ALICE

Flow of heavy flavor hadrons in small systems in Run 3

Alexian Lejeune[1]

Supervision : Katarína Křížková Gajdošová[1], Jaroslav Bielčík[1]

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Děčín Workshop – 20th of September 2024

FJFI

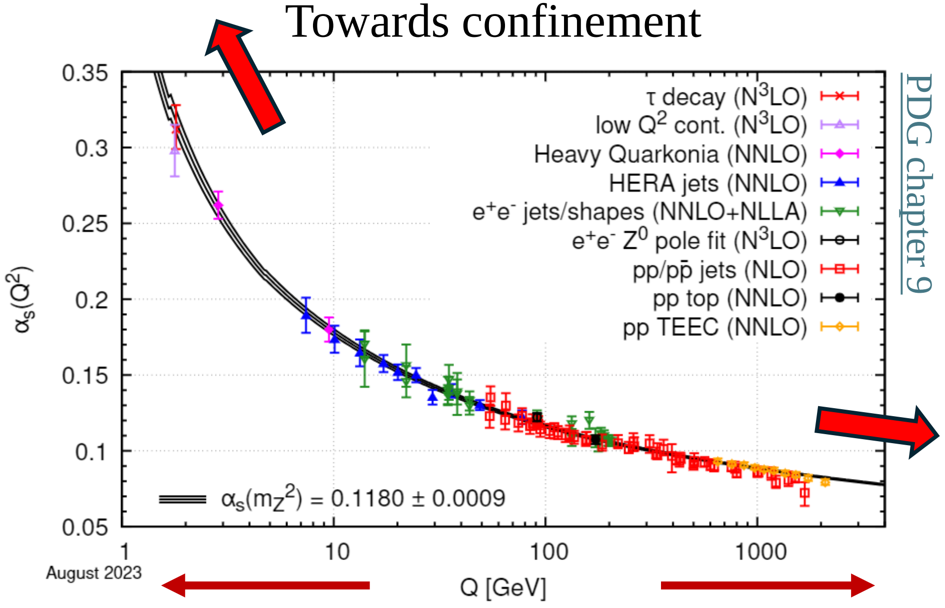
Introduction : the concept of quark gluon plasma

Key feature of Quantum Chromodynamics :

→ confinement !

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_s \hbar c}{r} + kr$$

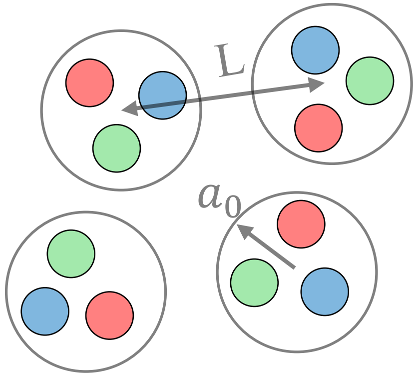
Towards confinement



PDG chapter 9

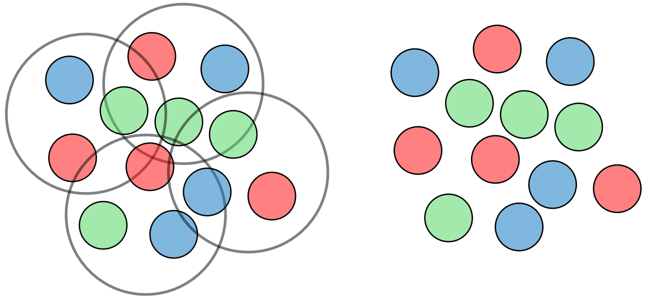
Towards asymptotic freedom

1. confinement



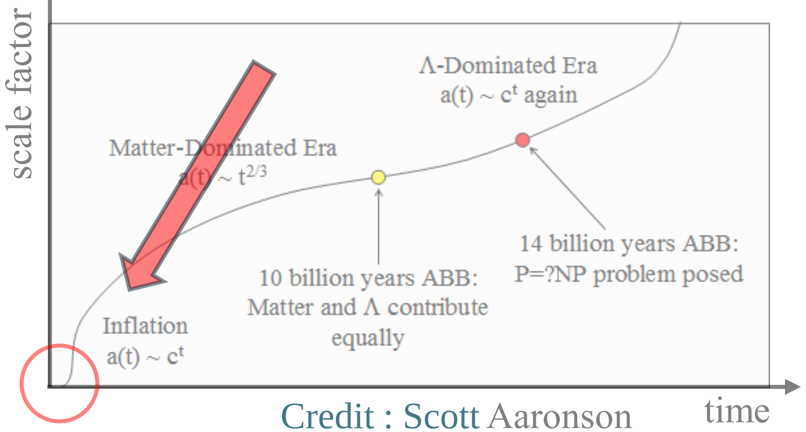
bring hadrons closer and closer

2. deconfinement



critical threshold : $L \sim a_0$

QGP in early universe ?



Credit : Scott Aaronson

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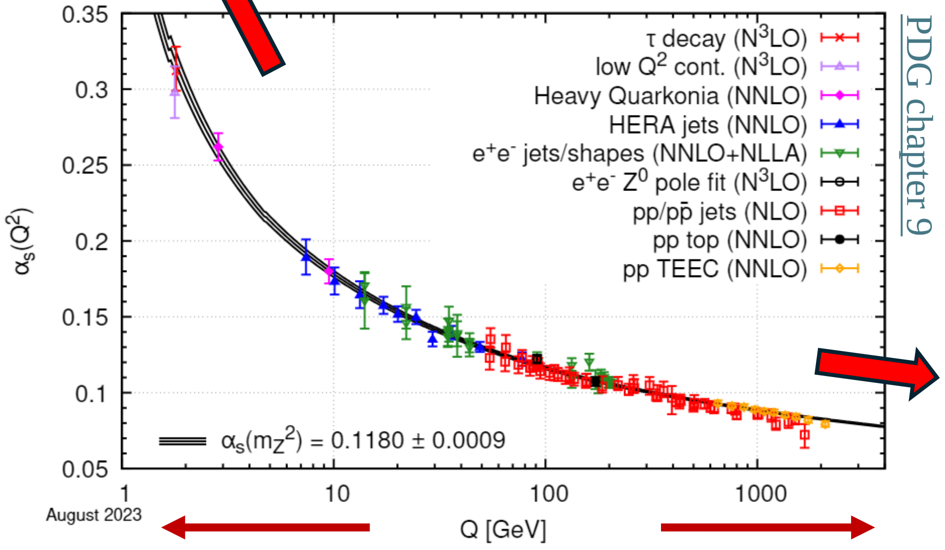

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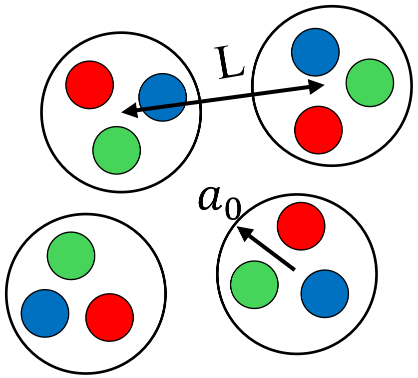

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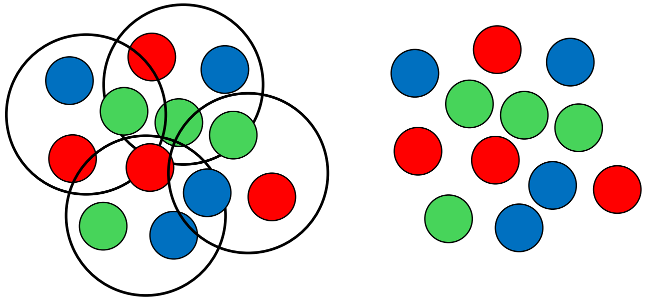

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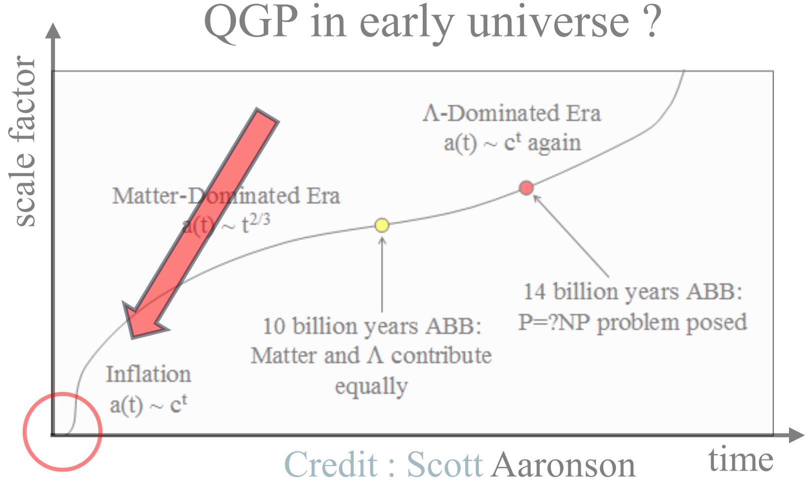

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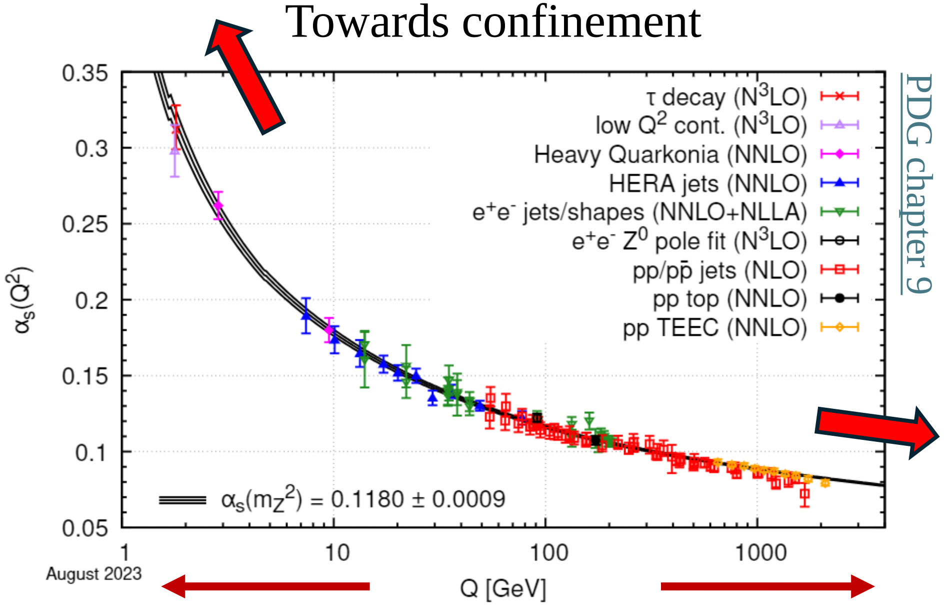

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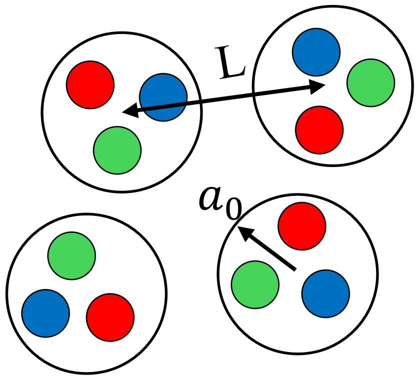

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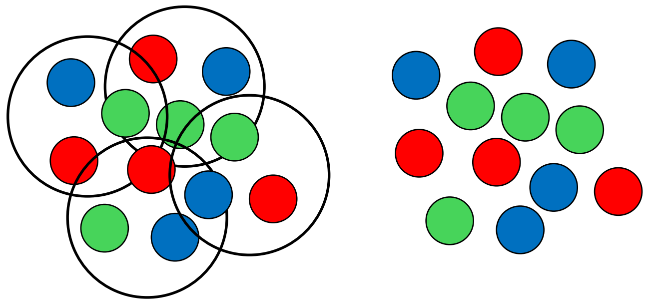

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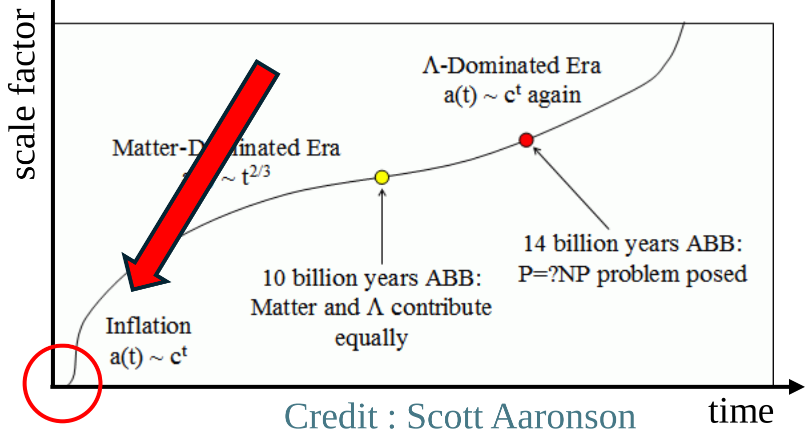
QGP in early universe ?



Credit : Scott Aaronson

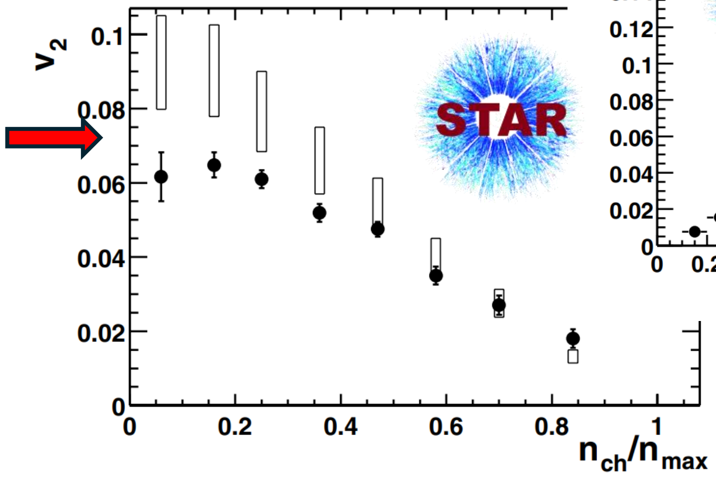
Introduction : signatures of the quark gluon plasma

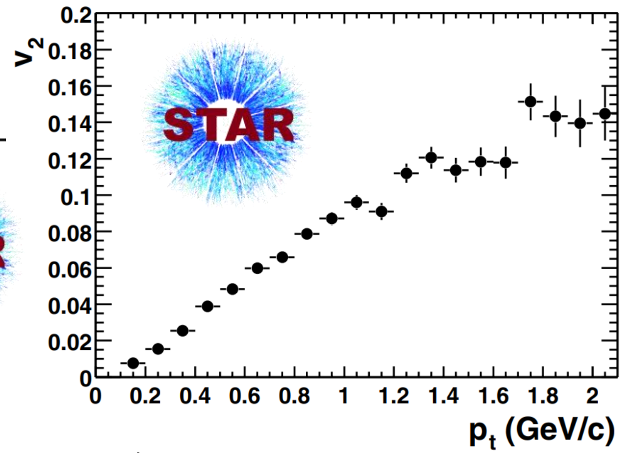
Signatures : many !

Au+Au collisions at $\sqrt{s} = 130$ GeV (RHIC)

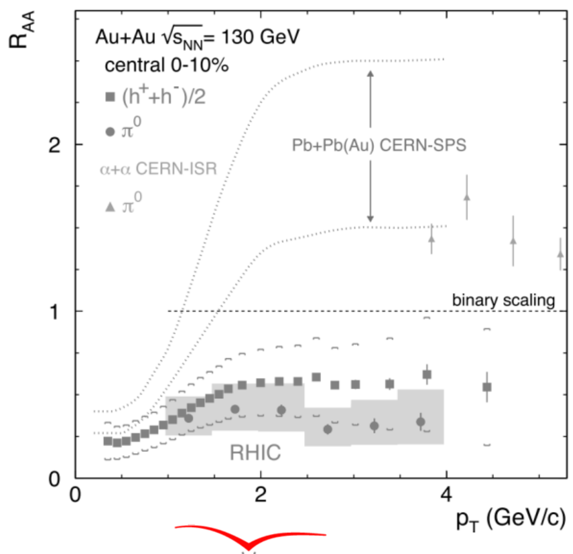
2001 : discovery of strong « elliptic » flow at STAR

2002 : discovery of jet quenching at PHENIX





Phys. Rev. Lett. 86, 402 (2001)



Phys. Rev. Lett. 88, 022301 (2002)

Many other signatures :

strangeness enhancement

quarkonia suppression

mass ordering

baryon-meson grouping

Summary of the discovery of QGP : arxiv:nucl-ex/0501009

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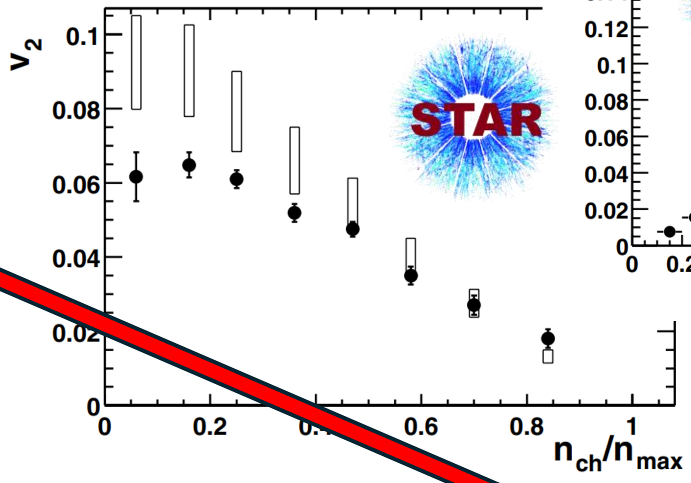

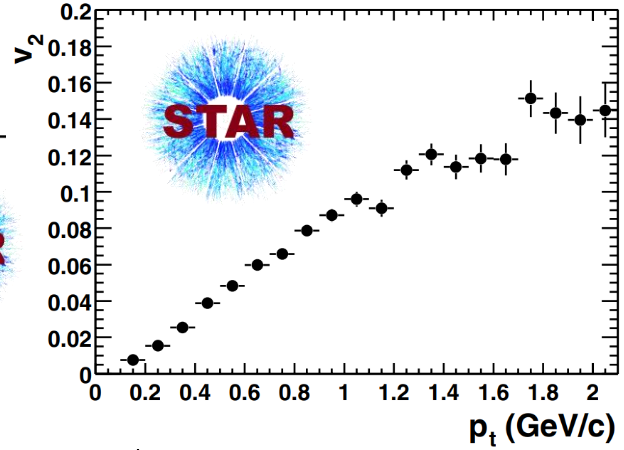

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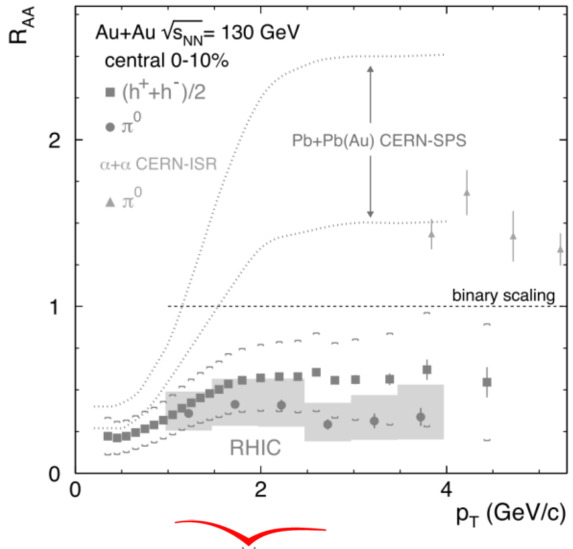
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

$$\Updownarrow$$

$1 \times (PbPb) \neq N \times (pp)$? (at same energy)



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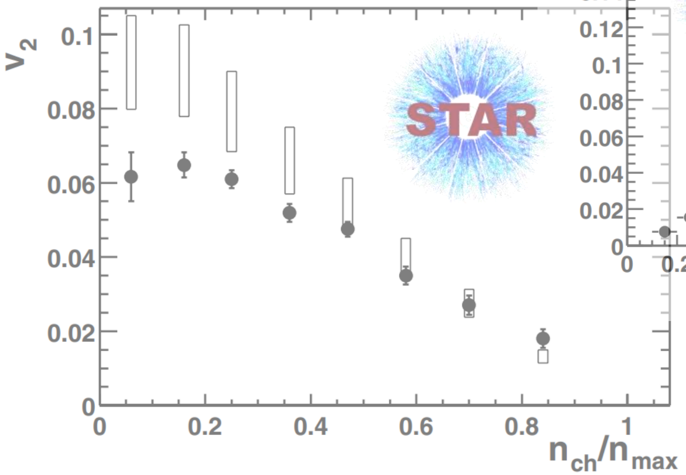

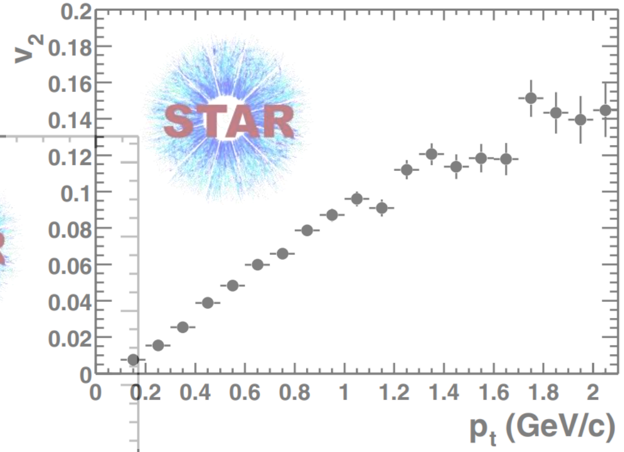

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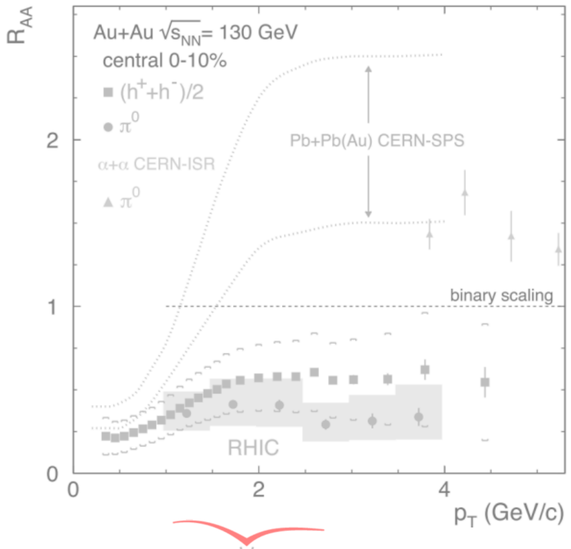

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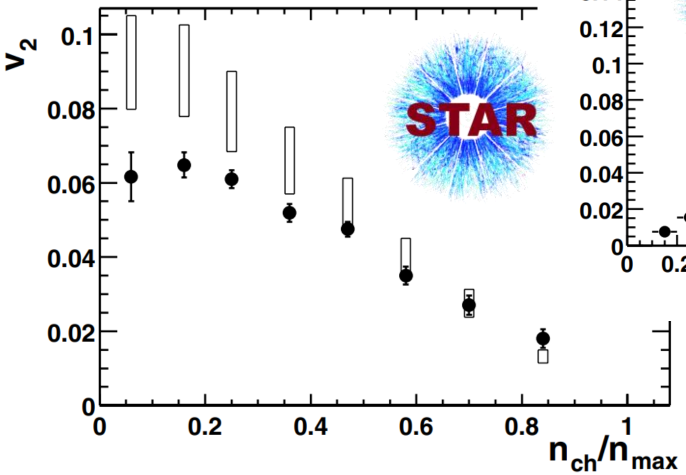

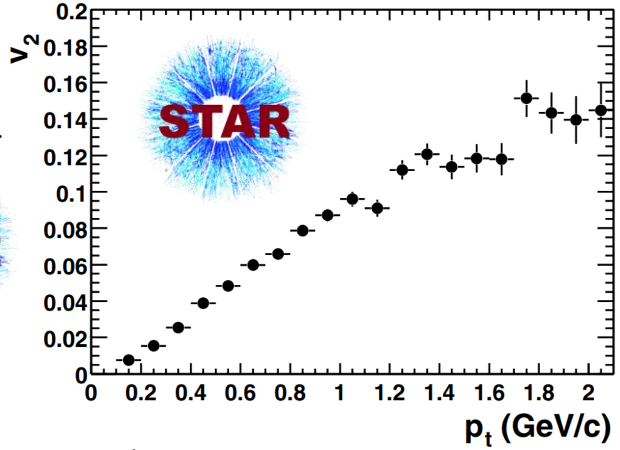

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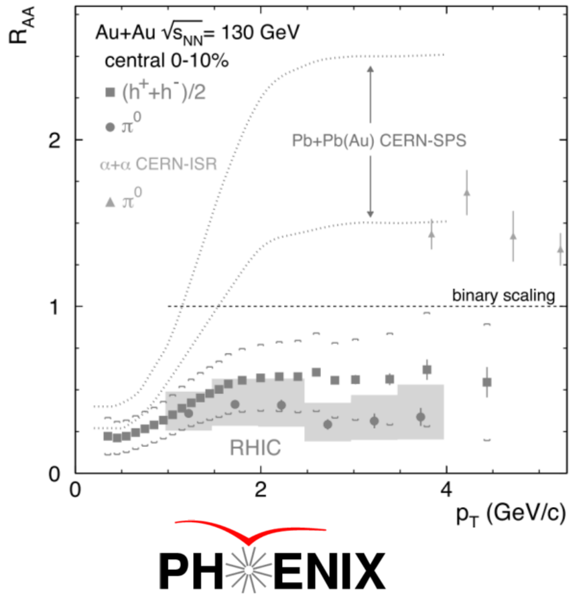

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Signatures used by SPS to try to claim QGP discovery in 2000 !

[Evidence for a New State of Matter : An Assessment of the Results from the CERN Lead Beam Programme]

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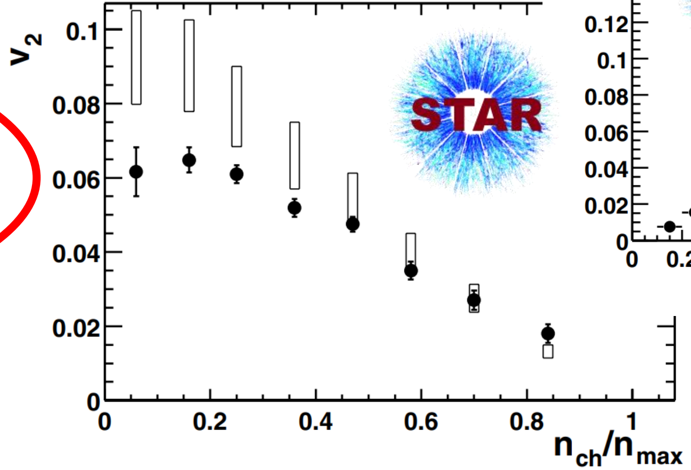

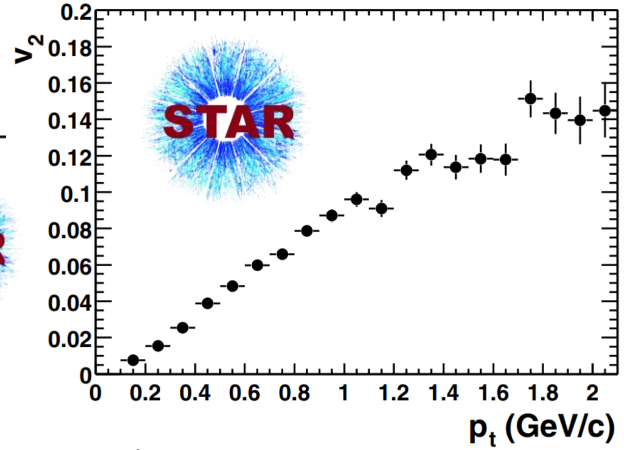

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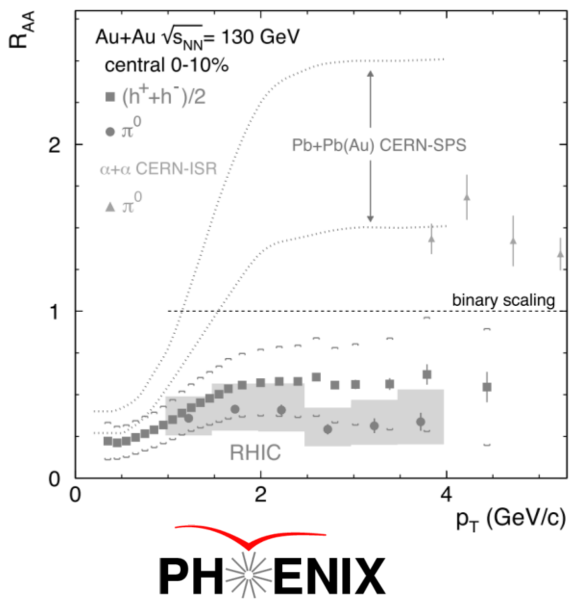

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Main signatures used for the discovery of the quark-gluon plasma at RHIC

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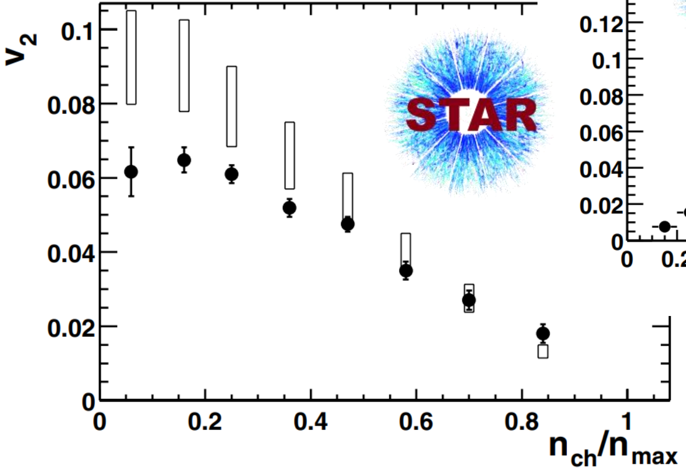

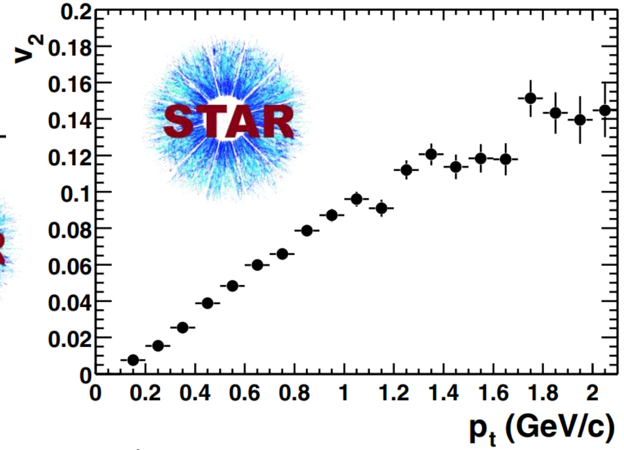

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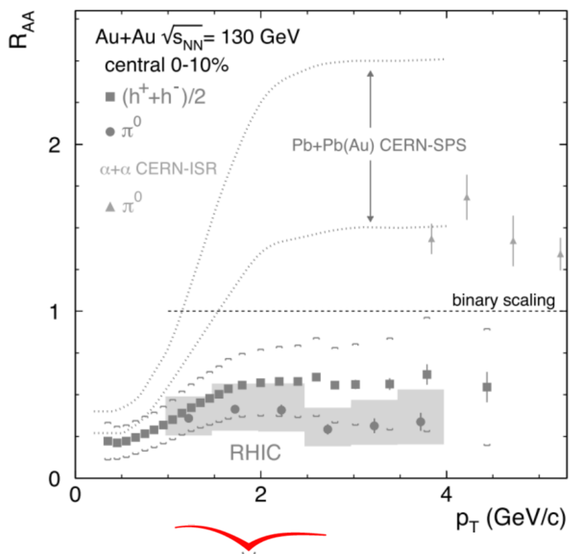

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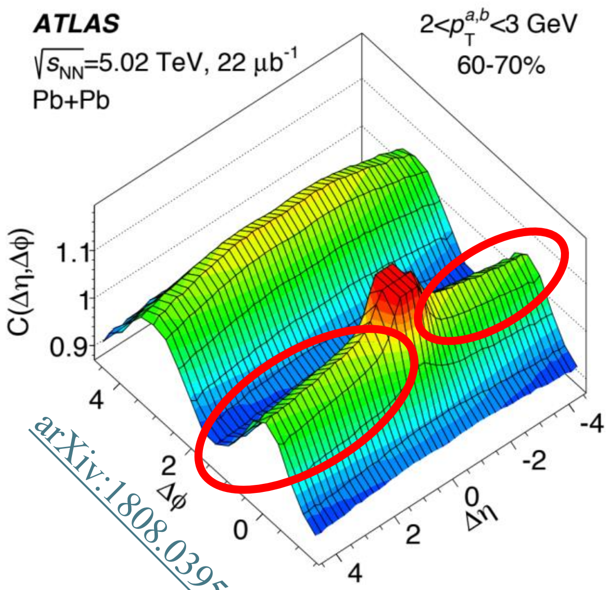
Take home message : **elliptic (anisotropic) flow** is a key feature to study QGP properties and was used since the beginning as an exclusive signature or the QGP in heavy-ion collisions !

Summary of the discovery of QGP : arxiv:nucl-ex/0501009

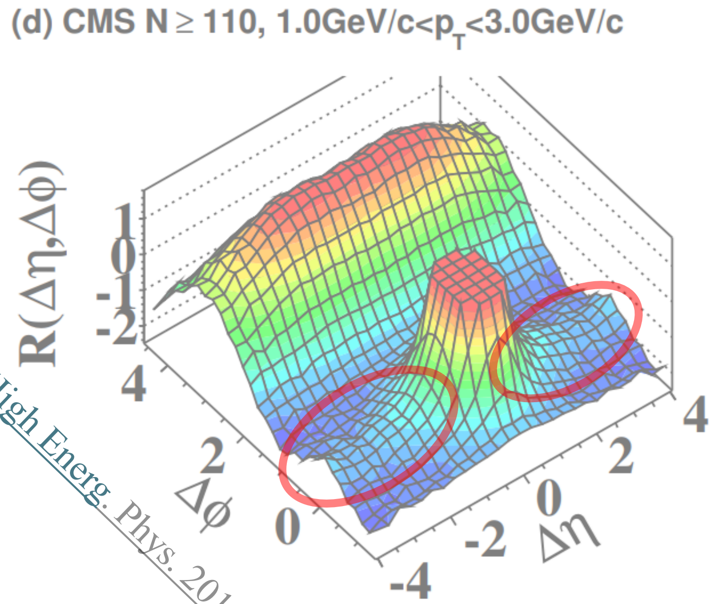
Introduction : **signatures?** of the quark gluon plasma

Near-side ridge in two-particle correlations was understood as a signature of QGP in heavy-ion collisions



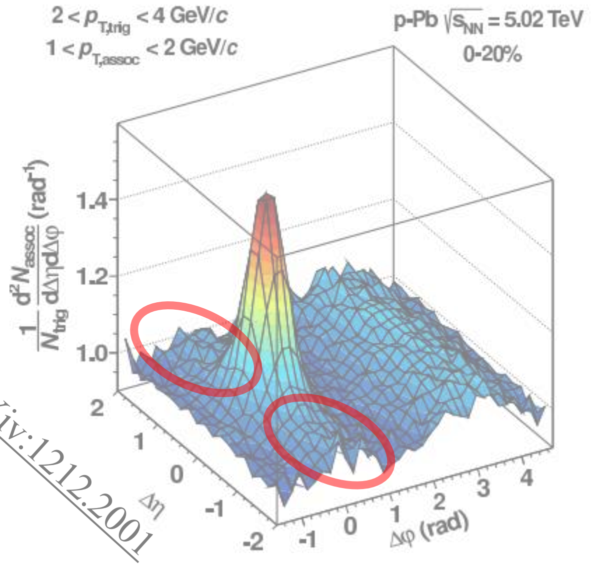
arXiv:1808.03951

Until CMS dropped a bomb in 2010 by observing a similar but less strong near-side ridge in pp collisions !



J. High Energ. Phys. 2010, 91 (2010)

Which started the hunt of QGP « signatures » in smaller systems ! The ridge was also later observed in pPb collisions



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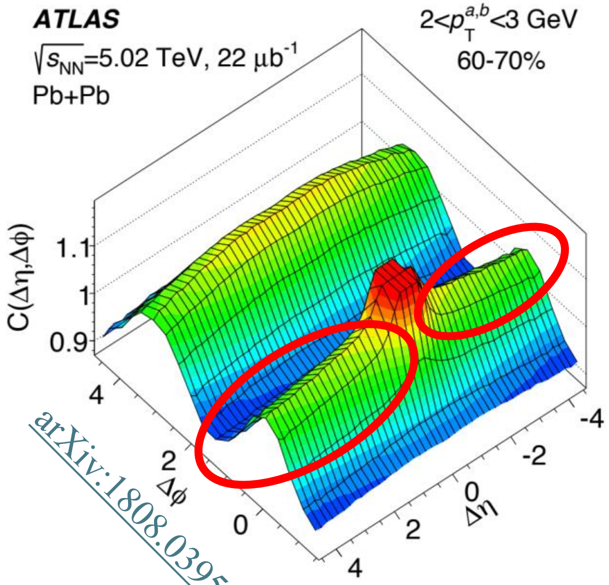

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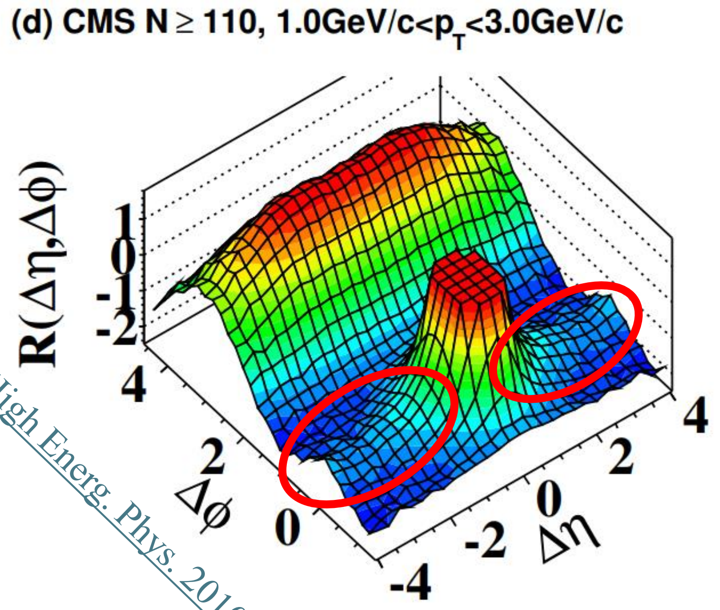

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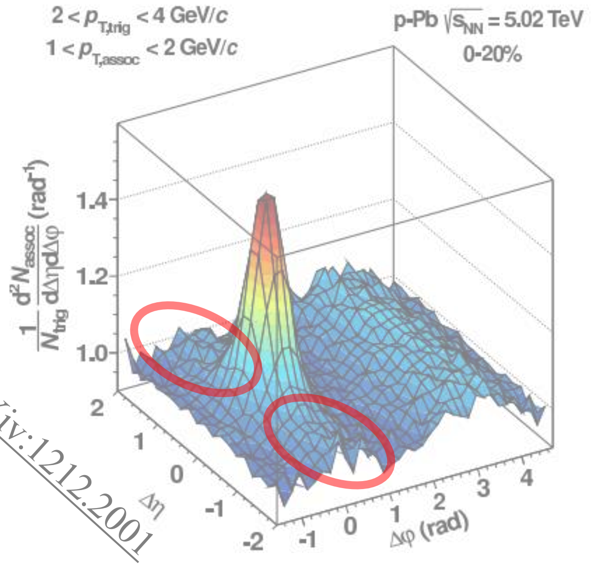

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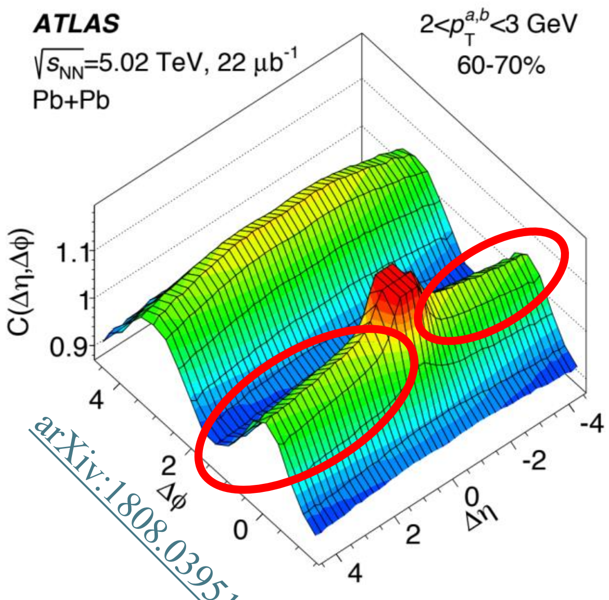

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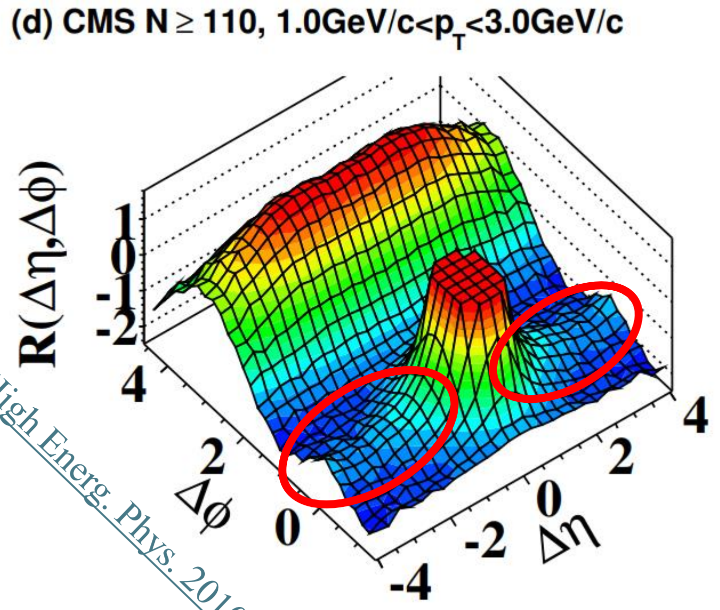

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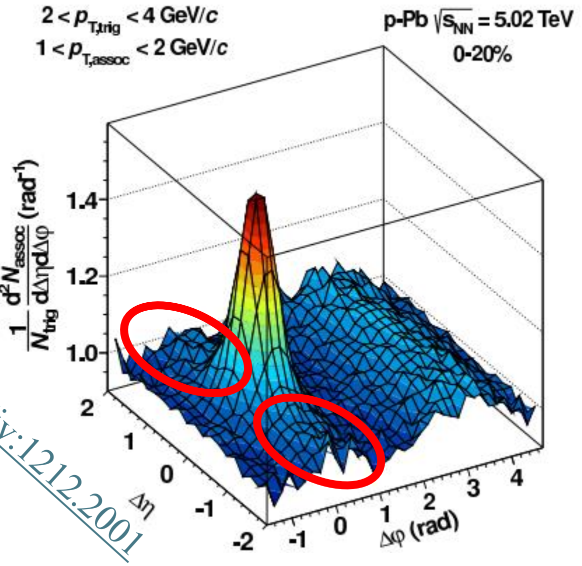

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Introduction : **signatures?** of the quark gluon plasma

ALICE

Digest of experimental results

measured and similar ✓
measured but different ✗
not measured —

From Katka's JCF seminar

OBSERVABLES	A—A	p—A (high mult.)	pp (high mult.)	pp (low mult.)	UPC	ep	e+e- (high mult.)	e+e-
Near-side ridge yield	✓ [1,2]	✓ [30,32,33]	✓ [30,31]	✓ [34]	—	✗ [74,75]	✓ [77]	✗ [76]
Anisotropic flow	✓ [3,4]	✓ [36,37,38,39]	✓ [35,37]	✓ [30]	✓ [72,73]	✗ [74,75]	? [77]	—
Multiparticle cumulants	✓ [5]	✓ [40-45]	✓ [40,41,45]	—	—	—	—	—
Mass ordering	✓ [6]	✓ [47-49]	✓ [46,48]	—	—	—	—	—
Baryon-meson grouping	✓ [6]	✓ [47-49]	✓ [46,48]	—	—	—	—	—
Flow decorrelations (p_T)	✓ [7,8]	✓ [50-51]	—	—				
Flow decorrelations (η)	✓ [9,10]	✓ [52]	✓ [53]	—				
Event-by-event v_n	✓ [11,12]	—	—	—				
v_n correlations	✓ [13,14]	✓ [54-57]	✓ [54,55,57]	—				
ψ_n correlations	✓ [15]	—	✓ [58]	—				
Nonlinear response of V_n	✓ [16-18]	—	✓ [59]	—				
ESE	✓ [19]	—	—	—				
rho(v_n^2,[p_T])	✓ [20,21]	✓ [60,61]	✓ [61]	—				
High-p_T flow	✓ [22,23]	✓ [63,65]	✓ [62,64]	—	—	—	—	—
Charm flow	✓ [24-27]	✓ [67,68]	✓ [66,67]	—	—	—	—	—
Bottom flow	✓ [28,29]	✓ [70]	✗ [69]	—	—	—	—	—

+ strangeness enhancement

+ quarkonia suppression in high multiplicity pp collisions

References in back-up slides

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Introduction : **signatures?** of the quark gluon plasma

ALICE

Digest of experimental results

measured and similar ✅
measured but different ❌
not measured —

From Katka's JCF seminar

OBSERVABLES	A—A	p—A (high mult.)	pp (high mult.)	pp (low mult.)	UPC	ep	e^+e^- (high mult.)	e^+e^-
Near-side ridge yield	✅ [1,2]	✅ [30,32,33]	✅ [30,31]	✅ [34]	—	❌ [74,75]	✅ [77]	❌ [76]
Anisotropic flow	✅ [3,4]	✅ [36,37,38,39]	✅ [35,37]	✅ [30]	✅ [72,73]	❌ [74,75]	? [77]	—
Multiparticle cumulants	✅ [5]	✅ [40-45]	✅ [40,41,45]	—	—	—	—	—
Mass ordering	✅ [6]	✅ [47-49]	✅ [46,48]	—	—	—	—	—
Baryon-meson grouping	✅ [6]	✅ [47-49]	✅ [46,48]	—	—	—	—	—
Flow decorrelations (p_T)	✅ [7,8]	✅ [50-51]	—	—	[illegible]	[illegible]	[illegible]	[illegible]
Flow decorrelations (η)	✅ [9,10]	✅ [52]	✅ [53]	—	[illegible]	[illegible]	[illegible]	[illegible]
Event-by-event v_n	✅ [11,12]	—	—	—	[illegible]	[illegible]	[illegible]	[illegible]
v_n correlations	✅ [13,14]	✅ [54-57]	✅ [54,55,57]	—	[illegible]	[illegible]	[illegible]	[illegible]
ψ_n correlations	✅ [15]	—	✅ [58]	—	[illegible]	[illegible]	[illegible]	[illegible]
Nonlinear response of V_n	✅ [16-18]	—	✅ [59]	—	[illegible]	[illegible]	[illegible]	[illegible]
ESE	✅ [19]	—	—	—	[illegible]	[illegible]	[illegible]	[illegible]
rho(v_n^2,[p_T])	✅ [20,21]	✅ [60,61]	✅ [61]	—	—	—	—	—
High-p_T flow	✅ [22,23]	✅ [63,65]	✅ [62,64]	—	—	—	—	—
Charm flow	✅ [24-27]	✅ [67,68]	✅ [66,67]	—	—	—	—	—
Bottom flow	✅ [28,29]	✅ [70]	❌ [69]	—	—	—	—	—

Jet quenching has yet to be observed in small collision systems !

References in back-up slides

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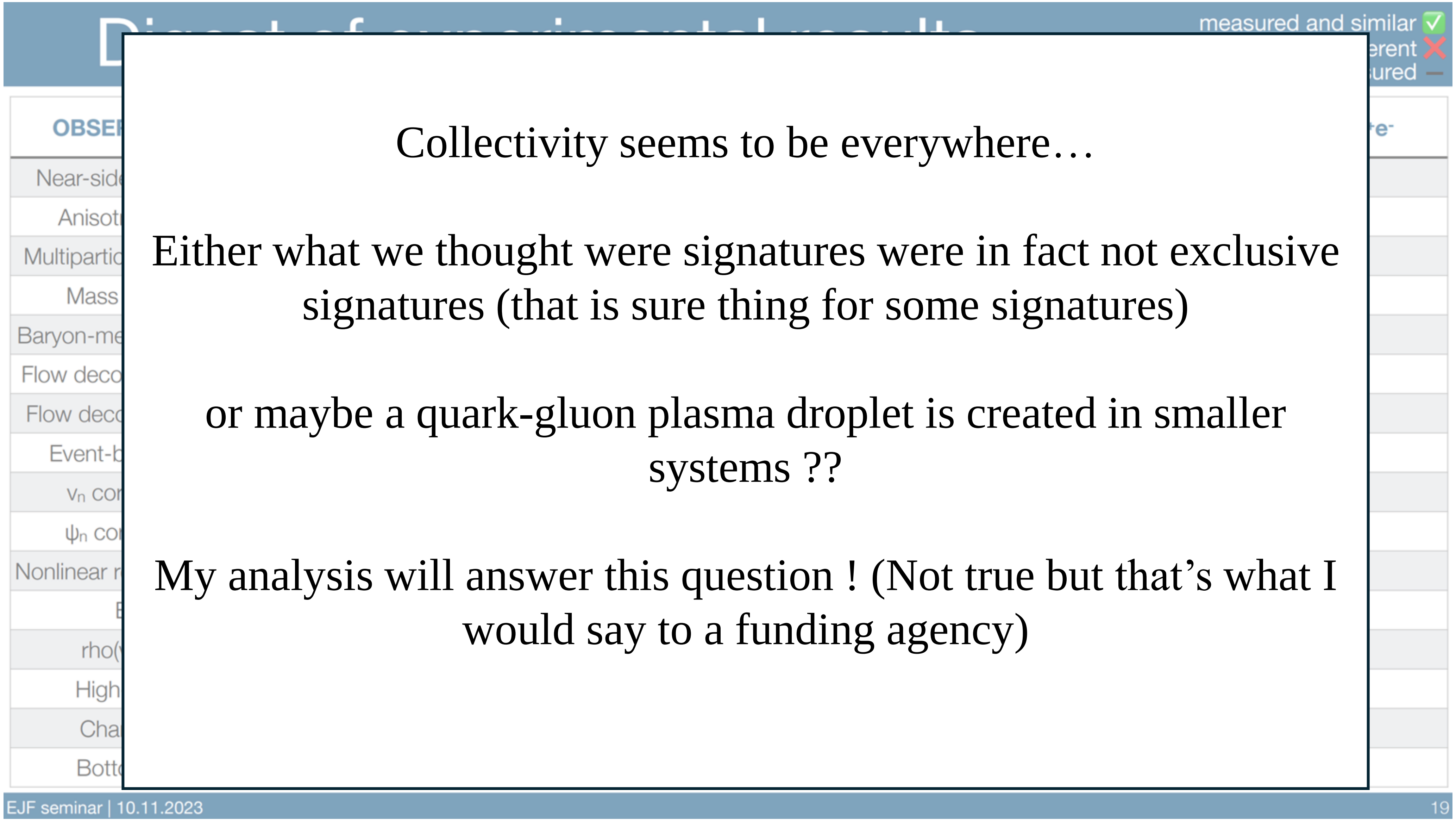
Introduction : **signatures?** of the quark gluon plasma

From Katka's JCF seminar



Collectivity seems to be everywhere…

Either what we thought were signatures were in fact not exclusive signatures (that is sure thing for some signatures)

or maybe a quark-gluon plasma droplet is created in smaller systems ??

My analysis will answer this question ! (Not true but that's what I would say to a funding agency)

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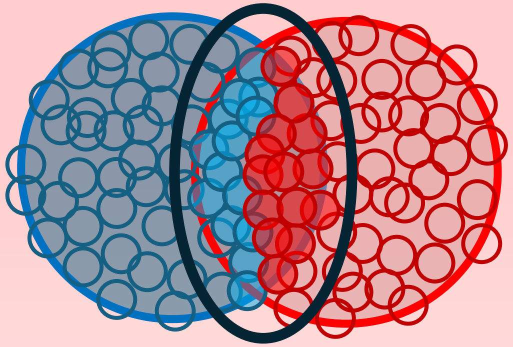
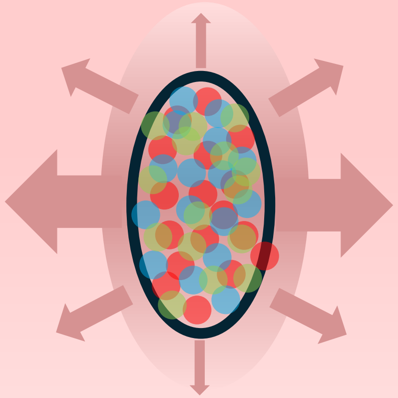
Anisotropic flow illustrated with heavy-ion collisions….

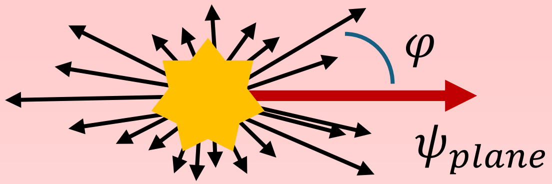
1 Initial spatial asymmetry



2 Collectively expanding medium



3 Particle are emitted with preferred direction



4 Angular modulation of their distribution

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

Quantifies particle correlation with symmetry plane ψ_n

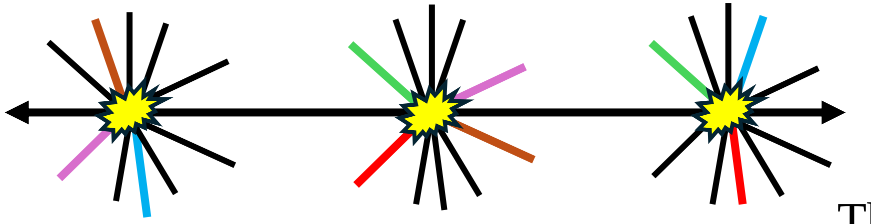
Two-particle correlations

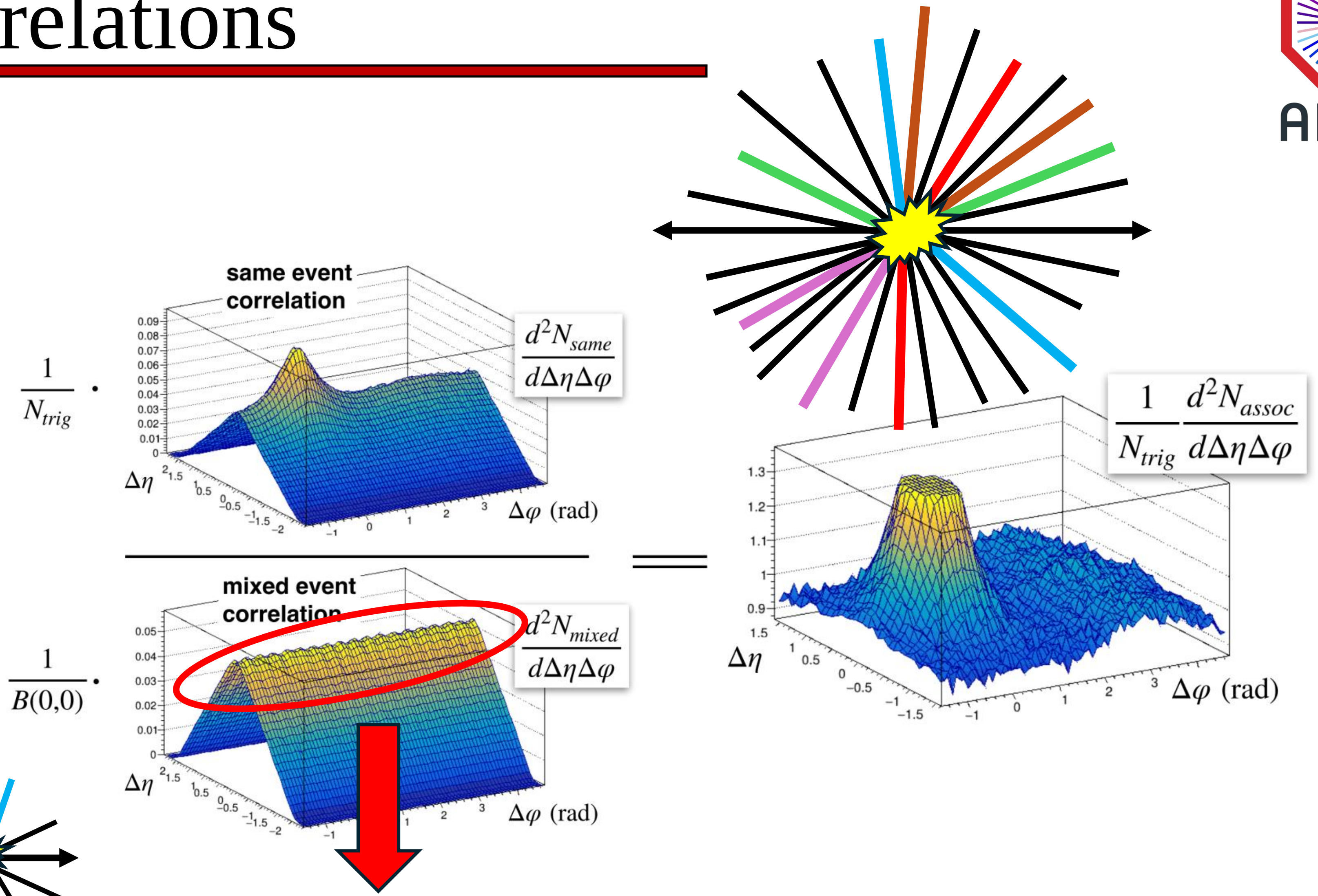
How to get two-particle azimuthal correlations ?

The correlation function :

$$C(\Delta\eta, \Delta\varphi) = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)} \begin{array}{l} \text{same event} \\ \text{mixed event} \end{array}$$

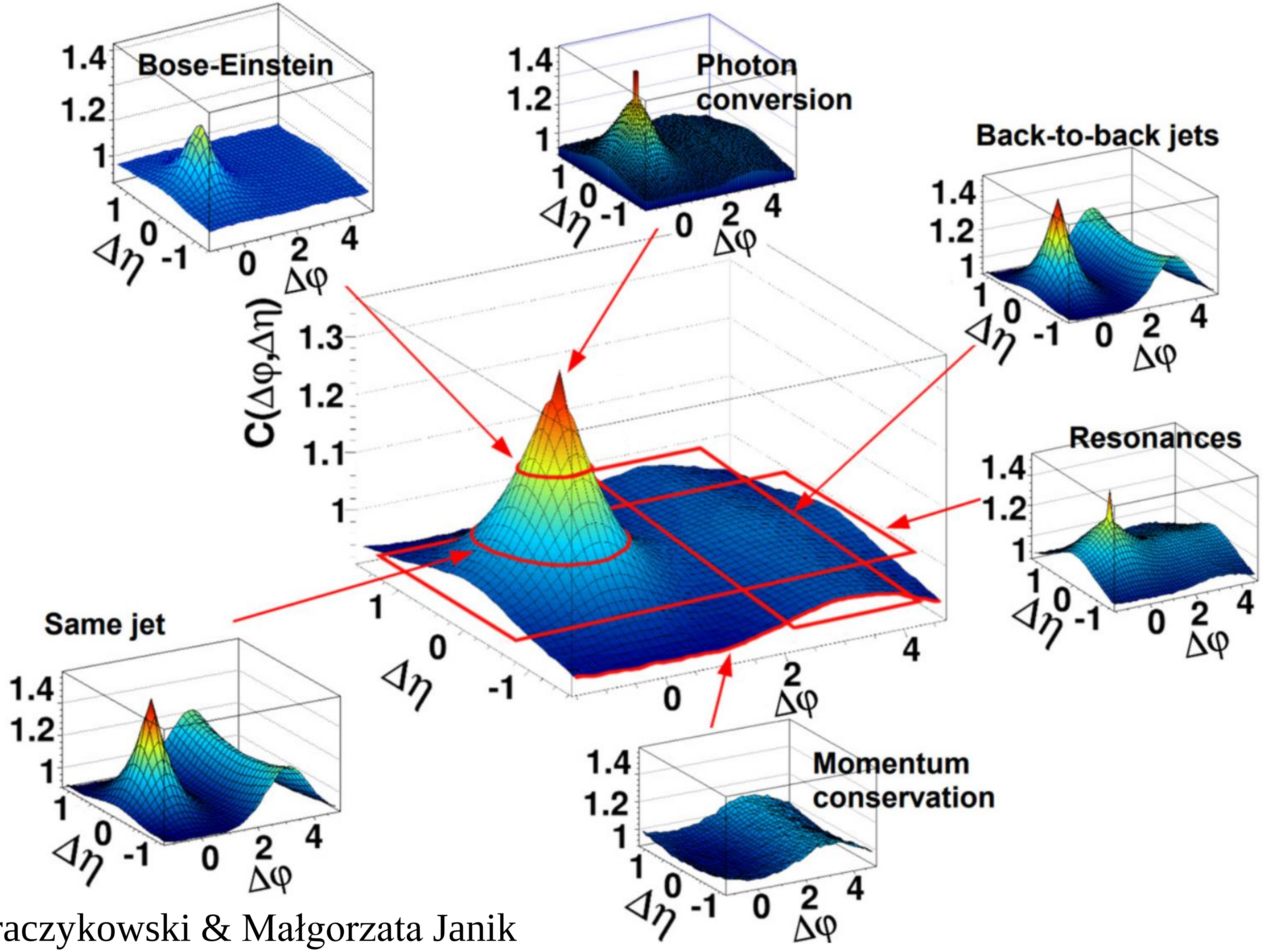
$\eta_1 - \eta_2$ $\varphi_1 - \varphi_2$





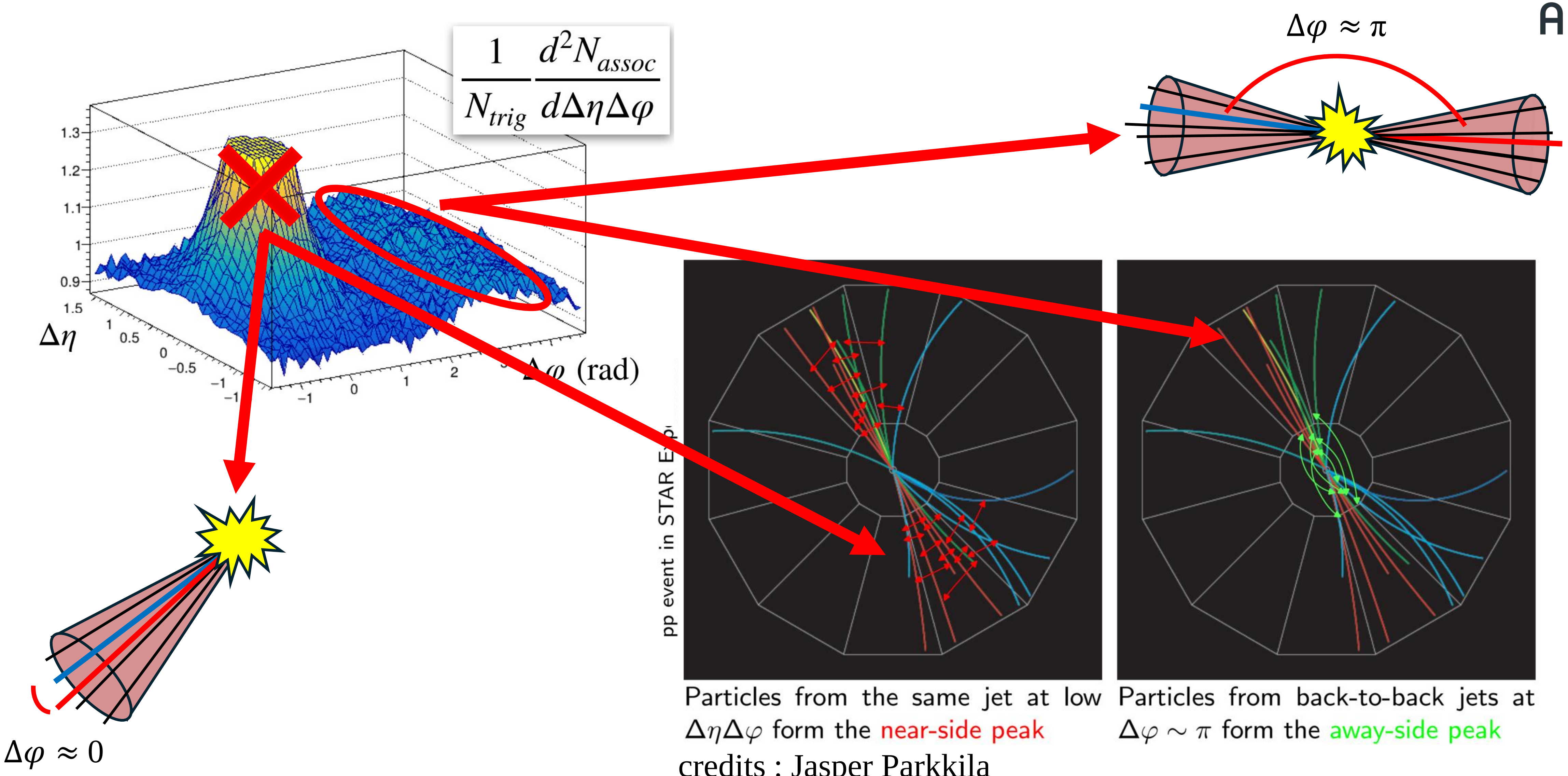
This typical triangular shape is caused by the limited detector acceptance

Understanding the 2D correlation function



credits : Łukasz Graczykowski & Małgorzata Janik

What is our interest in the 2D correlation function ?

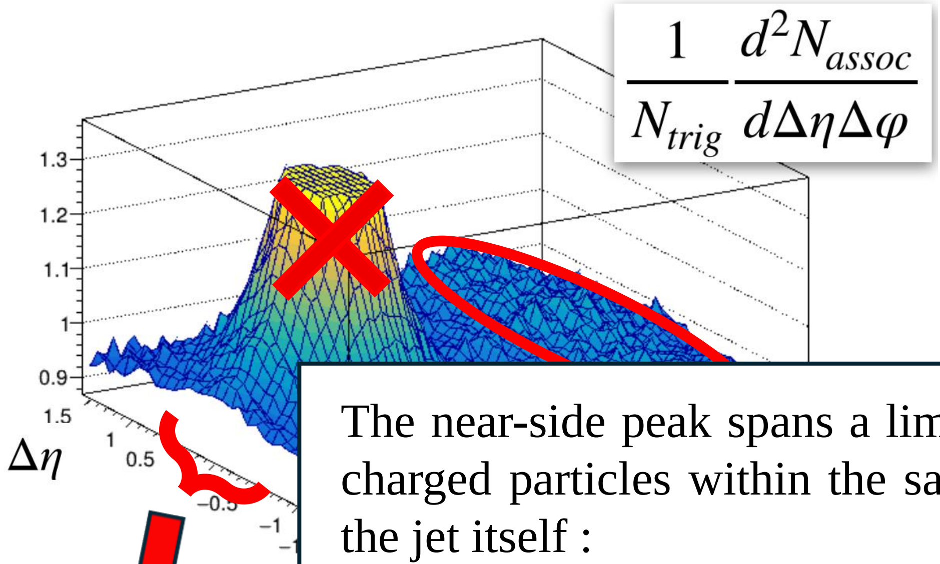


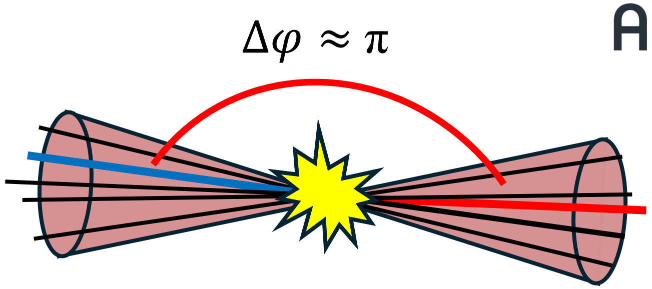
Particles from the same jet at low $\Delta\eta\Delta\varphi$ form the near-side peak

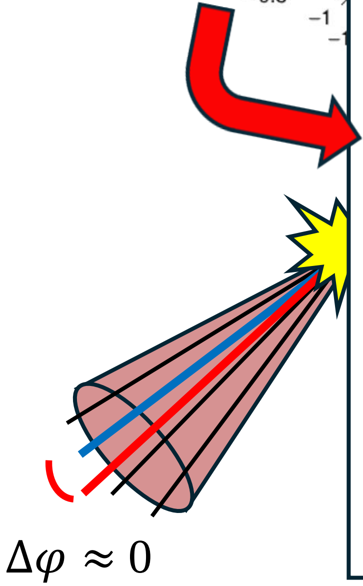
Particles from back-to-back jets at $\Delta\varphi \sim \pi$ form the away-side peak

credits : Jasper Parkkila

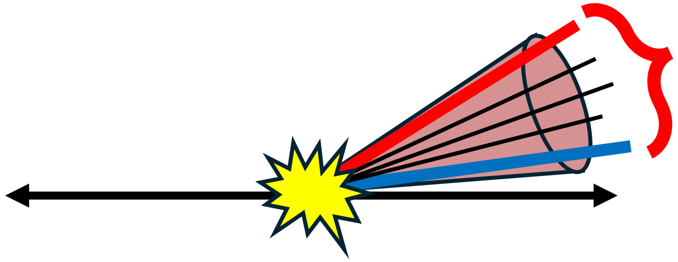
What is our interest in the 2D correlation function ?



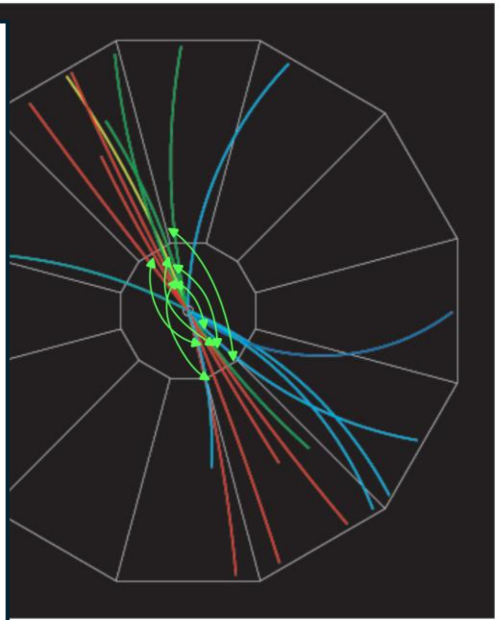




The near-side peak spans a limited $\Delta\eta$ range because the $\Delta\eta$ of two charged particles within the same jet is limited by the definition of the jet itself :



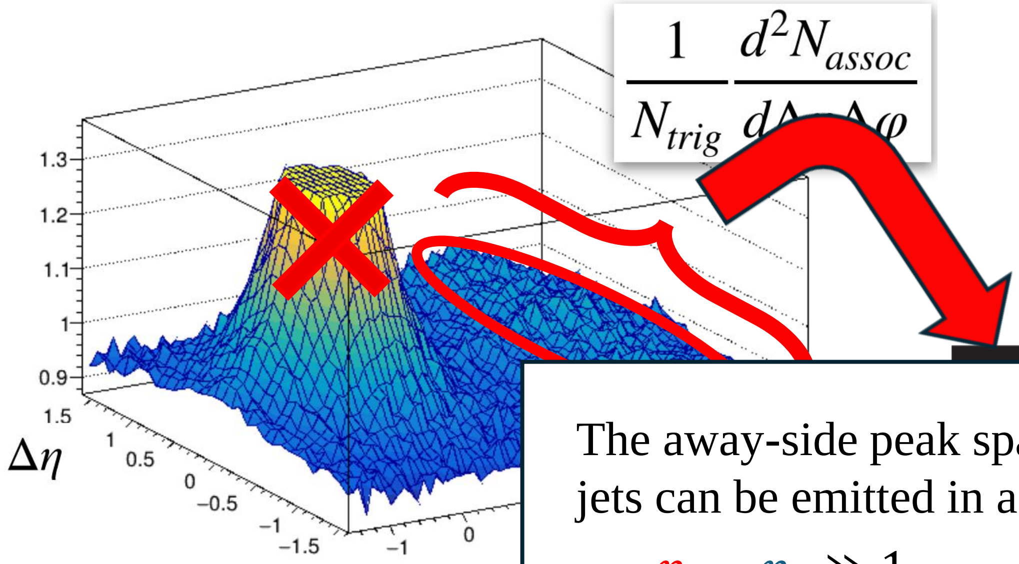
The near-side peak is bigger than the away-side peak for 2 reasons : more physics phenomena occur at this range and for each opposite-jet, there is 2 times the contribution of 1 same-jet correlations

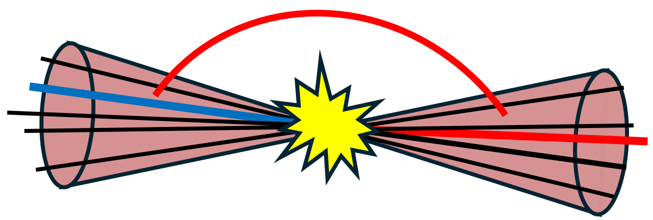


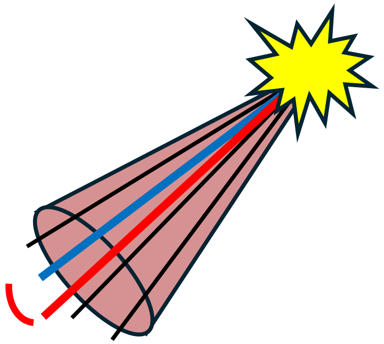
s from back-to-back jets at
form the away-side peak

credits : Jasper Parkkila

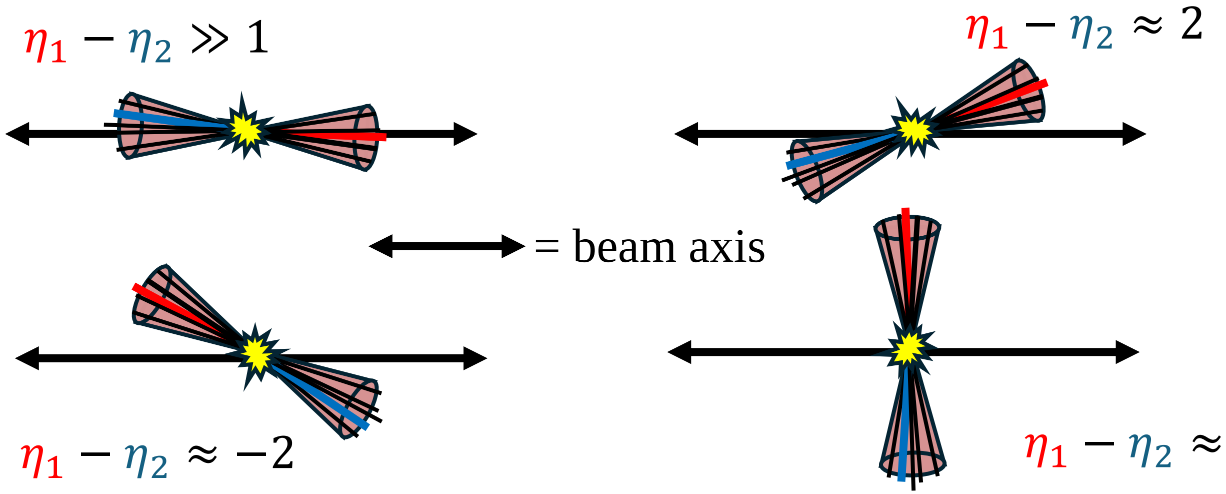
What is our interest in the 2D correlation function ?

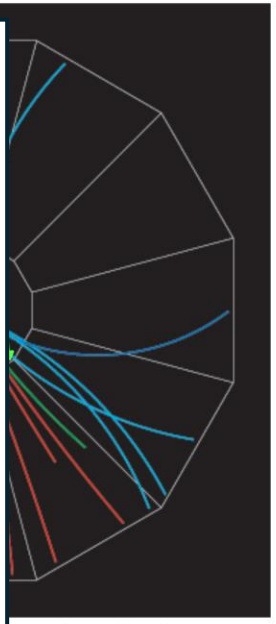




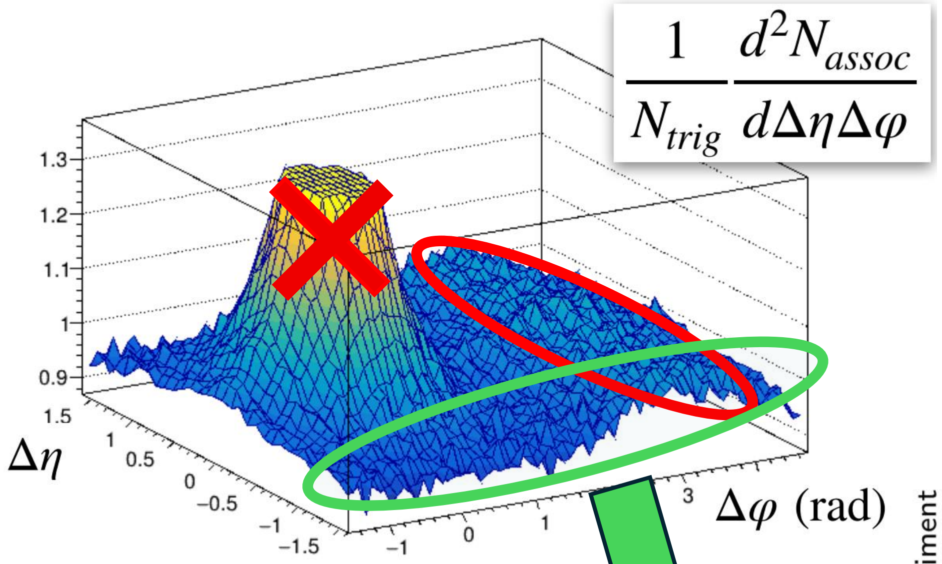


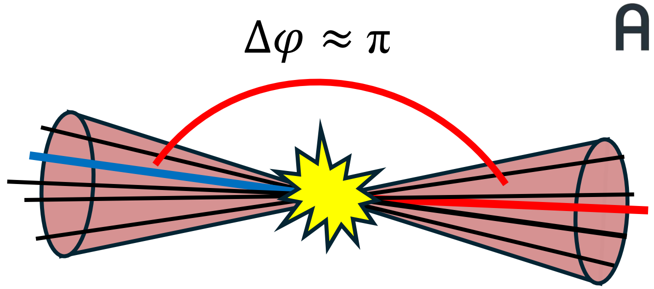
The away-side peak spans the whole $\Delta\eta$ range because opposite jets can be emitted in a variety of η range :

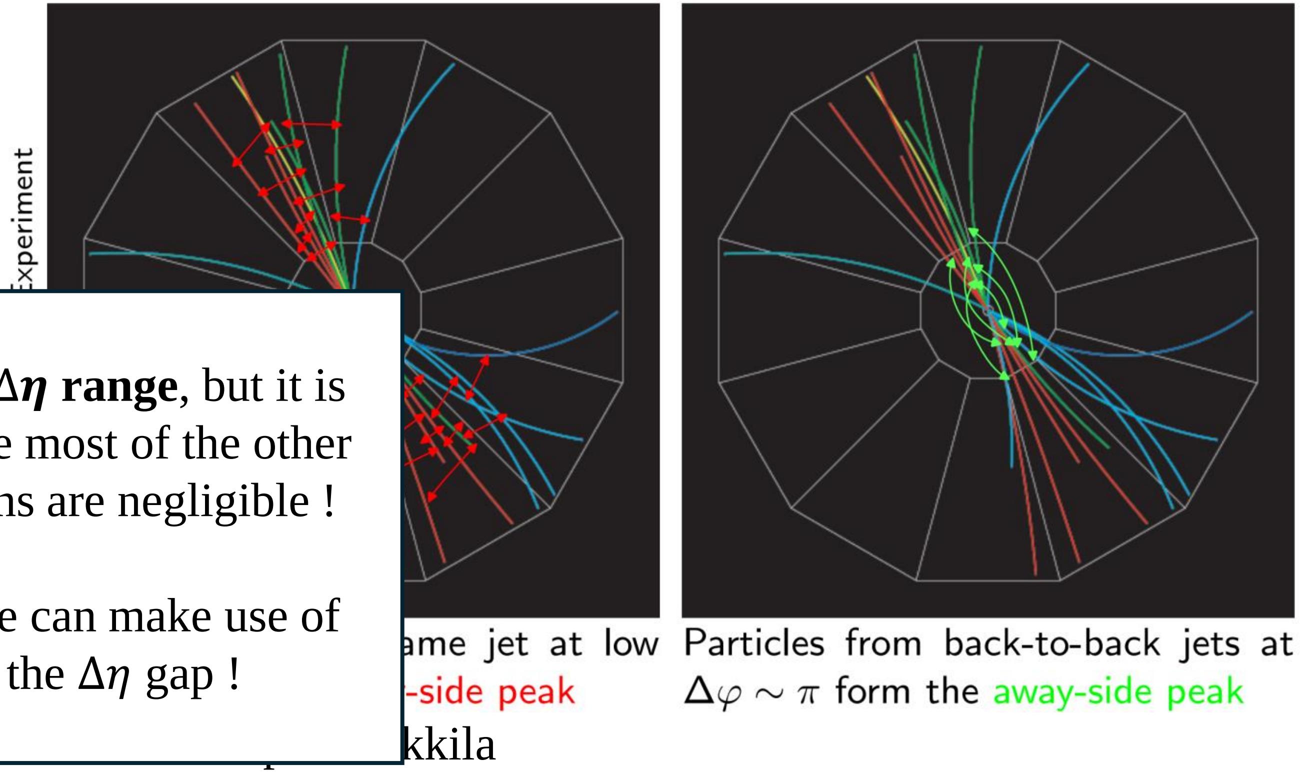




What is our interest in the 2D correlation function ?

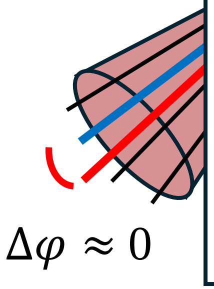






Flow signal **contributes across all $\Delta\eta$ range**, but it is **more visible in long-range**, because most of the other 2D correlation function contributions are negligible !

To study long-range correlations, we can make use of **forward detectors** to broaden the $\Delta\eta$ gap !

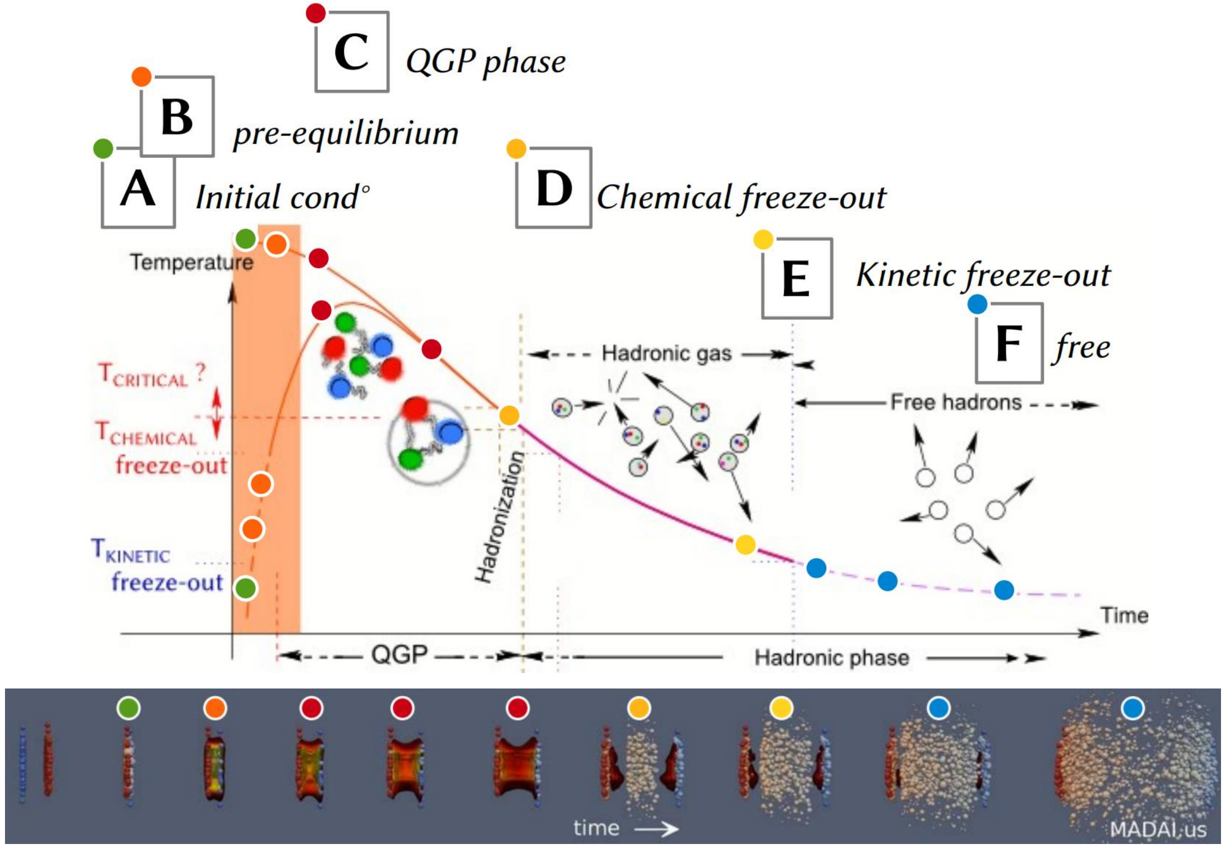


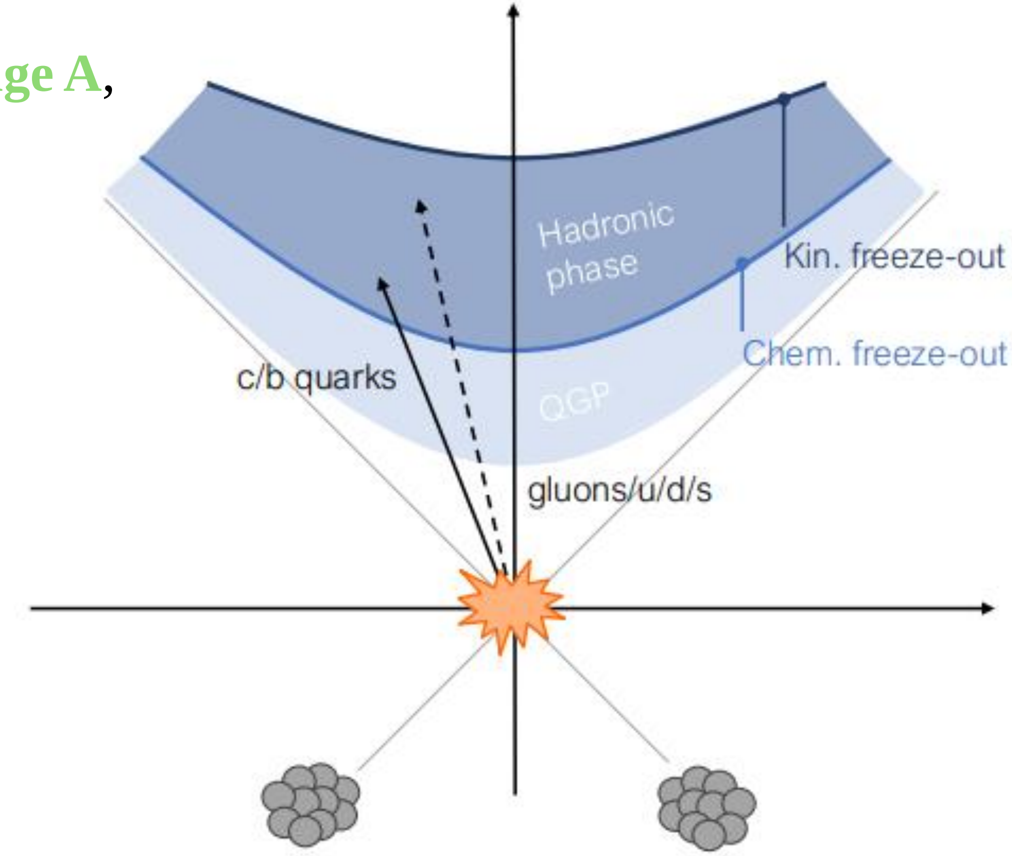
Why studying heavy flavor ?

Heavy flavor (charm, beauty) = hard probes !

(= coming from energetic processes at very early collision **stage A**,

which will later experience the QGP medium completely)

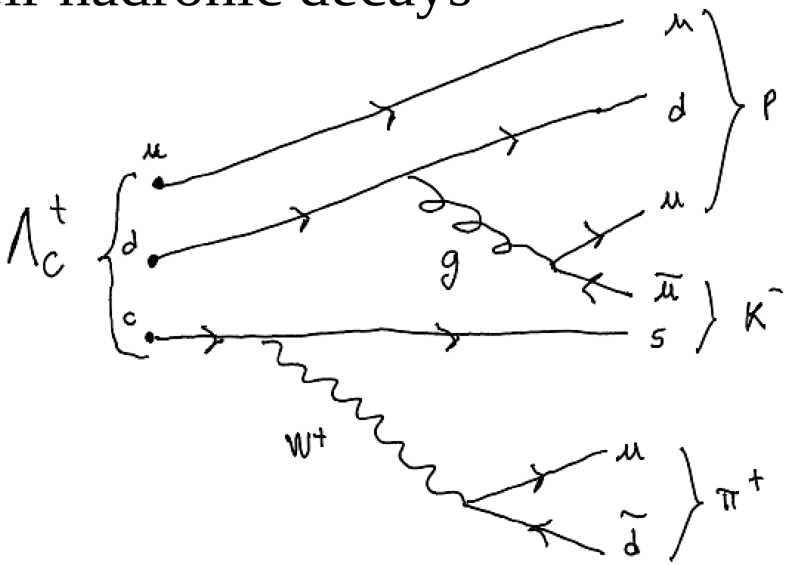


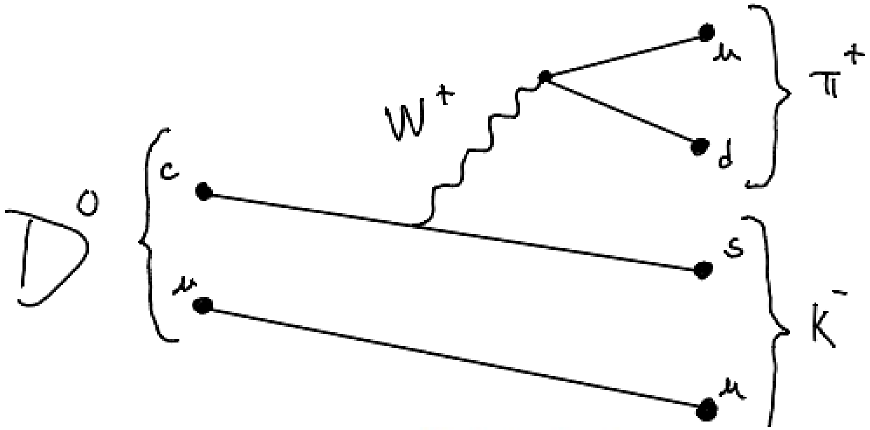


scheme credits : Emma Chizzali

Focusing on D^0 and Λ_c^+ but we will see what statistics allow us…

They are the lightest heavy-flavor hadrons and both hadrons will be reconstructed through their hadronic decays





Studying both a meson and a baryon will allow us

to study baryon/meson grouping and mass ordering !

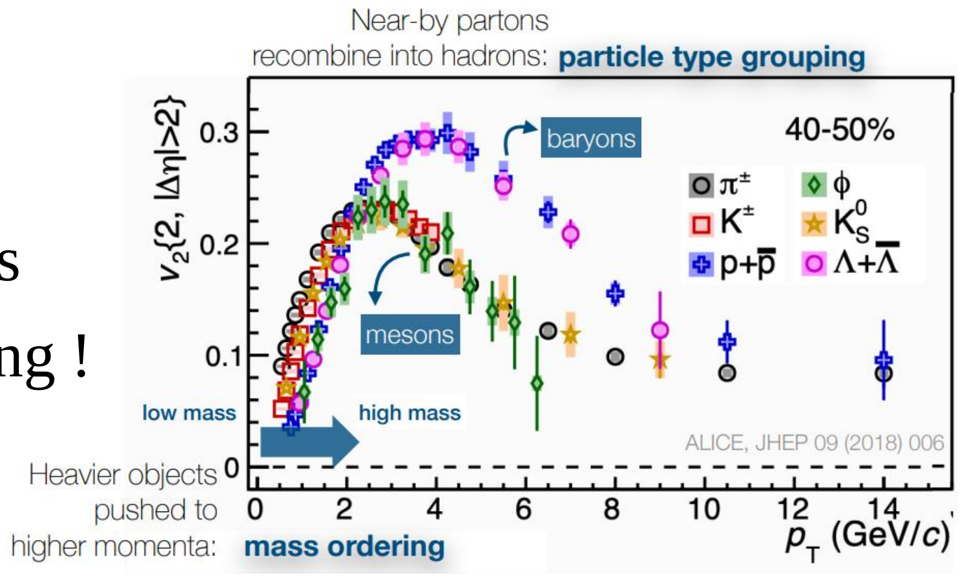


Figure from Katka's JCF seminar on 10/11/2023

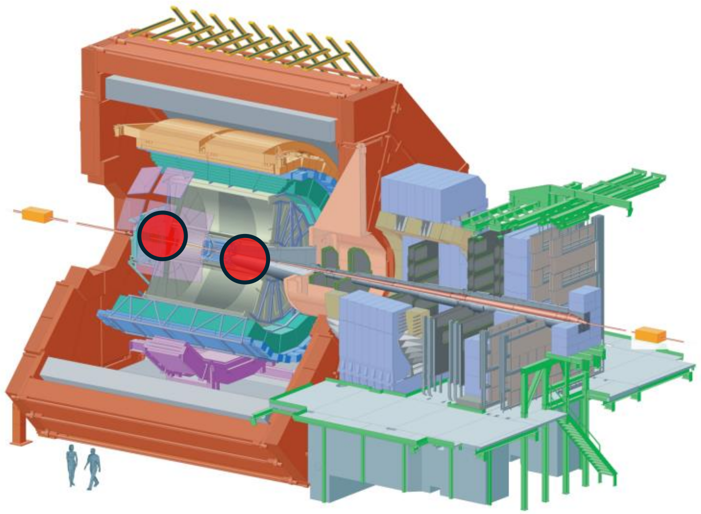
The ALICE detector

ALICE during RUN 2

ITS → 6 layers of silicon pixel detectors

TPC → Multi Wire Proportional Chambers

Forward detectors (of interest) → Forward Multiplicity Detectors on both sides



FMD already used to broaden η gap in : arXiv:2308.16590

ALICE during RUN 3

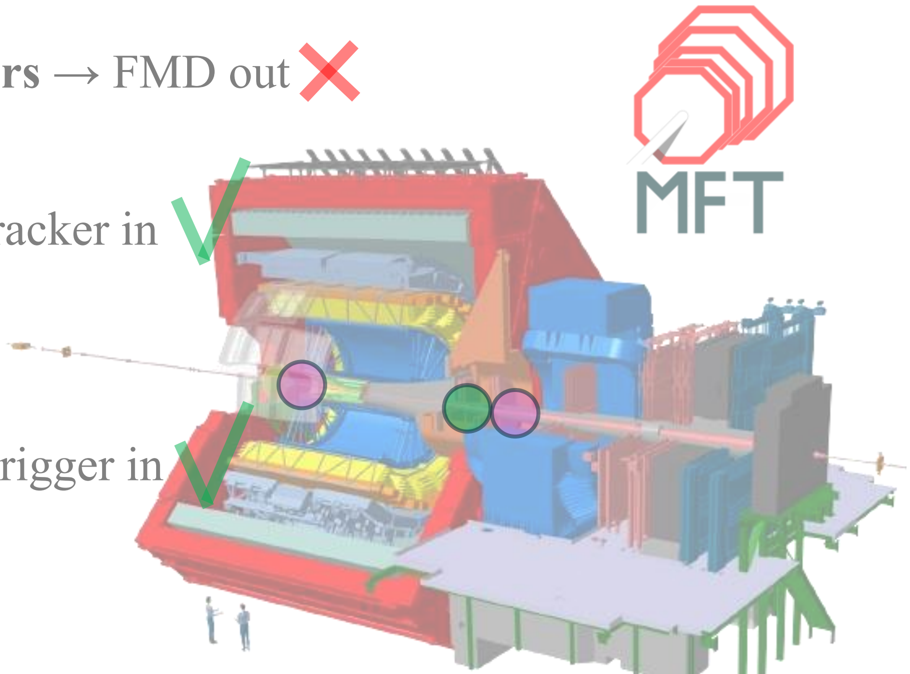
ITS → **7 layers** and 1st layer closer to interaction point

TPC → Gas Electron Multipliers + continuous readout

Forward detectors → FMD out

Muon Forward Tracker in (one side only)

Fast Interaction Trigger in (both sides)



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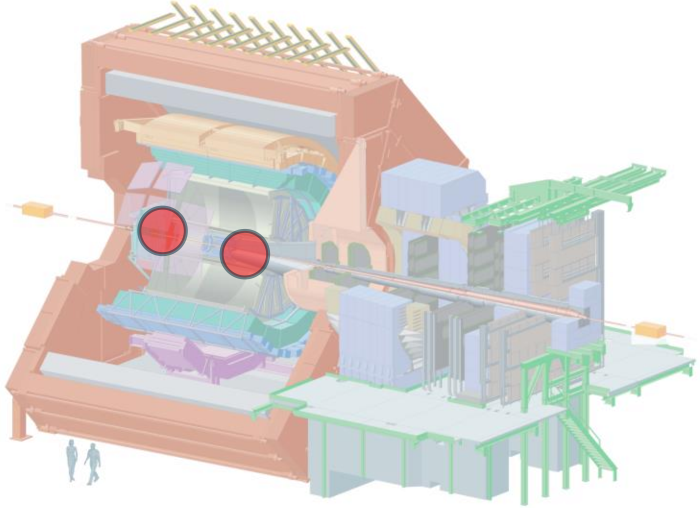

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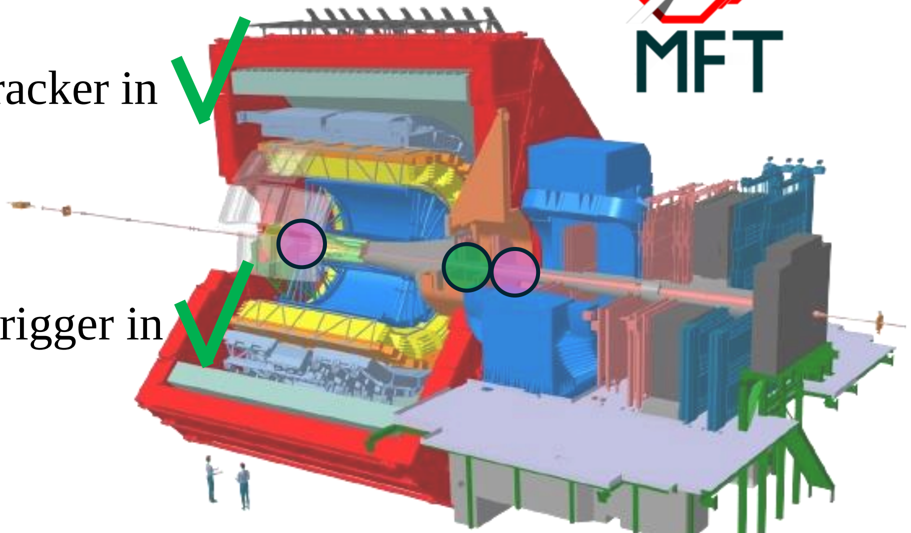
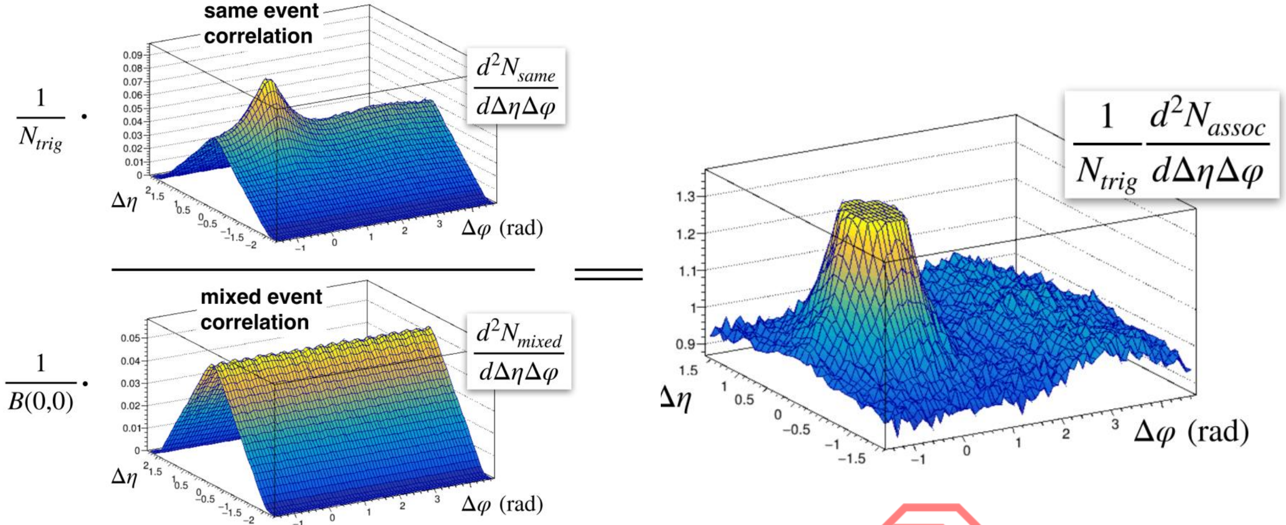
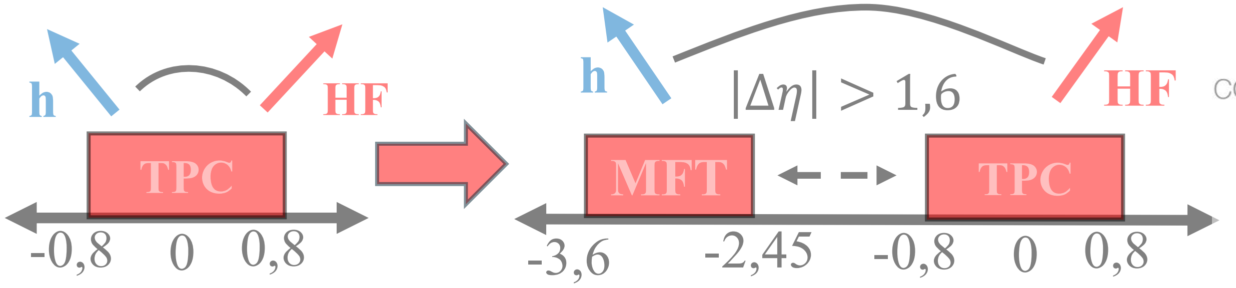


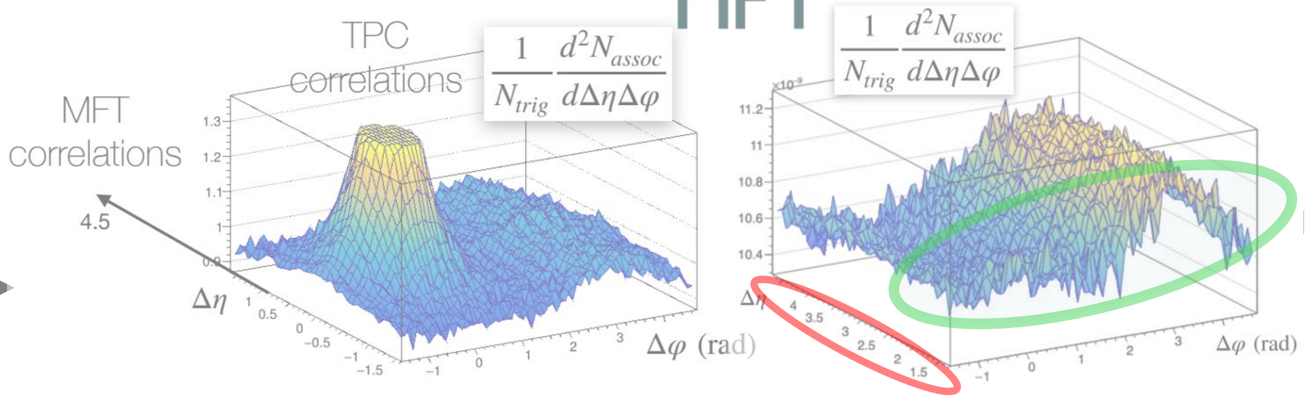
Analysis procedure (I)

1. Get two-particle azimuthal correlation



2. Remove jet-peak apply $\Delta\eta > 1.4$ and project on $\Delta\varphi$





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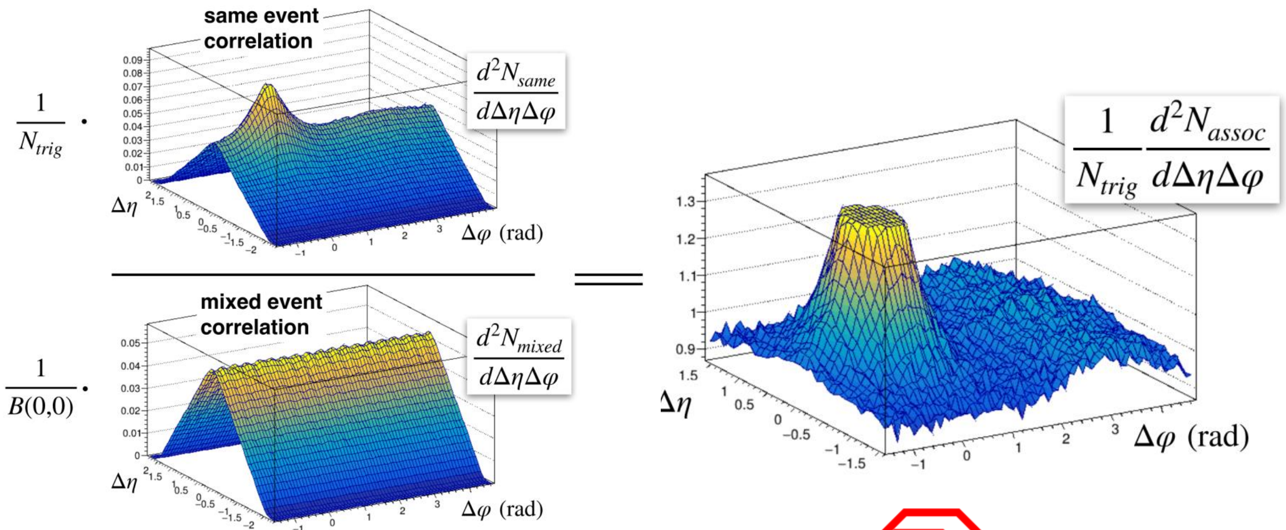
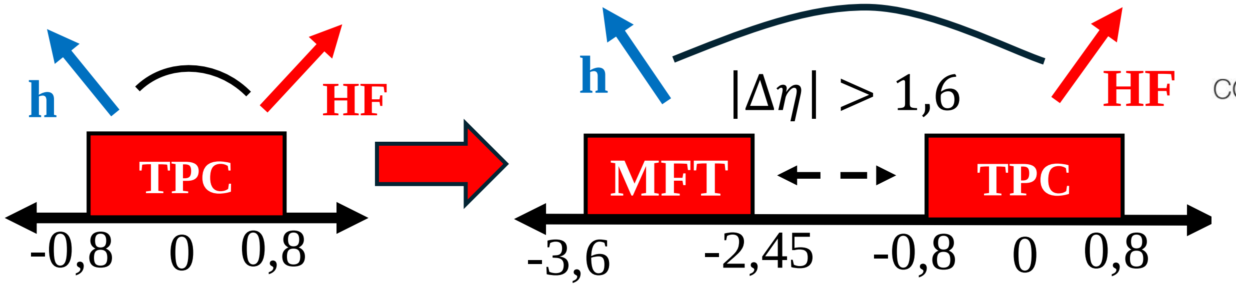
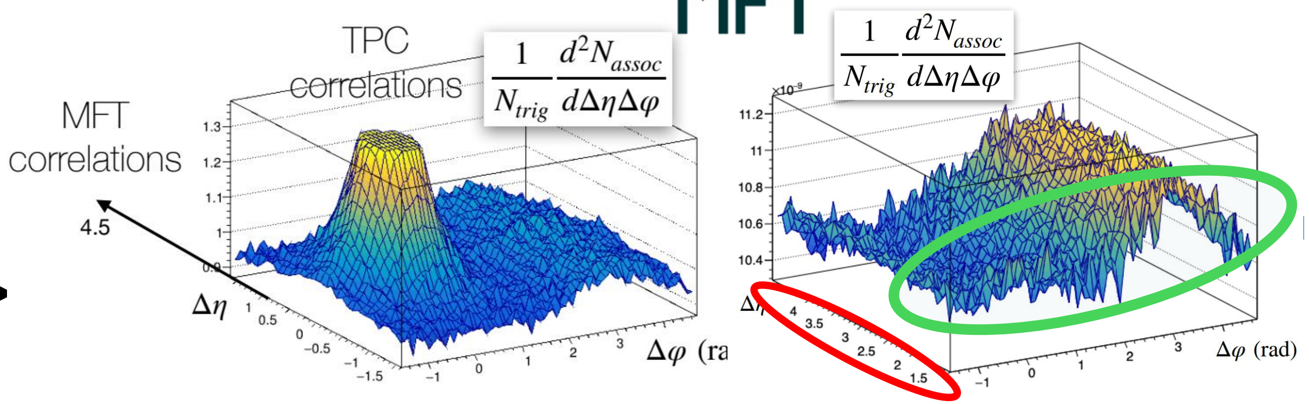
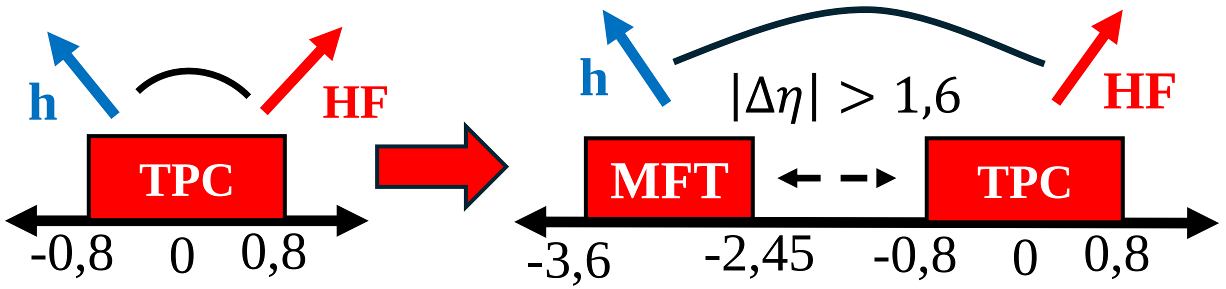


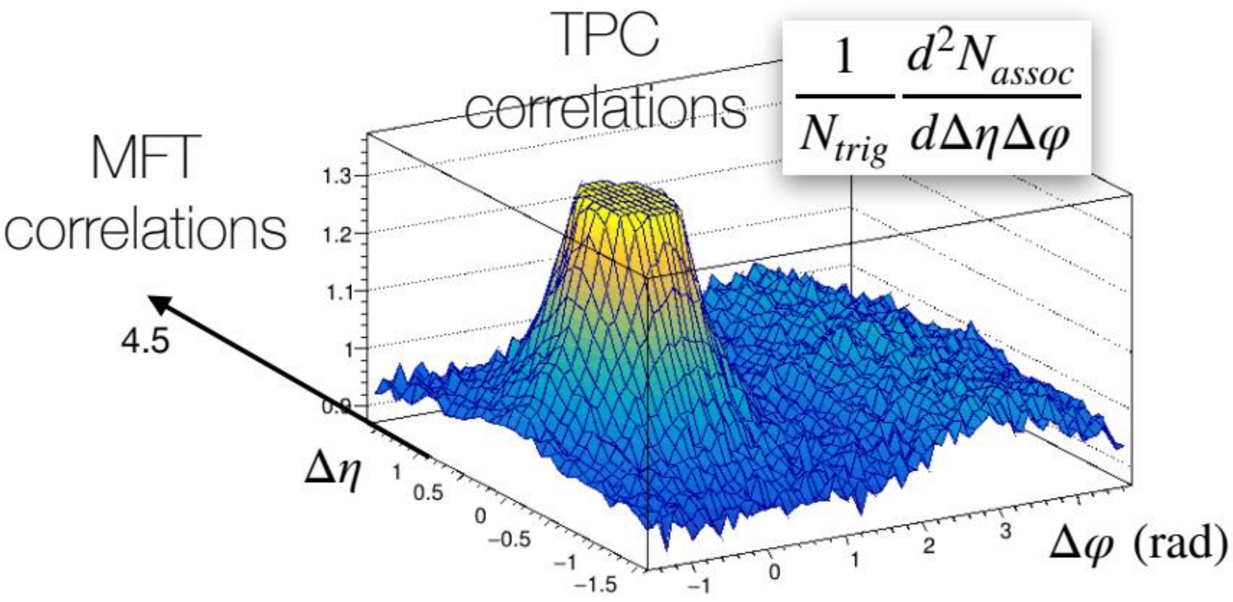


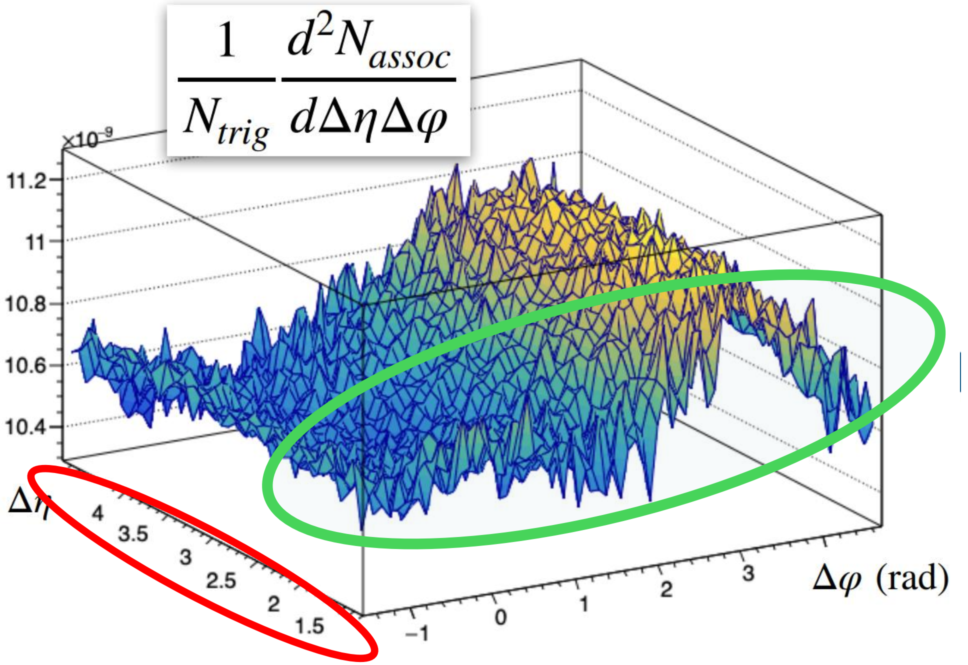


Why using MFT for correlations ?

Remove jet-peak apply $\Delta\eta > 1.4$ and project on $\Delta\varphi$







One consequence of using MFT for correlations

ALICE

When measuring the flow of identified particles (such as D^0 and Λ_c^+ here) we **must** cancel the effect of the reference flow (h-h correlations) so the final flow does not depend on the choice of reference

Using MFT introduces a bias in the forward region, and using the usual 2PC method isn't enough anymore..

How to cancel forward region reference flow ?

$$V_2^{HF} = \frac{\langle V_2^{HF} \cdot V_2^{MFT} \rangle}{\sqrt{\langle V_2^{TPC} \cdot V_2^{MFT} \rangle}}$$

We must also correlate the TPC from the other side with FV0, and then cancel the forward region reference flow by correlating MFT and FV0

$$V_2^{HF} = \sqrt{\frac{\langle V_2^{HF} \cdot V_2^{FV0} \rangle \langle V_2^{HF} \cdot V_2^{MFT} \rangle}{\langle V_2^{FV0} \cdot V_2^{MFT} \rangle}}$$

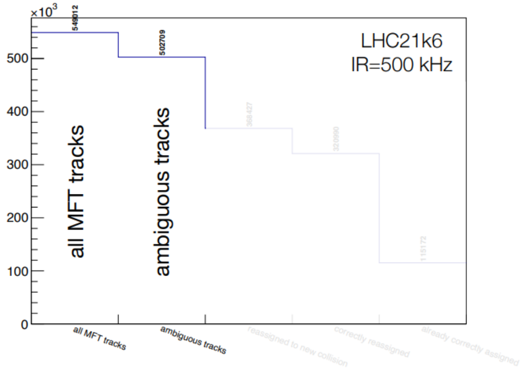
« 3x2PC » method first used in PHENIX : Phys. Rev. C 105, 024901 (2022)

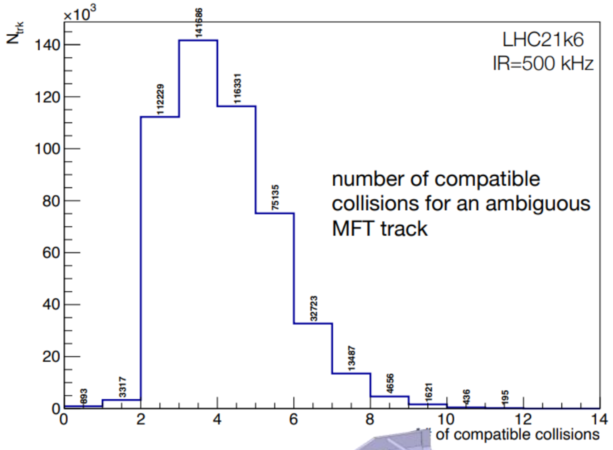
A potential problem with MFT

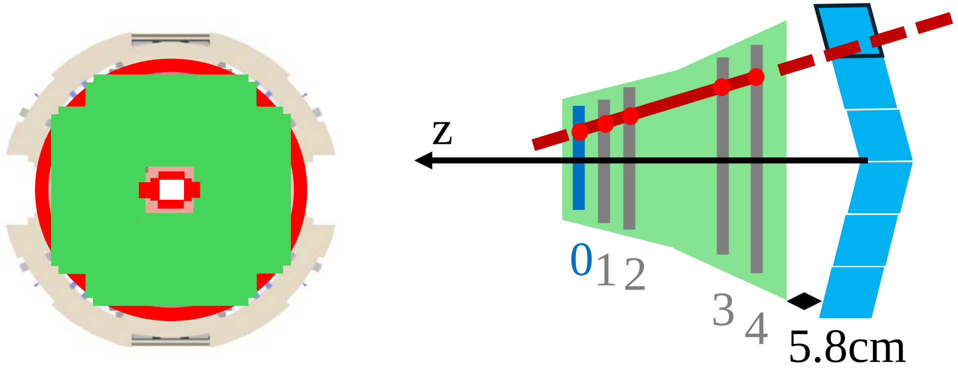
A potential problem with MFT tracks

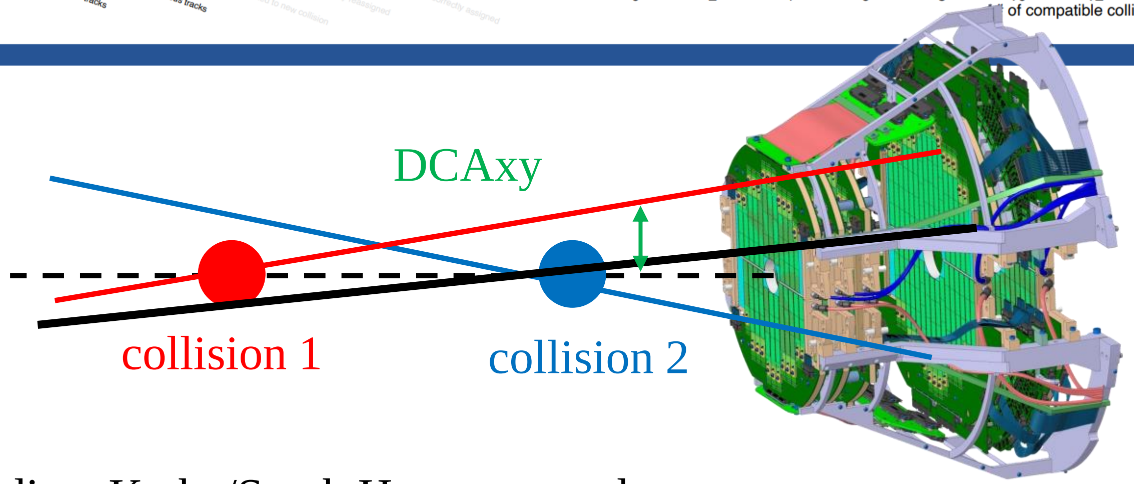
- MFT read-out time: 4 - 15 μs
- Interaction rate of 500 kHz → 1 collision every 2 μs
- MFT track would be **compatible** in time with **2 - 7 collisions** on average

- 92% of all tracks are ambiguous
- Note: we are talking about standalone tracks



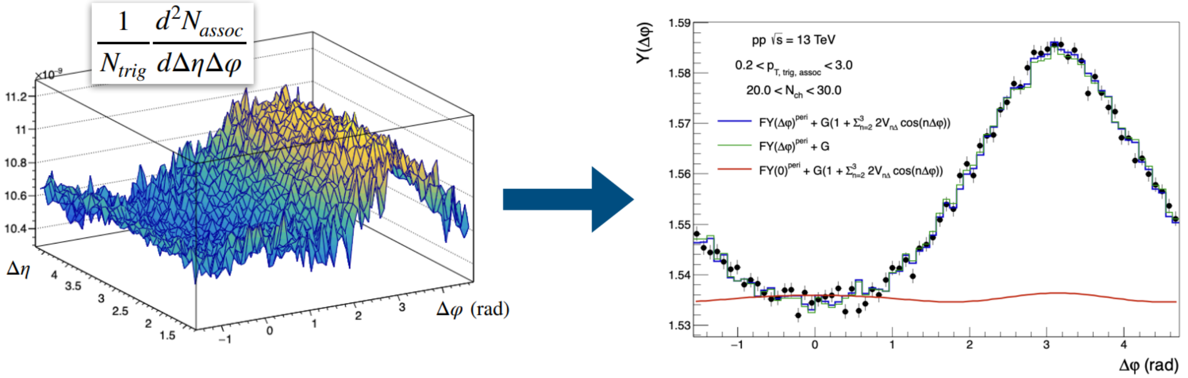


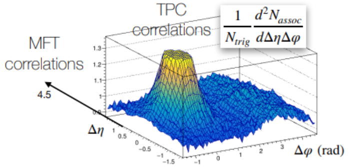




How much should we be worried (I)

Ideal case: MC simulations





- Correlations far from the jet peak contamination
- We can use (almost) all the available statistics
- Note: this is Pythia, so don't look for meaningful flow signal :)

credits : Katka/Sarah Hermann et al.

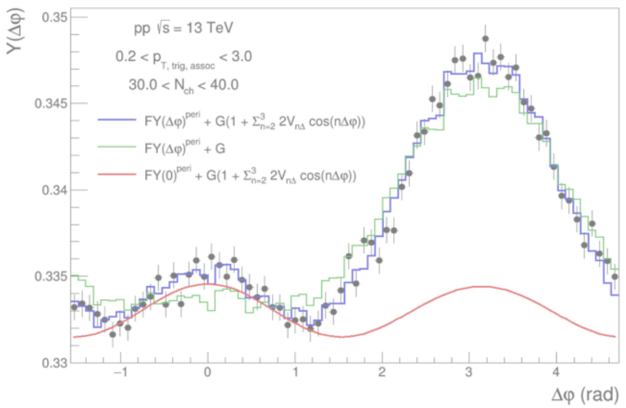
Analysis procedure (II)

2. Remove jet-peak apply $\Delta\eta > 1.4$ and project on $\Delta\varphi$

3. Perform template fit

$$Y^{template}(\Delta\varphi) = F \cdot Y^{peripheral}(\Delta\varphi) + Y^{ridge}(\Delta\varphi)$$

Our measurement | Non-flow component | **Collective flow component**



$$Y^{ridge}(\Delta\varphi) = G\left[1 + 2\sum_{n=2}^{3} V_{n\Delta} \cdot \cos(n\Delta\varphi)\right]$$

4. Get flow

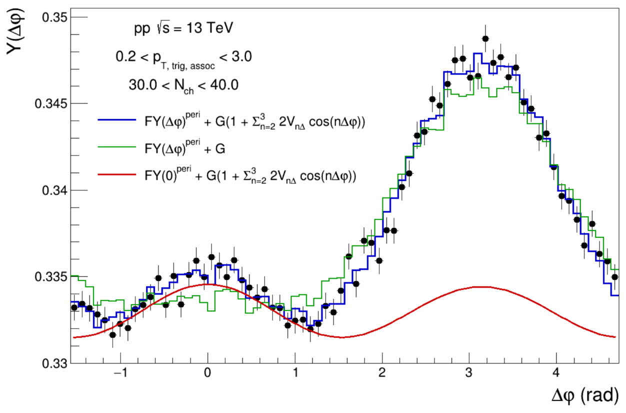
5. Reference flow

\+

Differential flow **5 bis.**

Analysis procedure (II)

2. Remove jet-peak apply $\Delta\eta > 1.4$ and project on $\Delta\varphi$ → **3.** Perform template fit



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Y^{templ}

Our measu

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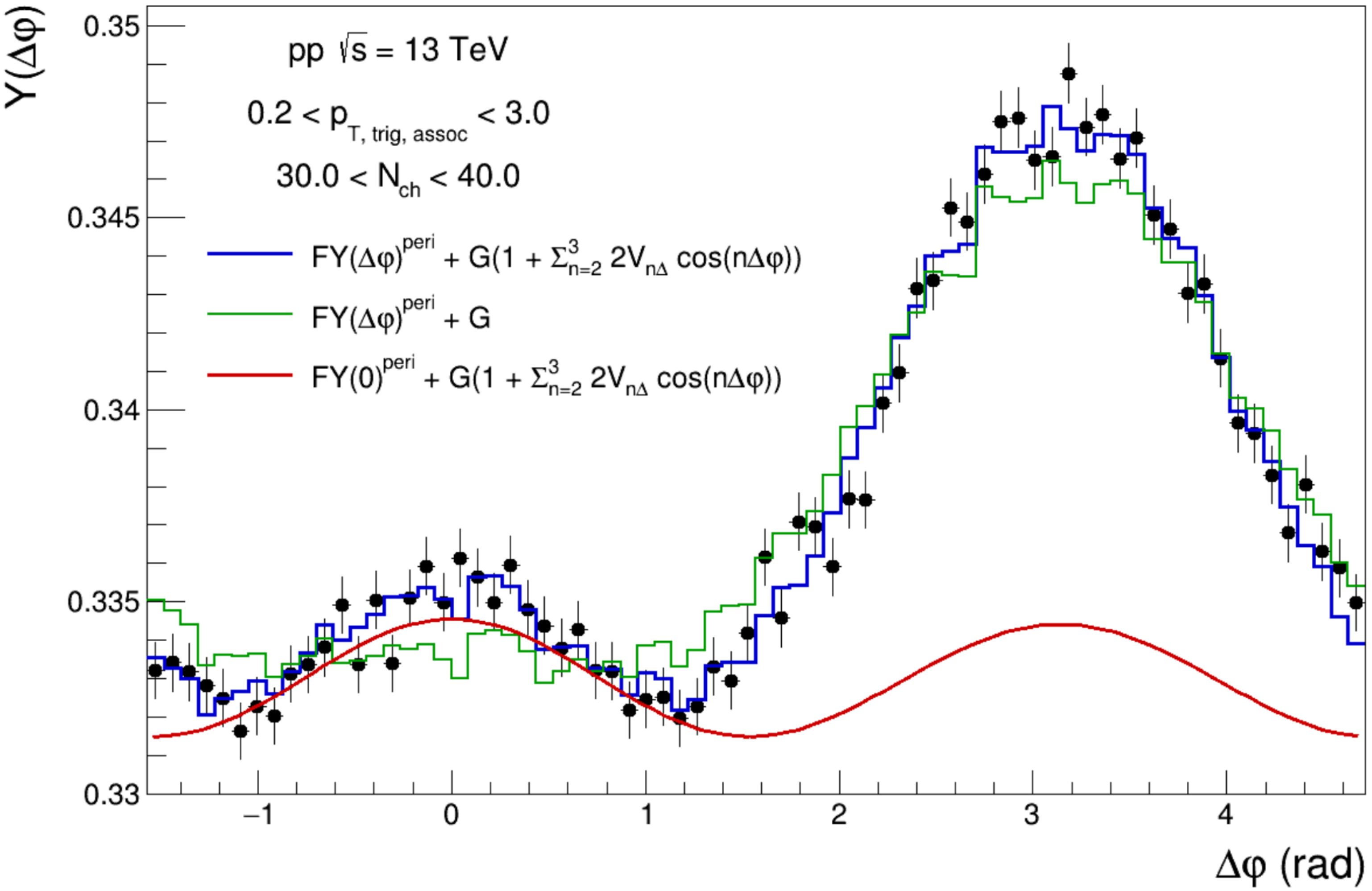

Differential flow

5 bis.

Analysis procedure (II)

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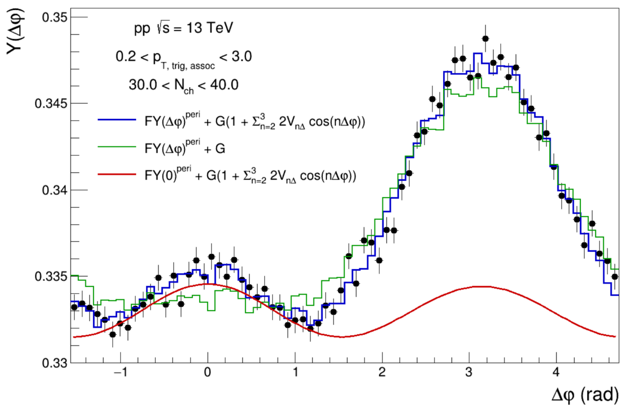

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4. Get flow

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+

Differential flow **5 bis.**

Analysis procedure (II)

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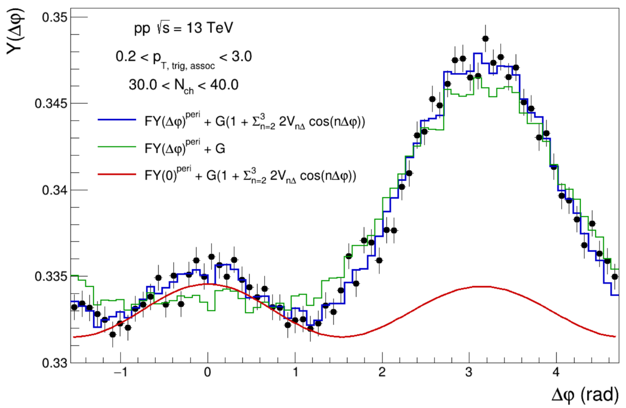

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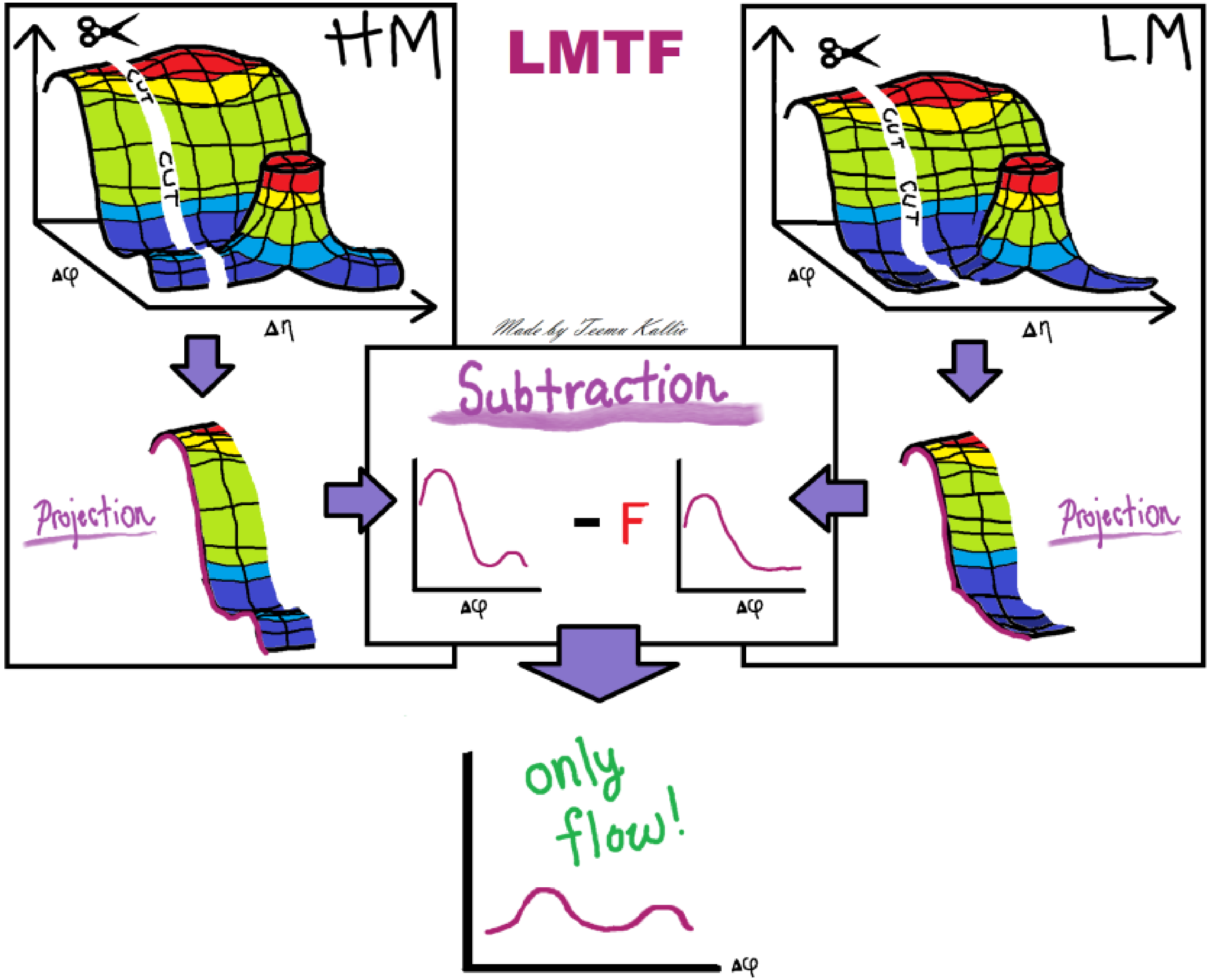
4. Get flow → **5.** Reference flow + **5 bis.** Differential flow

Template fit a nice scheme to understand more easily ☺



scheme credits : Maxim Virta

Summary

I tried to show the relevance of anisotropic flow measurements both in the QGP history and in the young field of the study of collective behavior in small systems

I hope to have described well enough for you to understand the measurement of anisotropic flow through two particle correlations

I hope to have well motivated the purpose of my analysis

And I hope to have highlighted the use of forward detectors to improve anisotropic results, and the challenges that they bring to the table

BACK UP

References from Katka's JCF seminar

References in heavy-ion collisions

Near-side long-range ridge yield
[1] CMS, Eur. Phys. J. C (2012) 72:2012
[2] ALICE, PLB 708 (2012) 249–264
Anisotropic flow
[3] CMS, JHEP02(2014)088
[4] ALICE, PRL 116, 132302 (2016)
Multiparticle correlations
[5] ALICE, JHEP07(2018)103
Mass ordering / baryon-meson grouping
[6] ALICE, JHEP 05 (2023) 243
Flow decorrelations (p_T)
[7] CMS, PRC **92**, 034911 (2015)
[8] ALICE, PRC 107 (2023) L051901
Flow decorrelations (η)
[9] ATLAS, PRL 126, 122301 (2021)
[10] ATLAS, Eur. Phys. J. C (2018) 78:142
Event-by-event v_n
[11] ATLAS, JHEP11(2013)183
[12] CMS, PLB 789 (2019) 643–665
Flow magnitude correlations/fluctuations
[13] ATLAS, PRC **92**, 034903 (2015)
[14] ALICE, PRL 117, 182301 (2016)
Symmetry plane correlations
[15] ATLAS, PRC **90**, 024905 (2014)
Nonlinear response of V_n
[16] CMS, *Eur.Phys.J.C* 80 (2020) 6, 534
[17] ALICE, PLB 773 (2017) 68–80
[18] STAR, PLB **839** (2023) 137755
Event-shape engineering of v_n
[19] ALICE, PRC **93**, 034916 (2016)
$\rho(v_n^2,[p_T])$
[20] ATLAS, Eur. Phys. J. C (2019) 79:985
[21] ALICE, PLB 834 (2022) 137393
High-p_T flow (hard scattering)
[22] ATLAS, *PRC* 105 (2022) 6, 064903
[23] CMS, PRL 109, 022301 (2012)
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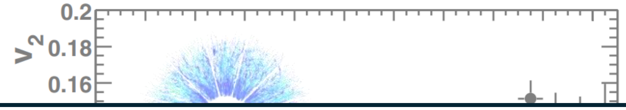
Introduction : signatures of the quark gluon plasma

Signatures : many !

Au+Au collisions at $\sqrt{s} = 130$ GeV (RHIC)



02 (2001)

2001 : discovery of strong «

2002 : discovery of jet quen

Many other signatures :

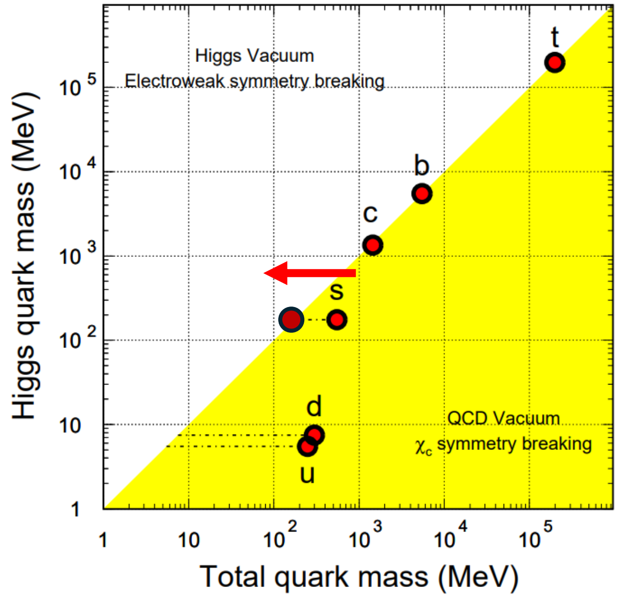
strangeness enhancement

quarkonia suppression

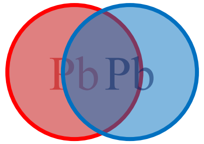
mass ordering

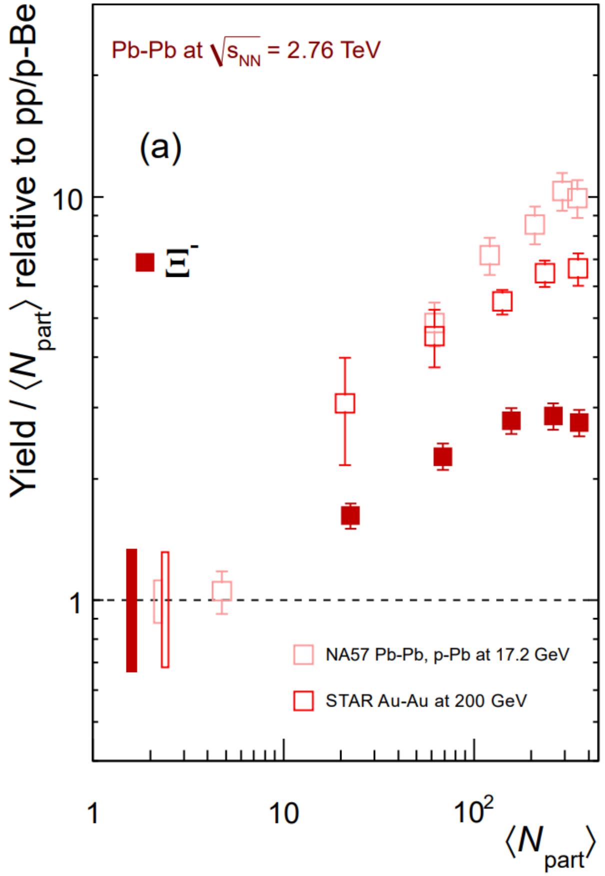
baryon-meson grouping

chiral symmetry partial restoration → $m_s \approx 100$ MeV < T_{QGP}



arXiv:hep-ph/0604178





arXiv:1307.5543

+ gluon fusion $gg \rightarrow s\bar{s}$ more frequent in QGP

Phys. Rev. Lett. 88, 022301 (2002)

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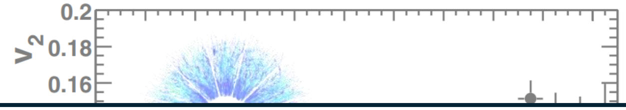

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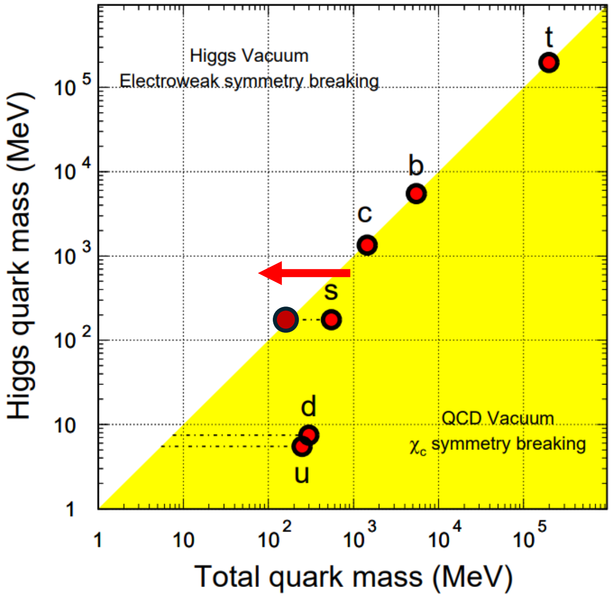

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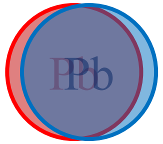

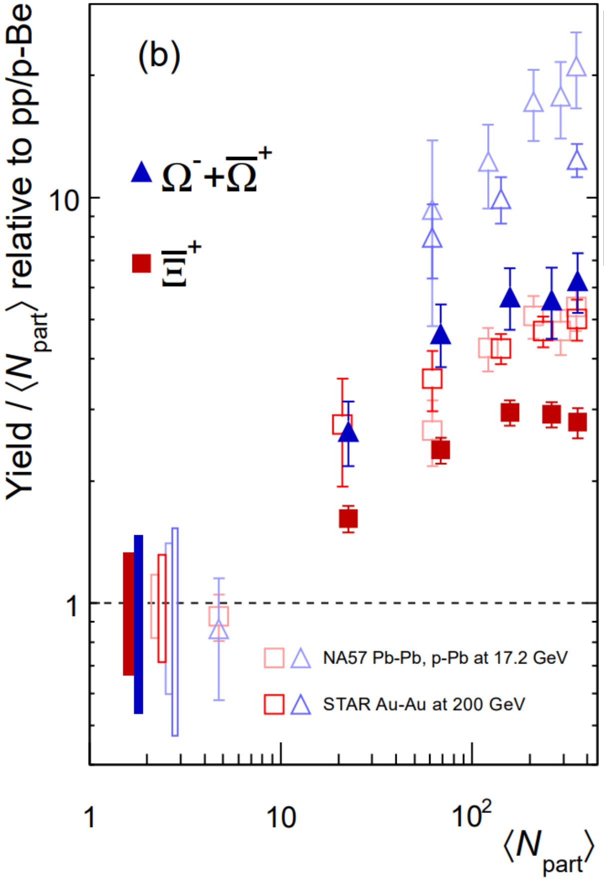

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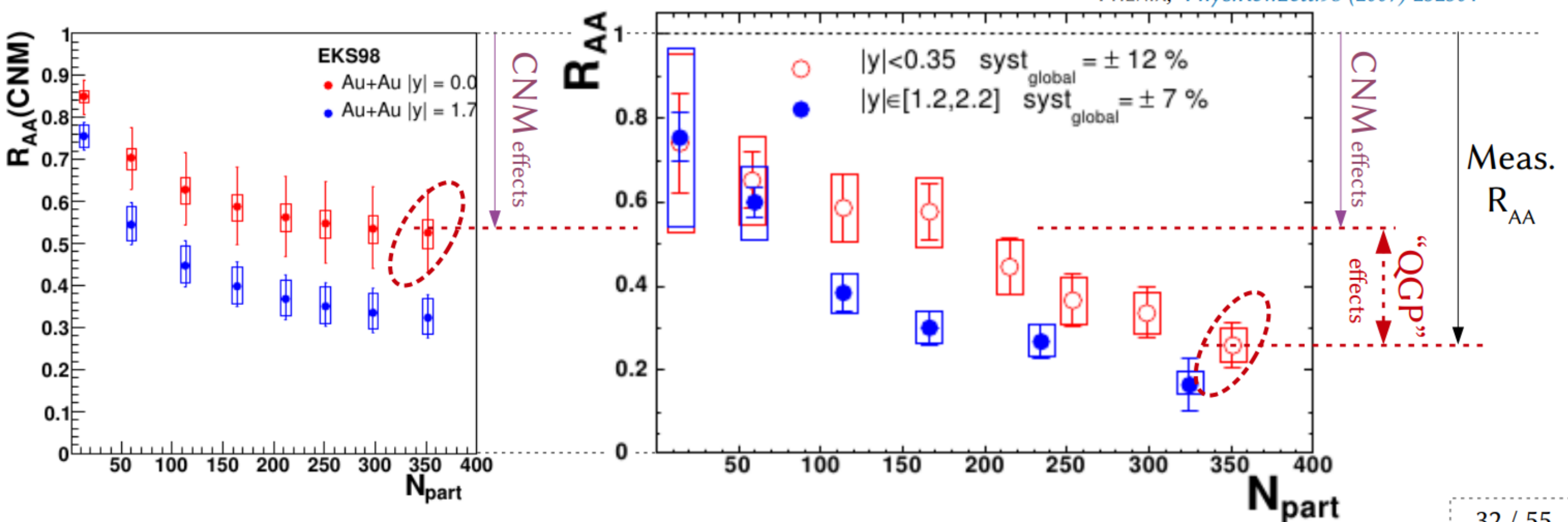
Quarkonia is even more suppressed in the presence of quark gluon plasma

Illustration : PHENIX case, J/ψ suppression in Au-Au

PHENIX, Phys.Rev.Lett.98 (2007) 232301



Brambilla et al, Eur.Phys.J.C71(2011) 1534
(p.127, Fig.87)

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v2022.0

From Antonin Maire's lecture : Strong interaction at hadron colliders

Phys. Rev. Lett. 88, 022301 (2002)

Summary of the discovery of QGP : arxiv:nucl-ex/0501009

Introduction : signatures of the quark gluon plasma

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Au+Au collisions at $\sqrt{s}$ = 130 GeV (RHIC)

v_2 0.2 0.18 0.16

02 (2001)

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Signature associated with the anisotropic flow of identified hadrons, explained by **quark coalescence**, a phenomenon exclusive to a QGP-like medium

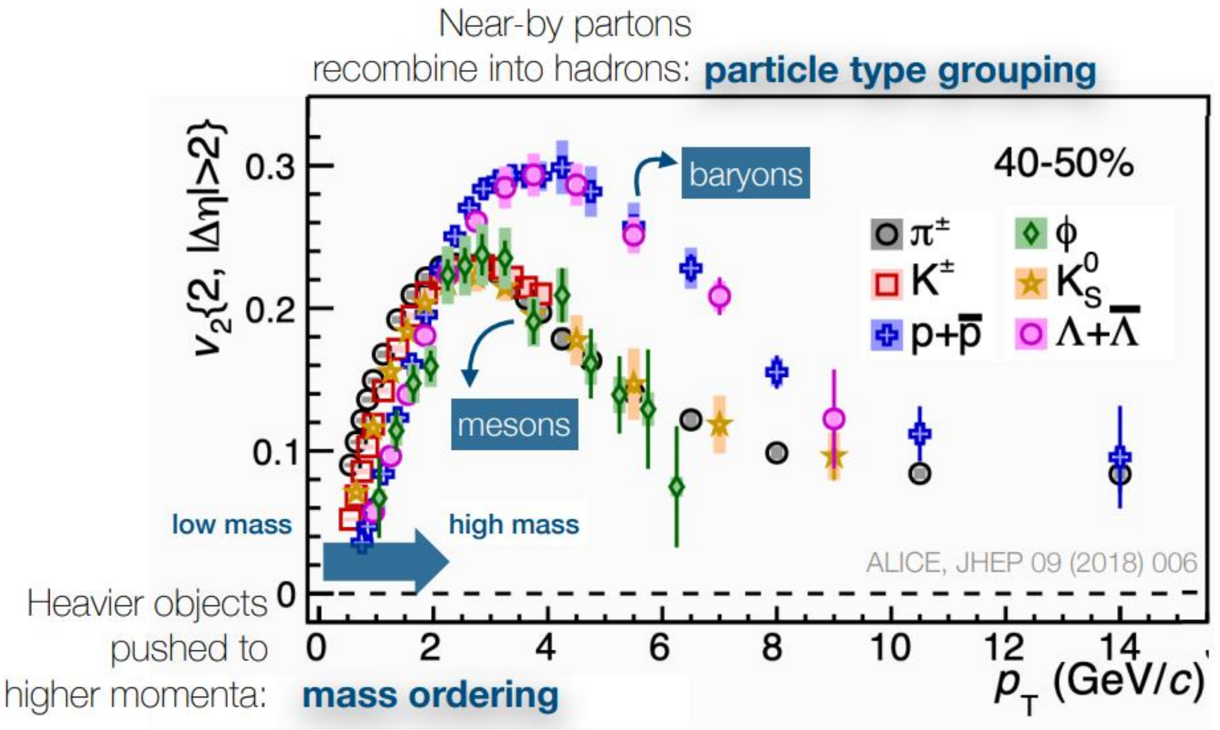

Figure from Katka's JCF seminar on 10/11/2023

Phys. Rev. Lett. 88, 022301 (2002)

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Template fit the principles detailed…

Perform template fit

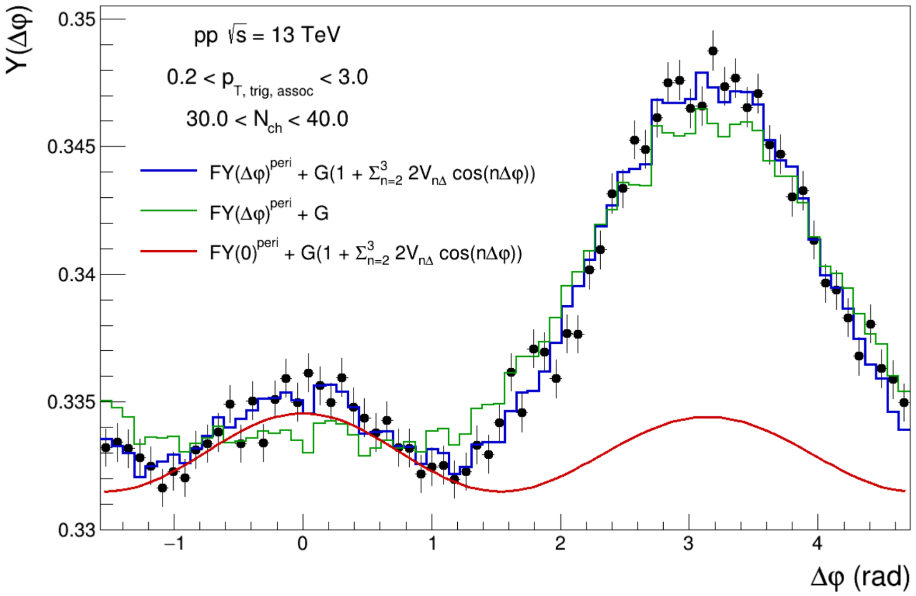
$$Y^{template}(\Delta\varphi) = F \cdot Y^{peripheral}(\Delta\varphi) + Y^{ridge}(\Delta\varphi)$$

$$Y^{ridge}(\Delta\varphi) = G\left[1 + 2\sum_{n=2}^{3} V_{n\Delta} \cdot \cos(n\Delta\varphi)\right]$$

Our measurement at given multiplicity → Contains **non-flow** & **collective effects**

Non-flow component
→ Assumption : **low-multiplicity** sample contains only **non-flow**

Collective flow component
→ Fourier expansion



Fit inputs :
→ measurement at high multiplicity
→ measurement at low multiplicity

Fit outputs :
→ F, G, $V_{n\Delta}$

Get reference and differential flow