Transverse momentum fluctuations in ultracentral Pb+Pb collisions at the LHC

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Exploring Quark-Gluon Plasma through soft and hard probes
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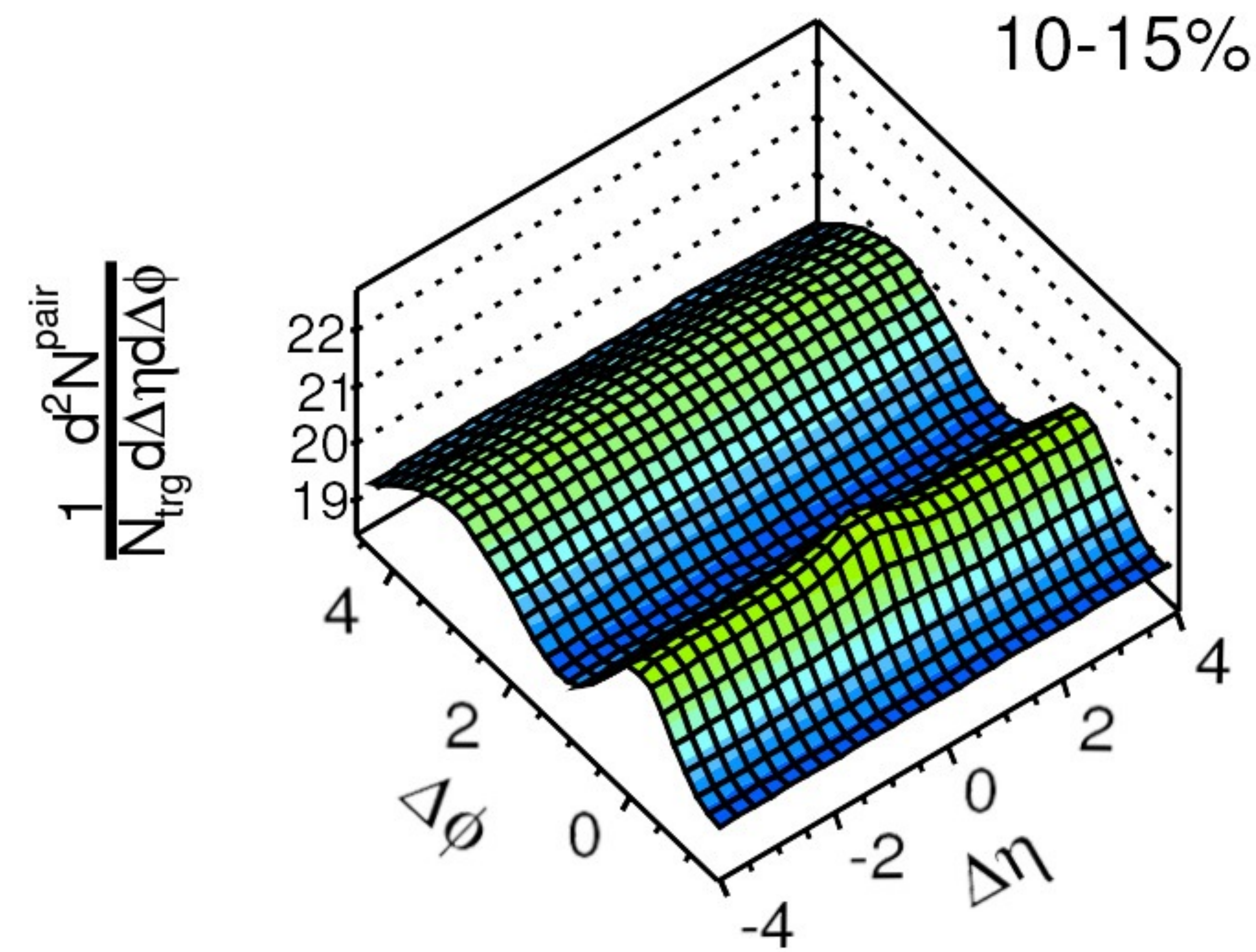
https://arxiv.org/abs/2303.15323

with Rupam Samanta, Somadutta Bhatta, Jiangyong Jia, Matt Luzum

Motivation

In the last ~20 years, experimental evidence for the formation of a little fluid in Pb+Pb collisions at the LHC has largely relied on azimuthal correlations between particles seen in detectors

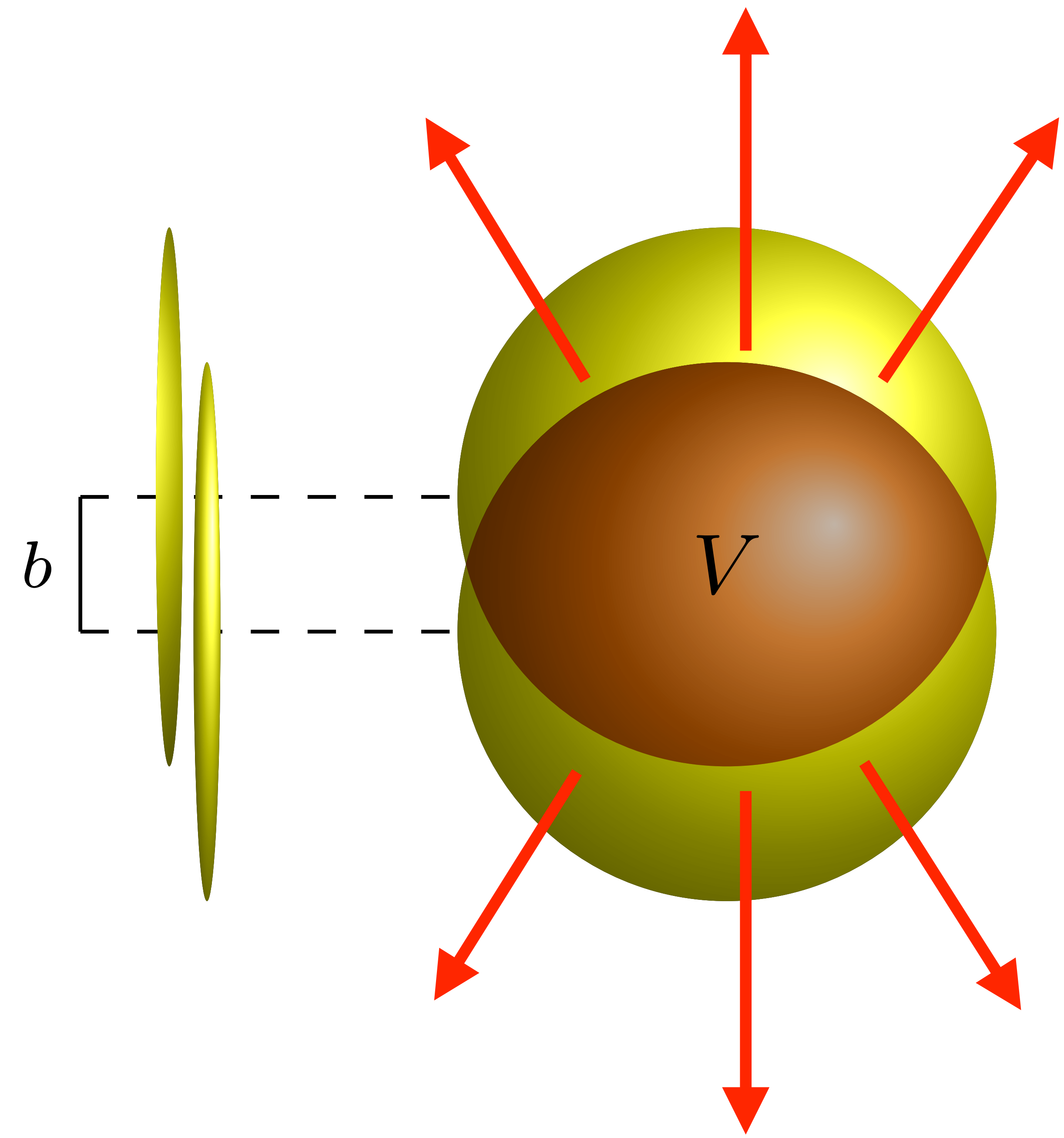


CMS 1201.3158

Motivation

Evidence is indirect :

1. Azimuthal distribution of particles is not isotropic
2. This anisotropy is driven by pressure gradients within a fluid



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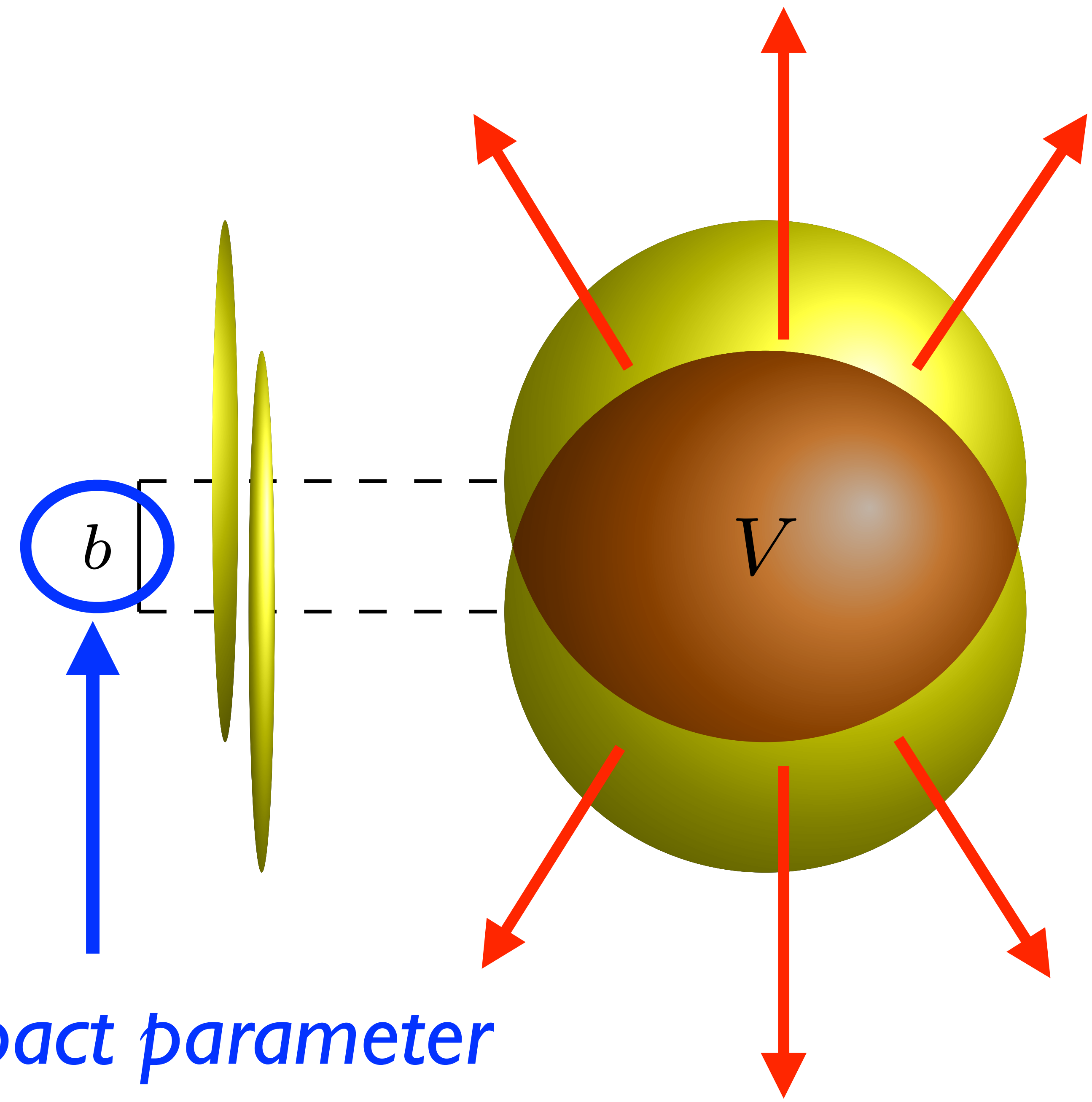


b = impact parameter
important in this talk!

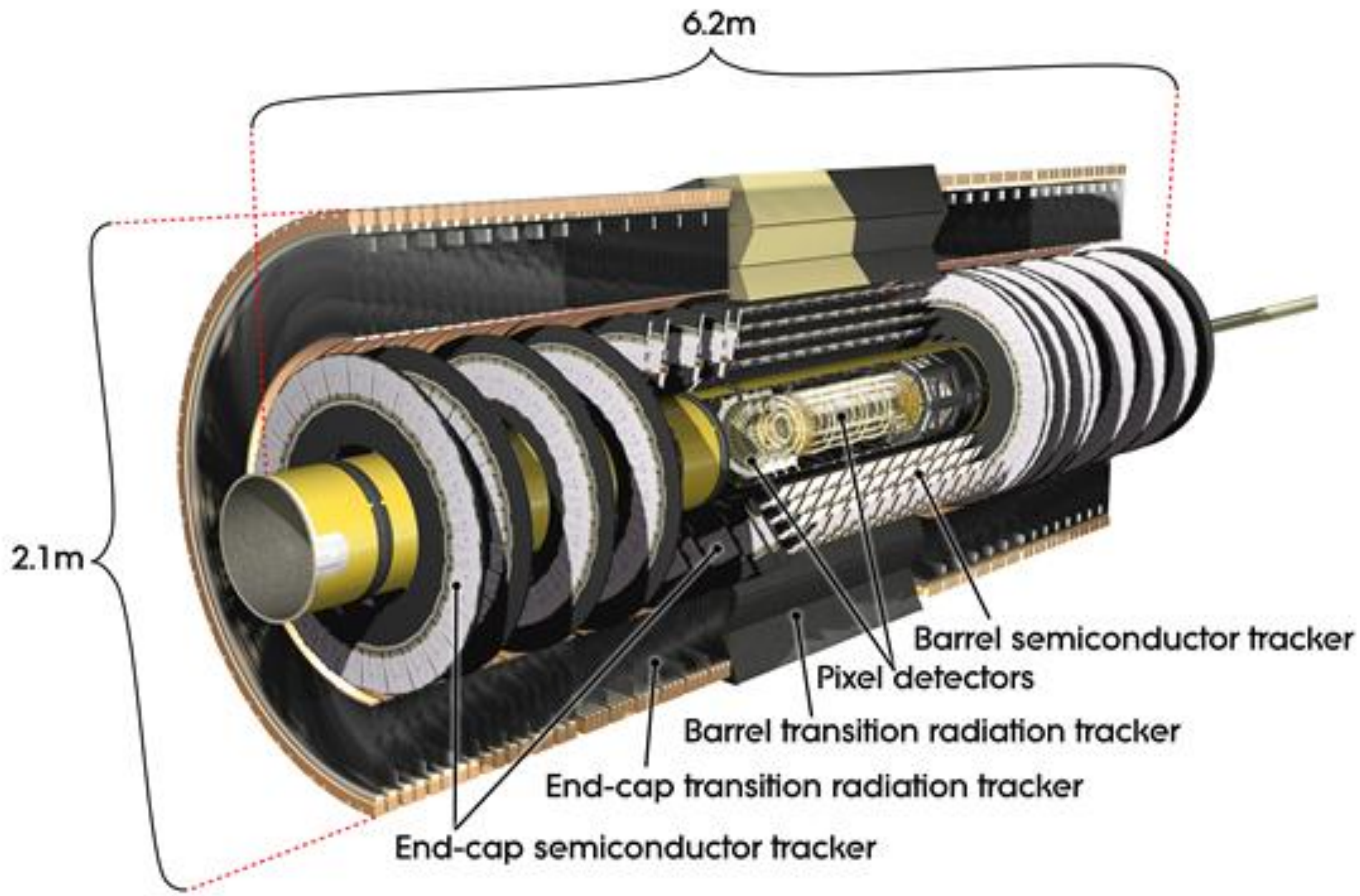
Motivation

Here I want to report more direct evidence of local thermalization in Pb+Pb collisions, which does not involve directions of outgoing particles, but solely their momenta

Outline

1. Motivation
2. What we see in data
   variance of momentum per particle versus collision multiplicity
3. What we see in simulations
4. How we match theory and data
   fluctuations of impact parameter at fixed multiplicity are essential
5. Further predictions

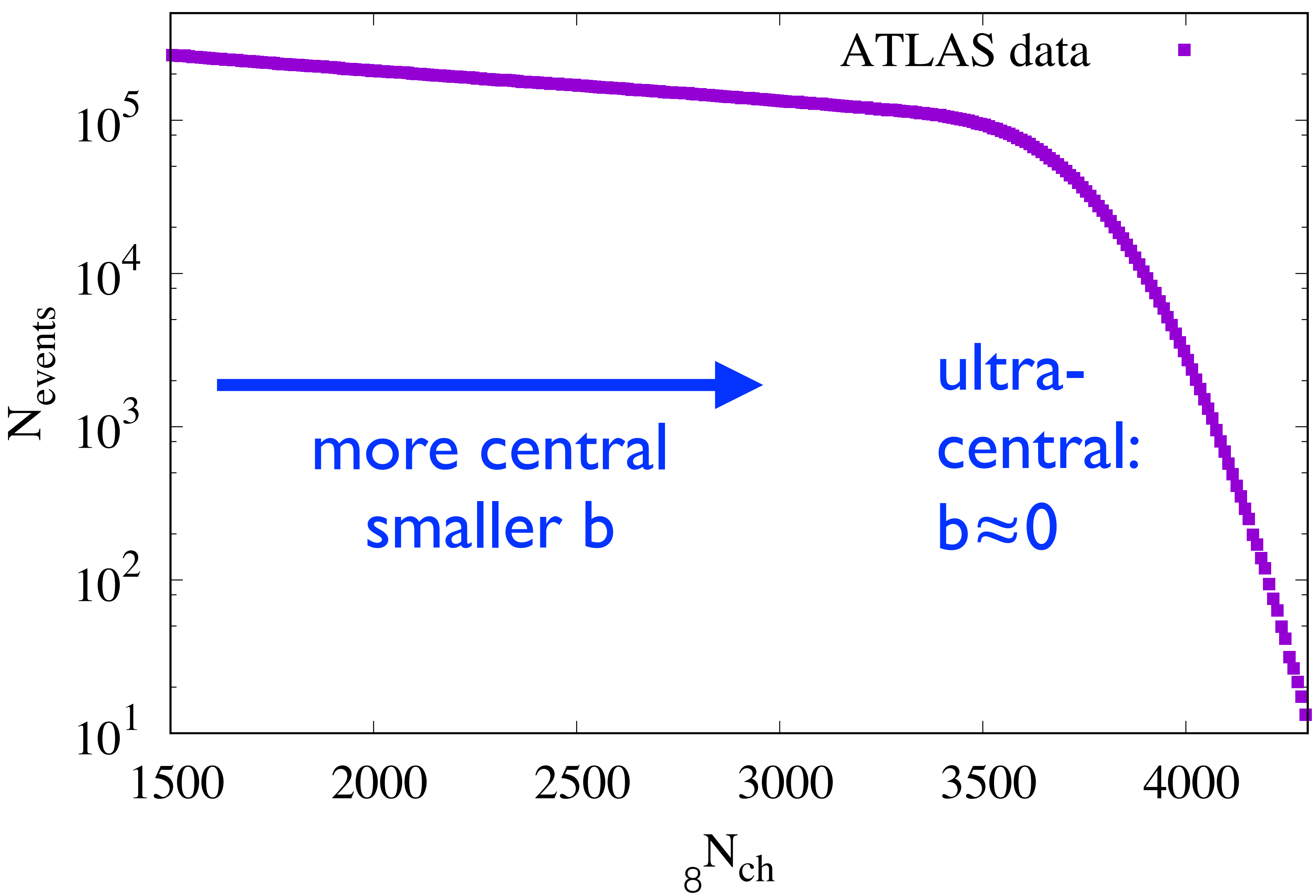
Experiment



The inner detector of ATLAS sees charged particles and measures their momenta in Pb+Pb collisions at 5.02 TeV

Analysis

1. Classify events according to the multiplicity of charged particles, N_{ch} (centrality classification)



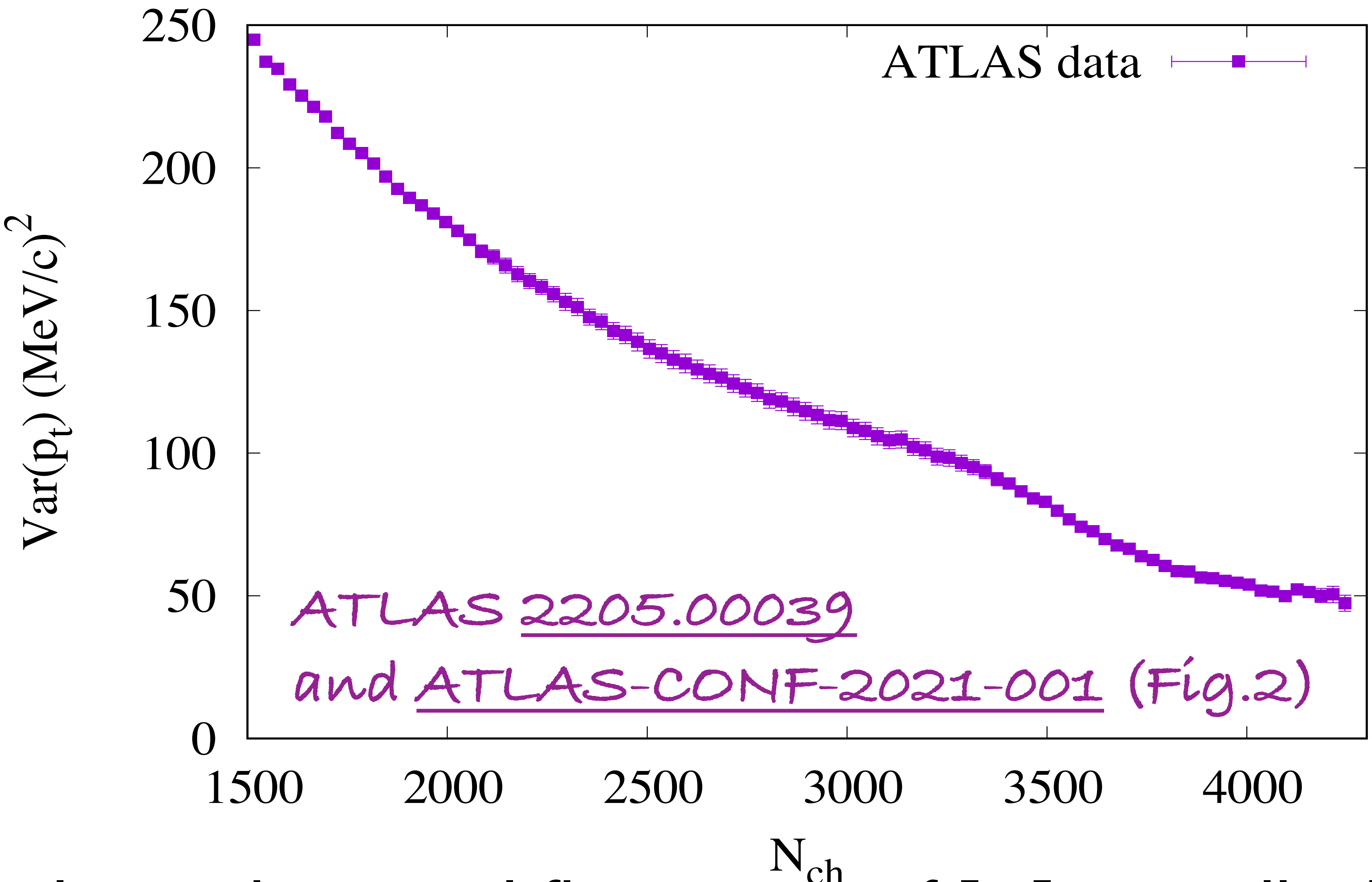
1st of the 2 data sets I use

Analysis

1. Classify events according to the multiplicity of charged particles, N_{ch} (centrality classification)
2. Measure the transverse momentum per charged particle $[p_t]$ in every event
3. Measure the variance of $[p_t]$ fluctuations across collision events with same N_{ch}
4. Subtract the trivial statistical fluctuation of $[p_t]$ due to finite multiplicity to isolate the dynamical variance, which I denote by $Var(p_t|N_{ch})$

- *In practice, 3. and 4. are done simultaneously by measuring a correlation, rather than a fluctuation*

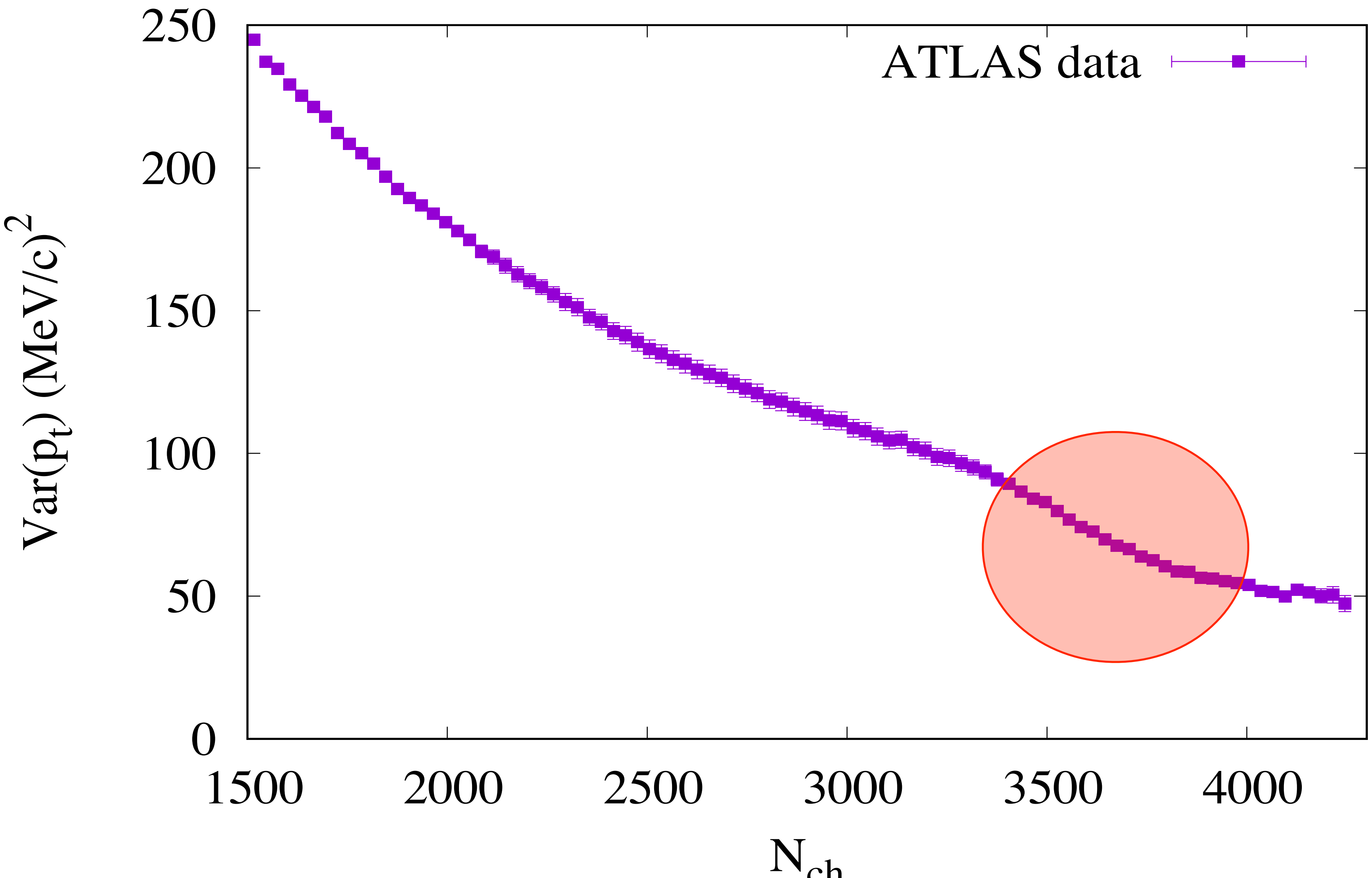
Variance of [p_t]



2nd of the 2 data sets I use

- The relative dynamical fluctuation of [p_t] is small ~1%

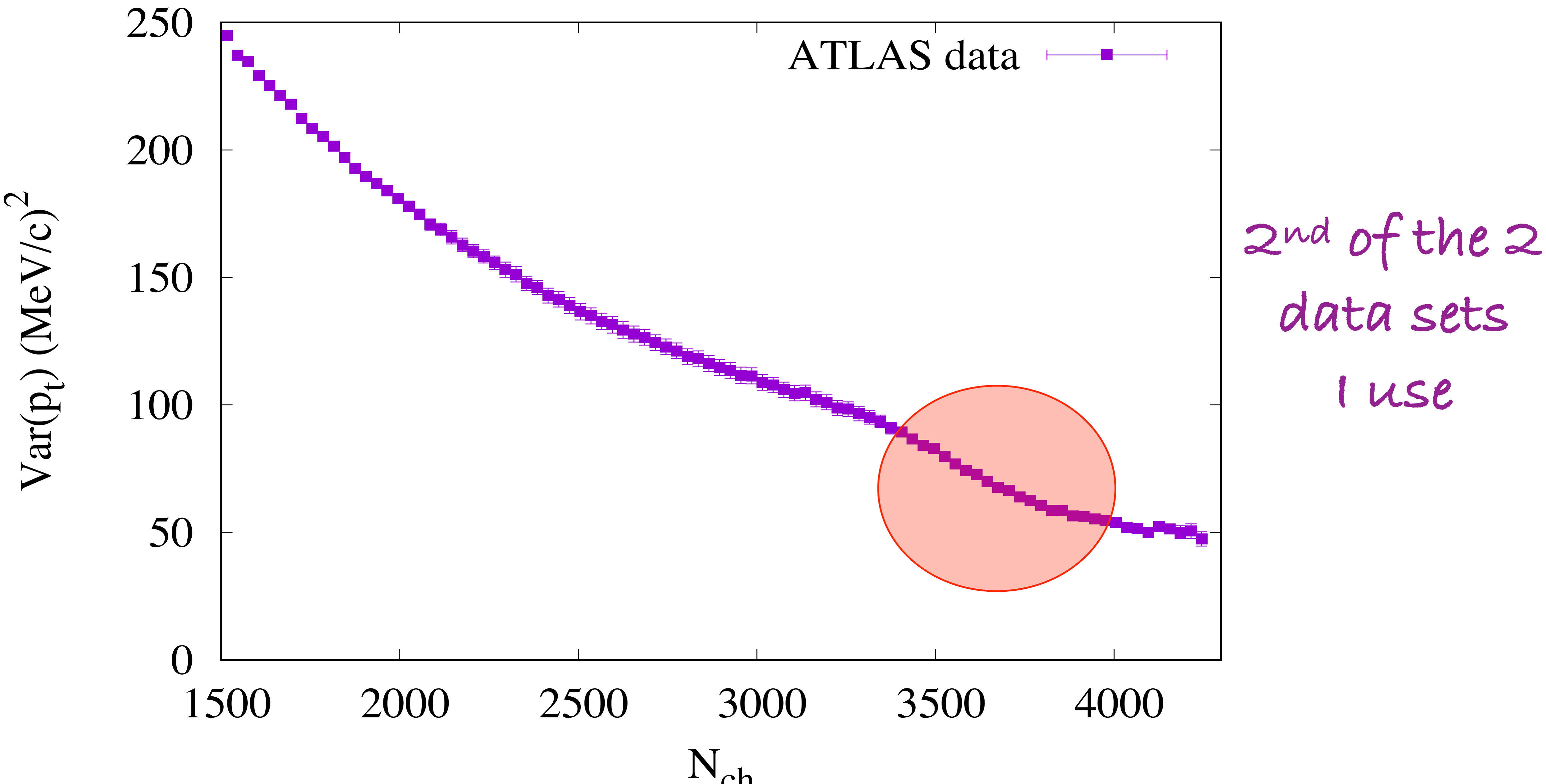
Variance of $[p_t]$



2nd of the 2 data sets I use

- The relative dynamical fluctuation of $[p_t]$ is small ~1%
- Puzzling observation: steep fall over a narrow range of N_{ch}

Variance of $[p_t]$

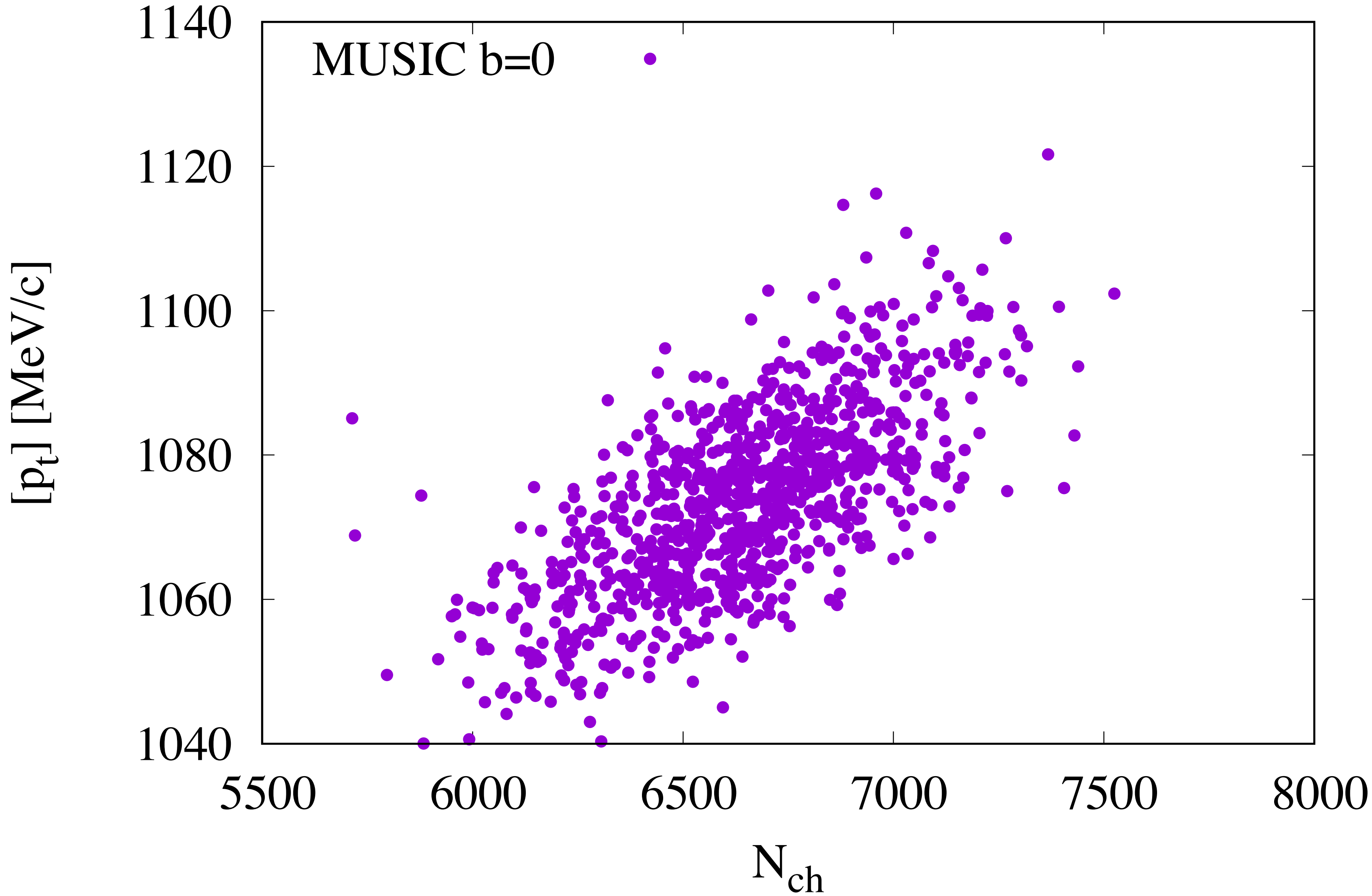


- The relative dynamical fluctuation of $[p_t]$ is small ~1%
- Puzzling observation: steep fall over a narrow range of N_{ch}
- I will show that this is a consequence of thermalization

Hydrodynamic simulations

- Hydro = standard modeling of heavy-ion collisions.
  assumes thermalization
- We simulate Pb+Pb collisions at fixed b.
  In experiment, one knows N_{ch}, not b, but
  In a simulation, b must be specified first, N_{ch} is only known at the end
- Hydro is deterministic. Collisions differ only by quantum fluctuations in initial conditions (from the Trento model)
- Viscous hydro code MUSIC
- We calculate N_{ch} and $[p_t]$ in every event

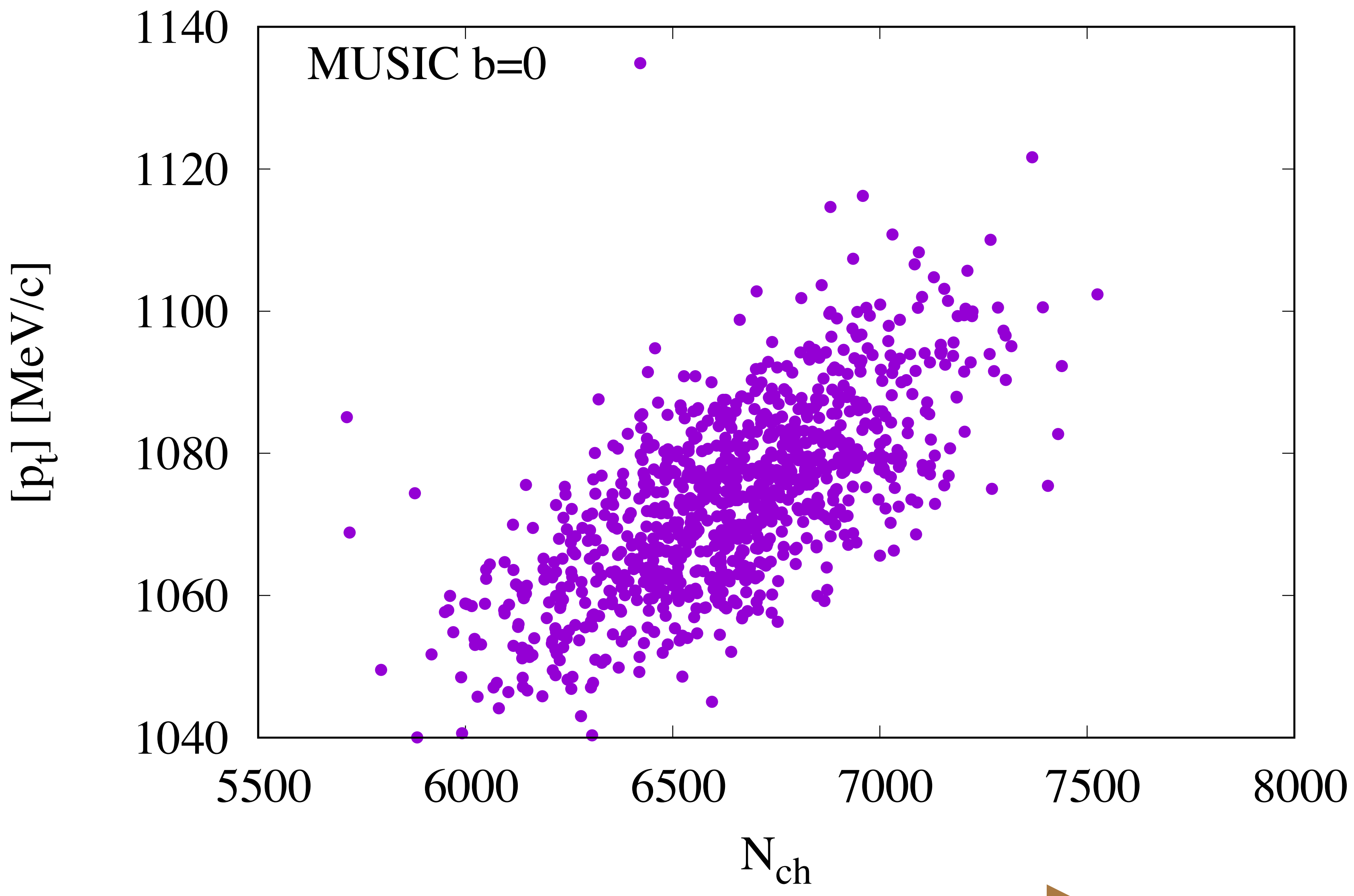
Hydrodynamic simulations



1 point = 1 collision
We simulate 1000 collisions

- Sizable multiplicity fluctuations, modest momentum fluctuations
- Strong **correlation** between N_{ch} and $[p_t]$

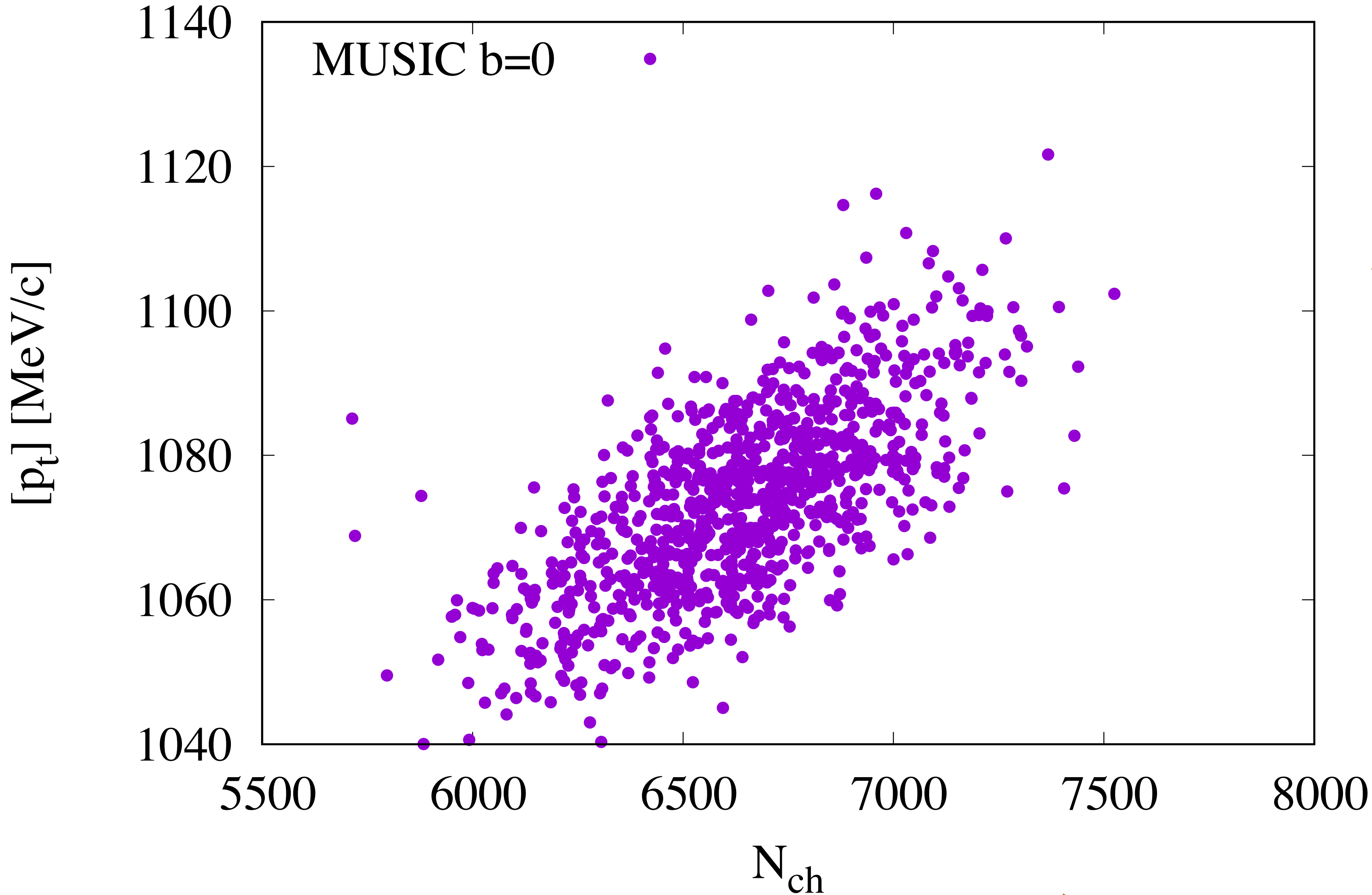
Origin of correlation



density increases

⇒ temperature increases

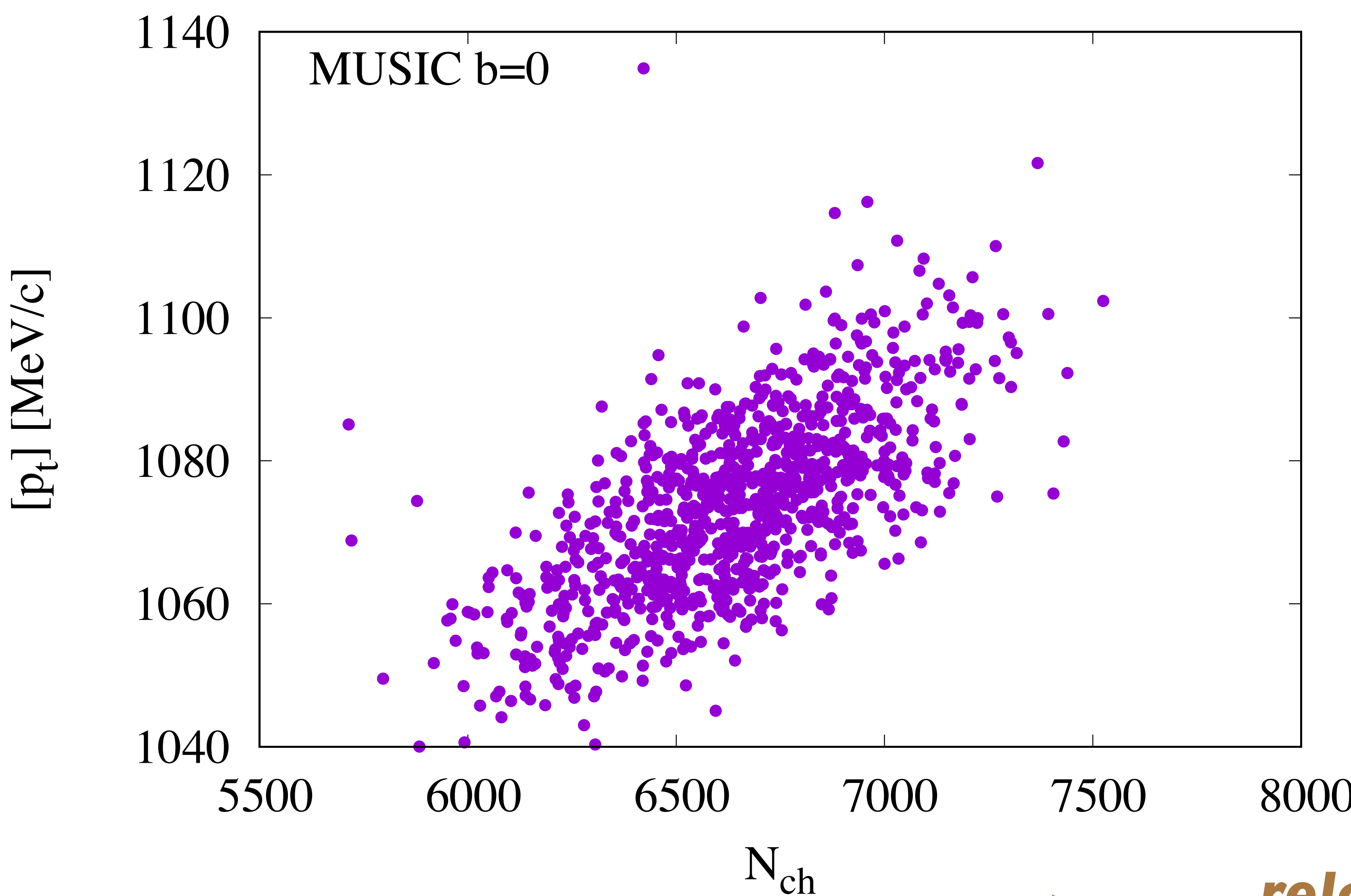
Origin of correlation



momentum per particle increases

density increases
⇒ temperature increases

Origin of correlation



momentum per particle increases

density increases
⇒ temperature increases

relativistic *effect: in non-relativistic thermodynamics, heating a system at fixed volume does not change its density, because no* ***particle creation*** *occurs.*

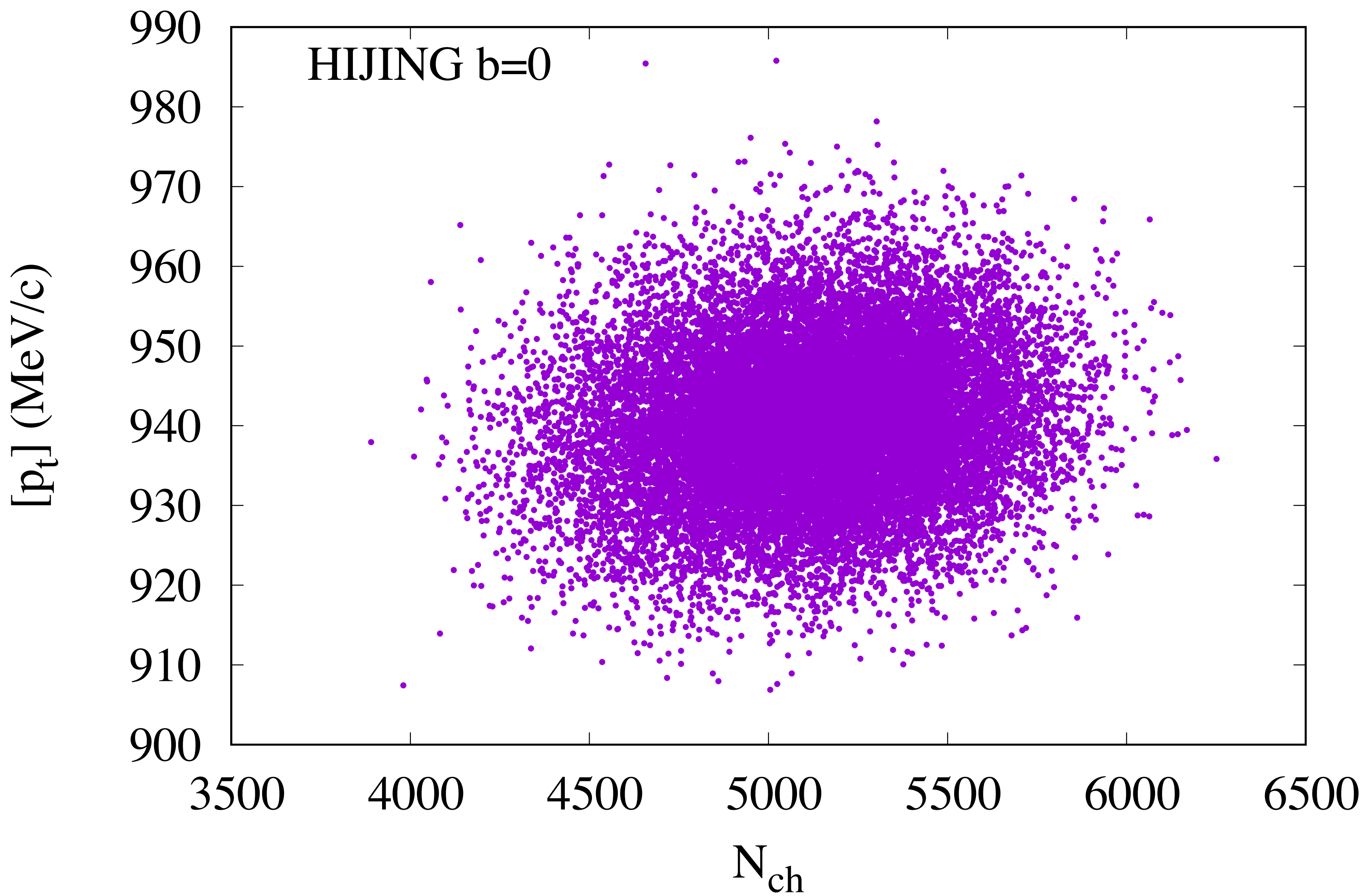
Simulations with HIJING

- HIJING is a widely used microscopic model of high-energy nucleus-nucleus collisions from the early 1990s which **does not assume thermalization**

- We use it to test whether the correlation is specific to a thermalized system.

Wang Gyulassy https://arxiv.org/abs/nucl-th/9502021

Simulations with HIJING

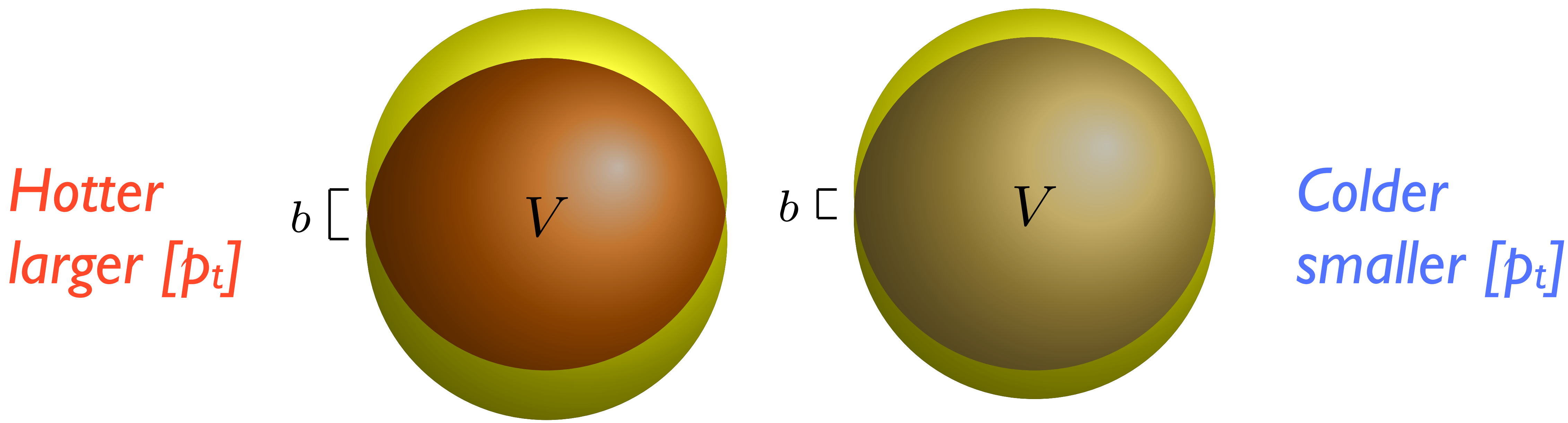


1 point = 1 collision
20000 collisions are shown

- Very small correlation (~10 x smaller)
- Hence the correlation is a signature of thermalization

Next: find thermalization in data

- Fluctuations of $[p_t]$ measured for fixed N_{ch}, not fixed b.
- The clue: Fixed N_{ch} → Finite range of b.



- The variation of b gives a contribution to the variance of $[p_t]$, which goes to 0 in ultracentral collisions.

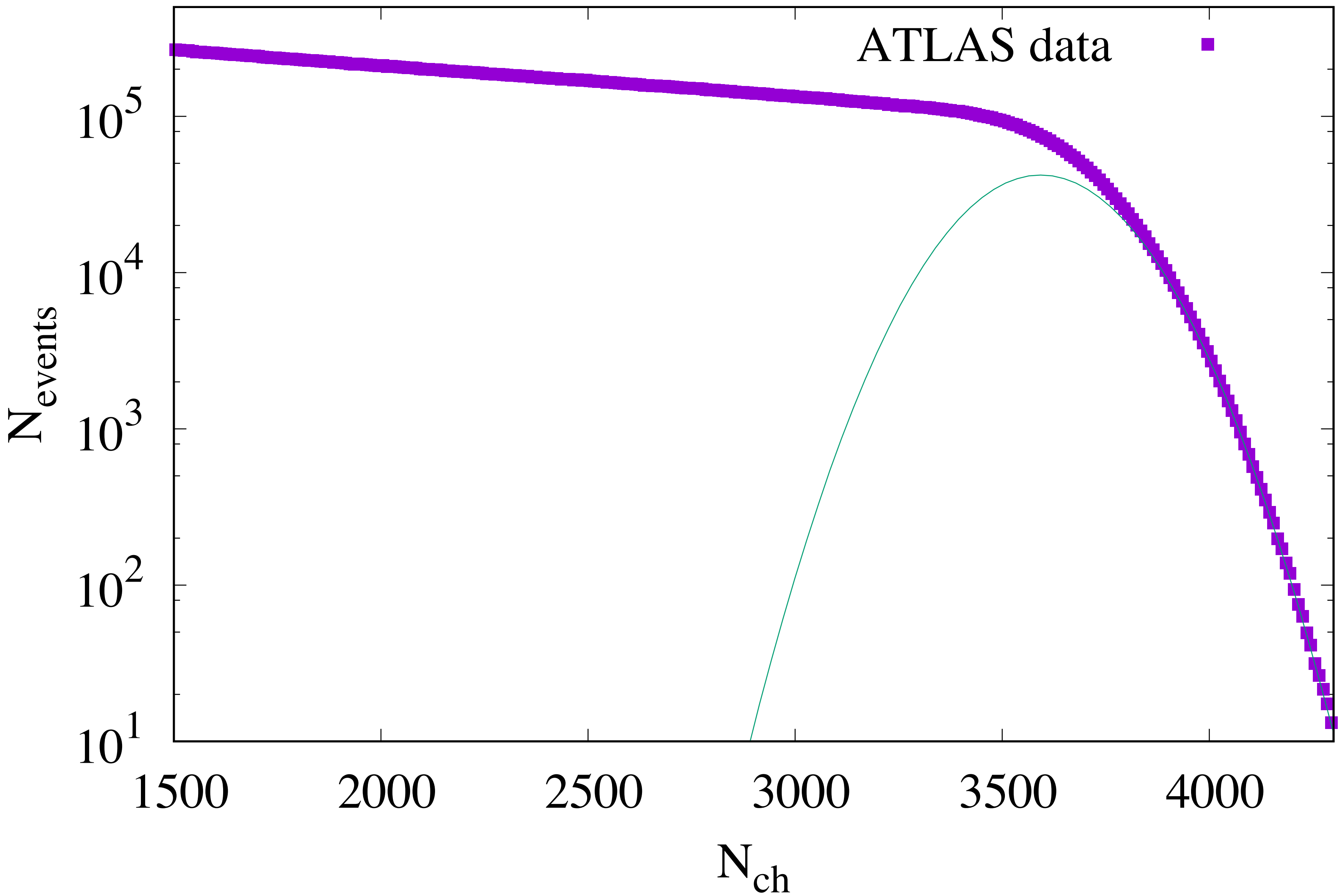
Bayesian reconstruction of $P(b|N_{ch})$

- First solve inverse problem:
  what is the distribution of N_{ch} at fixed b, $P(N_{ch}|b)$?

- Then apply Bayes' theorem
  $P(b|N_{ch})P(N_{ch}) = P(N_{ch}|b)P(b)$

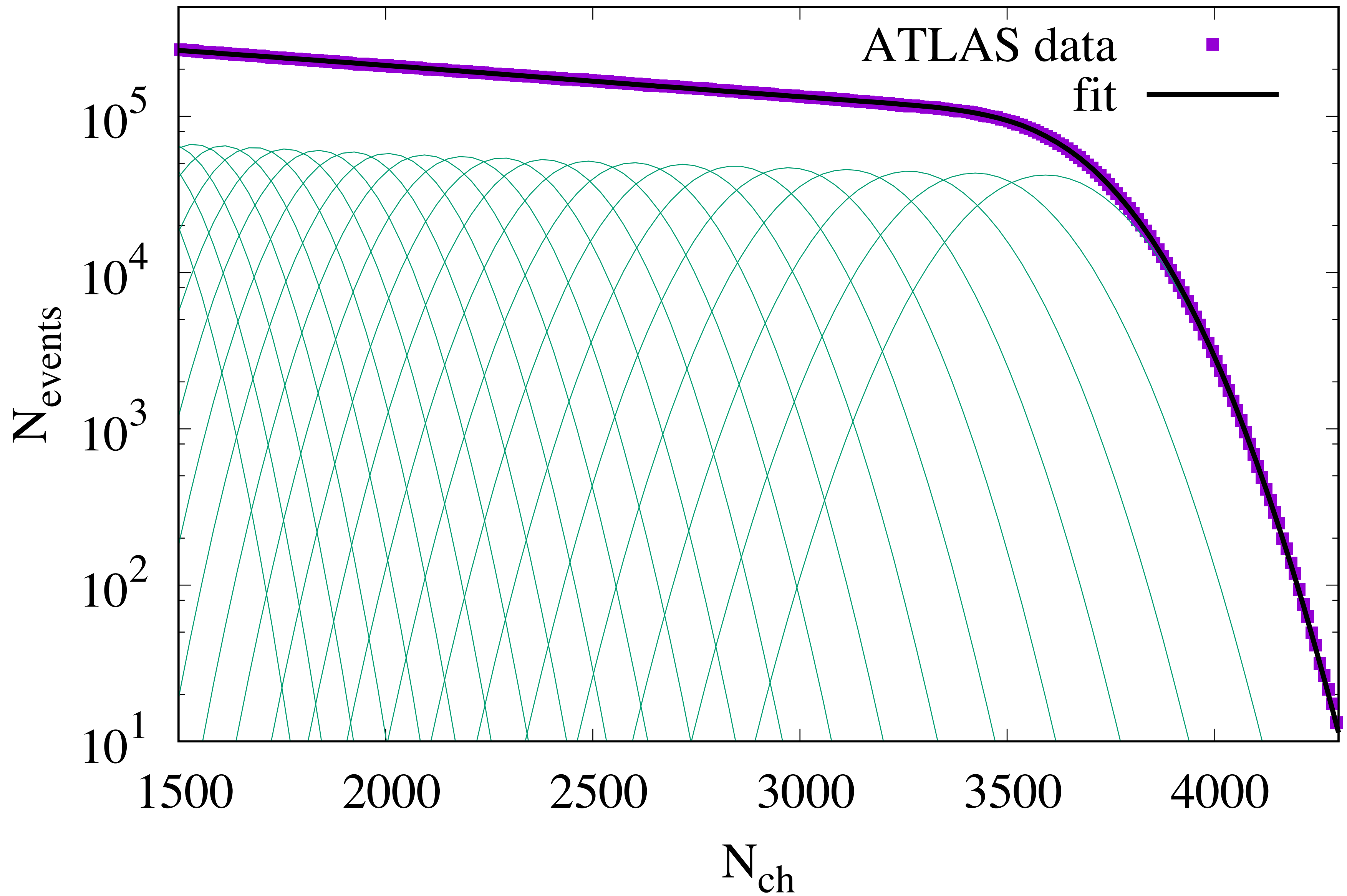
Das Giacalone Monard JYO https://arxiv.org/abs/1708.00081

Determining $P(N_{ch}|b)$ from $P(N_{ch})$



We assume that $P(N_{ch}|b)$ is Gaussian

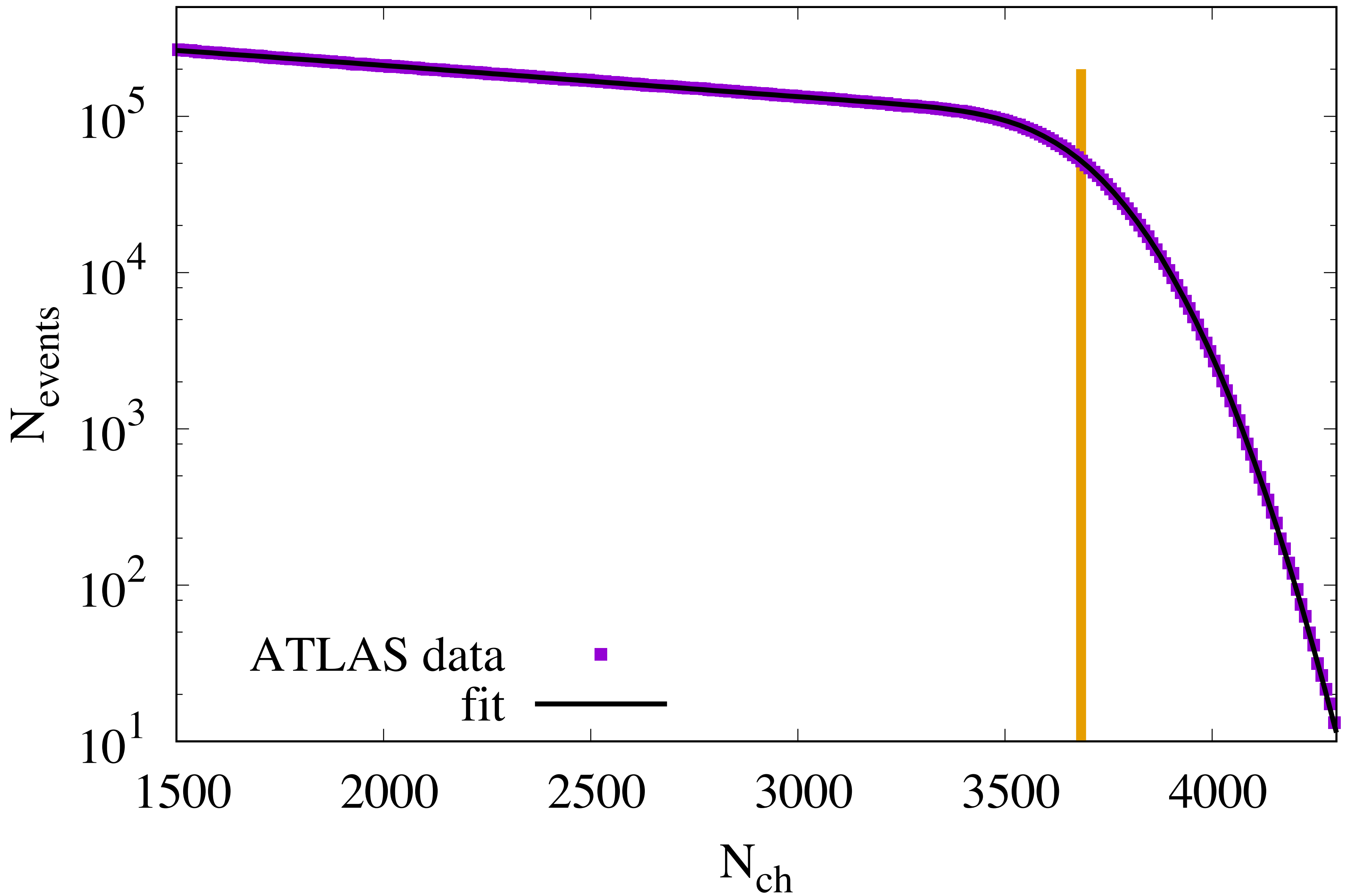
Determining $P(N_{ch}|b)$ from $P(N_{ch})$



We fit $P(N_{ch})$ as a sum of Gaussians

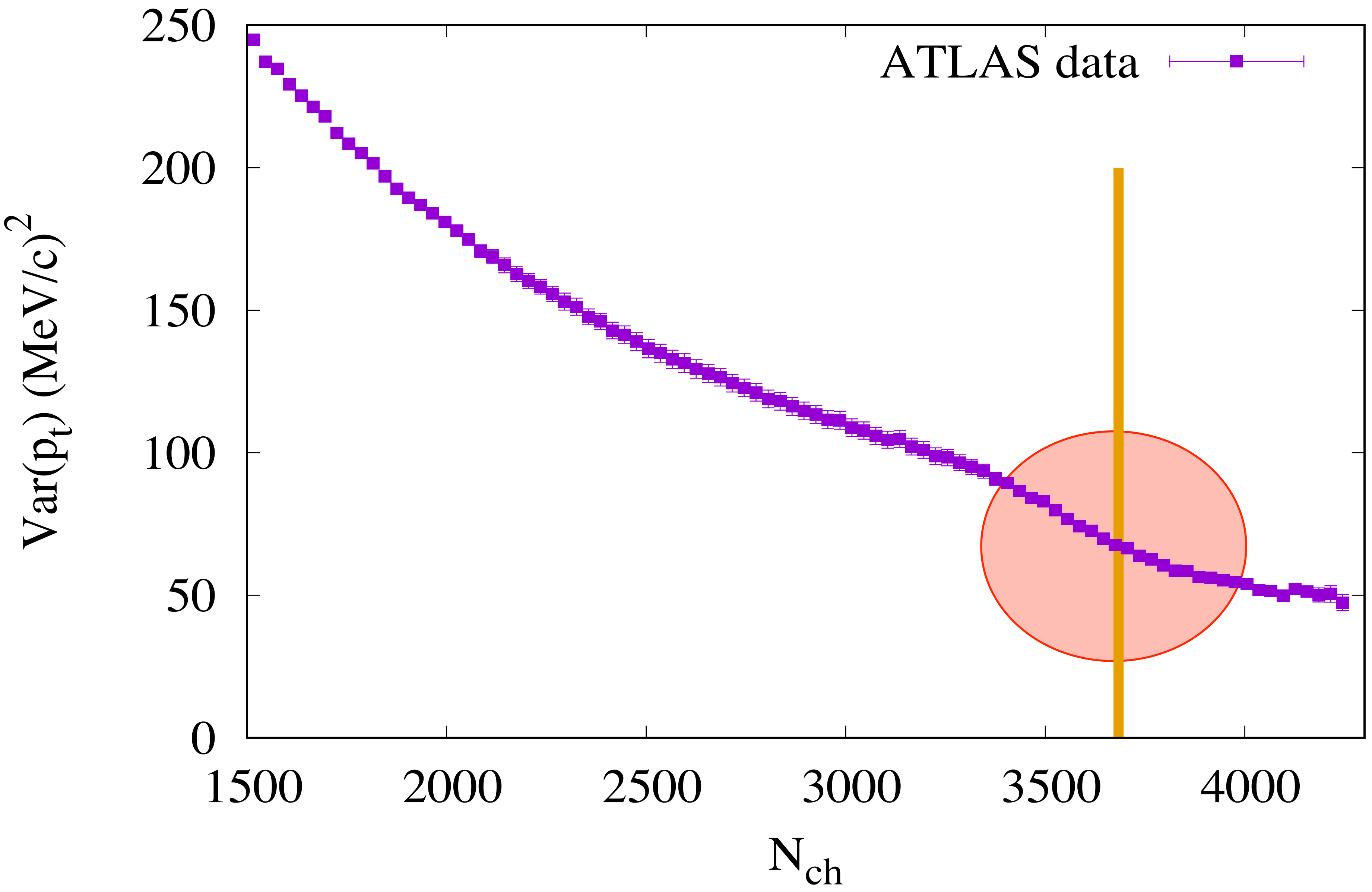
Das Giacalone Monard JYO https://arxiv.org/abs/1708.00081

Determining $P(N_{ch}|b)$ from $P(N_{ch})$



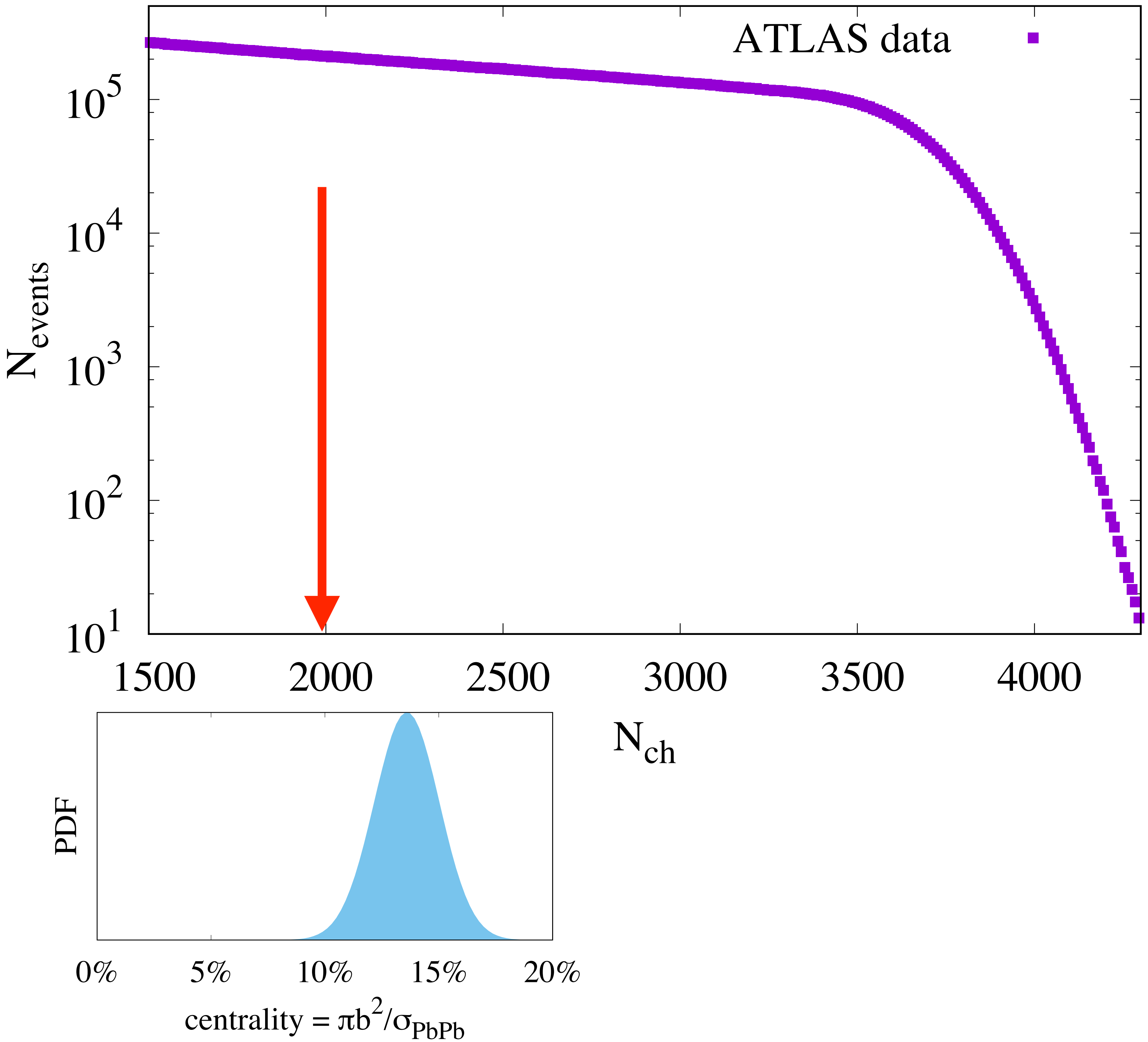
- We reconstruct precisely the knee ≡ mean N_{ch} at b=0
- Ultracentral collisions ≡ above the knee: 0.35% events

Variance of $[p_t]$



The steep fall of the variance precisely occurs at the knee

P(b|N_{ch}) from Bayesian reconstruction



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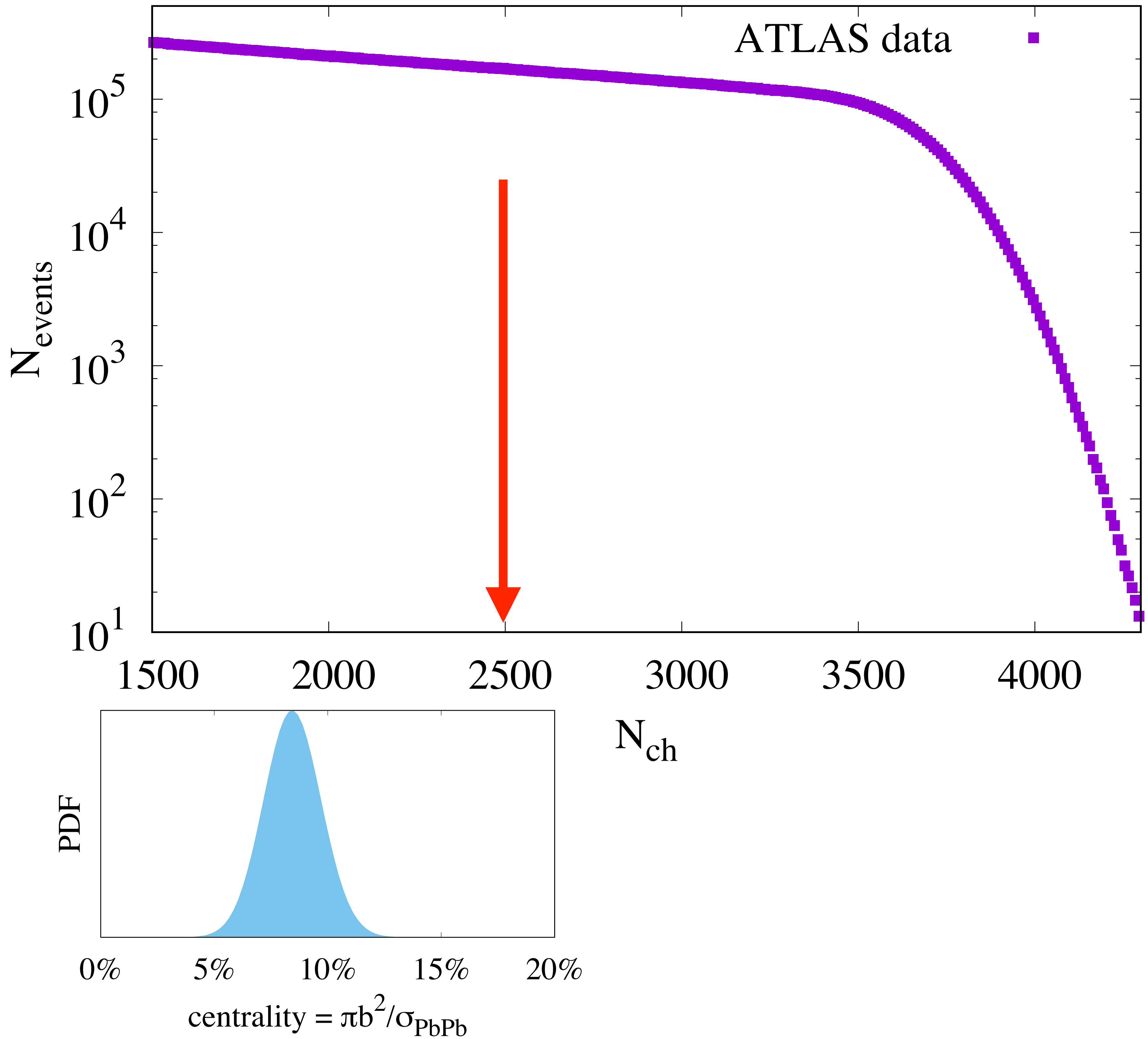
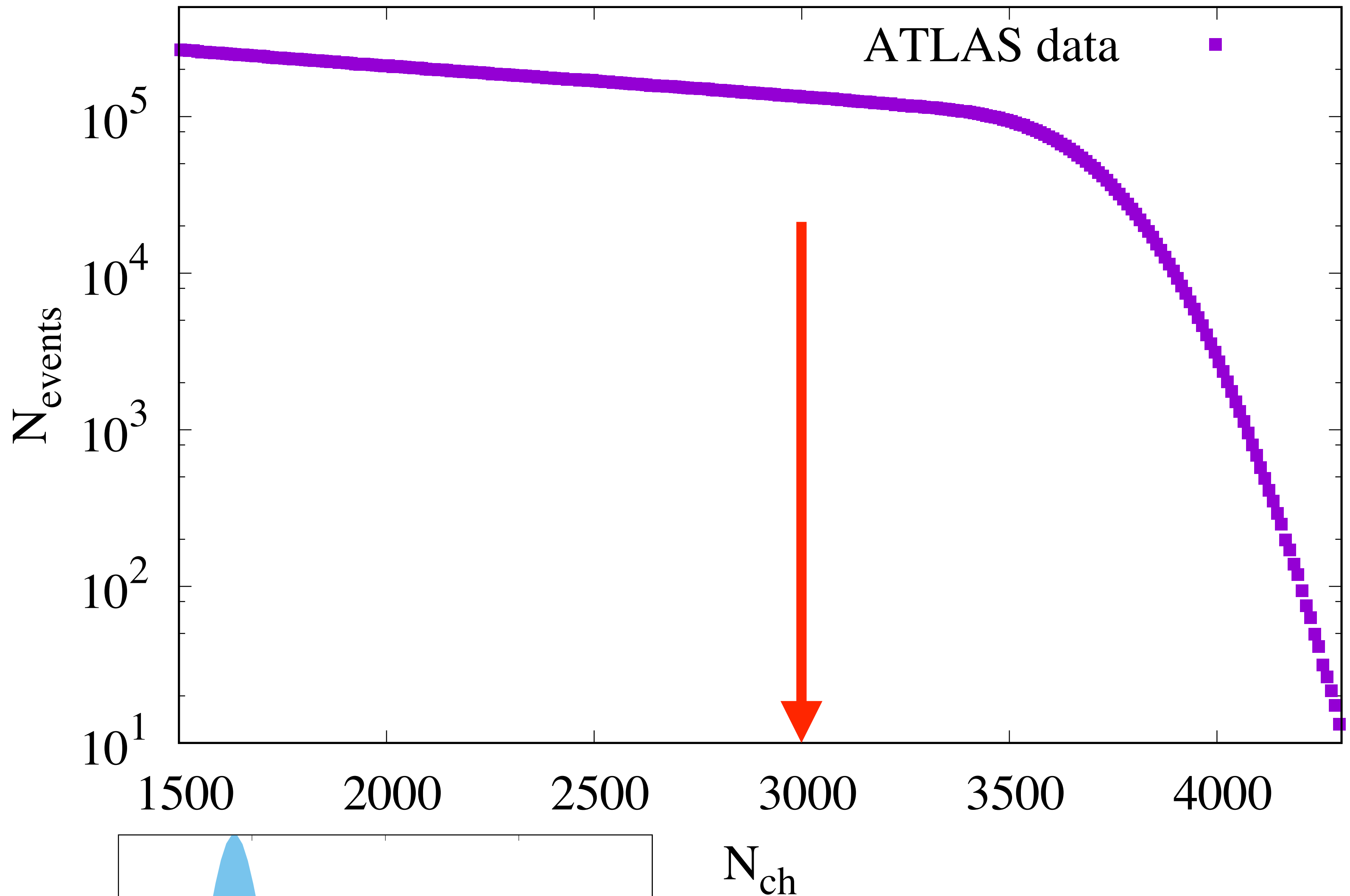
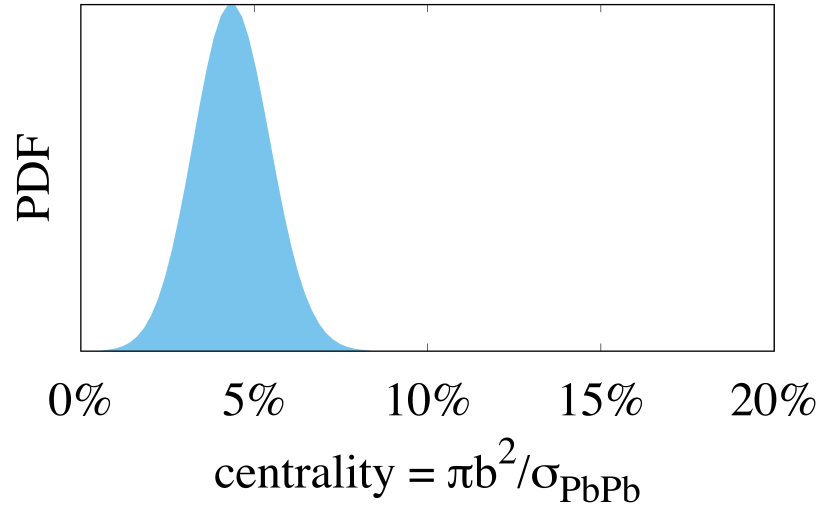
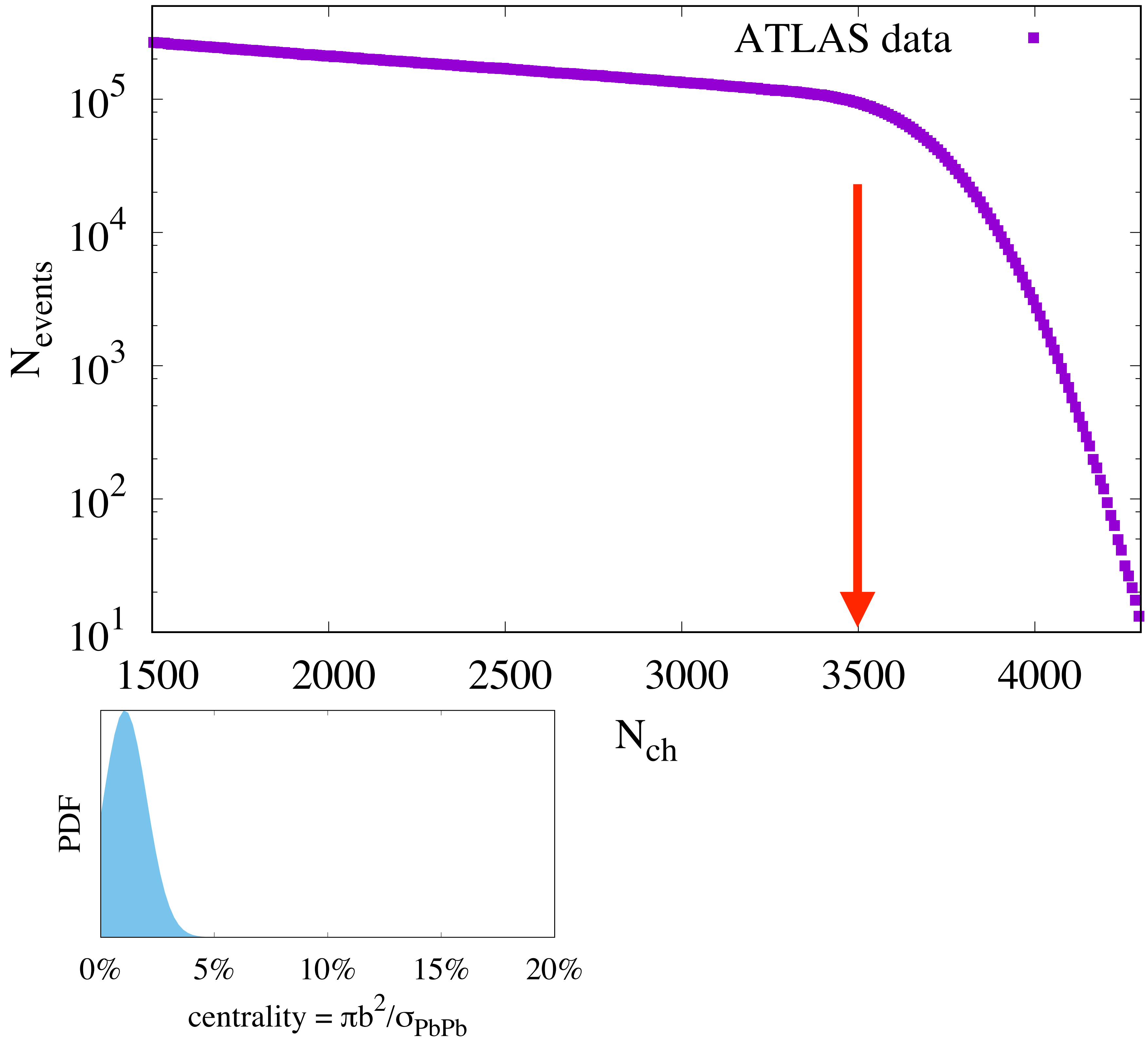


P(b|N_{ch}) from Bayesian reconstruction

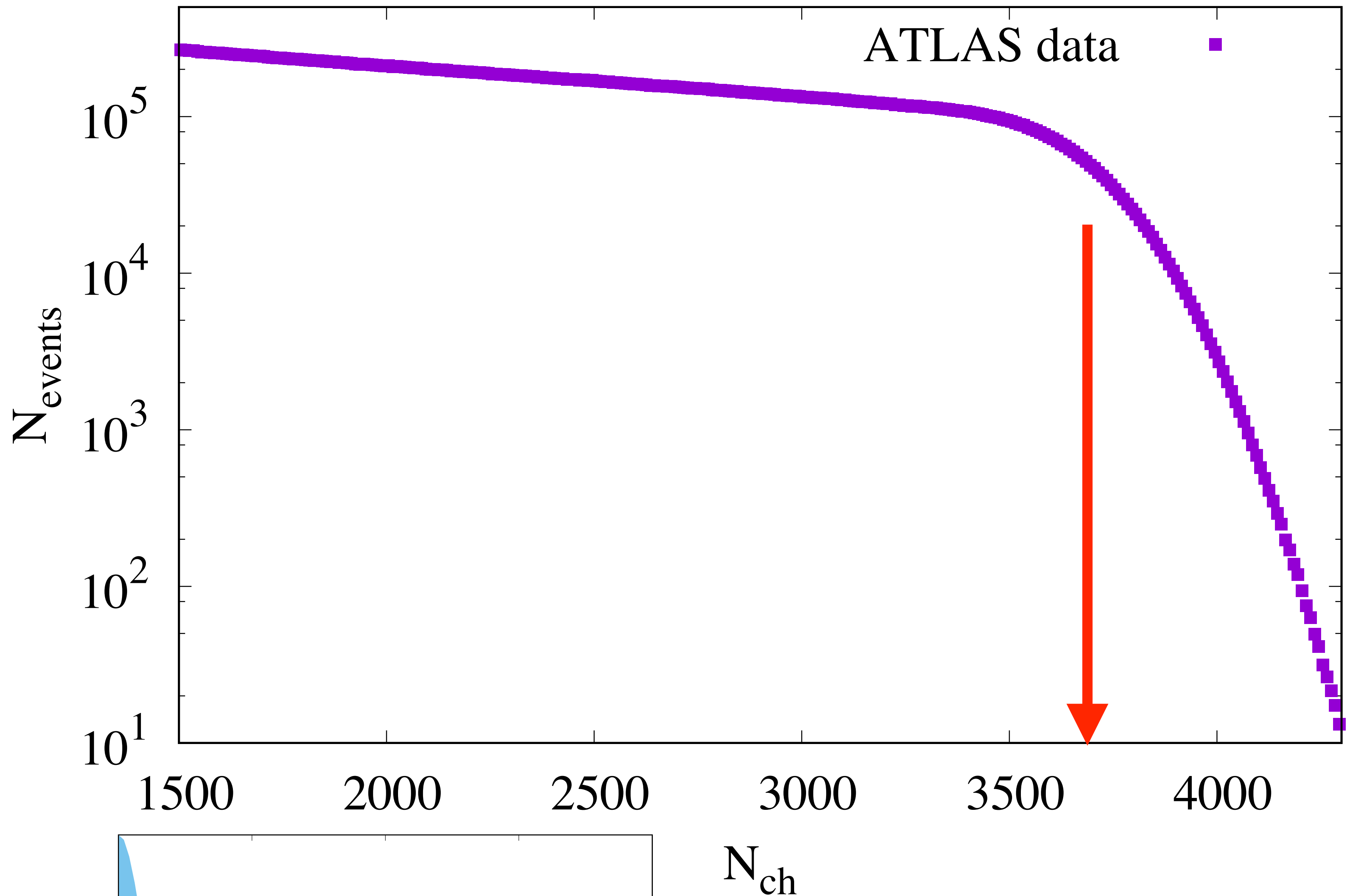


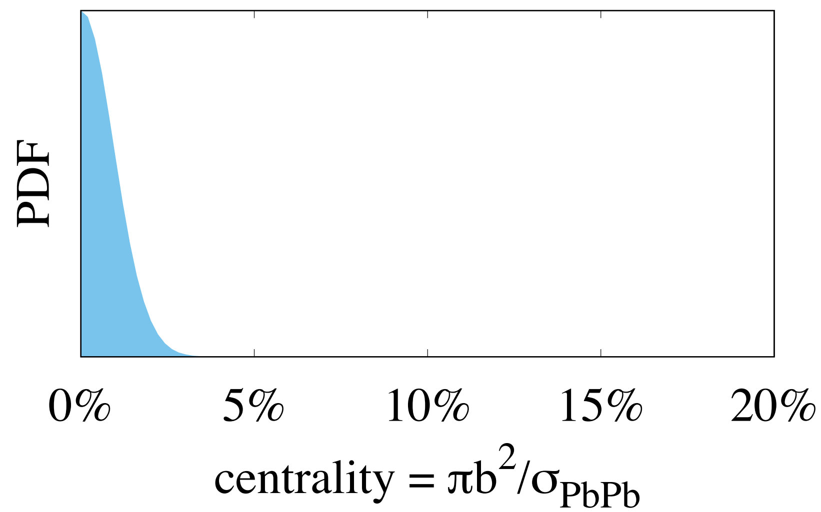


P(b|N_{ch}) from Bayesian reconstruction

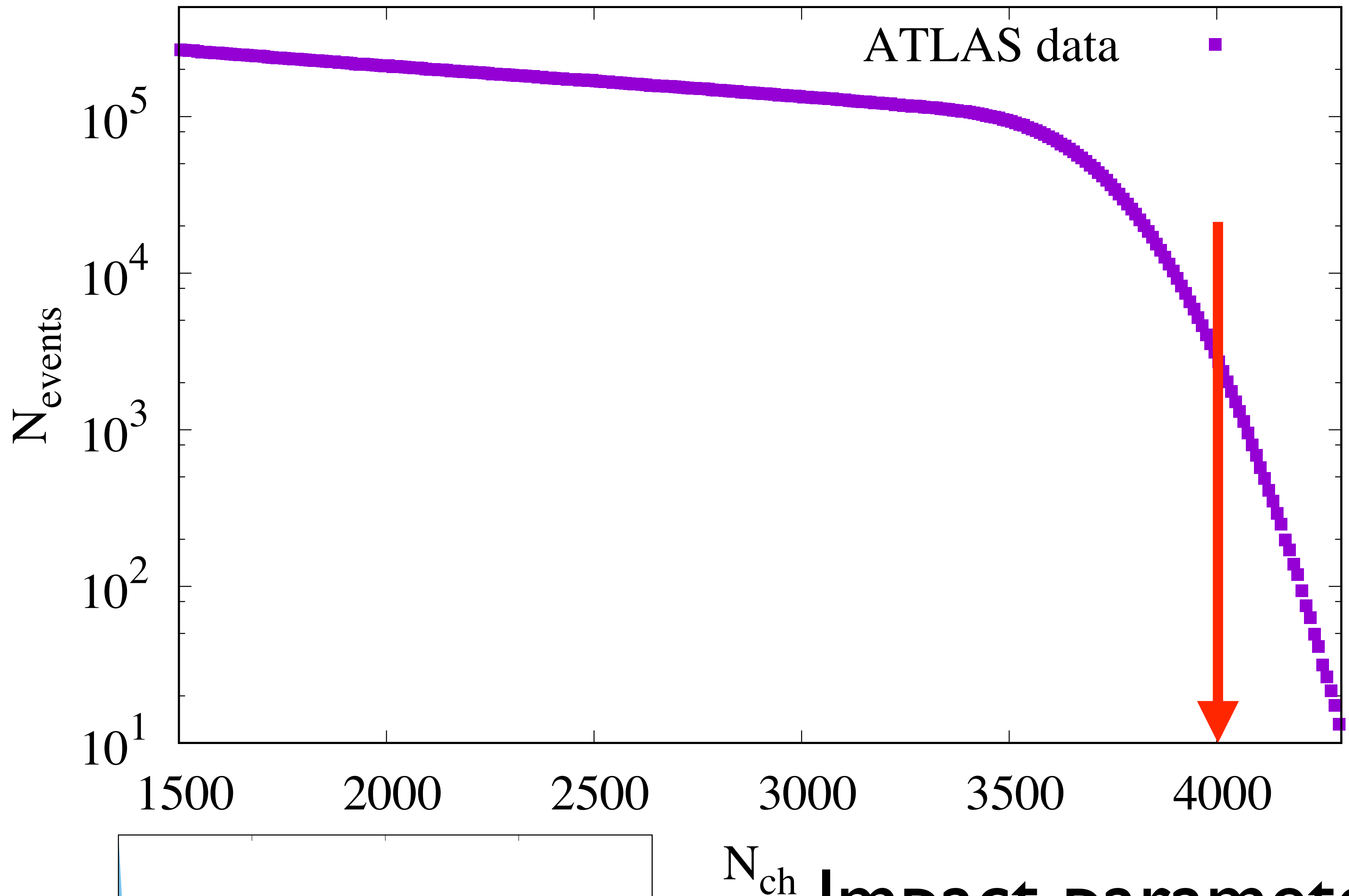


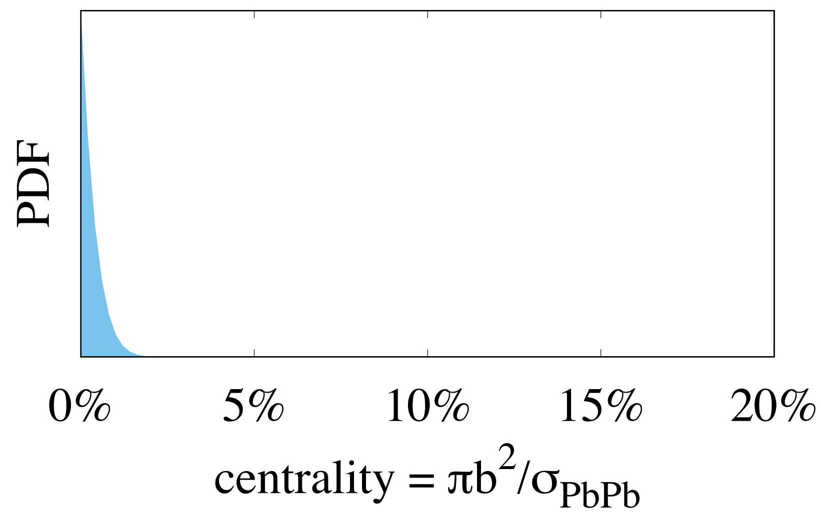
P(b|N$_{ch}$) from Bayesian reconstruction





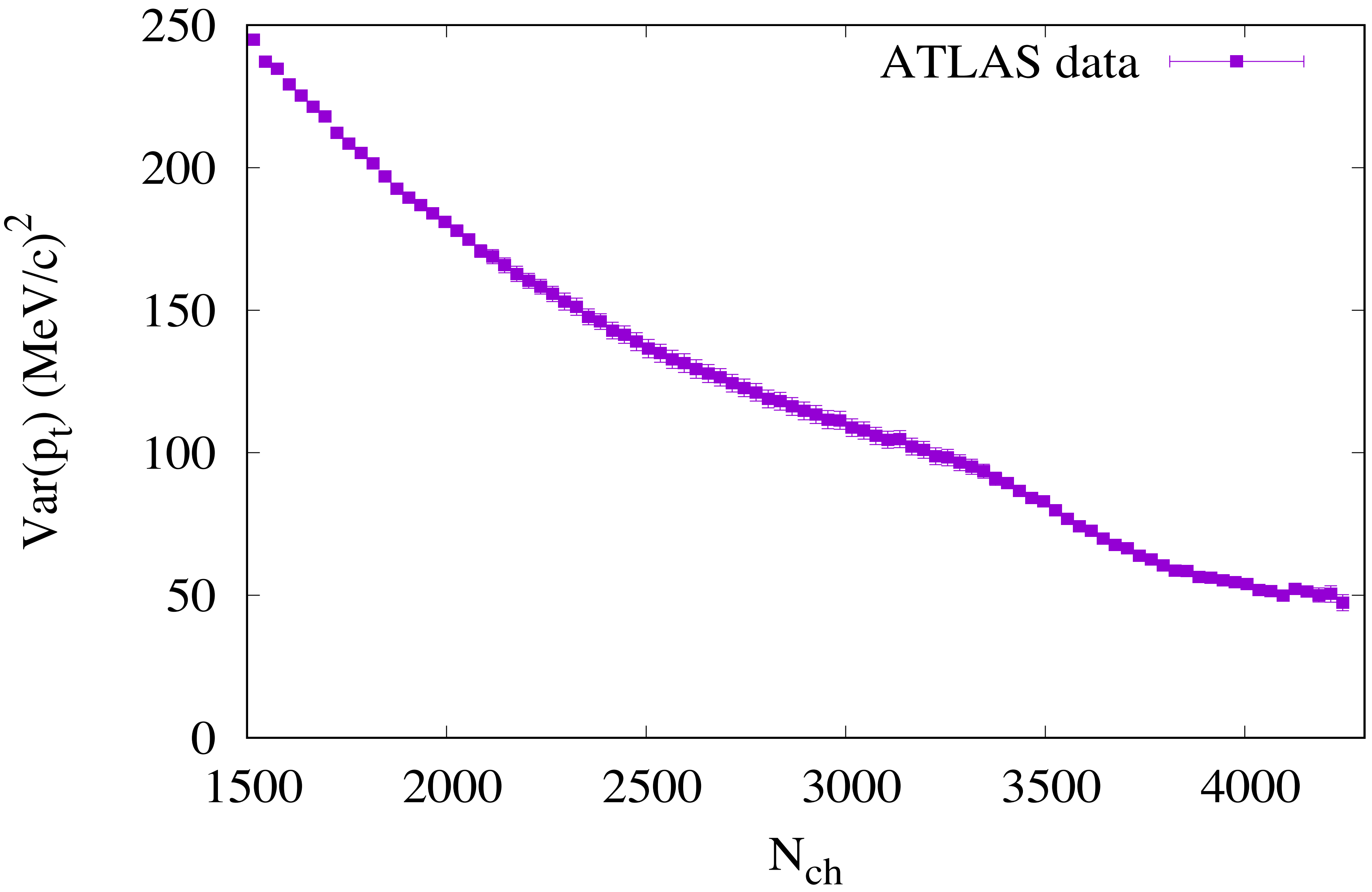
P(b|N$_{ch}$) from Bayesian reconstruction





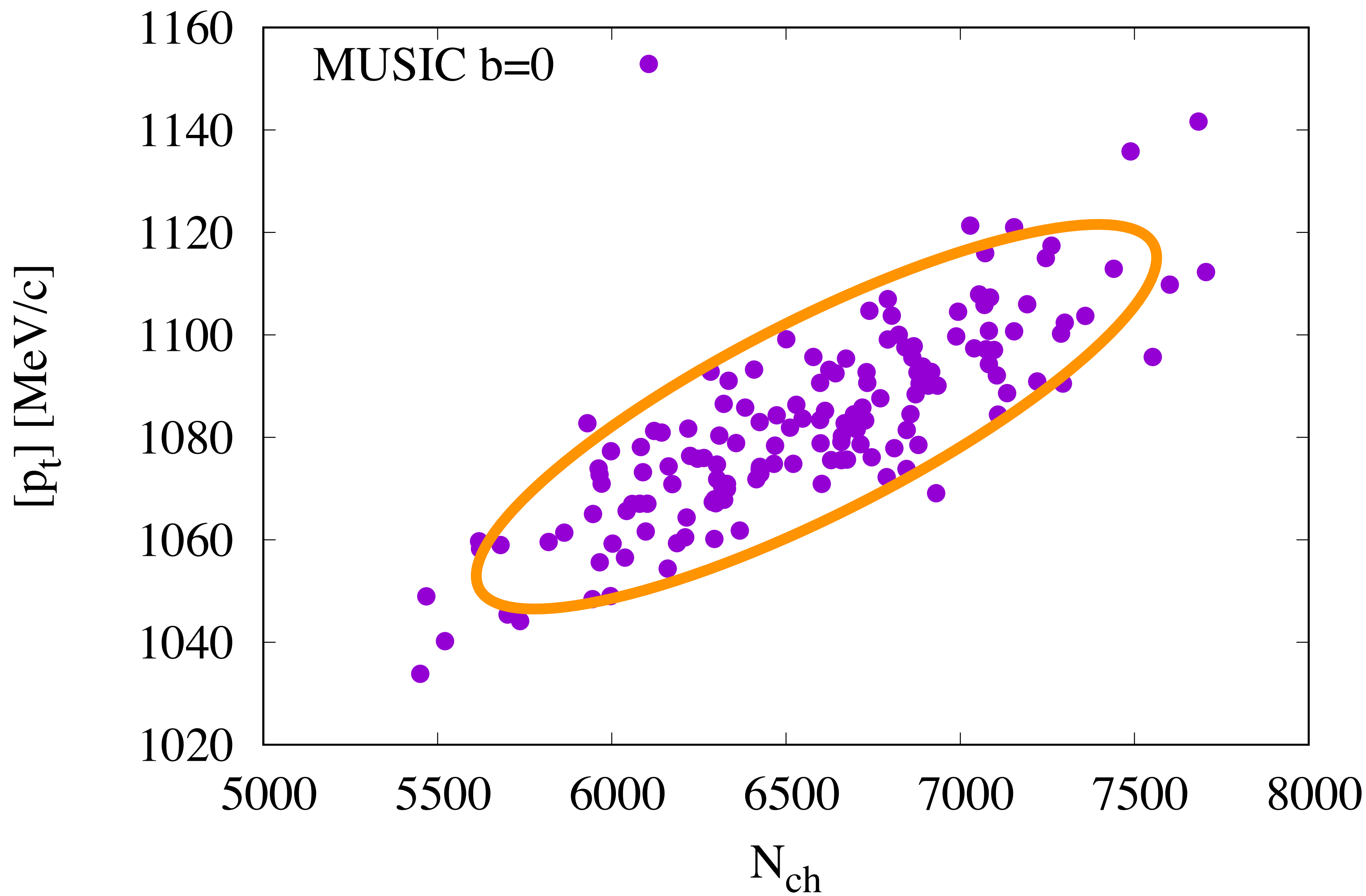
Impact parameter fluctuations gradually disappear above the knee

Understanding data on $[p_t]$ fluctuations



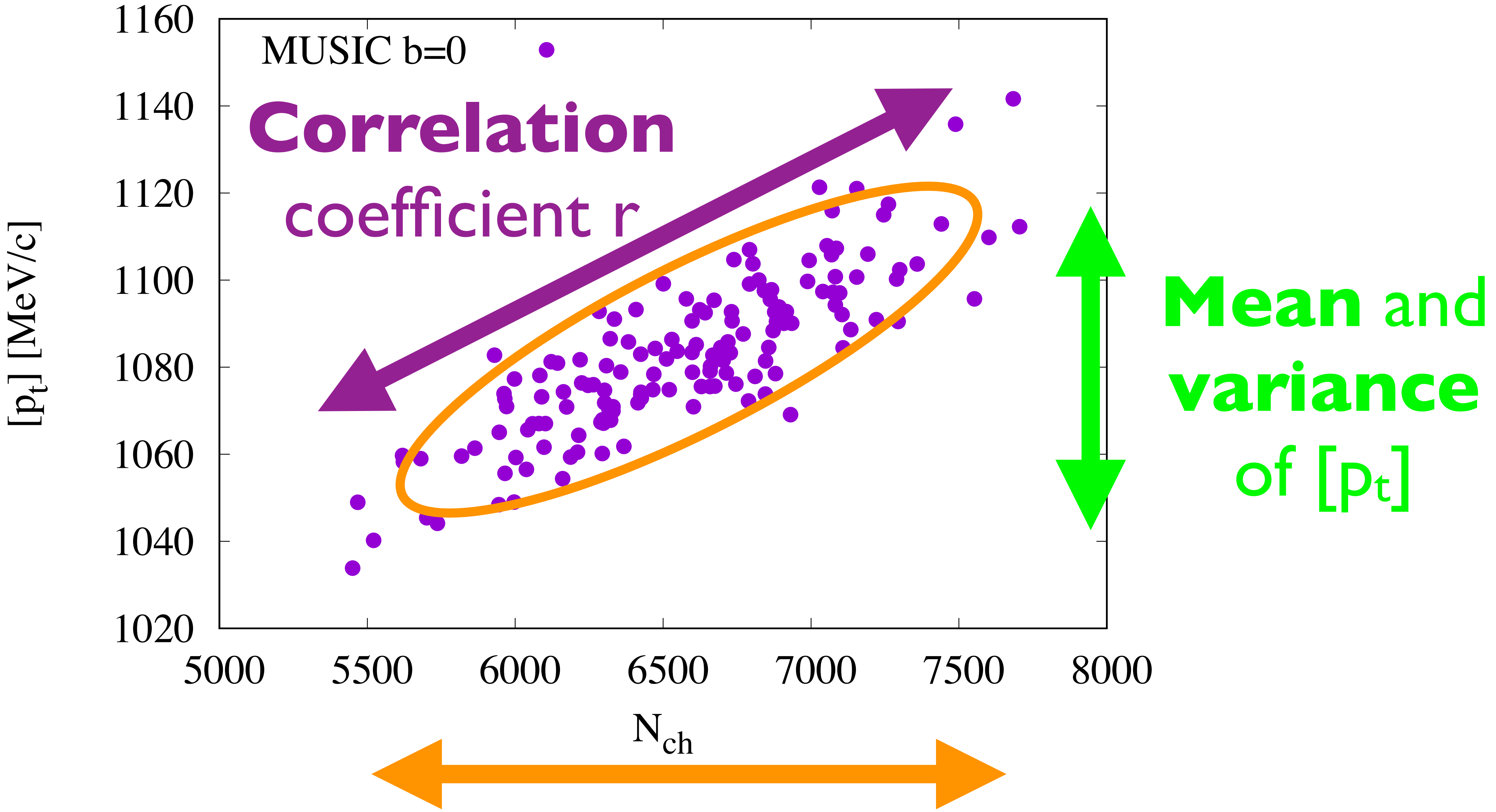
Idea: Build a simple model for the distribution of $[p_t]$ at fixed b, and adjust parameters to these data.

Parametrizing $P(N_{ch},[p_t]|b)$



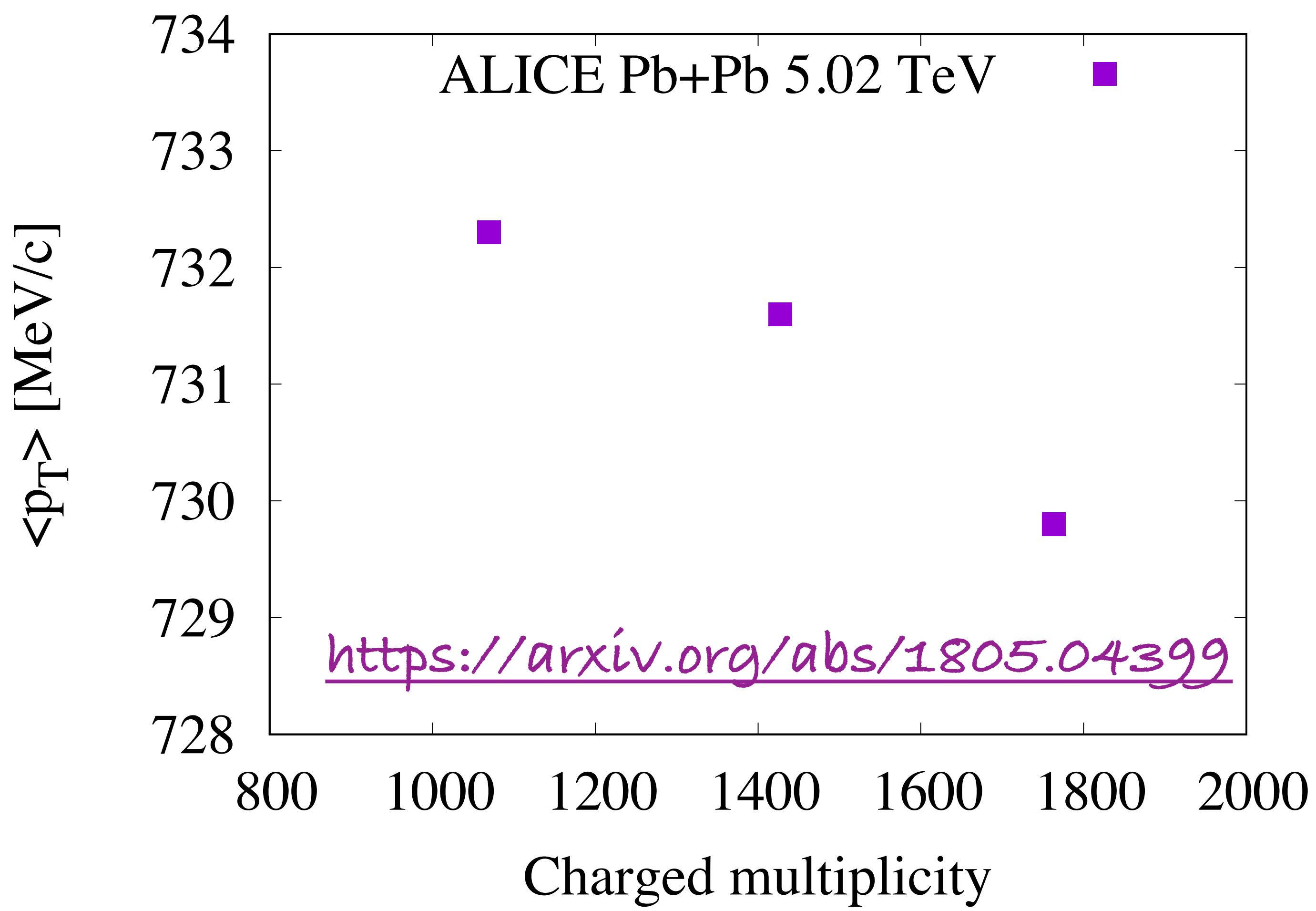
Inspired by hydro + simplicity: assume a correlated 2-dimensional Gaussian: 5 parameters (functions of b)

Parametrizing P(N_{ch},[p_t]|b)



Mean and **variance** of N_{ch}
(known from P(N_{ch}))

Mean value of $[p_t]$ at fixed b



Almost constant experimentally!
we assume it is independent of b and we only study the deviation from the mean : $\delta p_t \equiv [p_t]$-mean
so that we don't even need to know the mean.

Variance of $[p_t]$ at fixed b

We assume that it is a smooth function of the mean multiplicity, of the form

$$\sigma_{pt}^2(\tilde{N}_{ch}(0)/\tilde{N}_{ch}(b))^{\alpha}$$

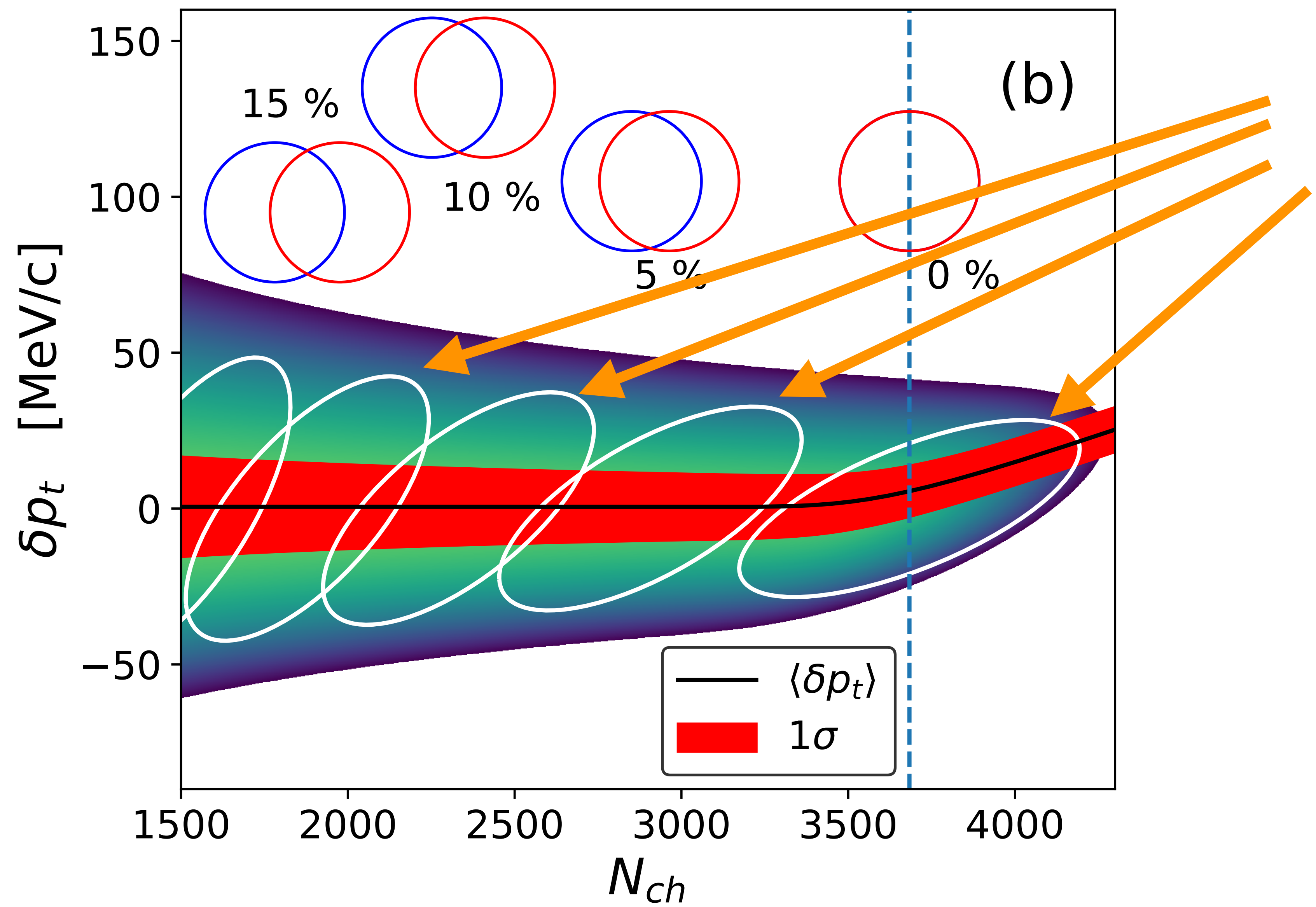
Correlation coefficient r

assumed independent of b for simplicity.

Fitting ATLAS data on $\mathrm{Var}([p_t]|N_{ch})$

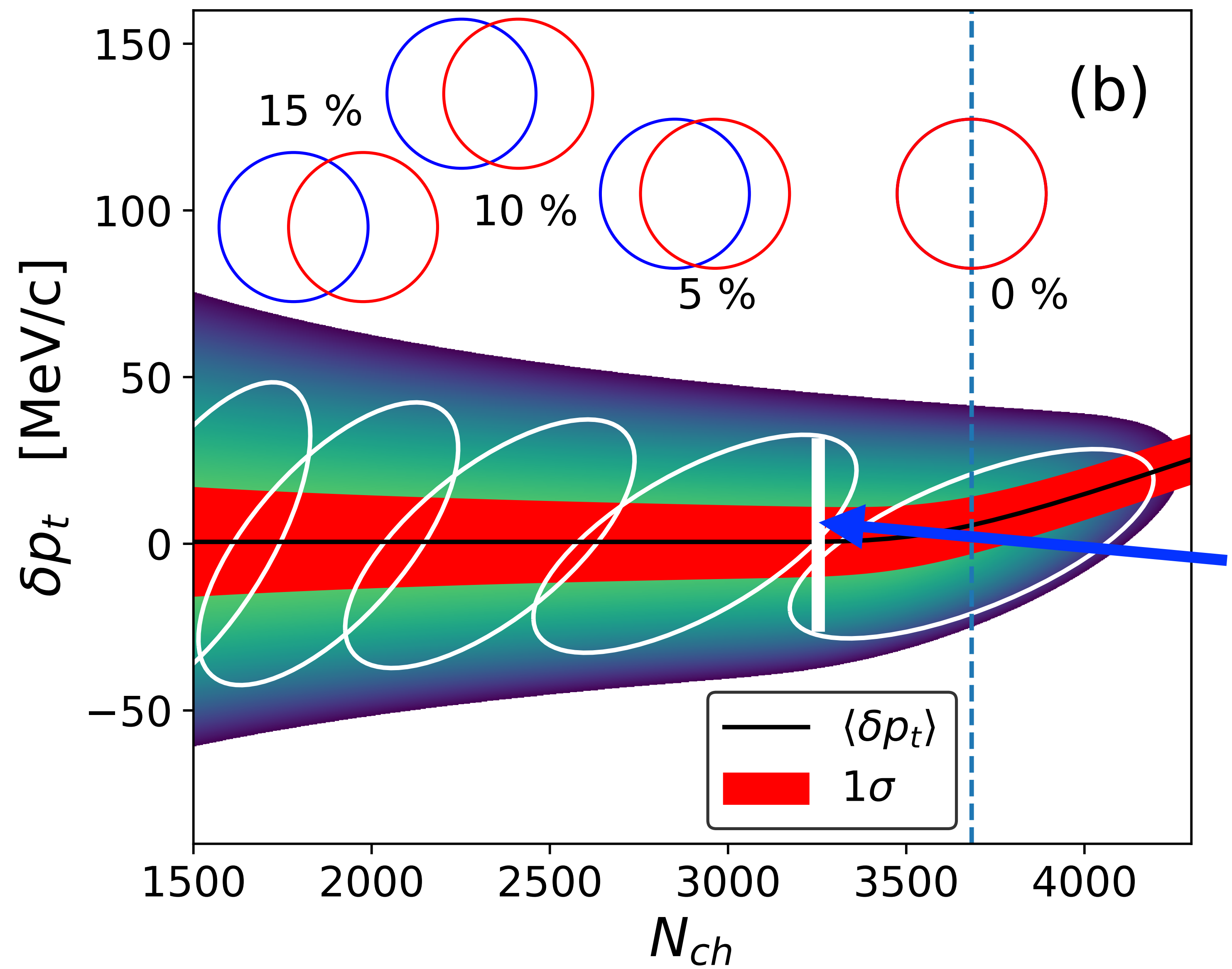
1. Integrate over b: $P(N_{ch},\delta p_t) = \int P(N_{ch},\delta p_t|b)P(b)db$
2. Conditional proba $P(\delta p_t|N_{ch}) = P(N_{ch},\delta p_t)/P(N_{ch})$
3. $\mathrm{Var}([p_t]|N_{ch})$ is the squared width of $P(\delta p_t|N_{ch})$
4. **We fit ATLAS data using σ_{pt}, α, r.**

Fit results: P(N_{ch},δp_t)



Gaussian distributions at fixed b

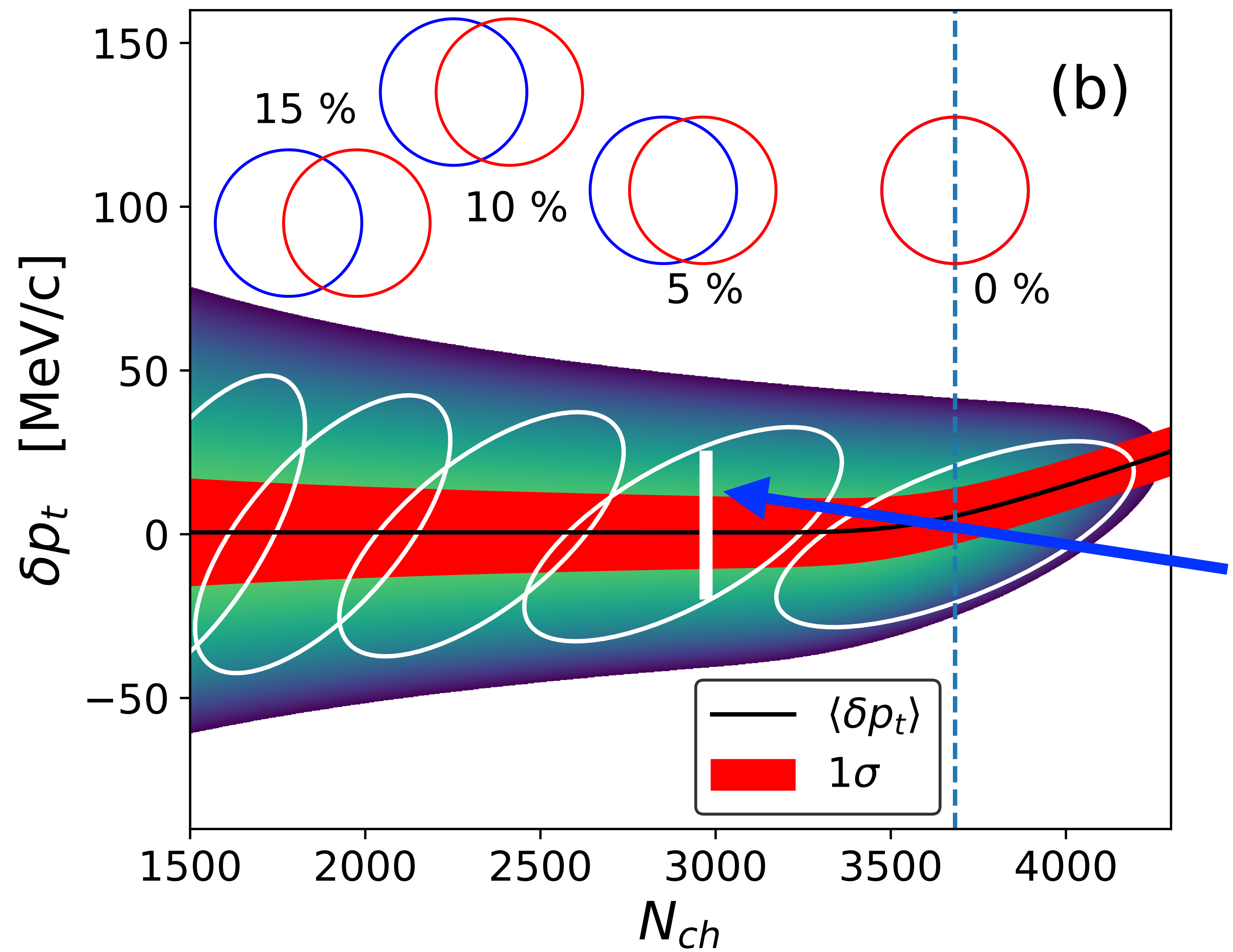
Fit results: P(N_{ch},δp_t)



At fixed N_{ch}, two contributions to the width in δp_t

1. fluctuations from the variation of b *(several ellipses contribute)*

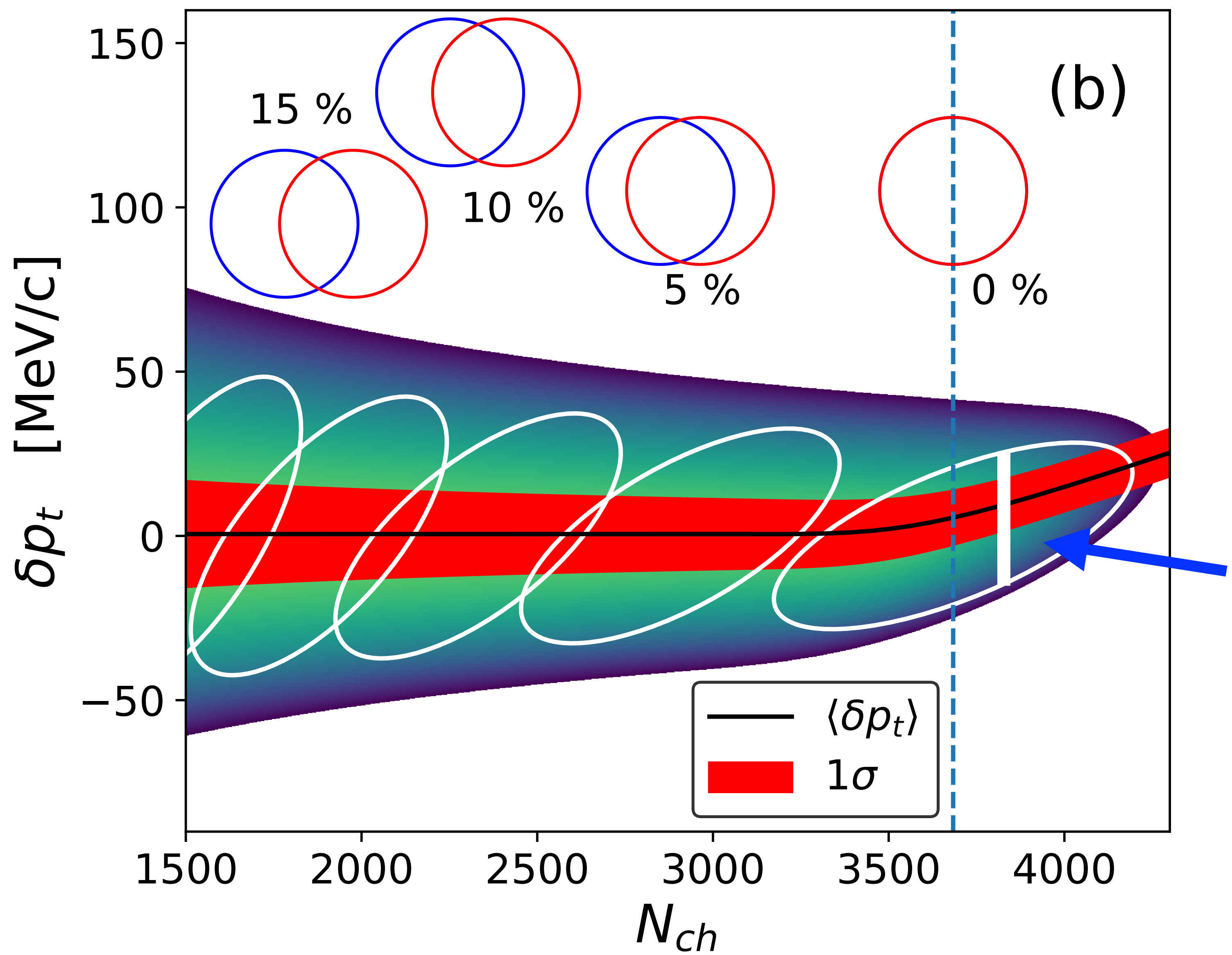
Fit results: P(N_{ch},δp_t)



At fixed N_{ch}, two contributions to the width in δp_t

2. fluctuations of δp_t at fixed b and N_{ch} *(height of a single ellipse)*

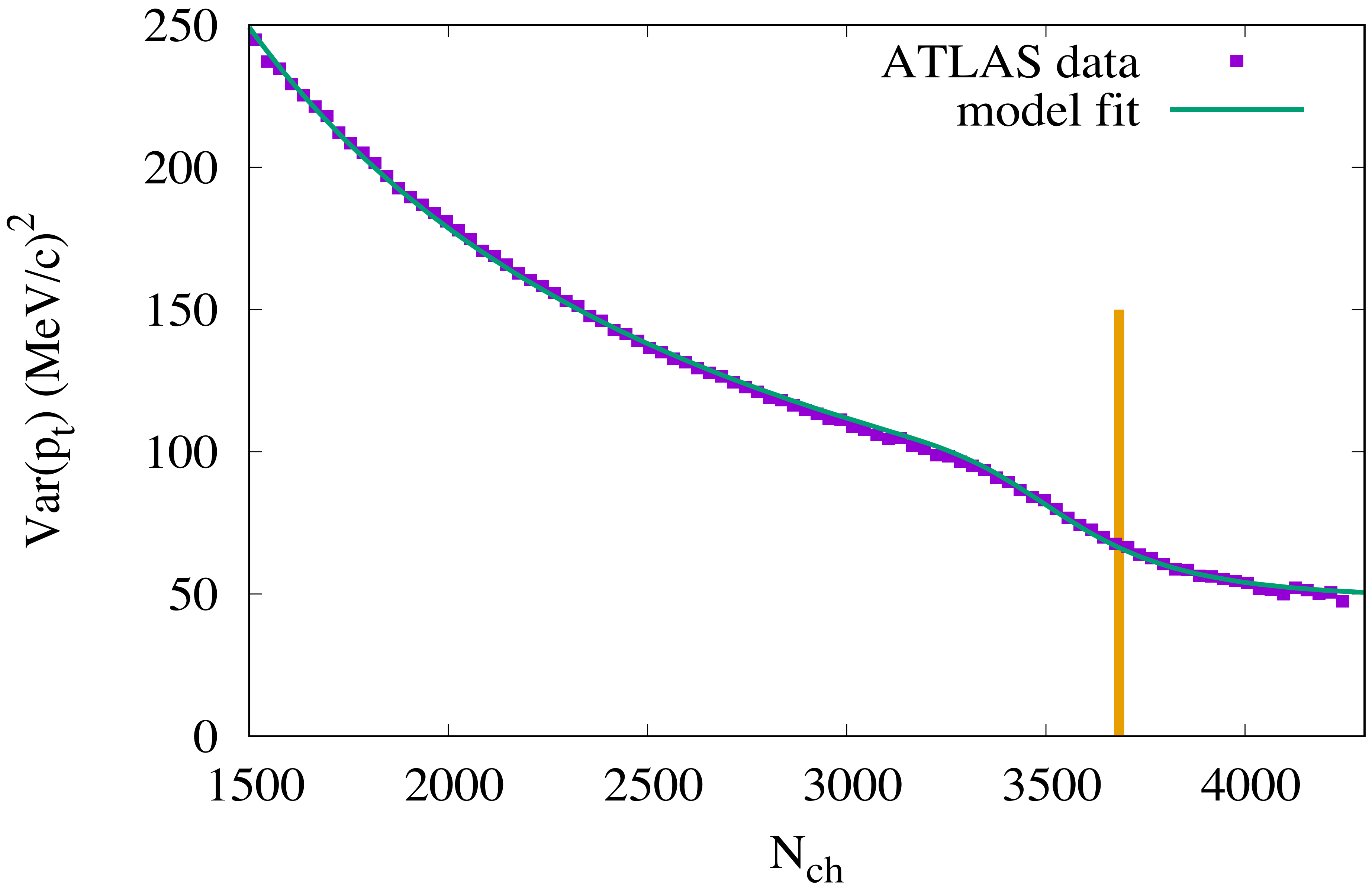
Fit results: P(N_{ch},δp_t)



At fixed N_{ch}, two contributions to the width in δp_t

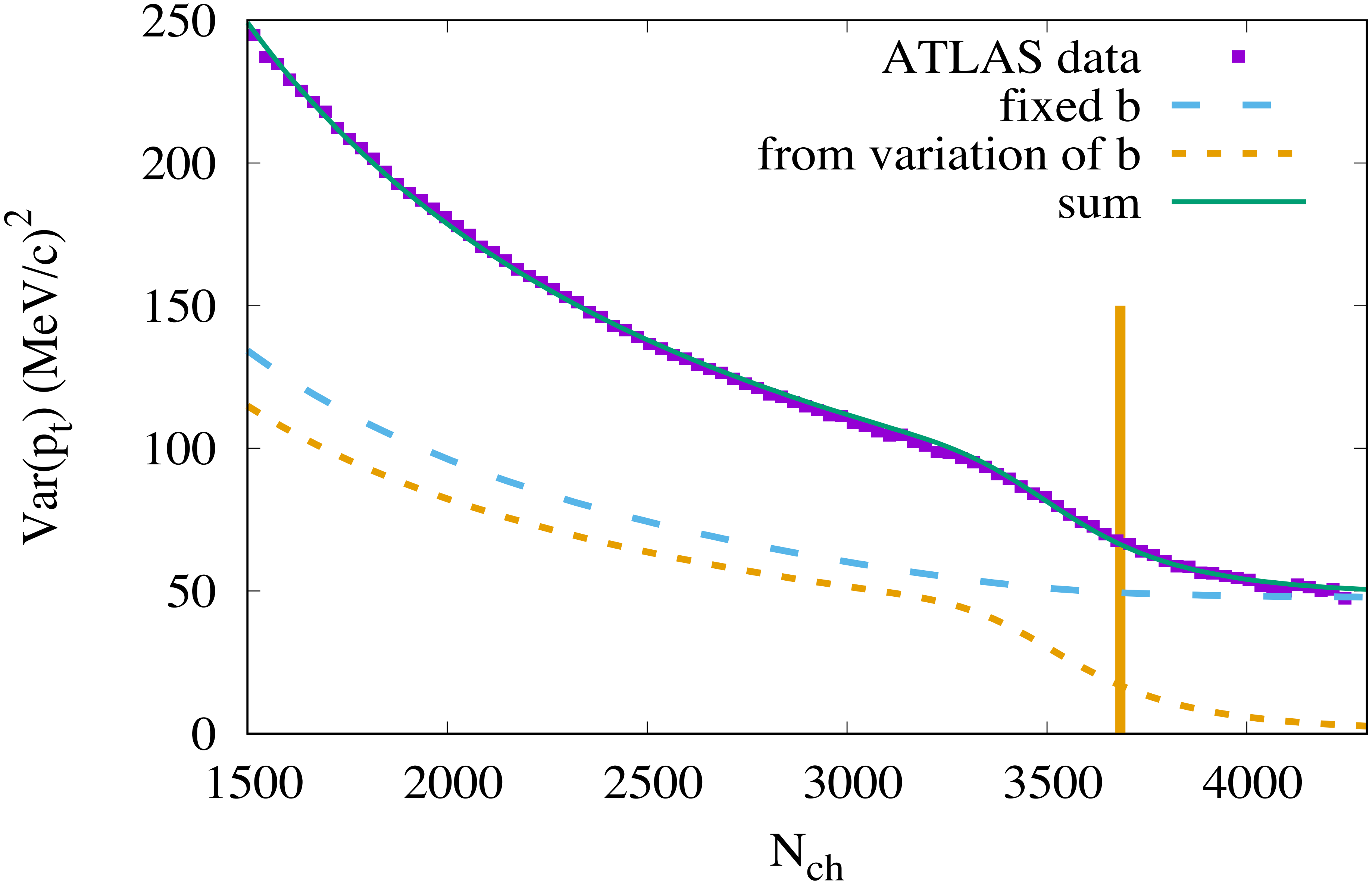
2. Only this second term remains in ultracentral collisions

Fit results: Var($[p_t]$) versus N_{ch}



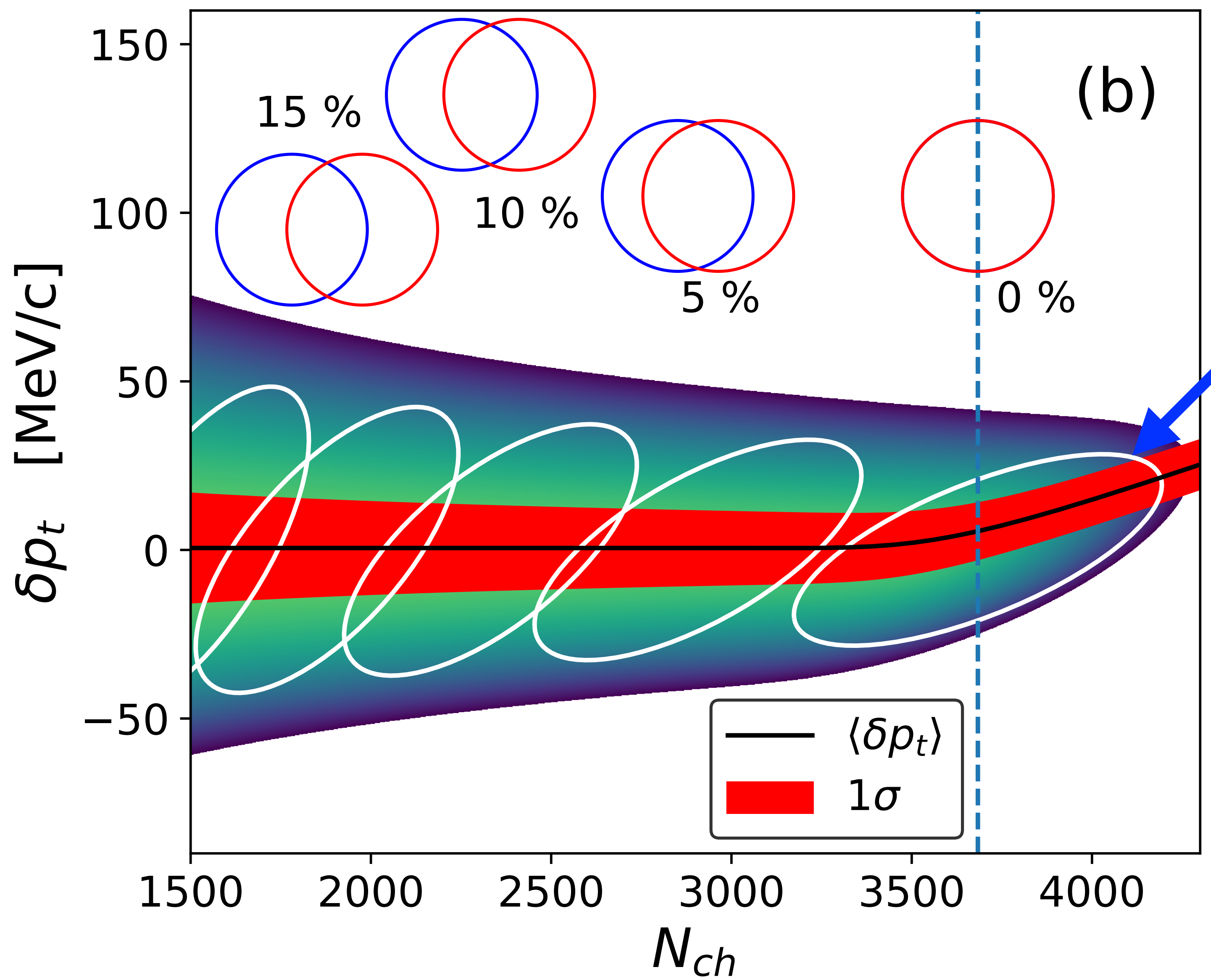
Our simple model naturally explains the observed fall in ultracentral collisions

Fit results: Var($[p_t]$) versus N_{ch}



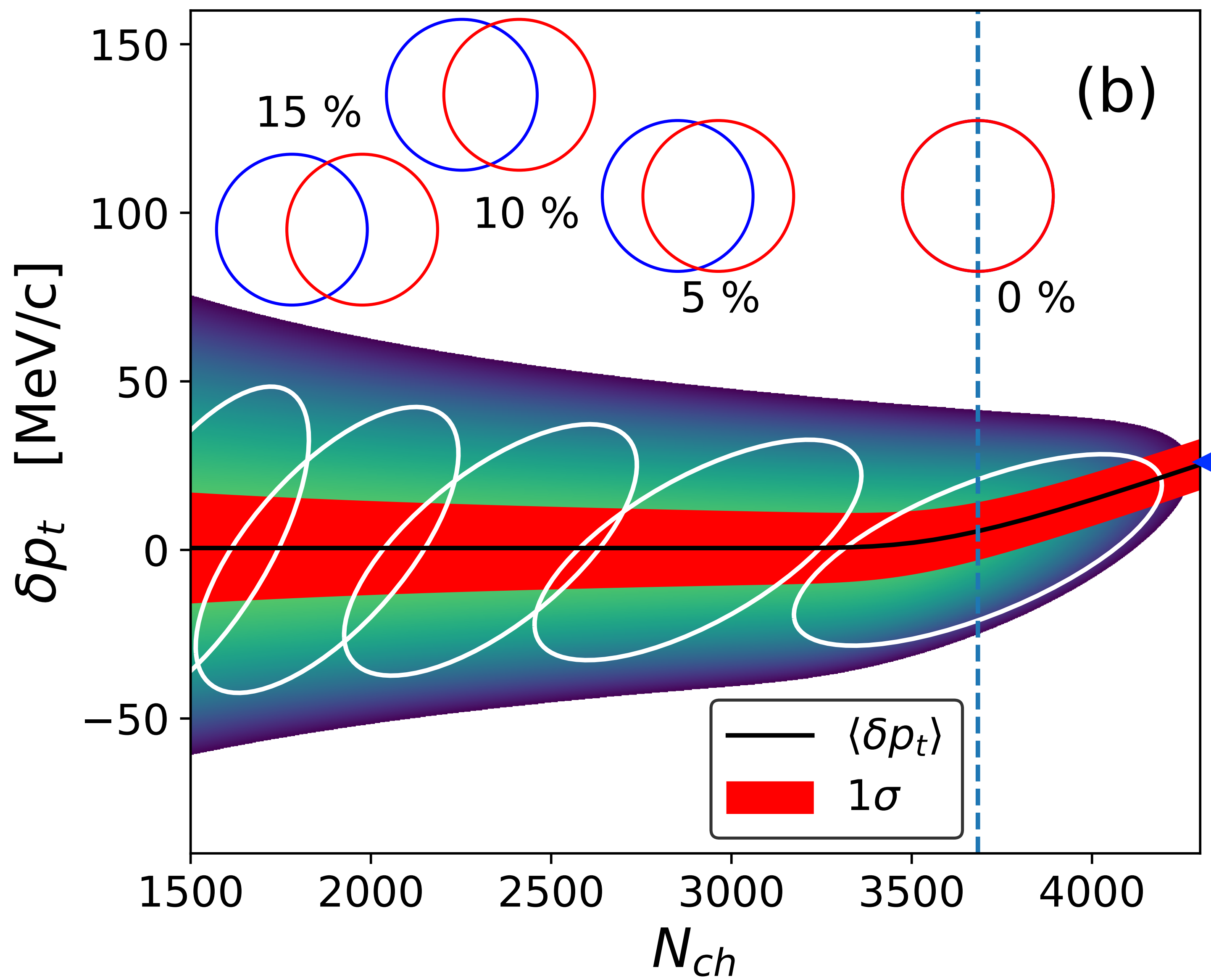
- Below the knee, half of the variance from variation of b
- This contribution gradually disappears around the knee

Thermalization observed!



The fit returns
r=0.679
→ Strong correlation between $[p_t]$ and N_{ch} at fixed b
→ the system thermalizes

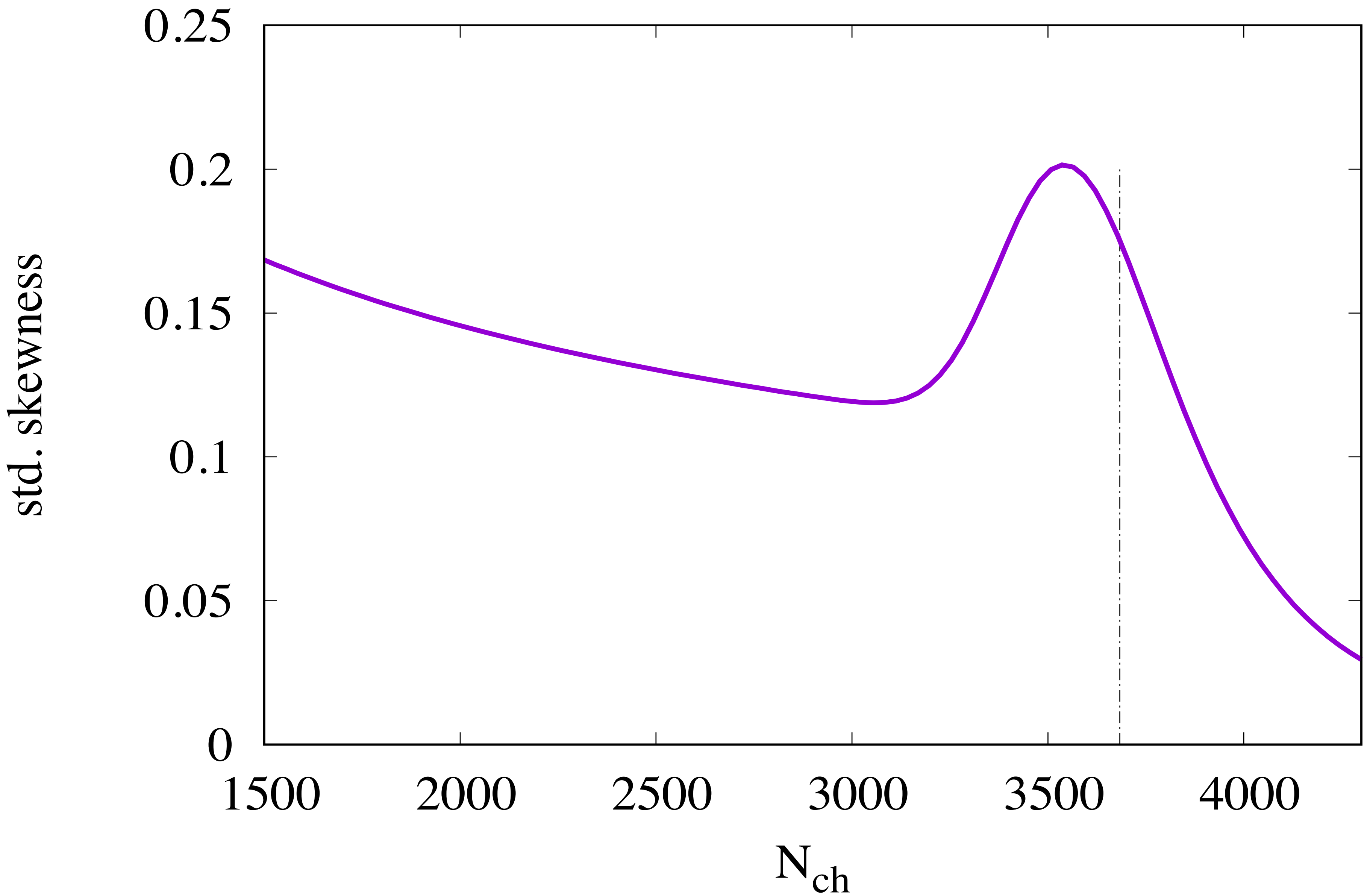
Further predictions



Slight increase of $<p_t>$ in ultracentral collisions

Gardim Giacalone JYO 1909.11609

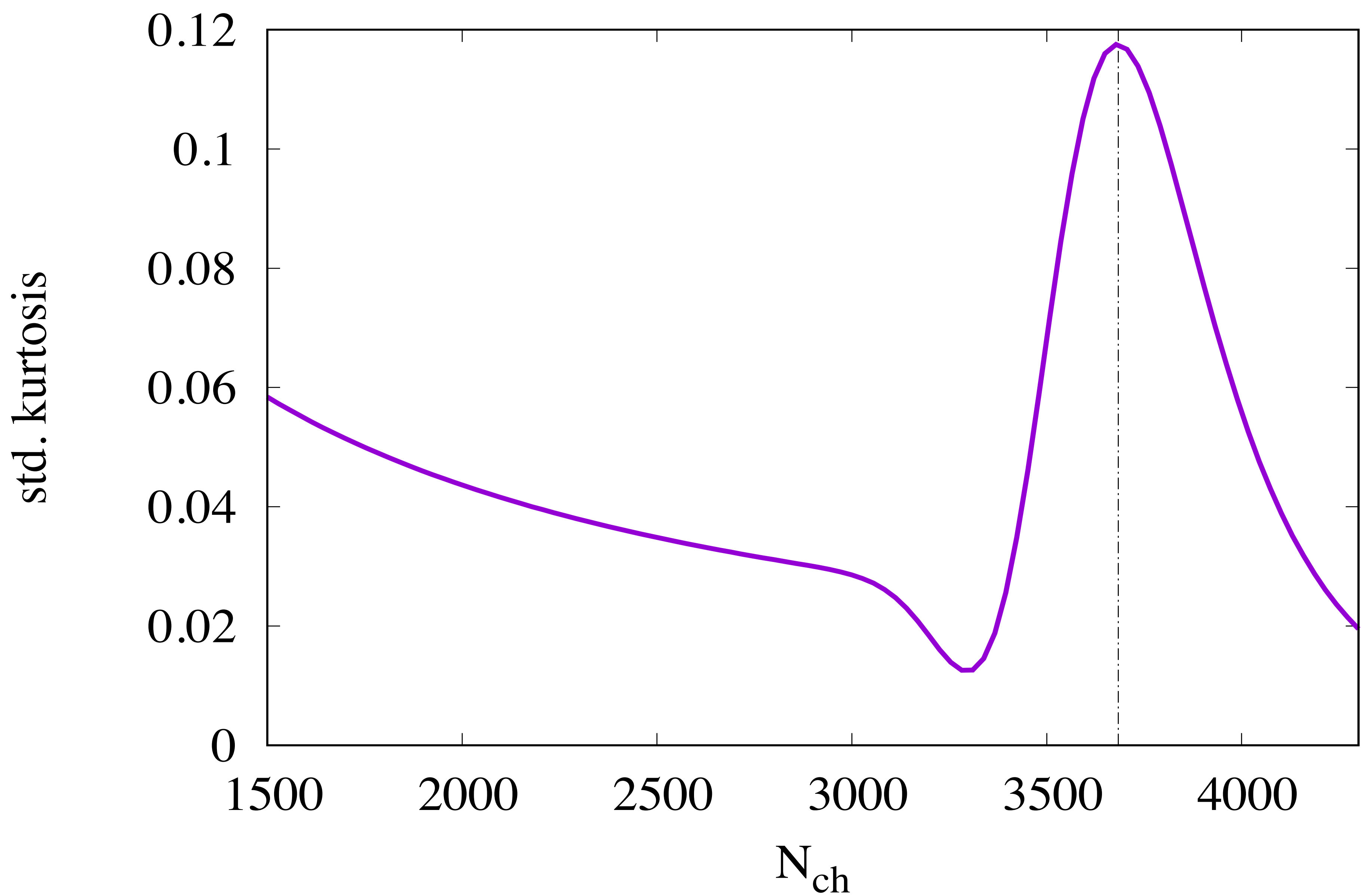
$[p_t]$ fluctuations are not Gaussian



Large skewness below the knee

Samanta Luzum JYO, 2306.xxxxx

$[p_t]$ fluctuations are not Gaussian



Large kurtosis at the knee

Samanta Luzum JYO, 2306.xxxxx

Conclusion

- Transverse momentum fluctuations in ultracentral collisions provide a new, direct probe of thermalization in ultrarelativistic nucleus-nucleus collisions.
- For phenomenology, it is essential to know the distribution of the observable used as a centrality estimator (e.g. multiplicity), which is not always made public by large collaborations (e.g. CMS).