



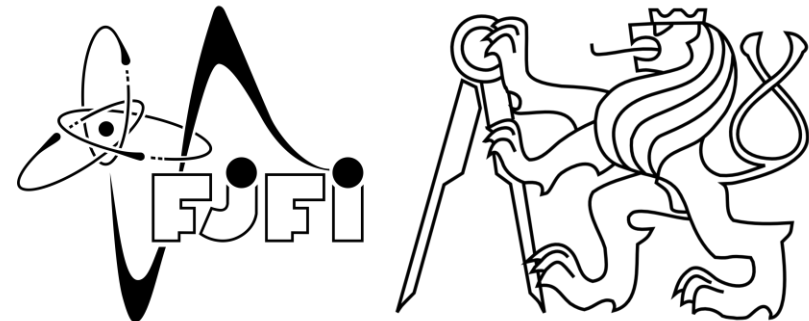
Toward long-range D0 flow in small systems with ALICE in Run 3

Alexian Lejeune¹

Supervision : Katarína Křížková Gajdošová¹, Jaroslav Bielčík¹

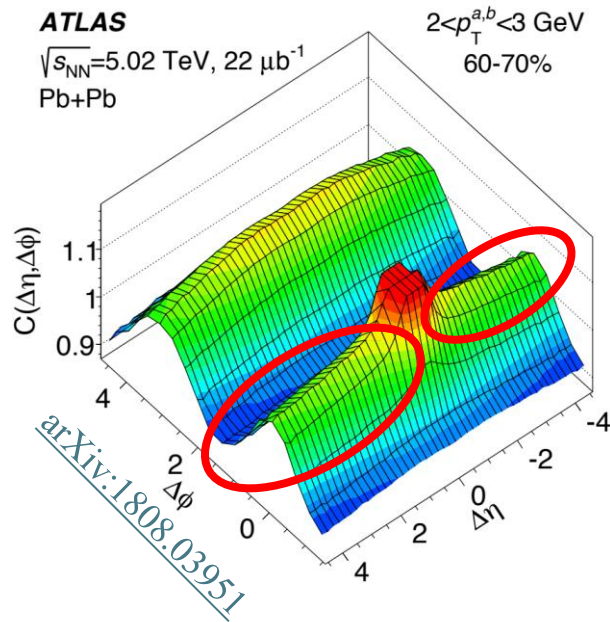
¹: Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

Děčín workshop – 16th of September 2025

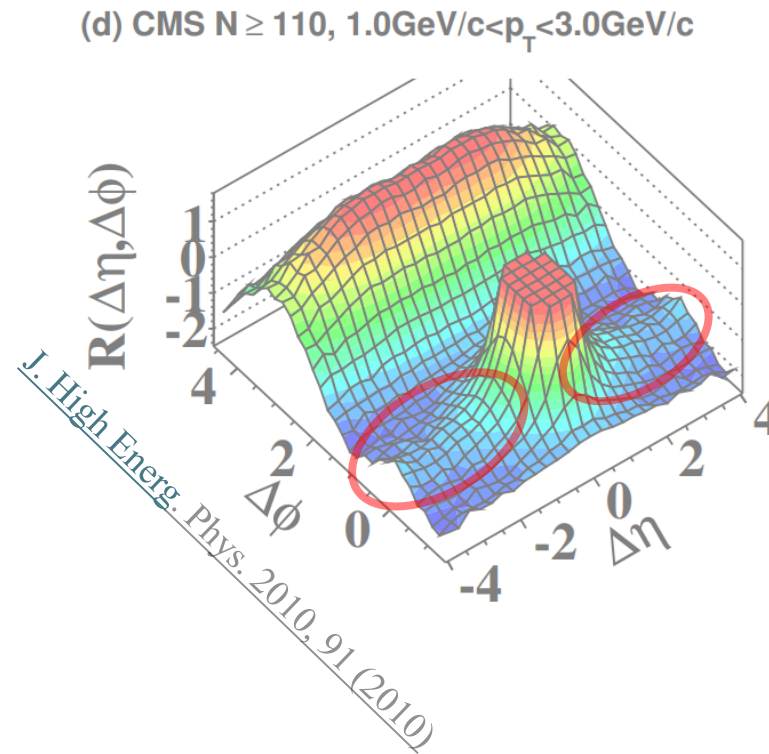


Introduction : what started it all

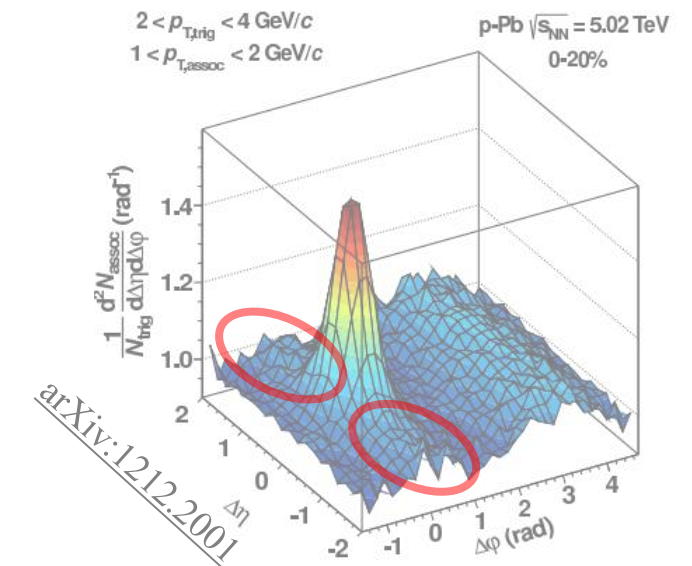
Near-side ridge in two-particle correlations was understood as a signature of collectivity in heavy-ion collisions



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



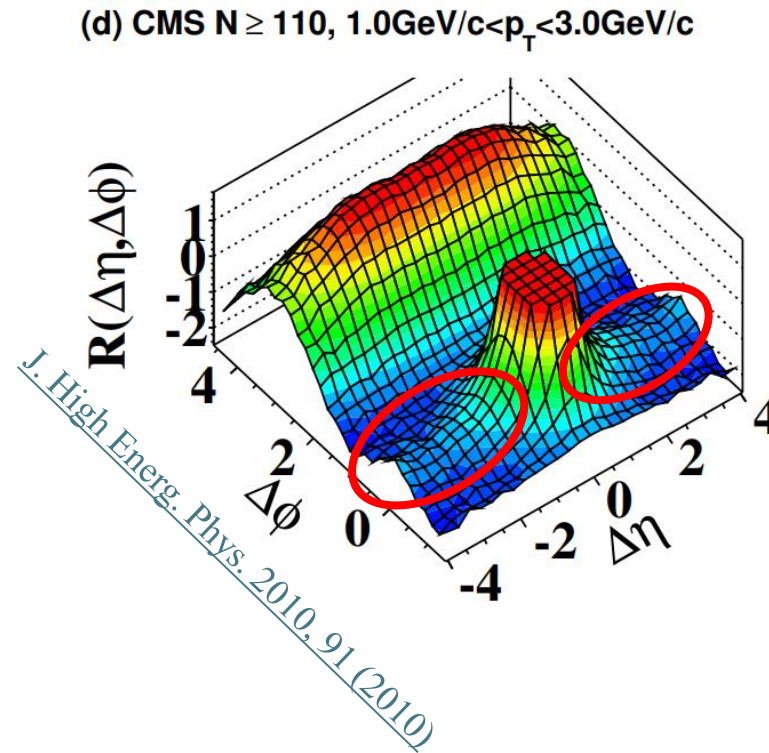
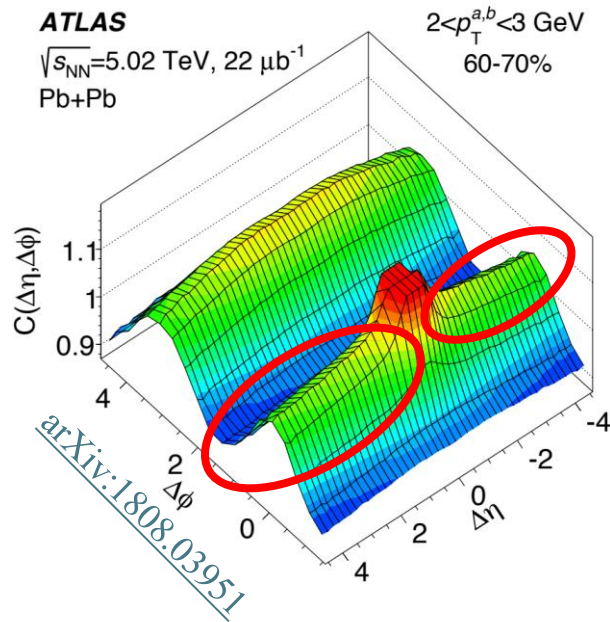
Which started the hunt of collectivity « signatures » in smaller systems !
The ridge was also later observed in pPb collisions



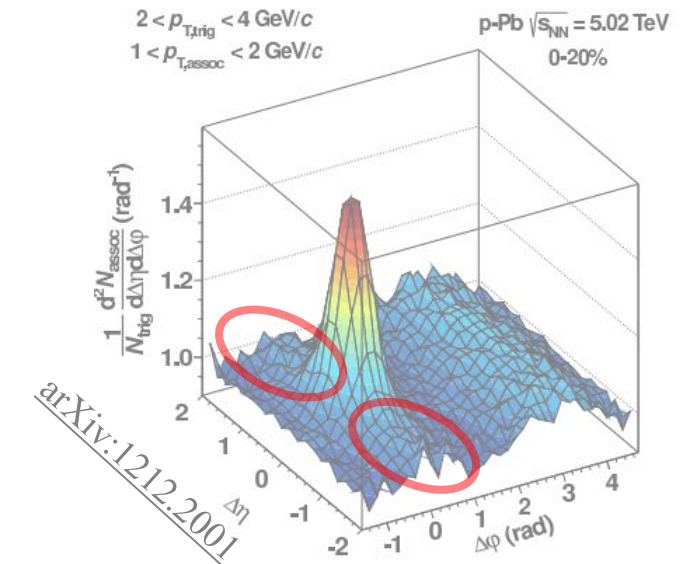
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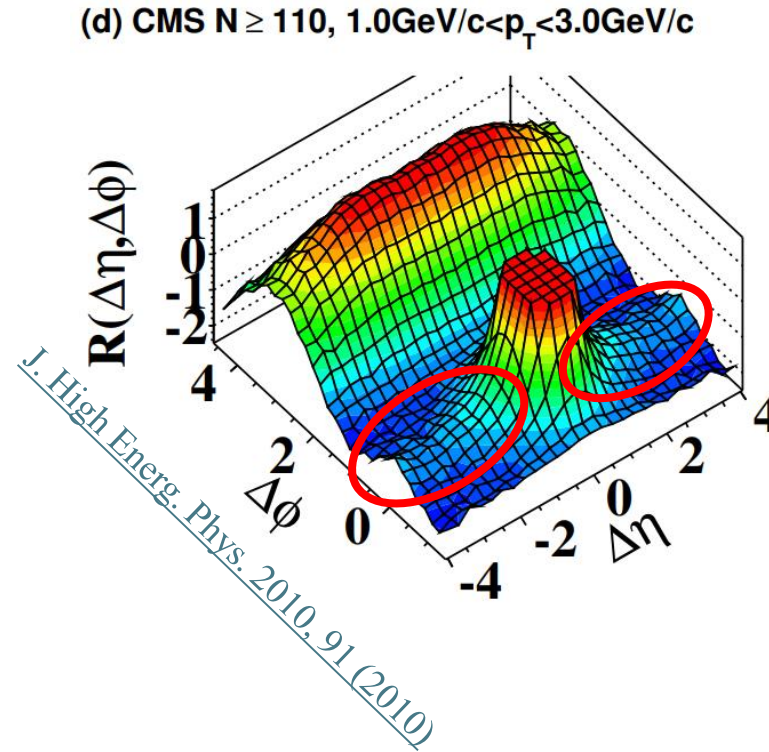
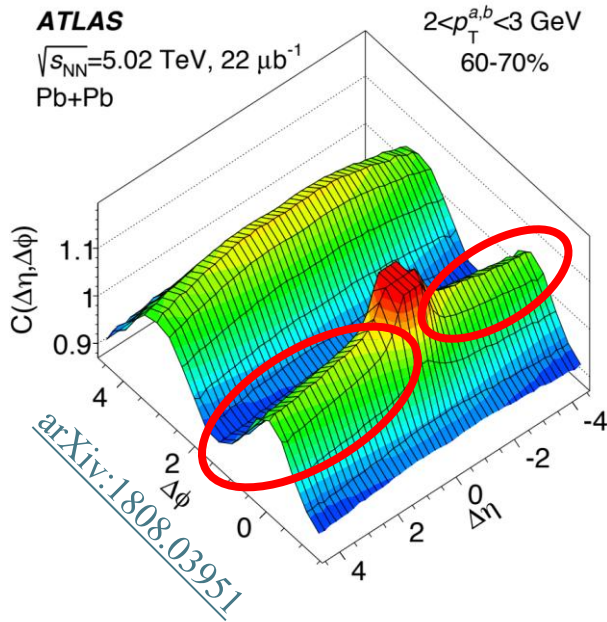
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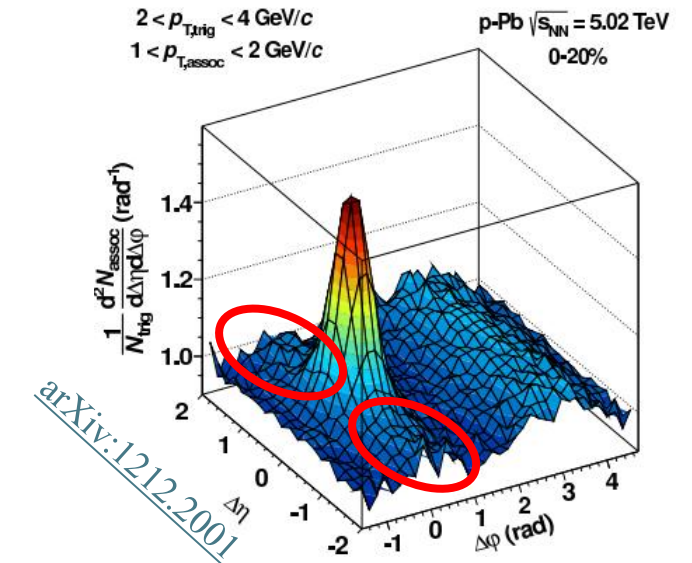
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Near-side ridge in two-particle correlations was understood as a signature of collectivity in heavy-ion collisions

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



Introduction : how it escalated



Digest of experimental results

measured and similar ✓
 measured but different ✗
 not measured —

From Katka's JCF seminar

References in back-up slides

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

Introduction : how it escalated

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measured and similar ✓
 measured but different ✗
 not measured —

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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]	—	—	Jet quenching has yet to be observed in small collision systems !						
Flow decorrelations (η)	✓ [9,10]	✓ [52]	✓ [53]	—							
Event-by-event v_n	✓ [11,12]	—	—	—							
v_n correlations	✓ [13,14]	✓ [54-57]	✓ [54,55,57]	—							
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measured and similar ✓
different ✗
measured —

OBSE

Near-side

Anisot

Multipartic

Mass

Baryon-me

Flow deco

Flow deco

Event-b

v_n cor

ψ_n cor

Nonlinear r

E

$\rho(\mu)$

High

Cha

Botto

Collectivity seems to be everywhere...

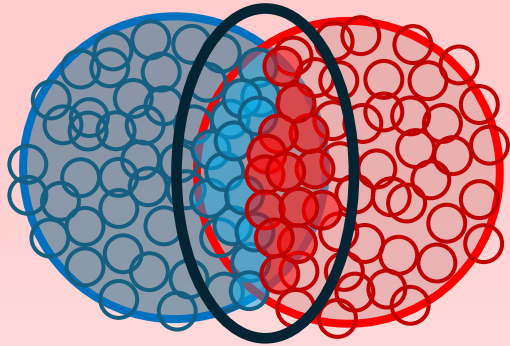
Either what we thought were signatures were in fact not exclusive signatures (that is sure thing for some signatures)

or maybe a droplet of deconfined matter is created in smaller systems ??

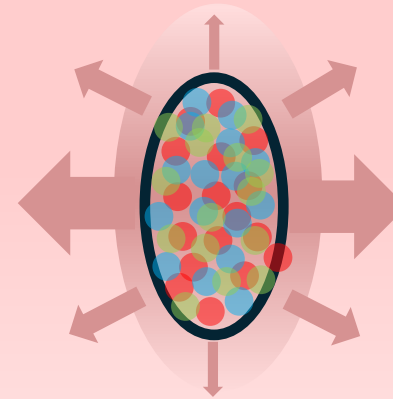
Anyway, interesting physics to be understood !

Anisotropic flow illustrated with heavy-ion collisions....

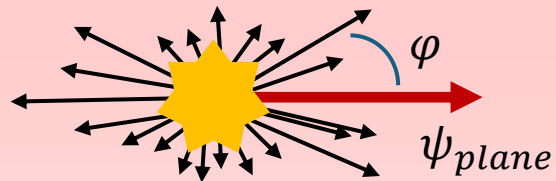
1 Initial spatial asymmetry



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

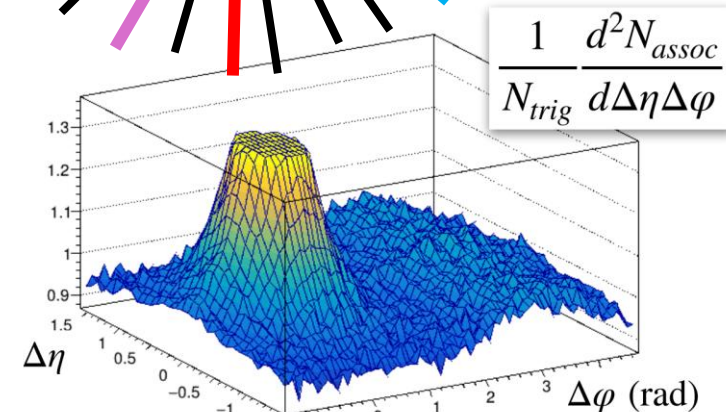
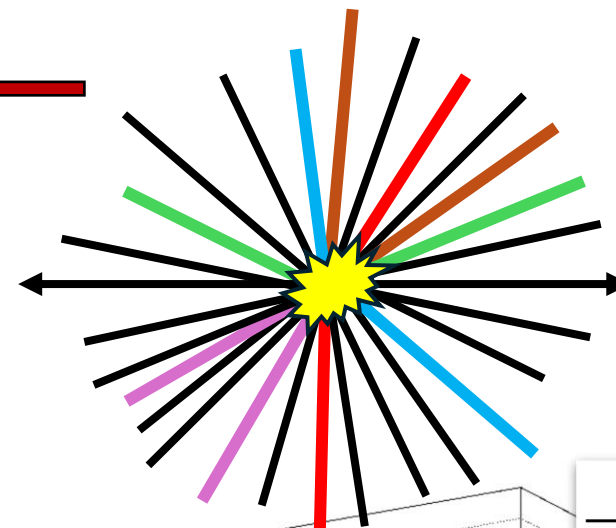
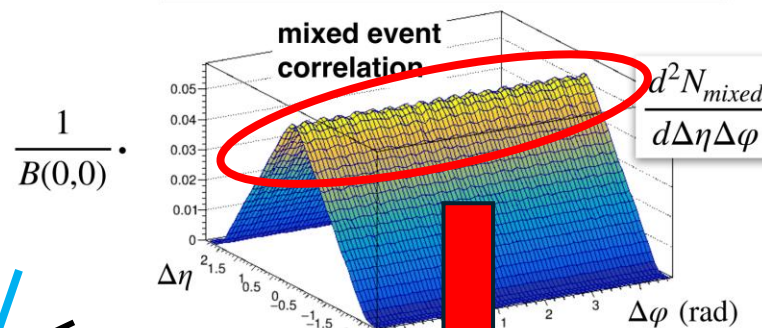
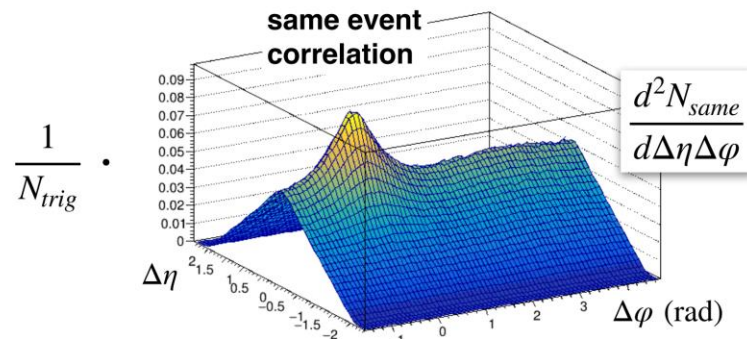
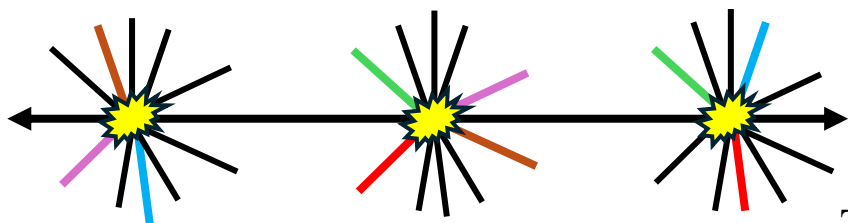
The paper that started it all:
<https://doi.org/10.1103/PhysRevD.46.229>

Two-particle correlations

How to get two-particle azimuthal correlations ?

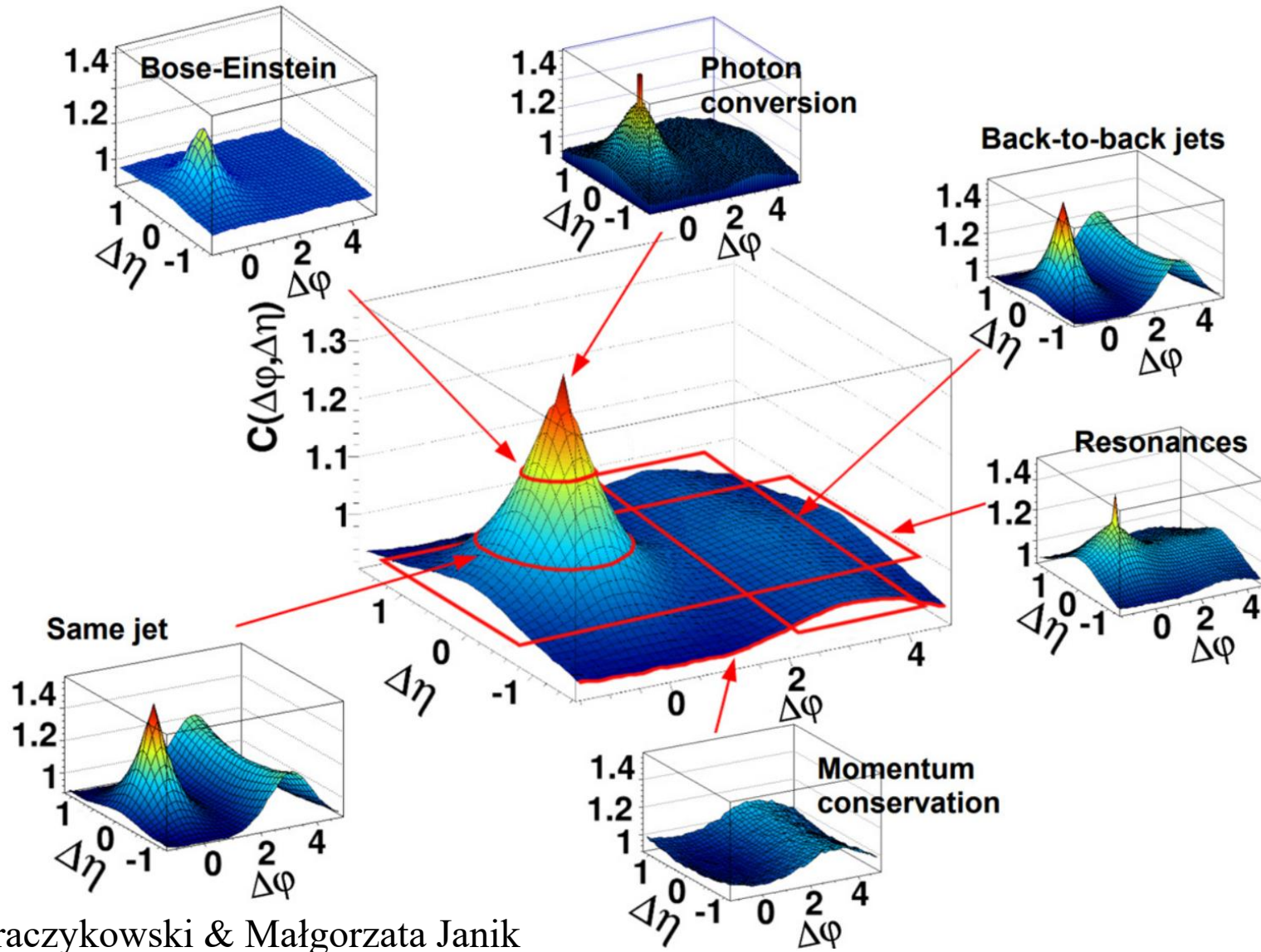
The correlation function :

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



This typical triangular shape is caused by the limited detector acceptance

Understanding the 2D correlation function

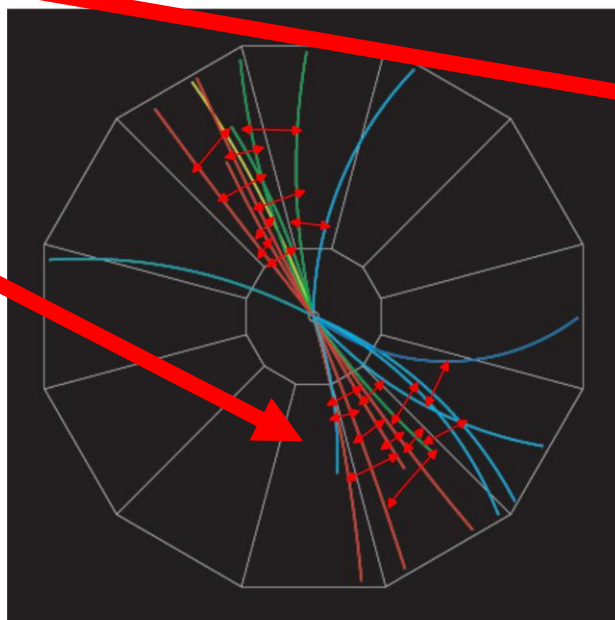
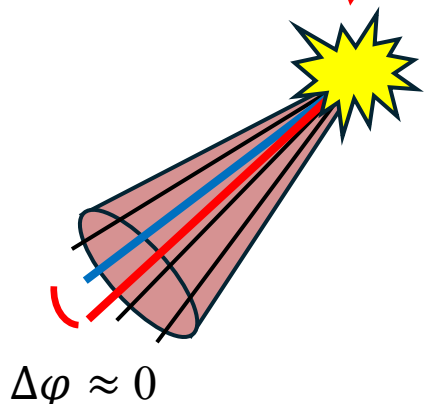
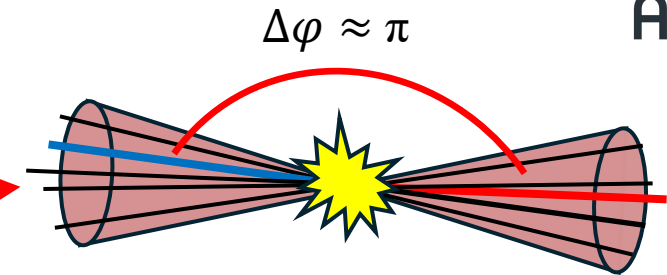
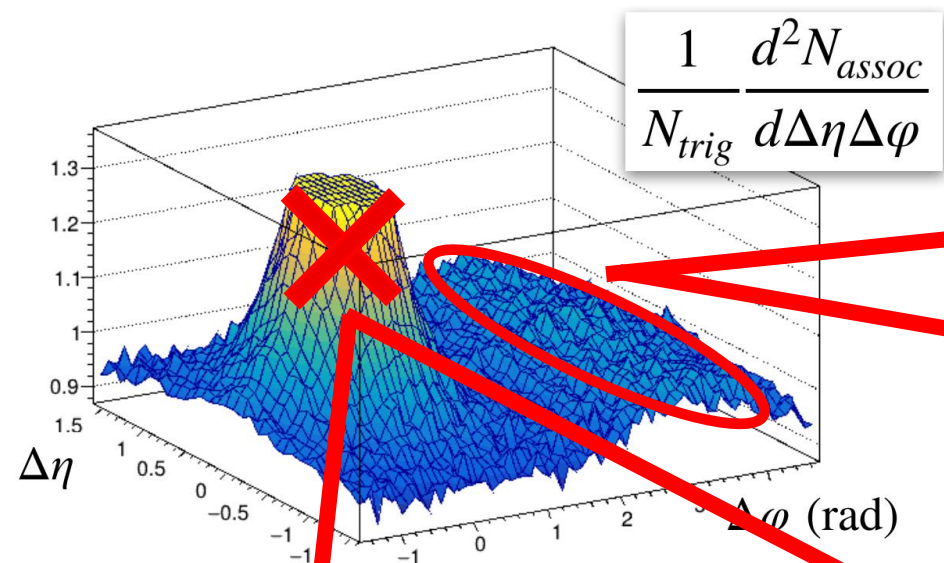


credits : Łukasz Graczykowski & Małgorzata Janik

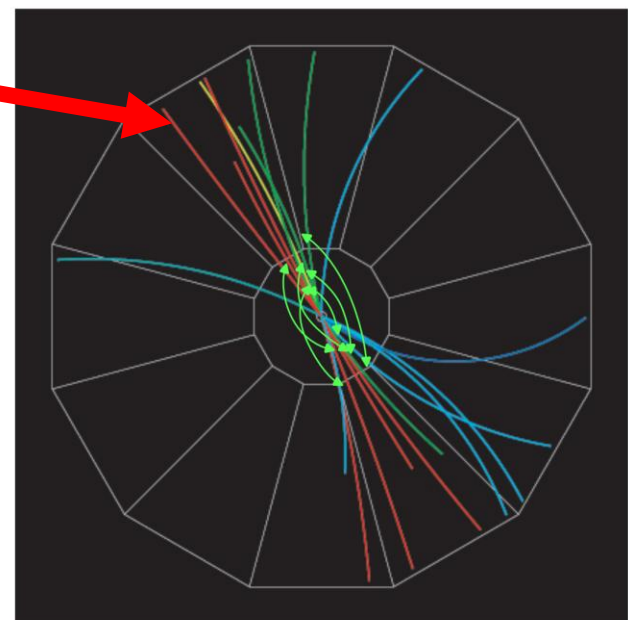
What is our interest in the 2D correlation function ?



ALICE



pp event in STAR Exp.
 Particles from the same jet at low $\Delta\eta\Delta\phi$ form the **near-side peak**
 credits : Jasper Parkkila

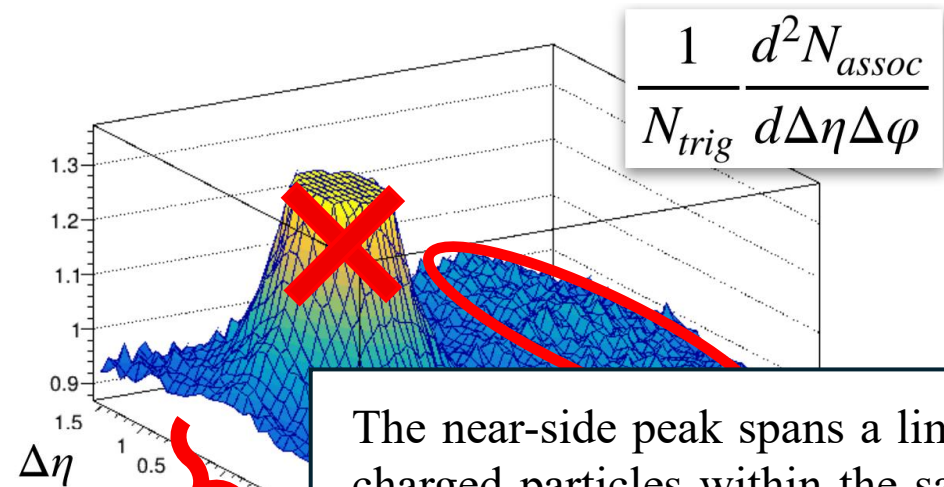
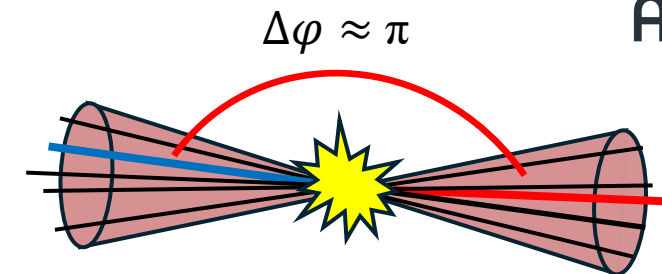


Particles from back-to-back jets at $\Delta\phi \sim \pi$ form the **away-side peak**

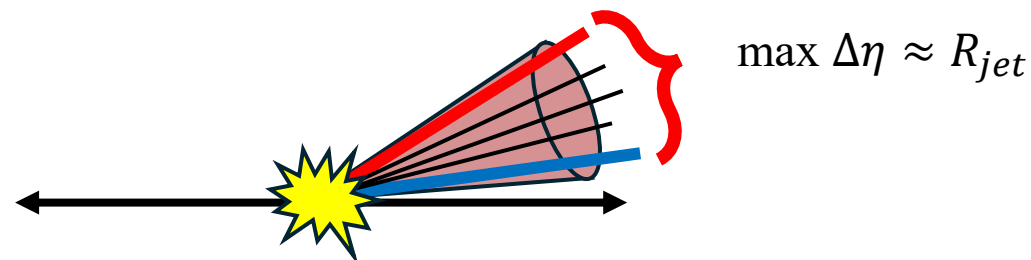
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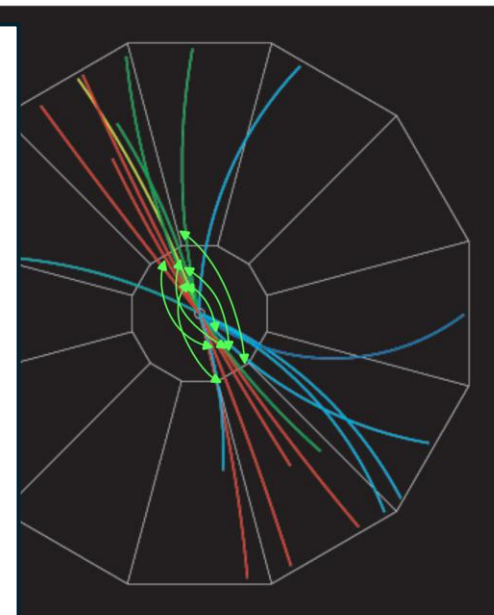
ALICE



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

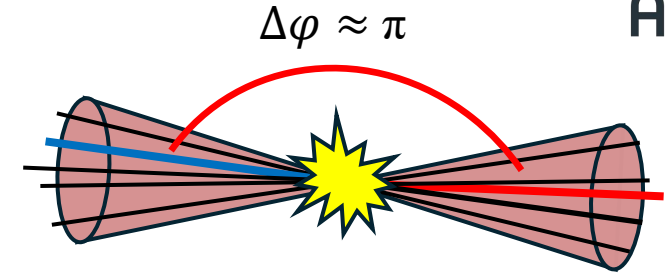
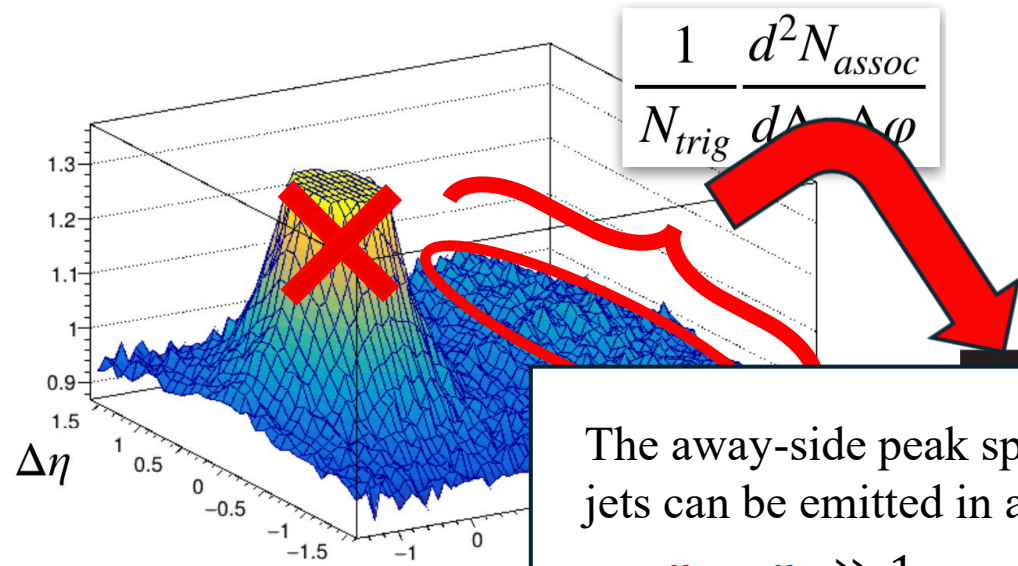


Tracks from back-to-back jets at $\Delta\phi \approx \pi$ form the **away-side peak**

credits : Jasper Parkkin

$\Delta\phi \approx 0$

What is our interest in the 2D correlation function ?

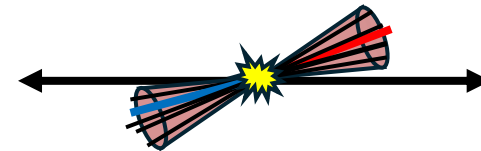


The away-side peak spans the whole $\Delta\eta$ range because opposite jets can be emitted in a variety of η range :

$$\eta_1 - \eta_2 \gg 1$$

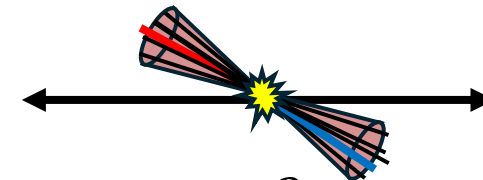


$$\eta_1 - \eta_2 \approx 2$$

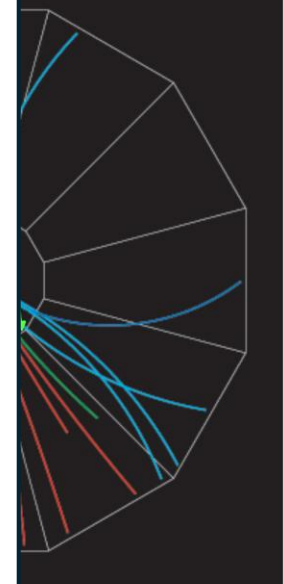
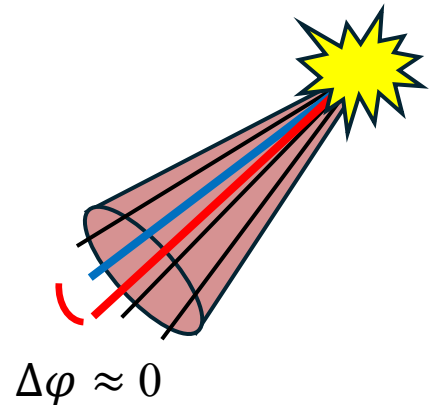
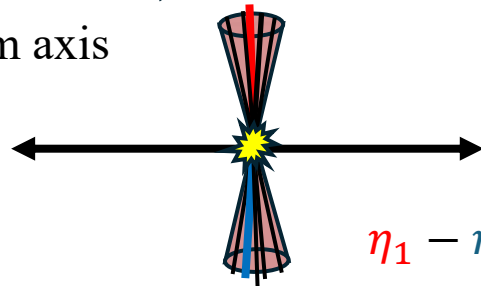


← → = beam axis

$$\eta_1 - \eta_2 \approx -2$$



$$\eta_1 - \eta_2 \approx 0$$



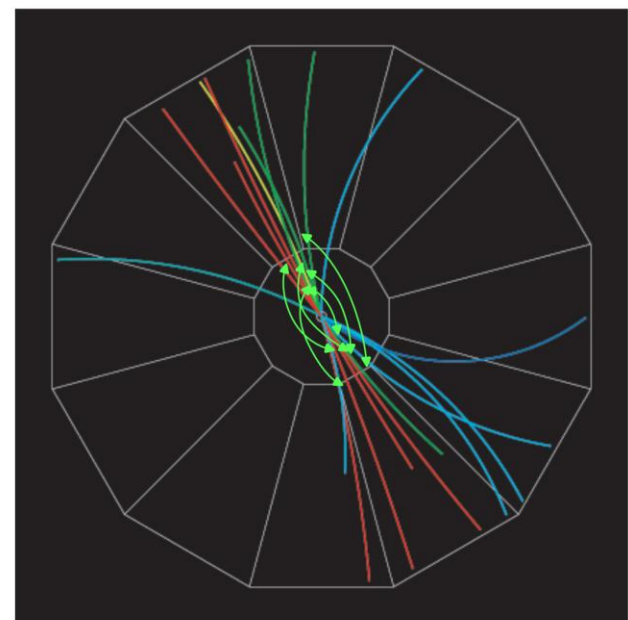
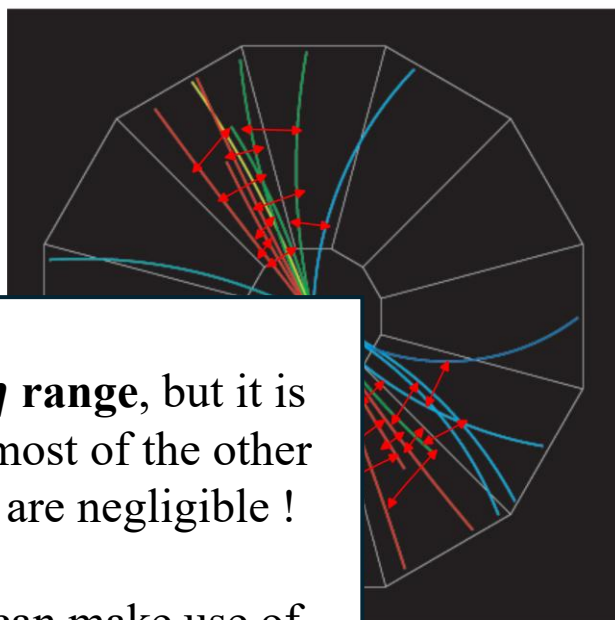
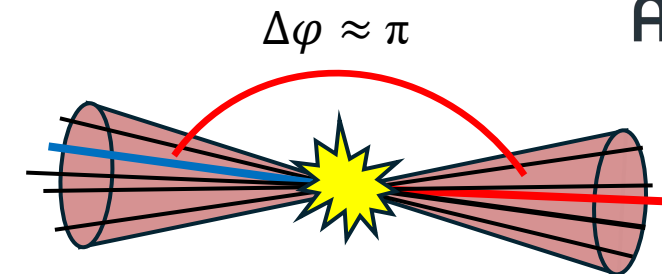
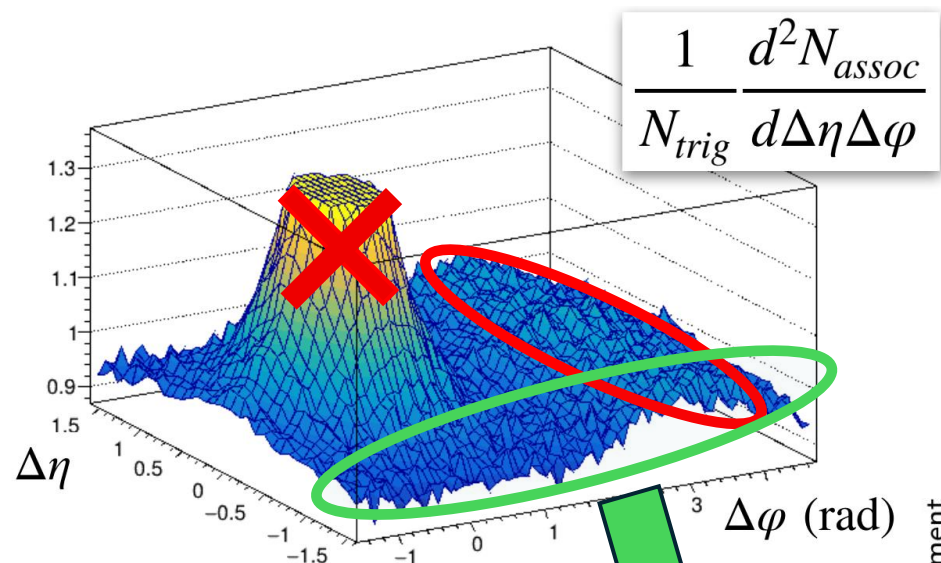
to-back jets at away-side peak

credits : Jasper Parkkin

What is our interest in the 2D correlation function ?

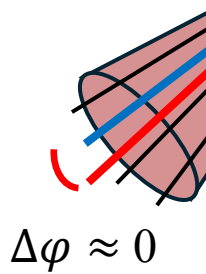


ALICE



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 !



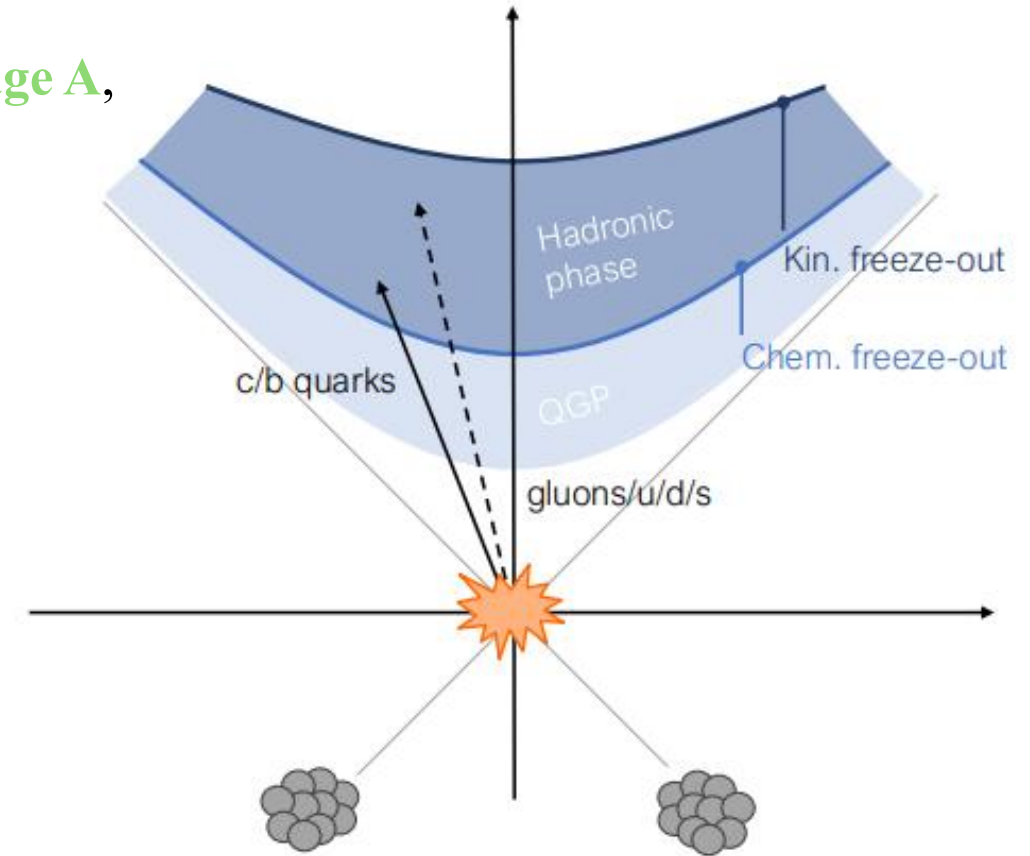
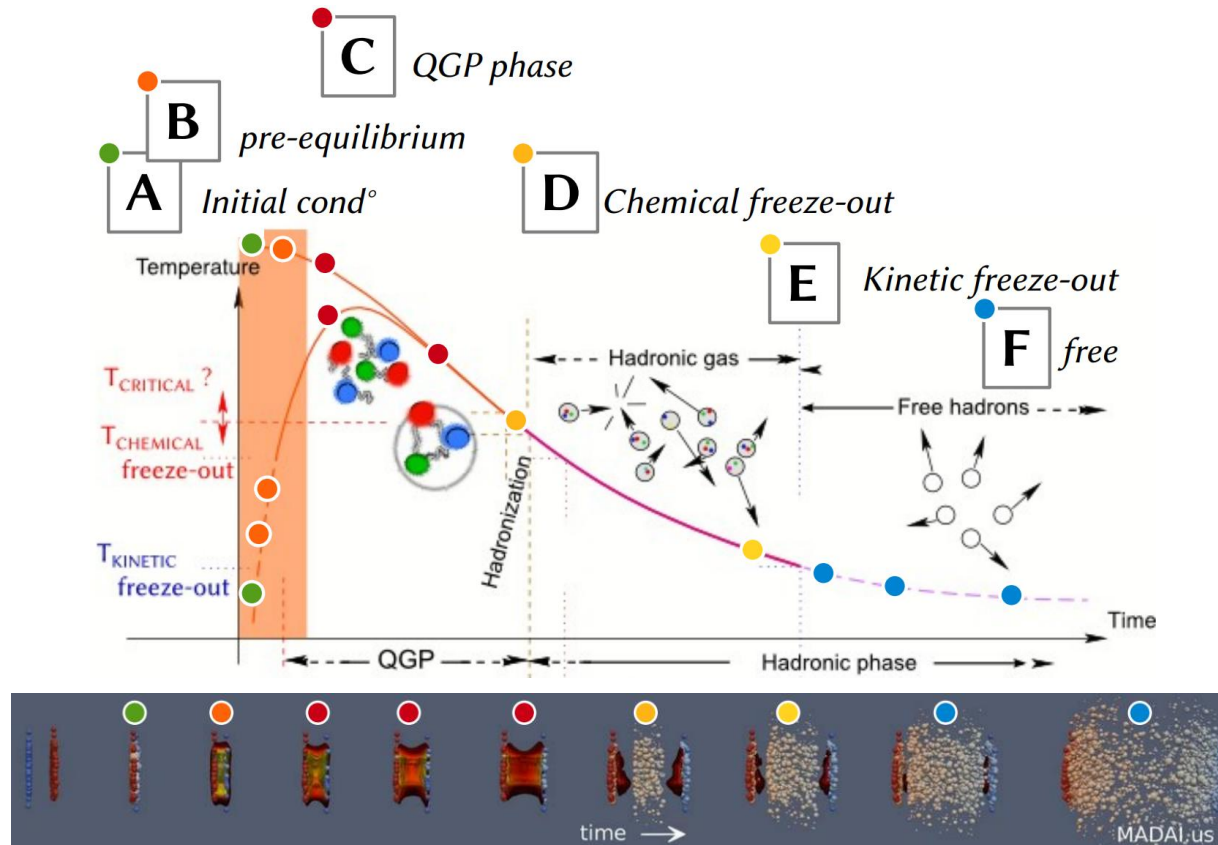
same jet at low $\Delta\phi$ forms the **near-side peak**

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

Why studying heavy flavor ?

Heavy flavor (charm, beauty) = hard probes !

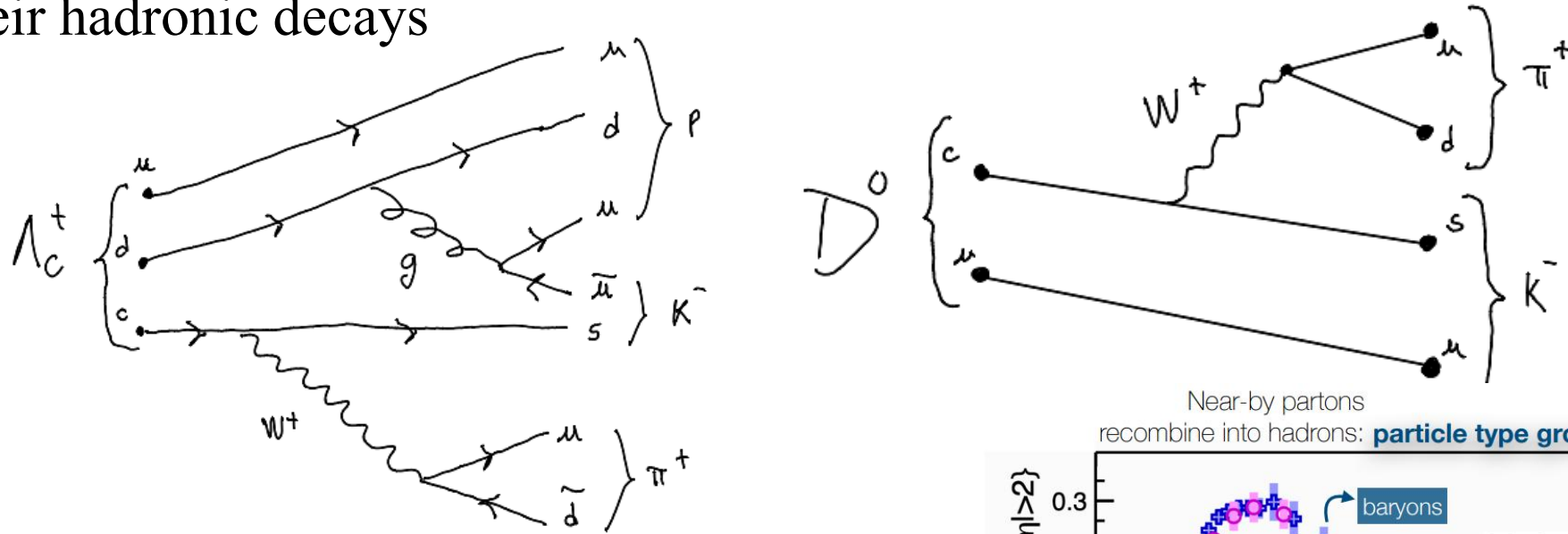
(= coming from energetic processes at very early collision **stage A**, which will later experience fully the medium)



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 !

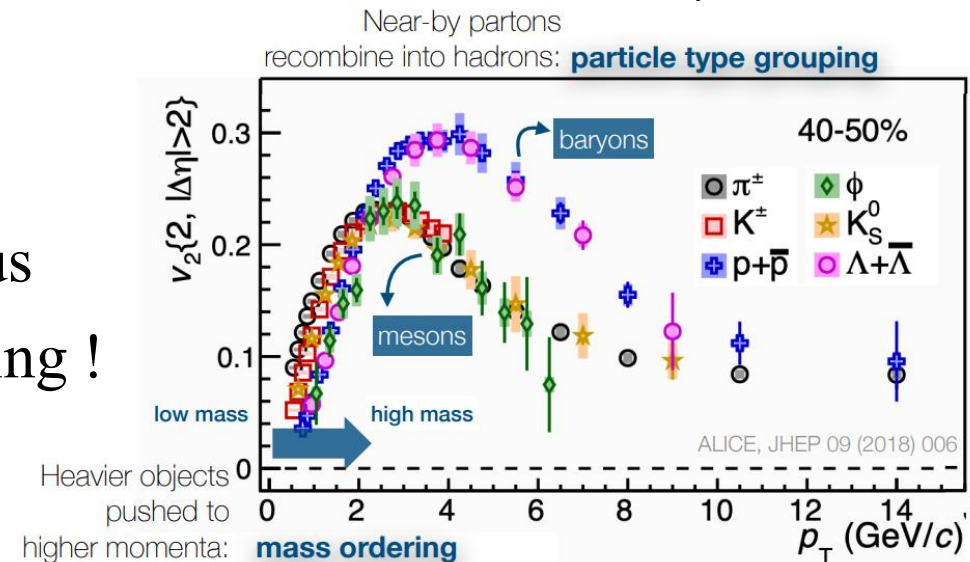


Figure from Katka's JCF seminar on 10/11/2023

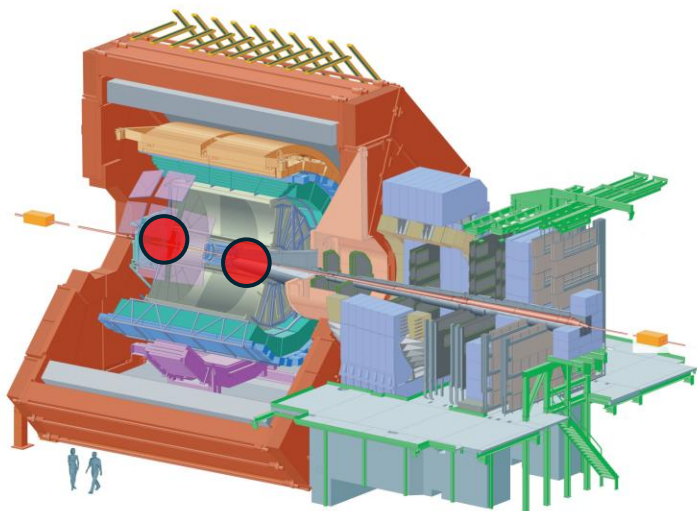
The ALICE detector

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](https://arxiv.org/abs/2308.16590)

ALICE during RUN 3

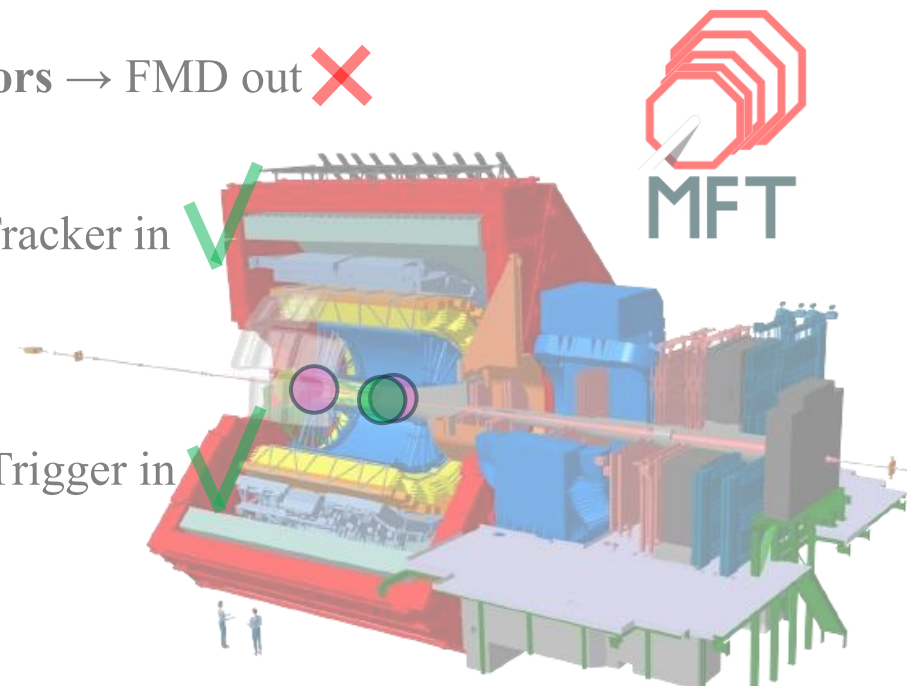
ITS → 7 layers and 1st layer closer to interaction point

TPC → Gas Electron Multipliers + continuous readout

Forward detectors → FMD out ✗

●
Muon Forward Tracker in
(one side only)

●
Fast Interaction Trigger in
(both sides)



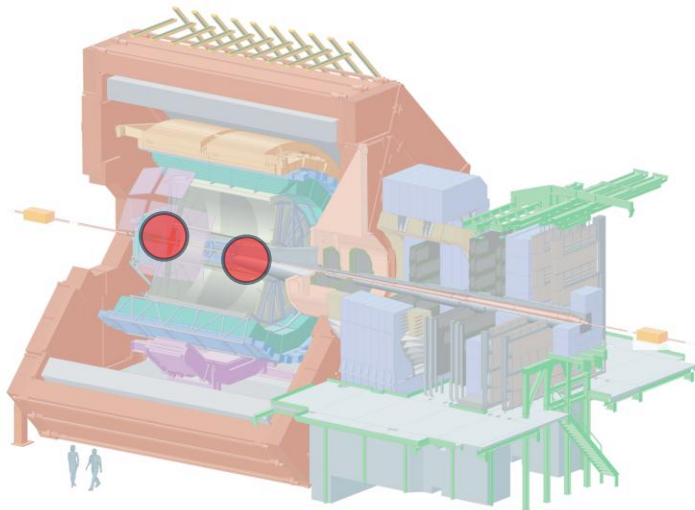
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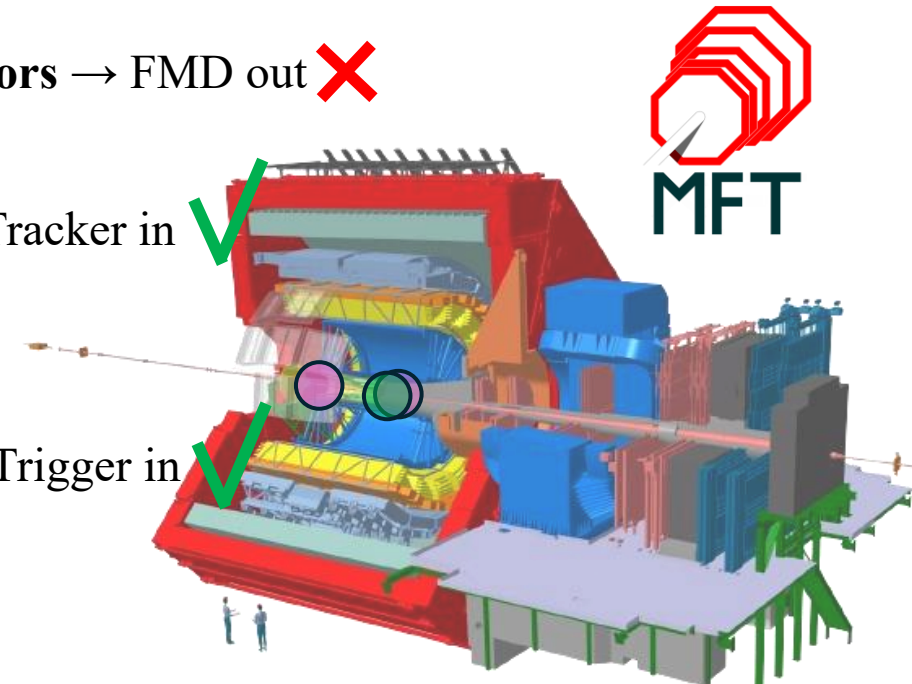
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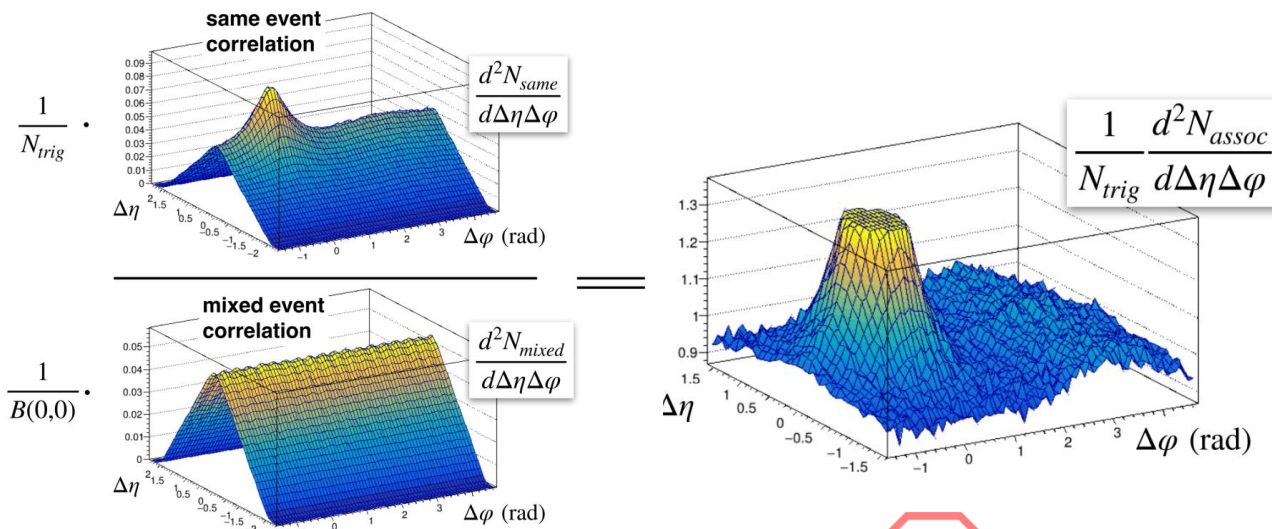
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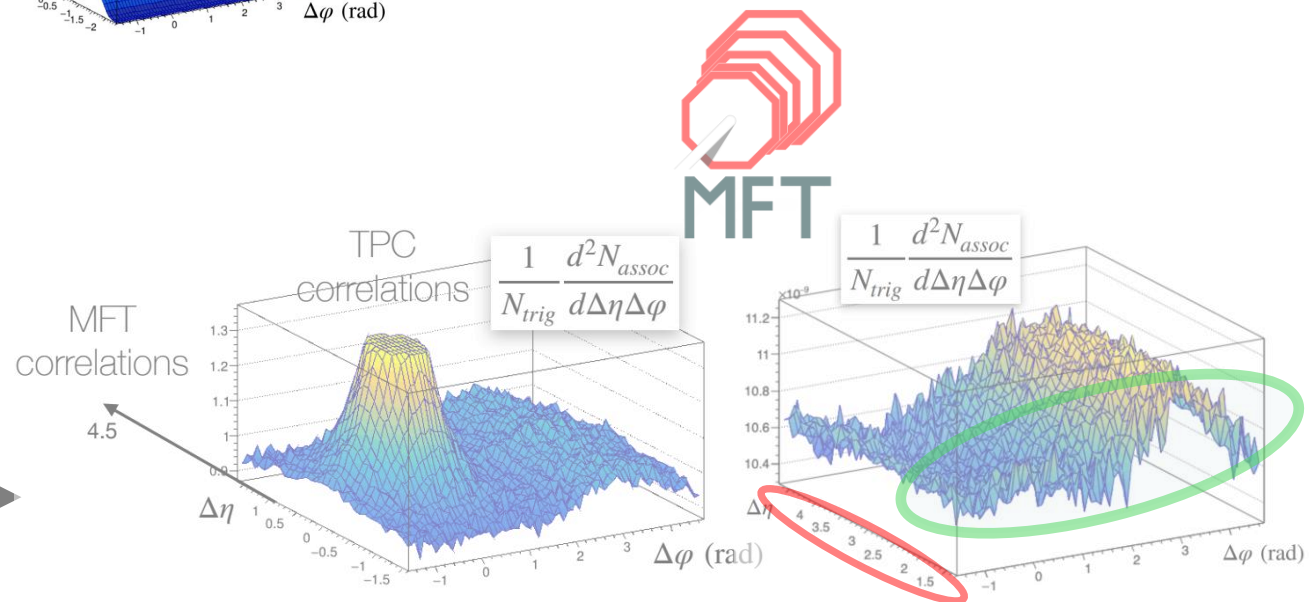
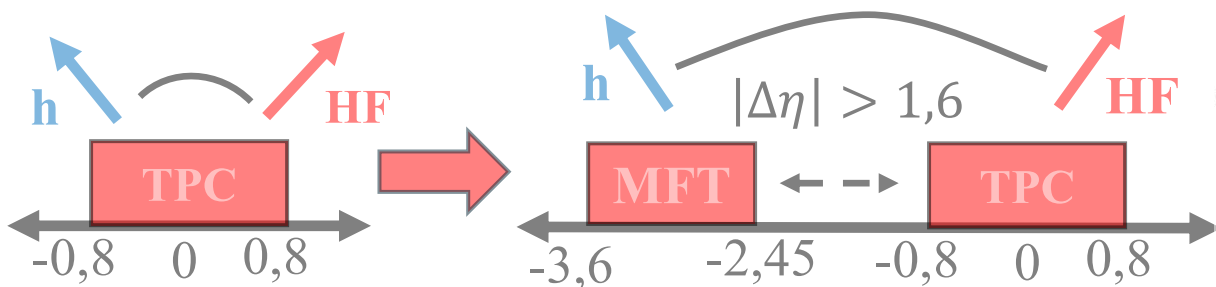


Analysis procedure (I)

1. Get two-particle azimuthal correlation

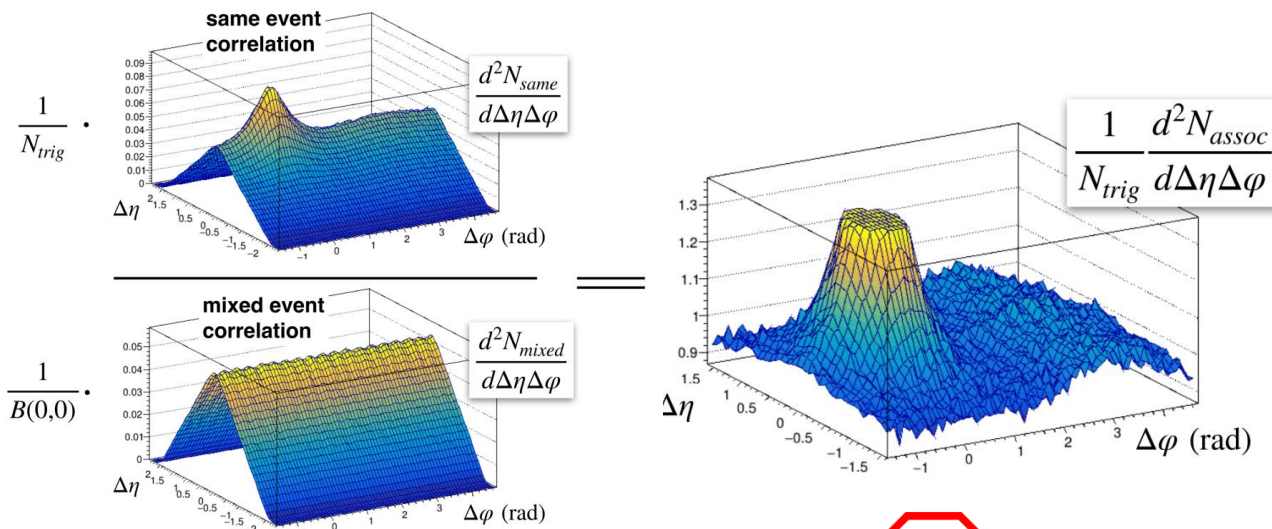


2. Remove jet-peak apply $\Delta\eta > 1.4$ and project on $\Delta\phi$

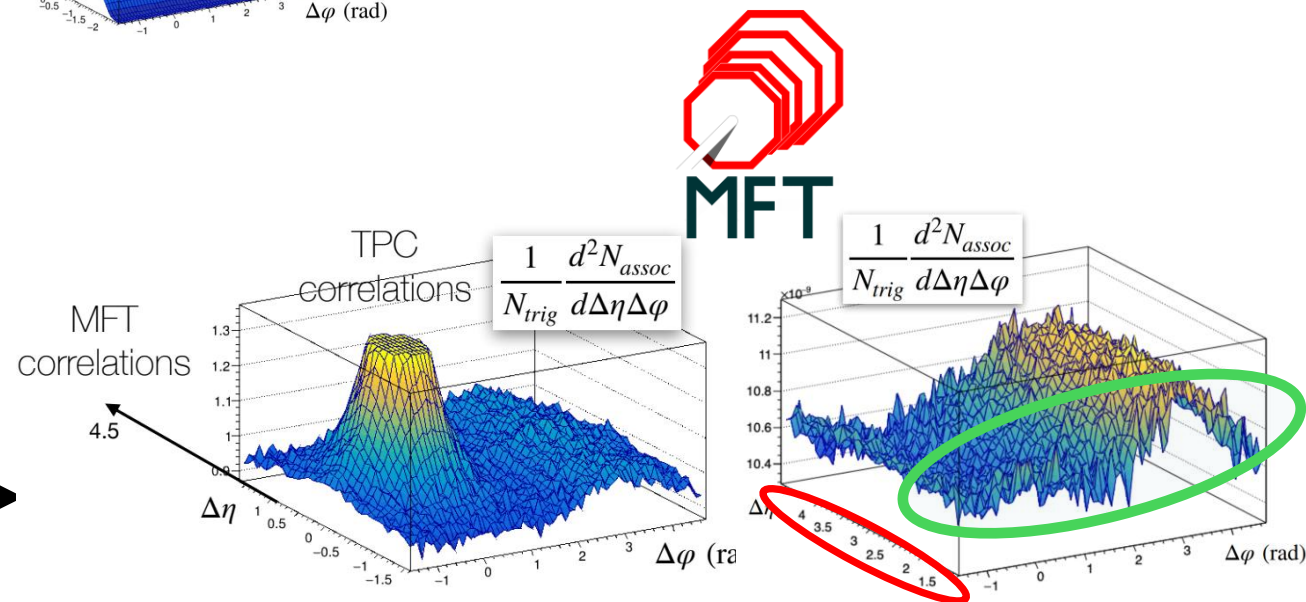
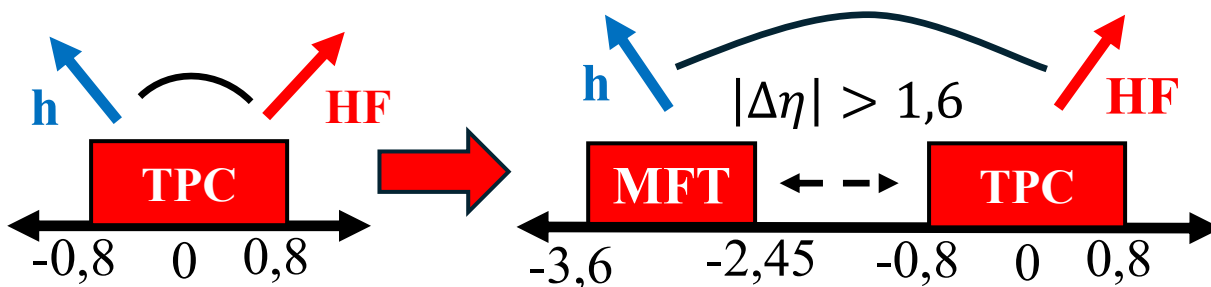


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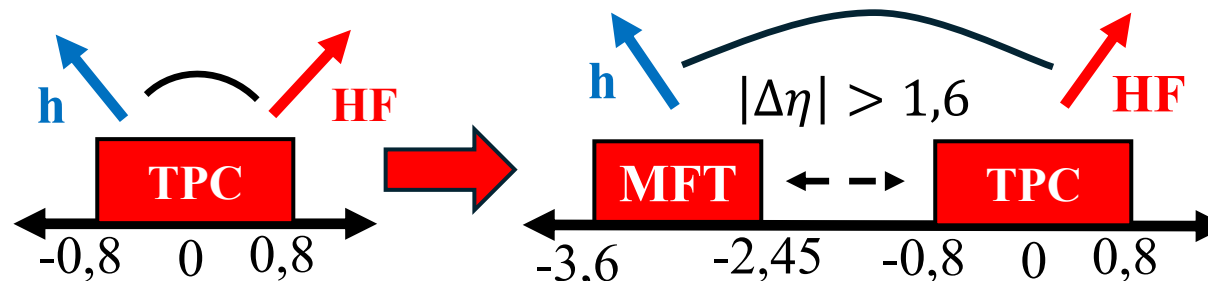


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Why using MFT for correlations ?

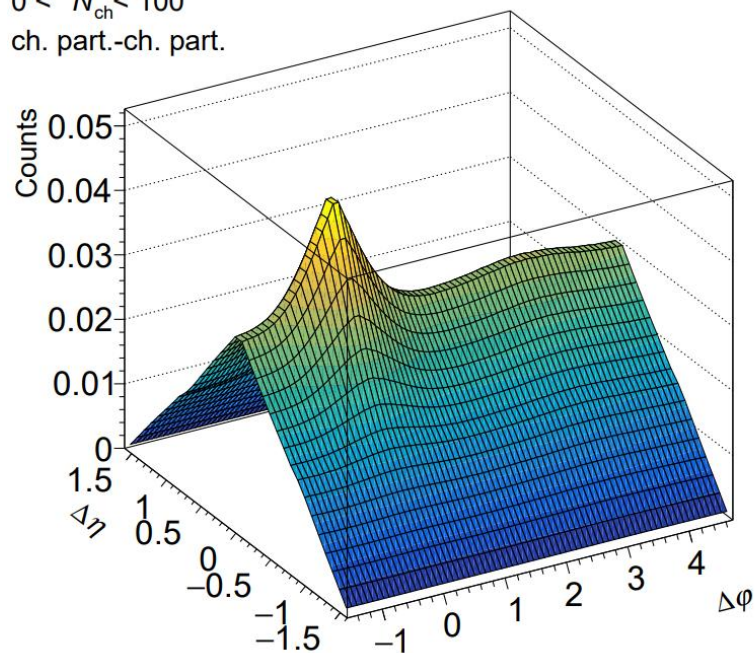
Remove jet-peak apply $\Delta\eta > 1.4$
and project on $\Delta\phi$



ALICE Performance

pp, $\sqrt{s} = 13.6$ TeV
 $0 < N_{ch} < 100$
ch. part.-ch. part.

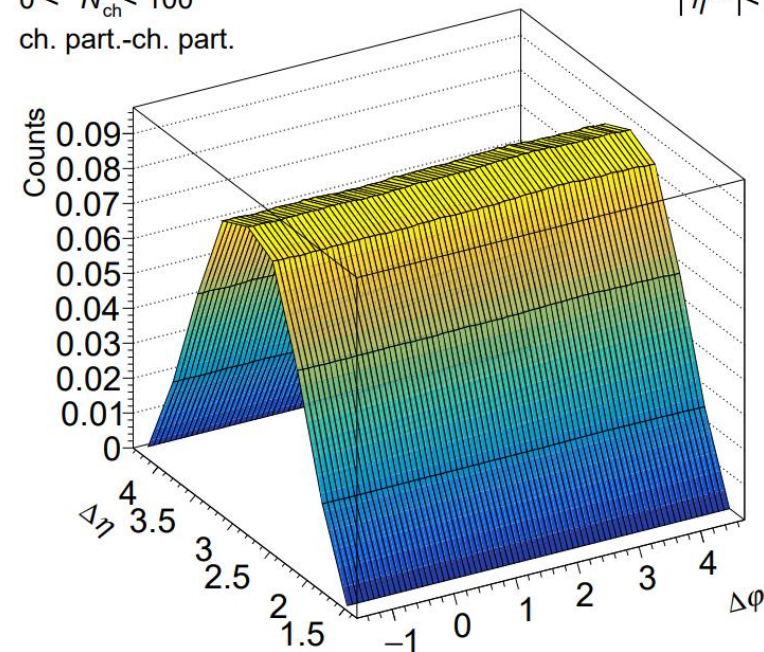
$p_T^{trig}, p_T^{assoc} > 0.2$ GeV/c
 $|\eta^{trig,assoc}| < 0.8$



ALICE Performance

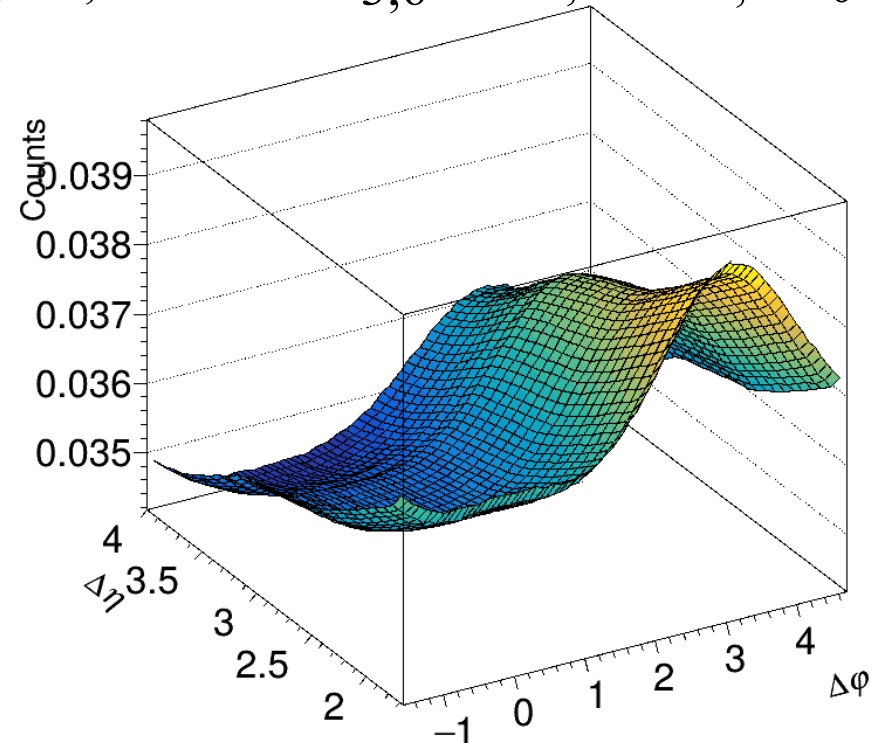
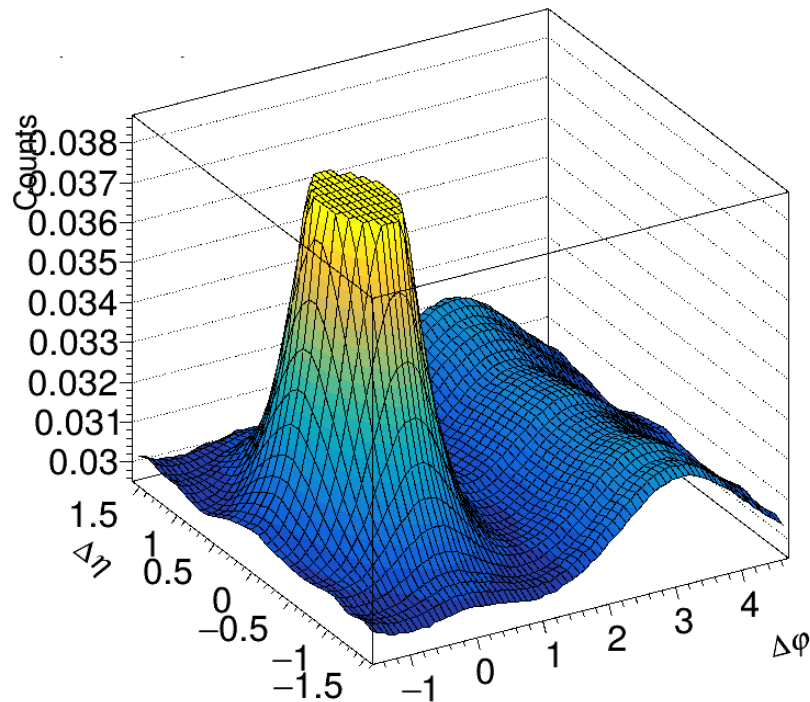
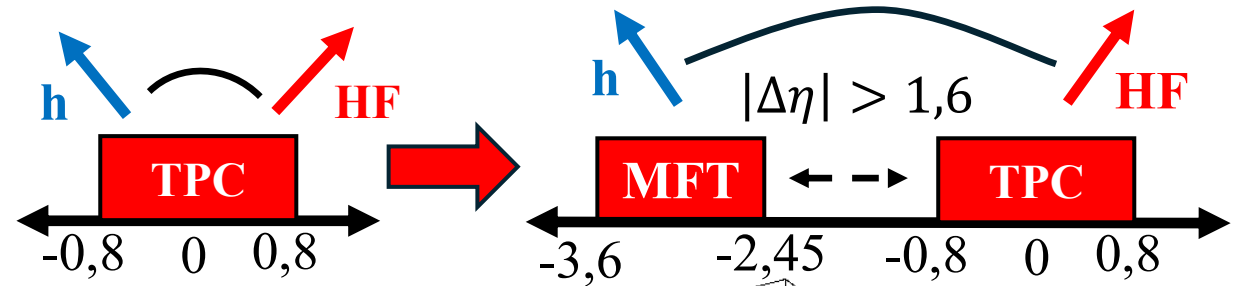
pp, $\sqrt{s} = 13.6$ TeV
 $0 < N_{ch} < 100$
ch. part.-ch. part.

$p_T^{trig}, p_T^{assoc} > 0.2$ GeV/c
 $-3.36 < \eta^{assoc} < -2.4$
 $|\eta^{trig}| < 0.8$



Why using MFT for correlations ?

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



One consequence of using MFT for correlations

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

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

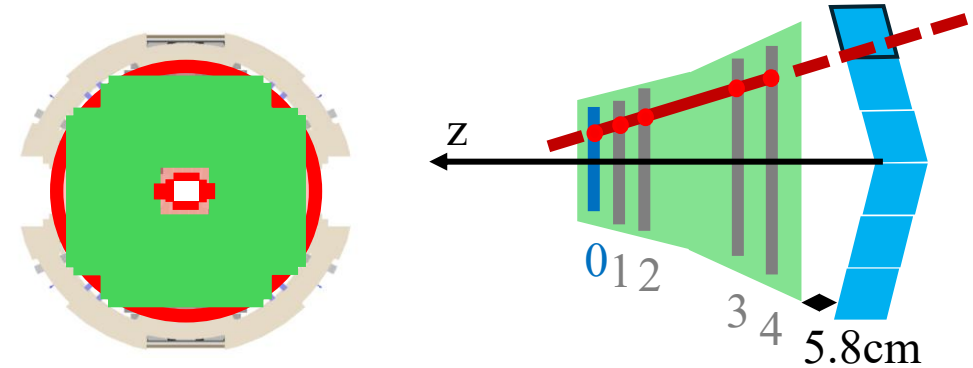
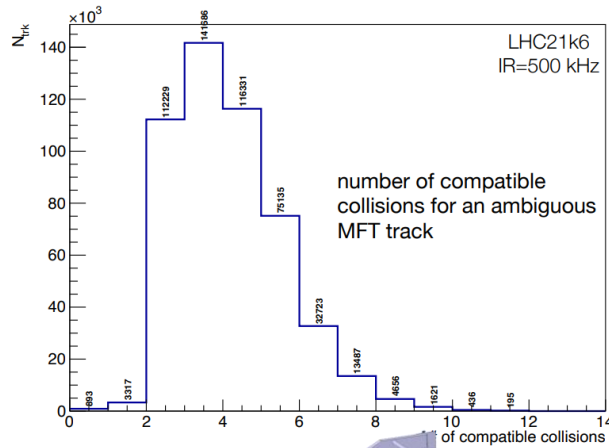
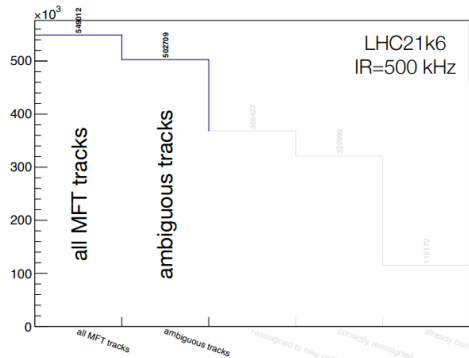
« 3x2PC » method first used in PHENIX : [Phys. Rev. C 105, 024901 \(2022\)](#)

Challenges (problems) of MFT

A potential problem with MFT tracks

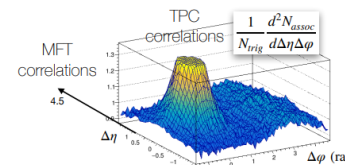
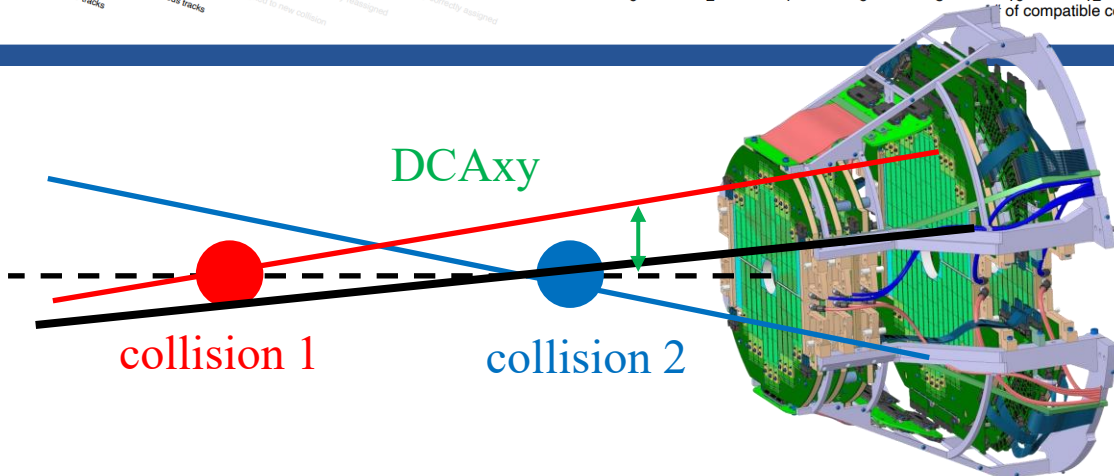
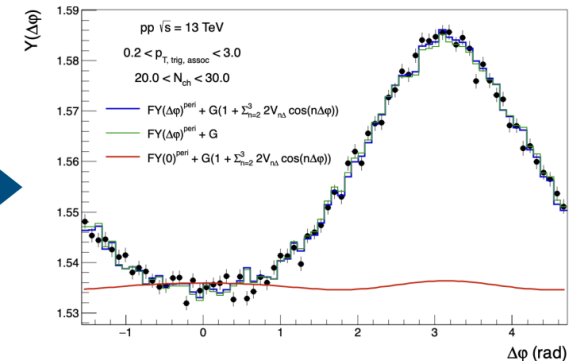
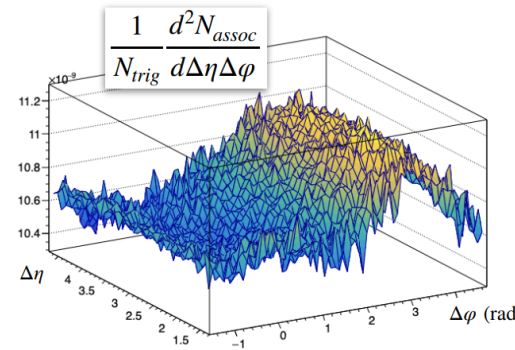
- MFT read-out time: 4 - 15 μ s
- Interaction rate of 500 kHz \rightarrow 1 collision every 2 μ s
- MFT track would be **compatible** in time with **2 - 7 collisions** on average

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



How much should we be worried (I)

Ideal case: MC simulations

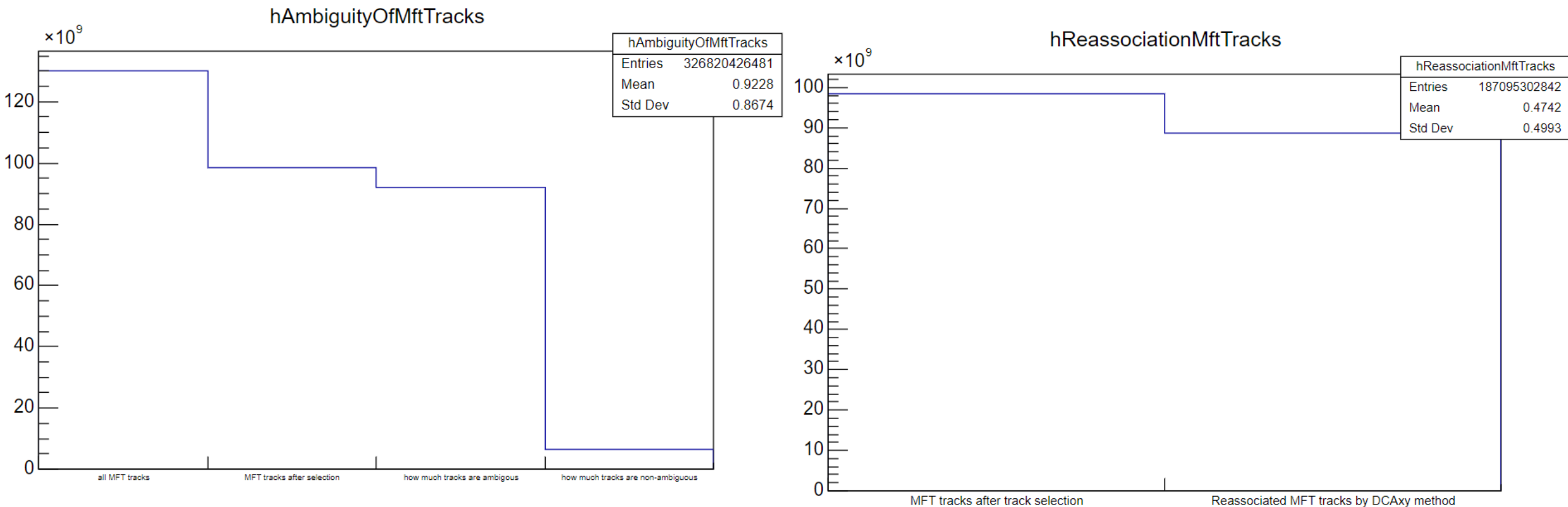


- Correlations far from the jet peak contamination
- We can use (almost) all the available statistics
- Note: this is Pythia, so don't look for meaningful flow signal :)

credits : Katka/Sarah Hermann et al.

MFT track reassociation, ambiguity in pp

- Ran over LHC22o_apass7_minBias_medium, 5 min clusters
- ~90% ambiguous tracks, 90% of ambiguous tracks get reassociated to a new coll.



Analysis procedure



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

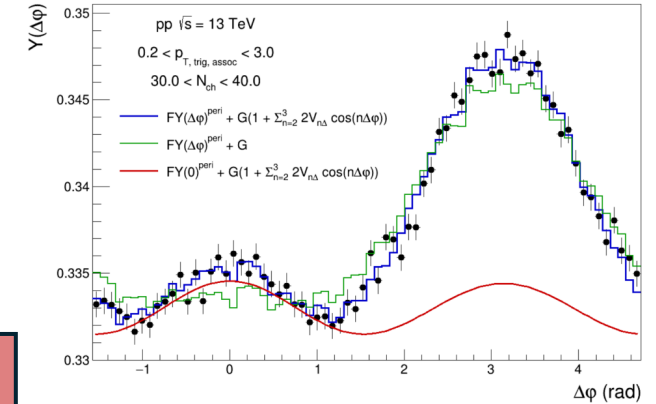
3. Perform template fit

$$\gamma_{\text{template}}(\Delta\varphi) = F \cdot \gamma_{\text{peripheral}}(\Delta\varphi) + \gamma_{\text{ridge}}(\Delta\varphi)$$

Our measurement

Non-flow component

Collective flow component



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

4.

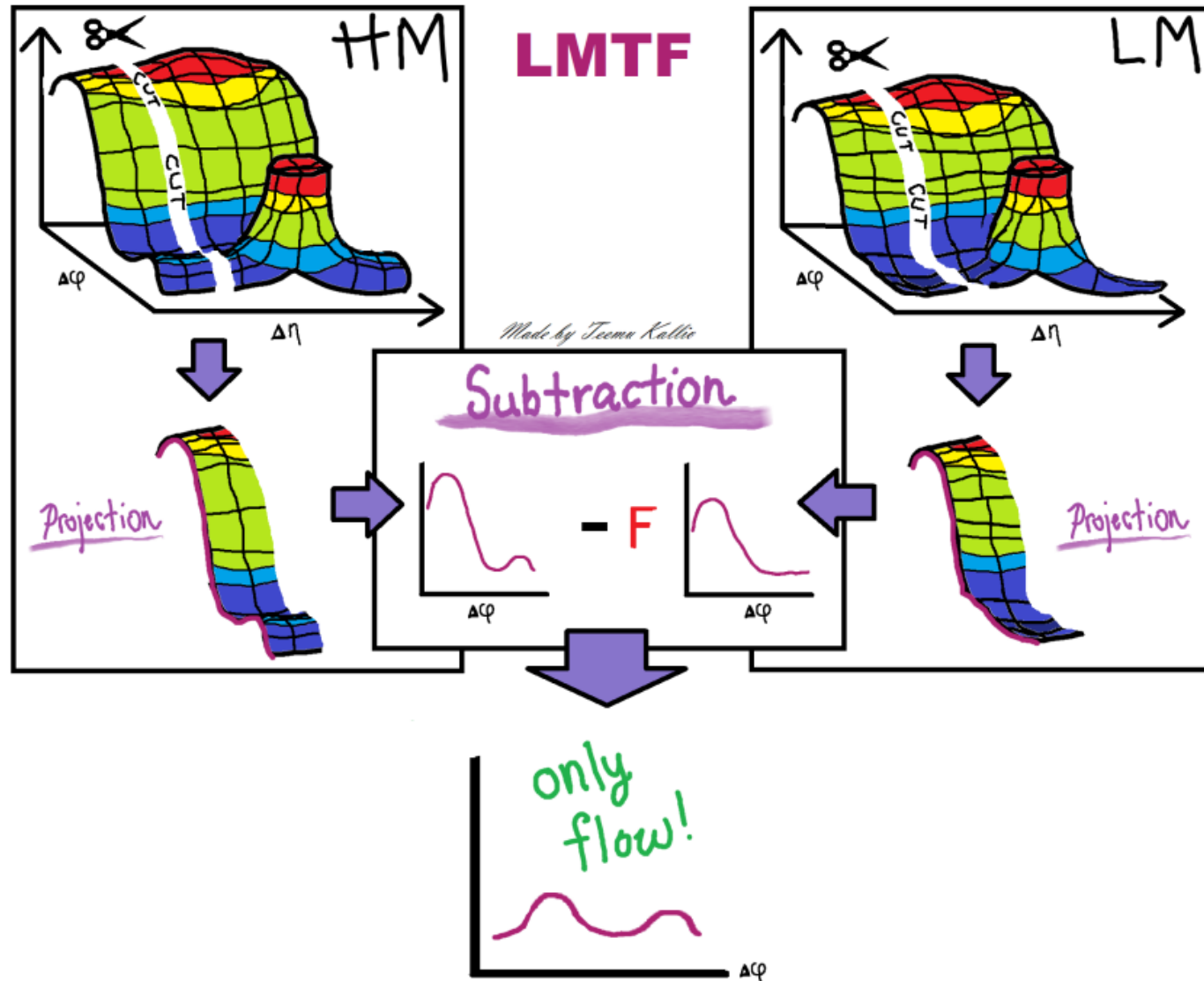
Get differential flow

Repeat for TPC-FV0 and MFT-FV0 !

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

Same formula for ch. part. – ch. part. correlations

Template fit a nice scheme to understand more easily ☺



scheme credits : Maxim Virta

Analysis procedure



ALICE

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



3. Perform template fit

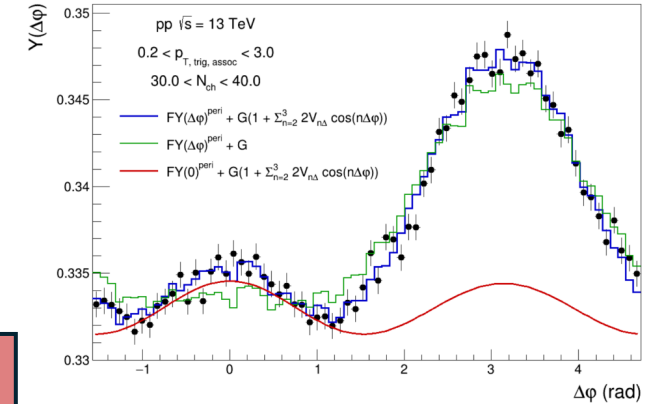


$$\gamma_{\text{template}}(\Delta\varphi) = F \cdot \gamma_{\text{peripheral}}(\Delta\varphi) + \gamma_{\text{ridge}}(\Delta\varphi)$$

Our measurement

Non-flow component

Collective flow component



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



4.

Get differential flow

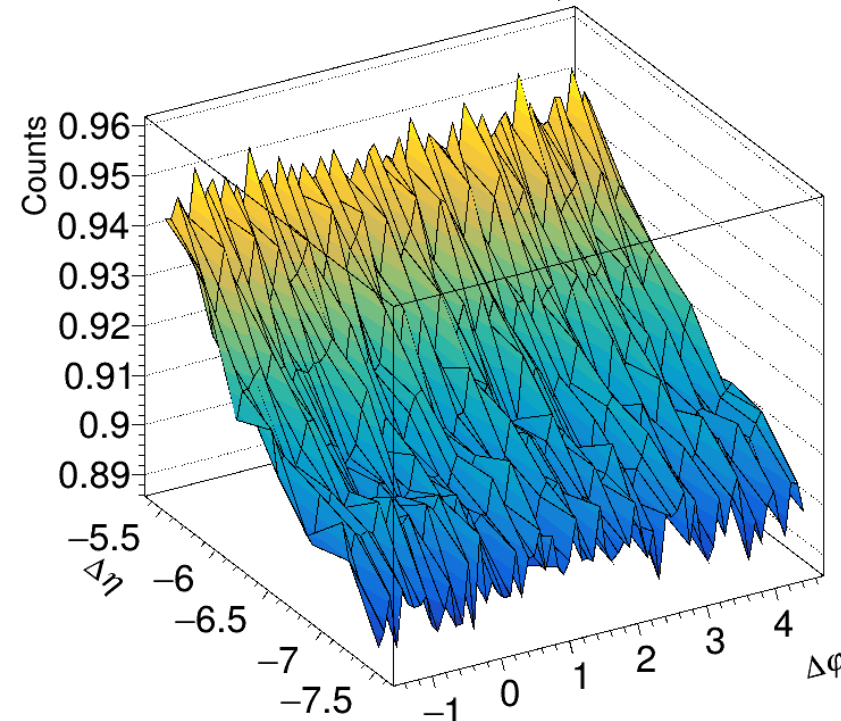
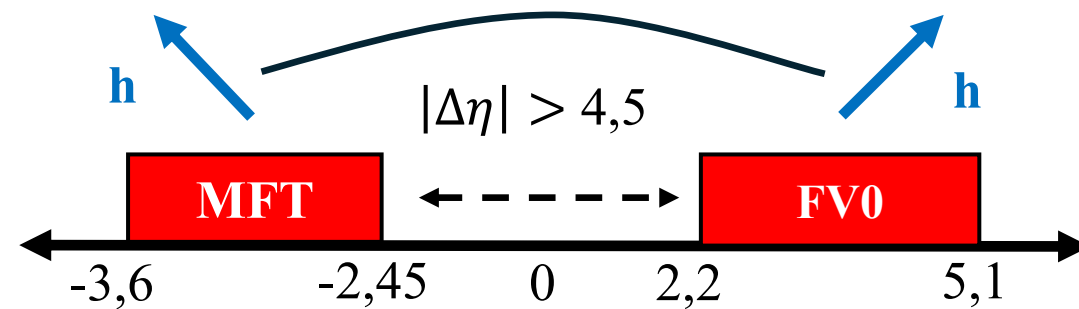
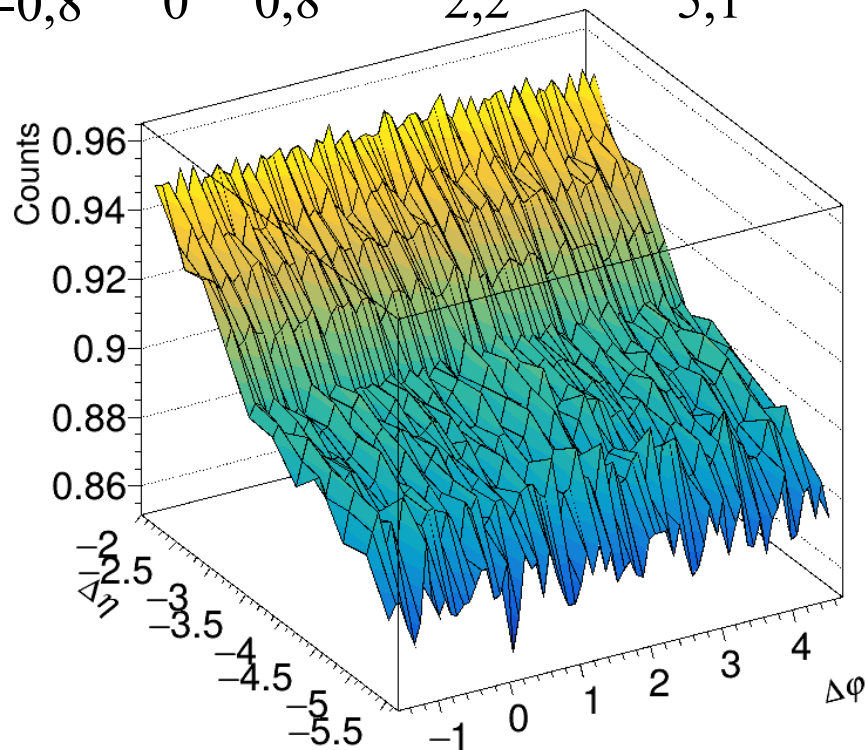
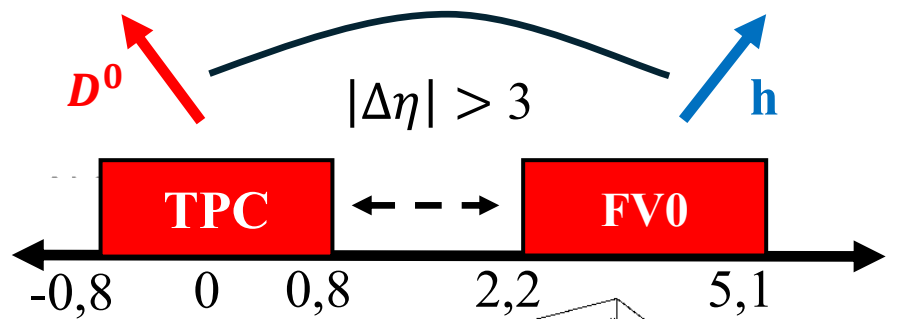
Repeat for TPC-FV0 and MFT-FV0 !

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

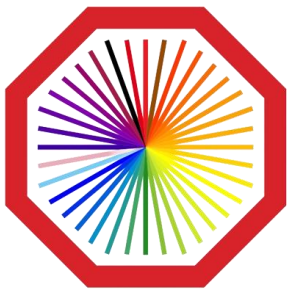
Same formula for ch. part. – ch. part. correlations

TPC-FV0 and MFT-FV0 correlations

Local results thus low statistics and also low multiplicity results (10-20)

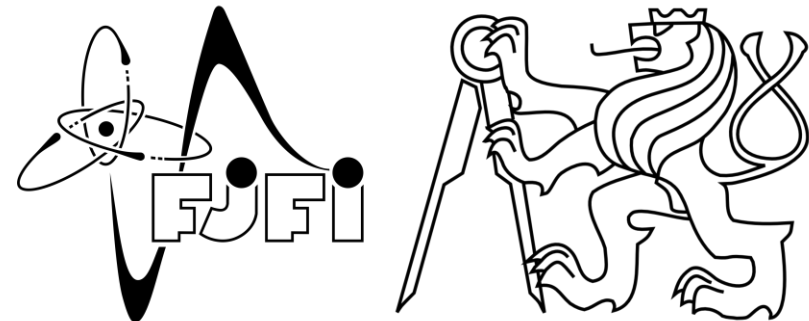


- Collectivity in small systems is a very dynamic field (especially lately with the light ions runs at the LHC)
- I am using heavy flavor probes to try to study it, using what seems to be the best methods (long-range flow + template fit), but recently I joined forces with other ALICE analyzers planning to do a quick light ion analysis, without the HF part
- Using MFT specifically is a challenge (to stay polite), let's hope it will be worth it
- I should have showed you some v_2 results, however I cannot run a hyperloop train properly so this is for next time



ALICE

BACK UP



Template fit the principles detailed...

Perform template fit

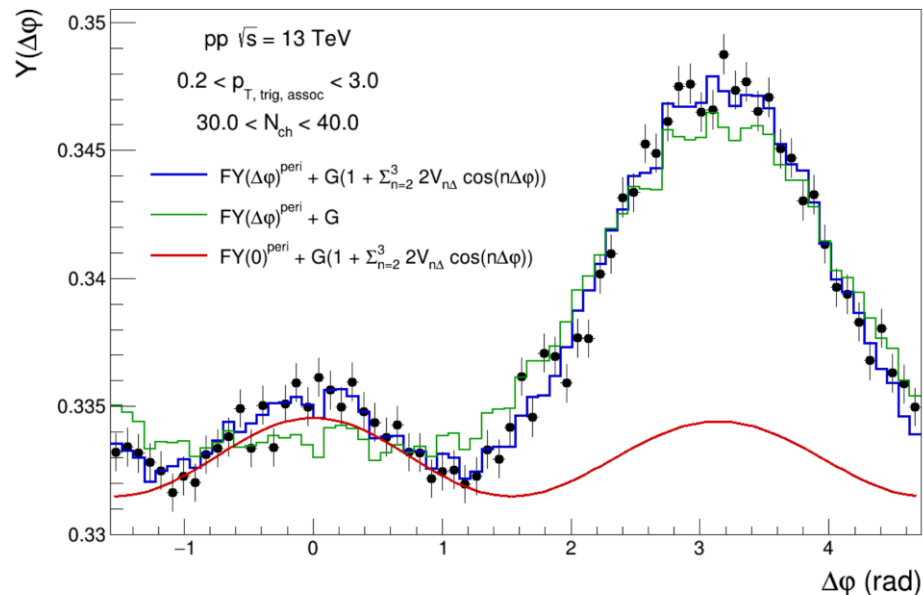
$$Y^{template}(\Delta\varphi) = F \cdot Y^{peripheral}(\Delta\varphi) + Y^{ridge}(\Delta\varphi)$$

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

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