Bose-Einstein results

from L3

1. Elongation of the Pion Source in $Z \Longrightarrow$ hadrons

2. Inter-W BEC (or lack thereof)

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Inter-W BEC

Method to study inter-W BEC:

Chekanov, De Wolf, Kittel; Eur. Phys. J. C6, 403 (1999)

Uses two-particle density in 4-momenta p_1, p_2

$$\rho(p_1,p_2) = \frac{1}{N_{\text{ev}}} \frac{\mathrm{d}n_{\text{pairs}}(p_1,p_2)}{\mathrm{d}p_1\,\mathrm{d}p_2}$$

If independent decay of $\mathrm{W^+W^-}$, for $\mathrm{W^+W^-} \longrightarrow \mathrm{q\bar{q}q\bar{q}}$ ρ is

$$\begin{aligned} \rho_{\text{4q}}(p_1,p_2) = & \quad \rho^+(p_1,p_2) & \text{1, 2 from W}^+ \\ + & \quad \rho^-(p_1,p_2) & \text{1, 2 from W}^- \\ + & \quad \rho^+(p_1)\rho^-(p_2) & \text{1 from W}^+\text{, 2 from W}^- \\ + & \quad \rho^+(p_2)\rho^-(p_1) & \text{1 from W}^-\text{, 2 from W}^+ \end{aligned}$$

Or, since $\rho^+ = \rho^- = \rho_{\text{2q}}$,

$$\rho_{\text{4q}}(p_1,p_2) = 2\rho_{\text{2q}}(p_1,p_2) + 2\rho_{\text{2q}}(p_1)\rho_{\text{2q}}(p_2)$$

If inter-W BEC exist, W decays are *not* independent

$\Longrightarrow$ this relation does *not* hold.

Experimentally measure

- $\rho_{\text{4q}}(p_1,p_2)$ from $\mathrm{e^+e^-} \longrightarrow \mathrm{W^+W^-} \longrightarrow \mathrm{q\bar{q}q\bar{q}}$
- $\rho_{\text{2q}}(p_1,p_2)$ from $\mathrm{e^+e^-} \longrightarrow \mathrm{W^+W^-} \longrightarrow \mathrm{q\bar{q}}\ell\nu$
- $\rho_{\text{2q}}(p_1)\rho_{\text{2q}}(p_2)$ from $\rho_{\text{mix}}(p_1,p_2)$ obtained by mixing $\mathrm{e^+e^-} \longrightarrow \mathrm{W^+W^-} \longrightarrow \ell^+\nu\mathrm{q\bar{q}}$ and $\mathrm{q\bar{q}}\ell^-\nu$ events

Inter-W BEC – $\Delta\rho$

So, if W decays are independent,

$$\rho_{4q}(p_1, p_2) = 2\rho_{2q}(p_1, p_2) + 2\rho_{mix}(p_1, p_2)$$

Hence, test independence by subtracting r.h.s. from l.h.s.

$$\Delta\rho(p_1, p_2) = \rho_{4q}(p_1, p_2) - [2\rho_{2q}(p_1, p_2) + 2\rho_{mix}(p_1, p_2)]$$

Other inter-W correlations are possible,
e.g., color reconnection
However, they affect all pairs of particles
and BE affects only identical bosons
And BE effects are mostly at small $Q^2 = -(p_1 - p_2)^2$
Therefore, compare

	$\Delta\rho_{\pm\pm}(Q)$	same sign
to	$\Delta\rho_{+-}(Q)$	opposite sign

$$\delta\rho(Q) = \Delta\rho_{\pm\pm}(Q) - \Delta\rho_{+-}(Q)$$

Assuming contributions to $\Delta\rho$ are additive
and charge-independent,
$\delta\rho$ is just the contribution of inter-W BE to ρ_{4q}:

$$\delta\rho(Q) = \Delta\rho^{BE}(Q)$$

Inter-W BEC – D and D'

Recall, if independent W decay,

$$\rho_{4q}(p_1, p_2) = 2\rho_{2q}(p_1, p_2) + 2\rho_{mix}(p_1, p_2)$$

Instead of subtracting r.h.s. from l.h.s. to get $\Delta\rho$, divide:

$$\begin{aligned} D(Q) &= \frac{\rho_{4q}(Q)}{2\rho_{2q}(Q) + 2\rho_{mix}(Q)} \\ &= \frac{\Delta\rho(Q)}{2\rho_{2q}(Q) + 2\rho_{mix}(Q)} + 1 \end{aligned}$$

and compare $D_{\pm\pm}$ to D_{+-}

To minimize effects of non-BE correlations,
detector systematics, *etc.*.,
use double ratio:

$$D'(Q) = \frac{D(Q)}{D_{\mathrm{MC,no\,BE}}(Q)}$$

and compare $D'_{\pm\pm}$ to D'_{+-}

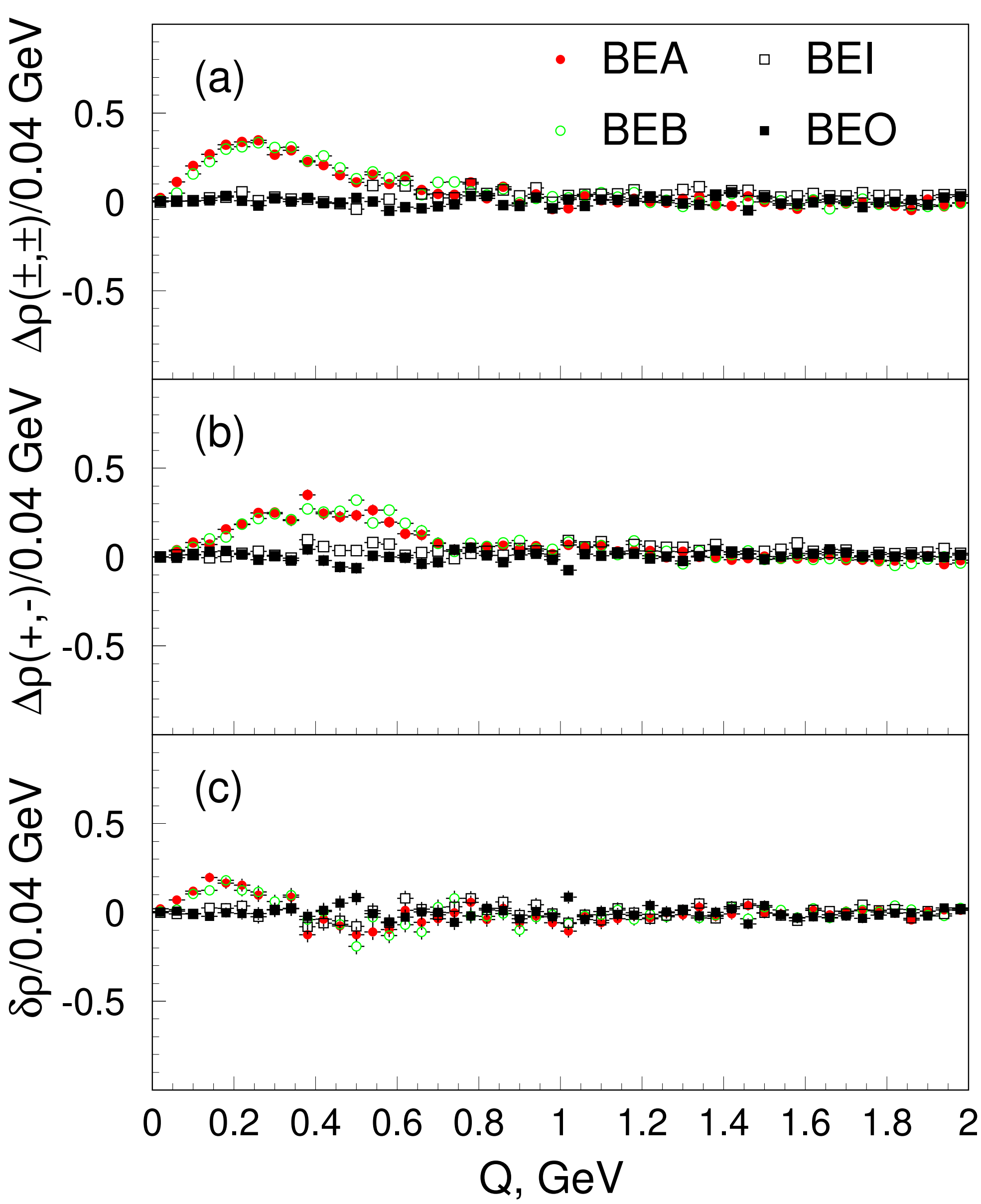
If W decays are independent,

$$\Delta\rho = 0 \qquad\qquad D = D' = 1$$

Monte Carlo test

First test on generator-level PYTHIA (LUBOEI)

BEA – BEC between all particles
BEB – BEC only for particles from different W's
$\boxed{\text{BEI}}$ – BEC only for particles from $\boxed{\text{same W}}$
BEO – no BEC



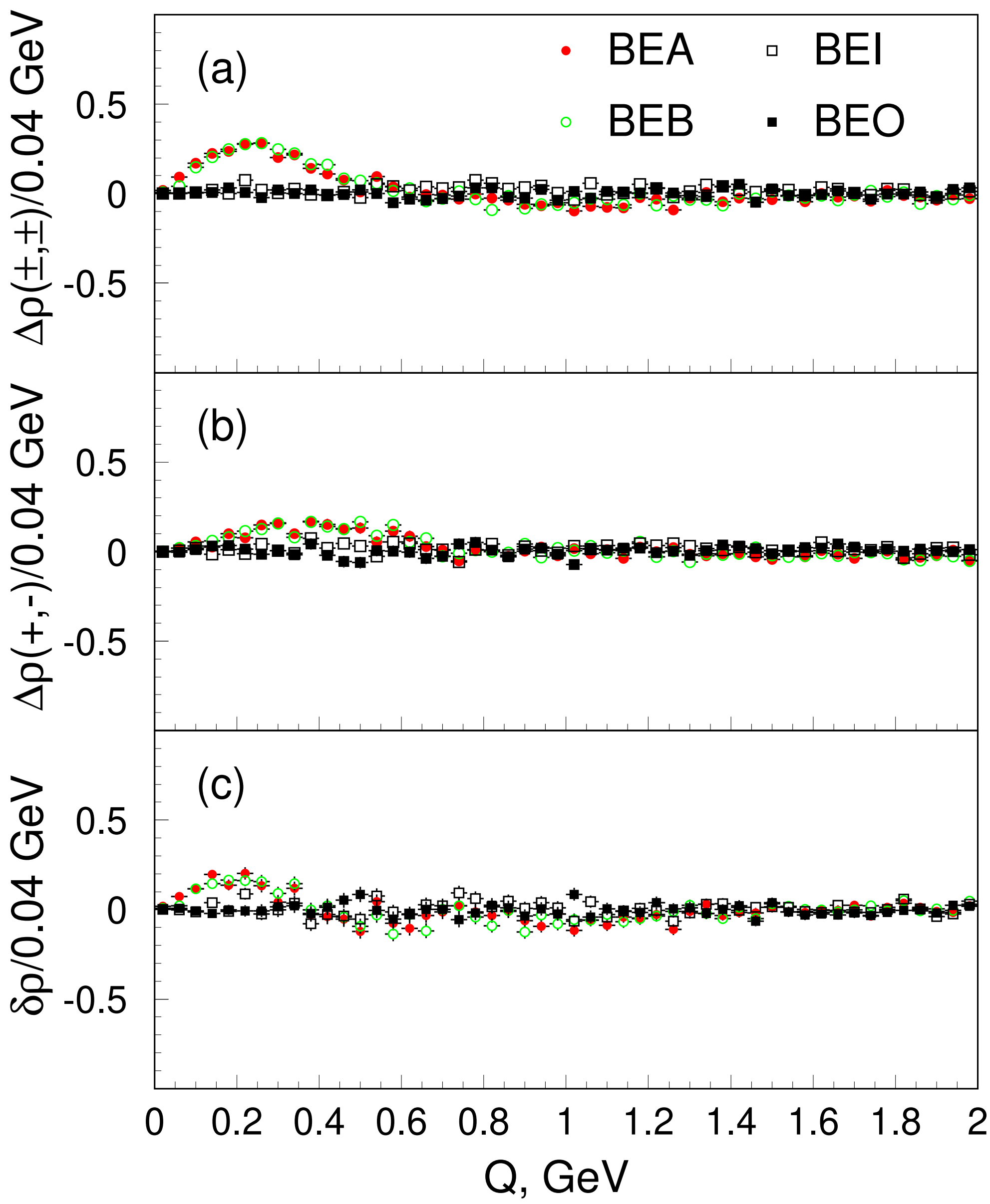
enhancement at small Q only if BE from different W's as expected

enhancement at larger Q if BE from different W's (LUBOEI!)

Monte Carlo test

First test on generator-level PYTHIA (BE_{32})

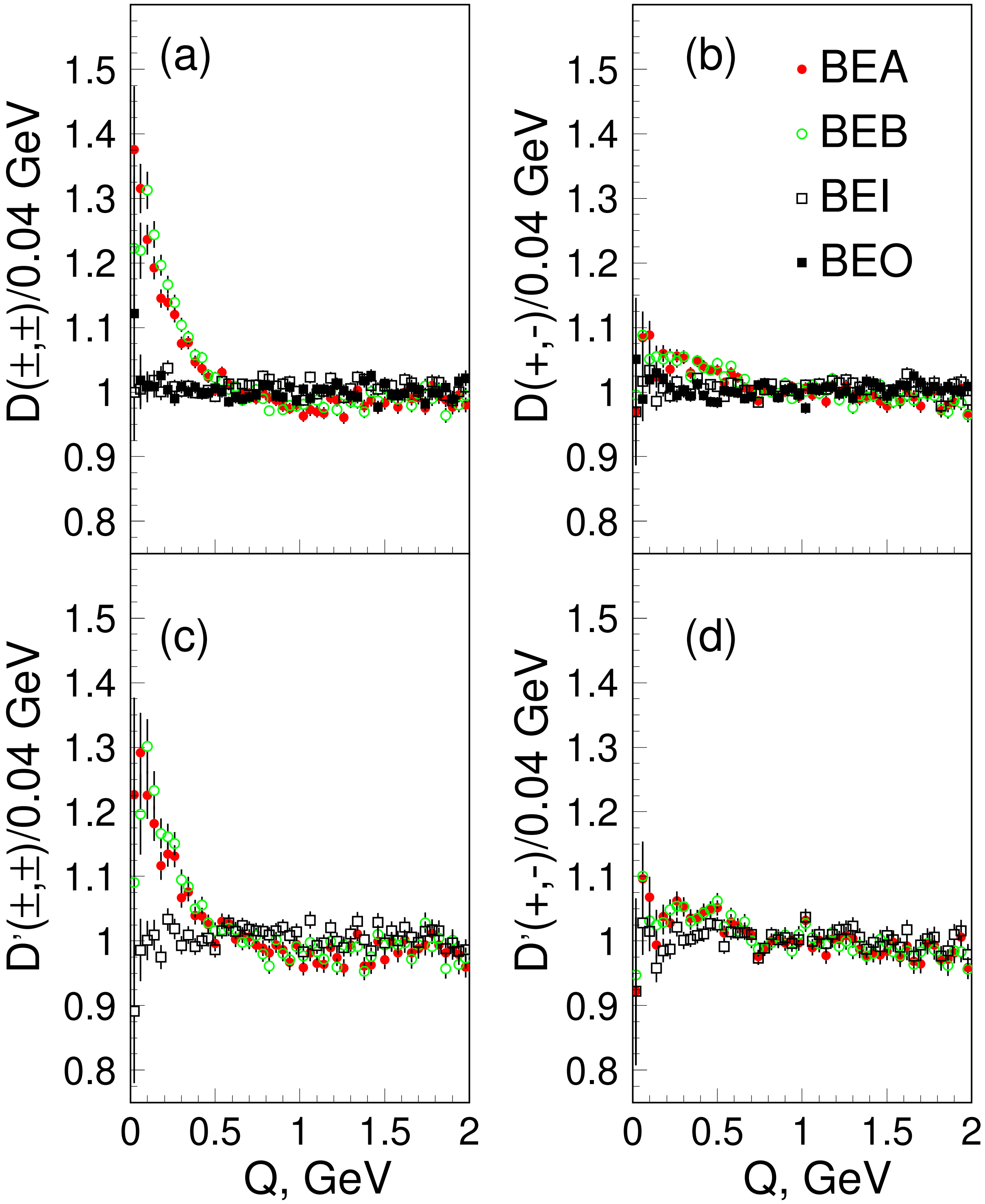
BEA – BEC between all particles
BEB – BEC only for particles from different W's
$\boxed{\text{BEI}}$ – BEC only for particles from $\boxed{\text{same W}}$
BEO – no BEC



enhancement at small Q only if BE from different W's as expected

small enhancement at larger Q if BE from different W's

Monte Carlo test $\mathbf{BE_{32}}$



If inter-W BEC,

- Large enhancement at small Q for both $D, D'_{\pm\pm}$
- Smaller enhancement extending to larger Q for $D, D'(+-)$

Data

1998 | 189 GeV | $\mathcal{L}$=176.4 pb^{-1}

After selection,

1026 semi-hadronic events ($q\bar{q}\ell\nu$)

1514 fully hadronic events ($q\bar{q}q\bar{q}$)

	efficiency (%)	background (%) ($q\bar{q}$,ZZ,Ze^+e^-)
$q\bar{q}e\nu$	75.3	6.0
$q\bar{q}\mu\nu$	78.5	4.1
$q\bar{q}\tau\nu$	49.4	12.2
$q\bar{q}q\bar{q}$	88.9	19.9

After selecting well-measured tracks,

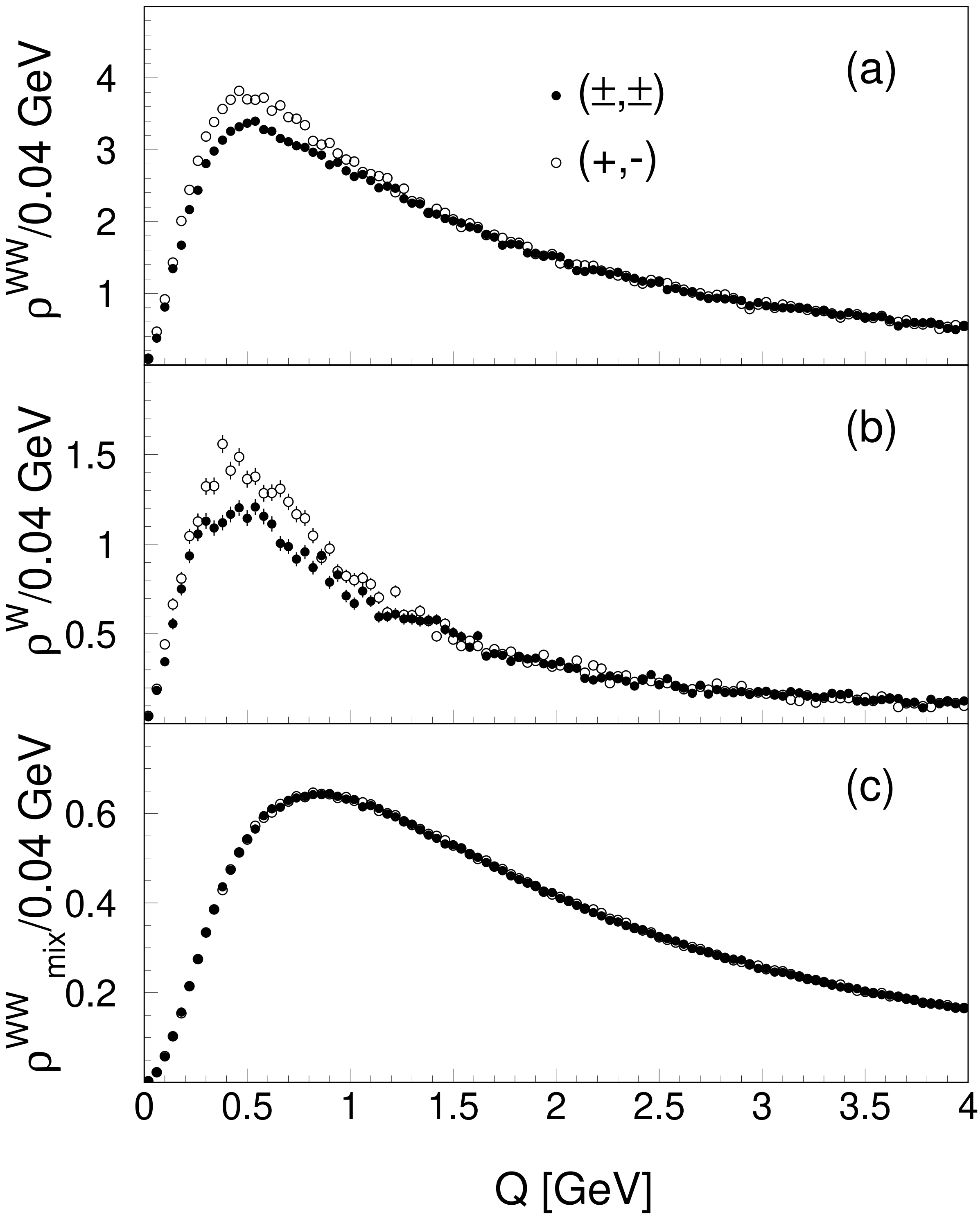
52k like-sign pairs in semi-hadronic events

302k like-sign pairs in fully hadronic events

Data

Raw data after background subtraction:

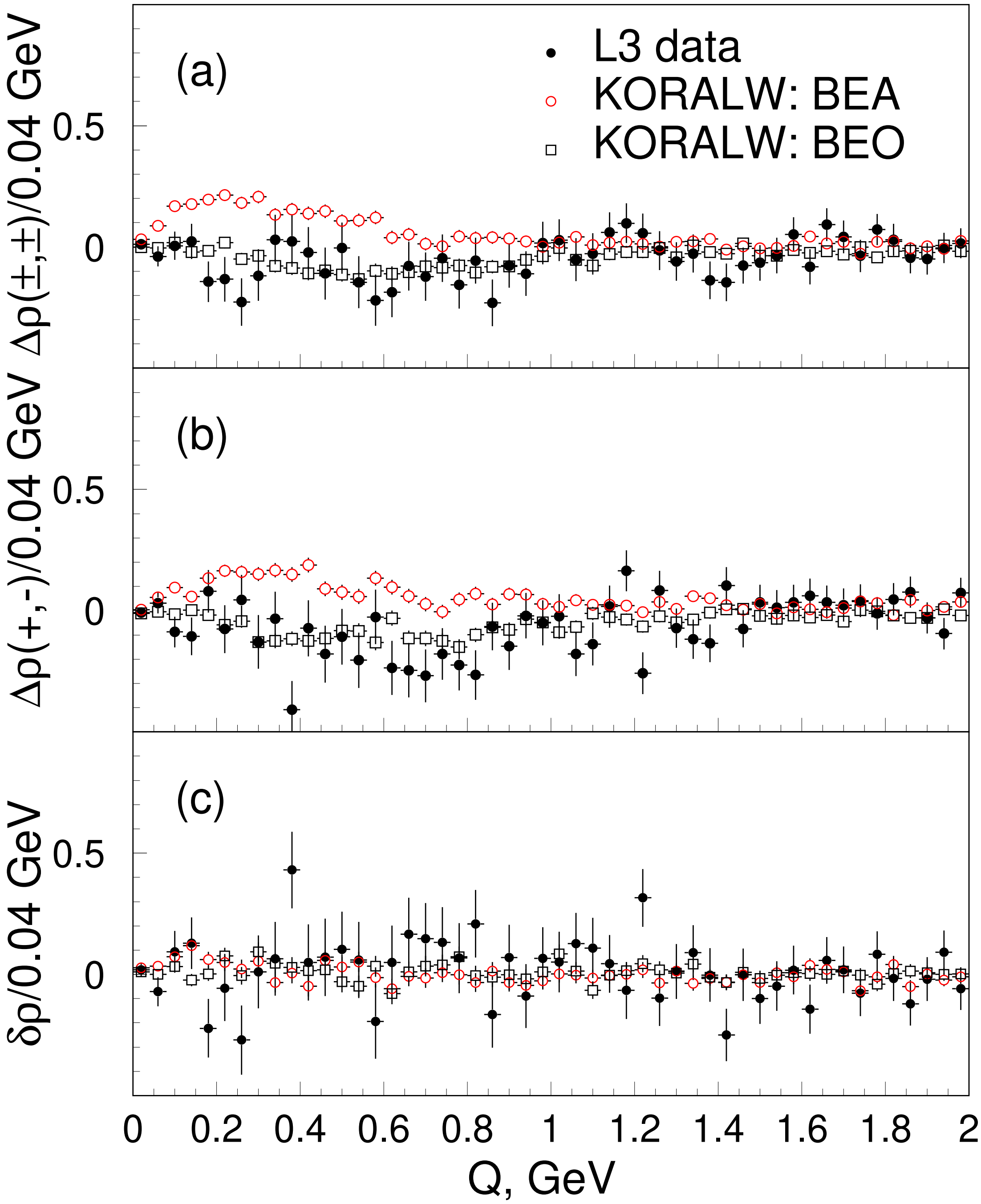
$$\Delta\rho(p_1,p_2) = \rho_{\mathsf{4q}}(p_1,p_2) - [2\rho_{\mathsf{2q}}(p_1,p_2) + 2\rho_{\mathsf{mix}}(p_1,p_2)]$$



Data

Raw data after background subtraction:
KORALW MC at detector level

– with BE (LUBOEI) for all particles (BEA)
– no BE (BEO)

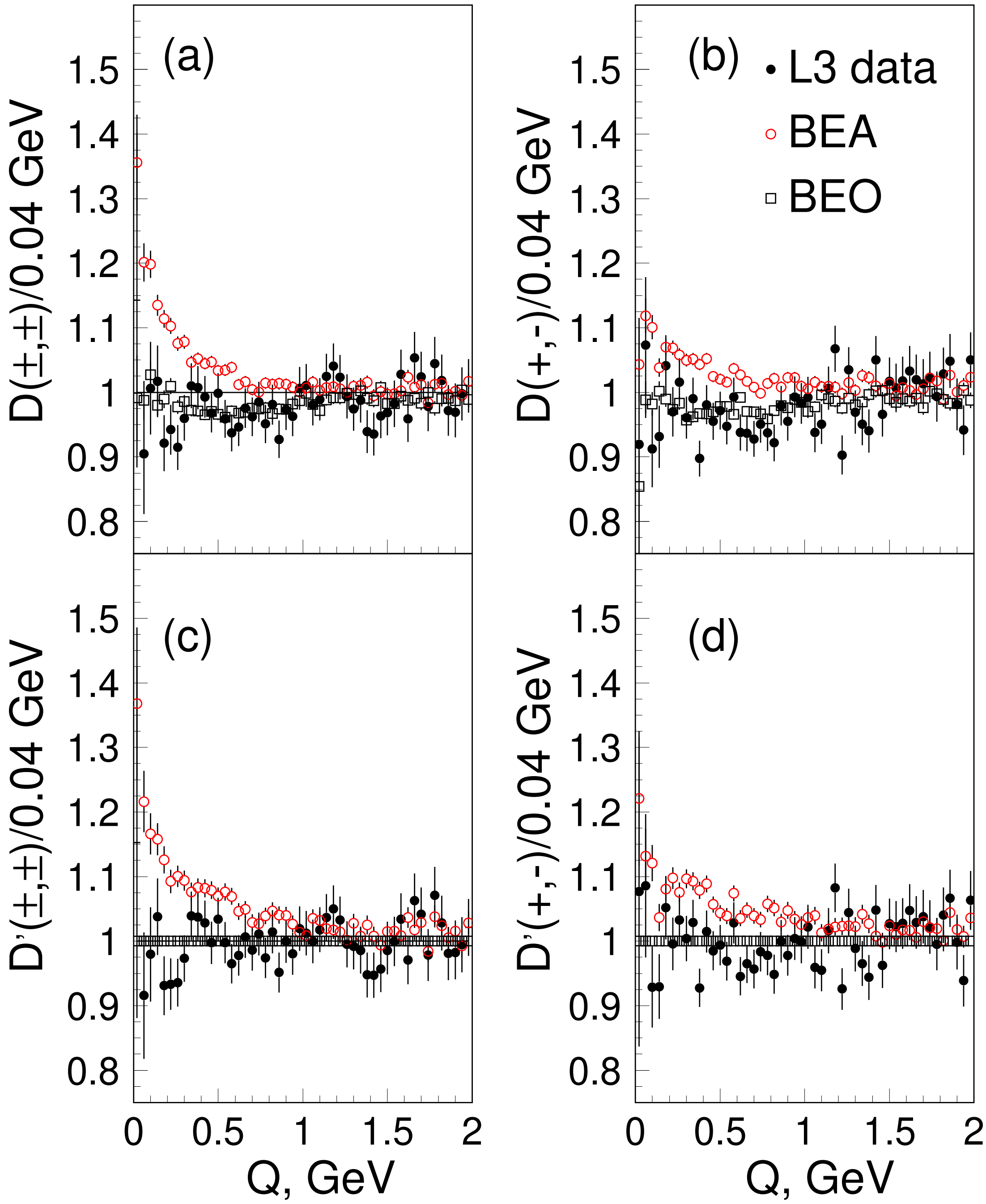


Data consistent with no BE MC and with $\Delta\rho = 0$
MC with BE has $\Delta\rho \neq 0$ at small Q

Data

Raw data after background subtraction:
KORALW MC at detector level

- with BE (LUBOEI) for all particles (BEA)
- no BE (BEO)



Data consistent with no BE MC and with $D = D' = 1$
MC with BE has $D \neq 1$ at small Q

Data – KORALW comparison

KORALW
- with BE (LUBOEI) for all particles (BEA)
- no BE (BEO)

	$0 < Q < 2$ GeV		$0 < Q < 0.6$ GeV	
	χ^2/NDF	C.L. (%)	χ^2/NDF	C.L. (%)
$\Delta\rho_{\pm\pm}$, BEA	$144/49$	$3 \cdot 10^{-9}$	$102/14$	$2 \cdot 10^{-13}$
$\Delta\rho_{\pm\pm}$, BEO	$39/49$	85	$15/14$	39
$\Delta\rho_{+-}$, BEA	$154/49$	$9 \cdot 10^{-11}$	$68/14$	$3 \cdot 10^{-6}$
$\Delta\rho_{+-}$, BEO	$58/49$	19	$14/14$	43
$\delta\rho$, BEA	$52/49$	36	$22/14$	8
$\delta\rho$, BEO	$49/49$	47	$21/14$	10
$D_{\pm\pm}$, BEA	$160/49$	$1 \cdot 10^{-11}$	$115/14$	$8 \cdot 10^{-16}$
$D_{\pm\pm}$, BEO	$39/49$	85	$15/14$	37
$D'_{\pm\pm}$, BEA	$136/49$	$5 \cdot 10^{-8}$	$97/14$	$2 \cdot 10^{-12}$
$D'_{\pm\pm}$, BEO	$40/49$	84	$15/14$	36

stat. errors only

KORALW with LUBOEI excluded

Summary

- At small Q data and MC without BE have

$$\begin{aligned} \Delta\rho_{\pm\pm}(Q) &= 0 \\ D_{\pm\pm}(Q) &= 1 \\ D'_{\pm\pm}(Q) &= 1 \end{aligned}$$

- Hence, no evidence for inter-W BEC
- KORALW with LUBOEI excluded

Ref.: L3 Note 2405
http://l3www.cern.ch/conferences/EPS99/papers/note_2405.ps

Elongation of the Pion Source in Z decays

Data from 1994 run of L3 at LEP, $\sqrt{s} \approx 91.2$ GeV $\approx M_{\mathrm{Z}}$

Select about 1 million hadronic events
with well-measured tracks.

Final data sample: ~36 million like-sign pairs

Recall, simplest assumption:
Space-time distribution of pion emission
is a 4-dimensional Gaussian $\Longrightarrow$

$$R(p_1, p_2) = \frac{\rho_2(p_1, p_2)}{\rho_0(p_1, p_2)} = 1 + \lambda \cdot \text{Gaussian in } (p_1 - p_2)$$

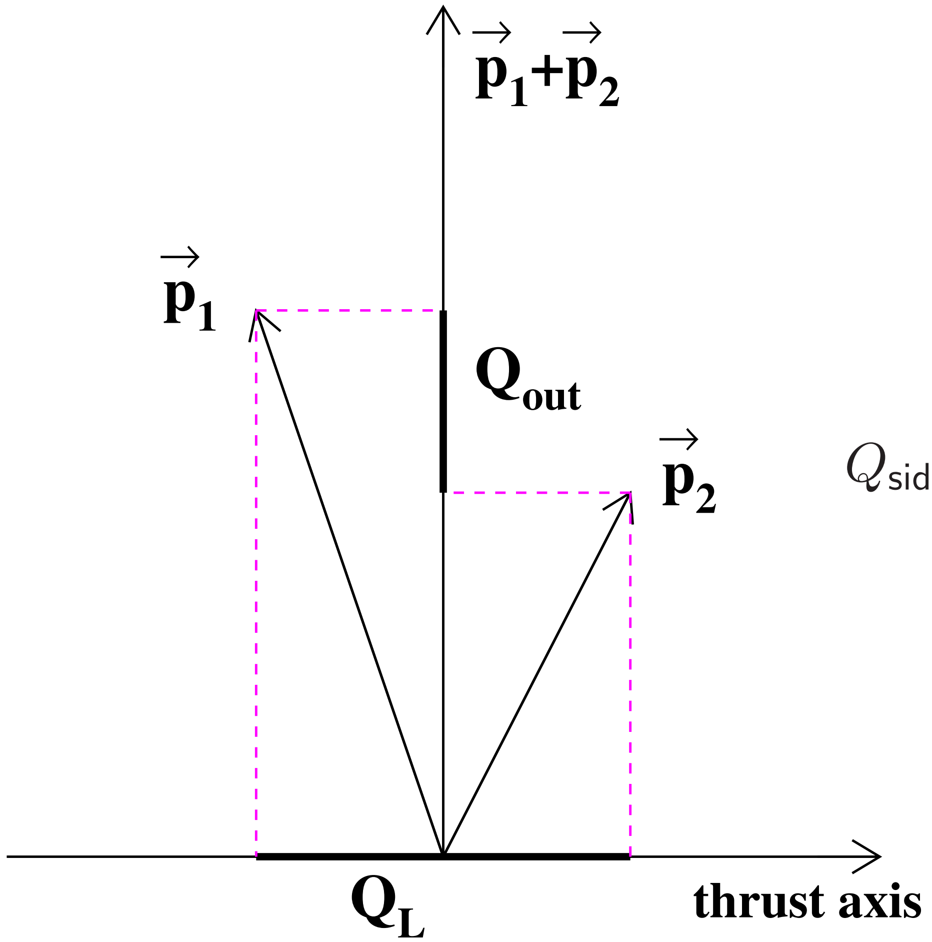
i.e., in the 4-momentum difference, $Q = p_1 - p_2$
where $\rho_0(p_1, p_2)$ = 2-particle density *if* no BE

Since BE effect occurs predominantly at small Q,
often parametrize R as 1-dimensional Gaussian in Q.

This assumes that the 4-dimensional Gaussian
is simply a product of 4 identical 1-dim. Gaussians.
But,
there is no reason to expect this symmetry in $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{q\bar{q}}$.
Therefore, we do a 3-dim. analysis.

LCMS

Boost each π-pair along thrust axis to its
Longitudinal Center of Mass System



$Q_{\text{side}} \perp (Q_{\text{L}}, Q_{\text{out}})$

Advantages of LCMS:

$$\begin{aligned} Q^2 &= Q_{\text{L}}^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 - (\Delta E)^2 \\ &= Q_{\text{L}}^2 + Q_{\text{side}}^2 + Q_{\text{out}}^2 \,(1 - \beta^2) \end{aligned}$$

where $\beta \equiv \frac{p_{\text{out}\,1} + p_{\text{out}\,2}}{E_1 + E_2}$

Thus, the energy difference,
and therefore the difference in emission time of the pions
couples only to the out-component, Q_{out}.

R in the LCMS

Thus,
Q_{L} and Q_{side} reflect only spatial dimensions of the source
Q_{out} reflects a mixture of spatial and temporal dimensions.

Writing R in terms of $\vec{Q} = (Q_{\mathrm{L}}, Q_{\mathrm{side}}, Q_{\mathrm{out}})$

$$R(\vec{Q}) = \frac{\rho_2(\vec{Q})}{\rho_0(\vec{Q})}$$

We measure $\rho_2(\vec{Q})$ from the data.

We measure $\rho_0(\vec{Q})$ from a sample obtained
by mixing tracks from different events

But mixing removes *all* correlations.
Correct $\rho_{\mathrm{mix}}(\vec{Q})$ by applying same procedure to MC events having no simulation of BE (JETSET or HERWIG)

$$\rho_0(\vec{Q}) = \rho_{\mathrm{mix}}(\vec{Q}) \cdot C_{\mathrm{mix}}(\vec{Q}) \ , \quad C_{\mathrm{mix}}(\vec{Q}) = \left[\frac{\rho_2(\vec{Q})}{\rho_{\mathrm{mix}}(\vec{Q})} \right]_{\mathrm{MC,\ noBE}}$$

$\rho_2(\vec{Q})$

$\rho_2(\vec{Q})$ is determined directly from the data

However, the ratio $\frac{\rho_2(\vec{Q})}{\rho_0(\vec{Q})}$ must still be corrected for detector acceptance, efficiency, and resolution to obtain $R(\vec{Q})$

Use multiplicative factor obtained from MC:

$$C_{\text{det}}(\vec{Q}) = \left(\frac{\rho_2(\vec{Q})}{\rho_{\text{mix}}(\vec{Q})}\right)_{\text{gen, pions}} \Bigg/ \left(\frac{\rho_2(\vec{Q})}{\rho_{\text{mix}}(\vec{Q})}\right)_{\text{det, all}}$$

at generator level, using only pions

after detector simulation, reconstruction,
event and track selection;
using all tracks, since L3 cannot identify pions

We use 3 MCs: JETSET with BE, JETSET without BE, HERWIG

Finally,

$$R(\vec{Q}) = \frac{\rho_2(\vec{Q})}{\rho_{\text{mix}}(\vec{Q})} \cdot \frac{1}{C_{\text{mix}}(\vec{Q})} \cdot C_{\text{det}}(\vec{Q})$$

In terms of numbers of events in 3-dimensional bins klm,

$$R_{klm} = \left[\frac{N_{klm}}{N_{klm}^{\text{mix}}}\right]_{\text{data}} \cdot \left[\frac{N_{klm}^{\text{mix}}}{N_{klm}}\right]_{\text{MC, noBE}} \cdot \left[\frac{N_{klm}^{\text{gen}}}{N_{klm}^{\text{gen, mix}}} \cdot \frac{N_{klm}^{\text{det, mix}}}{N_{klm}^{\text{det}}}\right]_{\text{MC}}$$

Parametrization of R

We parametrize $R(\vec{Q})$ by a 3-dimensional Gaussian

$$R(Q_{\mathsf{L}}, Q_{\mathsf{out}}, Q_{\mathsf{side}}) = \gamma \cdot B \cdot (1 + \lambda G)$$

where

- $\gamma =$ normalization (≈ 1)
- $B = (1 + \delta Q_{\mathsf{L}} + \varepsilon Q_{\mathsf{out}} + \xi Q_{\mathsf{side}})$ describes large Q (long-range correlations)
- $\lambda =$ "incoherence", or strength of BE effect
- $G =$ azimuthally symmetric Gaussian

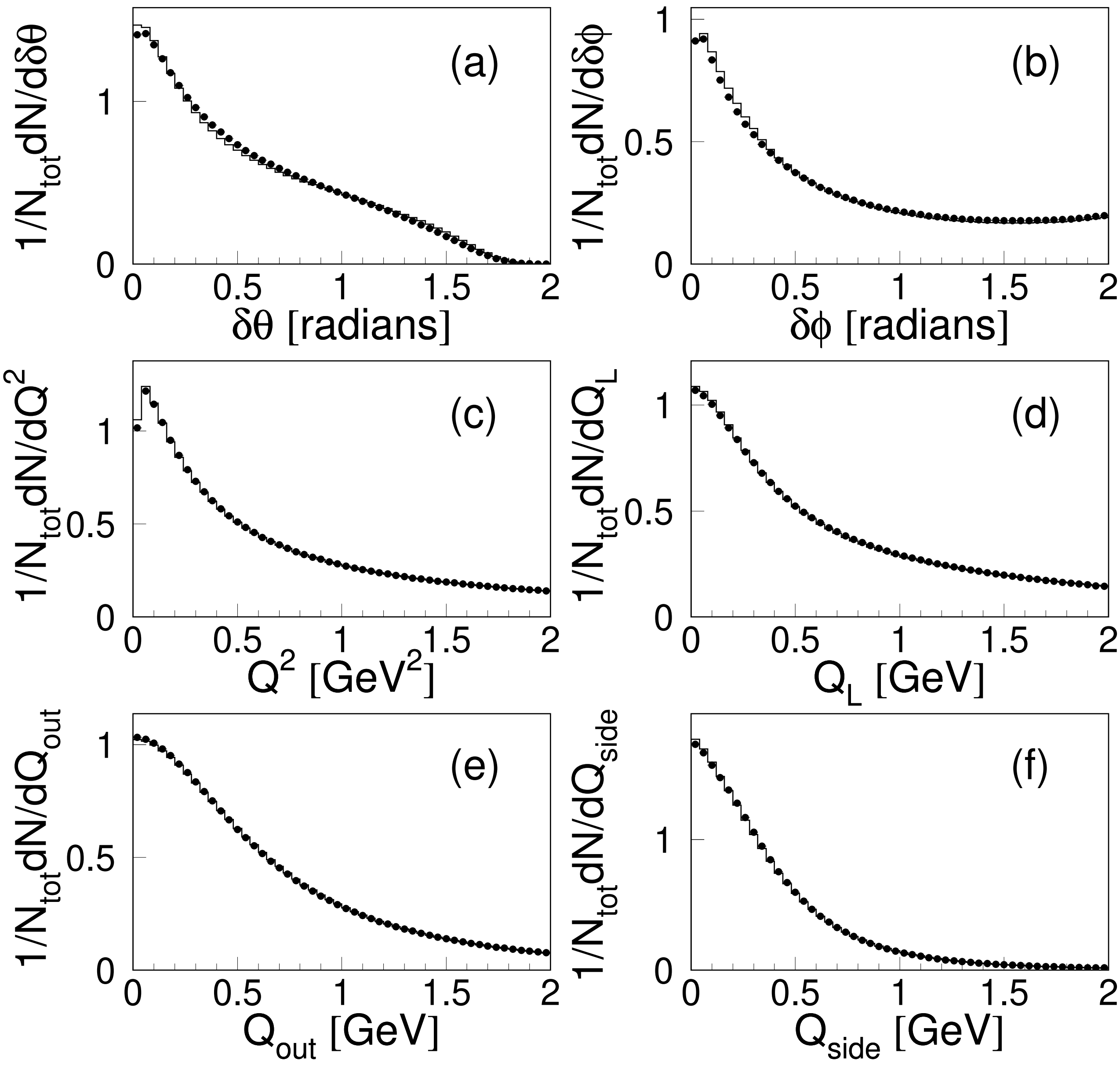
$$\begin{aligned} G &= \exp\big(-R_{\mathsf{L}}^2 Q_{\mathsf{L}}^2 - R_{\mathsf{out}}^2 Q_{\mathsf{out}}^2 - R_{\mathsf{side}}^2 Q_{\mathsf{side}}^2 \\ &\qquad + 2\rho_{\mathsf{L,out}} R_{\mathsf{L}} R_{\mathsf{out}} Q_{\mathsf{L}} Q_{\mathsf{out}}\big) \end{aligned}$$

Fit $R(Q_{\mathsf{L}}, Q_{\mathsf{out}}, Q_{\mathsf{side}})$ to the measured 3-dimensional histogram R_{klm}

Checks on the procedure

Correction procedures are very dependent on MC

- Does MC agree with raw data? YES



- Use different MCs: Differences $\Longrightarrow$ systematic errors

  $C_{\text{mix}}(\vec{Q})$ JETSET without BE, HERWIG

  $C_{\text{det}}(\vec{Q})$ JETSET with BE, JETSET without BE, HERWIG

Checks on the procedure

Analyze MC without BE (JETSET without BE, HERWIG)
as though it were data:

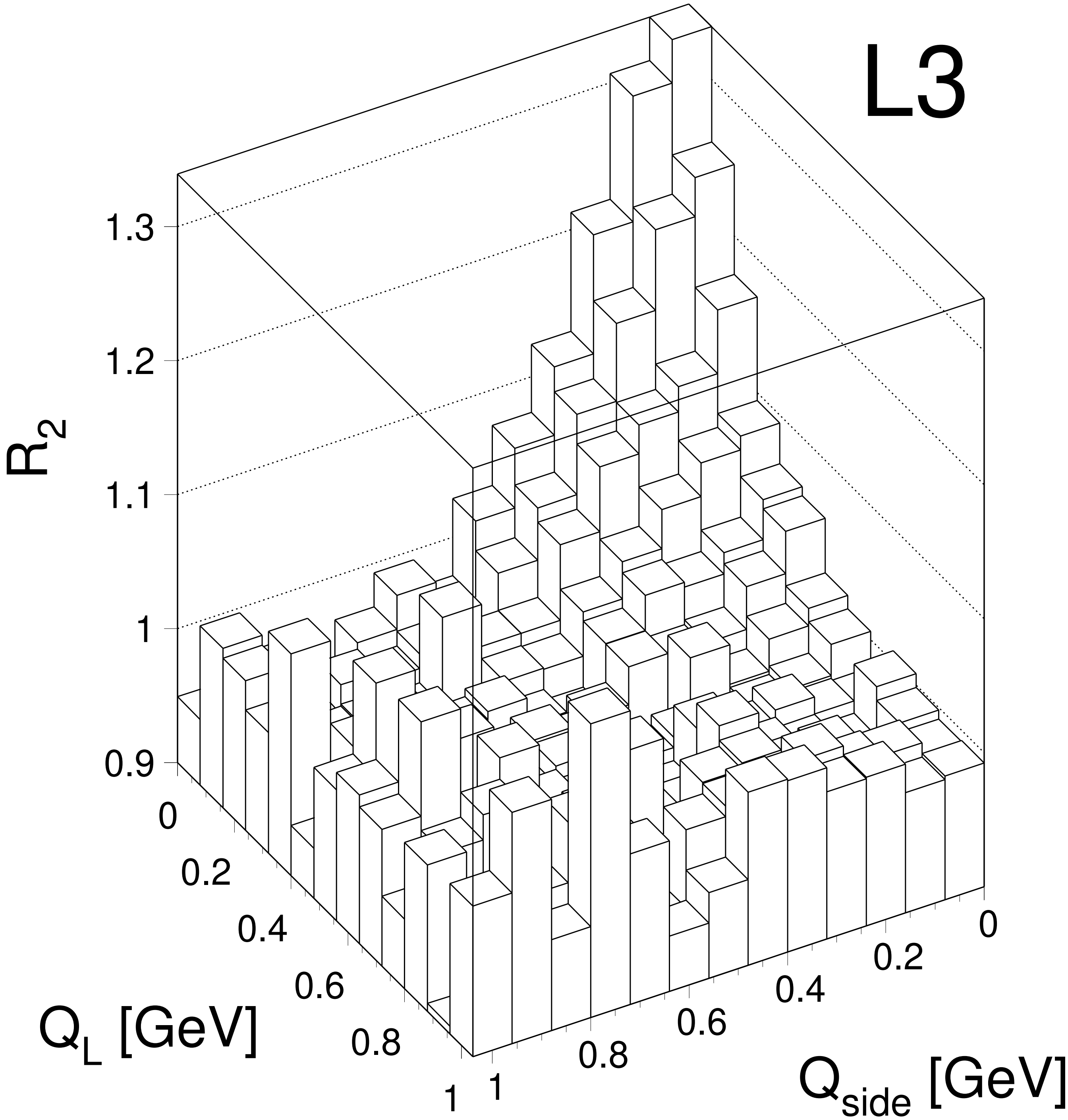
"Data"	C_{mix}	C_{det}
JETSET	JETSET without BE	JETSET with BE
(without BE)	JETSET without BE	HERWIG
	HERWIG	JETSET with BE
	HERWIG	HERWIG
HERWIG	JETSET without BE	JETSET with BE
	JETSET without BE	JETSET without BE
	HERWIG	JETSET with BE
	HERWIG	JETSET without BE

In all 8 cases $\chi^2/\text{DoF} \approx 1$, consistent with $\lambda = 0$
as expected for no BE

Vary track selection criteria,
and upper limit of fit range in Q
Differences $\Longrightarrow$ systematic errors

Results

Difficult to show 3-dim. histogram.
So a projection for $Q_{\text{out}} < 240\,\text{MeV}$:



Results of Gaussian fit to data

Fit $R(Q_{\mathsf{L}}, Q_{\mathsf{out}}, Q_{\mathsf{side}})$ to the measured 3-dimensional histogram R_{klm} in the range $Q_i < 1.04\,\mathsf{GeV}$

Off-diagonal term in Gaussian is consistent with 0
($\rho_{\mathsf{L,out}} = -0.008 \pm 0.057$)
So fix $\rho_{\mathsf{L,out}}$ to 0

Fit has $\chi^2/\mathsf{DoF} = 2314/2189$ – CL $= 3\%$ — not too good

Exponential is often used instead of Gaussian – CL is worse

An approximately Gaussian function can be expanded in terms of derivatives of the Gaussian (Edgeworth expansion)
Keeping only lowest-order non-Gaussian terms,
the Gaussian G in

$$R(Q_{\mathsf{L}}, Q_{\mathsf{out}}, Q_{\mathsf{side}}) = \gamma \cdot B \cdot (1 + \lambda G)$$

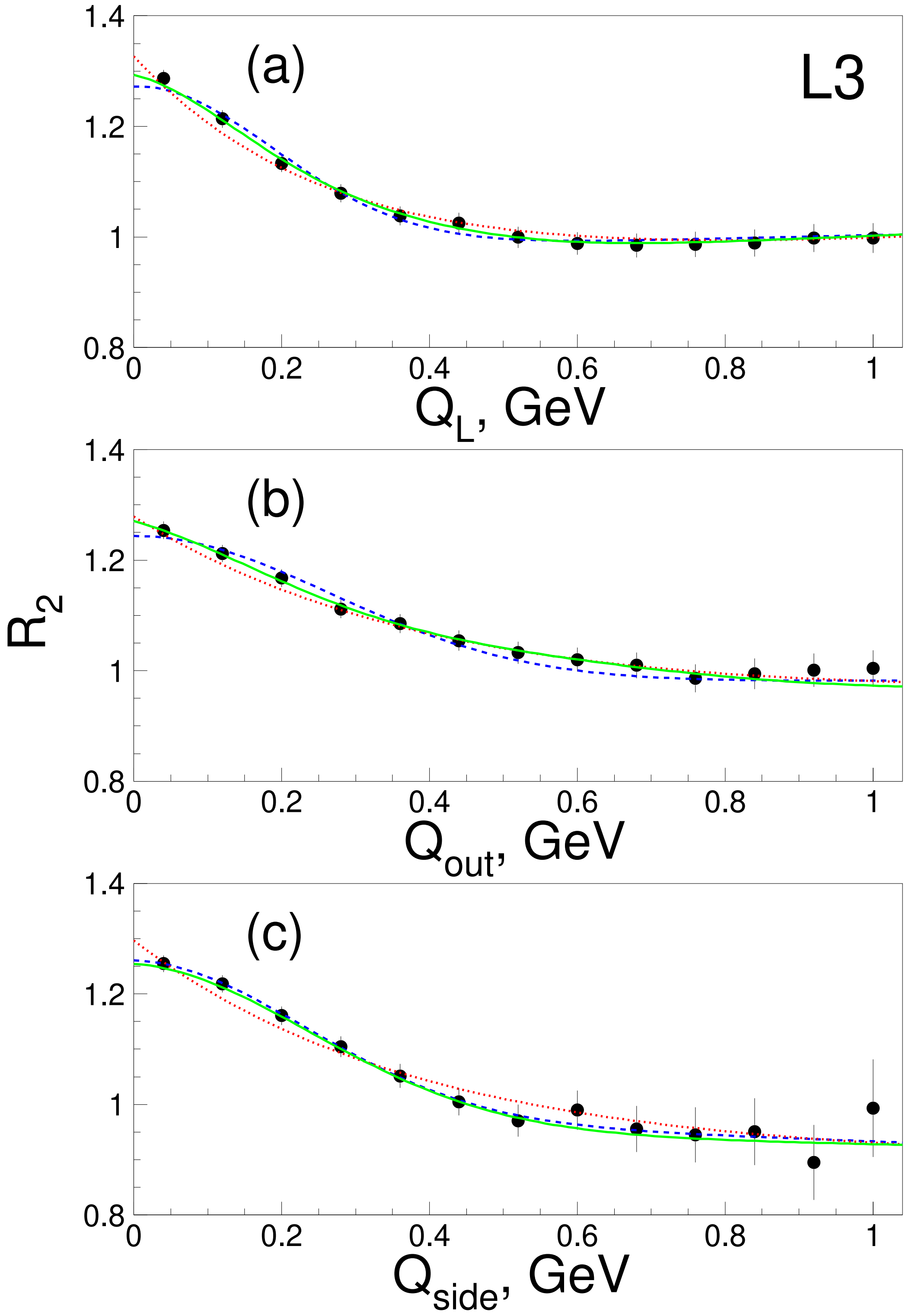
becomes (H_3 is third-order Hermite polynomial)

$$\begin{aligned} G \quad = \quad & \left[\exp\left(-R_{\mathsf{L}}^2 Q_{\mathsf{L}}^2 - R_{\mathsf{out}}^2 Q_{\mathsf{out}}^2 - R_{\mathsf{side}}^2 Q_{\mathsf{side}}^2\right)\right] \\ & \cdot \left[1 + \frac{\kappa_{\mathsf{L}}}{3!} H_3(R_{\mathsf{L}} Q_{\mathsf{L}})\right] \\ & \cdot \left[1 + \frac{\kappa_{\mathsf{out}}}{3!} H_3(R_{\mathsf{out}} Q_{\mathsf{out}})\right] \\ & \cdot \left[1 + \frac{\kappa_{\mathsf{side}}}{3!} H_3(R_{\mathsf{side}} Q_{\mathsf{side}})\right] \end{aligned}$$

Using this, we get CL $= 30\%$

Results

Projections, non-projected $Q_i < 240\,\text{MeV}$



· · · exponential, - - - Gaussian, — Edgeworth

Results

parameter	Gaussian	Edgeworth
λ	$0.41 \pm 0.01^{+0.02}_{-0.19}$	$0.54 \pm 0.02^{+0.04}_{-0.26}$
R_{L} (fm)	$0.74 \pm 0.02^{+0.04}_{-0.03}$	$0.69 \pm 0.02^{+0.04}_{-0.03}$
R_{out} (fm)	$0.53 \pm 0.02^{+0.05}_{-0.06}$	$0.44 \pm 0.02^{+0.05}_{-0.06}$
R_{side} (fm)	$0.59 \pm 0.01^{+0.03}_{-0.13}$	$0.56 \pm 0.02^{+0.03}_{-0.12}$
$R_{\mathsf{out}}/R_{\mathsf{L}}$	$0.71 \pm 0.02^{+0.05}_{-0.08}$	$0.65 \pm 0.03^{+0.06}_{-0.09}$
$R_{\mathsf{side}}/R_{\mathsf{L}}$	$0.80 \pm 0.02^{+0.03}_{-0.18}$	$0.81 \pm 0.02^{+0.03}_{-0.19}$
κ_{L}	–	$0.5 \pm 0.1^{+0.1}_{-0.2}$
κ_{out}	–	$0.8 \pm 0.1 \pm 0.3$
κ_{side}	–	$0.1 \pm 0.1 \pm 0.3$
δ	$0.025 \pm 0.005^{+0.014}_{-0.015}$	$0.036 \pm 0.007^{+0.012}_{-0.023}$
ϵ	$0.005 \pm 0.005^{+0.034}_{-0.012}$	$0.011 \pm 0.005^{+0.037}_{-0.012}$
ξ	$-0.035 \pm 0.005^{+0.031}_{-0.024}$	$-0.022 \pm 0.006^{+0.020}_{-0.025}$
χ^2/DoF	2314/2189	2220/2186
C.L. (%)	3.1	30

- $\lambda > 0$ — the BE effect

- $R_{\mathsf{side}}/R_{\mathsf{L}} < 0$ — more than 5 std. dev.
  Elongation along thrust axis

Conclusion

- Edgeworth fit significantly better than Gaussian
- Elongation of pion source along thrust axis
  $R_{\mathsf{side}}/R_{\mathsf{L}} = 0.81 \pm 0.02^{+0.03}_{-0.19}$

Models which assume a spherical source are too simple.

for transparencies:

`http://home.cern.ch/~metzger/talks.html`