Forward-Backward multiplicity analysis and cluster formation in pp collisions at $\sqrt{s}$ = 0.9, 7 and 8 TeV from the CMS experiment

Z. Ong*, P. Agarwal, H.W. Ang, A.H. Chan, C.H. Oh
Department of Physics, National University of Singapore
52nd International Symposium on Multiparticle Dynamics (ISMD 2023), 21-26 Aug 2023
*Email: `ongzongjin@u.nus.edu`

Abstract

The forward-backward multiplicity distributions of pp collisions at $\sqrt{s} = 0.9$, 7 and 8 TeV from the CMS experiment are analysed using a modified Chou-Yang scheme. The total multiplicity component was found to be well-described by a weighted superposition of a Negative Binomial Distribution and a Furry-Yule Distribution. The forward-backward asymmetry component revealed a continued increase of the mean cluster size formed with increasing collision energy, which is possibly related to an increase in the initial number of gluons produced.

Introduction

The Chou-Yang model, first proposed in 1984 [1] and subsequently modified by Lim *et al.* [2, 3] describes the forward-backward (FB) multiplicity distribution of particle collisions. The forward and backward multiplicities (n_F and n_B respectively) are described using the variables

$$n = n_\mathrm{F} + n_\mathrm{B}, \tag{1}$$

$$z \equiv n_\mathrm{F} - n_\mathrm{B}, \tag{2}$$

which are the total multiplicity and FB asymmetry of an event respectively. Chou and Yang noticed that $p\overline{p}$ collisions at $\sqrt{s} = 540$ GeV from the UA5 collaboration seemed to obey

$$\left[\left\langle z^2 \right\rangle \text{at fixed } n\right] = 2n, \tag{3}$$

which led them to propose describing the overall FB multiplicity distribution as

$$P(n,z) = \Psi\left(\frac{n}{\langle n\rangle}\right) C^{n/2}_{n_\mathrm{F}/2}\left[B\left(\frac{n}{2}\right)\right]^{-1}. \tag{4}$$

Their model comprises two components: the KNO function $\Psi\left(n/\left\langle n\right\rangle\right)$ describes the total multiplicity distribution and the remaining terms describe how the particles are distributed in the FB direction. $C^{n/2}_{n_\mathrm{F}/2} = C^{n/2}_{(n+z)/4}$ is a combinatorial factor describing the binomial distribution of z, and B is factor that normalises the overall equation: $B\left(n/2\right) = \sum_{n_\mathrm{F}} C^{n/2}_{n_\mathrm{F}/2}$. Below, we consider some modifications to the original Chou-Yang model.

Total multiplicity component

In this analysis, the KNO function is replaced by a weighted superposition of a Negative Binomial Distribution and a Furry-Yule Distribution:

$$P(n) = \alpha P_\mathrm{NBD}(n;\overline{n}_\mathrm{NBD},k) + (1-\alpha)P_\mathrm{FYD}(n;\overline{n}_\mathrm{FYD},k'), \tag{5}$$

where $\alpha \in [0,1]$. The NBD and FYD are defined as

$$P_\mathrm{NBD}(n;\overline{n},k) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)}\left[\frac{\overline{n}}{\overline{n}+k}\right]^n\left[\frac{k}{\overline{n}+k}\right]^k, \tag{6}$$

$$P_\mathrm{FYD}(n;\overline{n},k') = \frac{\Gamma(n)}{\Gamma(n-k'+1)\Gamma(k')}\left[\frac{\overline{n}-k'}{\overline{n}}\right]^{n-k'}\left[\frac{k'}{\overline{n}}\right]^{k'}. \tag{7}$$

Equation (5) describes the overall process of multiparticle production as a superposition of branching processes with lower and higher complexity. The NBD and FYD are particular solutions to the basic evolution equation

$$\frac{\partial P_n(t)}{\partial t} = a_{n+1}P_{n+1} + c_{n-1}P_{n-1} - (a_n + c_n)P_n, \tag{8}$$

where the NBD describes more complex branching with birth, death and immigration processes (with coefficients of the form $a_n = \alpha n$, $c_n = \beta n + \gamma$), whereas the FYD describes a simpler picture with only birth processes ($a_n = 0$, $c_n = \beta n$).

FB component

Lim *et al.* [2, 3] generalised equation (3) to become

$$\left[\left\langle z^2 \right\rangle \text{at fixed } n\right] = rn, \tag{9}$$

which modifies the Chou-Yang model with a new interpretation: it describes grouping of the n particles produced into r clusters first, before being redistributed in z according to the combinatorial scheme in the original Chou-Yang model. Therefore, the overall Chou-Yang model has been modified to become

$$P(n,z) = P(n)C^{n/r}_{n_\mathrm{F}/r}\left[B\left(\frac{n}{r}\right)\right]^{-1}. \tag{10}$$

Main Objectives

To analyse the FB multiplicity data of pp collisions from the CMS experiment at $\sqrt{s} = 0.9$, 7 and 8 TeV by:

1. Describing the total multiplicity component $P(n)$ using the NBD-FYD model by parameter fitting.
2. Measuring the mean cluster size formed r using equation (9).

About the data

Run 1 datasets from the CMS experiment comprising pp collisions at $\sqrt{s} = 0.9$, 7, 8 TeV and their corresponding Monte Carlo (MC) simulations were obtained from the CERN Open Data Portal (see Refs. 9-14 in [4]). The collision data is then processed with selection cuts and unfolded with MC data using an iterative "Bayesian unfolding method". Systematic error analysis was done partially, with contribution only from the unfolding process. More details of data treatment can be found in [4].

Results

Multiplicity component

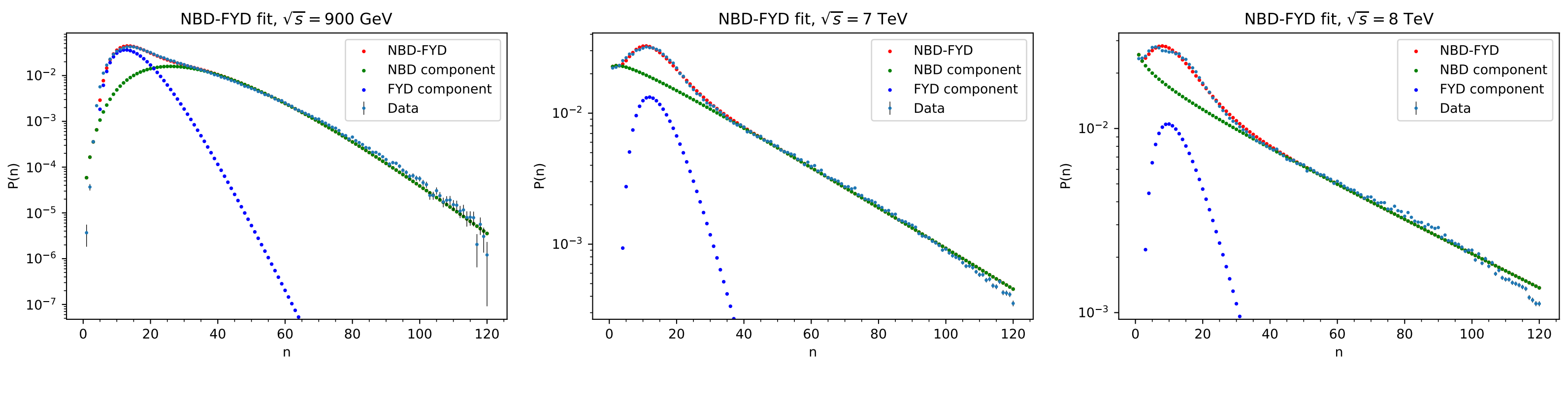

Figure 1: Fits of the NBD-FYD model to data for $1 \leq n \leq 120$, with their NBD and FYD components also shown.

Table 1: Best-fit parameters for NBD-FYD model

$\sqrt{s}$	900 GeV	7 TeV	8 TeV
α	0.395 ± 0.003	0.814 ± 0.001	0.846 ± 0.002
$\overline{n}_\mathrm{NBD}$	35.7 ± 0.1	29.56 ± 0.04	43.2 ± 0.1
k	6.55 ± 0.06	1.108 ± 0.003	0.886 ± 0.003
$\overline{n}_\mathrm{FYD}$	16.79 ± 0.03	15.15 ± 0.04	14.16 ± 0.06
k'	4.00 ± 0.04	4.00 ± 0.04	2.81 ± 0.03
χ^2/d.o.f.	10.52	11.44	13.76

FB component

Table 2: Measured mean cluster size r for hadronic collisions, compiled with previous studies at other energies

Collaboration	$\sqrt{s}$ (GeV)	r	Source
ISR (pp)	24	1.14 ± 0.04	Ref. [2]
	31	1.33 ± 0.05	
	45	1.29 ± 0.04	
	53	1.49 ± 0.04	
	63	1.55 ± 0.05	
UA5 ($p\overline{p}$)	200	1.88 ± 0.07	Ref. [2]
	546	2.23 ± 0.07	
	900	2.28 ± 0.07	
E735 ($p\overline{p}$)	300	2.15 ± 0.23	Ref. [5]
	546	2.78 ± 0.26	
	1000	2.81 ± 0.30	
	1800	2.62 ± 0.12	
CMS (pp)	900	2.3 ± 0.2	(New measurement)
	7000	3.07 ± 0.03	
	8000	3.28 ± 0.03	

Conclusion and Discussion

- The multiplicity distribution of pp collisions at $\sqrt{s} = 0.9$, 7 and 8 TeV are well-described by a weighted superposition of an FYD and an NBD (the larger-than-unity values of χ^2 in Table 1 is largely due to the underestimation of systematic errors). The FYD component diminishes with increasing collision energy, suggesting that the branching nature of the multiparticle production process was becoming more complex with emerging death and immigration processes.
- The mean cluster size r seems to increase with increasing collision energy, with the trend described by $r = \alpha \log\sqrt{s} + \beta$, with $\alpha = 0.35 \pm 0.03$ and $\beta = 0.1 \pm 0.2$.

Possible relation between cluster formation and gluon production

In a separate work by our research group [6], we studied numerical solutions to the full Giovannini equation, which models multiparticle production using the four fundamental QCD processes. For m quarks and n gluons at QCD evolution parameter t, we have:

$$\begin{aligned}\frac{\partial P_{m,n}}{\partial t} = &-\left(An + \widetilde{A}m + Bn + Cn\right)P_{m,n} + A(n-1)P_{m,n-1} + \widetilde{A}mP_{m,n-1}\\ &+ B(n+1)P_{m-2,n+1} + C(n-2)P_{m,n-2}\end{aligned} \tag{11}$$

where A, $\widetilde{A}$, B and C are the probabilities of the processes

$$\begin{aligned}&A : g \to gg \text{ (gluon bremsstrahlung)},\\ &\widetilde{A} : q \to qg \text{ (quark bremsstrahlung)},\\ &B : g \to q\overline{q} \text{ (quark pair creation)},\\ &C : g \to ggg \text{ (four-gluon vertex)}.\end{aligned} \tag{12}$$

It was found that for hadronic collisions, the values of A and C increase with increasing collision energy. The similar increase in mean cluster size observed in the modified Chou-Yang model could suggest a link between cluster formation and gluon production, which warrants further investigation.

Future Work

With Run 3 of the LHC under way, we look forward to more data being made available for analysis and extending this investigation to energies beyond 8 TeV.

References

[1] T. T. Chou and Chen Ning Yang. Binomial Distribution for the Charge Asymmetry Parameter. *Phys. Lett. B*, 135:175–178, 1984.

[2] S. L. Lim, Y. K. Lim, C. H. Oh, and K. K. Phua. Forward-backward multiplicity correlation in high energy hadron-hadron collisions. *Z. Phys. C*, 43:621, 1989.

[3] S. L. Lim, C. H. Oh, and K. K. Phua. The forward-backward multiplicity correlations, the single hemisphere multiplicity distributions and the mean cluster size in high-energy e^+e^- and hadron-hadron collisions. *Z. Phys. C*, 54:107–114, 1992.

[4] Z. Ong, P. Agarwal, H. W. Ang, A. H. Chan, and C. H. Oh. Forward-backward multiplicity distribution with the Chou-Yang model for pp collisions at $\sqrt{s} = 0.9$, 7 and 8 TeV from the CMS experiment. *Mod. Phys. Lett. A*, 38(03):2350014, 2023.

[5] E375 Collaboration. Charged particle multiplicity correlations in $p\overline{p}$ collisions at $\sqrt{s} = 0.3$-1.8 TeV. *Phys. Lett. B*, 353:155–160, 1995.

[6] Z. Ong, P. Agarwal, H. W. Ang, A. H. Chan, and C. H. Oh. Numerical solutions to Giovannini's parton branching equation up to TeV energies at the LHC. *Mod. Phys. Lett. A*, 35(39):2050325, 2020.

Acknowledgements

The authors would like to thank the National University of Singapore, and the support and helpful discussions with colleagues. We would also like to thank the CMS collaboration at CERN for the well-organised release of collision data to the public on the CERN Open Data Portal. This work is also supported by the NUS Research Scholarship.