

# Quantifying the Underlying Event: Investigating Angular Dependence of Multiplicity Classes and Transverse-momentum Spectra in High- energy pp Collisions at LHC Energies

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Support: *Hungarian OTKA grants, K135515, NKFIH 2019-2.1.11-TET-2019-00078*

*Wigner Scientific Computing Laboratory*

*Refs: J.Phys.G 47 (2020) 10, 105002, arXiv:2108.13938 (submitted to JPG)*

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**ELKH** | Eötvös Loránd  
Research Network

# 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

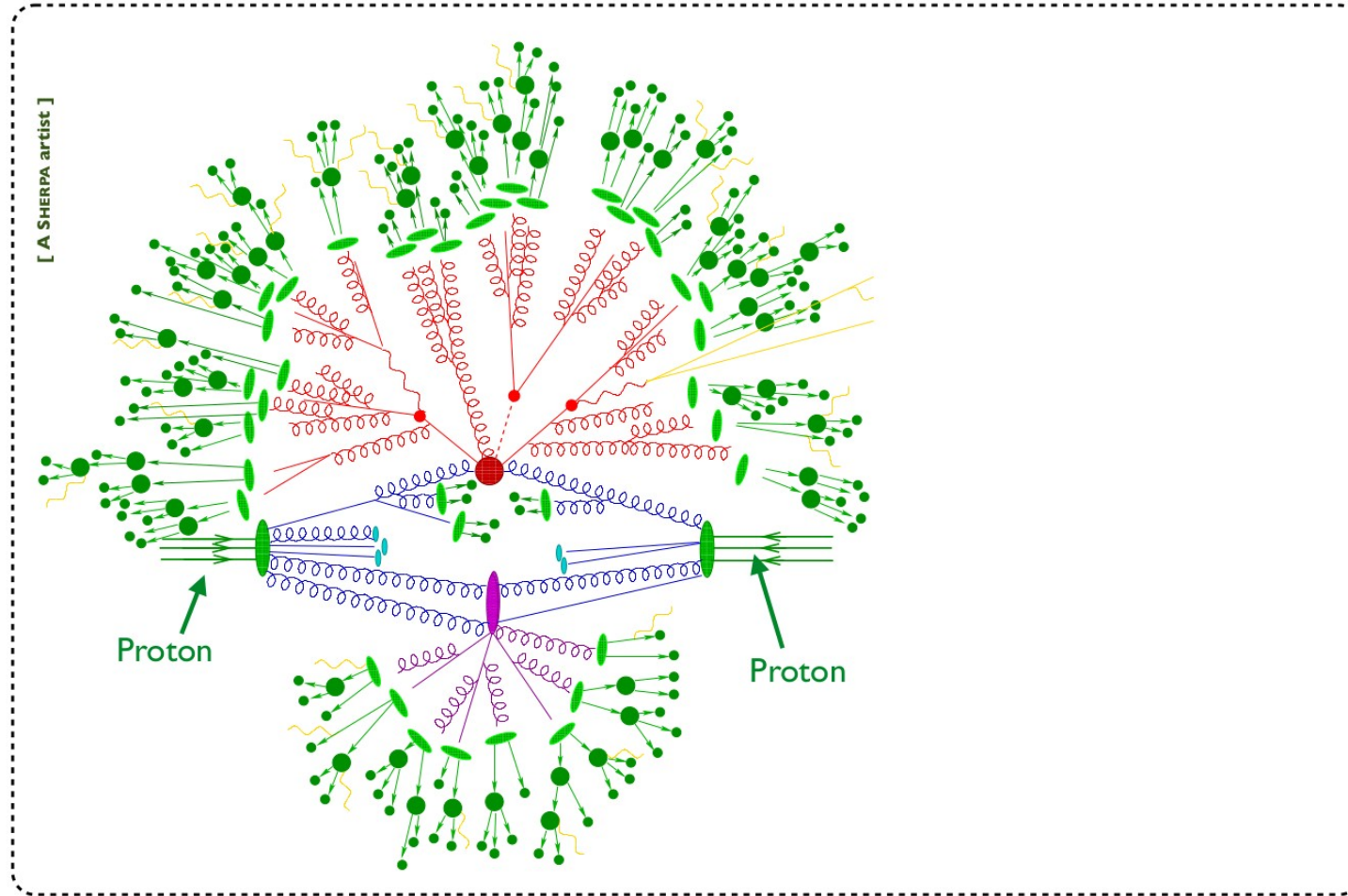
## 3) Comparison to event shape variable

- Sphericity measures and cross check

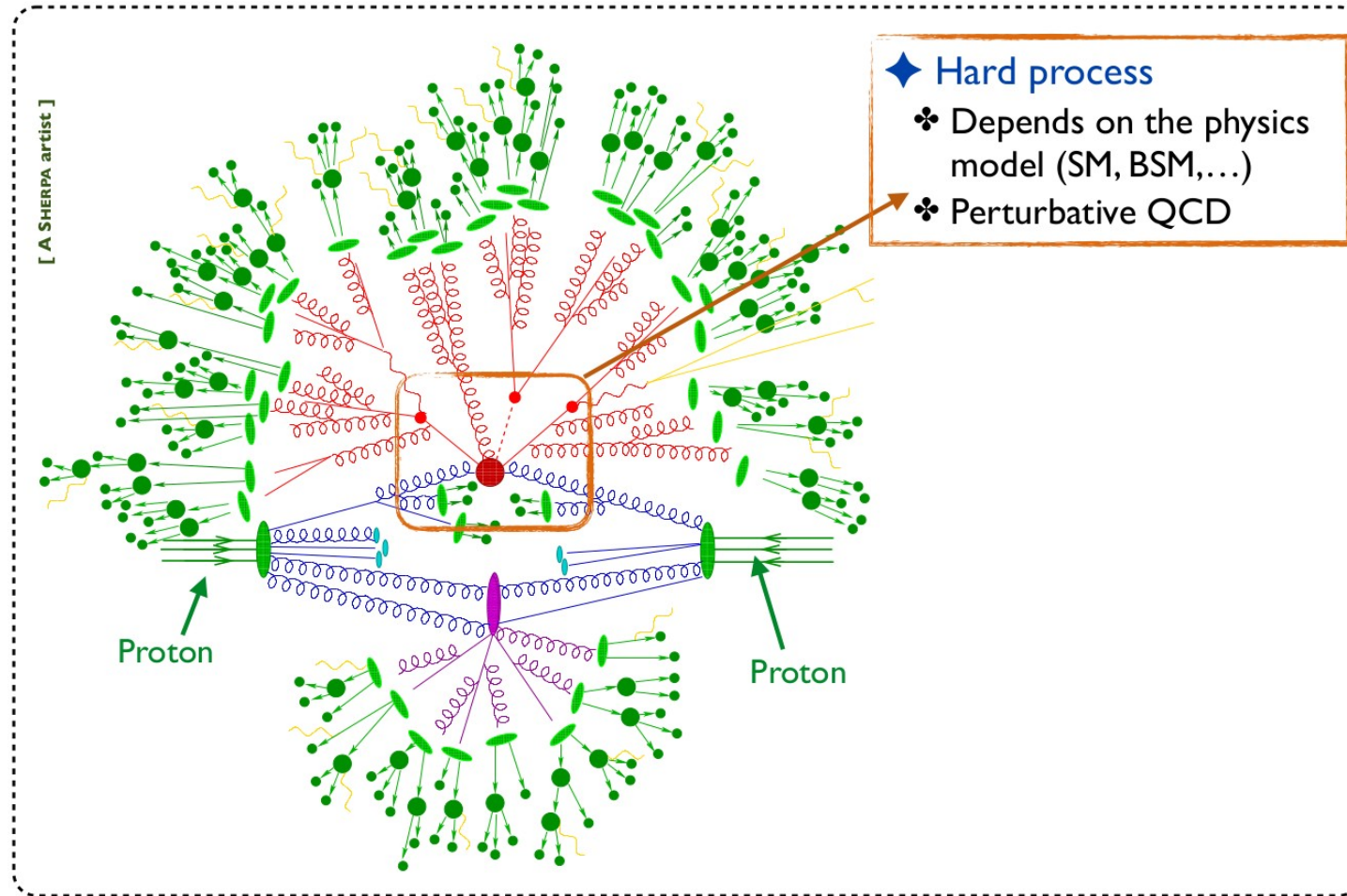
→ **Conclusions: Extended UE definition**



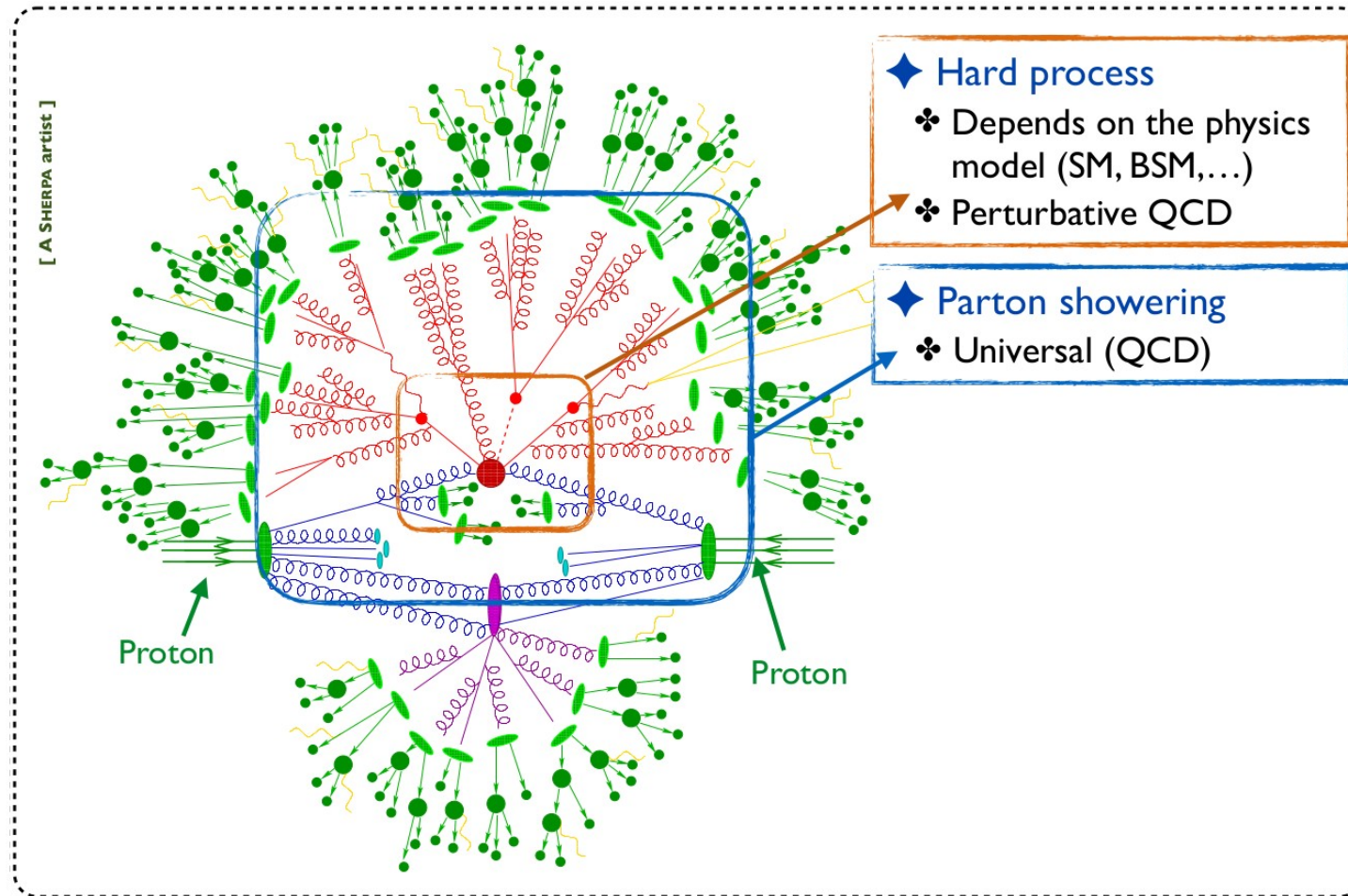
# Anatomy of a proton-proton event



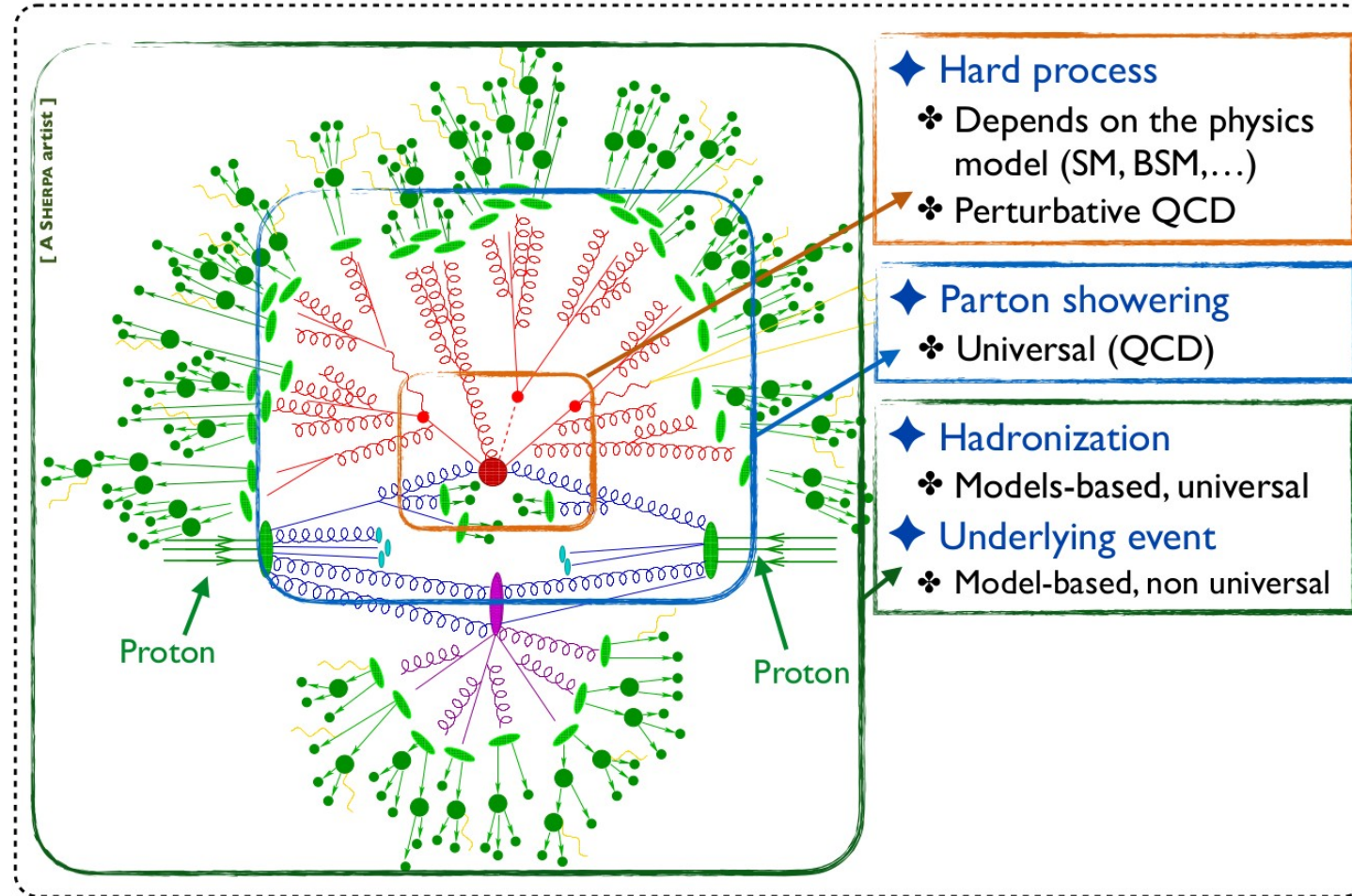
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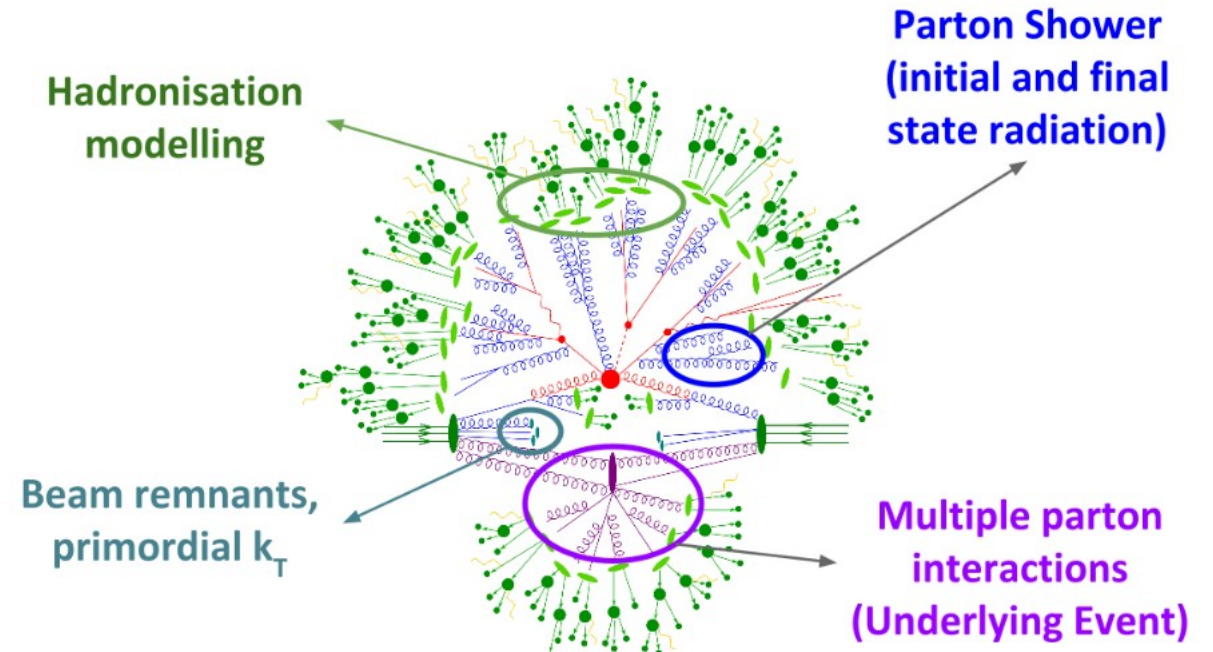


# Anatomy of a proton-proton event



# So what Underlying Event is?

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



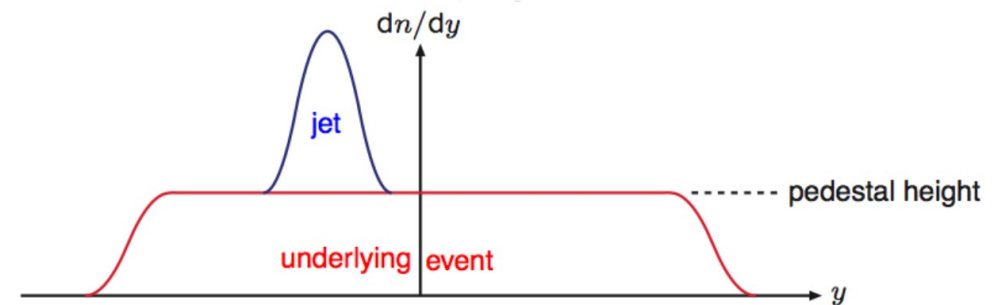
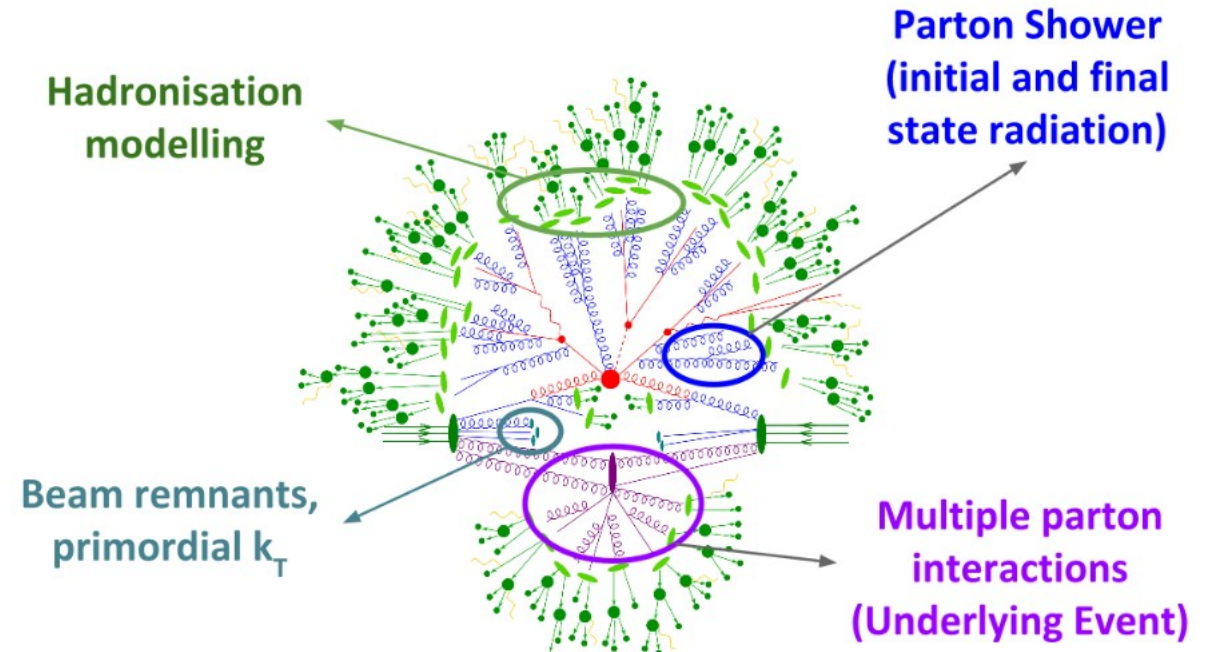
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- **Experimental point**

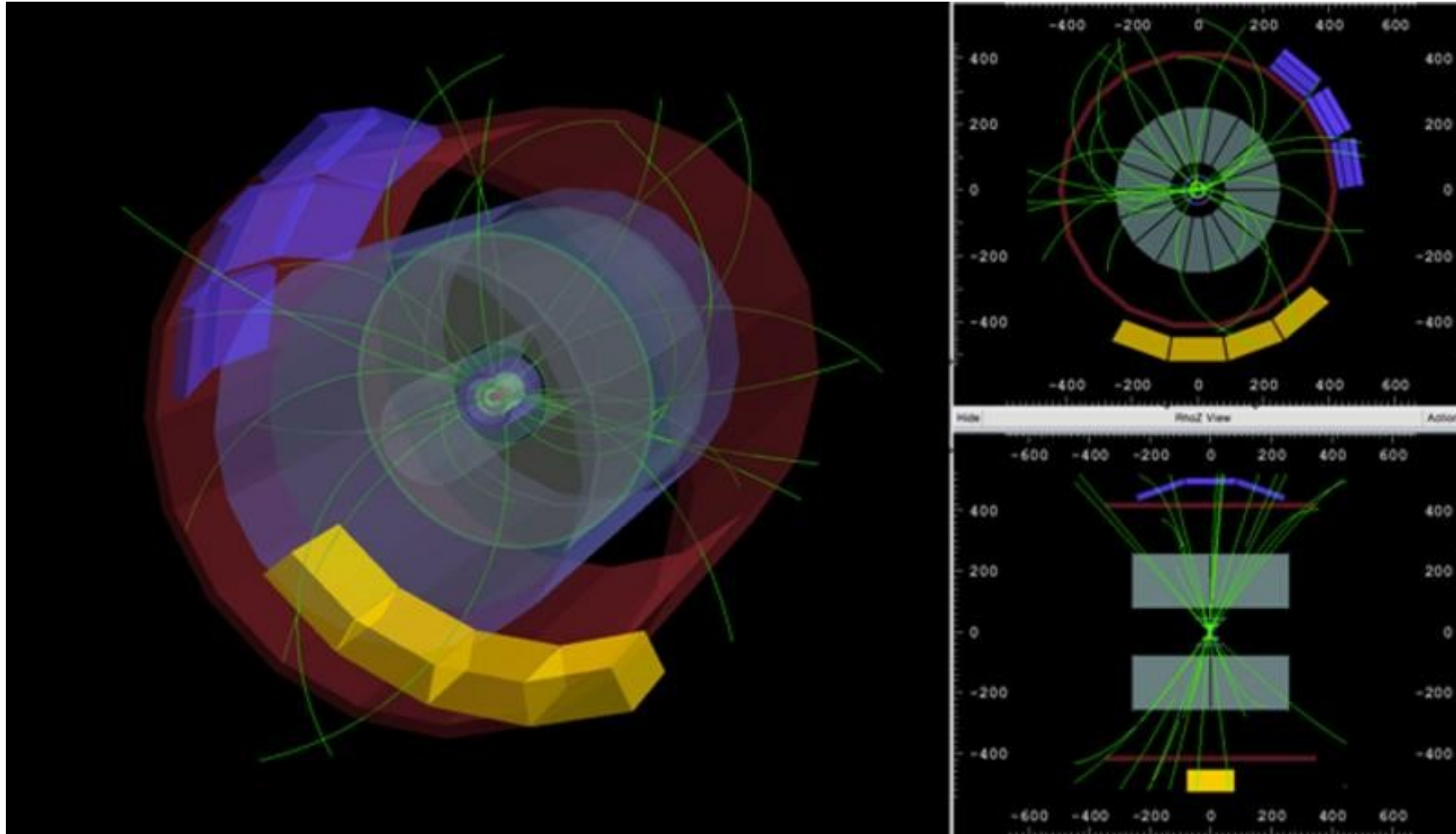
- Pedestal-like effects
  - Activity in the event over MB
  - Beam remnants (pile up)
  - Trigger bias (jet criterion)



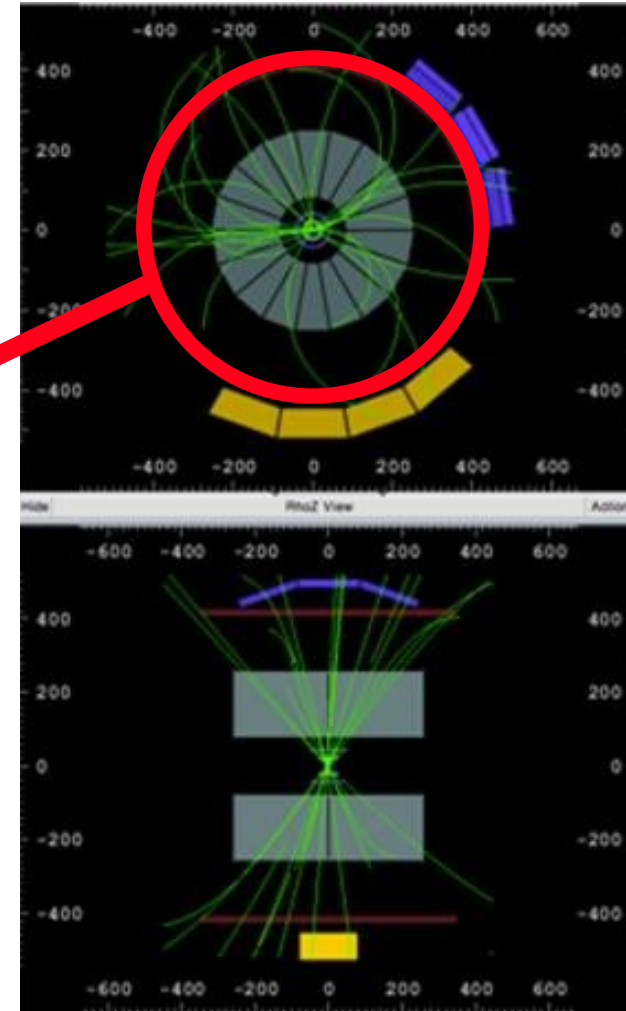
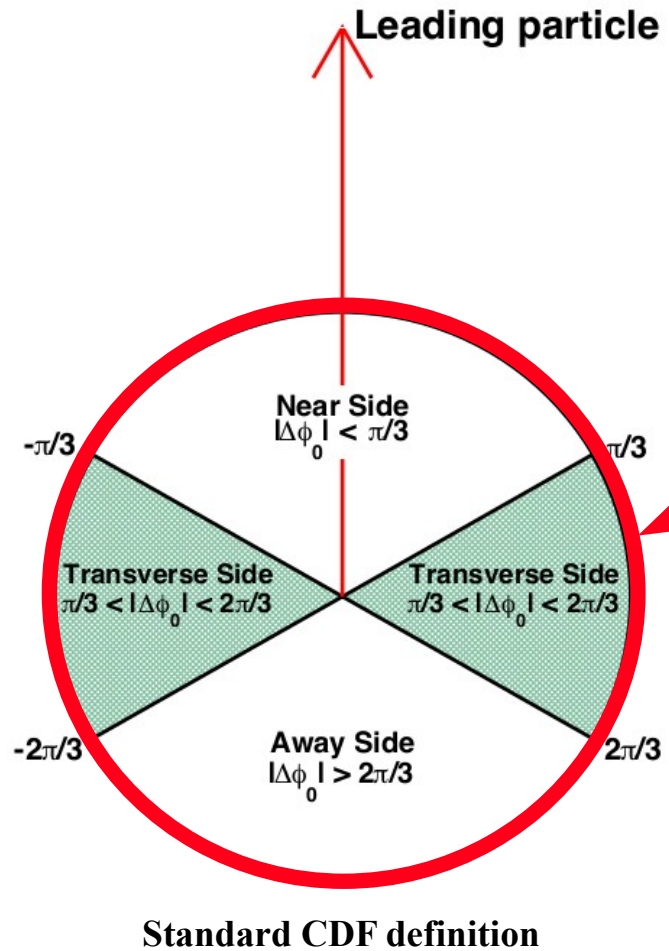


# Earlier studies, motivation

# Geometrical structure of an event



# Geometrical structure of an event



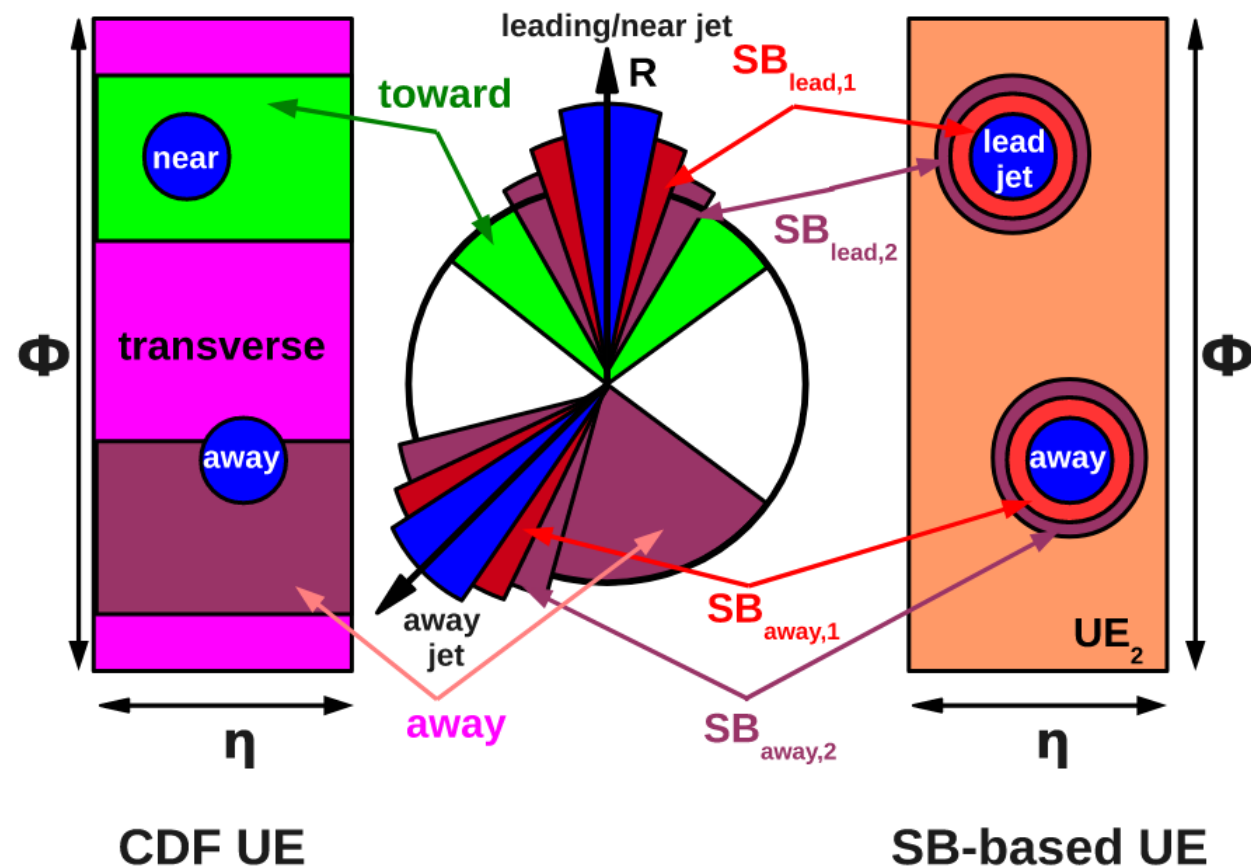
# How to separate jet & UE?

- **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
  - brute 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) 04006G.G. Barnafoldi: PP2023 - Margaret Island 2023

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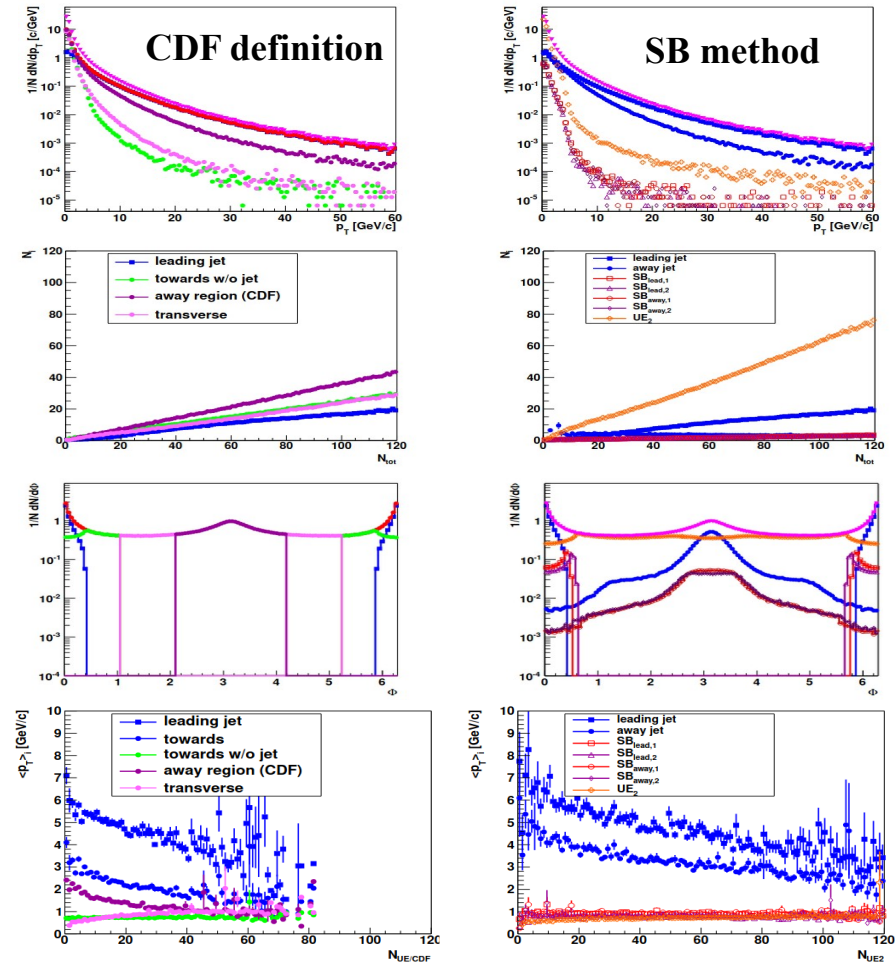
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# How to quantify & compare events?

- **Transverse sphericity:**

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

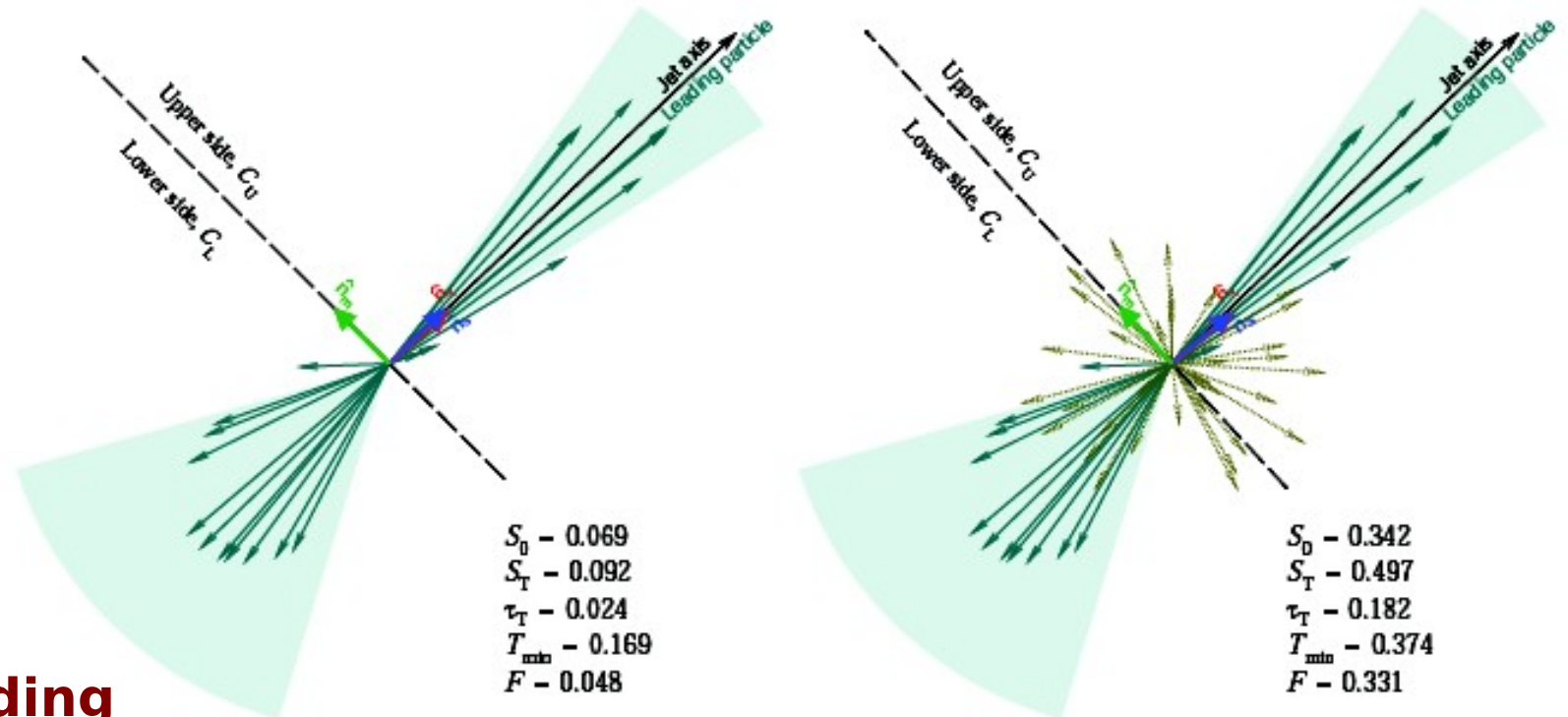
- **Thrust:**

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

→ **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)

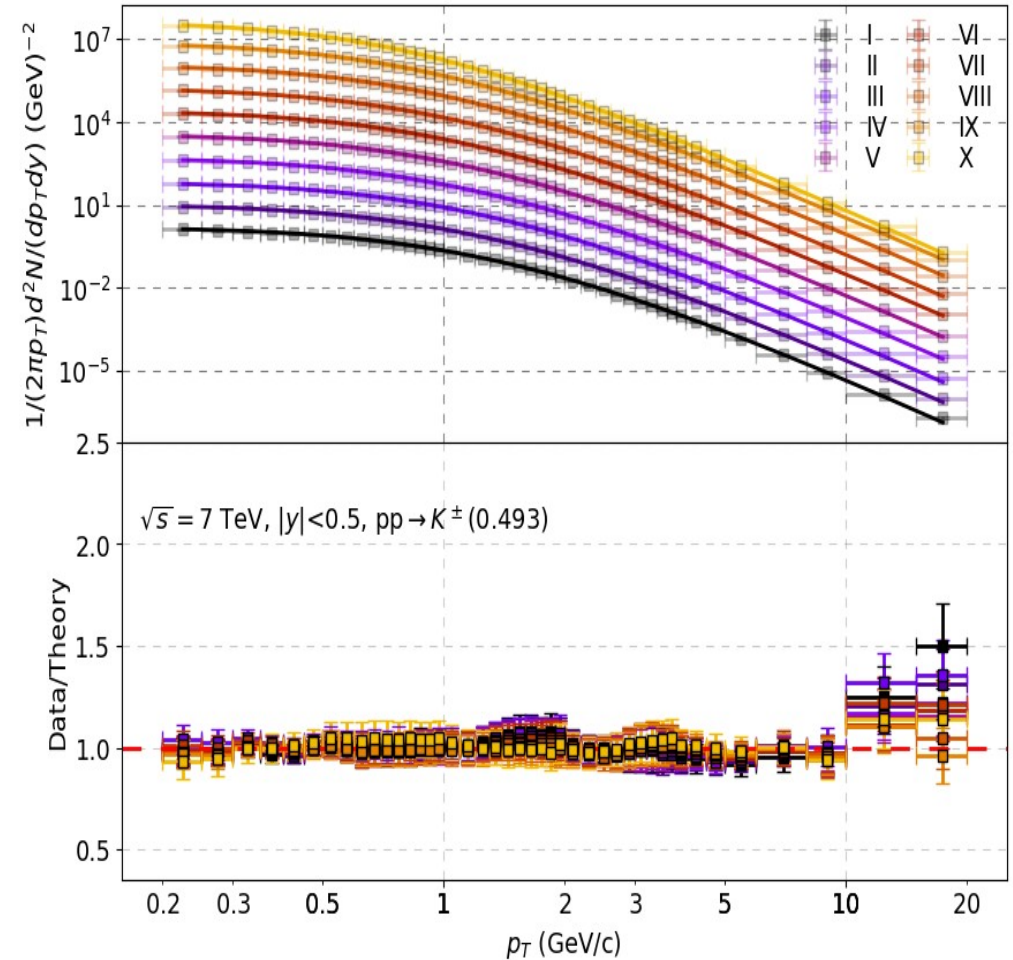
$$\left. \frac{dN_{\text{ch}}}{dy} \right|_{u=0} = 2\pi A T_s \left[ \frac{(2-q)m^2 + 2mT_s + 2T_s^2}{(2-q)(3-2q)} \right] \times \left[ 1 + \frac{q-1}{T_s} m \right]^{-\frac{1}{q-1}}$$

- **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  $\sqrt{s}$  & multiplicity

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

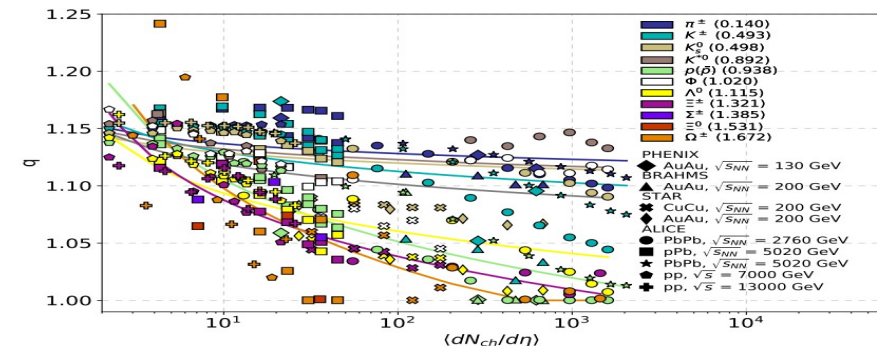
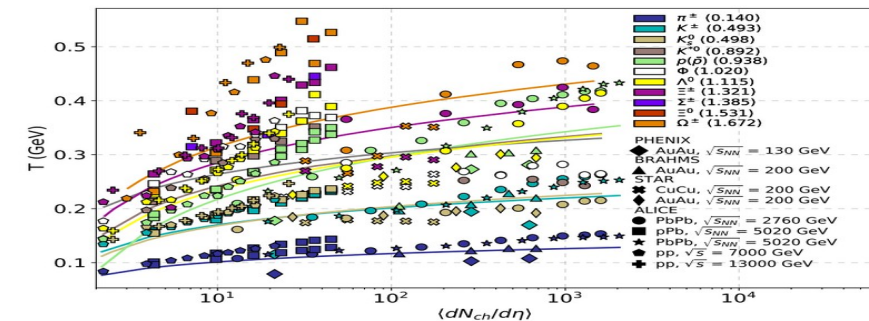
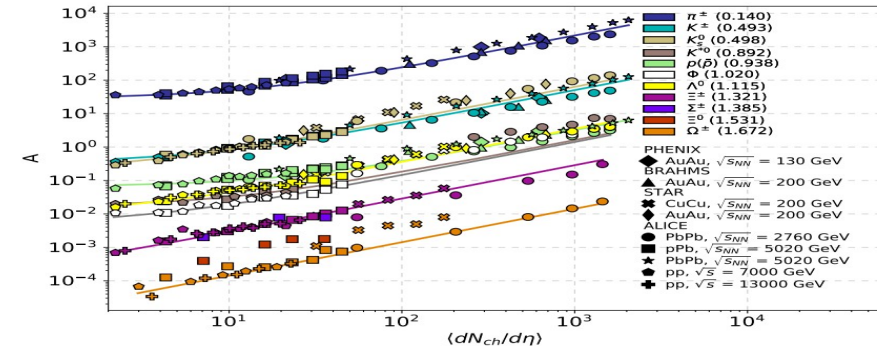
$$T(\sqrt{s_{NN}}, \langle N_{ch}/\eta \rangle, m) = T_0 + T_1 \ln \frac{\sqrt{s_{NN}}}{m} + T_2 \ln \ln \langle N_{ch}/\eta \rangle,$$

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

- Details:

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

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





# How to quantify & compare events?

## • QCD-inherited scaling properties

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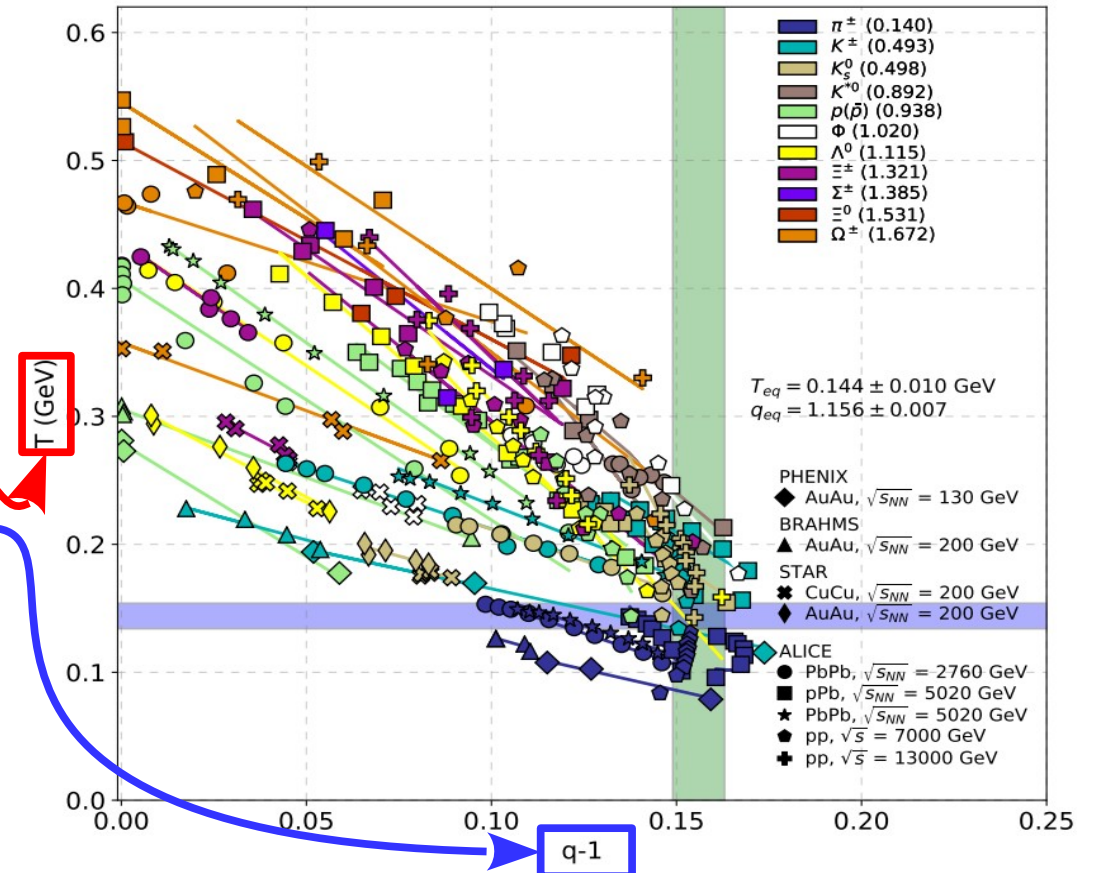
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## • Thermodynamical consistency

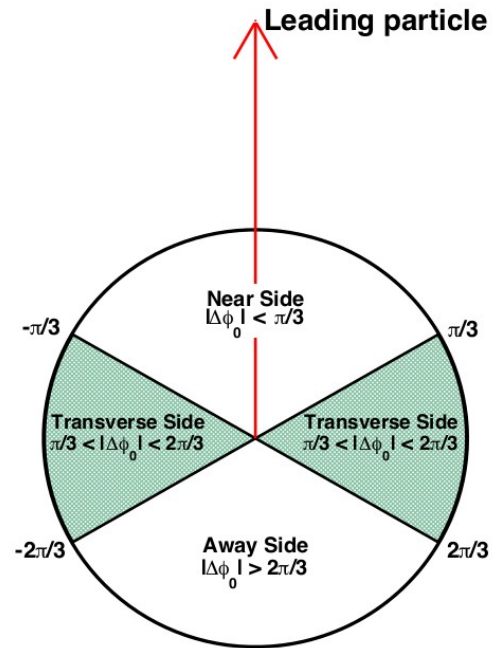
$$P = g \int \frac{d^3 p}{(2\pi)^3} T f, \quad N = nV = gV \int \frac{d^3 p}{(2\pi)^3} f^q,$$

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



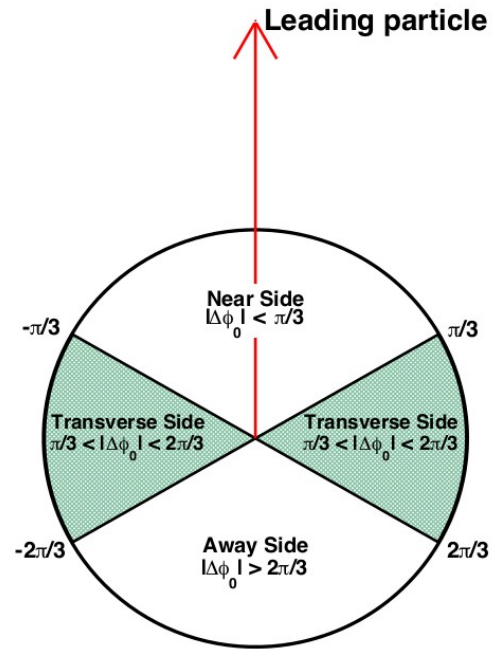
# New development to understand UE

# Angular structure of an event

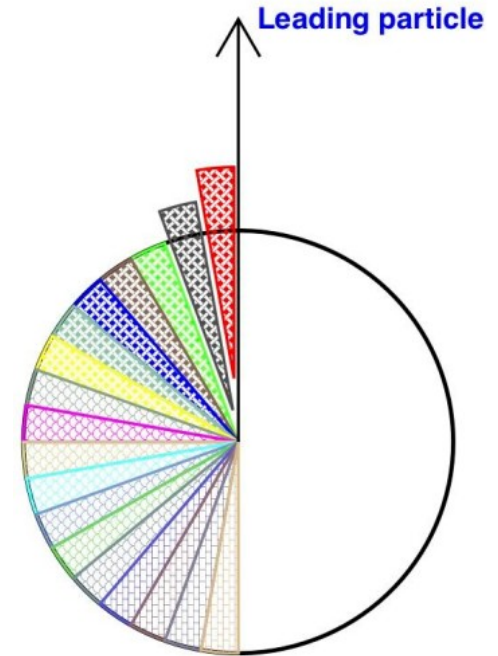


Standard CDF definition

# Angular structure of an event

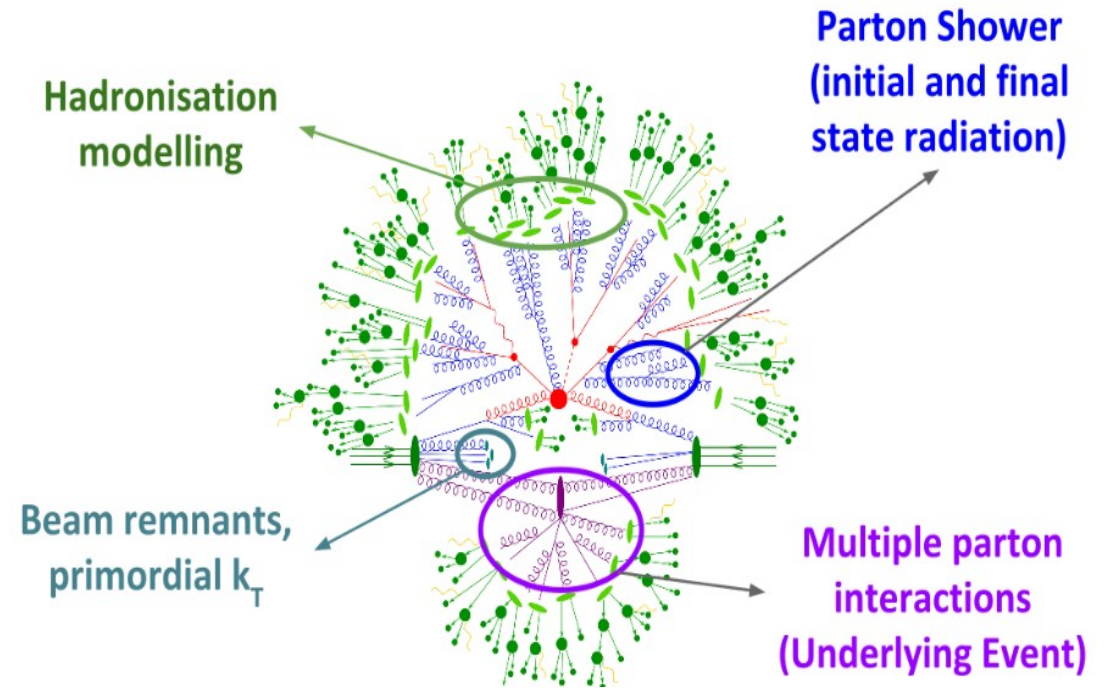


Standard CDF definition



# The simulated data

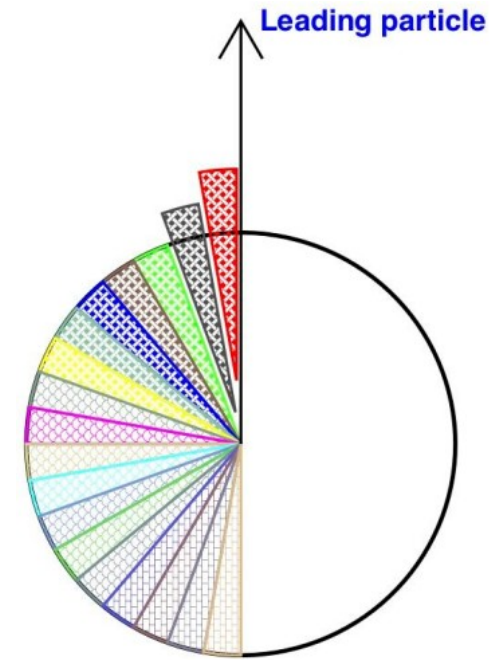
- **PYTHIA\_v8240 Monash 2013 tune**
  - 1 billion non-diffractive collisions of pp
  - C.m. energy:  $\sqrt{s} = 13$  TeV
  - Includes  $2 \rightarrow 2$  hard scattering process, followed by initial and final state parton showering, multiparton interactions, and the final hadronization process.
  - 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))



# Sliding angle, cake slices



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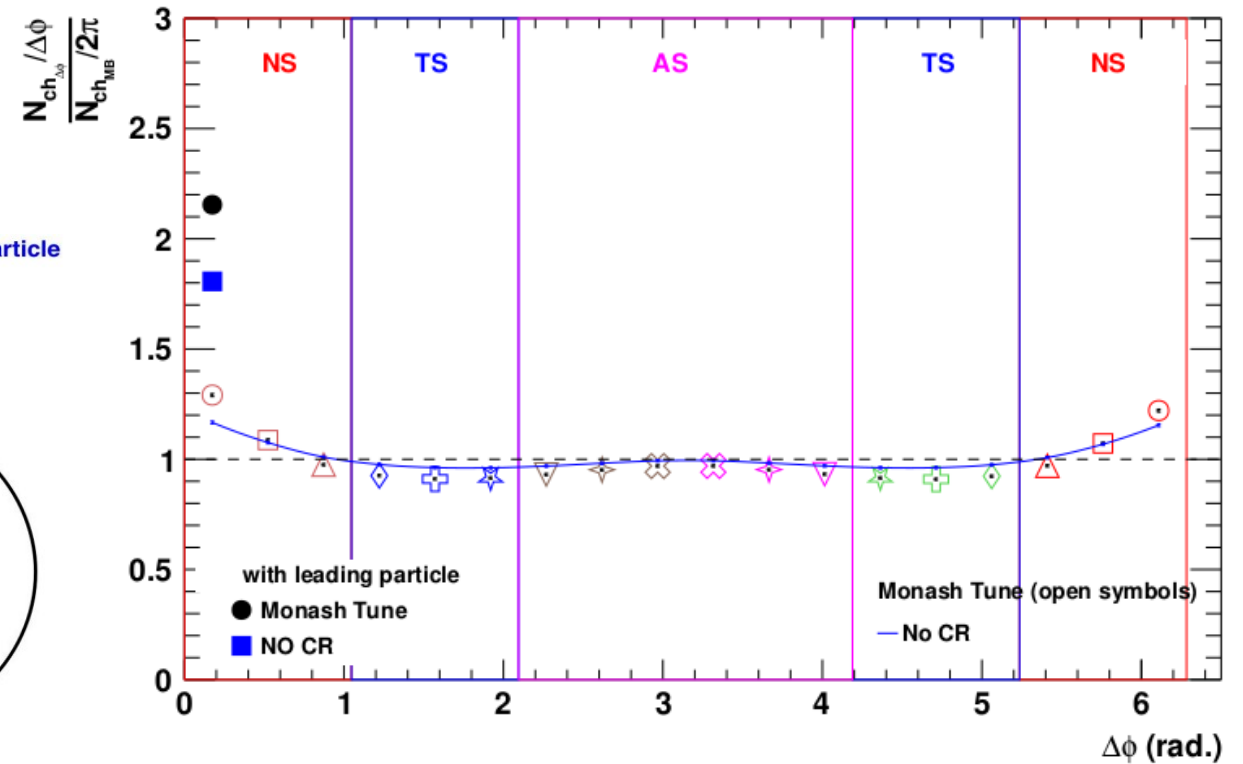
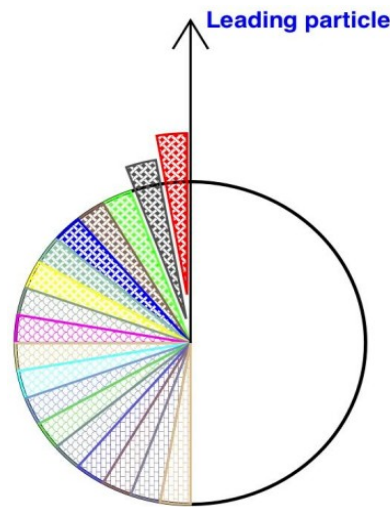


- We make slices of the  $\Delta\phi$  of size  $20^\circ$ . In this case, the results for the first bin  $0$  to  $20^\circ$ . are reported in two ways: including and excluding the leading particle in the result. Case II is a tool for exploring the geometrical structure of the Underlying Event.

# Multiplicity/MB

- **PYTHIA multiplicity with sliding angle**

- PYTHIA's model UE: CR & MPI
- Good fits with the parametrizations
- More multiplicity as NS
- TS & AS are mainly flat
- With leading particle deviation is increased

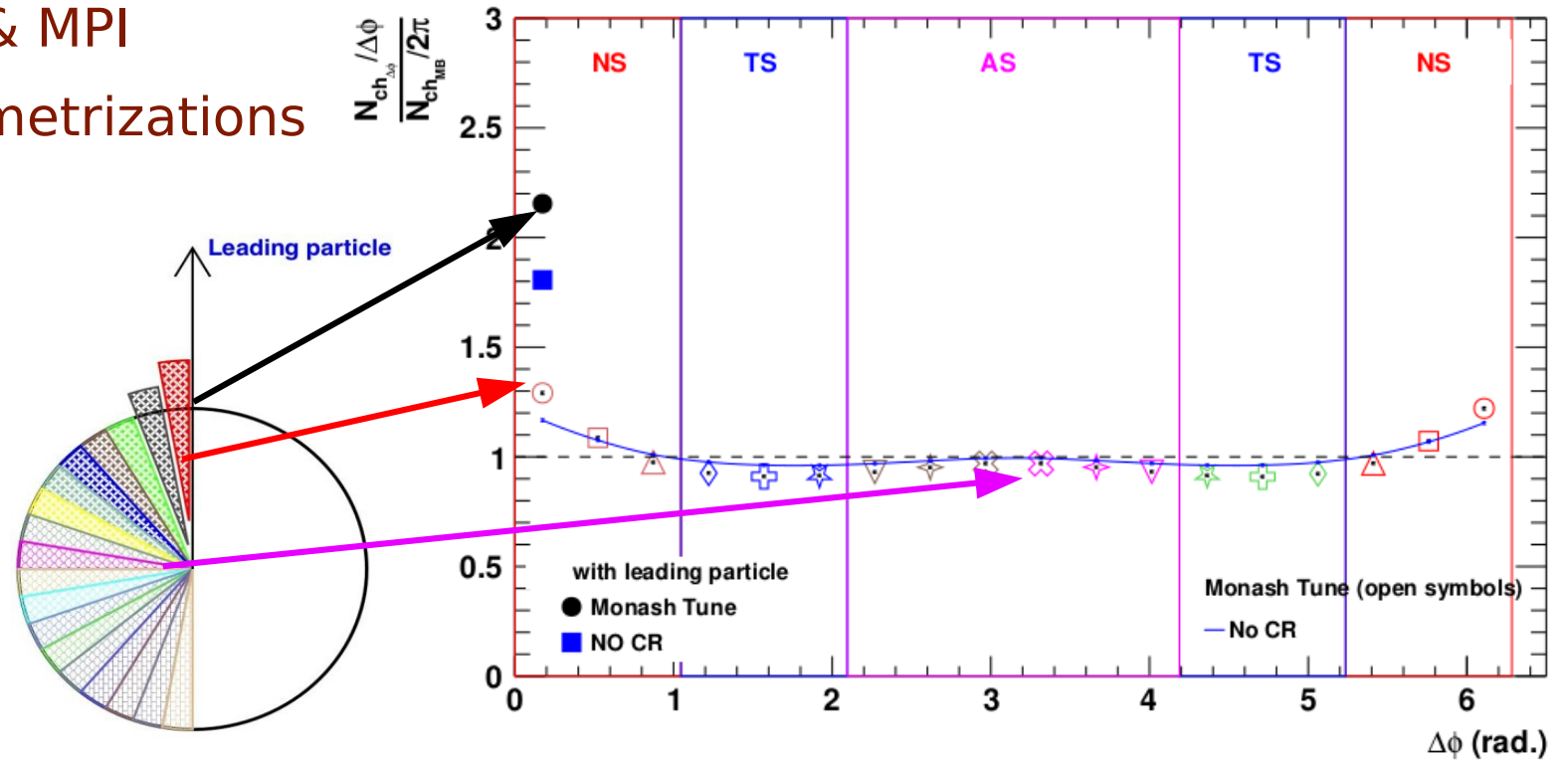




# Multiplicity/MB

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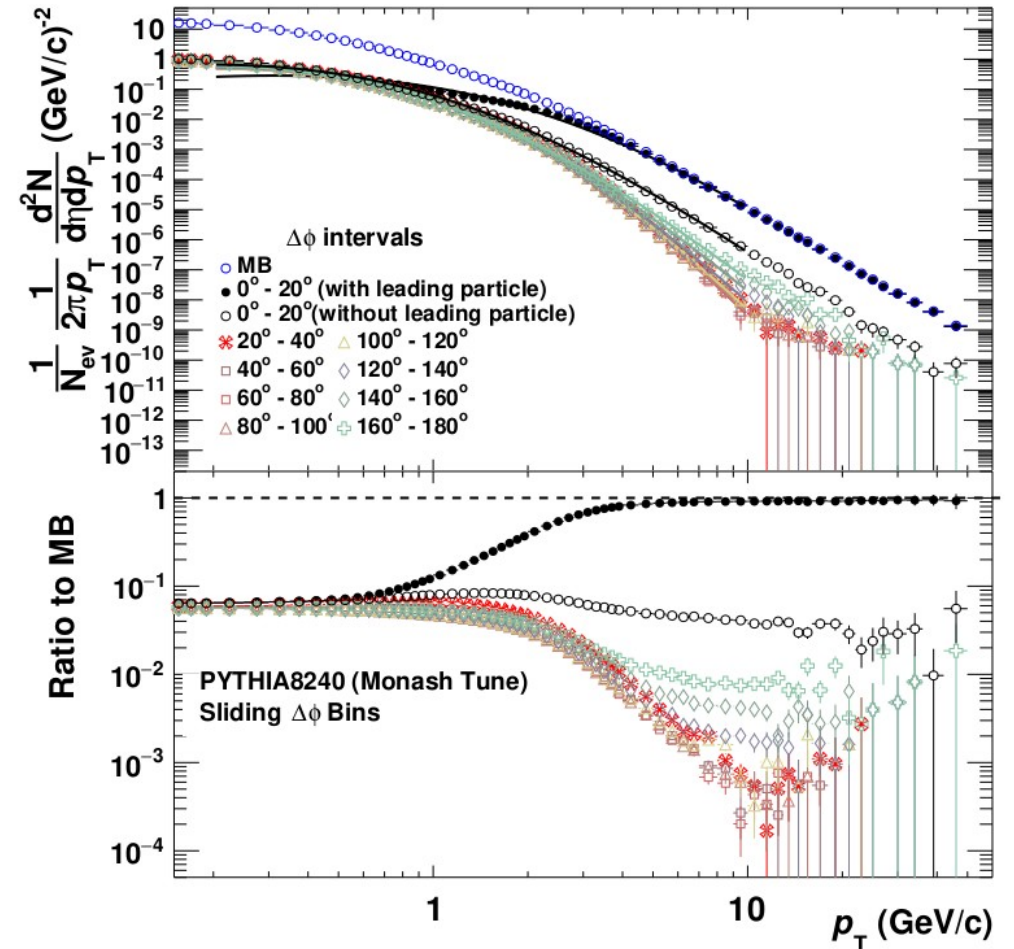
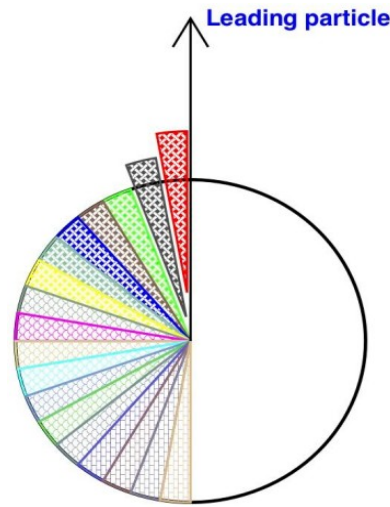
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# The $p_T$ spectrum

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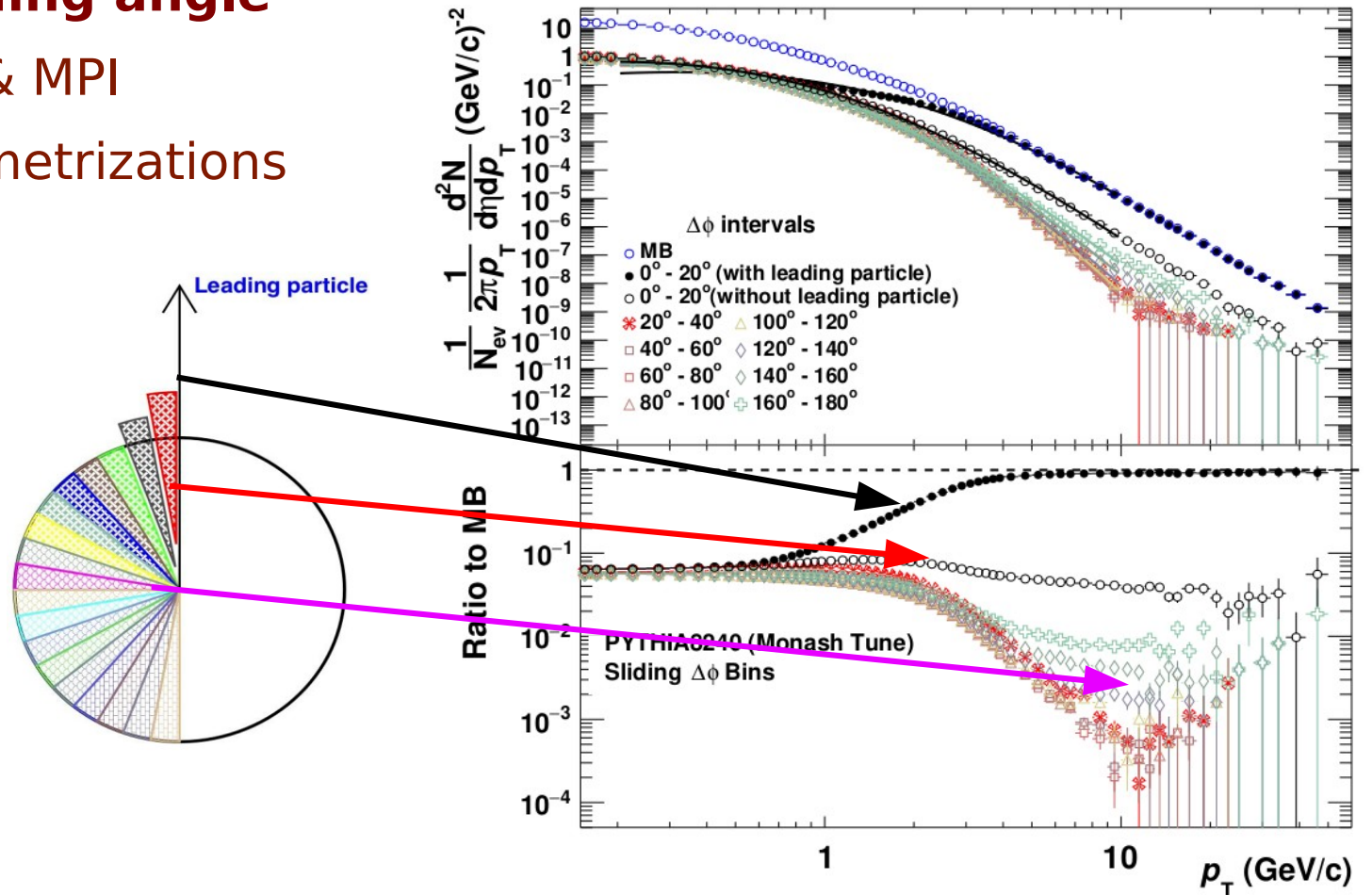
- PYTHIA model UE: CR & MPI
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- Low  $p_T$  is constant (T)
- High  $p_T$  varies (q)
- NS/AS are similar
- Need to consider w/o leading particle



# The $p_T$ spectrum

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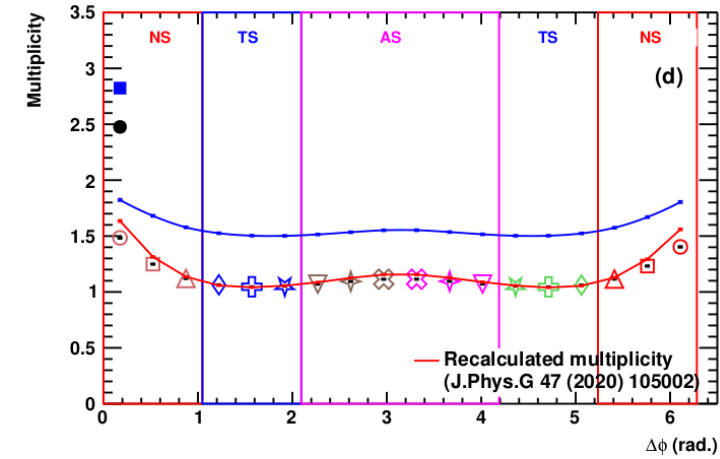
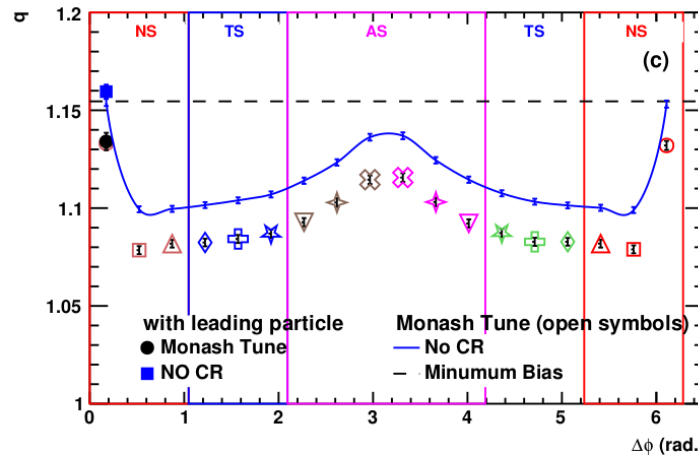
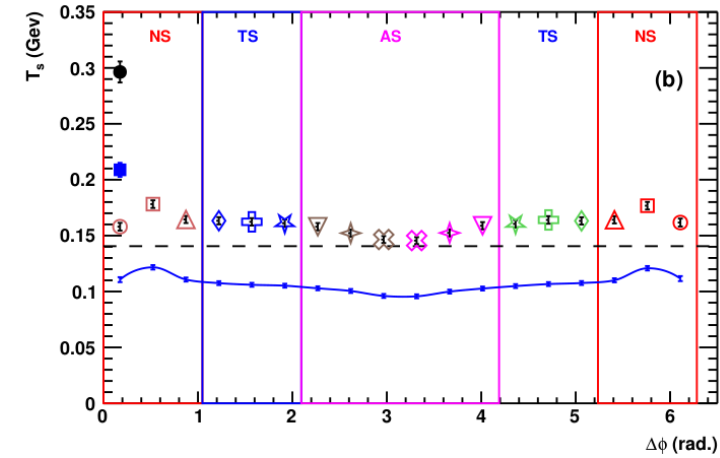
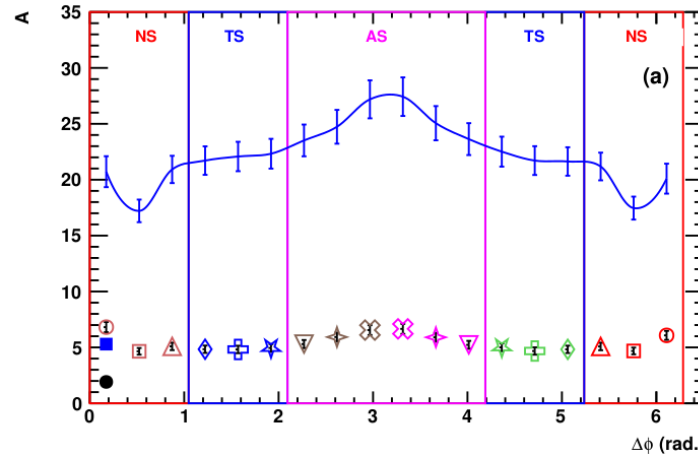
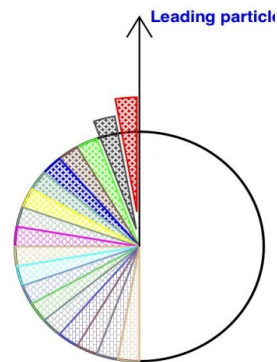
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# Tsallis fit parameters

- PYTHIA spectra with sliding angle**

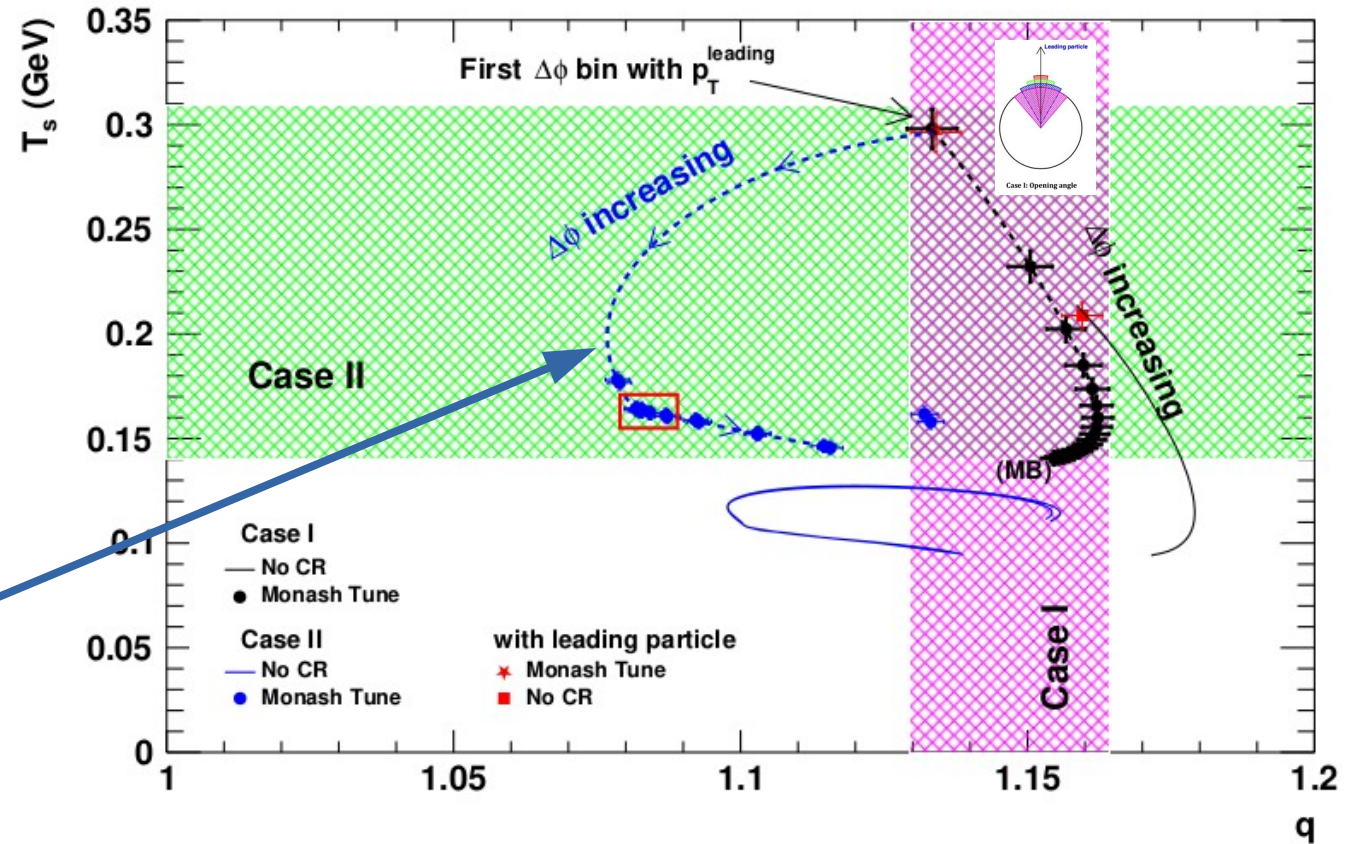
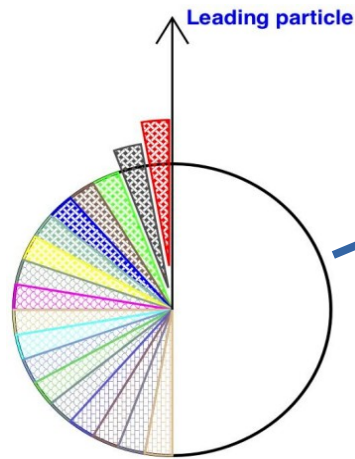
- PYTHIA's model UE: CR & MPI
- Good fits with the parametrizations (red line)
- NS  $\rightarrow$  highest  $T$
- NS/AS  $\rightarrow$  highest  $q$
- TS  $\rightarrow$  constant  $q, T$
- Multiplicity  $\sim A$



# On the Tsallis-thermometer

- **Sliding angle**

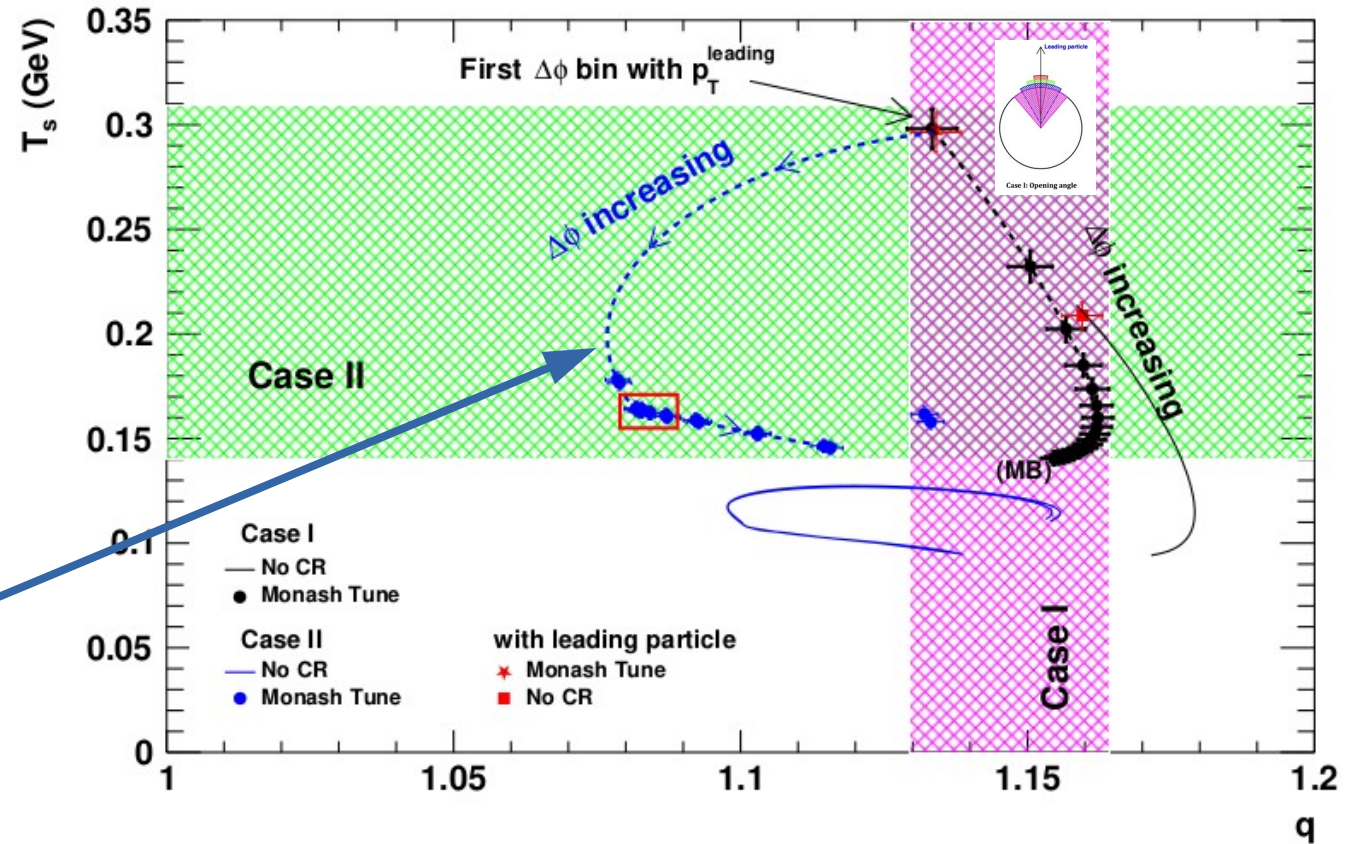
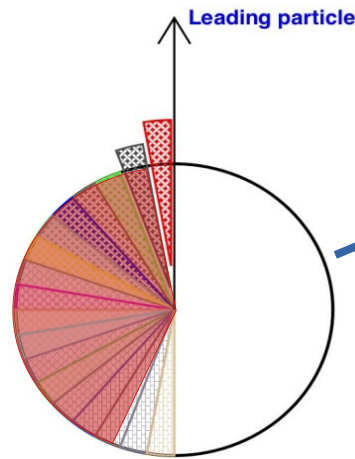
- Need UE in PYTHIA → CR & MPI
- NS (with leading) is fully different highest T & highest q
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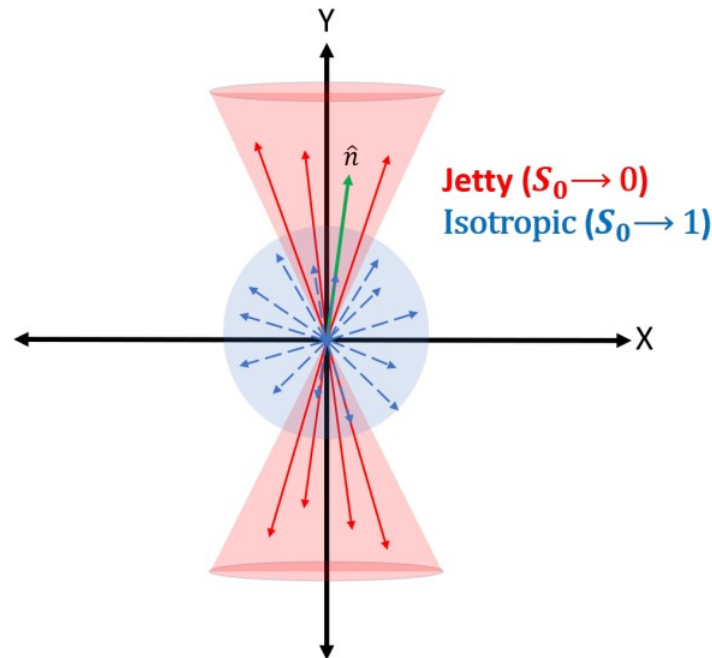
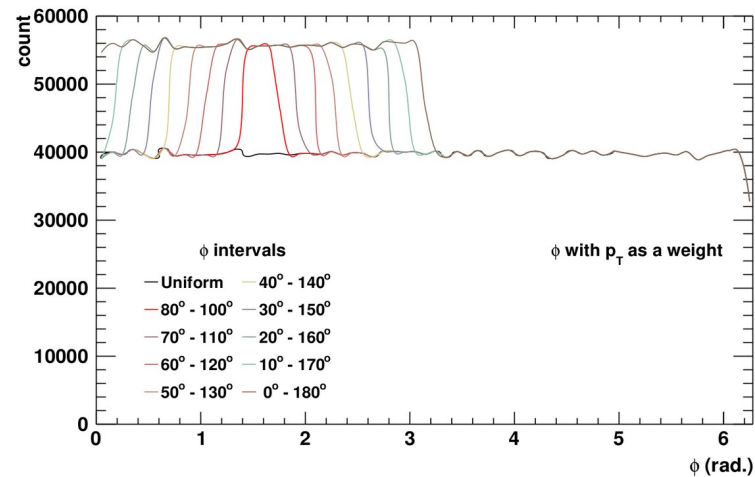


# Cross-check with event shape variable

# Event shape variable: sphericity

## Simple 2-component model

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

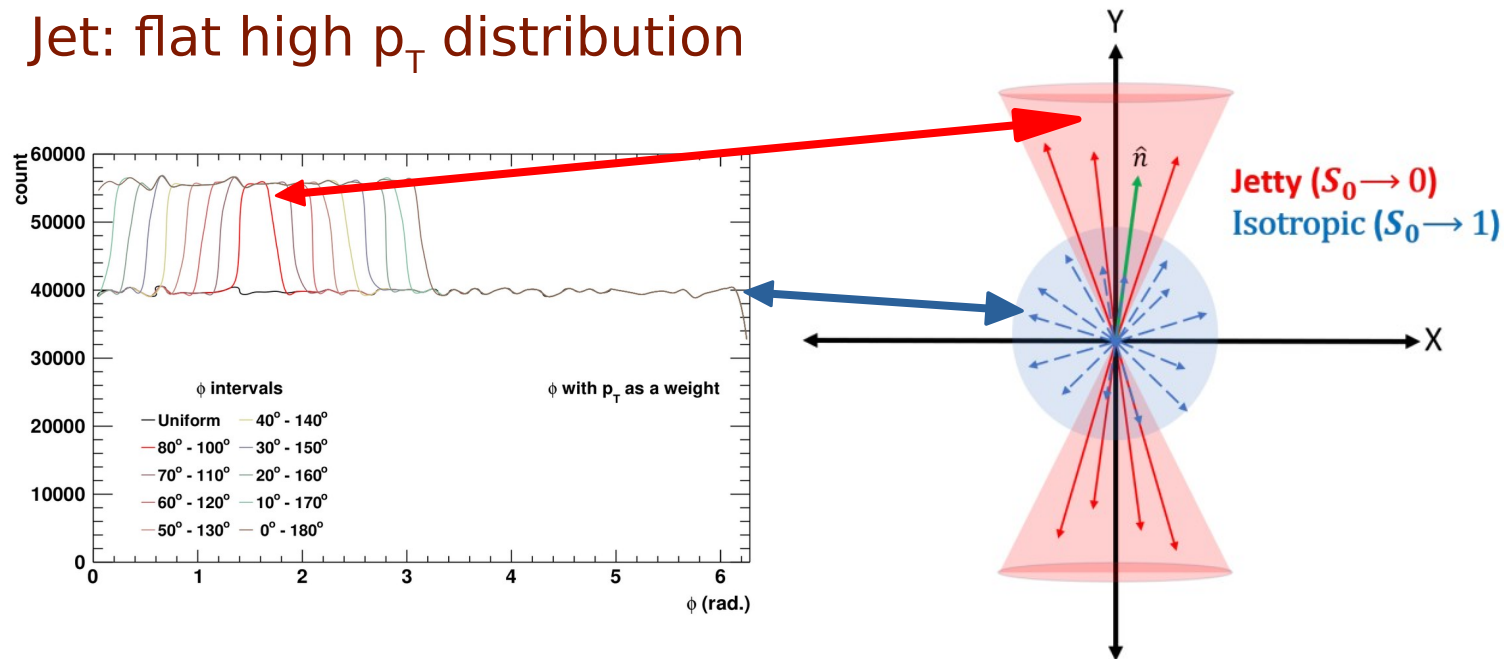




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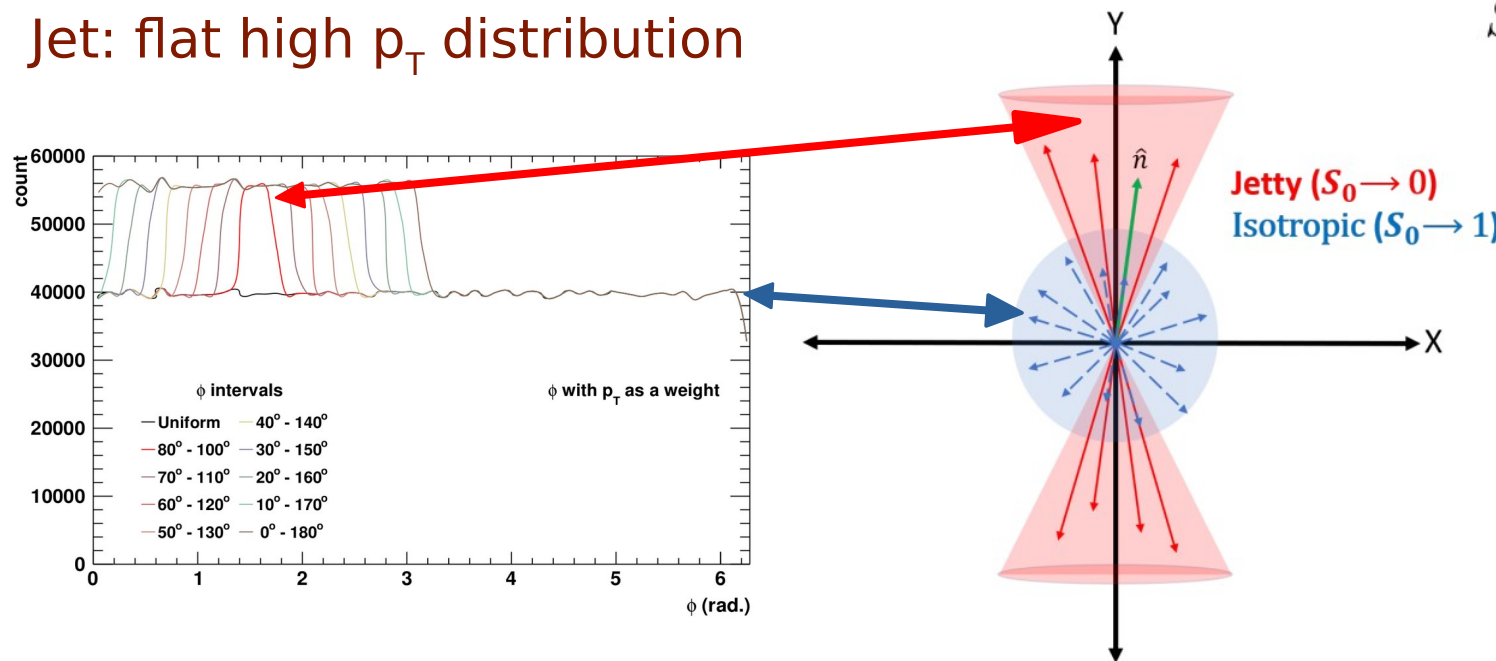
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## Sphericity definition

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



→ Event selection based on sphericity classes is available in ALICE

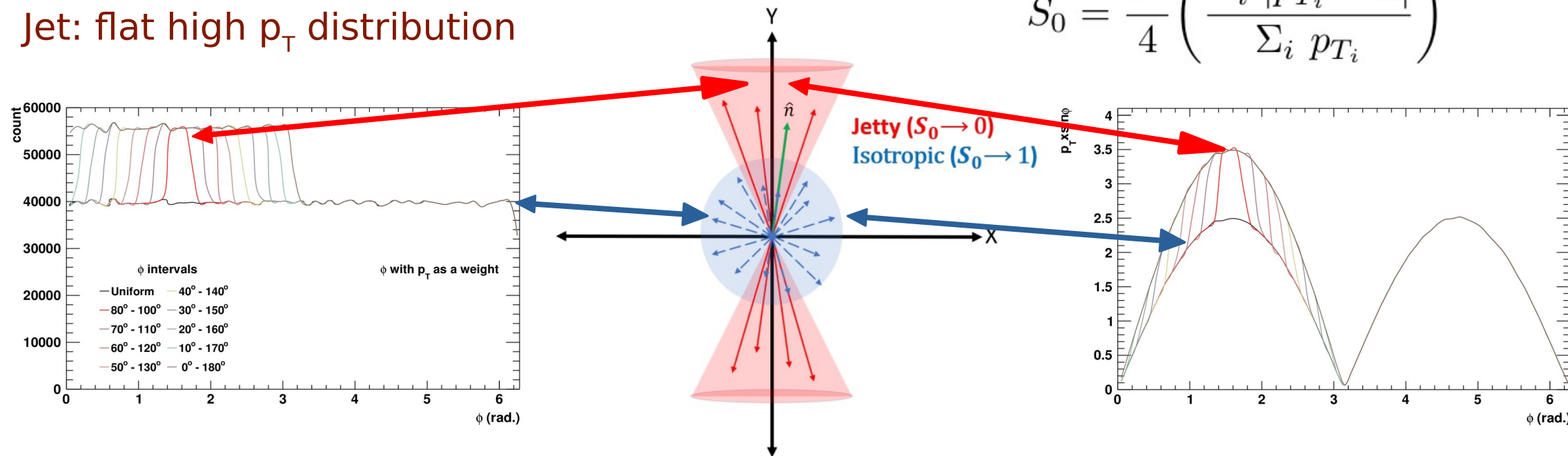
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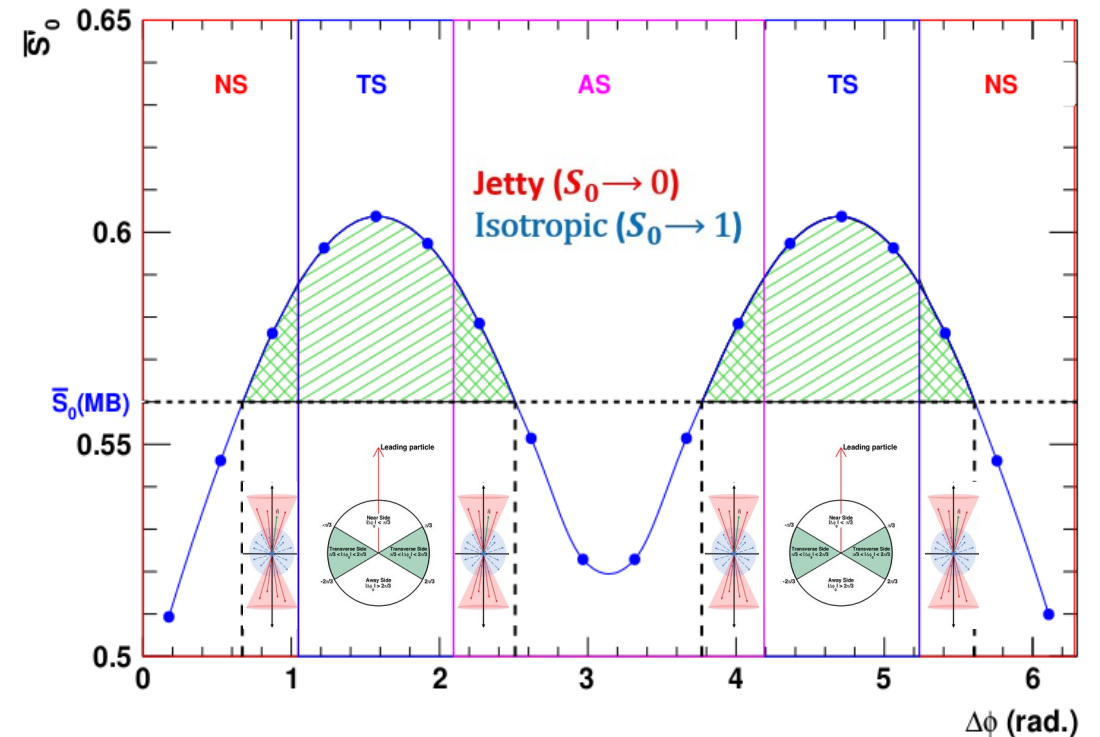
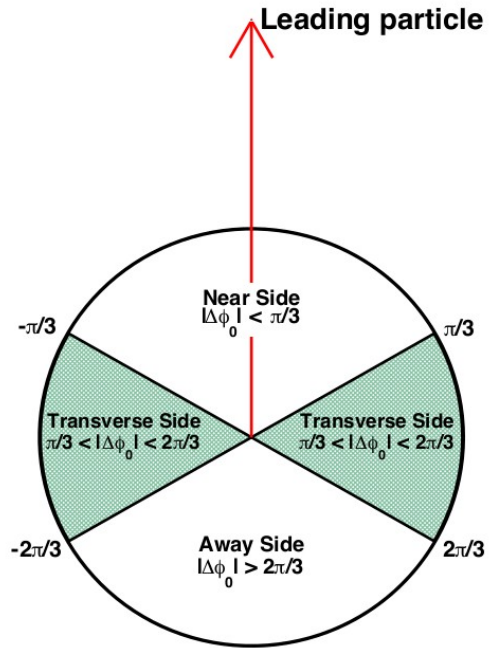
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# Case II: Spherocity vs. Tsallis thermometer

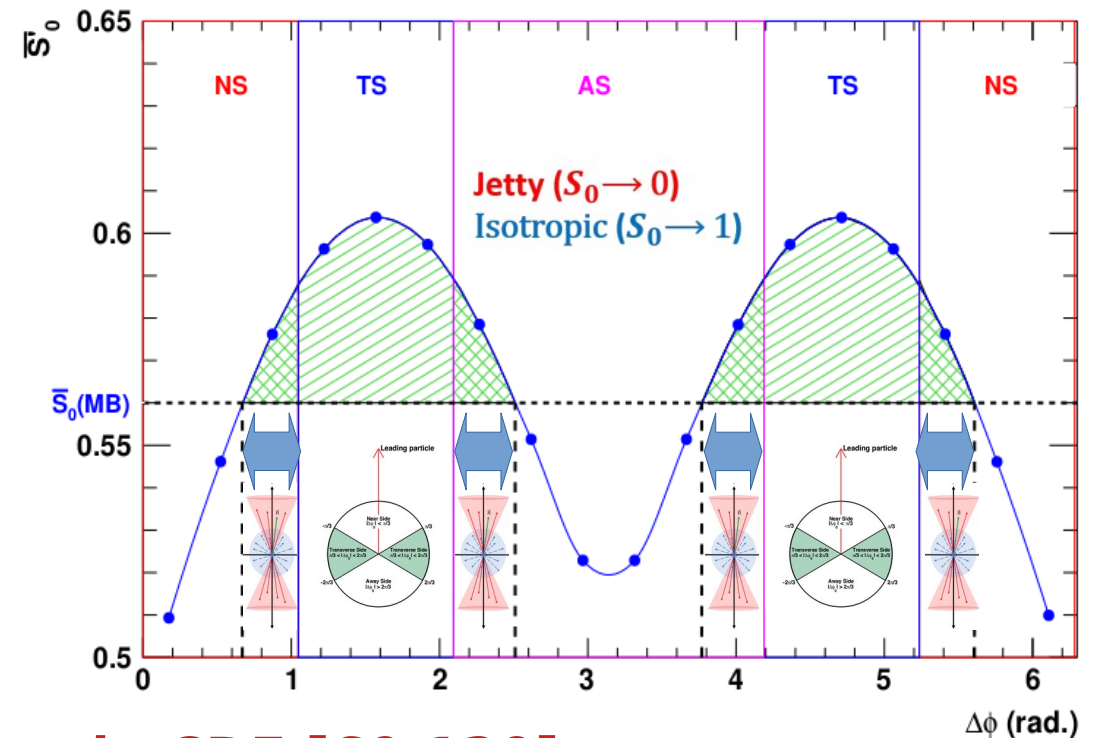
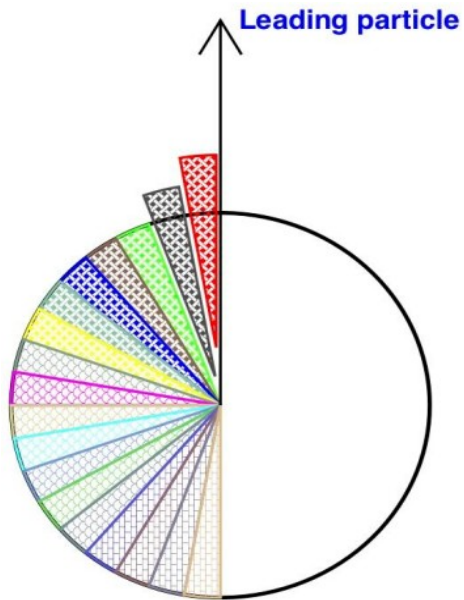
- Spherocity relative to the MB defines wider UE



→ CDF-based UE [40,140]

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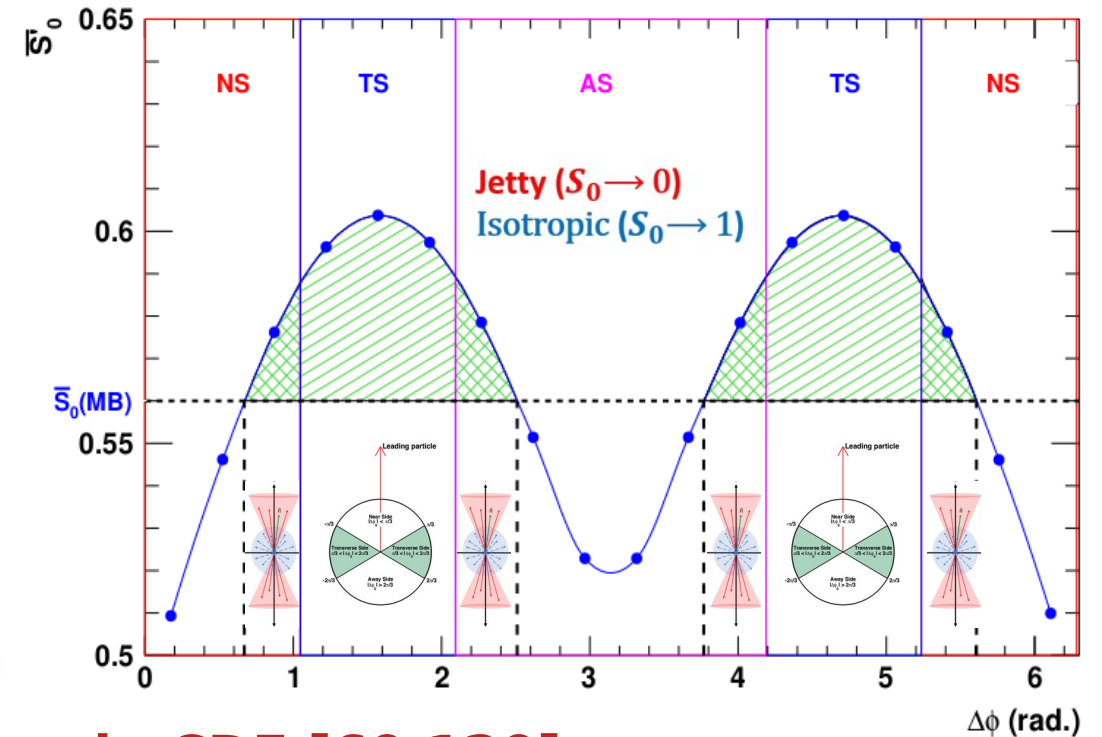
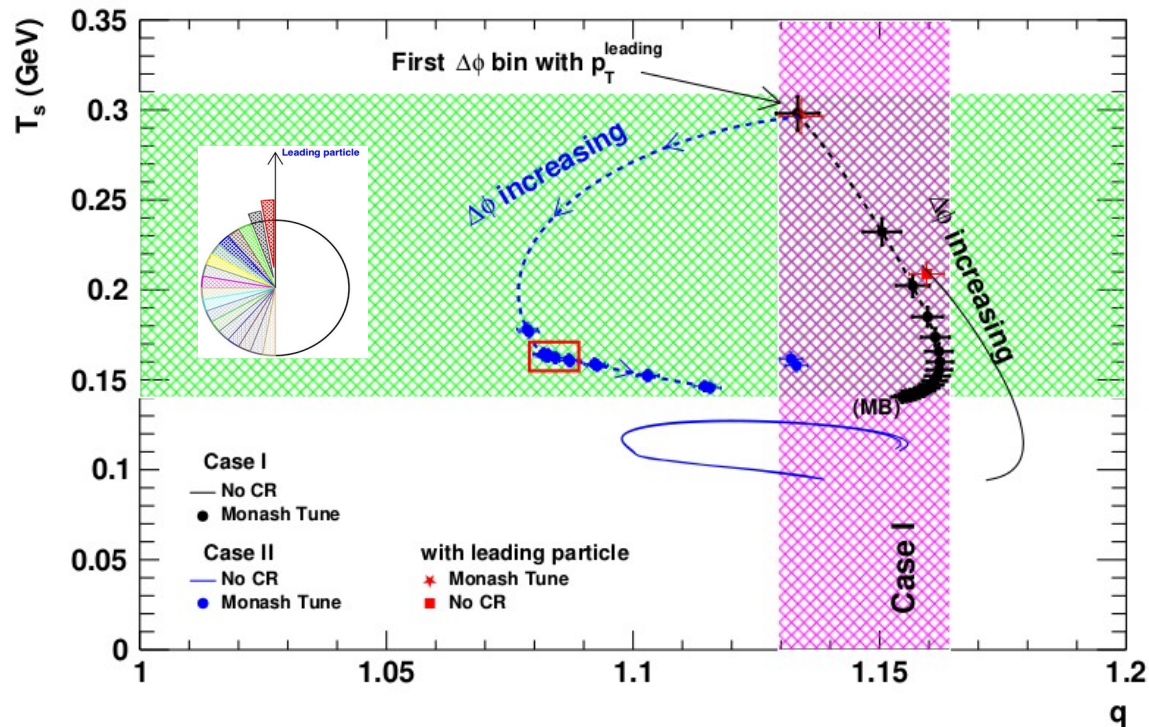
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→ Wider range of UE [40,140], than in CDF [60,120]

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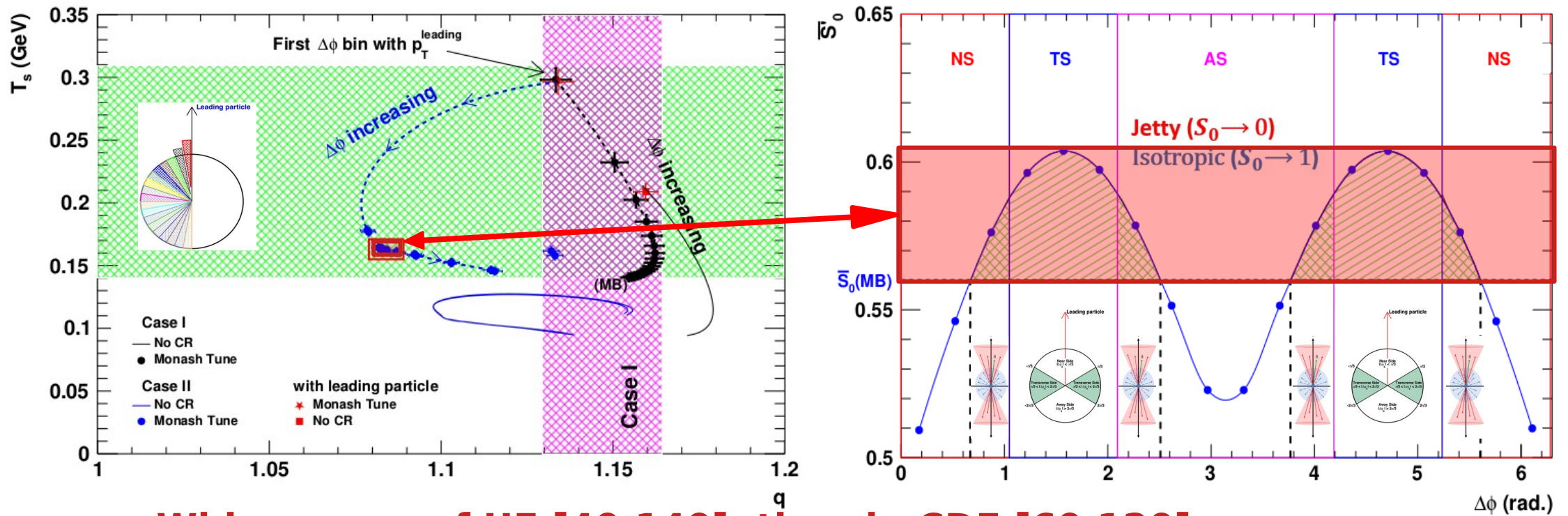
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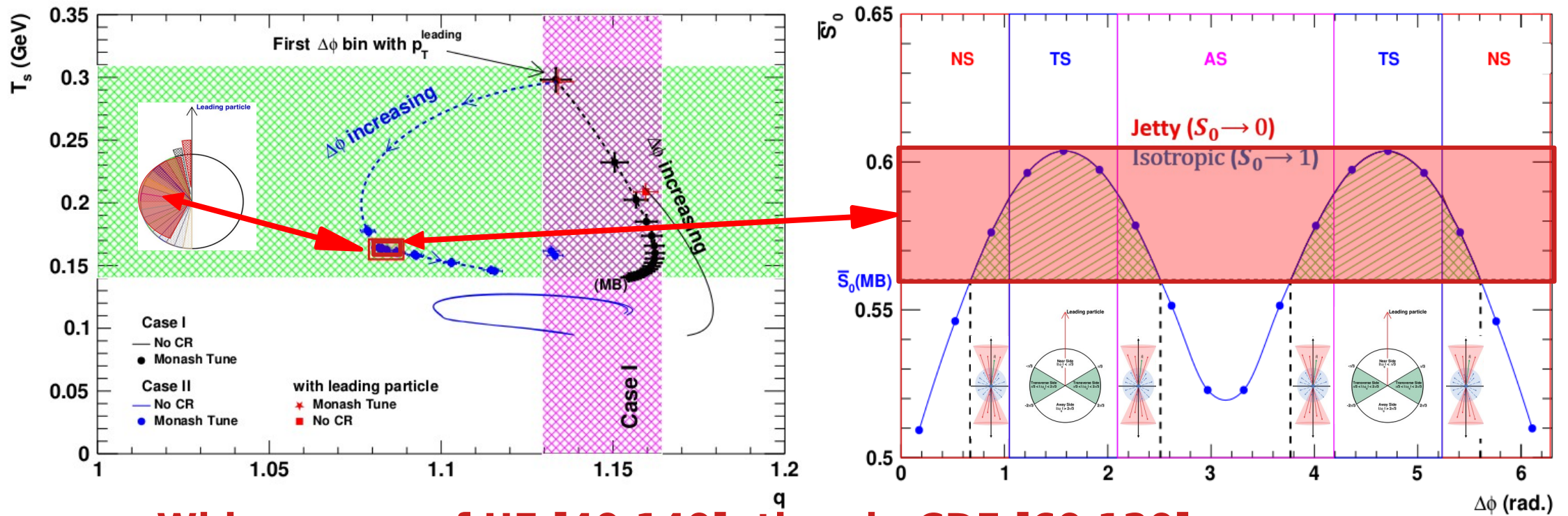
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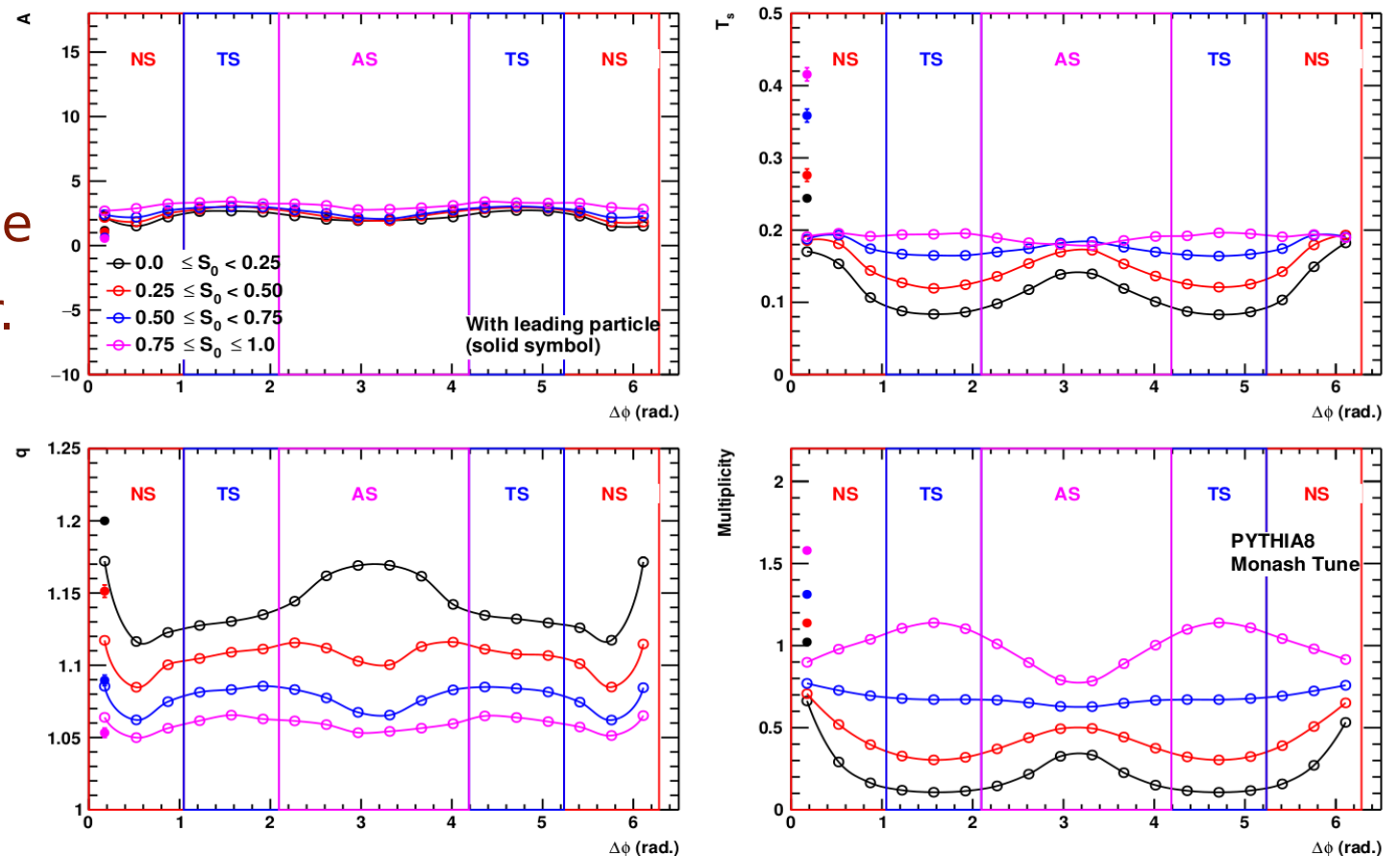
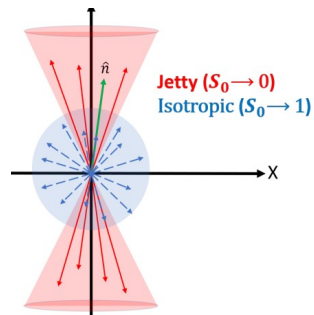


→ Wider range of UE [40,140], than in CDF [60,120]



# 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
- **Proposal to measure?**



# Conclusions

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  - **To take away...**
    - Tsallis-thermometer present wider UE
    - In degrees CDF: [60,120] → [40,140]
    - Event shape classification support the model
- Investigate this in larger systems, pA or AA?**



# BACKUP

# Derivatives of the parameters

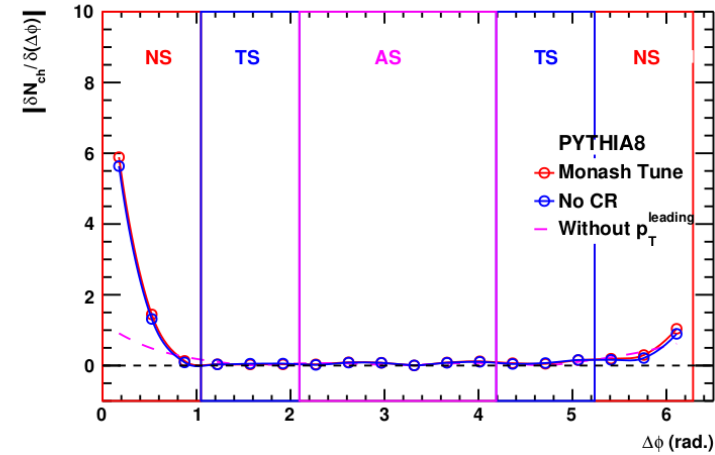
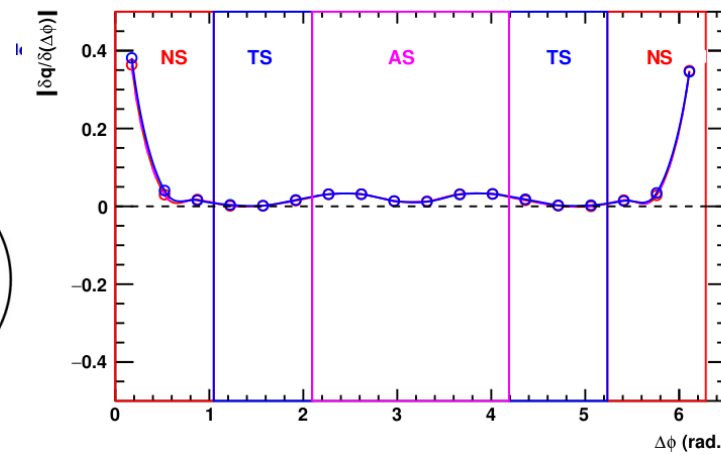
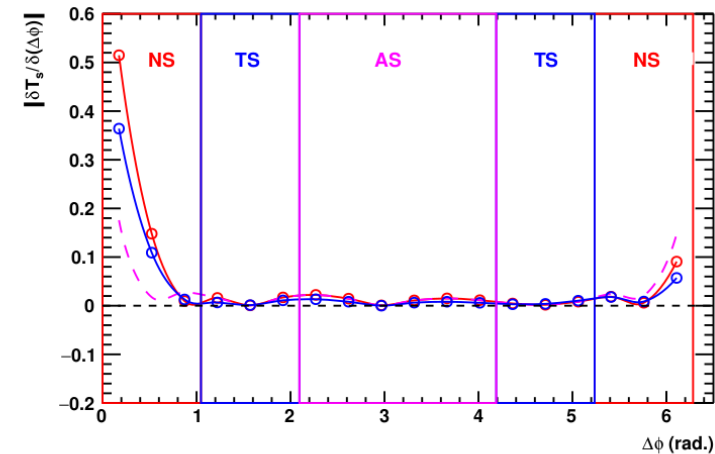
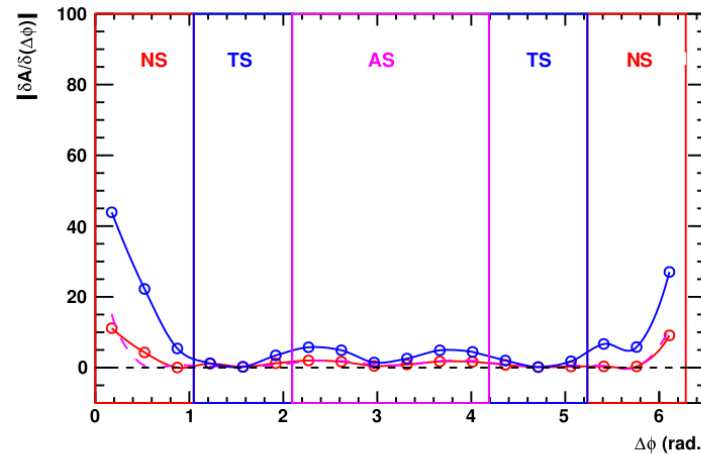
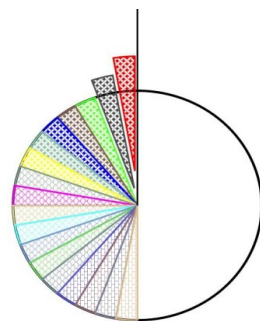
- PYTHIA spectra parameter derivatives with sliding angle**

- PYTHIA's model UE: CR & MPI
- TS (+AS) → constant T & q

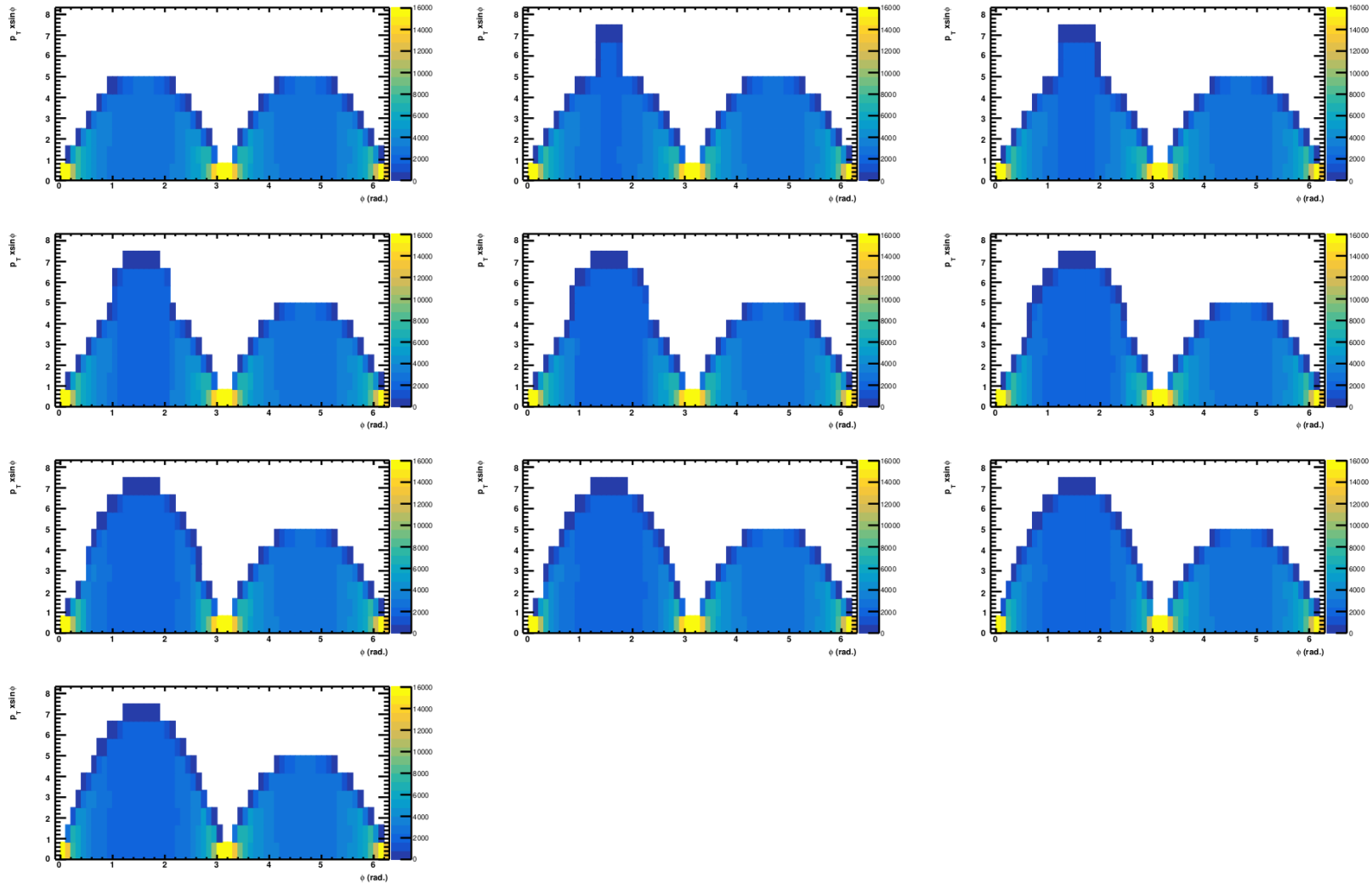
$$\frac{\delta T_s}{\delta(\Delta\phi)} \neq 0 \quad \& \quad \frac{\delta q}{\delta(\Delta\phi)} \neq 0 \quad (\text{for NS \& AS})$$

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

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



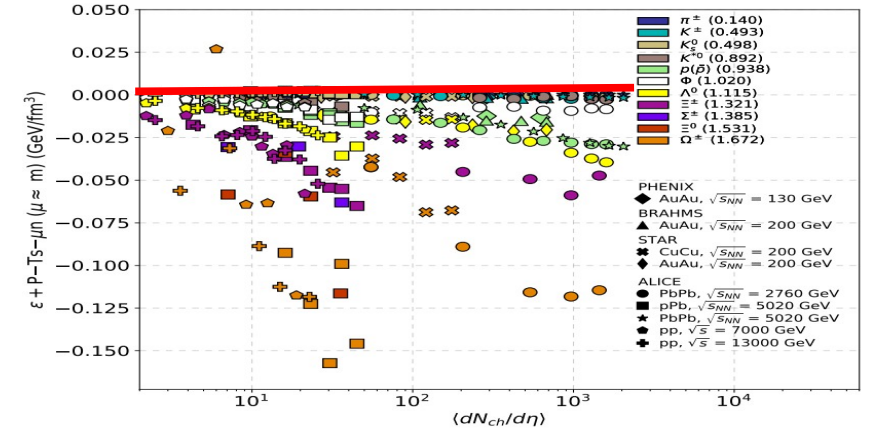
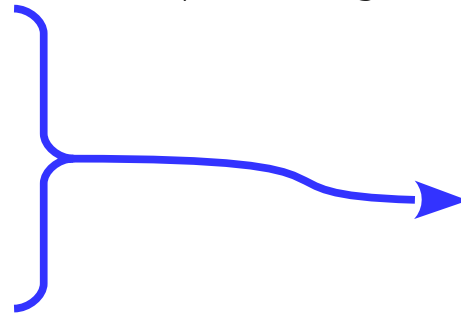
# Spherocity model with multiplicity



# Thermodynamical consistency?

**Thermodynamical consistency:** fulfilled up to a high degree

$$\begin{aligned}
 P &= g \int \frac{d^3 p}{(2\pi)^3} T f, \\
 N &= nV = gV \int \frac{d^3 p}{(2\pi)^3} f q, \\
 s &= g \int \frac{d^3 p}{(2\pi)^3} \left[ \frac{E - \mu}{T} f q + f \right], \\
 \varepsilon &= g \int \frac{d^3 p}{(2\pi)^3} E f
 \end{aligned}$$



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

