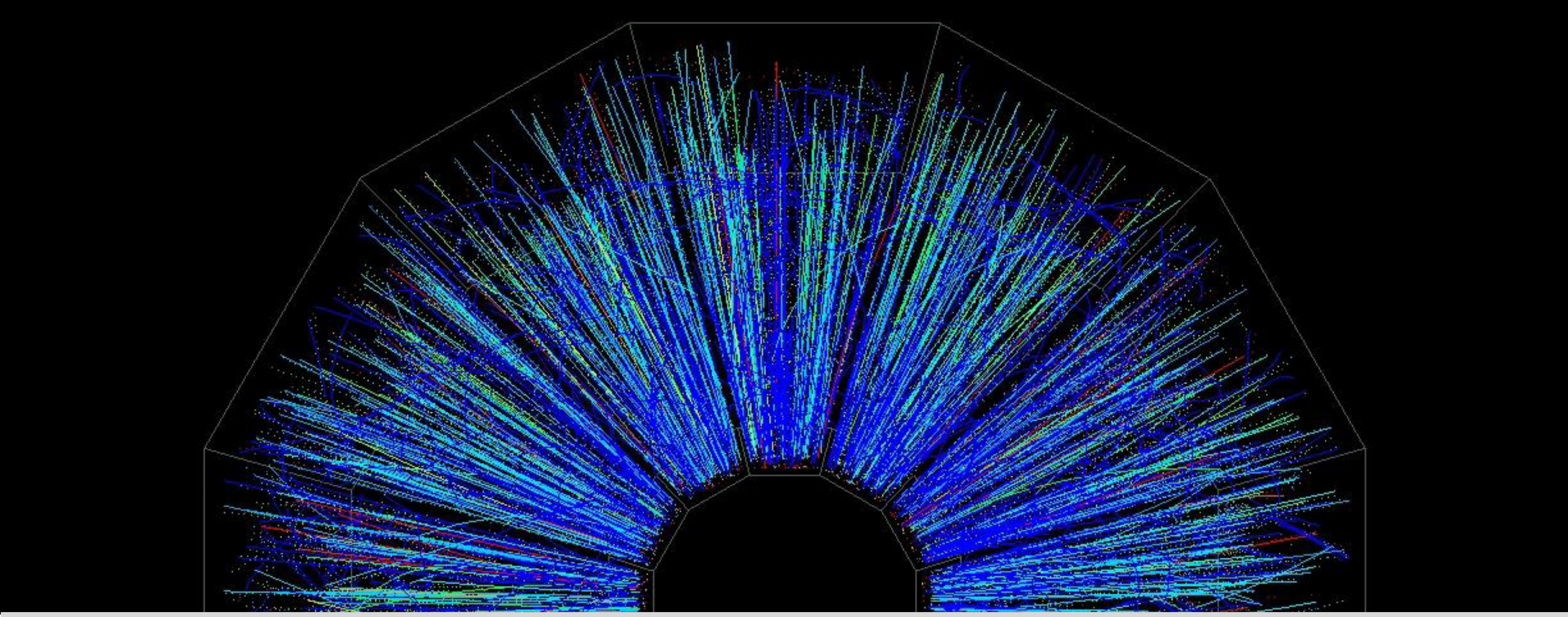

# Effects of cold nuclear matter on charm meson production

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Czech Technical University in Prague

Standard Model and Quantum Chromodynamics
8.10. – 9.10.2018, Prague

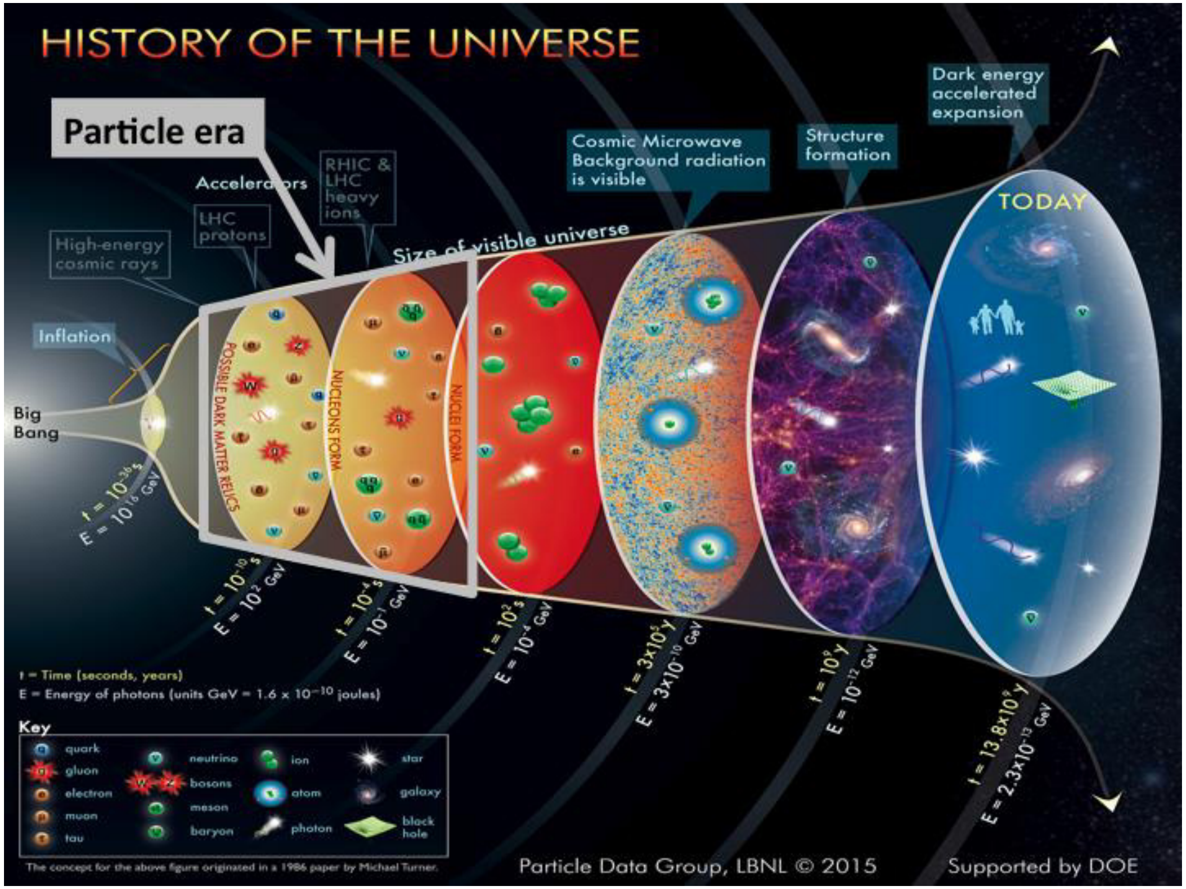
FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

# Content

- Probing quark-gluon plasma
- Cold nuclear matter effects
- Measured observables in pA and AA collisions
- The **S**olenoid **T**racker **A**t **R**HIC
- $D^0$ reconstruction with the TMVA Boosted Decision Trees in d+Au

# Quark-gluon plasma

- Hot and dense nuclear matter composed of deconfined quarks and gluons.



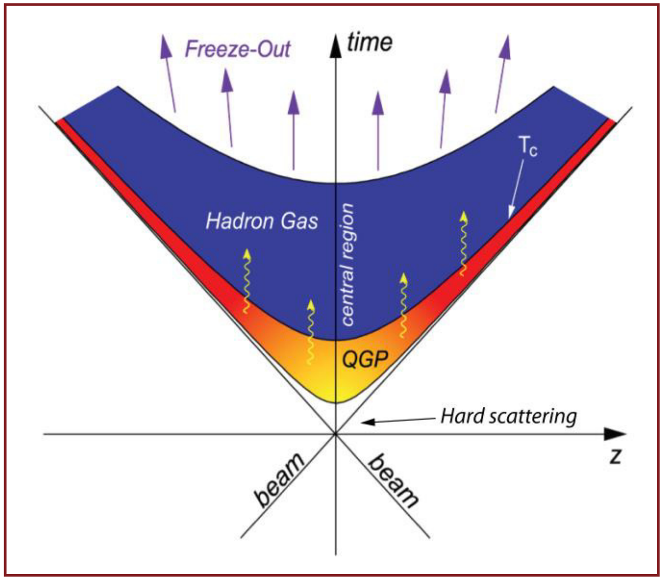

Expected to be present in the early universe, shortly after the Big Bang.

Studied in heavy-ion collisions at the **RHIC** and the **LHC**.

# Heavy-flavour quarks as a probe of QGP

- Heavy-flavour quarks possess **large masses**
  → they are produced primarily at the **initial stages of heavy-ion collisions**
  → they experience the **whole evolution of the medium**

- QGP absorbs energy of partons travelling through it
  → Heavy-flavour quarks are expected to **lose less energy** than light-flavour quarks

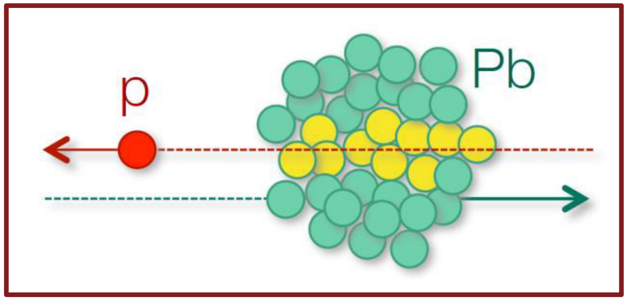



- **Collective behavior** of heavy-flavour quarks
  → sensitive to the degree of thermalization in the QGP
  → constrain the heavy-flavour quark diffusion coefficient

# Why run pA collisions?

**Traditional heavy-ion playbook**:

- **nucleus-nucleus** (AA) collisions
  - Quark-gluon plasma (QGP) creation
- **proton-nucleus** (pA) collisions:
  - Traditionally referred as control environment
  - Initial state effects
    - Additional nuclear matter can alter incoming wavefunction
    - Referred to as **cold nuclear matter (CNM)** effects
- **proton-proton** (pp) collisions
  - Establish baseline for observables in AA collisions
  - Study effects of colliding parton PDF on final meson spectra




**However, pA collisions themselves present interesting phenomena!**

Is there any hot medium (QGP droplets) created in pA?

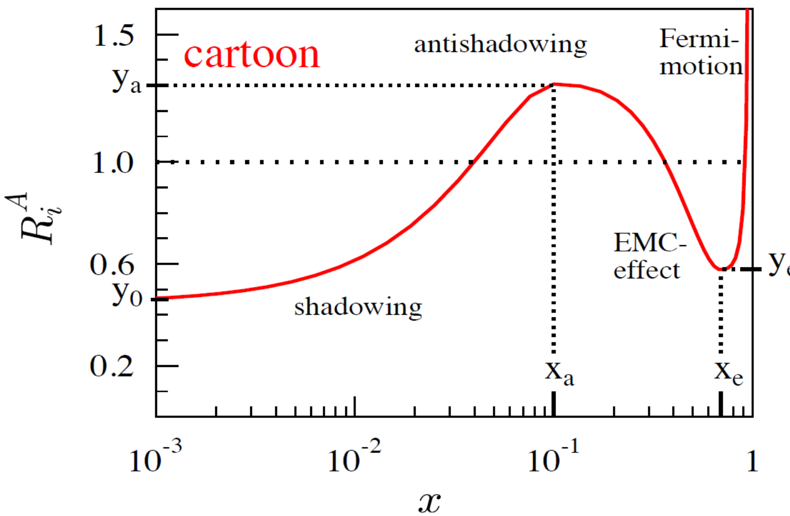
# Cold nuclear matter effects

**Modification of parton distribution function (PDF) in colliding nuclei**, with respect to colliding protons

- Different dynamics of partons within free protons with respect to those in nucleons
- These effects depend on *x* and on the scale of parton-parton interaction

Modification of PDF is expressed by:

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{A\, f_i^{\text{nucleon}}(x, Q^2)}, \quad f_i = q, \bar{q}, g$$



# Cold nuclear matter effects

## Parton saturation at small *x*

- Described within the **Colour Glass Condensate (CGC)** theoretical framework

## Multiple scattering of partons in the nucleus

- Before and/or after the hard scattering
- Leading to parton energy loss (radiative/collisional) or transverse momentum broadening (Cronin effect)

## Final-state inelastic interaction

- Nuclear absorption of quarkonium bound states when passing through nucleus

## Possible heavy quarkonia dissociation by comovers

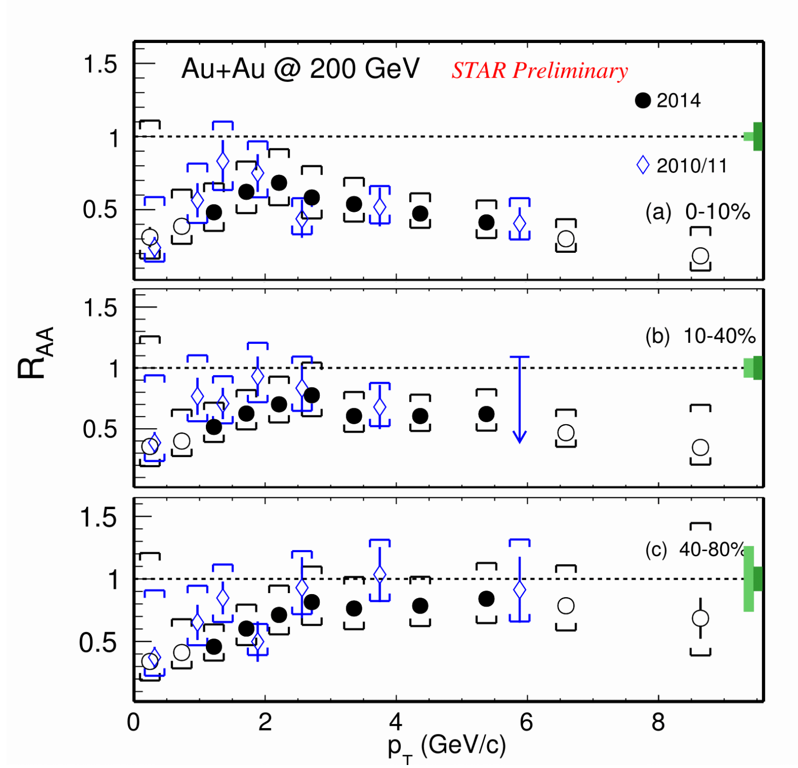
- Partons/hadrons close to quarkonium states at high energy may modify HF production
- The question is, if particles at high energy, produced in pA collisions could form a medium with some collectivity

# Nuclear modification factor

- Allows to study particle spectra **modification induced by nuclear matter**
- How far are observations in AA far from those in pp collisions?

$$R_{AA} \sim \frac{\text{Particle yield in pA or AA}}{\langle N_{bin} \rangle \times \text{particle yield in pp}}$$

$N_{bin}$ number of binary collisions in AA or pA

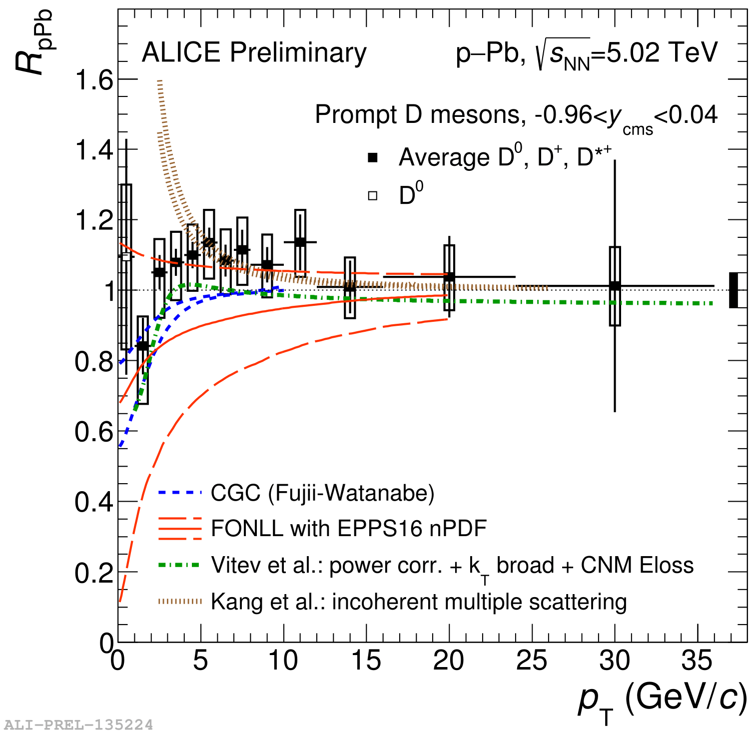



- $R_{AA}$ of $D^0$ (open charm) meson exhibits **strong suppression** at high transverse momentum $p_T$
- Suppression vanishes towards more peripheral collisions (smaller initial energy density)

G. Xie, for STAR Collaboration, Quark Matter 2018.

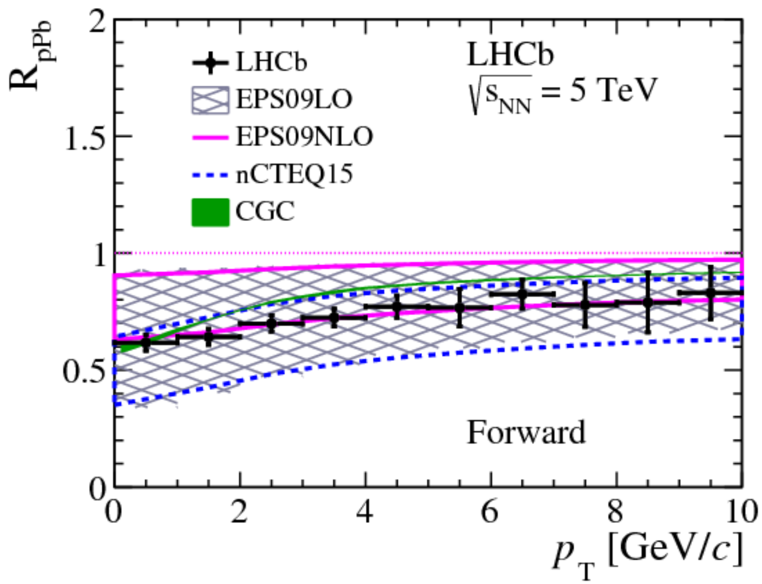
# Nuclear modification factor in p+Pb at ALICE

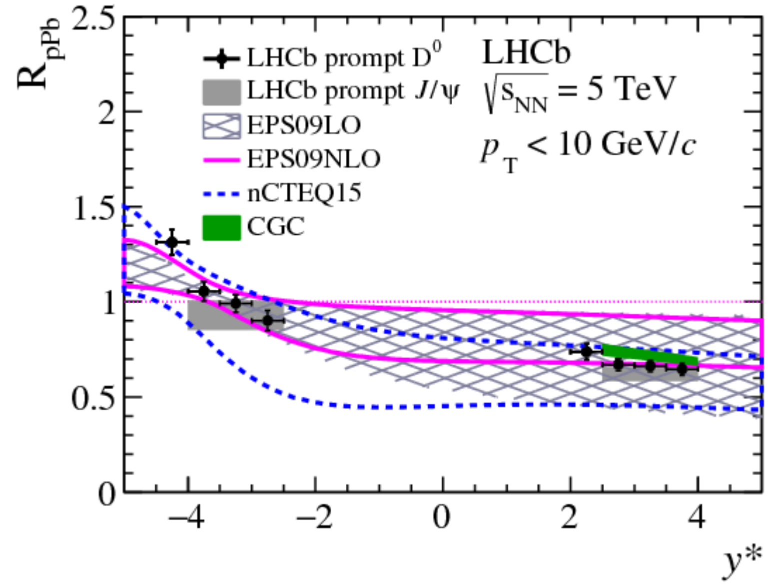
- $R_{pPb}$ of D mesons is consistent with unity within uncertainties
  - Only small indication of CNM effects at lower $p_T$ (< 2 GeV/c)
- Uncertainty of measured data does not **confirm or exclude** any of theoretical predictions



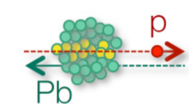

ALICE Collaboration, ALICE-PUBLIC-2017-008 (2017).

# Nuclear modification factor in p+Pb at LHCb




*rapidity defined with respect to the direction of proton*



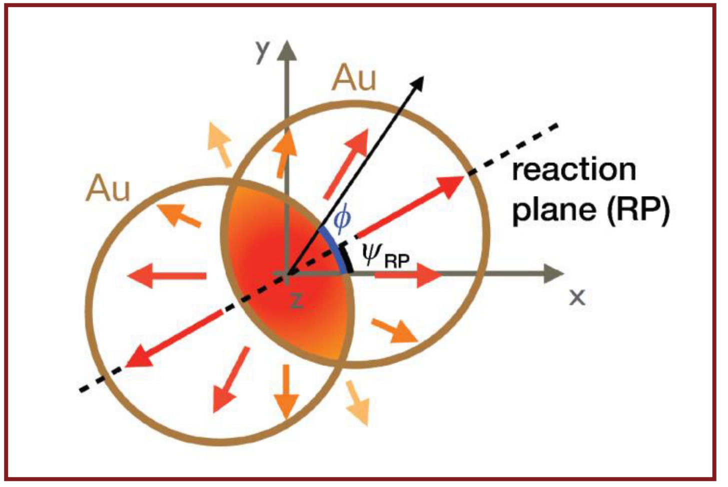

- Nuclear modification factors in p+Pb are **consistent for prompt $D^0$ and J/Ψ**
- **CGC describes the $D^0$ results as a function of both $p_T$ and rapidity**

- These measurements **do not consider** a classification in charged particle multiplicity
  - **Potential modifications** in high-multiplicity events are weakened

R. Aaij et al. (LHCb collaboration), JHEP 1710 (2017) 090.

# Elliptic and triangular flow

**Initial spatial anisotropy** translates into final momentum anisotropy (due to pressure gradients).



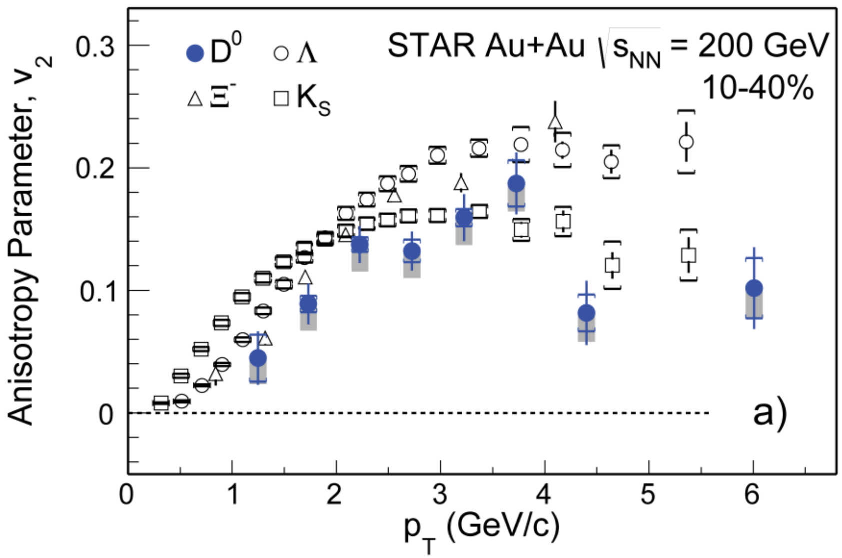

Fourier expansion of the **particle yield** with respect to the reaction plane:

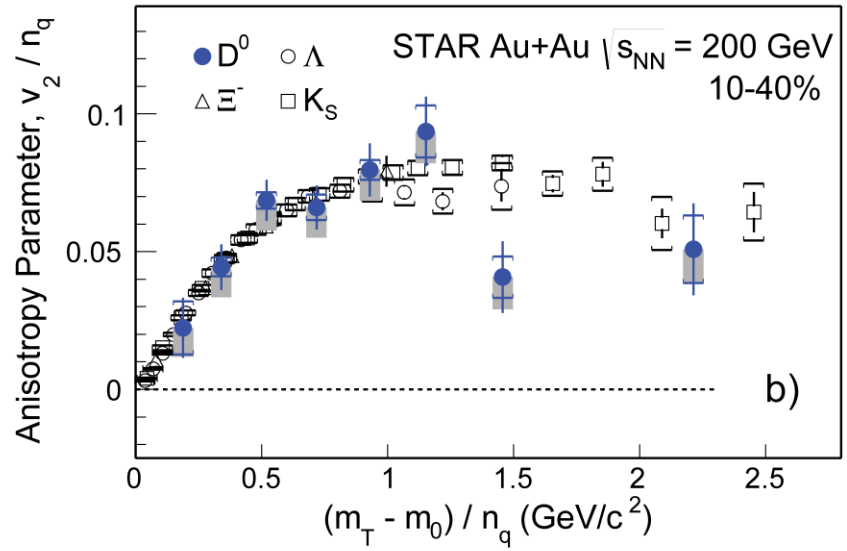
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi-\psi_{RP}\right)\right]\right)$$

$\boldsymbol{v_2}$: elliptic flow

$\boldsymbol{v_3}$: triangular flow

# Elliptic flow $v_2$ in Au+Au at STAR




- Light flavour $v_2$ suggests **hydrodynamic behavior** of a strongly interacting matter
- $D^0$ $v_2$:
  - $p_T < 2$ GeV/$c$: clear mass ordering
  - $p_T > 2$ GeV/$c$: consistent with light mesons

- $D^0$ $v_2$ follows NCQ (number of constituent quarks) scaling

  → suggesting that **charm quarks flow with the QGP**

Is collectivity in AA collisions coming only from QGP?

L. Adamczyk et al. (STAR collaboration), PRL 118 212301 (2017).

# Elliptic flow $v_2$ in p+Pb at CMS

Results from high energy and high multiplicity events shows **significant flow of light hadrons in small systems**.

Is it the same for heavy and light quarks?

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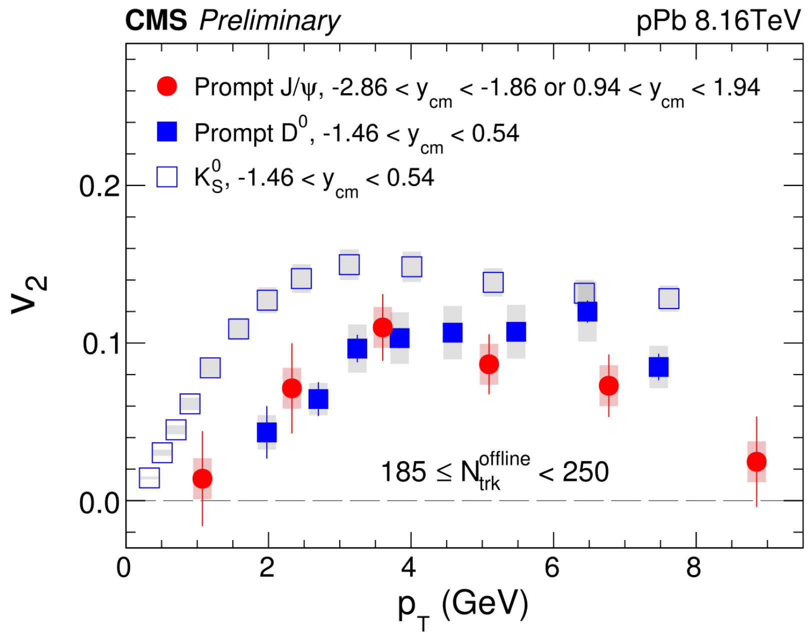
Results from high energy and high multiplicity events shows **significant flow of light hadrons in small systems**.

Is it the same for heavy and light quarks?

- Comparison of **elliptic flow $v_2$** of $D^0$ meson and *J/Ψ* and light $K^0_S$ meson
- $D^0$ meson $v_2$ may be driven by the light quark
  - *J/Ψ* may disentangle this effect
- All displayed mesons have common $v_2$ shape
- For $p_T$ > 4 GeV/*c*, $D^0$ $v_2$ seems to be higher than for *J/Ψ*

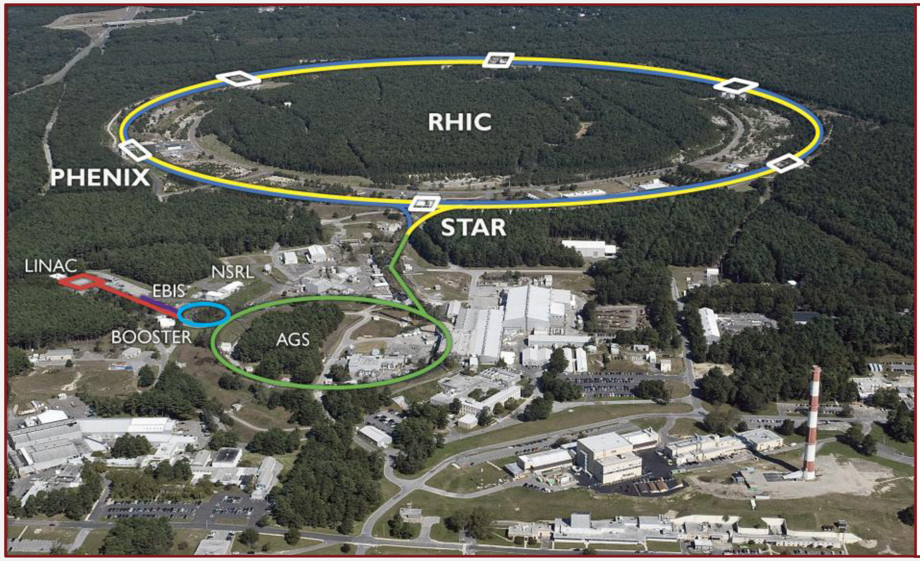


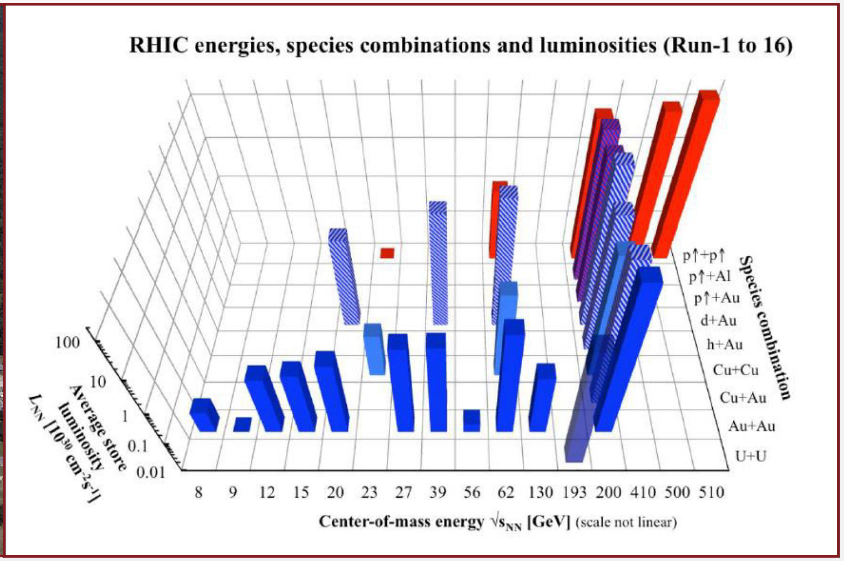

Hint of **weaker collective behavior** of heavy flavor quarks than light quarks.

CMS Collaboration, CMS-PAS-HIN-18-010 (2018).

# Relativistic Heavy-Ion Collider at BNL

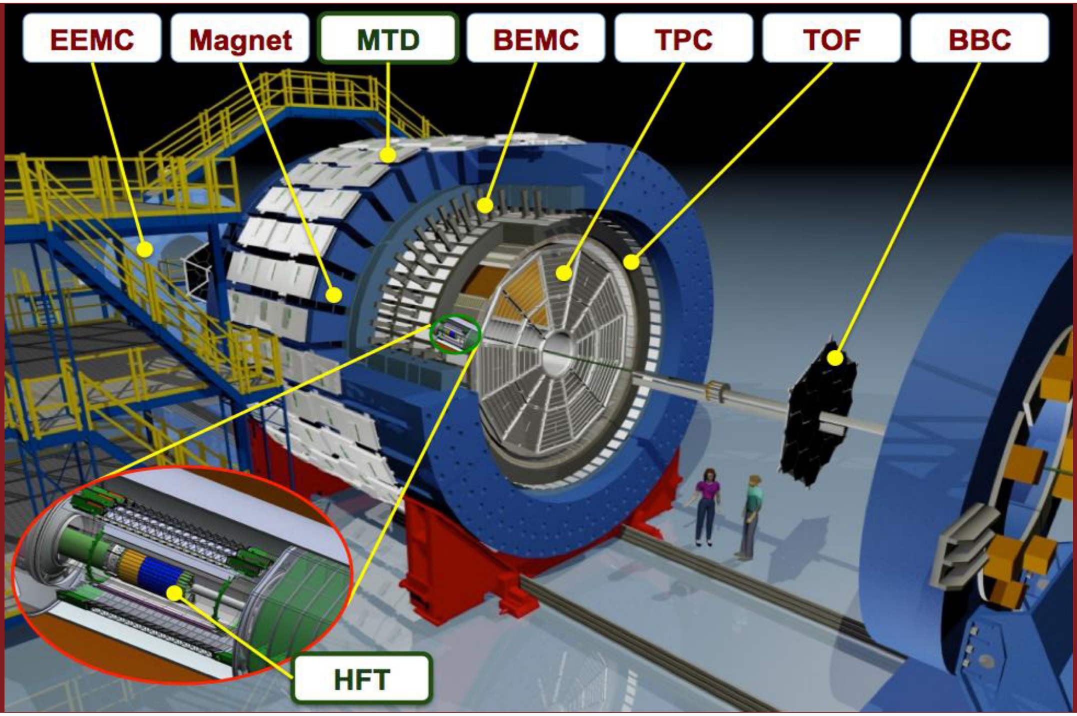
- **Extremely versatile**: has collected data colliding a large array of different heavy ions
- **Only polarized proton** collider in the world

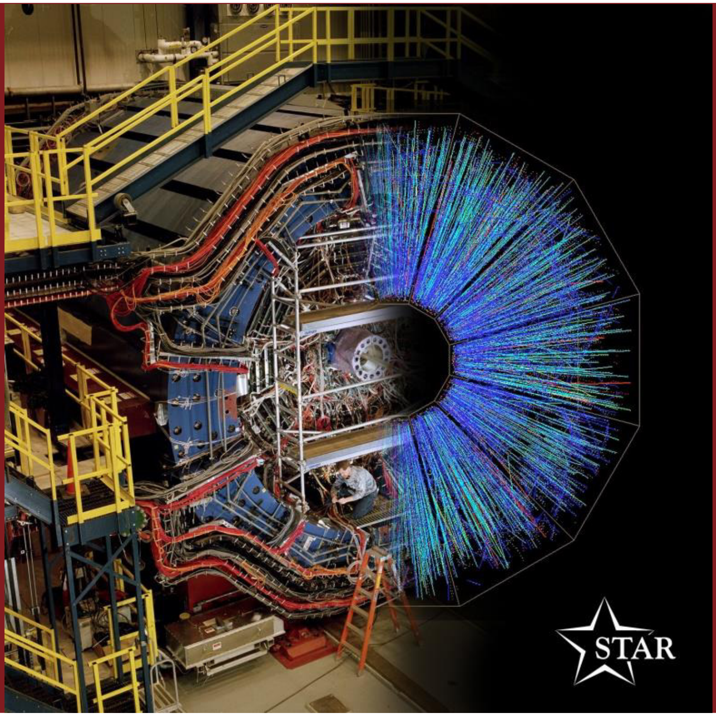


# The Solenoid Tracker At RHIC

- Designed to study the strongly interacting matter
- Excels in tracking and identification of charged particles at mid-rapidity with full azimuthal coverage
- Most of the subsystems are immersed in 0.5 T solenoidal magnetic field



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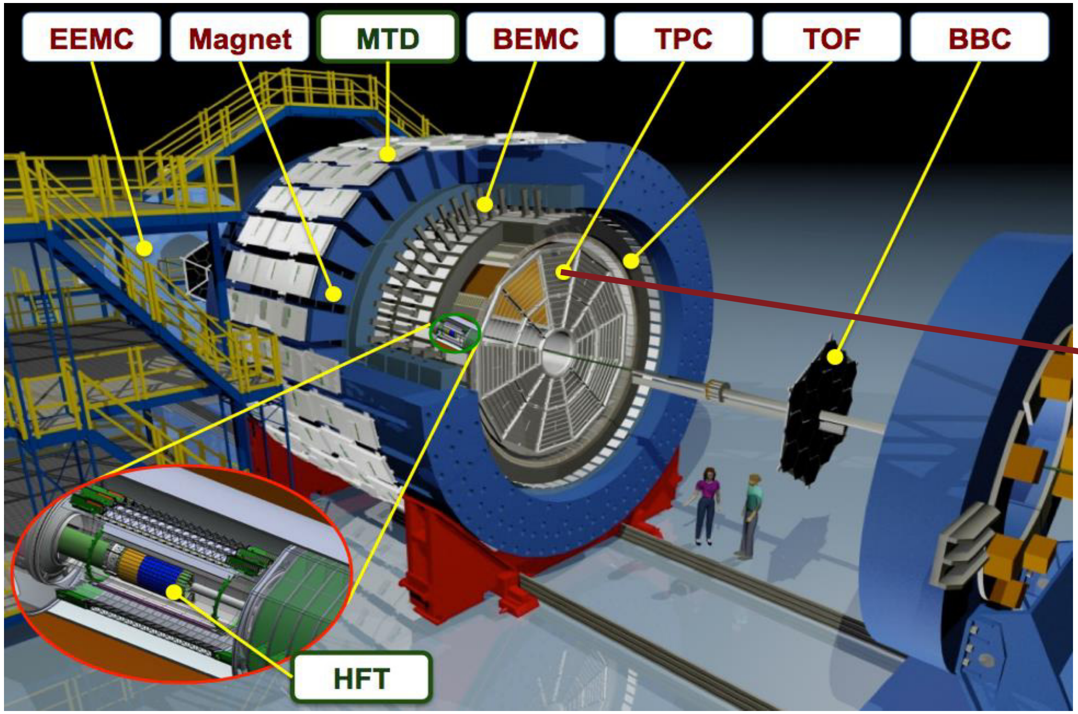


**Time projection chamber (TPC)**

- main tracking device; momentum determination
- particle identification via specific energy loss d*E*/d*x*
- being upgraded - wider pseudorapidity range, better resolution

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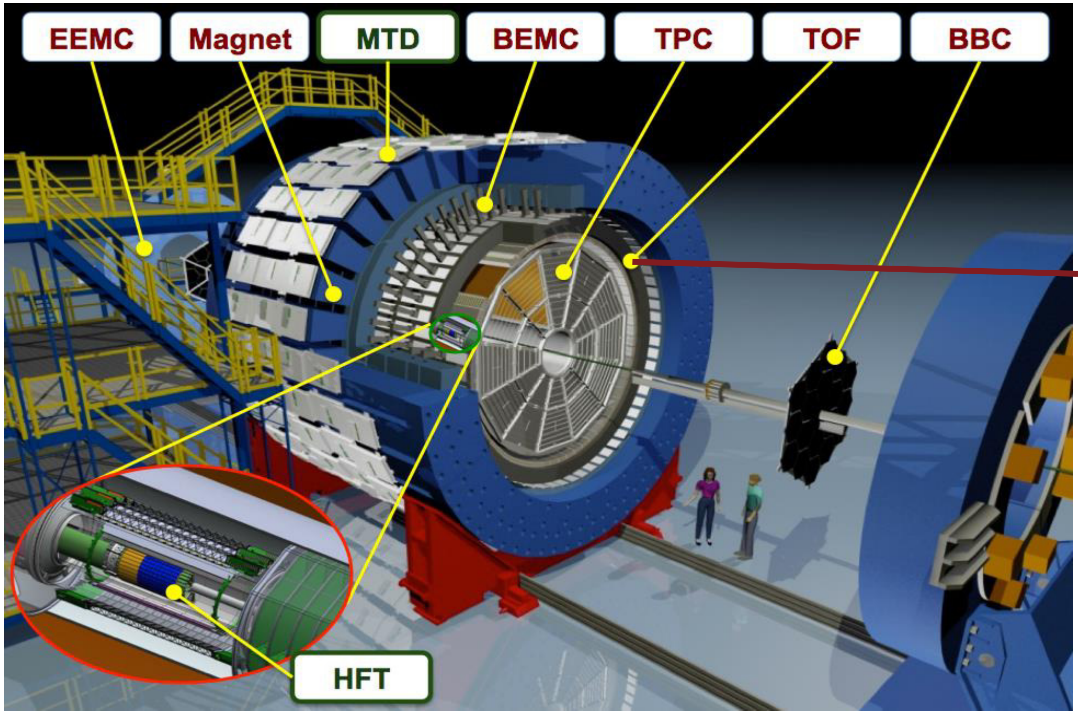


**Time of flight (TOF)**

- particle identification at low transverse momentum $p_T$ via velocity $\beta$

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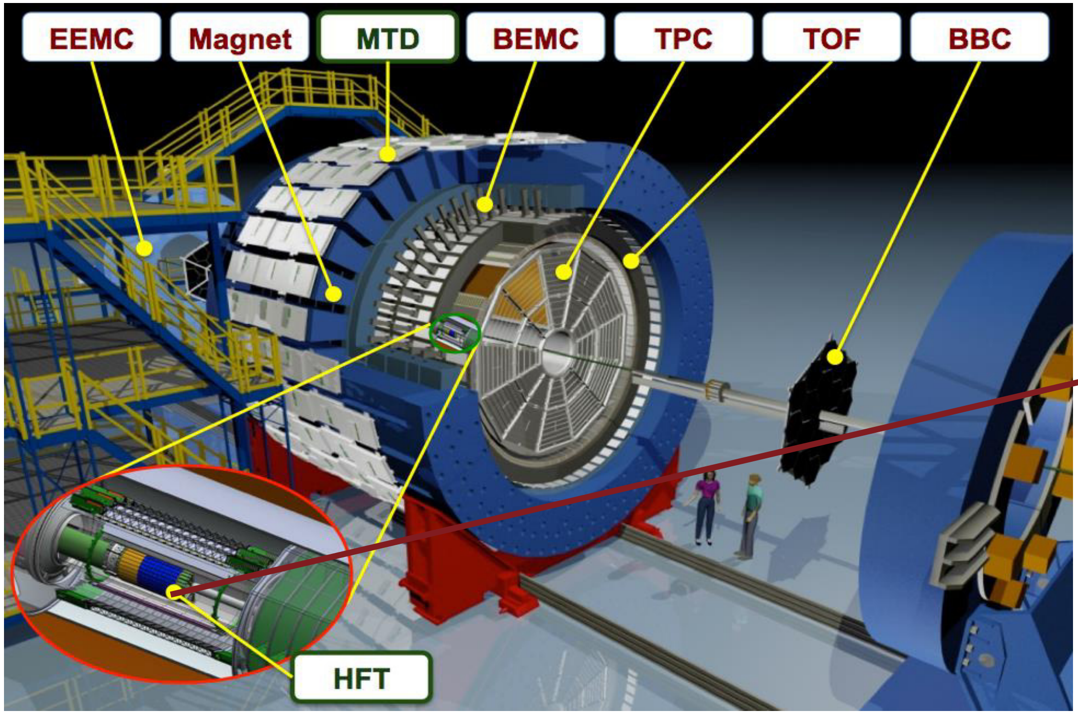


**Heavy Flavor Tracker (HFT)**

- Inner tracking system
- First application of MAPS in collider experiments
- Excellent **$DCA_{xy}$ and $DCA_z$ resolution: ~50 μm** for kaons at $p_T$ = 750 MeV/$c$

# Topological reconstrucion of $D^0$ mesons

Hadronic decay channel is used for reconstruction

- $D^0 \rightarrow K^-\pi^+$, branching ratio is (3.89 ± 0.04)%

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**DCA = distance of closest approach**

Topological properties of $D^0$ decays used for their reconstruction:

- **decay length** of D meson candidate
  - *ideally ~ 200 μm*
- **daughters DCA** to primary vertex (PV)
  - *ideally >> 0 μm*
- **DCA** between **daughter particles**
  - *ideally → 0 μm*
- **pointing angle** *θ* between reconstructed $D^0$ momentum and decay length vector
  - *ideally → 0*
- reconstructed **$D^0$** candidate **DCA** to primary vertex
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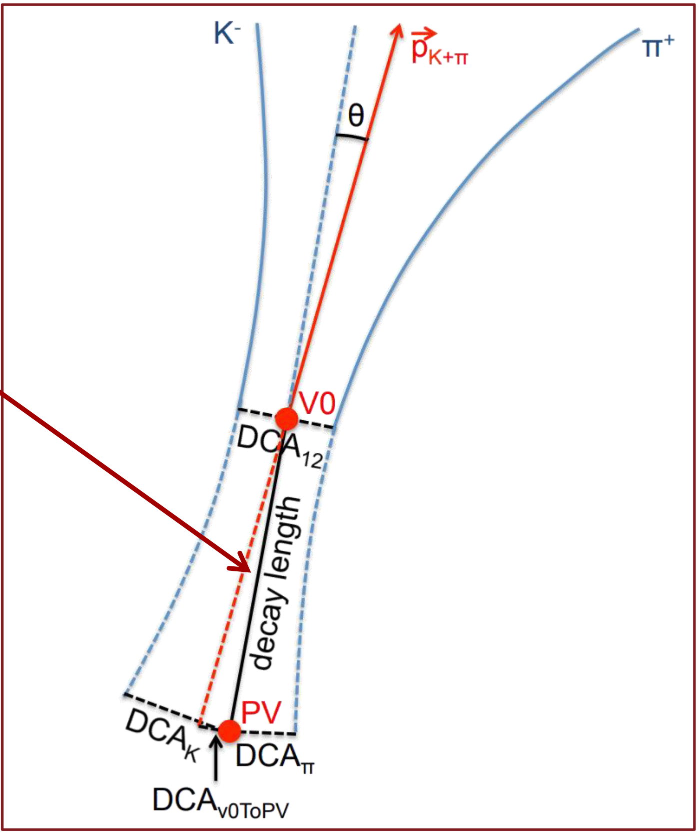

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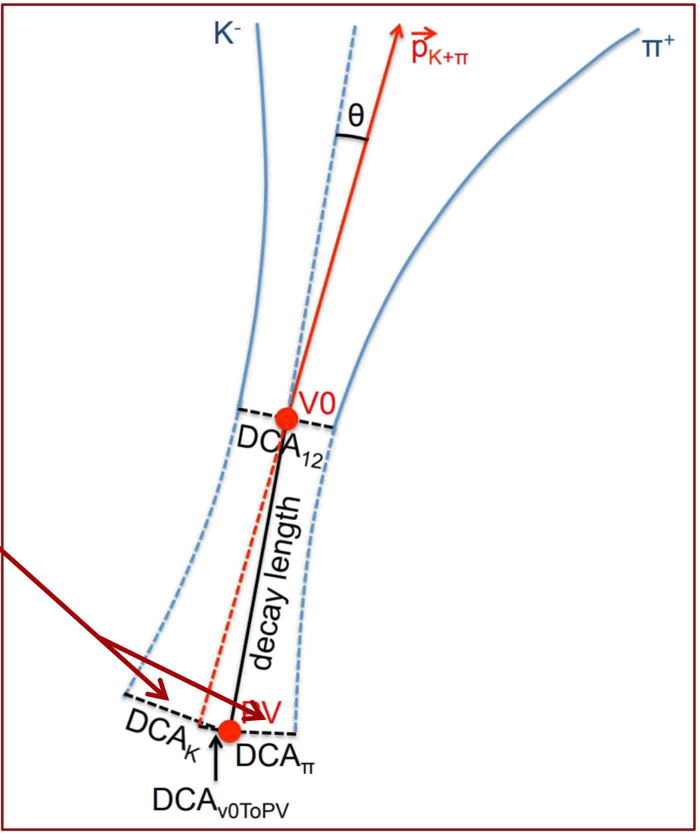

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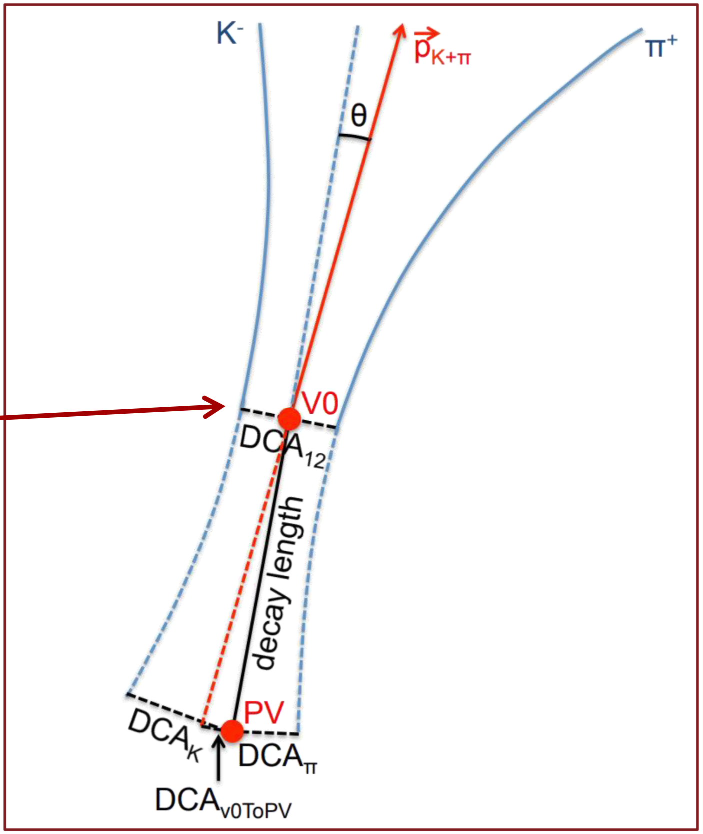

# Topological reconstrucion of $D^0$ mesons

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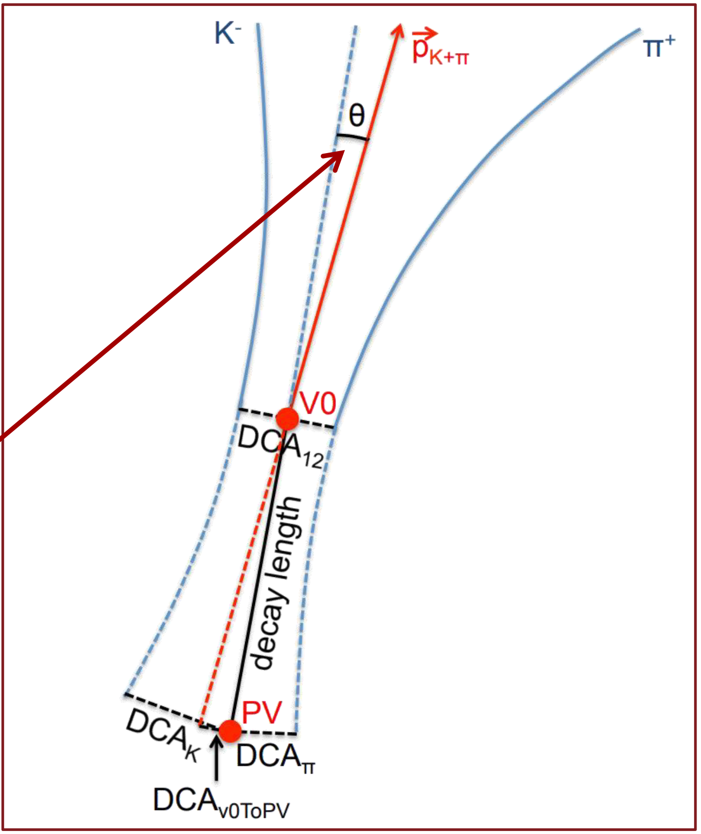

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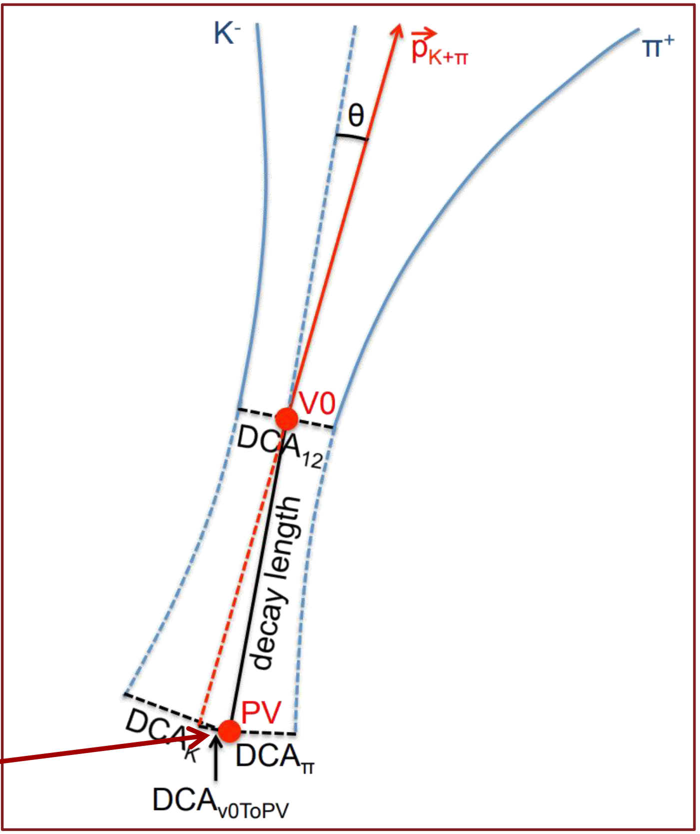
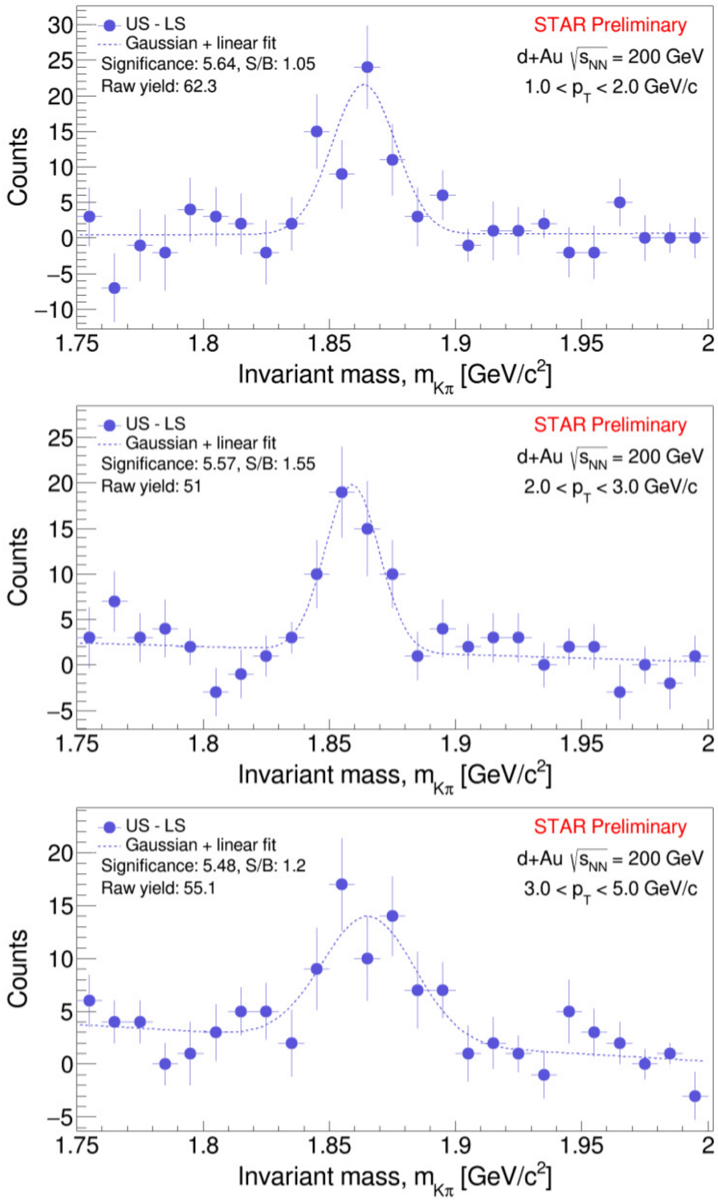


# $D^0$ raw yields in d+Au at STAR

- **Rectangular Cuts method in TMVA is used:**
  - This mode randomly samples different cut combinations and selects the one with the largest background rejection for a given signal efficiency

- Background are wrong (like) sign combinations of daughter particles ($K^-\pi^-$ , $K^+\pi^+$)
  - subtracted from the correct (unlike) sign combinations

- Intervals of pair $p_T$ used for analysis:
  - 1–2, 2–3, 3–5 GeV/*c*
- **Significance larger than 5** is achieved in all $p_T$ intervals

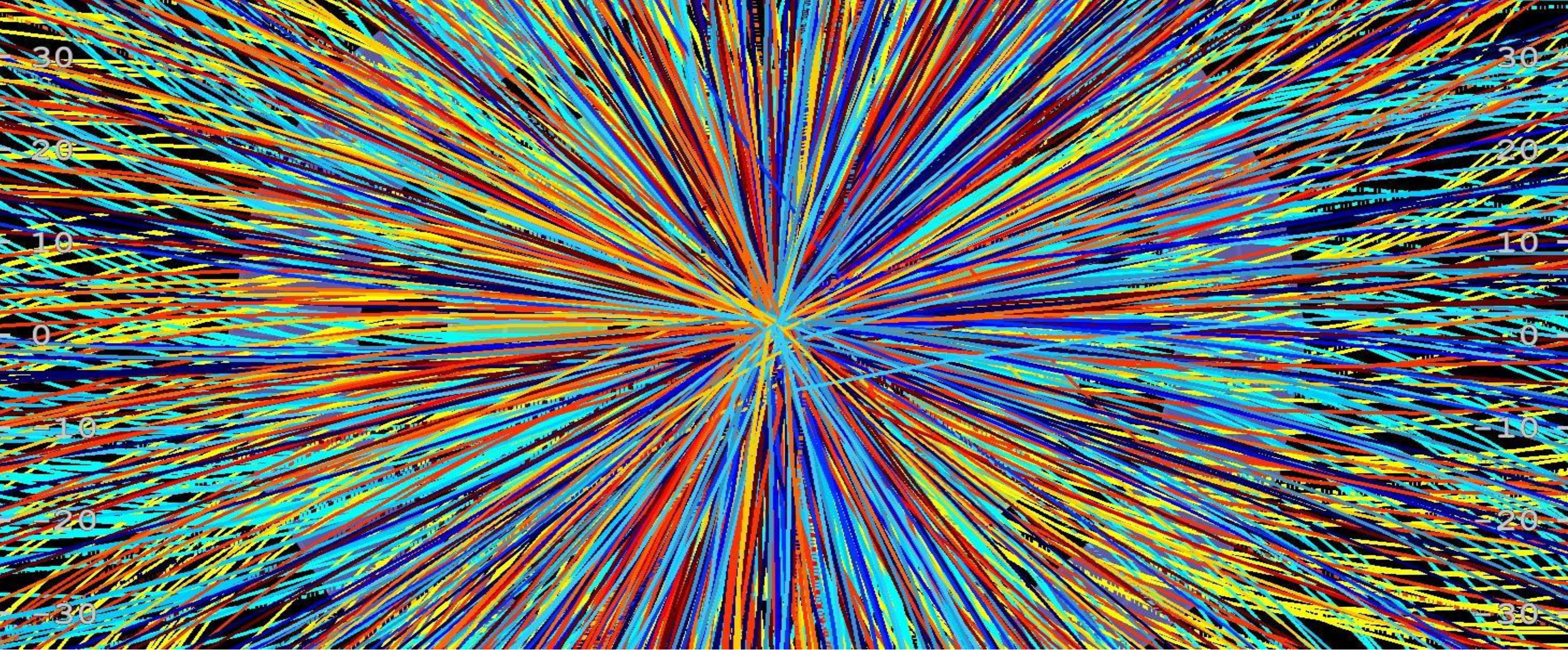



L. Kramarik, for STAR Collaboration, Quark Matter 2018.

# Conclusions and outlook

- Small systems (pA, pp collisions) are currently **not only benchmarks** for heavy ion physicists
- Understanding of excited QCD needs to be further tested in pp and pA collisions
  - **multiplicity biases** can affect the comparison among systems

- $D^0$ mesons are **reconstructed via their hadronic decay channels** in d+Au collisions with excellent precision at the **STAR experiment**
- Evaluations of the efficiency correction on **$D^0$ raw yield in d+Au collisions** and systematic uncertainties are under way to determine:
  - **nuclear modification factor** $R_{dAu}$
  - **elliptic anisotropy** $v_2$




***Thank you for your attention***

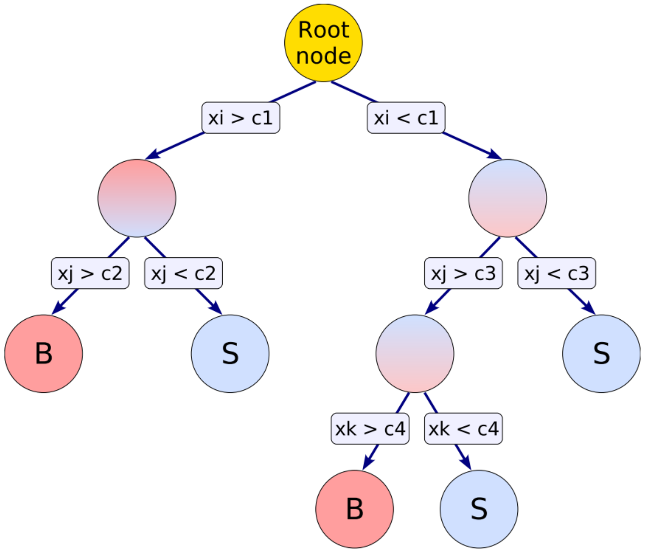
# *Backup*

# Topological reconstrucion of $D^0$ mesons

- Topological variables are optimized separately for different $p_T$ intervals using **Toolkit for Multivariate Data Analysis (TMVA)** package in ROOT
- TMVA contains multiple methods to separated signal

- **Rectangular Cuts:**
  - This mode randomly samples different cut combinations and selects the one with the largest background rejection for a given signal efficiency
  - Set of cuts with the greatest significance is used for raw yield extraction

- **Boosted Decision Trees (BDT):**
  - Classifier is a set of decision tree
  - Usually 850 trees are used with maximum depth 3
  - Divide the phase space into **multiple** signal-like and background-like hypercubes



# ELLIPTIC FLOW $V_2$ IN P+PB AT CMS

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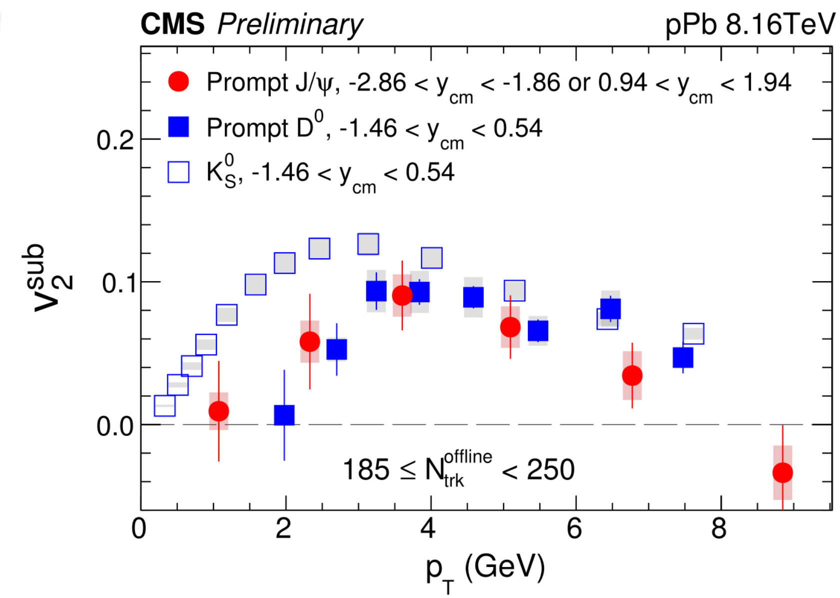


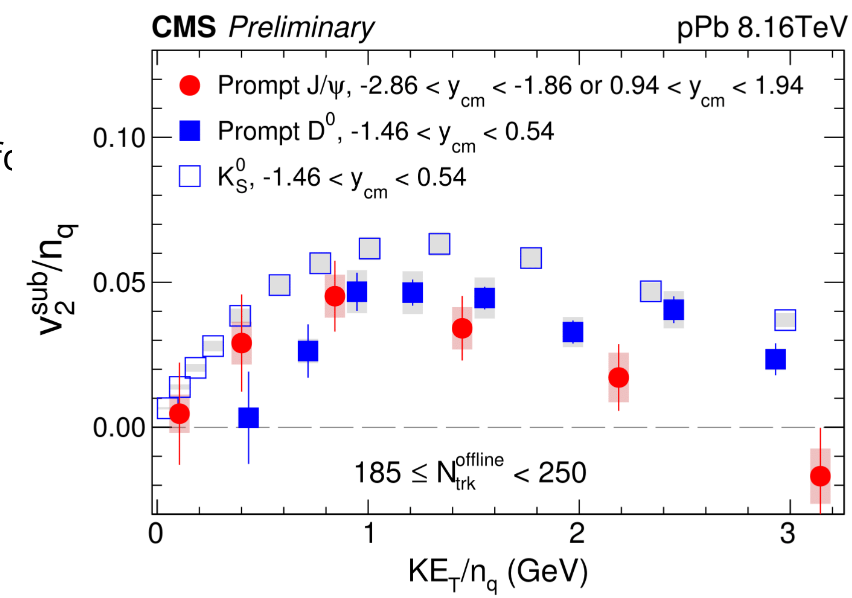


CMS Collaboration, CMS-PAS-HIN-18-010 (2018).