BEC: from e^+e^- to pp

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5th Day of Femtoscopy
Gyöngyös
31 October 2019

$e^+e^- \longrightarrow$ 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 $e^+e^- \longrightarrow q\bar{q}g$

- 2-jet: event hadronization axis is the $q\bar{q}$ direction, not the beam
  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
- use y_{23}, value of y_{cut} for which classification changes from 2- to 3-jet,
  to study dependcdence of 'jettiness'

BEC in the τ-model

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

Simplification:

- effective radius, R, defined by $R^{2\alpha} = \left(\frac{\Delta\tau}{2}\right)^{\alpha} \frac{a_1^\alpha + a_2^\alpha}{2}$ 2-jet: $a_i = \frac{1}{m_{ti}}$
- Assume 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:

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

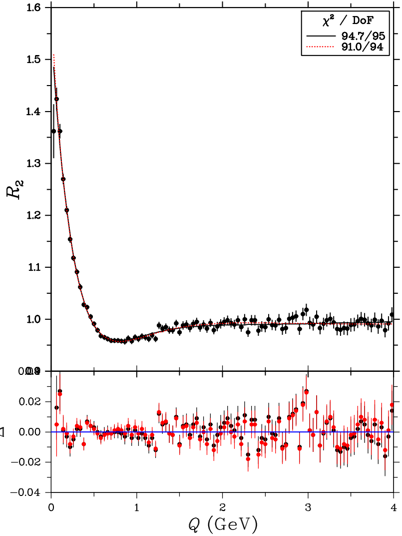
- R describes the BEC peak
- R_a describes the anticorrelation dip
- τ-model: both anticorrelation and BEC are related to 'width' $\Delta\tau$ of $H(\tau)$ and to m_t

τ-model– 3-jet events

- at $\sqrt{s} = M_Z$ almost all events are
  2-jet $\quad e^+e^- \longrightarrow q\bar{q}$ or 3-jet $\quad e^+e^- \longrightarrow q\bar{q}g$

- for 2-jet events hadronizaton is basically 1+1 dimension, which lead in the τ-model to the dependence on
  τ, the longitudinal proper time
  m_t, the transverse mass
- for 3-jet events this is more complicated
  So, not surprising that the τ-model works less well

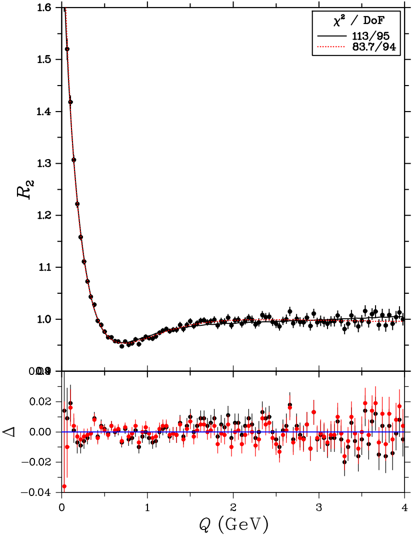
τ-model – 2-jet events



order	χ^2/DoF	CL
R_a constrained	94.7/95	49%
R_a free	91.0/94	57%

- Difference of two χ^2 is also a χ^2
- Small CL($\chi_1^2 - \chi_2^2$, DoF$_1$ − DoF$_2$) is reason to reject Hypothesis 1
- CL(94.7 – 91.0, 1 dof) = 5.4% Not small enough to reject R_a constrained
- R_a free does not give significant improvement

τ-model – 3-jet events



order	χ^2/DoF	CL
R_a constrained	113.2/95	10%
R_a free	83.7/94	77%

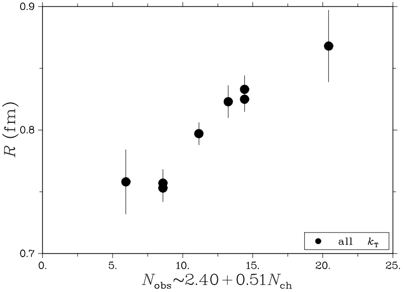
- CL(113.2 – 83.7, 1 dof)$= 6 \cdot 10^{-8}$
- R_a free gives significant improvement

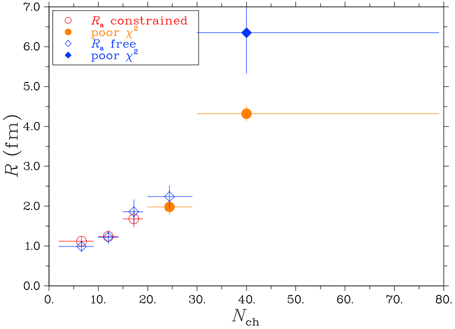
Conclusions – 3-jet events

significant improvement is obtained letting R_a free
i.e., by lessening the connection of simplified τ-model
between the BEC peak and antisymmetric dip
presumably due to the more complicated structure of the event

Multiplicity dependence

2-jet e^+e^- simplified τ-model





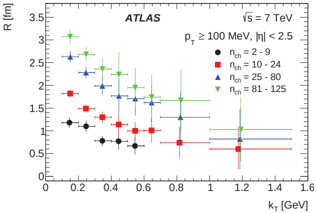
- R increases with N_{ch} both in e^+e^- and pp
- R much increases faster in pp
  more than doubles from $N_{ch} \approx 5$ to 30 for pp
  but only by about 10% for e^+e^-
- R increases a bit faster in pp for fits with R_a free

Dependence on $k_t = p_{t\,pair}/2 = |\vec{p}_{t1} + \vec{p}_{t2}|/2$

pp – conventional parametrizations

Un-Like Sign ref. sample

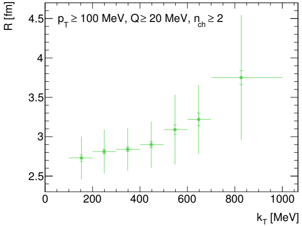
exponential



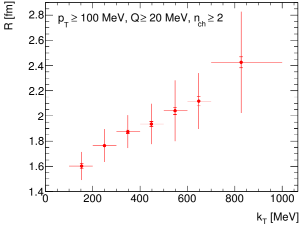
ATLAS, Arxiv.1502.07947v1

OHP ref. sample

sym. Lévy

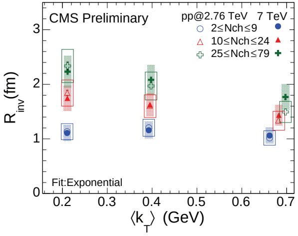


optical exponential



ATLAS Astaloš thesis

Mix S. Padula, WPCF2014, ArXiv:1502.05757

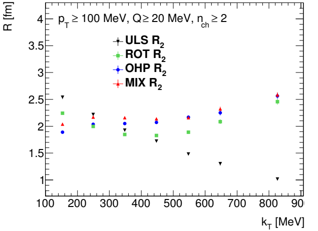


with ULS ref. sample, R decreases with k_t (all N_{ch})

with other ref. samples, behavior is different

low mult. less dependent on k_t then high mult.

exponential

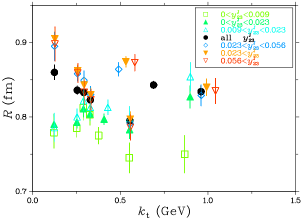


$k_t = |\vec{p}_{t1} + \vec{p}_{t2}|/2$ dependence

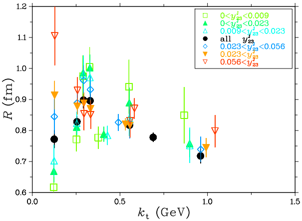
simplified τ-model

e^+e^-, w.r.t. thrust axis

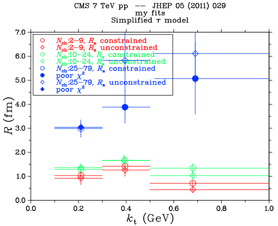
R_a constrained



e^+e^-, R_a free



pp, w.r.t. beam direction



in e^+e^- dependence of R on k_t depends on 'jettiness'

in e^+e^- 3-jet R decreases with k_t.

in e^+e^- 2-jet and in pp low mult. R seems first to increase and then fall with k_t.

k_t dependence of R is dependent on parametrization and on ref. sample

Jets and Rapidity

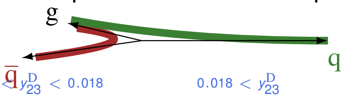
order jets by energy: $E_1 > E_2 > E_3$

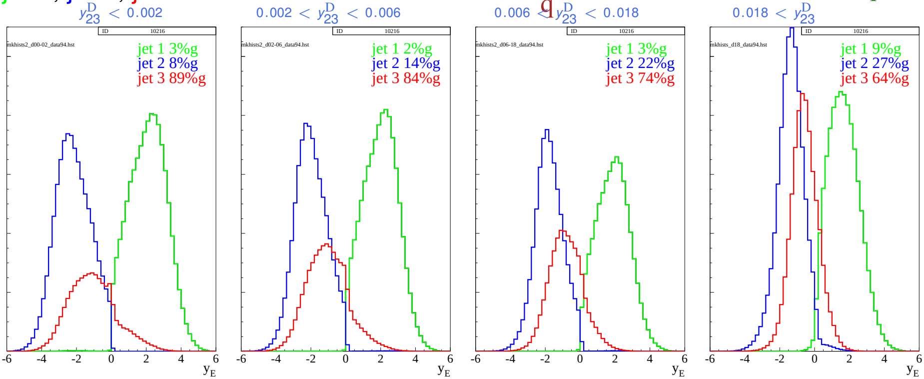
Note: thrust only defines axis $|\vec{n}_\mathrm{T}|$, not its direction.

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:

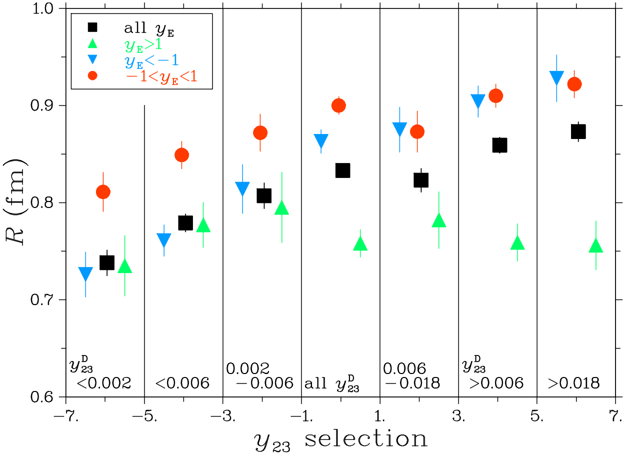




- $y_\mathrm{E} > 1$ almost all jet 1 — almost all quark
- $y_\mathrm{E} < -1$ mostly jet 2, some jet 3 — mostly quark
- $-1 < y_\mathrm{E} < 1$ jet-3 enriched — largely gluon

Dependence on the Rapidity of the pair

e^+e^-, + thrust axis = hemisphere of jet with highest E



- $R_{\text{all }y}$ and $R_{y<-1}$ increase with y_{23}
- but $R_{y>1}$ constant with y_{23}
- 2-jet: $R_{y>1} = R_{y<-1}$

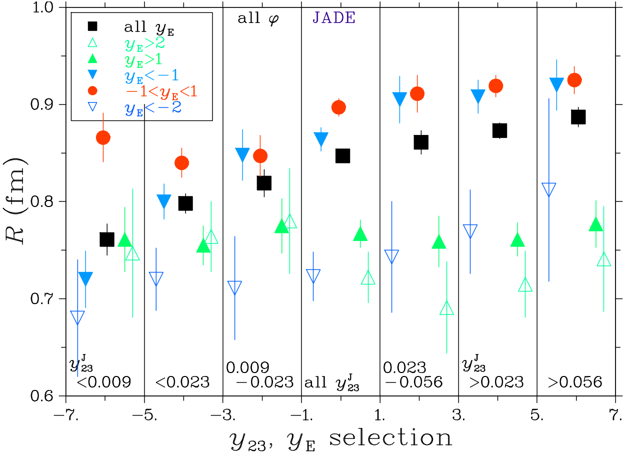
Conclusion: Increase in R is mainly due to gluon

$R_{-1<y<1} > R_{y>|1|}$ for 2-jet

gluon mini-jet in '2-jet sample'?

Dependence on the Rapidity of the pair

e^+e^-, + thrust axis = hemisphere of jet with highest E

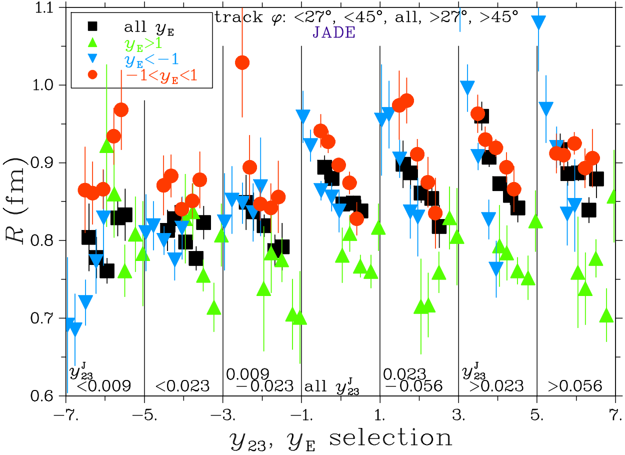


- JADE agrees with Durham (previous slide)
- $R_{y<-2}$ like 2-jet tracks from gluon do not extend so far in y

Dependence on ϕ

e^+e^-, + thrust axis = hemisphere of jet with highest E

Cut on ϕ between tracks and the event plane

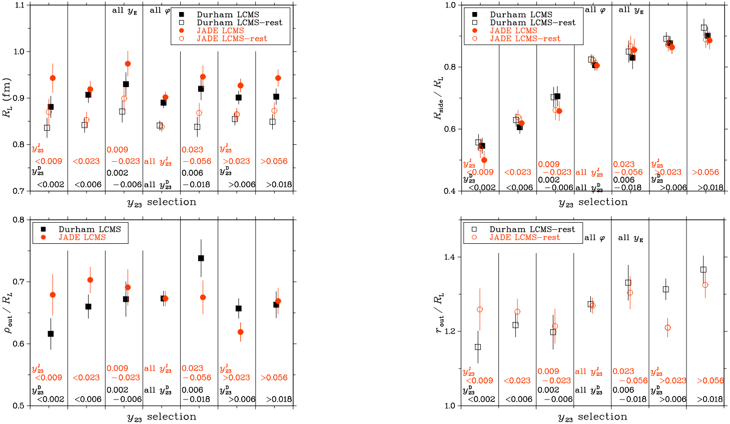


- 2-jet: event plane poorly defined
  little dependence on ϕ
- 3-jet $R_{y<-1}$ and $-1 < y < 1$:
  R larger for tracks in event plane

Simplified τ-model in LCMS, LCMS-rest

In τ-model: $R^2 Q^2 \Longrightarrow R_\mathrm{L}^2 Q_\mathrm{L}^2 + R_\mathrm{side}^2 Q_\mathrm{side}^2 + \rho_\mathrm{out}^2 Q_\mathrm{out}^2$ LCMS

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



- R_L, R_side from LCMS, LCMS-rest agree   Durham, JADE agree
- R_L, ρ_out constant with y_{23} R_side, increase with y_{23}, r_out ?

Conclusion: Increase in R is mainly due to increase in transverse plane particularly in side direction

Agrees with conclusion that increase is mainly due to harder gluon:

Lesson from e^+e^-

BEC R sensitive to jet structure of event

- R increases with N
  However, N increases with N_{jets}
  So increase of R with N may be simply due to gluon
- R increases with k_{t}; k_{t} larger for tracks in hard gluon jet
- R smaller for pions from quark jet than for those from gluon jet (y dependence)
- for 3-jet events, R larger for pions in the event plane
- R_{side} increases with hardness of gluon

What to look for in pp

1. k_t dependence (and its mult. dependence) still unclear
   associated with structure?
2. anti-correlation dip:
   - CMS finds that depth of dip decreases with multiplicity
   - associated with structure?

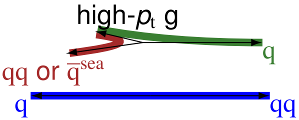
What to look for in pp

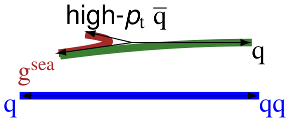
1. in analogy with e^+e^- 2-jet events
   $q\bar{q}$ string replaced by 2 q–(qq) strings

   Is structure (y dependence, mini-jets) observed? Mult. dependent?
   How much does this pp configuration look like 2 e^+e^- 2-jet events?
   - Do pions from different strings experience BEC?
   - LEP WW studies found minimal inter-string BEC?

   see LEP WW BEC studies; Chekanov, De Wolf, Kittel Eur. Phys. J. C6(1999)403

2. in analogy with e^+e^- 3-jet events





   How much does this pp configuration look like an e^+e^- 3-jet event?
   - Do pions from different strings experience BEC?
   - LEP WW studies found minimal inter-string BEC?

Where to start

In min. bias events:

- define direction of rapidity along beam axis using, *e*.g.,
  - hemisphere with highest p_t track
  - hemisphere with highest $\sqrt{\sum |p_\mathrm{t}^2| / N_\mathrm{trk}}$
  - using eigenvalues, a, b of planarity tensor, $P_{ij} = \sum_\mathrm{trks} p_i p_j$
    p_i, $i = 1, 2$, are components of $\vec{p}_\mathrm{t}$
  - some other measure of mini-jet contribution
- is there a difference between forward, central, backward regions in this y?
  larger difference if, *e*.g., $\frac{a-b}{a+b}$ difference of hemispheres is larger?

BACKUP

τ-model vs. sym. Lévy

- Simplified τ-model:

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

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

- R describes the BEC peak
- R_a describes the anticorrelation dip
- τ-model: Both anticorrelation and BEC are related to 'width' $\Delta\tau$ of $H(\tau)$ i.e. to the temporal distribution of production

- Symmetric Lévy parametrization:

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

- r describes the BEC peak
- the anticorrelation dip is NOT described
- BEC is related to the spatial distribution of the production points

But suppose we did not have the τ-model (or don't believe it):
What to do then?

BEC in e^+e^- and pp

Use (mostly) simplified τ-model with $\tau_0 = 0$

- L3: e^+e^- at $\sqrt{s} = M_Z$
  - $0.8 \cdot 10^6$ events
  - Durham $y_{cut} = 0.006$:
    $0.5 \cdot 10^6$ 2-jet events
    $0.3 \cdot 10^6 > 2$ jets, "3-jet"
  - mixed event ref. sample
- ATLAS: pp at $\sqrt{s} = 7\,\mathrm{TeV}$
  Astaloš thesis http://hdl.handle.net/2066/143448
  - 10^7 min. bias events
  - $|\eta| < 2.5$
  - opposite hemisphere ref. sample

Results are preliminary (unpublished)
and not approved by the collaborations

BOSE-EINSTEIN CORRELATIONS IN 7 TEV PROTON-PROTON COLLISIONS IN THE ATLAS EXPERIMENT

Doctoral thesis

to obtain the degree of doctor

from Radboud University Nijmegen
on the authority of the Rector Magnificus prof. dr. Th.L.M. Engelen,
according to the decision of the Council of Deans
and
from Comenius University Bratislava
on the authority of the Rector Magnificus prof. RNDr. Karol Mičieta, PhD.

to be defended in public on Wednesday, September 30, 2015
at 10:30 hrs

by

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Quantum Optics parametrizations

In addition to 'classic' and τ-model parametrizations,
Róbert Astaloš's thesis includes fits of parametrizations based on a quantum optical approach

Weiner, Phys. Rep. 327 (2000) 249

- Gaussian

$$R_2(Q) \propto 1 + 2p(1-p)\exp(-R^2Q^2) + p^2\exp(-2R^2Q^2)$$

- Lorentzian in R, exponential in Q

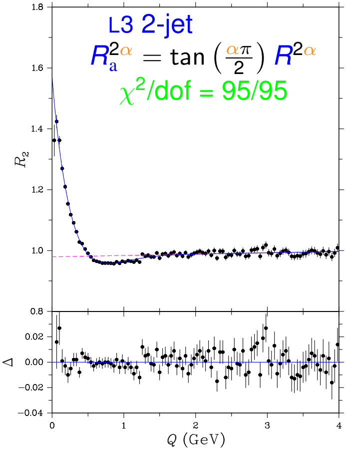
$$R_2(Q) \propto 1 + 2p(1-p)\exp(-RQ) + p^2\exp(-2RQ)$$

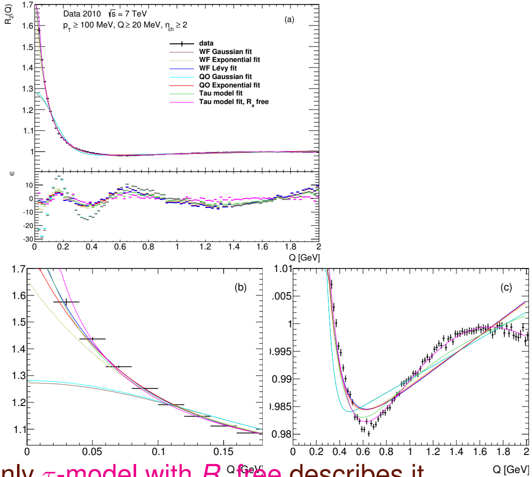
p is the degree of chaoticity of the pion emission

Note that for $p = \lambda = 1$ these reduce to the 'classical' Gaussian and exponential parametrizations

Like the 'classical' parametriazations, these parametrizations cannot accomodate anticorrelation

2-jet e^+e^- – All pp min. bias





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

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 $\chi^2(Q \leq 0.36) = 115, 116, 157, 186$

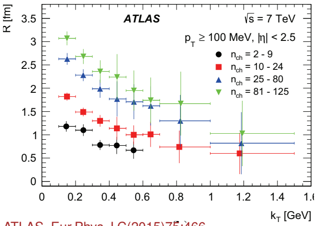
Only τ-model with R_a free describes entire range of Q

Dependence on $k_t = p_{t\,\mathrm{pair}}/2 = |\vec{p}_{t1} + \vec{p}_{t2}|/2$

pp – conventional parametrizations

Un-Like Sign ref. sample

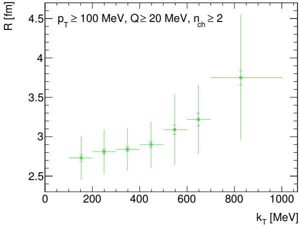
exponential



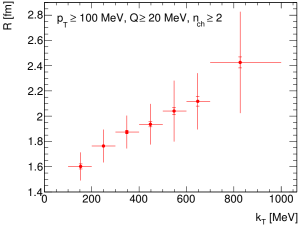
ATLAS, Eur.Phys.J.C(2015)75:466

OHP ref. sample

sym. Lévy

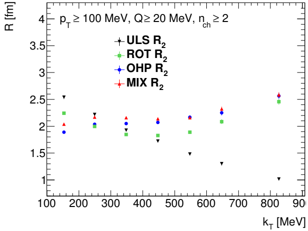


optical exponential



ATLAS Astaloš thesis

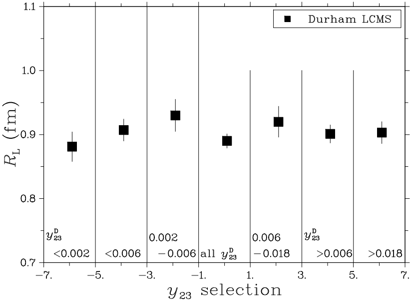
exponential

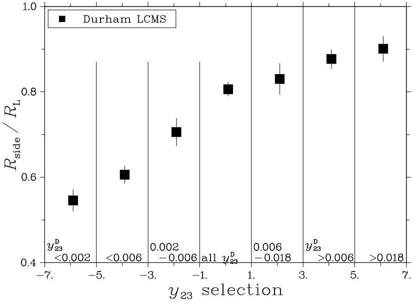


- exponential parametrization:
  ULS ref. sample: *R* decreases with k_t (all N_{ch})
  with other ref. samples, *R* is first constant, then increasing with k_t
- other 'classic parametrizations': *R* increases with k_t

Simplified τ-model in LCMS

In τ-model: $R^2 Q^2 \Longrightarrow R_\mathrm{L}^2 Q_\mathrm{L}^2 + R_\mathrm{side}^2 Q_\mathrm{side}^2 + R_\mathrm{out}^2 Q_\mathrm{out}^2$





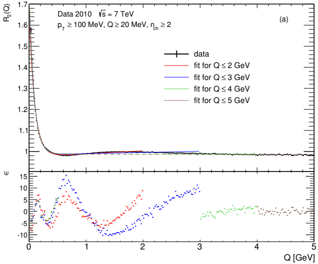
- R_L constant with y_{23} — R_side increases with y_{23}

Conclusion: Increase in R is mainly due to increase in transverse plane

Agrees with conclusion that increase is mainly due to harder gluon:
Gluon makes event ‘fatter’

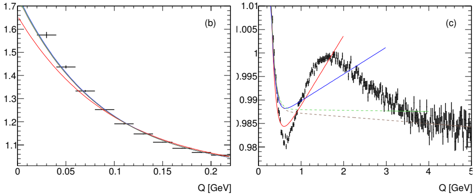
Effect of fit range

Besides ref. sample, another large systematic effect is the choice of fit range



Using the opposite hemisphere ref. sample,
and Exponential parametrization:

Q_U (GeV)	Q excl.	R (fm)	λ
2	-	2.02 ± 0.01	0.70 ± 0.01
3	-	2.28 ± 0.01	0.78 ± 0.01
4	0.5–3.0	2.30 ± 0.02	0.77 ± 0.01
5	0.5–4.0	2.29 ± 0.02	0.76 ± 0.01



$Q_U = 2, 3$: baseline tries to describe anticorrelation

Q_U larger, with excluded regions can lead to stable results,

but this is simply *bricolage*

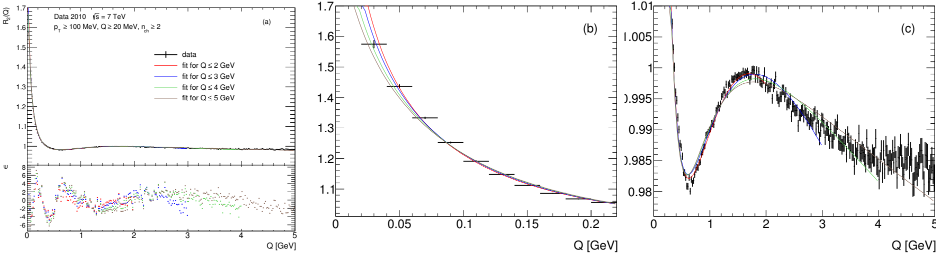
and it is a long extrapolation

Parametrization is just wrong

Effect of fit range

Better to use a parametrization that fits (better): τ-model with R_a free and Q_U sufficiently beyond the anticorrelation region

Using the opposite hemisphere ref. sample,



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

- much less dependent on fit range than other parametrizations
- α quite different from e^+e^- 2-jet value of $0.41 \pm 0.02^{+0.04}_{-0.06}$