Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Summary of recent developments in di-hadron correlations of identified particles (experiment & theory)

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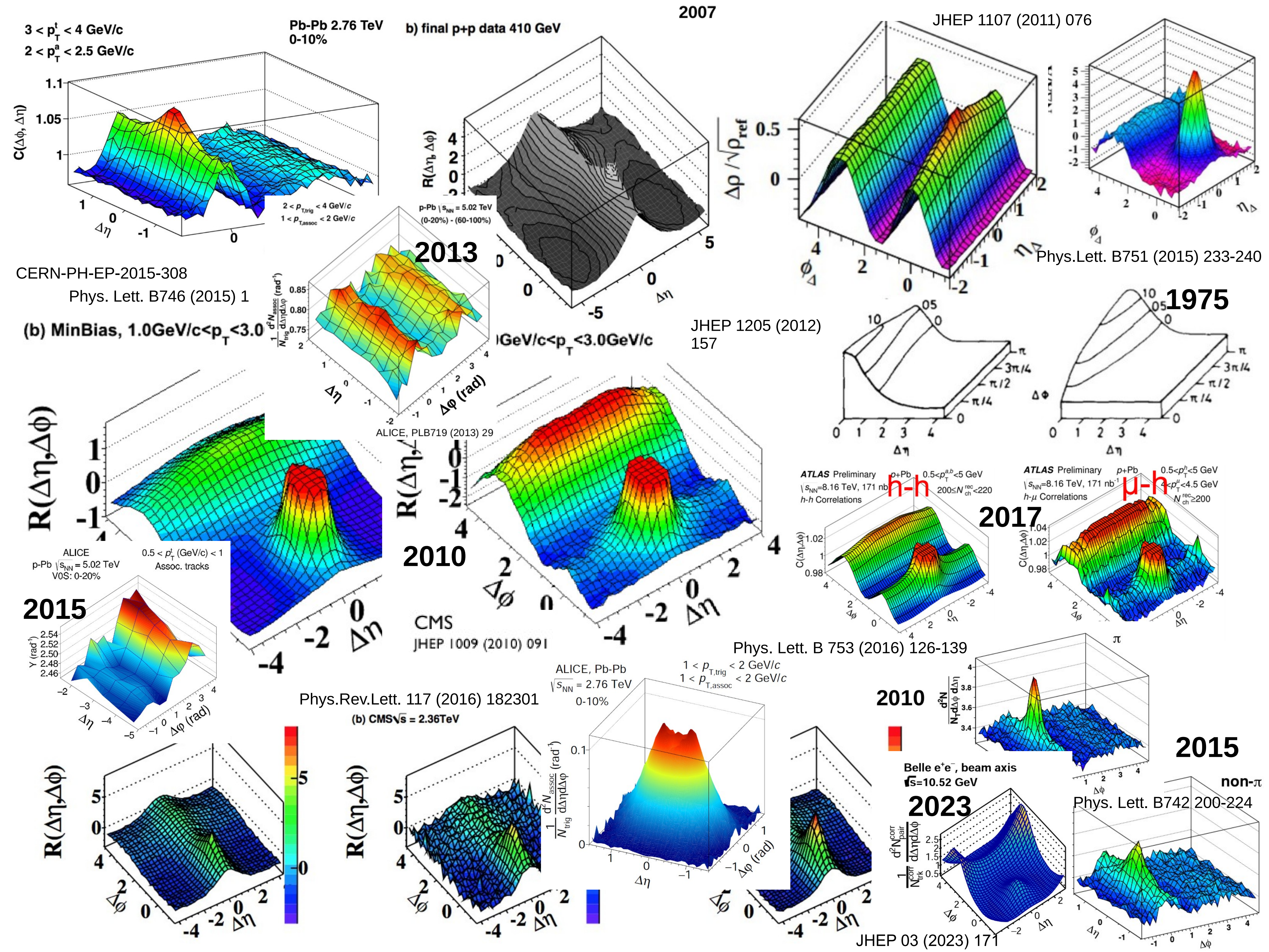
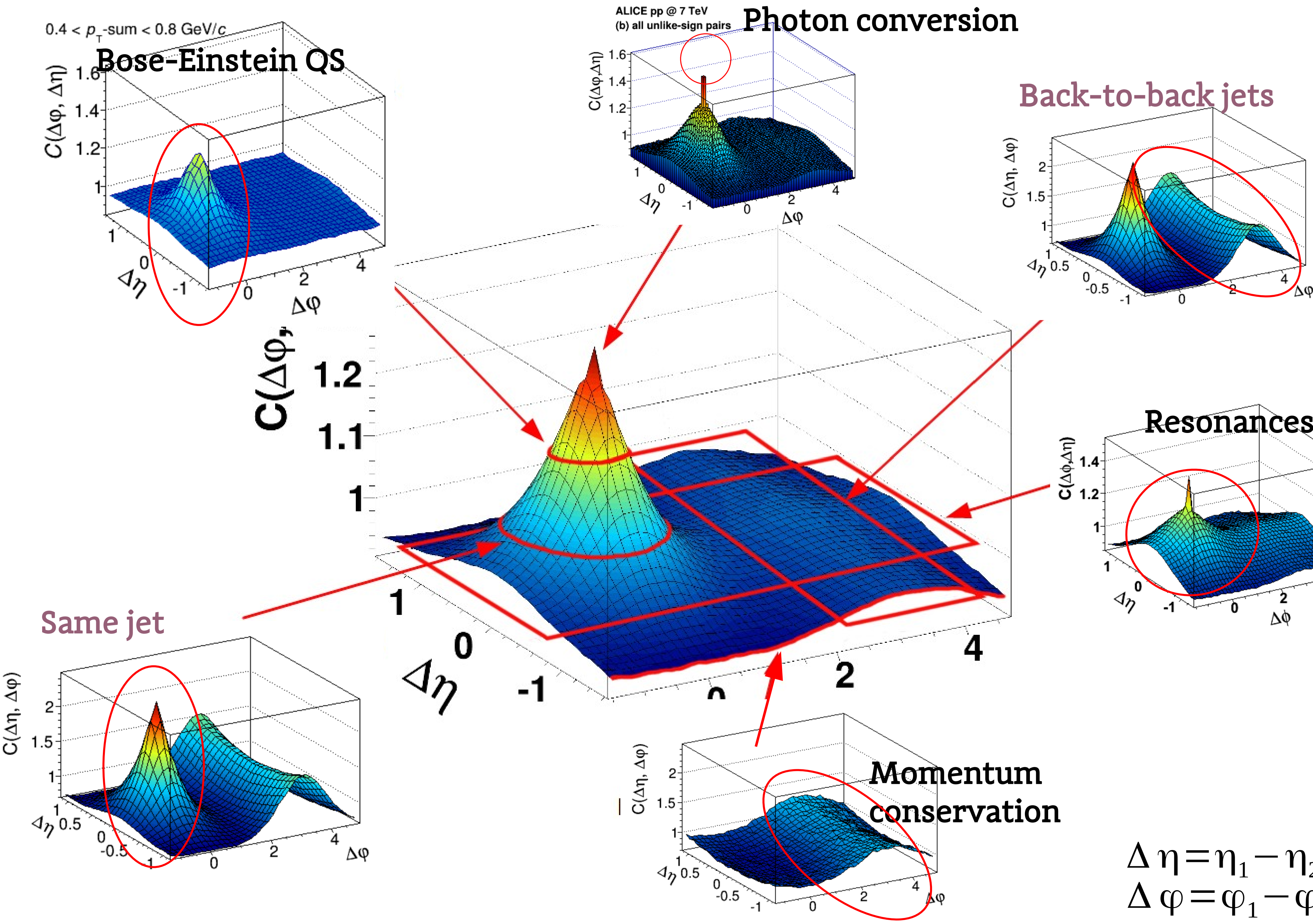
in collaboration with
Małgorzata Janik

52nd International Symposium on Multiparticle Dynamics
Gyöngyös, Hungary
22 August 2023

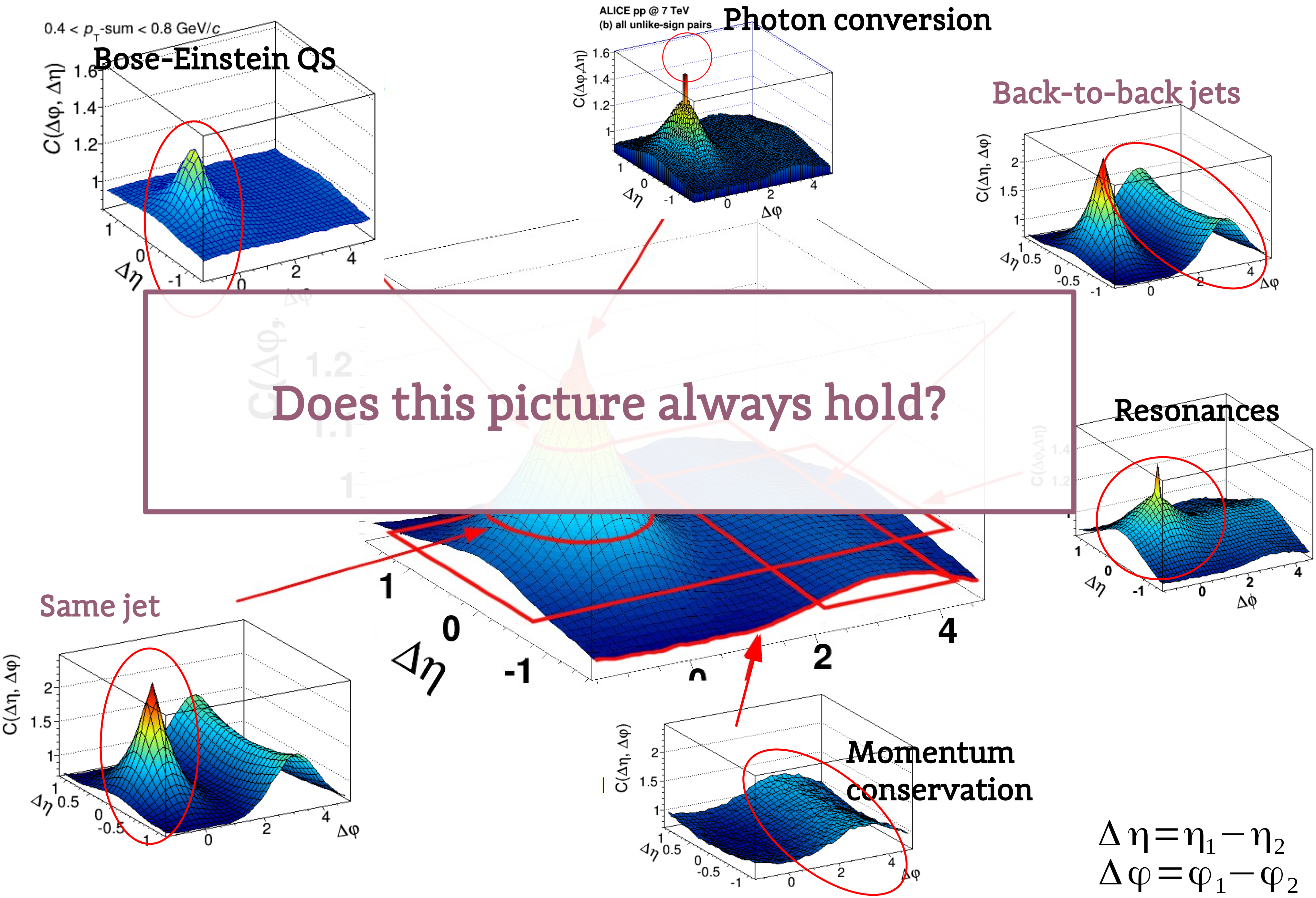
NATIONAL SCIENCE CENTRE POLAND



2007
JHEP 1107 (2011) 076
3 < p_T^t < 4 GeV/c
2 < p_T^a < 2.5 GeV/c
Pb-Pb 2.76 TeV
0-10%
b) final p+p data 410 GeV
C(Δφ, Δη)
R(Δη, Δφ)
Δρ / √ρ_ref
2 < p_T,trig < 4 GeV/c
1 < p_T,assoc < 2 GeV/c
p-Pb √s_NN = 5.02 TeV
(0-20%) - (60-100%)
2013
CERN-PH-EP-2015-308
Phys. Lett. B746 (2015) 1
Phys.Lett. B751 (2015) 233-240
1975
JHEP 1205 (2012)
157
(b) MinBias, 1.0GeV/c<p_T<3.0
GeV/c<p_T<3.0GeV/c
ALICE, PLB719 (2013) 29
Δη
Δφ (rad)
ATLAS Preliminary
p+Pb
√s_NN=8.16 TeV, 171 nb⁻¹
h-h Correlations
h-h
h-μ Correlations
μ-h
2017
2010
ALICE
p-Pb √s_NN = 5.02 TeV
V0S: 0-20%
0.5 < p_T^t (GeV/c) < 1
Assoc. tracks
2015
CMS
JHEP 1009 (2010) 091
Phys. Lett. B 753 (2016) 126-139
ALICE, Pb-Pb
√s_NN = 2.76 TeV
0-10%
1 < p_T,trig < 2 GeV/c
1 < p_T,assoc < 2 GeV/c
Phys.Rev.Lett. 117 (2016) 182301
(b) CMS√s = 2.36TeV
2010
2015
Belle e⁺e⁻, beam axis
√s=10.52 GeV
2023
non-π
Phys. Lett. B742 200-224
JHEP 03 (2023) 171



$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

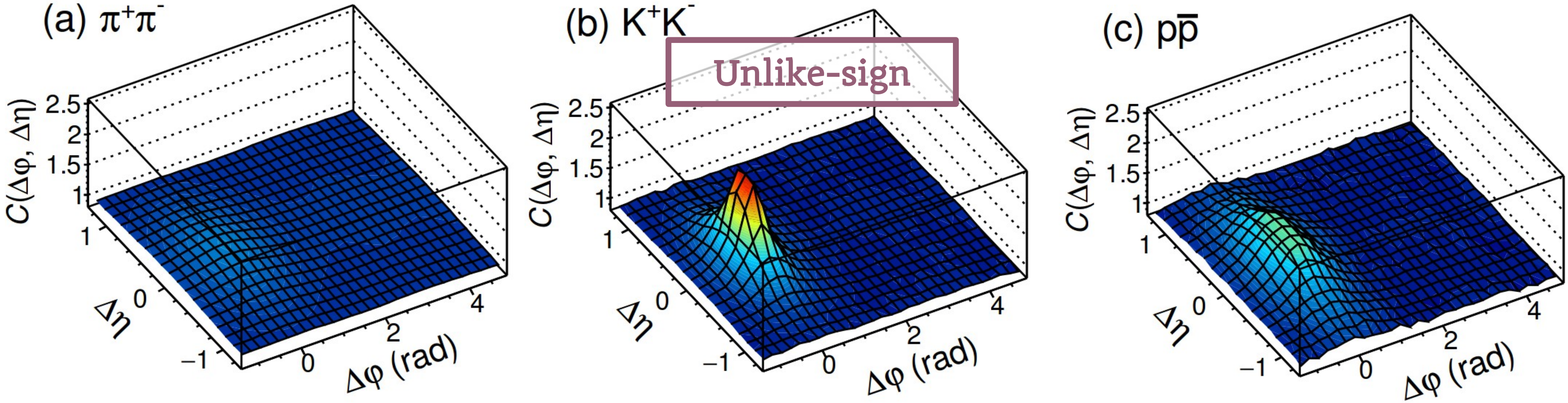


Does this picture always hold?

$\Delta\eta = \eta_1 - \eta_2$
$\Delta\varphi = \varphi_1 - \varphi_2$

ALICE 7 TeV pp data – identified particles

ALICE, Eur. Phys. J. C 77 (2017) 569, Ph.D. thesis of M. Janik https://cds.cern.ch/record/2093543

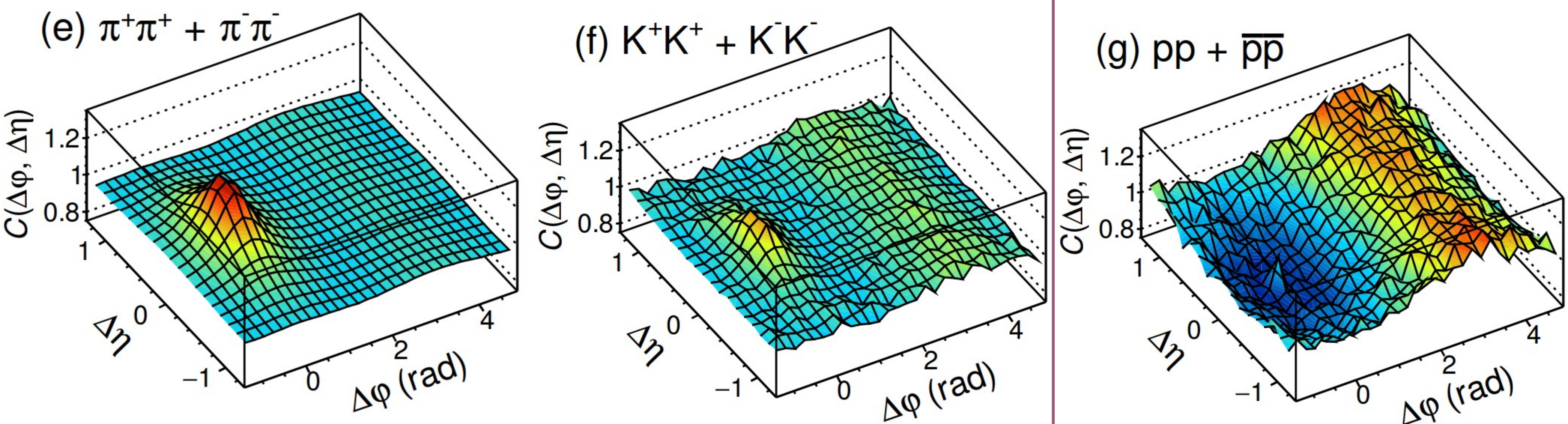


Unlike-sign

ALICE pp @ 7TeV

Like-sign

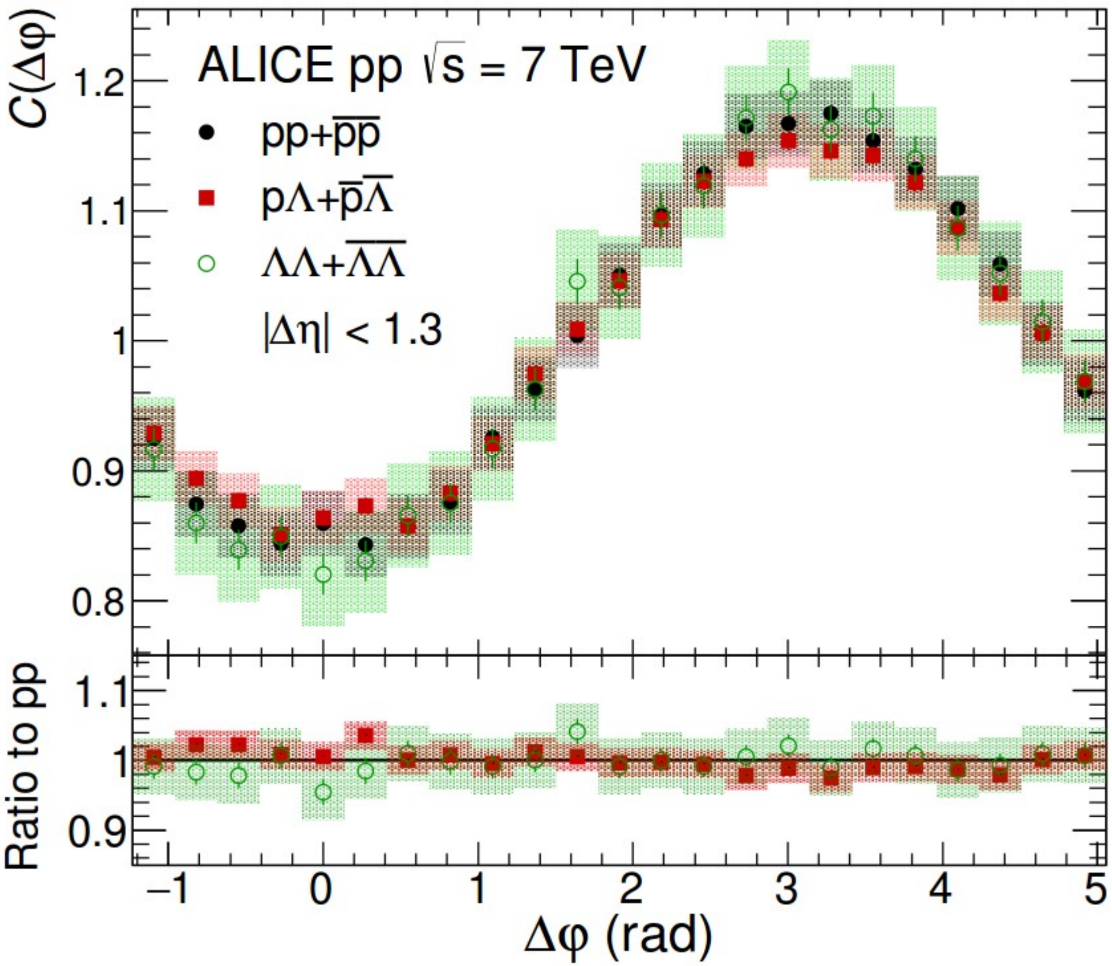
This one looks different!



ΛΛ and pΛ correlation functions

ALICE, Eur. Phys. J. C 77 (2017) 569

- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?
- Correlation functions were calculated for **ΛΛ and** pΛ pairs
- Λ baryons are neutral → no Coulomb repulsion
- p and Λ are not identical → no effect from Fermi-Dirac statistics
- **All observations from pp can be extended to ΛΛ and pΛ**



ALICE, Eur. Phys. J. C 77 (2017) 569

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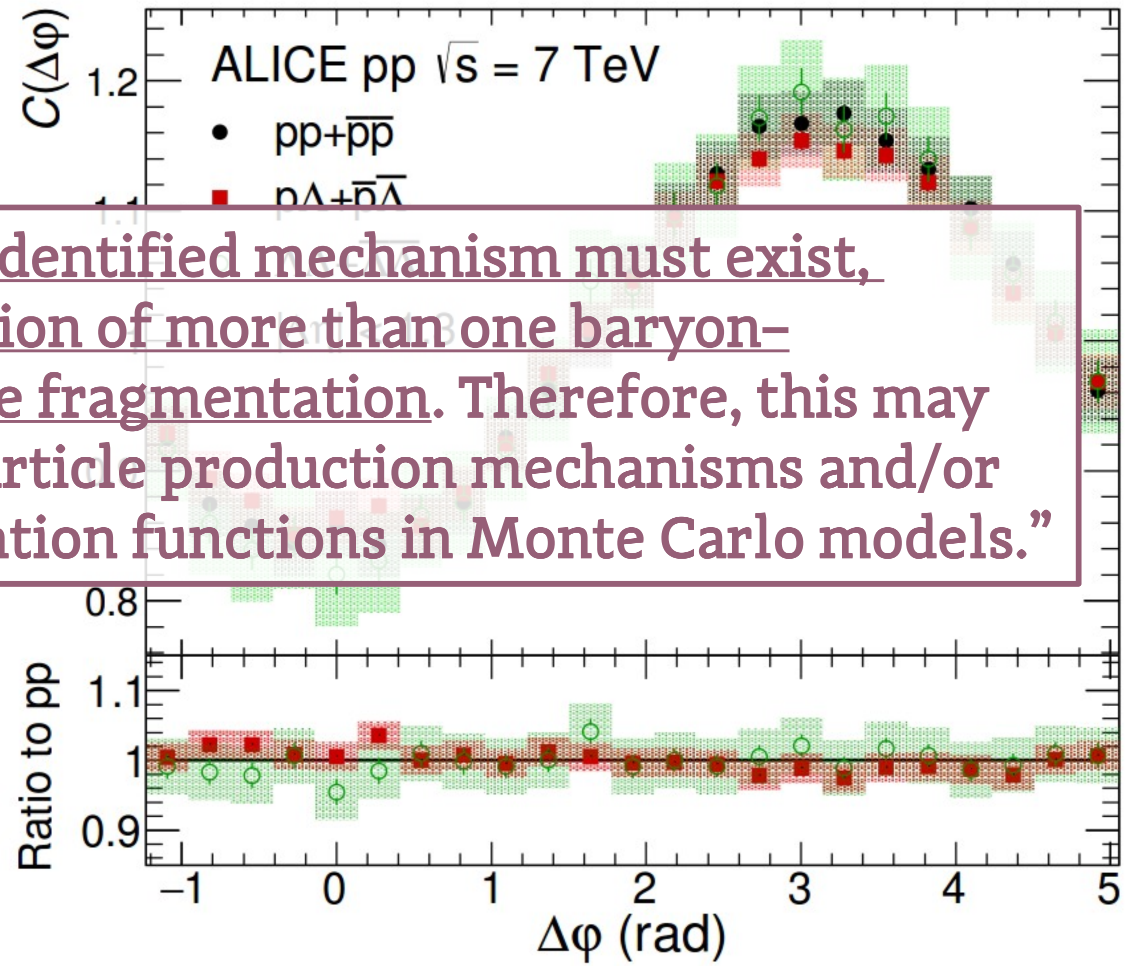
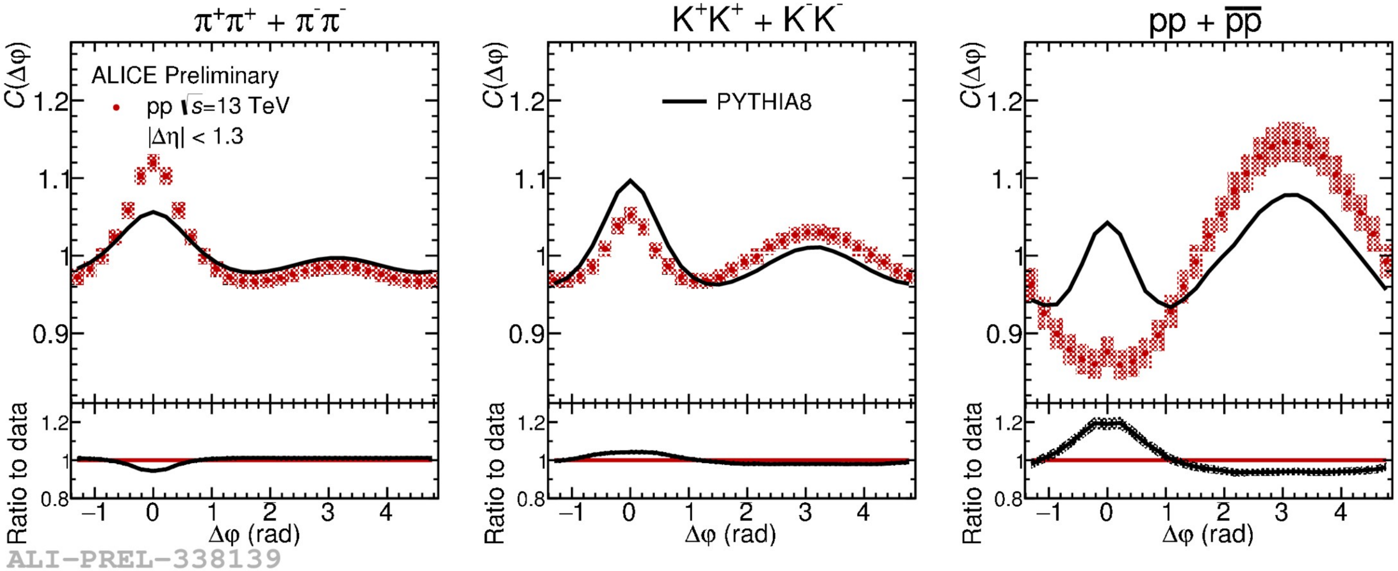
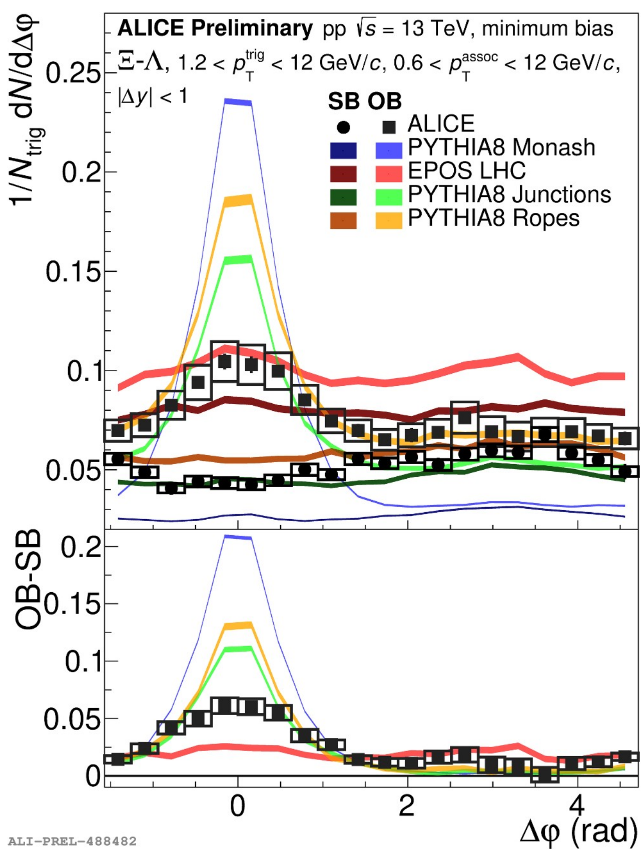


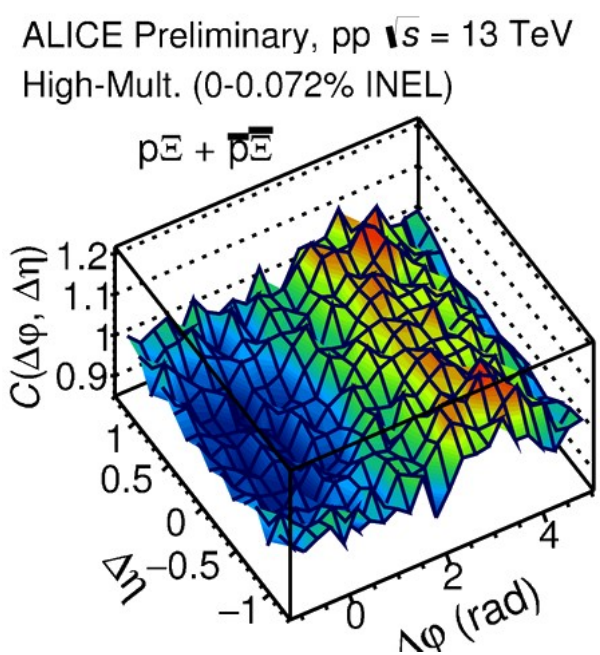
"(...) some <u>additional, not yet identified mechanism must exist, which suppresses the production of more than one baryon–antibaryon pair during a single fragmentation</u>. Therefore, this may suggest the need to modify particle production mechanisms and/or the modification of fragmentation functions in Monte Carlo models."

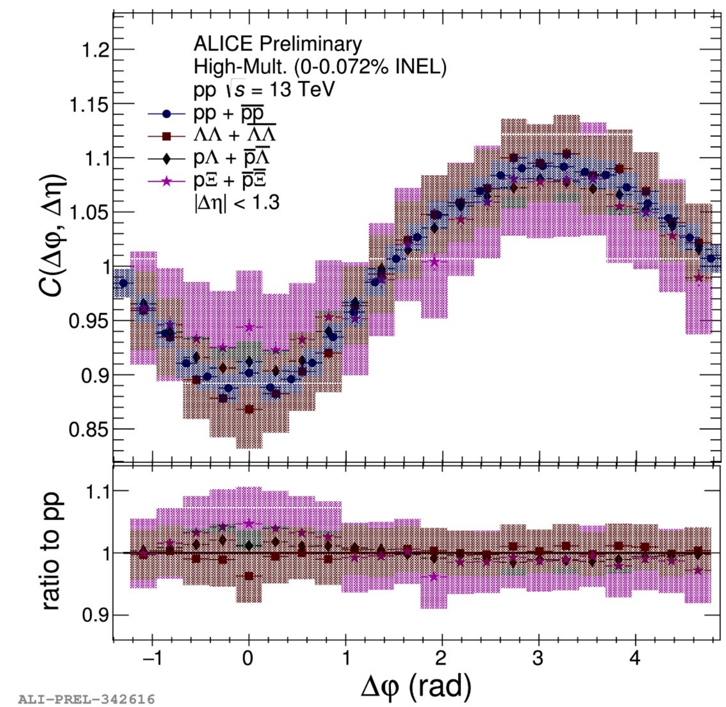
Are there any advances since the 2017 ALICE paper?

- The anticorrelation persists at 13 TeV collision energy
- It also persists for higher mass multi-strange baryons

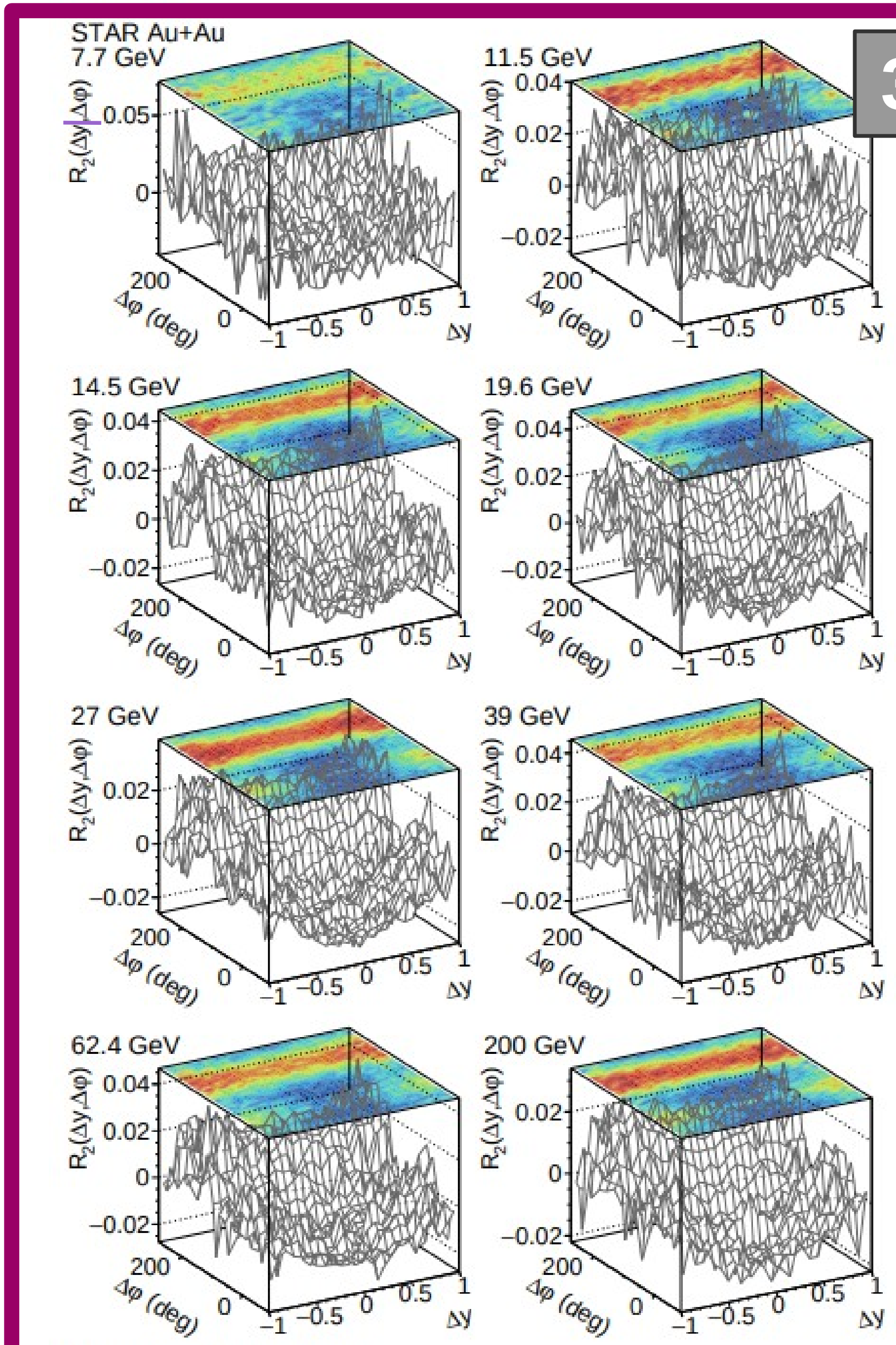








STAR Au-Au data - energy dependence



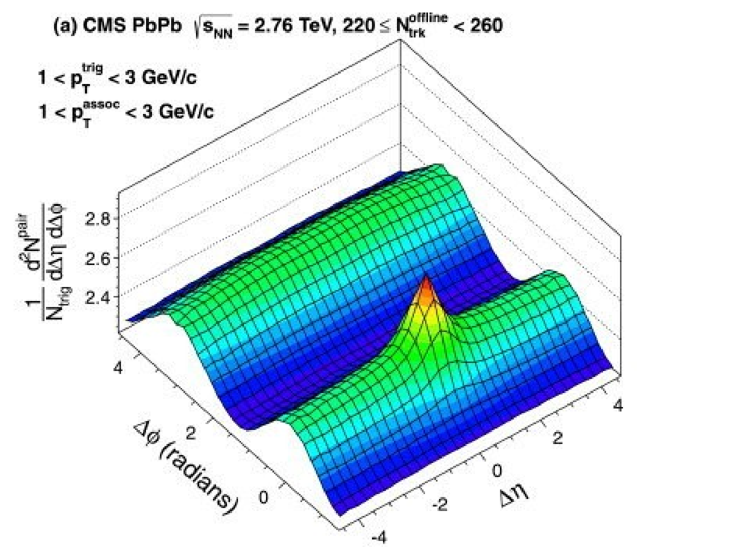
(a) Like-sign protons

30-40%

Au+Au collision energy

STAR, Phys. Rev. C 101, 014916 (2020)

- The anticorrelation effect is present for Au-Au results
- It is convoluted with the flow double-ridge structure



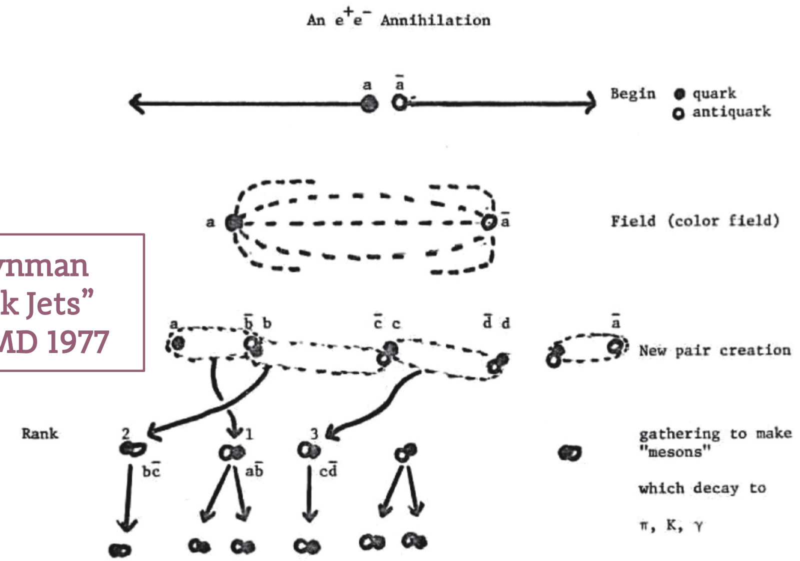
CMS, Phys. Lett. B 724 (2013) 213

What about the theory side?

Rapidity correlations at low energies

A Parametrization of the Properties of Quark Jets
R.D. Field, R.P. Feynman
Nucl. Phys. B 136 (1978) 131

<u>From mechanism of jet production</u>:
Two primary hadrons with the same **baryon number**
are separated by at least two steps in "rank"



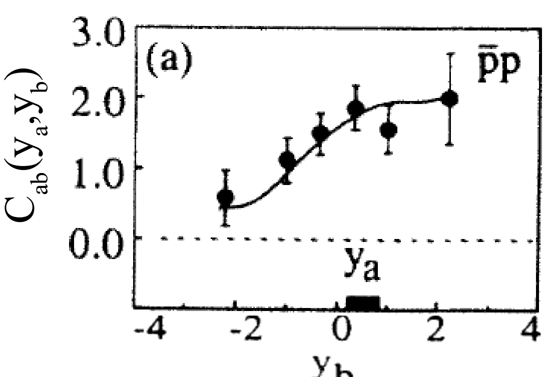
R. Feynman
"Quark Jets"
8th ISMD 1977

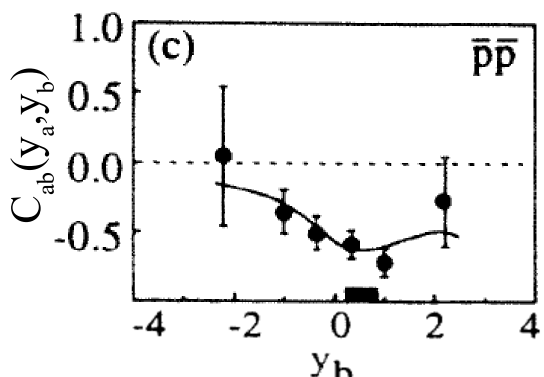
Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

We are not likely to find two baryons or two antibaryons very close to each other

***Local* baryon number conservation <u>partially</u> responbsible for anticorrelation at 29 GeV collision energy**

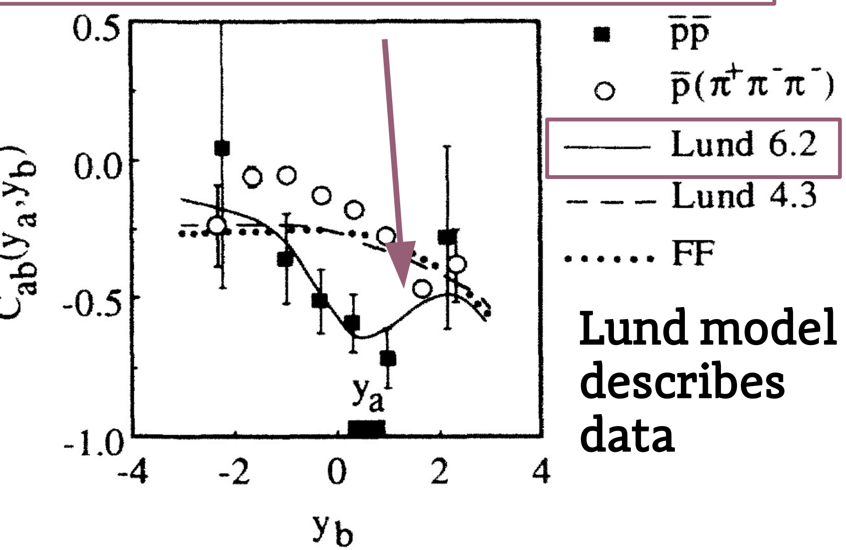
correlation **anti-correlation**





TPC/Two Gamma Collaboration, Phys.Rev.Lett. 57 (1986) 3140

Models at lower energies agree with observations seen in data

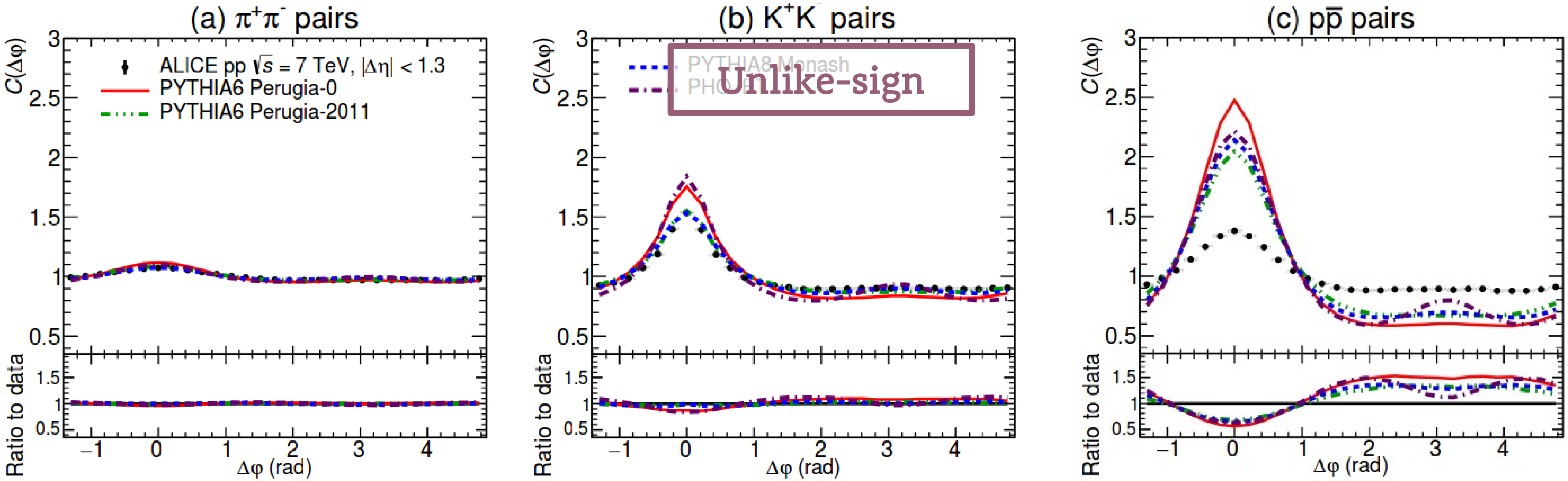


Lund model describes data

PHOJET, PYTHIA 6 and PYTHIA 8

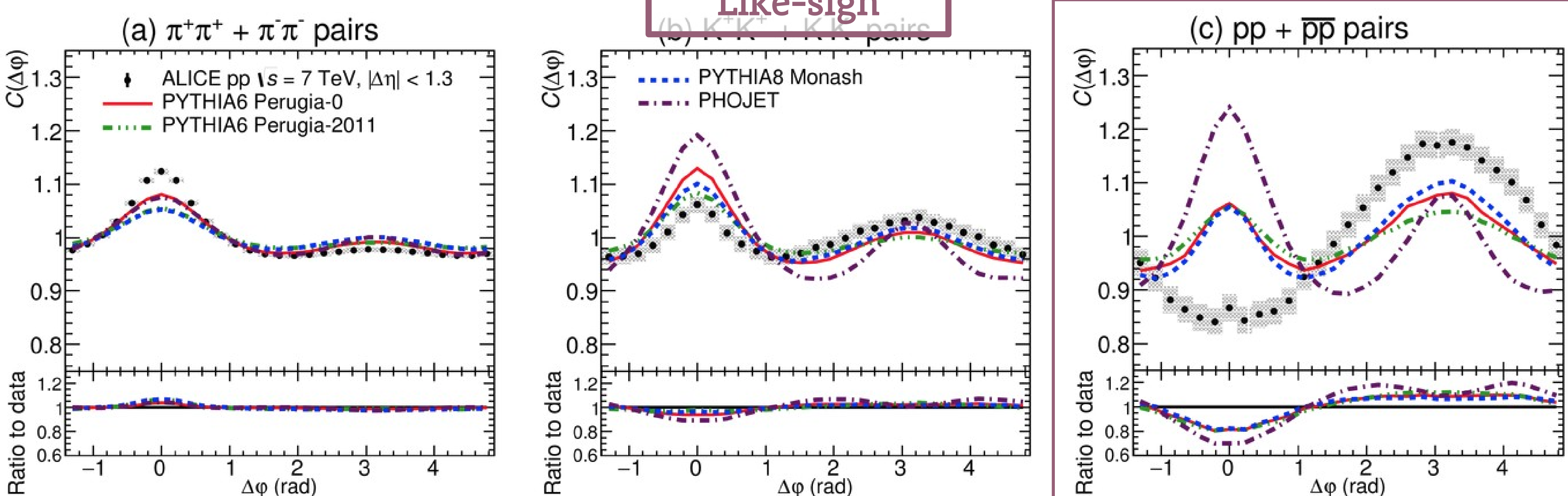
ALICE, Eur. Phys. J. C 77 (2017) 569

Unlike-sign



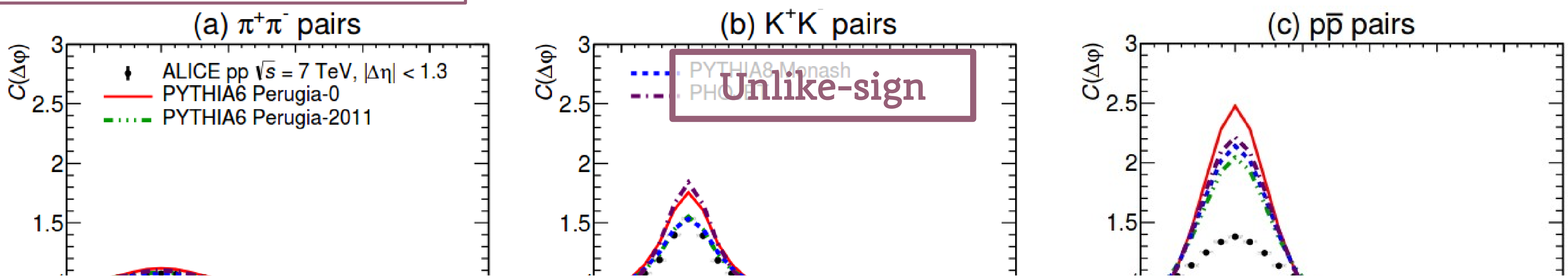
Like-sign

This one looks different!



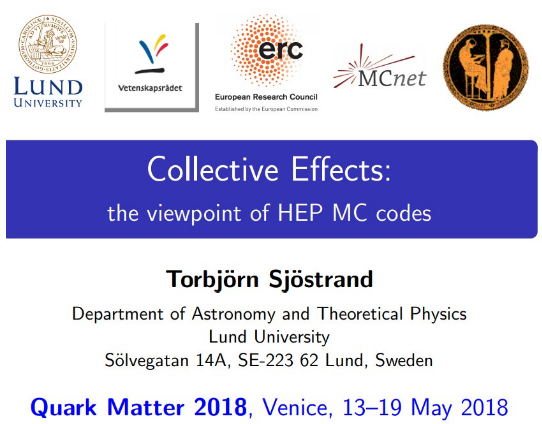
PHOJET, PYTHIA 6 and PYTHIA 8

ALICE, Eur. Phys. J. C 77 (2017) 569



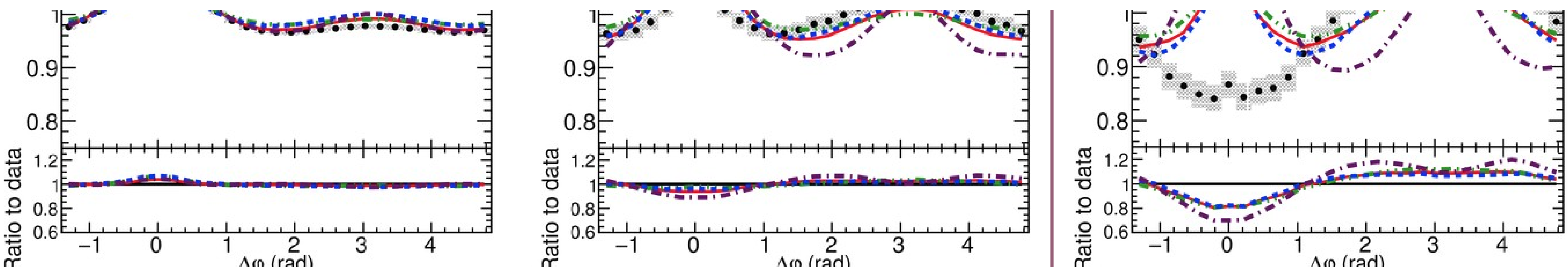
Unlike-sign

T. Sjostrand, QM 2018, plenary talk
https://indico.cern.ch/event/656452/contributions/2899749/



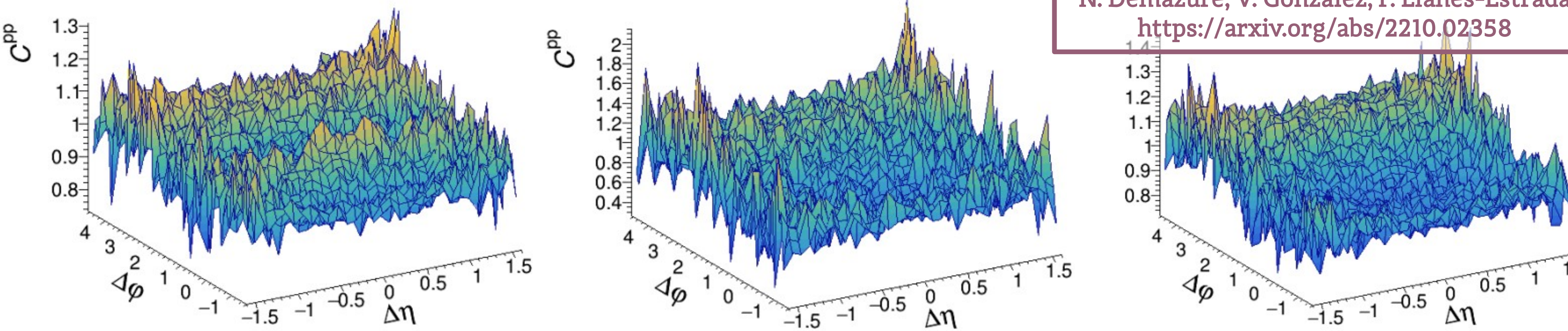
Nucl. Phys. A 982 (2019) 43-49

"The real problem is baryon production. [...] so it is clear we still lack some fundamental insight on baryon production, at least in the string context."

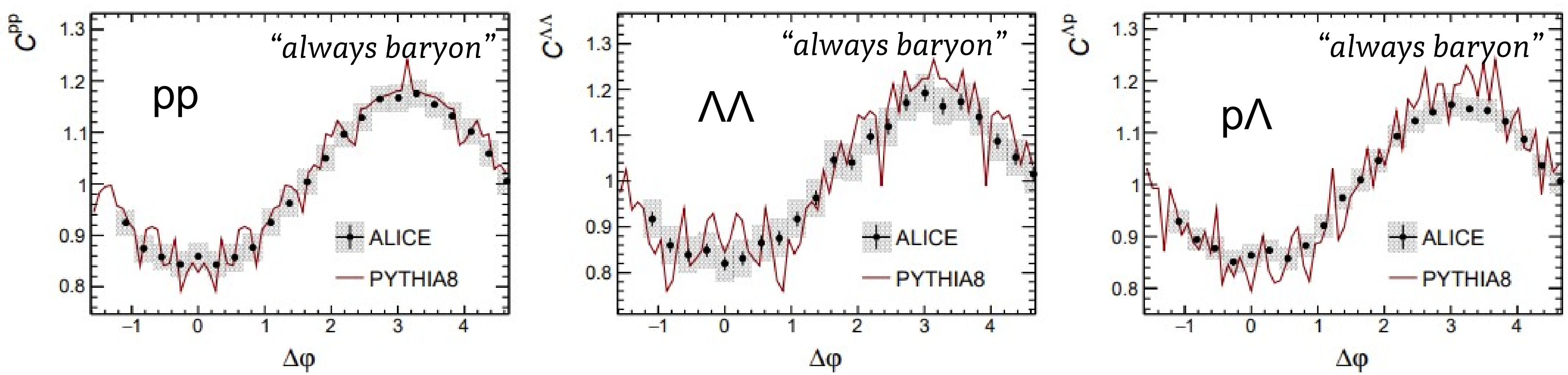


Modified PYTHIA

N. Demazure, V. Gonzalez, F. Llanes-Estrada
https://arxiv.org/abs/2210.02358



(a) pp C correlation with unmodified PYTHIA (b) pp C correlation, one-baryon per string policy (c) pp C correlation, always-baryon policy



- Two modifications to PYTHIA string fragmentation allow the model to describe the data:

  → *one baryon* – each string must *produce at most one baryon* (a way to impose Pauli principle to baryons, but lowers the baryon-to-meson ratio)

  → *always baryon* – each string must *always produce one baryon* (<u>no physical meaning</u>, but produces very good agreement with data)

Che-Ming Ko
https://indico.cern.ch/event/237345/contributions/1549128/

A multiphase transport (AMPT) model

Default: Lin, Pal, Zhang, Li &Ko, PRC 61, 067901 (00); 64, 041901 (01); 72, 064901 (05); http://www-cunuke.phys.columbia.edu/OSCAR

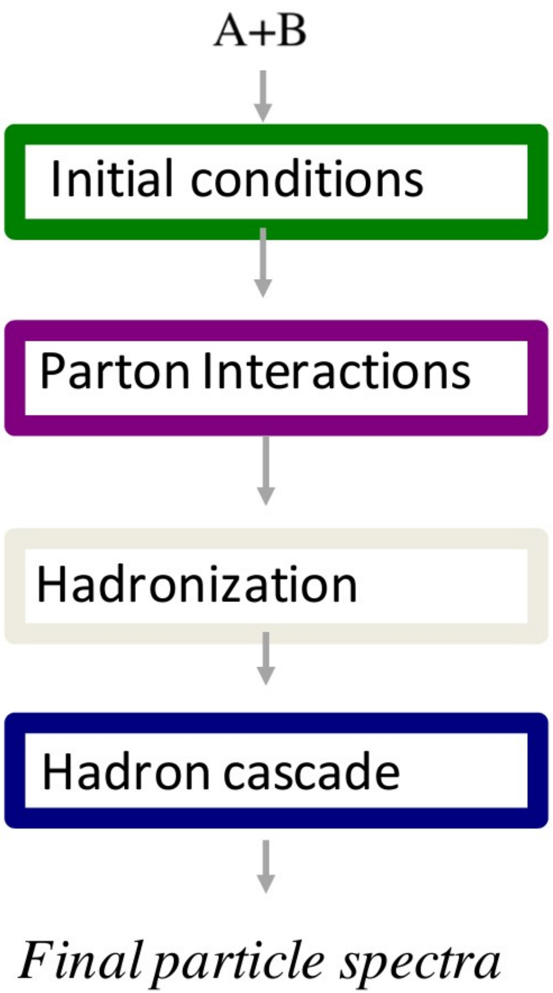
- Initial conditions: HIJING (soft strings and hard minijets)
- Parton evolution: ZPC
- Hadronization: Lund string model for default AMPT
- Hadronic scattering: ART

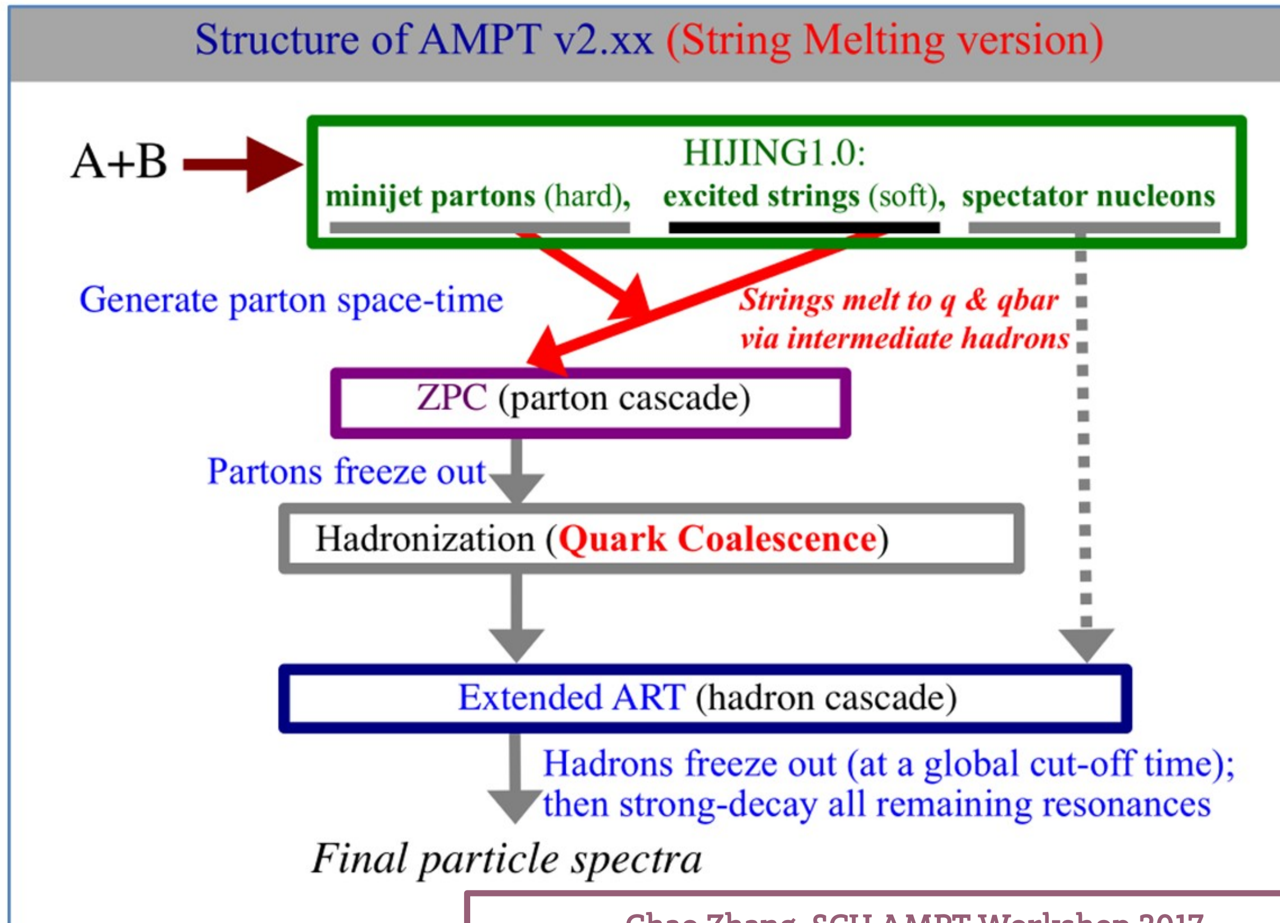
String melting: PRC 65, 034904 (02); PRL 89, 152301 (02)

- Convert hadrons from string fragmentation into quarks and antiquarks
- Evolve quarks and antiquarks with ZPC
- When partons stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon (coordinate-space coalescence)
- Hadron flavors are determined by the invariant mass of quarks

AMPT model

- Contains *4 main components* to describe the whole phase space of heavy-ion collisions
- *String melting:* convert hadrons from string fragmentation into quarks and antiquarks
- *Coalescence:* when partons stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon





Chao Zhang, SCU AMPT Workshop 2017
https://myweb.ecu.edu/linz/ampt/Ampt2017/ZhangC.pdf

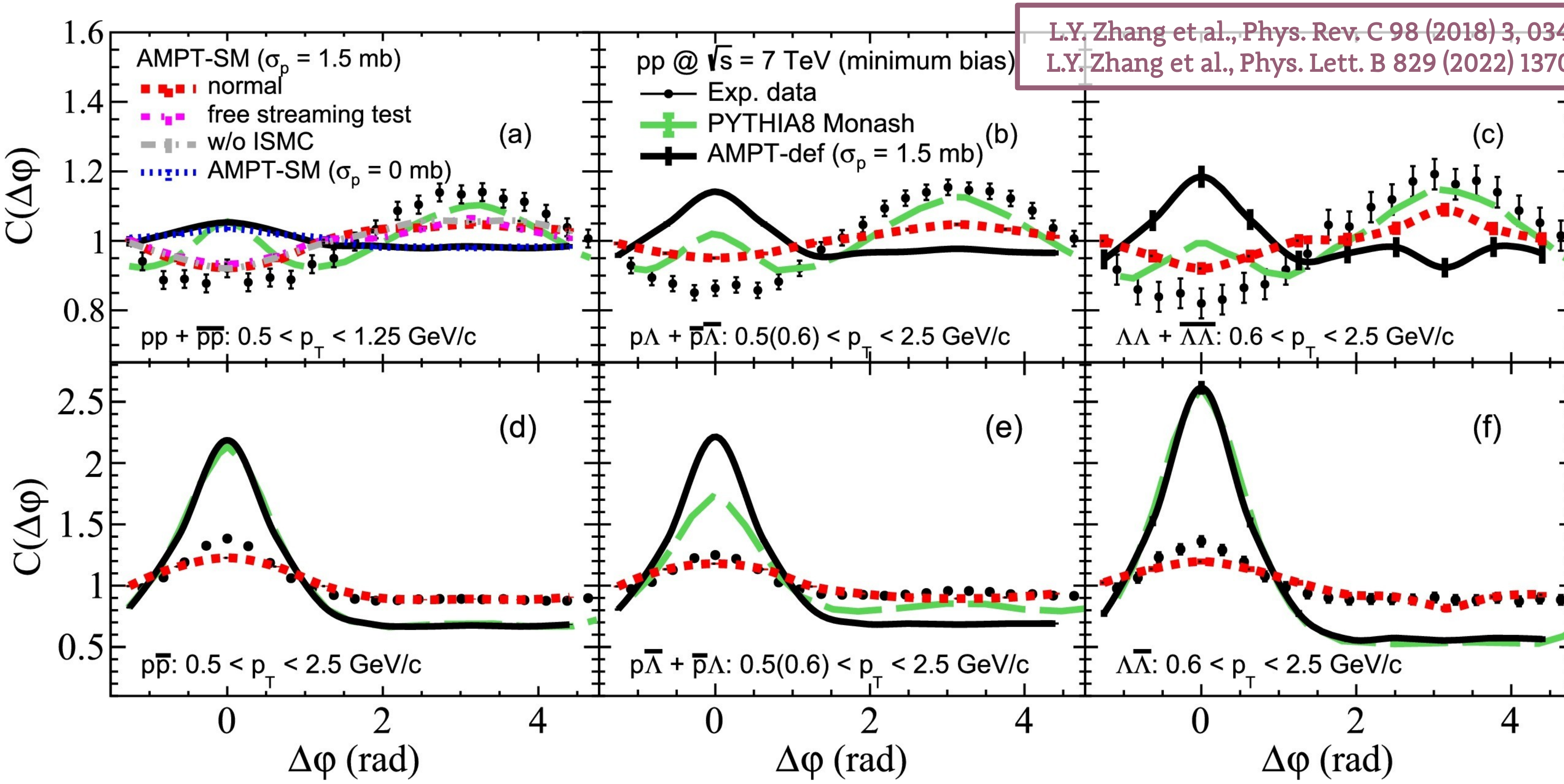
Modified AMPT

- *Improved* coalescence (removed separate conservation for mesons and baryons)
- String melting (SM) → parton degrees of freedom are expected in the initial state

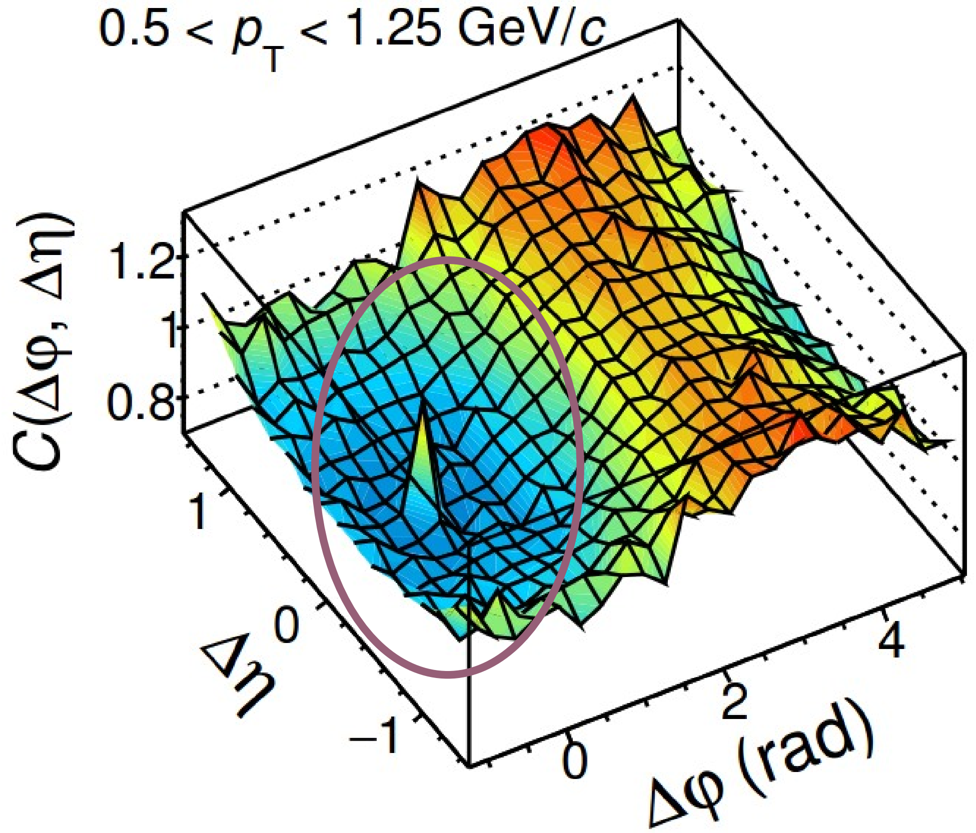
  → AMPT-SM with non-zero parton cross section desrcibes the data

  → test of SM with parton cross section set to 0 mb does not describe the data
- If initial state momentum correlation (ISMC) are removed → the result is similar to standard AMPT-SM version → describes anticorrelation

L.Y. Zhang et al., Phys. Rev. C 98 (2018) 3, 034912
L.Y. Zhang et al., Phys. Lett. B 829 (2022) 137063

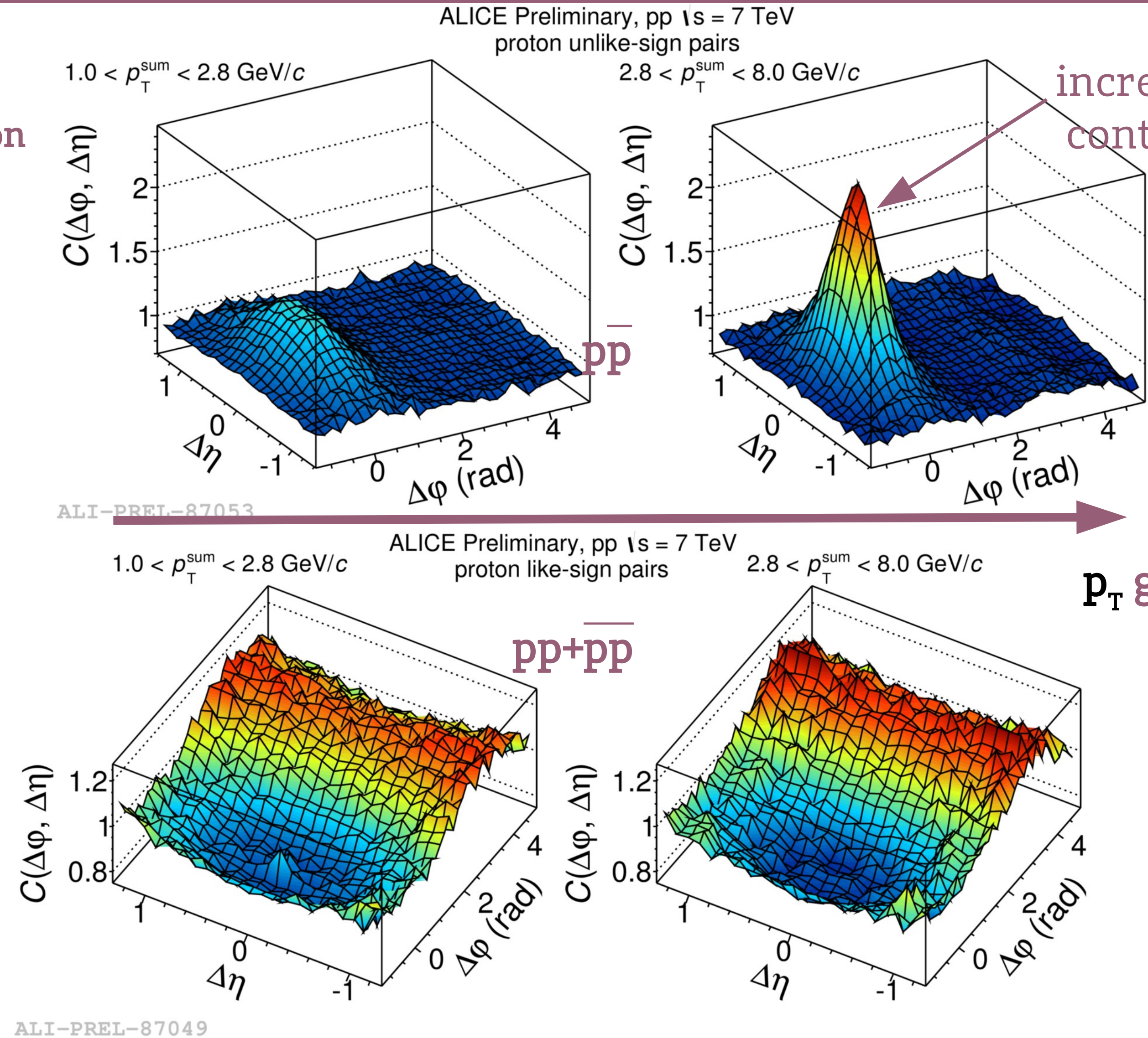


What is the origin of the "small peak" in pp correlations?



Baryon correlations in p_T

Near-side peak grows with p_T (more contribution from jets)



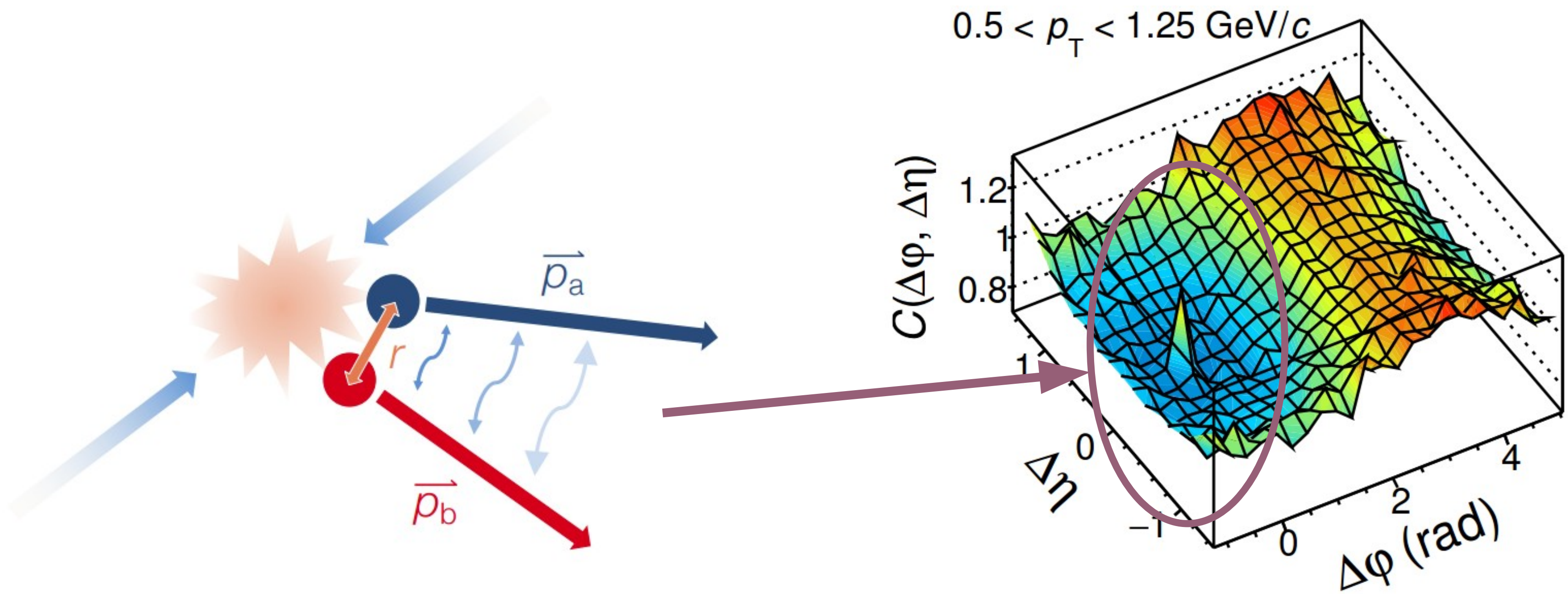
increasing jet contribution

p_T growth

small peak disappears for high p_T

- The small peak seems to behave **strangely** → decreases with increasing p_T
- Is it an unnoticed and not removed **detector effect** OR is there some **physics behind it**?

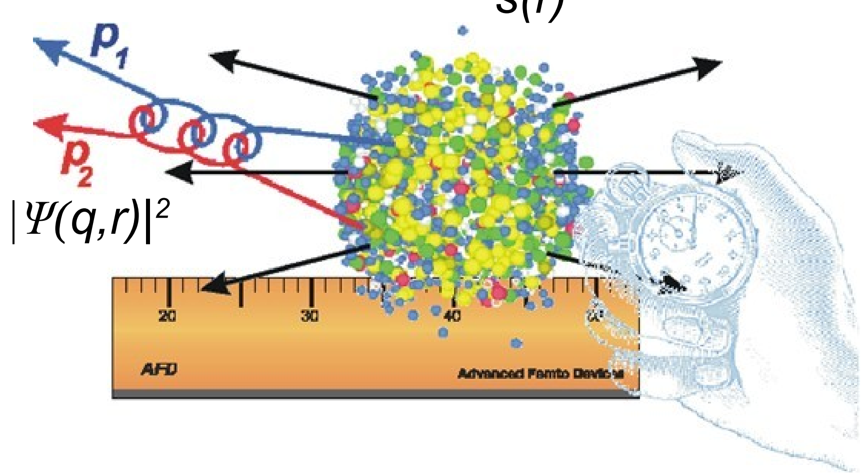
- In the ALICE paper we *hypothesized* the small peak could be of the strong final-state interaction (FSI) origin:



→ how do we measure strong FSI?

Femtoscopy

from M. Lisa and S. Pratt



$$C(\vec{q}) = \int S(r) |\Psi(q,r)|^2 d^3 r$$

measured correlation

Obtained by experiment

emission function (source size/shape)

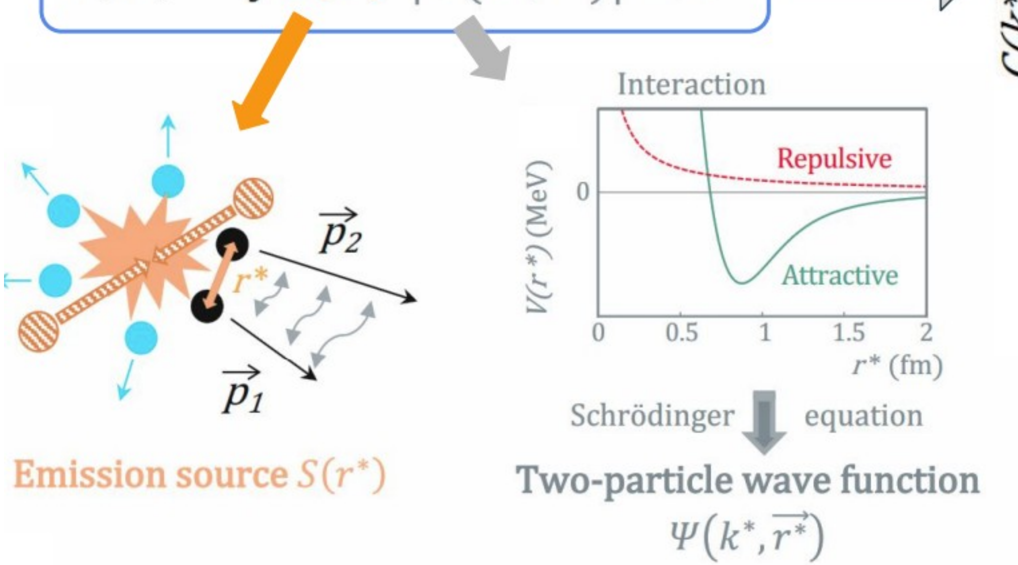
Known

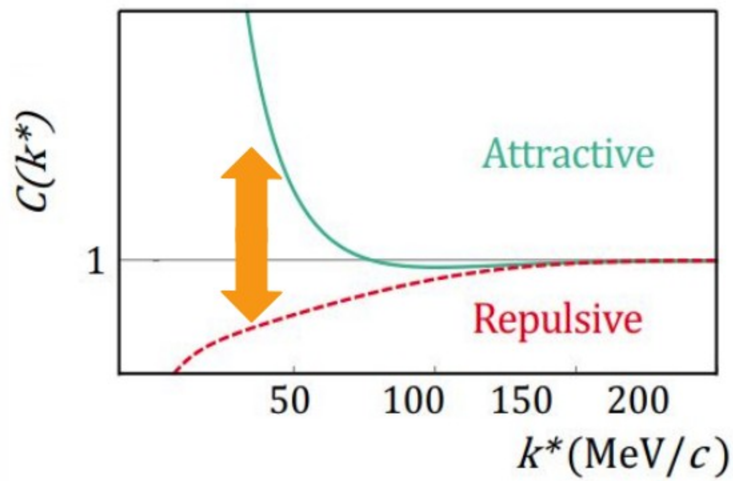
Two-particle wave function

Interaction unknown

$$q = 2 \cdot k^* = p_1 - p_2$$

$$C(k^*) = \int S(r^*)\ |\Psi(k^*, \vec{r^*})|^2\ d^3 r^*$$



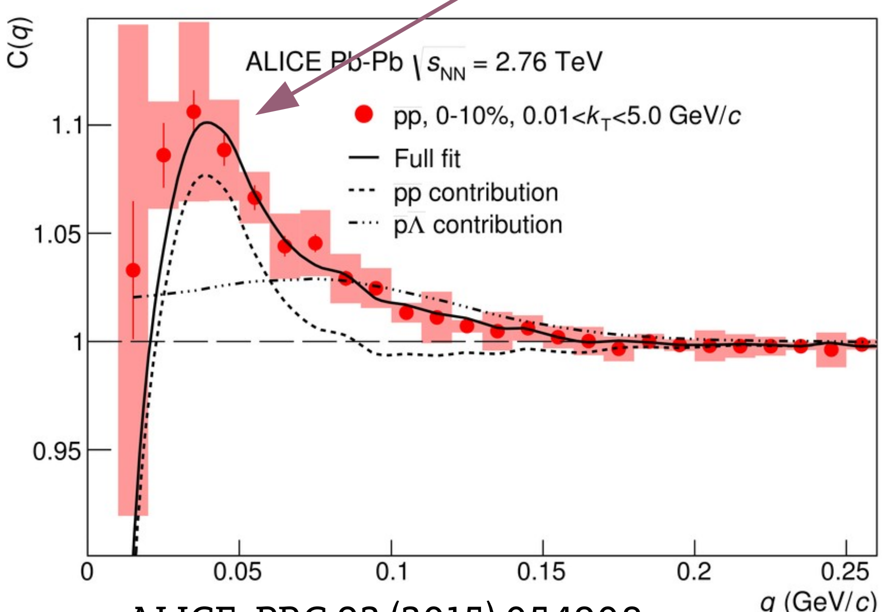


ALICE, Nature 588, 232-238 (2020)

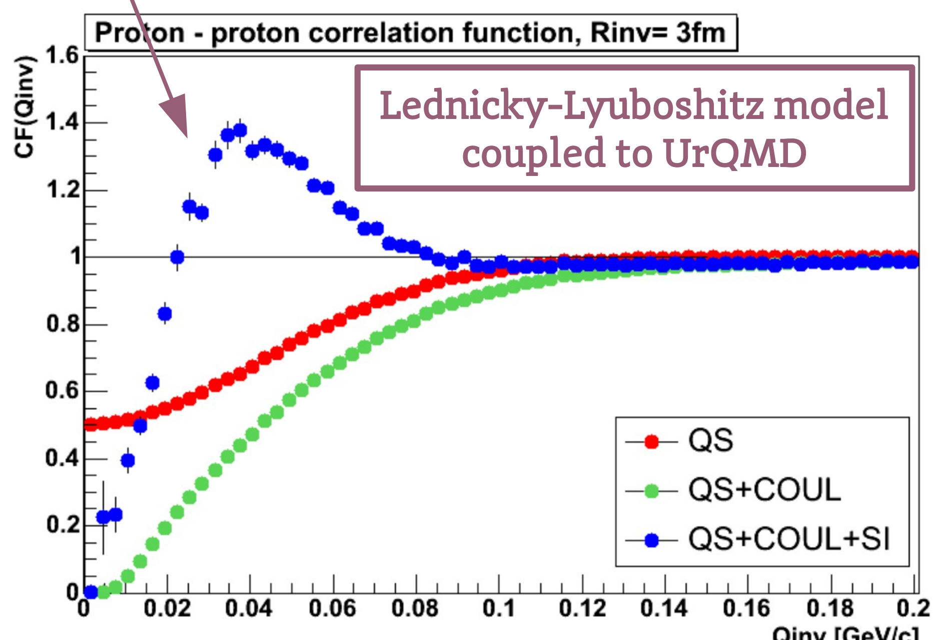
Femto correlations of pp pairs

Ingredients of the proton-proton femtoscopic correlation funcion:

- strong FSI is significant in pp femtoscopic correlation function
- dominant effect around q = 0.04 GeV/c
- **strong interaction** is the only source of positive correlation for baryons



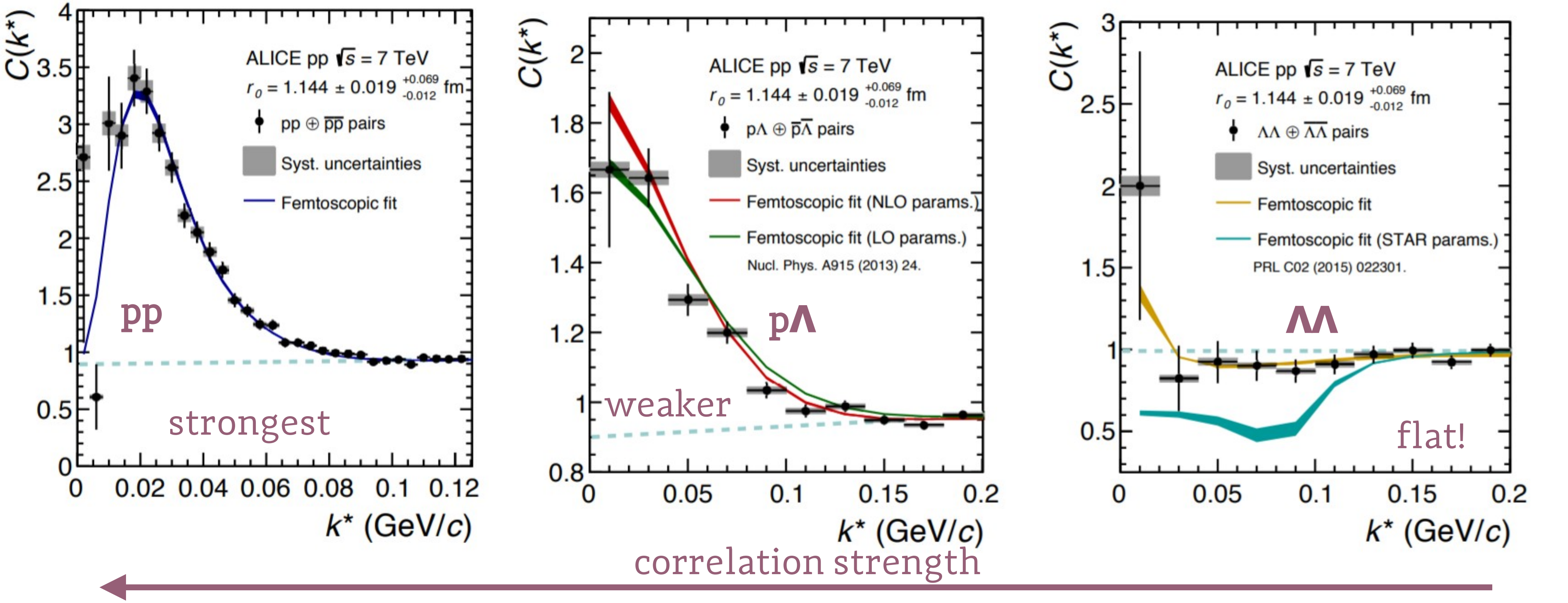
ALICE, PRC 92 (2015) 054908



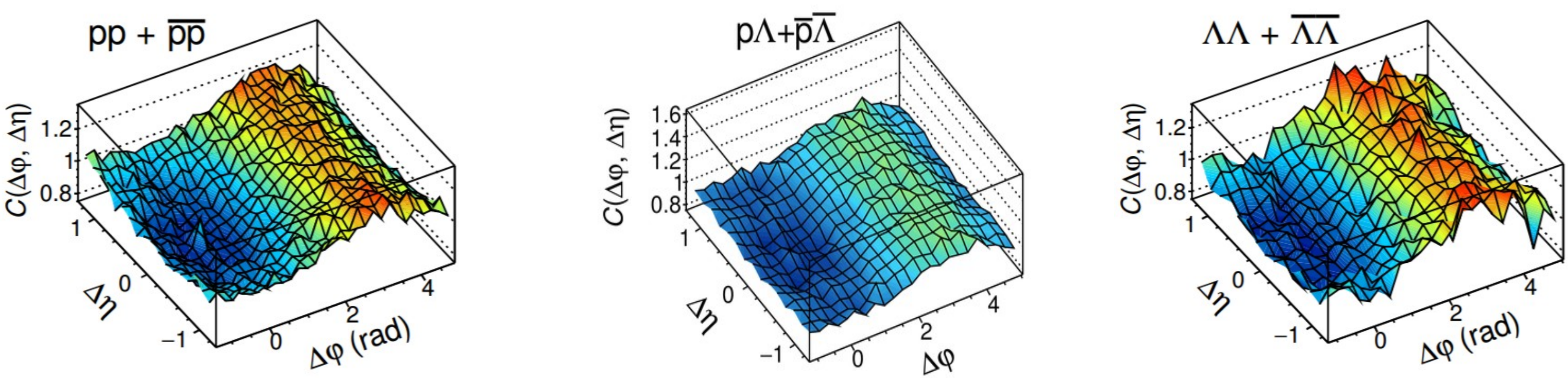
H. Zbroszczyk, PhD thesis

Strong FSI for other baryon pairs

ALICE, PRC 99, 024001 (2019)

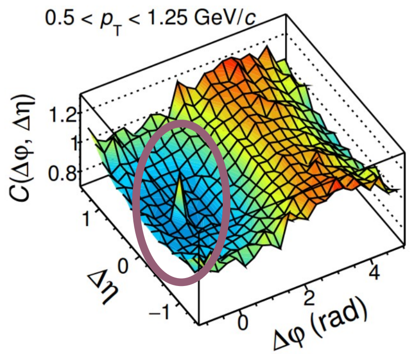


→ correlation **weakens** from pp to ΛΛ pairs, same as the small peak in angular correlations

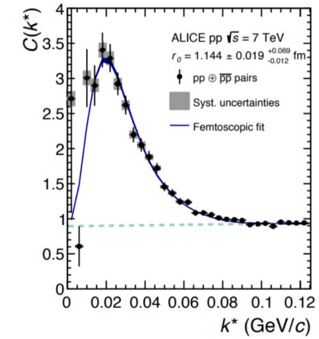


Ł.G. & M.J., PRC 104, 054909 (2021)

- **Direct transformation** from C(k*) to C(Δη,Δφ) is **not possible**



unfolding?



- **We propose a very simple Monte Carlo algorithm to unfold the angular correlation from the femtoscopic one**
  - we tested the method with PYTHIA 8 simulations coupled to Lednicky-Lyuboshitz (L-L) formalism for QS and FSI effects
  - we show how the effects of FSI and QS manifest in angular correlations

PHYSICAL REVIEW C **104**, 054909 (2021)

Unfolding the effects of final-state interactions and quantum statistics in two-particle angular correlations

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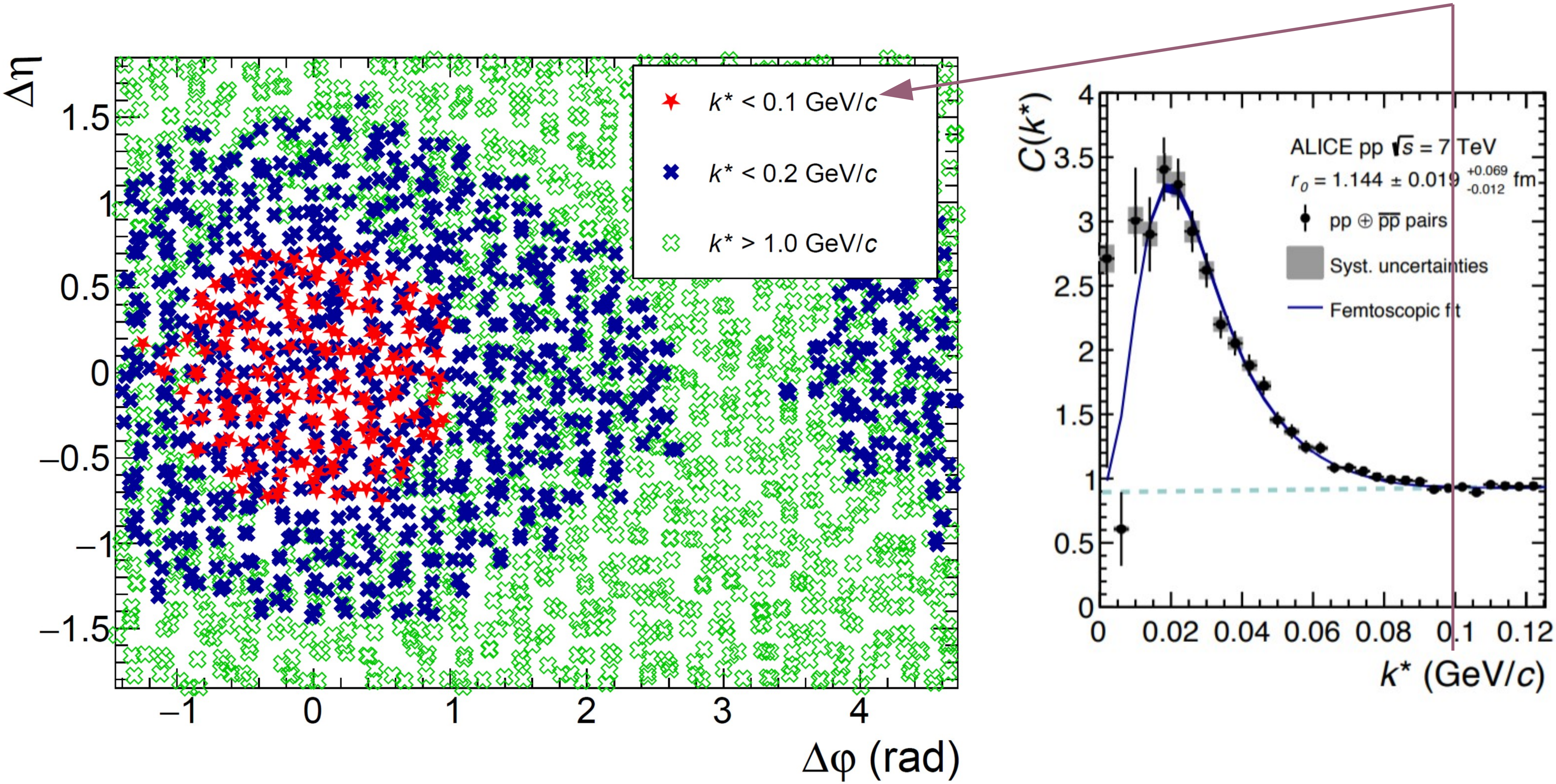
(Received 31 July 2021; accepted 11 November 2021; published 29 November 2021)

Relation between two correlations

- **Femtoscopic region** (small k*) translates directly to the near-side region (0,0) in the angular correlation

→ QS+FSI effects should be possible to be quite precisely unfolded from the femtoscopic correlation function



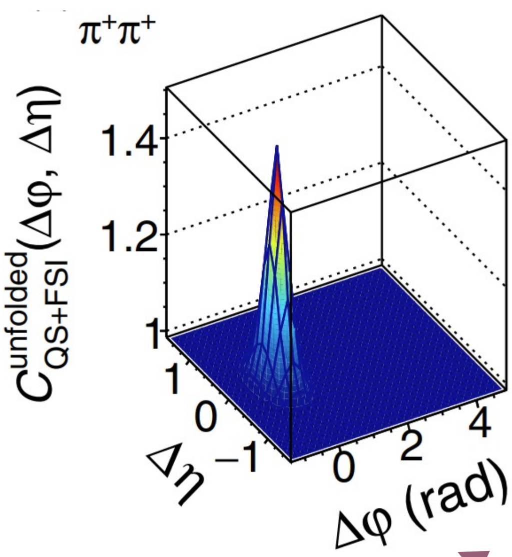
The unfolding of the QS+FSI works very well

Ł.G. & M.J., PRC 104, 054909 (2021)

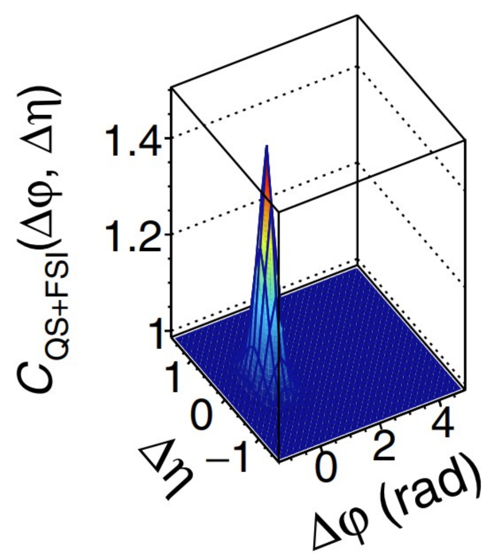
Lednicky-Lyuboshitz model coupled to PYTHIA 8

Pions

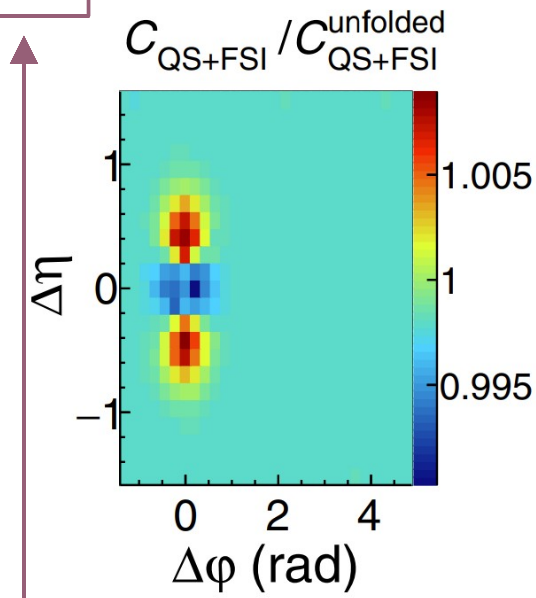
UNFOLDED FROM FEMTO CF QS+FSI



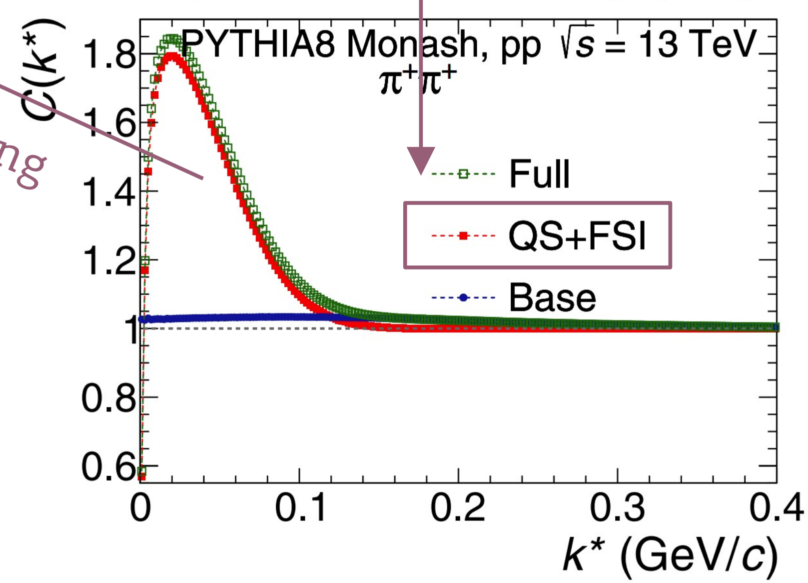
QS+FSI ONLY SIMULATED



RATIO



unfolding



Procedure validation with simulations

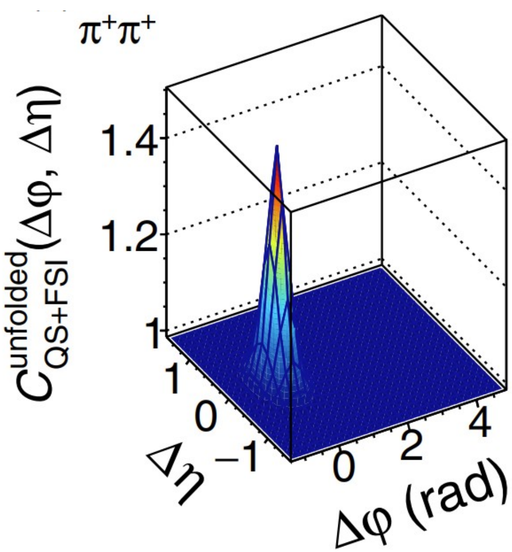
The unfolding of the QS+FSI works very well

Ł.G. & M.J., PRC 104, 054909 (2021)

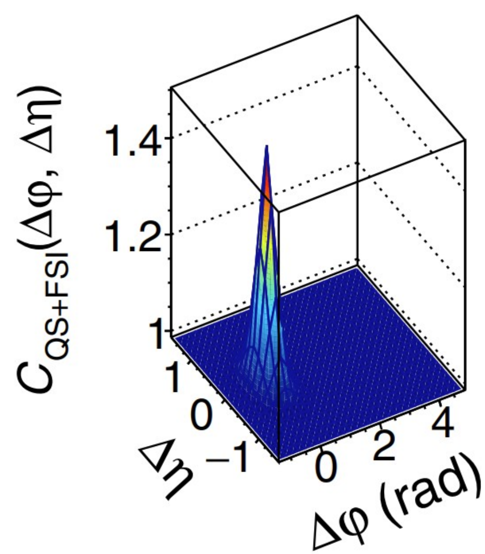
Lednicky-Lyuboshitz model coupled to PYTHIA 8

Pions

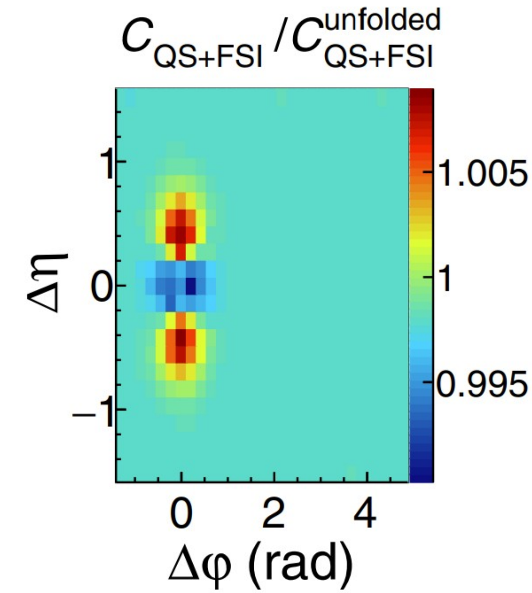
UNFOLDED FROM FEMTO CF QS+FSI



QS+FSI ONLY SIMULATED



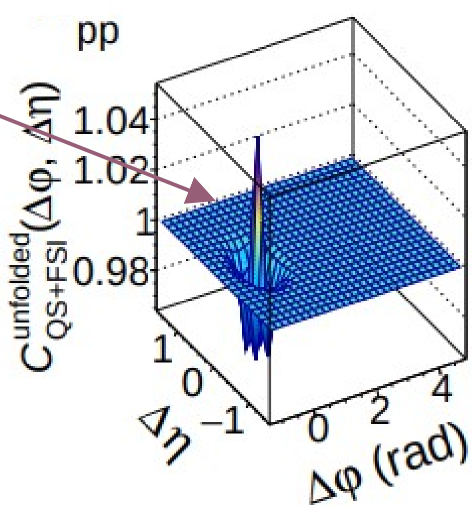
RATIO



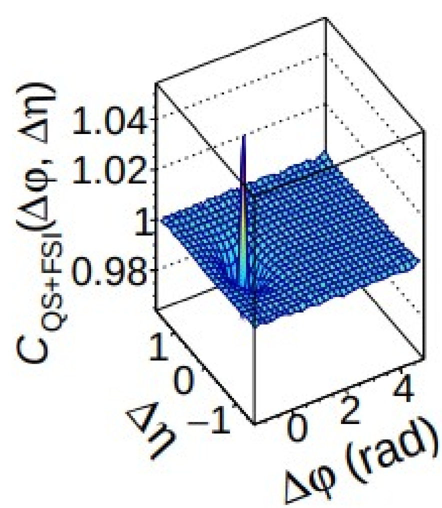
Protons

narrow dip + spike in the middle

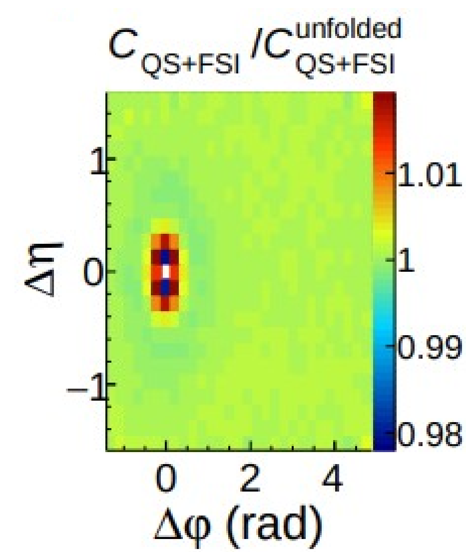
UNFOLDED FROM FEMTO CF QS+FSI



QS+FSI ONLY SIMULATED

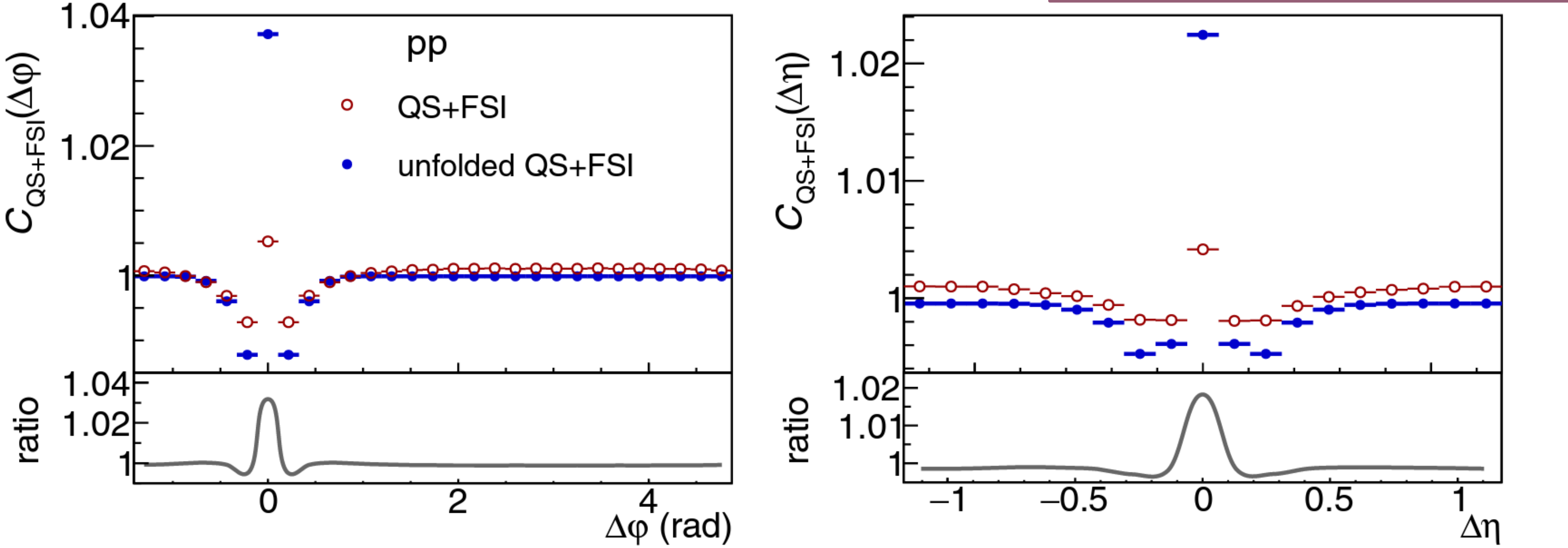


RATIO



Results for protons

Ł.G. & M.J., PRC 104, 054909 (2021)



a depletion in the correlation function around $(\Delta\eta, \Delta\varphi) \approx (0, 0)$ is visible with an additional peak structure directly at $(\Delta\eta, \Delta\varphi) = (0, 0)$. Although the magnitude of the peak is substantially smaller in the unfolded correlation, the procedure is able to describe the shape qualitatively. A qualitatively similar peak structure, located at $(\Delta\eta, \Delta\varphi) = (0, 0)$, in the middle of the depletion, was observed experimentally by the ALICE Collaboration and postulated to result from the strong two-proton interaction. This paper validates this ansatz.

Summary

Correlations of baryons reveal an interesting anticorrelation effect:

- Present also in 13 TeV pp ALICE data and in Au-Au collisions at various energies from STAR BES
- Interesting theoretical developments for AMPT and PYTHIA → are we on a good path to solving the puzzle? Is it a signature of a partonic matter (is it QGP?!) in small systems as AMPT authors claim?

Clear connection between femtoscopic and angular correlations:

- The small peak in pp correlations and the dip in pp proved to come from the strong FSI
- Femtoscopic correlations can be used to unfold the effects of QS+FSI in angular correlations, especially for pairs where MC models do not work (baryons)

THANK YOU!

BACKUP

Unfolding procedure

Ł.G. & M.J., PRC 104, 054909 (2021)

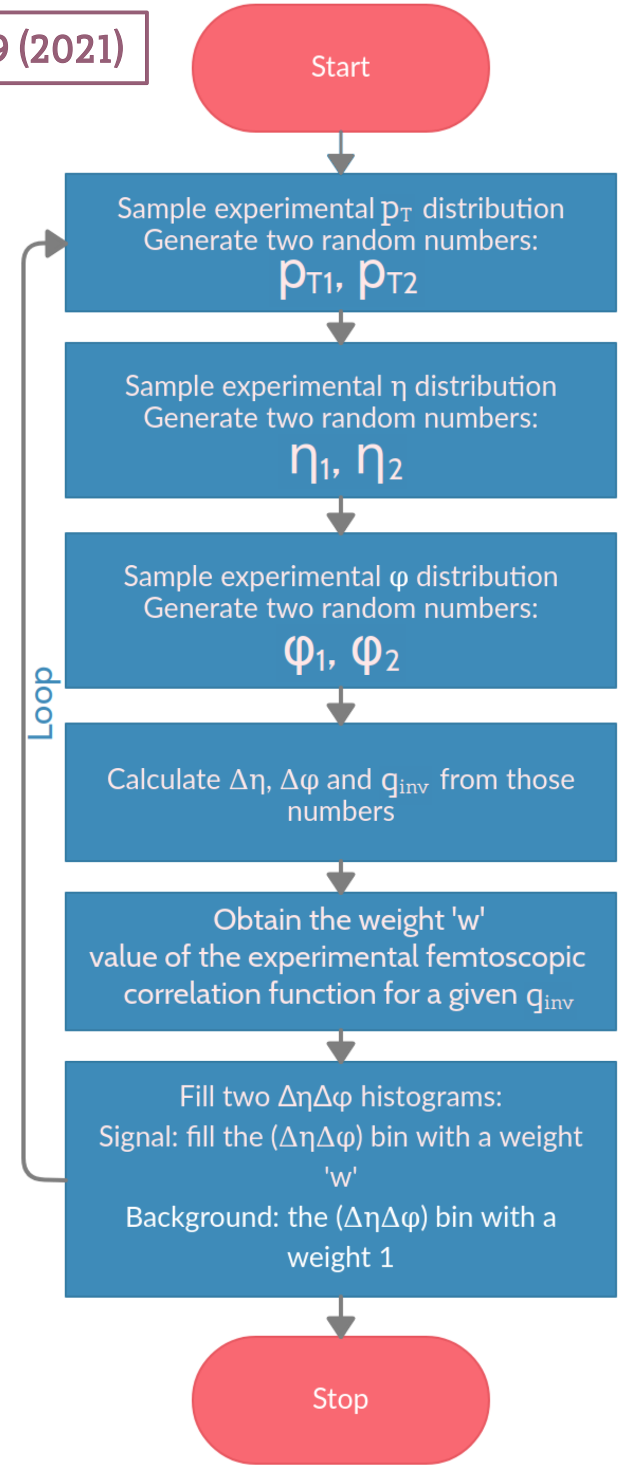
How does the unfolding work?

- we sample (twice) single-particle kinematic distributions (p_T, η, φ)
- for each iteration we calculate q_{inv} (or k^*) from those randomly sampled quantities
- we obtain the weight 'w' for a given q_{inv} (or k^*)

  → value of the femtoscopic correlation
- then, we calculate $\Delta\eta$ and $\Delta\varphi$ and fill two histograms
  → signal with the weight 'w'
  → background, with weight = 1

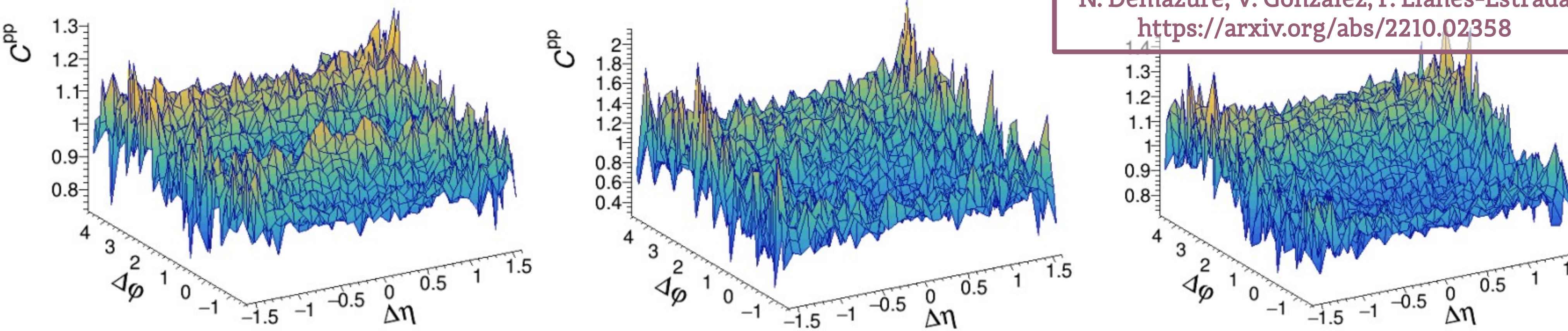
By definition, such simple procedure will work **ONLY** for those effects to which the femtoscopic CF is sensitive the most

It will **NOT** work for long-range effects (i.e. jets, momentum conservation)

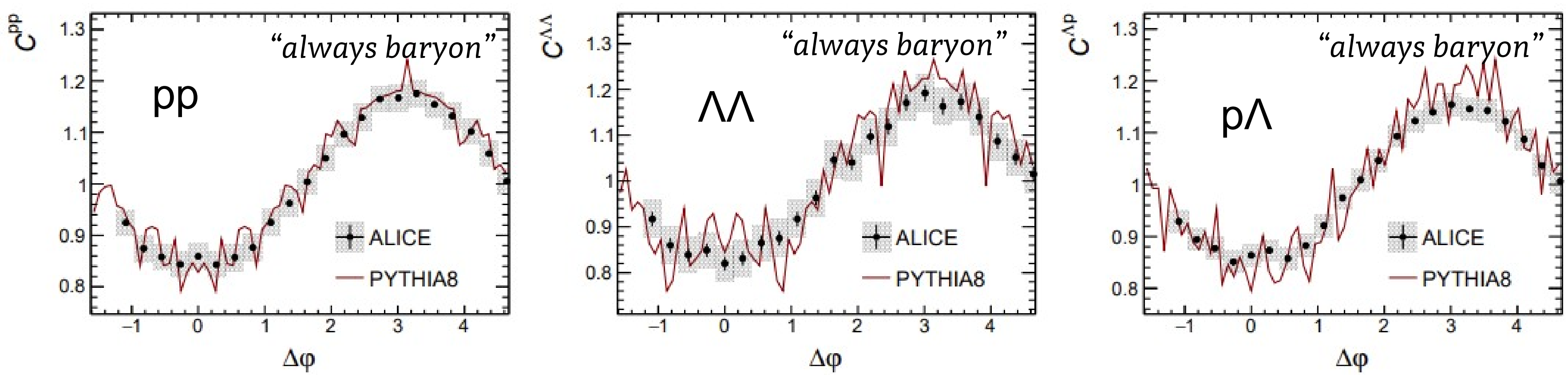


Modified PYTHIA

N. Demazure, V. Gonzalez, F. Llanes-Estrada
https://arxiv.org/abs/2210.02358



(a) pp C correlation with unmodified PYTHIA (b) pp C correlation, one-baryon per string policy (c) pp C correlation, always-baryon policy



The LEP baryon correlation data could be reasonably fit by PYTHIA as is, given that the color string did form linking a back-to-back primary quark-antiquark pair; this means that baryons from the same string did not form positive correlations near $\Delta\eta \simeq 0 \simeq \Delta\varphi$ in OPAL data, as they were somewhat randomized, with the string frame not too far from the laboratory frame.

At the LHC strings are however formed at various rapidities and azimuths, with a natal Lorentz boost. Because of that string boost, two baryons formed from the same string will create that positive correlation in the laboratory frame. Therefore, to avoid it and bring about the anticorrelation seen in the data, two-baryon production from the same string should be suppressed: our way of achieving it is the very rough pair of policies (one-baryon and all-baryon) that certainly need to be improved in future work.

Modified AMPT

- *Improved* coalescence (removed separate conservation for mesons and baryons)
- Strin… …ate
  → AM…
  → tes…
- If init… …lar to…

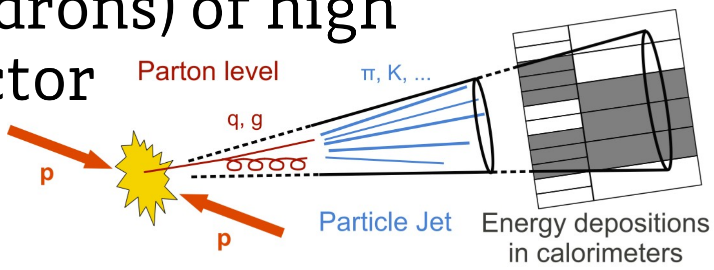
A physics picture for the near-side depression feature emerges out of these results: a parton matter is created and then expands to a finite volume, then the hadronization process (quark coalescence in the AMPT model for this study) converts parton degrees of freedom to primordial hadrons locally and produces multiple hadrons relatively close in the coordinate space including the spatial azimuth. The finite expansion of the parton matter creates a finite space-momentum correlation (often called the radial flow), and the transverse flow velocity of a local parton volume tends to change its hadrons from being close in spatial azimuth to being close in momentum azimuth. Results from the AMPT-SM model with a finite parton cross section are qualitatively consistent with the experimental data. In addition, the PYTHIA model with string fragmentation alone, the AMPT-SM model with no parton expansion, and the AMPT-def model that is dominated by the hadron cascade all fail to produce the depression feature. Therefore, our study implies a finite parton expansion before hadronization, where a prerequisite is the existence of parton degrees of freedom, in *pp* collisions $\sqrt{s} = 7$ TeV.

…34912
…37063

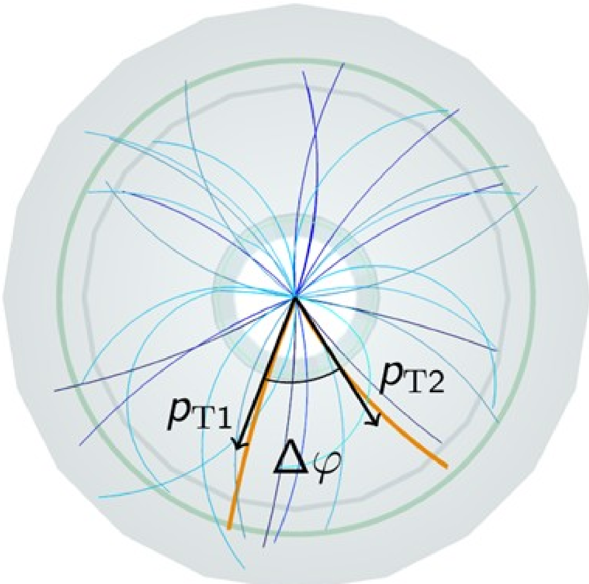
C(Δφ): 1.6, 1.4, 1.2, 1, 0.8
C(Δφ): 2.5, 2, 1.5, 1, 0.5
Δφ (rad): 0, 2, 4 | 0, 2, 4 | 0, 2, 4

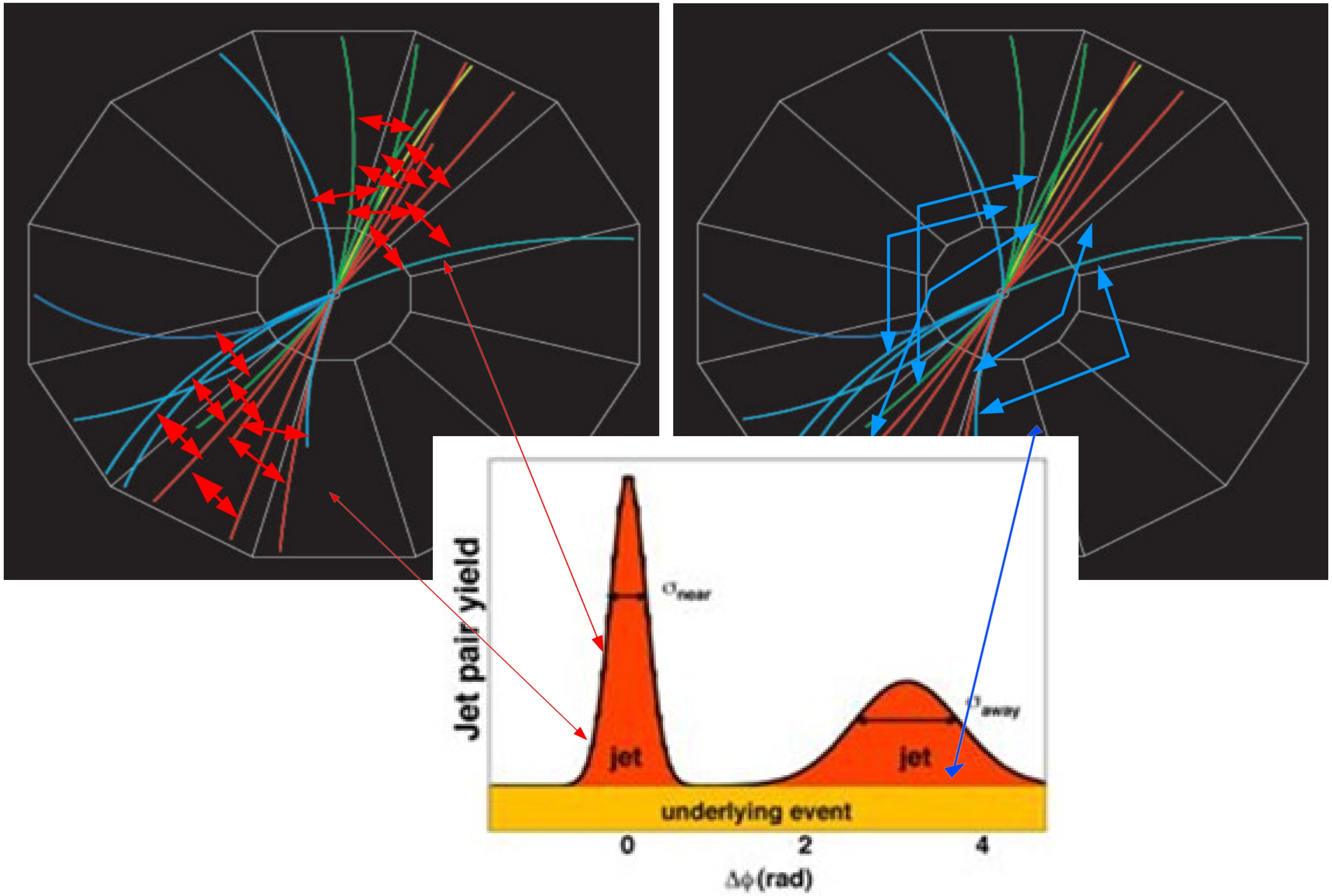
Jets

- "Jet" is a collimated stream of particles (hadrons) of high momentum (energy) which reach the detector



- How to experimentally measure jets?
- We can look at the collision in the transverse plane and calculate azimuthal angle difference distribution:





p_T - transverse momentum;
φ - azimuthal angle;

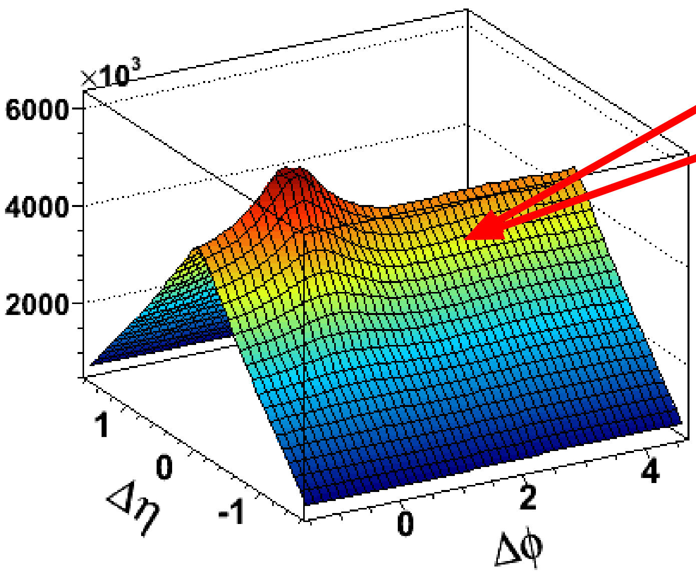
ALICE, Eur. Phys. J. C 77 (2017) 569

Fig. M. Janik

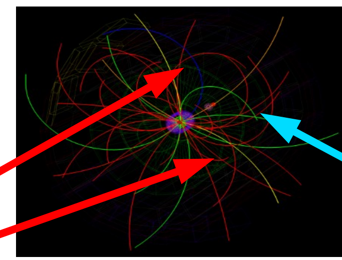
Signal distribution

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

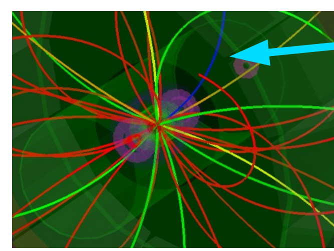
Same event pairs



Event 1



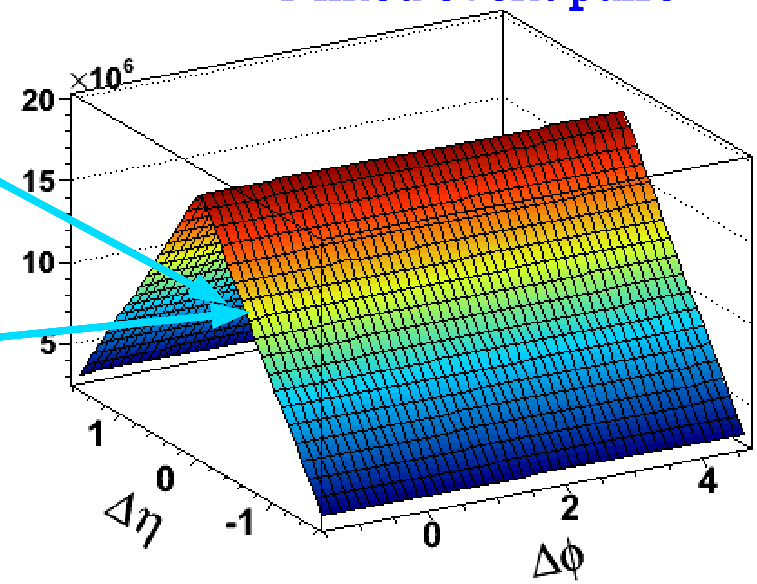
Event 2

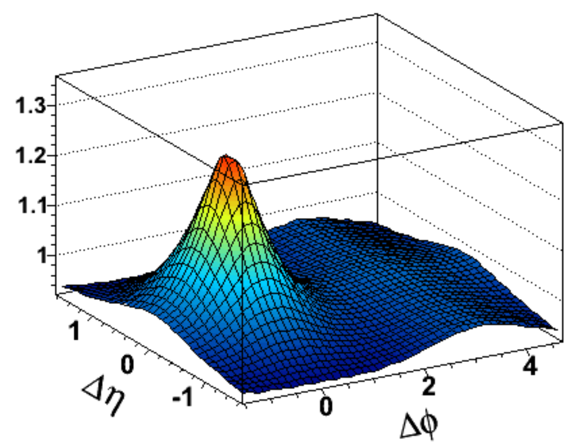


Uncorrelated reference

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

Mixed event pairs





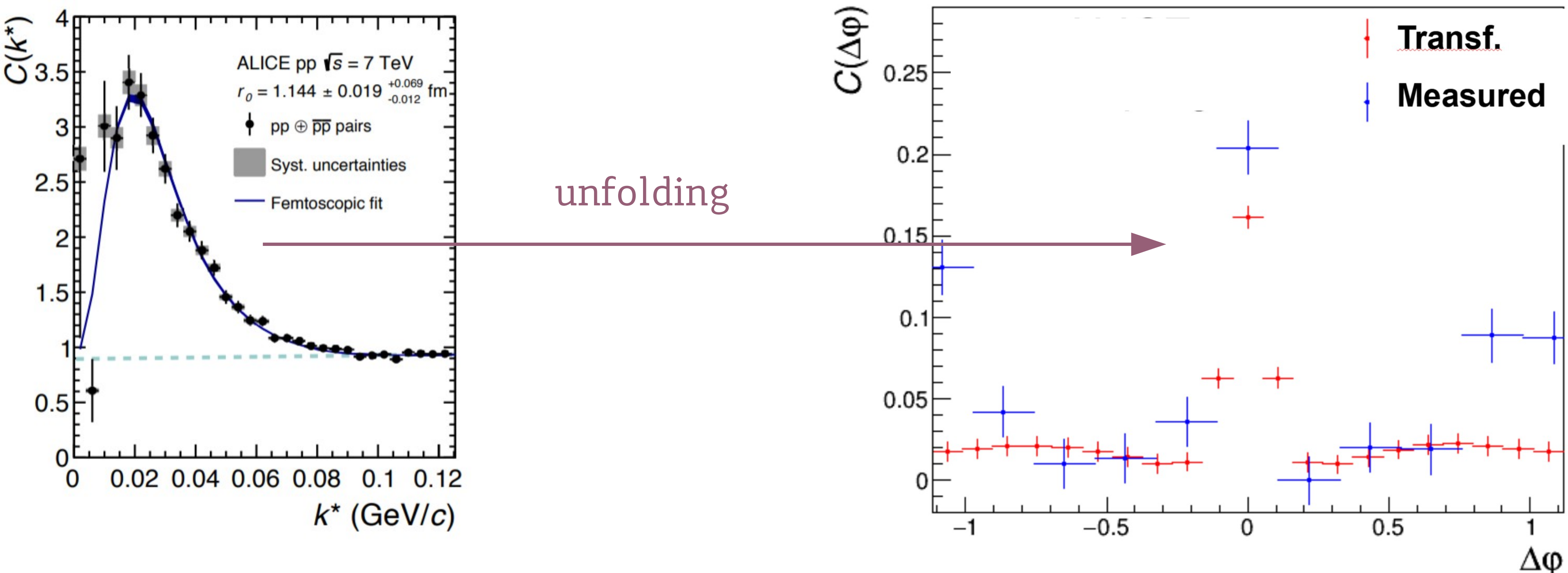
$$\Delta\eta=\eta_1-\eta_2$$
$$\Delta\varphi=\varphi_1-\varphi_2$$

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

Probability ratio

$$C(\mathbf{p}_1,\mathbf{p}_2)=\frac{P_{1,2}(\mathbf{p}_1,\mathbf{p}_2)}{P_1(\mathbf{p}_1)\cdot P_2(\mathbf{p}_2)}$$

Application of unfolding to ALICE data



- Femto correlation produces spike at (Δη,Δφ)=(0,0)
- Comparison of two peaks: 1-bin wide projection on Δφ (subtract minimum)
- **Both the height and the width of two peaks are comparable!**

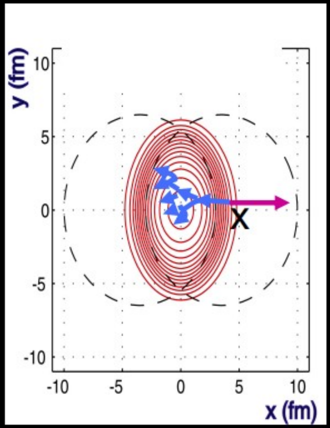
History – High Momentum Particle & Jet Correlations

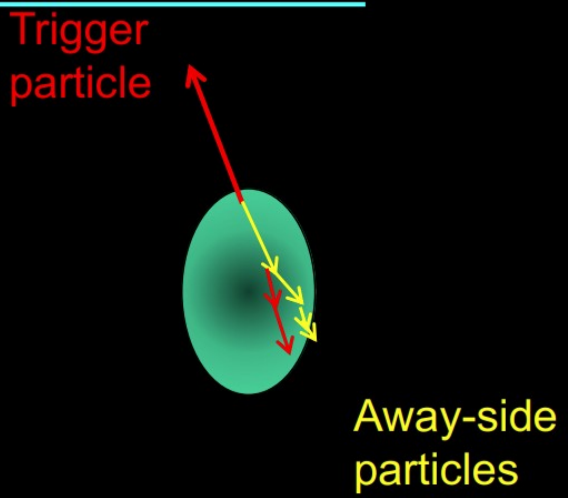
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.





Back-to-back Jets Away-side jets NOT quenched in pp collisions

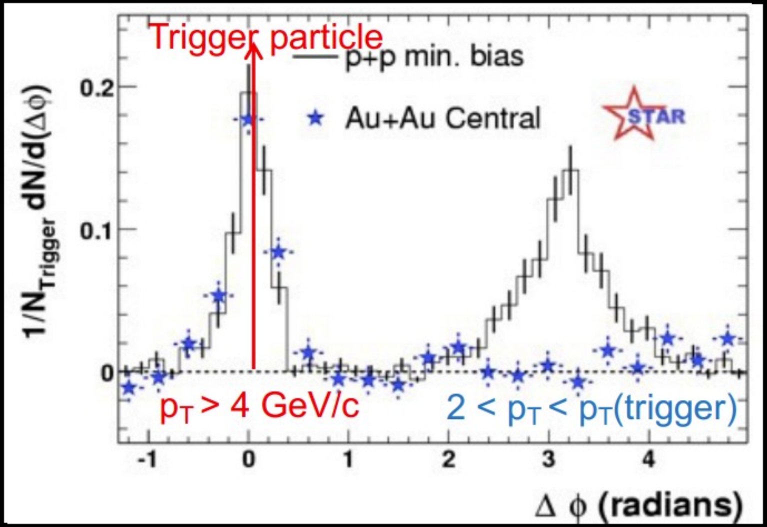
Back-to-back Jets Away-side jets observed as quenched in central Au + Au

Not quenched in Hi Mult d+Au

→ *trigger particle origin near surface*

→ strongly interacting medium

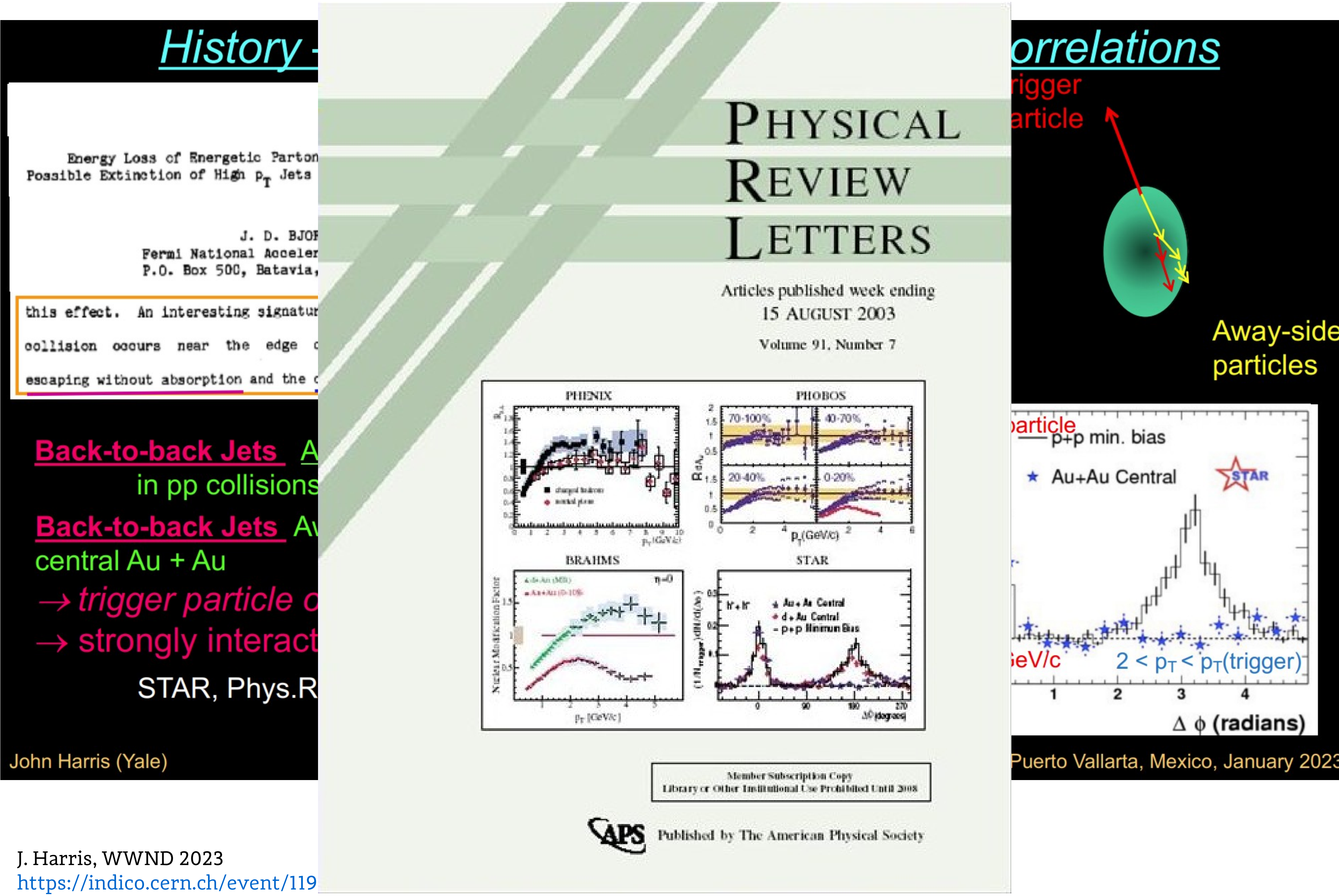
STAR, Phys.Rev.Lett. 91 (2003) 072304



John Harris (Yale)

Puerto Vallarta, Mexico, January 2023

J. Harris, WWND 2023
https://indico.cern.ch/event/1196342/contributions/5228272



J. Harris, WWND 2023
https://indico.cern.ch/event/119

ΛΛ and pΛ correlation functions

ALICE, Eur. Phys. J. C 77 (2017) 569

Baryon-Antibaryon | Baryon-Baryon

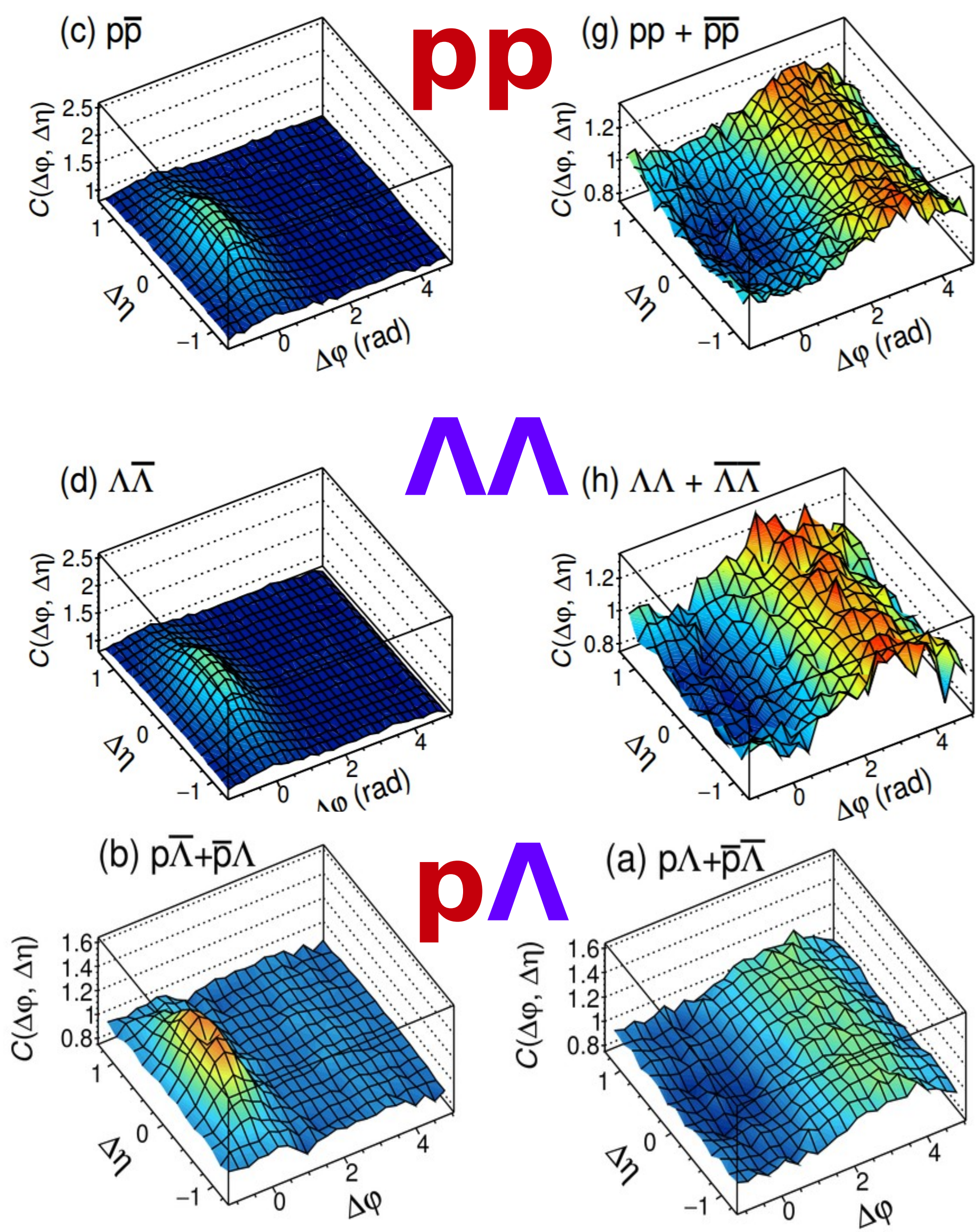
- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?

- Correlation functions were calculated for **ΛΛ and pΛ** pairs

- **Λ** baryons are neutral → no Coulomb repulsion

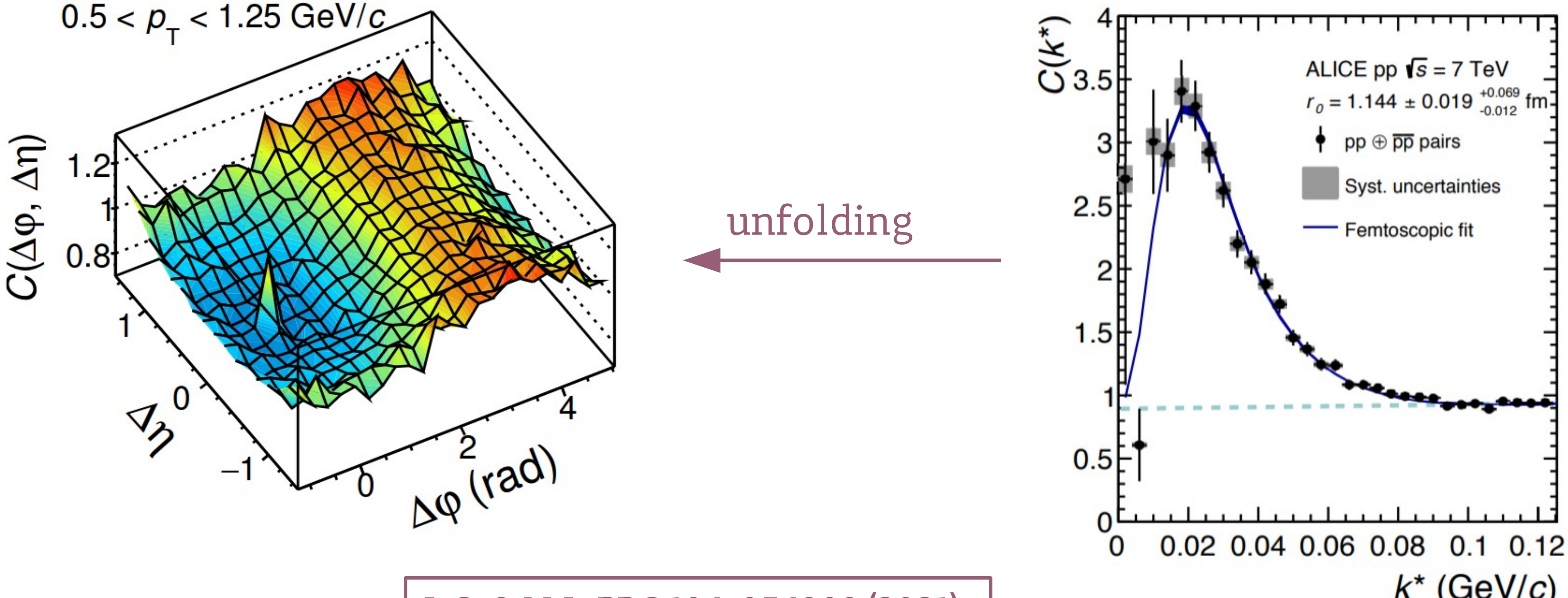
- **p** and **Λ** are not identical → no effect from Fermi-Dirac statistics

- **All observations from pp can be extended to ΛΛ and pΛ**



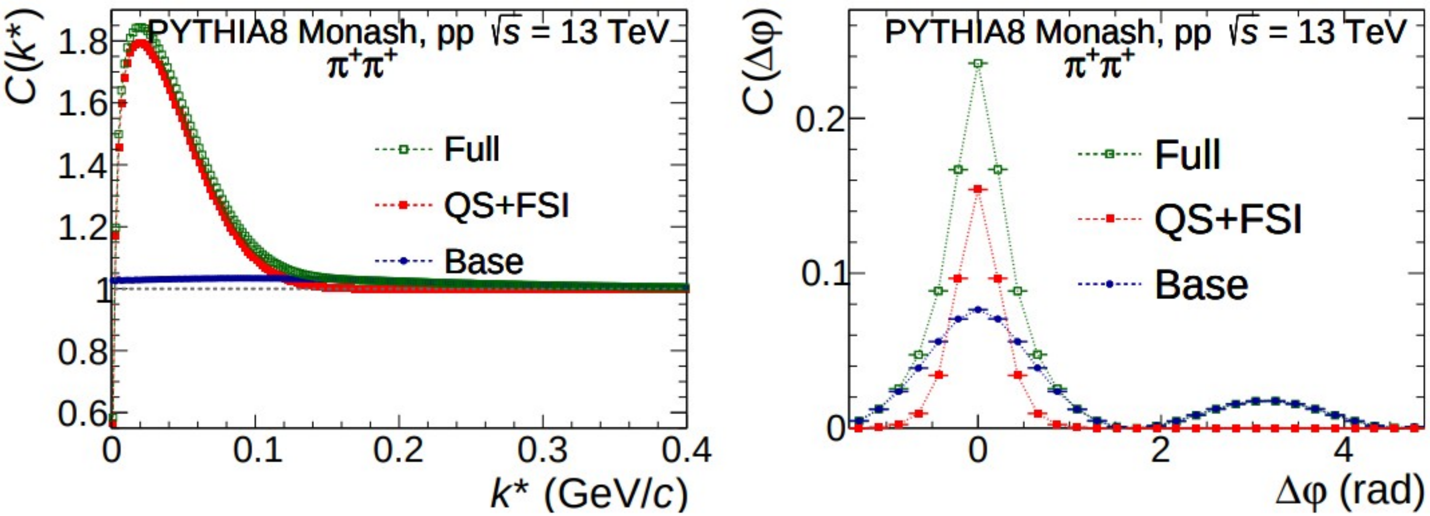
In our new paper we propose a **simple algorithm** to **unfold** the angular correlation from measured femtoscopic one

- we test the method with PYTHIA 8 simulations coupled to Lednicky and Lyuboshitz formalizm
- we show **how** the effects of **strong FSI and QS** manifest in angular correlations



Ł.G. & M.J., PRC 104, 054909 (2021)

Ł.G. & M.J., PRC 104, 054909 (2021)



1. $C_{\text{base}} = S/M$, where M is the mixed-event distribution, contains only the event-wide correlations, without the QS and FSI effects added by the afterburner;

2. $C_{\text{full}} = S_{\text{w}}/M$ contains the full information, that is the event-wide correlations with additional effects of QS and FSI added by the afterburner;

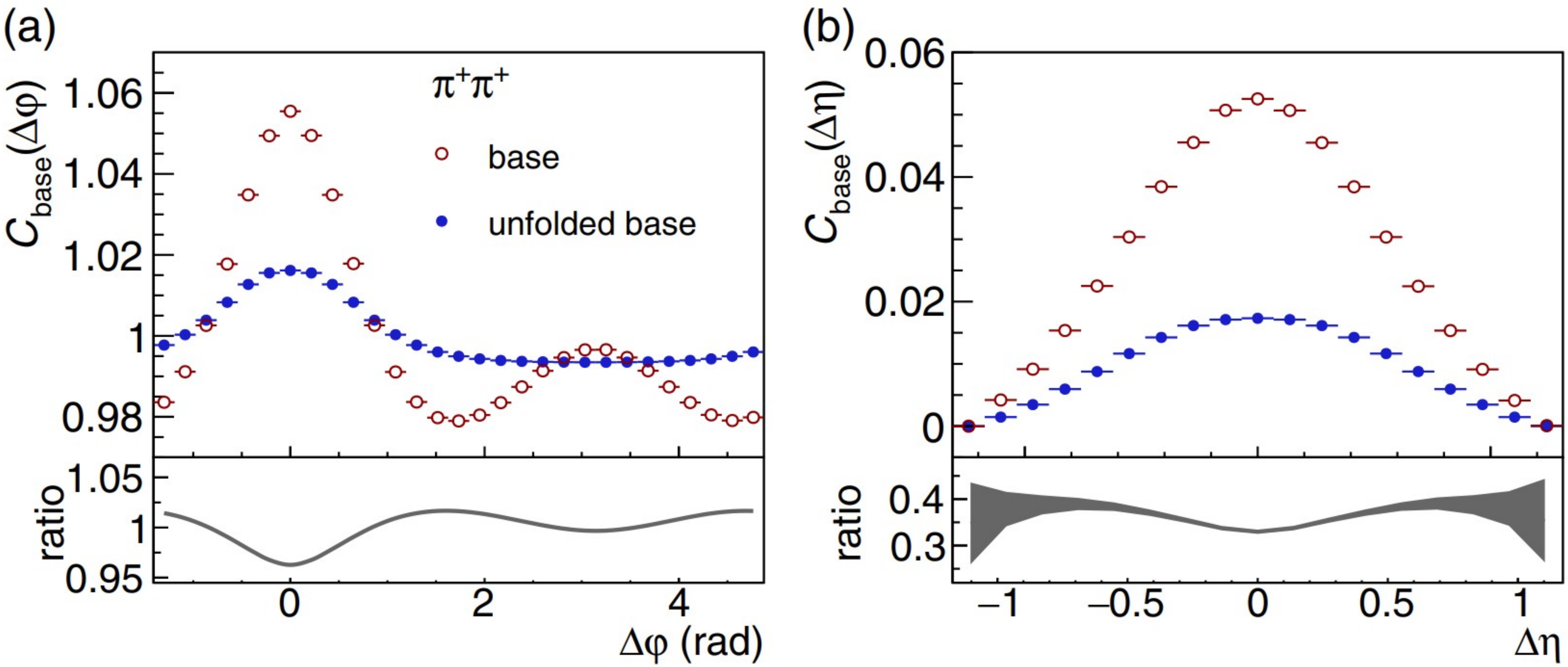
3. $C_{\text{QS+FSI}} = M_{\text{w}}/M$ contains only the effects related to QS and FSI and is an equivalent to numerical integration of Eq. (2).

S – same event distribution
M – mixed event distribution
w – weight from Lednicky model

Base CF unfolding, pions

Ł.G. & M.J., PRC 104, 054909 (2021)

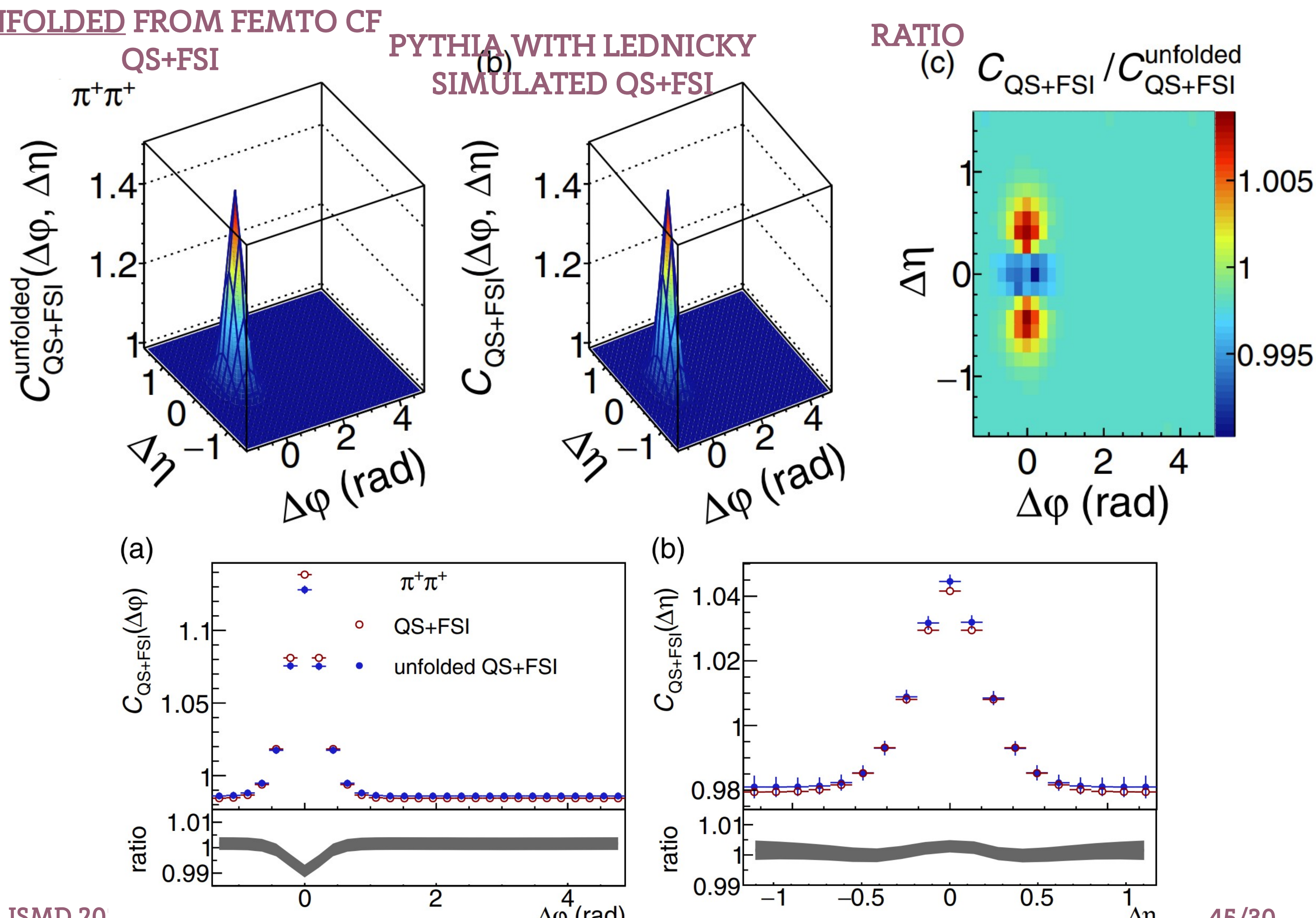
→ the global energy-momentum conservation shape is, obviously, not preserved in unfolded angular CF



QS+FSI unfolding, pions

Ł.G. & M.J., PRC 104, 054909 (2021)

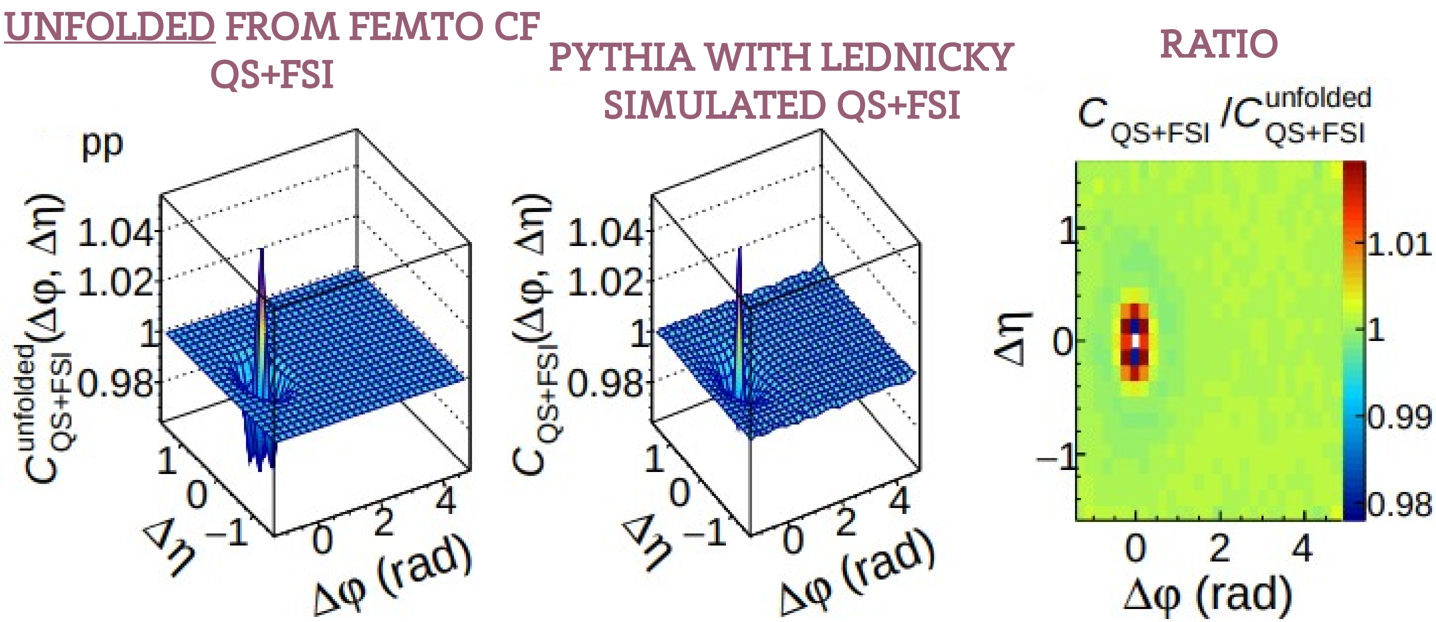
→ unfolding of the QS+FSI correlation, which is limited in k^*, works very well, here example for pions



QS+FSI unfolding, protons

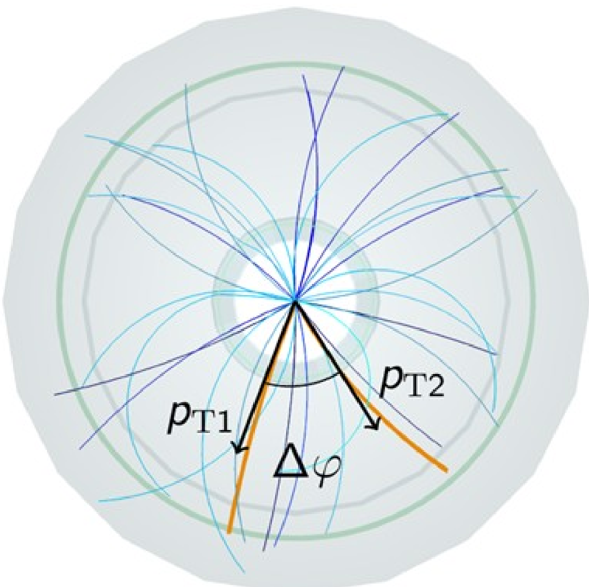
Ł.G. & M.J., PRC 104, 054909 (2021)

→ in the case of protons, the QS strong FSI is well-preserved and clearly seen as a sharp, narrow peak at (0,0), which proves the ALICE hypothesis

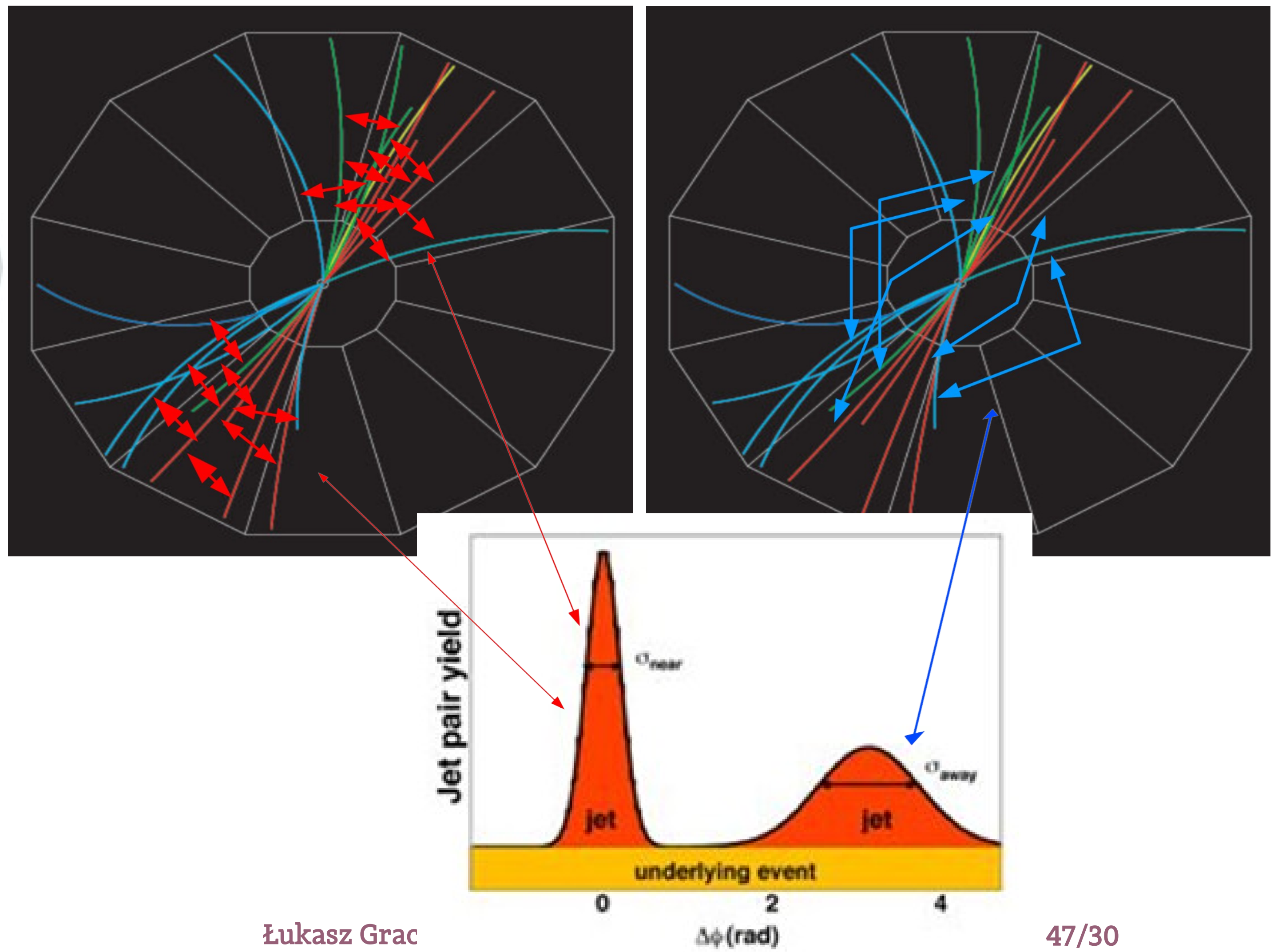


→ weaker femto CF for pΛ and ΛΛ pairs (weaker contribution from strong FSI) → less prominent "small peaks" in angular CF

- How to experimentally measure jets?
- We can look at the collision in the transverse plane and calculate azimuthal angle difference distribution:

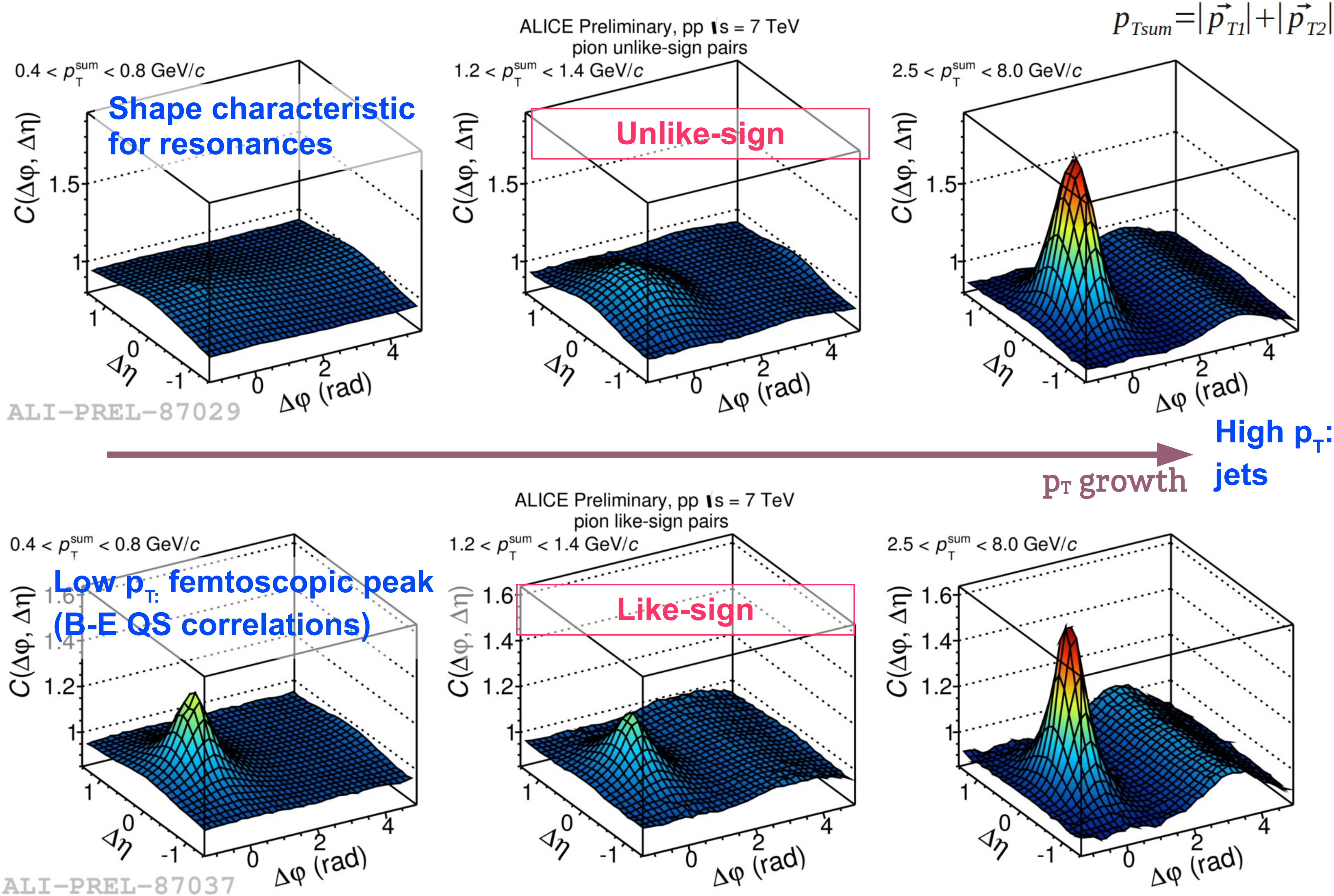


p_T - transverse momentum;
φ - azimuthal angle;



ALICE 7 TeV pp data - pions

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



Conservaltion LAws Model (CALM)

M. Janik, A. Kisiel, Ł. Graczykowski Nucl. Phys. A 956 (2016) 886-889

"Toy" Monte Carlo:

- Inclusion of conservation of energy, momentum and all quantum numbers local to the emission

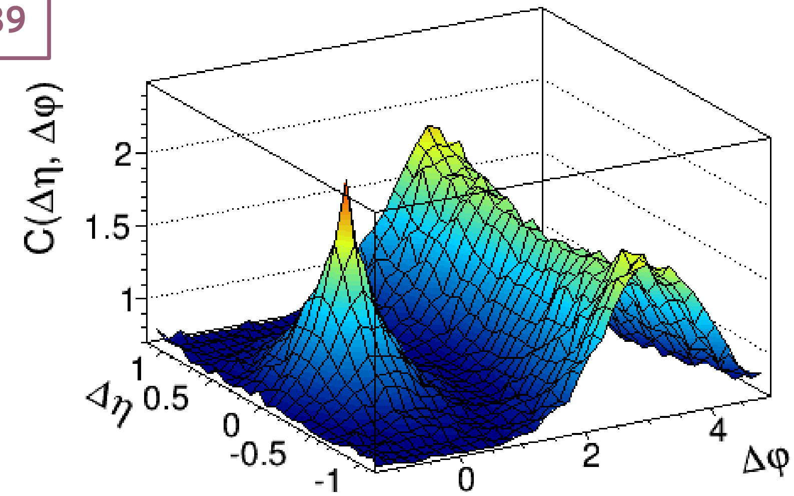
- Our toy MC reproduces the standard "jet" correlation shape with near-side peak and away-side ridge

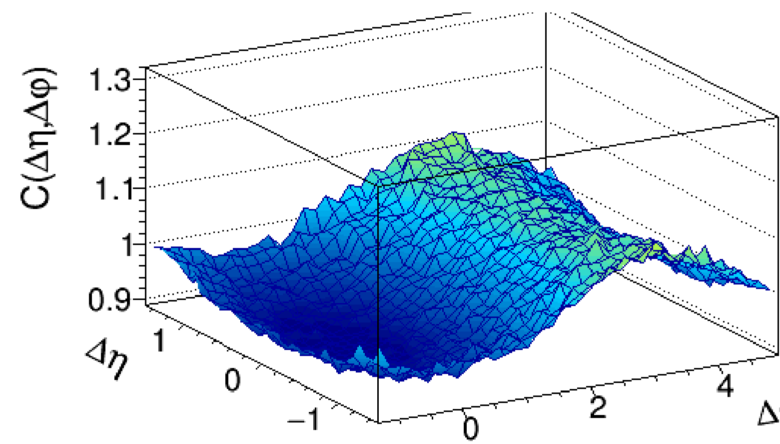
BUT

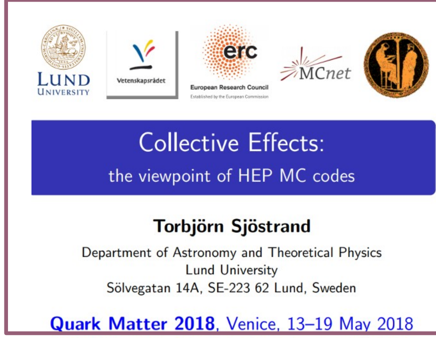
- Two-particle baryon-baryon correlation in data shows only global energy-momentum conservation features

- Yet, baryons **are** produced in jets (see e.g. proton-antiproton correlations), just no more than one

The puzzle remains unsolved!





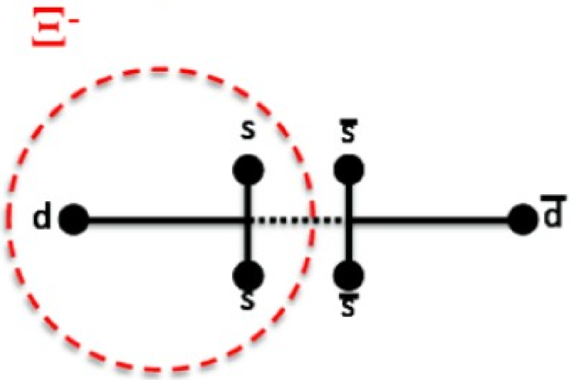


Nucl. Phys. A 982 (2019) 43-49

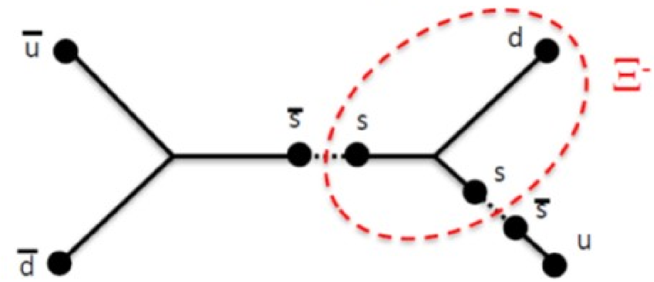
"The **real problem is baryon production**. [...] so it is clear we still lack some fundamental insight on baryon production, at least in the string context."

Further studies

PYTHIA (standard configuration):

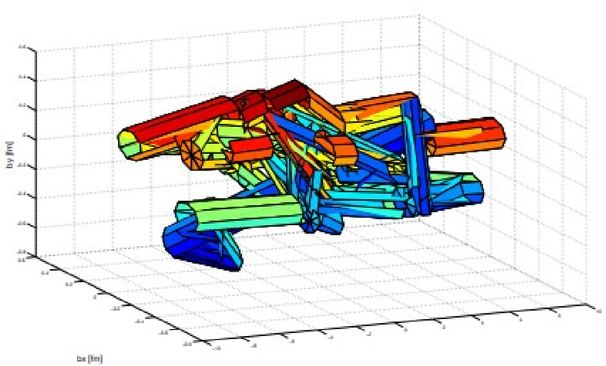


PYTHIA with junctions:

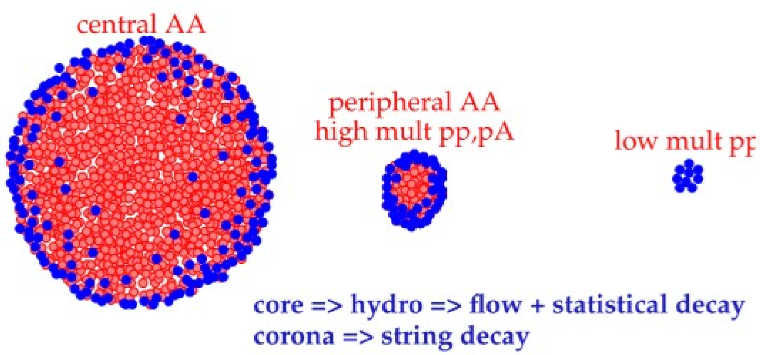


J. Adolfsson *et al.* *Eur. Phys. J. A* **56**, 288 (2020) (figures created by David Chinellato).

PYTHIA with ropes:



EPOS model:



C. Bierlich *et al.* *J. High Energ. Phys.* **2015**, 148
Bottom right: K. Werner. hal-02434245 (2019)

Predictions:

- PYTHIA: most quarks are produced at hadronisation ⇒ short-ranged correlations
- EPOS: quarks are produced in the core and diffuse before hadronisation ⇒ more long-ranged correlations

Three variants of CF

First, let's define three variants of the model correlation function:

1. $C_{\text{base}} = S/M$, where M is the mixed-event distribution, contains only the event-wide correlations, without the QS and FSI effects added by the afterburner;

2. $C_{\text{full}} = S_{\text{w}}/M$ contains the full information, that is the event-wide correlations with additional effects of QS and FSI added by the afterburner;

3. $C_{\text{QS+FSI}} = M_{\text{w}}/M$ contains only the effects related to QS and FSI and is an equivalent to numerical integration of $C(\mathbf{k}^*) = \int S(\mathbf{k}^*, \mathbf{r}^*) \; |\Psi(\mathbf{k}^*, \mathbf{r}^*)|^2 \, \mathrm{d}^4\mathbf{r}^*$;

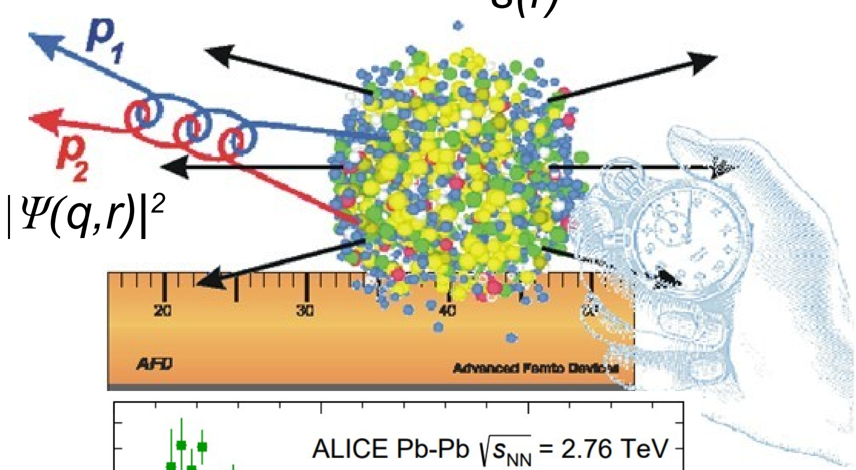
S – same event distribution
M – mixed event distribution
w – weight from Lednicky model

This can be done for <u>both</u> femtoscopic and angular CFs

Femtoscopy – "traditional"

from M. Lisa and S. Pratt

s(r)



$$C(q)=\int S(r)|\Psi(q,r)|^2 d^3 r$$

measured correlation

Obtained by experiment

emission function (source size/shape)

Unknown

Two-particle wave function

Interaction known

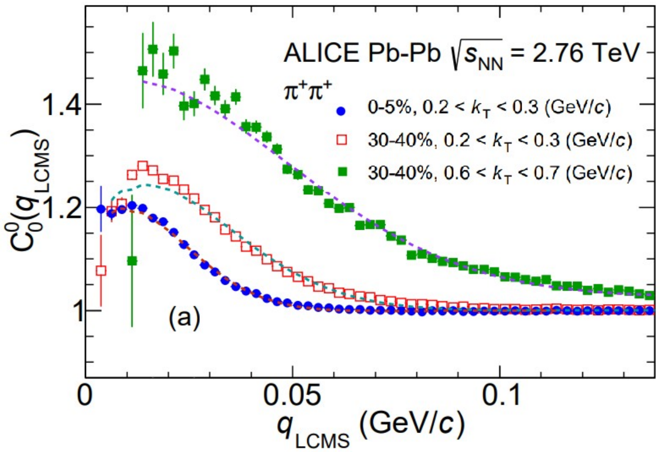
$$C(q)=N\frac{A(q)}{B(q)}$$

Probability ratio

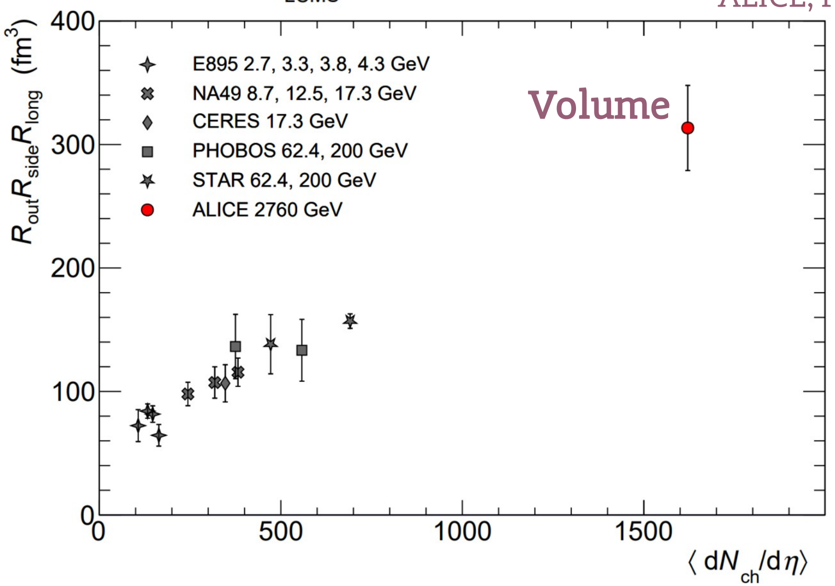
$$C(\mathbf{p_1},\mathbf{p_2})=\frac{P_{1,2}(\mathbf{p_1},\mathbf{p_2})}{P_1(\mathbf{p_1})\cdot P_2(\mathbf{p_2})}$$

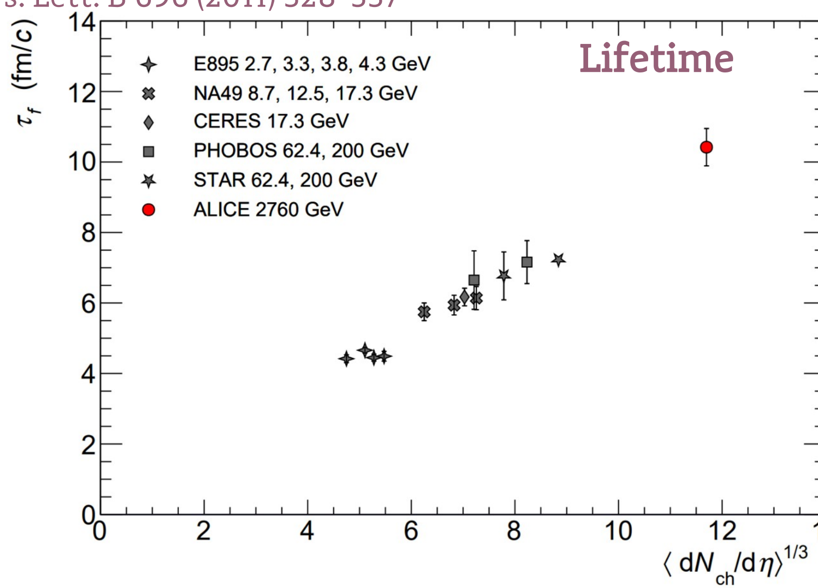
$$q=2\cdot k^*=p_1-p_2$$

$$r=x_1-x_2$$



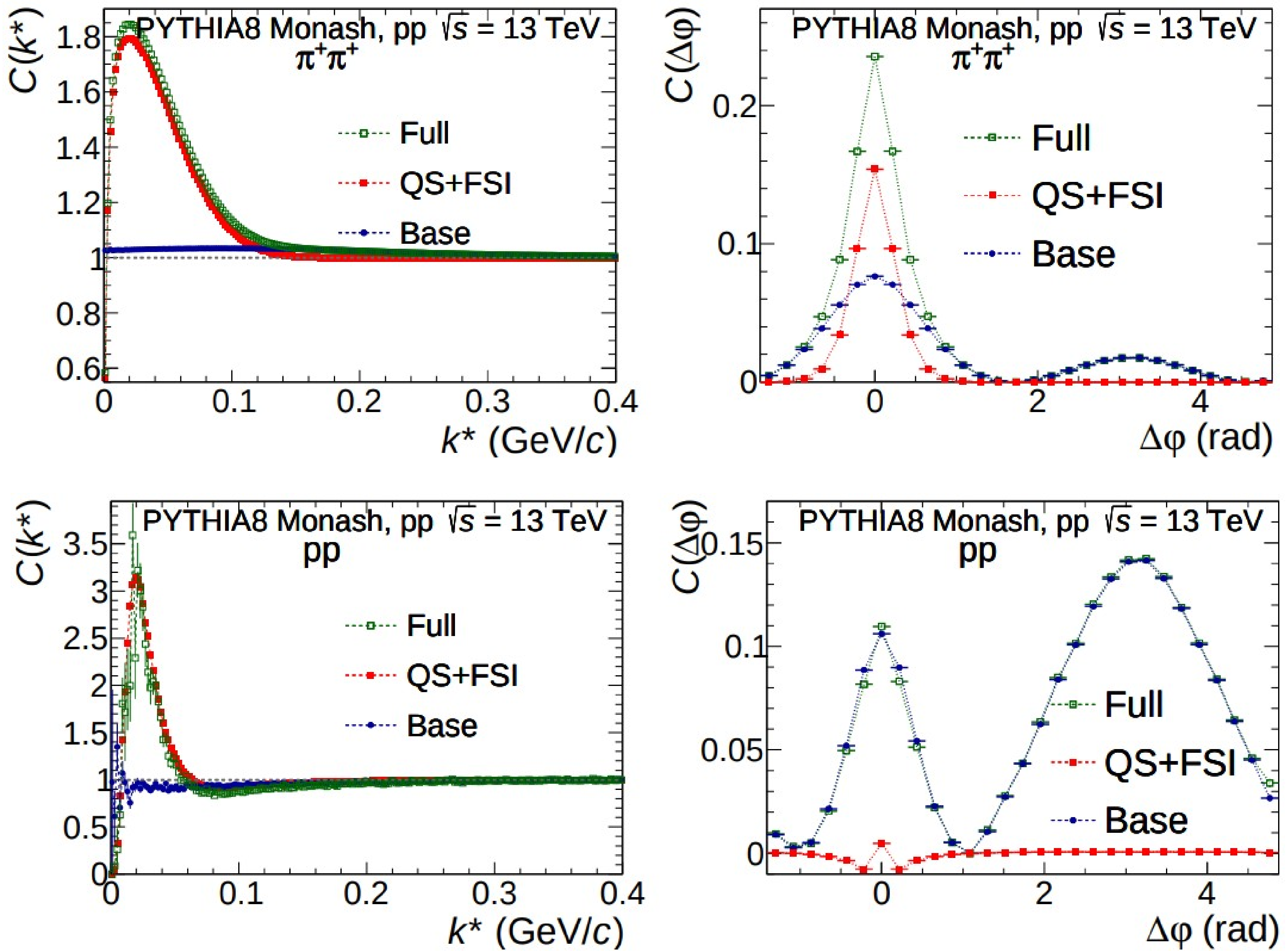
ALICE, Phys. Lett. B 696 (2011) 328-337





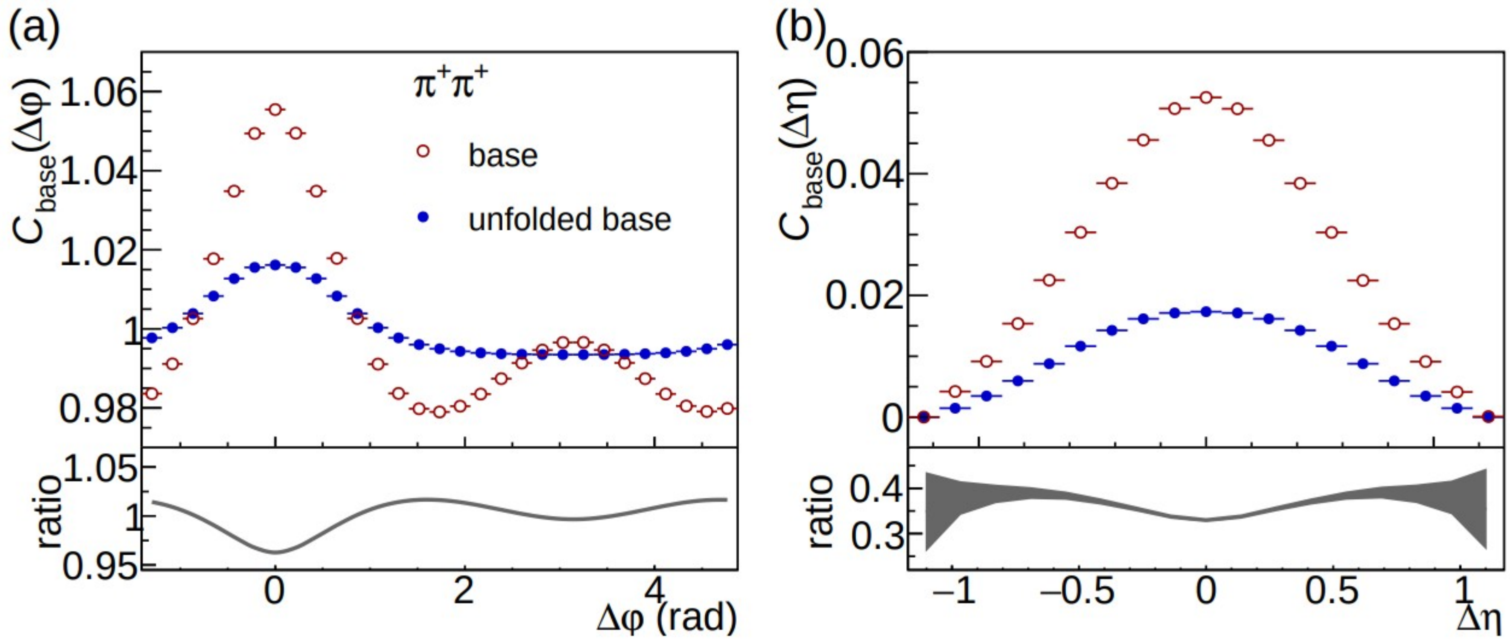
Three variants of CF

Calculated variants of femtoscopic and angular CFs using PYTHIA simulated events coupled to the L-L code



What about Base and Full variants?

- **The proposed unfolding procedure will work ONLY for short-range correlations, which include FSI and QS**
  - for long-range (large k^*) correlations, i.e. jets, our algorithm is **too simple**
    → i.e. no energy-momentum conservation with such simple sampling



- **Nevertheless, the algorithm works well for our use case and explains the origin of the small peak**

Lednicky-Lyuboshitz formula

$$C(q)=\int S(r)\left|\Psi(q,r)\right|^2 d^3 r \qquad q=2\cdot k^*=p_1-p_2$$

measured correlation — emission function (source size/shape) — pair wave function (includes cross section)

pair wave function → $\Psi=\exp(-ik^*r)+f\frac{\exp(ik^*r)}{r}$ s-wave scattering approximation

scattering amplitude → $f^{-1}(k^*)=\frac{1}{f_0}+\frac{1}{2}d_0 k^{*2}-ik^*$ effective range approximation

If **only** Strong FSI is present:

Lednicky-Lyuboshitz equation

$$C(k^*)=1+\sum_S \rho_S\left[\frac{1}{2}\left|\frac{f^S(k^*)}{R}\right|^2\left(1-\frac{d_0^S}{2\sqrt{\pi}R}\right)+\frac{2\Re f^S(k^*)}{\sqrt{\pi}R}F_1(2k^*R)-\frac{\Im f^S(k^*)}{R}F_2(2k^*R)\right]$$

Sov. J. Nucl. Phys., 35, 770 (1982)

where ρ_S are the spin fractions

The correlation function is characterized by **three parameters**:

- **radius** R, **scattering length** f_0, and **effective radius** d_0
- **cross section** σ **(at low** k*) is simply: $\sigma=4\pi|f|^2$