Bose–Einstein Correlation

Status Report QCD-10-003

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Intro: Bose–Einstein Correlation

- Wave function for identical boson particles (signal) is enhanced wrt uncorrelated case (reference) due to B–E statistics $R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$
- use a single variable $Q = \sqrt{-(p_1 - p_2)^2}$ (π hypothesis)
$$R(Q\{p_1, p_2\}) = \frac{\Pi(Q)_{signal}}{\Pi(Q)_{reference}}$$
- expect excess for R at low Q
$$R(Q) = C[1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q)$$
    - $\Omega(Qr)$ F. trasf. of emission region, with effective size r;
    - $\lambda < 1$ strength parameter;
    - δ factor accounts for long-distance correlations or biases due to reference sample.

BEC: bibliography

$\pi^+\pi^+$ BEC analyses		Parameter	
Reaction	E_{CM} [GeV]	R [fm]	λ
$e^+e^- \to h$ [29]	29	0.97 ± 0.11 (stat)	0.27 ± 0.04 (stat)
$e^+e^- \to h$ [30]	34	0.82 ± 0.07	0.35 ± 0.03
$e^+e^- \to h$ [31]	91	0.83 ± 0.03	0.31 ± 0.02
$\mu p \to h$ [32]	23	0.65 ± 0.03	0.80 ± 0.07
$\pi^+ p \to h$ [33]	21.7	0.83 ± 0.06	0.33 ± 0.02
$\bar{p}p \to h$ [34]	200 - 900	0.73 ± 0.03	0.25 ± 0.02
$e\, p \to e\, h$ [35]	$110 < Q^2_\gamma$ [GeV^2]	0.67 ± 0.04	0.43 ± 0.09
Other hadron species BEC analyses in $e^+e^- \to h$		Parameter	
hadron species	E_{CM} [GeV]	R [fm]	λ
$K^\pm K^\pm$ [36]	91	$0.48 \pm 0.04 \pm 0.07$	$0.82 \pm 0.11 \pm 0.25$
$K^0_S K^0_S$ [37]	91	$0.65 \pm 0.07 \pm 0.15$	$0.96 \pm 0.21 \pm 0.40$

[29] [MARKII Coll.], I. Juricic et al., Phys. Rev. D39 (1989) 1.

[30] [TASSO Coll.], M. Althoff et al., Z. Phys. C30 (1986) 355.

[31] [DELPHI Coll.] P. Abreu et al., Phys. Lett. B286 (1992) 201.

[32] [EMC Coll.], M. Arneodo et al., Z. Phys. C32 (1986) 1.

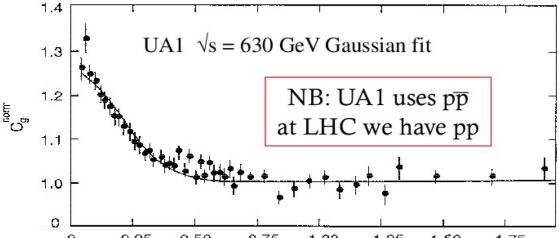
[33] [NA22 Coll.], M. Adamus et al., Z. Phys. C37 (1988) 347.

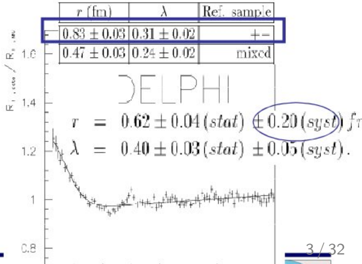
[34] [UA1 Coll.], C. Albajar et al., Phys. Lett. B226 (1989) 410.

[35] [ZEUS Coll.], M. Derrick Acta Phys. Polon. B33 (2002) 3281.

[36] [DELPHI Coll.], P. Abreu et al., Phys. Lett. B379 (1996) 330.

[37] [ALEPH Coll.], D. Buskulic et al., Z. Phys. C64 (1994) 361.



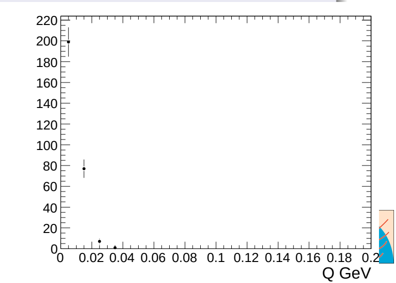


Events and track selections

- 900 GeV $\sim 280\ Kevts$ runs: 124009, 124020, 124022, 124023, 124024, 124027, 124030, 124230
- 2360 GeV $\sim 14\ Kevts$ runs: 124120, 124275
- `/MinimumBias/BeamCommissioning09-Dec19thReReco_336p3_v2/RECO`
- Trigger: BSC minbias, coincidence with bptx, veto beam halo:
  - 0 AND (40 OR 41) AND NOT (36 OR 37 OR 38 OR 39) also physics declared bit is requested;
  - $2 \leq N_{charged\ \ tracks} \leq 150$
- `CMSSW_3_3_6`
- MonteCarlo: NO BEC or Coulomb simulated in MC!
  - 900 GeV `/MinBias/Summer09-STARTUP3X_V8K_900GeV-v1/GEN-SIM-RECO`
  - 2360 GeV `/MinBias/Summer09-STARTUP3X_V8L_2360GeV-v1/GEN-SIM-RECO`

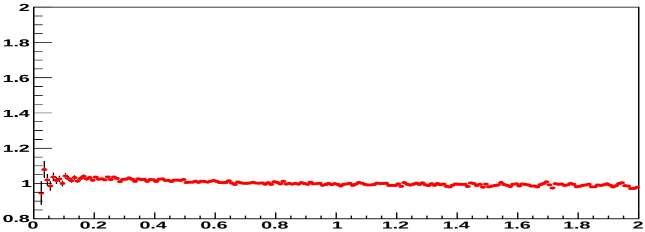
Tracks selections

- good charged tracks
  - high purity tracks
  - $p_t > 200\ MeV$
  - $d_{xy}^{(PV)} < 1.5\ mm$
  - $Ndof > 5$
  - $\chi^2/Ndof < 5$
  - $|\eta| < 2.4$
  - $R_{innermost\ \ hit} < 20\ cm$
- Split tracks veto:
  - reject two same sign tracks if:
    - $\cos(\theta_{i,j}) > 0.99996$
    - $\&\&\ \Delta p_{t\,i,j} < 0.040\ GeV$
  - affect only region $Q <\ 20\ MeV$



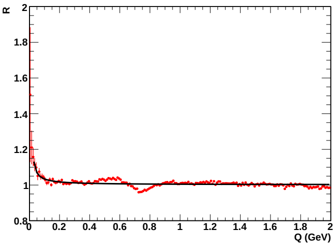
Signal: efficiency vs Q

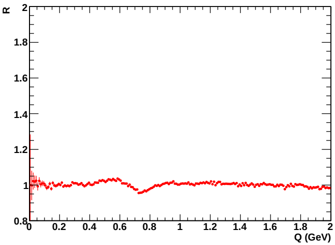
- BEC is present at very low Q; working with very close pairs of low p_t tracks: efficiency vs Q is critical;
- Q distribution is always normalized to a reference sample (w/o BEC), so ratio of $\epsilon_{signal}/\epsilon_{reference}$ is the relevant quantity
- $\epsilon(Q)$ ratio for signal/reference *opposite–hemisphere tracks (see below)* ($\vec{p}_2^{\,o} = -\vec{p}_2$)
- $\epsilon(Q)$ ratio is ~flat, small deviation from 1 (see after).



Coulomb correction

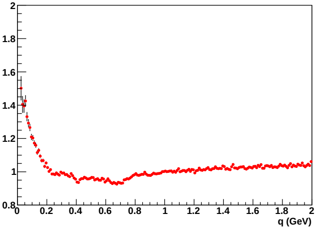
- Other effect present at low Q: Coulomb repulsion for same sign particles
- An analytical correction (Gamow factor) available
  $W_S(\eta) = \frac{e^{2\pi\eta}-1}{2\pi\eta} \qquad \eta = \alpha m_\pi / Q$
- tested in opposite charge pairs, dN/dQ data/MC (no Coulomb present in MC!)
- `left:` Q opposite charge with Gamow factor superimposed.
  `right:` same with Gamow factor applied.

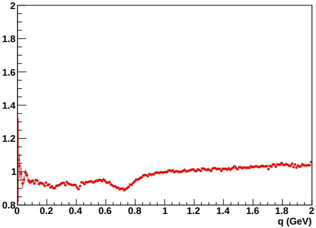




Reference sample: opposite charge tracks

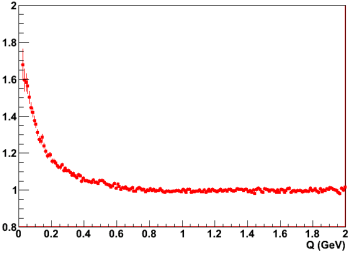
- several reference sample have been considered
- **Opposite charge tracks**
- Difficult: resonances ρ_0, K_0, ...
- Also BEC present as a consequence of virtual processes involving the ρ and higher-mass common states.
- `left:` dN/dQ Data – `right:` MC (no BEC present)

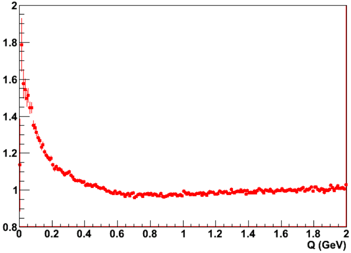




Opposite hemisphere and rotated Particles

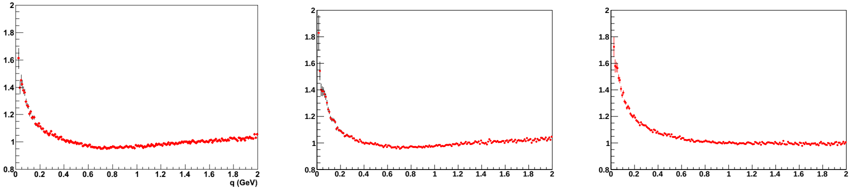
- **Opposite hemisphere tracks** 3D inversion of track momentum $Q_O = \sqrt{-(p_1 - p_2^o)^2}$, where $p_2^o = (E_2, -\vec{p_2})$;
- default reference sample
- **Rotated tracks** $\vec{p}$ inversion in trasverse plane $\vec{p}_2 = (-p_x, -p_y, p_z)_2$;
- `left:` dN/dQ Opposite hemisphere – `right:` rotated





Mixing events

- **Take two tracks from different events**
- three ways to choose the "other" event:
  1. fully randomly;
  2. randomly from event with similar (within 20%) track density, in 3 regions (forward $\eta > 0.8$, backward $\eta < -0.8$ and central);
  3. randomly from event with similar (within 20%) total invariant mass $\mathcal{M} = (\Sigma_i p_i)^2$;
- `left:` (1) – `center:` (2) – `right:` (3)
- note: the MC distribution reproduces well the slow raise at high Q



Determination of BEC Parameters

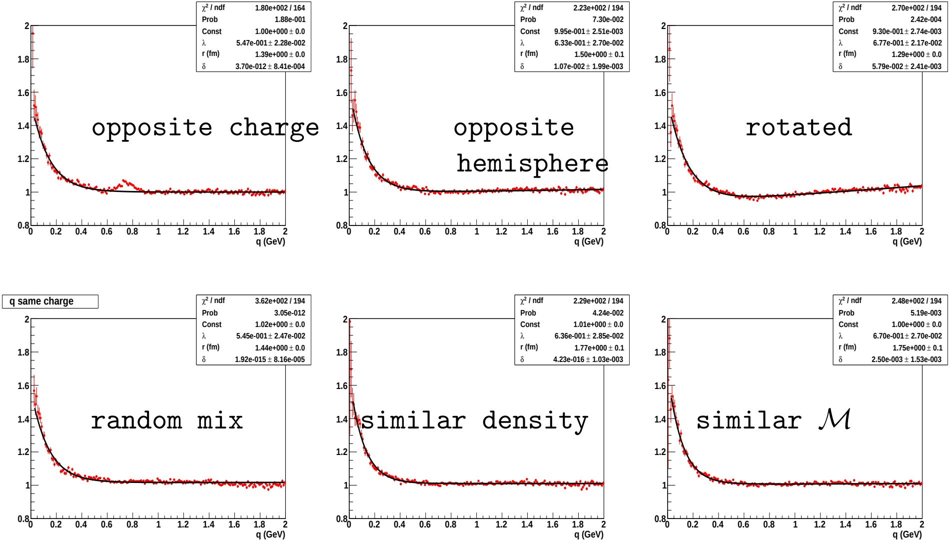
- Past BEC articles use gaussian function to fit data: we found a better description by using an exponential shape instead;

$$R(Q) = C\left(1 + \lambda e^{-(Qr)}\right) \cdot (1 + \delta Q)$$

- Moreover, in order to reduce systematics due to reference sample, we fit the double ratio $\mathcal{R} = R/R_{MC}$
  - R_{MC} is the signal to reference ratio computed in the simulated events generated without BEC;
  - for opposite charge, exclude ρ region from fit;
  - for all cases, fit region: $0.02 < Q < 2\ GeV$.

Reference Sample	p-value	C	λ	r (fm)	δ
Different charge (1)	1.88×10^{-1}	1.000 ± 0.001	0.547 ± 0.023	1.394 ± 0.043	~ 0
Opposite Hemisphere (2)	7.30×10^{-2}	0.995 ± 0.003	0.633 ± 0.027	1.497 ± 0.056	$(1.07 \pm 0.20) \times 10^{-2}$
Rotated (3)	2.42×10^{-4}	0.930 ± 0.003	0.677 ± 0.022	1.290 ± 0.039	$(5.79 \pm 0.24) \times 10^{-2}$
Event Mix (4a) (random order)	3.05×10^{-12}	1.017 ± 0.001	0.545 ± 0.025	1.441 ± 0.049	~ 0
Event Mix (4b) ($dN/d\eta$)	4.24×10^{-2}	1.010 ± 0.001	0.636 ± 0.029	1.771 ± 0.055	~ 0
Event Mix (4c) ($\mathcal{M}$)	5.19×10^{-3}	1.005 ± 0.002	0.670 ± 0.027	1.749 ± 0.056	$(2.50 \pm 1.5) \times 10^{-3}$

Double ratio exp fit with different reference samples



Fit function menu

- Gaussian shape (widely used in literature)

$$R(Q) = C\left[1 + \lambda e^{-(Qr)^2}\right] \cdot (1 + \delta Q)$$

- Exponential shape

$$R(Q) = C\left[1 + \lambda e^{-(Qr)}\right] \cdot (1 + \delta Q)$$

- Lévy shape (multiple randomly distributed gaussian) $(0 < \alpha < 2)$ [arXiv:hep-ex/0506015v1]

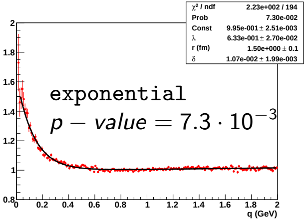
$$R(Q) = C\left[1 + \lambda e^{-(Qr)^\alpha}\right] \cdot (1 + \delta Q)$$

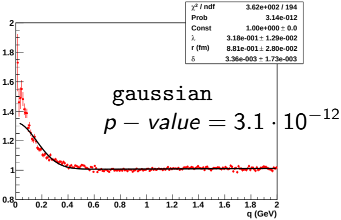
- Kozlov *et al* [Phys. Rev. C 68, 024901 (2003)]

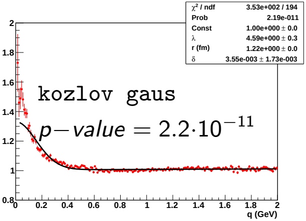
$$R(Q) = C\left[1 + \frac{2\alpha}{(1+\alpha)^2}\sqrt{\Omega(Qr)} + \frac{1}{(1+\alpha)^2}\Omega(Qr)\right](1+\delta Q)$$

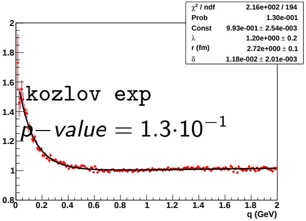
  - gaussian: $\Omega(Qr) = e^{-(Qr)^2}$
  - exponential: $\Omega(Qr) = e^{-(Qr)}$

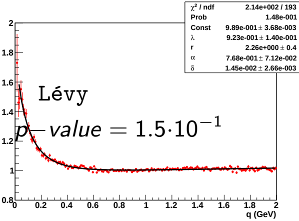
Double ratio opposite hemisphere different fits





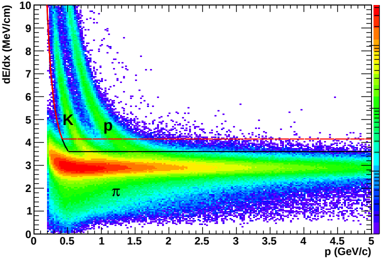


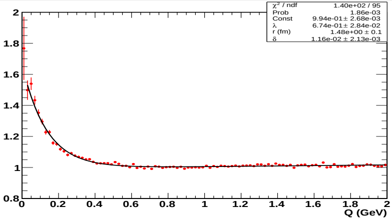


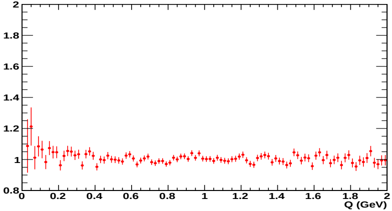


dE/dx cross check

Use PID of tracker (dE/dx): plot $\mathcal{R}$ (with exp fit) for $\pi - \pi$ pairs (top) vs non-correlating $\pi - not(\pi)$ (bottom).

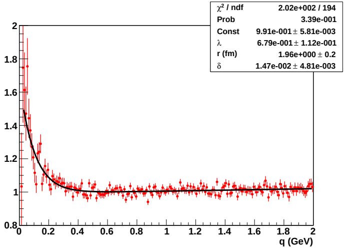






Data at $\sqrt{s} = 2.36$ TeV

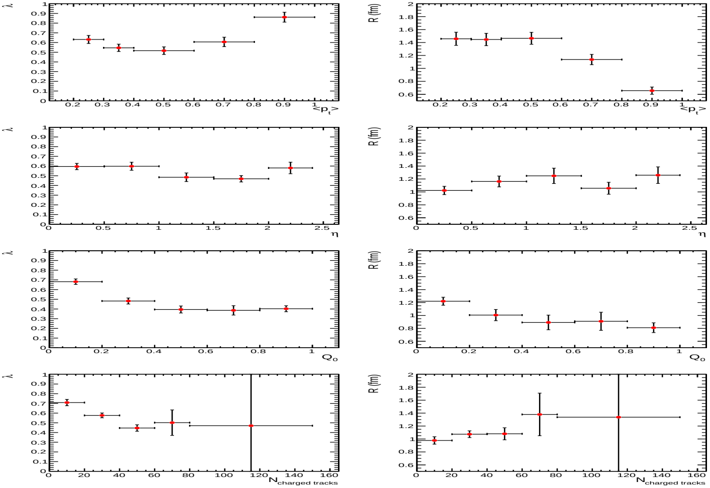
Limited statistics: show results (double R) only for opposite hemisphere reference sample and exponential fit.



Reference Sample	p-value	C	λ	r (fm)	δ
Opposite Hemisphere (2)	3.39×10^{-1}	0.991±0.006	0.68±0.11	1.96±0.20	$(1.47 \pm 0.48) \times 10^{-2}$

Dependence of BEC on Pair Kinematics

Dependence of BEC parameters (λ and r, exp. fit) on:
top to bottom $< p_t >$, η, $Q_0 = |E_i - E_j|$ and $N_{charged\ tracks}$



Extraction of BEC parameter from MC

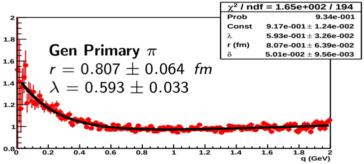
- Dedicated MC production with BEC enabled

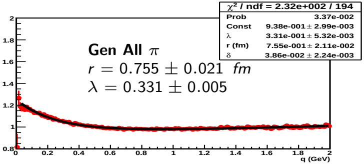
  PARJ(92)=0.4 (λ), PARJ(93)=0.25 ($r = 0.8$ *fm*) and MSTJ(51)=1 (exponential shape)

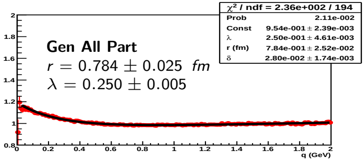
- Perform analysis using generated particles, same cut as reco (where applicable);
- Use standard MC as reference sample;
  - Consider 3 generated track samples: all, all pions, all primary pions (particles which undergo BEC)
  - BEC diluited for more inclusive sample;
  - Compare with analysis with reconstructed quantities: for R and $\mathcal{R}$ (double R);
  - see next slide for plots and fit results.
- Will consider the (small) bias for systematic uncertainties;
- Found r as in input, λ comparison less straigthforward (according to Pythia manual);
  - Tried also with gaussian shape: correctly found in R.

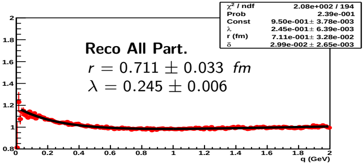
Estimate of the Analysis Bias

Single Ratio

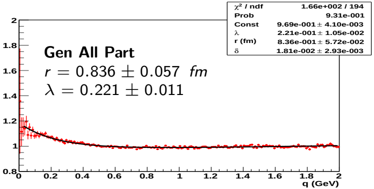


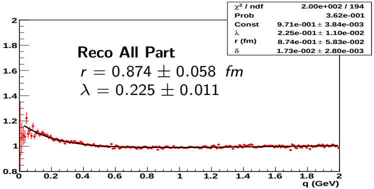






Double Ratio





Systematics and Results

- main systematics from choice of reference sample:
  - no golden sample avaialable;
  - use spread of results from different references to estimate it;
- other syst source is the bias found comparing generated and reconstructed quantities in MC w/ BEC.

Results (exp. fit): still under discussion. Feedback welcome!

Using opposite–hemisphere as central value and maximum deviation as sys ref (other choices possible):

$r = 1.50 \pm 0.06\ \text{(stat)} \pm 0.27\ \text{(sys ref)} \pm 0.15\ \text{(sys bias)}\ fm$

$\lambda = 0.633 \pm 0.027\ \text{(stat)} \pm 0.086\ \text{(sys ref)} \pm 0.005\ \text{(sys bias)}$

Using mean and RMS from the different references samples:

$r = 1.59 \pm 0.06\ \text{(stat)} \pm 0.19\ \text{(sys ref)} \pm 0.16\ \text{(sys bias)}\ fm$

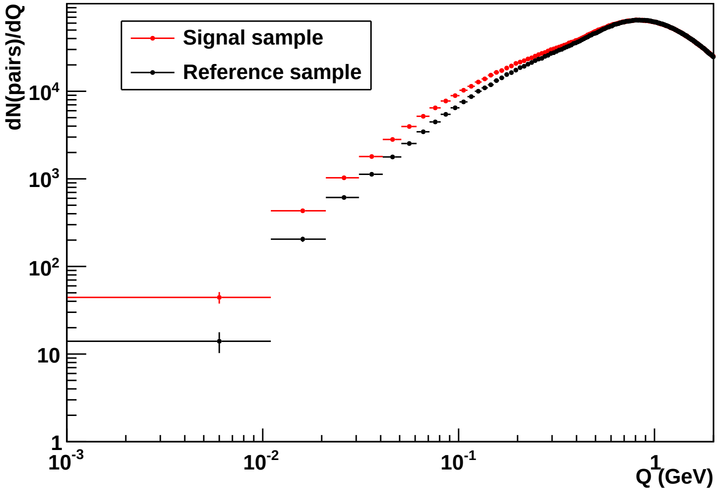
$\lambda = 0.618 \pm 0.027\ \text{(stat)} \pm 0.053\ \text{(sys ref)} \pm 0.005\ \text{(sys bias)}$

Conclusions

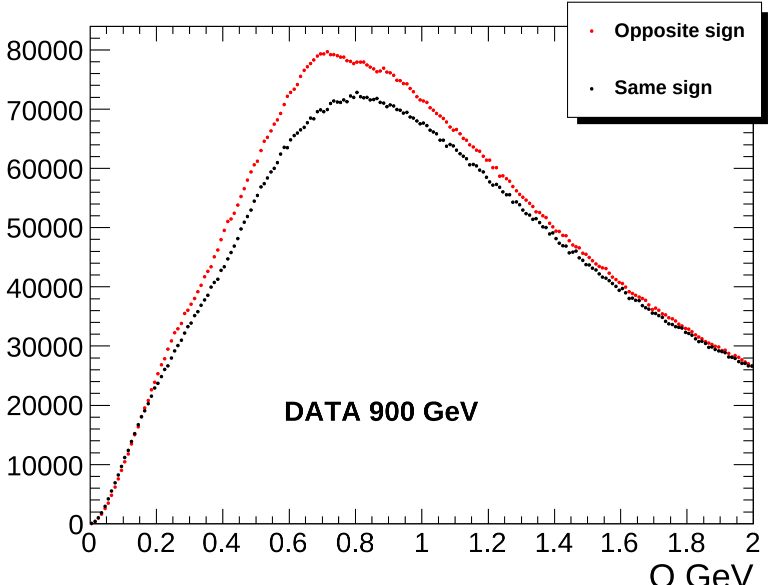
- Clean and robust Bose–Einstein Correlation signal found in 900 and 2360 GeV data;
    - several reference samples have been used;
    - tested with PID dE/dx;
    - tested with MC BEC;
    - used double ratio to reduce systematics;
    - several fit functions tried: exponential seems favored by data wrt gaussian;
- Finalizing AN and PAS.

BACKUP

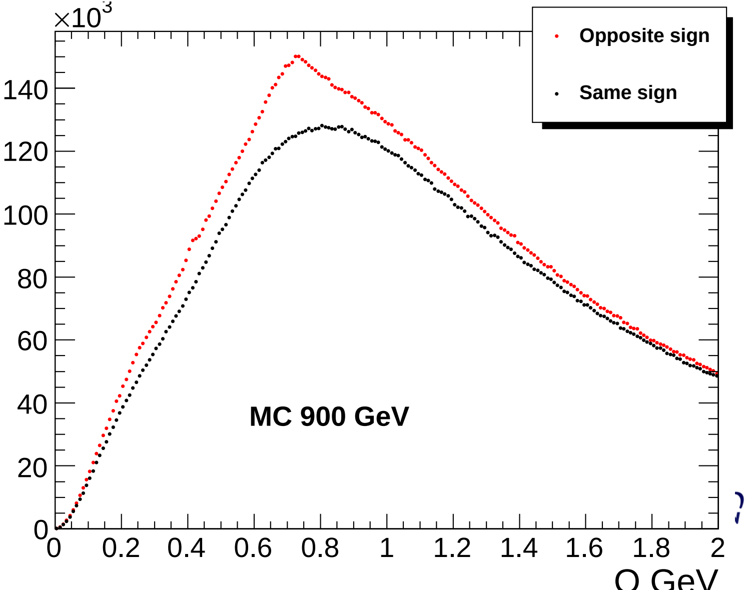
Q DATA: for Signal and Opposite Hemisphere



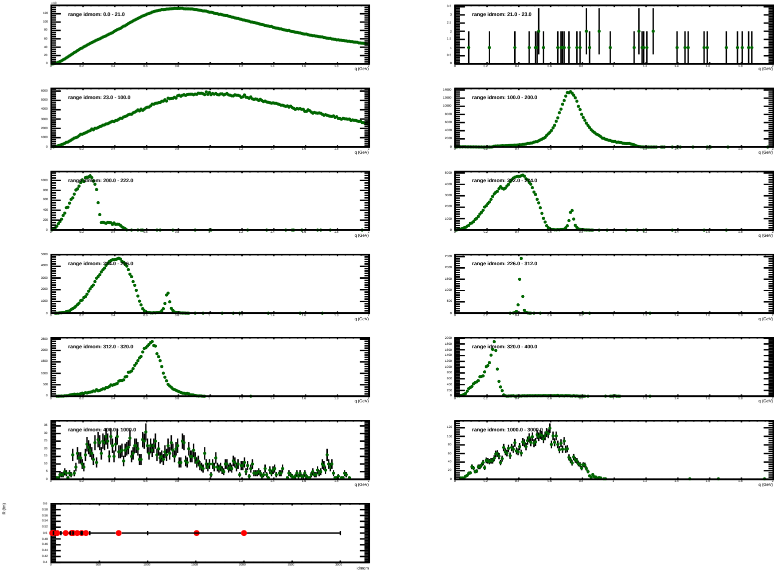
Q DATA: for Same Sign and Different Sign tracks



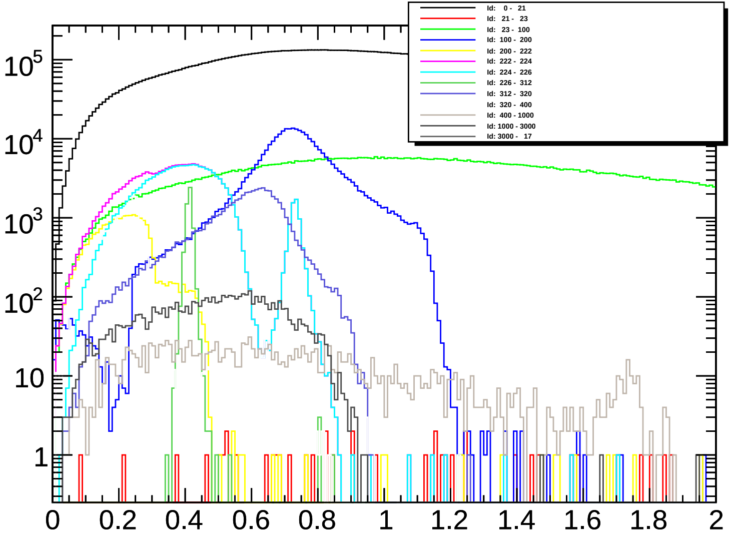
Q MC: for Same Sign and Different Sign tracks



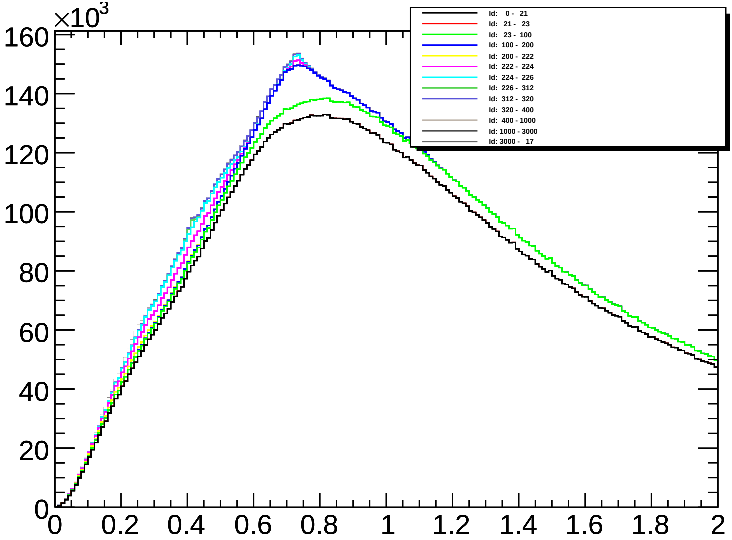
Opposite charge: mother ID



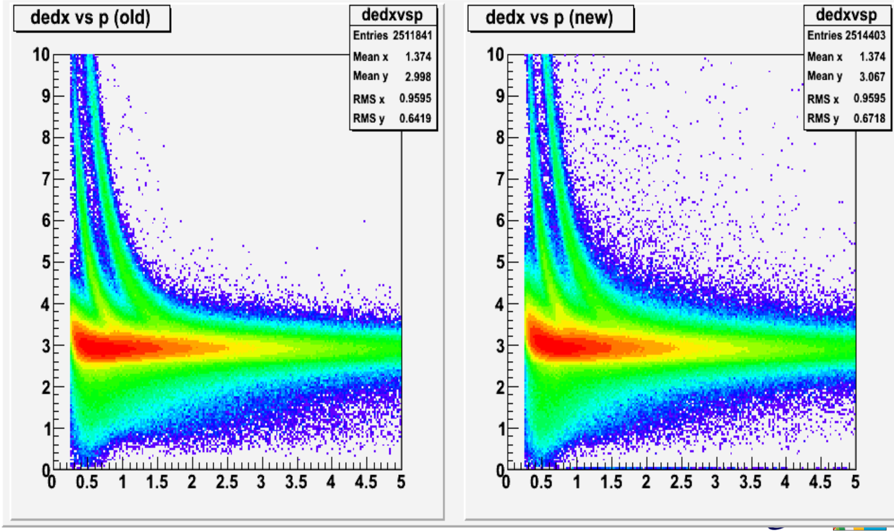
Opposite charge: mother ID



Opposite charge: mother ID



dE/dx w/ and w/o pixels

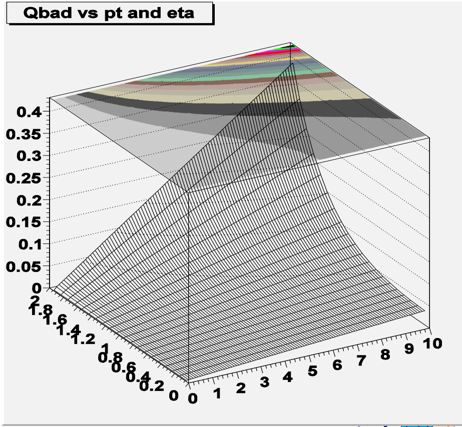


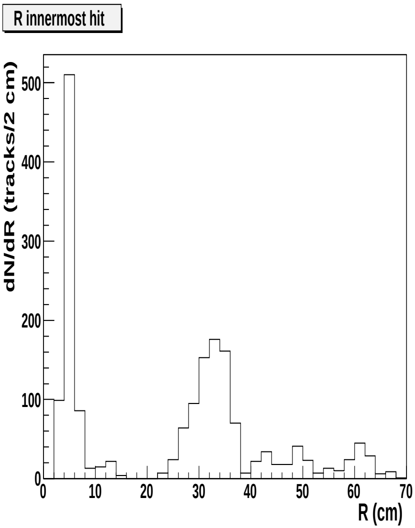
Method

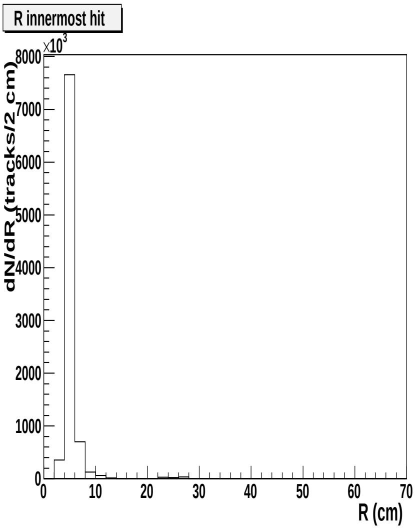
- For each P_t, η:
  - scan grid in $\Delta\phi$, $\Delta\eta$ for second track (assumed equal P_t)
  - compute Q-value of pair
  - compute distance on 3rd layer in xy and z views
  - Determine Q-values which correspond to track pair separations always larger than two pixel pitches in xy and in z

Minimum Q in grid of P_t and η

- Low P_t and $|\eta|<2$: $Q>0.02$ seems reasonable, given conservative choice of pitch separation
- Note that for Q below the curve shown, efficiency does not drop to zero immediately – it just starts to involve two "very close" pixel hits on third layer




R innermost hit
dN/dR (tracks/2 cm)
500
400
300
200
100
0
0 10 20 30 40 50 60 70
R (cm)


R innermost hit
dN/dR (tracks/2 cm)
$\times 10^3$
8000
7000
6000
5000
4000
3000
2000
1000
0
0 10 20 30 40 50 60 70
R (cm)