Nuclear Modification Factors and the Cronin Effect

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Agenda

concerning nuclear modification factors (NMFs):

- how is rescaling by N_{bin} determined?
- how are NMFs physically interpreted?
- how are NMFs related to LHC jets?

concerning the Cronin effect:

- effect first observed in Chicago-Princeton spectra
- how does the effect relate to C-P spectrum data?
- how are C-P spectra related to LHC jets?

2304.02170

PID Two-Component Model – TCM

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

$\boxed{\text{p-N:} \quad \bar{\rho}_h \approx \alpha \bar{\rho}_s^2}$

PID spectra: $\bar{\rho}_0(m_t, n_{ch}) \approx d^2\bar{n}_{ch} / m_t dm_t dy_z$

hadron species *i* $= S_i(m_t, n_{ch}) + H_i(m_t, n_{ch})$ **soft + hard**

2112.09790, 2112.12330 $= \bar{\rho}_{si}\, \hat{S}_{0i}(m_t) + \bar{\rho}_{hi}\, \hat{H}_{0i}(m_t, n_s)$ factorized

e.g. $\bar{\rho}_{si} = z_{si}(n_s)\bar{\rho}_s$

TCM model functions vs centrality:

fixed

unit-normal

variable

$\boxed{y_t = \ln\left[(m_t + p_t)/m\right]}$

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

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

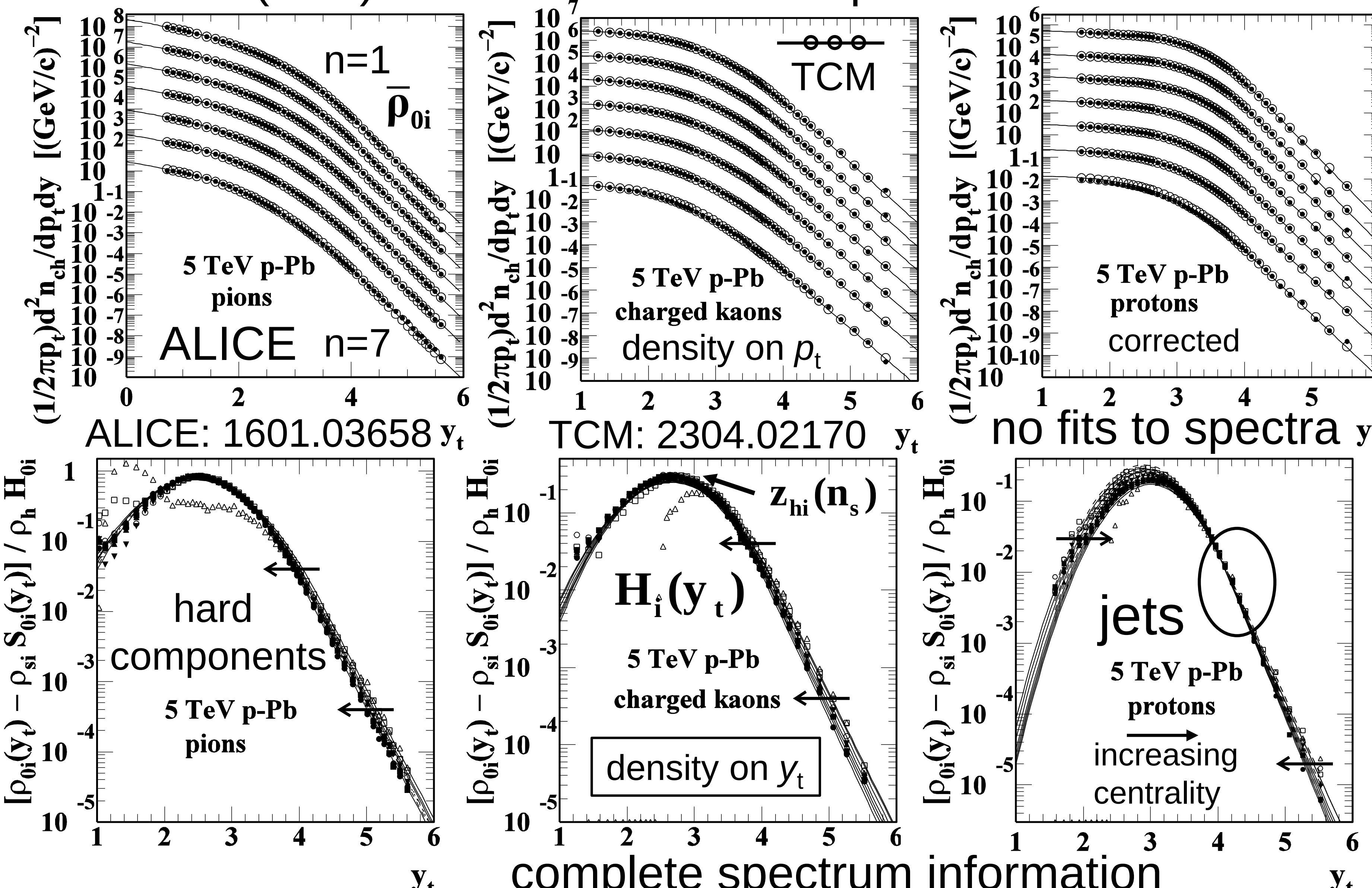
Exponential on m_t with power-law tail ↔ thermal system with *event-wise fluctuating* T

Gaussian on y_t with exponential tail ↔ *measured* jet spectra and fragmentation functions (FFs)

0901.3387

5 TeV *p*-Pb PID Spectrum Data

data (dots) described within their pointwise uncertainties



complete spectrum information

Nuclear Modification Factors

conventional definition: $\mathbf{R}_{\mathbf{pPb}} = \frac{\mathbf{1}}{\mathbf{N}_{\mathbf{bin}}} \frac{\bar{\boldsymbol{\rho}}_{\mathbf{0pPb}}(\mathbf{p}_{\mathbf{t}})}{\bar{\boldsymbol{\rho}}_{\mathbf{0pp}}(\mathbf{p}_{\mathbf{t}})} \quad \left[\frac{NSD}{MB}?\right]$

where from?

unrescaled TCM version:

$$\mathbf{R}'_{\mathbf{pPb}} = \frac{z_{si}(n_s)\bar{\rho}_s \hat{S}_{0i}(p_t) + z_{hi}(n_s)\bar{\rho}_h \hat{H}_{0ip\mathrm{Pb}}(p_t, n_s)}{z_{sipp}\bar{\rho}_{spp}\hat{S}_{0i}(p_t) + z_{hipp}\bar{\rho}_{hpp}\hat{H}_{0ipp}(p_t)}$$

low p_t $\rightarrow$ $$\frac{z_{si}(n_s)(N_{part}/2)\bar{\rho}_{sNN}\cancel{\hat{S}_{0ipPb}(p_t)}}{z_{sipp}\bar{\rho}_{spp}\cancel{\hat{S}_{0ipp}(p_t)}}$$ nuclear transparency

high p_t $\rightarrow$ $$\frac{z_{hi}(n_s)N_{bin}\bar{\rho}_{hNN}\hat{H}_{0ip\mathrm{Pb}}(p_t, n_s)}{z_{hipp}\bar{\rho}_{hpp}\hat{H}_{0ipp}(p_t)}$$

for strict p-N linear superposition: (N-N$\rightarrow$p-N $\equiv$ p-p)

low $p_t \rightarrow$ $\mathrm{N}_{\mathrm{part}}/2$

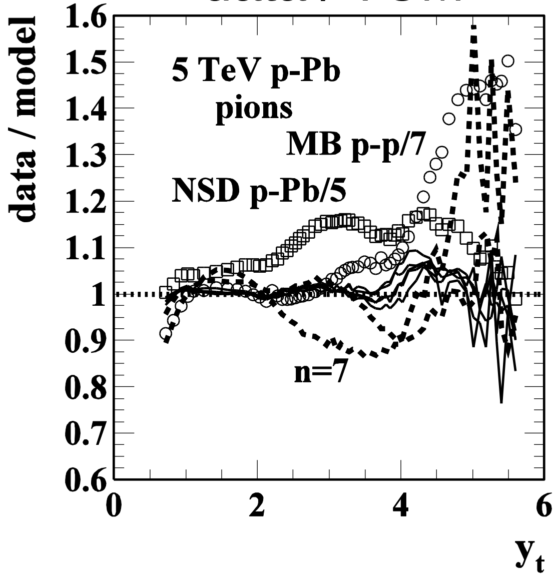
high $p_t \rightarrow$ $\mathrm{N}_{\mathrm{bin}}\hat{\mathrm{H}}_{\mathrm{0pPb}}(\mathrm{p}_{\mathrm{t}})/\hat{\mathrm{H}}_{\mathrm{0pp}}(\mathrm{p}_{\mathrm{t}})$

$\boxed{\mathrm{N}_{\mathrm{part}} = \mathrm{N}_{\mathrm{bin}} + 1 \text{ for p-Pb}}$

nuclear modification?

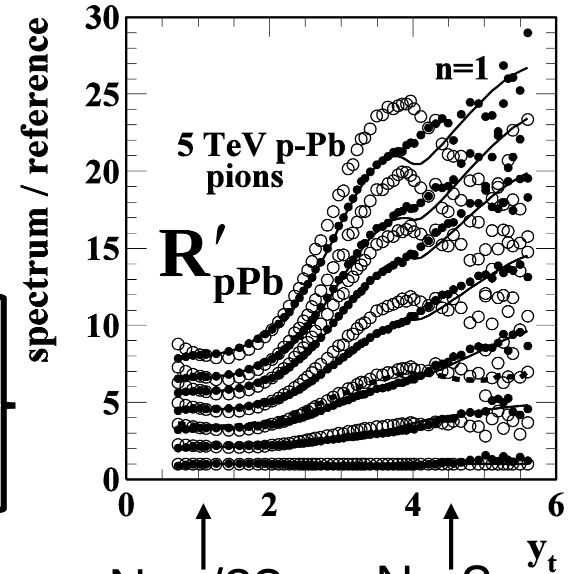
NMF Ratio Data

data / TCM



data/TCM – solid, dashed
NSD p-Pb/n=5 – boxes
MB p-p/n=7 – circles

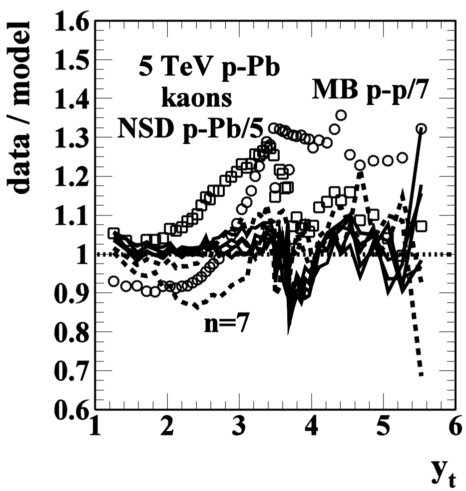
data/data 7 – circles
data/TCM 7 – dots
TCM/TCM 7 – curves

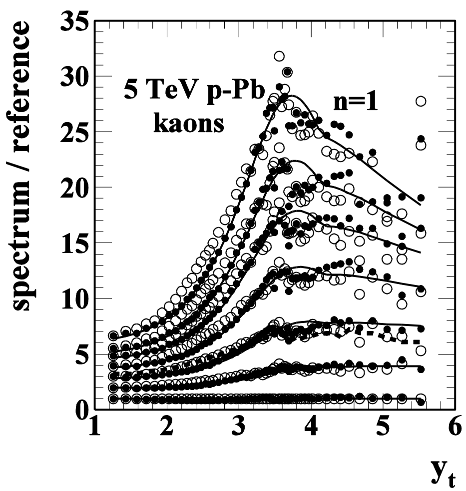


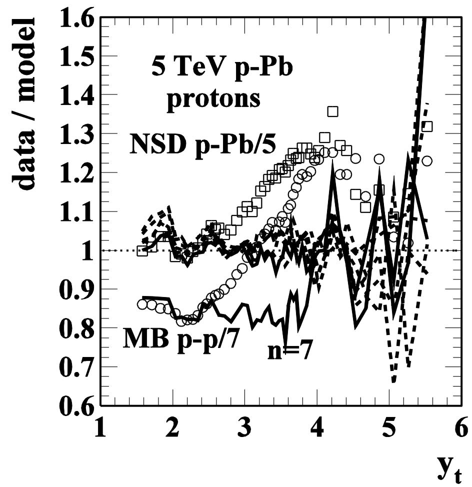
$N_{part}/2$? N_{bin}?

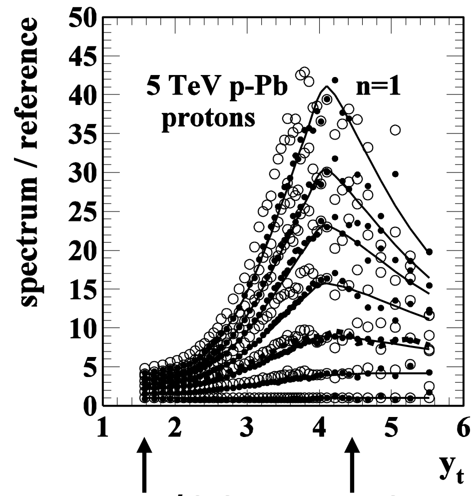
TCM ⇔ data

NMF assumptions fail









$N_{part} = N_{bin} + 1$ for p-Pb

$N_{part}/2$? N_{bin}?

Variable vs Fixed $H_0(p_t)$ Models

The TCM with *variable* hard component describes data within their uncertainties

With *fixed* hard components H_0 model factors cancel

What remain at high p_t are factors

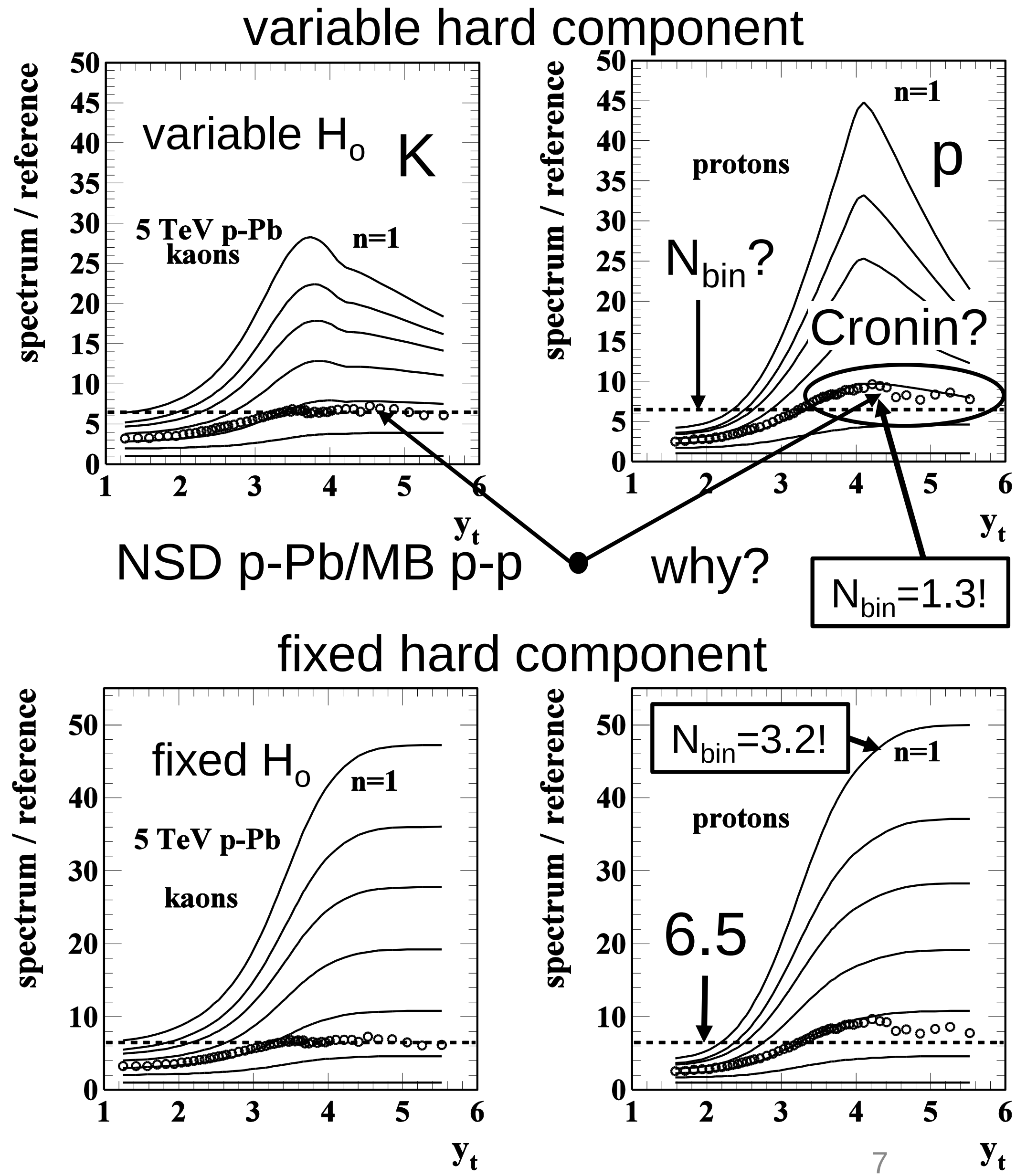
$N_{bin}\, z_{hiNN}\, \rho_{hiNN} / z_{hipp}\, \rho_{hipp}$

$$\bar{\rho}_h \propto \bar{\rho}_s^2 \quad \text{for } p\text{-N}$$

$$\bar{\rho}_{s1} / \bar{\rho}_{s7} \approx 4 \qquad \bar{\rho}_{h1} / \bar{\rho}_{h7} \approx 16$$

n=1: $N_{bin} \approx 3.2$

ratio → 50



Species/species Spectrum Ratios

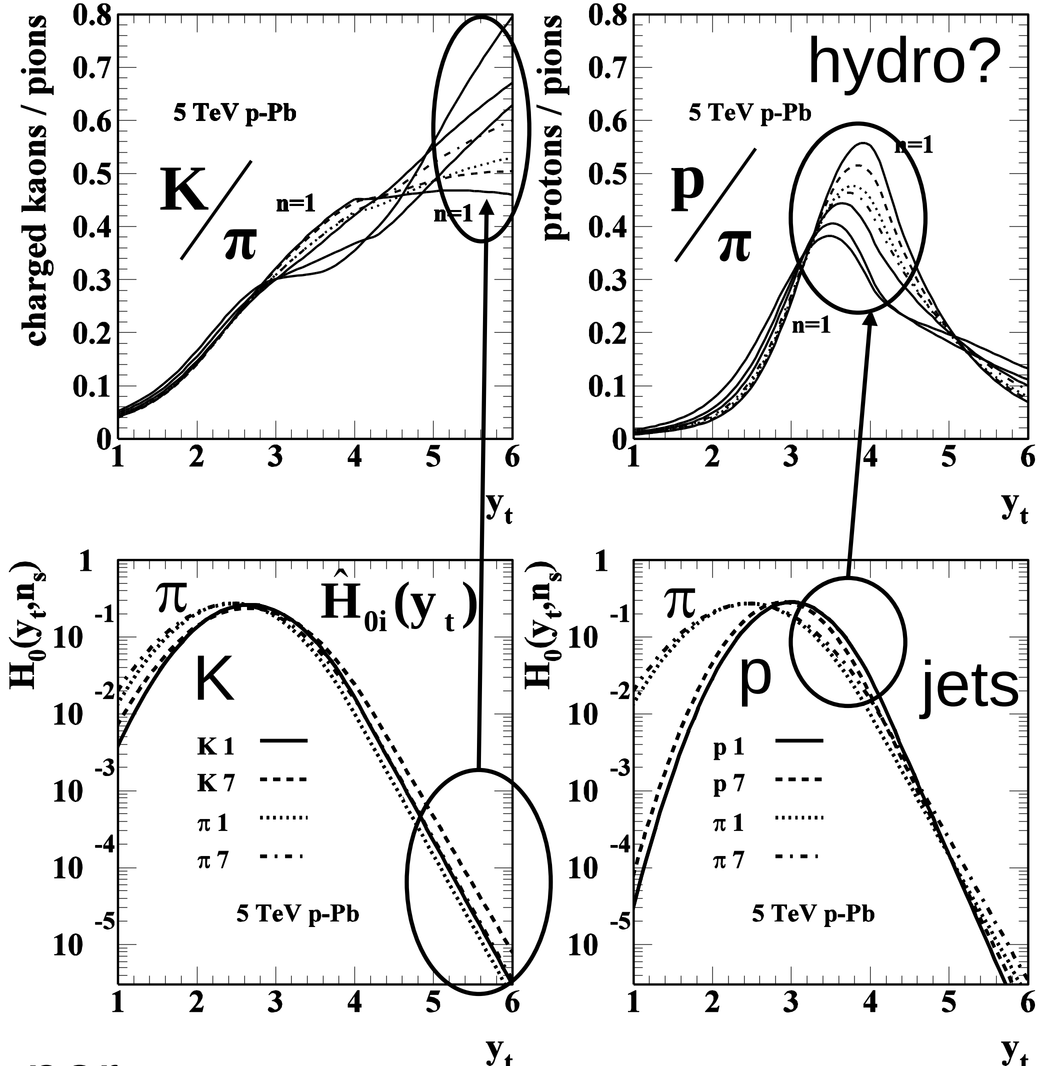
These spectrum ratios reflect differences between hadron species relating to *jets*

different species, same centrality

ρ_s, ρ_h cancel

i / j

$$
\begin{aligned}
R_{ij} &= \frac{z_{si}(n_s)\bar{\rho}_s \hat{S}_{0i}(p_t) + z_{hi}(n_s)\bar{\rho}_h \hat{H}_{0ip\mathrm{Pb}}(p_t, n_s)}{z_{sj}(n_s)\bar{\rho}_s \hat{S}_{0j}(p_t) + z_{hj}(n_s)\bar{\rho}_h \hat{H}_{0jp\mathrm{Pb}}(p_t, n_s)} \\
&\to \frac{z_{si}(n_s)\hat{S}_{0i}(p_t)}{z_{sj}(n_s)\hat{S}_{0j}(p_t)} \quad \text{for low } p_t \\
&\to \frac{z_{hi}(n_s)\hat{H}_{0ip\mathrm{Pb}}(p_t, n_s)}{z_{hj}(n_s)\hat{H}_{0jp\mathrm{Pb}}(p_t, n_s)} \quad \text{for high } p_t.
\end{aligned}
$$



evolution of hard components per TCM describe PID ratios accurately

expected from PID FFs

hep-ph/0606249

Chicago-Princeton (C-P) PID Spectra

Cronin effect?

J. Cronin *et al*.

PRD 11, 3105 (1975)
PRD 19, 764 (1979)

Fixed-target experiments with proton beams at 200, 300 and 400 GeV

Targets: H_2, Be, Ti and W

Published C-P spectra include cross section σ_{pA} in units of cm^2

differential *cross section* for hadron species *i*

$$E\frac{d\sigma_{pA}}{d^3p} = \sigma_{pA}\frac{1}{N_{evt}}\frac{n_i\ \text{yield}}{p^2\Delta\Omega\Delta p / p} \rightarrow \sigma_{pA}\frac{d^2n_i}{2\pi m_t dm_t dy_z}$$

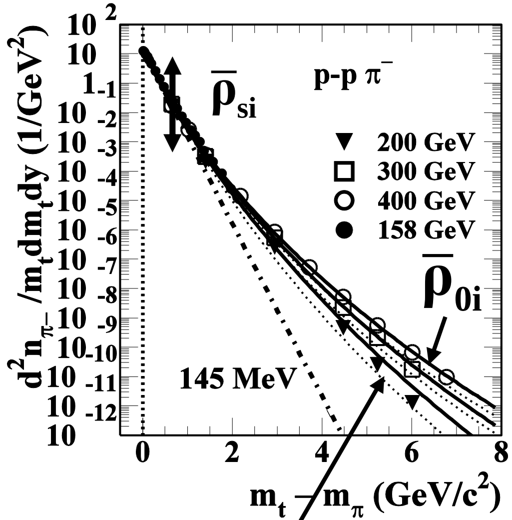
In what follows the C-P data have been multiplied by $2\pi 10^{27} / \sigma_{pA}(\text{mb})$

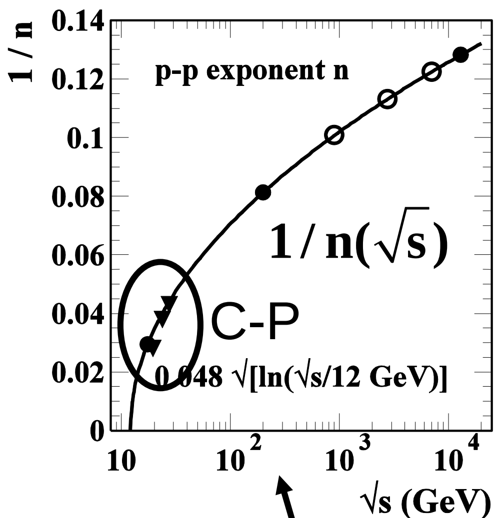
Gives particle densities in the form $\bar{\rho}_{0i}(m_t) \equiv \dfrac{d^2n_i}{m_t dm_t dy_z}$

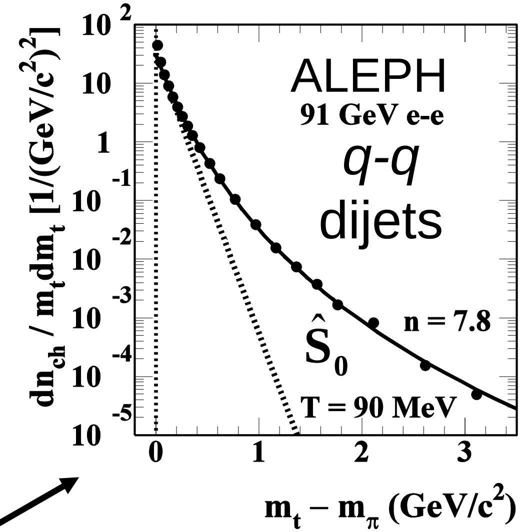
TCM requires √s and A dependence

Soft-component √s from *p-p*

p-p pion spectra







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perpendicular to thrust axis

$$\hat{S}_0(m_t;T,n) = \frac{C}{[1+(m_t - m_i)/nT]^n}$$

soft-component energy dependence dominates *p-p* spectra

energy dependence lies in Lévy exponent *n* that represents in this case p_t variance increase via *Gribov diffusion* 1912.07612

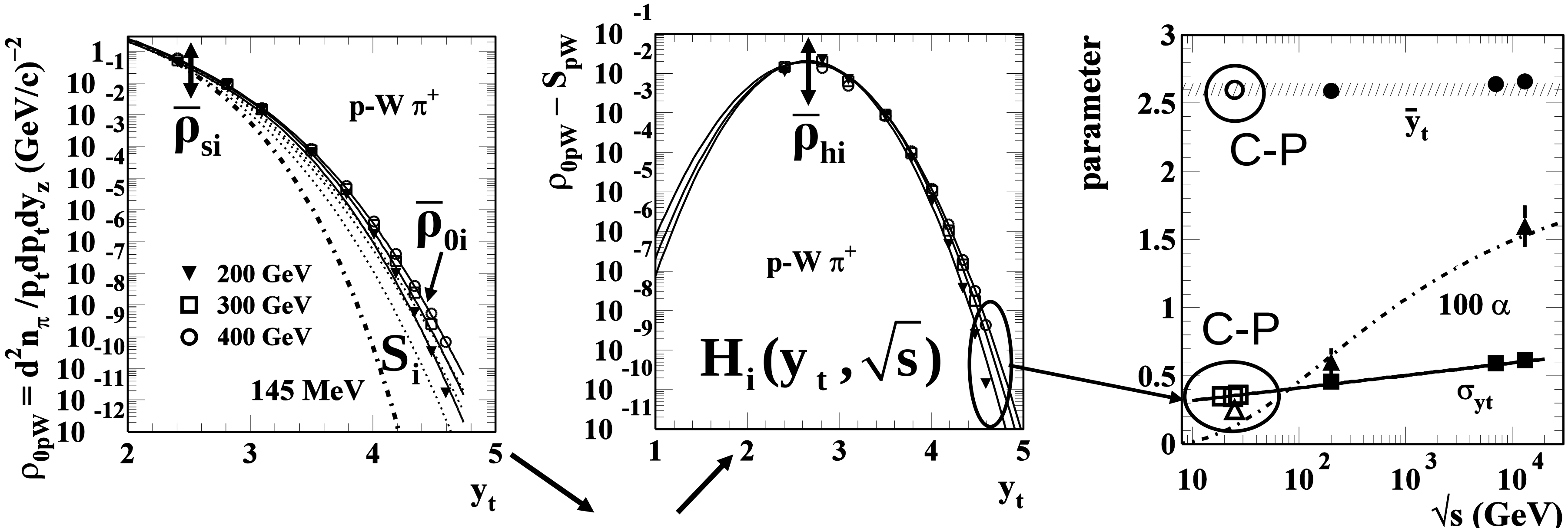
$$1/n \approx 0.05\sqrt{\ln(\sqrt{s}/12\,\mathrm{GeV})}$$

same process in *q-q* dijets

C-P *n* values follow *prediction*

Hard Component $\sqrt{s}$ from *p*-W

p-W pion spectra



$$H_i(y_t) = \bar{\rho}_{0i}(y_t) - S_i(y_t)$$

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for given A

C-P H_0 width *varies as predicted*

C-P TCM: $$\bar{\rho}_{0i}(m_t;\sqrt{s}) = \bar{\rho}_{si}\,\hat{S}_{0i}(m_t,\sqrt{s}) + \bar{\rho}_{hi}\,\hat{H}_{0i}(m_t,\sqrt{s})$$

same as *p-p*

n varies

width σ_{yt} varies

$\bar{\rho}_{si}$ $\bar{\rho}_{hi}$ densities don’t vary over C-P energy interval

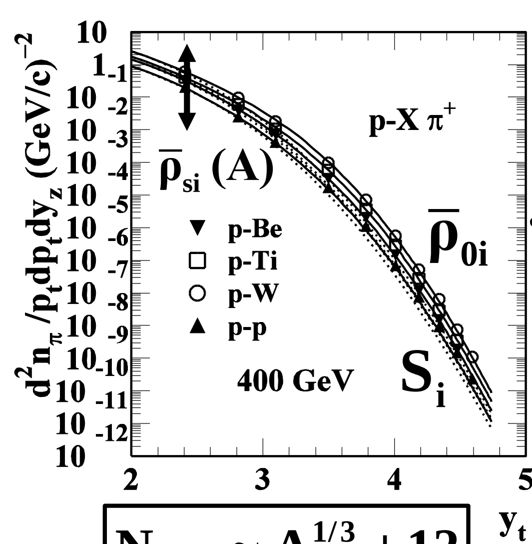
C-P PID Spectra – A Dependence

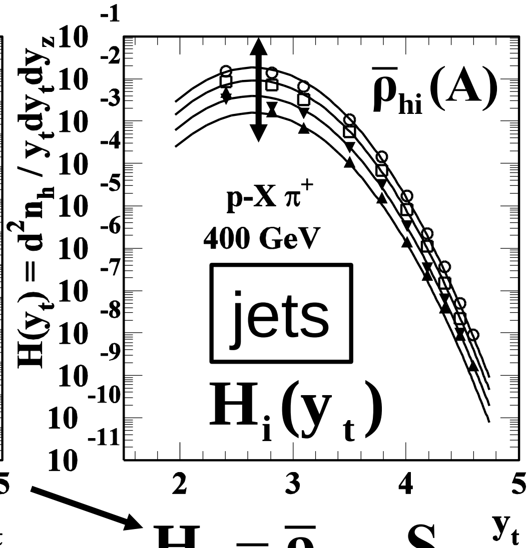
p-A spectra – 400 GeV

A = H, Be, Ti, W

A-dependent charge densities:

pions



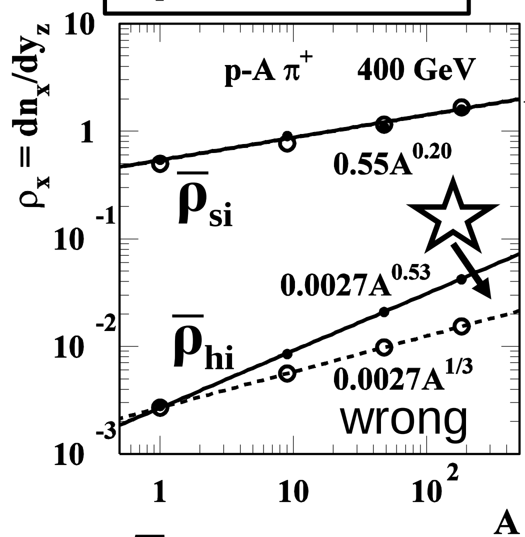


$$\bar{\rho}_{si} \propto A^{0.20} \quad \bar{\rho}_{hi} \propto A^{0.50}$$

$N_{part} \approx A^{1/3} + 1?$

$H_i = \bar{\rho}_{0i} - S_i$

component *shapes* are (almost) A independent



nuclear transparency

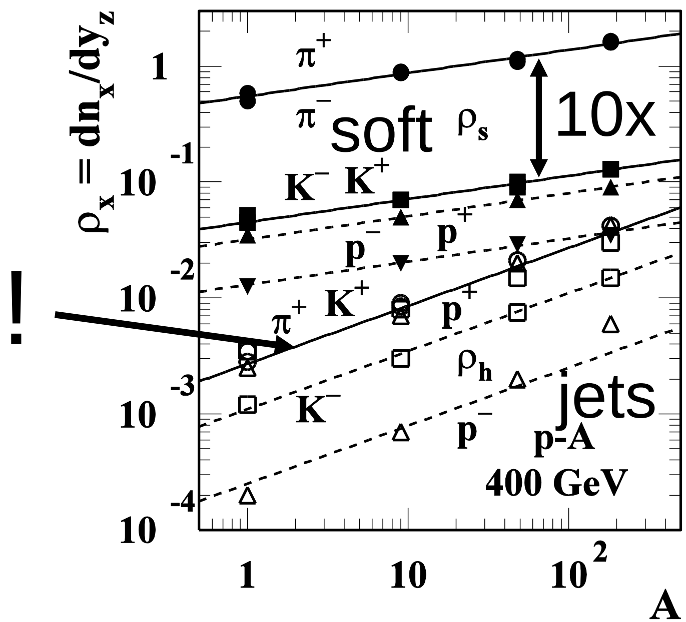
the real Cronin effect

C-P data described by TCM within uncertainties

Full C-P TCM factorization:

$$\bar{\rho}_{0i}(m_t; \sqrt{s}, A) = \underbrace{\bar{\rho}_{si}(A)\hat{S}_{0i}(m_t, \sqrt{s})}_{p\text{-}p} + \underbrace{\bar{\rho}_{hi}(A)\,\hat{H}_{0i}(m_t, \sqrt{s})}_{p\text{-W}}$$

C-P Spectra vs Hadron Species



$\propto \mathbf{A}^{0.20}$

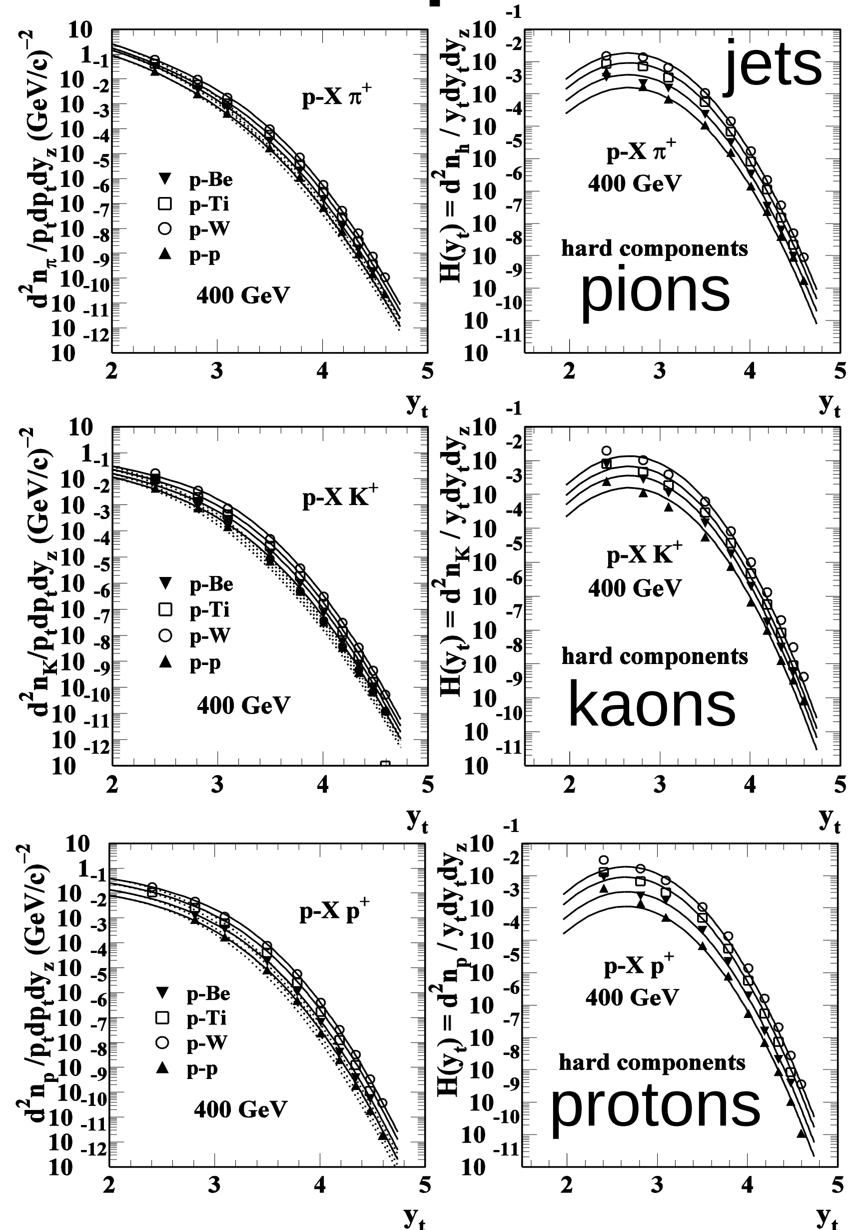
27 GeV

$\propto \mathbf{A}^{0.50}$

pion fragments from projectile dissociation (soft) are 10x more abundant than kaons or protons

positive pion, kaon and proton jet fragments (hard) are *equal*

negative hadrons are complicated



NMF Ratios vs Cronin Effect

C-P spectra compared as *rescaled* spectrum *ratios*

hep-ph/0212148

$$R_{AB} = \frac{B}{A}\frac{E d\sigma_{pA} / d^3p}{E d\sigma_{pB} / d^3p}$$

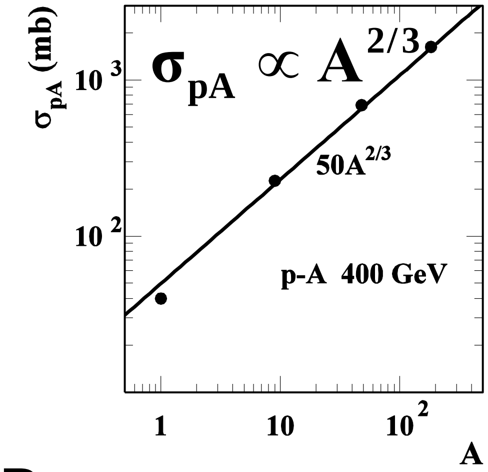
differential *cross sections* rescaled by atomic weights A, B

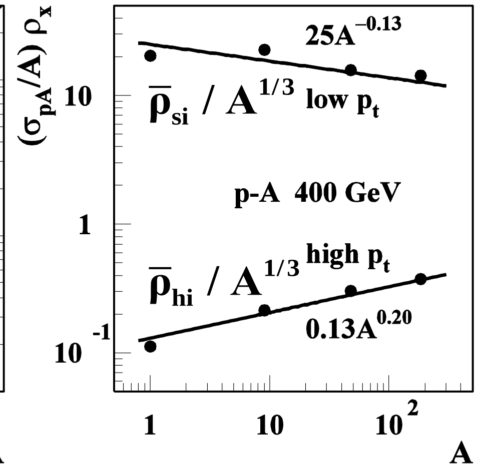
$$\frac{1}{A}\left[\sigma_{pA}\bar{\rho}_0(m_t)\right] \rightarrow A^{-1/3}\bar{\rho}_0(m_t)$$

$$A^{1/3} \sim N_{bin}$$

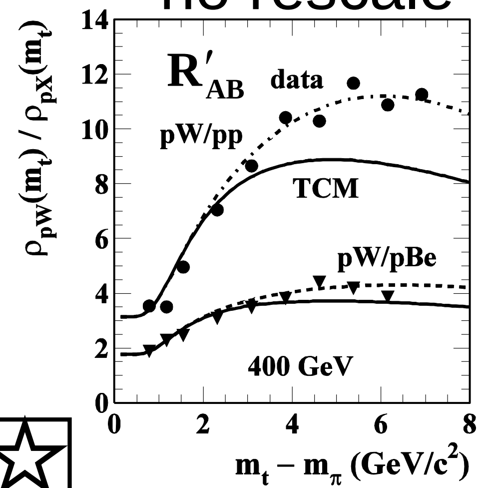
$$\bar{\rho}_{si} / A^{1/3} \propto A^{-0.13}$$ low p_t

$$\boxed{\bar{\rho}_{hi} / A^{1/3} \propto A^{0.20}}$$ high p_t ☆

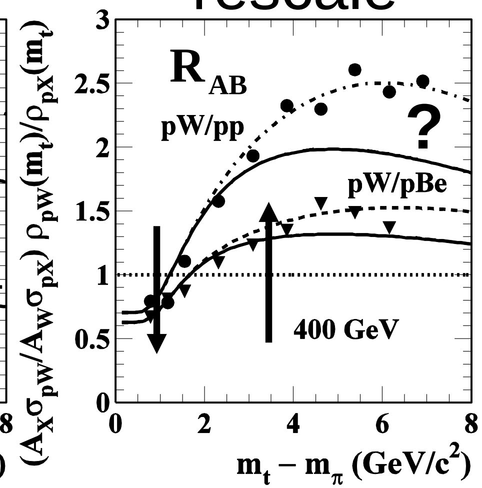




no rescale



rescale

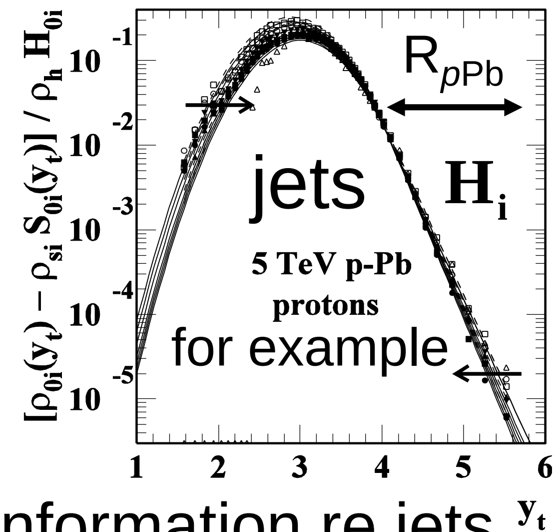


NMF ratios ***uninterpretable***

R_{AB} discards most spectrum information and causes great confusion for fifty years

NMF, C-P Relation to LHC Jets

TCM:



<u>all</u> information re jets

2% ratios relevance

$$\bar{\rho}_h \approx \alpha\, \bar{\rho}_s^2$$

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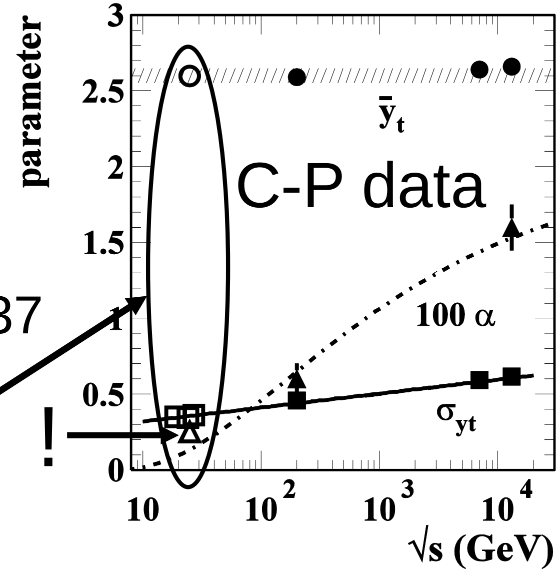
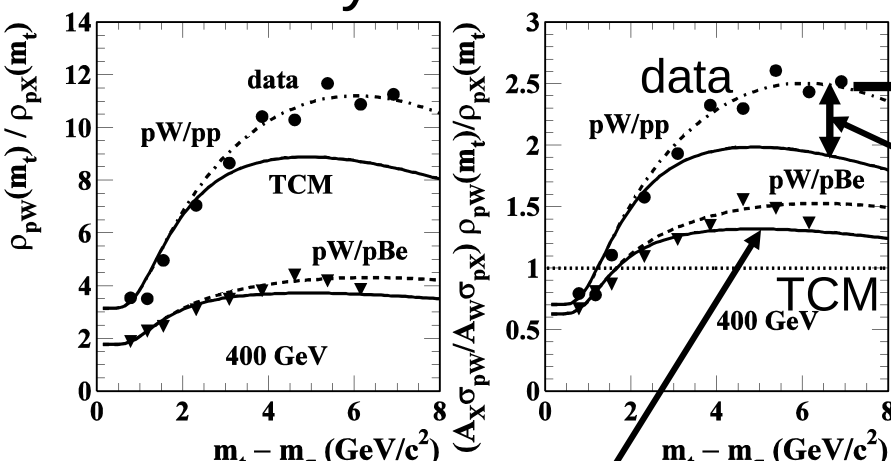


these numbers predict solid curve below

NSD *p-p*

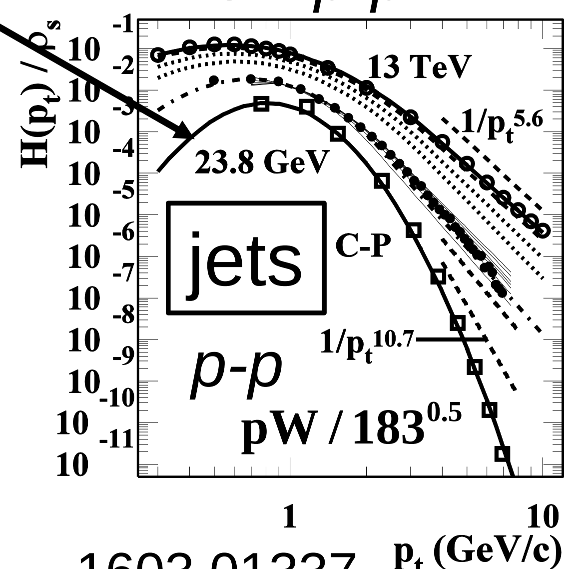
Ratios: very little information re jets



not 1

2% width change

H_0 width independent of A



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Summary

- Nuclear Modification factors (NMFs) $\leftrightarrow$ spectrum ratios
- NMFs supposed to reveal jet modification within QGP

- TCM accurately describes PID hadron spectra
- TCM precisely isolates *100%* of jet contribution

- NMF ratios abandon information carried by spectra
- NMFs are not physically interpretable

- TCM reveals jet contributions to low-energy C-P spectra
- “Cronin effect” is a jet manifestation near threshold

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Spectrum ratios serve as a projection screen

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