National Science Centre

Angular correlations measured in pp collisions at the LHC by the ALICE experiment

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HUMAN CAPITAL
NATIONAL COHESION STRATEGY

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EUROPEAN SOCIAL FUND

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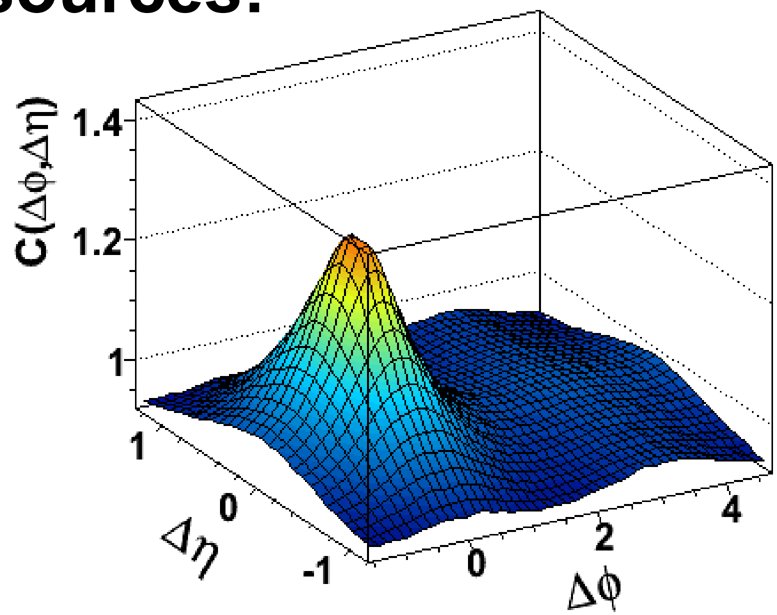
Physics goals

Characterize different correlation sources:

- **minijets**
- **femtoscopic correlations**
- **resonances**
- photon conversion
- momentum conservation
- …



Since each correlation source has a **unique distribution** on (Δη,Δφ) we would like to quantify their contributions to the overall shape using **fitting procedure**.

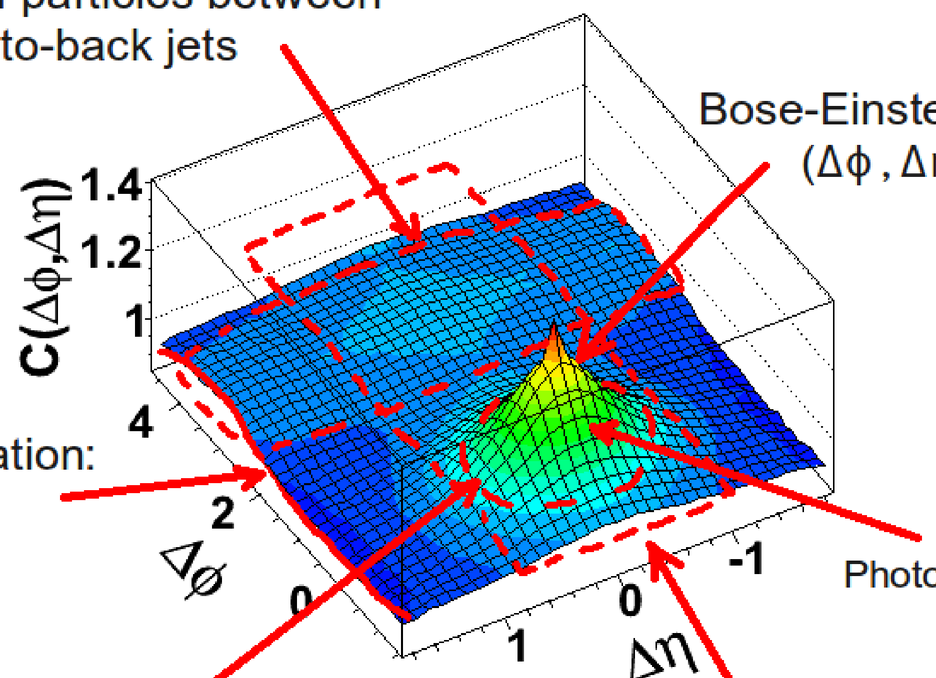
Useful to perform analysis in a more refined way:

- **charge dependence**
- **identified particles**

Anatomy of the ΔηΔφ correlation function

„Away-side” (Δϕ ~ π) jet correlations:
Correlation of particles between
back-to-back jets

Bose-Einstein correlations:
(Δϕ, Δη)~(0, 0)



Momentum conservation:
~ -cos(Δϕ)

Photon conversion

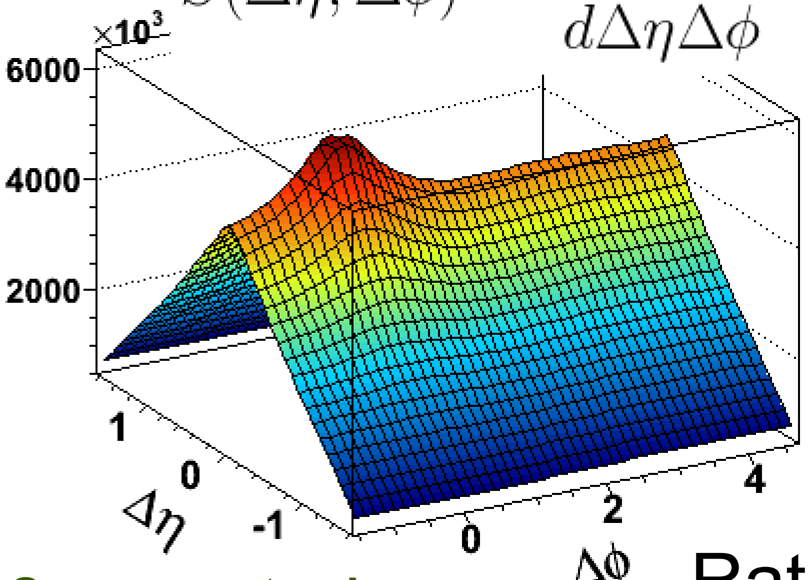
„Near-side” (Δϕ ~ 0) jet peak:
Correlation of particles within
a single jet

Resonances, string fragmentation

ΔηΔφ Experimental Correlation Function

Signal distribution

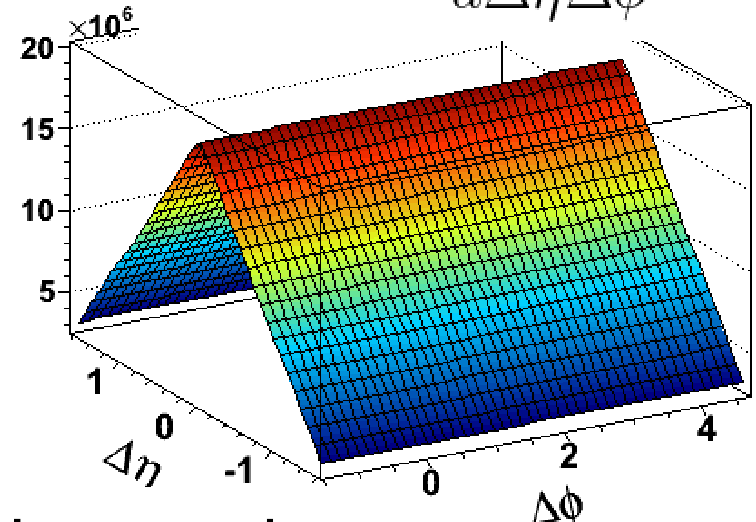
$$S(\Delta\eta, \Delta\phi) = \frac{d^2N^{signal}}{d\Delta\eta\Delta\phi}$$



Same event pairs

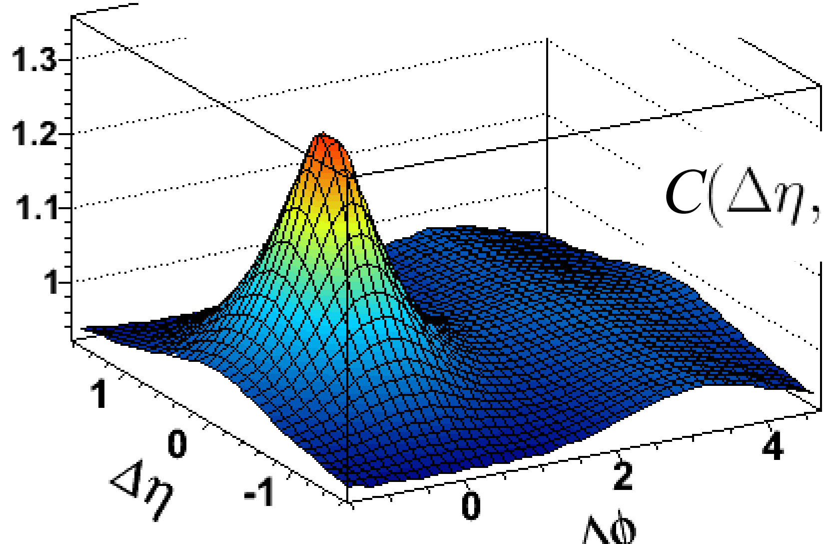
Background distribution

$$B(\Delta\eta, \Delta\phi) = \frac{d^2N^{mixed}}{d\Delta\eta\Delta\phi}$$



Mixed event pairs

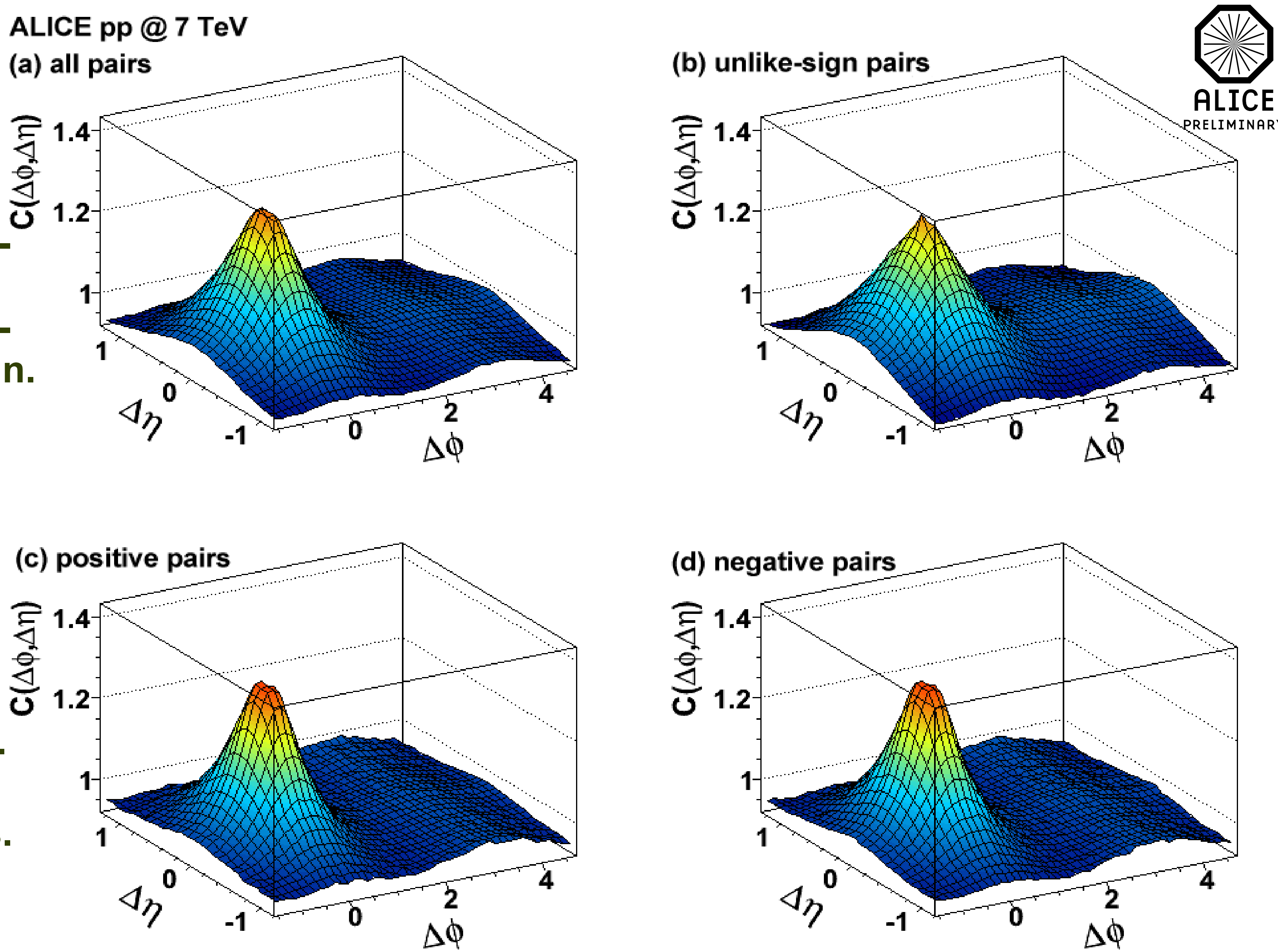
Ratio signal/background



$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\phi = \phi_1 - \phi_2$$

$$C(\Delta\eta, \Delta\phi) = \frac{N^{mixed}_{pairs}}{N^{signal}_{pairs}} \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

Charge dependence



Shape of near-side peak differs for like- and unlike-sign.

Femtoscopic correlations enhance near-side peak for like-sign pairs.

pp 7 TeV

Multiplicity dependence

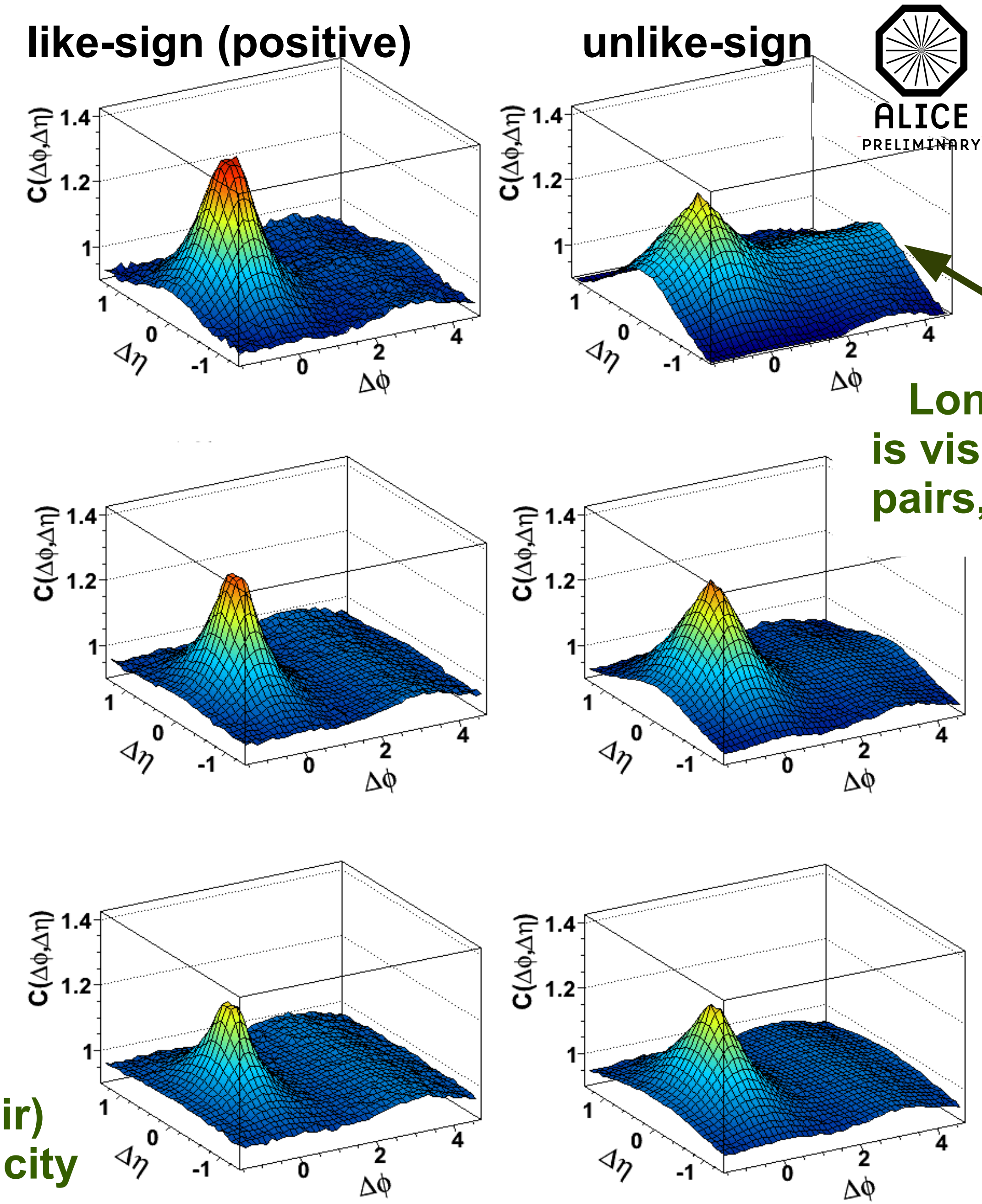
increasing multiplicity

$N_{ch}<12$

$17 \leq N_{ch} \leq 22$

$42 \leq N_{ch} \leq 51$

like-sign (positive) **unlike-sign**



Longitudinal ridge structure is visible only for unlike-sign pairs, for low multiplicities

Decreasing correlation (per pair) with rising multiplicity

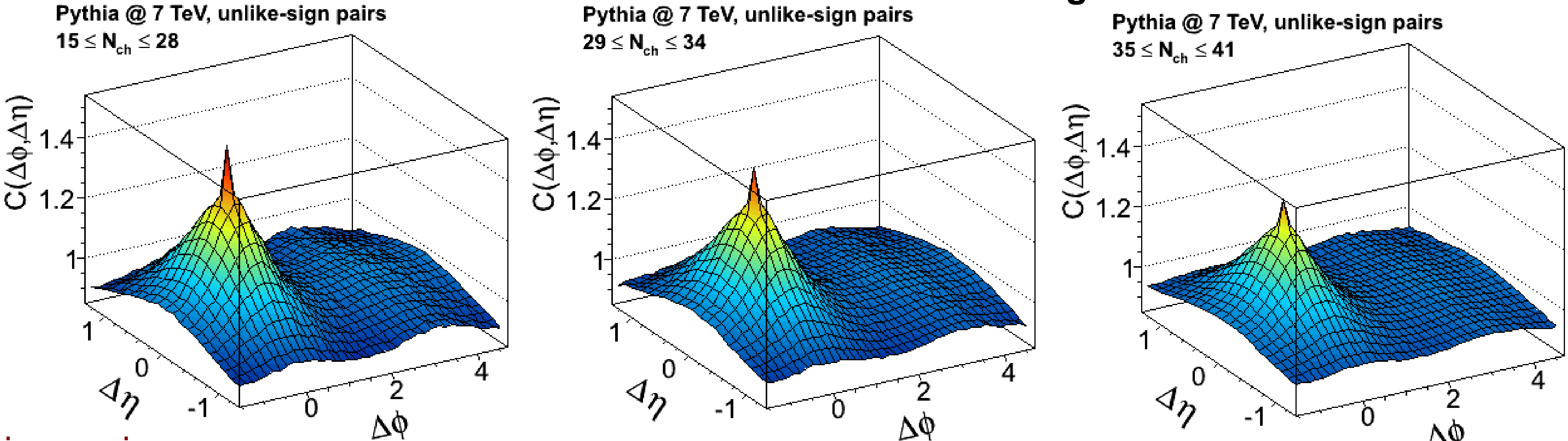
p_T>0.12 GeV/c

$|\eta|$<1.0

Results for Pythia

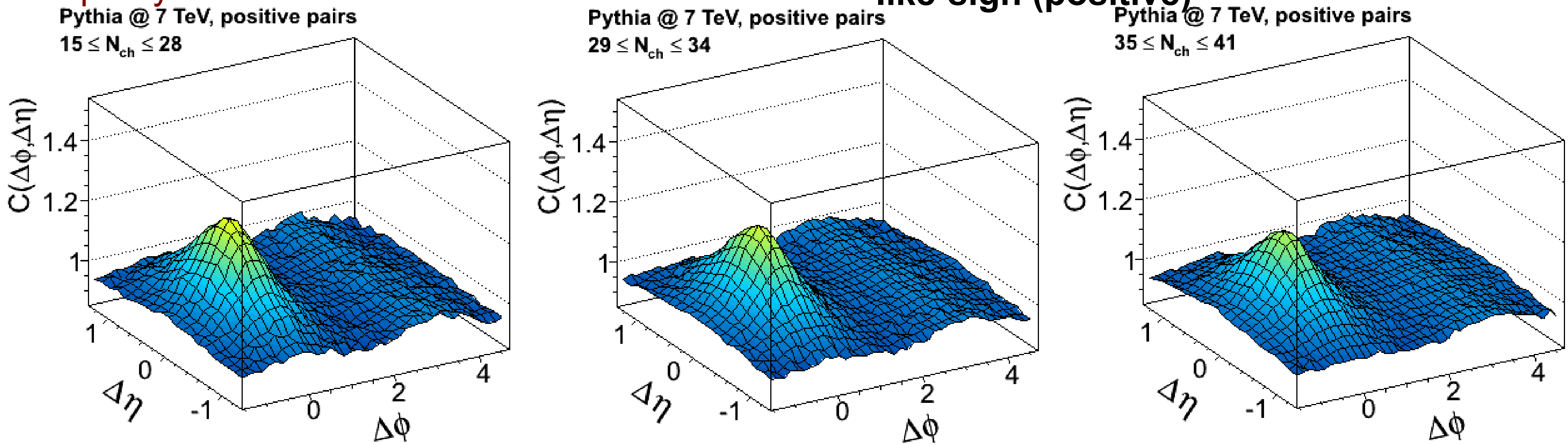
Monte Carlo Simulation

unlike-sign



increasing multiplicity

like-sign (positive)

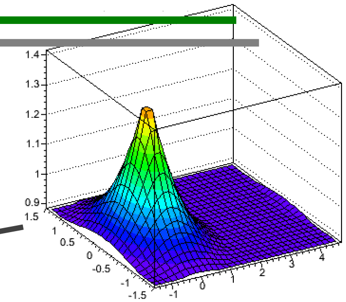


Fitting function

We fit a function of the following form:

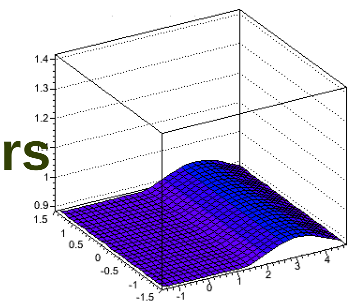
1 parameter **4 parameters**

$$
\begin{aligned}
C(\Delta\eta,\Delta\phi) = N \\
&+ M_M \cdot \exp\left[-\left(\frac{\Delta\phi^2}{2\sigma_{M\phi}^2}+\frac{\Delta\eta^2}{2\sigma_{M\eta}^2}\right)^{e_M}\right] + M_M \cdot \exp\left[-\left(\frac{(\Delta\phi-2\pi)^2}{2\sigma_{M\phi}^2}+\frac{\Delta\eta^2}{2\sigma_{M\eta}^2}\right)^{e_M}\right] \\
&+ M_A \cdot \exp\left[-\left(\frac{(\Delta\phi-\pi)^2}{2\sigma_{A\phi}^2}\right)^{e_A=1}\right] + M_A \cdot \exp\left[-\left(\frac{(\Delta\phi+\pi)^2}{2\sigma_{A\phi}^2}\right)^{e_A=1}\right] \\
&+ M_L \cdot \exp\left[-\left(\frac{\Delta\eta^2}{2\sigma_{L\phi}^2}\right)^{e_L=1}\right] \\
&+ P \cdot \Delta\eta^2
\end{aligned}
$$



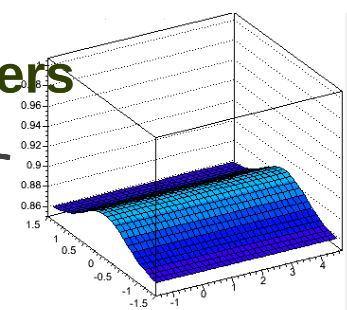
2D Gauss for near-side peak

2 parameters



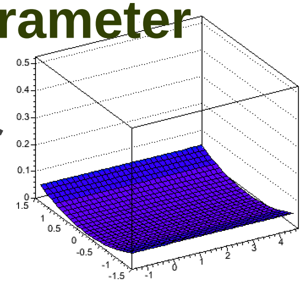
1D Gauss for away-side ridge

2 parameters



1D Gauss for longitudinal ridge

1 parameter

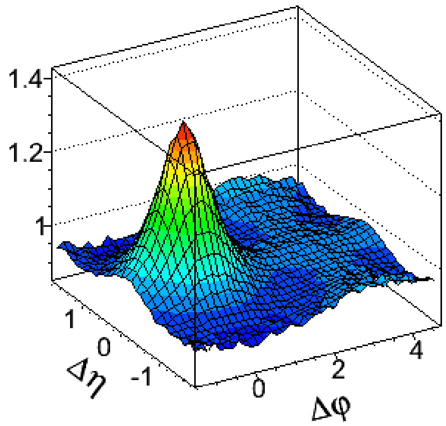


1D Parabola for wings

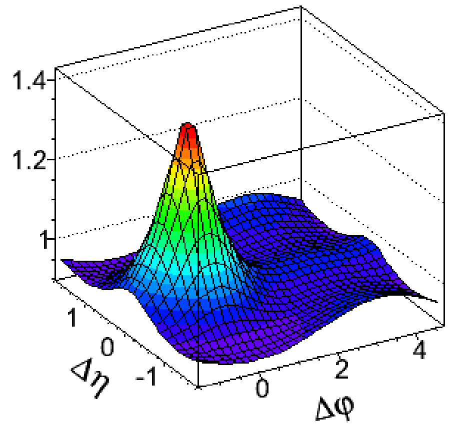
= 10 parameters

Fitting results (example)

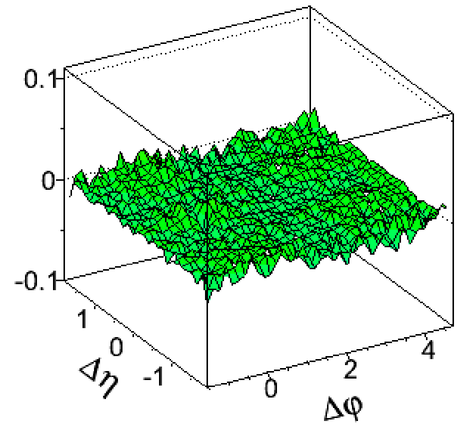
Correlation function



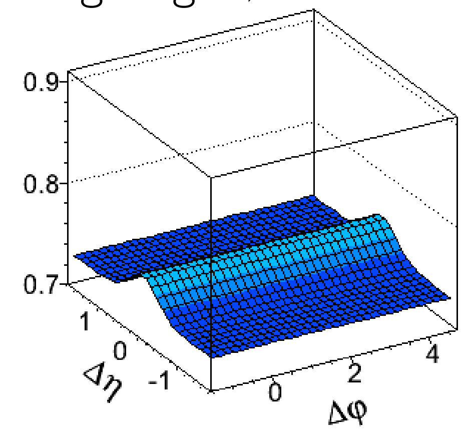
Fitted function

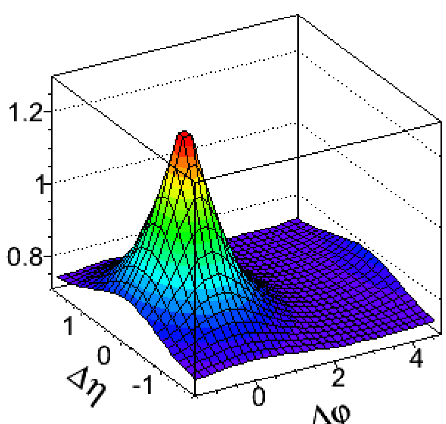


Subtraction

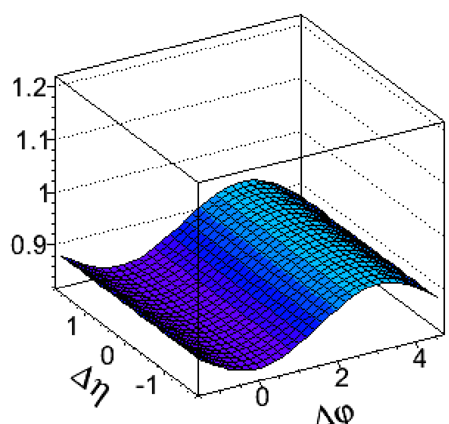


Longitudinal ridge
(string fragm., resonances)

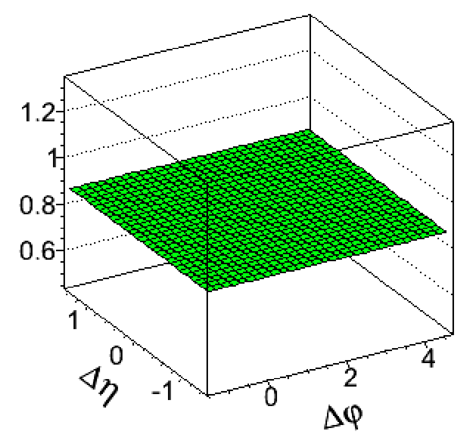




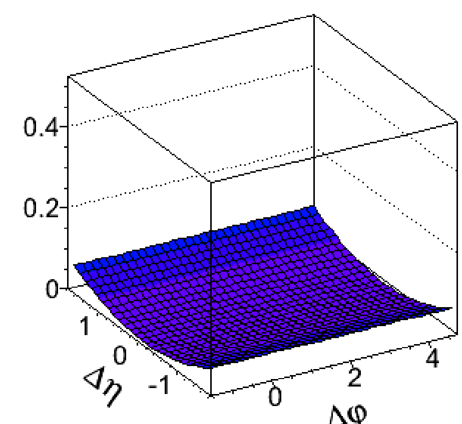
Near-side peak
(minijets, HBT, resonances)



Away-side ridge
(minijets)

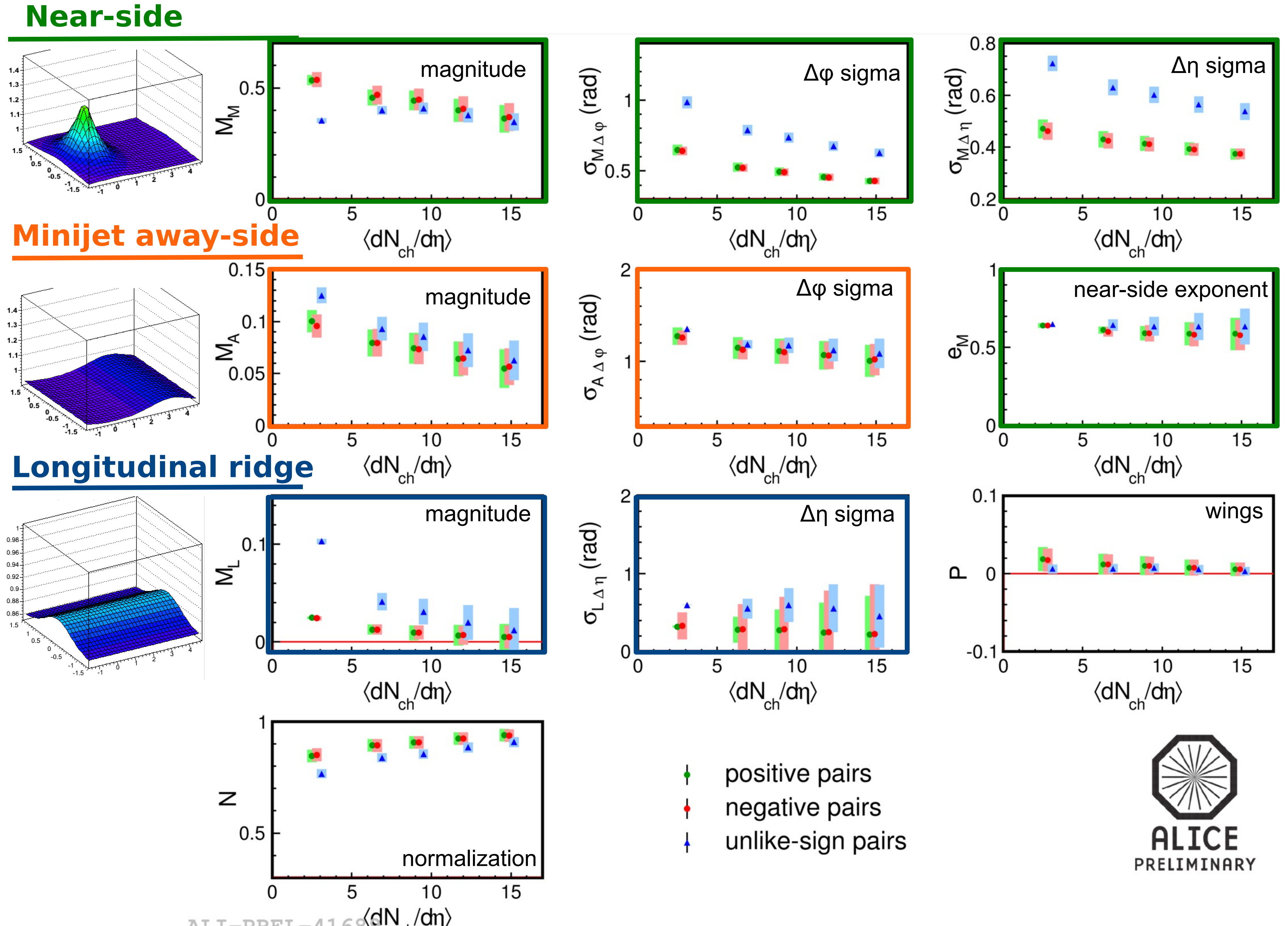


Normalization



Wings
(detector effects)

Function fitted to the histogram obtained from analysis



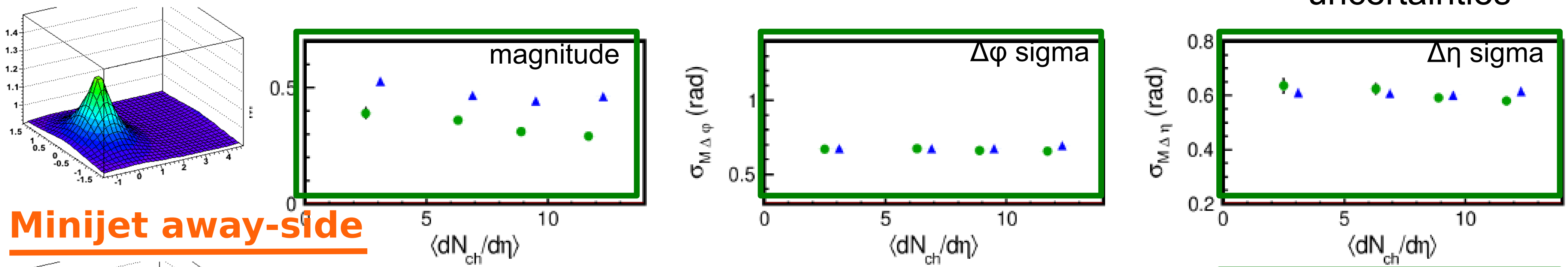
Near-side
Minijet away-side
Longitudinal ridge
magnitude
Δφ sigma
Δη sigma
near-side exponent
wings
normalization
M_M
$\sigma_{M\Delta\varphi}$ (rad)
$\sigma_{M\Delta\eta}$ (rad)
M_A
$\sigma_{A\Delta\varphi}$ (rad)
e_M
M_L
$\sigma_{L\Delta\eta}$ (rad)
P
N
$\langle dN_{ch}/d\eta \rangle$
positive pairs
negative pairs
unlike-sign pairs
ALICE
PRELIMINARY
ALI-PREL-41689

Results for Pythia

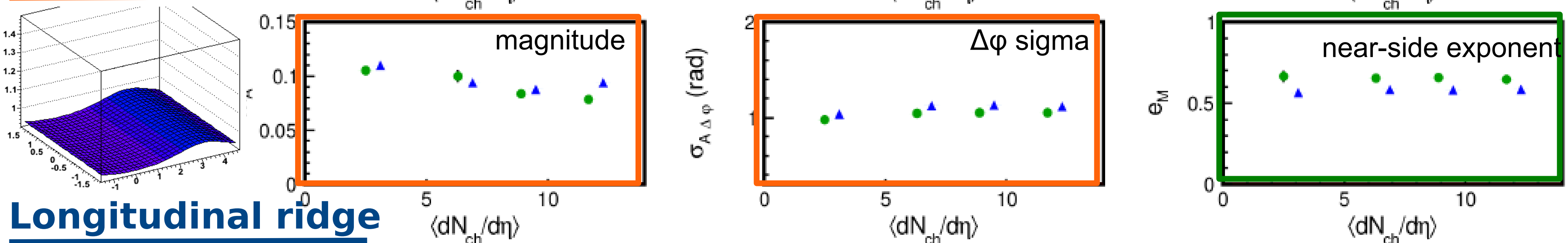
Fit to Monte Carlo

Without systematic uncertainties

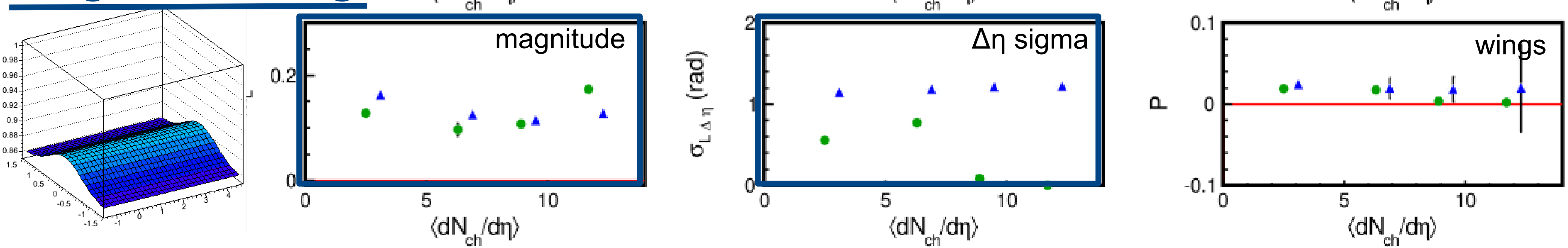
Near-side



Minijet away-side



Longitudinal ridge



Like-sign / Unlike-sign

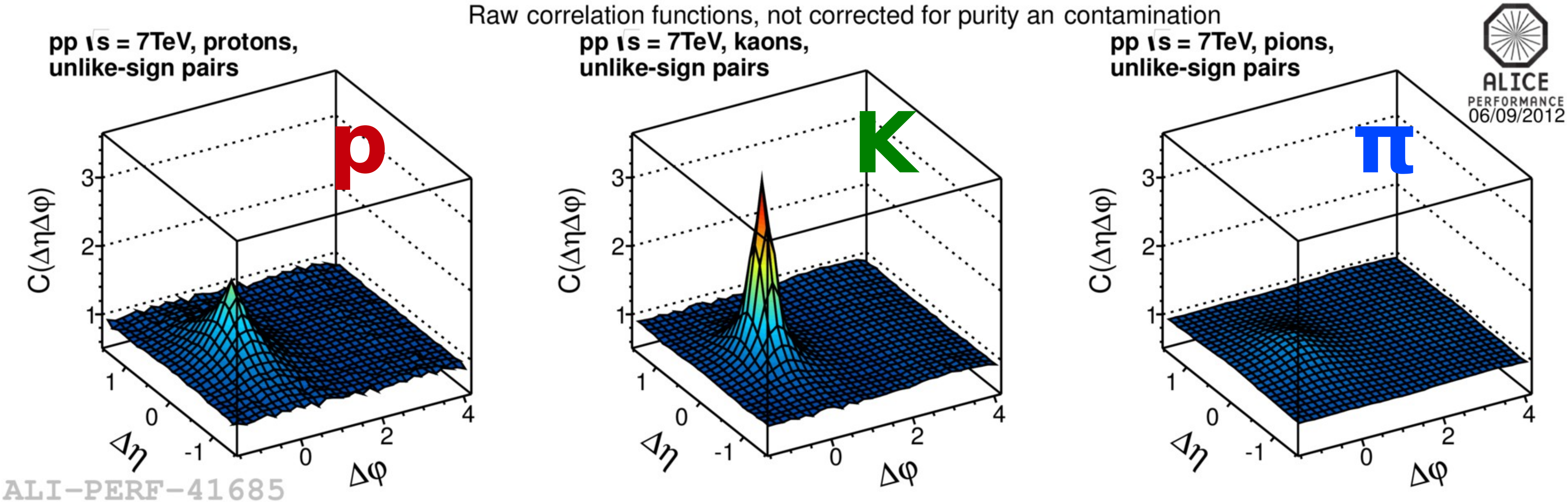
- **No femtoscopic correlations**
- **Same width of near-side peak for like- and unlike-sign, magnitude higher for unlike-sign (opposite to the data)**
- **Away-side comparable (as in data)**

$\Delta\eta\Delta\varphi$ of identified particles

- In addition to the correlation sources mentioned earlier, we expect the **conservation laws** to play a relatively large role for correlations of identified particles
- Can be strong constraint on the way quantum numbers are conserved in models
- For this reason the study of correlation functions for **particles with different quark content**, i.e. pions, kaons, protons, is particularly interesting

	conservation laws			
particles	momentum	charge	strangeness	baryon number
pions	✓	✓		
kaons	✓	✓	✓	
protons	✓	✓		✓

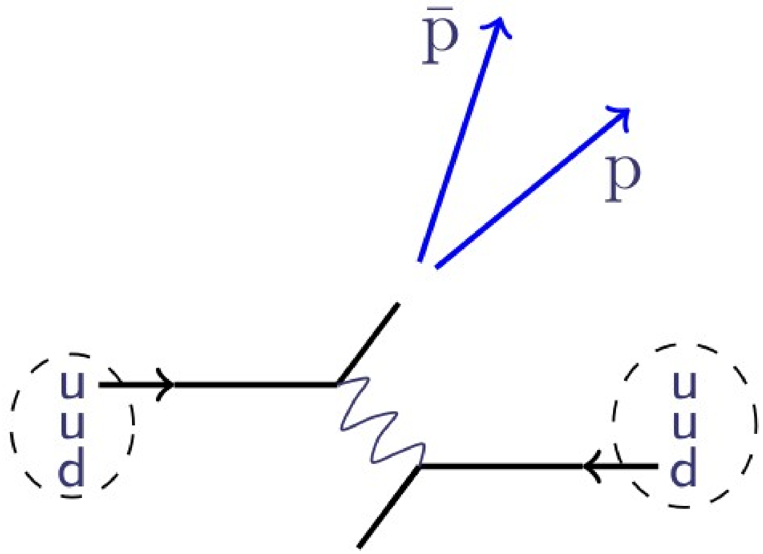
Unlike-sign pairs = particle/antiparticle



- The **strength of the correlation** depends on the energetic **price of the alternative solution**. The larger the difference in prices between basic and alternative solutions, the stronger the correlation.
  - for **pions** the alternative solution is just another opposite-charge particle,
  - for **protons** another antibaryon (charged, or neutral plus additional charged particle),
  - for **kaons**, which carry the strange quark, the strangeness must be conserved, so the alternative solution would be at least a lambda together with another baryon.

Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

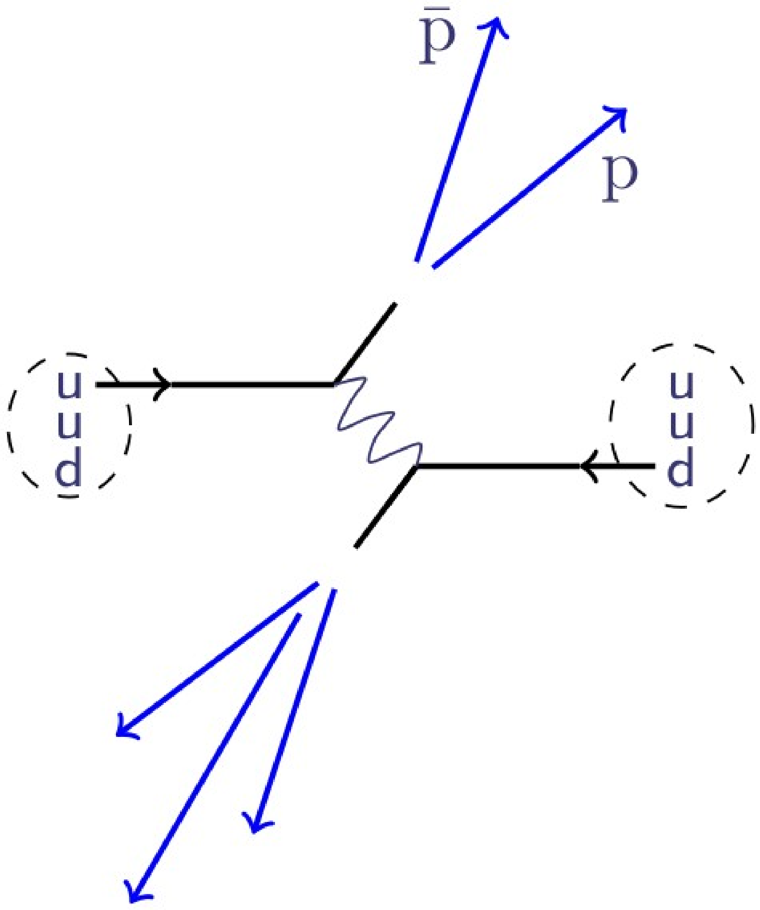


Basic solution:

- for **protons:** antiproton

Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

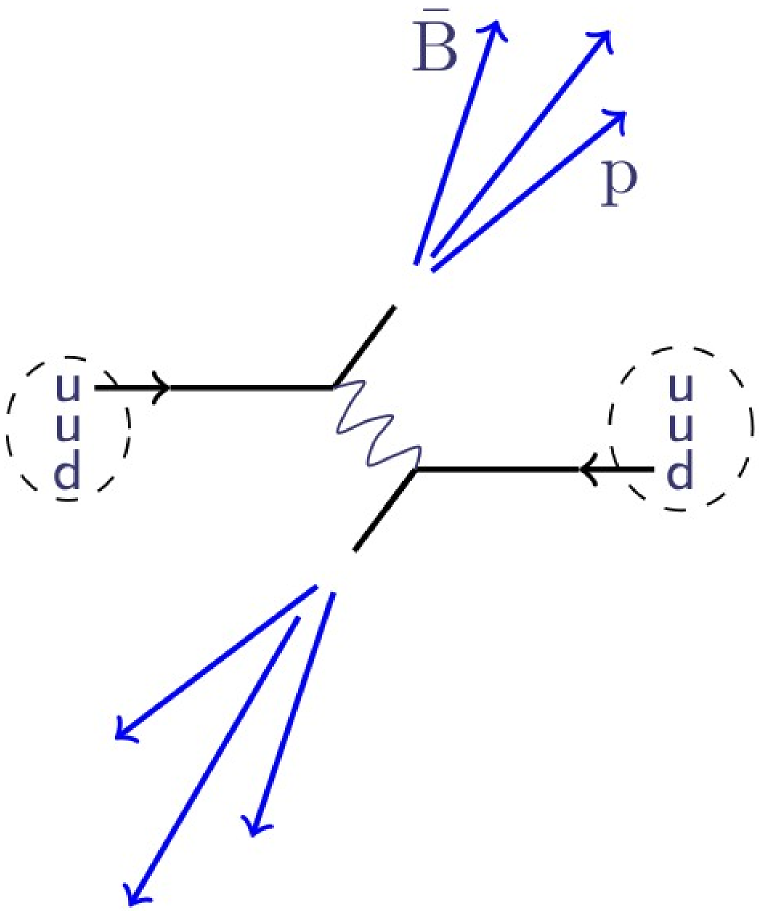


Basic solution:

- for **protons:** antiproton
- then we have only to compensate for the momentum

Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

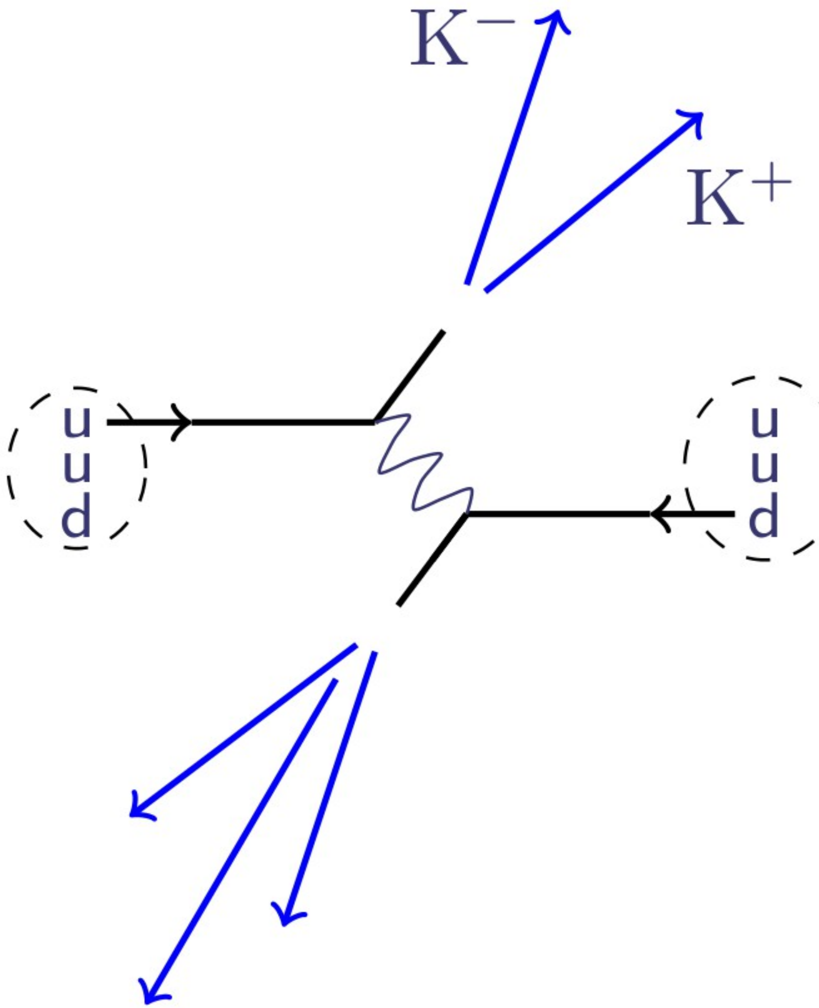


Alternative solution:

- for **protons** another antibaryon (charged, or neutral plus additional charged particle),
- charge, **baryon number** and momentum conserved

Unlike-sign pairs (kaons)

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

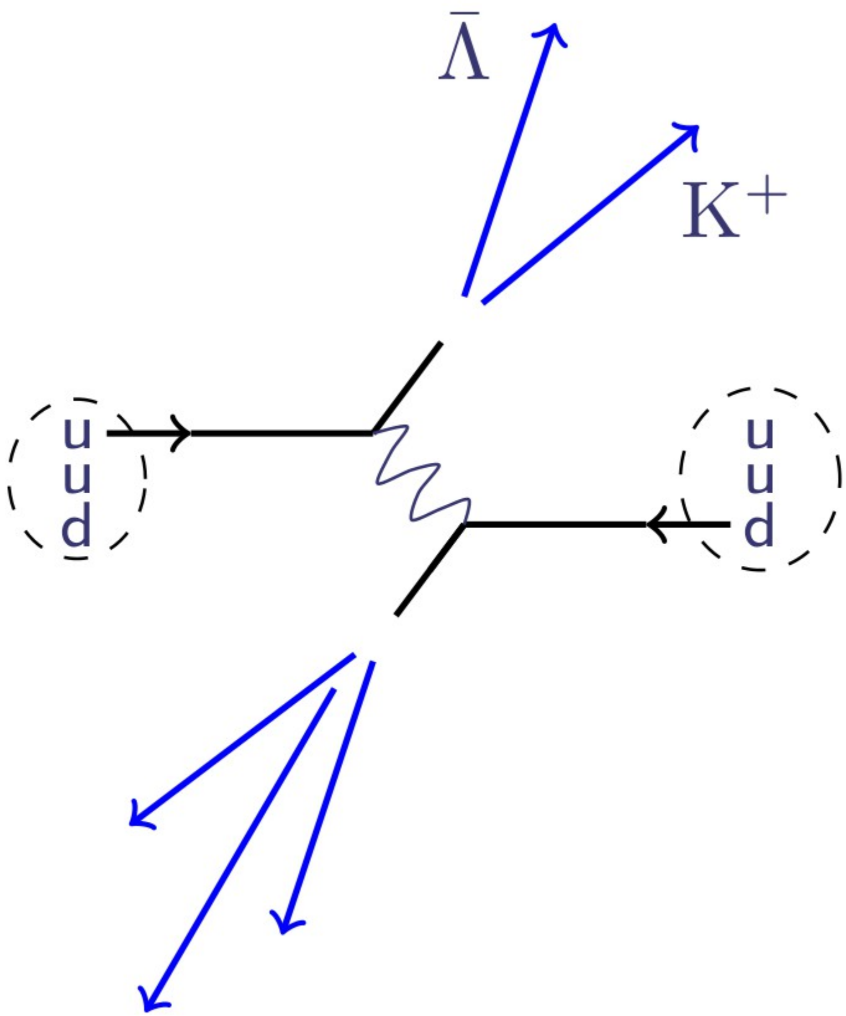


Basic solution:

- for **kaons:** kaon of opposite sign

Unlike-sign pairs

- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**

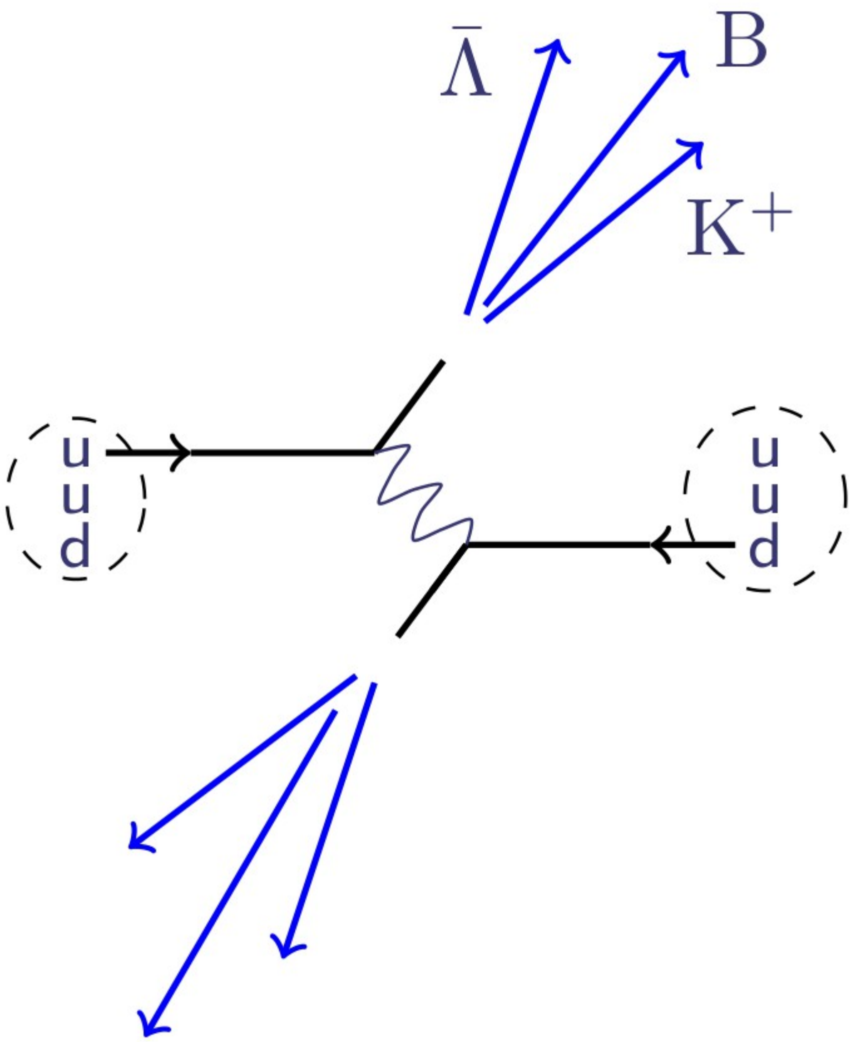


Alternative solution:

- for **kaons:** another strange particle, at least **lambda**

Unlike-sign pairs

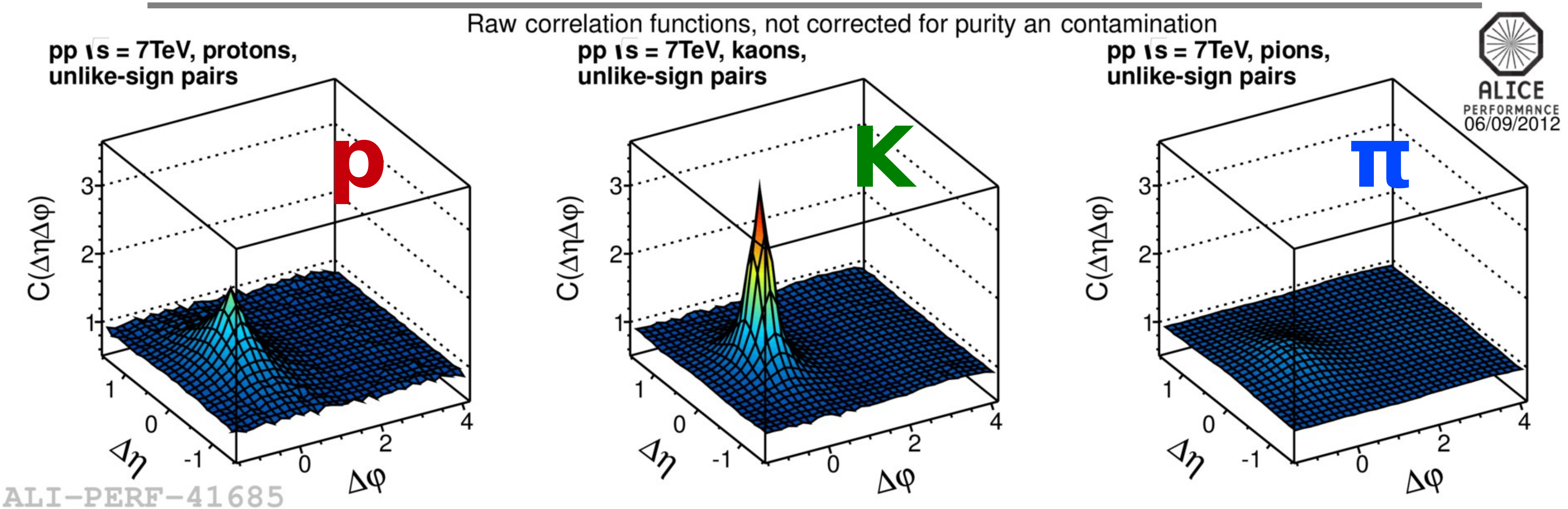
- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair.**



Alternative solution:

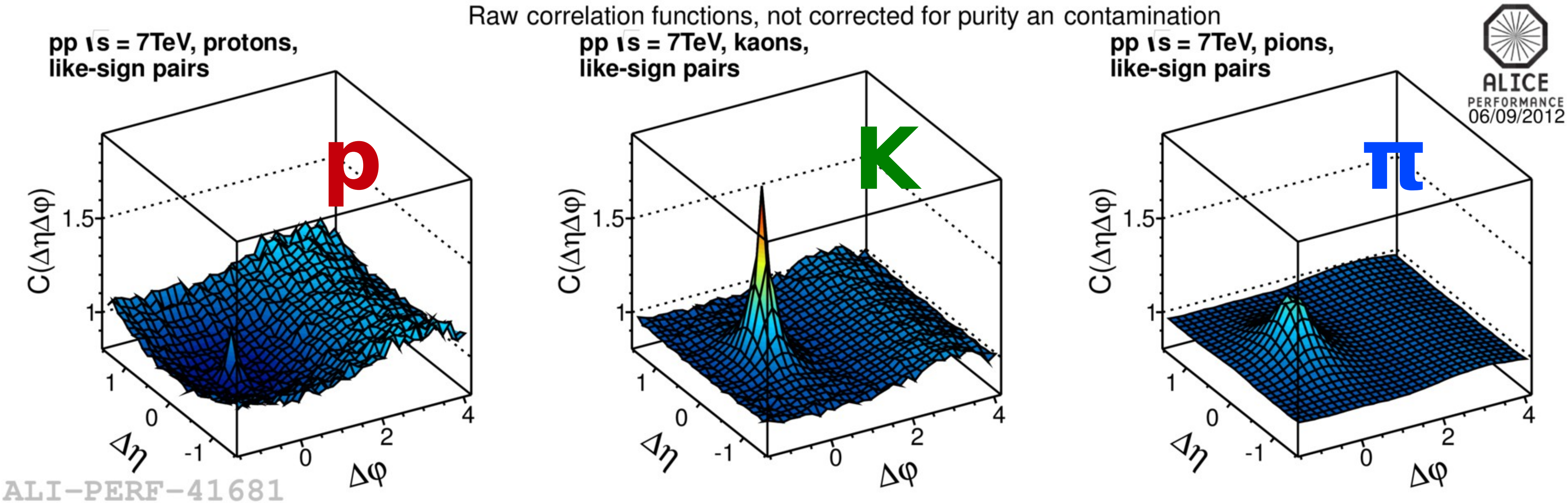
- for **kaons:** another strange particle, at least **lambda**
- since lambda is baryon, we need **another baryon** to conserve baryon number
- **Very expensive solution!**

Unlike-sign pairs



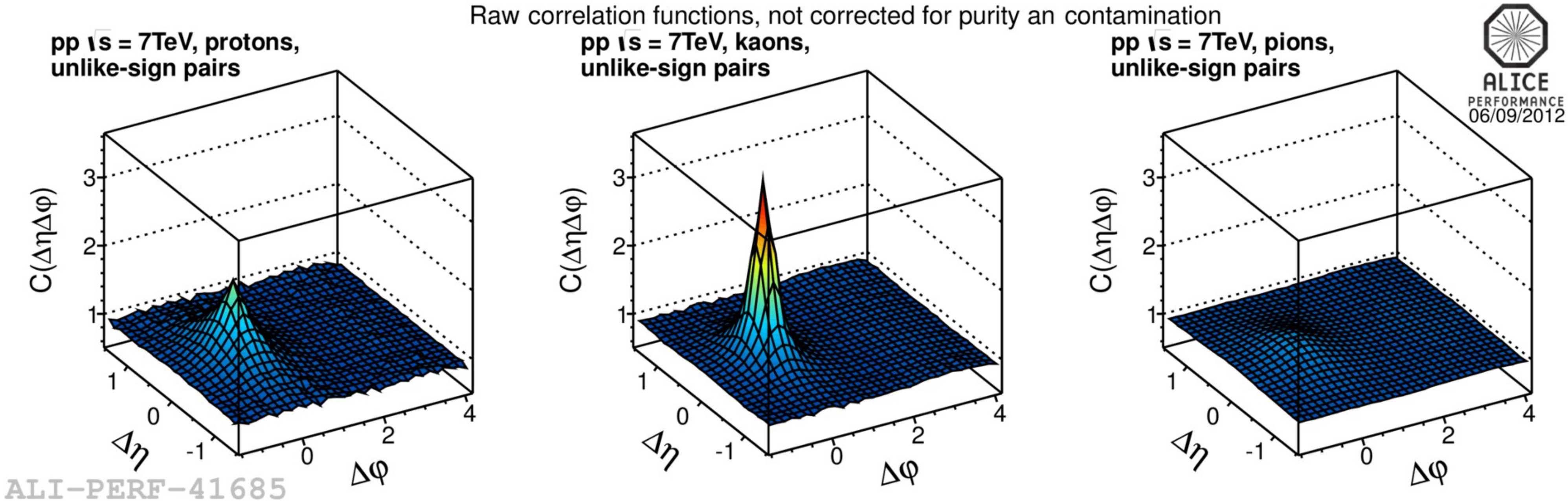
- While creating unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair. Such pairs produce the strong near-side peak in the identified correlations**.
- The **strength of the correlation** depends on the energetic **price of the alternative solution**. The larger the difference in prices between basic and alternative solutions, the stronger the correlation.
  - for **pions** the alternative solution is just another opposite-charge particle,
  - for **protons** another antibaryon (charged, or neutral plus additional charged particle),
  - for **kaons**, which carry the strange quark, the strangeness must be conserved, so the alternative solution would be at least a lambda together with another baryon.

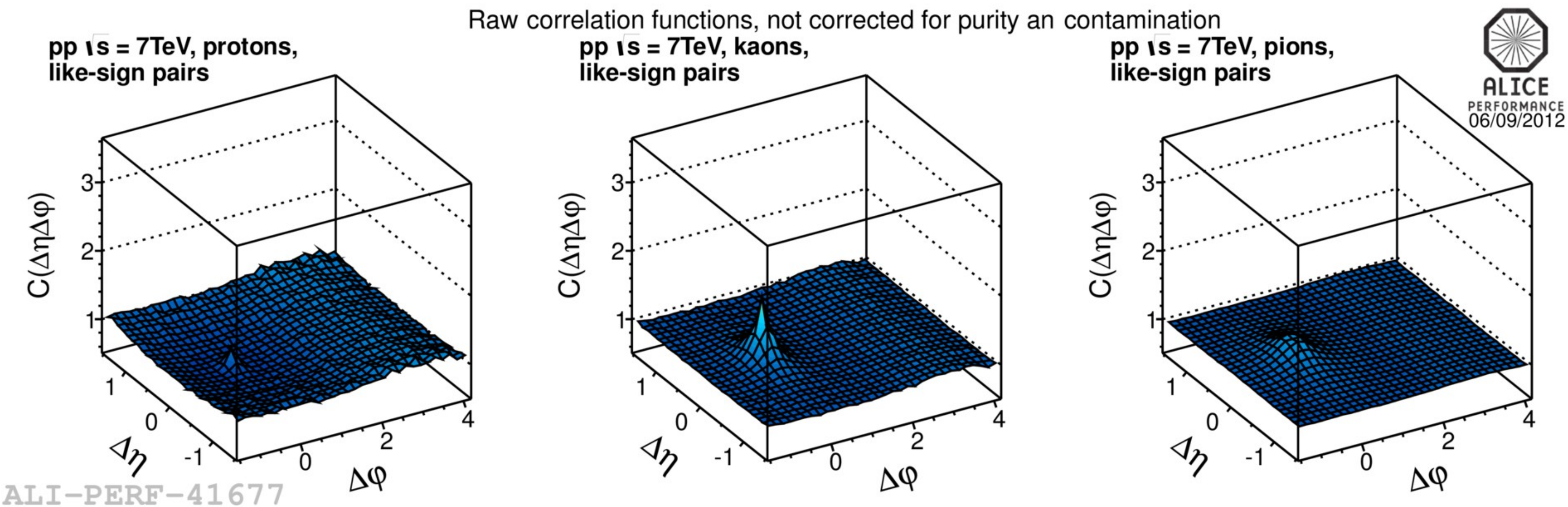
Like-sign pairs



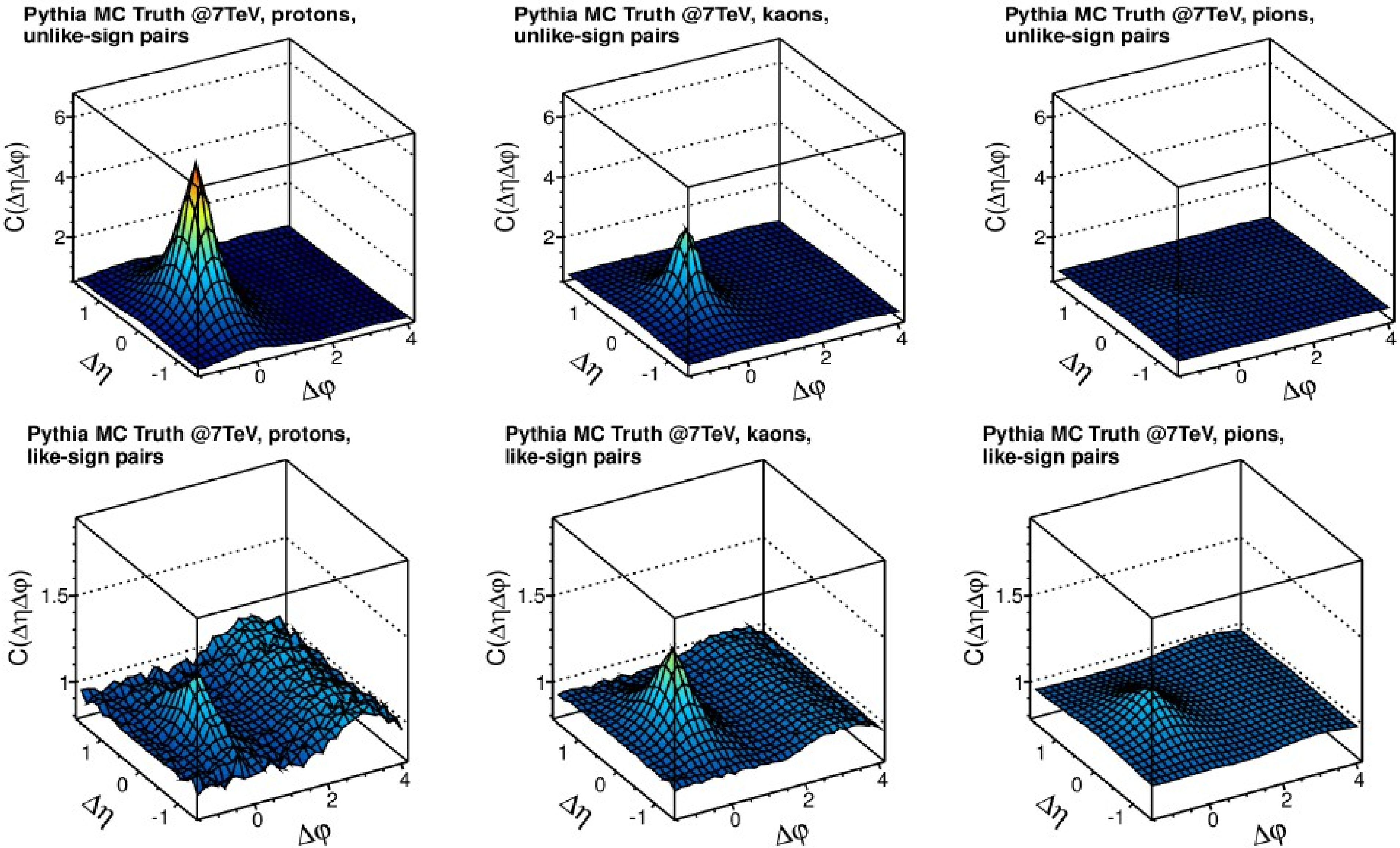
- For like-sign particles **producing two identical particles is not the cheapest** energetically like for particle – antiparticle case
- **Masses of the particles play significant role**
  - still for **kaons** and **pions** we can see the prominent near-side peak in the correlation function (due to the minijets, femtoscopic correlations, resonances)
  - for **protons** a large dip near the $(\Delta\eta, \Delta\varphi) = (0,0)$ is present: by producing two very heavy identical particles going in roughly the same direction we would have to produce also two baryons (two antiprotons), so another two heavy particles. The price of such solution is very high.

ΔηΔφ of identified particles





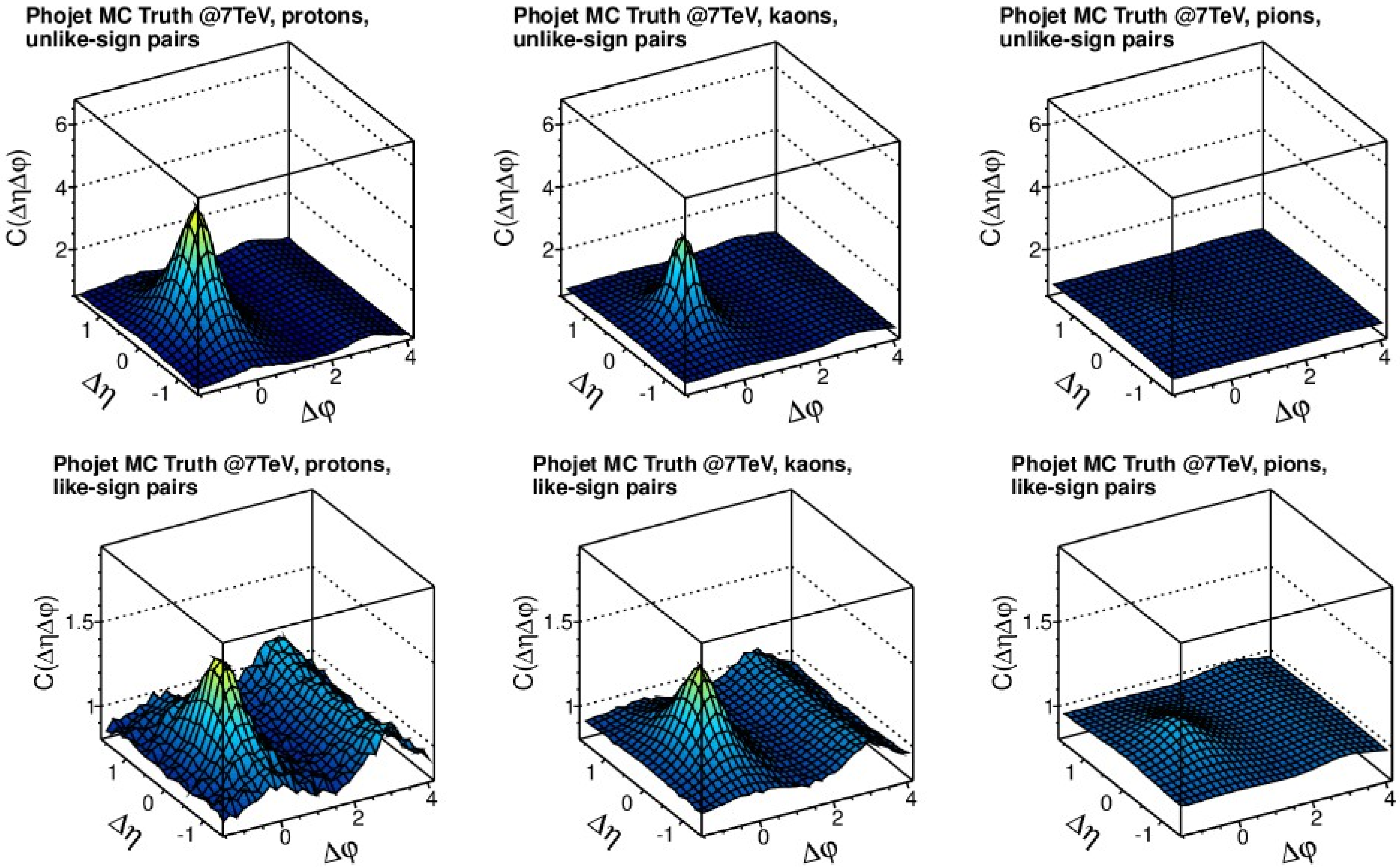
Pythia



Pythia **does not reproduce the shape** of the correlation function for identified particles. Suggests that local quantum number conservation processes are not modeled correctly.

Phojet

Monte Carlo Simulations



Phojet **does not reproduce the shape** of the correlation function for identified particles. Suggests that local quantum number conservation processes are not modeled correctly.

Summary

- **The analysis of pp data at 7 TeV over 5 multiplicity ranges and vs. pair charge combination was performed.**
- The results were quantified using fitting procedure.
- **The study of the correlation functions was performed for identified particles (pions, kaons, protons)**
- **Conservation laws seem to play a significant role determining the shape of $\Delta\eta\Delta\varphi$ correlation functions**

- **Monte Carlo models should be strongly constrained** (fragmentation)
  - conservation of all quantum numbers for each fragmentation separately
  - constrain on the way the conservation laws are taken into account

- Particularly interesting in future studies
  - quantitatively describe (fit) features seen in the data for identified particles

Backup

Data samples & analysis

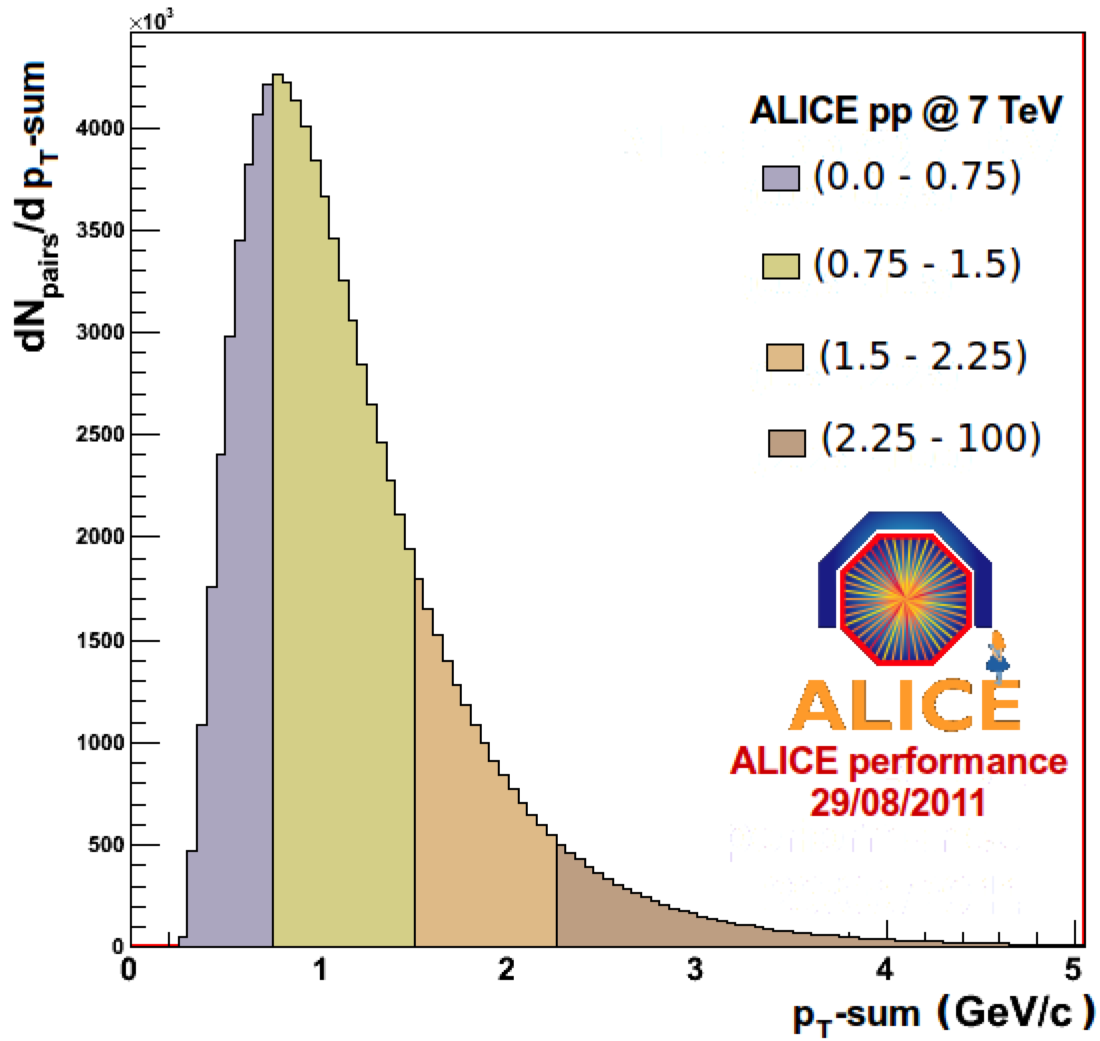
- **pp events at 7 TeV registered by ALICE in 2010 were used for the analysis:**
  - ~153M minimum bias events.
- **Corresponding analysis on Monte Carlo generators (Pythia, Phojet) was performed.**
- The analysis was performed on **primary particles** within the acceptance range of $|\eta|<1.0$ and transverse momentum range $p_T>0.12$ ***GeV/c*** which were reconstructed by the ALICE **Time Projection Chamber (TPC)** and **Inner Tracking System (ITS)** detectors.
- **Electron-positron pairs coming from gamma conversion were removed.**
- We observe a combination of undesired physics effects (gamma conversions), true physics correlations (Coulomb interaction) and detector effects (track splitting/merging) in the (0,0) bin. Their systematic study is under way.
- The systematics are not shown in the plots.

p_T-sum dependence cut

Since femtoscopic effects are strongest for small pair transverse momenta, we needed to develop a cut dependent on such observable.

We chose the sum of transverse momenta of both particles:

$$p_{Tsum} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$$



Bins of p_T-sum:

0.0 – 0.75 GeV/c

0.75 – 1.5 GeV/c

1.5 – 2.25 GeV/c

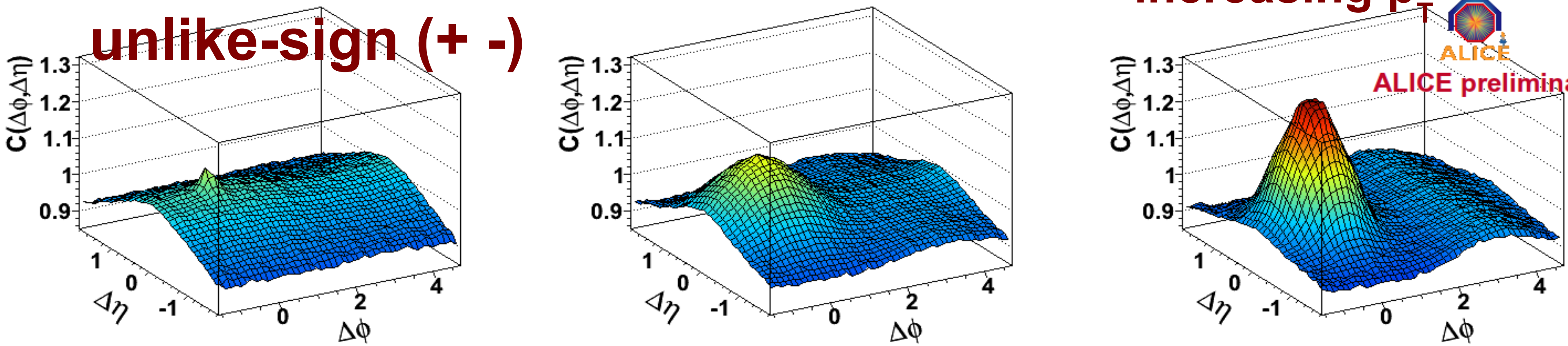
2.25 – 100 GeV/c

7 TeV, p_T-sum dependence

No Bose-Einstein correlations for unlike-sign pairs

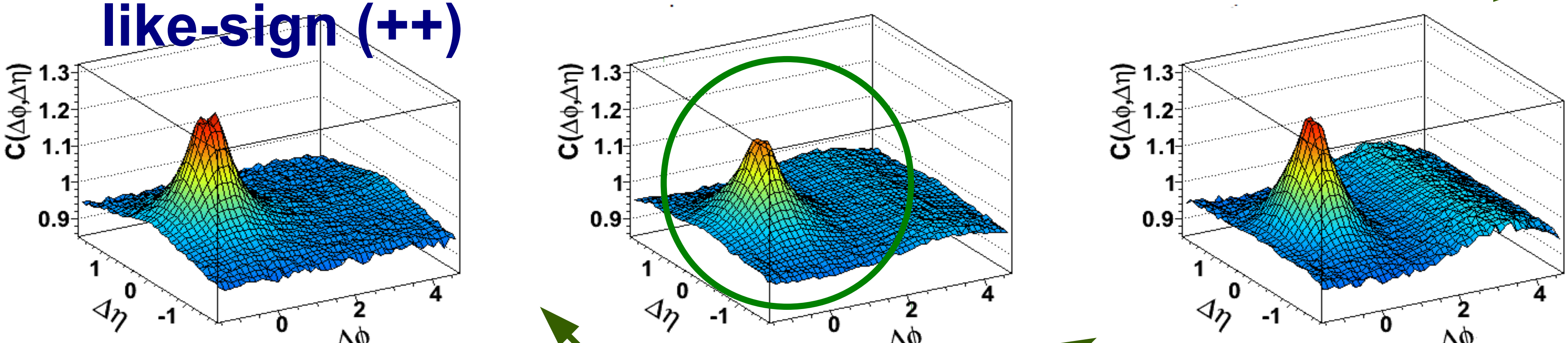
Correlations coming from "minijets" increase with increasing p_T

unlike-sign (+ -)



$0 < p_{Tsum} < 0.75\,(\mathrm{GeV}/c)$ $\quad 0.75 < p_{Tsum} < 1.5\,(\mathrm{GeV}/c)$ $\quad 1.5 < p_{Tsum} < 2.55\,(\mathrm{GeV}/c)$

like-sign (++)



Bose-Einstein correlations decrease with increasing p_T

smaller

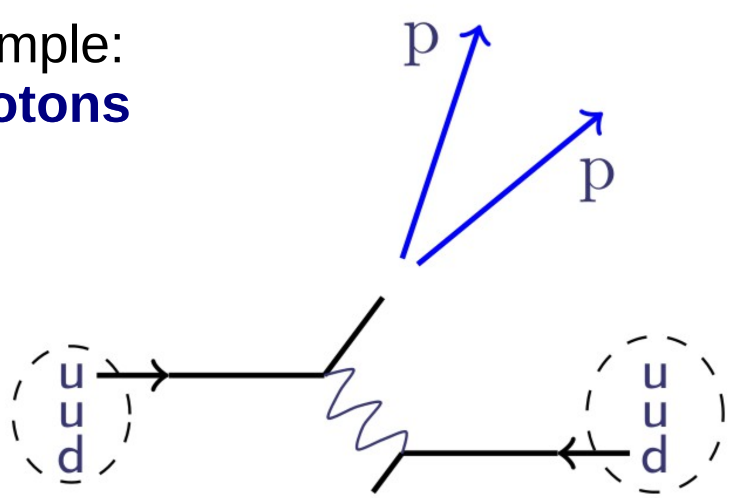
Correlations coming from "minijets" increase with increasing p_T also for like-sign pairs

$$p_{Tsum} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$$

Laws conserved globally

Each of the conservation laws must be obeyed **in the whole event.**

Example:
protons



- momentum
- charge

  $q = e + e$
- strangeness

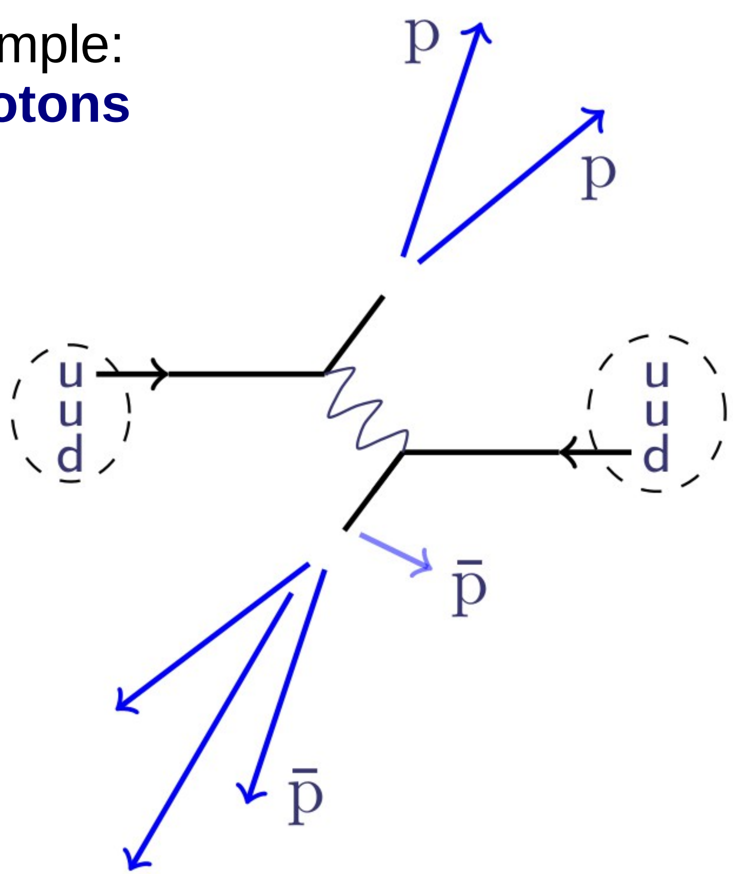
  $S = 0$
- baryon number

  $B = 1 + 1$

Laws conserved globally

Each of the conservation laws must be obeyed **in the whole event.**

Example:
protons



- momentum
- charge

  $q = e + e - e - e = 0$
- strangeness

  $S = 0$
- baryon number

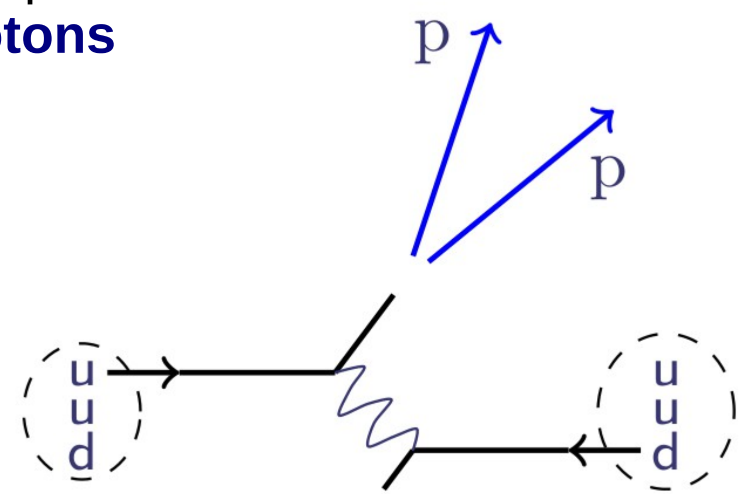
  $B = 1 + 1 - 1 - 1 = 0$

Laws conserved locally

Each of the conservation laws must be obeyed **for each fragmentation separately:**

- For each minijet charge, strangeness and baryon number must be conserved
- Momentum of the minijet has to be balanced with the momenta of the particles going in the opposite direction.

Example:
protons



- charge

  $q = e + e$

- strangeness

  $S = 0$

- baryon number

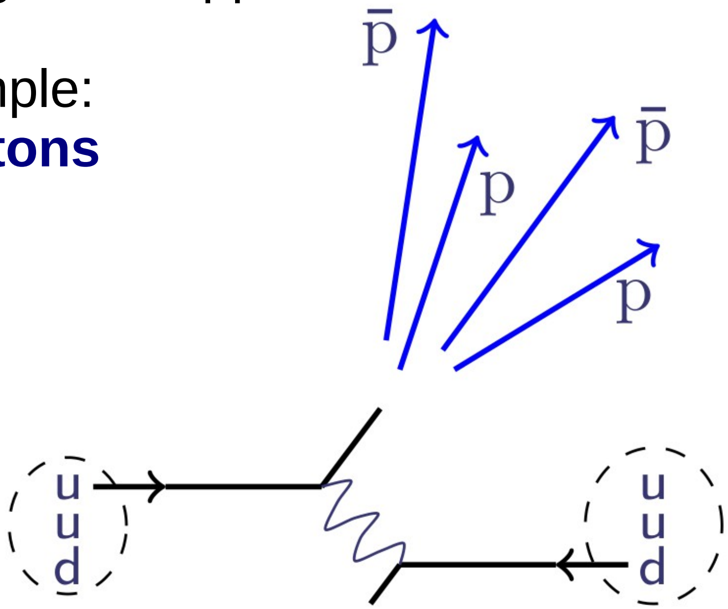
  $B = 1 + 1$

Laws conserved locally

Each of the conservation laws must be obeyed **for each fragmentation separately:**

- For each minijet charge, strangeness and baryon number must be conserved
- Momentum of the minijet has to be balanced with the momenta of the particles going in the opposite direction.

Example:
protons



- charge

  $q = e + e - e - e = 0$
- strangeness

  $S = 0$
- baryon number

  $B = 1 + 1 - 1 - 1 = 0$

Laws conserved locally

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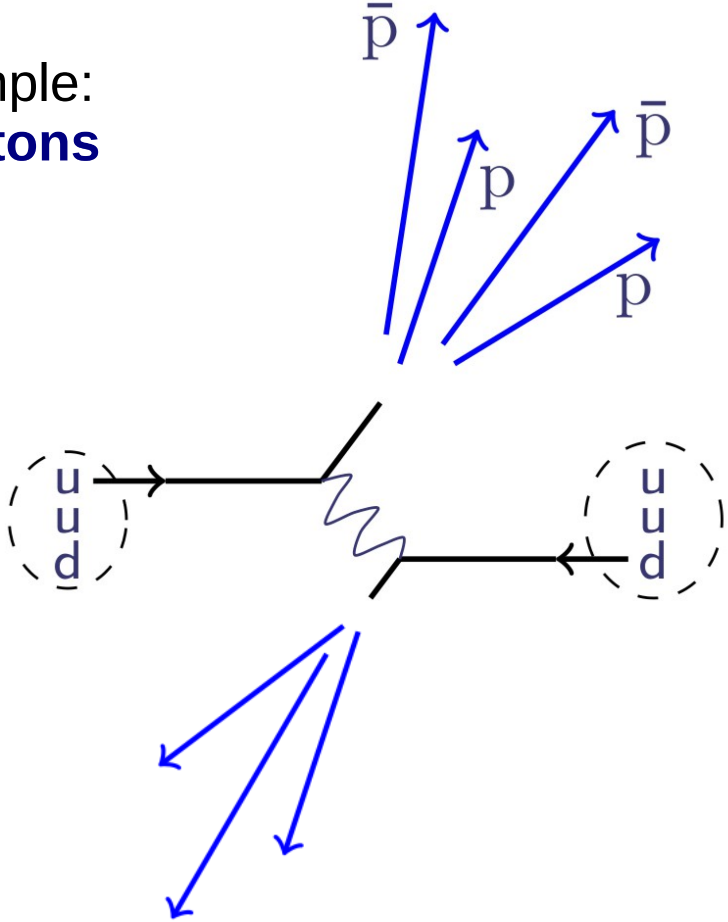


- charge

  $q = e + e - e - e = 0$
- strangeness

  $S = 0$
- baryon number

  $B = 1 + 1 - 1 - 1 = 0$
- momentum

pp 7 TeV

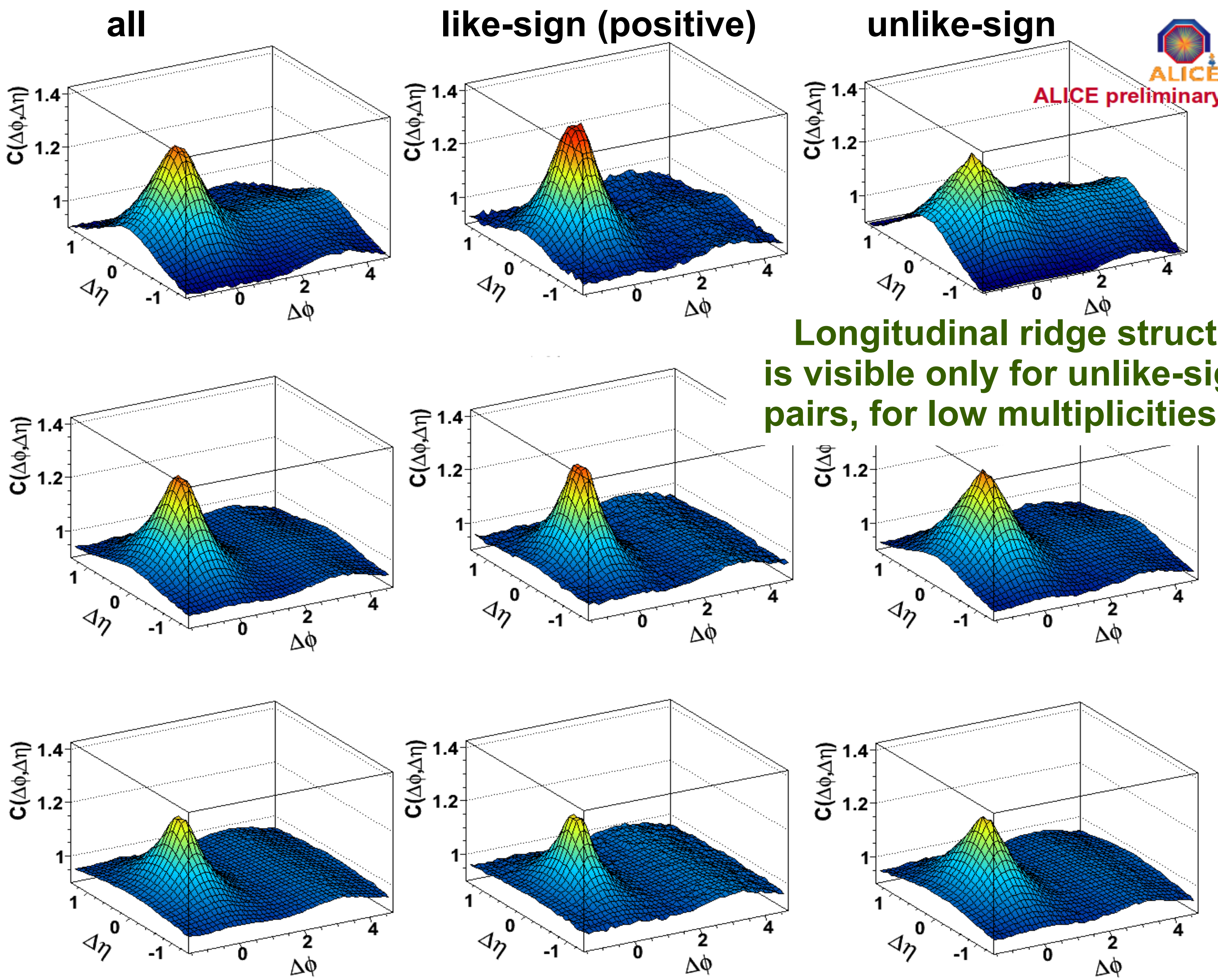
Multiplicity dependence

increasing multiplicity

$N_{ch}<12$

$17 \leq N_{ch} \leq 22$

$42 \leq N_{ch} \leq 51$



Longitudinal ridge structure is visible only for unlike-sign pairs, for low multiplicities

Decreasing correlation (per pair) with rising multiplicity

Pythia 7 TeV Multiplicity dependence

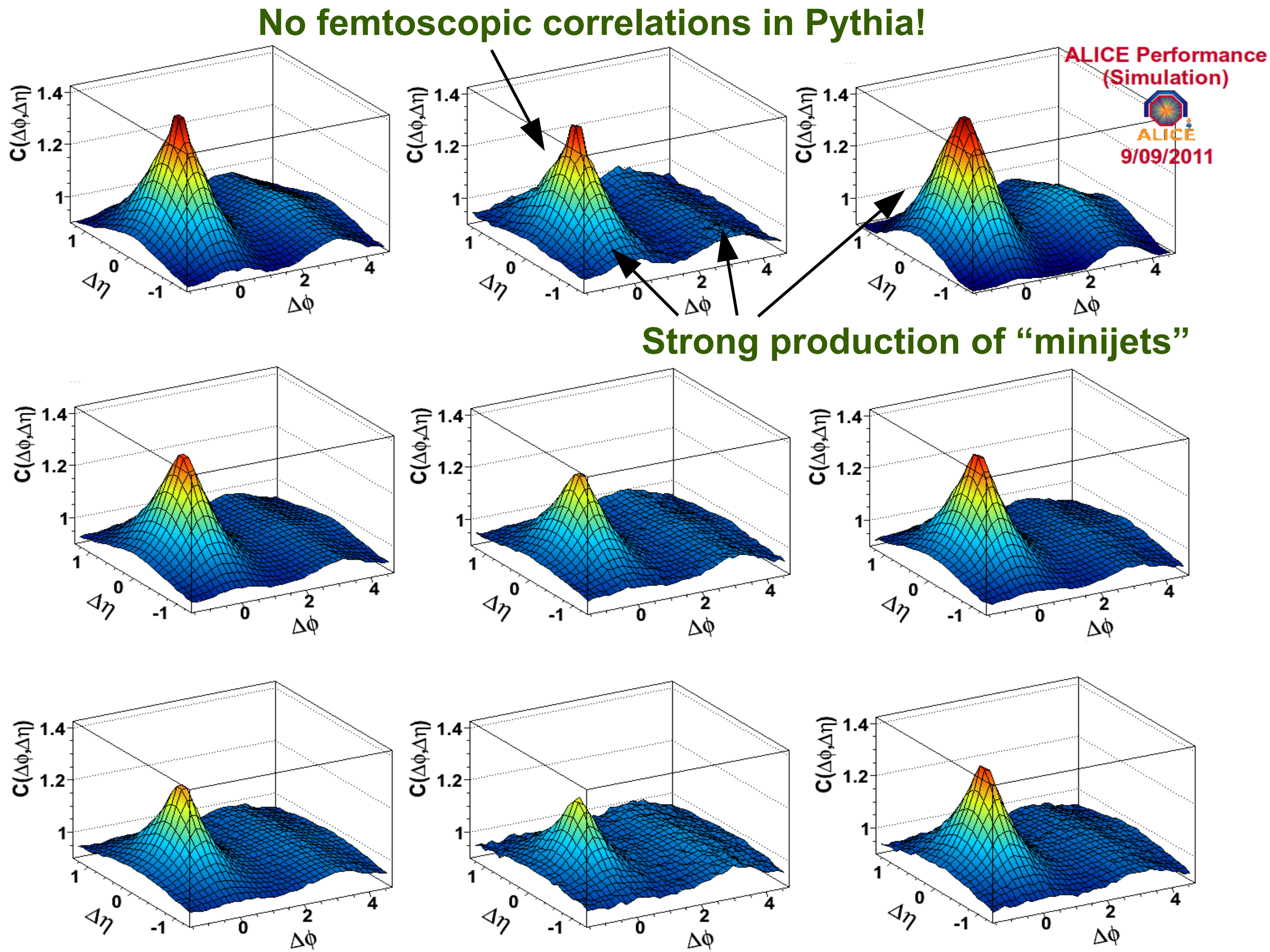
all | like-sign (positive) | unlike-sign

increasing multiplicity

$N_{ch}<12$

$17 \leq N_{ch} \leq 22$

$42 \leq N_{ch} \leq 51$

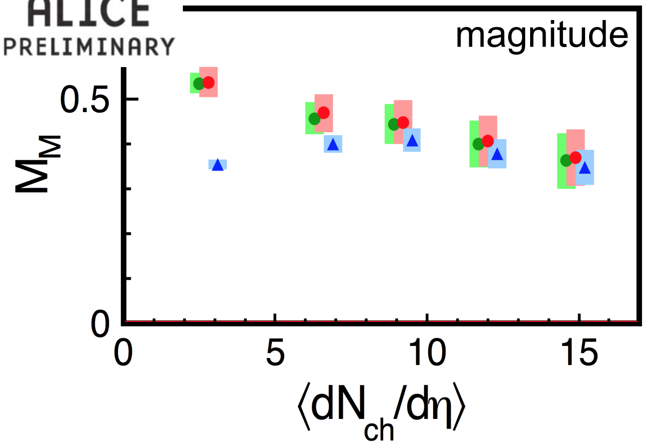


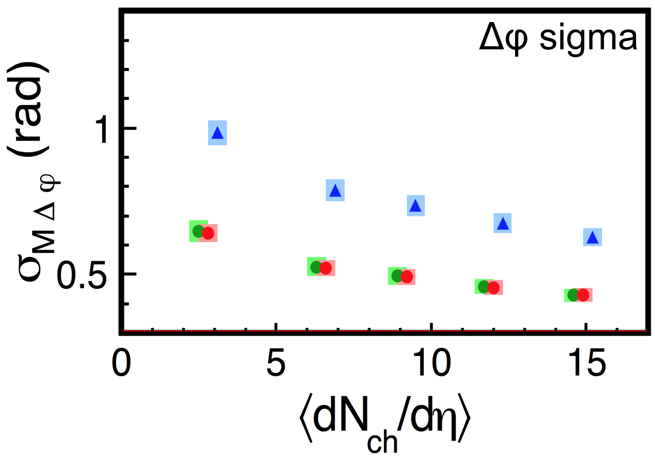
Decreasing correlation (per pair) with rising multiplicity

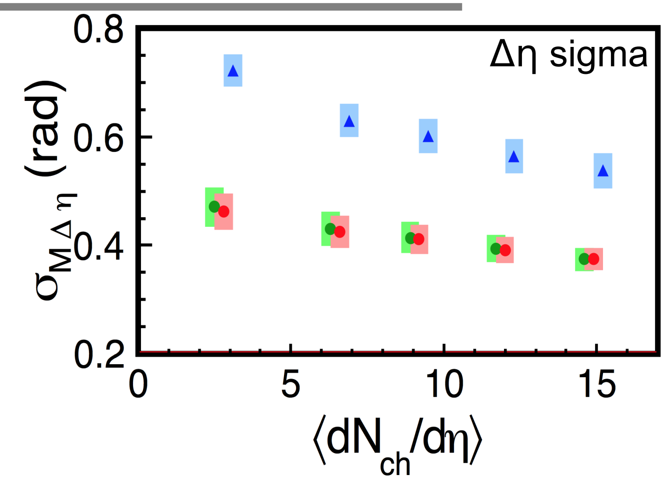
Near-side peak

Positive / Negative / Unlike-sign

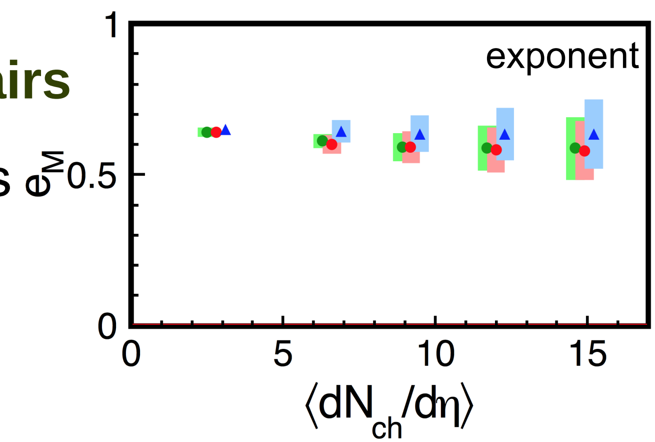
ALICE PRELIMINARY

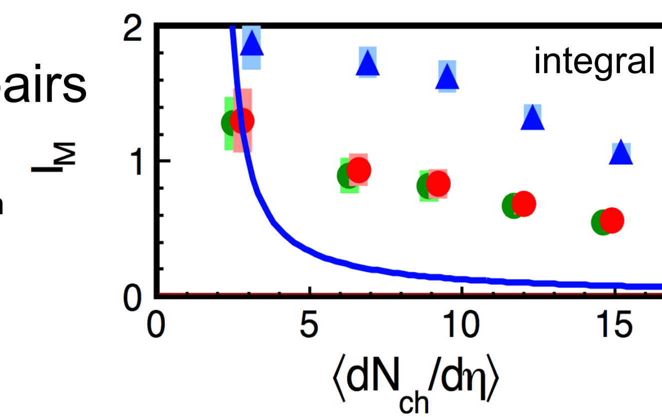




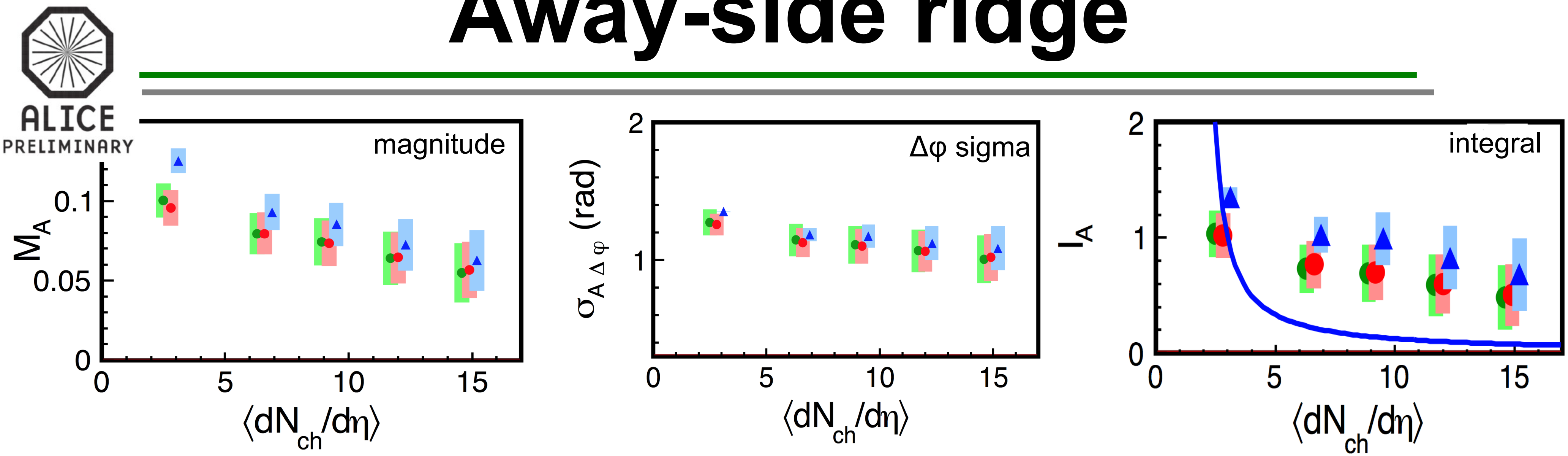


- **Width of the near-side peak bigger for unlike-sign pairs**
- Minijets produce stronger correlation for unlike-sign pairs – **local charge conservation**
- Also other correlation sources play significant role:
  - **Resonances** more prominent for unlike-sign pairs
  - **Femtoscopic correlations** exist only for like-sign pairs
- Correlations decrease with multiplicity slower than $1/N_{ch}$ – **do not follow trivial dilution 1/N**





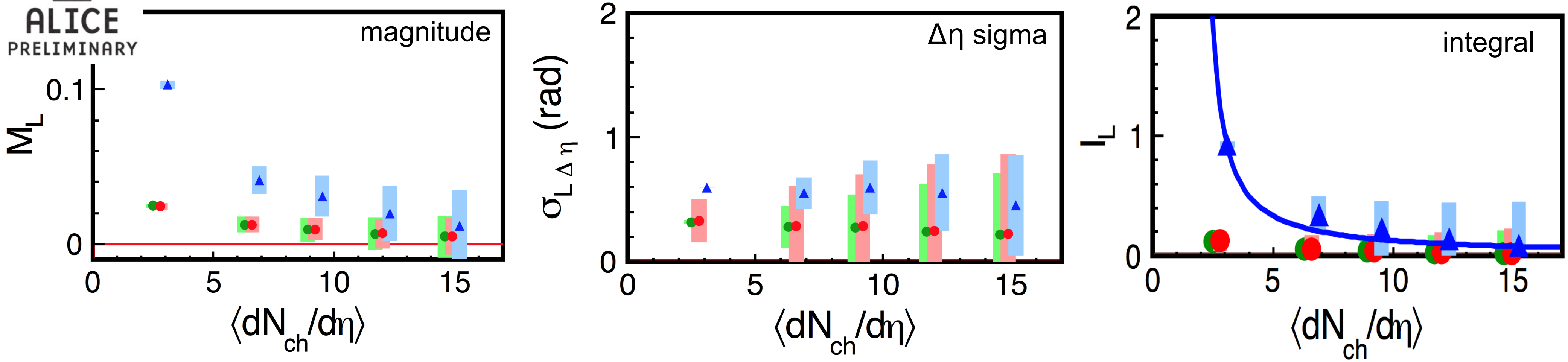
Away-side ridge



Positive / Negative / Unlike-sign

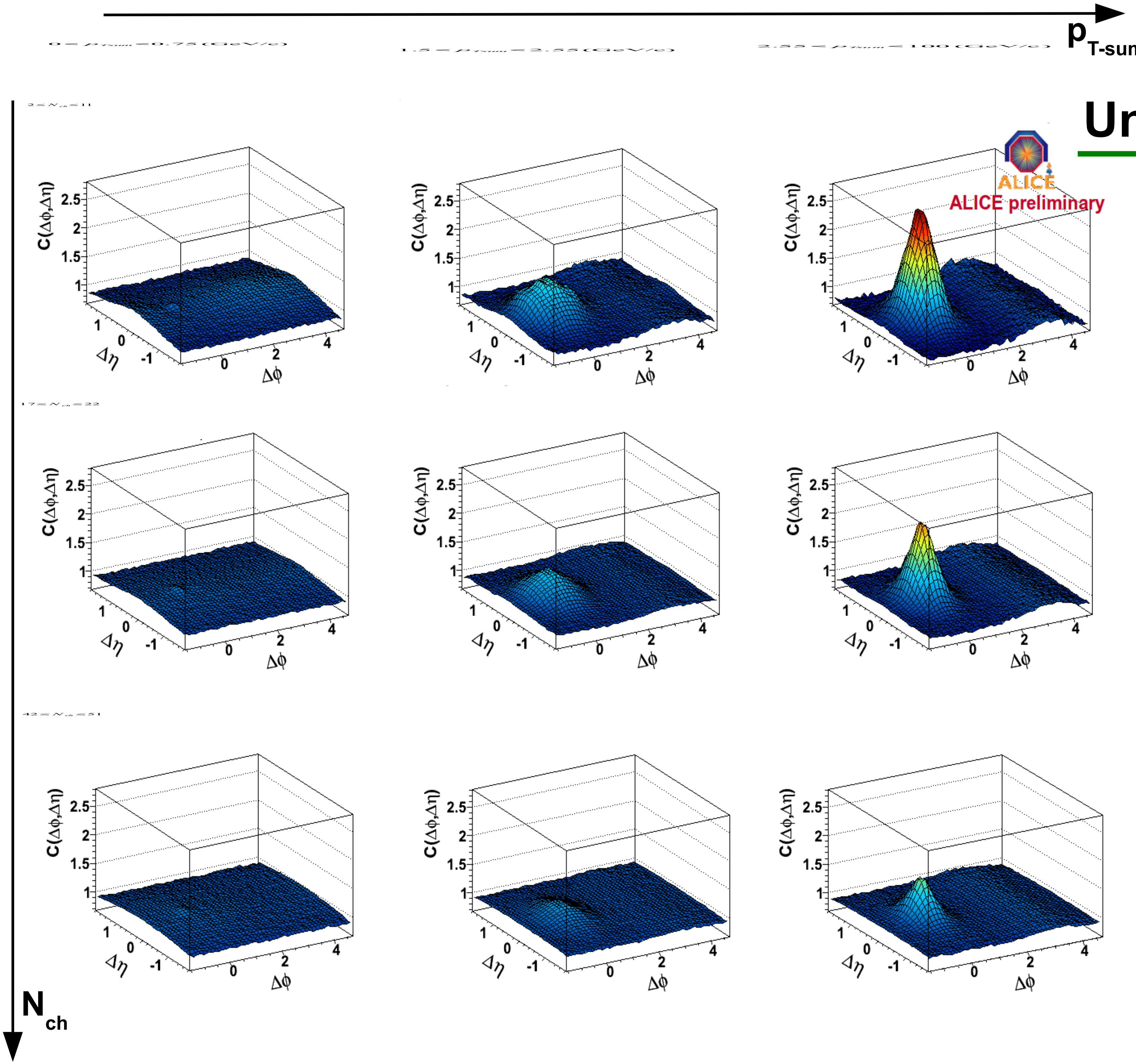
- **Away-side width and magnitude comparable**
- Minijets effect on away-side similar between same-sign and opposite sign
  - **Suggests that the differences in the near-side come from other correlation sources: resonances, conservation laws and/or femtoscopy**
- Femtoscopic correlations and resonances do not contribute to the away-side
- Correlations of the away-side do not follow trivial scaling 1/N

Longitudinal ridge



Positive / Negative / Unlike-sign

- **Longitudinal ridge present only for unlike-signs**
- Prominent for low multiplicities – but **follow 1/N scaling**
- Visible only at low transverse momenta
- The structure has been explained so far by other experiments by
  - Low-mass resonances
  - Decay of clusters with low p_T
  - Local charge conservation in longitudinally fragmenting strings

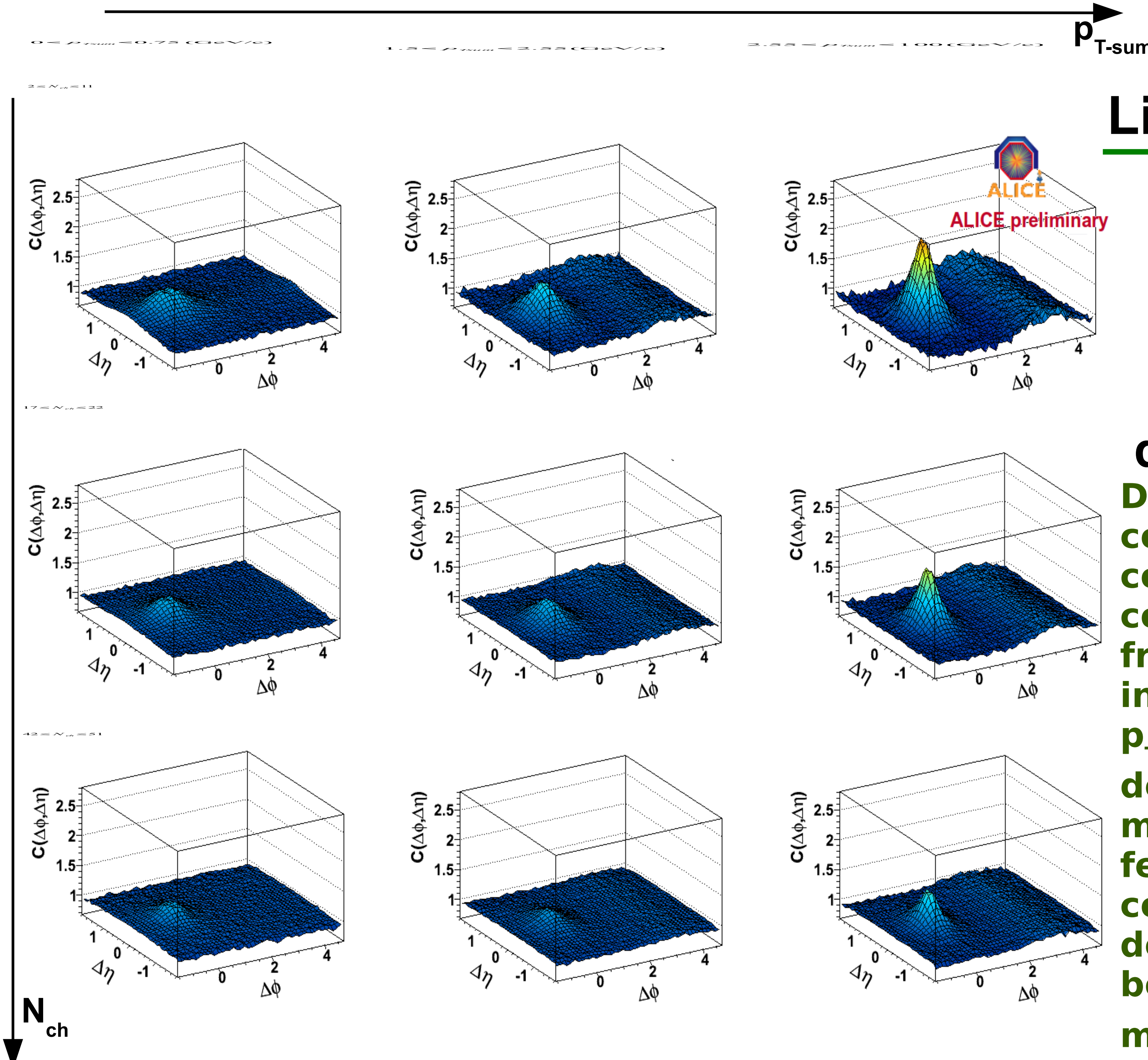


pp @ 7 TeV

Unlike-sign pairs

p_T-sum & multiplicity dependence

Correlations increase with p_T-sum and decrease with multiplicity, consistent with "minijets"



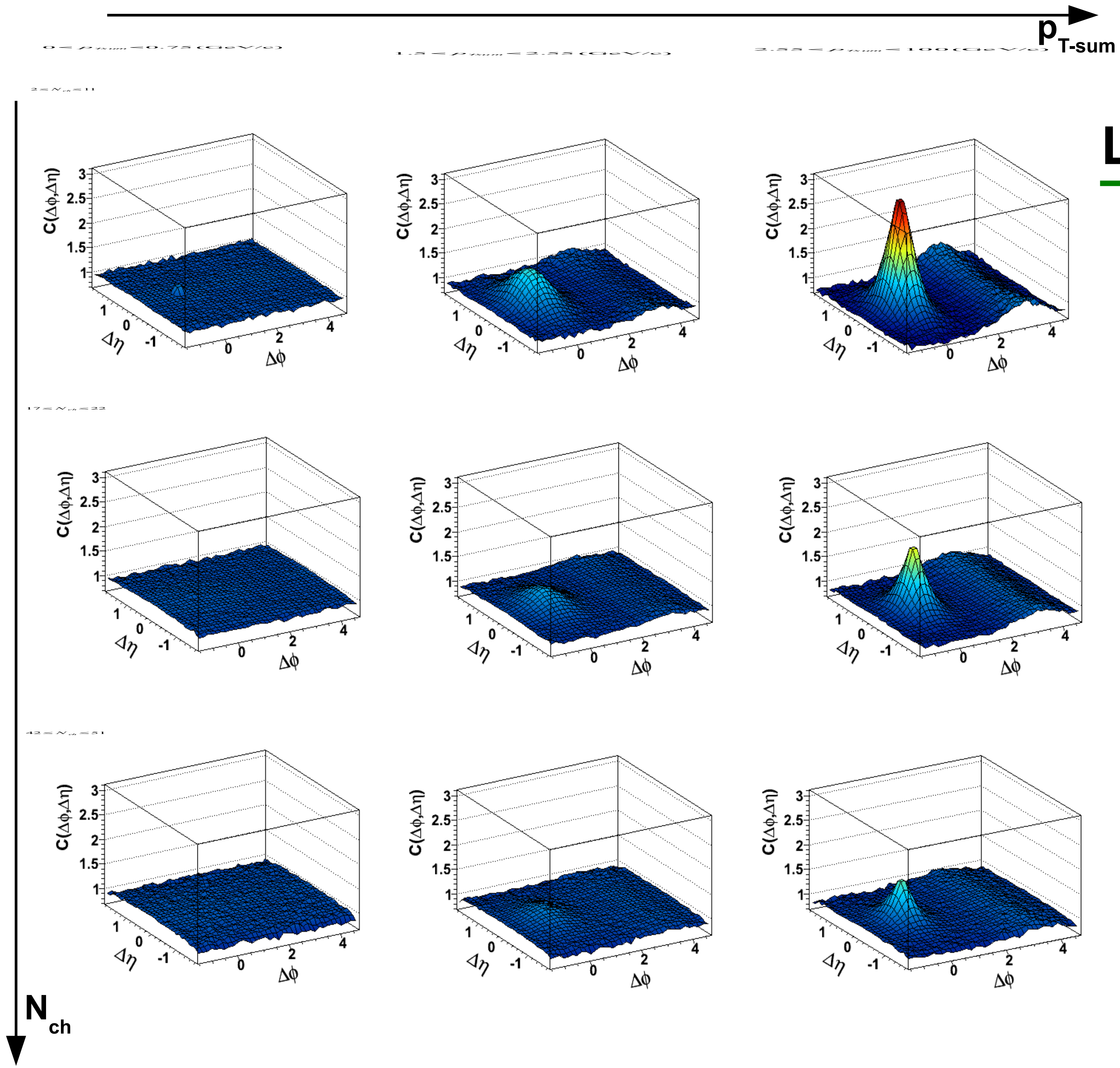
pp @ 7 TeV

Like-sign pairs

(positive)

p_T-sum & multiplicity dependence

Dependence consistent with combination of correlations coming from "minijets" increasing with p_T-sum and decreasing with multiplicity plus femtoscopic correlations decreasing with both p_T-sum and multiplicity.



Pythia Perugia-0

pp @ 7 TeV

Like-sign pairs

(positive)

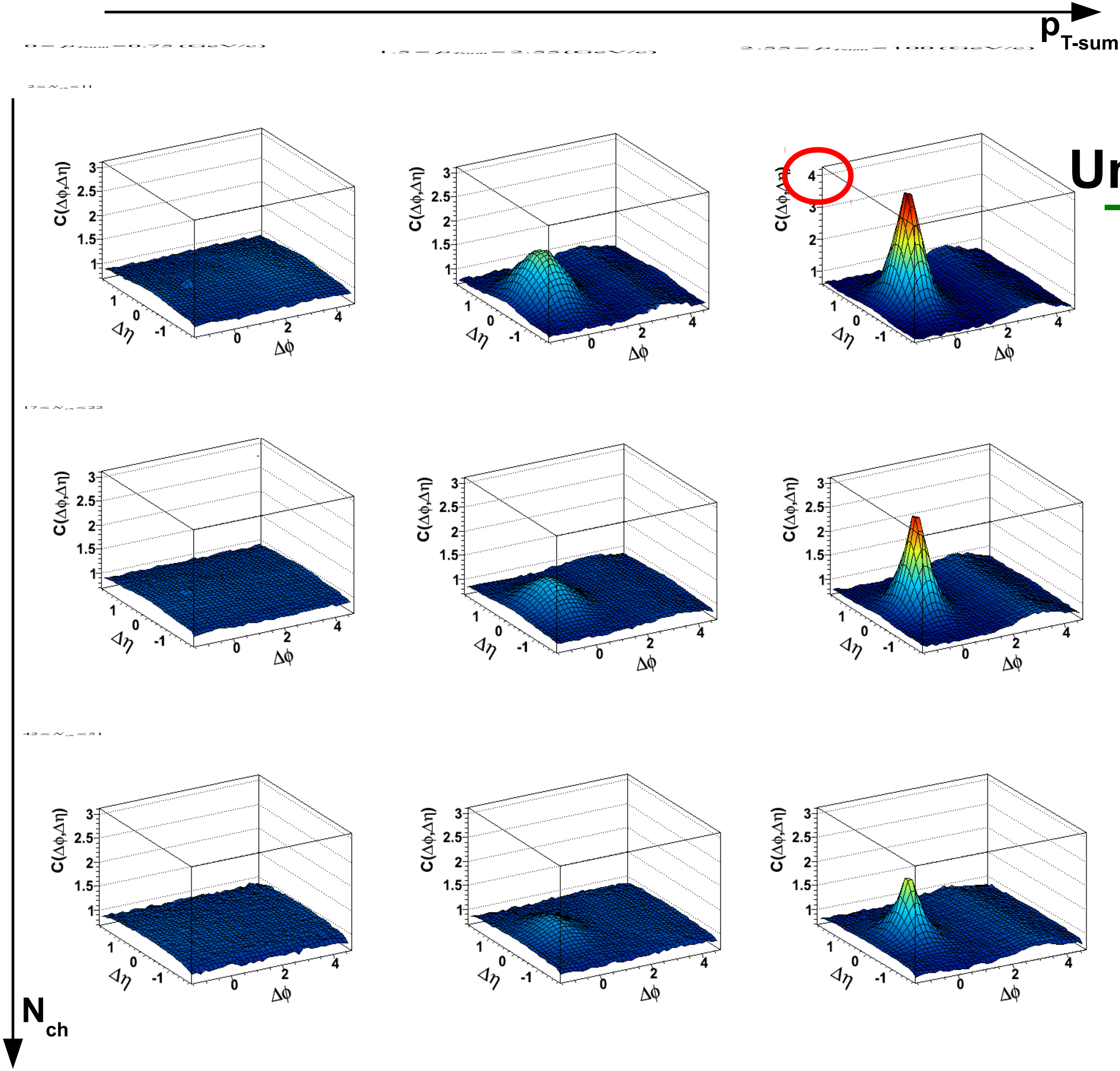
p_T-sum & multiplicity dependence

Correlations coming from "minijets" increase with p_T-sum and decrease with multiplicity.

No femtoscopic correlations for Pythia!

Pythia Perugia-0 pp @ 7 TeV

Unlike-sign pairs



p_T-sum & multiplicity dependence

Correlations coming from "minijets" increase with p_T-sum and decrease with multiplicity. Stronger for unlike-sign.

No femtoscopic correlations for Pythia!