Multihadron Production: Universality, Correlations & Search for New Physics

Edward SARKISYAN-GRINBAUM

(CERN and University of Texas at Arlington)

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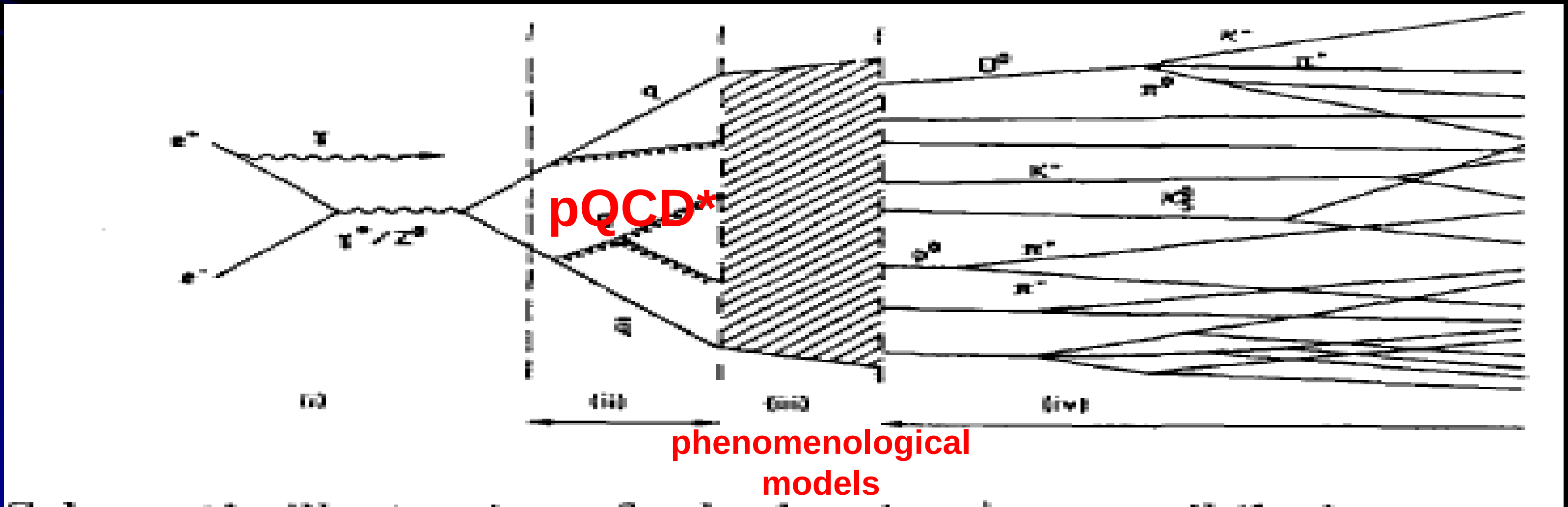
Multihadron production

- Multihadron production process - an ***important ingredient*** of high energy physics, provides **underlying** features of **strong** interactions
- Multihadron production still ***eludes*** its complete **understanding**
- The **theory of strong interactions**, **QCD** ***well reproduces*** the multiplicity distribution, energy dependence, while ***faces difficulties*** in describing **multi-particle correlations**
- Different ***phenomenological models*** used to describe *parton to hadron* transition



Schematic illustration of a hadronic e^+e^- annihilation event

Bulk observables

- Bulk observables - mean multiplicity and rapidity densities **- control parameters** of the formation and evolution of the collision initial state

- ***extensively*** studied in **particle and nuclear** collisions

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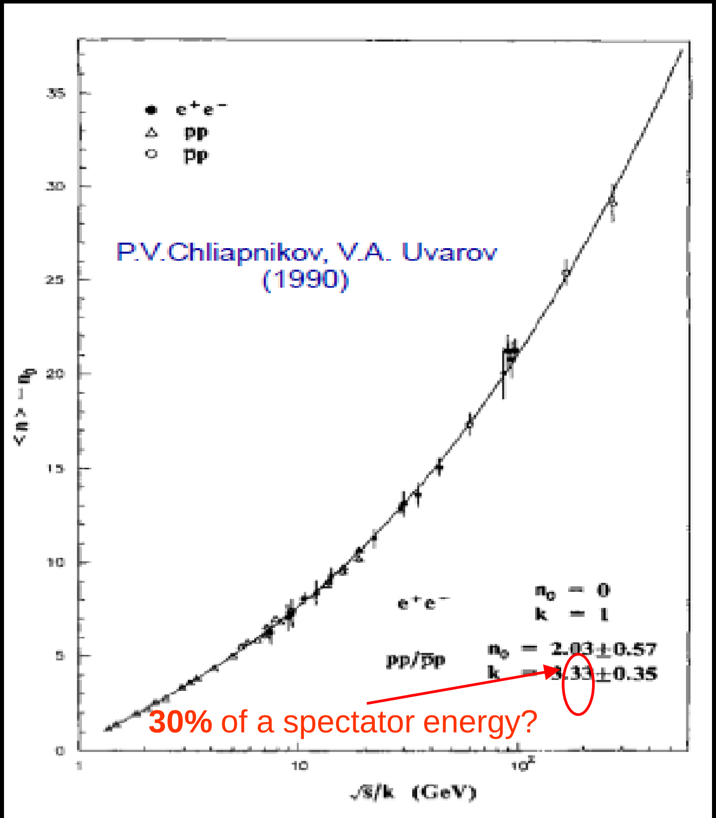

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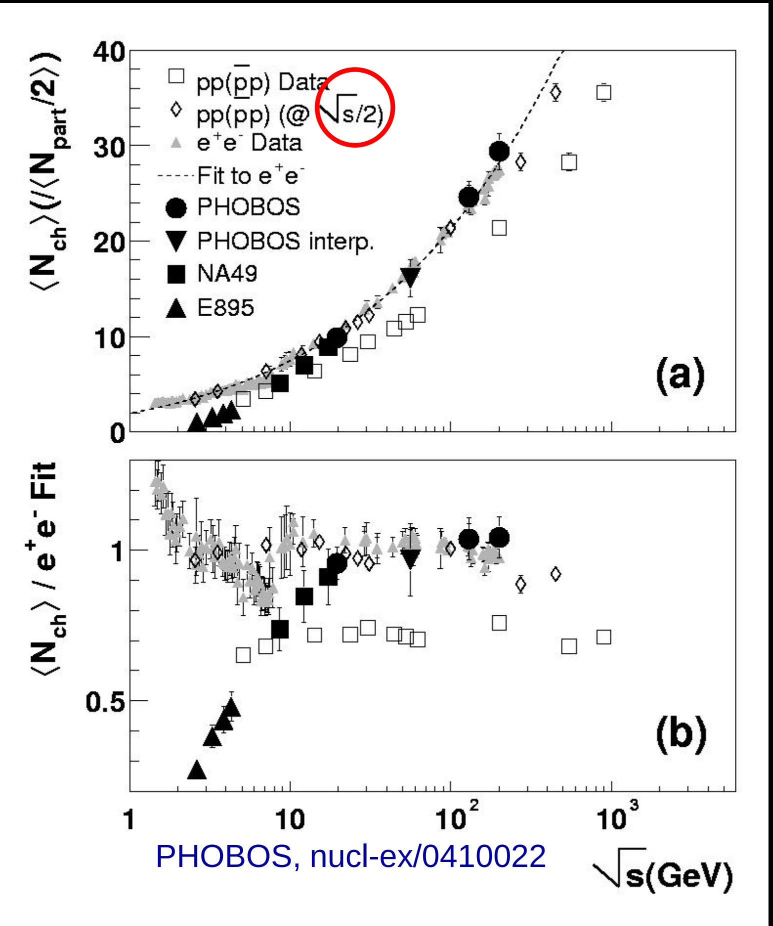
- **pp** multiplicity data ***needs to be scaled***



PHOBOS, nucl-ex/0410022

Bulk observables

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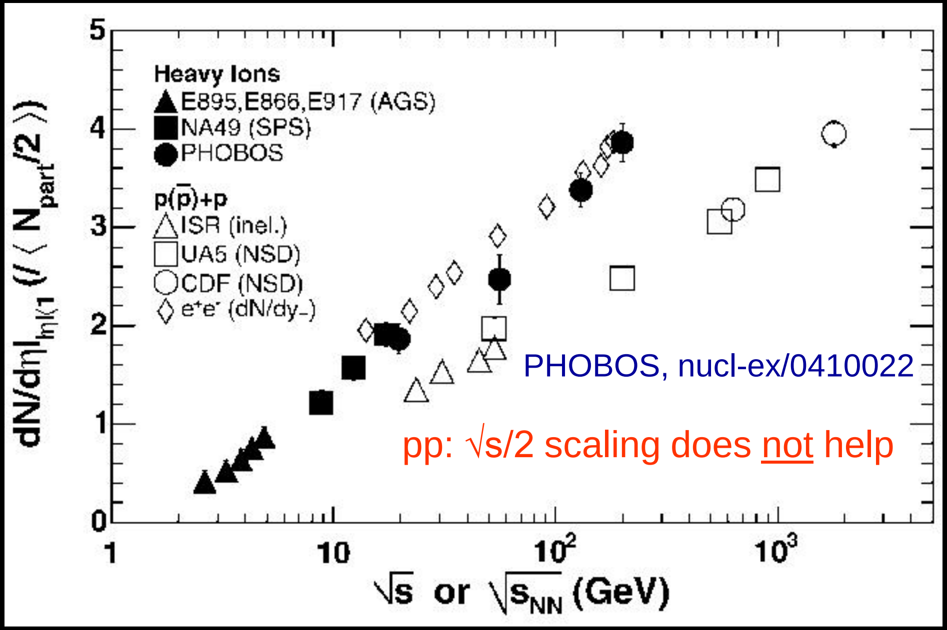
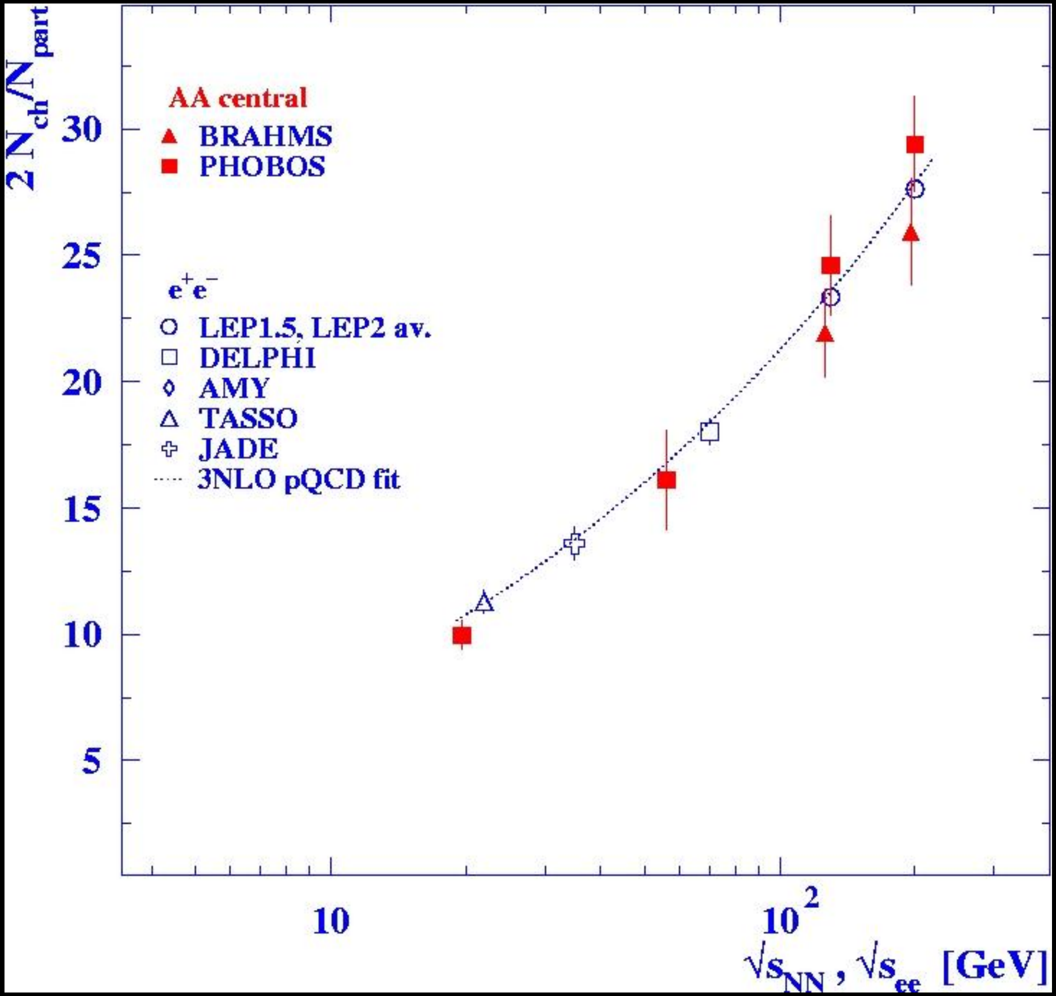
- ***extensively*** studied in **particle and nuclear** collisions
- **similarities** in e^+e^- and pp data: **universality** in multihadron production
- pp multiplicity data ***to be scaled***
- ***<u>not</u> the same*** scaling for ***<u>both</u>*** variables



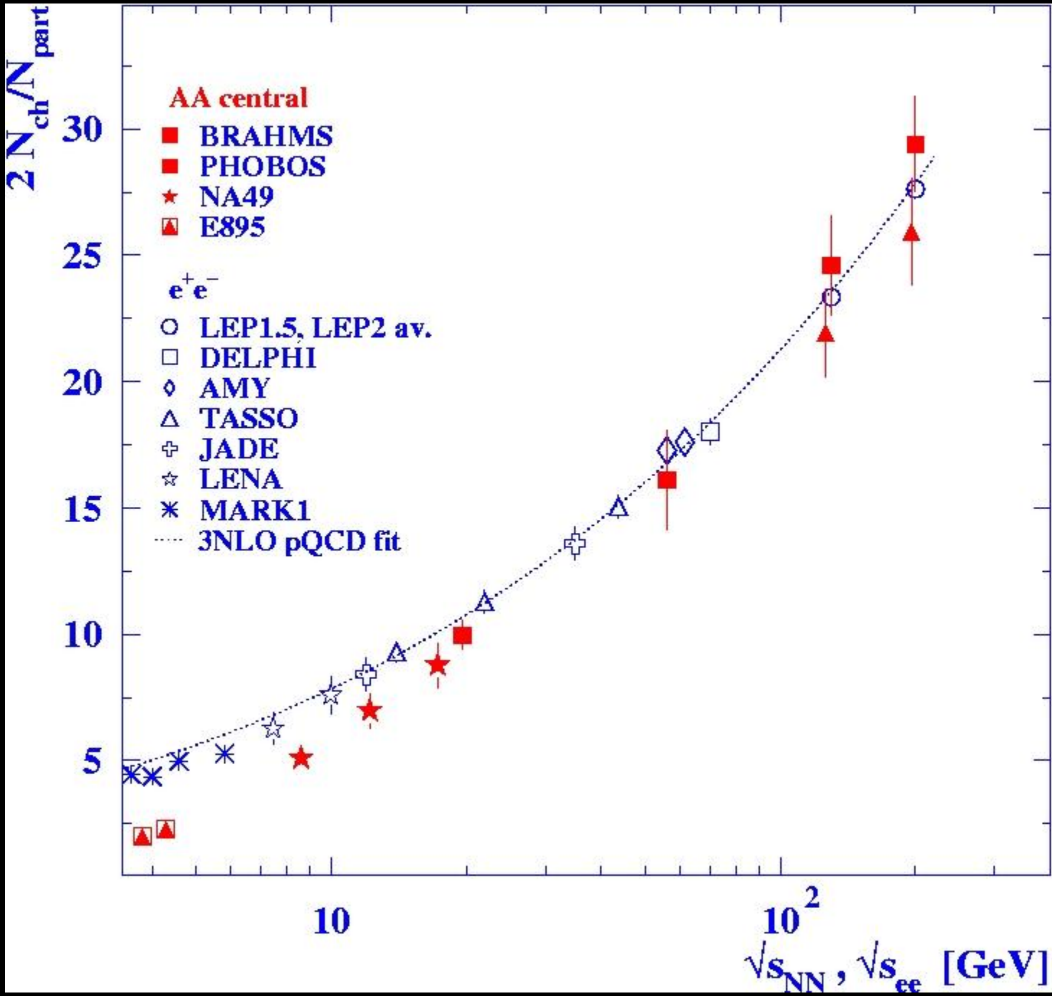
Multiplicity in e^+e^- and AA

- N_{ch} **e^+e^-** data ***similar*** to head-on **AA** data at RHIC energies
- well **reproduced** by 3NLO pQCD calcuations



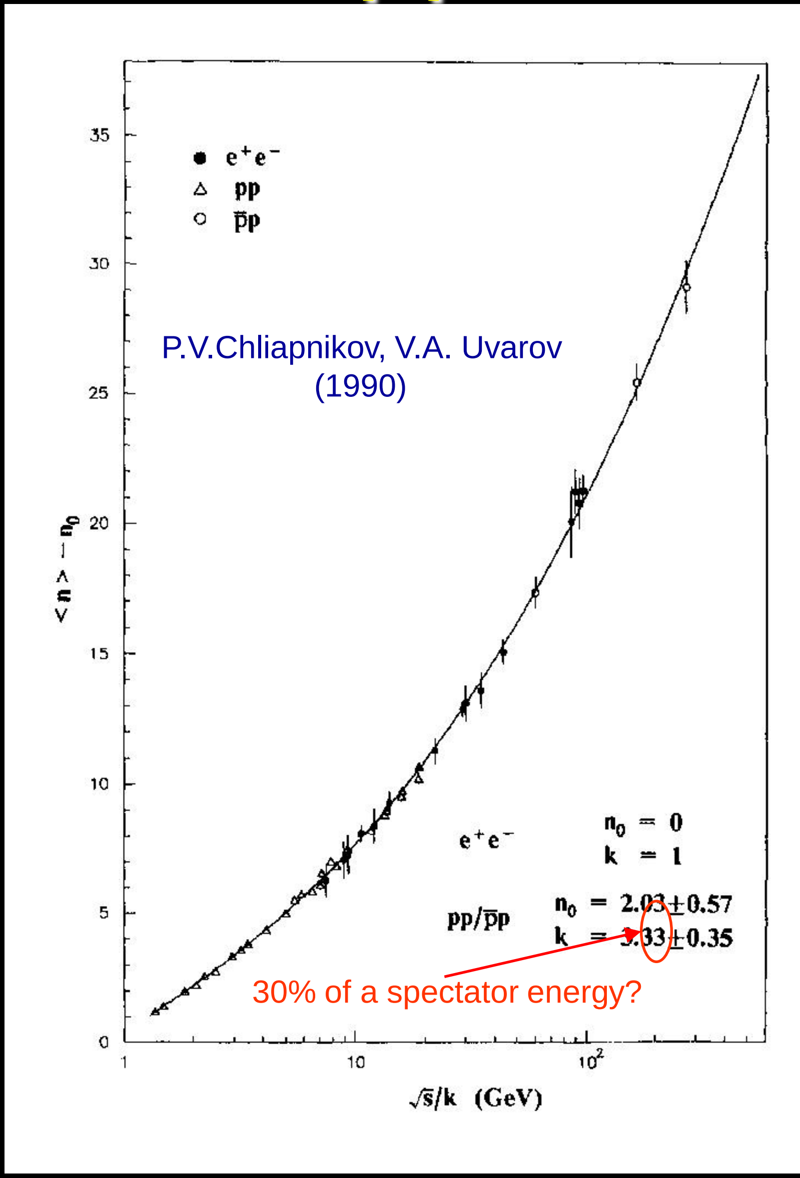
Multiplicity in e^+e^- and AA

- N_{ch} in **e^+e^-** ***similar*** to **AA** data
- well **reproduced** by 3NLO pQCD
- difference at the c.m. energy < 20 GeV: AA data lower than e^+e^- data (low energy fragments)



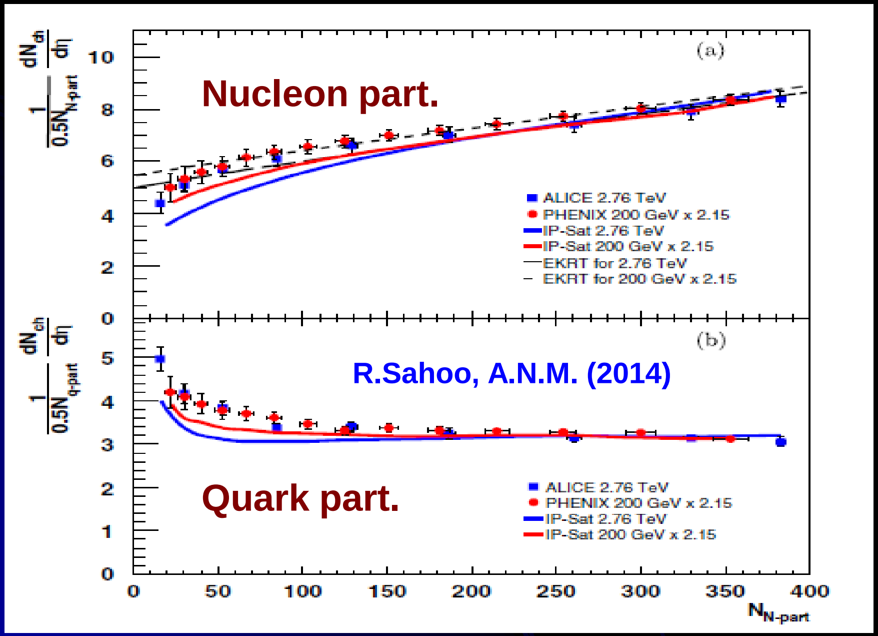
Multiplicity in e^+e^- and pp

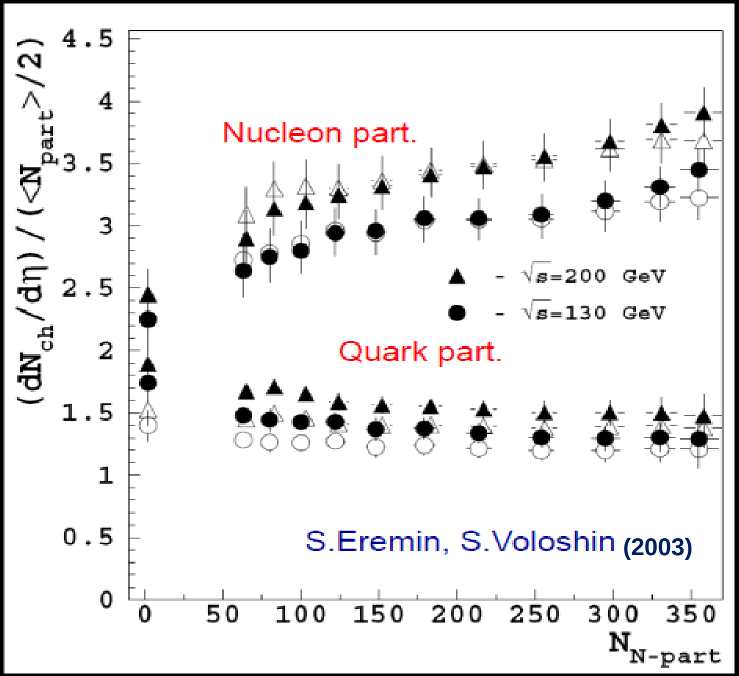
- N_{ch} in **e^+e^-** ***similar*** to **AA** data
- well **reproduced** by 3NLO pQCD theory
- N_{ch} in **pp** ***similar*** to e^+e^- (*and then to AA*) as $\sqrt{s_{ee}} = \sqrt{s_{pp}}/3$ indicating **quark-quark interaction plays a role**
- **observed at LEP *starting* days**



Constituent quark framework

No nucleon participant dependence as soon as densities calculated in the **constituent quark framework**



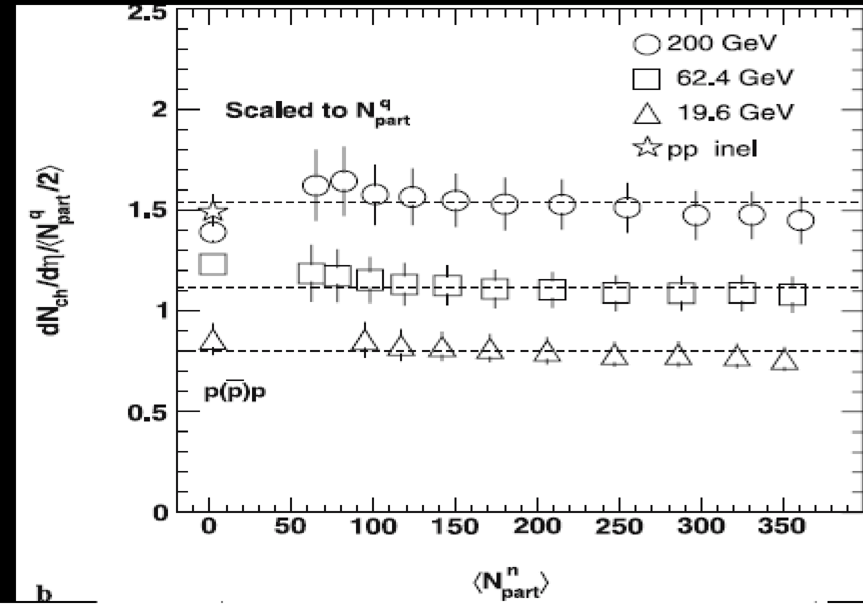


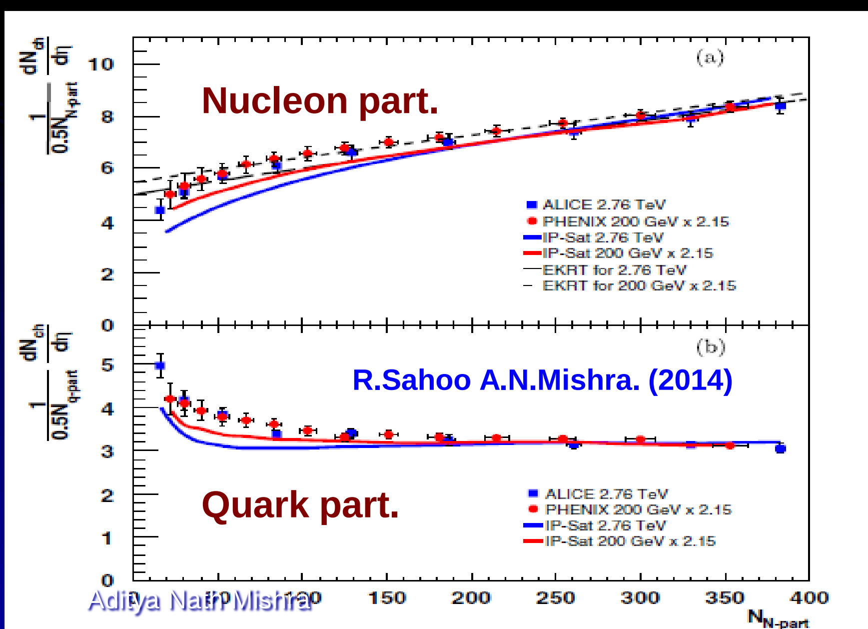
Nucleon Participants:
Open vs solid symbols: HIJING vs overlap model
Quark Participants:
Open vs solid symbols: different σ_{pp}

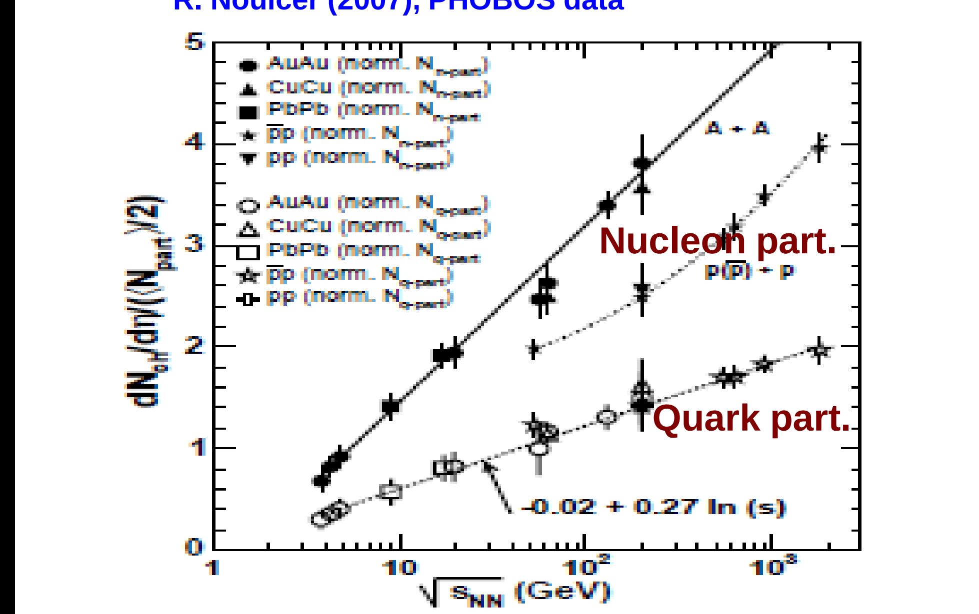
Constituent Quark Framework

***No* nucleon participant** dependence as soon as densities calculated in the **constituent quark framework**

AA* centrality** data are **similar** to **NSD *pp measurements







Aditya Nath Mishra

Constituent Quark Framework

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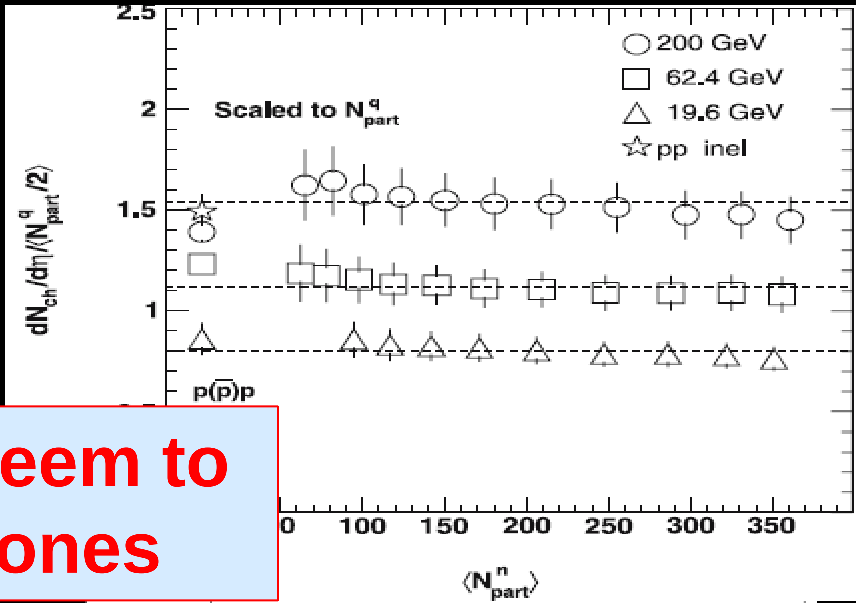
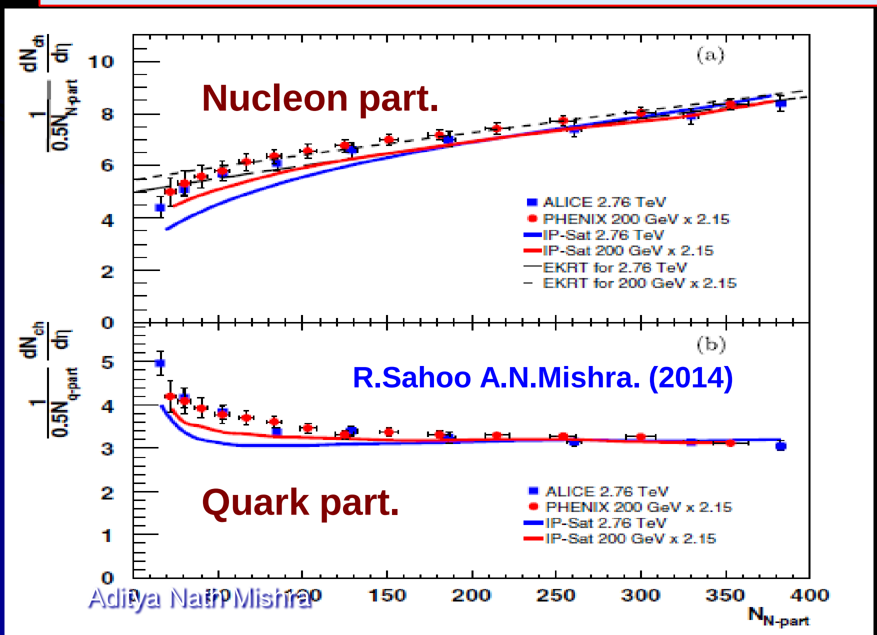
AA **centrality** data are **similar** to **NSD** ***pp*** measurements

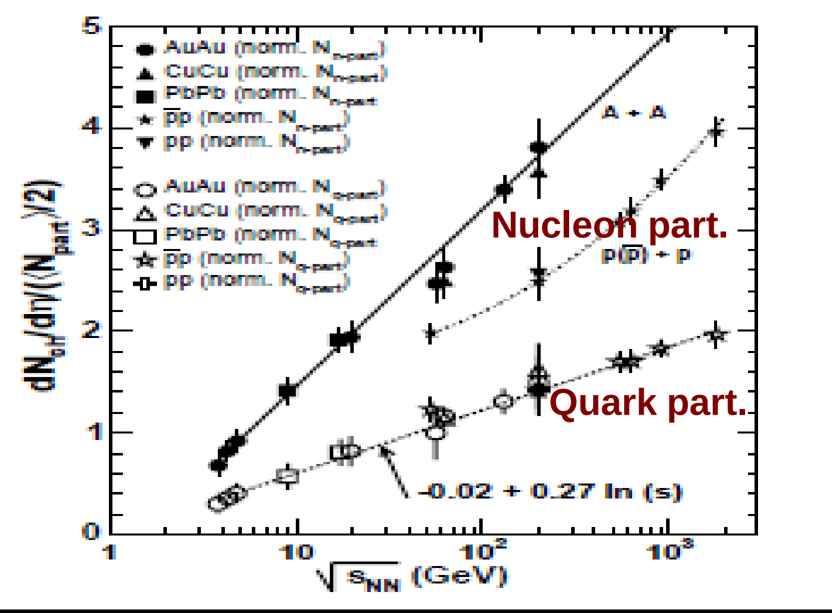


Quark degrees of freedom seem to play a role, *not* the nucleon ones



Aditya Nath Mishra

R. Nouicer (2007), PHOBOS data



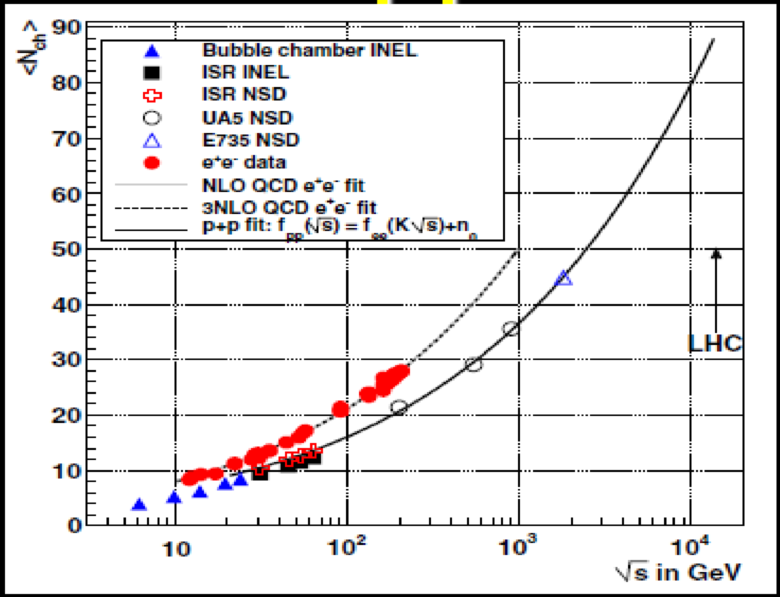
Energy scaling

- **e^+e^-** (structureless particles) annihilation - the ***total*** interaction ***energy*** is deposited in the initial state
- **pp** (superposition of three pairs of constituents) collision - ***only*** the *energy* of the interacting ***single quark pair*** is deposited in the initial state
- multiplicity and mid-rapidity density should be ***similar*** in pp at c.m. energy $\sqrt{s_{pp}}$ and e^+e^- at c.m. energy $\sqrt{s_{ee}} \approx \sqrt{s_{pp}}/3$
- **heavy ion (nuclear)** collisions***: more than one*** quark per nucleon participates
- ***head-on*** **nuclear** collisions: ***all three quarks*** participate nearly simultaneously and deposit **their** *energy* coherently into initial state
- multiplicity and mid-rapidity density should be ***similar*** in pp at c.m. energy $\sqrt{s_{pp}}$ and head-on AA at c.m. energy $\sqrt{s_{NN}} \approx \sqrt{s_{pp}}/3$

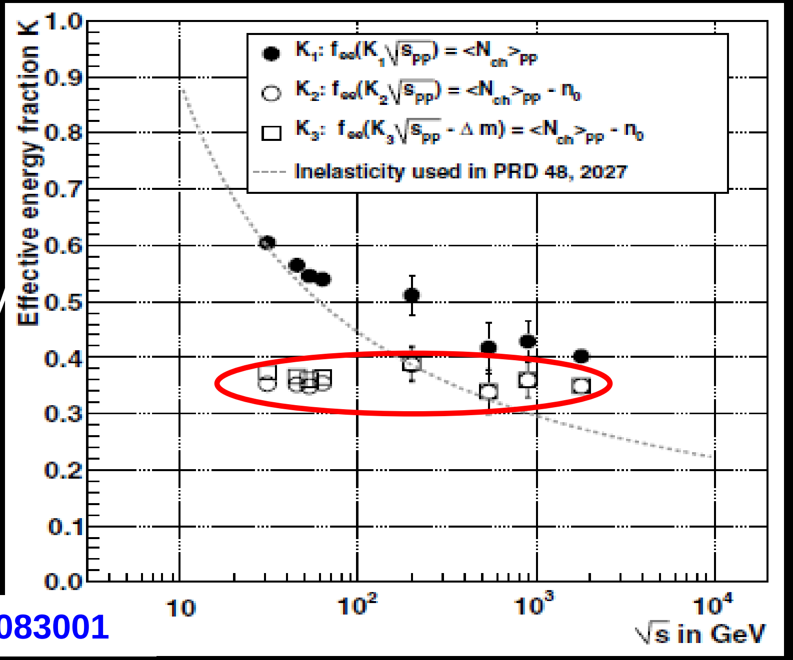
EKGS & A. Sakharov (2004) : dissipating energy participants

Multiplicity in e^+e^- and pp

- N_{ch} in $\mathbf{e^+e^-}$ ***similar*** to **AA** data
- well **reproduced** by 3NLO pQCD theory
- N_{ch} in **pp** ***similar*** to $\mathbf{e^+e^-}$ *(and AA)* as $\sqrt{s_{ee}} = \sqrt{s_{pp}}/3$



- **pp** data **similarly well reproduced** from e^+e^- theory (3NLO) fit ***up to highest*** LEP energies <u>assuming</u> $\mathbf{f_{pp} = f_{ee}(K\sqrt{s}) + n_0}$: $n_0=2$ characterizes the *number of **leading protons***, **K≈0.35** is the inelasticity and characterizes the fraction of ***effective*** energy (of produced particles), i.e. $\mathbf{\sqrt{s_{pp}} = 3\sqrt{s_{ee}}}$



- the inelasticity prefers the **0.35** value being ***energy-independent***

J.F. Grosse-Oetringhaus, K. Reygers, J. Phys. G 37 (2010) 083001

Universality in e^+e^-, ep and pp up to LHC

- **pp** data ***up to LHC*** are **well reproduced** *from QCD theory NNLO fit* for multiplicities **and for the midrapidity densities, *similar* to e^+e^- and ep** multiplicity data

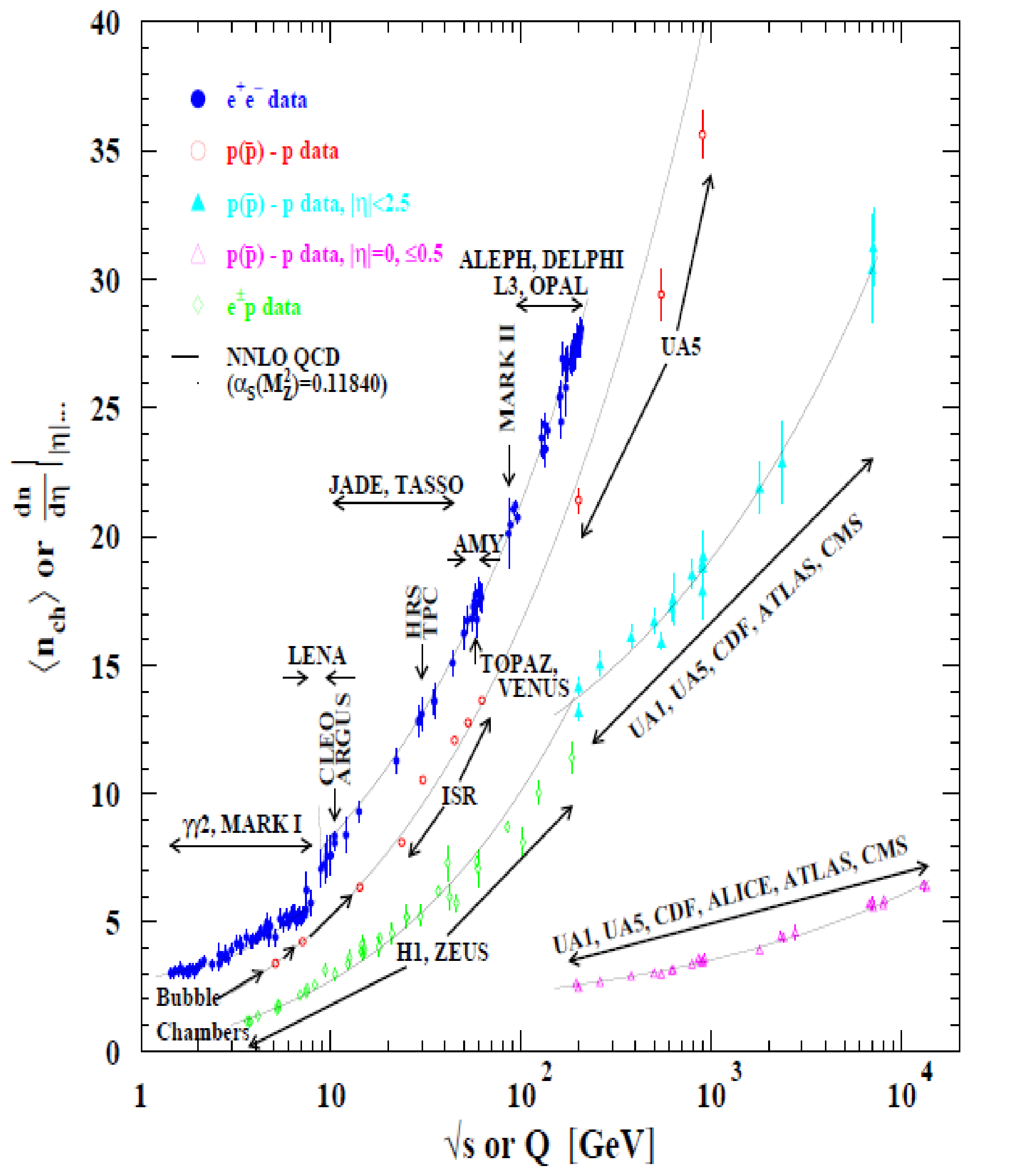


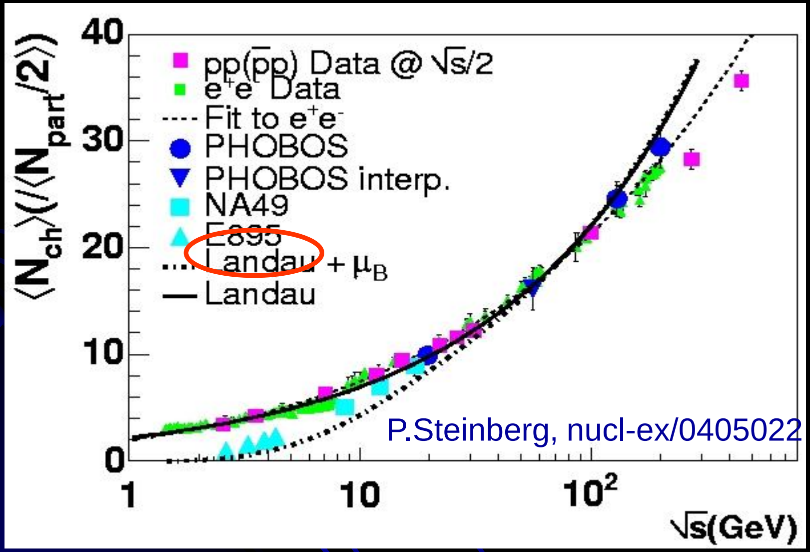
Figure 19.6: Average charged particle multiplicity $\langle n_{ch} \rangle$ as a function of $\sqrt{s}$ or Q for e^+e^- and $p\bar{p}$ annihilations, and pp and ep collisions.

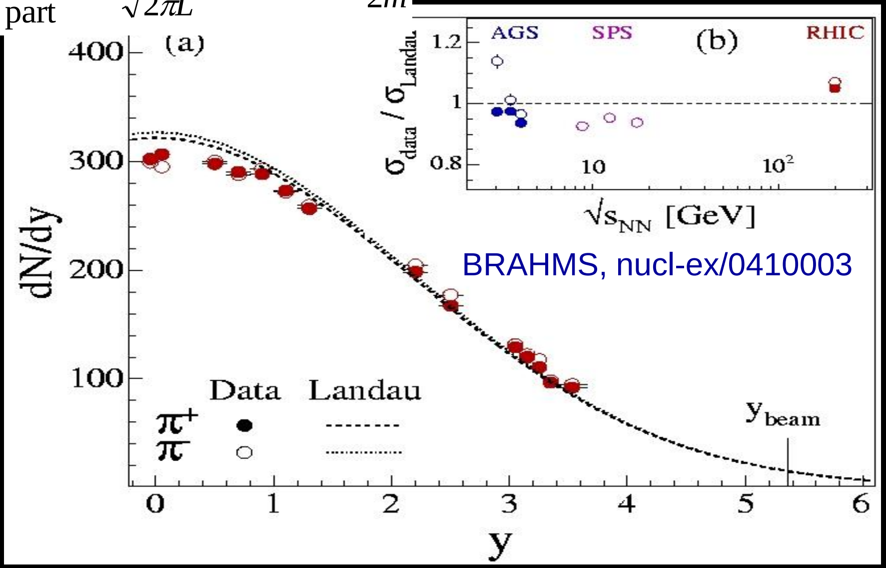
Particle Data Group, Review of Particle Physics (2018)

Hydrodynamics of collisions

- two head-on colliding Lorentz-contracted particles stop within overlapped zone
- formation of fully thermalised initial state at the collision moment
- the decay (expansion) of the initial state is governed by ***relativistic hydrodynamics*** **- Landau model**

$$\frac{2N_{ch}}{N_{part}}\frac{\exp\left(-y^2/2L\right)}{\sqrt{2\pi L}}, \quad L = \ln\frac{\sqrt{s}}{2m}$$





- **the production of particles is *defined* by the <u>energy</u> deposited into *the initial state*** (Heisenberg (1949), Fermi (1950), Landau (1953))

Hydrodynamics and energy scaling vs data

Landau Hydrodynamics + Constituent Quark approach

$$\rho(\mathbf{0}) = \rho_{\mathbf{pp}}(\mathbf{0}) \frac{\mathbf{2N_{ch}}}{\mathbf{N_{part} N_{ch}^{pp}}} \sqrt{\frac{\mathbf{L_{pp}}}{\mathbf{L_{NN}}}}$$

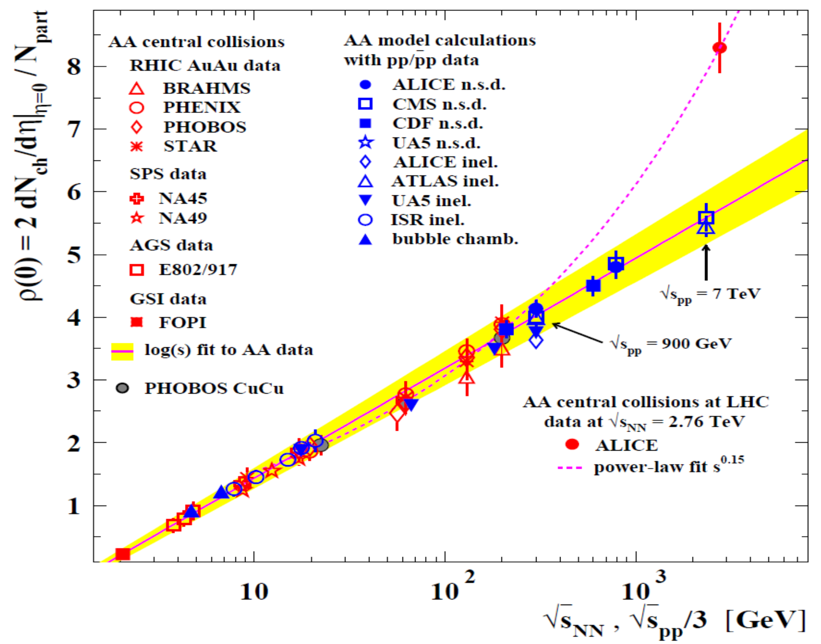
$$\mathbf{L} = \ln \frac{\sqrt{\mathbf{s}}}{\mathbf{2m}}$$

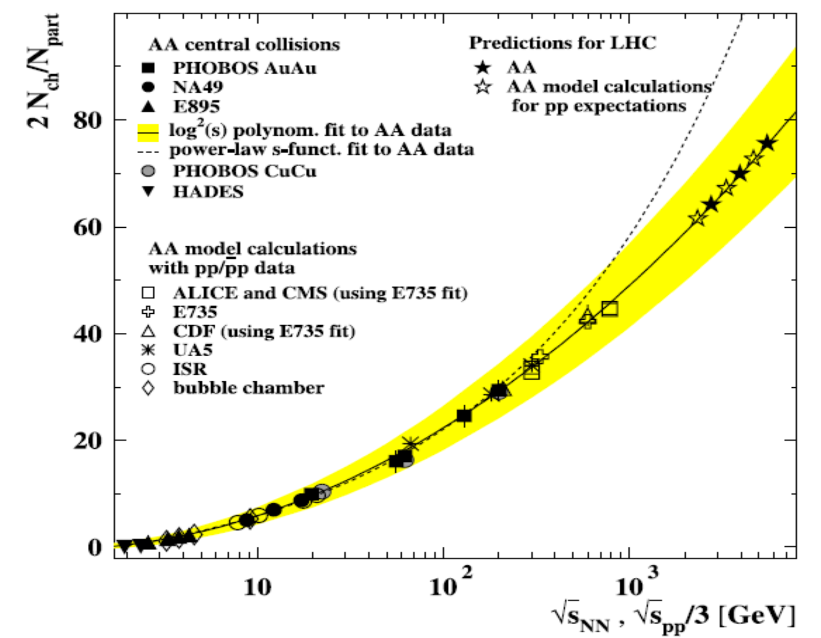
$$\sqrt{s_{NN}} = \sqrt{s_{pp}}/3$$

$$m = m_p, \tfrac{1}{3} m_p$$

$$\rho(\mathbf{0}) = \rho_{\mathbf{pp}}(\mathbf{0}) \frac{\mathbf{2N_{ch}}}{\mathbf{N_{part} N_{ch}^{pp}}} \sqrt{\mathbf{1} - \frac{\mathbf{4 \ln 3}}{\ln(\mathbf{4m_p^2}/\mathbf{s_{NN}})}}$$

- ✓ Nuclear data *both* on the midrapidity density *and* the mean multiplicity energy dependences well reproduced up to top RHIC energy





EKGS & A.S. Sakharov, Eur. Phys. J. C 70 (2010) 533

Hydrodynamics and energy scaling vs data

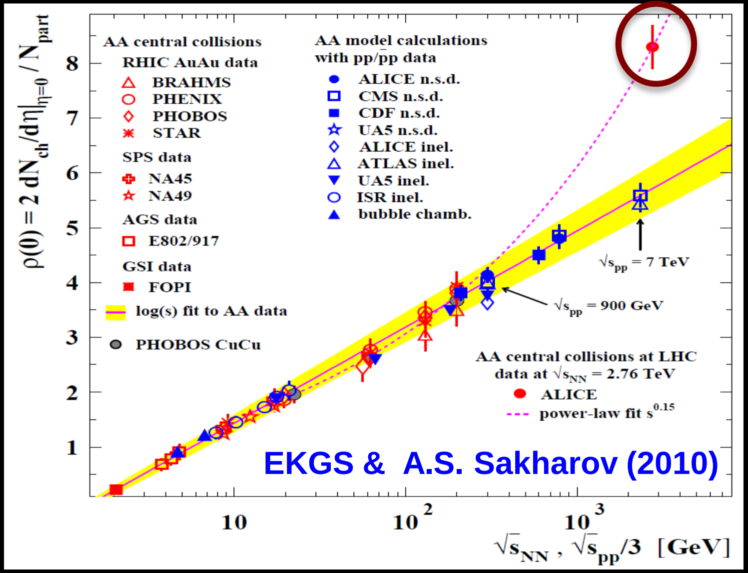
Landau Hydrodynamics

$$\rho(0) = \rho_{pp}(0)\frac{2N_{ch}}{N_{part}N_{ch}^{pp}}\sqrt{\frac{L_{pp}}{L_{NN}}}$$

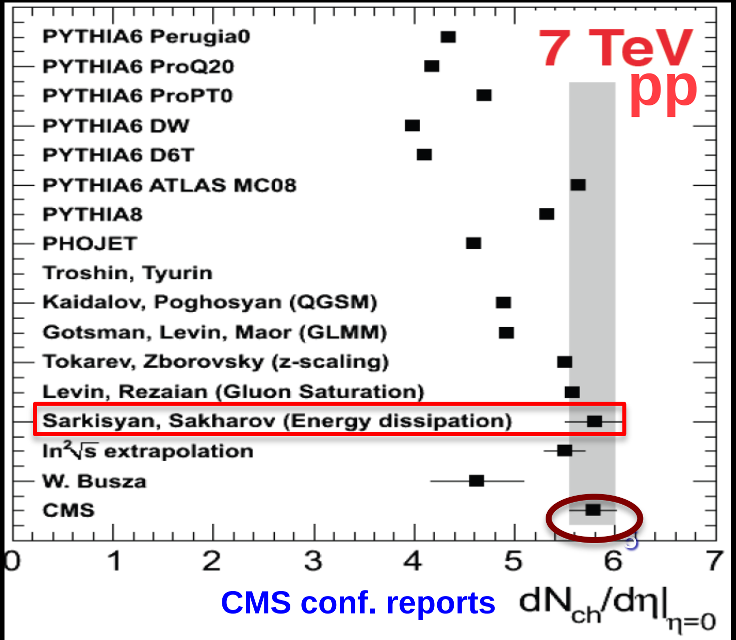
$$L = \ln\frac{\sqrt{s}}{2m}$$

Landau Hydrodynamics+ Constituent Quark approach

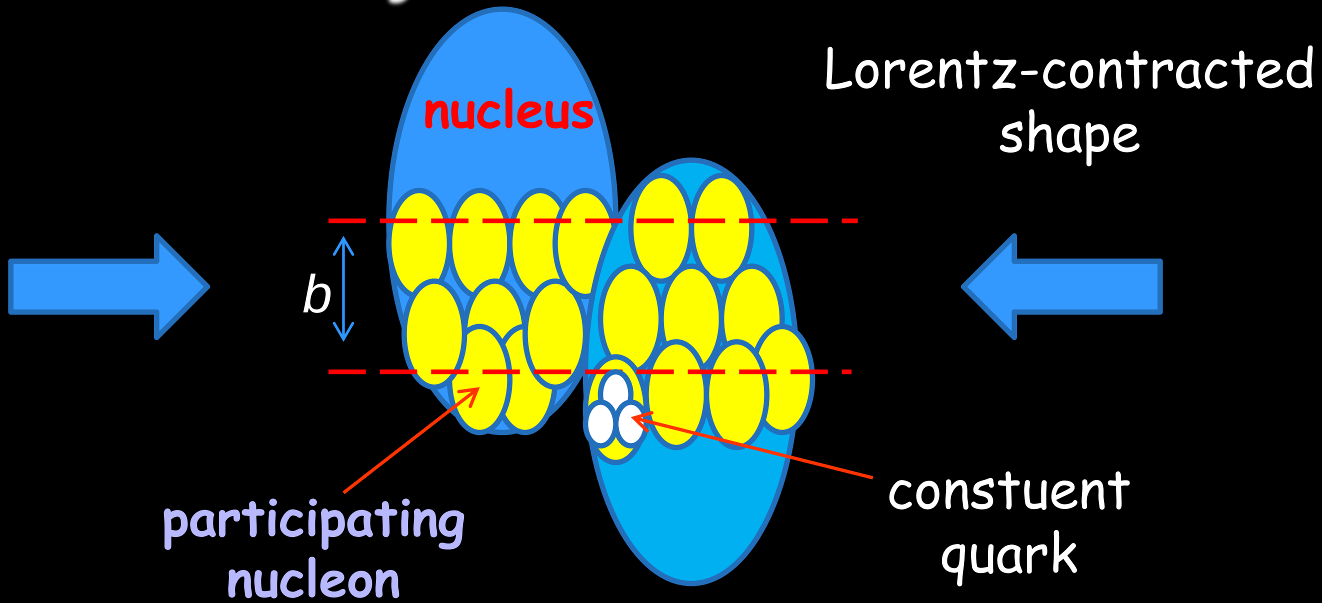
$$\rho(0) = \rho_{pp}(0)\frac{2N_{ch}}{N_{part}N_{ch}^{pp}}\sqrt{1-\frac{4\ln 3}{\ln(4m_p^2/s_{NN})}}$$



- ✓ Nuclear data ***both*** on midrapidity density *and* mean multiplicity energy dependence **well reproduced** up to top RHIC energy
- ✓ **pp data at the LHC energy of 2-7 TeV well predicted**
- ✓ **Heavy-ion collisions at the LHC *indicate* a transition to a possibly *new regime*** with more degrees of freedom



Centrality in nuclear collisions



``Centrality'' *α* characterizes the area of the overlap of the nuclei, described by the ***impact factor, b.***

The ***more central*** the collision is ***the smaller*** the impact factor ***b***, and then the centrality are. The centrality is measured in % characterizing the rate of cross-section.

The ***number of participants*** N_{part} increases as the centrality *decreases.*

Hydrodynamics and effective energy

Effective energy:

Effective energy can be calculated as following:

$$\epsilon_{\mathbf{NN}} = \sqrt{\mathbf{s}_{\mathbf{NN}}}(\mathbf{1} - \alpha)$$

Here α is centrality percentile.

e.g. For 0-5% centrality collision, α = 0.025

Hydrodynamics and effective energy

Effective energy:

Effective energy can be calculated as following:

$$\epsilon_{NN} = \sqrt{s_{NN}}(1 - \alpha)$$

this is "colliding" energy of participants

Here α is centrality percentile.

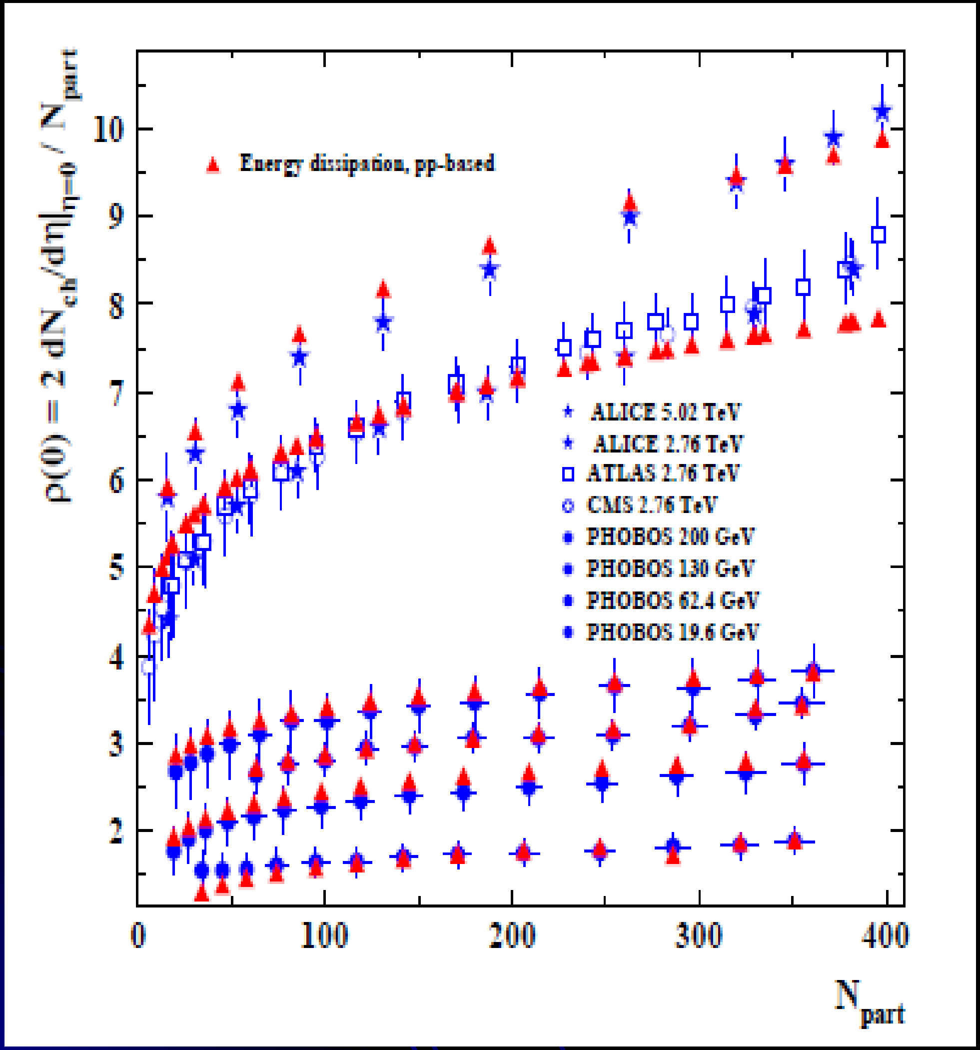
e.g. For 0-5% centrality collision, α = 0.025

$$\rho(0) = \rho_{pp}(0)\frac{2N_{ch}}{N_{part}N_{ch}^{pp}}\sqrt{1 - \frac{2\ln 3}{\ln(2m_p/\epsilon_{NN})}}$$

$$\epsilon_{NN} = \sqrt{s_{pp}}/3$$

$N_{ch}/(N_{part}/2)$ comes from the *most central* collisions

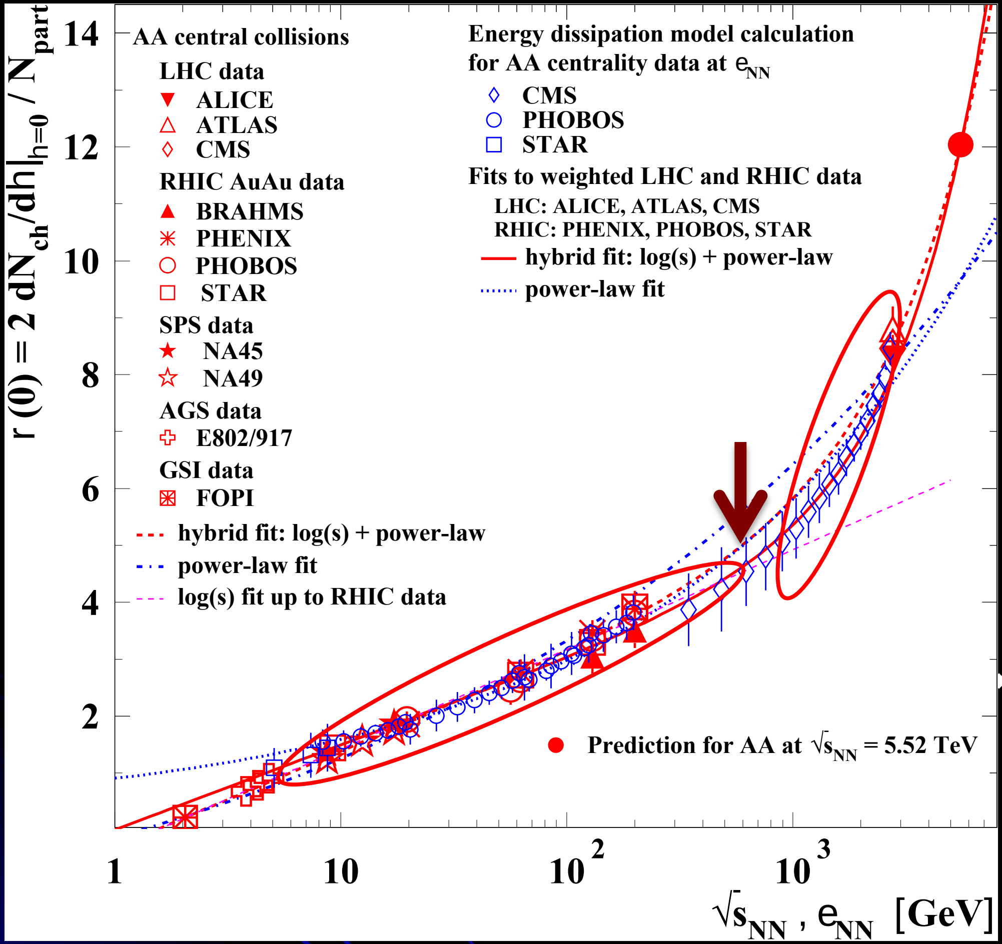
Effective energy vs data up to LHC



- ***Effective-energy*** **(based on dissipating energy)** ***calculations*** **have a very good agreement with data up to LHC**
- ***Similarity*** in all the data from peripheral to the most central ones

EKGS, A.N.Mishra, R.Sahoo, A.S. Sakharov, Phys.Rev. D 94 (2016) 011501R

Effective energy vs data up to LHC

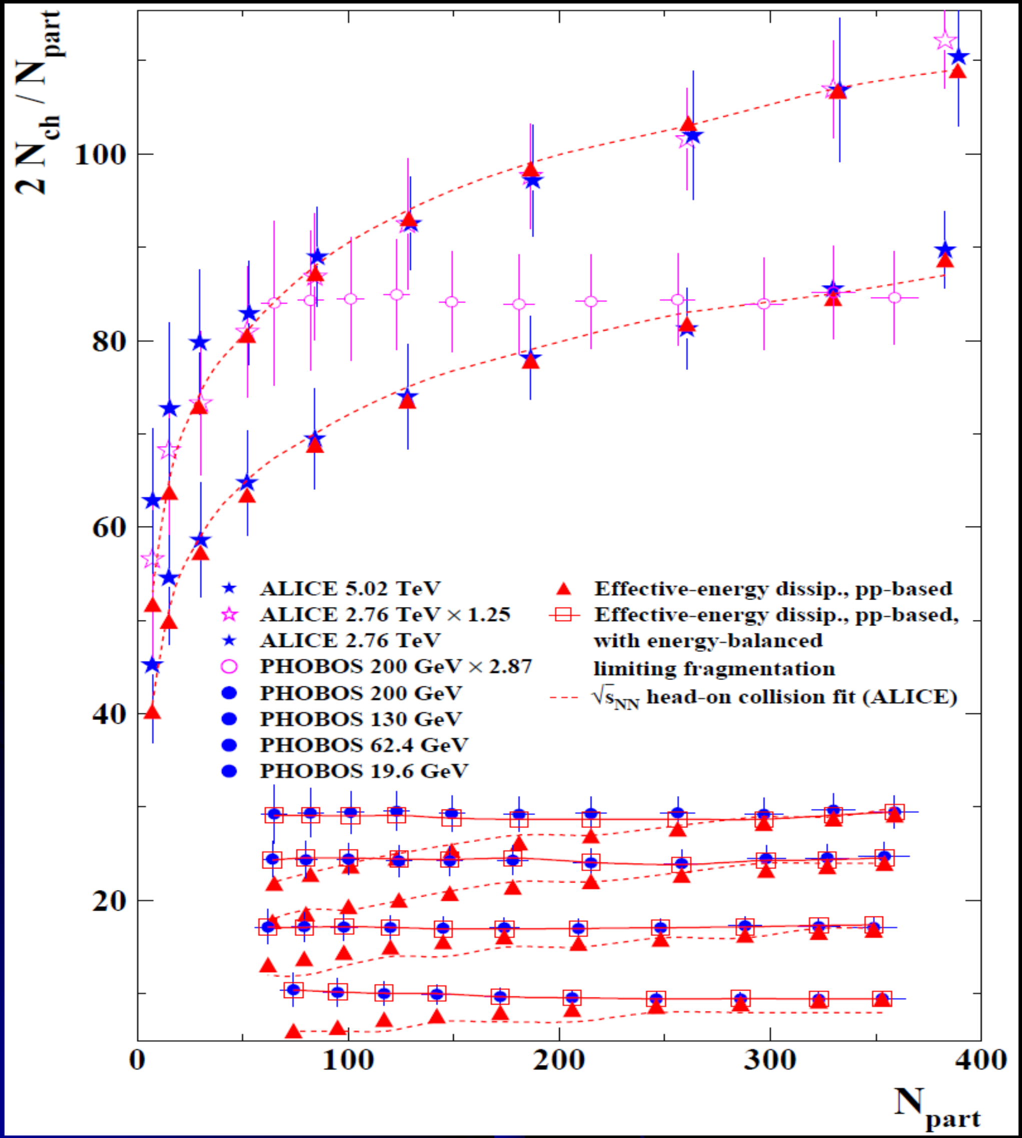


- ***Effective-energy*** **(based on dissipating energy model)** ***calculations*** **have a very good agreement with data**
- ***Similarity*** in all the data **from peripheral to the most central ones** follow the same energy behavior
- The combined data indicate ***possible transition to a new regime*** at $\sqrt{s_{NN}}$=0.5-1.0 TeV

Effective-energy approach stresses *underlying* **similarity between head-on and non-central** heavy-ion collisions

A.N. Mishra, EKGS, R. Sahoo, A.S. Sakharov, Eur. Phys. J. C 74 (2014) 3147
EKGS, A.N.Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 94 (2016) 011501R

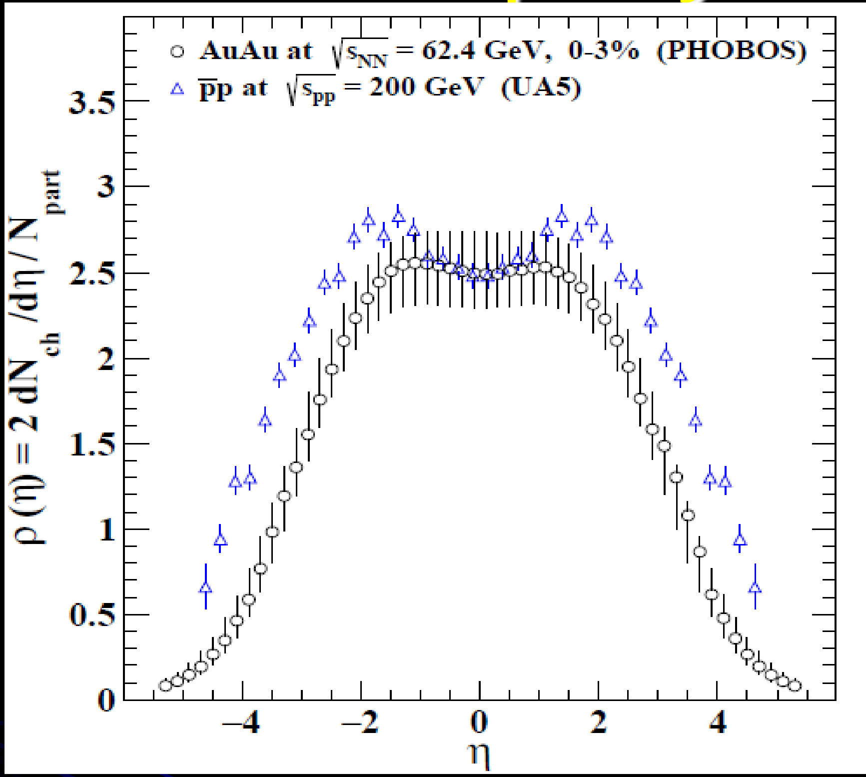
Total multiplicity centrality dependence

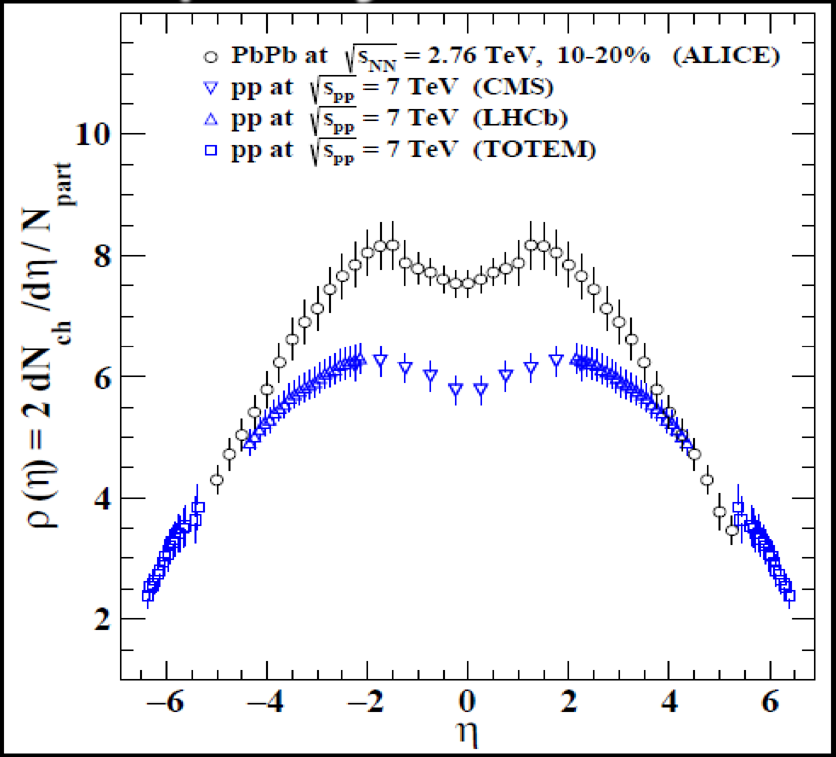


EKGS, A.N.Mishra, R.Sahoo, A.S. Sakharov,
Phys. Rev. D 93 (2016) 054046 & arXiv:1803.01428

- ***Effective-energy*** **(based on dissipating energy)** ***calculations*** **have a very good agreement with LHC data**
- ***Calculations*** are *below* the RHIC *less central* data
- ***Difference*** between LHC (TeV) and RHIC (GeV) measurements
- ALICE $\sqrt{s_{NN}}$ (few GeV to few TeV) fit to *most central* data ***follows*** the effective energy calculations

From mid-rapidity to full-rapidity distribution

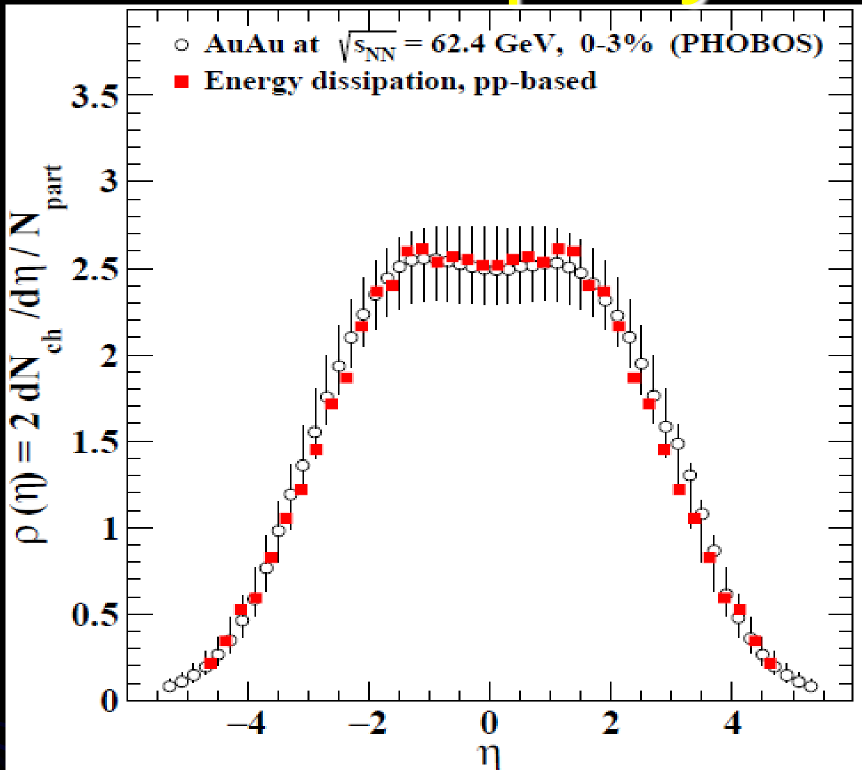


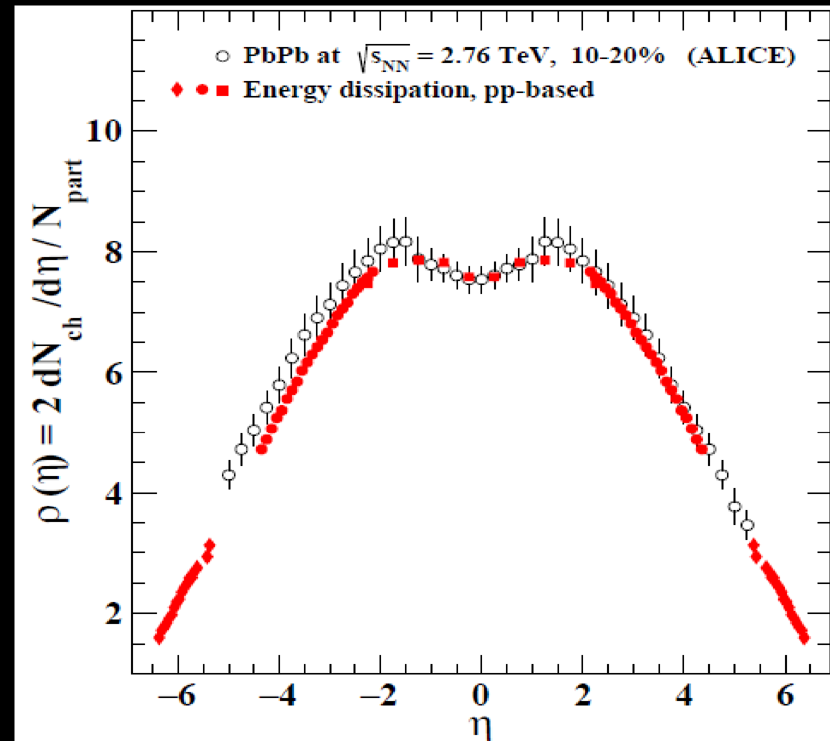


- **pp data vs <u>high-central</u> *AA* data at** $\sqrt{s_{pp}} \approx 3\sqrt{s_{NN}}$ (or $3\varepsilon_{NN}$)
- At **LHC** energy, pp measurements from *three different* experiments

EKGS, A.N.Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

From mid-rapidity to full-rapidity distribution



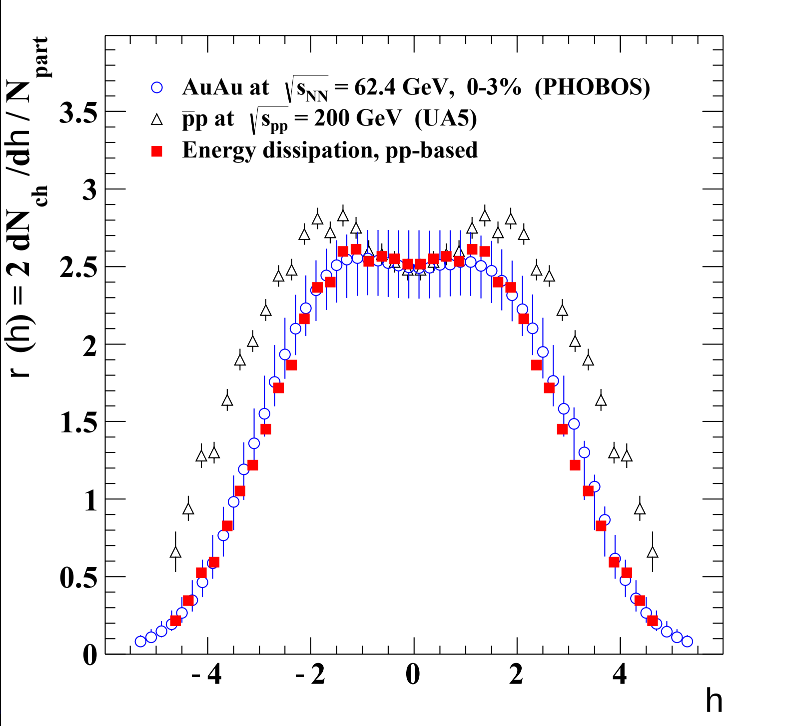


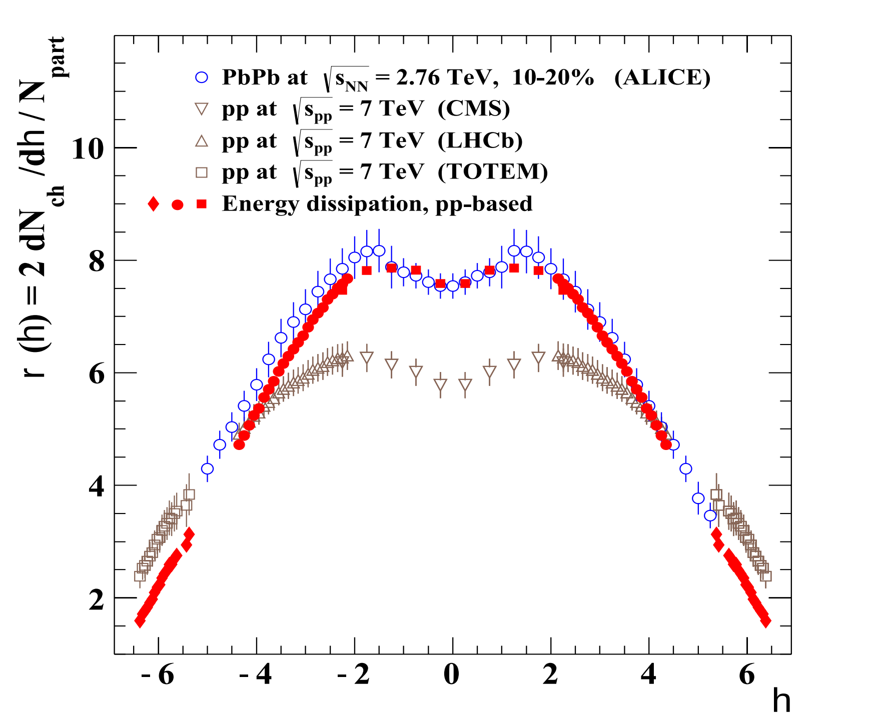
$$\frac{\rho(\eta)}{\rho_{pp}(\eta)} = \frac{2N_{\rm ch}}{N_{\rm part}N_{\rm ch}^{pp}}\sqrt{1+\frac{2\ln 3}{L_{NN}}}\exp\left[\frac{-\eta^2}{L_{NN}(2+L_{NN}/\ln 3)}\right]$$

$$L = \ln(\sqrt{s}/2m) \quad \sqrt{s_{NN}} = \sqrt{s_{pp}}/3 \quad m = m_p, \tfrac{1}{3}m_p$$

EKGS, A.N.Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

From mid-rapidity to full-rapidity distribution



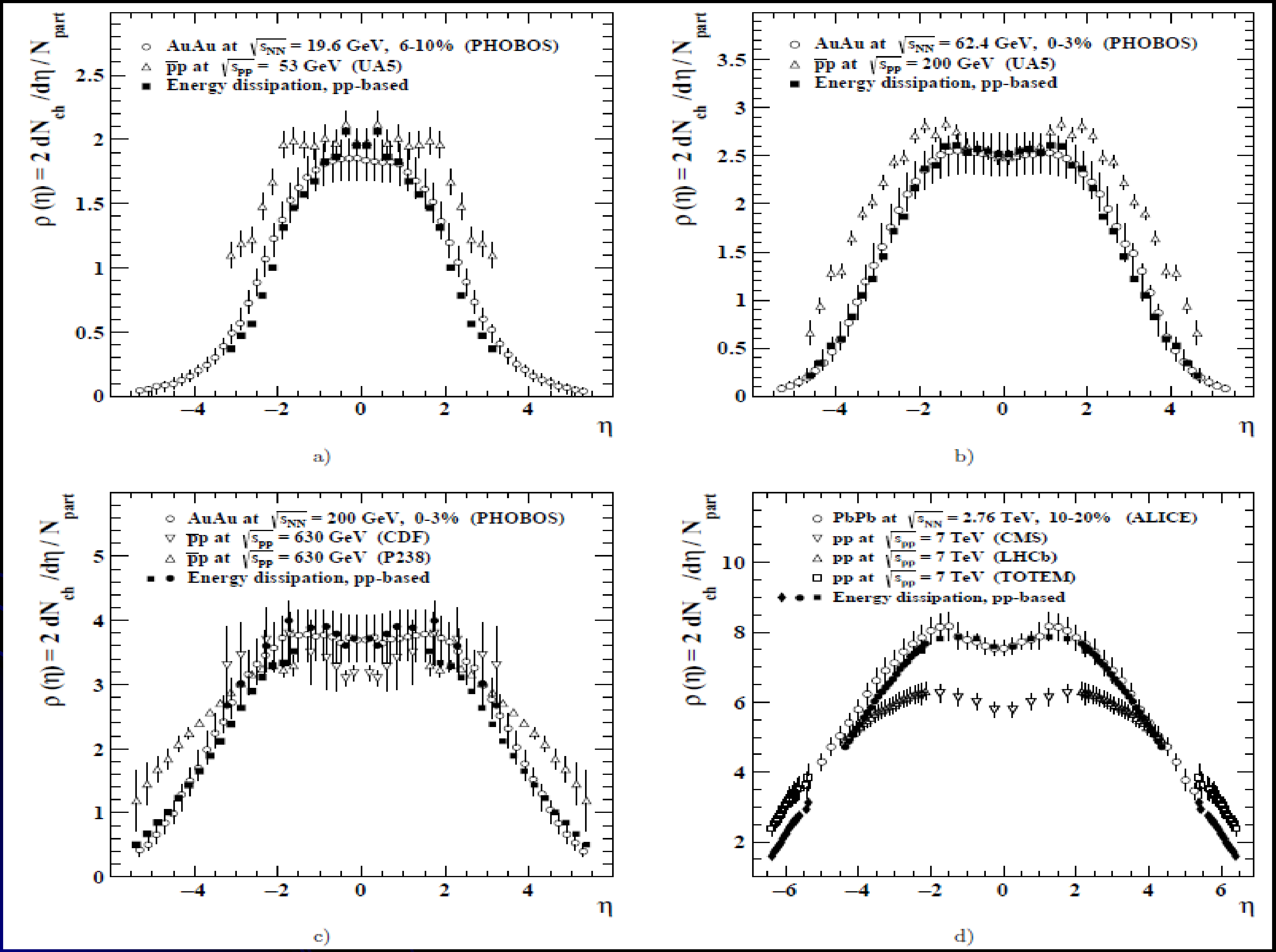


- **Calculations for <u>high-central</u> collisions are in very good agreement with the measurements.**
  Agreement found for all available data $\sqrt{s_{NN}}$ = 20 GeV to a few TeV

- At LHC energy, pp measurements from *three different* experiments are used and ***reproduce*** AA data

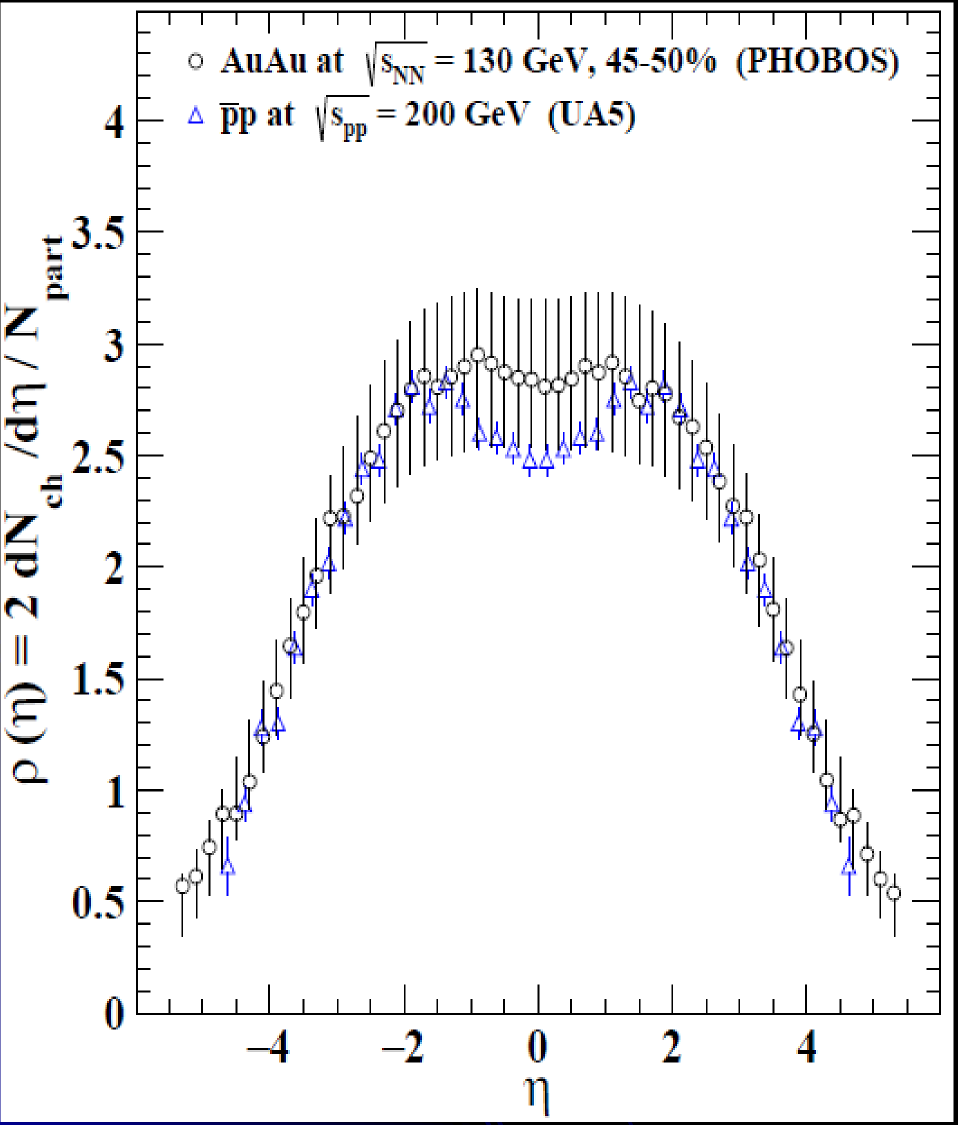
EKGS, A.N.Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

From mid-rapidity to full-rapidity distribution



EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

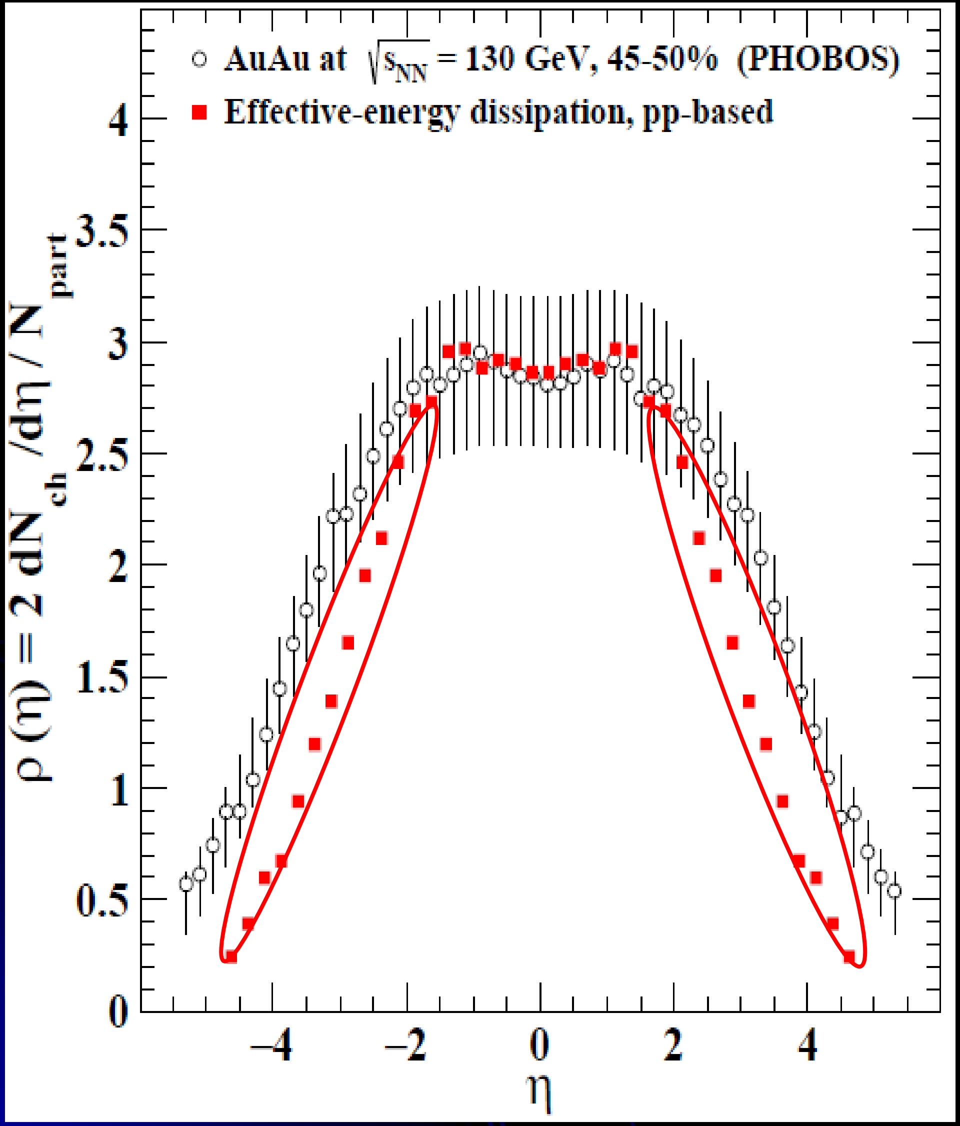
Non-central collisions



- pp data vs. **non-central** AA data at $\sqrt{s_{pp}} \approx 3\varepsilon_{NN}$

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

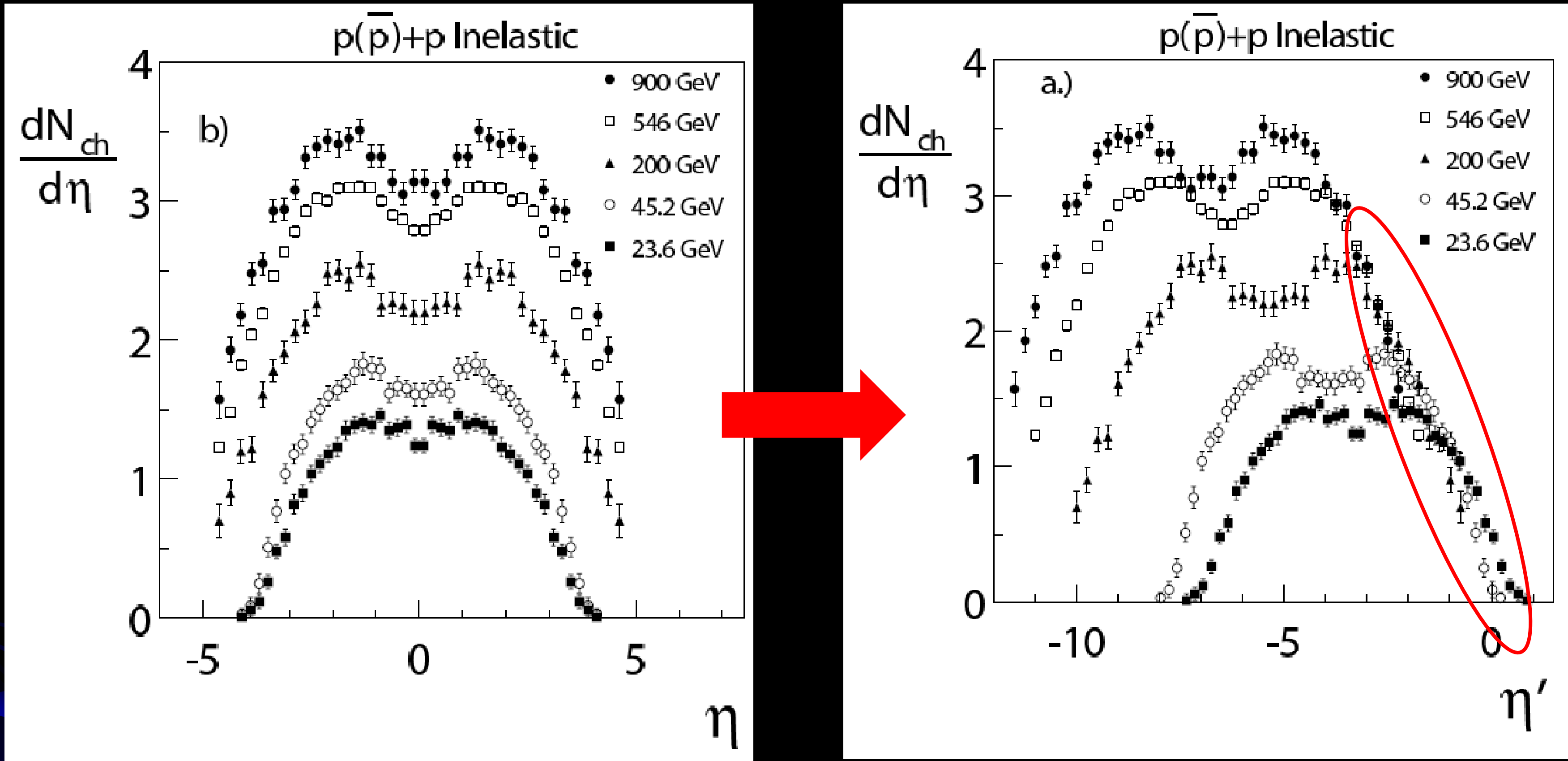
Non-central collisions



- Calculations for **non-central** collisions **agree well** with the measurements in the **central η region** while **fall below the data outside this region**

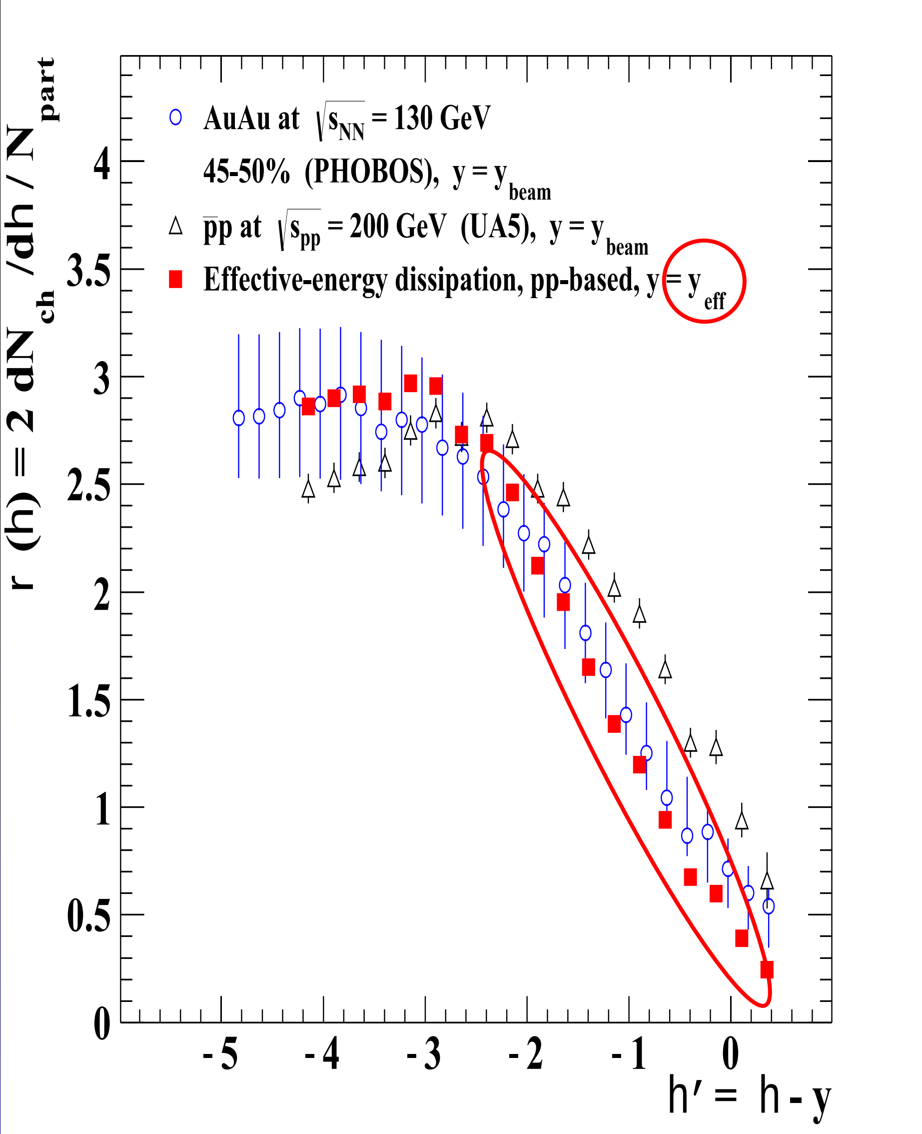
EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

Limiting fragmentation scaling



- The ***fragmentation area*** of ρ(η) is ***collision*-energy-*in*dependent in the beam (target) rest frame,** i.e. under ρ(η) transformation to (shift by) $\boldsymbol{\eta' = \eta - y_{eff}}$, where $y_{eff} = ln(\sqrt{s_{pp}}/m_p)$ **J. Benecke, T.T. Chou, C.N. Yang, E. Yen (1969)**
- Holds for *all* types of collisions

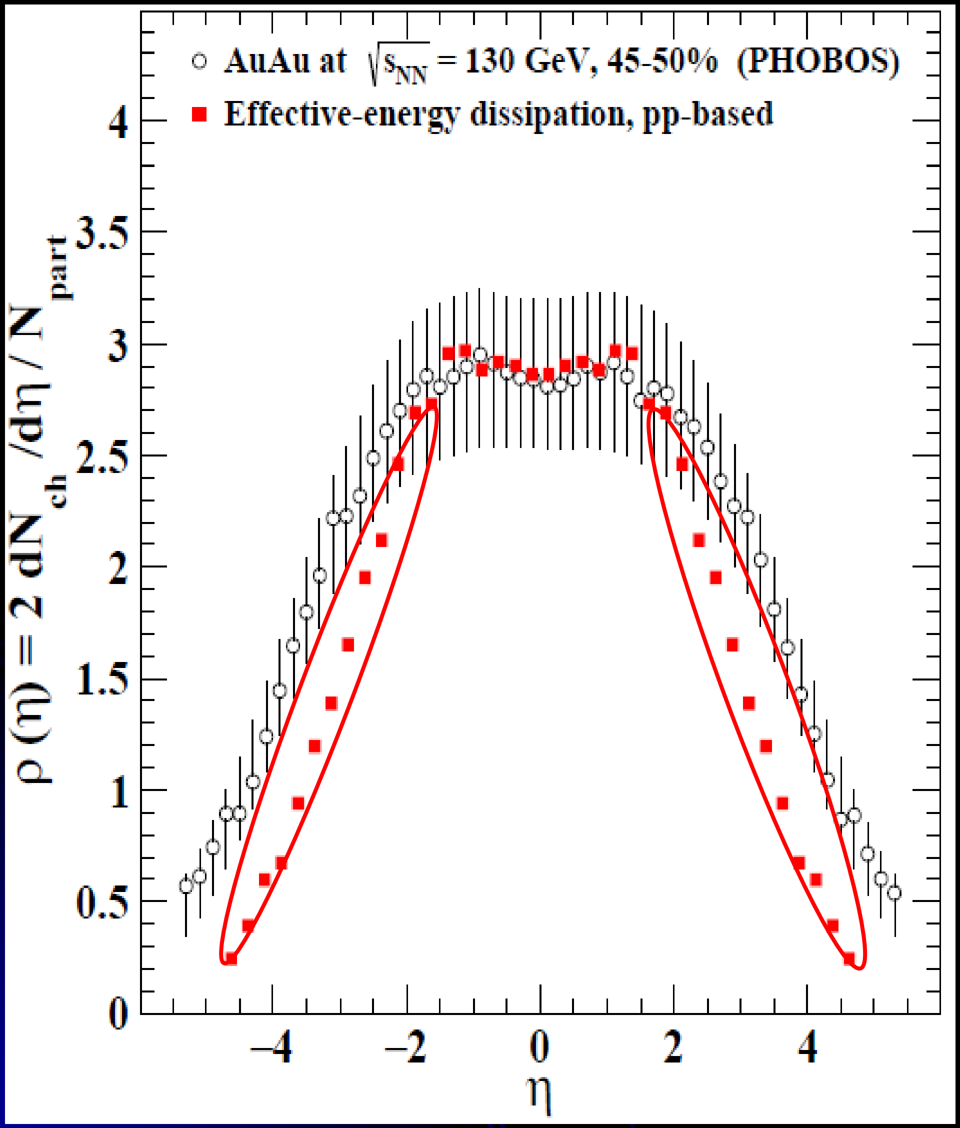
Energy-balanced Limiting Fragmentation



- <u>Within the effective-energy approach</u>, one expects the limiting fragmentation scaling of ρ(η) (***fragmentation area of ρ(η) independence of collision energy in the beam/target rest frame***) <u>measured</u> **at $\sqrt{s_{NN}}$** to be ***similar*** to that of the <u>calculated</u> distribution but **taken at the effective energy ε_{NN}**, i.e. $\eta \rightarrow \eta - y_{eff}$, where $y_{eff} = ln(\varepsilon_{NN}/m_p)$

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

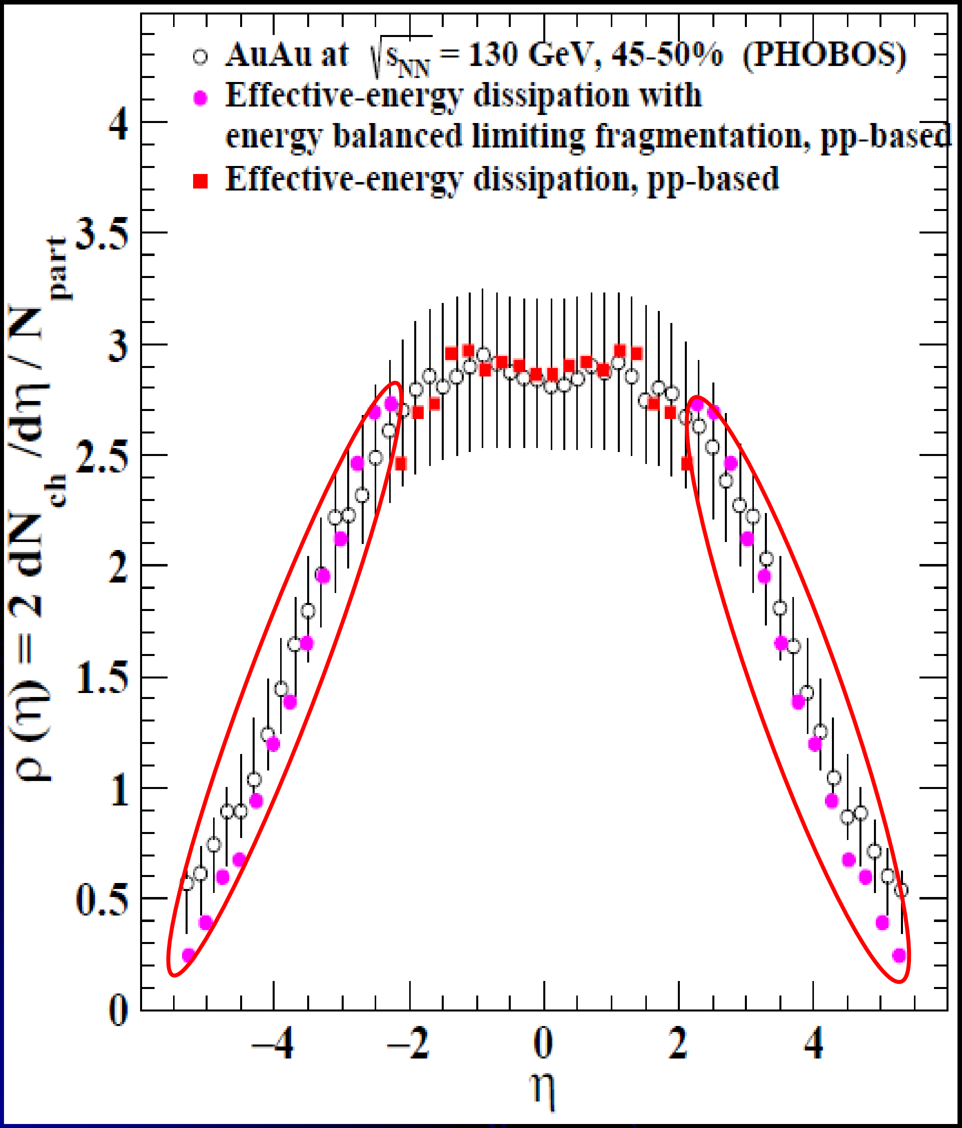
Non-central collisions



- Calculations for **non-central** collisions **agree well** with the measurements in the **central η region** while **fall below the data outside this region**

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

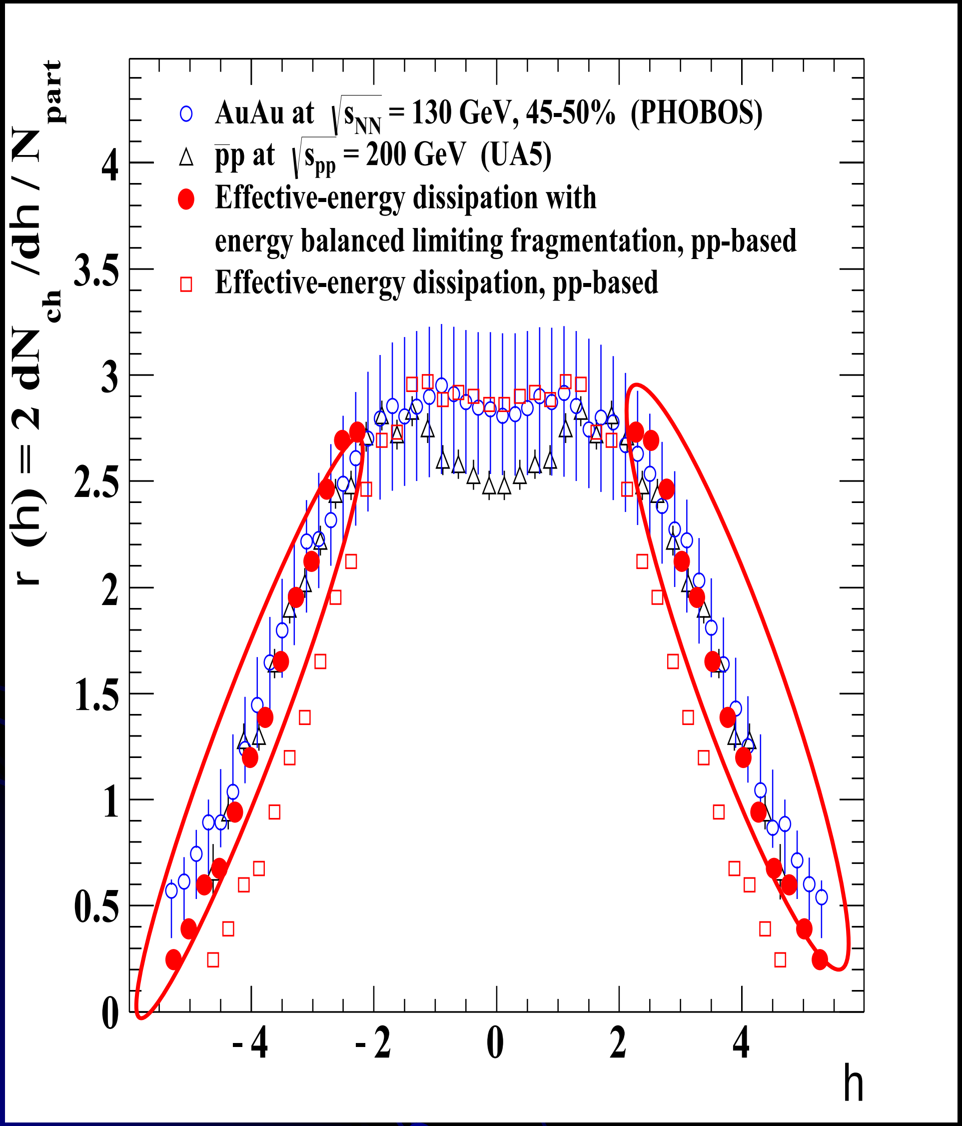
Energy-balanced Limiting Fragmentation



- The **measured** distribution $\rho(\eta)$ is **shifted by the beam rapidity, y_{beam}**, while the calculated distribution is shifted by $y_{eff} = \ln(\varepsilon_{NN}/m_p)$ and becomes a function of $\eta' = \eta - y_{eff}$
- **The *newly calculated* distribution $\rho(\eta)$ needs to be <u>shifted by the difference ($y_{eff} - y_{beam}$)</u> in the fragmentation region**: $\eta \rightarrow \eta - (y_{eff} - y_{beam})$ $= \eta - \ln(1 - \alpha)$. This represents **the ``<u>energy balanced</u> limiting fragmentation scaling"**

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

Energy-balanced Limiting Fragmentation



- The **measured** distribution $\rho(\eta)$ is **shifted by the beam rapidity, y_{beam}**, while the calculated distribution is shifted by $y_{eff} = \ln(\varepsilon_{NN}/m_p)$ and becomes a function of $\eta' = \eta - y_{eff}$
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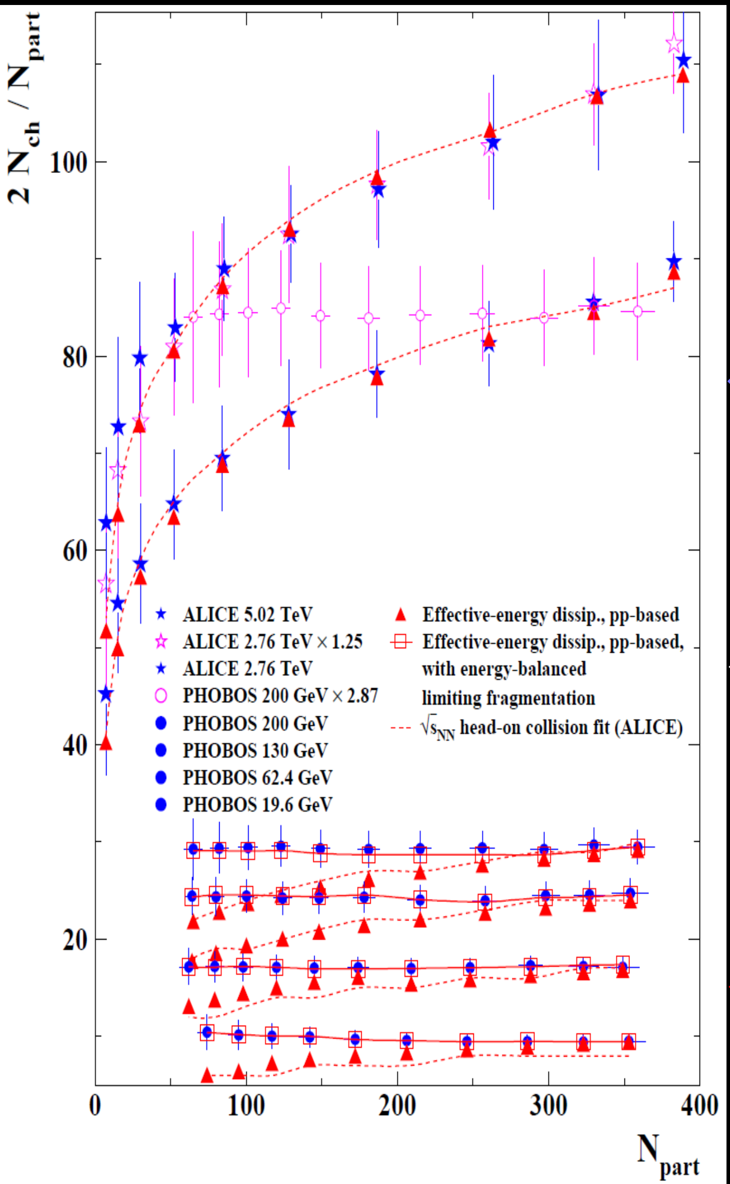
EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

Energy-balanced Limiting Fragmentation



- The shift adds the needed **energy balanced ingredient** to the calculations providing the description of the measured pseudorapidity density distribution in ***the full η range in non-central*** heavy-ion collision

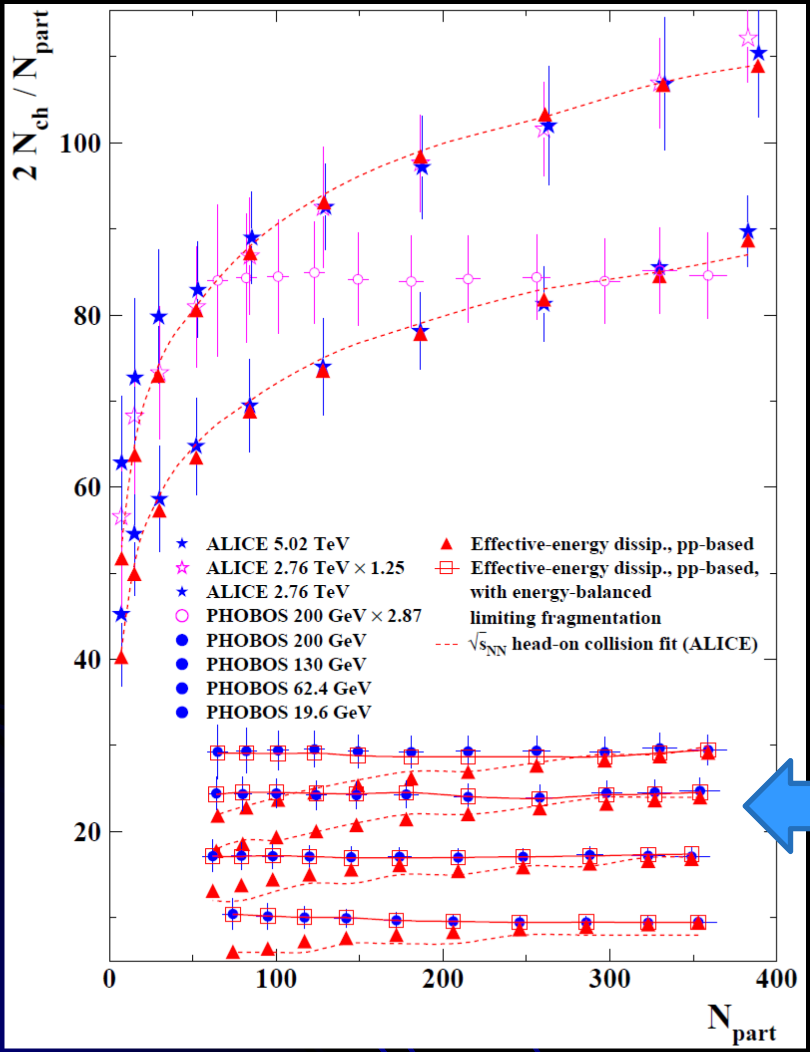
- With the **new scaling**, which adds a **needed ingredient** to balance *the energy of a collision and of nucleon participants*, the measured ρ(η) distribution is **reproduced for *all centralities***

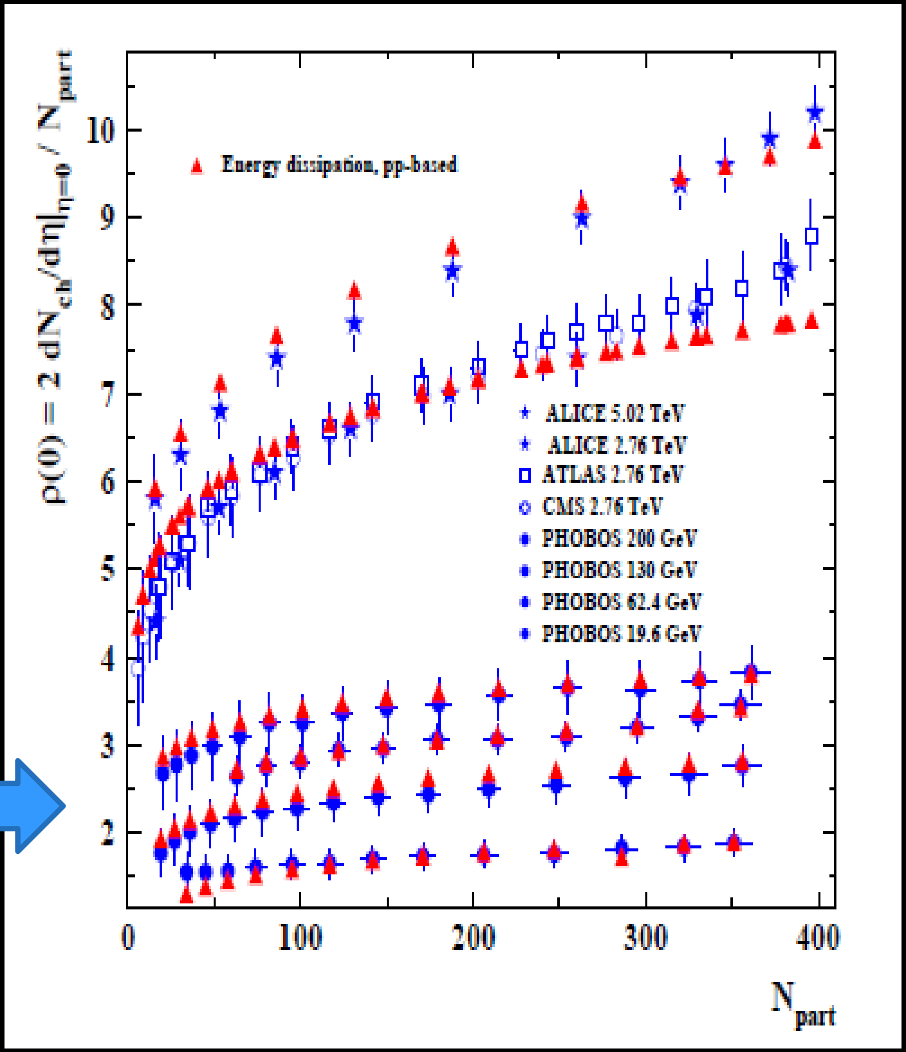
- In order to describe the LHC mean multiplicity data, almost **no additional contribution is needed** for the participant dissipating energy calculations

- The calculations, driven by the centrality-defined effective c.m. energy ***well reproduce*** measurements from RHIC ***after* removing energy-balanced contribution**

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys.Rev. D93 (2016) 054046 & arXiv:1803.01428

Energy-balanced Limiting Fragmentation

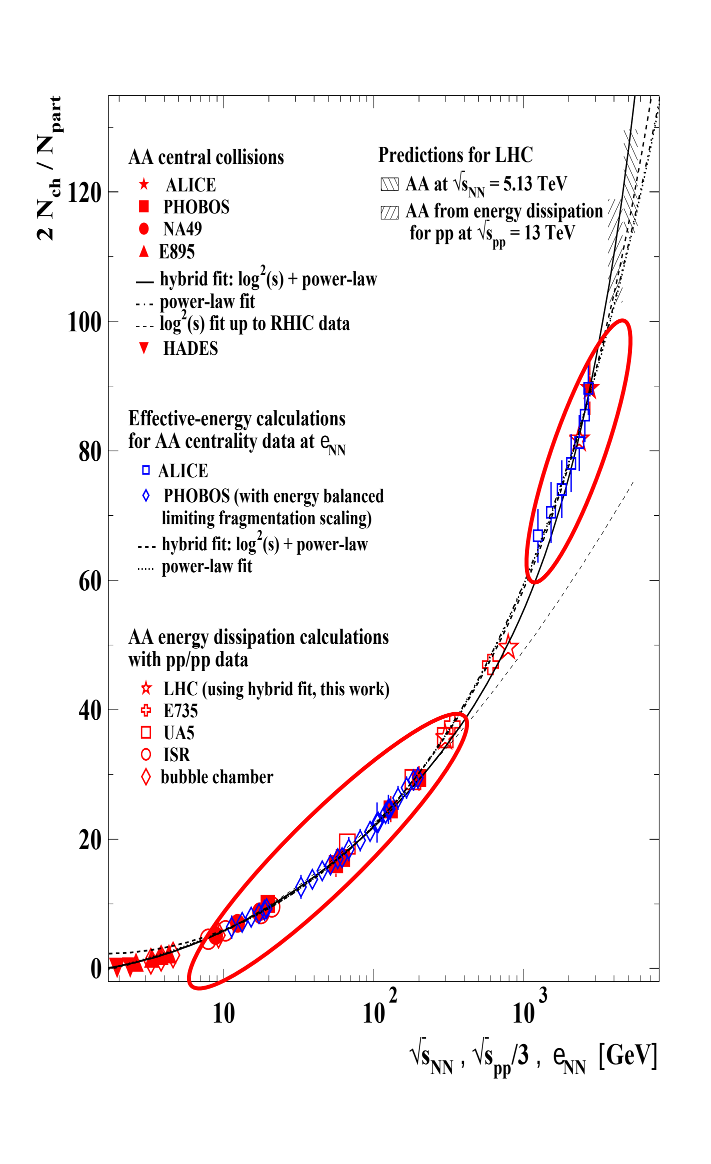




Explains the **difference** in the *centrality dependence* of the ***multiplicity*** and the ***midrapidity density at RHIC*** (``RHIC puzzle''), not seen at LHC

EKGS, A.N. Mishra, R. Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

Energy-balanced Limiting Fragmentation



- The shift adds the needed **energy-balanced ingredient** to the calculations providing the description of the measured pseudorapidity density distribution in ***the full η range in non-central*** heavy-ion collision

- With the **new scaling**, which adds a **needed ingredient** to balance *the energy of a collision and of nucleon participants*, the measured ρ(η) distribution is reproduced for **all centralities**

- ***Effective-energy*** **dependent centrality data are *compliment* to c.m. energy dependent head-on collision data**

EKGS, A.N. Mishra, R.Sahoo, A.S. Sakharov, Phys. Rev. D 93 (2016) 054046

(Intermediate) Conclusions

- The **universality** of hadroproduction process is pointed out based on the **picture of the *effective* dissipating *energy of participants***
- The AA measurements are **well reproduced** under the assumption of the ***effective energy driving the multiparticle production*** process and pointing to the **same energy behaviour for all types of heavy-ion collisions**, from peripheral to the most central collisions
- A ***new* scaling**, called **the *energy-balanced* limiting fragmentation scaling**, which takes into account the *balance between the collision energy and the energy shared by the participants*, is introduced
- Energy-balanced limiting fragmentation scaling provides **a solution of the RHIC "puzzle"** of the difference between the centrality independence of the mean multiplicity vs. the monotonic decrease of the midrapidity pseudorapidity density with the increase of centrality
- Under the concept of the effective energy and using the energy-balanced limiting fragmentation scaling, ***the centrality data are found to follow the head-on collisions $\sqrt{s_{NN}}$ dependence***
- A possible **transition to a new regime** at $\sqrt{s_{NN}}$ ~1 TeV is indicated

Two-particle rapidity correlations

$$C_2(y_1,y_2)=\rho(y_1,y_2)-\rho(y_1)\rho(y_2)$$

← 2-particle rapidity correlation function

$$\rho(y)=\frac{1}{\sigma_{in}}\frac{d\sigma_{in}}{dy},\ \rho_2(y_1,y_2)=\frac{1}{\sigma_{in}}\frac{d^2\sigma_{in}}{dy_1dy_2}$$

one- and two-particle densities

$$\int dy_1dy_2\,C(y_1,y_2)=D^2-<n>$$ (= 0 for *independent* emission)

$$K_2(y_1,y_2)=\frac{C_2(y_1,y_2)}{\rho(y_1)\rho(y_2)}=\frac{1}{\sigma_{in}}\frac{d^2\sigma_{in}}{dy_1dy_2}\Big/\frac{1}{\sigma_{in}{}^2}\frac{d\sigma_{in}}{dy_1}\frac{d\sigma_{in}}{dy_2}-1$$

$$F_2=\frac{<n(n-1)>}{<n>^2}=\frac{D^2}{<n>^2}-\frac{1}{<n>}+1,\quad D^2=<n^2>-<n>^2$$

Scaled factorial moment

Generalization to *higher-orders* is straightforward:

I.M.Dremin and W.J.Gary, Phys. Rept.349 (2001) 301

E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Rep. 270 (1996) 1

2-particle azimuthal and (pseudo)rapitity correlations

$$R(\Delta\eta,\Delta\phi)=\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

$$\Delta\eta=\eta_1-\eta_2 \quad ; \quad \Delta\phi=\phi_1-\phi_2$$

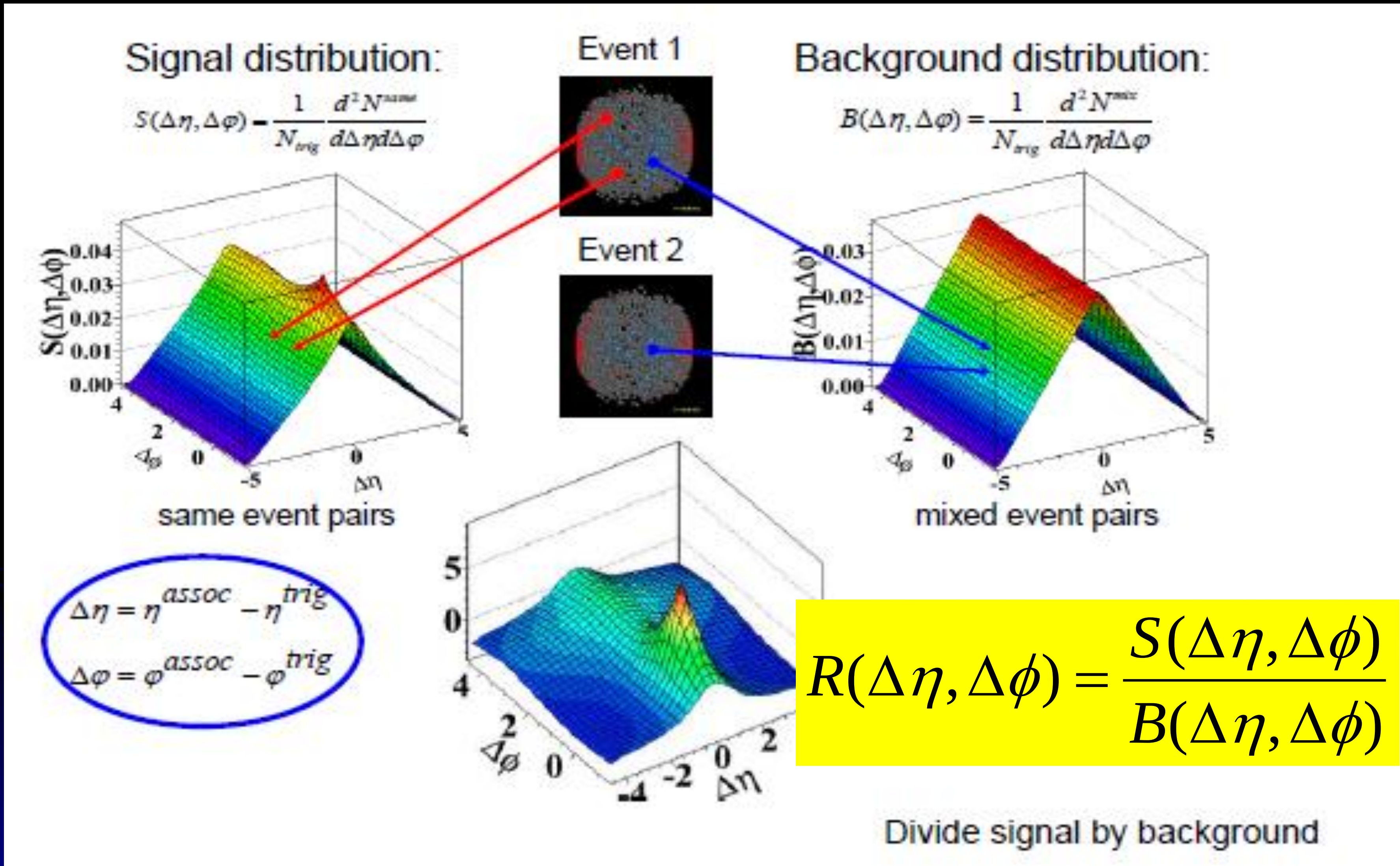
S(Δη, Δϕ): particle pair distribution from ***the same*** event

B(Δη, Δϕ): particle pair distribution from ***different*** events

Complex structure of 2-dimensional plot in pp, pA and AA collisions

seen by ALICE, ATLAS, and CMS at the LHC

2-particle azimuthal and (pseudo)rapitity correlations

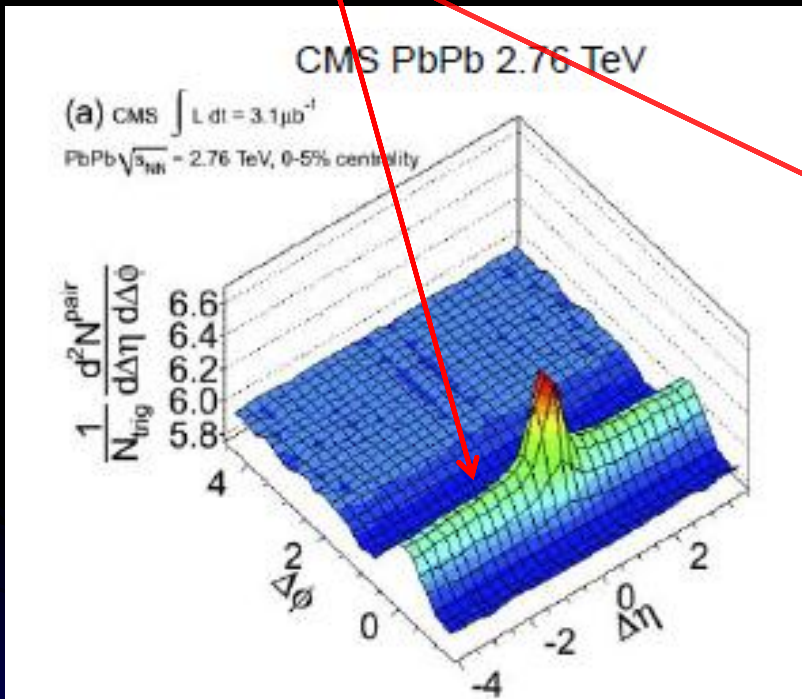


S(Δη, Δϕ): particle pair ***signal*** distribution from ***the same*** event

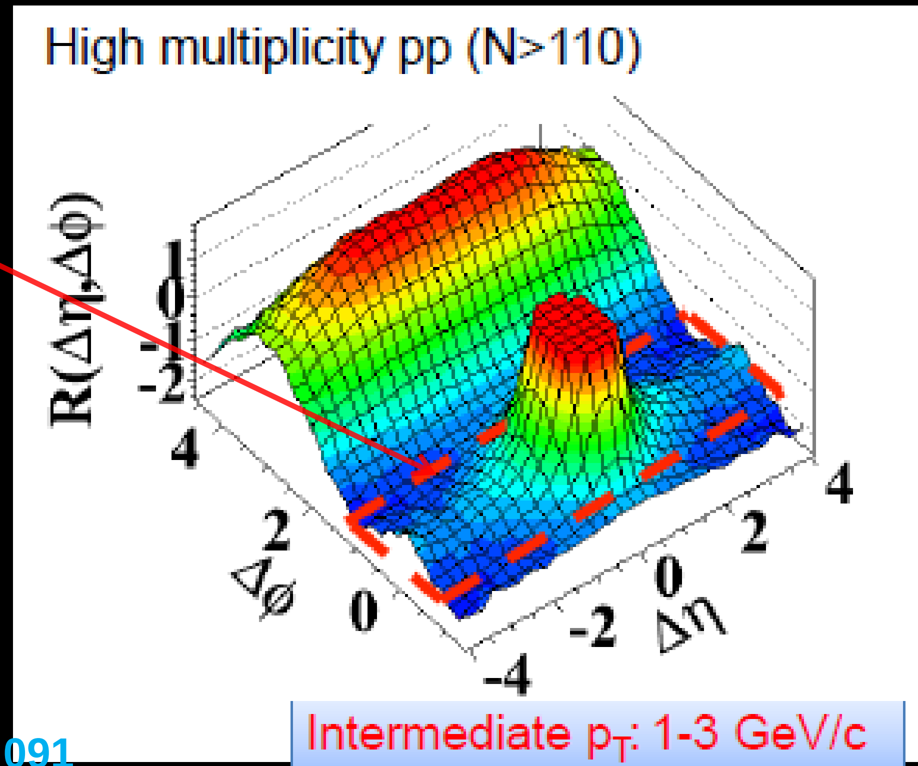
B(Δη, Δϕ) : particle pair ***background*** distribution from ***different*** events

Ridge structure

``Ridge" structure *extending over Δη at Δϕ = 0*



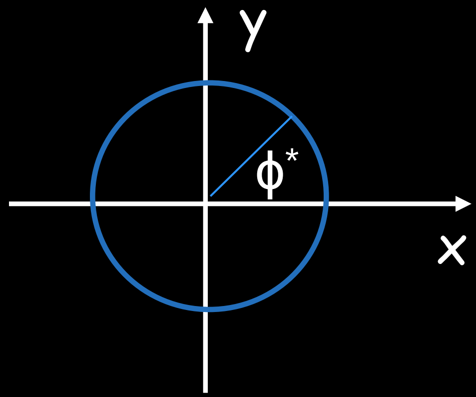
CMS Collab. J. High Energy Phys. 1009 (2010) 091



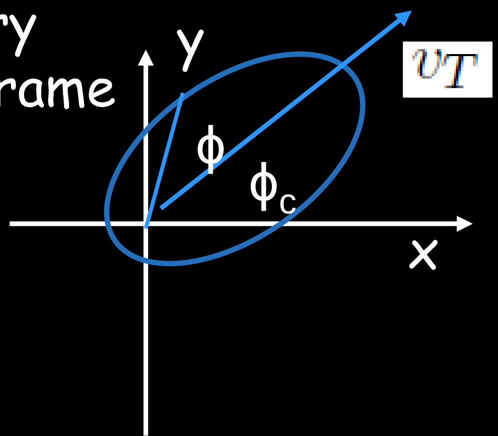
- **Expected in heavy-ion collisions (*hydro, high density*)**
- **Unexpected in pp (and pA) interactions**
- **Similarity in pp *and* heavy-ion collisons!**
- ***No explanation* so far, while many models proposed**

Correlated-cluster model

cluster
reference frame



laboratory
reference frame



Lorentz boost γ_T

- Azimuthal dependence

  1) ***Isotropic* cluster emission**

  2) ***Isotropic* particle emission in clusters:** $w^*(\phi^*) = \text{constant}$

- **Gaussians** for *cluster and particle* distributions inside clusters

$$\rho^{(c)}(y_c, \phi_c) \sim \exp\left[-\frac{y_c^2}{2\delta_{cy}^2}\right], \rho^{(1)}(y, \phi; y_c, \phi_c) \sim \exp\left[-\frac{(y-y_c)^2}{2\delta_y^2}\right] \exp\left[-\frac{(\phi-\phi_c)^2}{2\delta_\phi^2}\right]$$

The cluster correlation length $\delta_{cy}^2 \gg \delta_y^2 \lesssim 1$ the cluster decay "width",

and the cluster azimuthal decay "width" $\delta_\phi \sim \frac{1}{v_T \ \gamma_T}$

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

Correlated-cluster model

Short-range — Long-range

$$\rho_2(y_1,\phi_1,y_2,\phi_2) \;=\; \langle N_c\rangle\, \bar{\rho}^{(1)2}\, E_s^{SR}(y_1,\phi_1,y_2,\phi_2) \;+\; \langle N_c(N_c-1)\rangle\, \bar{\rho}^{(1)2} E_s^{LR}(y_1,\phi_1,y_2,\phi_2)$$

$\bar{\rho}^{(1)}$ average particle density for single-cluster decay

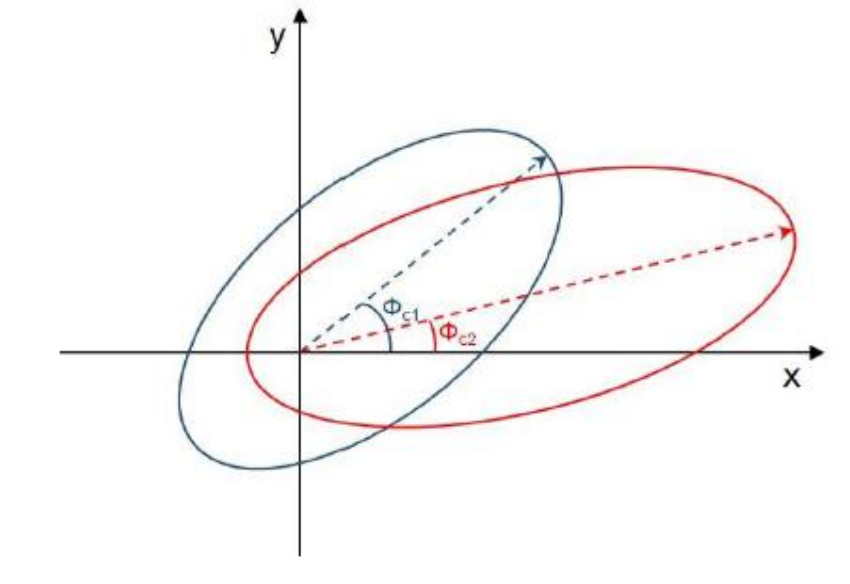
$\langle N_c\rangle$ average number of clusters

Factorization

$$E_b(y_1,\phi_1,y_2,\phi_2) \;=\; E_b^L(y_1,y_2)\cdot E_b^T(\phi_1,\phi_2)$$
$$E_s(y_1,\phi_1,y_2,\phi_2) \;=\; E_s^L(y_1,y_2)\cdot E_s^T(\phi_1,\phi_2)$$

Cluster correlation function **considers (partial) longitudinal momentum conservation and implements cluster azimuthal correlations (transverse plane)**

$$\rho_2^{(c)}(y_{c1},\phi_{c1},y_{c2},\phi_{c2}) \sim \exp\left[-\frac{(y_{c1}+y_{c2})^2}{2\delta_{cy}^2}\right]\exp\left[-\frac{(\phi_{c1}-\phi_{c2})^2}{2\delta_{c\phi}^2}\right]$$



M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

Correlated-cluster model

$$\rho_2(y_1,\phi_1,y_2,\phi_2) = \langle N_c\rangle\, \bar{\rho}^{(1)2}\, E_s^{SR}(y_1,\phi_1,y_2,\phi_2) + \langle N_c(N_c-1)\rangle\, \bar{\rho}^{(1)2} E_s^{LR}(y_1,\phi_1,y_2,\phi_2)$$

Short-range   Long-range

Factorization

$$E_b(y_1,\phi_1,y_2,\phi_2) = E_b^L(y_1,y_2)\cdot E_b^T(\phi_1,\phi_2)$$
$$E_s(y_1,\phi_1,y_2,\phi_2) = E_s^L(y_1,y_2)\cdot E_s^T(\phi_1,\phi_2)$$

Upon the integration over cluster rapidity and azimuth:

- for two particles from *the same* cluster (SR),

$$E_s^L(y_1,y_2) \sim \exp\left[-\frac{\delta_{cy}^2(y_1-y_2)^2}{2\delta_y^2(\delta_y^2+2\delta_{cy}^2)}\right] \exp\left[-\frac{(y_1^2+y_2^2)}{2(\delta_y^2+2\delta_{cy}^2)}\right]$$

$$E_s^T(\phi_1,\phi_2) \sim \exp\left[-\frac{(\phi_1-\phi_2)^2}{4\delta_\phi^2}\right]$$

- for two particles from *two different* clusters (LR)

$$E_s^L(y_1,y_2) \sim \exp\left[-\frac{(y_1+y_2)^2}{2(2\delta_y^2+\delta_{cy}^2)}\right]$$

$$E_s^T(\phi_1,\phi_2) \sim \exp\left[-\frac{(\phi_1-\phi_2)^2}{2(2\delta_\phi^2+\delta_{c\phi}^2)}\right]$$

- for background function

$$E_b^L(y_1,y_2) \sim \exp\left[-\frac{(y_1^2+y_2^2)}{2(\delta_y^2+\delta_{cy}^2)}\right]$$

$$E_b^T(\phi_1,\phi_2) \sim \text{const.}$$ (isotrpoic decay)

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Correlated-cluster model

Signal (*s*):

$$\rho_2(y_1,\phi_1,y_2,\phi_2) \;=\; \langle N_c\rangle \;\bar{\rho}^{(1)2}\; E_s^{SR}(y_1,\phi_1,y_2,\phi_2) \;+\; \langle N_c(N_c-1)\rangle \;\bar{\rho}^{(1)2} E_s^{LR}(y_1,\phi_1,y_2,\phi_2)$$

Background (*b*):

$$\rho_{\rm mixed}(y_1,\phi_1,y_2,\phi_2) \;= \langle N_c\rangle^2 \;\bar{\rho}^{(1)2}\; E_b(y_1,\phi_1,y_2,\phi_2)$$

Upon the integration over the particle pairs rapidty and azimuthal anngles, given $\Delta y = y_1 - y_2$ and $\Delta\phi = \phi_1 - \phi_2$ **:**

$$R(\Delta y,\Delta\phi) = \frac{s(\Delta y,\Delta\phi)}{b(\Delta y,\Delta\phi)}$$

$$= \frac{s^{SR}(\Delta y,\Delta\phi) + s^{LR}(\Delta y,\Delta\phi)}{b(\Delta y,\Delta\phi)} = 1 \;+\; \frac{h^{SR}(\Delta y,\Delta\phi)}{\langle N_c\rangle} \;+\; \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^2}\; h^{LR}(\Delta\phi)$$

near-side ridge

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

Correlated-cluster model

$$R(\Delta y, \Delta\phi) = \frac{s(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)}$$

$$= \frac{s^{\mathrm{SR}}(\Delta y, \Delta\phi) + s^{\mathrm{LR}}(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)} = 1 + \frac{h^{\mathrm{SR}}(\Delta y, \Delta\phi)}{\langle N_{\mathrm{c}}\rangle} + \frac{\langle N_{\mathrm{c}}(N_{\mathrm{c}}-1)\rangle}{\langle N_{\mathrm{c}}\rangle^2}\, h^{\mathrm{LR}}(\Delta\phi)$$

Short-range contribution:

$$h^{\mathrm{SR}}(\Delta y, \Delta\phi) = \frac{e_{\mathrm{s}}^{\mathrm{SR}}(\Delta y, \Delta\phi)}{e_{\mathrm{b}}(\Delta y, \Delta\phi)} = \exp\left[-\frac{\delta_{\mathrm{c}y}^2}{4\delta_y^2(\delta_y^2+\delta_{\mathrm{c}y}^2)}(\Delta y)^2\right]\exp\left[-\frac{(\Delta\phi)^2}{4\delta_\phi^2}\right]$$

Long-range contribution:

$$h^{\mathrm{LR}}(\Delta y, \Delta\phi) = \frac{e_{\mathrm{s}}^{\mathrm{LR}}(\Delta y, \Delta\phi)}{e_{\mathrm{b}}(\Delta y, \Delta\phi)} \simeq \exp\left[\frac{(\Delta y)^2}{4(\delta_y^2+\delta_{\mathrm{c}y}^2)}\right]\exp\left[-\frac{(\Delta\phi)^2}{2(2\delta_\phi^2+\delta_{\mathrm{c}\phi}^2)}\right]$$

near-side ridge

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Correlated-cluster model

$$R(\Delta y, \Delta\phi) = \frac{s(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)}$$

$$= \frac{s^{\rm SR}(\Delta y, \Delta\phi) + s^{\rm LR}(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)} = 1 + \frac{h^{\rm SR}(\Delta y, \Delta\phi)}{\langle N_{\rm c}\rangle} + \frac{\langle N_{\rm c}(N_{\rm c}-1)\rangle}{\langle N_{\rm c}\rangle^2}\, h^{\rm LR}(\Delta\phi)$$

Reduces at large $\langle N_c \rangle$

Short-range contribution:

$$h^{\rm SR}(\Delta y, \Delta\phi) = \frac{e_{\rm s}^{\rm SR}(\Delta y, \Delta\phi)}{e_{\rm b}(\Delta y, \Delta\phi)} = \exp\left[-\frac{(\Delta y)^2}{4\delta_y^2}\right] \exp\left[-\frac{(\Delta\phi)^2}{4\delta_\phi^2}\right]$$

Long-range contribution:

$$h^{\rm LR}(\Delta y, \Delta\phi) = \frac{e_{\rm s}^{\rm LR}(\Delta y, \Delta\phi)}{e_{\rm b}(\Delta y, \Delta\phi)} \simeq \exp\left[-\frac{(\Delta y)^2}{4(\delta_y^2 + \delta_{cy}^2)}\right] \exp\left[-\frac{(\Delta\phi)^2}{2(2\delta_\phi^2 + \delta_{c\phi}^2)}\right]$$

near-side ridge

For $\delta^2_{cy} >> \delta^2_y$

≈ 0.1 radians ($p_T \approx 1$ GeV)

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 766 (2017) 170

Correlated-cluster model

$$R(\Delta y, \Delta\phi) = \frac{s(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)}$$

$$= \frac{s^{\mathrm{SR}}(\Delta y, \Delta\phi) + s^{\mathrm{LR}}(\Delta y, \Delta\phi)}{b(\Delta y, \Delta\phi)} = 1 + \frac{h^{\mathrm{SR}}(\Delta y, \Delta\phi)}{\langle N_c \rangle} + \frac{\langle N_c(N_c - 1)\rangle}{\langle N_c \rangle^2}\, h^{\mathrm{LR}}(\Delta\phi)$$

Reduces at large $\langle N_c \rangle$

Short-range contribution:

$$h^{\mathrm{SR}}(\Delta y, \Delta\phi) = \frac{e_{\mathrm{s}}^{\mathrm{SR}}(\Delta y, \Delta\phi)}{e_{\mathrm{b}}(\Delta y, \Delta\phi)} = \exp\left[-\frac{(\Delta y)^2}{4\delta_y^2}\right] \exp\left[-\frac{(\Delta\phi)^2}{4\delta_\phi^2}\right]$$

Long-range contribution:

$$h^{\mathrm{LR}}(\Delta y, \Delta\phi) = \frac{e_{\mathrm{s}}^{\mathrm{LR}}(\Delta y, \Delta\phi)}{e_{\mathrm{b}}(\Delta y, \Delta\phi)} \simeq \exp\left[-\frac{(\Delta y)^2}{4(\delta_y^2 + \delta_{cy}^2)}\right] \exp\left[-\frac{(\Delta\phi)^2}{2(2\delta_\phi^2 + \delta_{c\phi}^2)}\right]$$

near-side ridge

For $\delta^2_{cy} >> \delta^2_y$

≈ 0.1 radians ($p_T \approx 1$ GeV)

MAIN RESULT: The *ridge* effect of 2-particle *correlations at small $\Delta\phi$ over a wide (pseudo)rapidity range* is naturally explained within **a model of clusters** ***correlated in the transverse plane***

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3-particle correlations

$$C_3(1,2,3) = \rho_3(1,2,3) + 2\rho(1)\rho(2)\rho(3) - \rho_2(1,2)\rho(3) - \rho_2(2,3)\rho(1) - \rho_2(1,3)\rho(2)$$

$$\rho_3(y_1, y_2, y_3, \phi_1, \phi_2, \phi_3) \;=\; \frac{1}{\sigma_{\rm in}} \frac{d^6\sigma}{dy_1 dy_2 dy_3 d\phi_1 d\phi_2 d\phi_3} \,.$$

3-partice density

Correlation function ratio:

$$c_3(\vec{\Delta y}, \vec{\Delta \phi}) = \frac{s_3 + 2b_3 - s_{123} - s_{231} - s_{132}}{b_3} \,,$$

$\vec{\Delta y}, \vec{\Delta \phi}$ for $\Delta y_{ij}, \Delta\phi_{ij}$

$\vec{y} = (y_1, y_2, y_3)\,,\ \vec{\phi} = (\phi_1, \phi_2, \phi_3)$

Signal (s):

$$s_3(\vec{\Delta y}, \vec{\Delta \phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho_3(\vec{y}, \vec{\phi})$$

$$d\vec{y}\; d\vec{\phi} \;= dy_1 dy_2 dy_2\; d\phi_1 d\phi_2 d\phi_3$$

$$\vec{\delta}(\Delta y) = \delta(\Delta y_{12} - y_1 + y_2)\; \delta(\Delta y_{13} - y_1 + y_3)$$

Background (b):

$$b_3(\vec{\Delta y}, \vec{\Delta \phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho(y_1,\phi_1)\; \rho(y_2,\phi_2)\; \rho(y_3,\phi_3)$$

$$s_{123}(\vec{\Delta y}, \vec{\Delta \phi}) \;=\; \int d\vec{y}\; d\vec{\phi}\; \vec{\delta}(\Delta y)\; \vec{\delta}(\Delta\phi)\; \rho(y_1,\phi_1)\; \rho_2(y_2,\phi_2,y_3,\phi_3)$$

+ permutations

M.-A .Sanchis-Lozano, ESG,
Phys. Rev. D 96 (2017) 074012

Correlated-cluster model: 3 clusters

$$\rho_3(\vec{y},\vec{\phi}) = \langle N_c \rangle \, \bar{\rho}^{(1)3} E_s^{(1)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1) \rangle \, \bar{\rho}^{(1)3} E_s^{(2)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1)(N_c-2) \rangle \, \bar{\rho}^{(1)3} E_s^{(3)}(\vec{y},\vec{\phi})$$

$\bar{\rho}^{(1)}$ average particle density for single-cluster decay

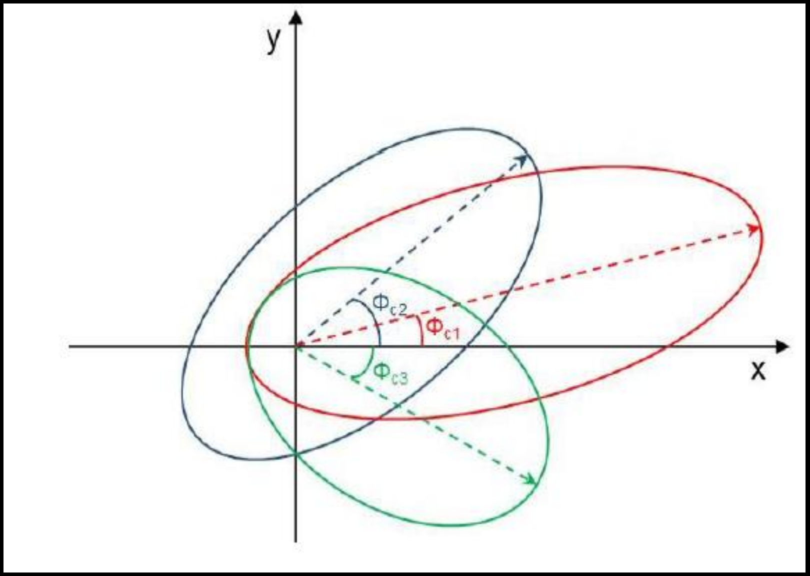
$\langle N_c \rangle$ average number of clusters

Factorization

$$E_b(\vec{y},\vec{\phi}) = E_b^L(\vec{y}) \cdot E_b^T(\vec{\phi})$$
$$E_s(\vec{y},\vec{\phi}) = E_s^L(\vec{y}) \cdot E_s^T(\vec{\phi})$$

Cluster correlation function **considers (partial) longitudinal momentum conservation and implements cluster azimuthal correlations (transverse plane)**

$$\rho_3^{(c)}(\vec{y_c},\vec{\phi_c}) \sim \exp\left[-\frac{(y_{c1}+y_{c2}+y_{c3})^2}{2\delta_{cy}^2}\right] \times \exp\left[-\frac{(\phi_{c1}-\phi_{c2})^2+(\phi_{c1}-\phi_{c3})^2+(\phi_{c2}-\phi_{c3})^2}{2\delta_{c\phi}^2}\right]$$



M.-A .Sanchis-Lozano, ESG, Phys. Rev. D 96 (2017) 074012

Correlated-cluster model: 3 clusters

$$\rho_3(\vec{y},\vec{\phi}) = \langle N_c\rangle\, \bar{\rho}^{(1)3} E_s^{(1)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1)\rangle\, \bar{\rho}^{(1)3} E_s^{(2)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1)(N_c-2)\rangle\, \bar{\rho}^{(1)3} E_s^{(3)}(\vec{y},\vec{\phi})$$

Upon the integration over cluster rapidities and azimuths, particle pair rapidities and azimuths:

- for three particles from *the same* cluster (1),

$$E_s^{(1)}(\vec{\Delta y}) \sim \exp\left[-\frac{(\Delta y_{12})^2+(\Delta y_{13})^2+(\Delta y_{23})^2}{6\delta_y^2}\right] \qquad E_s^{(1)}(\vec{\Delta\phi}) \sim \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2+(\Delta\phi_{23})^2}{6\delta_\phi^2}\right]$$

- for three particles from *two different* clusters (2)

$$E_s^{(2)}(\vec{y}) \sim \exp\left[-\frac{(\Delta y_{13})^2}{4\delta_y^2}\right] + \exp\left[-\frac{(\Delta y_{12})^2}{4\delta_y^2}\right] + \exp\left[-\frac{(\Delta y_{13})^2}{4\delta_y^2}\right]$$

$$E_s^{(2)}(\vec{\Delta\phi}) \sim \exp\left[-\frac{\delta_{c\phi}^2(\Delta\phi_{23})^2}{2\delta_\phi^2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right] \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2+(\Delta\phi_{23})^2}{2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right]$$

$$\exp\left[-\frac{\delta_{c\phi}^2(\Delta\phi_{13})^2}{2\delta_\phi^2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right] \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2+(\Delta\phi_{23})^2}{2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right], \exp\left[-\frac{\delta_{c\phi}^2(\Delta\phi_{12})^2}{2\delta_\phi^2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right] \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2+(\Delta\phi_{23})^2}{2(3\delta_\phi^2+2\delta_{c\phi}^2)}\right]$$

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Correlated-cluster model: 3 clusters

$$\rho_3(\vec{y},\vec{\phi}) = \langle N_c\rangle\, \bar{\rho}^{(1)3} E_s^{(1)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1)\rangle\, \bar{\rho}^{(1)3} E_s^{(2)}(\vec{y},\vec{\phi}) + \langle N_c(N_c-1)(N_c-2)\rangle\, \bar{\rho}^{(1)3} E_s^{(3)}(\vec{y},\vec{\phi})$$

Upon the integration over cluster rapidities and azimuths, particle pair rapidities and azimuths:

- for three particles from *three correlated* clusters (3)

$$E_s^{(3)}(\vec{\Delta y}) \sim \text{const.}$$

$$E_s^{(3)}(\vec{\Delta\phi}) \sim \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2+(\Delta\phi_{23})^2}{2(3\delta_\phi^2+\delta_{c\phi}^2)}\right]$$

- for three particles from *two (out of three) correlated* clusters (3)

$$E_s^{(3)}(\vec{\Delta y}) \sim \text{const.}$$

$$E_s^{(}(\vec{\Delta\phi}) \sim \exp\left[-\frac{(\Delta\phi_{12})^2}{2(2\delta_\phi^2+\delta_{c\phi}^2)}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2(2\delta_\phi^2+\delta_{c\phi}^2)}\right] + \exp\left[-\frac{(\Delta\phi_{23})^2}{2(2\delta_\phi^2+\delta_{c\phi}^2)}\right]$$

- for three particles from *three indpendently emitted* clusters (3)

$$E_s^{(3}(\vec{\Delta\phi}) \sim \text{const.}$$

- for background function

$$E_b^{(3)}(\vec{\Delta y}) \sim \exp\left[-\frac{(\Delta y_{12})^2+(\Delta y_{13})^2+(\Delta y_{23})^2}{6(\delta_y^2+\delta_{cy}^2)}\right]$$

$$E_b^T(\phi_1,\phi_2,\phi_3) \sim \text{const.}$$

(isotrpoic decay)

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Correlated-cluster model: 3 clusters

Signal (*s*):

$$\rho_3(\vec{y},\vec{\phi}) \;=\; \langle N_c\rangle\, \bar{\rho}^{(1)3} E_s^{(1)}(\vec{y},\vec{\phi}) \;+\; \langle N_c(N_c-1)\rangle\, \bar{\rho}^{(1)3} E_s^{(2)}(\vec{y},\vec{\phi}) \;+\; \langle N_c(N_c-1)(N_c-2)\rangle\, \bar{\rho}^{(1)3} E_s^{(3)}(\vec{y},\vec{\phi})$$

Background (*b*):

$$\rho_{\rm mixed}(\vec{y},\vec{\phi}) \;=\; \rho(y_1,\phi_1)\rho(y_2,\phi_2)\rho(y_3,\phi_3) \;=\; \langle N_c\rangle^3\, \bar{\rho}^{(1)} E_b(\vec{y},\vec{\phi})$$

Three-particle correlation function:

$$c_3(\vec{\Delta y},\vec{\Delta\phi}) = \frac{s_3^{(1)}(\vec{\Delta y},\vec{\Delta\phi}) + s_3^{(2)}(\vec{\Delta y},\vec{\Delta\phi}) + s_3^{(3)}(\vec{\Delta y},\vec{\Delta\phi})}{b_3(\vec{\Delta y},\vec{\Delta\phi})}$$

$$= \frac{1}{\langle N_c\rangle^2}\, h^{(1)}(\vec{\Delta y},\vec{\Delta\phi}) \;+\; \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^3}\, h^{(2)}(\vec{\Delta y},\vec{\Delta\phi}) \;+\; \frac{\langle N_c(N_c-1)(N_c-2)\rangle}{\langle N_c\rangle^3}\, h^{(3)}(\vec{\Delta y},\vec{\Delta\phi})$$

ridge effect

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Correlated-cluster model: 3 clusters

$$c_3(\vec{\Delta y}, \vec{\Delta\phi}) = \frac{s_3^{(1)}(\vec{\Delta y}, \vec{\Delta\phi}) + s_3^{(2)}(\vec{\Delta y}, \vec{\Delta\phi}) + s_3^{(3)}(\vec{\Delta y}, \vec{\Delta\phi})}{b_3(\vec{\Delta y}, \vec{\Delta\phi})}$$

ridge effect

$$= \frac{1}{\langle N_c\rangle^2}\, h^{(1)}(\vec{\Delta y}, \vec{\Delta\phi}) \ + \ \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^3}\, h^{(2)}(\vec{\Delta y}, \vec{\Delta\phi}) \ + \ \frac{\langle N_c(N_c-1)(N_c-2)\rangle}{\langle N_c\rangle^3}\, h^{(3)}(\vec{\Delta y}, \vec{\Delta\phi})$$

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Correlated-cluster model: 3 clusters

$$c_3(\vec{\Delta y}, \vec{\Delta \phi}) = \frac{s_3^{(1)}(\vec{\Delta y}, \vec{\Delta \phi}) + s_3^{(2)}(\vec{\Delta y}, \vec{\Delta \phi}) + s_3^{(3)}(\vec{\Delta y}, \vec{\Delta \phi})}{b_3(\vec{\Delta y}, \vec{\Delta \phi})}$$

$$= \frac{1}{\langle N_c \rangle^2} h^{(1)}(\vec{\Delta y}, \vec{\Delta \phi}) + \frac{\langle N_c(N_c-1)\rangle}{\langle N_c \rangle^3} h^{(2)}(\vec{\Delta y}, \vec{\Delta \phi}) + \frac{\langle N_c(N_c-1)(N_c-2)\rangle}{\langle N_c \rangle^3} h^{(3)}(\vec{\Delta y}, \vec{\Delta \phi})$$

Reducing at large ‹Nc›

ridge effect

Three-particle three-cluster contribution

for $\delta^2_{cy} >> \delta^2_y$ and $\delta^2_{c\Phi} >> \delta^2_\Phi$

$$h^{(3)}(\Delta y_{12}, \Delta y_{13}, \Delta \phi_{12}, \Delta \phi_{13}) \sim \exp\left[\frac{(\Delta y_{12})^2 + (\Delta y_{13})^2 + -(\Delta y_{12})(\Delta y_{13})}{3\delta^2_{cy}}\right]$$

$$\times \left(\exp\left[-\frac{(\Delta \phi_{12})^2 + (\Delta \phi_{13})^2 - \Delta \phi_{12}\Delta \phi_{13}}{\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta \phi_{12})^2}{2\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta \phi_{13})^2}{2\delta^2_{c\phi}}\right] + \exp\left[-\frac{(\Delta \phi_{12})^2 + (\Delta \phi_{13})^2 - 2\Delta \phi_{12}\Delta \phi_{13}}{2\delta^2_{c\phi}}\right]\right)$$

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Correlated-cluster model: 3 clusters

$$c_3(\vec{\Delta y}, \vec{\Delta\phi}) = \frac{s_3^{(1)}(\vec{\Delta y}, \vec{\Delta\phi}) + s_3^{(2)}(\vec{\Delta y}, \vec{\Delta\phi}) + s_3^{(3)}(\vec{\Delta y}, \vec{\Delta\phi})}{b_3(\vec{\Delta y}, \vec{\Delta\phi})}$$

$$= \frac{1}{\langle N_c\rangle^2}\, h^{(1)}(\vec{\Delta y}, \vec{\Delta\phi}) + \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^3}\, h^{(2)}(\vec{\Delta y}, \vec{\Delta\phi}) + \frac{\langle N_c(N_c-1)(N_c-2)\rangle}{\langle N_c\rangle^3}\, h^{(3)}(\vec{\Delta y}, \vec{\Delta\phi})$$

Reducing at large $\langle N_c \rangle$

ridge effect

Three-particle three-cluster contribution

for $\delta^2_{cy} >> \delta^2_y$ and $\delta^2_{c\Phi} >> \delta^2_\Phi$

$$h^{(3)}(\Delta y_{12}, \Delta y_{13}, \Delta\phi_{12}, \Delta\phi_{13}) \sim \exp\left[\frac{(\Delta y_{12})^2 + (\Delta y_{13})^2 + -(\Delta y_{12})(\Delta y_{13})}{3\delta_{cy}^2}\right]$$

$$\times \left(\exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - \Delta\phi_{12}\Delta\phi_{13}}{\delta_{c\phi}^2}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2}{2\delta_{c\phi}^2}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2\delta_{c\phi}^2}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2 + (\Delta\phi_{13})^2 - 2\Delta\phi_{12}\Delta\phi_{13}}{2\delta_{c\phi}^2}\right]\right)$$

MAIN RESULT: The *ridge* effect of 3-particle *correlations at small Δϕ over a wide (pseudo)rapidity range* is natural and to be observed as predicted in model of clusters *correlated in the transverse plane*

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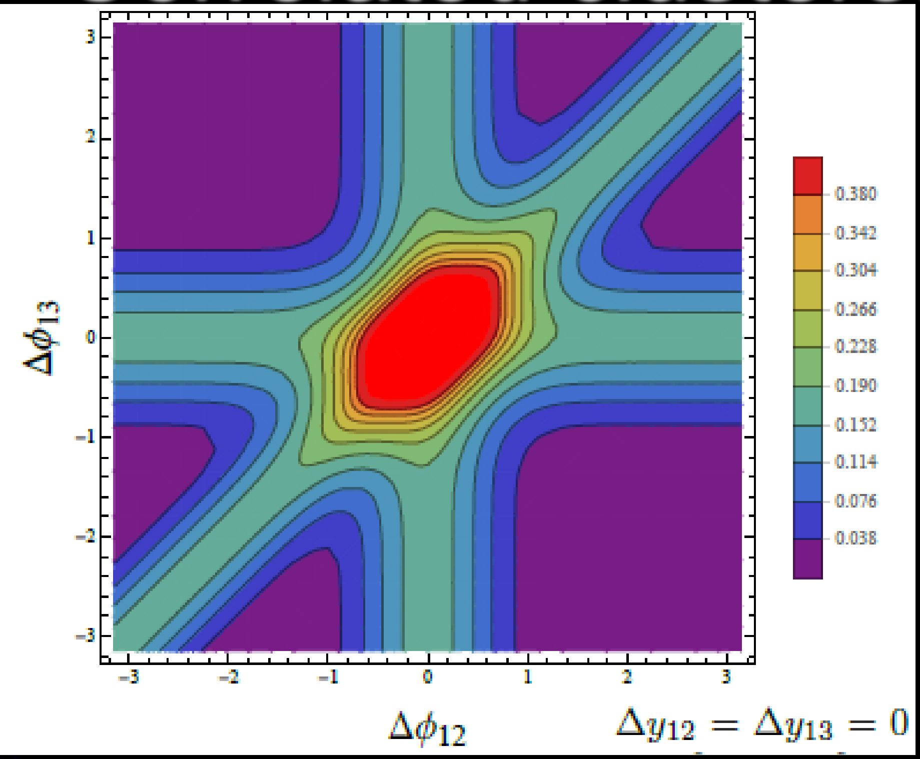
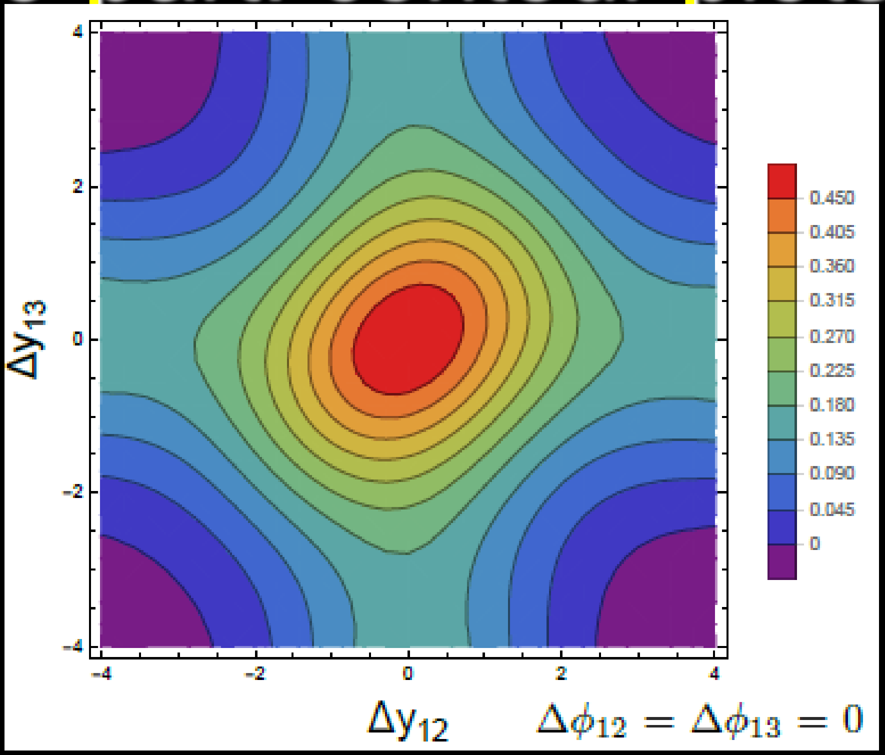
Correlated clusters: 3-part. contour plots





$\delta_y = 0.9,\ \delta_{cy} = 4,\ \delta_\phi = 0.14,\ \delta_{c\phi} = 0.5$

Left panel: *structured asymmetric* two-dimensional plot, results from the *two correlation scales* – a *short-range* azimuthal correlation scale set by *single cluster decay* vs. *long-range* correlation length *from $h^{(3)}$ term of three cluster formation*, the *ridge effect due to transversly correlated-cluster emission*

Right panel: rather *structureless* plot dominating by *sinlge cluster decay* short-range correlation scale

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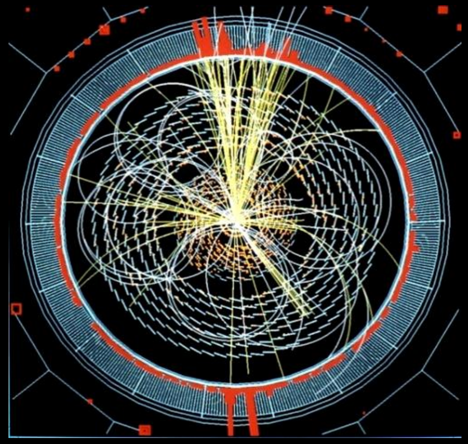
Usually expected signatures of New Physics @ LHC

Mainly on the **transverse plane**:

> Lower background

> Expected signatures such as

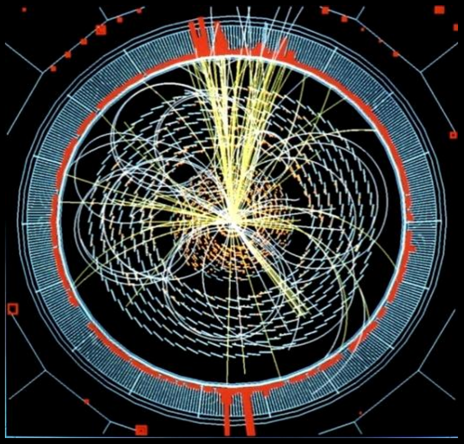
- high-p_T jets, leptons or photons
- missing transverse energy/momentum
- displaced vertices …
- mass peaks



LHC potential must be fully used

Usually expected signatures of New Physics @ LHC

Mainly on the **transverse plane**:



- **Lower background**
- **Expected signatures** such as
  - high-p_T jets, leptons or photons
  - missing transverse energy/momentum
  - displaced vertices …
  - mass peaks

LHC potential must be fully used

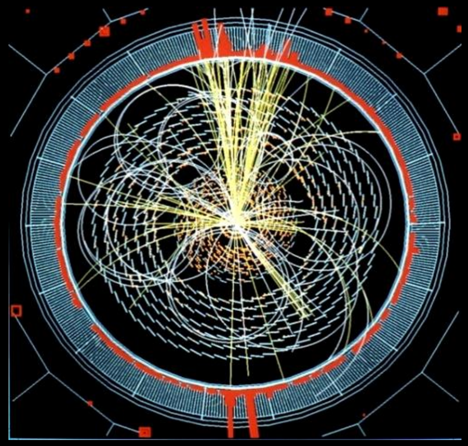
Novel **signals should not be overlooked however, e.g.**

- related to multiparticle production (***soft*** physics)
- but ***tagged by hard signals***

} *diffuse* signal

Usually expected signatures of New Physics @ LHC

Mainly on the transverse plane:



> Lower background

> Expected signatures such as

- high-p_T jets, leptons or photons
- missing transverse energy/momentum
- displaced vertices …
- mass peaks

LHC potential must be fully used

***Novel* signals should not be overlooked however, e.g.**

- related to multiparticle production (***soft*** physics)
- **but *tagged by hard signals***

} *diffuse* signal

May be helpful for ***discovery*** of a new stage of matter (**Hidden/Dark Sector**) manifesting in the parton cascade of high-energy pp collisions.

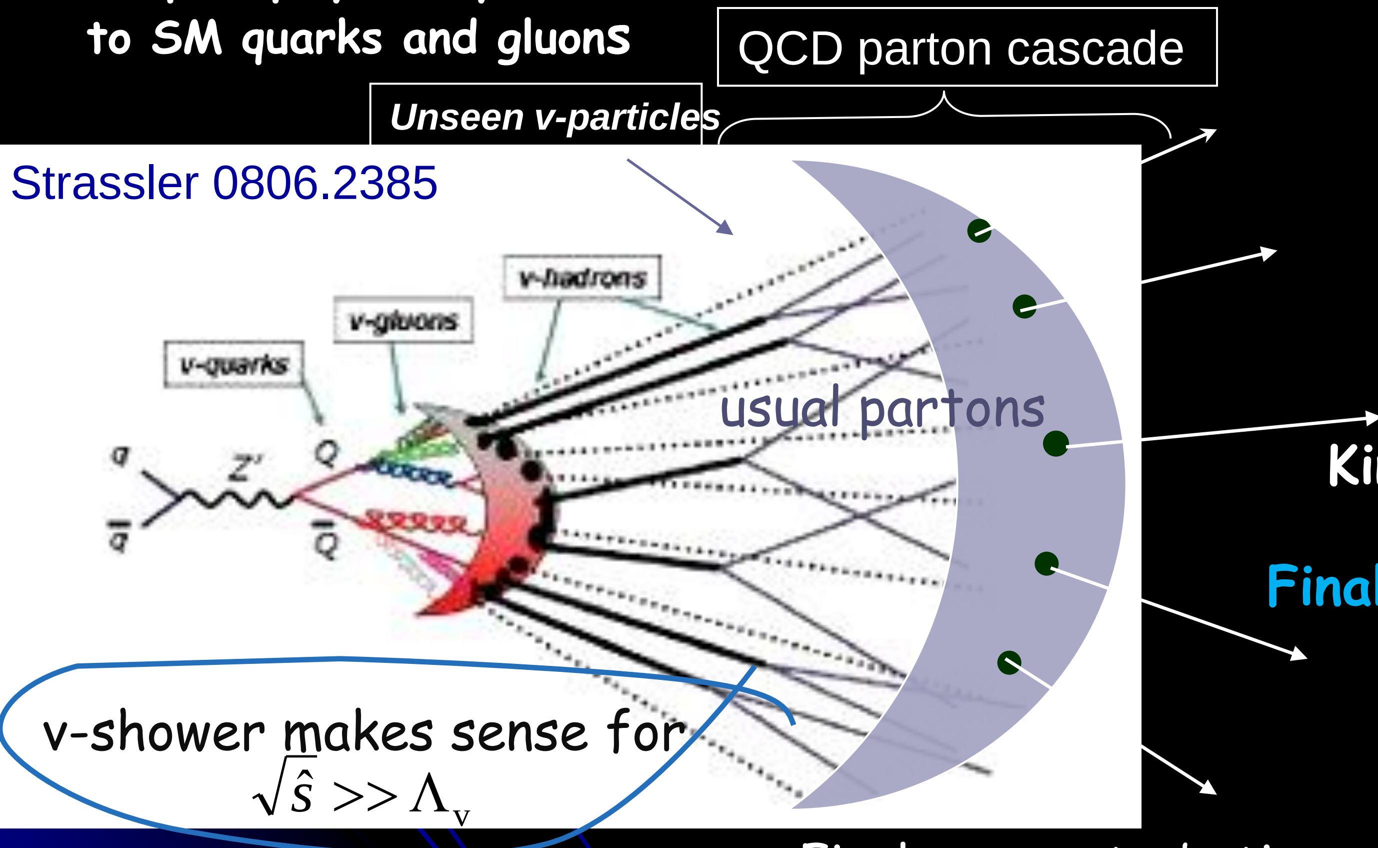
Not an easy task!

Techniques related to the quest for QGP in heavy-ion collisions

Hidden Valley + SM shower

Depending on the model parameters

Some v-particles can be stable, decay outside the detectors, **or promptly decay back to SM quarks and gluons**



Kind of diffuse signal

Final state SM particles

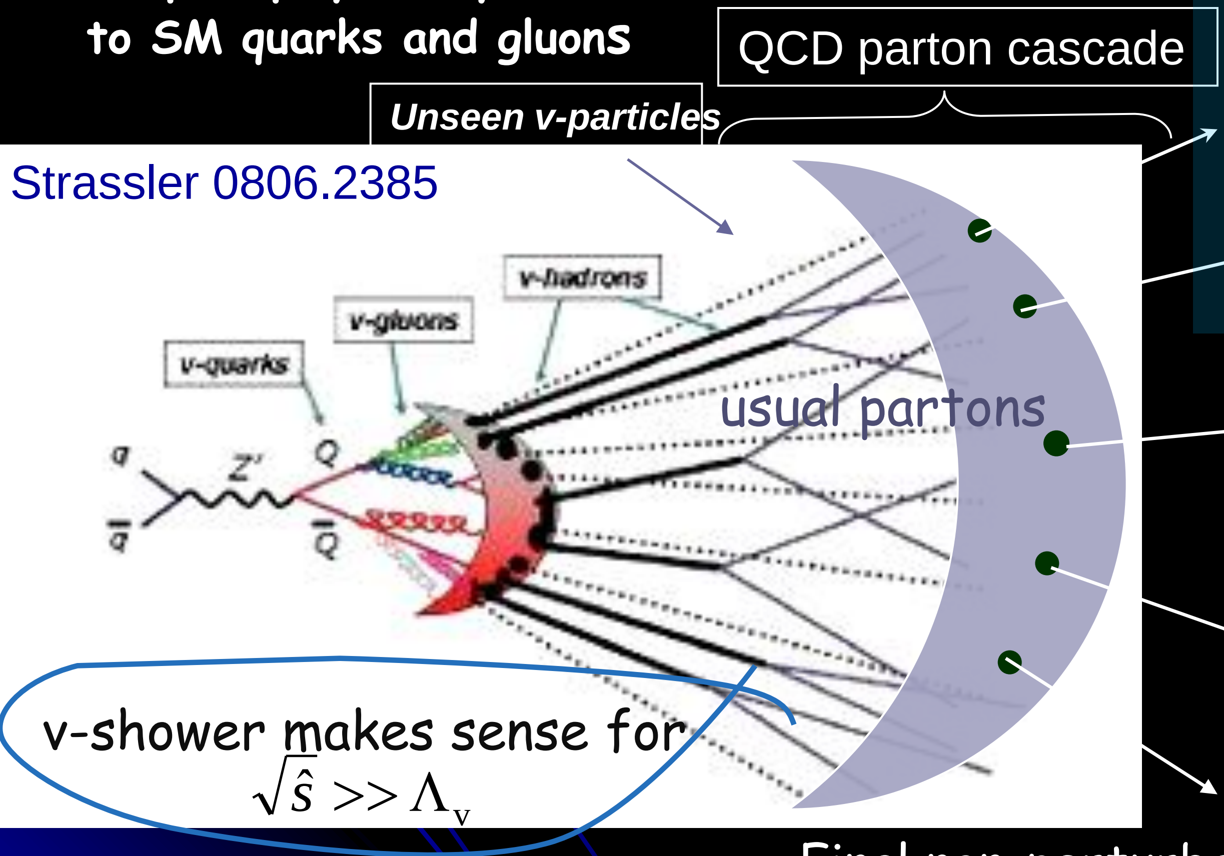
Final non-perturbative hadronization

One more (and different) step than in conventional QCD-parton showers

Hidden Valley + SM shower

Depending on the model parameters

Some v-particles can be stable, decay outside the detectors, **or promptly decay back to SM quarks and gluons**



Multiplicity distributions of final state particles and rapidity/azimuthal correlations can be affected by the extra step in the cascade

Kind of diffuse signal

Final state SM particles

One more (and different) step than in conventional QCD-parton showers

Effect of NP contribution in 3-step cascade

Two-particle density

$$\frac{1}{\sigma_{\rm in}}\frac{d^2\sigma}{d\phi_1 d\phi_2} = \int d\phi_{\rm s}\, \rho^{(\rm s)}(\phi_{\rm s})$$

$$\times \left[\int d\phi_{\rm c}\, \rho^{(\rm c)}(\phi_{\rm c};\phi_{\rm s})\, \rho_2^{(1)}(\phi_1,\phi_2;\phi_{\rm c}) + \int d\phi_{\rm c1}d\phi_{\rm c2}\, \rho_2^{(\rm c)}(\phi_{\rm c1},\phi_{\rm c2};\phi_{\rm s})\, \rho^{(1)}(\phi_1;\phi_{\rm c1})\rho^{(1)}(\phi_2;\phi_{\rm c2})\right]$$

$$+ \int d\phi_{\rm s1}d\phi_{\rm s2}\, \rho_2^{(\rm s)}(\phi_{\rm s1},\phi_{\rm s2}) \approx e^{-\frac{(\phi_{s1}-\phi_{s2})^2}{2\delta_{s\phi}^2}}$$

$$\times \int d\phi_{\rm c1}d\phi_{\rm c2}\, \rho^{(\rm c)}(\phi_{\rm c1};\phi_{\rm s1})\, \rho^{(\rm c)}(\phi_{\rm c2};\phi_{\rm s2})\, \rho^{(1)}(\phi_1,\phi_{\rm c1})\, \rho_1^{(1)}(\phi_2;\phi_{\rm c2})$$

We use again *Gaussians* to parametrize the effect of a hidden/dark sector

$$C(\Delta\phi) \approx \exp\left[-\frac{(\Delta\phi)^2}{2(\delta_{s\phi}{}^2 + 2\delta_{c\phi}^2 + 2\delta_\phi^2)}\right] \quad , \quad \delta_{s\phi}{}^2 >> \delta_{c\phi}{}^2 >> \delta_\phi{}^2$$

$\delta_{s\phi}^2$

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3-particle correlations in 3-step cascade

$$\Delta y_{12} = y_1 - y_2 \quad , \quad \Delta y_{12} = y_1 - y_2, \quad \Delta\phi_{12} = \phi_1 - \phi_2 \quad , \quad \Delta\phi_{13} = \phi_1 - \phi_3$$

Focusing on azimuthal variable

$$\frac{1}{\sigma_{\rm in}}\frac{d^3\sigma}{d\phi_1 d\phi_2 d\phi_3} = \int d\phi_{\rm s}\, \rho^{({\rm s})}(\phi_{\rm s})$$

$$\times \left[\rho^{({\rm c})}(\phi_{\rm c};\phi_{\rm s})\ \rho_3^{(1)}(\phi_1,\phi_2,\phi_3;\phi_{\rm c}) + \rho_2^{({\rm c})}(\phi_{\rm c1},\phi_{\rm c2};\phi_{\rm s})\ \rho^{(1)}(\phi_1;\phi_{\rm c1})\rho_2^{(1)}(\phi_2,\phi_3;\phi_{\rm c2})\right.$$

$$\left. + \rho_3^{({\rm c})}(\phi_{\rm c1},\phi_{\rm c2},\phi_{\rm c3};\phi_{\rm s})\ \rho^{(1)}(\phi_1;\phi_{\rm c1})\rho^{(1)}(\phi_2;\phi_{\rm c2})\rho^{(1)}(\phi_3;\phi_{\rm c3})\right] + \int d\phi_{\rm s1} d\phi_{\rm s2}\ \rho_2^{({\rm s})}(\phi_{\rm s1},\phi_{\rm s2})$$

$$\times \left\{\left[\rho^{({\rm c})}(\phi_{\rm c1};\phi_{\rm s1})\ \rho^{({\rm c})}(\phi_{\rm c2};\phi_{\rm s2})\ \rho^{(1)}(\phi_1,\phi_{\rm c1})\ \rho_2^{(1)}(\phi_2,\phi_3;\phi_{\rm c2},\phi_{\rm c3}) + \ {\rm combinations}\right]\right.$$

$$\left.\left[+\ \rho^{({\rm c})}(\phi_{\rm c1};\phi_{\rm s1})\ \rho_2^{({\rm c})}(\phi_{\rm c2},\phi_{\rm c3};\phi_{\rm s2})\ \rho^{(1)}(\phi_1;\phi_{\rm c1})\ \rho^{(1)}(\phi_2;\phi_{\rm c2})\ \rho^{(1)}(\phi_3;\phi_{\rm c3}) + \ {\rm combinations}\right]\right\}$$

$$+ \int d\phi_{\rm s1} d\phi_{\rm s2} d\phi_{\rm s3}\ \rho_3^{({\rm s})}(\phi_{\rm s1},\phi_{\rm s2},\phi_{\rm s3})$$

$$\times \left[\rho^{({\rm c})}(\phi_{\rm c1};\phi_{\rm s1})\ \rho^{({\rm c})}(\phi_{\rm c2};\phi_{\rm s2})\ \rho^{({\rm c})}(\phi_{\rm c3};\phi_{\rm s3})\ \rho^{(1)}(\phi_1;\phi_{\rm c1})\ \rho^{(1)}(\phi_2;\phi_{\rm c2})\ \rho^{(1)}(\phi_3;\phi_{\rm c3})\right]$$

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3-particle correlations from three hidden sources

$$c_3(\Delta\phi_{12}, \Delta\phi_{13}) = \frac{1}{\langle N_{\rm s}\rangle^2} h^{(1)}(\Delta\phi_{12}, \Delta\phi_{13}) + \frac{1}{\langle N_{\rm s}\rangle} h^{(2)}(\Delta\phi_{12}, \Delta\phi_{13}) + h^{(3)}(\Delta\phi_{12}, \Delta\phi_{13})$$

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3-particle correlations from three hidden sources

$$c_3(\Delta\phi_{12},\Delta\phi_{13}) = \frac{1}{\langle N_s\rangle^2} h^{(1)}(\Delta\phi_{12},\Delta\phi_{13}) + \frac{1}{\langle N_s\rangle} h^{(2)}(\Delta\phi_{12},\Delta\phi_{13}) + h^{(3)}(\Delta\phi_{12},\Delta\phi_{13})$$

Reducing at large $\langle N_c \rangle$

Three-particle contribution from three hidden sources

for $\delta^2_{s\Phi} >> \delta^2_{c\Phi} >> \delta^2_{\Phi}$

$$h^{(3)}(\Delta\phi_{12},\Delta\phi_{13}) \sim \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2-\Delta\phi_{12}\Delta\phi_{13}}{3\delta^2_{c\phi}+\delta^2_{s\phi}}\right]$$

$$+ \exp\left[-\frac{(\Delta\phi_{12})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right] + \exp\left[-\frac{(\Delta\phi_{13})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right] + \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2-2\Delta\phi_{12}\Delta\phi_{13}}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right]$$

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3-particle correlations from three hidden sources

$$c_3(\Delta\phi_{12},\Delta\phi_{13}) = \frac{1}{\langle N_s\rangle^2}h^{(1)}(\Delta\phi_{12},\Delta\phi_{13}) + \frac{1}{\langle N_s\rangle}h^{(2)}(\Delta\phi_{12},\Delta\phi_{13}) + h^{(3)}(\Delta\phi_{12},\Delta\phi_{13})$$

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Three-particle contribution from three hidden sources

for $\delta^2_{s\Phi} >> \delta^2_{c\Phi} >> \delta^2_{\Phi}$

$$h^{(3)}(\Delta\phi_{12},\Delta\phi_{13}) \sim \exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2-\Delta\phi_{12}\Delta\phi_{13}}{3\delta^2_{c\phi}+\delta^2_{s\phi}}\right]$$

$$+\exp\left[-\frac{(\Delta\phi_{12})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right]+\exp\left[-\frac{(\Delta\phi_{13})^2}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right]+\exp\left[-\frac{(\Delta\phi_{12})^2+(\Delta\phi_{13})^2-2\Delta\phi_{12}\Delta\phi_{13}}{2(2\delta^2_{c\phi}+\delta^2_{s\phi})}\right]$$

MAIN RESULT: The *effect of NP to be observed* in the three-particle correlations on top of the ridge phenomenon is predicted in **the model of clusters** ***correlated in the transverse plane***

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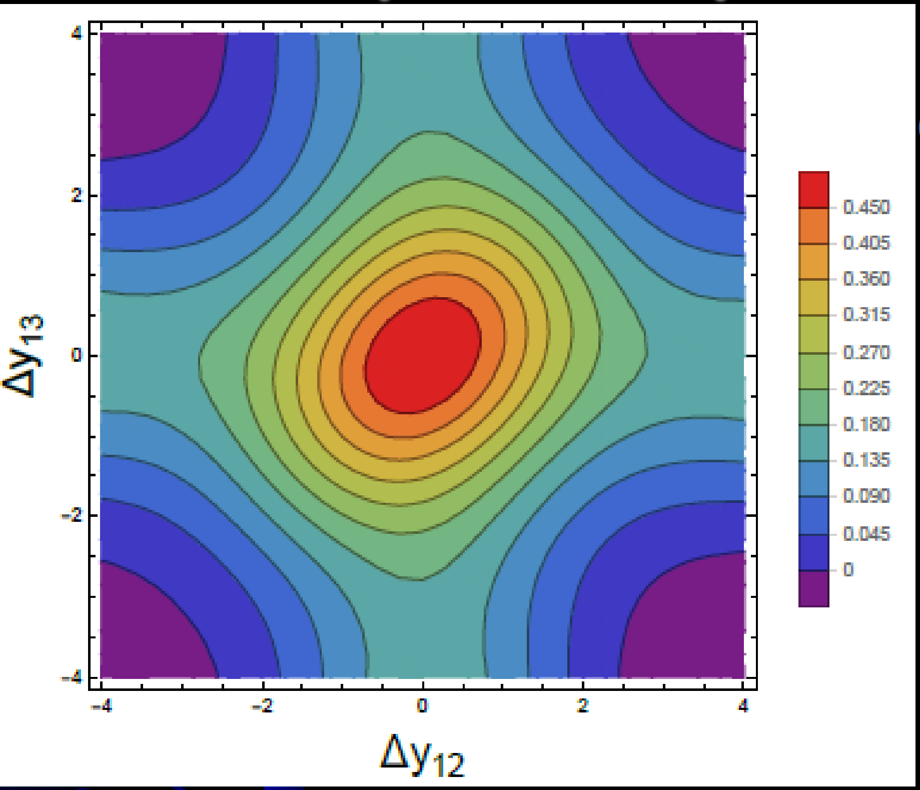
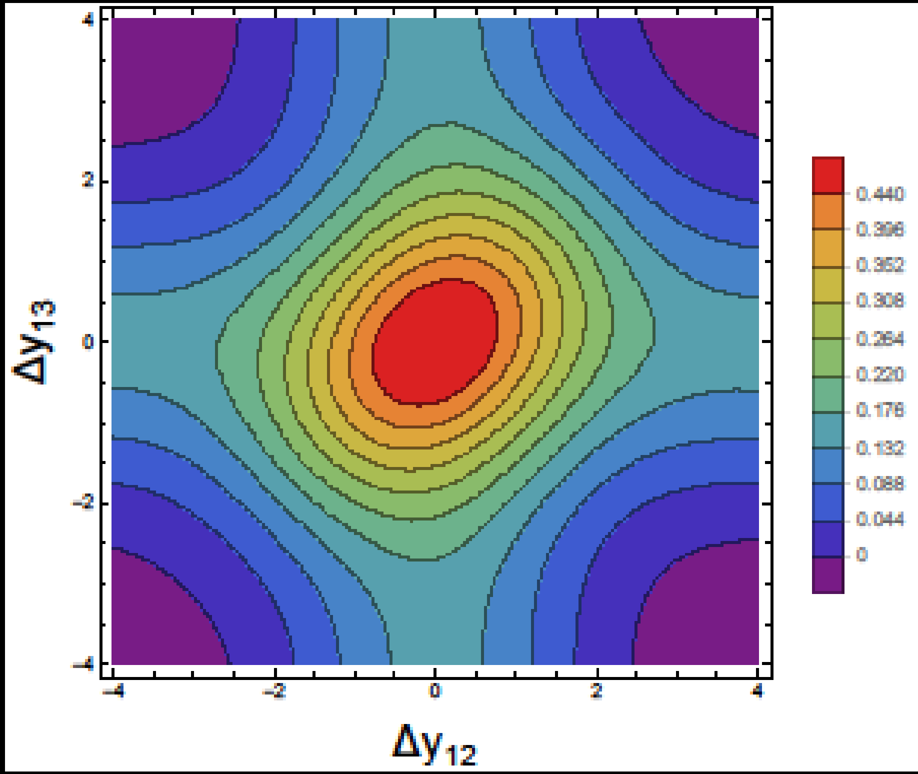
Three-particle pseudorapidity correlations



Almost no difference

NEW PHYSICS



SM

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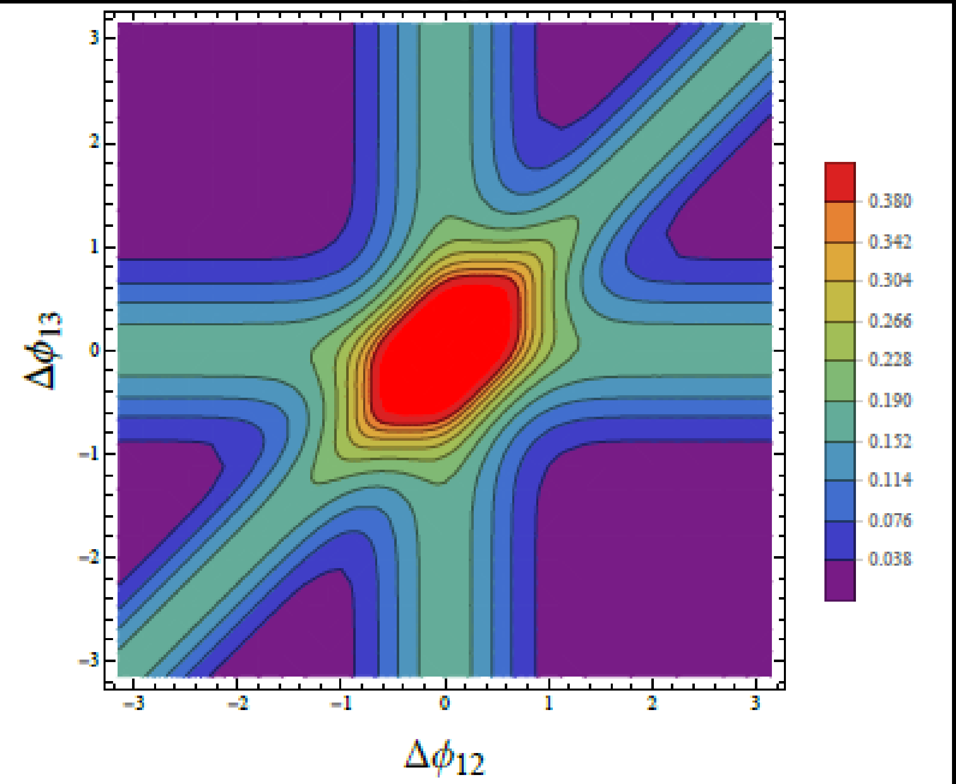
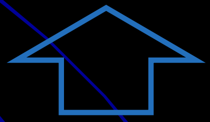
Three-particle azimuthal correlations





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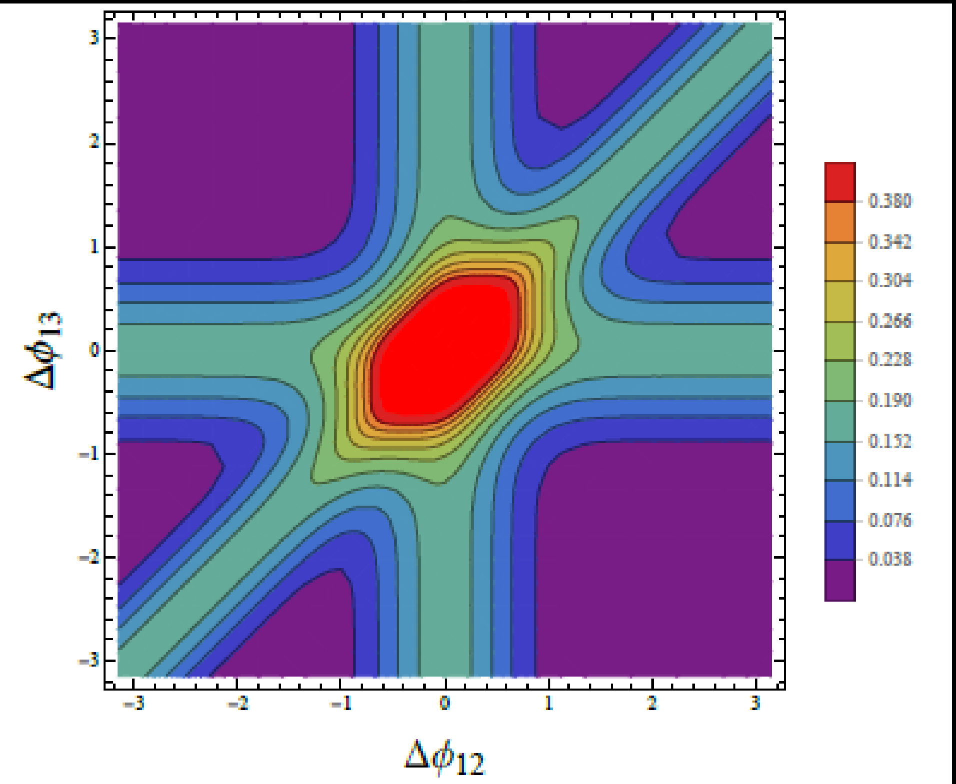
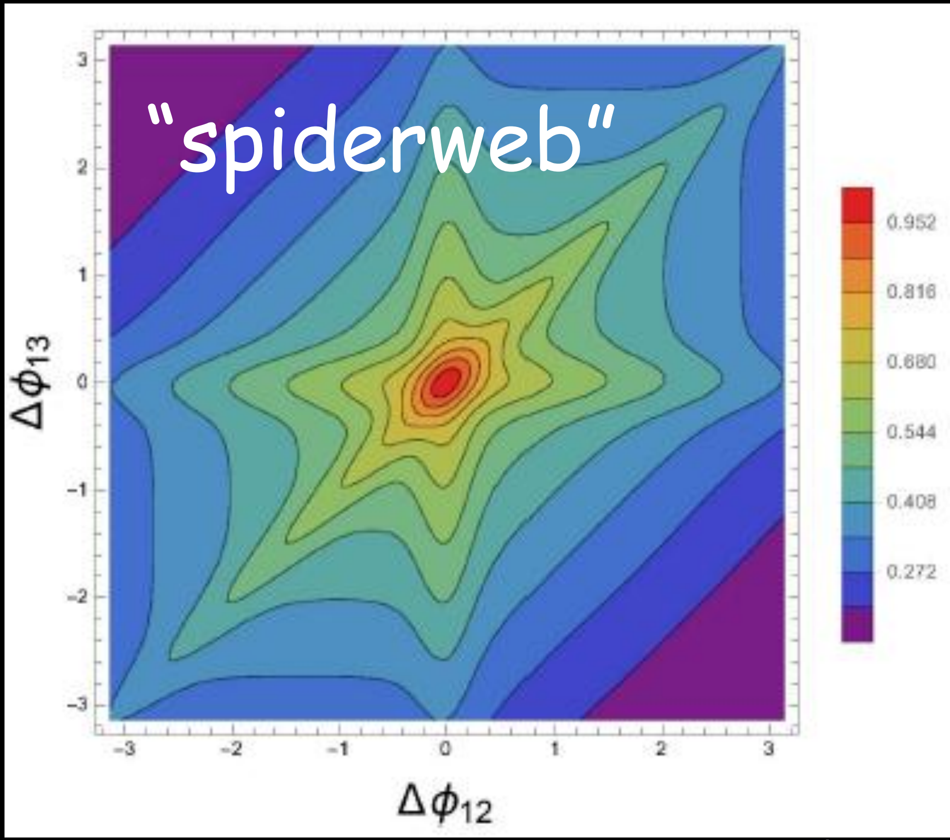
Three-particle azimuthal correlations



NEW PHYSICS



SM

NP effects should rather manisfest in azimuth!

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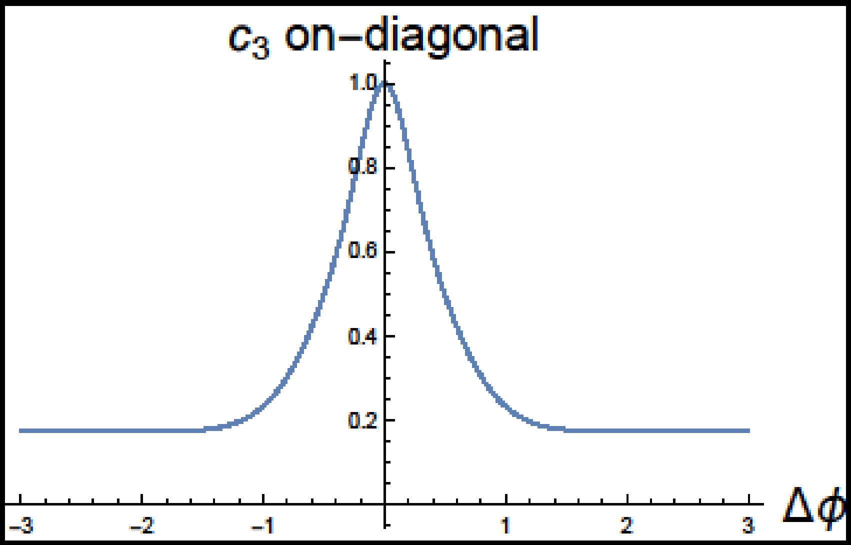
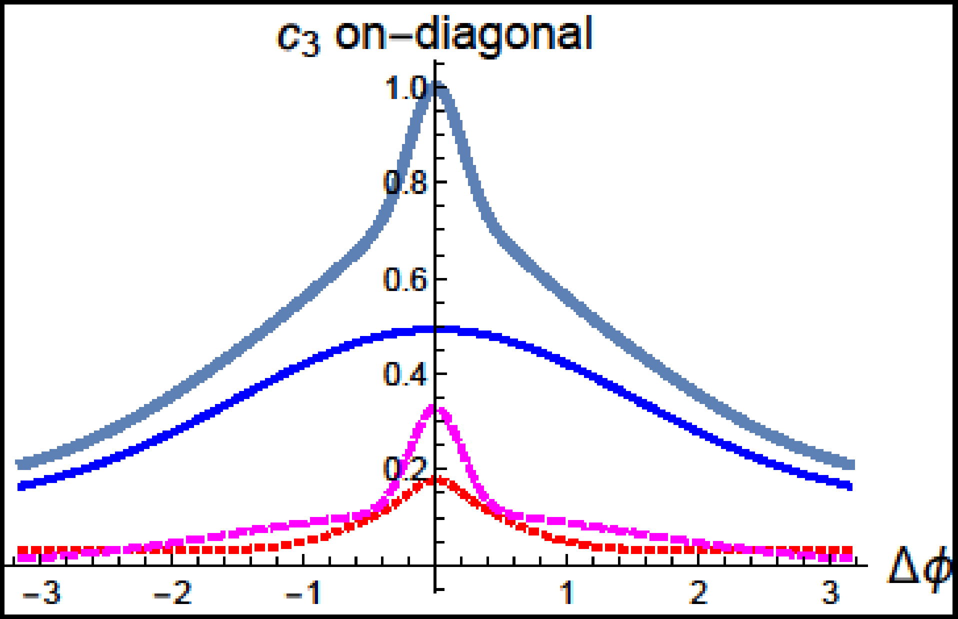
On-diagonal projection



SM

NEW PHYSICS



Can provide an estimate of $\delta_{s\phi}$

M.-A .Sanchis-Lozano, ESG, Phys. Lett. B 781 (2018) 505 and in preparation

Summary

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