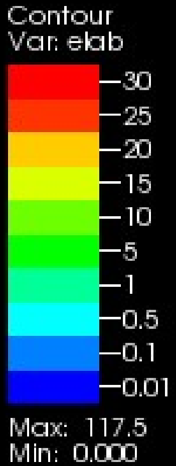
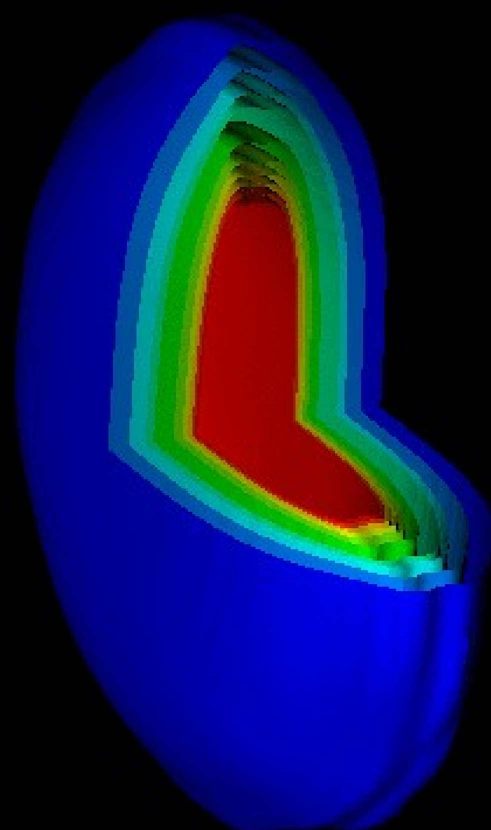


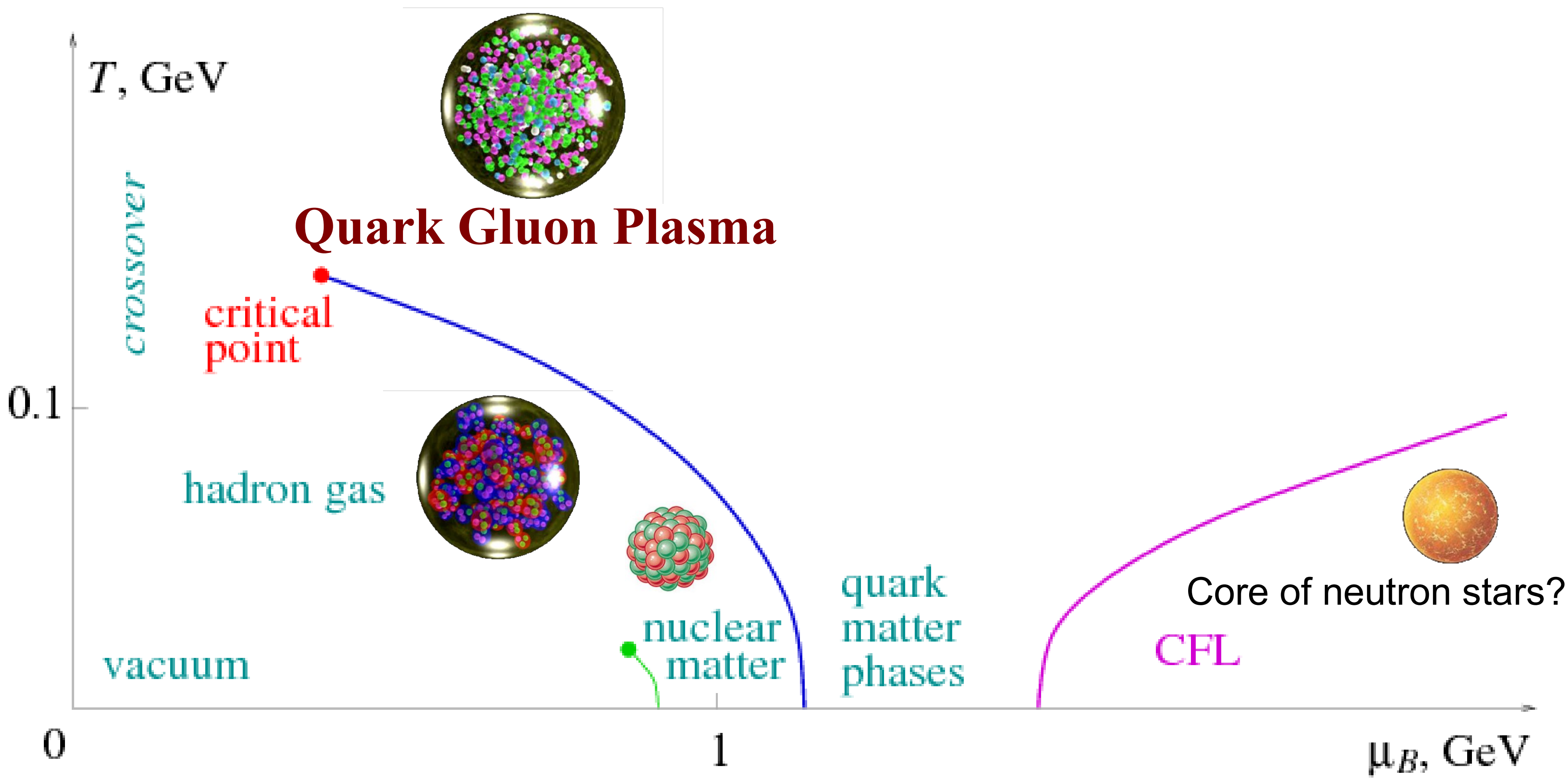
Measuring the energy density of the QGP



Christine Nattrass
University of Tennessee at Knoxville

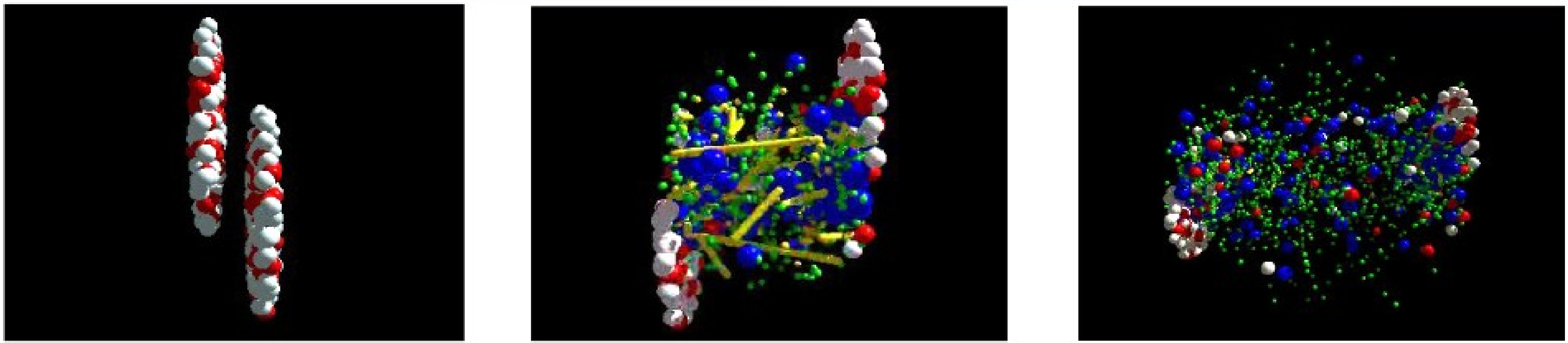
Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/

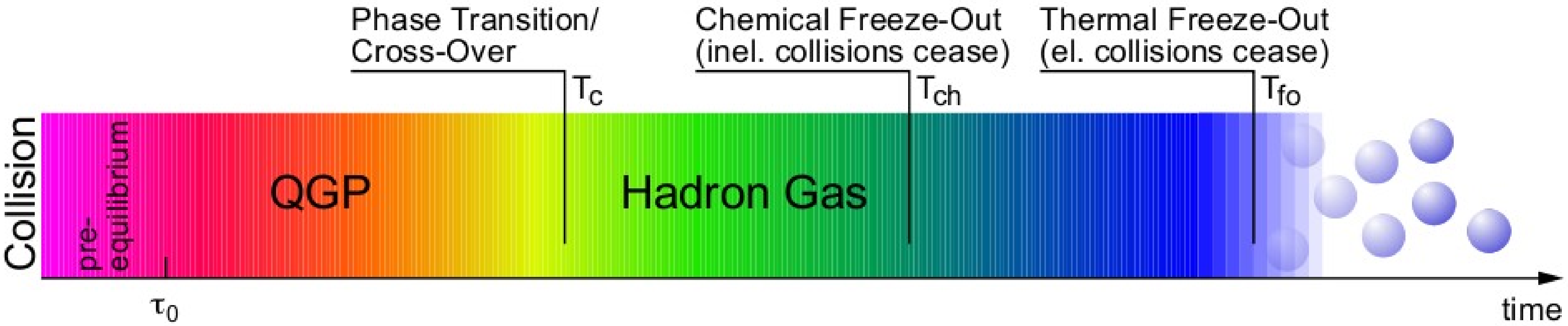
Phase diagram of nuclear matter



Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2{\cdot}10^{12}$K) – over a million times hotter than the core of the sun

The phase transition in the laboratory

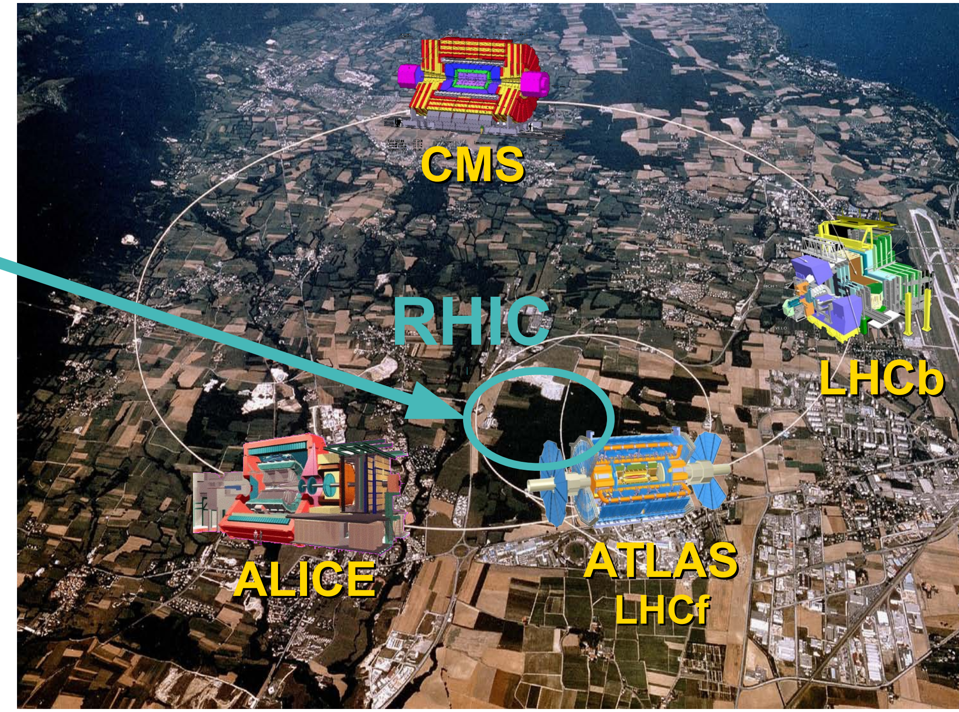




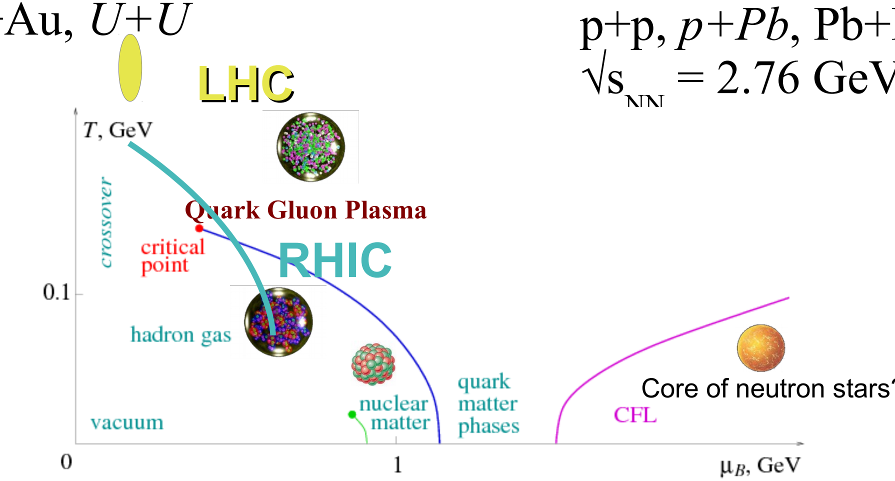
Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

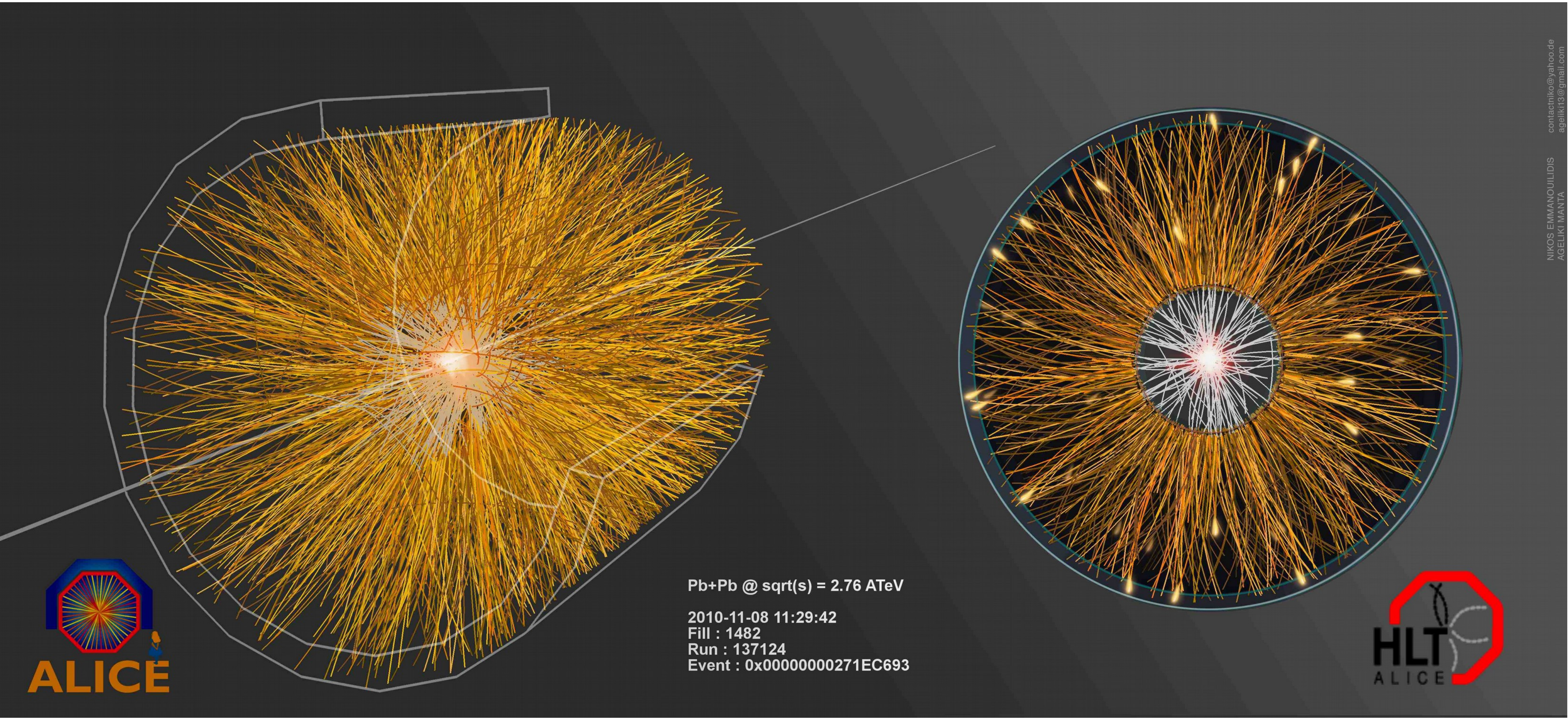
Large Hadron Collider



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*

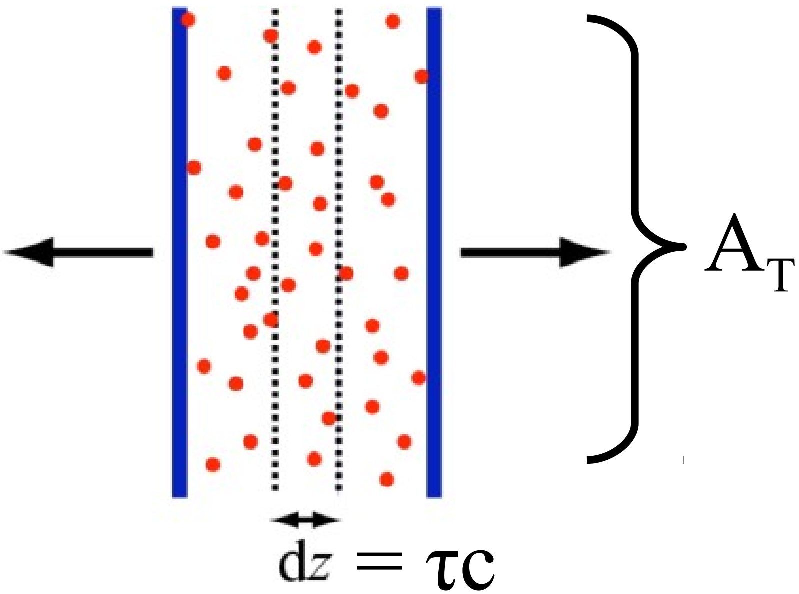


Pb+Pb collisions



How can we estimate the energy density?

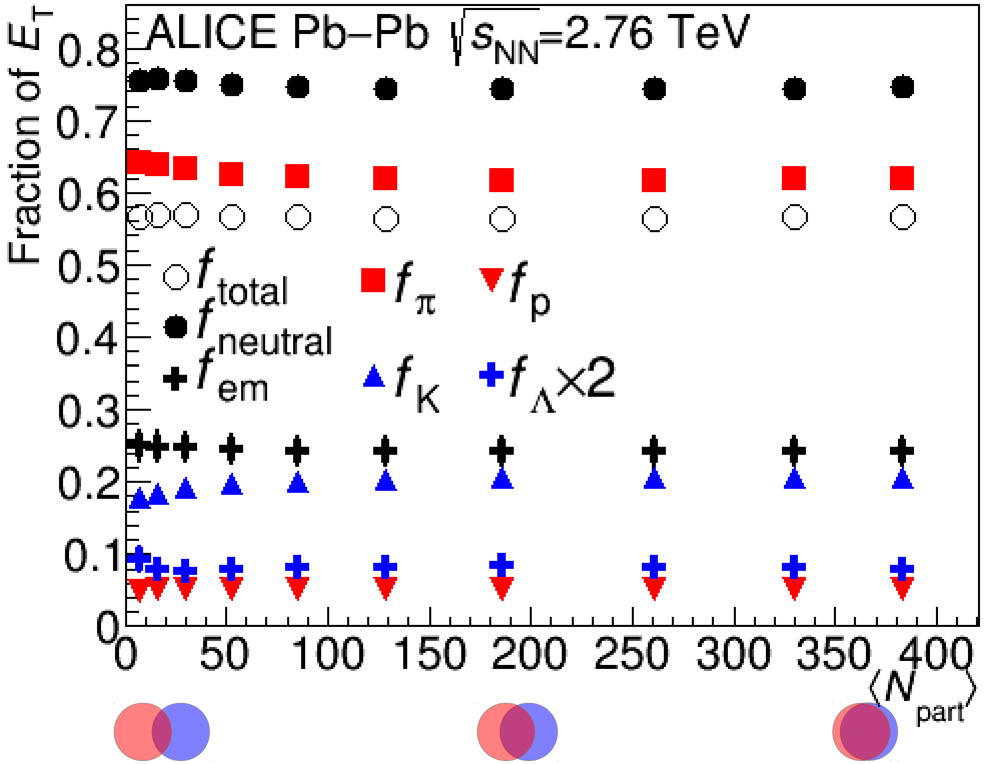
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



$$\epsilon = \frac{1}{V}\frac{dE_T}{dy} = \frac{J}{A_T \tau c}\frac{dE_T}{d\eta}$$

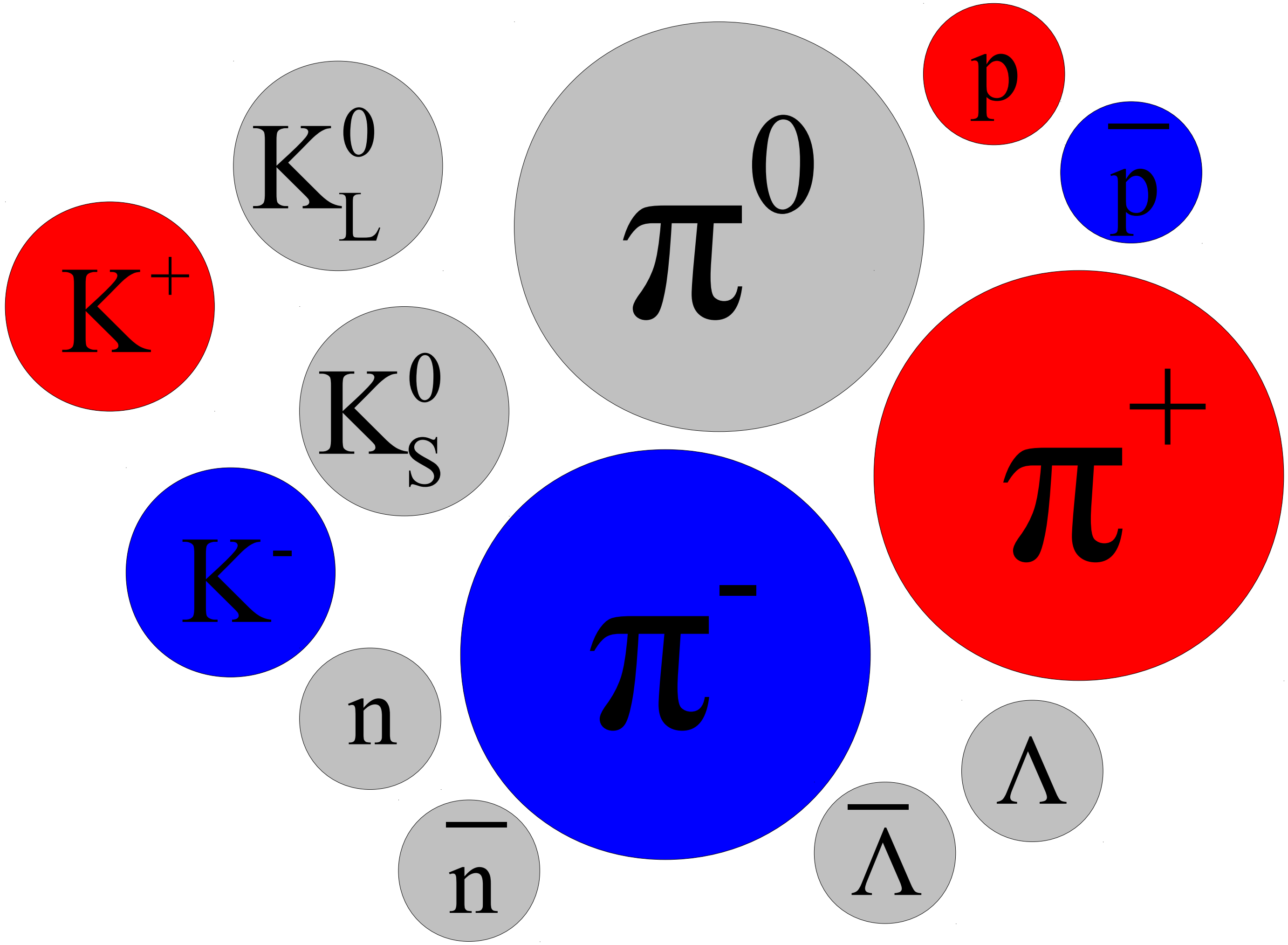
- QGP formation for $\varepsilon > 0.5$ GeV/fm^3

Where is the energy?



The distribution of energy is surprisingly centrality independent.

Where is the energy?



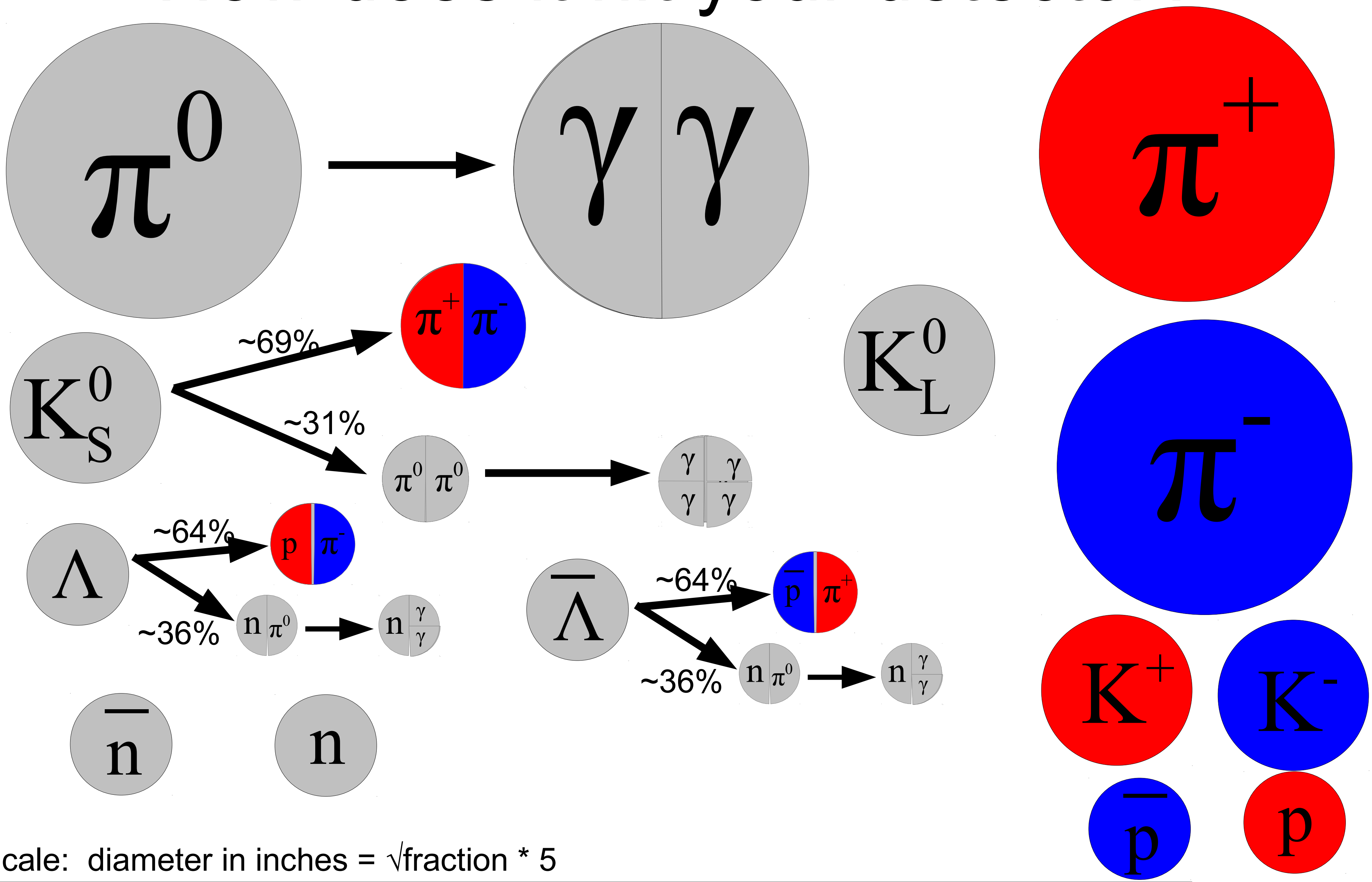
Scale: diameter in inches = √fraction * 5

Methods for measuring E_T

- CMS: Tracking + electromagnetic calorimeter + hadronic calorimeter
- PHENIX: Electromagnetic calorimeter
- STAR: Tracking + Electromagnetic calorimeter
- ALICE: Tracking*

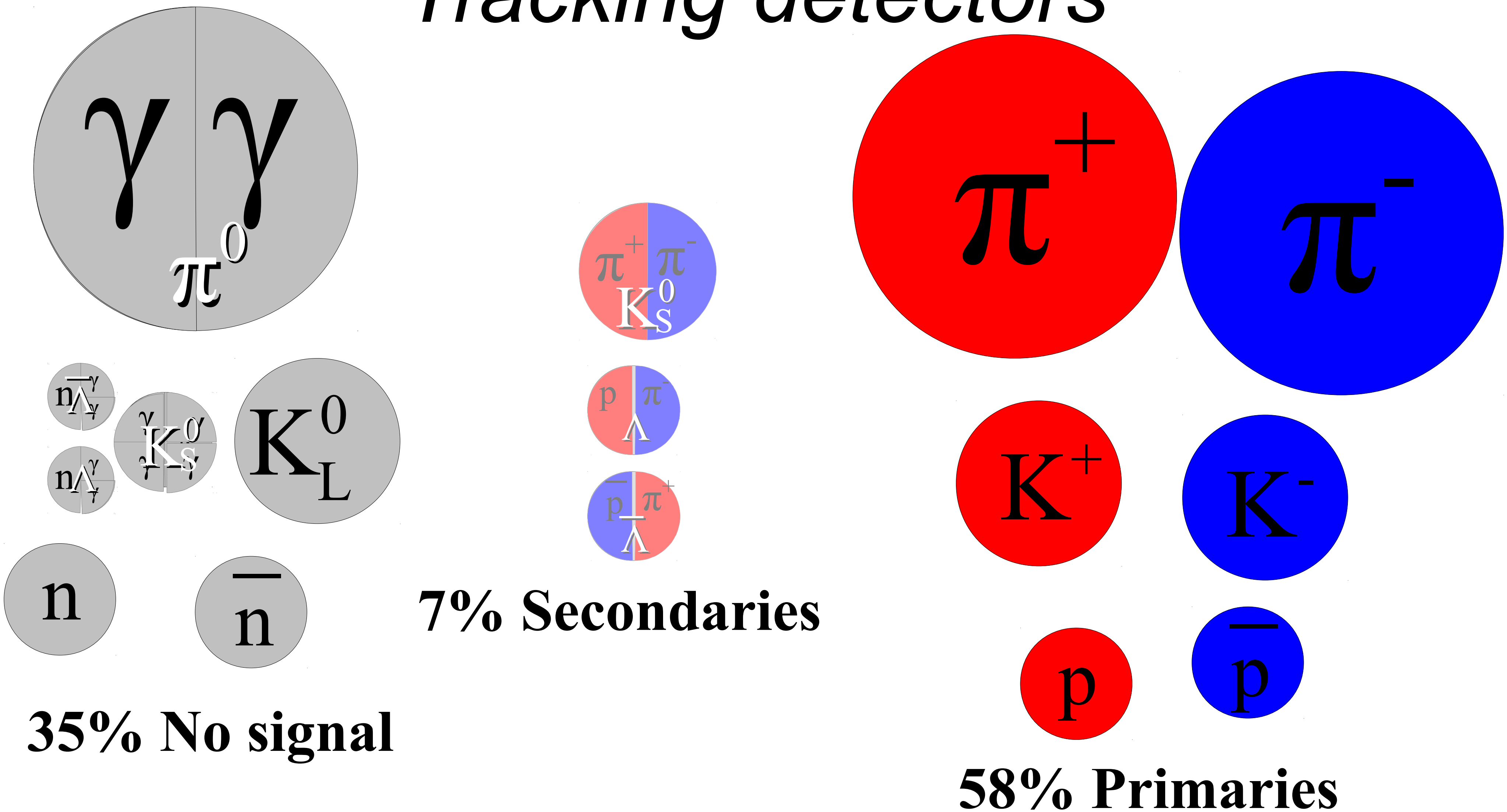
*Other methods tried – focusing on this one here

How does it hit your detector?



Scale: diameter in inches = √fraction * 5

How does it hit your detector?
Tracking detectors



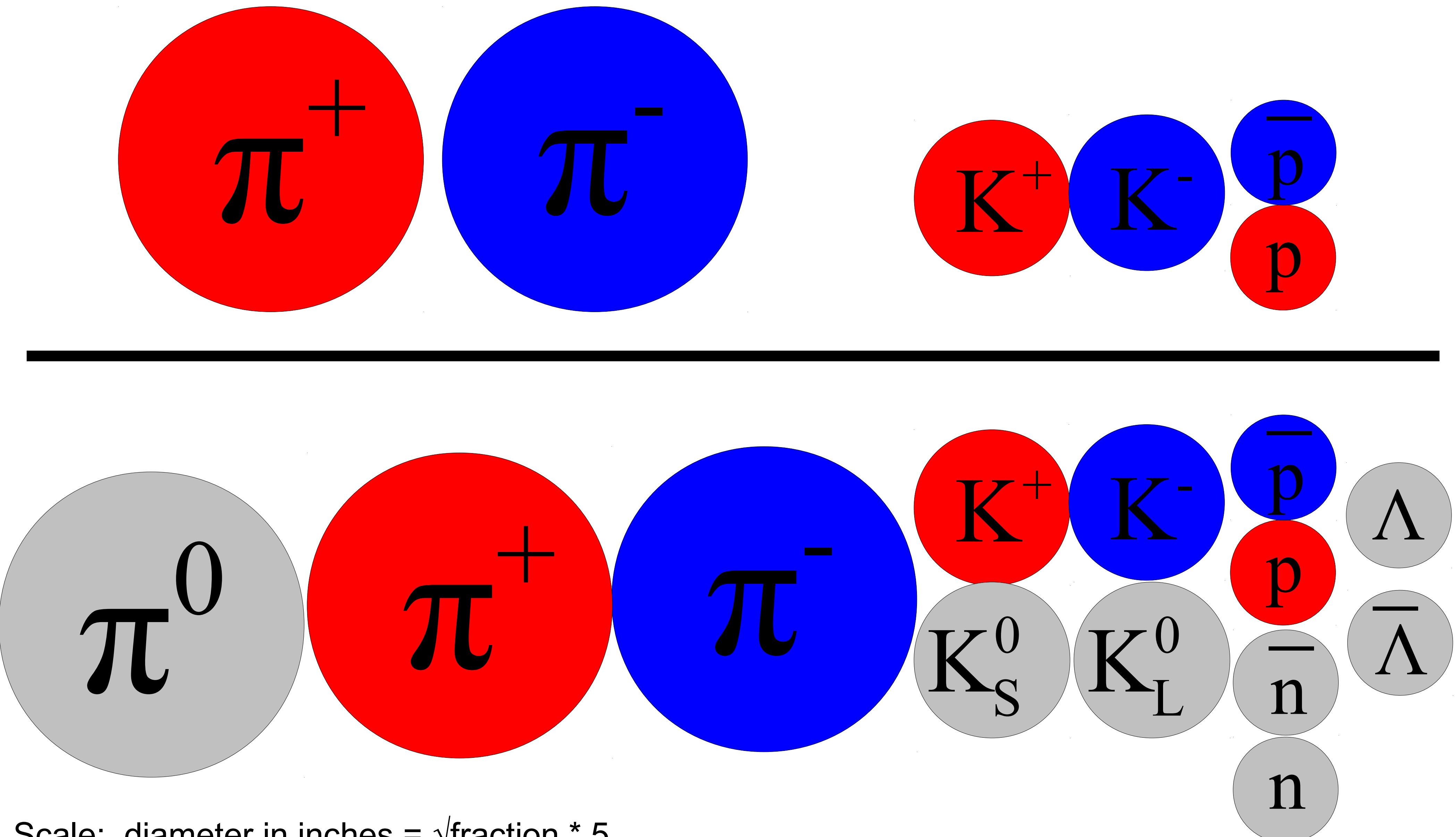
Scale: diameter in inches = √fraction * 5

ALICE

But known well!

$$E_T = \underbrace{\overset{3\%}{\frac{1}{f_{p_T cut}}} \; \underset{45\%}{\frac{1}{f_{total}}} \sum_{i=0}^{n} \overset{2\%}{f^{i}_{bg}(p_T)} \; \overset{3\%}{\frac{1}{f_{notID}}} \; \overset{40\%}{\frac{1}{eff\left(p_T^i\right)}}}_{\text{Corrections}} \; \underset{\text{What we measure directly}}{E_i \sin\left(\theta^i\right)}$$

ALICE: f_{total} = 0.567 ± 0.009



Scale: diameter in inches = √fraction * 5

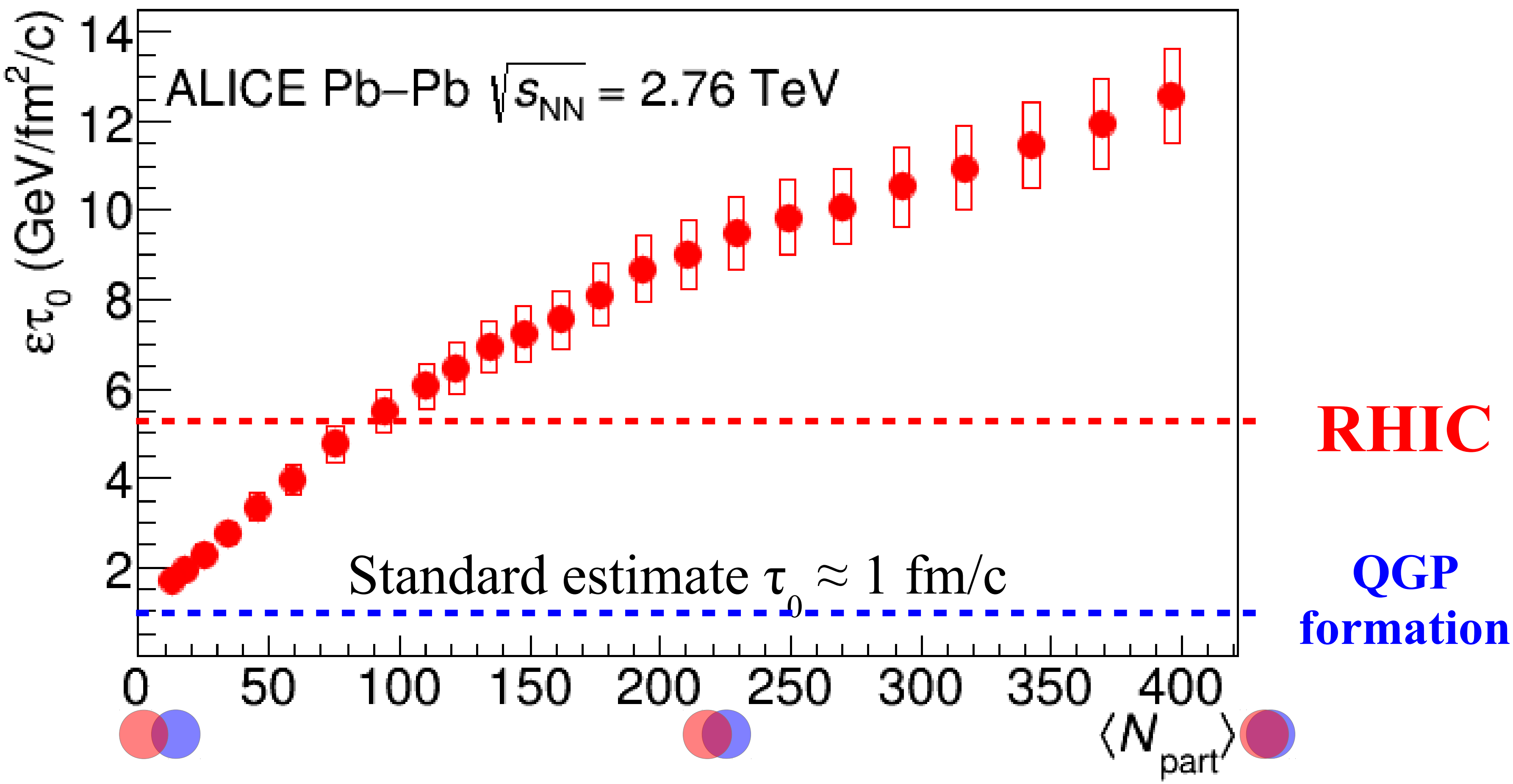
Measuring energy with tracking detectors

- f_{total} is robust
- Other corrections are either small or known well

What can we learn from measuring E_T?

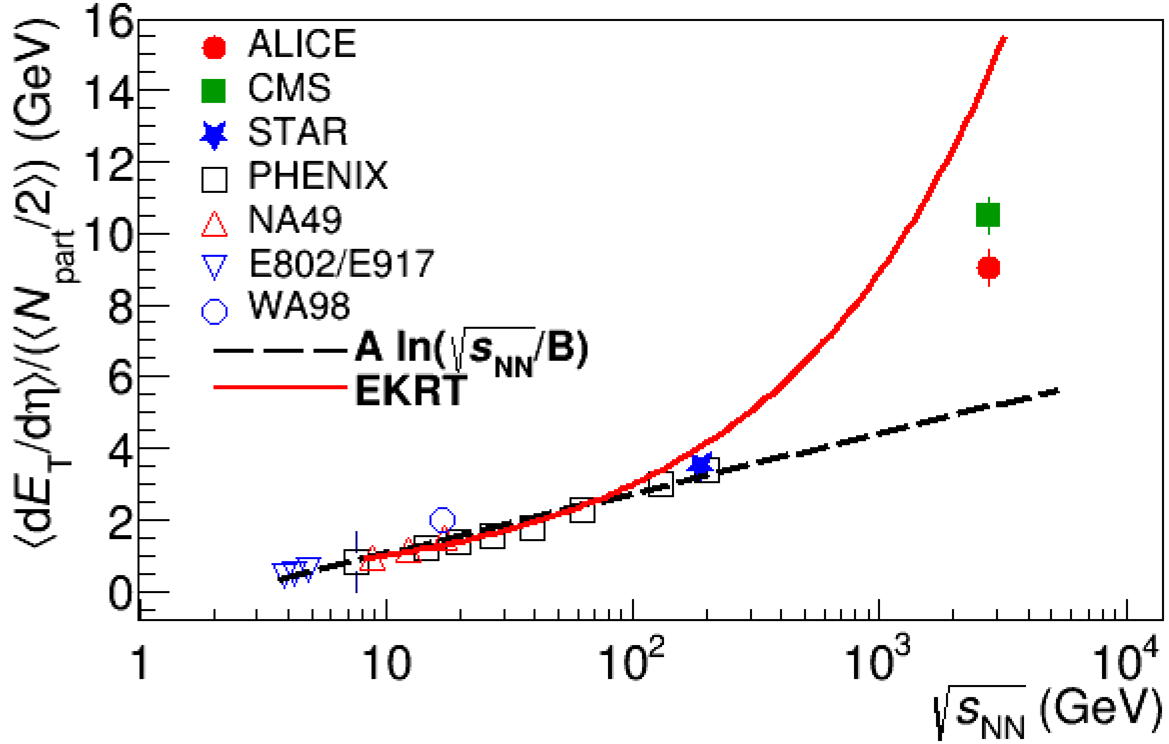
- ➔Reach energy densities around 10 GeV/fm^3, several times the energy density necessary to form QGP
- ➔E_T higher than expected at LHC
- ➔E_T seems to scale with N_{quark}
- ➔At LHC increasing energy → increasing energy/particle, not more particles

Energy density



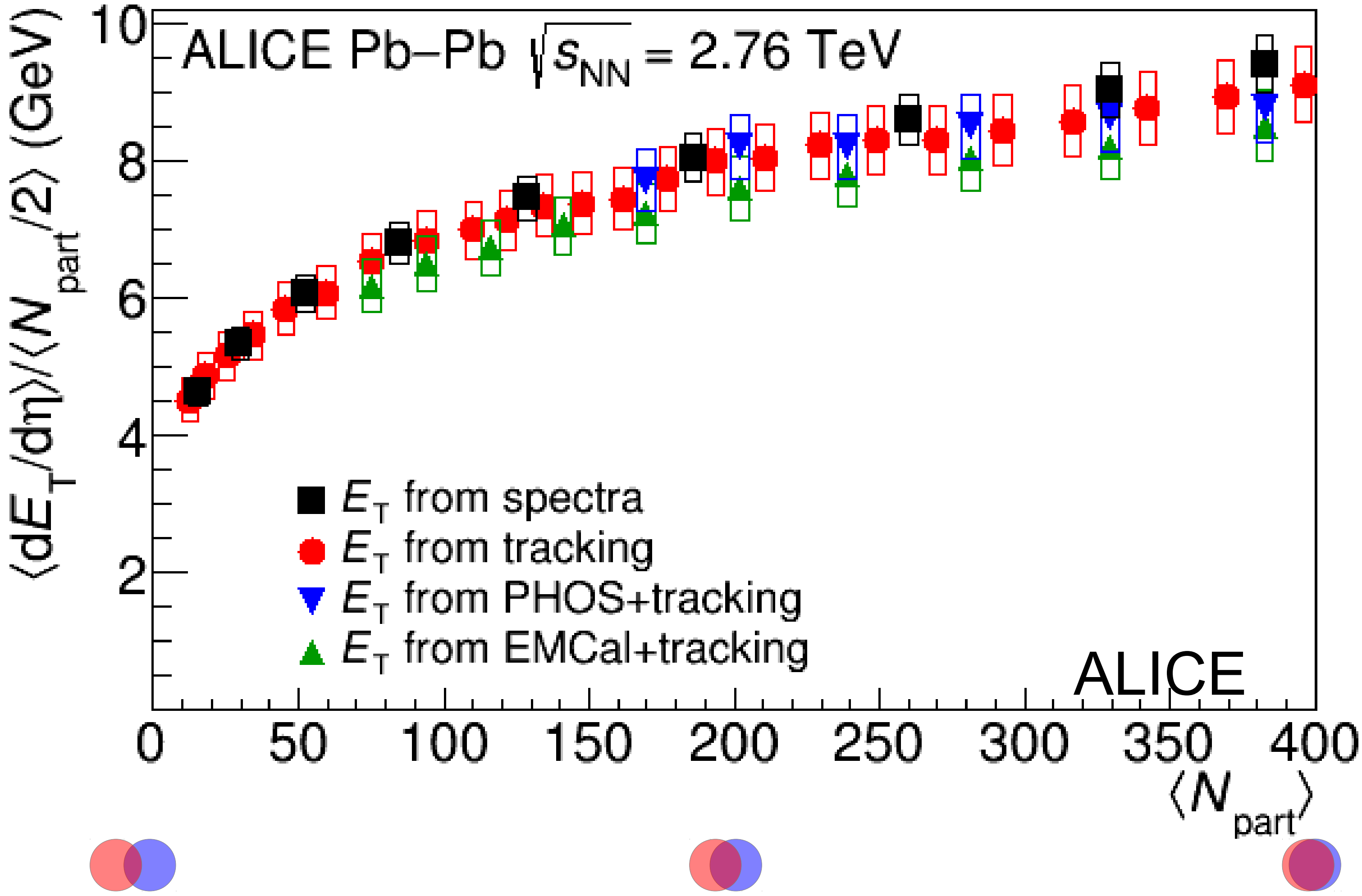
$$\epsilon = \frac{1}{A\, c\, \tau_0} \frac{dE_T}{dy}$$

Energy dependence

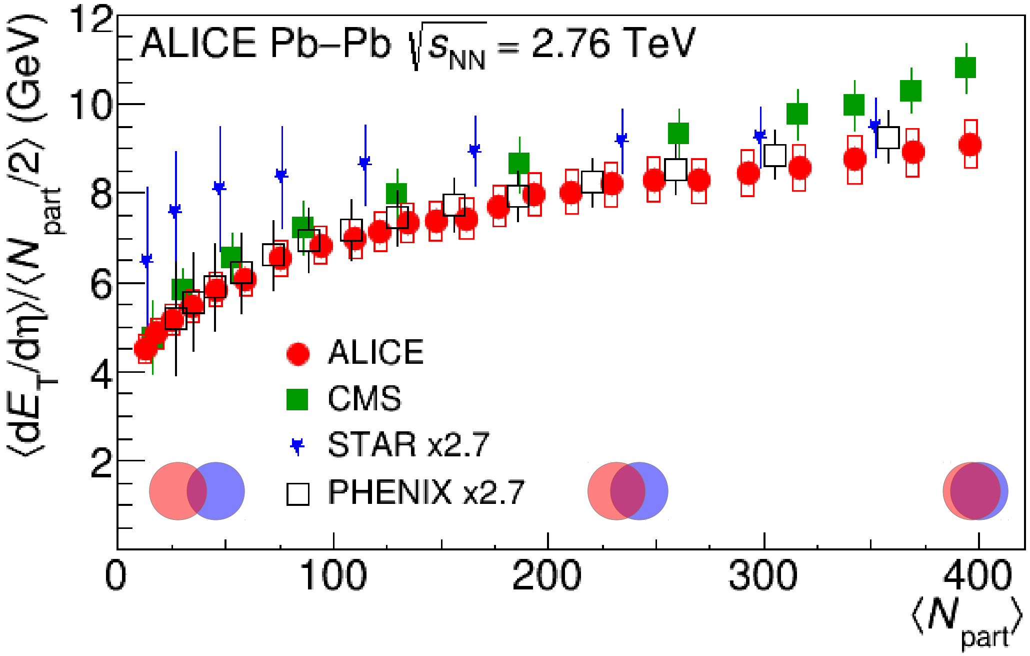


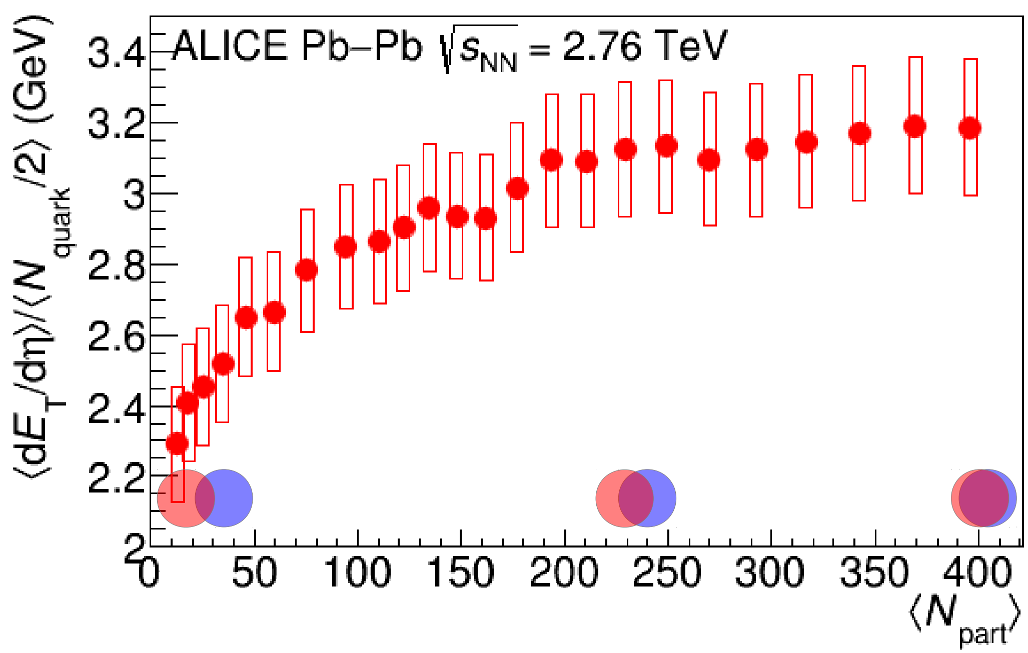
➔ Higher than extrapolations of RHIC data

Comparison of different methods



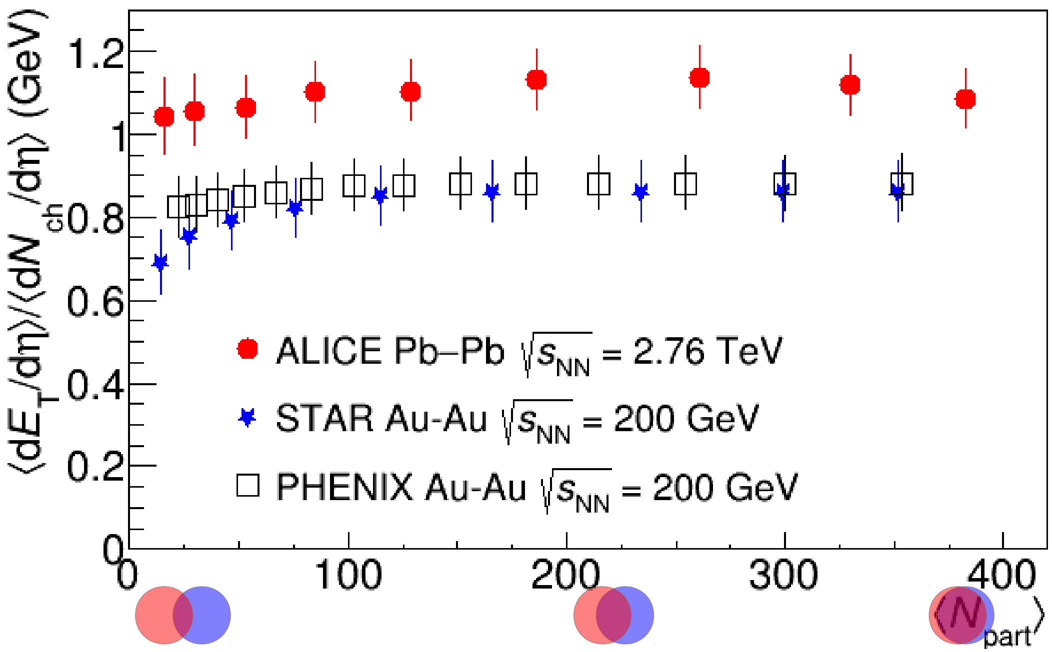
Scaling

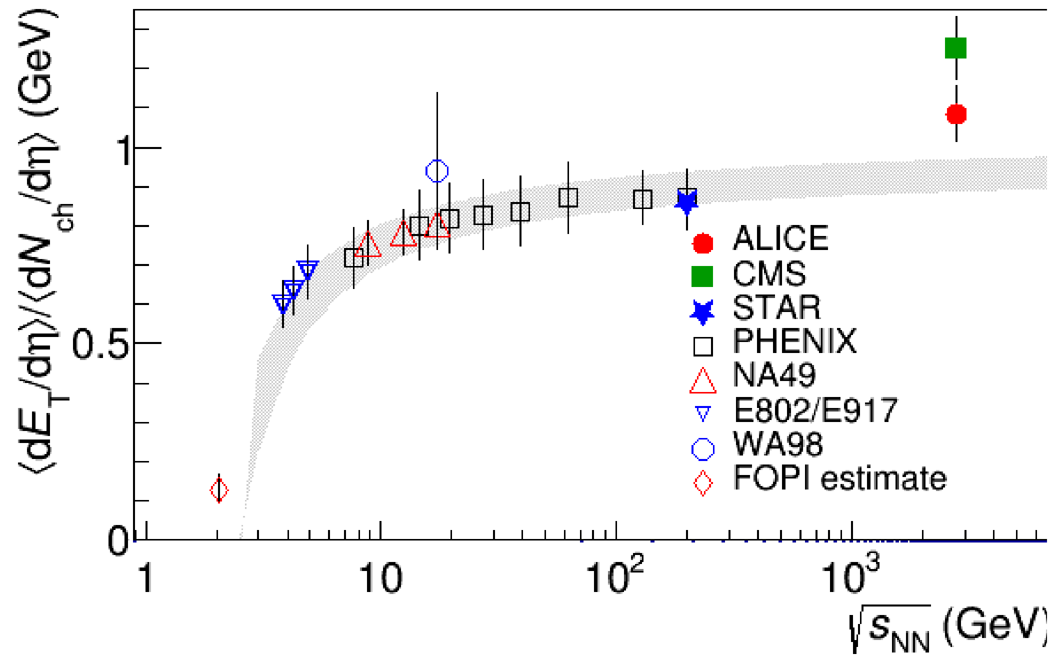




- Same centrality dependence as at RHIC
- E_T appears to scale better with N_{quark} than N_{part}

Average energy/particle



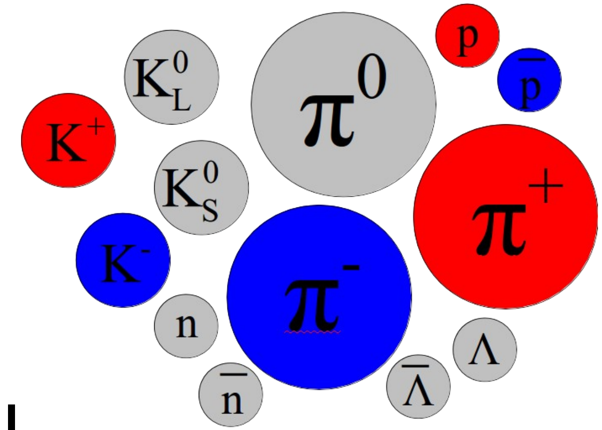


- Same centrality dependence as at RHIC
- At RHIC: more energy → more particles
  At LHC: more energy → higher energy/particle

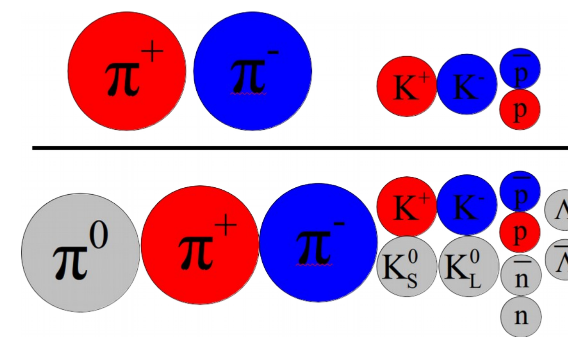
Conclusions:
What can we learn from measuring E_T?

- Reach energy densities around 10 GeV/fm^3, several times the energy density necessary to form QGP
- E_T higher than expected at LHC
- E_T seems to scale with N_{quark}
- At LHC increasing energy $\rightarrow$ increasing energy/particle, not more particles

Conclusions



- Energy distribution in an event:
  - NOT 1/3 neutral!
    ...but hits your detector as ~1/3 neutral



- Measurements of E_T: tracking only measurements highly accurate!
- E_T higher than expected at LHC

The End

Comparison of colliders

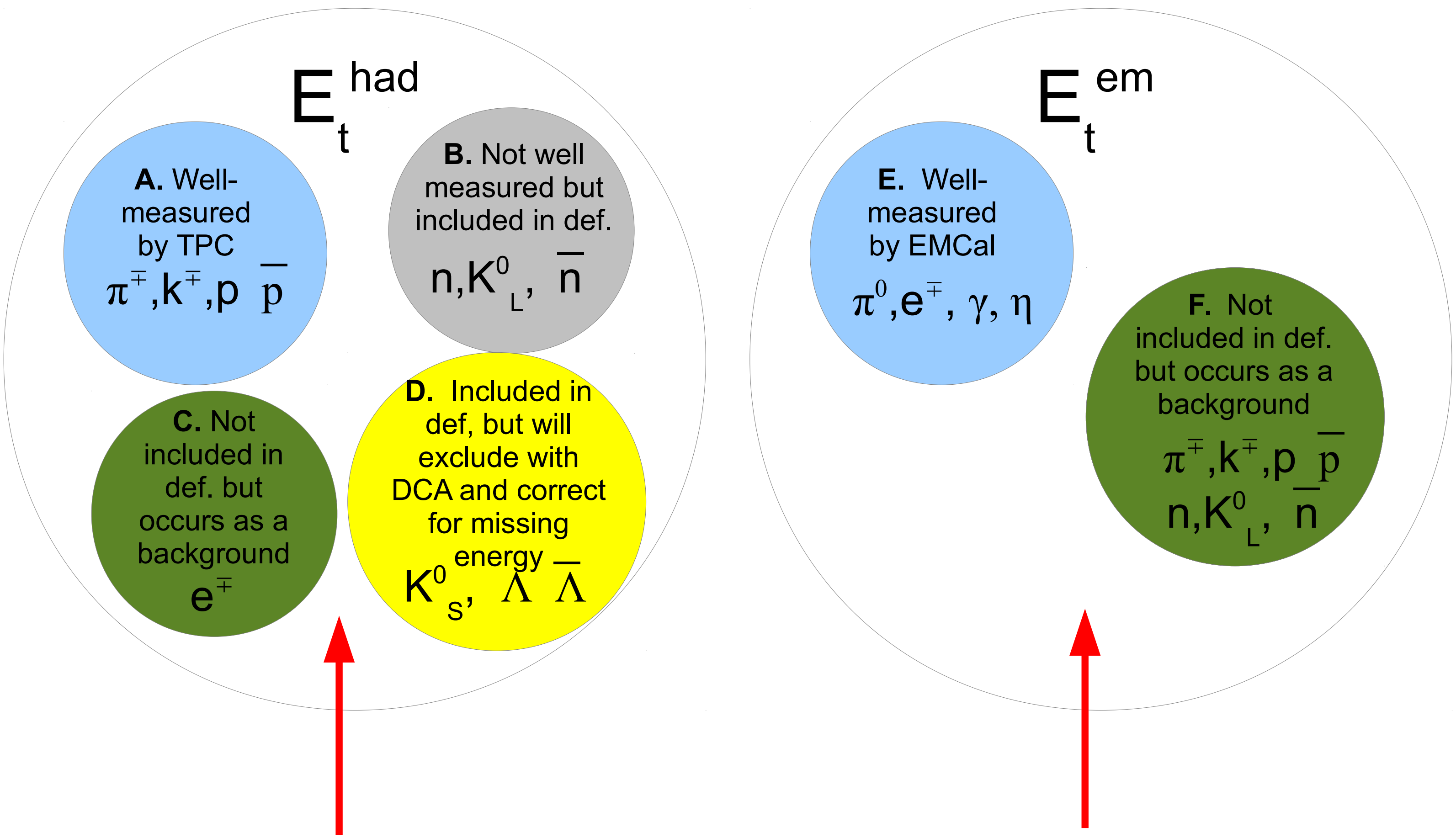
	RHIC	**LHC**	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	~15	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

RHIC and LHC:

Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$= 9 GeV –5.5 TeV)

To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

Hybrid method



Stuff the tracking detectors measure well

Stuff the EMCal measures well

Calculation from spectra

- Use spectra data and use Blast wave fits to extrapolate to higher and lower p_T
- Three assumptions

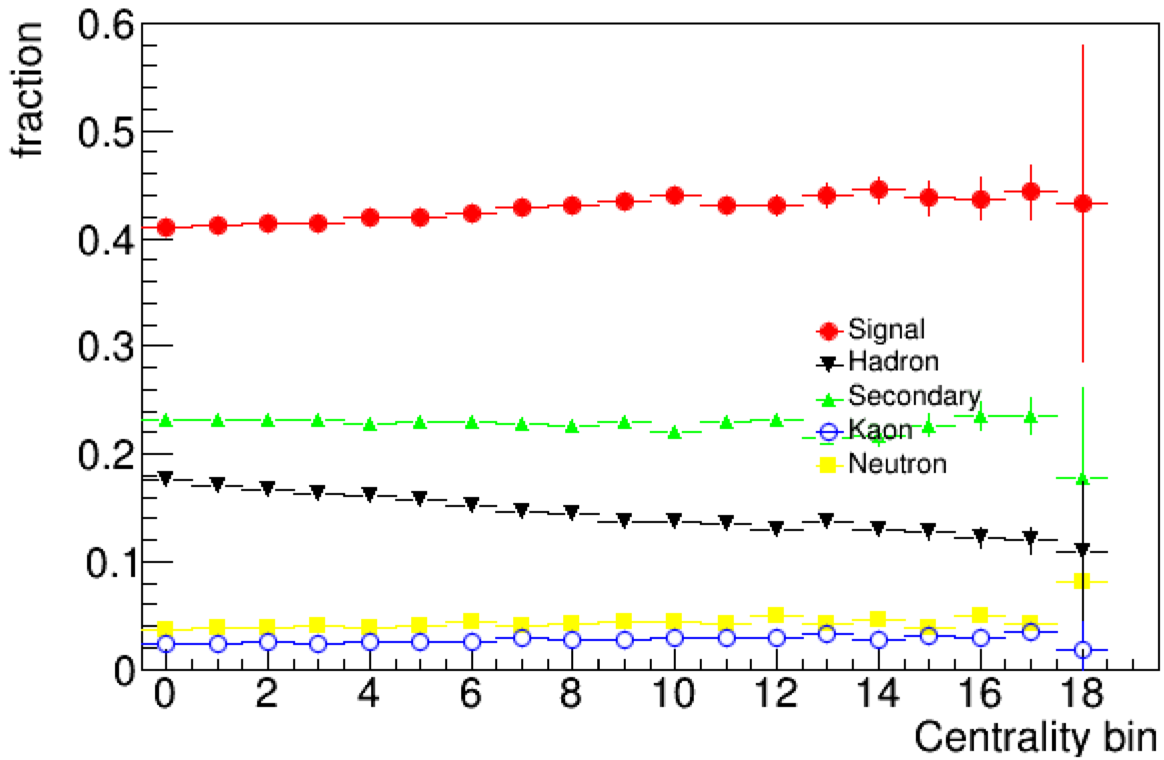
$$E_T^n = E_T^p$$
$$E_T^{\bar{n}} = E_T^{\bar{p}}$$
$$K^0_L = K^0_S$$

- Then, neglecting pseudorapidity dependence and assuming that the correction is the same for 900 GeV, 2.76 TeV, and 7 TeV:

$$E_T = E_T^{p,\bar{p}} + E_T^{n,\bar{n}} + E_T^{K} + E_T^{\pi} + E_T^{\Lambda,\bar{\Lambda}} + E_T^{\eta}$$

Everything else is negligible

What does the EMCal measure?



Note that this gets the fraction from kaons wrong. The fraction from kaons is actually about 10% of what we measure. Signal is actually ~30%.

Kaon deposits

- There are several kaon decays into pi0's and pi0's decay mostly into photons
- These will (mostly) not be matched to tracks
- Simulations are unreliable because of how far off simulations are for strange particles

$K_S^0 \rightarrow \pi^0\pi^0$ (30.7% B.R.)

$K^\pm \rightarrow \pi^\pm\pi^0$ (20.7% B.R.)

$K^\pm \rightarrow \pi^0 e^\pm \nu_e$ (5.1% B.R.)

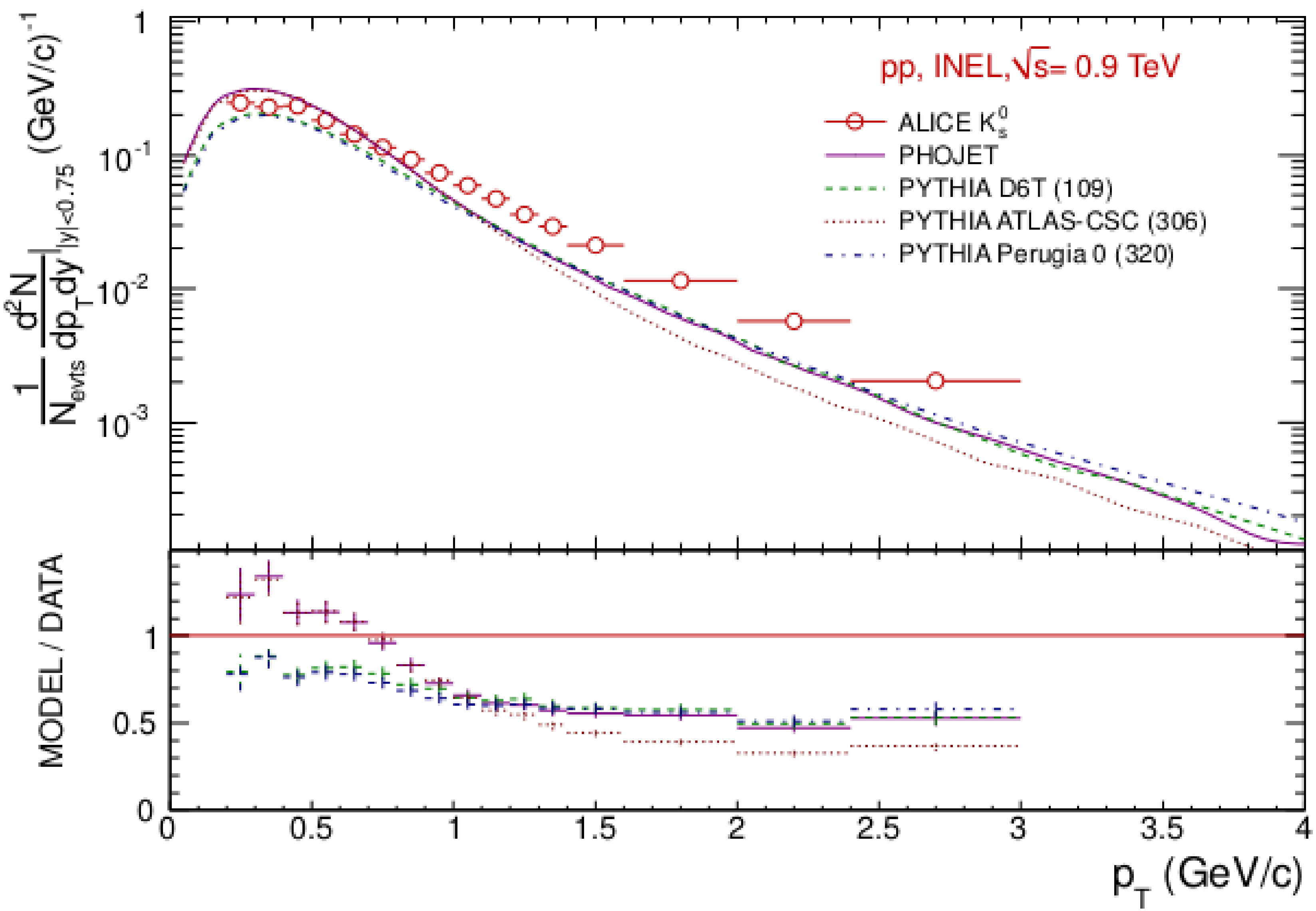
$K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu$ (3.4% B.R.)

$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ (1.8% B.R.)

$K_L^0 \rightarrow \pi^0\pi^0\pi^0$ (19.5% B.R.)

$K_L^0 \rightarrow \pi^+\pi^-\pi^0$ (12.5% B.R.).

Kaons – measured vs simulation



E_T^{em}

Sum over clusters

$$E_T^{em} = \frac{1}{f_{acc}} \frac{1}{f_{E_T min}} \left(\sum_i \delta_{matched} \frac{1}{\varepsilon_\gamma f_{nonlin}} E_i \sin(\theta_i) - E_T^{kaons} - E_T^{ch.} - E_T^{(anti)neutrons} - E_T^{secondary} \right)$$

Contributions to final E_T^{em} systematic error

Data driven

$\frac{1}{f_{acc}}$ Geometric acceptance, not including dead channels

$\frac{1}{f_{E_T min}}$ Correction for minimum energy threshold **~6%**

$\frac{1}{f_{nonlin}}$ Correction for nonlinearity of detector response **~0.5%**

E_T^{kaons} All energy deposited by K^0_S, K^0_L, $K^\pm$, including decays like $K^0_S \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ **<3%**

E_T^{ch} Correction for other charged hadron deposits in calorimeter **~10-20%**

Input from data

$E_T^{(anti)neutrons}$ Correction for (anti)neutron deposits in calorimeter **~1.5-5%**

$E_T^{secondary}$ Correction for deposits by particles from secondary interactions <4 **<5%**

ε_γ efficiency x acceptance within geometric acceptance of detector **~1%**

E_T^{had}

$$E_T^{had} = \frac{1}{f_{acc}} \frac{1}{f_{p_T cut}} \frac{1}{f_{neutral}} \sum_{i=0}^{n} f_{bg}^i(p_T) \frac{1}{f_{notID}} \frac{1}{eff(p_T^i)} E_i^{had} \sin(\theta^i)$$

$\frac{1}{f_{acc}}$ Correction for the geometric acceptance – 1, with acceptance due to sector boundaries, etc. rolled into the track efficiency

$\frac{1}{f_{p_T cut}}$ Correction for the low p_T cut off in the acceptance

$\frac{1}{f_{neutral}}$ Correction for neutral hadrons included in the definition but not measured well:
K^0_S, Λ, $\overline{\Lambda}$, K^0_L, n, $\overline{n}$
Not trying to measure K^0_S, Λ, $\overline{\Lambda}$ in TPC – apply DCA cut to eliminate, correct for missing energy

$f_{bg}^i(p_T)$ Correction for background not included in definition ($e^{\mp}$) or not measured easily event-by-event (K^0_S, Λ, $\overline{\Lambda}$)

$\frac{1}{f_{notID}}$ Correction for π, K, p not identified

$eff(p_T^i)$ Correction for tracking efficiency

$$E^{had} = \begin{array}{l} \sqrt{p^2+m^2} - m\,(nucleons) \\ \sqrt{p^2+m^2} + m\,(anti-nucleons) \\ \sqrt{p^2+m^2}\,(all\ others) \end{array}$$

Definition of energy to mimic the behavior of a calorimeter