Quantifying the Underlying Event in pp collisions at LHC energies using non-extensive statistics

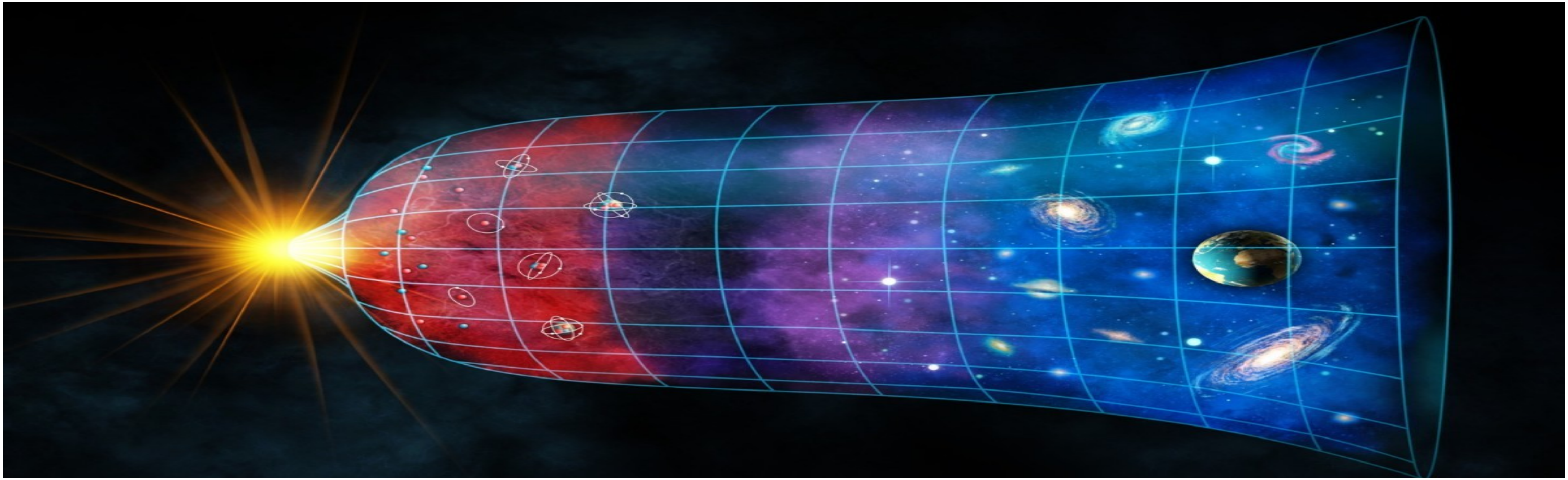
G.G. Barnaföldi in collaboration with A.N. Mishra, G. Paic, and G. Bíró

Support: *Hungarian OTKA grants, K135515, Wigner Scientific Computing Laboratory*

Refs: J.Phys.G 47 (2020) 10, 105002, arXiv:2108.13938 (accepted in J. Phys. G)

Theory & Experiment in HEP #1, Bratislava, 27th July 2023

QGP – the matter of the early Universe



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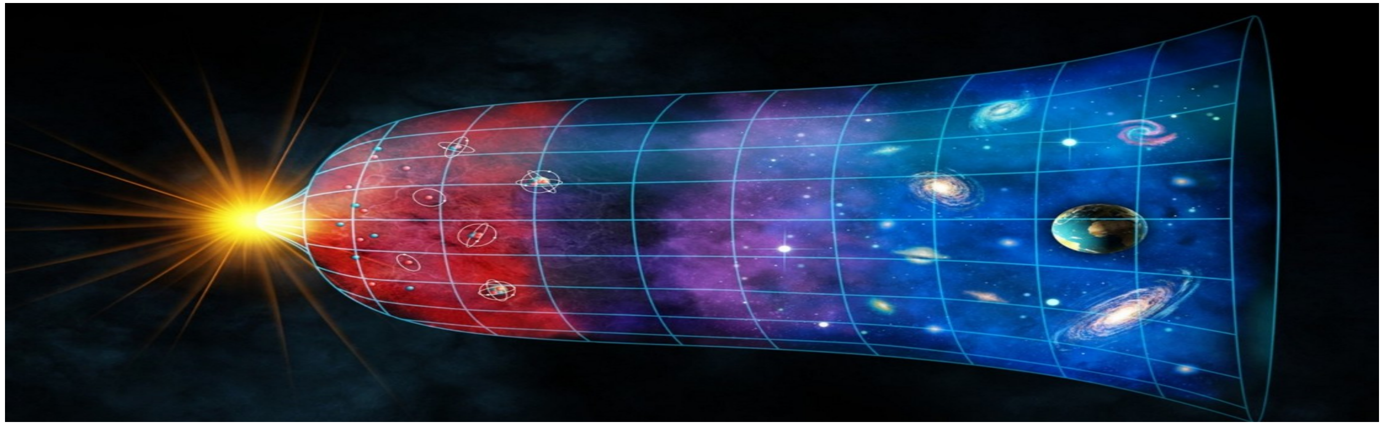
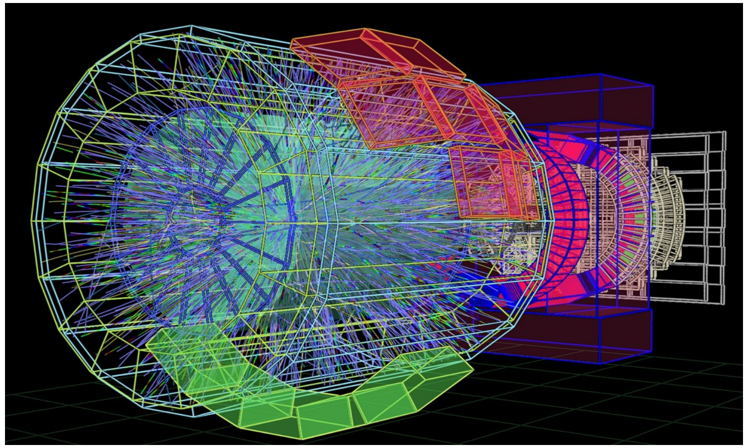


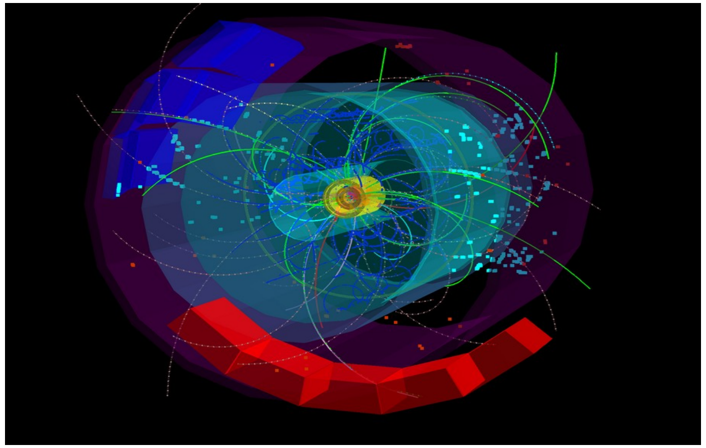
Which one is the "closest" to the early Universe?

A) PbPb collision



C) Abstain (now)

B) pp collision



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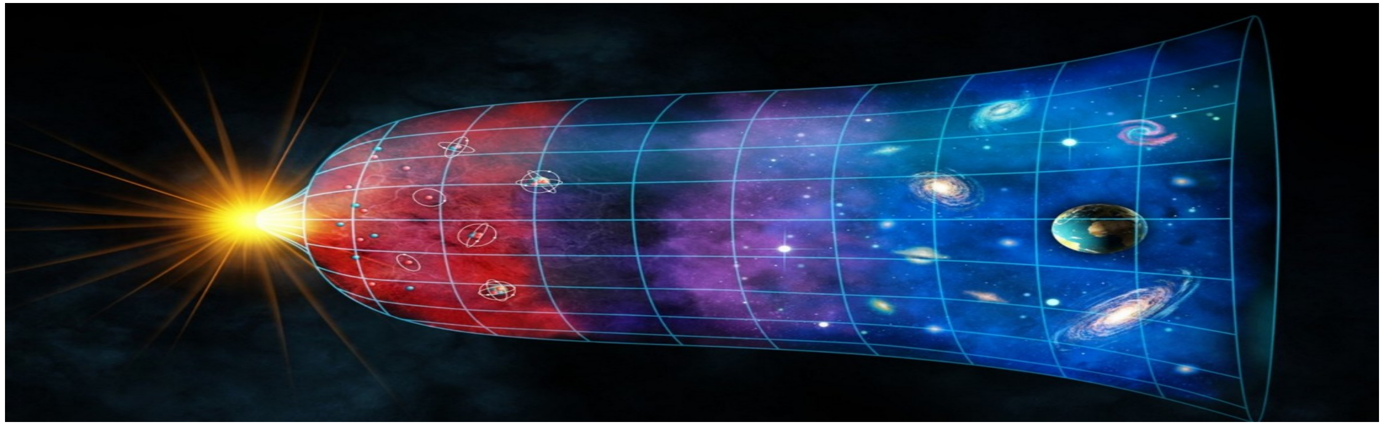

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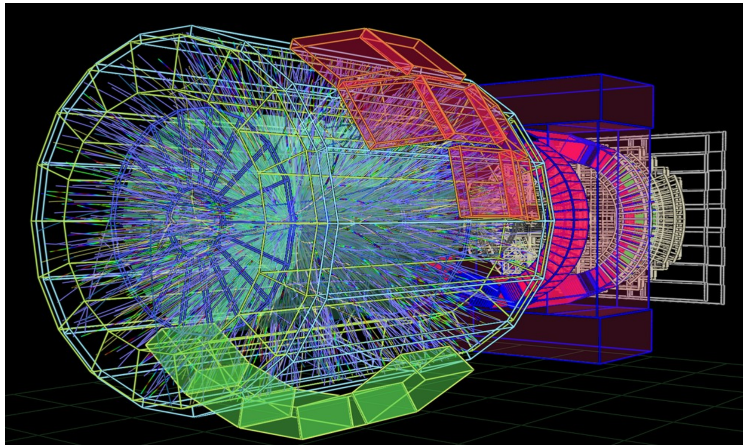
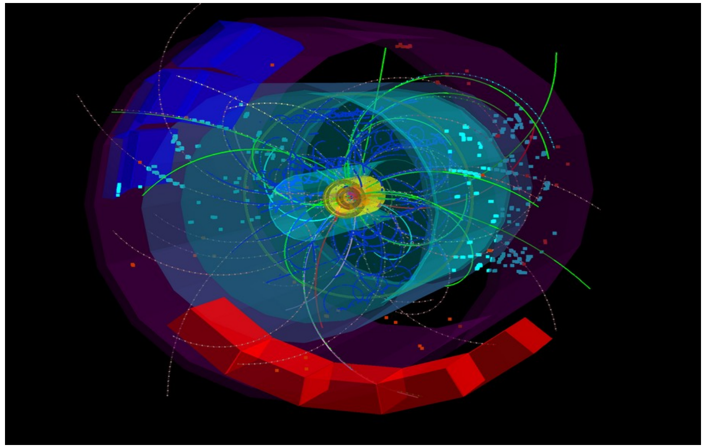


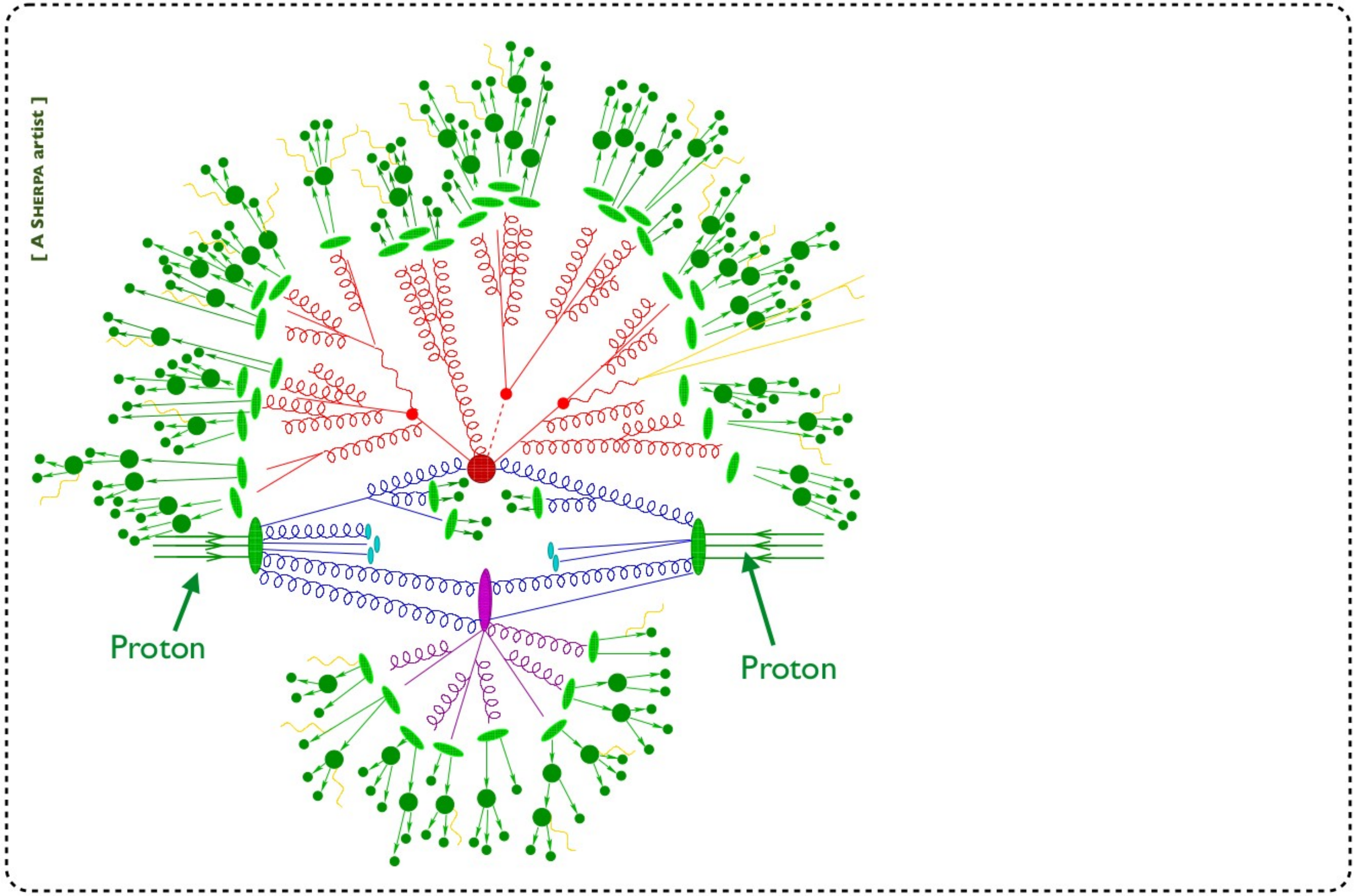
C) Cup of coffee

B) pp collision



UE

Anatomy of a proton-proton event



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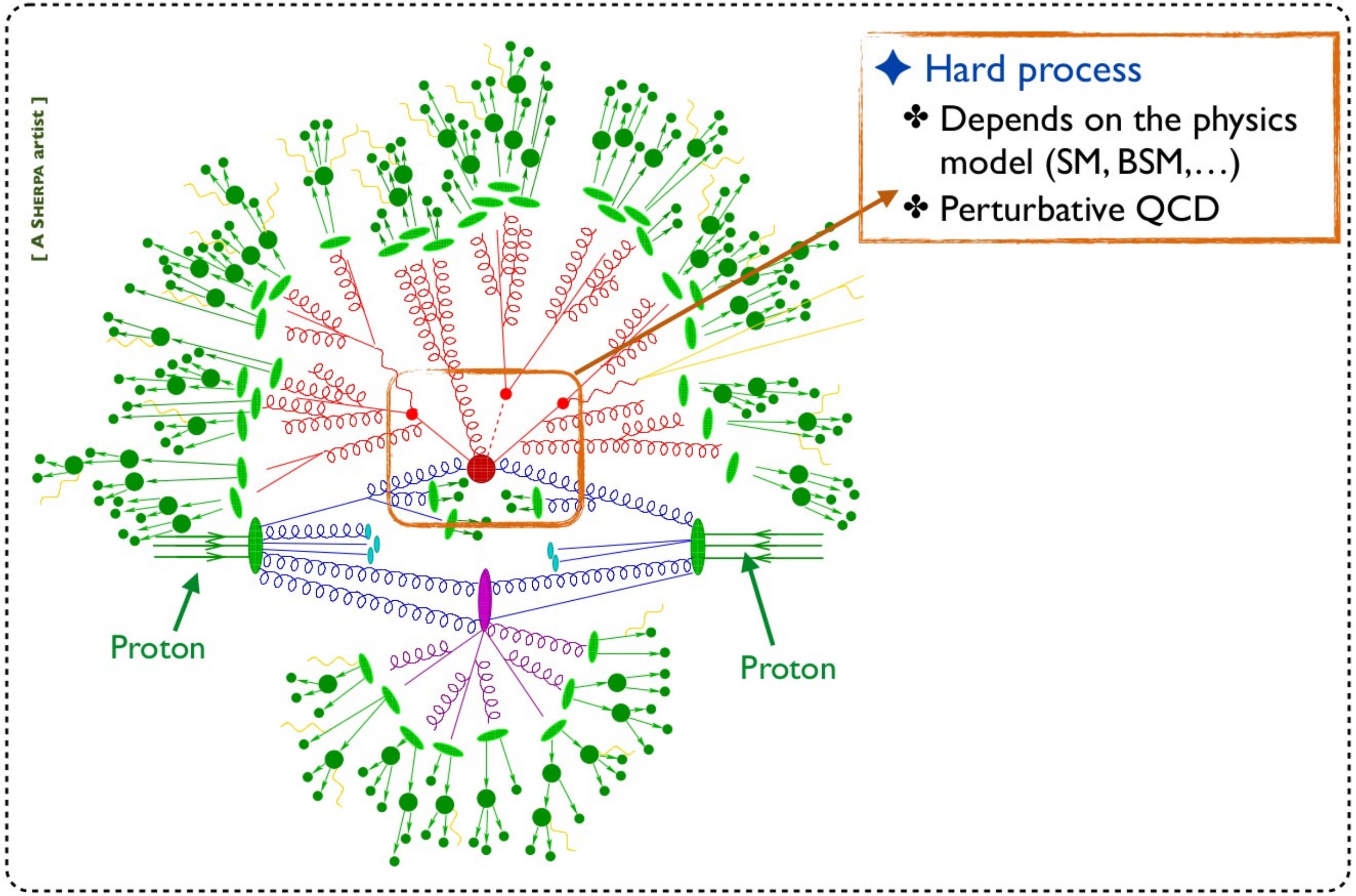

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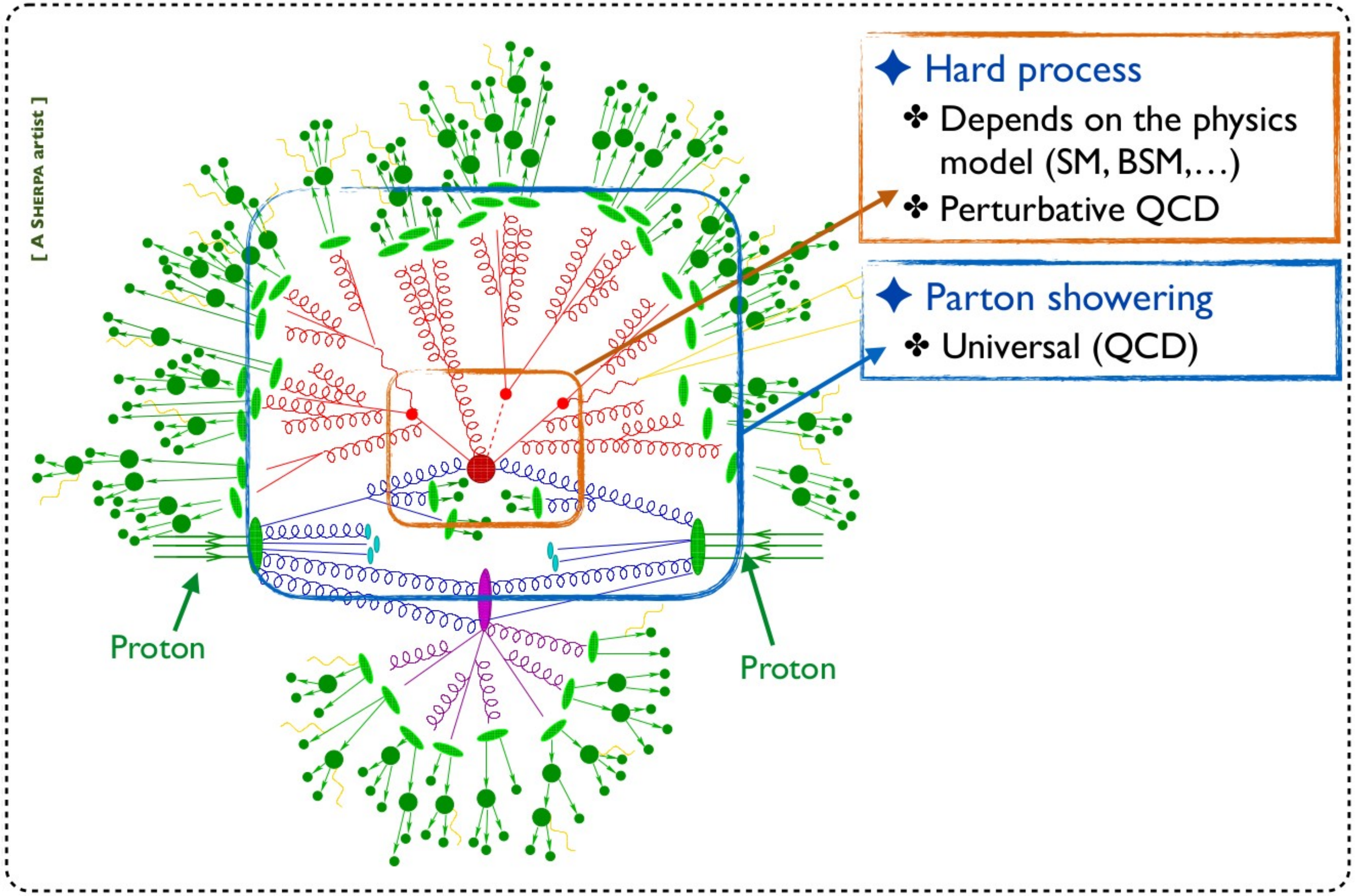

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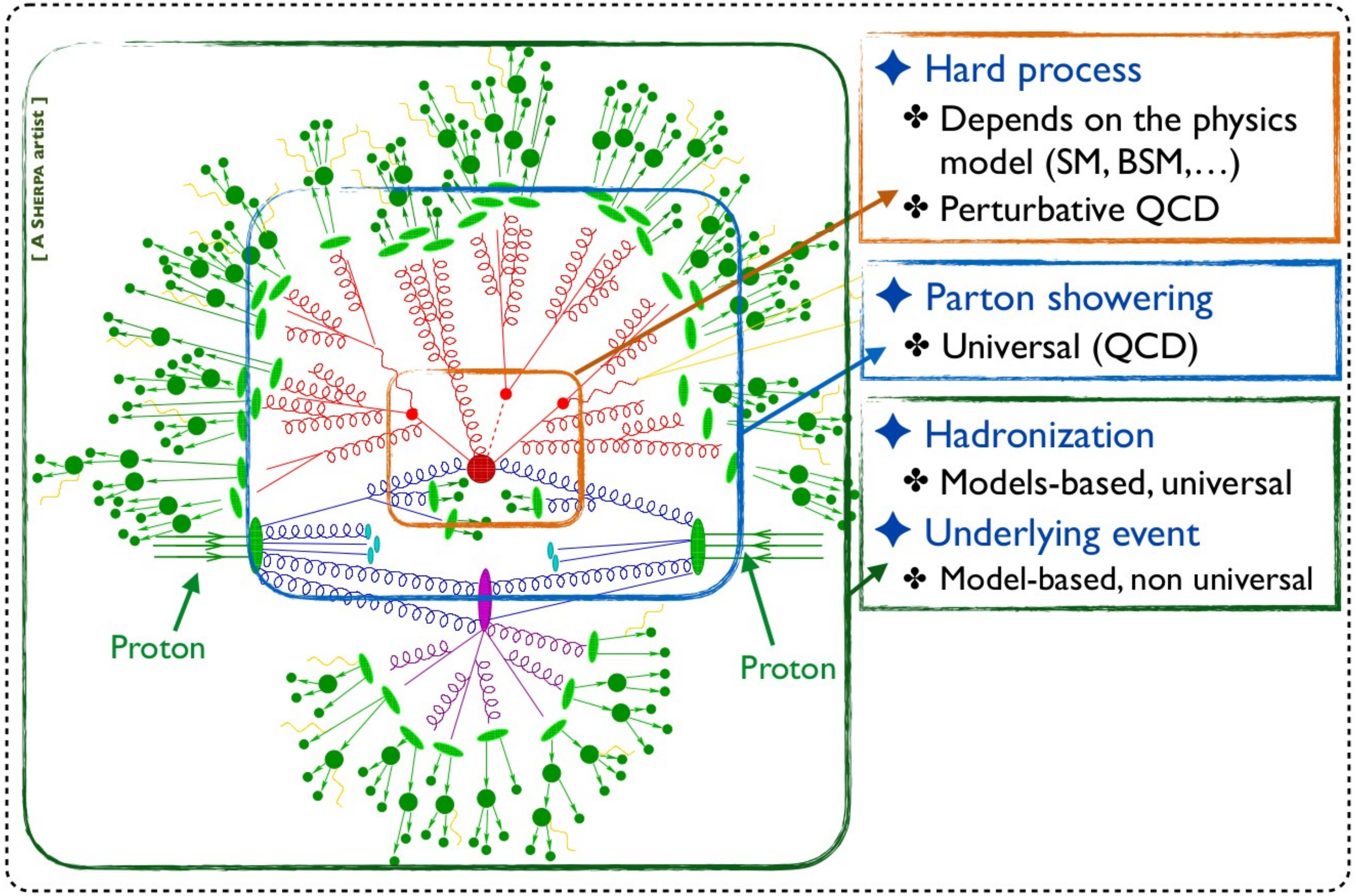
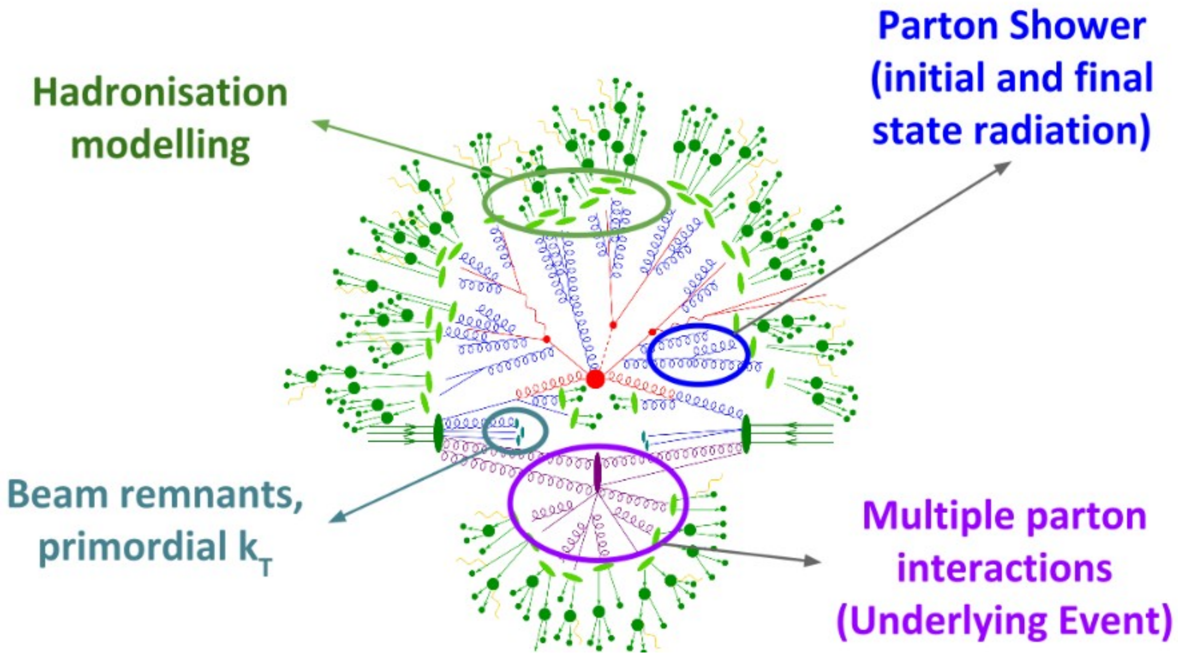


So what Uderlying Event is?

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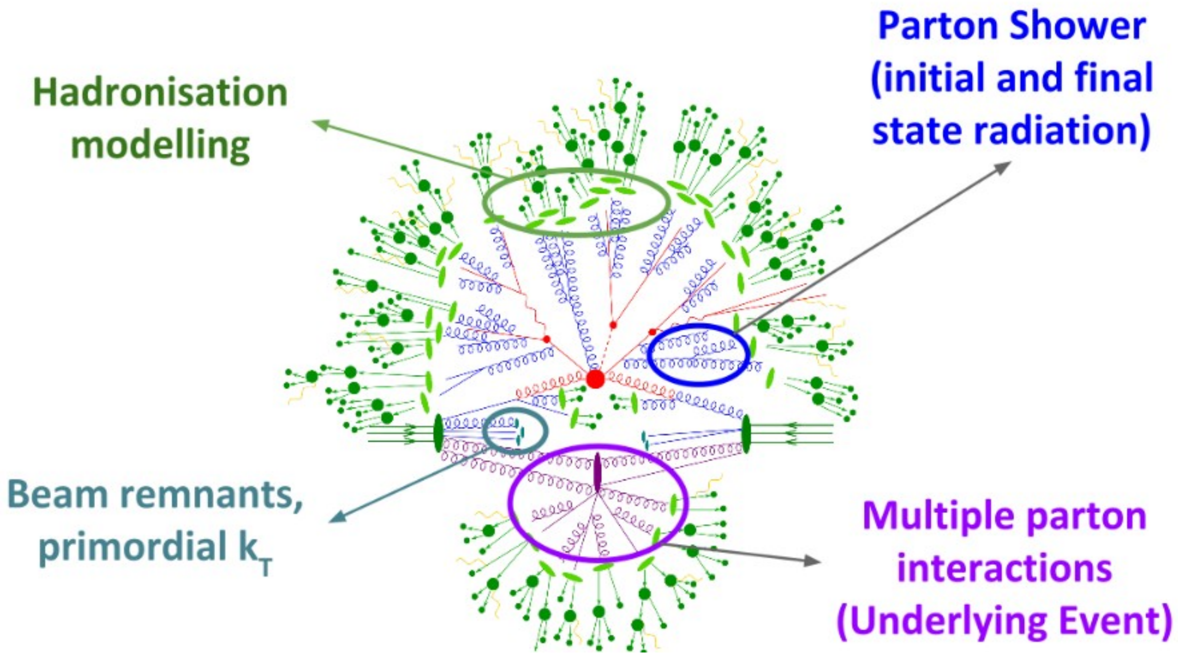
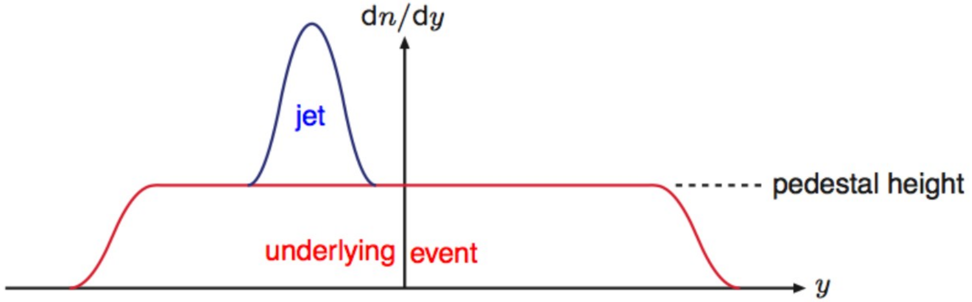
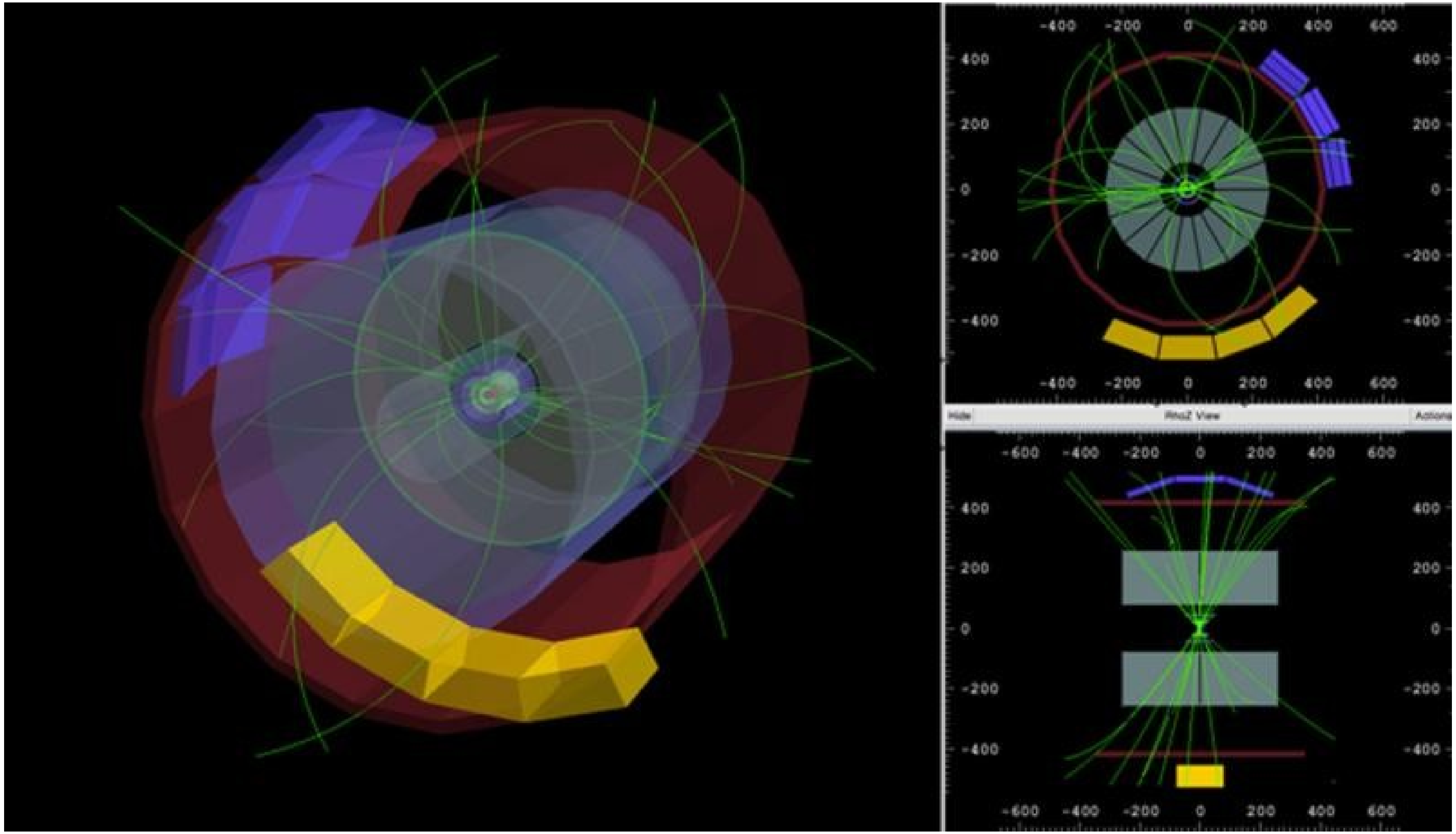
- **Experimental point**
  - Pedestal-like effects
    - → Activity in the event over MB
    - → Beam remnants (pile up)
    - → Trigger bias (jet criterion)





Earlier studies, motivation

Geometrical structure of an event



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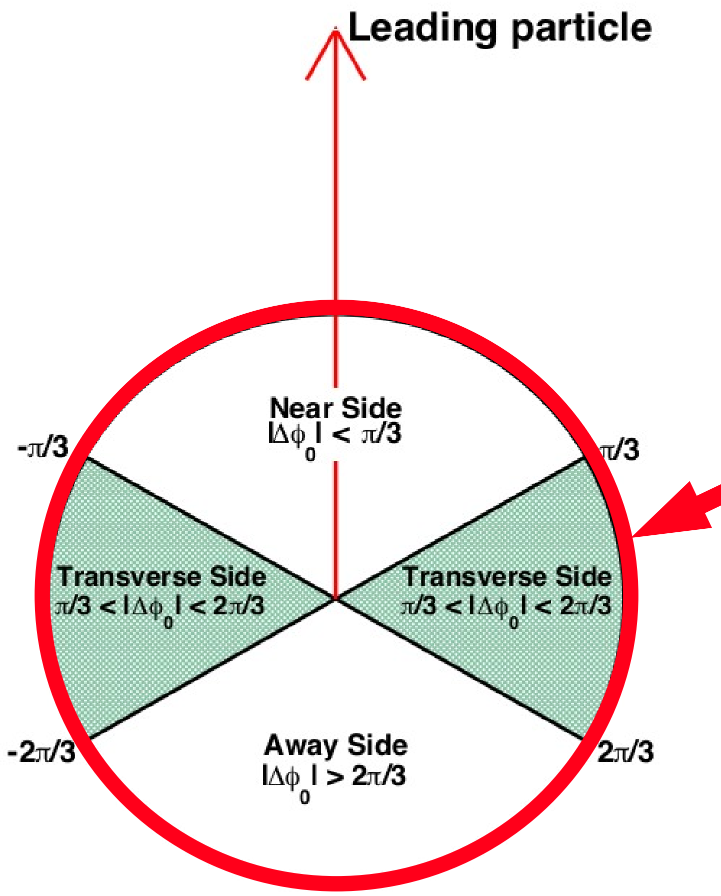
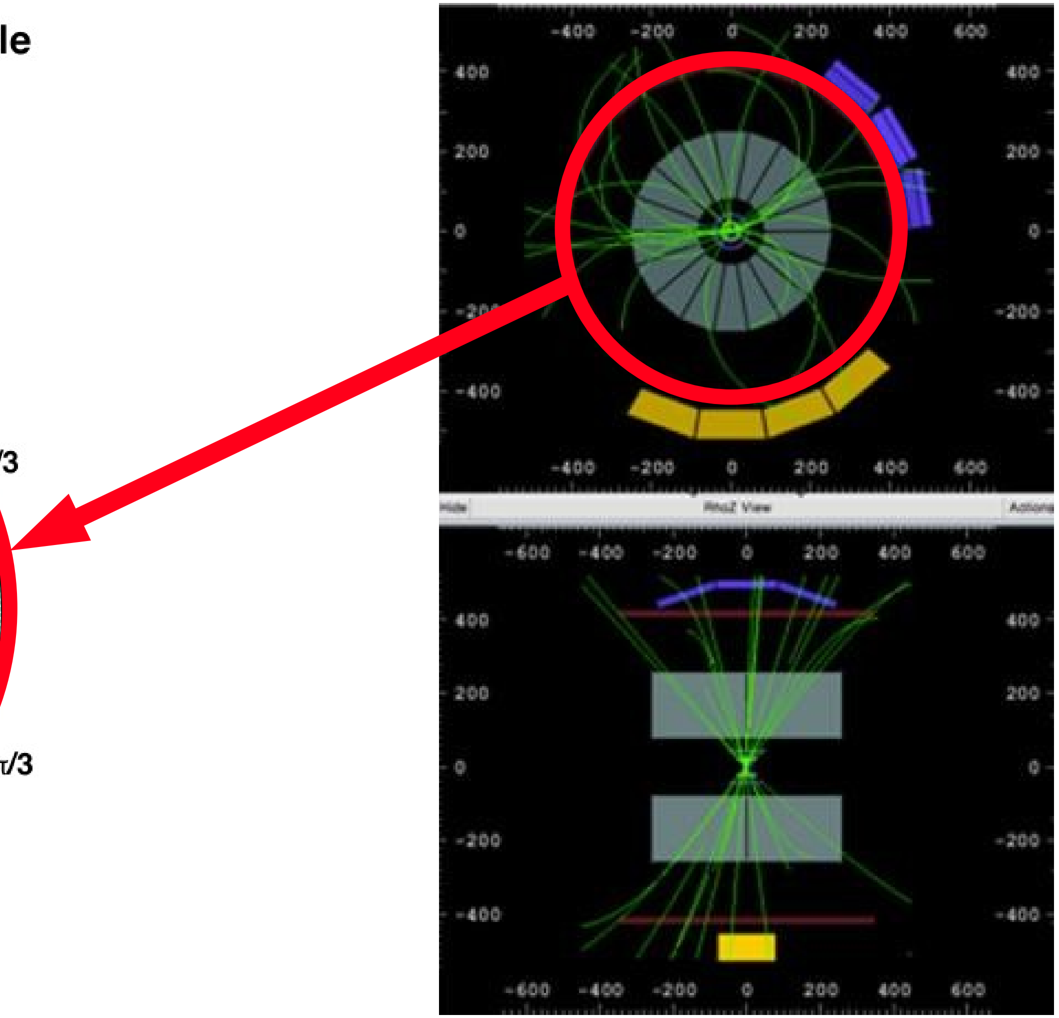
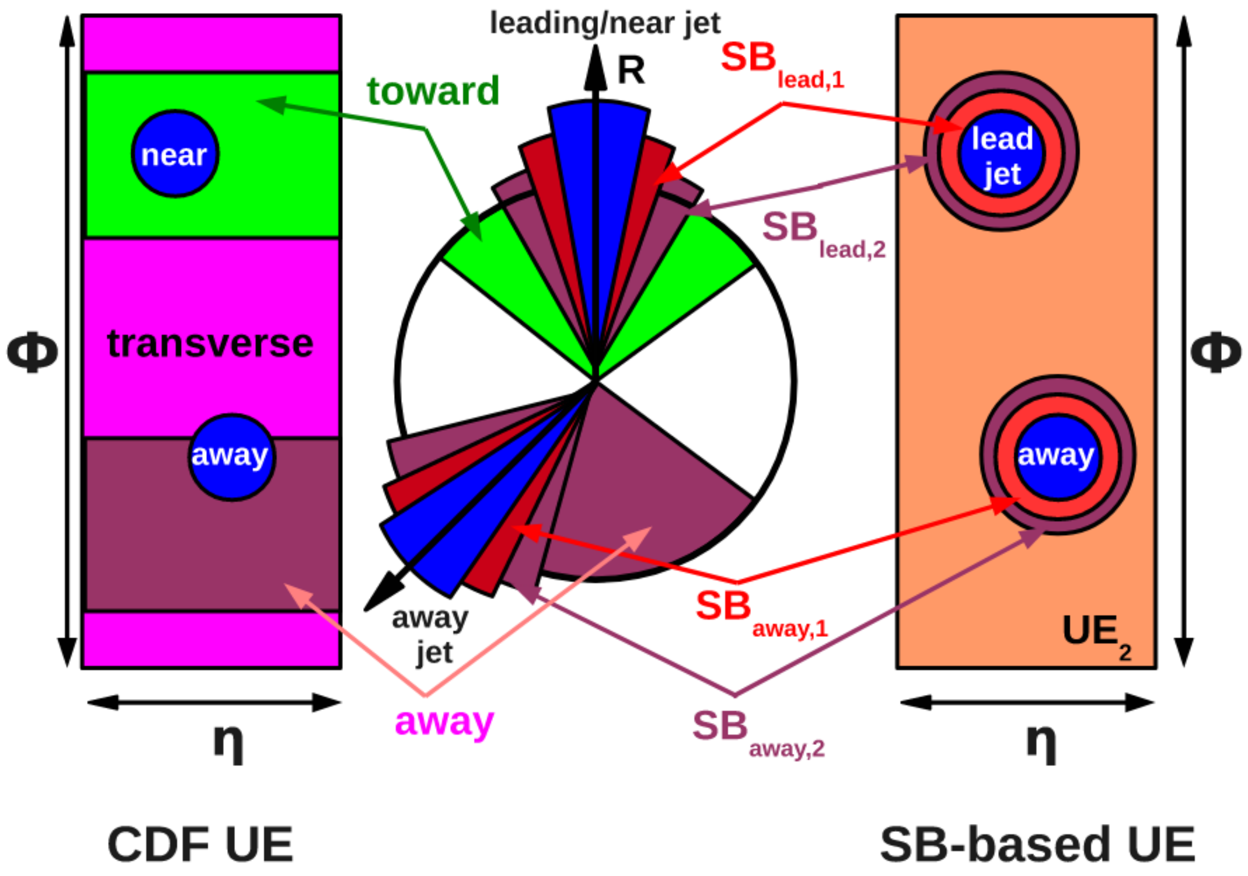


Standard CDF definition



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

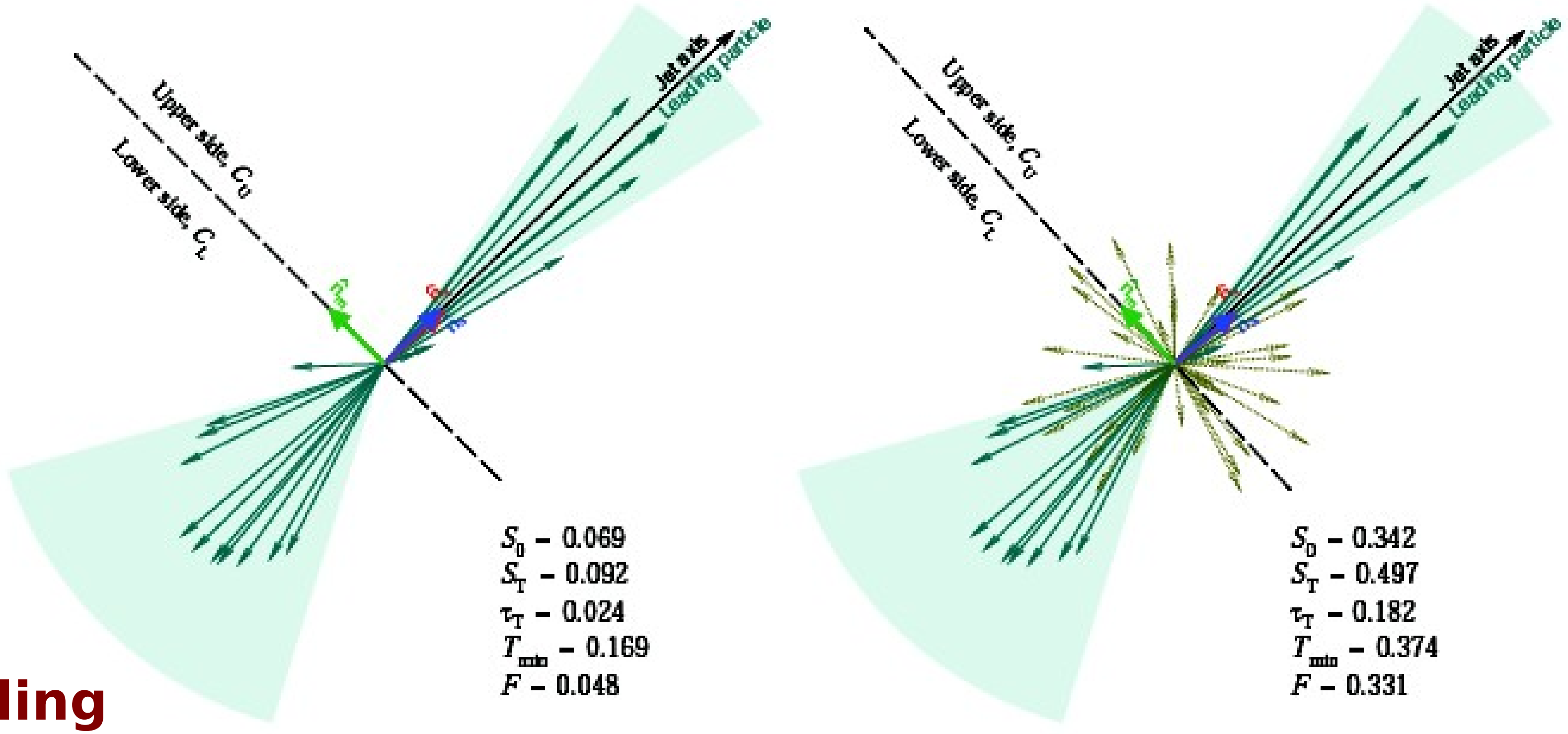
How to quantify & compare events?

- **Transverse spherocity:**

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

- **Thrust:**

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



→ **NO need for jet finding**

→ **Momentum & geometry infos**

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

How to quantify & compare events?

- **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)

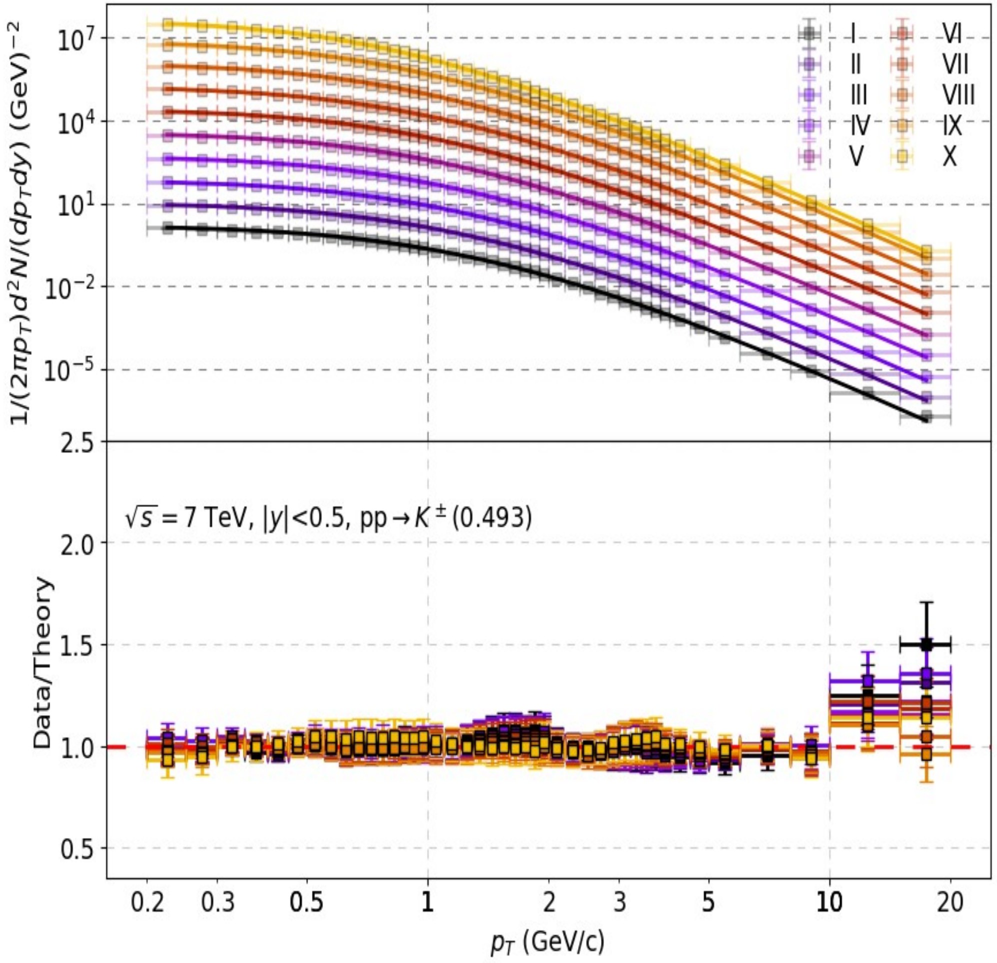
$$\left.\frac{\mathrm{dN_{ch}}}{\mathrm{dy}}\right|_{y=0} = 2\pi A T_s \left[\frac{(2-q)m^2+2mT_s+2T_s^2}{(2-q)(3-2q)}\right] \times \left[1+\frac{q-1}{T_s}m\right]^{-\frac{1}{q-1}}$$

  - 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 events?

- **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

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

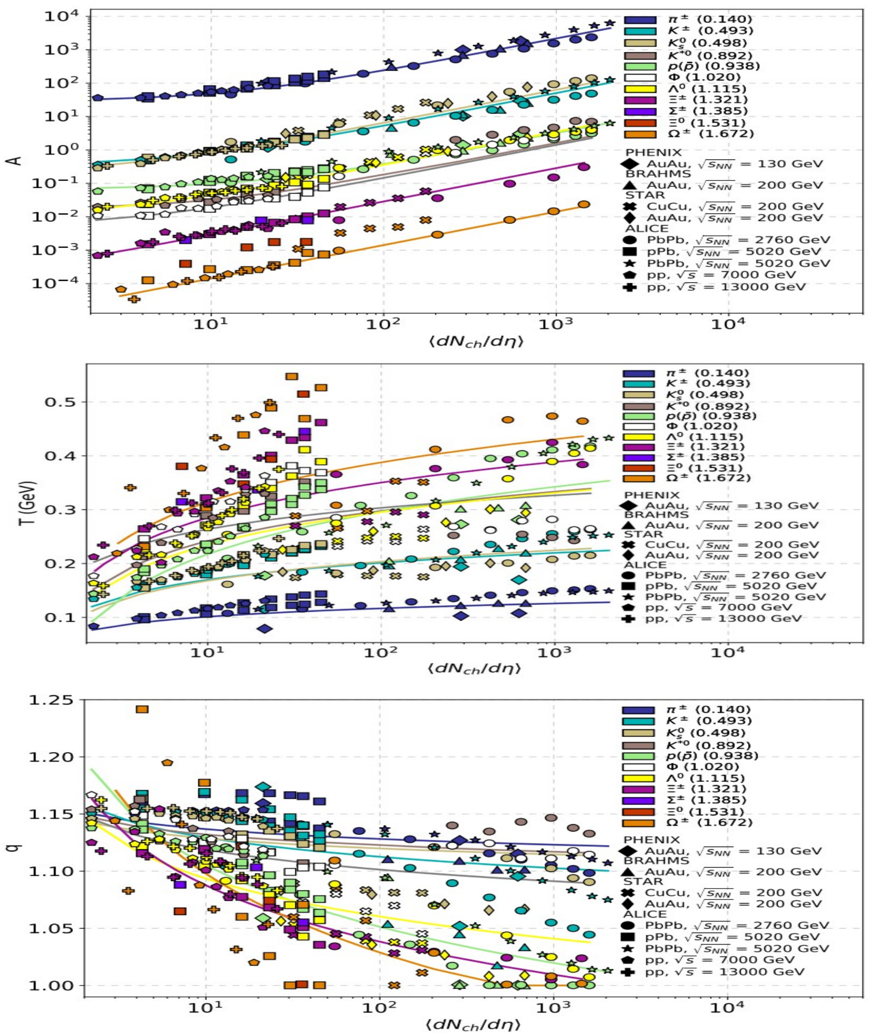
$$\mathrm{T}(\sqrt{s_{NN}}, \langle N_{ch}/\eta \rangle, m) = T_0 + T_1 \ln \frac{\sqrt{s_{NN}}}{m} + T_2 \ln\ln \langle N_{ch}/\eta \rangle,$$

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

  - Details:

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

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



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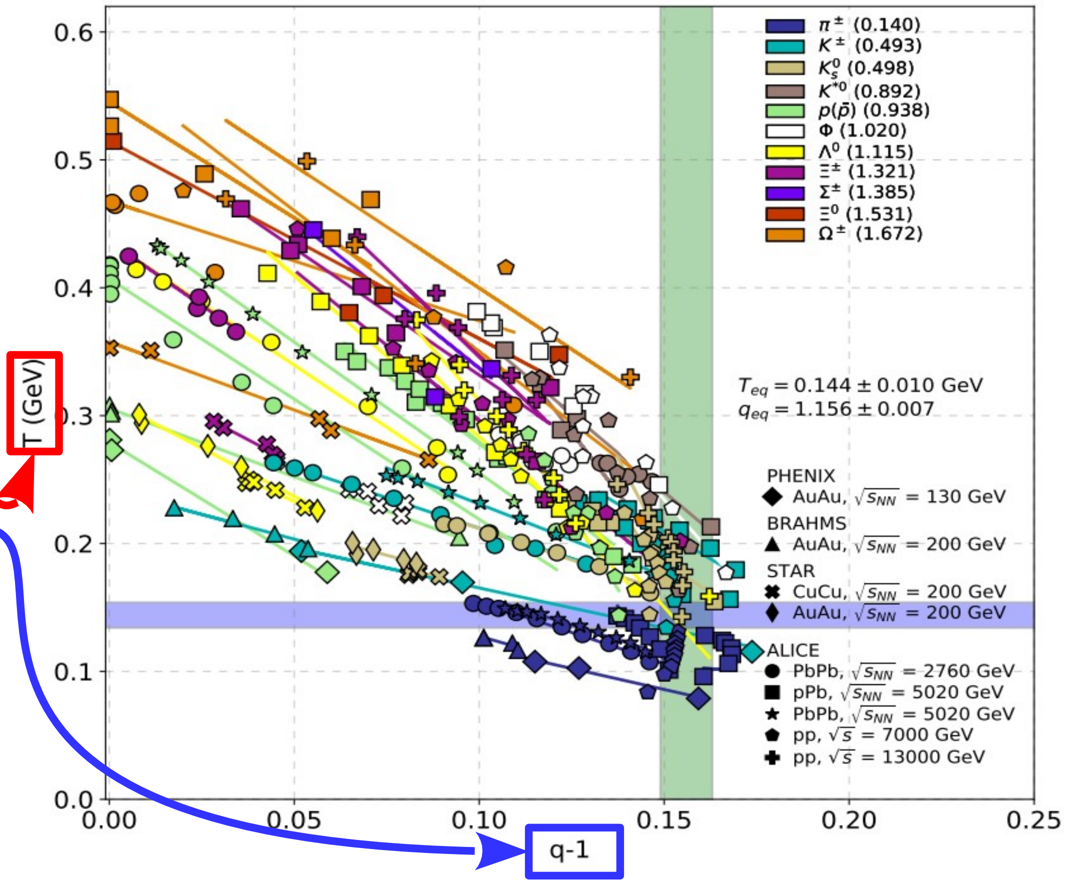


- **Thermodynamical consistency**

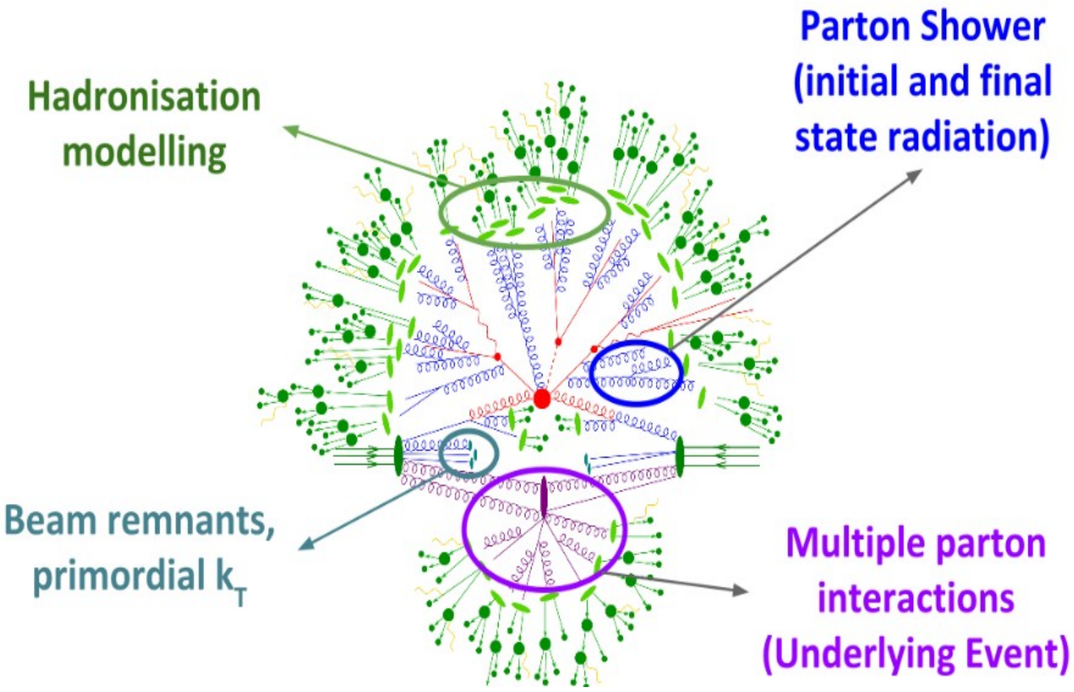
$$\mathrm{P} = \mathrm{g} \int \frac{d^3p}{(2\pi)^3} T f, \quad \mathrm{N} = \mathrm{nV} = \mathrm{gV} \int \frac{d^3p}{(2\pi)^3} f^q,$$

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

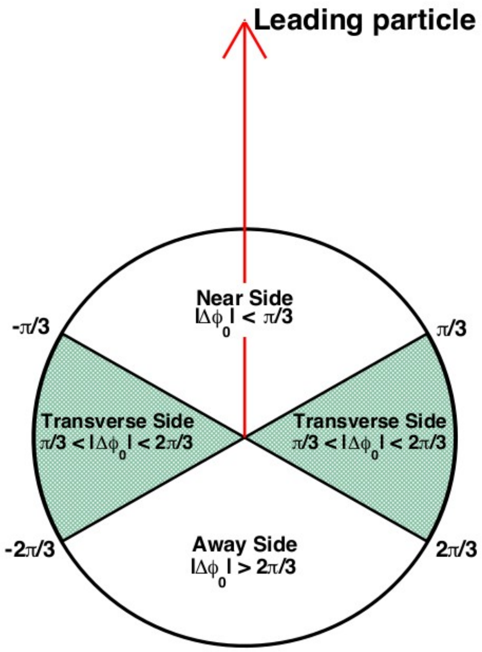
New development to understand UE

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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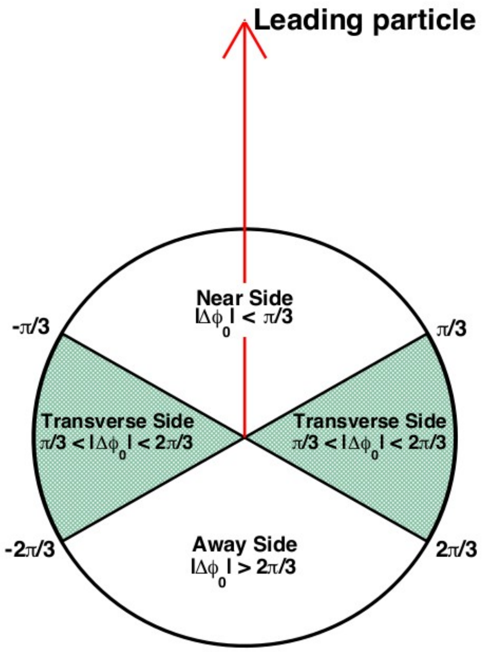

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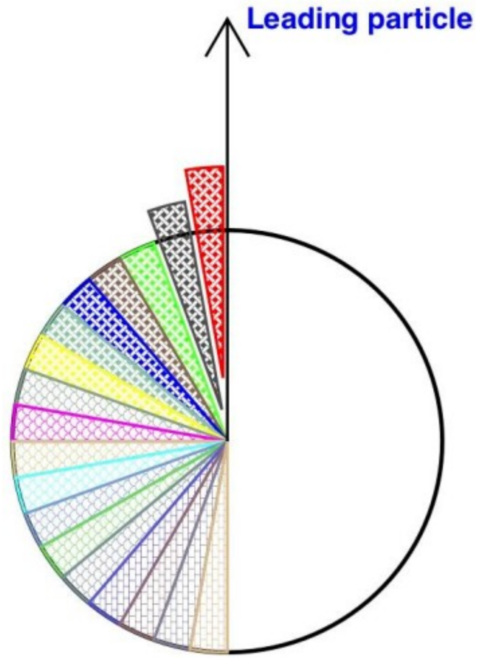

Sliding angle, cake slices

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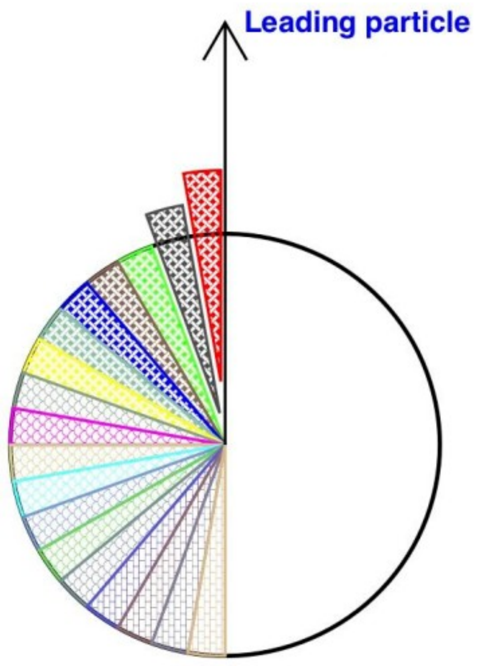
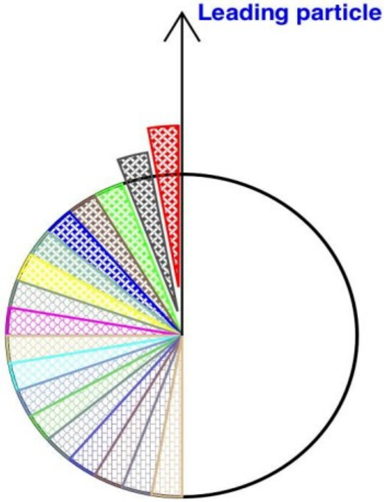
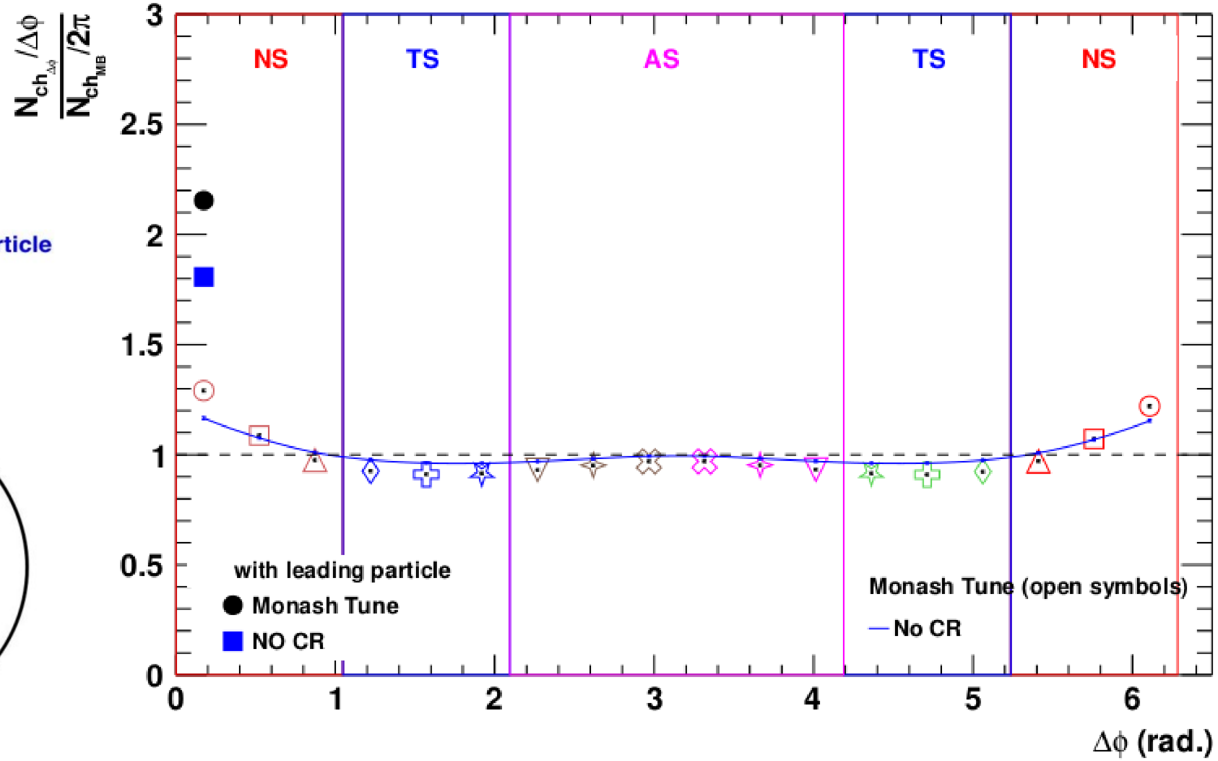


- We make slices of the Δφ of size 20◦. In this case, the results for the first bin 0 to 20◦. are reported in two ways: including and excluding the leading particle in the result. Case II is a tool for exploring the geometrical structure of the Underlying Event.

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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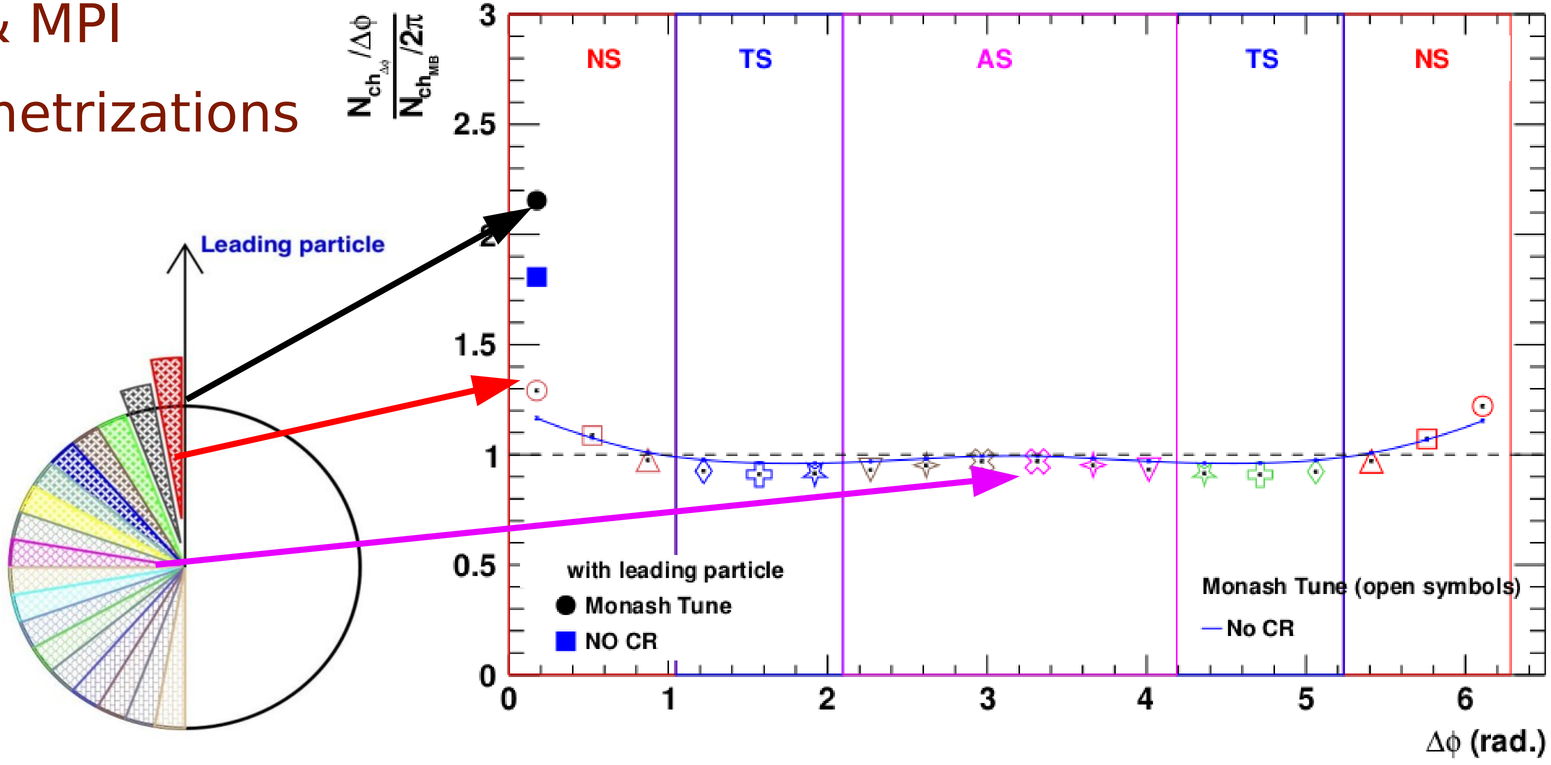

The p_T spectrum

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  - Low p_T is constant (T)
  - High p_T varies (q)
  - NS/AS are similar
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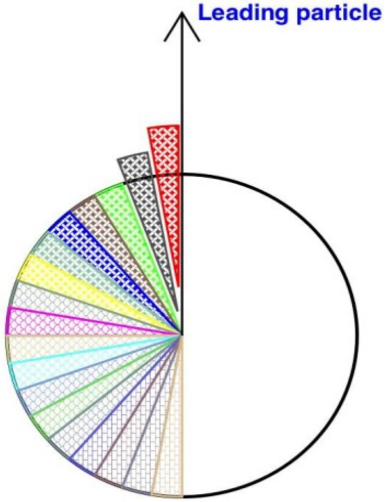

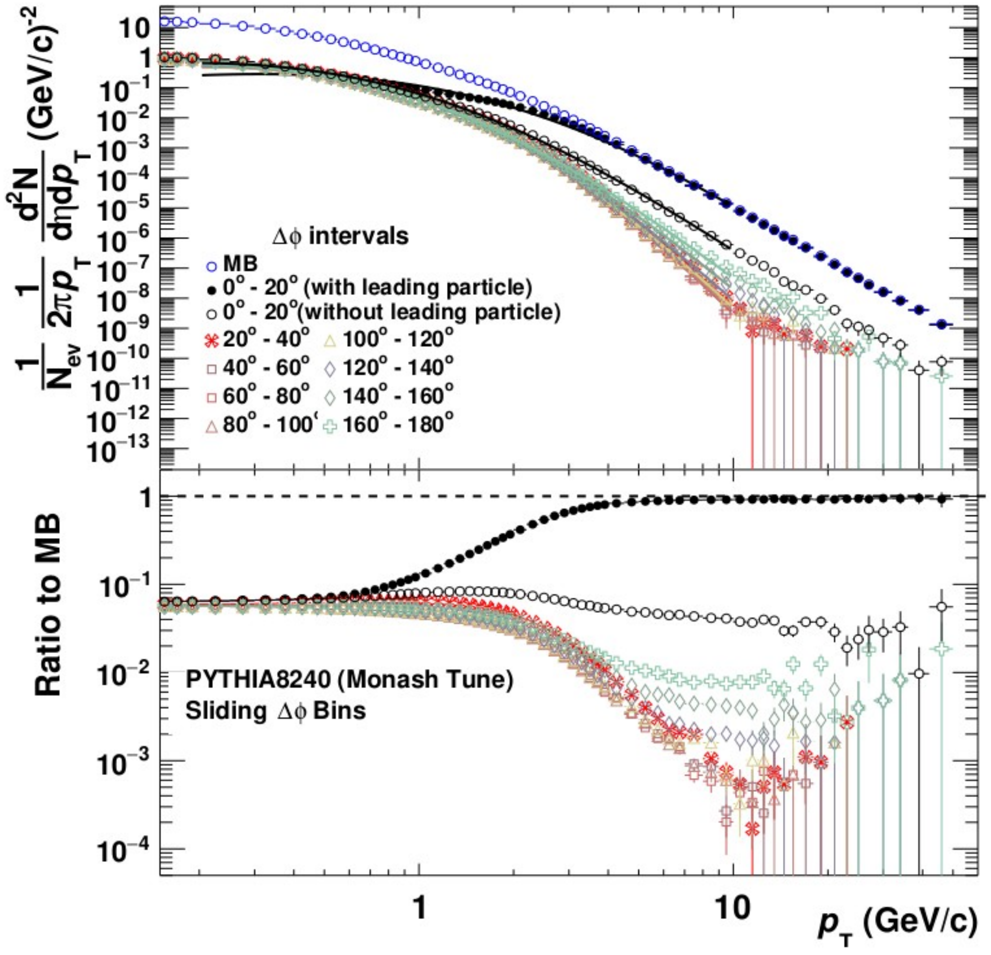

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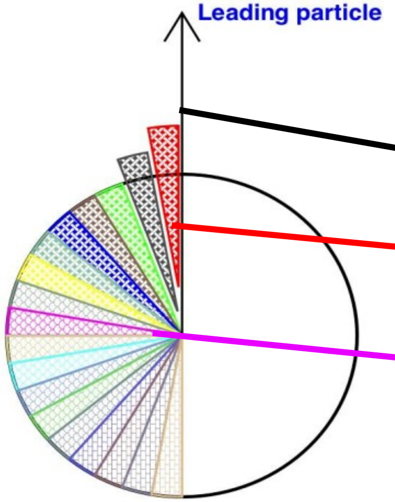
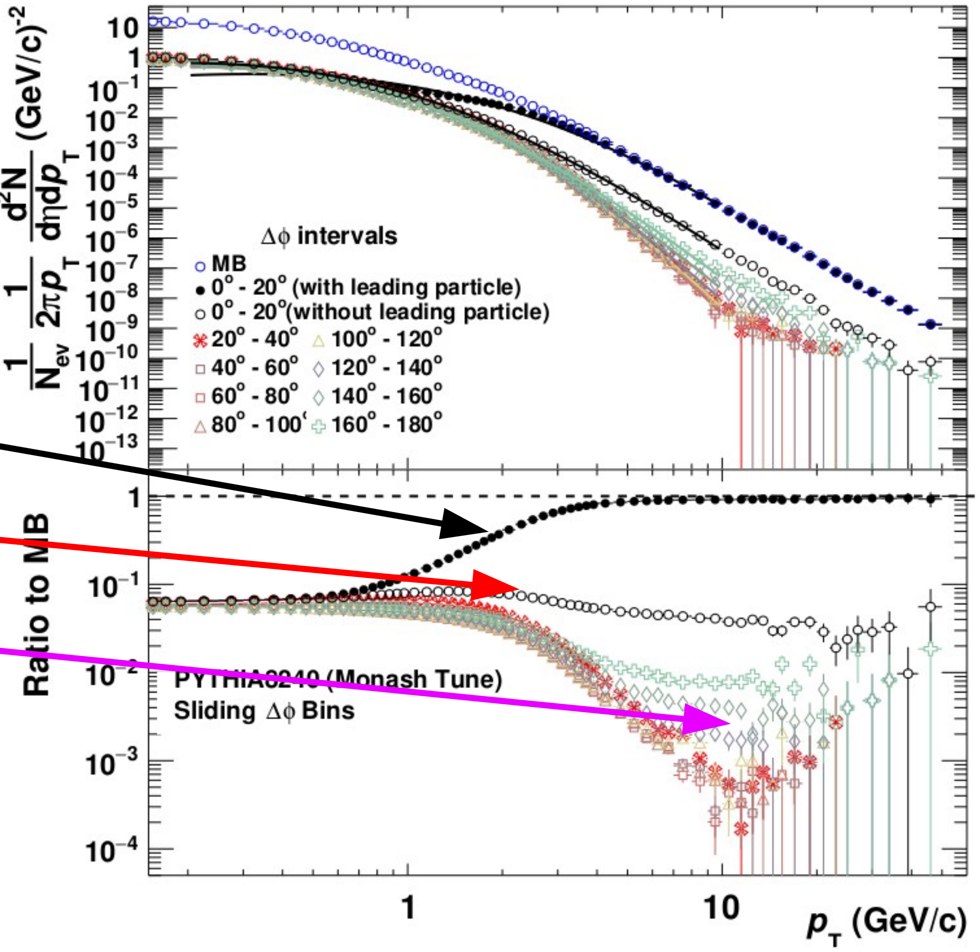
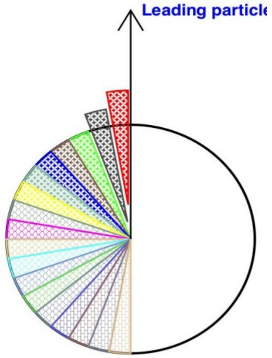
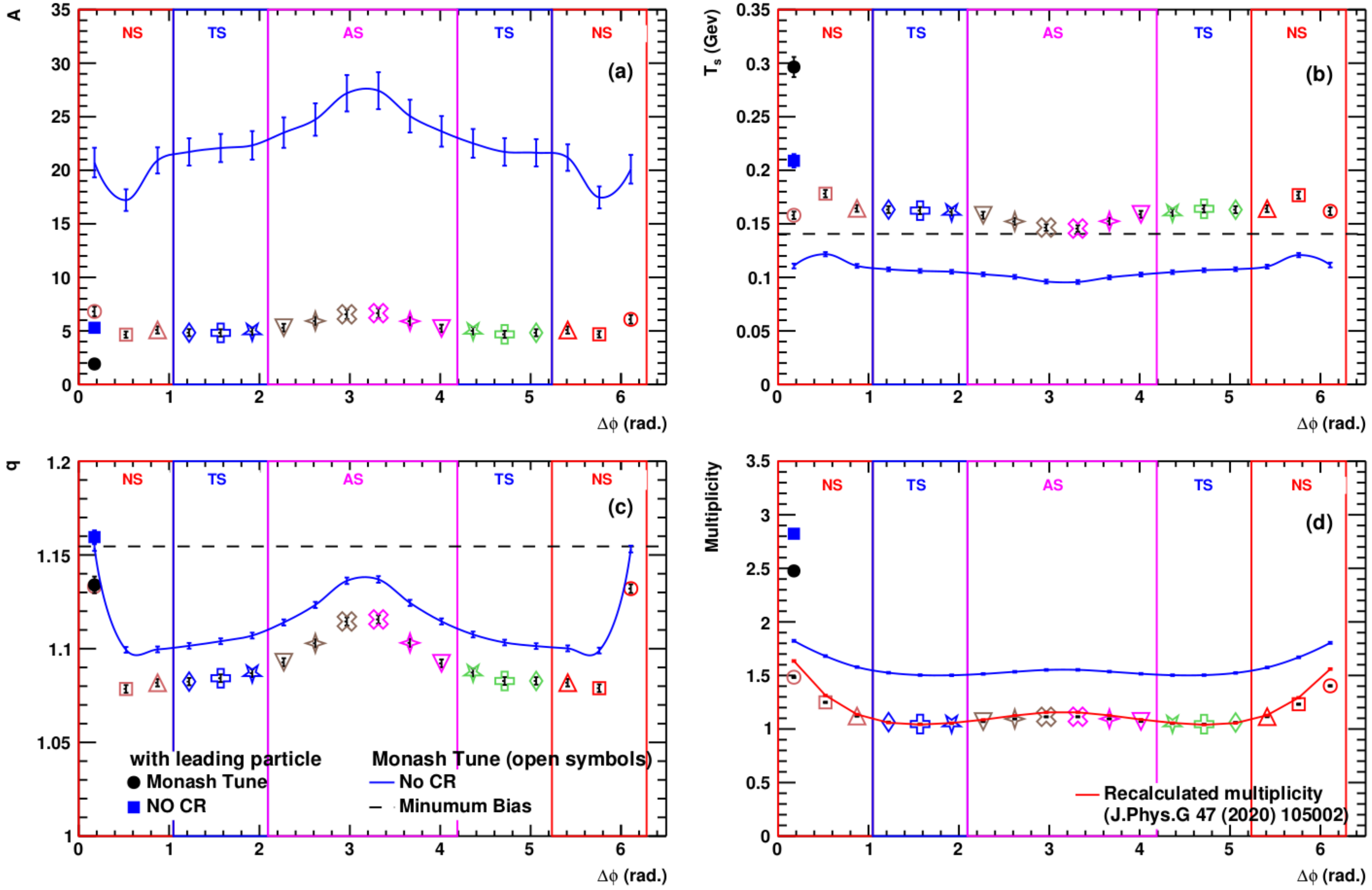




Tsallis fit parameters

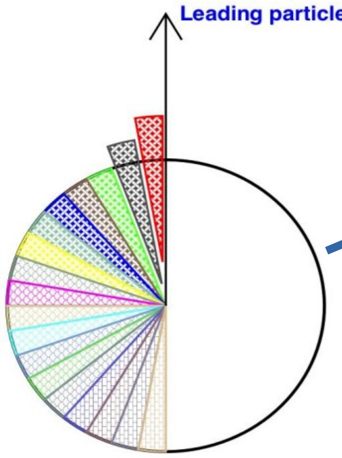
- **PYTHIA spectra with sliding angle**
  - PYTHIAs model UE: CR & MPI
  - Good fits with the parametrizations (red line)
  - NS → highest T
  - NS/AS → highest q
  - TS → constant q, T
  - Multiplicity ~ A

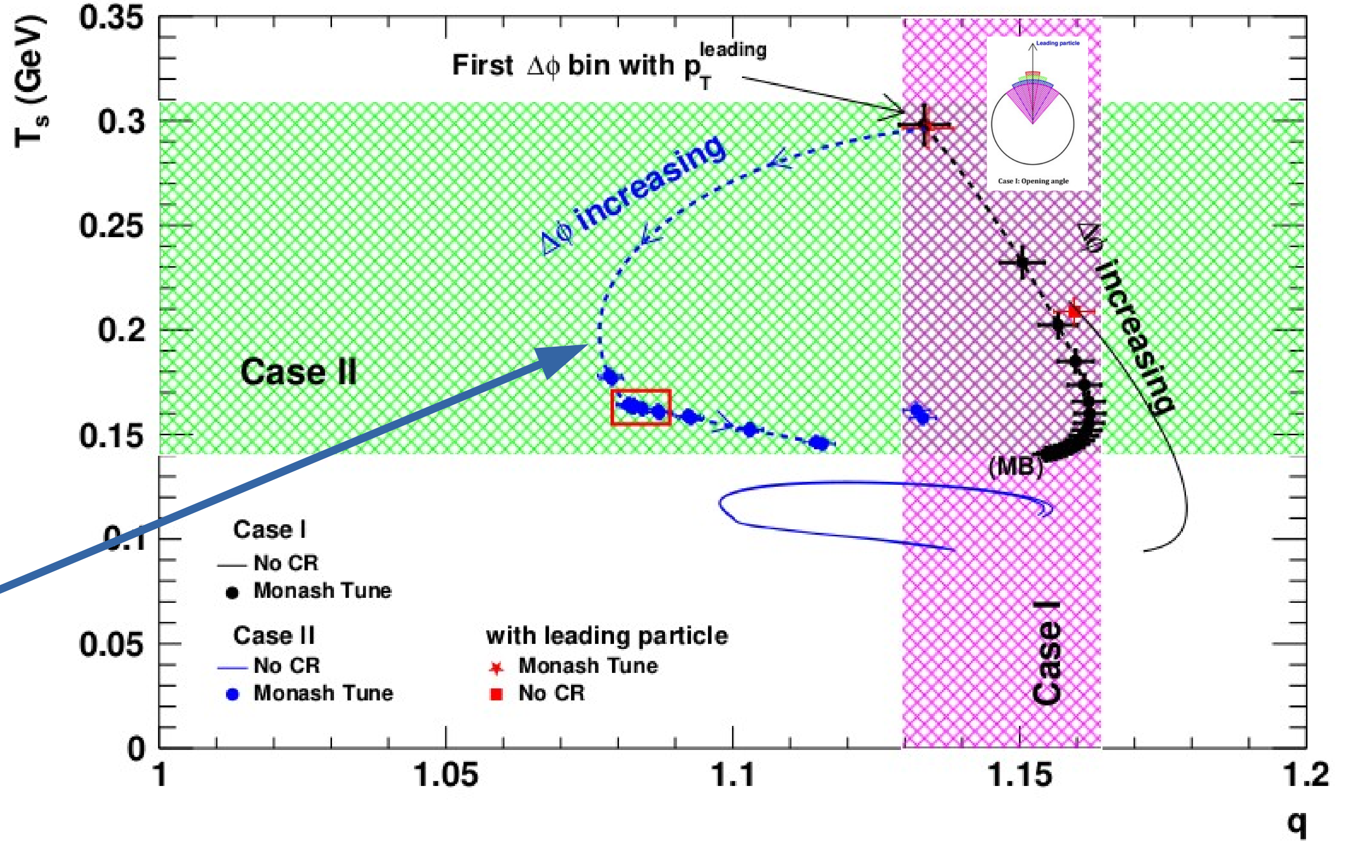




On the Tsallis-thermometer

- **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



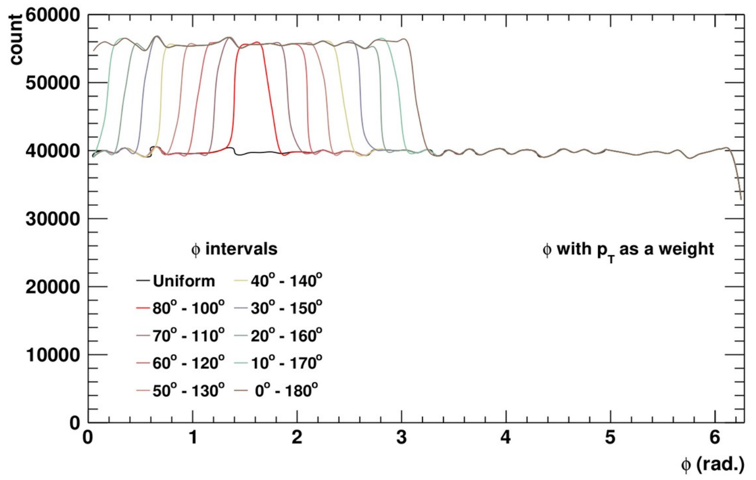


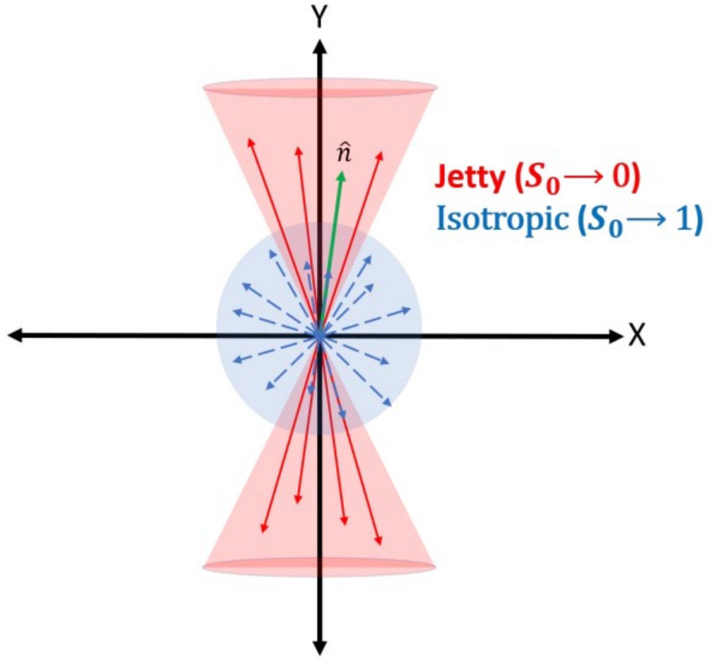
Cross-check with event shape variable

Event shape variable: spherocity

Simple 2-component model

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





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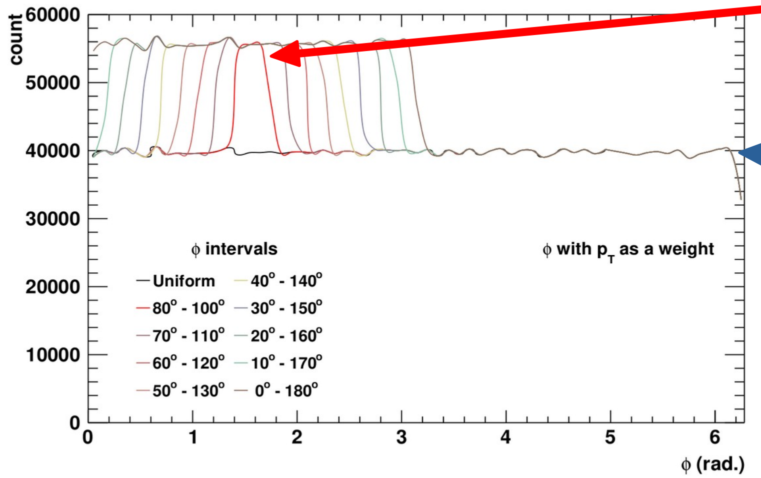

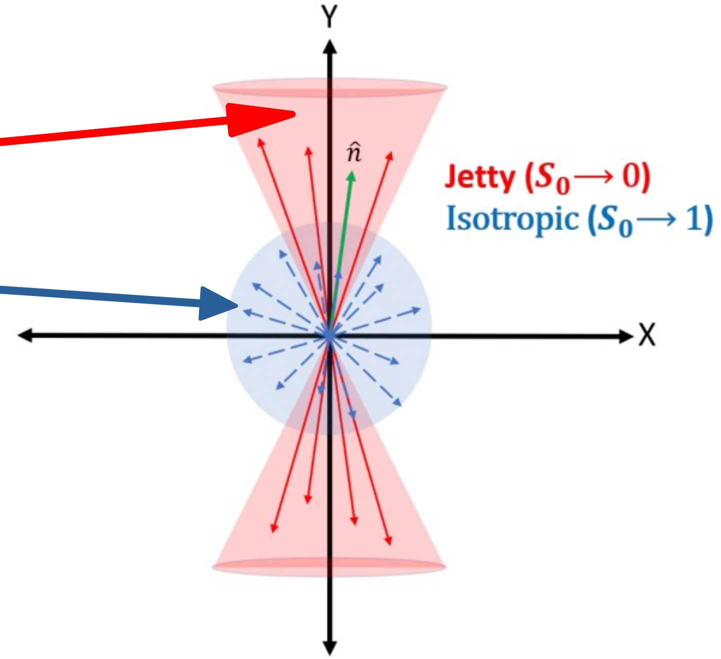

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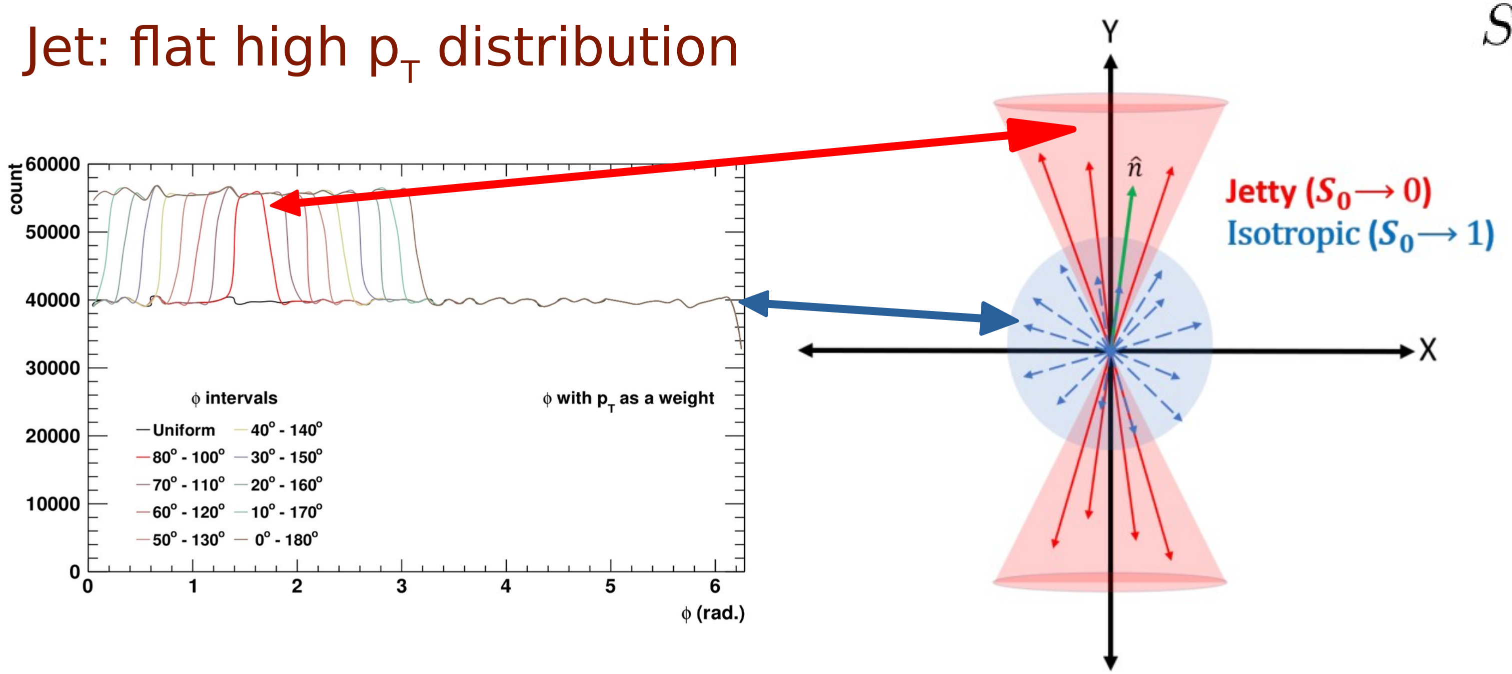
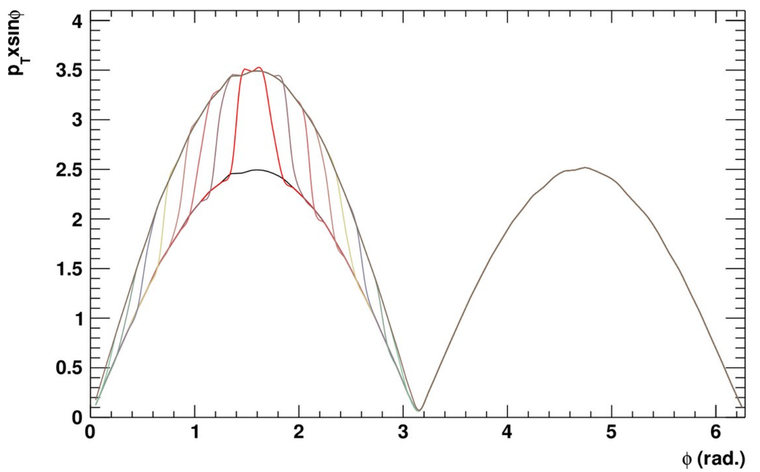


Spherosity definition

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



→ Event selection based on spherocity classes is available in ALICE

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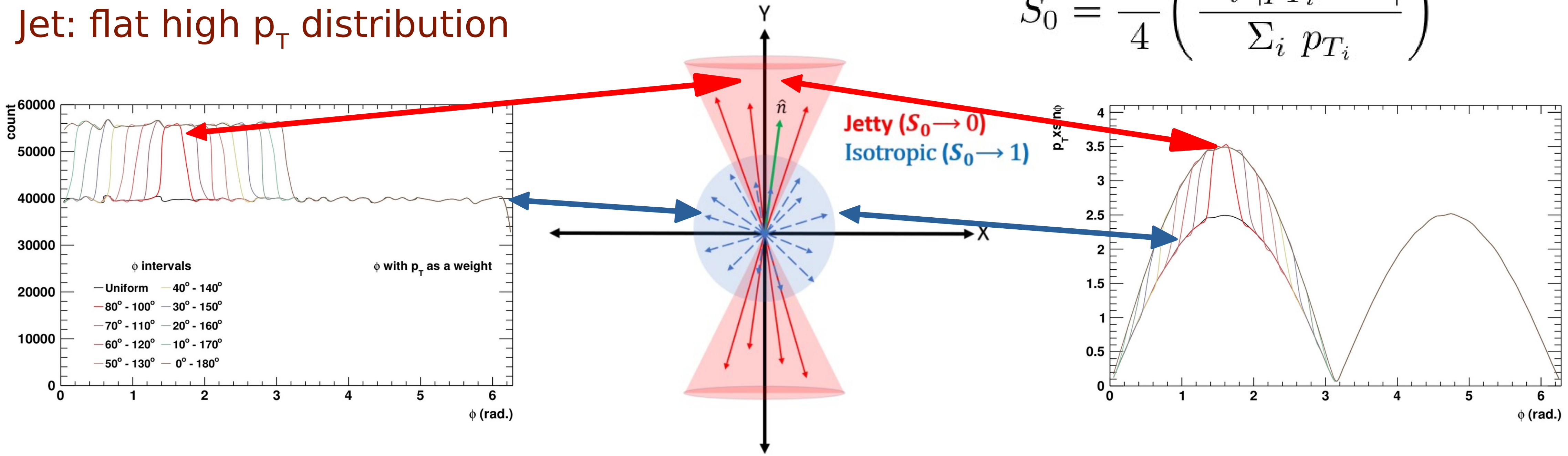

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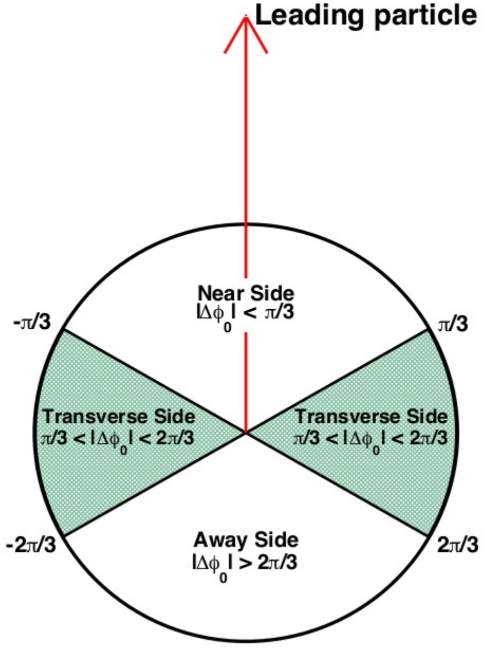
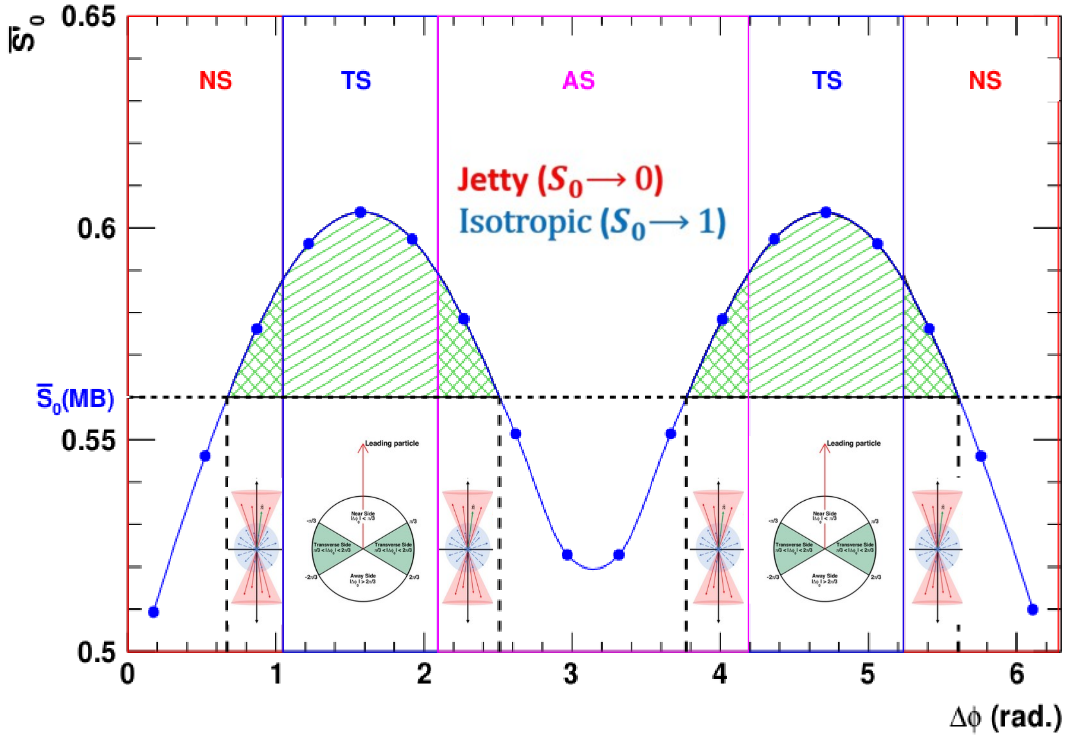
Spherocity vs. Tsallis termometer

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





→ CDF-based UE [40,140]

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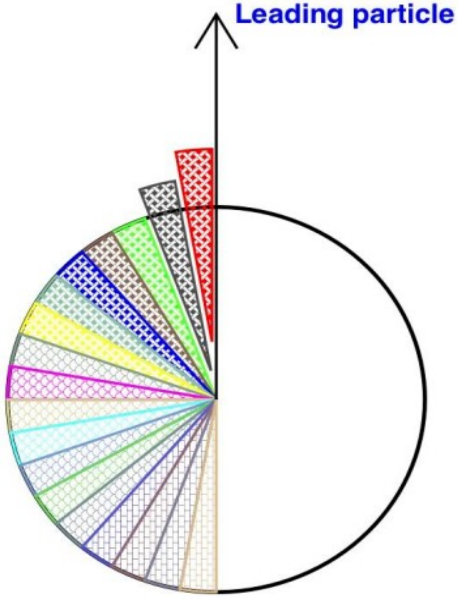
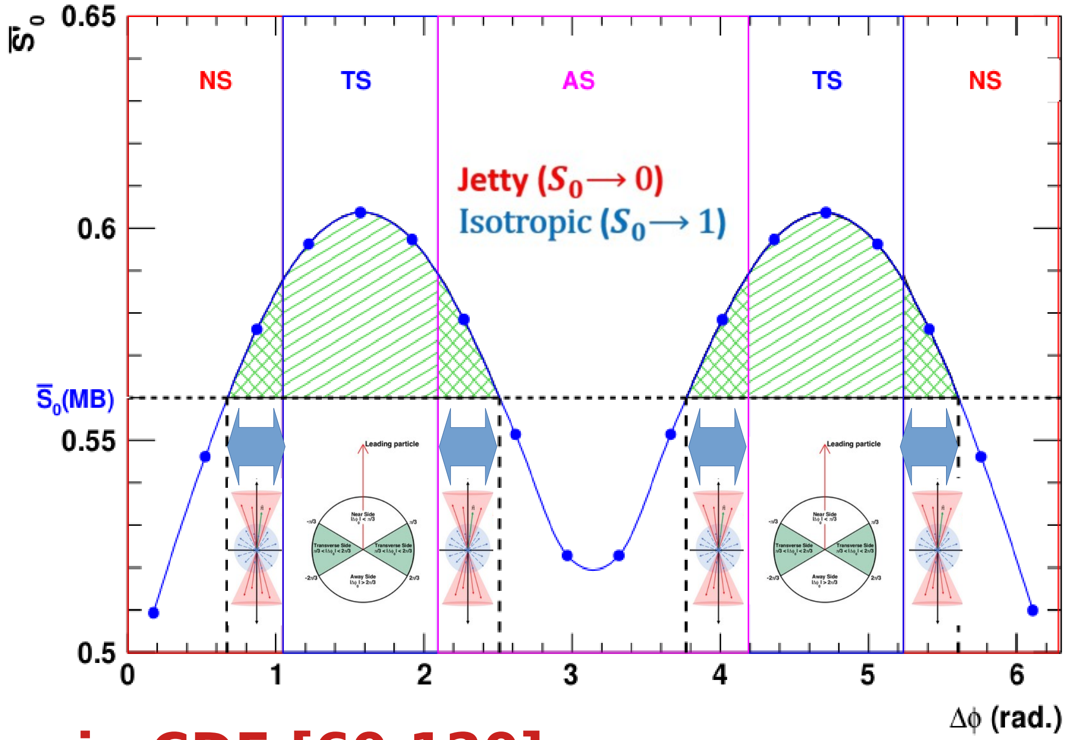
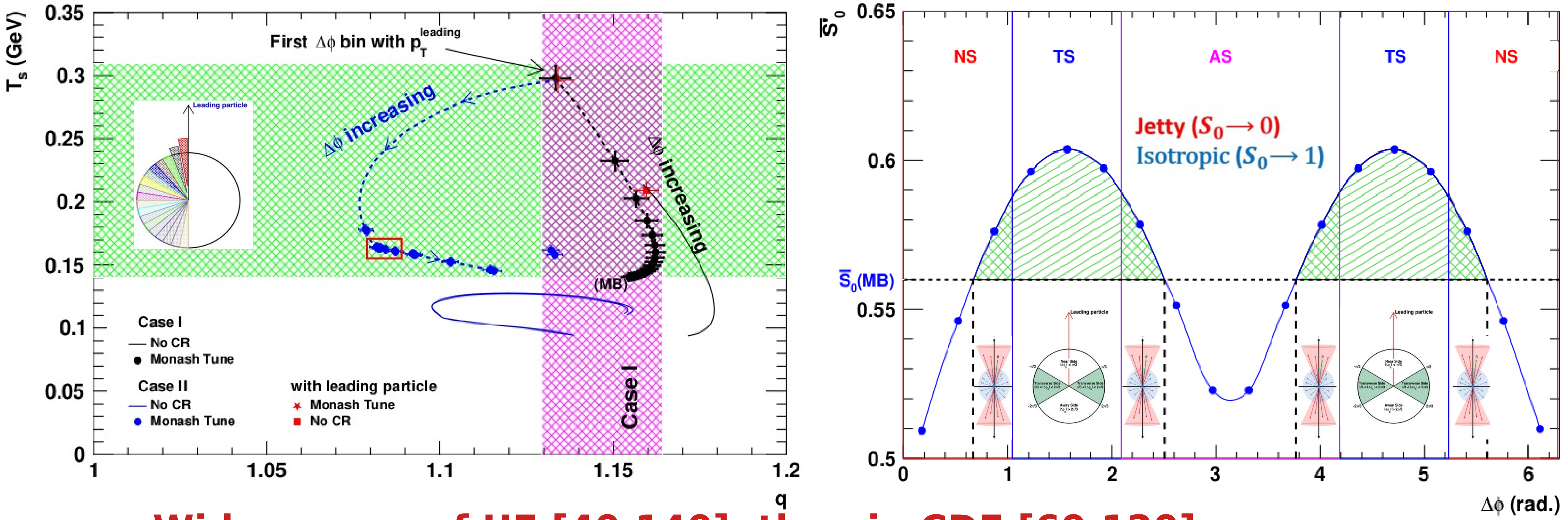




→ Wider range of UE [40,140], than in CDF [60,120]

Spherocity vs. Tsallis termometer

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



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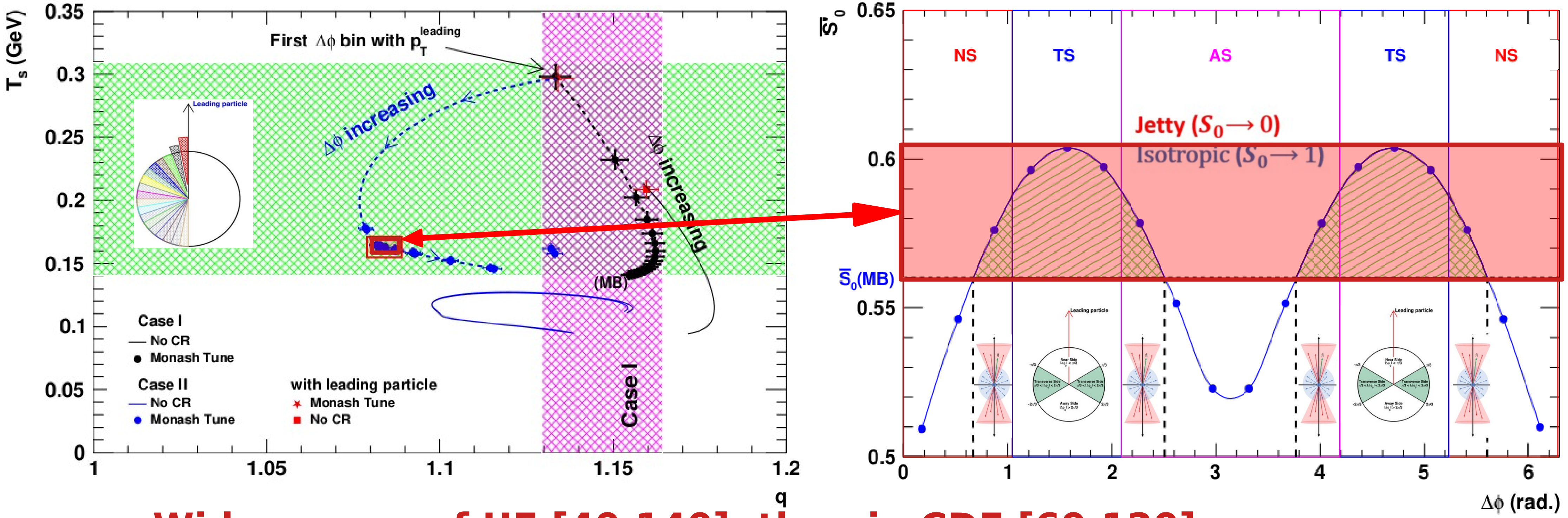
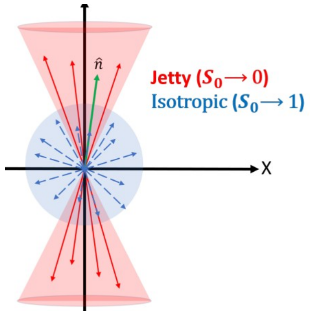
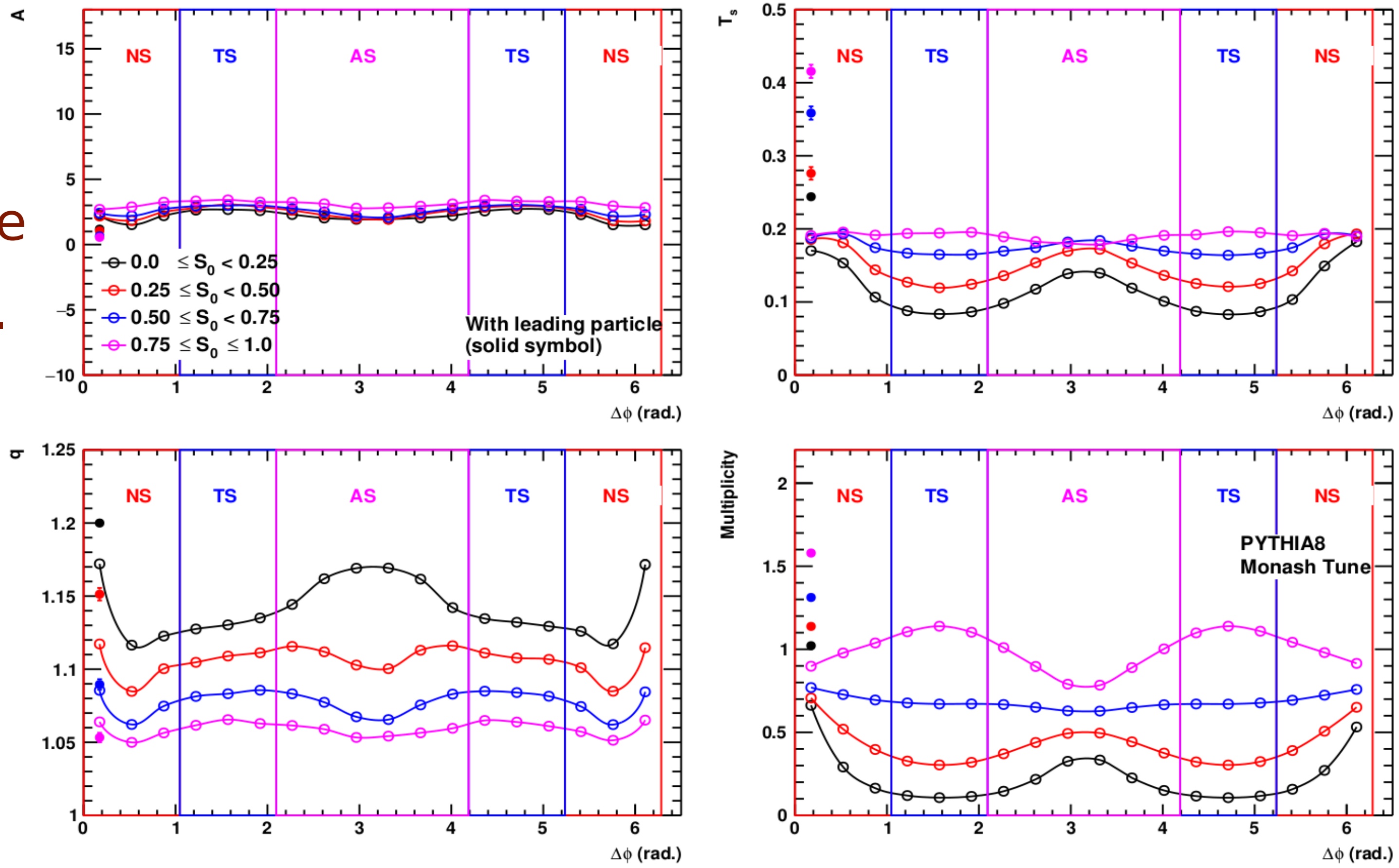


→ Wider range of UE [40,140], than in CDF [60,120]

Parameters in spherocity classes

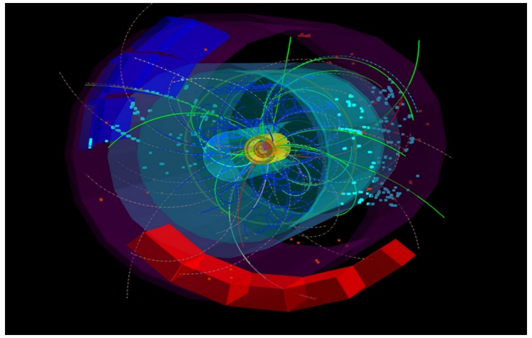
- **PYTHIA spectra with sliding angle in S_0 classes**
  - The more jetty the event, the angular variation is stronger.
  - Minimal activity (lowest q & T values are in the isotropic case.



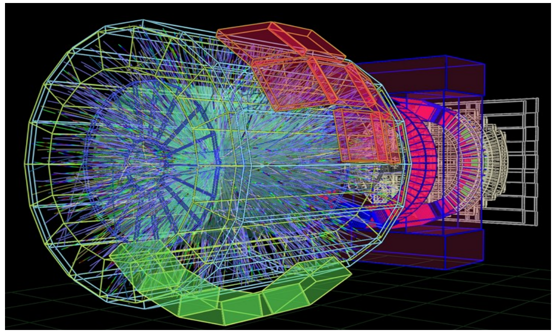


→ Isotropic events are closer to UE, activity is more than MB

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

→ Measure & investigate this in larger systems in pA or AA? At various energies.

Is UE strange and unknown?

...then what do you think about these, "strange things" in Bratislava...

Is UE strange and unknown?

ĎAKUJEM!

...then what do you think about these, "strange things" in Bratislava...

BACKUP

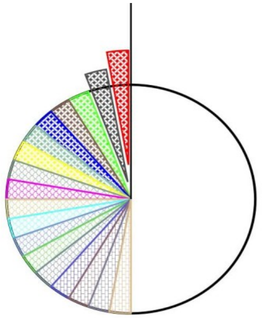
Derivatives of the parameters

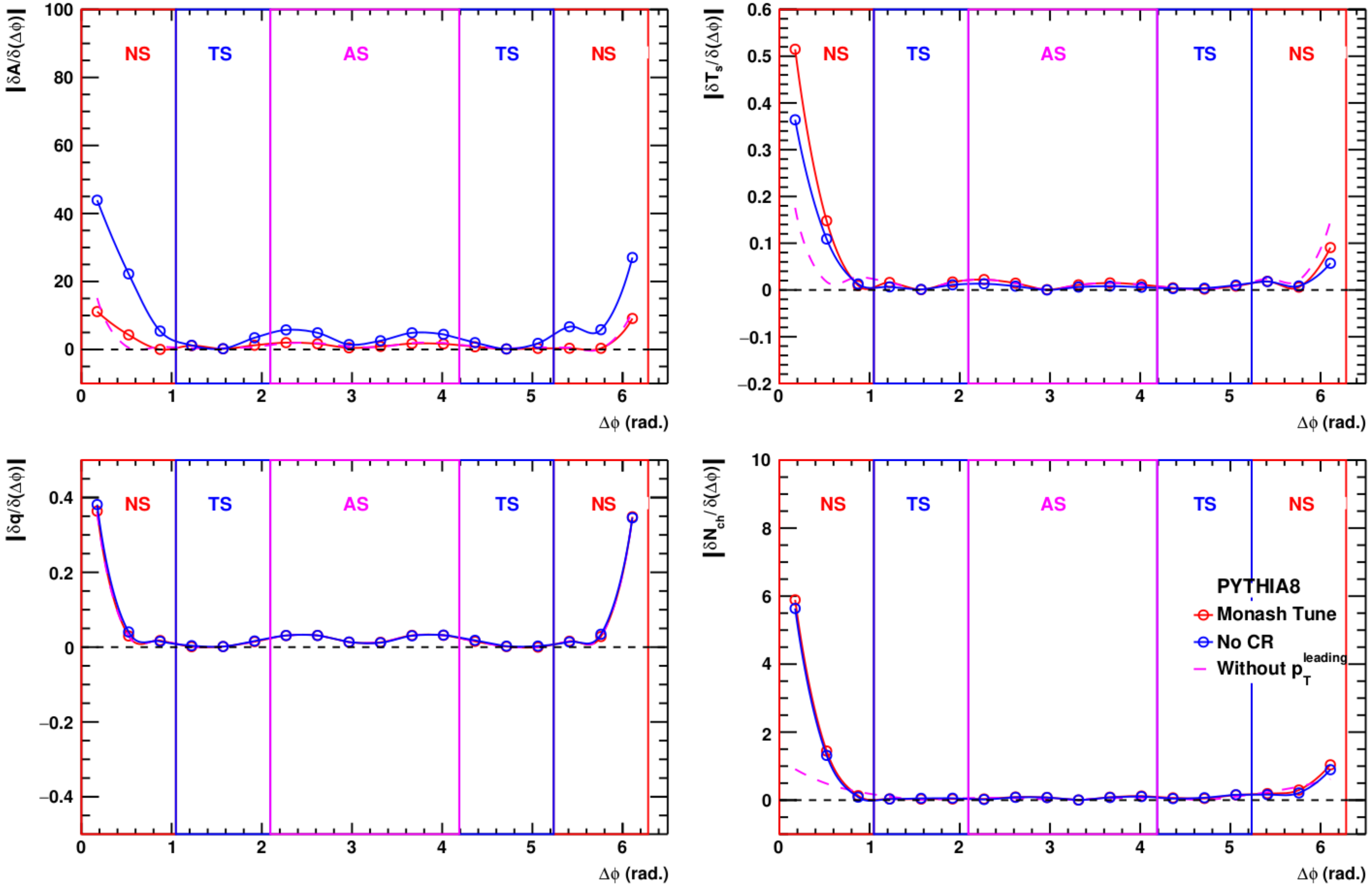
- **PYTHIA spectra parameter derivatives with sliding angle**
  - PYTHIAs model UE: CR & MPI
  - TS (+AS) → constant T & q

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

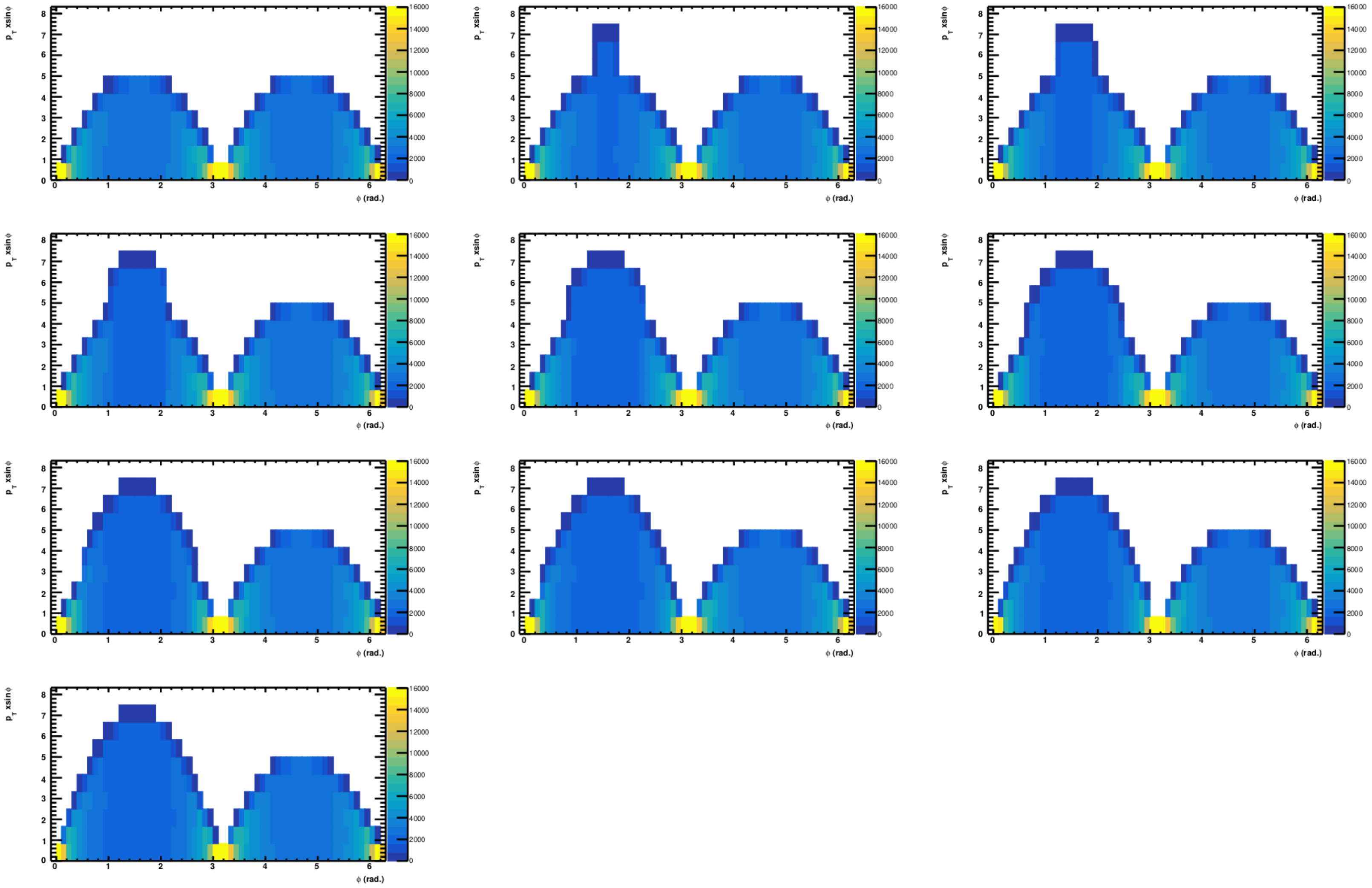
$$\frac{\delta T_s}{\delta(\Delta\phi)} \approx 0 \quad \& \quad \frac{\delta q}{\delta(\Delta\phi)} \approx 0 \qquad \text{(for TS)}$$

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





Spherocity model with multiplicity



Thermodynamical consistency?

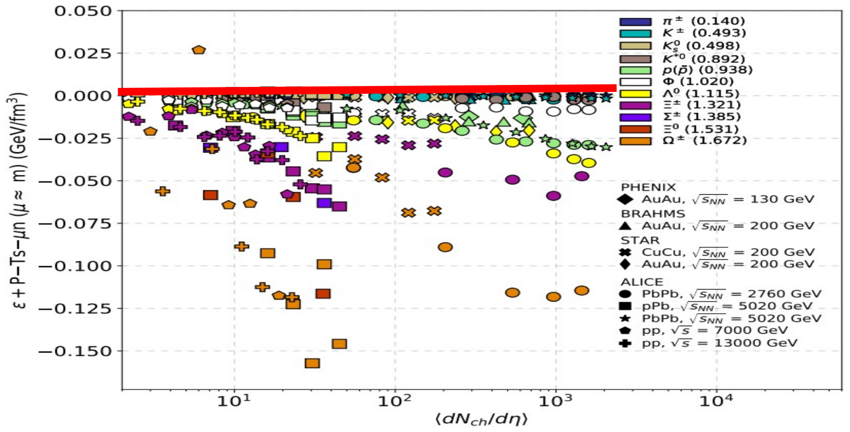
Thermodynamical consistency: fulfilled up to a high degree

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

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

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

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



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