Bose-Einstein and Other Correlations in Hadronic Z Decay

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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 $\left(Q_3^2 = M_{123}^2 - 9m_\pi^2 = Q_{12}^2 + Q_{23}^2 + Q_{13}^2\right)$

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

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

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

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

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

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

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

where $\omega = \cos(\phi_{12} + \phi_{23} + \phi_{13})$

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

Completely incoherent particle production implies

$$\lambda = 1 \qquad\qquad \omega = 1$$

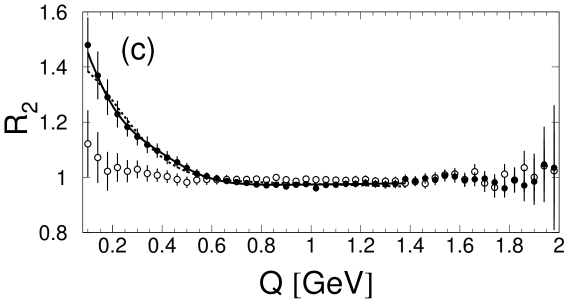
3-particle BEC

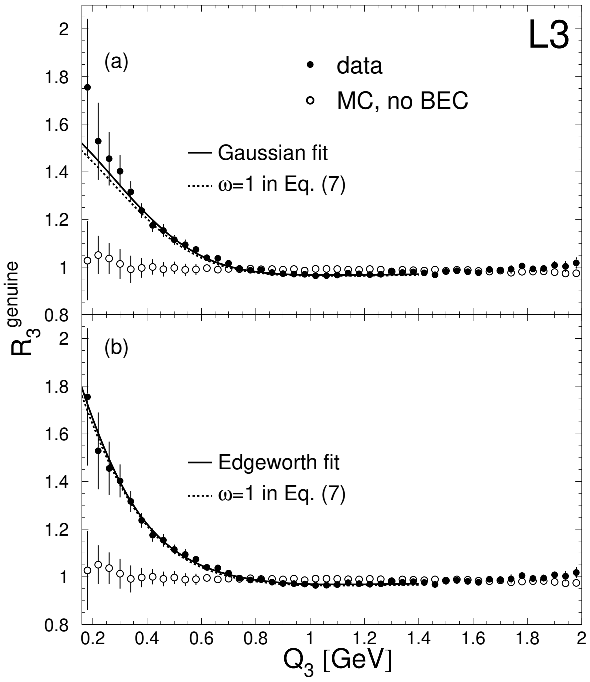
Completely incoherent particle production implies

$$\lambda = 1 \qquad\qquad \omega = 1$$

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

L3 measures R_2, R_3, R_3^{nongen}, R_3^{genuine} Phys. Lett. B540(2002)185



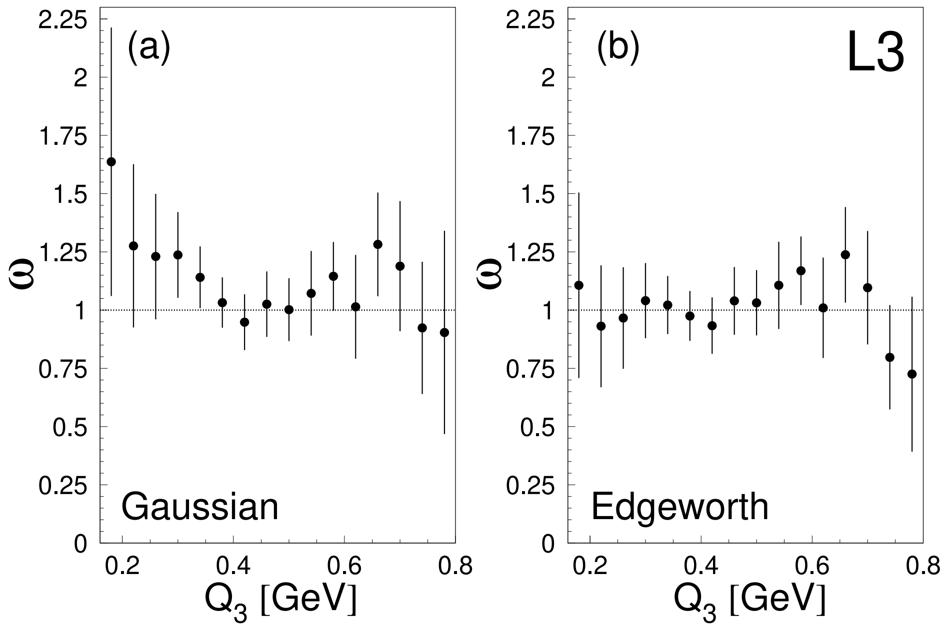


R_2:
- - - Gaussian $\chi^2 = 60$, 29 dof
——Edgeworth $\chi^2 = 26$, 28 dof

R_3^{genuine}:
Gaussian $\chi^2 = 30$, 27 dof
Edgeworth $\chi^2 = 18$, 26 dof

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

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



Conclusion: Data consistent with $\omega = 1$,

$i.e.$, with completely incoherent pion production

Possibly a problem for string models!

Fit results:

from		Gaussian	Edgeworth
R_2	λ	$0.45 \pm 0.06 \pm 0.03$	$0.72 \pm 0.08 \pm 0.03$
R_3^{genuine}		$0.47 \pm 0.07 \pm 0.03$	$0.75 \pm 0.10 \pm 0.03$
R_2	R	$0.65 \pm 0.03 \pm 0.03$	$0.74 \pm 0.06 \pm 0.02$
R_3^{genuine}	(fm)	$0.65 \pm 0.06 \pm 0.03$	$0.72 \pm 0.08 \pm 0.03$

Values of λ, R from Gaussian, Edgeworth are different

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

2-particle BEC $\pi^0\pi^0$ and $\pi^\pm\pi^\pm$

- Many measurements of BEC with charged π's
- but few with π^0's
  in e^+e^-: L3, P.L. B524 (2002) 55
  OPAL, CERN-EP/2003-005, accepted P.L.B

Selection:

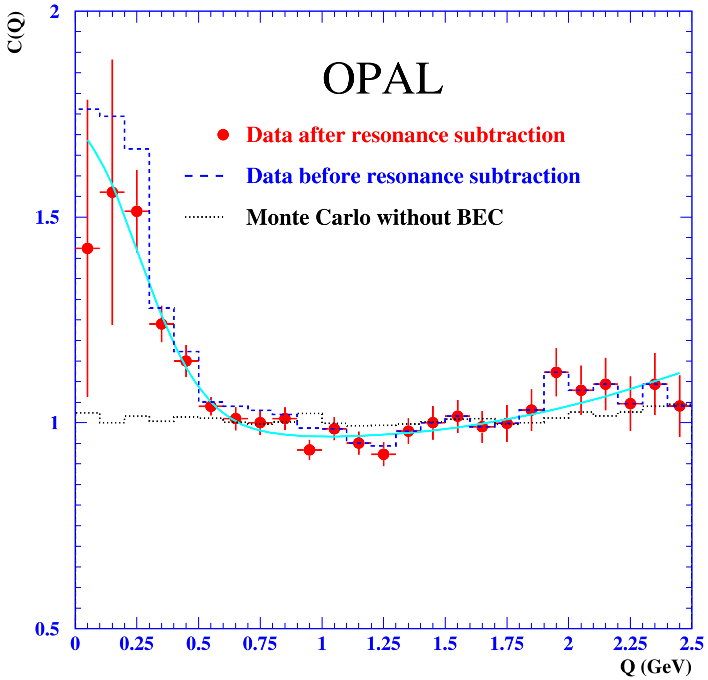
OPAL	L3
$p_{\pi^0} > 1.0$ GeV	$E(\pi^0) < 6.0$ GeV
2-jet, $T > 0.9$	all events

- Naively expect same BEC for $\pi^0\pi^0$ and $\pi^\pm\pi^\pm$

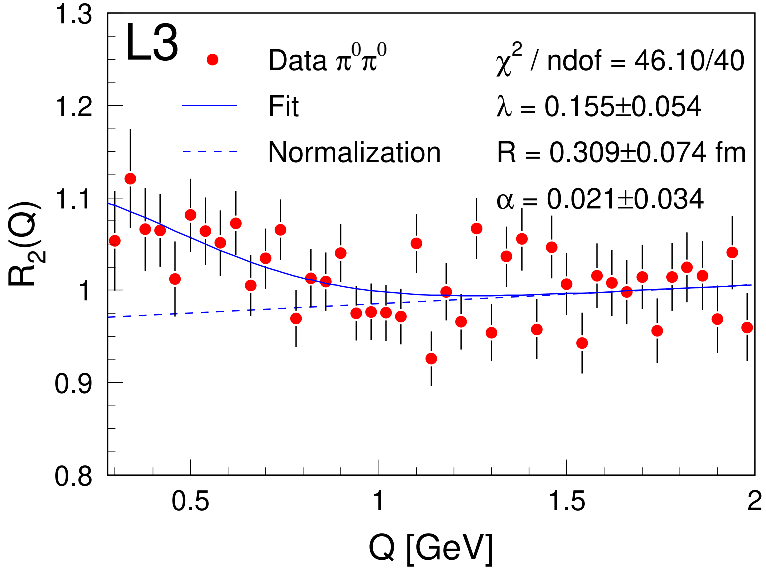
- Hadronization with local charge conservation,
  e.g., string, $\Longrightarrow R_{00} < R_{\pm\pm}$

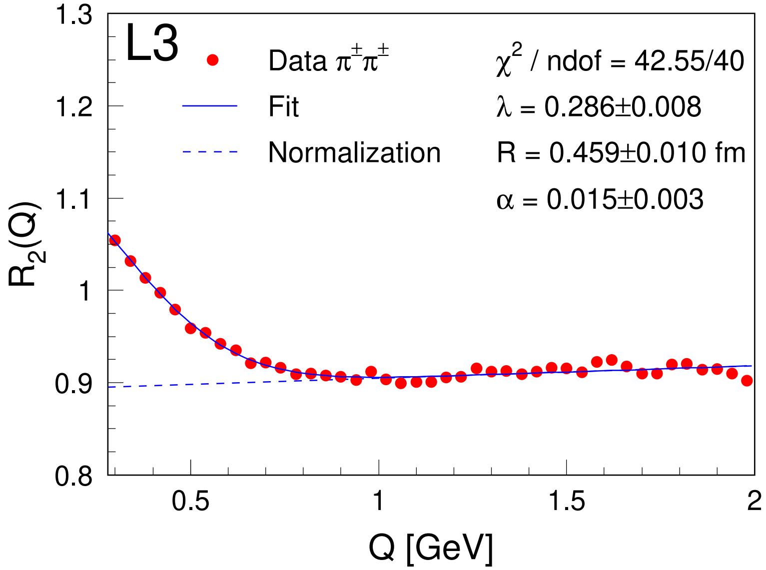
- But most π's from resonances — dilutes this effect.

2-particle BEC $\pi^0\pi^0$ and $\pi^\pm\pi^\pm$



λ=0.55±0.10±0.10
R=0.59±0.08±0.05 fm





Bose-Einstein Correlations

BEC results from hadronic Z decays
- ρ_0 from event mixing or MC (no BEC)
- Gaussian parametrization

	Expt.	R (fm)	λ
$\pm\pm$	ALEPH	0.52 ± 0.02	0.30 ± 0.01
	DELPHI	0.47 ± 0.03	0.24 ± 0.02
	OPAL	0.79 ± 0.02	0.58 ± 0.01
	L3	0.65 ± 0.04	0.45 ± 0.07
	L3 3-π	0.65 ± 0.07	0.47 ± 0.08
	L3 $E_\pi < 6$ GeV	0.46 ± 0.01	0.29 ± 0.03
00	L3 $E_\pi < 6$ GeV	0.31 ± 0.10	0.16 ± 0.09
	OPAL $E_\pi > 1$, 2-jet	0.59 ± 0.09	0.55 ± 0.14

- L3: $R_{00} < R_{\pm\pm}$ and $\lambda_{00} < \lambda_{\pm\pm}$, both 1.5σ

- L3 and OPAL $\pi^0\pi^0$ results disagree by 2σ

- But L3 $R_{\pm\pm}(\text{all } \pi) > R_{\pm\pm}(< 6\,\text{GeV})$,
  $\lambda_{\pm\pm}(\text{all } \pi) > \lambda_{\pm\pm}(< 6\,\text{GeV})$

- Is the L3-OPAL $\pi^0\pi^0$ difference
  due to $E < 1$ GeV and/or 2-jet ???
  Will OPAL do a charged track analysis with these cuts?

BEC and Factorial Cumulants

Partition momentum space in M bins
Normalized Factorial Moments (NFM)

$$F_q(M) = \frac{1}{M} \sum_{m=1}^{M} \frac{\langle n_m(n_m-1)...(n_m-q+1)\rangle}{\langle n_m\rangle^q}$$

where n_m = multiplicity in bin m
$\langle ... \rangle$ = average over all events

- F_q measure correlations among q particles
- To remove contribution of correlations among $< q$ particles, use Factorial Cumulants K_q

$$\begin{aligned} K_2 &= F_2 - 1 \\ K_3 &= F_3 - 3F_2 + 2 \\ K_4 &= F_4 - 4F_3 - 3\overline{F_2^2} + 12F_2 - 6 \end{aligned}$$

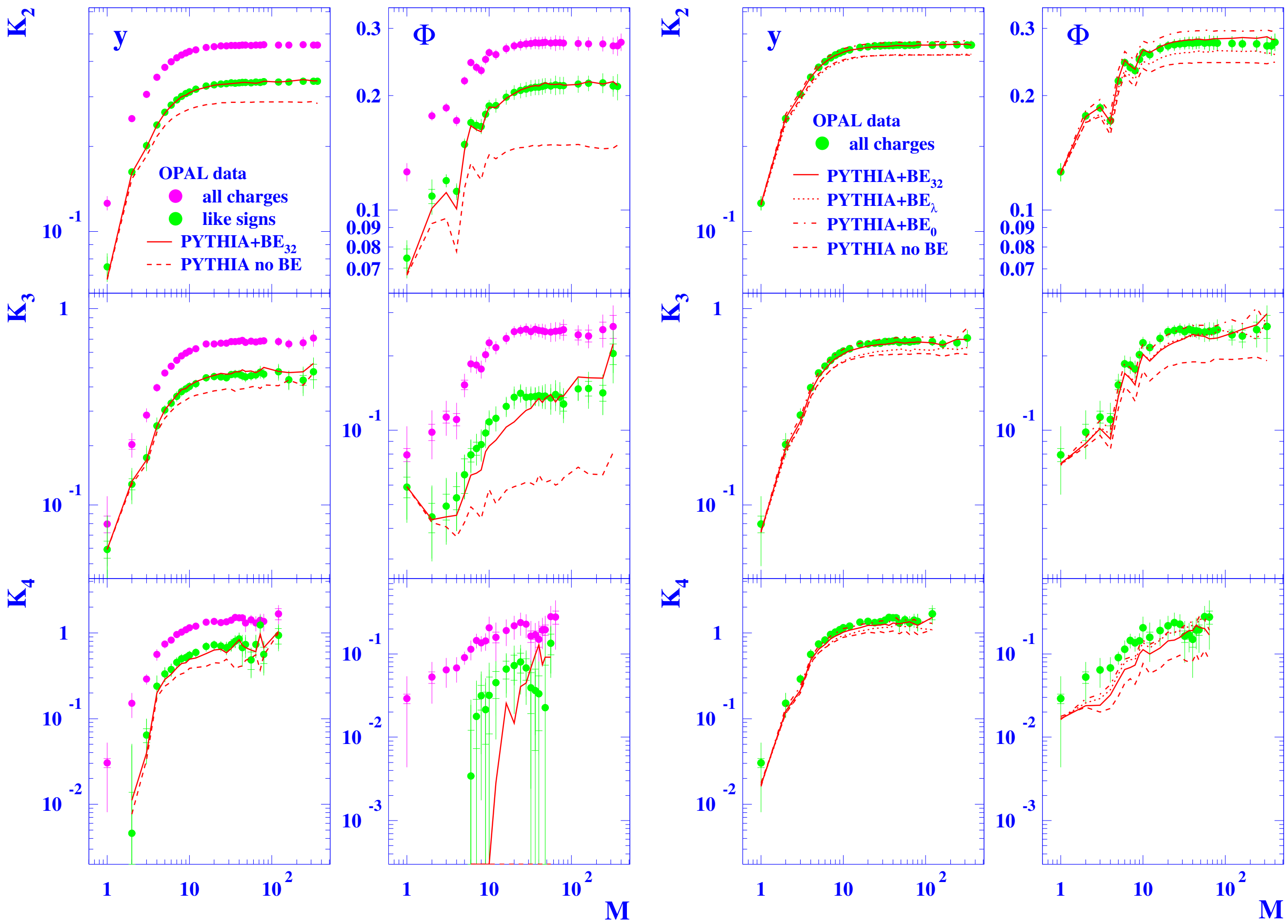
- K_q measure genuine correlations among q particles

BEC should influence the F_q, K_q

OPAL studies the K_q for all
and for like-sign charged particles

BEC and Factorial Cumulants – OPAL

$|y| < 2.0,\ 0.1 < p_t < 2.0$ Phys. Lett. B523(2001)35



- PYTHIA with BE$_{32}$ describes like-sign K_2 well
  PYTHIA without BE does not

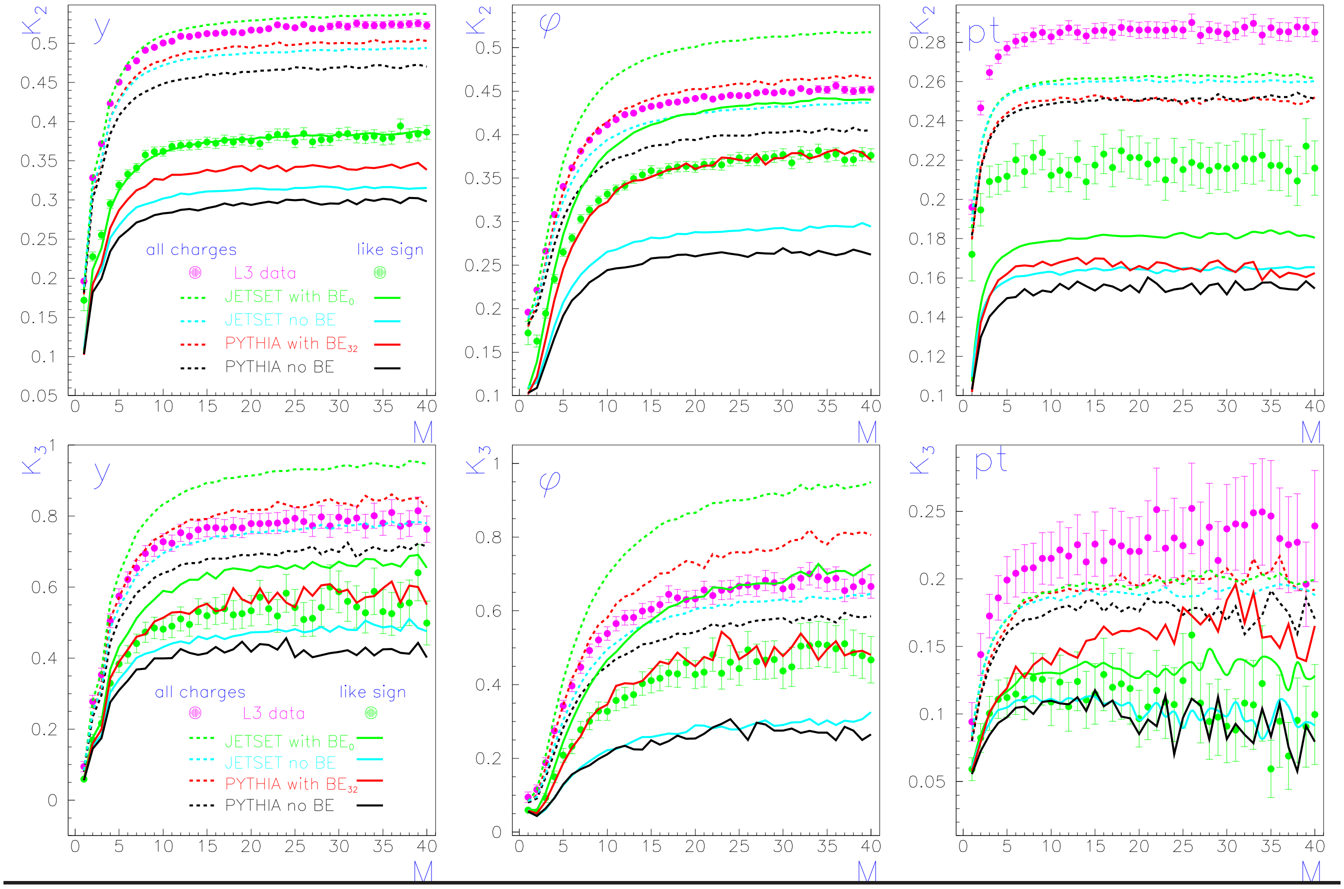
- This is also true even for K_3 and K_4
  even though BE$_{32}$ works only on pairs of particles

- BE$_{32}$ also describes all-particle K_q well

- Other BE models work somewhat less well
  and no-BE is worse still

BEC and Factorial Cumulants – L3

$|y| < 2.0,\ 0.1 < p_{\mathrm{t}} < 2.0$ VERY PRELIMINARY

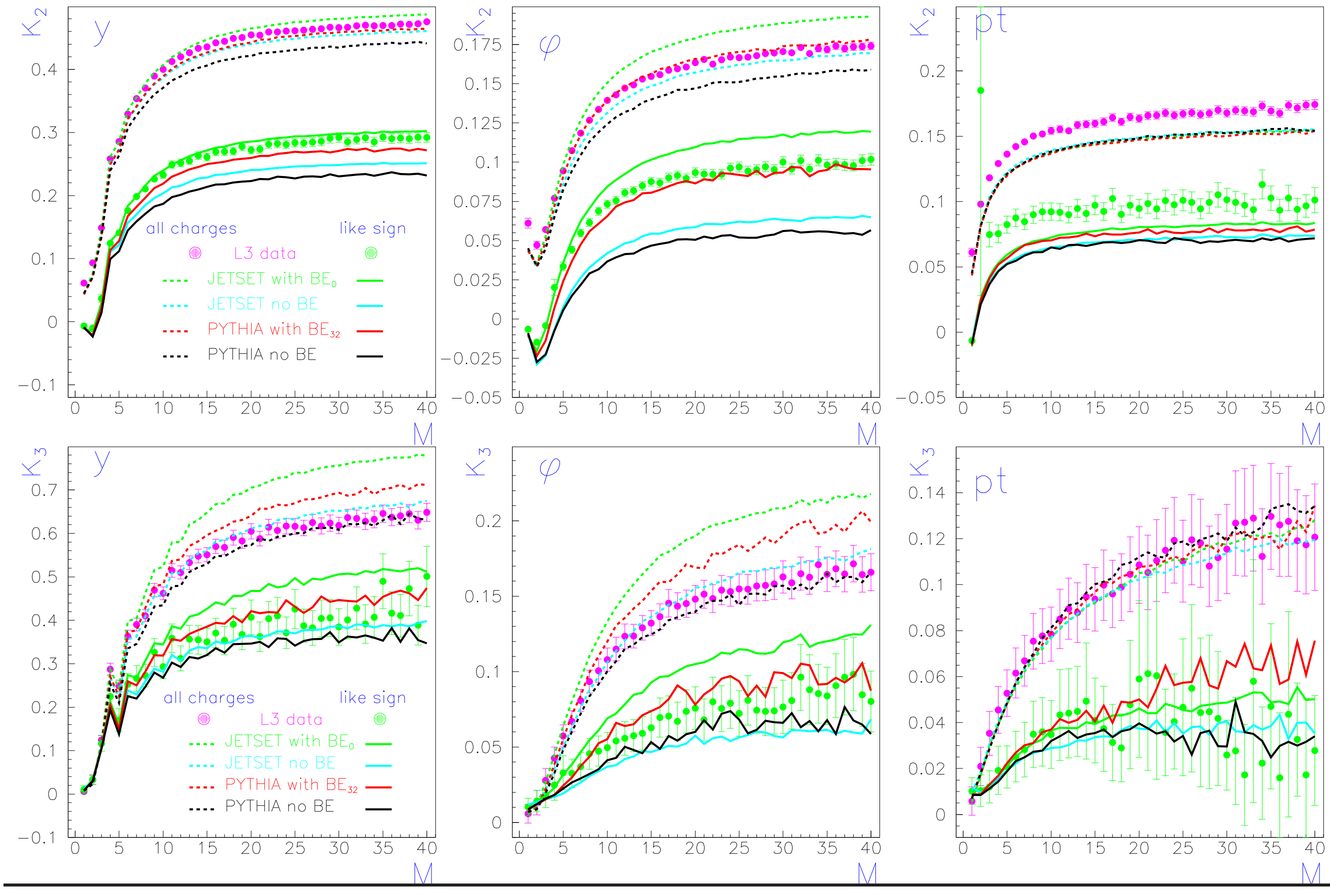


		y:all/ like	ϕ:all/ like	p_{t}:all/ like
K_2	JS BE$_0$	★ / ★★★	/	★ /
	JS no BE	★ /	★★ /	/
	PY BE$_{32}$	★ / ★	★★ / ★★★	★ /
	PY no BE	/	/	★ /
K_3	JS BE$_0$	/ ★	/	★★ / ★★
	JS no BE	★★ / ★★	★★ /	★★ / ★★★
	PY BE$_{32}$	★★ / ★★★	★ / ★★★	★ / ★★★
	PY no BE	★ / ★	/	/

PYTHIA BE$_{32}$ best, but not everywhere good

BEC and Factorial Cumulants – L3

full phase space VERY PRELIMINARY



		y:all / like	ϕ:all / like	p_{t}:all / like
K_2	JS BE$_0$	$\star\star$ / $\star\star$	/	$\star$ /
	JS no BE	$\star\star$ /	$\star$ /	/
	PY BE$_{32}$	$\star\star$ / $\star$	$\star\star\star$ / $\star\star$	/ $\star$
	PY no BE	/	/	$\star$ /
K_3	JS BE$_0$	/ $\star$	/	$\star\star\star$ / $\star\star\star$
	JS no BE	$\star\star$ / $\star\star$	$\star\star$ /	$\star\star\star$ / $\star\star\star$
	PY BE$_{32}$	$\star\star$ / $\star\star\star$	$\star$ / $\star\star\star$	$\star\star\star$ / $\star\star$
	PY no BE	$\star$ / $\star$	/	$\star\star\star$ / $\star\star\star$

PYTHIA BE$_{32}$ best, but not everywhere good

BEC – Summary

- 3-π BEC: π production is incoherent
- $\pi^0\pi^0$: apparent L3/OPAL discrepancies
  Due to different cuts ??
- Factorial Moments: BE_{32} better than other BE models,
  but far from perfect