Bose-Einstein Correlations in e^+e^- annihilation and pp interactions

W.J. Metzger

Radboud University Nijmegen

XII Workshop on Particle Correlations and Femtoscopy
Amsterdam
12–16 June 2017

$e^+e^- \longrightarrow$ hadrons

- a clean environment for studying hadronization
- everything is jets – no spectators
- at $\sqrt{s} = M_Z$ almost all events are

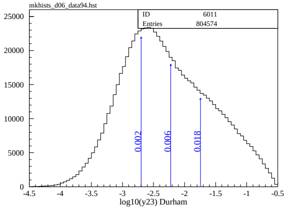
  2-jet $e^+e^- \longrightarrow q\bar{q}$ or 3-jet $e^+e^- \longrightarrow q\bar{q}g$

- event hadronization axis is the $q\bar{q}$ direction
  estimate by the thrust axis, *i*.e., axis $\vec{n}_T$ for which
  $T = \frac{\sum |\vec{p}_i \cdot \vec{n}_T|}{\sum |\vec{p}_i|}$ is maximal
- 3-jet events are planar.
  Estimate event plane by thrust, major axes.
  Major is analogous to thrust, but in plane perpendicular to $\vec{n}_T$.
- Require $\vec{n}_T$ within central tracking chamber
  $\Longrightarrow 4\pi$ acceptance

Jets in e^+e^-

Jets — JADE and Durham algorithms

- force event to have 3 jets:
  - normally stop combining when all ‘distances’ between jets are $> y_{\mathrm{cut}}$
  - instead, stop combining when there are only 3 jets left
  - y_{23} is the smallest ‘distance’ between any 2 of the 3 jets
- y_{23} is value of y_{cut} where number of jets changes from 3 to 2



define regions of y_{23}^{D} (Durham):

		or		
			$y_{23}^{\mathrm{D}} < 0.002$	narrow two-jet
two-jet	$y_{23}^{\mathrm{D}} < 0.006$		$0.002 < y_{23}^{\mathrm{D}} < 0.006$	less narrow two-jet
three-jet	$0.006 < y_{23}^{\mathrm{D}}$		$0.006 < y_{23}^{\mathrm{D}} < 0.018$	narrow three-jet
			$0.018 < y_{23}^{\mathrm{D}}$	wide three-jet

and similarly for y_{23}^{J} (JADE): 0.009, 0.023, 0.056

The τ-model

T.Csörgő, W.Kittel, W.J.Metzger, T.Novák, Phys.Lett.**B663**(2008)214
T.Csörgő, J.Zimányi, Nucl.Phys.**A517**(1990)588

- Assume avg. production point of a particle is highly correlated with its momentum:

$$\overline{x}^{\mu}(p^{\mu}) = a\tau p^{\mu}$$

  where for 2-jet events, $a = 1/m_{\rm t}$

  $\tau = \sqrt{\bar{t}^2 - \bar{r}_z^2}$ is the "longitudinal" proper time

  and $m_{\rm t} = \sqrt{E^2 - p_z^2}$ is the "transverse" mass

  and dist. of prod. points about their mean is very narrow (δ-function)

- Then, with $H(\tau)$ the distribution of proper time

$$R_2(p_1, p_2) = 1 + \lambda\, \mathrm{Re}\widetilde{H}\left(\frac{a_1 Q^2}{2}\right)\widetilde{H}\left(\frac{a_2 Q^2}{2}\right), \qquad \widetilde{H}(\omega) = \int \mathrm{d}\tau H(\tau) \exp(i\omega\tau)$$

- Assume a one-sided Lévy distribution for $H(\tau)$
  3 parameters:
  - α is the index of stability;
  - τ_0 is the proper time of the onset of particle production;
  - $\Delta\tau$ is a measure of the width of the distribution.

BEC in the τ-model

Then, 2-π correlation function, R_2, depends on $Q = \sqrt{-(p_1 - p_2)^2}$, a_1, a_2:

$$R_2(Q, a_1, a_2) = \gamma \left\{ 1 + \lambda \cos \left[\frac{\tau_0 Q^2 (a_1 + a_2)}{2} + \tan\left(\frac{\alpha\pi}{2}\right) \left(\frac{\Delta\tau Q^2}{2}\right)^{\alpha} \frac{a_1^{\alpha} + a_2^{\alpha}}{2} \right] \cdot \exp\left[-\left(\frac{\Delta\tau Q^2}{2}\right)^{\alpha} \frac{a_1^{\alpha} + a_2^{\alpha}}{2} \right] \right\} \cdot (1 + \epsilon Q)$$

Simplification:

- effective radius, R, defined by $R^{2\alpha} = \left(\frac{\Delta\tau}{2}\right)^{\alpha} \frac{a_1^{\alpha} + a_2^{\alpha}}{2}$
- Particle production begins immediately, $\tau_0 = 0$
- Then

$$R_2(Q) = \gamma \left[1 + \lambda \cos\left((R_a Q)^{2\alpha} \right) \exp\left(-(RQ)^{2\alpha} \right) \right] \cdot (1 + \epsilon Q)$$

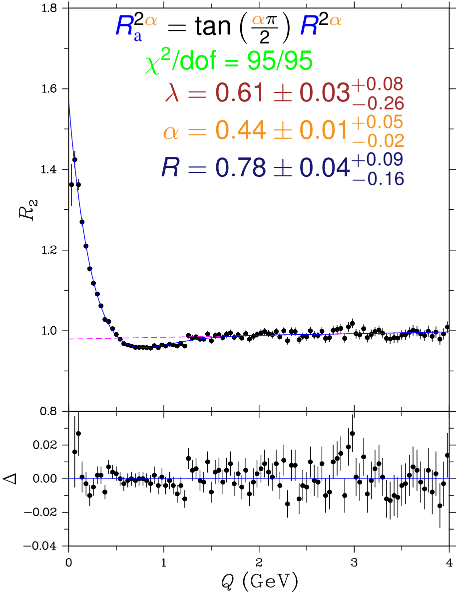
where $R_a^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha}$

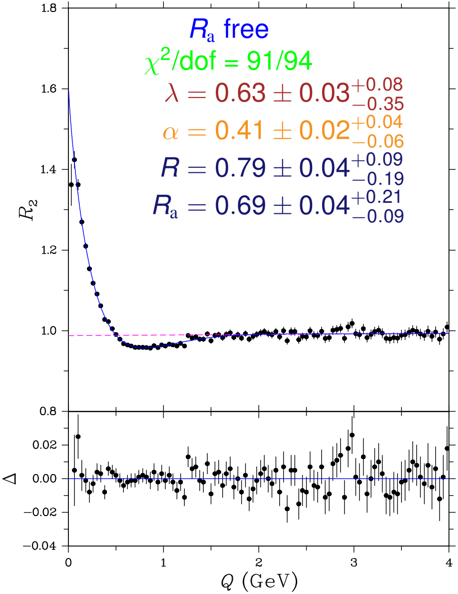
Compare to sym. Lévy parametrization:

$$R_2(Q) = \gamma \left[1 + \lambda \qquad\qquad \exp\left[-|rQ|^{\alpha} \right] \right] (1 + \epsilon Q)$$

- R describes the BEC peak
- R_a describes the anticorrelation dip
- τ-model: both anticorrelation and BEC are related to 'width' $\Delta\tau$ of $H(\tau)$

2-jet Results on Simplified τ-model from L3 Z decay





Extension of Simplified τ-model to 3D

In τ-model $R_2 = R_2(Q)$ depends on Q, but not on its components separately
$\Longrightarrow$ emission volume is spherically symmetric.

In particular, $R_{\text{side}} = R_{\text{L}}$

LCMS: $$Q^2 = Q_{\text{L}}^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 - (\Delta E)^2$$
$$= Q_{\text{L}}^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 \left(1 - \beta^2\right) \ , \qquad \beta = \frac{p_{1\text{out}} + p_{2\text{out}}}{E_1 + E_2}$$

Replace $$R^2 Q^2 \Longrightarrow A^2 = R_{\text{L}}^2 Q_{\text{L}}^2 + R_{\text{side}}^2 Q_{\text{side}}^2 + \rho_{\text{out}}^2 Q_{\text{out}}^2$$

Then in τ-model,

$$R_2(Q_{\text{L}}, Q_{\text{side}}, Q_{\text{out}}) = \gamma \left[1 + \lambda \cos\left(\tan\left(\frac{\alpha\pi}{2}\right) A^{2\alpha}\right) \exp\left(-A^{2\alpha}\right)\right]$$
$$\cdot \left(1 + \epsilon_{\text{L}} Q_{\text{L}} + \epsilon_{\text{side}} Q_{\text{side}} + \epsilon_{\text{out}} Q_{\text{out}}\right)$$

for 2-jet events:

			χ^2/dof	CL
	τ-model	$R_{\text{side}}/R_{\text{L}} = 0.61 \pm 0.02$	14847/14921	66%
	consistent with conventional Gaussian Edgeworth parametrization			
	Edgeworth	$r_{\text{side}}/r_{\text{L}} = 0.64 \pm 0.02$	14891/14919	56%

emission volume is elongated

Conclusion: τ-model must be modified: Q-dependence $\Longrightarrow$ $\vec{Q}$-dependence

Nevertheless

- simplified τ-model provides good parametrization of $R_2(Q)$
- with “radius” parameters:
  - R describing BE correlation
  - R_a describing anti-correlation dip

So we continue to use this parametrization.

Fit parameters α and R are highly correlated.
To stabilize fits against this large correlation, fix $\alpha = 0.44$

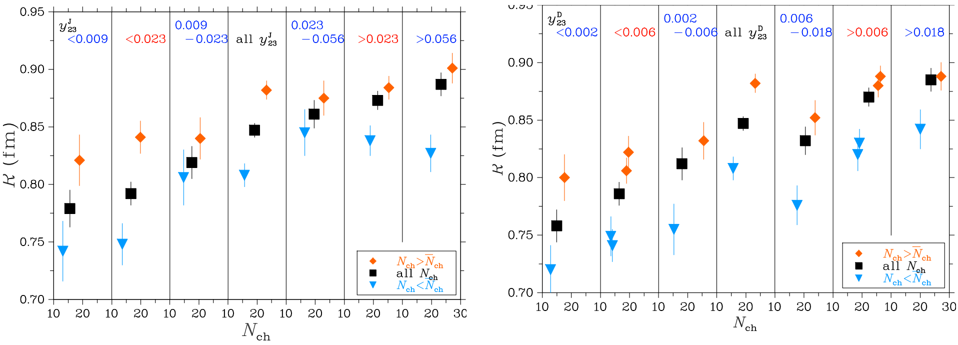
Multiplicity dependence in τ-model

Using simplified τ-model, $\alpha = 0.44$, $\tau_0 = 0$

L3 PRELIMINARY

JADE

Durham



- R increases with y_{23}, *i.e.*, going from narrow 2-jet to wide 3-jet
- R increases with multiplicity at all y_{23}

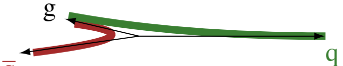
Jets and Rapidity

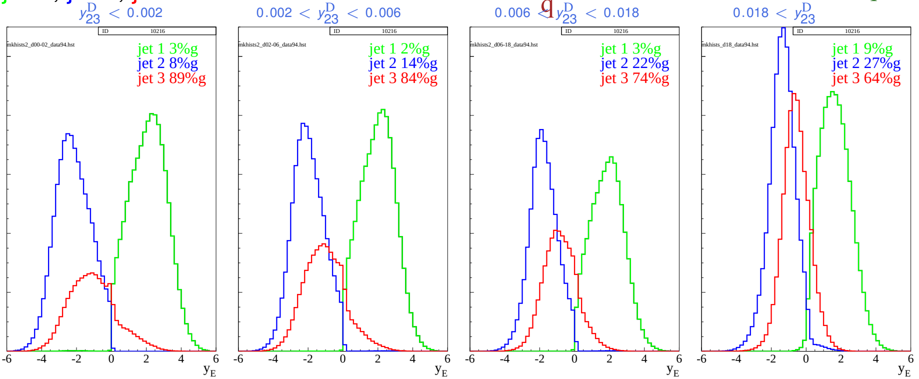
Note: thrust only defines axis $|\vec{n}_\mathrm{T}|$, not its direction.

order jets by energy: $E_1 > E_2 > E_3$

Choose positive thrust direction such that jet 1 is in positive thrust hemisphere

rapidity, y_E, of particles from
jet 1, jet 2, jet 3:



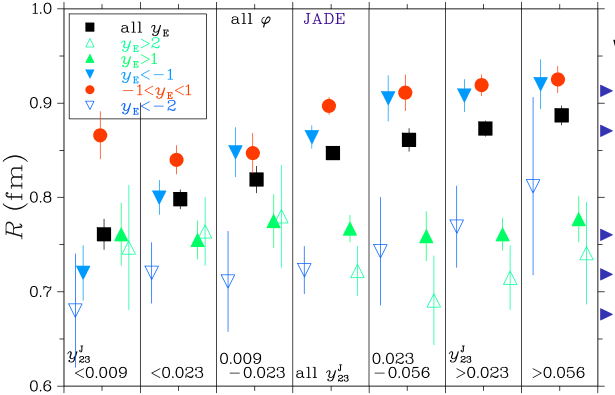


$y_\mathrm{E} > 1$	almost all jet 1	almost all quark
$y_\mathrm{E} < -1$	mostly jet 2, some jet 3	mostly quark
$-1 < y_\mathrm{E} < 1$	jet-3 enriched	largely gluon

Jets and Rapidity – simplified τ-model – L3 preliminary

To stabilize fits against large correlation of α, R, fix $\alpha = 0.44$

Select particle pairs by rapidity y_{E} of pair



With y_{23}^{J},

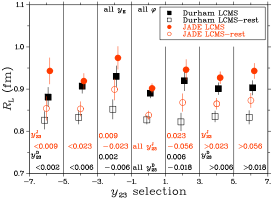
- all y: R increases
- ‘pure’ q jet, $y_{\mathrm{E}} > 1$, or $y_{\mathrm{E}} < -1$ & y_{23}^{J} small, or $y_{\mathrm{E}} < -2$: R const.
- $R_{-1<y_{\mathrm{E}}<1} > R_{\text{‘pure’ q}}$
- $R_{y_{\mathrm{E}}<-1}$ increases
- at large y_{23}^{J} $R_{-1<y_{\mathrm{E}}<1} = R_{y_{\mathrm{E}}<-1}$

Conclusion (Durham agrees):
Increase in R with y_{23}^{J} is due to appearance of gluon jet

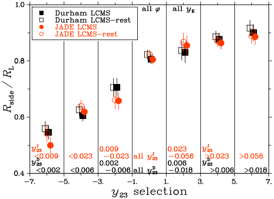
3D τ-model *ad hoc* extension – L3 preliminary

$$R^2 Q^2 \Longrightarrow R_{\mathrm{L}}^2 Q_{\mathrm{L}}^2 + R_{\mathrm{side}}^2 Q_{\mathrm{side}}^2 + \rho_{\mathrm{out}}^2 Q_{\mathrm{out}}^2 \qquad \text{LCMS}$$

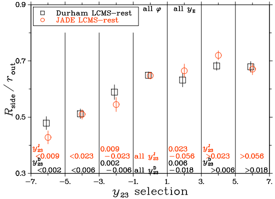
$$R^2 Q^2 \Longrightarrow R_{\mathrm{L}}^2 Q_{\mathrm{L}}^2 + R_{\mathrm{side}}^2 Q_{\mathrm{side}}^2 + r_{\mathrm{out}}^2 q_{\mathrm{out}}^2 \qquad \text{LCMS-rest}$$



R_{L} constant with y_{23}

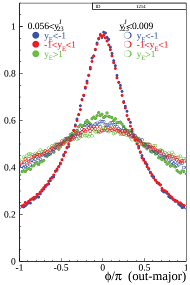


R_{side} increases



r_{out} increases but less than R_{side}

- jets with gluon contribution (3-jet with $y_{\mathrm{E}} < 1$):
  out direction preferentially in event plane
  'pure quark' jet ($y_{23}^{\mathrm{J}} < 0.009$ or $y_{\mathrm{E}} > 1$):
  out direction more isotropic in ϕ
- Conclusion: Increase in R is mainly due to increase in transverse plane, particularly out of event plane
- Agrees with conclusion that increase is mainly due to harder gluon: Gluon makes event 'fatter'



Anti-Correlation Region in pp min. bias

In addition to L3 observation of anticorrelation in e^+e^- ($E_{cms} = M_Z$),

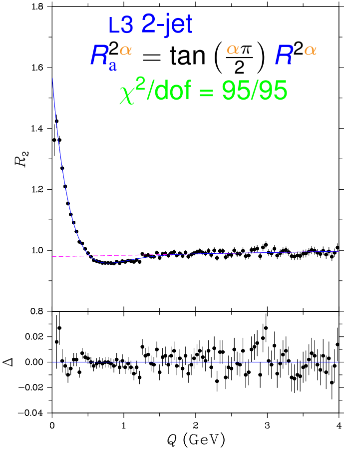
CMS has observed it in pp min. bias at 7 TeV JHEP 05 (2011) 29
and found that τ-model parametrization gives reasonable description

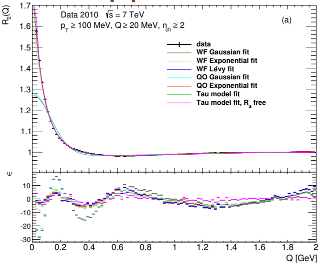
And it is also seen in ATLAS data $\sqrt{s} = 7\,\mathrm{TeV}$ R. Astaloš PhD thesis 2015 http://hdl.handle.net/2066/143448

but unpublished and not (yet?) approved by collaboration

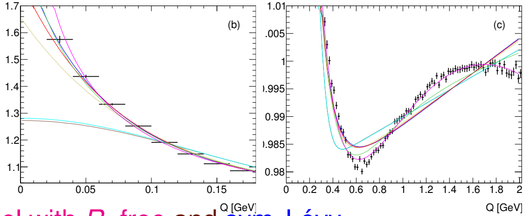
We next look at the ATLAS data and make some comparisons between
e^+e^-: L3 data, $0.8 \cdot 10^6$ events, $\sqrt{s} = M_Z$,
min. bias pp: ATLAS data (Astaloš thesis) 10^7 events, $\sqrt{s} = 7\,\mathrm{TeV}$, $|\eta| < 2.5$

2-jet e^+e^- — pp 7 TeV min. bias





(Astaloš thesis)



BEC peak best described by τ-model with R_a free and sym. Lévy

BEC peak next best described by a quantum optical exponential parametrization

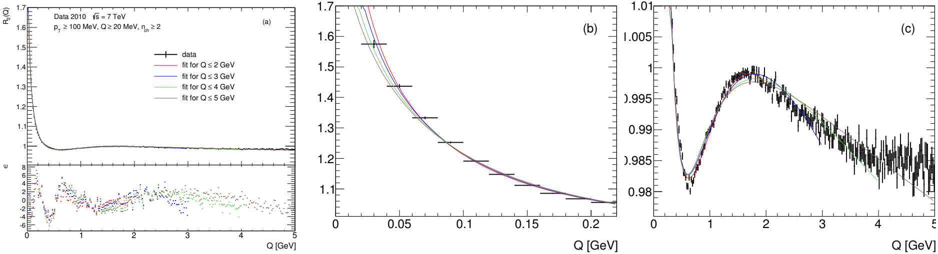
and by τ-model (R_a constrained) $\chi^2(Q \leq 0.36) = 115, 116, 157, 186$

anticorrelation region also in pp – only τ-model with R_a free describes it

Only τ-model with R_a free describes entire range of Q

Effect of fit range

So, use the parametrization that fits (best): τ-model with R_a free and Q_U sufficiently beyond the anticorrelation region

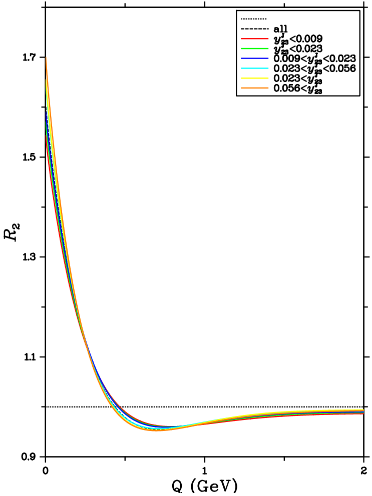


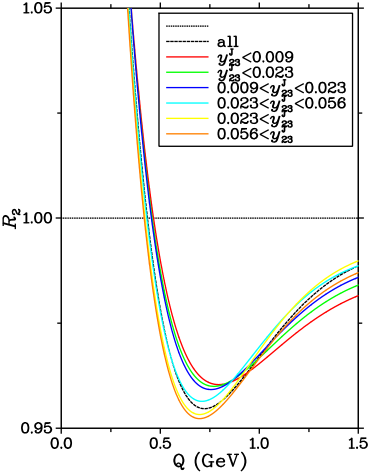
Q_U	2 GeV	3 GeV	4 GeV	5 GeV
α	0.108 ± 0.001	0.186 ± 0.005	0.235 ± 0.003	0.261 ± 0.003
R (fm)	17.8 ± 0.7	6.7 ± 0.5	4.1 ± 0.2	3.3 ± 0.1
R_a (fm)	43.4 ± 1.2	3.0 ± 0.2	1.80 ± 0.04	1.52 ± 0.02
λ	3.08 ± 0.05	1.91 ± 0.10	1.36 ± 0.05	1.15 ± 0.03

- syst. dependence on fit range, but much less than other parametrizations
- $\alpha \approx 0.25$ somewhat less than e^+e^- 2-jet value of $0.41 \pm 0.02^{+0.04}_{-0.06}$
- R, R_a larger than in e^+e^- 0.79, 0.69 fm

Anti-Correlation Region

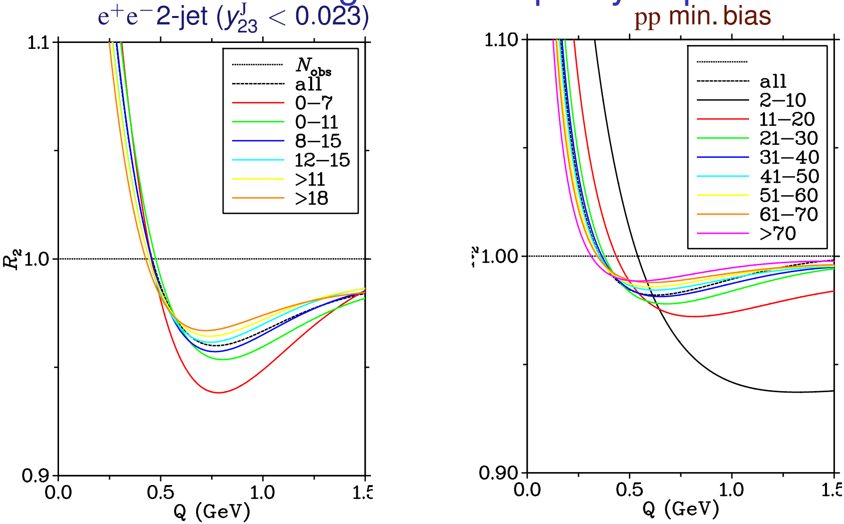
e^+e^- jet dependence:





Going from narrow 2-jet to wide 3-jet,
anticorrelation region becomes deeper and moves slightly lower in Q

Anti-Correlation Region – Multiplicity dependence



anticorrelation region is deeper and at higher Q in e^+e^- than in pp

with increasing N minimum moves to lower Q (effect is larger in pp than in e^+e^-)

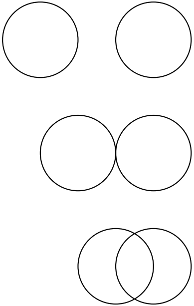
and becomes less deep (also seen by CMS)

Another way to get Anti-correlation

Białas and Zalewski, Phys. Lett. B727(2013)182

Białas, Florkowski and Zalewski, Phys. Lett. B748(2015)9

Pions are not point particles.



pions far apart – BEC

pions close together

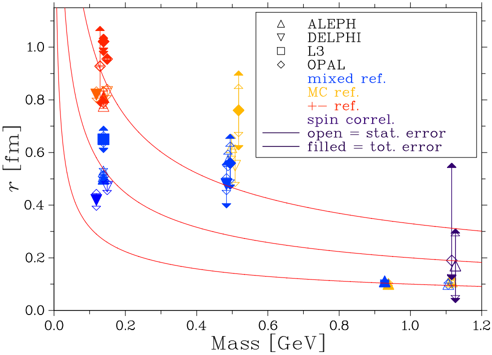
pions overlapping – no longer pions – So, no BEC

This excluded volume leads to anti-correlation dip.
at approx. the right place – different for Long, side, out

Mass dependence of r — BEC and FDC

e^+e^- $\sqrt{s} = M_Z$

Gaussian parametrization



Large systematic dependence on ref. sample – So, using mixed ref. sample:

No evidence for $r \sim 1/\sqrt{m}$

$r_{\pi\text{-}\pi} \approx r_{\text{K-K}}$

$r(\text{mesons}) > r(\text{baryons})$

$r(\text{baryons})$ is very small — $r_{\text{p}} = 0.1$ fm while size of p is 1 fm ???

If correct, seems to rule out Białas-Zalewski

Are there pp or heavy-ion results on $r(\text{baryons})$?

Conclusions

- τ-model parametrization of BEC provides a good description of 2π BEC
  - in $\mathrm{e}^+\mathrm{e}^-$ and
  - in pp min. bias, especially if R_a is a free parameter
- anti-correlation:
  - in $\mathrm{e}^+\mathrm{e}^-$ deeper than in pp
  - in heavy-ion, anti-correlation is missing (so far as I know)
  - speculation: $\mathrm{e}^+\mathrm{e}^-$: 1 string; pp: a few strings; heavy-ion: a great many strings
    With additional strings, 2 components to BEC:
    - π's from same string (τ-model, anti-correlaton, small R)
    - or from different strings (classical parametrization, no anti-correlation, larger R)
- But $R_2(Q)$ needs to be extended to $R_2(\vec{Q})$
- in $\mathrm{e}^+\mathrm{e}^-$ and pp R increases with increasing N_ch
- in $\mathrm{e}^+\mathrm{e}^-$ R depends on jet structure
  - R increases with y_{23}
  - much, but not all, of increase is due to increase in y_{23}
  - this increase is in transverse plane, not in longitudinal direction
  - anti-correlation region becomes deeper with increasing y_{23}
- R and R_a larger and α smaller in pp than in $\mathrm{e}^+\mathrm{e}^-$ 2-jet
  but large syst errors from fit range in pp