The Effects of Multiple-Parton Interactions on the Production of Charged Particles and Pentaquarks

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November 15, 2024

Outline

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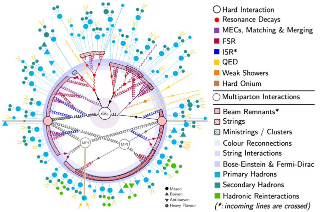
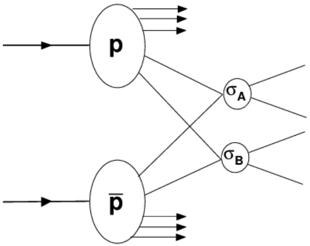
Multiple-Parton Interactions

- More than one pair of partons from each incoming hardons interact within a single hardon collision, which are called the **Multiple-Parton Interactions (MPIs)**.
- MPIs have both "hard" (Double Parton Scattering) and "soft" (underlying event) contributions.
- The aim of this work is to investigate the MPI-sensitivity of a list of observables.





MPI Model (Sjöstrand & van Zijl, 1987)

- differential perturbative QCD $2 \to 2$ cross-section

$$\frac{d\sigma}{dp_T^2} = \sum_{i,j,k} \iiint f_i\left(x_1, Q^2\right) f_j\left(x_2, Q^2\right) \frac{d\hat{\sigma}_{ij}^k}{d\hat{t}} \delta\left(p_T^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) dx_1 dx_2 d\hat{t}$$

- The average number of MPIs

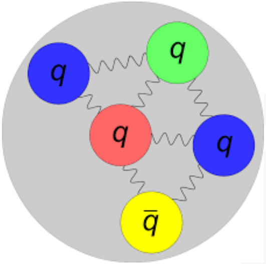
$$\langle n_{\mathrm{MPI}}(p_{T\mathrm{min}})\rangle = \frac{\sigma_{\mathrm{hard}}(p_{T\mathrm{min}})}{\sigma_{tot}}, \quad \sigma_{\mathrm{hard}}(p_{T\mathrm{min}}) = \int_{p_{T\mathrm{min}}^2}^{s/4} \frac{d\sigma}{dp_T^2} dp_T^2$$

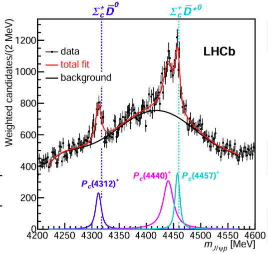
- Assume independent interactions and no impact-parameter dependence. $n_{\mathrm{MPI}}(p_{T\mathrm{min}})$ follows Poissonian distribution. Ordered by the "hardness" scale, $\sqrt{s}/2 > p_{T1} > p_{T2} > \cdots > p_{Tn} > p_{T\mathrm{min}}$. $p_{T\mathrm{min}} \sim 0.2\ \mathrm{GeV} < 2\ \mathrm{GeV}$

$$\frac{d\mathcal{P}}{dp_{Ti}} = \frac{1}{\sigma_{\mathrm{tot}}} \frac{d\sigma}{dp_{Ti}} \exp\left(-\int_{p_{Ti}}^{p_{Ti-1}} \frac{1}{\sigma_{\mathrm{tot}}} \frac{d\sigma}{dp'_{Ti}} dp'_T\right)$$

Pentaquark

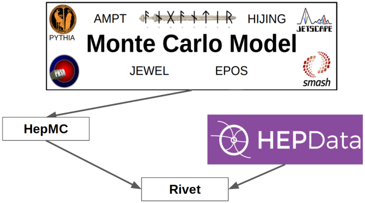
- M. Gell-Mann & G. Zweig (1964): Quark model. Five-quark particle.
- H.J. Lipkin (1987): coined name **pentaquark**.
- . . .
- LHCb (2015): $J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi K^- p$ decays. $P_c^+(4380)$ and $P_c^+(4457)$.
- LHCb (2019): $P_c^+(4312)$, $P_c^+(4440)$ and $P_c^+(4457)$.





State	M [MeV]	Γ [MeV]
$P_c^+(4312)$	4311.9 ± 0.7	9.8 ± 2.7
$P_c^+(4440)$	4440.3 ± 1.3	20.6 ± 4.9
$P_c^+(4457)$	4457.3 ± 0.6	6.4 ± 2.0

Monte Carlo Event Generator



- An **Event Generator** is a numerical algorithm that can simulate the outcome of a collision.
- Non-analytic structure (e.g. PDF) $\Rightarrow$ Monte Carlo Methods
- Why MC event generator?
  i. Based on known or hypothetical laws of nature.
  ii. Predict the results of experiments.
  iii. Give hints and check the validity of our theories.
- For this research, only Pythia till now.

MPI Parameters

- Cross-section regularization

$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha^2(p_T^2)}{p_T^4} \to \frac{\alpha^2(p_{T0}^2 + p_T^2)}{(p_T^2 + p_{T0}^2)^2}$$

Replace the sharp cutoff $p_{T\mathrm{min}}$ with a smooth turn-off p_{T0}

$$p_{T0}(\sqrt{s}) = \mathtt{pT0Ref} \cdot \left(\frac{\sqrt{s}}{\mathtt{ecmRef}}\right)^{\mathtt{ecmPow}}$$

- `bProfile`: Choice of impact parameter profile for the incoming hadron beams. (none, Gaussian (simple, double), exponential, etc.)
- Larger range, more reconnections!

$$\mathcal{P}_{\mathrm{CR}} = p_{T0\mathrm{Rec}}^2 / (p_{T0\mathrm{Rec}}^2 + p_T^2)$$
$$p_{T0\mathrm{Rec}} = \mathtt{range} \cdot p_{T0}$$

MPI Parameters	range
Cross-section parameter	
`MultipartonInteractions:alphaSvalue`	0.06~0.25
Cross-section regularization	
`MultipartonInteractions:pT0Ref`	0.5~10.0
`MultipartonInteractions:ecmRef`	1.~
`MultipartonInteractions:ecmPow`	0.0~0.5
Impact-parameter dependence	
`MultipartonInteractions:bProfile`	0~4
`MultipartonInteractions:coreRadius`	0.1~1.
`MultipartonInteractions:coreFraction`	0.~1.
`MultipartonInteractions:expPow`	0.4~10.
MPI-based CR	
`ColourReconnection:range`	0.~10.

Table: Common tunable MPI parameters

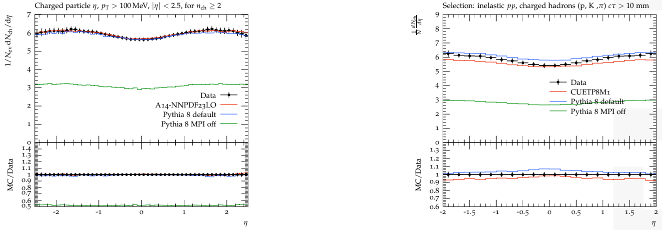
Tunes

A **tune** is a set of parameters that best fits the experimental data.

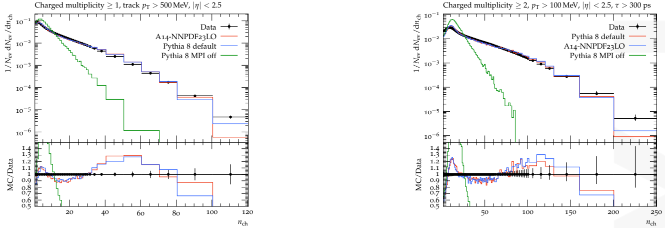
	Pythia-Monash (default)	**4C**
`MultipartonInteractions:pT0Ref`	2.28	2.085
`MultipartonInteractions:ecmRef`	7000.	1800
`MultipartonInteractions:ecmPow`	0.215	0.19
`MultipartonInteractions:bProfile`	3	3
`MultipartonInteractions:coreRadius`	0.4	$\sim$
`MultipartonInteractions:coreFraction`	0.5	$\sim$
`MultipartonInteractions:expPow`	1.85	2
`ColourReconnection:range`	1.8	1.5

	A14-NNPDF23LO	**CUETP8M1-NNPDF23LO**
`MultipartonInteractions:pT0Ref`	2.09	2.402
`MultipartonInteractions:ecmRef`	$\sim$	7000.
`MultipartonInteractions:ecmPow`	$\sim$	0.252
`MultipartonInteractions:bProfile`	3	3
`MultipartonInteractions:coreRadius`	$\sim$	$\sim$
`MultipartonInteractions:coreFraction`	$\sim$	$\sim$
`MultipartonInteractions:expPow`	1.85	1.8
`ColourReconnection:range`	1.87	1.8

Minimum bias

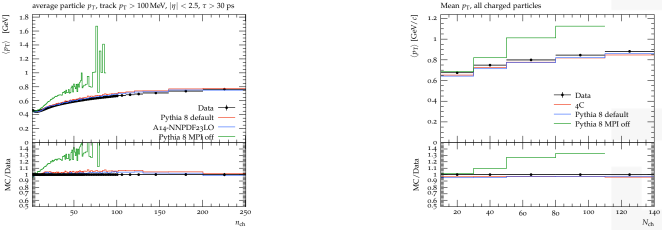


(a) Charged η distribution. Left: ATLAS (8 TeV). Right: CMS (13 TeV)

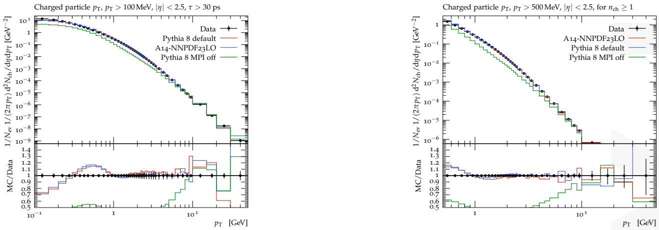


(b) Charged multiplicity distribution. Left: ATLAS (8 TeV). Right: ALTAS 13(TeV)

Minimum Bias



(a) $\langle p_T \rangle$ vs. N_{ch}. Left: ATLAS (13 TeV). Right: CMS (7 TeV)



(b) Charged p_T distribution. Left: ATLAS (13 TeV). Right: ATLAS (8 TeV)

Underlying Events

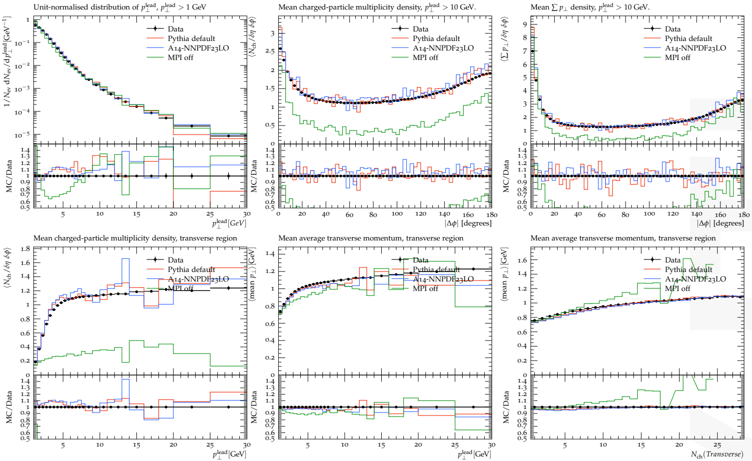


Figure: Measurement of charged-particle distributions sensitive to the underlying event (ATLAS, 2017)

Some brief comments

- MPIs have significant effects on minimum bias and the underlying event, in which charged multiplicity shows high MPI-sensitivity.
- Low p_T region is more sensitive to MPIs than high p_T region, because MPI plays a major role in low p_T region while perturbative QCD masters the high p_T region.
- MPI tunes have provided a good model for minimum bias and the underlying event.
- The MPI is an essential part of the collision simulation. A good model for MPIs can help us to understand the background event and reduce uncertainty.

Pentaquarks in MC simulations

- The study of both MPIs and pentaquarks will enhance our understanding of the non-perturbative behaviours of QCD.
- In general, the modelling of pentaquarks in the event generator is still an open question!
- A possible approach through hadronic rescattering has been provided by the PYTHIA developers since PYTHIA 8.3.

A Framework for Hadronic Rescattering in pp Collisions

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Abstract

In this article, a framework for hadronic rescattering in the general-purpose PYTHIA event generator is introduced. The starting point is the recently presented space–time picture of the hadronization process. It is now extended with a tracing of the subsequent motion of the primary hadrons, including both subsequent scattering processes among them and decays of them. The major new component is cross-section parameterizations for a range of possible hadron–hadron combinations, applicable from threshold energies upwards. The production dynamics in these collisions has also been extended to cope with different kinds of low-energy processes. The properties of the model are studied, and some first comparisons with LHC pp data are presented. Whereas it turns out that approximately half of all final particles participated in rescatterings, the net effects in pp events are still rather limited, and only striking in a few distributions. The new code opens up for several future studies, however, such as effects in pA and AA collisions.

Pentaquarks in MC simulations

Hadronic Rescattering

- After hadrons have been produced, outgoing hadrons can interact in secondary collisions.
- The probability of rescattering interaction

$$\mathcal{P} = \mathcal{P}(b, \sigma_{\text{tot}})$$

$$\sigma_{\text{tot}}(\sqrt{s}, \texttt{Beams:idA}, \texttt{Beams:idB})$$

- Impact parameter dependency
  i. Gaussian: $\mathcal{P}(b) = \mathcal{P}_0 e^{-b^2/b_0^2}$
  ii. Disk model: $\mathcal{P}(b) = \mathcal{P}_0 \Theta(b - b_0)$
- Algorithm
  1. Start with an event right after hadronization.
  2. For each hadron pair, test whether they could interact. If do, record in a time-ordered list. Simulate the collision from the earliest interaction.
  3. Repeat Step 2 until no more potential rescatterings.

Pentaquark as a molecular state

Pentaquarks are treated as $\Sigma_c^+ \bar{D}^0 / \Sigma_c^+ \bar{D}^{*0}$ molecular states. The following molecular model (Y.-H. Lin & B.-S. Zou, 2019) is adopted.

	$P_c^+(4312)$	$P_c^+(4440)$	$P_c^+(4457)$
$\Lambda_c^+ \bar{D}^0$	3.0×10^{-1}	2.7	1.2
$\Lambda_c^+ \bar{D}^{*0}$	1.1×10^1	1.2×10^1	6.9
$\Sigma_c^+ \bar{D}^0$	-	3.4	9.0×10^{-1}
$\Sigma_c^{*+} \bar{D}^0$	-	9.0×10^{-1}	7.2
$n\pi^+$	8.5×10^{-1}	1.0×10^{-1}	3.0×10^{-1}
$n\rho^+$	4.0×10^{-4}	2.0×10^{-1}	5.0×10^{-2}
$p\pi^0$	8.5×10^{-1}	1.0×10^{-1}	3.0×10^{-1}
$p\rho^0$	4.0×10^{-4}	2.0×10^{-1}	5.0×10^{-2}
$p\omega$	3.0×10^{-3}	1.5	4.0×10^{-1}
$p\eta_c$	4.0×10^{-1}	7.0×10^{-2}	3.0×10^{-3}
pJ/ψ	1.0×10^{-1}	6.0×10^{-1}	6.0×10^{-1}
$p\chi_{c0}$	-	1.0×10^{-1}	3.0×10^{-3}

Table: Partial widths in [MeV]

Pentaquarks in MC simulations

The contribution ratio is defined as

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to pJ/\psi)}{\mathcal{B}(\Lambda_b^0 \to pJ/\psi K^-)}$$

$$\Rightarrow \mathcal{B}(\Lambda_b^0 \to P_c^+ K^-) = \mathcal{B}(\Lambda_b^0 \to pJ/\psi K^-)\frac{\mathcal{R}}{\mathcal{B}(P_c^+ \to pJ/\psi)}$$

where the branching ratio $\mathcal{B}(\Lambda_b^0 \to pJ/\psi K^-) = 3.2^{+0.6}_{-0.5} \times 10^{-4}$ measured by LHCb (2016) and $\mathcal{R}$ are measured by LHCb (2019) as well.

	$P_c^+(4312)$	$P_c^+(4440)$	$P_c^+(4457)$
$\mathcal{R}$ [%]	$0.3 \pm 0.07^{+0.34}_{-0.09}$	$1.11 \pm 0.33^{+0.22}_{-0.10}$	$0.53 \pm 0.16^{+0.15}_{-0.13}$
$\mathcal{B}(P_c^+ \to pJ/\psi)$	7.6×10^{-3}	2.7×10^{-2}	3.4×10^{-2}
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)$	1.3×10^{-4}	1.3×10^{-4}	5.1×10^{-5}

In hadronic rescattering framework, the pentaquark production is extremely low, e.g. at least $\sim 10^4$ events per P_c^+.

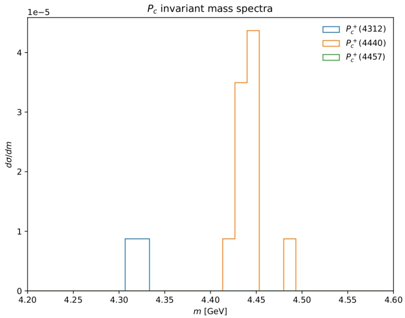


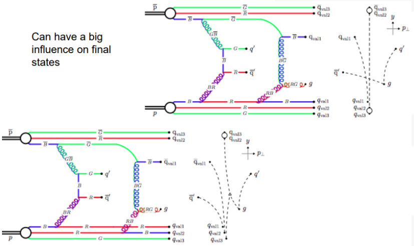
Figure: Invariant mass spectra for P_c generated by 10M events

Q: Can we make the signal more clear by changing MPI parameters?

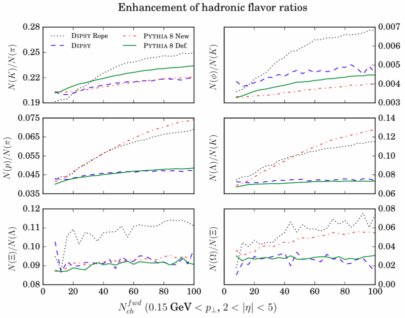
Colour Reconnection may help.

Colour Reconnections

Can have a big influence on final states



- The colour flows of produced partons are reconnected to form **colourless** hadrons with **minimum energy**.
- Can happen due to MPIs if the partons are closed enough in space
- **Leading colour (LC) approximation**: $N_c \to \infty$ with $\alpha_s N_c$ fixed.
- Can have a big influence in final states! Can change the momentum and space distribution of the decay products.
- This part of the work is still in process...



Comments on Pentaquark Simulation

- Pentaquark simulation is generally hard because of the lack of our understanding of soft QCD and the experimental results.
- Pentaquark simulation is also technically hard. Due to the rarity of pentaquarks, a large number of simulations are required.

Conclusion

- The MPI effects on charged particles are well studied.
- The effect of MPIs on pentaquark production is under determined.
- The MPI, as a powerful tool, could be used to analyse many colliding processes and reduce uncertainties.
- **Future Plan**:
  i. More Detailed analysis for tretaqaurks and pentaquarks.
  ii. More MC generators (Herwig, Sherpa, etc.), more observables, more processes (Higgs, W boson, etc.)

Thank You !

Open Questions for MPIs I

- What is the correct behavior of $d\sigma/dp_T^2$ at small p_T? A sharp cutoff, below which cross-sections vanish, is not plausible.
- How to remove (or, if not, interpret) the class of events with no MPIs,currently represented by a $p_T = 0$ interaction?
- How to introduce an impact-parameter picture, giving more activity for central collisions and less for peripheral? This is needed to give an a bit wider n_{ch} distribution. Also, for UA1 jets the MPI formalism as it stands at this stage only gives about a quarter of the observed pedestal effect.
- How to achieve a better description of multiparton PDFs, that also consistently includes e.g., flavor conservation and correlations?
- Where does the baryon number go if several valence quarks are kicked out from a proton?
- How does the color singlet nature of the incoming beams translate into color correlations between the different MPIs?

Open Questions for MPIs II

- What is the structure and role of beam remnants?
- By confinement and the uncertainty relation the incoming partons must have some random non-perturbative transverse motion. How should such "primordial k_T" effects be included? These then have to be compensated in the remnants, and furthermore the remnant parts may have relative k_T values of their own.
- How should parton-shower effects be combined consistently between the systems? The flavor,color and beam-remnant issues reappear here.
- How important is ISR evolution where in a parton branches into two that participate in two separate interactions?
- How important is rescattering, i.e.,when one parton can scatter consecutively from two or more partons from the other hadron?

Open Questions for MPIs III

- How do diffractive topologies contribute to the picture? Typical experimental "minimum bias" triggers catch a fraction of these events, which have different properties from the non-diffractive ones. The low-multiplicity end of the n_{ch} distribution was left unexplained in the studies, with the motivation that it is dominated by diffraction.
- How do the results scale with collision energy? With a fixed $p_{T\mathrm{min}}$ scale it was possible to reproduce the $\langle n_{\mathrm{ch}} \rangle$ evolution from fixed-target to 900 GeV, and this was the basis for extrapolations.

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