Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

ALICE in particle wonderland

understanding the strong interaction with hadron correlations

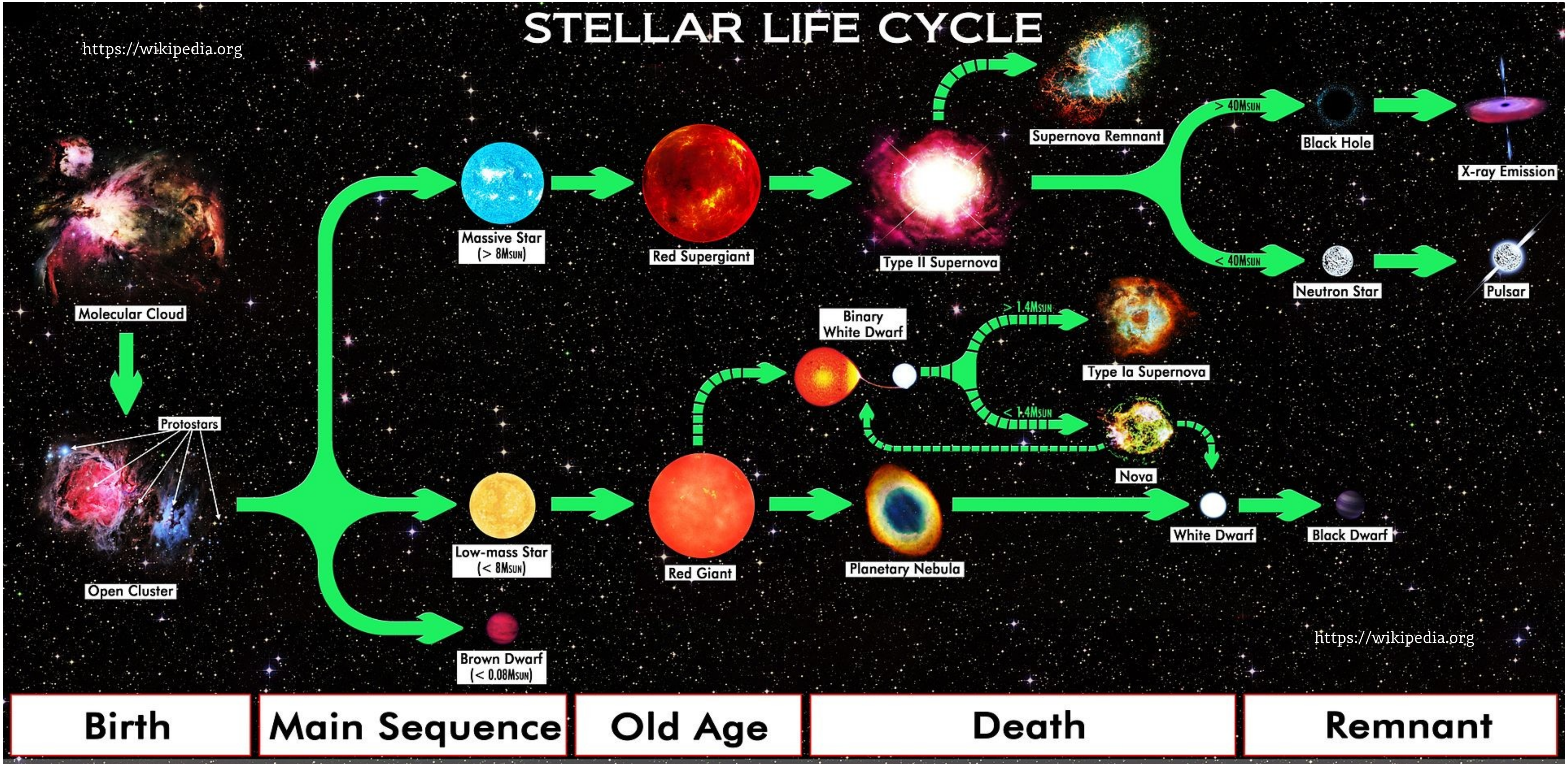
Łukasz Graczykowski

Institute of Nuclear Physics of the Polish Academy of Sciences
Kraków, Poland
June 13, 2023

Warsaw Telescope, Las Campanas, Chile
University of Warsaw

https://fuw.edu.pl

Life of a star



All stars die when the fusion reaction ceases

Massive stars end their life with Supernovae, which leaves:

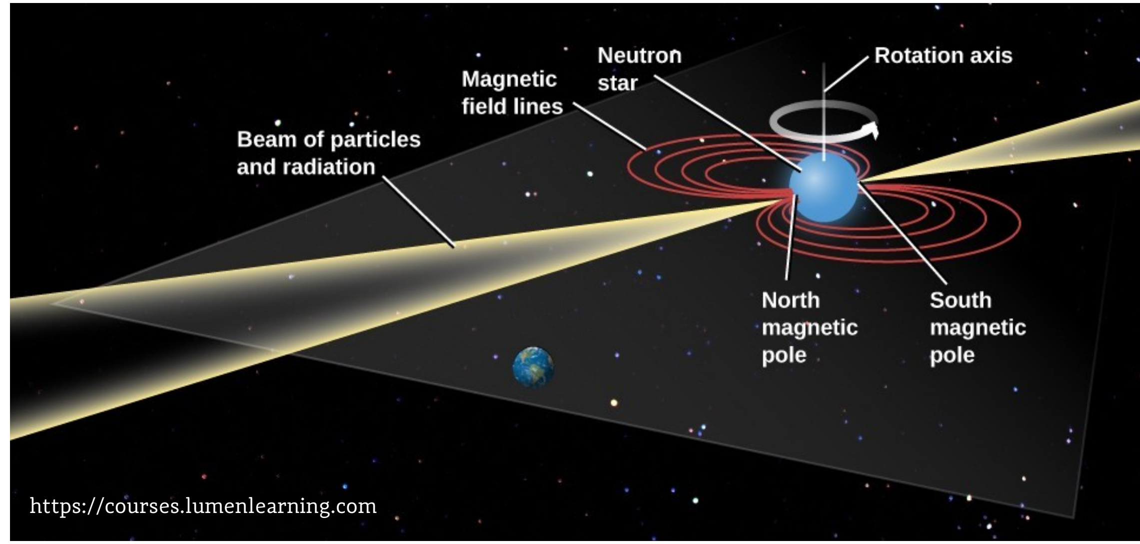
- Black hole
- **Neutron star** (NS)

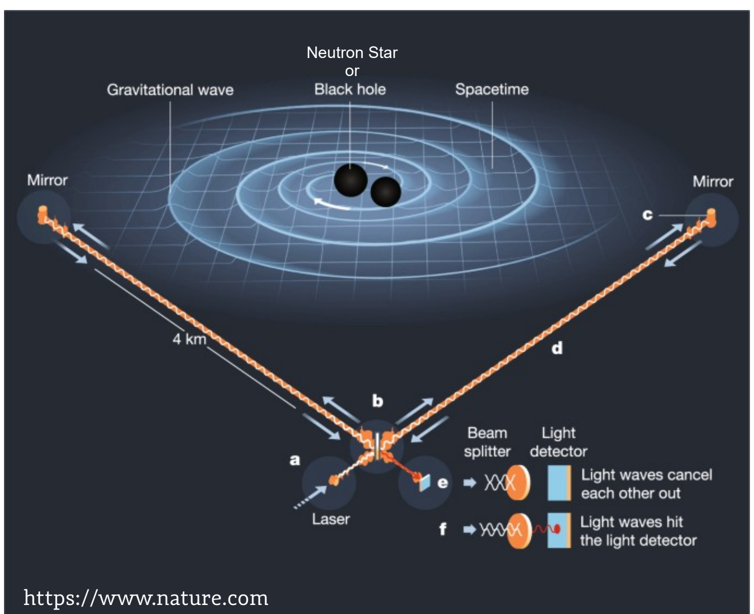
Detecting neutron stars

How do we detect NS?

Radiation from spinning in regular pulses (**pulsars**)

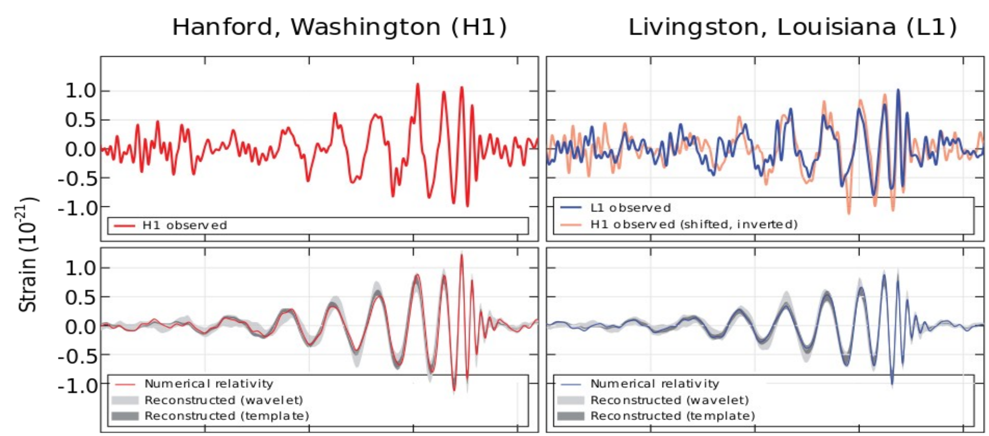
Gravitational waves from NS collisions (**mergers**)

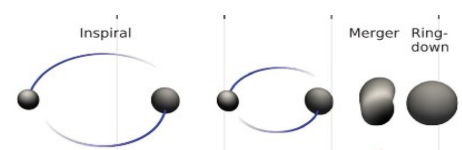




LIGO

VIRGO





Phys.Rev.Lett. 116, 061102 (2016)

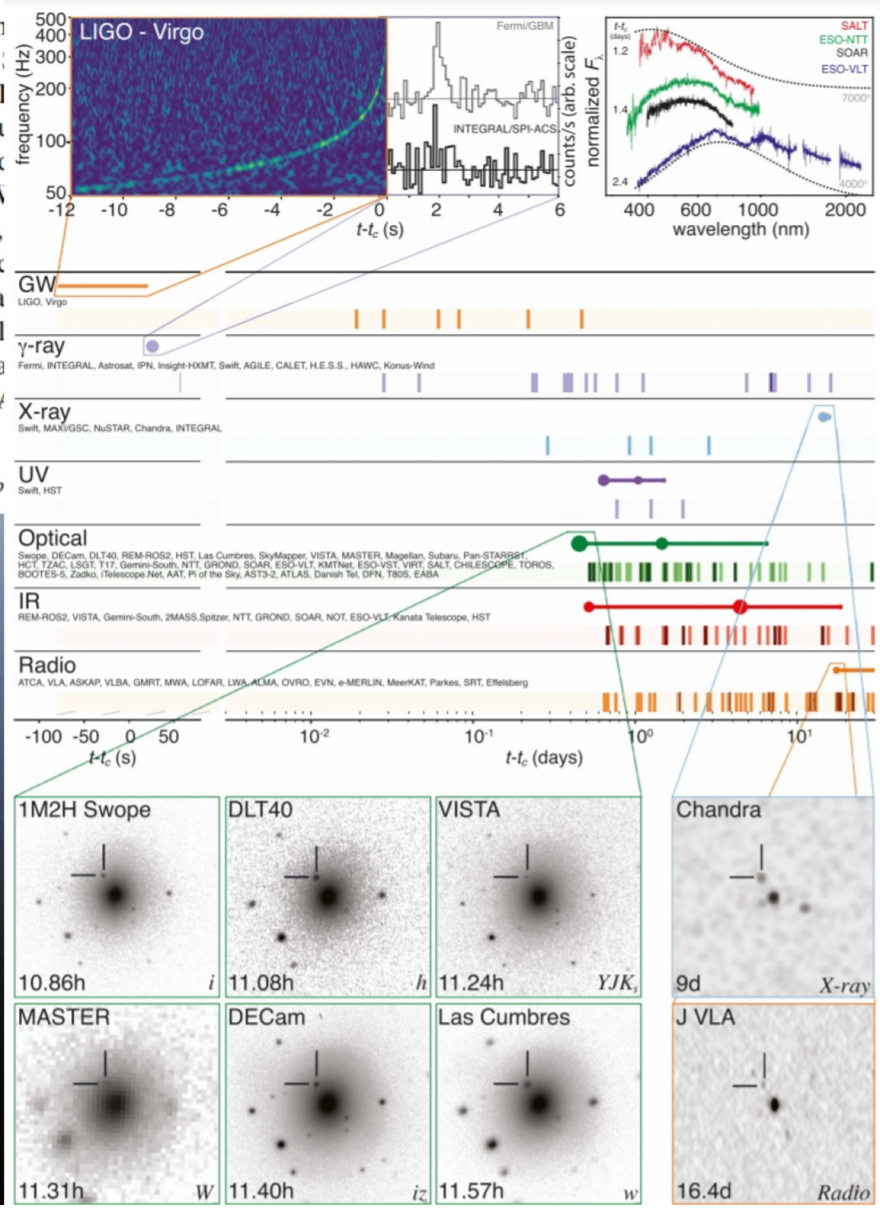
First detection of gravitational waves

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

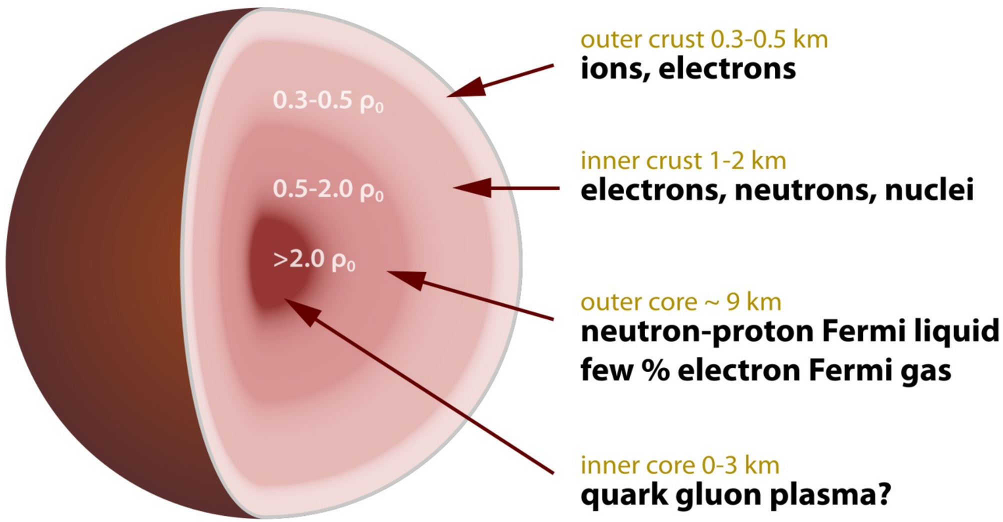
Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration
Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The
Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, T
GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Au
Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wi
and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GRO
NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium,
Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic
Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collabora
Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Coll
Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team a
Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SK
(See the end matter for the full list of authors.)

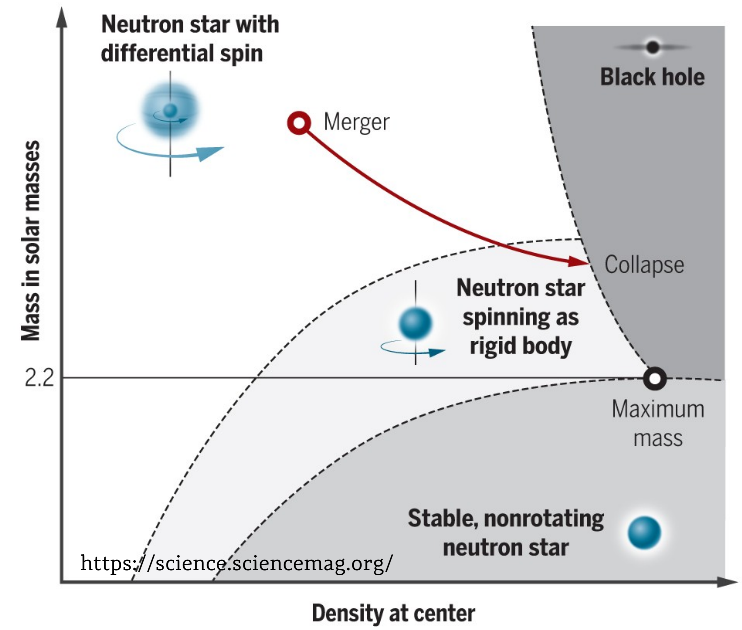
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 Octob



Properties of a NS

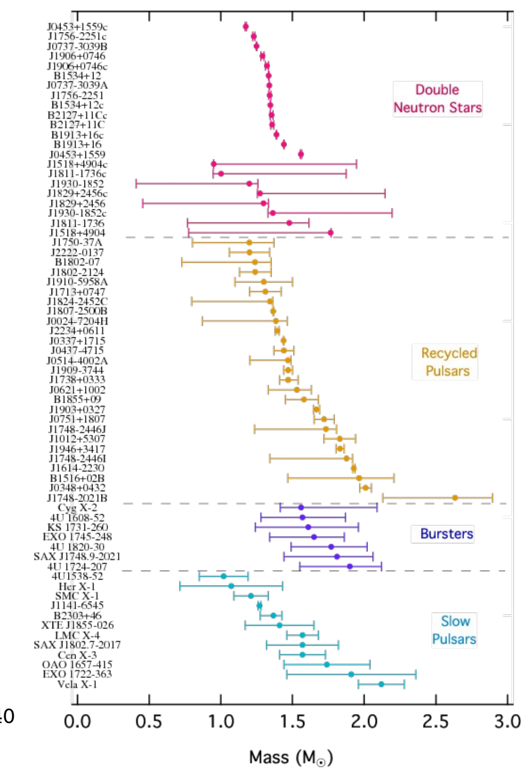


https://wikipedia.org



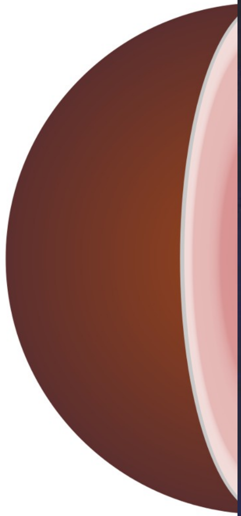
Neutron star properties:

- mass between 1.2-2.2 $M_{\odot}$ ($M_{\odot}$ – mass of the Sun)
- radius 10-15 km
- density and pressure grows towards the center
- composition of the inner core remains unknown

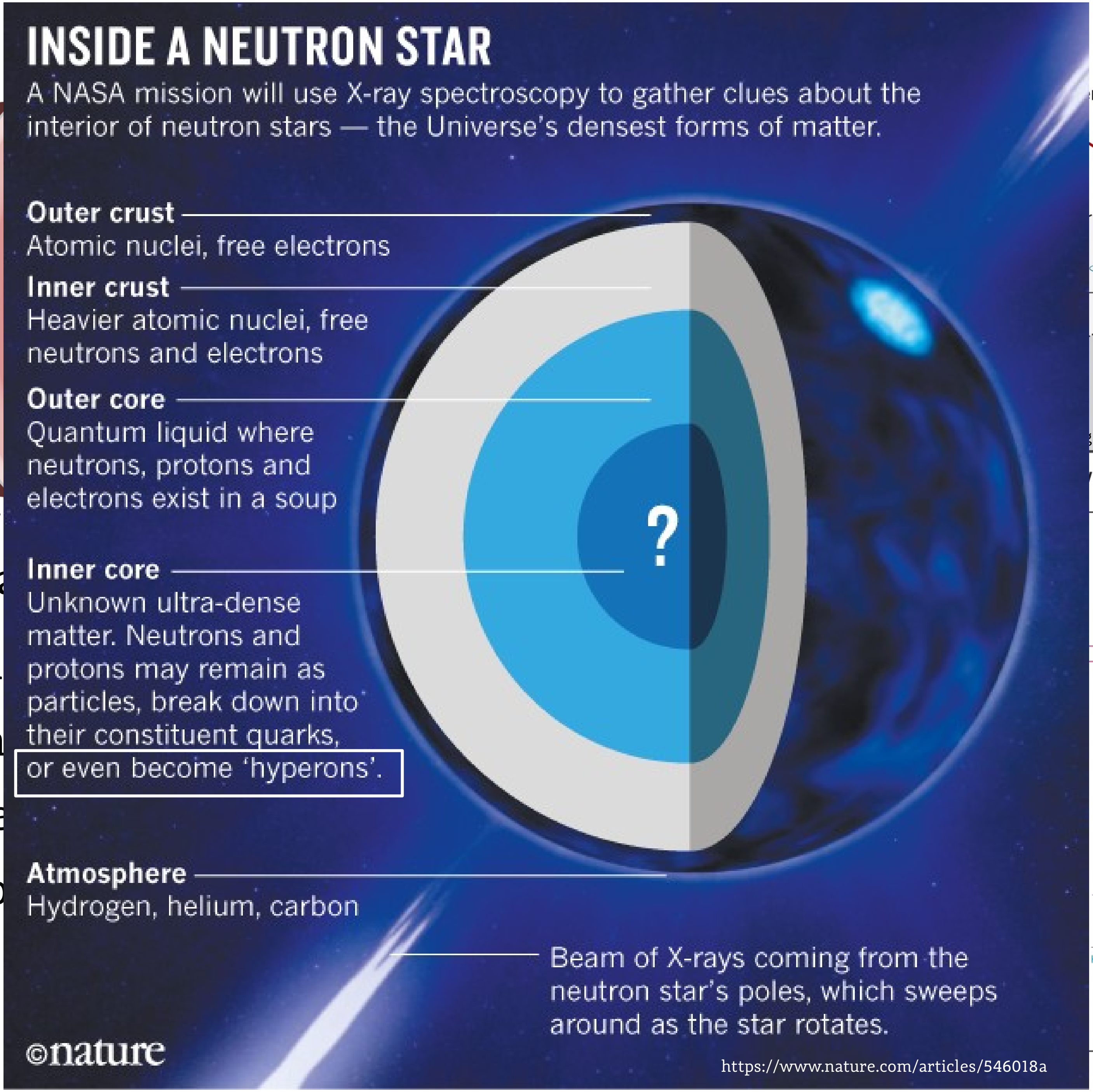


Ann.Rev.Astron.Astrophys. 54 (2016) 401-440

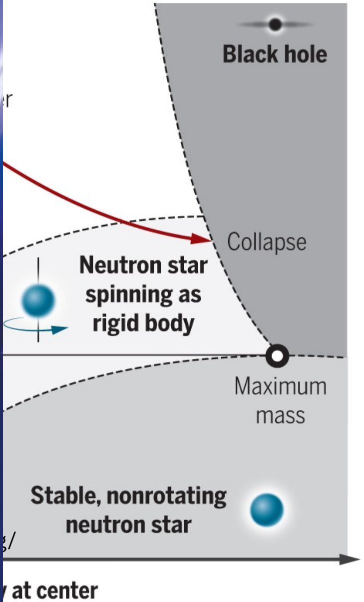
Properties of a NS

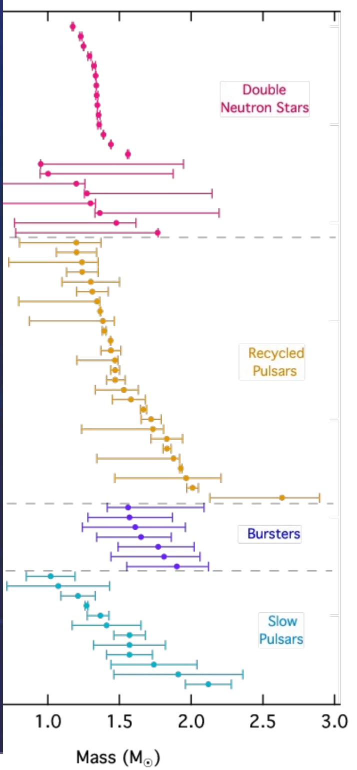


https://wikipedia.org



https://www.nature.com/articles/546018a

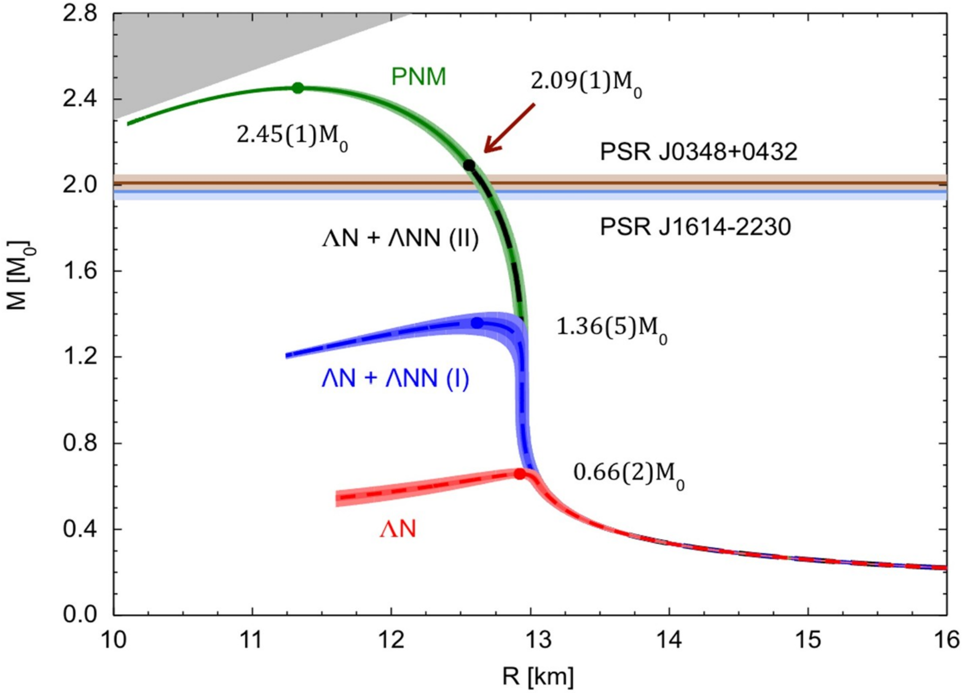




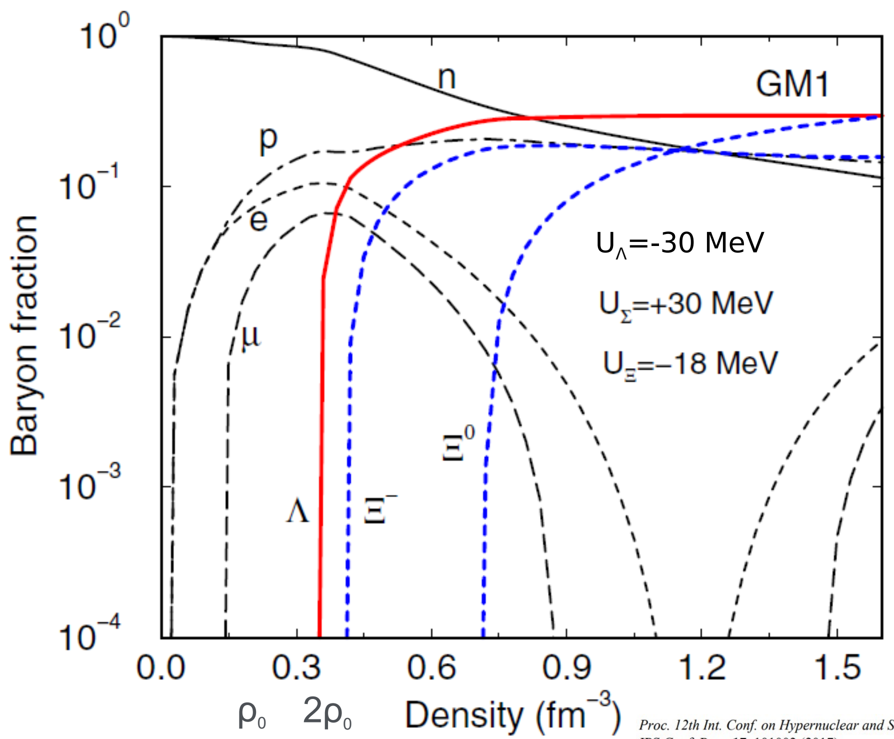
Neutron Sta

- m
- ra
- de
- co

- Due to very high density in the core of NS hyperons are expected to exist
- Introduction of hyperons in the NS Equation-of-State (EoS) leads to **disagreement between astronomical observations and theoretical calculations**
- EoS depends on the hyperon (Y) – nucleon (N) and YY interaction
  - YN, YY and three-body YNN, YYN, YYY interactions are **very poorly known**

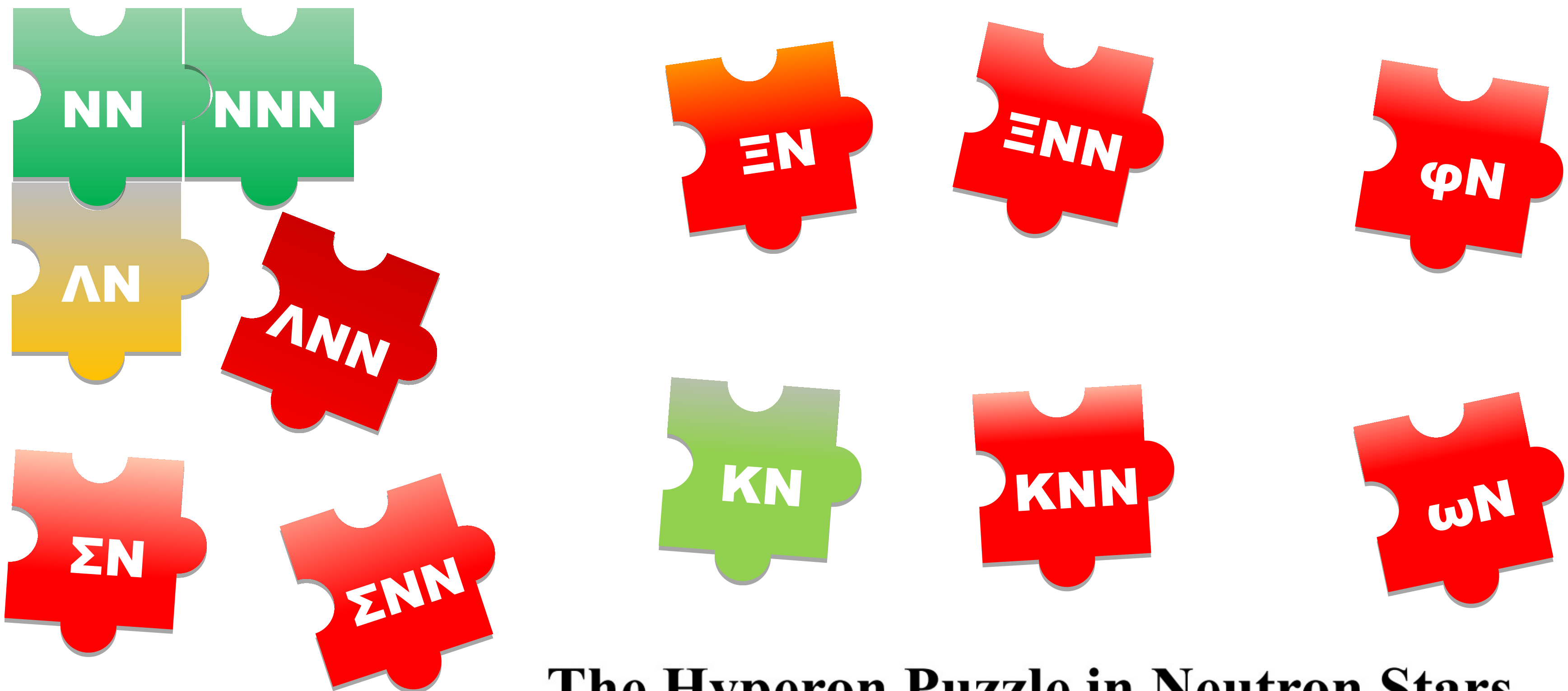


Adapted from D. Lonardoni et al., PRL 114, 092301 (2015)



Proc. 12th Int. Conf. on Hypernuclear and Strange Particle Physics (HYP2015)
JPS Conf. Proc. **17**, 101002 (2017)
https://doi.org/10.7566/JPSCP.17.101002

Neutron Star Hyperon Puzzle



The Hyperon Puzzle in Neutron Stars

Ignazio BOMBACI[1, 2, 3]

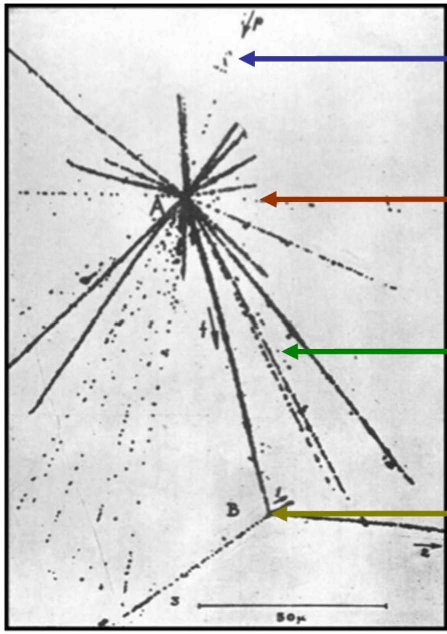
[1] *Dipartimento di Fisica, Universitá di Pisa, I-56127 Pisa, Italy*
[2] *INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[3] *European Gravitational Observatory, I-56021 S. Stefano a Macerata, Cascina Italy*

E-mail: ignazio.bombaci@unipi.it

Proc. 12th Int. Conf. on Hypernuclear and Strange Particle Physics (HYP2015)
JPS Conf. Proc. **17**, 101002 (2017)
https://doi.org/10.7566/JPSCP.17.101002

A.K. Wróblewski, Acta Phys. Polon. B 35 (2004) 3

Discovery of hypernuclei from cosmic rays by Marian Danysz (who had an electrical engineering degree from WUT, 1938) and Jerzy Pniewski



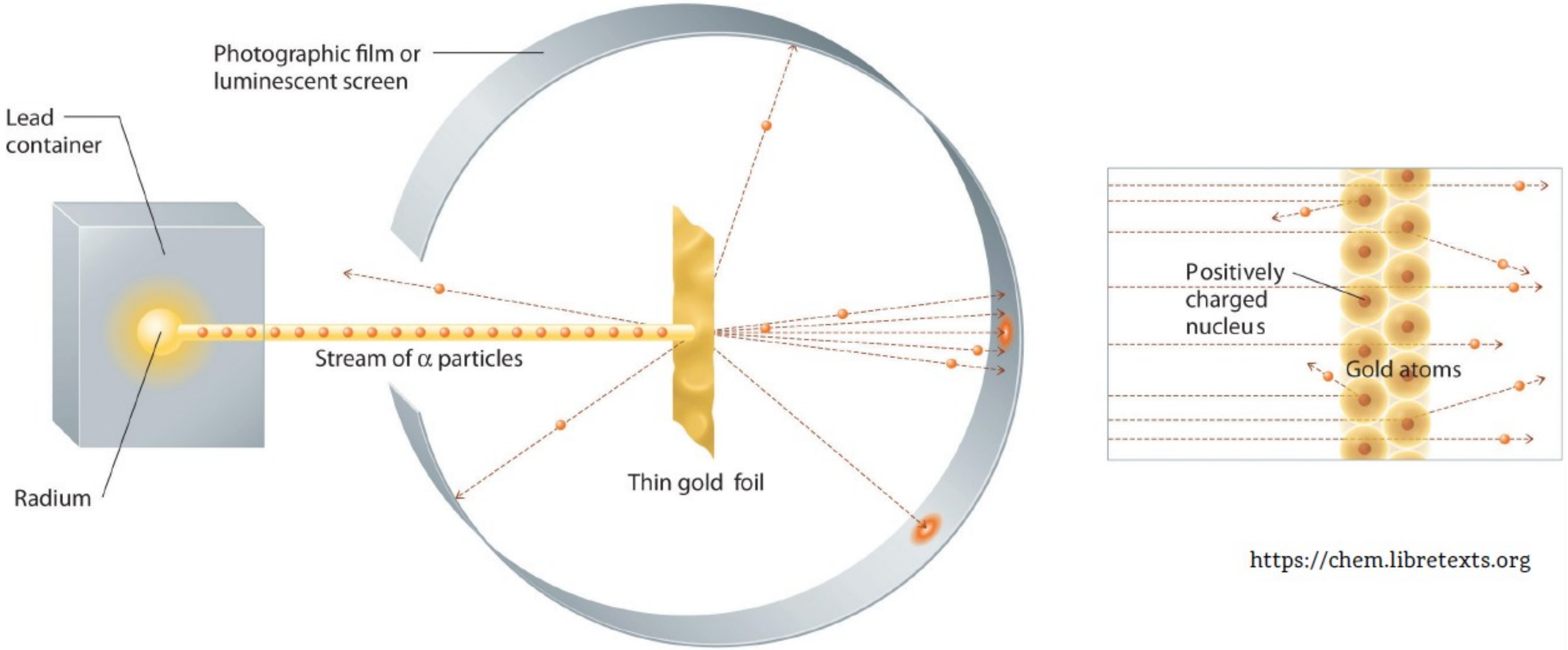
Incoming high energy cosmic ray (proton)

Collision with the nucleus

Nuclear fragments that eventually stop in the emulsion

One fragment containing a hyperon disintegrates weakly

I. Vidana, https://www.ggi.infn.it/talkfiles/slides/talk3205.pdf



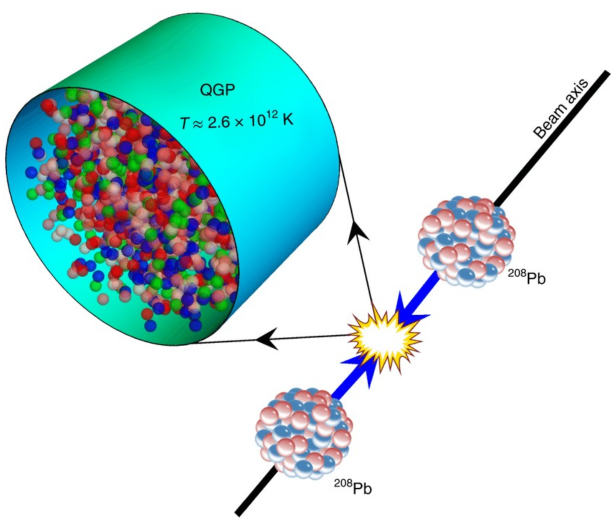
- NN interaction is precisely known from **scattering experiments**
  - beam of particles of one type bounces (scatters) off a specific target
  - idea similar to the Rutherford experiment from beginning of 1900s' (discovery of atomic nuclei)
  - **beams are easily available for stable and charged particles only!**

Quark-Gluon Plasma

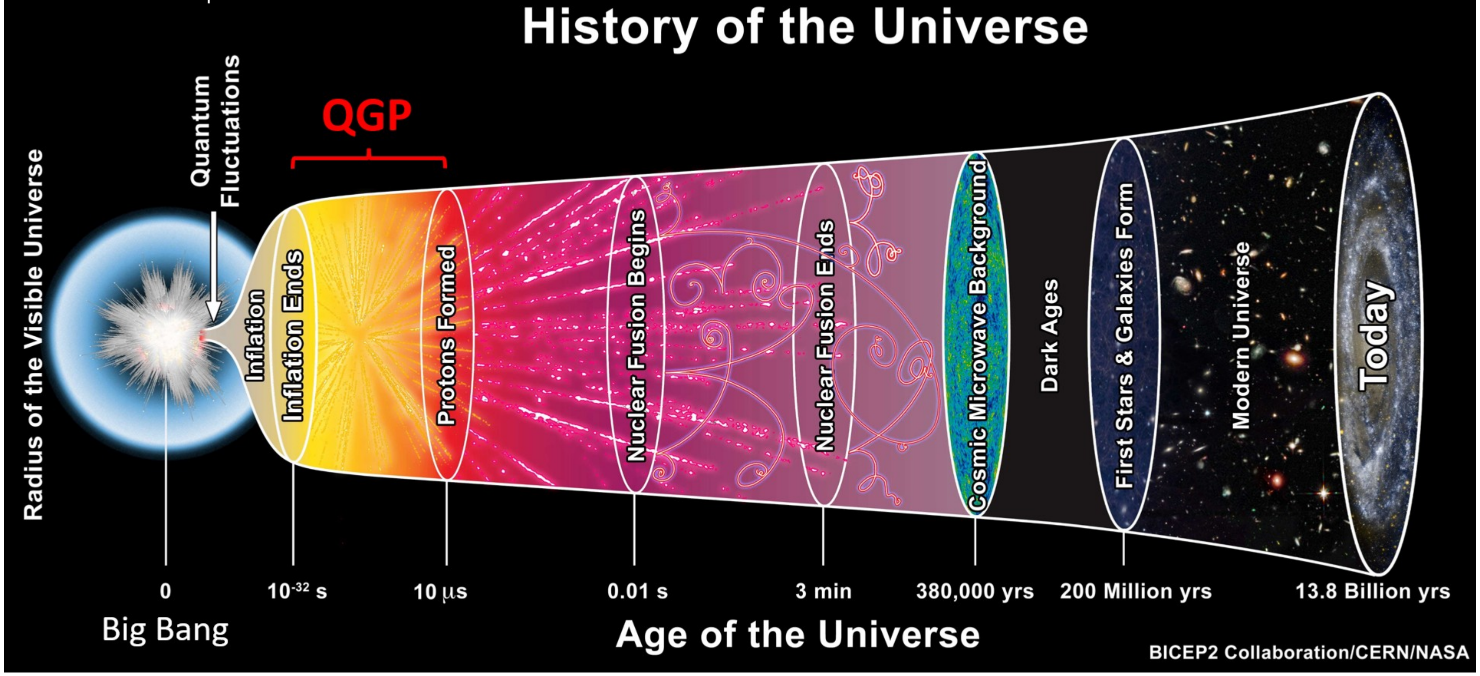
Quark-Gluon Plasma (QGP) is a state of **deconfined** quarks and gluons in a thermal equilibrium

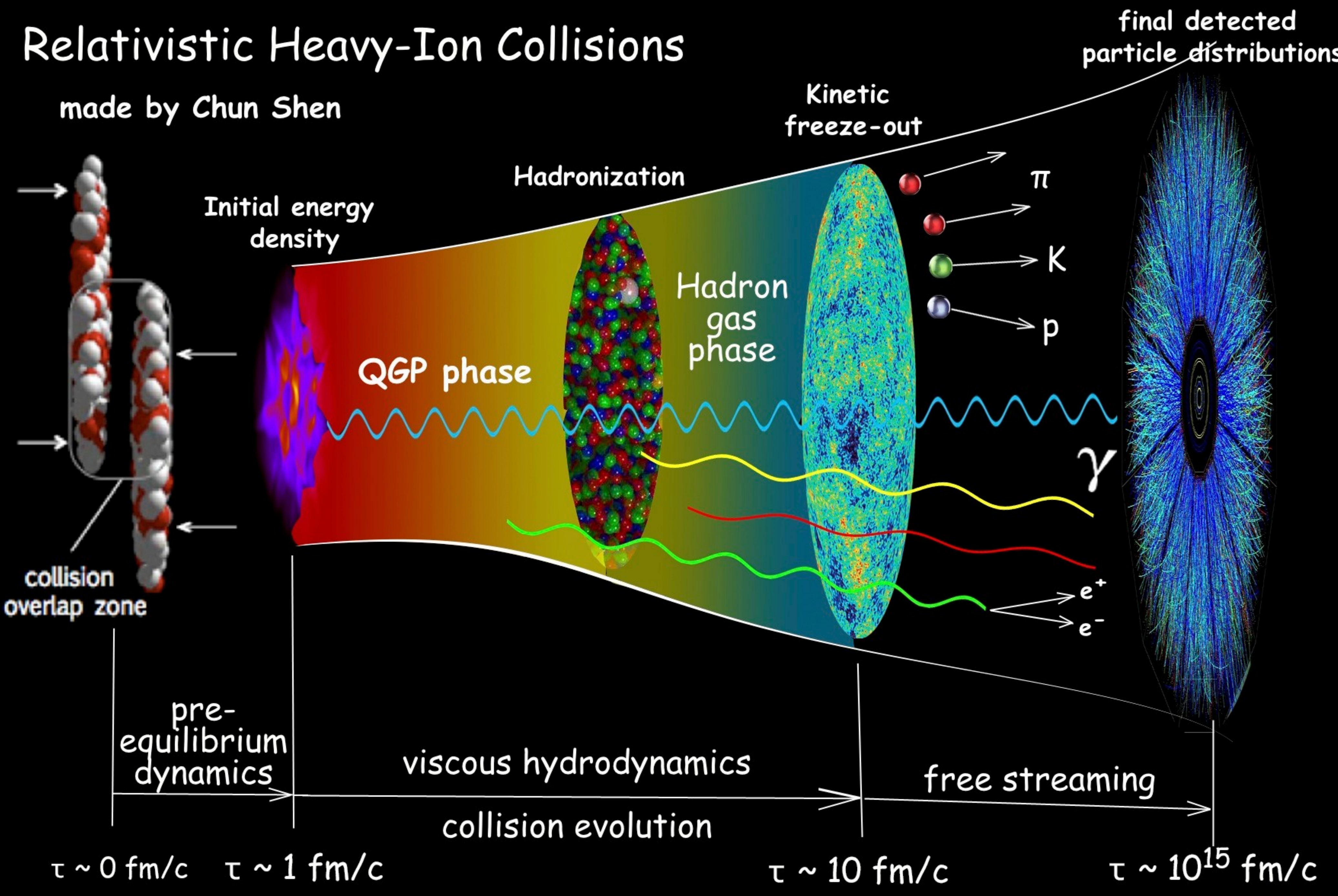
In a generally accepted model of the evolution of the Universe QGP existed in a such a state few microseconds after the Big Bang

Nature Physics 16, 615–619 (2020)

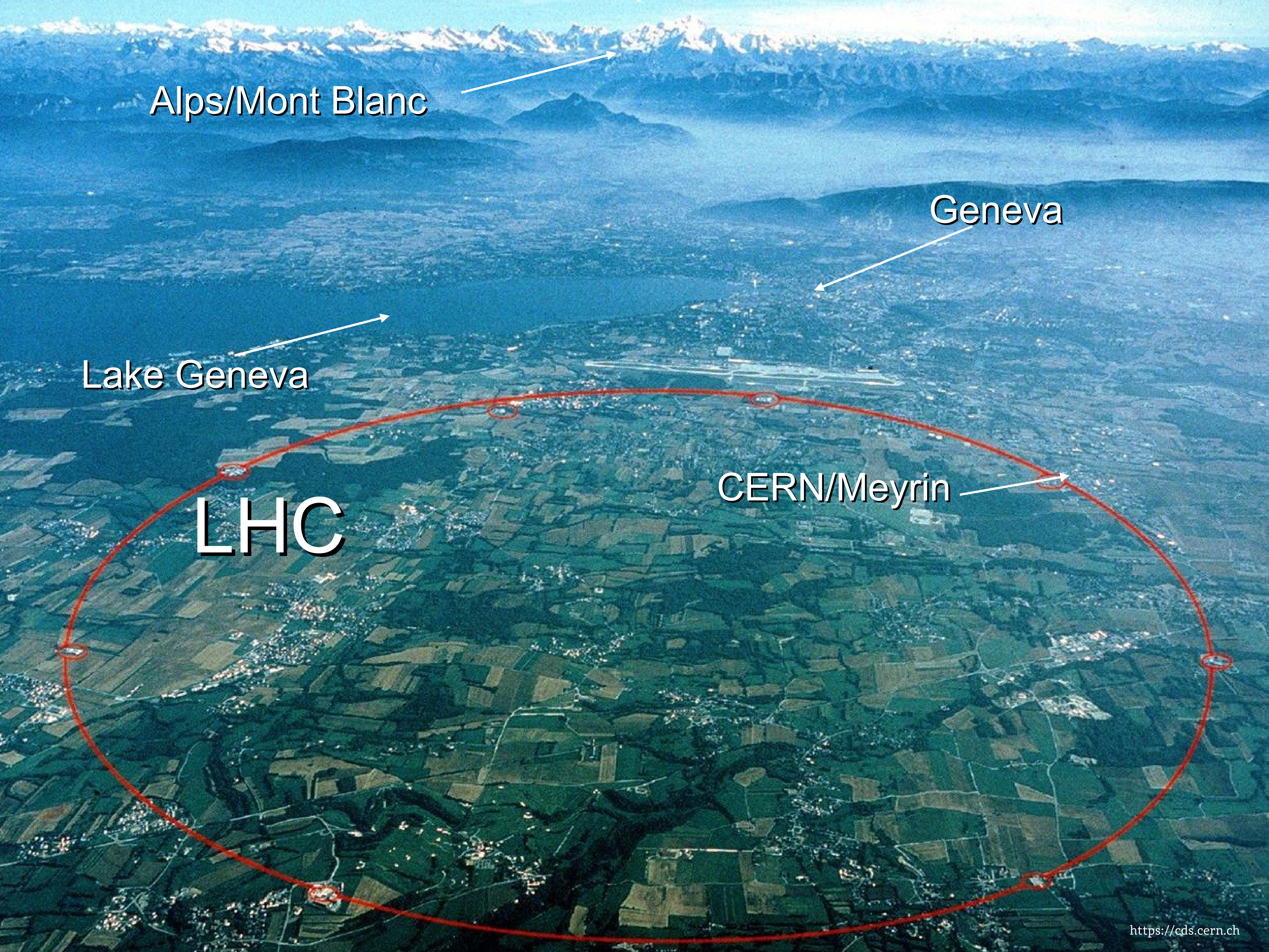


https://rolandkatz.com/



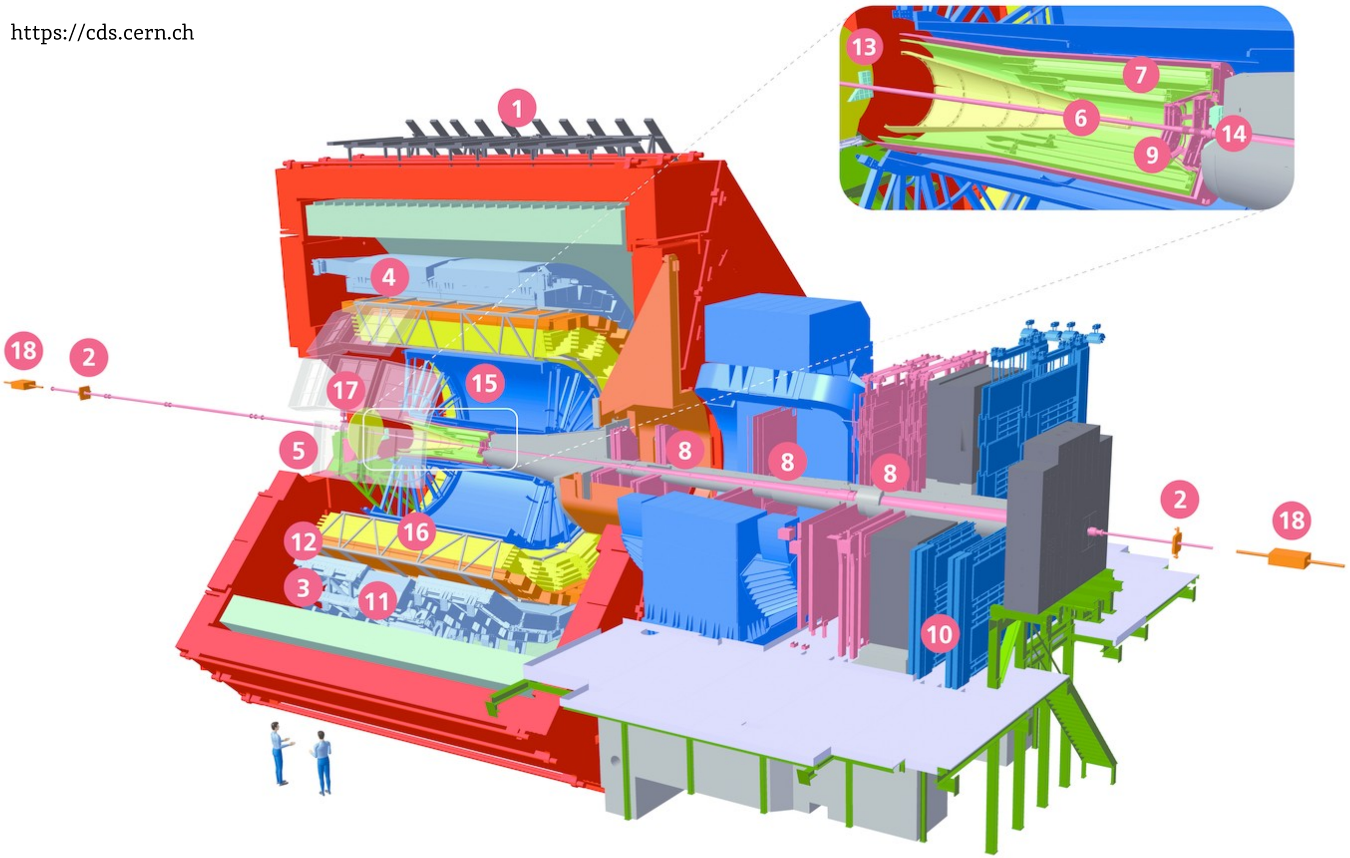


https://u.osu.edu/vishnu/2014/08/06/sketch-of-relativistic-heavy-ion-collisions/

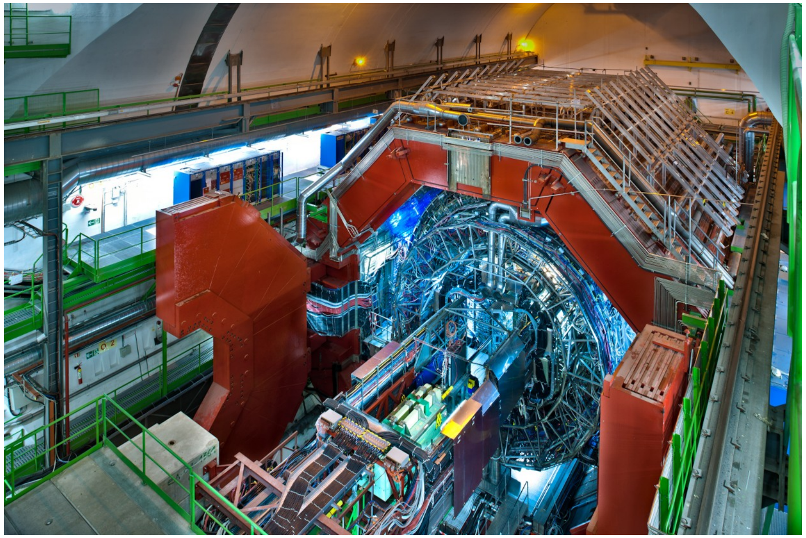

Alps/Mont Blanc
Geneva
Lake Geneva
CERN/Meyrin
LHC
https://cds.cern.ch

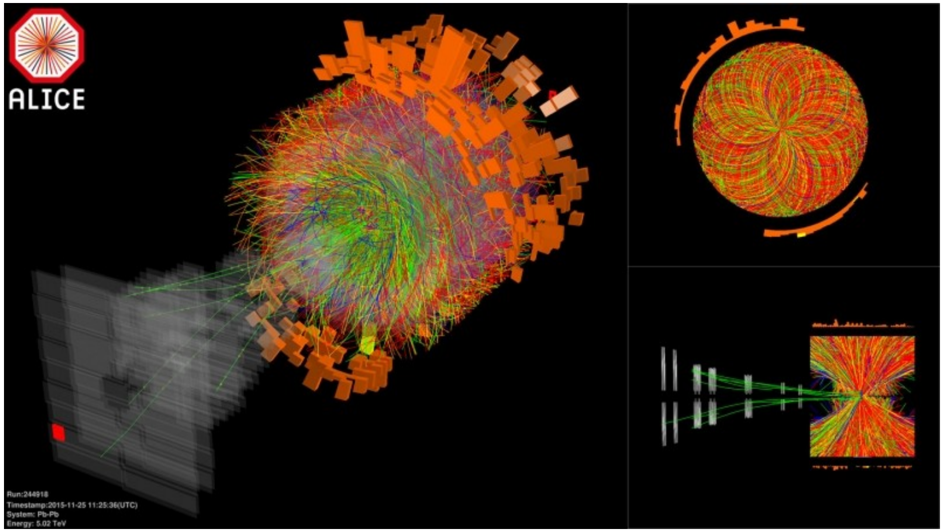
The ALICE experiment

https://cds.cern.ch

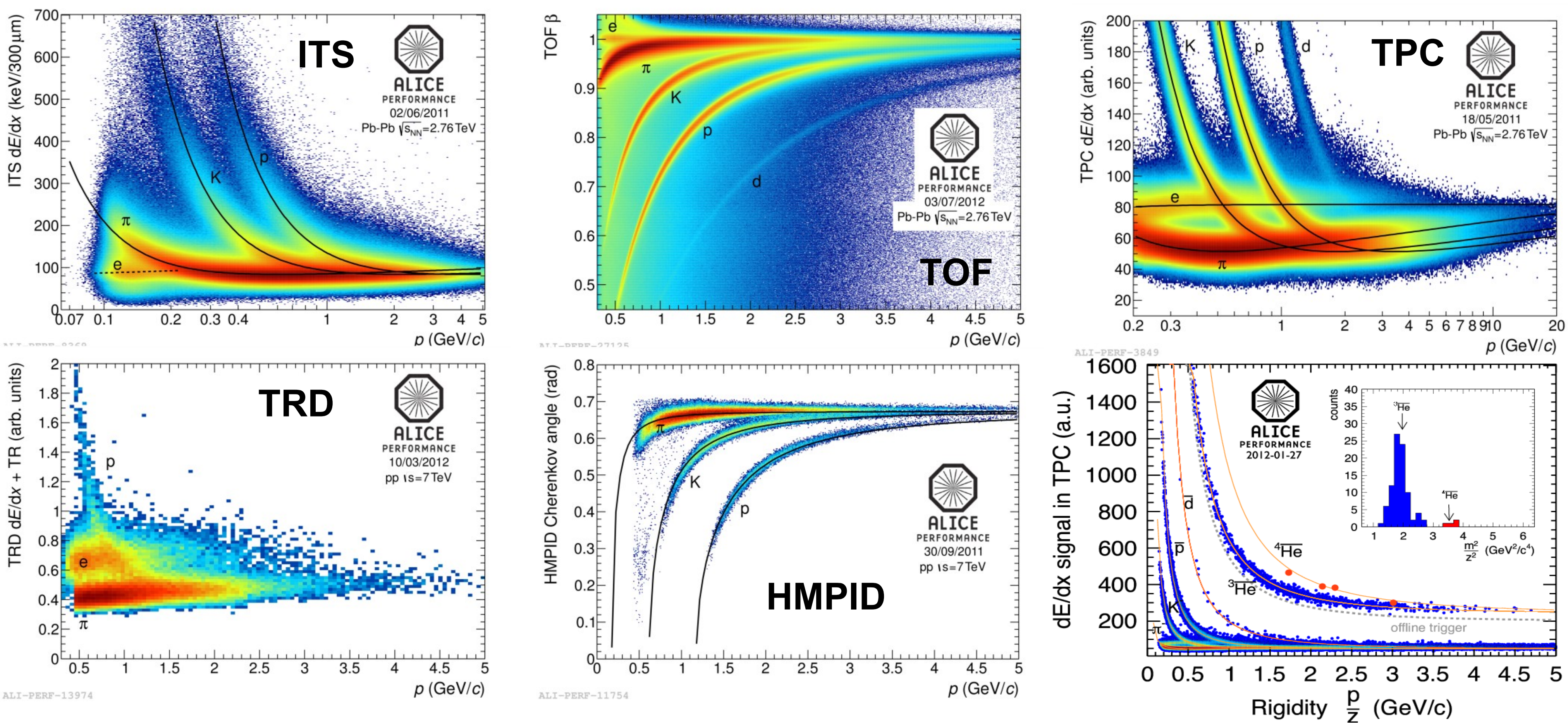


1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter



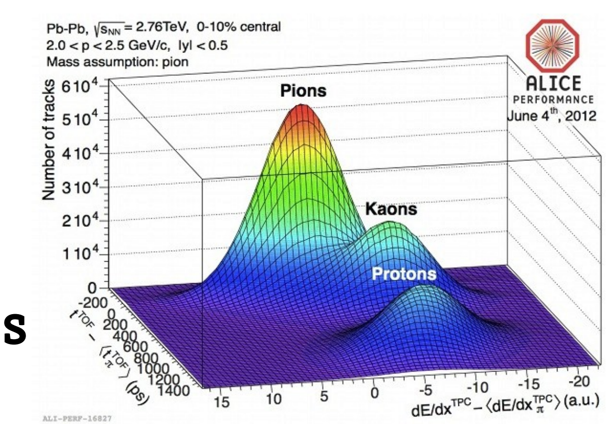


Particle Identification (PID)



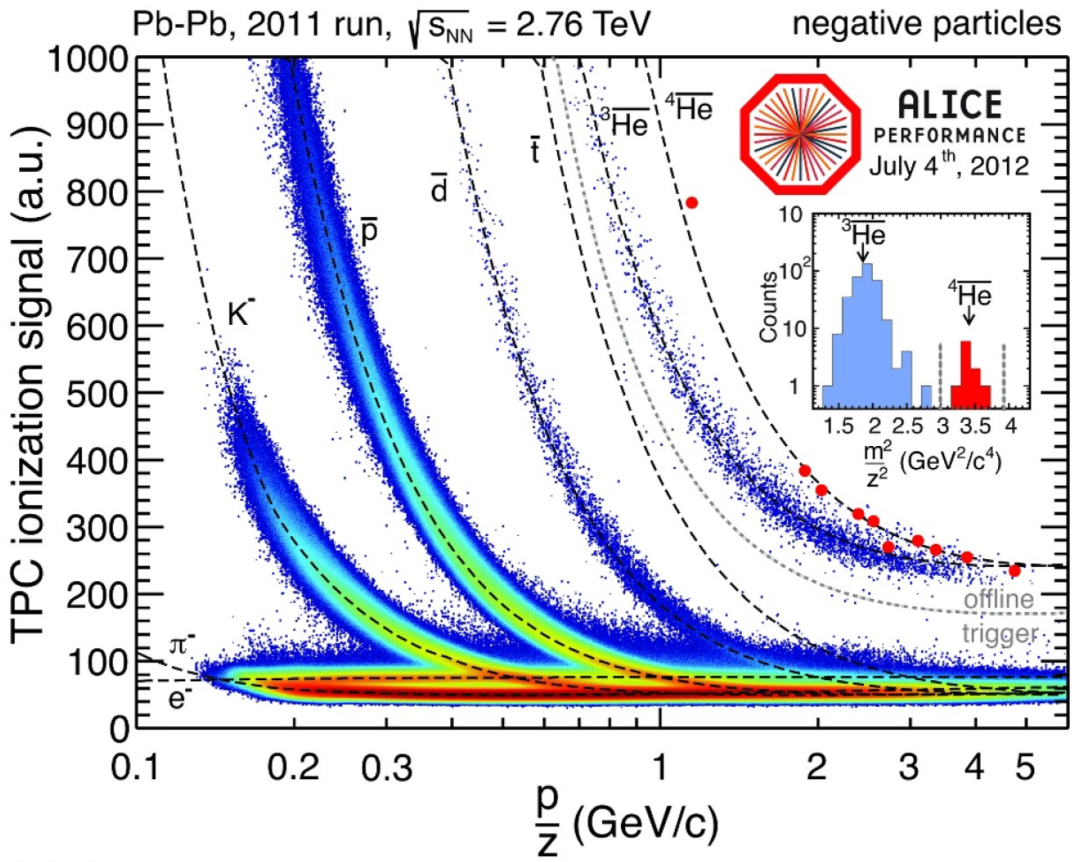
Practically a**ll known PID techniqu**es

energy loss, time-of-flight, Cherenkov radiation for hadrons, transition radiation for electrons, in a wide momentum range



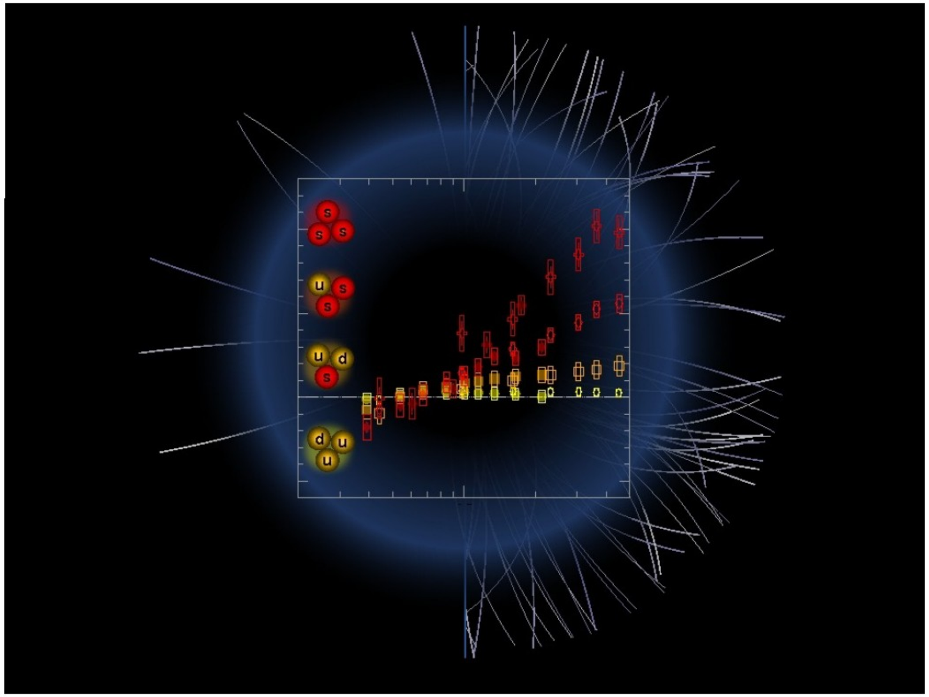
A perfect experiment to study a variety of particle species

Particle Identification (PID)



- ALICE has excellent PID capabilities:
  - can measure up to anti-^{4}He ions
- Such measurements are not possible in other LHC experiments

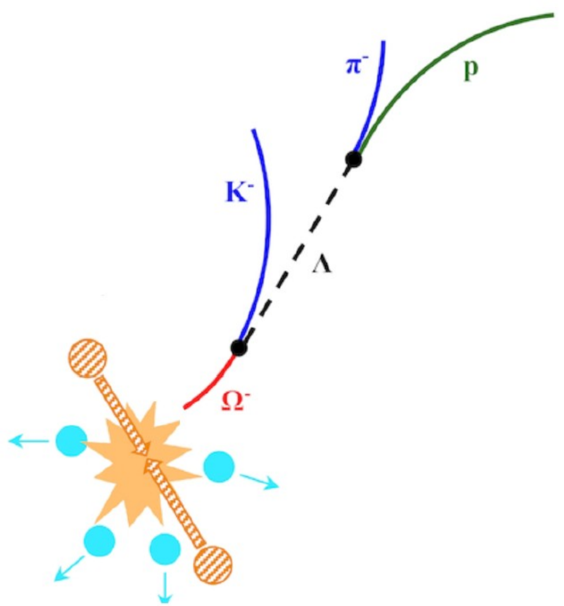
Nature Physics 13, 535–539 (2017)

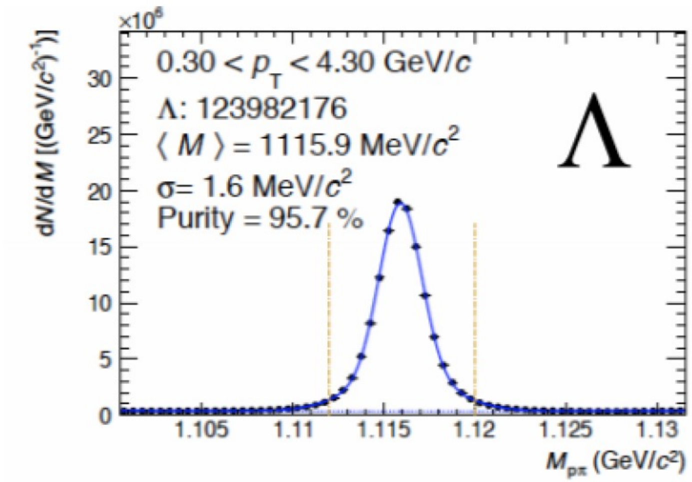


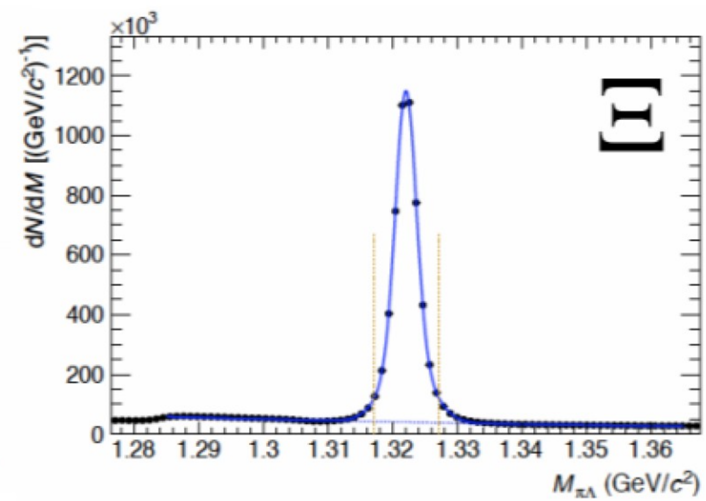
- LHC collisions are the factory of strange matter, even in proton-proton collisions (small system)
  - see Nature Physics 13, 535-539 (2017)

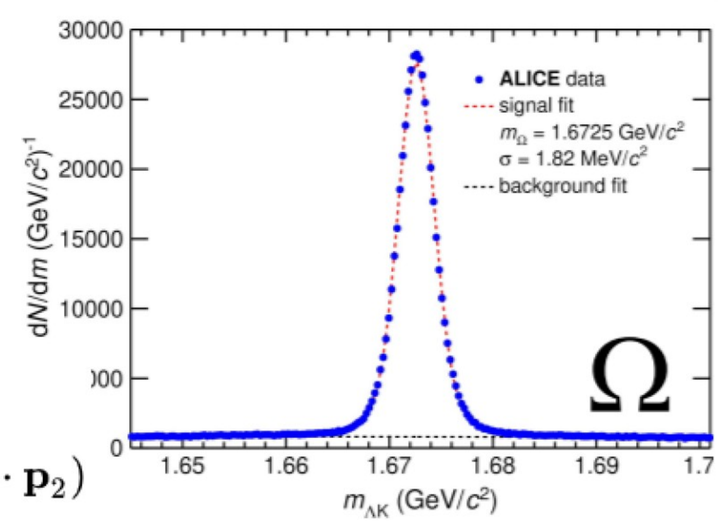
- Hyperons are reconstructed using their decay topology and their final decay products (charged particles) which are detected
- Selection is based on the calculated **invariant mass**

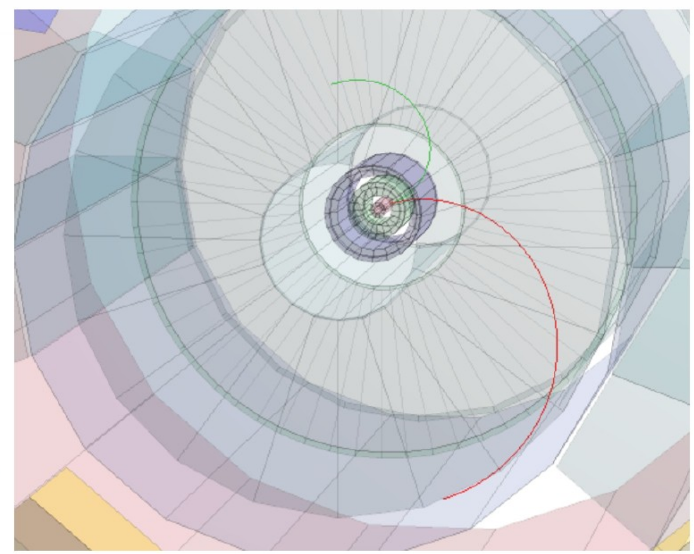
$$\Lambda \rightarrow p\pi^-$$
$$\Xi^- \rightarrow \Lambda\pi^-$$
$$\Omega^- \rightarrow \Lambda K^-$$











$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right)$$

Knowing the basics...

... we can now discuss the results!

Femtoscopy technique

Idea borrowed from Prof. Mike Lisa

PRL **96,** 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegabar Pressures

S. Juodkazis,[1] K. Nishimura,[1] S. Tanaka,[1] H. Misawa,[1] E. G. Gamaly,[2] B. Luther-Davies,[2] L. Hallo,[3] P. Nicolai,[3] and V. T. Tikhonchuk[3]

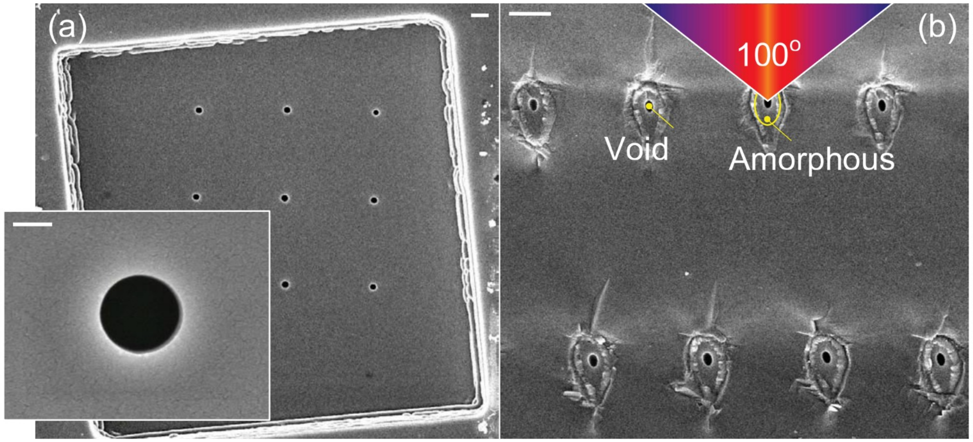
[1]*CREST-JST and Research Institute for Electronic Science, Hokkaido University, N21-W10, CRIS Building, Kita-ku, Sapporo 001-0021, Japan*

[2]*Centre for Ultrahigh Bandwidth Devices for Optical Systems, Laser Physics Centre, Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia*

[3]*Centre Lasers Intenses et Applications, UMR 5107 CEA CNRS - Université Bordeaux 1, 33405 Talence, Cedex, France*

(Received 24 November 2005; published 25 April 2006)

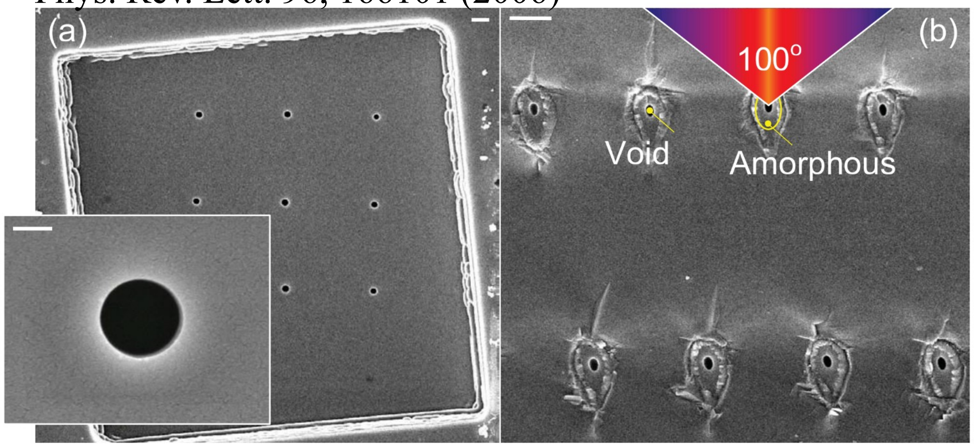
Extremely high pressures (~10 TPa) and temperatures (5×10^5 K) have been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/cm^2 converting material within the absorbing volume of ~0.2 μm^3 into plasma in a few fs. A pressure of ~10 TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by plasma hydrodynamics. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.



Femtoscopy technique

Idea borrowed from Prof. Mike Lisa

Phys. Rev. Lett. 96, 166101 (2006)

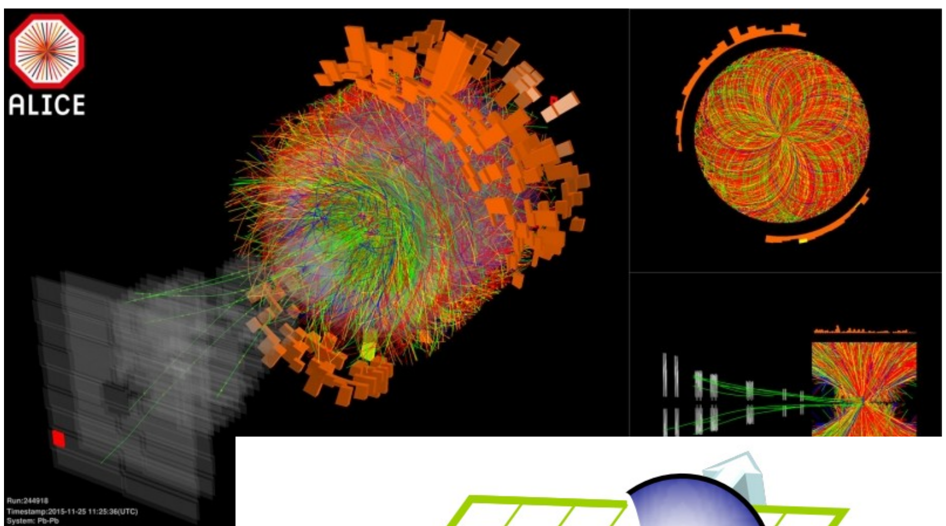


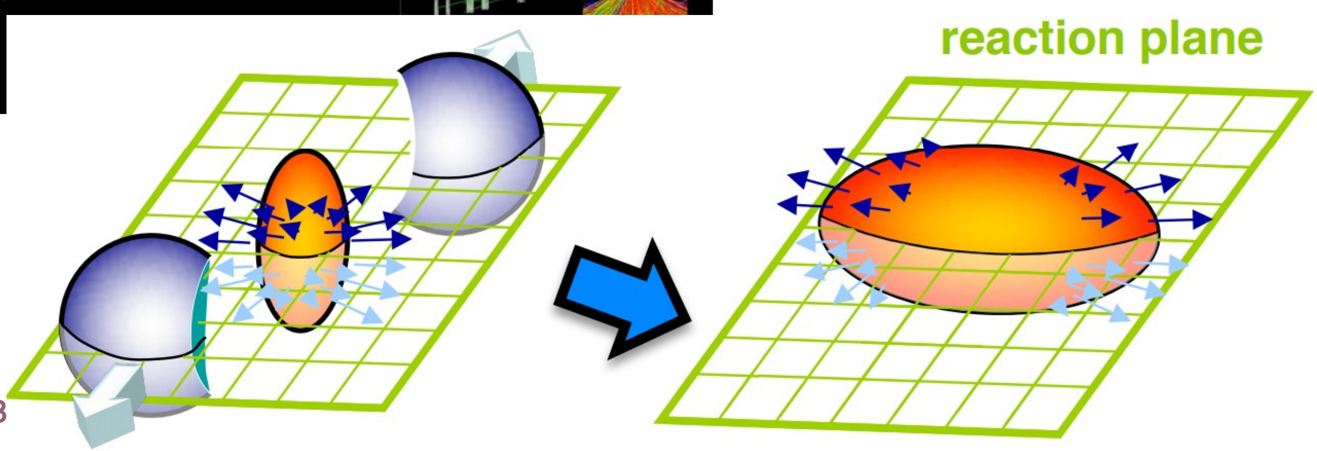
Does it look similar to RHIC?

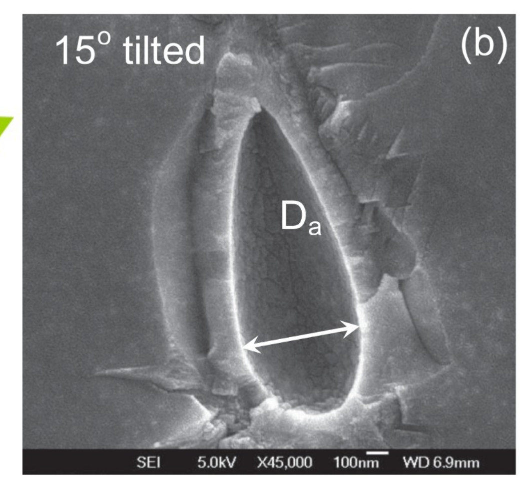
Let's see:

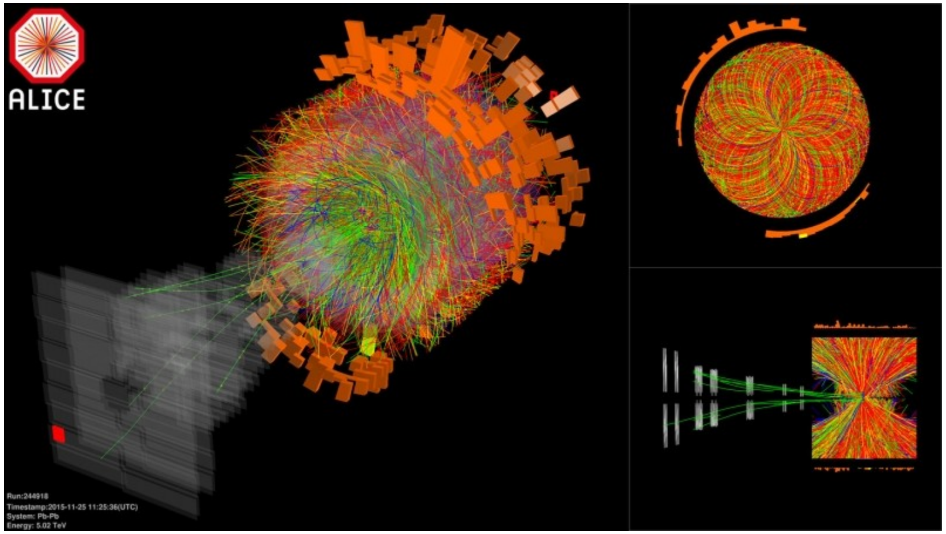
- energy quickly deposited
- enter plasma phase
- expand hydrodynamically

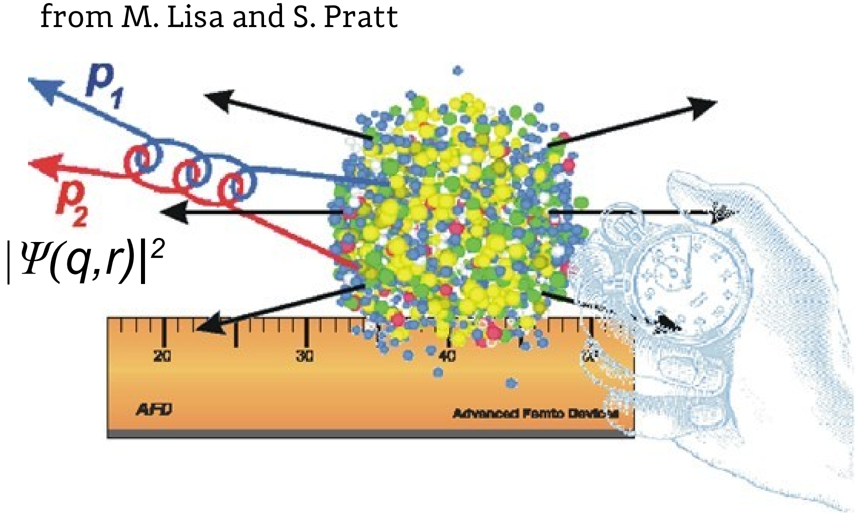
We can do a "post mortem" analysis to investigate i.e. the **source geometry**











Femtoscopy – measures space-time characteristics of the source using particle correlations in momentum space

$$C(\vec{p}_1,\vec{p}_2)=\frac{P_{12}(\vec{p}_1,\vec{p}_2)}{P_1(\vec{p}_1)P_2(\vec{p}_2)}$$

$$\vec{q}=\vec{p}_1-\vec{p}_2$$
$$\vec{r}=\vec{x}_1-\vec{x}_2$$

experiment

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

$A(\vec{q})$ - correlated pairs (“same events”)

$B(\vec{q})$ - uncorrelated pairs (“mixed events”)

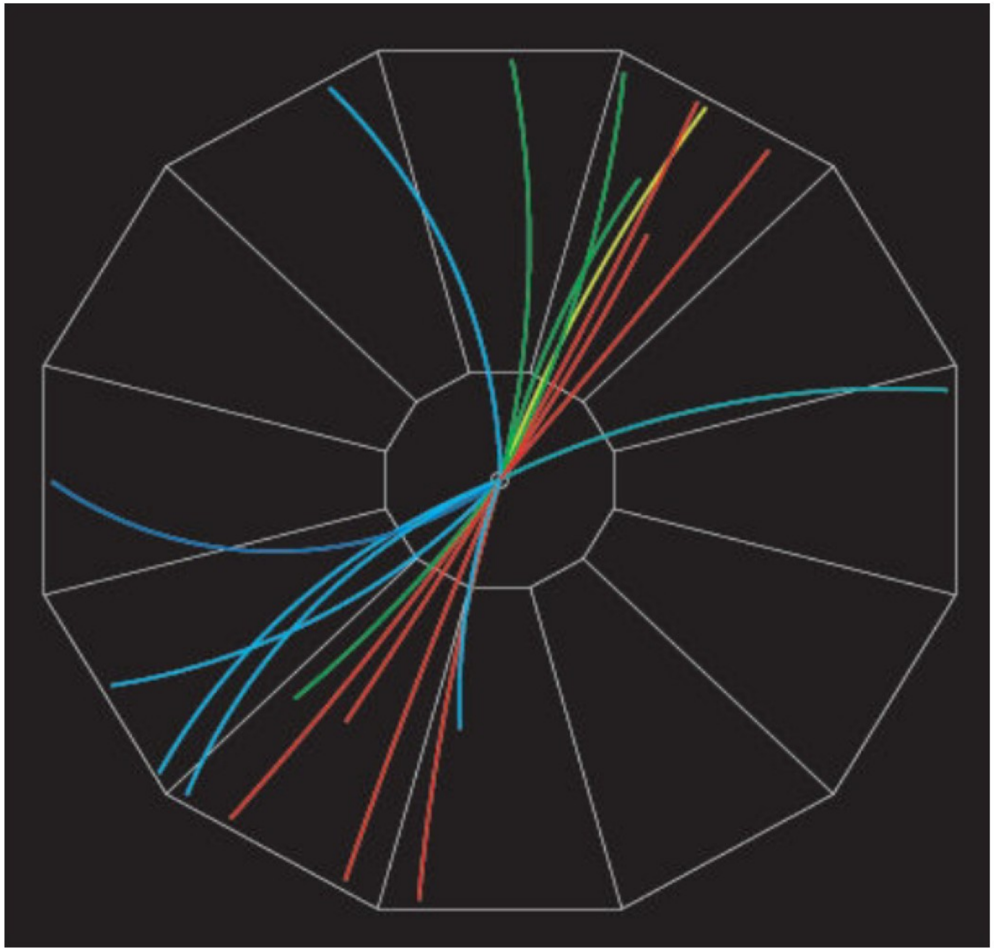
theory (models)

$$C(\vec{q})=\frac{\int d^3r\,S_{12}(\vec{q},\vec{r})|\Psi(\vec{q},\vec{r})|^2}{\int d^3x_1 S_1(\vec{x}_1,\vec{p}_1)\int d^3x_2 S_2(\vec{x}_2,\vec{p}_2)}$$

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

Femtoscopy technique

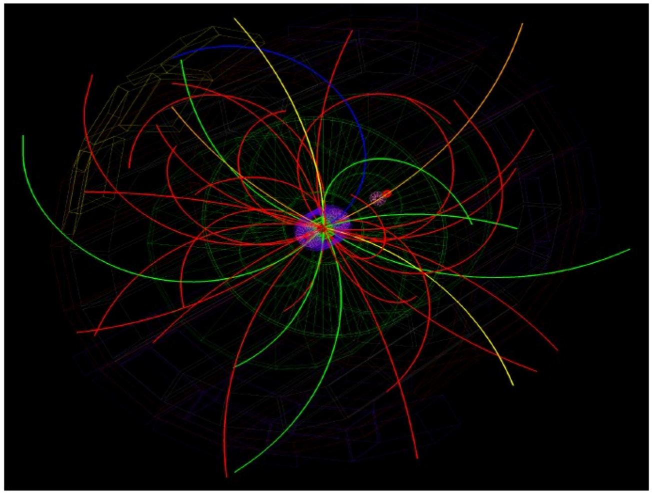
correlated pairs ("same events")



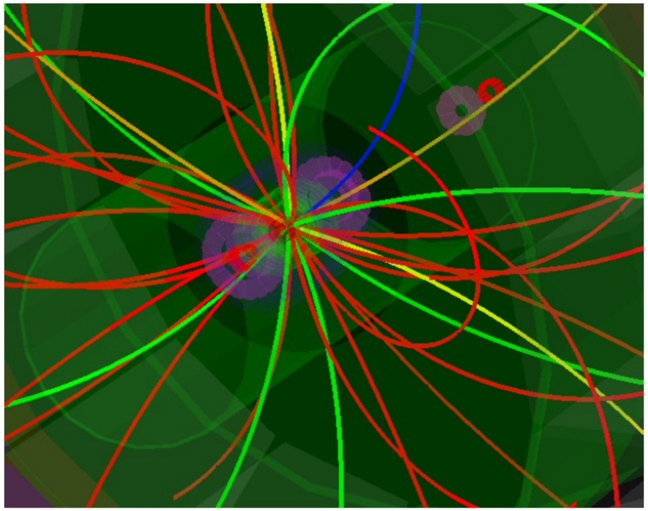
physics + detector effects
(acceptance, inefficiencies, etc.)

uncorrelated pairs ("mixed events")

Event 1



Event 2

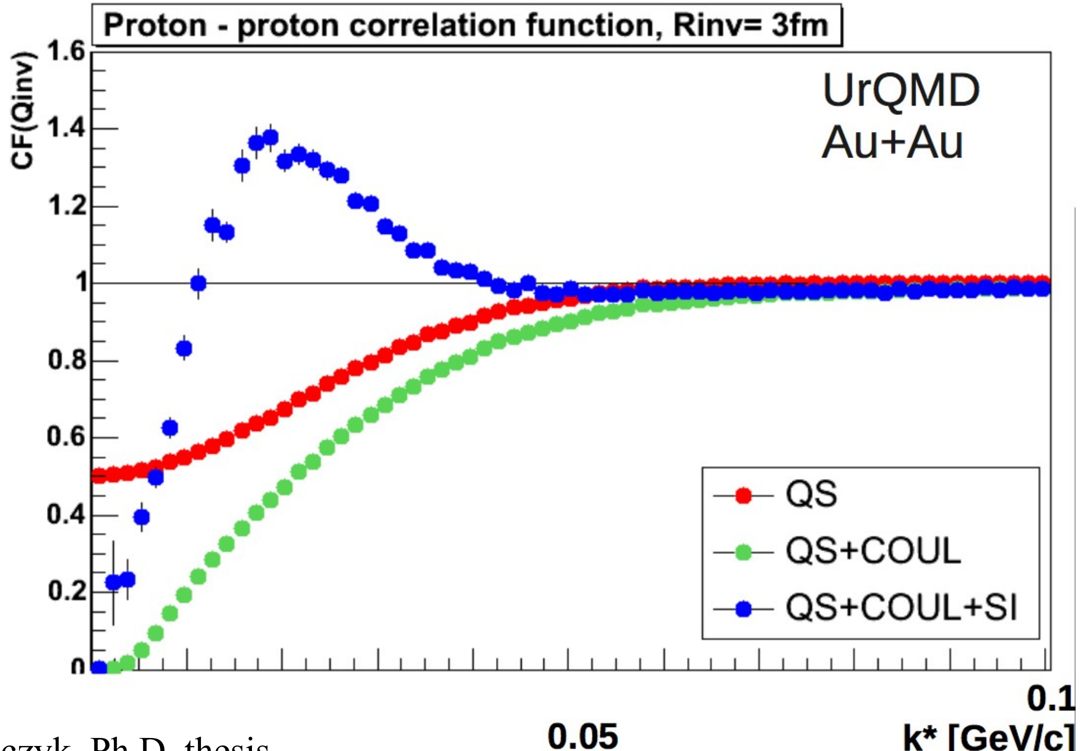


detector effects

Why are particles correlated?

Main sources of correlations:

- Quantum statistics (QS)
  - pairs of identical bosons (i.e. pions) – Bose-Einstein QS
  - pairs of identical fermions (i.e. protons) – Fermi-Dirac QS
- Final-state interactions (FSI)
  - strong interaction
  - Coulomb interaction



H. Zbroszczyk, Ph.D. thesis

“Traditional” femtoscopy

Measuring the system size

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

measured correlation

Obtained by experiment

emission function (source size/shape)

Unknown

Two-particle wave function

Interaction known

“Femtoscopy” - spatio-temporal characterization of the collision region on the femtometer scale

Region of homogeneity

In case of uncharged identical bosons, CF is a Fourier transformation of the Wave Function

Gaussian source

$$S(\vec{r}) \sim \exp\left(-\frac{r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2}\right)$$

$$|\Psi(\vec{q},\vec{r})|^2 = 1 + \cos(\vec{q}\,\vec{r})$$

Pair WF: Bose-Einstein QS

$$C = 1 + \lambda \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)$$

ELSEVIER

Physics Letters B 356 (1995) 525–530

PHYSICS LETTERS B

The HBT-interferometry of expanding sources

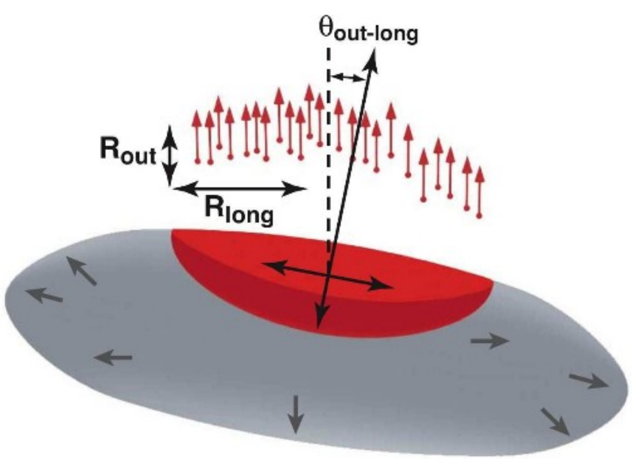
S.V. Akkelin, Yu.M. Sinyukov [1]

Institute for Theoretical Physics of the National Academy of Sciences, Kiev 252143, Ukraine

Received 16 February 1995; revised manuscript received 9 May 1995
Editor: R. Gatto

Abstract

The structure of the bosonic correlation function for expanding thermalized systems is obtained using the conception of the system's lengths of homogeneity. The analysis of the p_T-behavior of the *long*-, *out*- and *side*-interferometry radii is performed for radiating sources with relativistic transversal and longitudinal flows. Simple analytical formulas for all interferometry radii are obtained for typical classes of transversal flows.



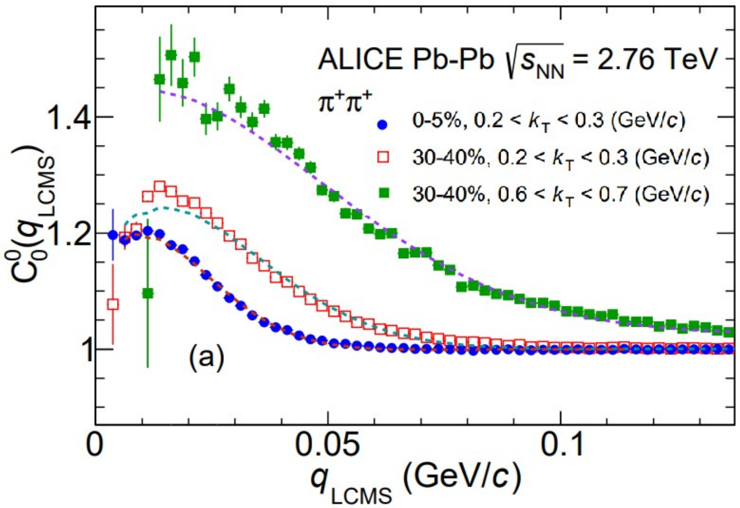
from Ann.Rev.Nucl.Part.Sci.55:357-402,2005

- The size (or sizes in 3D) R is referred to as the **"source radius"**
  → size of the **"region of homogeneity"**
  region from which particles are emitted with similar velocity

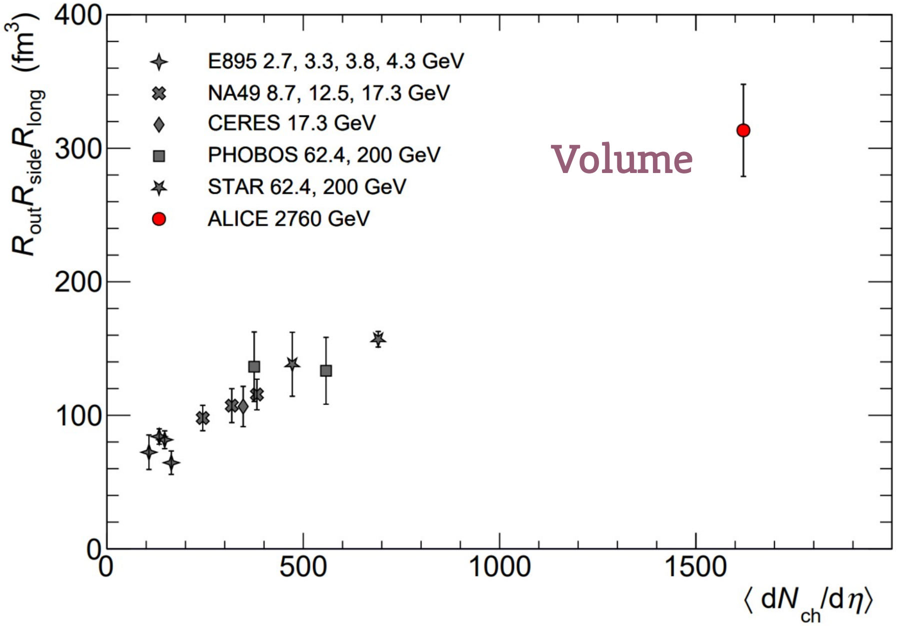
System size

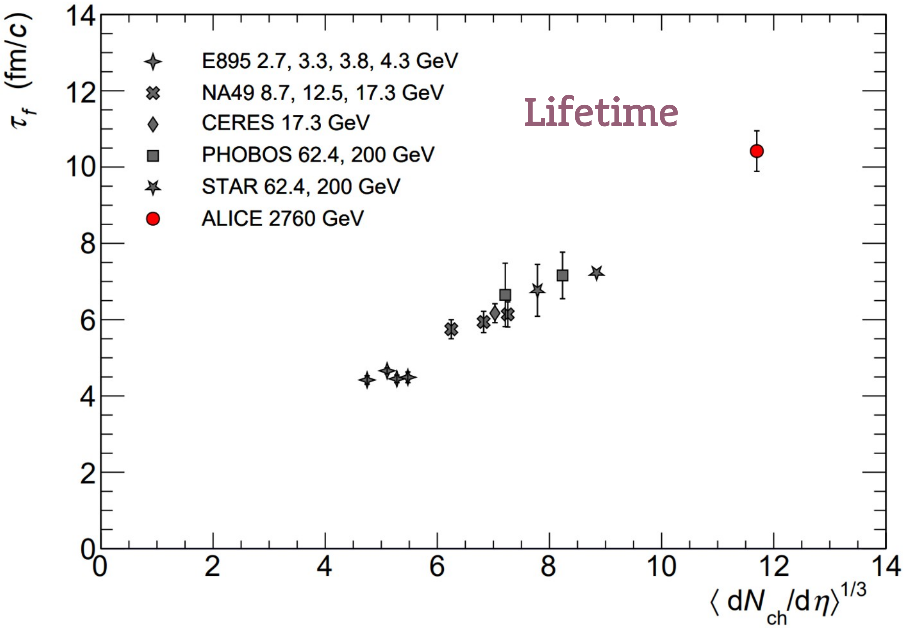
Lifetime and volume of the homogeneity region can be estimated from the fits

The fireball formed in heavy-ion collisions at LHC is hotter, lives longer and expands to a larger size that at lower energies



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

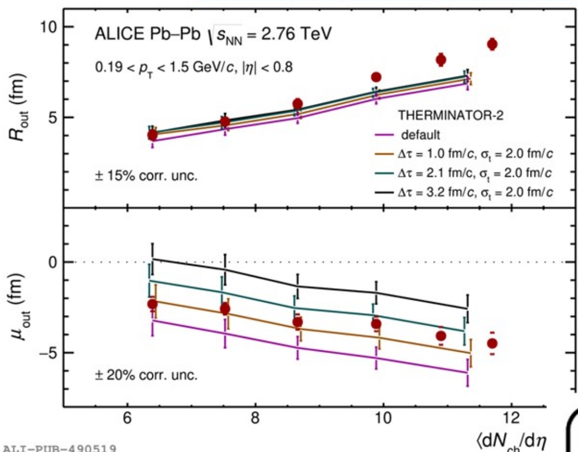




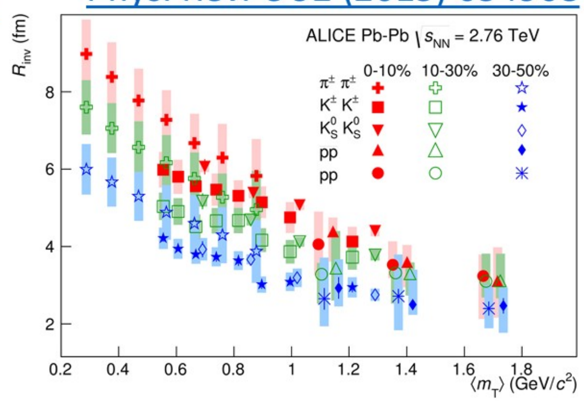
System size

Numerous results of identical and non-identical particle correlation studies

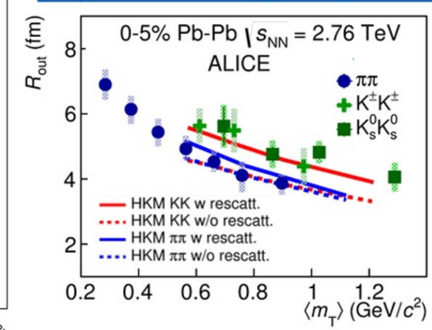
PLB 813 (2021) 136030

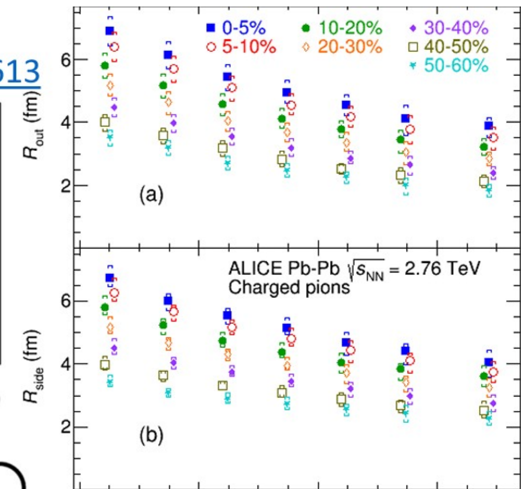


Phys. Rev. C 92 (2015) 054908



Phys. Rev. C96 (2017) 064613





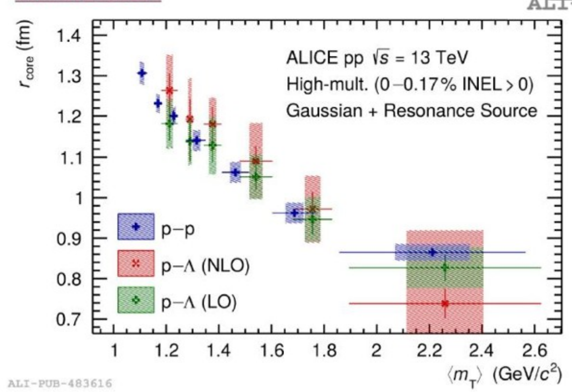
Phys. Rev. C93 (2016) 024905

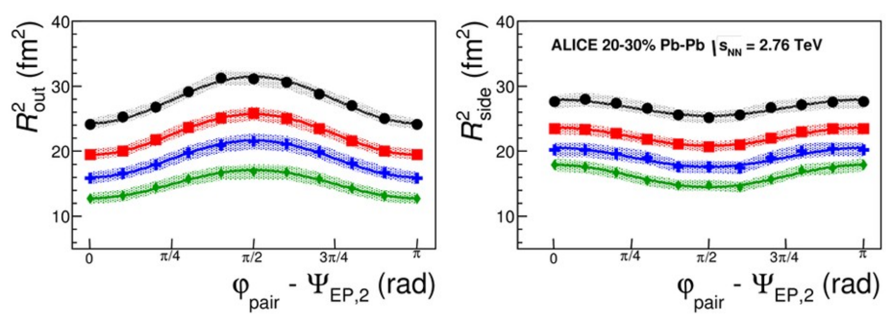
c

$$C(k^*) = \int S(r^*) \; |\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

ALI-PUB-483391

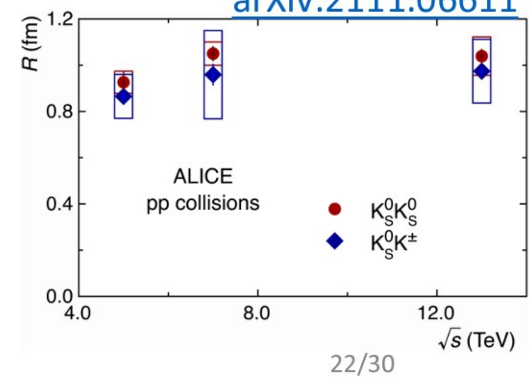
Phys. Lett. B 811 (2020) 135849
arXiv:2004.08018





Phys. Rev. Lett. 118 (2017) 222301

arXiv:2111.06611



Can we do something more with femtoscopy than QGP volume and lifetime measurements?

Beyond the system size

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

measured correlation

emission function (source size/shape)

pair wave function (includes cross section)

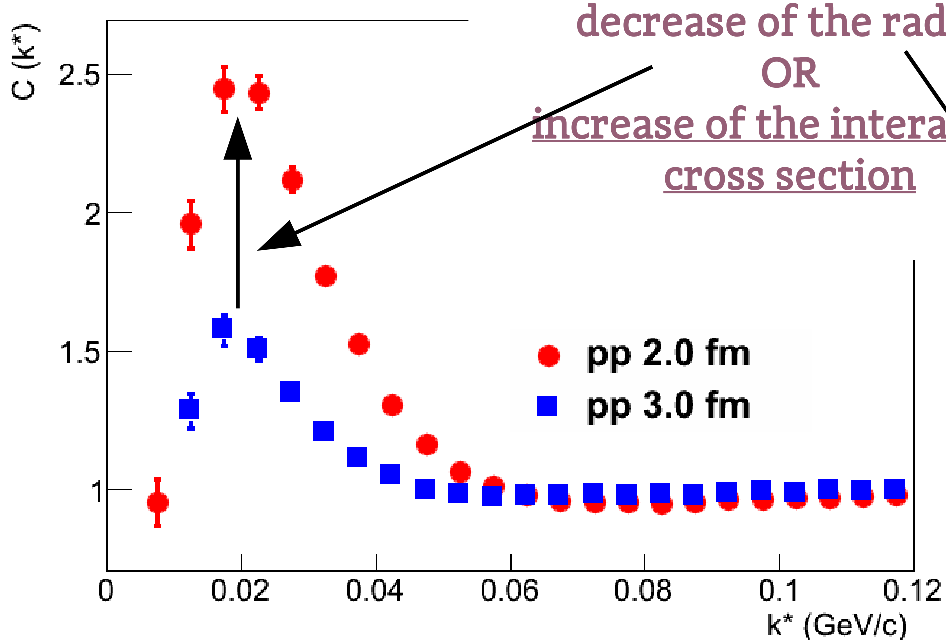
increase of (anti)correlation

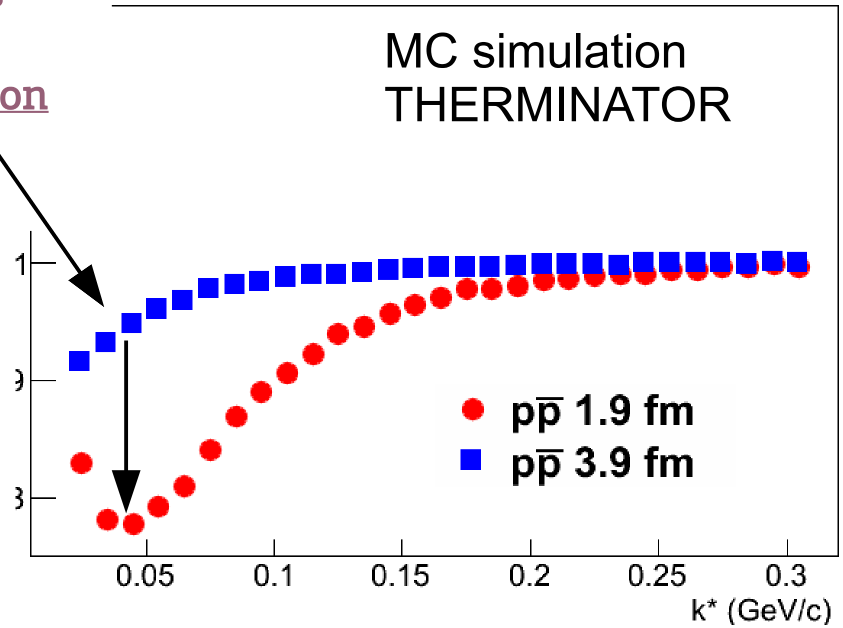
=

decrease of the radius

OR

increase of the interaction cross section





Beyond the system size

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

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)

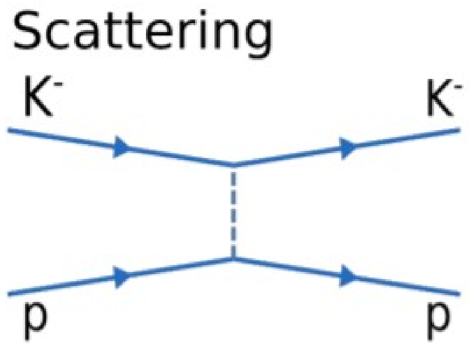
where ρ_S are the spin fractions

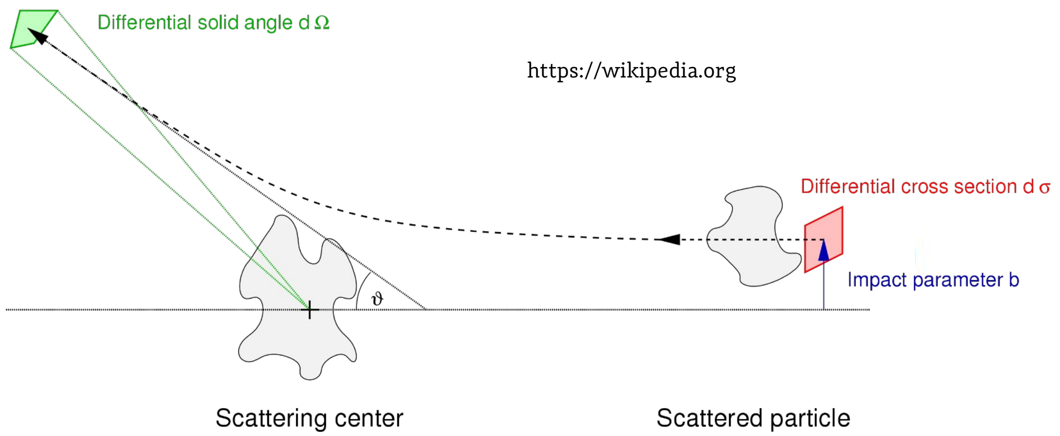
The correlation function is characterized by **three parameters**:

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

How can we measure interactions?

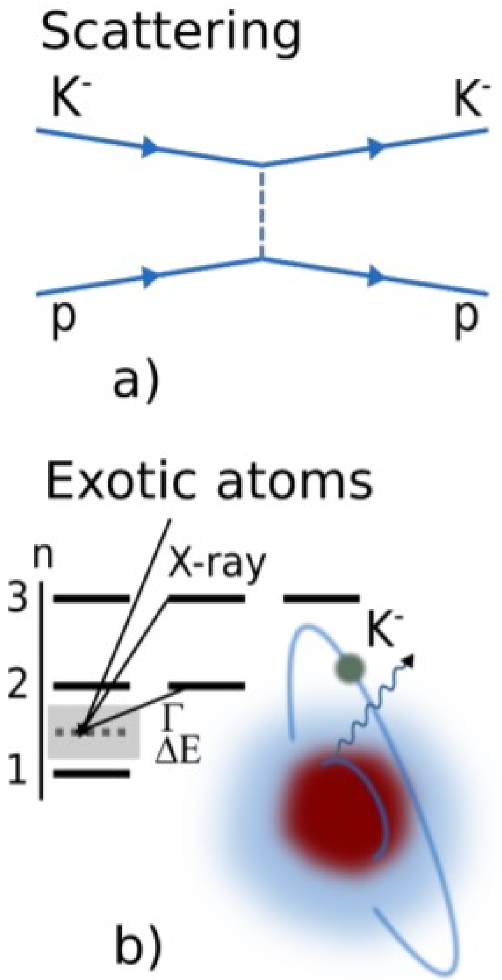
Phys. Rev. Lett. 124 (2020) 092301
Phys. Lett. B 822 (2021) 136708





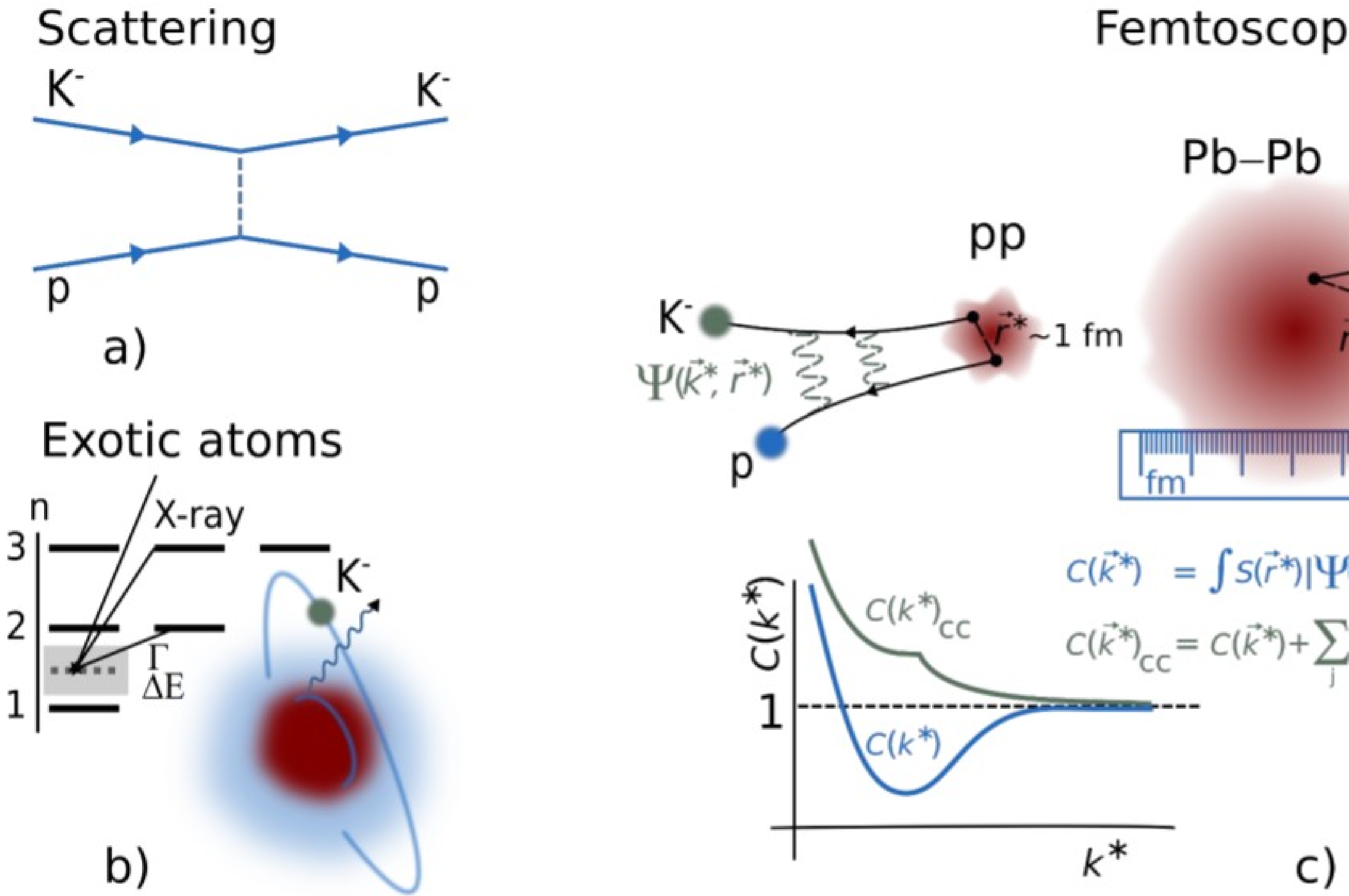
How can we measure interactions?

Phys. Rev. Lett. 124 (2020) 092301
Phys. Lett. B 822 (2021) 136708



How can we measure interactions?

Phys. Rev. Lett. 124 (2020) 092301
Phys. Lett. B 822 (2021) 136708

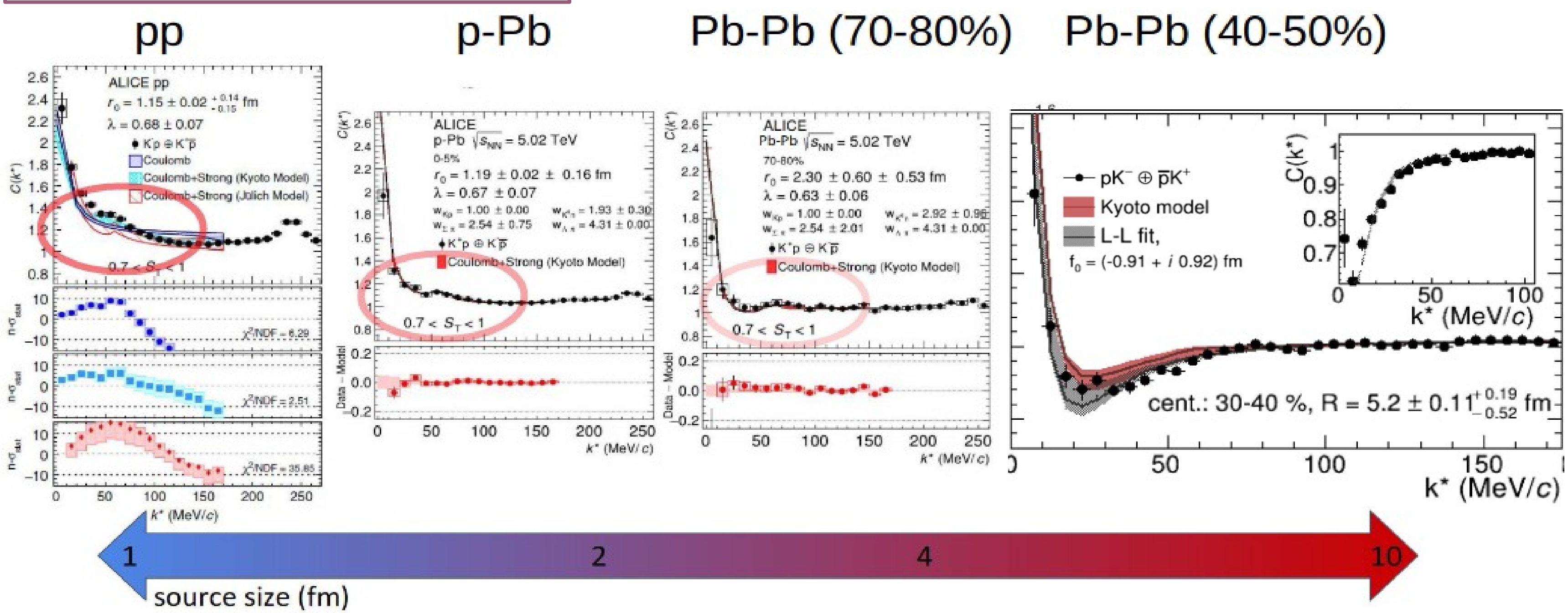


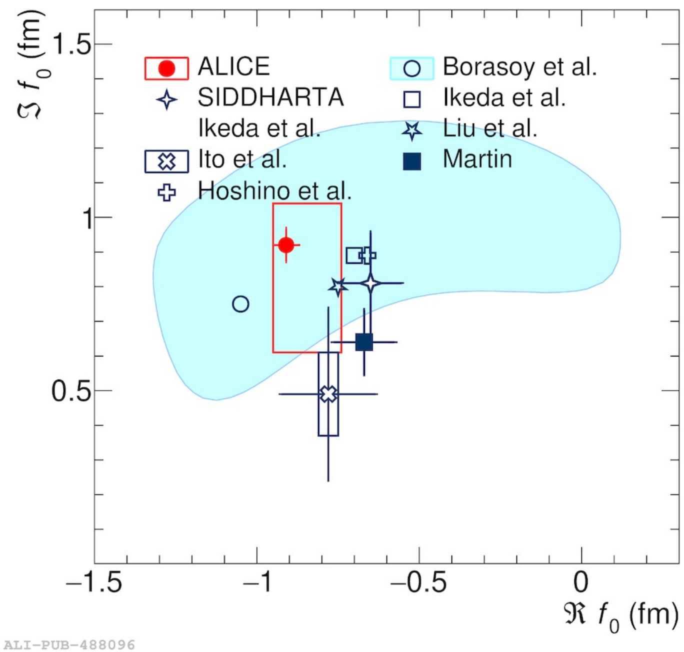
$$C(\vec{k}^*) = \int S(\vec{r}^*)|\Psi(\vec{k}^*,\vec{r}^*)|^2 d^3r^*$$

$$C(\vec{k}^*)_{CC} = C(\vec{k}^*) + \sum_j \omega_j \int S_j(\vec{r}^*)|\Psi_j(\vec{k}^*,\vec{r}^*)|^2 d^3r^*$$

Kaon-proton correlations

Phys. Rev. Lett. 124 (2020) 092301
Phys. Lett. B 822 (2021) 136708

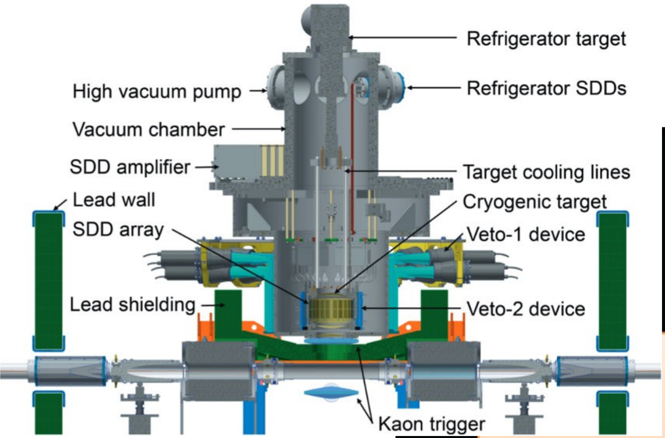


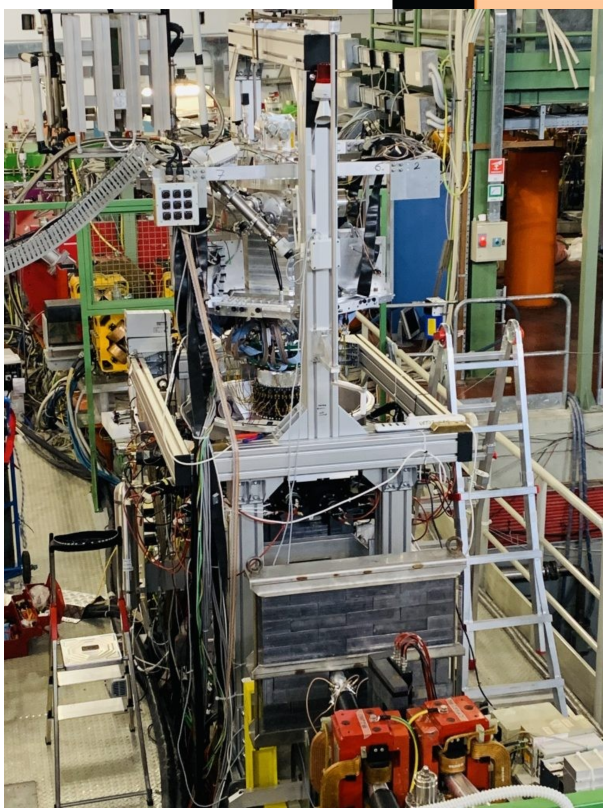


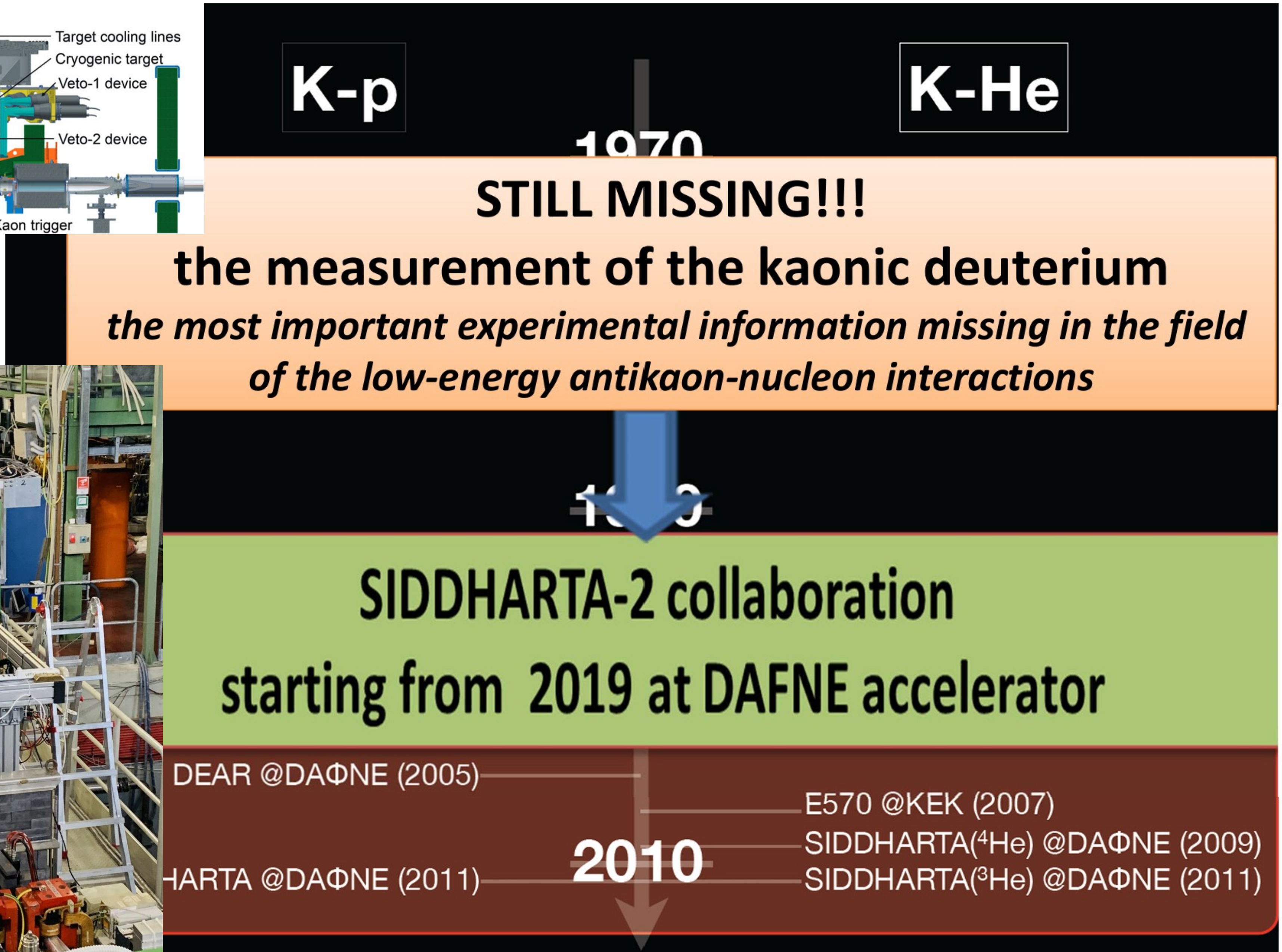
- Measured in all collision systems (different system size)
- Re f_0 and Im f_0 in agreement with available data and theory calculations!
- Complementary to dedicated exotic atoms and scattering experiments

Kaon-deuteron correlations

D. Sirghi, XIII Confinement and the Hadron Spectrum
https://indico.cern.ch/event/648004/contributions/3033140/



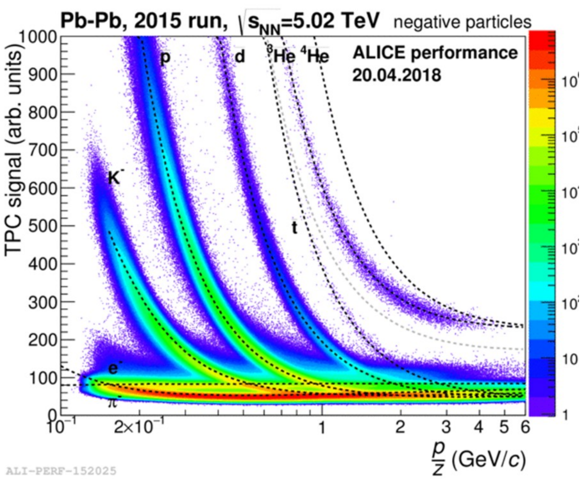


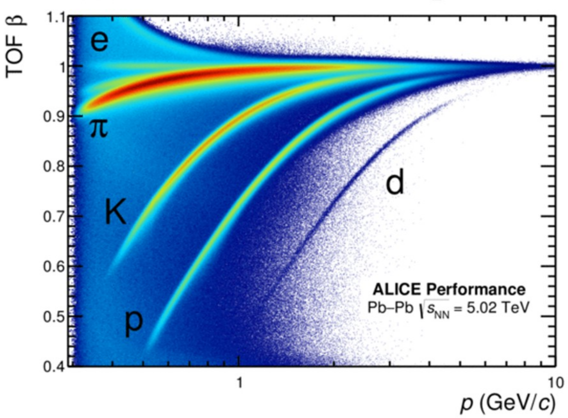


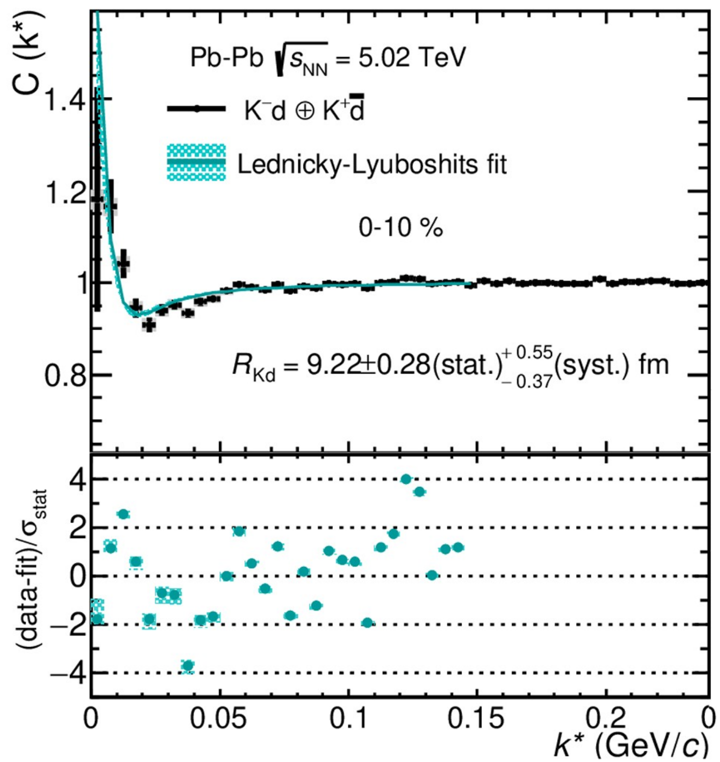
Kaon-deuteron correlations

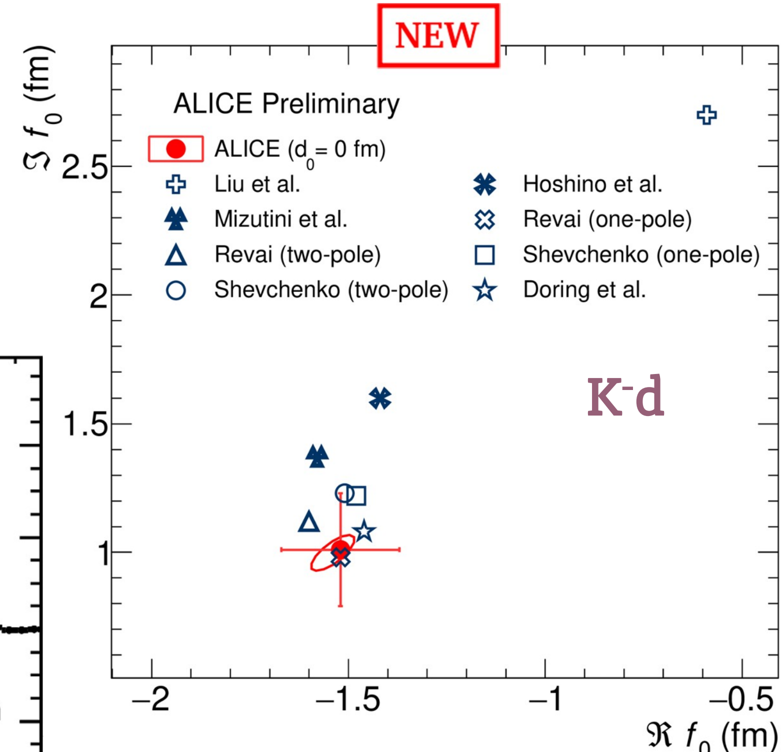
- First ever measurements of kaon-deuteron scattering lengths

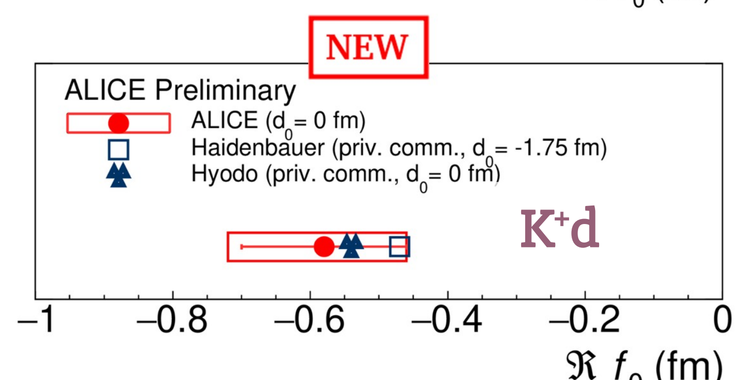
W. Rzęsa, HADRON 2023
https://agenda.infn.it/event/33110/contributions/197931/







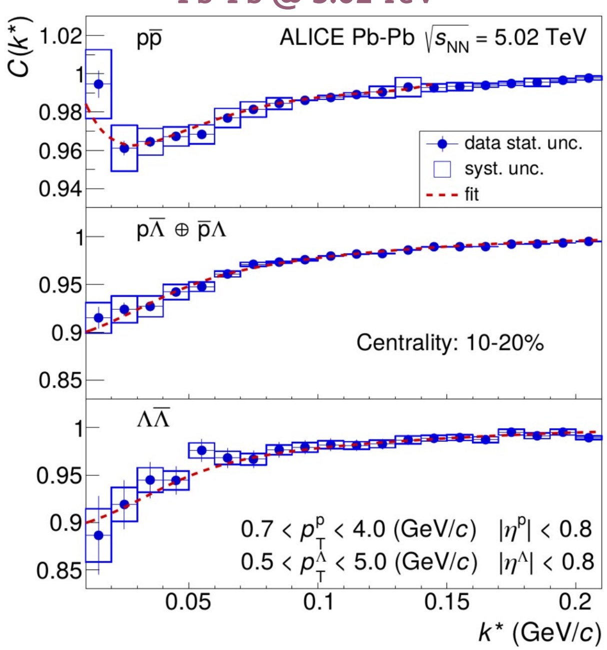


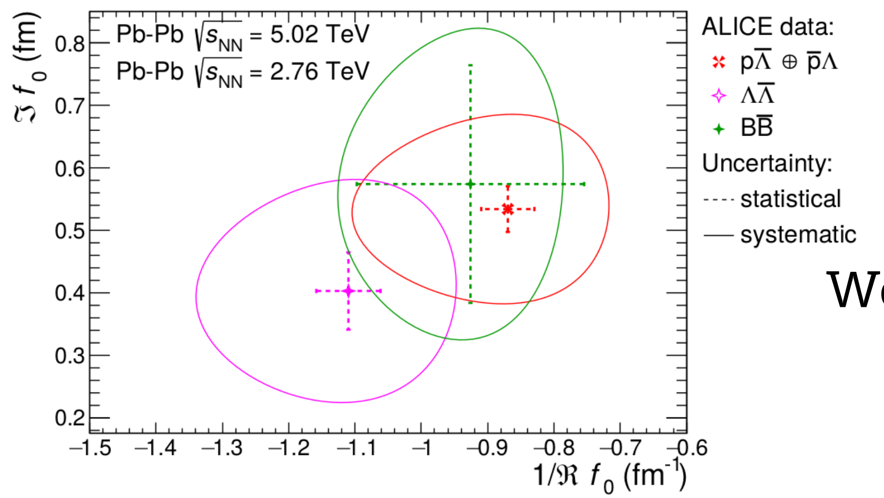


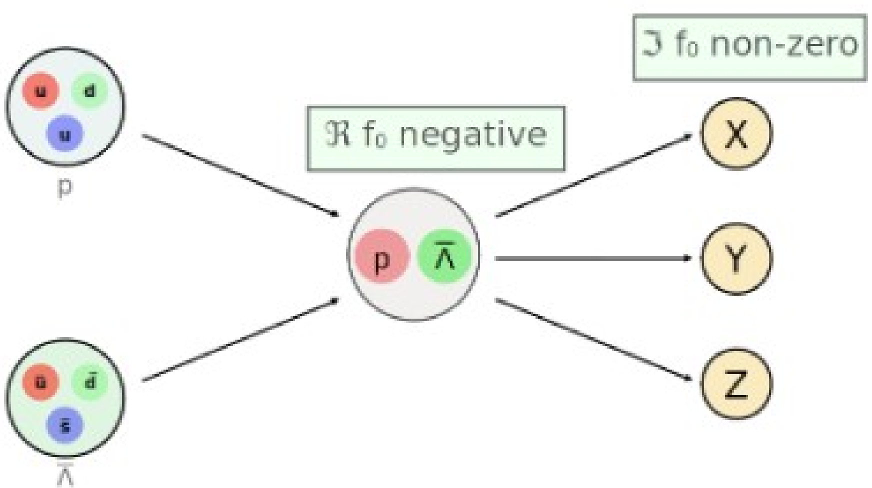
Baryon-antibaryon correlations

Phys. Lett. B 802 (2020) 135223

Pb-Pb @ 5.02 TeV







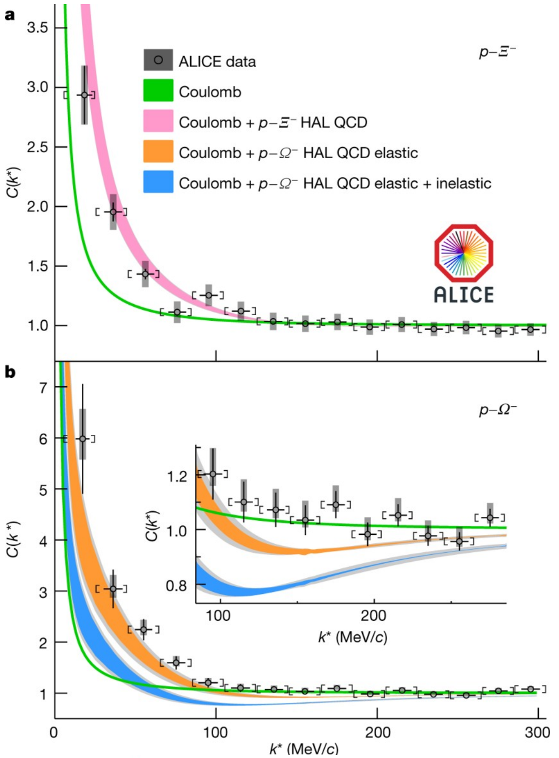
Scattering parameters for **all baryon-antibaryon pairs are similar to each other**

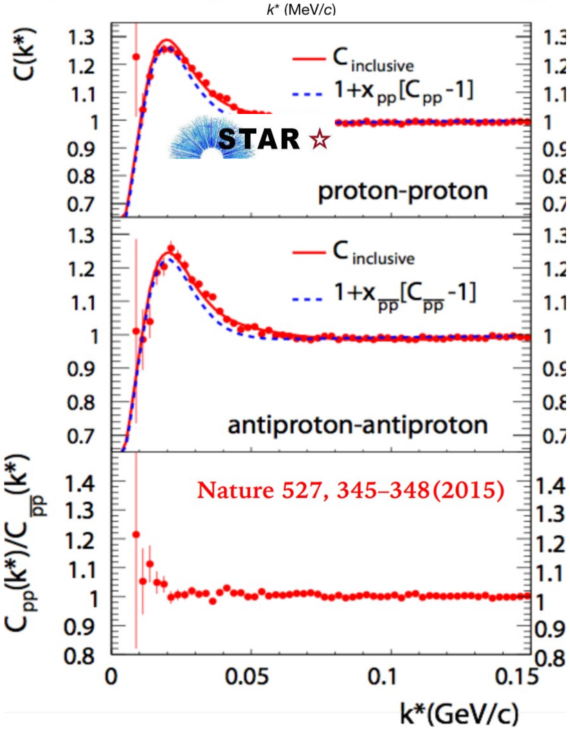
We observe a **negative real part of scattering length** → repulsive strong interaction OR creation of a bound state (existence of **baryon-antibaryon states (baryonia)?**)

Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation

LHC → matter-antimatter pair factory

Femtoscopy in “Nature”





nature

Explore content | About the journal | Publish with us | Subscribe

nature > letters > article

Published: 04 November 2015

Measurement of interaction between antiprotons

The STAR Collaboration

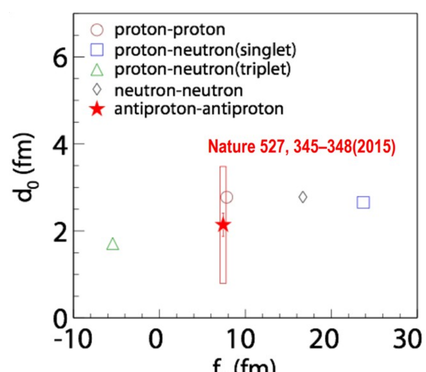
Nature 527, 345–348 (2015) | Cite this article

STAR

This article has been updated

Abstract

One of the primary goals of nuclear physics is to understand the force between nucleons, which is a necessary step for understanding the structure of nuclei and how nuclei interact with each other. Rutherford discovered the atomic nucleus in 1911, and the large body of knowledge about the nuclear force that has since been acquired was derived from studies made on nucleons or nuclei. Although antinuclei up to antihelium-4 have been discovered[1] and their masses measured, little is known directly about the nuclear force between antinucleons. Here, we study antiproton pair correlations among data collected by the STAR experiment[2] at the Relativistic Heavy Ion Collider (RHIC)[3], where gold ions are collided with a centre-of-mass energy of 200 gigaelectronvolts per nucleon pair. Antiprotons are abundantly produced in such collisions, thus making it feasible to study details of the antiproton–antiproton interaction. By applying a technique similar to Hanbury Brown and Twiss intensity interferometry[4], we show that the force between two antiprotons is attractive. In addition, we report two key parameters that characterize the corresponding strong interaction: the scattering length and the effective range of the interaction. Our measured parameters are consistent within errors with the corresponding values for proton–proton interactions. Our results provide direct information on the interaction between two antiprotons, one of the simplest systems of antinucleons, and so are fundamental to understanding the structure of more-complex antinuclei and their properties.



nature

Explore content | About the journal | Publish with us

nature > articles > article

Article | Open Access | Published: 09 December 2020

Unveiling the strong interaction among hadrons at the LHC

ALICE Collaboration

Nature 588, 232–238 (2020) | Cite this article

ALICE

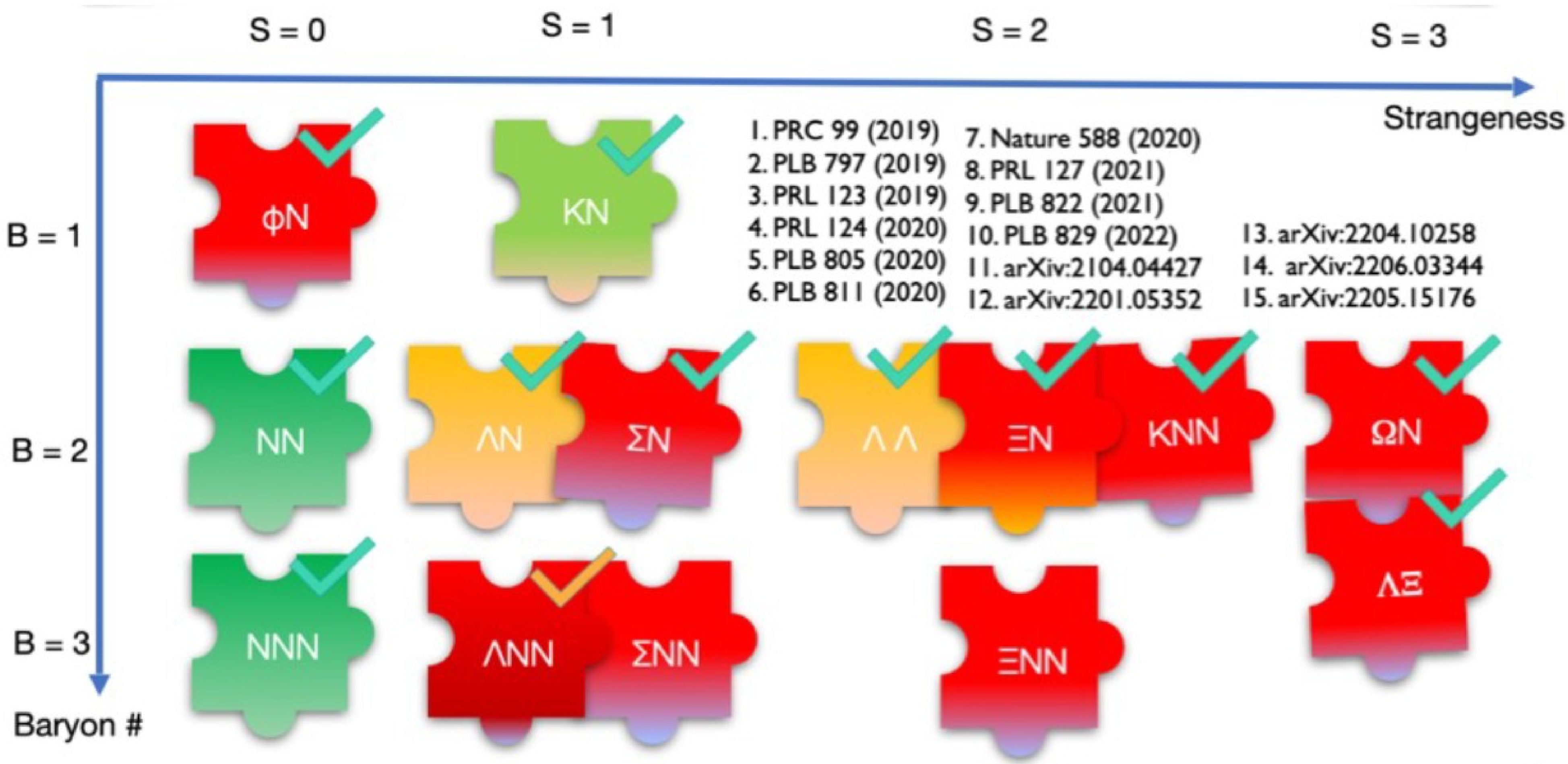
A Publisher Correction to this article was published on 15 January 2021

This article has been updated

Abstract

One of the key challenges for nuclear physics today is to understand from first principles the effective interaction between hadrons with different quark content. First successes have been achieved using techniques that solve the dynamics of quarks and gluons on discrete space-time lattices[1,2]. Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or impossible for unstable hadrons[3,4,5,6] and so high-quality measurements exist only for hadrons containing up and down quarks[7]. Here we demonstrate that measuring correlations in the momentum space between hadron pairs[8,9,10,11,12] produced in ultrarelativistic proton–proton collisions at the CERN Large Hadron Collider (LHC) provides a precise method with which to obtain the missing information on the interaction dynamics between any pair of unstable hadrons. Specifically, we discuss the case of the interaction of baryons containing strange quarks (hyperons). We demonstrate how, using precision measurements of proton–omega baryon correlations, the effect of the strong interaction for this hadron–hadron pair can be studied with precision similar to, and compared with, predictions from lattice calculations[13,14]. The large number of hyperons identified in proton–proton collisions at the LHC, together with accurate modelling[15] of the small (approximately one femtometre) inter-particle distance and exact predictions for the correlation functions, enables a detailed determination of the short-range part of the nucleon-hyperon interaction.

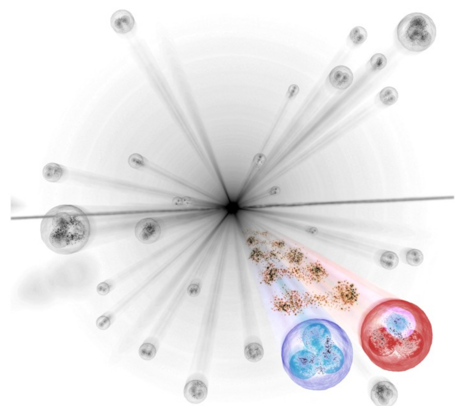
ALICE, Nature 588, 232-238 (2020)
STAR, Nature 527, 345-348 (2015)



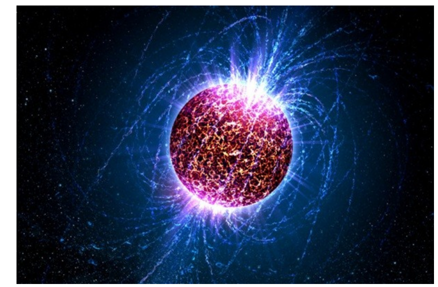
from L. Fabbietti

ALICE experiment

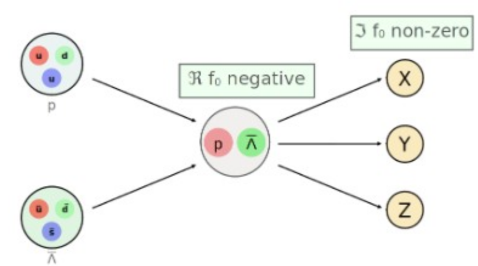
Strong Interction Potentials



Neutron Stars



Exotic hadrons

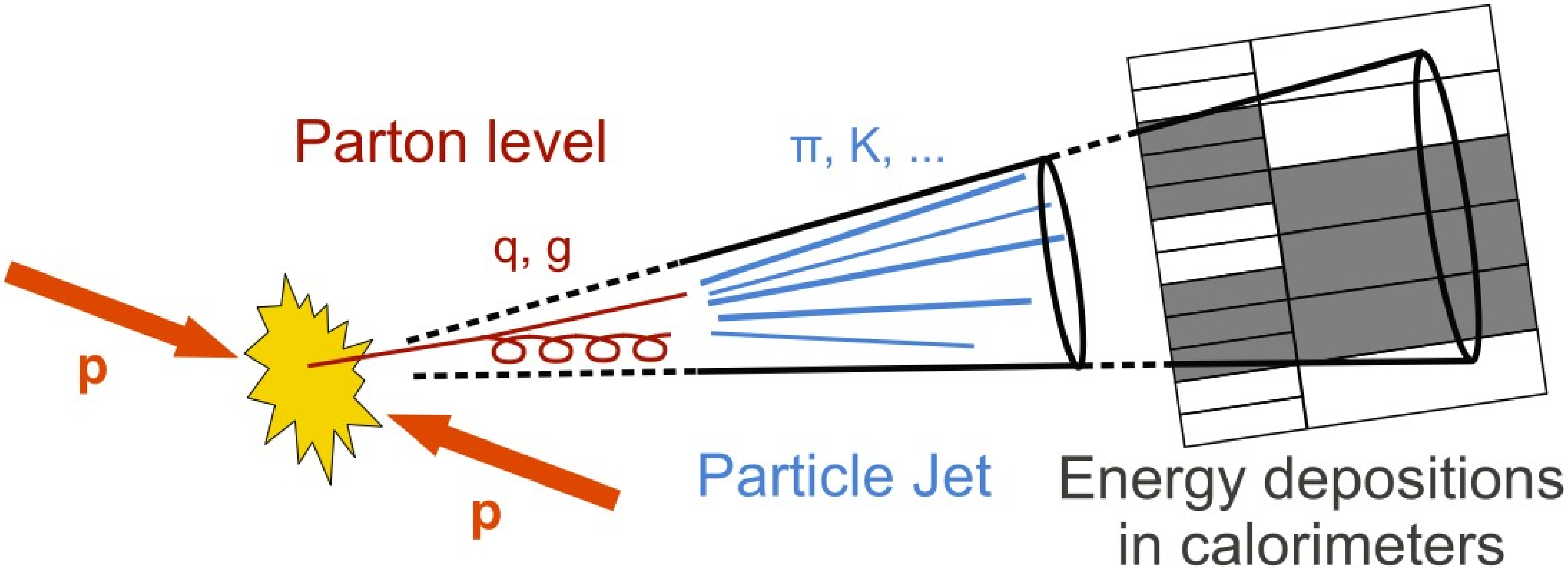


Baryonia

Baryon correlations puzzle

Jets

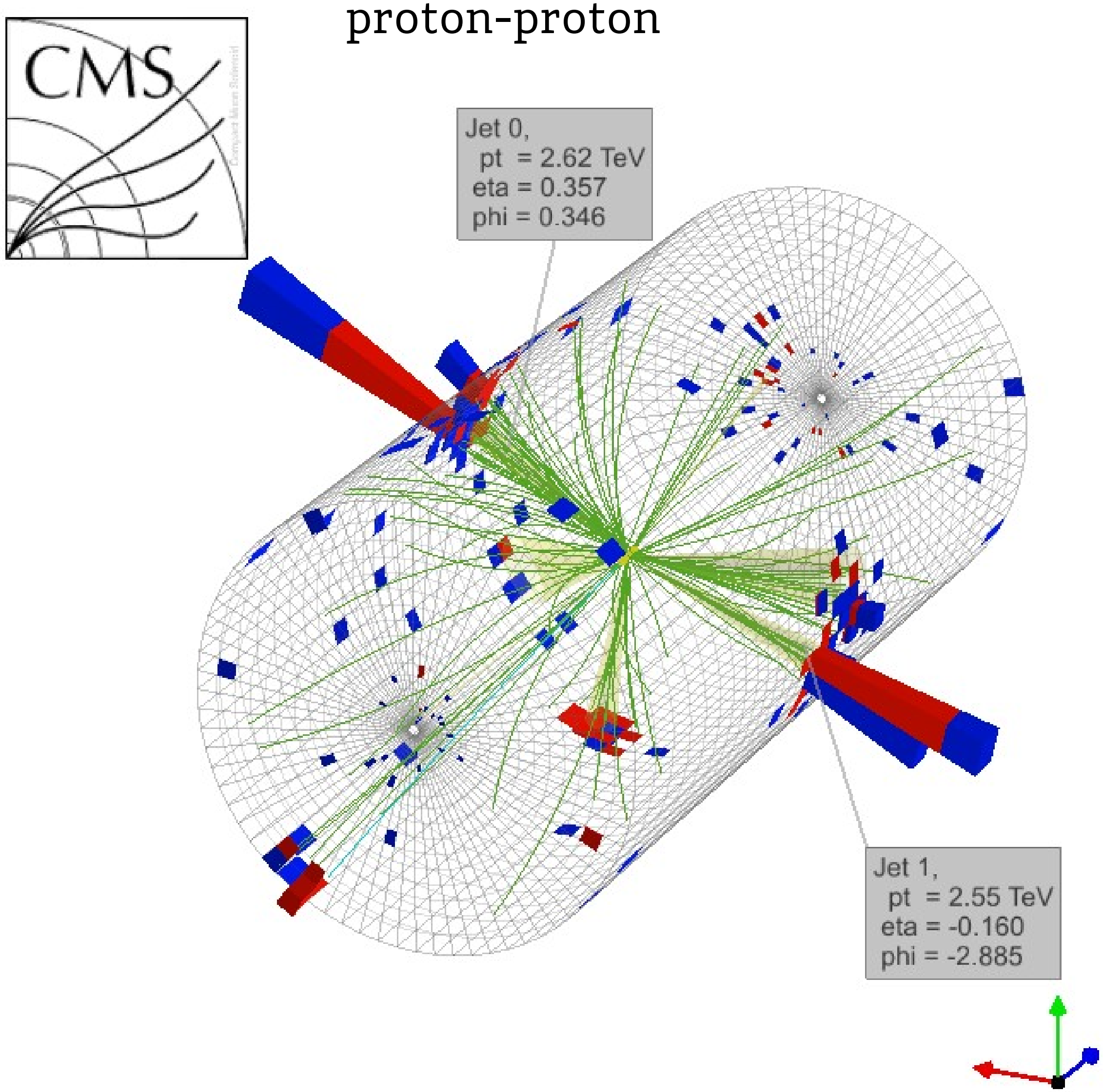
- Initial partons (quarks or gluons) with **high momentum** cause the creation of so-called "jets":



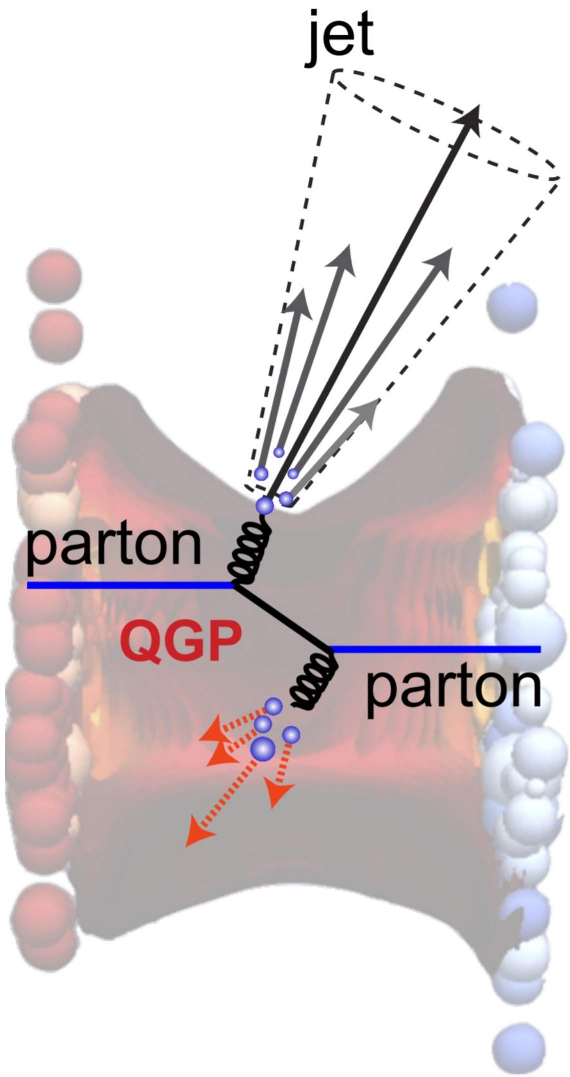
https://cms.cern/sites/default/files/field/image/Sketch_PartonParticleCaloJet.png

- "Jet" is a collimated stream of particles (hadrons) of high momentum (energy) which reach the detector
- Usually (energy-momentum conservation) in a collision we have two (sometimes more) jets

proton-proton

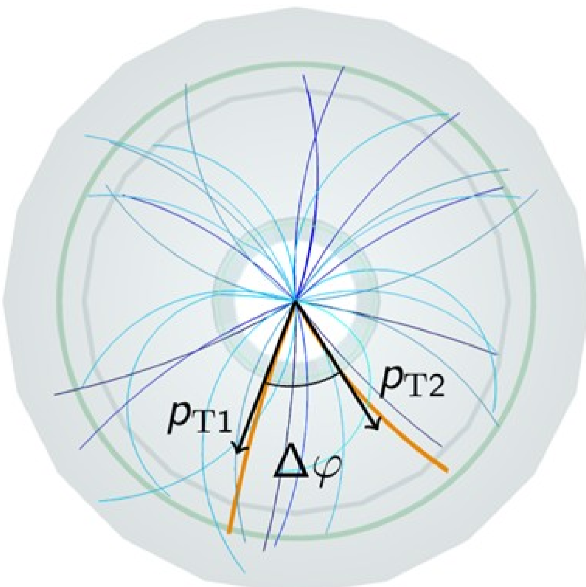


Pb-Pb

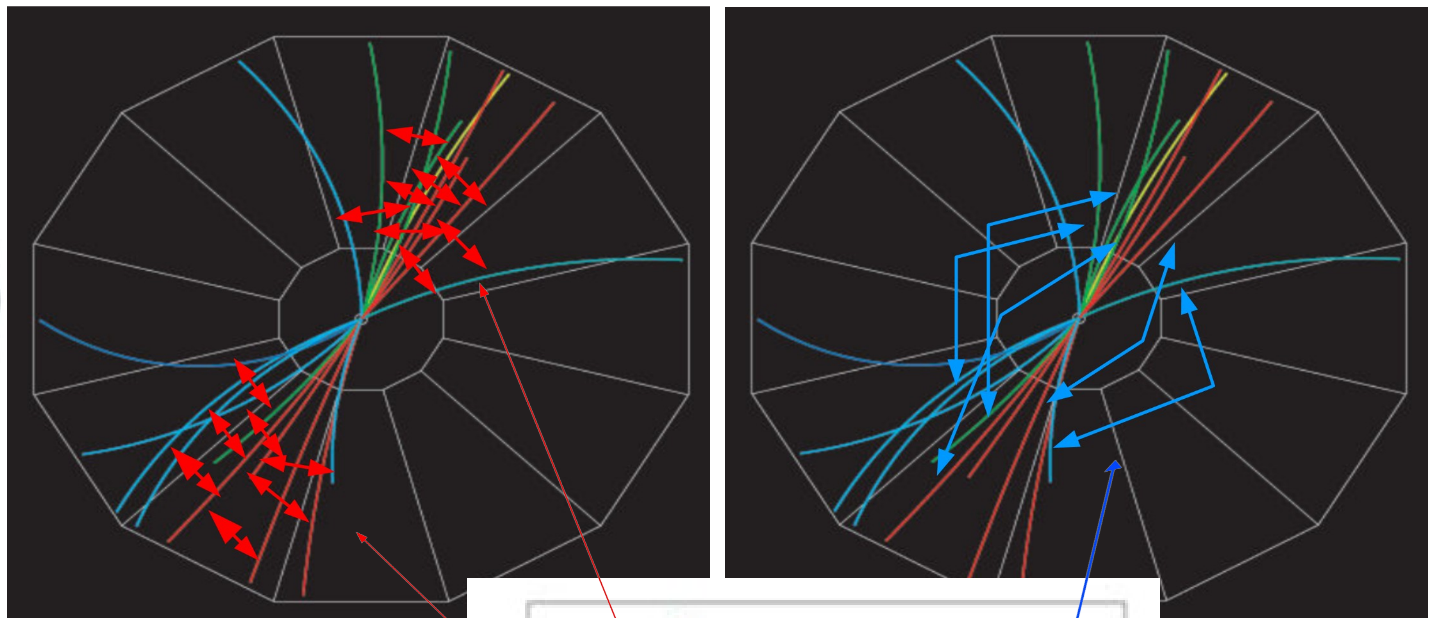


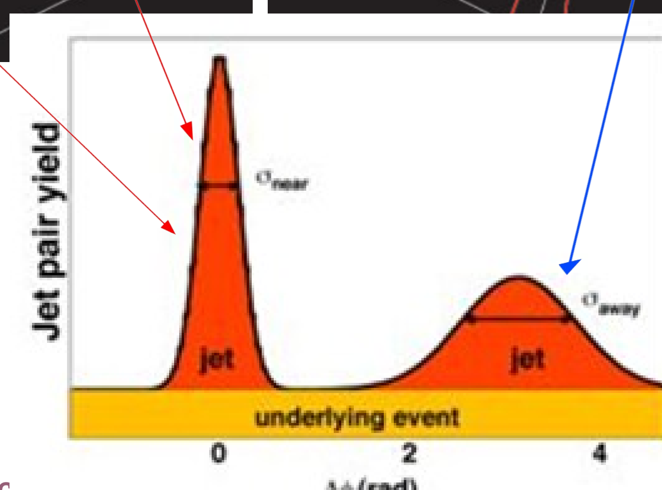
- In heavy-ion collisions one jet is being quenched (suppressed) in the created QGP medium

- 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;



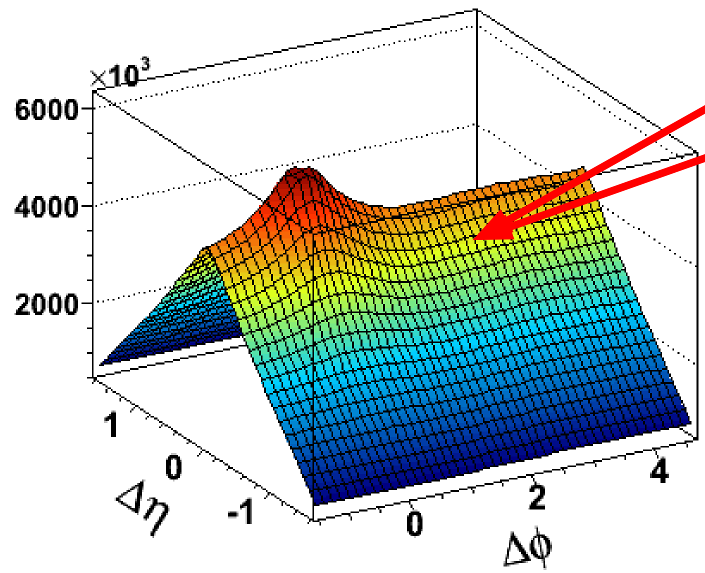


[H6] Eur. Phys. J. C 77 (2017) 569

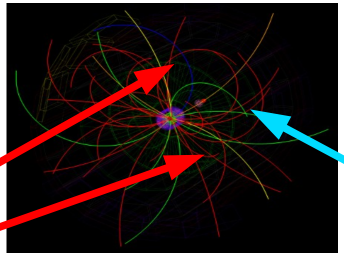
Fig. M. Janik

Signal distribution

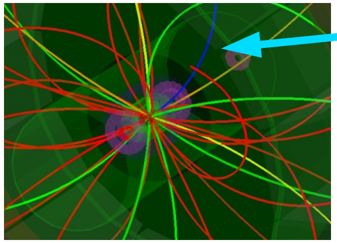
$$S(\Delta\eta,\Delta\varphi)=\frac{d^2 N^{signal}}{d\Delta\eta\Delta\varphi}$$



Event 1

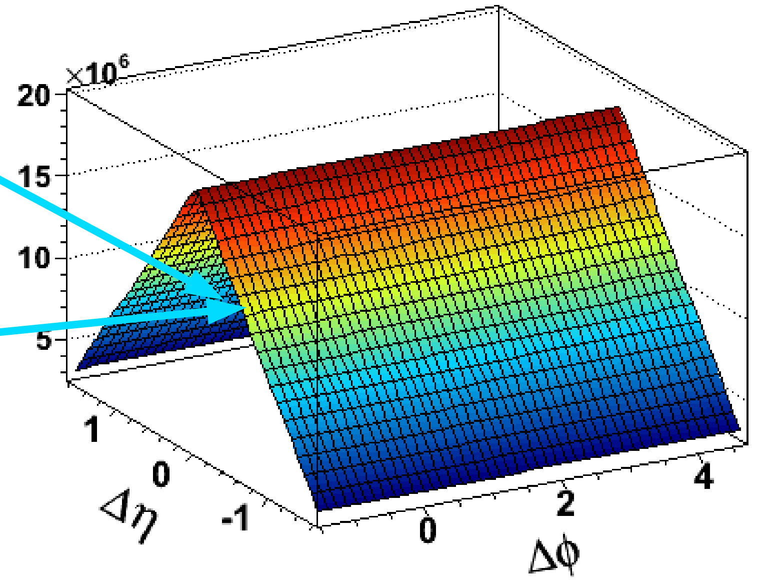


Event 2



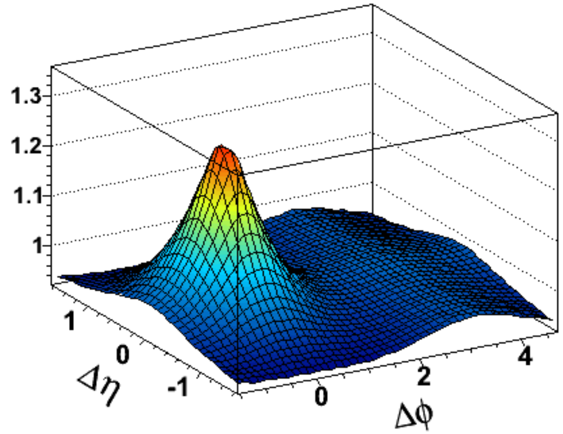
Uncorrelated reference

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



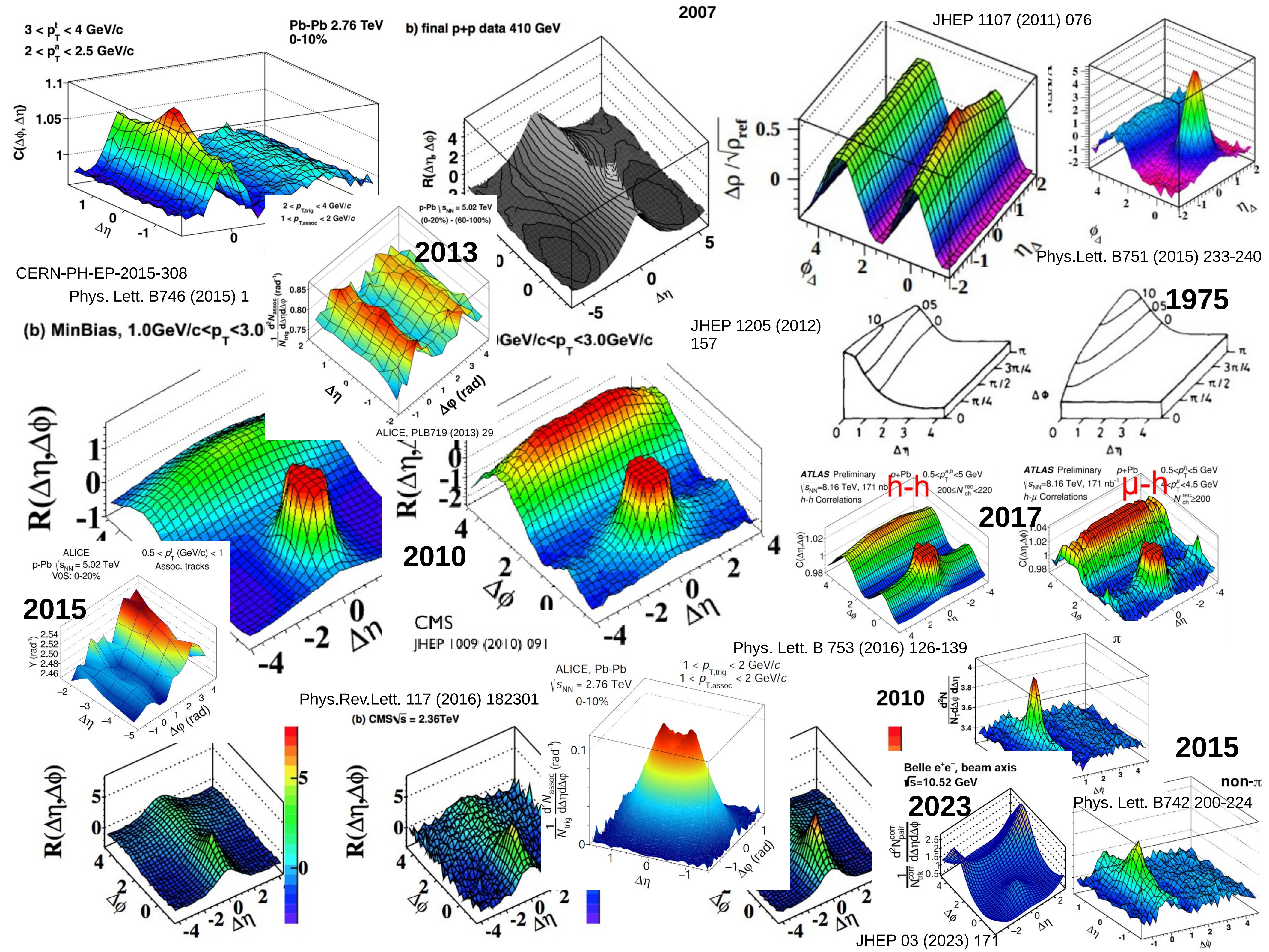
Same event pairs

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



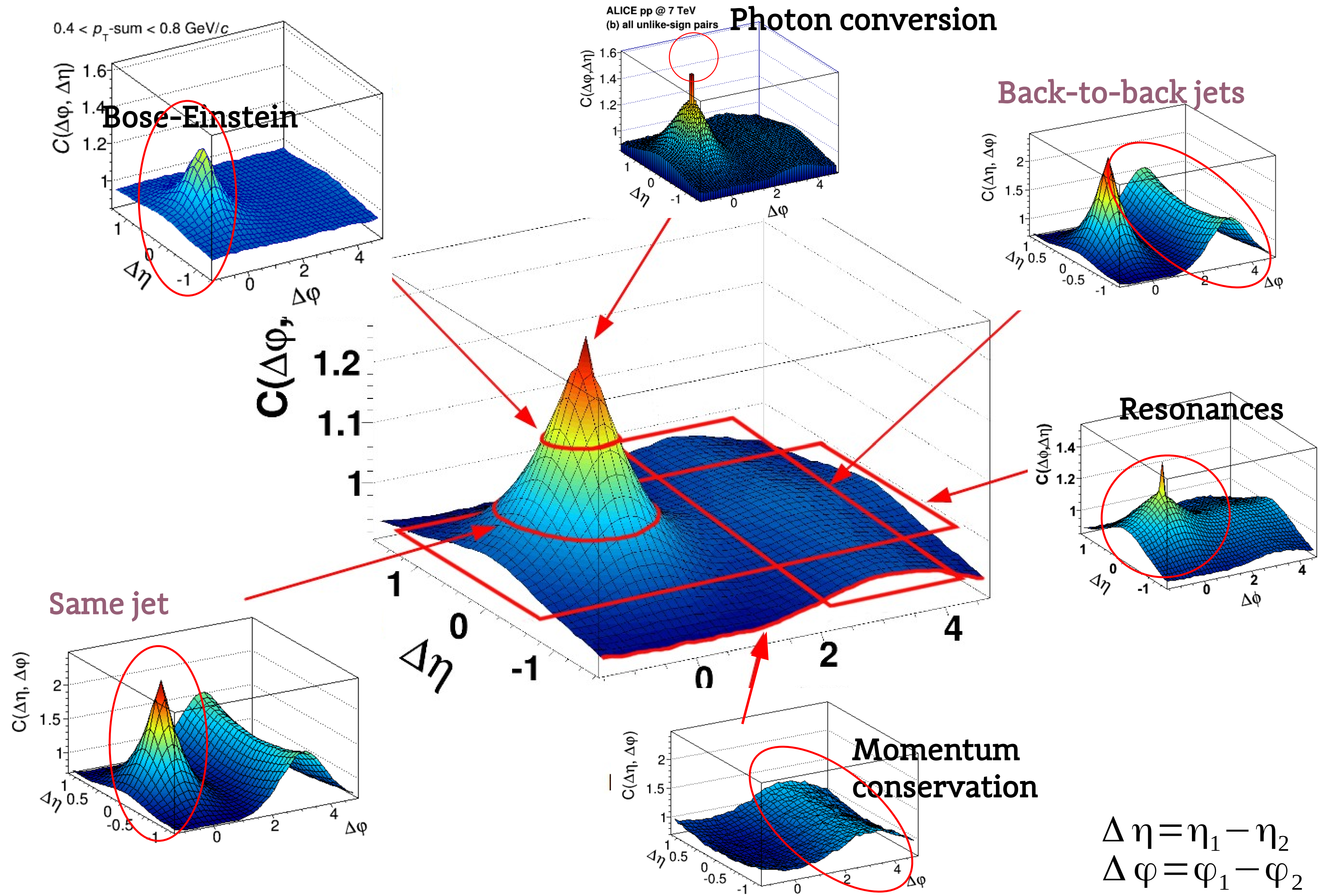
Mixed event pairs

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

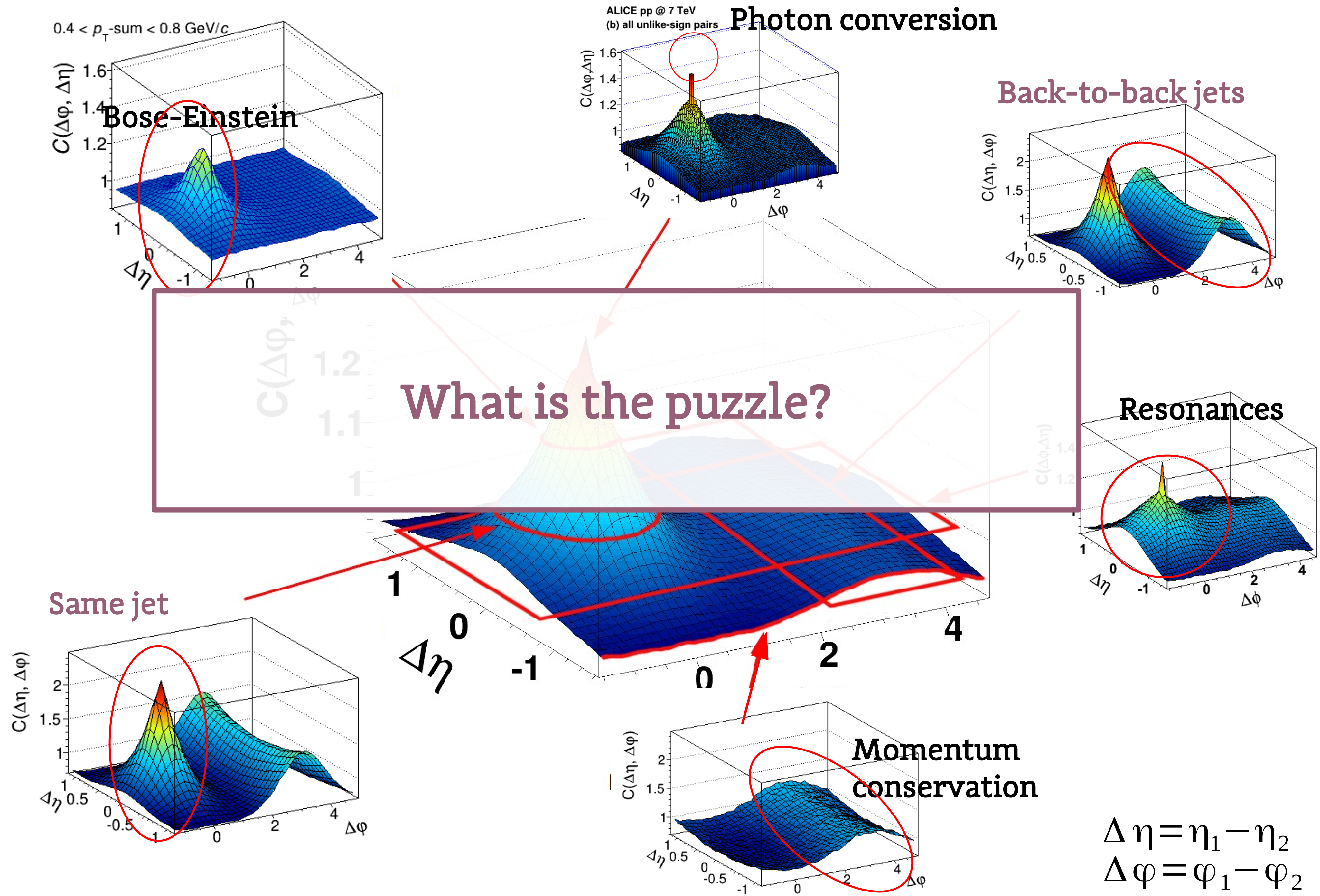


2007
JHEP 1107 (2011) 076
Pb-Pb 2.76 TeV
0-10%
b) final p+p data 410 GeV
CERN-PH-EP-2015-308
Phys. Lett. B746 (2015) 1
2013
ALICE, PLB719 (2013) 29
Phys.Lett. B751 (2015) 233-240
1975
JHEP 1205 (2012) 157
(b) MinBias, 1.0GeV/c<p_T<3.0
2010
CMS
JHEP 1009 (2010) 091
ATLAS Preliminary
h-h
μ-h
2017
h-h Correlations
h-μ Correlations
2015
ALICE
p-Pb
V0S: 0-20%
Assoc. tracks
Phys. Lett. B 753 (2016) 126-139
Phys.Rev.Lett. 117 (2016) 182301
(b) CMS√s = 2.36TeV
ALICE, Pb-Pb
0-10%
2010
2015
Belle e+e−, beam axis
√s=10.52 GeV
2023
non-π
Phys. Lett. B742 200-224
JHEP 03 (2023) 171

ΔηΔφ angular correlations



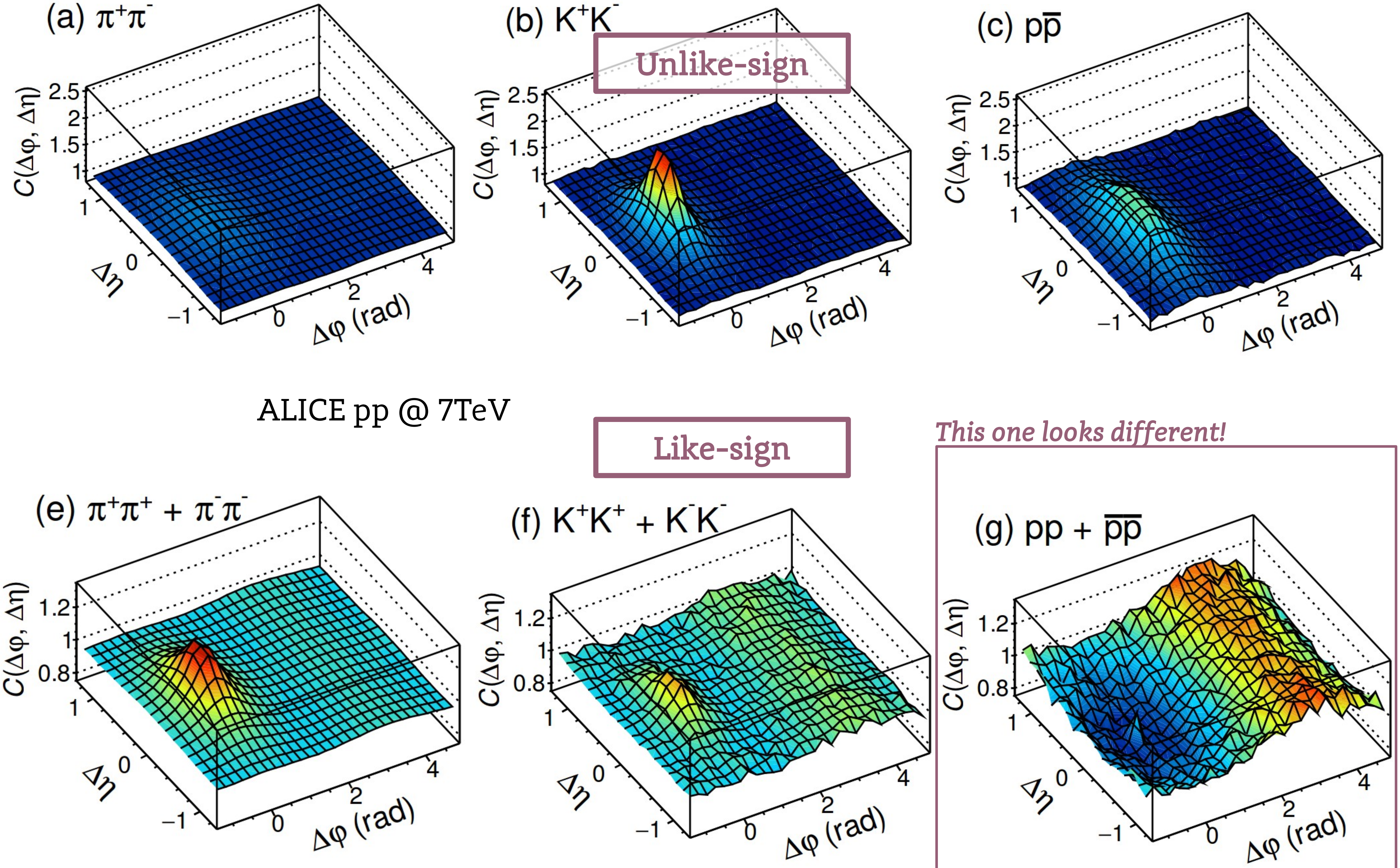
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



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

ΔηΔφ angular correlations

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



Unlike-sign

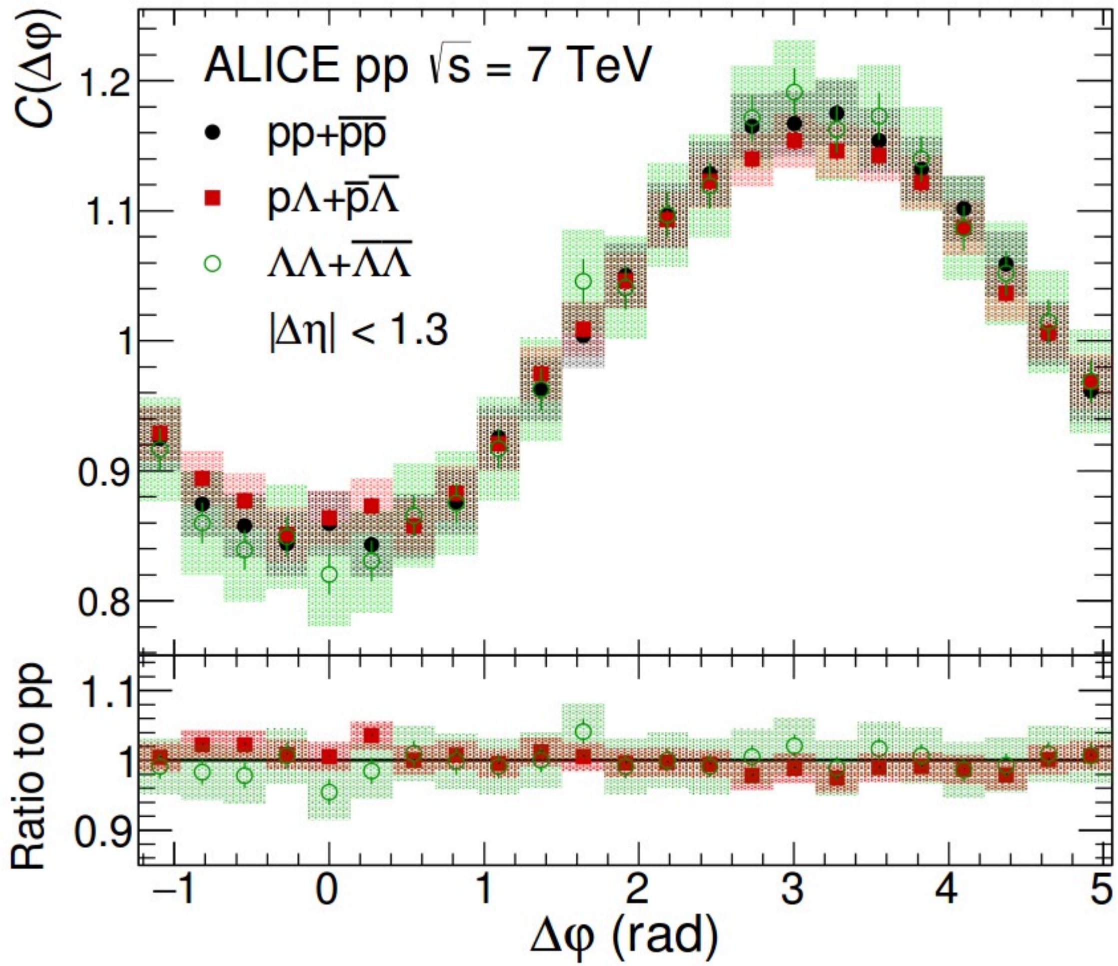
ALICE pp @ 7TeV

Like-sign

This one looks different!

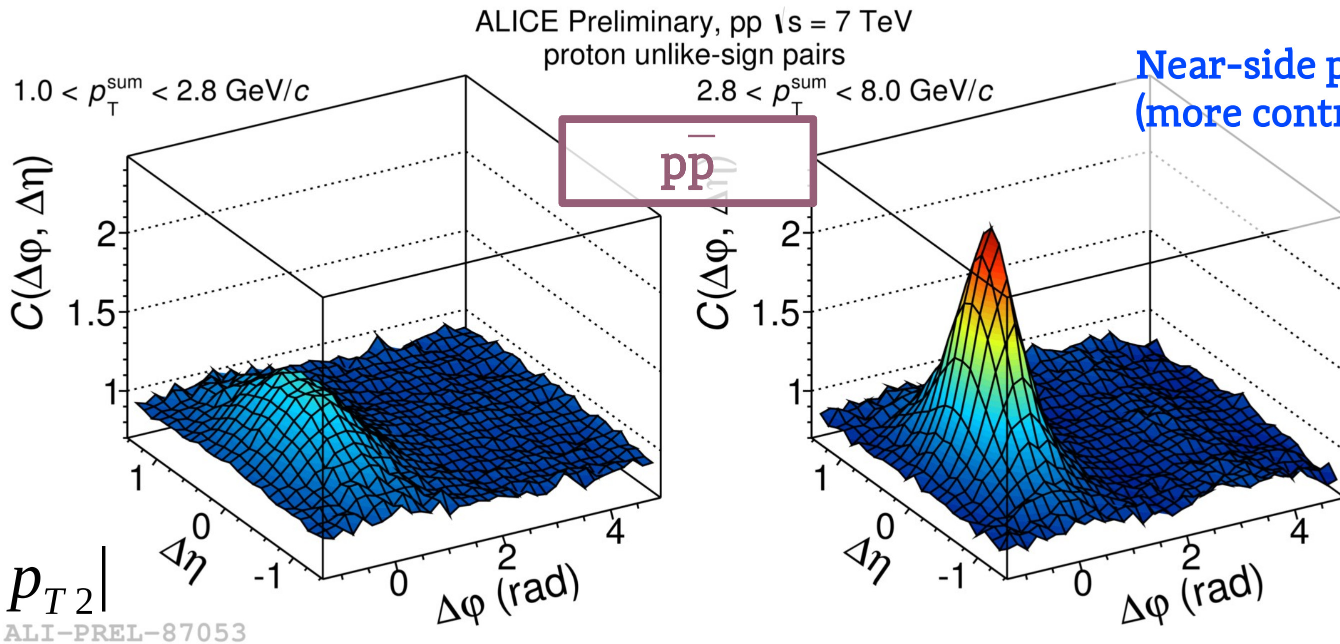
Eur. Phys. J. C 77 (2017) 569

- **The anticorrelation effect is surprising**
- **Is this a common effect for all baryons?**
- Correlation functions were measured also for **ΛΛ** and **pΛ** pairs
- **Λ** baryons are neutral
  → **no Coulomb repulsion** as in pp
- **p** and **Λ** are not identical
  → **no effect from Fermi-Dirac quantum statistics**
- **Conclusion:**
  → **all observations from pp pairs can be extended to ΛΛ and pΛ**



ΔηΔφ angular correlations

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

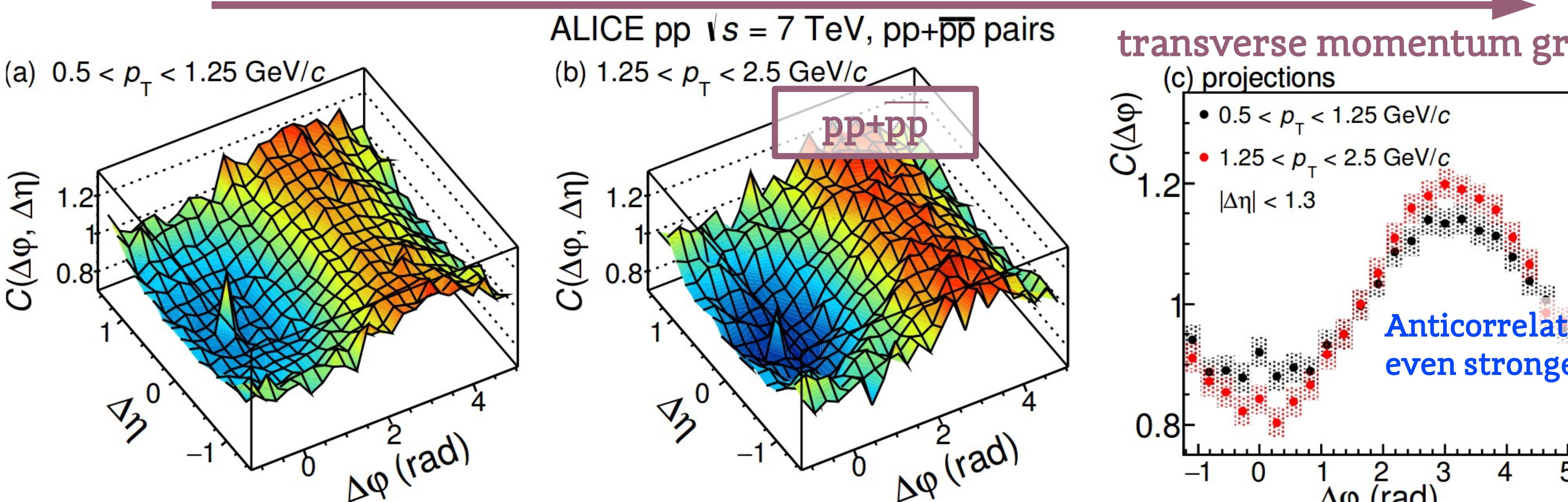


$p\bar{p}$

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

$$p_T^{sum} = |p_{T\,1}| + |p_{T\,2}|$$

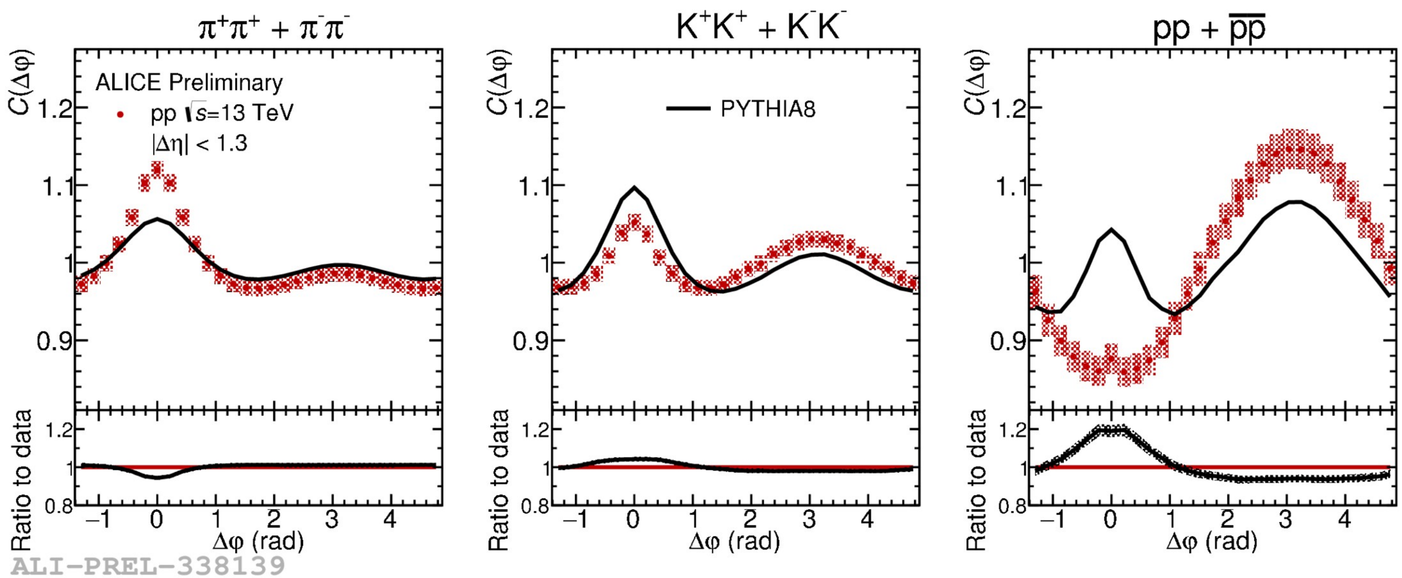
transverse momentum growth

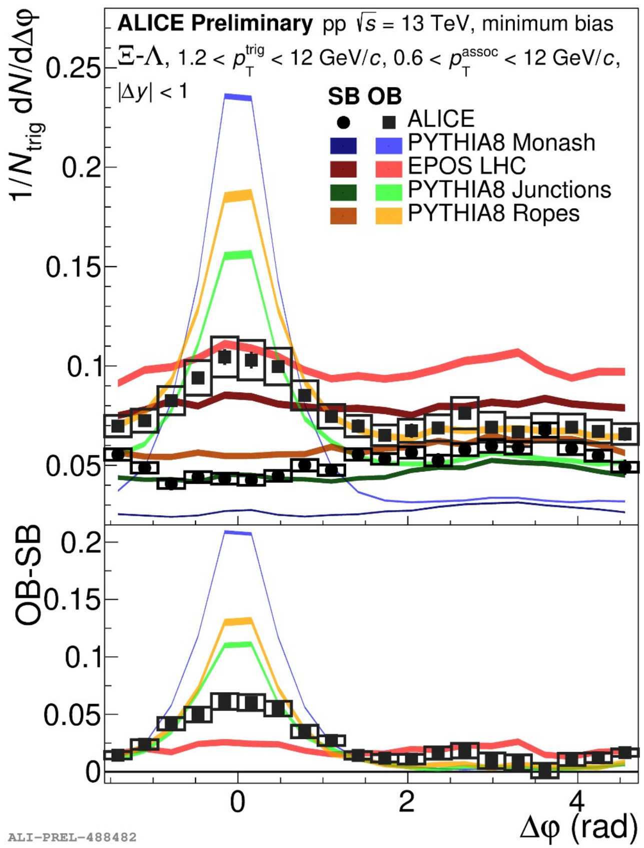


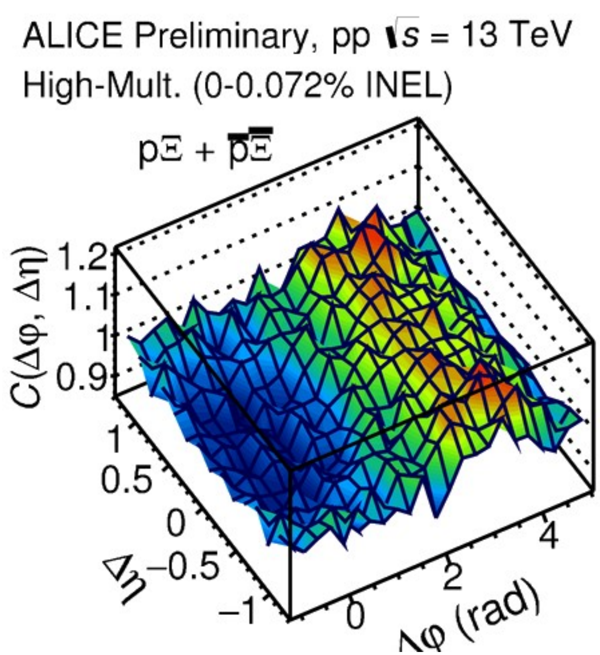
pp+$\bar{p}\bar{p}$

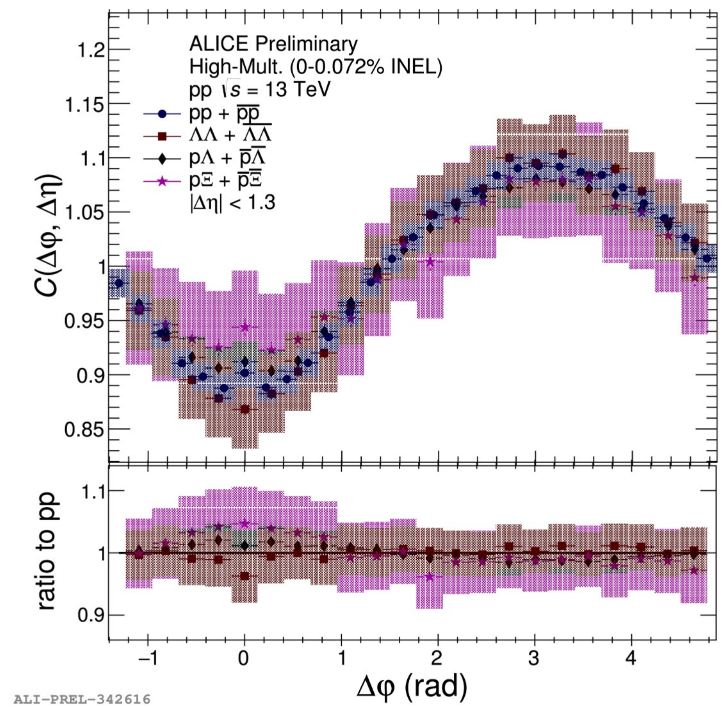
Anticorrelation even stronger!

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









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

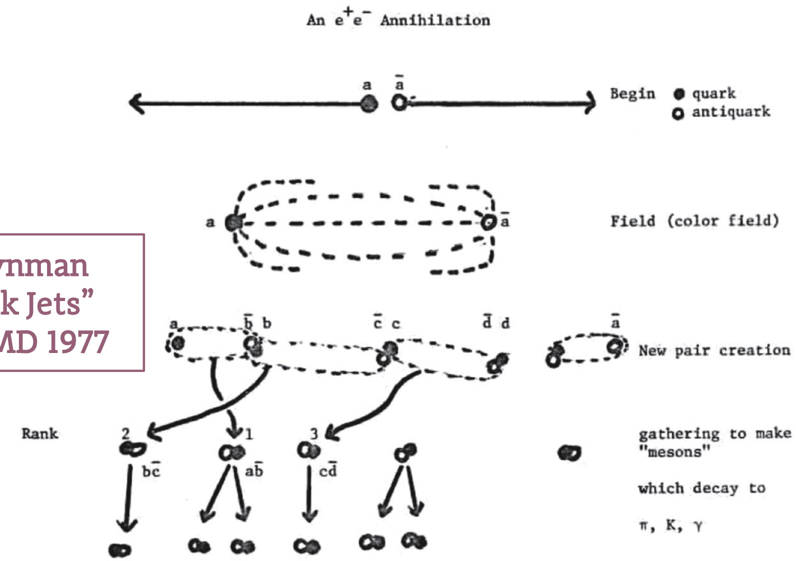


Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

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

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

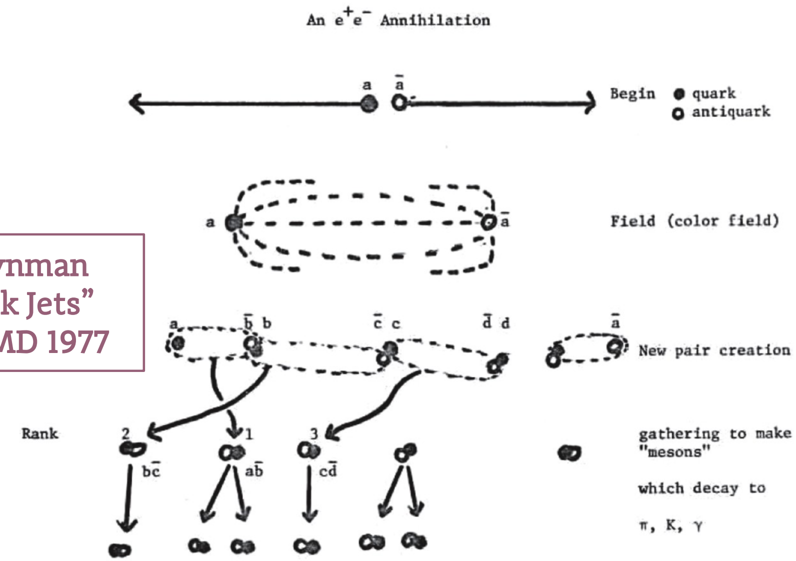


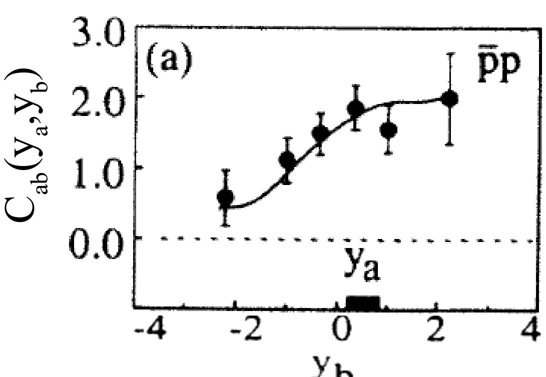
Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

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

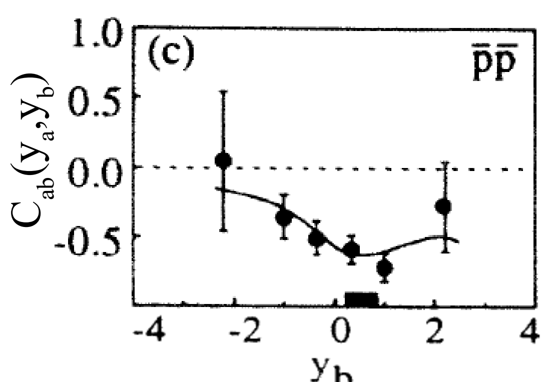
Local **baryon number conservation** <u>**partially**</u> **responbsible for anticorrelation at 29 GeV collision energy**

Models at lower energies agree with observations seen in data

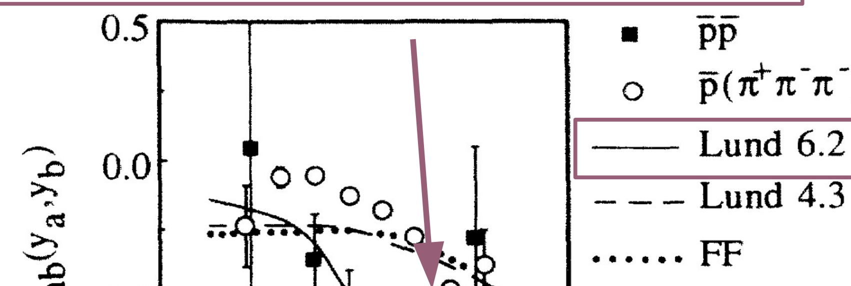
correlation



anti-correlation



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



Lund model describes data

ISMD conference 40 years later....

https://indico.nucleares.unam.mx/event/1180/session/19/contribution/108

POLITECHNIKA WARSZAWSKA WARSAW UNIVERSITY OF TECHNOLOGY

ALICE A JOURNEY OF DISCOVERY

What can we learn from femtoscopic and angular correlations of identified particles in ALICE?

Łukasz Graczykowski

for the ALICE Collaboration

Faculty of Physics

WARSAW UNIVERSITY OF TECHNOLOGY

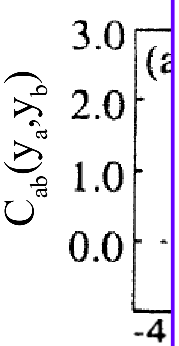
XXLVII International Symposium on Multiparticle Dynamics

Tlaxcala, Mexico

15/09/2017

We are ... antibar...

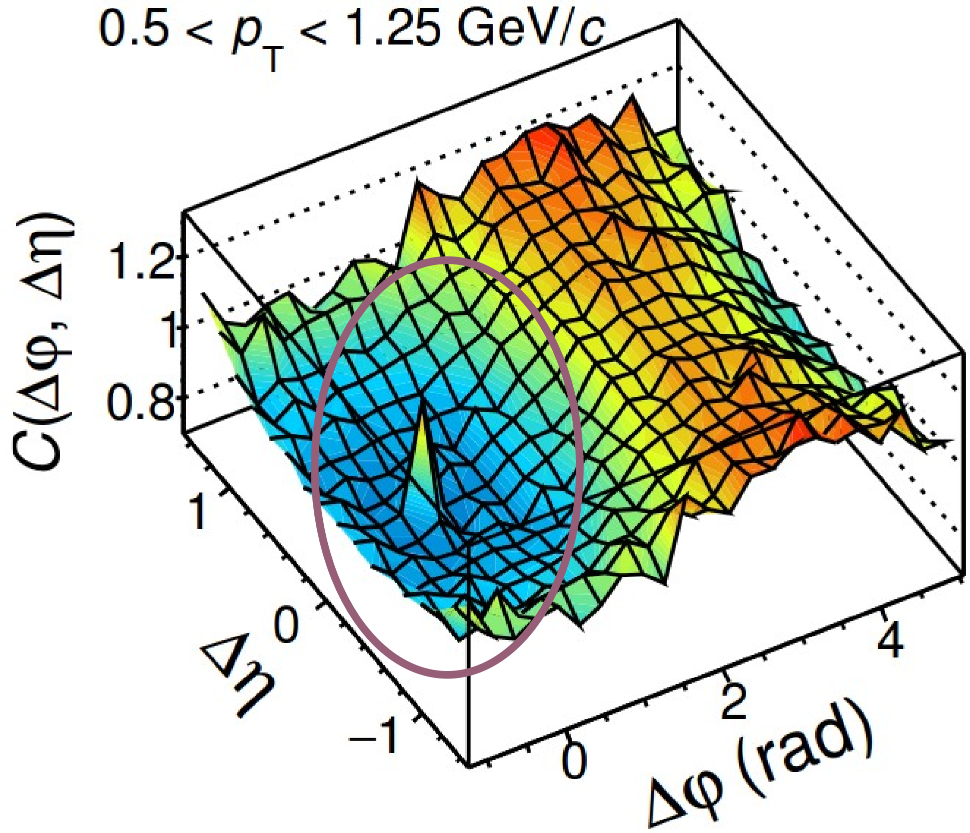
Local b... theore...



k ... quark ... field) ... reation ... to make ... y to ... fragment into ... sberg, France, ... e ... $^+\pi^-\pi^-$) ... d 6.2 ... d 4.3 ... nodel ... pes

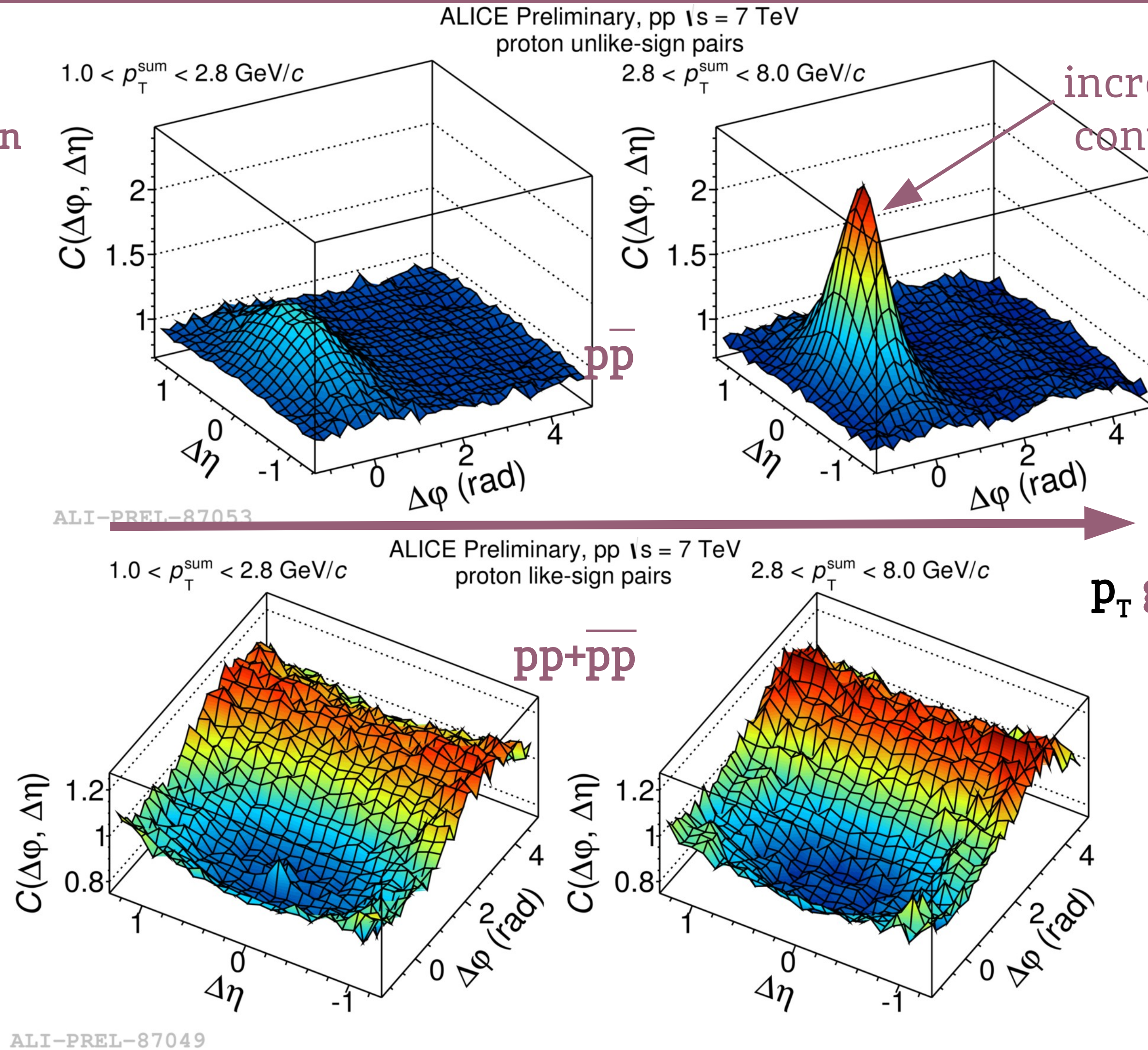
TPC/Two Ga...

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

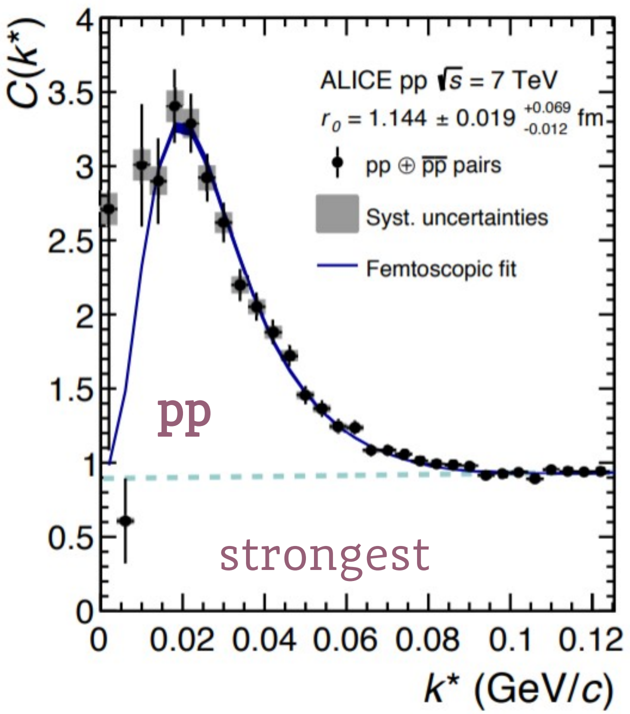
p_T growth

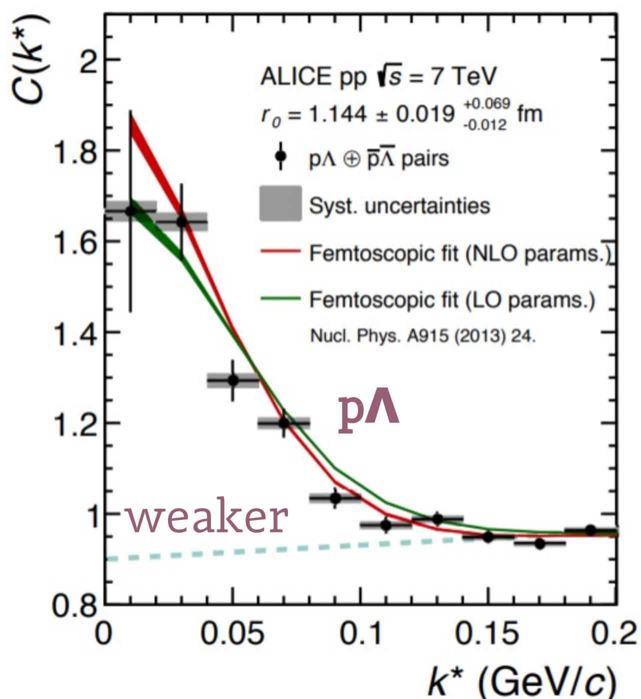
small peak <u>disappears</u> for high p_T

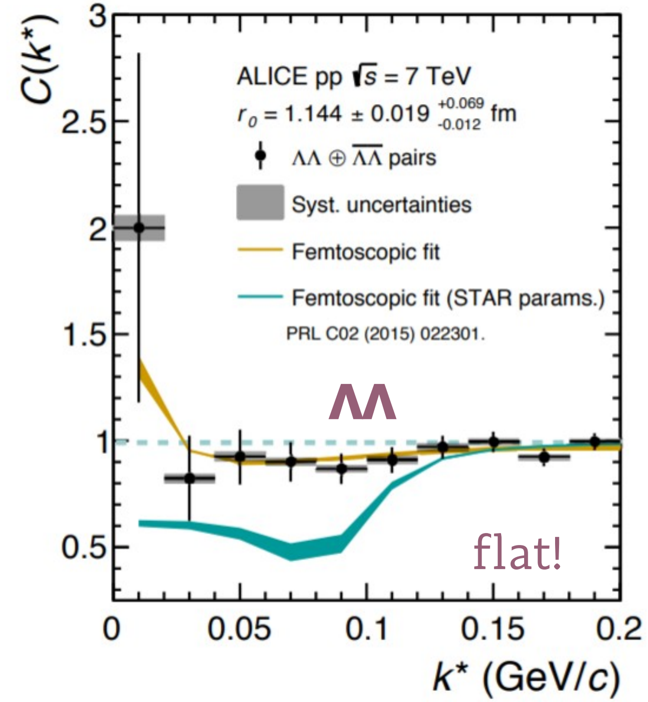
- The small peak seems to behave **strangely** → decreases with increasing p_T
- Is it an unnoticed and not removed **detector effect** OR is there some **physics behind it**?

Strong FSI for other baryon pairs

ALICE, PRC 99, 024001 (2019)

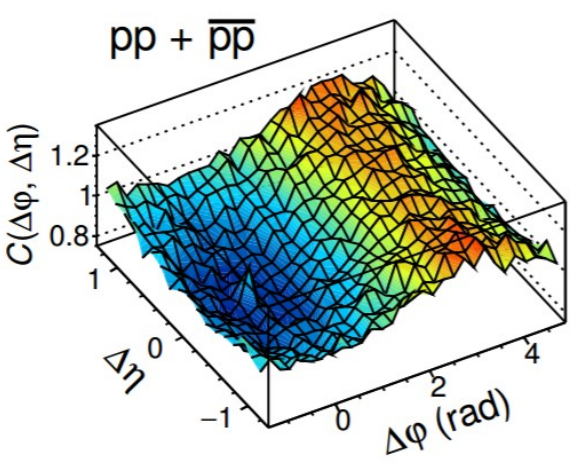


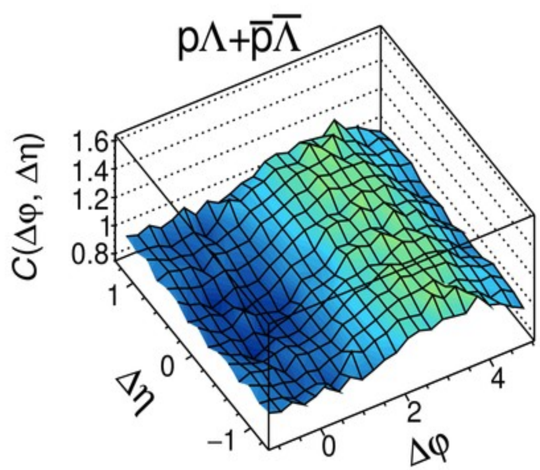


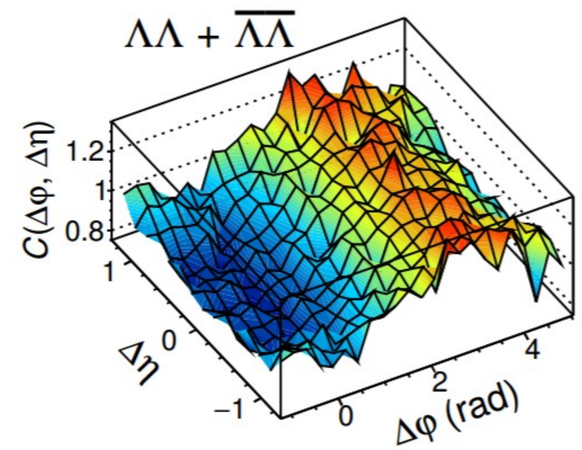


correlation strength

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

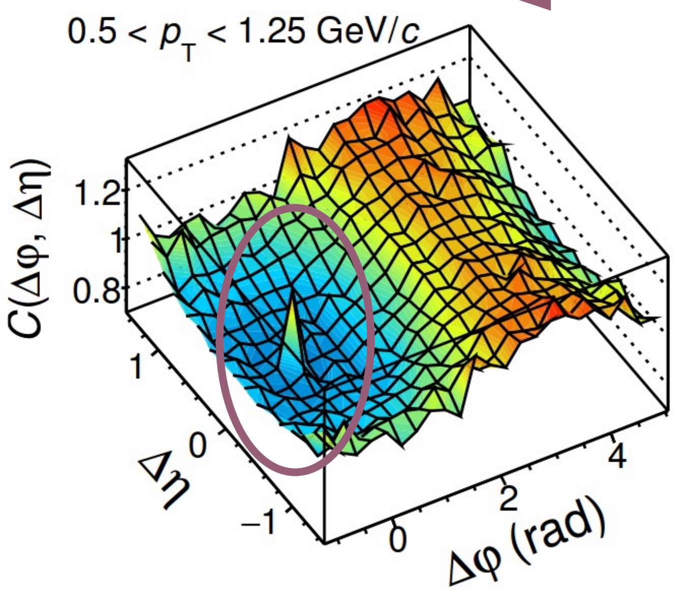


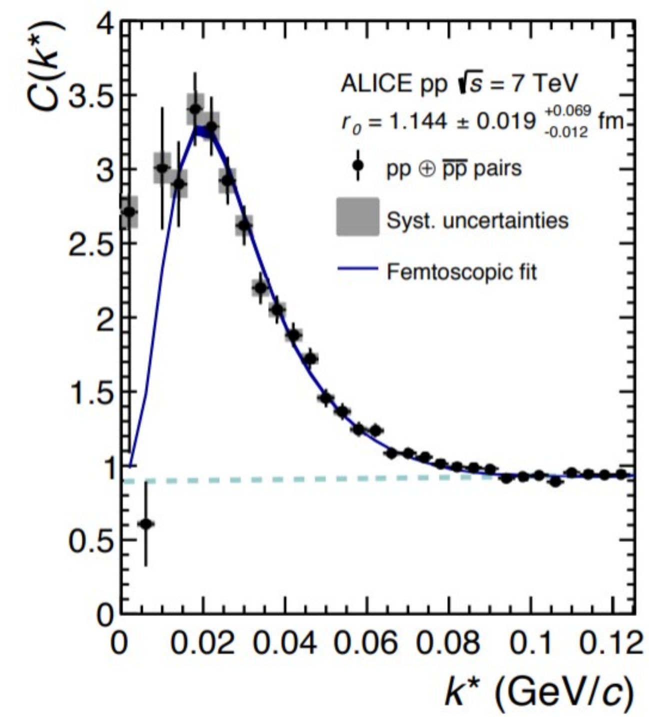




Can we then use femtoscopic correlations to prove the ALICE hypothesis for the small peak?

unfolding?





Ł.G. & M.J., PRC 104, 054909 (2021)

- **Direct transformation** from $C(k^*)$ to $C(\Delta\eta,\Delta\varphi)$ is **not possible**
- **We propose a very simple Monte Carlo algorithm to unfold the angular correlation from the femtoscopic one**

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

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

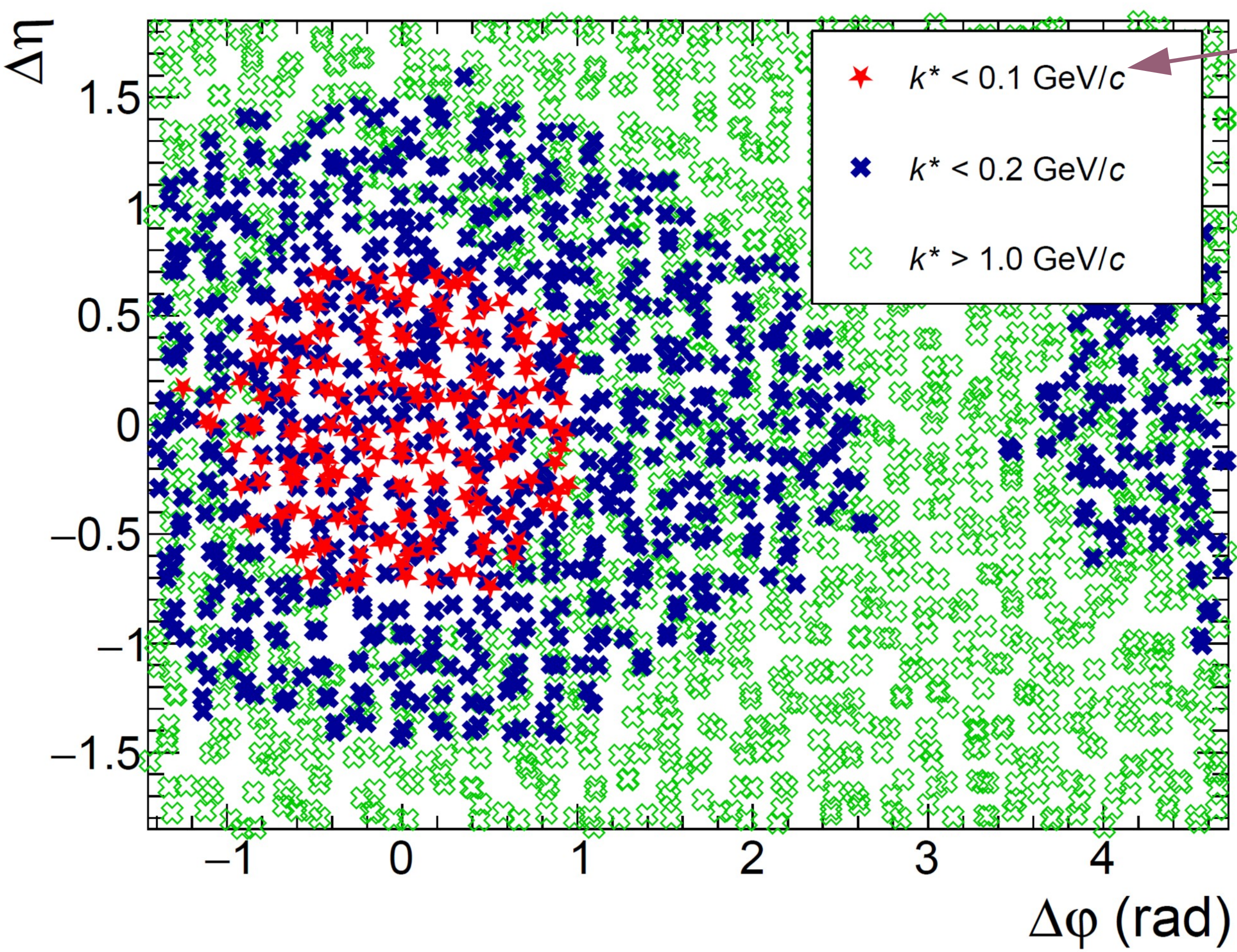
Łukasz Kamil Graczykowski [*] and Małgorzata Anna Janik [†]
Faculty of Physics, Warsaw University of Technology ul. Koszykowa 75, 00-662 Warszawa, Poland

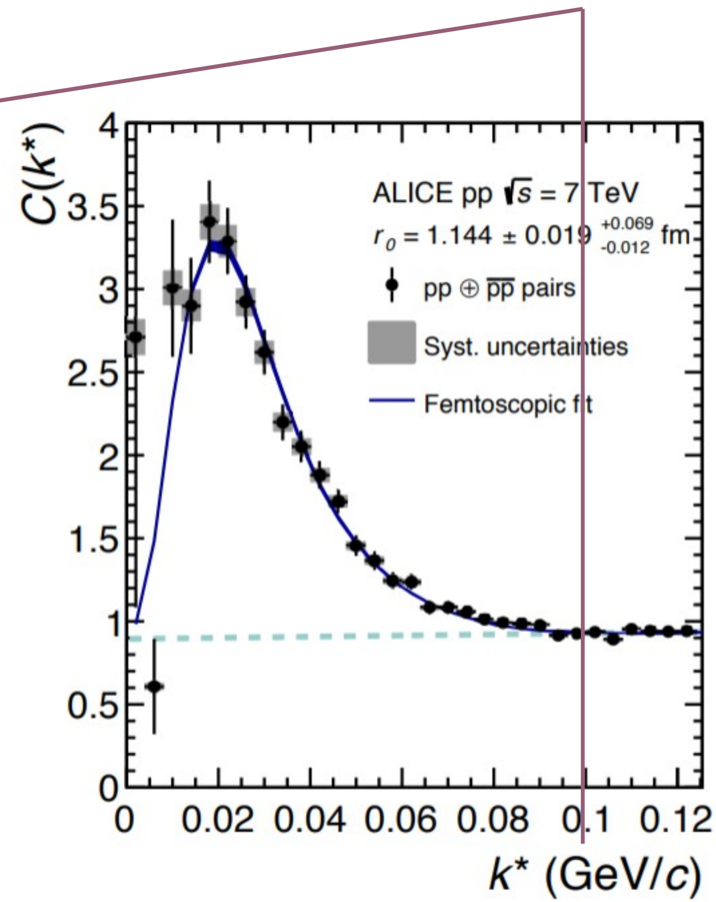
(Received 31 July 2021; accepted 11 November 2021; published 29 November 2021)

Relation between two correlations

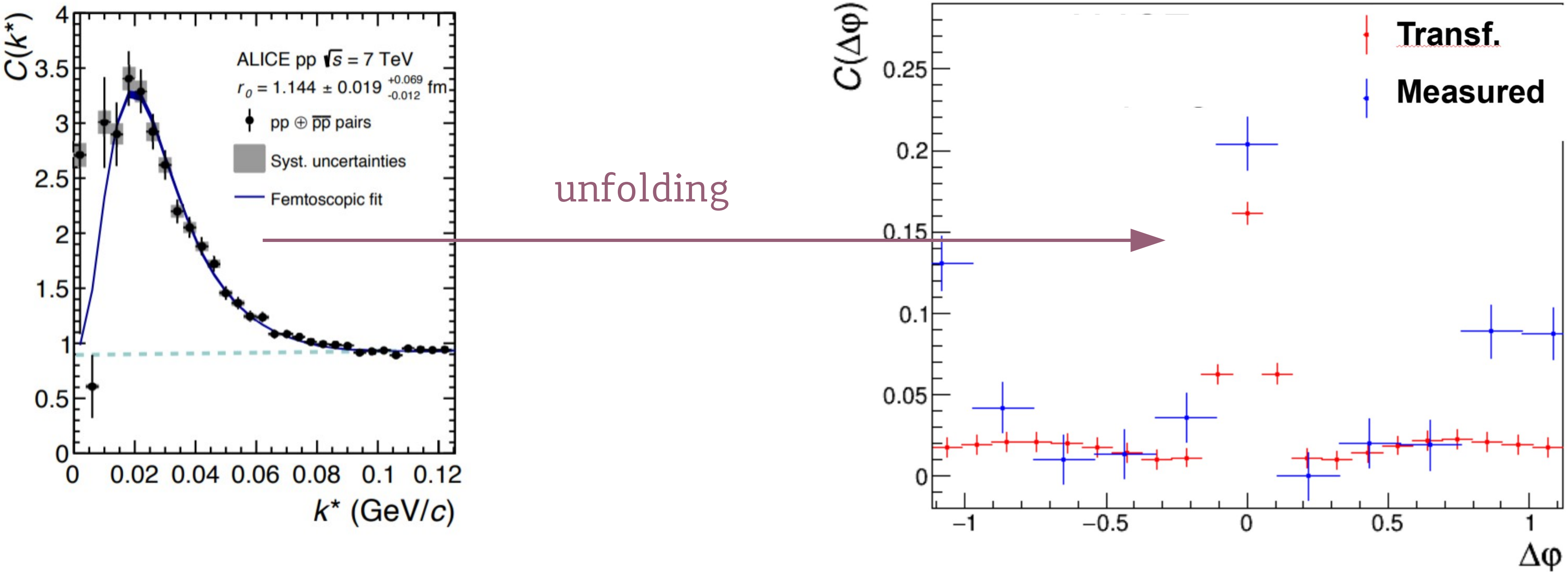
- **Femtoscopic region** (small k*) translates directly to the near-side region (0,0) in the angular correlation

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





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!**

Improving the ALICE analysis framework with Machine Learning PID

in collaboration with

Faculty of Electronics and Information Technology
WARSAW UNIVERSITY OF TECHNOLOGY

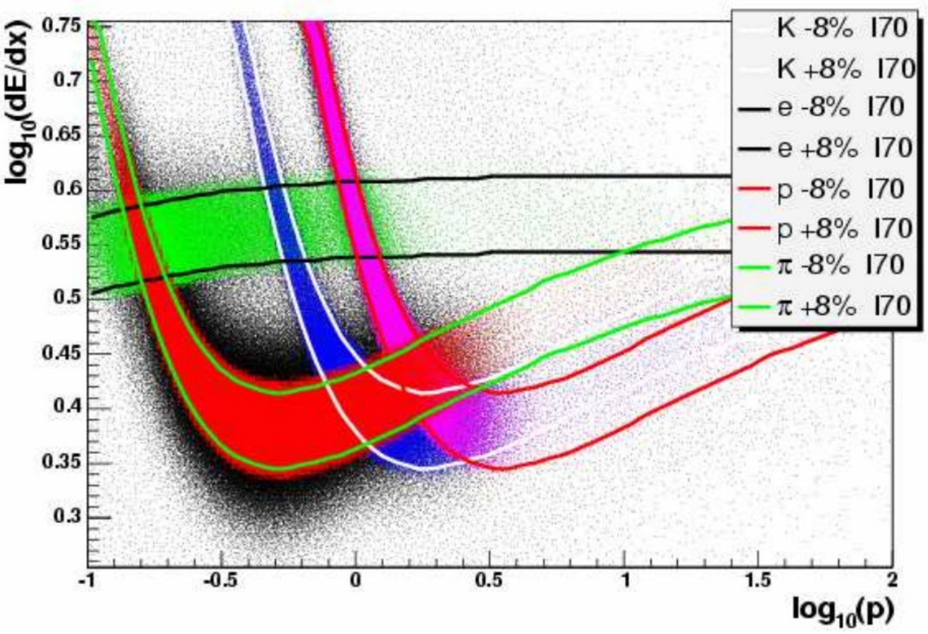
CERN

Faculty of Electrical Engineering
WARSAW UNIVERSITY OF TECHNOLOGY

Traditional vs ML PID

Traditional PID:

- a typical analyzer selects particles "manually" by cutting on certain quantities, like the number of standard deviations of a signal from the expected value ($n\sigma$)
- most limitations come in the regions where signals from different particle species cross
- "cut" optimization is a time-consuming task



https://arxiv.org/pdf/nucl-ex/0505026.pdf

Machine learning PID:

- perfect task for Machine Learning
- can learn non-trivial relations between different track parameters and PID
- no "trial and error" approach

Proposed solution for PID

ITRSCP, Springer 2020, 3-17
JINST 17 (2022) C07016

Objectives:

1) Build a ML classifier that can outperform traditional PID

2) Train and validate the classifier on Monte Carlo simulations and experimental data

3) Create a simple-to-use interface for users (ALICE physicists):

   – first attempts in 2019 (Random Forest) for LHC Run 2 (AliRoot)
     → proof-of-concept work

   – new, much more advanced, project for LHC Run 3 (O^2)
     → still in the research phase

Limitations:

Quality of the classifier will depend on the MC sample (need to handle discrepancies between data and MC)

No easy way to calculate systematic uncertainties from the ML procedure

The classifier is a “black box” - no easy way to tell what’s going on inside

Domain adaptation

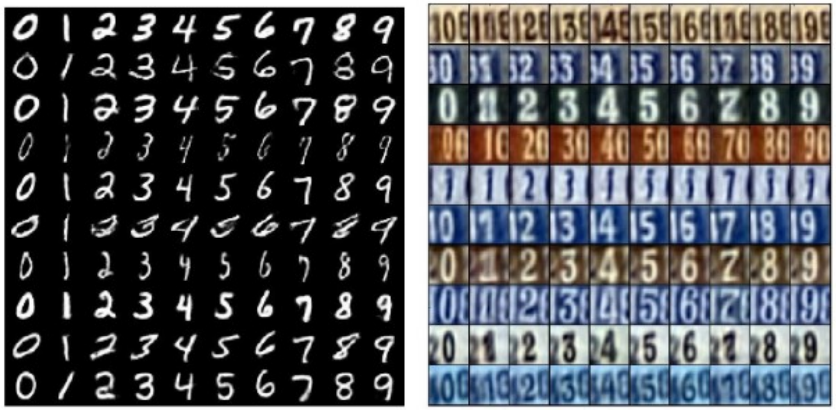
JINST 17 (2022) C07016

ALICE is undergoing a major upgrade with completely new software framework O²

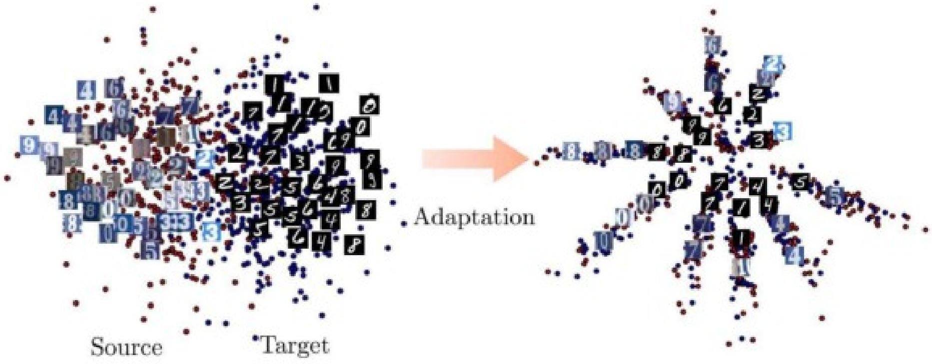
We explore the Unsupervised Domain Adaptation for ML PID

- problem of transferring the knowledge from a **labeled source domain** to **unlabeled target domain**, when both domains have different distributions of attributes (as in the case of MC and data)

Preliminary implementation in O² ready, but research work still ongoing


(a) MNIST (b) SVHN

MNIST and SVHN datasets



Visualization of domain adaptation

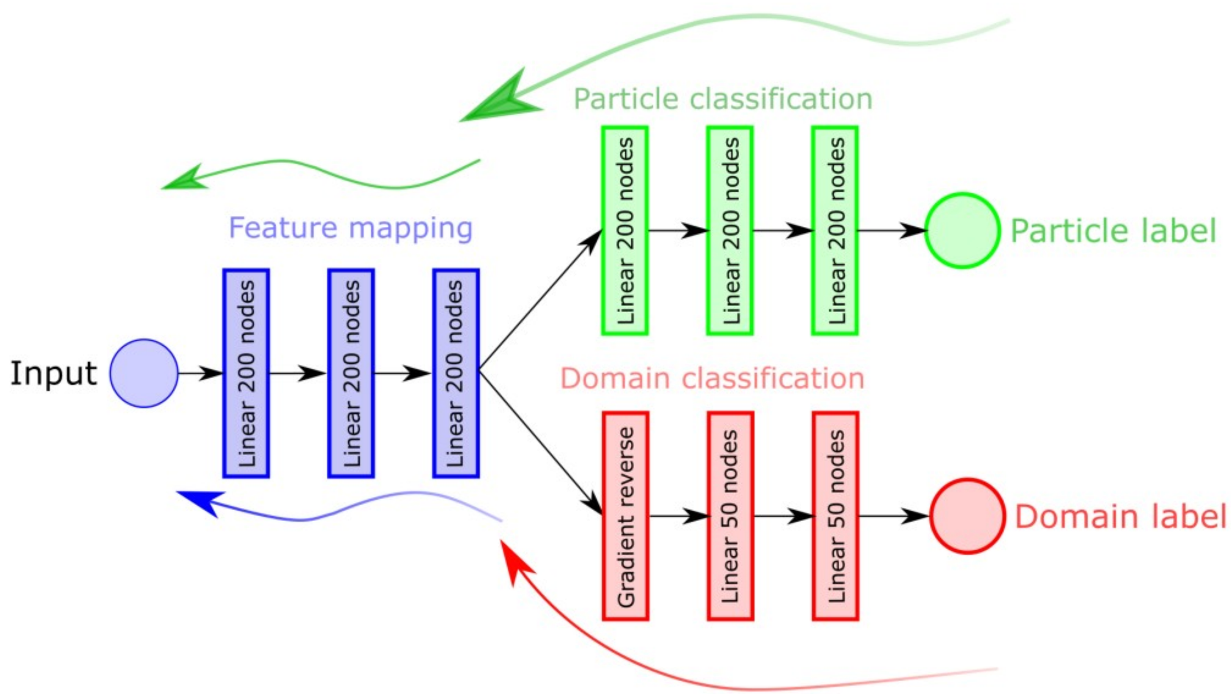
Proposed model

JINST 17 (2022) C07016

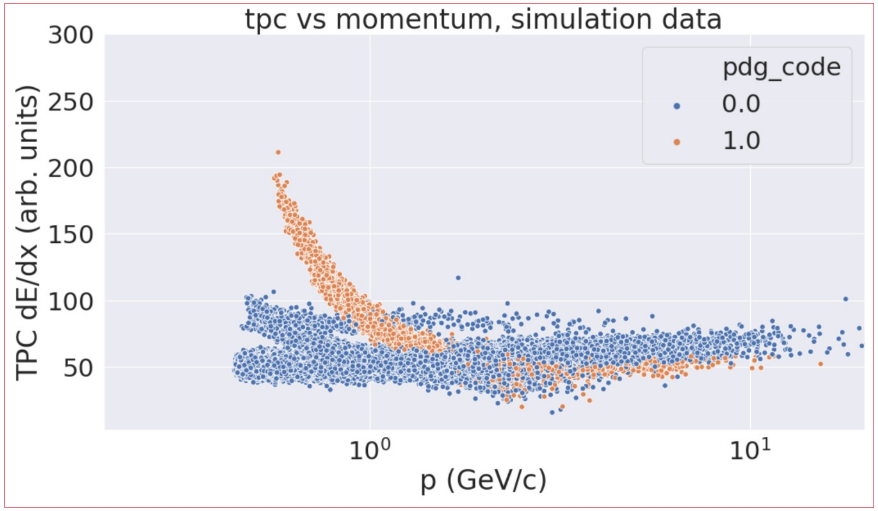
Model based on Domain Adversarial Training of Neural Networks

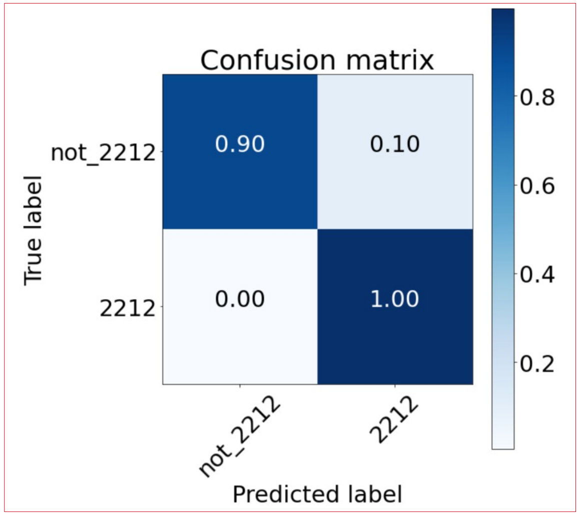
Architecture consists of three neural networks:

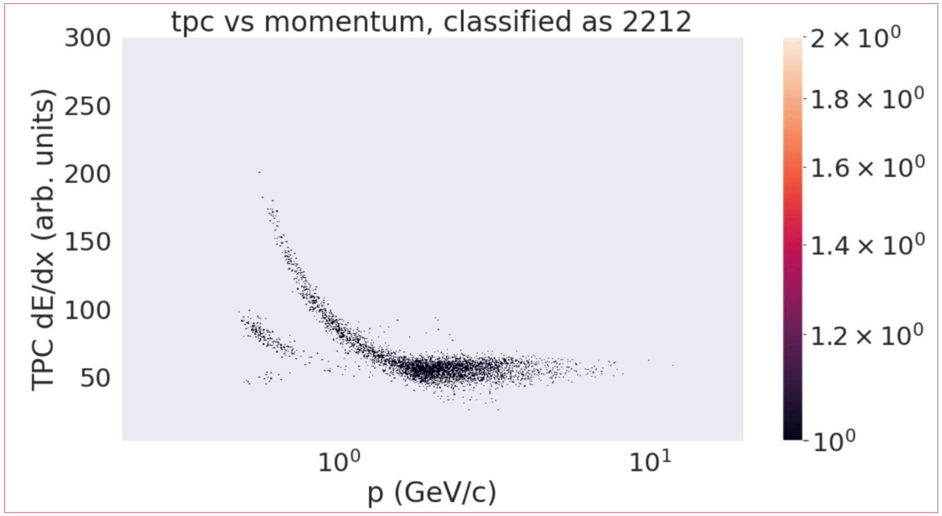
- **feature mapping network**, which maps features of both data sets into common, domain invariant latent space
- **particle classification network**, which classifies particles basing on domain invariant latent space
- **domain discriminator network**, which classifies domain of each particle



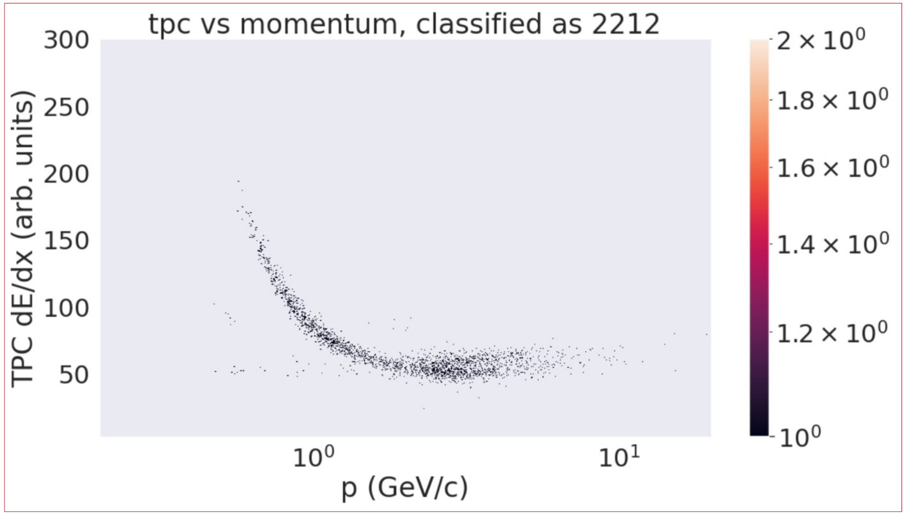
JINST 17 (2022) C07016







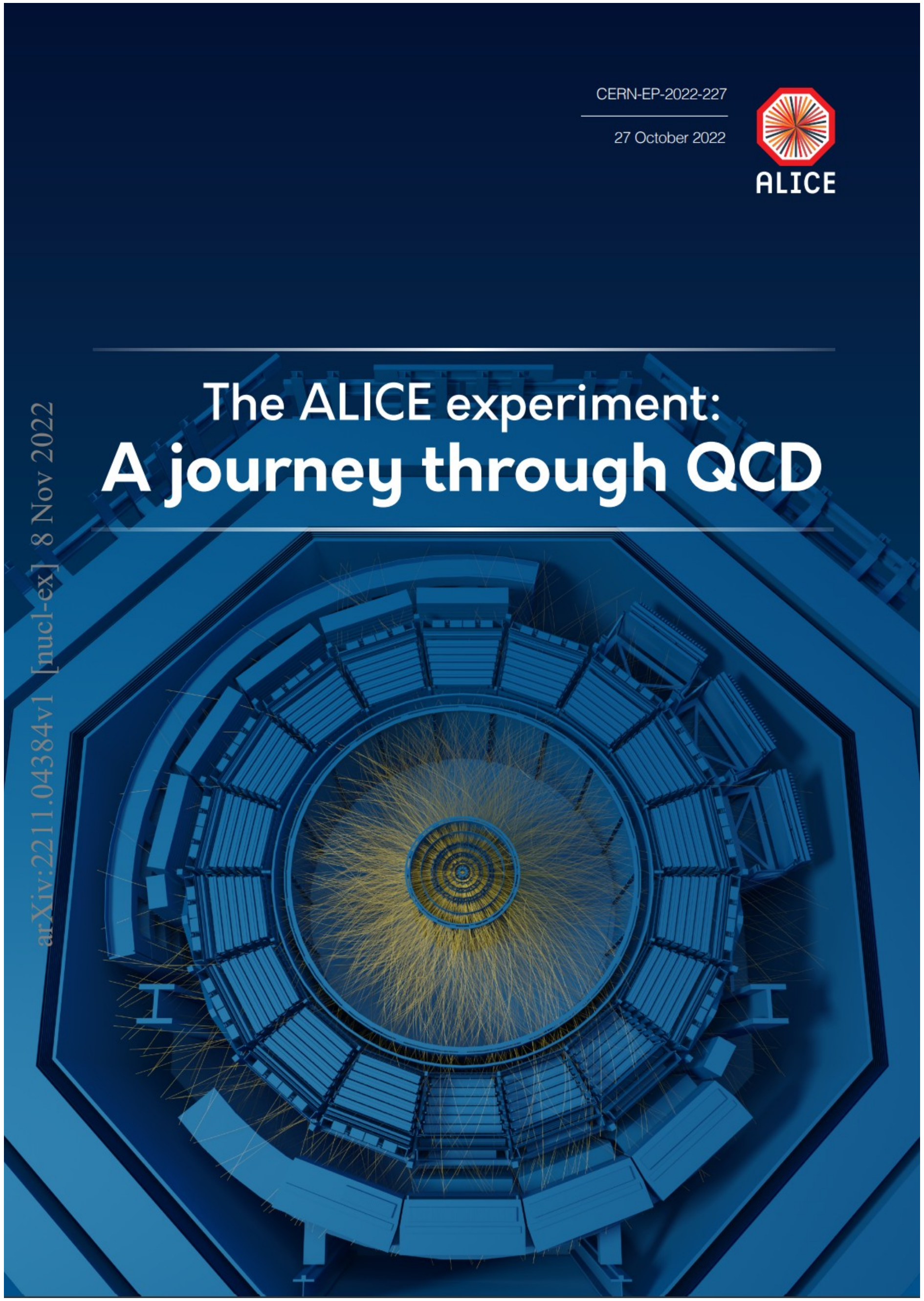
No Domain Adaptation



Domain Adaptation

Instead of a summary...

10+ years of ALICE operation



https://arxiv.org/abs/2211.04384
submitted to Eur. Phys. J. C

- ALICE Review Paper of the last 10+ years of operation
- Overview of the most important results from LHC Run 1 (2009-2013) & LHC Run 2 (2015-2018)
- 328 pages, 9 chapters
- Written as a collaborative effort, coordinated by the Steering Group (24 members)
  - SG divided into 9 Topical Groups
  - I was leading TG1, together with Dr. Francesca Bellini from the University of Bologna (Italy)
- A perfect place to learn about the HI physis @ LHC from the very basics


PROTON PHYSICS : STABLE BEAMS
PHYSICS
PROTON PHYSICS: STABLE BEAMS
ALICE
A Large Ion Collider Experiment

THANK YOU FOR YOUR ATTENTION

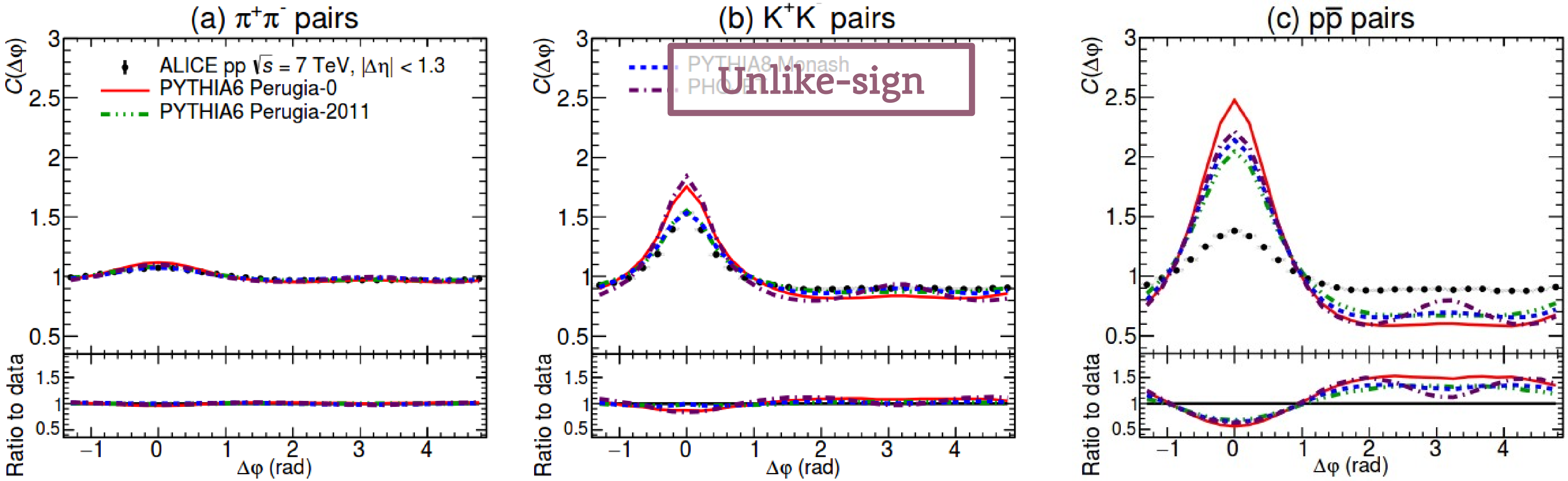
I am happy to answer any questions

lgraczyk@cern.ch
lukasz.graczykowski@pw.edu.pl

PHOJET, PYTHIA 6 and PYTHIA 8

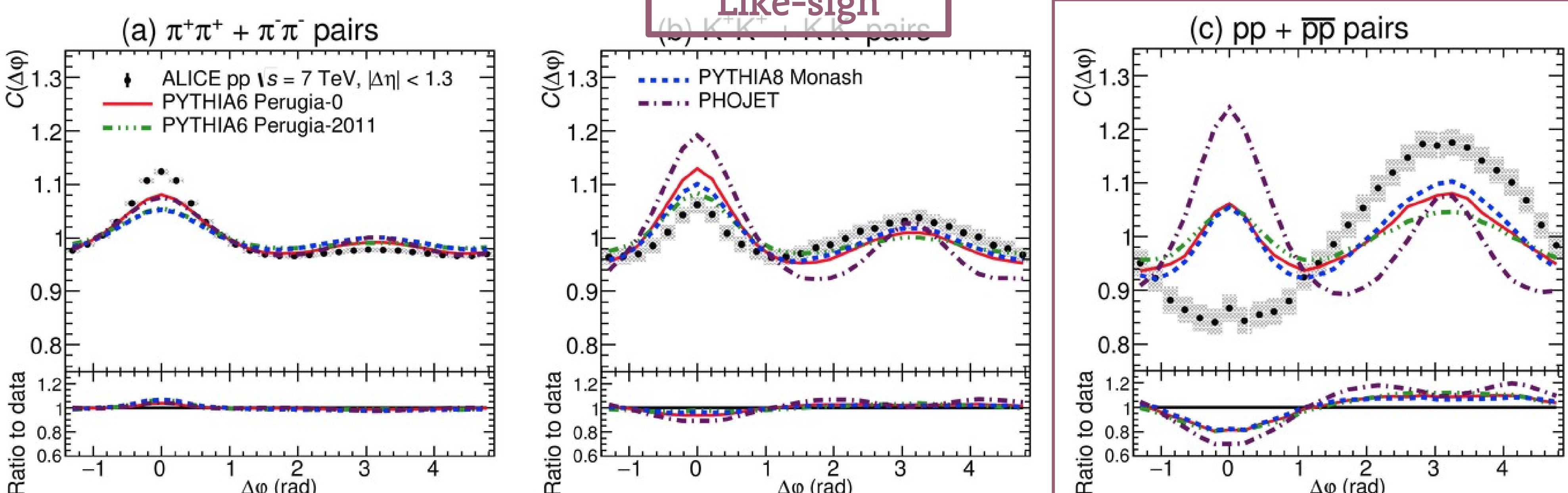
ALICE, Eur. Phys. J. C 77 (2017) 569

Unlike-sign



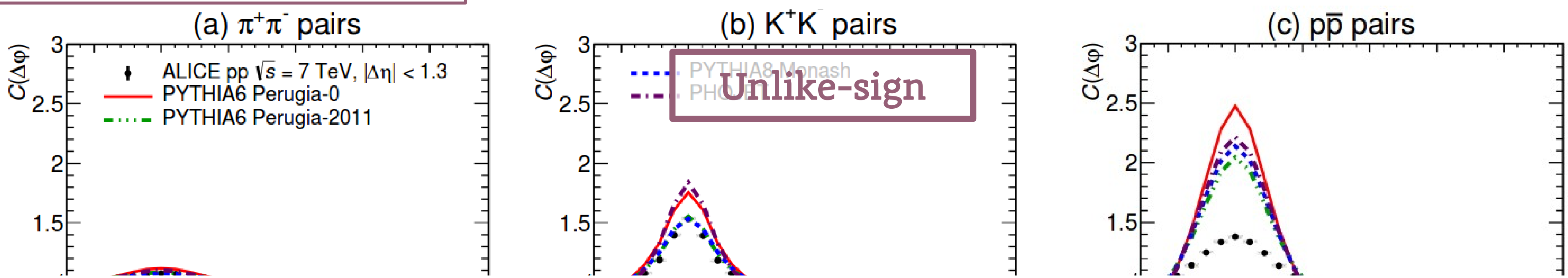
Like-sign

This one looks different!



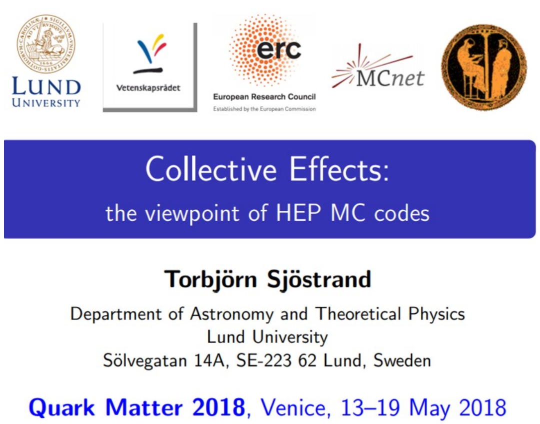
PHOJET, PYTHIA 6 and PYTHIA 8

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



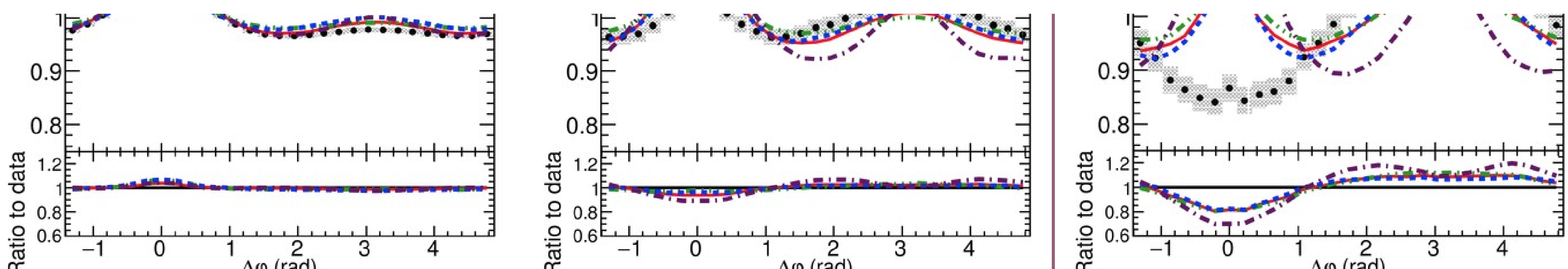
Unlike-sign

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



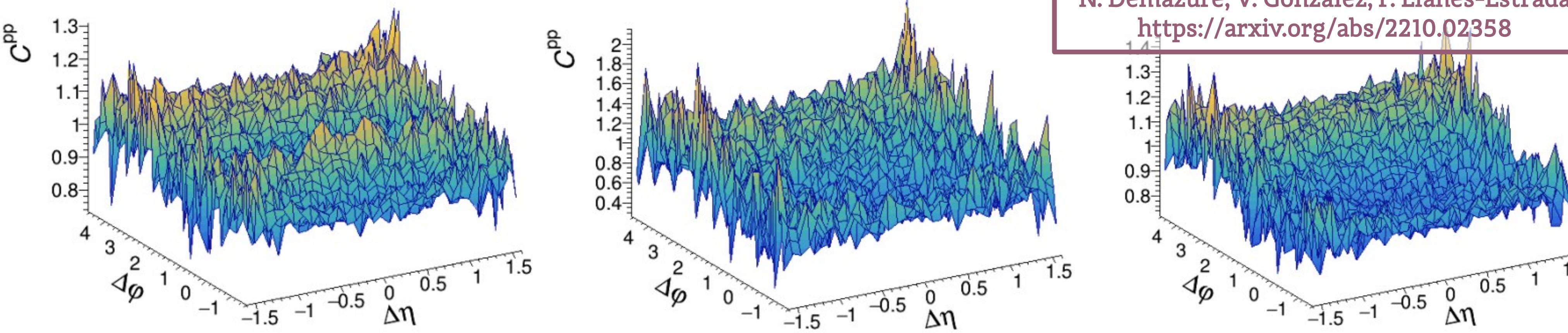
Nucl. Phys. A 982 (2019) 43-49

"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."

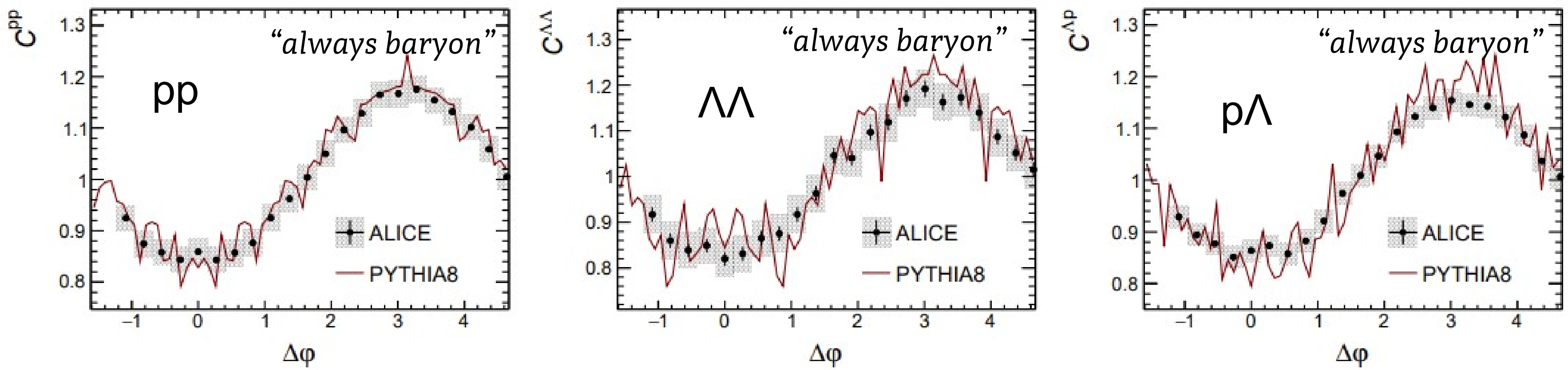


Modified PYTHIA

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



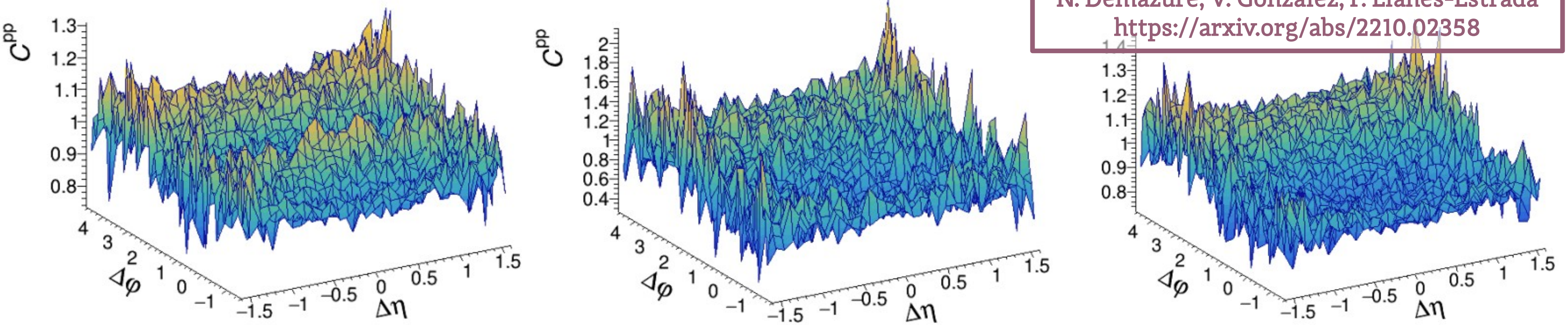
(a) pp C correlation with unmodified PYTHIA (b) pp C correlation, one-baryon per string policy (c) pp C correlation, always-baryon policy



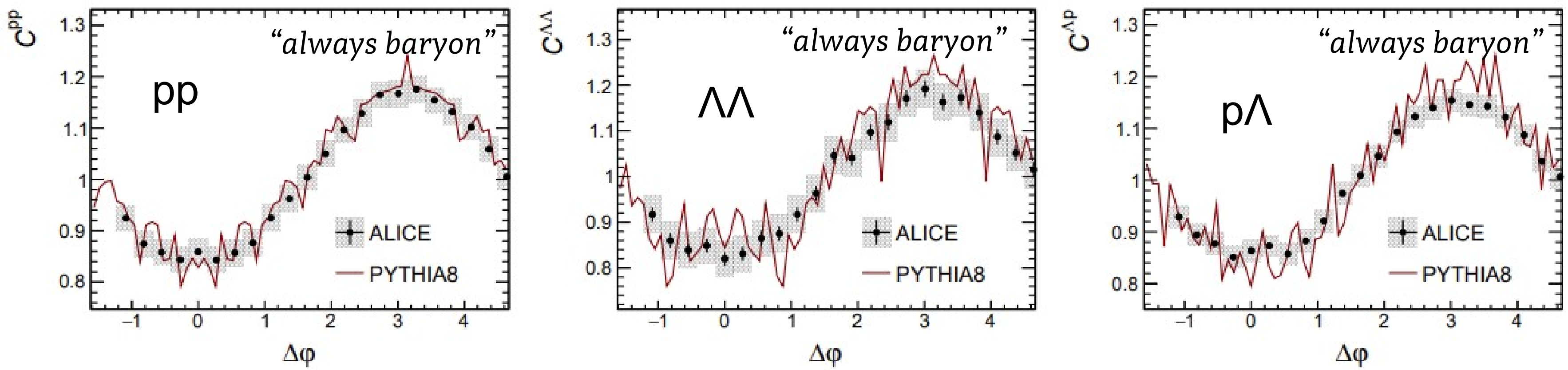
- Two modifications to PYTHIA string fragmentation allow the model to describe the data:
  - → *one baryon* – each string must *produce at most one baryon* (a way to impose Pauli principle to baryons, but lowers the baryon-to-meson ratio)
  - → *always baryon* – each string must *always produce one baryon* (no physical meaning, but produces very good agreement with data)

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.

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

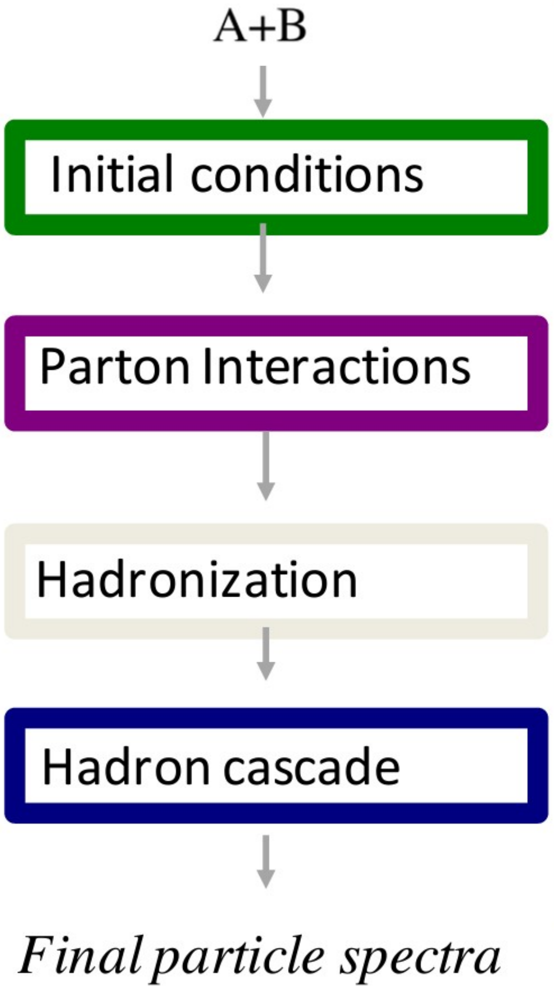
- Initial conditions: HIJING (soft strings and hard minijets)
- Parton evolution: ZPC
- Hadronization: Lund string model for default AMPT
- Hadronic scattering: ART

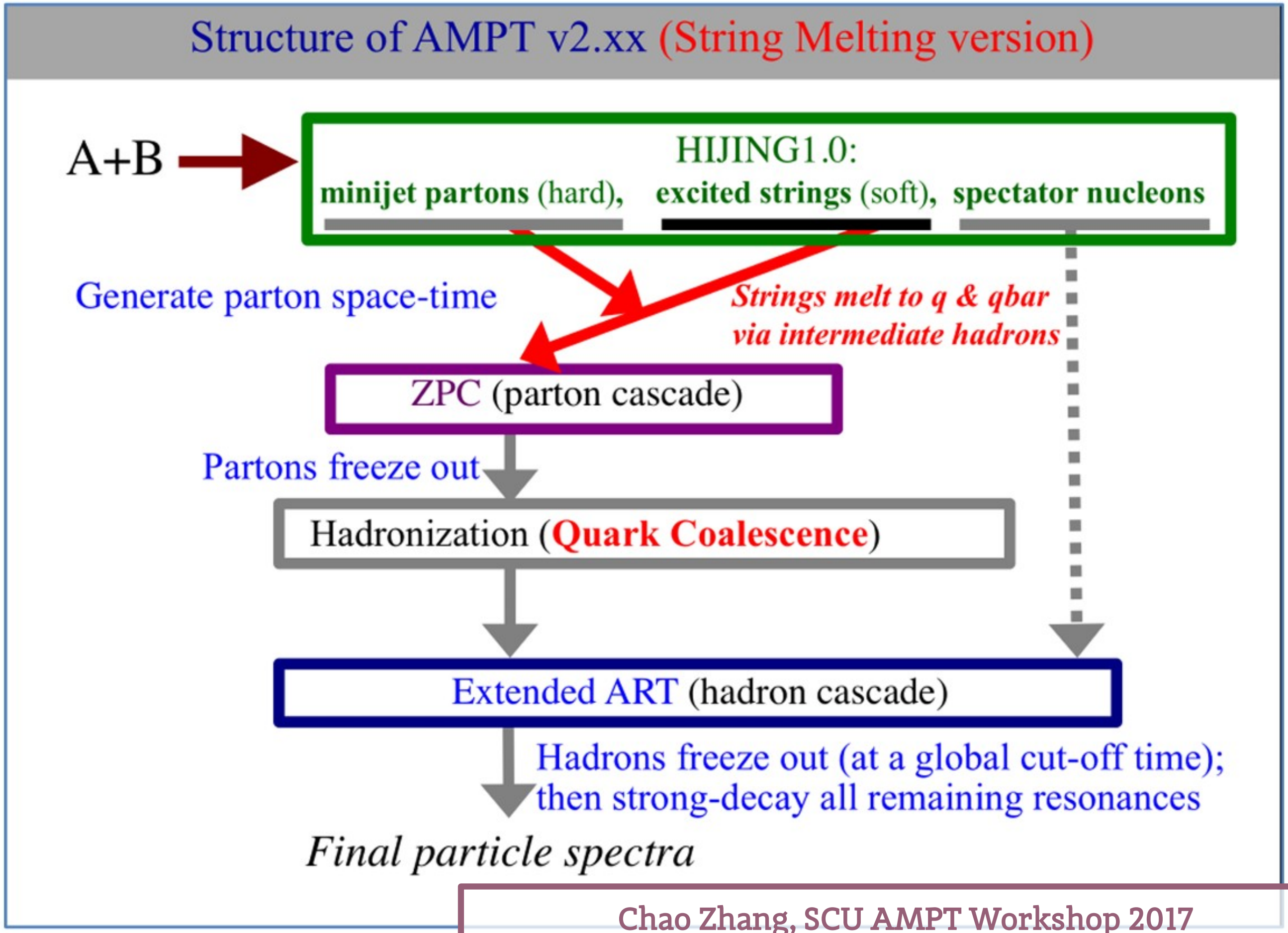
String melting: PRC 65, 034904 (02); PRL 89, 152301 (02)

- 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

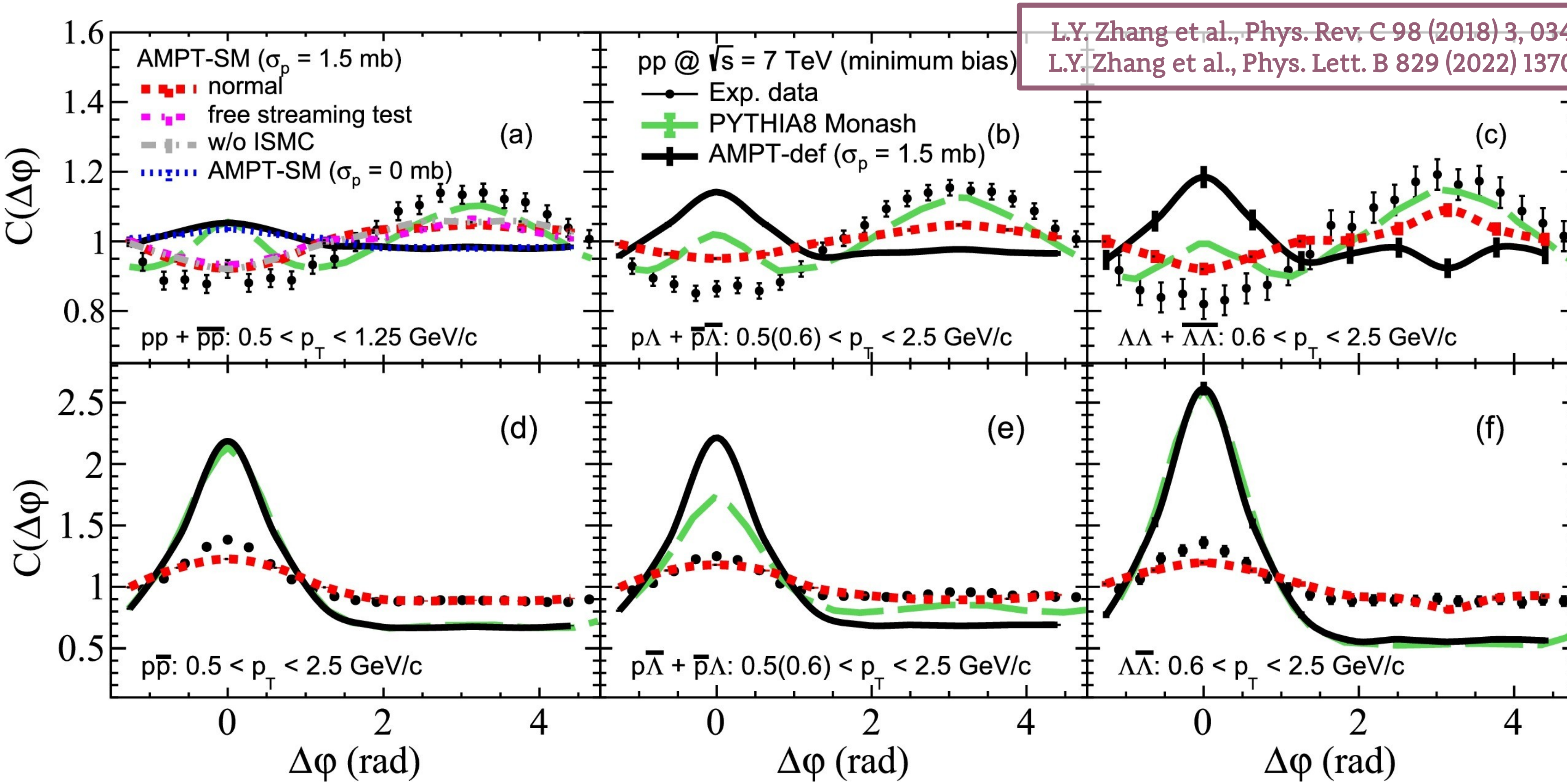
Modified AMPT

- *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



Procedure validation with simulations

The unfolding of the QS+FSI works very well

Ł.G. & M.J., PRC 104, 054909 (2021)

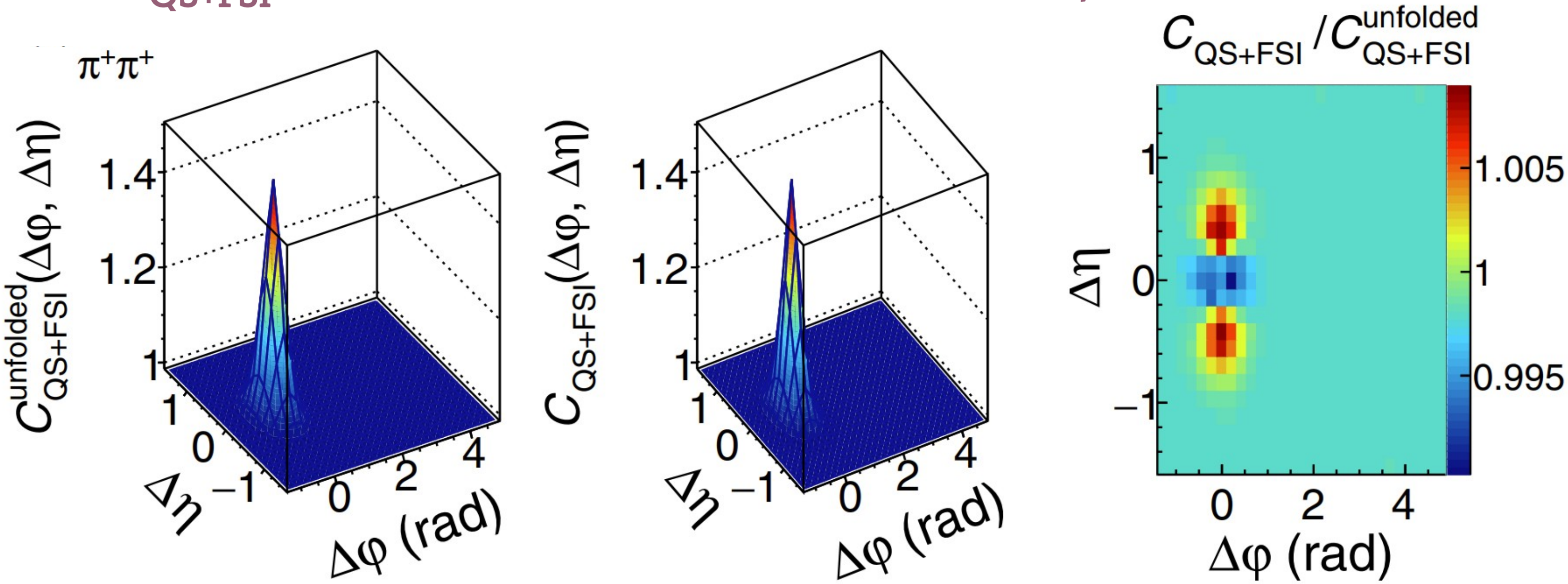
Lednicky-Lyuboshitz model coupled to PYTHIA 8

Pions

UNFOLDED FROM FEMTO CF QS+FSI

QS+FSI ONLY SIMULATED (Lednicky)

RATIO



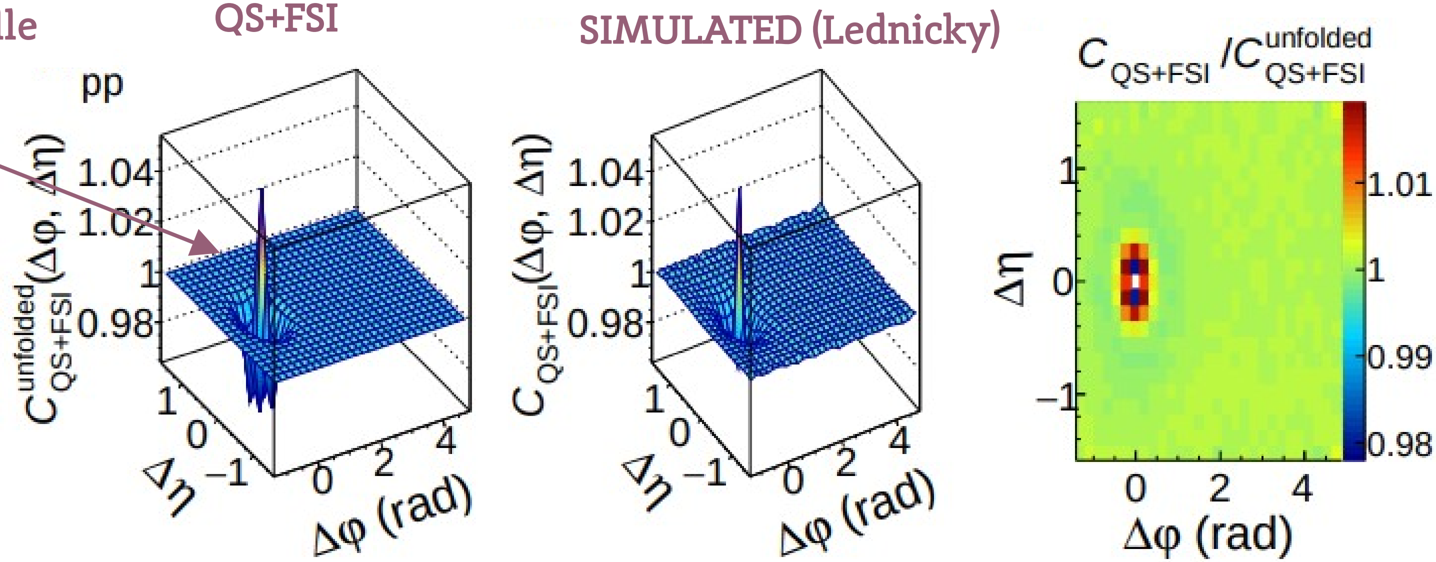
Protons

narrow dip + spike in the middle

UNFOLDED FROM FEMTO CF QS+FSI

QS+FSI ONLY SIMULATED (Lednicky)

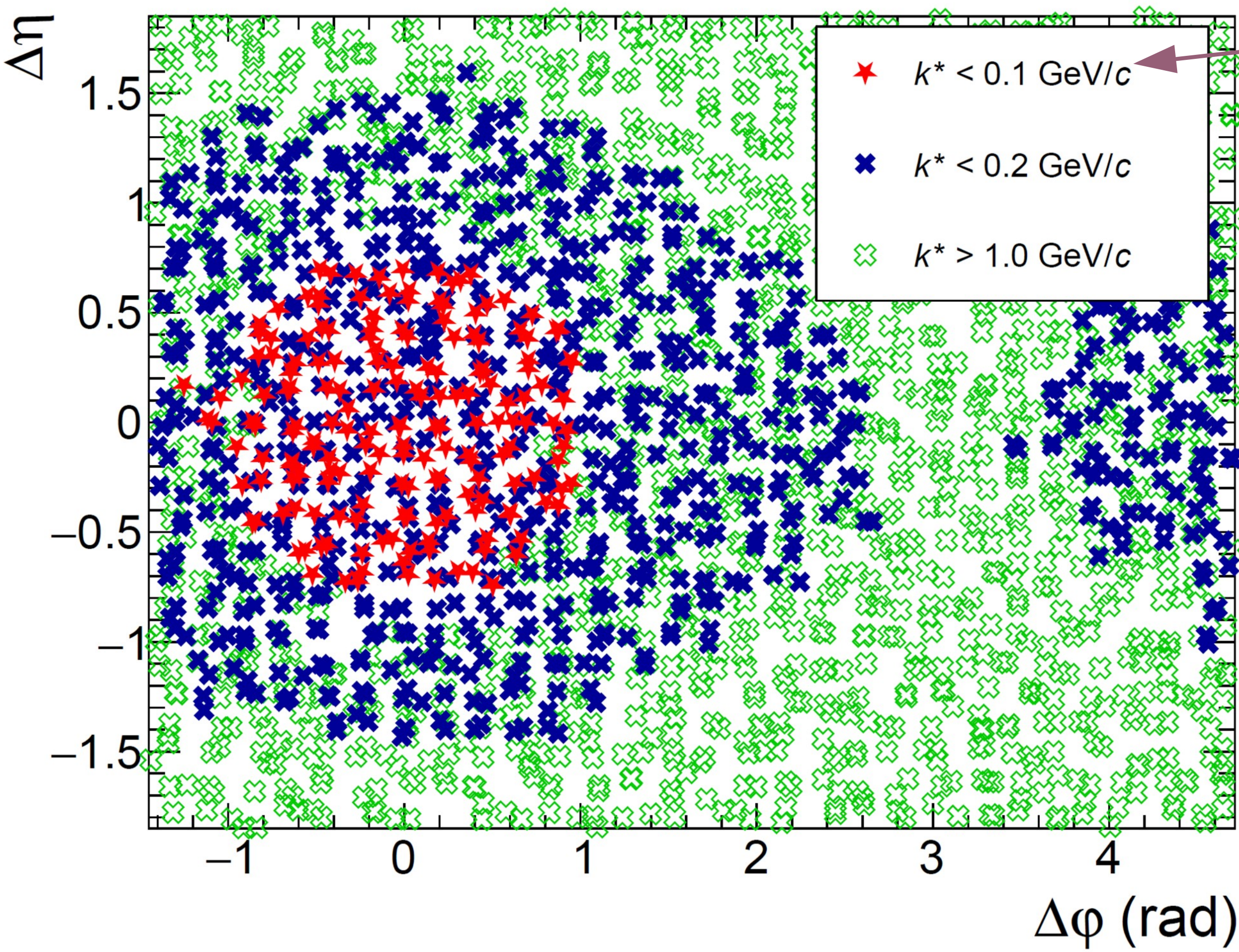
RATIO

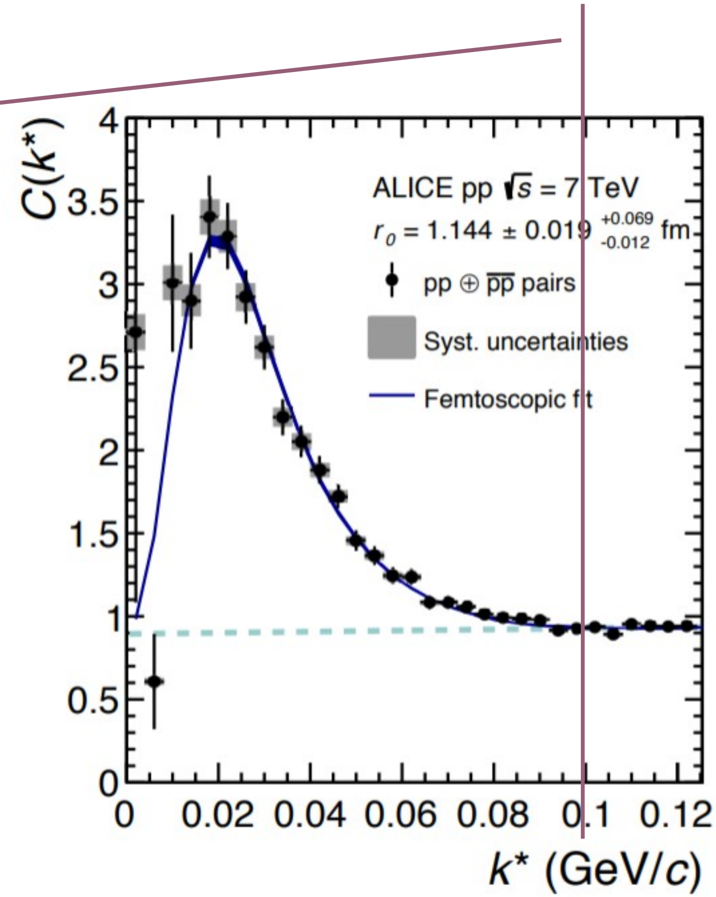


Relation between two correlations

- **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





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} → 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 <u>ONLY</u> 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)