Bose-Einstein correlations with first LHC data in CMS

2nd CMS Physics result with LHC data (approved yesterday!)

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IFAE2010
7-9 Apr 2010, Roma (Italy)

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CMS

Introduction

- Bose-Einstein correlation (BEC) in the production of light hadrons of integer spin is expected
  - Due to constructive interference of the multi-particle wave function
  - Seen as an enhanced probability for identical bosons to be emitted with small relative momenta
- Measurement of BEC can give informations about the size, shape and space-time development of the primary particle emitting source
- First observation achieved in pion-production reactions with 1.05 GeV/c proton-antiproton annihilations
  - G.Goldhaber et al. Phys. Rev. 120 (1960), 300
- A large number of measurements have followed
  - Most from HEP experiments using charged pion pairs, neutral pairs, kaon pairs, multiplets…

Parametrizations

- In general two-particle interference correlation is studied using the ratio R between:
  - The joint probability of emission of pair of bosons $P(p_1,p_2)$
  - The individual probabilities $P(p_1)$, $P(p_2)$

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

- R may be expressed as a function of the pair Q-value, defined as

$$Q = \sqrt{M_{\pi\pi}^2 - 4m_\pi^2}$$

- Among the various parametrizations for R(Q) we choose a Lorentz-invariant form describing the emission from a spherical region:

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

- The $\Omega(Qr)$ function is the Fourier transform of the emission region form whose effective size is measured by r, λ is a strength parameter, δ allows for long-range correlations in the Q distribution of the reference sample.

Reference samples (I)

- Experimentally we use tracks
- R(Q) is measured by dividing:

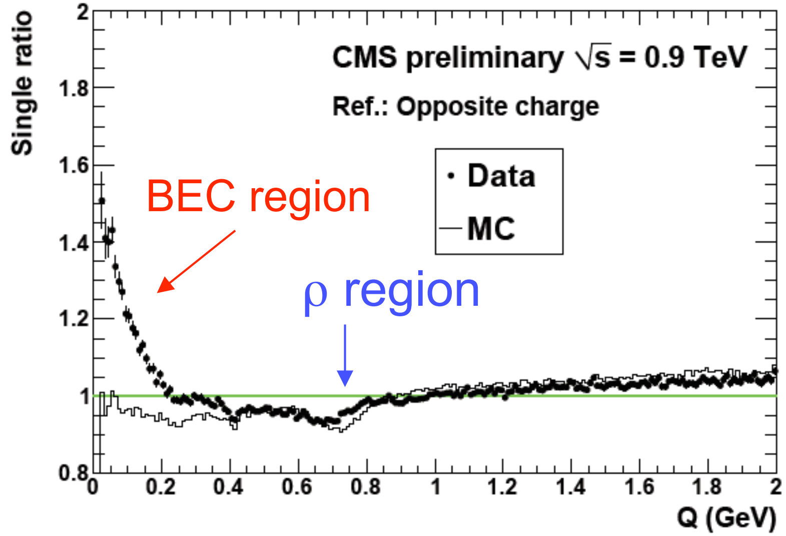
$$R = \left(\frac{dN/dQ_{sig}}{dN/dQ_{ref}} \right)$$

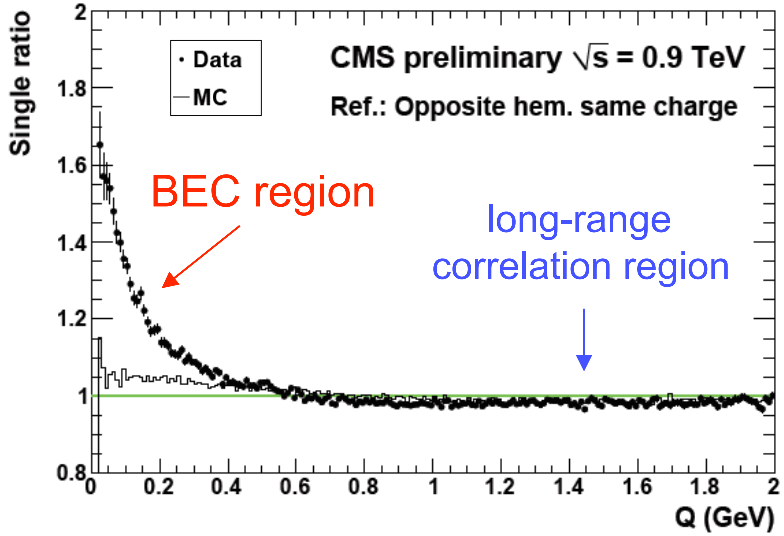
  - the Q-value distribution of pairs of same charge tracks
  - by a similar distribution constructed with non-interfering track pairs (→ reference sample)

- Choice of the reference samples (details in backup slides)
  - Several possibilities, widely explored in the literature.
  - We consider 7 options by combining both same or opposite charge tracks to form pairs:
    - where one track has ($\bar{p} \rightarrow -\bar{p}$) or ($\bar{p}_t \rightarrow -\bar{p}_t$)
    - with tracks from mixed events (randomly, by similar multiplicity, by similar total invariant mass)

Reference samples (II)

- Ratio between signal and reference samples shows a clear evidende of BEC in data
  - No BEC in simulation
- Opposite charge reference sample is not straightforward to use (resonances)
  - e.g. ρ◊ππ produces a dip in the region 0.6<Q<0.9 GeV
  - We exclude the ρ region from the fit
- All the reference samples show some long-range correlations (of various nature and shape) outside BEC region of interest
  - Very well reproduced by the simulation





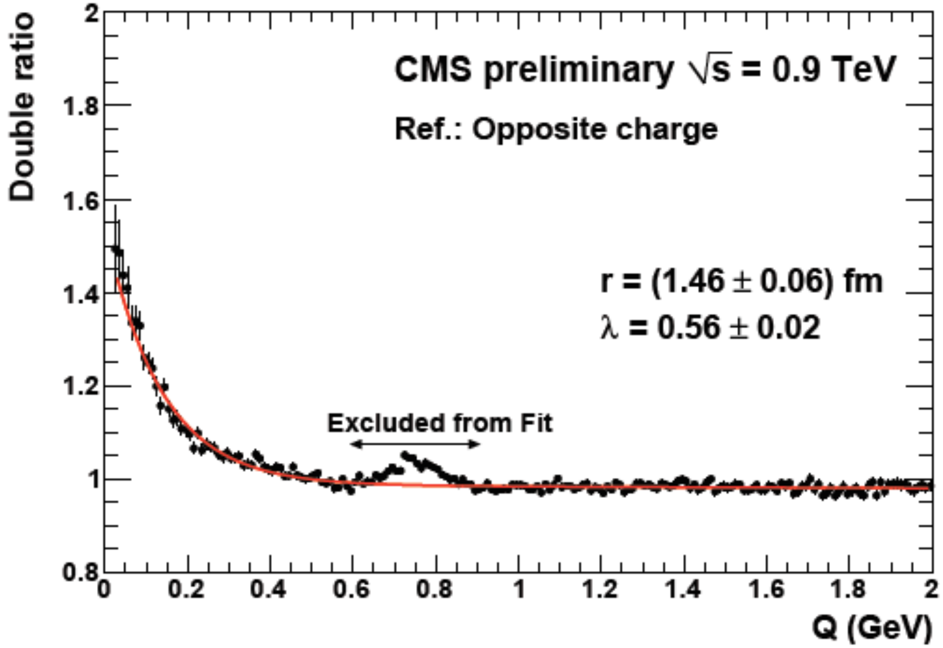
Double ratios

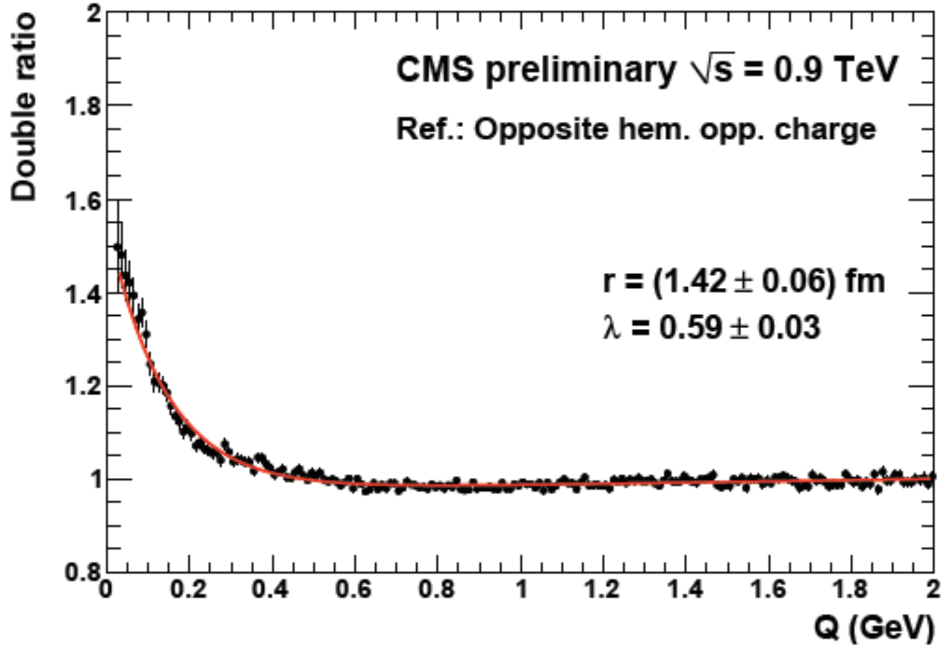
- To remove long-range and other possible correlations not dealing with BEC, we decide to use double ratios **R** to measure the Bose-Einstein correlation parameters.

$$\mathrm{R} = \frac{R}{R_{MC}} = \frac{\left(\frac{dN/dQ_{sig}}{dN/dQ_{ref}}\right)_{DATA}}{\left(\frac{dN/dQ}{dN/dQ_{ref}}\right)_{MC}}$$

- Our default fits are performed with the exponential form for the Fourier transform, $\Omega(Qr)=\exp(-Qr)$

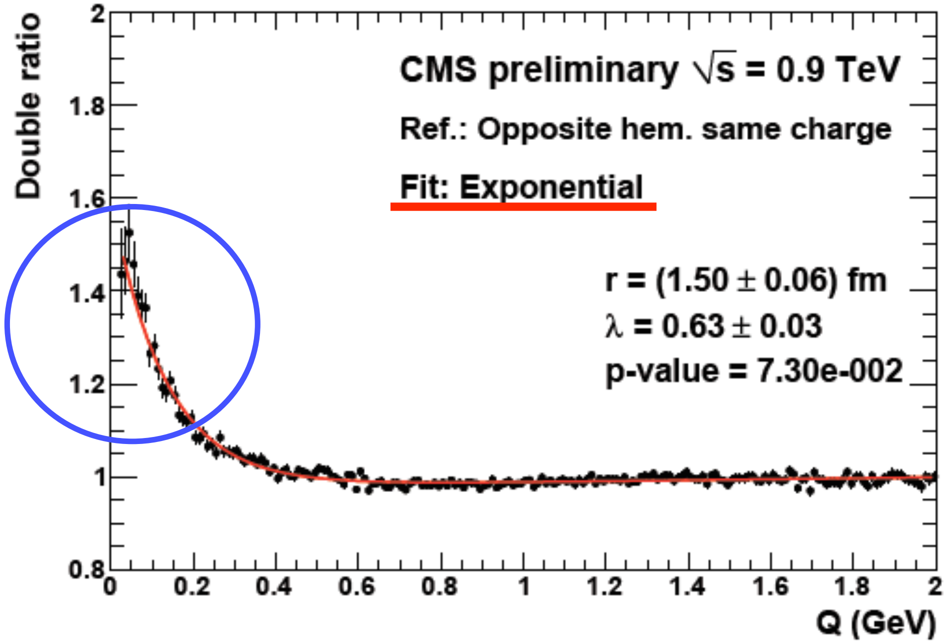
$$R(Q) = C \cdot [1 + \lambda \cdot \exp(-Qr)] \cdot (1 + \delta Q)$$

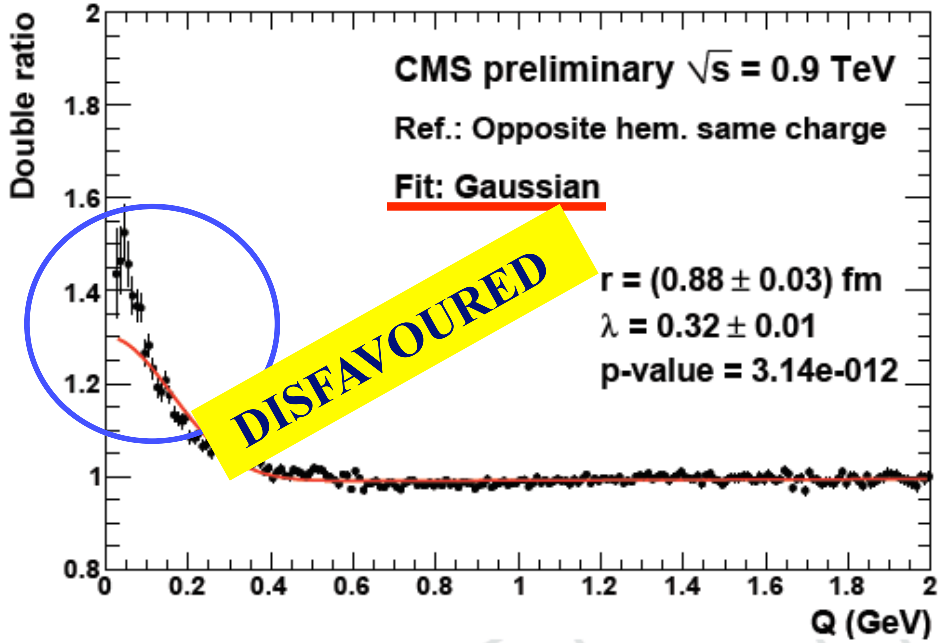




Alternative parametrizations

- Exponential form is not the one most used in the literature
- We then show results with both exponential [$\Omega(Qr)=\exp(-Qr)$] and Gaussian [$\Omega(Qr)=\exp(-Q^2r^2)$]

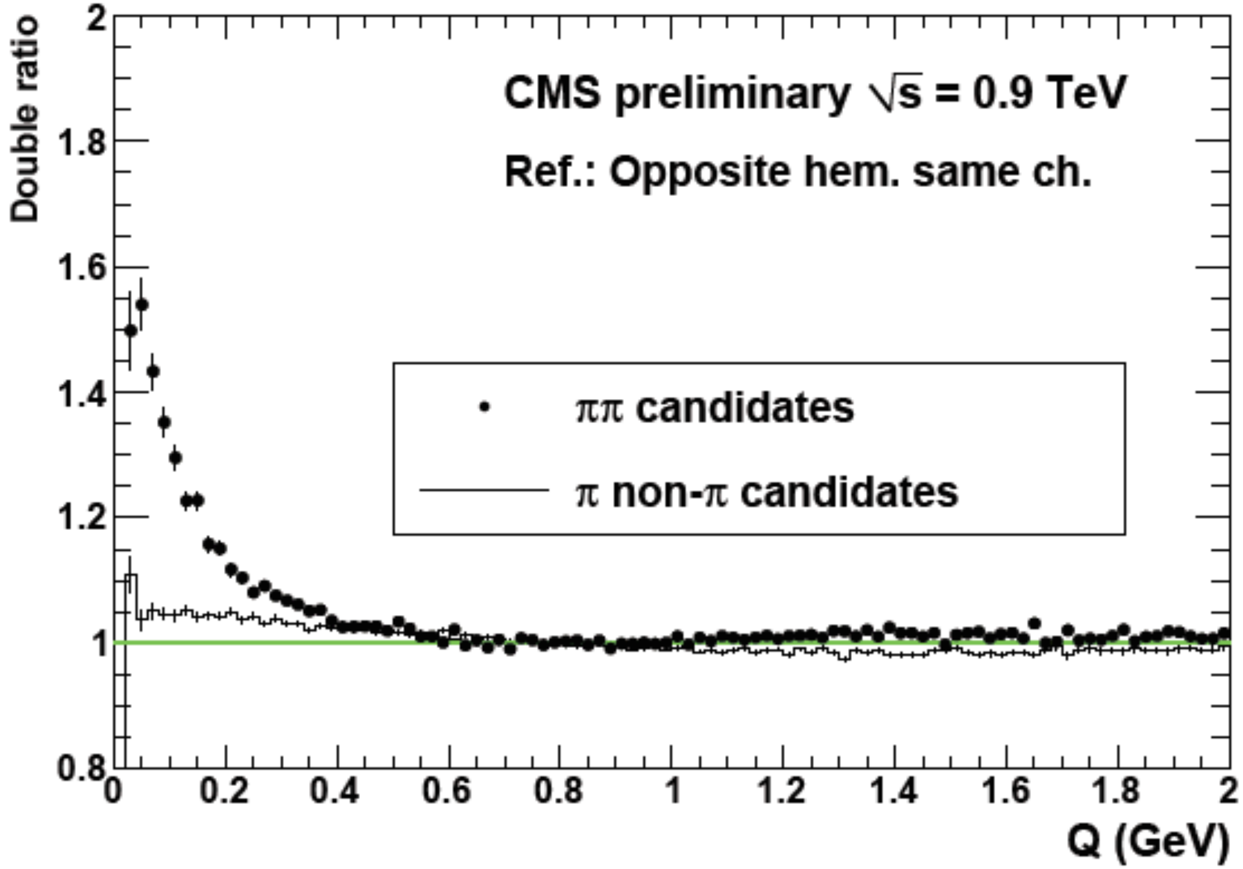




Are we measuring BEC?

Are we measuring BEC? Anti-panic plot

- As a check, we can construct two samples by using dE/dx to select:
  - ππ candidates (the BEC is expected and clearly visible)
  - π non-π candidates (the BEC is not present)



Which value? Systematics?

Reference sample	P-value	C	λ	r (fm)	δ (GeV^{-1})
Opposite charge	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	$(1.4 \pm 0.2) \times 10^{-2}$

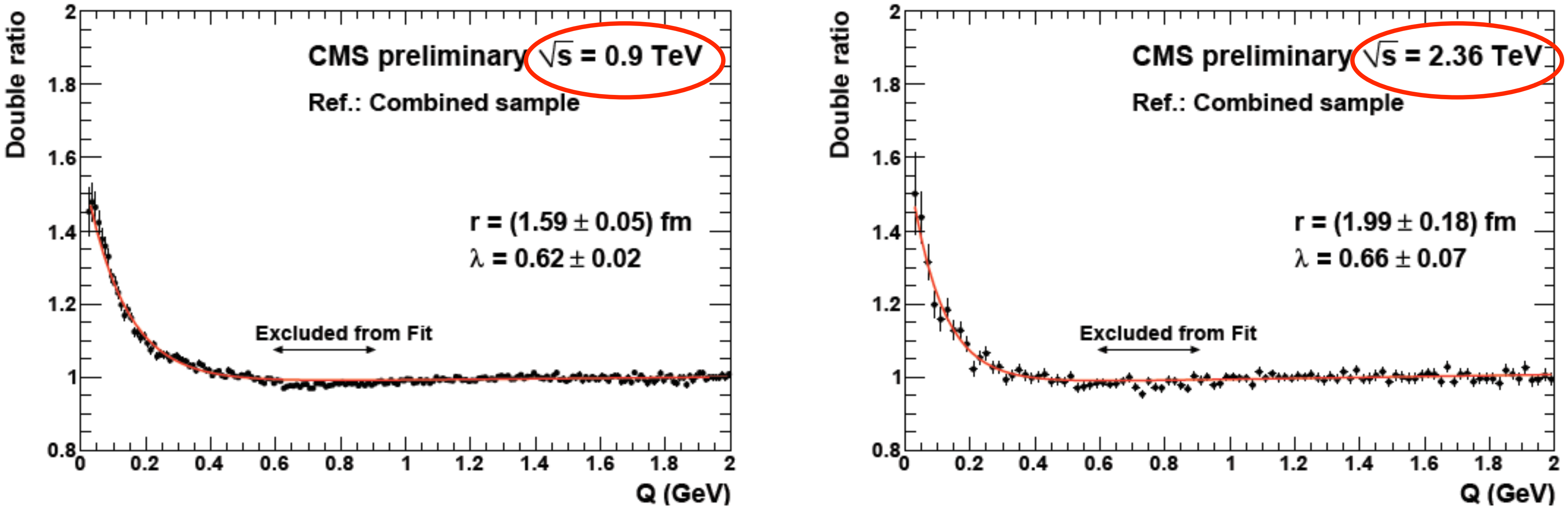
$\delta\lambda = 0.042 = 7\%$ $\delta r = 0.19$ fm $= 12\%$

- A sizable spread can still be observed in the measurements with different reference samples
  - r.m.s. spread of measurements quoted as systematic uncertainty
- No single reference sample appears *a priori* preferable to the others

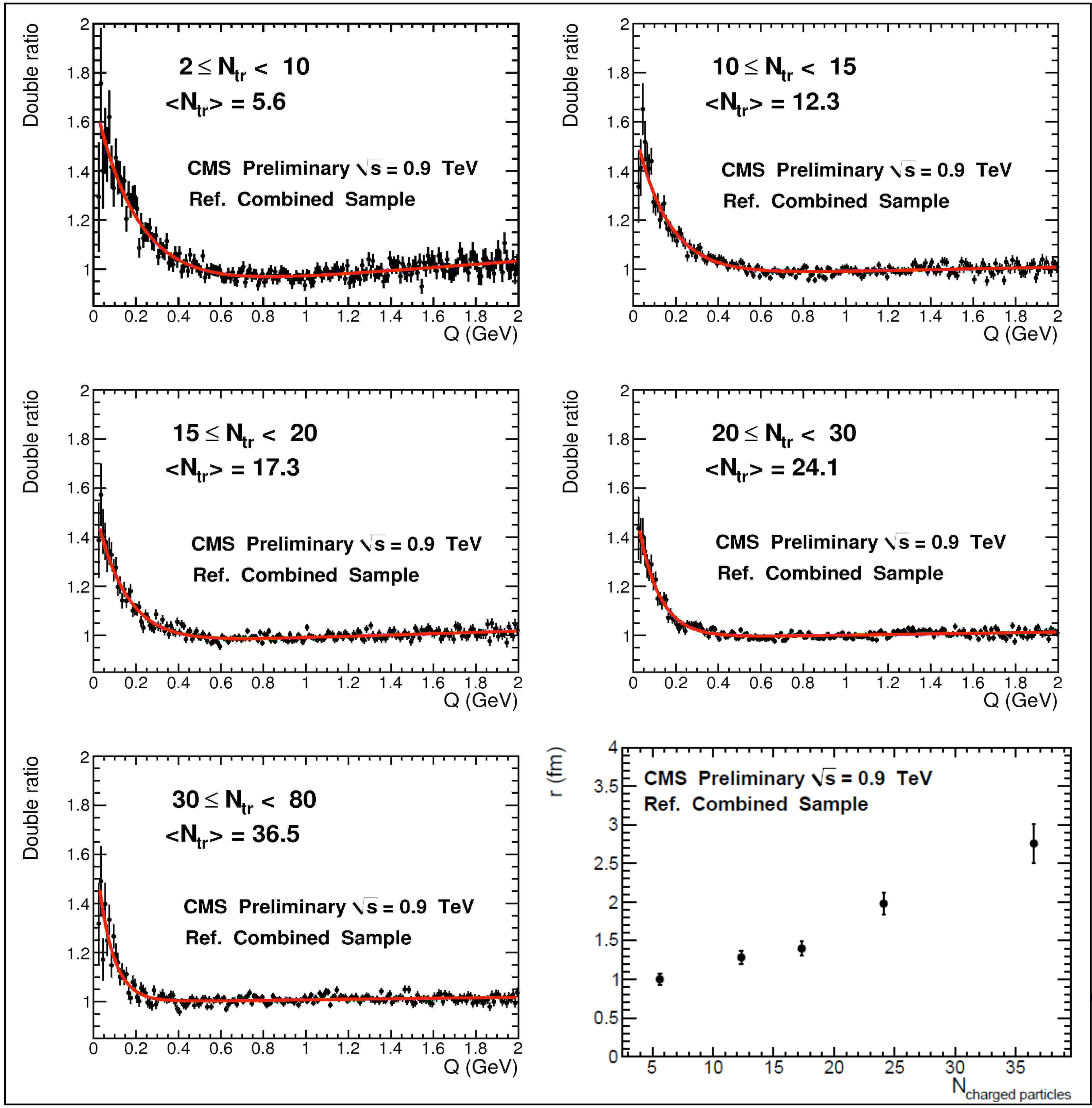
The combined reference sample

- We then provide a single value by combining all the reference samples:

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



Dependence on kinematics



- We observe a significant increase of the size of the emission region r as the charged track multiplicity in the event increases

- This kind of trend does exist in the literature
  - still ambiguous

Conclusions

- We have isolated a signal of Bose-Einstein correlations in pp collisions at the center mass energy of 0.9 and 2.36 TeV for the first time
- The signal is statistically significant and stable when studied with different reference samples
- Our data seem to prefer an Exponential shape for the Fourier transform of the emission region $\Omega(Qr)$
- We propose the combination of seven different reference samples to produce a measurement of the size of the emission region r and the strength of the effect λ
- We estimate systematics with the r.m.s. spread of measurements obtained with different reference samples
- We observe a dependence of the r parameter on event multiplicity
- We measure: (errors: stat., syst.)
  - at 0.9 TeV: $r = (1.59 \pm 0.05 \pm 0.19)$ fm , $\lambda = 0.625 \pm 0.021 \pm 0.046$
  - at 2.36 TeV: $r = (1.99 \pm 0.18 \pm 0.24)$ fm , $\lambda = 0.662 \pm 0.073 \pm 0.048$

Comparison with previous measurement

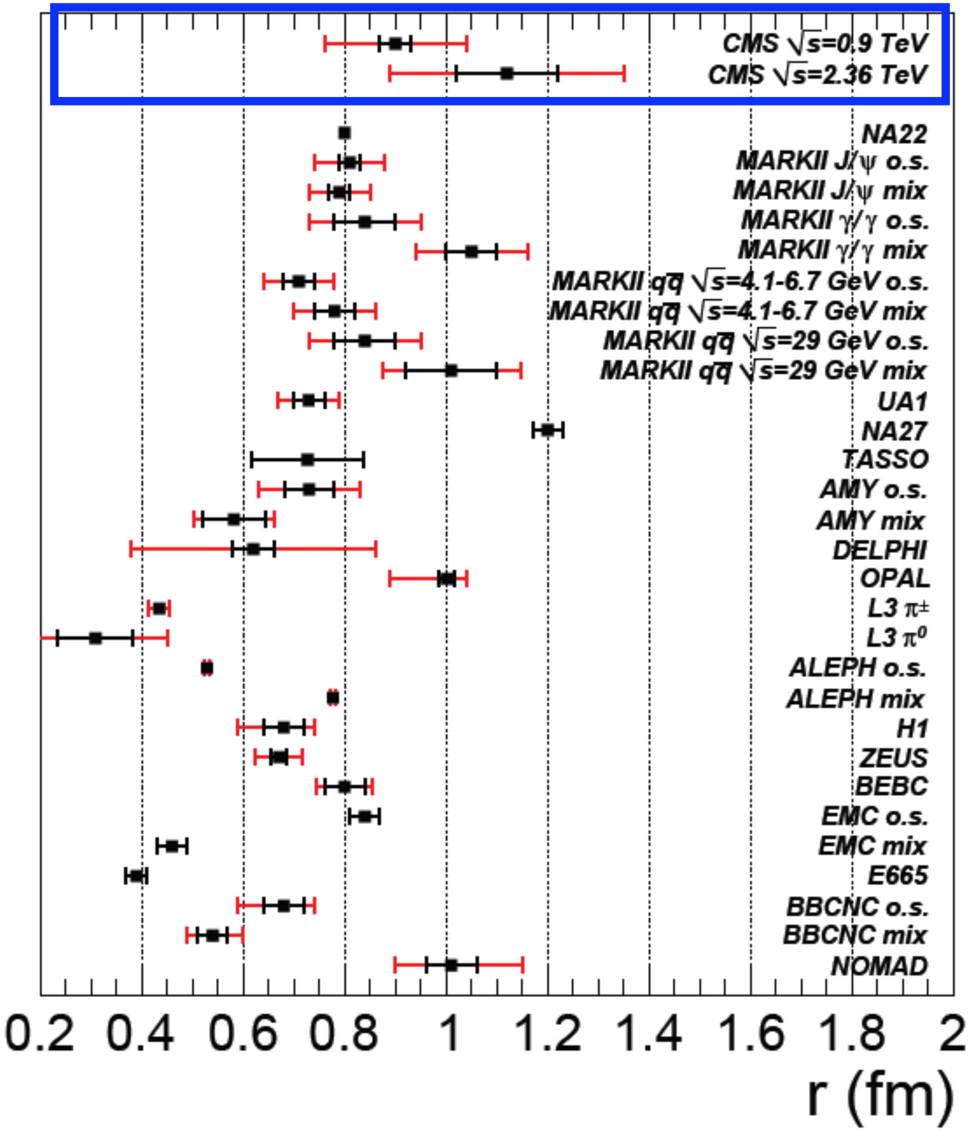
- For an exponential

$$< Q >_{\exp} = \frac{1}{r}$$

- For the half-Gaussian

$$< Q >_{gaussian} = \frac{1}{(r/\sqrt{\pi})}$$

- When comparing the size of the emission region r extracted from Exponential fits to the Gaussian ones, a scale factor is involved, $\sqrt{\pi} = 1.77$, to normalize the first momentum of the two distributions.



Backup slides

Previous measurements

- First observation of the phenomenon: pion production in 1.05 GeV/c proton-antiproton annihilations – Goldhaber et al., Phys. Rev. 120 (1960) 300.
- Scores of measurements since then
  - **Mark II**: Phys. Rev. D39 (1989) 1 (electron-positron)
  - **TASSO**: Z. Phys. C30 (1986) 355 (electron-positron)
  - **NA22**: Z. Phys. C37 (1988) 347 (meson-proton)
  - **UA1**: Phys. Lett. B226 (1989) 410 (proton-antiproton)
  - **NA27**: Z. Phys. C54 (1992) 21 (proton-proton)
  - **DELPHI**: Phys. Lett. B286 (1992) 201 (electron-positron)
  - **L3**: Phys. Lett. B524 (2002) 55 (electron-positron)
  - **ZEUS**: Acta Phys. Polon. B33 (2002) 3281 (lepton-proton)
  - **OPAL**: Phys. Lett. B559 (2003) 131 (electron-positron)
  - **ALEPH**: Eur. Phys. J. C36 (2004) 147 (electron-positron)
  - **NOMAD**: Nucl. Phys. B686 (2004) 3 (neutrino-nucleon)
  - **ZEUS**: Acta Phys. Polon. B33 (2002) 3281
  - Breakstone et al. - Z. Phys. C 33 (1987) 333-338
  - Apologies to the others not quoted here
- And a thick literature of theoretical studies

Dependence from multiplicity in literature

- Big Bubble Chamber Neutrino Collaboration (BBCNC) - link
- ISR article (Breakstone et al.) - link
- H1 Collaboration - link
- OPAL Collaboration - link
- E735 Collaboration - link
- NA27 - Z. Phys. C54 (1992) 21
- NOMAD Collaboration - Nucl. Phys. B686 (2004) 3
- UA1 Collaboration - Phys. Lett. B226 (1989) 410

- Apologies to the others not quoted here

Reference samples

- Measurement relies on dividing the Q-value distribution for same-sign pairs (containing BEC) by the Q-value of a reference sample of pairs which are not correlated
- There are several possibilities, widely explored also in the literature.
  We considered:
  1) Opposite charge pairs
  2) Same charge pairs where one track has its three-momentum inverted ($\overline{p} \rightarrow -\overline{p}$)
  3) Opposite charge pairs where one track has its three-momentum inverted ($\overline{p} \rightarrow -\overline{p}$)
  4) Same charge "rotated" pairs with one track inverted in the transverse plane ($\overline{p}_t \rightarrow -\overline{p}_t$)
  5) Pairs formed with tracks from randomly mixed events
  6) Multiplicity event mixing: as above, but mixed events have similar distribution of $dN/d\eta$.
  7) Invariant mass event mixing: as above, but mixed events have similar total mass of charged tracks

- Although derived from the same experimental data and the same tracks, the Q-values thus constructed do not significantly "talk" to each other in the fit region

Track Selection

- We apply a number of requirements on the charged tracks we use in our measurement, to increase their purity, remove pathologies, ensure high efficiency
  - $N_{dof}>5$
  - $p_t > 200$ MeV/c
  - Fit $\chi^2 < 5.$
  - $|\eta| < 2.4$
  - $|d_{xy}|^{BS} < 0.15$cm
  - $R_{xy} < 20$ cm (innermost hit)

- The selection retains 2,903,754 tracks in 0.9 TeV data, and 188,140 tracks in 2.36 TeV data. These are our basis for the construction of pion-pair candidates.

Fourier transforms and r scales

- An exponential form $\Omega(Qr) = \exp(-Qr)$ is the Fourier transform of a Cauchy distribution

- There is nothing bad in a Cauchy distribution as the shape of an interference region
  - In the form $1/(r^2+x^2)$, r has the meaning of the half FWHM, so it may still be seen as an effective radius

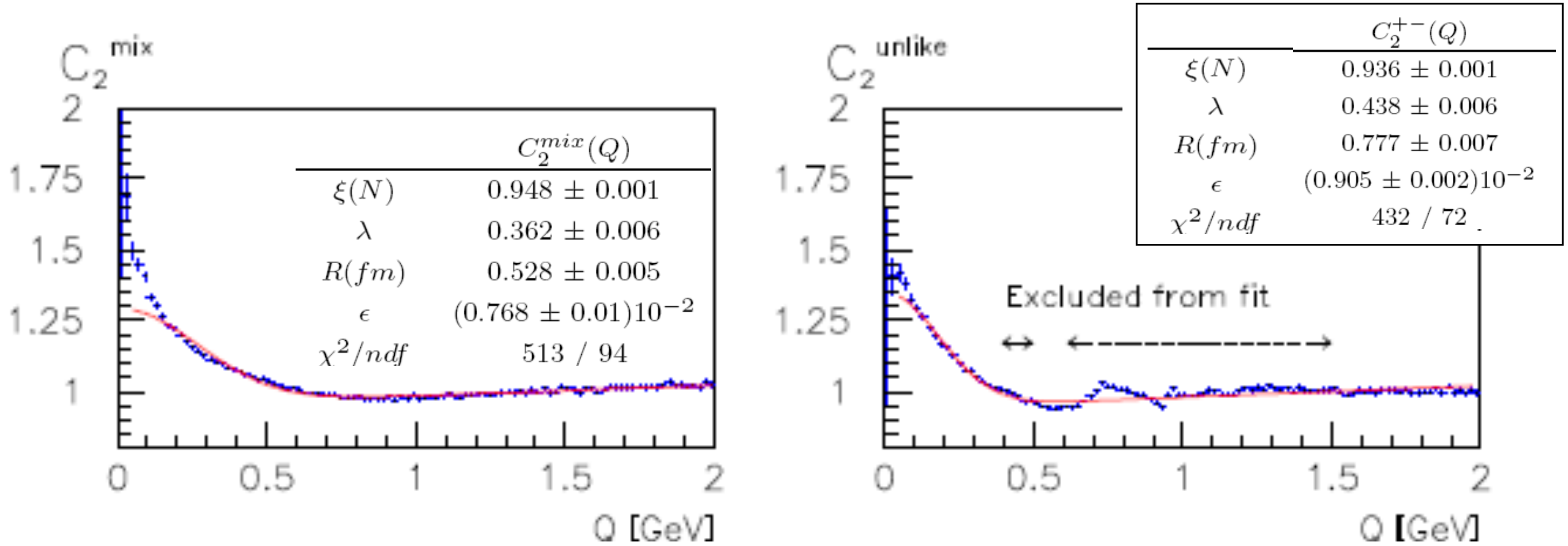
- While $\langle Q \rangle$ for an exponential is $\langle Q \rangle_{exp}=1/r$, for the half-Gaussian is not $1/r$ but $\langle Q \rangle_G=1 / [r / \pi^{0.5}]$,

- Therefore, *when comparing the size of the emission region r extracted from exponential fits to the ones present in the literature, which are derived from Gaussian fits, a scale factor is involved,*

  $\pi^{0.5} = 1.77$, *to normalize the first momentum of the two distributions*.

Results by Aleph

- Aleph used two reference samples: opposite-charge tracks (right), and tracks from mixed events (left)
- They use the Gaussian parametrizations (red curves) to describe the effect
- Results are quite different with the two methods for both λ and r
- Aleph chose to publish them together
- Another thing to note: fits have a disturbingly bad χ^2
  - Typical value: 500/74
  - regardless of excluding resonance regions



The H1 case

H1 also finds results more in line with an exponential shape than with a Gaussian one.

From C.Adloff *et al.*, Z.Phys. C75 (1997) 437:

"The quality of the fit for the exponential is slightly better than for the Gaussian parametrization (85/72 vs 96/72) and confirms previous observations that the BE correlation function is decreasing faster with T than a Gaussian."