Bose–Einstein Correlation with CMS Detector at the LHC @ 900 GeV and 2.36 TeV

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Outline

Introduction

Bose–Einstein Correlation

- Wave-function of identical bosons produced in High–Energy Collision overlaps, Bose–Einstein statistics changes their dynamics;
- Seen as an enhancement probability for identical boson with small relative momenta.
- BEC measurements can give info about size, shape and space-time development of the emitting source
- First seen in HEP by Goldhaber *et al* in π production in 1.05 GeV $p\bar{p}$ annihilations (1960).
- Large number of measurements since then using different initial states: e^+e^- $\bar{p}p$, pp, πN, ep, and ν_μN.
- Also known as Hanbury–Brown and Twiss (HTB) effect in astronomy.

How to measure

Correlation is studied using the ratio R between join probability of emission of a pair of bosons and the individual probabilities.

$$R = \frac{P(p_1, p_2)}{P(p_1)\ P(p_2)}$$

$R = R(Q)$ expressed in term of: $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{inv}^2 - 4m_\pi^2}$

R is Q-value distribution of same charged tracks (π) normalized to distribution of a reference sample w/o BEC.

$$R(Q) = \frac{dN/dQ}{dN/dQ_{ref}}.$$

Parametrization

$$R(Q) = C\,[1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q).$$

where $\Omega(Qr)$ represent the Fourier transform of the emission region (in static model), with effective radius r and strength λ.
δ allows for long range correlation.

Outline

Reference samples

Using 7 reference samples, widely used in literature, for measurements and systematic uncertainties estimation.

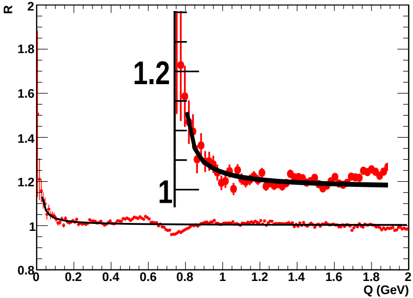
1. Opposite charge pairs;
2. Opposite charge pairs with one track $\vec{p}$ inverted;
3. Same charge pairs with $\vec{p}$ inverted;
4. Same charge pairs with $\vec{p}$ rotated in transverse plane;
5. Pairs of tracks from different events, chosen randomly;
6. Pairs of tracks from different events with similar $dN_{tracks}/d\eta$;
7. Pairs of tracks from different event with similar total invariant mass of charged tracks.

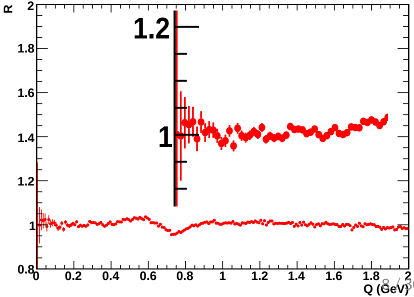
Coulomb correction

- Coulomb repulsion between same charged particles depletes the Q distribution at low Q.
- Corrected with Gamow factor:

$$W_S(\eta) = \frac{e^{2\pi\eta}-1}{2\pi\eta}$$
$$W_D(\eta) = \frac{1-e^{-2\pi\eta}}{2\pi\eta}$$
$$\eta = \frac{\alpha_{em} m_\pi}{Q}$$

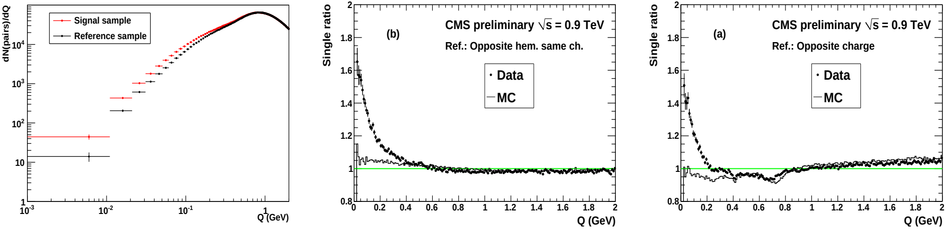
- Tested with opposite-charge Q-distribution normalized to MC (no coulomb effect simulated)
- Up: opposite charge Q distribution with Gamow factor superimposed (not fitted)
- Bottom: same after applying Coulomb correction





Single ratios and double ratios

- Q distribution for signal and one reference sample
- Enhancement at low-Q show the expected correlation
- MonteCarlo (w/o BEC simulation) is flat



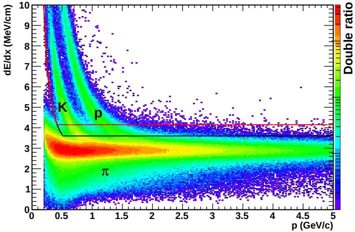
- Opposite charge distribution show structure due to resonances (ρ)
- Long range correlation well described by simulation

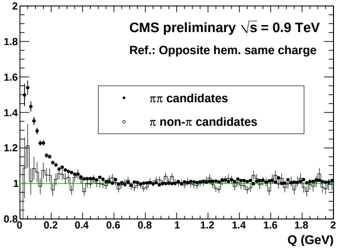
Use Double Ratio for measurement.

$$\mathcal{R} = R/R_{\mathrm{MC}} = \left(\frac{dN/dQ}{dN/dQ_{\mathrm{ref}}}\right) \Big/ \left(\frac{dN/dQ_{\mathrm{MC}}}{dN/dQ_{\mathrm{MC,ref}}}\right)$$

BEC with identical/non identical particles

- As check of signal, construct two samples with identical π and not-identical π, not-π particles, using PID in CMS ($\frac{dE}{dx}$ measurement with CMS silicon tracker)
- Enhancement present only in $\pi\pi$ candidates, not in π-notπ

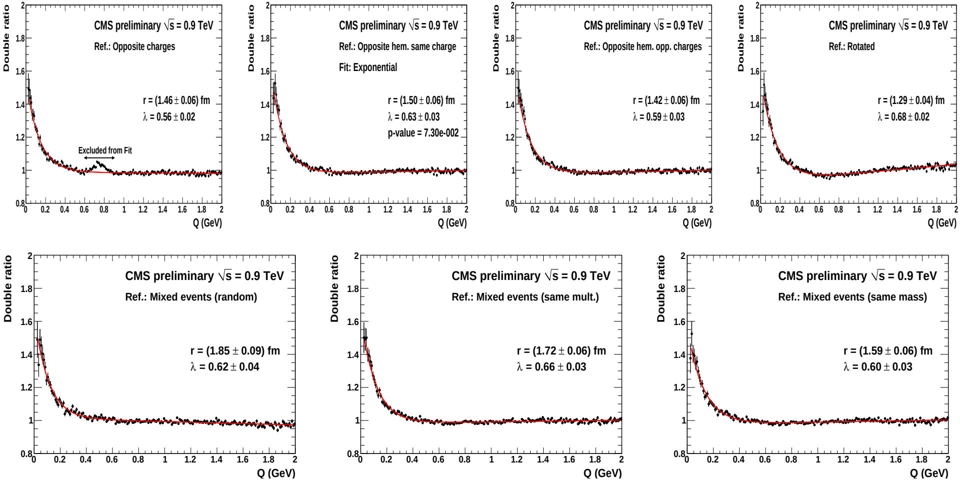




- Small π contamination in not-π
- PID works only for low p_{T} particles, not using π-notπ as reference sample.

Outline

R(Q) for all reference sample @ 900 GeV

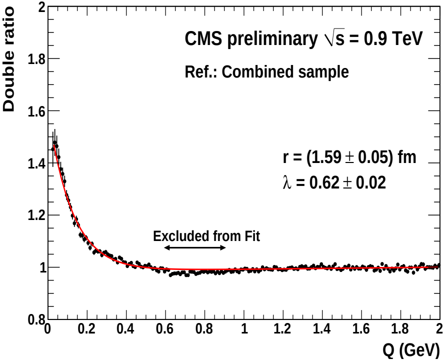


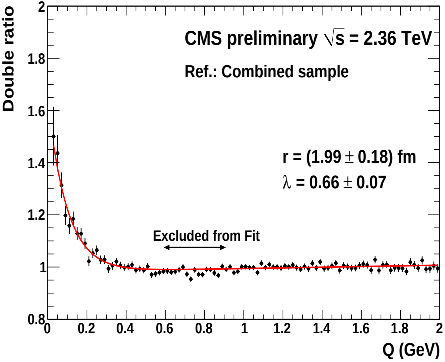
Fit with exponential form for Ω: $R(Q) = C\left[1 + \lambda e^{-(Qr)}\right] \cdot (1 + \delta Q)$.

Combined reference samples

Build a combined reference sample

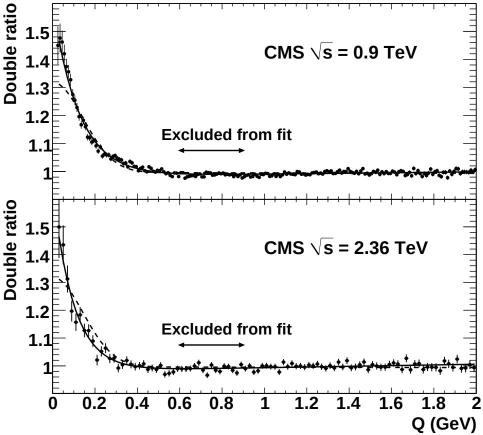
$$\mathcal{R}^{comb} = \frac{dN/dQ}{dN/dQ_{MC}} \left(\frac{\sum_{i=1}^{m} dN/dQ^{i}_{MC}}{\sum_{i=1}^{m} dN/dQ^{i}} \right).$$





Alternative parametrization

Exponential form for $\Omega(Qr) = e^{-Qr}$ fit much better data then the widely used Gaussian one $\Omega(Qr) = e^{-(Qr)^2}$.



Tried also Lèvy
$\Omega(Qr) = e^{-(Qr)^\alpha}$
and more complex R function [Kozlov, Biyajima].
Gaussian form is disfavoured by data.

Results and systematics

- Use spread between reference samples $\pm 7\%$ for λ and $\pm 12\%$ for r
- Coulomb correction syst by propagating agreement margin of opposite charge fit $\pm 2.8\%$ for λ and $\pm 0.8\%$ for r
- Compared BEC parameter at generation and reconstruction level with dedicated simulation: no bias, agreement within statistical errors.

Results at 900 GeV

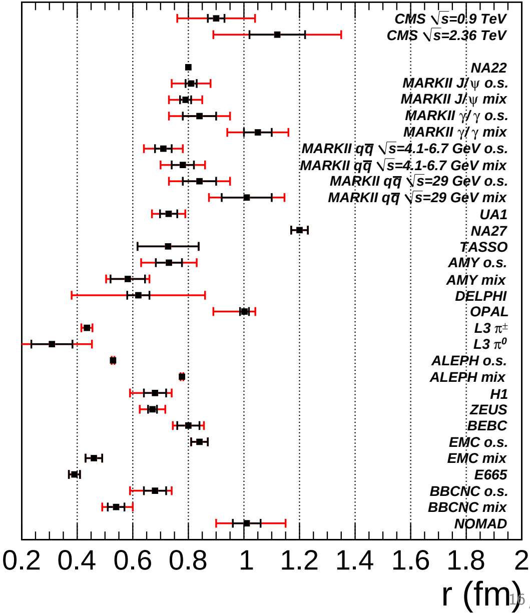
$r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) *fm*
$\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.)

Results at 2.36 TeV

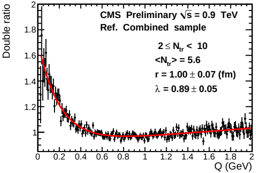
$r = 1.99 \pm 0.18$ (stat.) ± 0.24(syst.) fm
$\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.)

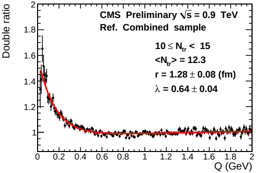
Previous experiment results

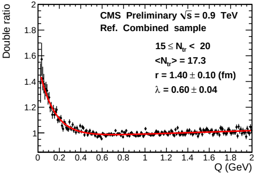
- Previous experiment used Gaussian parametrization.
- First moment of exponential: $1/r$, Gaussian $\frac{1}{r\sqrt{\pi}}$.
- CMS values with exponential fits scaled by $1/\sqrt{\pi}$
- Apologize for any missing past experiment!

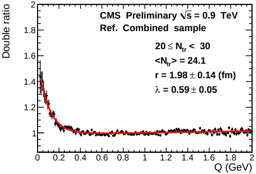


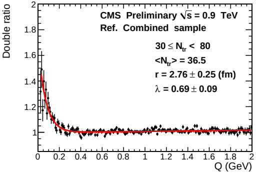
Dependence on $N_{\text{charged tracks}}$



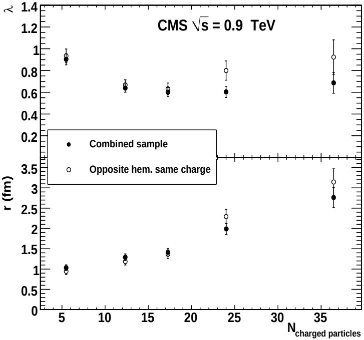








Clear dependence of effective radius with event charged tracks multiplicity



Outline

Conclusion

- Bose–Einstein Correlation measured 900 GeV and 2.36 TeV with CMS detector at LHC;
  - Used many reference samples and double ratios;
  - Used combined reference sample;
  - Estimate measurement systematics;

- Exponential shape fit better than gaussian;
- Clear dependence from track multiplicity;

- Measurement at 7 TeV is in progress

Backup

BACKUP

CMS inner tracker

Si Pixel surrounded by Si strips.
$|\eta| < 2.5$

Pixel

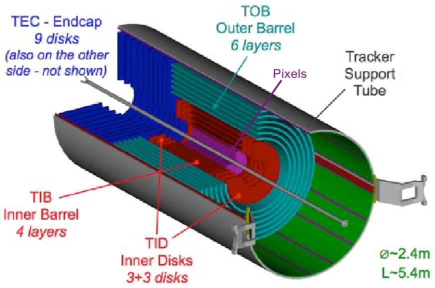
- 3 barrel layers ($r = 4, 7, 11$ cm)
- 2x2 endcap disks
- ≈ 1 m^2 of Si sensors
- $\approx 66M$ channels
- 1440 modules

Strips

- 10 barrel layers
- 9+3x2 endcap disks
- ≈ 200 m^2 of Si sensors
- $\approx 6.4M$ channels
- 15148 modules

Performances

- 2-track separation: 1 *mrad*
- different hits on 3^{rd} pixel layers $Q > 20$ MeV
- ≥ 3 hits for $p_{\mathrm{T}} > 100$ MeV
- $\Delta p_{\mathrm{T}}/p_{\mathrm{T}} \approx 1 - 2\%$ @ 1 GeV



Events and track selections

- data collected in December 2009 $\sqrt{s} = 0.9$ and 2.36 TeV.
- Trigger: MinimumBias. Activity in both Beam Scintillator Counters
- $NDoF > 5$;
- $\chi^2/NDoF < 5$;
- Trasverse impact parameter $d_{xy} < 1.5\ mm$;
- Innermost hit $R < 20\ cm$ impact point;
- $|\eta| < 2.4$;
- $p_{\mathrm{T}} > 200$ MeV;
- $2 \leq N_{trk} \leq 150$
- @ 900 GeV: 270 472 events and 2 903 754 track pairs;
- @ 2.36 TeV: 13 548 events and 188 140 track pairs.

Detailed results @ 900 GeV

Results of fits to 0.9 TeV data

Reference sample	P-value	C	λ	r (fm)	δ (GeV^{-1})
Opposite charges	2.19×10^{-1}	0.988 ± 0.003	0.557 ± 0.025	1.46 ± 0.06	$(-3.5 \pm 2.4) \times 10^{-3}$
Opposite hem. same ch.	7.30×10^{-2}	0.978 ± 0.003	0.633 ± 0.027	1.50 ± 0.06	$(1.1 \pm 0.2) \times 10^{-2}$
Opposite hem. opp. ch.	1.19×10^{-1}	0.975 ± 0.003	0.591 ± 0.025	1.42 ± 0.06	$(1.3 \pm 0.2) \times 10^{-2}$
Rotated	2.42×10^{-4}	0.929 ± 0.003	0.677 ± 0.022	1.29 ± 0.04	$(5.8 \pm 0.2) \times 10^{-2}$
Mixed evts. (random)	1.90×10^{-2}	1.014 ± 0.002	0.621 ± 0.038	1.85 ± 0.09	$(-2.0 \pm 0.2) \times 10^{-2}$
Mixed evts. (same mult.)	1.22×10^{-1}	0.981 ± 0.002	0.664 ± 0.030	1.72 ± 0.06	$(1.1 \pm 0.2) \times 10^{-2}$
Mixed evts. (same mass)	1.70×10^{-2}	0.976 ± 0.002	0.600 ± 0.030	1.59 ± 0.06	$(1.4 \pm 0.2) \times 10^{-2}$
Combined sample	2.92×10^{-2}	0.984 ± 0.002	0.625 ± 0.021	1.59 ± 0.05	$(8.2 \pm 0.2) \times 10^{-3}$

Results of fits to 0.9 TeV data

Multiplicity range	P-value	C	λ	r (fm)	δ (GeV^{-1})
2 - 9	9.7×10^{-1}	0.90 ± 0.01	0.89 ± 0.05	1.00 ± 0.07 (stat.)± 0.05 (syst.)	$(7.2 \pm 1.2) \times 10^{-2}$
10 - 14	3.8×10^{-1}	0.97 ± 0.01	0.64 ± 0.04	1.28 ± 0.08 (stat.)± 0.09 (syst.)	$(1.8 \pm 0.5) \times 10^{-2}$
15 - 19	2.7×10^{-1}	0.96 ± 0.01	0.60 ± 0.04	1.40 ± 0.10 (stat.)± 0.05 (syst.)	$(2.8 \pm 0.5) \times 10^{-2}$
20 - 29	2.4×10^{-1}	0.99 ± 0.01	0.59 ± 0.05	1.98 ± 0.14 (stat.)± 0.45 (syst.)	$(1.3 \pm 0.3) \times 10^{-2}$
30 - 79	2.8×10^{-1}	1.00 ± 0.01	0.69 ± 0.09	2.76 ± 0.25 (stat.)± 0.44 (syst.)	$(1.0 \pm 0.3) \times 10^{-2}$

Detailed results @ 2.36 TeV

Results of fits to 2.36 TeV data					
Reference sample	P-value	C	λ	r (fm)	δ (GeV^{-1})
Opposite charges	5.71×10^{-1}	1.004 ± 0.008	0.529 ± 0.081	1.65 ± 0.23	$(-1.57 \pm 0.58) \times 10^{-2}$
Opposite hem. same ch.	4.19×10^{-1}	0.977 ± 0.006	0.678 ± 0.110	1.95 ± 0.24	$(1.49 \pm 0.48) \times 10^{-2}$
Opposite hem. opp. ch.	4.61×10^{-1}	0.969 ± 0.005	0.700 ± 0.107	2.02 ± 0.23	$(2.36 \pm 0.47) \times 10^{-2}$
Rotated	4.24×10^{-1}	0.933 ± 0.007	0.610 ± 0.070	1.49 ± 0.15	$(5.75 \pm 0.59) \times 10^{-2}$
Mixed evts. (random)	2.26×10^{-1}	1.041 ± 0.005	0.743 ± 0.154	2.78 ± 0.36	$(-4.02 \pm 0.41) \times 10^{-2}$
Mixed evts. (same mult.)	3.52×10^{-1}	0.974 ± 0.005	0.626 ± 0.096	2.01 ± 0.23	$(2.03 \pm 0.46) \times 10^{-2}$
Mixed evts. (same mass)	7.31×10^{-1}	0.964 ± 0.005	0.728 ± 0.107	2.18 ± 0.23	$(2.84 \pm 0.46) \times 10^{-2}$
Combined sample	8.90×10^{-1}	0.981 ± 0.005	0.663 ± 0.073	1.99 ± 0.18	$(1.31 \pm 0.41) \times 10^{-2}$

Results of fits to 2.36 TeV data		
2 - 19	0.65 ± 0.08	1.19 ± 0.17 (stat.)
20 - 60	0.85 ± 0.17	2.38 ± 0.38 (stat.)
Results of fits to 0.9 TeV data		
Multiplicity range	λ	r (fm)
2 - 19	0.65 ± 0.02	1.25 ± 0.05 (stat.)
20 - 60	0.63 ± 0.05	2.27 ± 0.12 (stat.)

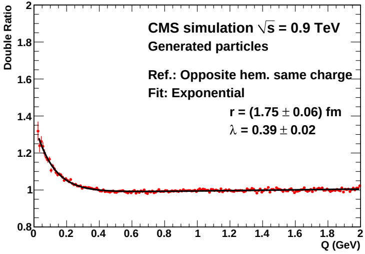
Correlation coefficient of exponential fit

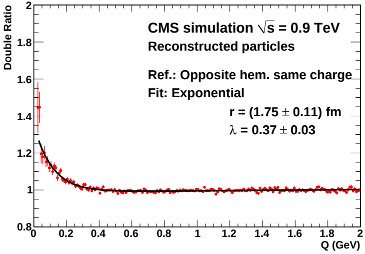
Table: Correlation coefficients for the fit parameters obtained with the combined reference samples. Left: coefficients from the fit to 0.9 TeV data; right: coefficients from the fit to 2.36 TeV data.

	0.9 TeV				2.36 TeV			
	C	λ	r	δ	C	λ	r	δ
C	1				1			
λ	0.33	1			0.27	1		
r	0.72	0.82	1		0.62	0.83	1	
δ	-0.97	-0.30	-0.67	1	-0.96	-0.24	-0.57	1

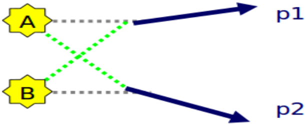
Test for reconstruction Bias

- Dedicated MonteCarlo simulation with BEC enabled
- Pythia, exponential shape
  `MSTJ(51)=1, PARJ(92)=0.9, PARJ(93)=0.125`
- Performed analysis at Generated (left) and Reconstruction (right) level
- found no bias within the statistical uncertainties





Physics of Bose–Einstein Correlation



Two particles

1. from source A, momentum p_1
2. from source B, momentum p_2

System wave-function

$\Psi_A(1) = f_A e^{-i\vec{p}_1\vec{x}_A}, \ldots$

Complete wave-funtion for Bosons is

$\Psi(1,2) = (\Psi_A(1)\Psi_B(2) + \Psi_B(1)\Psi_A(2))/\sqrt{2}$

Joint probability is just the product of P of single particles.

$< \Pi_{12} >= (f_A^2 + f_B^2 + [f_A^* f_B e^{i\vec{p_1}(\overrightarrow{x_A - x_B})} + c.c.])(\ldots e^{i\vec{p_2}(\overrightarrow{x_A - x_B})} \ldots)$

In a chaotic source $f_A^* f_B + c.c.$ fluctuate randomly and drop out of expectation value.

$$R = \frac{<\Pi_{12}>}{<\Pi_1><\Pi_2>} = \frac{|\Psi(1,2)|^2}{|\Psi(1)|^2|\Psi(2)|^2} = 1 + 2\frac{2f_A^2 f_B^2}{(f_A^2+f_B^2)^2}\cos(\Delta x \Delta p)$$

Previous experiment results: table

Experiment	source	$\sqrt{s}$ (GeV)	r (fm)	ref. sample
NA22 [?]	$Kp, \pi p$	250	0.800	uses q_t
MARK II [?]	J/ψ	3.1	$0.810 \pm 0.020 \pm 0.050$	opp. sign
	J/ψ	3.1	$0.790 \pm 0.020 \pm 0.040$	mix event
	$\gamma\gamma$	39	$0.840 \pm 0.060 \pm 0.050$	opp. sign
	$\gamma\gamma$	39	$1.050 \pm 0.050 \pm 0.060$	mix event
	$q\bar{q}$	$4.1 \div 6.7$	$0.710 \pm 0.030 \pm 0.040$	opp. sign
	$q\bar{q}$	$4.1 \div 6.7$	$0.780 \pm 0.040 \pm 0.040$	mix event
	$q\bar{q}$	29	$0.840 \pm 0.060 \pm 0.050$	opp. sign
	$q\bar{q}$	29	$1.010 \pm 0.090 \pm 0.046$	mix event
UA1 [?]	pp	$200 \div 900$	$0.729 \pm 0.031 \pm 0.029$	opp. sign
NA27 [?]	pp	400	1.200 ± 0.030	mix event
TASSO [?]	e^+e^-	34	0.727 ± 0.110	
AMY [?]	e^+e^-	58	$0.730 \pm 0.047 \pm 0.053$	opp. sign
	e^+e^-	58	$0.582 \pm 0.062 \pm 0.016$	mix event
DELPHI [?]	e^+e^-	91	$0.620 \pm 0.04 \pm 0.20$	opp. sign + mix event
OPAL [?]	e^+e^-	91	$1.002 \pm 0.016^{+0.023}_{-0.096}$	opp. sign
L3 [?]	e^+e^-	91	$0.435 \pm 0.010 \pm 0.010$	$\pi^\pm$ MonteCarlo
	e^+e^-	91	$0.309 \pm 0.074 \pm 0.070$	π^0 MonteCarlo
ALEPH [?]	e^+e^-	91	0.529 ± 0.005	mix event
ALEPH [?]	e^+e^-	91	0.777 ± 0.005	opp. sign
H1 [?]	ep	230	$0.680 \pm 0.040^{+0.020}_{-0.050}$	
ZEUS [?]	ep	230	$0.671 \pm 0.016 \pm 0.030$	opp. sign
BEBC [?]	$\nu_\mu N$	10	$0.800 \pm 0.040 \pm 0.160$	
EMC [?]	μp	23	0.840 ± 0.030	opp. sign
	μp	23	0.460 ± 0.030	mix event
E665 [?]	μN	30	0.39 ± 0.02	mix event
BBCNC[?]	μN	> 10	$0.68 \pm 0.04^{+0.020}_{-0.050}$	opp. sign
	μN	> 10	$0.54 \pm 0.03^{+0.030}_{-0.020}$	mix event
NOMAD [?]	$\nu_\mu N$	8	$1.010 \pm 0.05^{+0.09}_{-0.06}$	opp. sign + mix event

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