SPRACE

Searches for strong electromagnetic fields in heavy-ion collisions at the LHC: an experimental discussion

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SPRACE - UNESP

Second Latin American Workshop on Electromagnetic Effects in QCD

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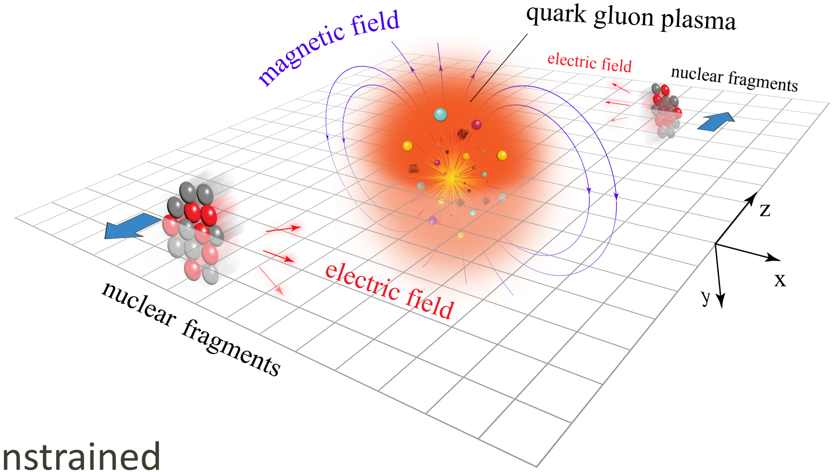
Searches for strong EM fields in AA collisions

After/during the collision, electric charges from ultra-relativistic nuclei could lead to very strong electromagnetic (EM) field

- Strongest B-field in nature
  - Magnitude reaching: $\sim 10^{18} - 10^{19}$ G
  - Vanish very fast: $c\tau \sim 0.05 - 0.5$ fm
  - Collision energy dependent
  - Can affect charged particles momentum



- Magnitude and time evolution is not well constrained

Phys. Rev. X **14** 011028 (2024)

- Many novel phenomena in heavy-ion collisions involve strong EM fields in the quark-gluon plasma (QGP): CME, chiral phase transitions, etc…

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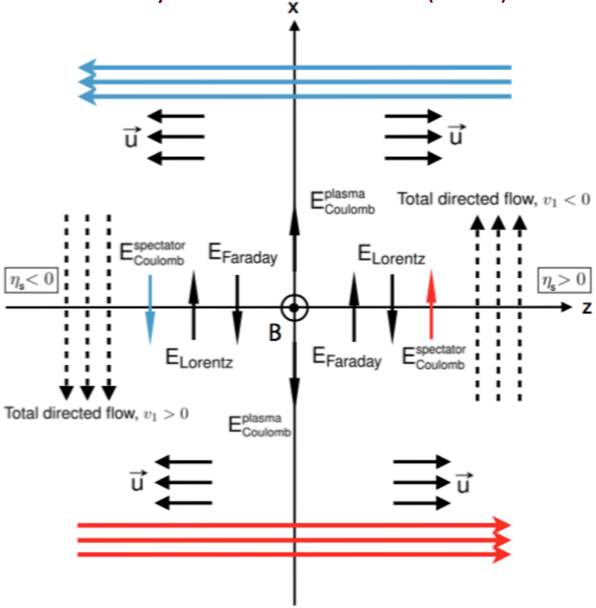
Phys. Rev. C **98** 055201 (2018)



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Outline

Detail on the analysis procedures to probe effects from strong EM field produced in heavy-ion collisions

Examples using the CMS experiment at the LHC

Similar procedures used in other experiments at the LHC and RHIC

Two parts: methods using possible effects on

- Collective flow observables
- Z bosons properties

Outline

Detail on the analysis procedures to probe effects from strong EM field produced in heavy-ion collisions

Examples using the CMS experiment at the LHC

Similar procedures used in other experiments at the LHC and RHIC

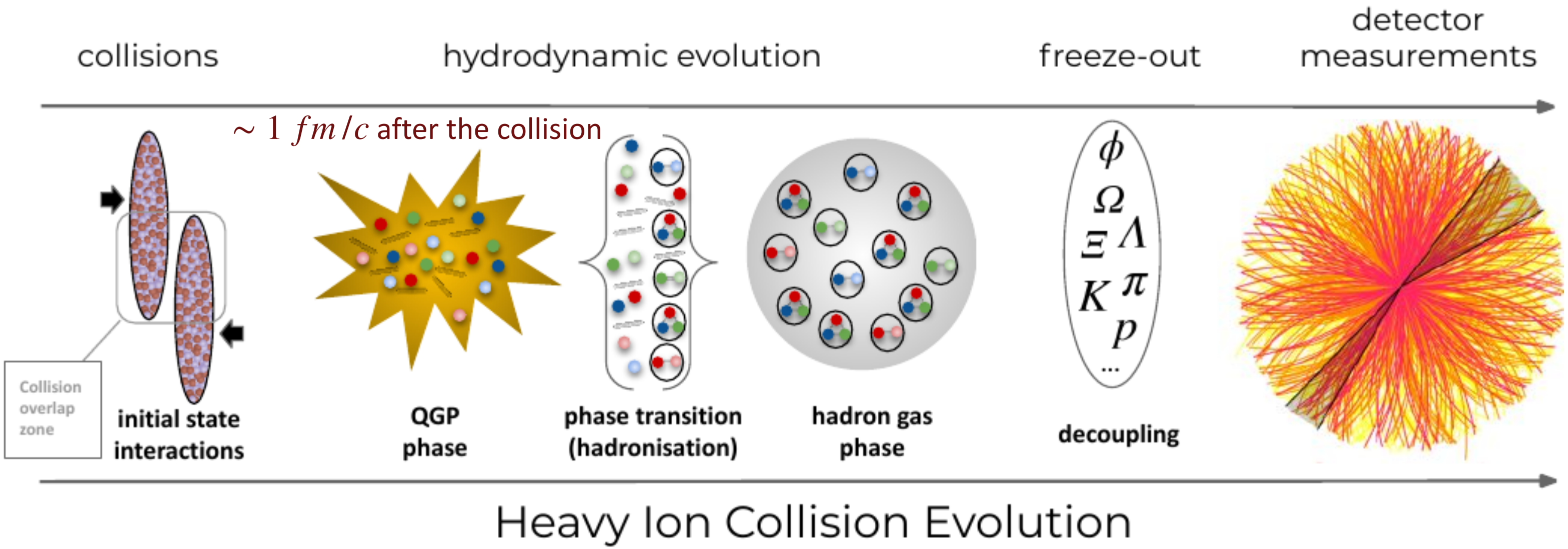
Main goal: use observables accessing different stages of the collision to experimentally investigate the EM field magnitude and evolution

Using collective flow measurements

Ultrarelativistic heavy ion collisions

Measurements + simulations ⇒ “standard model” of the physics of heavy ions

- Strong evidence of the formation of quark-gluon plasma (QGP) phase and very small shear viscosity over entropy density (η/s)



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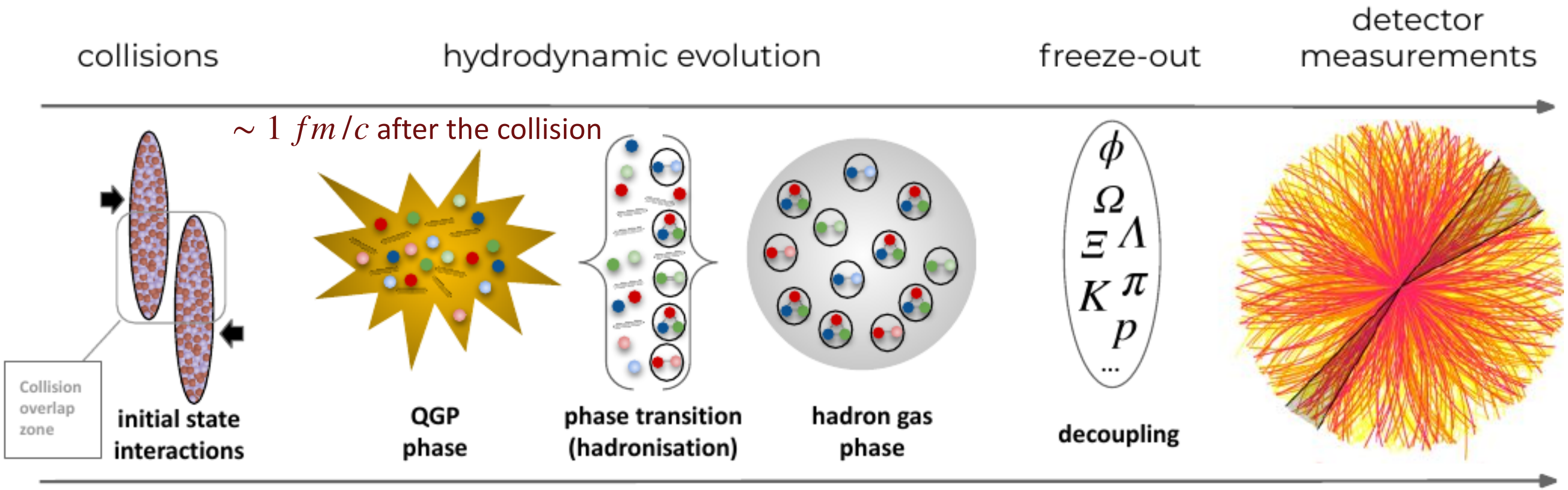
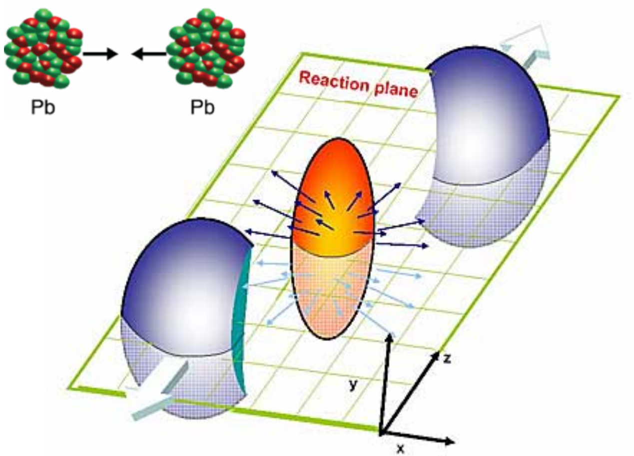


Can we constrain properties of the QGP by measuring strong EM field effects in final state observables?

Azimuthal anisotropic flow

Initial geometry and pressure anisotropy



They are converted in anisotropy in momentum space ⇒ two-particle correlations

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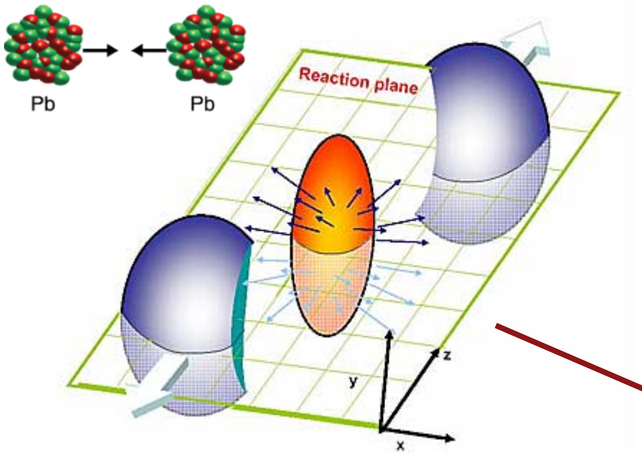

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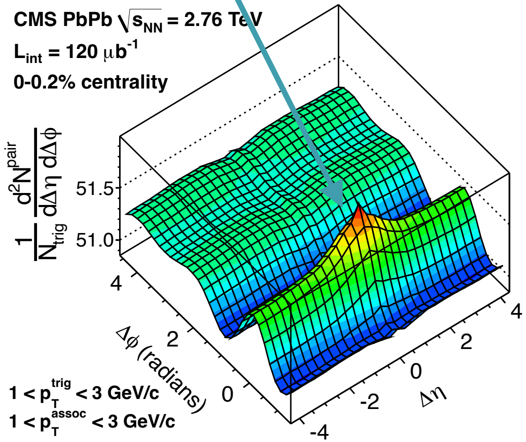
Jets,
femtoscopic correlations, etc…



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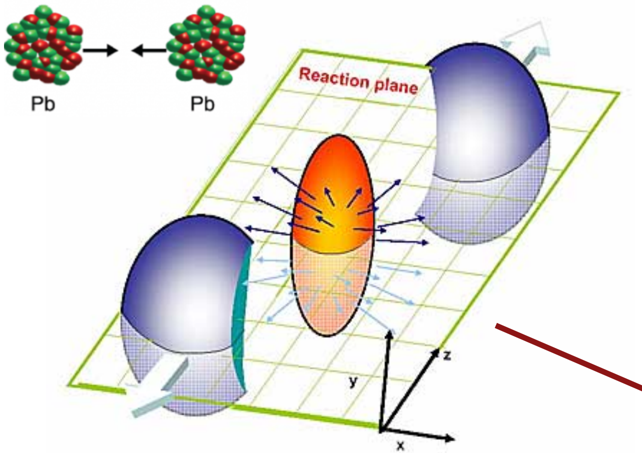

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Projecting in $\Delta\phi$ in the long-range ($|\Delta\eta| > 2$)

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left(1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

$$V_{n\Delta} = v_n^2$$

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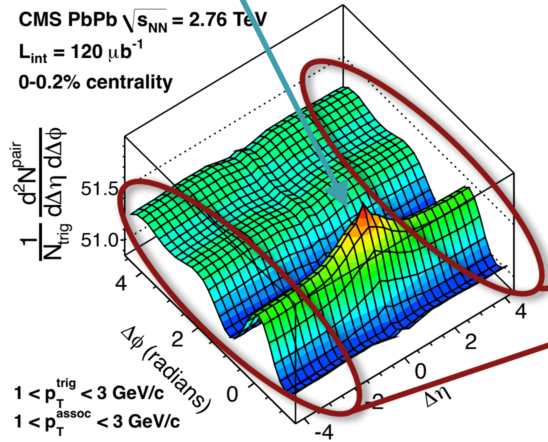
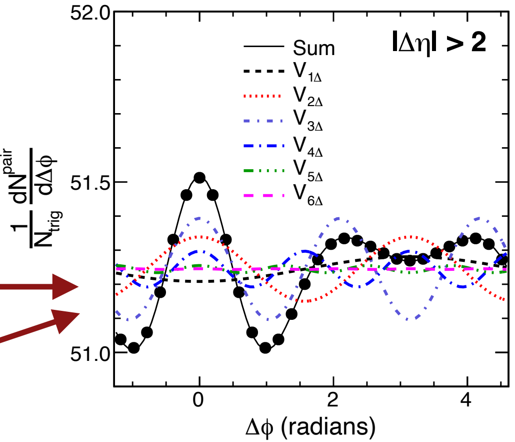


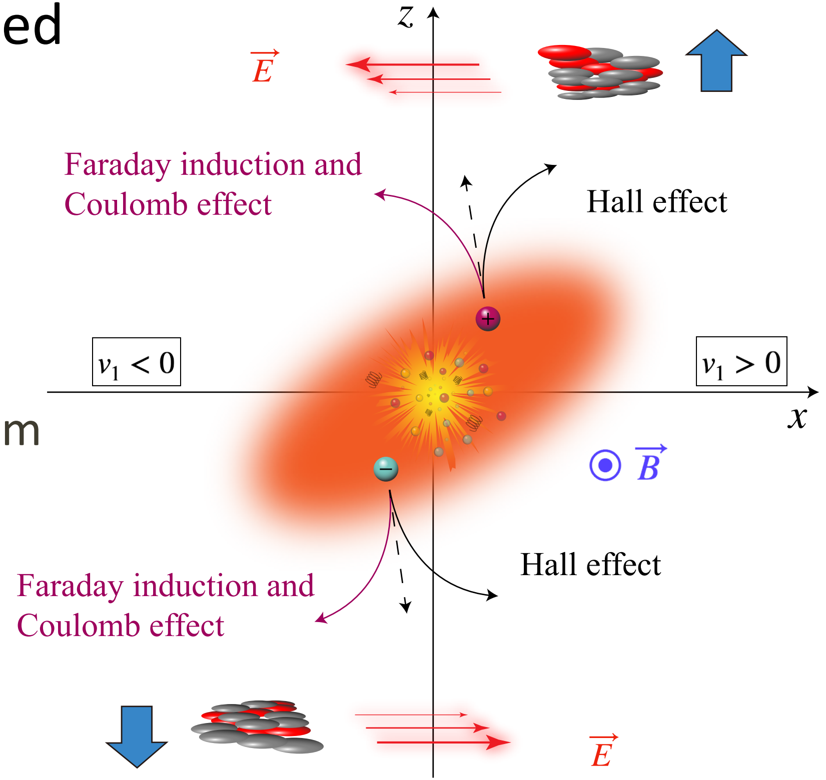


v_1 (directed flow), v_2 (elliptic flow) & v_3 (triangular flow)

Influence of strong EM field in directed flow (v_1)

Directed flow describes collective sideward (x-axis) motion of produced particles and nuclear fragments

Phys. Rev. X **14** 011028 (2024)



- Strong EM field can influence v_1
  - Depends on the production mechanism
  - Can have opposite effect comparing positive and negative charges

Effect on Δv_1 of $D^0(\bar{u}c)$ mesons

Charm quarks produced in primordial stages of the collision ($\sim 0.1\ \mathrm{fm}/c$)

- $m_{\mathrm{charm}} \gg$ typical medium temperatures $\Rightarrow$ lower probability to be produced in the QGP phase

Peak magnitude of EM field $\sim 0.1 - 0.2\ \mathrm{fm}/c$

Non-zero Δv_1 mainly due to magnetic field from spectators

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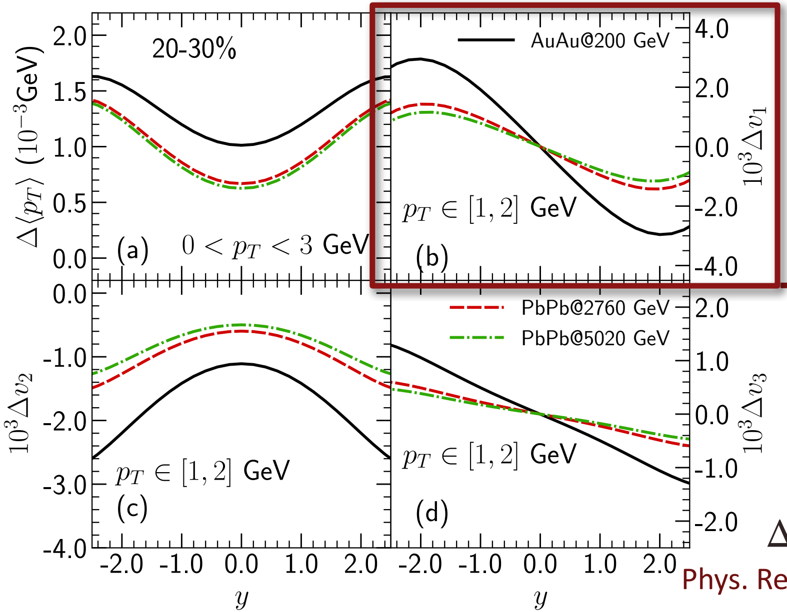
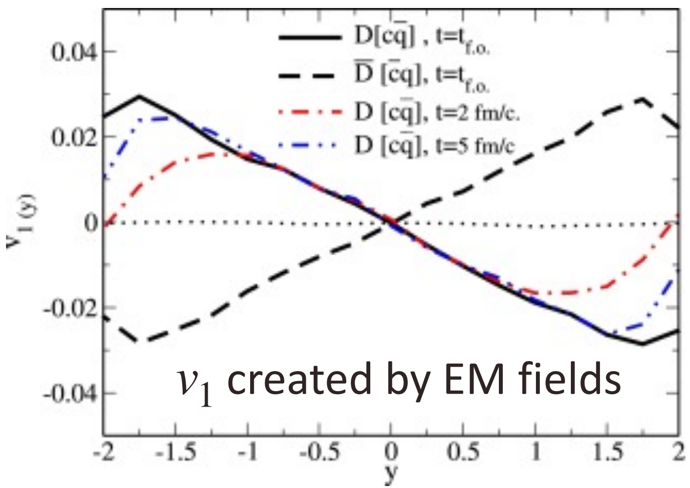


Larger effect on D mesons

$\Delta \equiv \pi^+ - \pi^-$

Phys. Rev. C **98** 055201 (2018)

Phys. Lett. B **768** 206 (2017)



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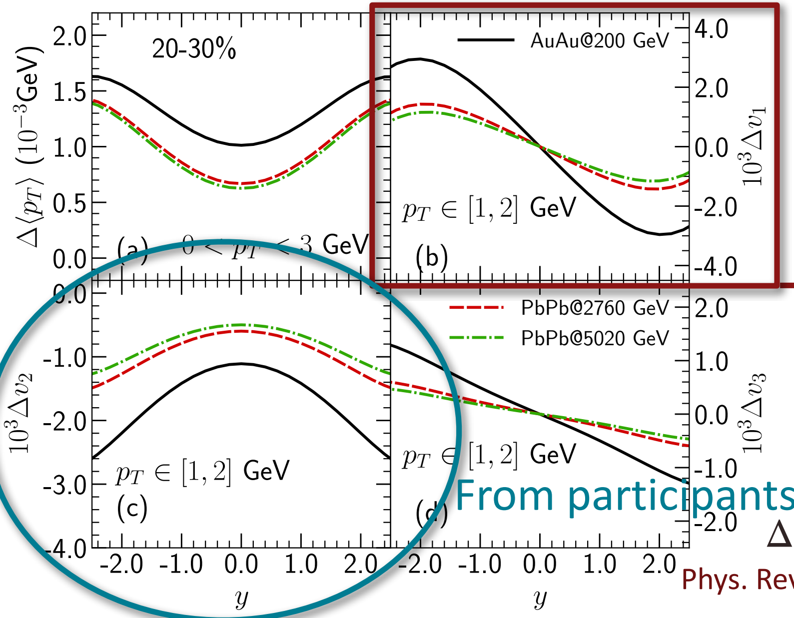

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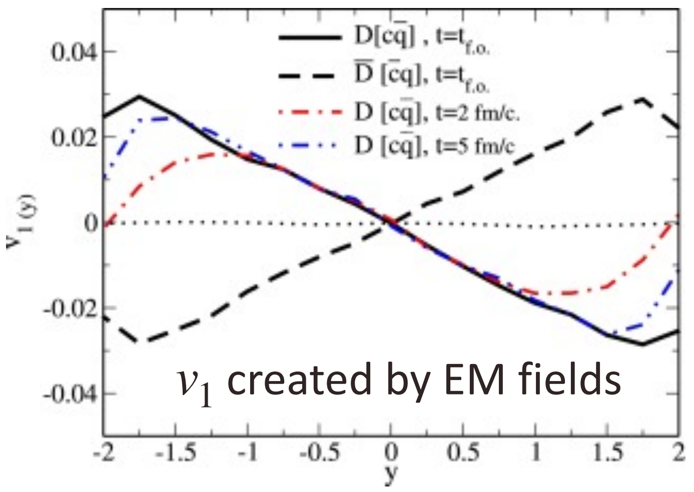
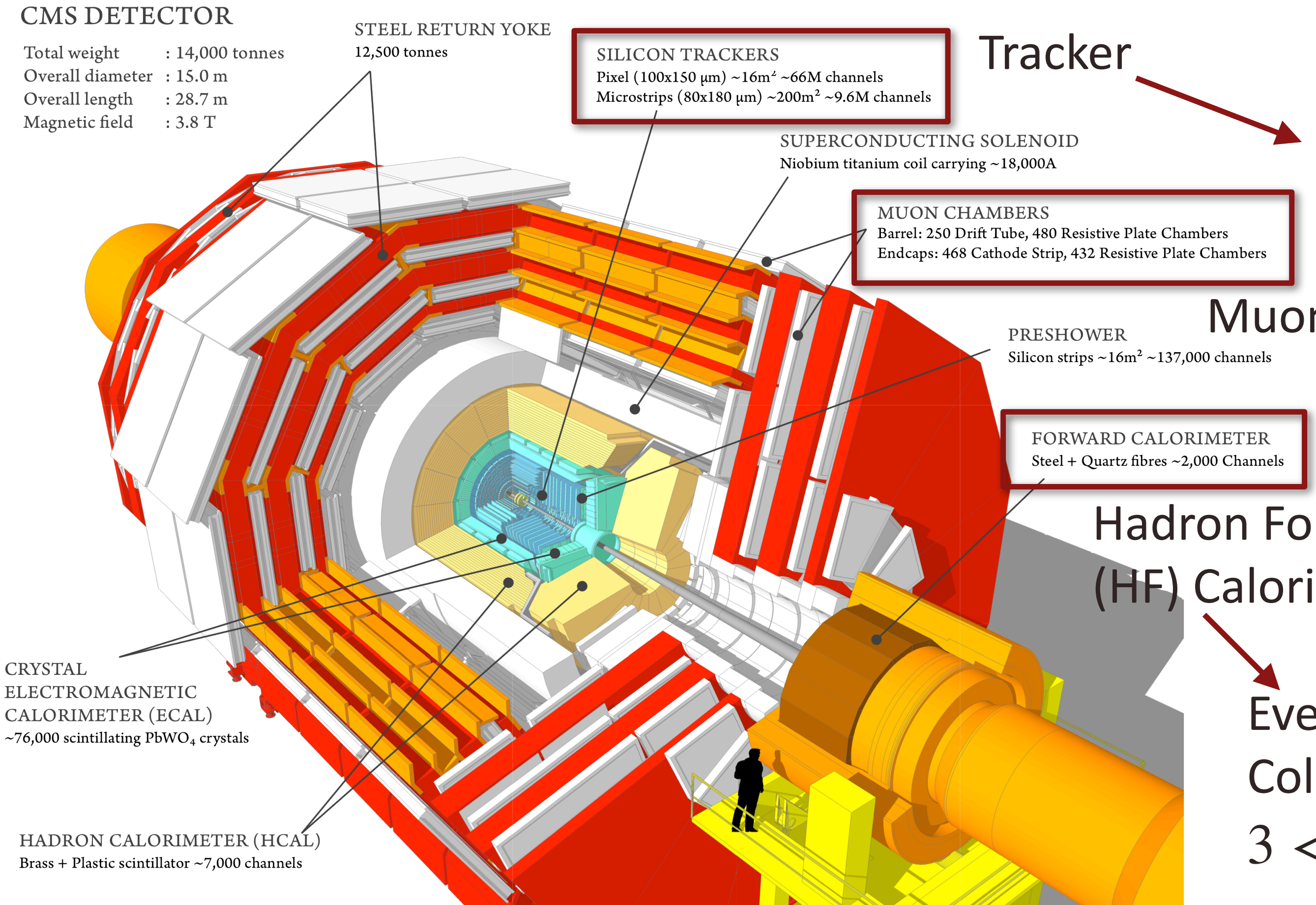


The CMS detector

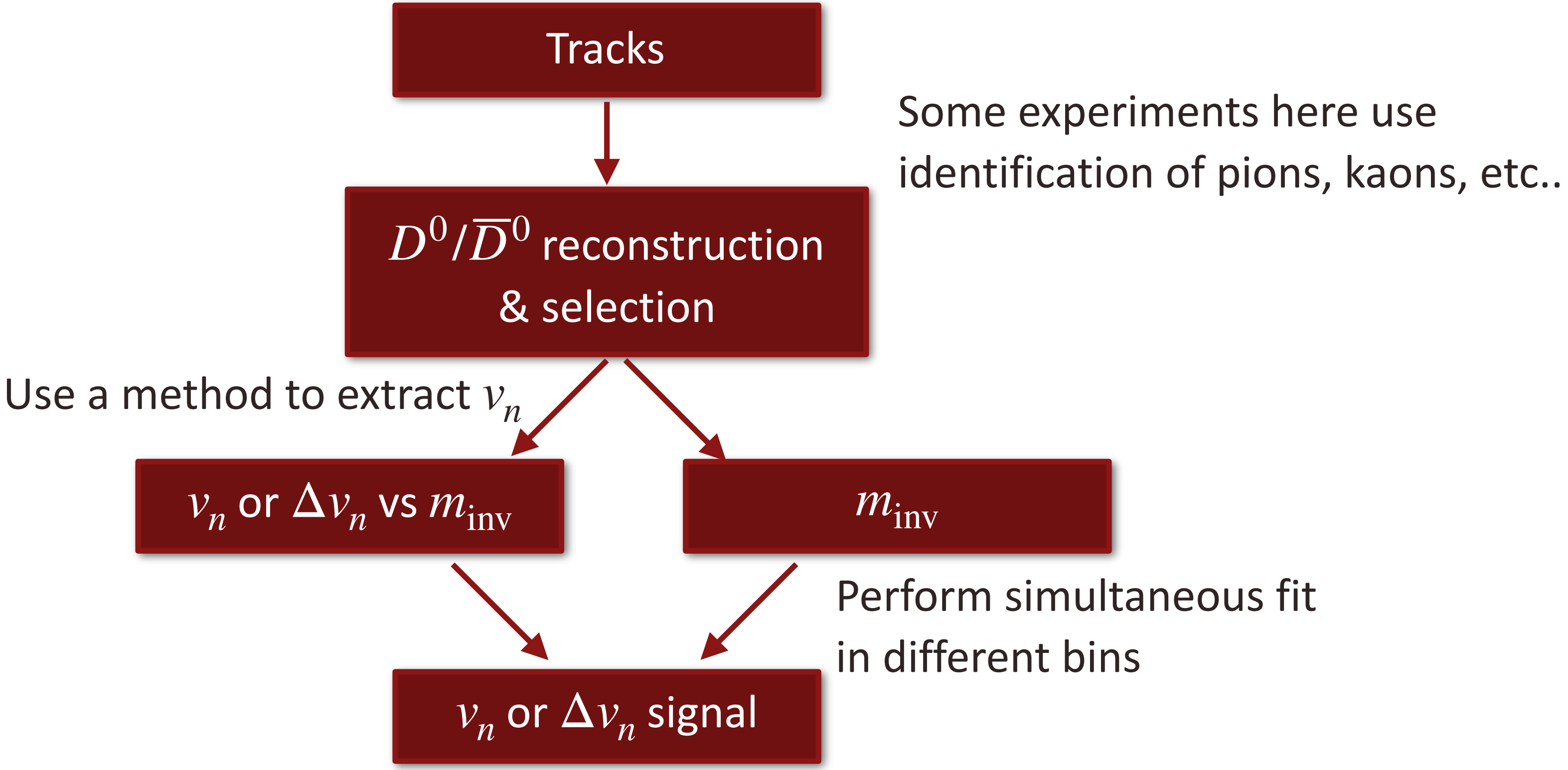


Tracker → Charged particles (tracks) $|\eta| < 2.4$

Muons, $|\eta| < 2.4$

Hadron Forward (HF) Calorimeters → Event selection, Collision centrality, $3 < |\eta| < 5$

Analysis overview - v_n or Δv_n of $D^0(\bar{u}c)$ mesons



Samples & event selection

Data

- Minimum bias trigger
  - Select events with good detector conditions
    - In 2018: 4B MB events for CMS

Monte Carlo (MC) simulations: embedded (Hydjet+Pythia) + Geant4

- Prompt D^0 & Non-prompt D^0
  - Usually tens of million events for each

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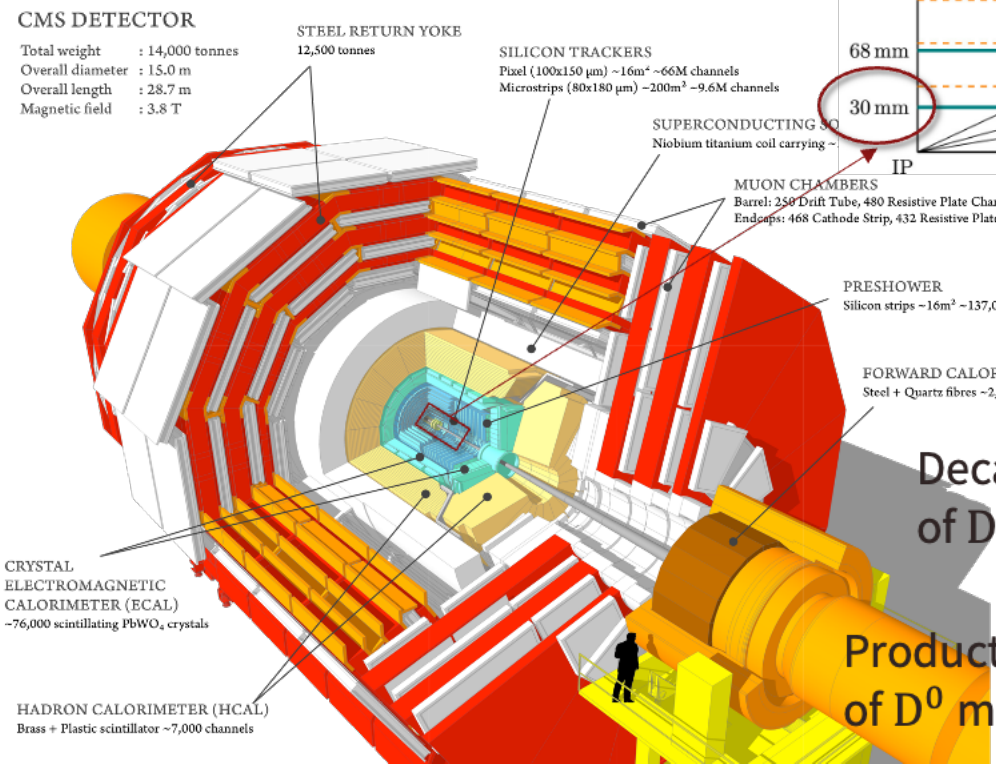
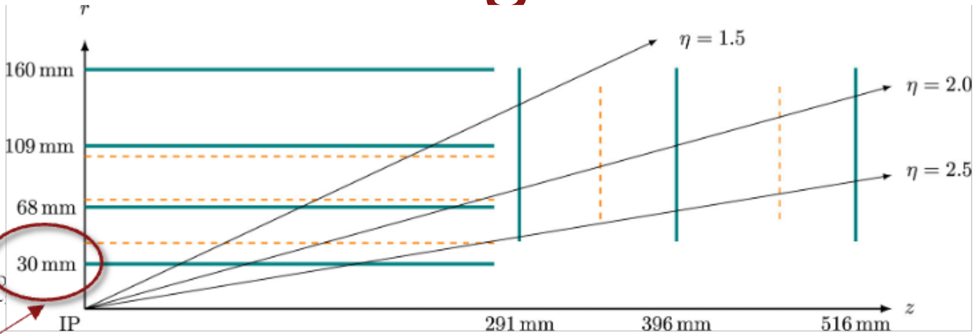
Event selection

- **Primary vertex:** |z| < 25 cm, |r| < 2 mm, number of tracks >= 2
- **HF coincidence:** at least 2 towers in each side of HF with 4 GeV each
- **Cluster compatibility:** look at the cluster shape in the pixel detector em compare with z position of the vertex
- Pile-up collisions effects in PbPb are very small in 2018 data-taking

Prompt D^0 meson detection using CMS

From decay products (π and K)

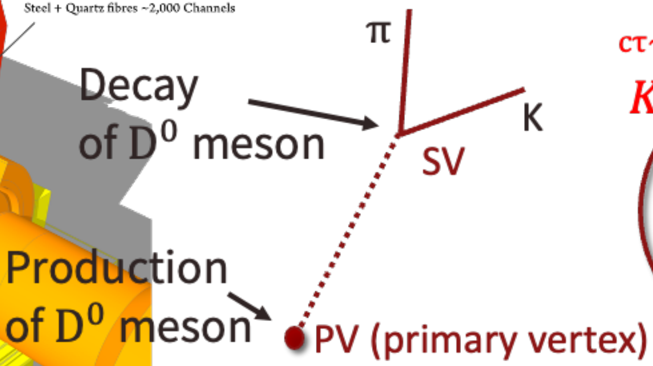


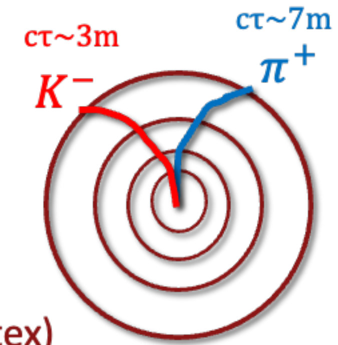


$D^0(\bar{u}c) \rightarrow K^-\pi^+$, BR = 3.95 ± 0.03 %

Mass = 1864.83(5) MeV/c^2, c$\tau(D^0)$ = 122.9 μm

Reconstruct secondary vertex (SV)





Prompt D^0 meson reconstruction & selection

We first filter the tracks

- ML based selections, momentum resolution, quality of the trajectory fit, etc…
- $p_T > 1\ GeV$ and $|\eta| < 2.4$

Look for the decay: $D^0 \rightarrow \pi K$

Prompt D^0 meson reconstruction & selection

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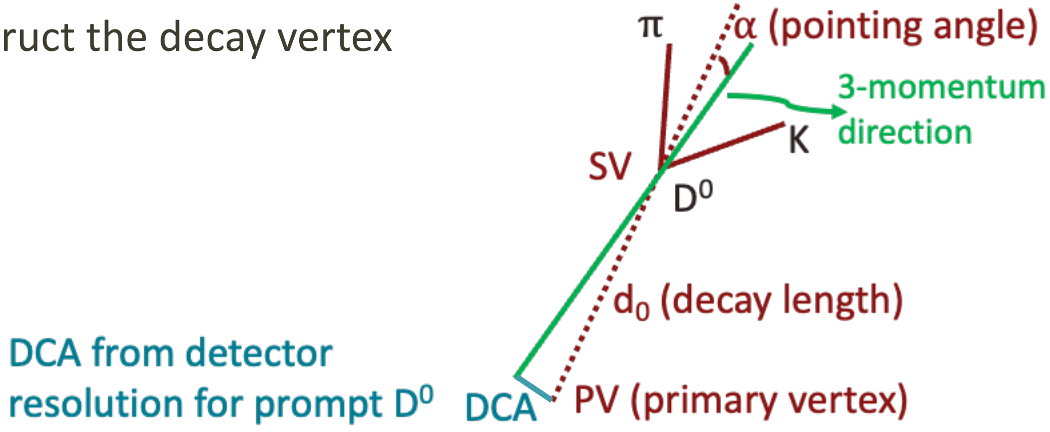
Look for the decay: $D^0 \rightarrow \pi K$

- We do not identify pions and kaons, but combine all pairs of tracks with opposite charge
- Then do a kinematic fit to reconstruct the decay vertex

After kinematic vertex fit

- $\alpha_{3D} < 1$ (pointing angle)
- $1.72 < D^0$ mass $< 2.01\ GeV$
- $D^0 pT > 1\ GeV$



Prompt D^0 meson selection

BDT training

- **Background:** candidates in data using track pairs with wrong sign (+ +, - -)
- **Signal:** candidates in MC matched to generator information

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Variables for training

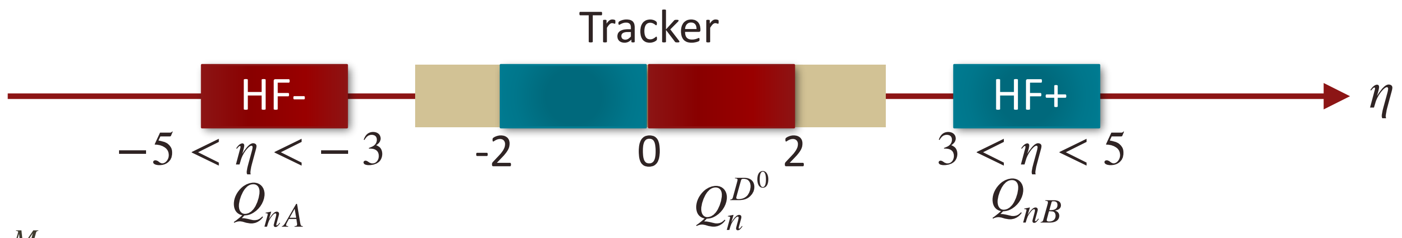
- D^0 mesons
  - Vertex probability, decay length, decay length significance, pointing angle, etc…
- For the two daughters (pion and kaons tracks)
  - Momentum relative uncertainty, DCA significance, number of hits, etc…

Need to optimize BDT score for each analysis bin

We use the scalar product method to measure v_n

Scalar Product method

- Using all the selected D^0 meson candidates
- Use η-gap to reduce effects from correlations not related to medium collectivity (non-flow)
- To measure v_n of D^0 mesons



- $Q_n = \sum_j^M w_j e^{in\phi_j}$ ($w_j := E_T$ for HF; $w_j :=$ track p_T for Tracker; $w_j := 1$ for D^0)

Phys. Rev. Lett. **120** 202301(2018)

- $v_n\{SP\} = \dfrac{\langle Q_n^{D^0} Q_{nA}^* \rangle}{\sqrt{\langle Q_{nA} Q_{nB}^* \rangle}}$, $\langle \ldots \rangle$ mean over all events

Example for D^0 in the positive η

We use the scalar product method to measure v_n

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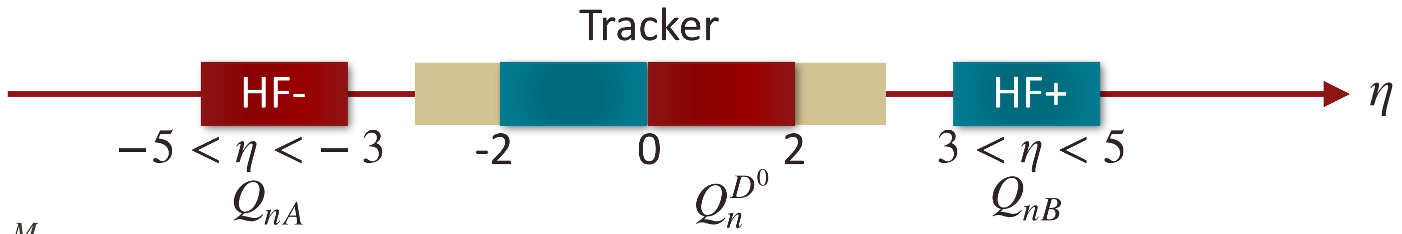

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Phys. Rev. Lett. **120** 202301(2018)

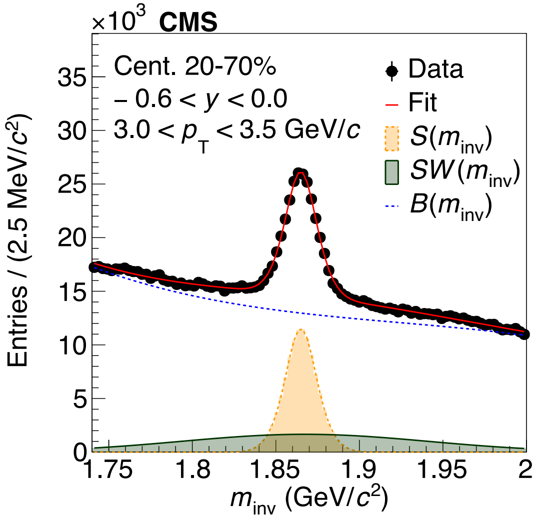
- $$\Delta v_n\{SP\} = \frac{\langle Q_n^{D^0} Q_{nA}^{*} \rangle - \langle Q_n^{\overline{D}^0} Q_{nA}^{*} \rangle}{\sqrt{\langle Q_{nA} Q_{nB}^{*} \rangle}}$$, $\langle \ldots \rangle$ mean over all events

Example for D^0 and $\overline{D}^0$ in the positive η

Signal Δv_n extraction (I)

Fit Δv_n as a function of mass simultaneously with the candidate invariant mass

- Invariant mass fit
  - **Combinatorial background:** third order polynomial
  - **Signal:** two Gaussians with same mean and different widths
  - **Swap (incorrect mass assignment $\pi \leftrightarrow K$):** Gaussian



Signal Δv_n extraction (II)

Fit Δv_n as a function of mass simultaneously with the candidate invariant mass

- Invariant mass fit
  - **Combinatorial background:** third order polynomial
  - **Signal:** two Gaussians with same mean and different widths
  - **Swap (incorrect mass assignment $\pi \leftrightarrow K$):** Gaussian

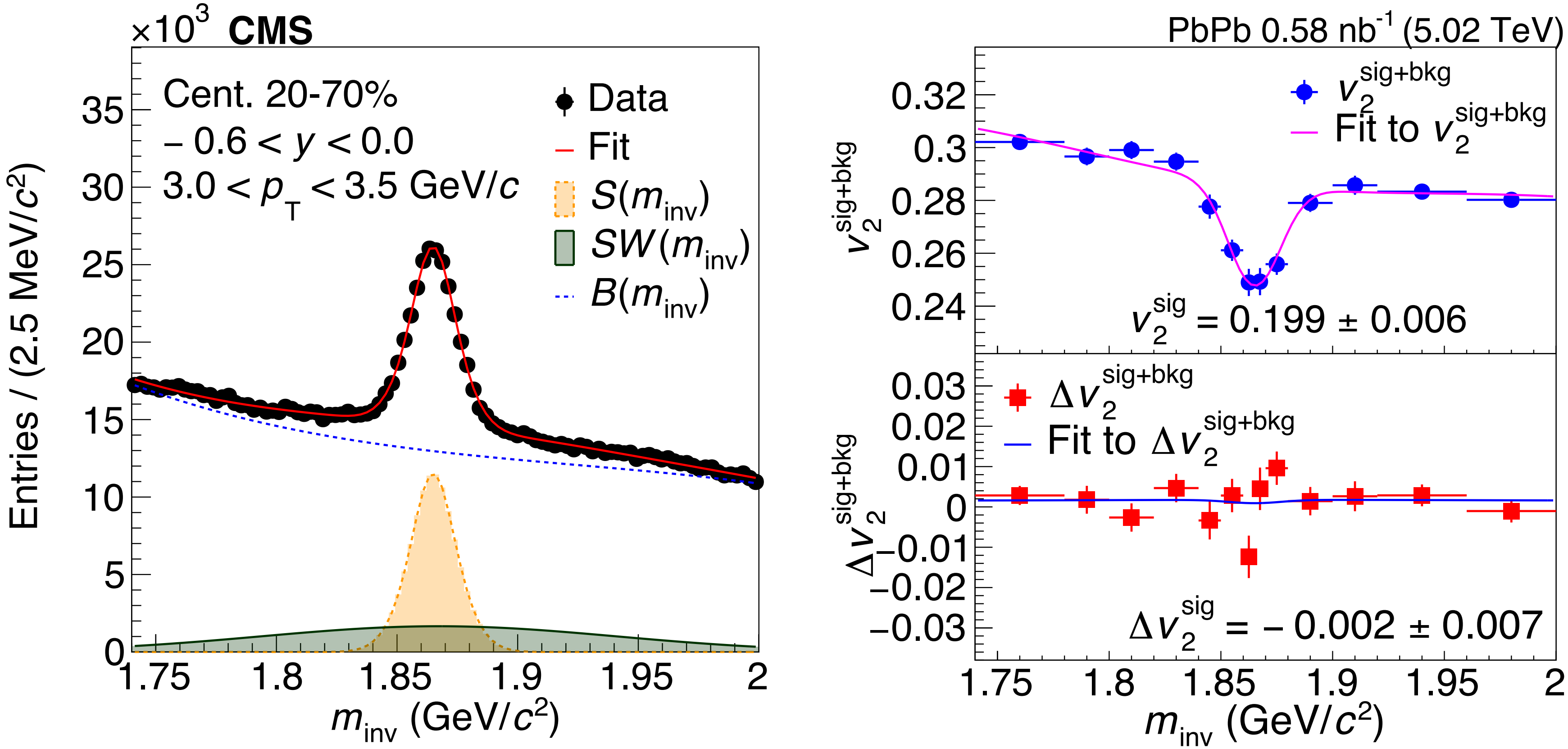
Not used for Δv_n extraction

- $v_n^{sig+bkg} = \alpha(m_{inv})v_n^{sig} + (1 - \alpha(m_{inv}))v_n^{bkg}$
  - $\alpha(m_{inv}) = [sig(m_{inv}) + swap(m_{inv})]/[sig(m_{inv}) + swap(m_{inv}) + bkg(m_{inv})] = \alpha^{sig}(m_{inv}) + \alpha^{swap}$

For Δv_n extraction

- $\Delta v_n^{sig+bkg} = \Delta v_n^{sig}[\alpha^{sig}(m_{inv}) - \alpha^{swap}(M_{inv})] +$ const.

Signal Δv_n extraction (III)



Systematic uncertainties

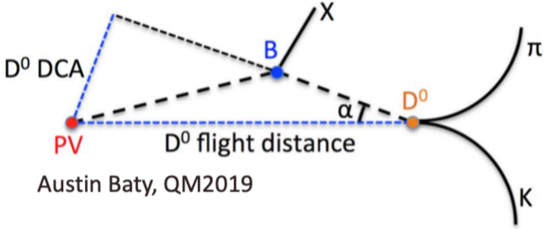
BDT selection

Background mass PDF variation

Background Δv_n PDF variation

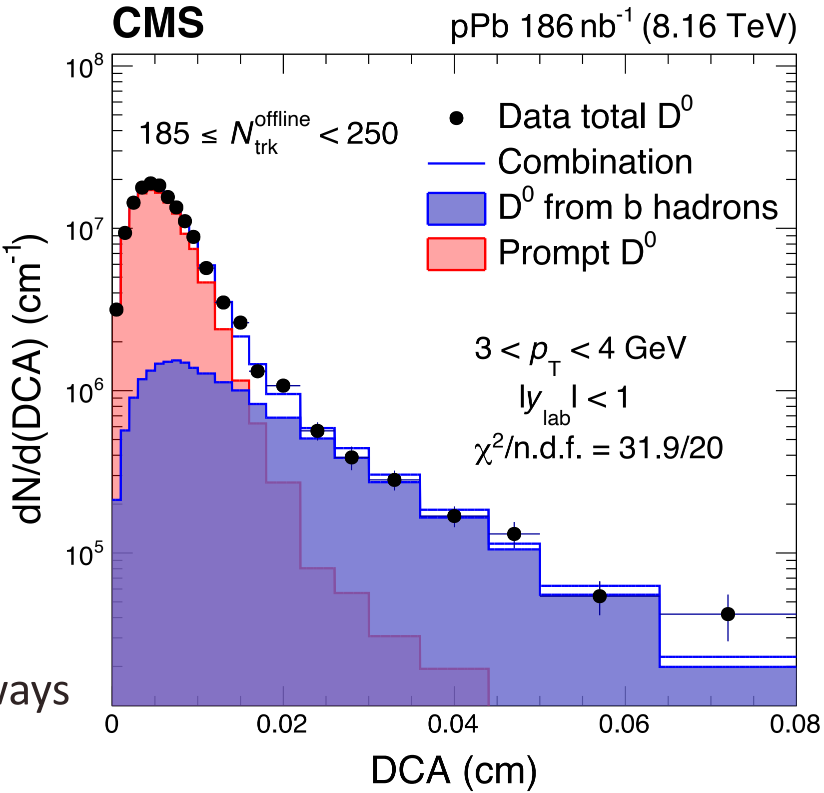
D^0 efficiency corrections using MC simulations

Non-prompt D^0 contamination



Non-prompt D^0 fraction always below 12%

Phys. Lett. B **813**, 136036 (2021)



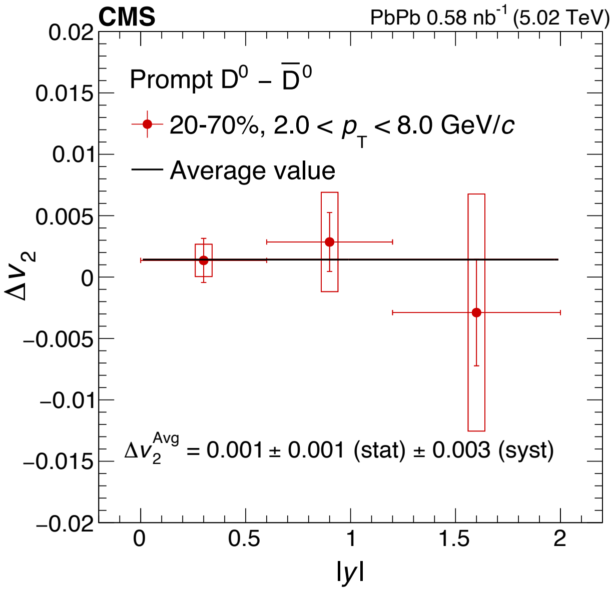
Few selected results using similar techniques

$\Delta v_2(D^0 - \overline{D}^0)$ as function of rapidity

Within uncertainty consistent with zero

Dominated by systematic uncertainty (boxes). How to improve it?

- Large contribution from v_n background modeling and BDT selection



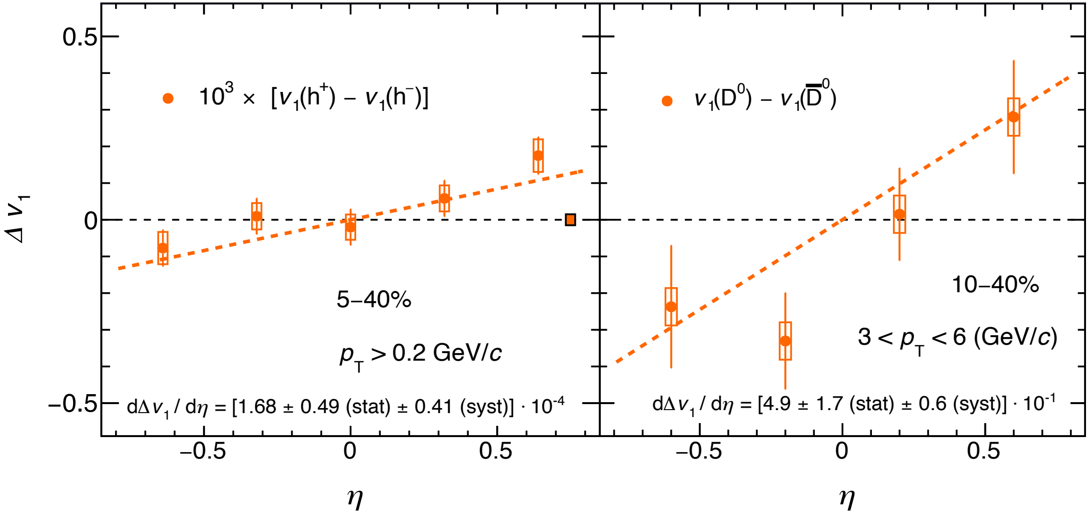
Phys. Lett. B **816** 136253 (2021)

$$\Delta v_2^{Fit} = 0.001 \pm 0.001(stat) \pm 0.003(syst)$$

Considerable effect in Δv_1 of D^0 mesons in the ALICE Collaboration

Still a considerable statistical uncertainty

Positive Δv_1 with significance level around 3σ

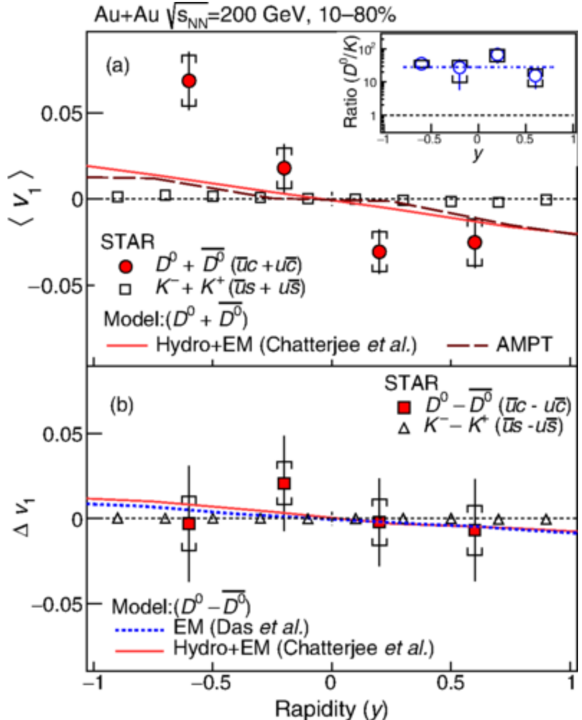


Phys. Rev. Lett. **125** 022301 (2020)

Not clear signal of Δv_1 of D^0 mesons in the STAR Collaboration

Large statistical uncertainties

- ❑ Δv_1 consistent with zero and also with possible EM field effect

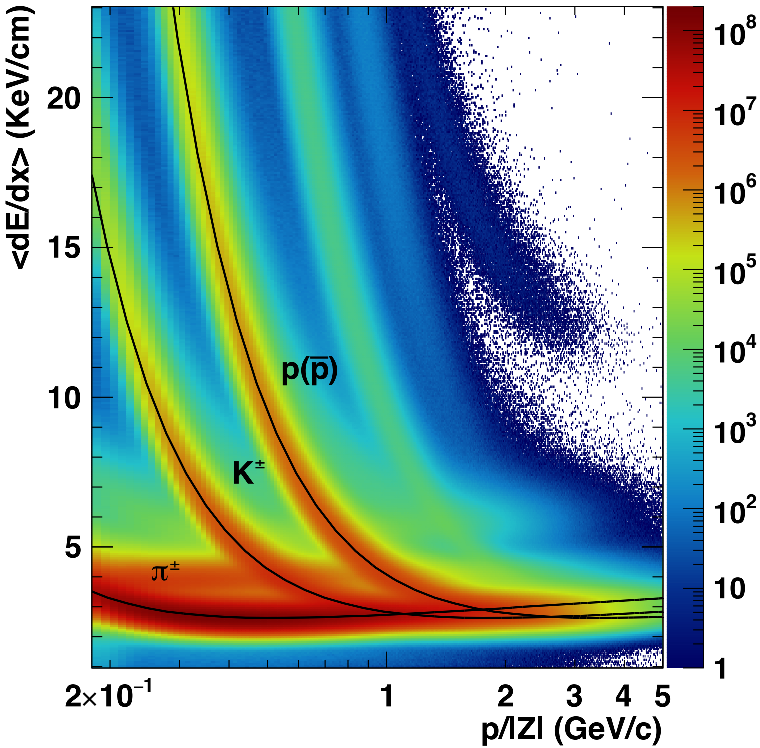


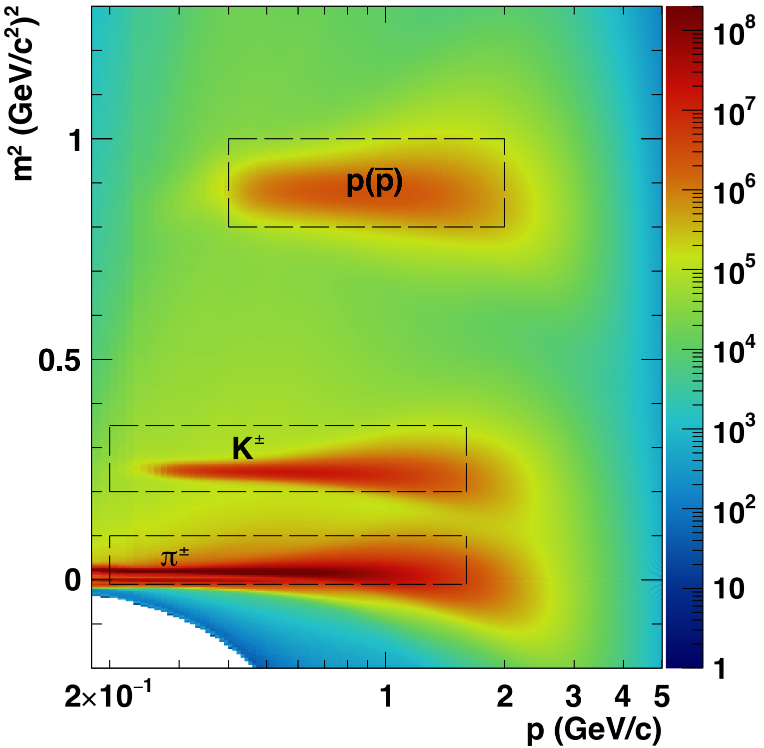
Phys. Rev. Lett. **123** 162301 (2019)

STAR results with pions, kaons and protons

Identification using dE/dx

Phys. Rev. X **14** 011028 (2024)

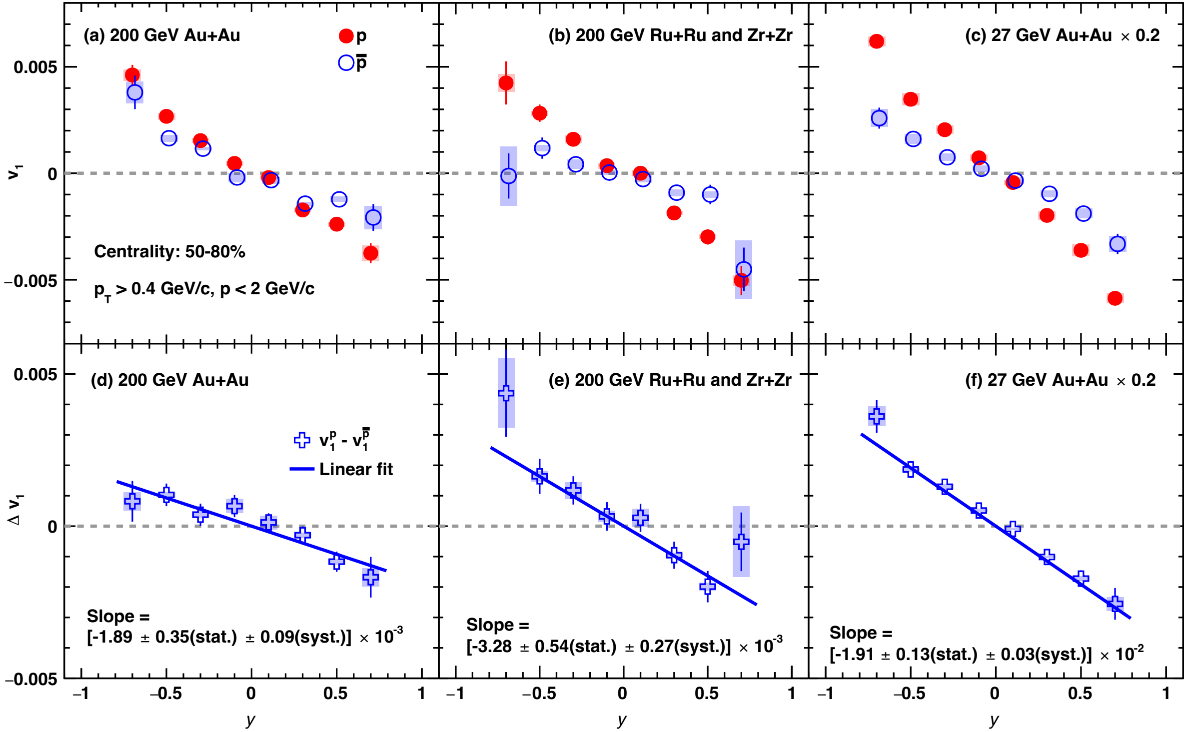




STAR results using protons and antiprotons

Significant difference between p and $\overline{p}$ for different collision systems and energies

Phys. Rev. X **14** 011028 (2024)



Signals consistent with EM field effect on the QGP in symmetric systems with >5σ significance

EM field expected to take more time to vanish at lower collision energy

==>

Stronger effects on v1

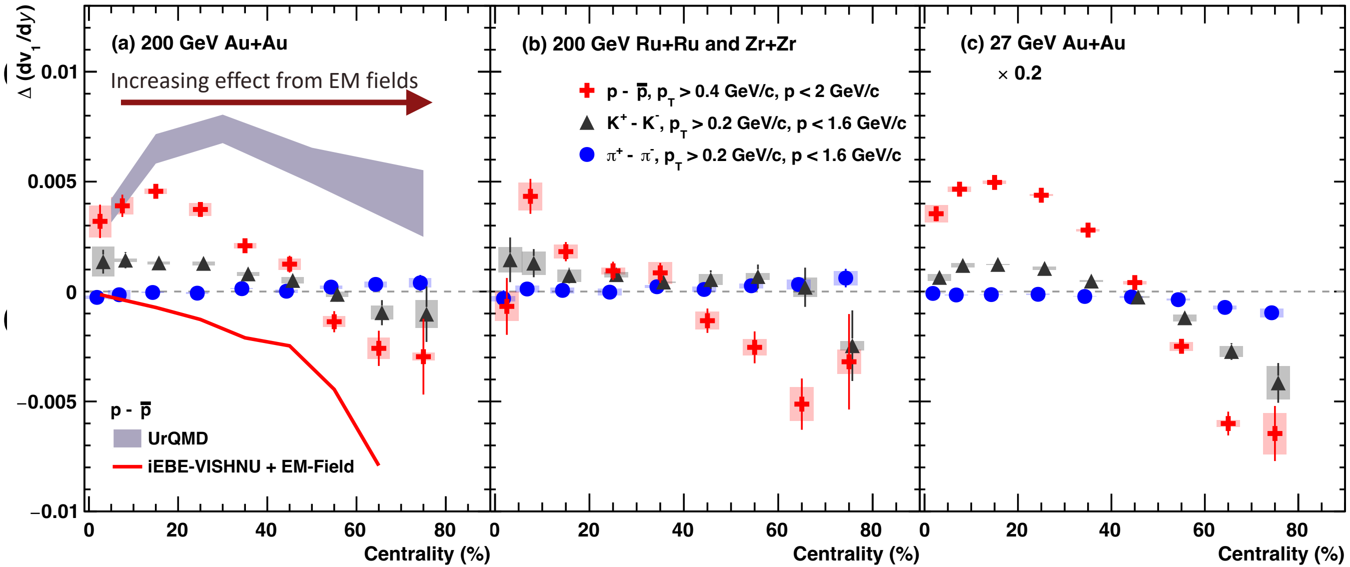
Phys. Rev. D **110** 094032 (2024)

STAR results for different species vs centrality

Production mechanisms can have different contributions depending on centrality

- For mid-central stronger impact from EM field
- Effect of transported u/d quarks from incident nucleons (proton formation through quark recombination) plays an important hole
  - Very complicated to model both effects together

Phys. Rev. X **14** 011028 (2024)



Summary of part 1

LHC

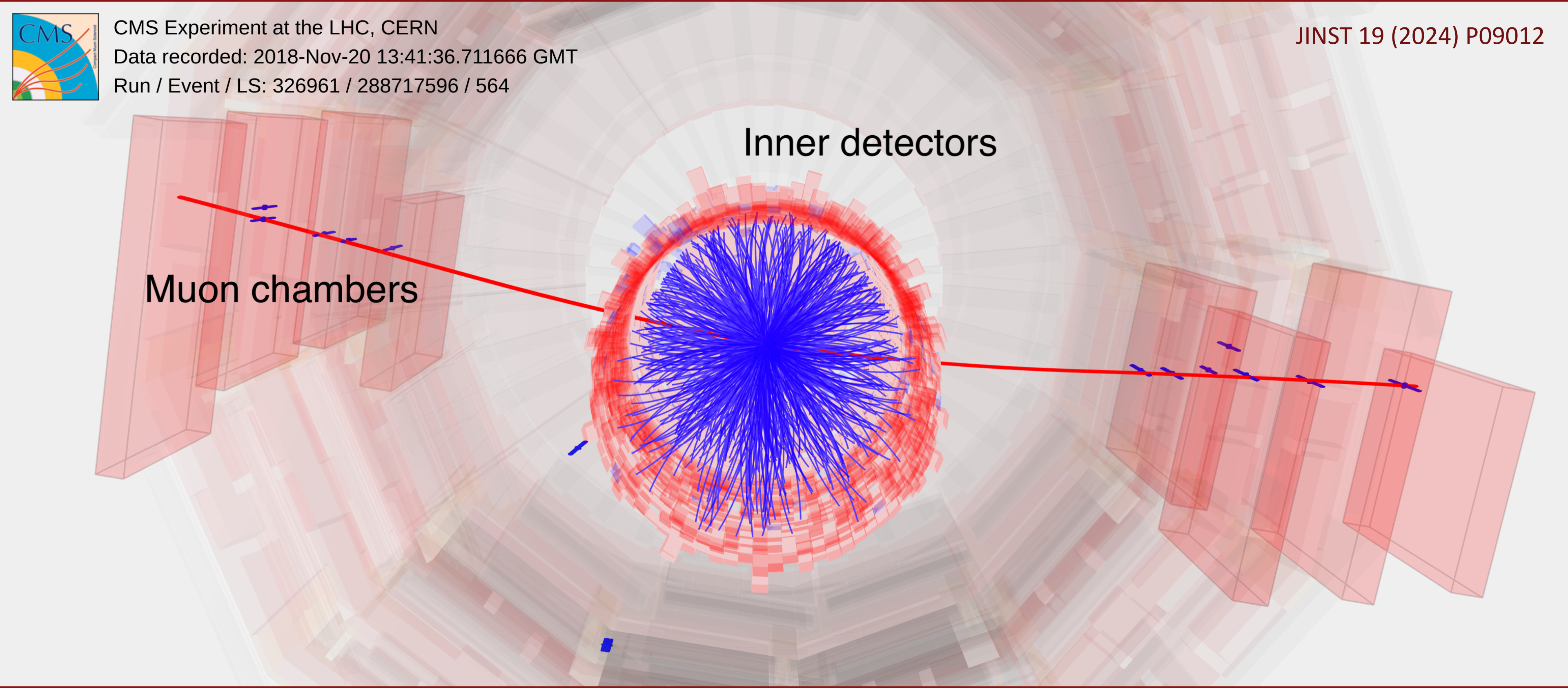
- Perform measurements with full Run3 statistics in PbPb
  - Precise v_1 of D^0 mesons
  - New techniques to diminish systematic uncertainties

RHIC

- Charge-splitting effect in light-hadrons directed flow: qualitative agreement with theoretical calculations
- Theoretical models require full simulations incorporating both transported-quark effects and magnetic field effects
- Charge-dependent directed flow of light hadrons at different collision energies: help explore the beam energy dependence of the magnetic field

Using $Z \rightarrow ll$ bosons measurements

Probe the EM field when its magnitude is at maximum!



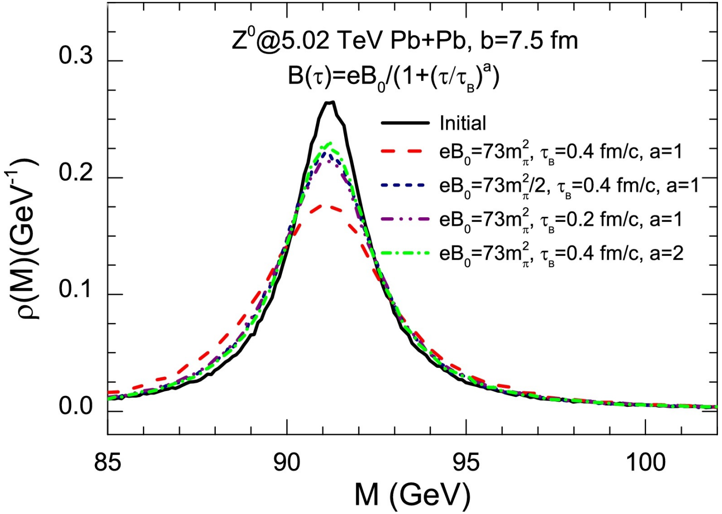
JINST 19 (2024) P09012

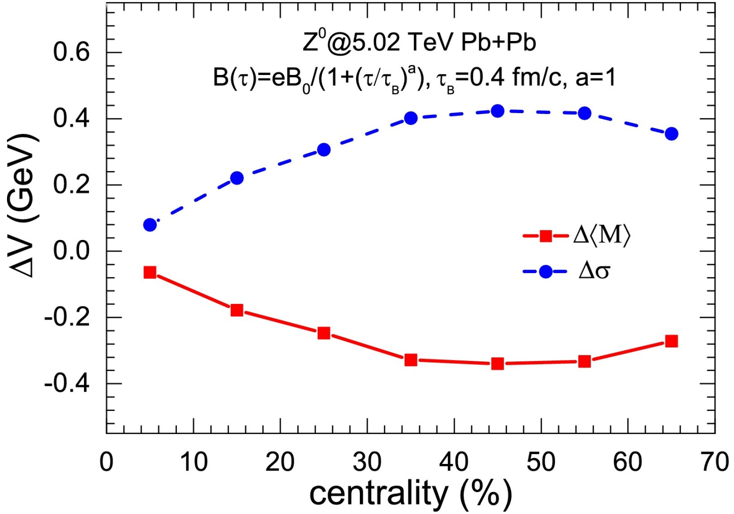
Probing the EM Field via leptonic decay of the Z boson

Strong EM field can leave imprints in charged leptons from Z boson decay

PLB 827 (2022) 136962

- Modification of invariant mass of Z
  - EM field produces Lorentz force on decaying leptons traversing the field modifying their momenta
    - Shift in mass + increase in width
    - Predicted shift on the order of 400 MeV for strongest field
- Strength of modification is dependent on centrality
  - Maximal for semi-central collisions



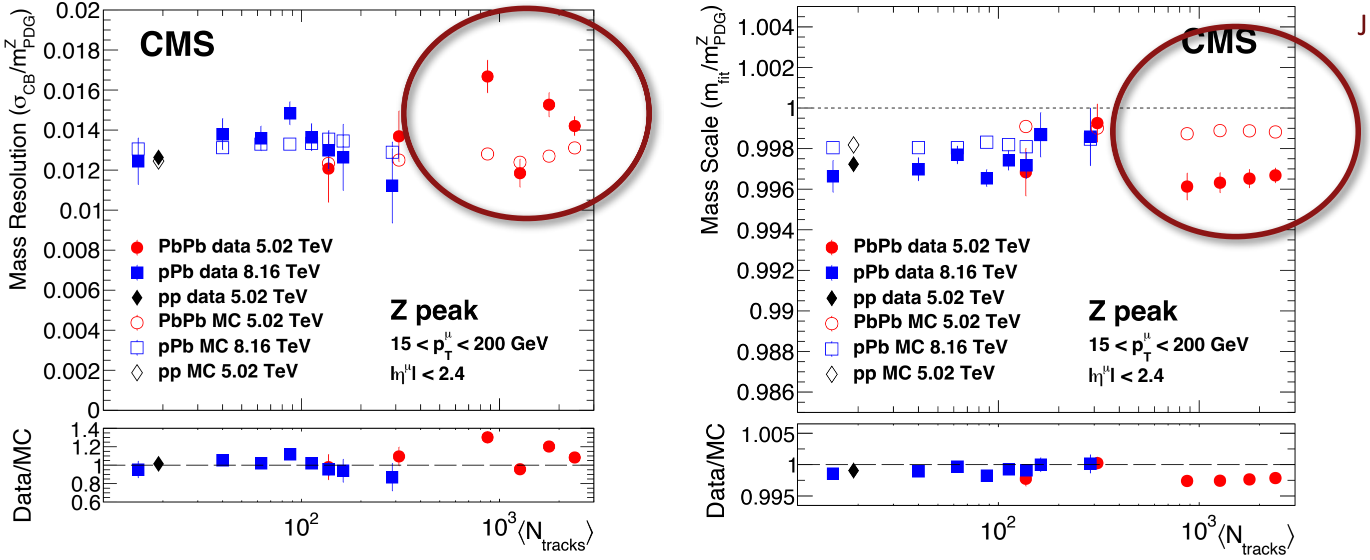


CMS muon performance study

Mass resolution and scale of Z boson: pp, pPb and PbPb

- Fit to Z boson: Breit-Wigner (BW) convolved with Crystal Ball (CB) function
- BW width fixed to Z boson width ($\Gamma_{BW} \sim 2.5GeV$): resolution from σ_{CB}

Larger discrepancy between Data and MC for PbPb



JINST 19 (2024) P09012

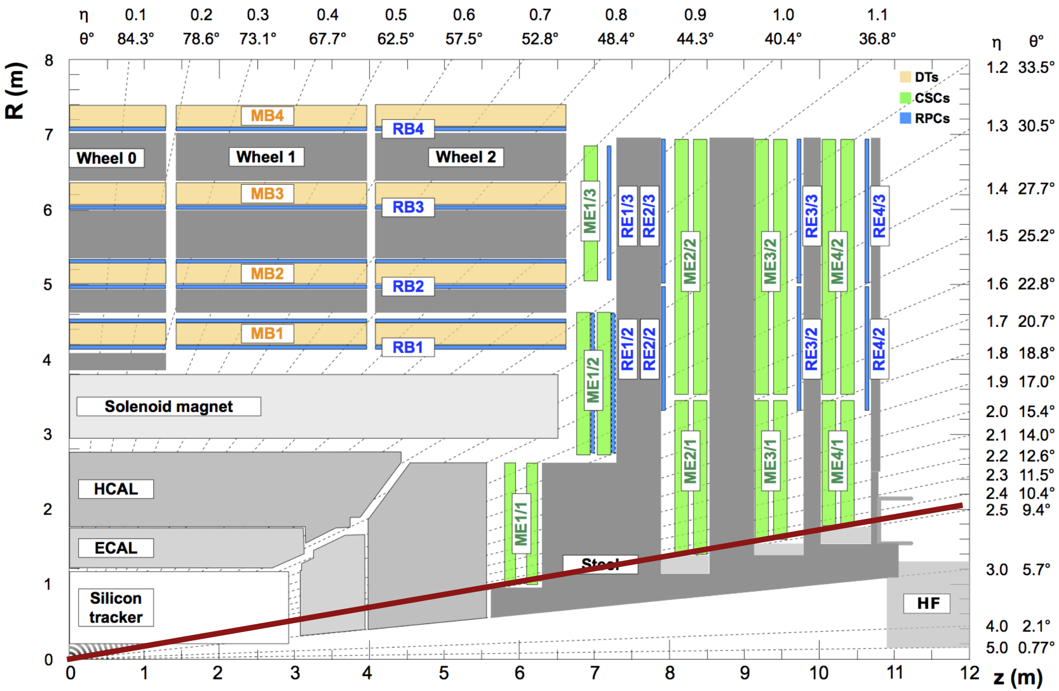
Event selection & lepton selection

Event selection

- ❑ Primary vertex filter
- ❑ Cluster compatibility filter
- ❑ HF coincidence filter
- ❑ Centrality bin selection

Muon selection

- ❑ $|\eta| < 2.4$ and $p_T > 20GeV$
- ❑ Tight muon ID cuts
- ❑ Opposite-charge pairs
- ❑ Vertex probability > 0.001
- ❑ $60 < m_{\mu\mu} < 120GeV$



Analysis goal: Characterizing Z boson mass & width

Constrain magnitude of the EM field in HI collisions using PbPb and pp data

Is there a difference in the invariant mass distribution of the Z boson in PbPb compared to pp?

- How to do it?
  - Mass: measure mean/pole of invariant mass distribution
  - Width: measuring broadness of invariant mass distribution

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- How to do it?
  - Mass: measure mean/pole of invariant mass distribution
  - Width: measuring broadness of invariant mass distribution
- Some procedures implemented in CMS
  - Window counting: calculate mean and standard deviation from mass spectrum histogram (after background subtraction with a fit) [proposed in PLB 827 (2022) 136962]
  - Fit PDF: fit mass distribution with signal + background PDF
  - Template fit: generate MC template, re-weight to obtain large family of curves, compare each to data choose best χ^2

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Calibrations, resolution and natural width appear in both, but EM effect expected only in PbPb

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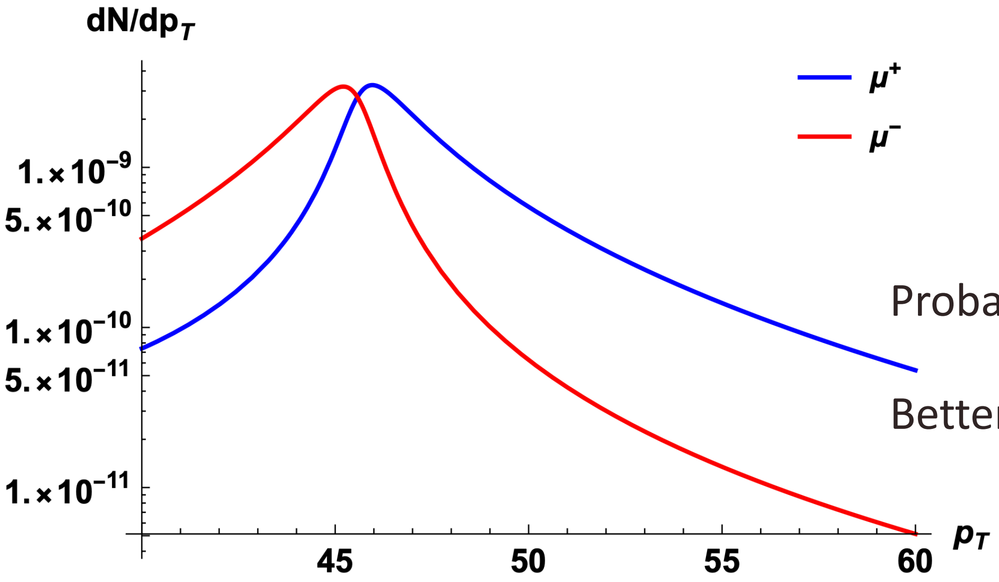
Measure the differences: $\Delta M = M_{\mathrm{PbPb}} - M_{\mathrm{pp}}$, $\Delta\sigma = \sigma_{\mathrm{PbPb}} - \sigma_{\mathrm{pp}}$

- Large cancelation of systematics
- Absolute values for M and σ in principle very different, but comparison between PbPb should be consistent and with different systematic level

New studies

Predicted to modify the p_T spectrum of the múons from Z decay



See Alejandro Ayala's talk at 9th Conference on Chirality, Vorticity and Magnetic Fields in Quark Matter

Probably quantify as $\frac{p_T^{\mu^+} - p_T^{\mu^-}}{p_T^{\mu^+} + p_T^{\mu^-}}$?

Better to cancel systematic uncertainties.

- The μ^+ peak is shifted towards larger values compared to the μ^- peak
  - Order of 2 GeV

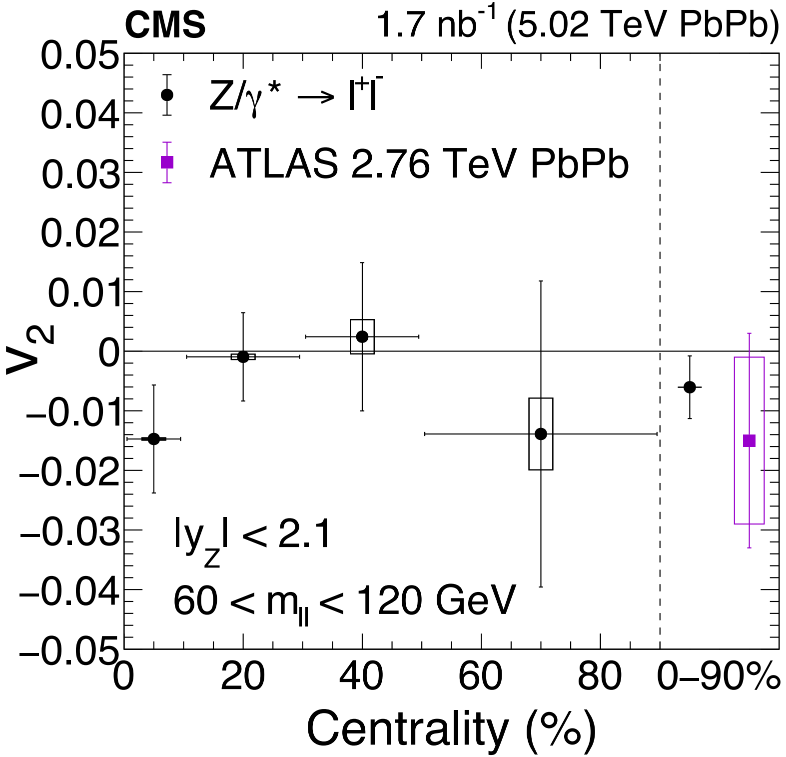
Run 3 projections

Current analysis: 2018 PbPb 5.02 TeV (1.72/nb)

- Around 5k Z bosons after selection (muon/electron channels)
  => expect stat. uncert. larger than syst. uncert.

Run 3: expect around 6-7/nb in total for PbPb 5.36 TeV

- Plus improvements on selections
  => around 7-10x more statistics



Summary of part 2

Ongoing analysis in CMS on the Z boson mass and width

- Expectation: statistical uncertainties to be much larger than systematics

Run 3 will give a considerable gain in statistics

Probably also try Δv_1 between positive and negative leptons

SPRACE

Thank You!

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