



Extracting the speed of sound of QCD from transverse momentum fluctuations

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5th International Workshop on
Emergent QCD Collectivity Across Scales: From Small System Collisions to Jets
June 29, 2026
Rice Global Paris Center

Outline

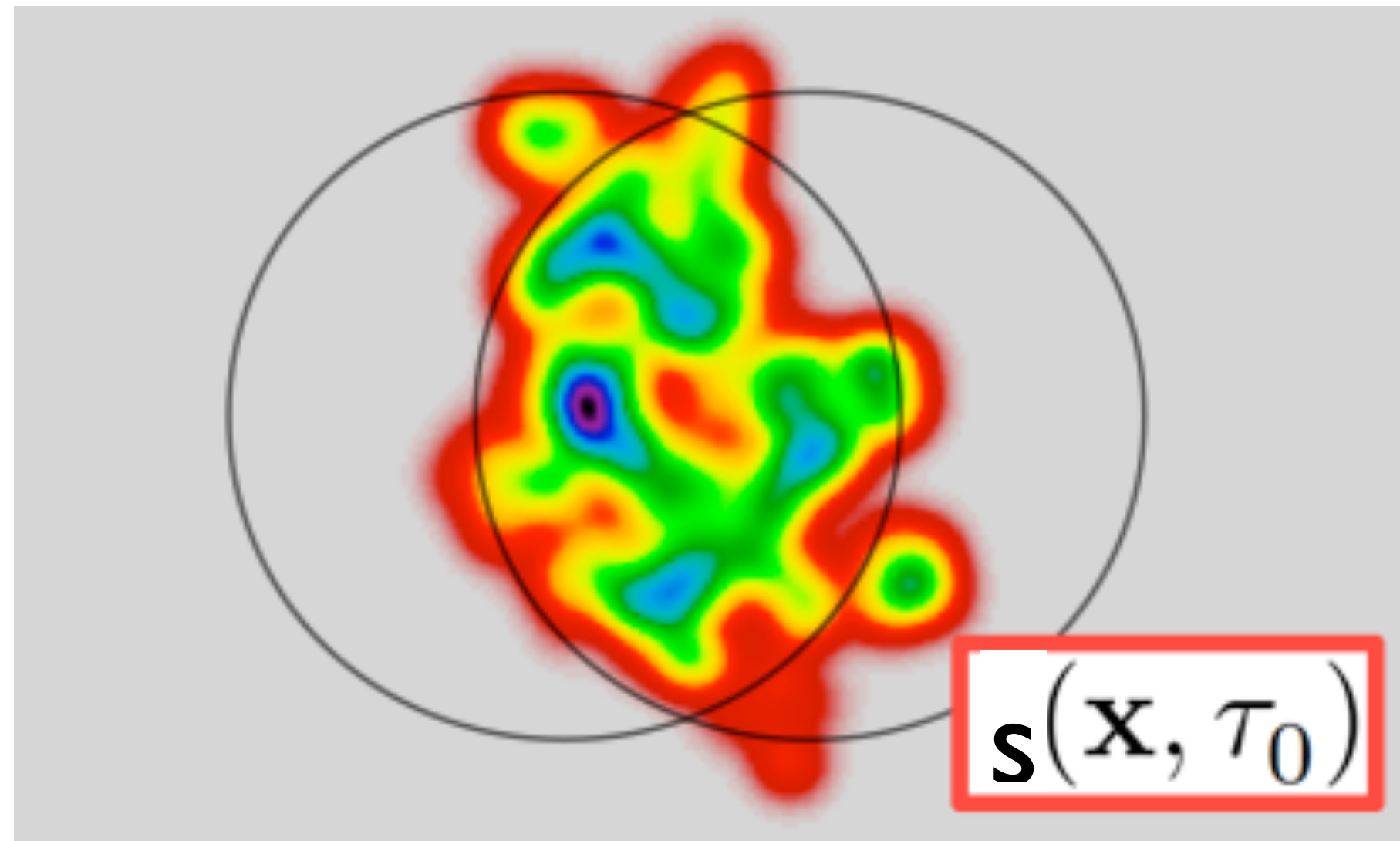
1. Collective flow: relating **final-state** observables to initial state
 2. **Initial-state** fluctuations: quantum and classical
 3. Centrality fluctuations, ultracentral collisions
 4. Transverse momentum fluctuations in ultracentral collisions
 5. Determination of the speed of sound of QCD using ATLAS data
- Alqahtani Parida JYO 2603.09647*
6. Perspectives: What else we could learn: Zero-point fluctuations in the nucleus, and the ultracentral flow puzzle.

I. Flow

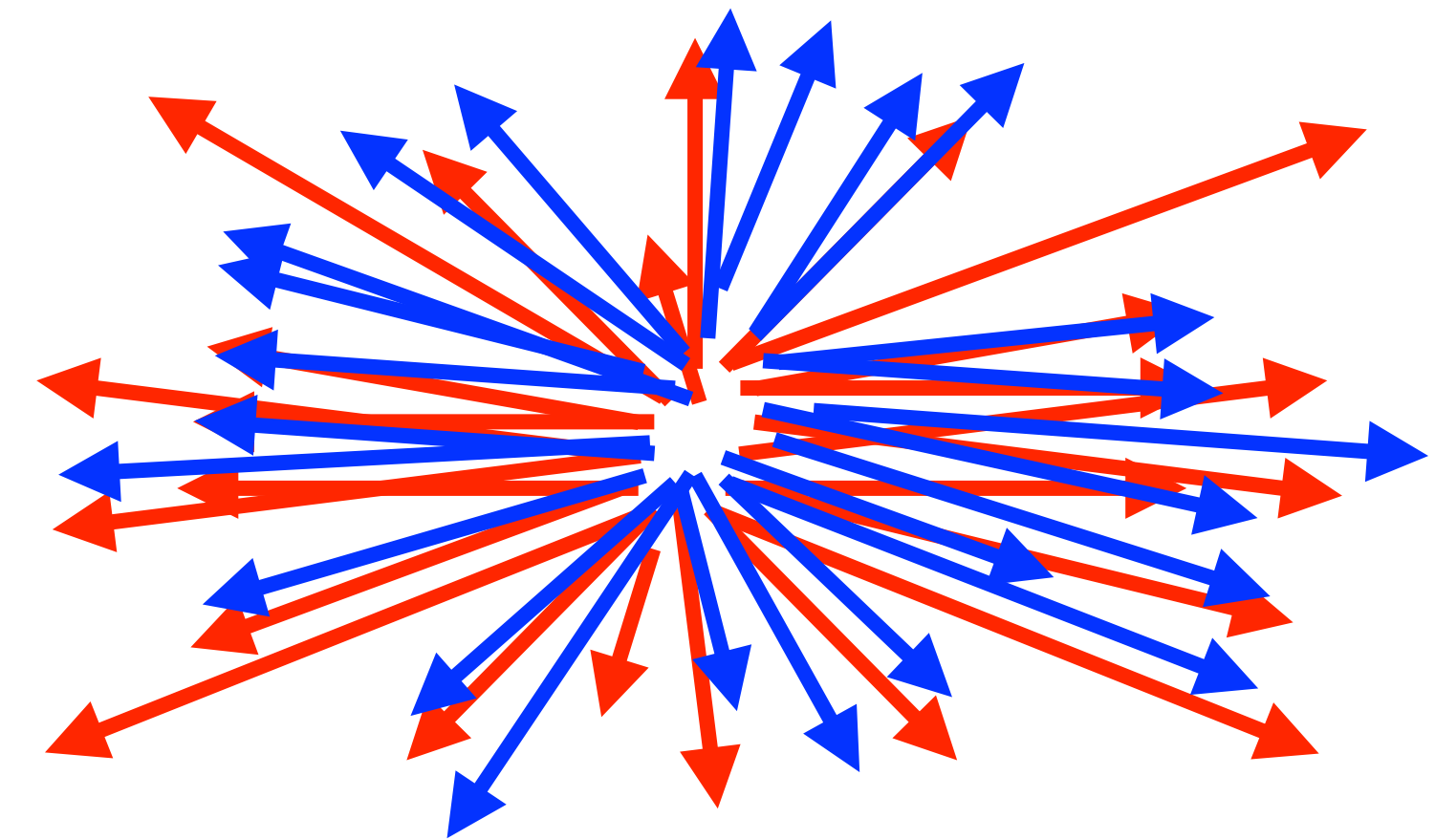
- ~99% of particle production in **Pb+Pb collisions at the LHC** is accurately understood as resulting from the formation of a **fluid** at a short time ($t \sim 1 \text{ fm}/c \ll R_{Pb}$) after the collision, which freely expands into the vacuum until it transforms into hadrons at $T \approx 150 \text{ MeV}$.
- **Hydrodynamic equations** are **deterministic**. Outgoing particle distributions are solely determined by the **initial entropy (or energy) density profile**.
- Hydro equations are usually solved numerically. Here, I use instead **simple response relations** between **global observables** and **initial density**.

I. Hydrodynamic response

Initial state



Final state



(Note: in hydro, final state = also continuous)

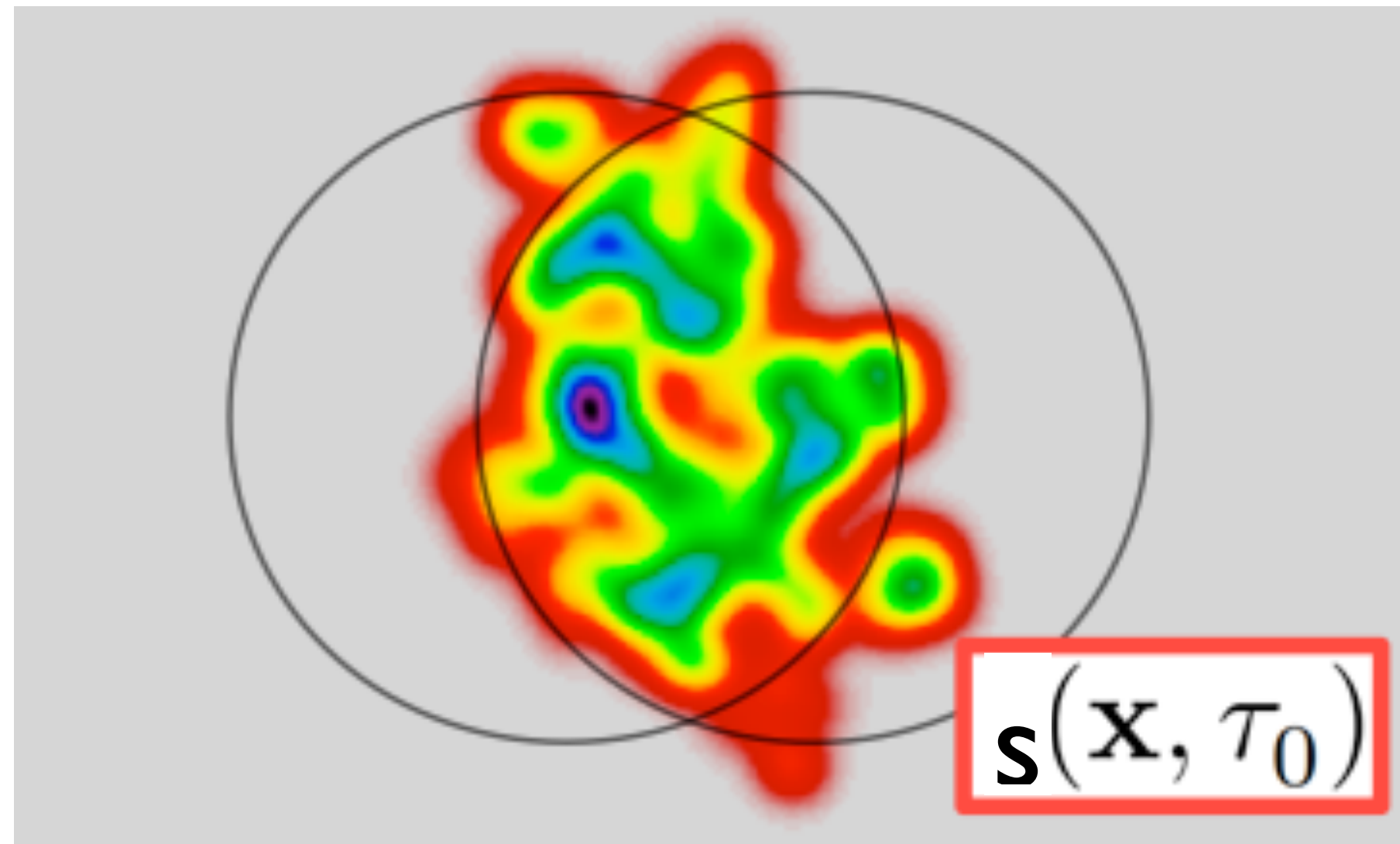
Entropy density profile (courtesy G. Giacalone)

- Total entropy S
- **Size**: mean square radius (or area) R^2

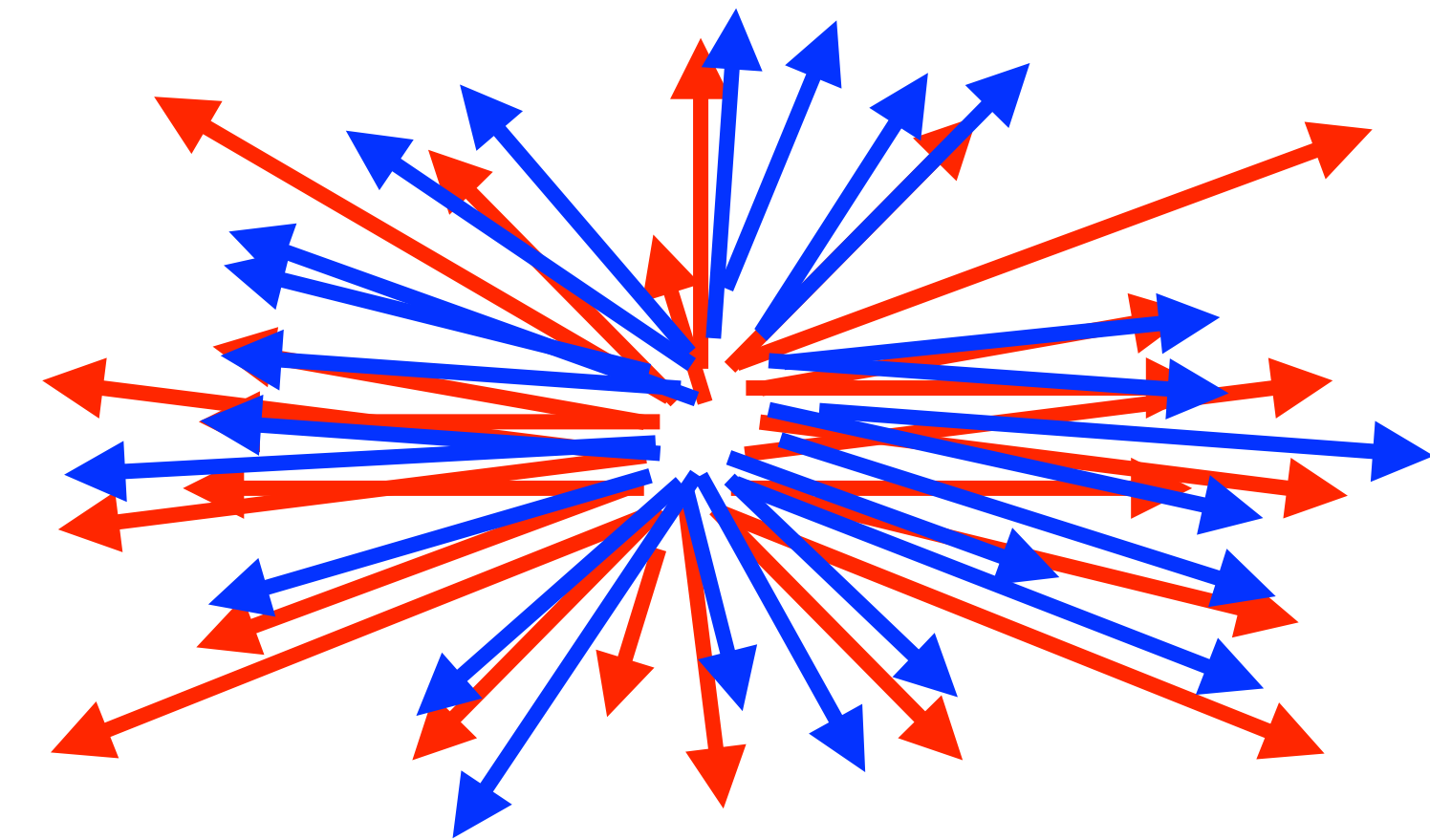
- Total multiplicity N_{ch}
- Momentum per particle $[p_T]$

I. Hydrodynamic response

Initial state



Final state



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Entropy density profile (courtesy G. Giacalone)

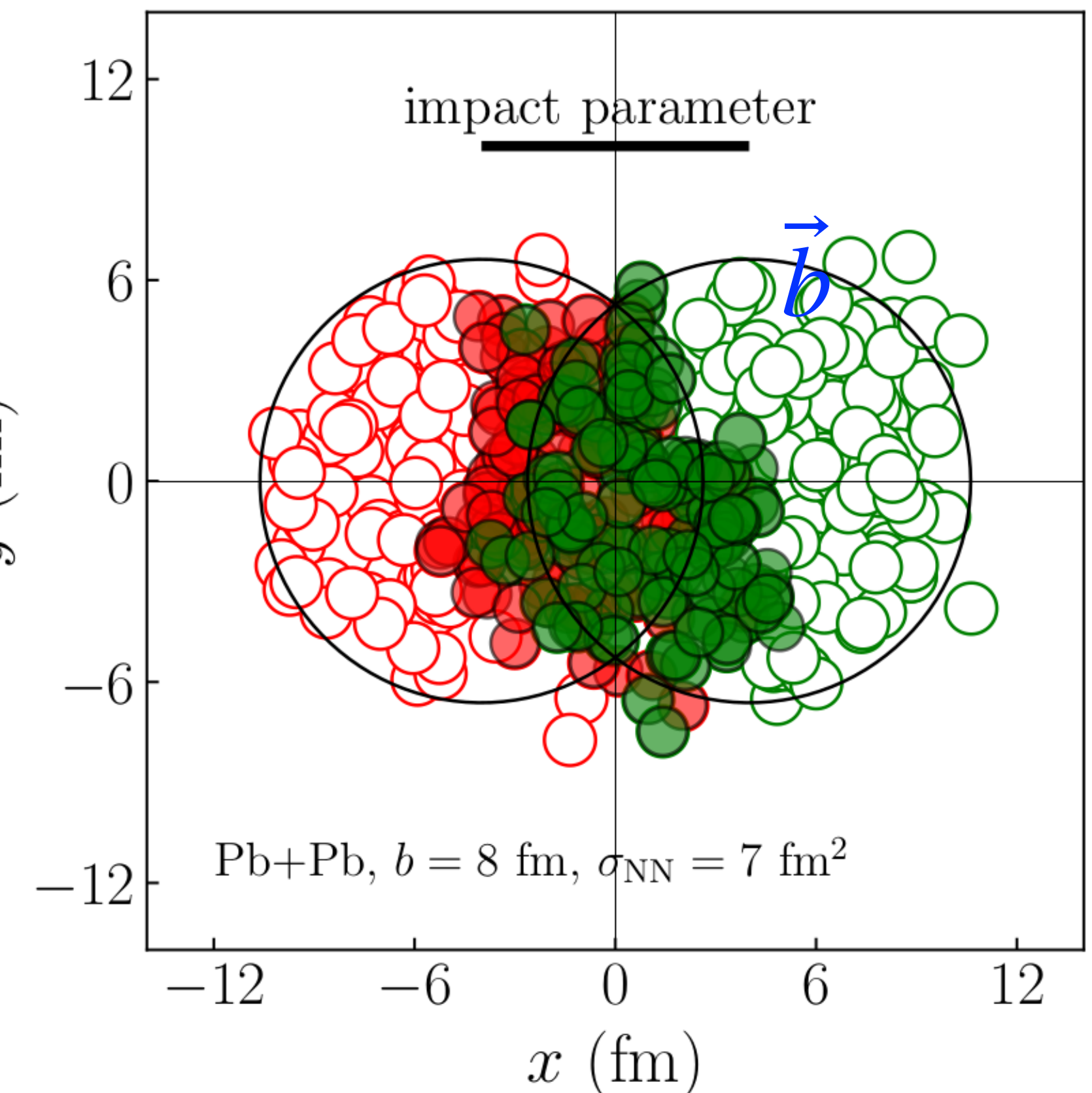
- $N_{ch} \approx 0.15 S$ Hanus Mazeliauskas Reygers 1908.02792
- $[p_T] \approx 3 T_{\text{eff}}$ (effective temperature) depends on entropy density $s_{\text{eff}} \propto S/R^3$
Gardim Giacalone Luzum JY0 1908.09728
Broniowski Chojnacki Obara 0907.3216

2. Event-by-event fluctuations

All collisions are different! Global observables fluctuate event by event

- **Classical fluctuations** : The impact parameter vector \vec{b} of a Pb+Pb collision varies event to event. Quantum uncertainty on \vec{b} is negligible at the LHC.
- **Quantum fluctuations** : Different collisions with the same \vec{b} differ only by quantum fluctuations, which are mostly from the **positions of nucleons within nuclei** at the time of impact.

Giacalone 2101.00168



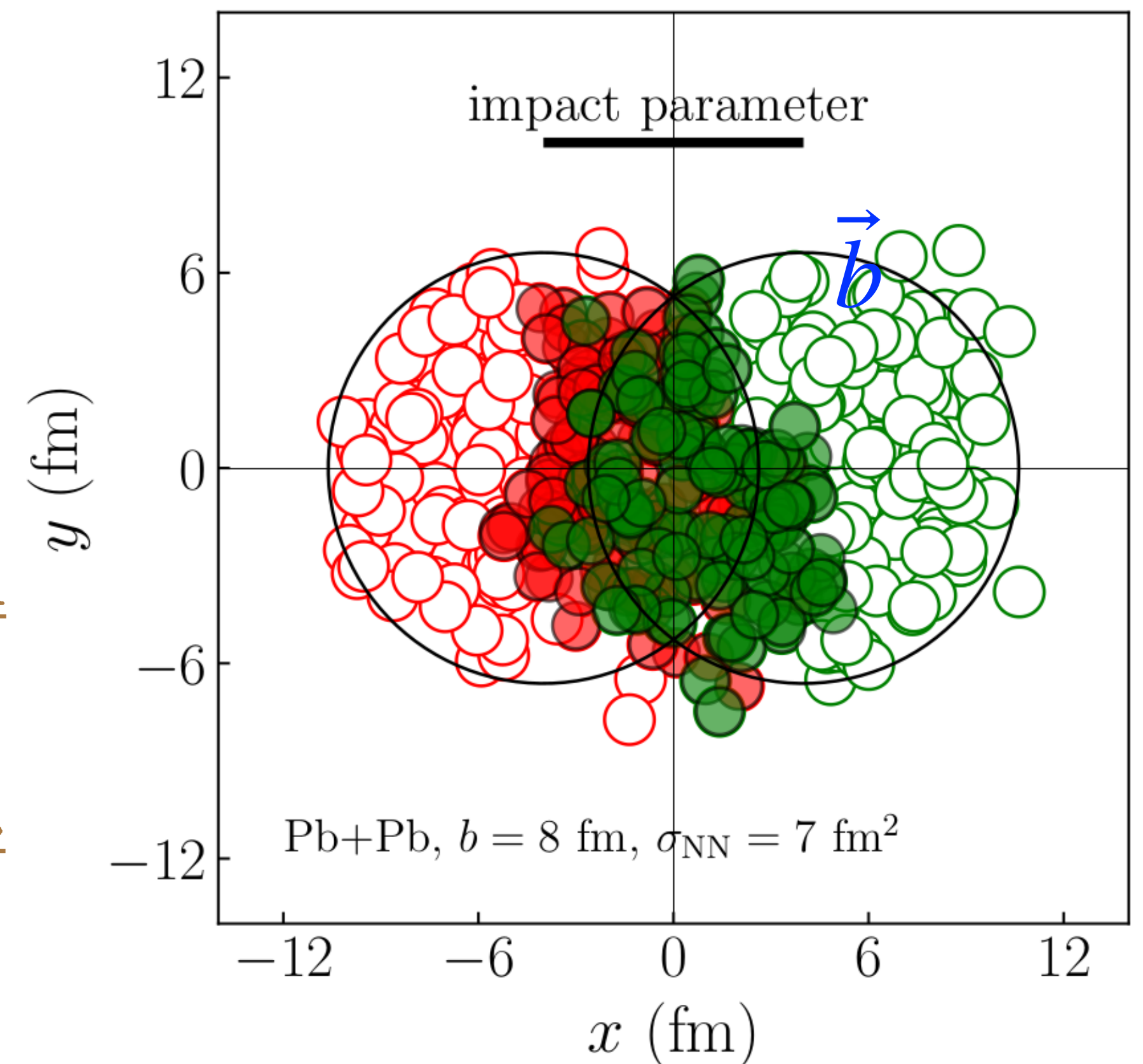
Samanta Bhatta Jia Luzum JY0 2303.15323

2. Quantum fluctuations are simple

In the initial state, one sees a large number of independent nucleons with random positions. The central limit theorem applies to fluctuations of global quantities, which are small and nearly Gaussian at fixed \vec{b} :

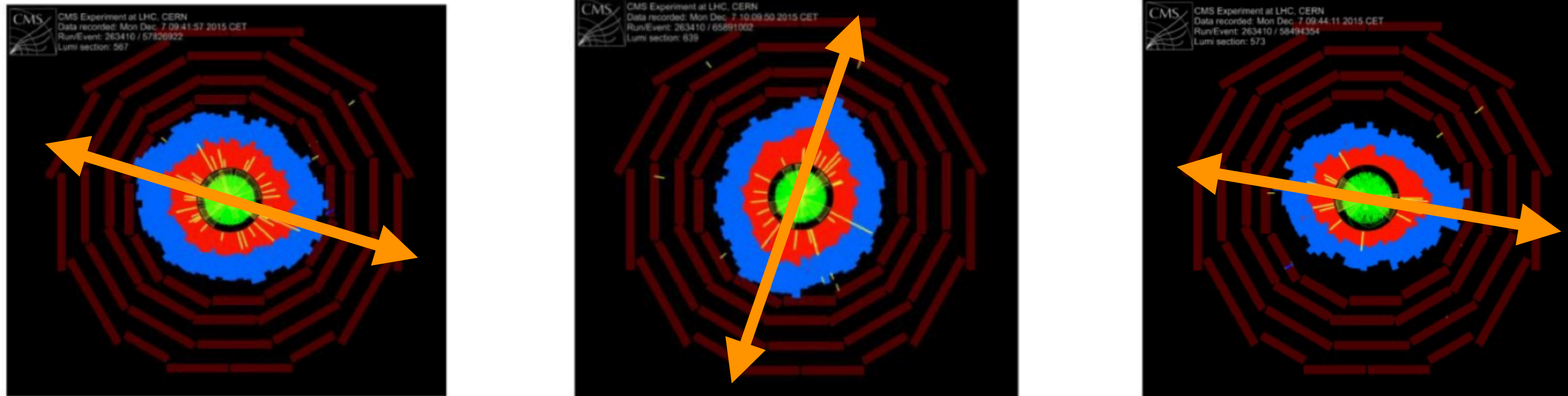
- S and N_{ch} fluctuations ($\sim 3\%$ at $b=0$)
Das Giacalone Monard JY0 1708.00081
- R^2 ($\sim 3\%$) and $[p_T]$ ($\sim 1\%$) fluctuations
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Giacalone 2101.00168



2. Classical (\vec{b}) fluctuations

- **Direction of \vec{b}** : Most important initial-state fluctuation!!
Seen *by eye* on event displays, via elliptic flow



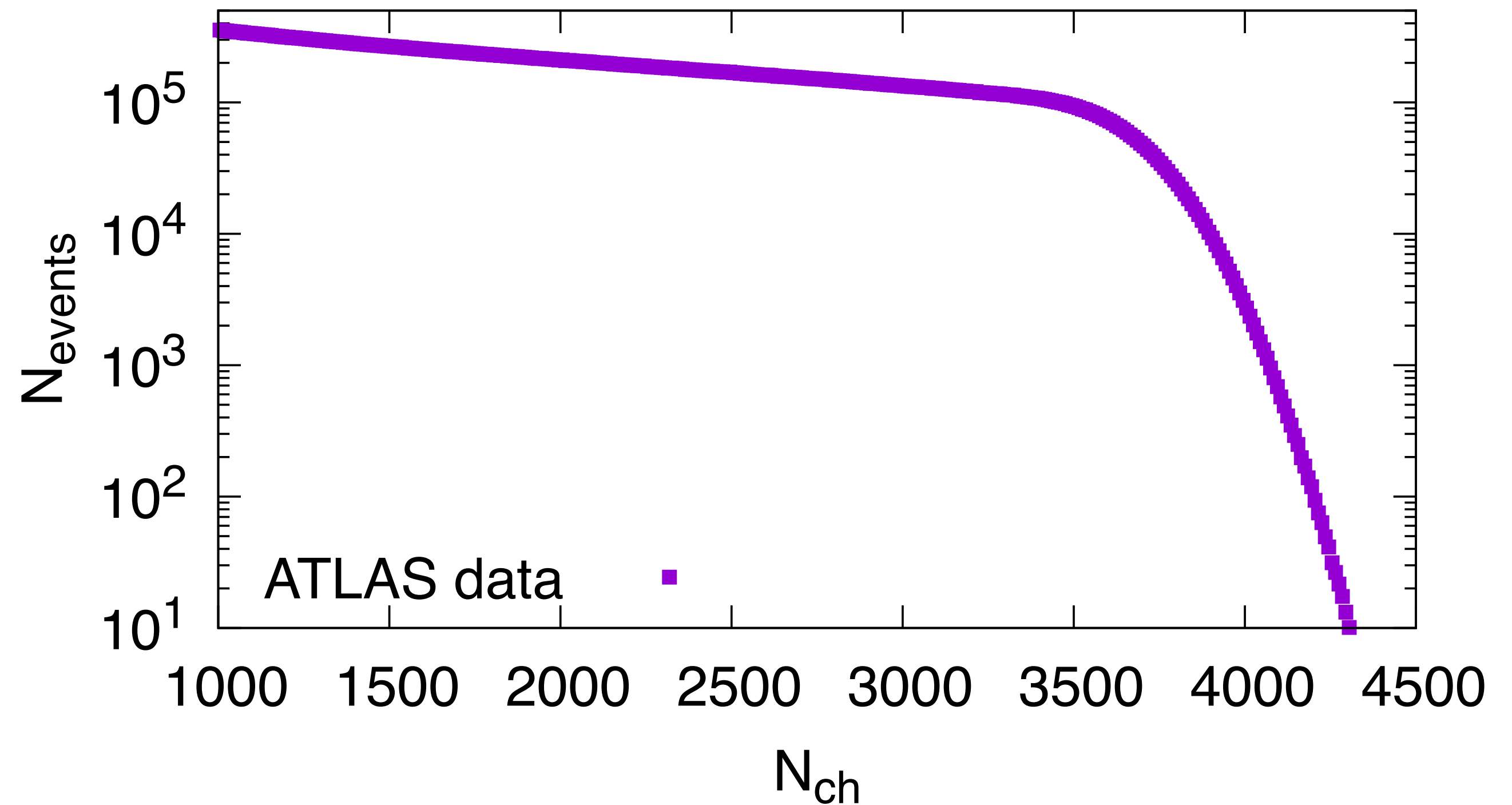
3 Pb+Pb collisions seen by CMS (Georgios Konstantinos Krintiras, Moriond 2021)

- **Magnitude**: Within a class of events (e.g., same multiplicity N_{ch}), b varies. The **size** and **shape**, which are essential for flow, strongly depend on b .
Fluctuations of b are not yet accurately modeled in state-of-the-art global theory-to-data comparisons (Jetscape, Trajectum, Duke).

3. Bayesian reconstruction of b fluctuations

Events are sorted into "centrality" classes according to a specific observable (e.g., N_{ch}).

Even in a very narrow N_{ch} interval, the true centrality $c \equiv \pi b^2 / \sigma_{PbPb}$ fluctuates. The probability distribution $p(c | N_{ch})$ can be precisely reconstructed, using just data, no underlying theory (Glauber, etc.)

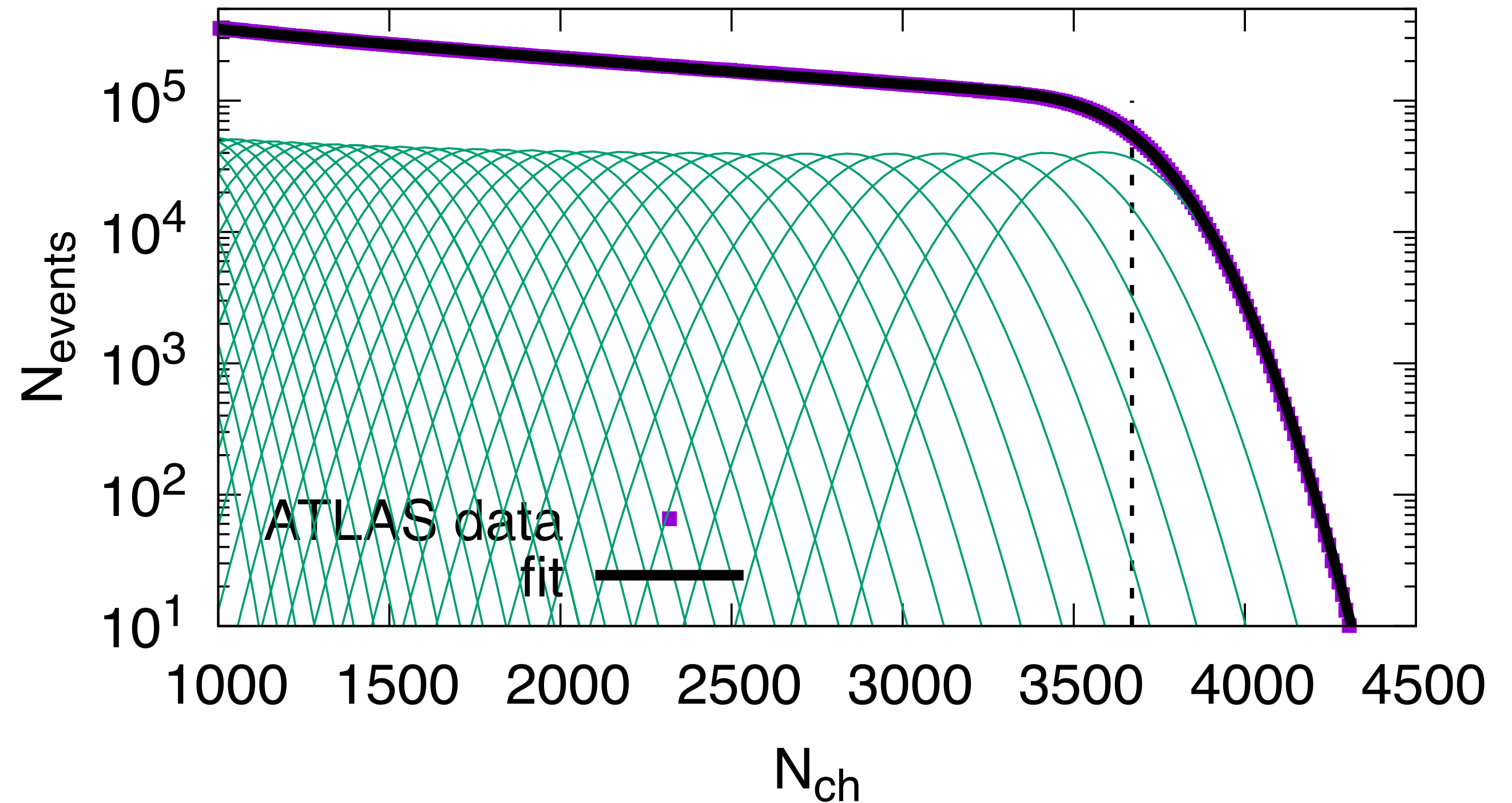


3. Bayesian reconstruction of b fluctuations

- Quantum fluctuations of N_{ch} at fixed b (=fixed c) are Gaussian.
- Fit histogram as a sum of Gaussians and reconstruct $P(N_{ch} | c)$
- Bayes' theorem then gives

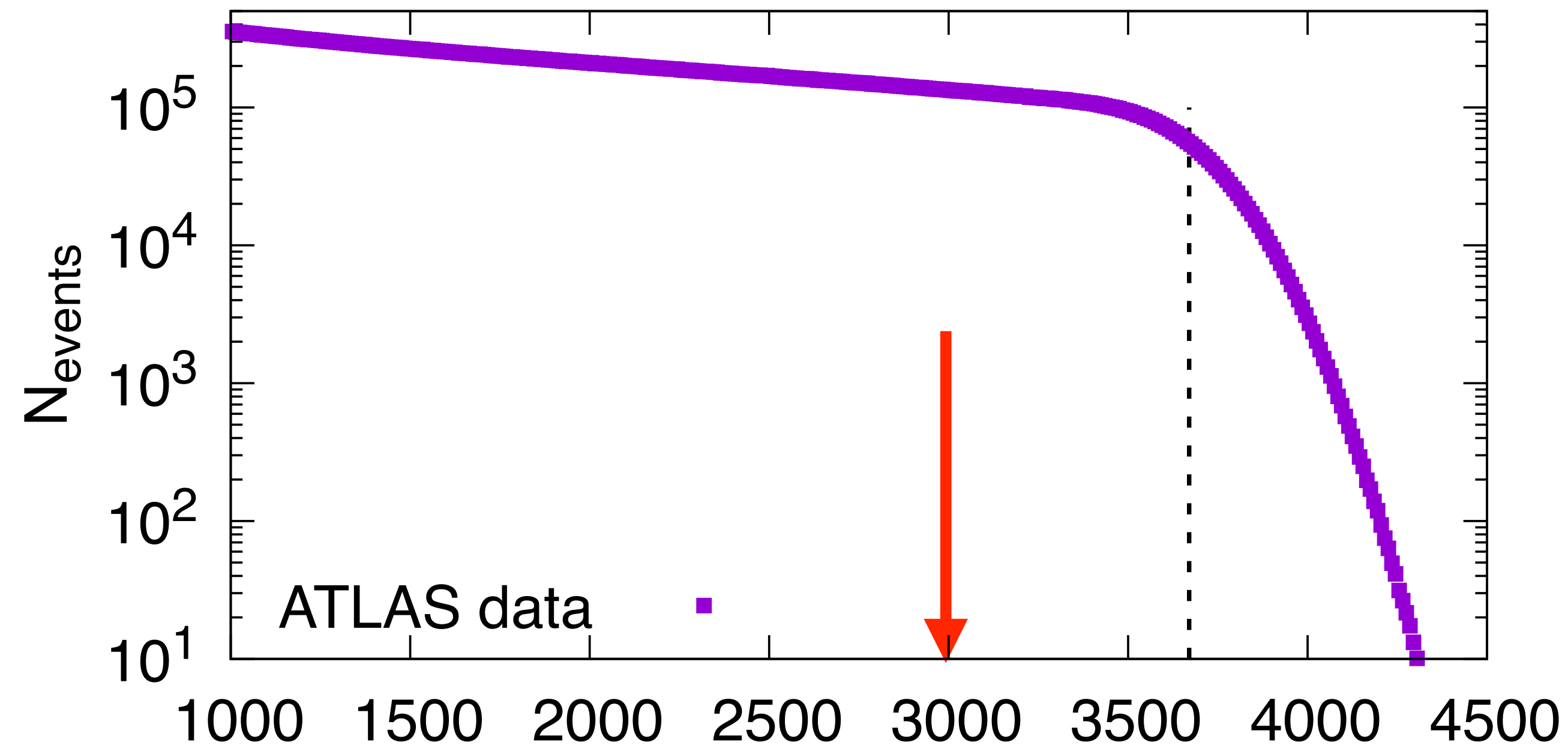
$$P(c | N_{ch}) = \frac{P(N_{ch} | c)P(c)}{P(N_{ch})} = \frac{P(N_{ch} | c)}{P(N_{ch})}$$

Das Giacalone Monard JY0 1708.00081

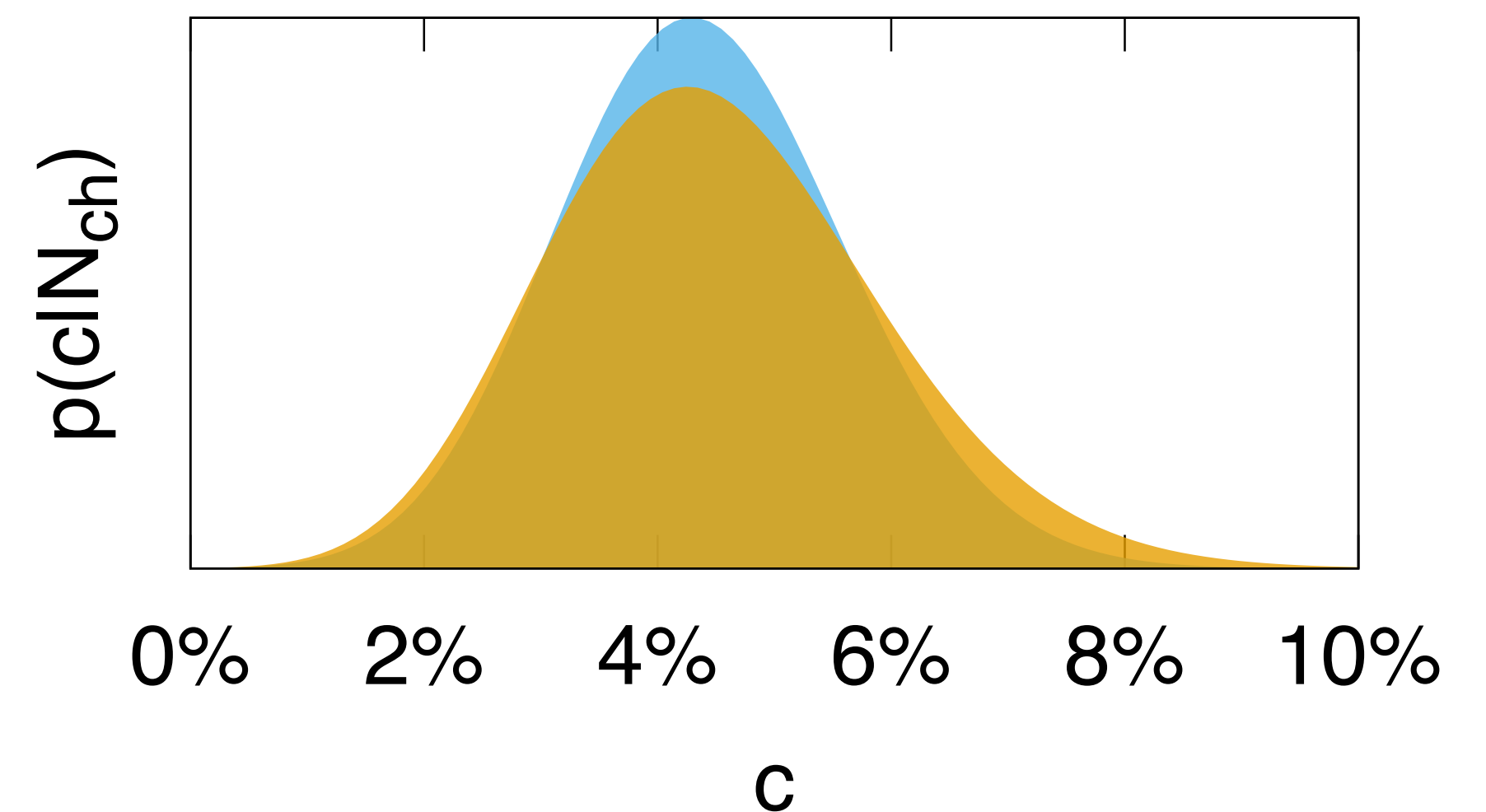


It is crucial to use the distribution of N_{ch} (of the centrality classifier) for calibrating theory to data comparisons: not done yet.

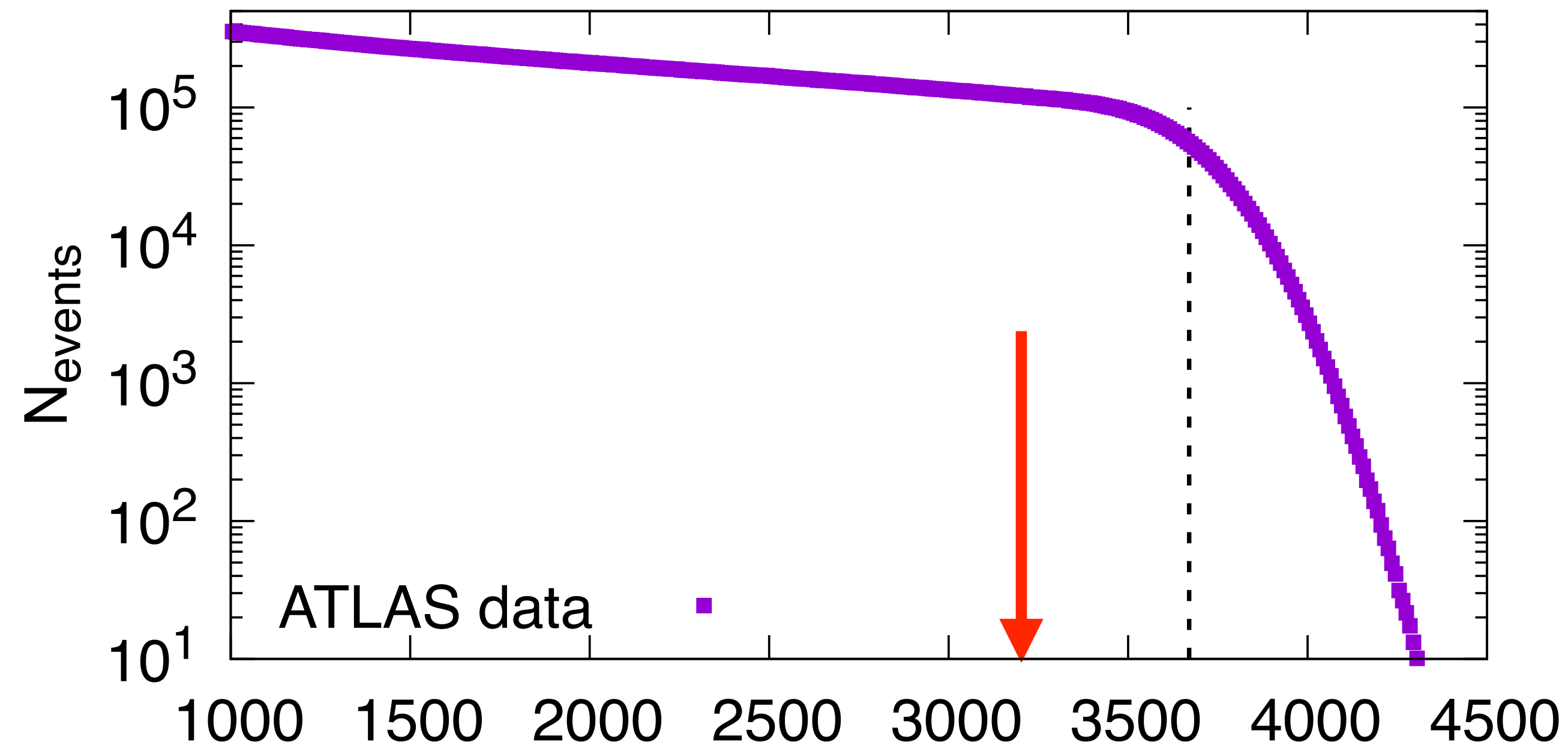
3. Bayesian reconstruction of b fluctuations



Distribution of centrality at fixed N_{ch}
= Gaussian of width $\approx 1.2\%$
Colors = *reconstruction* *uncertainty*

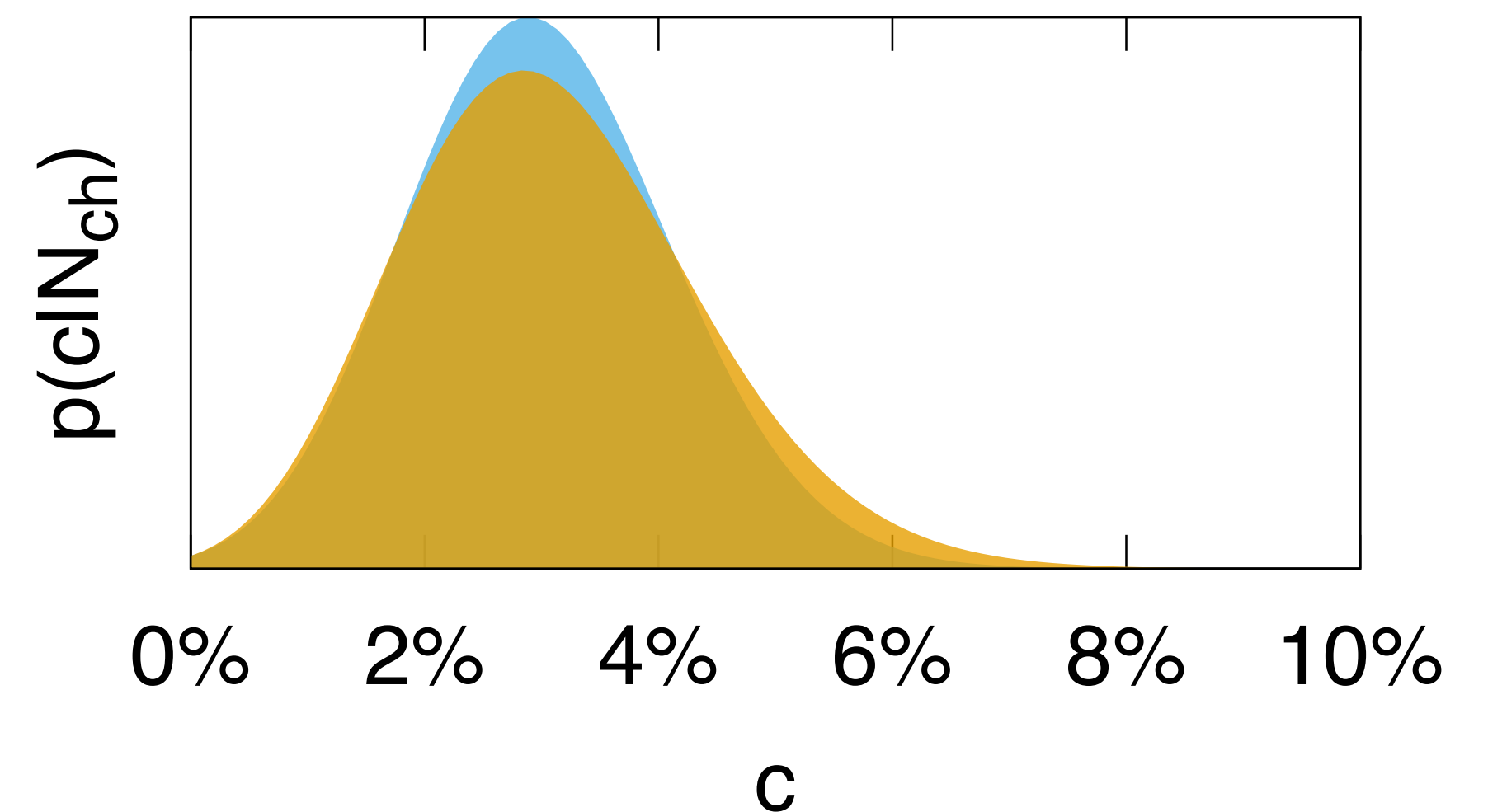


3. Bayesian reconstruction of b fluctuations

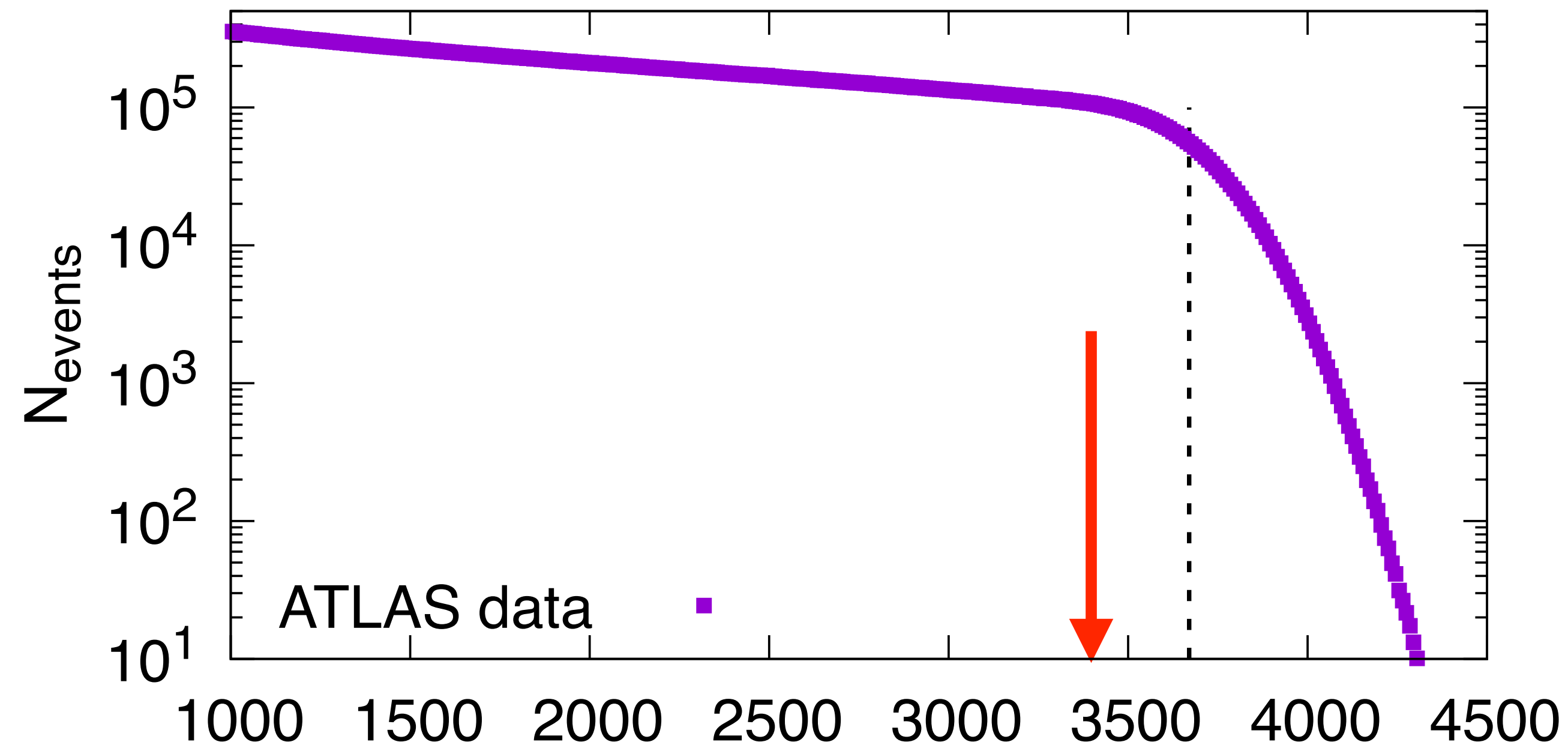


As N_{ch} increases, the distribution of centrality gets shifted towards smaller values.

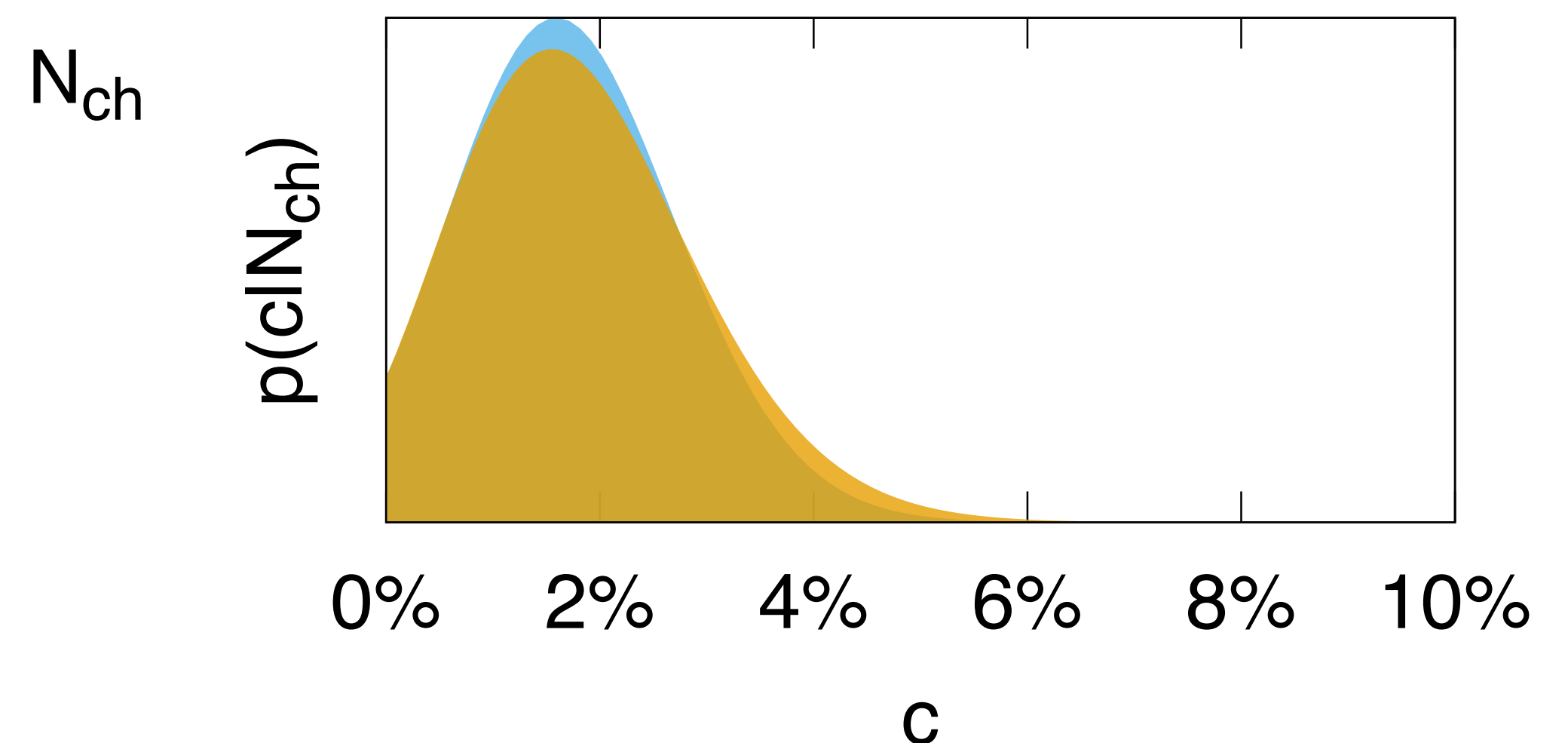
N_{ch}



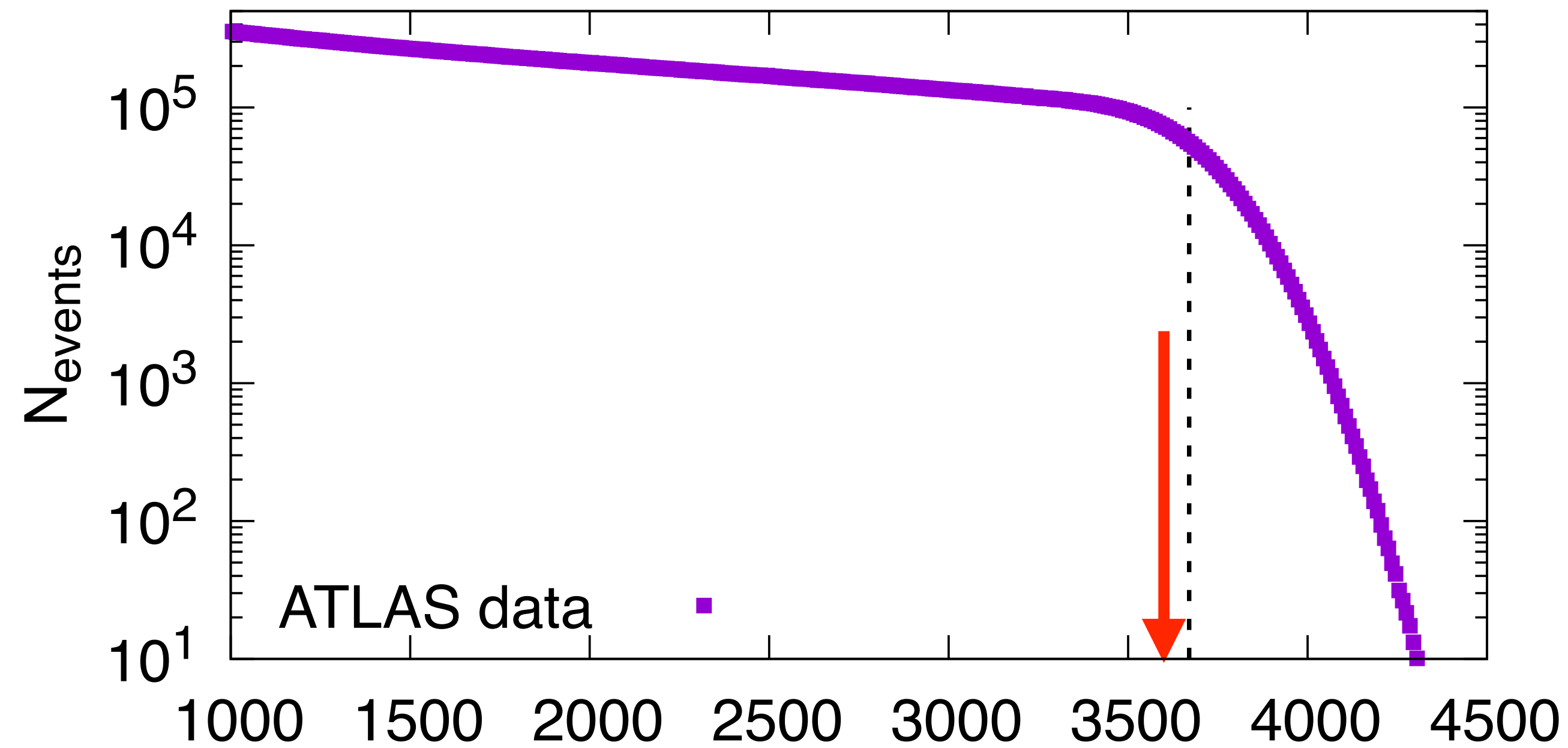
3. Bayesian reconstruction of b fluctuations



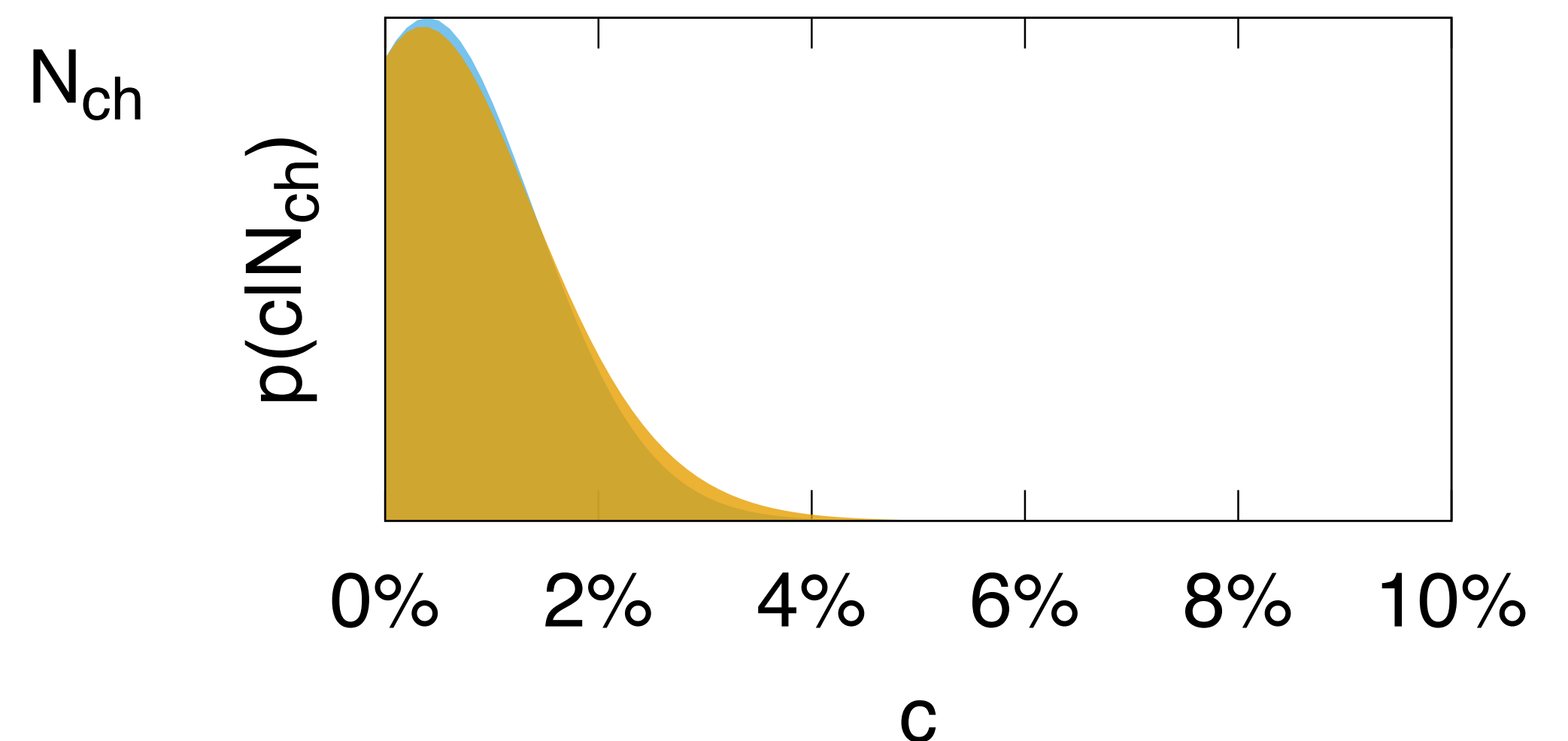
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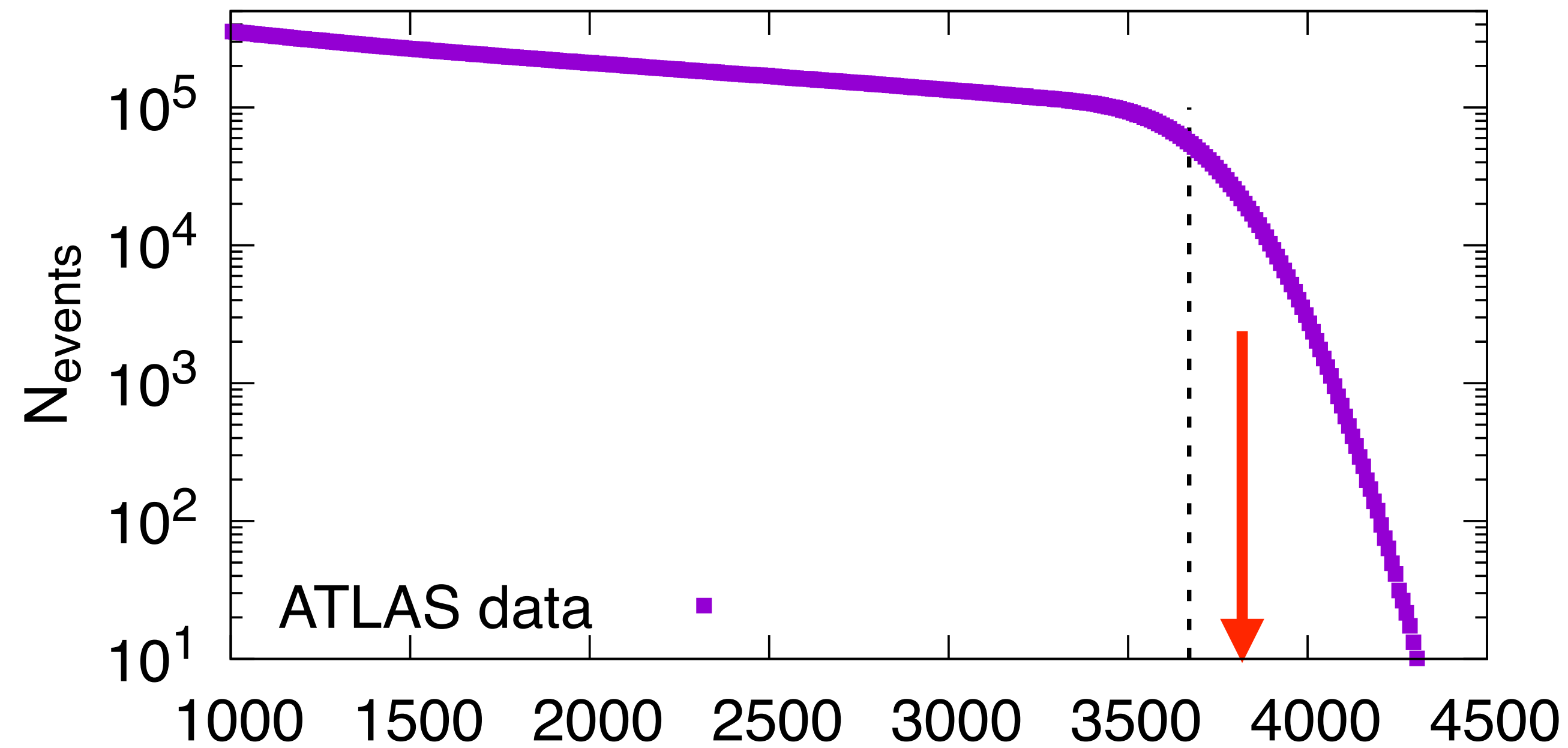
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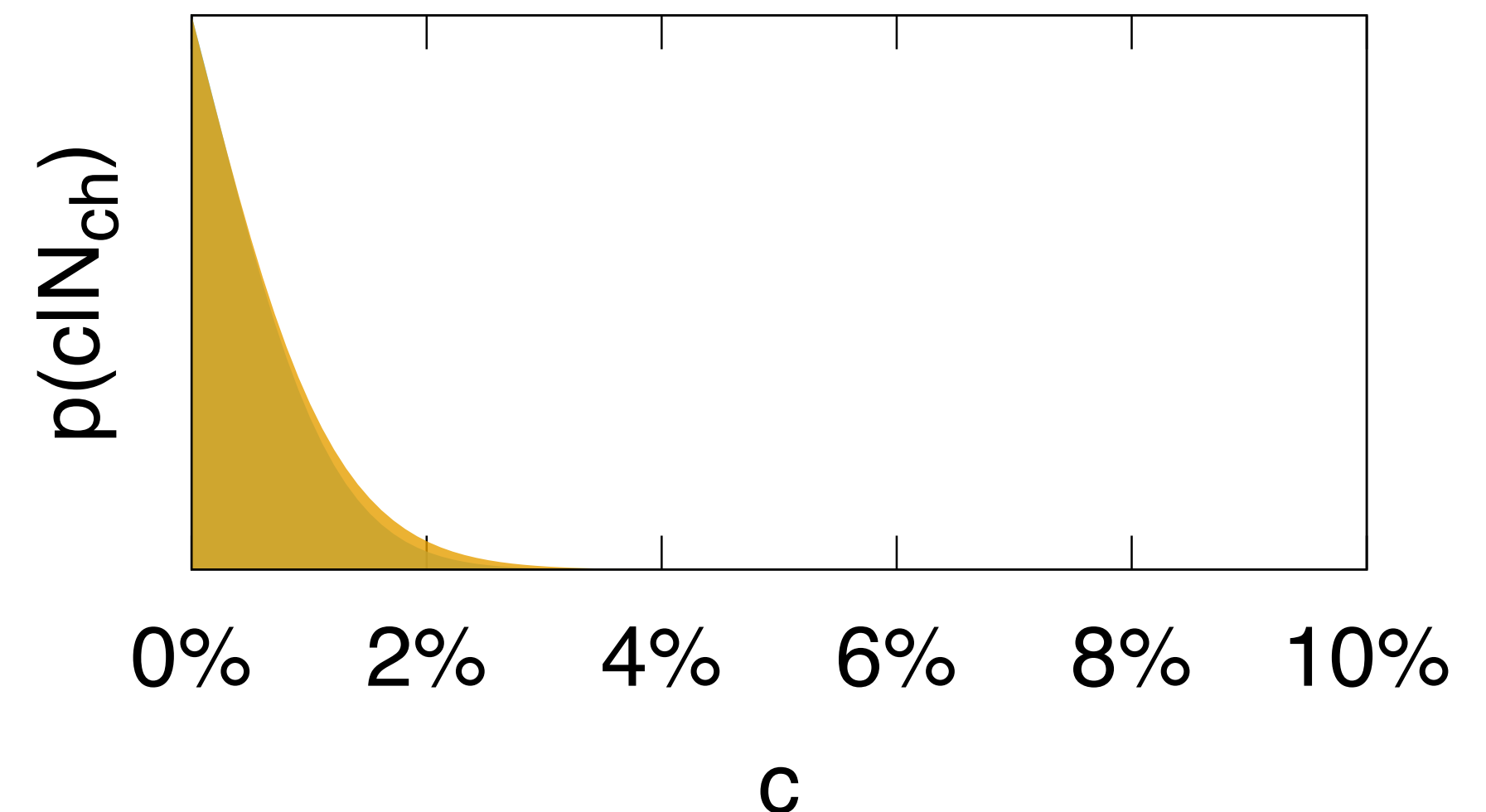
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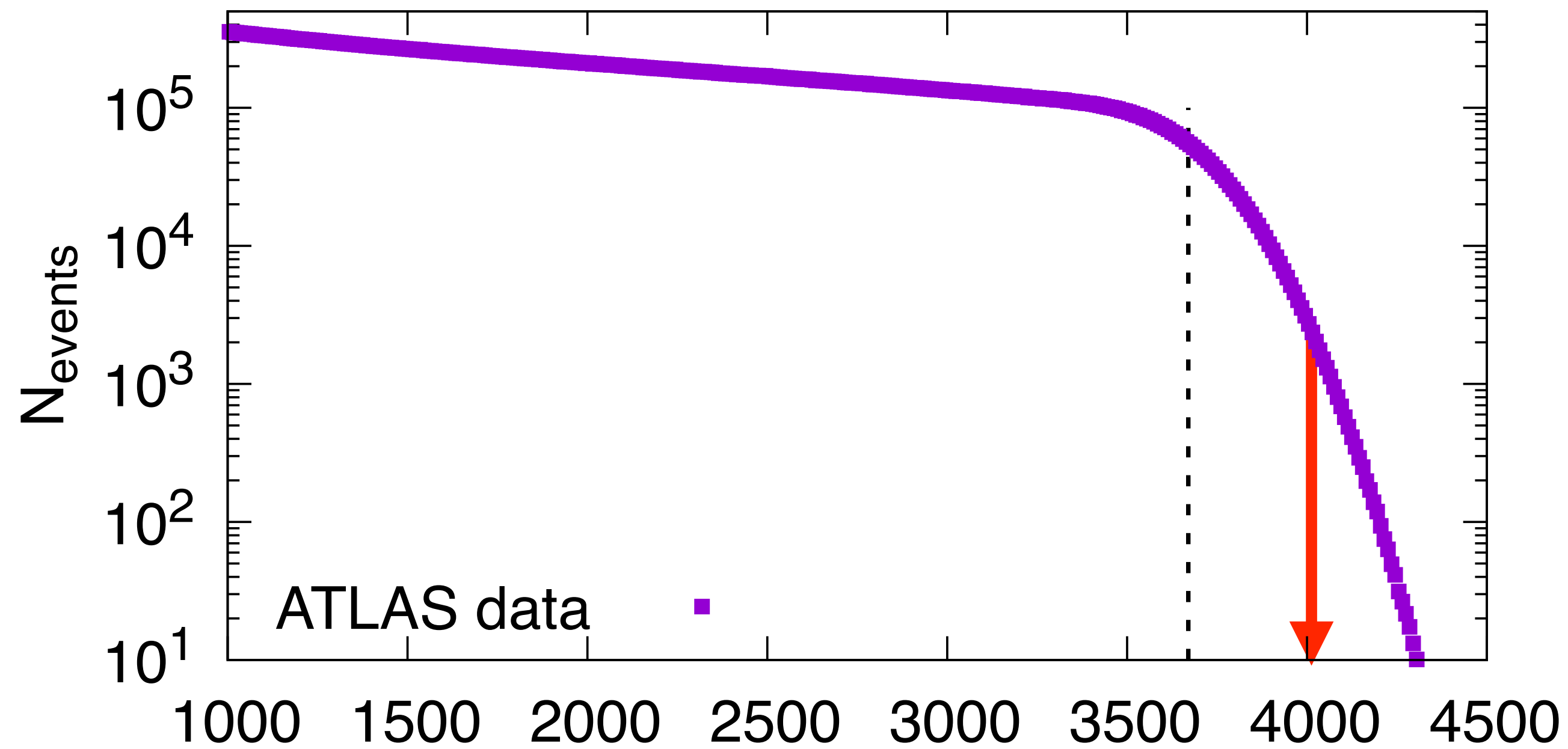
3. Bayesian reconstruction of b fluctuations



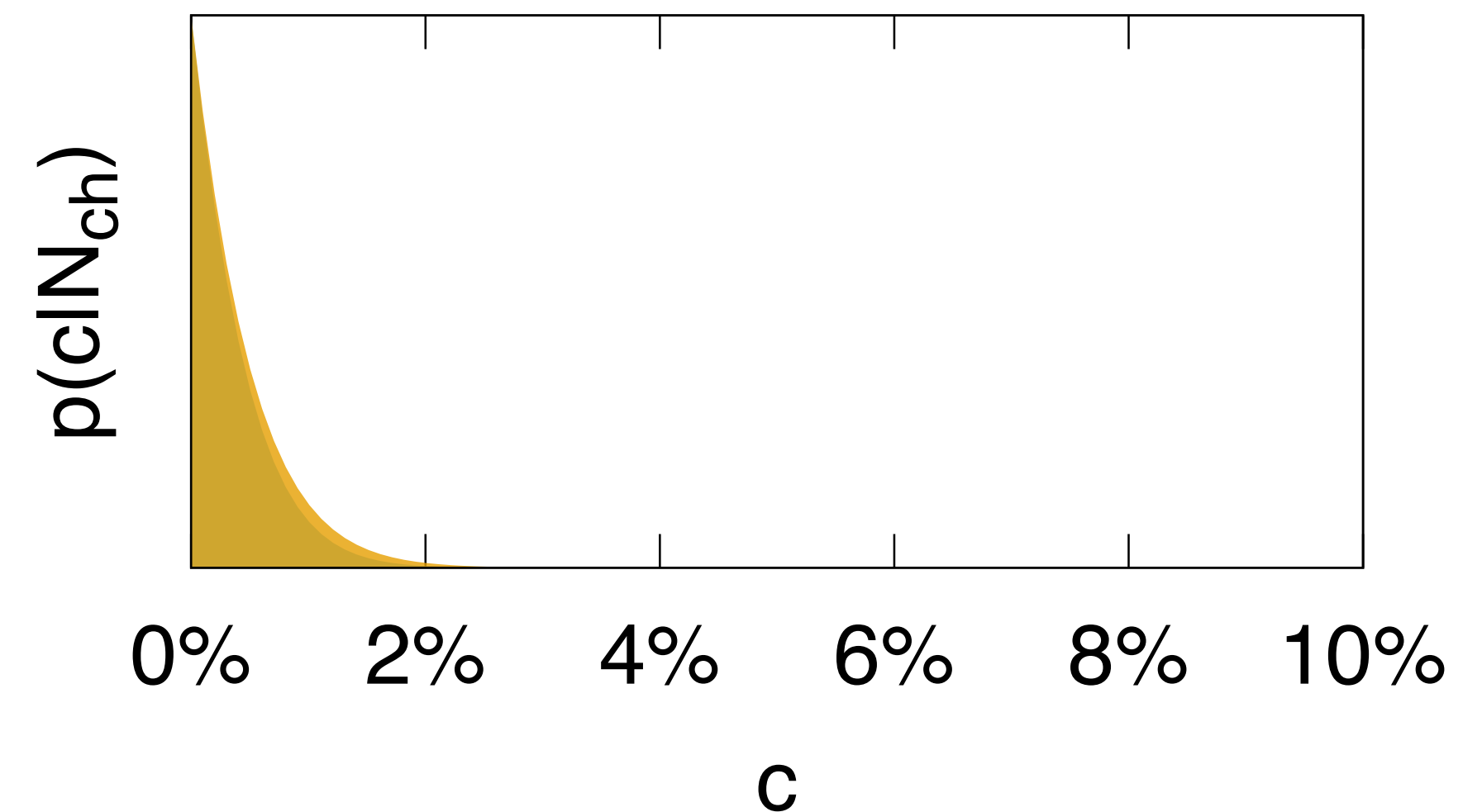
Above the knee (\equiv mean N_{ch} at $b = 0$), centrality fluctuations gradually disappear: **ultracentral** collisions!



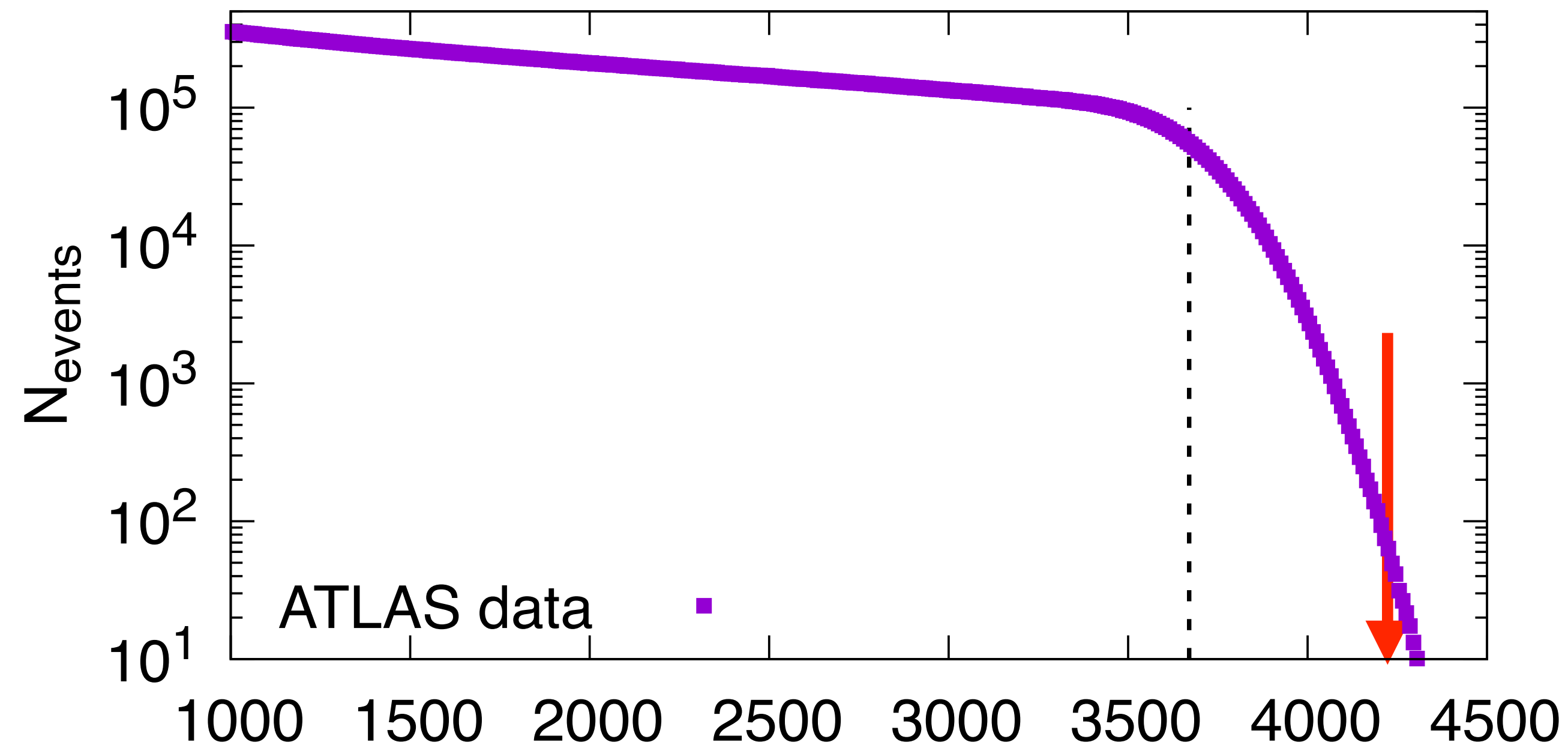
3. Bayesian reconstruction of b fluctuations



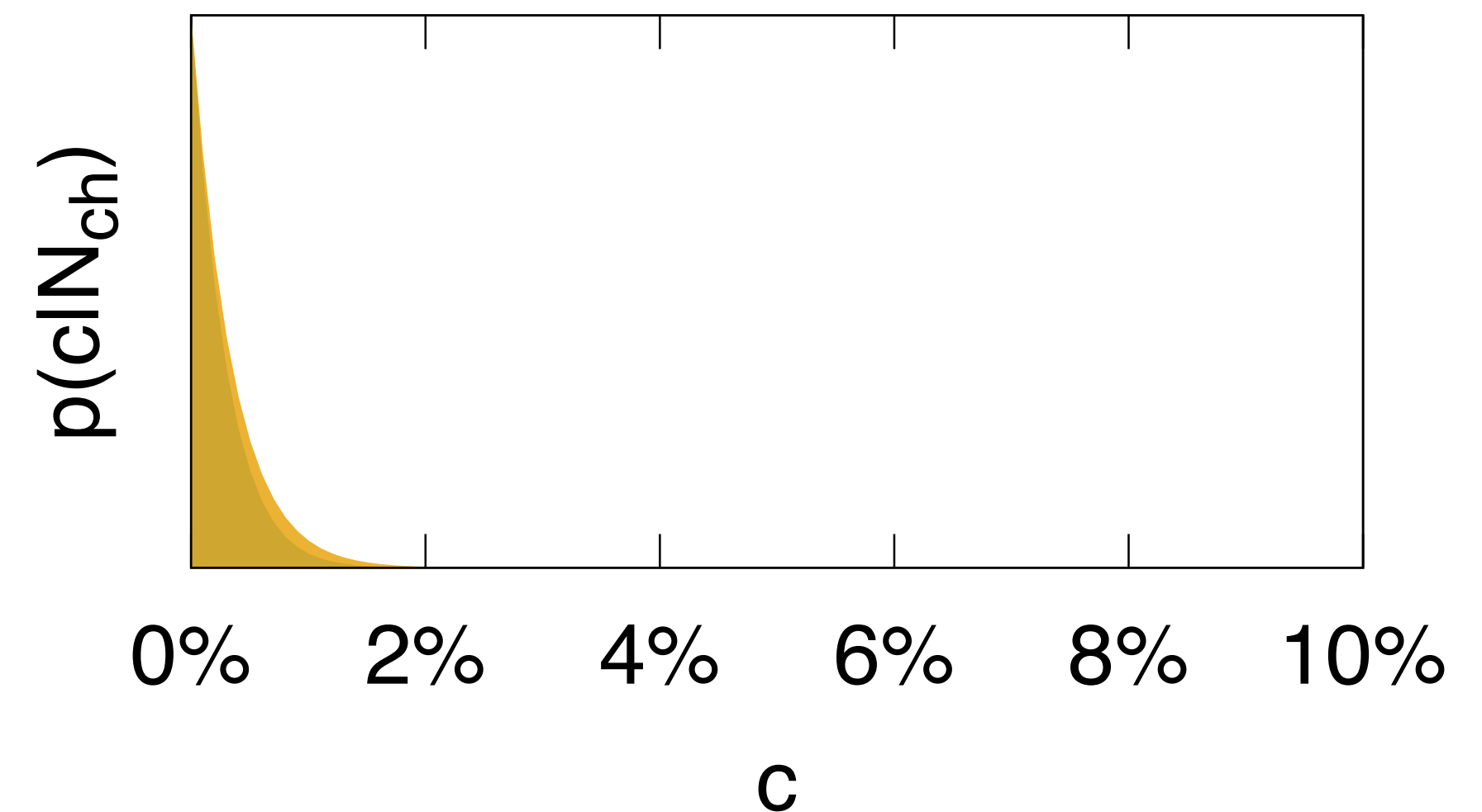
Above the knee (\equiv mean N_{ch} at $b = 0$), centrality fluctuations gradually disappear: **ultracentral** collisions!



3. Bayesian reconstruction of b fluctuations



Above the knee (\equiv mean N_{ch} at $b = 0$), centrality fluctuations gradually disappear: **ultracentral** collisions!



4. Increase of the mean of $[p_T]$ in ultracentral coll.

- $[p_T] \approx 3 T_{\text{eff}}$ depends on entropy density $s_{\text{eff}} \propto S/R^3 \propto N_{ch}/R^3$

- Increase of mean $[p_T]$:

$$\frac{\delta[p_T]}{[p_T]} = \frac{\delta T_{\text{eff}}}{T_{\text{eff}}} = c_s^2 \frac{\delta s_{\text{eff}}}{s_{\text{eff}}} \approx c_s^2 \frac{\delta N_{ch}}{N_{ch}}$$

- Speed of sound c_s from LHC data?

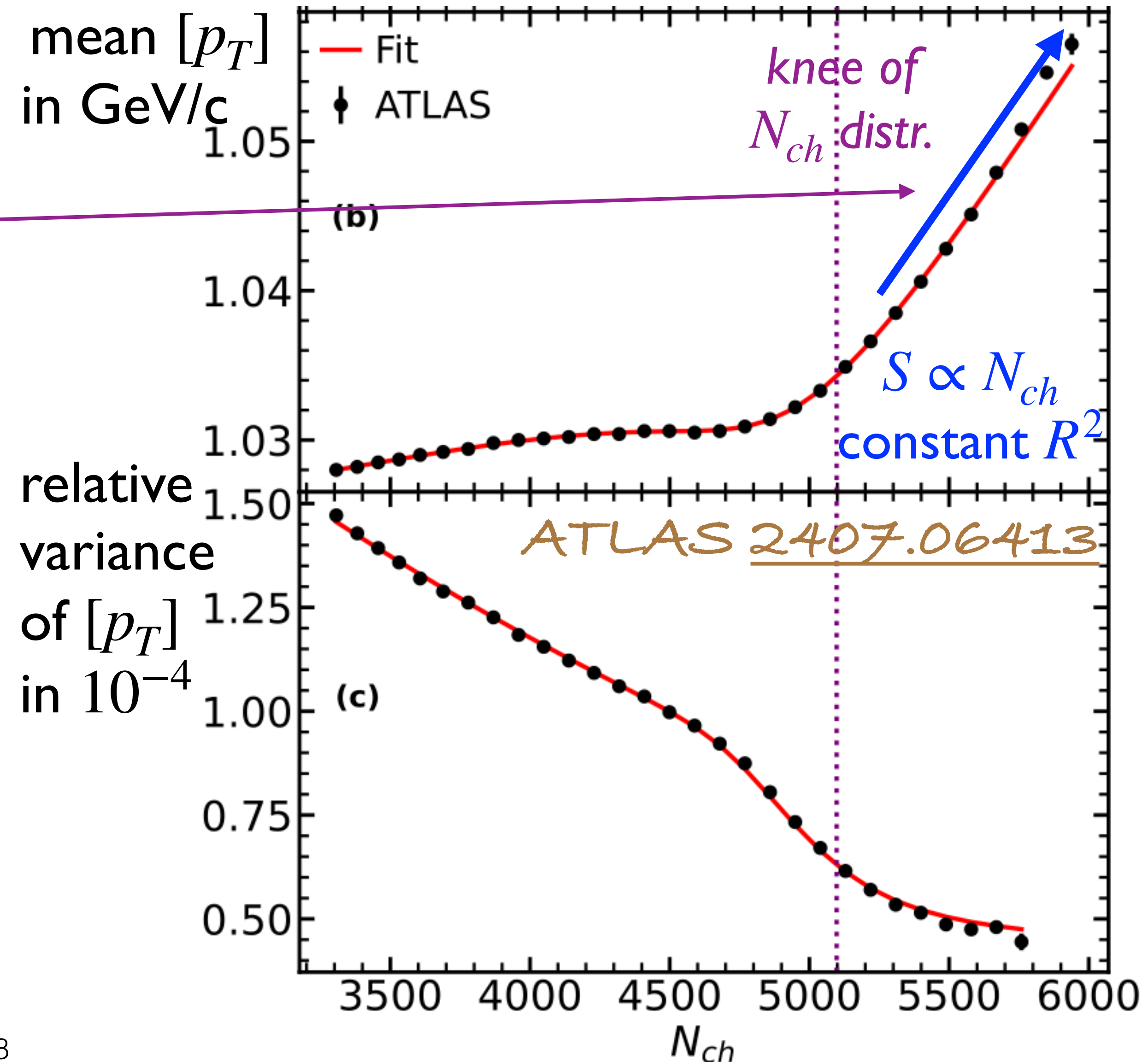
Gardim Giacalone JY0 [1909.11609](#)

CMS Collaboration [2401.06896](#)

- Caveats raised! More work needed

Nijs van der Schee [2312.04623](#)

ALICE Collaboration [2506.10394](#)



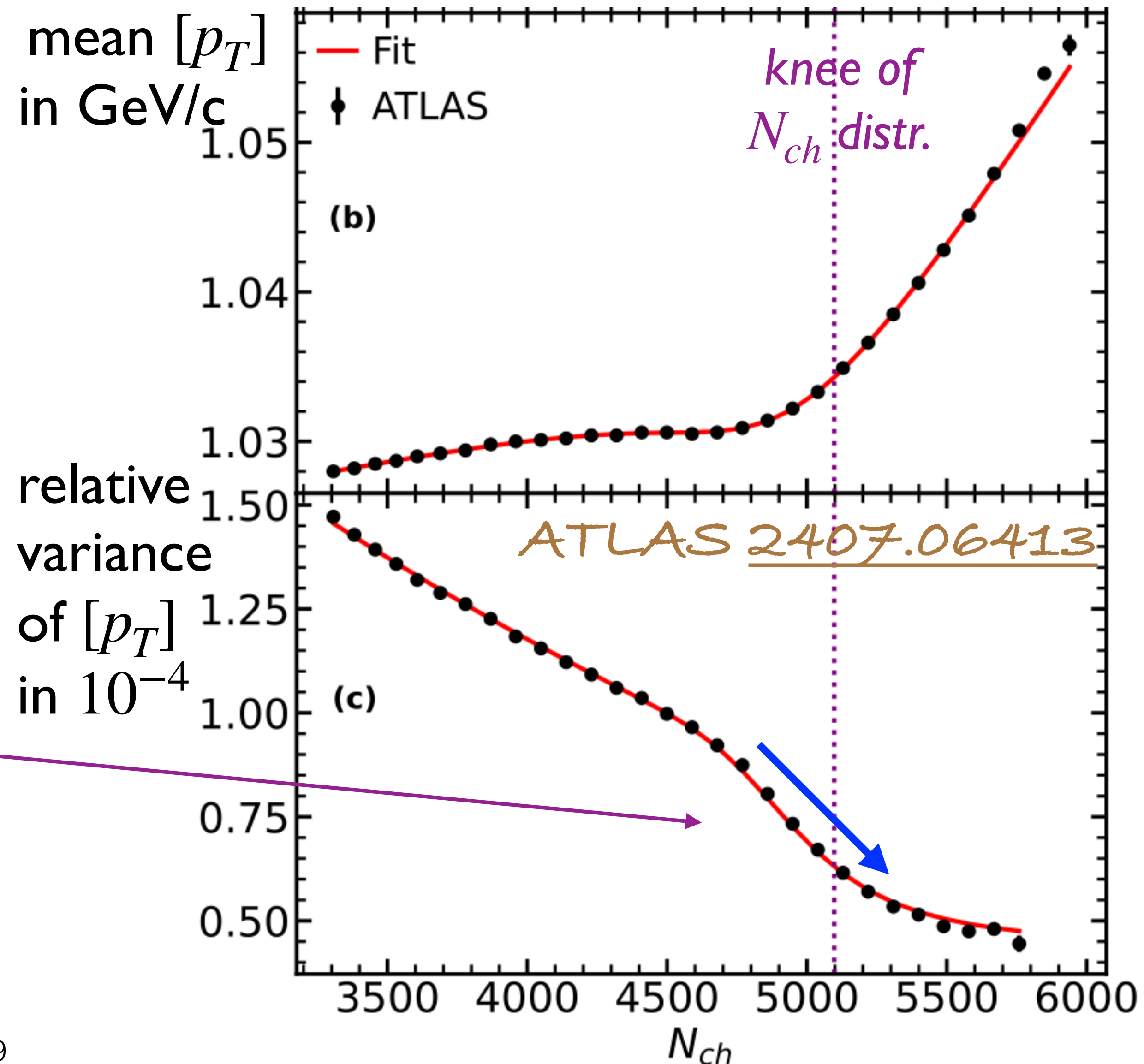
4. Decrease of the variance of $[p_T]$

- $[p_T] \approx 3 T_{\text{eff}}$ depends on entropy density $s_{\text{eff}} \propto S/R^3 \propto N_{ch}/R^3$
- Fluctuations of $[p_T]$ at fixed N_{ch} induced by size (R^2) fluctuations

Broniowski Chojnacki Obara 0907.3216

- The decrease of the variance in ultracentral collisions is explained by the disappearance of classical (b) fluctuations of R^2 : only quantum fluctuations remain

Samanta Bhatta Jia Luzum JY0 2303.15323



5. Resolving the problems in extracting c_s from data

A detailed analysis within the Trajectum theory framework lists many possible biases. We resolve them one by one. *Nijs van der Schee [2312.04623](#)*

- A. Choosing the appropriate centrality estimator.
- B. Taking into account the **kinematic** (p_T) **cuts**
- C. **Shot noise** from hadronization of the fluid
(usually referred to "self-correlation")
- D. Does an ultracentral selection favor a smaller or larger QGP?
- E. Combined fit to mean and variance, results.

A. Bias from centrality estimator

- The pioneering analysis by CMS bins events according to the energy E_T in forward and backward calorimeters.
CMS 2401.06896
- There are non-trivial correlations between E_T and observables of interest (N_{ch} and $[p_T]$), which are hard to model (rapidity decorrelation in particular).
- It is better to bin events directly in N_{ch} and study $[p_T]$ fluctuations (mean, variance...) directly in these bins. This is what the recent ATLAS analysis does (see also ALICE, centrality estimator I).
ATLAS 2407.06413
ALICE 2506.10394

B. Bias from kinematic (p_T) cuts

- ATLAS only sees charged particles with $p_T > 0.5 \text{ GeV}/c \approx$ half of total.
- The **fraction** of particles with $p_T > 0.5 \text{ GeV}/c$ varies event by event:

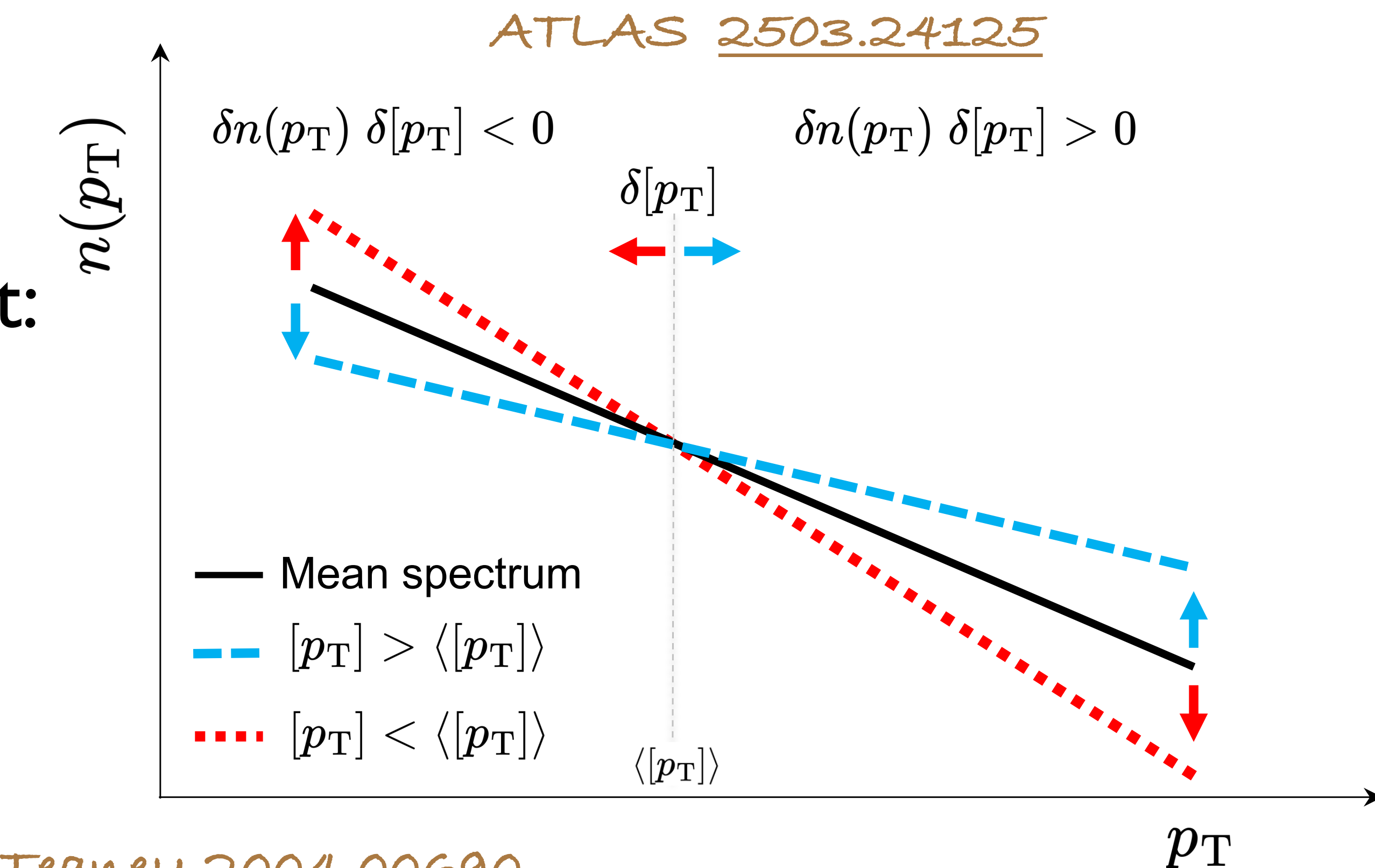
The normalized spectrum $n(p_T)$ depends on $[p_T]$ (fluid temperature)

- For a small variation $\delta[p_T]$, the variation of the spectrum $\delta n(p_T)$ is:

$$\frac{\delta n(p_T)}{n(p_T)} = \frac{v_0(p_T) \delta[p_T]}{v_0 [p_T]}$$

Schenke Shen Teaney 2004.00690

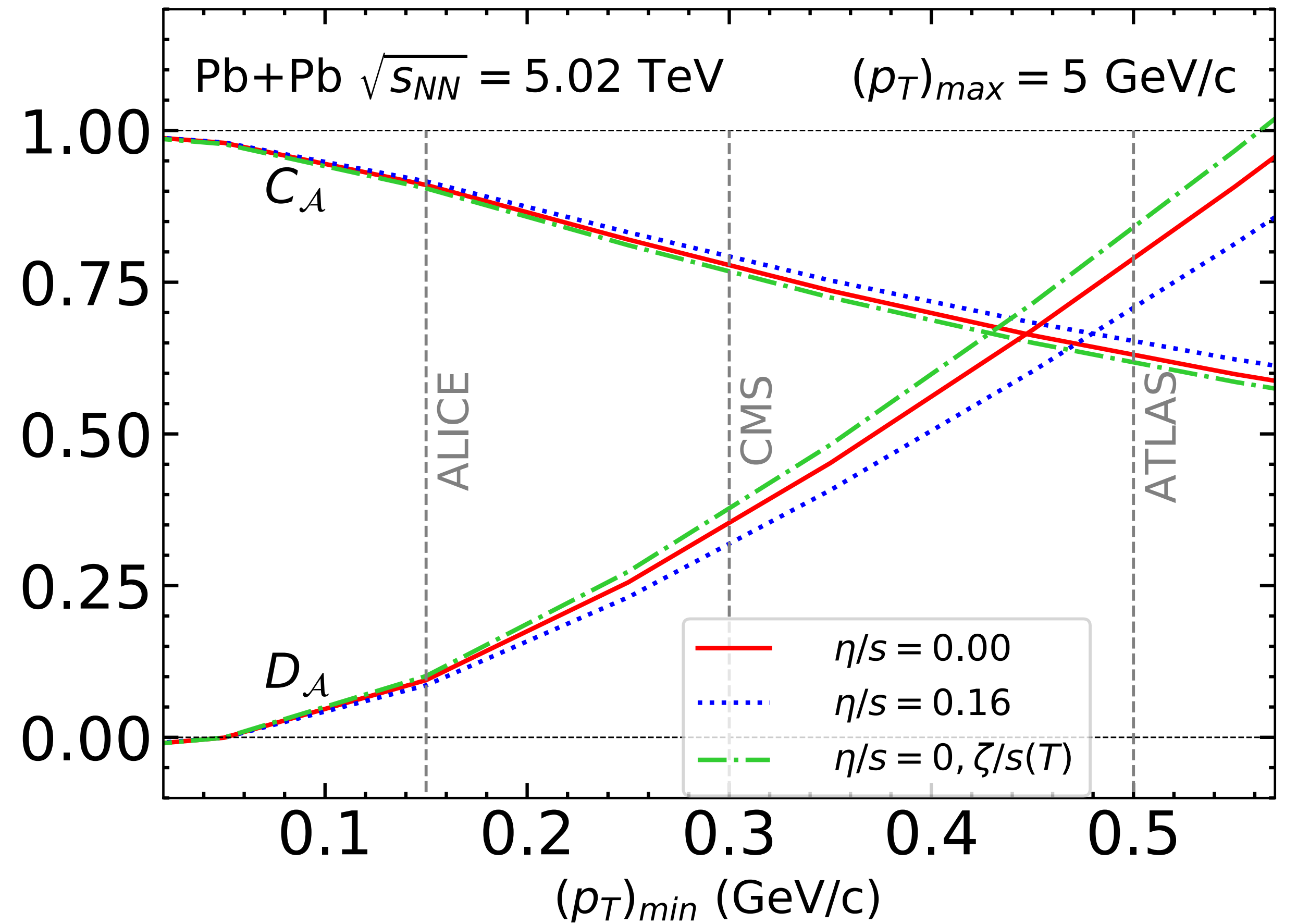
- $v_0(p_T)$ has been recently measured!



ATLAS 2503.24125 ALICE 2504.04796

B. Bias from kinematic (p_T) cuts

- N_{ch} and $[p_T]$ seen in detector, which I denote by N_A and $[p_{TA}]$, are obtained upon integration over acceptance:
- $$\frac{\delta N_A}{N_A} = \frac{\delta N_{ch}}{N_{ch}} + D_A \frac{\delta [p_T]}{[p_T]}$$
- $$\frac{\delta [p_{TA}]}{[p_{TA}]} = C_A \frac{\delta [p_T]}{[p_T]}$$
- where C_A and D_A = dimensionless acceptance factors obtained by integrating $v_0(p_T)$

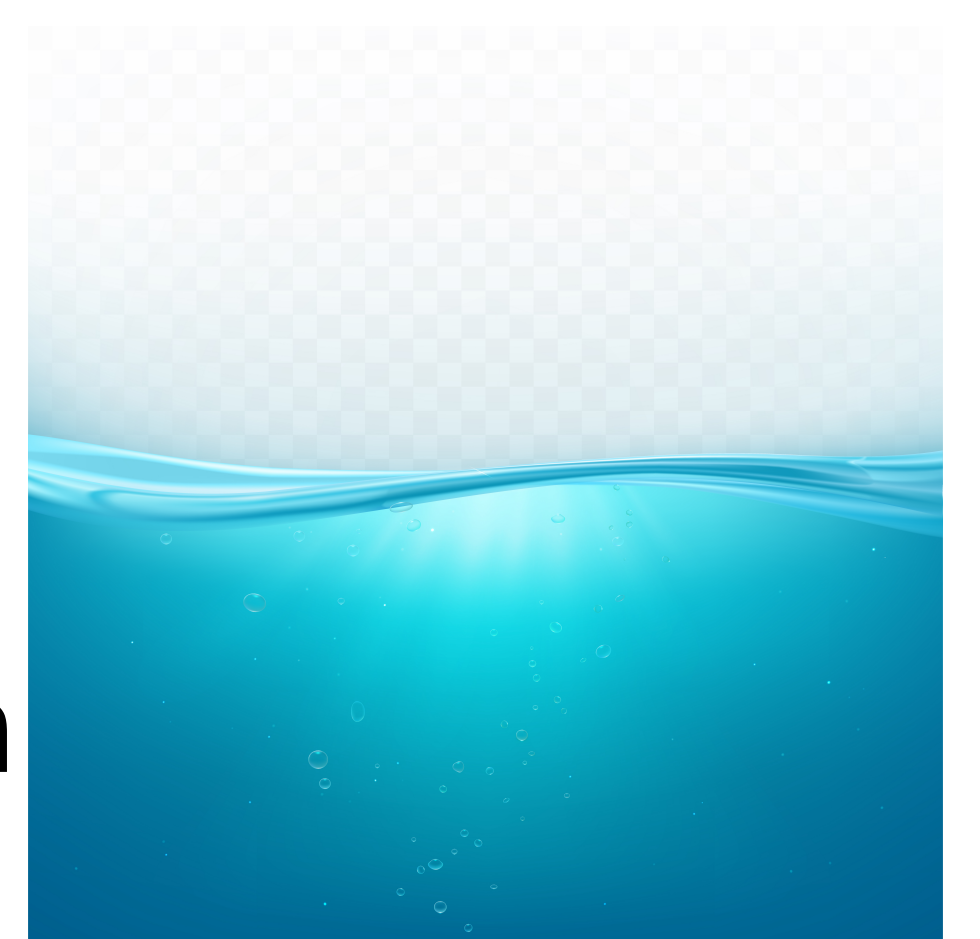


Alqahtani Parida JY0 2603.09647

B. Bias from kinematic (p_T) cuts

- Cuts change the relation between final-state observables N_A , $[p_{TA}]$ and initial state quantities S , R^2 .
- N_A no longer just proportional to S . It also depends on $[p_T]$, i.e., on R^2 , which is a non-trivial **bias** induced by the detector acceptance, and a large one in the case of ATLAS.
- Information about fluctuations of R^2 is in the variance of $[p_{TA}]$.
- Therefore, extraction of c_s^2 from data requires not only the mean, but also the variance of $[p_{TA}]$ (combined fit).

C. Deblurring hadronization



- Hydrodynamics is a **continuous** description.
- Fragmentation into **discrete hadrons** is a shot noise which blurs the smooth image of the fluid.
- In order to make contact between **data** and **hydro**, we need to model hadronization (Poisson fluctuations at freeze-out) and unfold the resulting fluctuations.
- Why? The increase of N_{ch} in ultracentral collisions is partly due to statistical fluctuations, which have no effect on $[p_T]$. c_s^2 is underestimated by $\approx 27\%$ if not properly corrected.
- Even the reconstruction efficiency matters ($\approx 10\%$ effect)

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D. Does ultracentral selection affect QGP size?

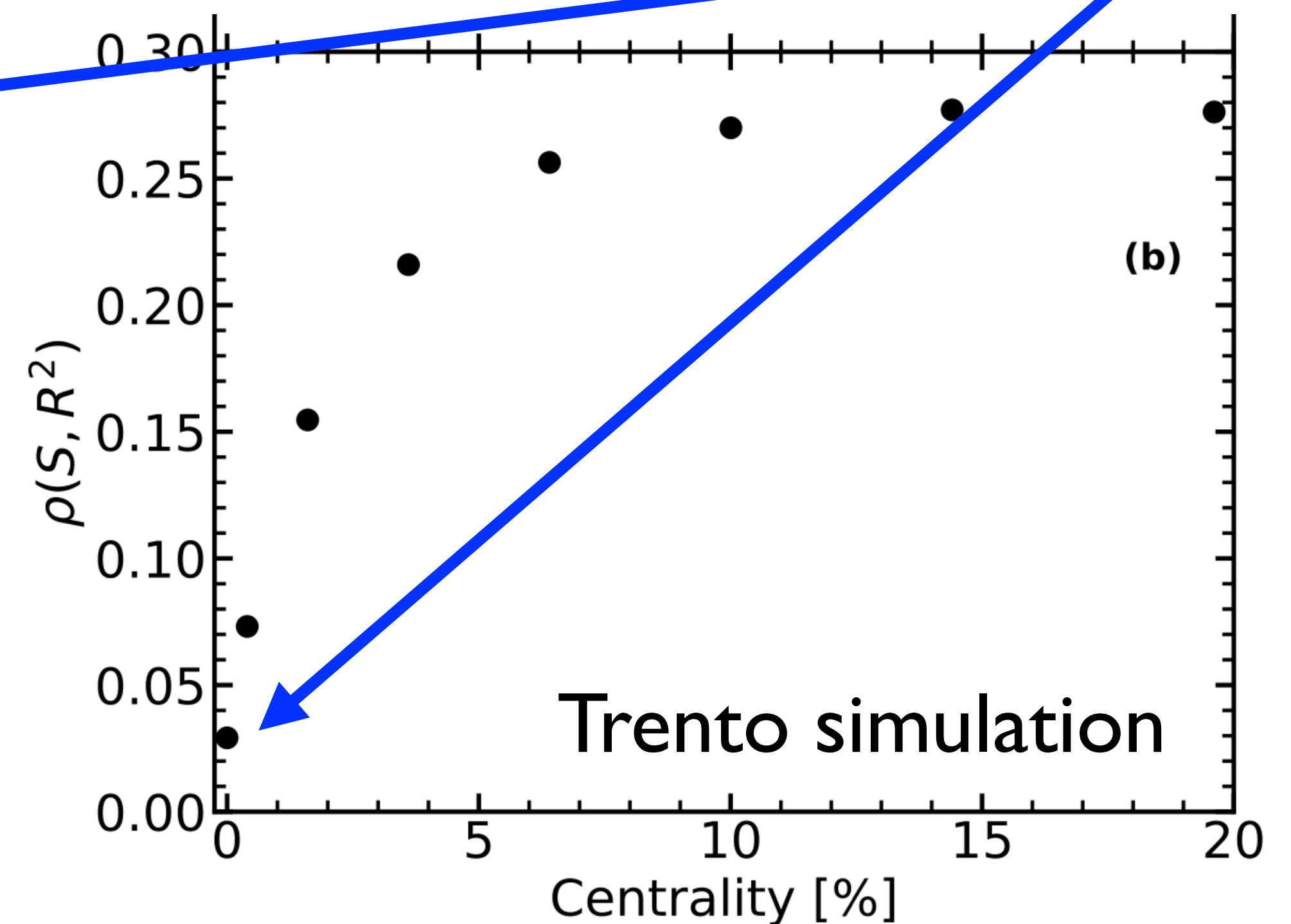
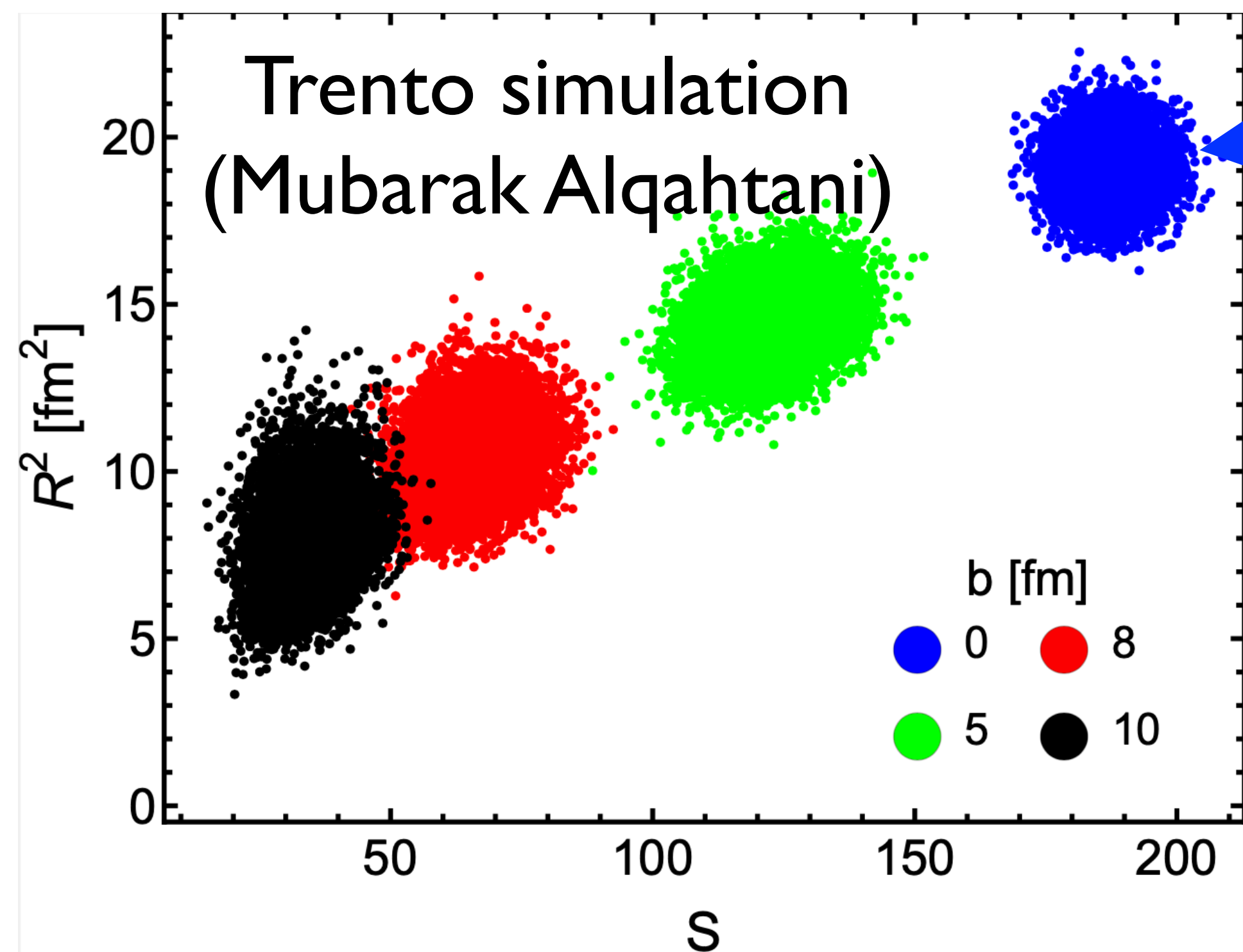
- The original picture is that an increase in multiplicity/entropy S at $b=0$ doesn't imply a change in the system size R^2 , or, equivalently, that the relative excess entropy is distributed uniformly.
- Nijs and van der Schee pointed out that this depends on details of the model of initial conditions: depending on the parametrization, the QGP may swell or shrink as multiplicity increases, which has a direct effect on the density, hence on the "slope" of $\langle p_T \rangle$ versus N_{ch} .
- I will argue that theory+data support that S and R^2 are uncorrelated at $b=0$ but we don't yet have an error bar on this statement.

Zhou Giacalone JY0 2511.04605

- Note that it is the *only irreducible theory bias* in extracting c_s^2 from data.

D. Correlation between entropy and size

- Global theory-to-data comparisons (Duke, Jetscape, Trajectum) strongly support an initial entropy deposition proportional to $\sqrt{T_A T_B}$, which is also the scenario preferred by "first principles" theory.
- Implies that the correlation between S and R^2 almost vanishes at $b=0$.



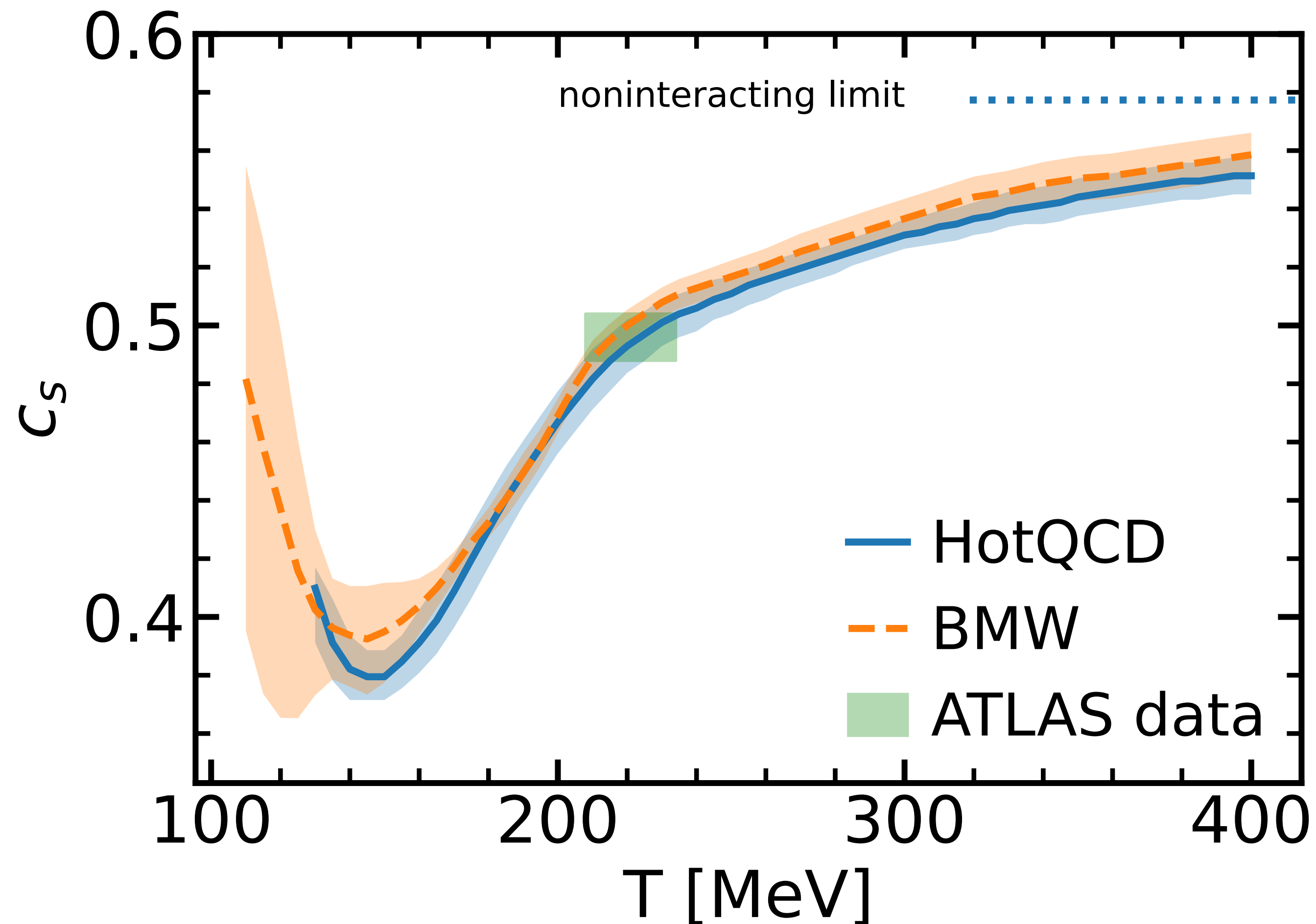
E. Fitting procedure

Assumptions:

- Gaussian fluctuations of S and R^2 at fixed b .
- Correlation between S and R^2 vanishes at $b = 0$.
- Parameters of Gaussian are smooth functions of b^2 : 7 fit parameters: 3 for $\langle [p_{TA}] | b \rangle$, 3 for $\langle \text{Rel. Var}([p_{TA}] | N_A, b) \rangle$, and c_s^2
- Simplified hydro response as described above:

$$\begin{pmatrix} \frac{\delta N_A}{\langle N_A \rangle} \\ \frac{\delta [p_{TA}]}{\langle [p_{TA}] \rangle} \end{pmatrix} = \begin{pmatrix} 1 + D_A c_s^2 & -\frac{3}{2} D_A c_s^2 \\ C_A c_s^2 & -\frac{3}{2} C_A c_s^2 \end{pmatrix} \begin{pmatrix} \frac{\delta S}{\langle S \rangle} \\ \frac{\delta R^2}{\langle R^2 \rangle} \end{pmatrix}.$$

E. Comparison between ATLAS data and lattice QCD



- Perfect agreement: most precise comparison between lattice and data on equation of state.
- Value of c_s from fit is very robust.
- Largest error is on the effective temperature, at which we measure c_s (can be improved with more hydro simulations)

6. What else we can learn

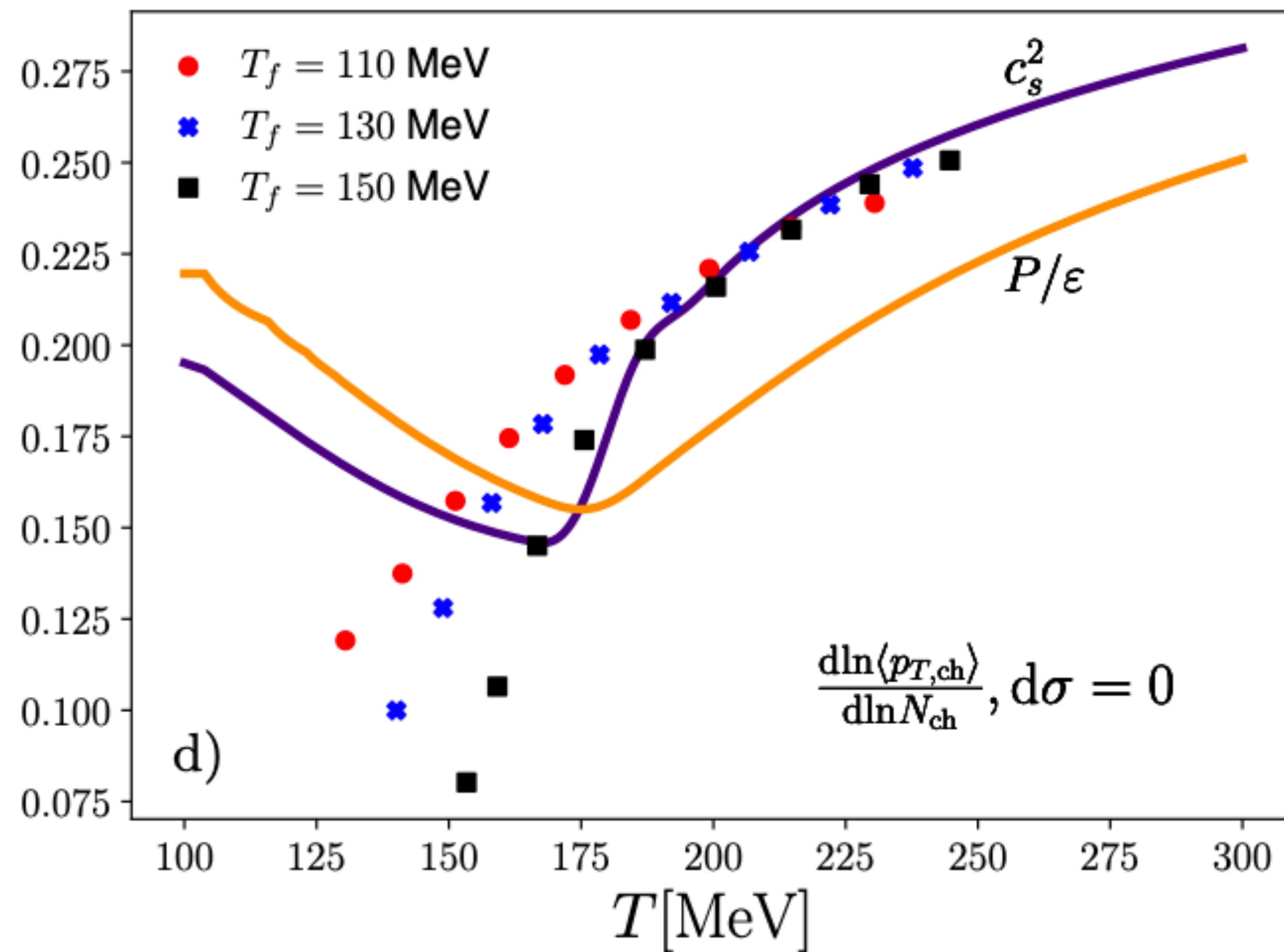
- Another output of the fit is the relative standard deviation of R^2 at $b = 0$: $3.09 \pm 0.15 \%$.
- Smaller than initial state simulations (e.g. Trento) which all give $> 4 \%$.
- Suggest that the usual **classical** Glauber-type sampling of nucleons **overestimates fluctuations**.
- The nucleus in the ground state is a **quantum object**: Pauli principle **reduces fluctuations** (excitations are only possible around the Fermi surface)
work in progress with Jean-Paul Blaizot
- A similar effect probably explains the "ultracentral flow puzzle" that v_2/v_3 is larger than expected
EXTREME Collaboration 2203.17011
- Reduction of quadrupole (ε_2) fluctuations due to quantum correlations.
B.G. Zakharov 2008.07304

Backup

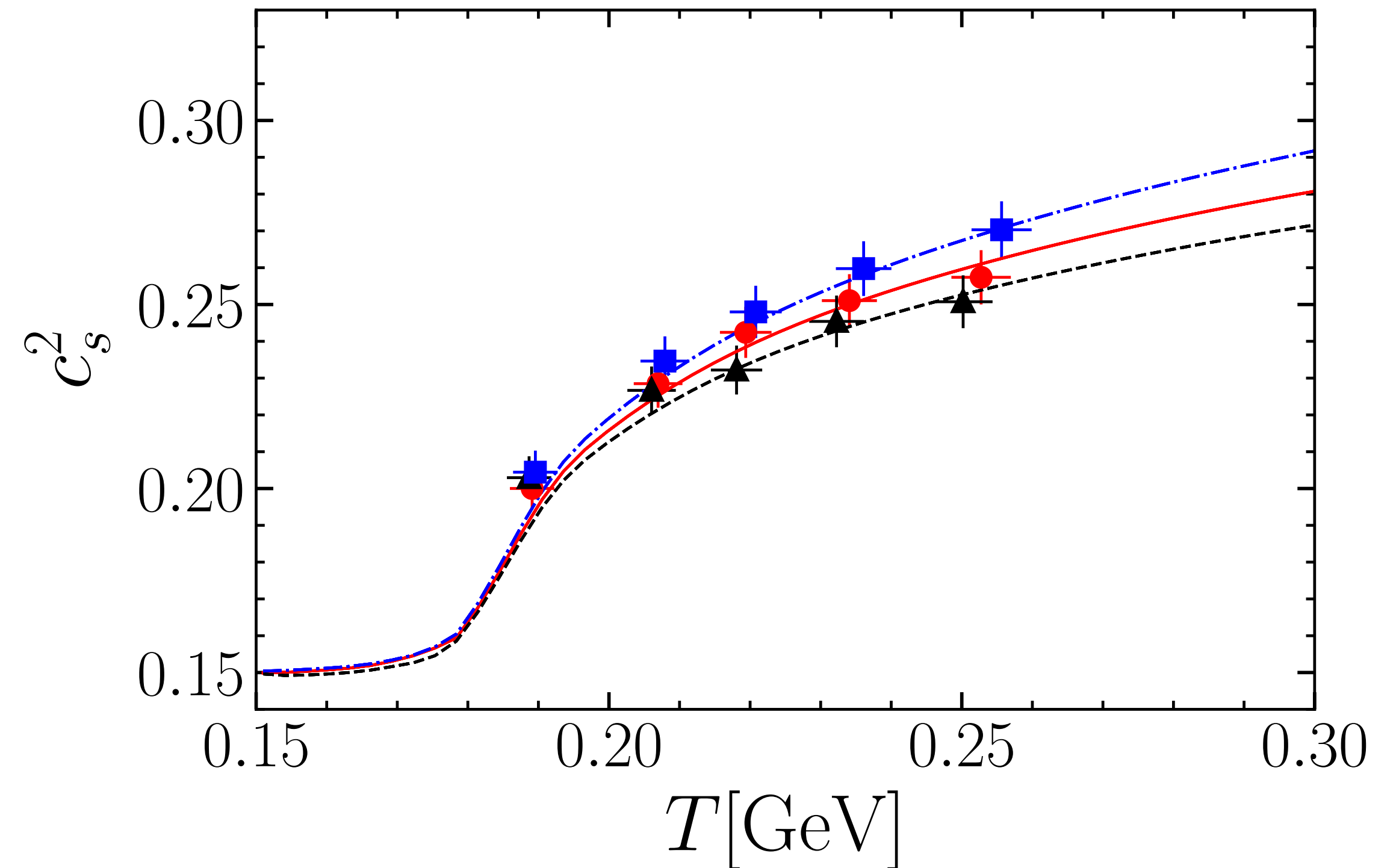
Testing $c_s^2(T_{\text{eff}}) = d \ln \langle p_T \rangle / d \ln N_{ch}$ in hydro

Various freeze-out temperatures & energies

Various equations of state & energies



Gavassino Hirvonen Paquet Singh
SoaresRocha 2503.20765



Gardim Giannini JY
2403.06052