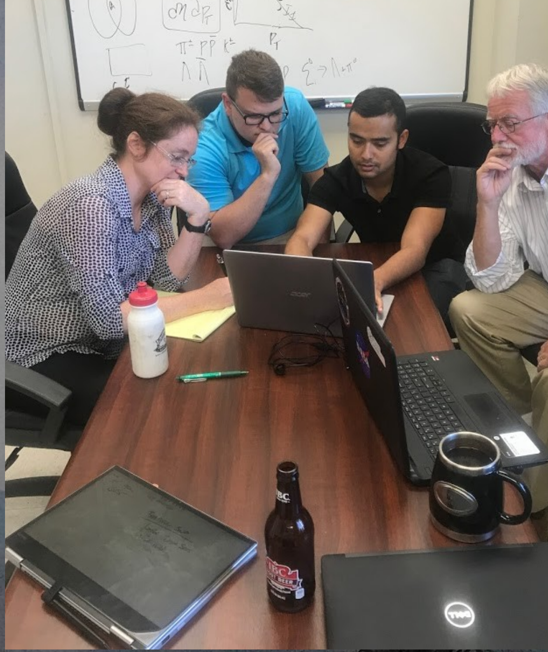
$$\frac{1}{2\pi p_T}\frac{d^2N}{dy\,dp_T} \rightarrow \frac{dE_T}{d\eta}$$

using STAR Data



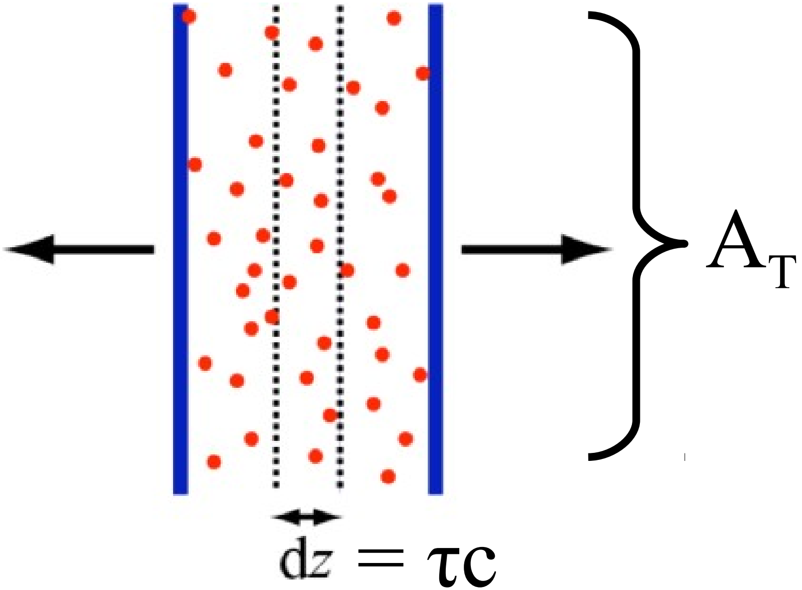
Christine Nattrass, Biswas Sharma, Soren Sorensen, Ben Smith, Tanner Mengel, Charles Hughes, Nathan Webb

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

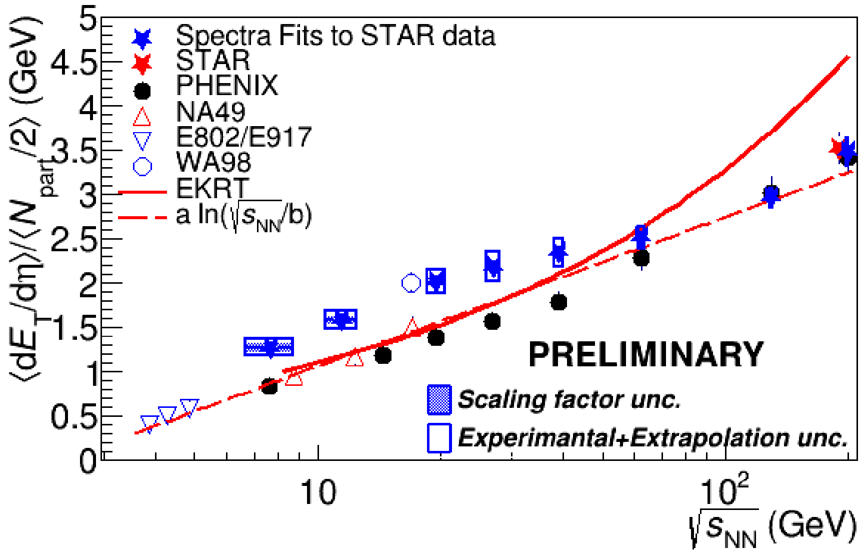
$$\epsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d\eta}$$

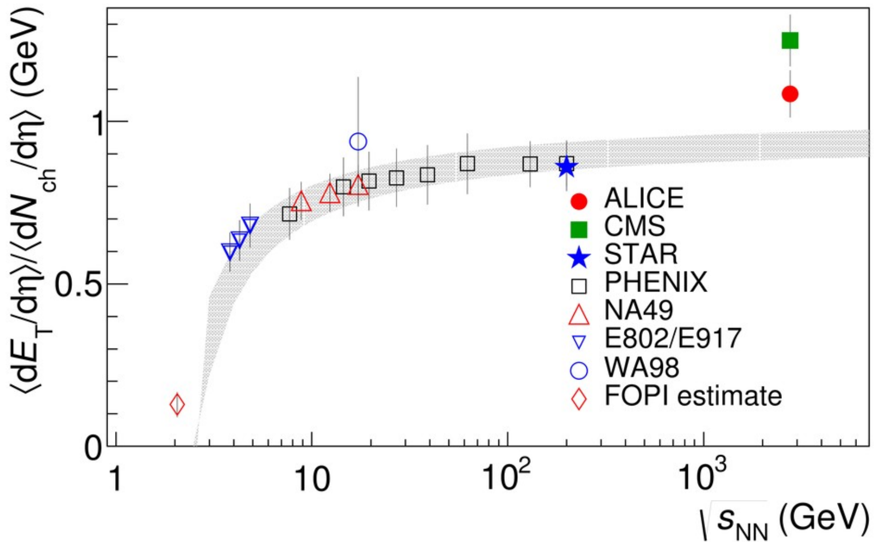
- QGP formation for $\varepsilon > 0.5$ GeV/fm^3



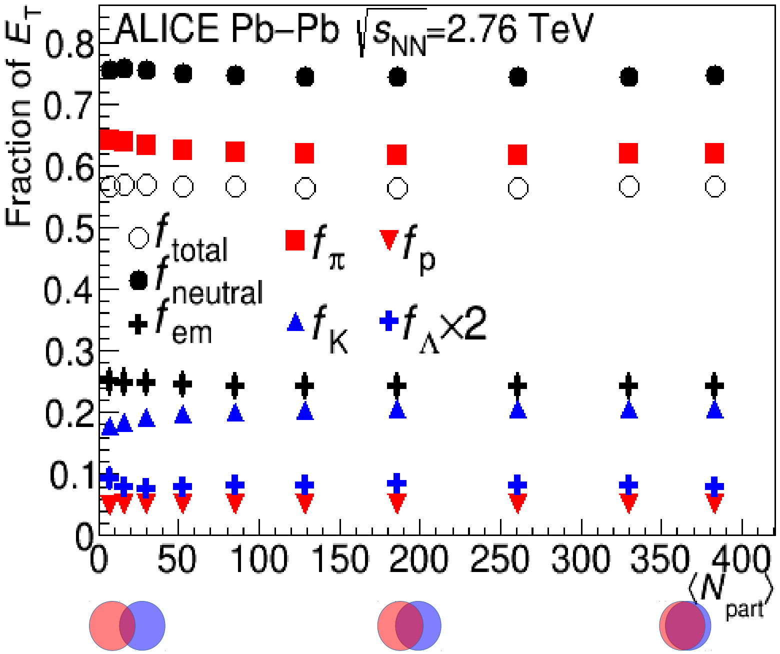
Motivation

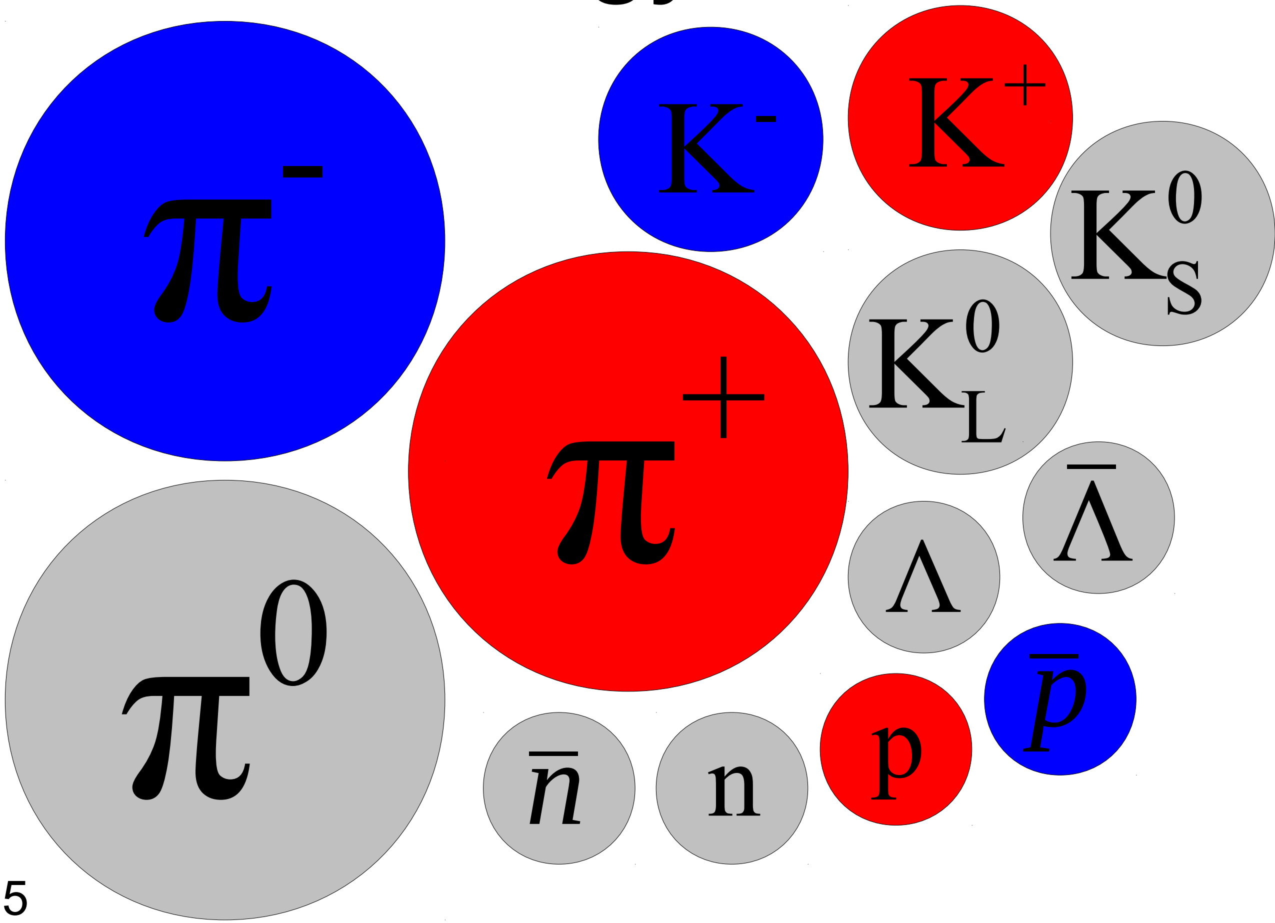
- Cross check data
- Study PID distribution of energy
- Understand E_T/N_{ch} better





Where is the energy?

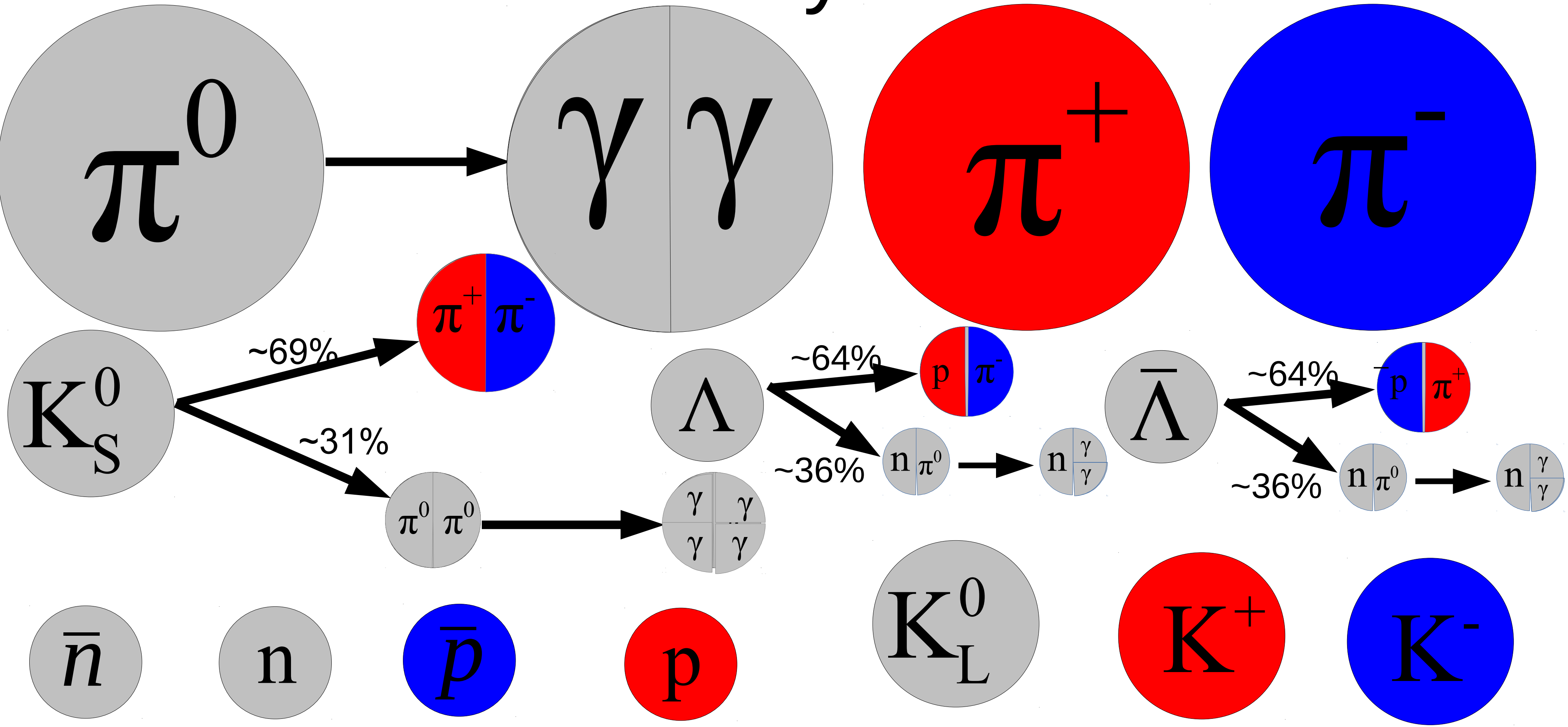




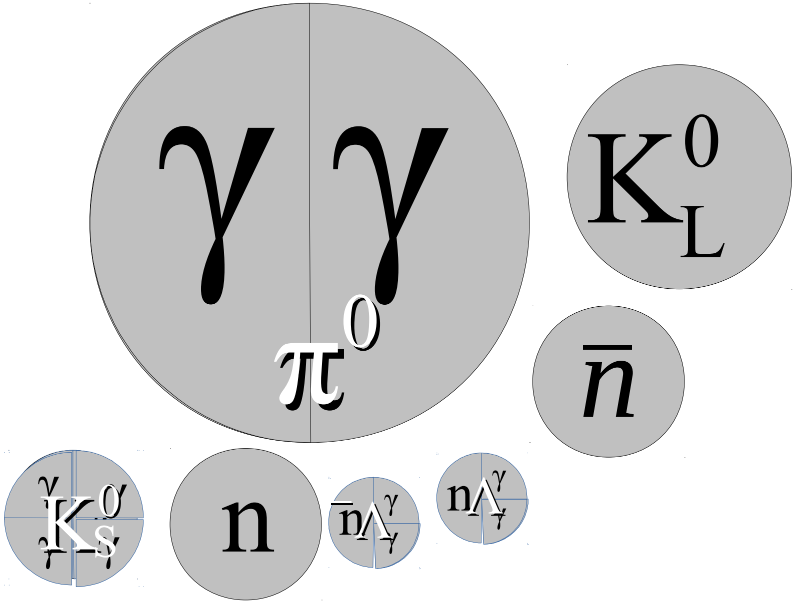
Scale: diameter in inches = √fraction * 5

Numbers from 2.76 TeV Phys. Rev. C 94 (2016) 034903

How does it hit your detector?

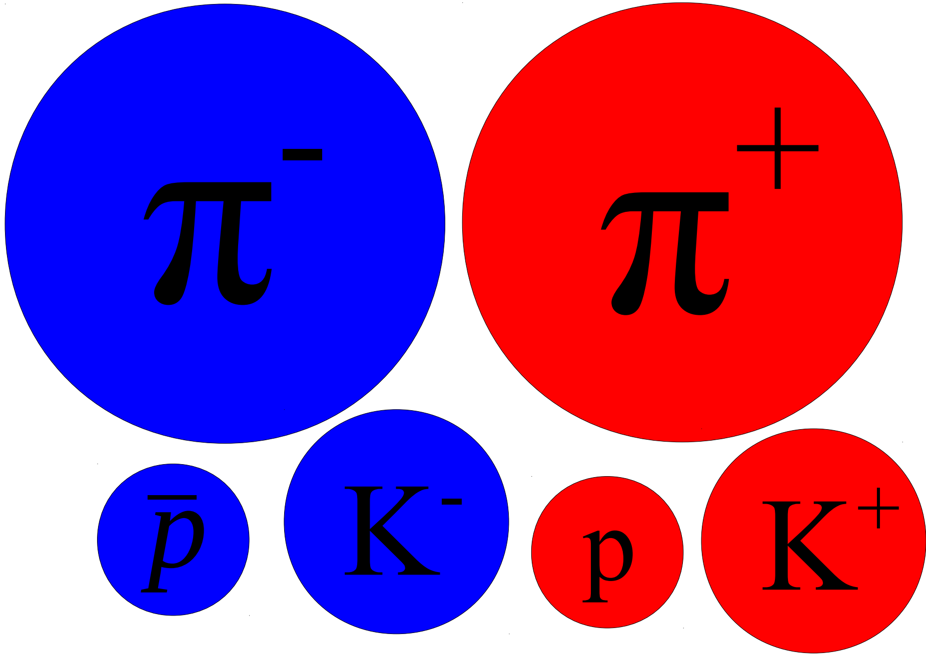


How does it hit your detector?



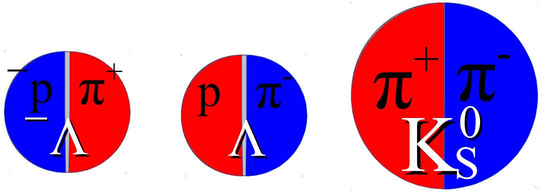
35% neutral

11% in neutral hadrons



65% charged

7% in secondaries

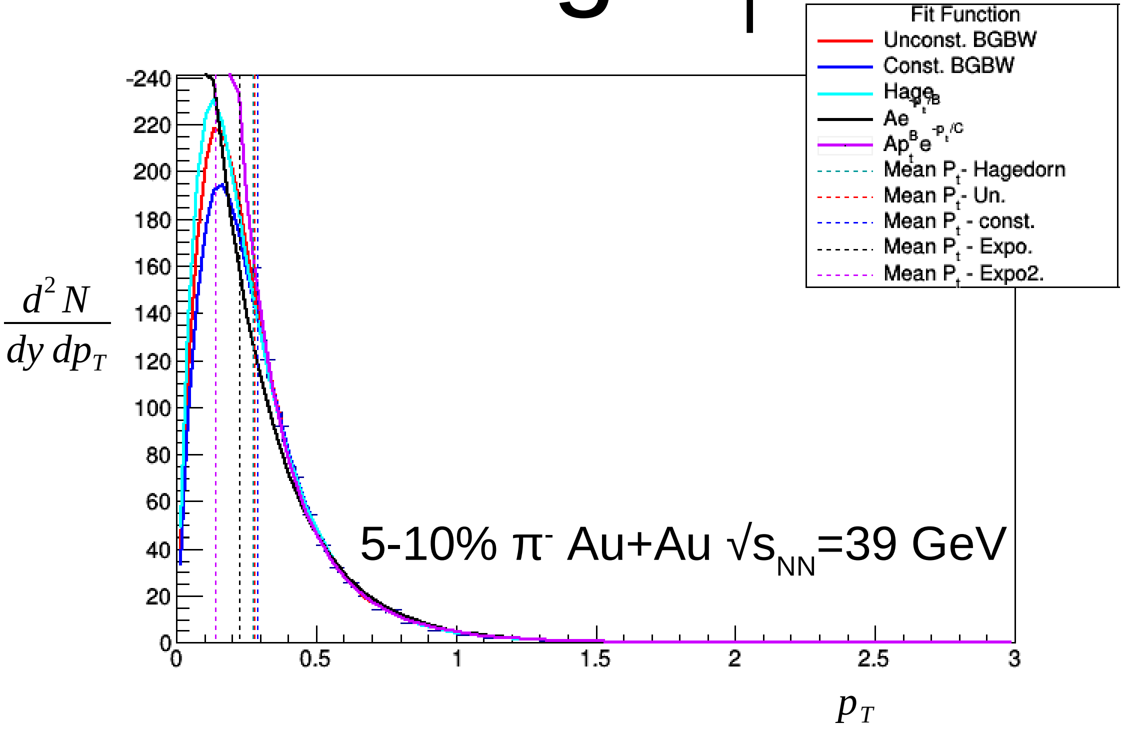


Methods for measuring E_T

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

*Other methods used as cross checks

Calculating E_T from spectra

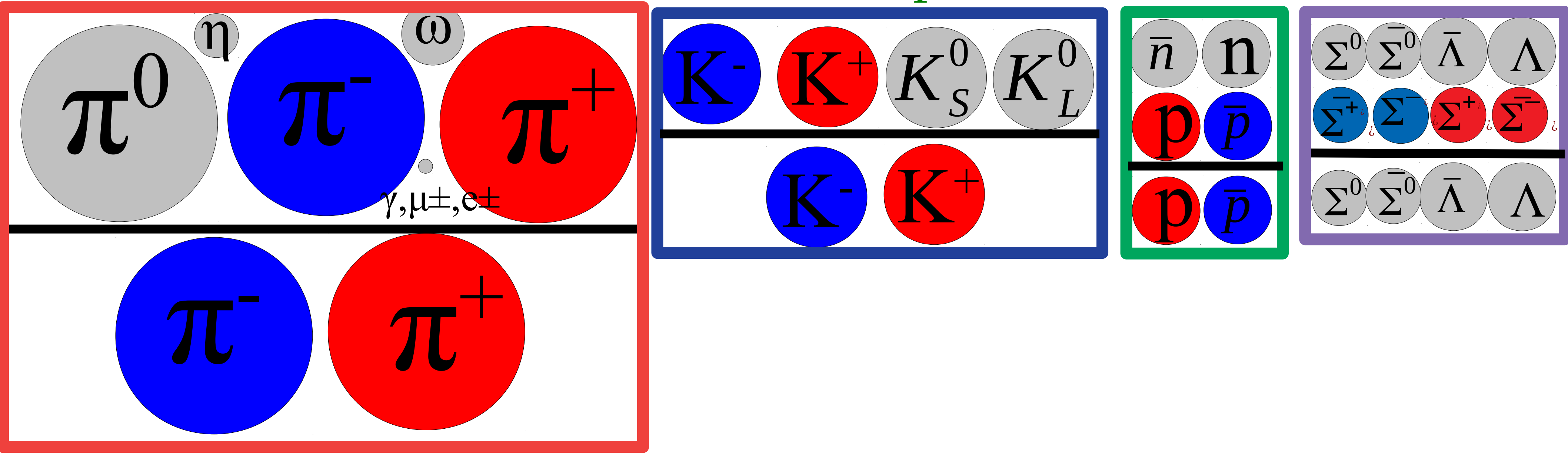


$$E_T = \sum_{j=1}^{M} E_T^{particle\ j}$$

$$E_T^{PID} = \underbrace{\int_0^{p_T^{min}} f(p_T) E_T \, dp_T}_{\textbf{Fit}} + \underbrace{\sum_{i=1}^{N} \frac{d^2 N_i}{dy\, dp_T} E_T(p_T^i, m)}_{\textbf{Data}} + \underbrace{\int_{p_T^{max}}^{\infty} f(p_T) E_T \, dp_T}_{\textbf{Fit}}$$

Calculating E_T from published spectra

$$E_T = f_\pi E_T^{\pi^\pm} + f_K E_T^{K^\pm} + f_p E_T^{p,\bar{p}} + f_\Lambda E_T^{\Lambda,\bar{\Lambda}}$$

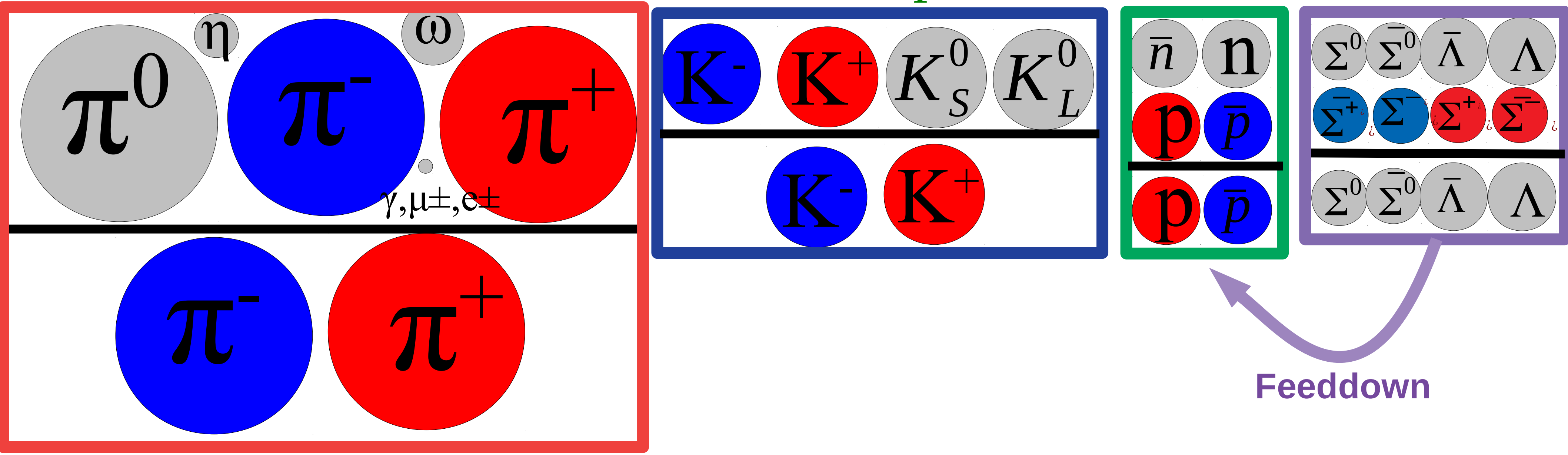


STAR Spectra

- Strange hadron production in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, and 39 GeV
  arXiv:1906.03732 [nucl-ex]
  $\Lambda, \bar{\Lambda}, K_S^0$
- Bulk Properties of the Medium Produced in Relativistic Heavy-Ion Collisions from the Beam Energy Scan Program
  Phys. Rev. C 96, 044904 (2017)
  $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
  Distance of closest approach to primary vertex< 3 cm
  - **Includes most but not all $\Lambda, \bar{\Lambda}, K_S^0$ daughters**

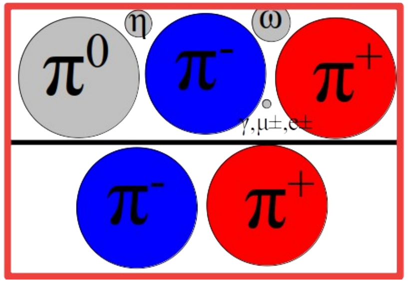
Calculating E_T from published spectra

$$E_T = f_\pi E_T^{\pi^\pm} + f_K E_T^{K^\pm} + f_p E_T^{p,\bar{p}} + f_\Lambda E_T^{\Lambda,\bar{\Lambda}}$$

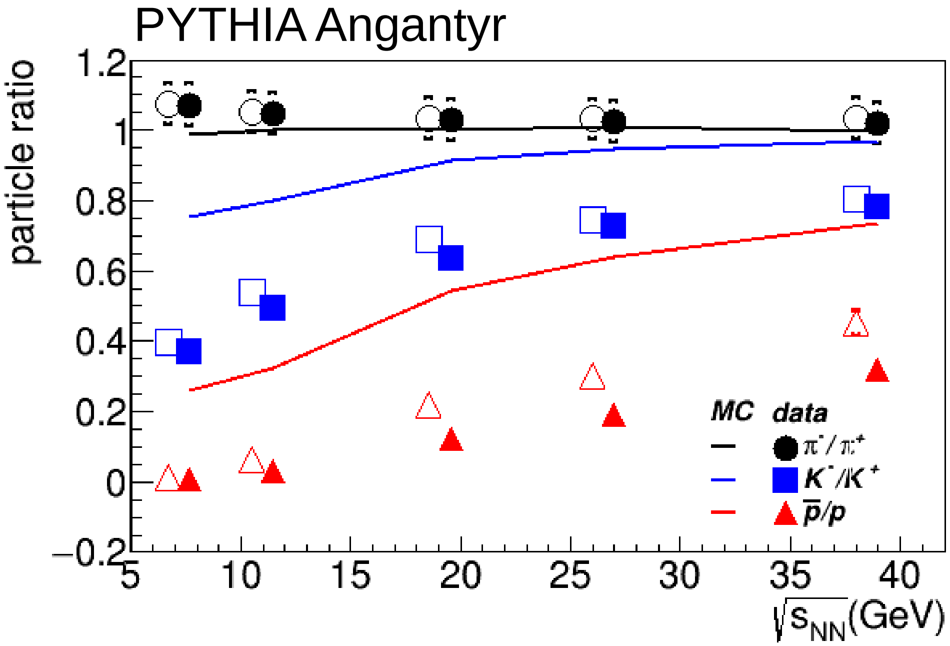


Pion correction f_π

- Pion ratios influenced by short-lived resonances, dominated by η & ω
- Measured ratio of $\pi^0/\pi^\pm$ roughly consistent with PYTHIA*

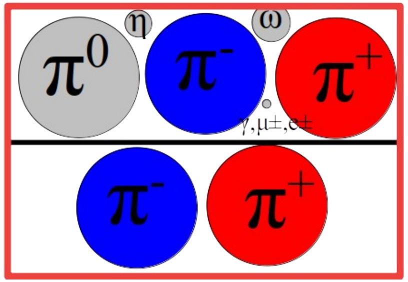


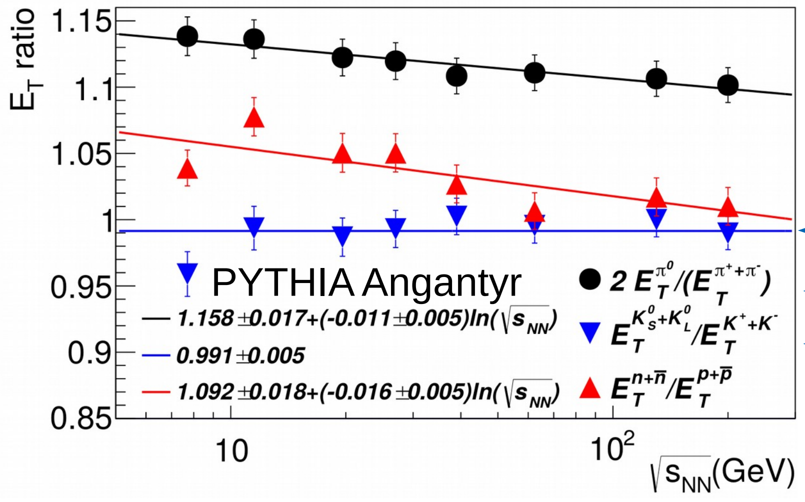
decay	BR (%)
$\eta \to \gamma\gamma$	39.4
$\eta \to \pi^0\pi^0\pi^0$	32.7
$\eta \to \pi^+\pi^-\pi^0$	22.9
$\eta \to \pi^+\pi^-\gamma$	4.2
$\omega \to \pi^+\pi^-\pi^0$	89.2
$\omega \to \pi^0\gamma$	8.3
$\omega \to \pi^+\pi^-$	1.5



*Yuri Kharlov, internal ALICE presentation

Pion correction f_π





decay	BR (%)
$\eta \rightarrow \gamma\gamma$	39.4
$\eta \rightarrow \pi^0\pi^0\pi^0$	32.7
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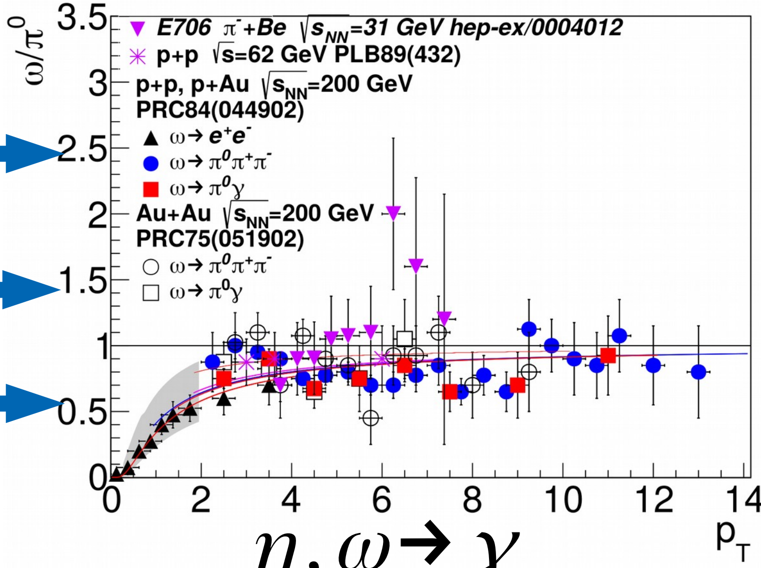
$\eta \rightarrow \pi^+\pi^-\gamma$	4.2
$\omega \rightarrow \pi^+\pi^-\pi^0$	89.2
$\omega \rightarrow \pi^0\gamma$	8.3
$\omega \rightarrow \pi^+\pi^-$	1.5



$$\eta,\omega,X \rightarrow \pi^0,\pi^\pm$$

$$f_\pi = 1.56 \pm 0.02$$

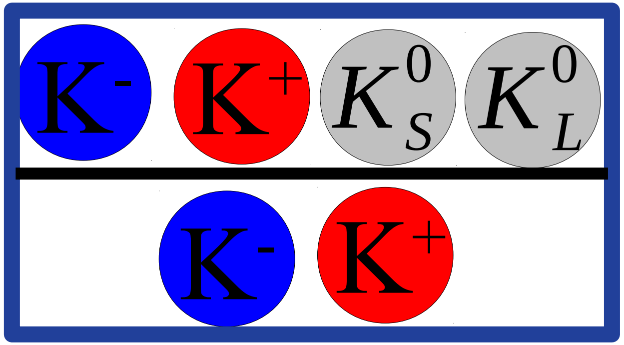
$$\eta,\omega \rightarrow \gamma$$

- m_T scaling
- match to η/π^0 & ω/π^0 data
- 100% uncertainties

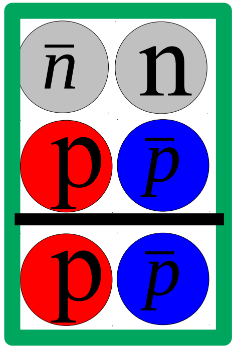
Kaon correction f_K

- Also potentially impacted by resonances
- Used ratios of the (preliminary) yields from BES data

$$f_K = 1.8 \pm 0.2$$



Proton correction f_p



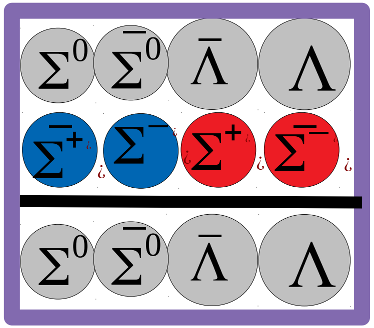
- Lower limit: $f_p = 2$
- Upper limit:
  Yield=Primordial+Generated
  Antibaryons=Generated
  Baryons=Primordial+Generated
  Primordial n/p = N/Z

$$\frac{N_n + N_{\bar{n}}}{N_p + N_{\bar{p}}} = \frac{N/Z + (2 - N/Z) N_{\bar{p}}/N_p}{1 + N_{\bar{p}}/N_p}$$

$\sqrt{s_{NN}}$	$\frac{N_{\bar{p}}}{N_p}$	Ref.	f_p
7.7	$0.0073 \pm 0.0002 \pm 0.0006$	[3]	2.49 ± 0.49
11.5	$0.0331 \pm 0.0002 \pm 0.0028$	[3]	2.46 ± 0.46
14.5	$0.0641 \pm 0.0005 \pm 0.0109$	[2]	2.43 ± 0.43
19.6	$0.1216 \pm 0.0003 \pm 0.0104$	[3]	2.39 ± 0.39
27	$0.1892 \pm 0.0003 \pm 0.0162$	[3]	2.34 ± 0.34
39	$0.3204 \pm 0.0003 \pm 0.0274$	[3]	2.25 ± 0.25
62.4	0.469 ± 0.026	[5]	2.18 ± 0.18
130	0.708 ± 0.036	[5]	2.08 ± 0.08
200	0.769 ± 0.055	[5]	2.06 ± 0.06

[1] J. Adam et al. (ALICE), Phys. Rev. C94, 034903 (2016), 1603.04775.
[2] J. Adam et al. (STAR) (2019), 1908.03585.
[3] L. Adamczyk et al. (STAR), Phys. Rev. C96, 044904 (2017), 1701.07065.
[4] J. Adam et al. (STAR) (2019), 1906.03732.
[5] B. I. Abelev et al. (STAR), Phys. Rev. C79, 034909 (2009), 0808.2041.

Lambda correction f_Λ

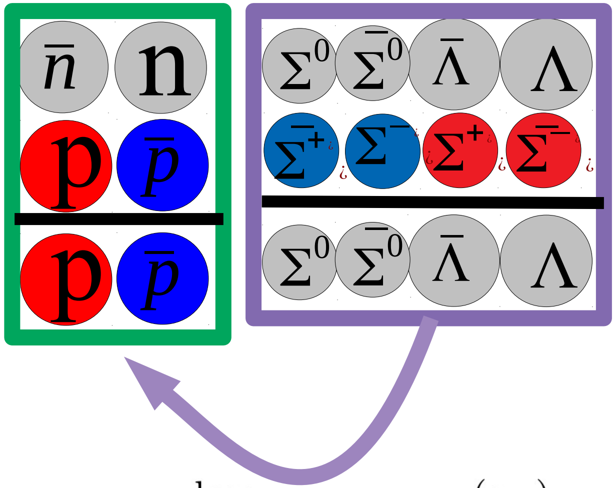


- Sigma: Yield ratios
  - Isospin scaling: 1.5
  - PYTHIA: 1.67
  - HIJING: 1.532

➔ 1.585 ± 0.085

decay	$c\tau$ (cm)
$\Sigma^0 \rightarrow \Lambda\gamma$ (100%)	$2 \times 10^{-}9$
$\Sigma^+ \rightarrow p\pi^0$ (52%)	2.4
$\Sigma^+ \rightarrow n\pi^-$ (48%)	
$\Sigma^- \rightarrow n\pi^-$ (100%)	4.4

Lambda correction f_Λ



- STAR BES DCA to PV<3 cm
  Feeddown due to K^0_S done
  Feeddown to p due to Λ not done
- STAR published spectra at $\sqrt{s_{NN}}$=200 GeV (Phys.Rev.Lett.97:152301,2006) with and without feeddown*

  → Calculate E_T^Λ feeddown
- Does not provide a lot of constraint

  → Use branching ratio

$$\rightarrow 0.68 \pm 0.32$$

$$f_\Lambda = 1.08 \pm 0.51$$

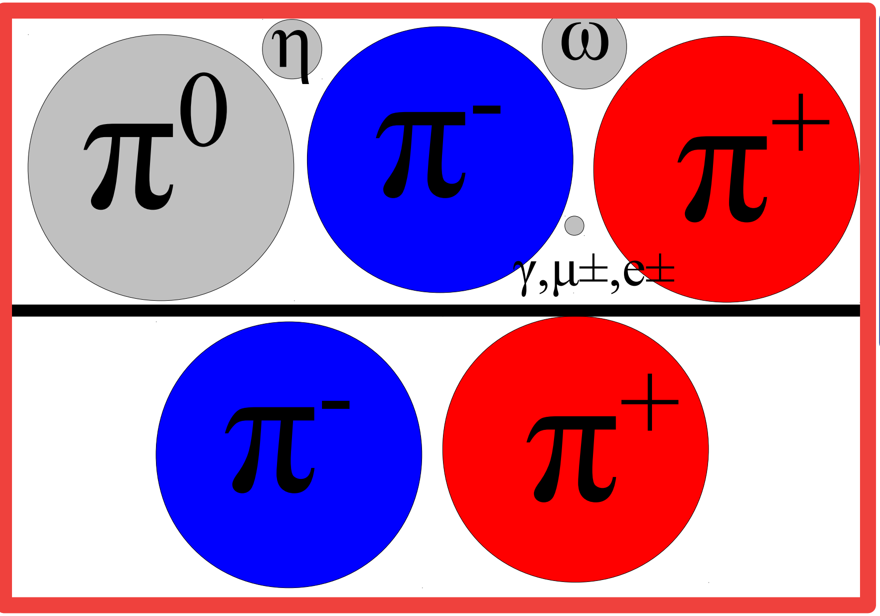
decay	$c\tau$ (cm)
$\Lambda \to p\pi^-$ (64%) $\Lambda \to n\pi^0$ (36%)	7.9
$K^0_S \to \pi^+\pi^-$ (69%) $K^0_S \to \pi^0\pi^0$ (31%)	2.7
$K^0_L \to \pi^\pm e^\mp \nu_e$	1534

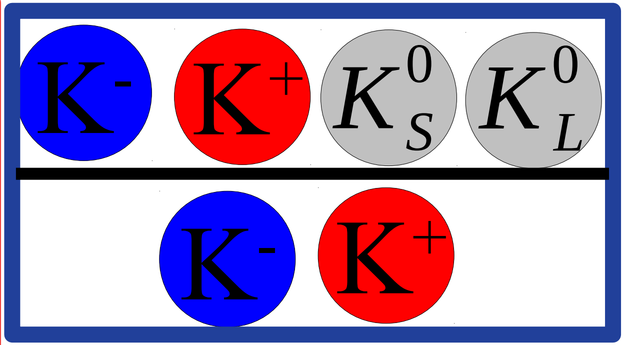
centrality	E_T^{fd}/E_T^Λ
0–12%	0.68 ± 0.18
10–20%	0.78 ± 0.22
20–40%	0.79 ± 0.2
40–60%	0.80 ± 0.21
60–80%	0.75 ± 0.27

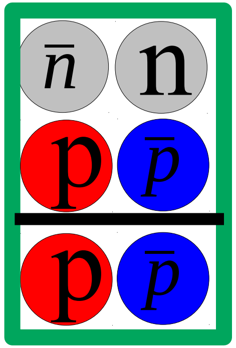
*Thanks to Ron Belmont for pointing this out to us

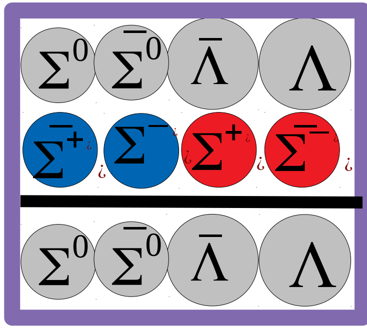
Calculating E_T from published spectra

$$E_T = f_\pi E_T^{\pi^\pm} + f_K E_T^{K^\pm} + f_p E_T^{p,\bar{p}} + f_\Lambda E_T^{\Lambda,\bar{\Lambda}}$$







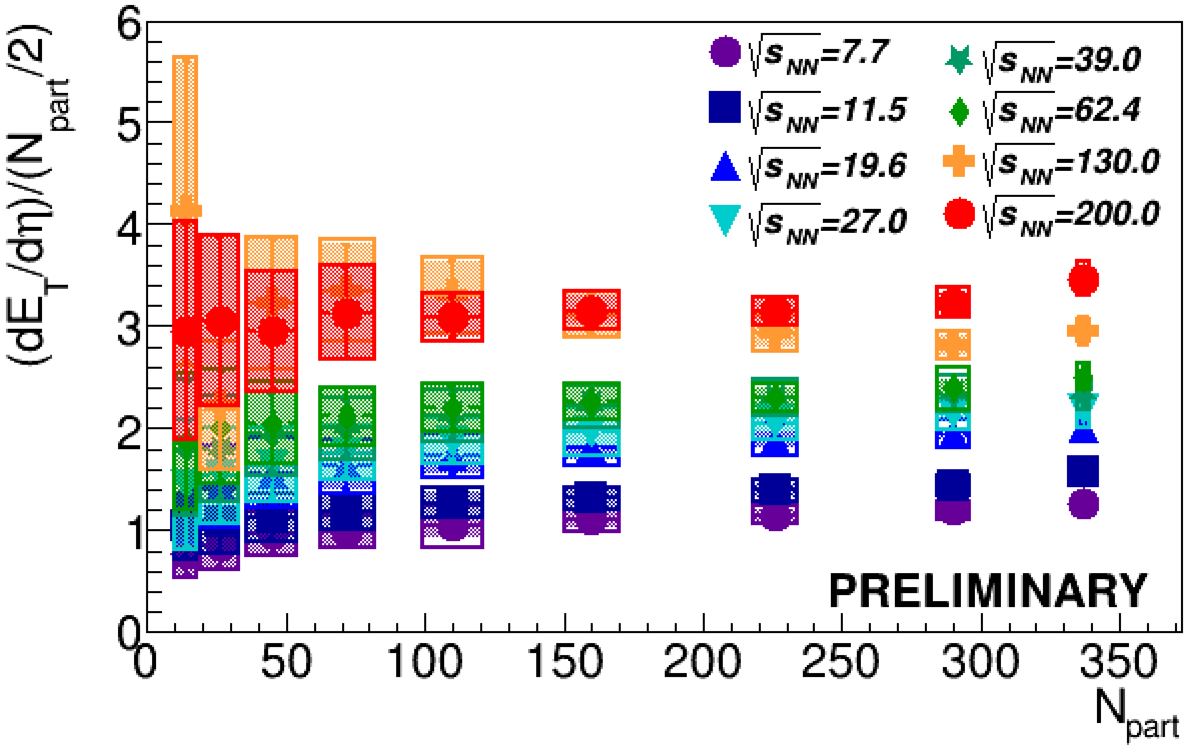


$f_K = 1.8 \pm 0.2$ $\quad 2 < f_p < 3$

$f_\Lambda = 1.08 \pm 0.51$

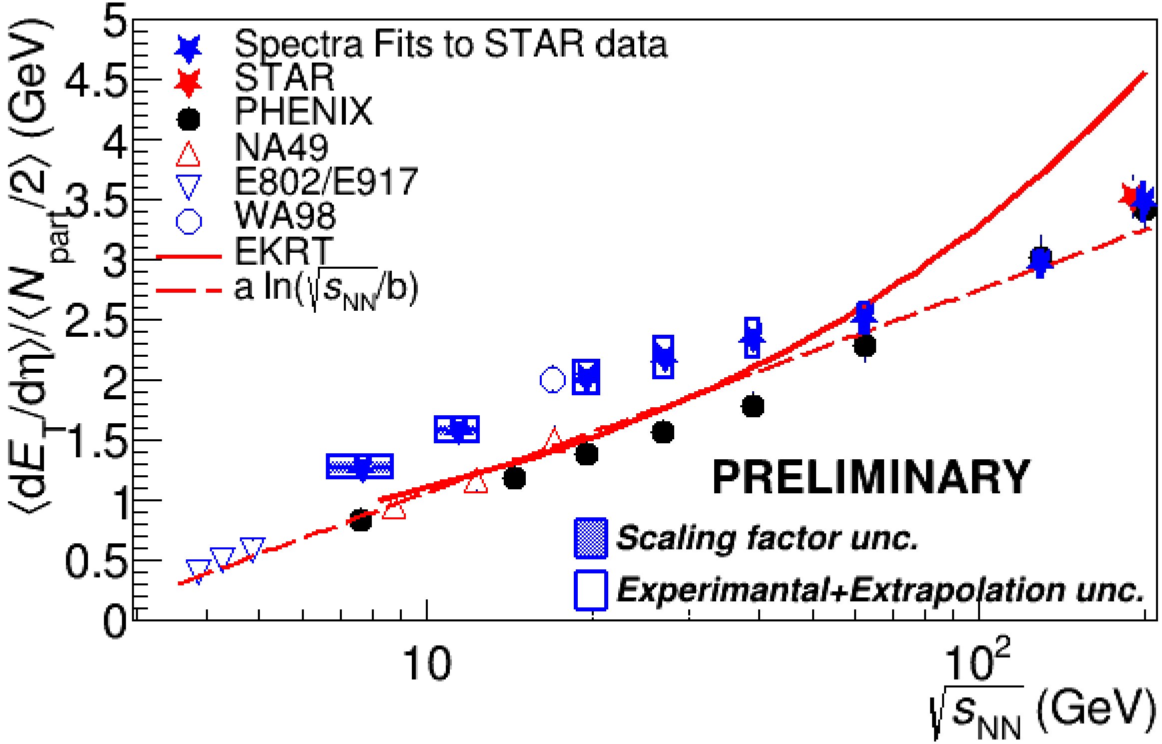
$f_\pi = 1.56 \pm 0.02 + (E_T^\eta + E_T^\omega)/(E_T^\pi)$

Results


$(dE_T/d\eta)/(N_{part}/2)$
N_{part}
$\sqrt{s_{NN}}$=7.7
$\sqrt{s_{NN}}$=11.5
$\sqrt{s_{NN}}$=19.6
$\sqrt{s_{NN}}$=27.0
$\sqrt{s_{NN}}$=39.0
$\sqrt{s_{NN}}$=62.4
$\sqrt{s_{NN}}$=130.0
$\sqrt{s_{NN}}$=200.0
PRELIMINARY
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350


Original Fruit
Skittles
TASTE THE RAINBOW

Results



Spectra Fits to STAR data
STAR
PHENIX
NA49
E802/E917
WA98
EKRT
a ln($\sqrt{s_{NN}}$/b)
PRELIMINARY
Scaling factor unc.
Experimantal+Extrapolation unc.
$\langle dE_T/d\eta\rangle/\langle N_{part}/2\rangle$ (GeV)
$\sqrt{s_{NN}}$ (GeV)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
10^2

Q&A

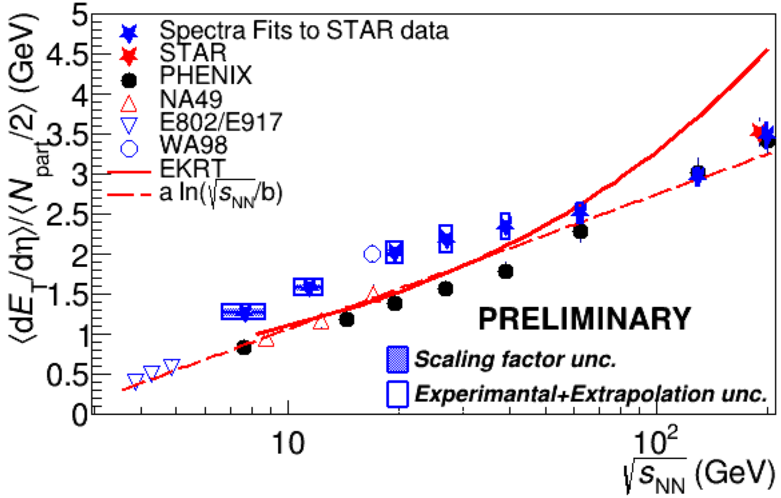
Q: Why not do this for PHENIX spectra as well?
A: PHENIX spectra only for p_T>0.5 GeV/c, large extrapolation uncertainty

Q: Why not look at energy distribution by particle type?
Q: Why not look at E_T/N_{ch}?
A: We are. To be continued…

Q: Why not look at small systems?
A: We will. To be continued…

Conclusions

- Tracking detectors can measure E_T well
- E_T calculated from STAR spectra do not agree with PHENIX E_T



What we need to do

- Double check fits
- Separate uncertainties from extrapolation to p_T=0
- Finalize corrections and uncertainties
- Write the paper
- Calculations in small systems?

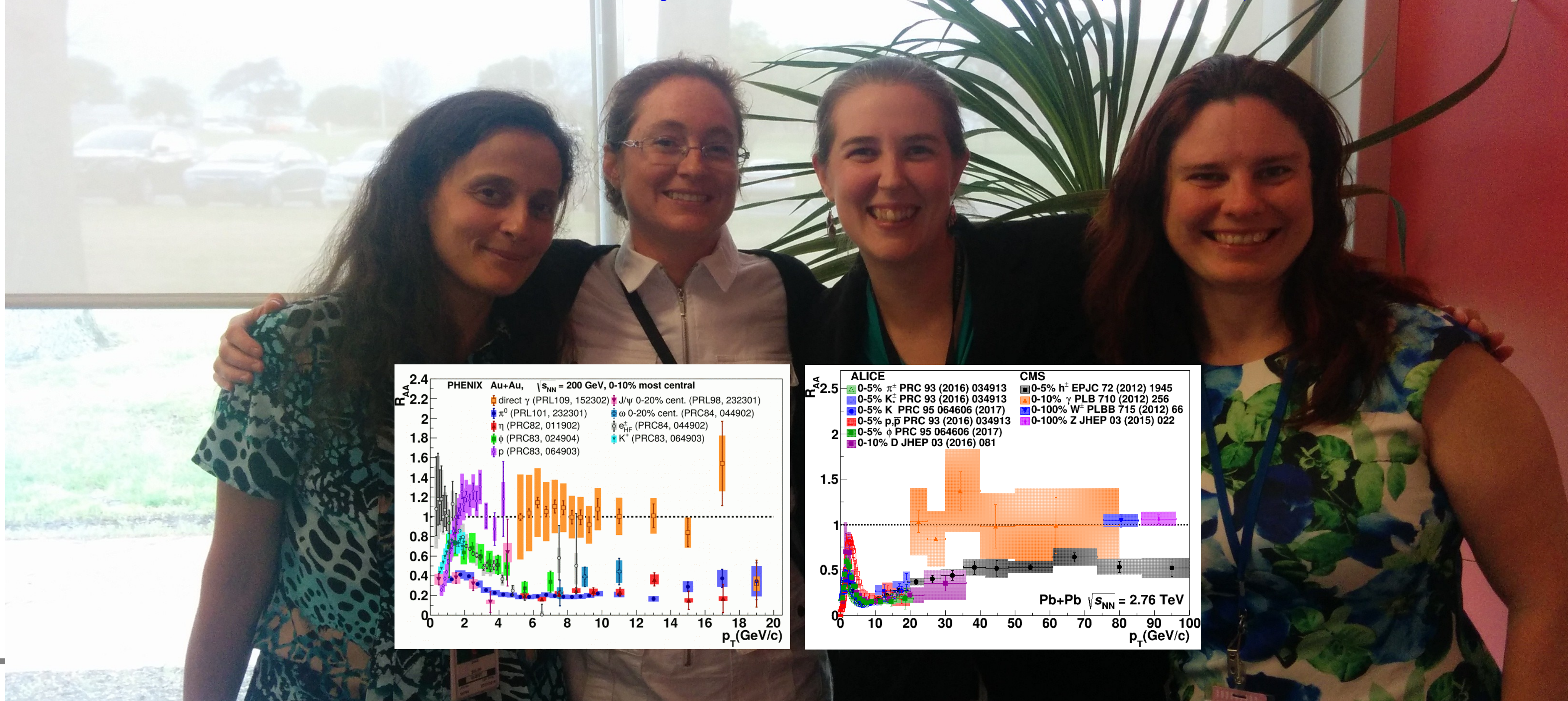
Suggestions for you

- STAR: BES E_T measurement
- PHENIX: BES spectra measurements
- sPHENIX E_T measurement

Life in John's group

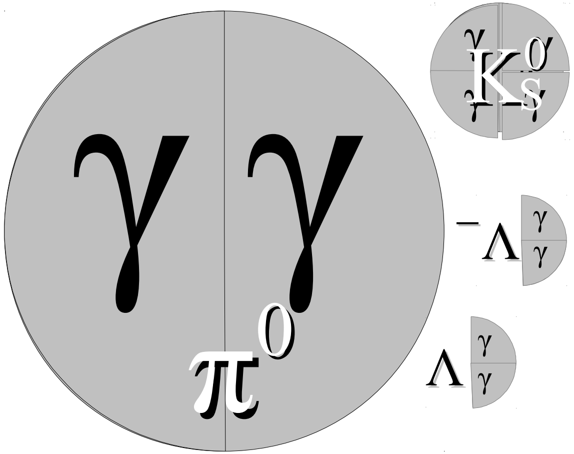
Connors, Nattrass, Reed, & Salur

Rev. Mod. Phys. 90, 025005 (2018)



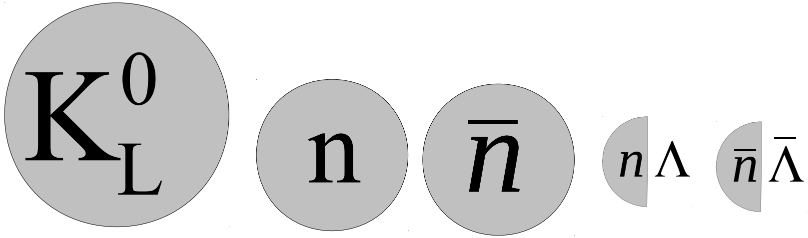
CMS

Hadronic calorimeter



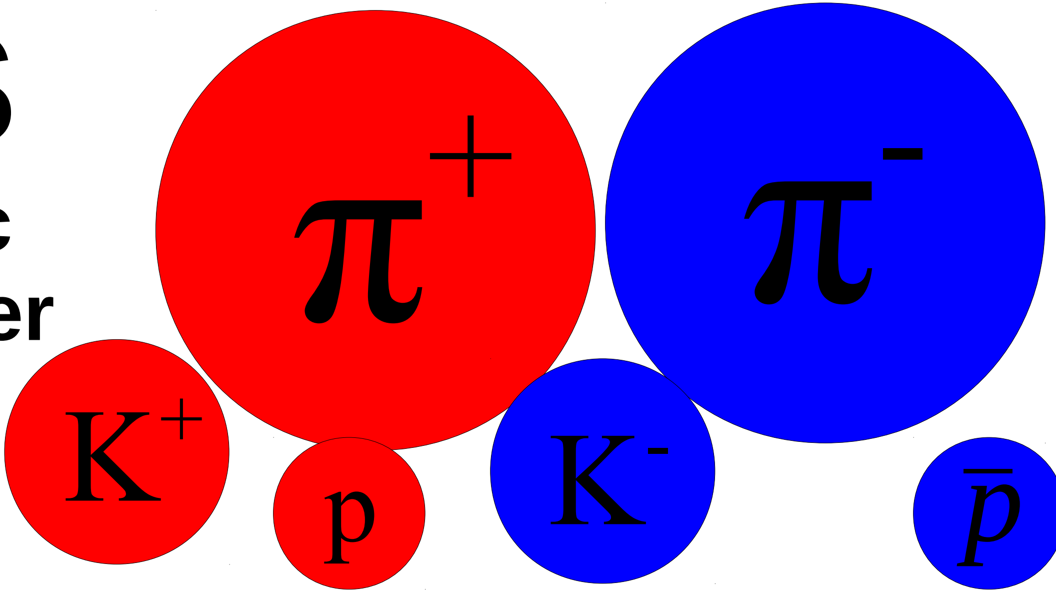
24% as a γ

Measure in electromagnetic calorimeter

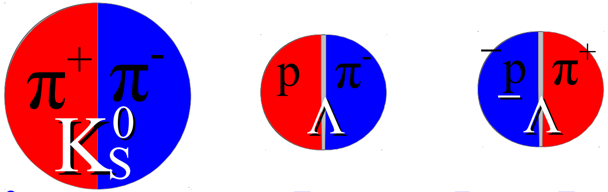


11% as a neutral hadron

Measure in hadronic calorimeter



58% in primary hadrons

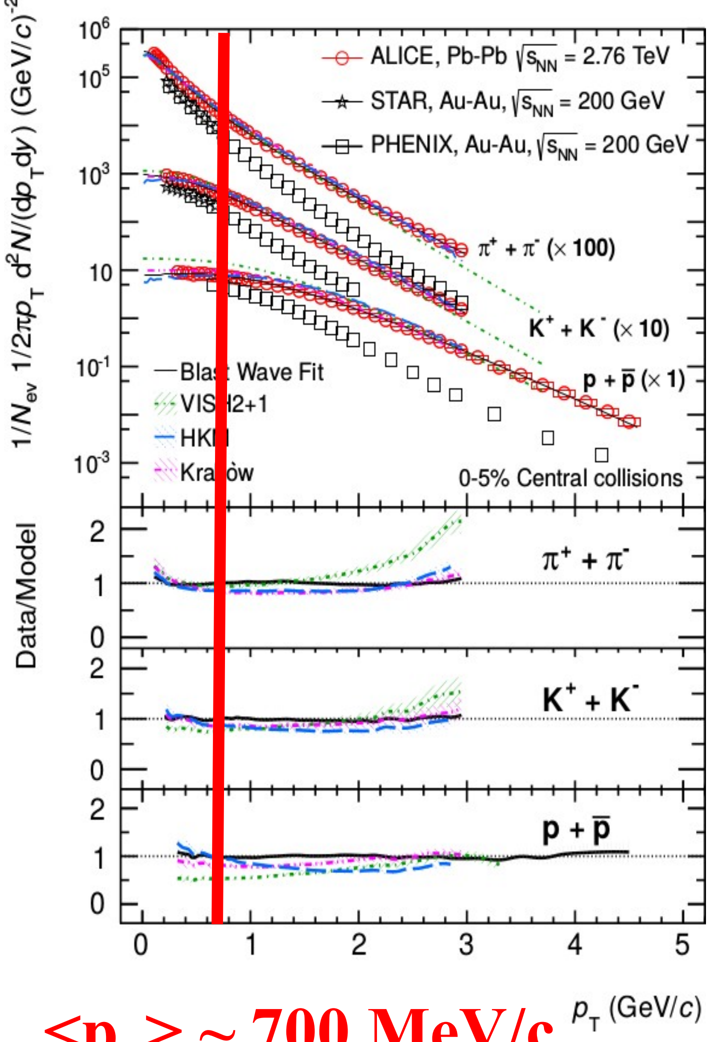


7% in secondary hadrons

Measure in tracking detectors and hadronic calorimeter

CMS

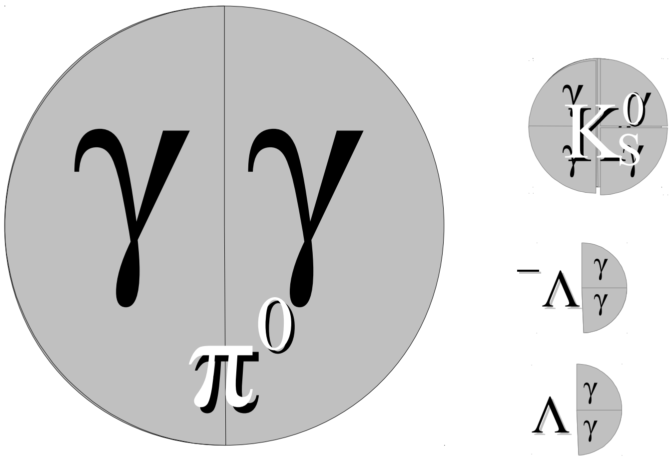
Tracks: p_T>900 MeV/c
Clusters: limited by B
→ ~62% of energy measured



$<p_T>$ ~ 700 MeV/c

Phys. Lett. B 727 (2013) 371-380

Phys. Rev. Lett. 109 252301 (2012)



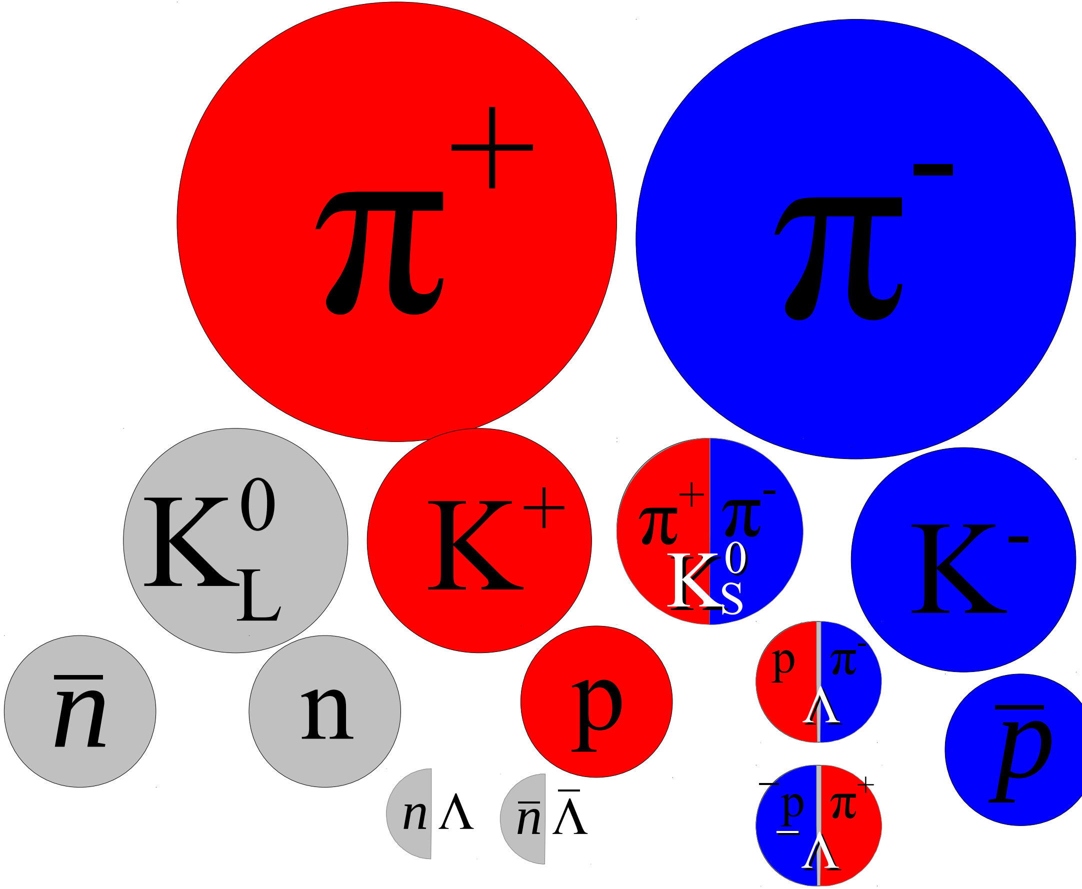
Deposit 100% of energy

35% of energy in event

PHENIX

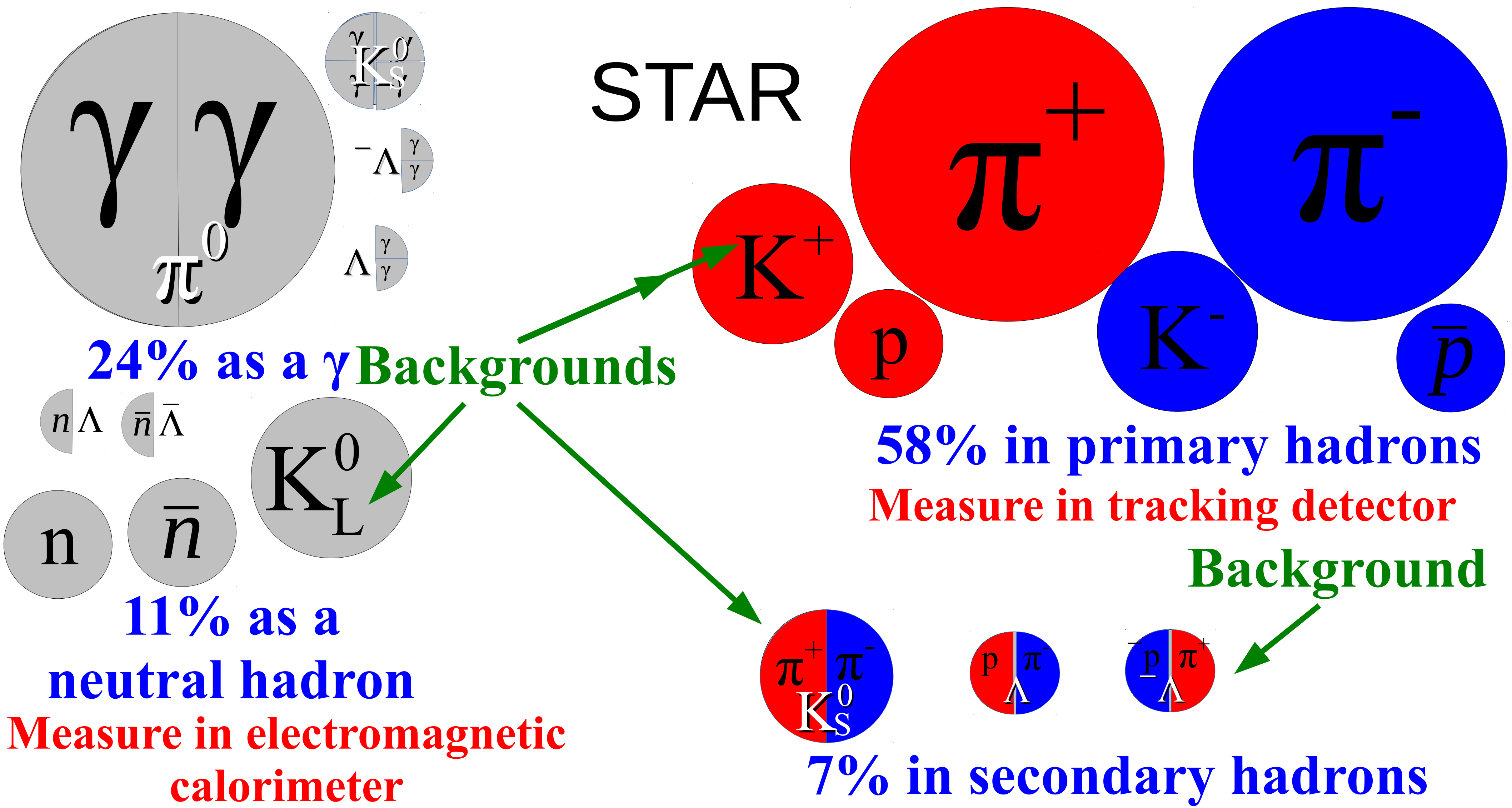
Electromagnetic calorimeter

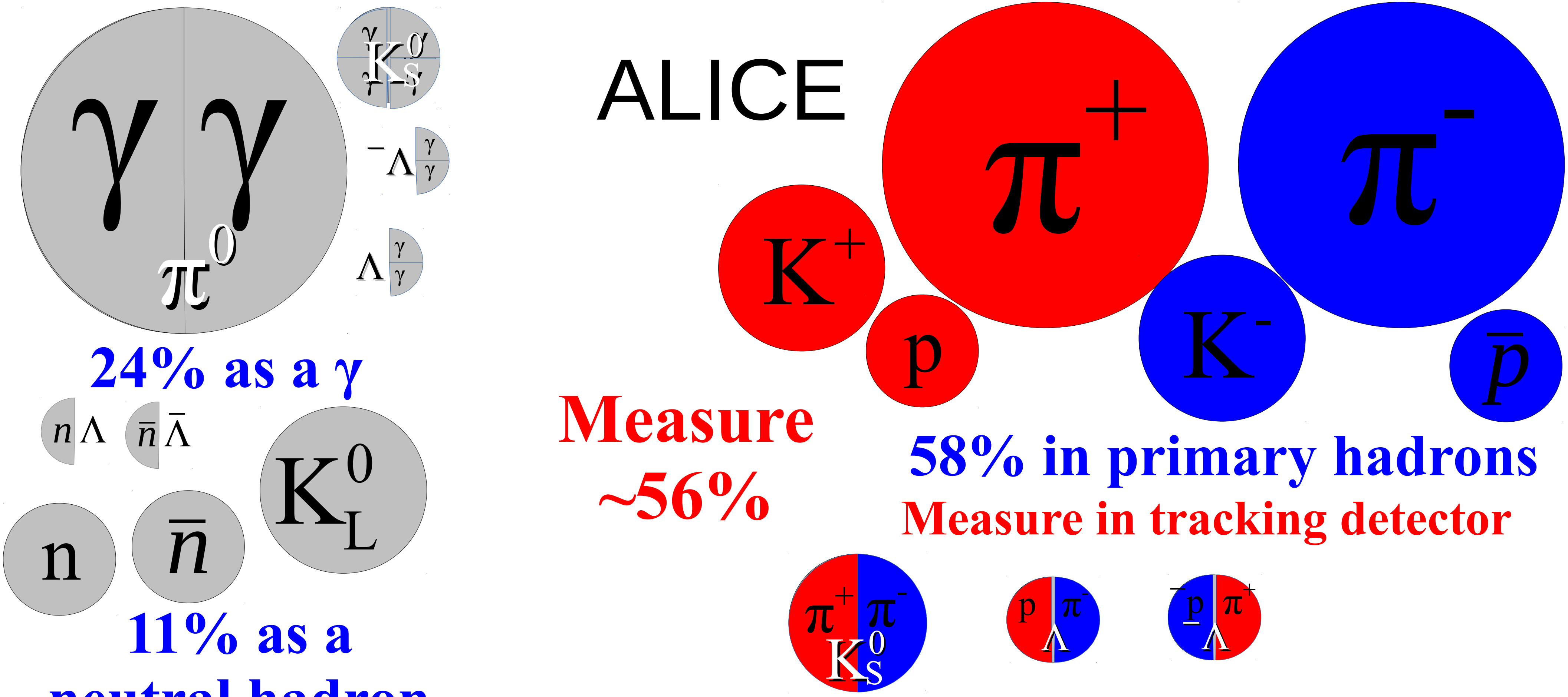
→ Measure ~57% of energy



Deposit about 1/3 of energy

65% of energy in event


STAR
γ γ
π0
K0S
Λ
n Λ
n̄ Λ̄
K0L
n
n̄
24% as a γ
Backgrounds
11% as a neutral hadron
Measure in electromagnetic calorimeter
π+
π-
K+
p
K-
p̄
58% in primary hadrons
Measure in tracking detector
Background
π+ π-
K0S
p π-
Λ
p̄ π+
Λ̄
7% in secondary hadrons



ALICE

24% as a γ

11% as a neutral hadron

Don't measure

Measure ~56%

58% in primary hadrons

Measure in tracking detector

7% in secondary hadrons

Cut out using tight DCA cut

ALICE

3% 2% 3% 40% But known well!

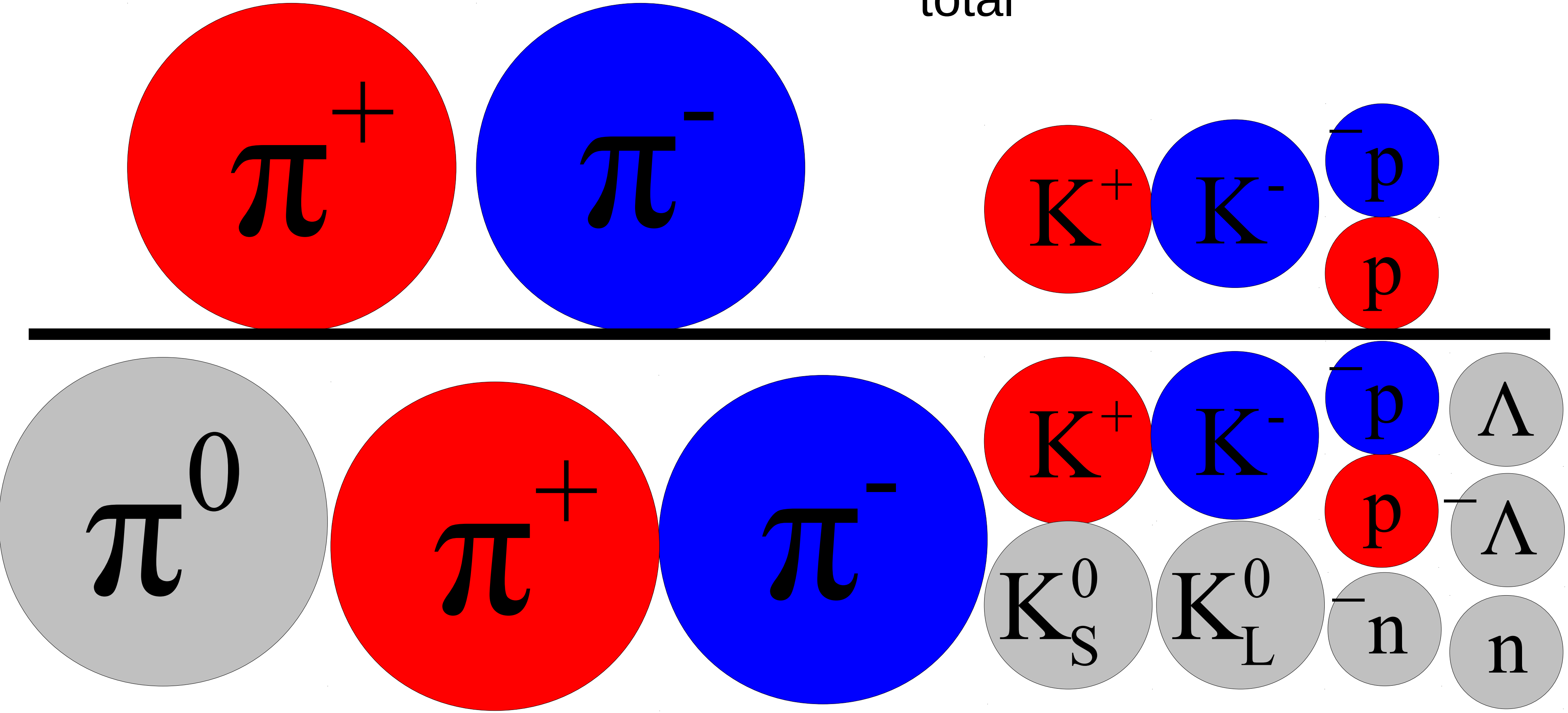
$$E_T = \frac{1}{f_{p_T cut}} \frac{1}{f_{total}} \sum_{i=0}^{n} f_{bg}^{i}(p_T) \frac{1}{f_{notID}} \frac{1}{eff(p_T^i)} E_i \sin(\theta^i)$$

45%

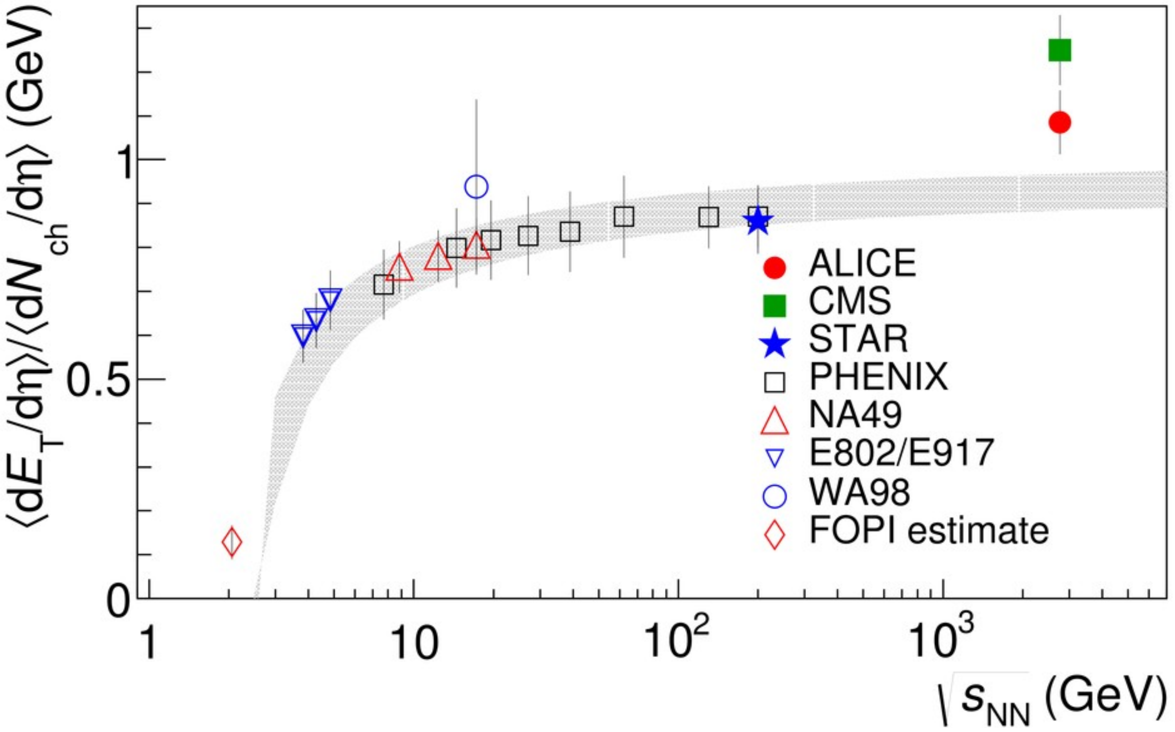
What we measure directly

Corrections

ALICE: $f_{total} = 0.567 \pm 0.009$



ALICE E_T



⟨dE_T/dη⟩/⟨dN_ch/dη⟩ (GeV)
1
0.5
0
1
10
10^2
10^3
√s_NN (GeV)
ALICE
CMS
STAR
PHENIX
NA49
E802/E917
WA98
FOPI estimate