10th Asian Triangle Heavy-Ion Conference - ATHIC 2025

Gopalpur, 13-17 January

System size, energy and event shape dependence of the mean transverse momentum fluctuations with ALICE at the LHC

Tulika Tripathy

(on behalf of the ALICE Collaboration)

Laboratoire de Physique de Clermont Auvergne (LPCA), UCA, Clermont Ferrand, France

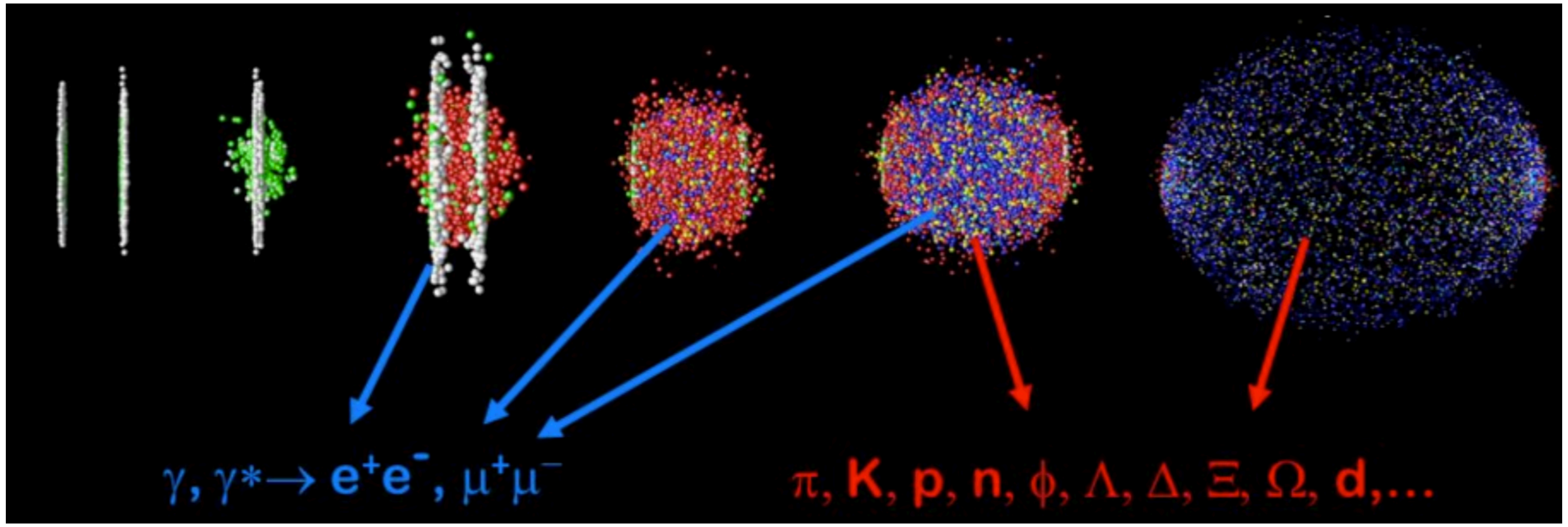
Based on ALICE, arXiv:2411.09334 [nucl-ex]

Introduction and motivation

Why event-by-event fluctuation?

Introduction and motivation

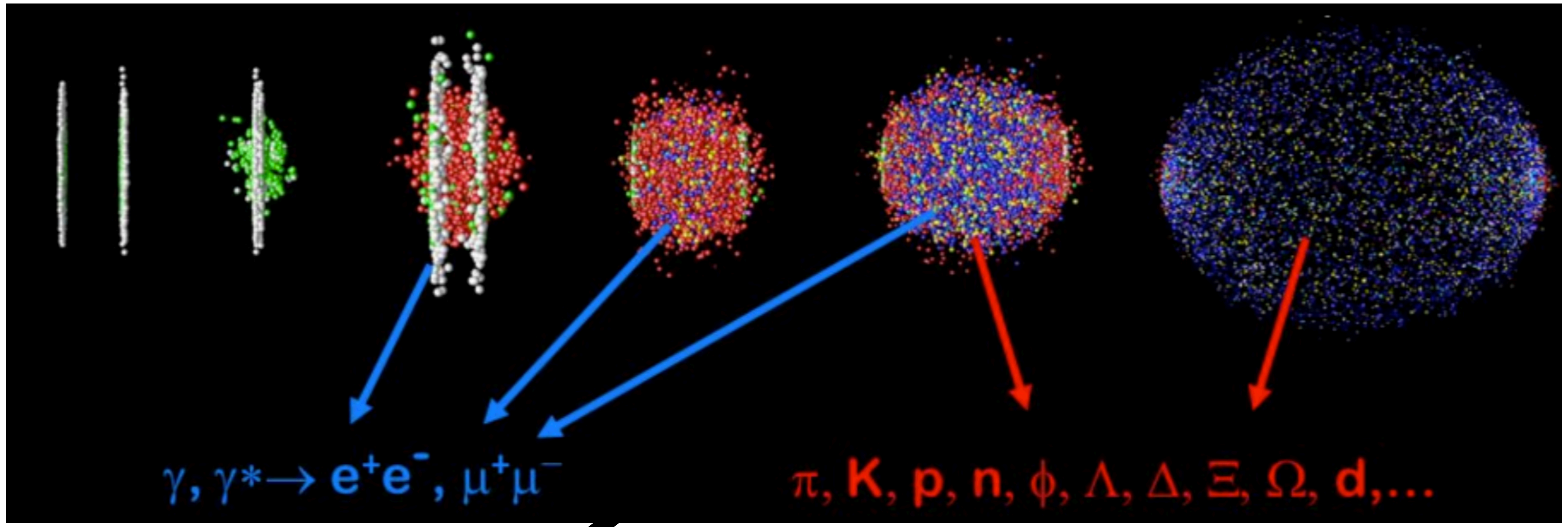
Why event-by-event fluctuation? →



https://indico.bnl.gov

Introduction and motivation

Why event-by-event fluctuation?

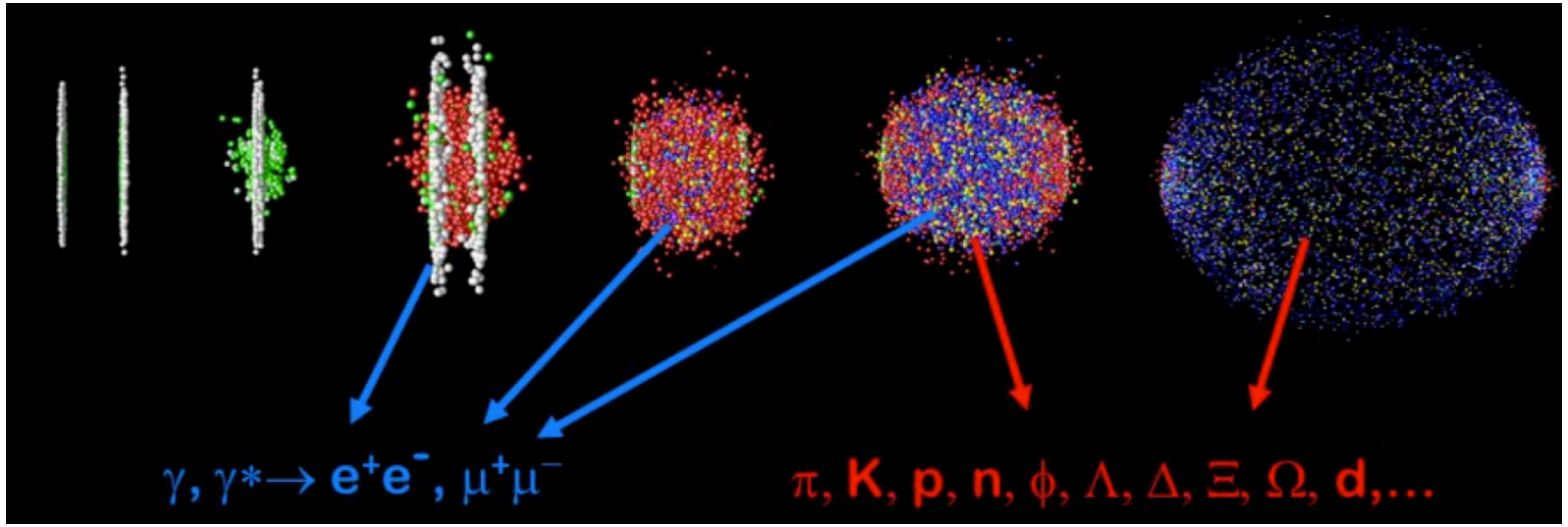


https://indico.bnl.gov

A large number of particles per event

Introduction and motivation

Why event-by-event fluctuation?

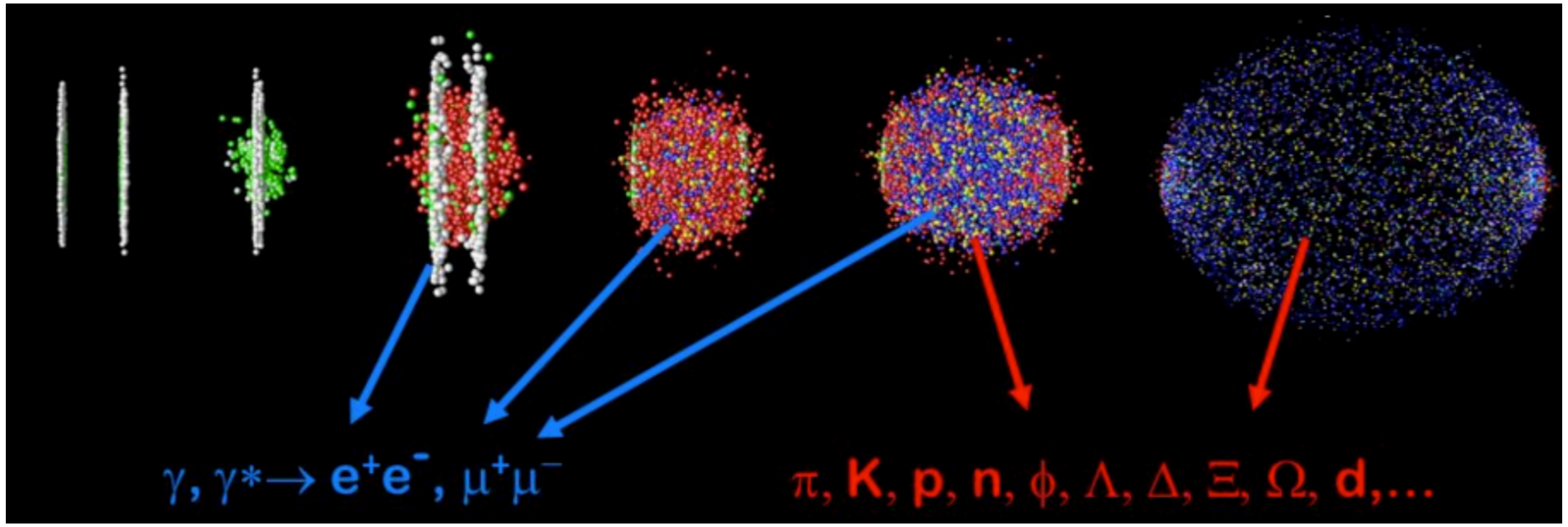


https://indico.bnl.gov

A large number of particles per event → Thermodynamic state

Introduction and motivation

Why event-by-event fluctuation?

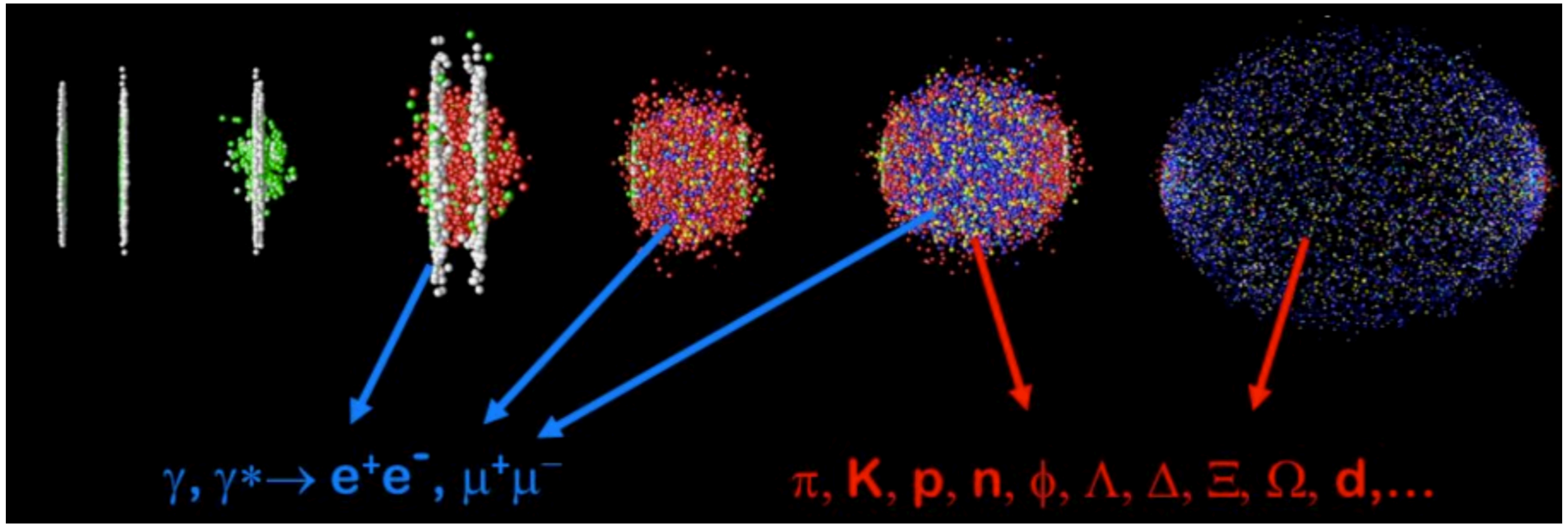


https://indico.bnl.gov

A large number of particles per event → Thermodynamic state → Local temperature (T_{chem})

Introduction and motivation

Why event-by-event fluctuation? →



https://indico.bnl.gov

A large number of particles per event → Thermodynamic state → Local temperature (T_{chem})

↓

The energy and particles can be transferred: Grand canonical ensemble

←

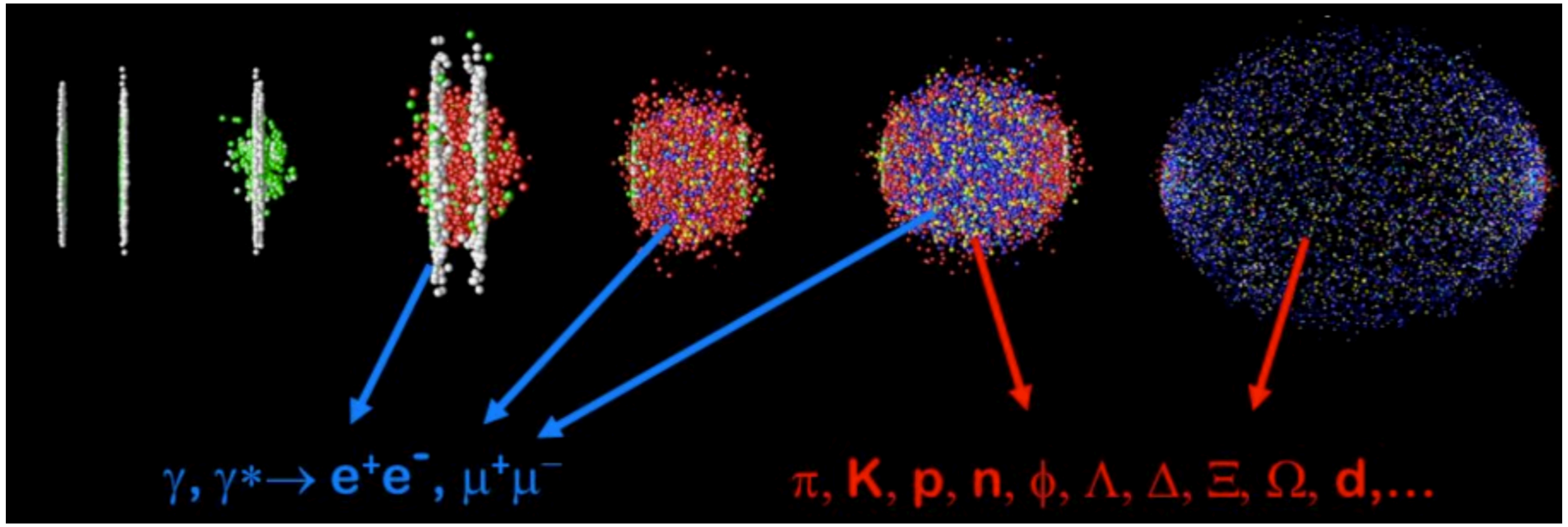
$$(\Delta T)^2 = \overline{(T - \overline{T})^2}$$

$$C^{-1} = \frac{(\Delta T)^2}{T^2}$$

L. Stodolsky, Phys. Rev. Lett. 75, 1044

Introduction and motivation

Why event-by-event fluctuation?



https://indico.bnl.gov

A large number of particles per event → Thermodynamic state → Local temperature (T_{chem})

The energy and particles can be transferred: Grand canonical ensemble

$$(\Delta T)^2 = \overline{(T - \overline{T})^2}$$

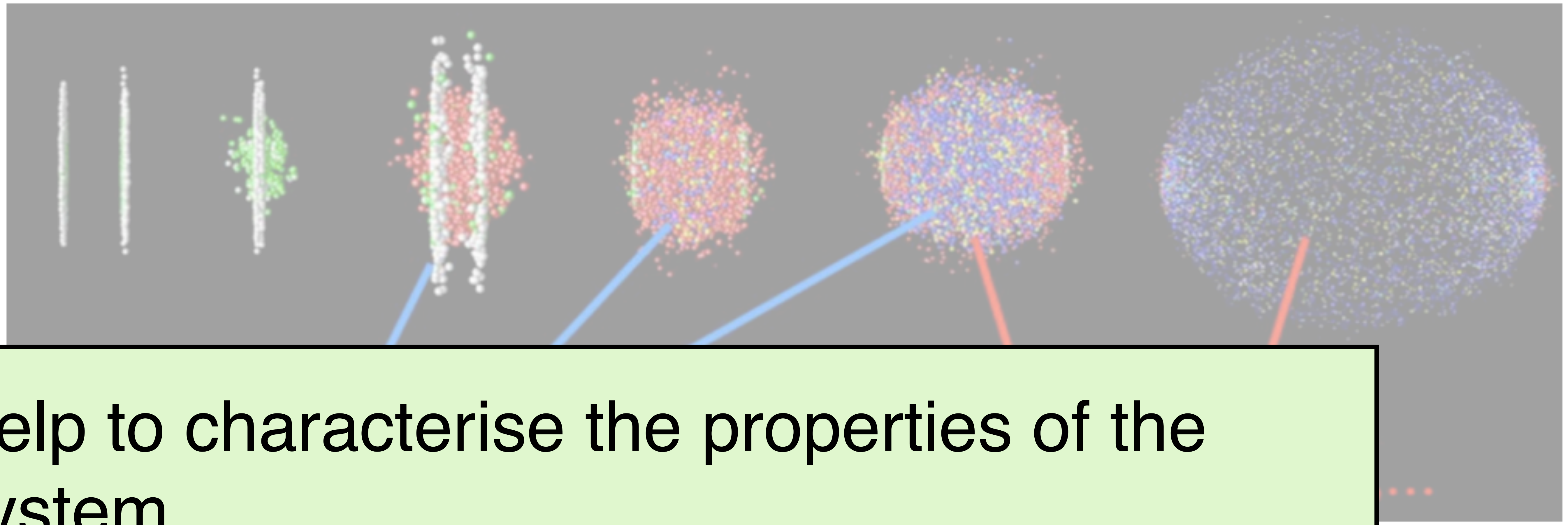
$$C^{-1} = \frac{(\Delta T)^2}{T^2}$$

L. Stodolsky, Phys. Rev. Lett. 75, 1044

Irregular behaviour of C could be a characteristic of phase transition.

Introduction and motivation

Why e-by-e fluctuation?



https://indico.bnl.gov

- Fluctuations help to characterise the properties of the "bulk" of the system.
- They are closely related to the **dynamics of the phase transitions.**

A large number of particles per event

…temperature (T_{chem})

Irregular behaviour of C is the characteristic of phase transition.

$$(\Delta T)^2 = \overline{(T - \overline{T})^2}$$

$$C^{-1} = \frac{(\Delta T)^2}{T^2}$$

L. Stodolsky, Phys. Rev. Lett. 75, 1044

The energy and particles can be exchanged: Grand canonical ensemble

Observable: Two-particle correlator

The p_T distribution can be described by:

$$f(E) = \frac{1}{Ae^{E/kT}}$$

Introduction and motivation

Observable: Two-particle correlator

The p_{T} distribution can be described by:

$$\mathrm{f}(E) = \frac{1}{\mathrm{A}e^{E/kT}}$$

$$\implies \langle \mathrm{f}(E) \rangle \propto T$$

Observable: Two-particle correlator

The p_T distribution can be described by:

$$f(E) = \frac{1}{Ae^{E/kT}}$$

$$\implies \langle f(E) \rangle \propto T$$

$E = m_T \, cosh y$

$m_T = \sqrt{m^2 + p_T^2}$

$\langle p_T \rangle$ is a proxy for a local temperature of the system.

Introduction and motivation

Observable: Two-particle correlator

The p_{T} distribution can be described by:

$$f(E) = \frac{1}{Ae^{E/kT}}$$

$$\Longrightarrow \langle f(E) \rangle \propto T$$

$$E = m_{\mathrm{T}}\, coshy$$

$$m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$$

$\langle p_{\mathrm{T}} \rangle$ is a proxy for a local temperature of the system.

$$\langle\langle \Delta p_{\mathrm{i}} \Delta p_{\mathrm{j}} \rangle\rangle = \left\langle \frac{\sum_{i,j\neq i} (p_{\mathrm{i}} - \langle p_{\mathrm{T}} \rangle)(p_{\mathrm{j}} - \langle p_{\mathrm{T}} \rangle)}{N_{\mathrm{ch}}(N_{\mathrm{ch}} - 1)} \right\rangle$$

Introduction and motivation

Observable: Two-particle correlator

The p_T distribution can be described by:

$$f(E) = \frac{1}{Ae^{E/kT}}$$

$$\implies \langle f(E) \rangle \propto T$$

$$E = m_T \cosh y$$

$$m_T = \sqrt{m^2 + p_T^2}$$

$\langle p_T \rangle$ is a proxy for a local temperature of the system.

$$\langle\langle \Delta p_i \Delta p_j \rangle\rangle = \left\langle \frac{\sum_{i,j\neq i} (p_i - \langle p_T \rangle)(p_j - \langle p_T \rangle)}{N_{ch}(N_{ch} - 1)} \right\rangle$$

$$\implies \langle\langle \Delta p_i \Delta p_j \rangle\rangle = \left\langle \frac{(Q_1)^2 - Q_2}{N_{ch}(N_{ch} - 1)} \right\rangle - \left\langle \frac{Q_1}{N_{ch}} \right\rangle^2$$

G. Giacalone, Phys. Rev. C 103, 024910 (2021)

$$\text{where, } Q_n = \sum_{i=1}^{N} (p_i)^n$$

Observable: Two-particle correlator

The p_T distribution can be described by:

$$\mathrm{f}(E) = \frac{1}{\mathrm{A}e^{E/kT}}$$

$$\implies \langle \mathrm{f}(E) \rangle \propto T$$

$$E = m_T \cosh y$$

$$m_T = \sqrt{m^2 + p_T^2}$$

$\langle p_T \rangle$ is a proxy for a local temperature of the system.

$$\langle\langle \Delta p_i \Delta p_j \rangle\rangle = \left\langle \frac{\sum_{i,j\neq i} (p_i - \langle p_T \rangle)(p_j - \langle p_T \rangle)}{N_{ch}(N_{ch} - 1)} \right\rangle$$

$$\implies \langle\langle \Delta p_i \Delta p_j \rangle\rangle = \left\langle \frac{(Q_1)^2 - Q_2}{N_{ch}(N_{ch} - 1)} \right\rangle - \left\langle \frac{Q_1}{N_{ch}} \right\rangle^2$$

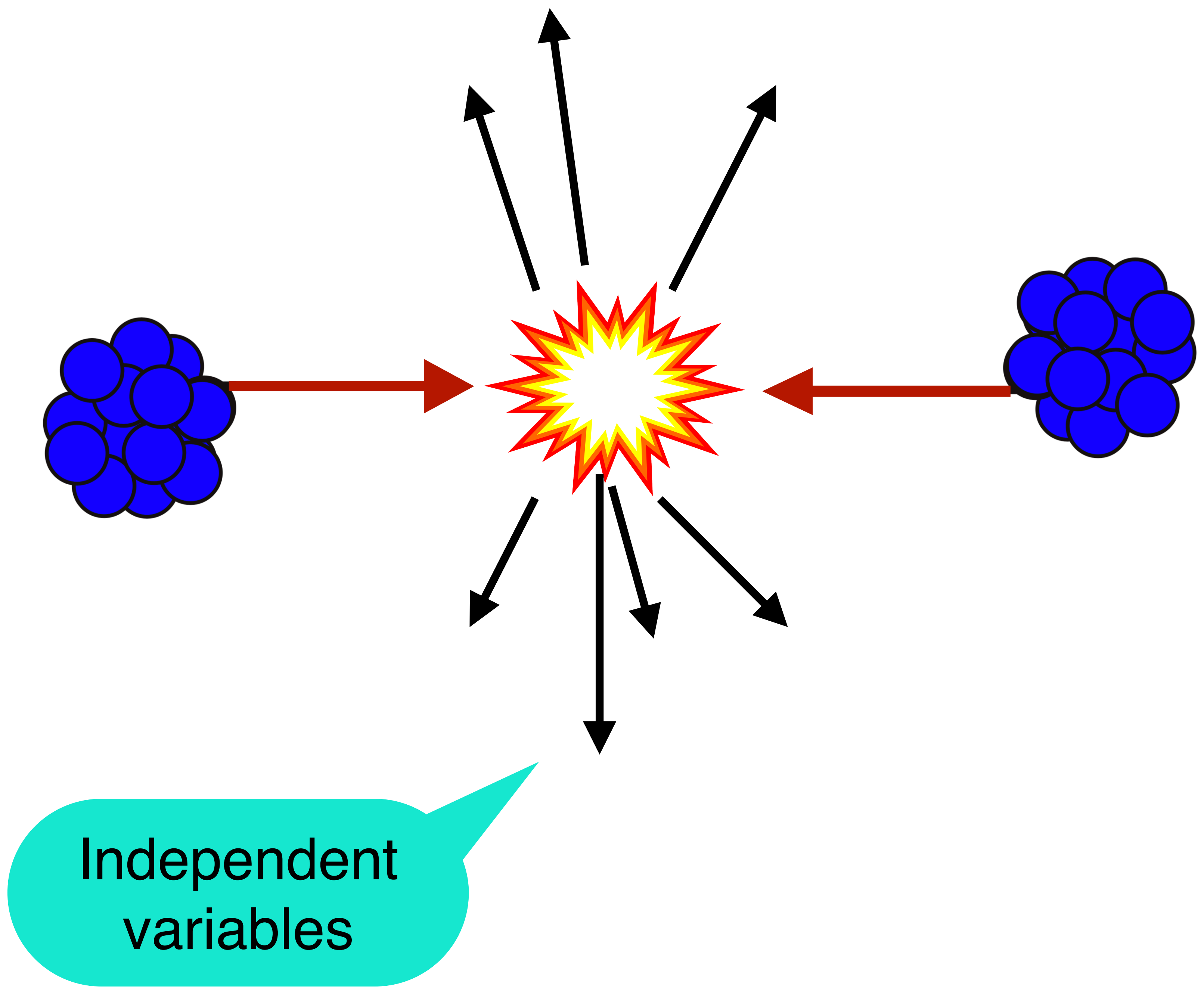
G. Giacalone, Phys. Rev. C 103, 024910 (2021)

$$\text{where, } Q_n = \sum_{i=1}^{N} (p_i)^n$$

$$\sqrt{\langle\langle \Delta p_{Ti} \Delta p_{Tj} \rangle\rangle} / \langle\langle p_T \rangle\rangle$$

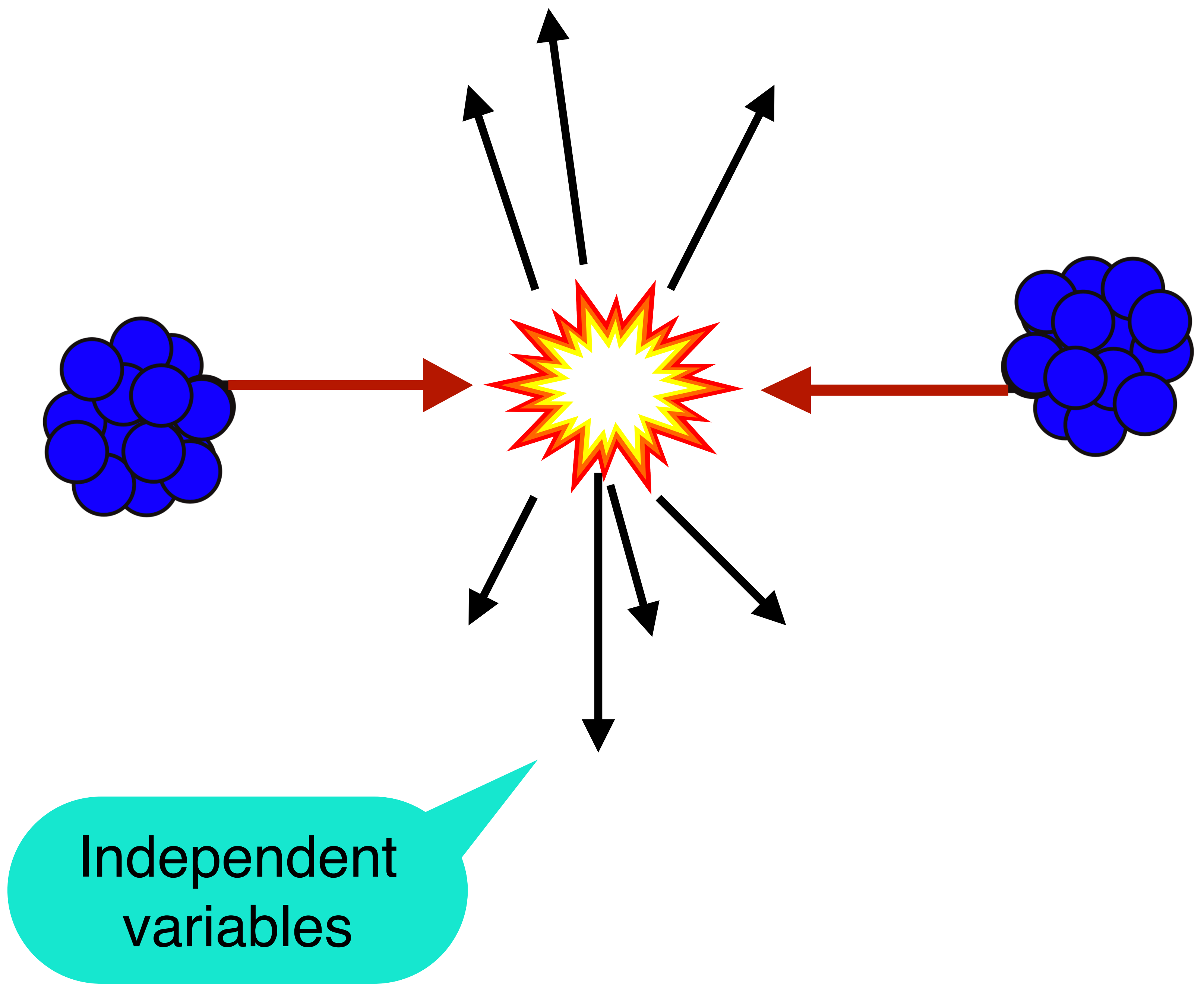
Observable: Two-particle correlator

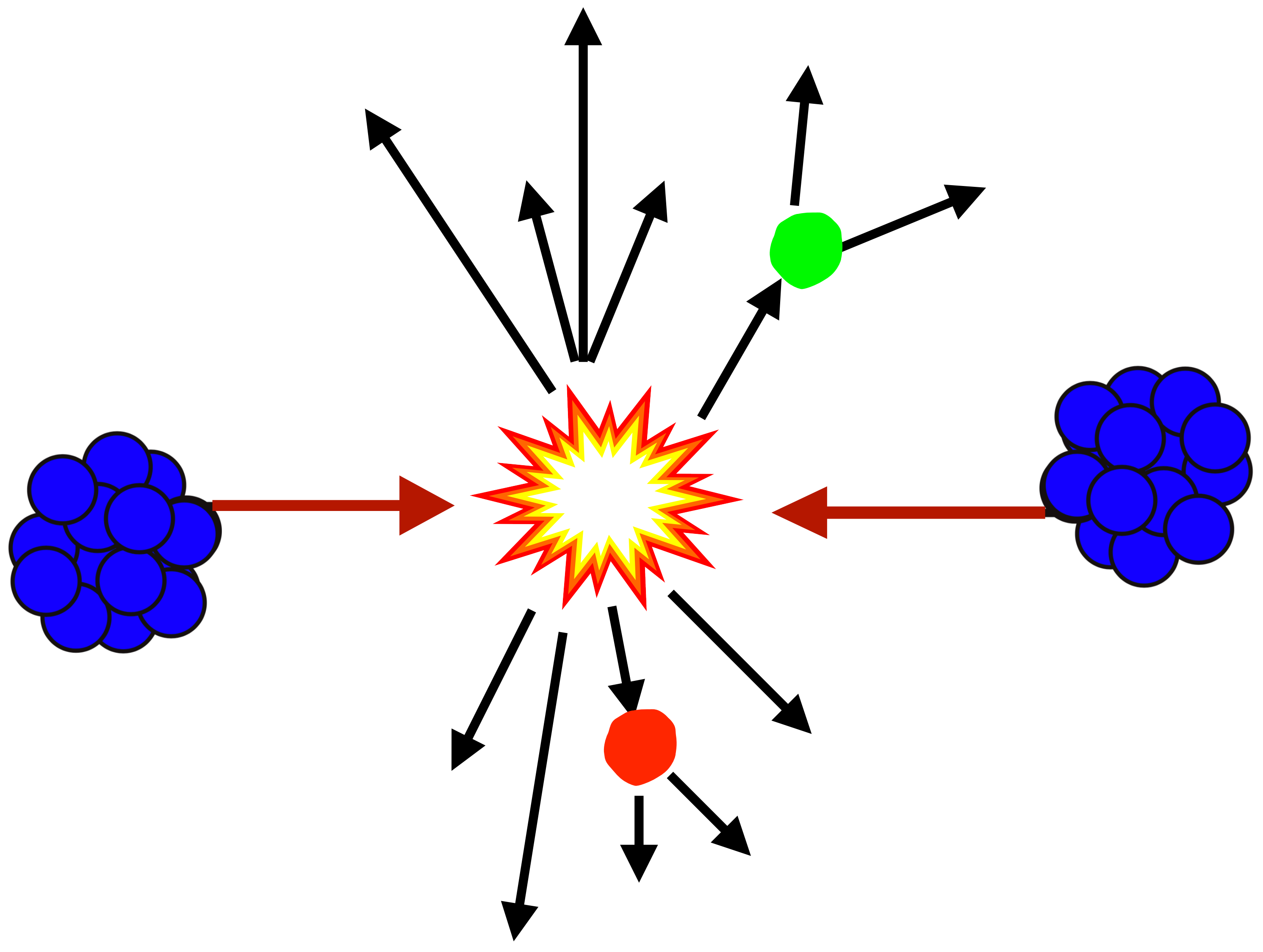
Statistical fluctuation



Observable: Two-particle correlator

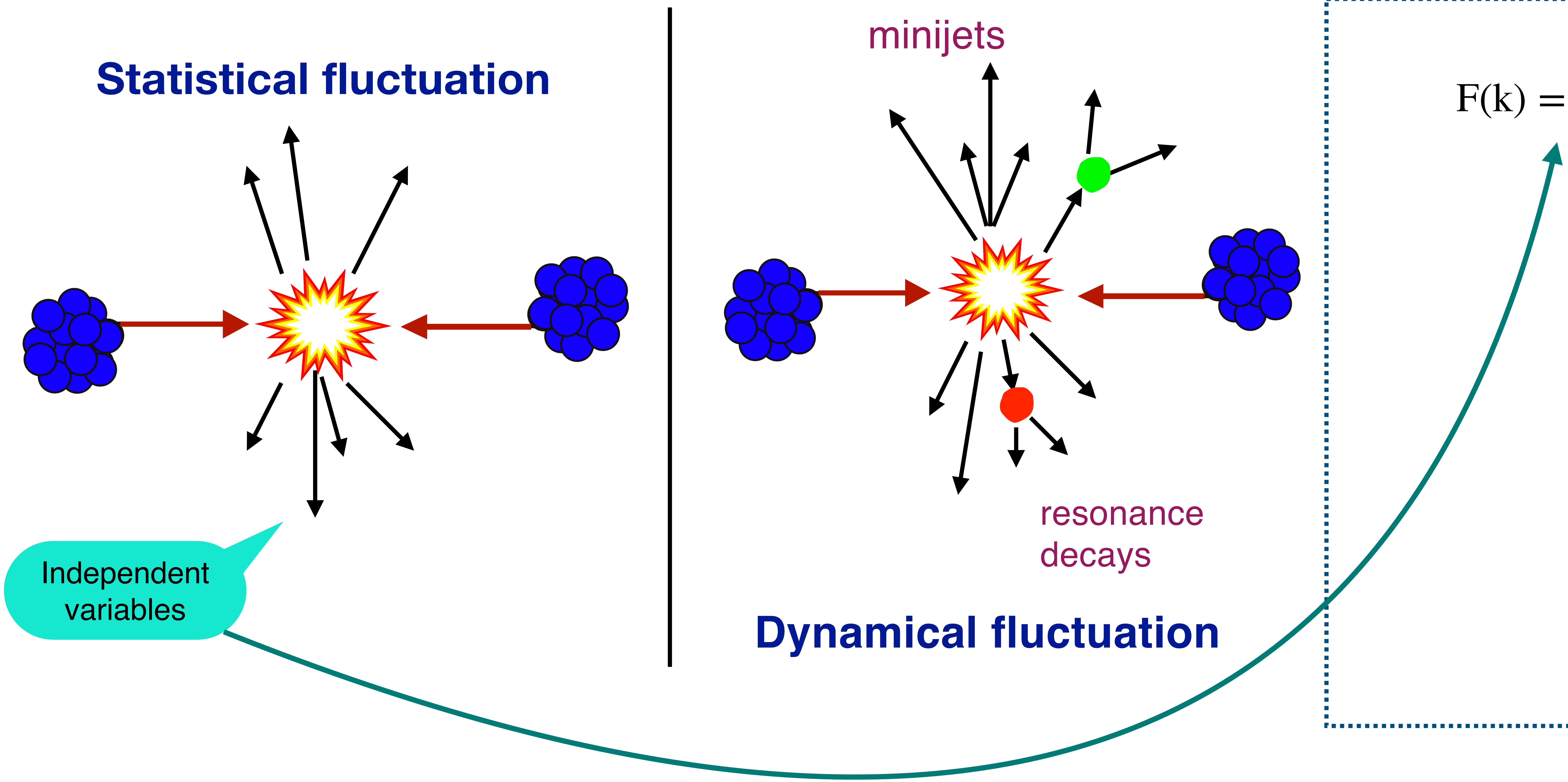
Statistical fluctuation





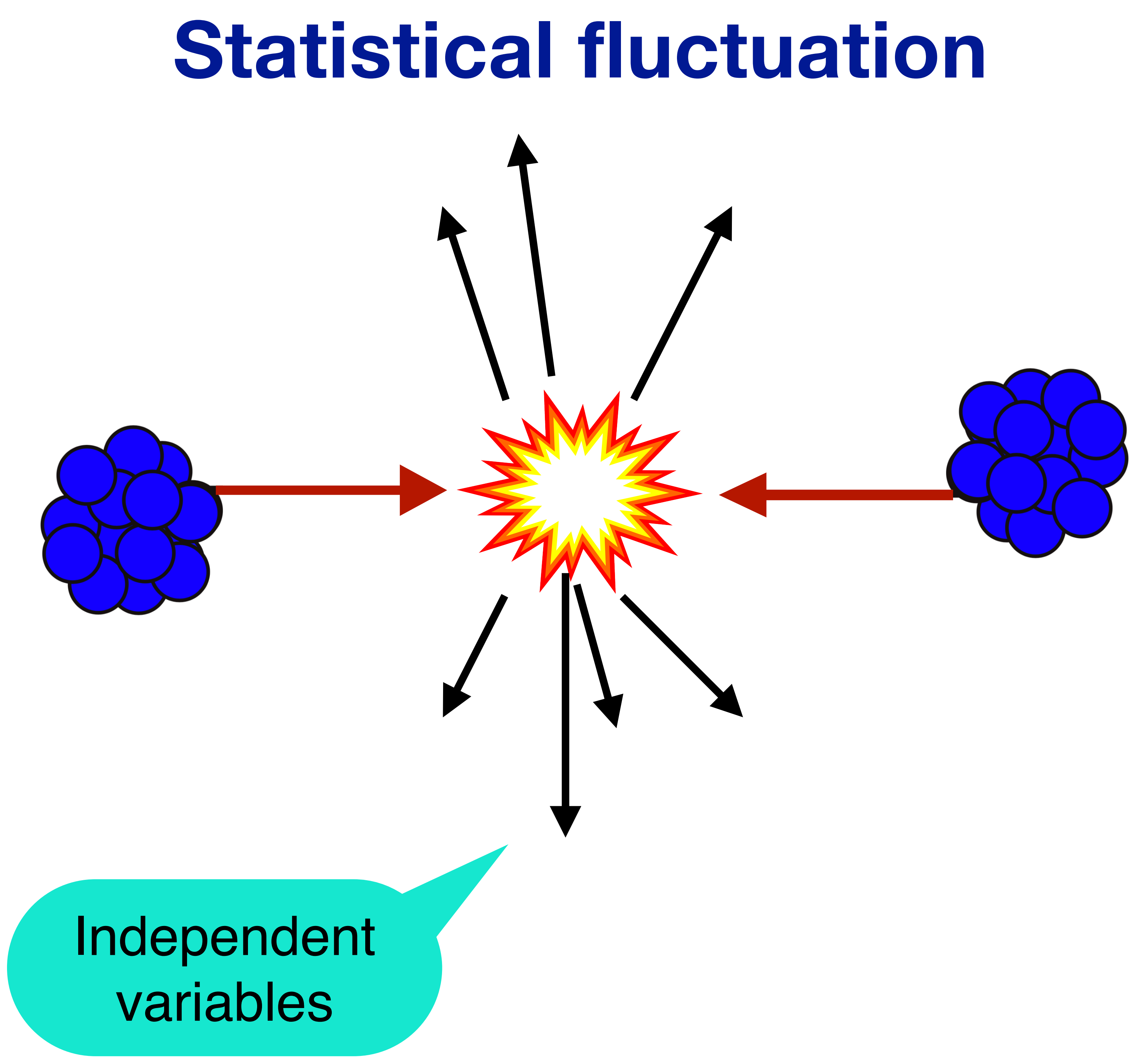
Dynamical fluctuation

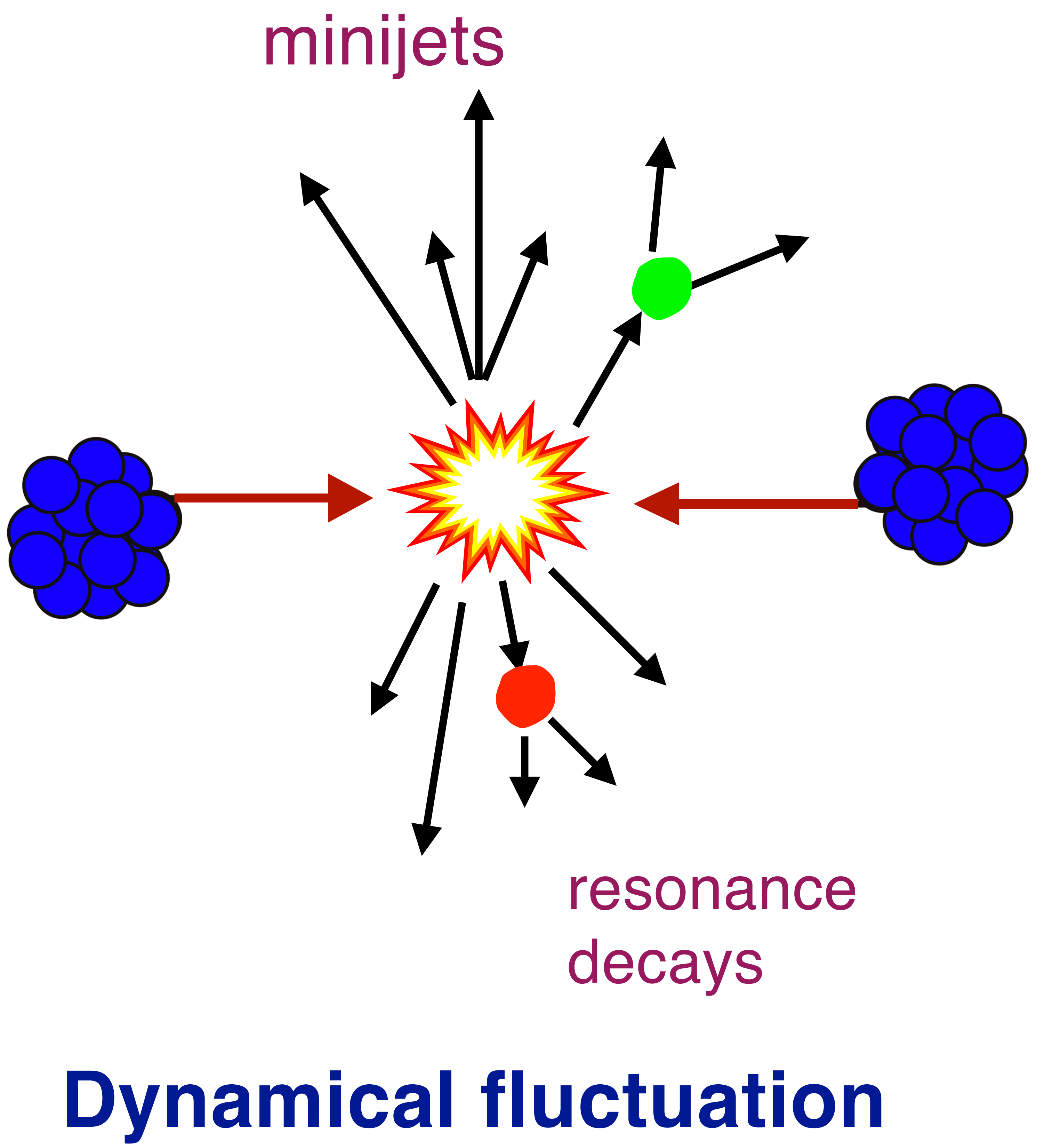
Observable: Two-particle correlator



$$F(k) = e^{-\lambda}\frac{\lambda^{k}}{k!}$$

Observable: Two-particle correlator





$$F(k) = e^{-\lambda}\frac{\lambda^k}{k!}$$

$$\implies \langle F(k) \rangle = \lambda$$

$$Cov(x, y) = E[x, y] - E[x]E[y]$$

$$\implies \lambda_1\lambda_2 - \lambda_1\lambda_2 = 0$$

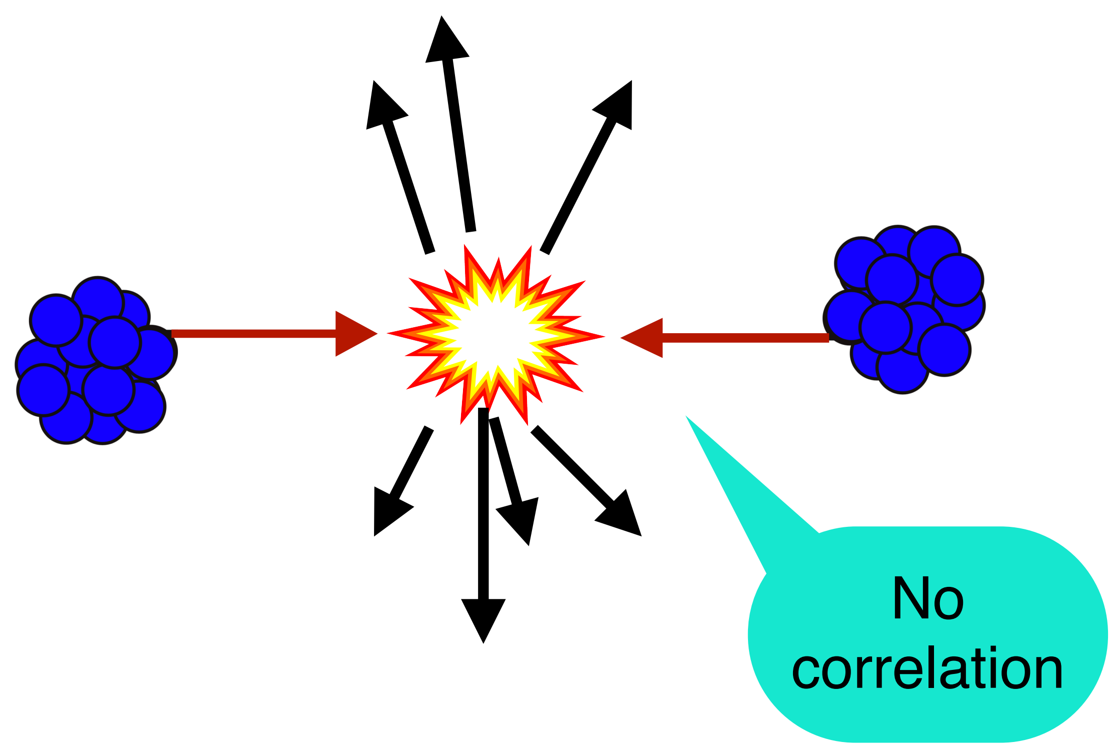
$$C=0$$

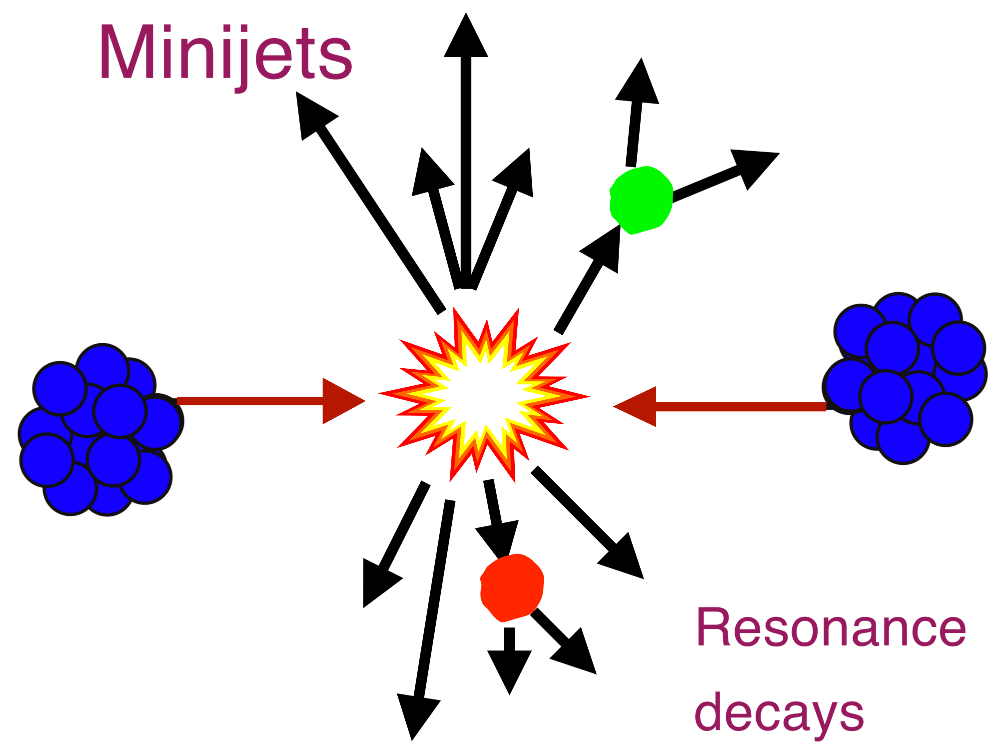
No **statistical** fluctuation

Introduction and motivation

Observable: Two-Particle Correlator

Statistical fluctuation:





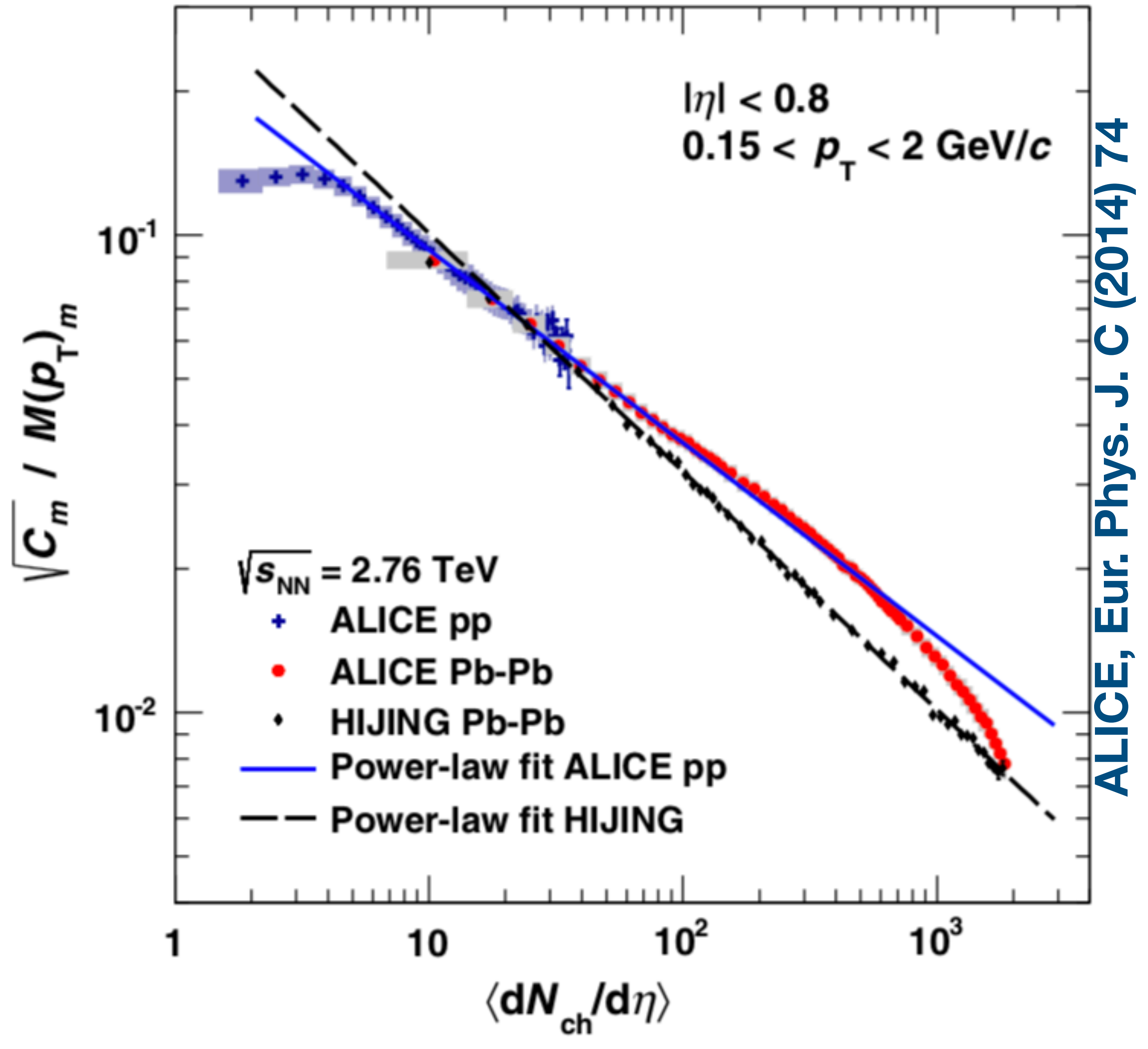
Presence of correlation

$$F(k) = e^{-\lambda}\frac{\lambda^k}{k!} \implies \langle F(k) \rangle = \lambda$$

$$Cov(x,y) = E[x,y] - E[x]E[y] \implies \lambda_1\lambda_2 - \lambda_1\lambda_2 = 0$$

$$C=0$$

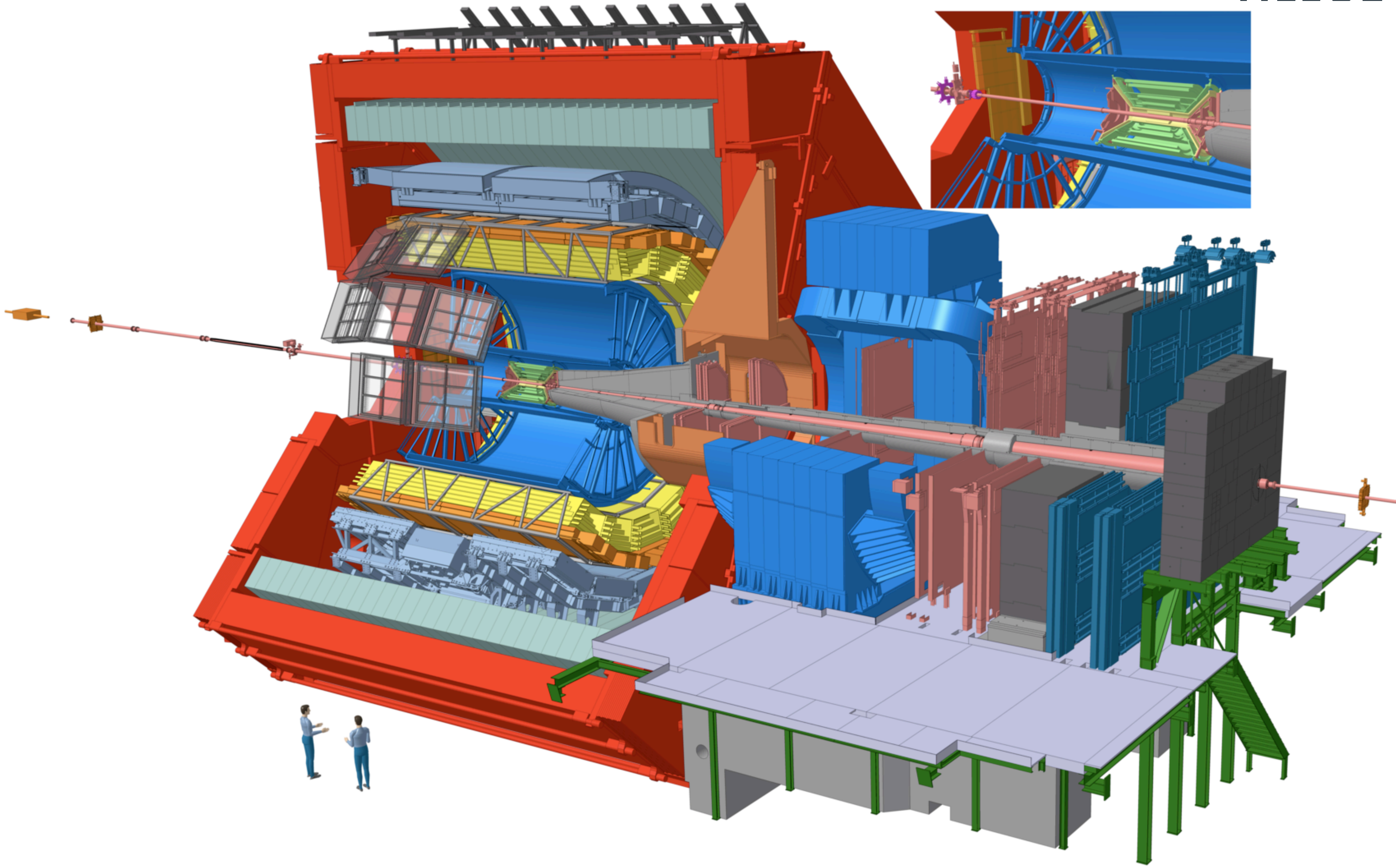
No **statistical** fluctuation



- In peripheral Pb–Pb collisions, fluctuations are in very good agreement with the extrapolation of a power-law fit to pp
- At larger multiplicities, the Pb–Pb results deviate from the pp extrapolation

Key physics goals: System size, energy and event shape dependence of event-by-event fluctuations at the LHC

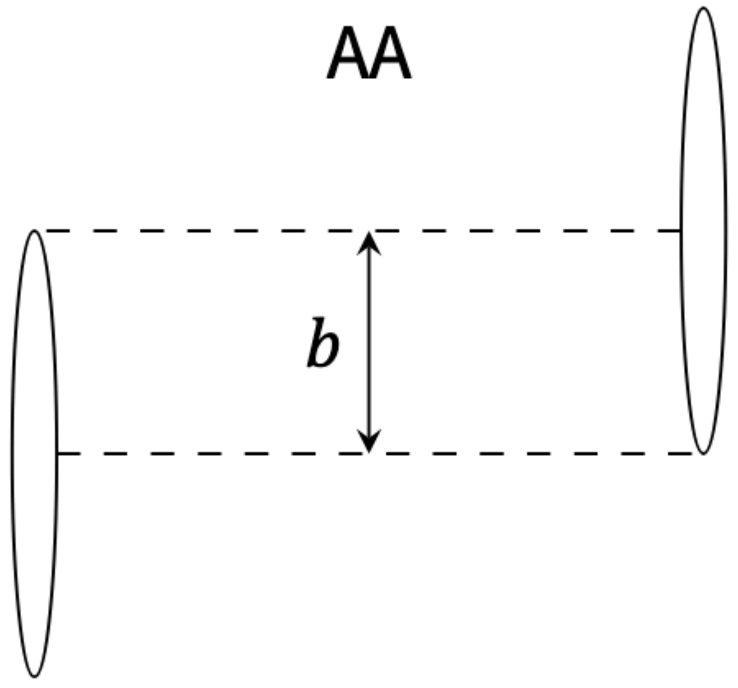
A Large Ion Collider Experiment

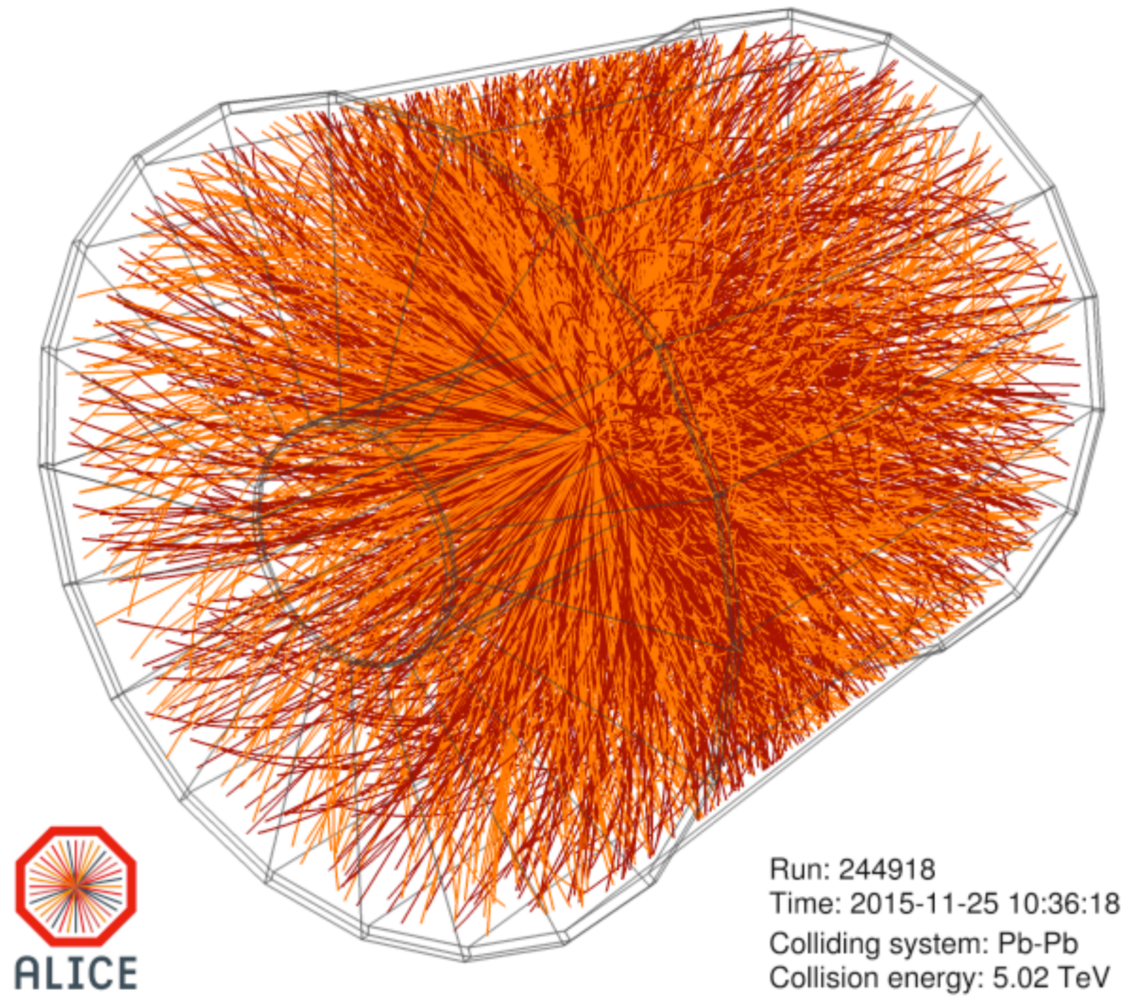


(Run 2 Schematics)

System	Years Run 1 | Run 2	$\sqrt{s_{NN}}$ (TeV)
Pb—Pb	2010, 2011 2015, 2018	2.76 5.02
Xe—Xe	2017	5,44
p—Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13

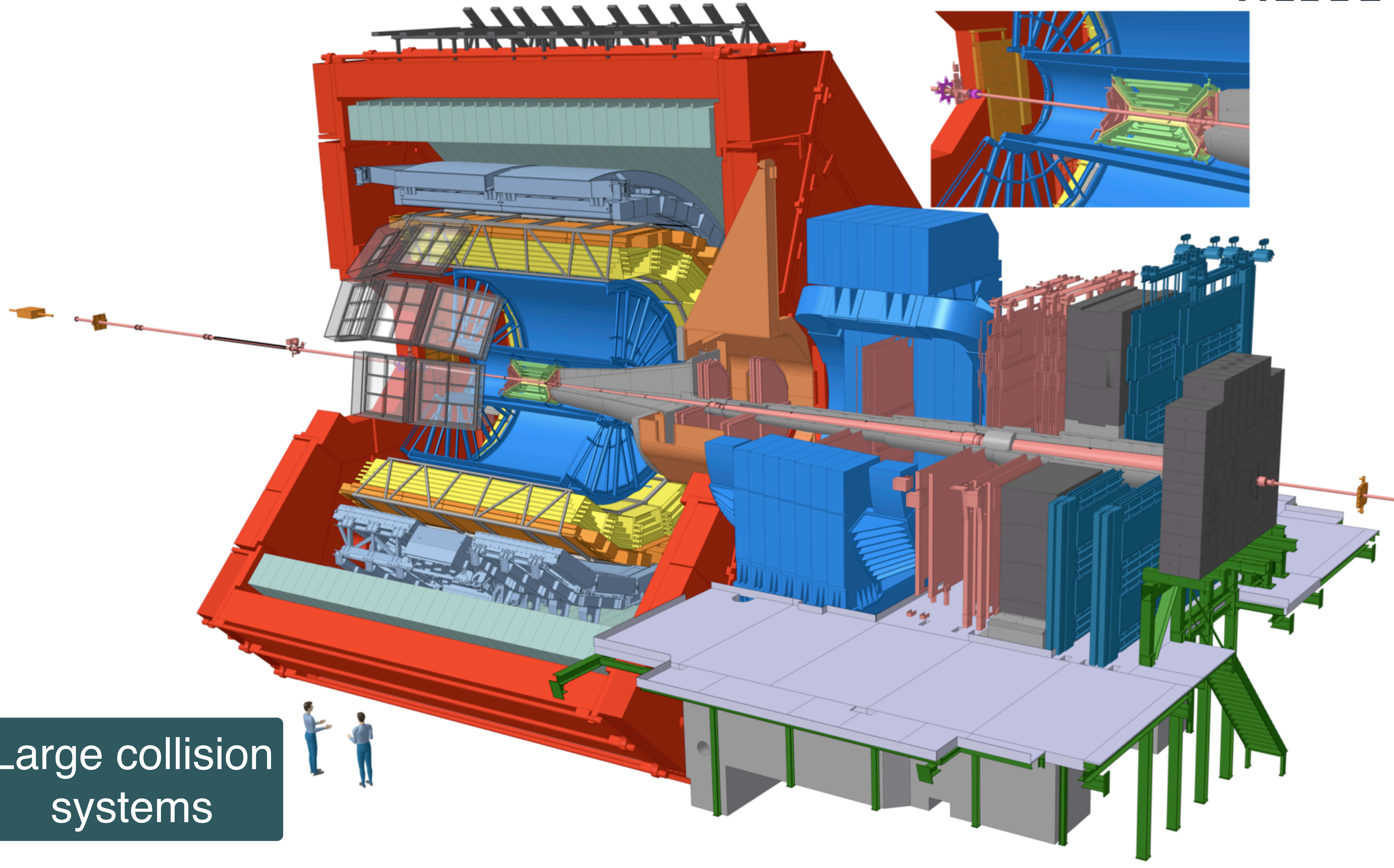
A Large Ion Collider Experiment





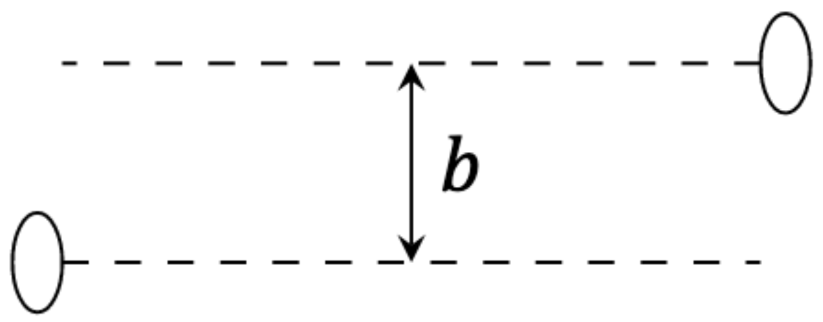
System	Years Run 1 I Run 2	$\sqrt{s_{NN}}$ (TeV)
Pb—Pb	2010, 2011 2015, 2018	2.76 5.02
Xe—Xe	2017	5,44
p—Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13

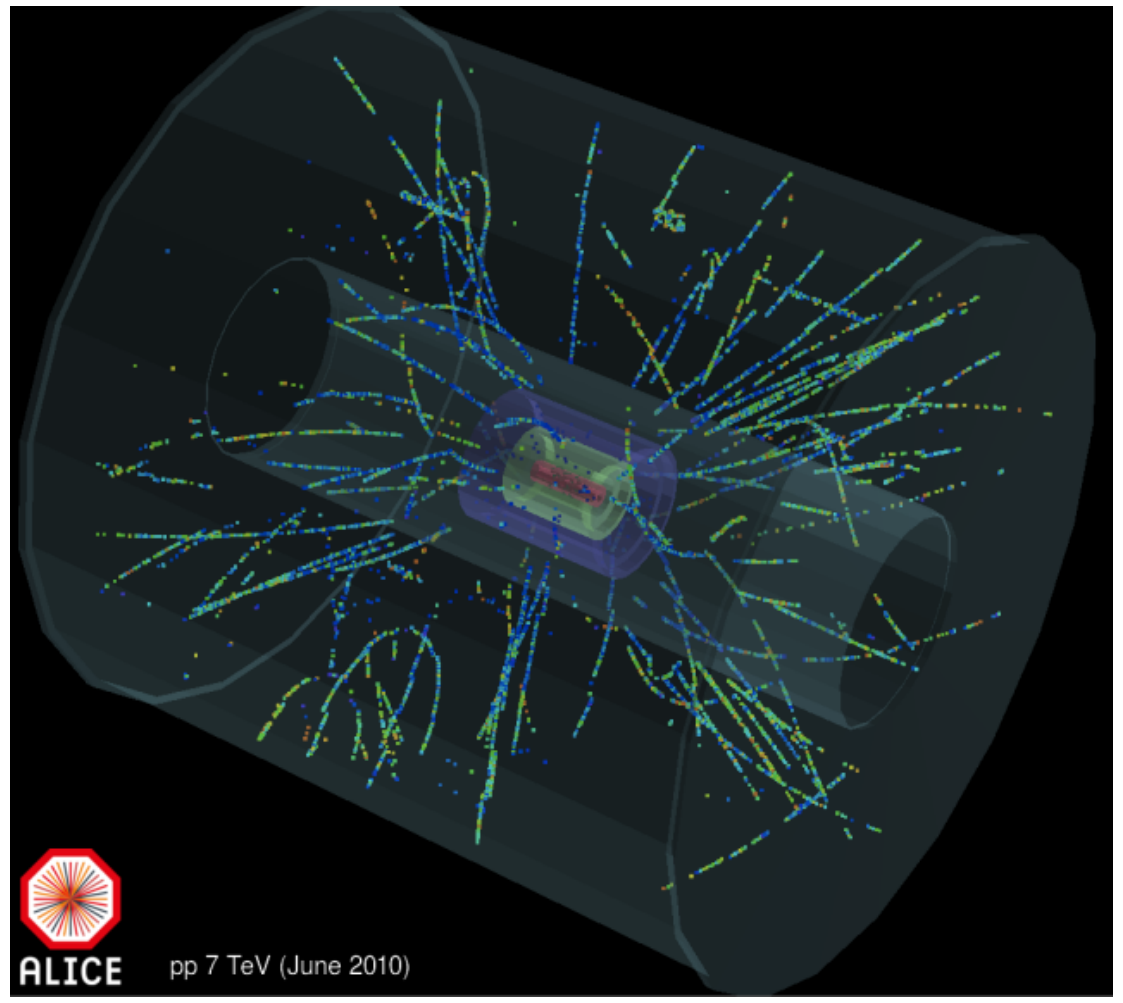
Large collision systems

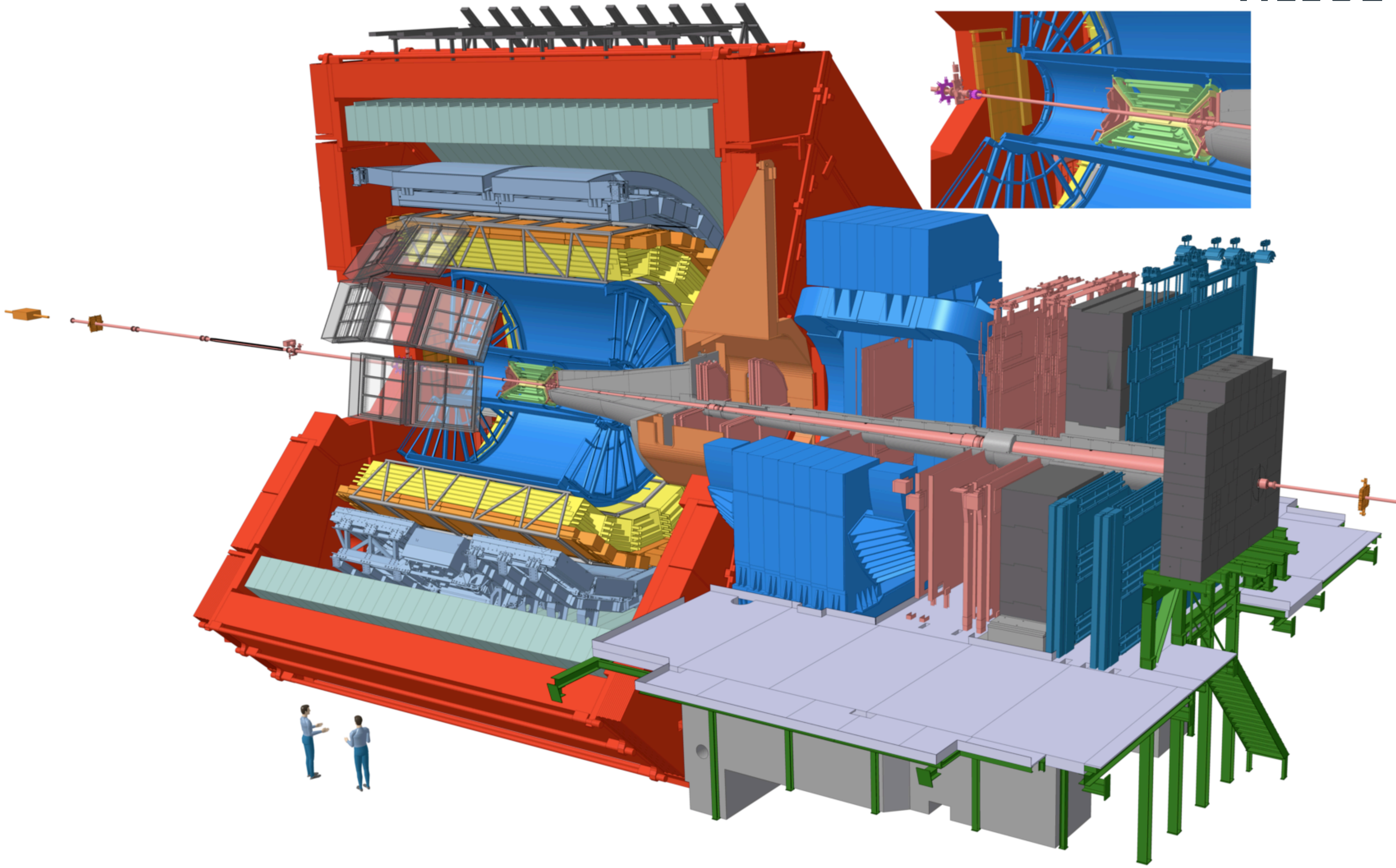

(Run 2 Schematics)

A Large Ion Collider Experiment

pp







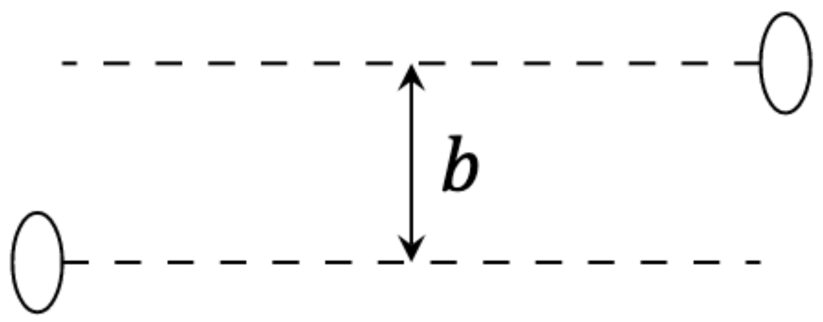
(Run 2 Schematics)

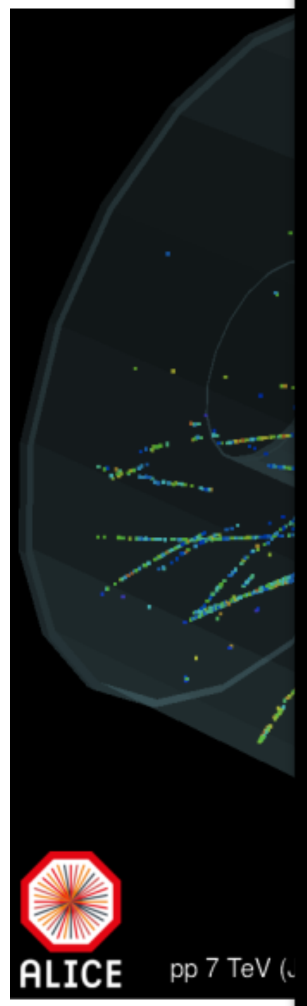
System	Years Run 1 | Run 2	$\sqrt{s_{NN}}$ (TeV)
Pb—Pb	2010, 2011 2015, 2018	2.76 5.02
Xe—Xe	2017	5,44
p—Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13

Small collision systems

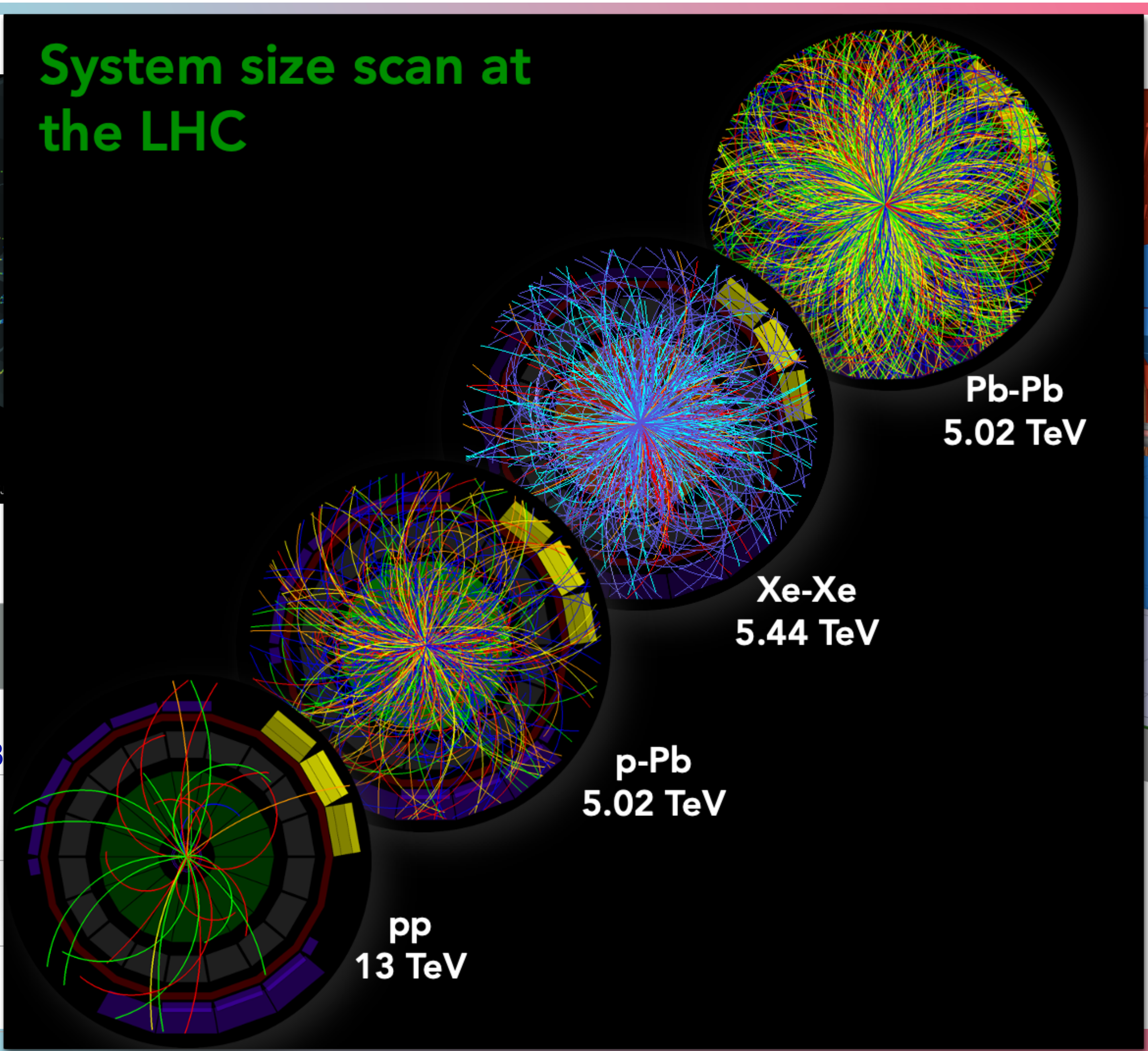
A Large Ion Collider Experiment

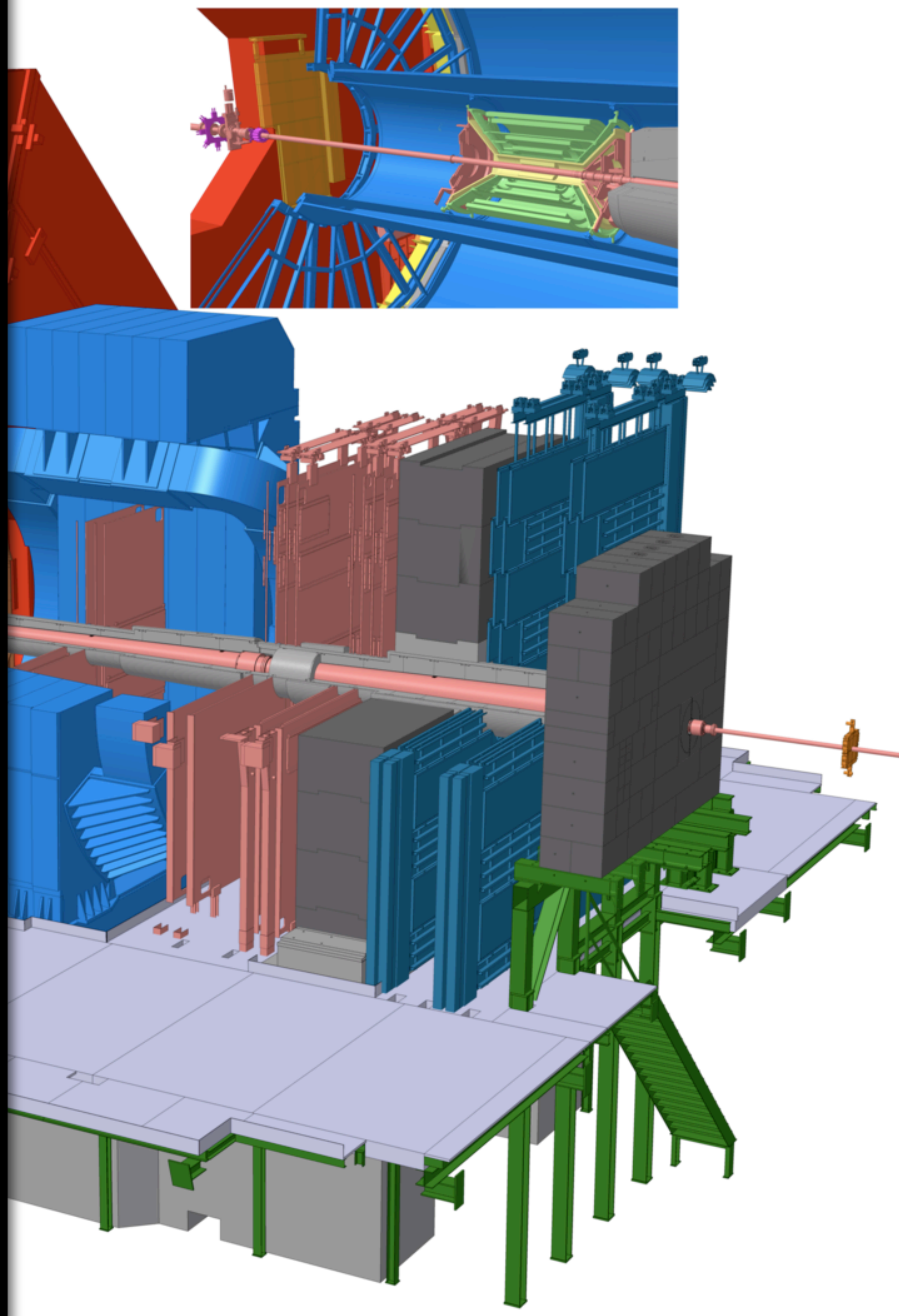
pp



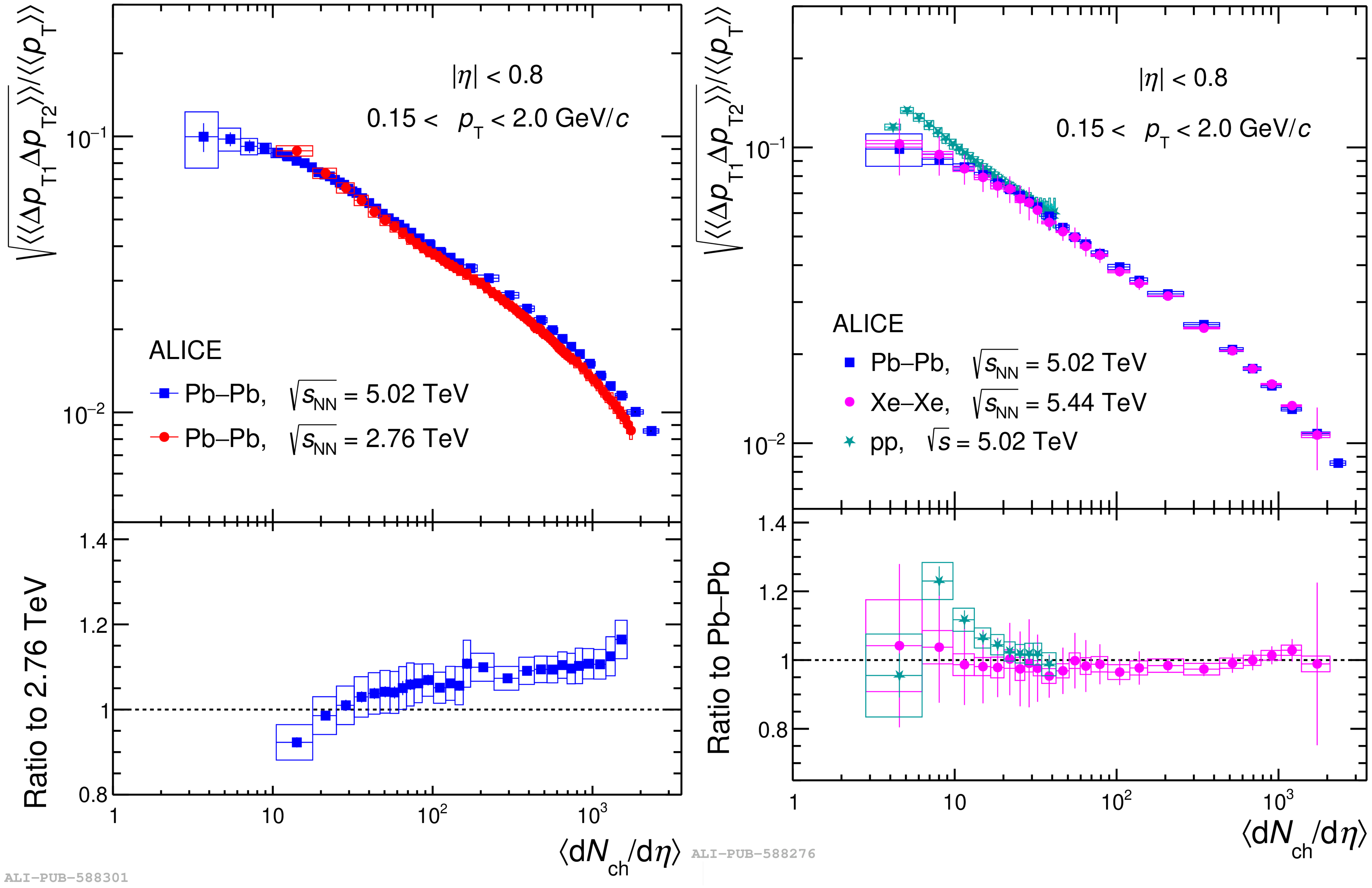


System	Years Run 1 I Run
Pb—Pb	2010, 2011 2015, 2018
Xe—Xe	2017
p—Pb	2013 2016
pp	2009-2013 2015-2018





Results: Energy and system size scan

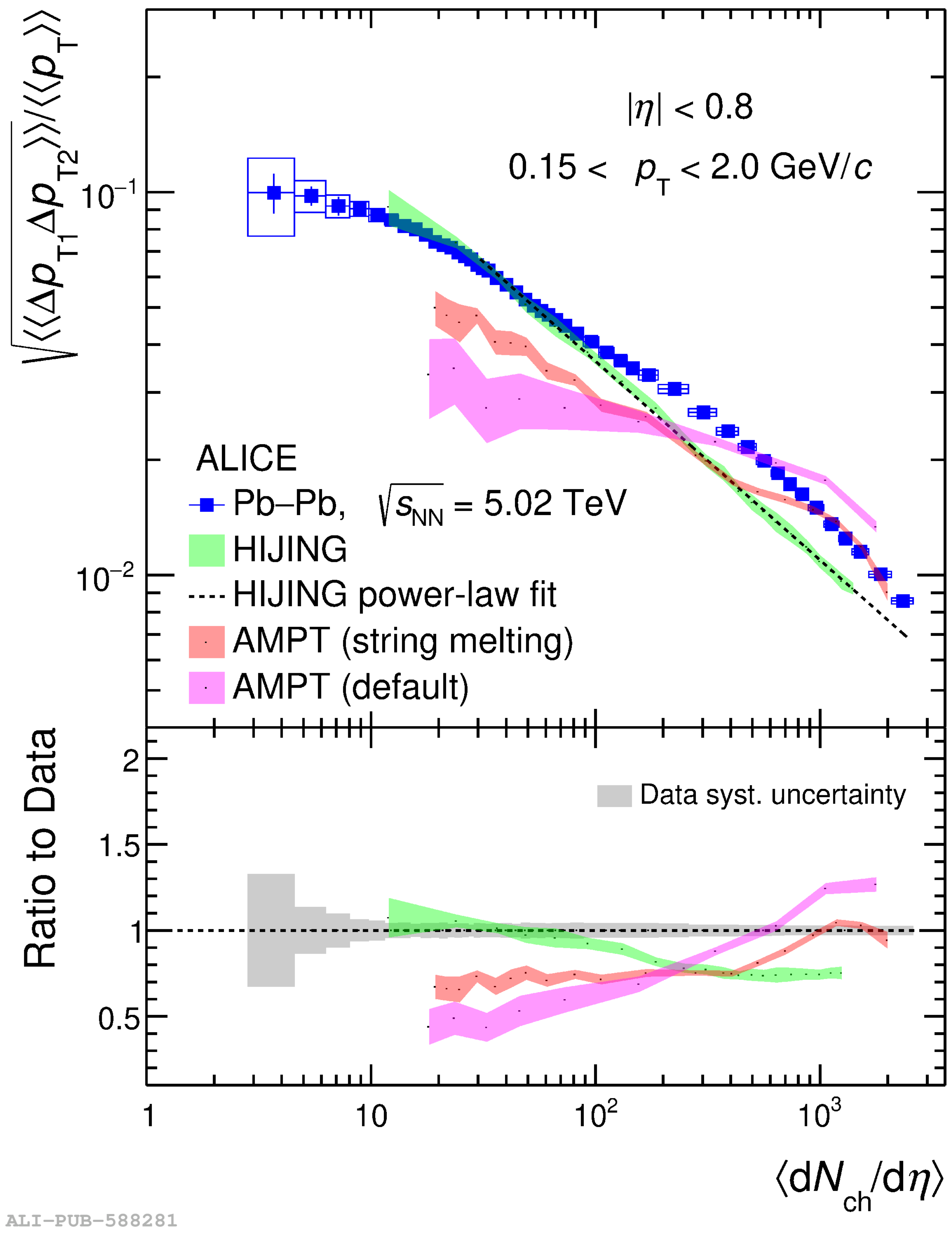


- Modest increase with beam energy in mid to central Pb-Pb collisions.
- pp values are similar to Pb—Pb and Xe—Xe collisions in 20-45 and follows a similar slope up to 600.

Evolution of the correlator strength with charged-particle density as a function of (a) beam energy (b) system size

ALICE, arXiv:2411.09334 **[nucl-ex]**

Results: model comparisons



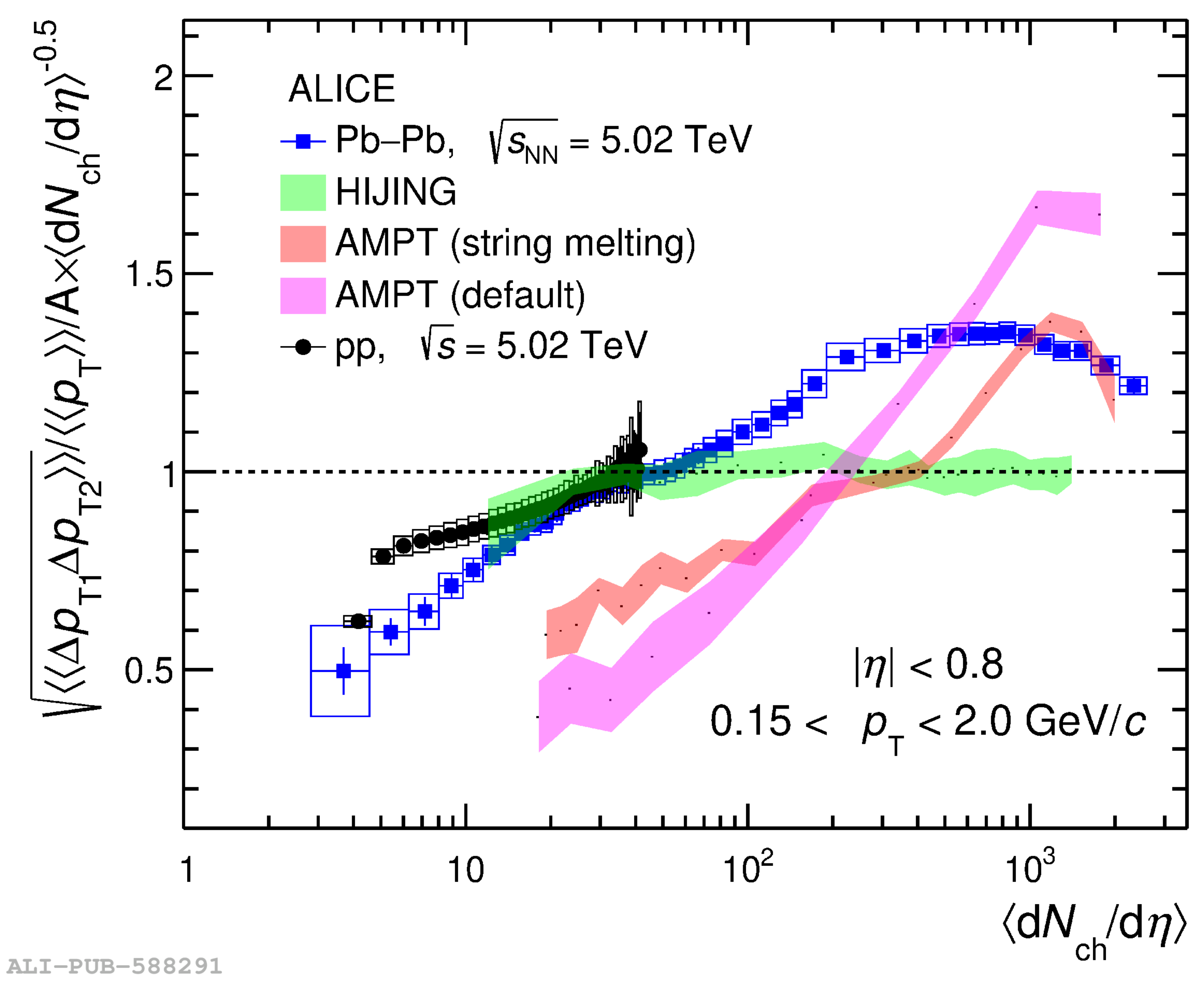
Power-law fit: $\propto \langle dN_{ch}/d\eta \rangle^b \quad (b = -0.5)$

corresponds to a simple superposition scenario

- HJING exhibits perfect scaling as expected from a model with no re-interactions or re-scattering.
- Significant deviation of Pb—Pb data from HIJING in central collisions.
- Both AMPT versions exhibit a pronounced fall-off in central collisions which is in qualitative agreement with the data.

ALICE, arXiv:2411.09334 **[nucl-ex]**

Results: system size scan

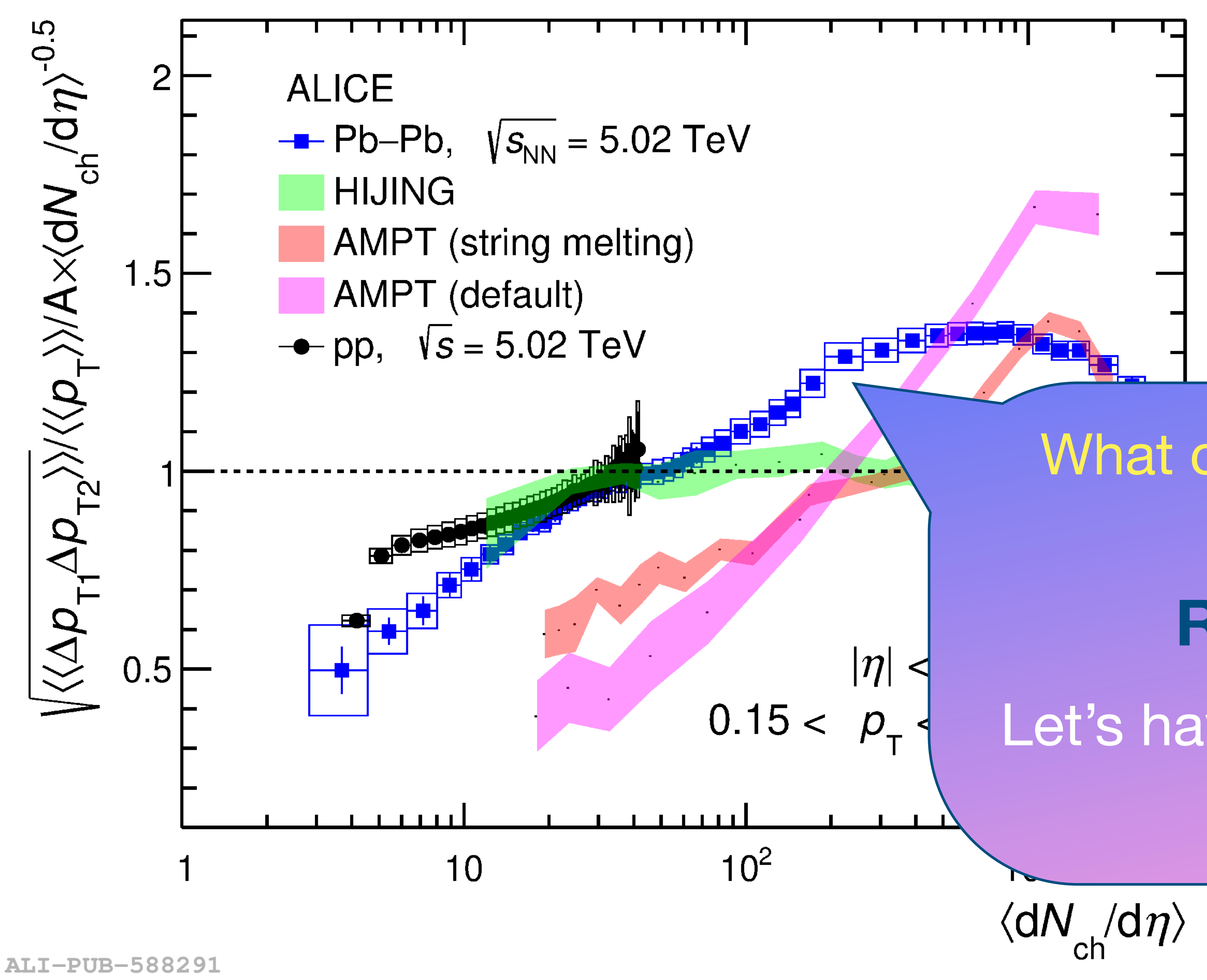


ALICE, arXiv:2411.09334 [nucl-ex]

- pp : seems to have perfect scaling for high multiplicity.
- A—A : Scaling clearly violated in mid-to central collisions: anticipated from strong radial flow, flow velocity fluctuations and temperature fluctuations.
- Both AMPT versions exhibit a pronounced fall-off in central collisions which is in qualitative agreement with the data.

Evolution of the correlator strength scaled by the charged particle density as a function of $\langle dN_{ch}/d\eta \rangle$ in pp and A—A collisions: Straight line shows perfect scaling.

Results: system size scan



ALICE, arXiv:2411.09334 [nucl-ex]

- pp : seems to have perfect scaling for high multiplicity.
- A—A : Scaling clearly violated in mid-to central collisions: anticipated from strong radial flow, flow velocity fluctuations and temperature fluctuations.

What could be the source of deviation from perfect scaling in heavy-ion collisions ?

Radial flow or **presence of jets** ???

Let's have a look at the **smallest system** at the LHC, i.e. **pp collisions**

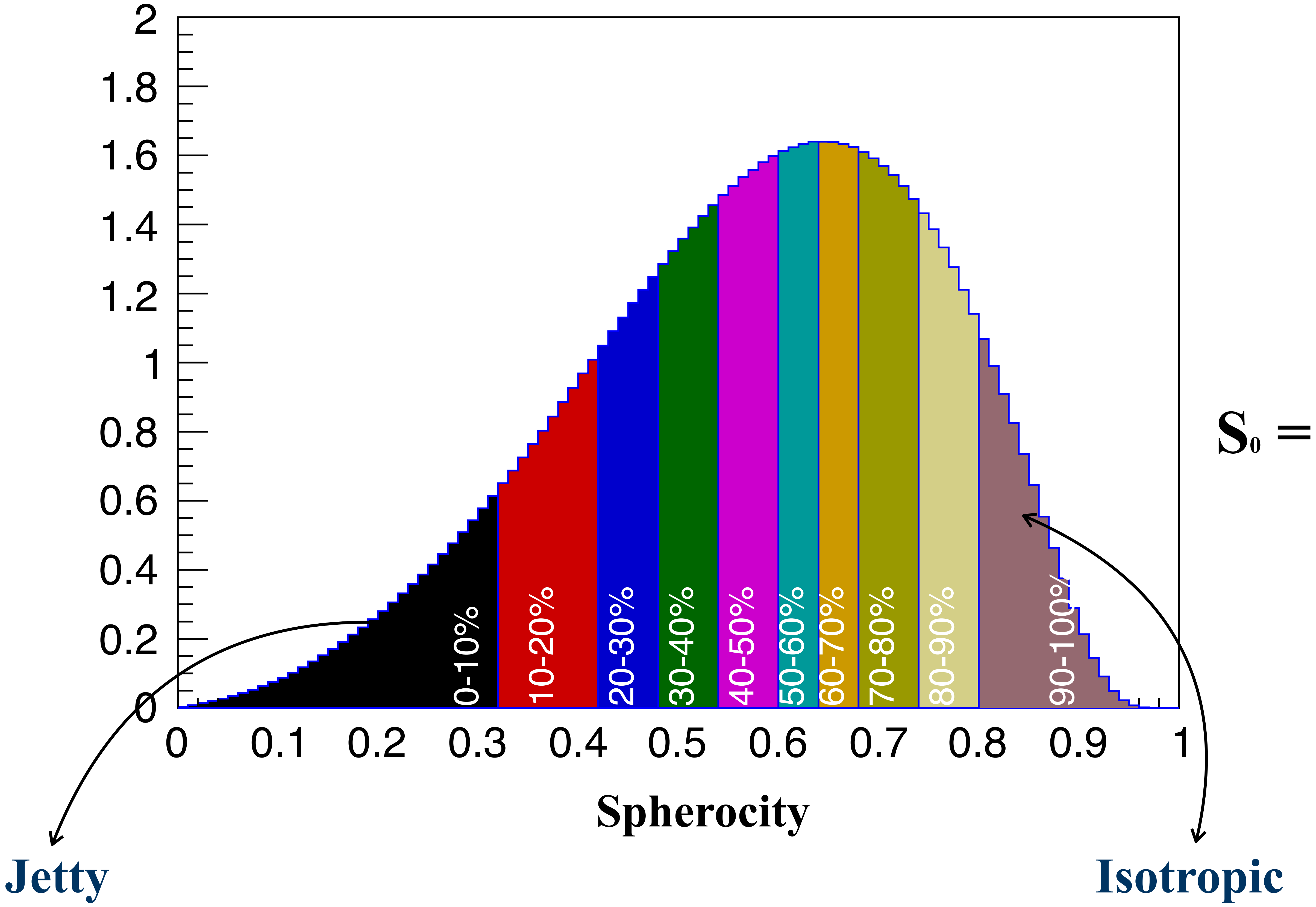
$\langle dN_{ch}/d\eta\rangle$ in pp and A—A collisions:
Straight line shows perfect scaling.

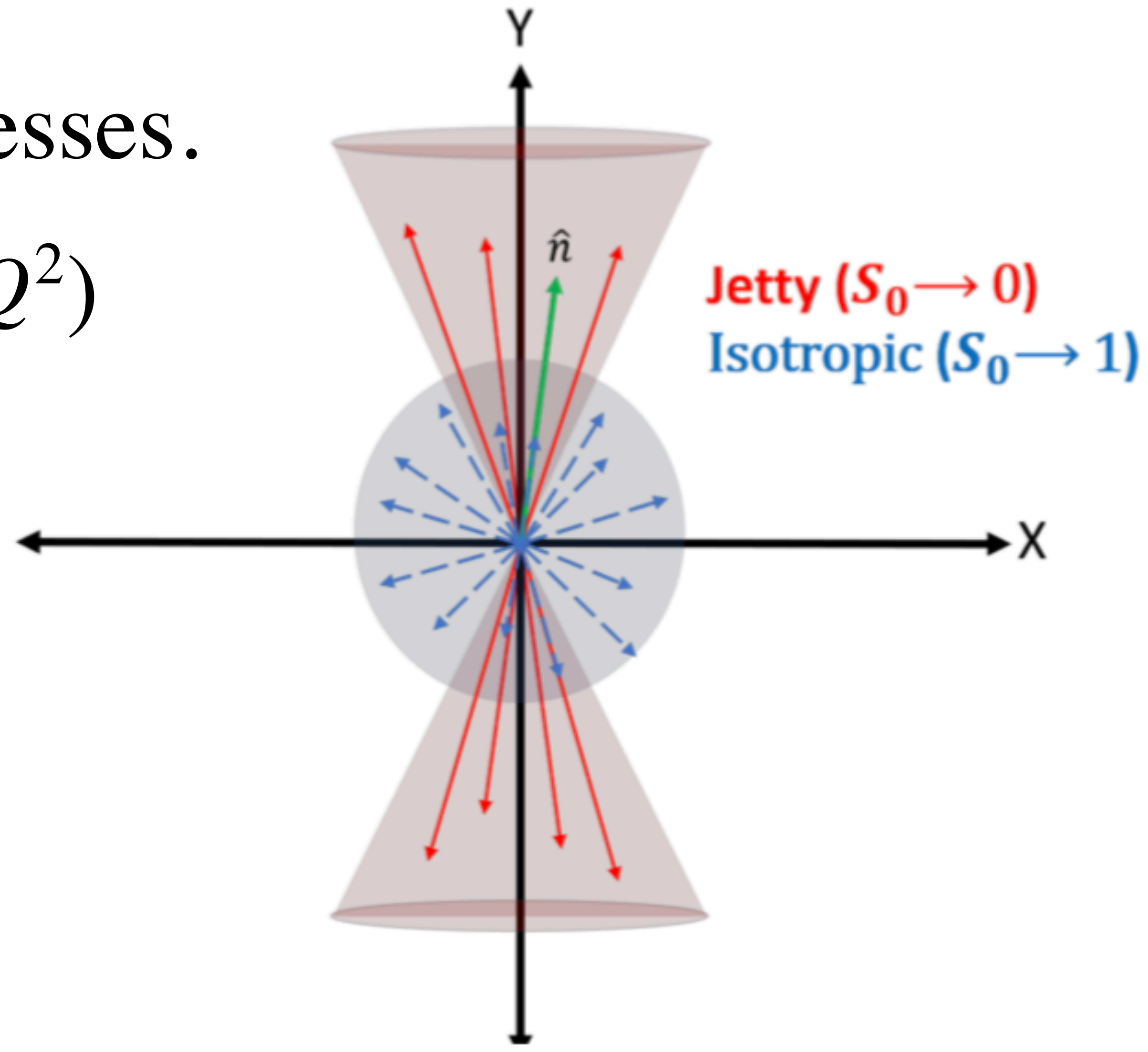
Transverse spherocity:

Transverse spherocity discriminates between hard and soft processes.

1. Jetty: Back-to-back structure, indication of hard QCD (High Q^2)

2. Isotropic: enhances UE, soft QCD (Low Q^2)





A. Khuntia, S. Tripathy, A. Bisht and R. Sahoo, J. Phys. G48, 035102 (2021)

Event shapes are characterized using transverse spherocity S_0.

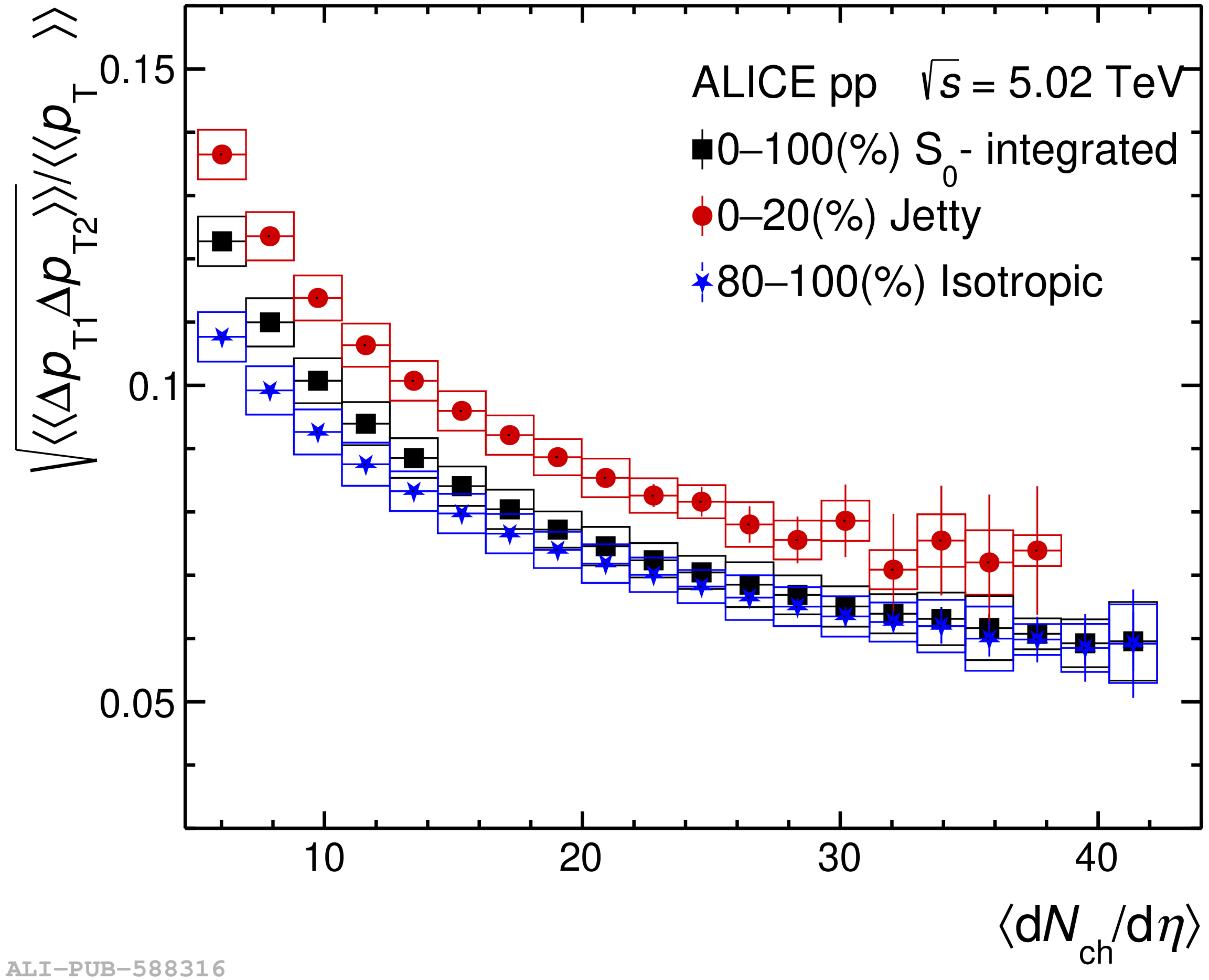
$$S_0 = \begin{cases} 0, & \text{Jetty limit} \\ 1, & \text{Isotropic limit} \end{cases}$$

$$S_o = \frac{\pi^2}{4} \min_{\hat{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{Ti} \times \hat{n}|}{\sum_i p_{Ti}} \right)^2$$

$\hat{n}$ is a two-dimensional unit vector in the transverse plane

Event-shape Variable: This variable ranges from 0 for pencil-like events to a maximum of 1 for circularly symmetric events.

Transverse Spherocity dependent study of mean-p_T fluctuations



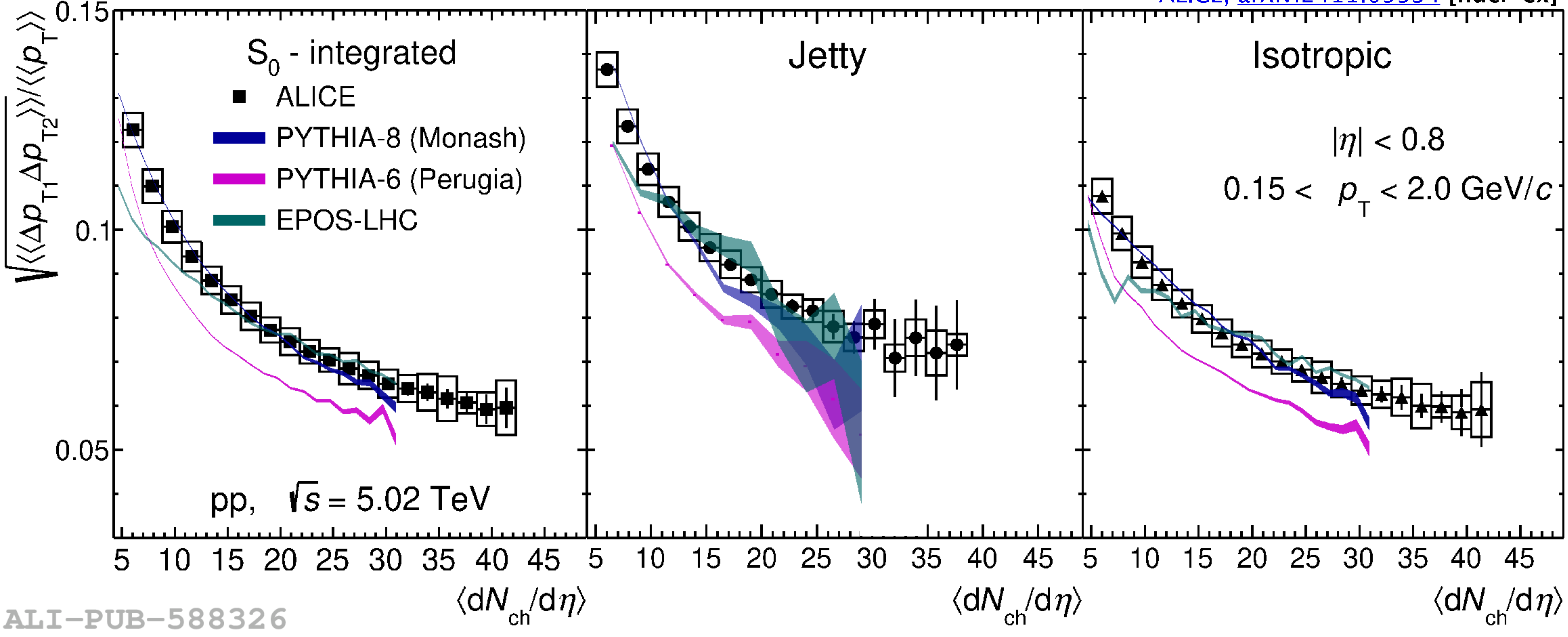
- The presence of jets enhances the magnitude of the correlator by about 20%.
- Particles from jets, being emitted in a “narrow” cone, are more correlated on average than other particles: the correlator strength is thus enhanced significantly by the presence of jets in the events.

ALICE, arXiv:2411.09334 **[nucl-ex]**

Evolution of $\sqrt{\langle\langle\Delta p_{T1}\Delta p_{T2}\rangle\rangle}/\langle\langle p_T\rangle\rangle$ with the spherocity of collisions measured as function of the spherocity in pp collisions at 5.02 TeV.

Comparison of correlator vs spherocity classes with models

ALICE, arXiv:2411.09334 [nucl-ex]



- PYTHIA 6 significantly underestimates the magnitude of correlation in general.
- PYTHIA 8 and EPOS-LHC reproduce the data rather well in both jetty and isotropic events.

Summary

- Scaling violation of the strength of the correlator (vs. particle density) seen in **both Xe—Xe and Pb—Pb collisions;**
- Correlator strength shows very modest dependence on **collision system size;**
- Clear dependence on **collision energy** observed when studied as a function of density (multiplicity);
- Clear dependence on spherocity is observed. **Jetty events show higher fluctuations** as compared to isotropic events **due to presence of jets**.

Thank you for your attention