# How the Blast-Wave Model Describes PID Hadron Spectra from 5 TeV p-Pb Collisions

Tom Trainor

University of Washington

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# Agenda

Do Blast-Wave model fits demonstrate flow?

How should spectrum models be evaluated?

Is there a better spectrum model?

What role do jets play in nuclear collisions?

Is QGP formed in small collision systems?

**2206.07791**

collectivity?

# Blast-Wave Spectrum Model

$$\frac{dN}{m_t dm_t} \propto m_t \int_0^R r dr\, K_1\left(\frac{m_t \cosh\rho}{T_{kin}}\right) I_0\left(\frac{p_t \sinh\rho}{T_{kin}}\right)$$

$dy_z$ **?**

$$\rho(r) = \tanh^{-1}\beta_t, \quad \beta_t = \beta_s (r/R)^n$$

"radial flow"

**SSH** - nucl-th/9307020

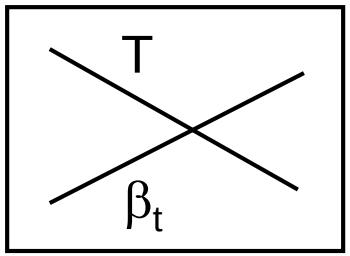
Landau and Hagedorn
Cooper and Frye
Siemens and Rasmussen
Bevalac/AGS *collectivity*

ALICE - 1307.6796 5 TeV *p*-Pb

fit parameters: $(T_{\rm kin}, \langle\beta_{\rm T}\rangle, n)$

central

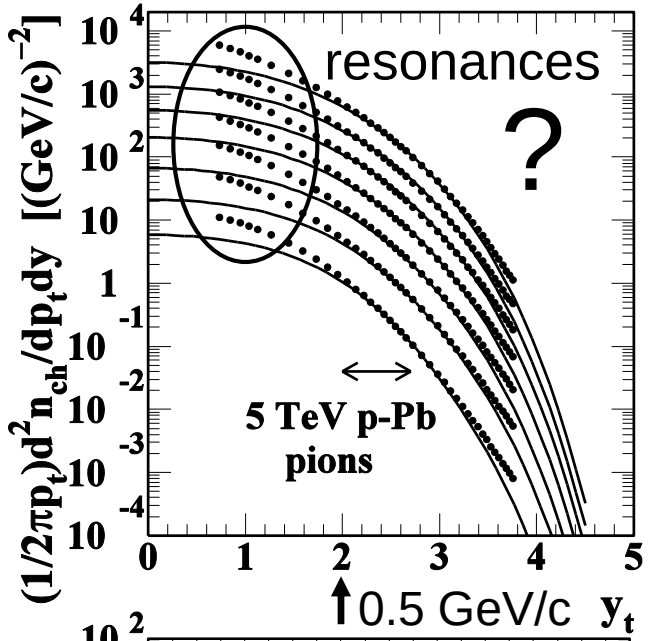
| $n$ | $\sigma'/\sigma_0$ | $\langle\beta_T\rangle$ | $T_{kin}$ (GeV) | $n$ | $\chi^2$/ndf |
|---|---|---|---|---|---|
| 1 | 0.025 | 0.547 | 0.143 | 1.07 | 0.27 |
| 2 | 0.075 | 0.531 | 0.147 | 1.14 | 0.33 |
| 3 | 0.15 | 0.511 | 0.151 | 1.24 | 0.36 |
| 4 | 0.30 | 0.478 | 0.157 | 1.41 | 0.35 |
| 5 | 0.50 | 0.428 | 0.164 | 1.73 | 0.43 |
| 6 | 0.70 | 0.36 | 0.169 | 2.4 | 0.54 |
| 7 | 0.90 | 0.26 | 0.166 | 3.9 | 0.84 |




- centrality +
isentropic expansion?


?

# BW Description of PID Spectra




$$y_{ti} = \ln\left[\left(m_{ti} + p_t\right)/m_i\right]$$

transverse rapidity

ALICE - 1307.6796

arrows: fit intervals

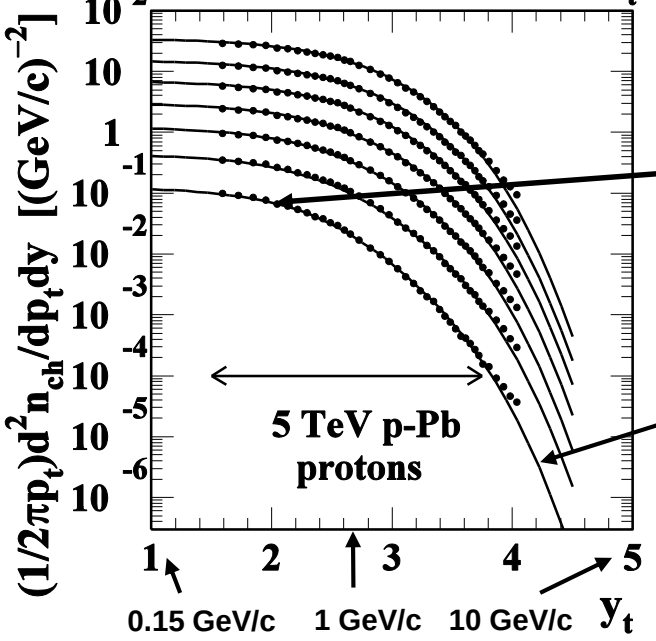
densities on $p_t$ vs $y_t$

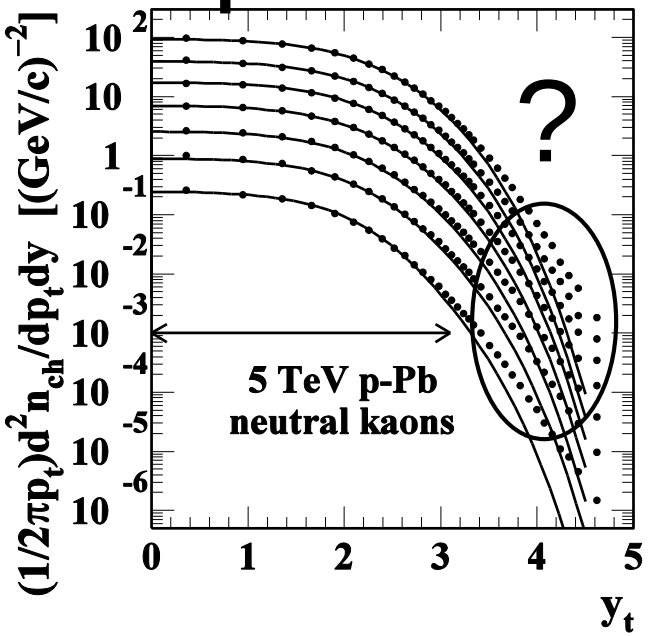
$\propto A - m_0 \cosh(y_t)/T$

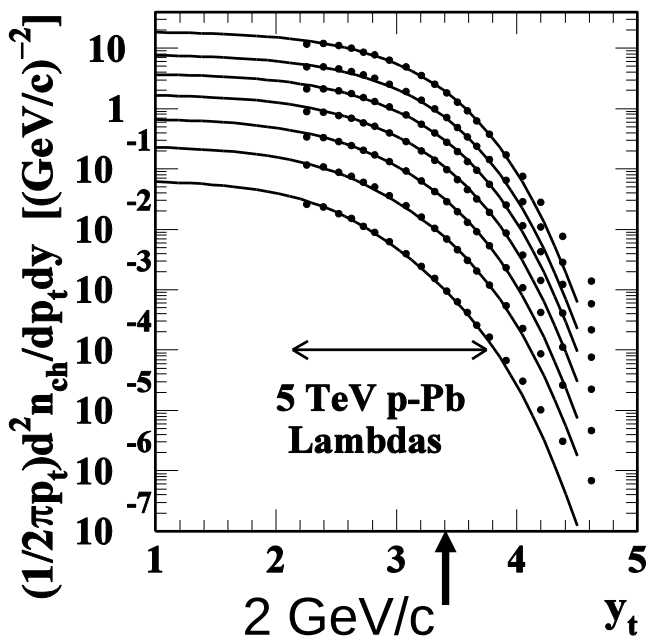
at low $p_t$

BW model

good or bad?



# PID Two-Component Model

## Identified hadrons from 5 TeV p-Pb collisions

$\bar{\rho}_0 \approx \bar{\rho}_s + \bar{\rho}_h$ describes nonPID *p*-Pb charge densities

1801.05862
1812.01151

hadron species *i*

**charge densities:** $\bar{\rho}_{0i}(y_t, n_{ch}) \equiv d^2\bar{n}_{chi} / m_{ti} dm_{ti} dy_{zi}$

$= S_i(y_t, n_{ch}) + H_i(y_t, n_{ch})$ **soft + hard**

2112.09790, 2112.12330

$= z_{si}\bar{\rho}_s \hat{S}_{0i}(y_t) + z_{hi}\bar{\rho}_h \hat{H}_{0i}(y_t)$ factorized

$(z_{si}, z_{hi})$ are *fractions* of nonPID densities

simple functions of $n_s$

**TCM fixed model functions:**

$\hat{S}_{0i}(y_t; T, n)$ soft model function

Exponential on $m_t$ with power-law tail ↔ thermal system with *fluctuating* T parameter

$\hat{H}_{0i}(y_t; \bar{y}_t, \sigma_{y_t}, q)$ hard model function

Gaussian on $y_t$ with exponential tail ↔ *measured* jet spectra and fragmentation functions

0901.3387

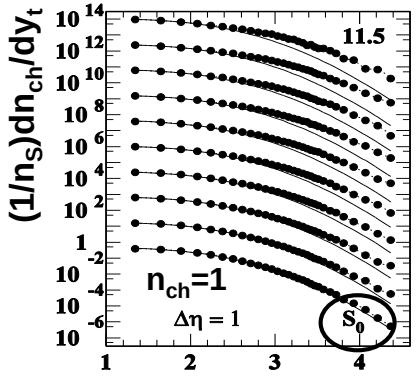
# TCM Physics

☺ 1976

**Soft component**: spectrum limit as $n_{ch} \to 0$

nuclear transparency

STAR 2006

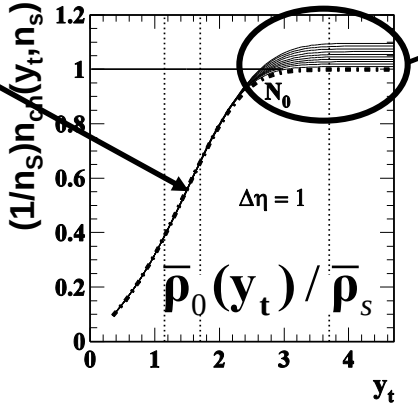



200 GeV p-p spectra

$/\,\bar{\rho}_s \quad \hat{S}_0(m_t)$

*data* running integrals on $y_t$

$\int dy_t S_0(y_t)$




$\propto \bar{\rho}_s$

$H(y_t)/\bar{\rho}_s$

$\propto \mathrm{erf}(y_t)$

jets $\propto \bar{\rho}_s^2$

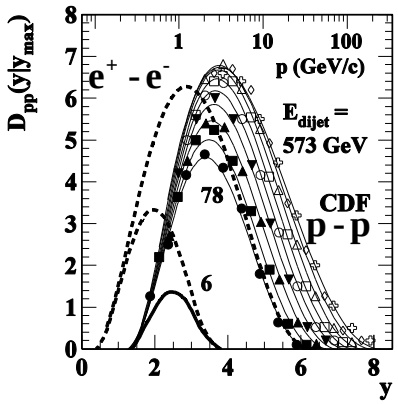
nucl-ex/0606028

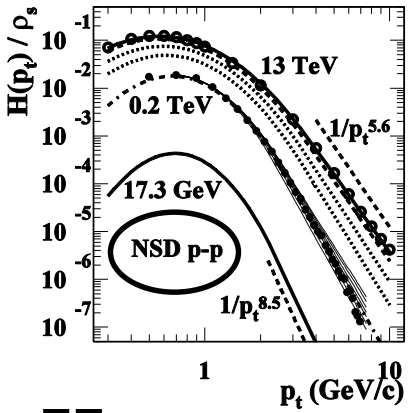
1701.07866

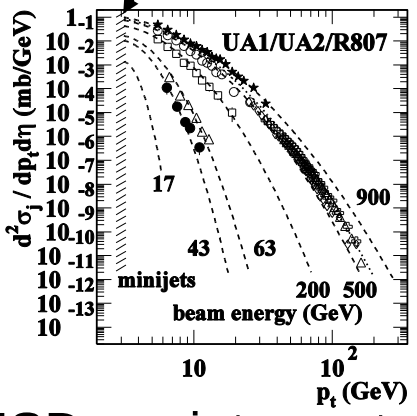
3 GeV lower bound

**Hard component**: convolute *measured* FFs with *measured* jet spectra: $\hat{H}_0(y_t)$

p-p hard components – data and TCM



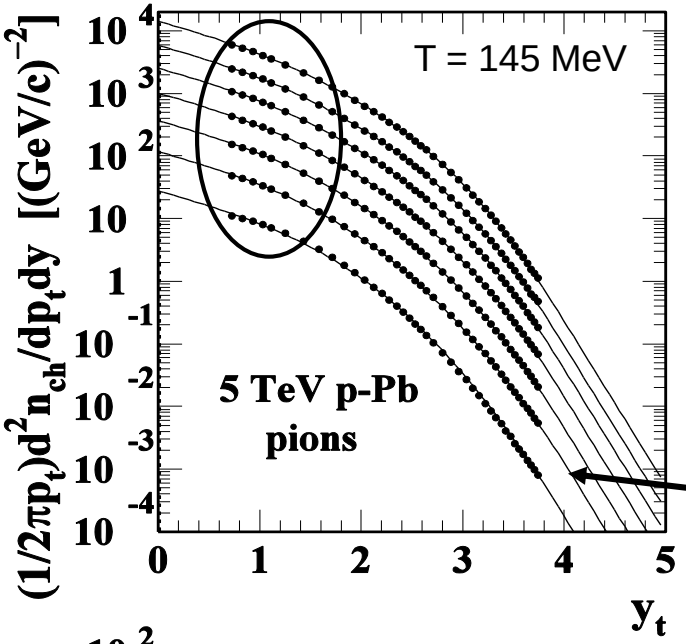




p-p fragmentation functions – FFs

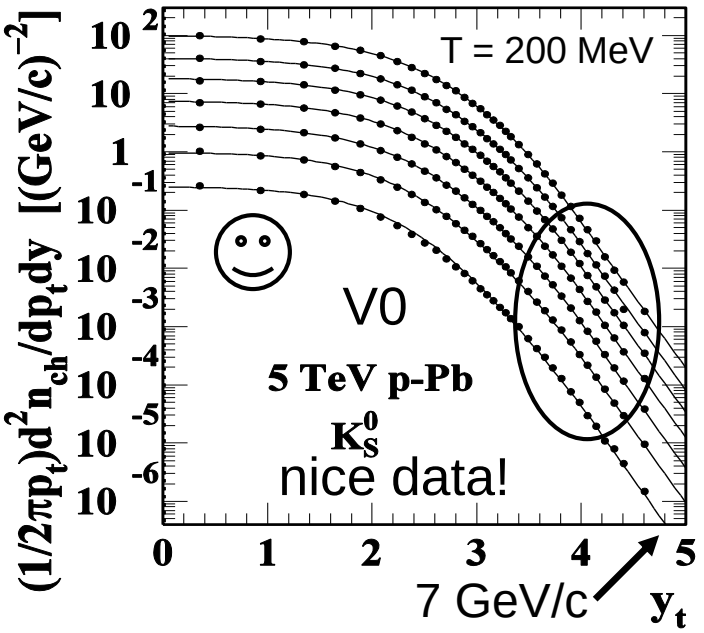
NSD p-p jet spectra

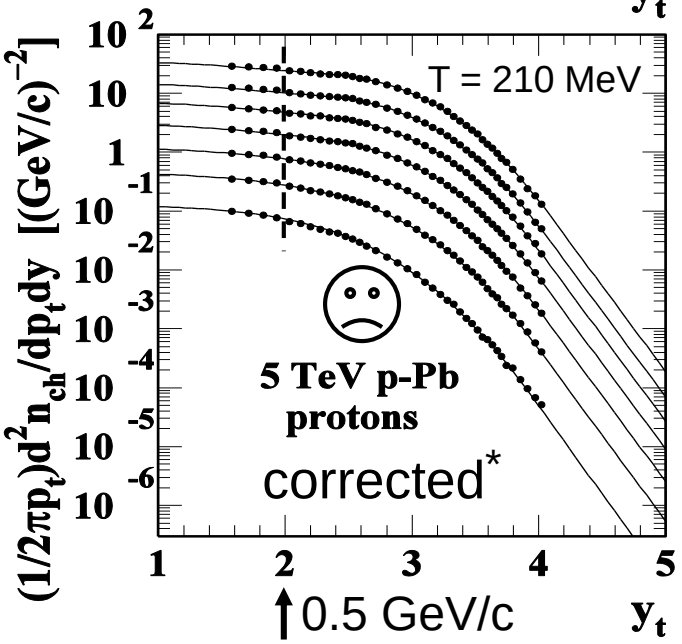
# TCM Description of PID Spectra




TCM is *not* fitted to individual spectra

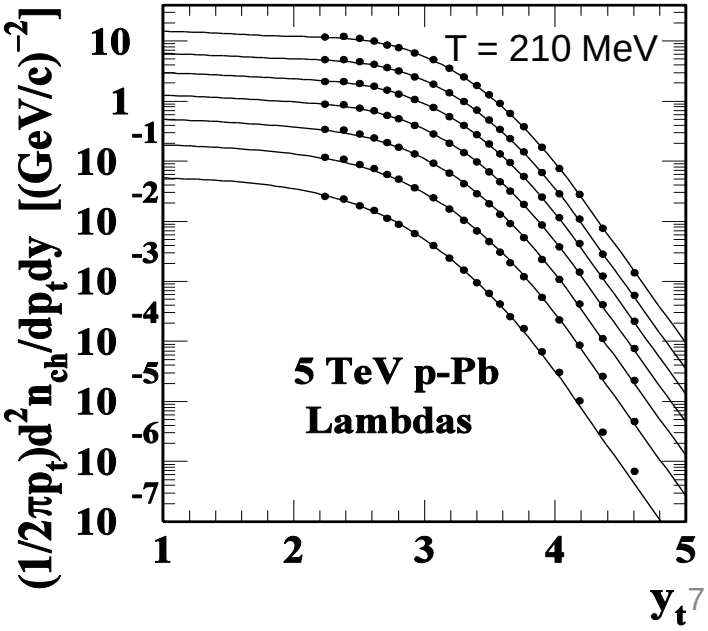
2112.09790*
2112.12330




data described within *statistical* uncertainties

new information is obtained on strangeness and baryon production!

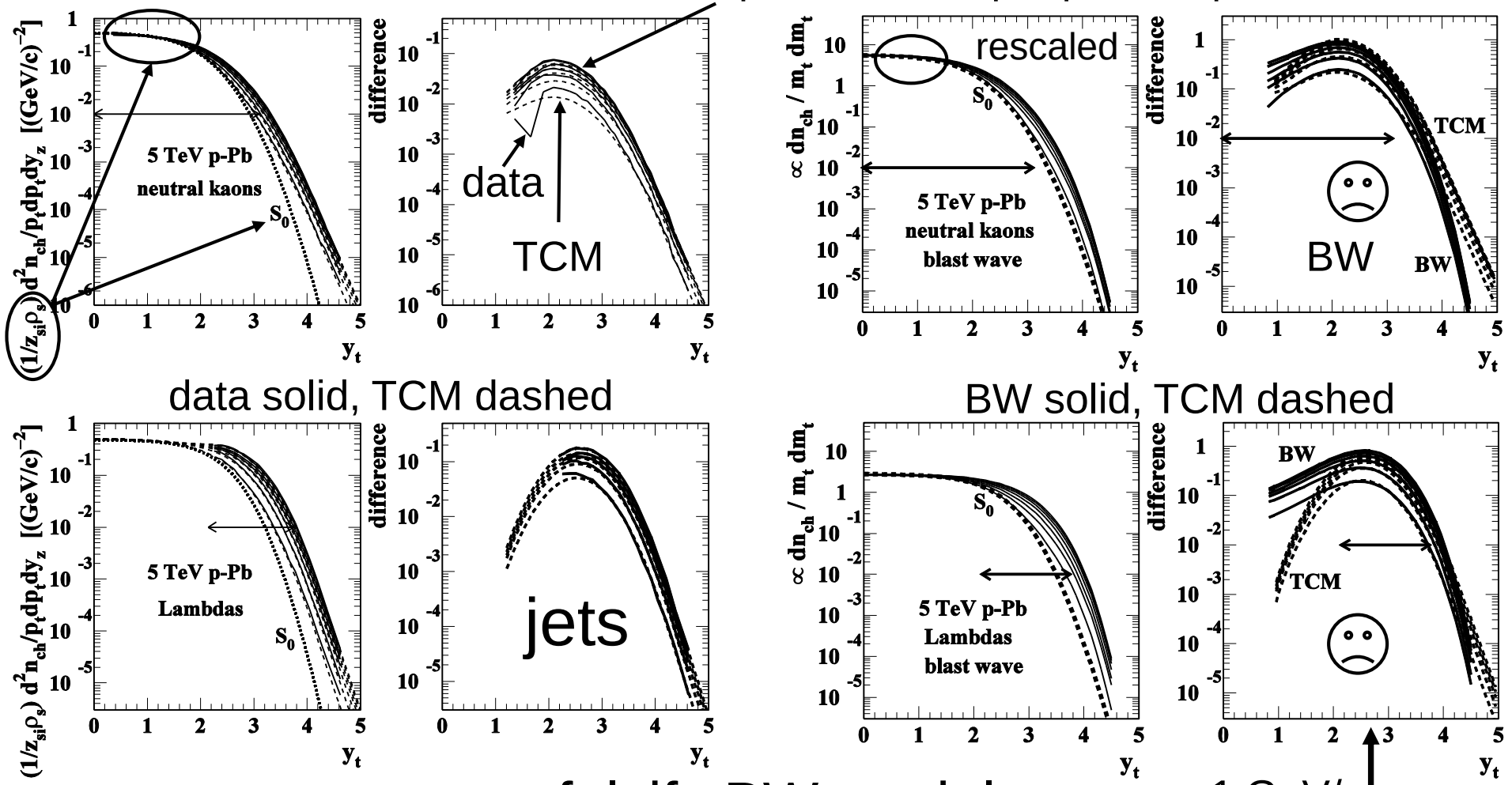


# BW Test: Spectrum Differences

*model-independent* spectrum *shape* analysis

"…we are only interested in the **shape** of the spectra to reveal the dynamics of the collision zone at freezeout." **SSH**

other spectra minus peripheral spectrum



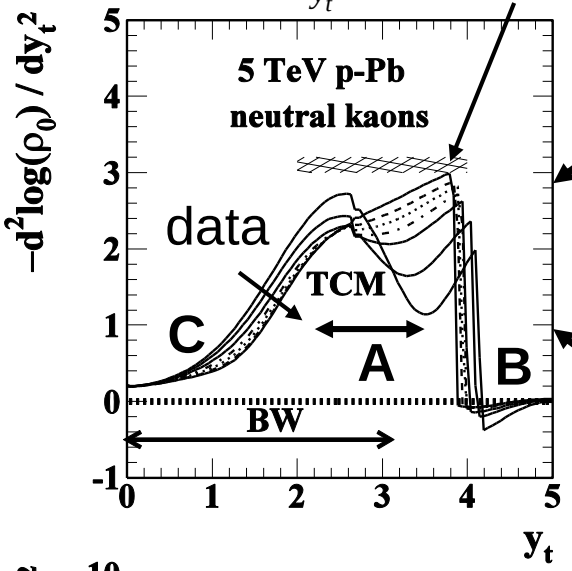

arrows: BW fit intervals

falsify BW model

# BW Test: Logarithmic Derivatives

another model-independent shape measure – **local curvature**

$1/\sigma^2_{y_t}$ measured




hard component

$$-\frac{d^2 \ln[\bar{\rho}_0(y_t)]}{dy_t^2} \to 1/\sigma^2_{y_t} \quad \textbf{A}$$

$$\approx 0 \quad \textbf{B}$$

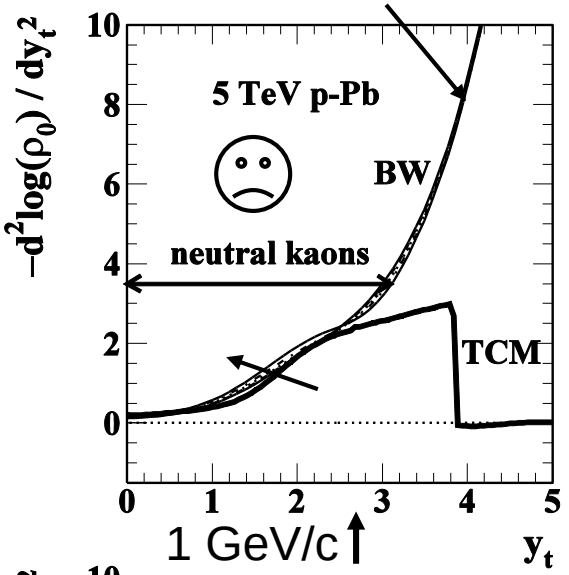
soft component

$$-\frac{d^2[A - m_0 \cosh(y_t)/T]}{dy_t^2}$$

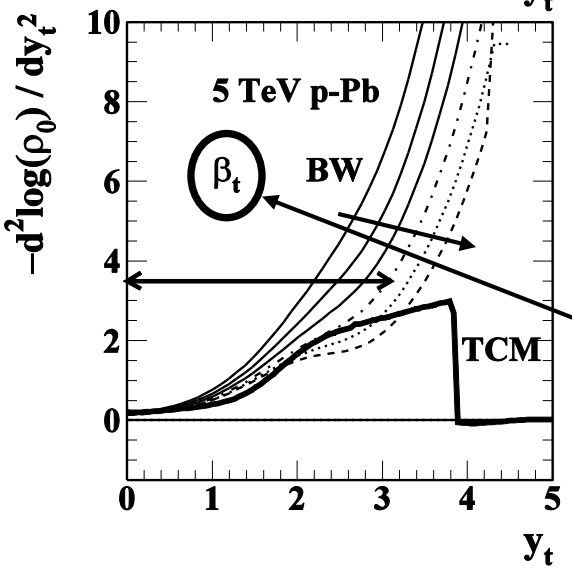
$$\to m_0 \cosh(y_t)/T \quad \textbf{C}$$

Boltzmann on $m_t$

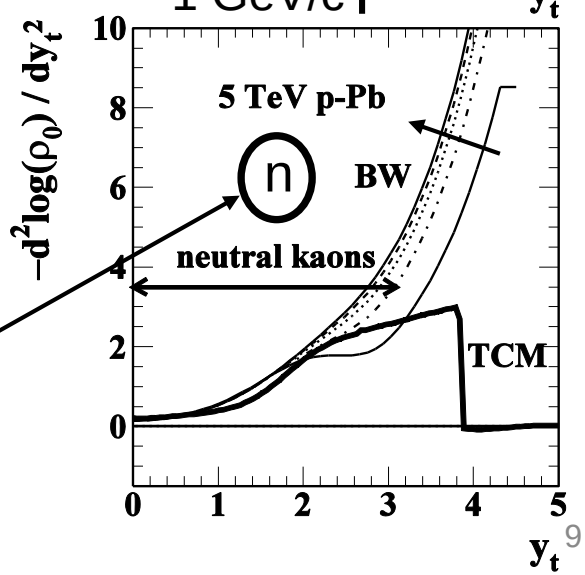
BW fits




1 GeV/c




single parameter varies

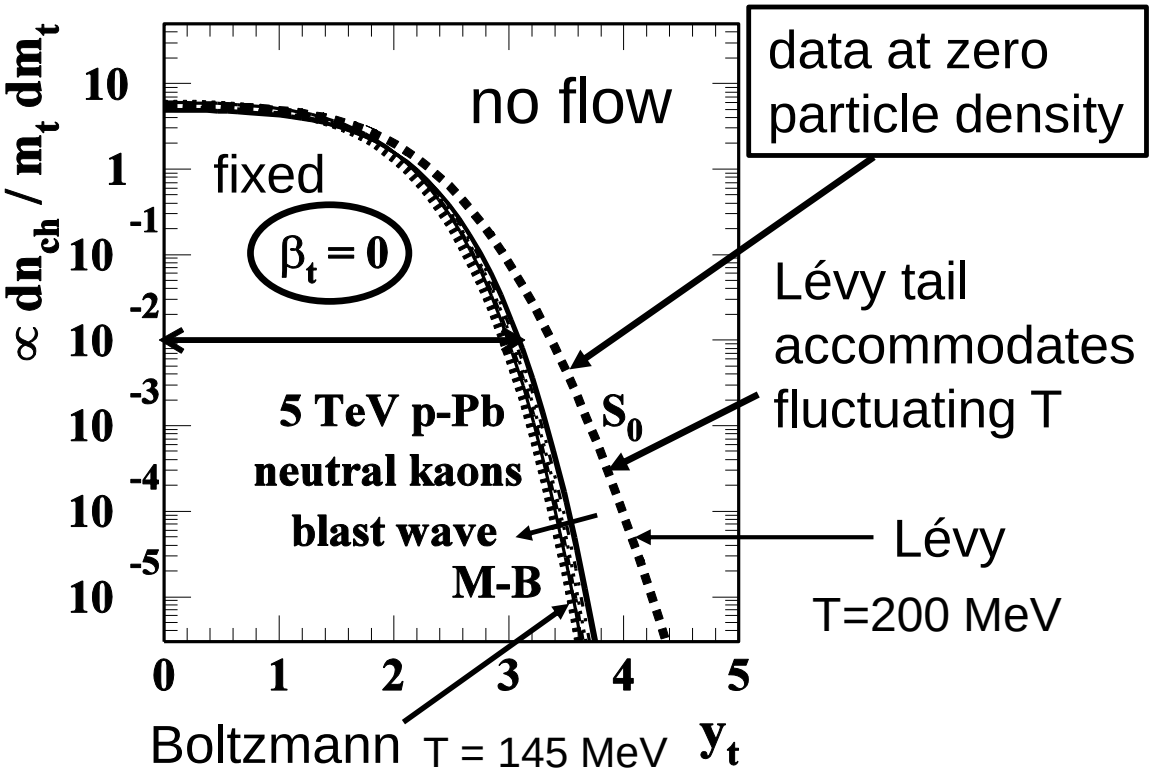


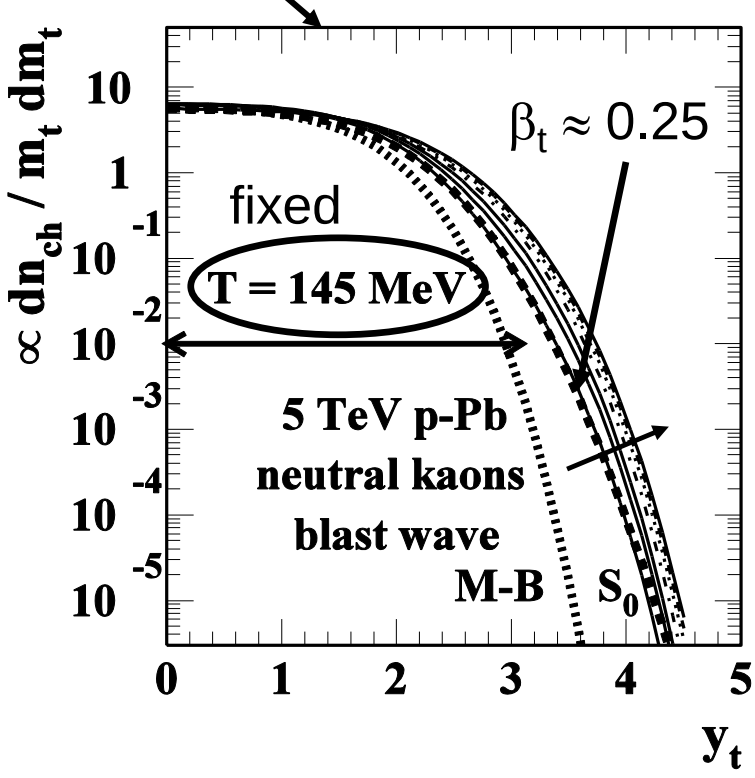

falsify BW model

# Single BW Parameters Held Fixed

other parameters vary as fitted

BW model describes *zero-density data* model $S_0(y_t)$ if $\beta_t \approx 0.25$




BW model with zero radial flow reverts to Boltzmann exponential (bold dotted) on $m_t$ [~ cosh($y_t$)]

BW model with fixed T = 145 MeV and fitted transverse speed approximates TCM $S_0$ (bold dashed)

# BW Test: Z-scores and Significance

**spectrum ratio:** $\frac{\text{data}}{\text{model}} - 1 \approx \frac{\text{data} - \text{model}}{\text{error}} \times \frac{\text{error}}{\text{data}}$

spectrum ratios may be *quite deceptive*

**Z-scores** **extraneous factor**

Z-scores: $Z_i = \frac{D_i - M_i}{\sigma_i}$

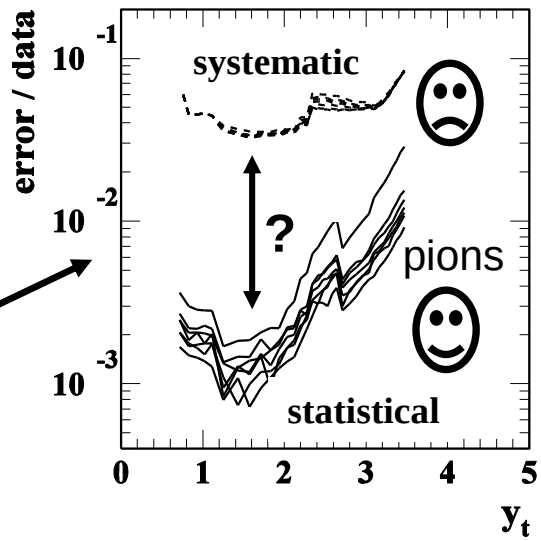
r.m.s ≈ 1 signals acceptable model

error → data uncertainty

should be statistical, *not* systematic, uncertainty

published errors

$\frac{\text{error}}{\text{data}} \ll 1$




hides serious model problems in spectrum ratios

lies, damn lies and statistics… Disraeli

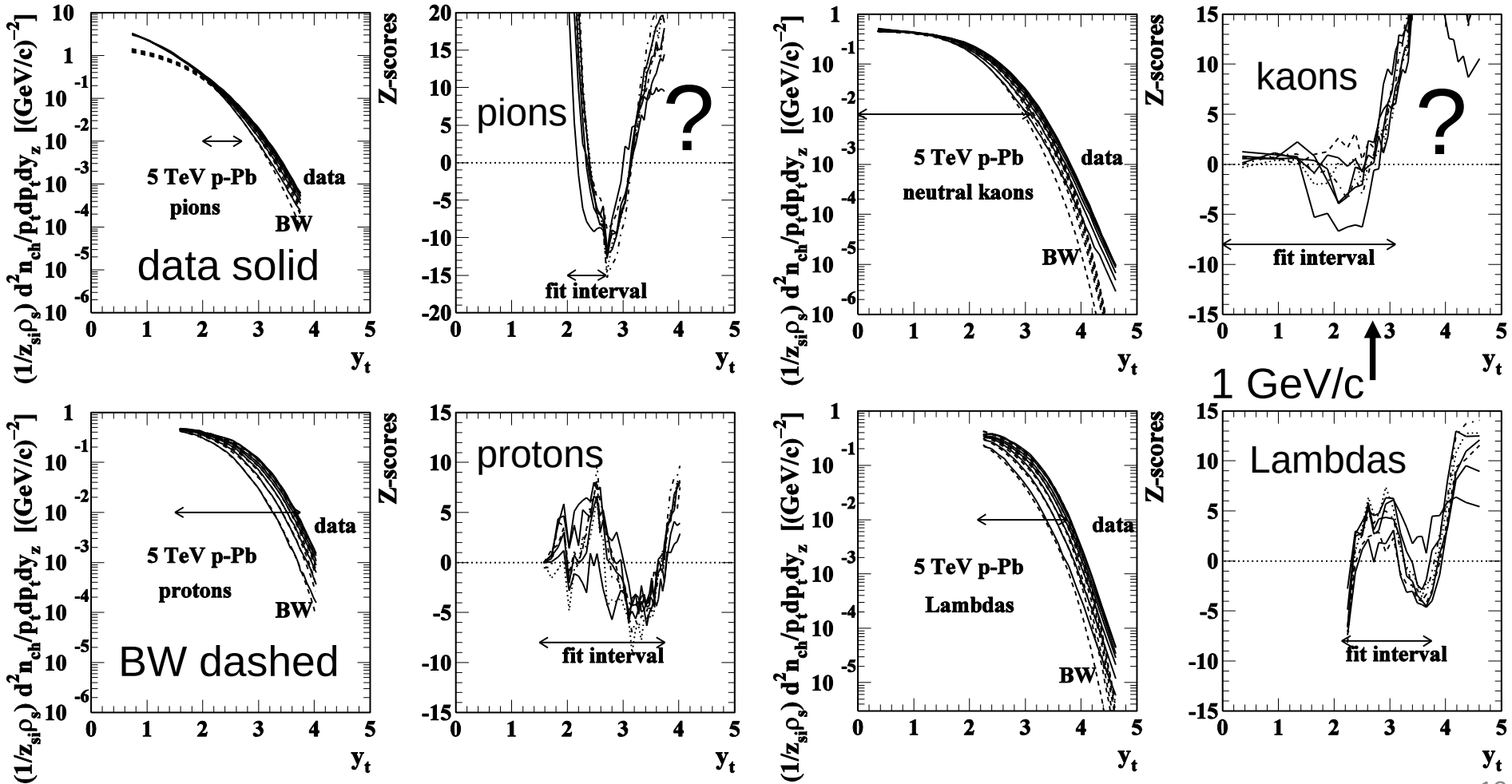
$\chi^2 = \sum_i Z_i^2$

conveys little information, may be deceptive

# Z-Scores with Statistical Errors

BW model with fitted parameter values from ALICE – 1307.6796

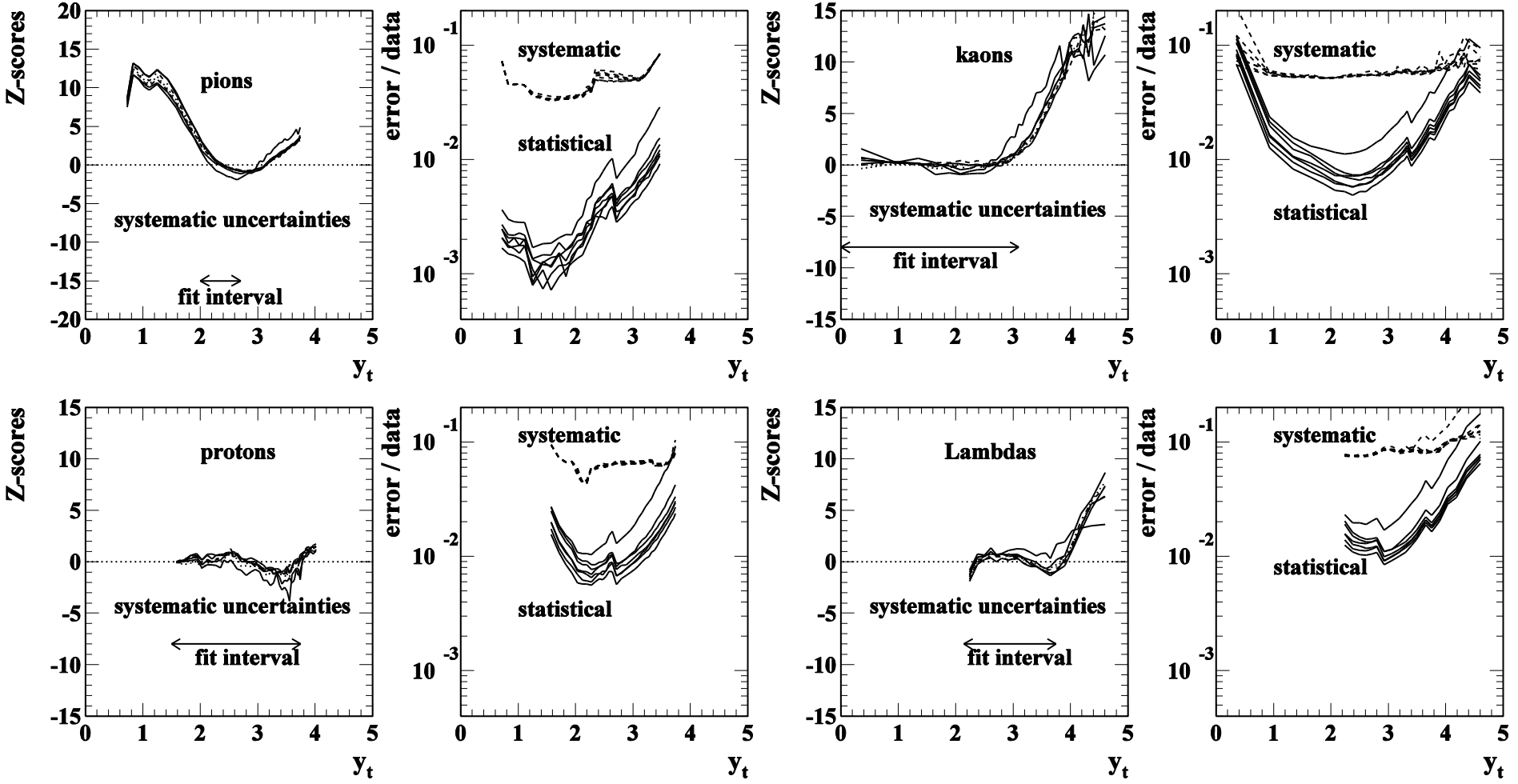
large *systematic* deviations falsify BW model



# Z-Scores with Systematic Errors

BW Z-scores using published *total systematic* uncertainties

consistent with $\chi^2$ values from 1307.6796

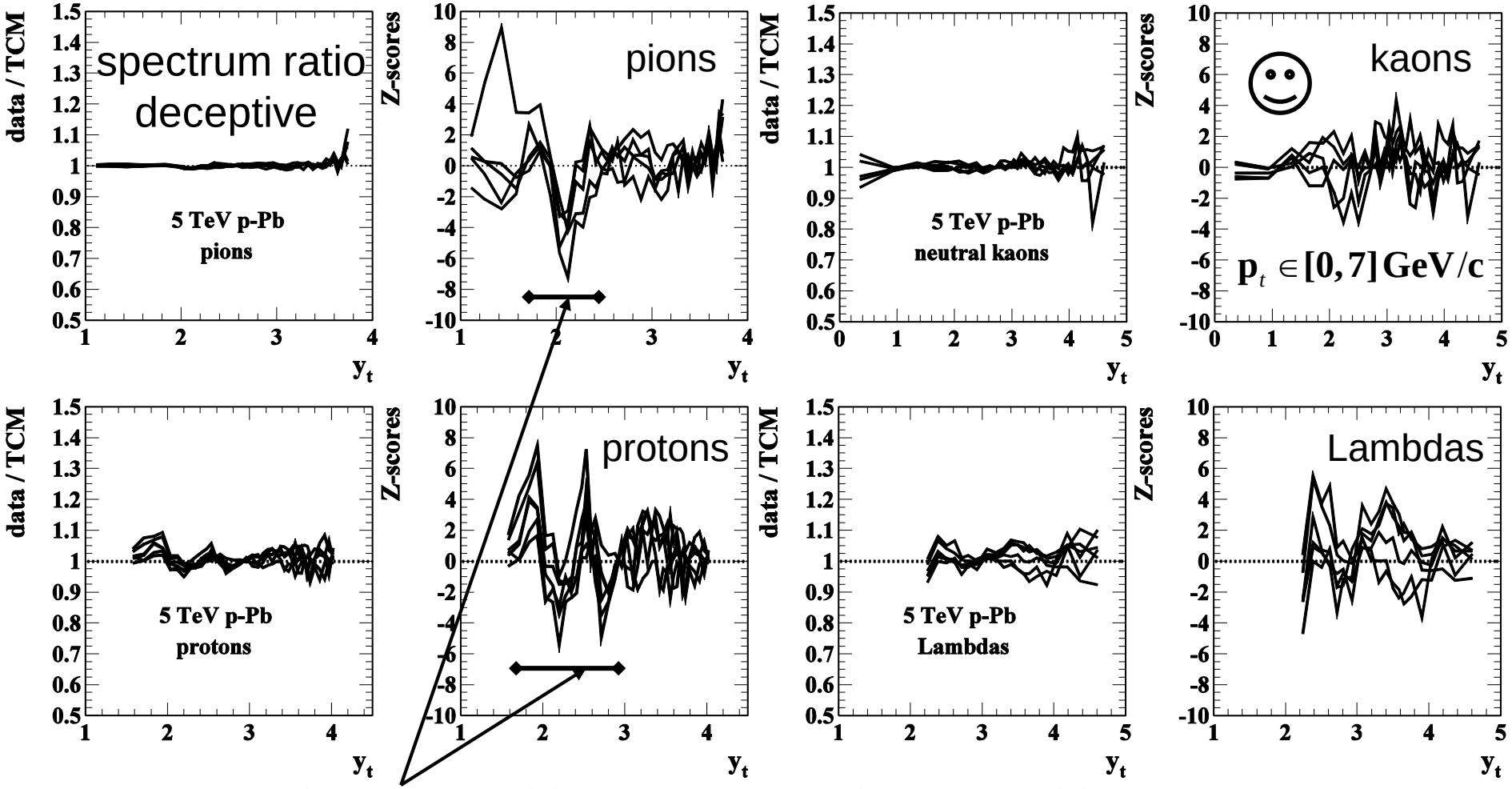



misleading impression of fit quality

# TCM Z-Scores with Statistical Errors

Z-scores acceptable, but with isolated excursions

TCM describes data over *entire detector acceptance*




correlated across $n_{ch}$ bins, uncorrelated across $y_t$ bins

# Are Small Systems Elementary?

## evidence for "collectivity" in small A-B?

TCM
- Blast-wave model fits → radial flow ⊗
- "Hardening" of PID $p_t$ spectra – more so for protons ⊗
- → "Mass-ordering fingerprint" → e.g. $v_2(p_t)$
- The "ridge" in *p*-*p* collisions and "ridges" in *p*-Pb
- $v_2$, $v_3$, $v_4$, … $v_?$ "higher harmonics" or cumulants

Small System Collectivity in Relativistic Hadronic and Nuclear Collisions
J. Nagle and W. Zajc
Ann. Rev. Nucl. Part. Sci **68**, 211 (2018)

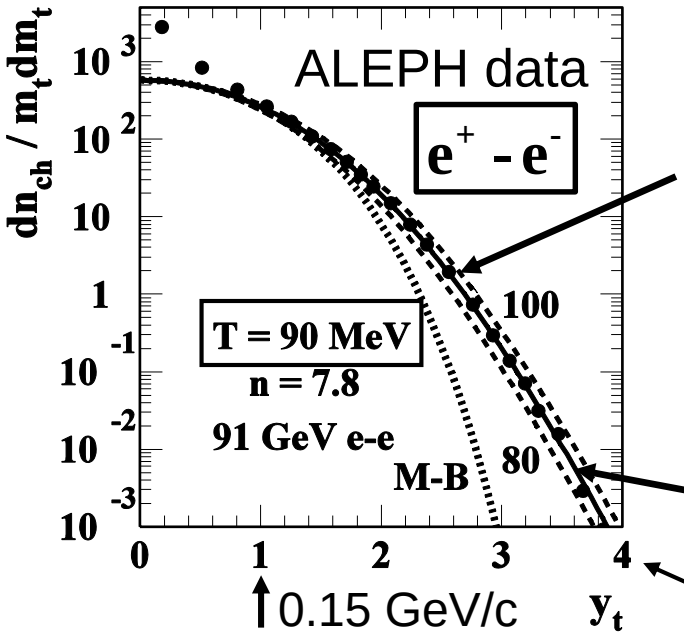
"The field of R.H.I.P is in the midst of a revolution…driven by the *experimental observation of* ***flow-like features*** in…small hadronic systems."

# Elementary Collisions – Dijets

*p*-Pb, *p*-*p*? ⟶ $e^+ - e^- \rightarrow Z \rightarrow q - \bar{q}$ 91.25 GeV

$p_t$ spectrum *perpendicular* to dijet thrust axis well described by TCM $S_0$

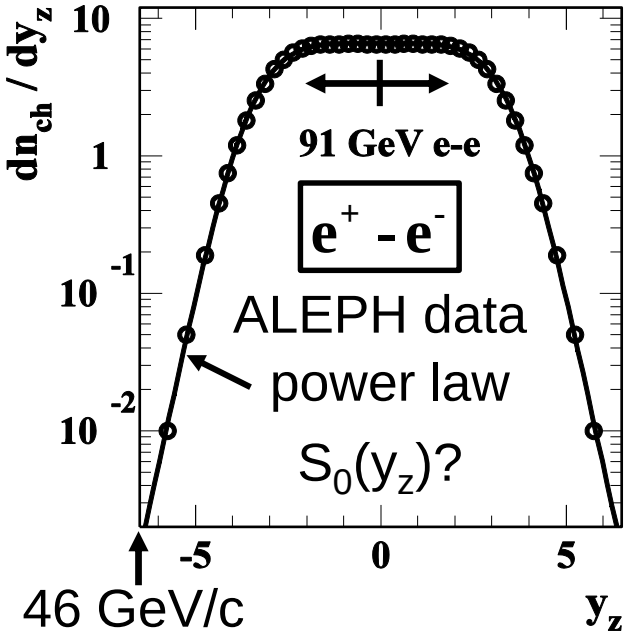
$p_z$ distribution *parallel* to dijet thrust axis consistent with soft component




**parton cascades** consistent with TCM soft component

dijet momentum distributions

$S_0(y_t)$




radial flow?

D. Buskulic *et al*. Z Phys C **55**, 209 (1992)

"flow-like features"

Bjorken expansion?

# Summary

- Model-independent shape measures falsify BW
- Proper (statistical error) Z-scores falsify BW model
- BW flow parameter mimics nonjet soft component
- BW parameters fail to describe dijet contribution
- p-Pb data features are consistent with $e^+$-$e^-$ data
- Each TCM component represents parton cascades

No flow or “collectivity” in small systems

**2206.07791**