Quantifying the Underlying Event in high-energy pp collisions from RHIC to LHC

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Support: *Hungarian OTKA grant K135515, 2019-2.1.11-TÉT-2019-00078, Wigner Scientific Computing Laboratory*

Refs: J.Phys.G 47 (2020) 10, 105002, J. Phys. G50 (2023) 9,095004

Zimányi Winter School 2023,Budapest, 8th December 2023

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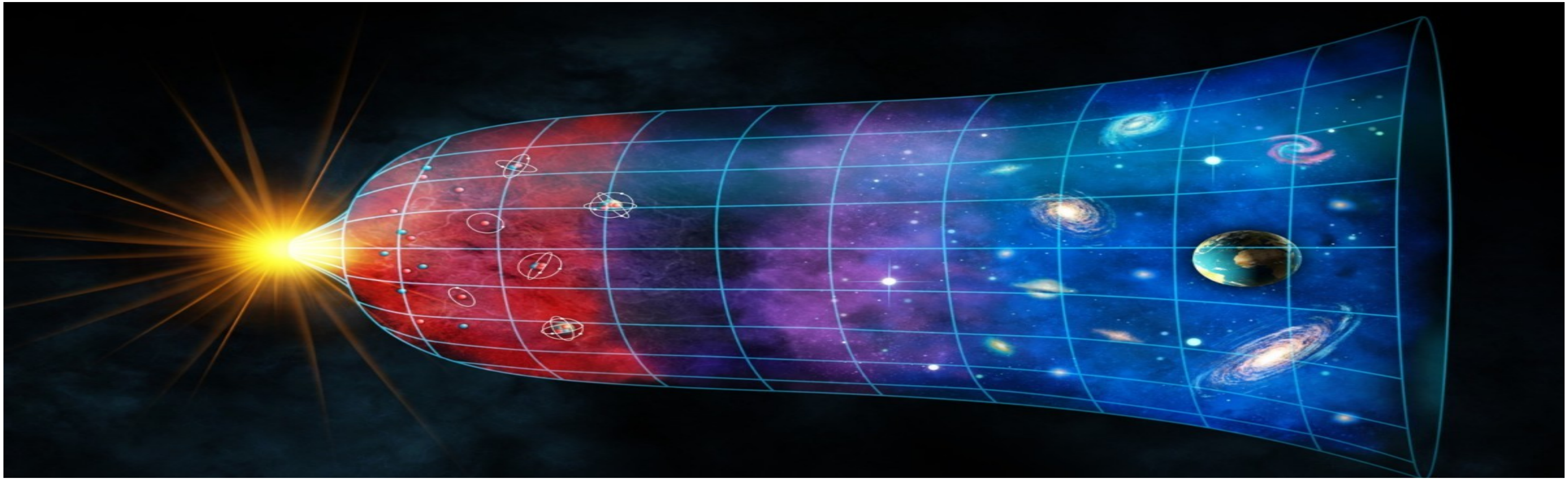
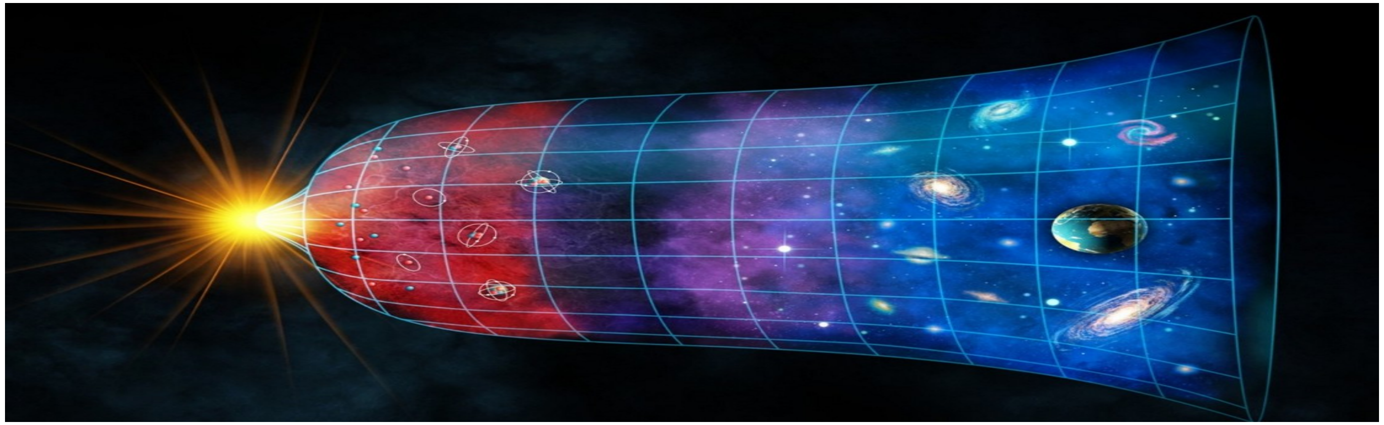
QGP – the matter of the early Universe

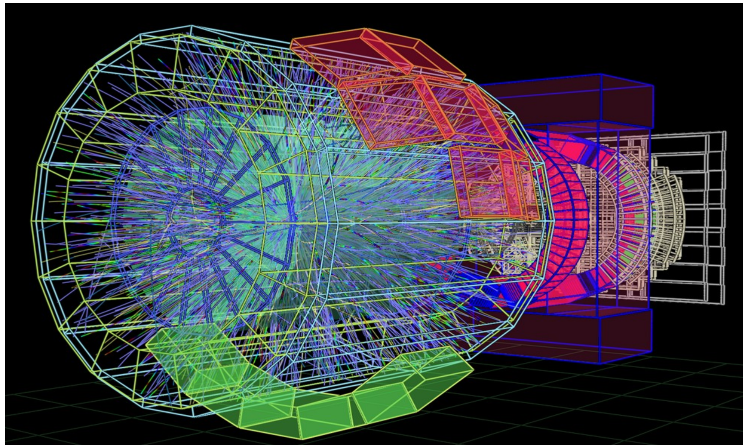


QGP – the matter of the early Universe



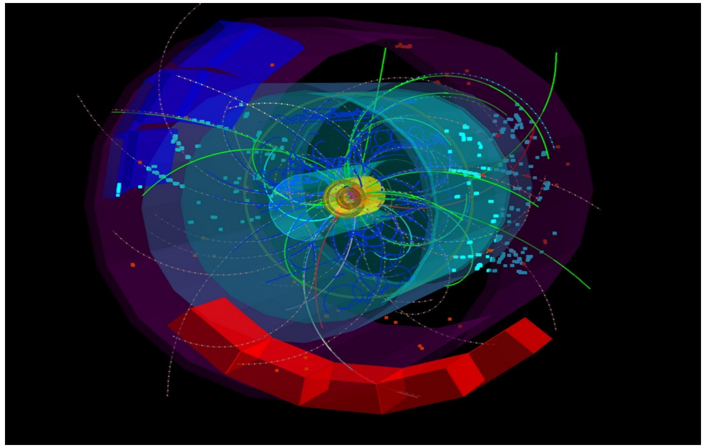
Which one is the "closest" to the early Universe?

A) PbPb collision



C) Abstain (now)

B) pp collision



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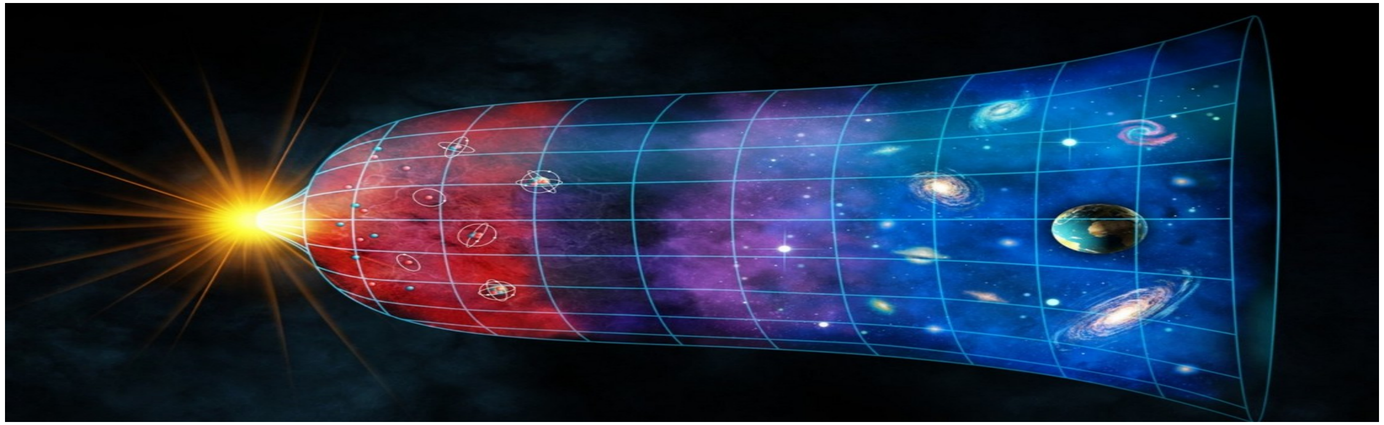

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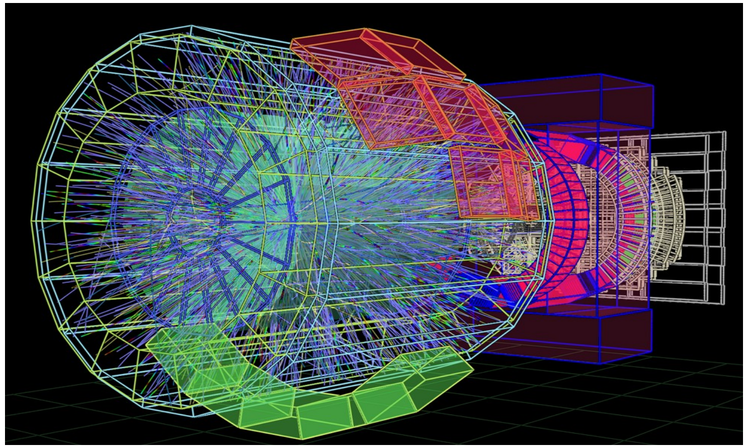
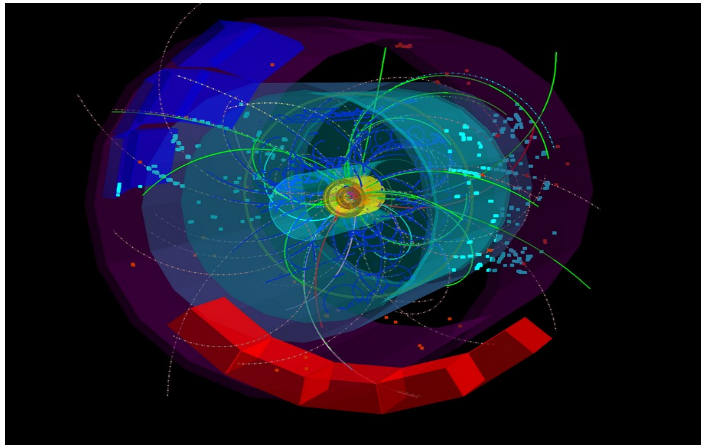


C) Cup of coffee

B) pp collision



Outline

1) Earlier studies

- What is UE? Why is this important for in HEP?

  → theory, experiment, measures

2) New developments on UE

- Angular properties measures

  → multiplicity, p_T spectra, parameter derivatives

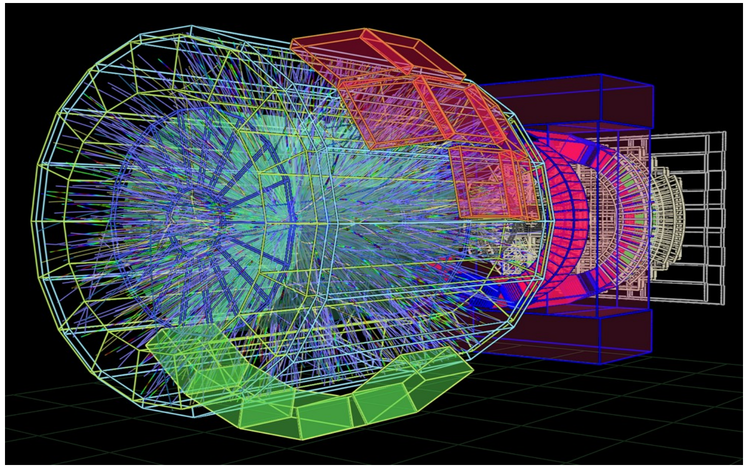
  → Tsallis thermometer

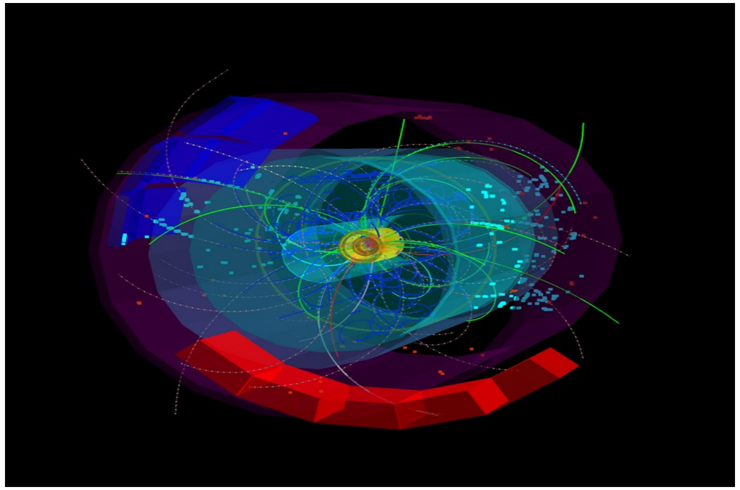
3) Comparison to event shape variable

- Spherocity measures and cross check

4) Collision energy dependence

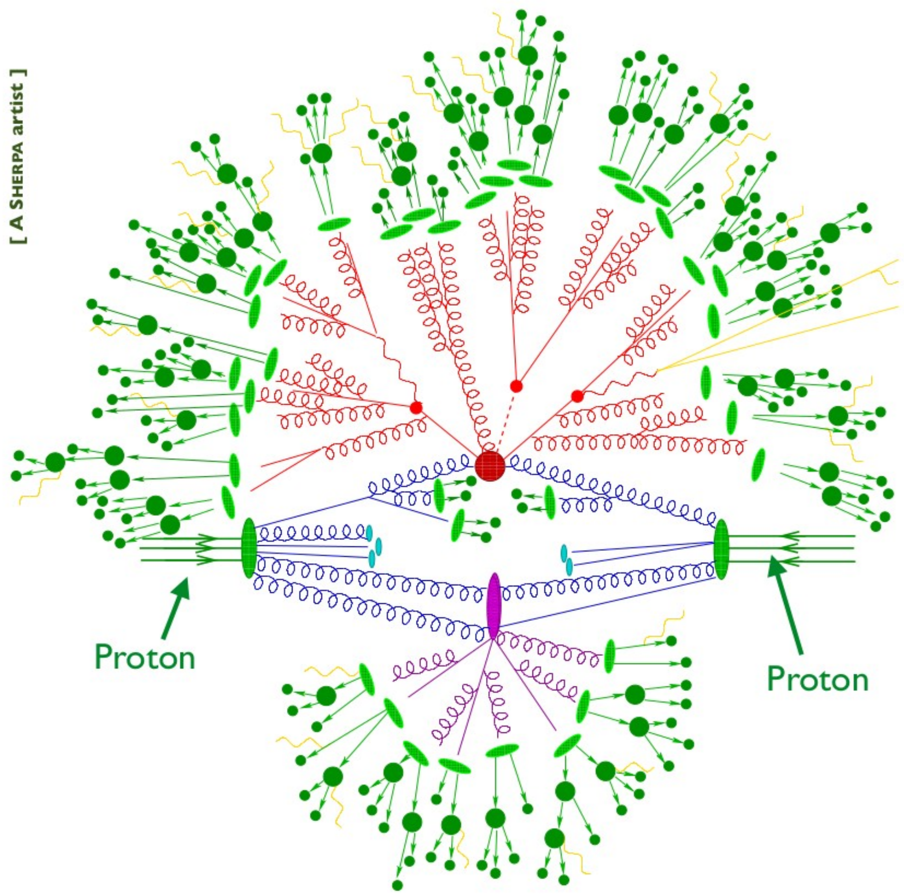
→ Can we quantify the UE definition?





UE

Anatomy of a proton-proton event



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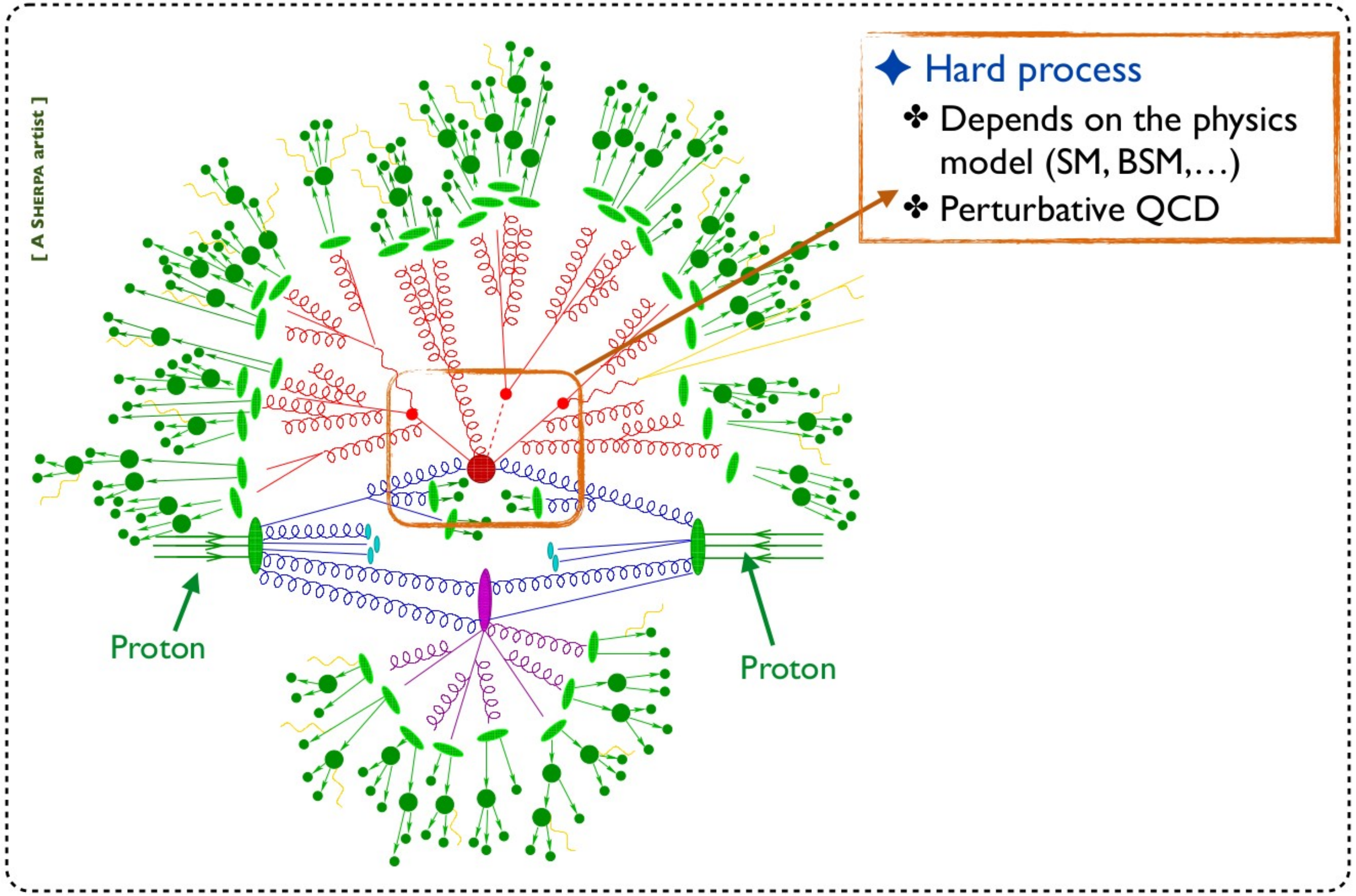

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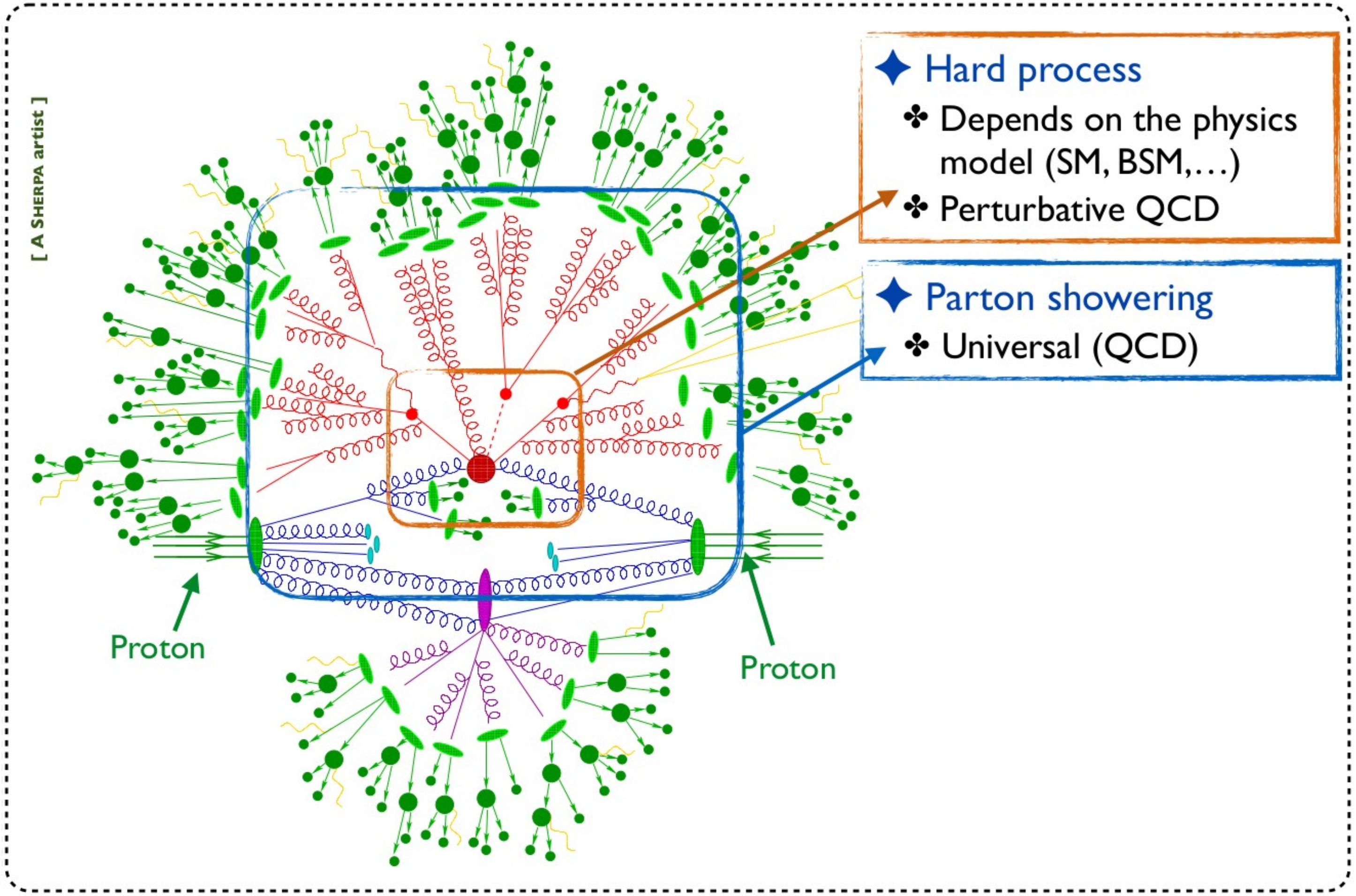

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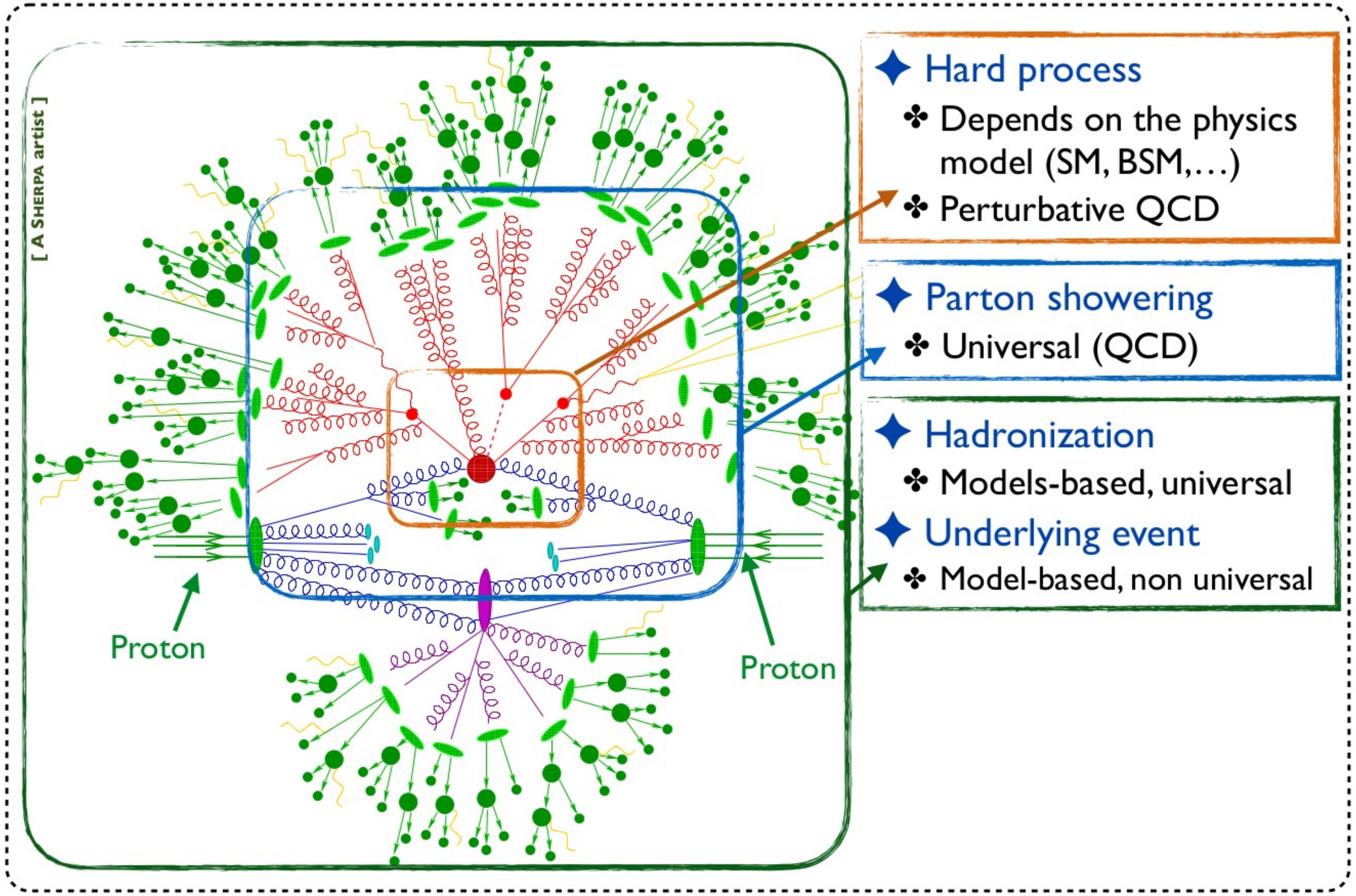
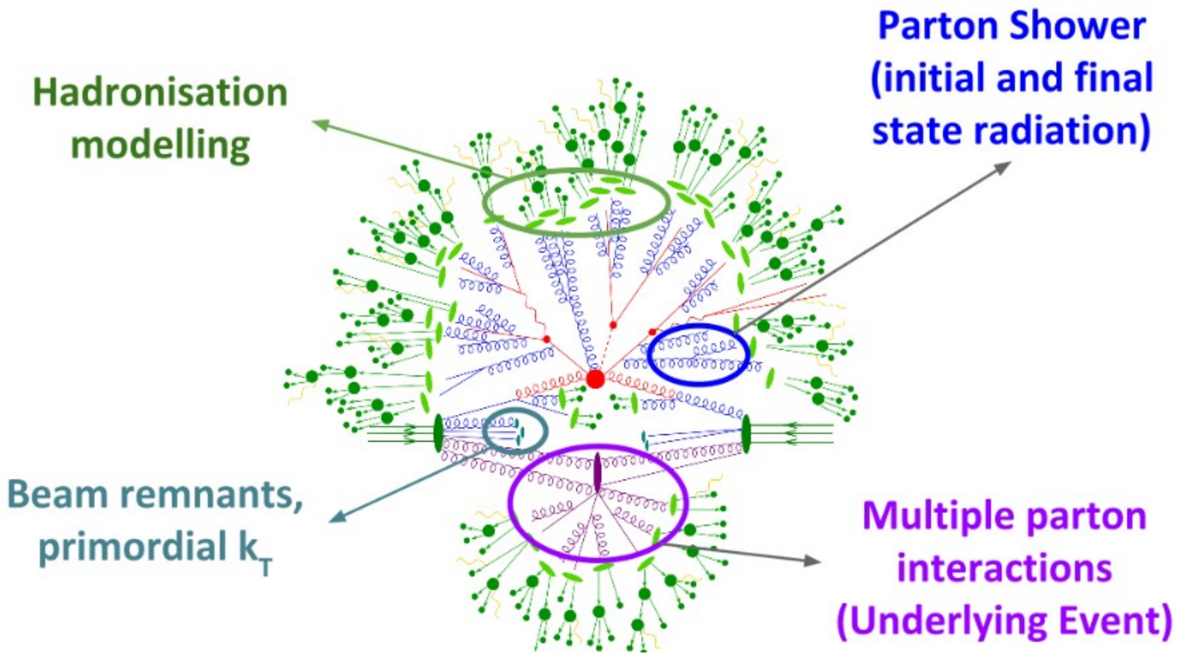


So what Uderlying Event is?

- **Theoretical point:**
  - Mainly non-perturbative QCD effect
    - → Initial & final state radiation
    - → Multiple parton interaction
    - → Color Reconnection (CR)
    - → intrinsic k_T
    - → Hadronization



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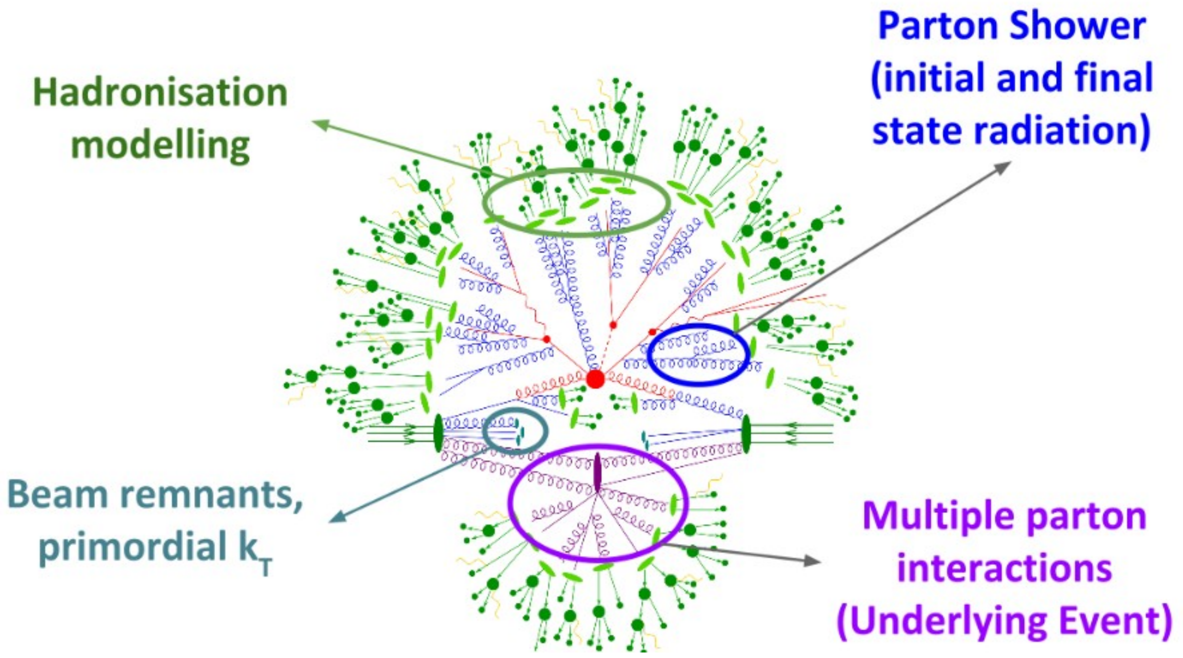
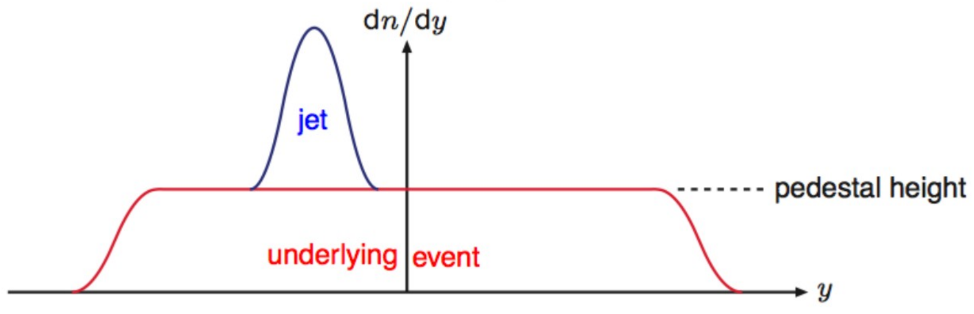
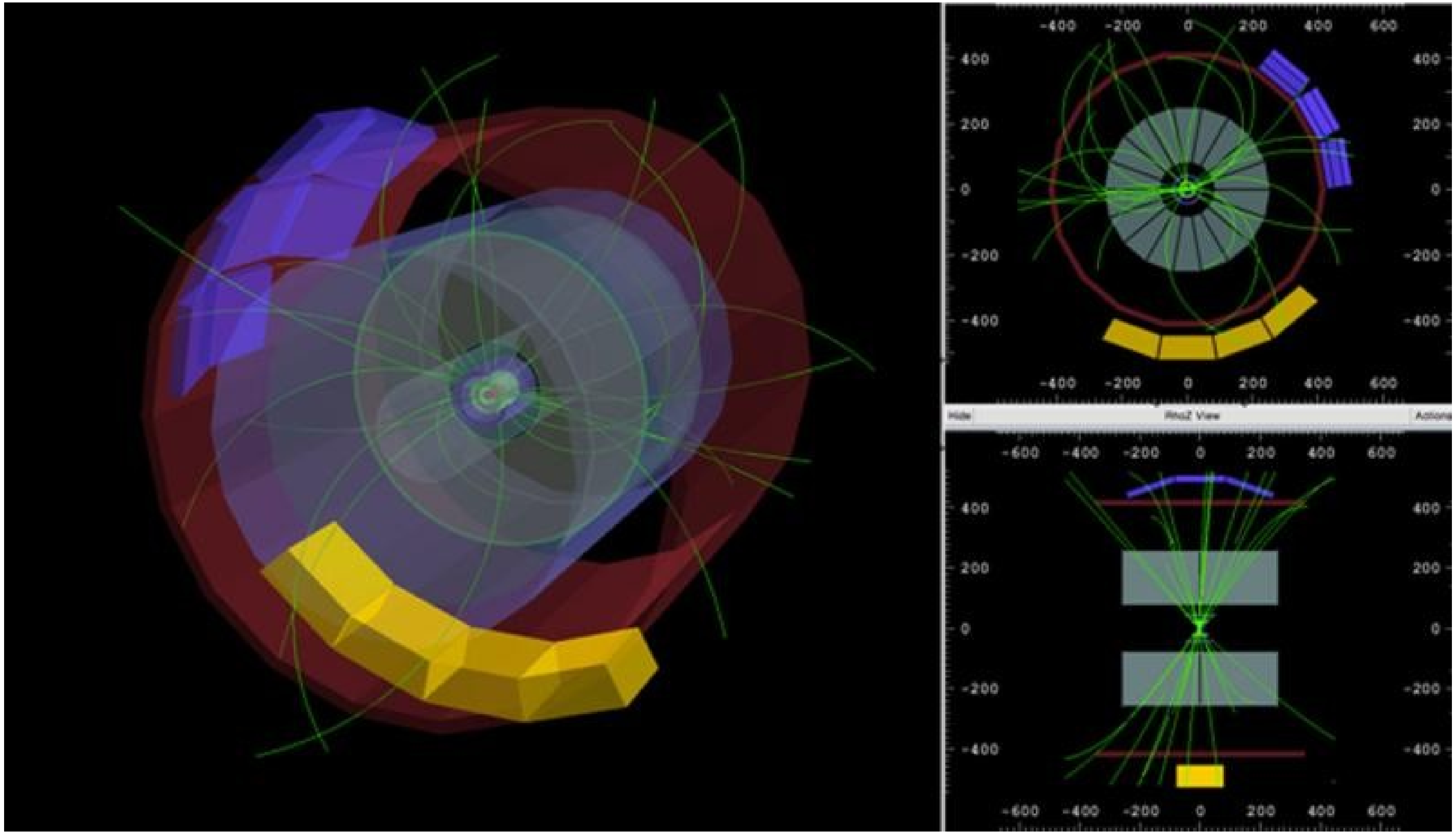
- **Experimental point**
  - Pedestal-like effects
    - → Activity in the event over MB
    - → Beam remnants (pile up)
    - → Trigger bias (jet criterion)





Earlier studies, motivation

Geometrical structure of an event



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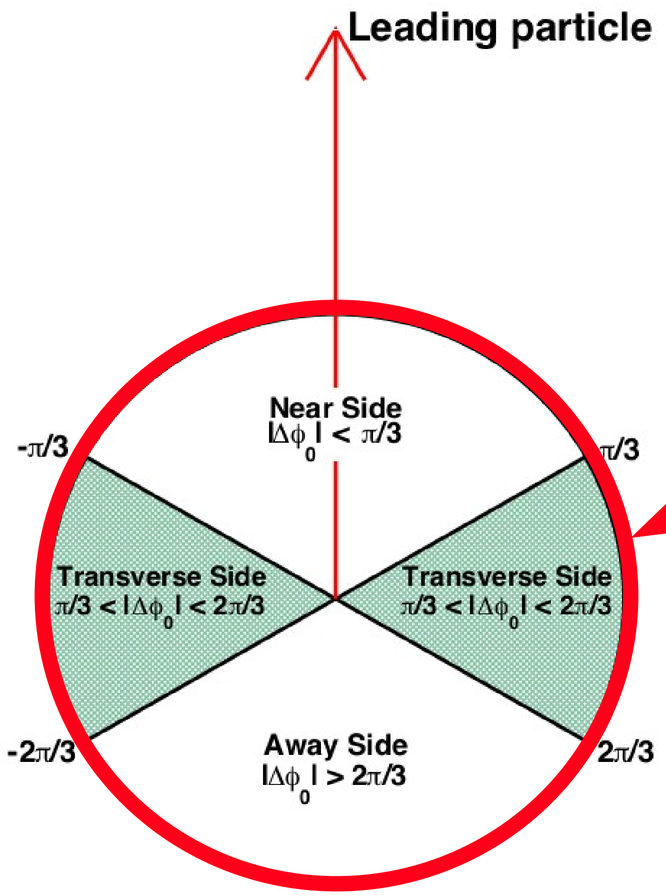
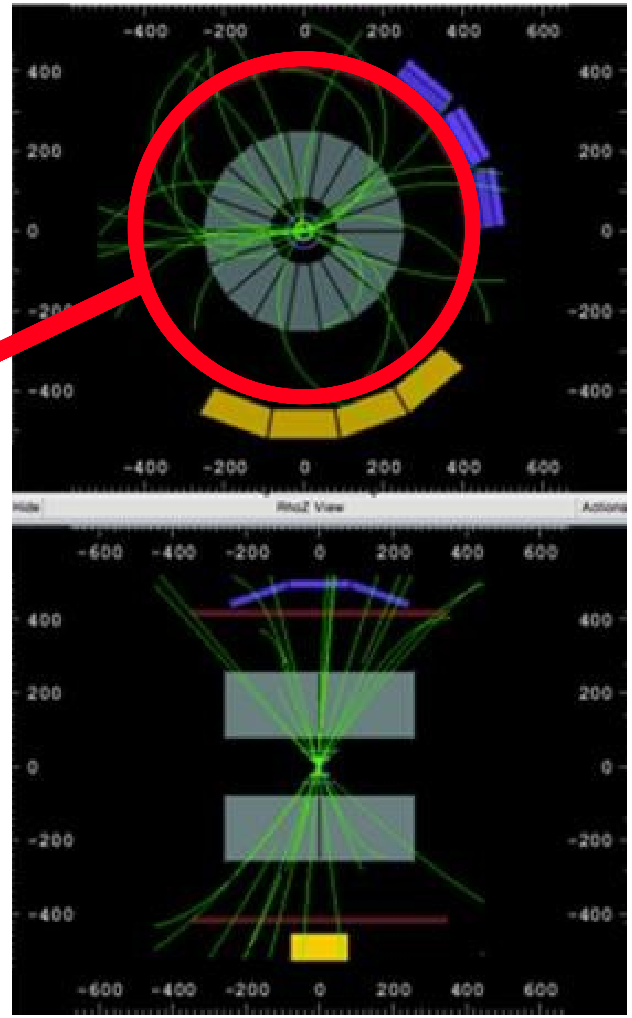


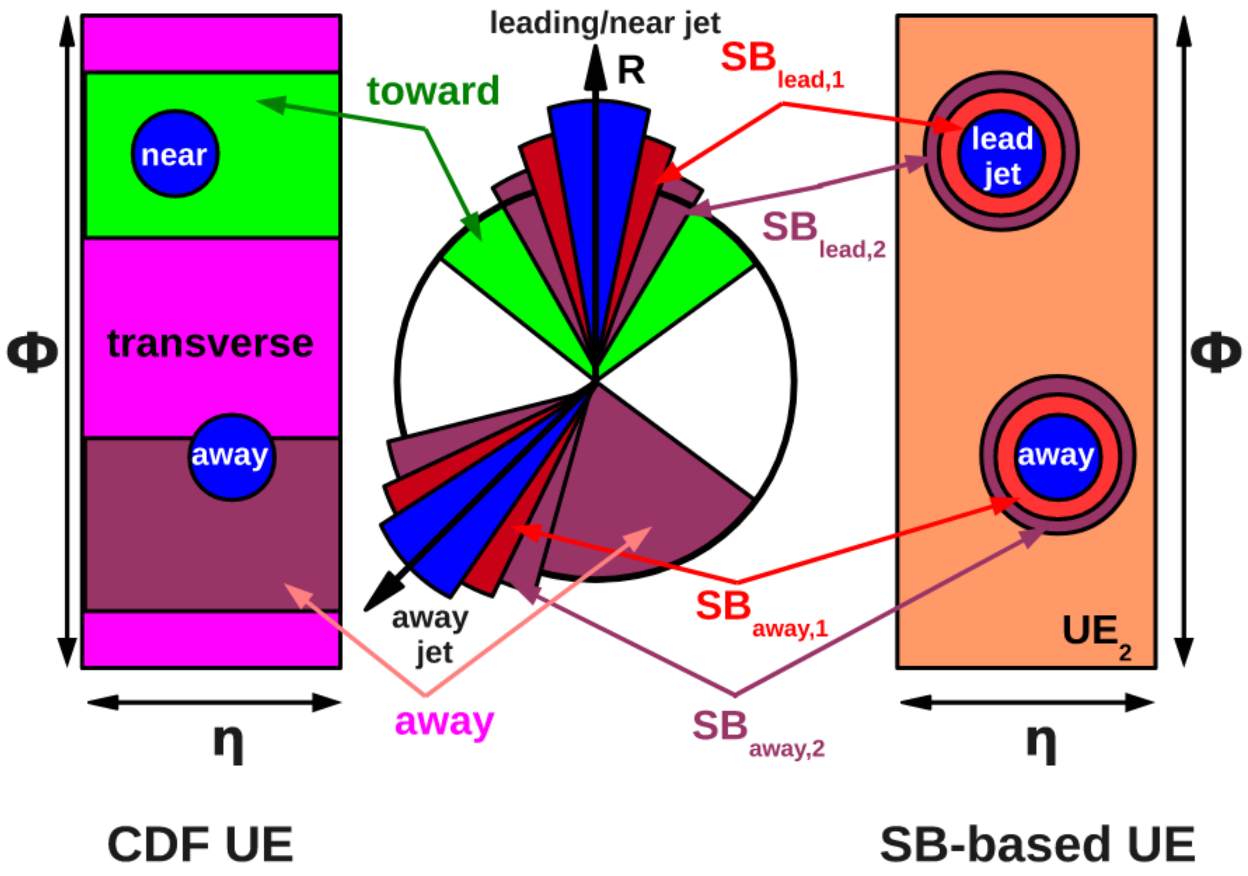
Standard CDF definition



How to separate jet & UE?

- **Jet finding & elimination:**
  - Surrounding Band (SB method), Find a jet, THEN define SBs
  - IF SB_1 and SB_2 are equal, THEN eliminate the jet
    - → expensive (high statistics)
    - → sensitive to cuts
- **Correlation & background**
  - Traditional method by CDF
    - → burte force
    - → geometry info only

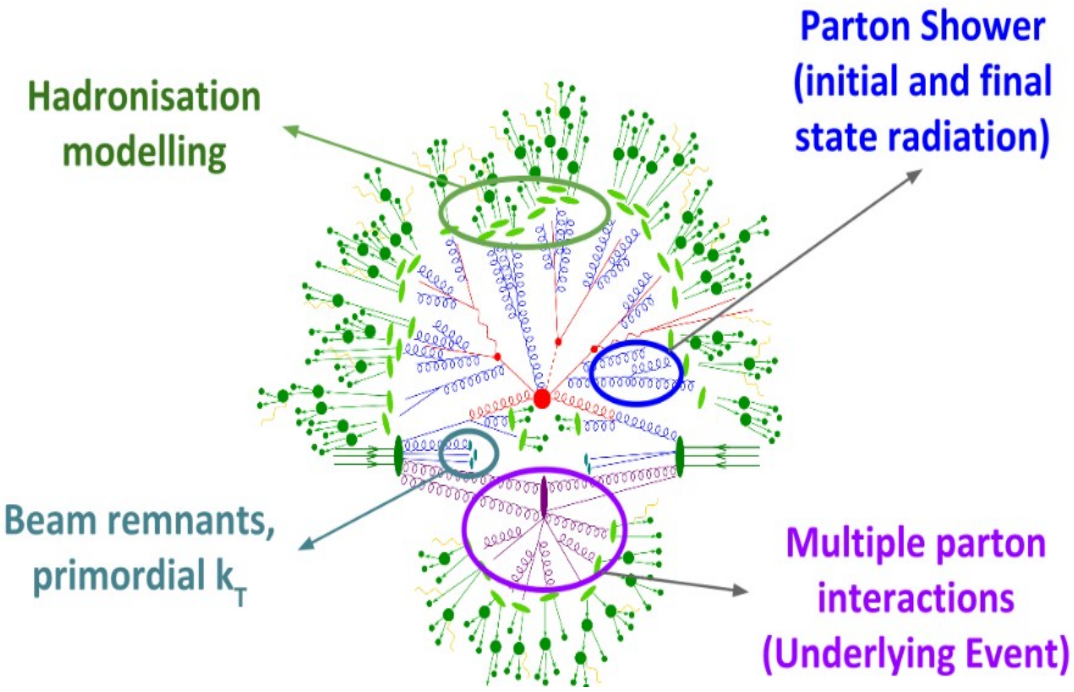
See: BGG et al: J.Phys.Conf.Ser. 270 (2011) 012017,AIP Conf.Proc. 1348 (2011) 124, EPJ Web Conf. 13 (2011) 04006



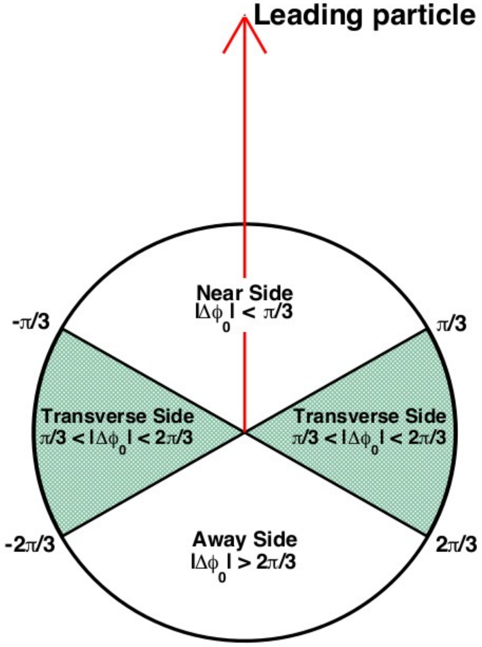
New development to understand UE

The simulated data

- **PYTHIA_v8240 Monash 2013 tune**
  - 1 billion non-diffractive collisions of pp
  - C.m. energy: $\sqrt{s}$ = 13 TeV
  - Includes 2→ 2 hard scattering process, followed by initial and final state parton showering, multiparton interactions, and the final hadronization process.
  - The events having at least three primary charged particle with transverse
  - Min. momentum: $p_T > 0.15$ GeV/c
  - Pseudorapidity: $|\eta| < 0.8$
  - UE: Color Reconnection (CR, Multiple Parton Interaction (MPI)



Angular structure of an event



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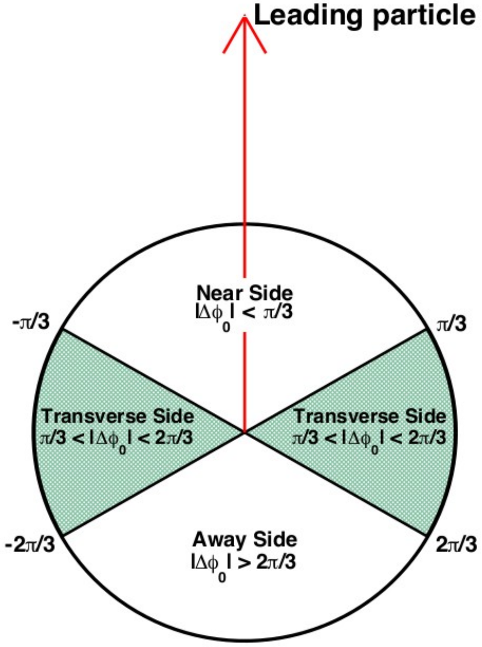

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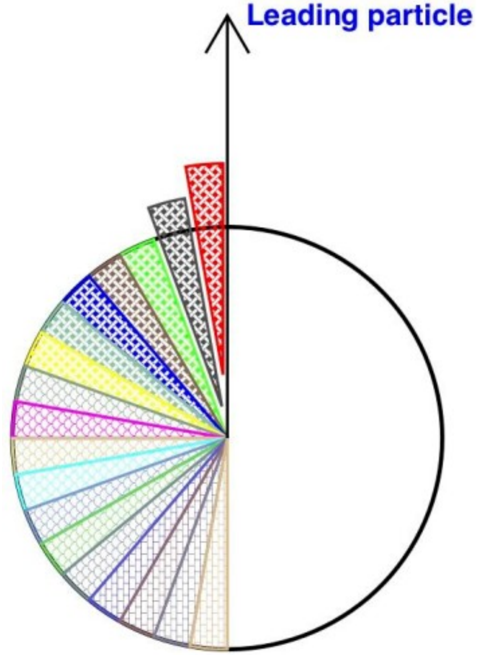

Sliding angle, cake slices

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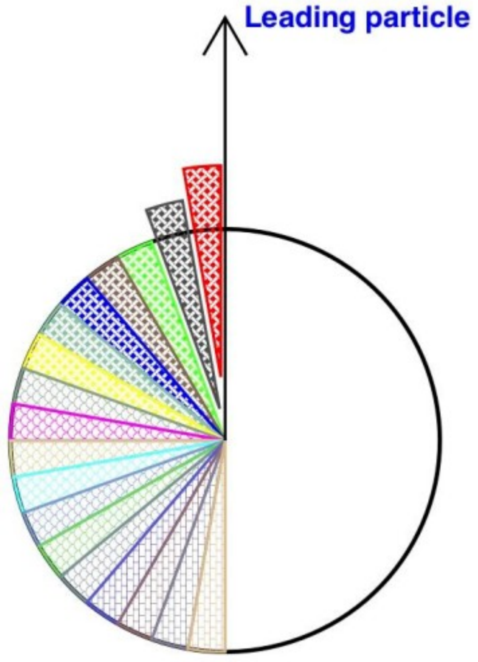
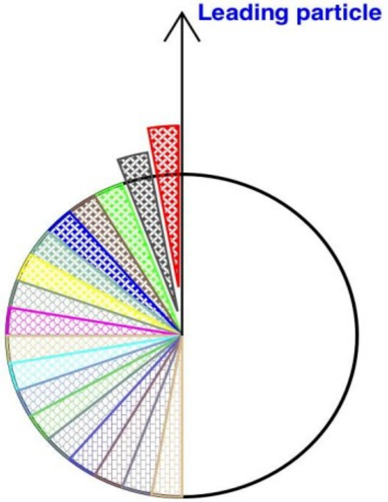
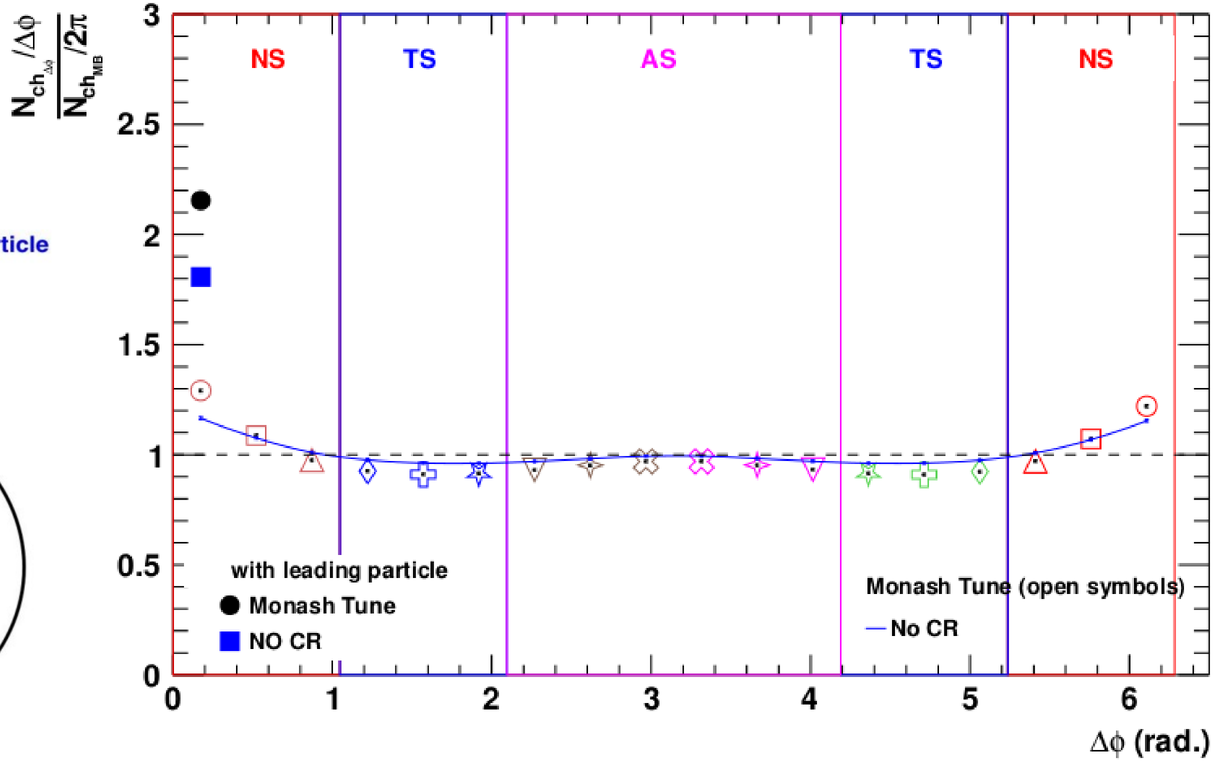


- We make slices of the Δφ of size 20◦. In this case, the results for the first bin 0 to 20◦. are reported in two ways: including and excluding the leading particle in the result. Case II is a tool for exploring the geometrical structure of the Underlying Event.

Multiplicity/MB

- **PYTHIA multiplicity with sliding angle**
  - PYTHIAs model UE: CR & MPI
  - Good fits with the parametrizations
  - More multiplicity az NS
  - TS & AS are mainly flat
  - With leading particle deviation is increased





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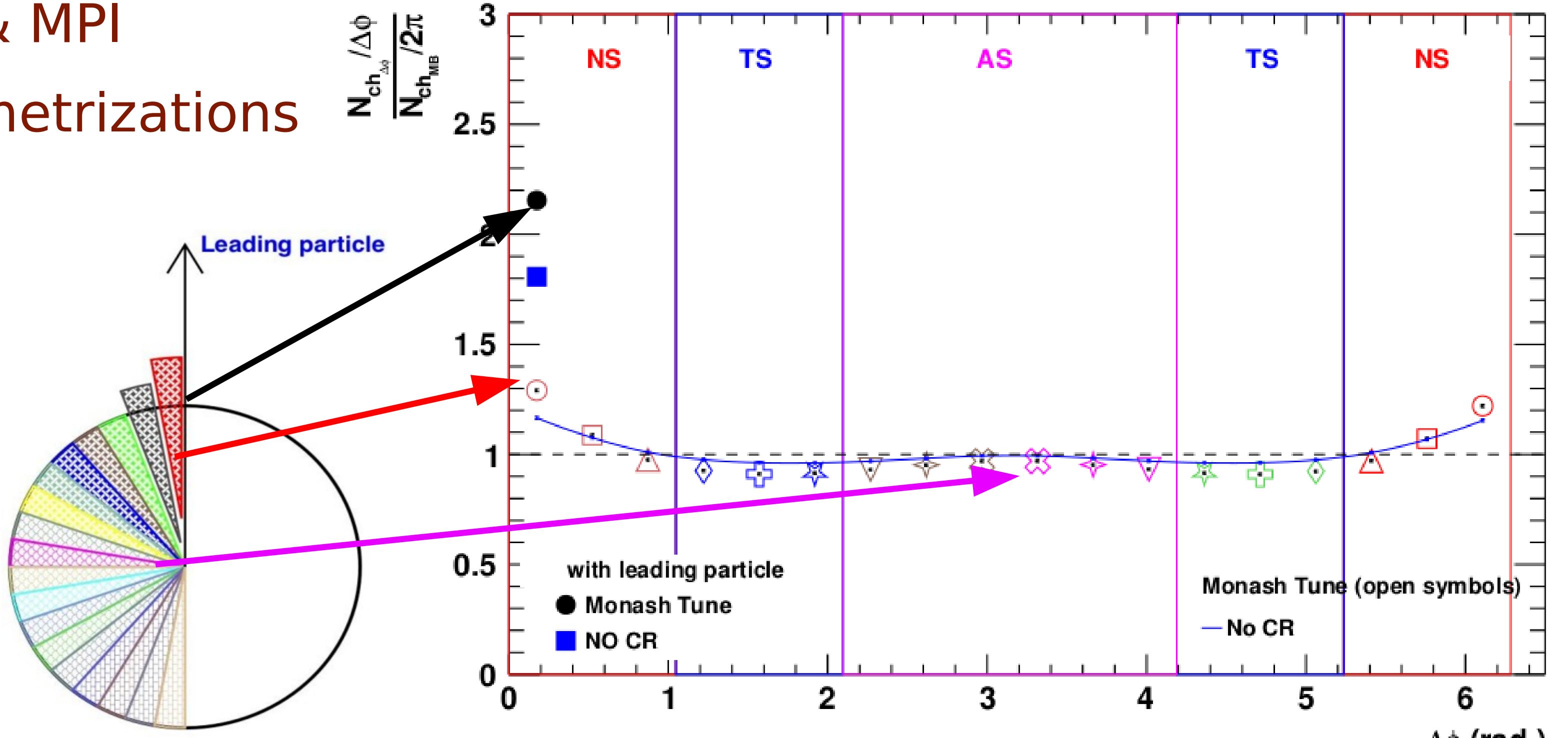

The p_T spectrum

- **PYTHIA spectra with sliding angle**
  - PYTHIAs model UE: CR & MPI
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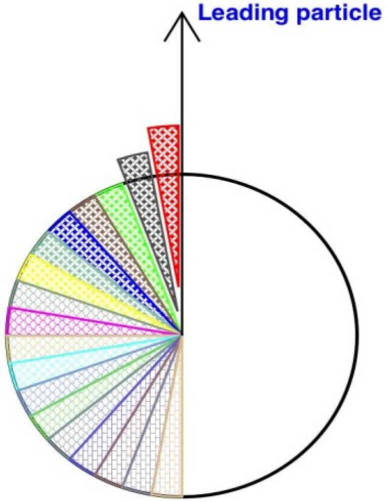
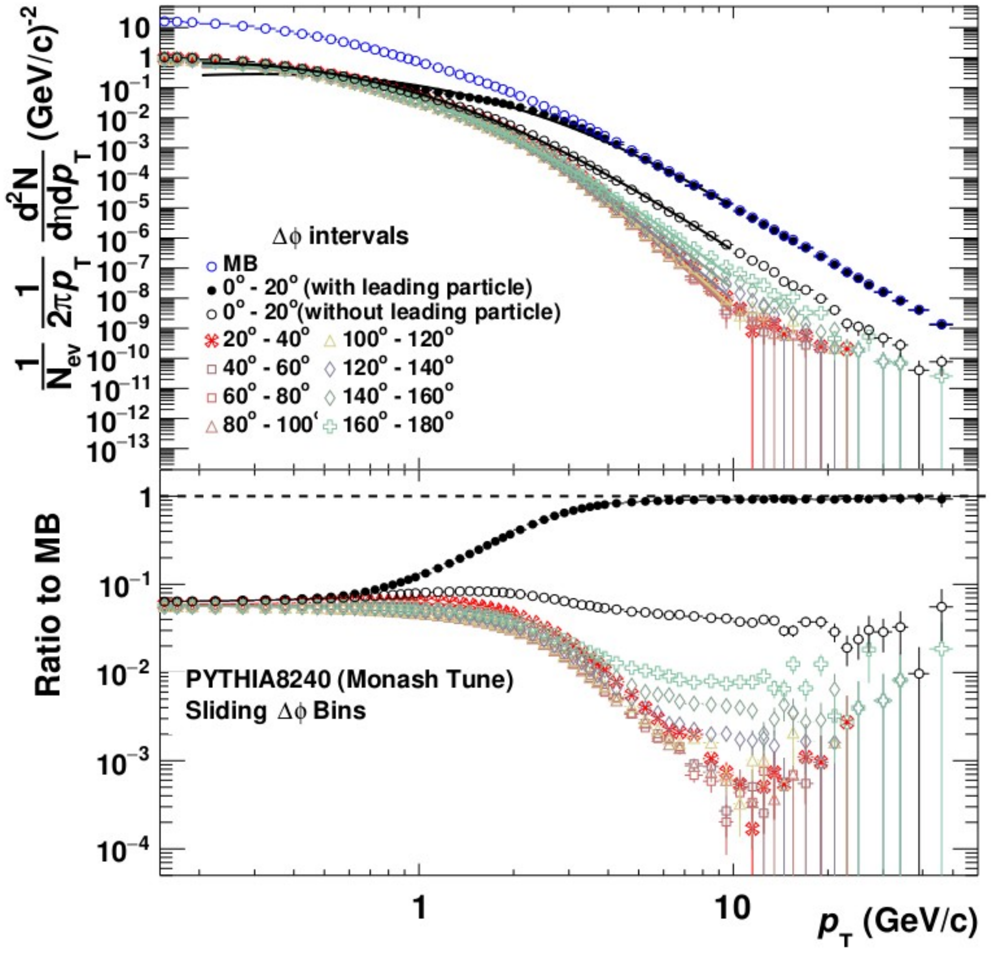
  - Low p_T is constant (T)
  - High p_T varies (q)
  - NS/AS are similar
  - Need to consider w/o leading particle





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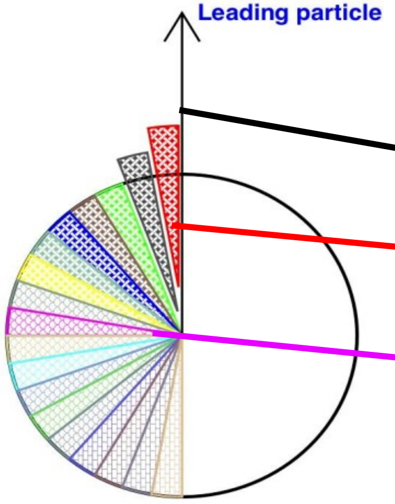
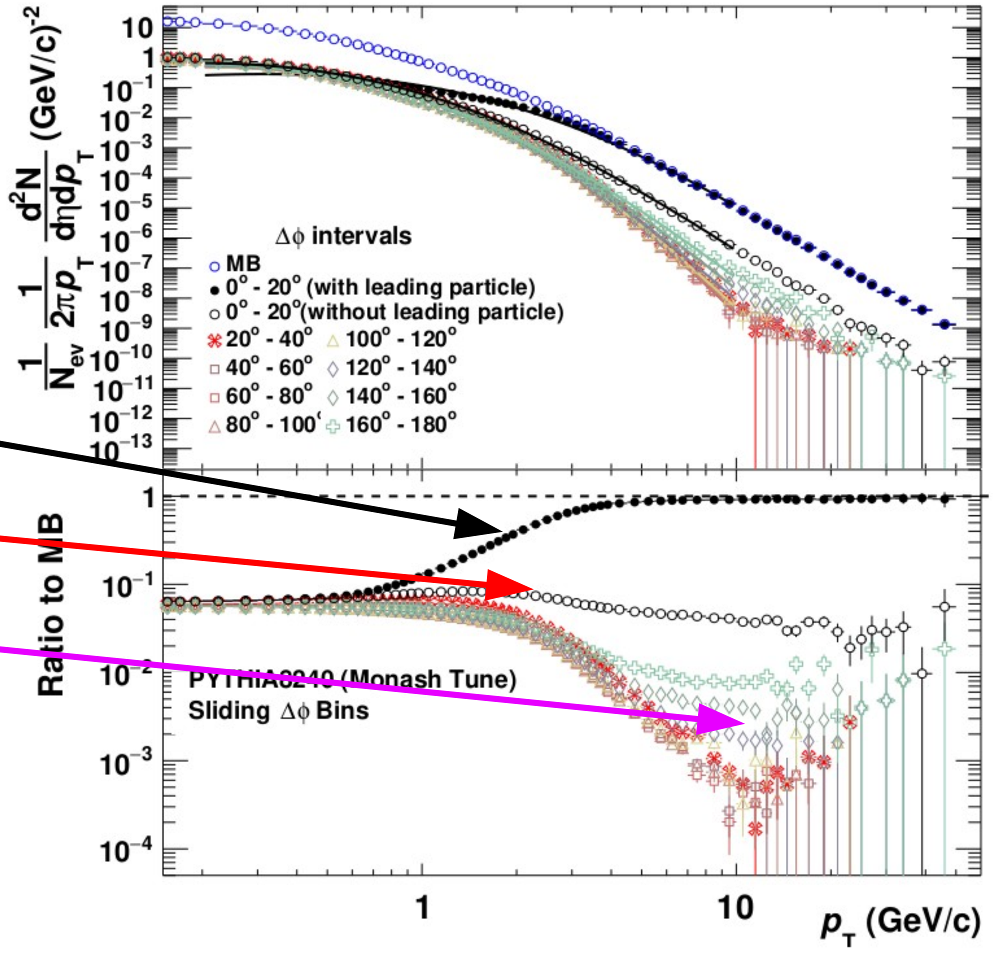




How to quantify & compare these?

- **Precise spectra description**
  - from low- to high-p_T

$$f(m_T) = A \cdot \left[1 + \frac{q-1}{T_s}(m_T - m)\right]^{-\frac{1}{q-1}}$$

  - in multiplicity classes (pp, pA, AA)

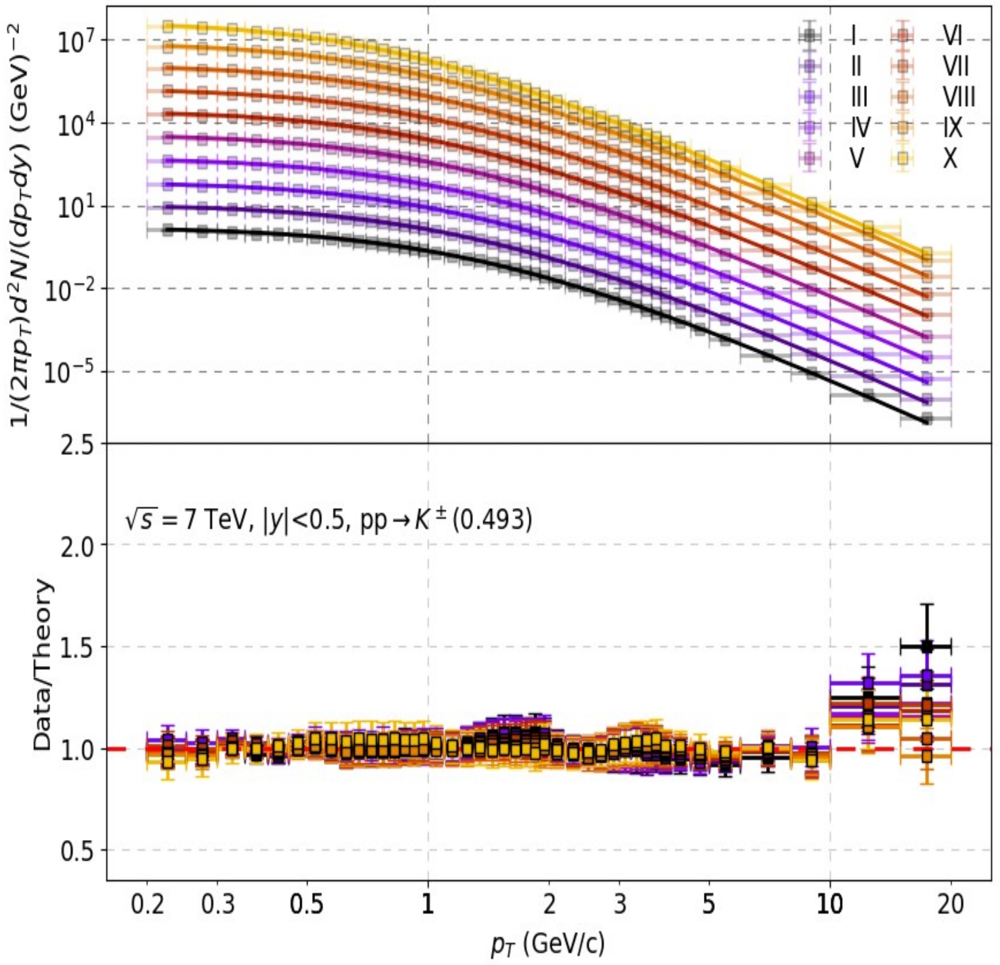
$$\left.\frac{\mathrm{dN_{ch}}}{\mathrm{dy}}\right|_{y=0} = 2\pi A T_s \left[\frac{(2-q)m^2+2mT_s+2T_s^2}{(2-q)(3-2q)}\right] \times \left[1 + \frac{q-1}{T_s}m\right]^{-\frac{1}{q-1}}$$

  - With PID:

$$\pi^{\pm}, K^{\pm}, K_s^0, K^{*0}, p(\bar{p}), \Phi, \Lambda, \Xi^{\pm}, \Sigma^{\pm}, \Xi^0, \Omega$$

  - Wide range:

	pp	pA	AA
CM energy (GeV)	7000, 13000	5020	130-5020
Multiplicity range	2.2-25.7	4.3-45	13.4-2047



How to quantify & compare these?

- **QCD-inherited scaling properties**

$$f(m_T) = A \cdot \left[1 + \frac{q-1}{T_s}(m_T - m)\right]^{-\frac{1}{q-1}}$$

  - Parameter scaling with √s & multiplicity

$$\mathrm{A}(\sqrt{s_{NN}}, \langle N_{ch}/\eta \rangle, m) = A_0 + A_1 \ln \frac{\sqrt{s_{NN}}}{m} + A_2 \langle N_{ch}/\eta \rangle$$

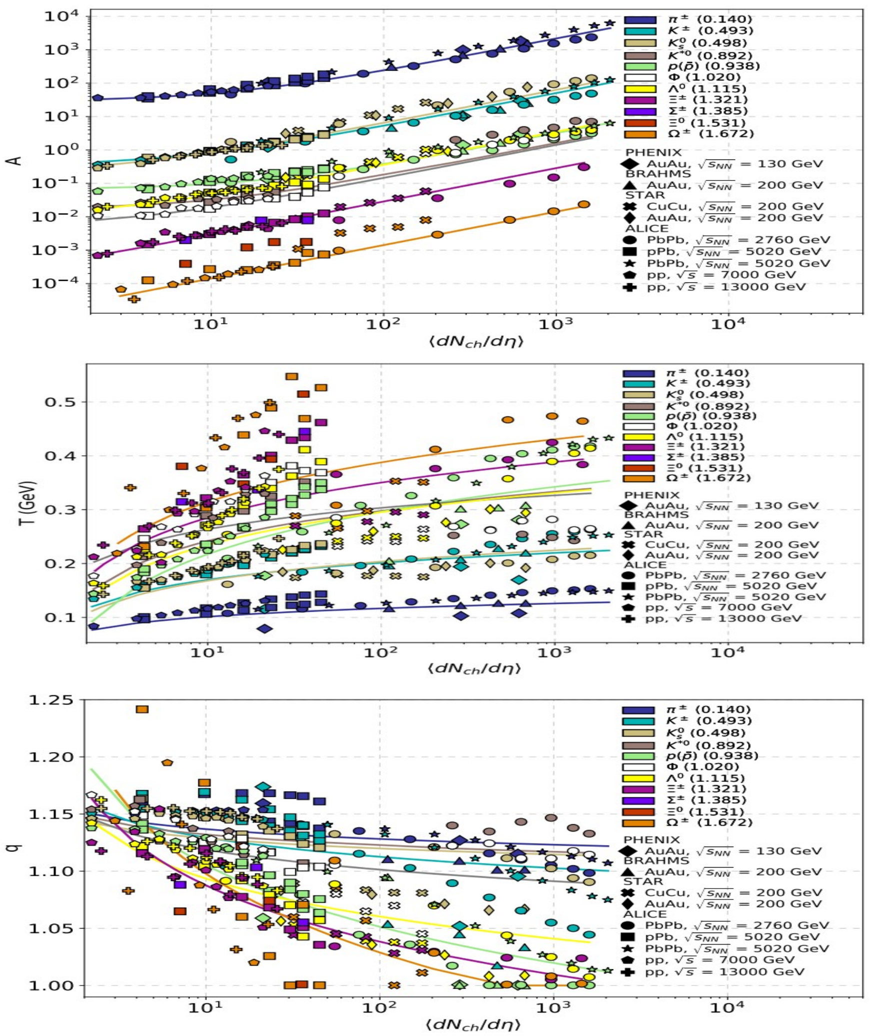
$$\mathrm{T}(\sqrt{s_{NN}}, \langle N_{ch}/\eta \rangle, m) = T_0 + T_1 \ln \frac{\sqrt{s_{NN}}}{m} + T_2 \ln\ln \langle N_{ch}/\eta \rangle,$$

$$\mathrm{q}(\sqrt{s_{NN}}, \langle N_{ch}/\eta \rangle, m) = q_0 + q_1 \ln \frac{\sqrt{s_{NN}}}{m} + q_2 \ln\ln \langle N_{ch}/\eta \rangle,$$

  - Details:

    G. Biró et al: *J.Phys.G 47 (2020) 10, 105002*

    A. Ortiz: Phys.Rev.D 104 (2021) 076019



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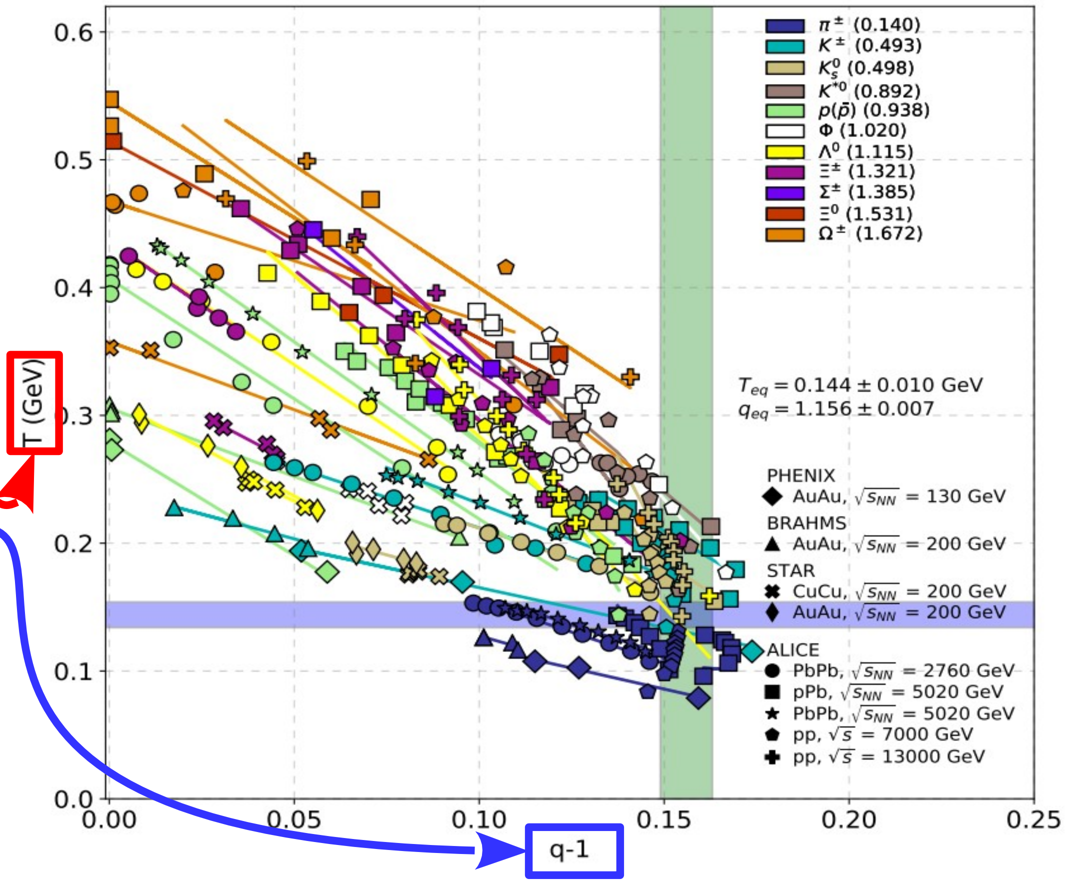


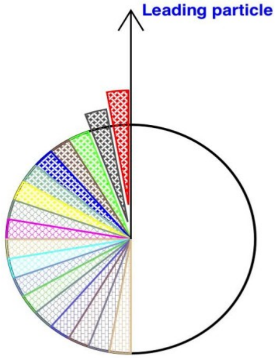
- **Thermodynamical consistency**

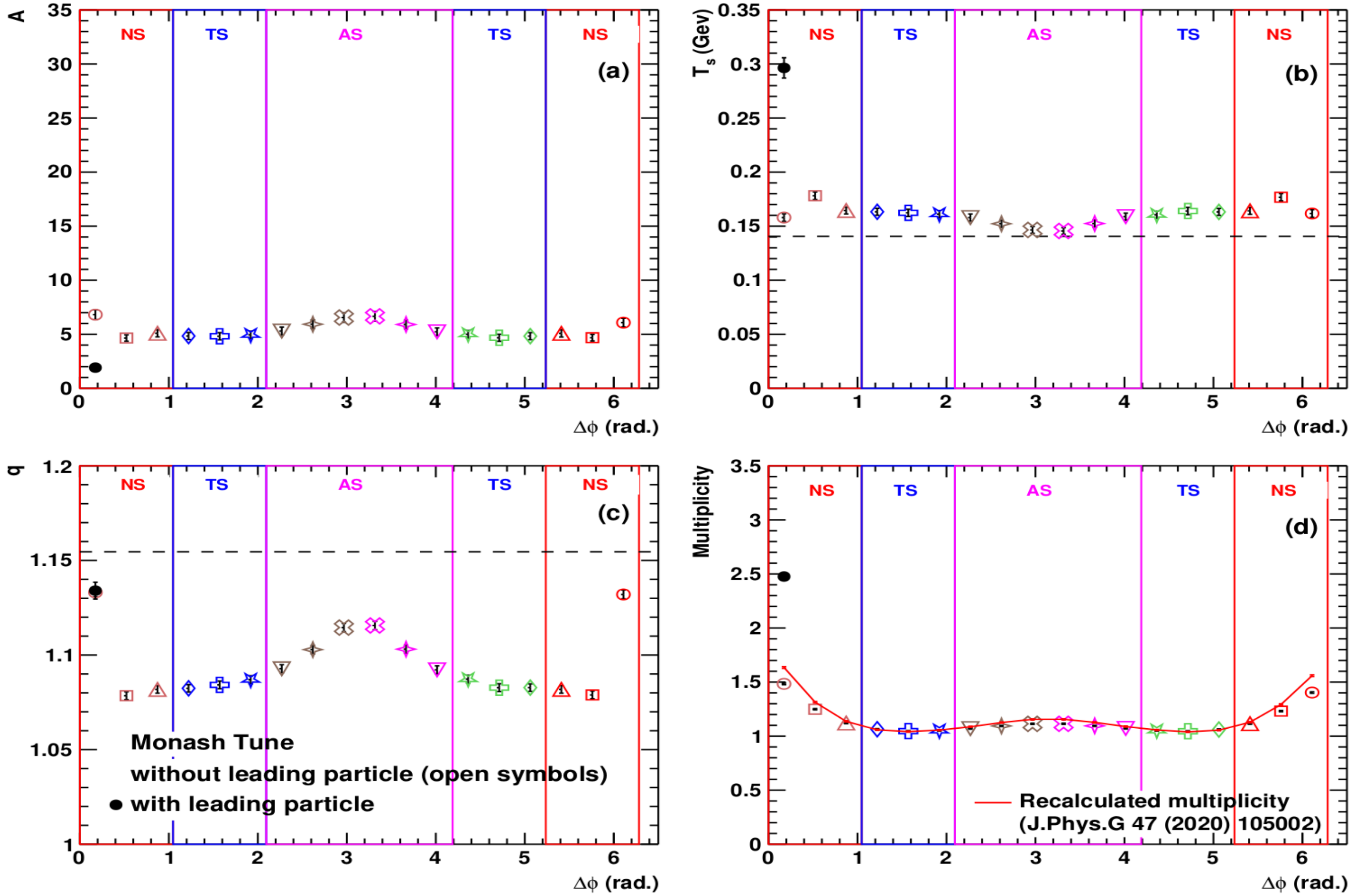
$$\mathrm{P} = \mathrm{g} \int \frac{d^3p}{(2\pi)^3} T f, \quad \mathrm{N} = \mathrm{nV} = \mathrm{gV} \int \frac{d^3p}{(2\pi)^3} f^q,$$

$$\mathrm{s} = \mathrm{g} \int \frac{d^3p}{(2\pi)^3} \left[\frac{E-\mu}{T} f^q + f\right], \quad \varepsilon = g \int \frac{d^3p}{(2\pi)^3} E f$$

Tsallis fit parameters

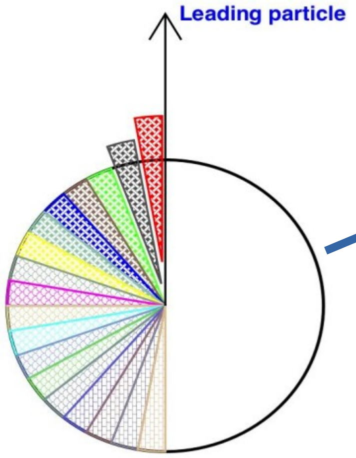
- **PYTHIA spectra with sliding angle**
  - PYTHIAs model UE: CR & MPI
  - Good fits with the parametrizations (red line)
  - NS → highest T
  - NS/AS → highest q
  - TS → constant q, T
  - Multiplicity ~ A

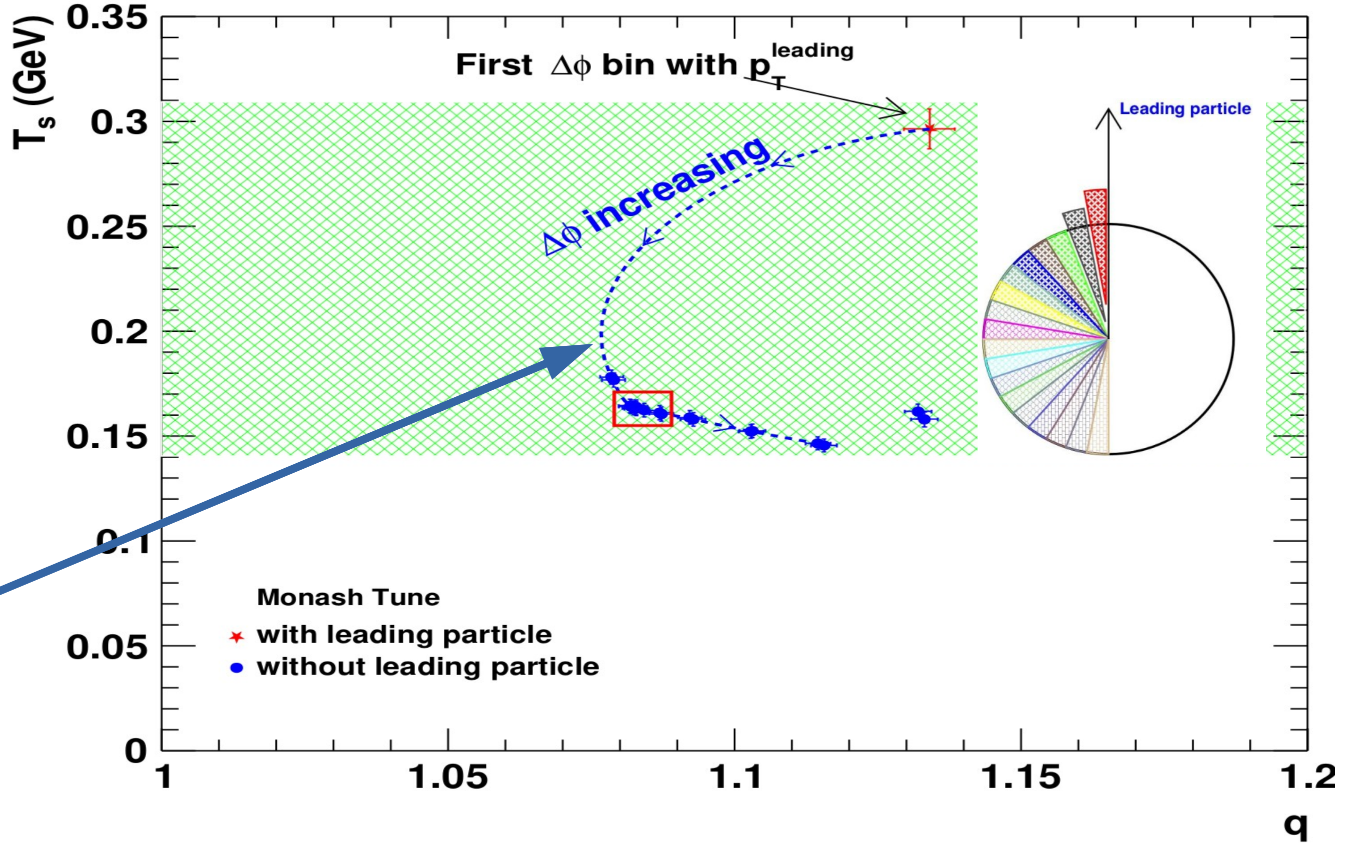




On the Tsallis-thermometer

- **Sliding angle**
  - Need UE in PYTHIA → CR & MPI
  - NS (with leading) is fully different highest T & highest q
  - Beyond NS T is getting constant
    → Wider range of UE, than in CDF





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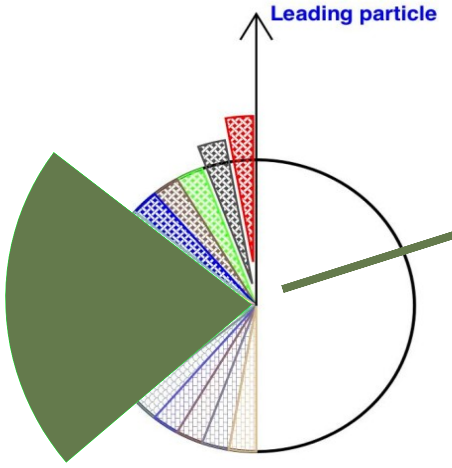

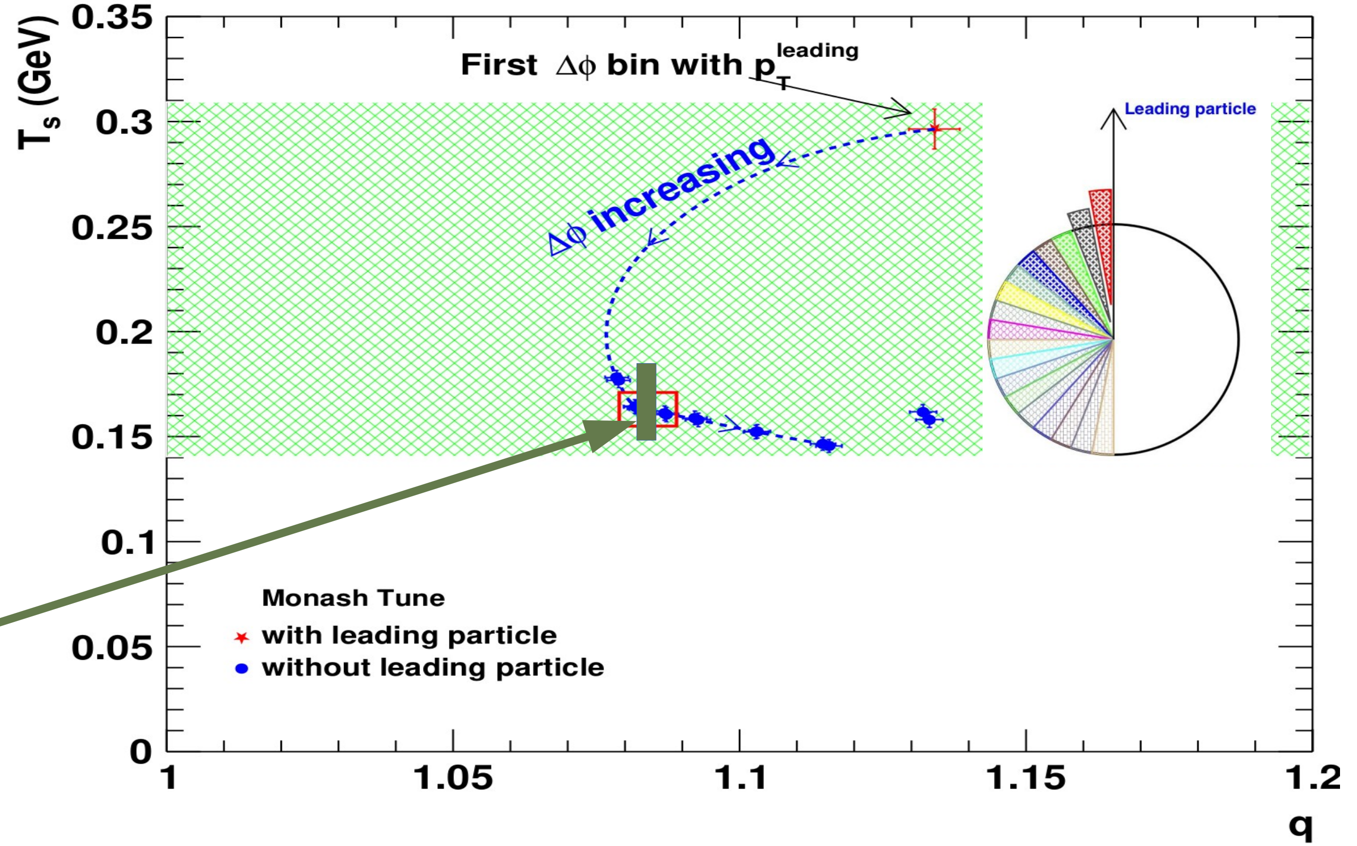

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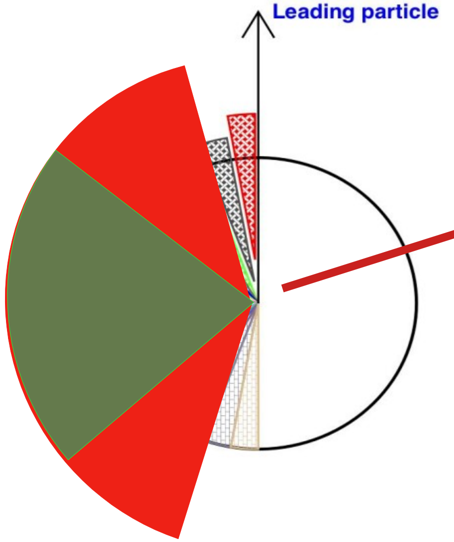
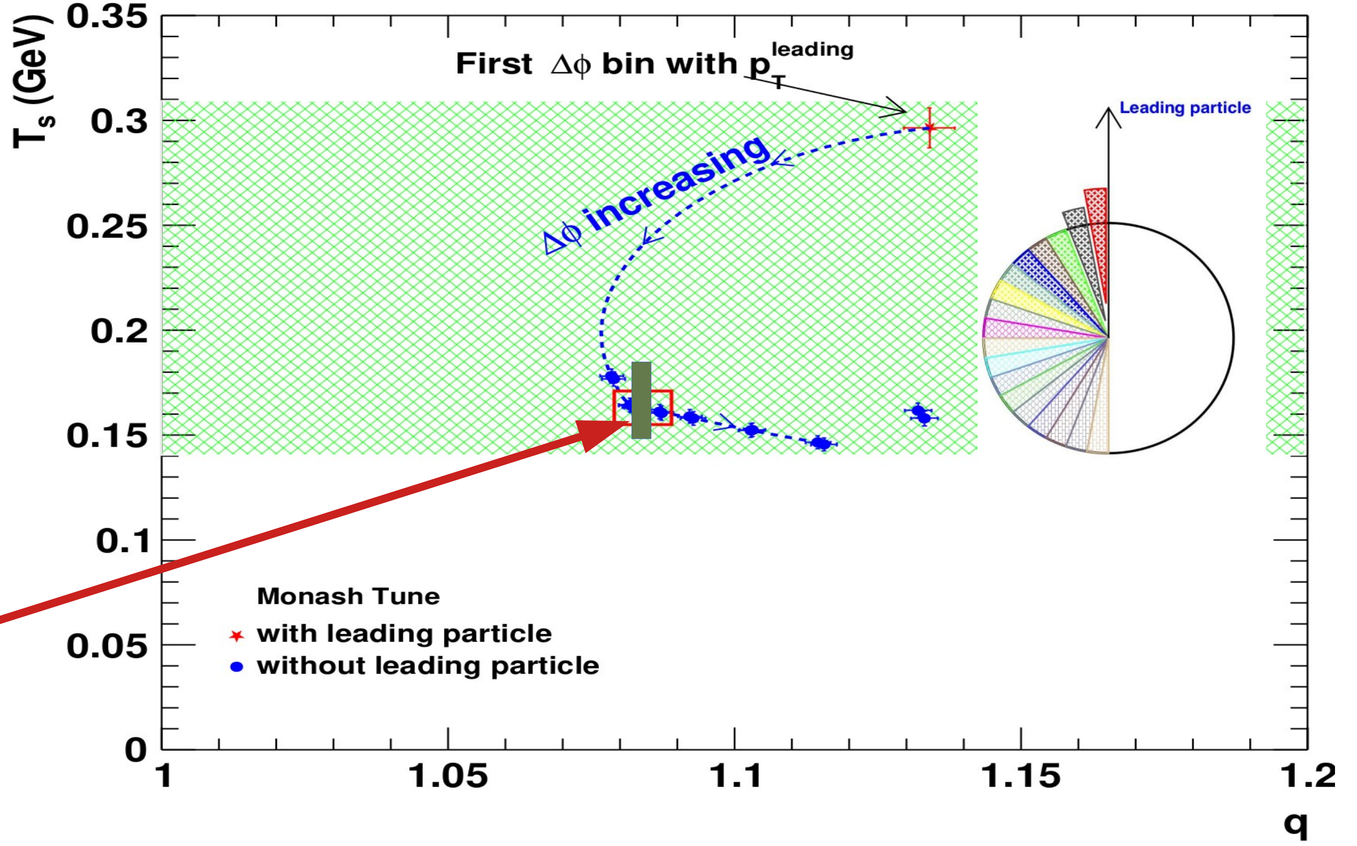




Cross-check with event shape variable

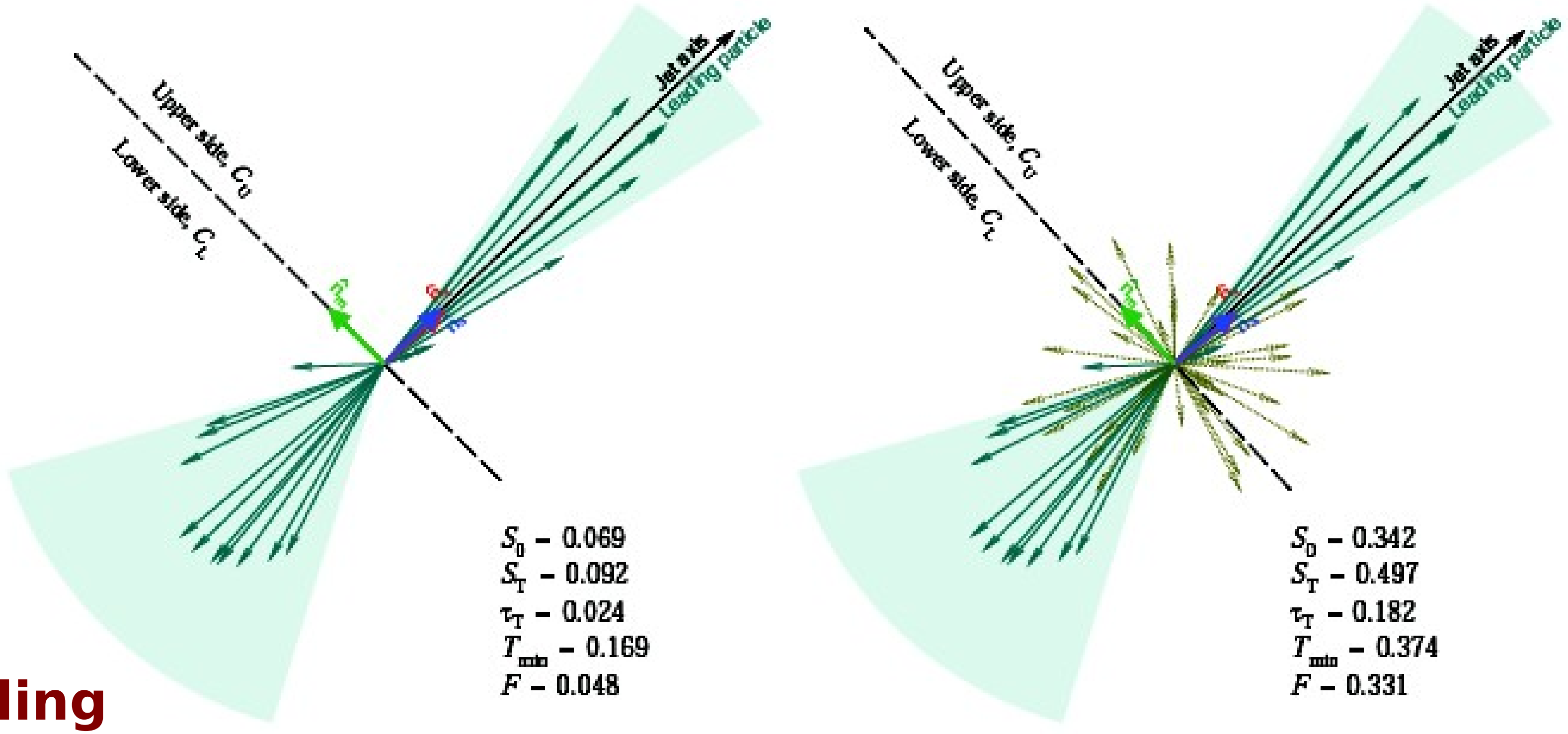
How to quantify & compare events?

- **Transverse spherocity:**

$$S_0 = \frac{\pi^2}{4}\left(\frac{\sum_i |\vec{p_{\mathrm{T}}}_i \times \hat{\mathbf{n}}|}{\sum_i p_{\mathrm{T}i}}\right)^2$$

- **Thrust:**

$$T_{\min} \equiv \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_m|}{\sum_i p_{\mathrm{T},i}}$$



→ NO need for jet finding

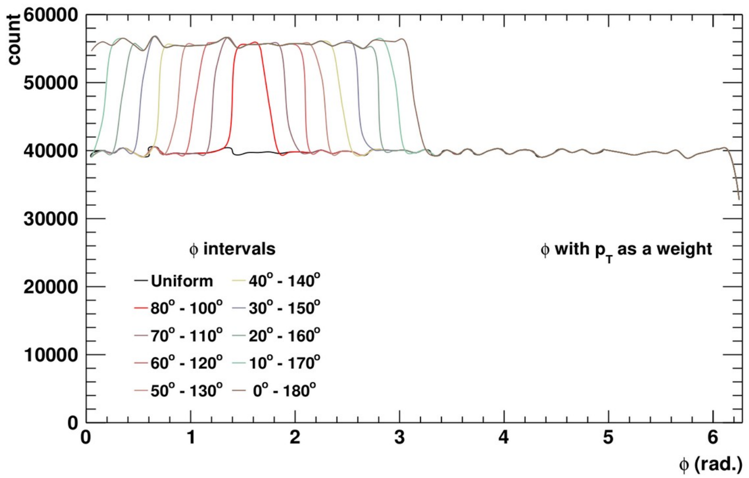
→ Momentum & geometry infos

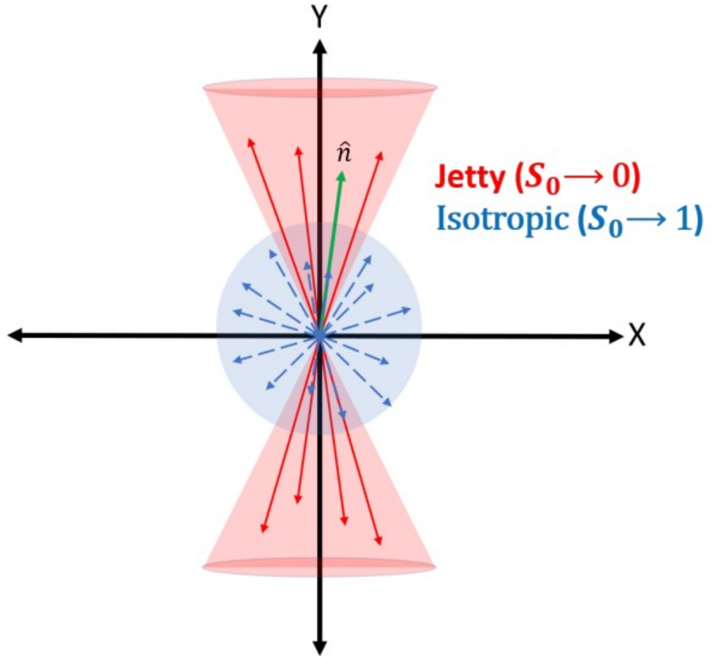
G. Bencédi et al: Phys.Rev.D 104 (2021) 076019

Event shape variable: spherocity

Simple 2-component model

- Isotrope: flat low p_T distribution
- Jet: flat high p_T distribution





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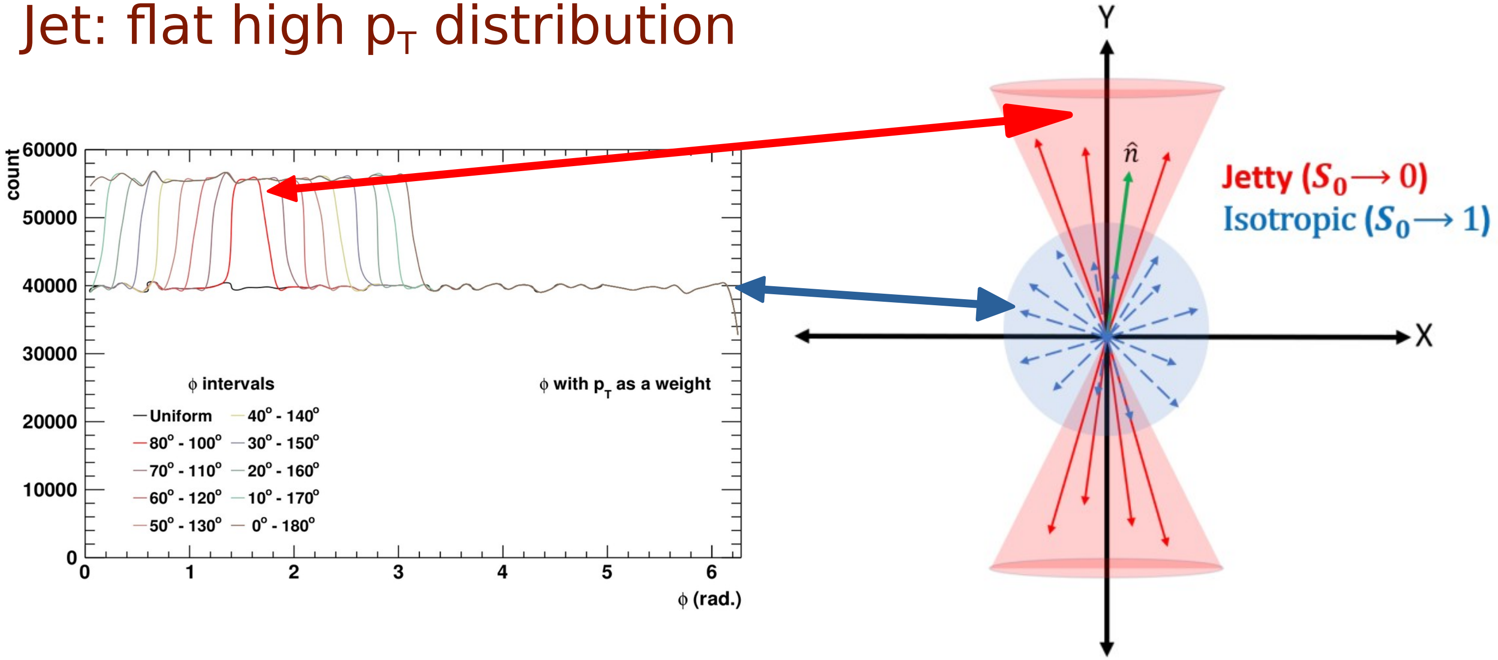

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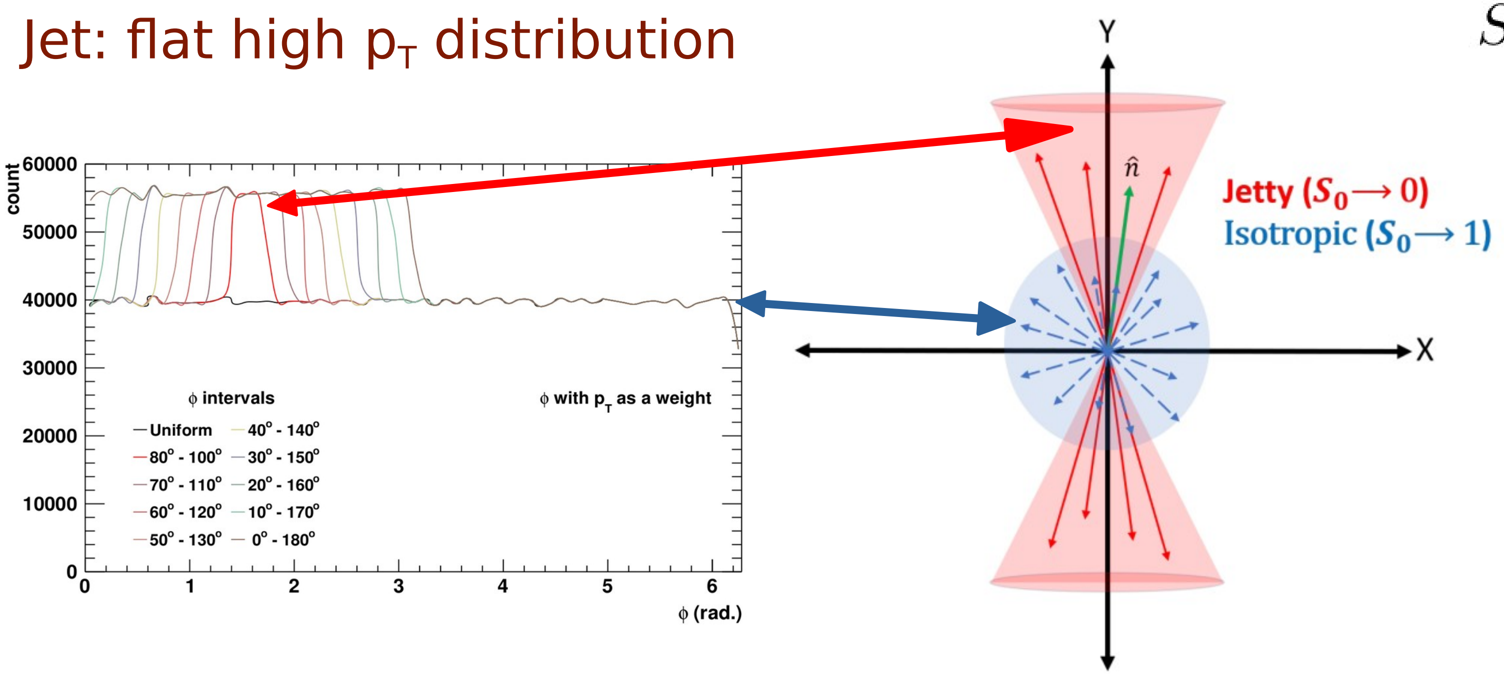
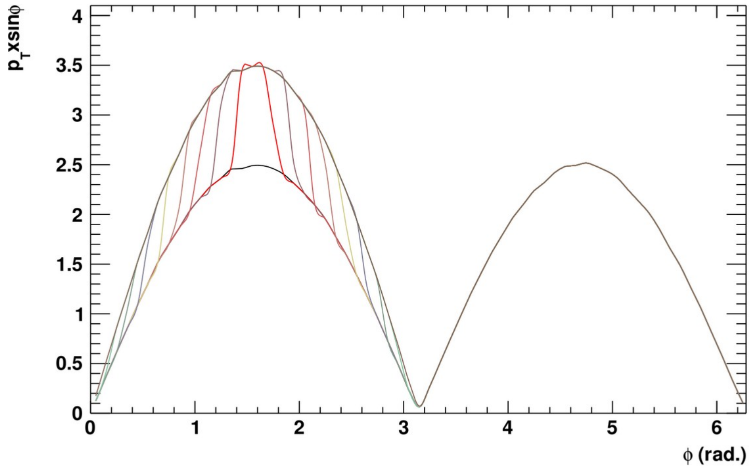
Spherosity definition

$$S_0 = \frac{\pi^2}{4}\left(\frac{\Sigma_i\ |\vec{p}_{T_i} \times \hat{n}|}{\Sigma_i\ p_{T_i}}\right)^2$$





→ Event selection based on spherocity classes is available in ALICE

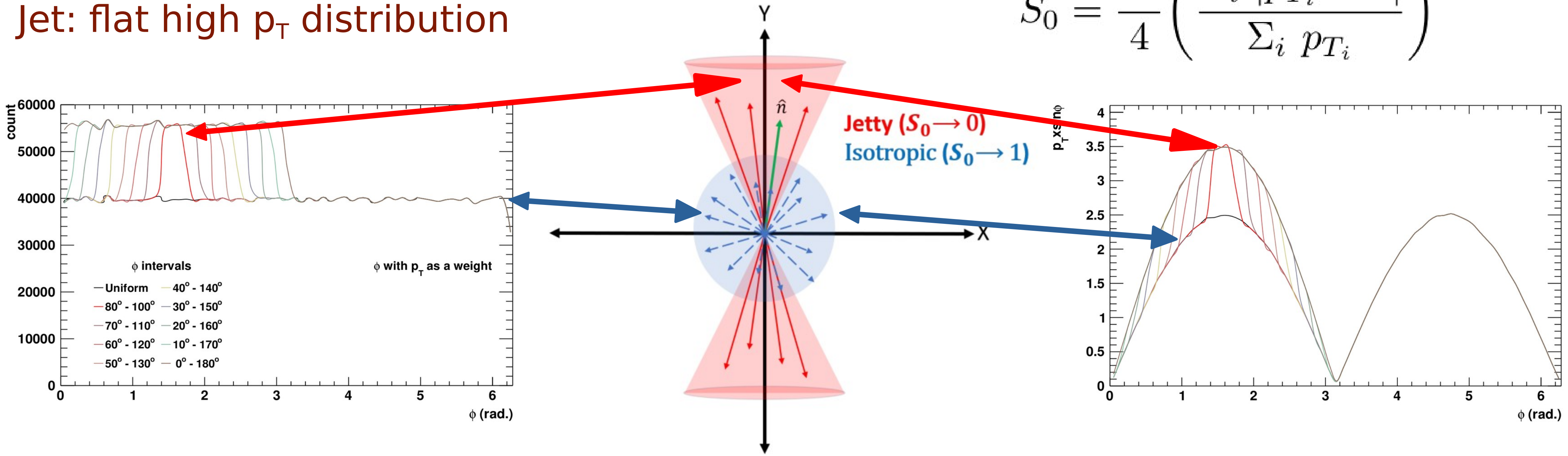
Event shape variable: spherocity

Simple 2-component model

- Isotrope: flat low p_T distribution
- Jet: flat high p_T distribution

Spherosity definition

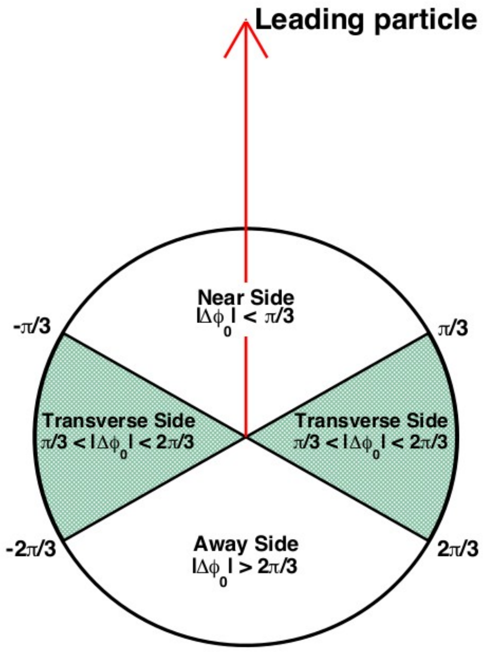
$$S_0 = \frac{\pi^2}{4}\left(\frac{\Sigma_i\ |\vec{p}_{T_i} \times \hat{n}|}{\Sigma_i\ p_{T_i}}\right)^2$$

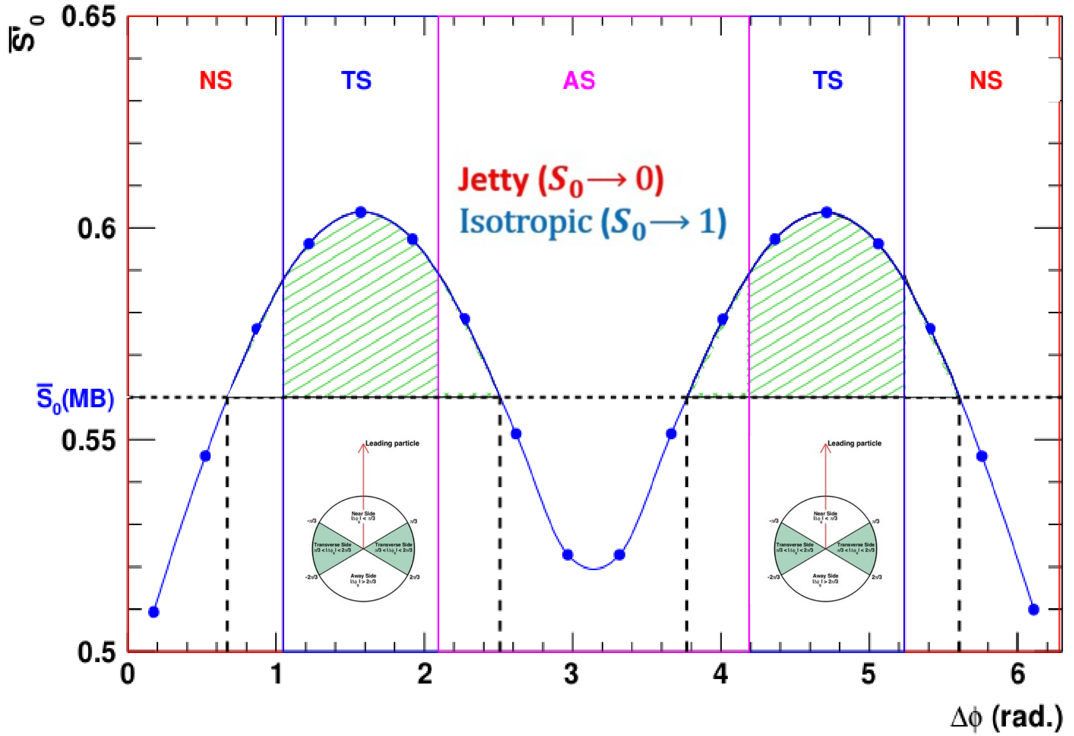


→ Event selection based on spherocity classes is available in ALICE

Spherocity vs. Tsallis termometer

- **Spherocity relative to the MB defines wider UE**





→ CDF-based UE [40,140]

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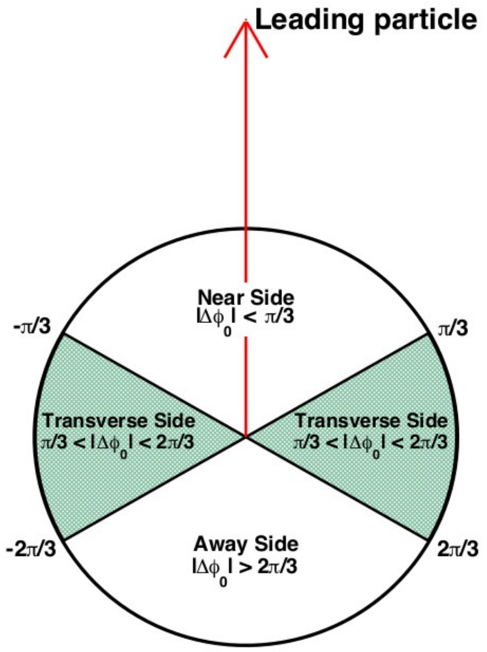

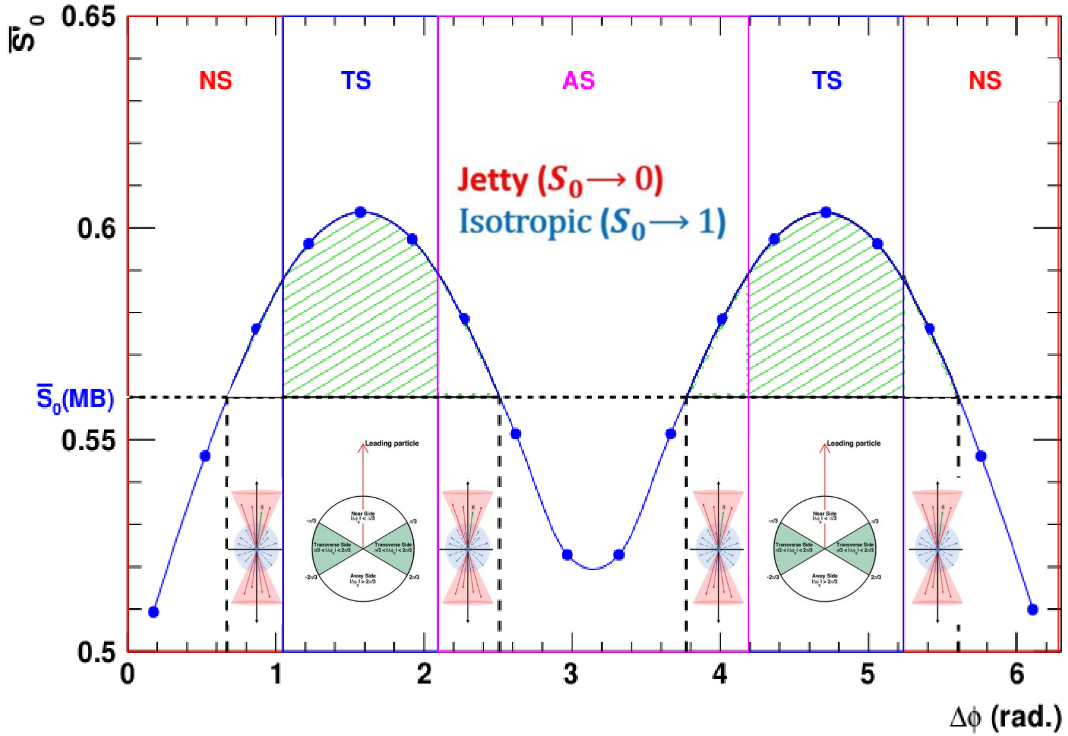

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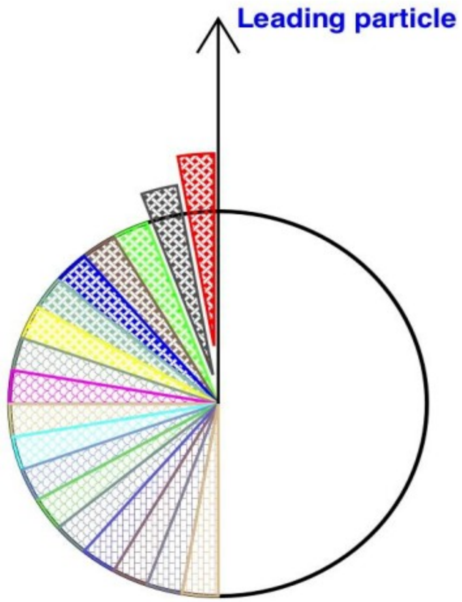
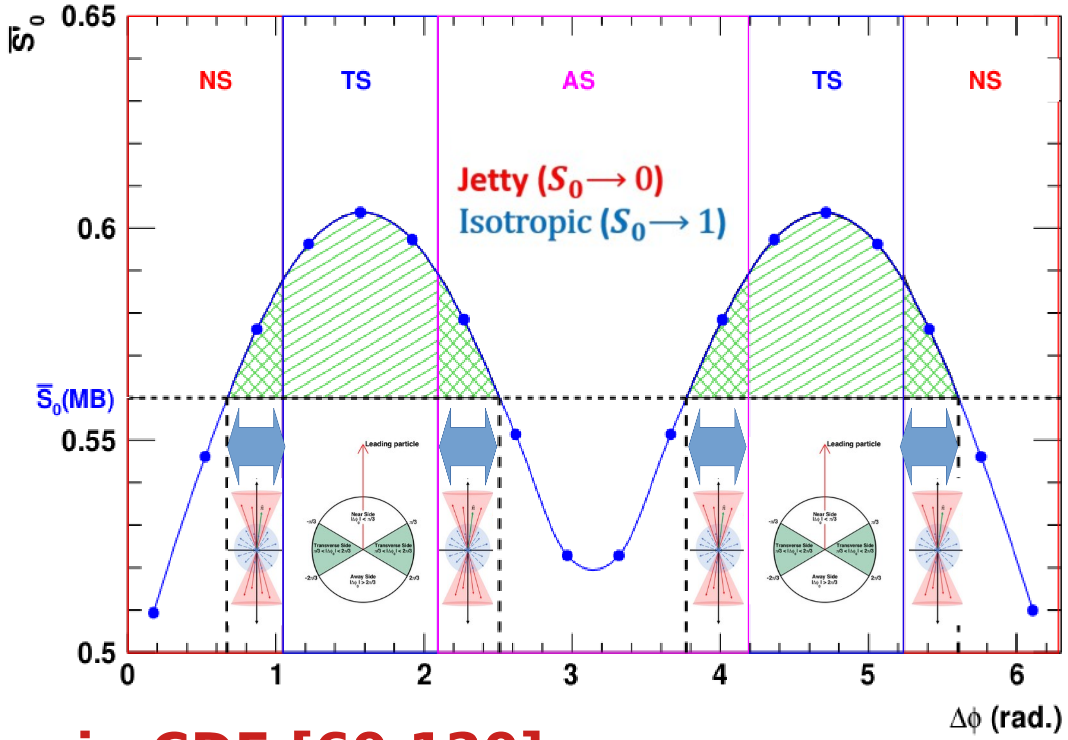
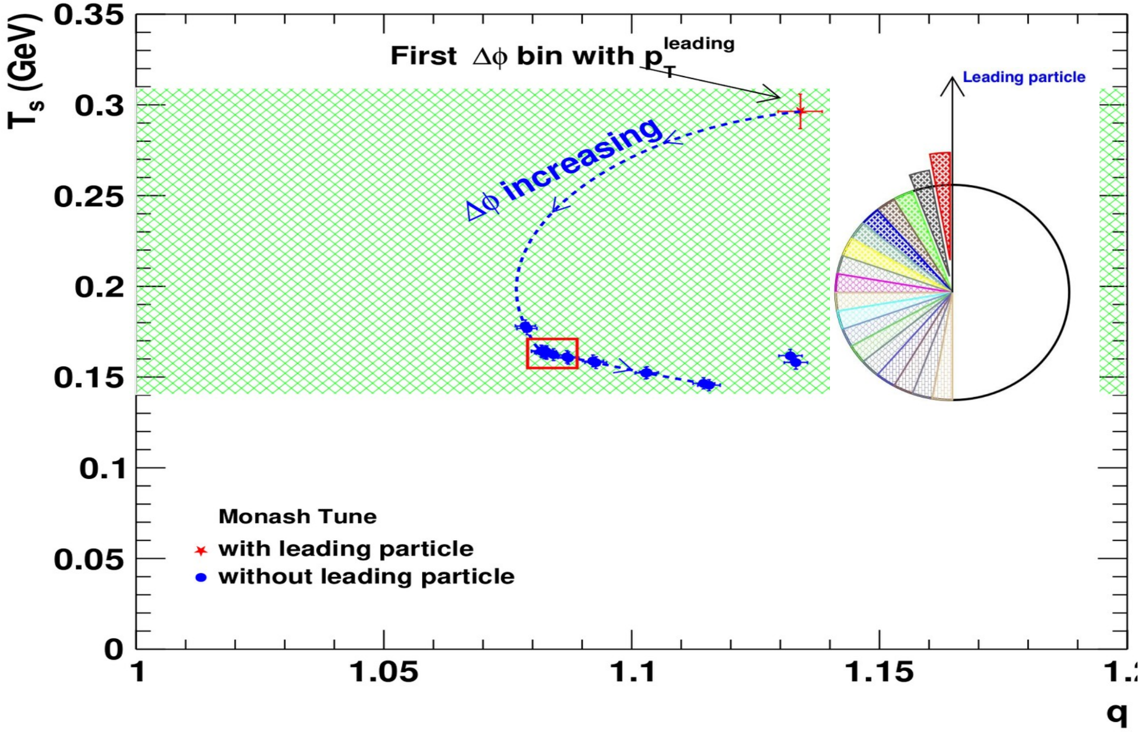


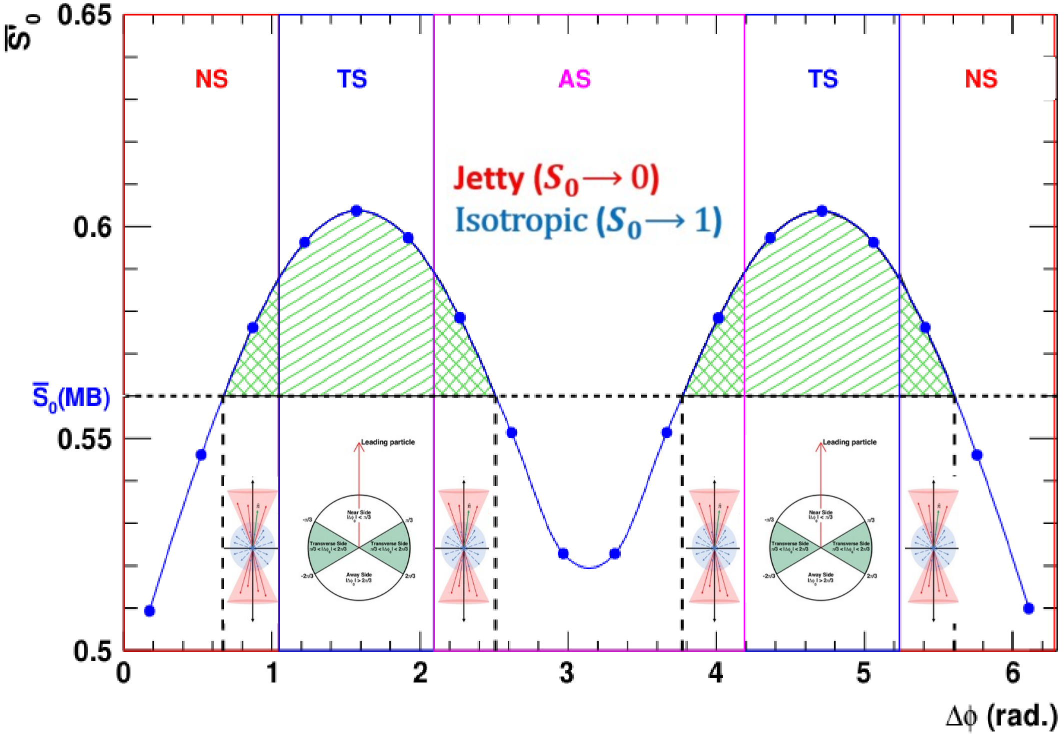


→ Wider range of UE [40,140], than in CDF [60,120]

Spherocity vs. Tsallis termometer

- **Spherocity relative to the MB defines wider UE**
- **Tsallis-thermometer presents the same**





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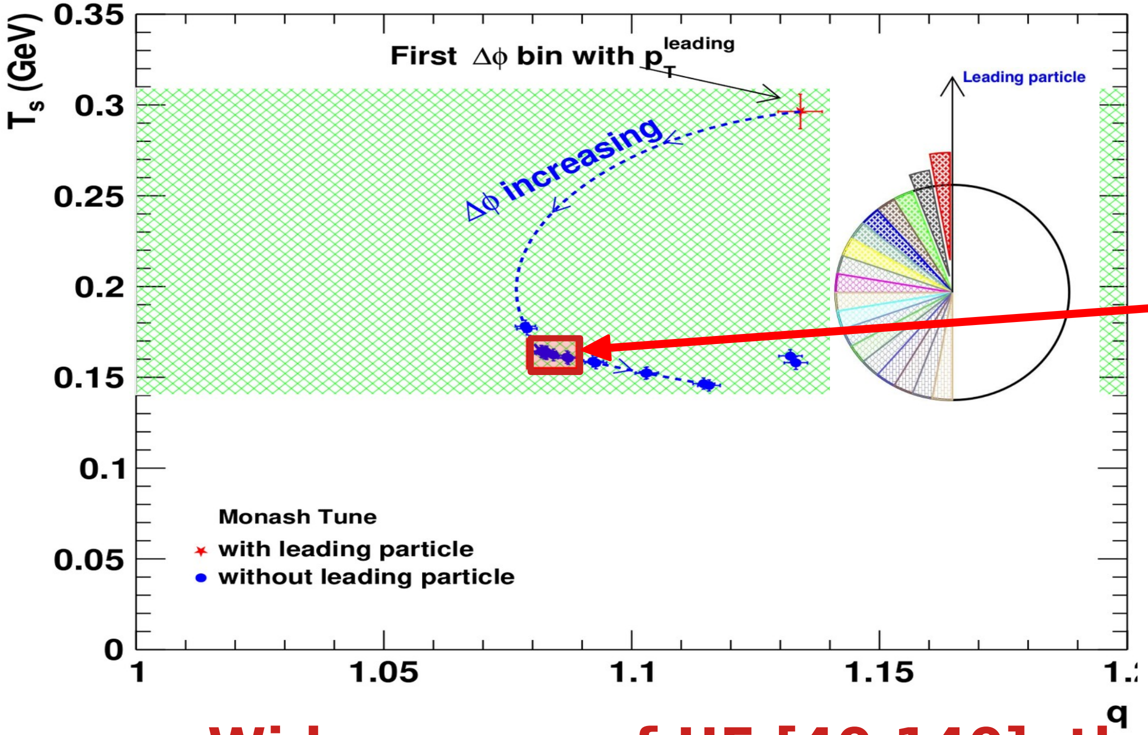
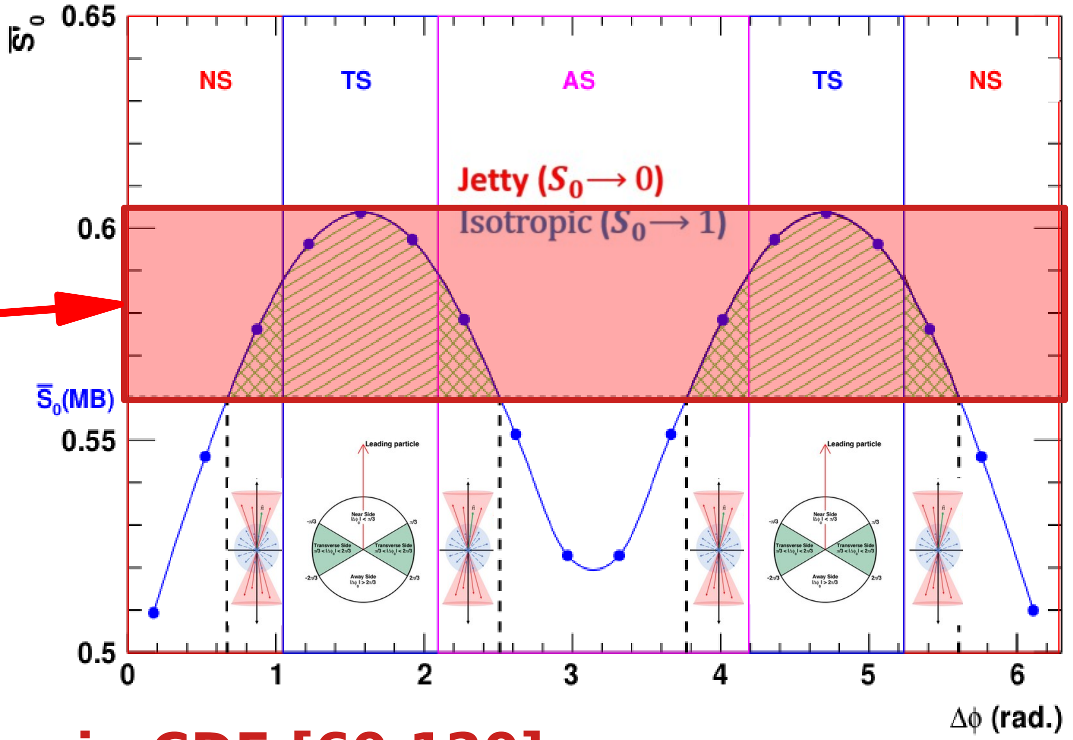
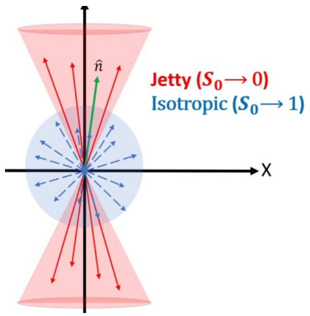


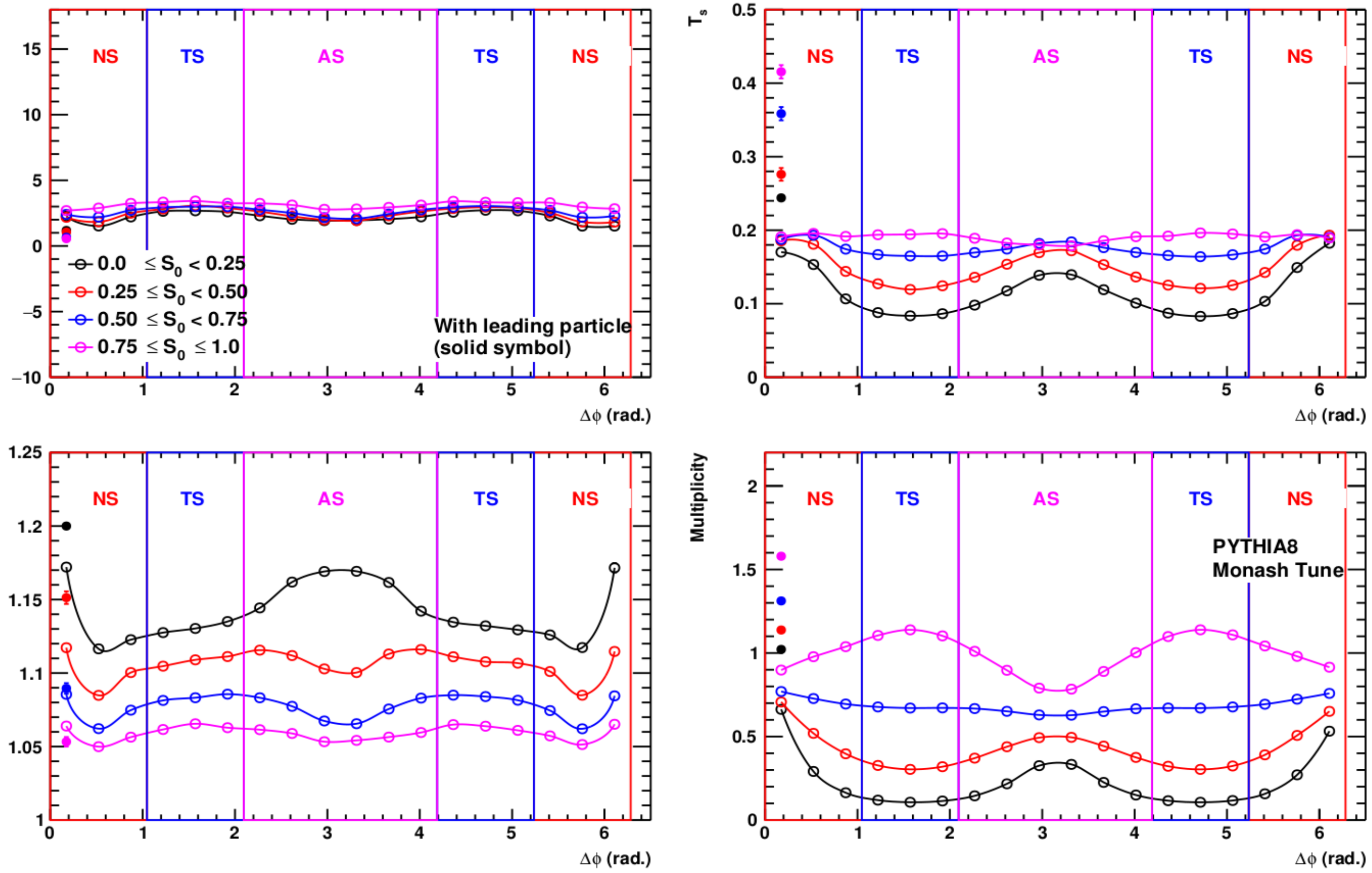


→ Wider range of UE [40,140], than in CDF [60,120]

Parameters in spherocity classes

- **PYTHIA spectra with sliding angle in S_0 classes**
  - The more jetty the event, the angular variation is stronger.
  - Minimal activity (lowest q & T values are in the isotropic case.



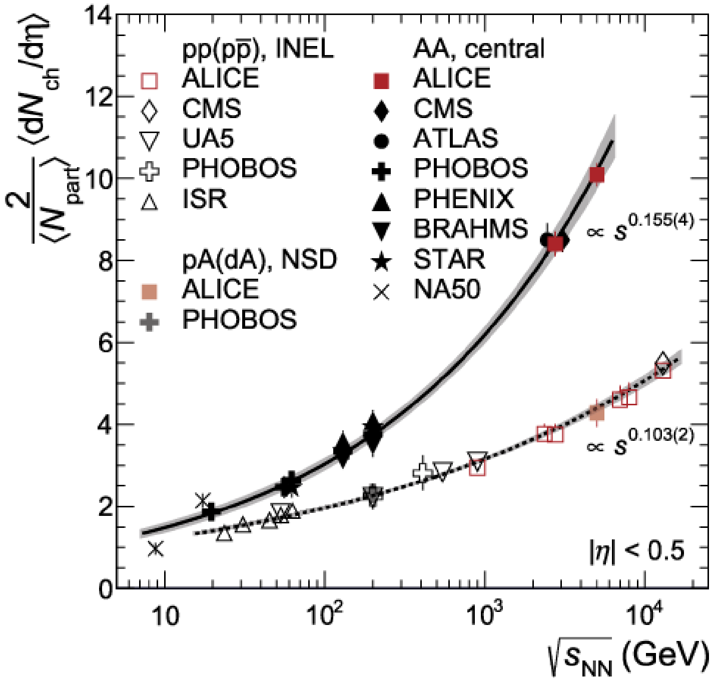


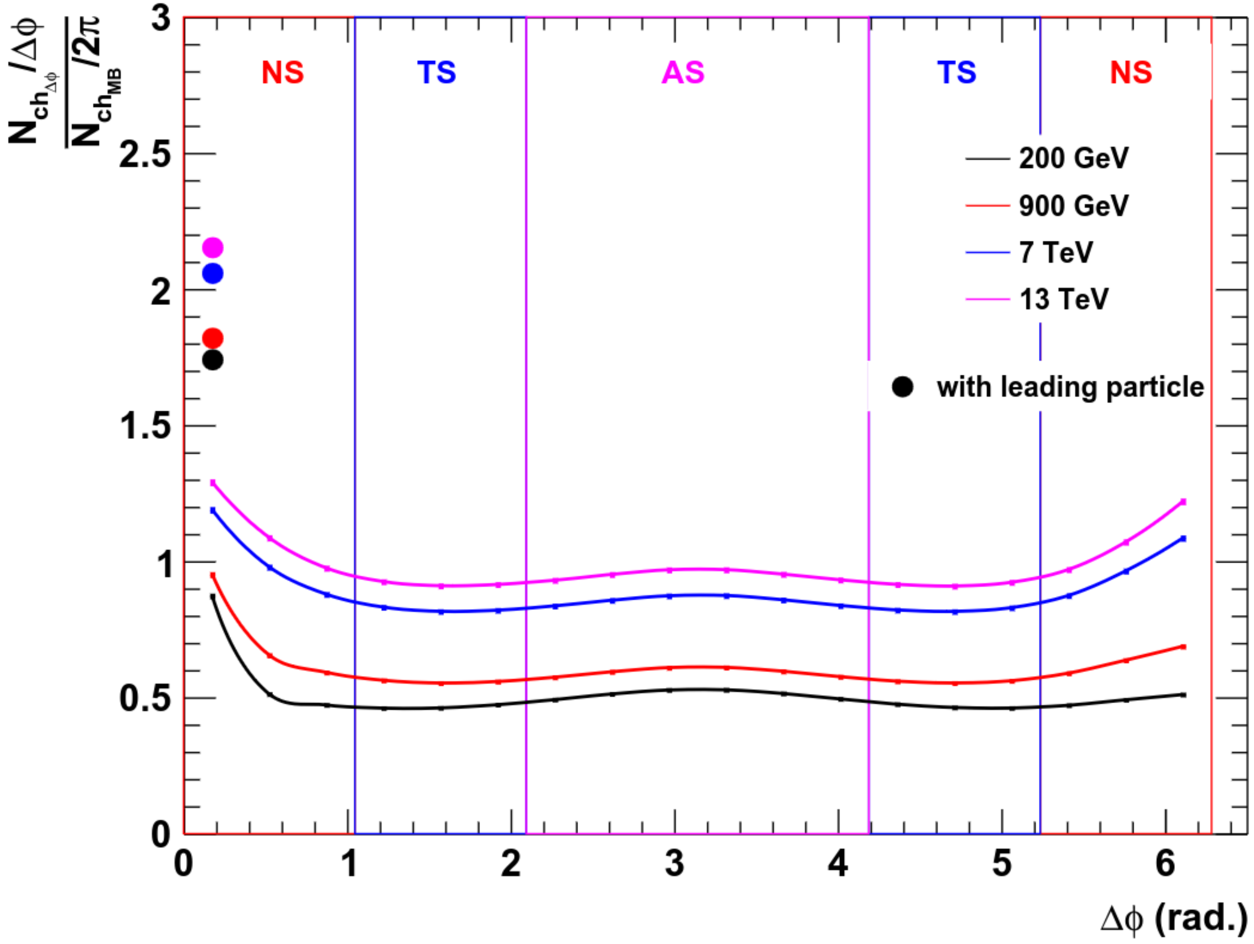
→ Isotropic events are closer to UE, activity is more than MB

Dependence on c.m. energy

Multiplicity scaling from RHIC to LHC

- **PYTHIA spectra with sliding angle from RHIC to LHC**
  - Multiplicity goes with the logarithm of the c.m. energy





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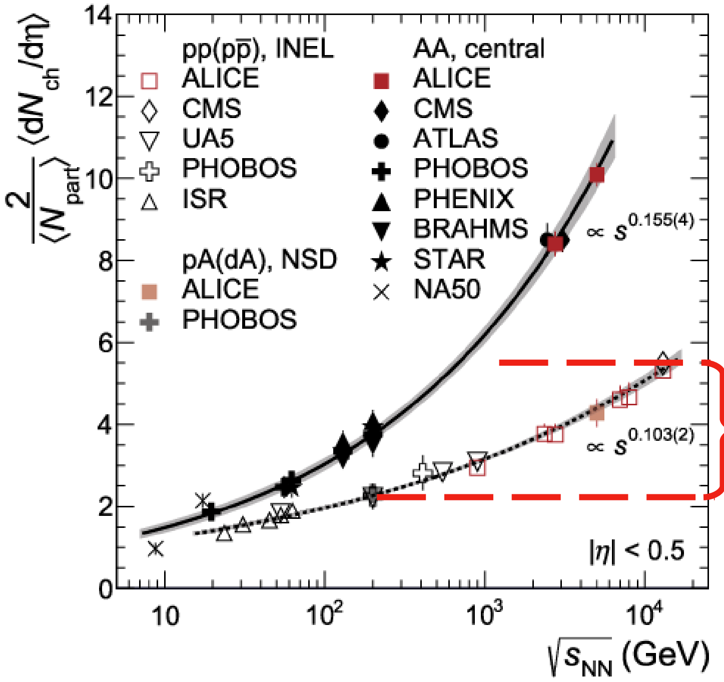
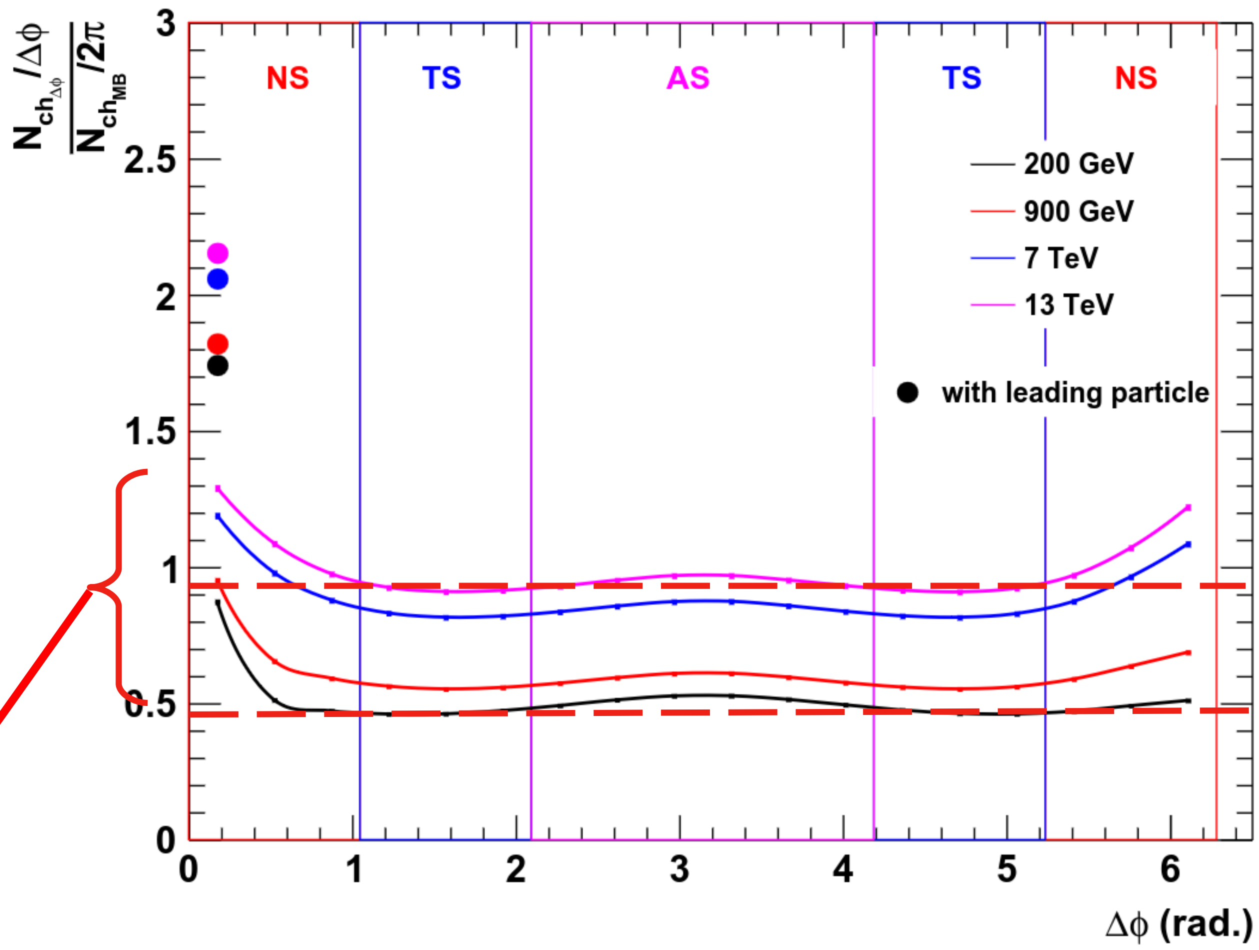
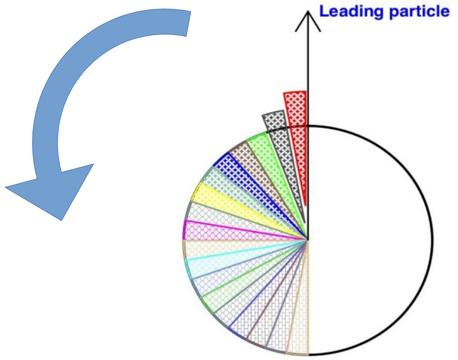
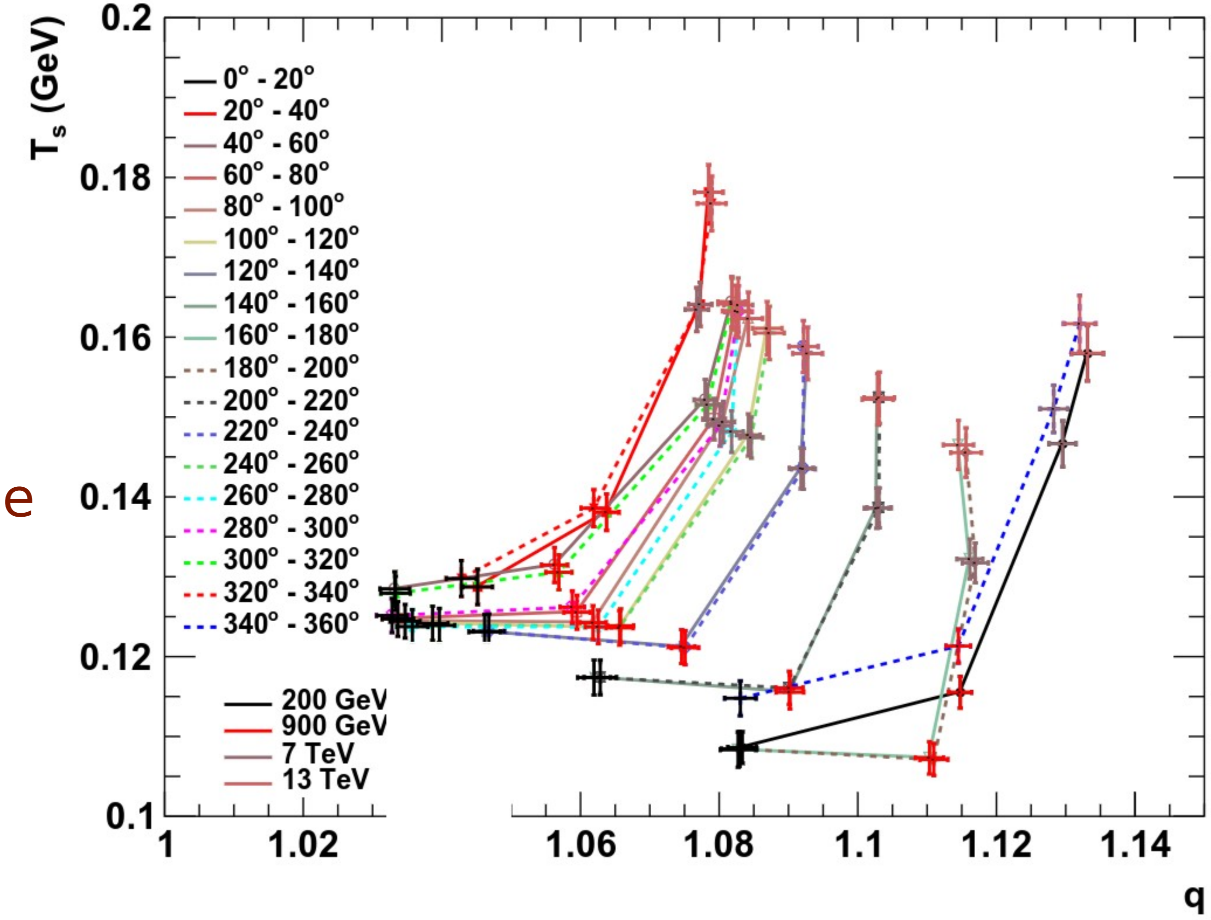




Tsallis-thermometer from RHIC to LHC

- **PYTHIA spectra with sliding angle from RHIC to LHC**
  - Multiplicity goes with the logarithm of the c.m. energy
  - Leading particle line is the outlier
  - The structure of the curve is stable





  - → **Nice c.m. energy scaling trends**

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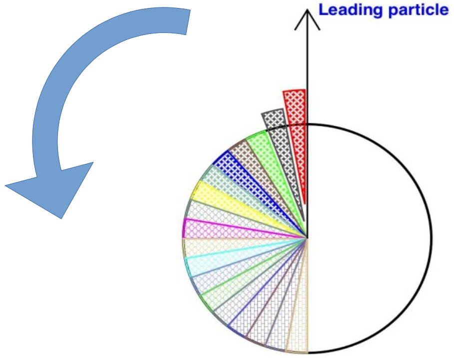

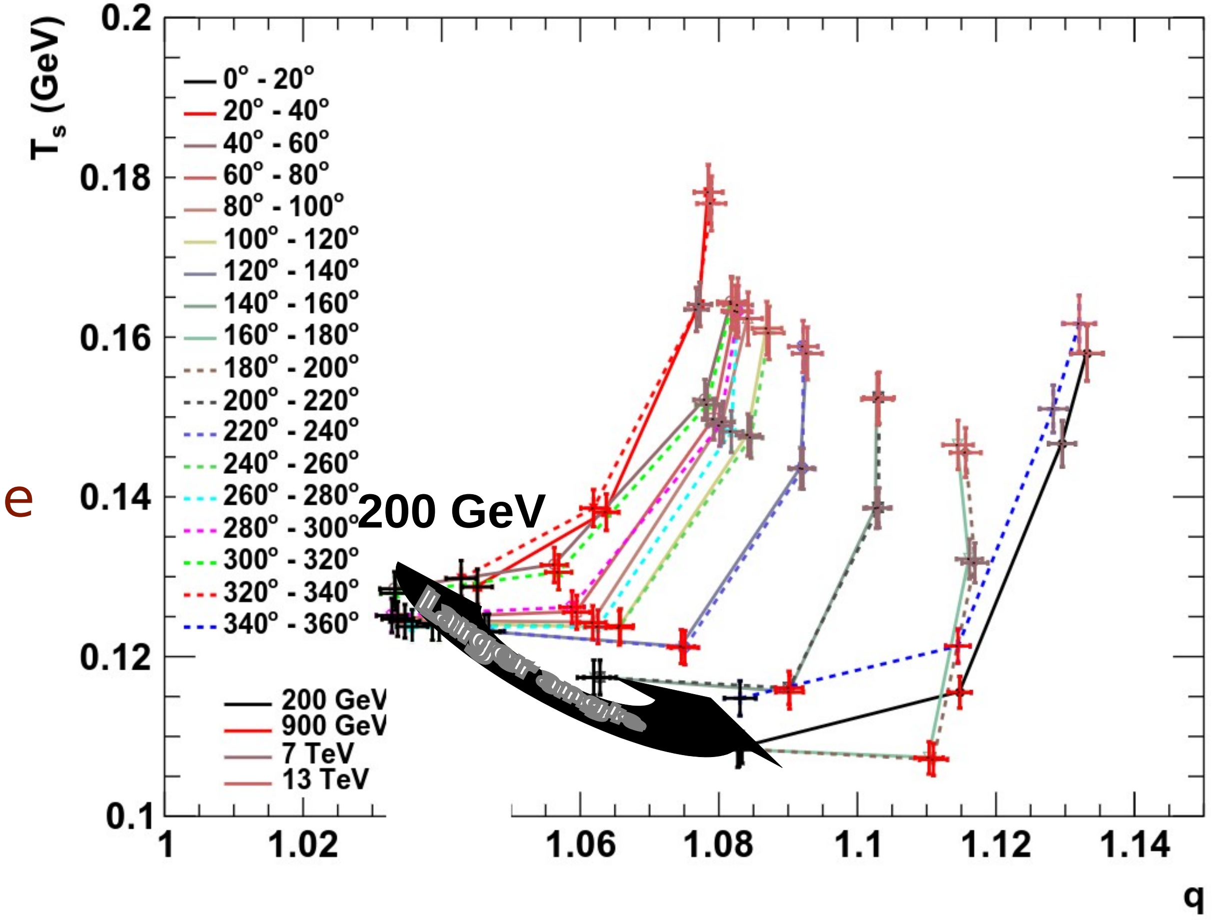

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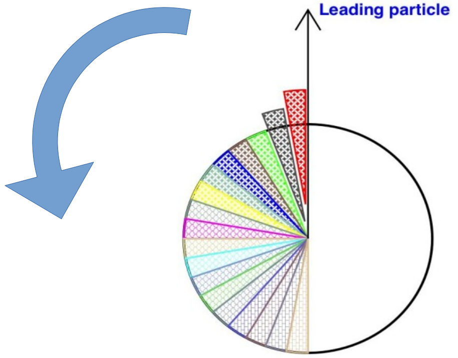

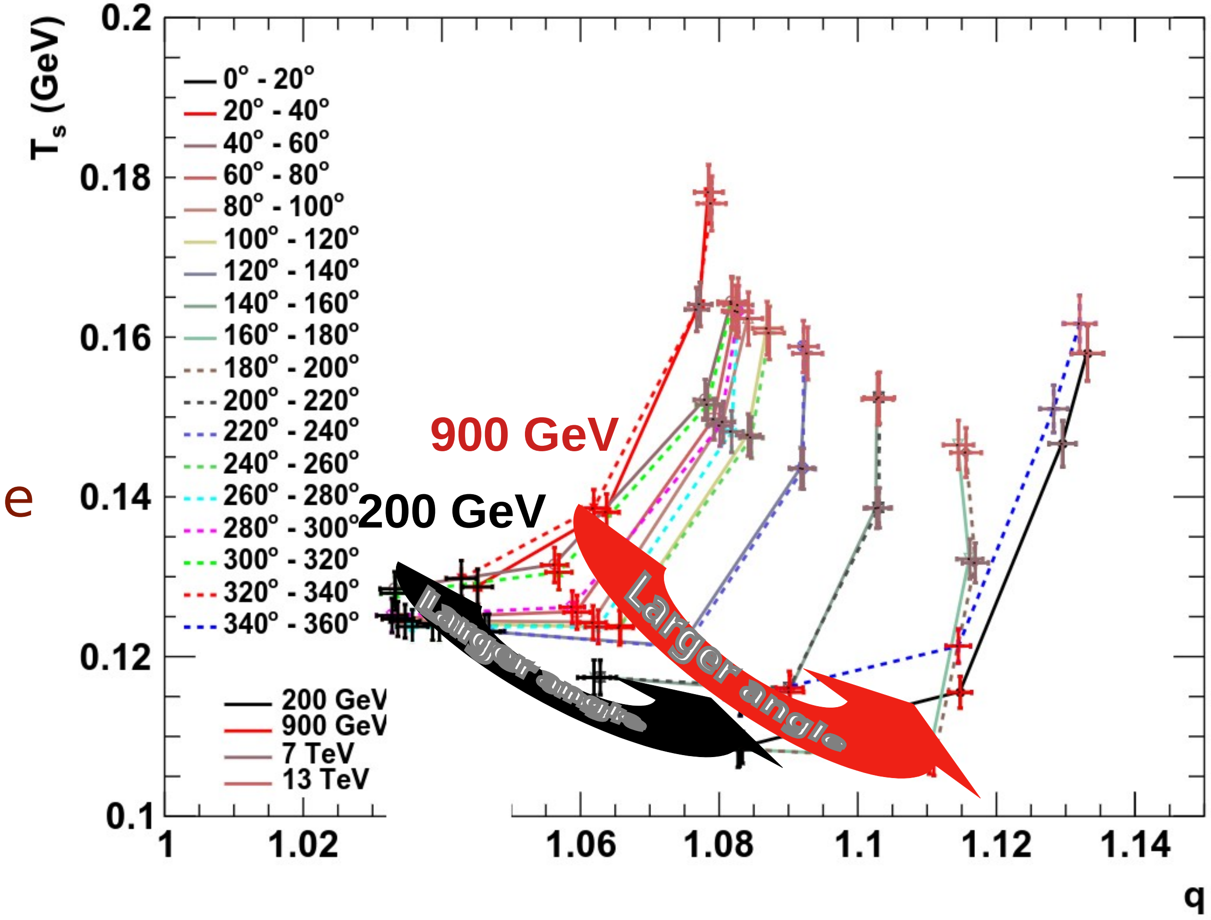

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Tsallis-thermometer from RHIC to LHC

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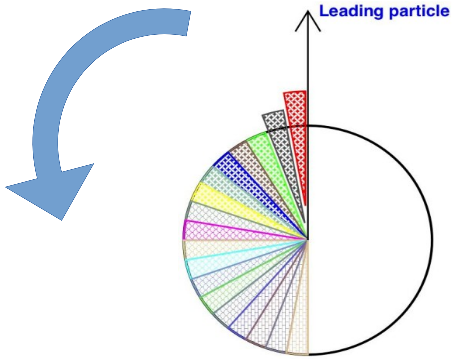

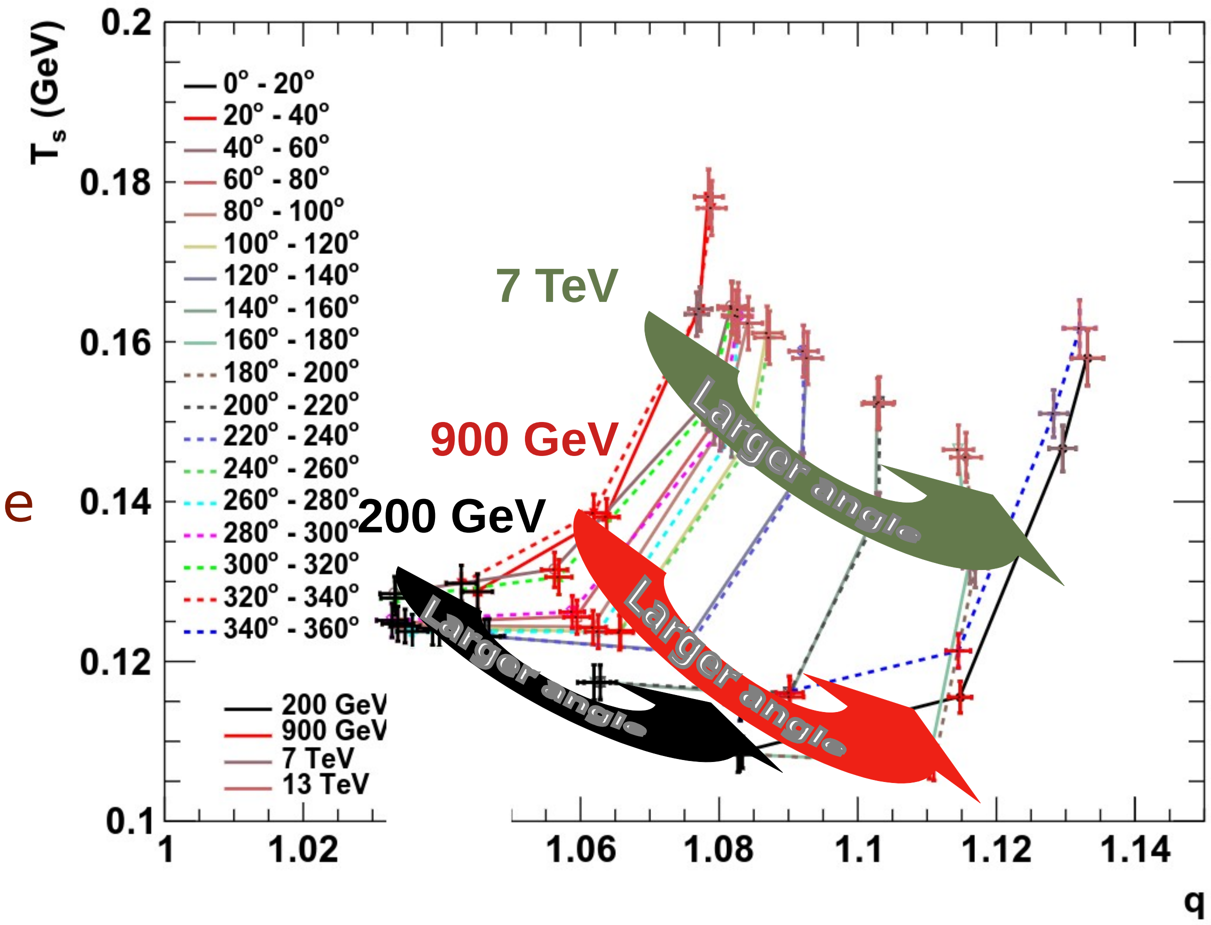

  - → **Nice c.m. energy scaling trends**

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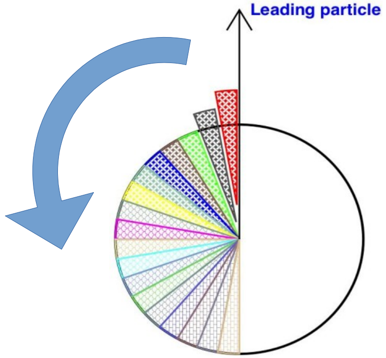
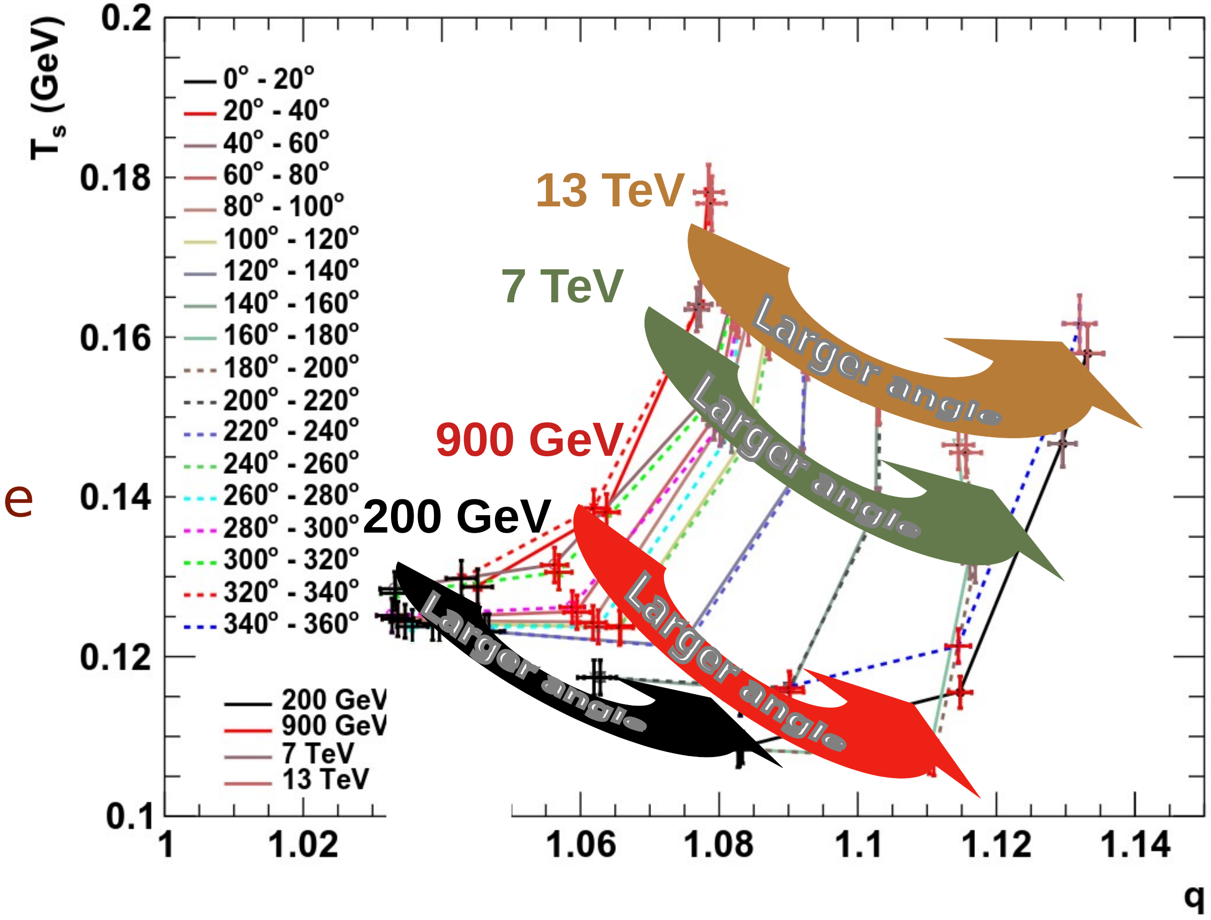
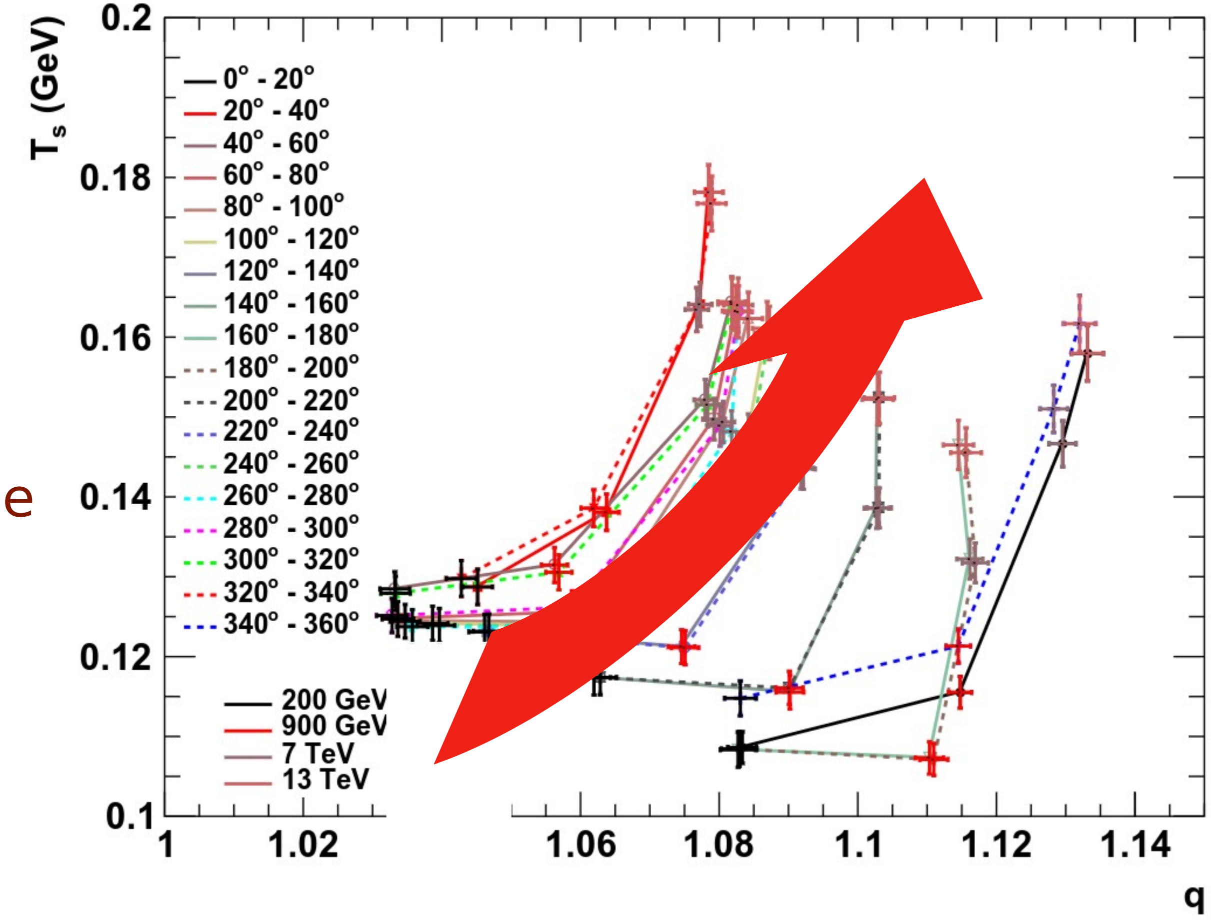




  - → **Nice c.m. energy scaling trends**

Tsallis-thermometer from RHIC to BB

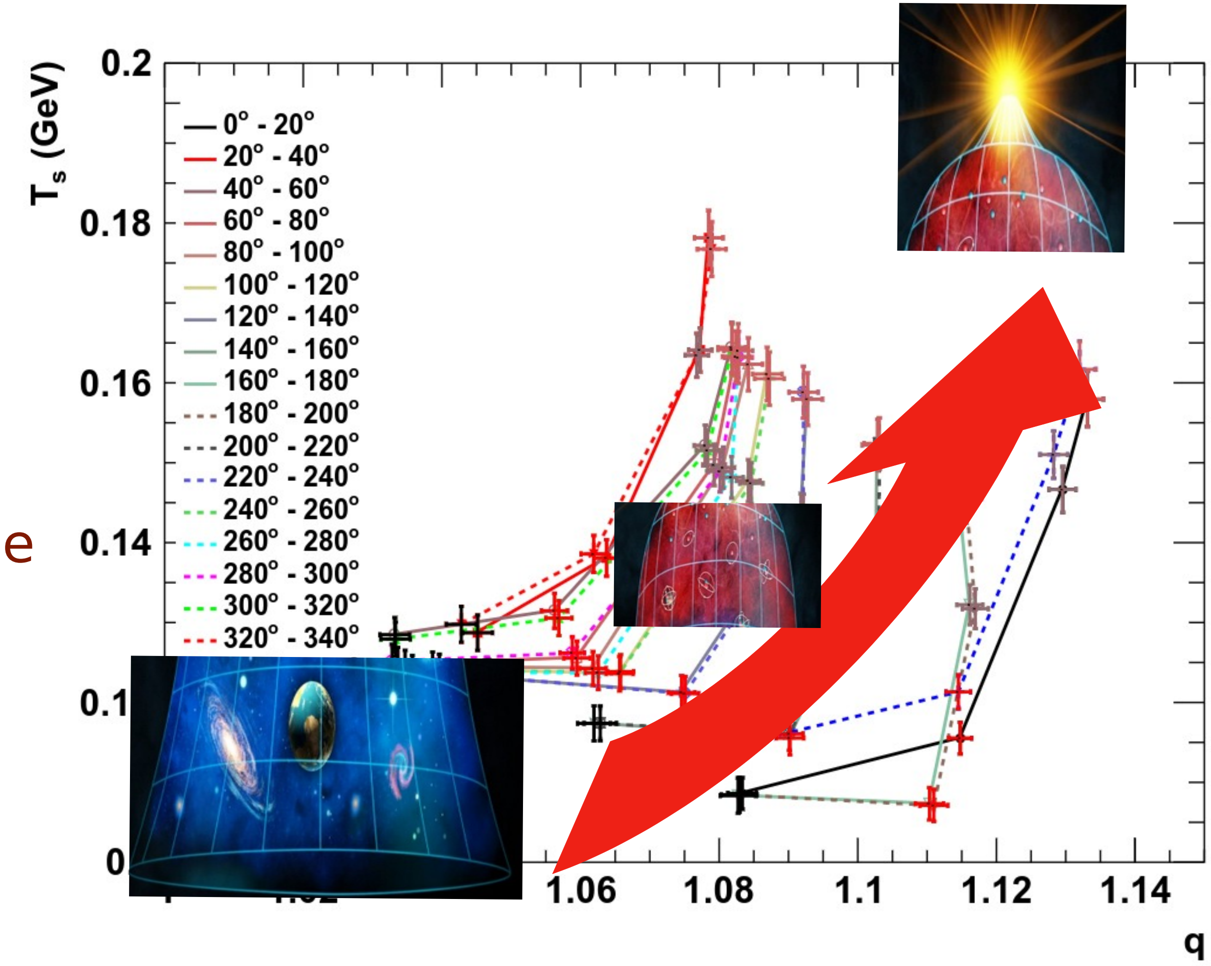
- **PYTHIA spectra with sliding angle from RHIC to LHC**
  - Multiplicity goes with the logarithm of the c.m. energy
  - Leading particle line is the outlier
  - The structure of the curve is stable



→ **Nice c.m. energy scaling trends even further?**

Tsallis-thermometer from RHIC to BB

- **PYTHIA spectra with sliding angle from RHIC to LHC**
  - Multiplicity goes with the logarithm of the c.m. energy
  - Leading particle line is the outlier
  - The structure of the curve is stable



→ **Nice c.m. energy scaling trends even further?**

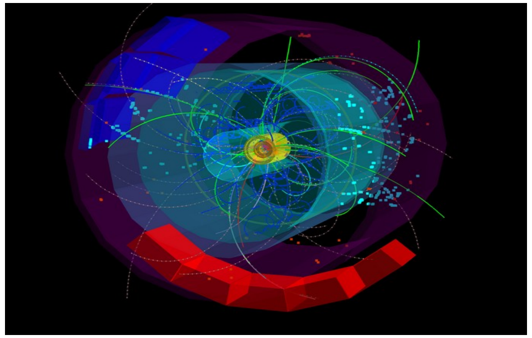
Conclusions

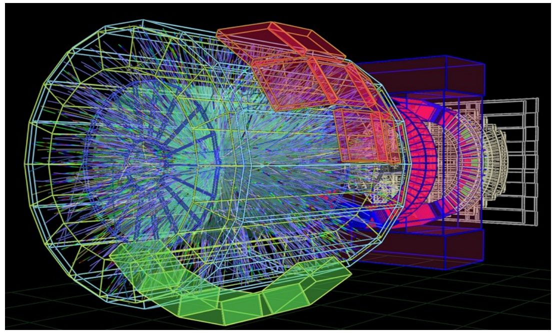
- **Could we understand UE?**
  - Not yet, but getting closer by quantifying them
    - → Model UE: PYTHIA (CR, MPI), HIJING (minijet)
    - → UE properties has been charaterized
    - → Tsallis-Pareto fits well in narrow slices
- **To take away...**
  - Tsallis-thermometer present wider UE

    In degrees CDF: [60,120] → [40,140]
  - Event shape classification support the model
  - Scales with c.m. energy well

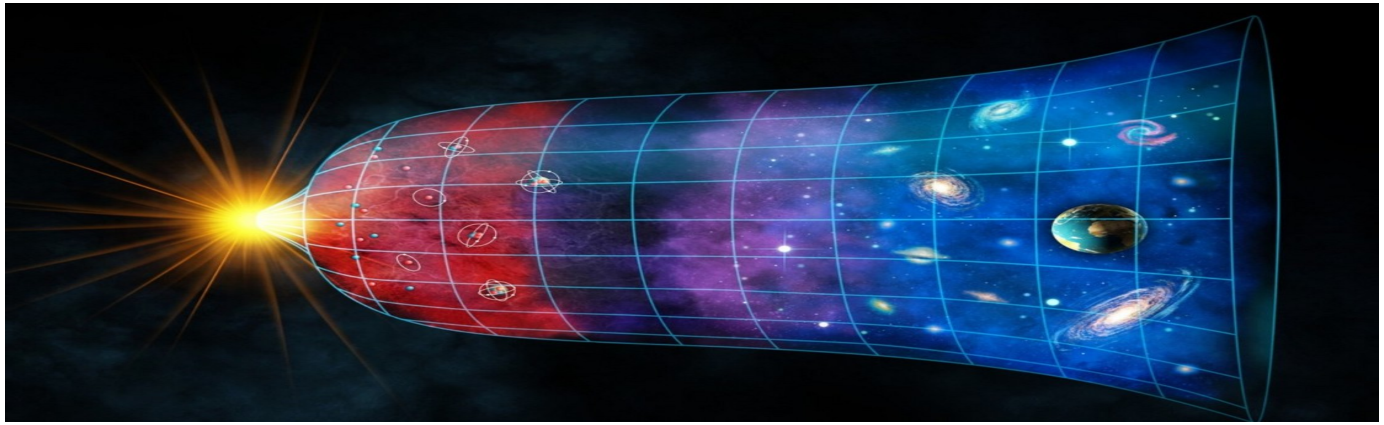
→ UE has been quantified, next step...

Measure & investigate in pA or AA?



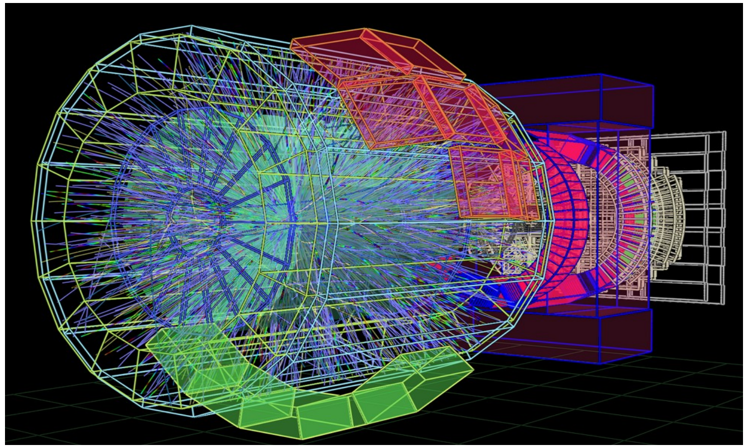


So, again….



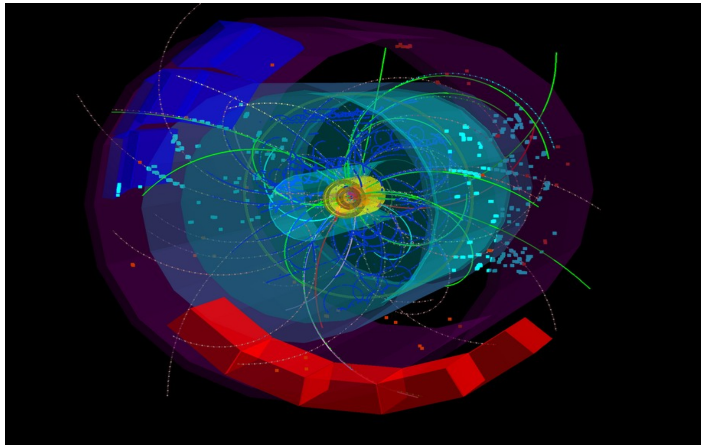
Which one is the "closest" to the early Universe?

A) PbPb collision



C) Cup of coffee

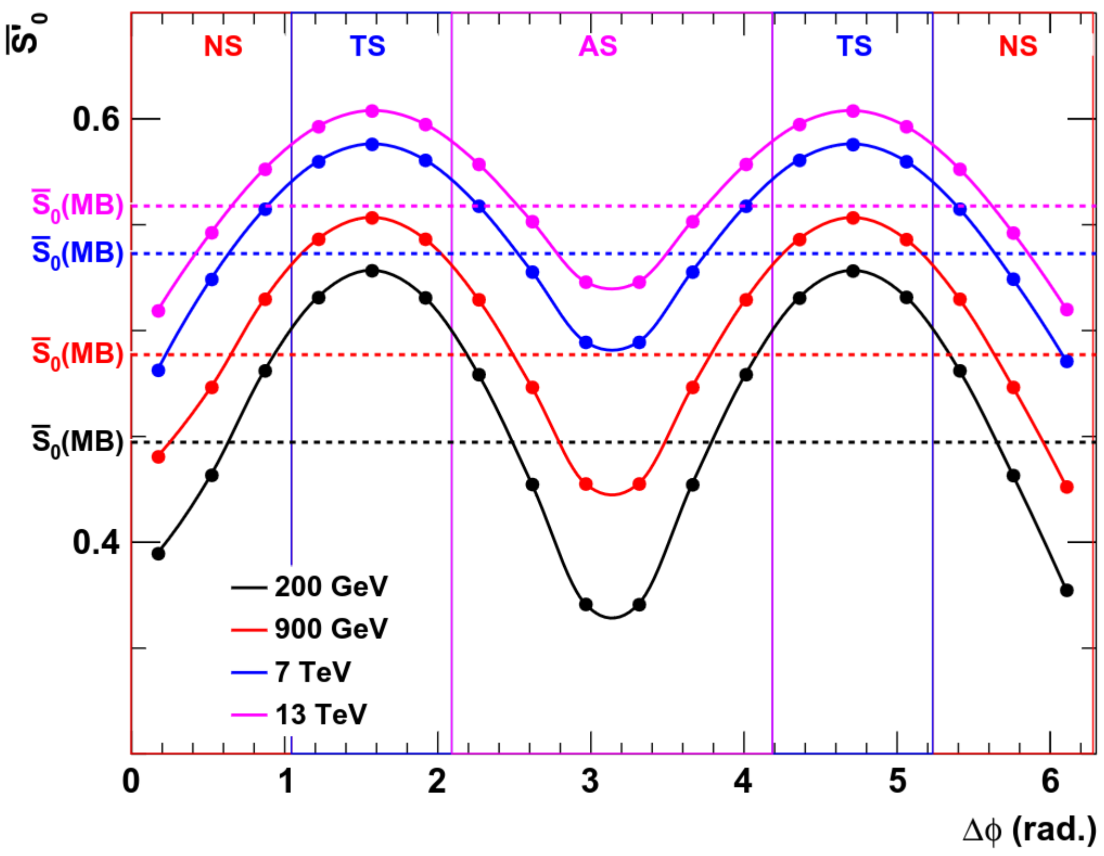
B) pp collision



Thank You!

Tsallis-thermometer from RHIC to LHC

- **PYTHIA spectra with sliding angle from RHIC to LHC**
  - Multiplicity goes with the logarithm of the c.m. energy
  - Leading particle line is the outlier
  - The structure of the curve is stable
  - Spherocity is increasing, but the size of the effect is the same



  - → **Nice c.m. energy scaling trends, in spherocity as well**

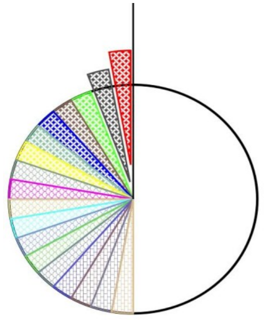
Derivatives of the parameters

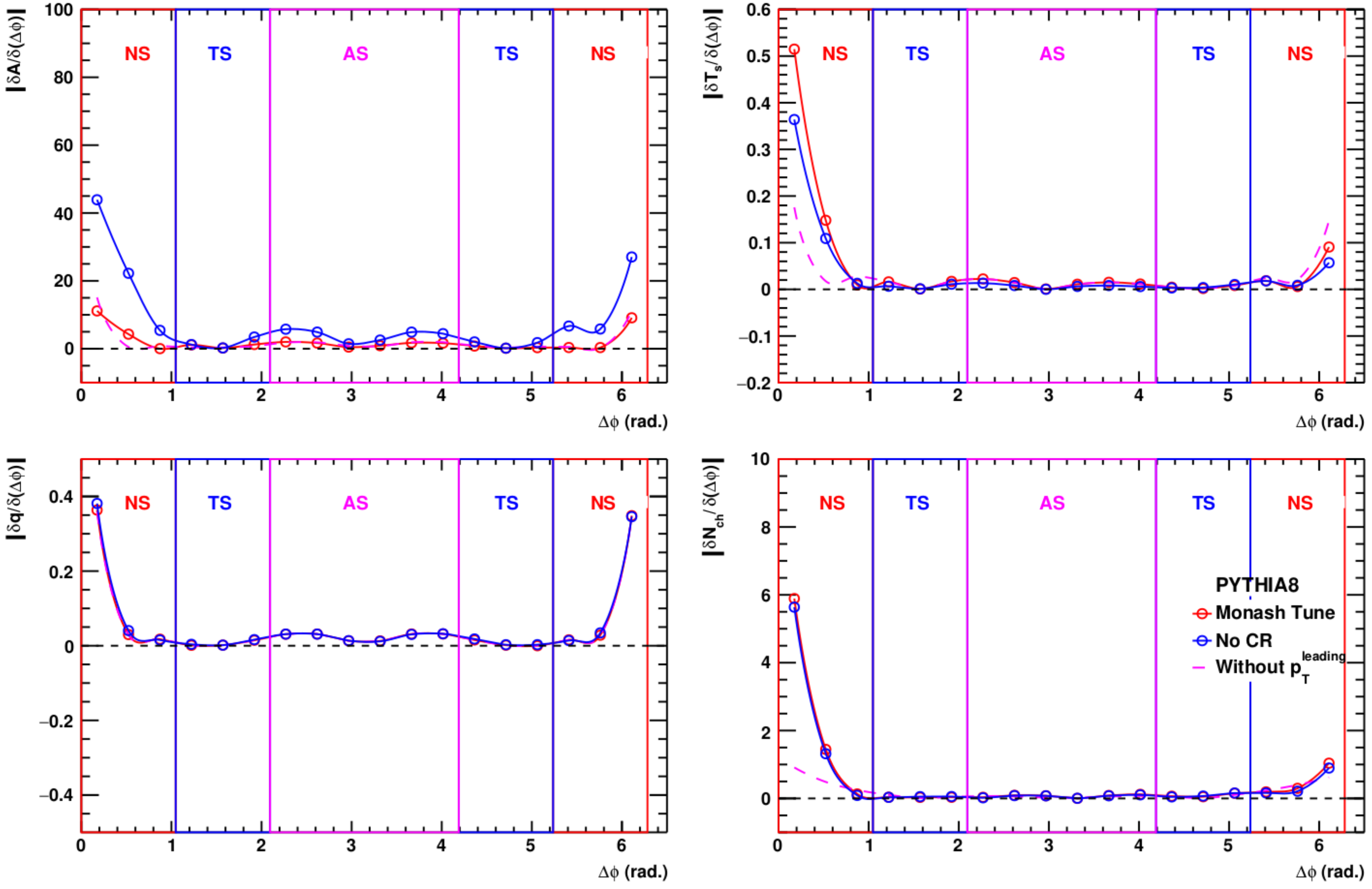
- **PYTHIA spectra parameter derivatives with sliding angle**
  - PYTHIAs model UE: CR & MPI
  - TS (+AS) → constant T & q

$$\frac{\delta T_s}{\delta(\Delta\phi)} \neq 0 \quad \& \quad \frac{\delta q}{\delta(\Delta\phi)} \neq 0 \quad \text{(for NS \& AS)}$$

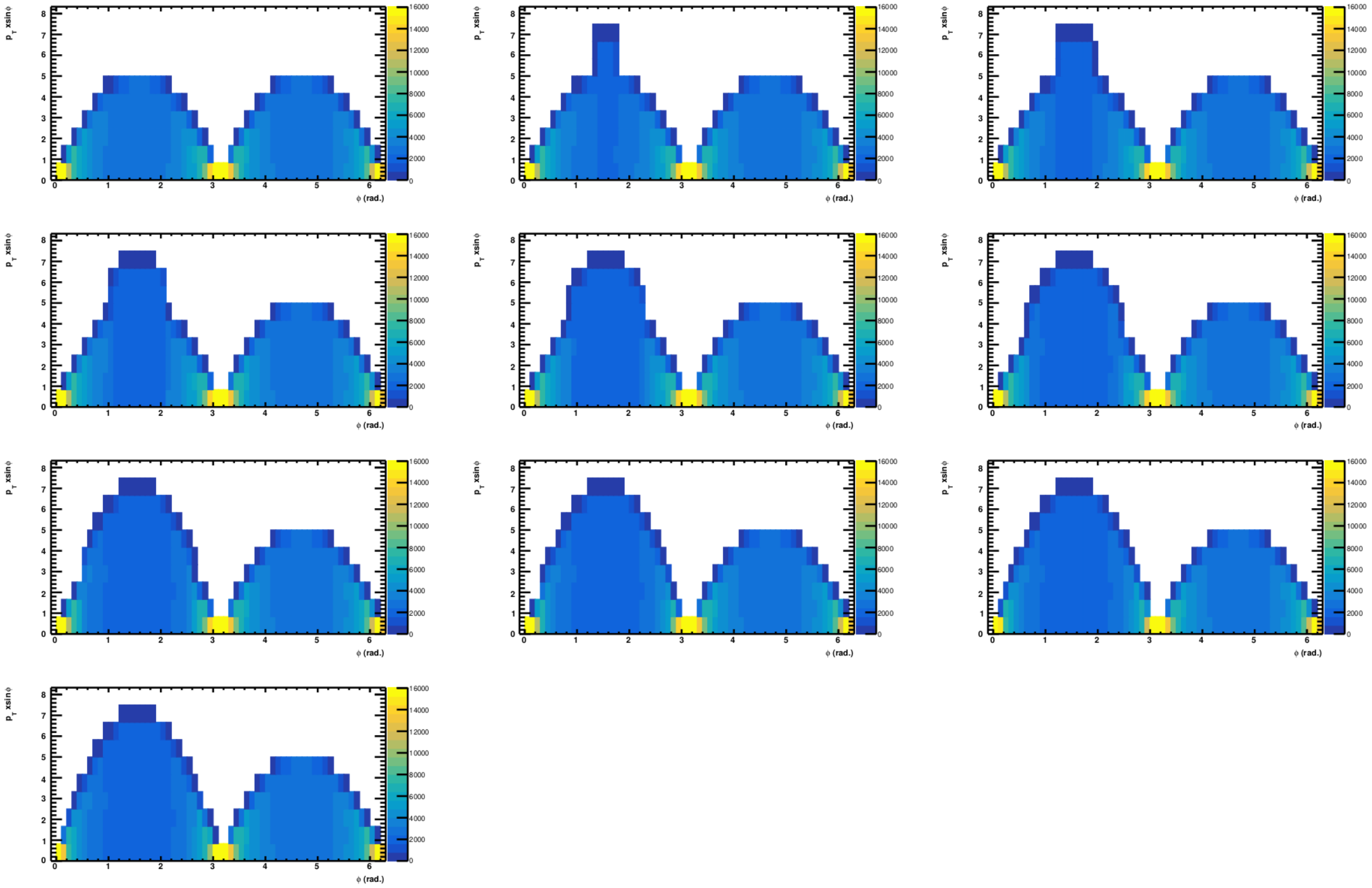
$$\frac{\delta T_s}{\delta(\Delta\phi)} \approx 0 \quad \& \quad \frac{\delta q}{\delta(\Delta\phi)} \approx 0 \quad \text{(for TS)}$$

  - NS → highest T
  - NS/AS → highest q
  - Multiplicity ~ A





Spherocity model with multiplicity



Thermodynamical consistency?

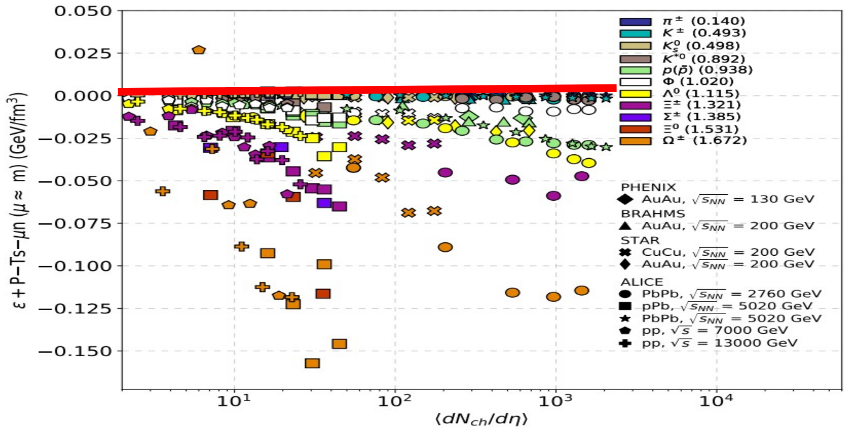
Thermodynamical consistency: fulfilled up to a high degree

$$P = g \int \frac{d^3p}{(2\pi)^3} T f,$$

$$N = nV = gV \int \frac{d^3p}{(2\pi)^3} f^q,$$

$$s = g \int \frac{d^3p}{(2\pi)^3} \left[\frac{E-\mu}{T} f^q + f \right],$$

$$\varepsilon = g \int \frac{d^3p}{(2\pi)^3} E f$$



Compare EoS to data: Lattice QCD (parton) & Biró-Jakovác parton-hadron