High-p_T particle production, correlations, and observables sensitive to energy loss in small (and large) collision systems

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UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

Centre of Excellence in Quark Matter

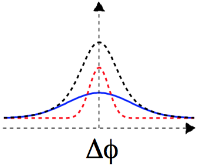
Jet Fragmentation - two stage process

Soft QCD Rad. Showering

$Q^2 >> \lambda_{QCD}$

$z << 1$

Angular Ordering

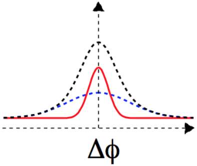


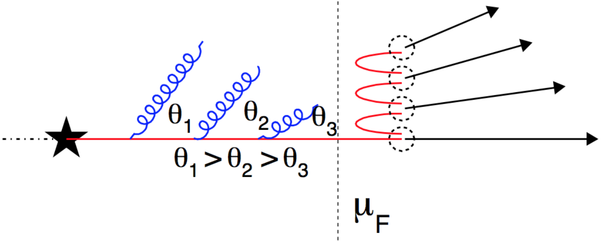
Hadronization

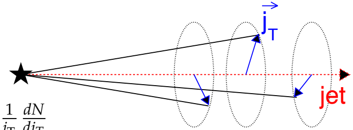
$Q^2 \approx \lambda_{QCD}$

$z >> 0$

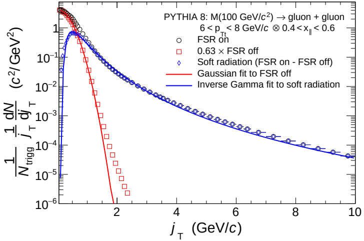
Lund String frag.







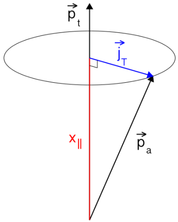
$\frac{1}{j_T}\frac{dN}{dj_T}$

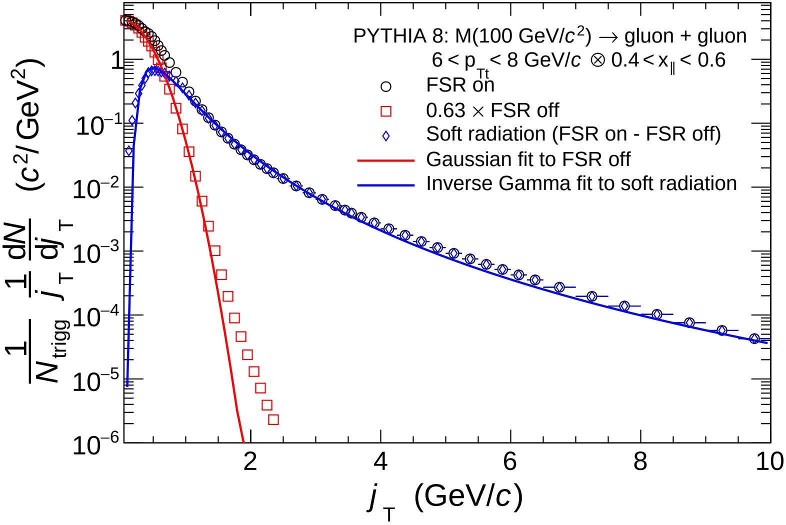


ALICE, JHEP 1903 (2019) 169, arXiv:1811.09742

- QCD showering can be separated from hadronization (Two component j_T via two particle correlation)

Decomposition, Shower and Hadronization





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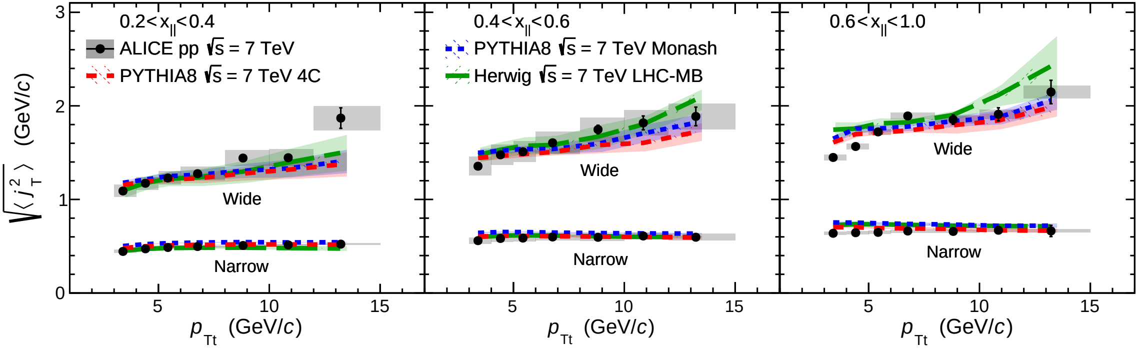
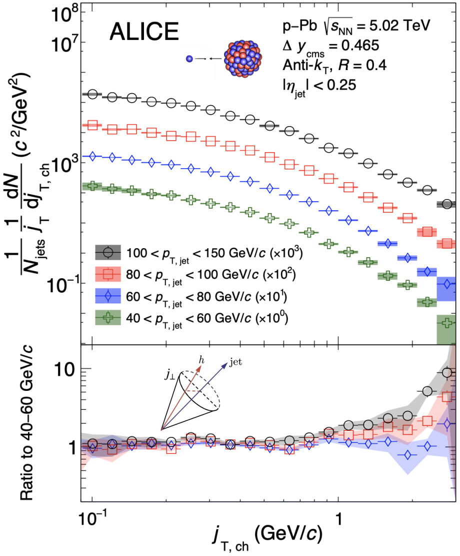
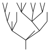
Decomposition, Shower and Hadronization

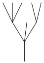
Di-hadron analysis, two distinct components, ALICE(JHEP 1903 (2019) 169)



Results- j_T distributions



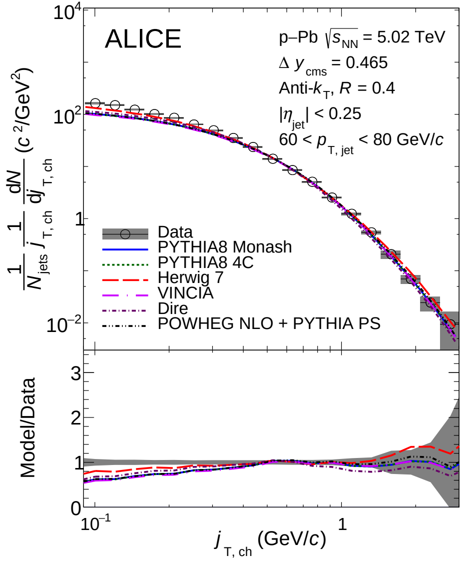




- j_T for four jet p_T bins > 40 GeV/c
- low j_T - no jet p_T dependence
- higher j_T > 1 GeV/c increase with increasing jet p_T

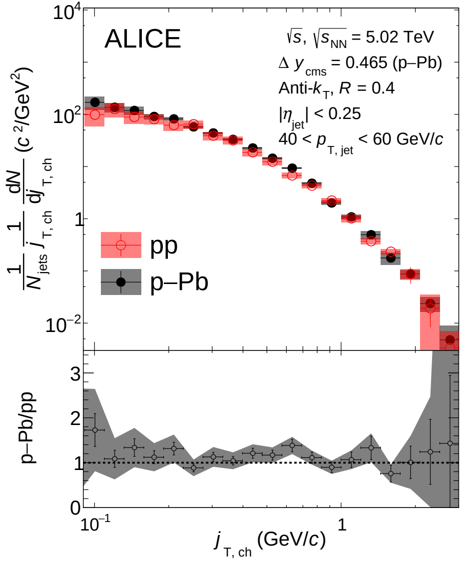
ALICE, JHEP09 (2021) 211

Results- j_T distributions, Model comparison



- Sensitivity in low and high j_T regions

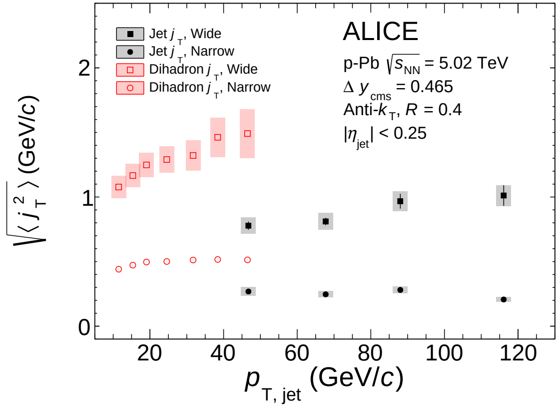
Results- j_T distributions, pp vs pPb



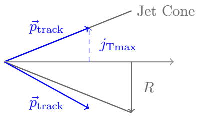
- No modification of the j_T distribution in pPb w.r.t pp

ALICE, JHEP09 (2021) 211

Comparison to dihadron j_T

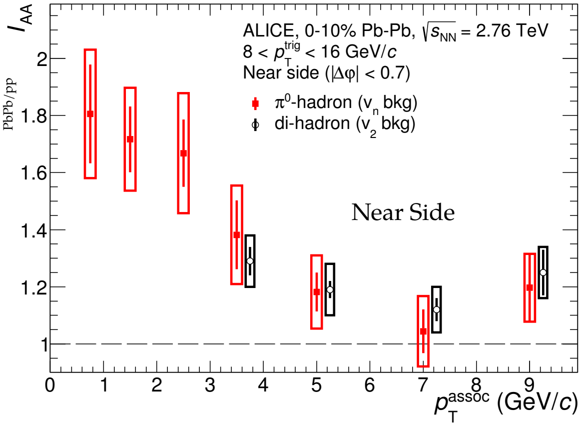


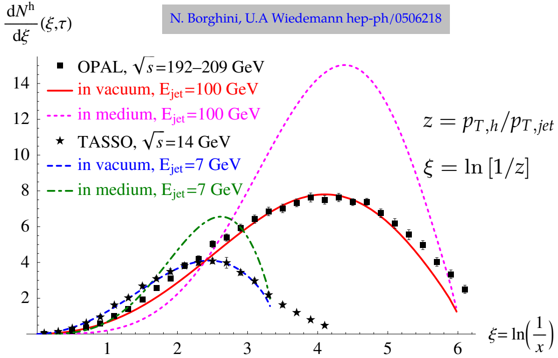
ALICE, JHEP09 (2021) 211



- A direct comparison between jet and dihadron j_T measurements is not possible.
  - Different R parameters: $j_{T,max} \approx p \cdot R$
  - Leading tracks versus jet as reference
  - Harder jets in dihadron analysis
  - quark and gluon jet fractions
  - the details are in the paper

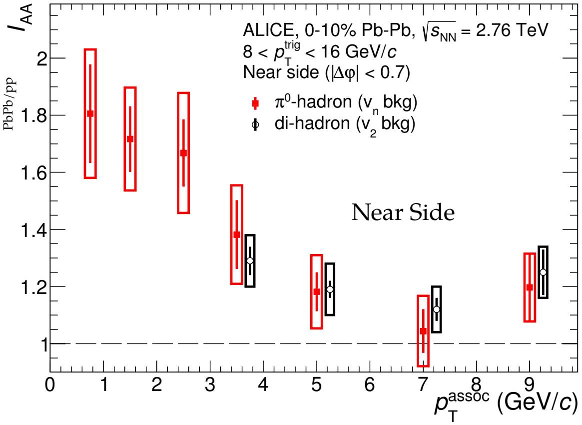
Medium induced gluon radiation

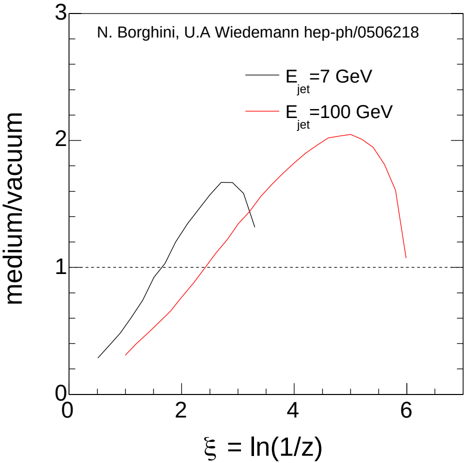




- At low p_T, both for Near side $\approx \times$ 2-5 $\rightarrow$ Enhancement
- At high p_T, moderate Enhancement for Near side and large Suppression for Away side.

Medium induced gluon radiation

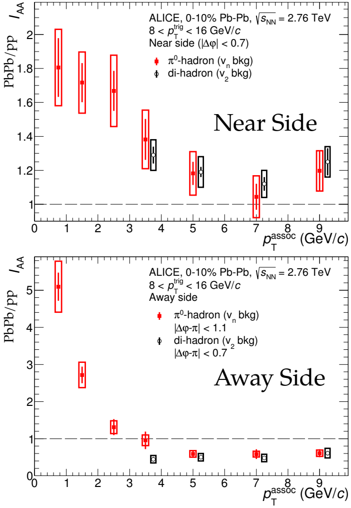




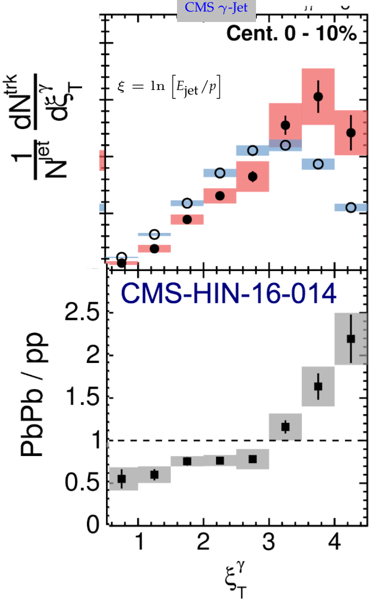
- At low p_T, both for Near and Away side $\approx \times$ 2-5 $\rightarrow$ Enhancement
- At high p_T, moderate Enhancement for Near side and large Suppression for Away side.

Medium induced gluon radiation is Observed and Quark/Gluon suppression

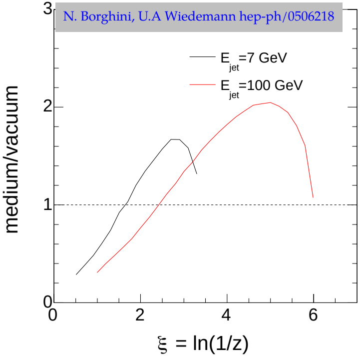
ALICE, PLB 763 (2016) 238-250



CMS γ-Jet

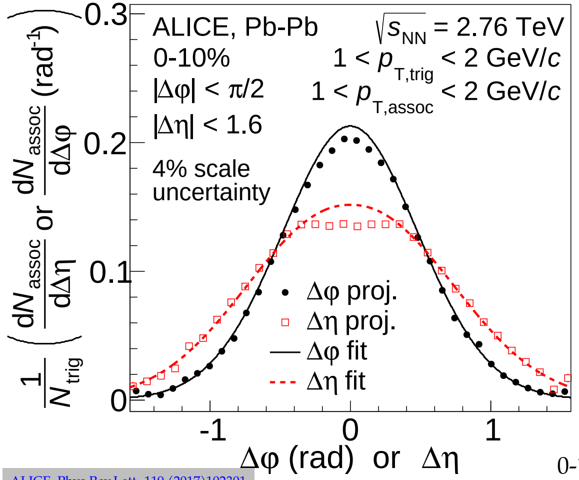


N. Borghini, U.A Wiedemann hep-ph/0506218

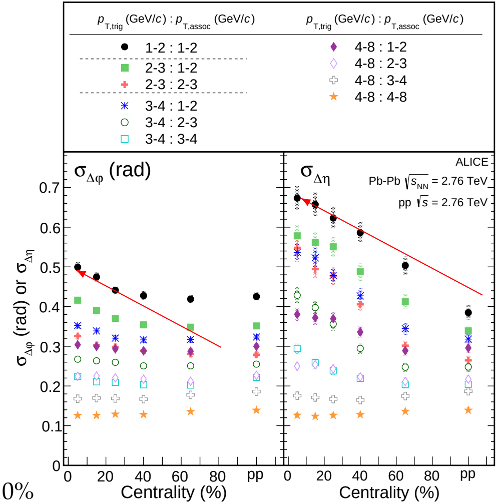


- Intermidiate p_T or z regions, effective guark/gluon contribution $\approx \times 1/2 \rightarrow$ Suppression

Broadening of jets



0-10%



p_T

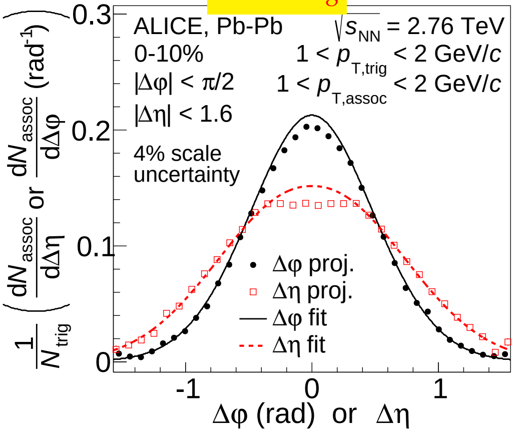
pp

ALICE, Phys.Rev.Lett. 119 (2017)102301

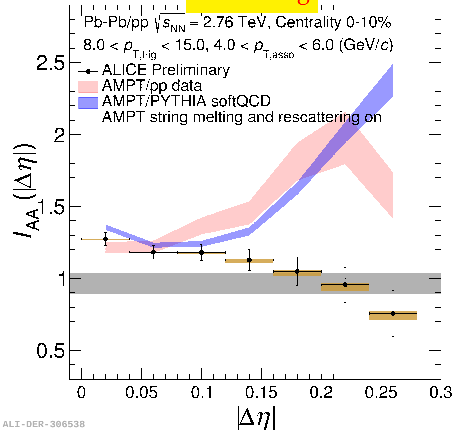
- Broadening in various kinematic regions.

Broadening → Narrowing in different kinematic regions

Broadening



Narrowing



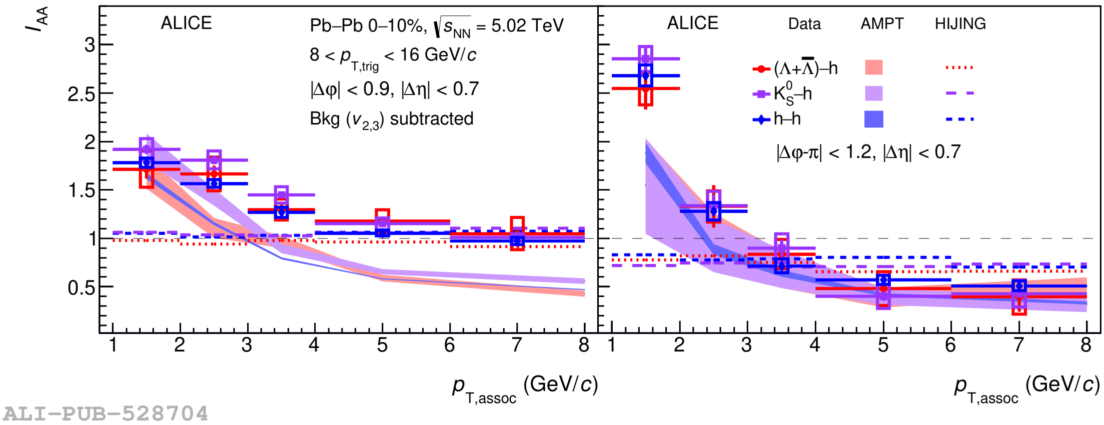
ALICE, Phys.Rev.Lett. 119 (2017)102301

- low p_T, jet medium interaction, effect of radial flow?
- Intermediate p_T, effective guark/gluon contributions?
- Multi-scale problem during jet shower in the medium [1].

[1] http://jetscape.wayne.edu

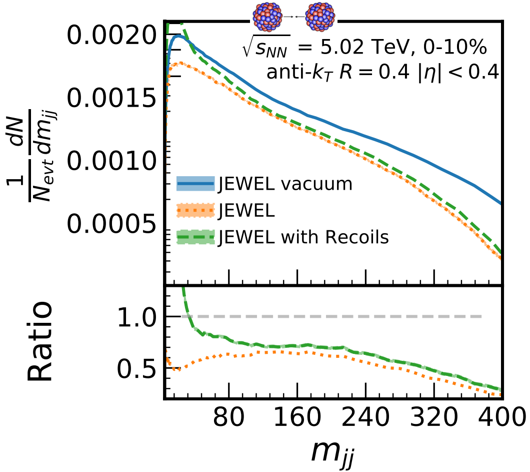
No PID dependence, is it expected?

ALICE, arXiv:2211.01197



- The relative hadron production rates in quark and gluon jets differ for K^0_s and Λ (OPAL, Eur.Phys.J.C8:241-254,1999)
- Different fragmenations, U. Wiederman, looking for the paper

m_{jj}, Jet virtuality evolution



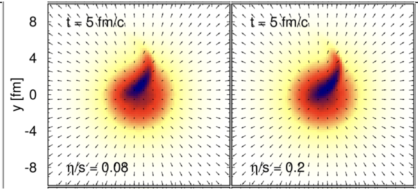
- Proving L dependence via di-jets[1]

$$M_{\mathrm{jj}}^2 = (p_1 + p_2)^2$$
$$\approx 2p_{\mathrm{T},1}p_{\mathrm{T},2}\left(\cosh(\Delta\eta) - \cos(\Delta\phi)\right),$$

- No modification in pPb MB within the uncertainties (ALICE Preliminary)
- Check HM events in lower M_{jj}^2?
- PbPb measurements?
  - significant modifications
  - clear M_{jj}^2 dependence can be checked?
  - low M_{jj}^2, clear recoil effect

[1] PRC 75 (2007) 054910, JEWEL(JHEP 1707 (2017) 141)

+α Mach Cone searches

char	large	small (tiniest substance in nature)
fig		
v_{medium}	≈ 0	$\approx 0.65 \times c$
v_{jet}	$\approx$ 5km/hour	$\approx$ 20-200 GeV/c
viscosity/entropy	>>1	$\approx 1/4\pi$ ($\approx$0.08), perfect fluid
substance	H_2O	gluons and quarks
scale	$\approx$ cm	$\approx$ 1fm (0.0000000000010 cm)

- There has been no evidence of the mach signal so far.
- The modification of the away side jets turned out to be odd harmonic flow signal, ALICE Phys. Rev. Lett. 107, 032301 (2011).

$+\alpha$ Mach Cone searches

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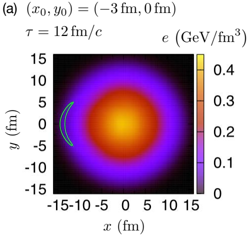
fig		
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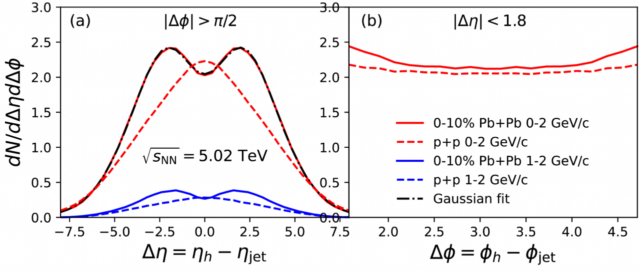
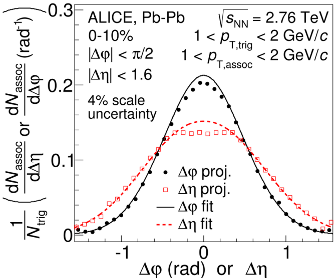
substance	H_2O	gluons and quarks
scale	$\approx$ cm	$\approx$ 1fm (0.0000000000010 cm)

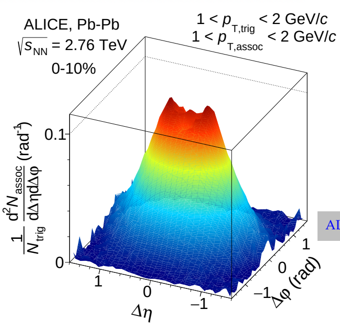
- Radial flow influnces the shape of the signal as well as hard scattering points(random in the collison zone) (T. Hirano et. al, Phys. Rev. C 90, 024904, Phys. Rev. C 93, 054907 (2016)) $\rightarrow$ need new way?

Double peak structure in η is from Diffusion Wake



X.N. Wang et al. Phys.Lett.B 777 (2018) 86-90



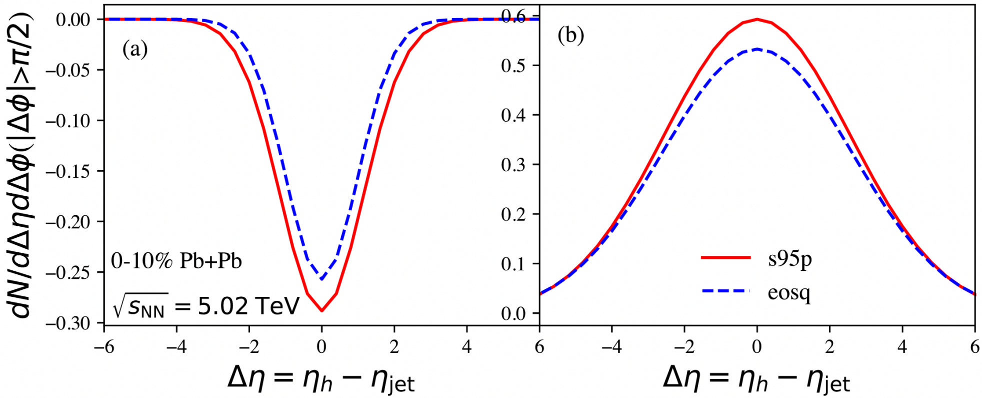


ALICE, Phys.Rev.Lett. 119 (2017)102301

- doulbe hump peaks around $\Delta\eta \approx 2$ from jets in a model
- low p_T 2PC shows similar shape in much smaller region (also seen in AMPT String melting model)
- not so clear in $\Delta\phi$ for both results
- the origin is the same?

Diffusion wake is sensitive to EoS?

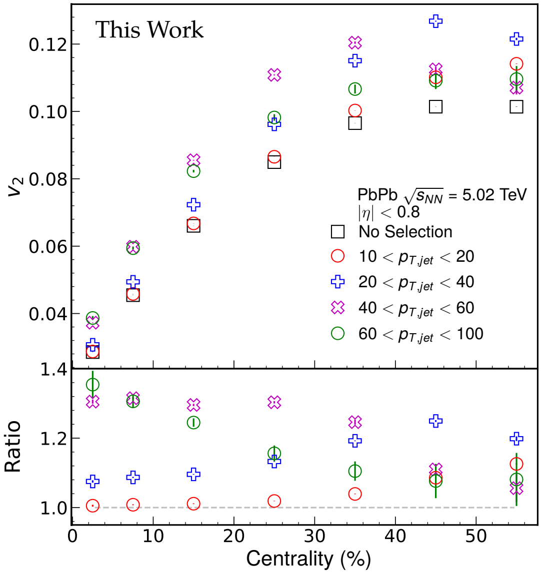
X.N. Wang et al. Phys.Lett.B 777 (2018) 86-90



$< c_s >_{eosq} \quad > \quad < c_s >_{s95p}$

- Hardening of spectra → reduction of soft hadron yield and DFW valley
- Larger Mach cone angle → shallower DFW valley

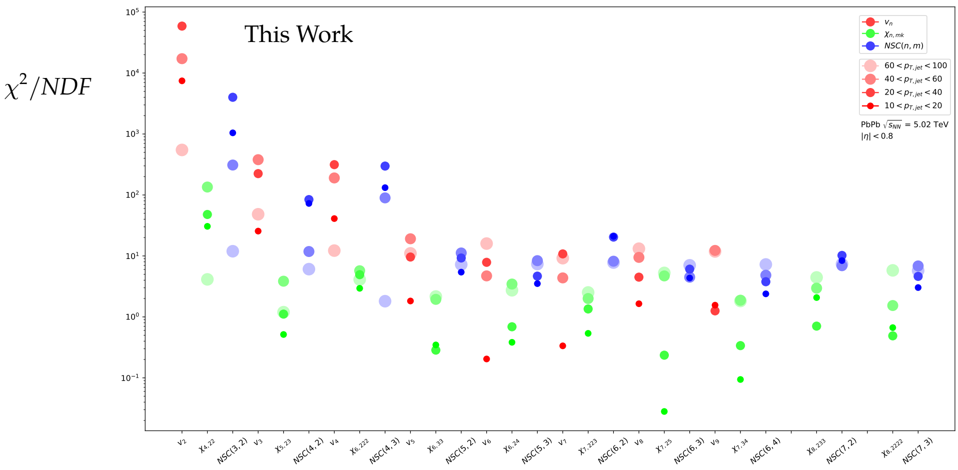
+α The modification of v_2 in the presence of jets → evidence of Mach signal?



- Clear deviation on v_2, up to 40% difference w.r.t No Selection
- The deviation is quantified for various flow observables.
- Maxim's Master thesis (`https://helda.helsinki.fi/handle/10138/343236`)

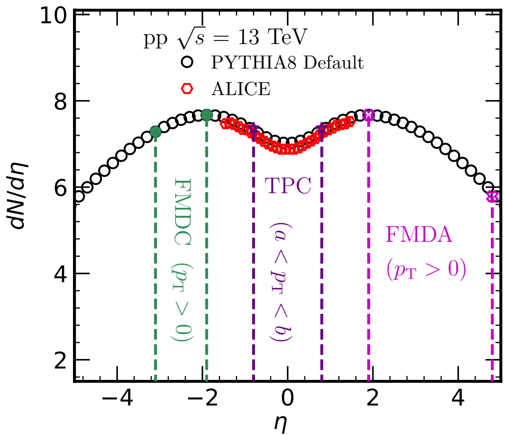
Flow observables in the presence of jets → evidence of Mach signal?

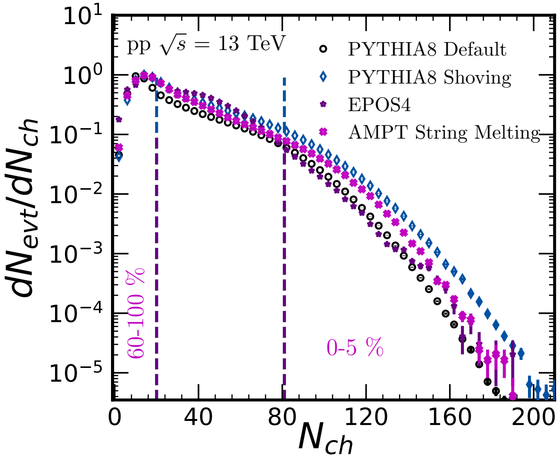
χ^2 to "No Selection"



- largest on v_2, higher orders are not very sensitive because of jet shower size.

Soft and Hard components in small systems

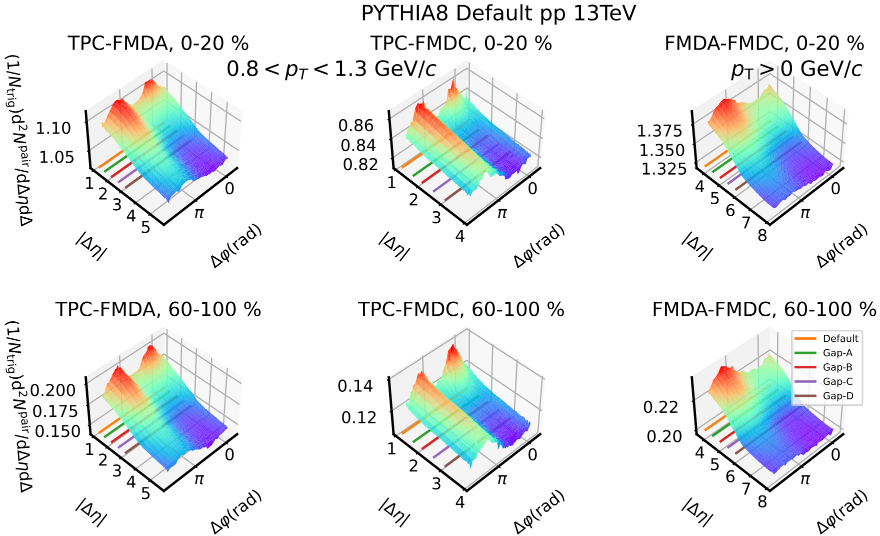




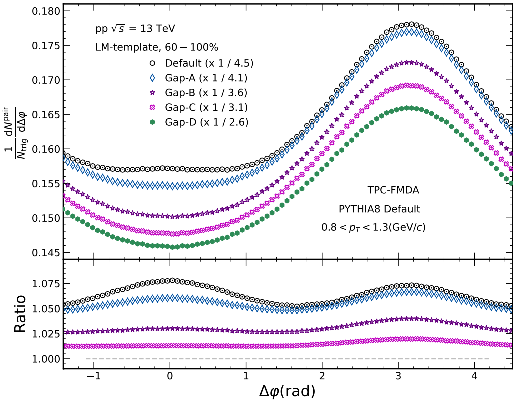
- large η-gap to remove the non-flow with different combinations of mid-forward dectectors
- mini-jets in larger η often not taken care of

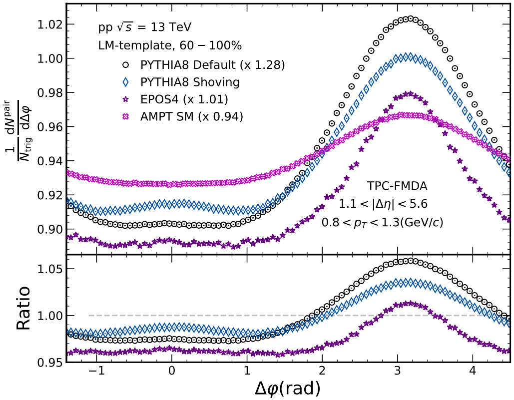
	char	comments
PYTHIA8 Default	jets only and no flow	
PYTHIA8 Shoving	jets and flow	
AMPT	jets and flow	String melting
EPOS	jets and flow	EPOS4

Soft and Hard components in small systems



Soft and Hard components in small systems

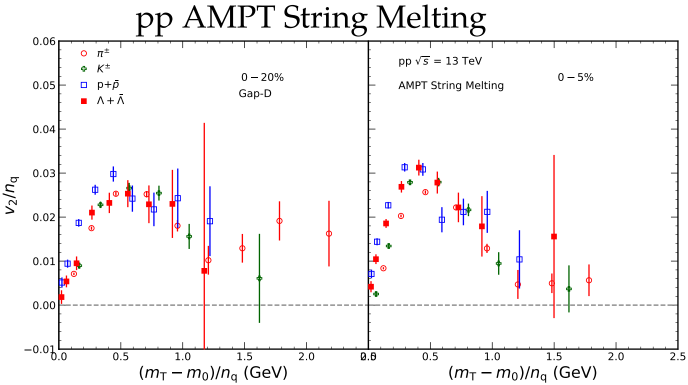


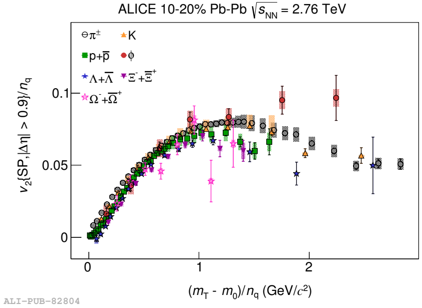


- Only way to extract flow in small systems - 2PC
- But assumption borken in models: no flow in LM-Templates
- Multiplicity definitions are different
- Su-Jeong's talk, WWND2023

$$v_n(p_{\mathrm{T,TPC}}) = \sqrt{\frac{v_{n,n}^{\mathrm{TPC-FMDA}} \cdot v_{n,n}^{\mathrm{TPC-FMDC}}}{v_{n,n}^{\mathrm{FMDA-FMDC}}}}$$

Soft and Hard components in small systems



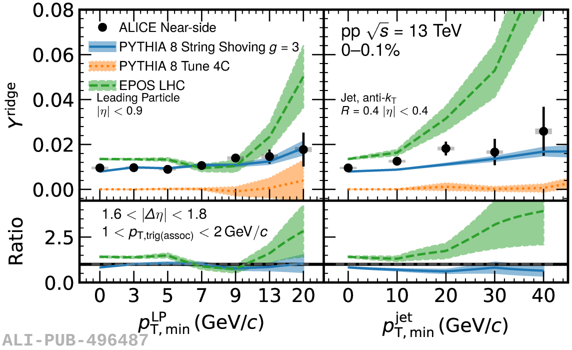


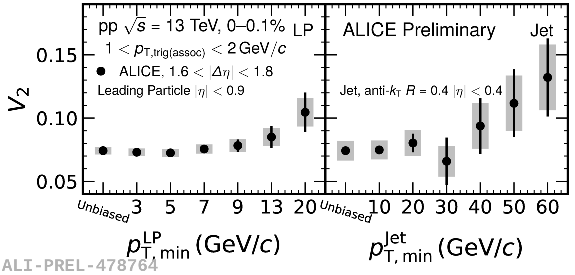
ALICE, JHEP 06 (2015) 190

- Mass ordering in larger systems → collective flow
- ordering is in pp AMPT but different from PbPb data

Ridge and flow in the present of jets

ALICE, JHEP 06 (2015) 190



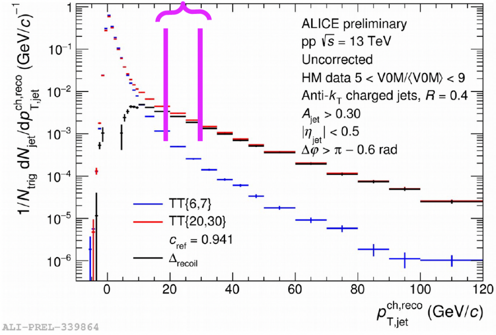


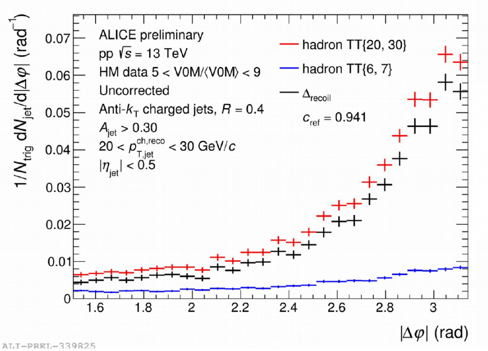
- Weak or no sensitivity to event-scale selection with the uncertainties
- However, some cautions on the model interpretation

Search for jet quenching in small systems, using hadron-jet acoplanarity

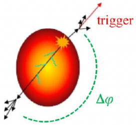
- pp minimum bias (MB)
- pp high-multiplicity (HM) : 5x larger multiplicity in V0 detector w.r.t. MB

$$\Delta_{\mathrm{recoil}}(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{20,30\}\,\&\,p_{\mathrm{T,jet}}^{\mathrm{ch}}} - c_{\mathrm{ref}}\cdot\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{6,7\}\,\&\,p_{\mathrm{T,jet}}^{\mathrm{ch}}}$$

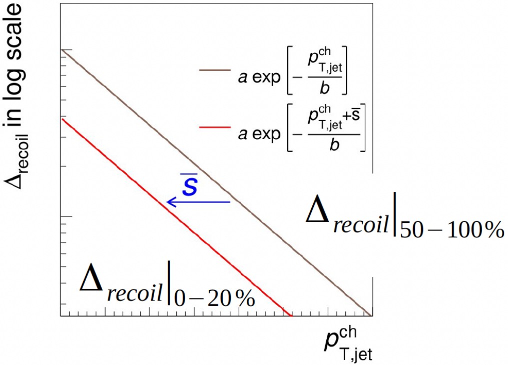


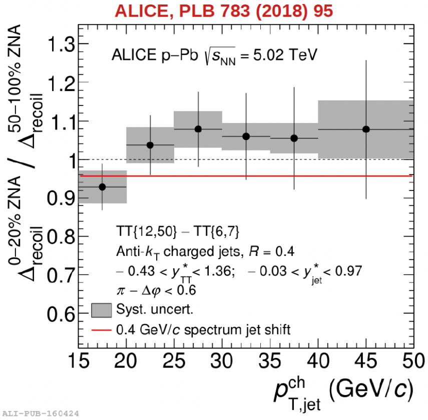


TT{X,Y} means
X< $p_{\mathrm{T,trig}}$ < Y GeV/c



Limit on energy transport out of R = 0.4 in p-Pb

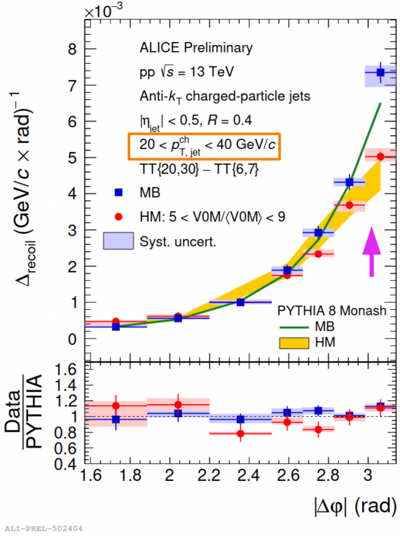


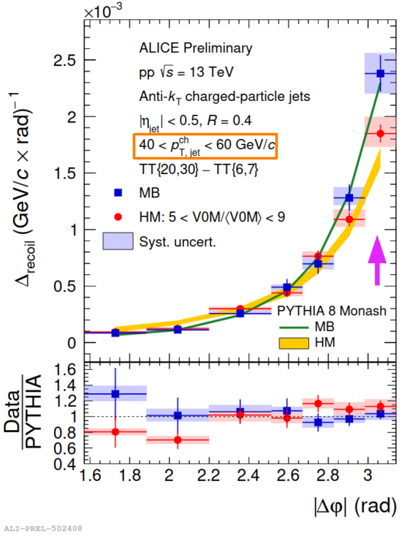


$$\frac{\Delta_{\mathrm{recoil}}|_{0-20\,\%}}{\Delta_{\mathrm{recoil}}|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$

Medium-induced charged energy transport out of R = 0.4 cone is less than 0.4 GeV/c (90% CL)

Bias to understand jet quenching in pp?





- PYTHIA 8 Monash shows similar suppression pattern
- Need to understand this bias for jet quenching effect

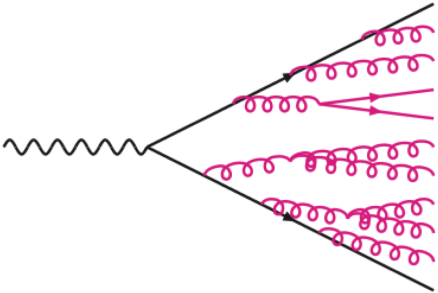
Summary

- Decomposition of parton shower and hadronization, can be measured in PbPb?
- Two particle correlation results can be revisited with state-of-art jet quenching models?
- Hints of shock wave in PbPb - rethink the double-peaks in $\Delta\eta$, similarly in a recent model calculations
- A new way of proving the shock wave is proposed.
- Jet quenching in small systems - few ways to dig into the data
- However, interplay between jets or jet quenching and flow measurements is not clear in data as well as in models

Thank You!

Parton shower in models

Program	name	characteristics
PYTHIA8	Simple Showers	PYTHIA6, default in PYTHIA8
PYTHIA8	VINCIA Showers	pT-ordered 2→3 branchings
PYTHIA8	Dire Showers	pT-ordered dipole shower
HERWIG	angular-ordered parton showers	
MLLA [2]	leading-logarithmic approximation (LLA) of QCD	
TMDFF [3]	universality aspects of QCD factorization	contain nonperturbative QCD information



$$dP_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz, \tag{1}$$

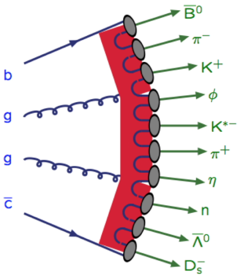
- $Q^2 = E_a^2\theta_{a\to bc}^2 \approx m^2/(z(1-z))$; angular-ordered shower(HERWIG)
- $Q^2 = {p_T}^2 \approx m^2(z(1-z)$; transverse-momentum-ordered(PYTHIA) : ensures the ordering in the hardness and also effectively favours large angles [1]

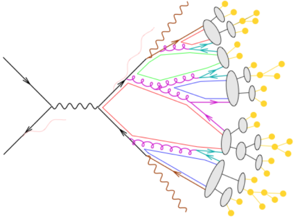
[1] T. Sjöstrand, Eur.Phys.J.C39:129-154,2005

[2] F. Arleo et al. Phys. Rev. Lett. 100, 052002 (2008).

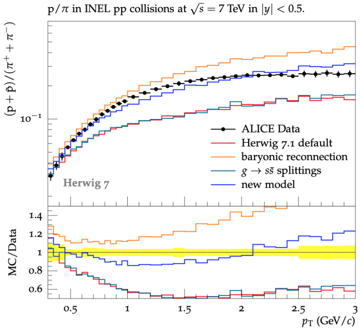
[3] M.G. Echevarria et al. Phys. Rev. D 93, 011502 (2016), F. Ringer et al. JHEP 1711 (2017) 068

Hadronizations





courtesy of T. Sjöstrand

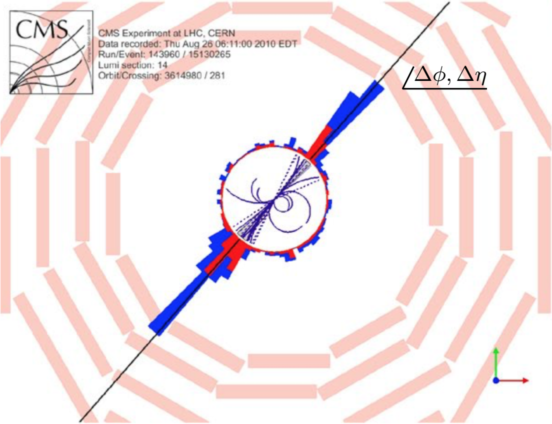


S. Gieseke et al. Eur.Phys.J. C78 (2018) no.2, 99

Program	PYTHIA	HERWIG
Model	string	cluster
energy-momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

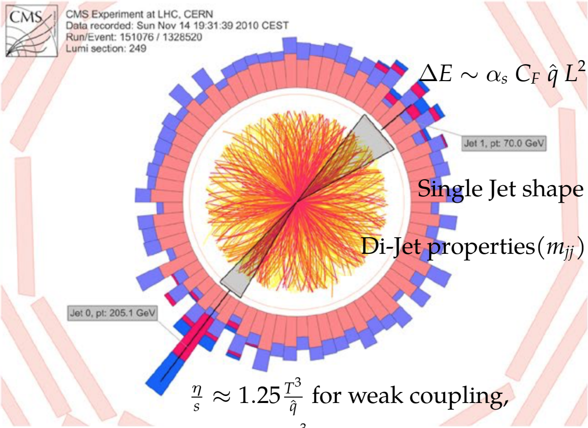
Di-Jet, Jet quenching can be seen visually

Proton + Proton



$\Delta\phi, \Delta\eta$

Pb + Pb



$\Delta E \sim \alpha_s\, C_F\, \hat{q}\, L^2$

Single Jet shape

Di-Jet properties(m_{jj})

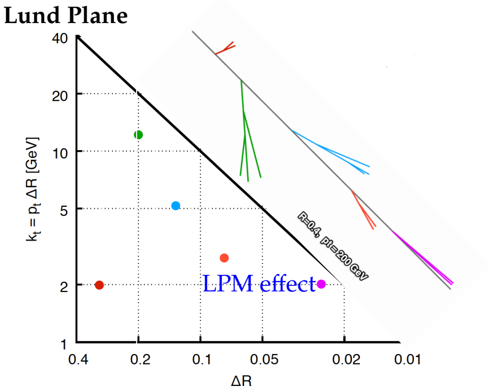
$\frac{\eta}{s} \approx 1.25\frac{T^3}{\hat{q}}$ for weak coupling,

$\frac{\eta}{s} \gg 1.25\frac{T^3}{\hat{q}}$ for strong coupling,

(Phys. Rev. Lett., 99:192301, 2007)

- We can see a clear away side jet suppression for this special PbPb event (Jet Quenching in QGP).
- Deeper understanding of jet quenching is not an option.

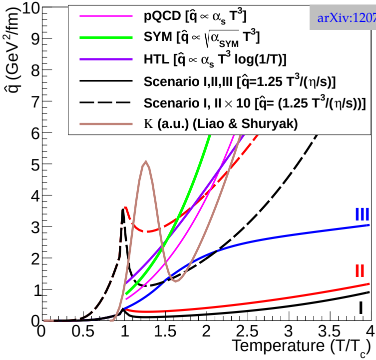
Deeper understanding of jet quenching is not an option



Gavin P. Salam, Dreyer, Soyez, GPS, in progress

$$< p_\perp{}^2 >= \hat{q}L,$$
$$\Delta E \sim \alpha_s\, C_F\, \hat{q}\, L^2.$$

$C_F = 3$(gluon) and $4/3$(quark)

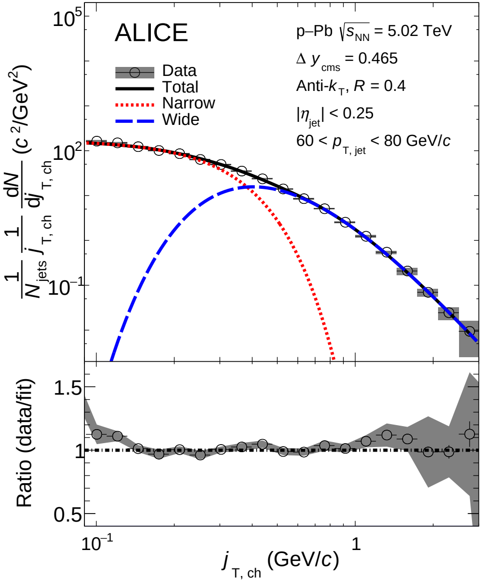


arXiv:1207.6378

- An unambiguous determination of both sides of [the equation] from experimental data ? (Phys. Rev. Lett., 99:192301, 2007)

$$\frac{\eta}{s} \left\{ \begin{matrix} \approx \\ \gg \end{matrix} \right\} 1.25\,\frac{T^3}{\hat{q}} \qquad \left\{ \begin{matrix} \text{for weak coupling,} \\ \text{for strong coupling.} \end{matrix} \right.$$

QUANTIFYING j_{T} DISTRIBUTIONS



Two components : Gaussian and Inverse Gamma functions

$$\frac{B_2}{B_1\sqrt{2\pi}}e^{-\frac{j_{\mathrm{T}}^2}{2B_1^2}} + \frac{B_3 B_5^{B_4}}{\Gamma(B_4)}\frac{e^{-\frac{B_5}{j_{\mathrm{T}}}}}{j_{\mathrm{T}}^{B_4+1}}, \quad (2)$$

The narrow component RMS:

$$\sqrt{\langle j_{\mathrm{T}}^2 \rangle} = \sqrt{2}B_1, \quad (3)$$

The wide component RMS:

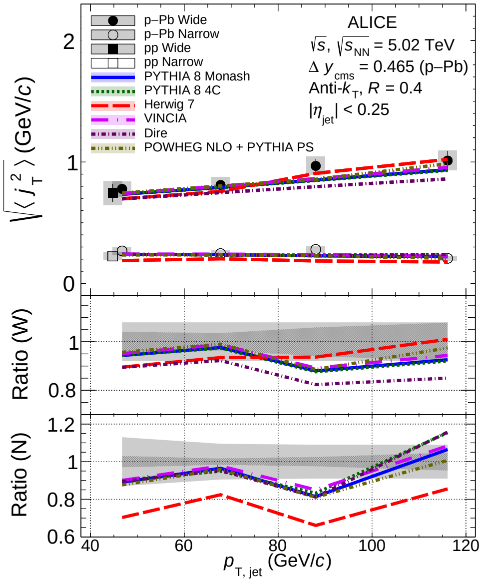
$$\sqrt{\langle j_{\mathrm{T}}^2 \rangle} = \frac{B_5}{\sqrt{(B_4-2)(B_4-3)}}, \quad (4)$$

where it is required that $B_4 > 3$.

- Gaussian alone doesn't fit the j_{T} distribution
- Narrow ← the hadronisation process
- Wide ← the perturbative part of the fragmentation process

ALICE, JHEP09 (2021) 211

Two component fit results



- Narrow component - no jet p_T dependence - Universal hadronization
  - good description by PYTHIA settings
  - Herwig7 underestimates the data
- Wide component RMS increases with increasing jet p_T
  - good description by Herwig7
  - most of PYTHIA shower models can describe the data very well
  - PYTHIA Dire shower underestimates the data and weak jet p_T dependence.

ALICE, JHEP09 (2021) 211