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
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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.

1. Flow

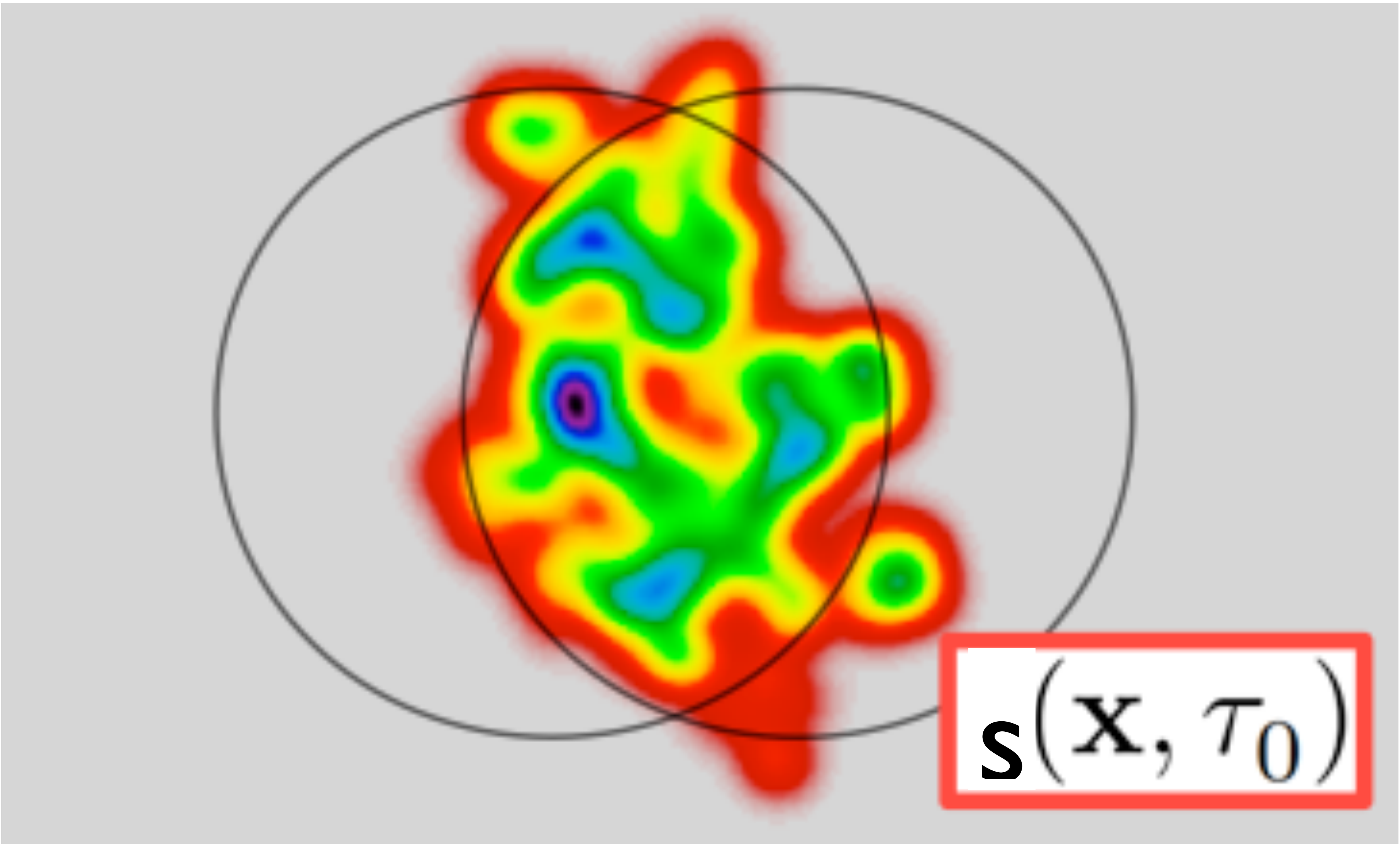
- ~99% of particle production in Pb+Pb collisions at the LHC is accurately understood as resulting from the formation of a fluid at a short time (t~1 fm/c $\ll R_{Pb}$) after the collision, which freely expands into the vacuum until it transforms into hadrons at $T \approx 150$ MeV.

- 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.

1. Hydrodynamic response

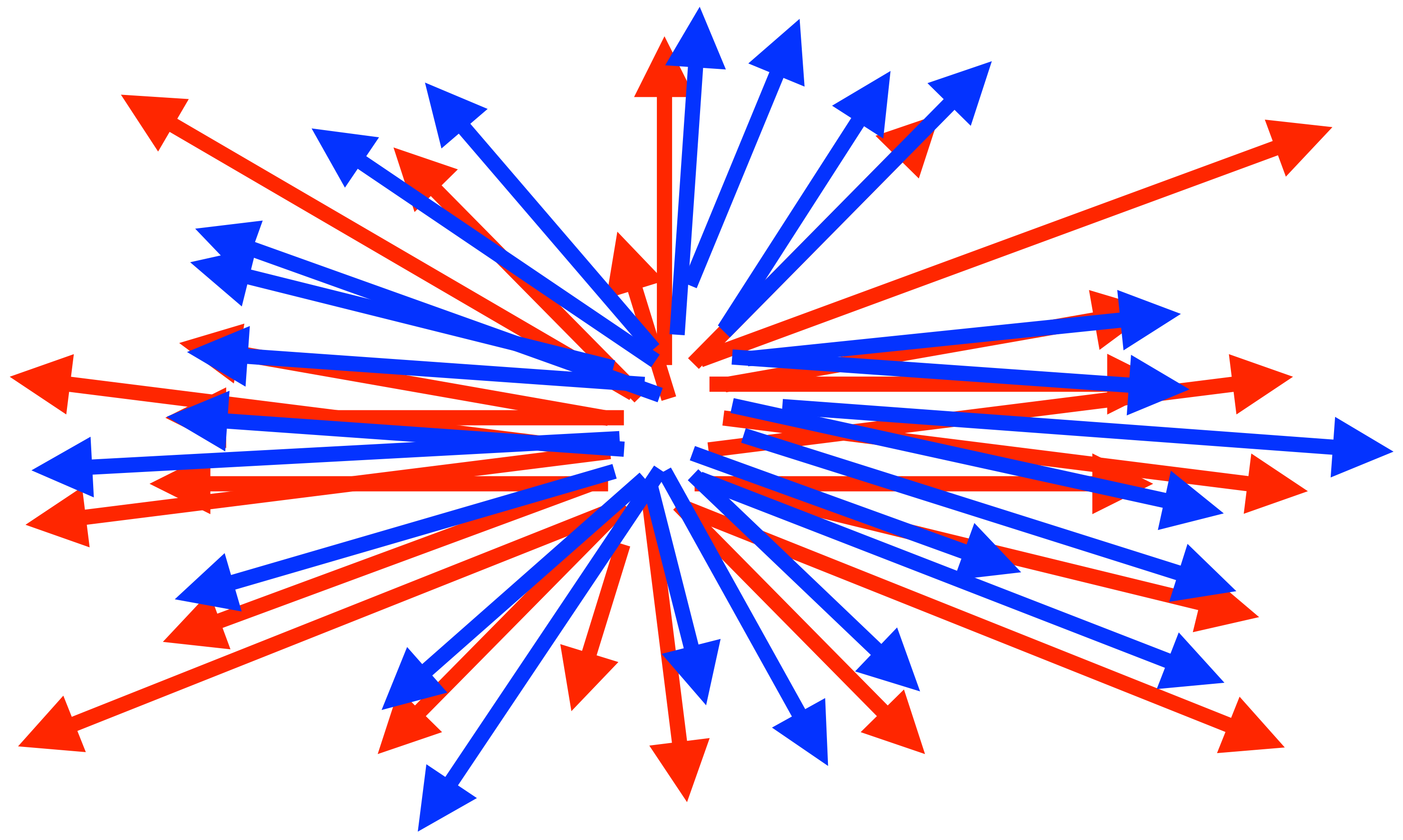
Initial state



Entropy density profile (courtesy G. Giacalone)

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

Final state

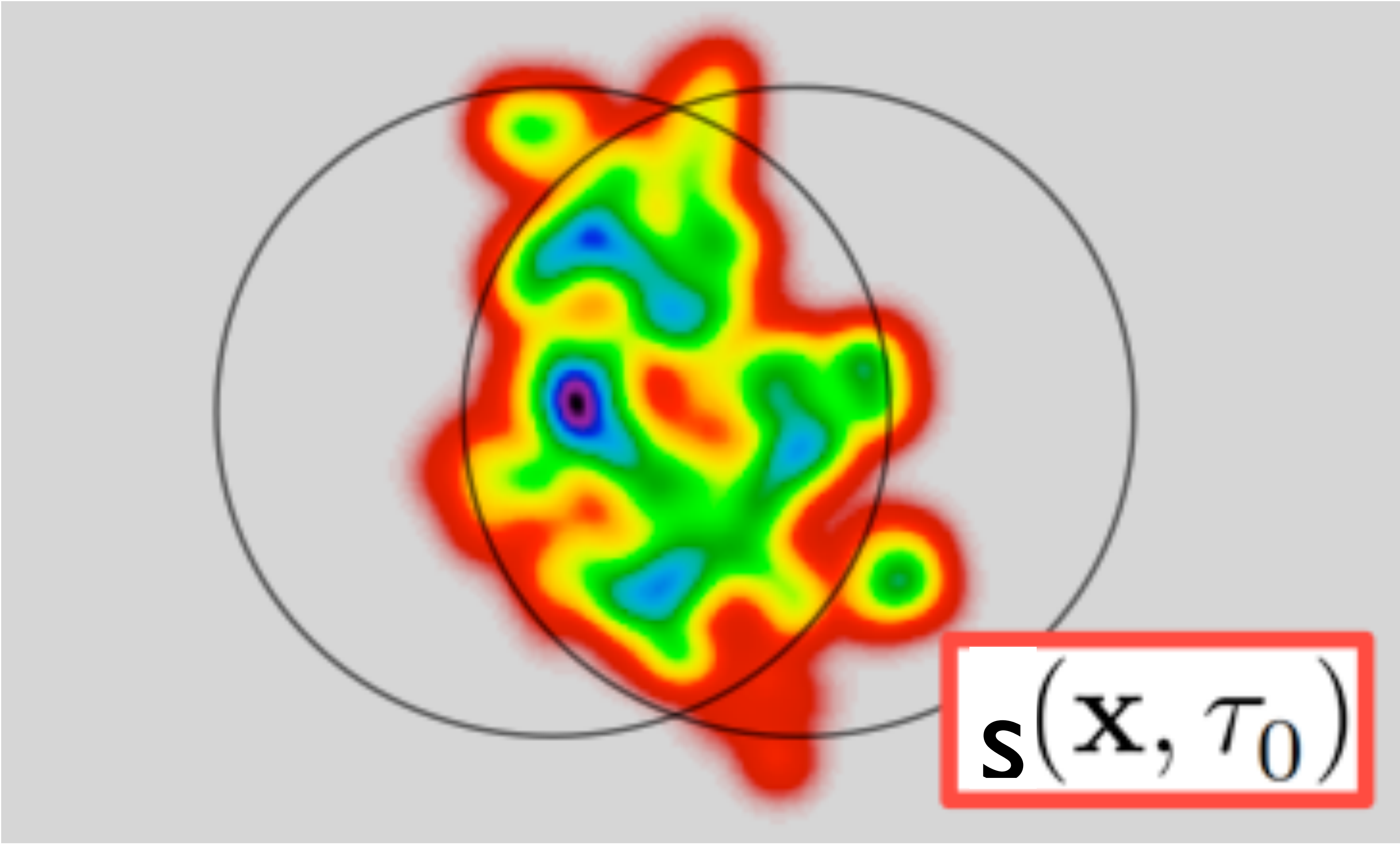


(Note: in hydro, final state = also continuous)

- Total multiplicity of charged hadrons seen in detector N_{ch}
- Transverse momentum per charged hadron $[p_T]$

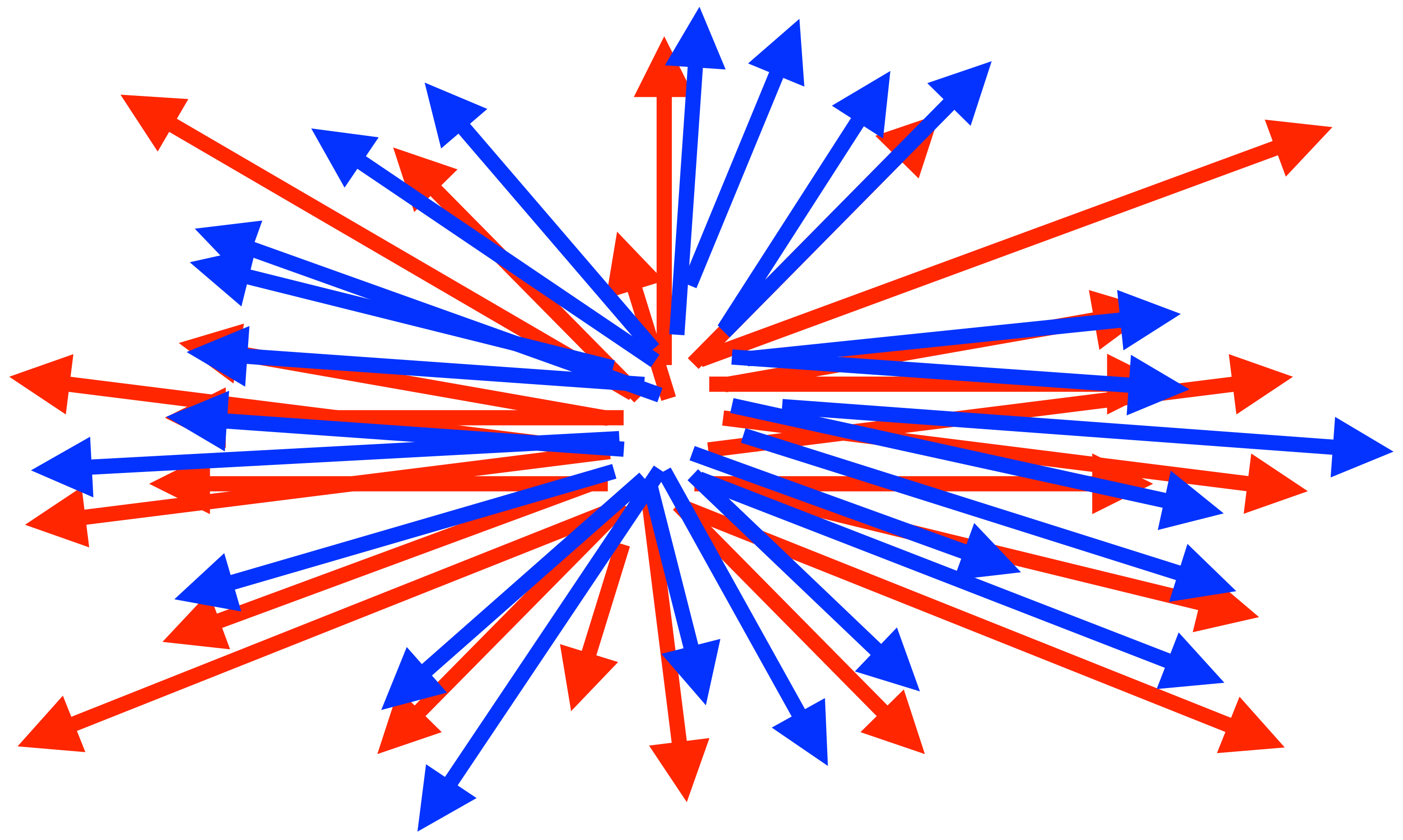
1. Hydrodynamic response

Initial state



Entropy density profile (courtesy G. Giacalone)

Final state



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

- $N_{ch} \approx 0.15\, S$ Hanus Mazeliauskas Reygers 1908.02792
- $[p_T] \approx 3\, T_{\rm eff}$ (effective temperature) depends on entropy density $s_{\rm eff} \propto S/R^3$

(next talk by Jean-Francois Paquet)

Gardim Giacalone Luzum JYO 1908.09728
Broniowski Chojnacki Obara 0907.3216

2. Event-by-event fluctuations

All collisions are different! Global observables fluctuate event by event

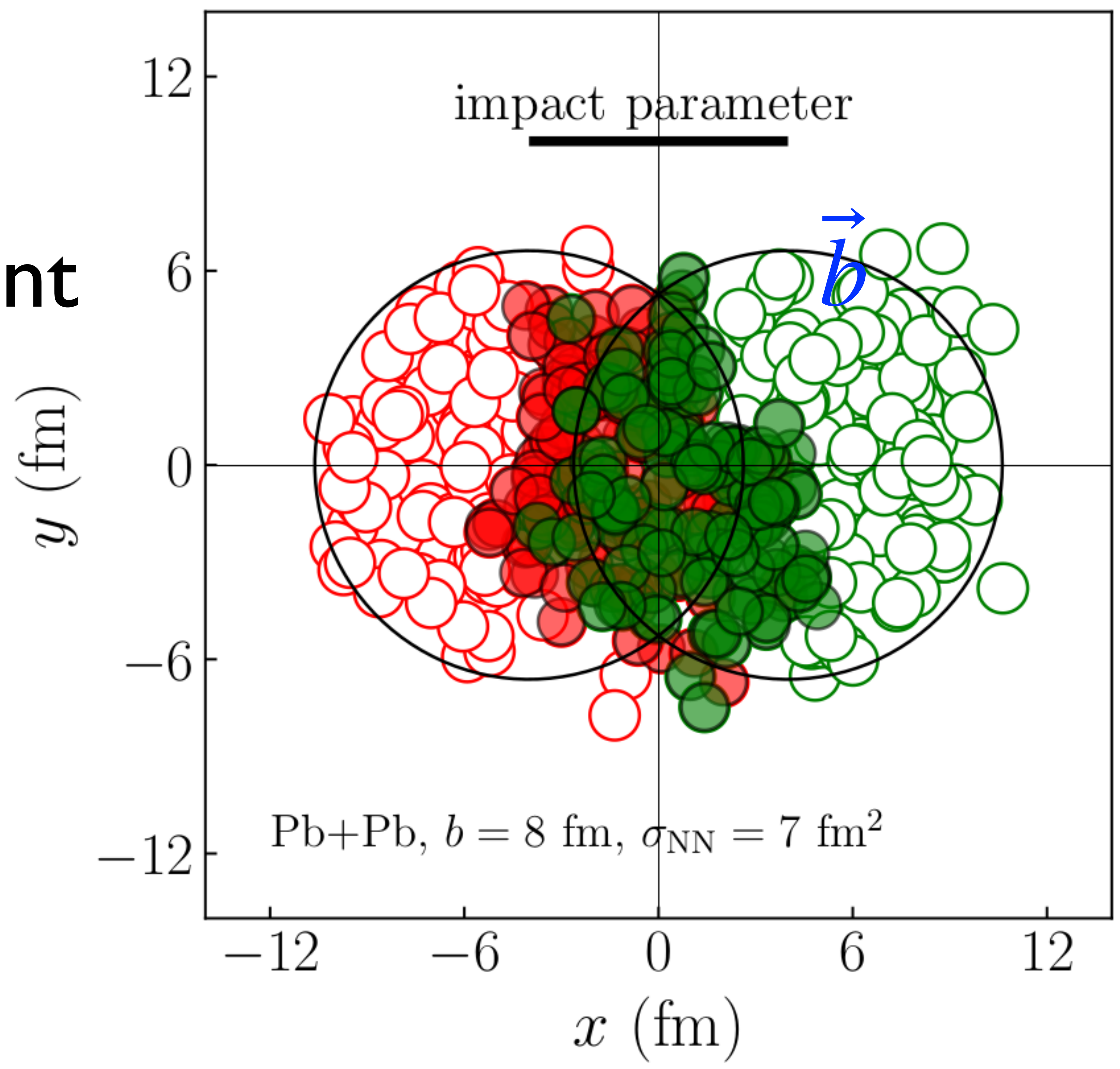
- Hydro is deterministic → *all* fluctuations stem from initial state, except for the *shot noise* from hadronization. I classify them into:
- Classical fluctuations : The impact parameter vector $\vec{b}$ of a Pb+Pb collision varies event to event & quantum uncertainty on $\vec{b}$ is negligible

  Samanta Bhatta Jia Luzum JYO 2303.15323

- 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

  Alver et al, PHOBOS collaboration, nucl-ex/0610037

Giacalone 2101.00168



2. Quantum fluctuations are simple

In the initial state, one sees a large number of 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 (~3% at b=0)

  Das Giacalone Monard JYO 1708.00081

- R^2 (~3%) and $[p_T]$ (~1%) fluctuations

  Samanta Bhatta Jia Luzum JYO 2303.15323

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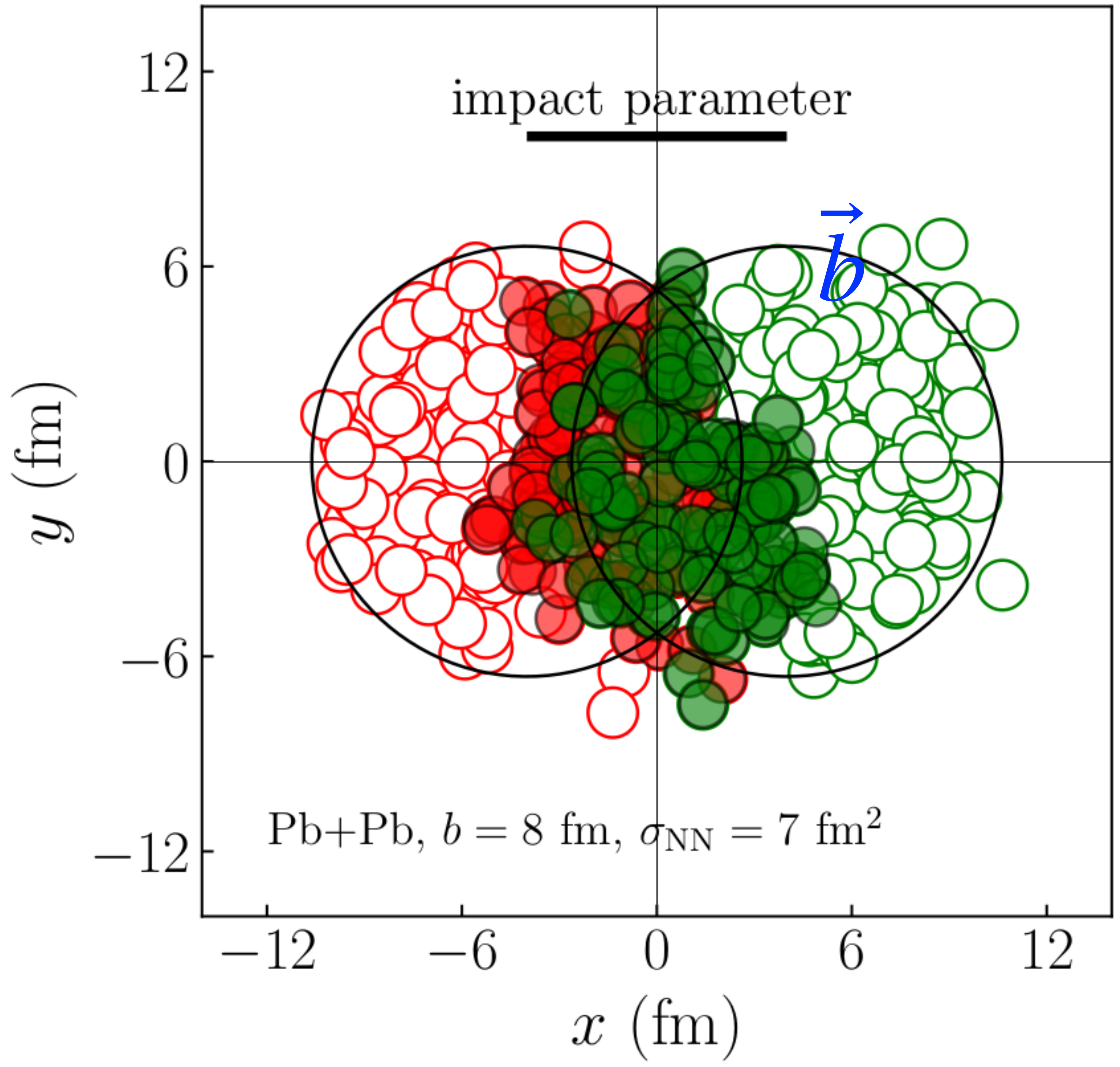
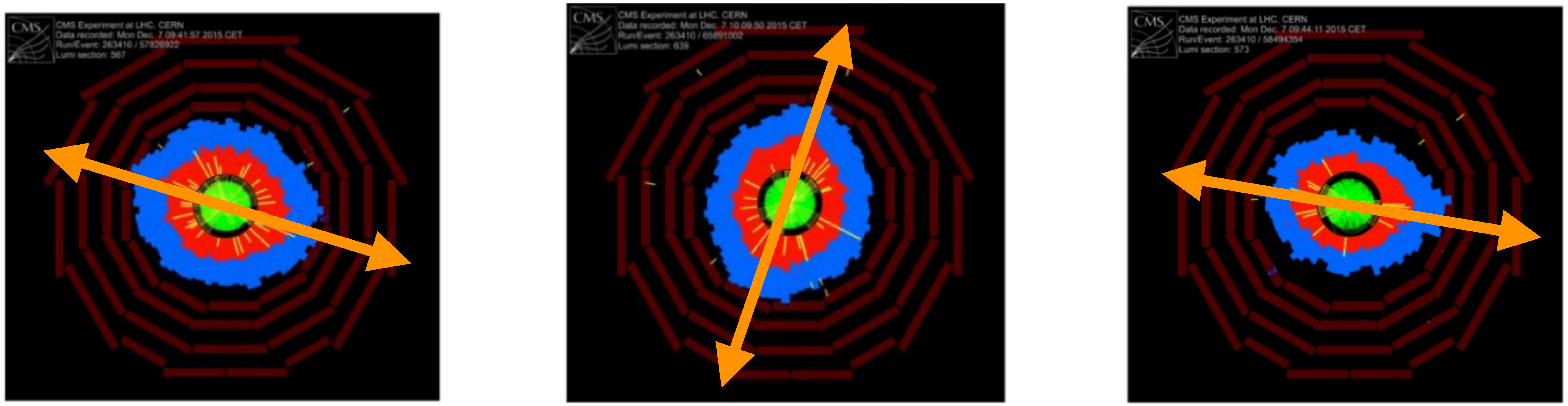


2. Classical ($\vec{b}$) fluctuations

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



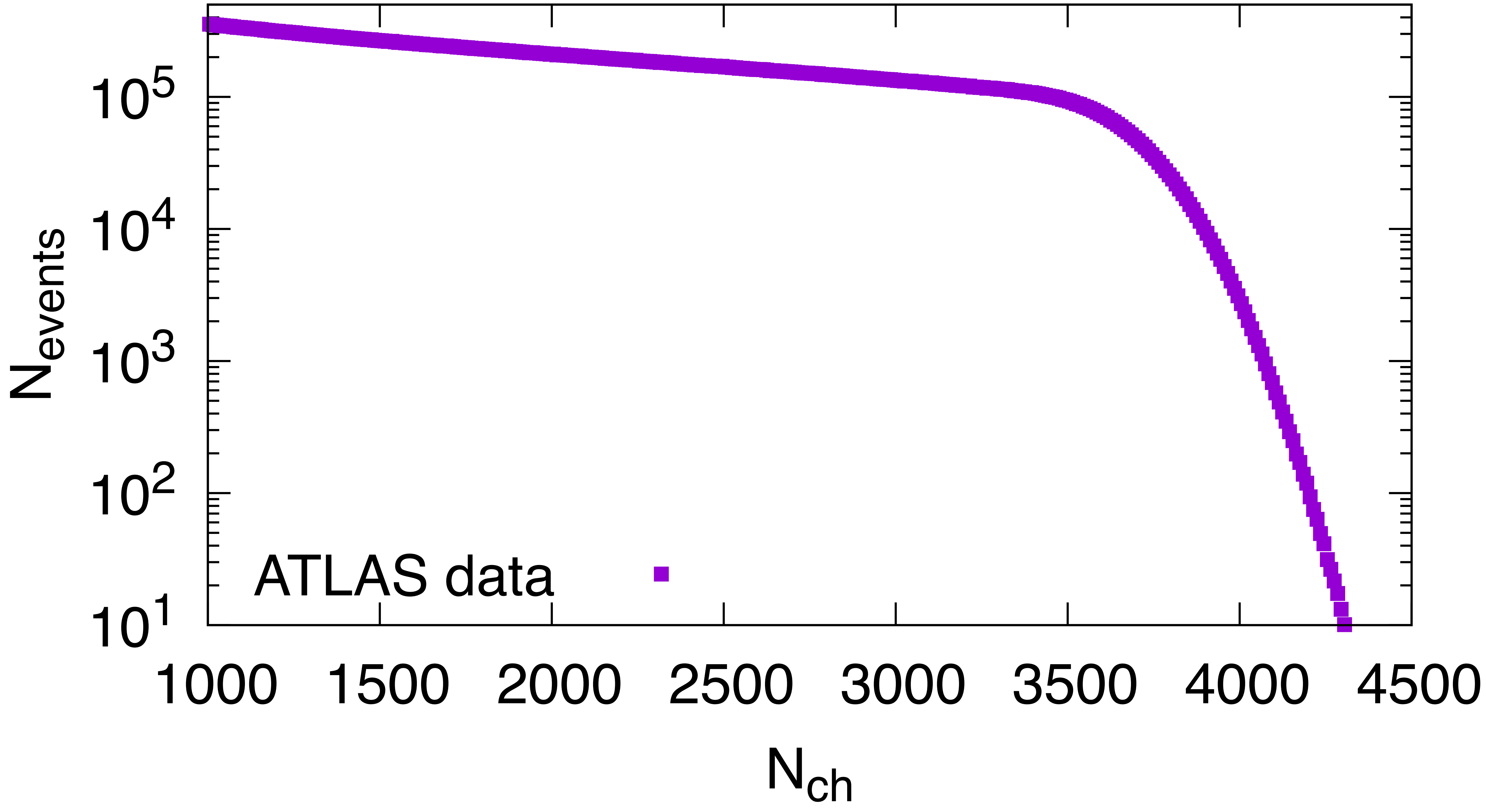
3 Pb+Pb collisions seen by CMS (Georgios Konstantinos Krintiras, Moriond 2021)

- 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. *We accurately model fluctuations of b. This is essential for ultracentral collisions, and not yet done 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.)

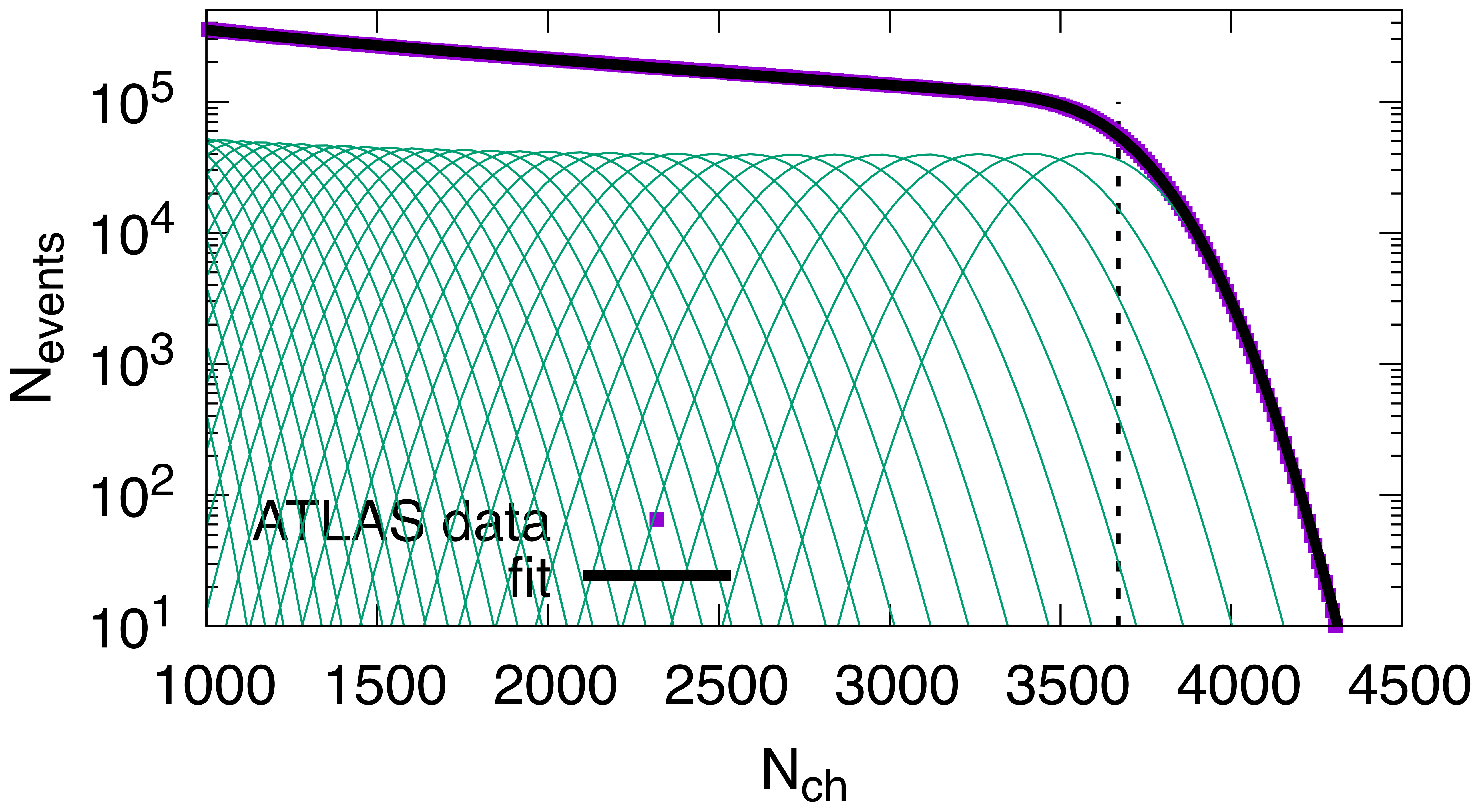


3. Bayesian reconstruction of b fluctuations

- 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

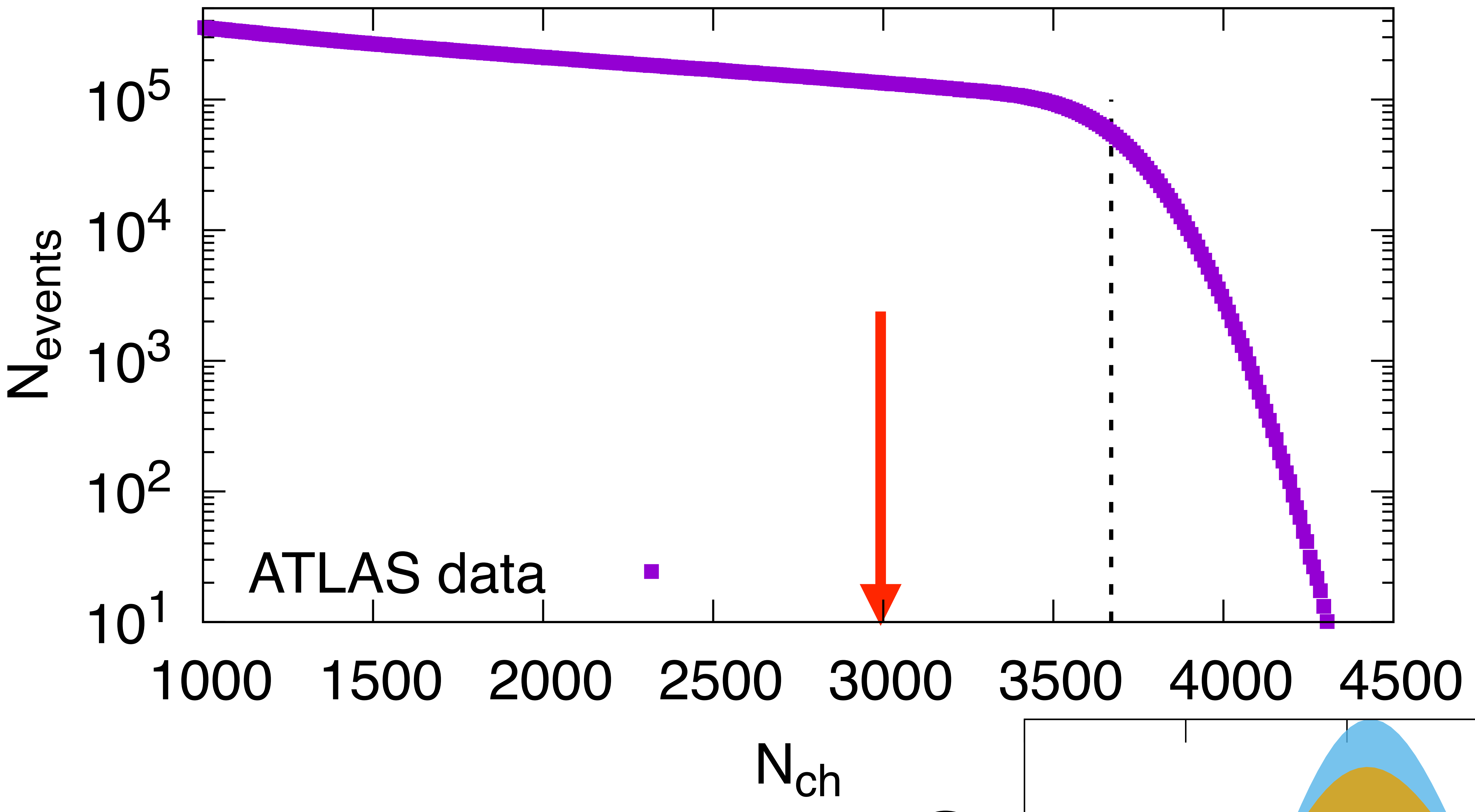
$$P(c|N_{ch}) = \frac{P(N_{ch}|c)P(c)}{P(N_{ch})} = \frac{P(N_{ch}|c)}{P(N_{ch})}$$

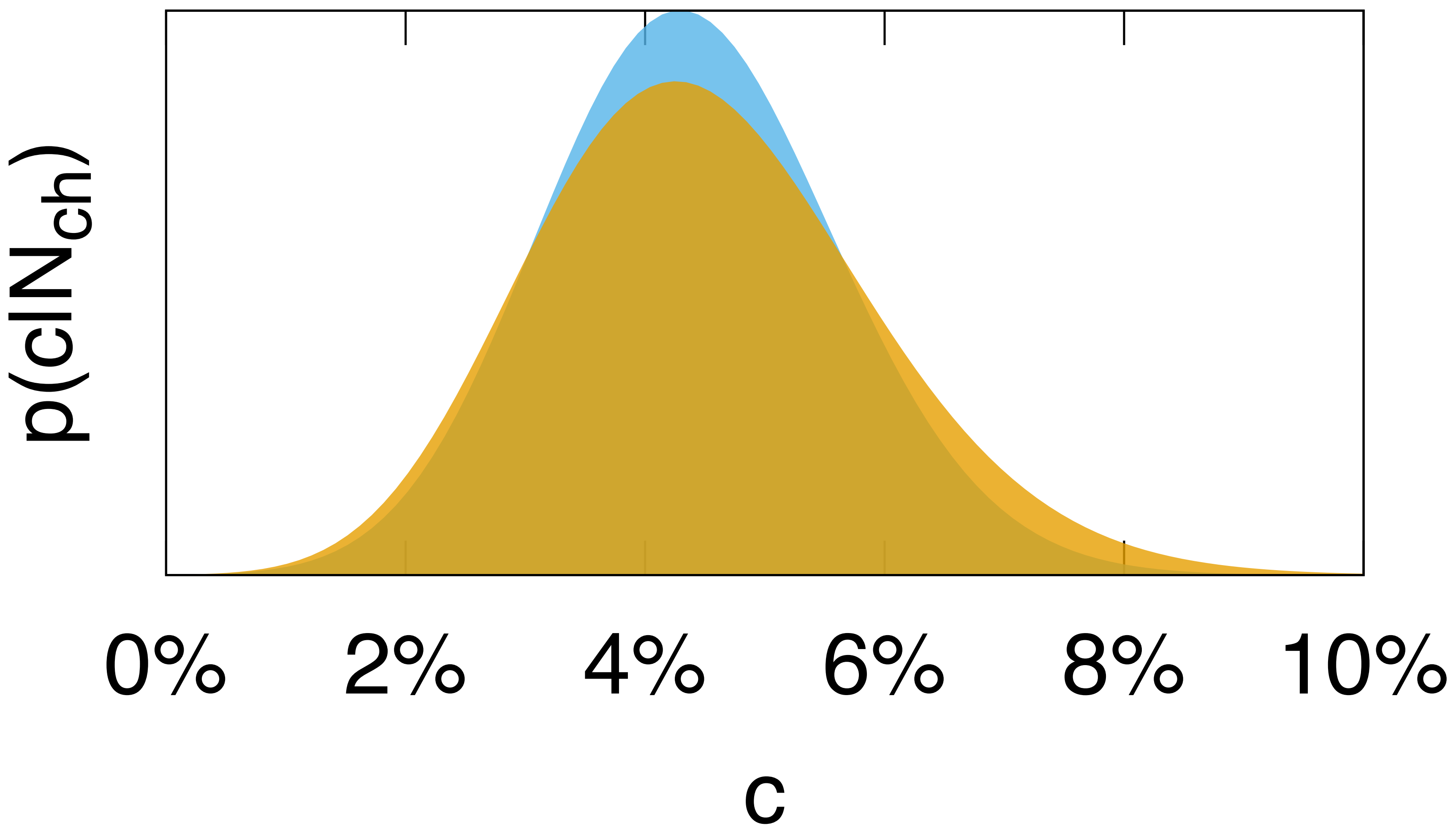
Das Giacalone Monard JYO 1708.00081



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

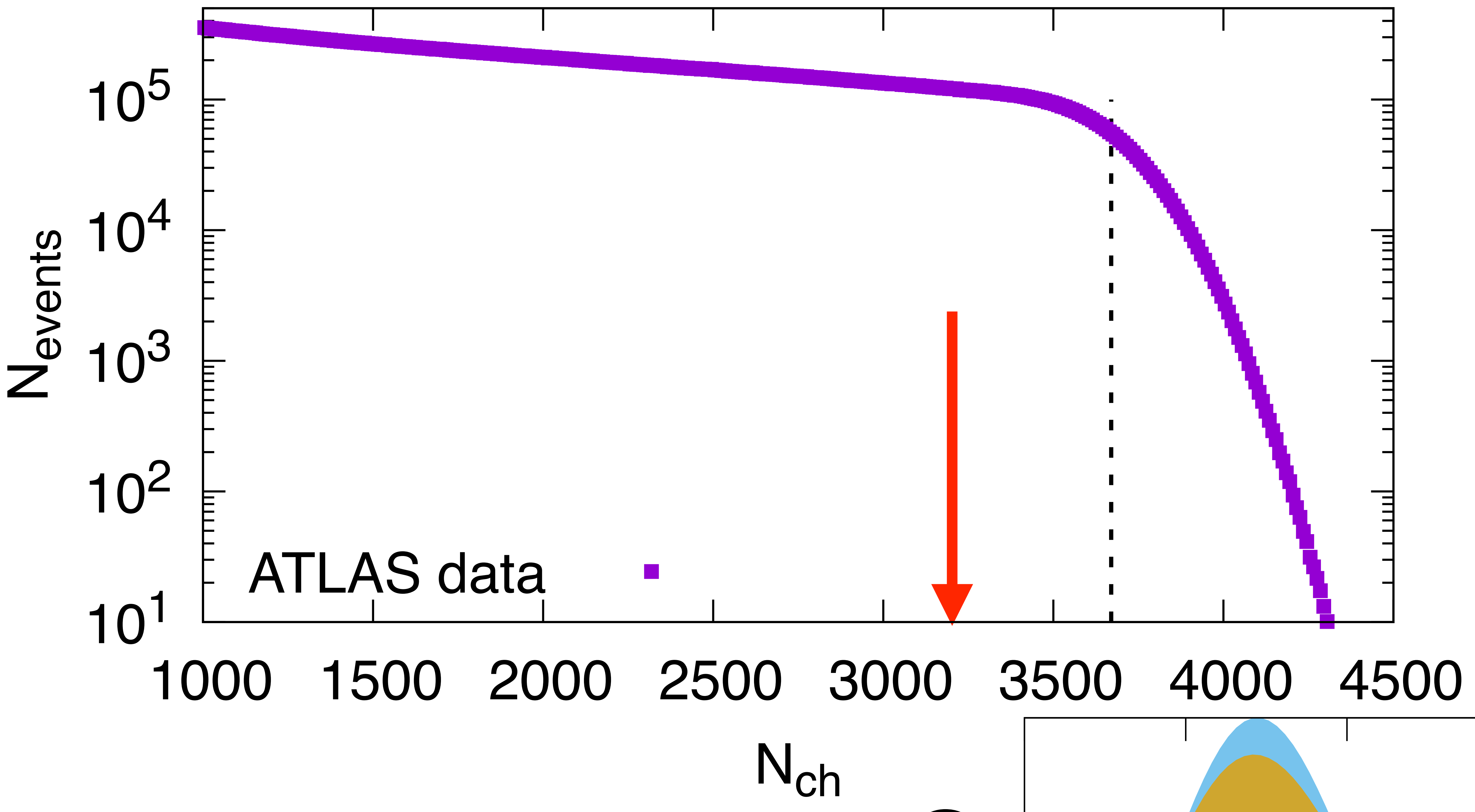




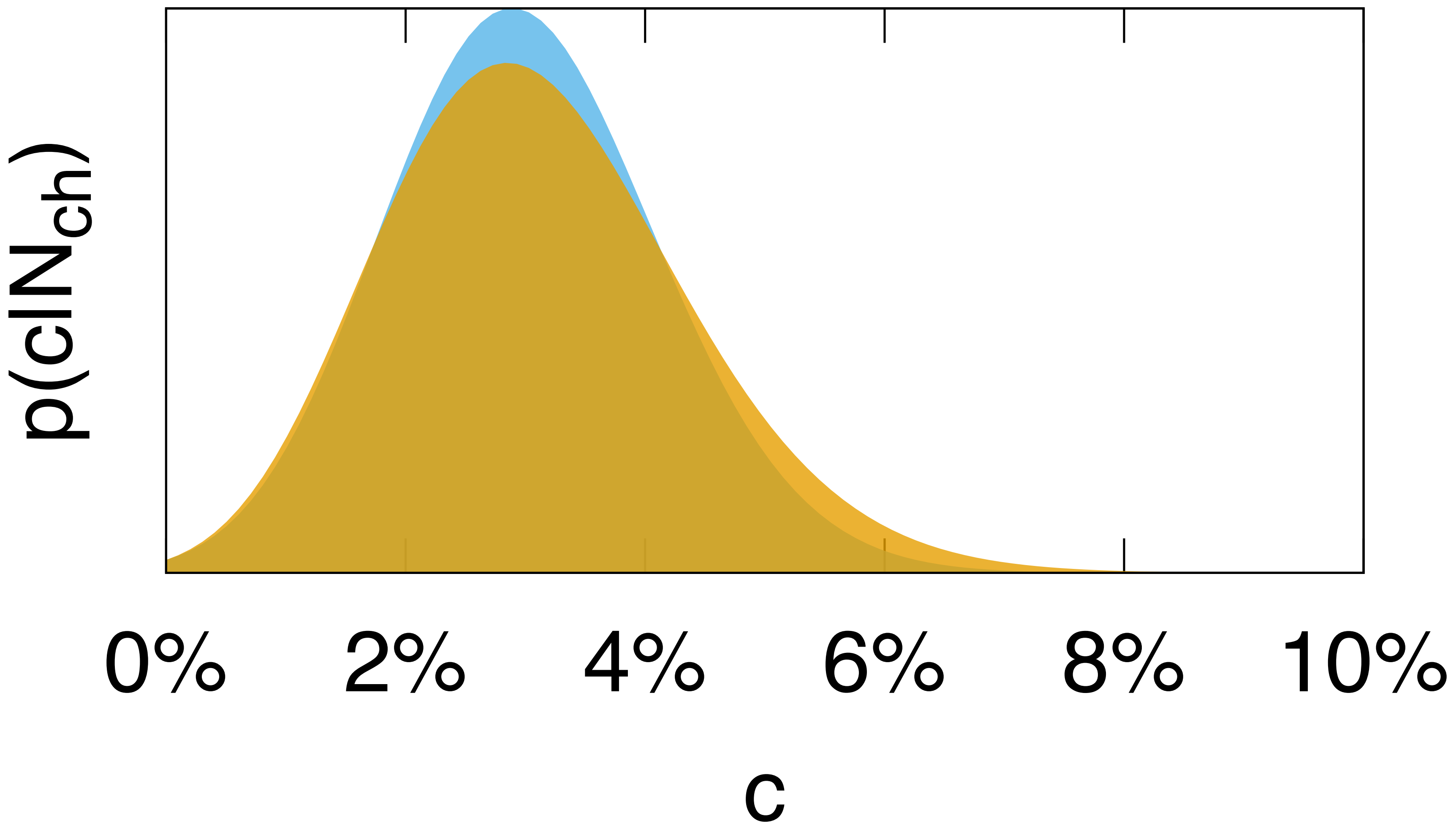
Distribution of centrality at fixed N_{ch}

Colors= reconstruction uncertainty

3. Bayesian reconstruction of b fluctuations



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



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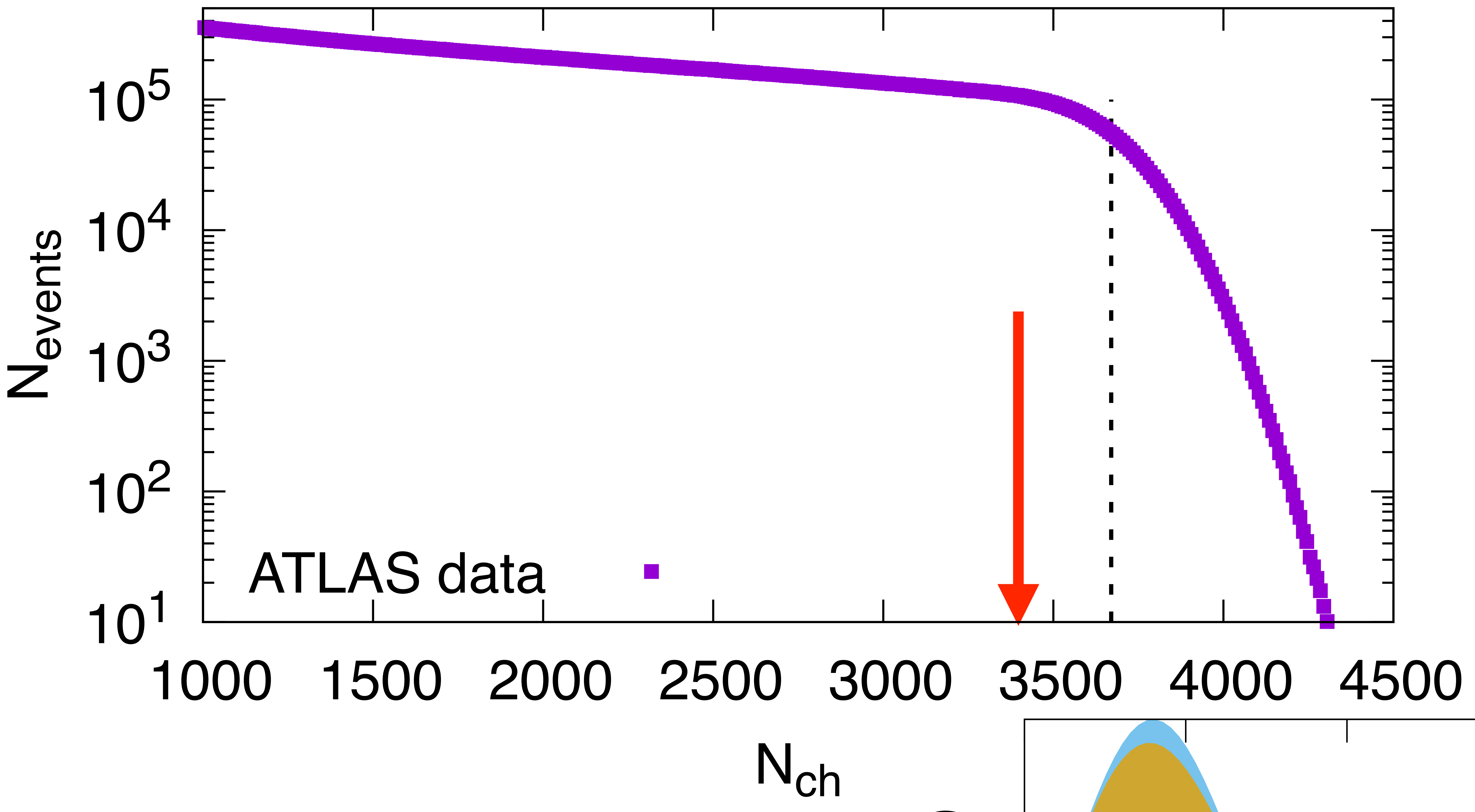

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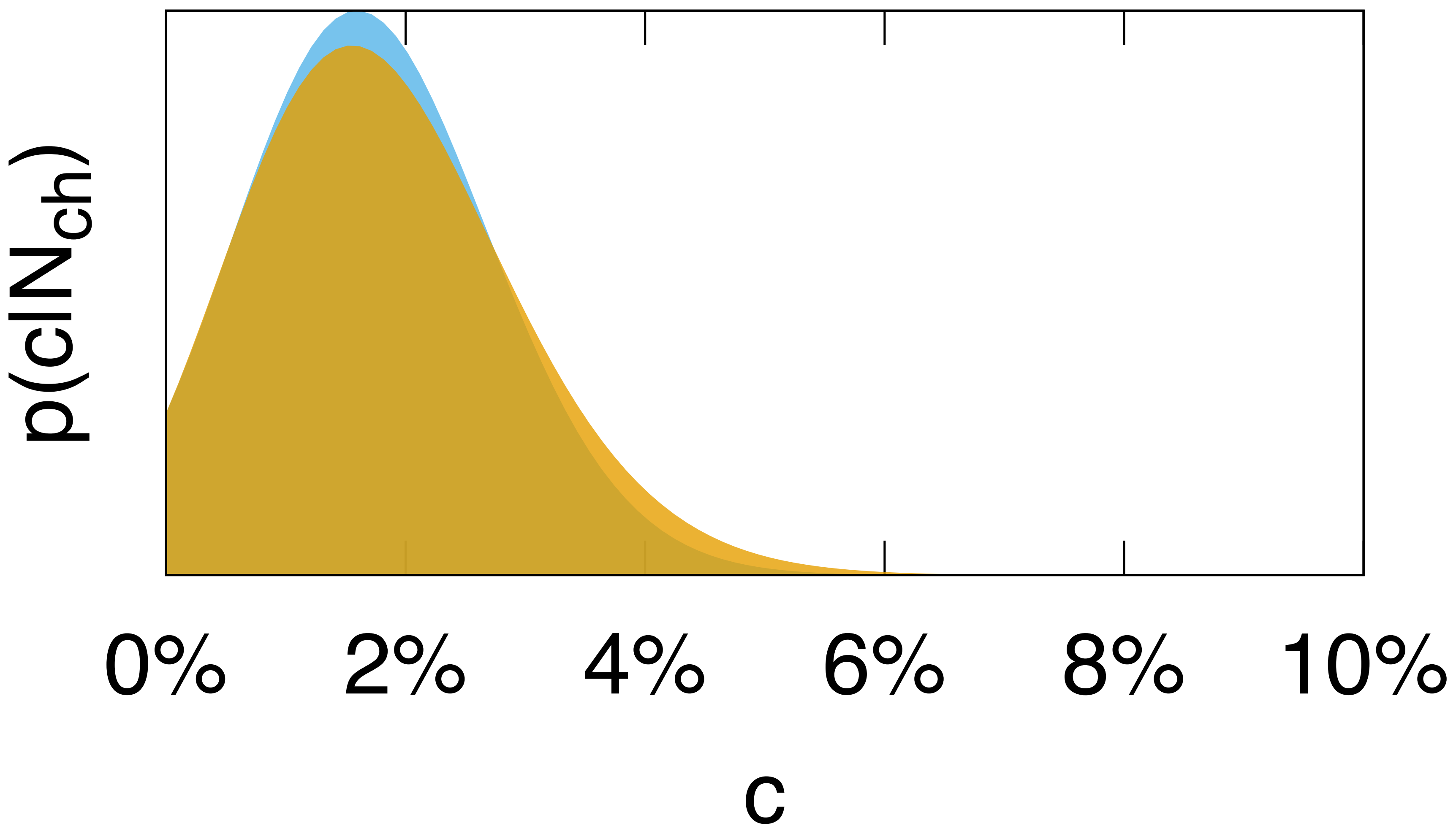

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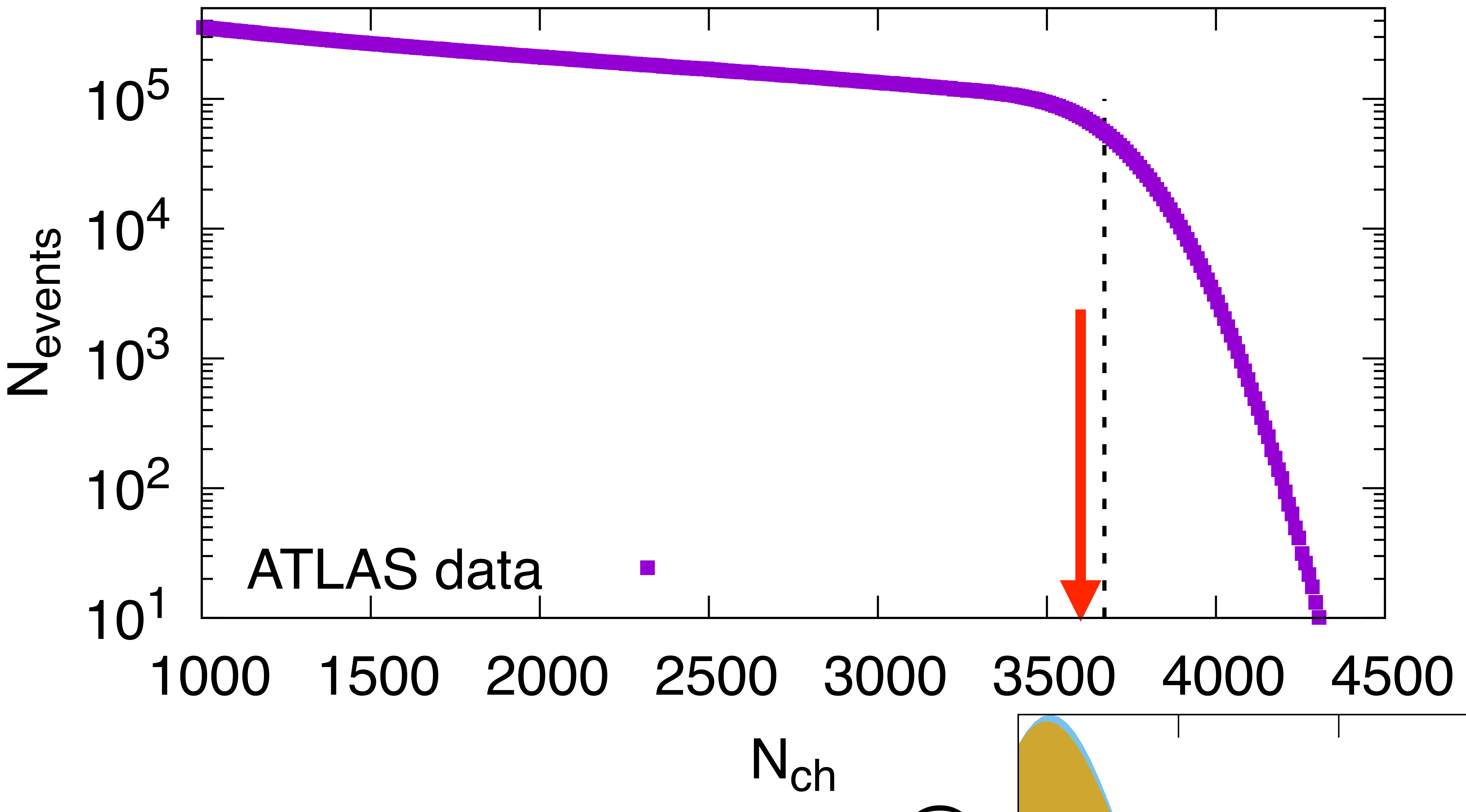

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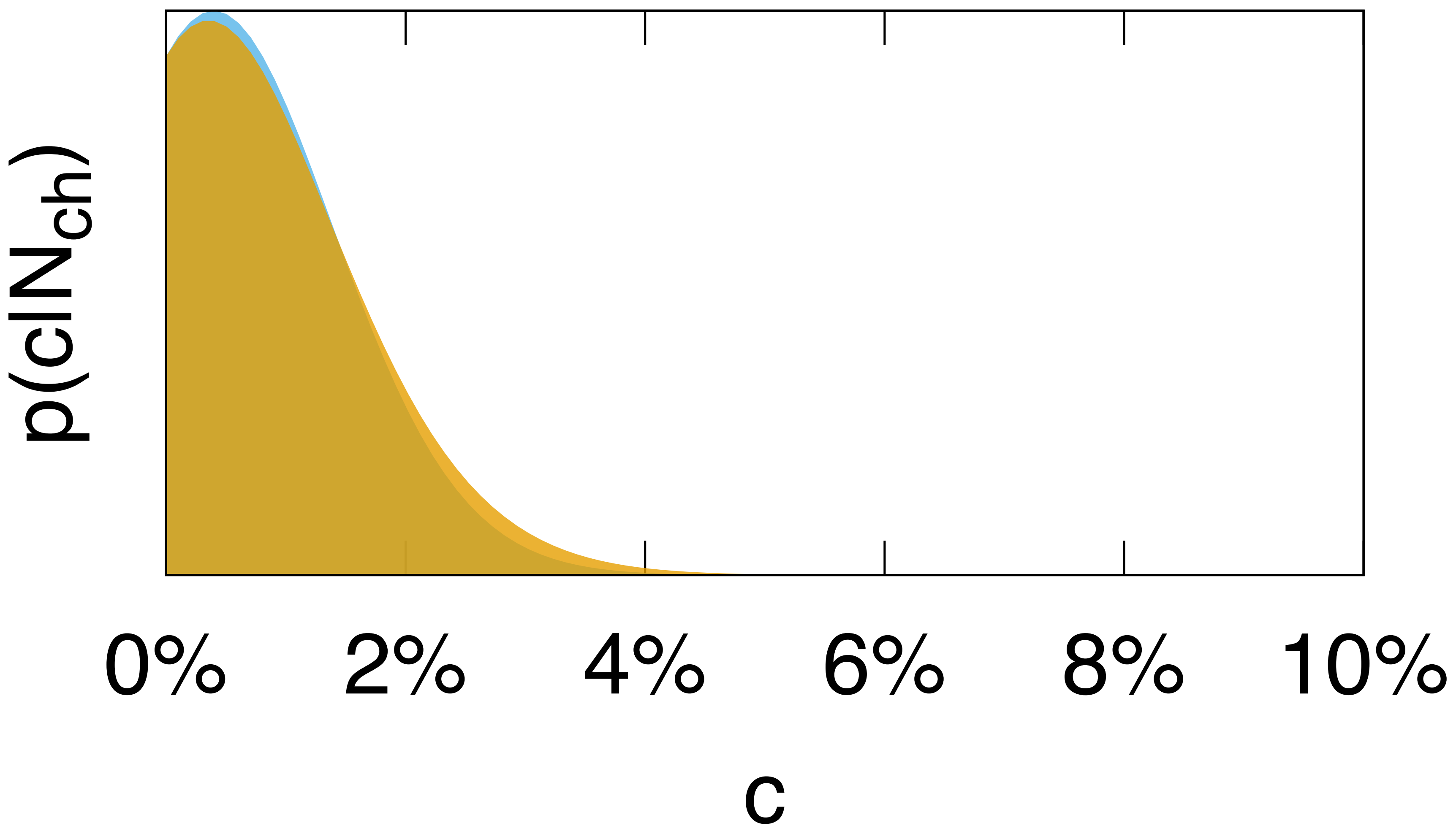
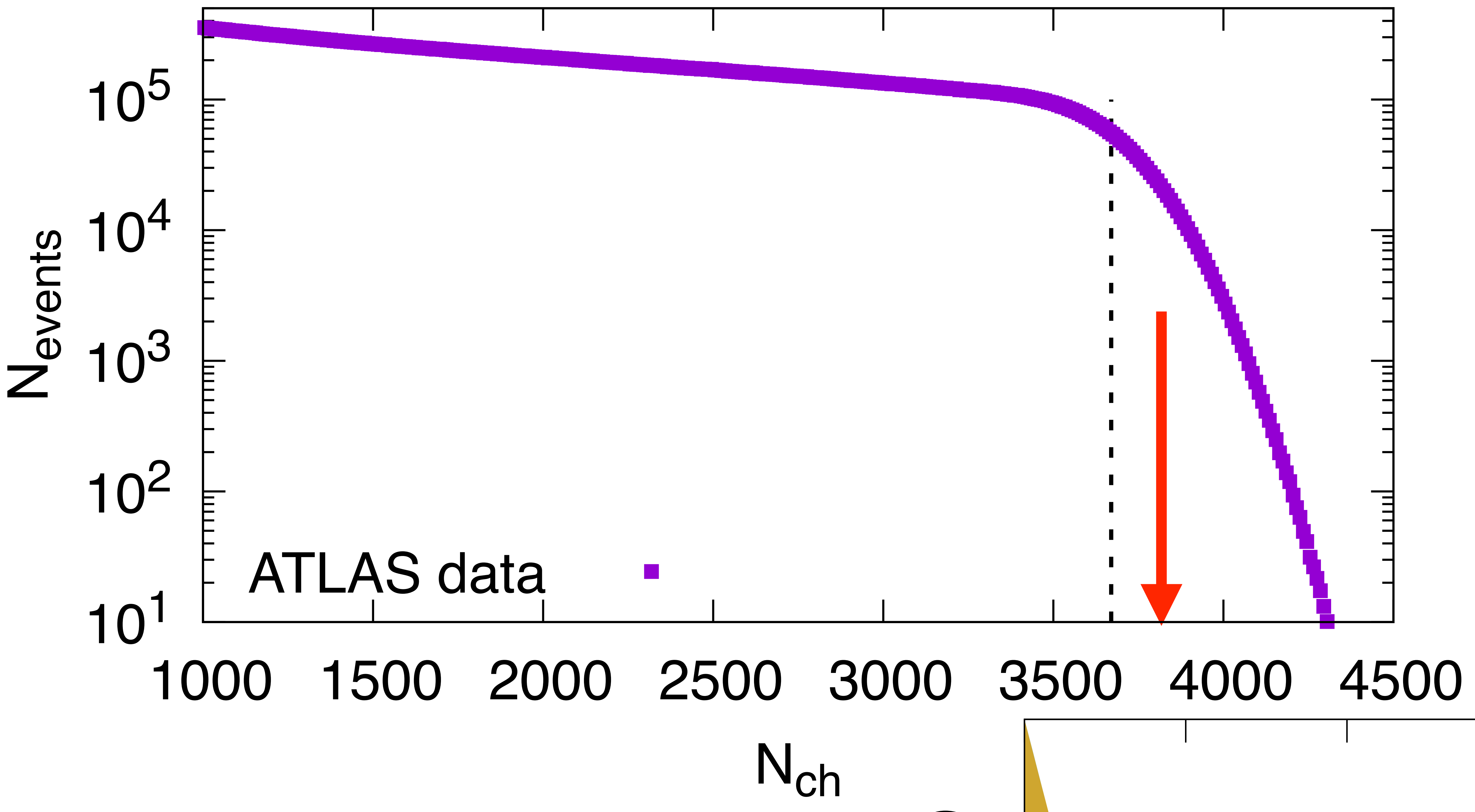
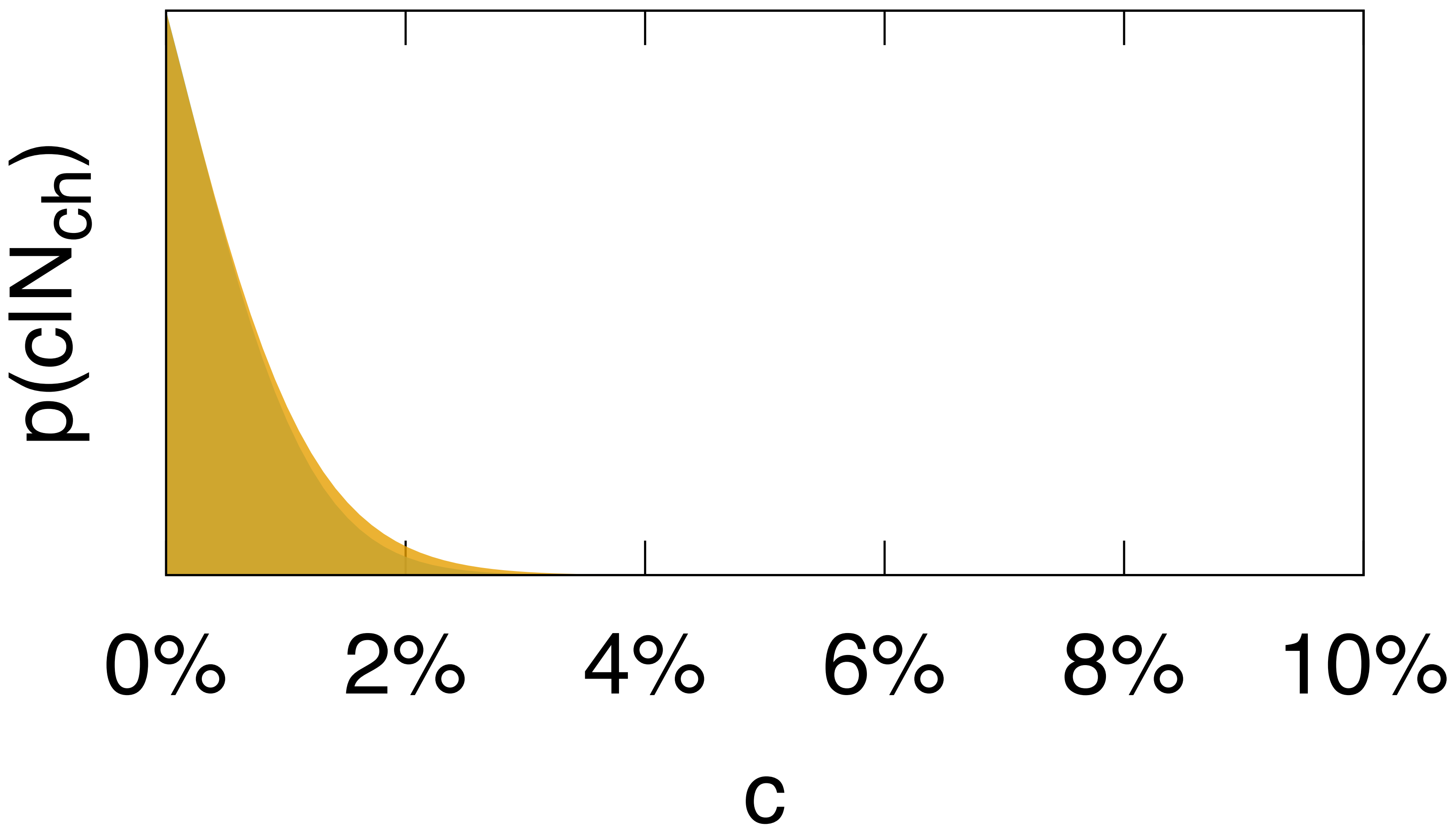


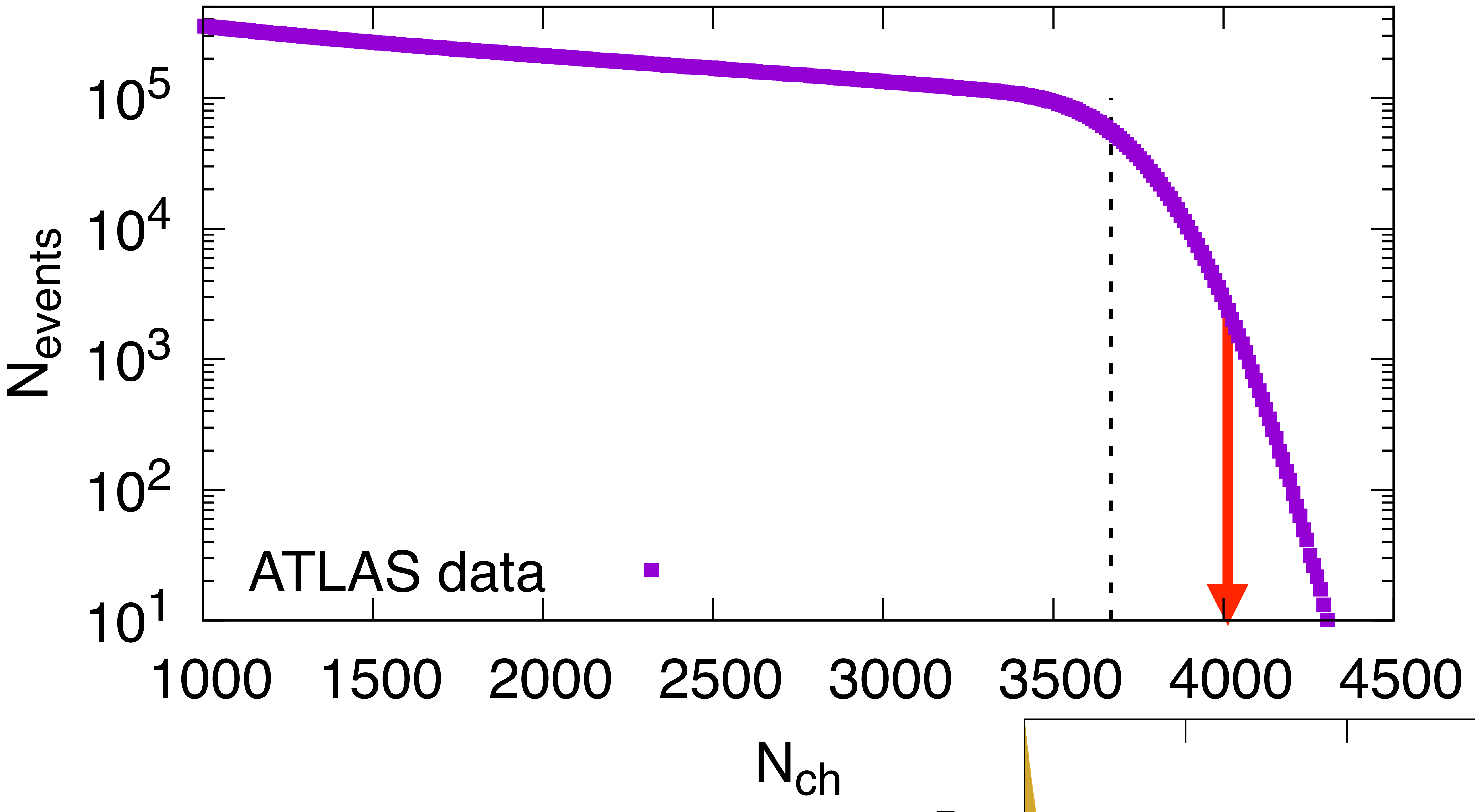
3. Bayesian reconstruction of b fluctuations



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



3. Bayesian reconstruction of b fluctuations



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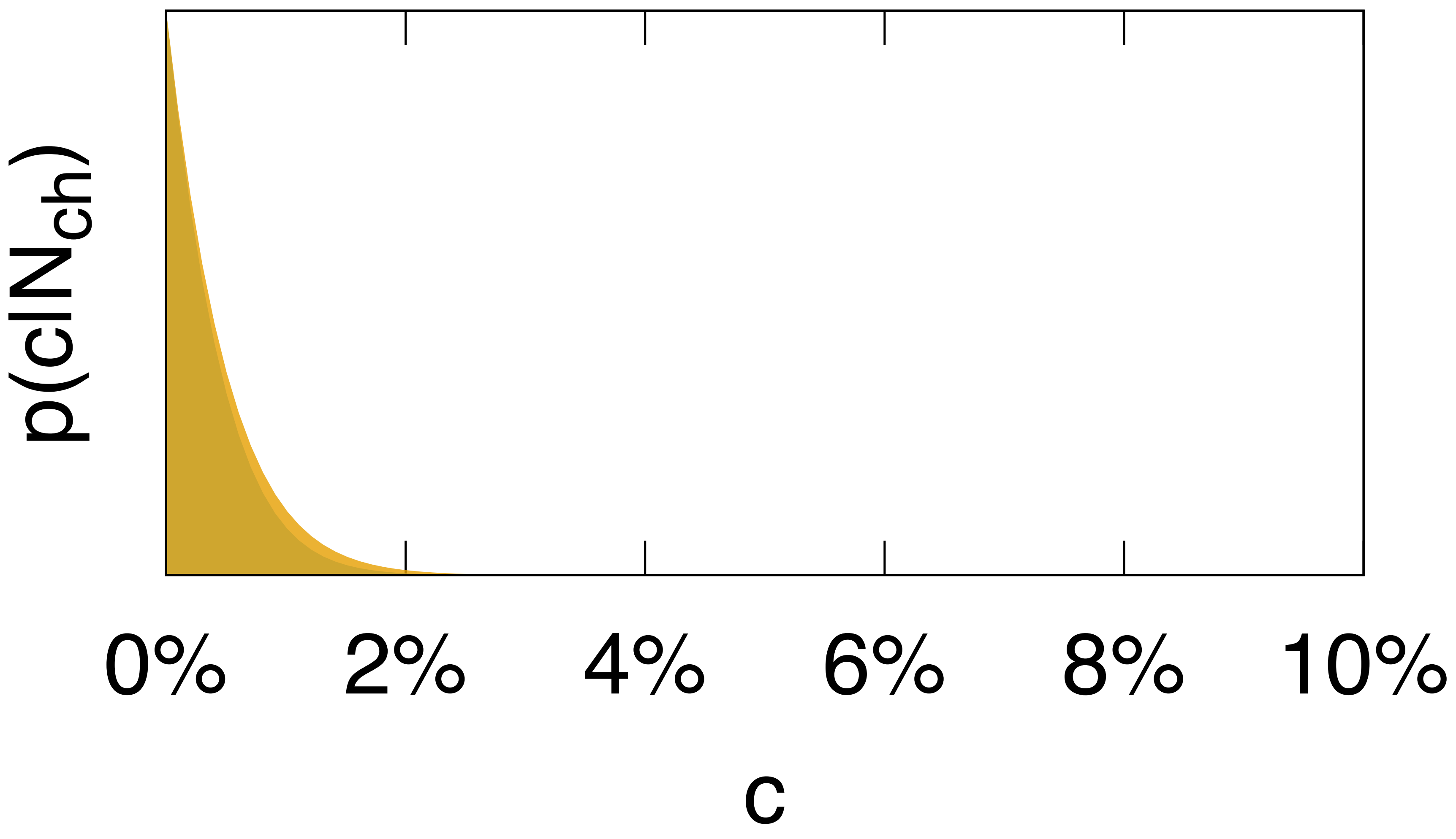
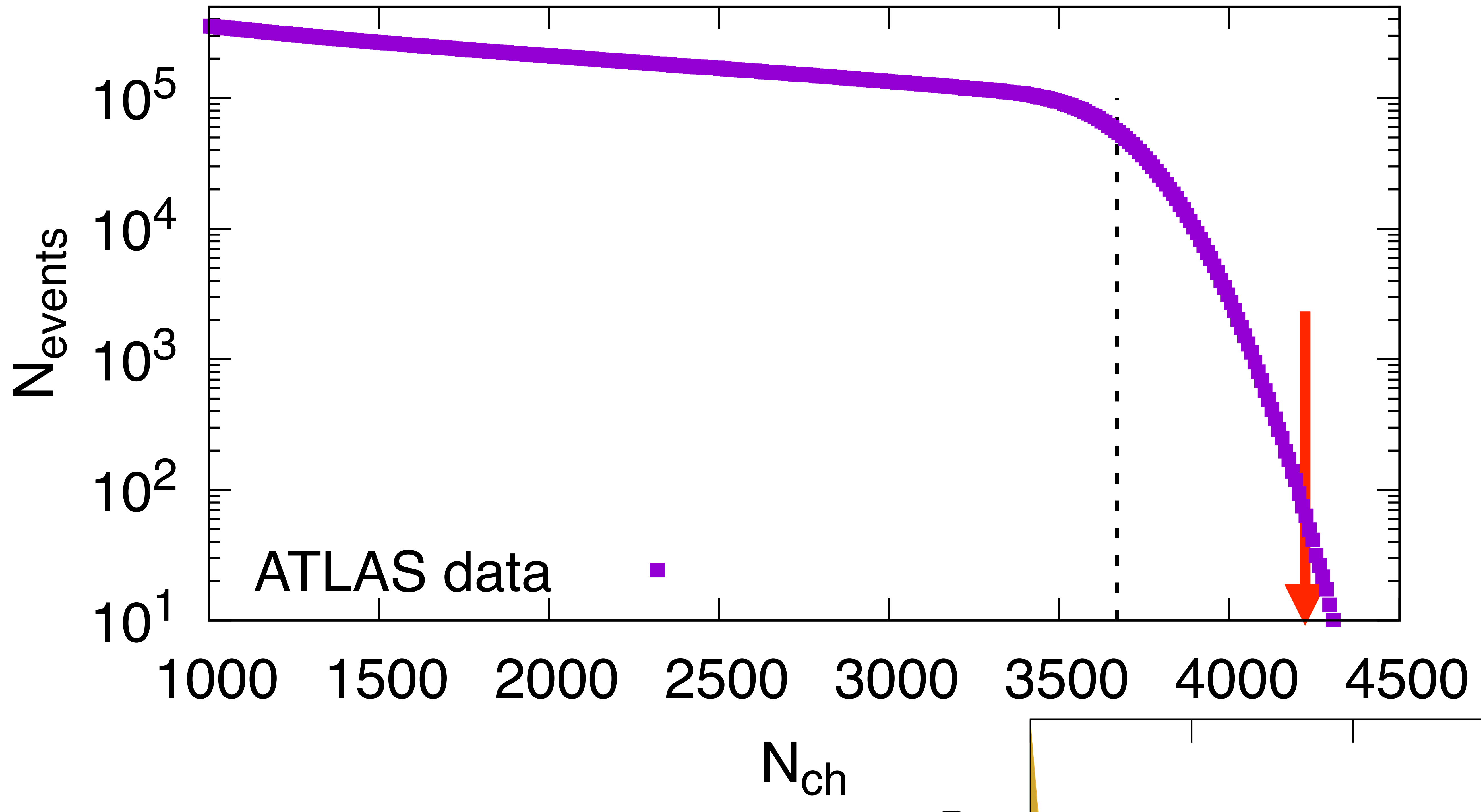
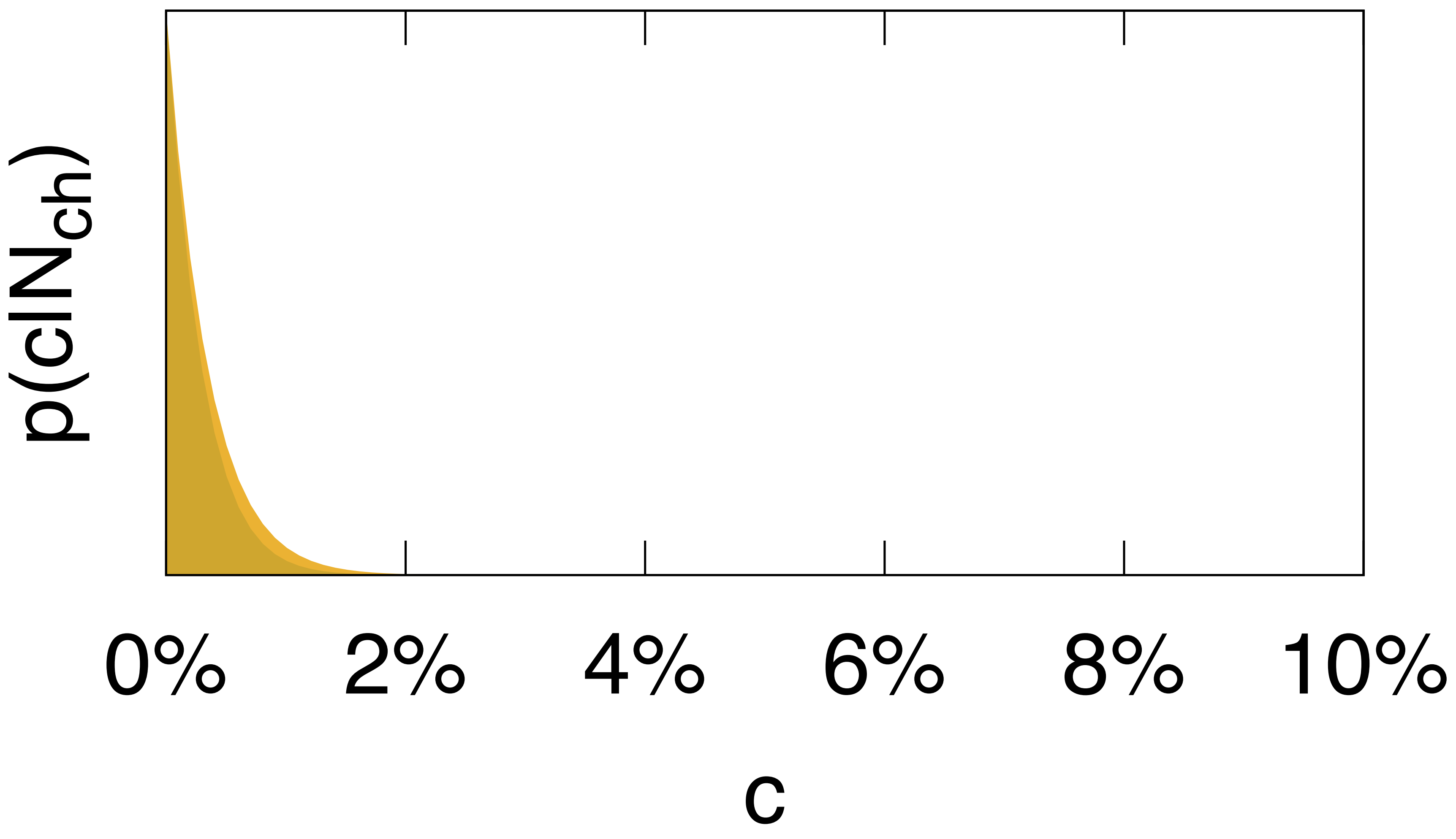


3. Bayesian reconstruction of b fluctuations





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

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

- $[p_T] \approx 3\,T_{\rm eff}$ depends on entropy density $s_{\rm eff} \propto S/R^3 \propto N_{ch}/R^3$
- Increase of mean $[p_T]$:

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

- *Speed of sound c_s from LHC data?*

Gardim Giacalone JYO 1909.11609

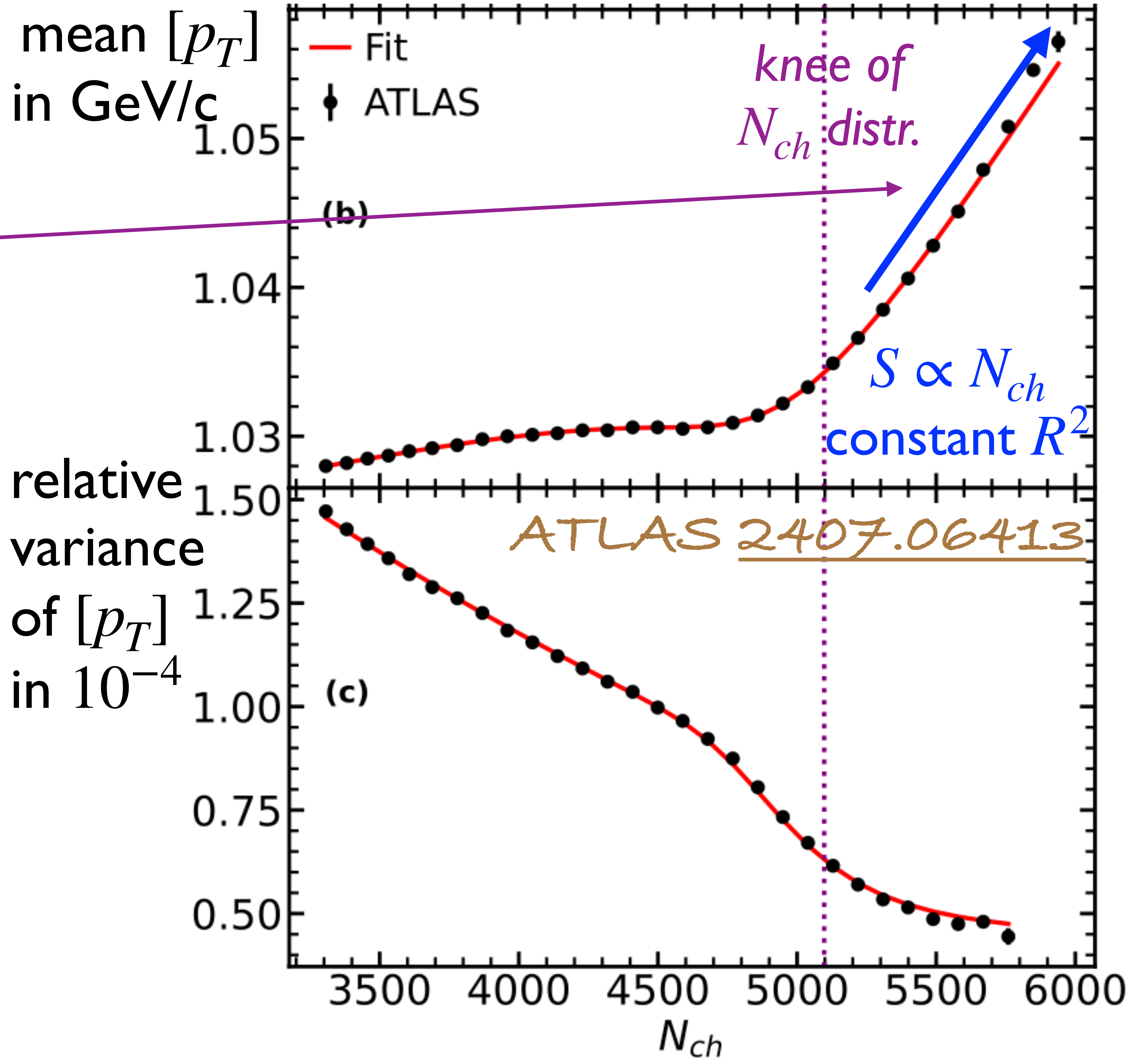
CMS Collaboration 2401.06896

- *Caveats raised! More work needed*

Nijs van der Schee 2312.04623

Gavassino Hirvonen Paquet Singh SoaresRocha 2503.20765

ALICE Collaboration 2506.10394



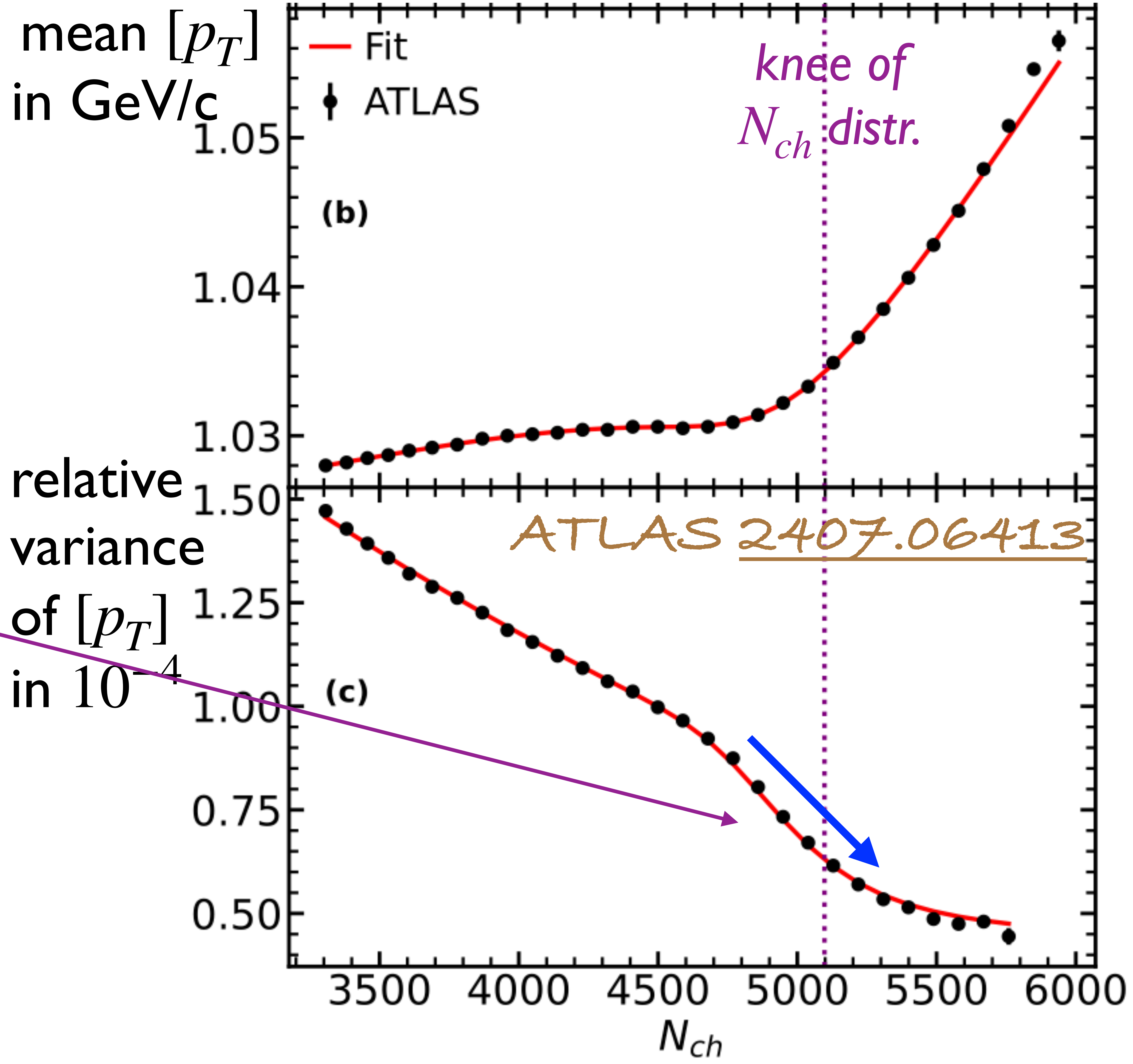
4. Decrease of the variance of $[p_T]$

- $[p_T] \approx 3\,T_{\rm eff}$ depends on entropy density $s_{\rm eff} \propto S/R^3 \propto N_{ch}/R^3$
- 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 JYO 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. Removing the shot noise from hadronization of the fluid (usually referred to as a "self correlation")

D. Is the assumption of constant QGP size R^2 valid in ultracentral collisions?

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 $p_T > 0.5$ GeV/c ≈ half of total.
- The fraction of particles with $p_T > 0.5$ 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:

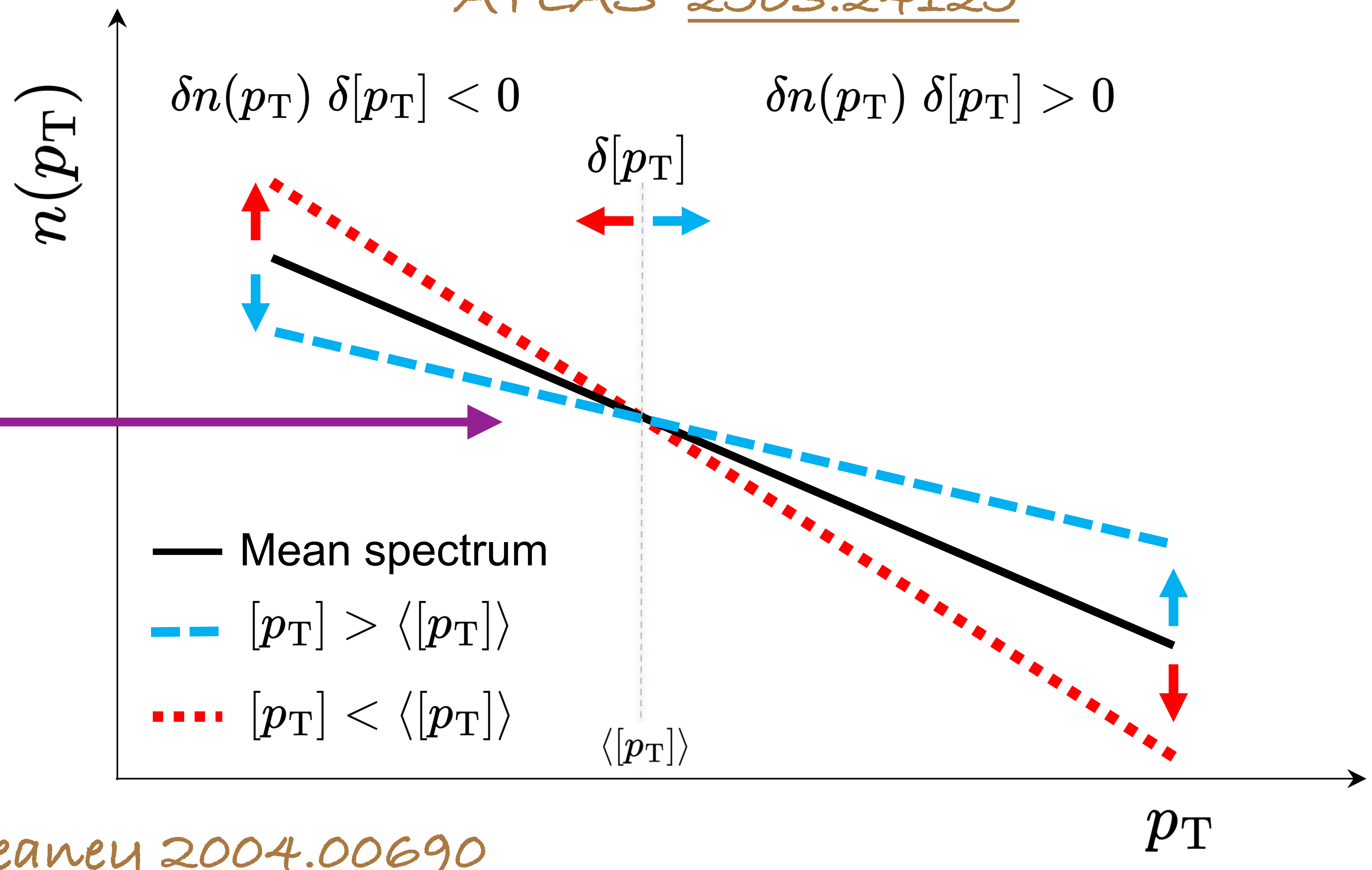
$$\frac{\delta n(p_T)}{n(p_T)} = \frac{v_0(p_T)}{v_0}\frac{\delta[p_T]}{[p_T]}$$

Schenke Shen Teaney 2004.00690

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

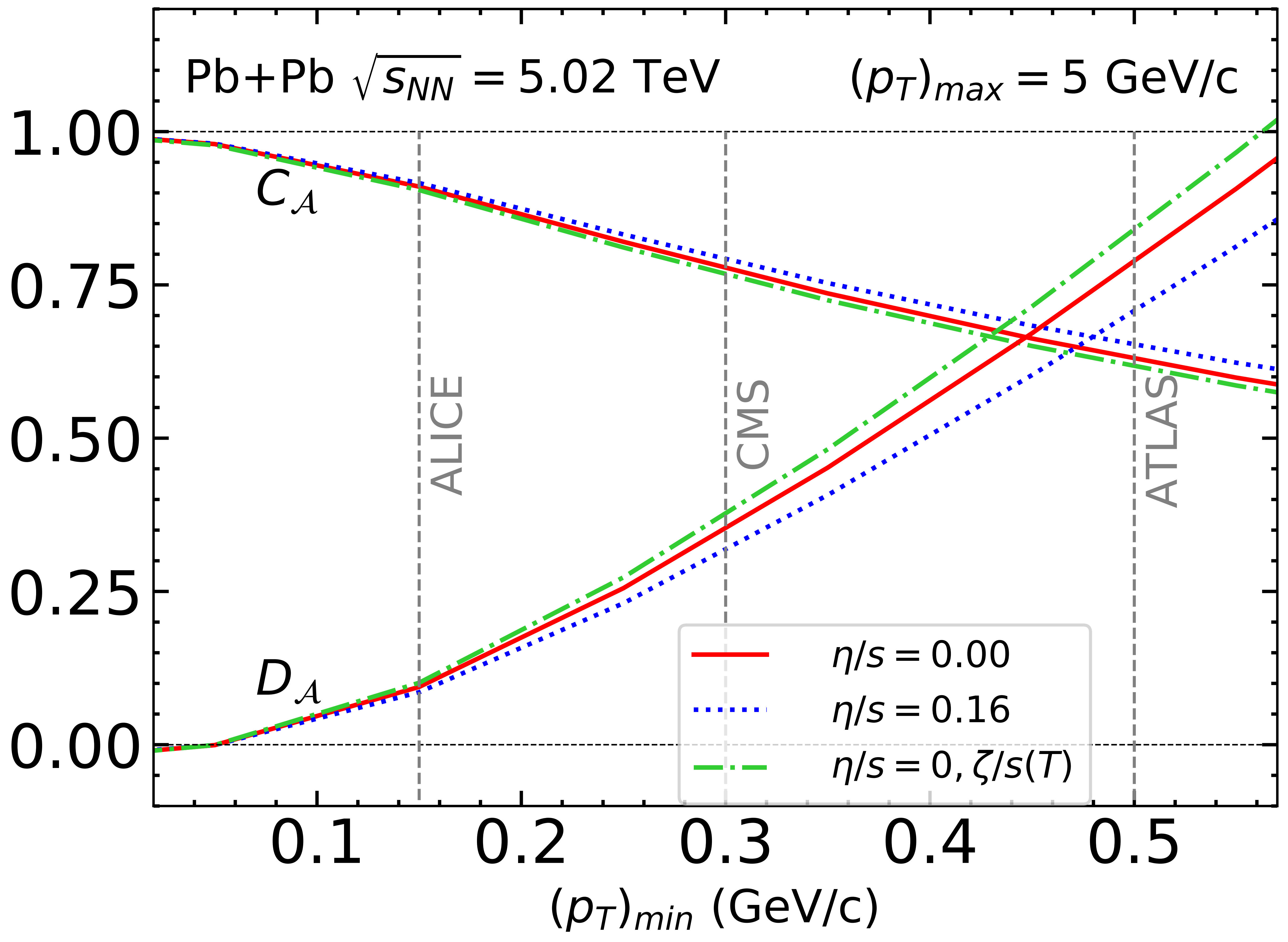
ATLAS 2503.24125 ALICE 2504.04796

ATLAS 2503.24125



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 $v_0(p_T)$

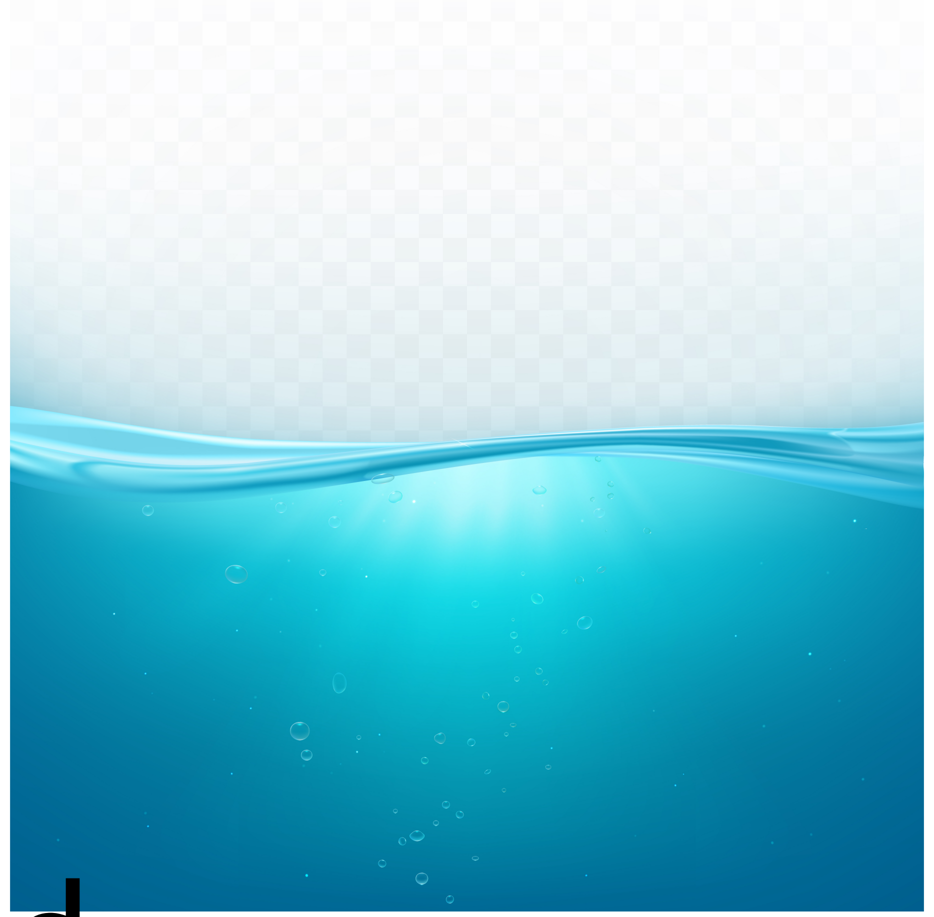


Alqahtani Parida JYO 2603.09647

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 gets a contribution from 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)

Alqahtani Parida JYO 2603.09647

D. Does ultracentral selection affect QGP size?

- The original picture is that an increase in multiplicity or 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 across the volume
- 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 JYO 2511.04605

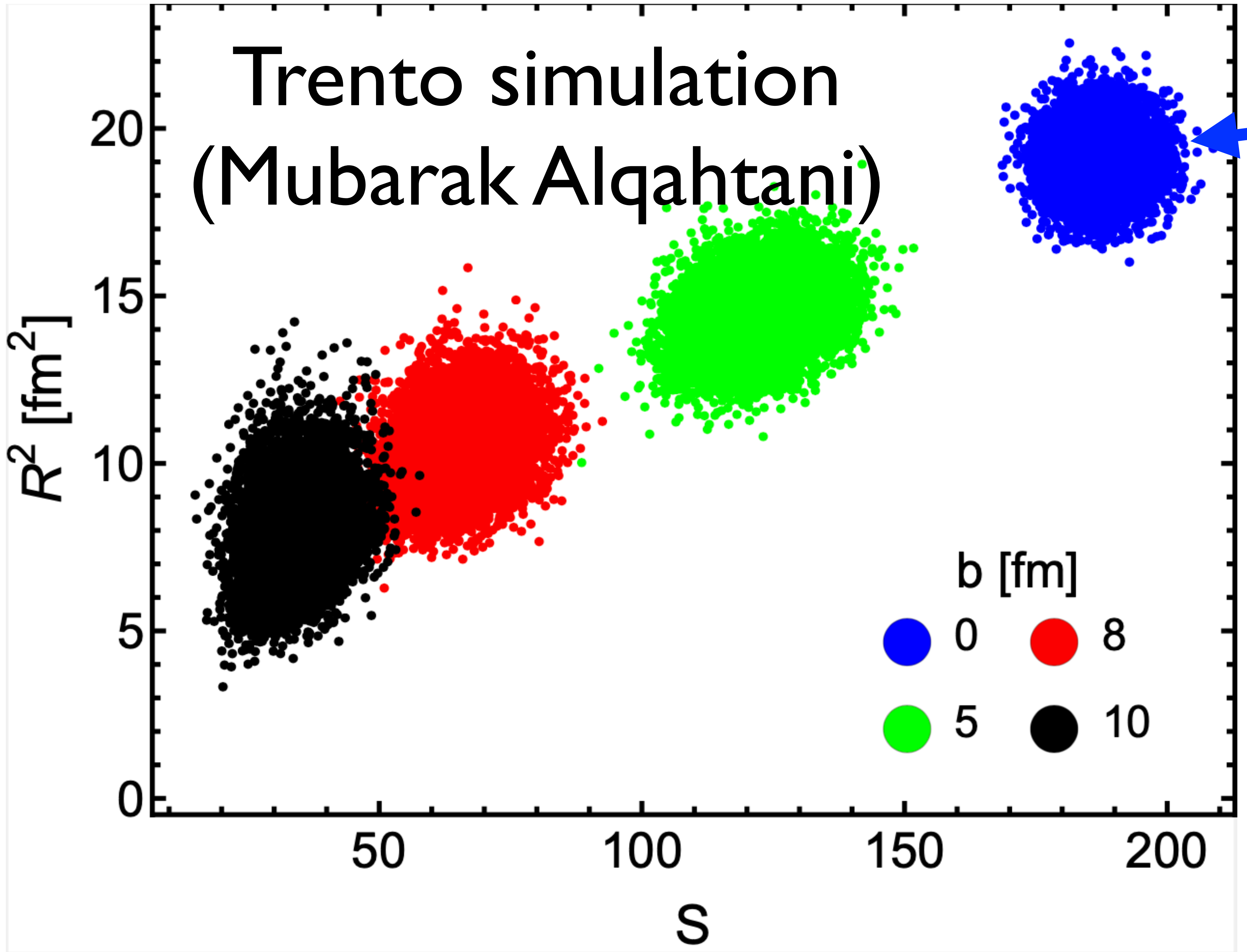
- It is the *only irreducible theory bias* in extracting c_s^2 from data

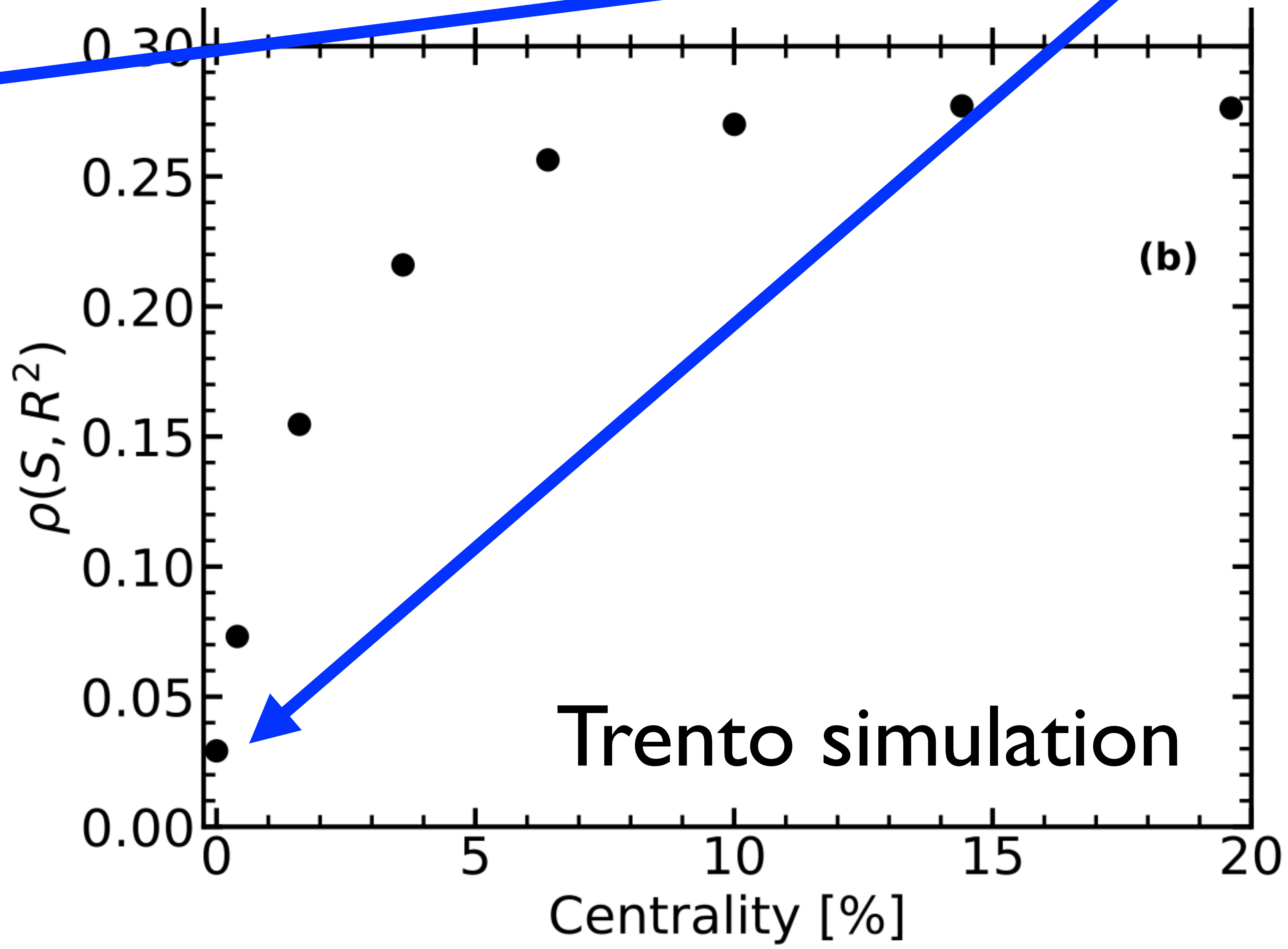
D. Correlation between entropy and size

- 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

Zhou Giacalone JYO 2511.04605

- Implies that the correlation between S and R^2 almost vanishes at b=0





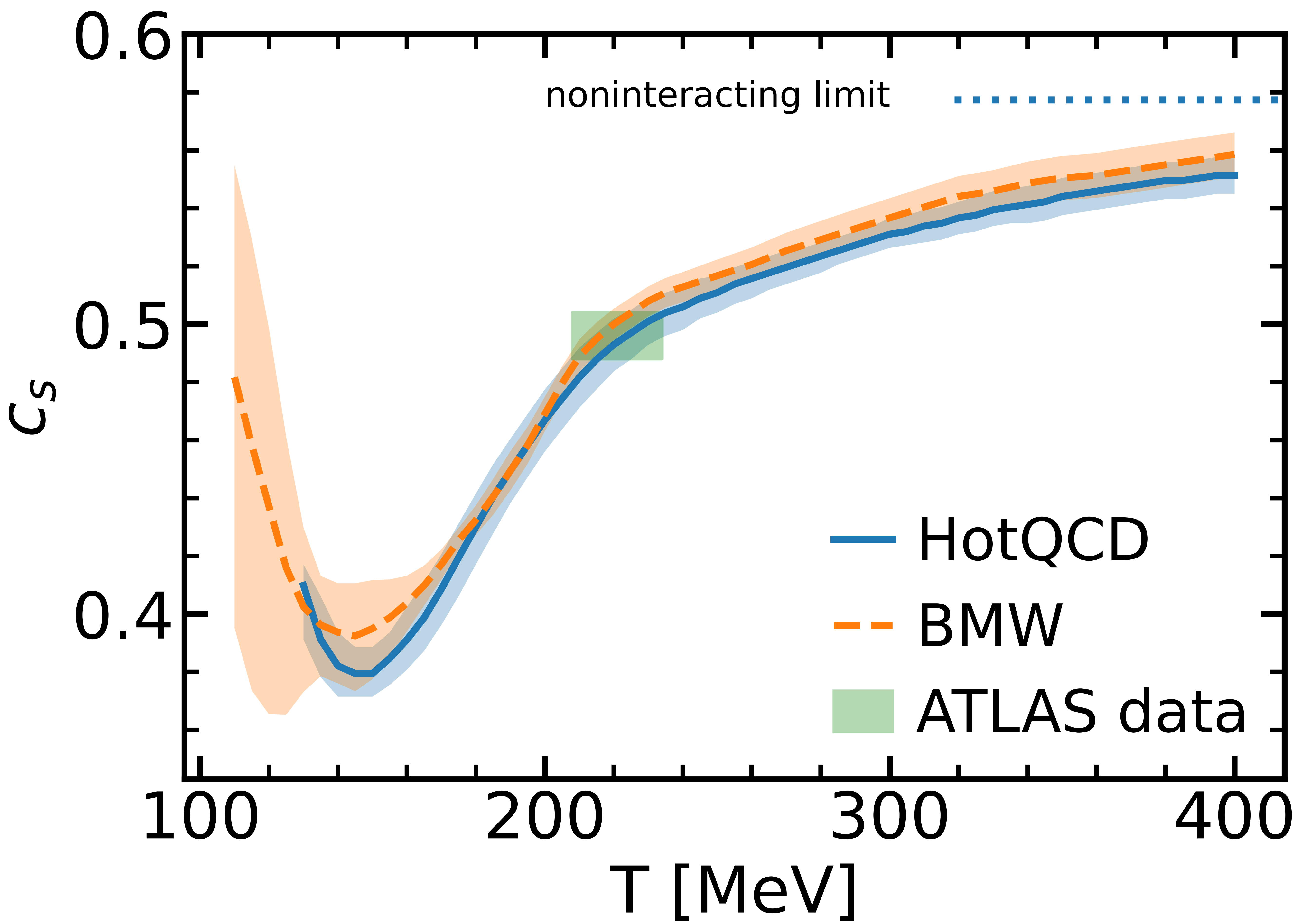
E. Fitting procedure

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 $\langle \mathrm{Rel\,.\,Var}([p_{TA}]) \,|\, N_A, b \rangle$, and c_s^2
- Simplified hydro response as described above:

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

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 smaller than expected

ExTrEMe Collaboration 2203.17011

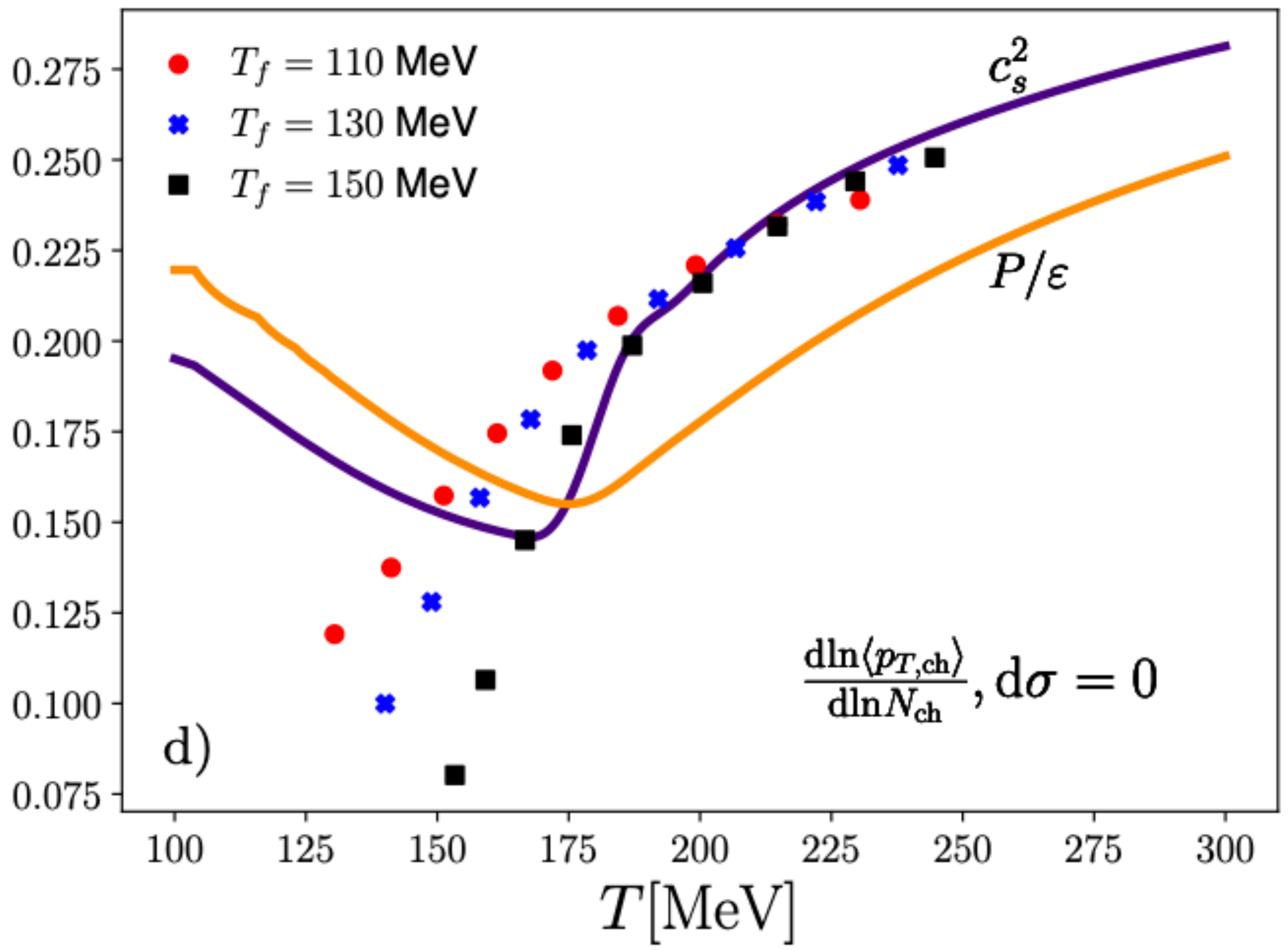
- Reduction of quadrupole (ε_2) fluctuations due to quantum correlations

B.G. Zakharov 2008.07304

Backup

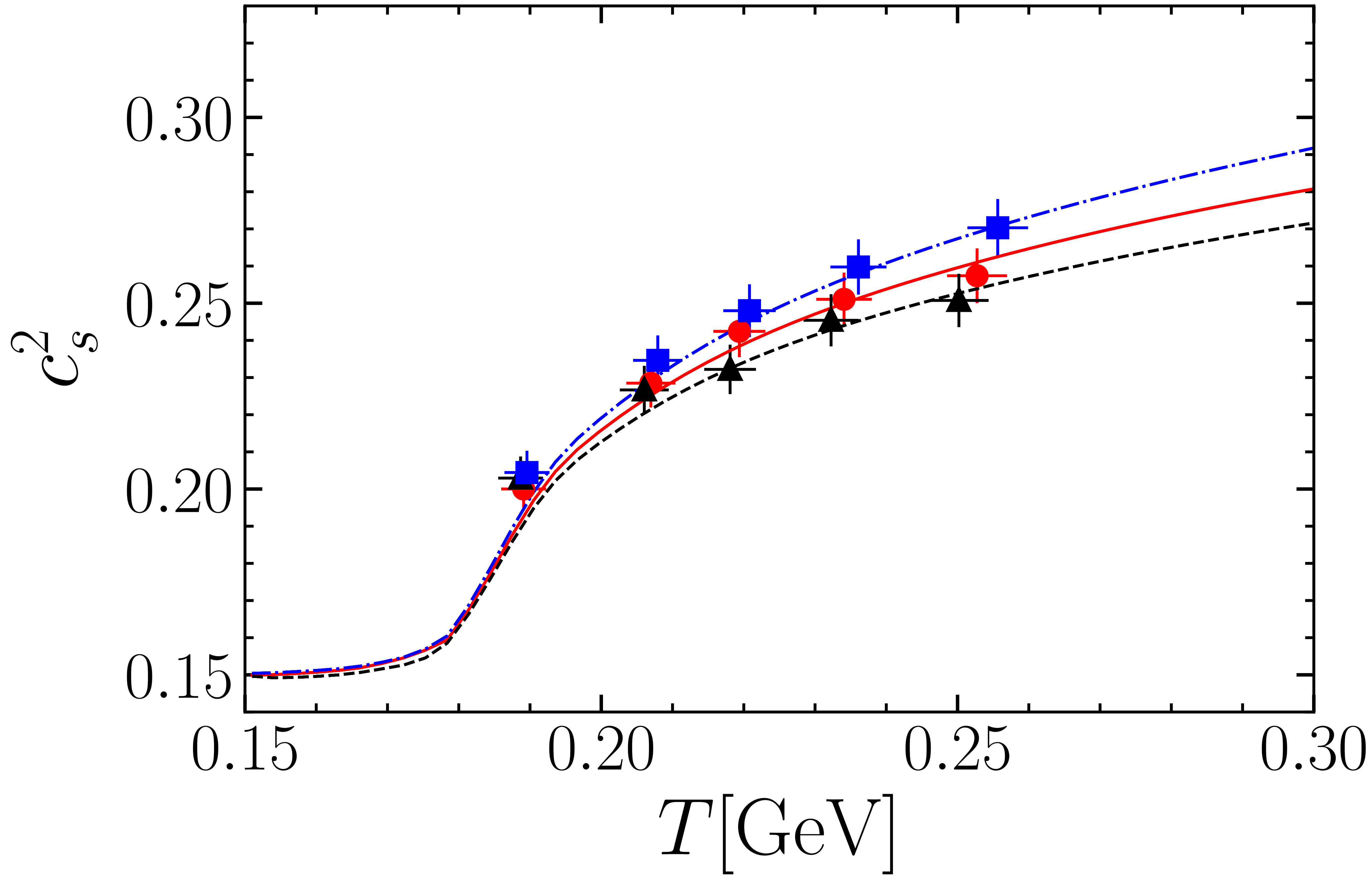
Testing $c_s^2(T_{\text{eff}}) = d\ln\langle p_T\rangle / d\ln N_{ch}$ in hydro

Various freeze-out temperatures & energies



Gavassino Hirvonen Paquet Singh SoaresRocha 2503.20765

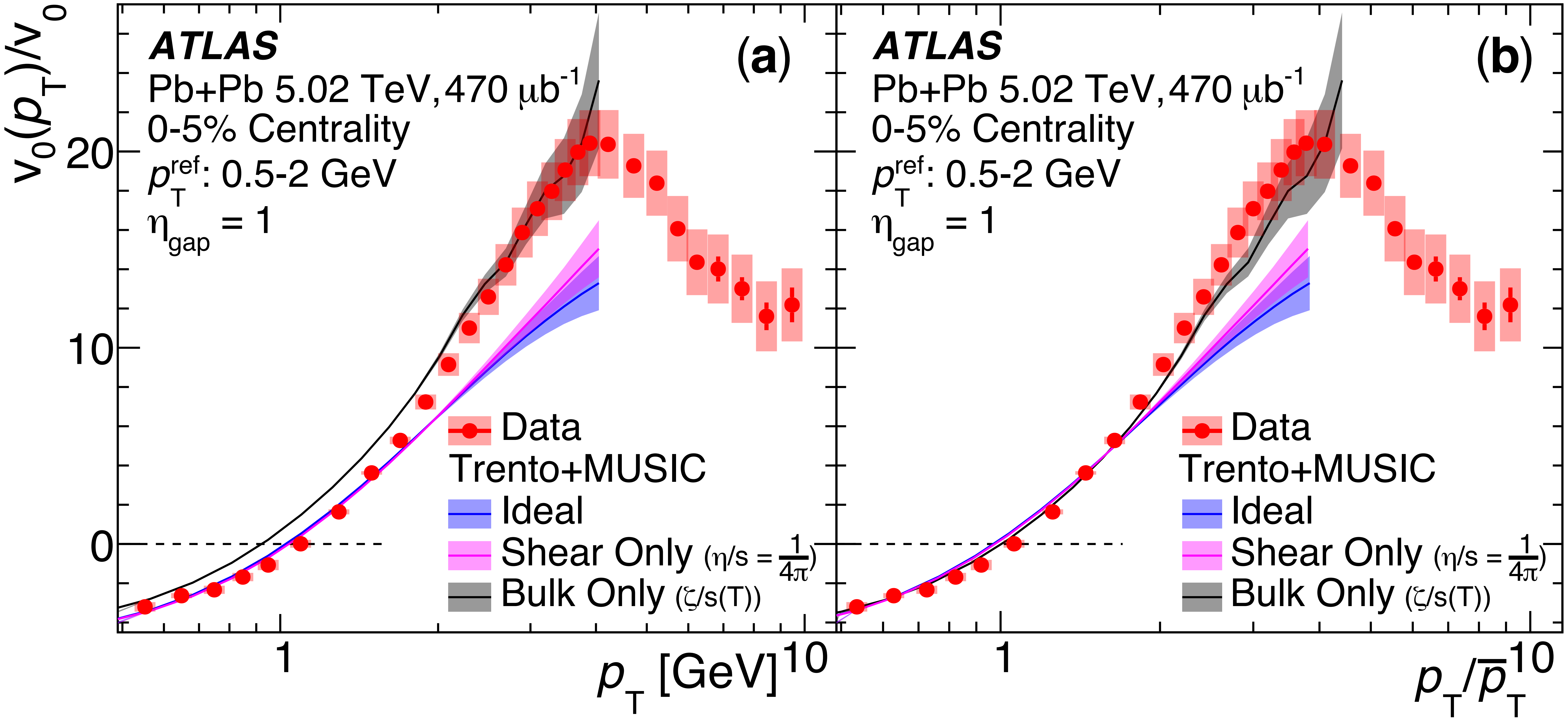
Various equations of state & energies



Gardim Giannini JYO 2403.06052

ATLAS data on $v_0(p_T)/v_0$

ATLAS 2503.24125



Needed to evaluate acceptance corrections C_A and D_A

Robustness of acceptance corrections

Samanta Parida JYO 2407.17313

- One source of uncertainty (not the largest) in the determination of c_s^2 is the uncertainty on $v_0(p_T)$, which is needed to evaluate C_A and D_A
- We use hydrodynamic simulations, which are calibrated to data using the variation of σ_{p_T}, the standard deviation of $[p_T]$, with the upper p_T cut.