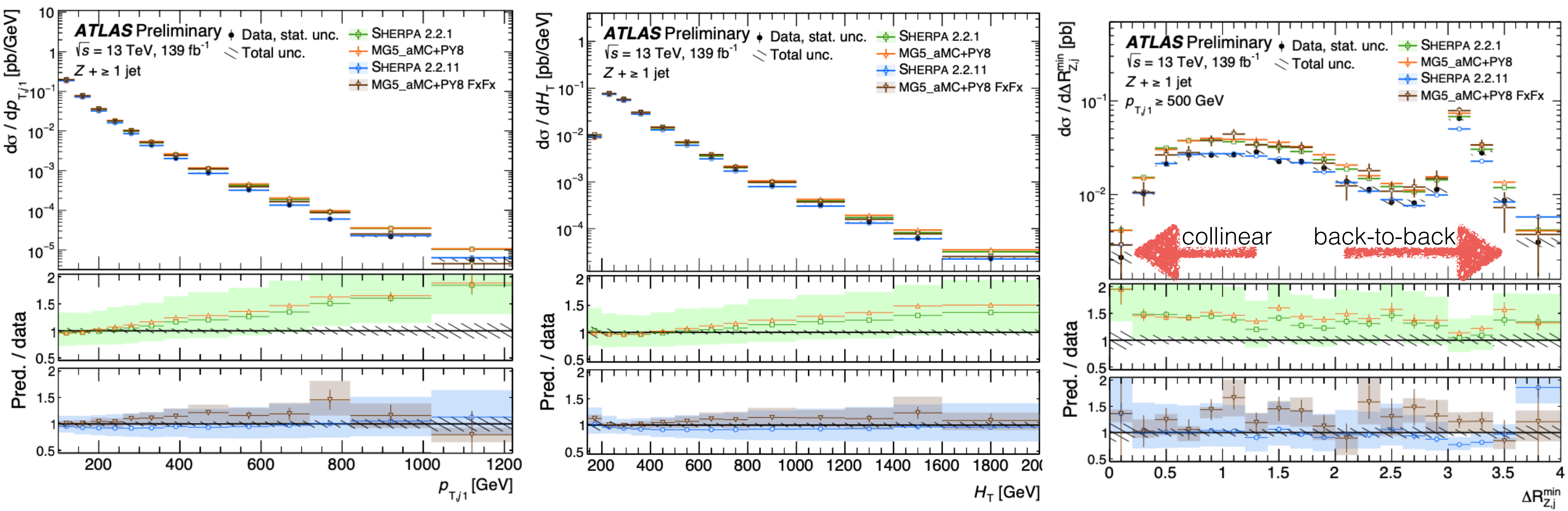
ATL-CONF-2021-033

- Provides powerful test of perturbative QCD.
- With high energy jets, it allows to probe the interplay of QCD with higher order electroweak processes.

$p_T(\ell) \geq 25\ GeV \quad |\eta(\ell)| < 2.5$
$71 < m_{\ell\ell} < 111\ GeV$
$p_T(j) \geq 100\ GeV \quad |\eta(j)| < 2.5$

Dominant uncertainties:
JER/JES, unfolding, luminosity, data statistics at > ~500 GeV

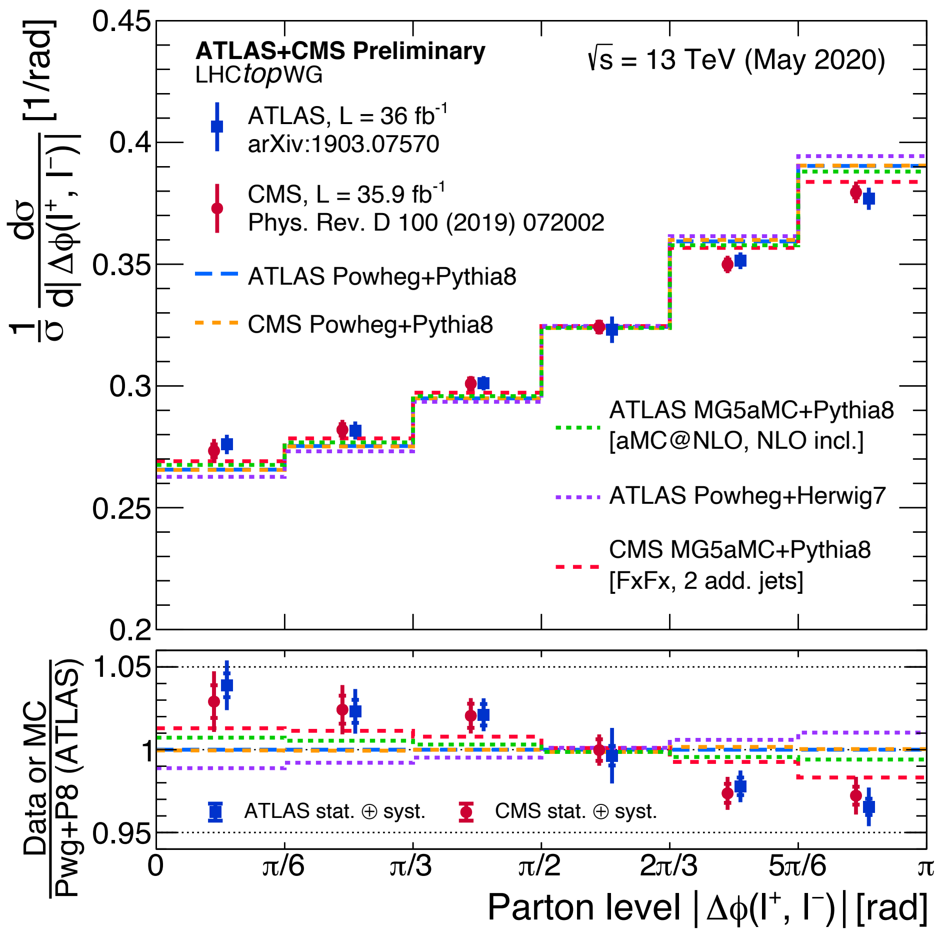
Process	Generator	Order pQCD	
$Z\to \ell\ell$ (ℓ=e, μ, τ)	Sherpa v.2.2.1	0-2p NLO, 3-4p LO	
$Z\to \ell\ell$ (ℓ=e, μ)	MG5_aMC+Py8 CKKWL	0-4p LO	—> MG5_aMC v2.2.2
$Z\to \ell\ell$ (ℓ=e, μ)	Sherpa v.2.2.11	0-2p NLO, 3-5p LO	+ NLO virtual EWK corrections
$Z\to \ell\ell$ (ℓ=e, μ)	MG5_aMC+Py8 FxFx	0-3p NLO	—> MG5_aMC v2.6.5
EW $Zjj(\to \ell\ell$ (ℓ=e, μ))	Herwig7.1.5, Vbfnlo v3.0.0	NLO	—> treated as background

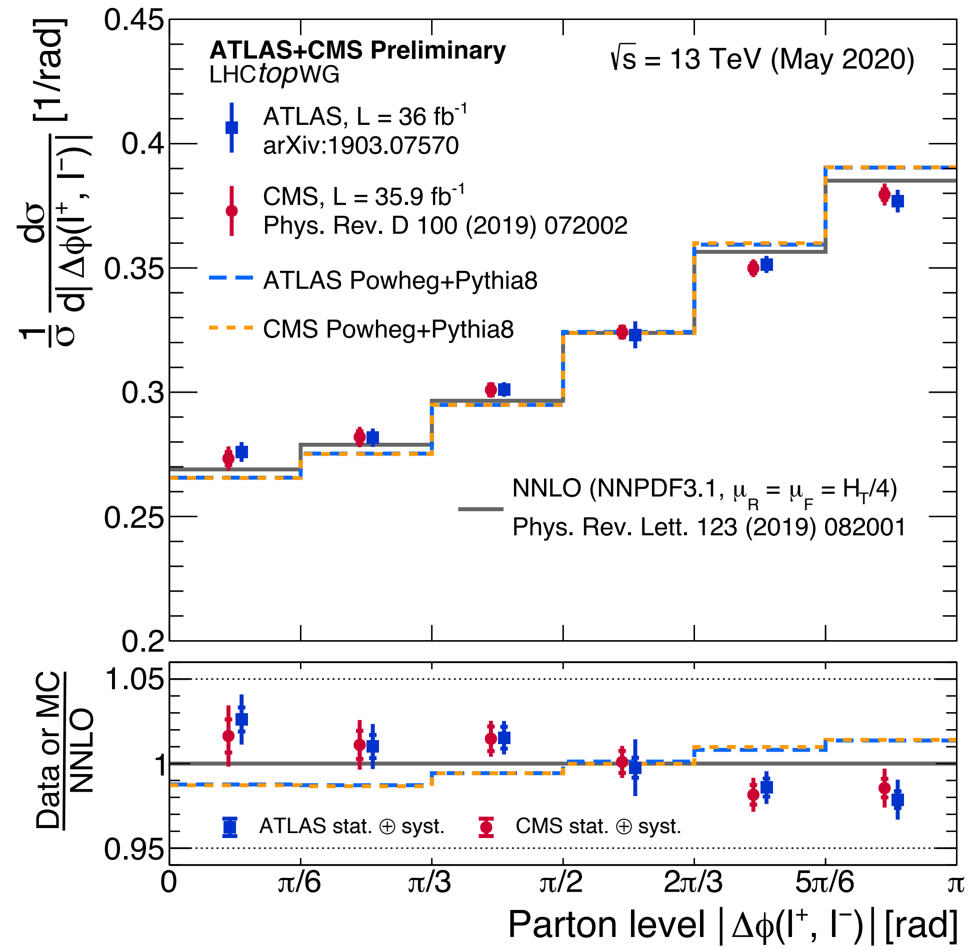


- MG5_aMC v.2.2.2+PY8 CKKWL and Sherpa v.2.2.1 overestimates the cross section for large pT(leading jet), large H_T ($=\Sigma p_T(j)$), and large S_T ($=\Sigma p_T(j)+p_T(l)$)
- Upgraded generators MG5_aMC (v.2.6.5) and Sherpa V.2.2.11 provides the best modelling.

Top Quark pair spin correlation

Normalized cross sections at the parton level.





- Very good agreement between ATLAS and CMS data and between ATLAS and CMS main MC predictions.
- Good agreement of data with MG5_aMC@NLO with FXFX merging (2 additional jets at NLO from the matrix element).
- Fair agreement with the NNLO calculation.
- Paves the way for first 13 TeV ATLAS+CMS combination from TOPLHCWG.
- Towards common ttbar MC settings for ATLAS and CMS —> CMS-NOTE-2021-005 / ATL-PHYS-PUB-2021-016.

Some other recent noteworthy results

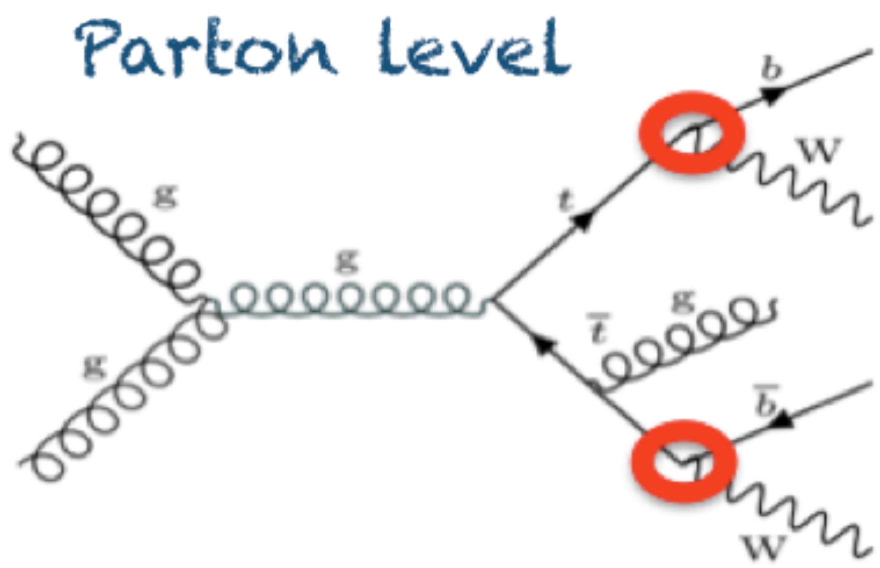
- Soft QCD
  - ATLAS Pythia 8 tune A3 with Run1 and Run2 minimum bias and inelastic XS
  - UE in Z events at 13 TeV with ATLAS
- Jets
  - Multijet simulation for 13 TeV ATLAS analyses
  - Hadronic event shapes with multijets at 13 TeV with ATLAS
- Photons
  - Modelling of isolated multi-photon production in ATLAS
  - Isolated photon pair production cross section at 13 TeV with ATLAS
- V+Jets
  - Z+jets, γ+jets, and of Z emission collinear with a jet at 13 TeV with CMS
  - Z+b(b) measurement at 13 TeV with ATLAS
- Dibosons
  - EWK WW production — ATLAS+CMS simulation comparisons
- Top quark
  - b quark fragmentation function using charmed mesons inside b jets from ttbar at 13 TeV with CMS
  - Differential ttbar cross sections with lepton+jets with CMS and with ATLAS and high-pt top at 13 TeV with CMS
  - New summary plots on tt, ttbb, and ttV cross sections from CMS, on top mass, t+x, and cross sections from ATLAS.

All ATLAS public results
All CMS public results

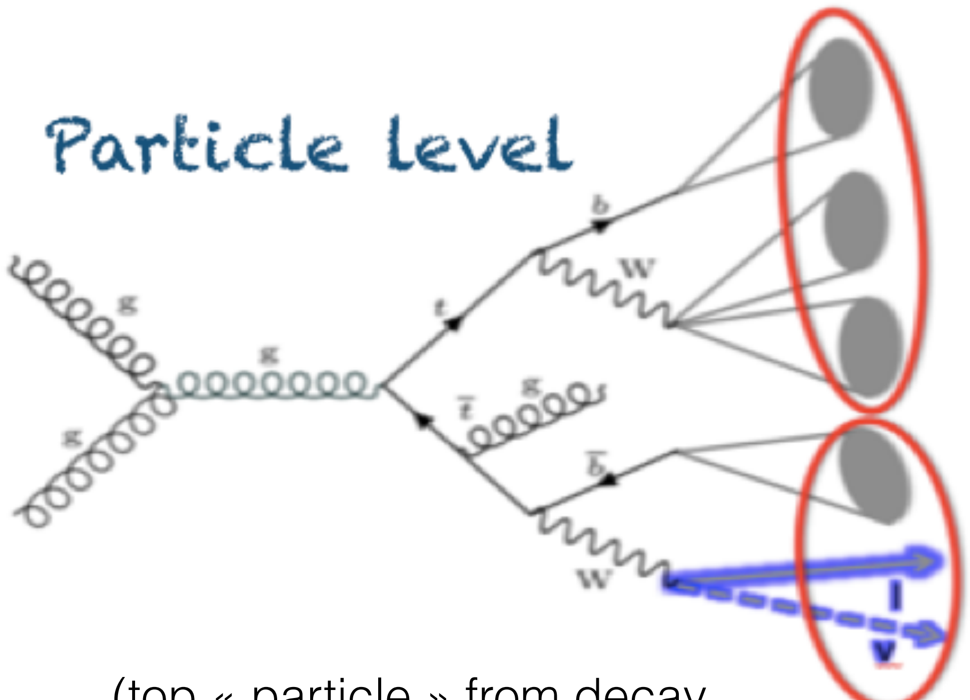
Additional Slides

Improving uncertainties: Object Definitions for Top Particle

CMS-NOTE-2017-004

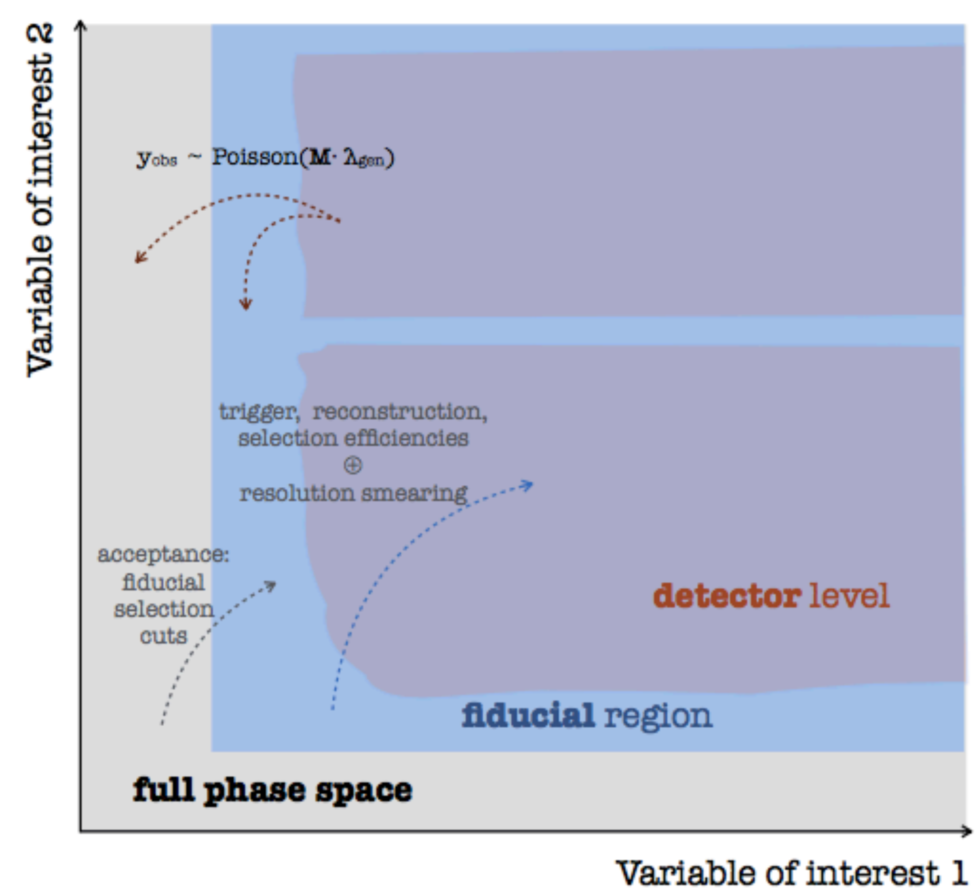


(before decay after radiation)



(top « particle » from decay products after hadronization)

- Parton level top ill-defined - more so at NLO
- Construct tops only from observed final-state = particle level top.
  - Fundamental aspect of performing current and future measurements of top quark differential production cross sections.



Underlying Event in ttbar events

Source	% Uncertainty									
	N_{ch}	$\sum p_{\mathrm{T}}$	$\sum p_z$	$\overline{p_{\mathrm{T}}}$	$\overline{p_z}$	$\lvert\vec{p}_{\mathrm{T}}\rvert$	S	A	C	D
Statistical	0.1	0.2	0.3	0.2	0.2	0.3	0.1	0.1	0.1	0.1
	Experimental									
Background	1.2	1.6	1.8	0.4	0.7	1.6	0.4	0.7	0.3	0.7
Tracking eff.	4.4	4.2	4.9	0.8	0.4	4.0	0.4	0.6	0.2	0.6
	Theory									
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$	0.5	0.8	1.0	0.3	0.3	1.0	0.1	0.1	0.1	0.2
Resummation scale	0.2	0.8	0.5	1.1	0.2	1.6	0.8	0.4	0.2	0.7
$\alpha_S^{\mathrm{FSR}}(M_{\mathrm{Z}})$	0.5	0.7	0.7	0.8	1.7	0.7	0.2	1.0	0.2	1.2
$\alpha_S^{\mathrm{ISR}}(M_{\mathrm{Z}})$	0.1	0.3	1.1	1.2	0.7	0.4	0.2	0.5	0.1	1.3
UE model	0.1	0.1	0.2	1.0	0.4	0.5	0.2	0.2	0.1	0.9
m_{t}	0.4	0.7	1.5	0.6	0.9	0.5	0.1	0.1	0.1	0.7
$p_{\mathrm{T}}(\mathrm{t})$	1.4	4.4	4.5	2.8	2.1	6.7	0.2	0.5	0.2	0.3
Total	4.9	6.5	7.3	3.7	3.1	8.2	1.1	1.6	0.6	2.4

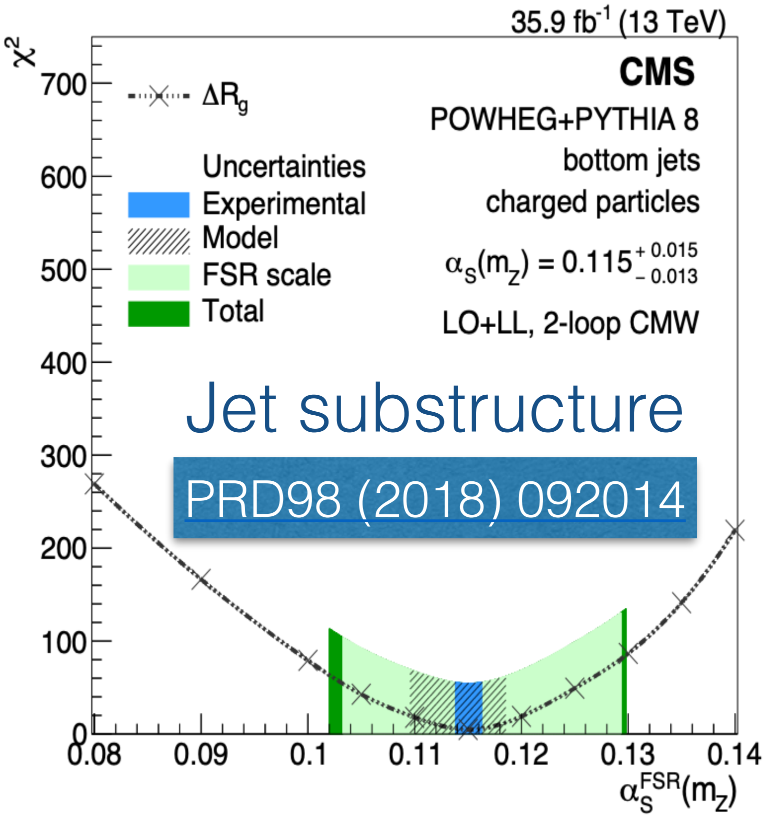
Uncertainties affecting the measurement of the average of the UE observables. The values are expressed in% and the last row reports the quadratic sum of the individual contributions.

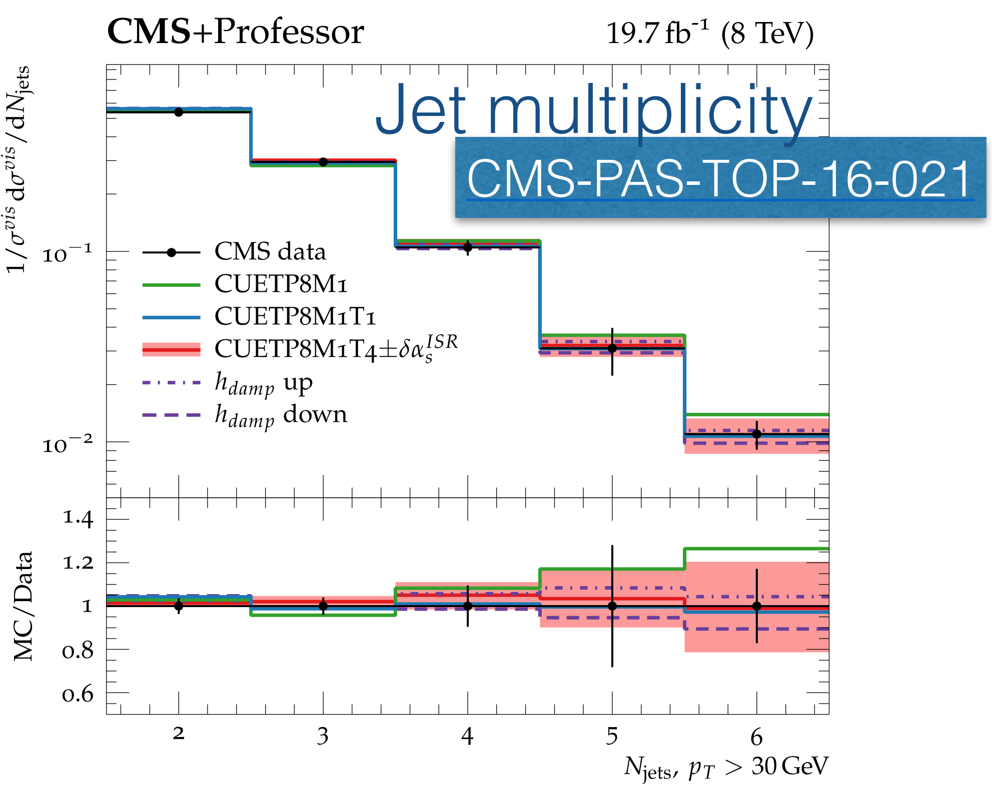
Underlying Event in ttbar events

Table 5 Variations of the Pw+Py8 setup used for the comparison with the measurements. The values changed with respect to the CUETP8M2T4 tune are given in the columns corresponding to each model. Further details on parameters or specificities of the models can be found in Refs. [4,5,17,32,32–34,73]. For the Rope hadronization model two variations are considered: one with no CR and the other with the default CR model. The settings for the former are denoted in parenthesis in the last column

Parameter	Pw+Py8 simulation setups									
	CUETP8M2T4	Extreme variations		Fine grain variations						
				MPI/CR	Parton shower scale		CR including $t\bar{t}$			
		No MPI	No CR	UE up/down	ISR up/down	FSR up/down	ERD on	QCD based [32]	Gluon move [5]	Rope (no CR) [33,34]
PartonLevel										
MPI	On	Off								
SpaceShower										
renormMultFac	1.0				4/0.25					
alphaSvalue	0.1108									
TimeShower										
renormMultFac	1.0					4/0.25				
alphaSvalue	0.1365									
MultipartonInteractions										
pT0Ref	2.2			2.20/2.128				2.174	2.3	
ecmPow	0.2521							0.2521		
expPow	1.6			1.711/1.562				1.312	1.35	
ColorReconnection										
reconnect	On		Off							(Off)
range	6.59			6.5/8.7						
mode	0							1	2	
junctionCorrection								0.1222		
timeDilationPar								15.86		
m0								1.204		
flipMode									0	
m2Lambda									1.89	
fracGluon									1	
dLambdaCut									0	
PartonVertex										
setVertex										On
Ropewalk										
RopeHadronization										On
doShoving										On
doFlavour										On
PartonLevel										
earlyResDec	Off						On	On	On	On

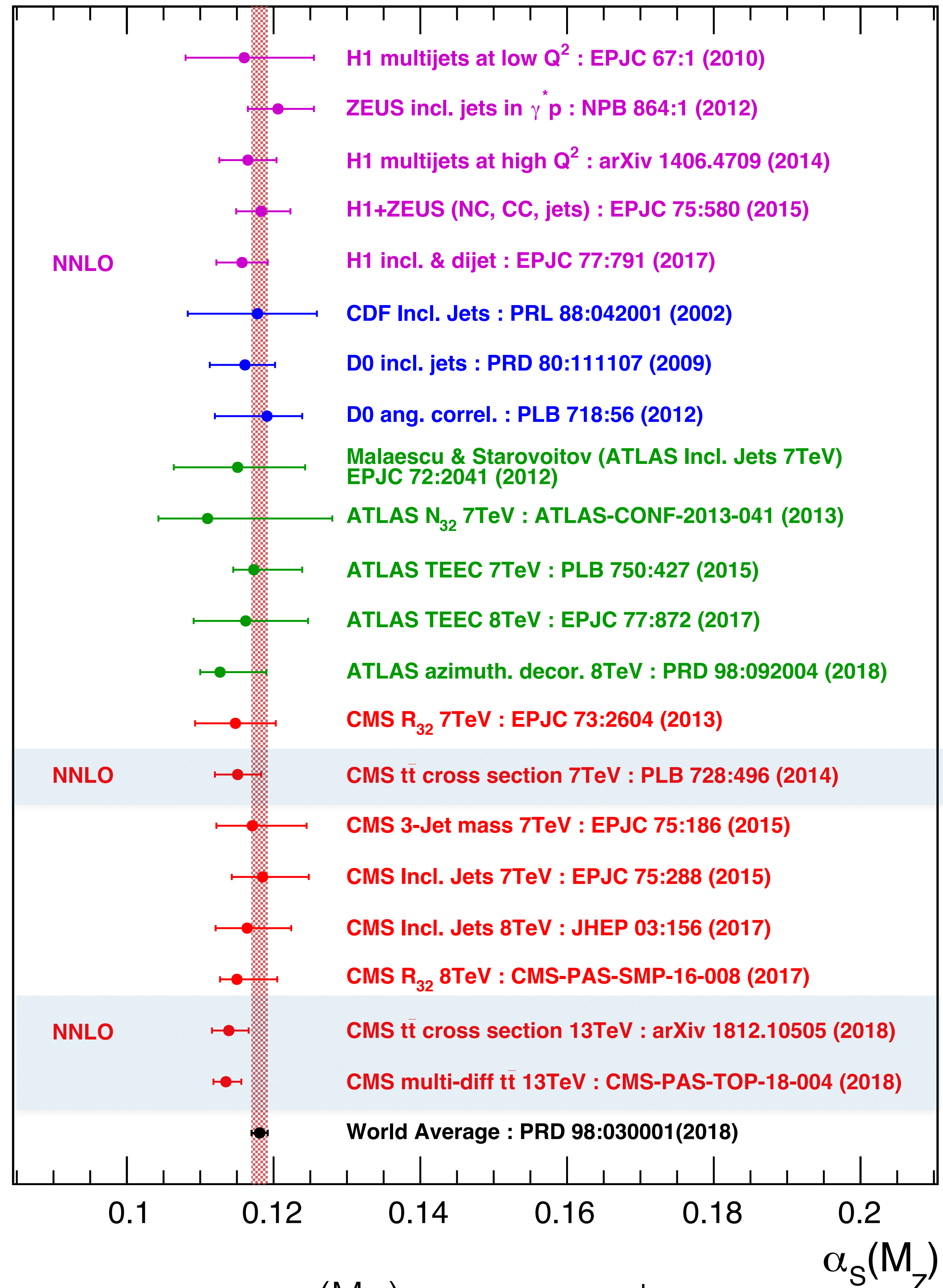
$\alpha_S^{FSR}(M_Z)$ and $\alpha_S^{ISR}(M_Z)$ from ttbar events





$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$

$$h_{damp} = 1.581^{+0.658}_{-0.585} m_t$$



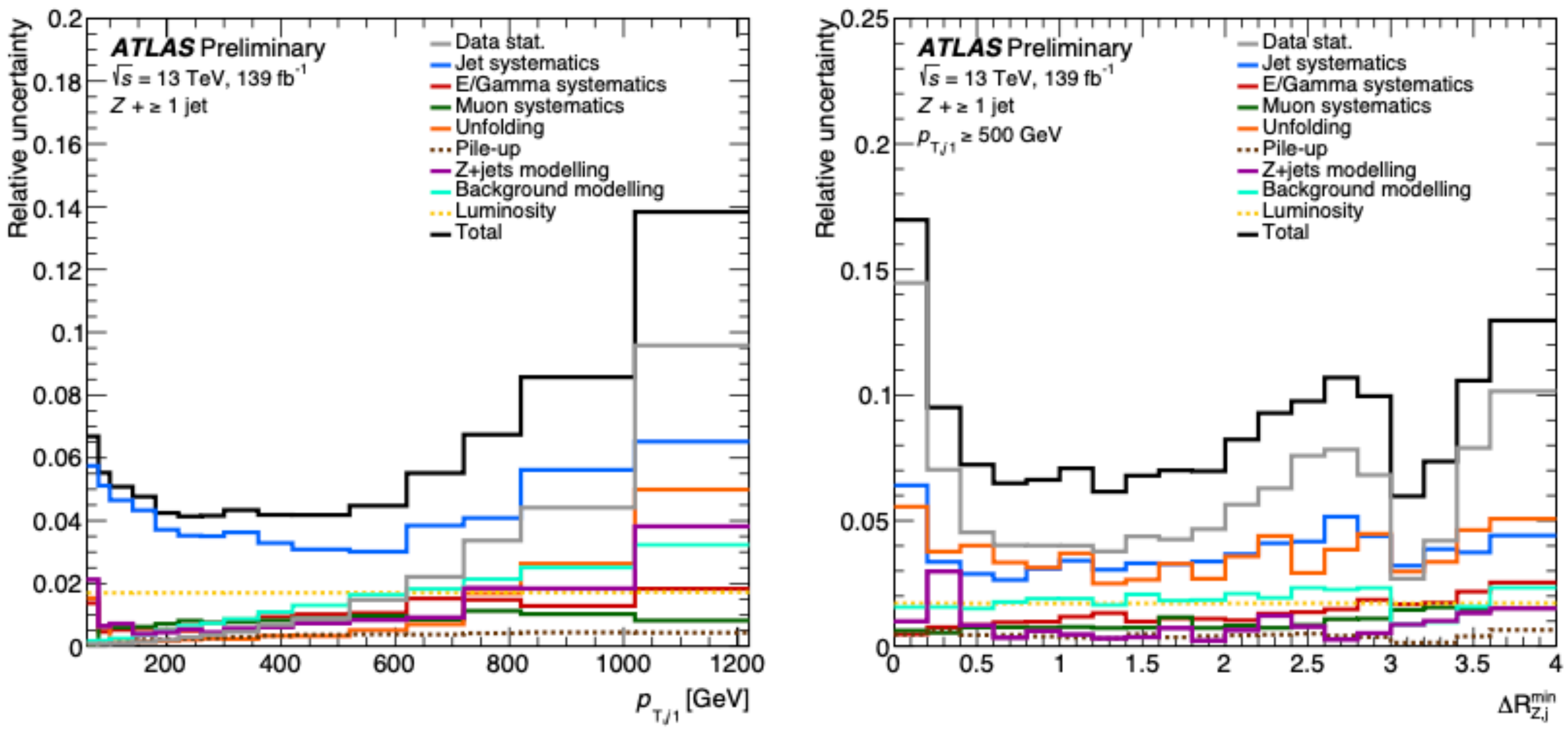
$\alpha_S(M_Z)$ measurements using hadrons.

Systematic uncertainties in Z+Jets production

ATL-CONF-2021-033

Relative uncertainty for $\sigma(Z(\rightarrow \ell^+\ell^-) + \text{jets})$ [%]					
Uncertainty source	*Inclusive*	*High-p_T*	*Collinear*	*Back-to-back*	*High-S_T*
Jet JER/JES	4.4	3.4	3.3	3.8	3.7
Muon	0.5	1.1	0.7	1.4	0.8
Electron	0.7	1.1	0.9	1.3	0.8
Luminosity	1.7	1.7	1.7	1.7	1.7
Pile-up	0.2	0.4	0.4	0.3	0.4
Unfolding	0.9	3.2	4.0	3.8	1.7
Background modelling	0.3	1.7	1.8	1.5	1.5
Signal modelling	0.5	0.6	0.6	0.6	0.6
Total syst. uncertainty	4.9	5.6	5.9	6.2	5.0
Stat. uncertainty	0.1	2.2	2.9	2.9	1.2
Total uncertainty	4.9	6.0	6.6	7.0	5.1

- Unfolding uncertainty
  - Stat. Uncertainties of the MC inputs to the unfolding are propagated to the unfolded cross sections using pseudo-experiments.
  - Mismodelling of the data by the MC on unfolding: Sherpa v.2.2.1 Z+jets reweighed at the particle level. The reweighed MC simulation is unfolded with the non-reweighed response matrix . Uncertainty=compare unfolded result against the reweighed distribution at the particle level.



(a) (b)

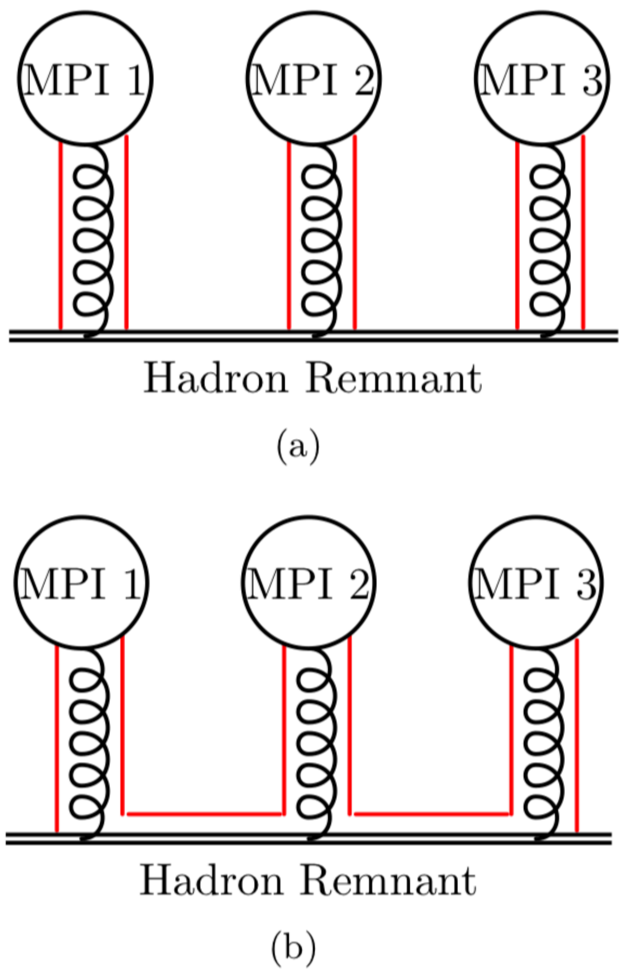
Figure 3: Fractional uncertainties in the differential cross section measurements of $p_{T,j1}$ in the *inclusive* region (left) and $\Delta R^{\text{min}}_{Z,j}$ in the *high-p_T* region (right) in the combined $Z \rightarrow \ell\ell$ measurement.

More details on Sherpa v.2.2.11 Z+Jets

ATL-CONF-2021-033

- ME elements up to 5 partons at LO and up to 2 partons at NLO
- Modified Catani-Seymour subtraction scheme (dipole subtraction method for NLO corrections in QCD with massive partons.)
- Hessian NNPDF3.0 NLO set
- Continuous enhancement technique which transforms the probability density function from which events are samples with an analytic biasing function of a set of observables and the phase-space point.
- Cross section in the high pT region reduced switching to an improved matching scheme w/ a different treatment of unordered histories.
- NLO EW + QCD used additive scheme but a systematics band derived from the envelope of additive, multiplicative and exponential schemes.

Colour Reconnection (CR)



Christiansen, J.R. & Skands, P.Z. J. High Energ. Phys. (2015) 2015: 3.

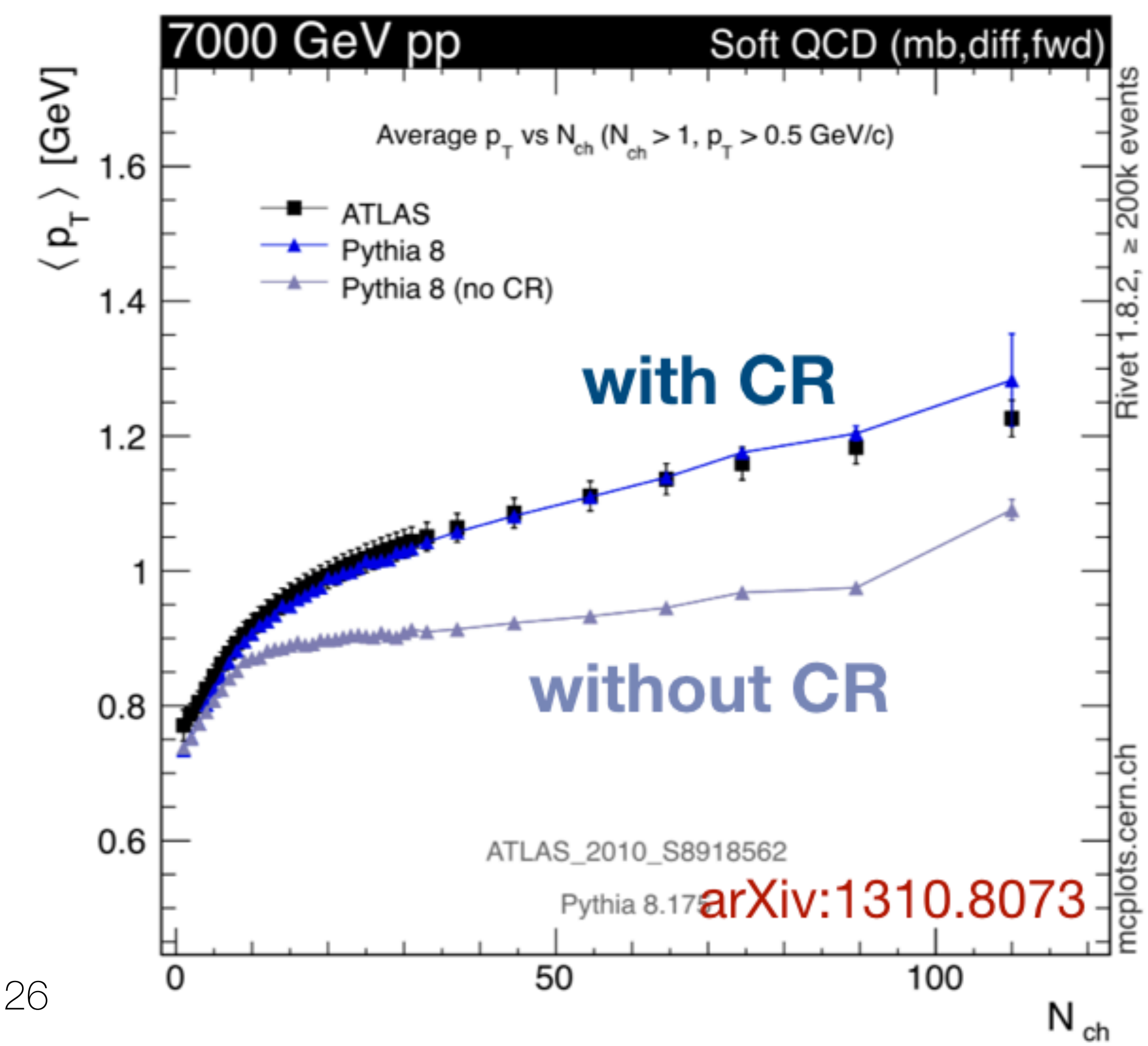
Leading colour (LC) approximation:

- Each MPI is viewed as separate from all other systems in colour space. Each MPI increases the color by two units.
- No strings stretched between different MPI systems.

Color reconnection allows different MPI systems to be colour-connected to each other. MPI hadronize collectively.

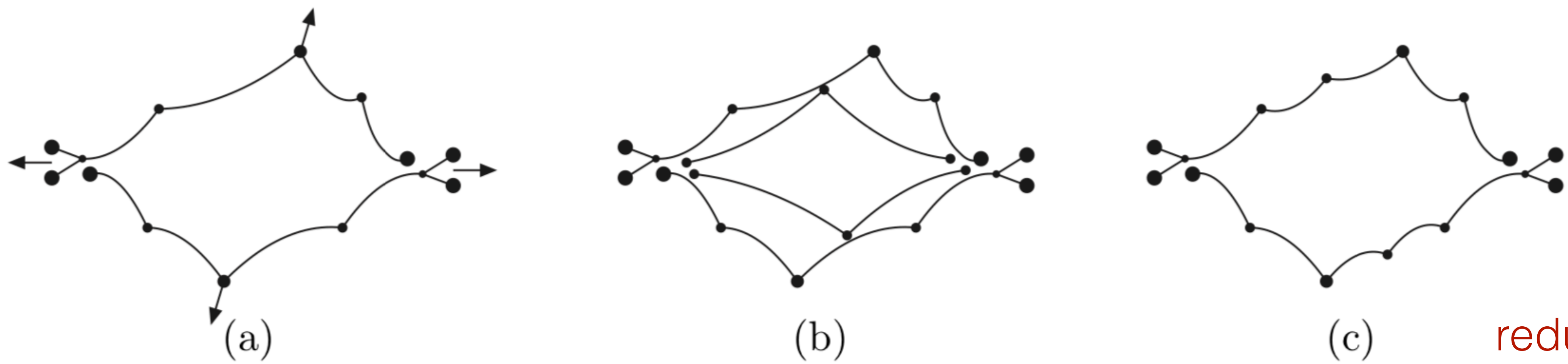
- Total colour charge reduced w.r.t. LC approximation.

- Rising trend of $\langle p_\perp \rangle(nch)$:
  - first observed by UA1 [Nucl. Phys. B335 (1990)]
  - Color reconnection is needed to describe the data.
- $dN/d\eta$, and N_{ch} data requires CR to be described (shown in later slides).



MPI-based CR model in PYTHIA8

- The simplest CR model in event generators with only one free parameter.



reduced λ

First hard scattering: outgoing gluons are colour connected

A second hard scattering: gives new strings connected to the remnants.

gluons are colour reconnected, so that the total string length (λ) becomes as short as possible.

Reconnection probability

$$P = \frac{(R_{rec} \times p_{T_0})^2}{(R_{rec} \times p_{T_0})^2 + p_T^2}$$

ColourReconnection:range
(free parameter of the model)

The higher this number is the more reconnections can occur.

Reduce λ by adding partons of the lower-pT system to the strings defined by the higher-pT system

$$\lambda \approx \sum_{i,j} \ln\left(\frac{m_{ij}^2}{m_0^2}\right)$$

$p_T \downarrow \Rightarrow P_{rec} \uparrow$

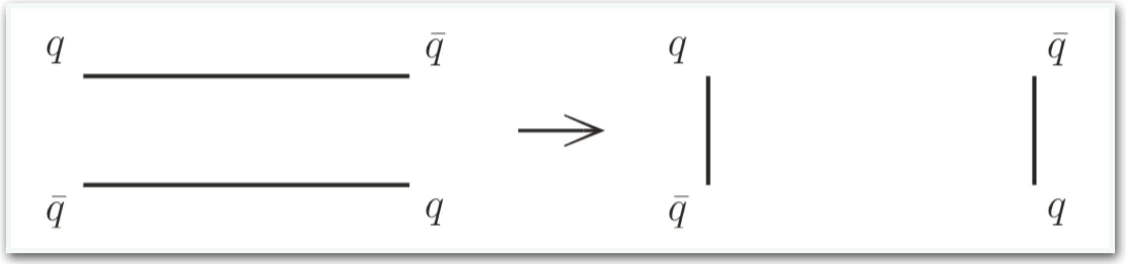
softer systems easier to reconnect

G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

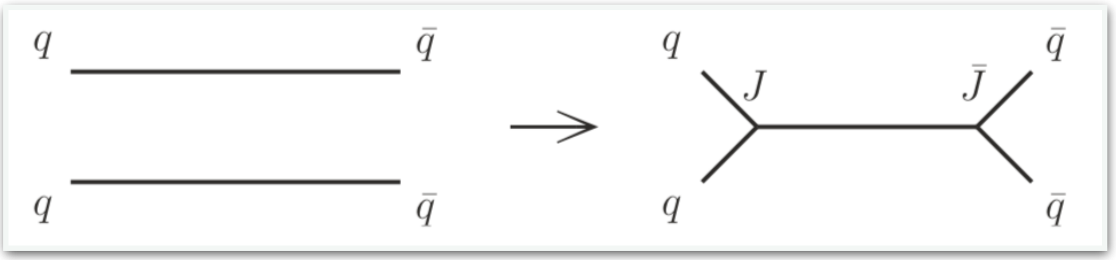
QCD-inspired CR model in PYTHIA8

Alternative approach for reconnection ⇒ introduce "junctions"

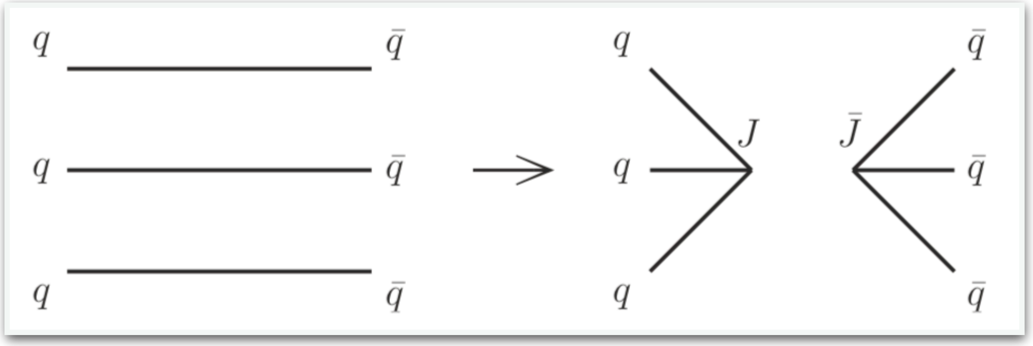
- More realistic; Adds QCD colour rules (SU(3) colour algebra) in addition to the minimisation of the string length.



ordinary string reconnection



double junction reconnection



triple junction reconnection

- More types of junction reconnections available..
- Additional junction structures simulates higher order effects in CR.
- Improves description of baryon production —> the only PYTHIA8 tune that can simultaneously describe Λ production at LEP and LHC.

Some free parameters:

m0: variable used in the λ measure for the string length.

timeDilationPar: controls the time of two strings to resolve each other between formation and hadronization.

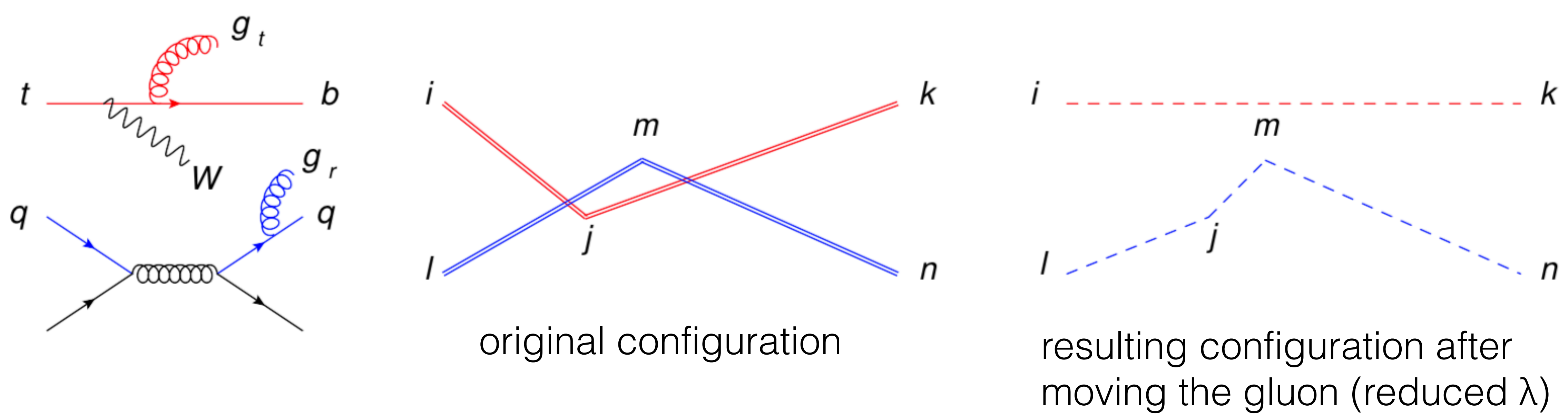
junctionCorrection: multiplicative factor to control junction production.

Christiansen, J.R. & Skands, P.Z. J. High Energ. Phys. (2015) 2015: 3.

gluon-move CR model in PYTHIA8

Similar to other CR models, it aims to reduce the total "string length" λ.

→ A gluon j originally attached to a string piece, ik, can be moved to a different string piece, lm, if it leads to a smaller total string length λ.



$$\Delta\lambda(j, lm) = \lambda_{j;lm} - \lambda_{j;ik} = \lambda_{lj} + \lambda_{jm} + \lambda_{ik} - (\lambda_{ij} + \lambda_{jk} + \lambda_{lm}) \,.$$

$$\min_{j,lm} \Delta\lambda(j, lm) \leq \Delta\lambda_{\text{cut}}$$

→ Quarks are not reconnected. To give the quarks the possibility to be reconnected, flip mechanism may be introduced. This also allows junctions to take part in the flip step.

We don't use flip mechanism since no considerable differences expected (may be except in the pull angle in ttbar).

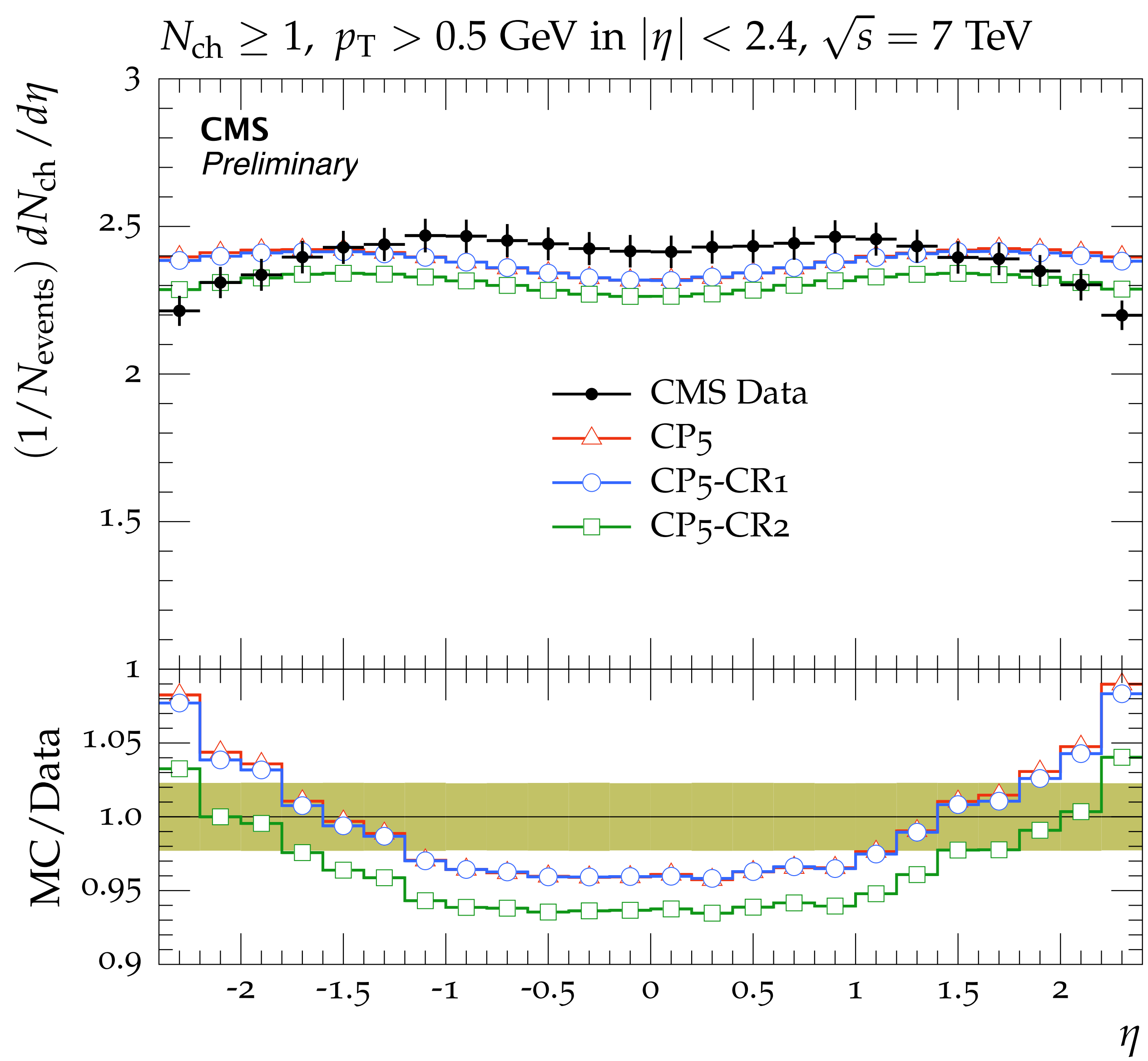
Some free parameters:

m2Lambda: variable used in the definition of λ.

fracGluon: probability that a given gluon will be considered for being moved.

10.1007/JHEP11(2014)043

New CMS PYTHIA8 CR Tunes: MinBias at 7 TeV



- Not used in the fits.
- Observable sensitive to softer part of the MPI spectrum.
- At most ~10% deviation.
- Predictions from CP5 and CP5-CR1 agree very well with each other. CP5-CR2 predicts less number of particles compared to CP5 and CP5-CR1.