Bose-Einstein Correlations and Colour Reconnection in Particle Physics

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- Bose-Einstein correlations of bosons.
- Experimental procedure and data analysis.
- Choice of the reference sample.
- Bose-Einstein correlations of pions and kaons.
- Bose-Einstein correlations in WW events.
- Colour reconections in WW events.
- Systematic uncertainties of W mass from BEC and CR.
- Why it`s interesting to study higher order BEC at LHC?

Why we study BEC at LEP?

- LEP was a unique laboratory to study and test the evolution of hadronic system - the space-time development of a hadronic system is still poorly understood

- Models are necessary to transform a partonic system, governed by perturbative QCD, to final state hadrons observed in the detectors.

- On WW events were very interest to study separately:

◆ one single evolving hadronic system - one of the W bosons decaying semi-leptonically, the other decaying hadronically,

◆ and compare it with two hadronic systems evolving at the same time -- both W bosons decaying hadronically.

Interconnetion effects at WW bosons

Interconnection effects between the products of the hadronic decays of the two W bosons (in the same event) are expected because the lifetime of the W bosons ($\tau W \simeq 0.1$ fm/c) is an order of magnitude smaller than the typical hadronization times.

These effects can happen at two levels:

- in the evolution of the parton shower, between partons from different hadronic systems by exchanging coloured gluons – effect of CR -- Colour Reconnection;

- between the final state hadrons, due to quantum-mechanical interference, mainly due to BEC -- Bose-Einstein Correlations -- between identical bosons -- pions with the same charge.

Bose-Einstein correlations effect

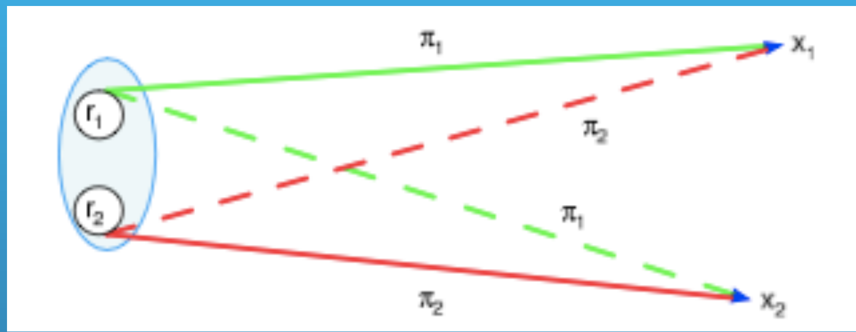
- The two-particle intensity interferometry method has been exploited in 1950`s by Harbury-Brown & Twiss (HBT) on astronomy.
- On 1959/60 by Golghaber et al.(GGLP) first time introduced method of analysis the Bose-Einstein correlations(BEC) on *pp* annihilations. Correlation function in the completely chaotic limit is equal:

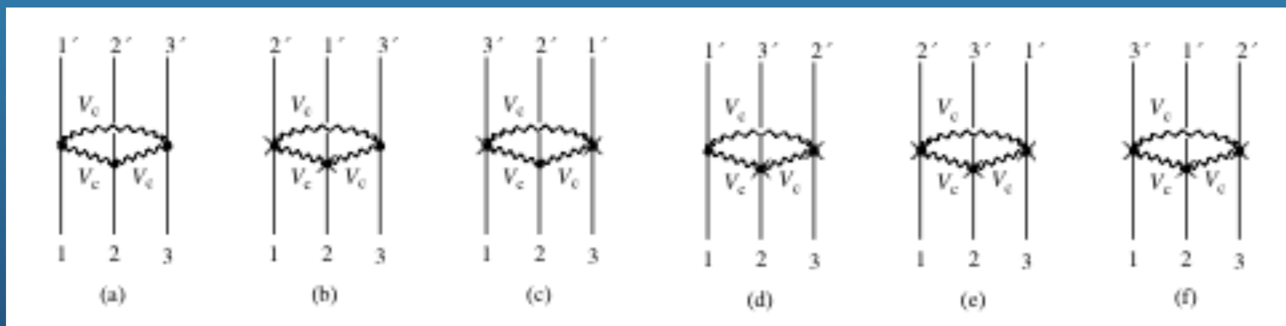
$$C_2(Q) = N(1 + \lambda_2 e^{-r_G^2 Q^2})$$

in the completely coherent case it is equal 1. λ – chaoticity parameter, *r* - source .

- Another favourite parametrisation is proposed by Kopylov&Podgoretsky(KP).
- The KP correlation investigations requore higher statistical data sample that those needed for the BEC analysis.

Diagrams for description the emission of two and three identical bosons





Reference sample for BEC

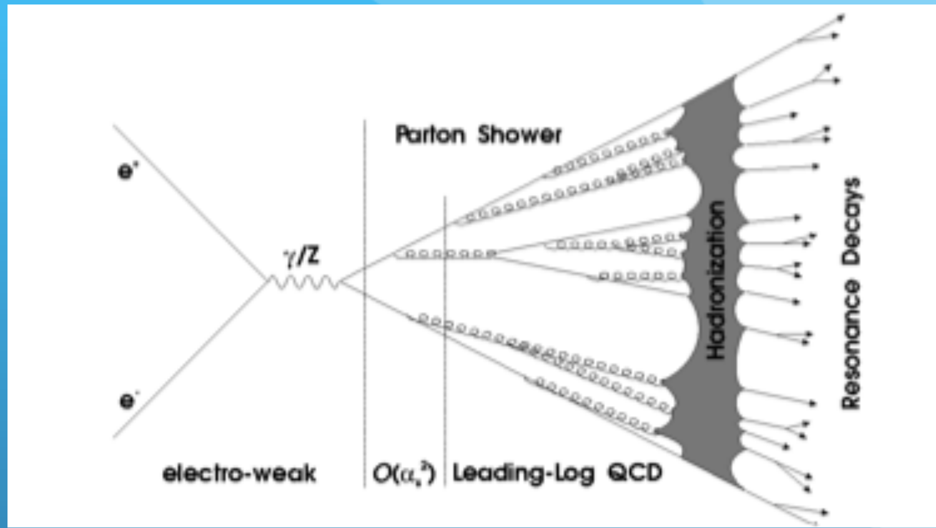
For measure BEC needs reference sample which should be identical to the analysed data but free from BE effect. An ideal solution does not exist.

It`s two categories of RS:

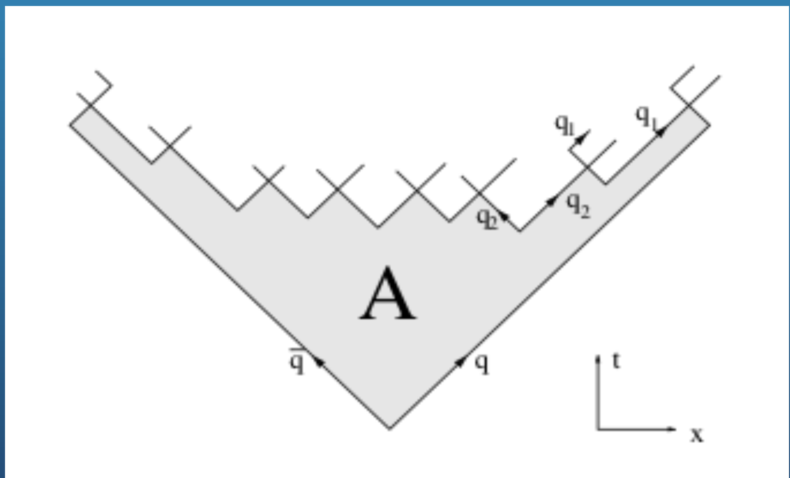
- Reference samples derived from the data – preferred as they are expected to retain many of the kinematic and dynamical data correlations:
  - Sample which is constructed from opposite charged pion-pairs in same data sample.
  - Frequently used "mixed-event" sample - one couples two identical pions each originating from different data event.
  - Reference sample constructed by folding each data event – rotate the event.
- Monte Carlo generated reference samples.

Monte Carlo generated reference samples

Diagram of productions the hadrons



used 3 models: the Lund string fragmentation model in JETSET MC



the cluster model in HERWIG MC

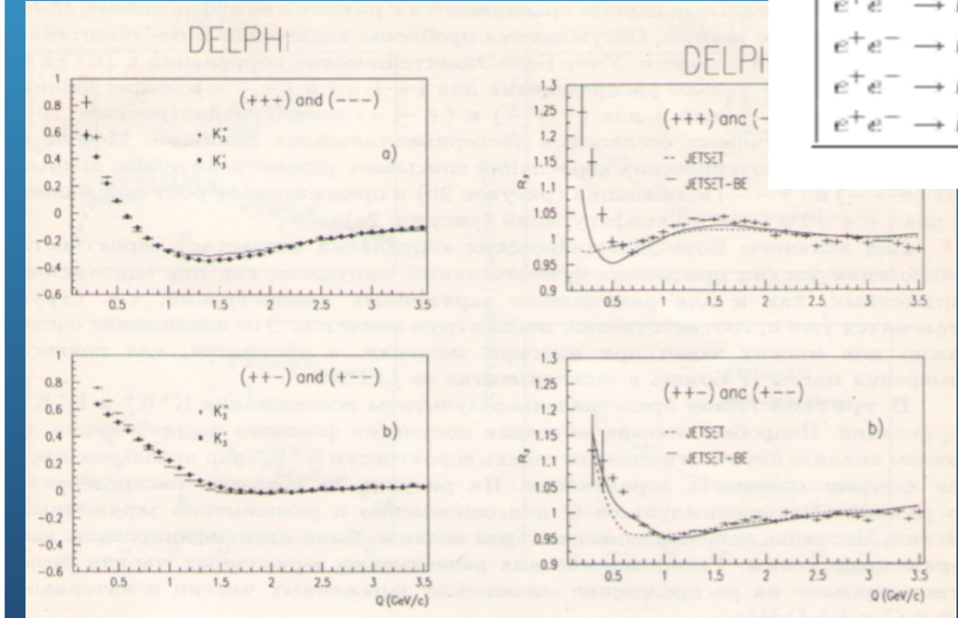
the cascad model in ARIADNE MC

Observation of higher order BEC at LEP

- Results of DELPHI experimen

$$\lambda_3 = 0.31 \pm 0.04(stat) \pm 0.07(syst)$$

$$r_3 = 0.63 \pm 0.03(stat) \pm 0.04(syst)\ f$$

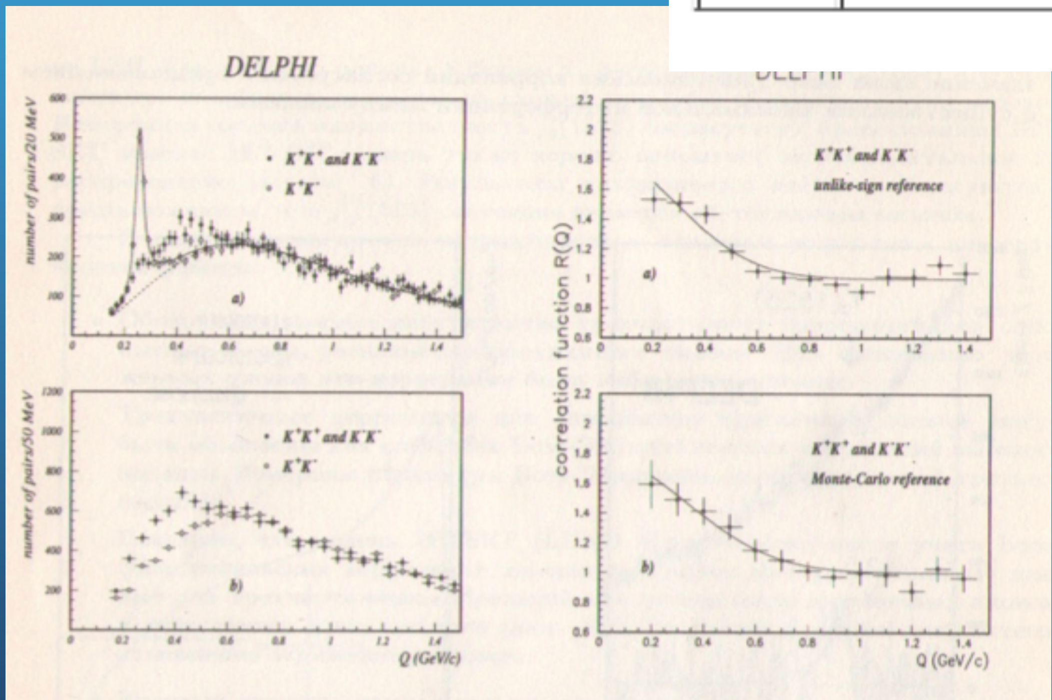


2π and 3π BEC analyses			Parameter	
Reaction		E_{CM} [GeV]	r_3 [fm]	r_3/r_2
$\pi^+p, K^+p \to h$	[96]	22	0.51 ± 0.01 (g)	0.61 ± 0.12
$pp \to h$	[97]	26	0.58 ± 0.07 (n)	0.58 ± 0.25
$pp \to h$	[70]	27.4	0.54 ± 0.01 (n)	0.45 ± 0.07
$pp \to h$	[71]	63	0.41 ± 0.02 (n)	0.50 ± 0.13
$e^+e^- \to h$	[24]	3.1	0.53 ± 0.03 (n)	0.65 ± 0.17
$e^+e^- \to \gamma\gamma$	[24]	5	0.55 ± 0.03 (n)	0.65 ± 0.20
$e^+e^- \to h$	[24]	4–7	0.45 ± 0.04 (n)	0.63 ± 0.18
$e^+e^- \to h$	[24]	29	0.64 ± 0.06 (n)	0.77 ± 0.25
$e^+e^- \to h$	[58]	29–37	0.52 ± 0.07 (n)	0.59 ± 0.21
$e^+e^- \to h$	[93]	91	0.66 ± 0.05 (g)	0.80 ± 0.16
$e^+e^- \to h$	[94]	91	0.58 ± 0.05 (g)	0.73 ± 0.13
$e^+e^- \to h$	[95]	91	0.65 ± 0.07 (g)	1.00 ± 0.12

BEC at LEP

h h	λ_2	r_2 [fm]	Experiment	
$\pi^\pm\ \pi^\pm$	–	$0.78 \pm 0.01 \pm 0.16$	LEP1 Average	[102]
$K^\pm\ K^\pm$	$0.82 \pm 0.11 \pm 0.25$	$0.48 \pm 0.04 \pm 0.07$	DELPHI	[79]
	$0.82 \pm 0.22\ ^{+0.17}_{-0.12}$	$0.56 \pm 0.08\ ^{+0.07}_{-0.06}$	OPAL	[80]
$K^0_S\ K^0_S$	$1.14 \pm 0.23 \pm 0.32$	$0.76 \pm 0.10 \pm 0.11$	OPAL	[103]
	$0.96 \pm 0.21 \pm 0.40$	$0.65 \pm 0.07 \pm 0.15$	ALEPH	[104]
	$0.61 \pm 0.16 \pm 0.16$	$0.55 \pm 0.08 \pm 0.12$	DELPHI	[79]
$\bar{p}\ \bar{p}$	–	$0.15 \pm 0.02 \pm 0.04$	OPAL	[101]
$\Lambda\ \Lambda$	–	$0.11 \pm 0.02 \pm 0.01$	ALEPH	[100]
$\Lambda\ \Lambda$	Spin Analysis	$0.19\ ^{+0.37}_{-0.07} \pm 0.02$	OPAL	[98]
	"	$0.11\ ^{+0.05}_{-0.03} \pm 0.01$	DELPHI	[99]
	"	$0.17 \pm 0.13 \pm 0.04$	ALEPH	[100]

BEC of Kaons at DELPHI



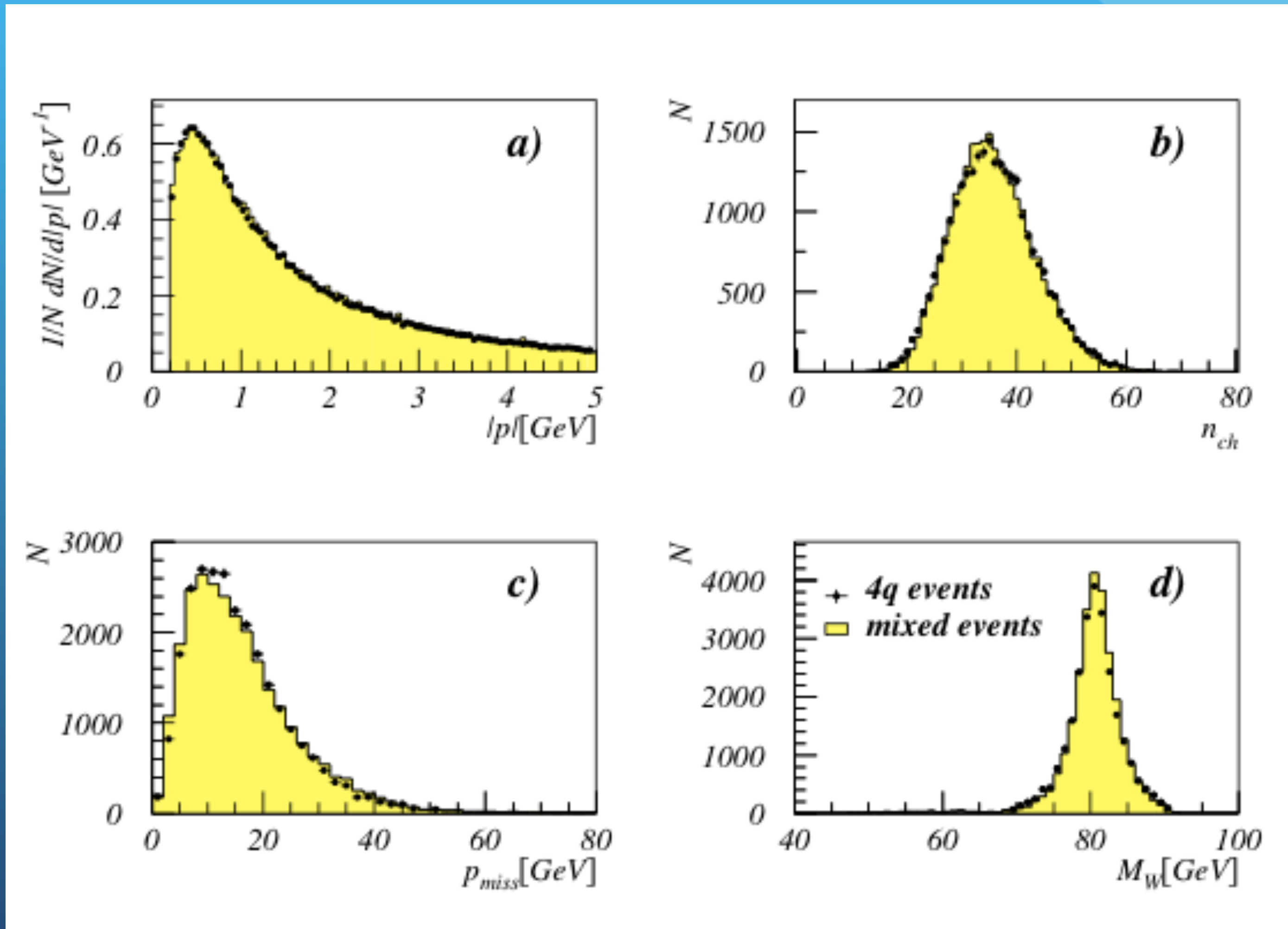
Inter WW Bose-Einstein correlations

Mixing WW:

- The mixed two-particle density was constructed by combining the hadronically - mix decaying W's from pairs of different semi-leptonic WW events, from which the lepton was removed and irrespective of the charge of the W's.
- Pairings where the two W polar angles were within 10° after inverting the z-component of one W were also accepted.
- The momenta of the W's were then approximatively balanced by rotating one W around the beam axis so that the W's became back-to-back in the plane transverse to the beam axis

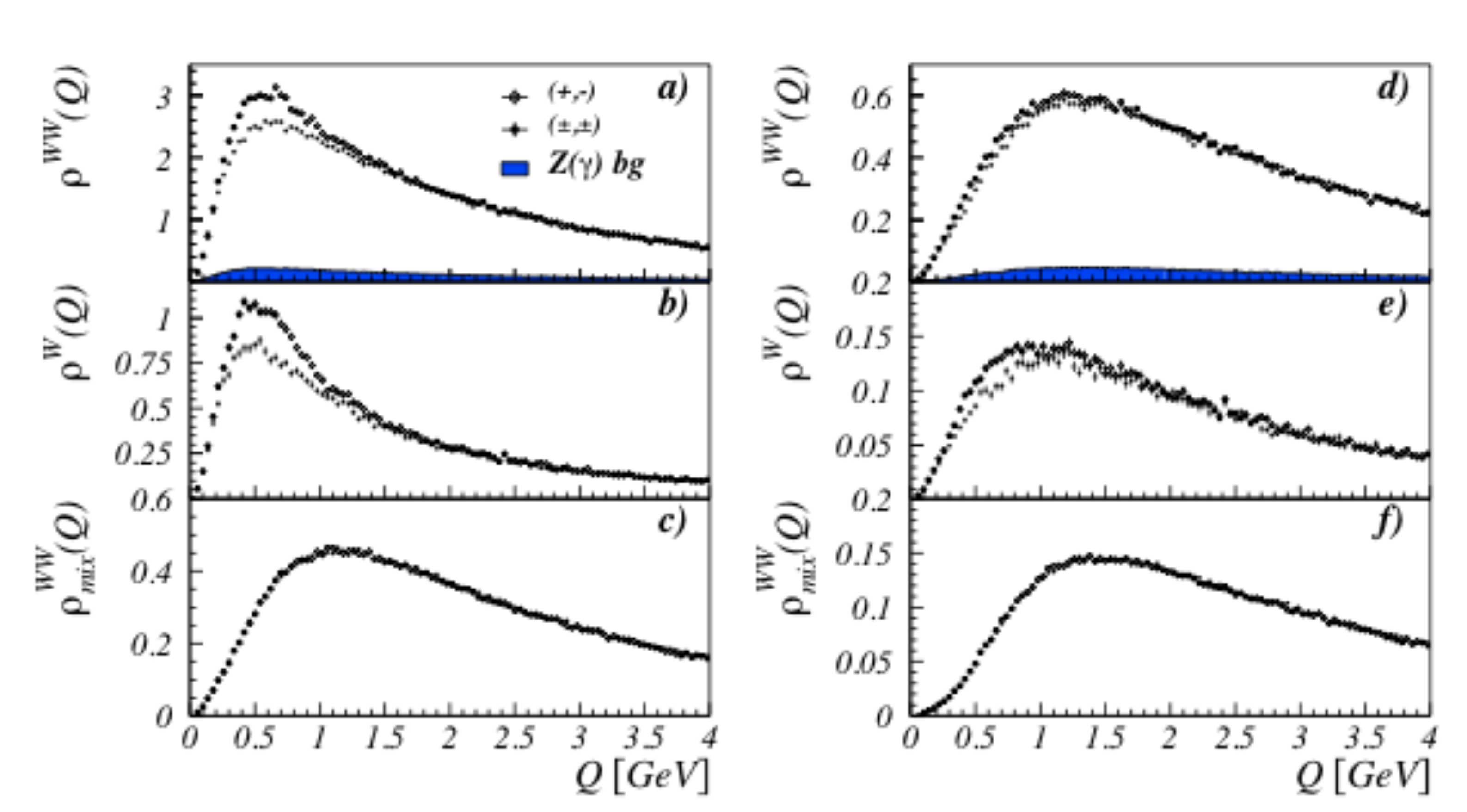
Inter WW effect

Comparison between simulated fully-hadronic events and mixed events



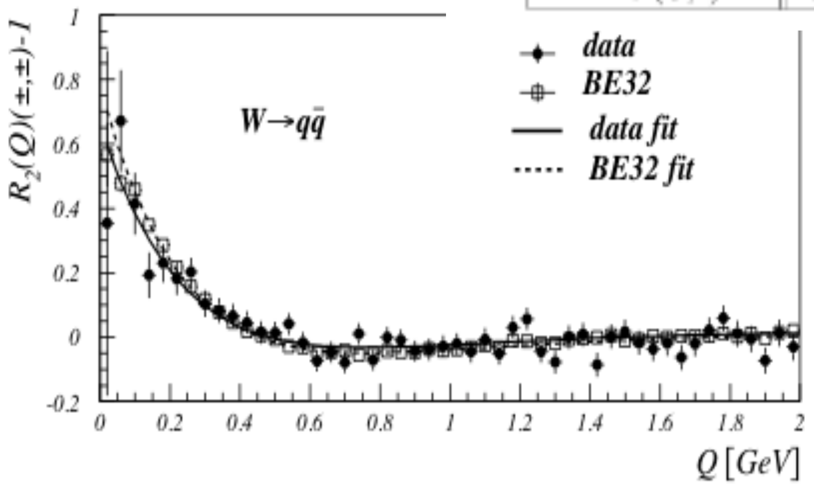
Inter WW effect

The two-particle densities, for like-sigh & unlike-sigh pairs, with (a-c) and without (d-f) pair weights applied



Inter WW BEC

sample/parameter	Λ_I	$R(fm)$	ϵ_d	δ_N	χ^2/ndf
R free and ϵ_d fixed to BEA values					
BEA (±,±)	1.50 ± 0.06	0.72 ± 0.02	-0.50 ± 0.03	-0.010 ± 0.002	116.4/96
Data (±,±)	1.42 ± 0.63	1.14 ± 0.33	-0.50	-0.002 ± 0.020	88.3/97
BEA (+,−)	0.30 ± 0.03	0.41 ± 0.03	-0.60 ± 0.09	-0.010 ± 0.002	110.8/96
Data (+,−)	0.43 ± 0.22	0.45 ± 0.15	-0.60	0.000 ± 0.020	93.2/97
R and ϵ_d fixed to BEA values					
Data (±,±)	0.82 ± 0.29	0.72	-0.50	-0.005 ± 0.020	89.9/98
BEI (±,±)	0.10 ± 0.05	0.72	-0.50	-0.009 ± 0.004	99.3/98
BE0 (±,±)	0.02 ± 0.02	0.72	-0.50	-0.010 ± 0.002	98.0/98
Data (+,−)	0.40 ± 0.18	0.41	-0.60	-0.001 ± 0.020	93.2/98
BEI (+,−)	0.01 ± 0.03	0.41	-0.60	-0.005 ± 0.003	137.5/98
BE0 (+,−)	-0.04 ± 0.02	0.41	-0.60	-0.009 ± 0.002	138.0/98



Colour Reconnection effect

The final state partons may coexist in space and time, cross-talk between the two evolving hadronic systems may be possible during fragmentation through soft gluon exchange. It`s 2 models:

- The Sj¨ostrand-Khoze “Type 1” CR model SK-I, is based on the Lund string fragmentation phenomenology. The strings are considered as colour flux tubes with some volume, and reconnection occurs when these tubes overlap. The probability of reconnection in an event is parameterised by the value κ, according to the space-time volume overlap of the two strings

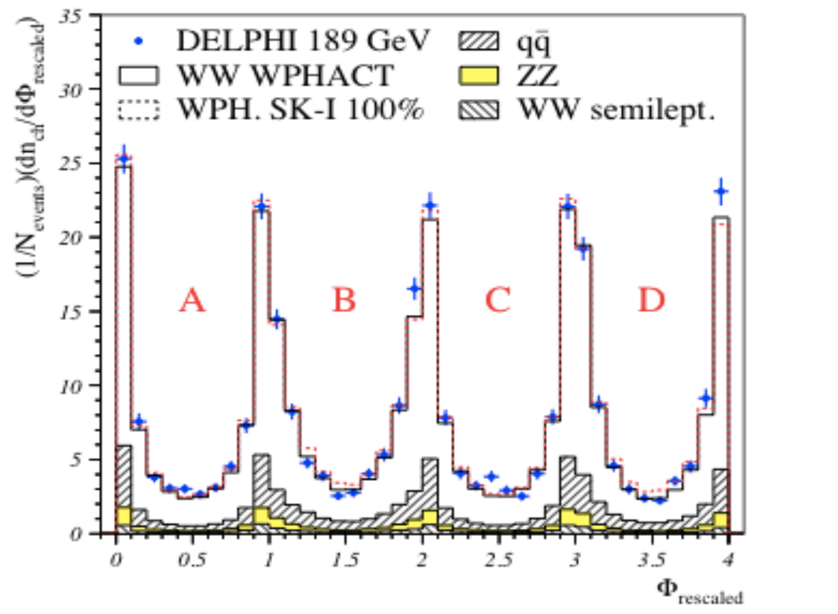
$$\mathcal{P}_{\text{reco}}(\kappa) = 1 - e^{-\kappa V_{\text{overlap}}}$$

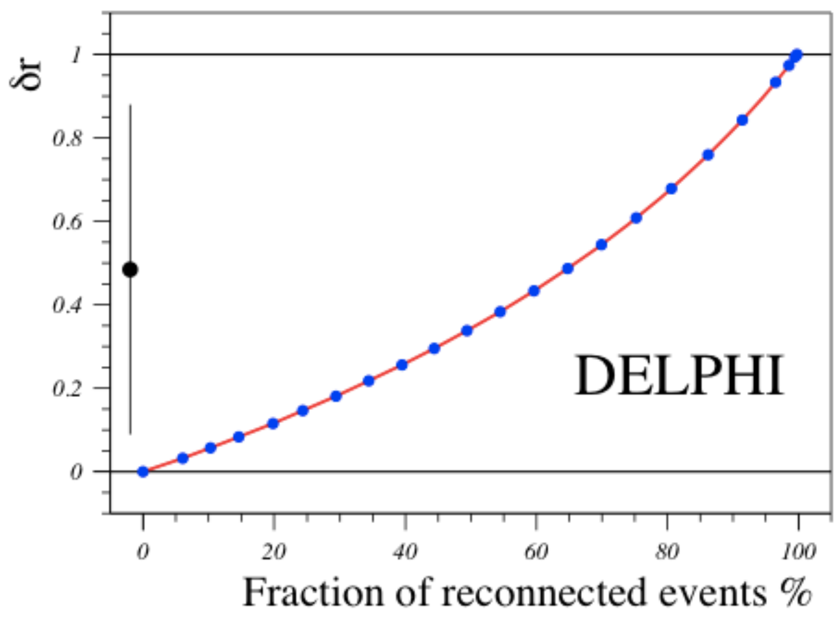
- Another model was proposed by the same authors SK-II, considering the colour flux tubes as infinitely thin, which allows for Colour Reconnection in the case the tubes cross each other and provided the total string length is reduced

CR effect

- Charged-particle flow

$$R = \frac{\int_{0.2}^{0.8} dn_{\rm ch}/d\Phi(A+C)d\Phi}{\int_{0.2}^{0.8} dn_{\rm ch}/d\Phi(B+D)d\Phi}\,.$$





$$\langle R\rangle = 0.979 \pm 0.032({\rm stat}) \pm 0.035({\rm syst})\,.$$

$$\kappa_{\rm SK-I} = 2.2^{+2.5}_{-1.3}$$

$$\mathcal{P}_{\rm reco} = 52\%$$

Contributions to the systematic error on the W mass measurement

Γ_W Systematic Errors (MeV/c^2) at 205 GeV		
Sources of Systematic Error	$\ell\overline{\nu}_\ell q\bar{q}'$	$q\bar{q}'\bar{q}q'$
Statistical Error on Calibration	15	9
Lepton Corrections	48	-
Jet Corrections	38	169
Fragmentation	29	8
Electroweak Corrections	11	9
Background	43	51
Bose-Einstein Correlations	-	20
Colour Reconnection	-	247

Why it`s interesting to study BEC at LHC?

- Higher order BEC -- Alice already showing result.
- Bose condensate – the average interatomic separation is inversely proportional to the square-root of the atomic mass. When bosonic atoms are cooled down below a critical temperature, the atomic wave-packets overlap and the equal identity of the particles becomes significant. At this temperature, these atoms undergo a quantum mechanical phase transition and form a Bose condensate, a coherent cloud of atoms all occuping the same quantum mechanical state.
- Bose star – axion?