Role of string fusion mechanism in fluctuations studies

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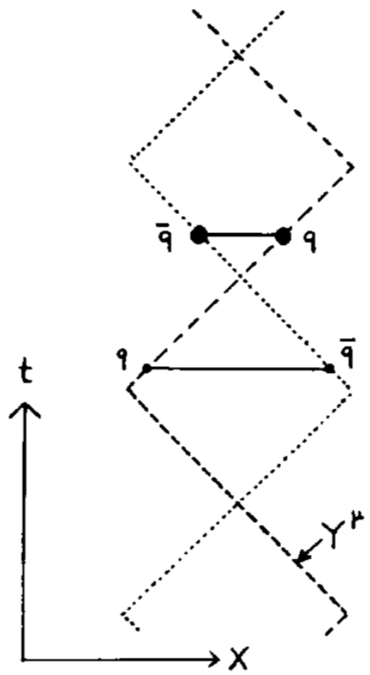
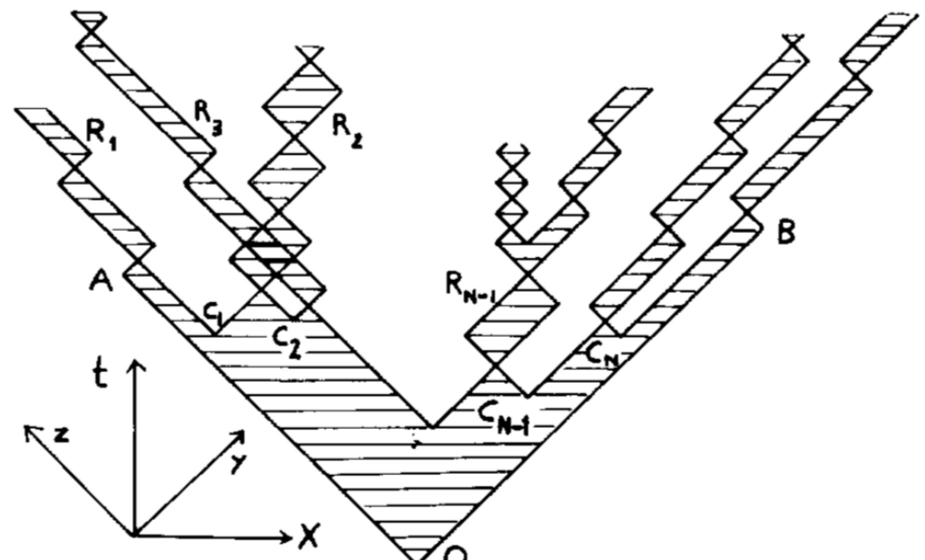
Outline

1. Phenomenological model of quark-gluon strings as particle emitting sources
2. Strings interaction and fusion
3. Developed MC model of interacting quark-gluon strings of finite length in rapidity space
4. Fitting the world data on p+p interactions with the model
5. Fluctuation studies and quantities of interest
6. Model results in comparison with MC event generators
7. Conclusions and future plans

Phenomenological model of quark-gluon strings as particle emitting sources

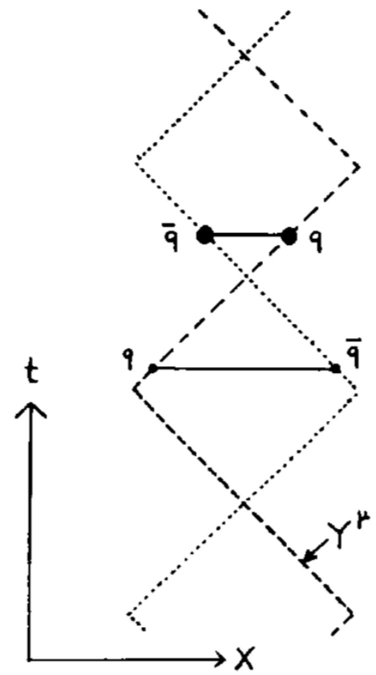


- Two-stage particle production scenario in a non-perturbative Regge approach to describe the **soft particle spectra**
- Colorless hadron represented by the oscillating Jo-Jo solution
- Strings' remnants can be associated with colorless hadrons or with strings that still can break with the further string expansion



[X. Artru and G. Menessier Nuclear Physics B70 (1974) 93 - 115]

Phenomenological model of quark-gluon strings as particle emitting sources



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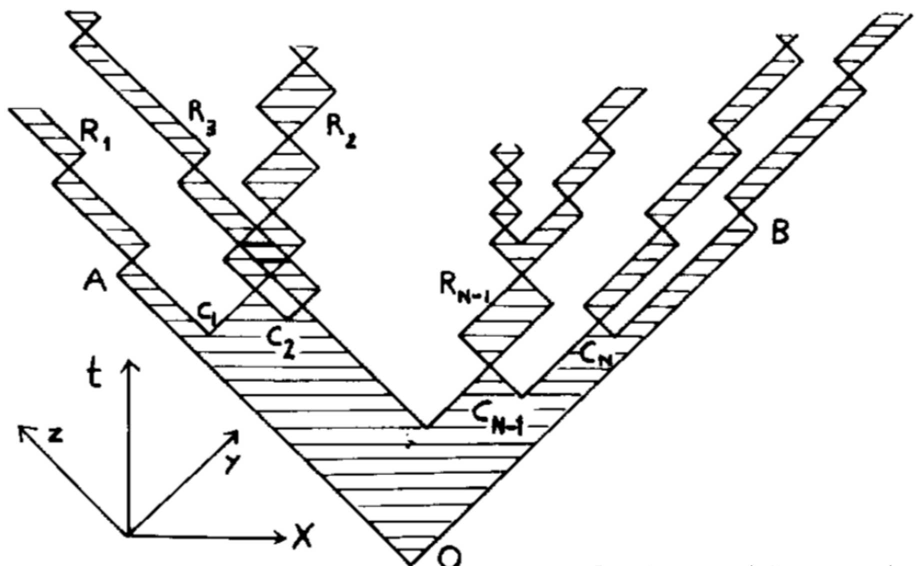

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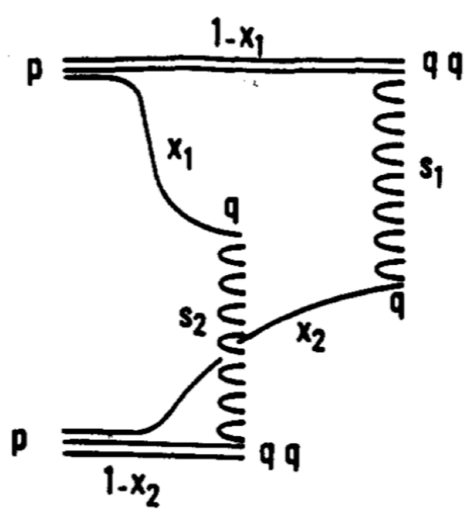
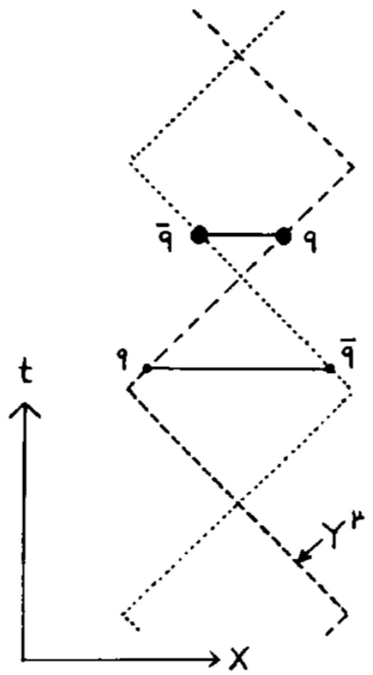


- Unitarity cut of the cylindrical Pomeron diagram results in two-chain diagram, thus **one pomeron exchange corresponds to the formation of two strings** that later fragment to particles

[Capella A. et al Physics Reports 236, Nos. 4 & 5 (1994) 225 - 329]

Phenomenological model of quark-gluon strings as particle emitting sources



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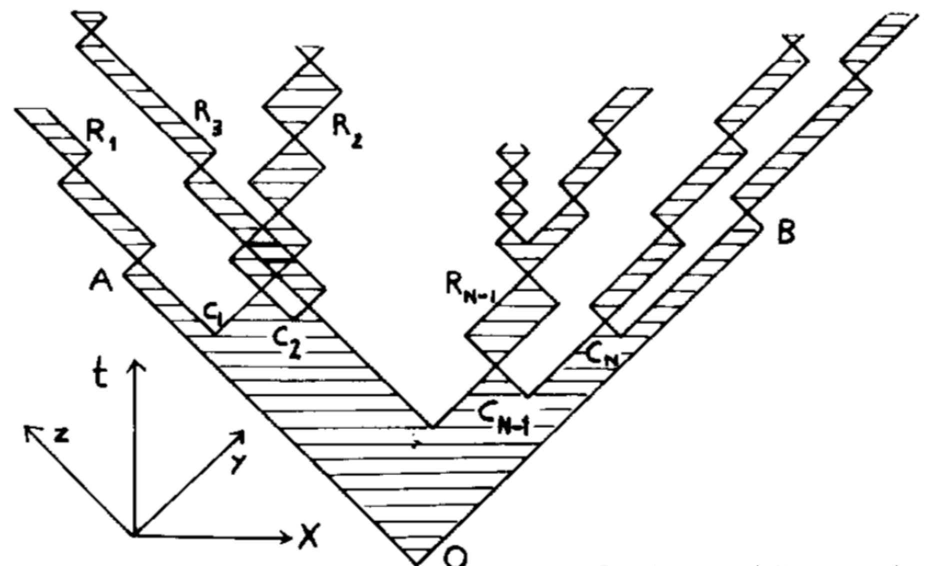

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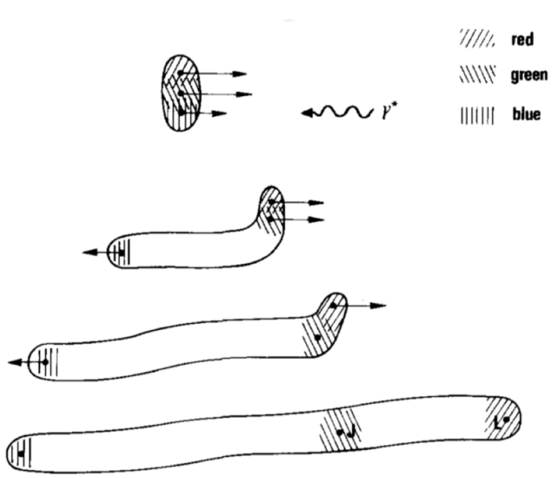
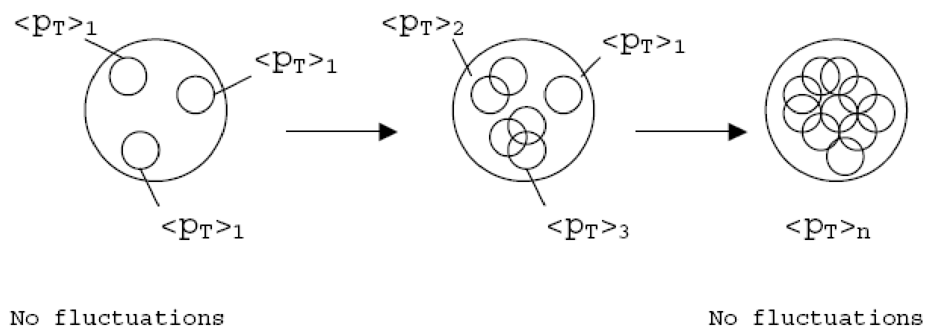


- Longitudinally extended object stretched between the flying outwards wounded quarks and **formed by the color field lines gathered together due to the gluon self-interaction**

[Andersson B. et al *Physics Reports* **97**, 31–145 (1983)]

Strings interaction and fusion

- Strings have **finite size in transverse dimension**, therefore they can overlap, **which brings the additional fluctuations into the system:**



[Pajares, C. *Eur. Phys. J. C* **43**, 9–14 (2005)]

- Their interaction changes the properties of particles emitting sources by **modification of color field density**

[Braun, M. A., Kolevatov, R. S., Pajares, C. Vechernin, V. V. EPJ C, **32**, 535–546 (2004)]

$$\langle \mu \rangle_k = \mu_0 \sqrt{k} \qquad \langle p_T^2 \rangle_k = p_0^2 \sqrt{k},$$

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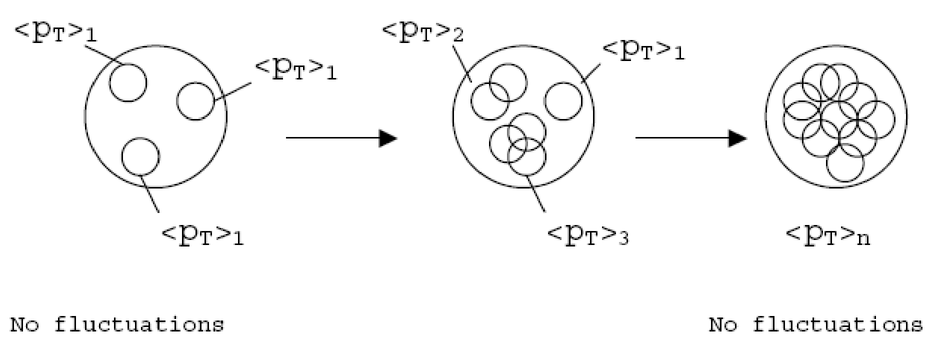

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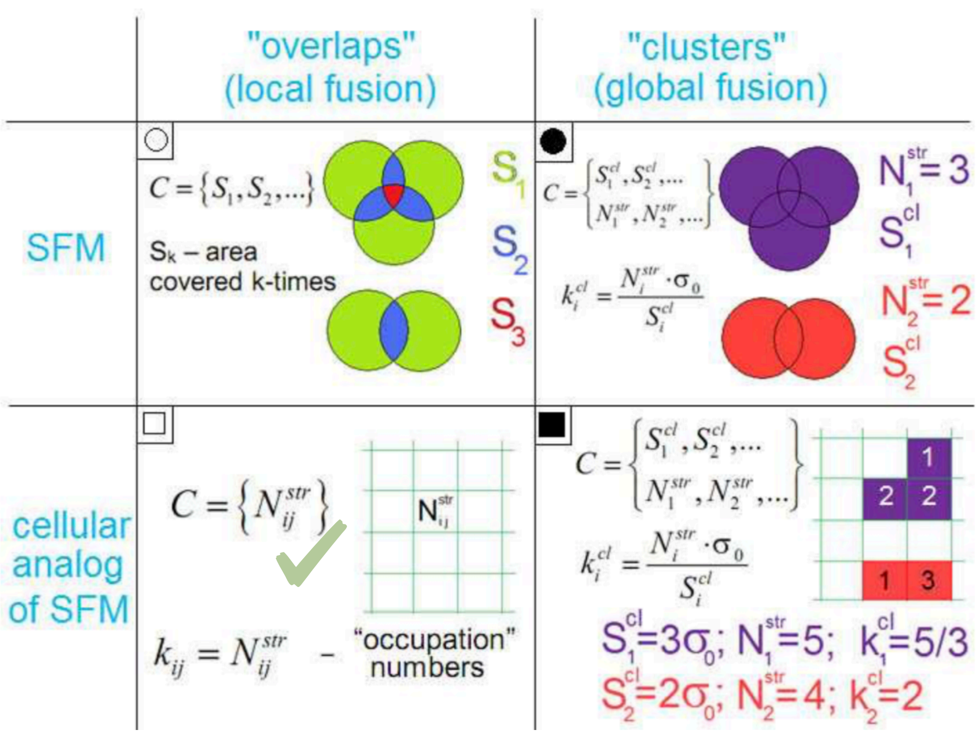

$$\langle\mu\rangle_k = \mu_0\sqrt{k} \qquad \langle p_T^2\rangle_k = p_0^2\sqrt{k},$$

- One can profit from using a **simplified procedure** of string fusion description: by considering them on grid and look for string centers positions instead of counting squares of overlap

[V. Vechernin, I. Lakomov PoS(Baldin ISHEPP XXI)072 (2012)]

Developed MC model of interacting strings of finite length in rapidity space

First toy-implementation of the model: D.P., V.N. Kovalenko, Phys. Part. Nucl. 51, 323 (2020)

- We start with the number of strings sampled from **pomeron number distribution:**

N. Armesto, D.A. Derkach, G.A. Feofilov Phys.Atom.Nucl. 71 (2008) 2087-2095
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E.V. Andronov, V.N. Kovalenko Theor.Math.Phys. 200 (2019) 3, 1282-1293, Teor.Mat.Fiz. 200 3, 415-428

$$\sim \frac{1}{z \cdot N_{pom}} \left(1 - e^{-z} \sum_{l=0}^{N_{pom}-1} \frac{z^l}{l!}\right)$$

$$z = \frac{2C\gamma s^{\Delta}}{R^2 + \alpha' \log(s)},\ \Delta = 0.139,\ \alpha' = 0.21\ \mathrm{GeV}^{-2},\ \gamma = 1.77\ \mathrm{GeV}^{-2},\ R_0^2 = 3.18\ \mathrm{GeV}^{-2},\ C = 1.5$$

- For each string we create two quarks (valence or sea) by sampling their **x from PDFs** and finding their flavors from the proportion of PDFs at a specific x. It is repeated until string energy is enough to decay into two pions:
  Sx > 2*m_pion, where Sx = sqrt(sNN*x1*x2)

- We find initial quark rapidities (rapidities of string ends) having set **current masses for all the quarks**

$$y_q = \operatorname{arcsinh}\left(x_q \sqrt{\frac{s}{4m_q^2} - 1}\right)$$

- Next, we assume that string should be shrinked in rapidity space as color field tension slows down flying outwards quarks. Therefore, for each string we calculate y_loss: https://arxiv.org/pdf/2203.04685.pdf:

$$\langle y_{\text{loss}}\rangle(y_{\text{init}}) = A y_{\text{init}}^{\alpha_2} [\tanh(y_{\text{init}})]^{\alpha_1 - \alpha_2}$$

where we set y_init = abs(y_q_1-y_q_2)/2. We map a logit distribution of Y= logit(x) = log(x/(1 – x)) that is spread between 0 and 1 to the limits of y_loss (from 0 to y_init), having <y_loss> at 1/2 by solving a second order polynomial equation. x is sampled from gauss distribution with mean = 0 and some variance

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Strings are **non-uniformly distributed in rapidity** - source of fluctuations that we account for

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Developed MC model of interacting strings of finite length in rapidity space

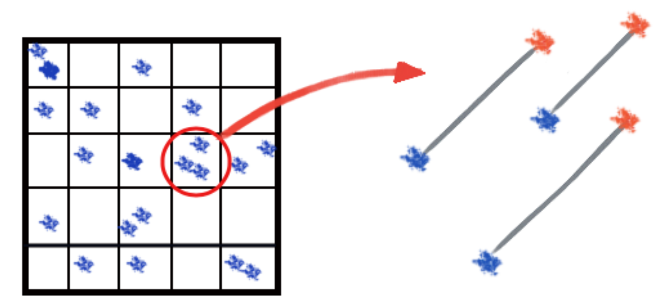
- We also scatter prepared strings in **transverse plane** according to gauss distribution with 0 mean and σ_t = 0.5, having the cell size (bin) equals 0.3

- If strings **centers lie in the same transverse cell** we consider that string fusion occurs and change strings characteristics [V. Vechernin, I. Lakomov PoS(Baldin ISHEPP XXI)072 (2012)]

- Prepared strings are discretized in longitudinal direction into units of length ε

- For each unit we find a mean multiplicity as ε*μ0*sqrt(k) and sample the actual **multiplicity from Poisson distribution**. μ0 - mean multiplicity per rapidity unit, k - number of strings overlapped in transverse cell and rapidity

- For each of these particles we find rapidity from gauss distribution with mean being equal to unit mean and variance being equal to ε. We sample transverse momentum from:



$$f(p_t) = \frac{\pi p_t}{2\langle p_t\rangle_k^2} \exp\left(-\frac{\pi {p_t}^2}{4\langle p_t\rangle_k^2}\right)$$

$$\langle \mu \rangle_k = \mu_0 \sqrt{k}$$

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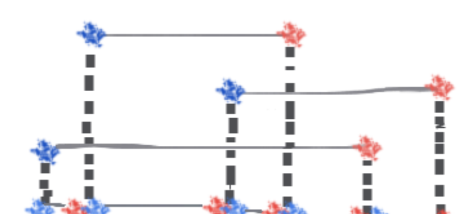

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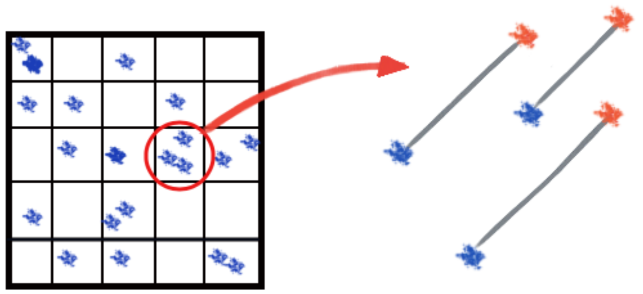

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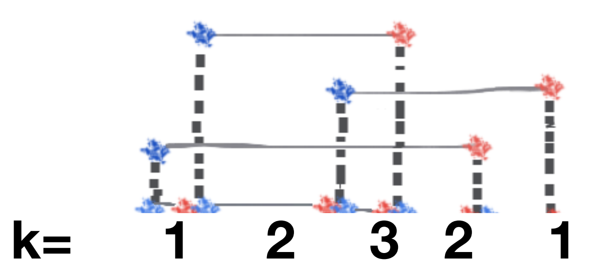
μ0 we change to fit the data
σ_t, ε, pT0 are the global parameters of our model



In this realization we have:
σ_t = 0.5
ε = 0.1
pT0 = 0.3 GeV/c

Fitting the world data on p+p interactions with the model

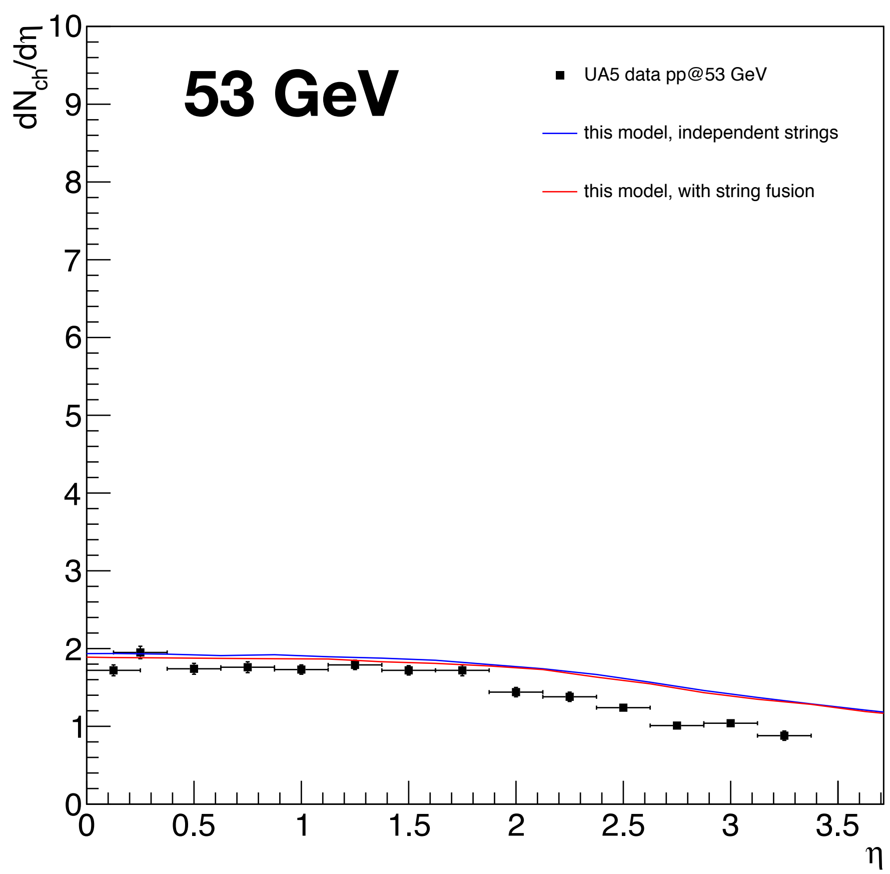
We tune model parameters to **fit the experimental data on dN/dη and multiplicity for p+p collisions**:

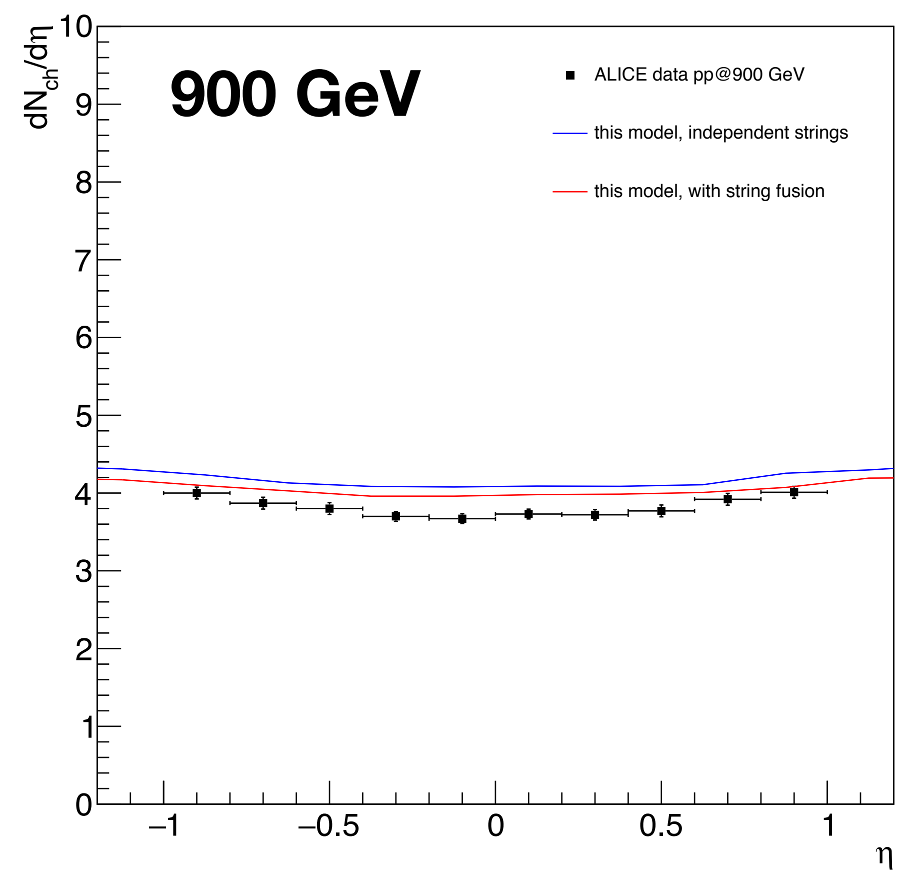
- @53 GeV by UA5 ($|\eta| < 3.5$, all pT)
- @200 GeV by UA5 ($|\eta| < 3$, all pT)
- @900 GeV by ALICE ($|\eta| < 1$, pT > 0.05 GeV, Nch > 0)
- @7000 GeV by ALICE ($|\eta| < 1$, all pT, Nch > 0)

Found fit parameters

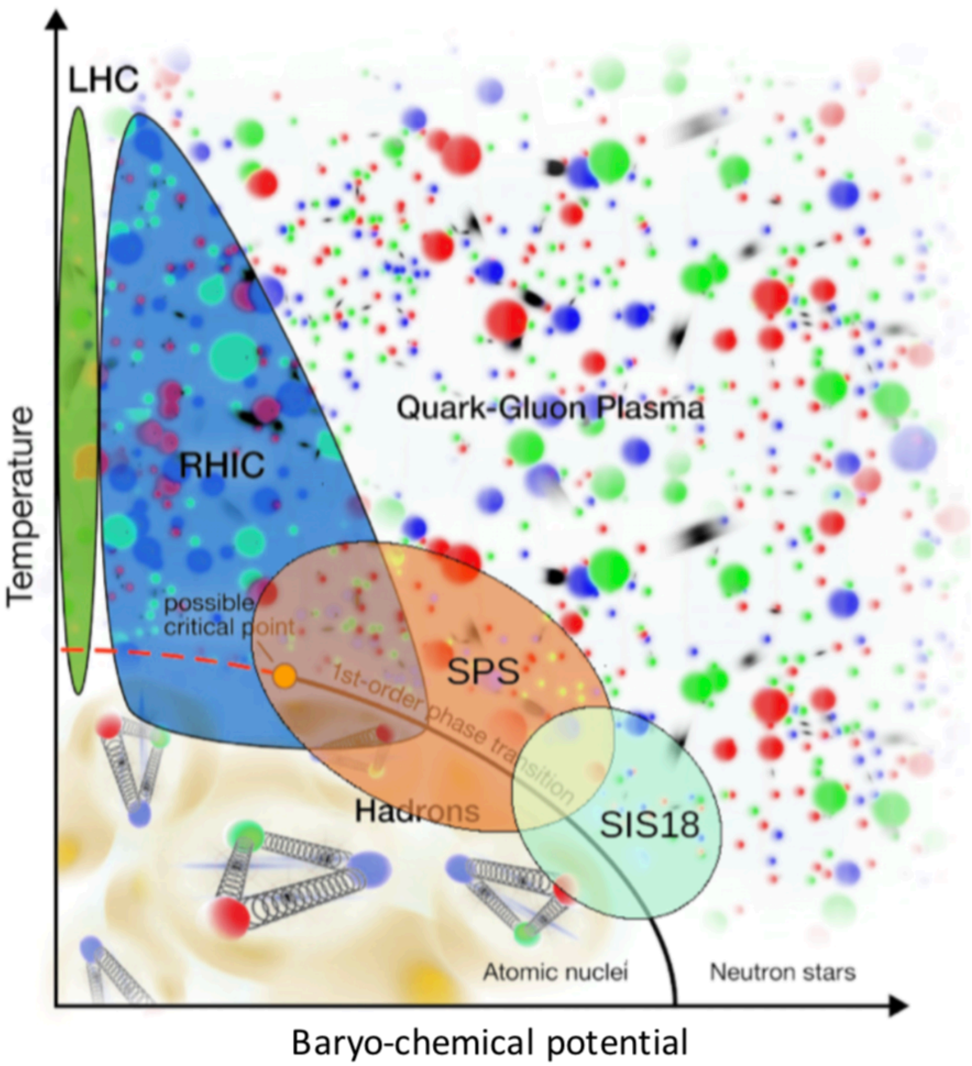
	A	alpha1	alpha2	var	µ0
53 GeV	2.6	0.6	2.1	0.1	0.65
200 GeV	3.0	0.9	1.2	0.1	0.65
900 GeV	3.1	1.0	1.1	0.1	0.65
7000 GeV	3.2	1.1	1.0	0.1	0.8

See below example for **dN/dη distributions**:

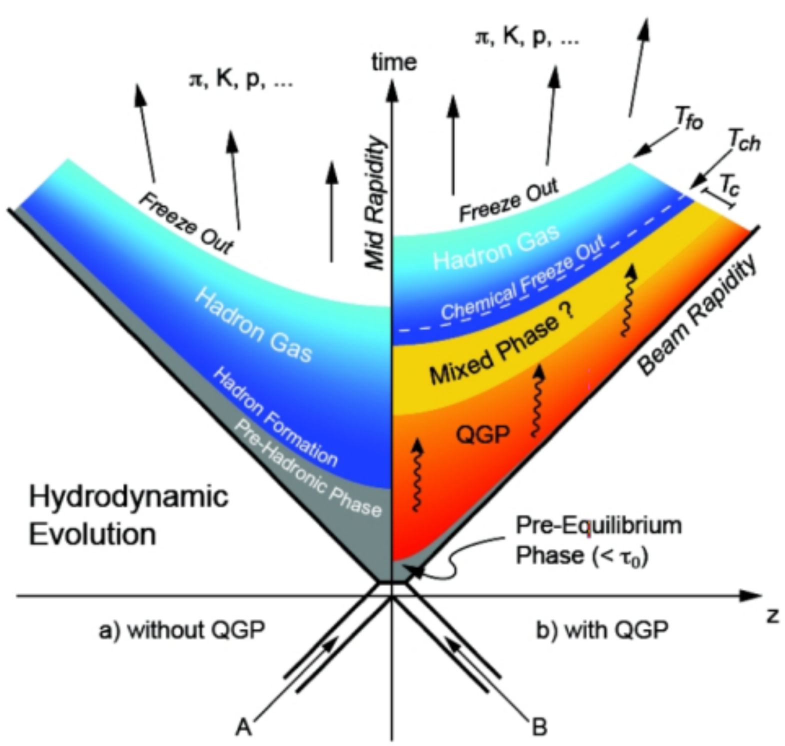




Fluctuation studies and quantities of interest



- study of the event-by-event fluctuations is the key method in the search for the hypothetical **critical point** of strongly interacting matter
- in the vicinity of the critical point system becomes scale-invariant and starts to **exhibit fluctuations** at all the scales
- to catch this signal in data, one has to get rid of the **trivial volume fluctuations** and, in general, all types of inevitable fluctuations that accompany a collision
- possible solution: study the **special fluctuation measures** that are independent both of the system volume and fluctuations of it



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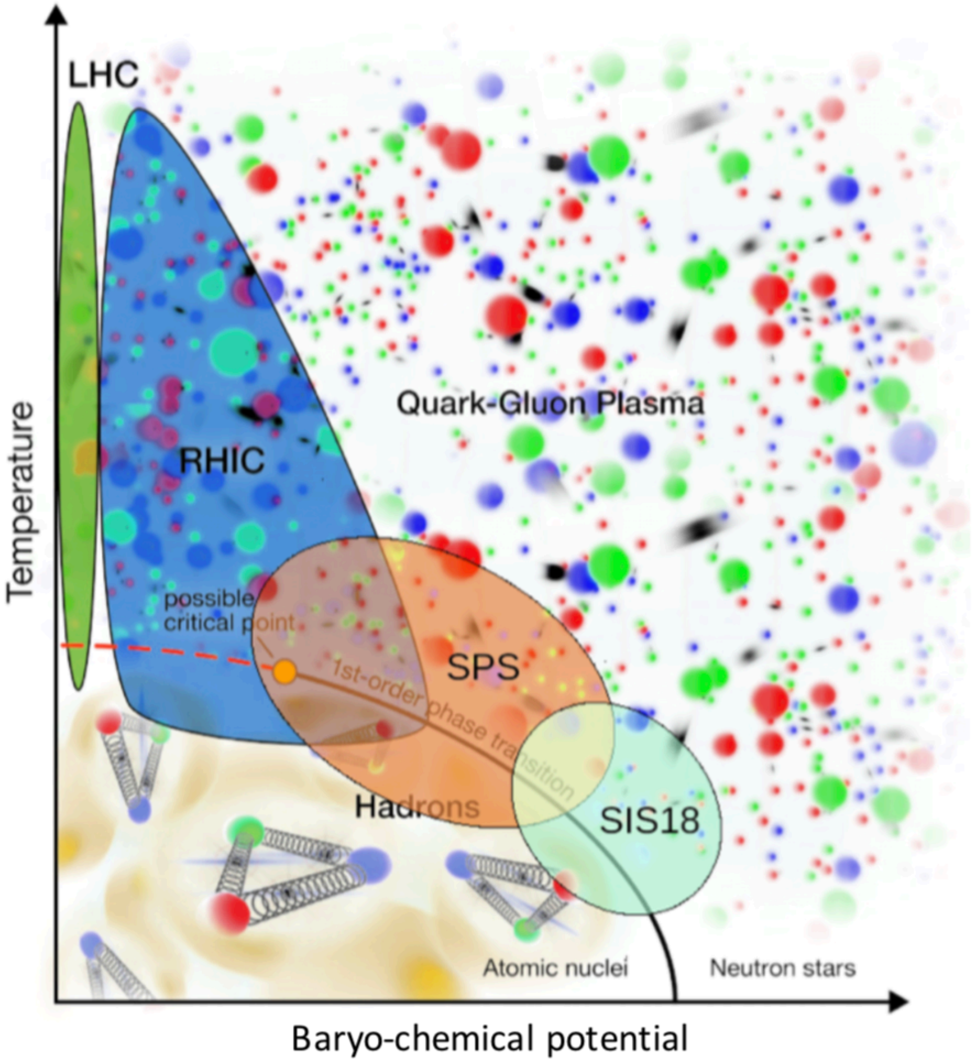

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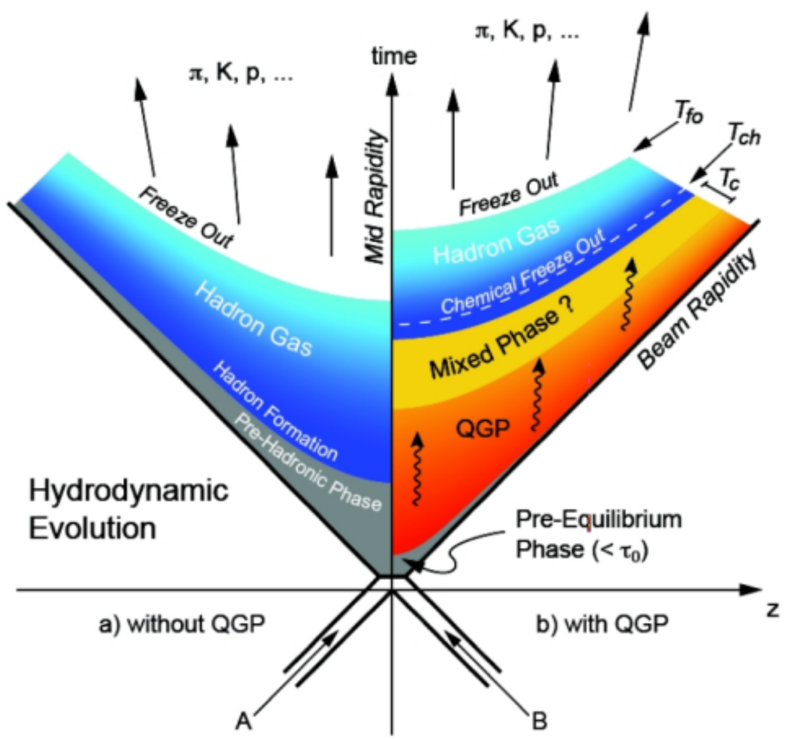
We assume that our model is useful in fluctuations studies as it allows to estimate the influence of **initial conditions** on the final fluctuation measures and to define the non-critical background of fluctuations



Fluctuation studies and quantities of interest

Strongly intensive quantities (SIQs) Δ[PT,N] and Σ[PT,N]

$$\omega[N] = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}, \quad \omega[P_T] = \frac{\langle P_T^2\rangle - \langle P_T\rangle^2}{\langle P_T\rangle}, \quad \omega(p_T) = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$$

$$\Sigma[P_T, N] = \frac{1}{C_\Sigma}\left[\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2\cdot(\langle P_T \cdot N\rangle - \langle P_T\rangle\langle N\rangle)\right]$$

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[M. I. Gorenstein and M. Gaździcki, Physical Review C **84**, 014904 (2011)]

One can study them **as a function of rapidity acceptance size**, which corresponds to the change of rapidity-averaged baryo-chemical potential at the freeze-out stage

[Becattini F, Manninen J and Gazdzicki M PRC 73 044905]

See some NA61/SHINE results:
D.P. (2019) EPJ Web of Conferences **204** 07013

Reference values:

- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for independent particle model
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for the IBG in GCE and CE
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Strongly intensive Σ[NF,NB] in two kinematically separated regions of η:

$$\Sigma[\mathrm{N_F}, \mathrm{N_B}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N_B}\rangle\omega[\mathrm{N_F}] + \langle \mathrm{N_F}\rangle\omega[\mathrm{N_B}] - 2\cdot(\langle \mathrm{N_F}\cdot \mathrm{N_B}\rangle - \langle \mathrm{N_F}\rangle\langle \mathrm{N_B}\rangle)\right]$$

[E. V. Andronov, Theoretical and Mathematical Physics **185**, 1383 (2015)]

One can study them **as a function of rapidity gap size**, which is supposed to be sensitive to the initial conditions of particle production and short- and long-range multiplicity correlations

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Strongly intensive quantities (SIQs) Δ[PT,N] and Σ[PT,N]

$$\omega[\mathrm{N}] = \frac{\langle \mathrm{N}^2\rangle - \langle \mathrm{N}\rangle^2}{\langle \mathrm{N}\rangle}, \quad \omega[\mathrm{P_T}] = \frac{\langle \mathrm{P_T^2}\rangle - \langle \mathrm{P_T}\rangle^2}{\langle \mathrm{P_T}\rangle}, \quad \omega(\mathrm{p_T}) = \frac{\overline{\mathrm{p_T^2}} - \overline{\mathrm{p_T}}^2}{\overline{\mathrm{p_T}}}$$

$$\Sigma[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] + \langle \mathrm{P_T}\rangle\omega[\mathrm{N}] - 2\cdot(\langle \mathrm{P_T}\cdot\mathrm{N}\rangle - \langle \mathrm{P_T}\rangle\langle \mathrm{N}\rangle)\right]$$

$$\Delta[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Delta}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] - \langle \mathrm{P_T}\rangle\omega[\mathrm{N}]\right], \qquad \mathrm{C}_\Sigma = \mathrm{C}_\Delta = \langle \mathrm{N}\rangle\omega(\mathrm{p_T})$$

[M. I. Gorenstein and M. Gaździcki, Physical Review C **84**, 014904 (2011)]

One can study them **as a function of rapidity acceptance size**, which corresponds to the change of rapidity-averaged baryo-chemical potential at the freeze-out stage

[Becattini F, Manninen J and Gazdzicki M PRC 73 044905]

See some NA61/SHINE results:
D.P. (2019) EPJ Web of Conferences **204** 07013

Reference values:

- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for independent particle model
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for the IBG in GCE and CE
- $\Sigma[P_T, N] = \Delta[P_T, N] = 0$ in the absence of fluctuations

We calculate SIQs in the model since string impacts to the **wide rapidity range** → essential tool for studying long-range correlations and fluctuations

[X. Artru, G. Mennessier, Nuclear Physics B **70**, 93 (1974), X. Artru, Physics Reports **97**, 147 (1983)]
[N.S.Amelin, N.Armesto, M.A.Braun, E.G.Ferreiro,and C.Pajares, Phys Rev Let **73**, 2813 (1994)]

Strongly intensive Σ[NF,NB] in two kinematically separated regions of η:

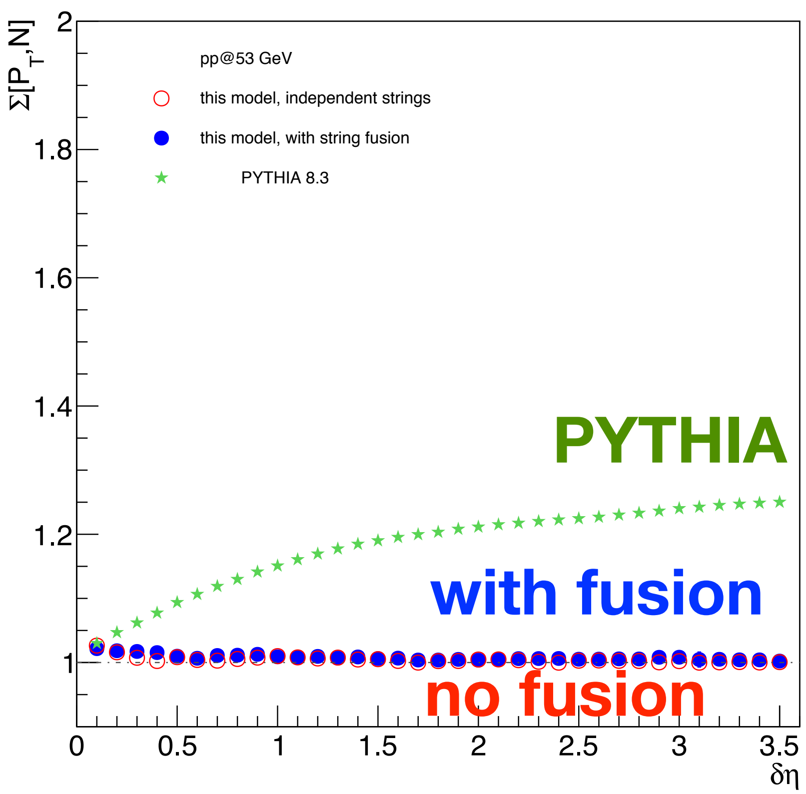
$$\Sigma[\mathrm{N_F},\mathrm{N_B}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N_B}\rangle\omega[\mathrm{N_F}] + \langle \mathrm{N_F}\rangle\omega[\mathrm{N_B}] - 2\cdot(\langle \mathrm{N_F}\cdot\mathrm{N_B}\rangle - \langle \mathrm{N_F}\rangle\langle \mathrm{N_B}\rangle)\right]$$

[E. V. Andronov, Theoretical and Mathematical Physics **185**, 1383 (2015)]

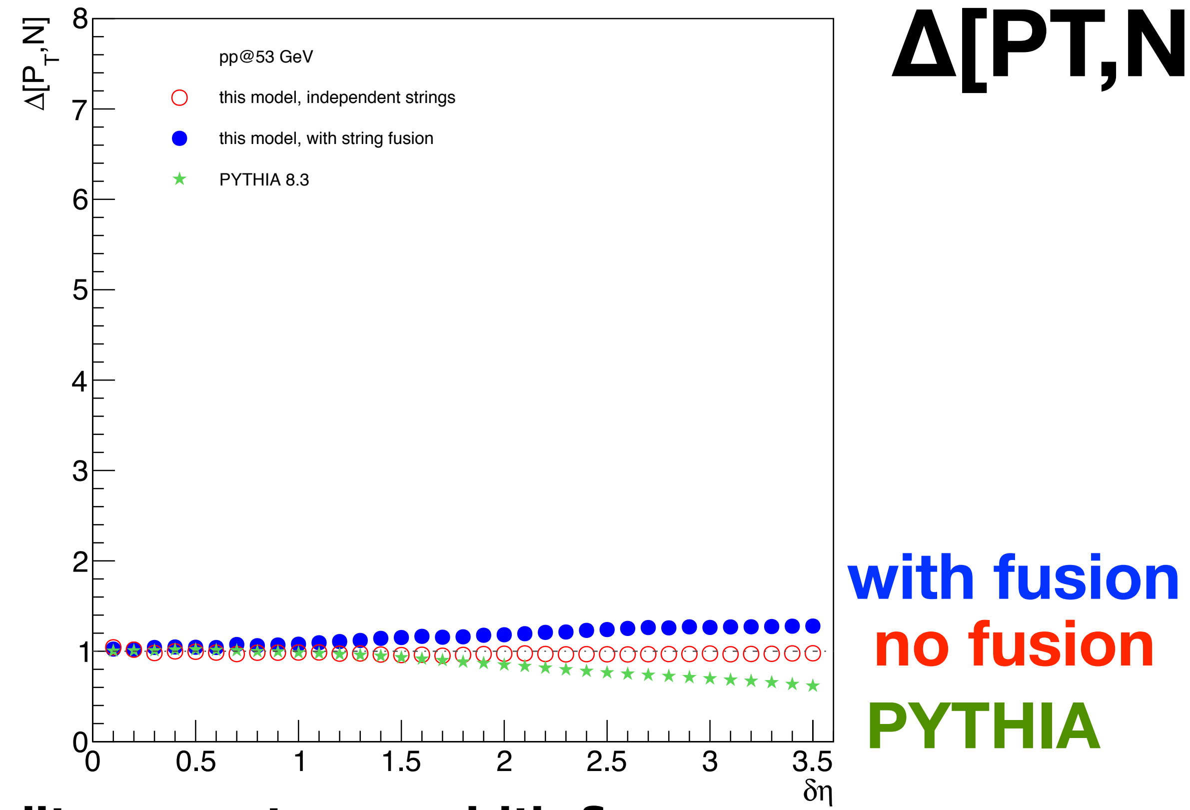
One can study them **as a function of rapidity gap size**, which is supposed to be sensitive to the initial conditions of particle production and short- and long-range multiplicity correlations

Model results in comparison with MC event generators: p+p @53 GeV

Σ[PT,N]

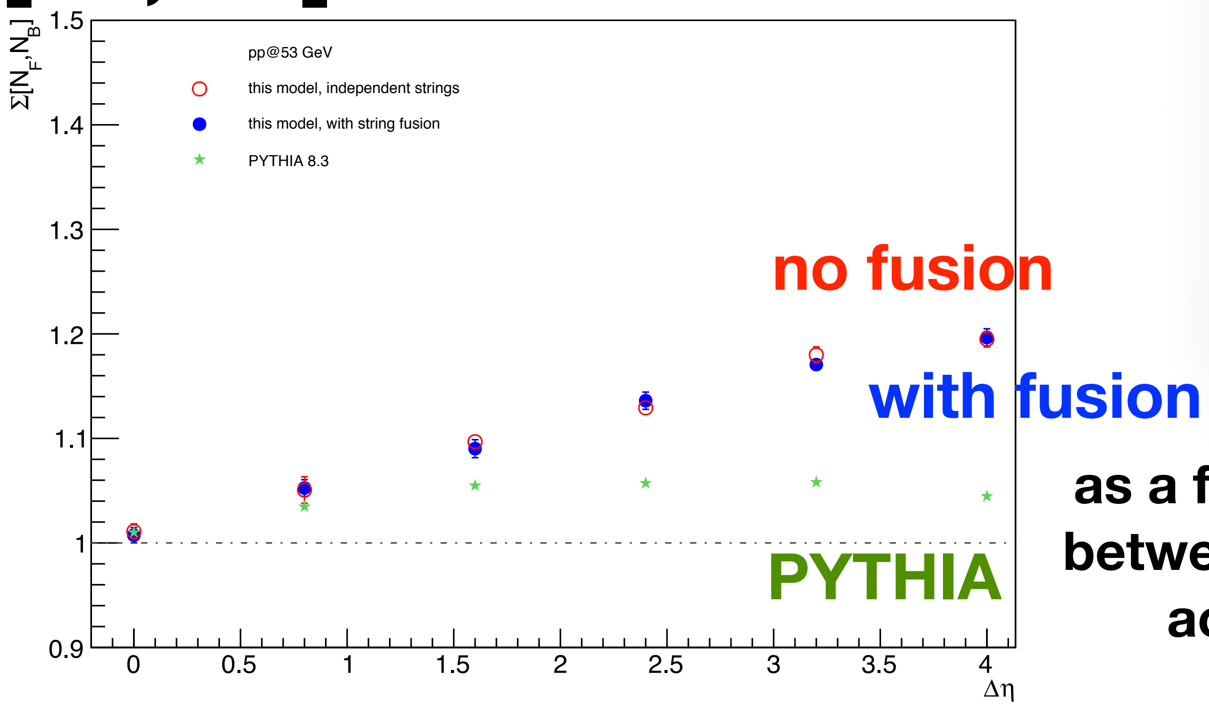


Δ[PT,N]



as functions of the rapidity acceptance width δη

Σ[NF,NB]

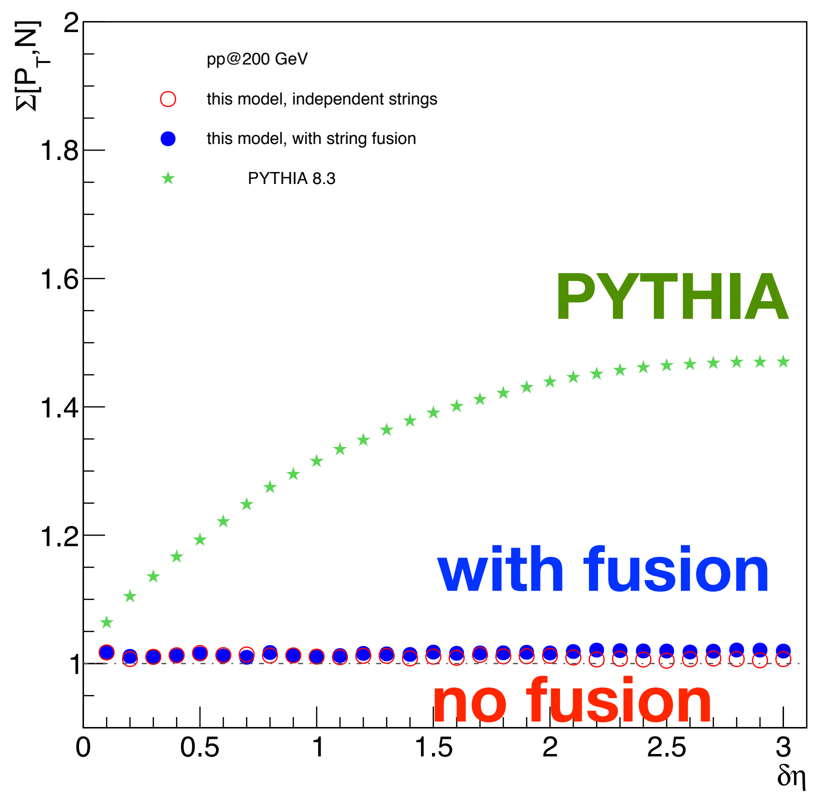


For no-fusion case Δ[PT,N] and Σ[PT,N] stay at 1, whereas for interacting sources one can see the grows with rapidity acceptance width. Model results differ from PYTHIA predictions. Σ[NF,NB] exhibits a rise with Δη, but is very close for independent and interacting strings scenarios. Although, one could argue that results for interacting strings lie below values for independent strings.

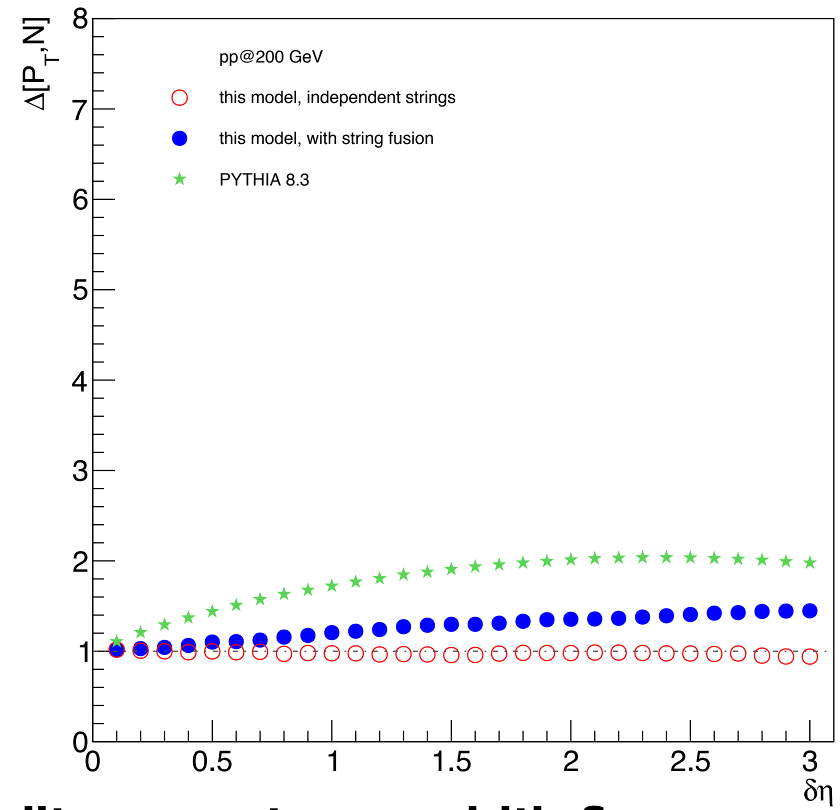
as a function of the distance Δη between Forward and Backward acceptance windows δη

Model results in comparison with MC event generators: p+p @200 GeV

Σ[PT,N]

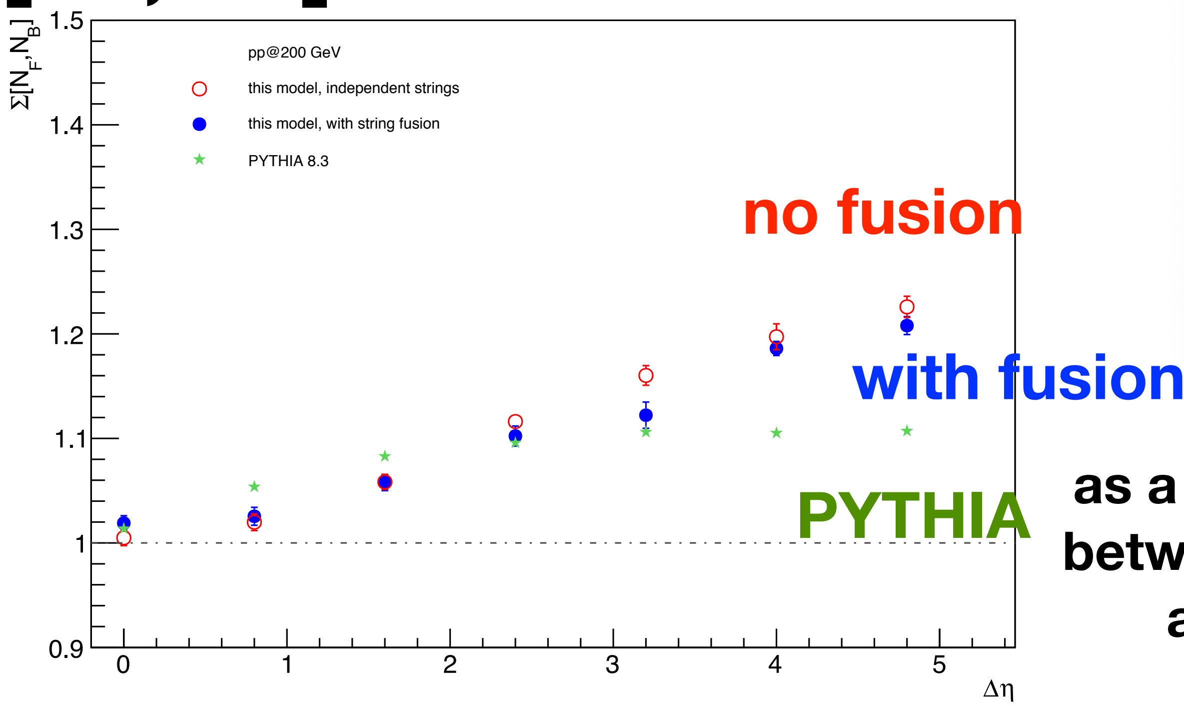


Δ[PT,N]



as functions of the rapidity acceptance width δη

Σ[NF,NB]

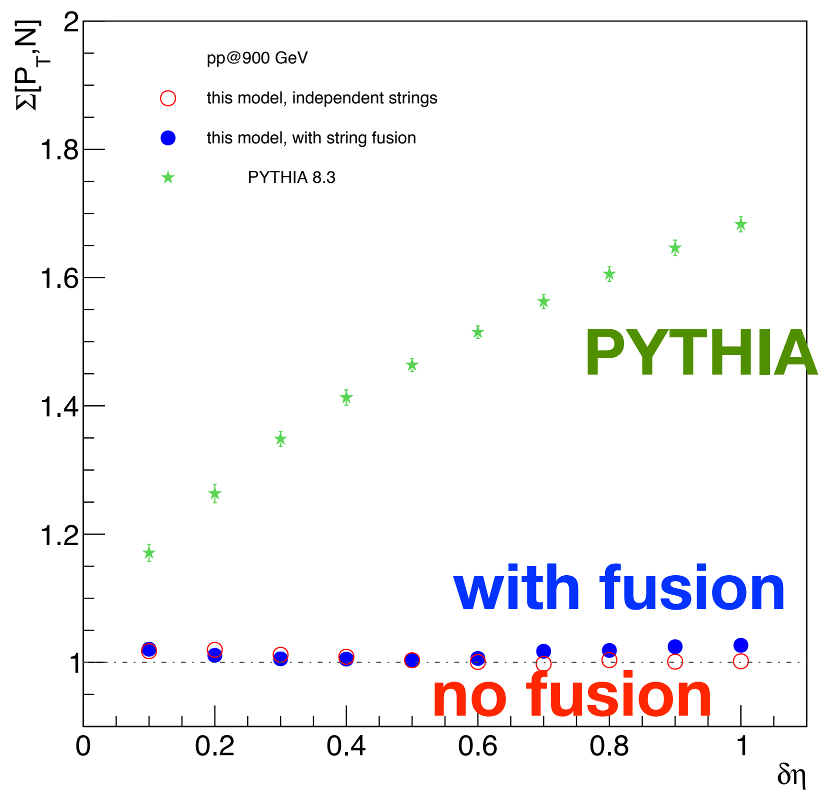


For no-fusion case Δ[PT,N] and Σ[PT,N] stay at 1, whereas for interacting sources one can see the grows with rapidity acceptance width. Model results differ from PYTHIA predictions. Σ[NF,NB] exhibits a rise with Δη, but is very close for independent and interacting strings scenarios. Although, one could argue that results for interacting strings lie below values for independent strings.

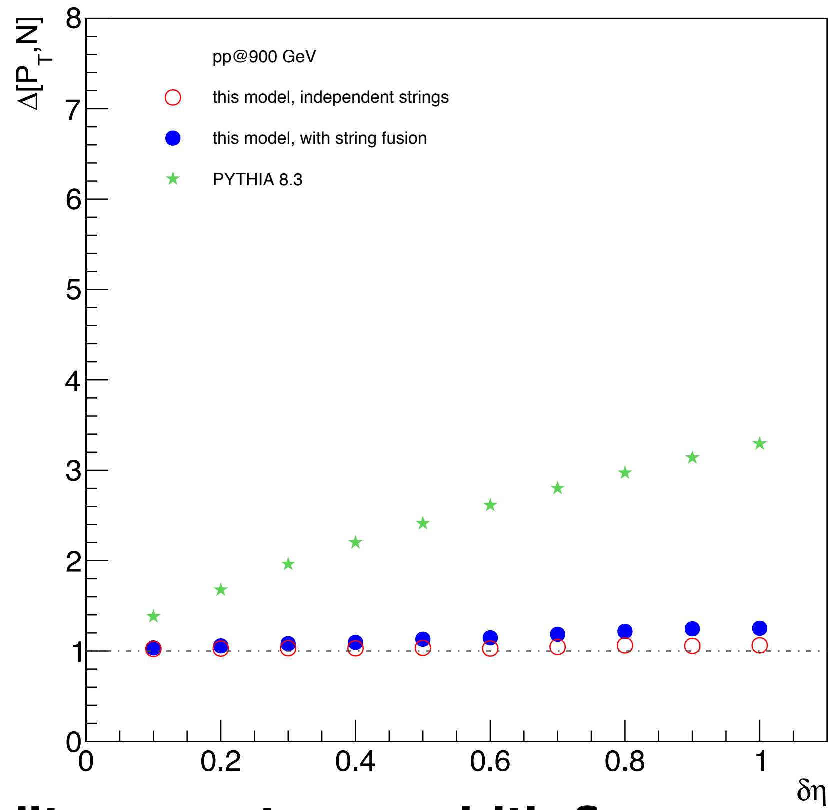
as a function of the distance Δη between Forward and Backward acceptance windows δη

Model results in comparison with MC event generators: p+p @900 GeV

Σ[PT,N]



Δ[PT,N]



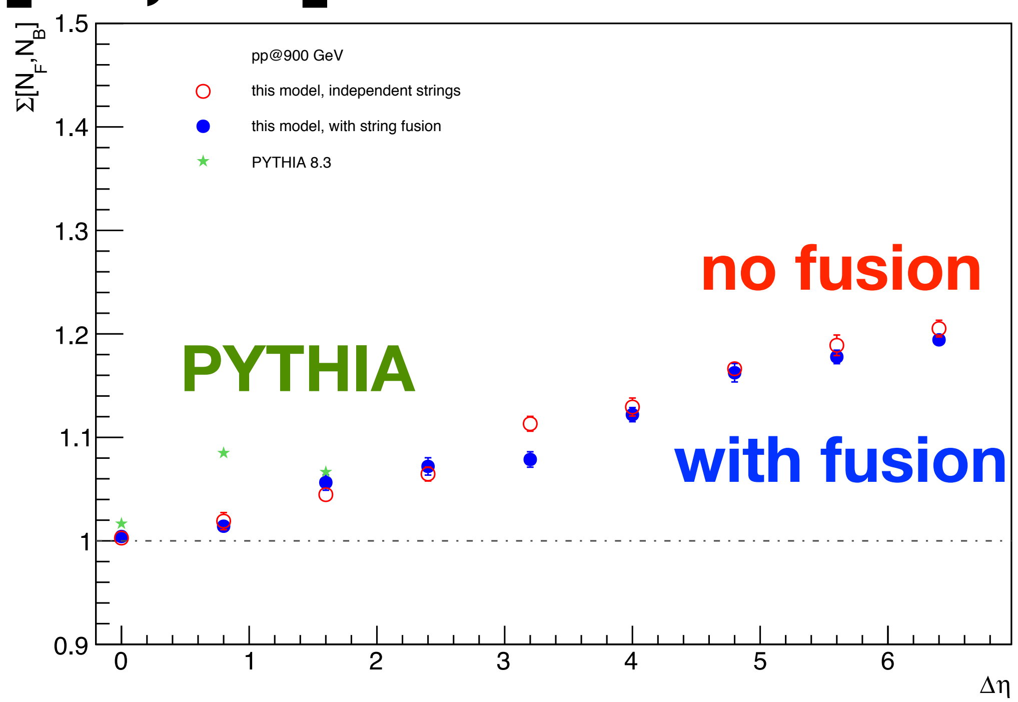
PYTHIA

with fusion

no fusion

as functions of the rapidity acceptance width δη

Σ[NF,NB]

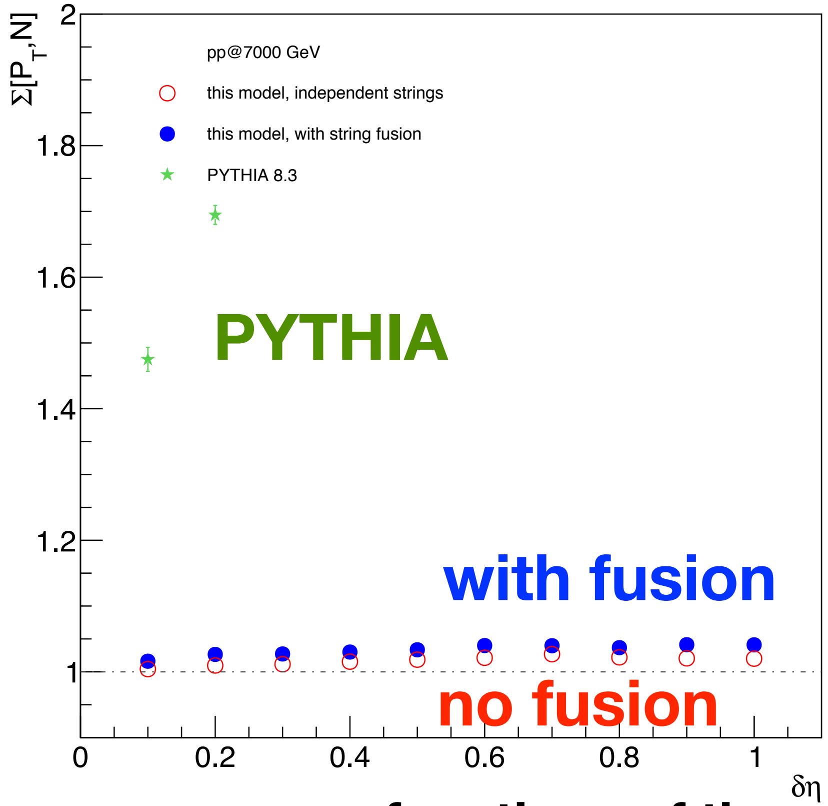


For no-fusion case Δ[PT,N] and Σ[PT,N] stay at 1, whereas for interacting sources one can see the grows with rapidity acceptance width. Model results differ from PYTHIA predictions. Σ[NF,NB] exhibits a rise with Δη, but is very close for independent and interacting strings scenarios. Although, one could argue that results for interacting strings lie below values for independent strings.

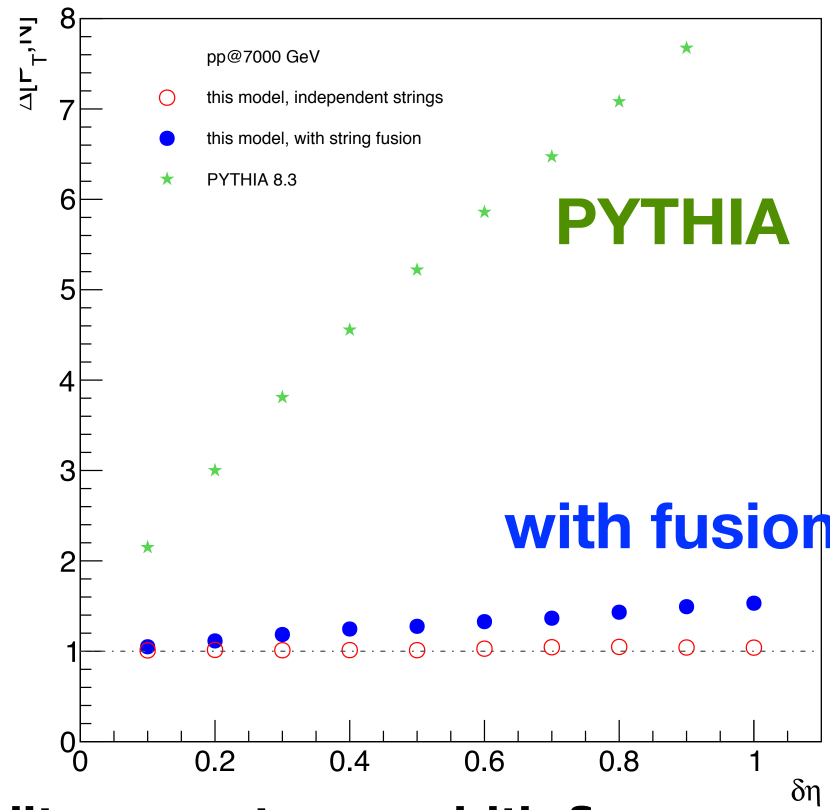
as a function of the distance Δη between Forward and Backward acceptance windows δη

Model results in comparison with MC event generators: p+p @7000 GeV

Σ[PT,N]



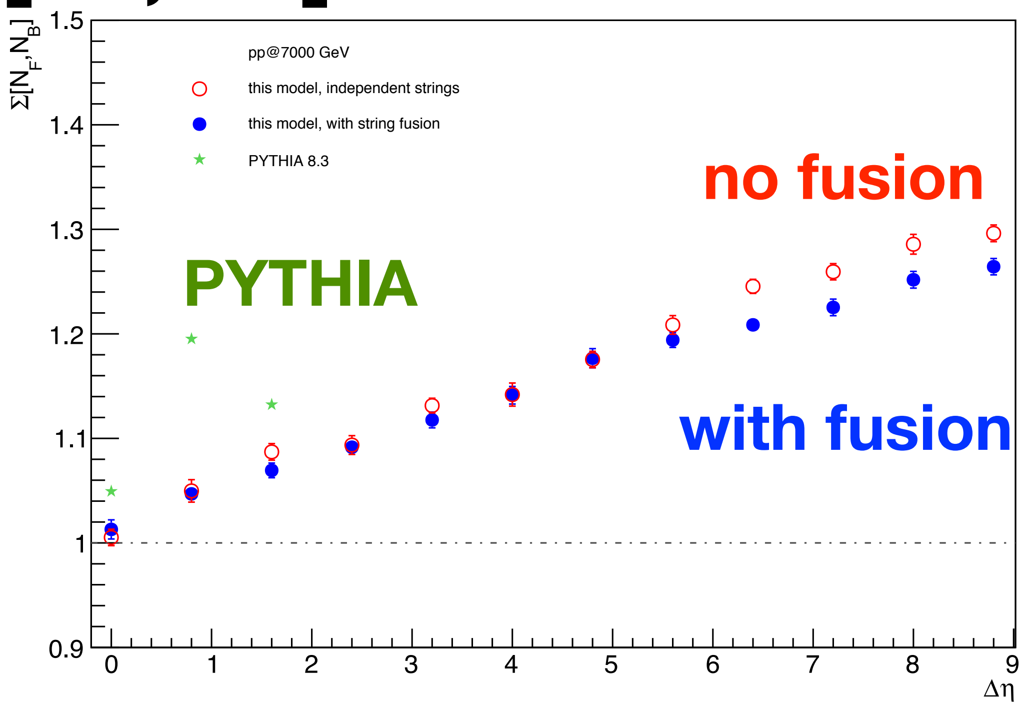
Δ[PT,N]



no fusion

as functions of the rapidity acceptance width δη

Σ[NF,NB]



For no-fusion case Δ[PT,N] and Σ[PT,N] stay at 1, whereas for interacting sources one can see the grows with rapidity acceptance width. Model results differ from PYTHIA predictions. Σ[NF,NB] exhibits a rise with Δη, but is very close for independent and interacting strings scenarios. Although, one could argue that results for interacting strings lie below values for independent strings.

as a function of the distance Δη between Forward and Backward acceptance windows δη

Conclusions and future plans

We calculated strongly intensive quantities Δ[PT,N], Σ[PT,N] and Σ[NF,NB] in the Model (tuned to experimental p+p data) of interacting quark-gluon strings that takes into account non-uniform distribution of strings ends in rapidity space :

- Δ[PT,N] and Σ[PT,N] stay strongly intensive in the case of independent strings, however, for interacting strings they start to exhibit some dependence on δη and on sqrt(Snn)
- Σ[NF,NB] exhibits a rise with Δη, but its values are very close for independent and interacting strings scenarios. Although, one could argue that results for interacting strings lie below values for independent strings.

1. We plan to try different multiplicity distributions (instead of Poisson)
2. Next step will be to tune the model on data for <pT> - N correlations

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Thank you for your attention!

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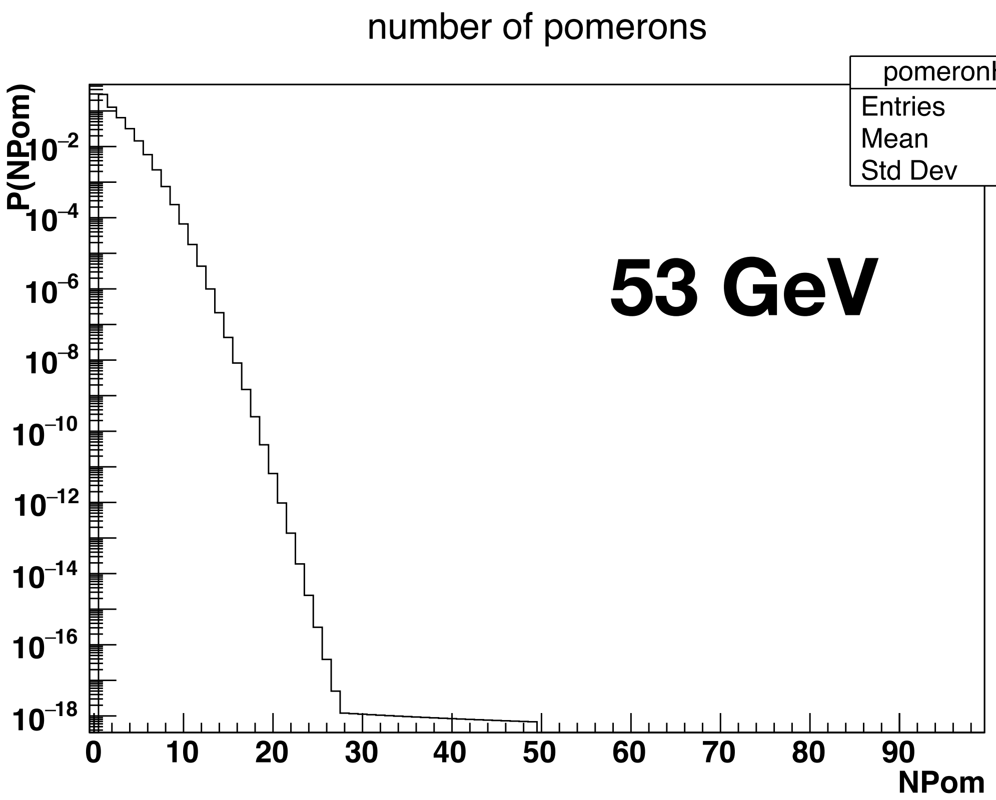
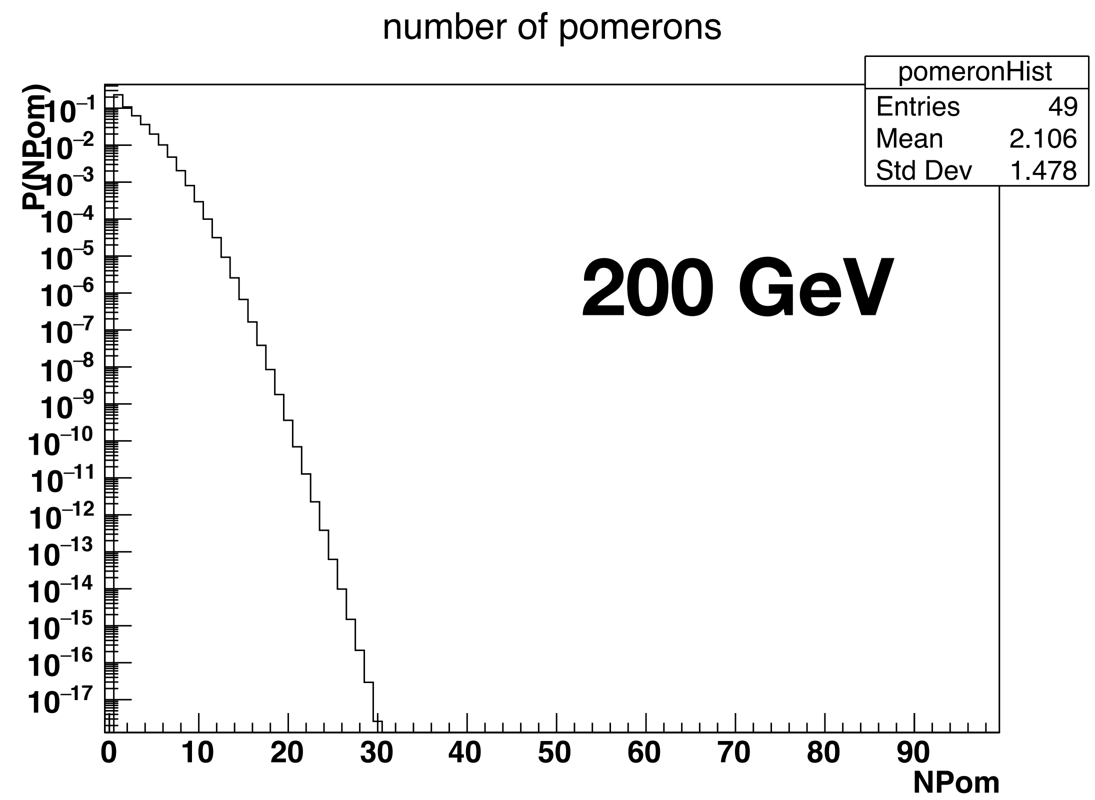
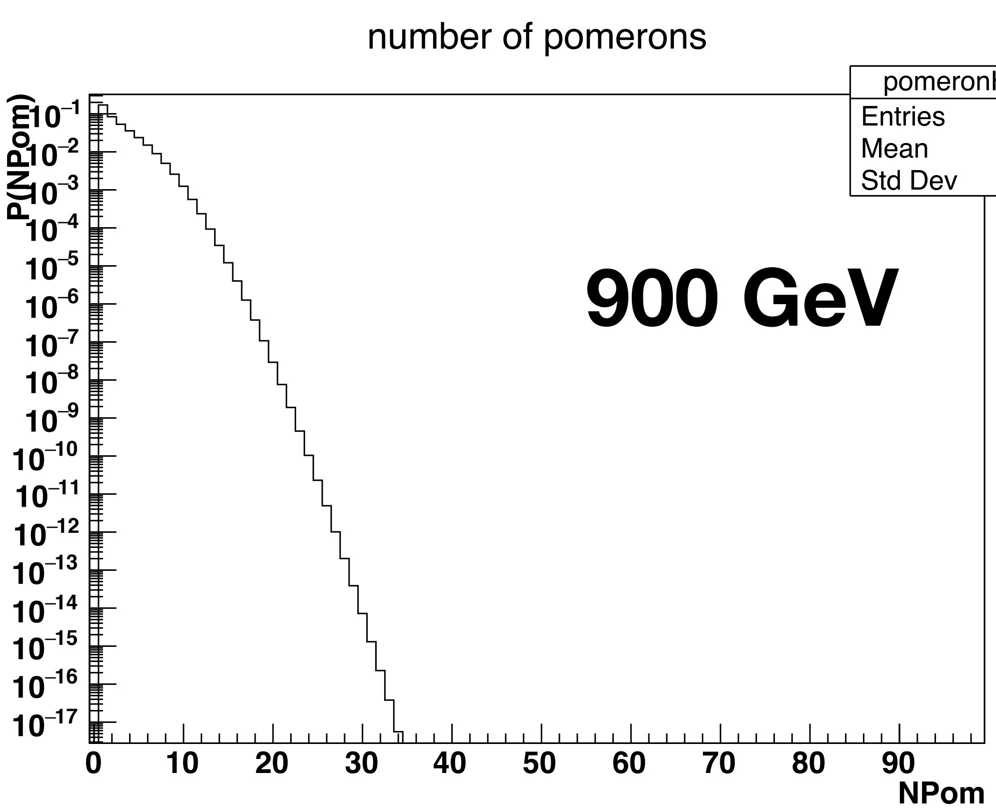
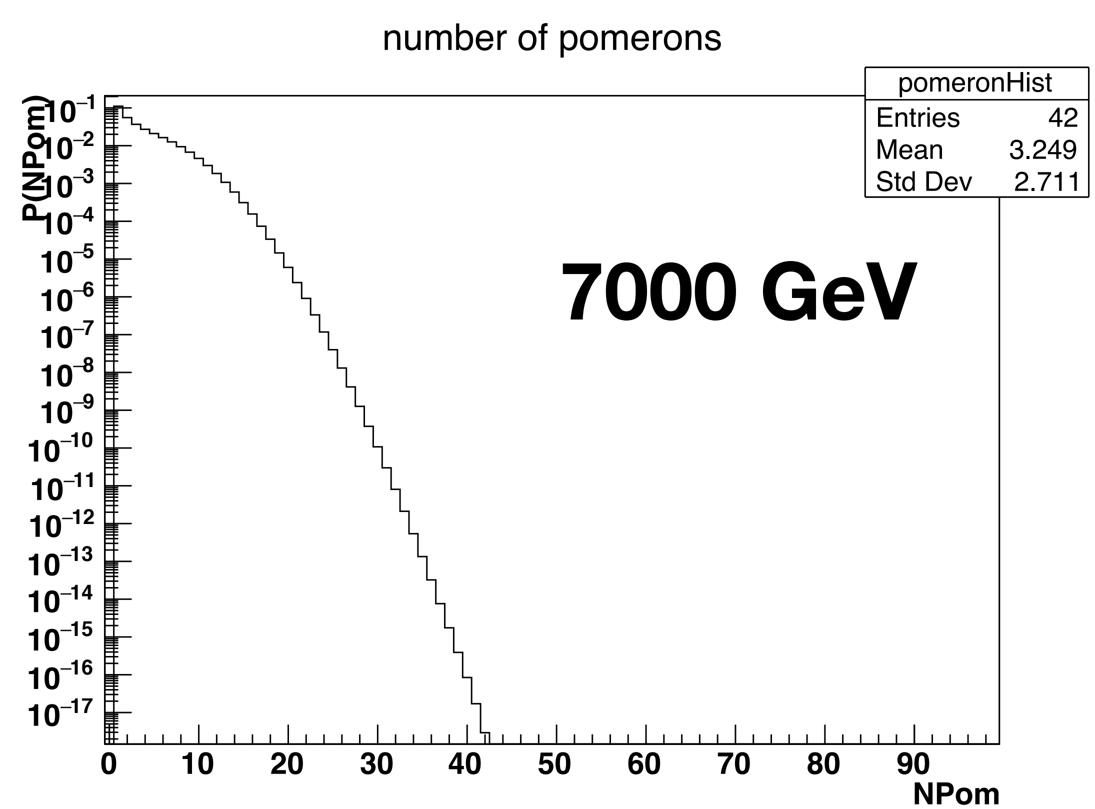
BACK-UP

Pomeron number distribution used to define the number of strings in event (x2)









HEP data on inelastic p+p interactions used to tune the model

- **53 GeV:**
  https://www.hepdata.net/record/ins233599
  https://www.hepdata.net/record/ins176647

- **200 GeV:**
  https://www.hepdata.net/record/ins233599
  http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,nch,,,UA5_1989_S1926373

- **900 GeV:**
  http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,eta#pp900
  http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,nch#pp900

- **7000 GeV:**
  http://mcplots-dev.cern.ch/?query=plots,ppppbar,mb-inelastic,eta#pp7000
  https://www.hepdata.net/record/ins1419652

Fluctuation studies and quantities of interest

Combinants of multiplicity distribution Cj:

- common assumption is that multiplicity N is directly influenced only by its neighboring multiplicities N±1

$$(N+1)P(N+1) = g(N)P(N), \quad g(N) = \alpha + \beta N$$

- but in PHYSICAL REVIEW D 99, 094045 (2019) it is proposed to connect all multiplicities with the following coefficients:

$$(N+1)P(N+1) = \langle N \rangle \sum_{j=0}^{N} C_j P(N-j)$$

$$\langle N \rangle C_j = (j+1)\left[\frac{P(j+1)}{P(0)}\right] - \langle N \rangle \sum_{i=0}^{j-1} C_i \left[\frac{P(j-i)}{P(0)}\right]$$

The intriguing oscillatory behavior is observed in data:

We aim to check whether string fusion mechanism can give this effect in the model

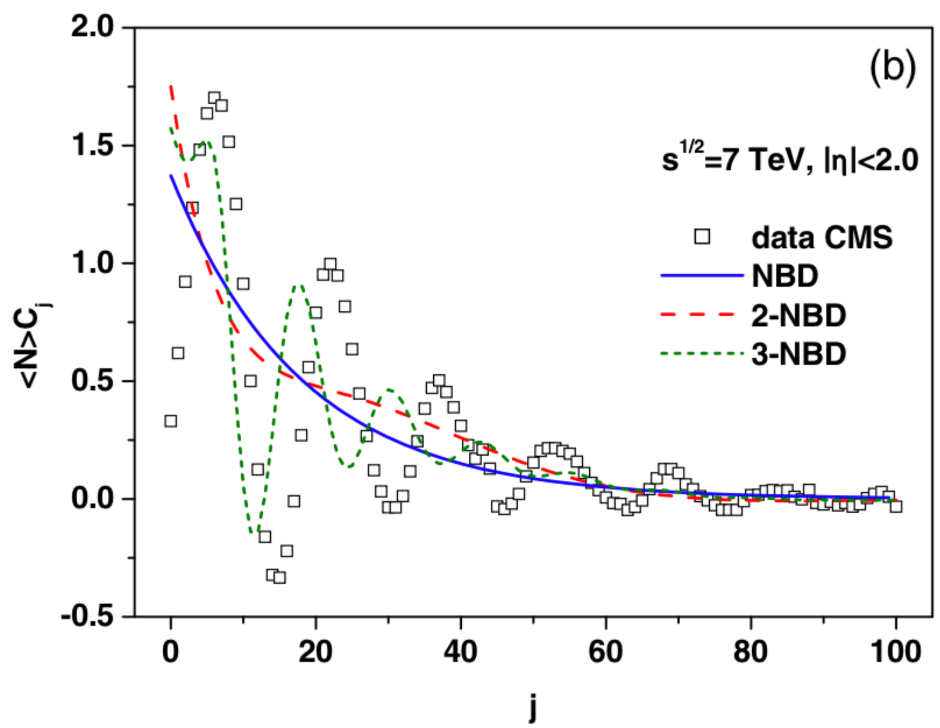


FIG. 1. (a) Charged hadron multiplicity distributions for the pseudorapidity range $|\eta| < 2$ at $\sqrt{s} = 7$ TeV, as given by the CMS experiment [15] (squares), compared with a NBD for parameters $\langle N \rangle = 25.5$ and $k = 1.45$ (full blue line), with the two-component NBD with parameters from [7] (red dashed line) and with a three-component NBD with parameters from [9] (dotted green line). (b) The corresponding modified combinants C_j emerging from the CMS data (squares) compared with the same choices of NBD as used in (a).