Measurement of Bose-Einstein Correlations in the first LHC-CMS data

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on behalf of
CMS Collaboration

Pheno 2010 (Madison) – May 10-12, 2010

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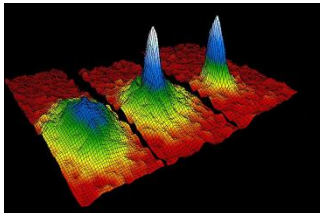
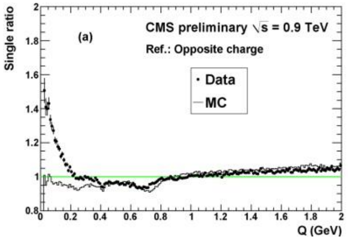
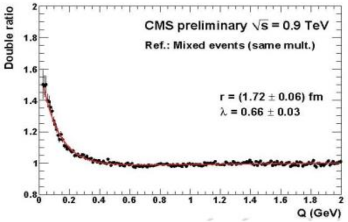
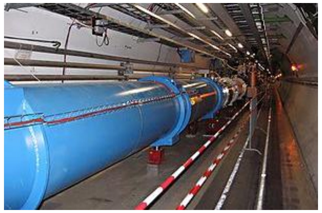


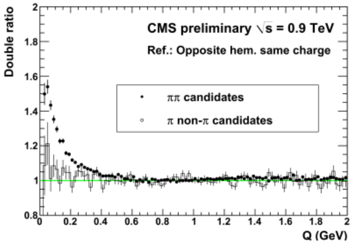


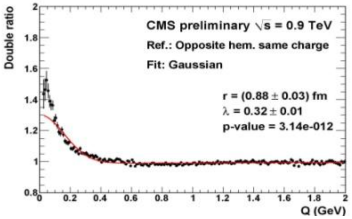


Outline:

- *BEC* in High-Energy Physics:
  - A long story…
- Effect clearly evident in our data:
  - Different reference samples.
  - Particle identification.
- What we measured:
  - Double ratio data/MC.
  - Fit with exp. and gaussian shape.



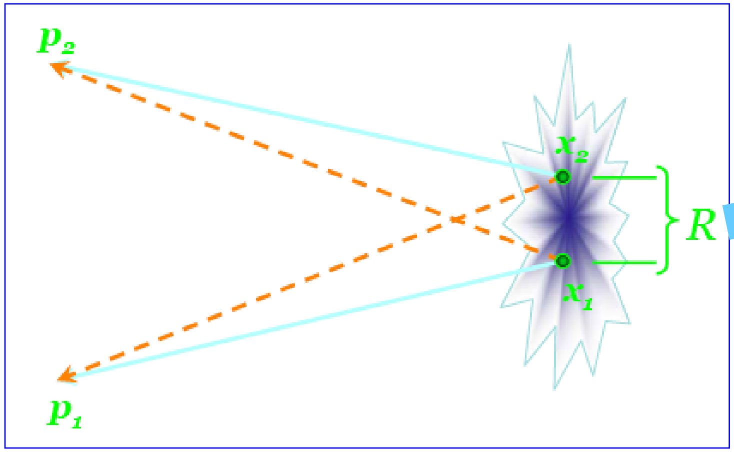


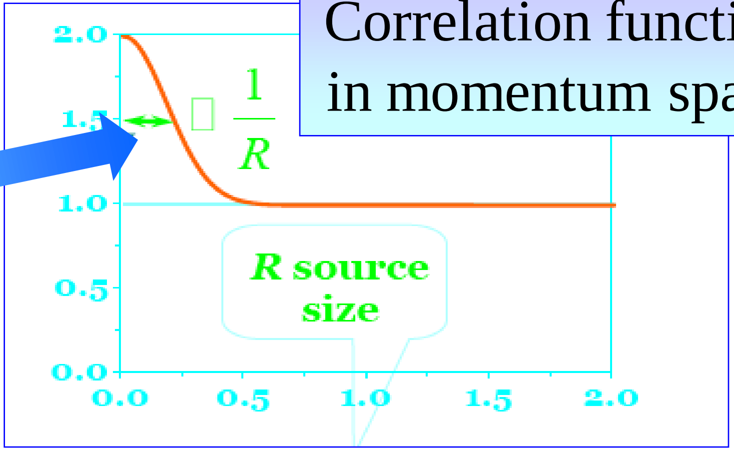


BEC in High Energy Physics

During high-energy collisions, bosons are created at small distance in a “fireball”

Their wave functions overlap, and the Bose-Einstein statistics changes their dynamics





Correlation function in momentum space

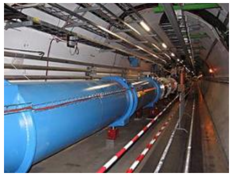
This is essentially the only way to measure the size of a source at the Fermi scale

Why measure BEC again?

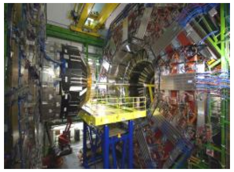
This is ***not*** a new phenomenon:

1. measured for the first time in HEP by Goldhaber (1960);
2. Since then, many measurements with different detectors and different initial states (e^+e^-, pp, $p\bar{p}$, πN *and* $\nu_\mu N$).

However…



1. We have a new accelerator (***LHC***), and therefore higher energies (2.36 TeV in December, now 7 TeV).
2. We have a new, hopefully more powerful detector (***CMS***).



This is one of the ***first*** physics measurements done with real data!

How to measure BEC?

Theoretically, we need to study the ratio between the joint probability of emission of a pair of bosons, and the individual probabilities

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

Experimentally, we have to produce the distributions of a "proximity" quantity in the data and in a reference sample (***Coulomb corrected***)

$$R = \frac{dN/dQ_{data}}{dN/dQ_{ref}}$$

To measure the proximity between 2 particles, we chose the difference of 4-momentum (assuming all pions):

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{m_{inv}^2 - 4m_\pi^2}$$

To calculate R:

1. Take all (charged) tracks.
2. Construct Q.
3. Repeat for the reference sample.

Reference samples

We used 7 reference samples, mainly taken from literature:

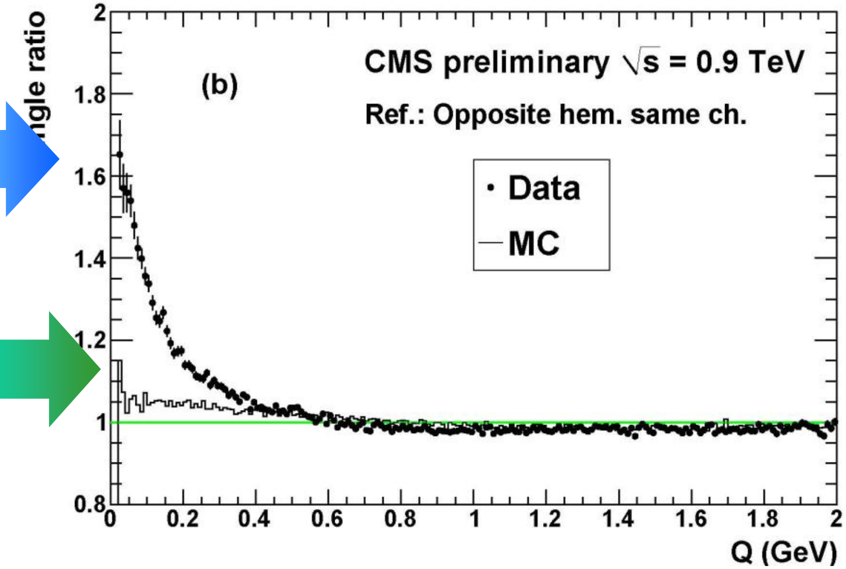
1. ***Opposite charge*** pairs;
2. ***Opposite charge*** pairs where one track has its ***three-momentum inverted***;
3. ***Same-charge*** pairs where one track has its ***three-momentum inverted*** ;
4. ***"rotated" pairs***: same charge with one track inverted in the transverse plane;
5. Event mixing 1: every pair has one track from one event, the other from the ***following selected event***;
6. Event mixing 2: as above, but events are paired such that they have ***similar distribution of*** $dN_{tracks}/d\eta$;
7. Event mixing 3: as above, but events are paired such that they have ***similar total invariant mass of charged tracks***;

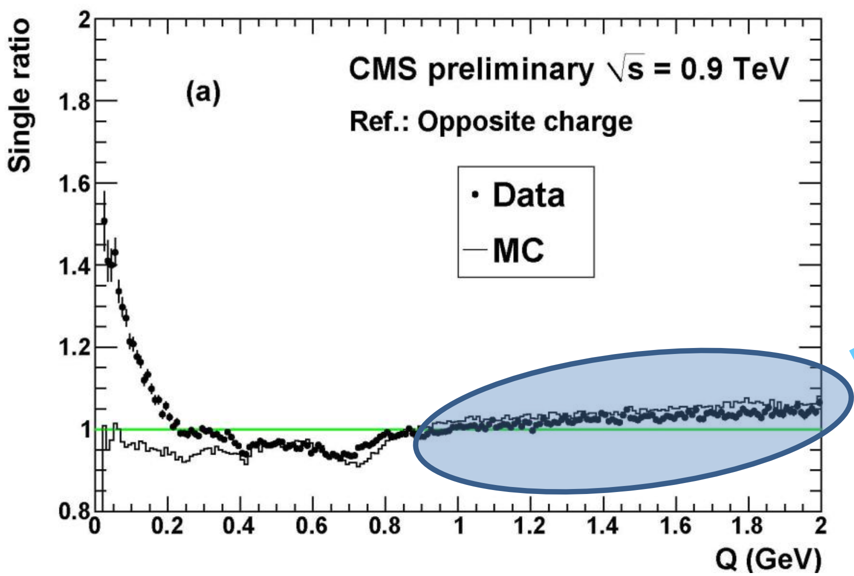
None of these reference samples is "golden" → We used all of them for our analysis

Evidence of the effect

The enhancement at Q=0 shows the expected correlations

MC is essentially flat (no BEC in the simulations)





Data are well reproduced by MC

Spectra are ***not flat***, in particular for some reference samples

Double ratio data / MC

Every reference sample,
“natural” (opposite-sign) or “artificial”,
is distorted if compared with the real event

Part of the distortion is due to the kinematics or decays,
well described by the MC simulation

To remove the long-range bias, evident in some of the reference samples, we used the double ratio between data and MC

$$\Re = \frac{R}{R_{MC}} = \frac{\left(\dfrac{dN/dQ}{dN/dQ_{ref}}\right)}{\left(\dfrac{dN/dQ}{dN/dQ_{ref}}\right)_{MC}}$$

Parametrizations

To perform the fit of the double-ratio spectra, we used the function:

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

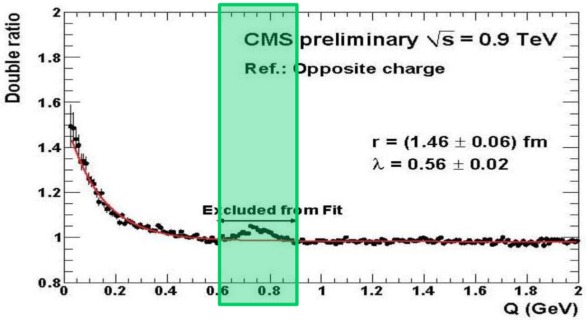
Where λ measures the strength for incoherent boson emission from independent source, δ accounts for long-distance correlations, and ***C*** is a normalization factor.

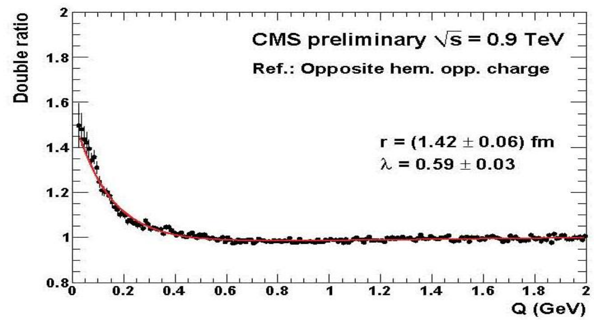
In a static model of particle emission, the $\Omega(Qr)$ function is the ***Fourier transform of the emission region***, whose effective size is measured by r.

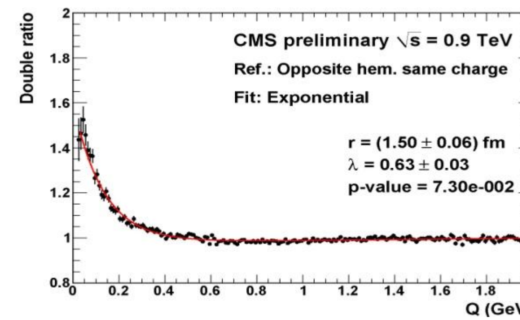
We chose two parametrizations:

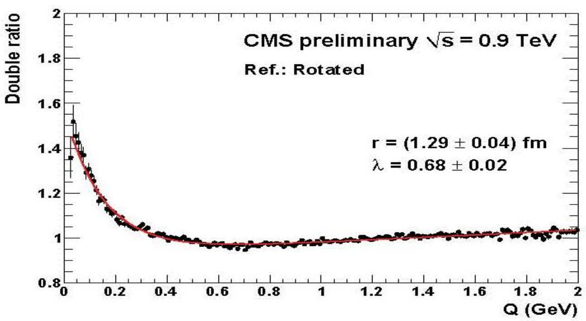
1. $\Omega(Qr) = exp(-Qr)$ – ***Exponential***, our default.
2. $\Omega(Qr) = exp(-Q^2r^2)$ – ***Gaussian***, widely used.

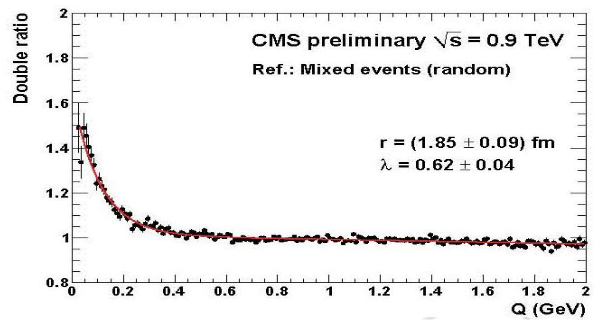
Fits for data @ 900 GeV



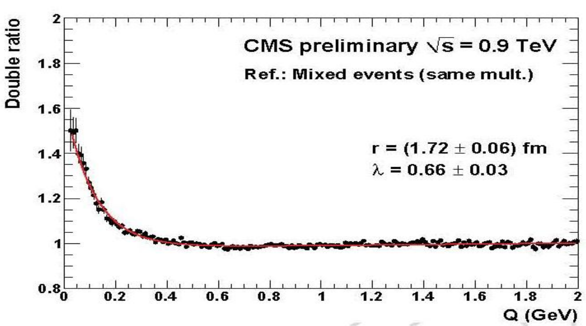


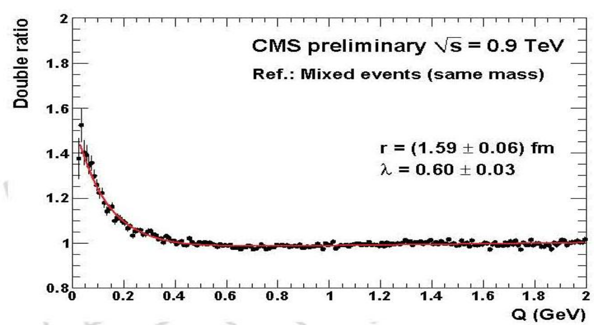






Results are between 1.29 and 1.85 for *r*, 0.56 and 0.68 for λ





For the opposite charge, we removed the region with sizeable contribution from $\rho \rightarrow \pi^+ \pi^-$

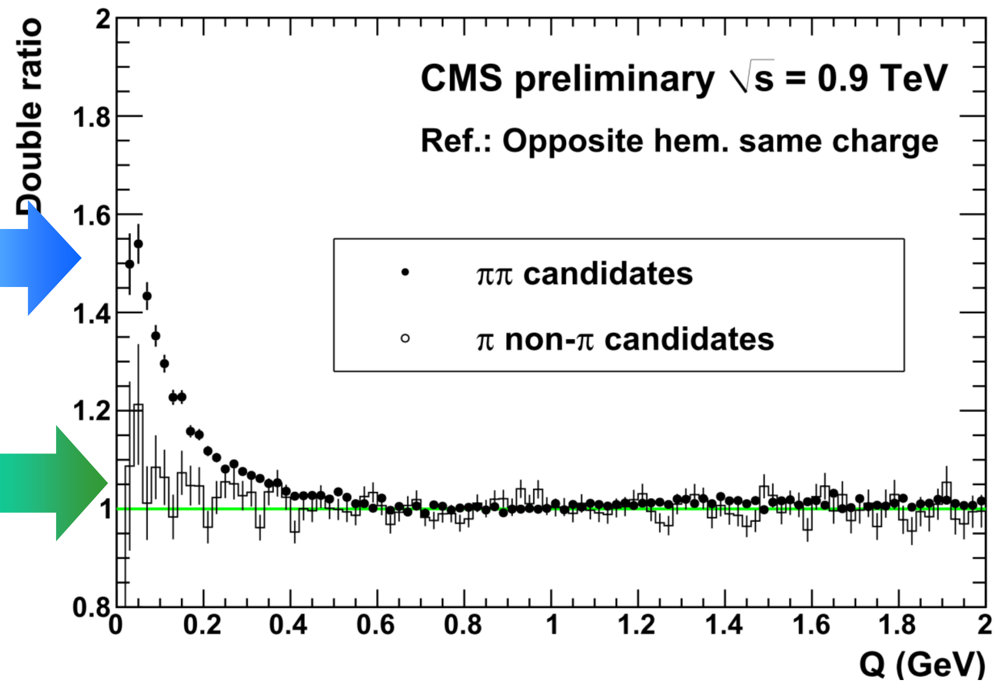
Additional check

In our data, many particles have small momentum (p < 2 GeV)

The energy loss in the tracker allows to select π and non-π

Signal is ***really due*** to BEC (enhanced for $\pi\pi$ pairs)

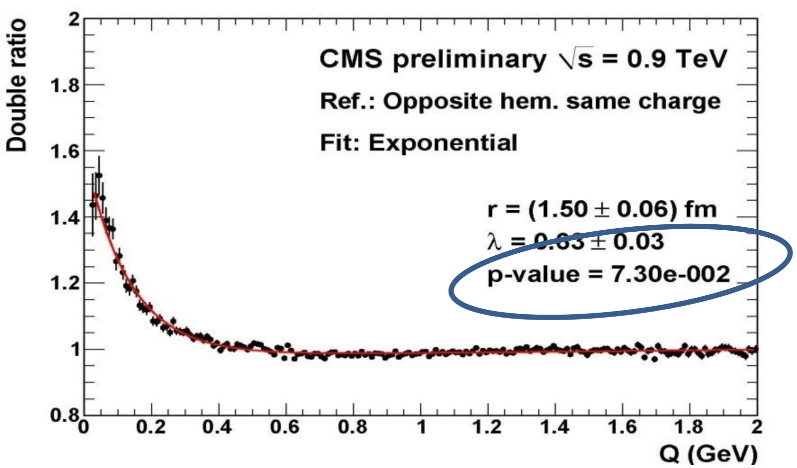
The plot is almost flat for particles of different type



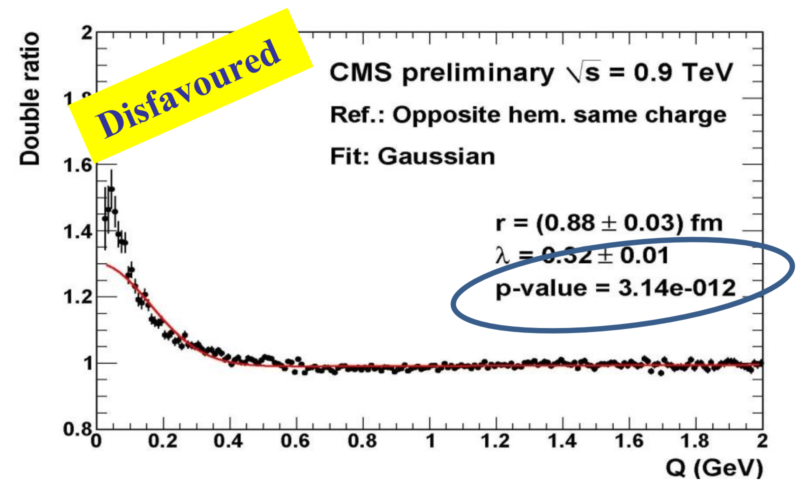
Different parametrizations

We tested: exponential, Gaussian, Levy,
and those described by Kozlov and Biyajima

$\Omega(Qr) = exp(-Qr)$ – ***Exponential***



$\Omega(Qr) = exp(-Q^2r^2)$ – ***Gaussian***



All functions with the Gaussian form have to be ruled out:
the others give equally good results

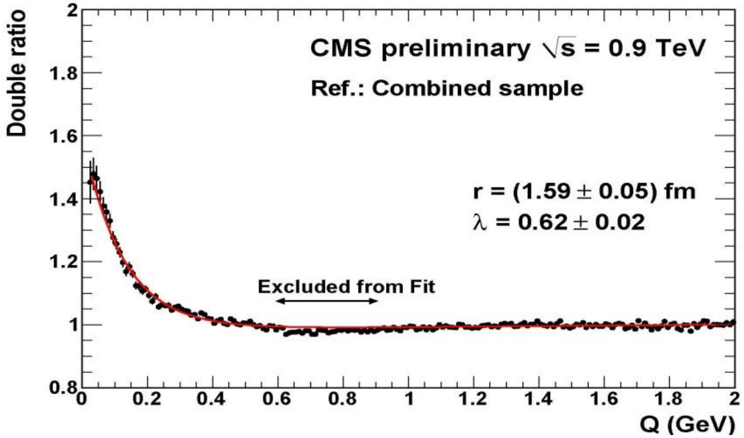
Combined reference sample

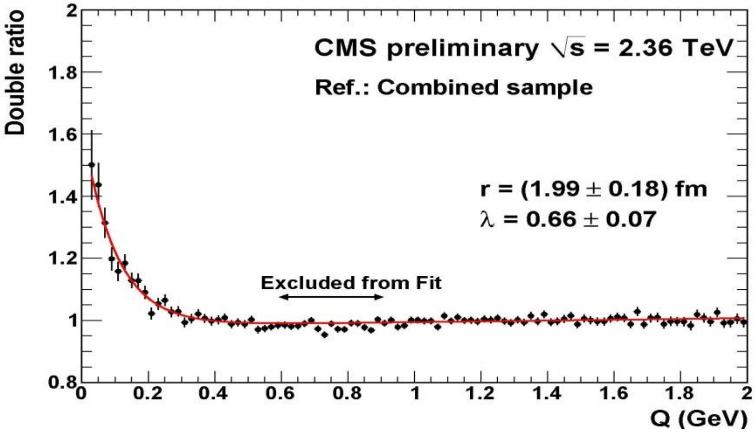
We consider it valuable to provide a single value,
together with a conservative estimate of the systematic error

Since the samples are correlated, we cannot simply calculate the average of r and λ

$$\Re^{avg} = \frac{dN/dQ}{dN/dQ_{MC}} \frac{\sum_{i=1}^{m} dN/dQ^{i}_{MC}}{\sum_{i=1}^{m} dN/dQ^{i}}$$

Then we performed an exp. fit for both sets of data:





Systematic uncertainties

No reference sample is perfect, and none can be discarded → ***r.m.s.*** of fit results ($\pm7\%$ for λ, $\pm12\%$ for r)

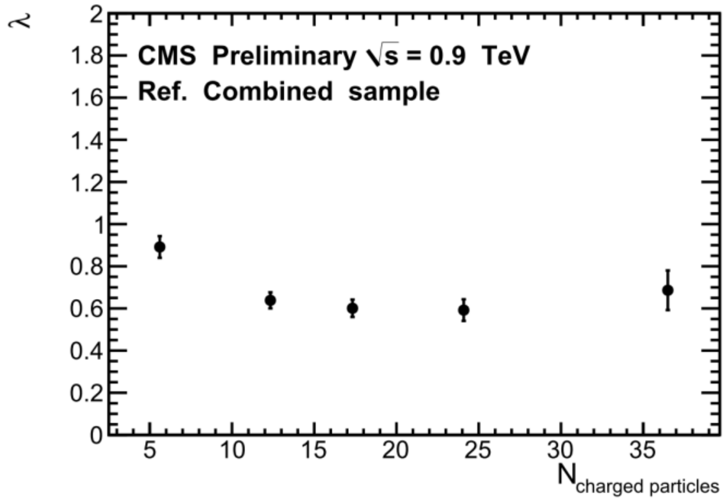
Gamow factor to correct Coulomb effects ($\pm15\%$) → Propagate agreement margin ($\pm2.8\%$ for λ, $\pm0.8\%$ for r)

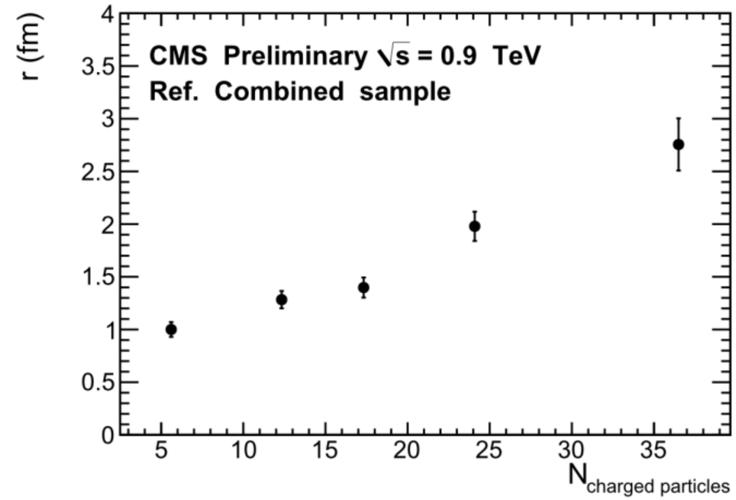
By comparing MC (***with BEC***) at the reconstruction and generation level, we noticed that variations are within errors.

Data @ 900 GeV:
$r = 1.59 \pm 0.05_{stat.} \pm 0.19_{syst.}$ fm; $\lambda = 0.625 \pm 0.021_{stat.} \pm 0.046_{syst.}$
Data @ 2.36 TeV:
$r = 1.99 \pm 0.18_{stat.} \pm 0.24_{syst.}$ fm; $\lambda = 0.663 \pm 0.073_{stat.} \pm 0.048_{syst.}$

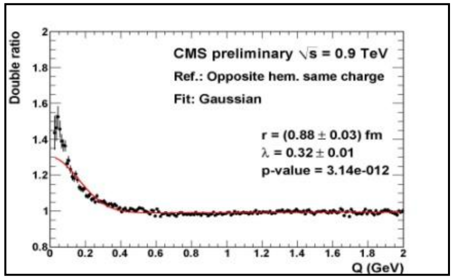
Dependence on event topology

Significant dependence of the *r* parameter with the charged-particle multiplicity in the event for ***all reference samples***

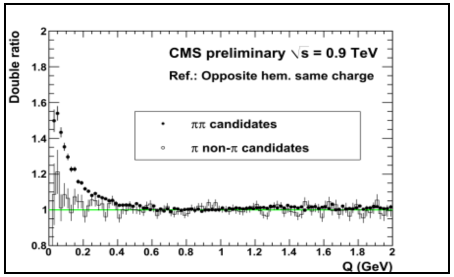




Our results confirm what was noticed with previous experiments in a wide range of energies and initial states



In short…

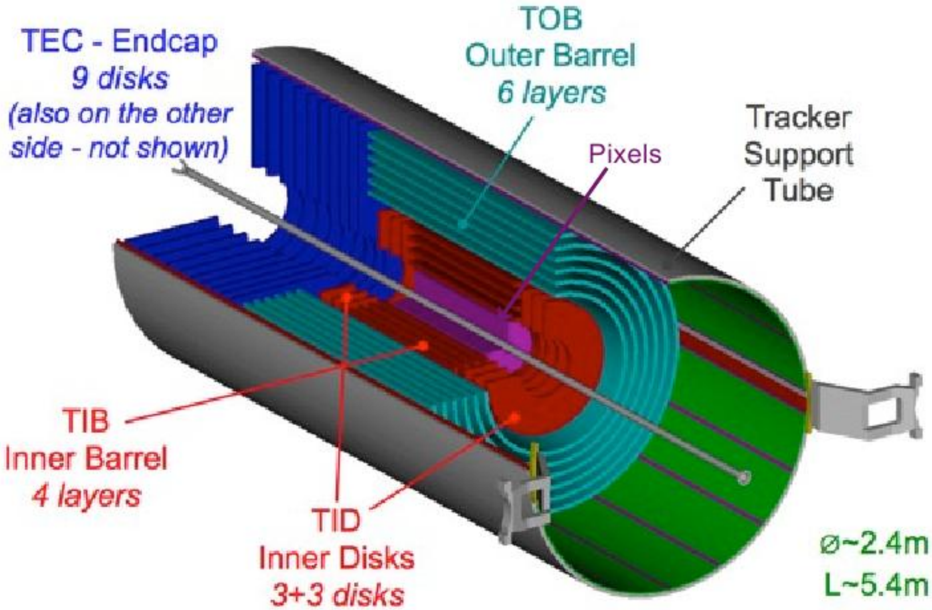


- We immediately saw the effect (as expected):
  - Clearly visible also in the single ratio.
  - Checked with particle identification.
- Measurement and systematic uncertainties:
  - We used the double ratio data/MC.
  - Fit (exp. and Gaussian) with many reference samples.
- We tried to give a single number:
  - Combined reference sample.
  - Dependence from the (charged) track multiplicity.

Backup slides

The CMS Silicon Tracker

- ***Pixel***:
  - ~1 m^2 of Si sensors;
  - 66M channels, 1440 modules;
  - 3 barrel layers (R=4, 7, 11 cm),
    2 endcap disks;
- ***Strips***:
  - ~198 m^2 of Si sensors;
  - 9.6M channels, 15148 modules;
  - 10 barrel layers,
    9+3 endcap wheels per side;
  - $|\eta| < 2.5$.



- ***From simulation studies***
  - Tracking efficiency > 99% (μ),
    > 90% (hadrons)
  - Resolution: $\Delta p/p$ ~ 1-2%
    (@100 GeV, $|\eta| < 1.6$)

Additional selections

A track was used if:

1. $p_T > 200$ MeV (to cross all 3 layers of ***pixel*** detectors);
2. $|\eta| < 2.4$;
3. $N_{dof} > 5$ and $\chi^2/N_{dof} < 5.0$;
4. $|d_{xy}| < 0.15$ cm and $R_{innermost} < 20$ cm.

0.02 GeV < Q < 2.0 GeV

Avoid not well-separated or duplicated tracks

Allows to check a good matching data – ref. sample

Gamow factors

The Coulomb interaction modifies the Q-value distribution of same-charge and different-charge pairs

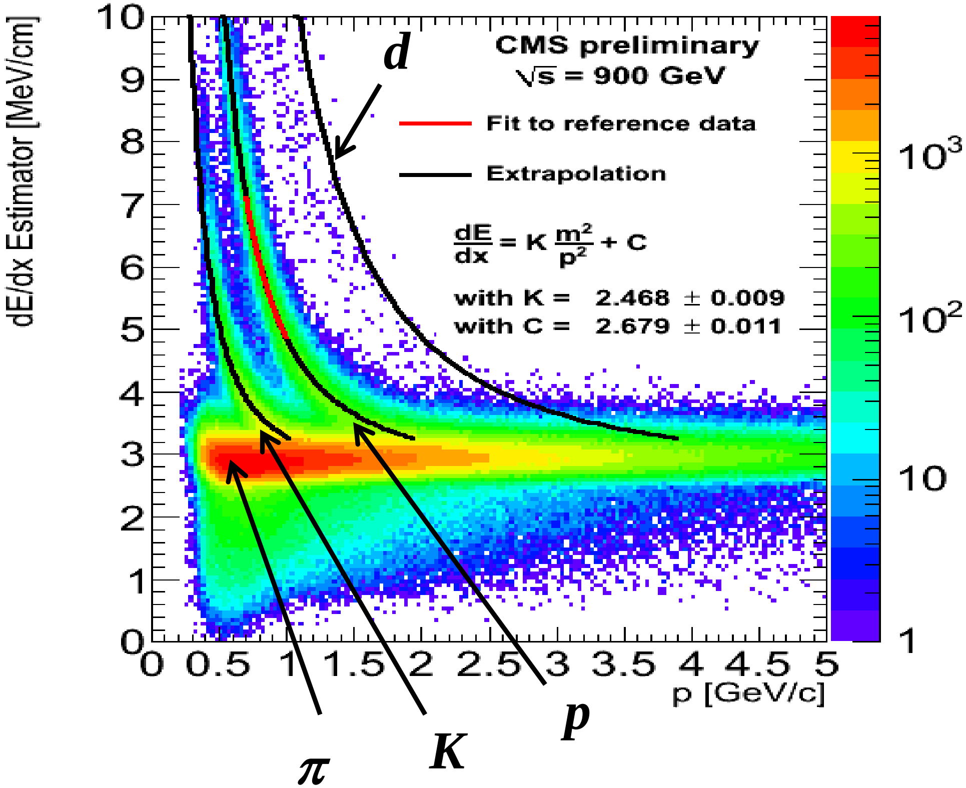
We need to correct this effect, and this is usually done by applying the Gamow factors W_S and W_D

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

We checked this correction on the ratio data/MC with opposite-charge tracks

Particle Identification

Charged particles with low momentum can be identified using the energy loss in the silicon due to ionization



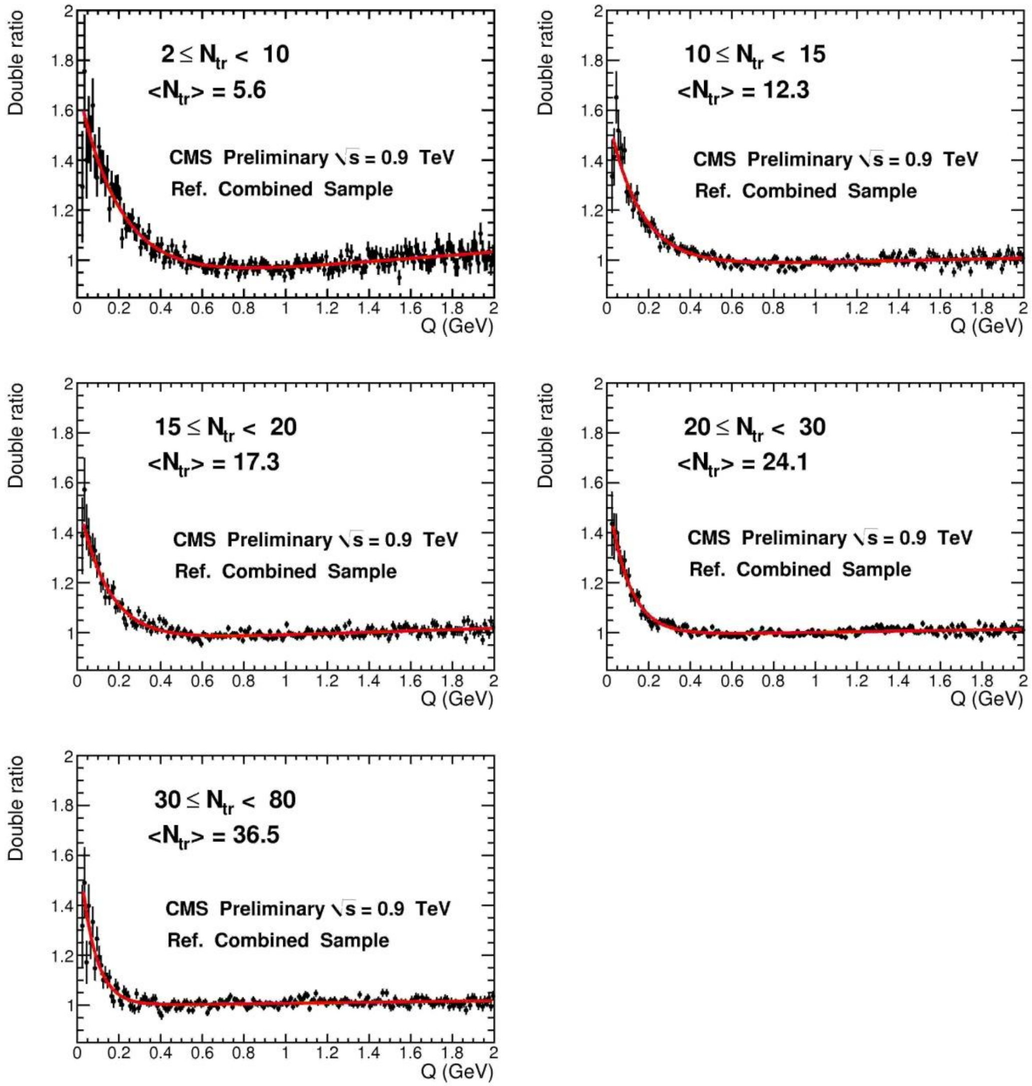
We considered a particle a π ***if***:

- *dE/dx* < 3.6 MeV;
- ***Or if***:
  - *dE/dx* > 3.6 MeV ***and***
  - $M < M_K - 200$ MeV.

A non-π has, at the same time:

- *dE/dx* > 4.15 MeV ***and***
- $M > M_K - 200$ MeV.

Dependence on event topology



Exponential fits of combined samples for different values of the track multiplicity

Shape which clearly changes with the charged-tracks multiplicity