Universality of Particle Production and Energy Balance in Hadronic and Nuclear Collisions

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QCD Challenges from pp to AA

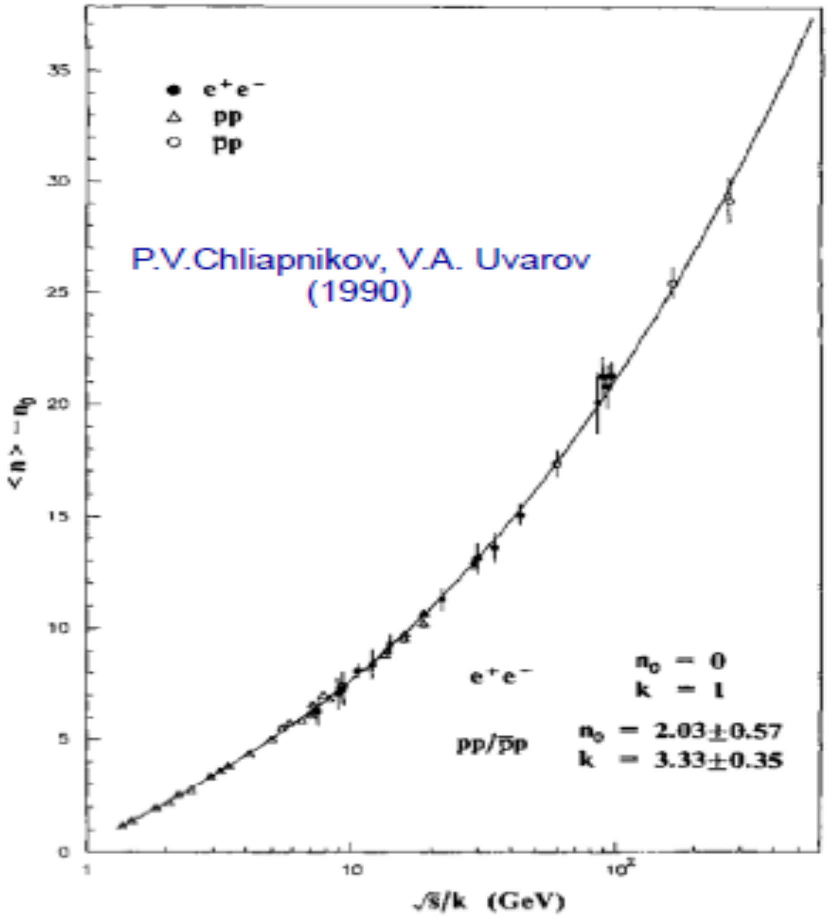
Instituto de Ciencias Nucleares UNAM

Motivation

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

- Extensively studied in heavy-ion collisions at RHIC and LHC

- Similarities with e^+e^- and pp data: universality in multihadron production



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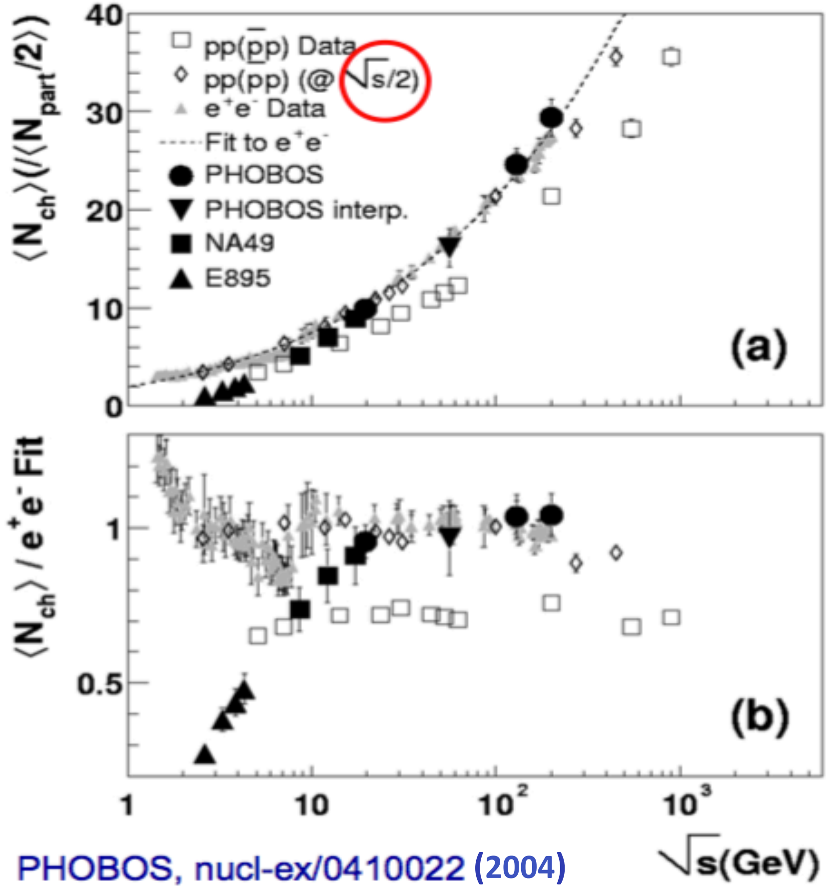
- **pp multiplicity needs scaling to show universality**



PHOBOS, nucl-ex/0410022 (2004)

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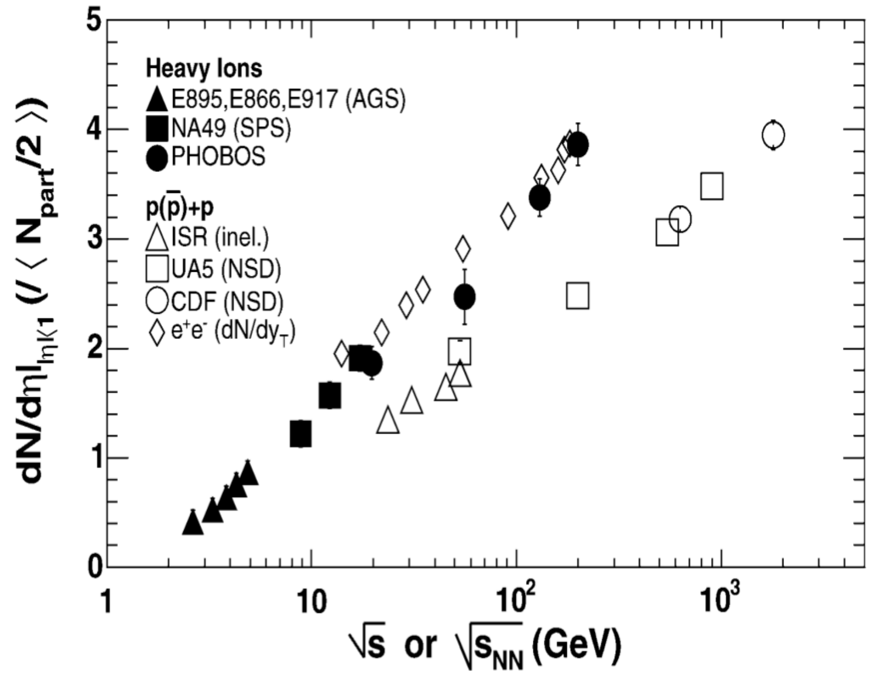

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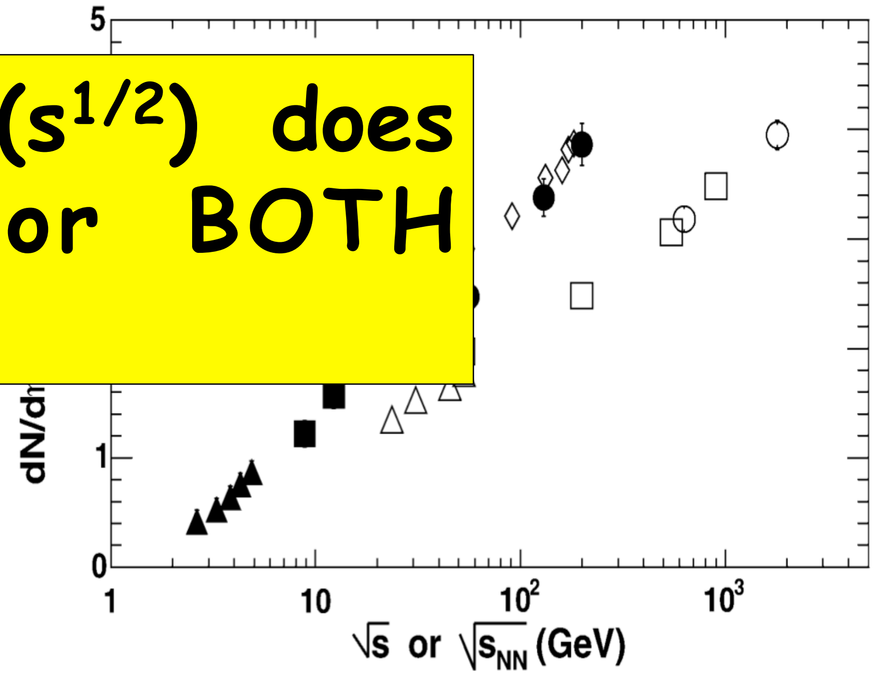
Same scaling ($s^{1/2}$) does NOT work for BOTH variables



Energy Scaling vs. Types of Collisions

- e^+e^- (structure-less 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

- Both *multiplicity* and *midrapidity density* should be similar in pp at c.m. energy $\sqrt{s_{pp}}$ and e^+e^- at c.m. energy $\sqrt{s_{ee}} \approx \sqrt{s_{pp}}/3$

- Head-on heavy ion collisions: ***all three quarks*** participate nearly simultaneously and deposit their energy coherently into initial state

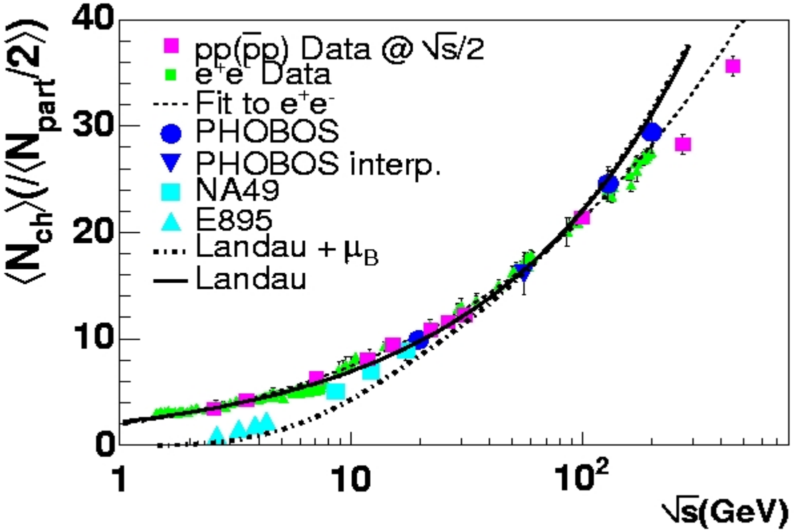
- ***Both multiplicity* and *midrapidity density* should be similar in pp at c.m. energy $\sqrt{s_{pp}}$ and head-on AA at c.m. energy $\sqrt{s_{NN}} \approx \sqrt{s_{pp}}/3$**

E. Sarkisyan & A. Sakharov (2004) : dissipating energy participants

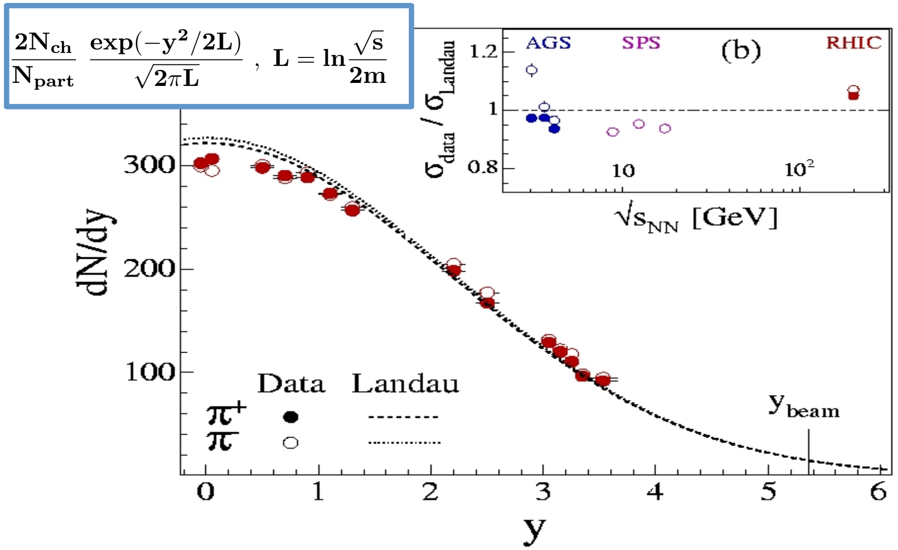
Hydrodynamics of the collisions

Two head-on colliding Lorentz-contracted particles stop within the overlapped zone

- Formation of fully thermalized initial state at the collision moment
- The decay (expansion) of the initial state is governed by relativistic hydrodynamics - Landau model (1953)



P. Steiberg (2005)



BRAHMS Collaboration, nucl-ex/0410003

The production of secondaries is defined by the energy deposited into the initial state

Hydrodynamics of the collisions

Landau Hydrodynamics: Relation between pp and AA

$$\frac{\rho(0)}{\rho_{pp}(0)} = \frac{2N_{ch}}{N_{part}\ N_{ch}^{pp}}\sqrt{\frac{L_{pp}}{L_{NN}}}, L = \ln\frac{\sqrt{s}}{2m} \qquad \text{------(1)}$$

Landau Hydrodynamics + Constituent Quark approach

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

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

Here,
N_{part} - number of participants,
N_{ch} - mean multiplicities in nucleus-nucleus collisions
N_{ch}^{pp} - mean multiplicities in nucleon-nucleon collisions and m_p is the mass of proton in nucleus-nucleus collisions and effective mass of constituent quark, $m_p/3$ in nucleon-nucleon collisions.

Effective Energy Approach

Effective Energy: A fraction of the center of mass energy available for particle production in a collision.
Effective energy can be calculated as following:

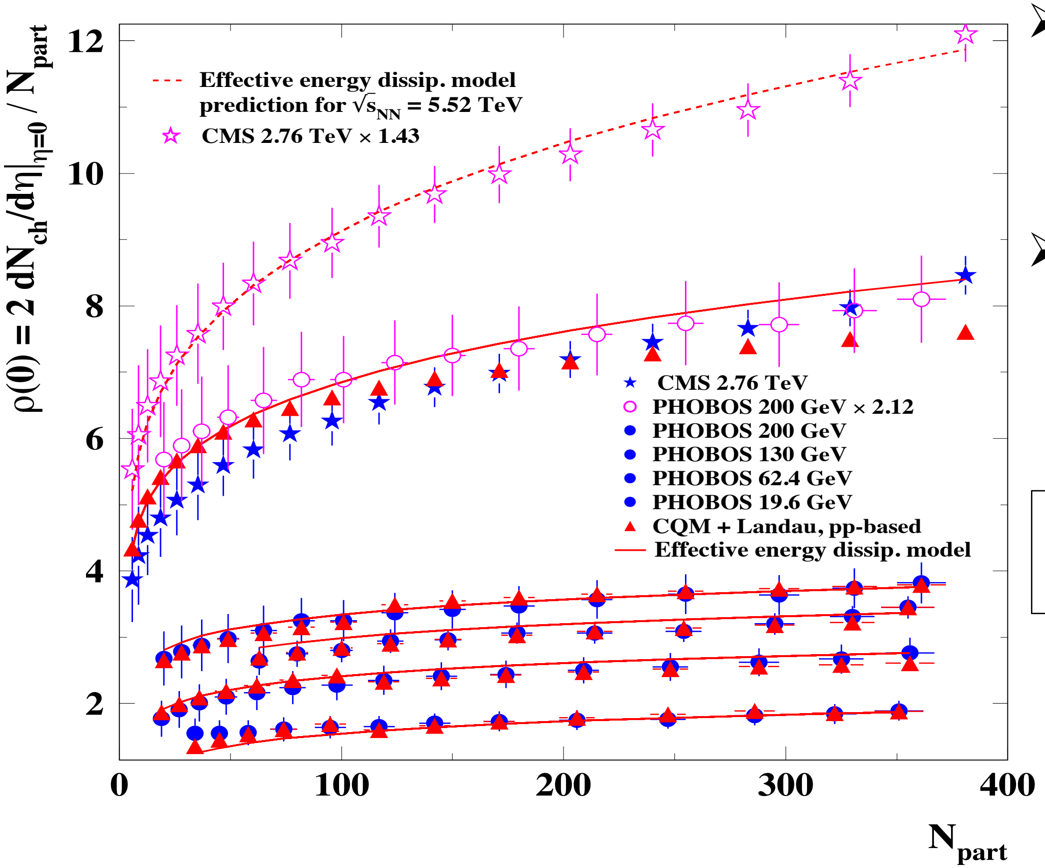
$$\epsilon_{NN} = \sqrt{s_{NN}}(1 - \alpha)$$

Here α is centrality percentile, e.g. for 0-5% central collision α = 0.025

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

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

Centrality Dependences



A.N. Mishra, R. Sahoo, E.K.G. Sarkisyan, A.S. Sakharov
Eur. Phys. J. C 74 (2014) 11, 3147

- **CQM + Landau calculations have a very good agreement with data from RHIC to LHC energies.**
- Effective energy dissipation (red line of the fit to centrality data energy dependence [next slide]) also explains data.

N_{ch} is taken at $\sqrt{s_{NN}} = \varepsilon_{NN}$
$\rho_{pp}(0)$ and N^{pp}_{ch} are taken at $\sqrt{s_{pp}} = 3\varepsilon_{NN}$

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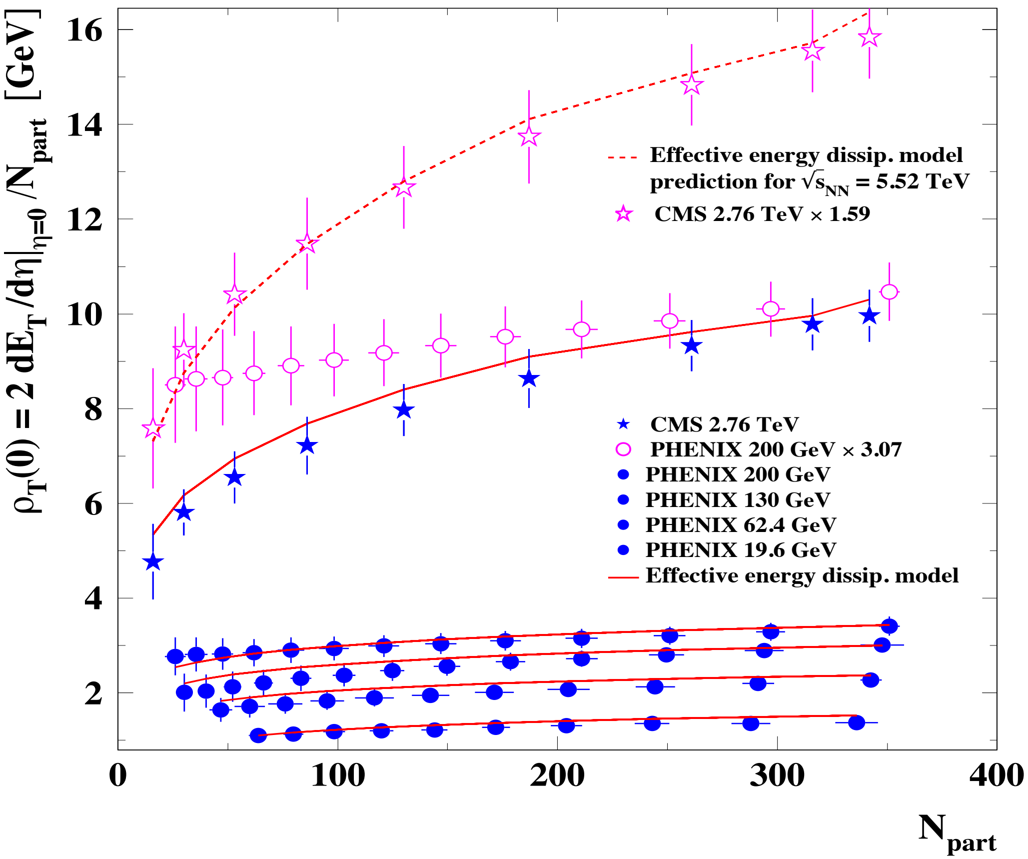

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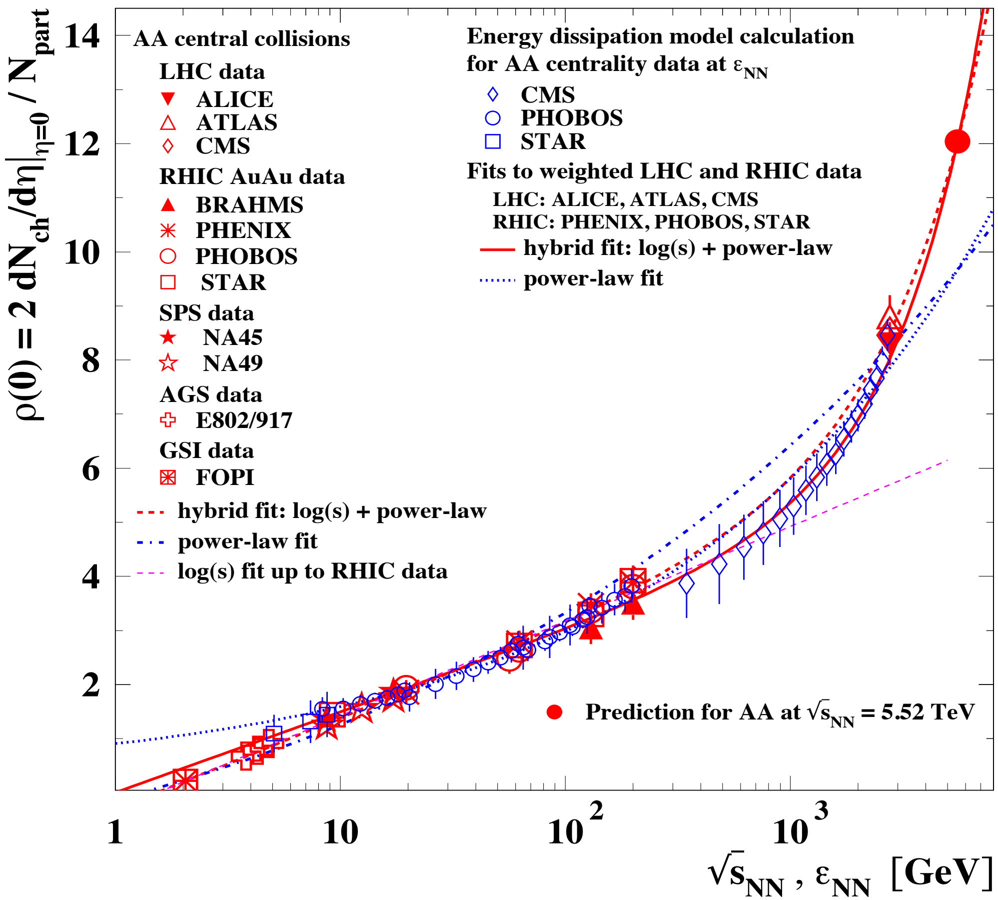
Similar behaviour is found for transverse energy.

Center of Mass Energy Dependences



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- Model well reproduces the data under the assumption of the effective energy deriving the multi-particle production process
- Centrality data are shown as a function of the effective c.m. energy ε_{NN}
- **Similarity** in the data *from peripheral to the most central* collisions: all the data follow the same (effective) energy behavior

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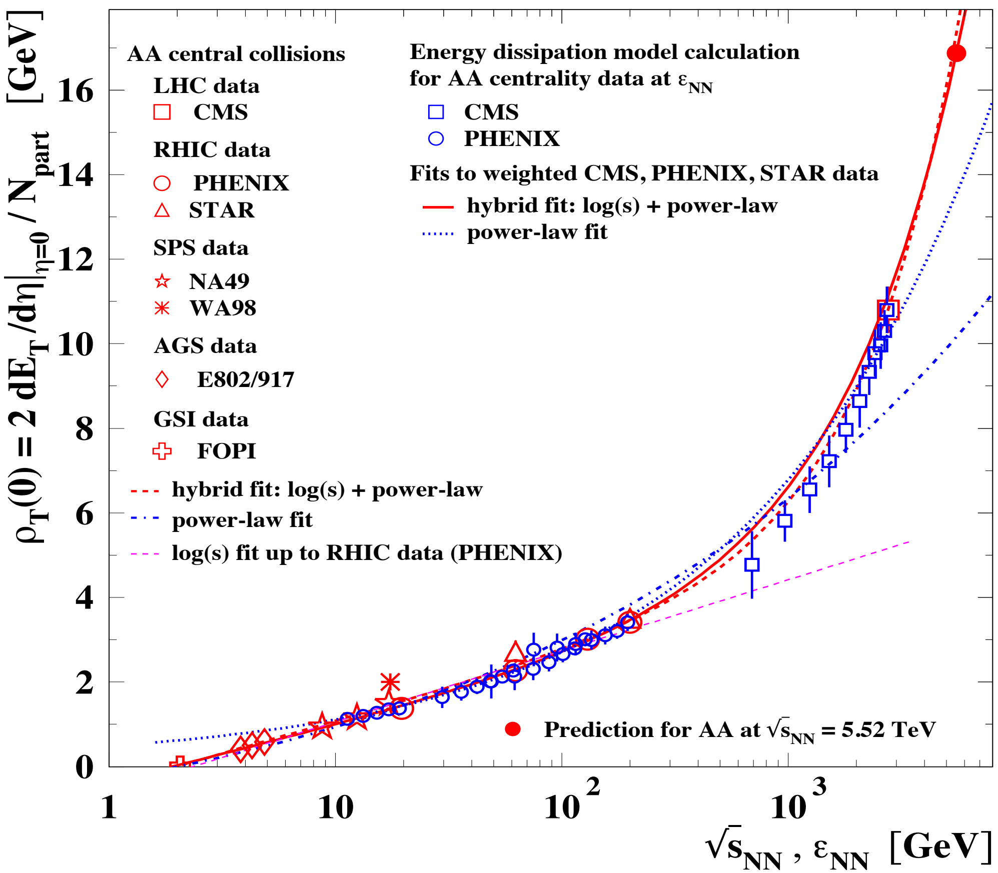

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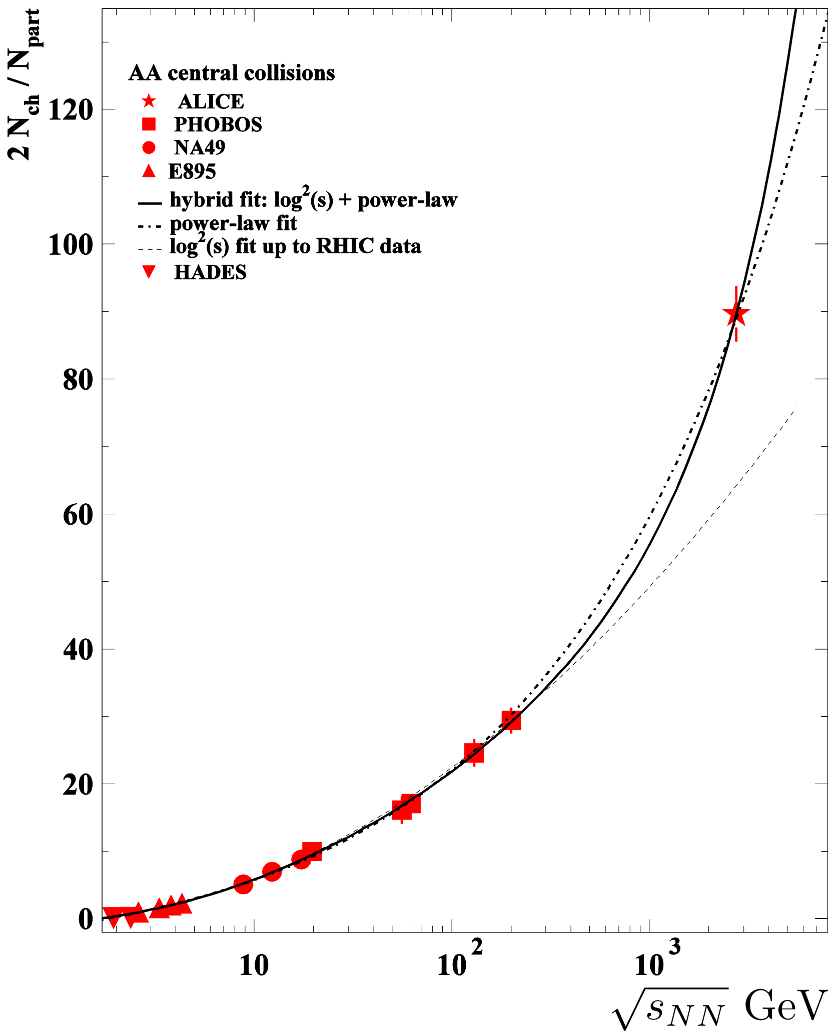
Similar behaviour is found for transverse energy.

Effective energy approach provides a good description of *both* the pseudorapidity and transverse energy densities at midrapidity in heavy-ion collisions

Mean Multiplicity Energy Dependence



- Hybrid and power-law functions provide good fits for *all available AA data* and are almost indistinguishable up to LHC energy
- LHC data departs from log^2-polynomial fit at $\sqrt{s_{NN}}$ about 1 TeV, indicates **a possible transition to a new regime** in heavy-ion collisions

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Phys. Rev. D 93, 054046 (2016).

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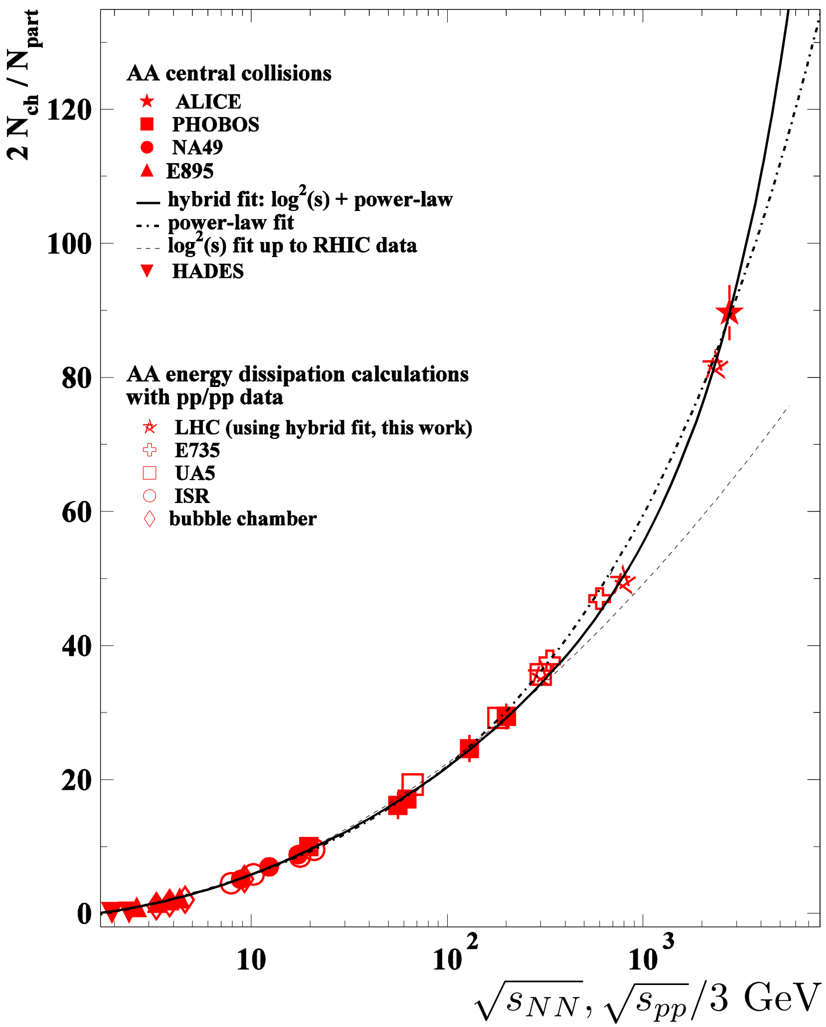

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- Charged particles mean multiplicities *calculated* from the dissipation energy approach for AA data, using the pp/ppbar measurements, **well describe** the heavy-ion measurements

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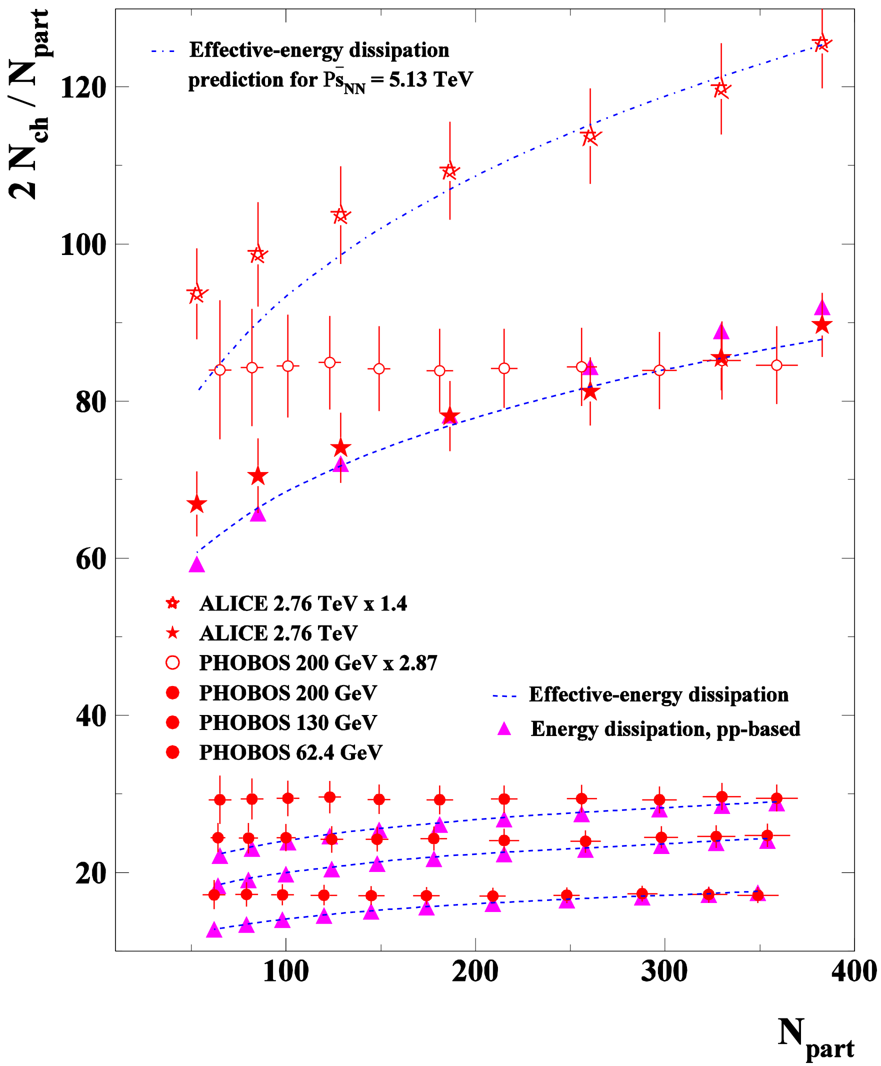
Mean Multiplicity Centrality Dependence



- The dotted lines represent the **calculations from the effective-energy approach**
- The <u>calculations</u>, driven by the *centrality-defined effective c.m. energy* ε_{NN}, **well reproduce** the **LHC** data
- **RHIC** data show a significant **difference** with the calculations <u>for peripheral collisions</u>

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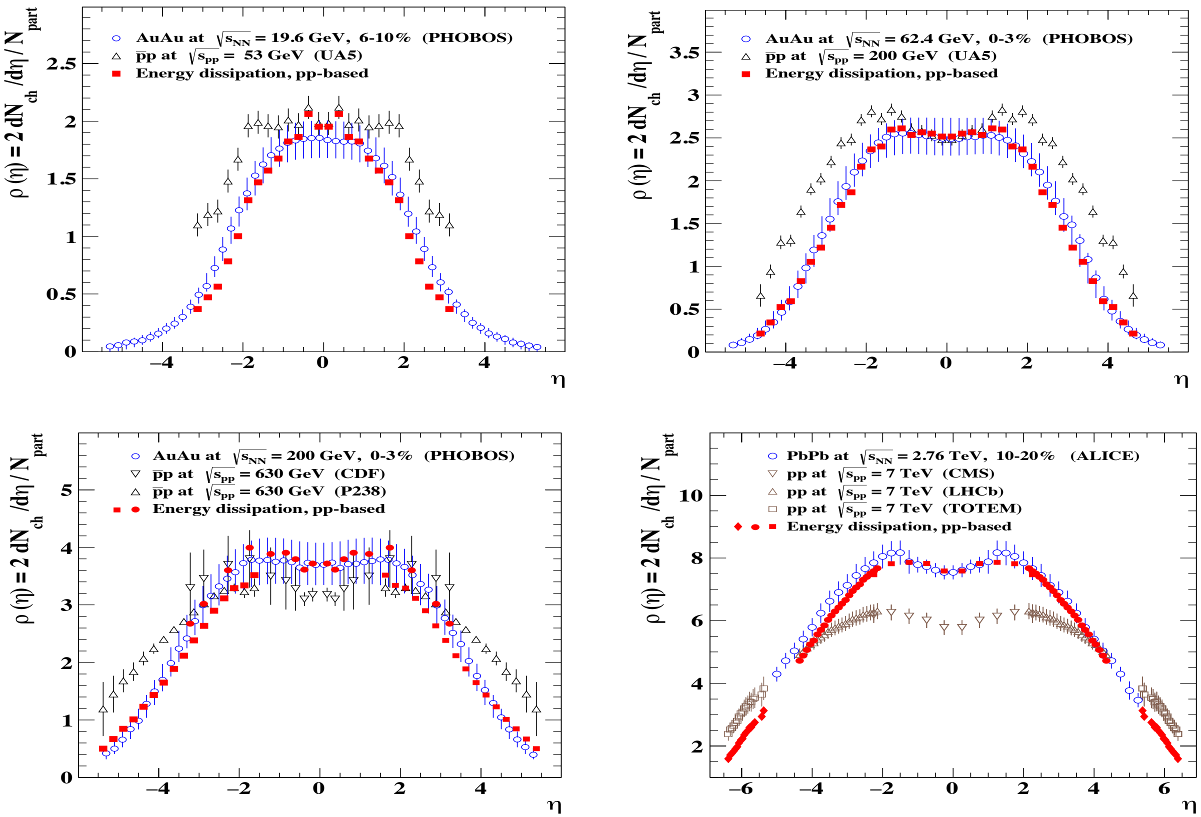
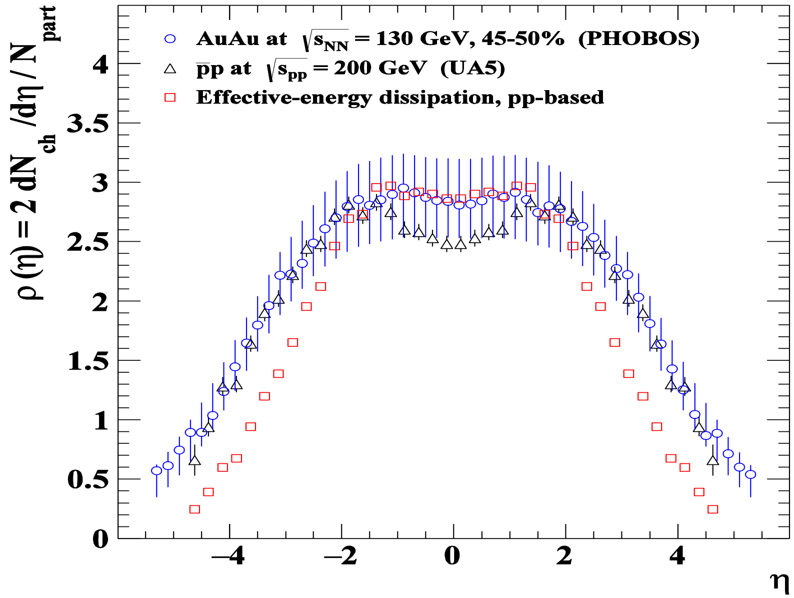
Pseudorapidity Distributions (Most Central Collisions)



- Calculations for <u>high-central</u> collisions, are in **very good agreement** with the measurements.
- At **LHC** energy, pp measurements from the <u>three different experiments</u> are used and shown to **reproduce** AA data

E.K.G. Sarkisyan, A.N.M., R. Sahoo, A.S. Sakharov Phys. Rev. D 93, 054046 (2016).

Pseudorapidity Distributions (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

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

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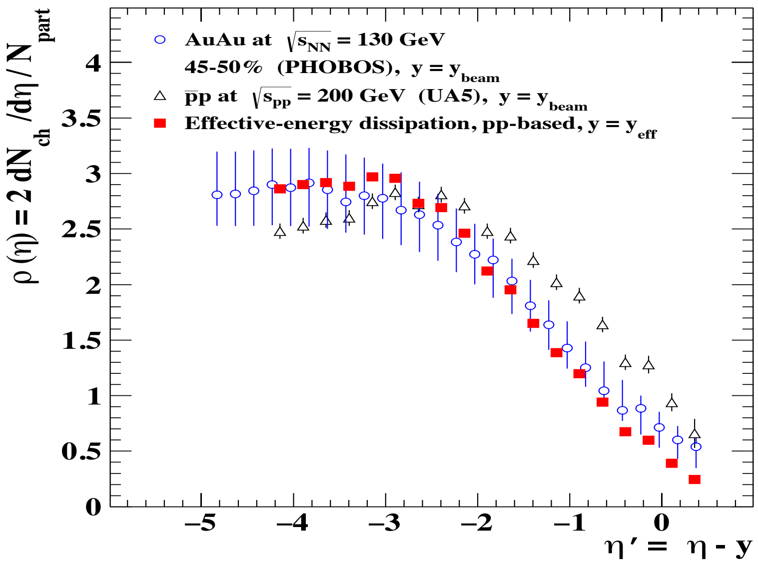
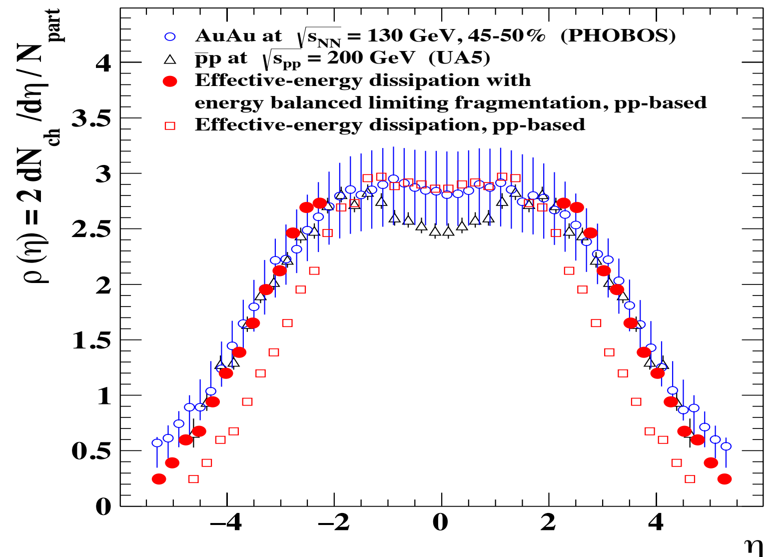
Energy Balanced Limiting Fragmentation





- The *measured* distribution ρ(η) 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 $\eta' = \eta - y_{eff}$. Then **the distributions coincide** as expected.

- The *newly calculated* distribution ρ(η) needs to be shifted by the difference ($y_{eff} - y_{beam}$) in the fragmentation region: $\eta \rightarrow \eta - (y_{eff} - y_{beam}) = \eta - \ln(1 - \alpha)$.

- These represent **the *energy balanced* limiting fragmentation scaling** phenomena

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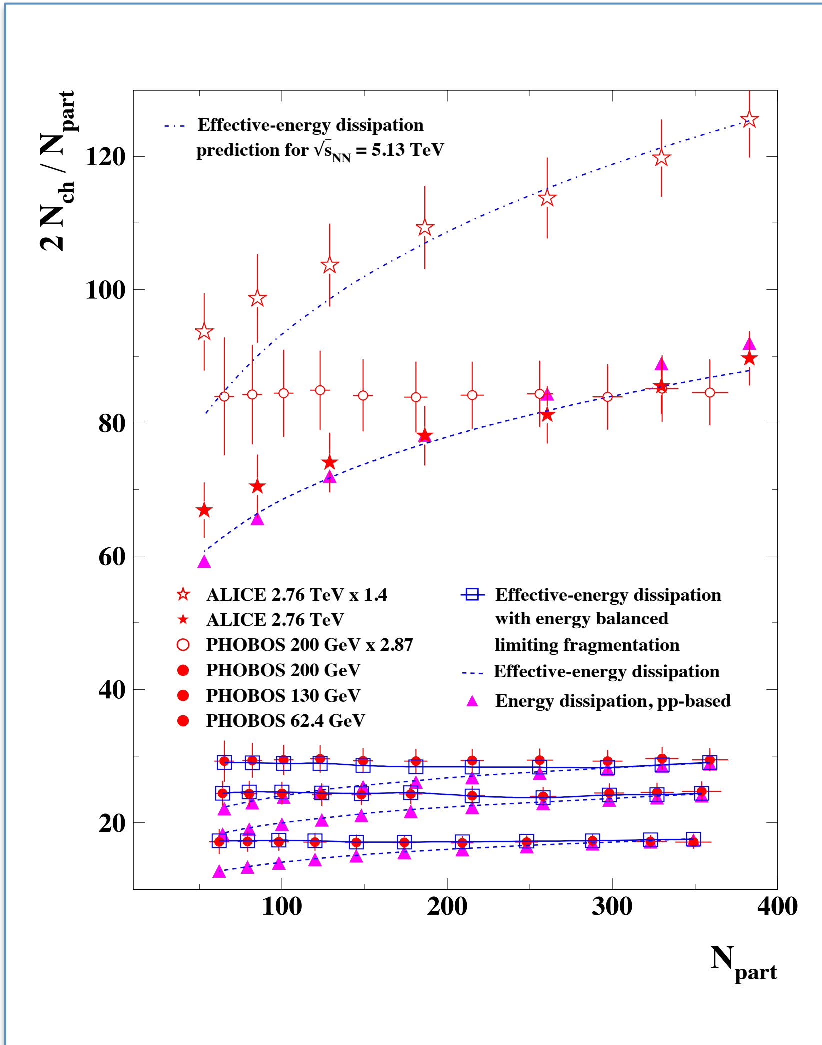

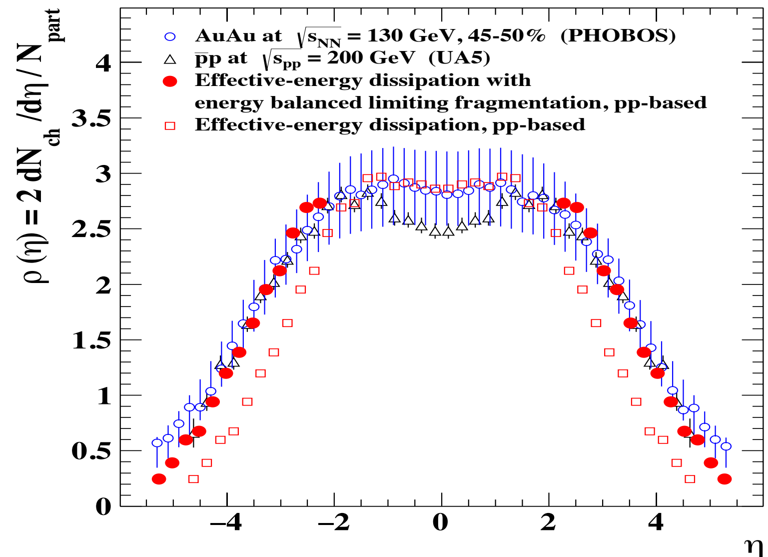

Energy Balanced Limiting Fragmentation scaling gives solution of the difference between our calculation and experimental measurement for peripheral collisions.

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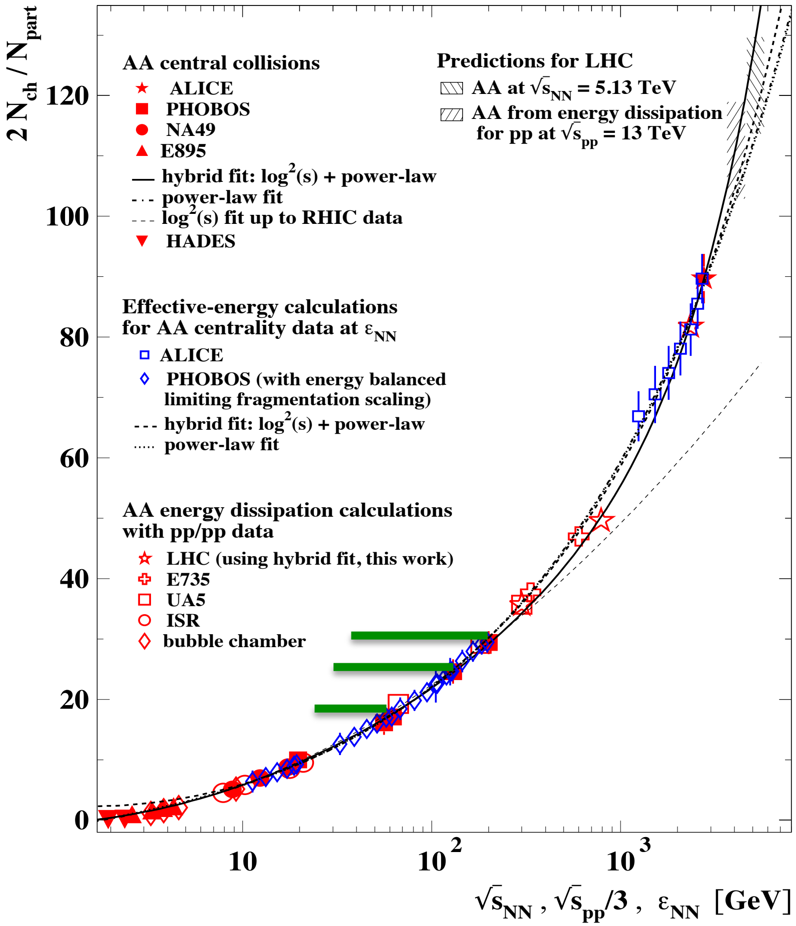
Phys. Rev. D 93, 054046 (2016).

Mean Multiplicity Energy Dependence



- Charged particles mean multiplicities *calculated* from the dissipation energy approach for AA data, using the pp/ppbar measurements, **well describe** the heavy-ion measurements

- The centrality data show the energy dependence similar to head-on data as soon as the centrality data are considered in terms of the effective energy. The RHIC data are recalculated by using the **Energy Balanced Limiting Fragmentation Scaling**

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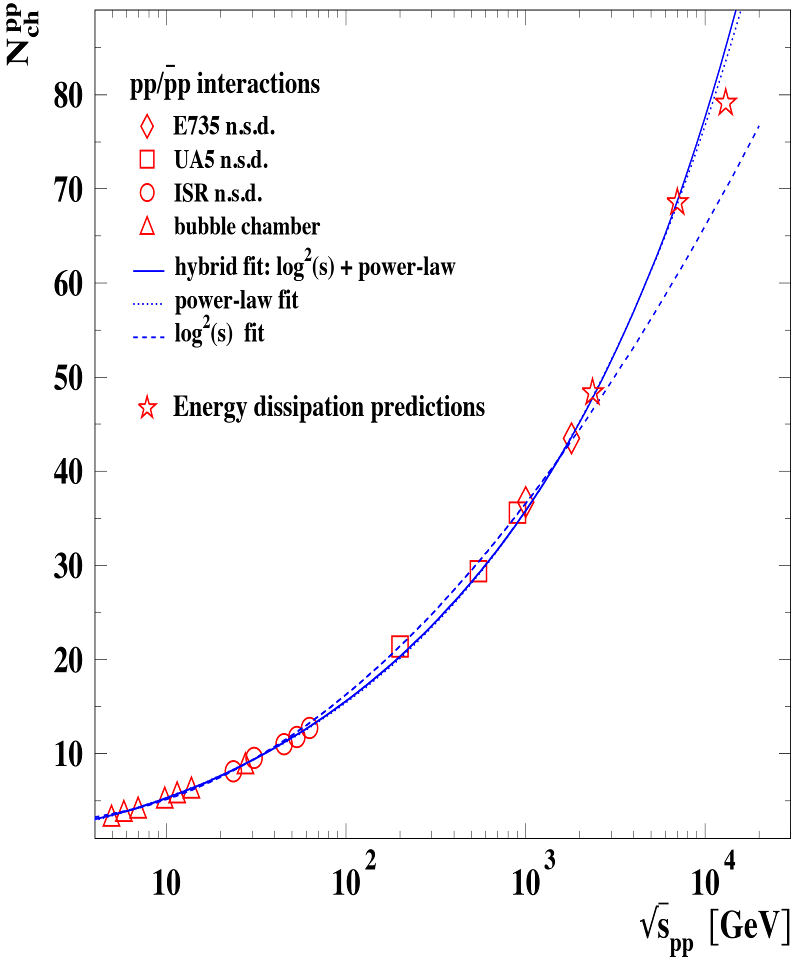
Phys. Rev. D 93, 054046 (2016).

Mean Multiplicity Energy Dependences in pp Interactions



- *The power-law and hybrid* fit functions **fit well** the data in the **entire c.m. energy** region and are seen to overlap up to $\sqrt{s_{pp}}$= 10 TeV
- Log^2-polynomial fit function is also very *close* to the power-law fit even for $\sqrt{s_{pp}}$ > 2 TeV
- No change in the multihadron production *in pp interactions* up to the top LHC energy in contrast to a new regime possibly occurred at $\sqrt{s_{NN}} \approx$ 1 TeV in heavy-ion collisions
- **pp participant dissipating energy approach predictions are given**

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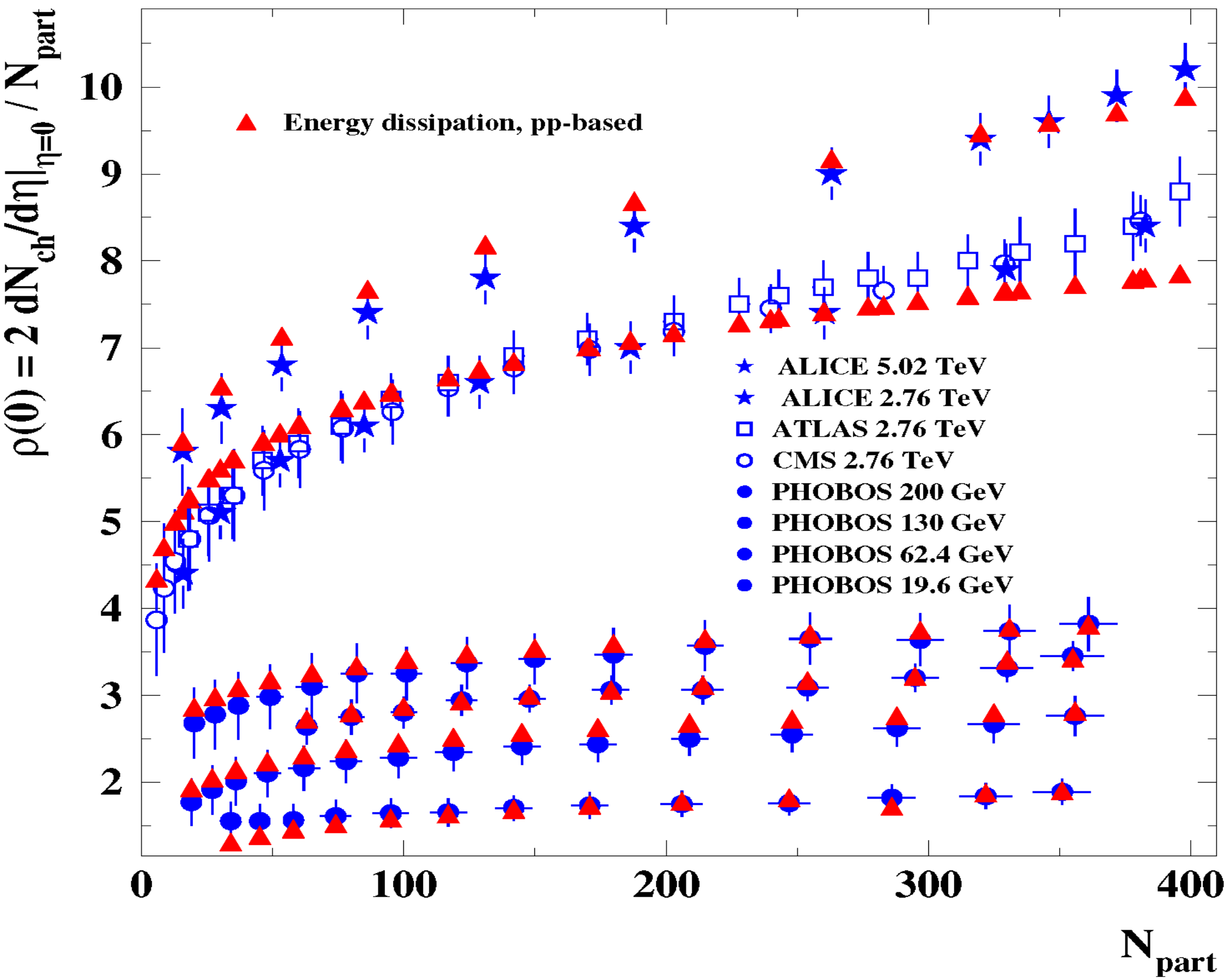
Application of the PDE Approach



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Summary

- ☑ **The AA multiplicity and pseudorapidity measurements are well reproduced** under the assumption of ***the effective energy*** deriving 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**

- ☑ pp based calculations show a very good agreement with heavy-ion data from 19.6 GeV up to 5.02 TeV


Thank you