
# Study of multiplicity and transverse momentum fluctuations in the Monte-Carlo model of interacting quark-gluon strings

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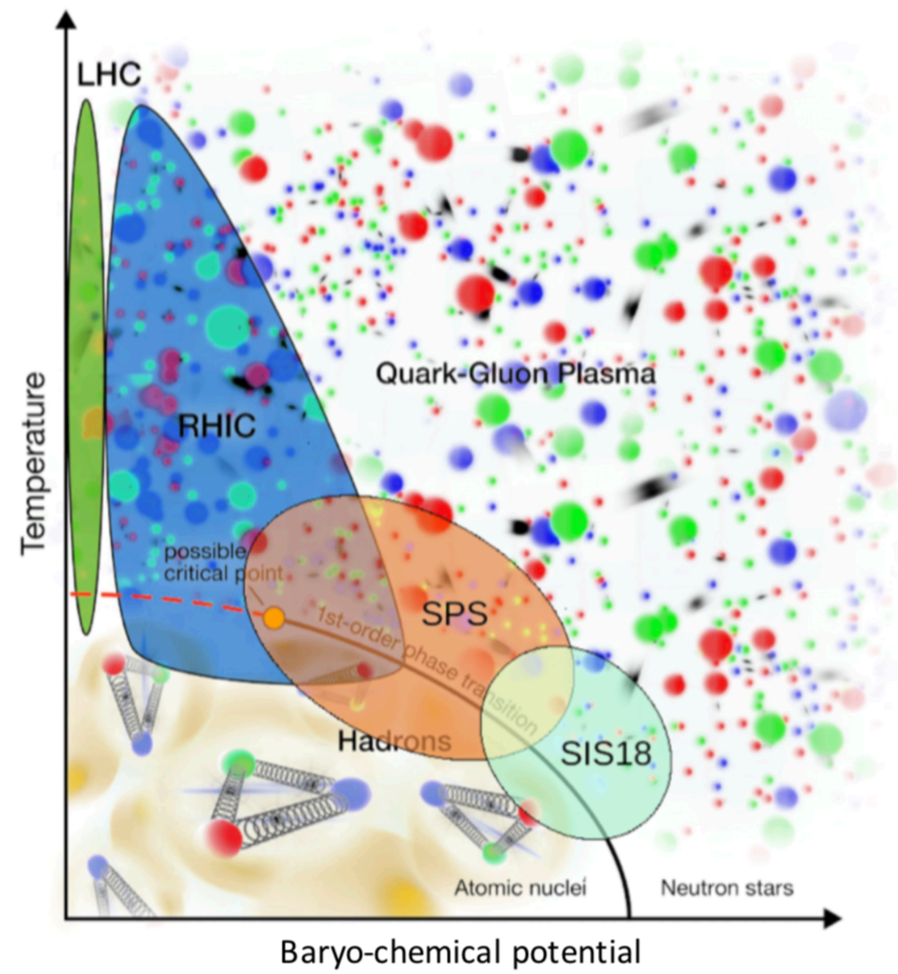
# Outline

1. Study of fluctuations in the search for CP
2. Quark-gluon string models of particle production
3. String fusion in Monte-Carlo model
4. Results
5. Outlook

# Study of fluctuations in the search for CP

**Expected phase diagram of strongly interacting matter**




**We know about hadron and QGP phases.
What is in between?**

# Study of fluctuations in the search for CP

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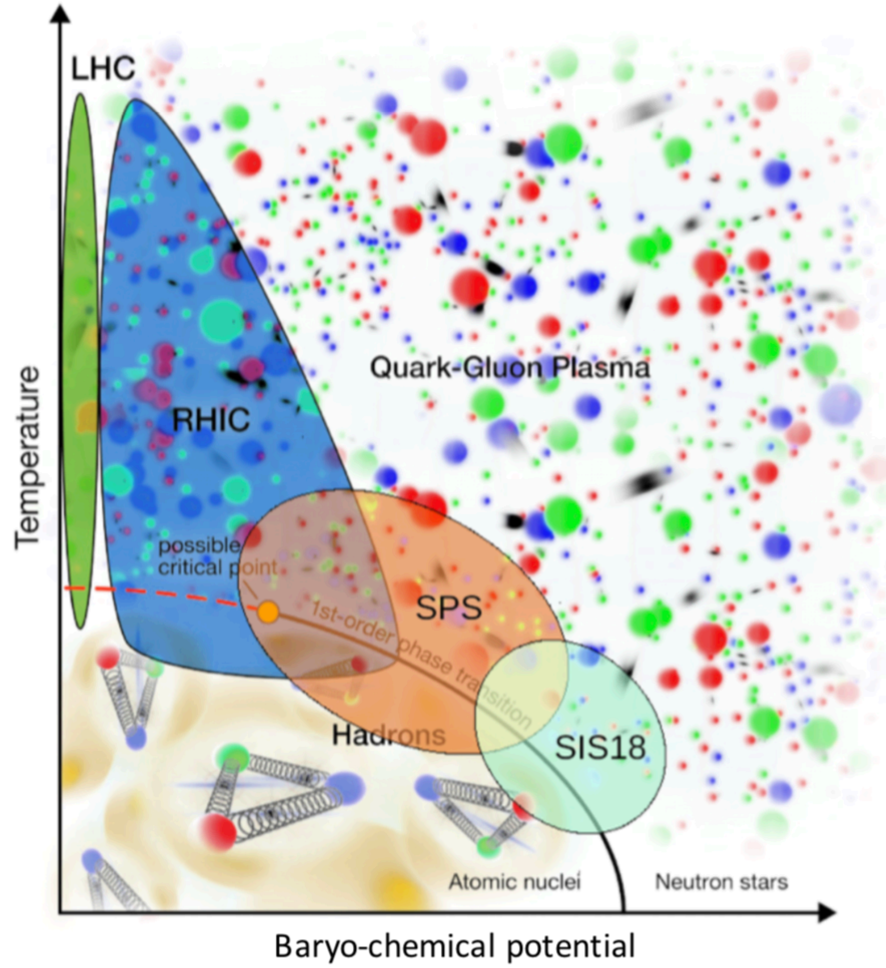
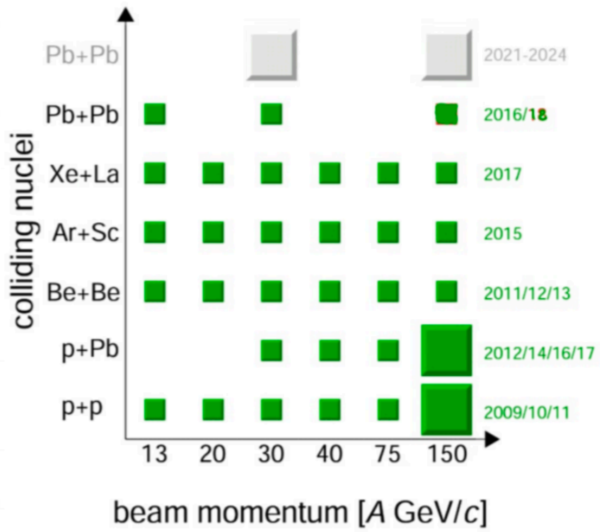
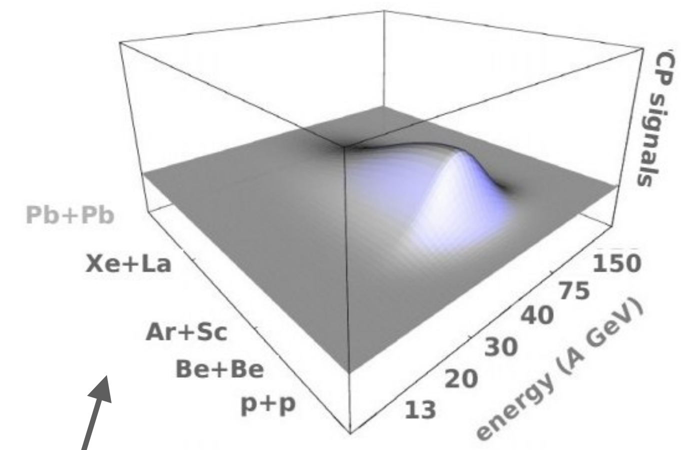



**NA61/SHINE @ SPS CERN**



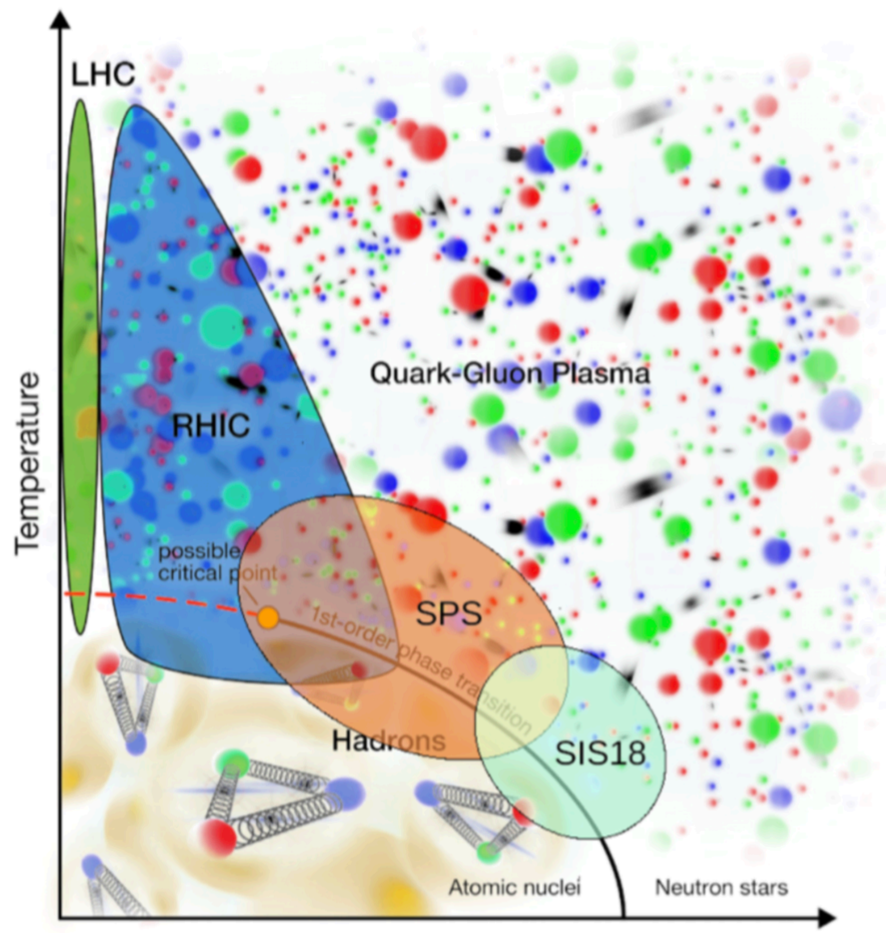

[Gazdzicki, M. and Seyboth, P. *Acta Phys. Pol. B* **47**, 1201 (2016)]




**Experimental System size vs Energy scan to spot the critical point by the anticipated signal of enhanced fluctuations**

# Study of fluctuations in the search for CP

### Expected phase diagram of strongly interacting matter

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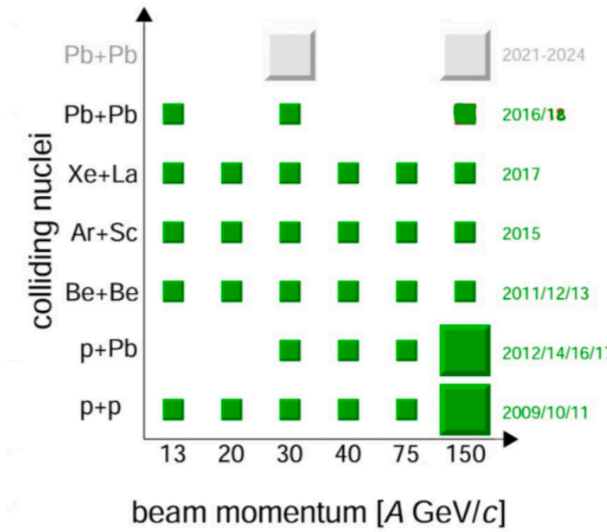


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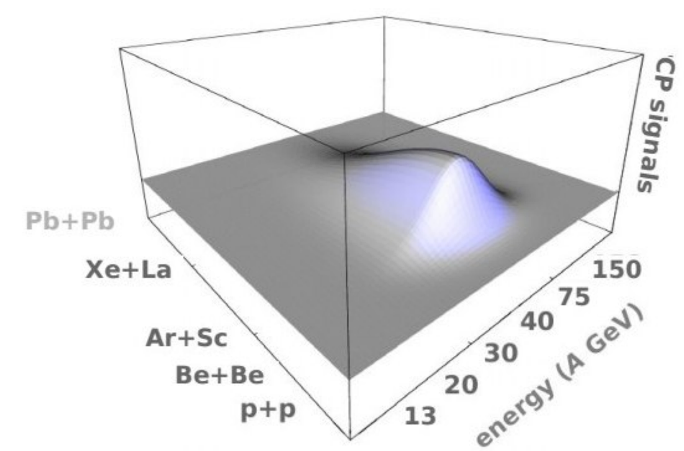


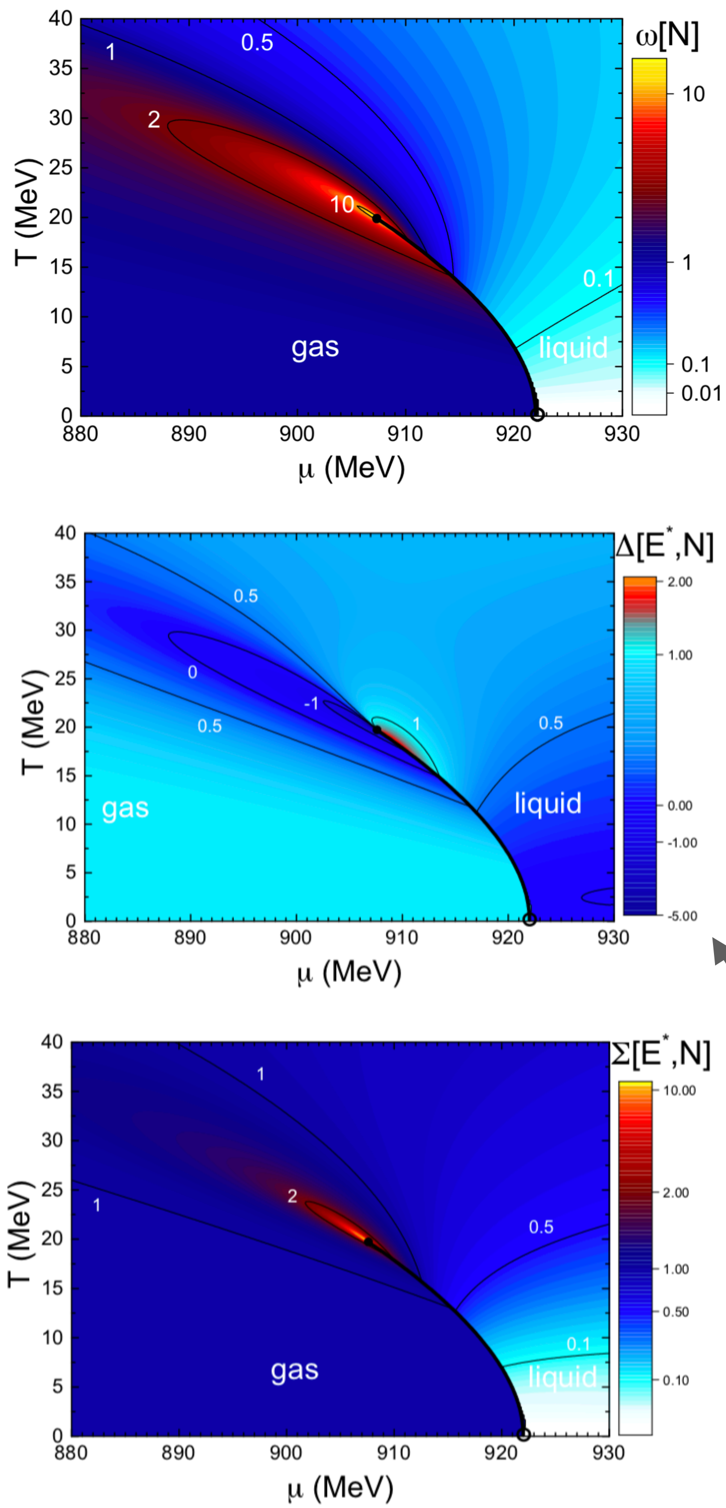

**Study of the special strongly intensive quantities that are independent of the volume and fluctuations of the volume within GCA or independent sources model**

$$\Delta[A,B] = \frac{1}{C_\Delta}\left[\langle B\rangle\omega[A] - \langle A\rangle\omega[B]\right]$$

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

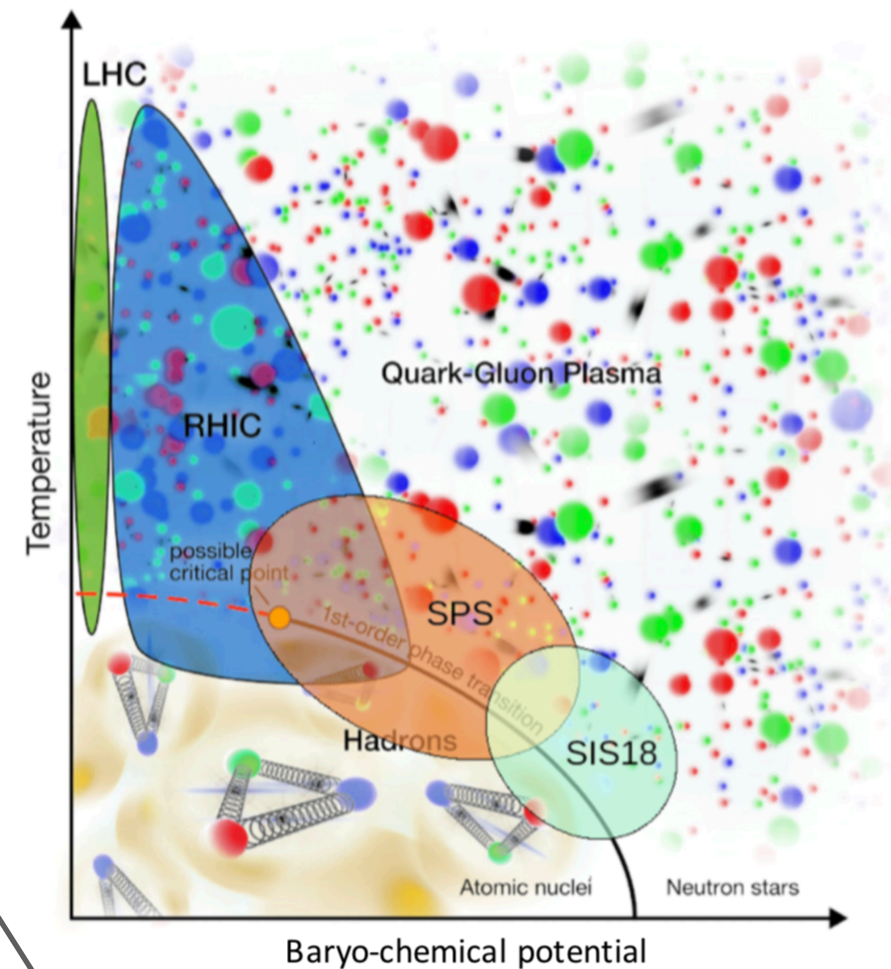
$$\Sigma[A,B] = \frac{1}{C_\Sigma}\left[\langle B\rangle\omega[A] + \langle A\rangle\omega[B] - 2(\langle AB\rangle - \langle A\rangle\langle B\rangle)\right]$$

# Study of fluctuations in the search for CP




[Vovchenko, Gorenstein, Stoecker, PRL 118:182301]

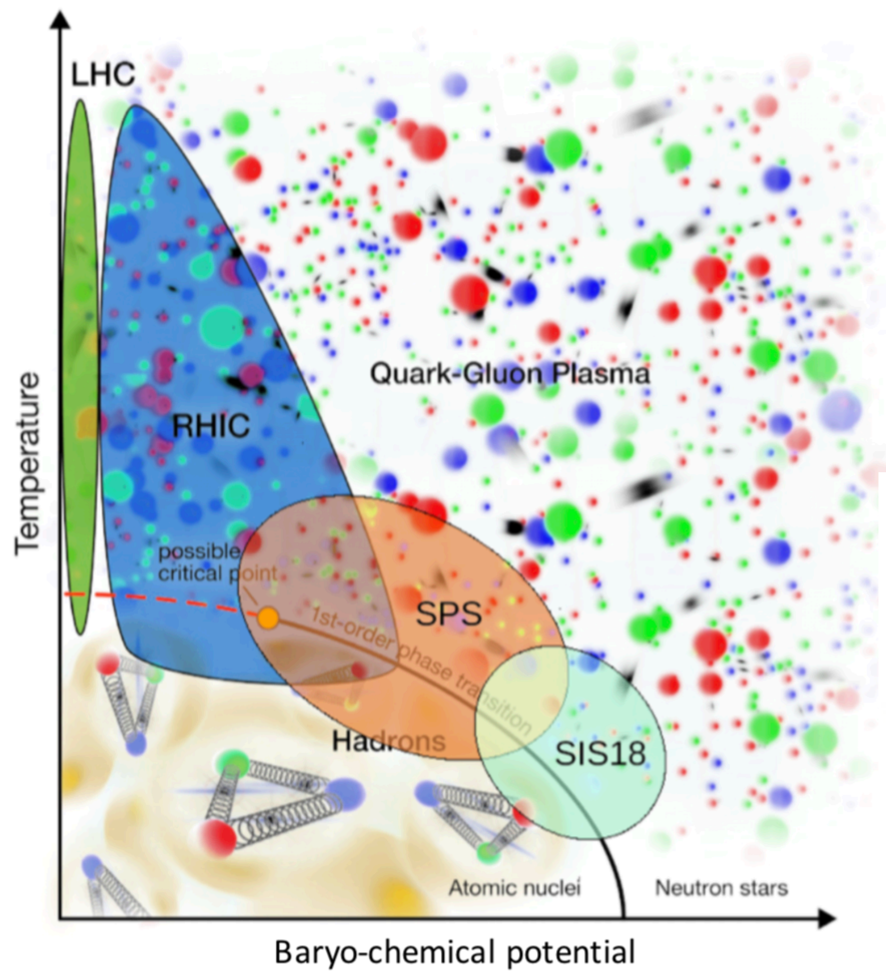
## Expected phase diagram of strongly interacting matter



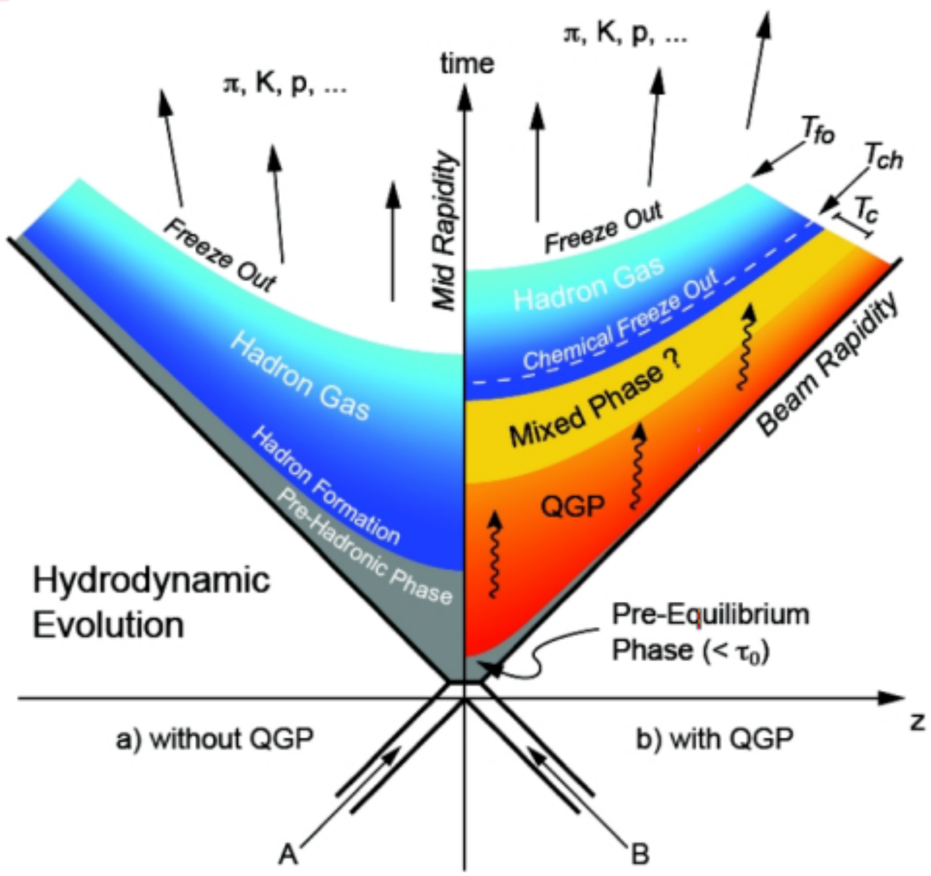

**Possible sensitivity: nucleon system with van der Waals EOS in GCE formulation in the vicinity of the Critical Point**

# Study of fluctuations in the search for CP

**Expected phase diagram of strongly interacting matter**




**Picture of the collision as we think we understand it**



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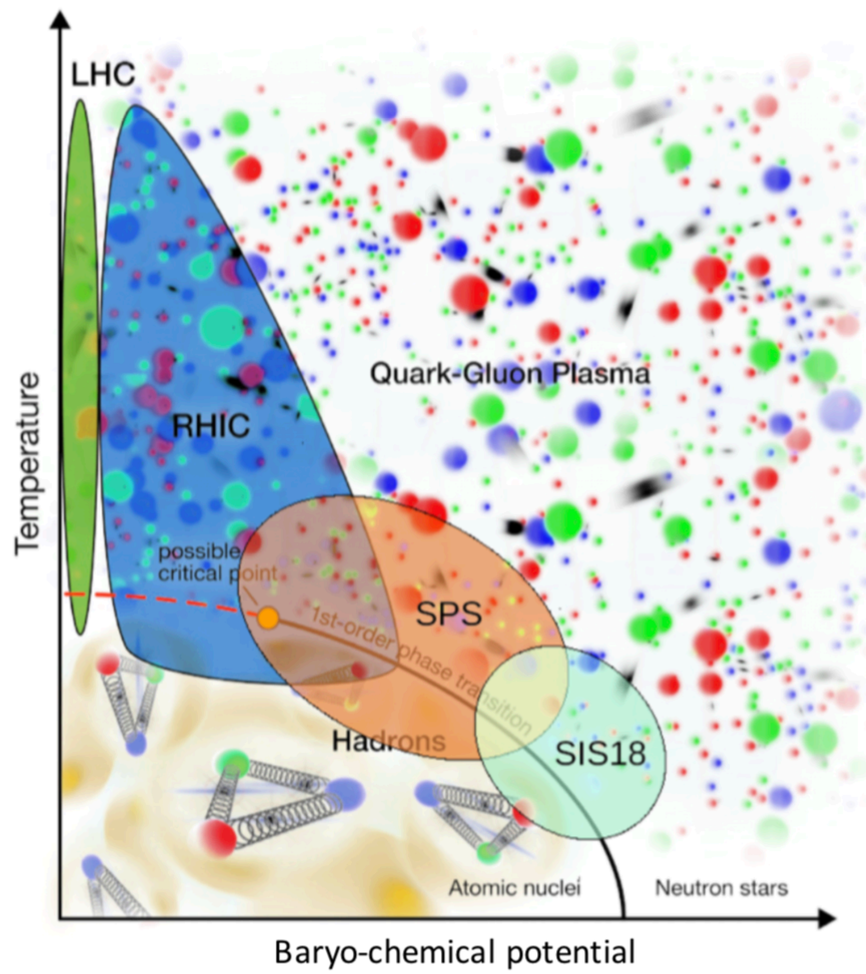
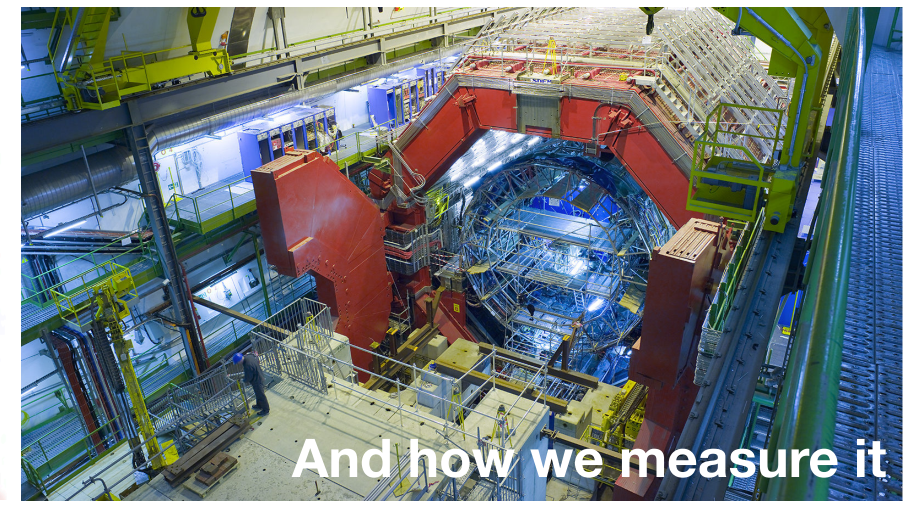
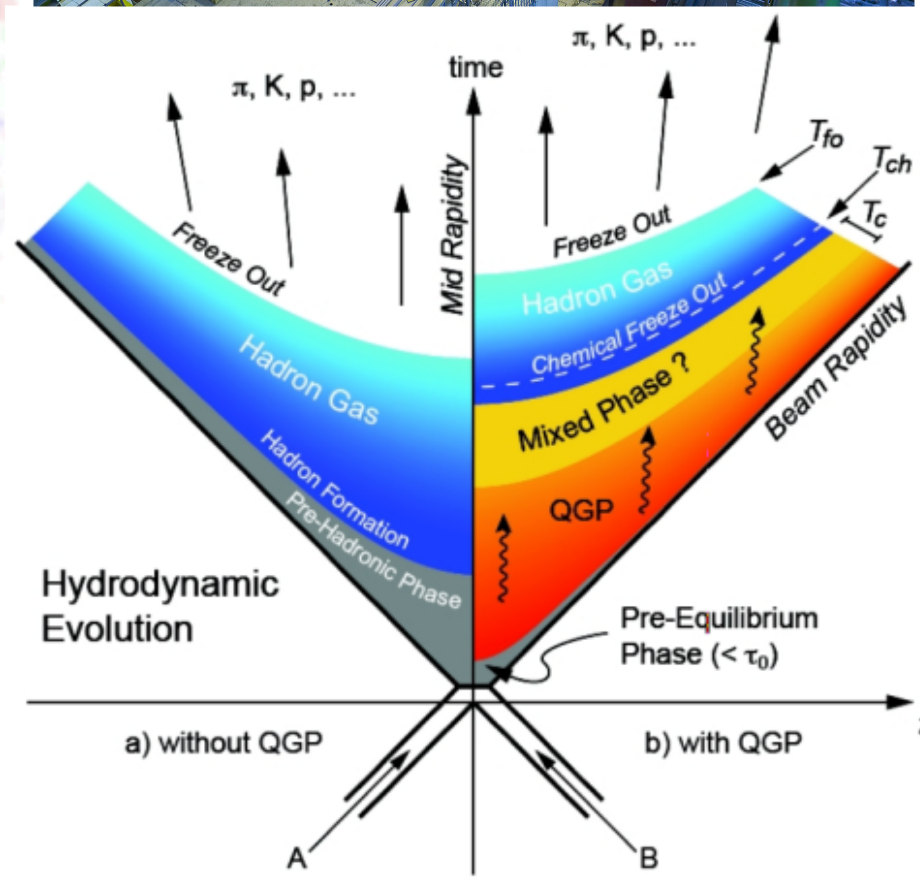



Mona Schweizer, CERN




**Picture of the collision as we think we understand it**

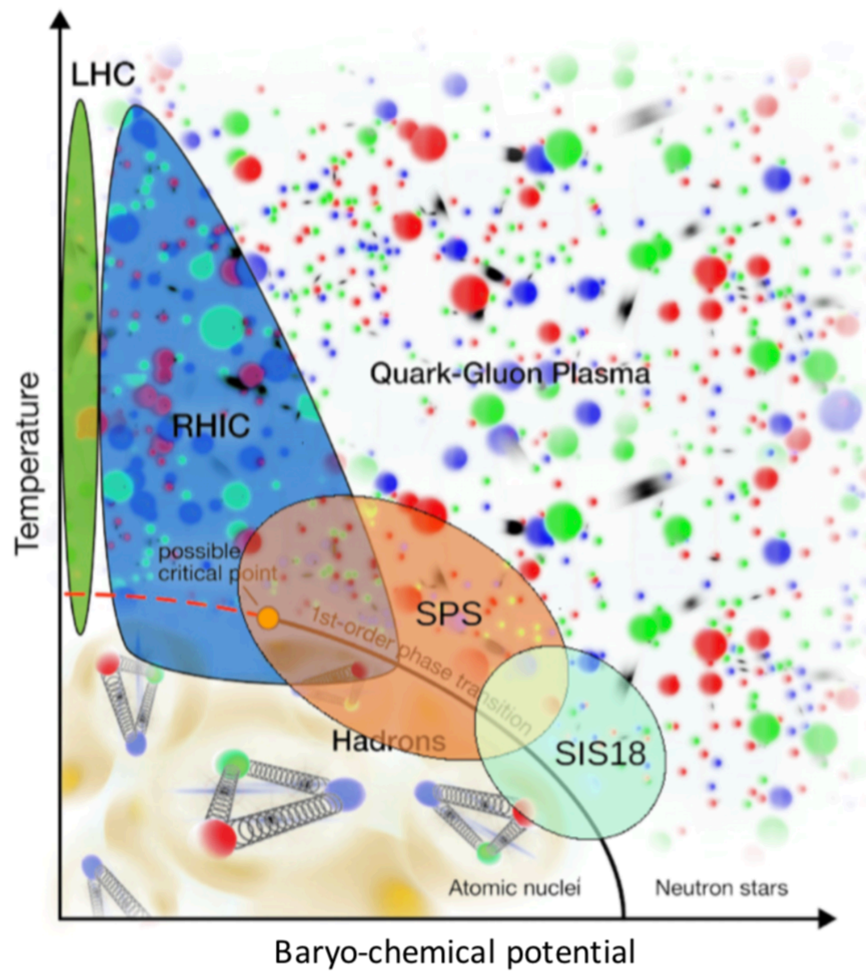
# Study of fluctuations in the search for CP

**One can study:**

- the fluctuations of multiplicity, transverse momentum
- moments of net electric charge or net baryon charge
- correlation coefficients to reveal the collective behavior

**But the fluctuation background has to be subtracted to catch the CP!**

**Expected phase diagram of strongly interacting matter**

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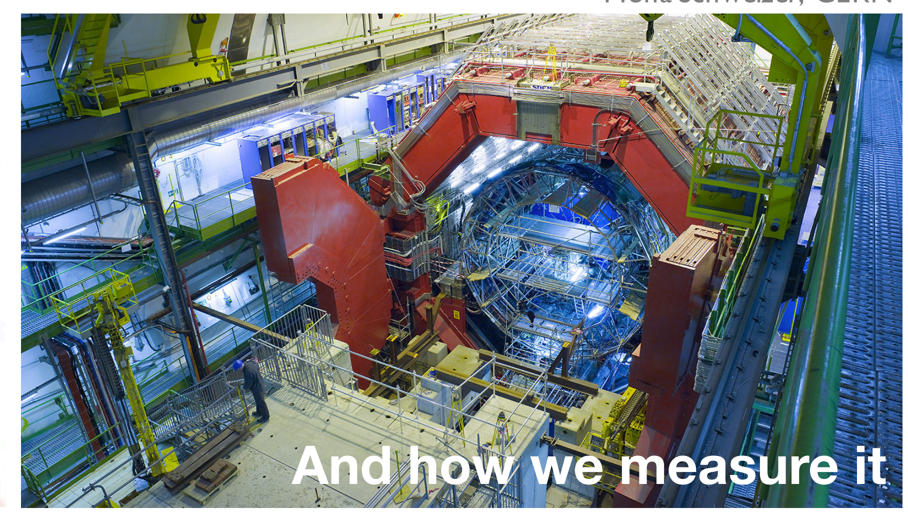


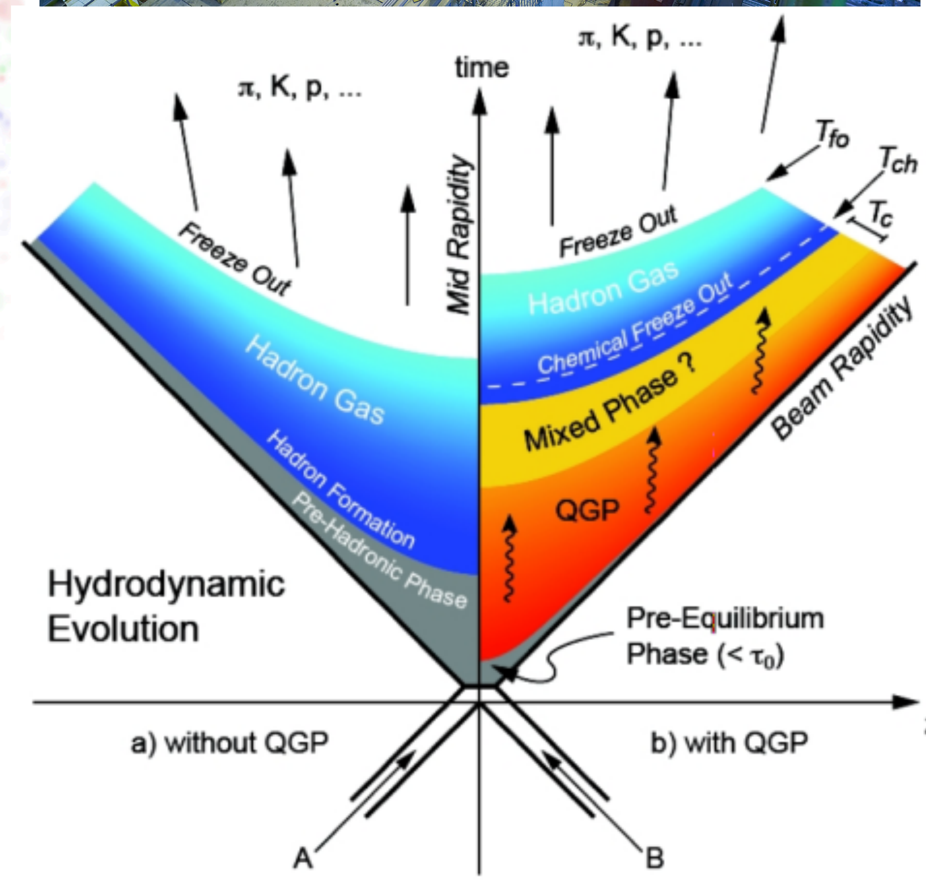


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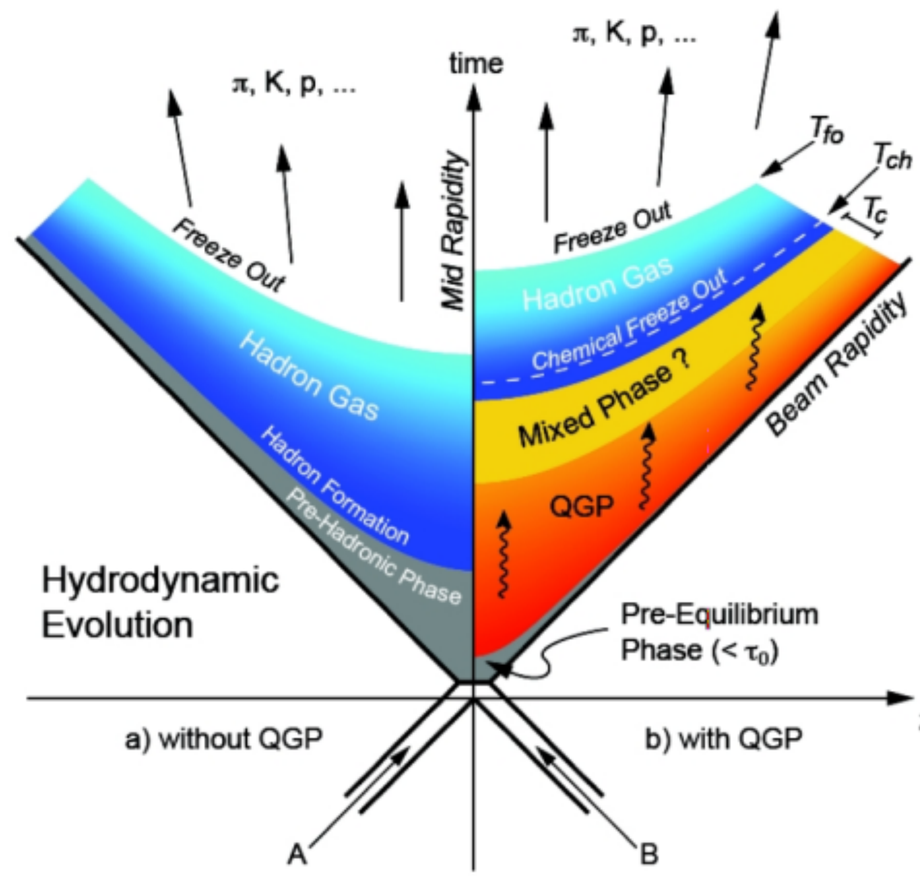
# Quark-gluon string models of particle production

## What are they, string models:

- Non-perturbative Regge approach to describe the soft particle spectra (< 1 GeV/c)



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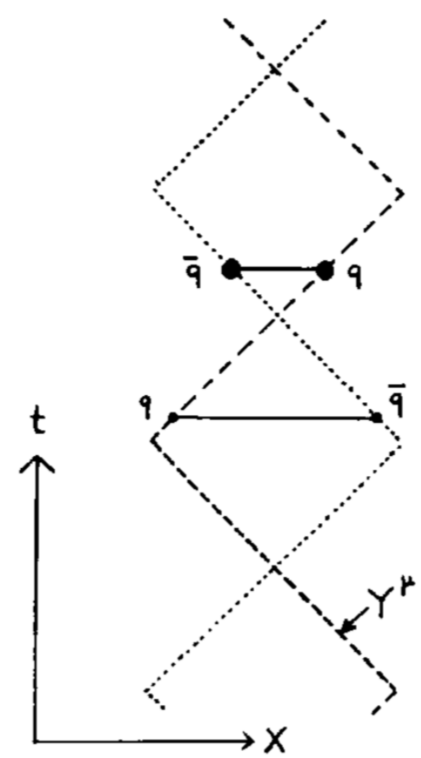


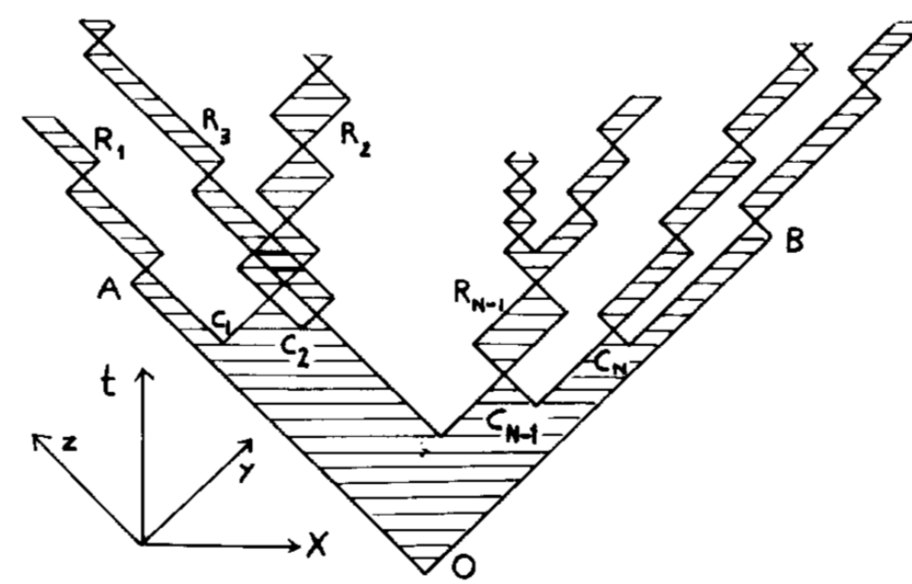


[X. Artru and G. Menessier Nuclear Physics B70 (1974) 93 - 115]

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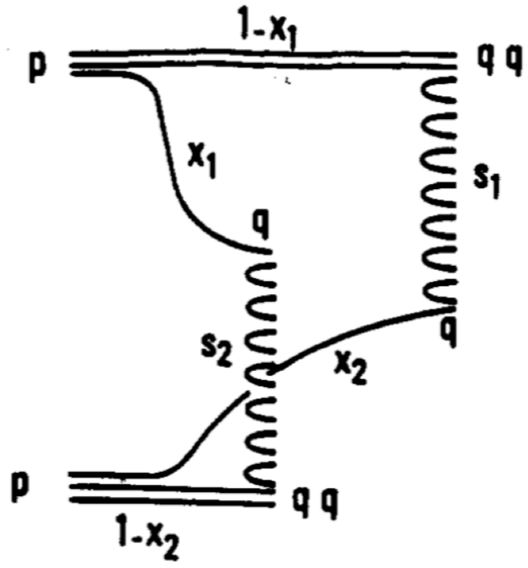
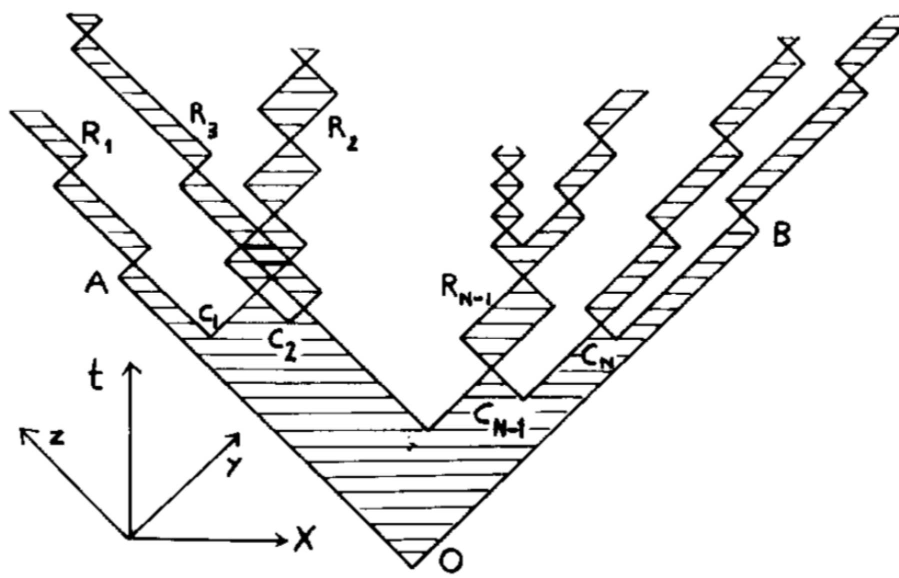



[Capella A. et al Physics Reports 236, Nos. 4 & 5 (1994) 225 - 329]

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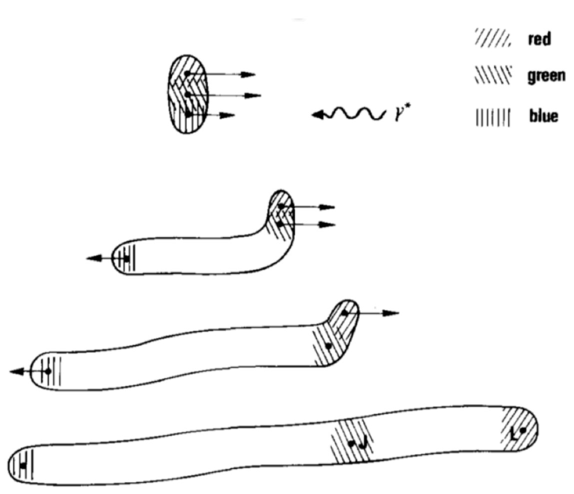
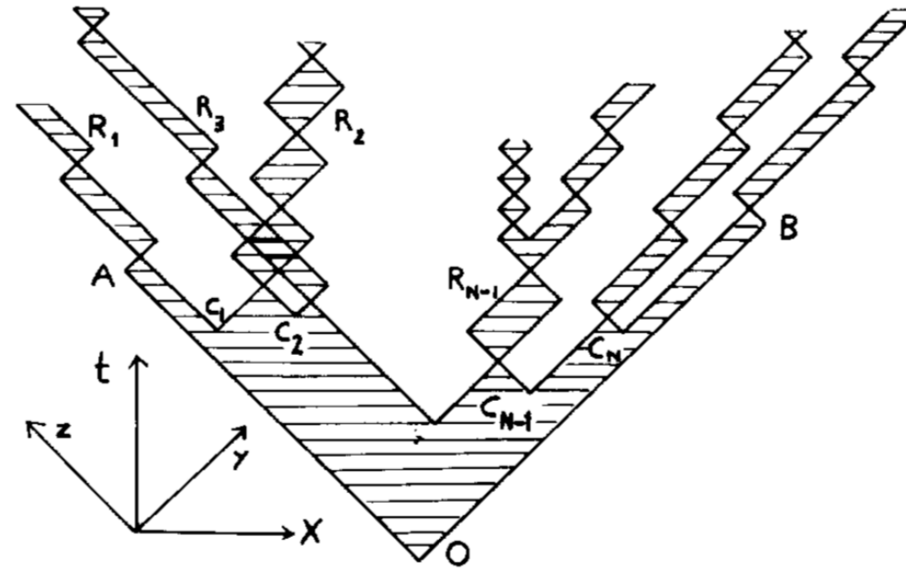
- Lund model: longitudinally extended object stretched between the flying outwards wounded quarks and formed by the color field lines gathered together due to the gluon self-interaction




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

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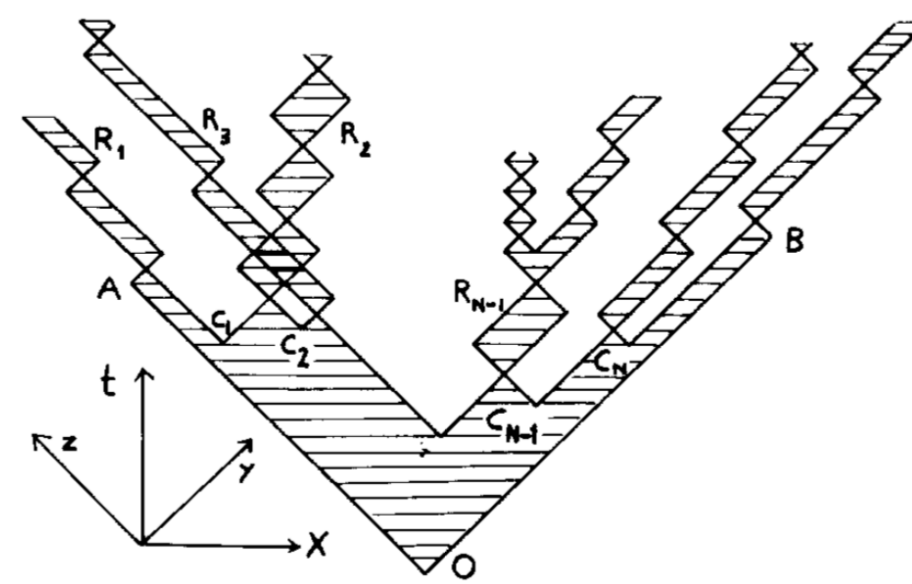
[X. Artru, G. Mennessier, Nuclear Physics B **70**, 93 (1974), X. Artru, Physics Reports **97**, 147 (1983)]

- String as a particle emitting source impact to the **wide rapidity range** with the plateau at mid-rapidity → essential tool for studying long-range correlations and fluctuations

[N.S.Amelin, N.Armesto, M.A.Braun, E.G.Ferreiro,and C.Pajares, Phys Rev Let **73**, 2813 (1994)]

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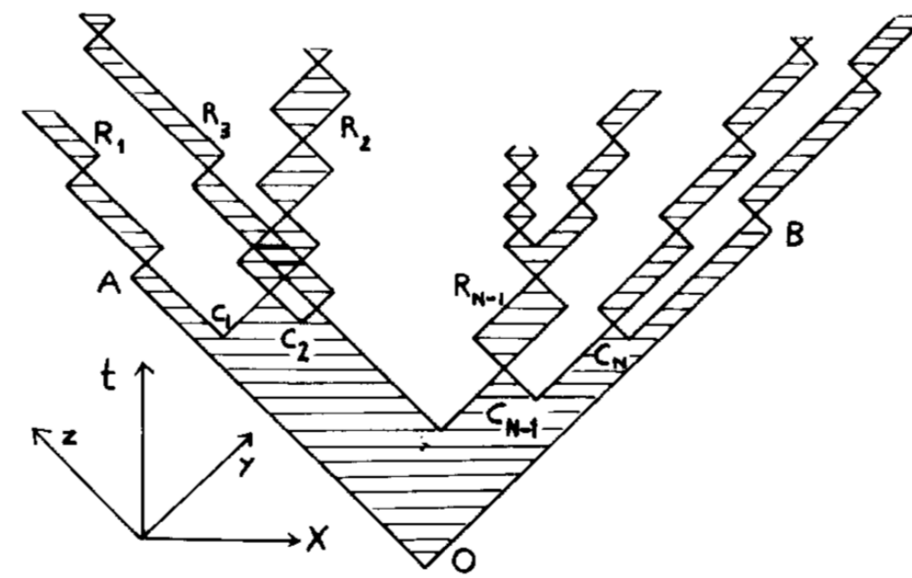

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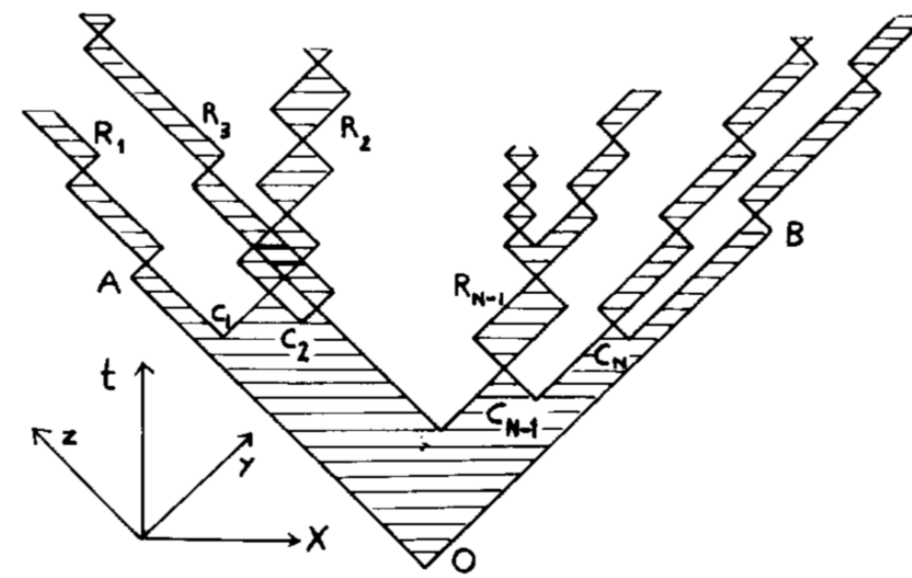


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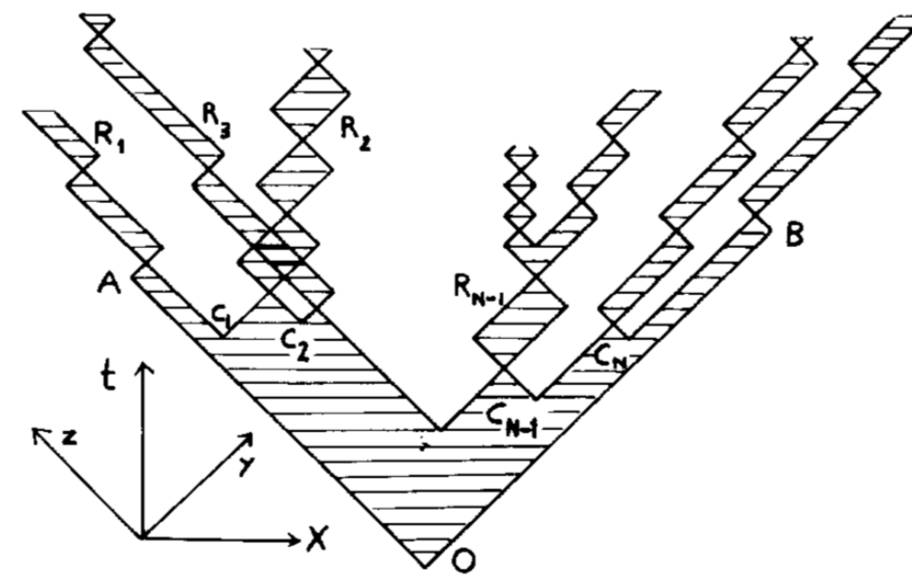
**+ consider also string interactions**

[V. Abramosvkii and V. Kancheli, JETP letters 31, 566 (1980)
M. A. Braun and C. Pajares, Phys Let B **287**, 154 (1992)
M. Braun and C. Pajares, Nuclear Physics B **390**, 559 (1993)
N. S. Amelin, M. A. Braun, and C. Pajares, Phys Let B **306**, 312 (1993)
N.S.Amelin, M.A.Braun, and C.Pajares, Zeitschriftfür Physik C Particles and Fields **63**, 507 (1994)
I. Altsybeev, AIP Conference Proceedings **1701**, 100002 (2016)]

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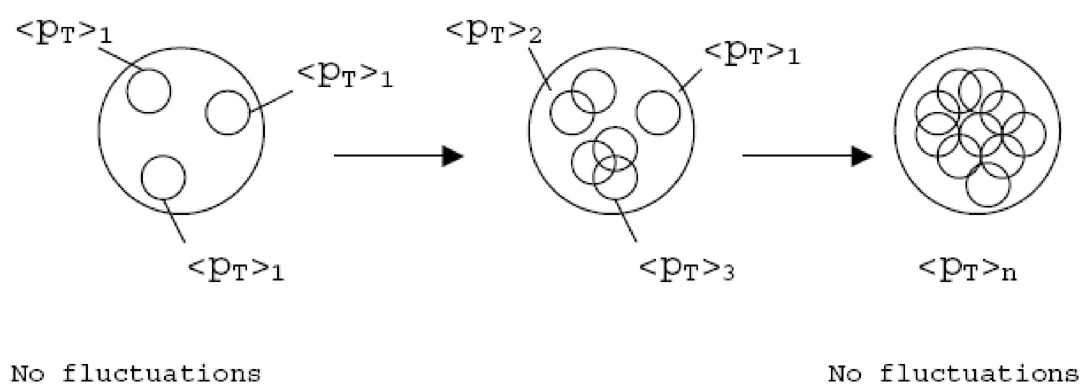
# String interactions

**The string transverse position fluctuations changes the type of particle emitting sources**

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



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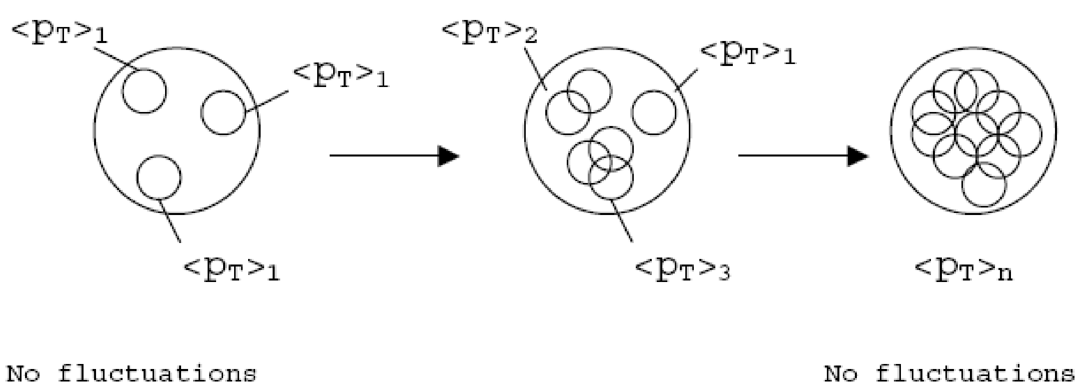
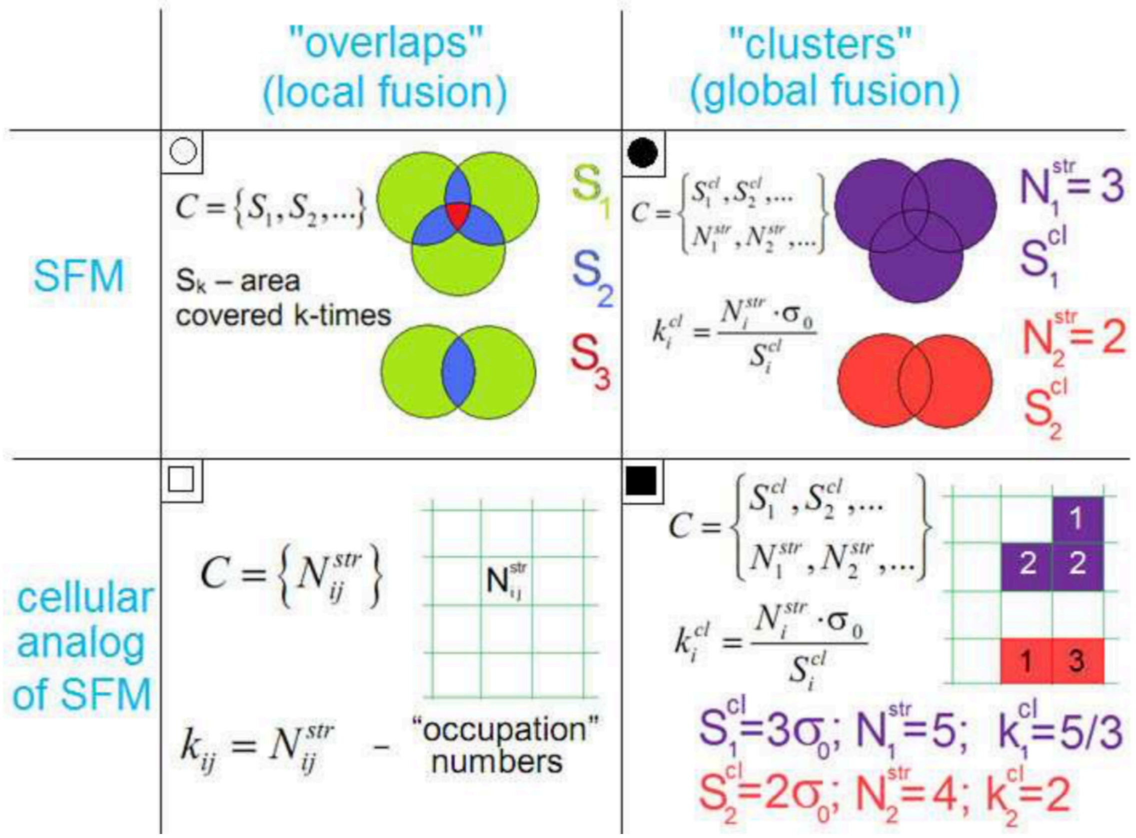



## Simplification of the transverse picture

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



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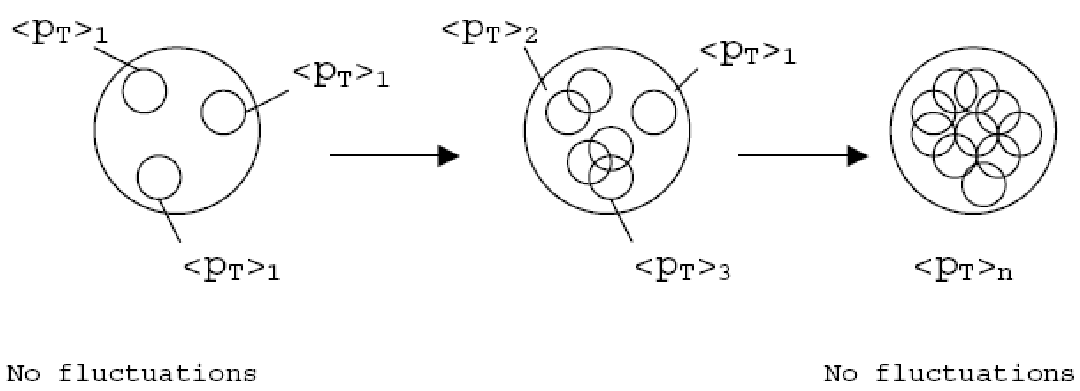


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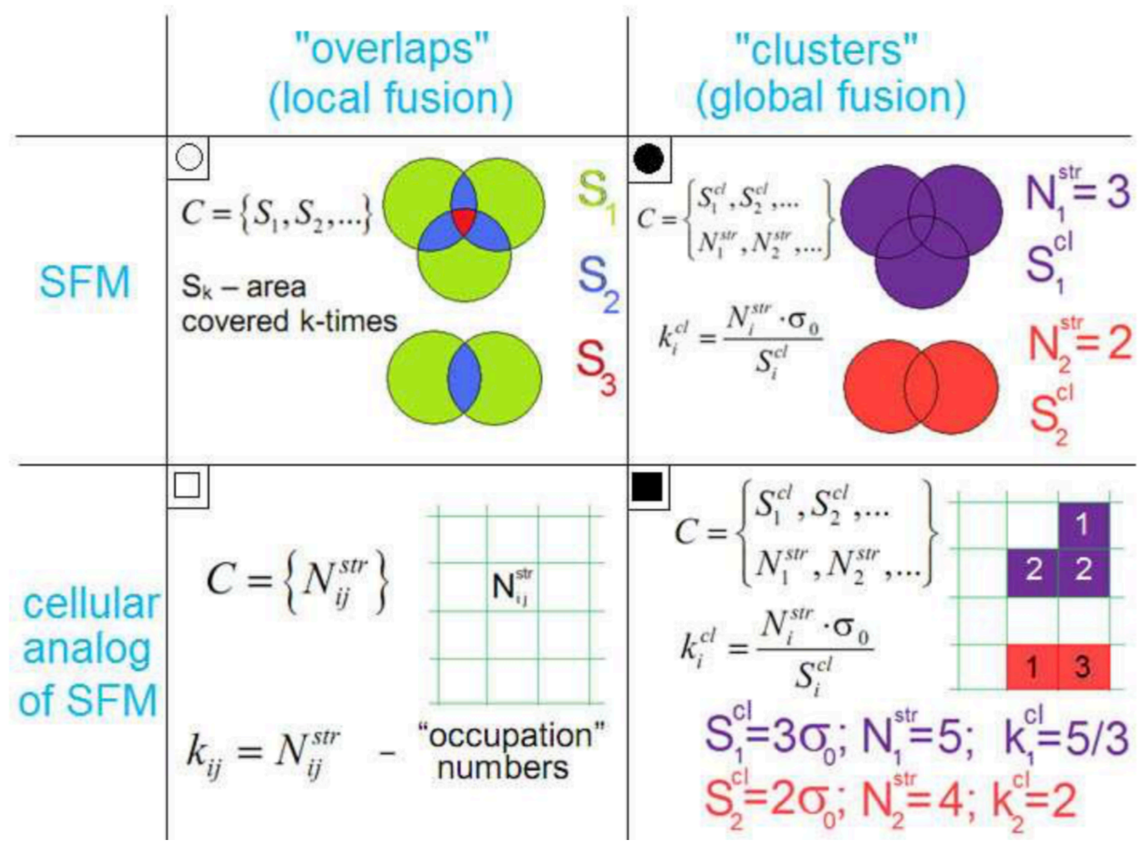


**String fusion** modifies the color field density [Braun, M. A., Kolevatov, R. S., Pajares, C. Vechernin, V. V. EPJ C, **32**, 535–546 (2004)]

This affects the mean multiplicity by the string and the mean transverse momentum of produced particles

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

Variations in the string length, location and interaction introduce additional fluctuations

# Monte-Carlo model of interacting quark-gluon strings

## Previous realization of the model:

[D. P., V.N. Kovalenko / (2020) / Study of Forward-Backward multiplicity fluctuations and correlations with pseudorapidity/ Journal Physics of Elementary Particles and Atomic Nuclei / Vol. 51 (3) / p. 323-326 / https://doi.org/10.1134/S1063779620030247]

| Old one | New one (this report) |
|---|---|
| no quarks | quarks flavors and their directions of flight are sampled |
| string ends randomly distributed in rapidity space | string ends position in rapidity space calculated from quarks' PDFs |
| string impact calculated only in pseudorapidity intervals of interest | strings are discretized in rapidity with ε step |
| only multiplicities are calculated, «particles» do not exist | «particle» produced by a string has pT and rapidity |
| mean number of strings in event is fixed, actual number is sampled from Poisson distribution for each event | |
| strings’ transverse position is sampled, if strings are in the same cell - string fusion occurs | |

# Quantities of interest

## Strongly intensive quantities Δ[PT,N] and Σ[PT,N]

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

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

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

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

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

**+ their dependence on the rapidity interval width**

**Normalization:**

- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ 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

In the analysis of the experimental data this one window studies correspond to changing rapidity-averaged baryo-chemical potential at the freeze-out stage [Becattini F, Manninen J and Gazdzicki M PRC 73 044905]

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

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

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

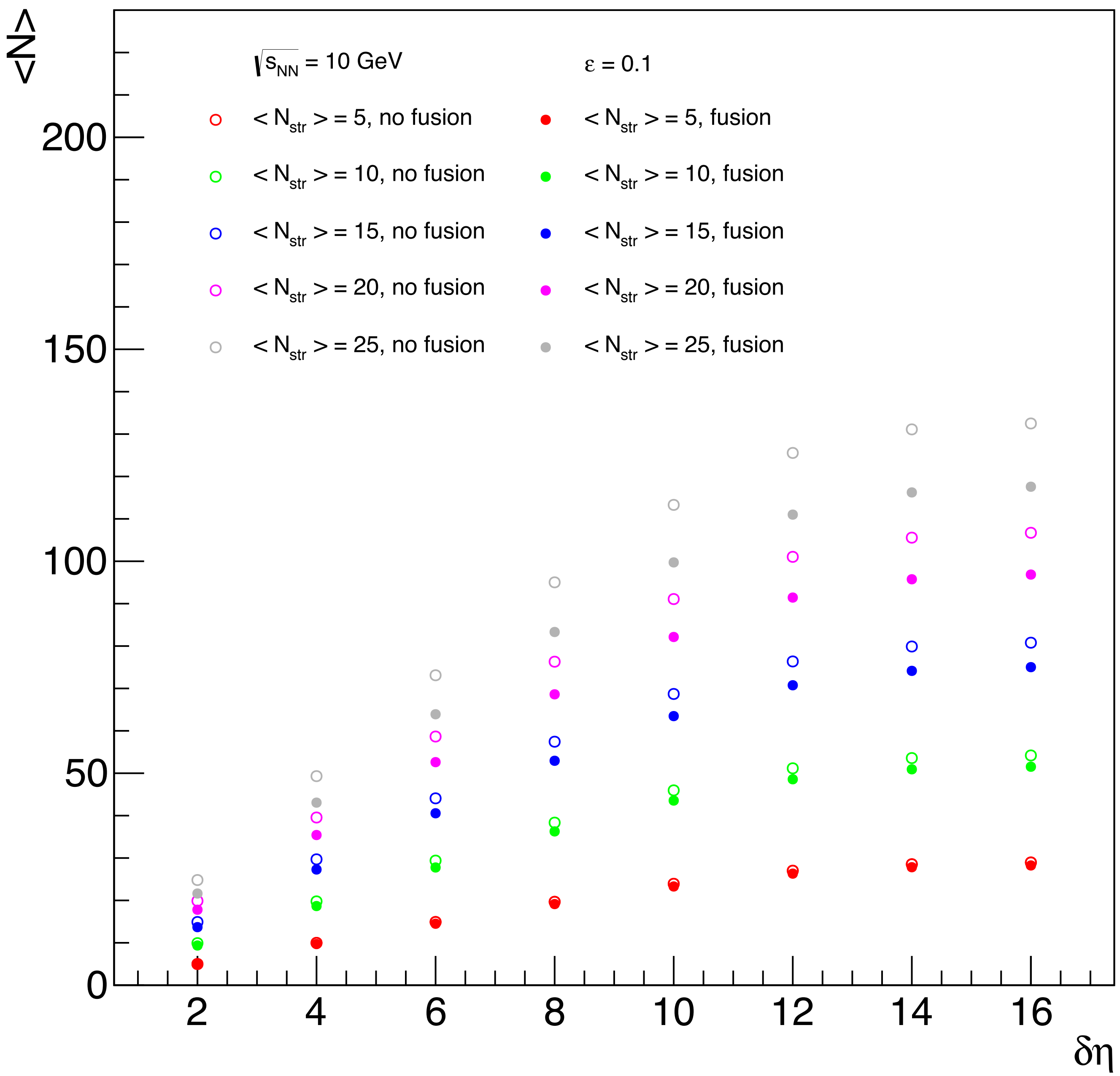
[E. V. Andronov, Theoretical and Mathematical Physics **185**, 1383 (2015)]

**+ its dependence on the distance between Forward and Backward rapidity intervals**

It is supposed to be sensitive to the initial conditions of particle production and short- and long-range multiplicity correlations [E. Andronov, V. Vechernin, 1808.09770]

# Results in MC model of interacting quark-gluon strings

## <N> as a function of the rapidity window width δη



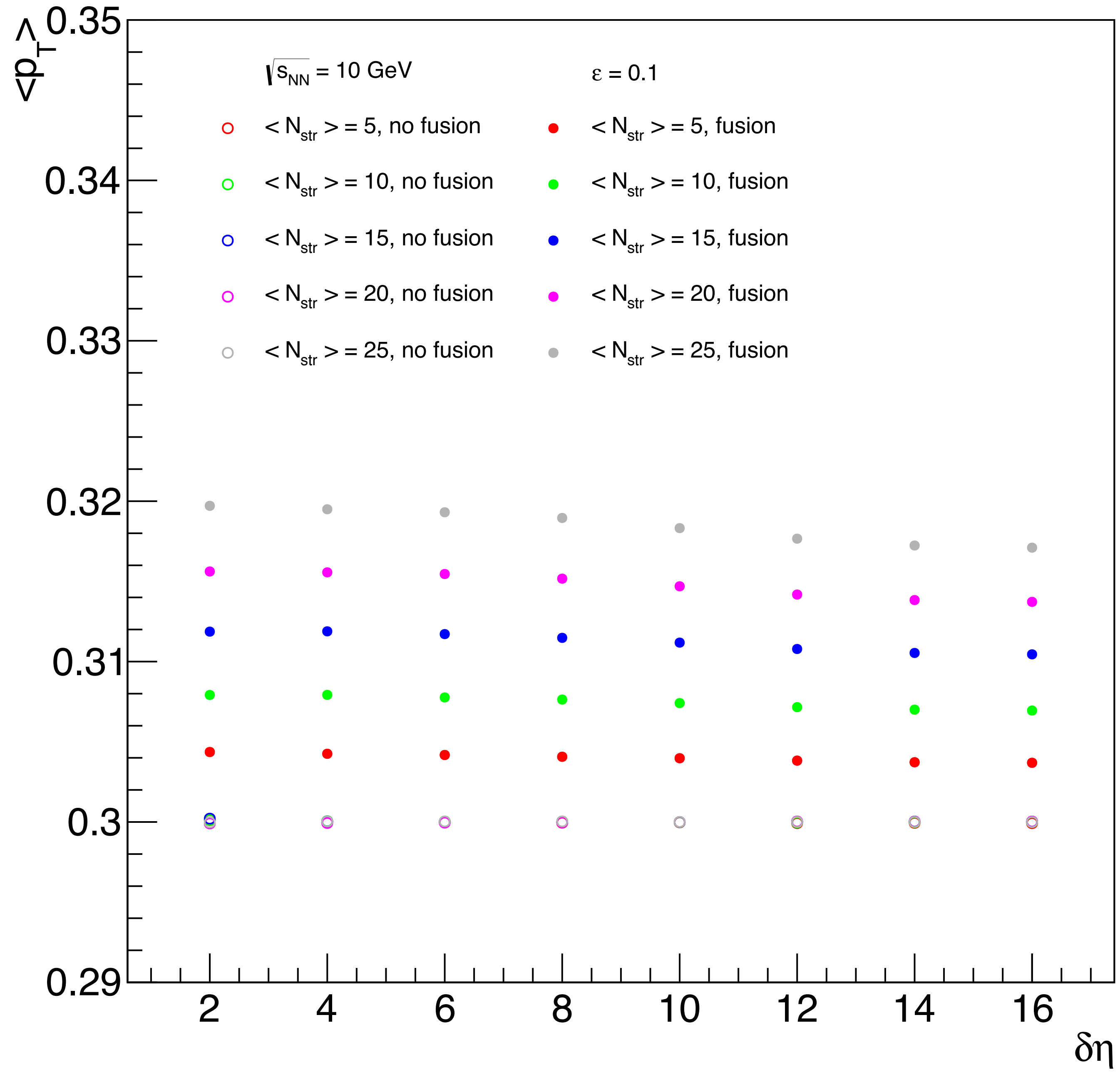

- **<N> grows with the rapidity window width**
- **<N> grows with the number of strings in event**
- **string fusion causes the decrease of <N>**

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

- **the larger the number of strings in event, the bigger the difference between fusion and non-fusion**

# Results in MC model of interacting quark-gluon strings

## <pT> as a function of the rapidity window width δη



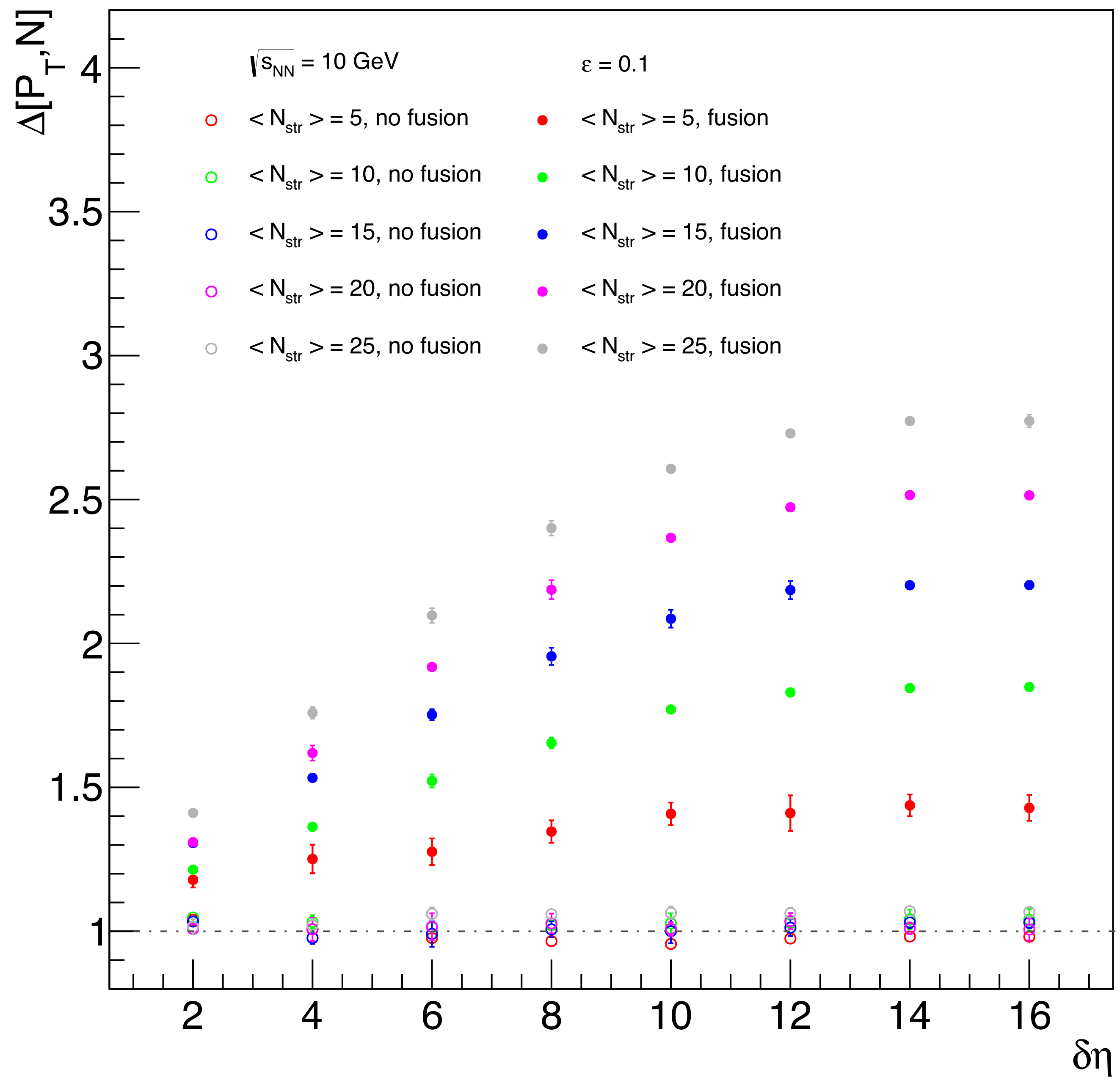

- **<pT> is constant with the rapidity window width**
- **<pT> grows with the number of strings in event**
- **string fusion causes the increase of <pT>**

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

- **the larger the number of strings in event, the bigger the difference between fusion and non-fusion**

# Results in MC model of interacting quark-gluon strings

## Δ[PT,N] as a function of the rapidity window width δη

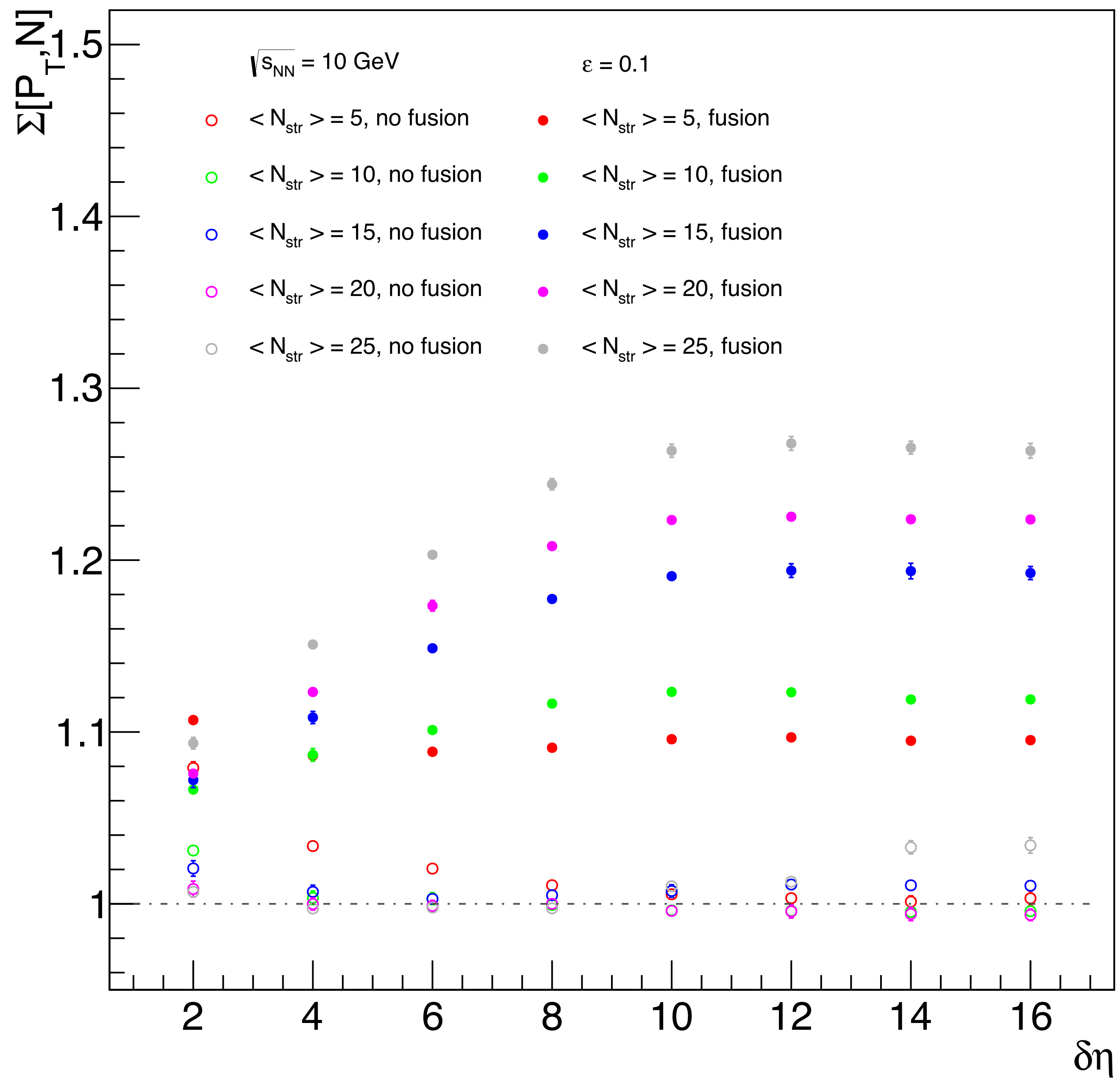



$$\Delta[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Delta}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] - \langle \mathrm{P_T}\rangle\omega[\mathrm{N}]\right]$$

- **for no-fusion Δ[PT,N] fluctuates around 1**
- **string fusion causes the increase of Δ[PT,N] with the rapidity window width**
- **for fusion the larger number of strings in event, the larger the value of Δ[PT,N]**

# Results in MC model of interacting quark-gluon strings

## Σ[PT,N] as a function of the rapidity window width δη

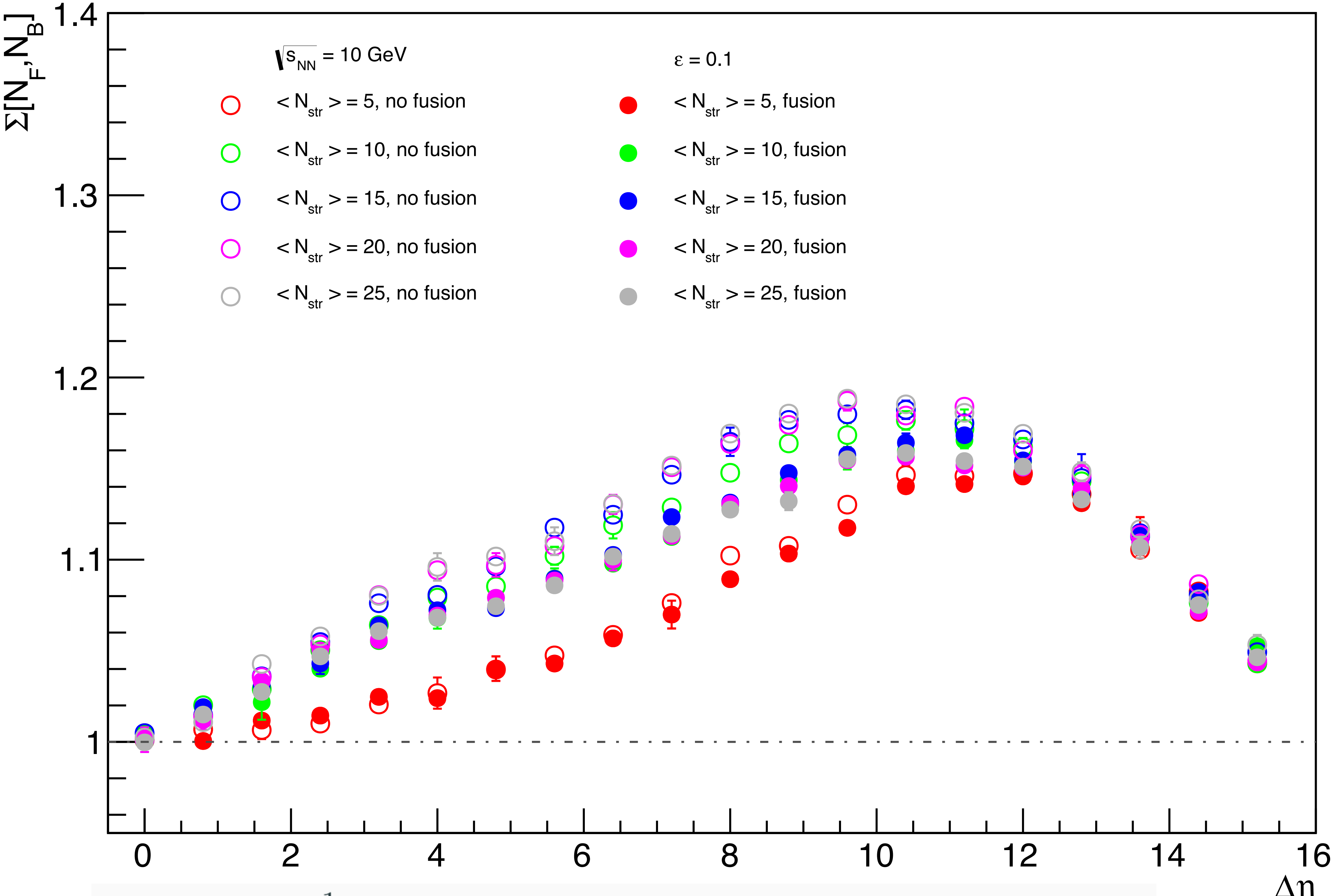



$$\Sigma[\mathrm{P_T},\mathrm{N}] = \frac{1}{\mathrm{C}_\Sigma}\left[\langle \mathrm{N}\rangle\omega[\mathrm{P_T}] + \langle \mathrm{P_T}\rangle\omega[\mathrm{N}] - 2\cdot(\langle \mathrm{P_T}\cdot \mathrm{N}\rangle - \langle \mathrm{P_T}\rangle\langle \mathrm{N}\rangle)\right]$$

- for no-fusion Σ[PT,N] fluctuates around 1, but more then Δ[PT,N]
- string fusion causes the increase of Σ[PT,N] with the width of the rapidity window
- for fusion the larger the number of strings in event, the larger the value of Σ[PT,N]

# Results in MC model of interacting quark-gluon strings

## Σ[NF,NB] as a function of the gap Δη between two rapidity windows



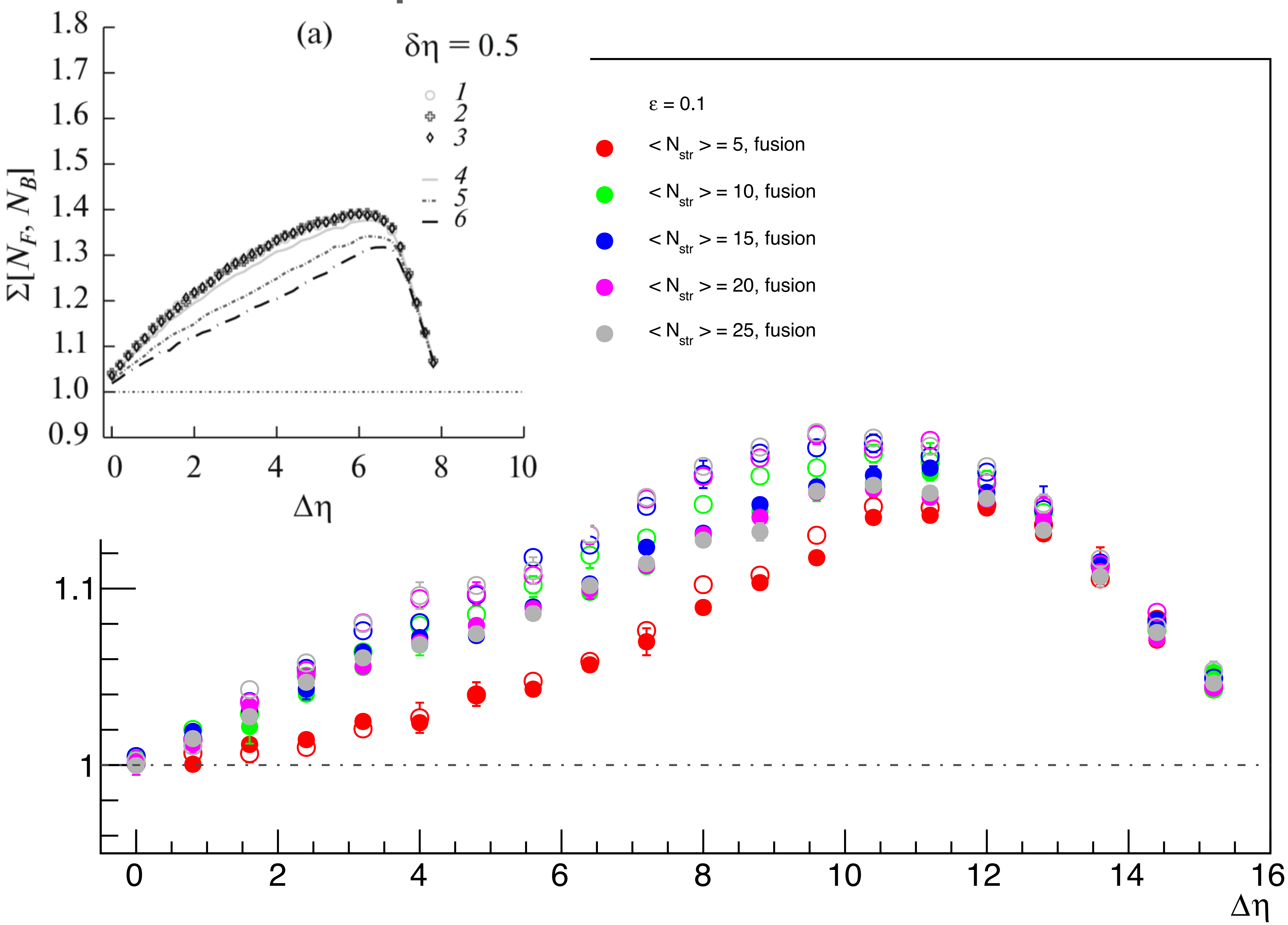

- values of Σ[NF,NB] for no-fusion are larger than the ones for fusion
- Σ[NF,NB] grows with the distance between rapidity windows
- Σ[NF,NB] decreases at high distances between rapidity windows due to the lack of statistics

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

# Results in MC model of interacting quark-gluon strings

## Results in the previous version of the model

D. P., V.N. Kovalenko (2020) PEPAN **51** (3) 323-326




- values of Σ[NF,NB] for no-fusion are larger than the ones for fusion
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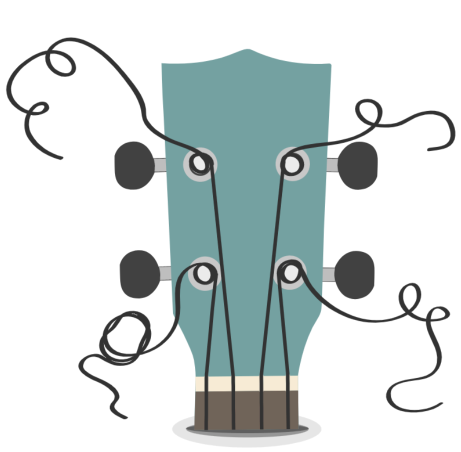
# Outlook



1. Introduce charges of the produced particles
2. Introduce baryons and mesons
3. Implement the explicit energy dependence of the string number




LUHEP SPb SU

## Thank you for your attention!

This work is supported by the RFBR research project no. 18-02-40097

# Backup

# Monte-Carlo model of interacting quark-gluon strings

**Procedure: prerequisites**

1) Take quarks x_f probability distribution functions from LHAPDF
2) Number of strings in event is sampled from the poisson distribution with the given mean number
3) Mean number of particles produced by the rapidity unit of a string: mu=1
4) Mean pT of particles produced by the string: pTmean=0.3
5) sqrt(s_NN)=10GeV
6) Mean active piece of the string: 0.1, 0.2, 0.4
7) Size of a transverse plane of cells: 25

# Monte-Carlo model of interacting quark-gluon strings

**Procedure: string formation**

1) For each event sample a number of strings Nstr
2) Define number of quarks as 2*Nstr
3) Generate the quark content by the random number and fulfilling the ratio u:ubar:d:dbar:s:sbar:c:cbar = 6:2:4:2:2:2:1:1
4) Generate the direction of the quark moving: +1 or -1
5) Define quark rapidities (+y for positive direction and -y for negative) according to:

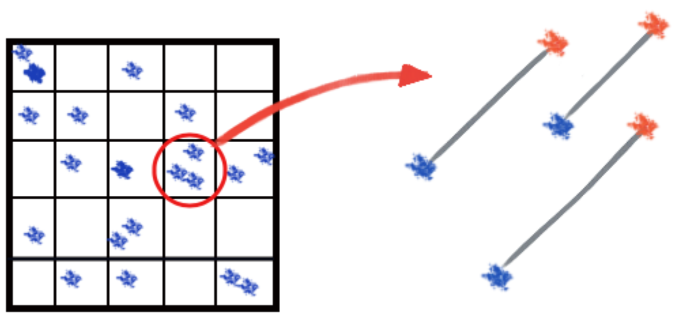
$$y_q = \text{arcsinh}\left(x_q\sqrt{\frac{s}{4m_q^2} - 1}\right)$$

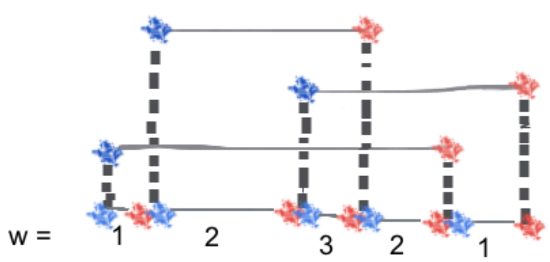
6) Define the largest one as a forward yq and vice versa
7) String is formed if forward_end-backward_end>0.1, otherwise the loop is repeated
8) Created primary strings in event, sample their position in transverse plane

# Monte-Carlo model of interacting quark-gluon strings

**Procedure: string fusion**

1) For no fusion option strings for particle production are our prepared strings
2) For no fusion ON option we check if strings overlap in transverse plane and if so form a new list of strings (shorter ones, but with a higher weights)





# Monte-Carlo model of interacting quark-gluon strings

**Procedure: particles**

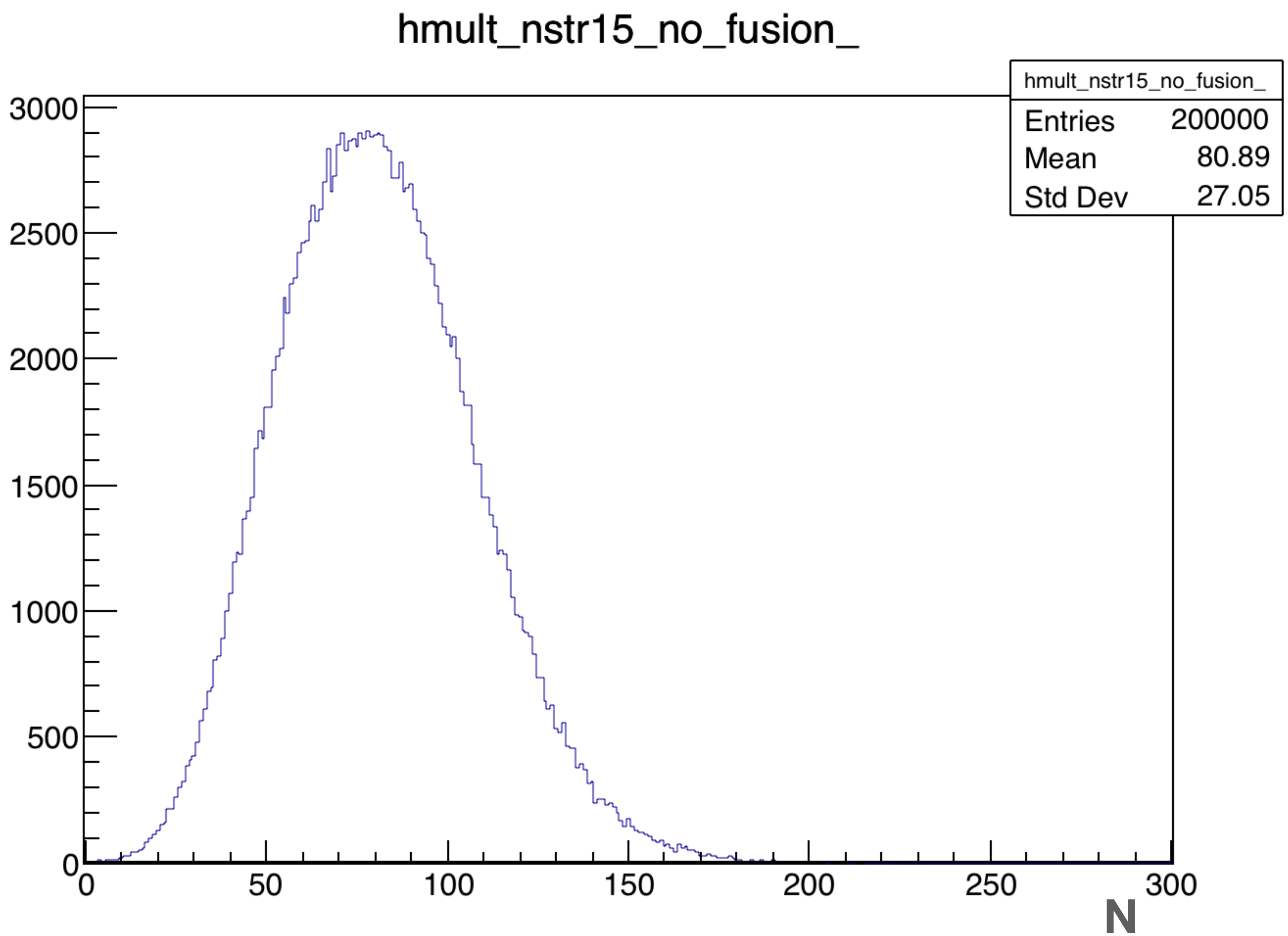
1) For the prepared set of strings find all active pieces of a predefined length and calculate their mean eta and mean multiplicity proportional to this length and weight defined by the number of the primary strings fused at this eta range due to the overlap in the transverse plane
2) Then find multiplicity by this piece from the Poisson distribution with the found mean - this is the number of particles, for each the pT is sampled from with the mean 0.3:

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

3) Fill histograms of final quantities

# Monte-Carlo model of interacting quark-gluon strings

## Basic distributions



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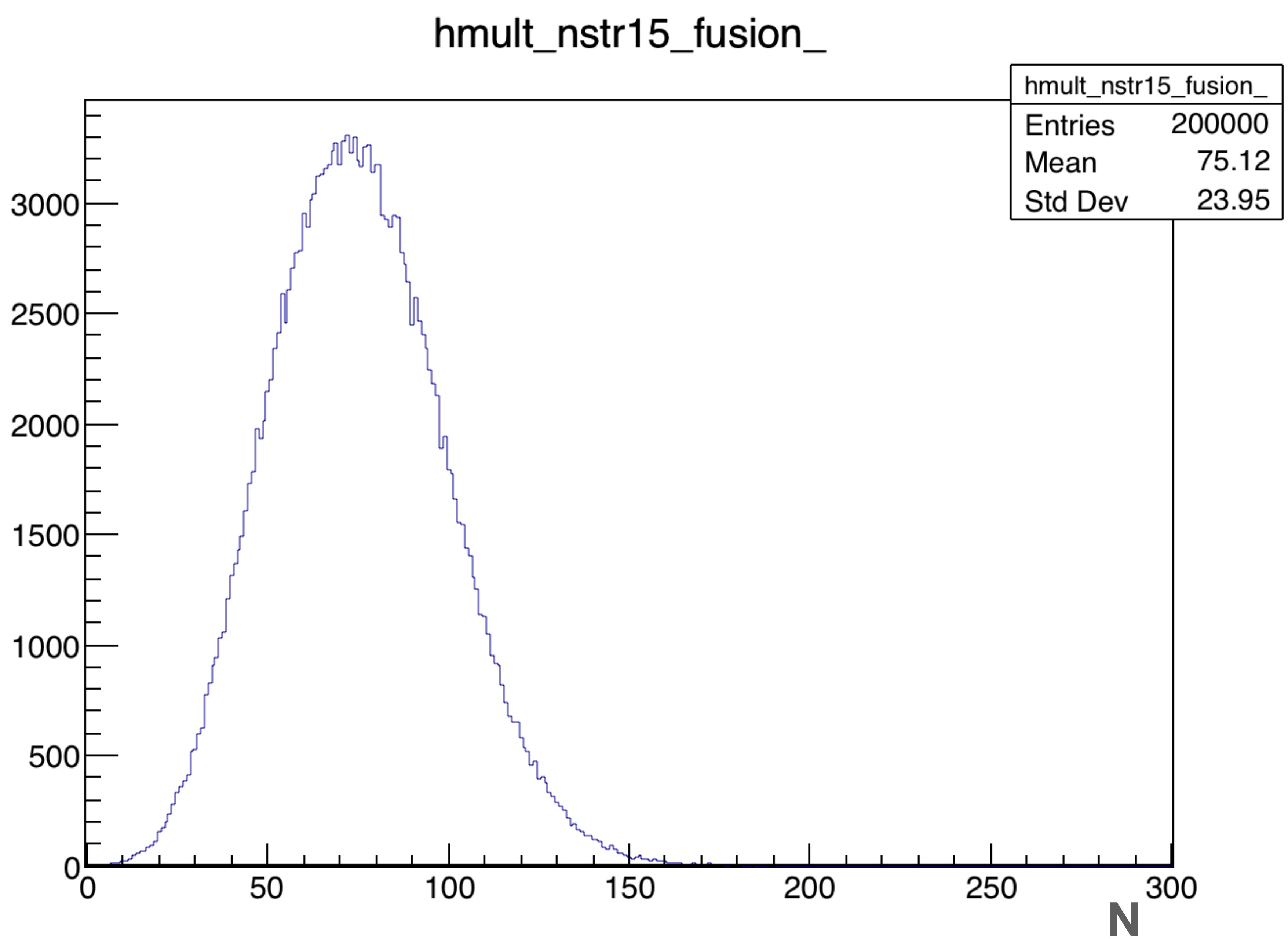

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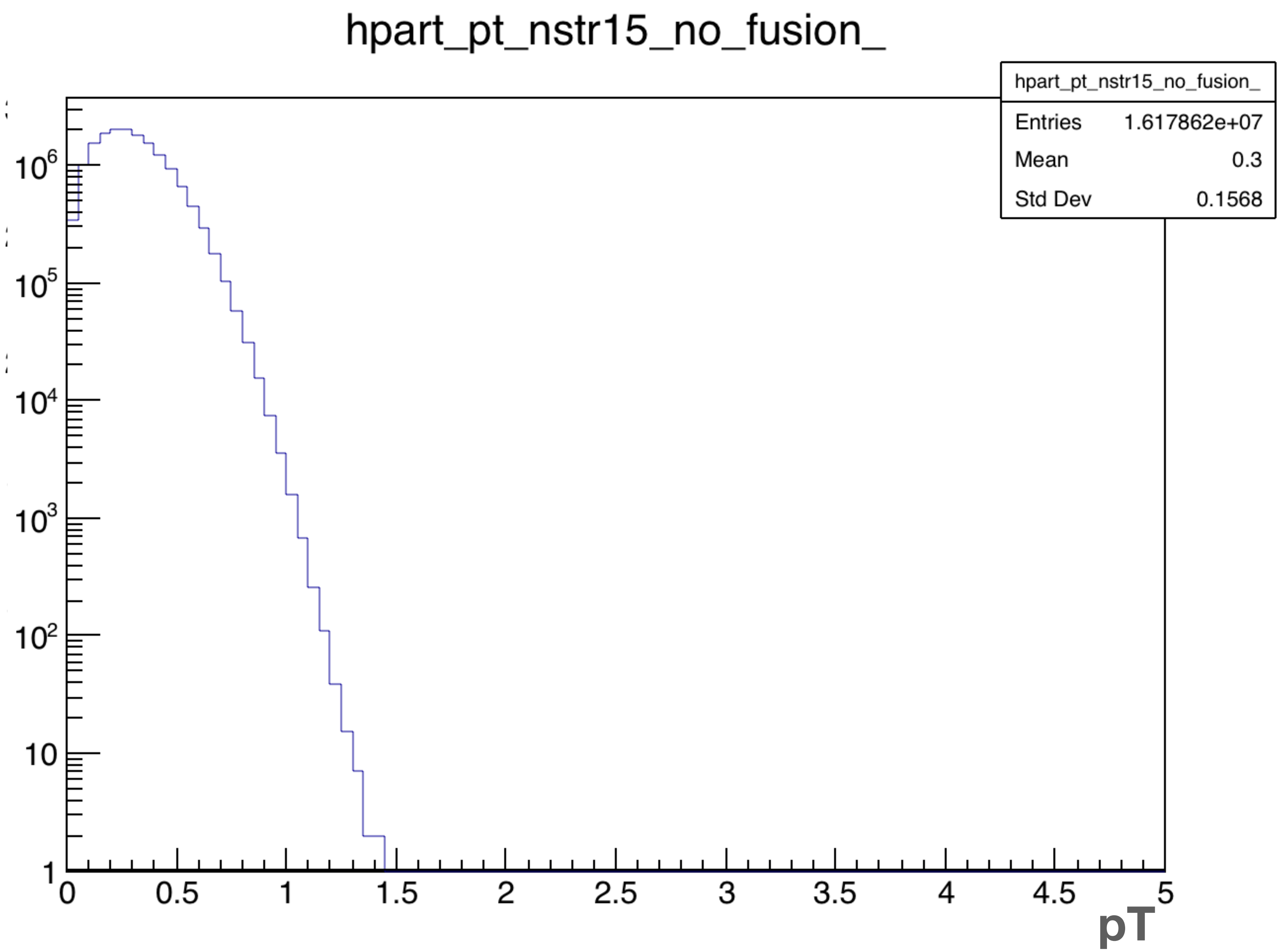

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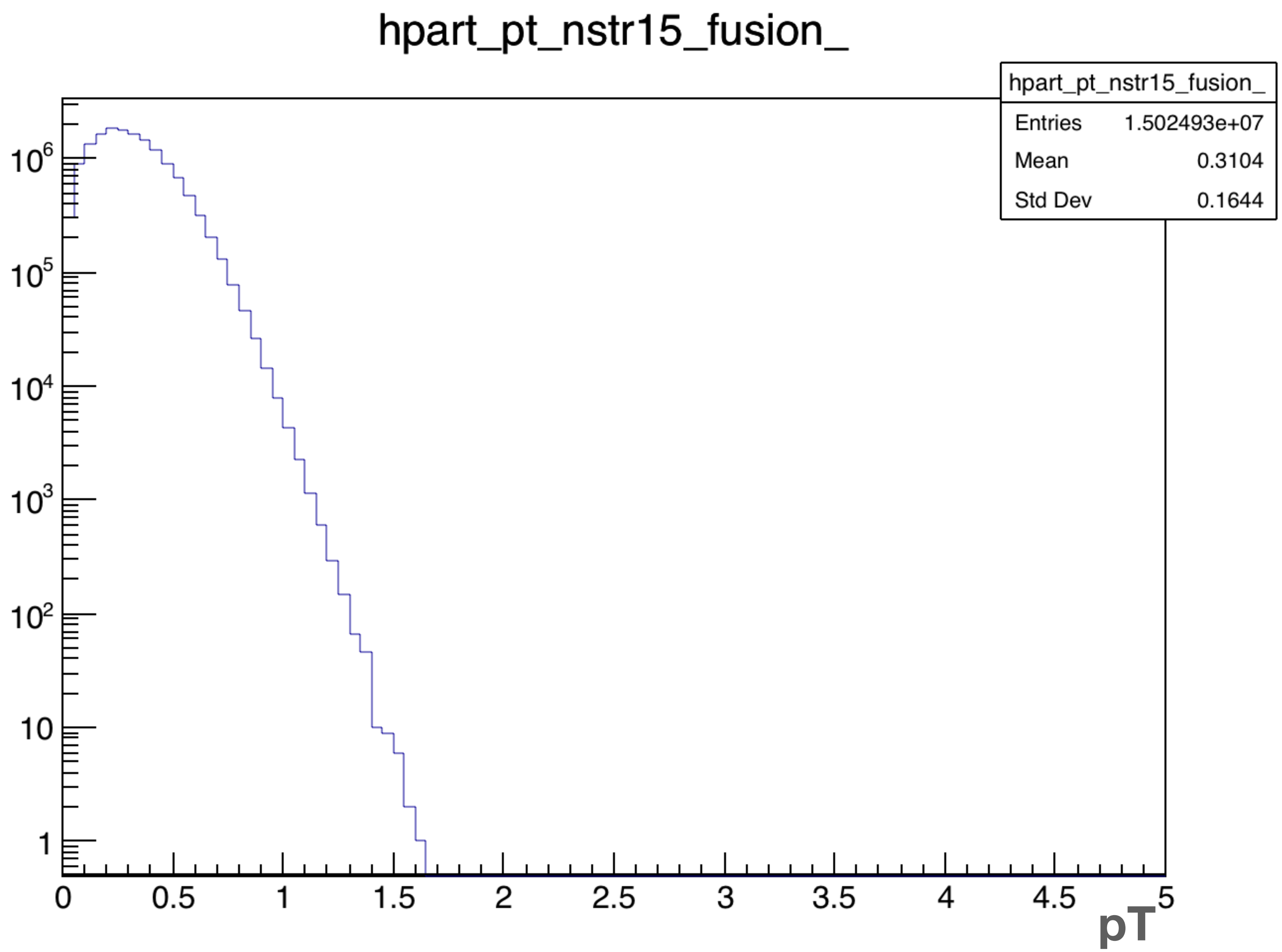

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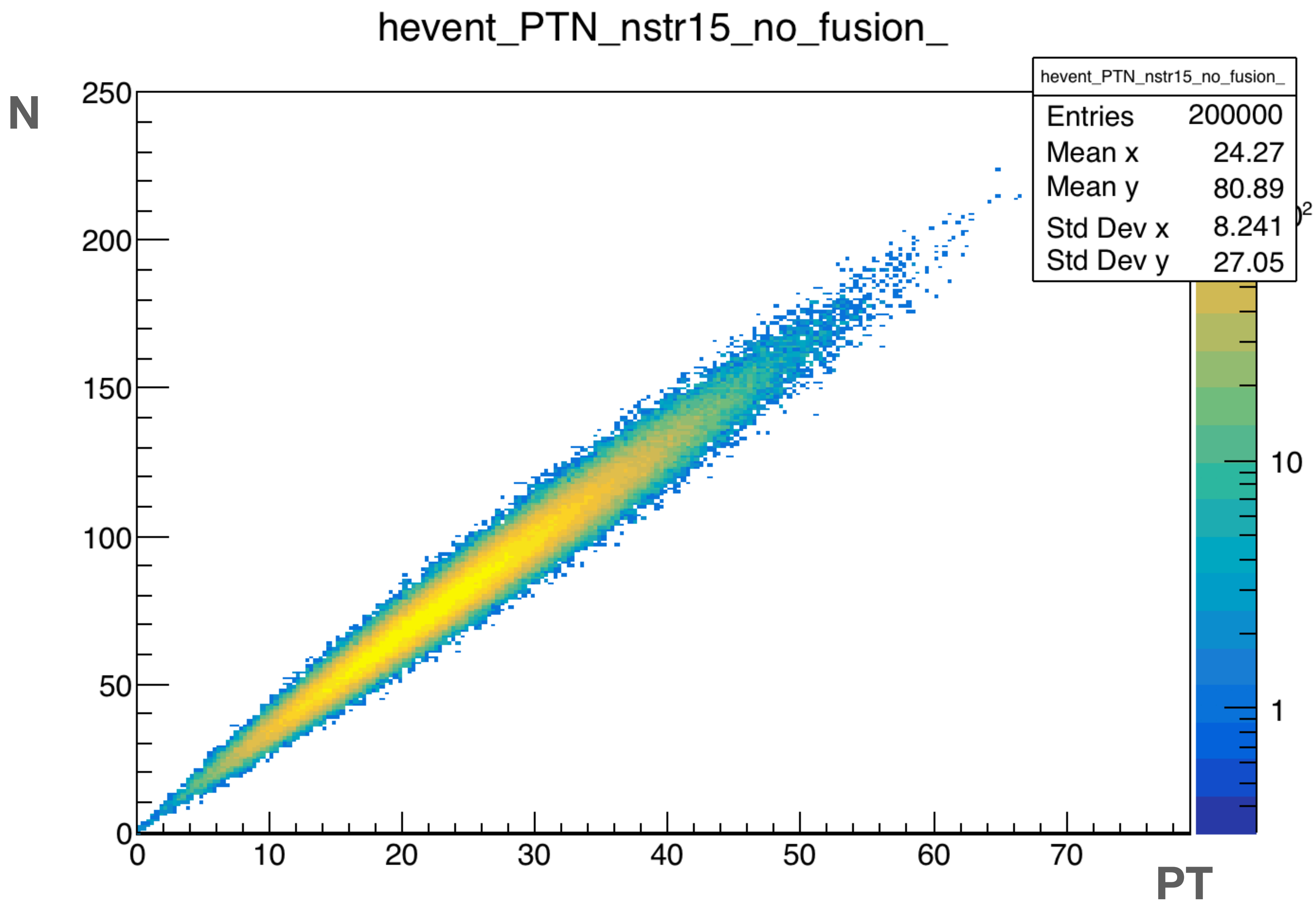

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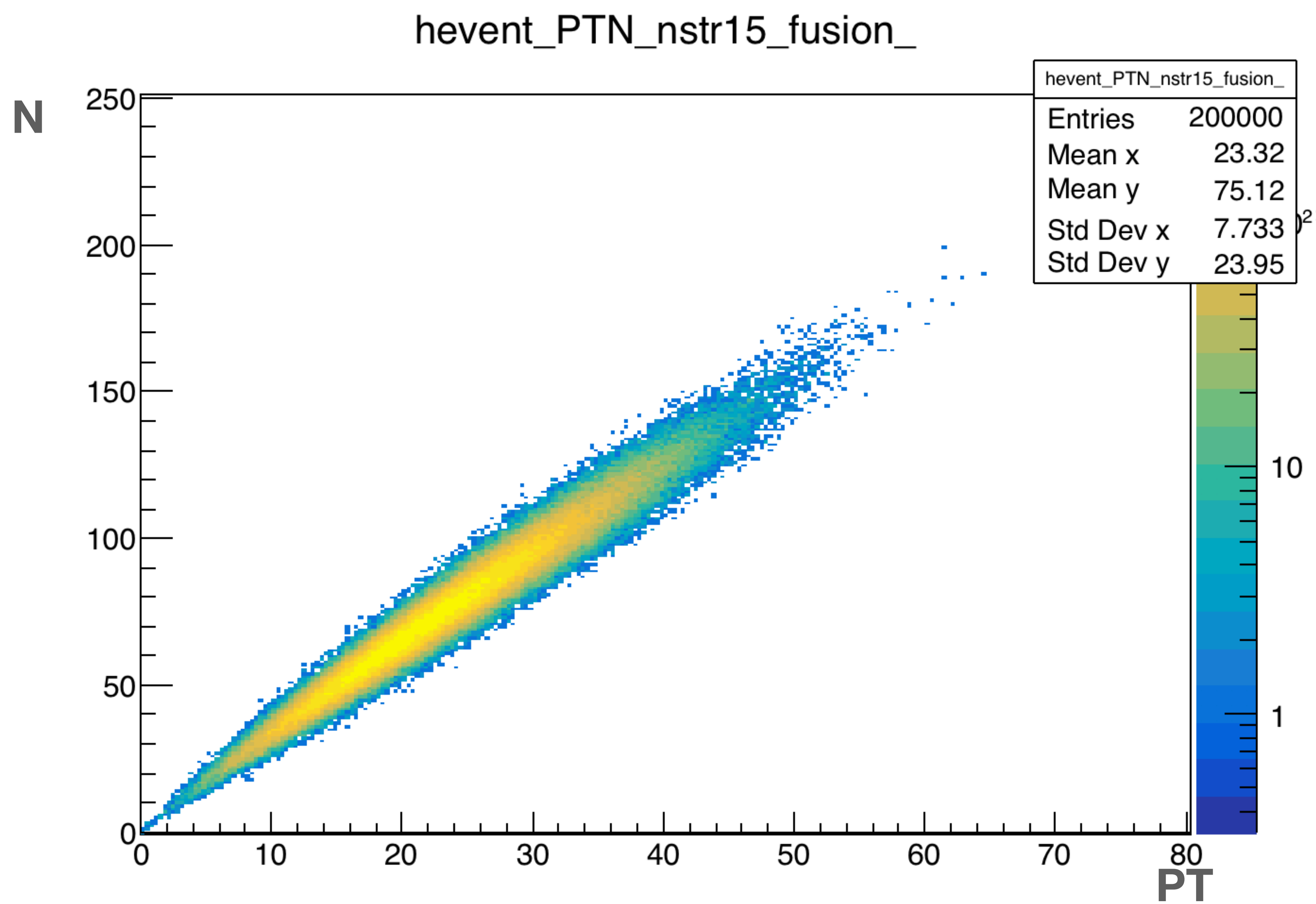

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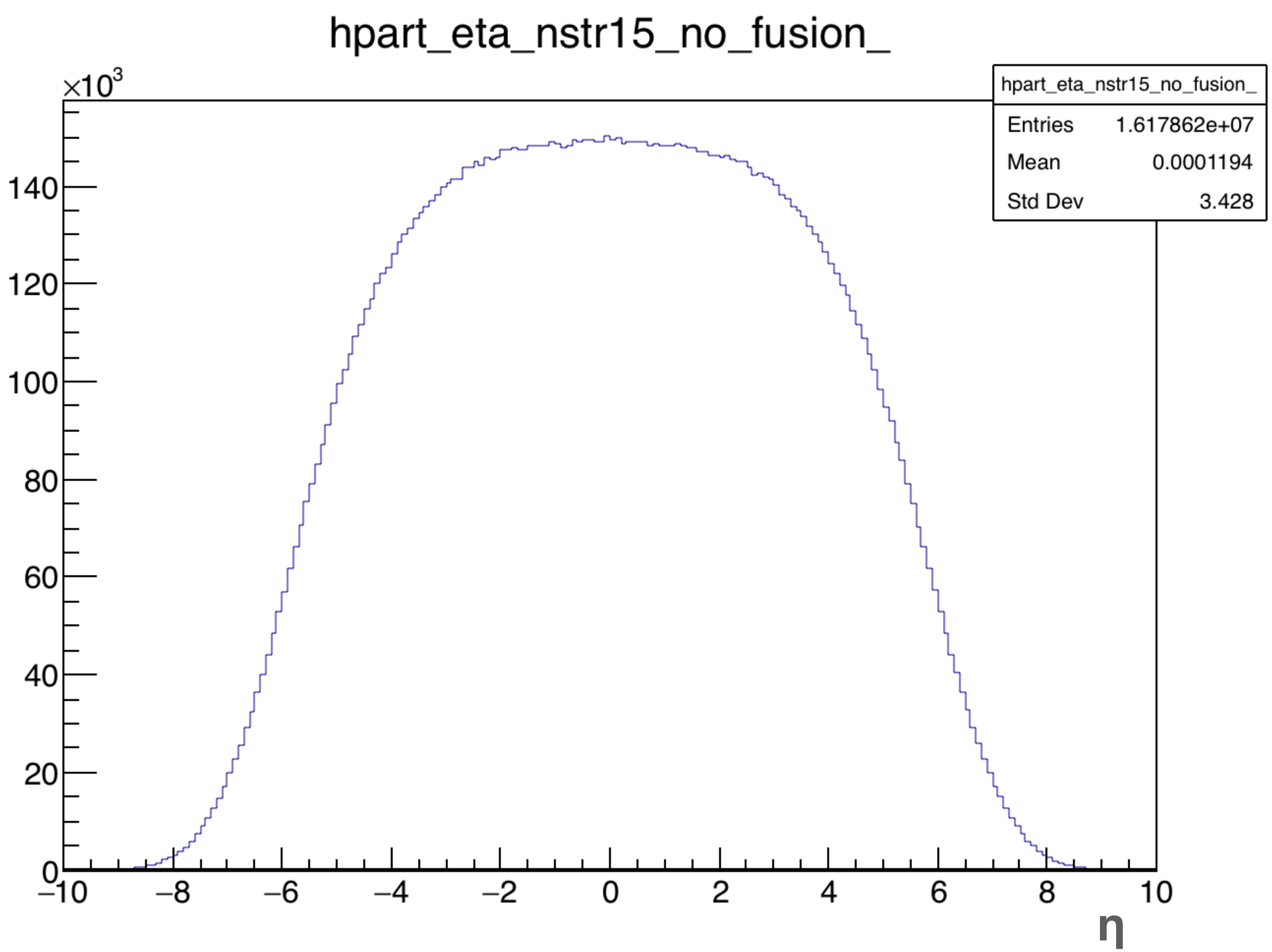

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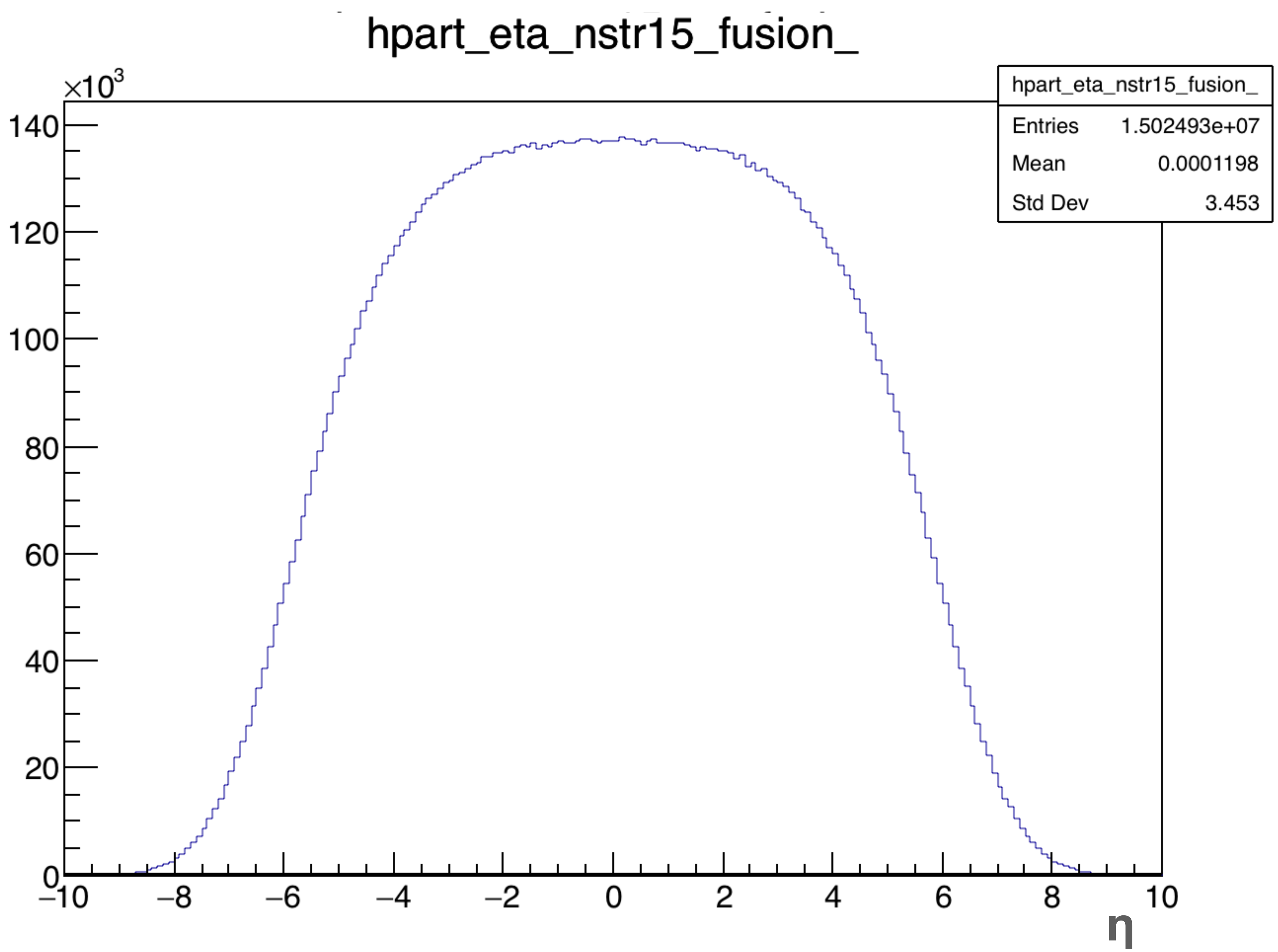

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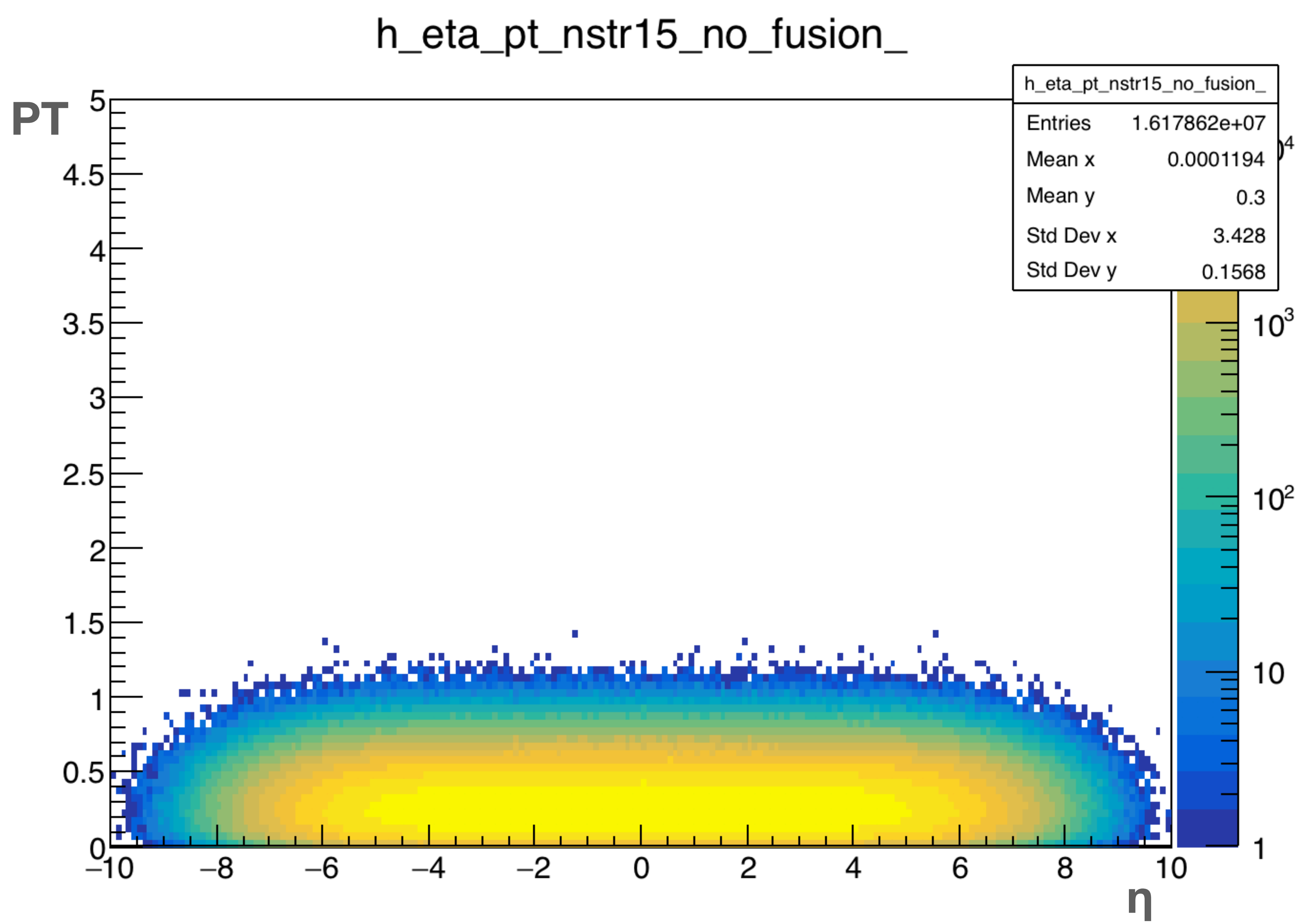

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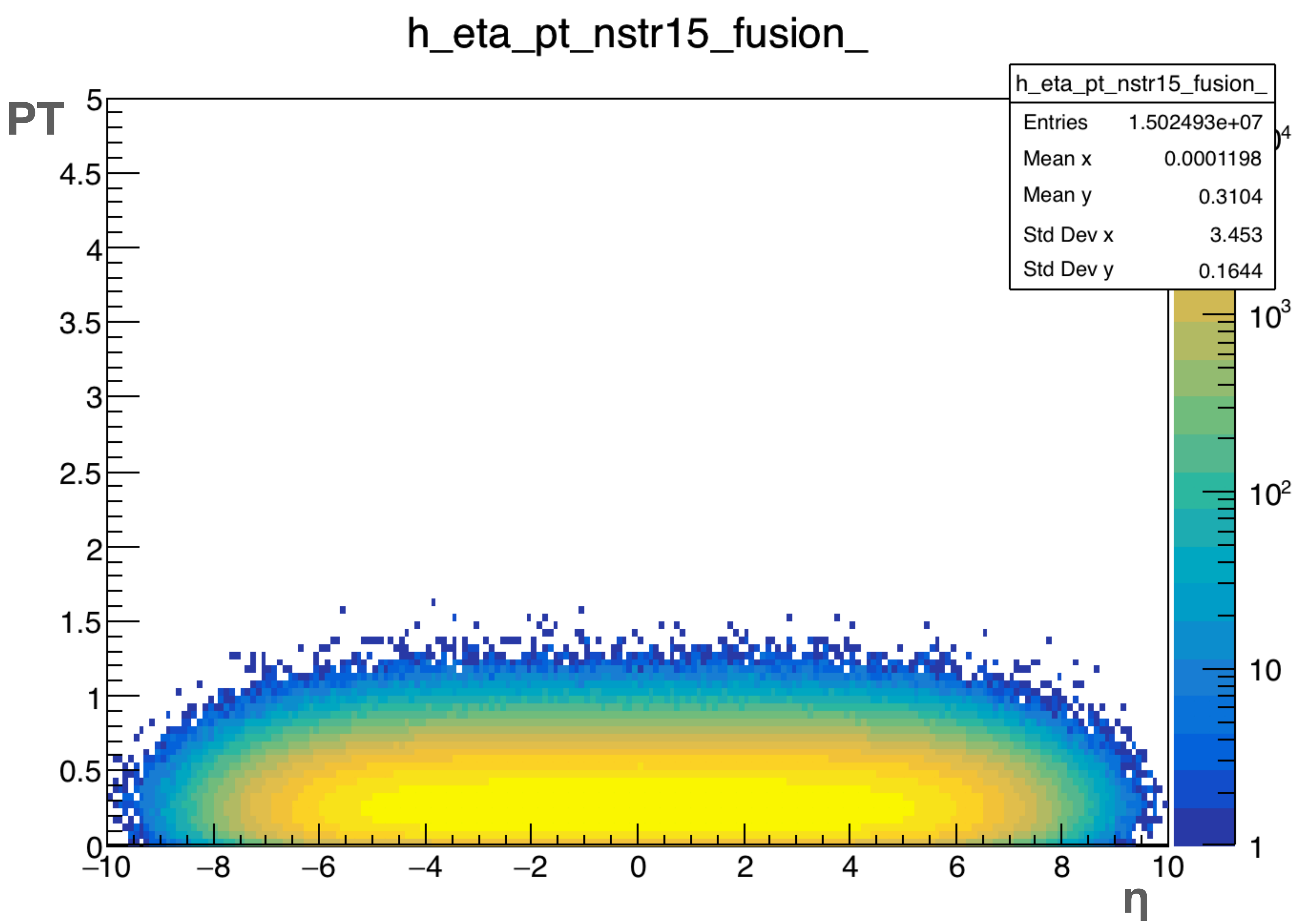

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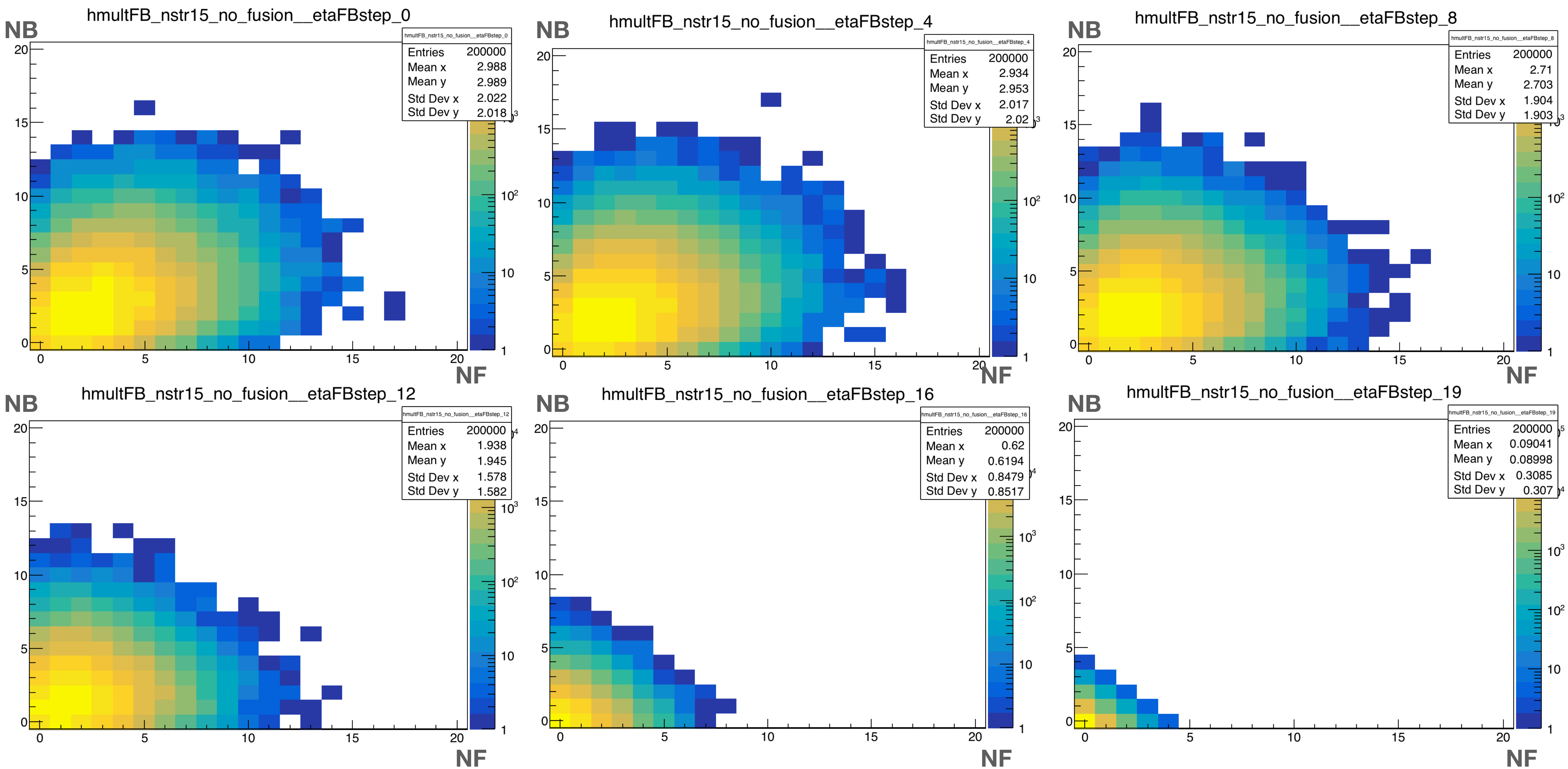

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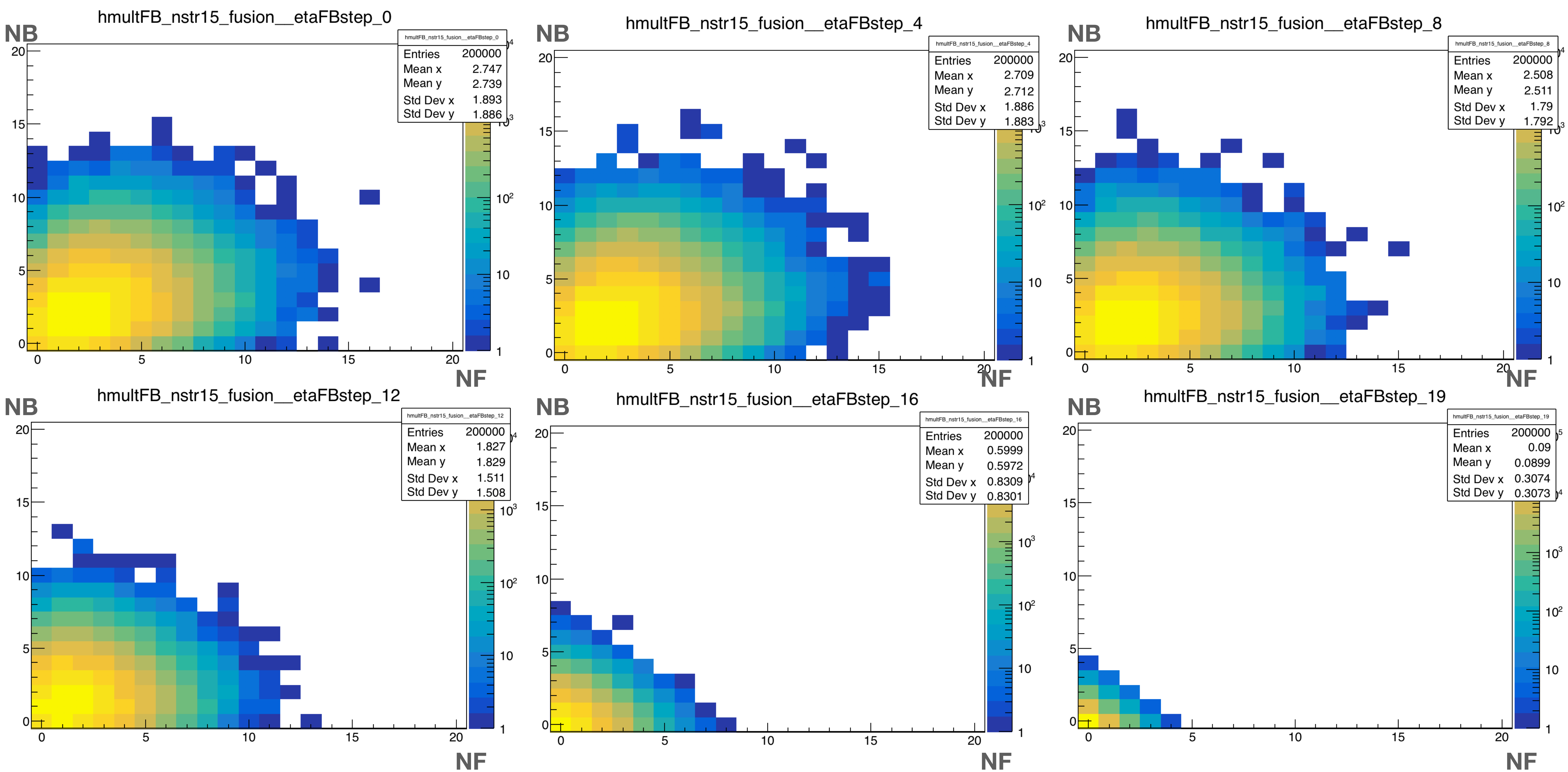
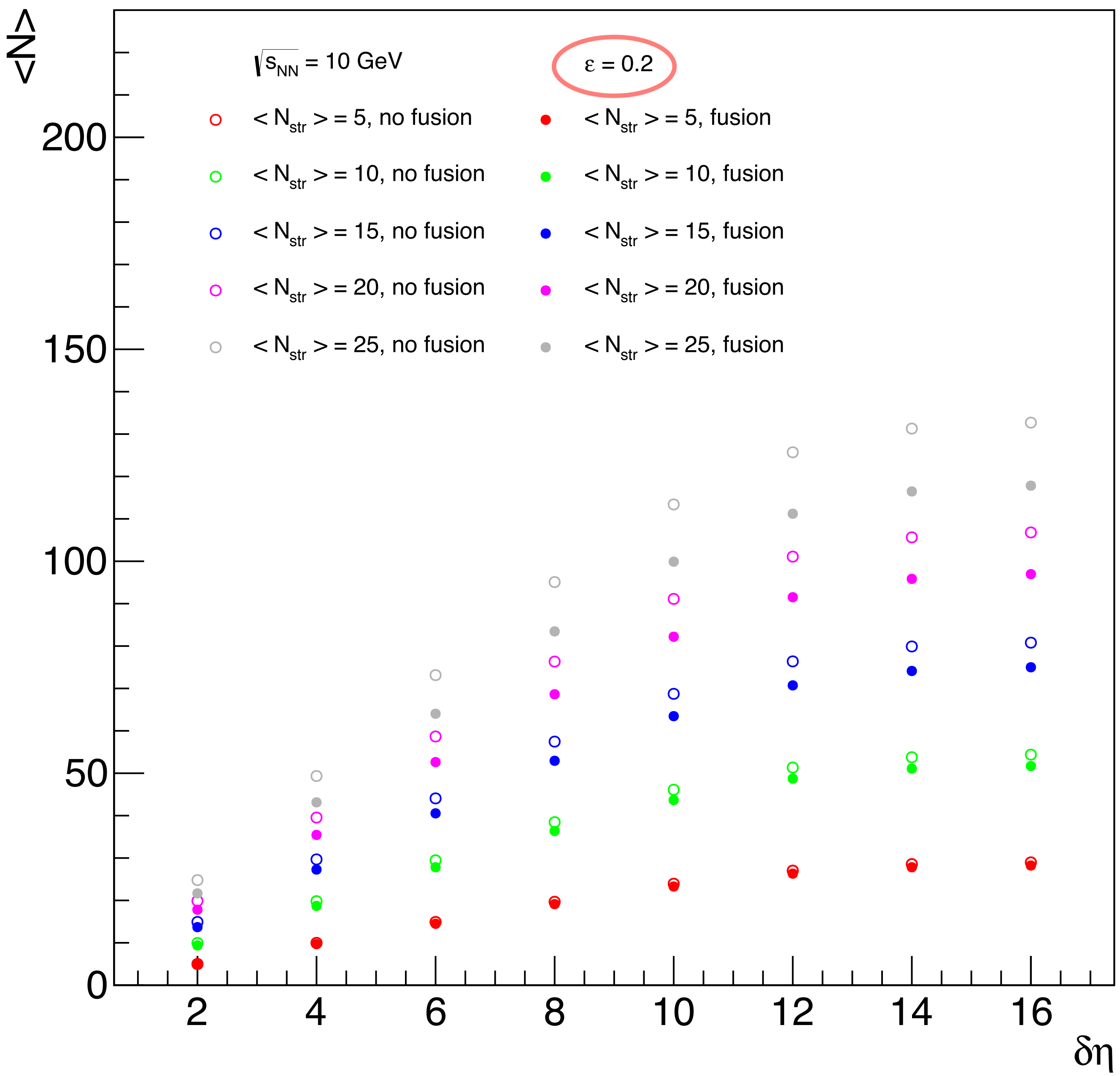


# Results in MC model of interacting quark-gluon strings

## <N> as a function of the rapidity window width δη




- **<N> grows with the rapidity window width**
- **<N> grows with the number of strings in event**
- **string fusion causes the decrease of <N>**
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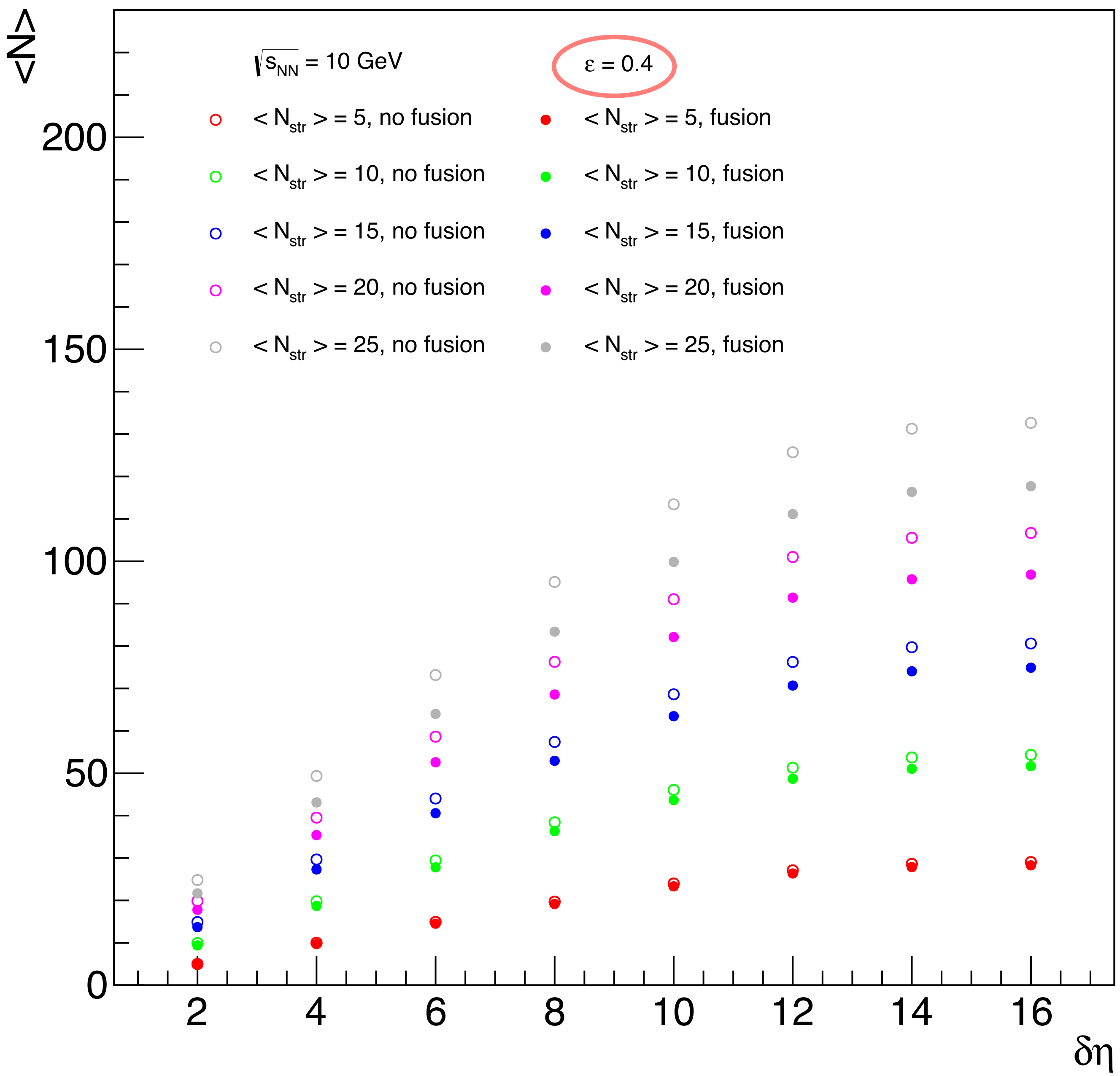


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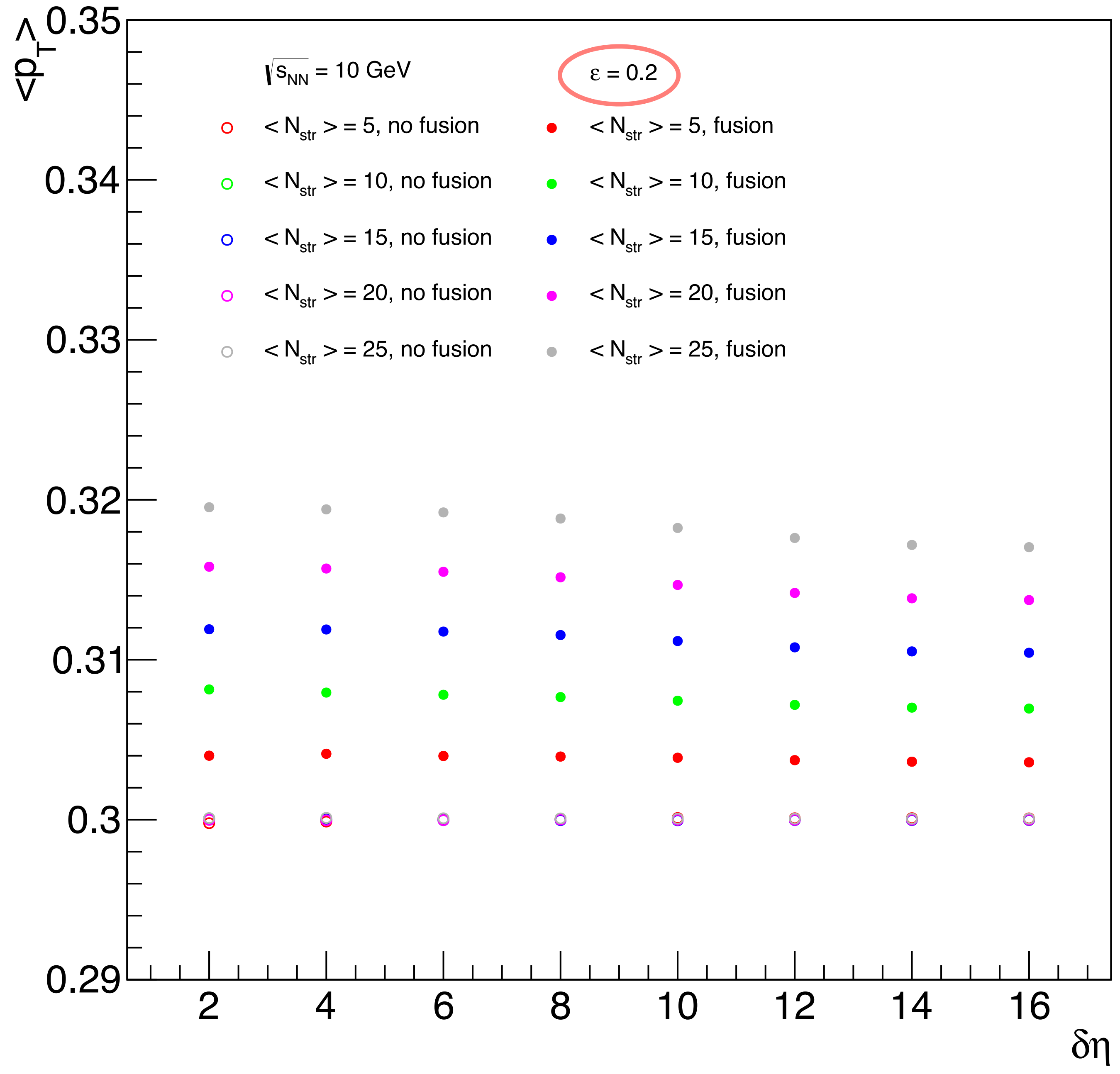
# Results in MC model of interacting quark-gluon strings

## <pT> as a function of the rapidity window width δη




- <N> is constant with the rapidity window width
- <N> grows with the number of strings in event
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# Results in MC model of interacting quark-gluon strings

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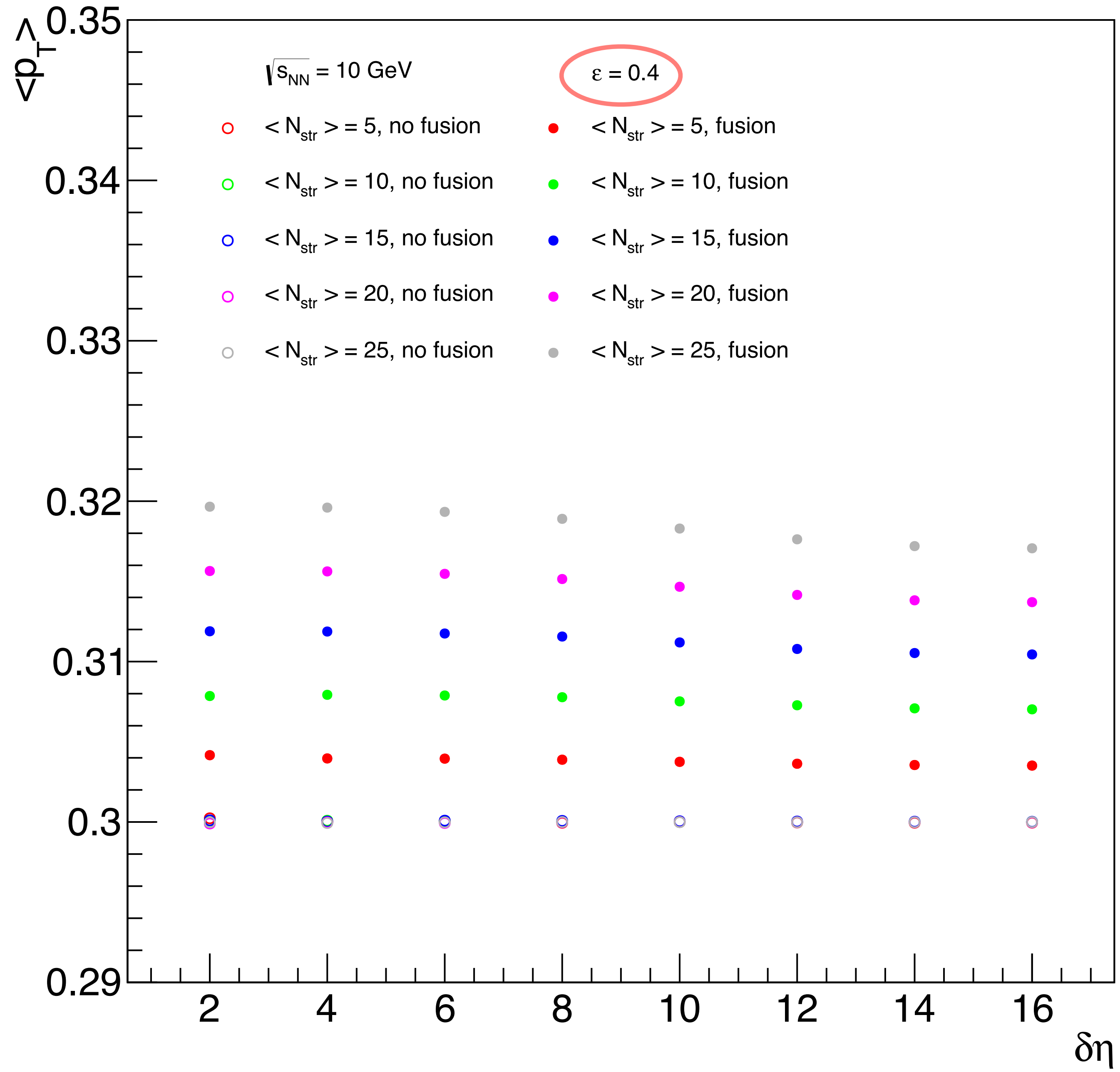


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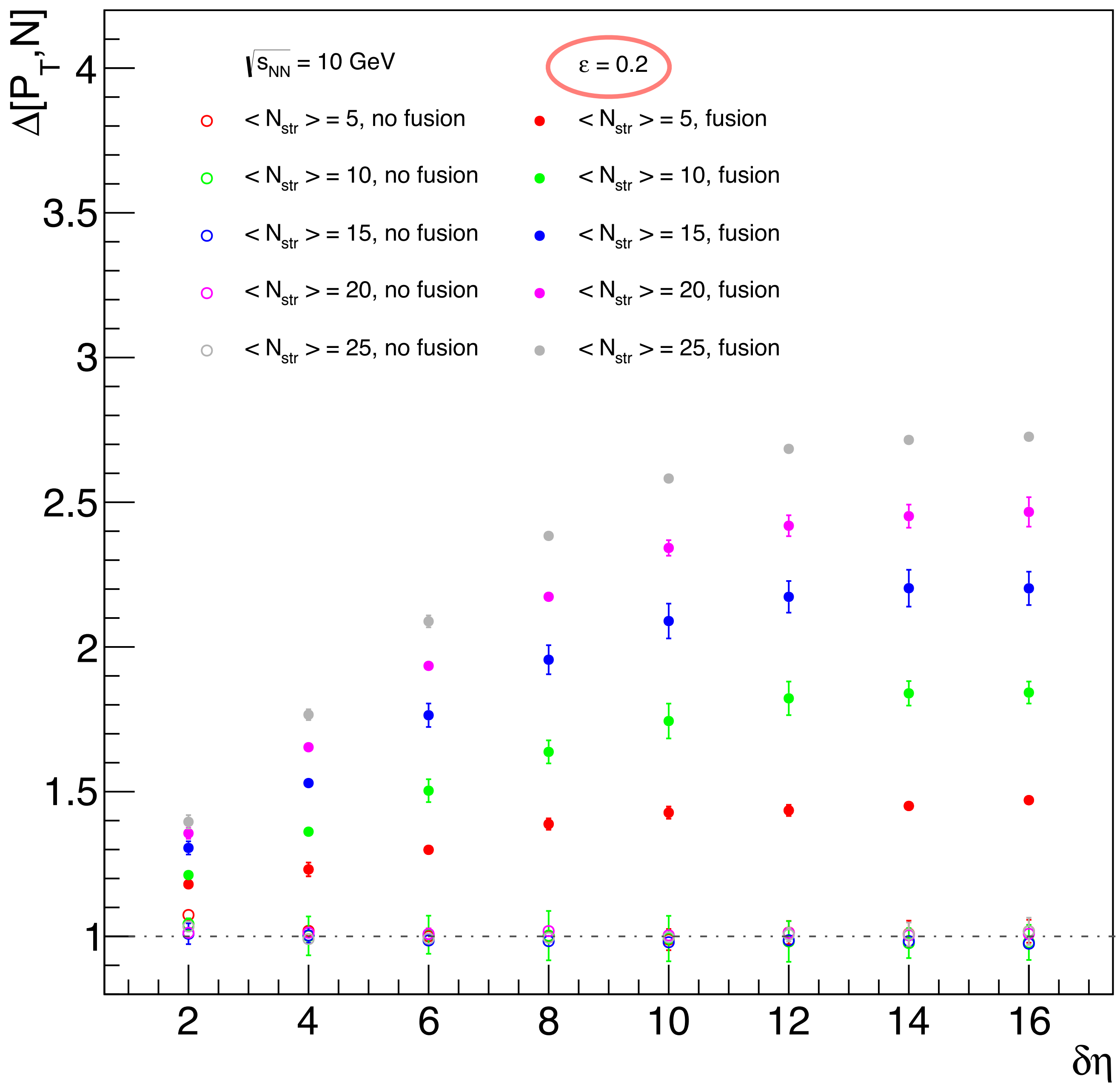


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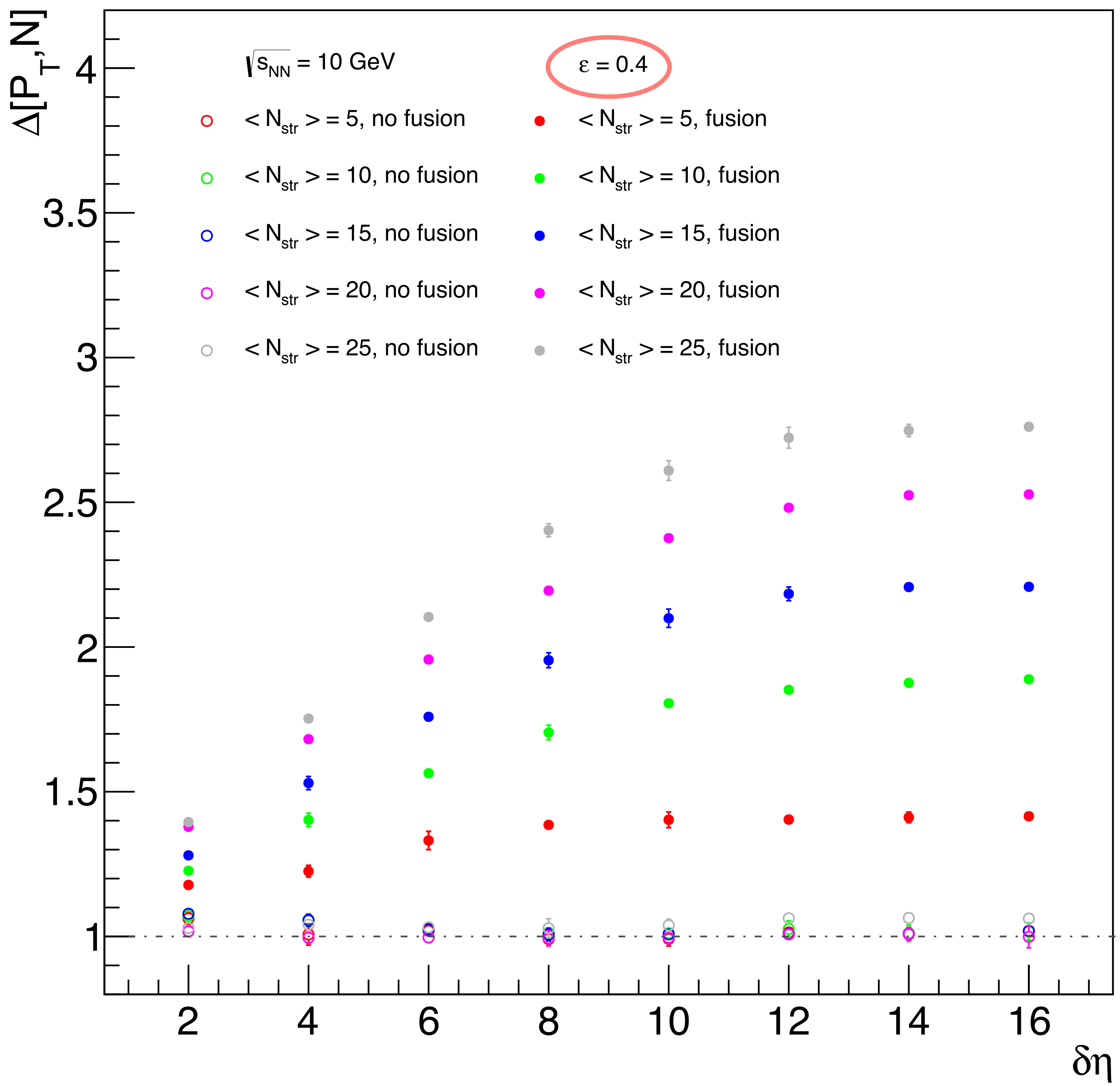


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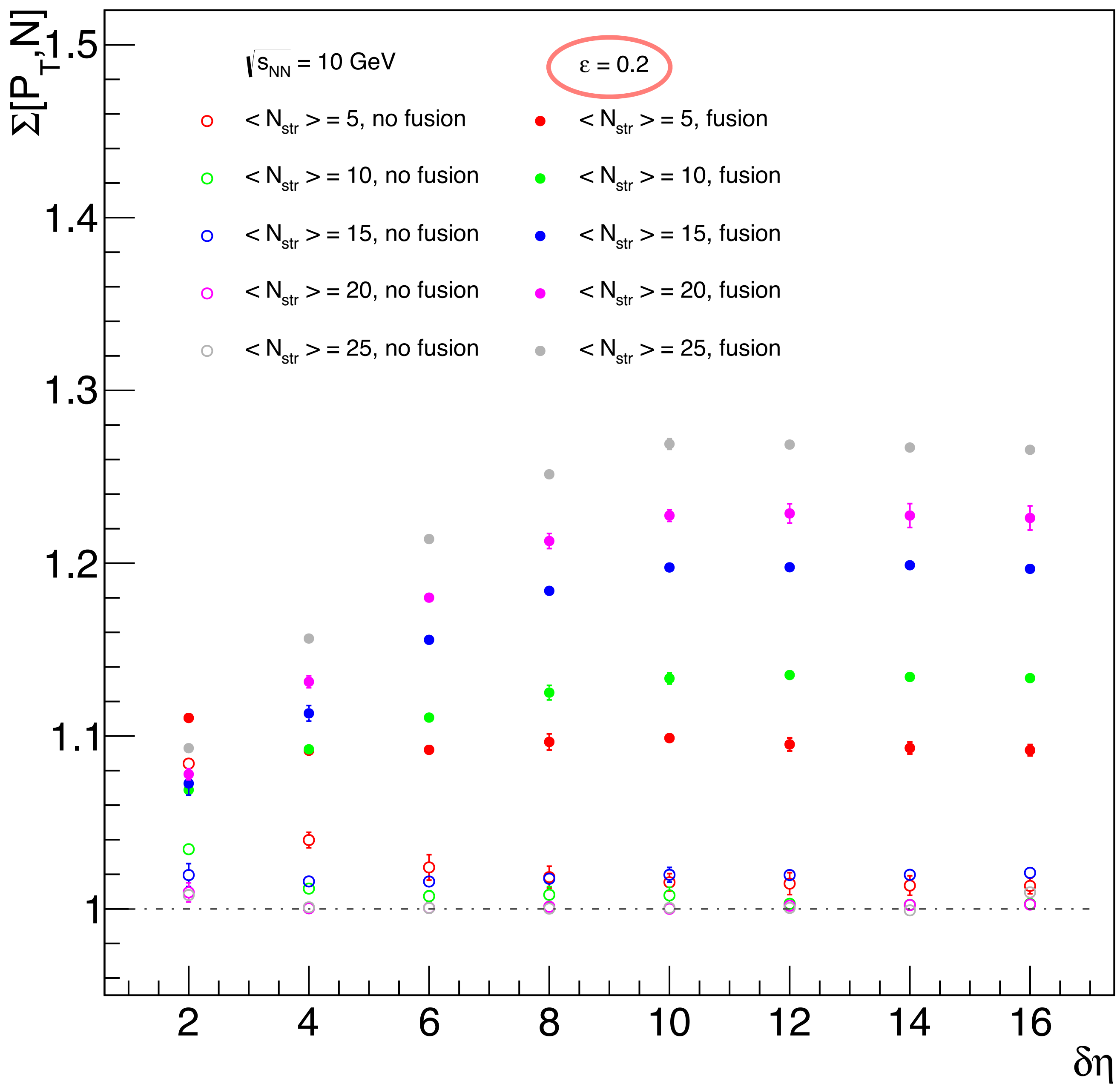


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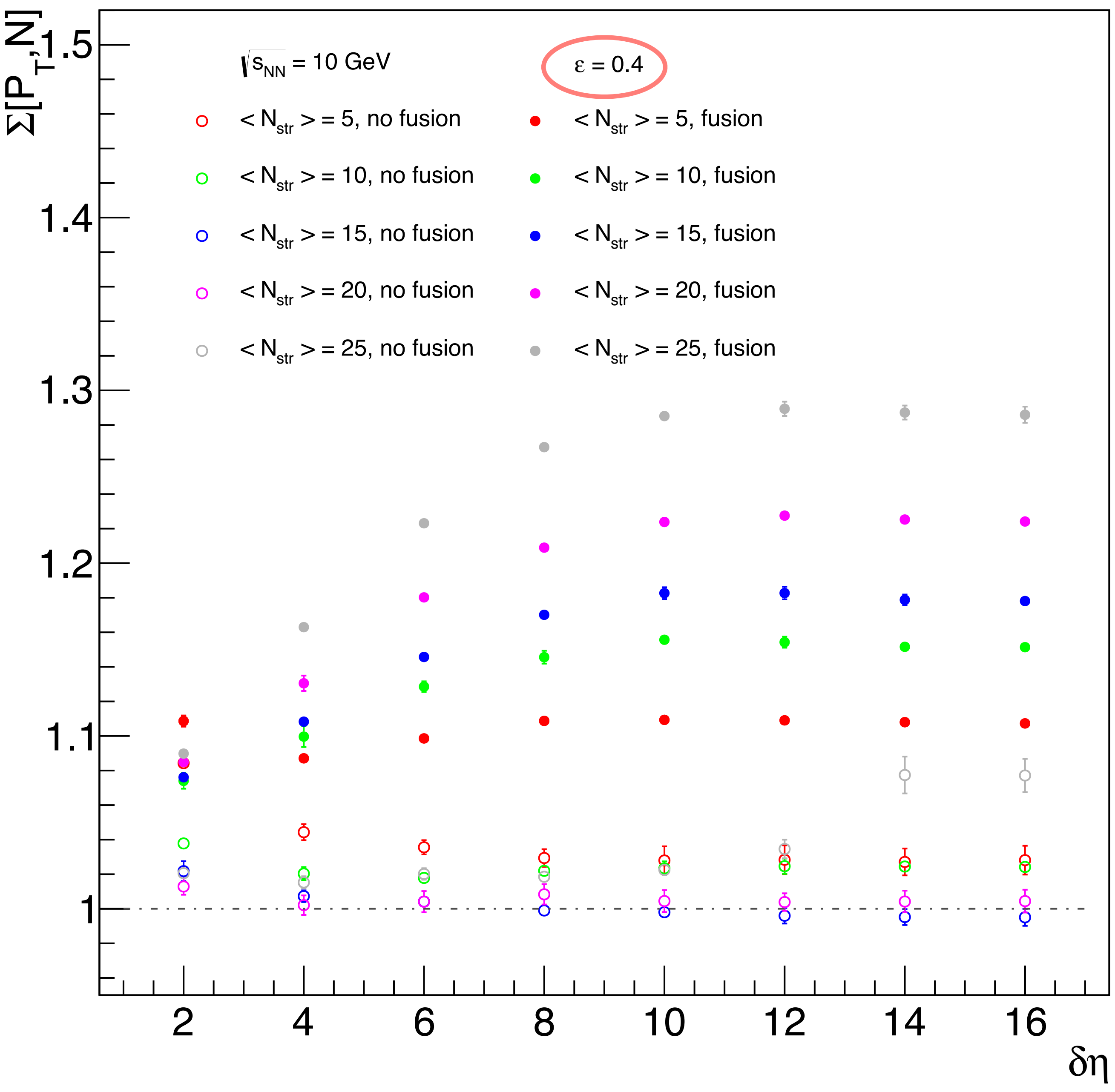


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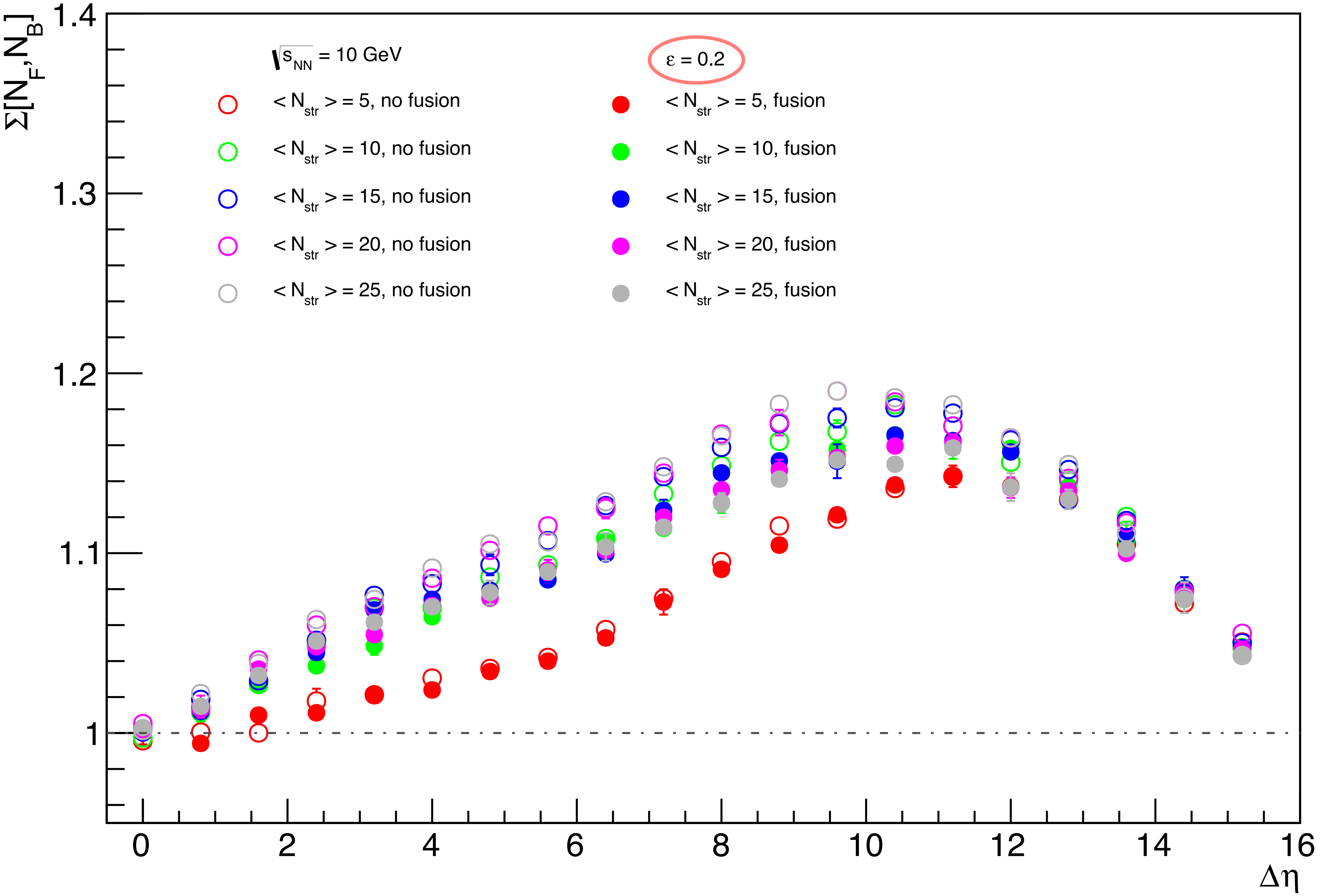


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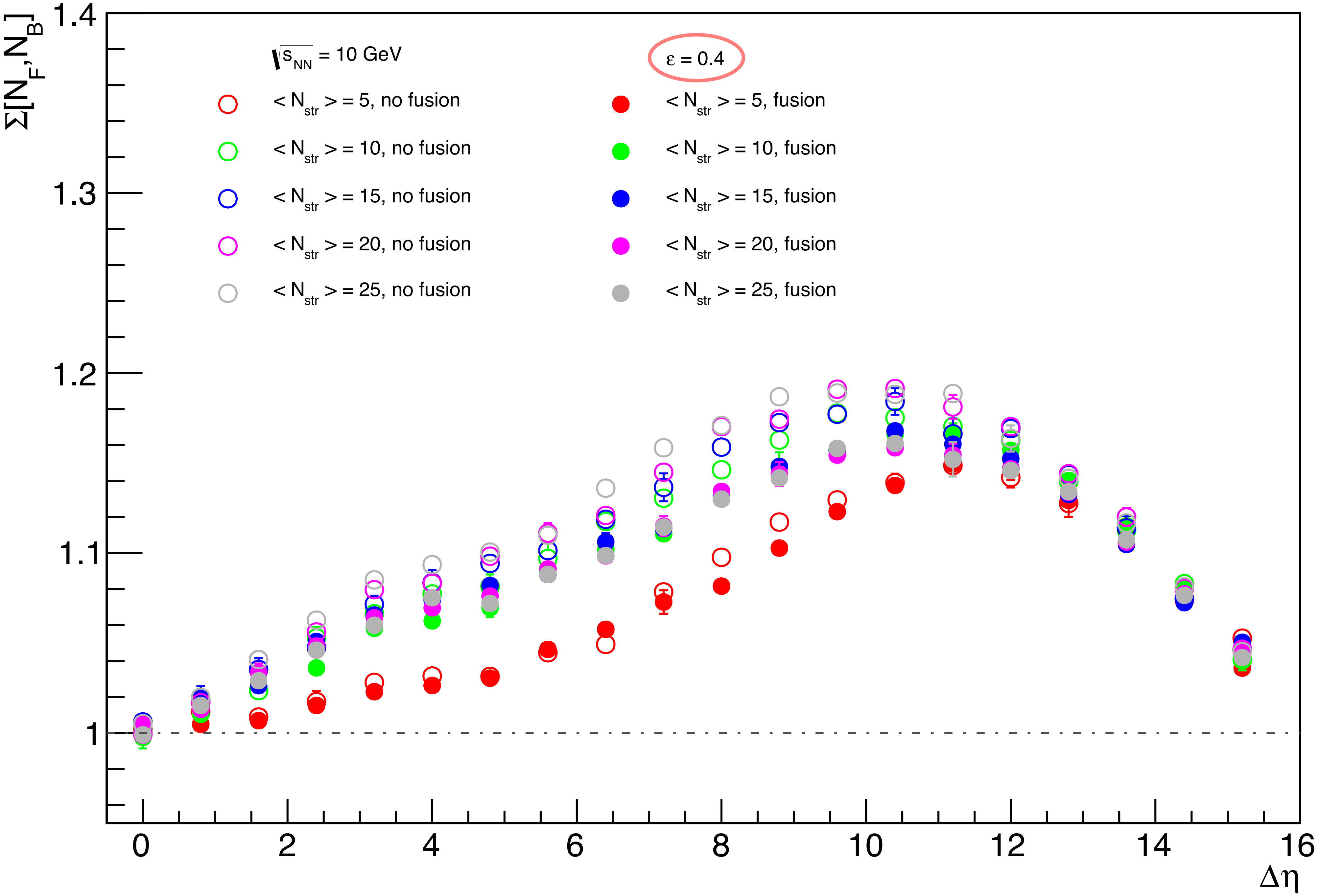


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