New Bose-Einstein Results from L3:

1. Comparison of π^0-π^0 to $\pi^\pm$-$\pi^\pm$

2. 3-particle, $\pi^\pm$-$\pi^\pm$-$\pi^\pm$

in Hadronic Z Decay

W. J. Metzger

(M. Sanders, J. van Dalen, W. Kittel, W.J. Metzger)

University of Nijmegen

XXXI ISMD

Datong

China

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2-particle BEC $\pi^0\pi^0$ *vs.* $\pi^\pm\pi^\pm$

– Bose-Einstein correlations (BEC) of neutral pions:
  rarely studied, never in e^+e^-

– π^0 source smaller than $\pi^\pm$ source ?

2-particle BEC are studied in terms of correlation function

$$R_2(p_1,p_2) = \frac{\rho(p_1,p_2)}{\rho_0(p_1,p_2)}$$

where $\rho =$ number density

$\rho_0 =$ number density if no BEC (reference sample)

$p_i =$ 4-momentum of particle i

Since BEC at small $Q = \sqrt{-(p_1-p_2)^2} = \sqrt{M_{12}^2 - 4m_\pi^2}$,

$$R_2(Q) = \frac{\rho(Q)}{\rho_0(Q)}$$

Assuming incoherent particle production
and source density $f(x)$ in space-time,

$$R_2(Q) = 1 + \lambda |G(Q)|^2$$

where $G(Q) = \int \mathrm{d}x\, e^{iQx} f(x)$ is the Fourier transf. of $f(x)$

$\lambda \neq 1$ if production not completely incoherent

Assuming $f(x)$ is a Gaussian with radius $R \Longrightarrow$

$$R_2(Q) \propto 1 + \lambda e^{-Q^2R^2}$$

Data π^0

$e^+e^- \rightarrow Z \rightarrow$ hadrons 1994, 1995 78 pb^{-1} L3 at LEP

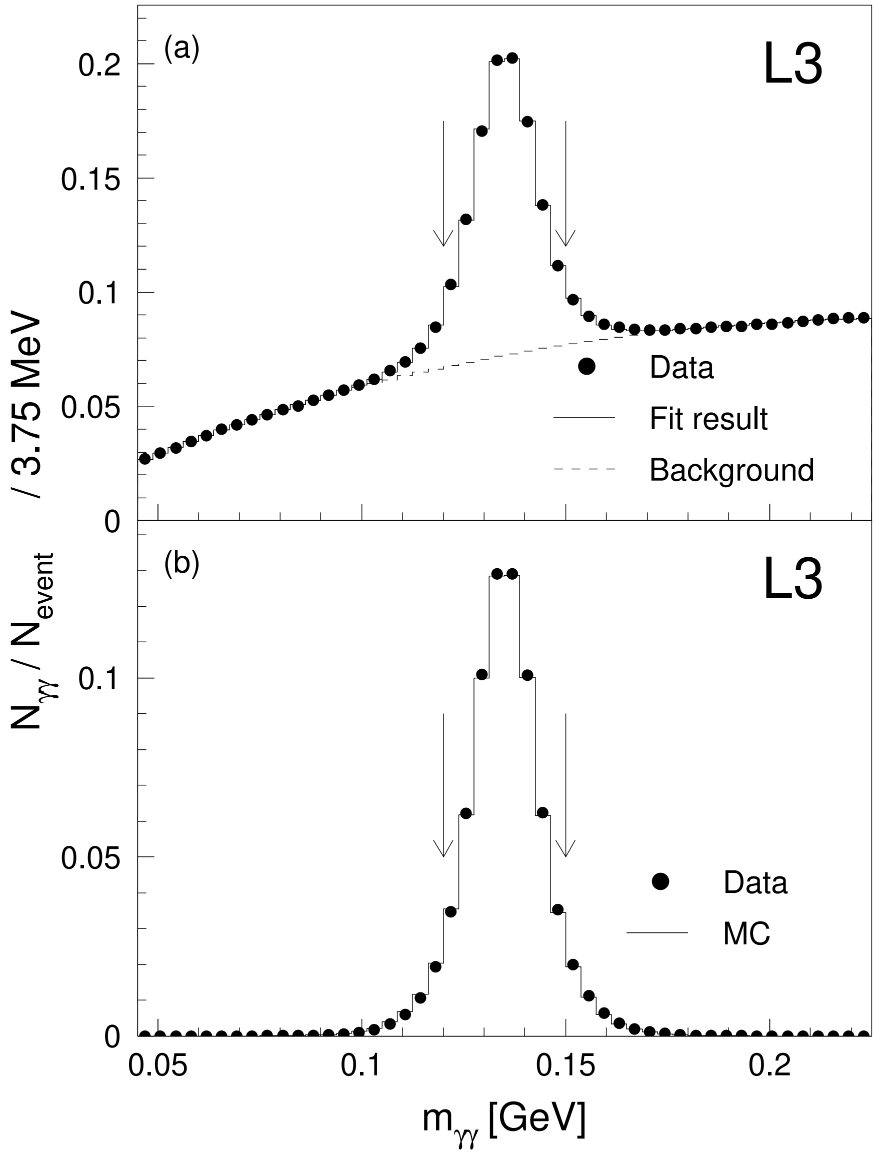
Select photons, $E_\gamma > 100\,\mathrm{MeV}$, using neural network based on shower shapes in BGO EM calorimeter

and no charged track pointing to photon cluster

Require $E_{\gamma\gamma} < 6\,\mathrm{GeV}$ – photons separated in calorimeter

We see π^0's:

in agreement with MC



Eff. = 17% Purity = 54% Mass Resolution = 7.4 MeV

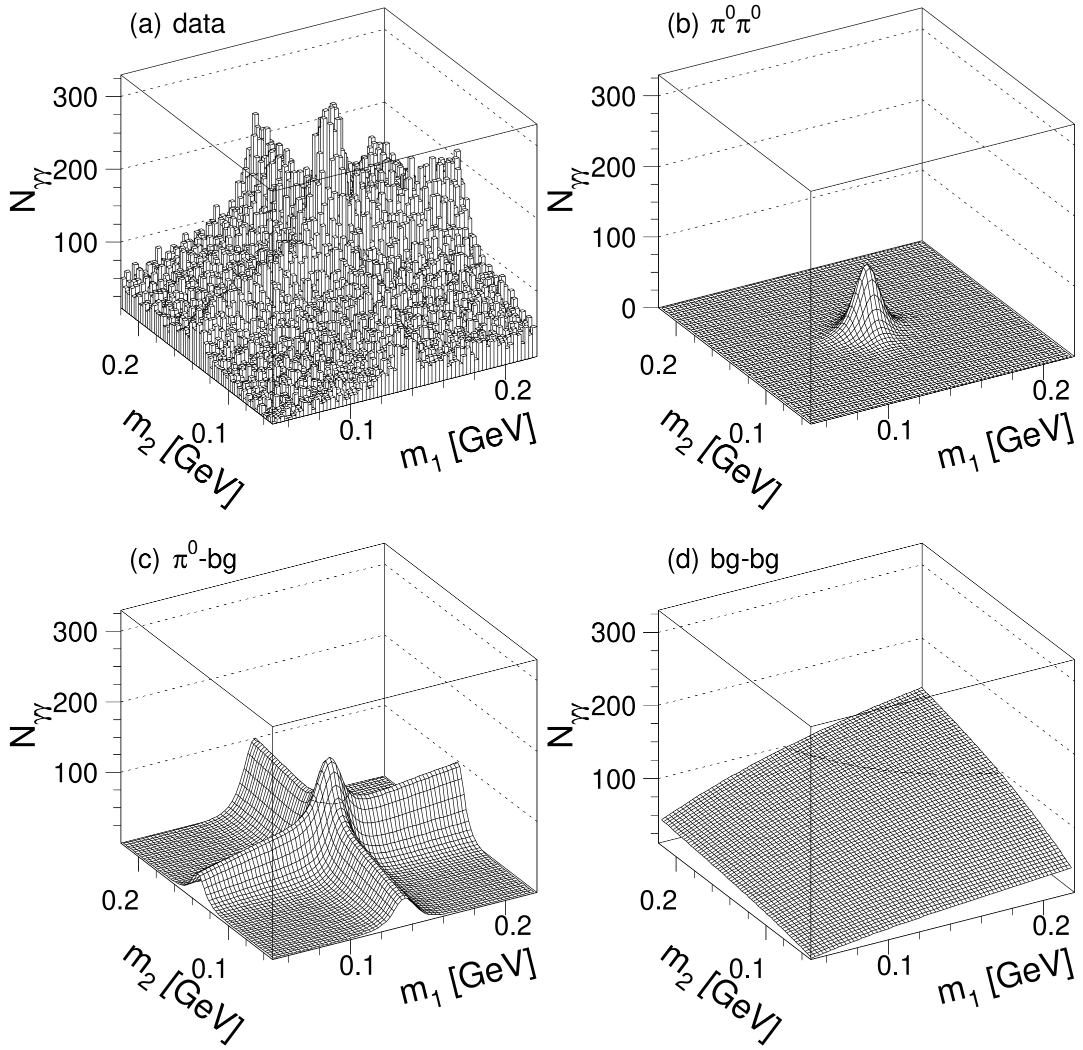
π^0 - π^0

Fit $M_{\gamma_1\gamma_2}$ *vs.* $M_{\gamma_3\gamma_4}$ in bins of $Q(\gamma_1\gamma_2, \gamma_3\gamma_4)$ with

$$\begin{aligned} f(M_{\gamma_1\gamma_2}, M_{\gamma_3\gamma_4}) &= A_{\pi\pi} f_\pi(M_{\gamma_1\gamma_2}) f_\pi(M_{\gamma_3\gamma_4}) \\ &+ A_{\pi\mathrm{bg}} \left[f_\pi(M_{\gamma_1\gamma_2}) f_{\mathrm{bg}}(M_{\gamma_3\gamma_4}) \right. \\ &\qquad \left. + f_\pi(M_{\gamma_3\gamma_4}) f_{\mathrm{bg}}(M_{\gamma_1\gamma_2}) \right] \\ &+ A_{\mathrm{bgbg}} f_{\mathrm{bgbg}}(M_{\gamma_1\gamma_2}, M_{\gamma_3\gamma_4}) \end{aligned}$$

$\Longrightarrow$ number of π^0-π^0 pairs, $A_{\pi\pi}(Q)$

E.g., $0.48 < Q < 0.52$ GeV



π^0 - π^0

Exclude region $Q < 300\,\text{MeV}$ because

- Efficiency strongly dependent on MC generator
- For $\eta \rightarrow \pi^0\pi^0\pi^0$, $Q(\pi^0, \pi^0) < 311.7\,\text{MeV}$

$\pi^\pm$ - $\pi^\pm$

Using well-measured tracks,
As for π^0 - π^0,

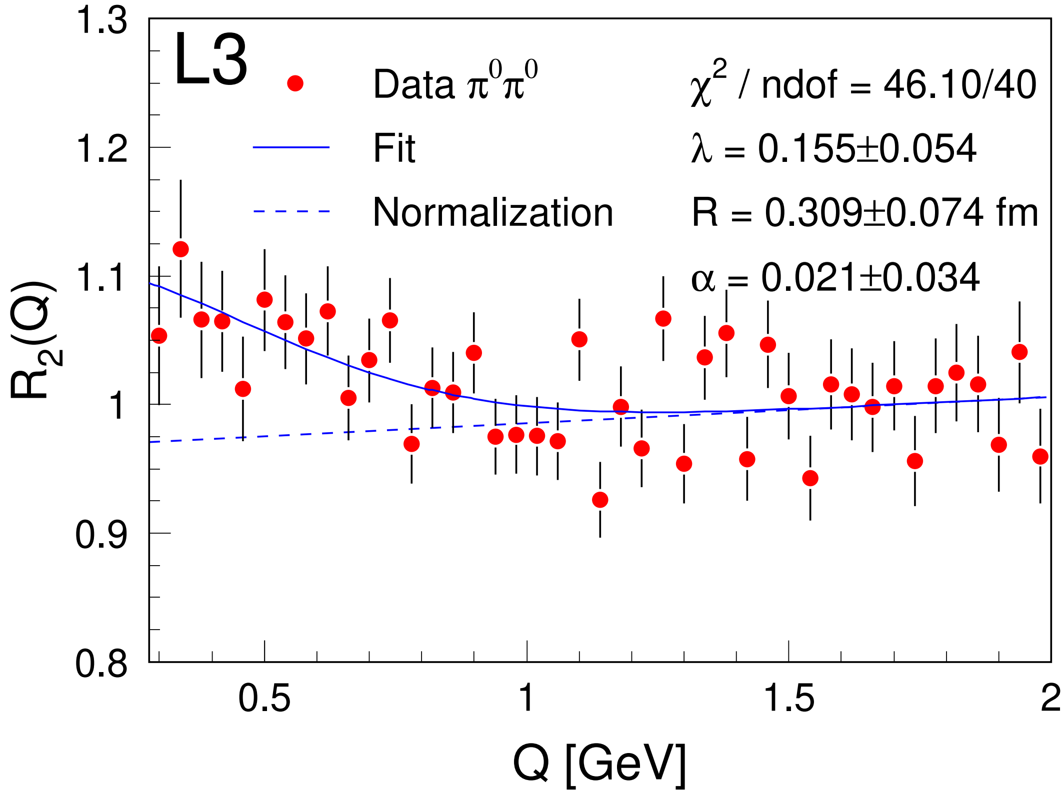
- Require $0.2 < E_\pi < 6$ GeV

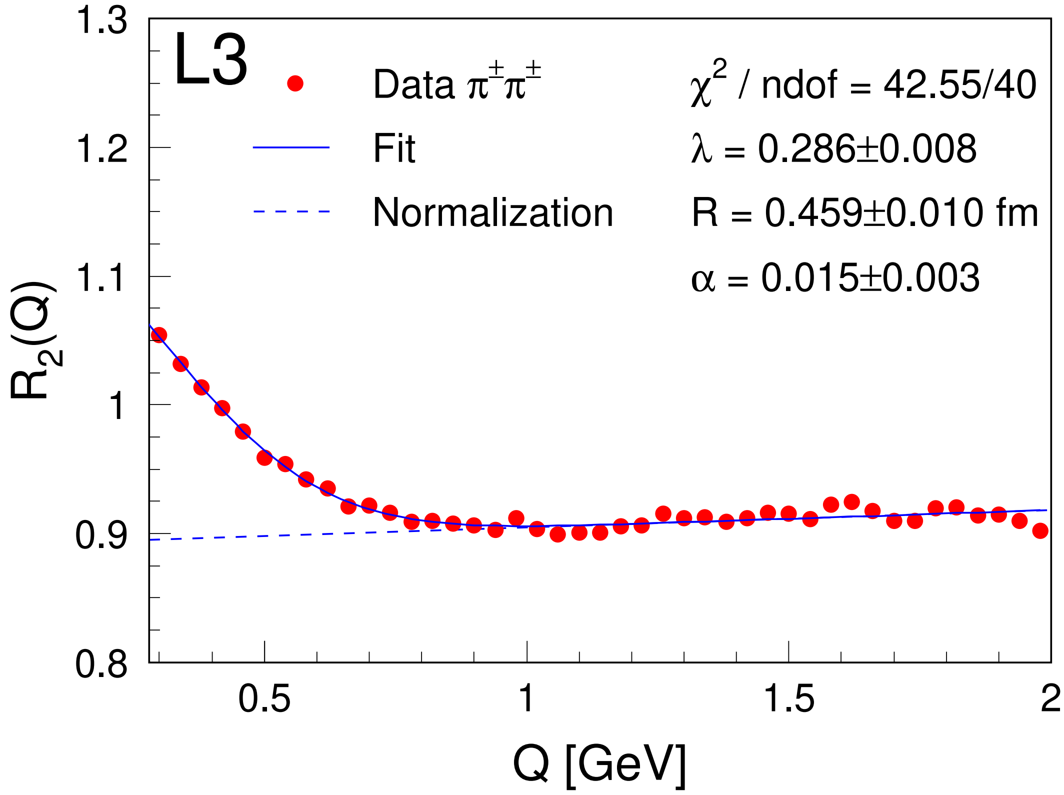
Reference Sample ρ_0

Use JETSET MC with no BE for both π^0 and $\pi^\pm$.

π^0 - π^0 *vs.* $\pi^\pm$ - $\pi^\pm$

Using $$R_2(Q) = \frac{\rho(Q)}{\rho_0(Q)} \propto (1 + \alpha Q)(1 + \lambda e^{-Q^2R^2})$$





π^0 - π^0 *vs.* $\pi^\pm$ - $\pi^\pm$

	$\pi^\pm$-$\pi^\pm$	π^0-π^0
λ	$0.286 \pm 0.008 \pm 0.025$	$0.155 \pm 0.054 \pm 0.072$
R (fm)	$0.459 \pm 0.010 \pm 0.010$	$0.309 \pm 0.074 \pm 0.070$

$$R_{\pm\pm} - R_{00} = 0.15 \pm 0.08 \pm 0.07 \text{ fm}$$

$$R_{00} \,/\, R_{\pm\pm} = 0.67 \pm 0.16 \pm 0.15$$

3-particle BEC

3-particle BEC are studied in terms of correlation function

$$R_3(p_1,p_2,p_3) = \frac{\rho_3(p_1,p_2,p_3)}{\rho_0(p_1,p_2,p_3)}$$

where

$$\begin{aligned}
\rho_3(p_1,p_2,p_3) &= \rho_1(p_1)\rho_1(p_2)\rho_1(p_3) \\
&+ \sum_{\substack{3 \\ \text{perm}}} \left[\rho_1(p_1)\left(\rho_2(p_2,p_3) - \rho_1(p_2)\rho_1(p_3)\right)\right] \\
&+ C_3(p_1,p_2,p_3)
\end{aligned}$$

C_3 (3rd-order cumulant) measures genuine 3-particle correlations

Since BEC at small Q_3 $\quad (Q_3^2 = M_{123}^2 - 9m_\pi^2 = Q_{12}^2 + Q_{23}^2 + Q_{13}^2)$

we use

$$\begin{aligned}
R_3(Q_3) &= \frac{\rho(Q_3)}{\rho_0(Q_3)} \\
R_3^{\text{noBEC}} &= 1 \qquad (\text{def. of } \rho_0) \\
R_3^{\text{nongen}}(Q_3) &= 1 + \sum_{\substack{3 \ \text{perm} \\ Q_3}} \frac{\rho_1\rho_2}{\rho_0} - 3 \\
R_3^{\text{genuine}}(Q_3) &= 1 + \frac{C_3(Q_3)}{\rho_0(Q_3)} \\
R_3(Q_3) &= R_3^{\text{nongen}}(Q_3) + R_3^{\text{genuine}}(Q_3) - 1
\end{aligned}$$

3-particle BEC

Assuming completely incoherent particle production
and source density $f(x)$ in space-time,
with Fourier transform $G(Q) = \int \mathrm{d}x\, e^{iQx} f(x) = Ge^{i\phi}$,
we have

$$R_2(Q) = 1 + \lambda |G(Q)|^2 \quad , \qquad \lambda = 1$$

$$R_3(Q_3) = 1 + \underbrace{\lambda \left(|G(Q_{12})|^2 + |G(Q_{23})|^2 + |G(Q_{13})|^2\right)}_{\text{from 2-particle BEC}}$$

$$+ \underbrace{2\lambda^{1.5}\, \mathrm{Re}\{G(Q_{12})G(Q_{23})G(Q_{13})\}}_{\text{from genuine 3-particle BEC}}$$

$$R_3^{\text{genuine}} = 1 + 2\lambda^{1.5}\, \mathrm{Re}\{G(Q_{12})G(Q_{23})G(Q_{13})\}$$

$$\cos\phi = \frac{R_3^{\text{genuine}}(Q_3) - 1}{2\sqrt{(R_2(Q_{12}) - 1)(R_2(Q_{23}) - 1)(R_2(Q_{13}) - 1)}}$$

where $\phi = \phi_{12} + \phi_{23} + \phi_{13}$

$$\cos\phi = \frac{R_3^{\text{genuine}}(Q_3) - 1}{2\sqrt{R_2(Q_3) - 1}} \qquad \text{if } f(x) \text{ is Gaussian}$$

Completely incoherent particle production implies

$$\lambda = 1 \qquad\qquad \cos\phi = 1$$

3-particle BEC

Completely incoherent particle production implies

$$\lambda = 1 \qquad\qquad \cos\phi = 1$$

But $\lambda < 1$ can occur for other reasons than coherence
$e.g.$, dilution from long-lived resonances,
large $R \Rightarrow$ BE effect only at very low (irresolvable) Q

Our main goal: to test if $\cos\phi = 1$

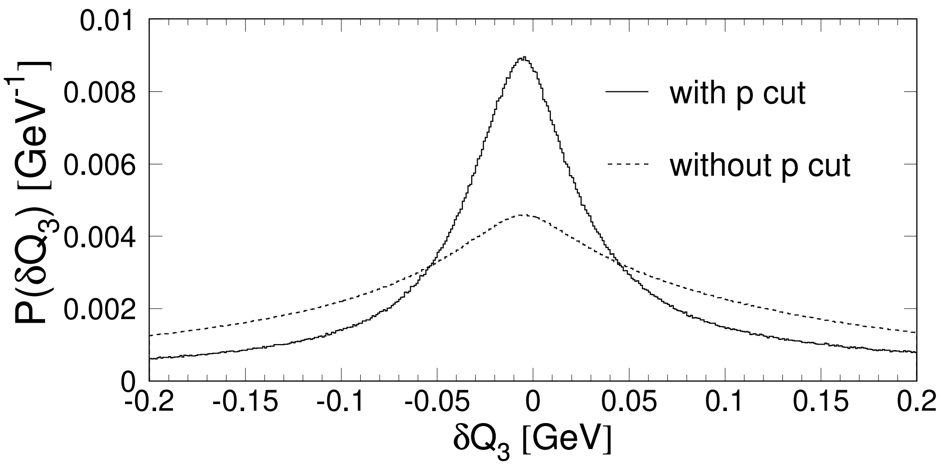
On the way, we measure R_2, R_3, R_3^{nongen}, R_3^{genuine}

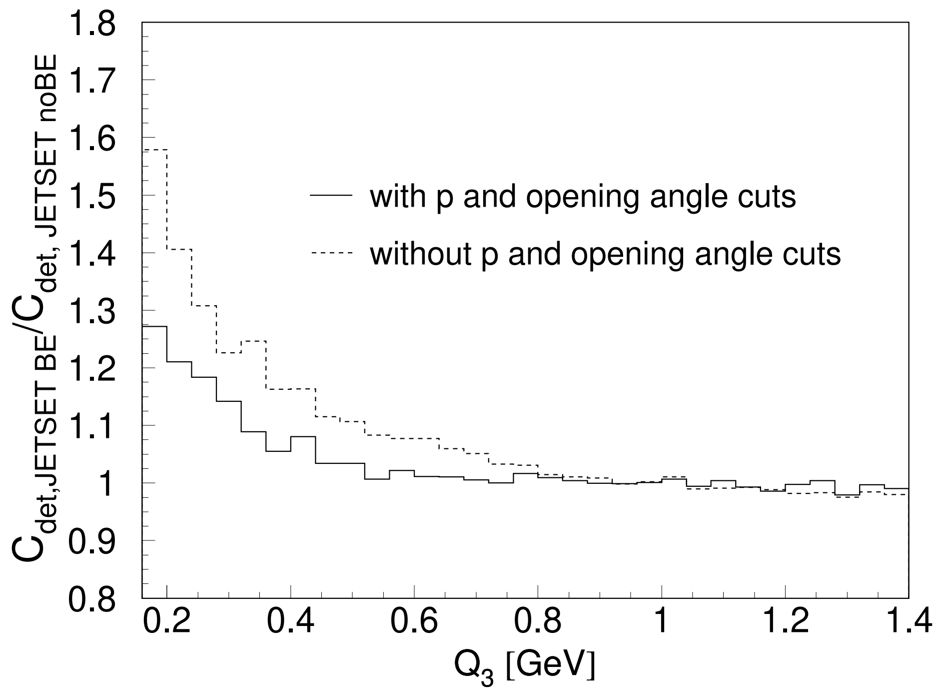
Data for 3-particle BEC

$e^+e^- \longrightarrow Z \longrightarrow$ hadrons 1994 $\sim$ 1M events L3 at LEP

Cuts to improve resolution and decrease MC dependence

- $|\vec{p}| < 1$ GeV
- opening angle of pairs of tracks $> 3°$





Corrections

Coulomb Correction

To remove effect of Coulomb repulsion on Q distribution of like-sign pairs,
weight pairs by inverse Gamow factor

$$W(\eta) = \frac{\exp(2\pi\eta) - 1}{2\pi\eta}\,, \quad \text{where } \eta = \frac{m_\pi \alpha}{Q}$$

and weight triplets by $W(\eta_{12})W(\eta_{23})W(\eta_{13})$

In smallest Q bin, correction is
$\sim$10% for R_3, $\sim$2% for R_2

Detector Correction

for resolution, acceptance, particle non-identification:

$$\rho = \rho_{\text{raw}} C_{\text{det}} \quad , \quad C_{\text{det}} = \left[\frac{\rho}{\rho_0}\right]_{\text{gen,pions}} \Bigg/ \left[\frac{\rho}{\rho_0}\right]_{\text{det,all}}$$

$\boldsymbol{R}$

ρ_0 is found from a mixed event sample:

1. Rotate all events so that thrust axis = z-axis
2. From an event make a mixed event by replacing each track by a track from a different, randomly chosen event having approx. same multiplicity

Event mixing removes ALL correlations.
Correct by MC with no BEC:

$$\rho_0 = \rho_{\text{mix}} C_{\text{mix}} \quad , \quad C_{\text{mix}} = \left[\frac{\rho}{\rho_{\text{mix}}} \right]_{\text{MC,noBE}}$$

Hence,

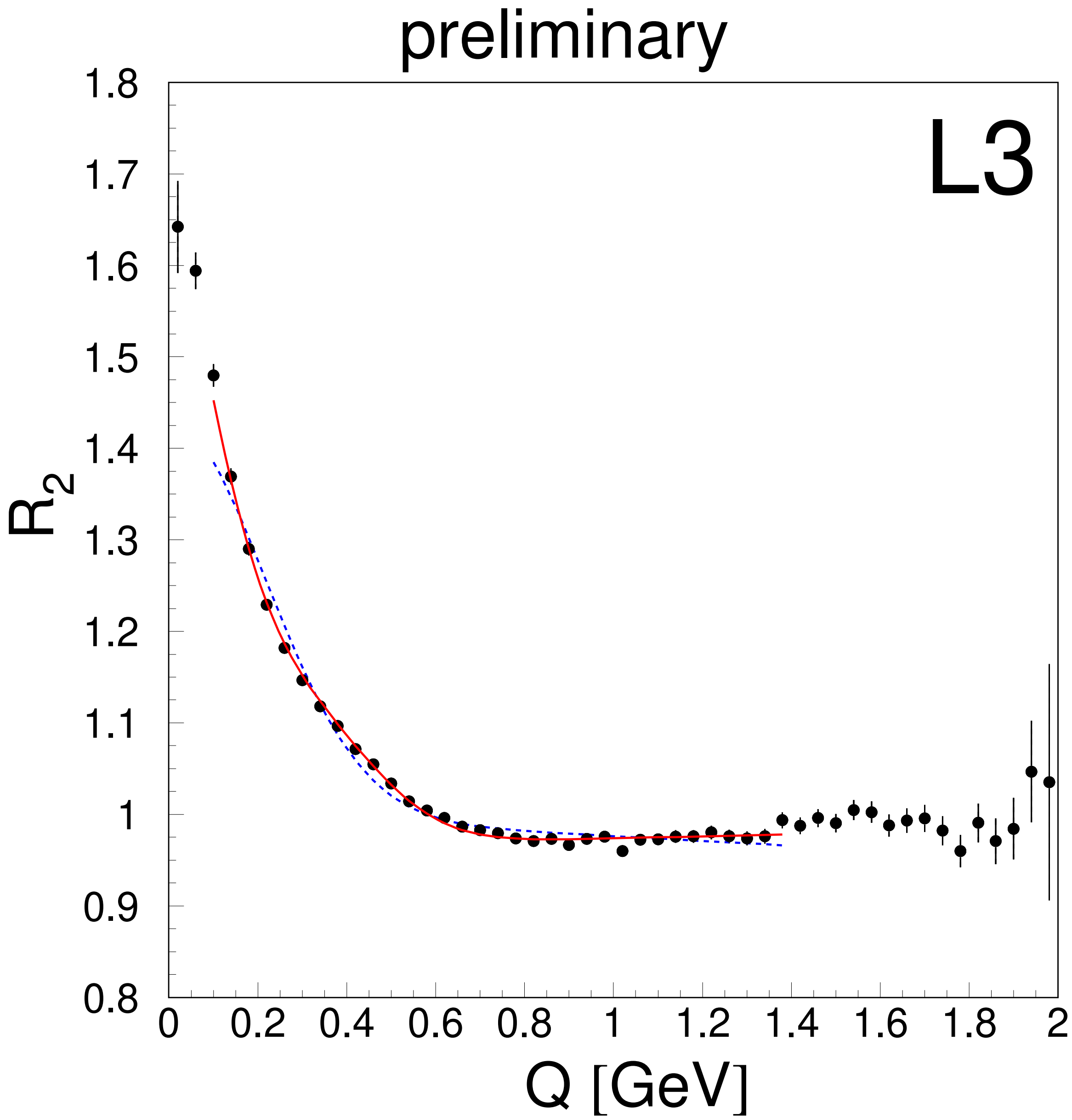
$$R = \frac{\rho}{\rho_0} = \frac{\rho_{\text{raw}}\, C_{\text{det}}}{\rho_{\text{mix}}\, C_{\text{mix}}}$$

C_{det} from JETSET+BE$_0$, JETSET NOBE, HERWIG

C_{mix} from JETSET NOBE, HERWIG
$\Longrightarrow$ **6** MC combinations for corrections
Differences $\longrightarrow$ systematic errors (dominant contrib.)
Other syst. errors from event, track selection

For $Q_3 < 0.16$ GeV, statistics poor and corrections large.
So do not use.
To be consistent, also do not use $Q < 0.08$ GeV.

R_2



Gaussian source:

$$- - - \ R_2 = \gamma(1+\epsilon Q)\left[1+\lambda e^{-R^2Q^2}\right]$$

Better fit for approx. Gaussian – Edgeworth expansion

cf. L3, *Phys. Lett.* **B458**(1999)517

$$\text{——}\ R_2 = \gamma(1+\epsilon Q)\left[1+\lambda e^{-R^2Q^2} \cdot \left(1+\kappa H_3(\sqrt{2}RQ)/6\right)\right]$$

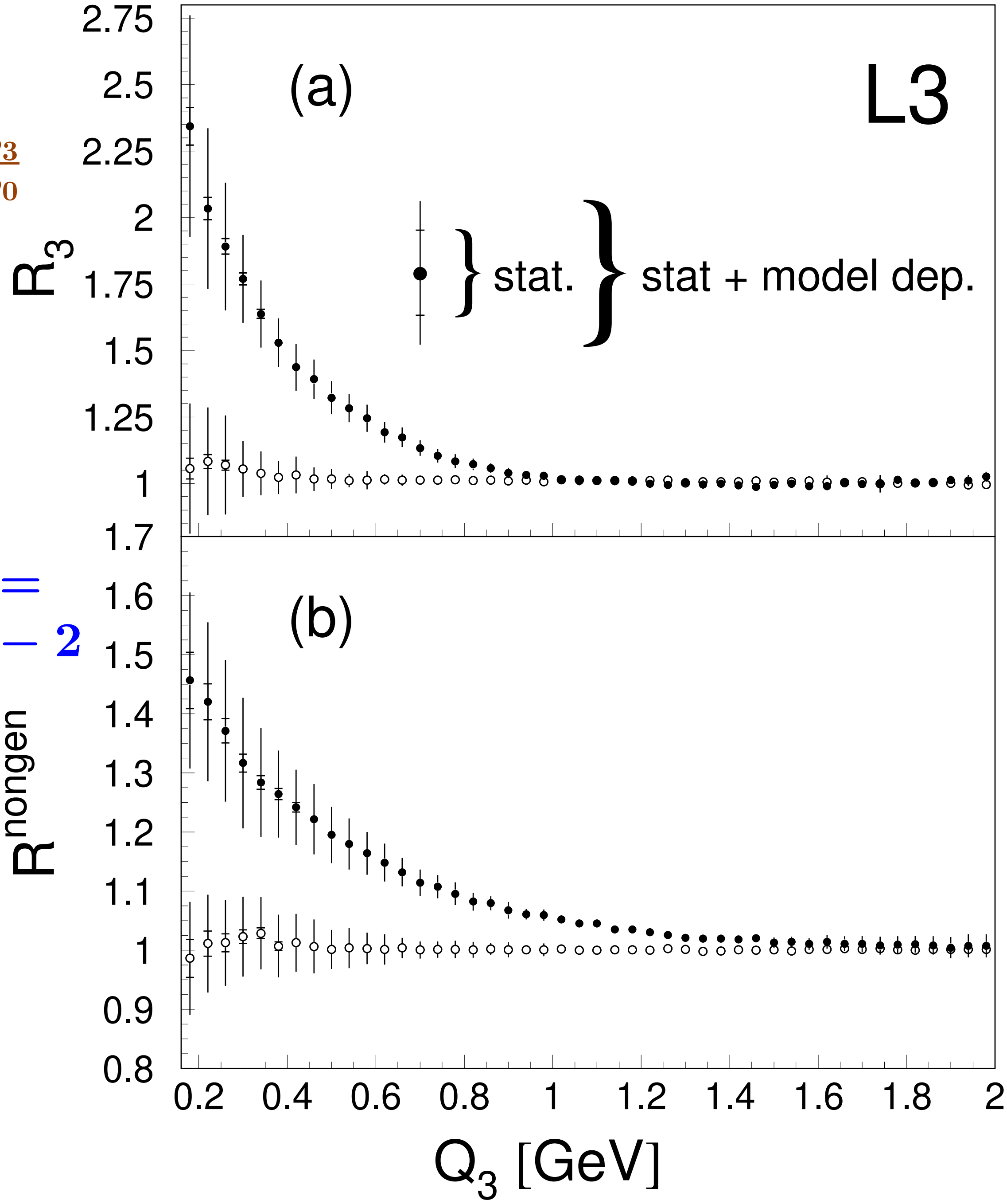
(H_3 = 3rd order Hermite polynomial)

R_3

preliminary

$R_3 = \frac{\rho_3}{\rho_0}$

$R_3^{\text{nongen}} = \sum \frac{\rho_1 \rho_2}{\rho_0} - 2$

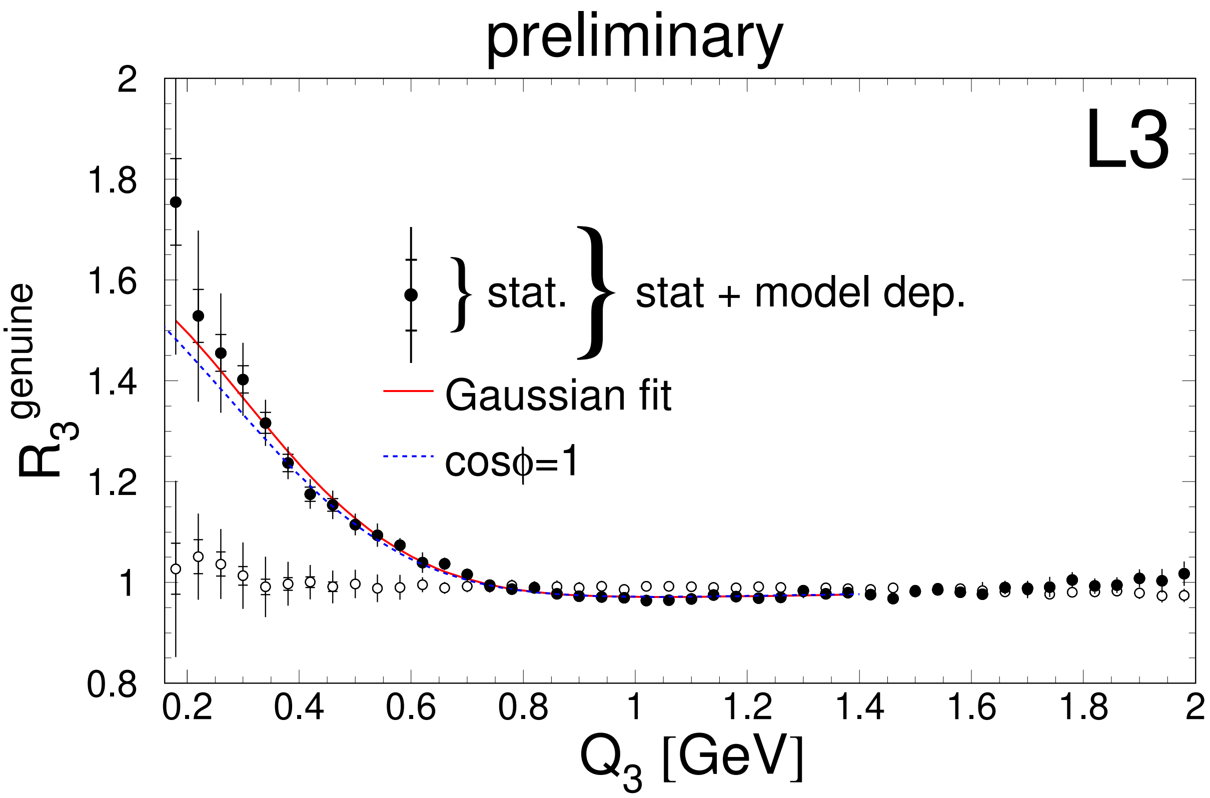


o – JETSET noBE instead of data

Then R_3^{genuine} from $R_3^{\text{genuine}}(Q_3) = R_3 - R_3^{\text{nongen}}(Q_3) + 1$

Syst. errors on R_3 and R_3^{nongen} are correlated.

R_3^{genuine}



o – JETSET noBE instead of data

Gaussian source:

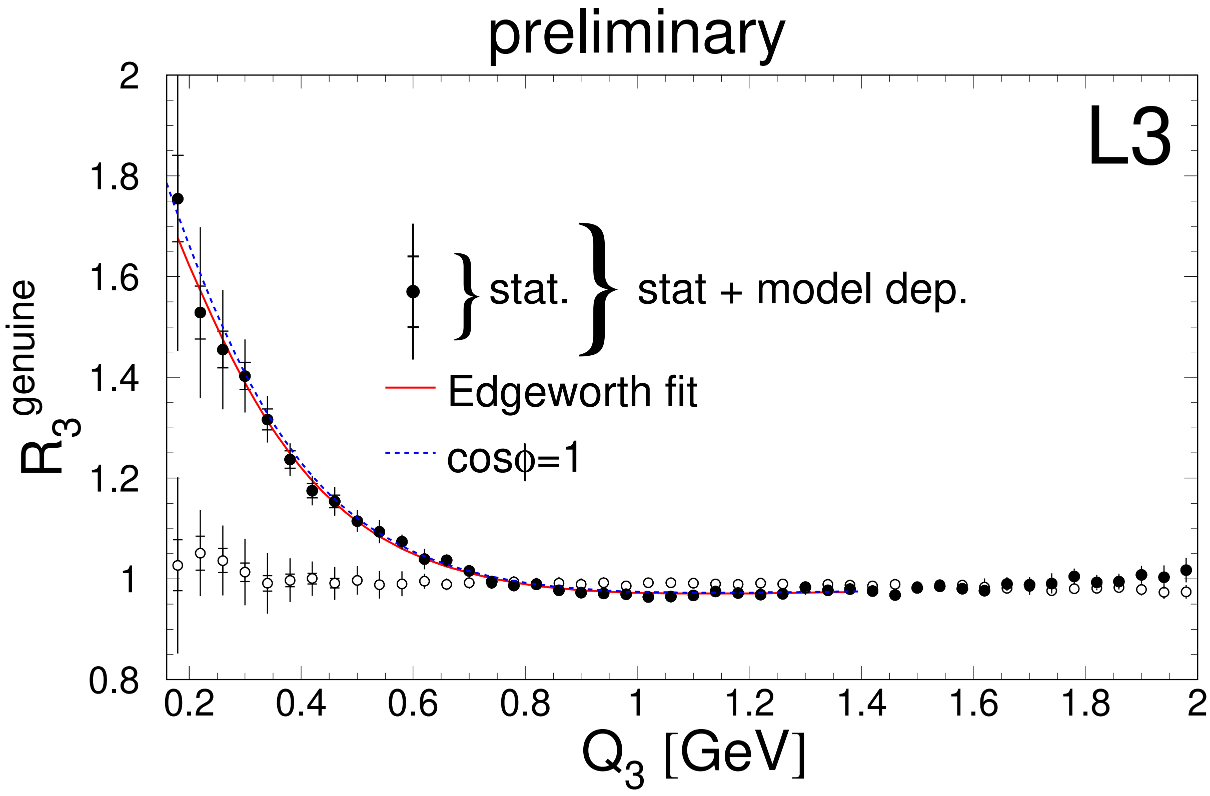
—— $R_3^{\text{genuine}}(Q_3) = \gamma(1+\epsilon Q_3)\left[1 + 2\lambda^{1.5} e^{-R^2 Q_3^2/2}\right]$

- - - Expectation from R_2 (Gaussian fit) assuming $\cos\phi = 1$,

$$R_3^{\text{genuine}}(Q_3) = 1 + 2\sqrt{R_2(Q_3) - 1}$$

$\Longrightarrow \cos\phi \approx 1$

R_3^{genuine}



Approx. Gaussian source (Edgeworth expansion):

— $R_3^{\text{genuine}}(Q_3)$ fit

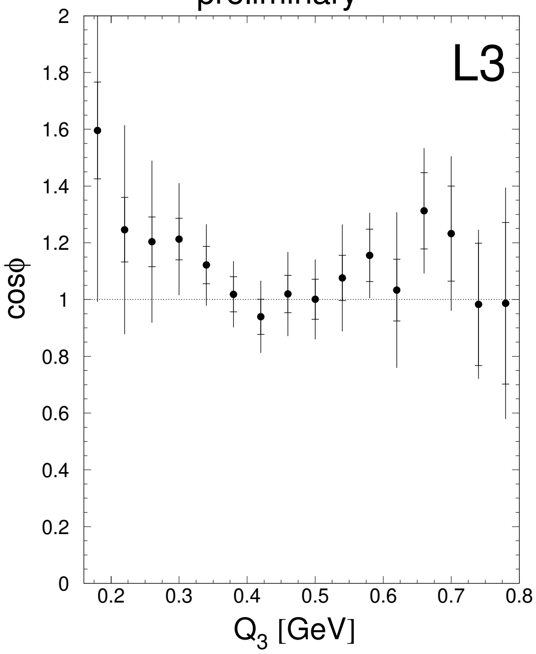
- - - Expectation from R_2 (Edgeworth fit) assuming $\cos\phi = 1$,

$\Longrightarrow \cos\phi \approx 1$

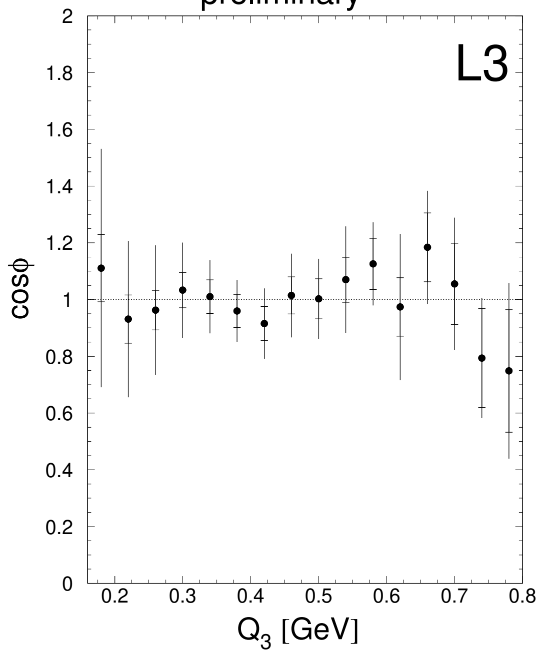
$$\cos\phi = \frac{R_3^{\text{genuine}}(Q_3)-1}{2\sqrt{R_2(Q_3)-1}}$$

Using R_3^{genuine} from data, R_2 from fit

Gaussian



Edgeworth



Conclusion: Data consistent with $\cos\phi = 1$,

Fit results:

from		Gaussian	Edgeworth
R_2	λ	$0.46 \pm 0.01 \pm 0.02$	$0.72 \pm 0.02 \pm 0.07$
R_3^{genuine}		$0.50 \pm 0.03 \pm 0.06$	$0.72 \pm 0.04 \pm 0.07$
R_2	R	$0.65 \pm 0.01 \pm 0.03$	$0.73 \pm 0.02 \pm 0.04$
R_3^{genuine}	(fm)	$0.66 \pm 0.03 \pm 0.05$	$0.72 \pm 0.04 \pm 0.05$

Values of λ, R from Gaussian, Edgeworth are different

Values of λ, R from R_2 and R_3^{genuine} are consistent.

Conclusions

1. Comparison of π^0-π^0 to $\pi^\pm$-$\pi^\pm$

$$
\begin{aligned}
R_{\pm\pm} - R_{00} &= 0.15 \pm 0.08 \pm 0.07 \text{ fm} \\
R_{00} \,/\, R_{\pm\pm} &= 0.67 \pm 0.16 \pm 0.15
\end{aligned}
$$

2. 3-particle, $\pi^\pm$-$\pi^\pm$-$\pi^\pm$

   Data consistent with $\cos\phi = 1$,
   $i.e.$, with completely incoherent particle production