Bose-Einstein correlations in *pp* collisions measured at LHC with CMS

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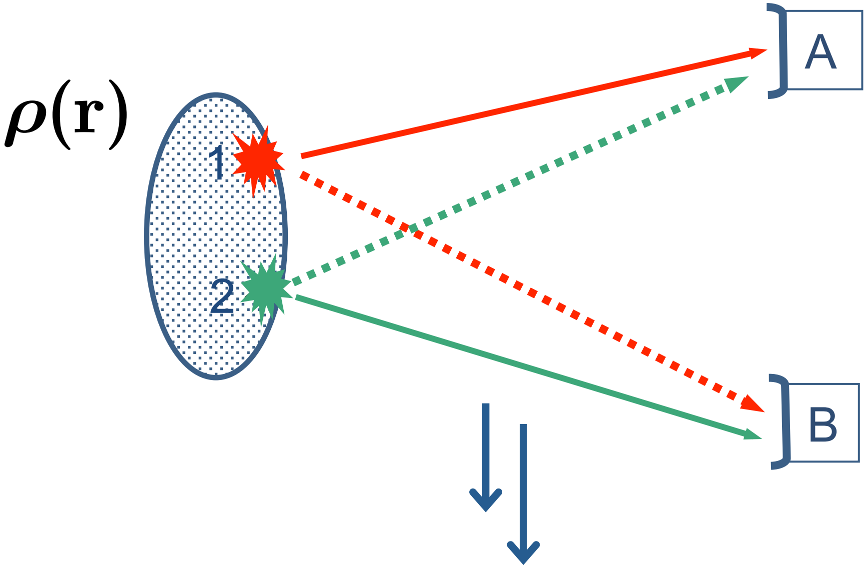
for the CMS Collaboration

HBT - BEC basics

- Detecting two identical bosons emitted from sources 1 & 2 at A & B



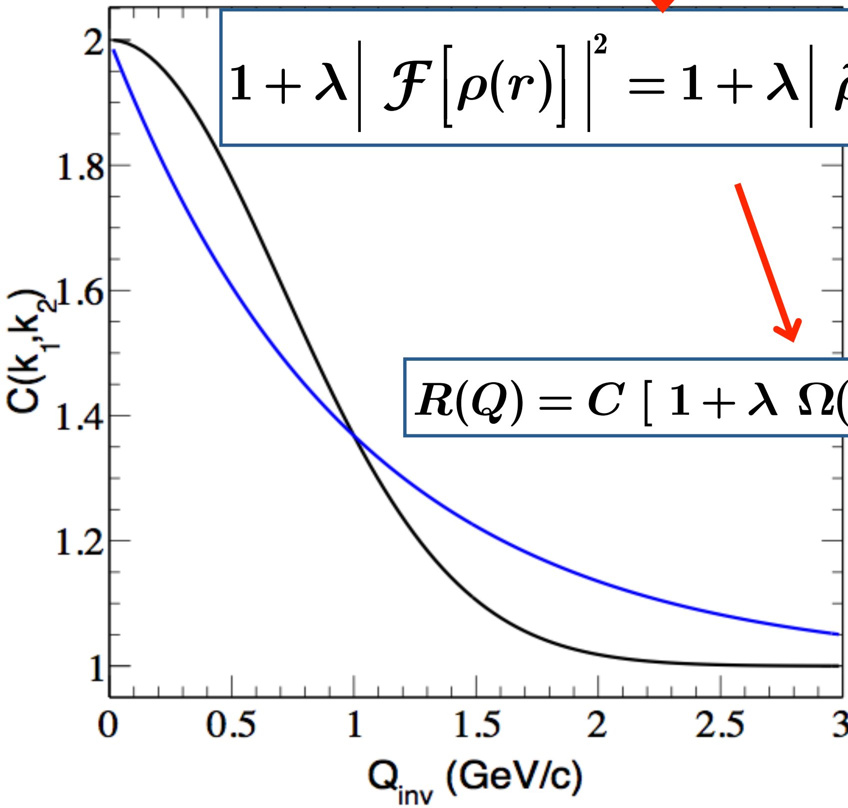
- Two-boson correlation function ⟶ reflects source dimensions

– Correlation Function:

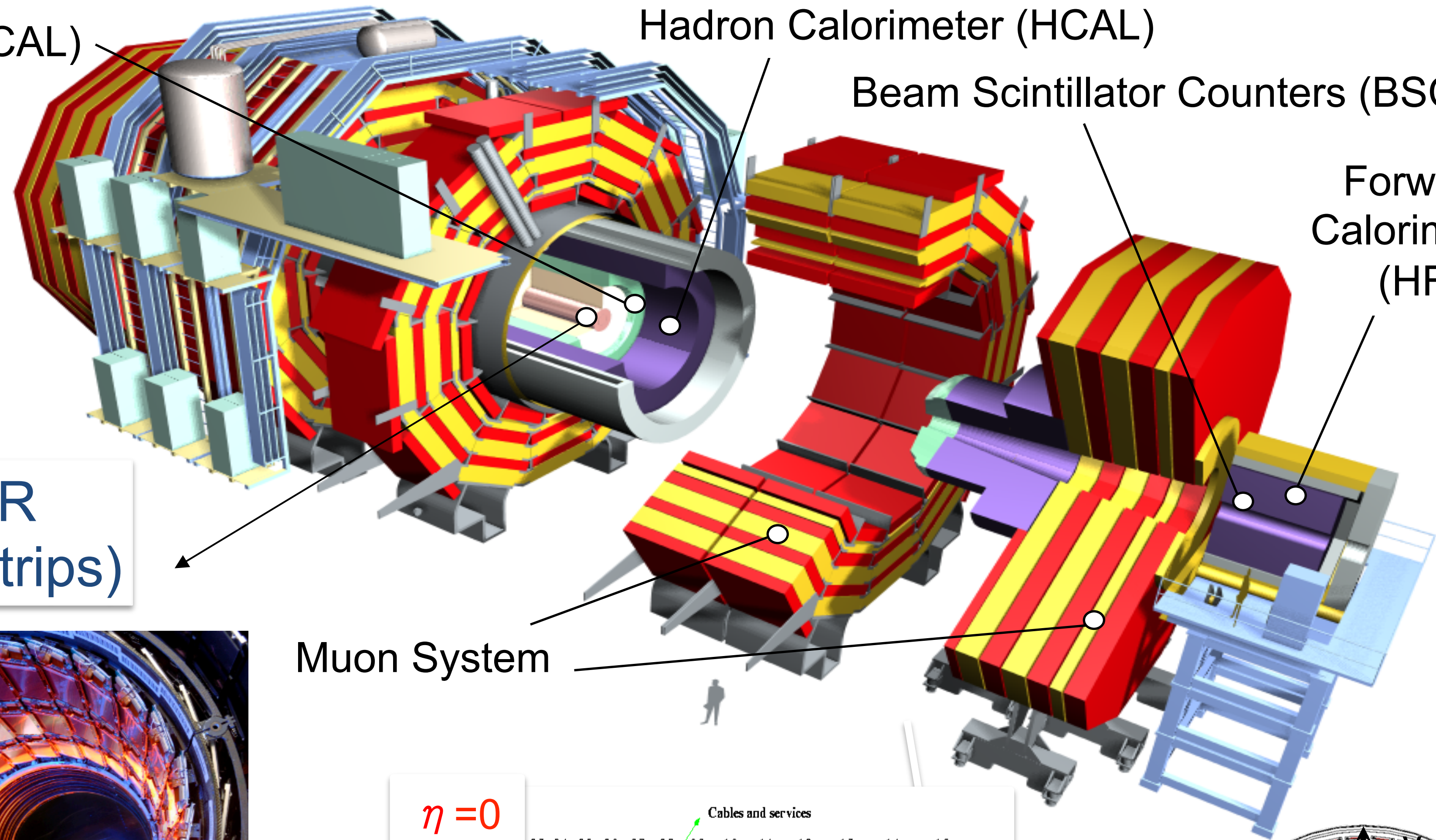
$$R\left(Q = k_1 - k_2\right) = \frac{P_2(k_1,k_2)}{P_1(k_1)P_1(k_2)}$$

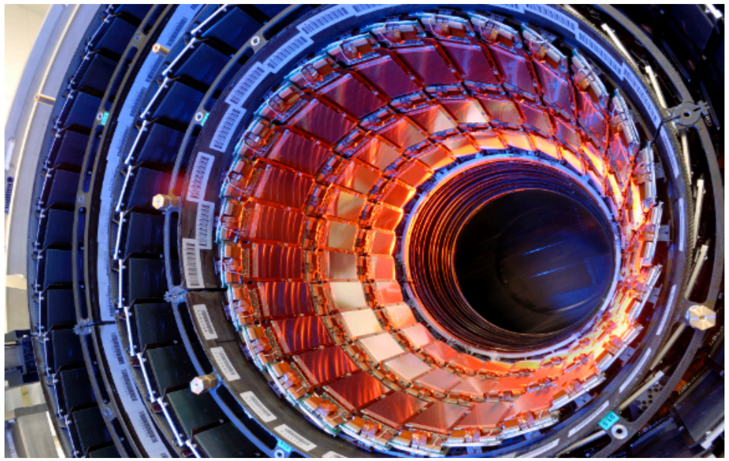
$$1 + \lambda \left| \mathcal{F}\left[\rho(r)\right] \right|^2 = 1 + \lambda \left| \tilde{\rho}(\mathrm{Q}) \right|^2$$ (ideal)

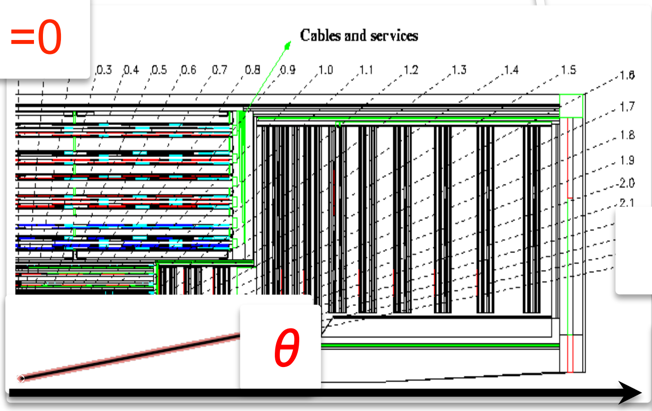
$$R(Q) = C\ [\ 1 + \lambda\ \Omega(Qr)\ ]\ (1 + \delta Q)$$

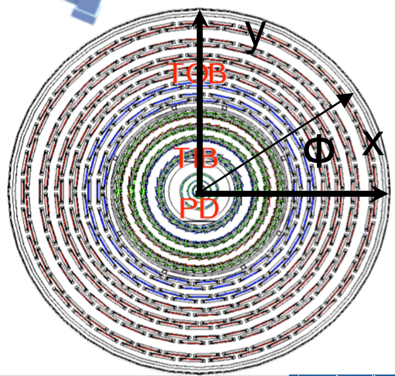


CMS Detector









Very large coverage ($|\Delta\phi| \leq 2\pi, |\Delta\eta| < 5$)!

BEC - pp @ 0.9 & 2.36 TeV - 2009 data

- Experimentally

$$R^{\exp}\left(Q = k_1 - k_2\right) = \frac{S(k_1, k_2)}{\mathcal{B}(k_1, k_2)}$$

Same event pairs (with BEC)

Different backgrounds (no BEC)

- Background pair selection
  - » Same event, opposite charges (☹ resonances)
  - » Rotation of 1 track of the pair
  - » Mixed events (☺)

Coulomb FSI
Gamow factor applied to data

$$\Upsilon_{SS}(\eta) = \frac{\eta / Q}{e^{\eta/Q} - 1}$$

$$\eta = 2\pi\alpha_{em} m_{\pi}$$

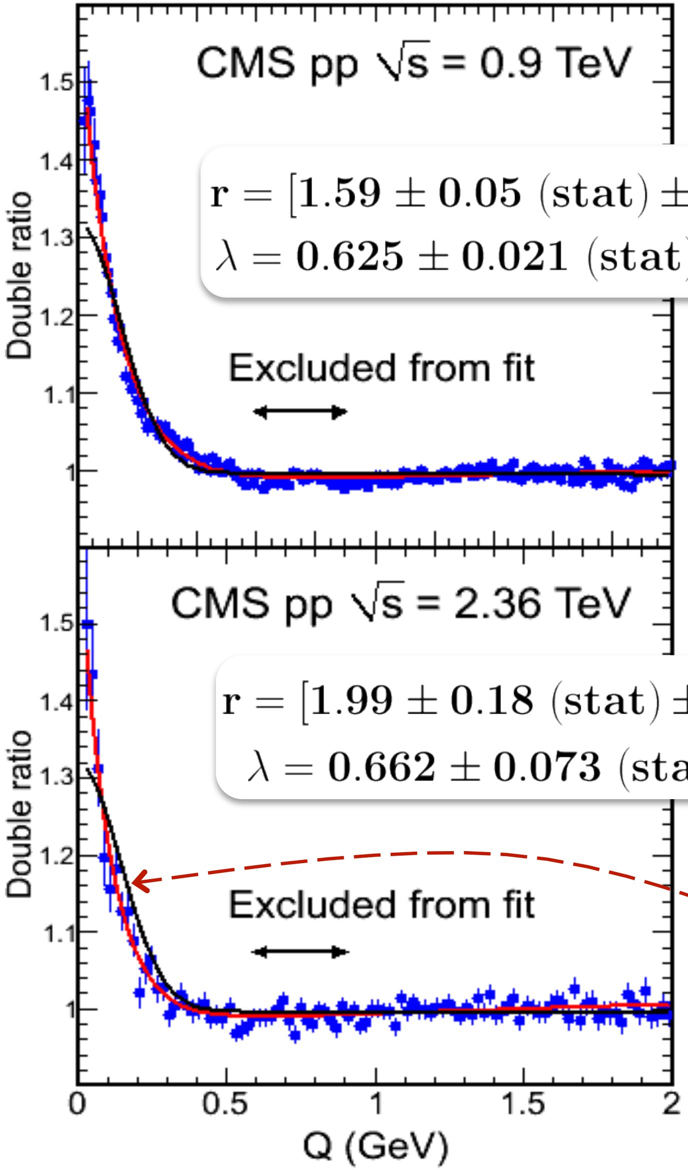
- Double ratios ⟶ reduce bias:

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \frac{\left(\dfrac{dN_{signal} / dQ}{dN_{ref} / dQ}\right)}{\left(\dfrac{dN_{MC,\ like} / dQ}{dN_{MC,\ ref} / dQ}\right)}$$

⟶ (No BEC in MC)

Summary of results – pp collisions @ 0.9 TeV

[PRL 105, 32001 (2010)]



$\mathrm{r} = [1.59 \pm 0.05\ (\mathrm{stat}) \pm 0.19\ (\mathrm{syst})]\ (\mathrm{fm})$

$\lambda = 0.625 \pm 0.021\ (\mathrm{stat}) \pm 0.046\ (\mathrm{syst})$

$\mathrm{r} = [1.99 \pm 0.18\ (\mathrm{stat}) \pm 0.24\ (\mathrm{syst})]\ (fm)$

$\lambda = 0.662 \pm 0.073\ (\mathrm{stat}) \pm 0.048\ (\mathrm{syst})$

– Leading syst. uncertainties: choice of ref. sample → r.m.s. spread between results ($\lambda = 7\%$; $r = 12\%$)

$$\mathcal{R}^{COMB} = \left(\frac{dN/dQ}{dN_{MC}/dQ}\right)\left(\frac{\sum_{i=1}^{7} dN/dQ^{i}_{MC}}{\sum_{i=1}^{7} dN/dQ^{i}}\right)$$

↓ Fit

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

$$\Omega(Qr) = \exp(-Qr)$$

$$\Omega(Qr) \propto \exp\left[-(Qr)^2\right]$$

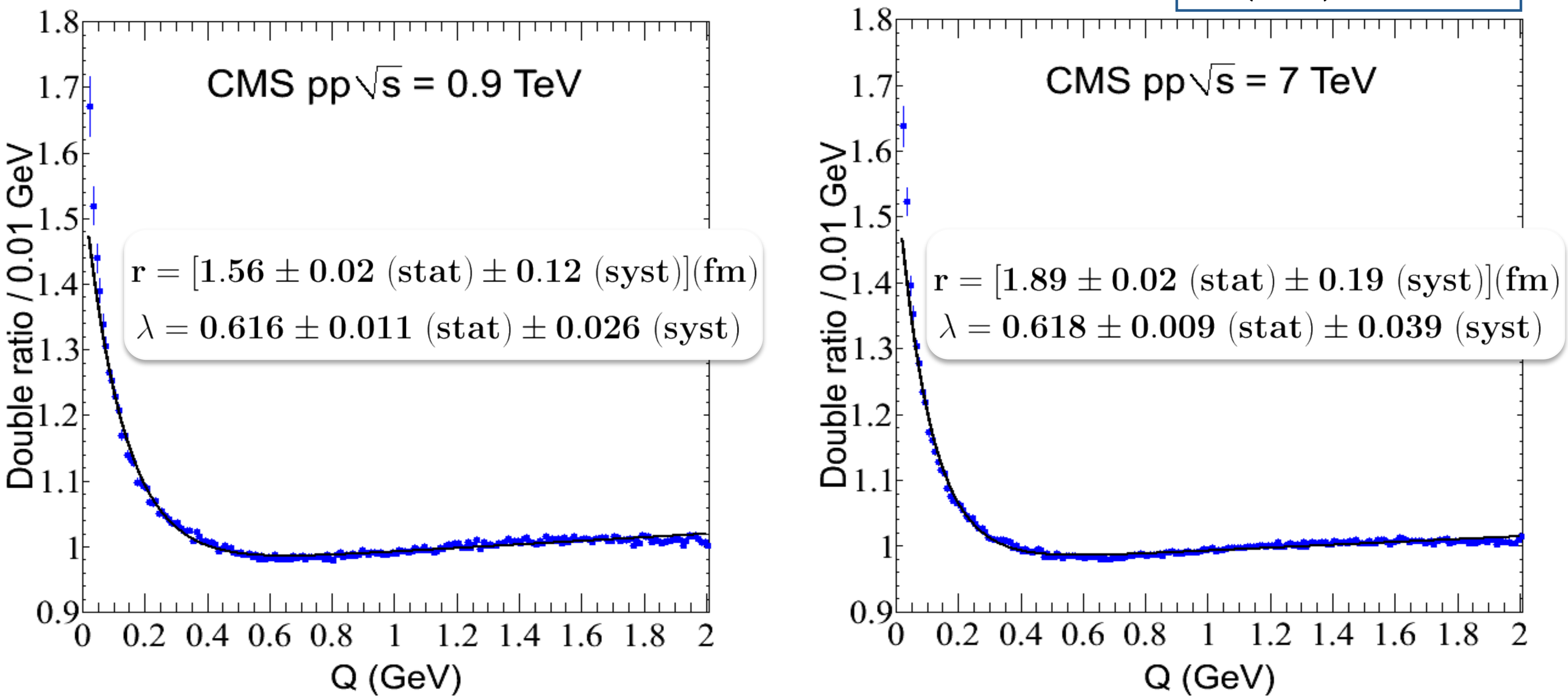
$$\to \chi^2 / N_{dof} > 9$$

$\sqrt{s}$	Min bias 2009	Min bias 2010
0.9 TeV	~ 280 k	~ 4.8 M
2.36 TeV	~ 14 k	
7 TeV		~ 2.7 M

2010 results - pp collisions 0.9 & 7 TeV

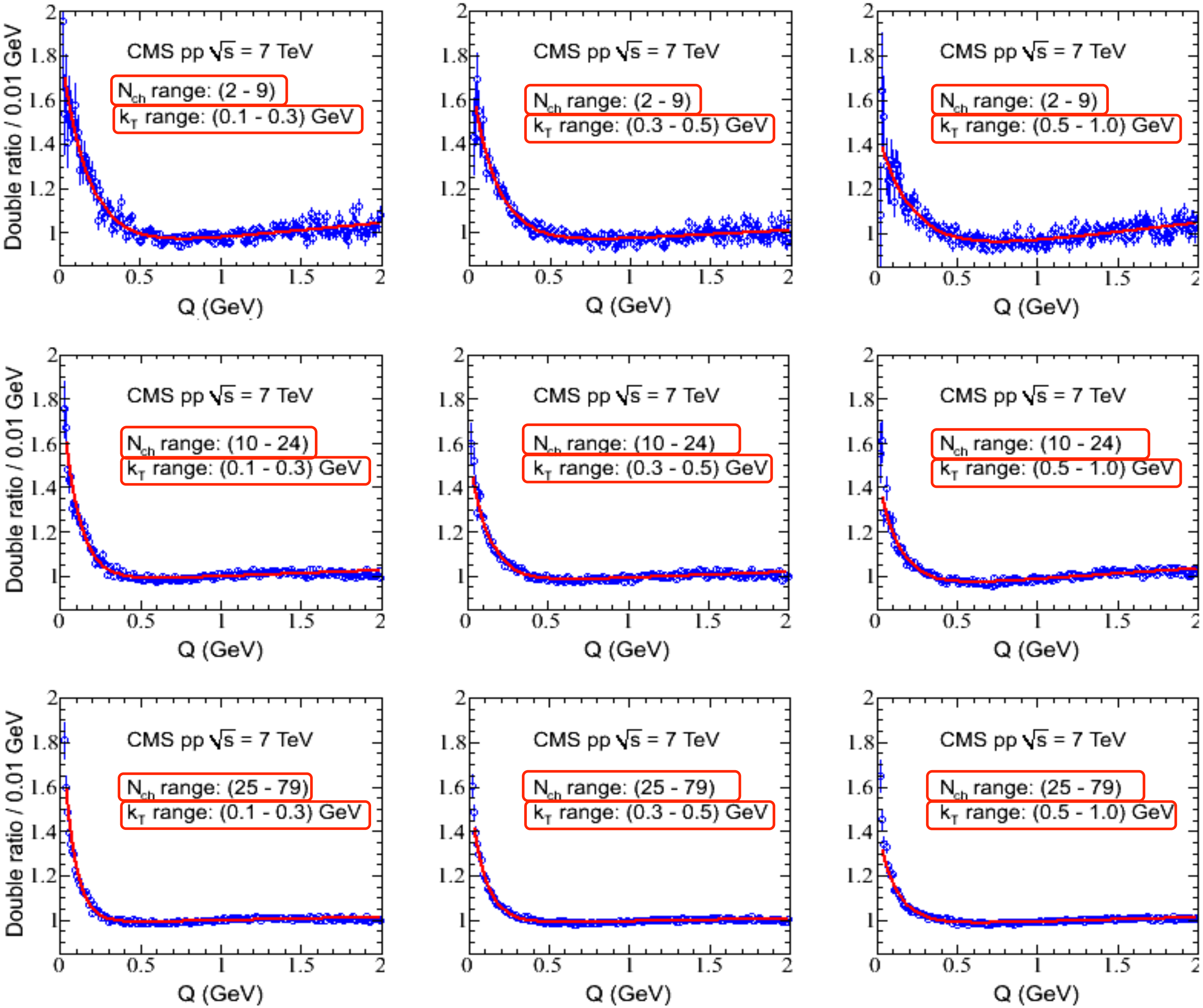
- Reference sample: same sign tracks, mixed events, ~ multiplicity
- MC simulation: Pythia 6 - Tune Z2

$$\Omega(Qr) = e^{-Qr}$$



[JHEP05 029 (2011)]

Dependence on k_T and N_{ch}



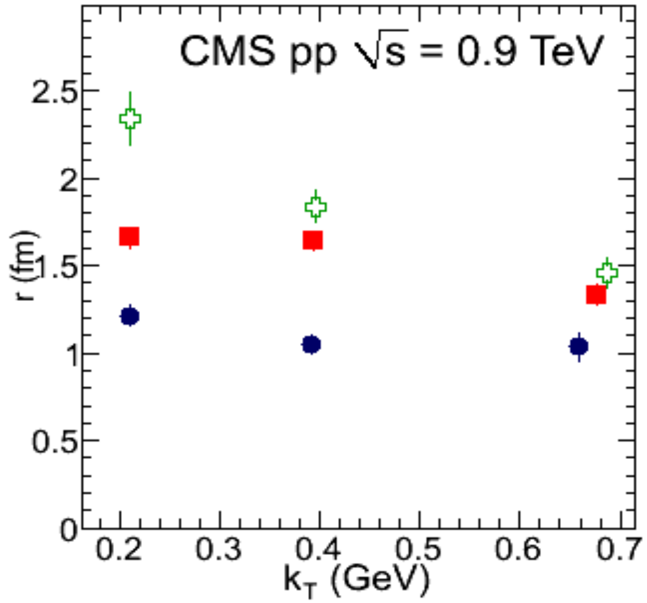
JHEP05 029 (2010)

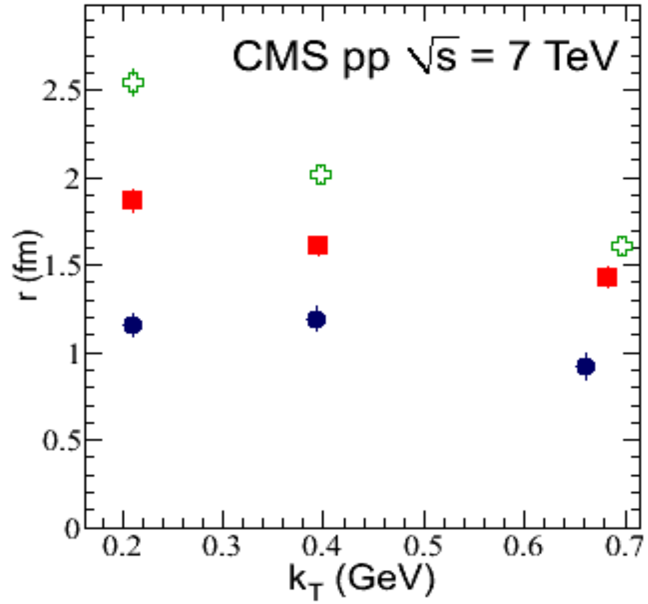
N_{ch}

$$\left|\vec{k}_T\right| = \frac{1}{2}\left|\vec{k}_{1_T} + \vec{k}_{2_T}\right|$$

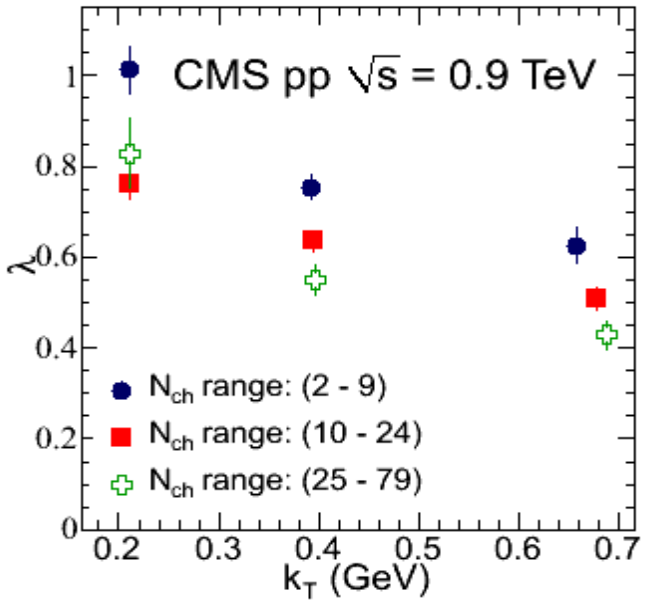
Fit parameters vs. k_T and N_{ch}

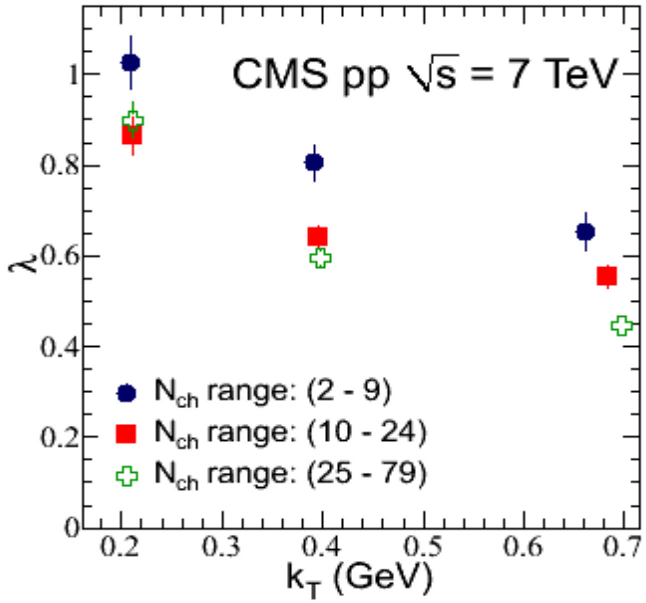
JHEP05 029 (2011)





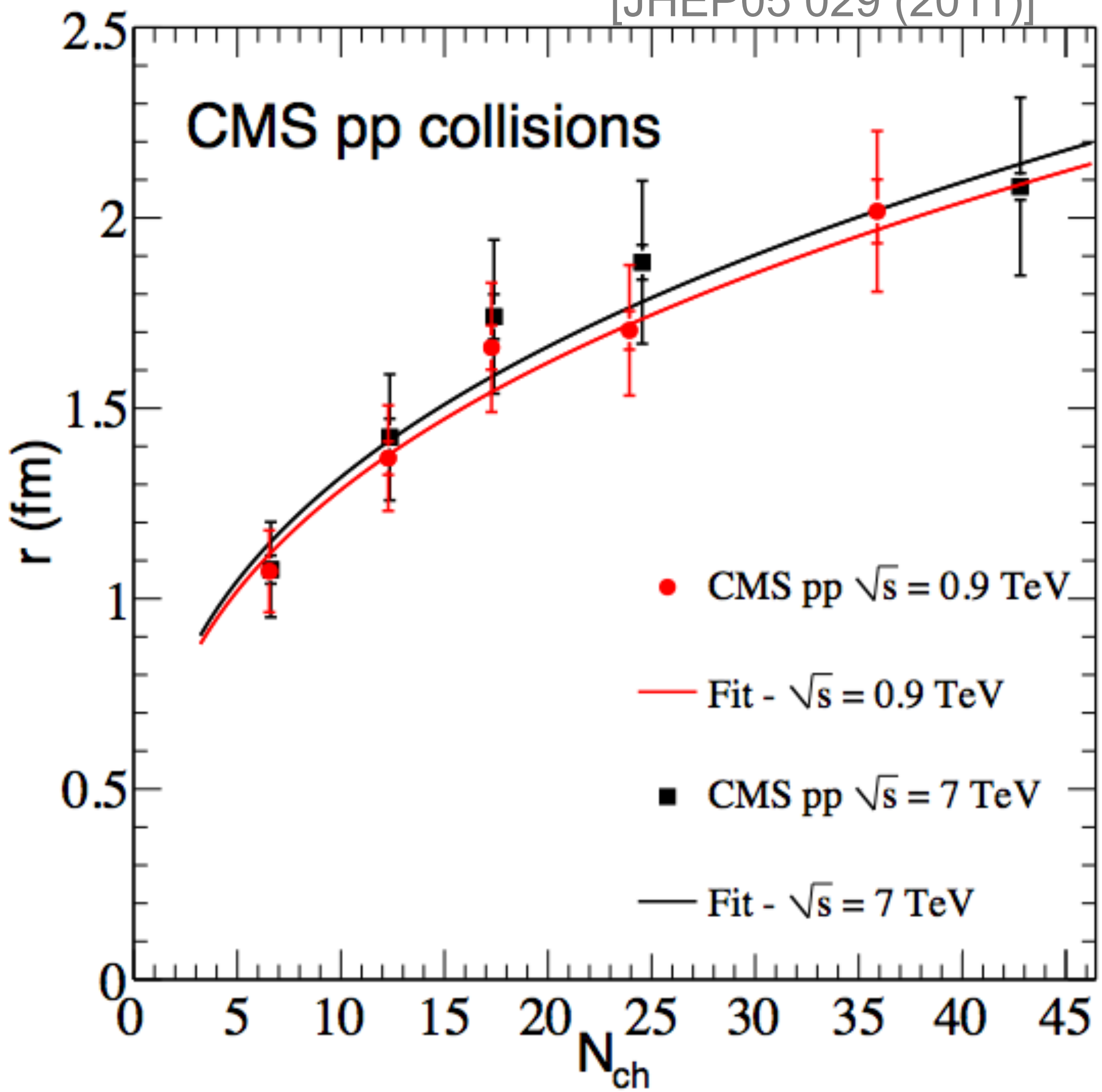
$$\Omega(Qr) = e^{-Qr}$$





r - dependence on N_{ch}

[JHEP05 029 (2011)]



– Fit to data

$$r\,(N_{ch}) = a \cdot N_{ch}^{1/3}$$

M. Lisa, AIP Conf. Proc. V. 828, 226 (2006)

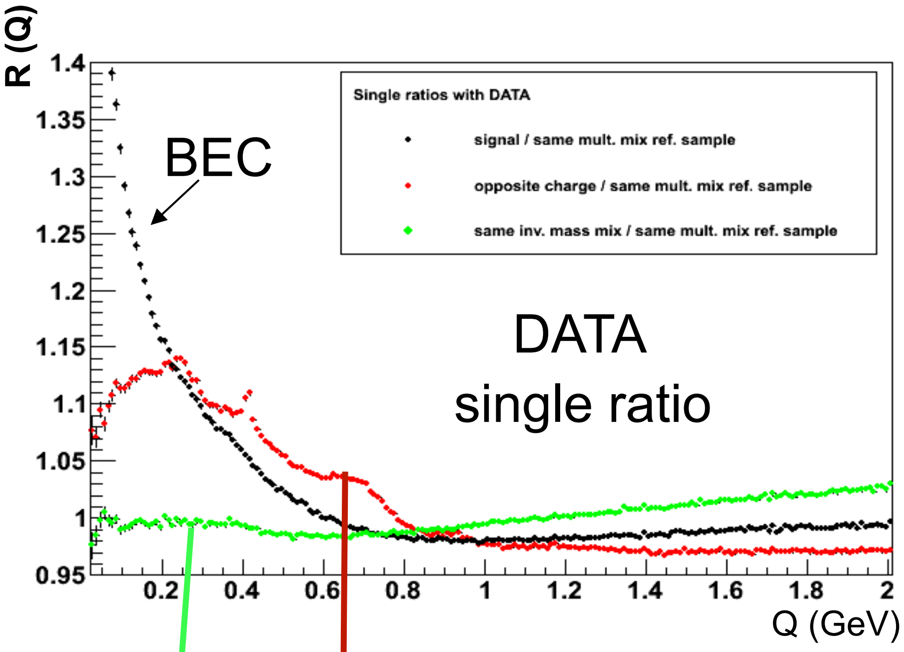
$a = [0.597 \pm 0.009(stat) \pm 0.057(syst)]\ fm$

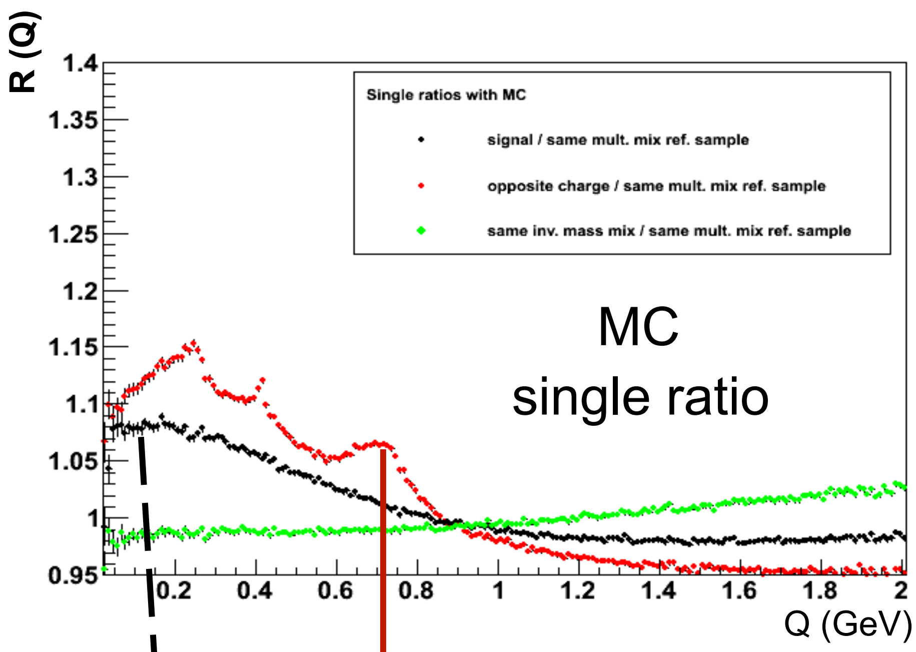
$\langle N_{ch} \rangle \sim 12.1$

$a = [0.612 \pm 0.007(stat) \pm 0.068(syst)]\ fm$

$\langle N_{ch} \rangle \sim 19.2$

The dip structure in HBT - *pp* collisions





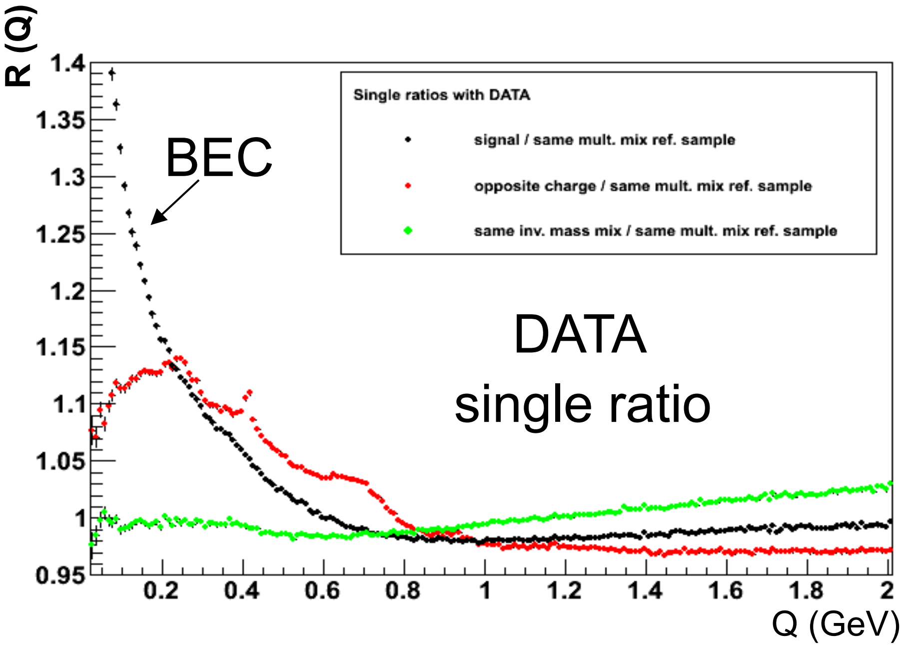
-- Ratio opposite charge pairs/reference sample
→ correlation on top of the resonances

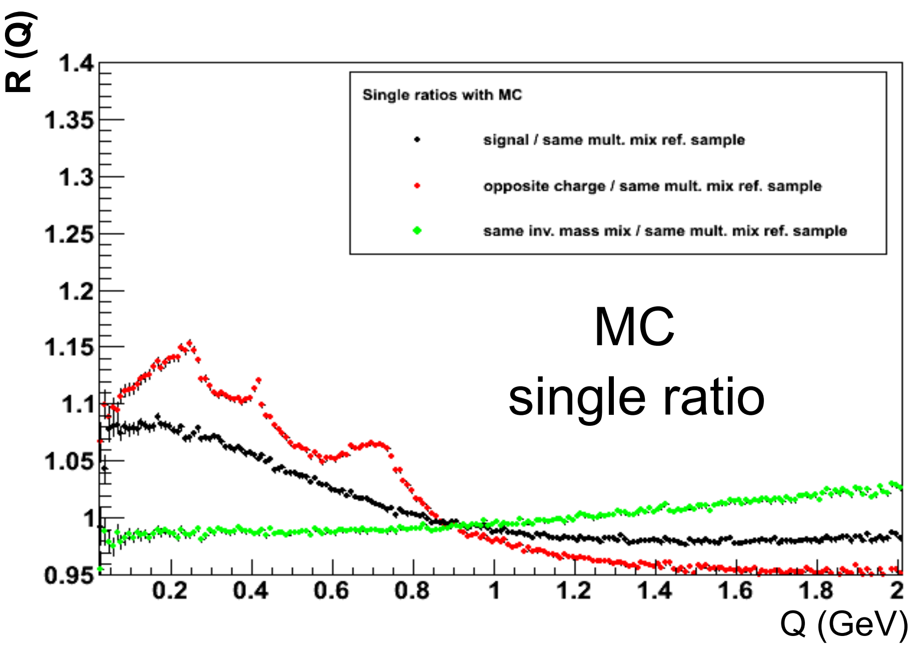
-- Mixing events breaks the above correlation

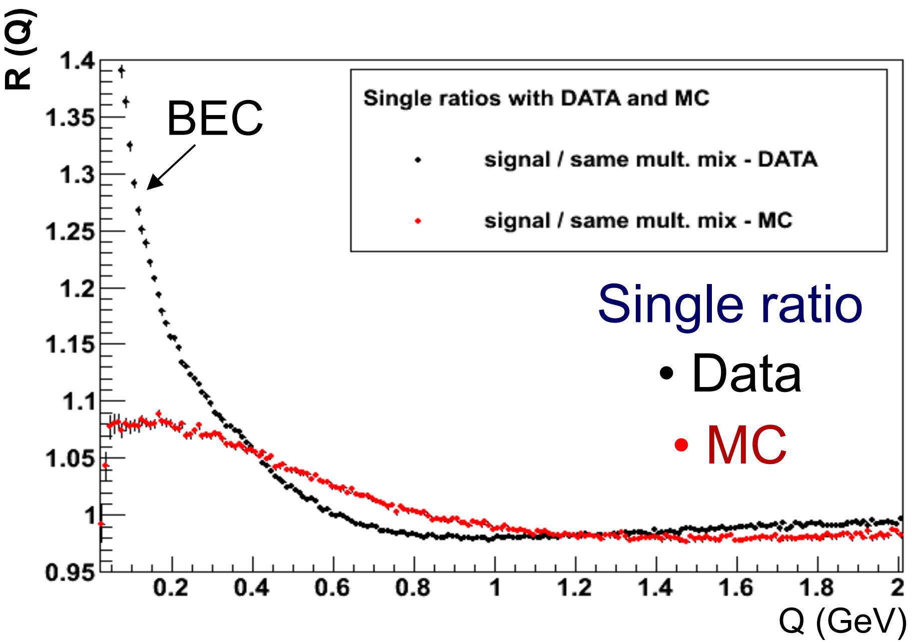
-- MC reproduces the resonance structure in the opposite charge

-- MC shows a correlation also in same charge (no BEC in MC)

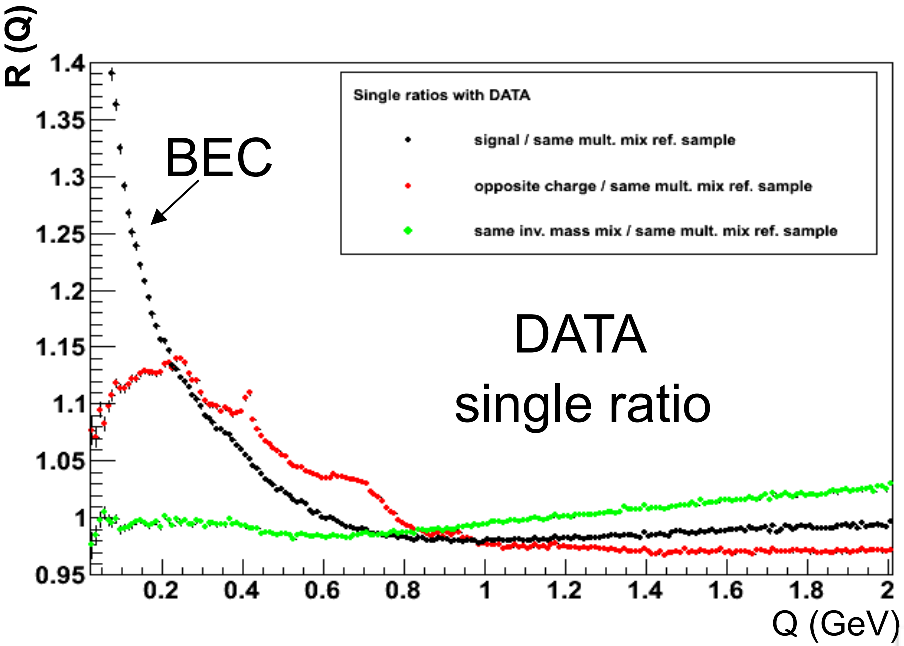
The dip structure step by step

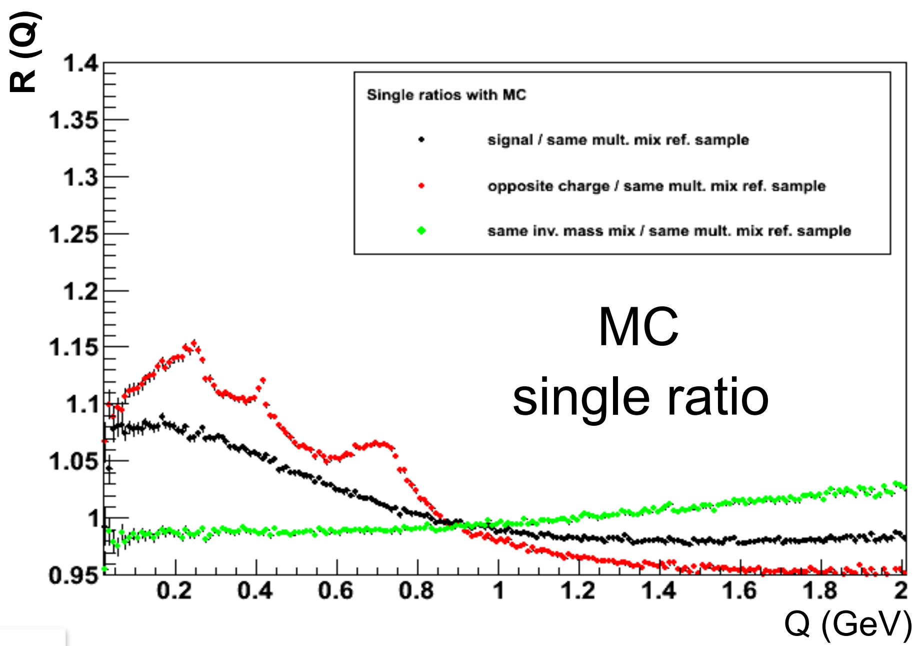


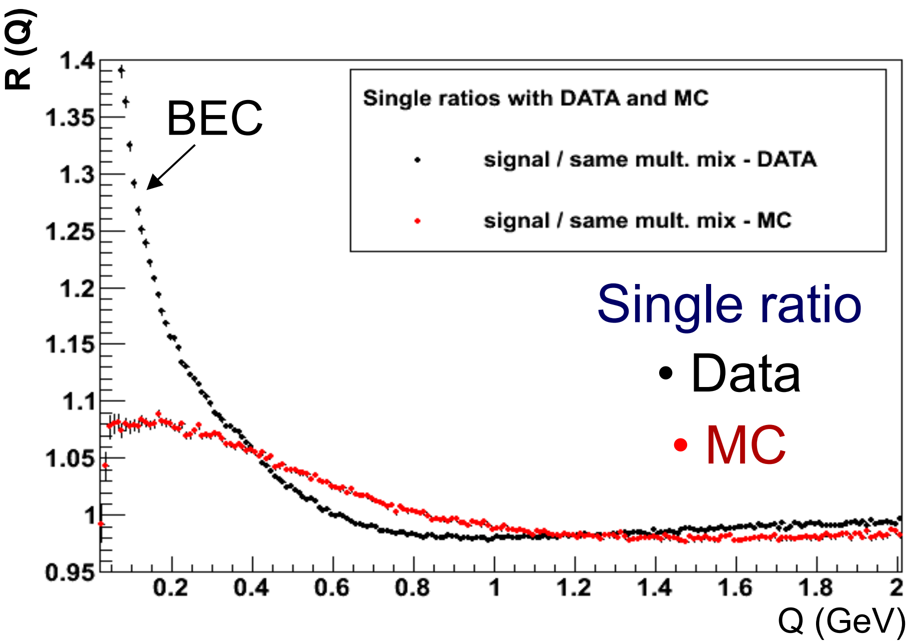




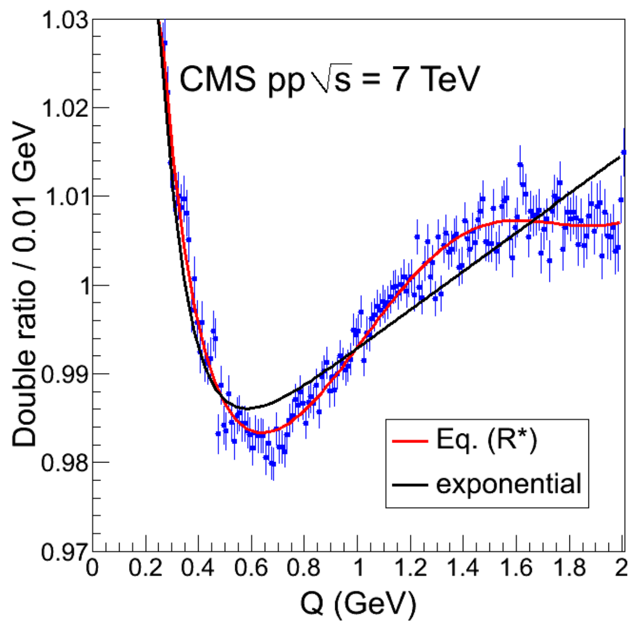
The dip structure step by step





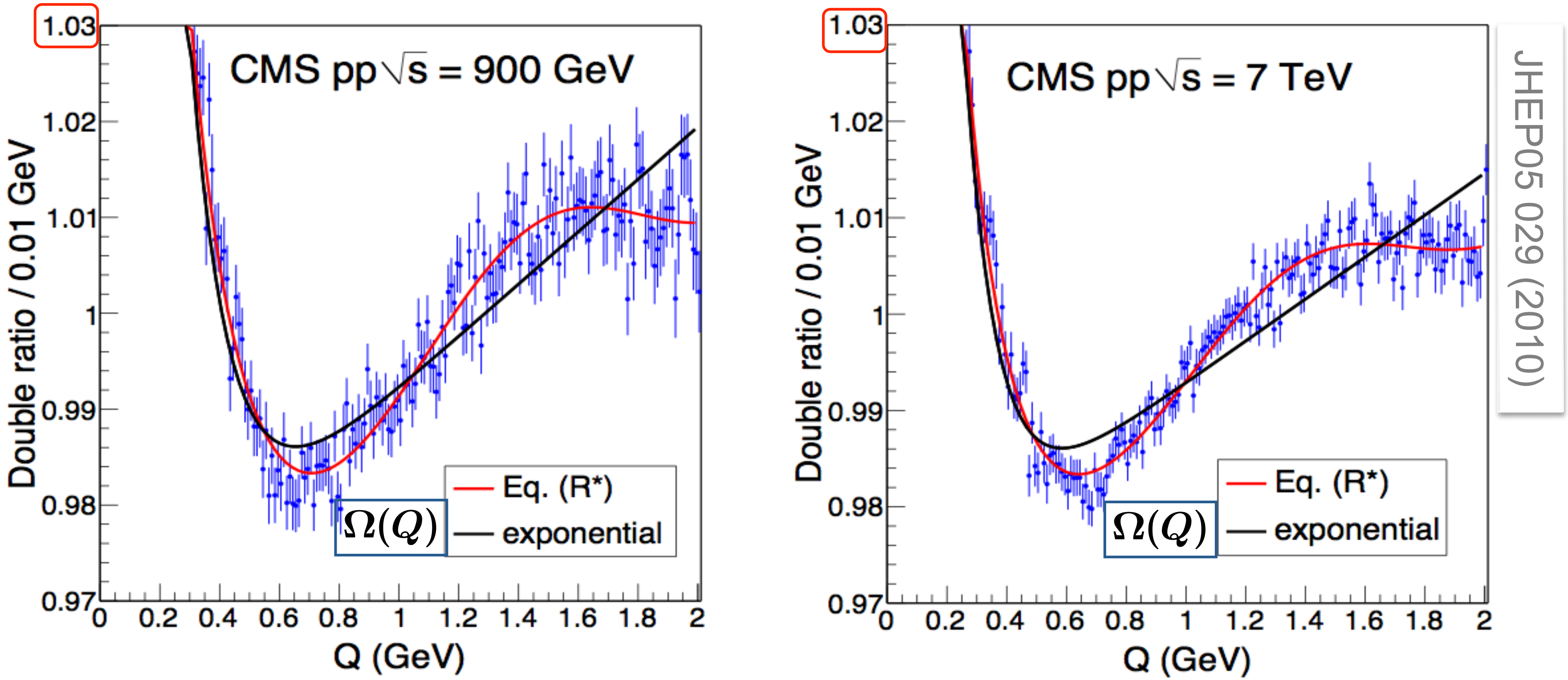


Eliminating this additional correlation requires a double ratio (DATA/MC)



The dip structure - 1

- For $\Omega = e^{-(Qr)}$: χ^2 / N_{dof} =485/194 (0.9 TeV) & 739/194 (7 TeV)
  - Reason: anticorrelation for same sign pairs (zoomed axis)



$$R^*(Q) = C\left[1 + \lambda\left(\cos\left[(r_0 Q)^2 + \tan(\alpha\pi / 4)(Qr_\alpha)^\alpha\right]e^{-(Qr_\alpha)^\alpha}\right)\right]\cdot(1+\delta Q)$$

[τ- model → Csörgő & Zimányi, N.P. A 517, 588 (1990); Metzger et al., P. L. B663, 114 (2008)]

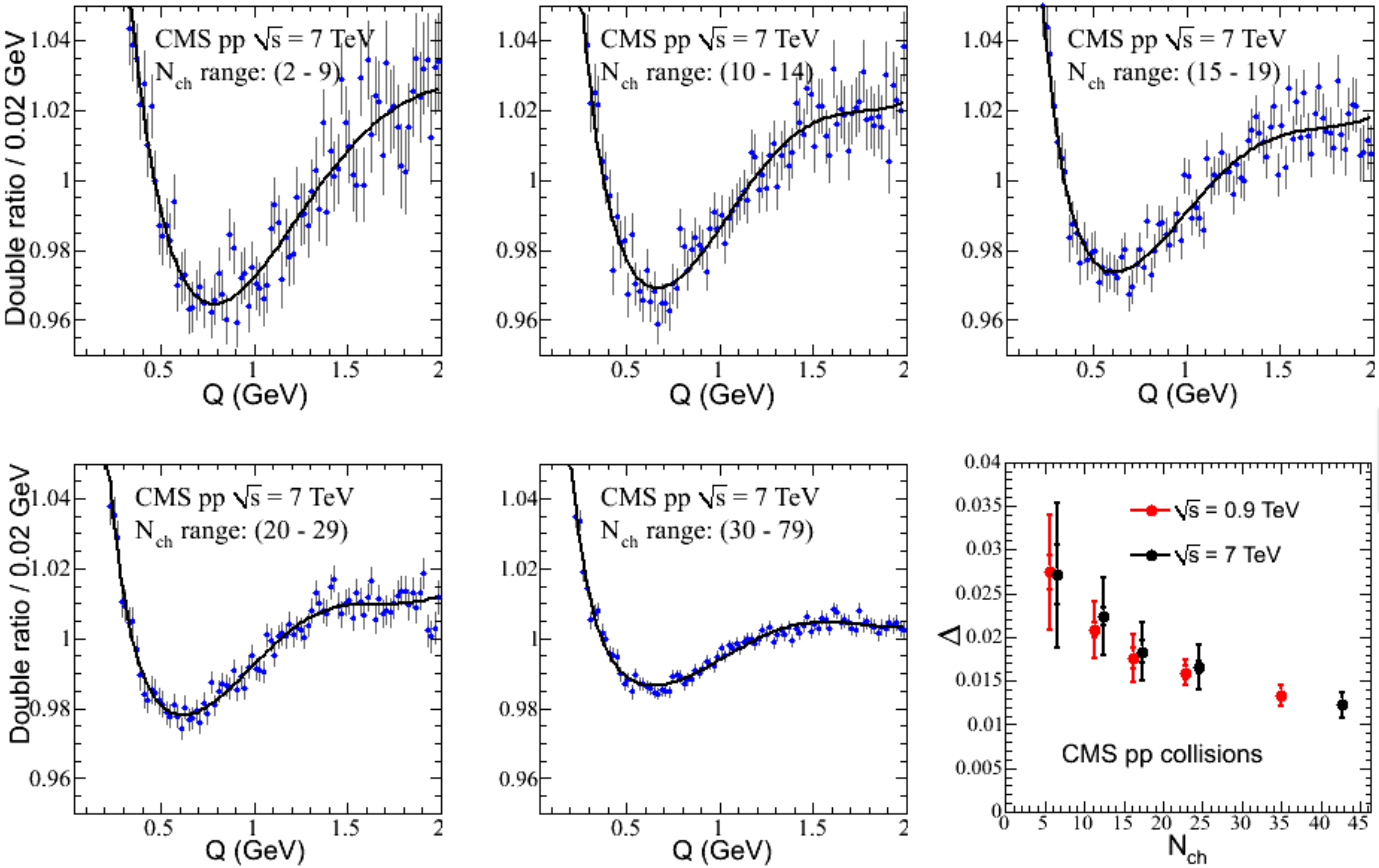
The dip structure - 2

» Observed in e^+e^- experiments at LEP [L3, Eur. Phys. J. C71, 1648 (2011)]

» This is the first observation of this anticorrelation in pp collisions!

» Using Eq. (R*) to fit data: χ^2 / N_{dof} = 213/192 (0.9 TeV) and χ^2 / N_{dof} = 215/192 (7 TeV)

[JHEP05 029 (2011)]



$$\Delta = C(1+\delta Q) - R^*$$

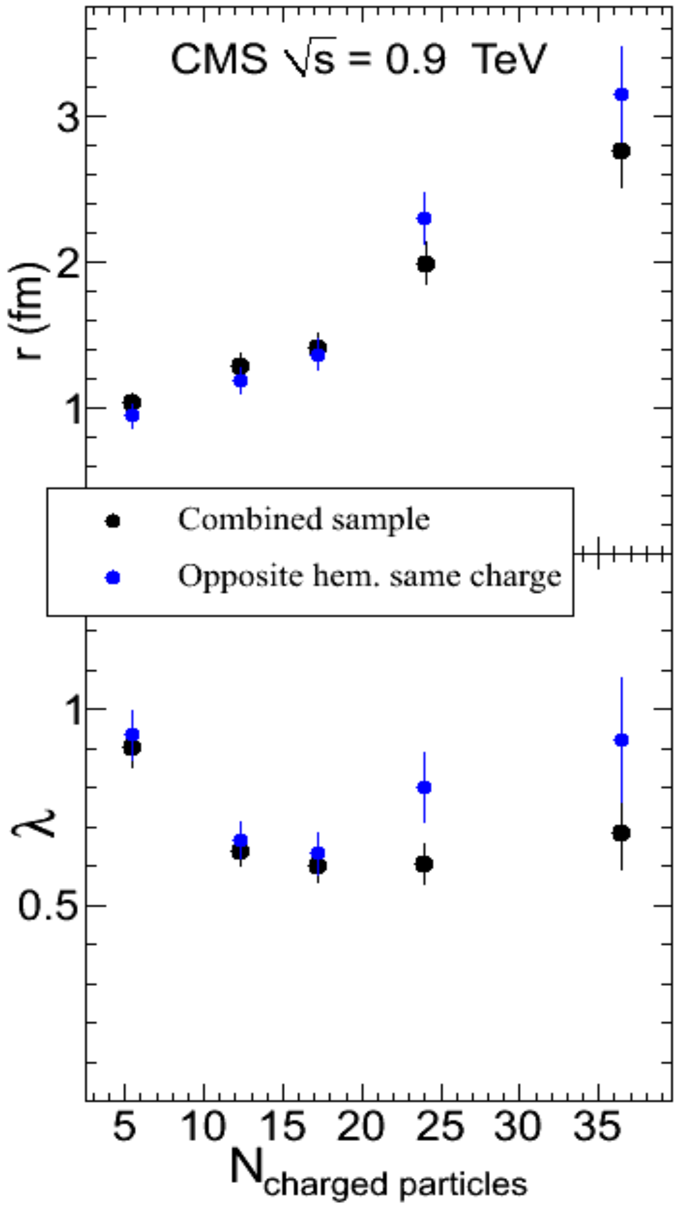
(at the minimum)

Summary & conclusions

- Bose-Einstein Correlations → measured at CMS detector in 0.9 TeV, 2.36 TeV and 7 TeV pp collisions
- Shown: BEC data & parameter fits $\longrightarrow \quad \boldsymbol{\Omega = e^{-(Qr)}}$
  - trends seen in parameters do not depend on fit function (checked with r first moments)
- Inclusive radius parameter : $\boldsymbol{r_{7\ TeV} > r_{0.9\ TeV}}$
  - reflects increase in N_{ch} with $\sqrt{\boldsymbol{s}}$
- Correlations as Double Ratios binned in N_{ch} & k_T
  - r decreases with k_T for high multiplicity events N_{ch}
    - » similar behavior with k_T is seen in AA collisions ($\longleftrightarrow$ collective behavior)
    - » in pp collisions also seen by E735 (Tevatron), STAR, PHENIX and ALICE
- Anticorrelation of like-sign pairs → 1st observation in pp collisions by CMS
  - Better χ^2/N_{dof} → param. describing time evolution of the source (assumes broad distr. in $\boldsymbol{\tau}$ and strong $\boldsymbol{x \times p}$ correlations)
  - Dip depth decreases with increasing N_{ch}

EXTRAS

More results - pp 0.9 TeV & 2.36 TeV



- Dependence of the fit parameters on charged multiplicity (N_{ch})

Mult. range	p val. (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})
2–9	97	0.90±0.01	0.89±0.05±0.20	1.00±0.07±0.05	72±12
10–14	38	0.97±0.01	0.64±0.04±0.09	1.28±0.08±0.09	18± 5
15–19	27	0.96±0.01	0.60±0.04±0.10	1.40±0.10±0.05	28± 5
20–29	24	0.99±0.01	0.59±0.05±0.17	1.98±0.14±0.45	13± 3
30–79	28	1.00±0.01	0.69±0.09±0.17	2.76±0.25±0.44	10± 3

Fit functions - pp sqrt{s}=0.9 & 7 TeV

– Double ratios

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

- Gaussian fit $\Omega(qr) \sim \exp[-(Qr)^2]$ bad (reduced $\chi^2 > 9$)

- Exponential fit $\Omega(qr) \sim \exp(-Qr)$

$\sqrt{s}$	χ^2/N_{dof}	C	λ	r (fm)	δ (10^{-2} GeV^{-1})
0.9 TeV	485/194	0.965 ± 0.001	0.616 ± 0.011	1.56 ± 0.02	2.8 ± 0.1
7 TeV	739/194	0.971 ± 0.001	0.618 ± 0.009	1.89 ± 0.02	2.2 ± 0.1

- Levy fit

$$\Omega(qr) \sim \exp[-(Qr)^\alpha]$$

$\sqrt{s}$	χ^2/N_{dof}	λ	r (fm)	α
0.9 TeV	453/193	0.847 ± 0.057	2.20 ± 0.17	0.806 ± 0.033
7 TeV	676/193	0.896 ± 0.051	2.83 ± 018	$0.792 \pm 0.0.024$

Dependence on k_T and N_{ch} - tables

- Double ratios (2010 pp data) - exponential fits

$$\Omega(Qr) = e^{-Qr}$$

k_T (GeV)	N_{ch} ($< N_{ch} >$)	χ^2/N_{dof}	C	λ	r (fm)	δ (10^{-2} GeV^{-1})
			$\sqrt{s} = 0.9$ TeV			
0.10 - 0.30	2 - 9 (6.6)	220/194	0.925 ± 0.006	1.011 ± 0.051	1.211 ± 0.057	6.1 ± 0.6
0.10 - 0.30	10 - 24 (15.5)	285/194	0.969 ± 0.002	0.761 ± 0.034	1.652 ± 0.057	2.9 ± 0.2
0.10 - 0.30	25 - 79 (31.2)	216/194	0.984 ± 0.002	0.828 ± 0.077	2.331 ± 0.153	1.6 ± 0.2
0.30 - 0.50	2 - 9 (6.6)	213/194	0.912 ± 0.007	0.754 ± 0.027	1.046 ± 0.049	6.0 ± 0.6
0.30 - 0.50	10 - 24 (15.5)	247/194	0.970 ± 0.002	0.636 ± 0.023	1.643 ± 0.051	2.3 ± 0.2
0.30 - 0.50	25 - 79 (31.2)	223/194	0.984 ± 0.002	0.549 ± 0.033	1.839 ± 0.089	1.2 ± 0.2
0.50 - 1.00	2 - 9 (6.6)	228/194	0.911 ± 0.009	0.626 ± 0.039	1.034 ± 0.079	6.6 ± 0.8
0.50 - 1.00	10 - 24 (15.5)	218/194	0.957 ± 0.003	0.508 ± 0.024	1.331 ± 0.059	3.4 ± 0.2
0.50 - 1.00	25 - 79 (31.2)	211/194	0.979 ± 0.003	0.428 ± 0.029	1.456 ± 0.086	1.5 ± 0.2
			$\sqrt{s} = 7$ TeV			
0.10 - 0.30	2 - 9 (6.6)	216/194	0.910 ± 0.008	1.025 ± 0.057	1.144 ± 0.062	7.3 ± 0.7
0.10 - 0.30	10 - 24 (16.4)	287/194	0.970 ± 0.002	0.865 ± 0.041	1.856 ± 0.065	2.8 ± 0.2
0.10 - 0.30	25 - 79 (38.5)	295/194	0.984 ± 0.001	0.899 ± 0.039	2.544 ± 0.076	1.5 ± 0.1
0.30 - 0.50	2 - 9 (6.6)	202/194	0.935 ± 0.008	0.807 ± 0.039	1.187 ± 0.066	4.1 ± 0.7
0.30 - 0.50	10 - 24 (16.4)	288/194	0.964 ± 0.002	0.639 ± 0.023	1.606 ± 0.050	2.8 ± 0.2
0.30 - 0.50	25 - 79 (38.5)	328/194	0.982 ± 0.001	0.592 ± 0.018	2.015 ± 0.048	1.3 ± 0.1
0.50 - 1.00	2 - 9 (6.6)	181/194	0.883 ± 0.013	0.655 ± 0.042	0.919 ± 0.078	9.4 ± 1.1
0.50 - 1.00	10 - 24 (16.4)	263/194	0.936 ± 0.003	0.554 ± 0.026	1.430 ± 0.057	5.2 ± 0.2
0.50 - 1.00	25 - 79 (38.5)	341/194	0.973 ± 0.001	0.446 ± 0.016	1.611 ± 0.048	2.0 ± 0.1

$r = 6.8\%$ (0.9 TeV) ; 11.1% (7 TeV)

Double ratios

– Construction of reference sample $\longleftrightarrow$ to reduce bias:

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \frac{\left(\dfrac{dN_{signal}/dQ}{dN_{ref}/dQ}\right)}{\left(\dfrac{dN_{MC,\,like}/dQ}{dN_{MC,\,ref}/dQ}\right)}$$

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

$$\Omega(Qr) = \exp(-Qr)$$

– Calculated for all 7 reference samples [PRL 105, 32001 (2010)]

Results of fits to 0.9data

Reference sample	p value (%)	C	λ	r (fm)	δ (10^{-3})
Opposite charge	21.9	0.988 ± 0.003	0.56 ± 0.03	1.46 ± 0.06	-4 ± 2
Opposite hem. same ch.	7.3	0.978 ± 0.003	0.63 ± 0.03	1.50 ± 0.06	11 ± 2
Opposite hem. opp. ch.	11.9	0.975 ± 0.003	0.59 ± 0.03	1.42 ± 0.06	13 ± 2
Rotated	0.02	0.929 ± 0.003	0.68 ± 0.02	1.29 ± 0.04	58 ± 3
Mixed evts. (random)	1.9	1.014 ± 0.002	0.62 ± 0.04	1.85 ± 0.09	-20 ± 2
Mixed evts. (same mult.)	12.2	0.981 ± 0.002	0.66 ± 0.03	1.72 ± 0.06	11 ± 2
Mixed evts. (same mass)	1.7	0.976 ± 0.002	0.60 ± 0.03	1.59 ± 0.06	14 ± 2
Combined	2.9	0.984 ± 0.002	0.63 ± 0.02	1.59 ± 0.05	8 ± 2

Systematic Uncertainties- 2010 pp run

- Choice of reference sample → main uncertainty in r
  - » Estimate with r.m.s. spread with $\neq$ ref. samples
  - » Additional → choice of MC sample (r.m.s. spread with $\neq$ samples)
  - » 7 TeV data more affected by MC choice

$\sqrt{s}$	0.9 TeV		7 TeV	
	λ	r (fm)	λ	r (fm)
Choice of the reference sample	0.017	0.11	0.015	0.10
Choice of MC dataset	0.009	0.05	0.032	0.16
Effect of Coulomb corrections	0.017	0.01	0.017	0.02
Fit range	0.014	0.08	0.016	0.08
Total	0.029	0.15	0.042	0.21

Coulomb FSI - Gamow factor

– Charged pairs: Coulomb interaction ⟶ affect the low-Q region
– Can be parametrized by Gamow factors:

$$\Upsilon_{SS}(\eta) = \frac{\eta / Q}{e^{2\pi\eta/Q} - 1} \; ; \; \Upsilon_{OS}(\eta) = \frac{\eta / Q}{1 - e^{-2\pi\eta/Q}} \quad (\eta = \alpha_{em} m_{\pi})$$

- Testing compatibility: $[dN_{OS}/dQ(data)]/[dN/dQ(MC)]$ vs $\Upsilon_{OS}(\eta)$