Probe QCD matters using heavy flavor quarks at the LHC with CMS experiment

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Rice University

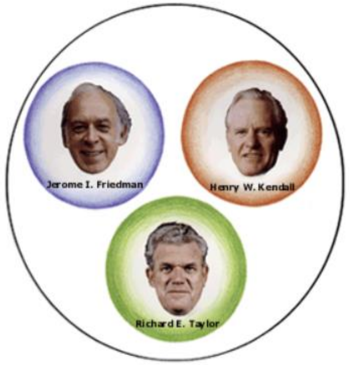
Thursday, February 16, 2023

Particle physics seminar @BNL

Quantum chromodynamics

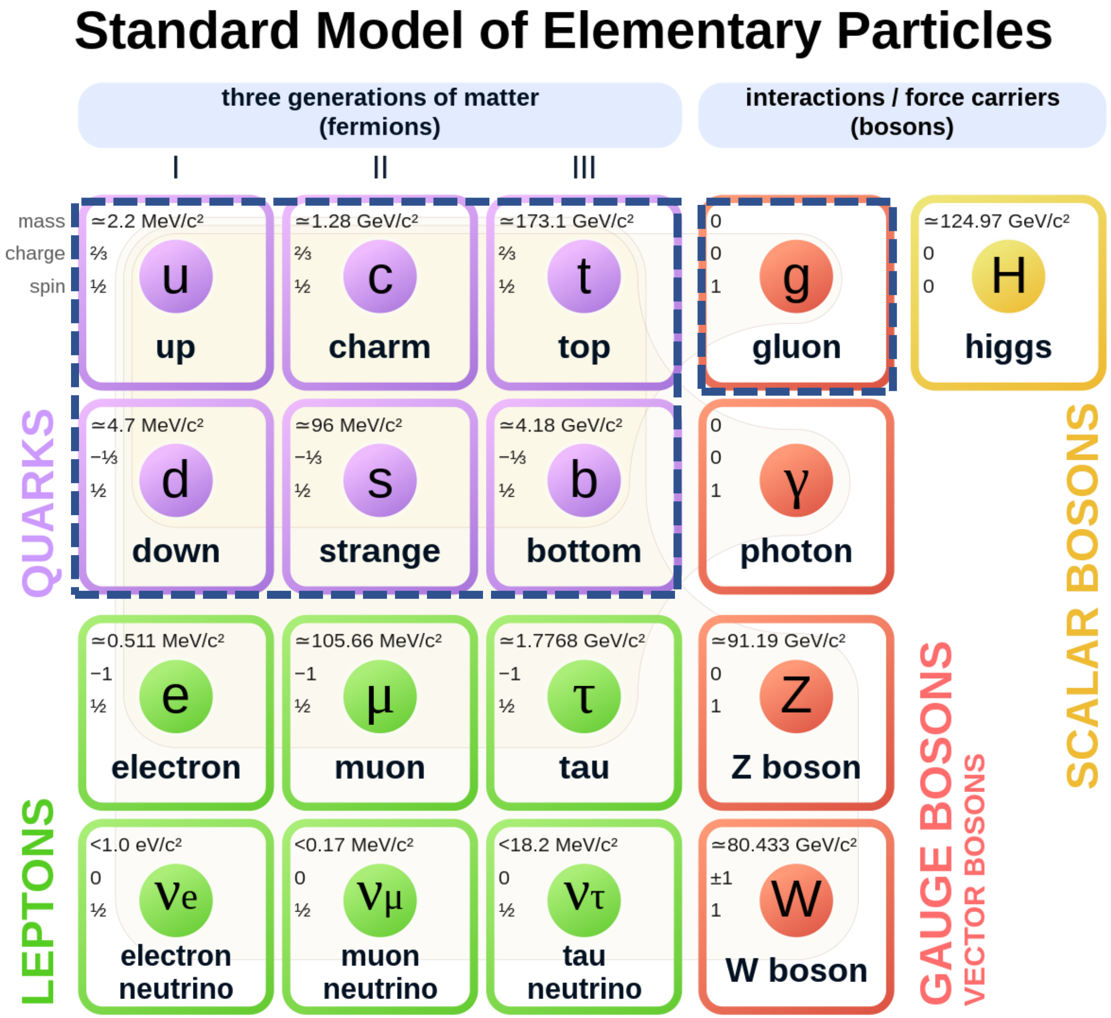
- Partons are confined in hadrons

The Nobel Prize in Physics 1990



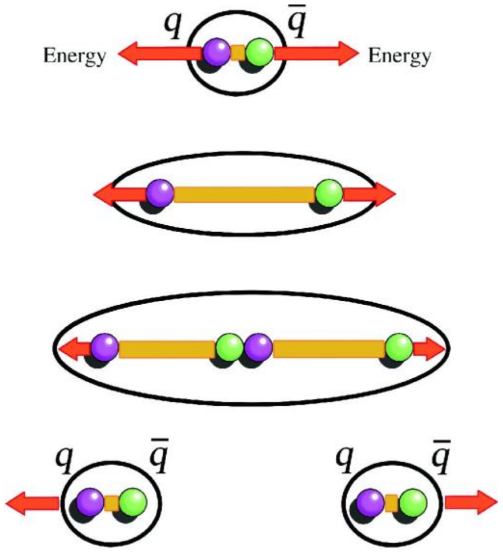
- Asymptotic freedom

The Nobel Prize in Physics 2004

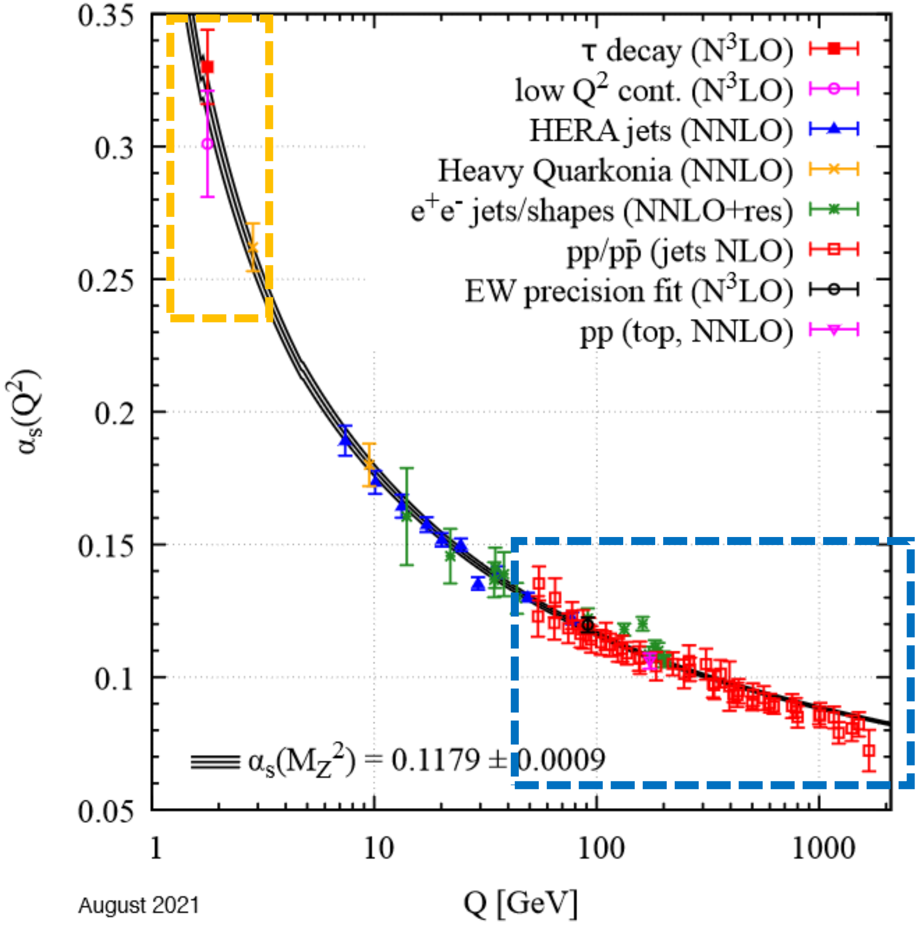


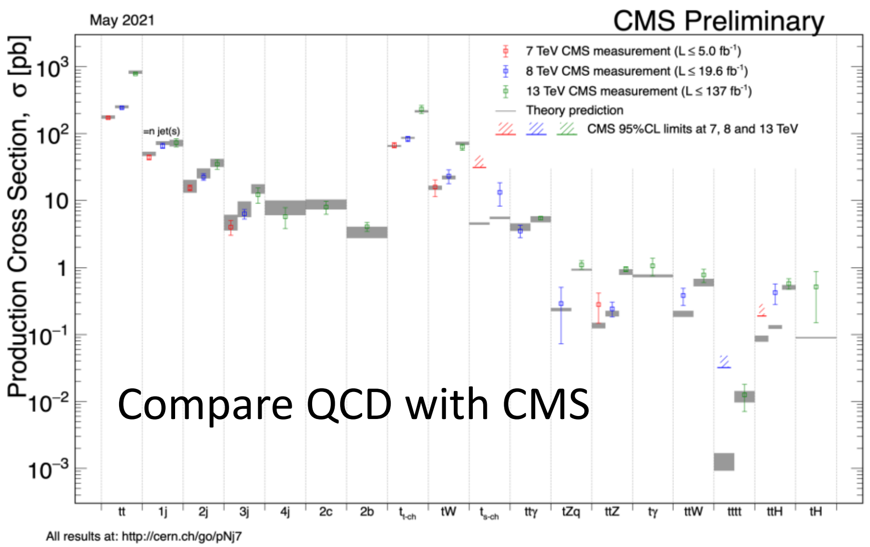
Running coupling strength

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



Prog. Theor. Exp. Phys. 2022, 083C01 (2022)





Confinement in non-perturbative regime

Successful perturbative QCD

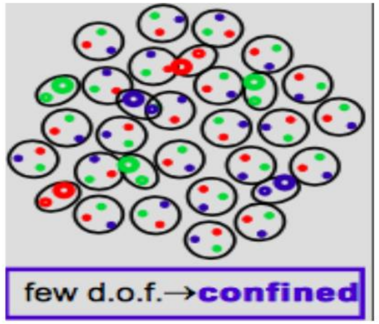
QCD Diagram

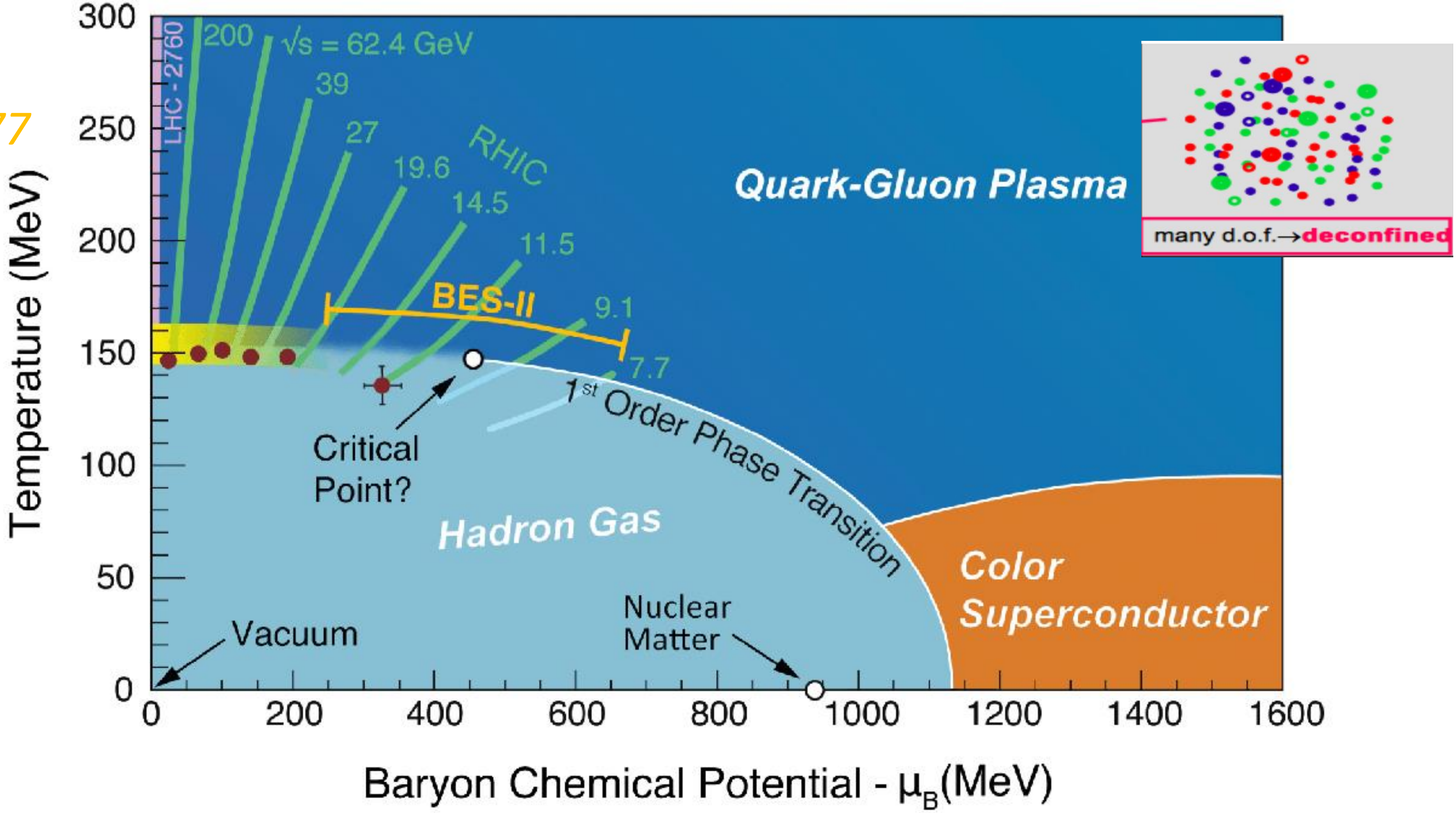
"More is different"

P. W. Anderson

Nobel prize in physics 1977

Credit: BNL





QGP in laboratory

- QGP can be created in relativistic heavy-ion collisions

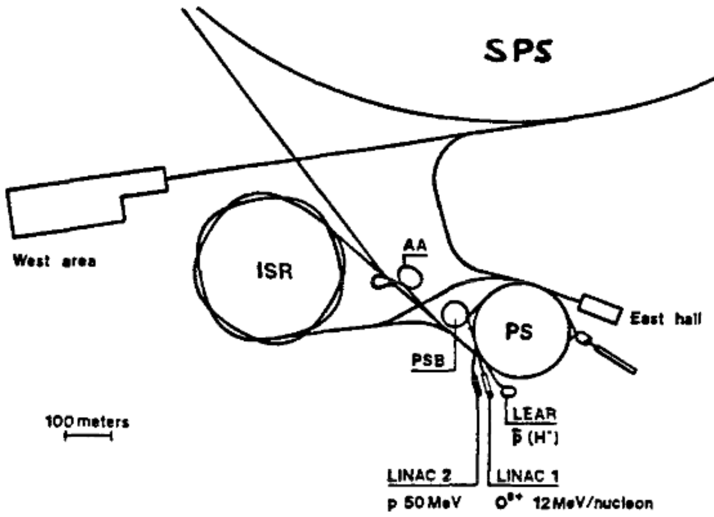
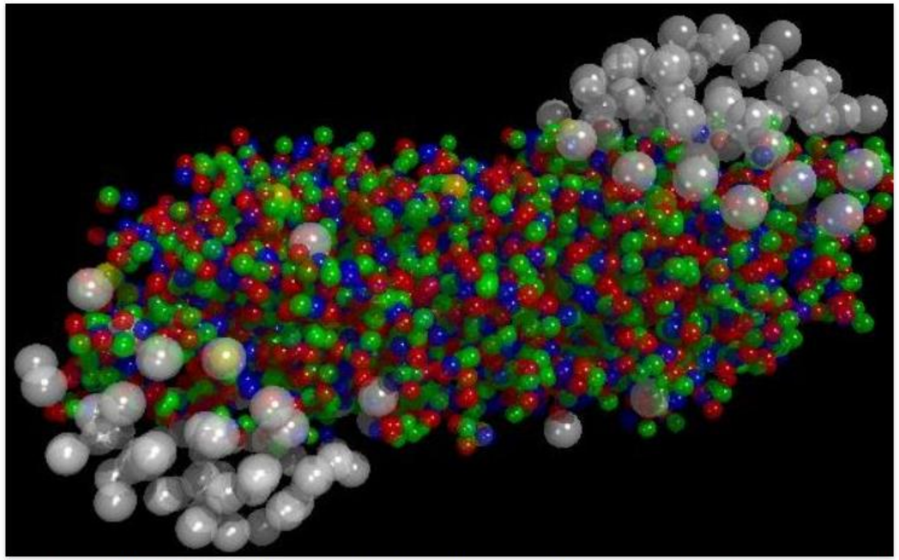


FIGURE 1

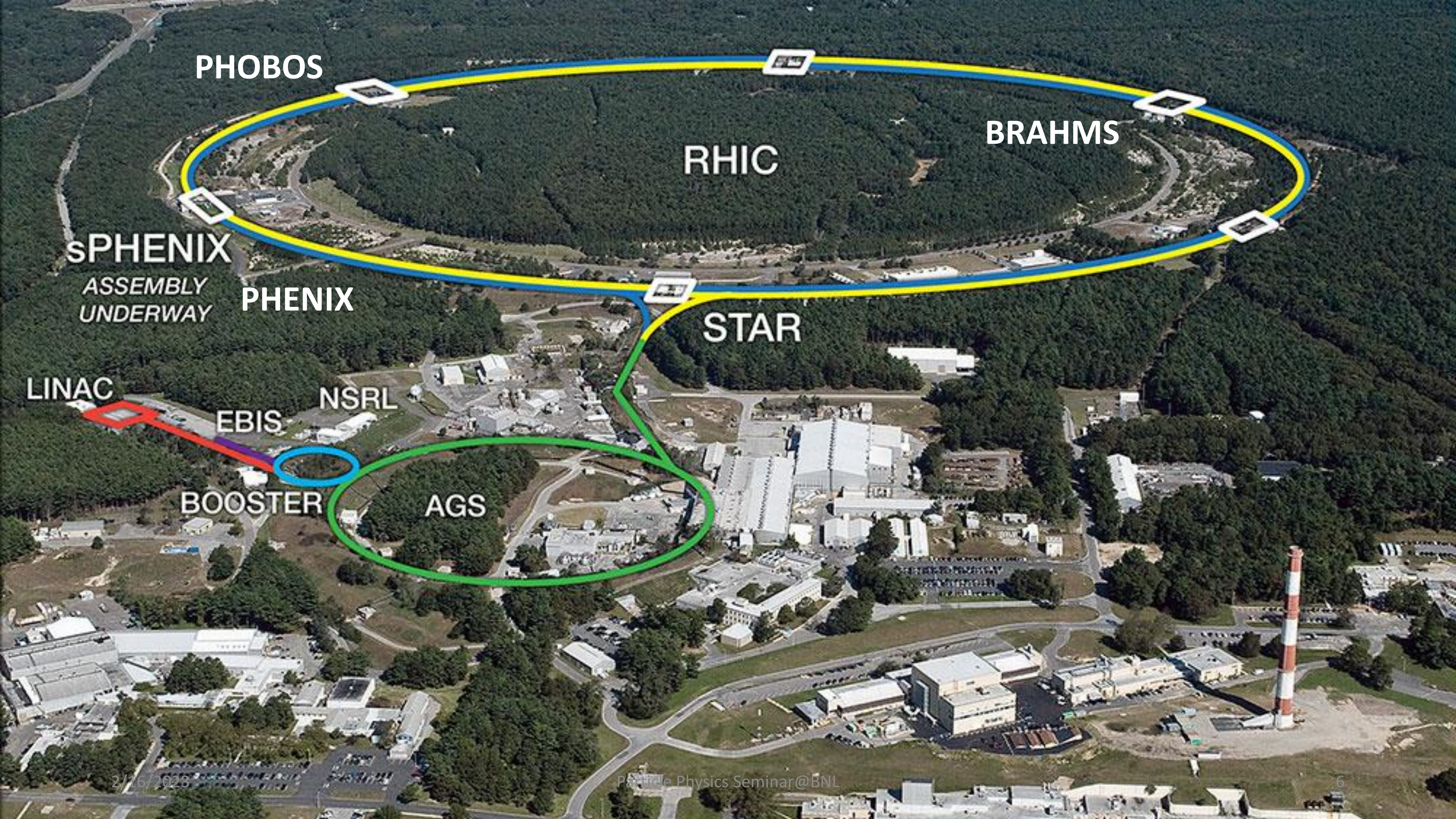
Layout of the CERN accelerators. Heavy ion running involves the new injector (Fig. 2), Linac 1, the Booster (PSB), the PS and SPS which extracts to the West and North (not shown) experimental areas.

New State of Matter created at CERN

10 FEBRUARY, 2000

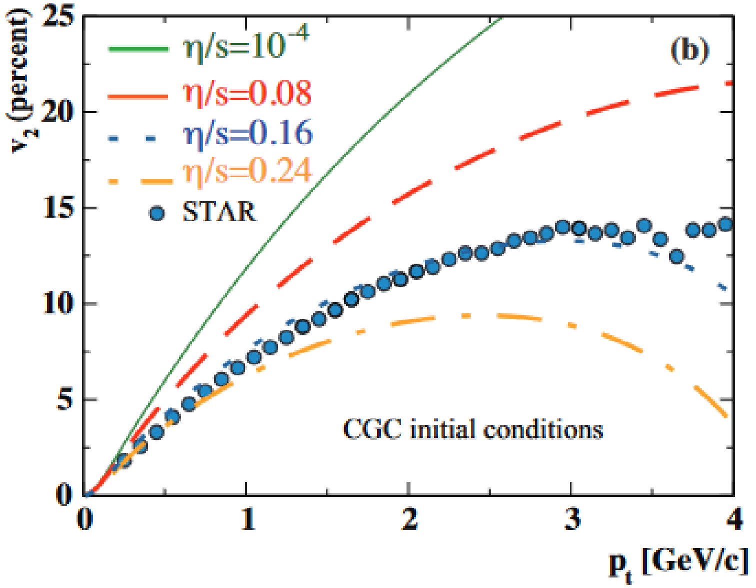


Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.


PHOBOS
BRAHMS
RHIC
sPHENIX
ASSEMBLY
UNDERWAY
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

Macroscopic properties of QGP

- Strongly coupled QGP and perfect liquid
- Smallest specific shear viscosity ever seen



RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

Phys. Rev. Lett. 86 (2001) 402

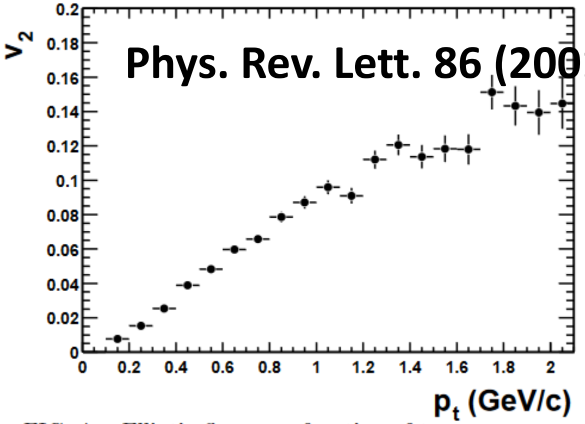
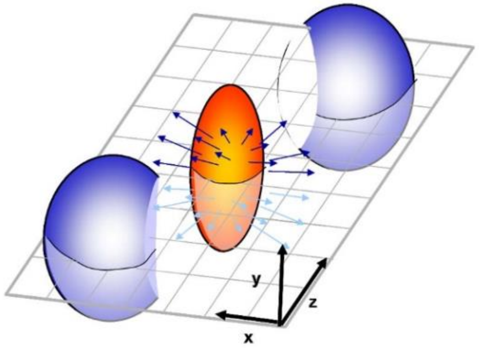


FIG. 4. Elliptic flow as a function of transverse momentum for minimum bias events.

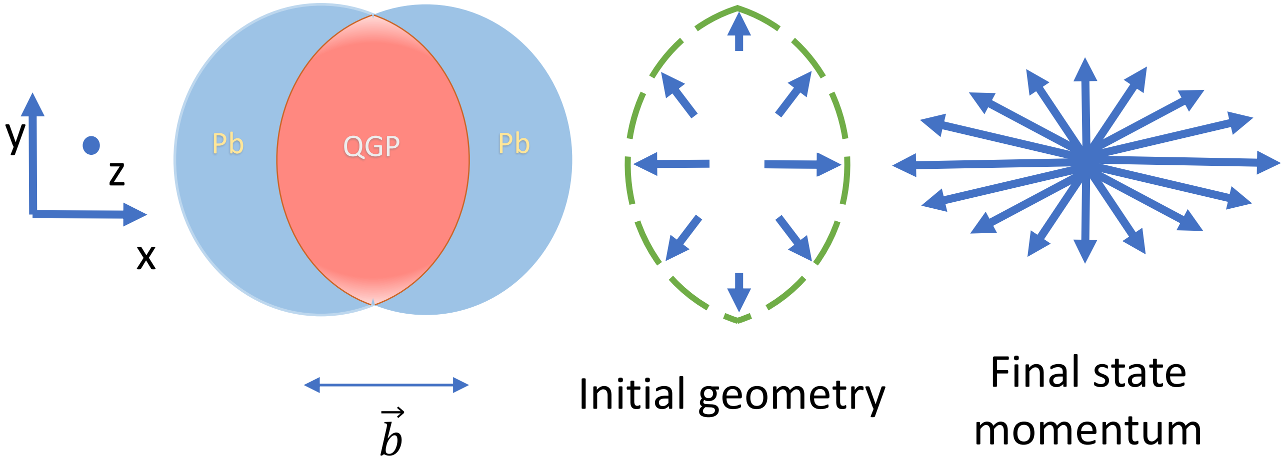
Hydrodynamics and elliptic flow



- Soft processes between QGP constituents
- Hydrodynamic view
  - expansion is driven by the pressure gradient
  - Momentum flow $p_x > p_y$ → $v_2 > 0$

$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$$

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})]\right)$$



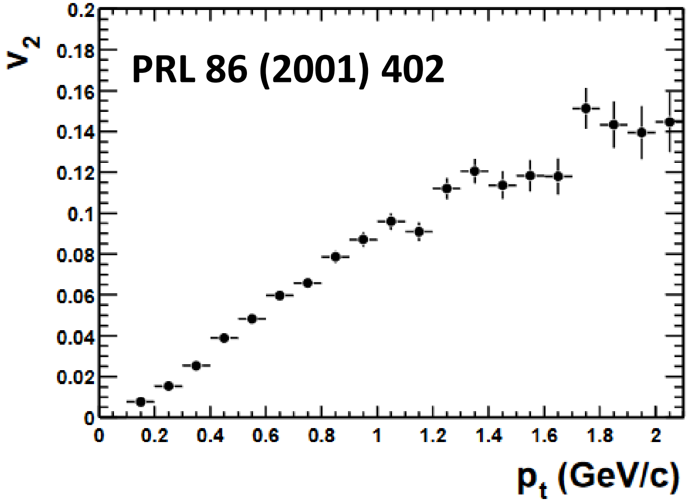


FIG. 4. Elliptic flow as a function of transverse momentum for minimum bias events.

Elliptic Flow in $Au + Au$ Collisions at $\sqrt{s_{NN}} = 130$ GeV

K. H. Ackermann *et al.* (STAR Collaboration)
Phys. Rev. Lett. **86**, 402 – Published 15 January 2001

NCQ scaling and v_2

- Close partons join together, *Number of Constituent Quark scaling*
  - Coalescence processes are visible at mediate p_T

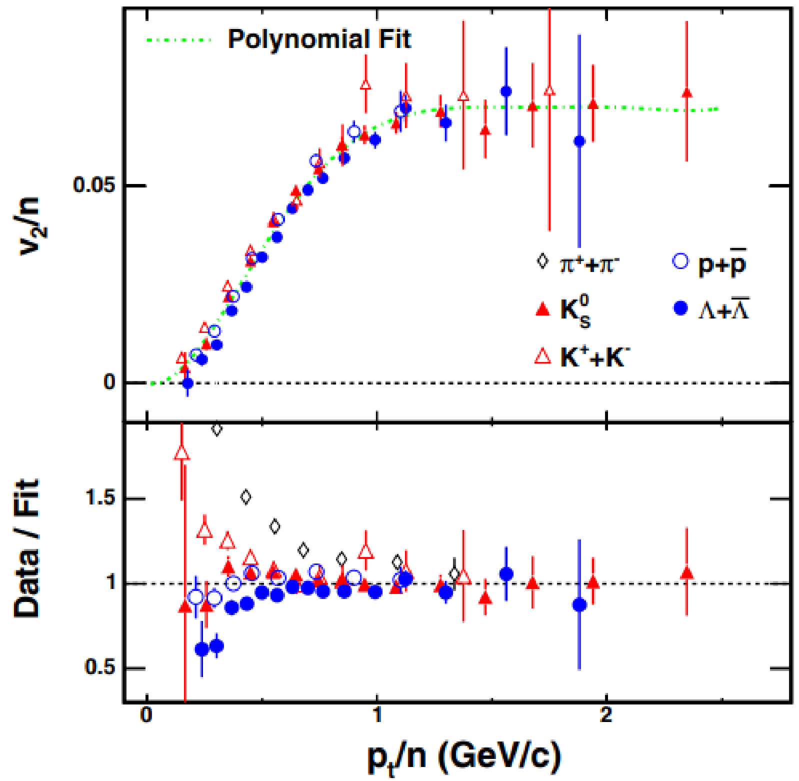
$$\frac{dN_B}{d^2p_\perp}(\vec{p}_\perp) = C_B(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/3)\right]^3$$

$$\frac{dN_M}{d^2p_\perp}(\vec{p}_\perp) = C_M(p_\perp)\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/2)\right]^2$$

$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right)$$

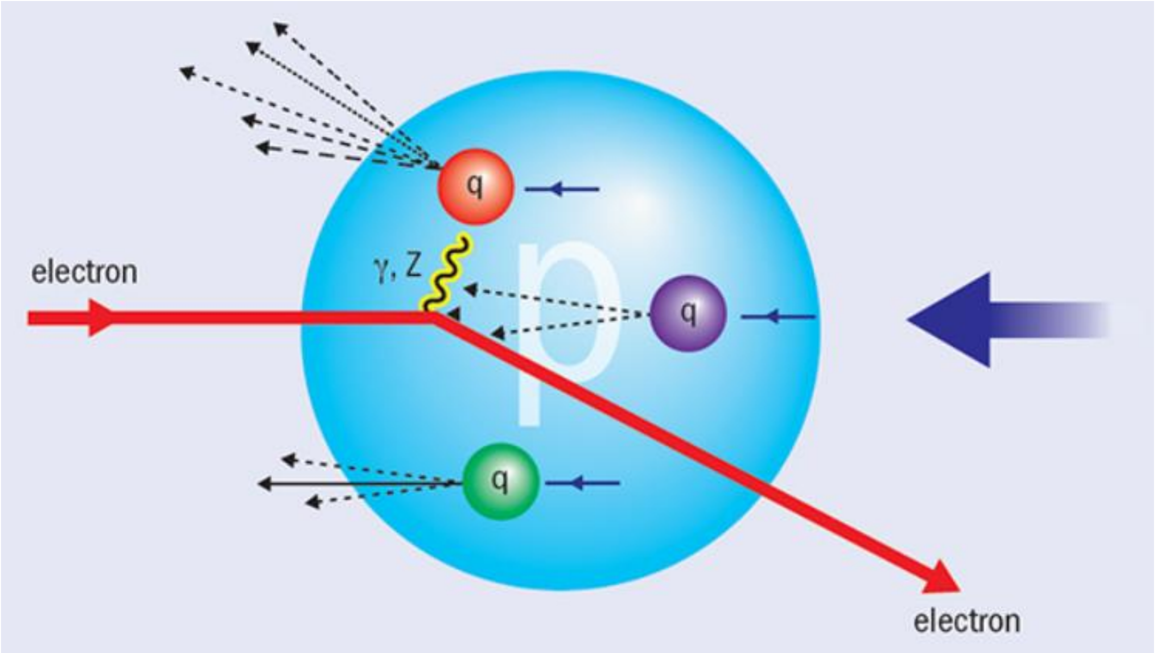
$$v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right)$$

Phys.Rev.Lett. 91 (2003) 092301



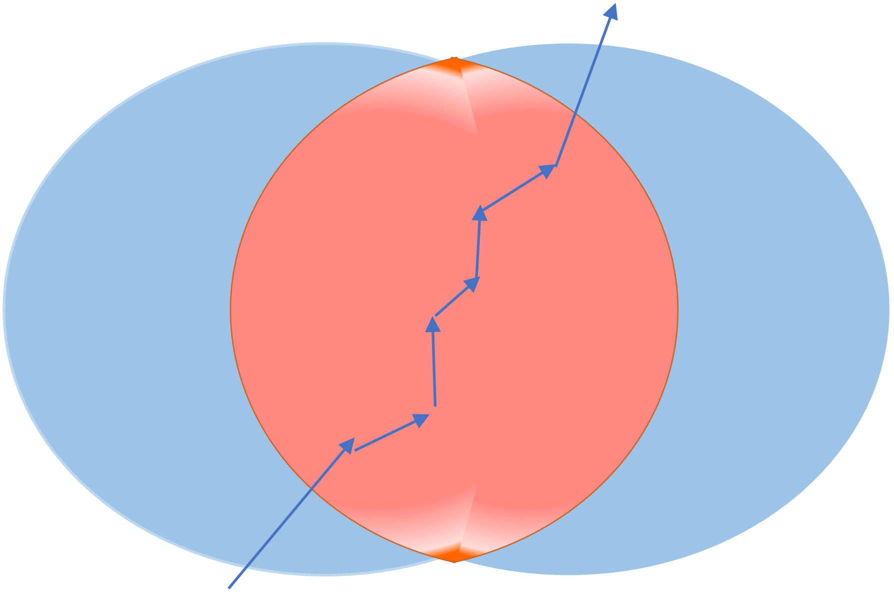
Probe microscopic properties of QGP

- Probe structure in protons
  - Proton is long-lived ☺



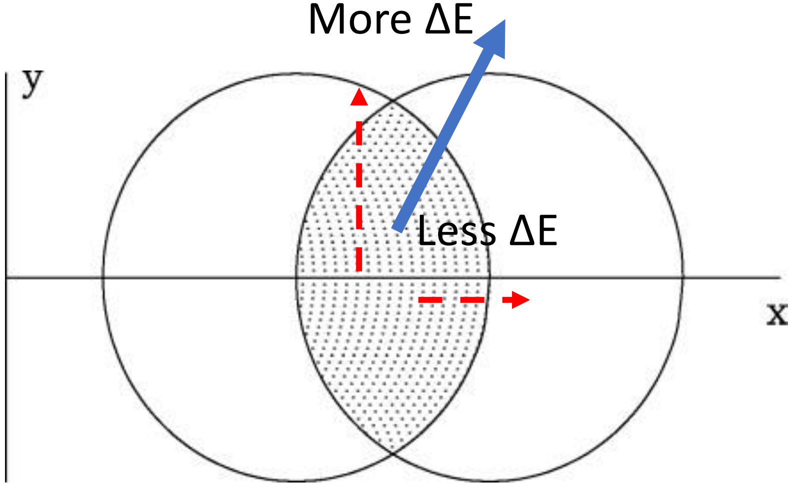
Credit: DESY

- Probe structure in QGP
  - QGP is short lived(<10fm/c) ☹
  - Jets and heavy flavor quarks at the initial stage



Jet quenching and v_2

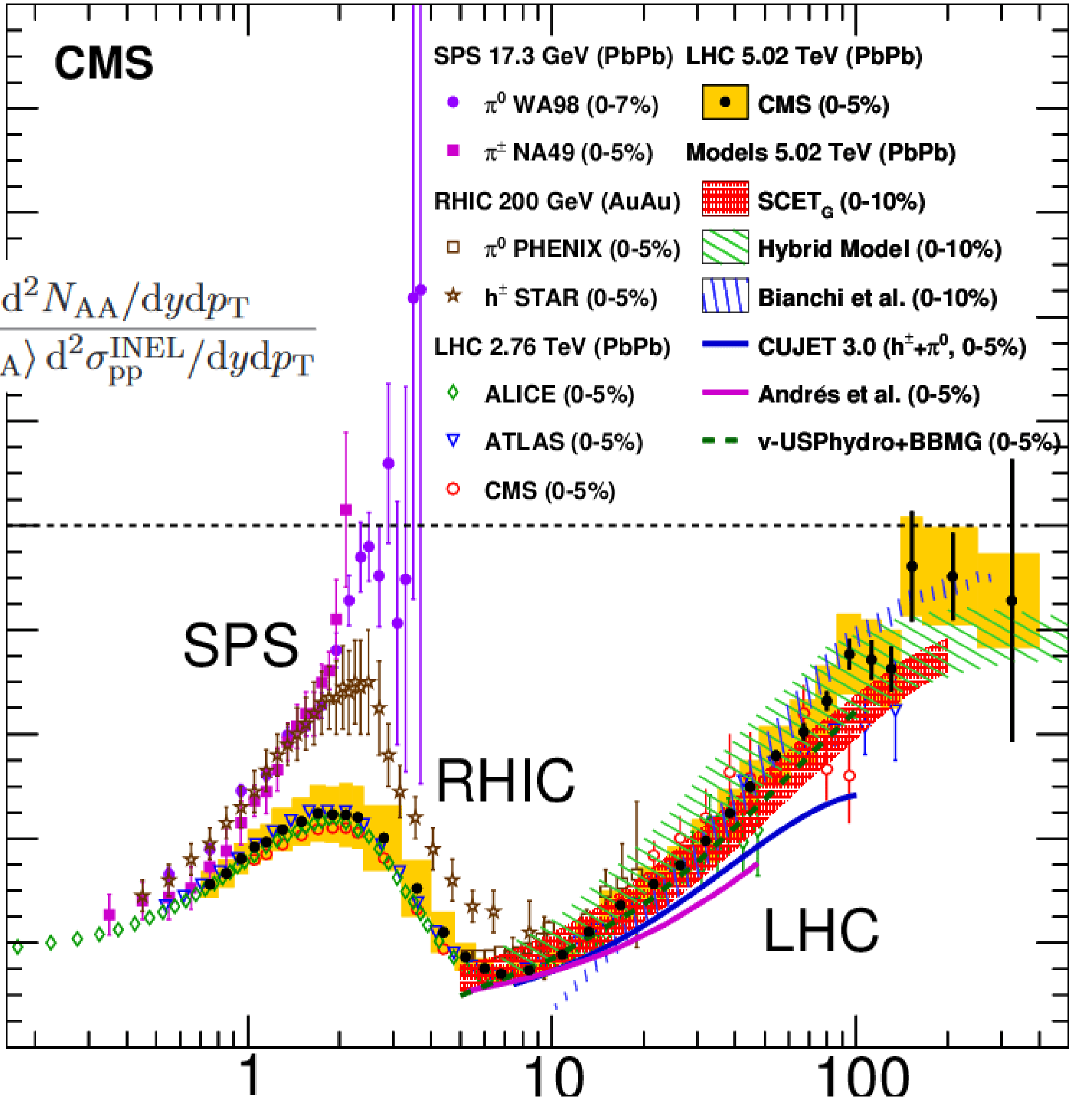
- Hard partons quenched in QGP
- HP suffer different energy losses in different directions – positive v_2



Jet Quenching and Azimuthal Anisotropy of Large p_T Spectra in Non-central High-energy Heavy-ion Collisions

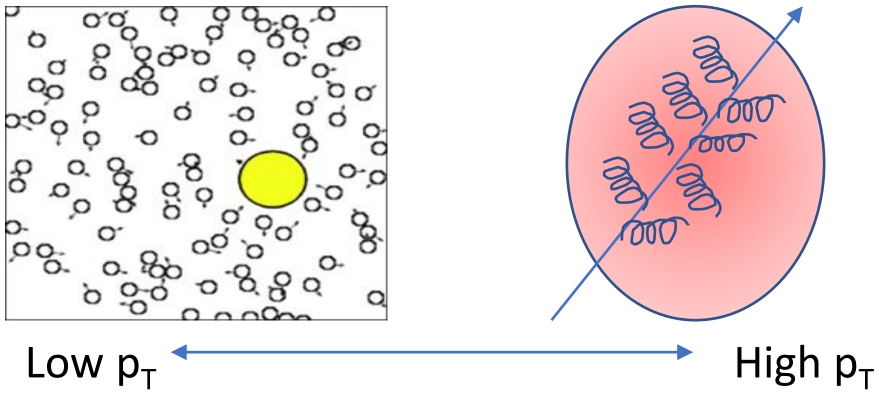
Xin-Nian Wang
Nuclear Science Division, Mailstop 70-319, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720.
(August 30, 2000)

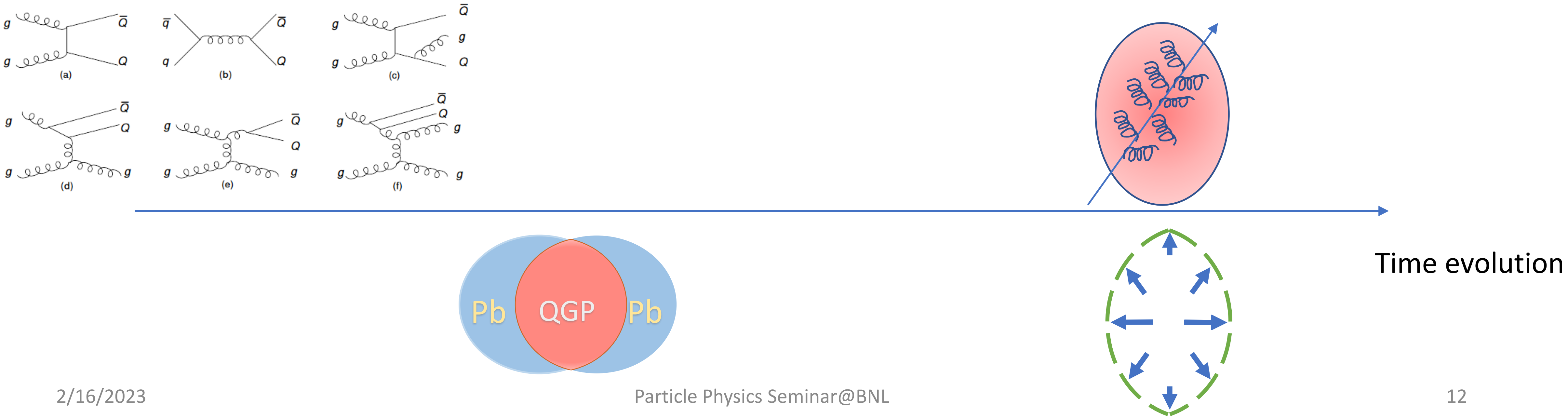
$$R_{AA} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}\rangle\, d^2\sigma_{pp}^{INEL}/dydp_T}$$



Heavy flavor quarks in QGP

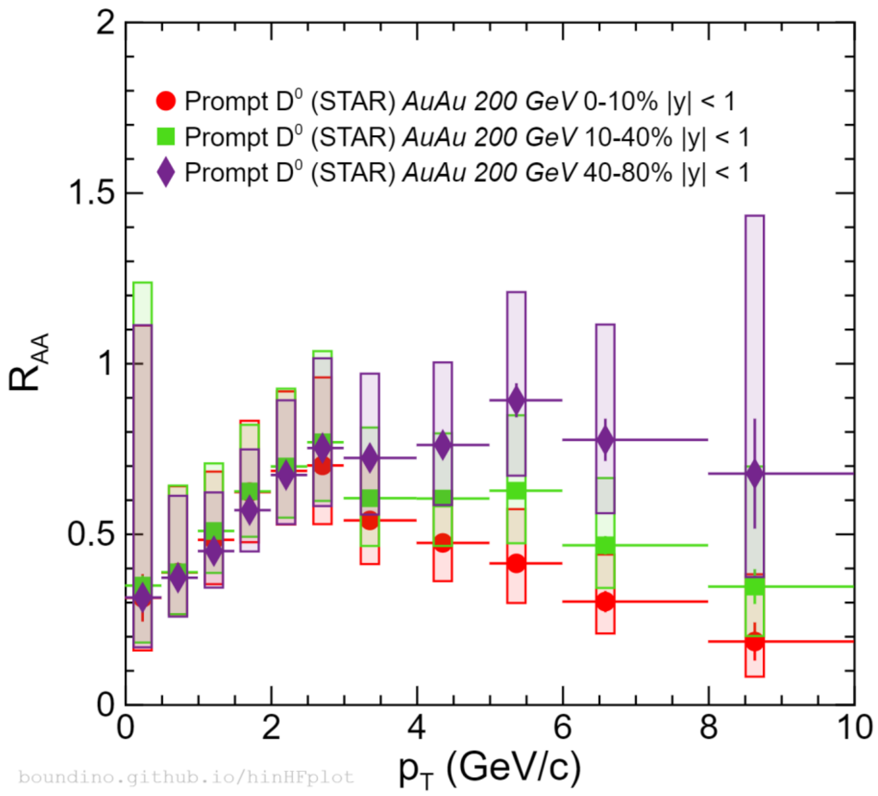
- Early productions in collisions
- Sensitive in full phase space
  - Brownian motions
  - Radiative energy losses



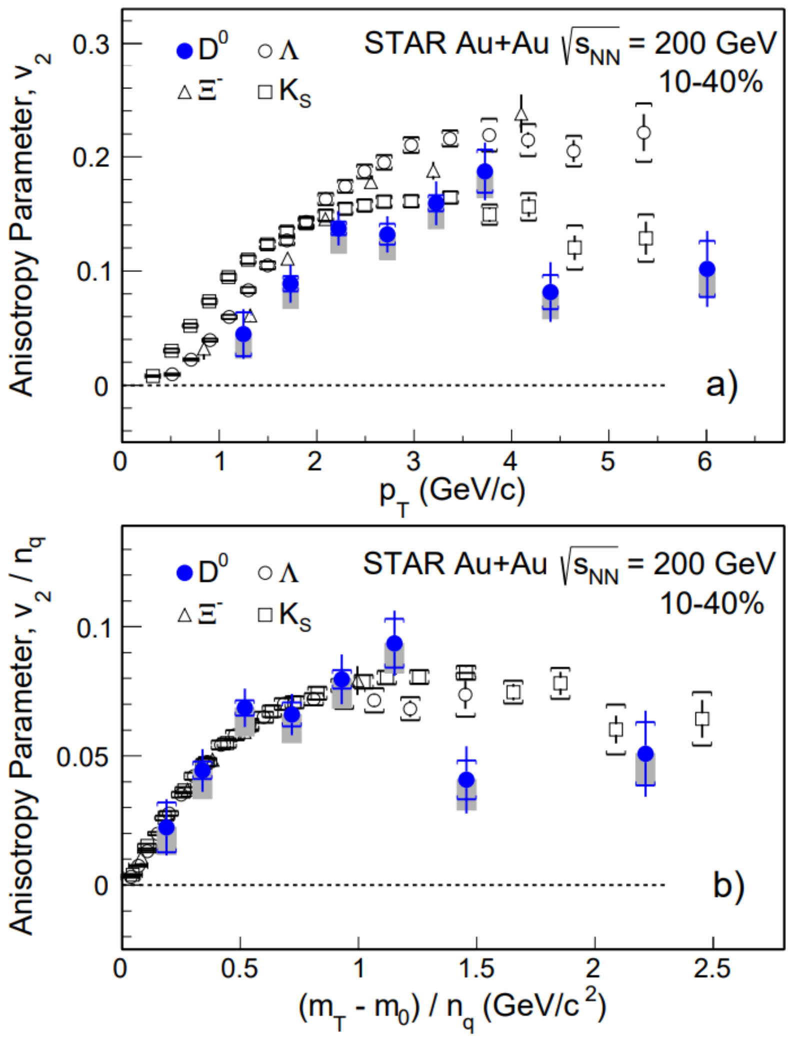


Opportunities of heavy flavor quarks

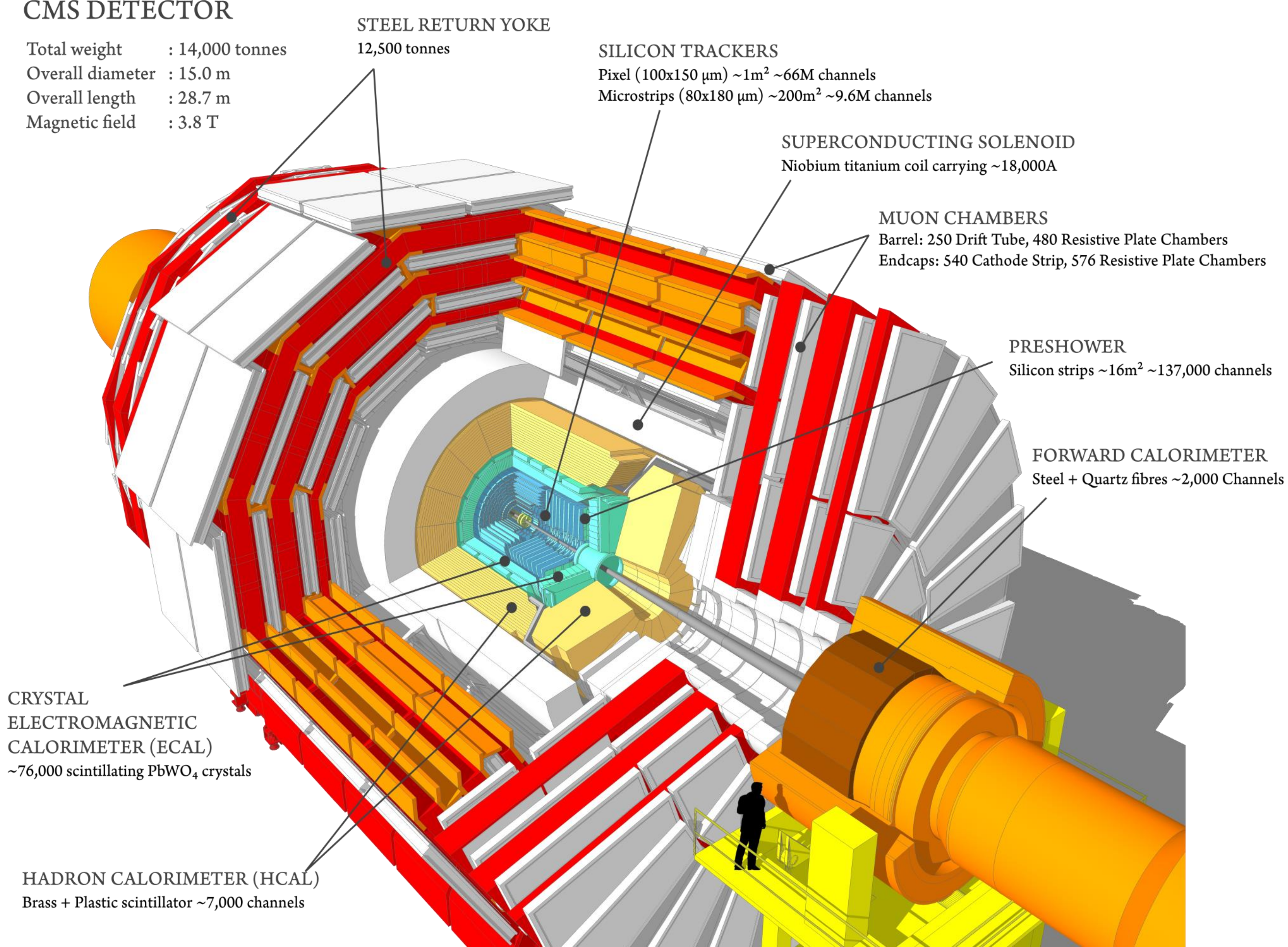
- Heavy flavor quarks strongly coupled with QGP!
  - Suffer energy loss in heavy ion collisions

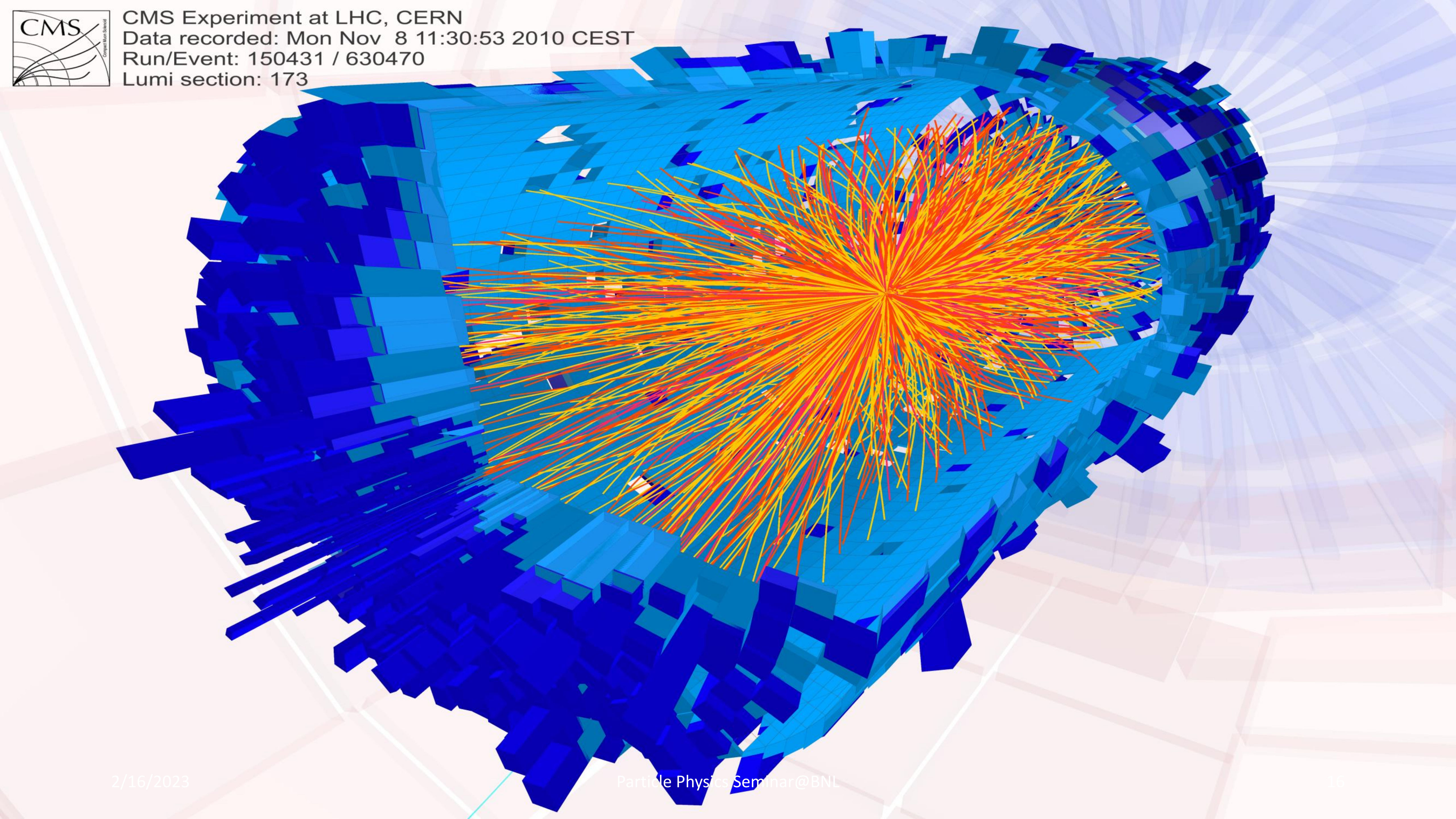


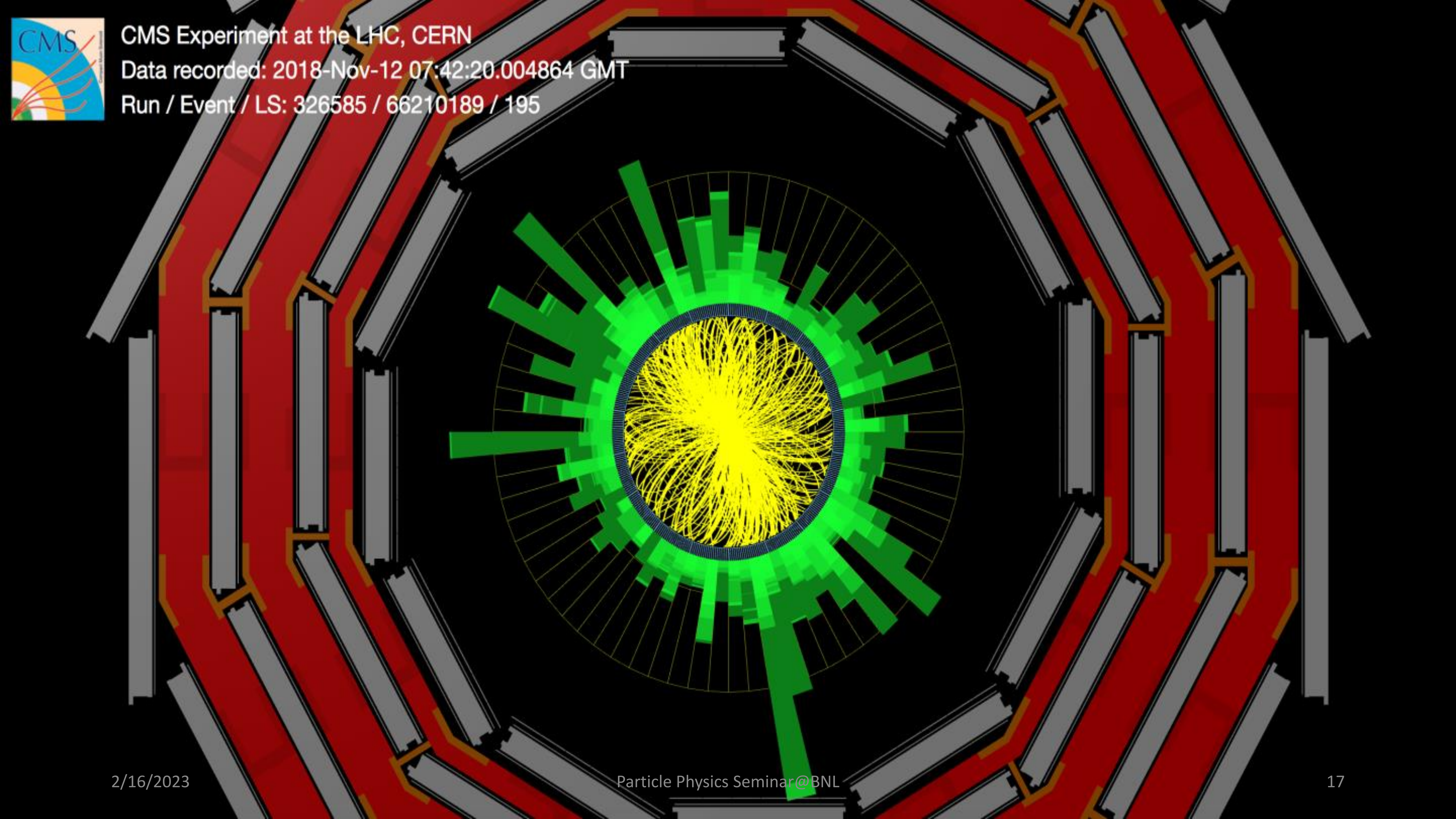
Phys. Rev. C 99, 034908 (2019)




LHCb
ATLAS
CERN
CERN
SUISSE
FRANCE
SPS 7 km
CMS
ALICE
CMS DETECTOR
THE ALICE DETECTOR
LHC 27 km

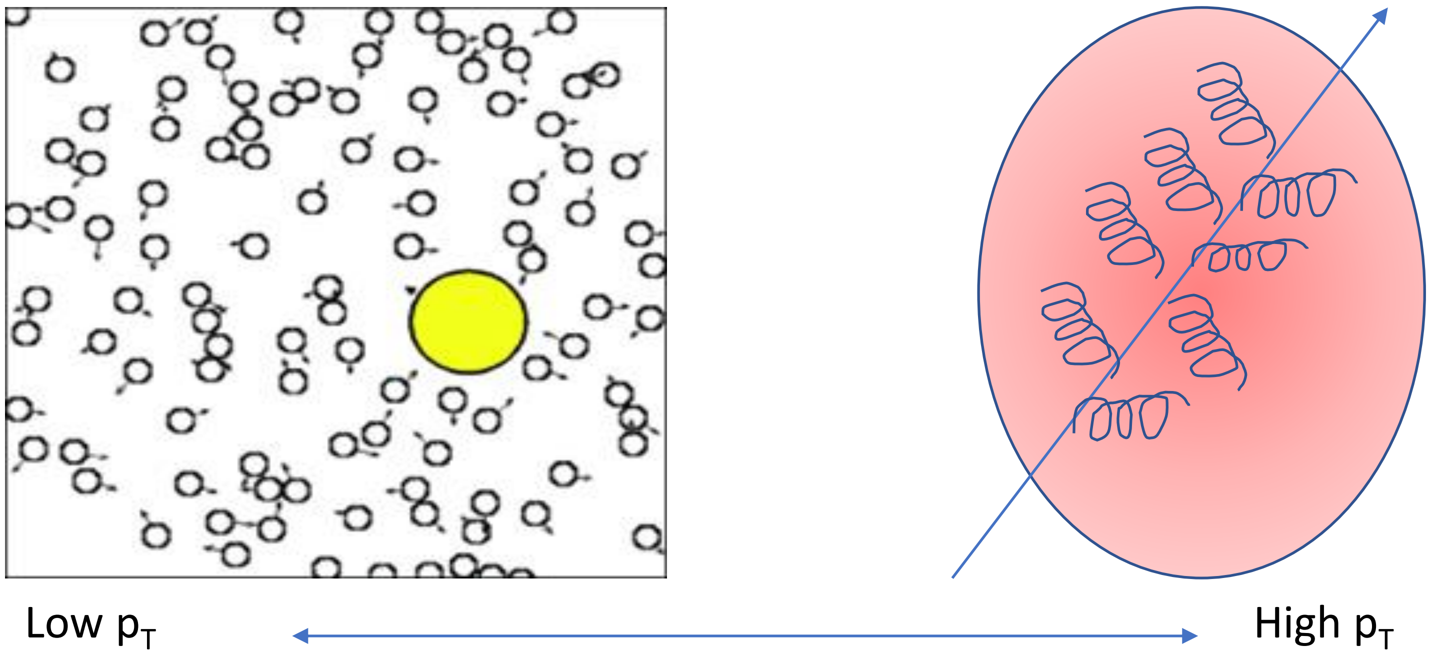

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173


CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-12 07:42:20.004864 GMT
Run / Event / LS: 326585 / 66210189 / 195

A few remarks on theory

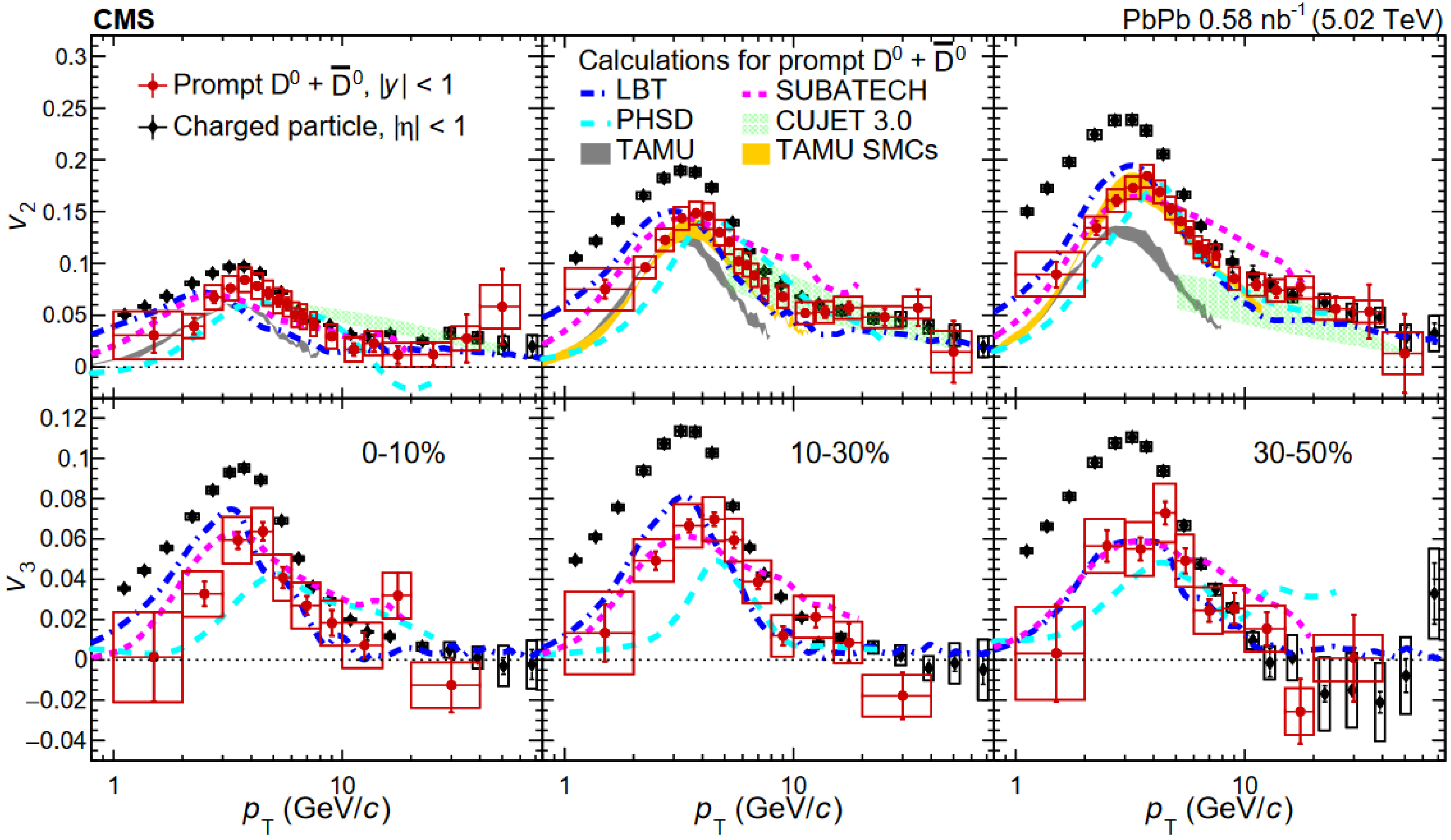
- Heavy quarks
  - Suffers collisional energy loss at small p_T
  - Suffers radiative energy loss at large p_T



Charm elliptic flow at LHC

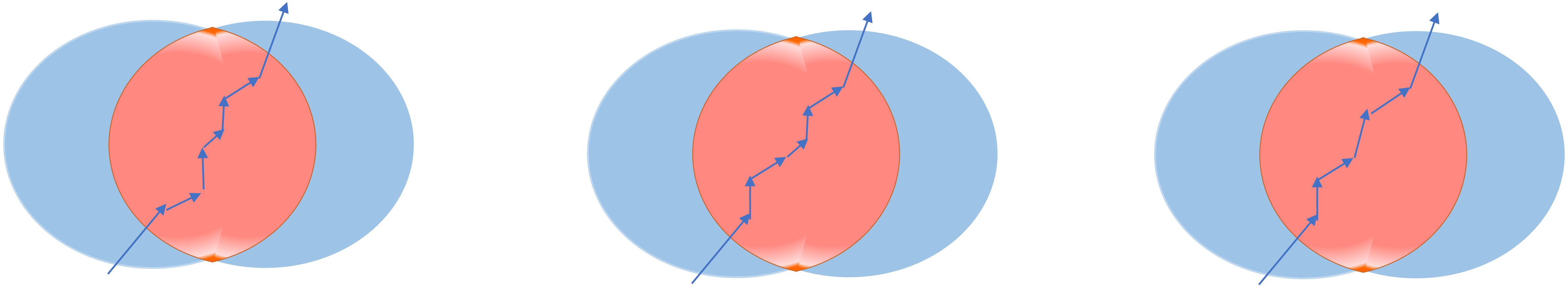
- No model can describe data in full p_T range

$$\langle\langle 2' \rangle\rangle = \langle\langle e^{i2(\varphi(D^0)_1 - \varphi^{ref}{}_2)} \rangle\rangle$$

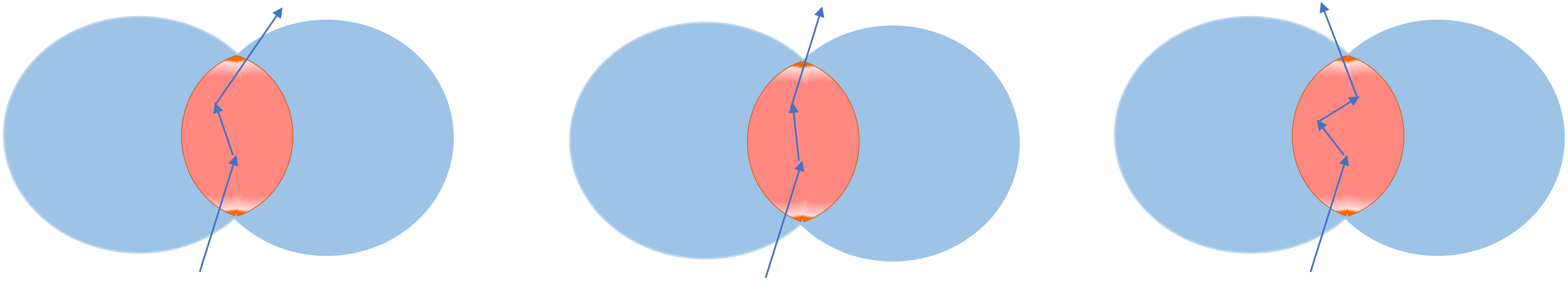


PLB 816 (2021) 136253

The fluctuations of energy losses



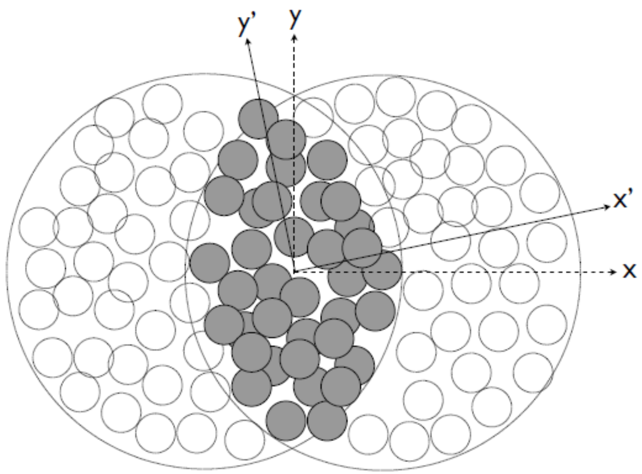
Fluctuations not visible

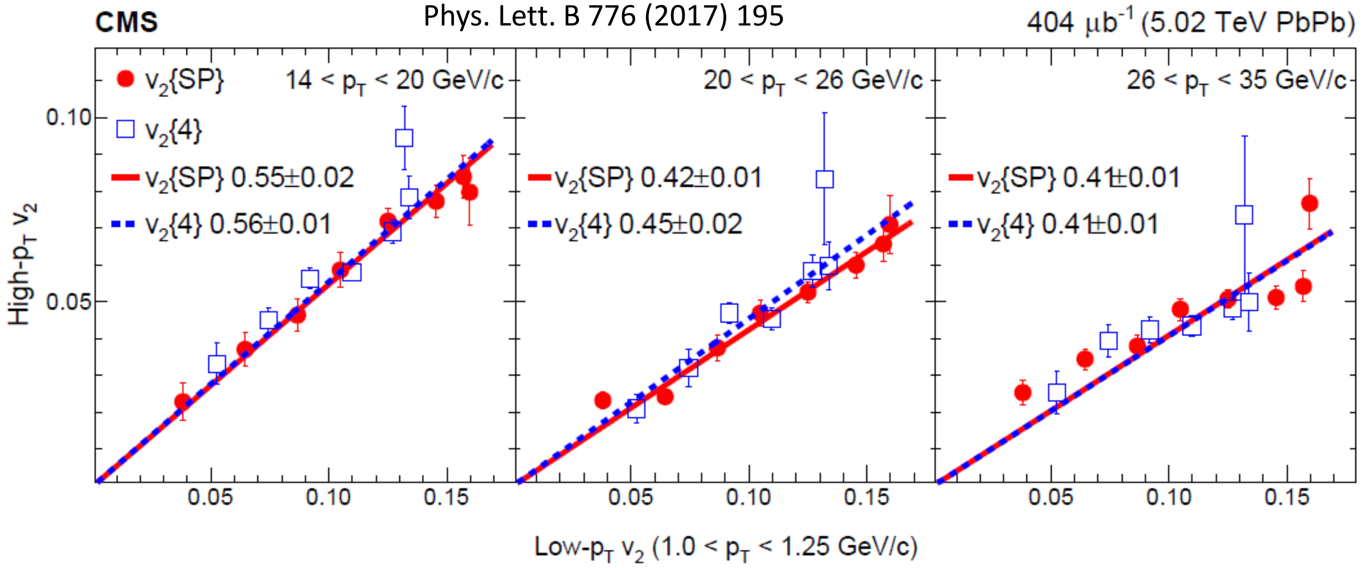


Fluctuations visible

Explore the energy loss with fluctuations

- $v_2 = k\,\epsilon_2$ where ϵ_2 is the eccentricity of the collision geometry



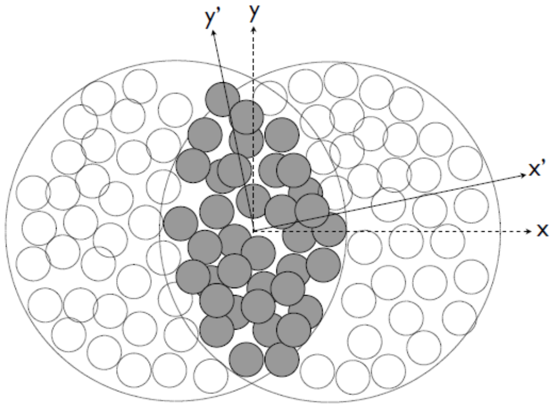


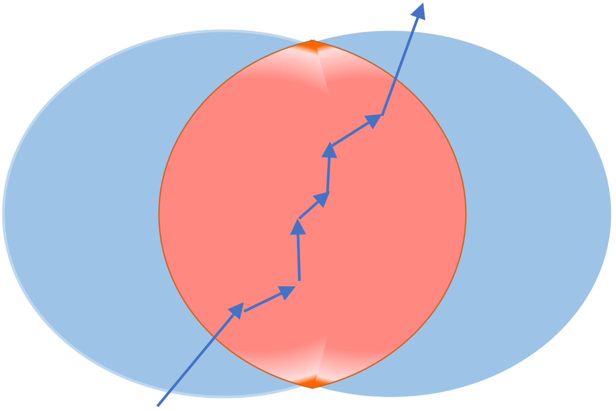
- Multiparticle correlations are sensitive to ϵ_2, $\dfrac{v_2\{4\}}{v_2\{2\}} = \dfrac{\epsilon_2\{4\}}{\epsilon_2\{2\}}$

$$v_2\{4\}^2 \approx v_2{}^2 - \sigma^2$$
$$v_2\{2\}^2 \approx v_2{}^2 + \sigma^2$$

The fluctuations of elliptic flow

- Initial ϵ_2 fluctuations vs. final state (in-medium) k fluctuations?



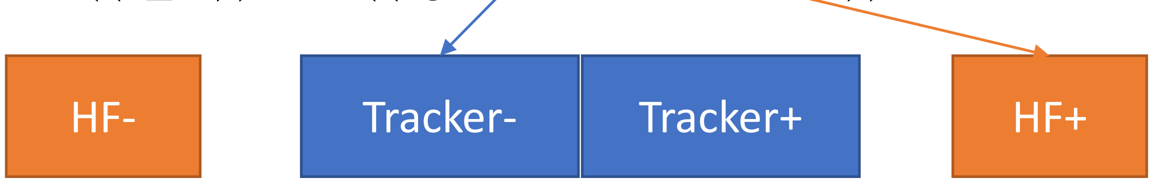


$$\frac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \frac{v_2\{4\}}{v_2\{2\}}$$

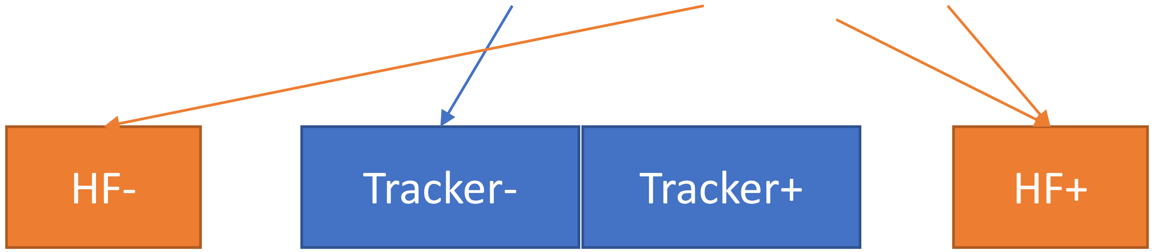
$$\frac{v_2\{4\}(pT)}{v_2\{2\}(pT)} = \frac{v_2\{4\}}{v_2\{2\}} + \sigma(pT)$$

Multi-particle correlations

- ***First time*** **to measure charm v_2 using** ***multiple particle correlator***
- Correlator
  - $\langle\langle 2' \rangle\rangle = \langle\langle e^{i2(\varphi(D^0)_1 - \varphi^{ref}{}_2)} \rangle\rangle$



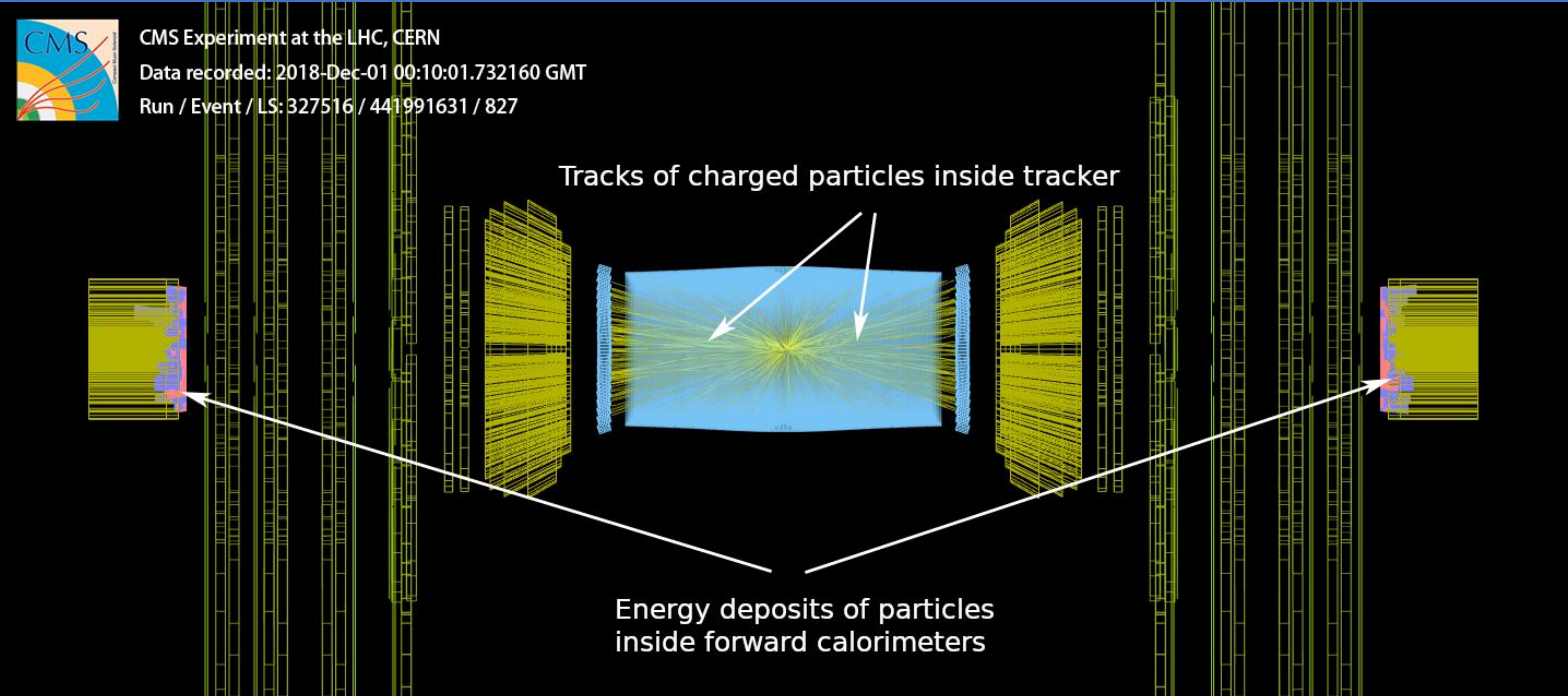
  - $\langle\langle 4' \rangle\rangle = \langle\langle e^{i2(\varphi(D^0)_1 + \varphi^{ref}{}_2 - \varphi^{ref}{}_3 - \varphi^{ref}{}_4)} \rangle\rangle$



- Cumulant and v_2 PRC 83 (2011) 044913
  - $c_2\{2\} = \langle\langle 2 \rangle\rangle$
  - $d_2\{2\} = \langle\langle 2' \rangle\rangle$
  - $v_2\{2\} = d_2\{2\}/\sqrt{c_2\{2\}}$
  - $c_2\{4\} = \langle\langle 4 \rangle\rangle - 2 \langle\langle 2 \rangle\rangle^2$
  - $d_2\{4\} = \langle\langle 4' \rangle\rangle - 2 \langle\langle 2 \rangle\rangle \langle\langle 2' \rangle\rangle$
  - $v_2\{4\} = -\frac{d_2\{4\}}{(-c_2\{4\})^{3/4}}$

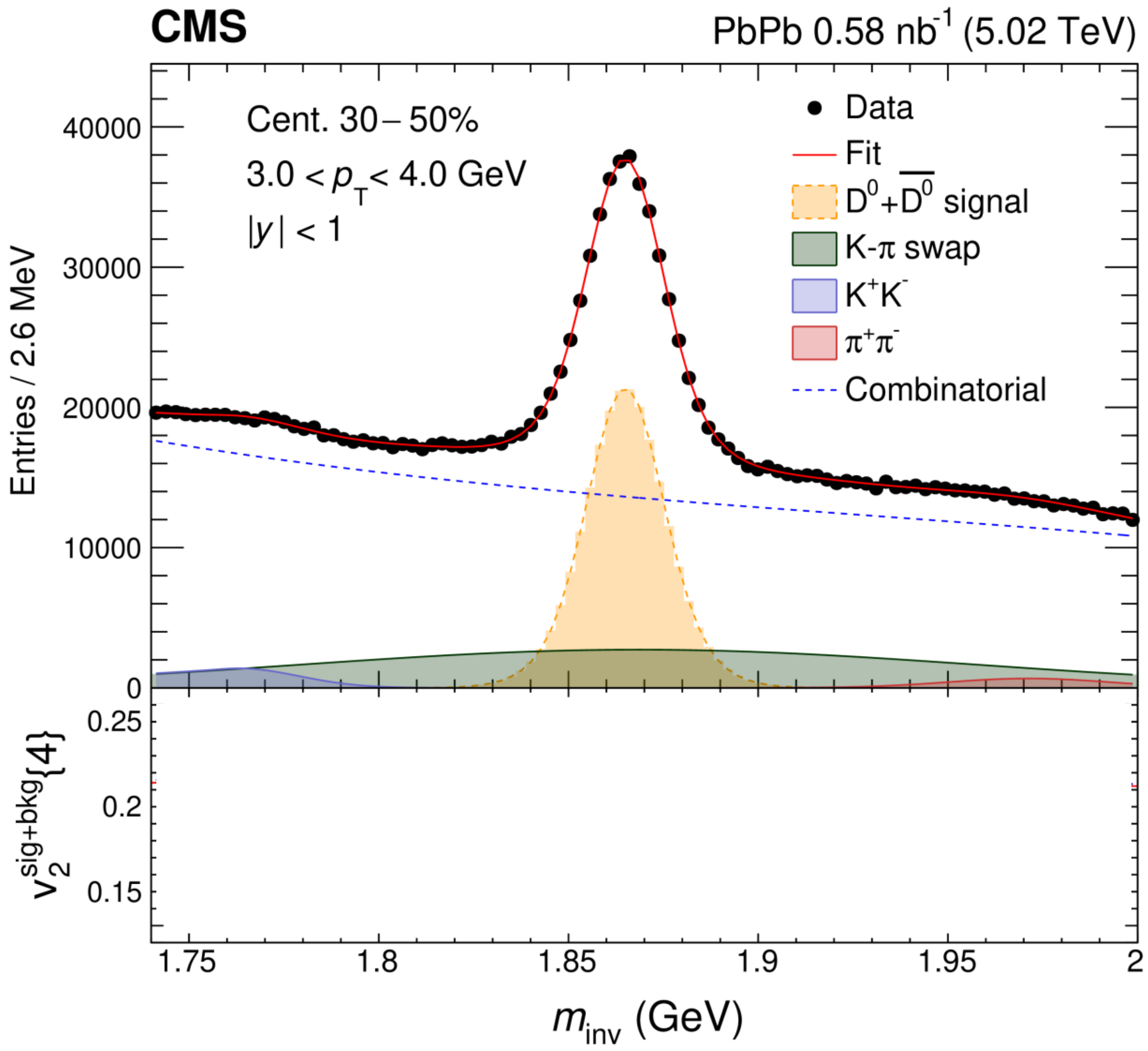
- $v_2\{4\}$ and $v_2\{2\}$ can be calculated from these correlator

Multiparticle correlations



v_2 extraction of D mesons

- D^0 reconstruction
  - $D^0 \rightarrow K^-\pi^+$
- Correlate D^0 with reference particles
- Signal extraction



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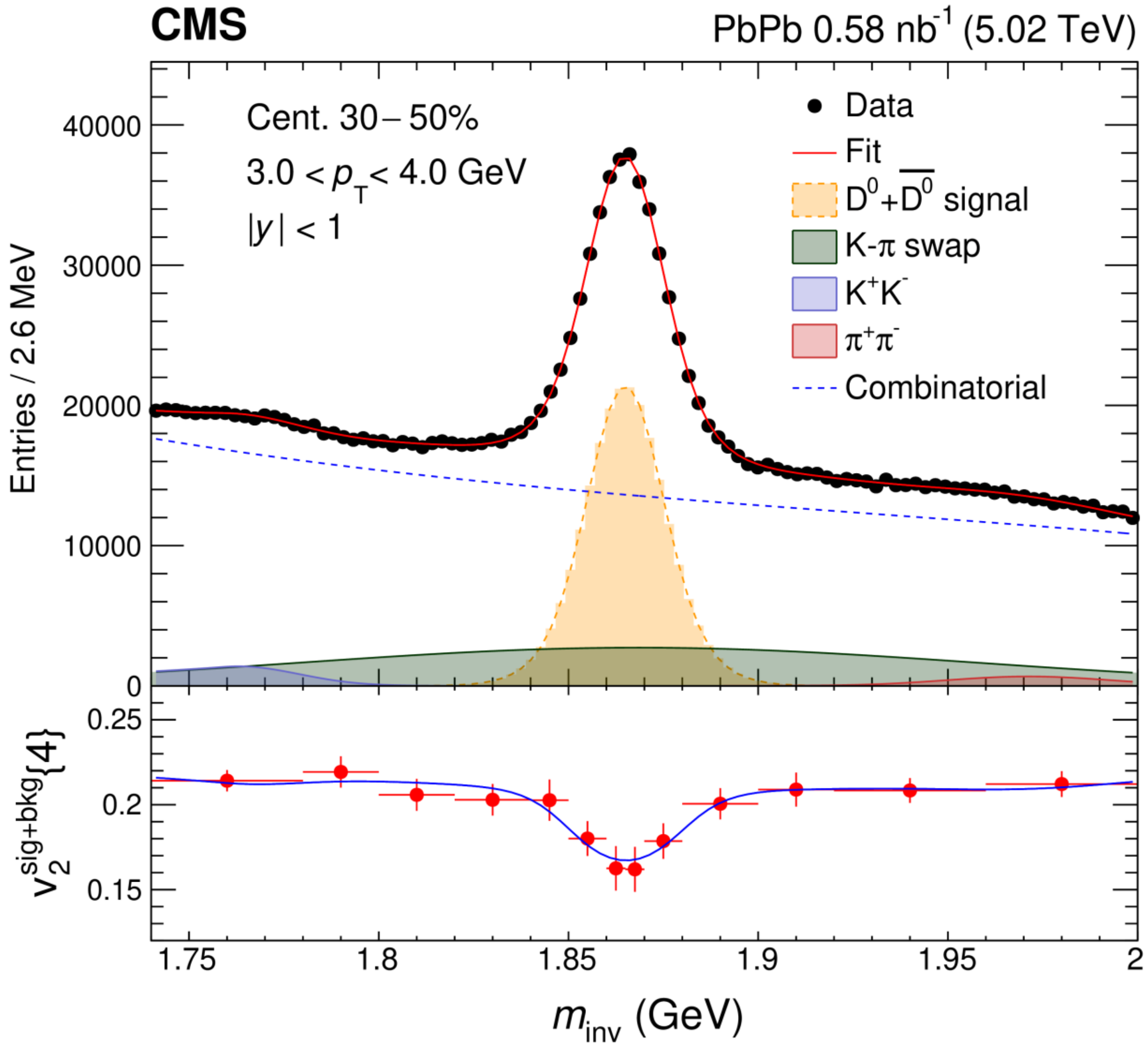
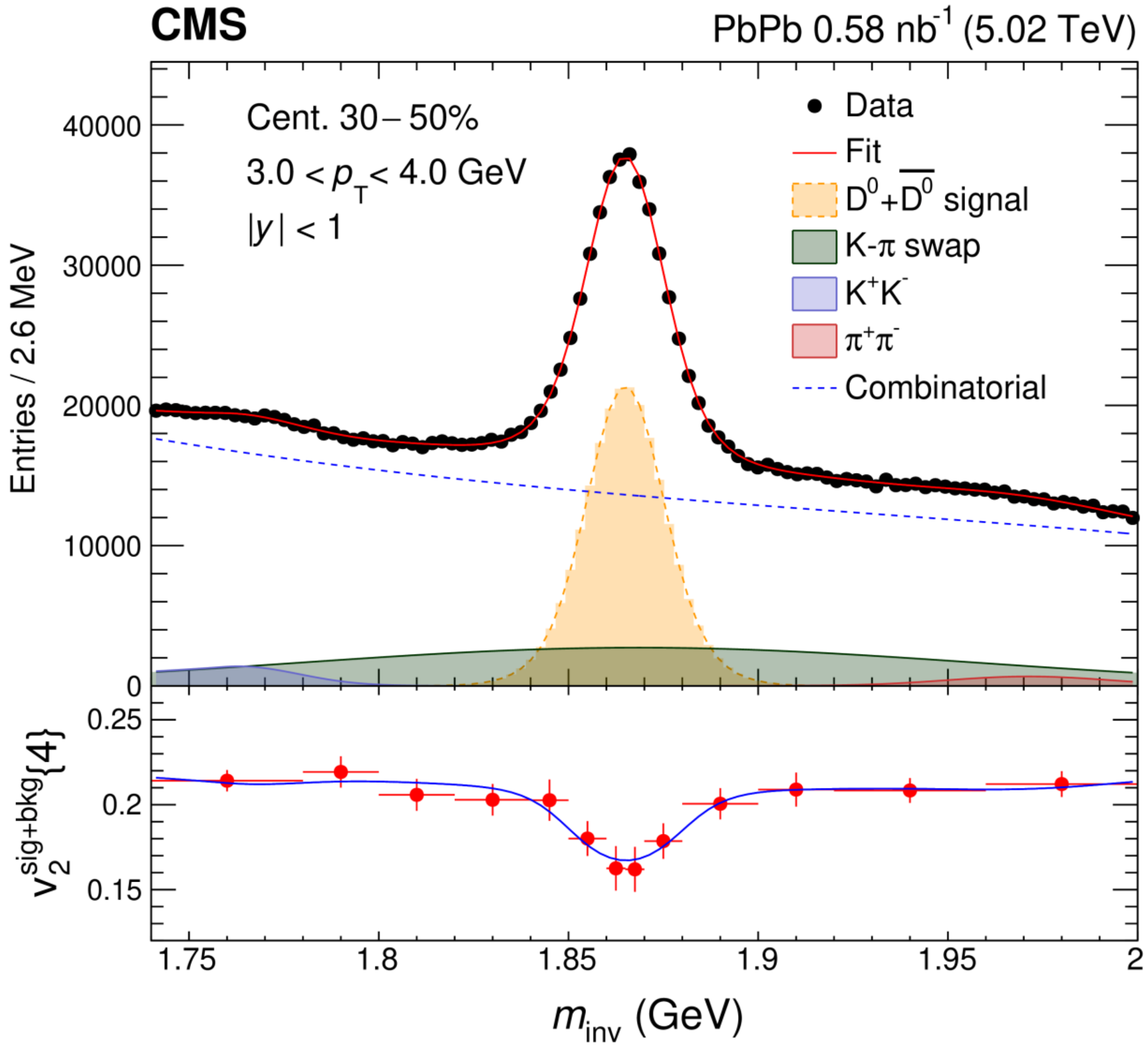


v_2 extraction of D mesons

- D^0 reconstruction
  - $D^0 \rightarrow K^-\pi^+$
- Correlate D^0 with reference particles
- Signal extraction

$$\alpha(m_{\rm inv}) = \frac{\text{Signal}(m_{\rm inv}) + \text{Swap}(m_{\rm inv}) + \text{K}^+\text{K}^-(m_{\rm inv}) + \pi^+\pi^-(m_{\rm inv})}{\text{Signal}(m_{\rm inv}) + \text{Swap}(m_{\rm inv}) + \text{K}^+\text{K}^-(m_{\rm inv}) + \pi^+\pi^-(m_{\rm inv}) + \text{Bkg}(m_{\rm inv})}$$

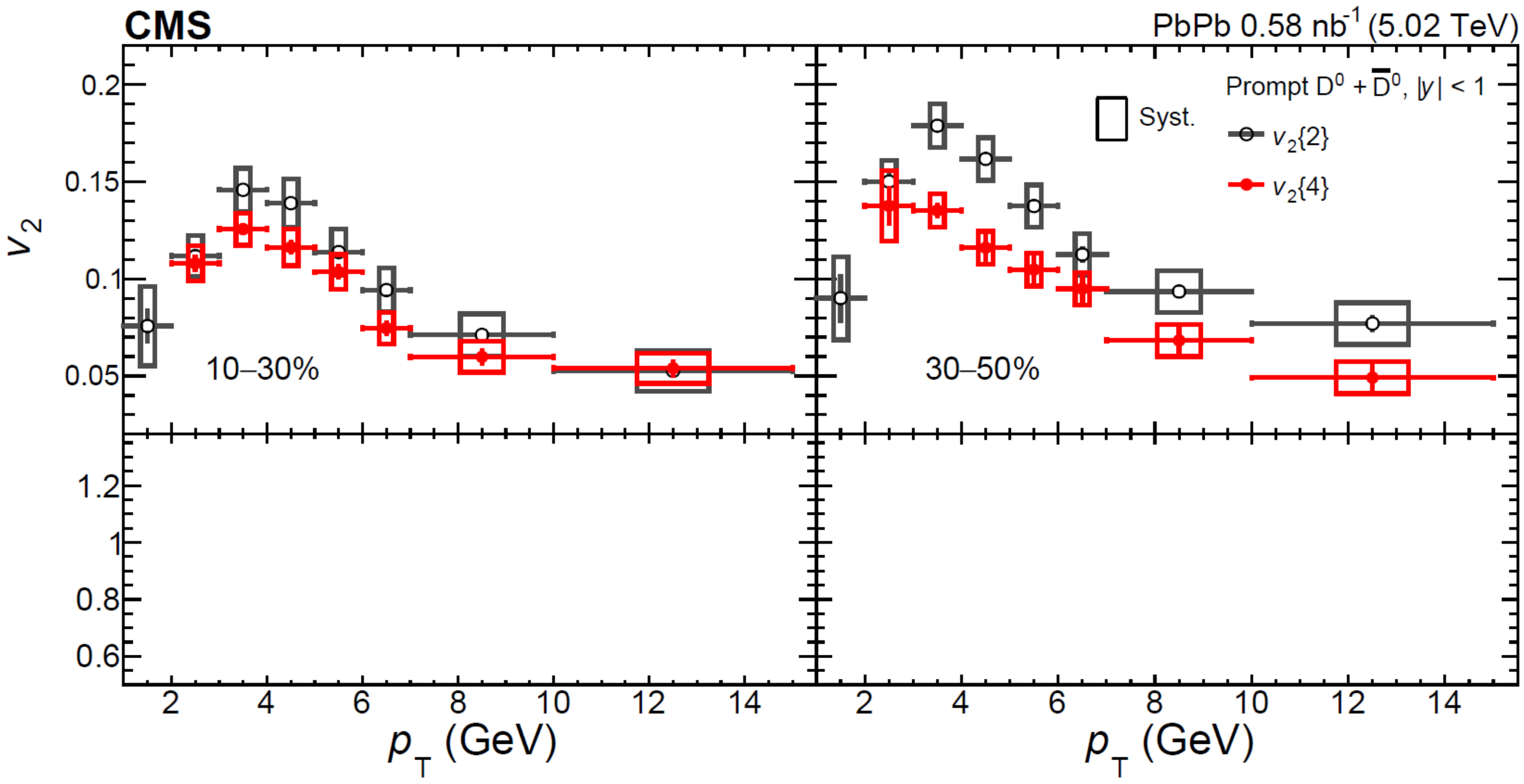
$$v_2^{\rm sig+bkg}(m_{\rm inv}) = v_2^{\rm sig} \times \alpha(m_{\rm inv}) + v_2^{\rm bkg}(m_{\rm inv})(1 - \alpha(m_{\rm inv}))$$



$v_2\{4\}$ for charm quarks

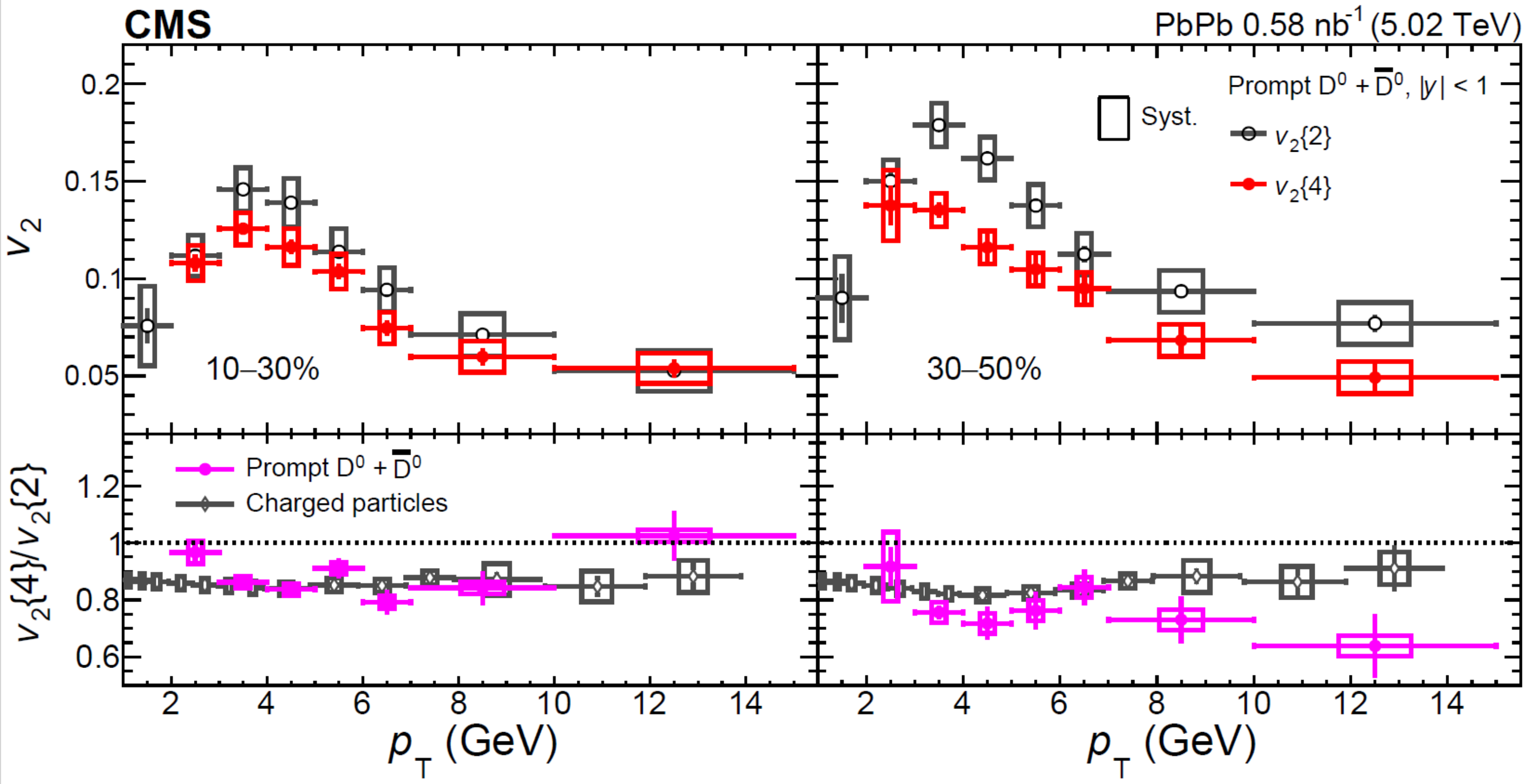
- Expected ordering between $v_2\{2\}$ and $v_2\{4\}$, $v_2\{4\} < v_2\{2\}$

$v_2\{4\}^2 \approx {v_2}^2 - \sigma^2$
$v_2\{2\}^2 \approx {v_2}^2 + \sigma^2$



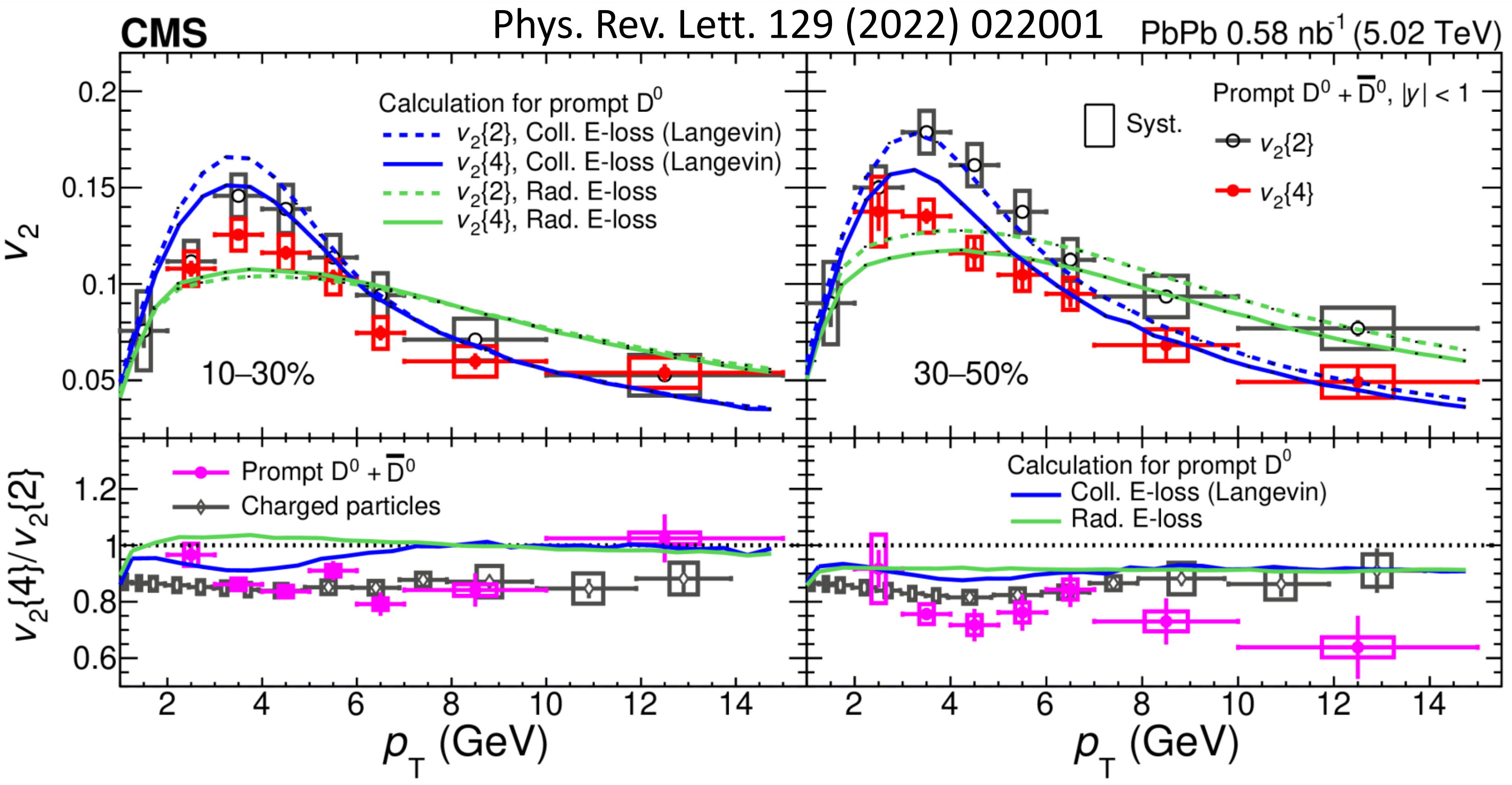
$v_2\{4\}$ for charm quarks

- The fluctuations of D^0 is comparable with charged particles
- Fluctuations are from ϵ_2 dominately



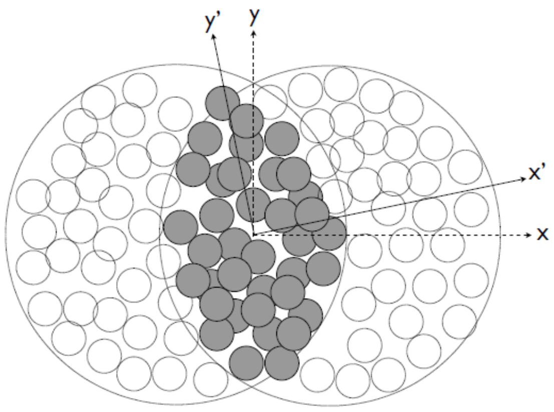
Comparisons with models

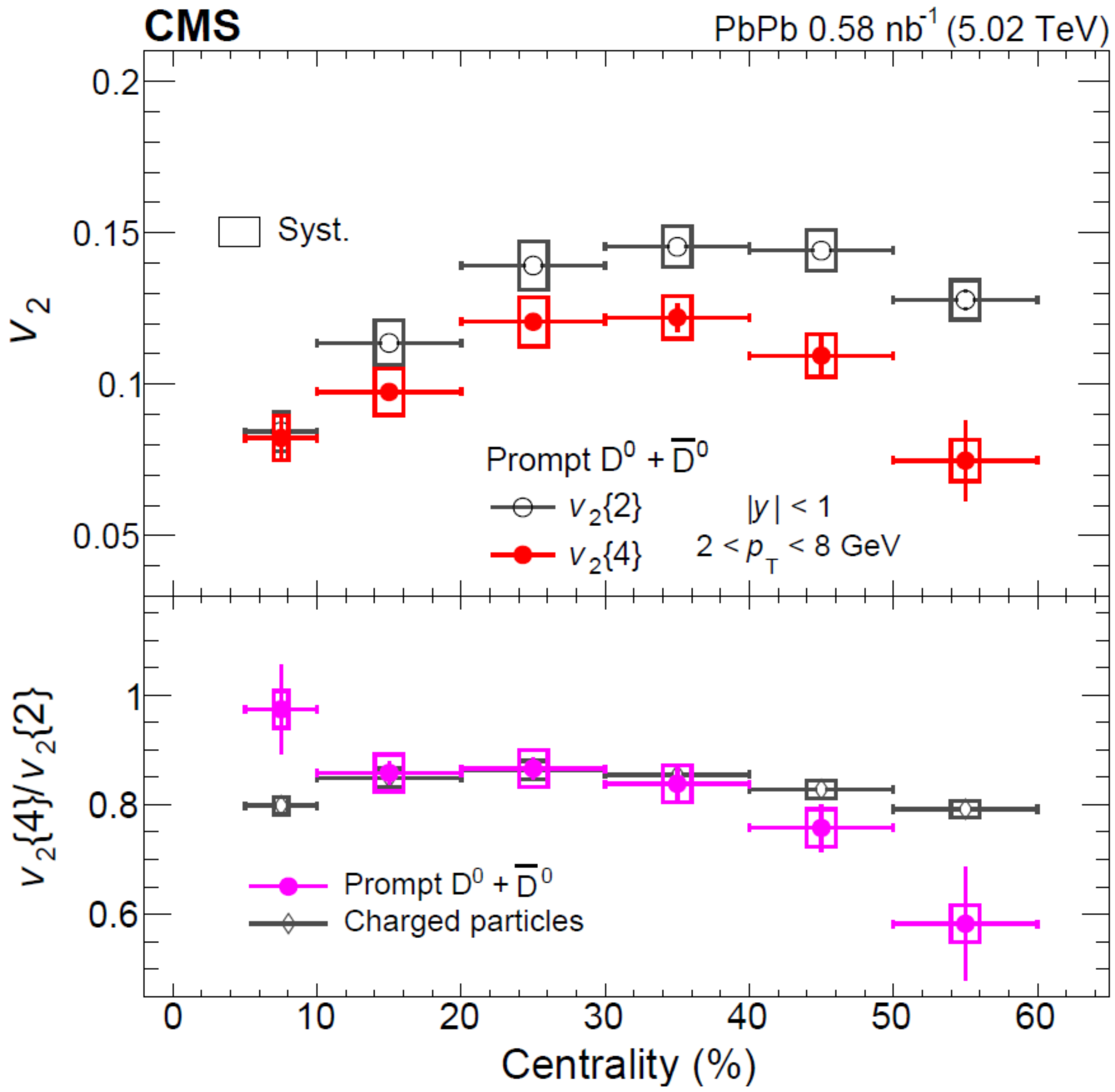
- Both Langevin processes and the processes of radiational energy loss describe the tendency but not quantitatively



System size scan

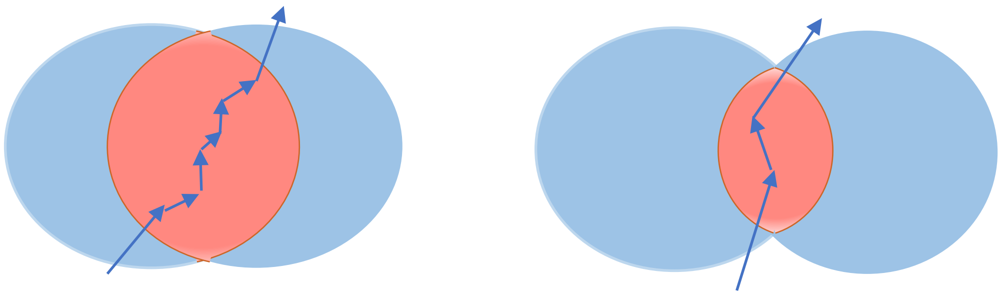
- $v_2\{4\}/v_2\{2\}$ for charm sectors ~ charged particles as constant
- fluctuations almost from initial geometry

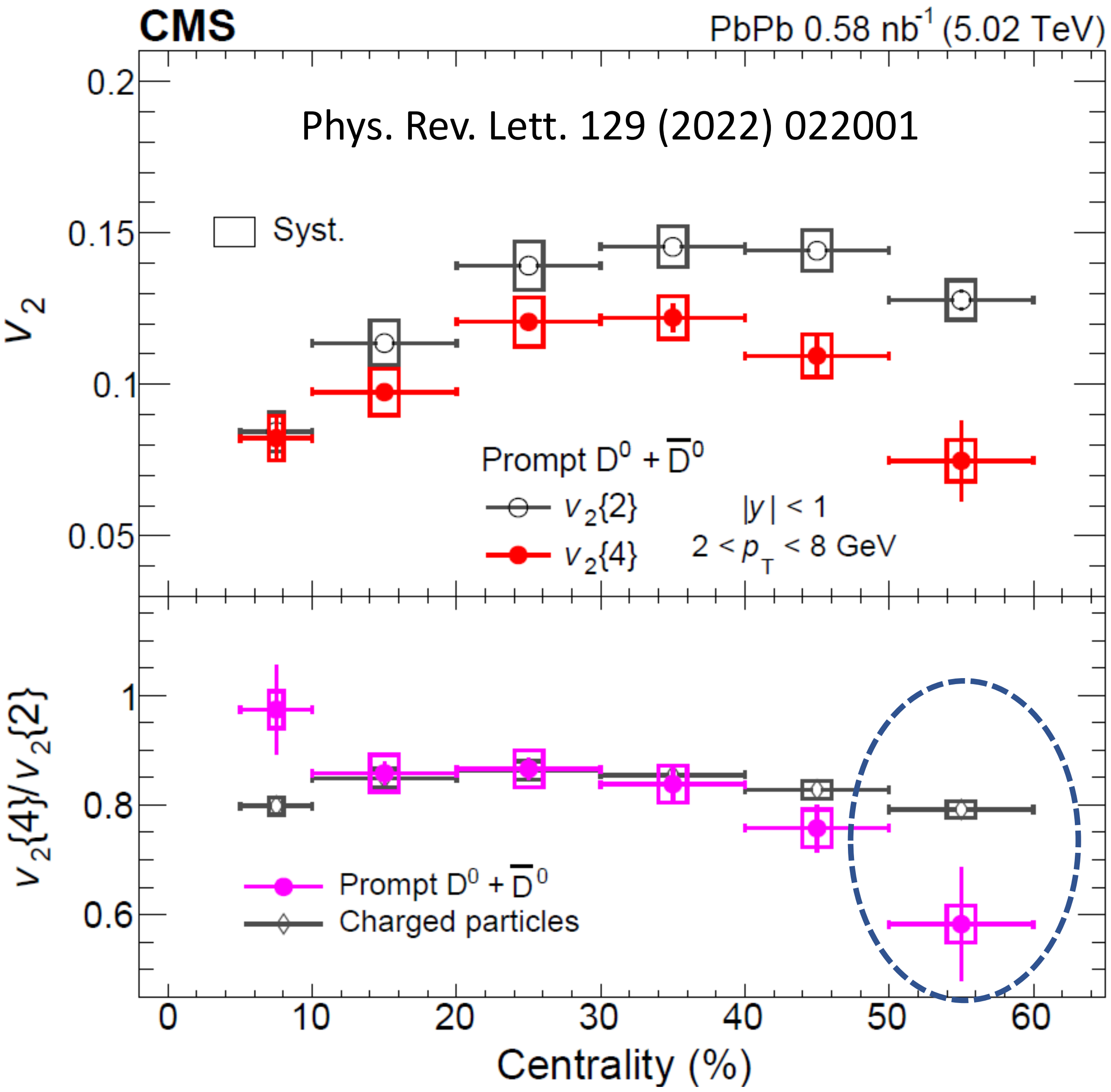




System size scan

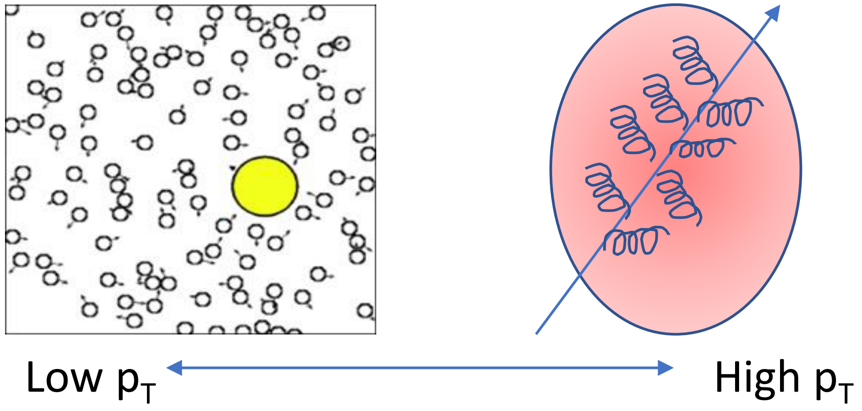
- Hint of fluctuations on energy loss towards <u>*smaller*</u> system?
- Possible findings in pPb and pp collisions <u>if medium effects exists</u>?

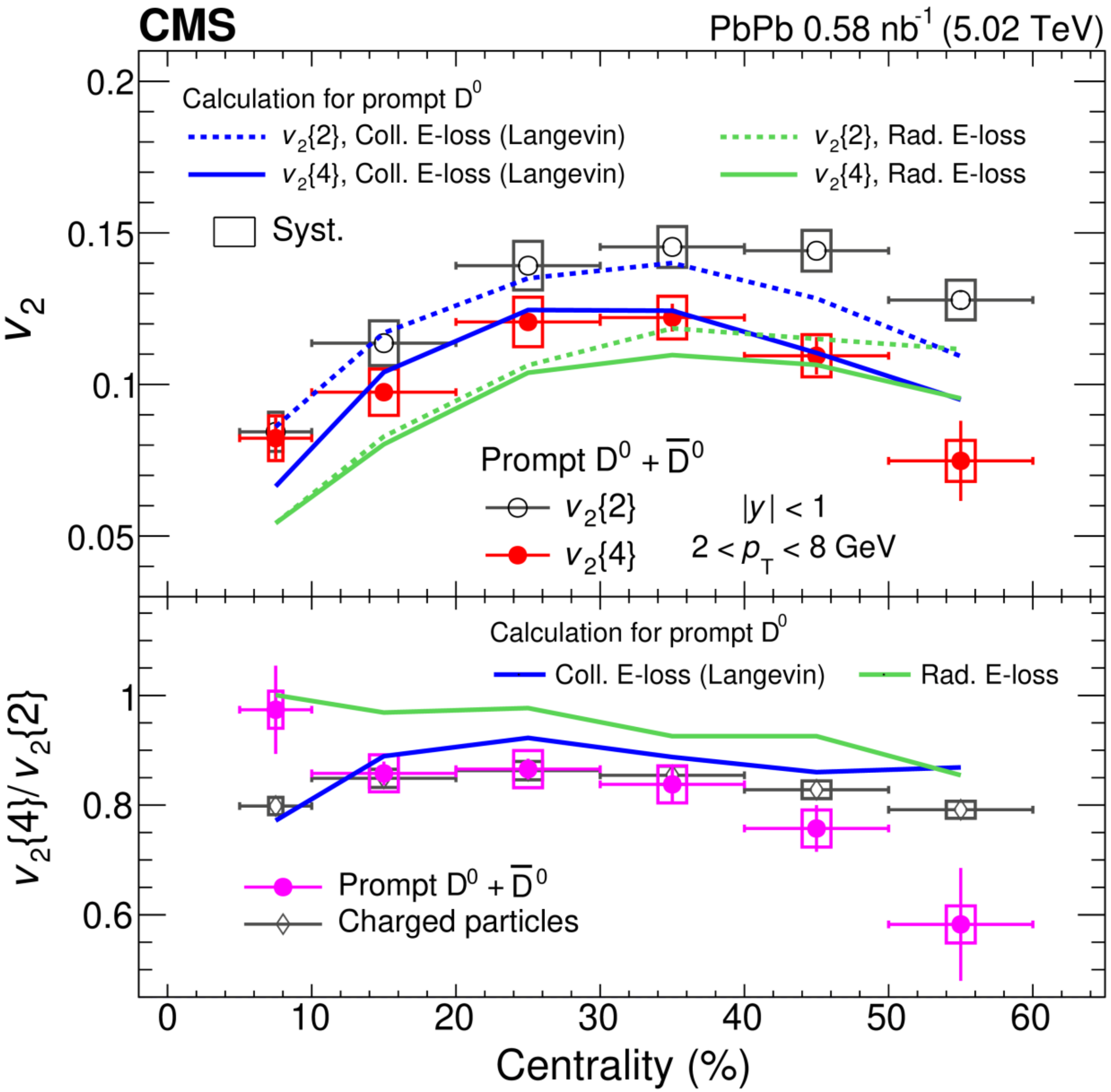




System size scan

- Both energy loss mechanisms describe the tendency
- Models cannot describe the data quantitatively

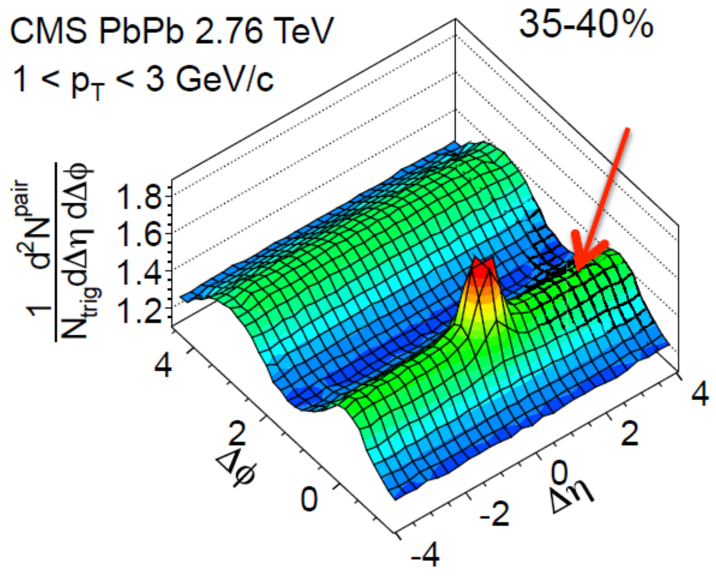




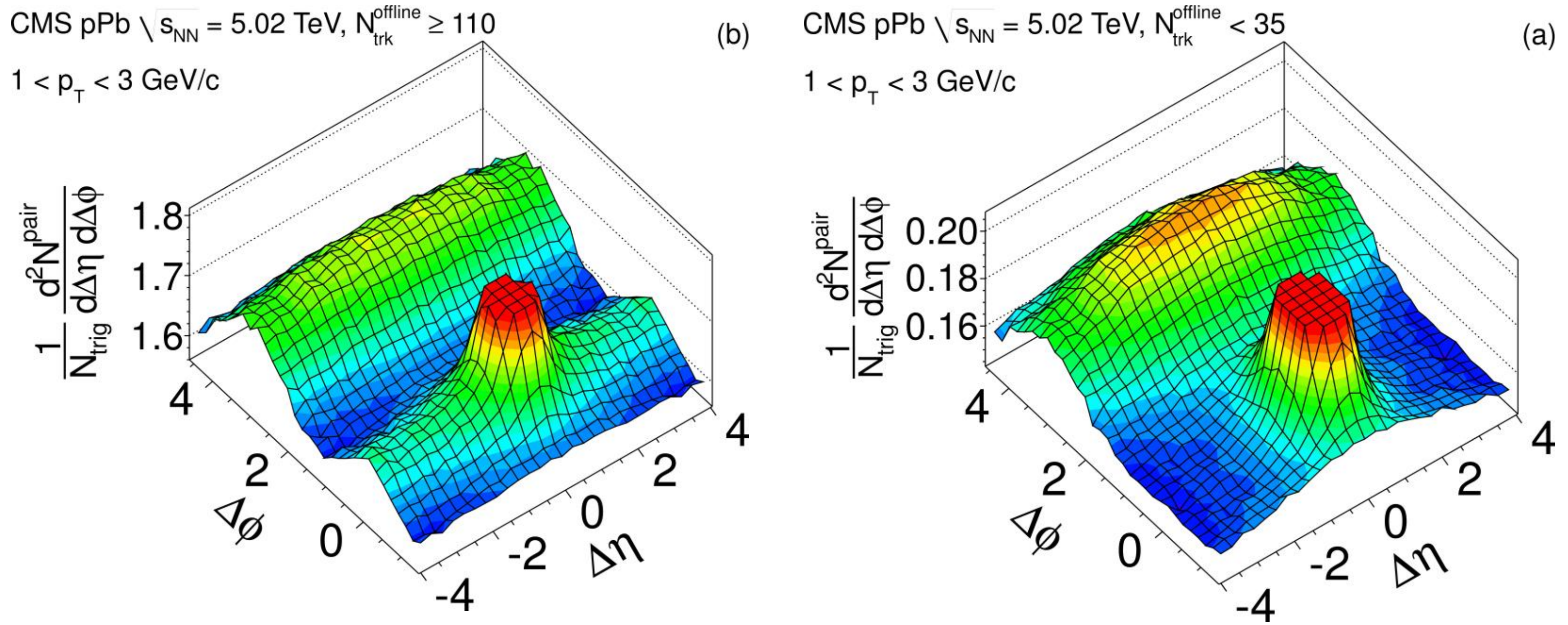
Striking ridge in high multiplicity events

- Long range correlations in large collisional systems
- Even hold true in high multiplicity small collisions!

Eur. Phys. J. C 72 (2012) 2012

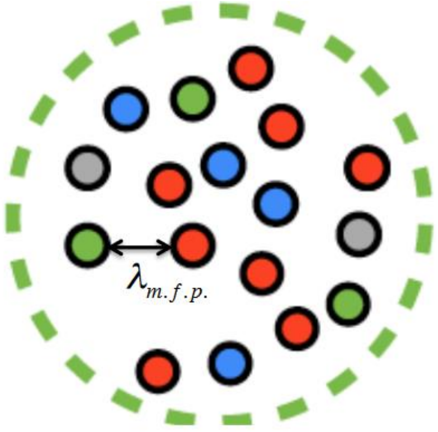


Phys. Lett. B 718 (2013) 795-814

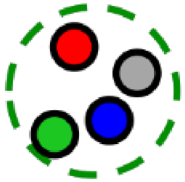


Debates on origin of flow

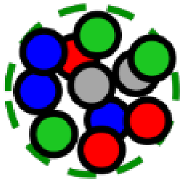
- A small QGP droplet created – in-medium and final state effects
  - Applicability: Relative system size $\frac{L}{\lambda_{m.f.p.}} \gg 1$
- Alternative explanations for collectivity:
  - Correlations established prior to collisions – initial state effects



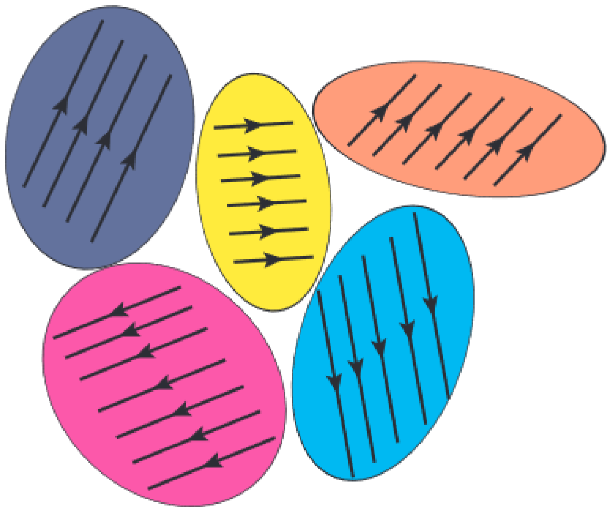
Large nuclei



Small nucleon, low temperature (low energy density)

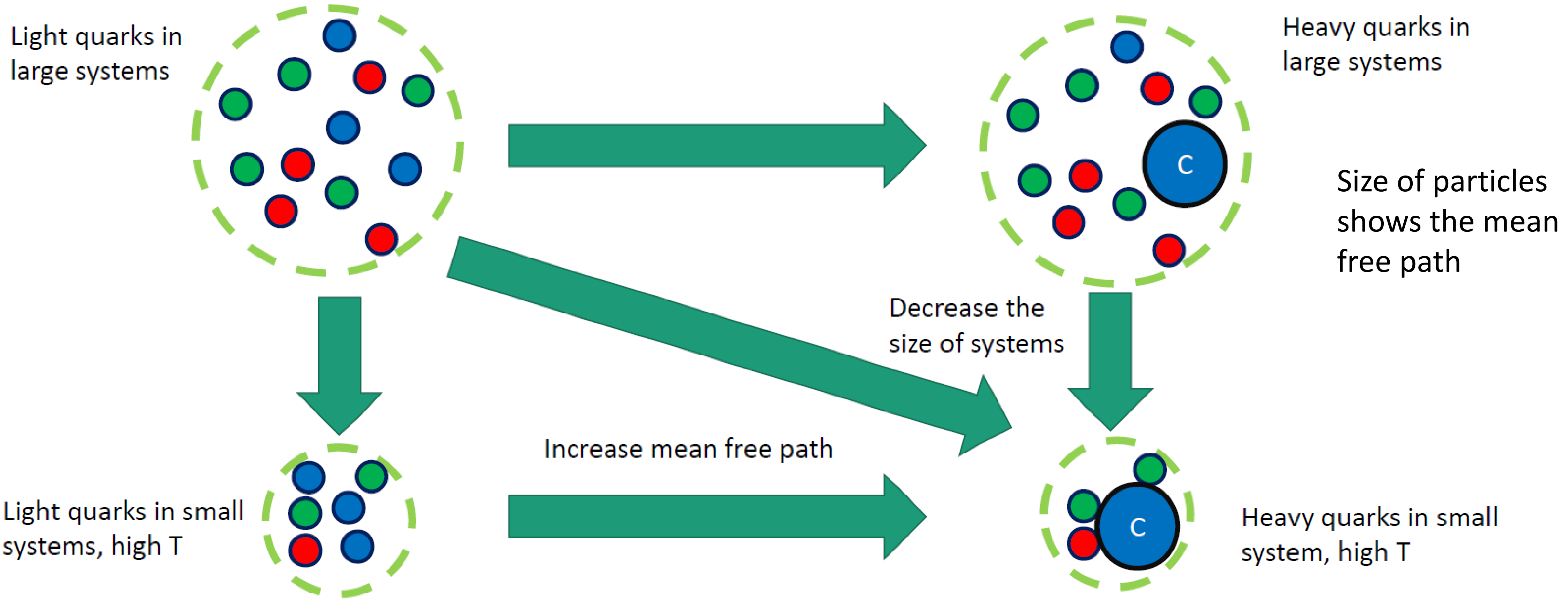


Small nucleon, high density



CGC

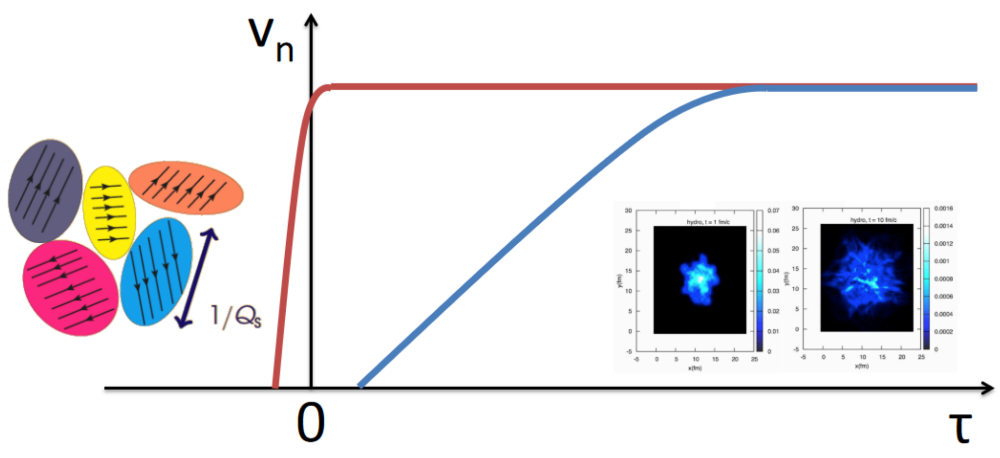
Explore the system size

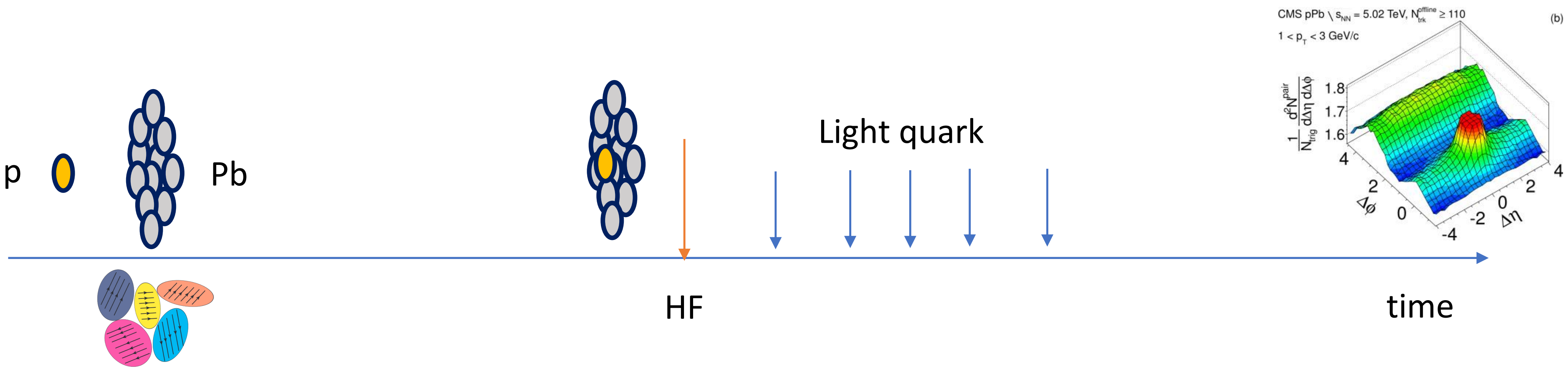


Novel probe using heavy flavor quarks

- Heavy quarks are sensitive to
  - Initial conditions
  - System evolution
  - Relative system size $\lambda_{m.f.p.}/L$ scan $\lambda_{m.f.p.}{}^{Q} \gg \lambda_{m.f.p.}{}^{q}$

Initial-state dynamics vs **Final-state interaction**

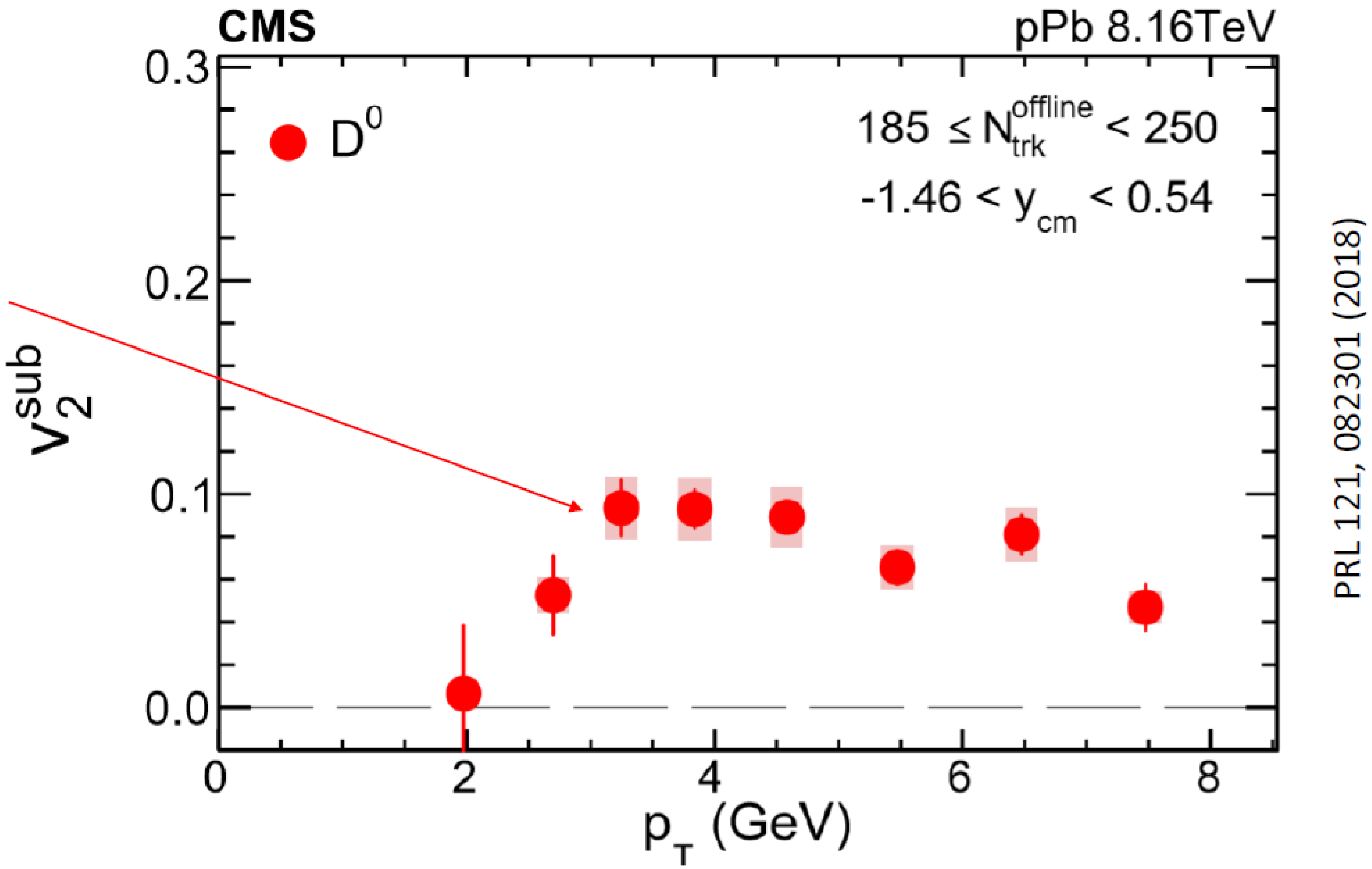




Charm flow in small systems

- Prompt D^0 ($c\bar{u}$)

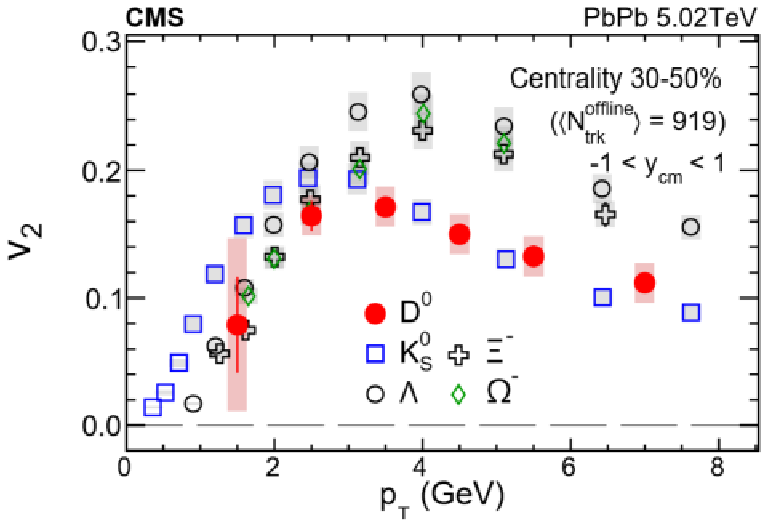
Positive v_2 signal in pPb

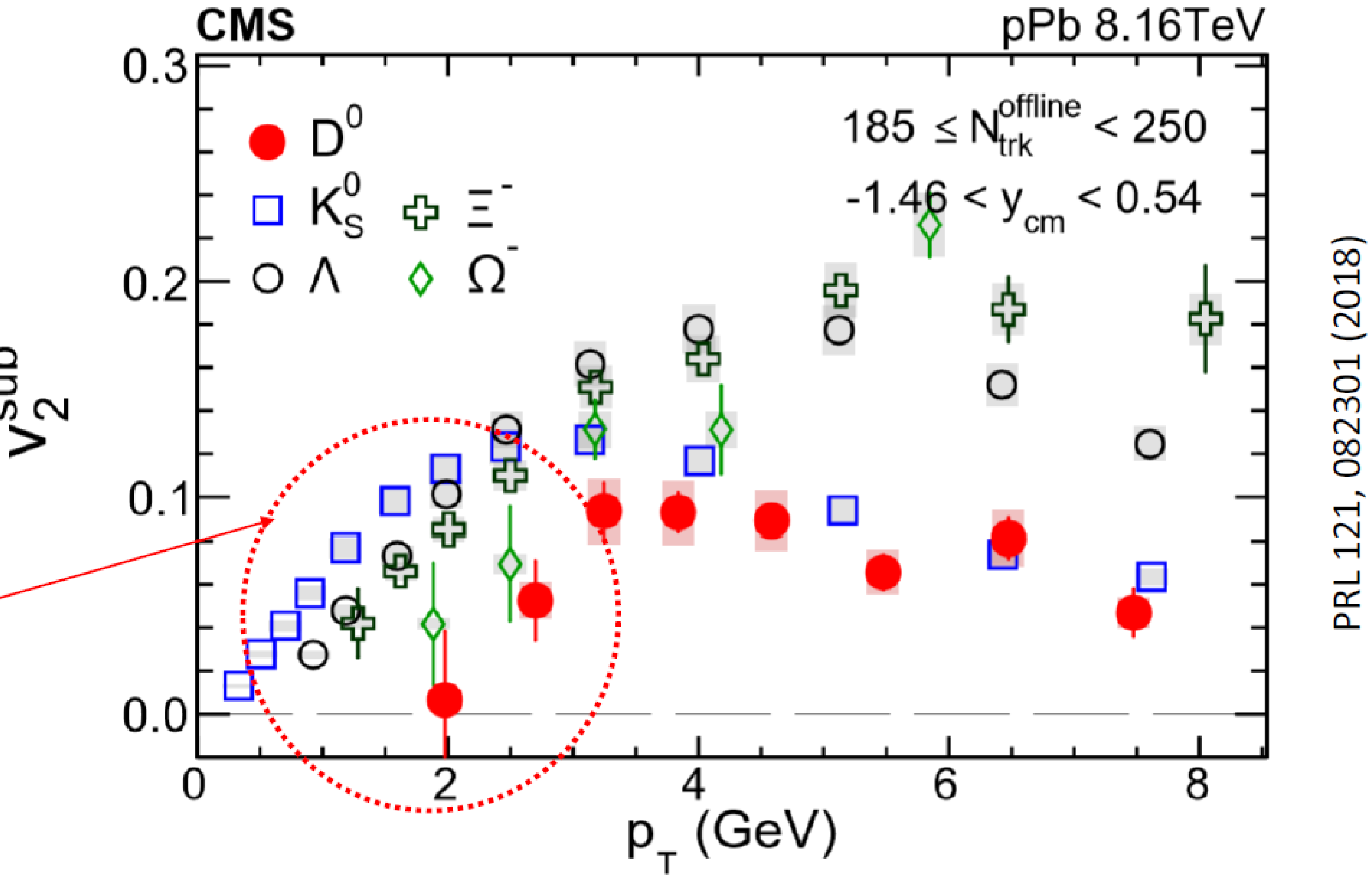


Charm flow in small systems

- Prompt D^0 ($c\bar{u}$)

PRL 120, 202301 (2018)



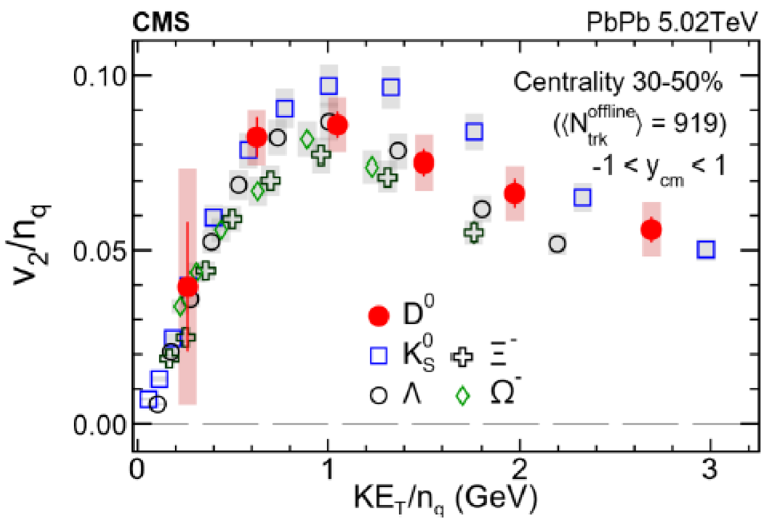


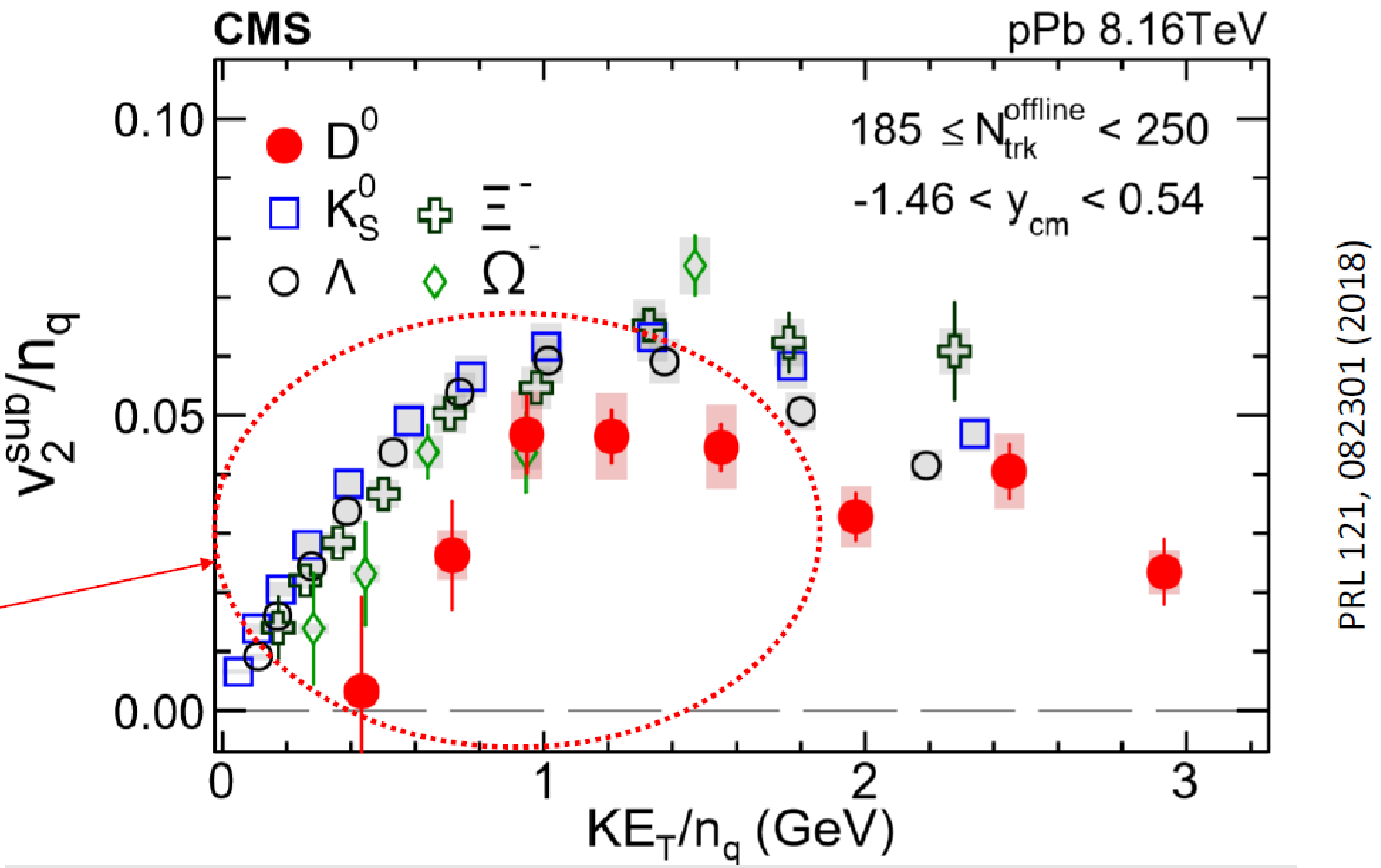
- Mass order at low p_T -- common flow veclocity
- Similar to PbPb

Charm flow in small systems

- Prompt D^0 ($c\bar{u}$)

PRL 120, 202301 (2018)

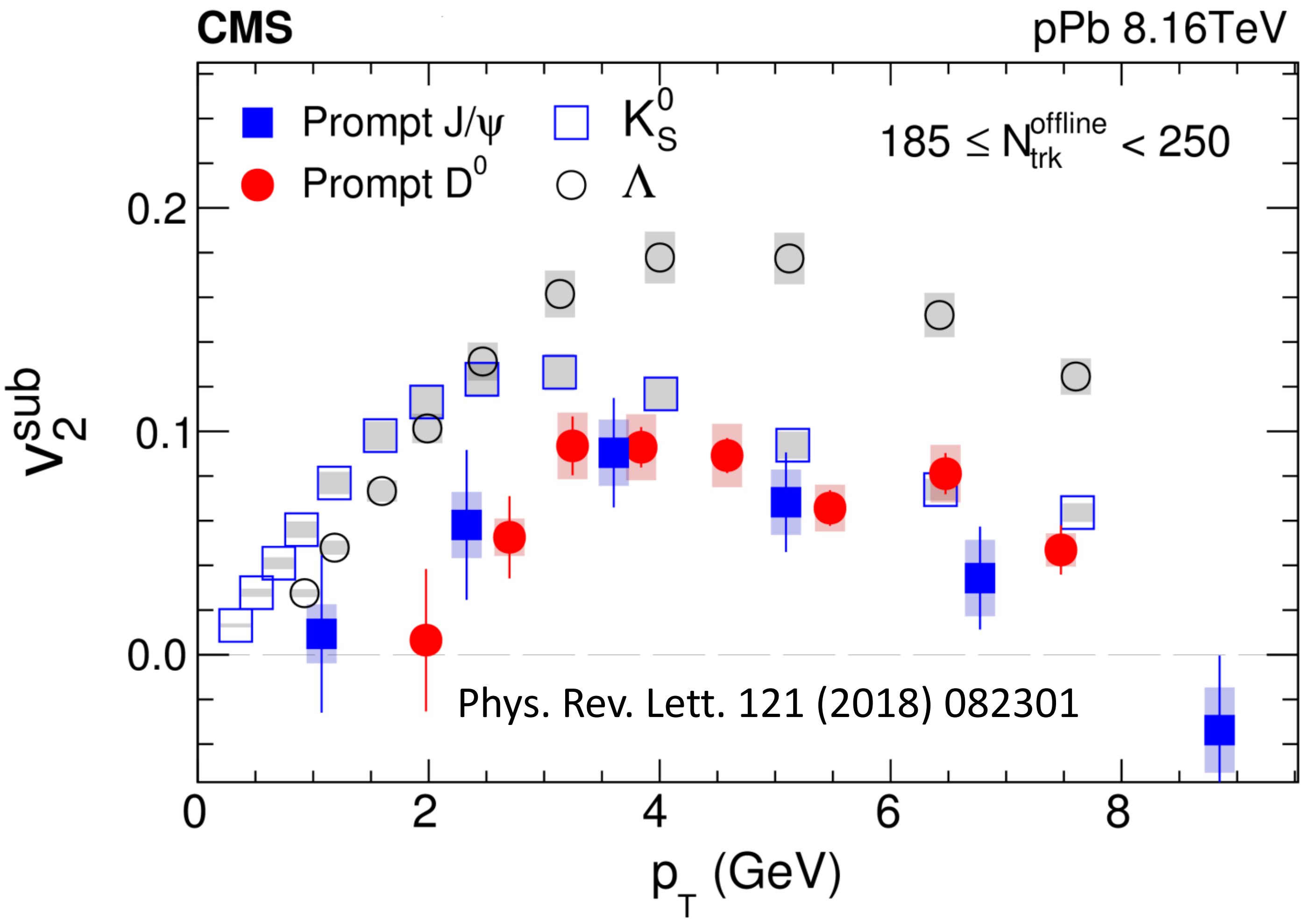




- Slightly weaker than light hadrons
- Different from PbPb

Charm flow in small systems

- Collectivity from ū in D^0 (cū)? Study the flow of prompt J/ψ ($c\bar{c}$)

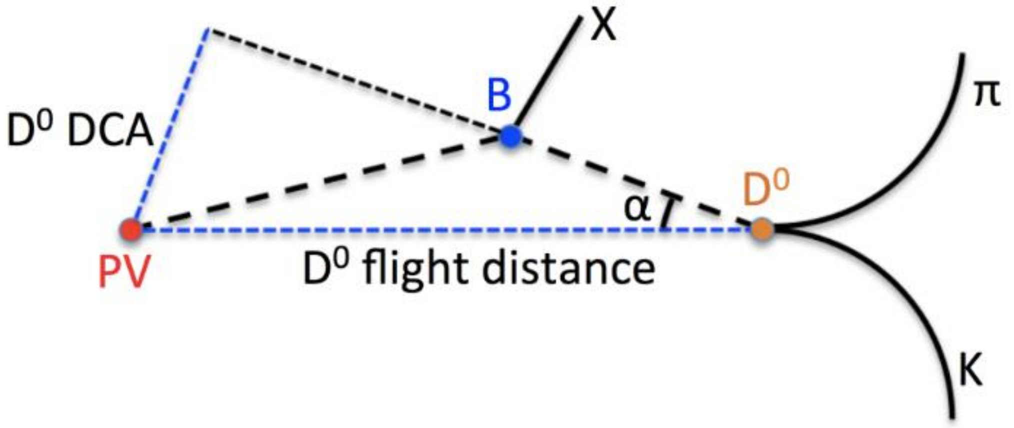


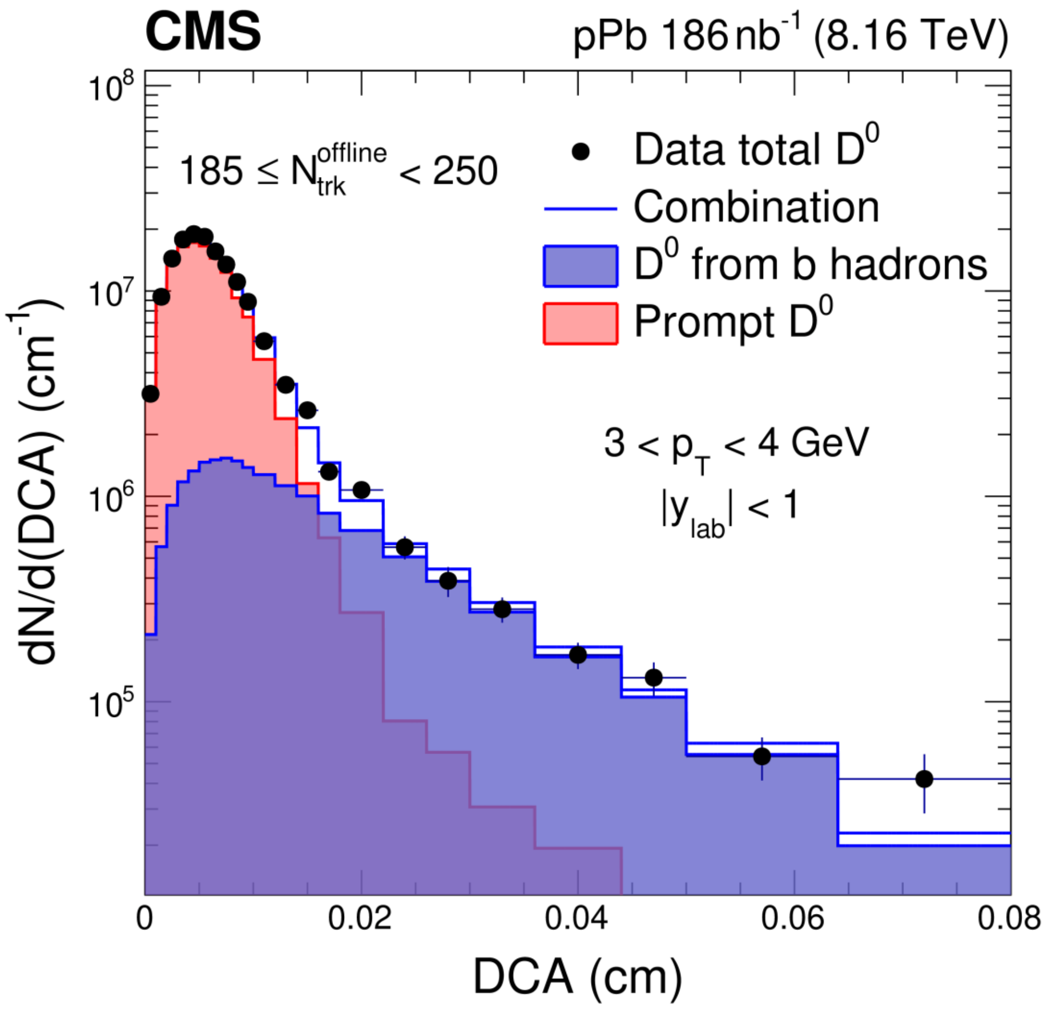
Bottom flow in pPb?

- Mean free path b > c
- Pushing relative size even smaller

b flow in pPb collisions

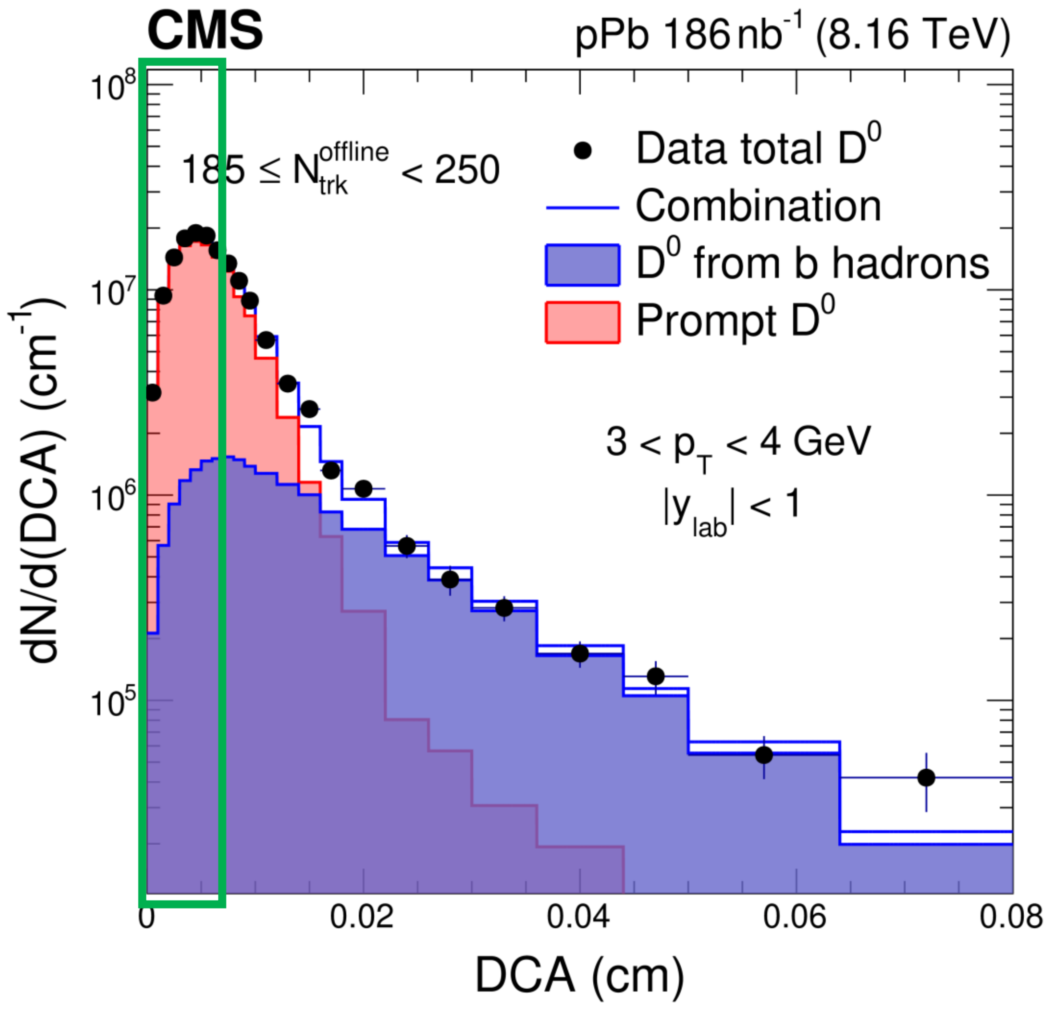
- Nonprompt D^0 originates form b hadron
- Distinguish prompt and nonprompt D^0 by DCA distribution





b flow in pPb collisions

- Evaluate $V_{2\Delta}^{signal}$ in each integrated DCA bin with two particle correlation function
- Extrapolate signal with linear fit
- v_2 obtained from using charged particles as reference



b flow in pPb collisions

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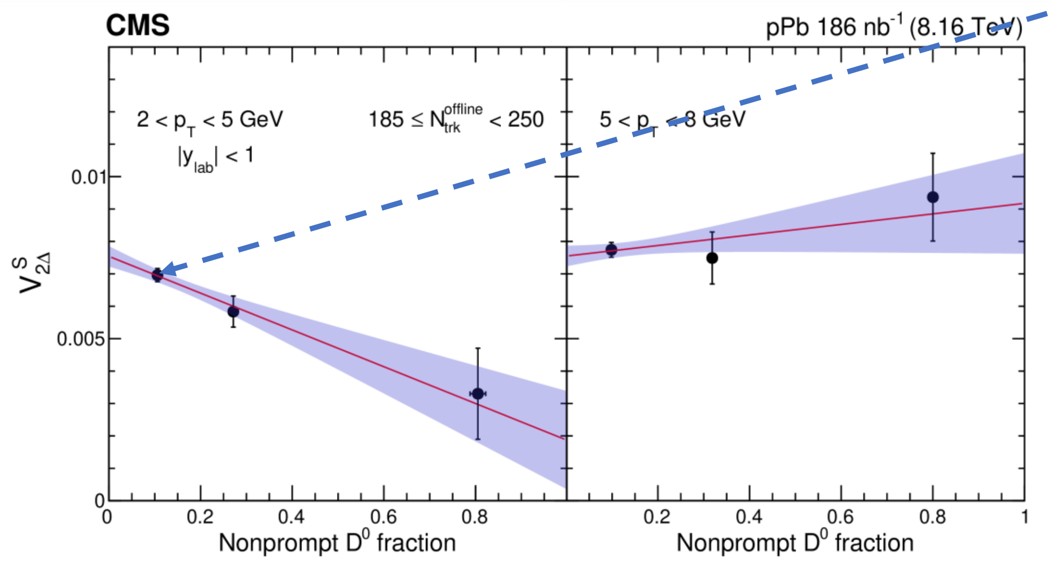
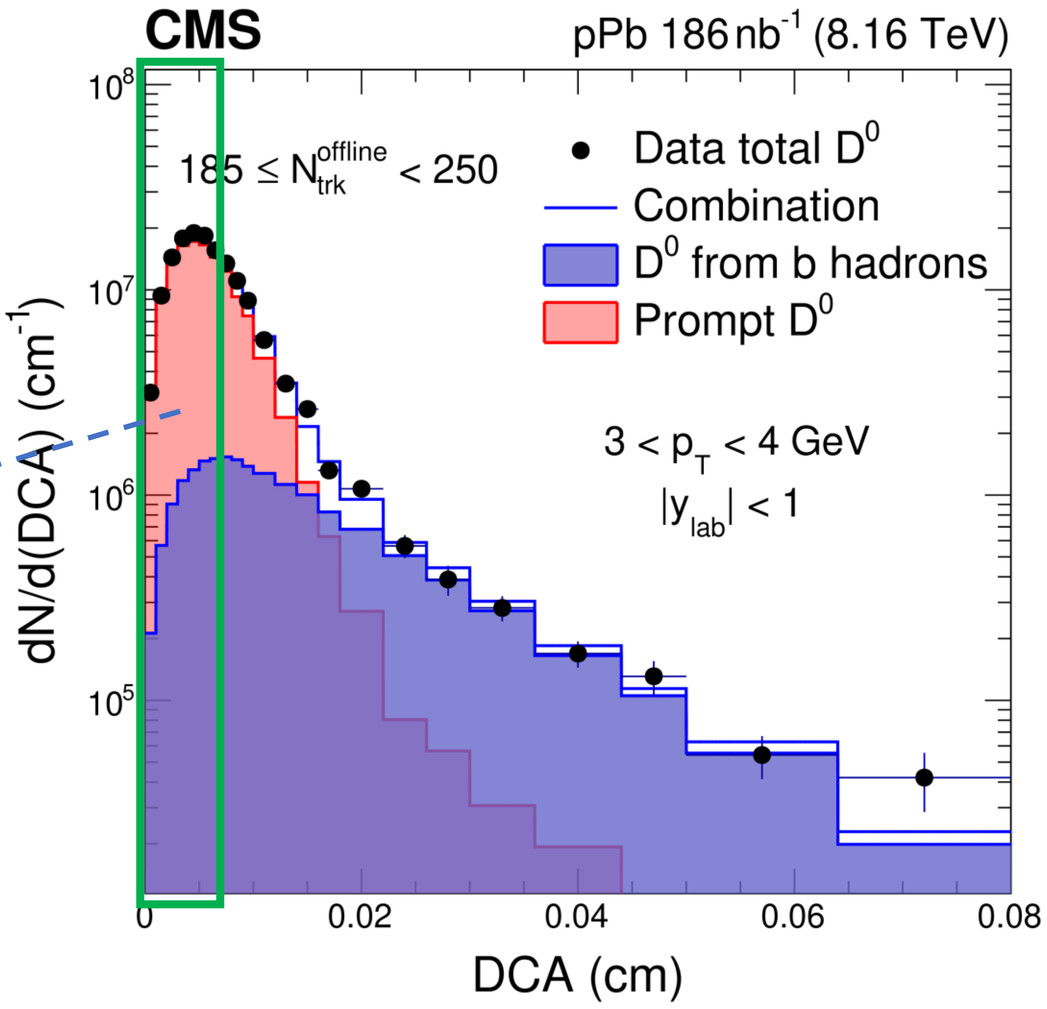
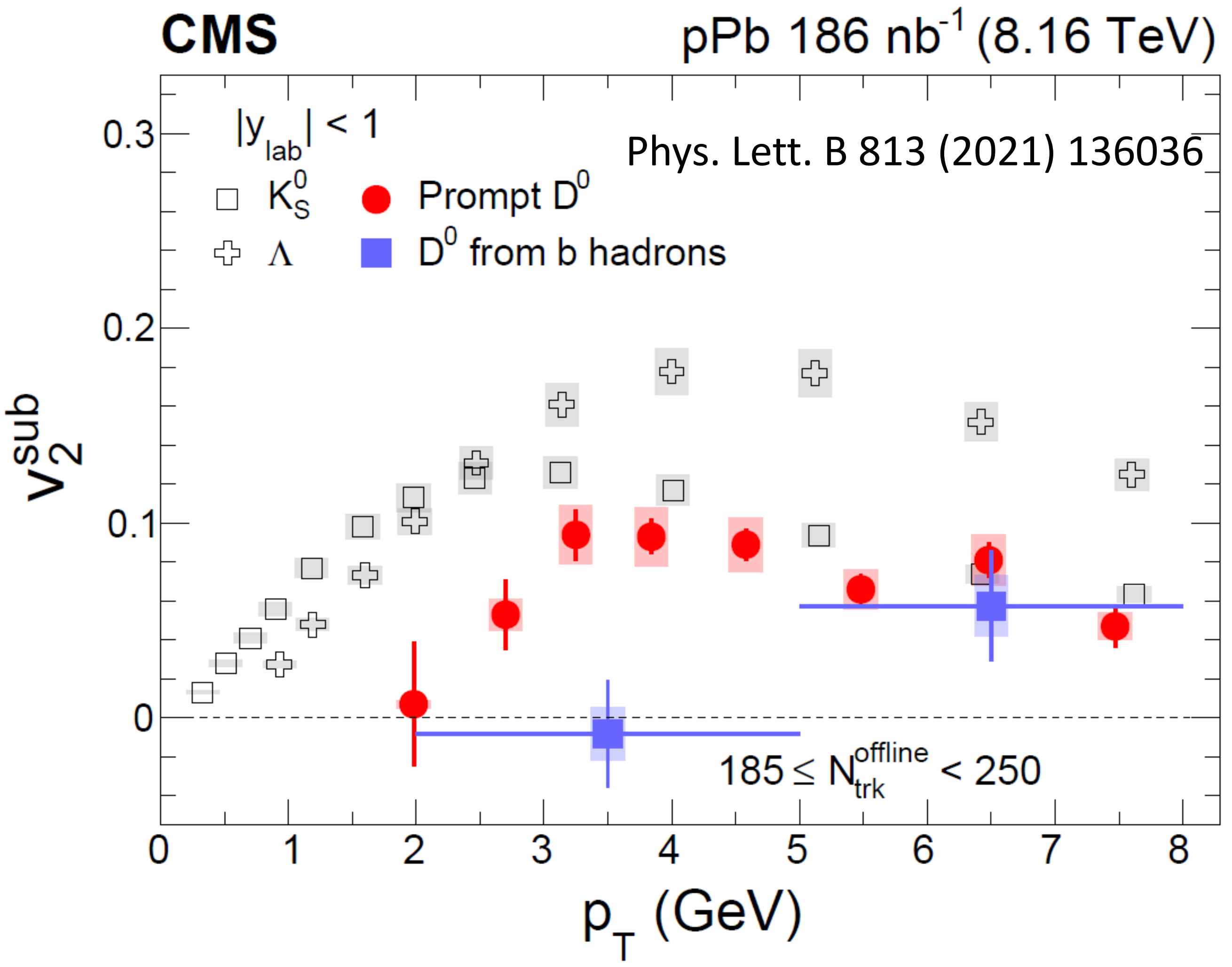




Flow for bottom hadrons

- Fist time in pPb collisions – vanishing v_2 for b hadrons via non-prompt D^0
- Indication of flavor hierarchy between charm and bottom hadrons at low p_T



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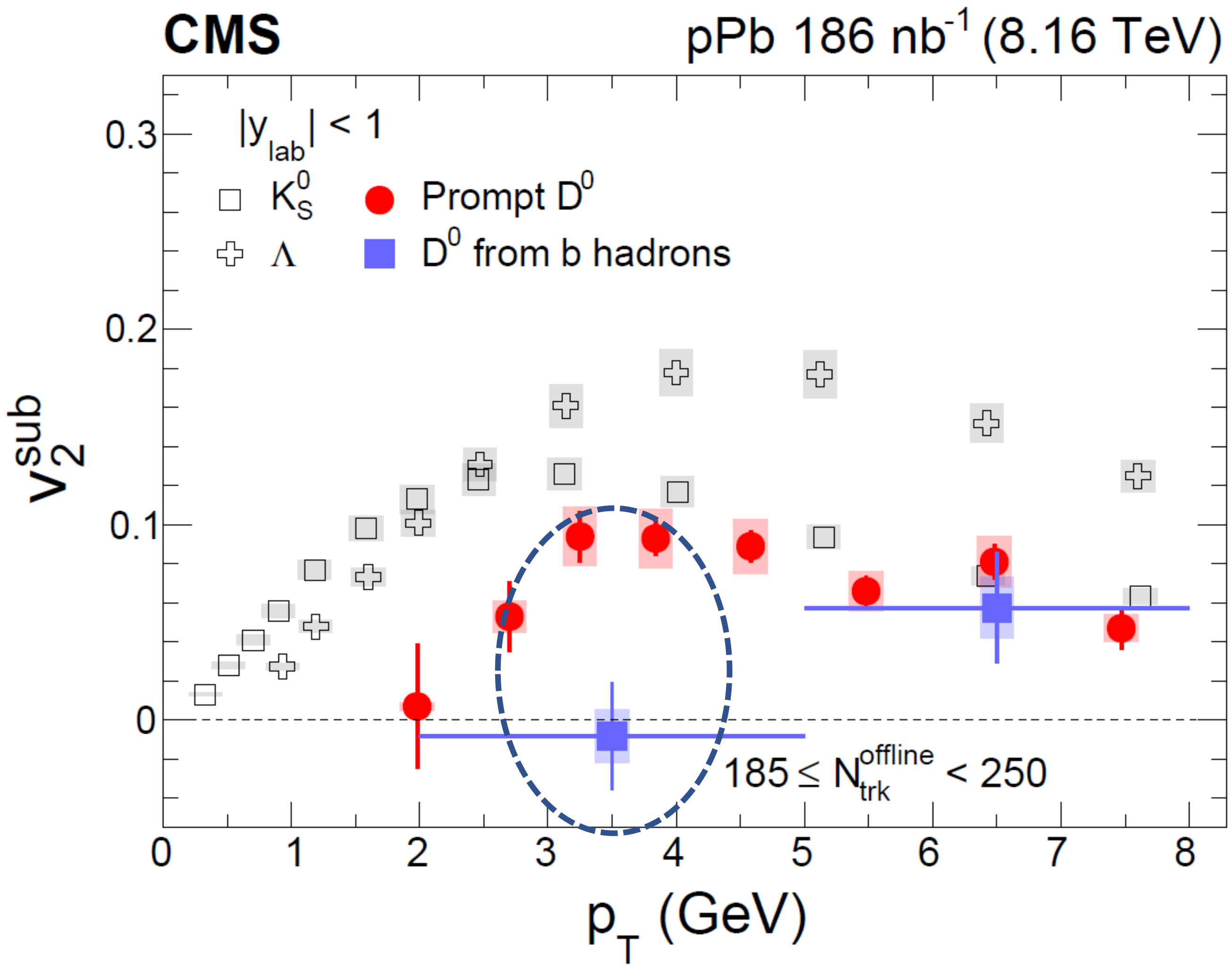
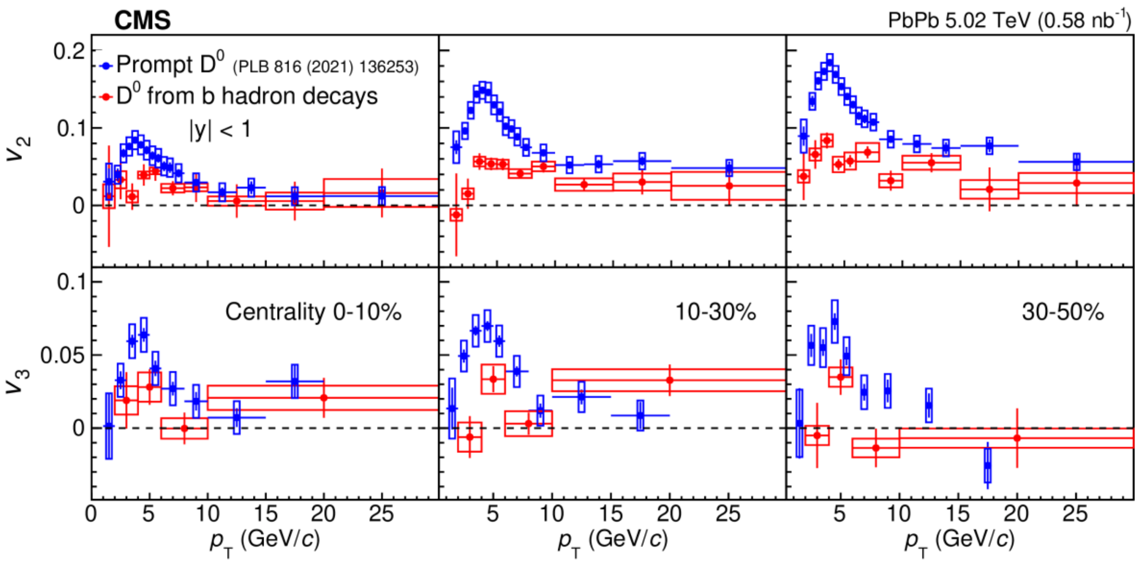
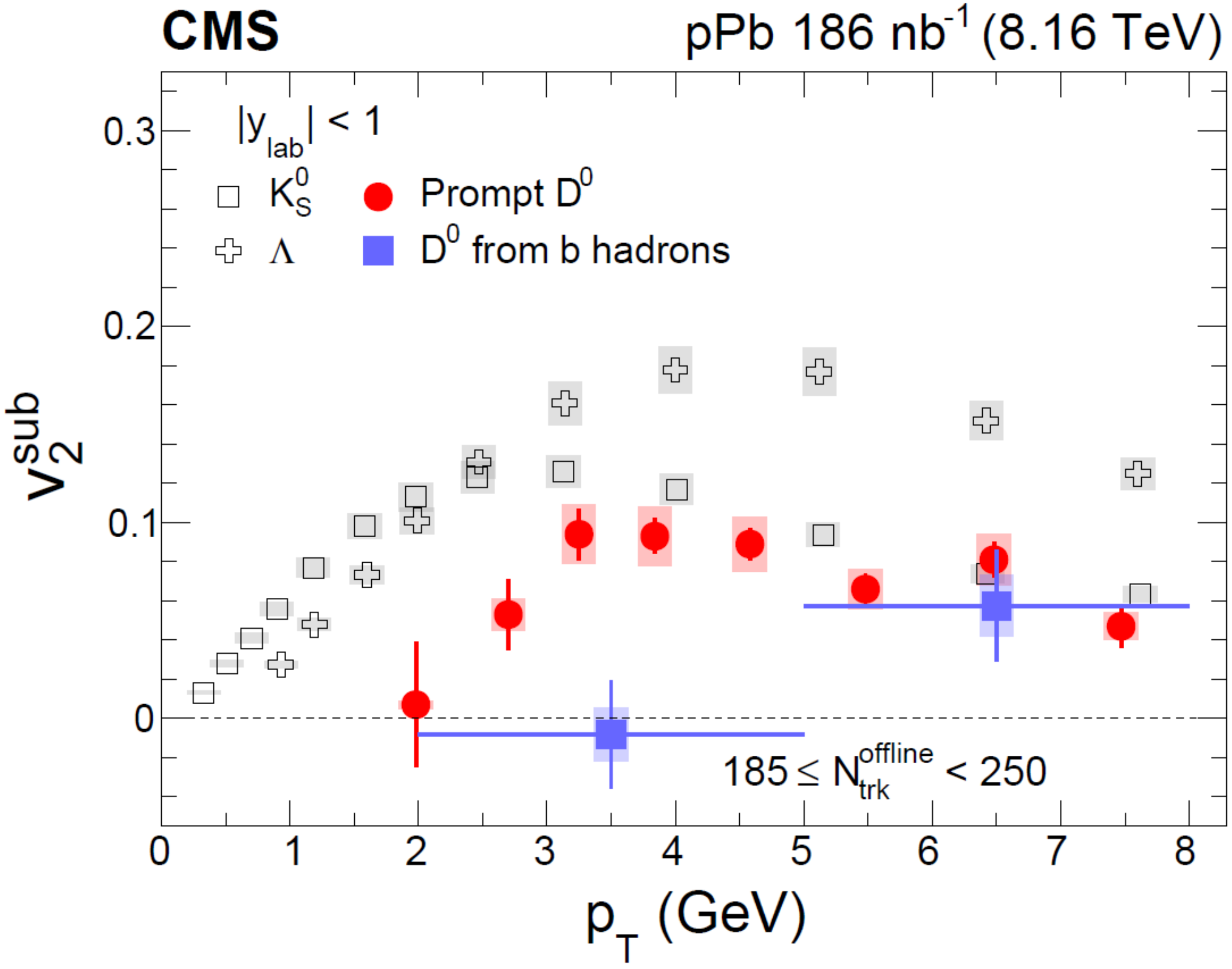


Elliptic flow for heavy flavor hadrons

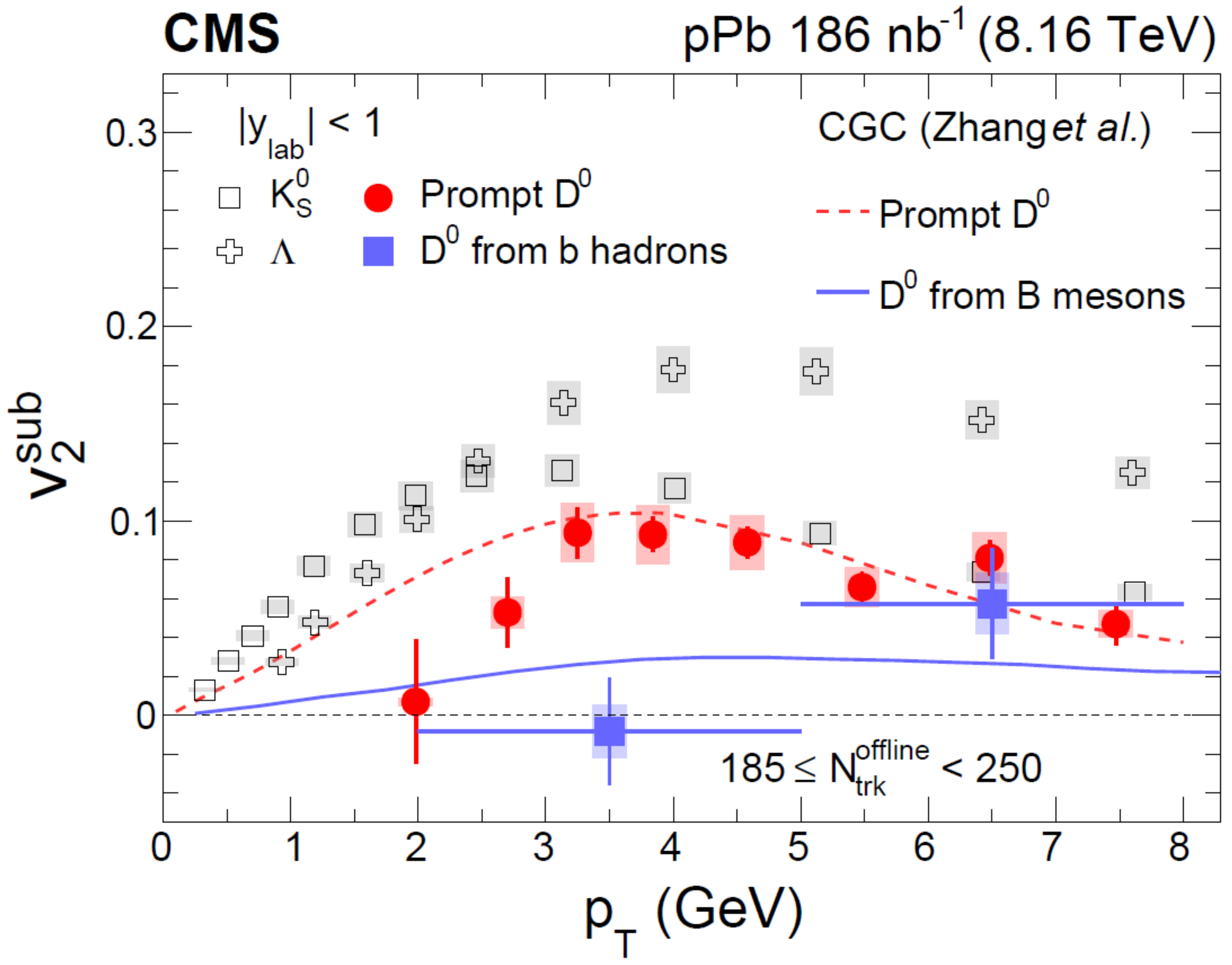
- Similar findings in large systems
  - Follow the same strategy as in pPb





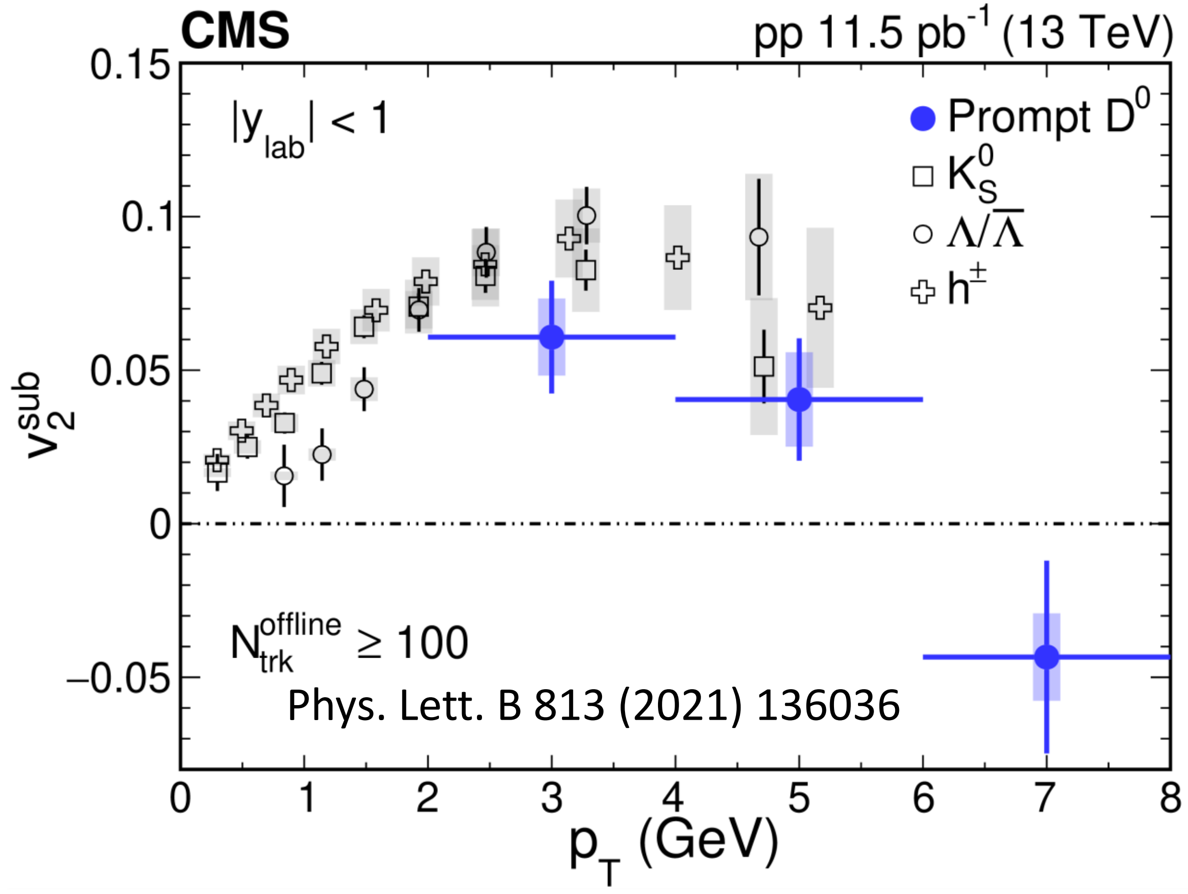
Comparisons with models

- Comparisons with CGC calculations – show consistency within large uncertainties
- Precision measurements in the future – HL-LHC

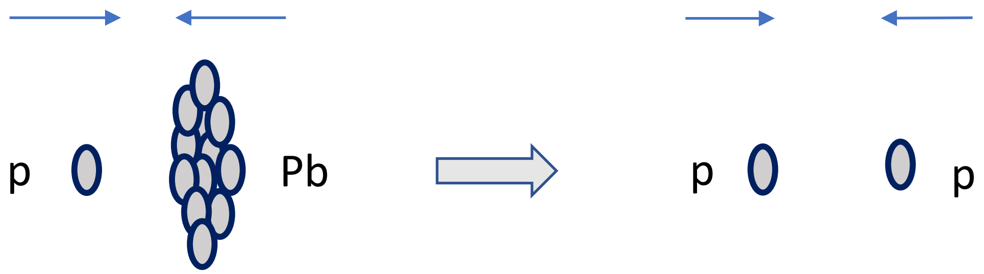


Towards small systems

- First measurement of prompt D^0 v_2 in high multiplicity pp collisions
- Indication of positive v_2 signal at $2 < p_T < 4$ GeV
- v_2 of prompt D^0 comparable with that of light hadrons

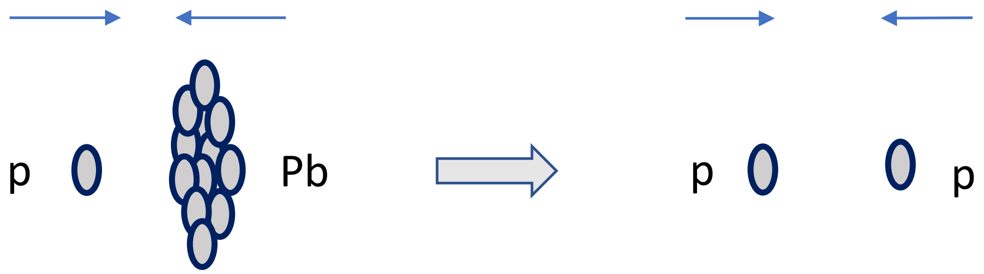


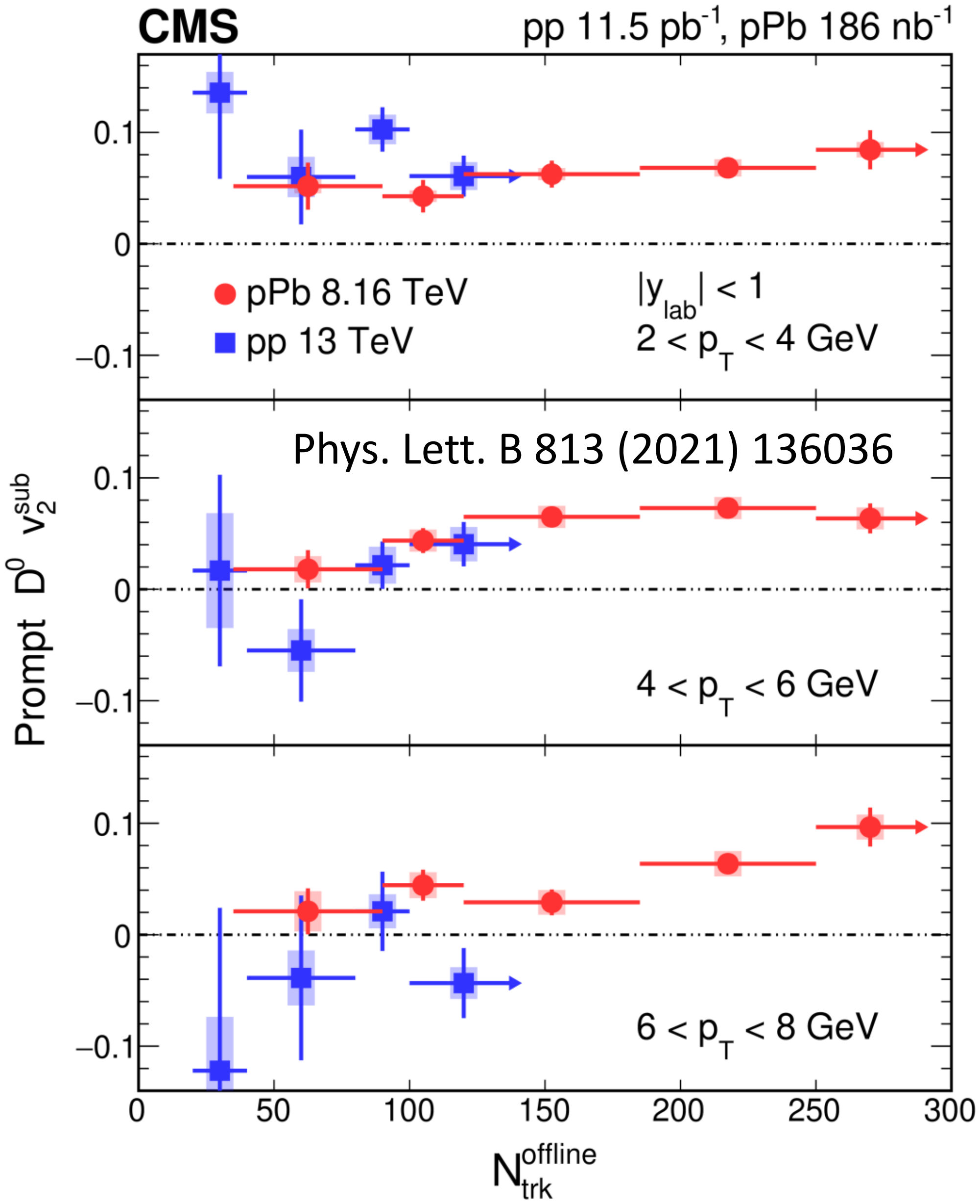
Phys. Lett. B 813 (2021) 136036



Comprehensive system scan

- Positive charm v_2 is observed in high multiplicity events
- Non-zero v_2 of prompt D^0 mesons diminish towards low-multiplicity regimes
- $v_2(pp) \sim v_2(pPb)$ given multiplicity

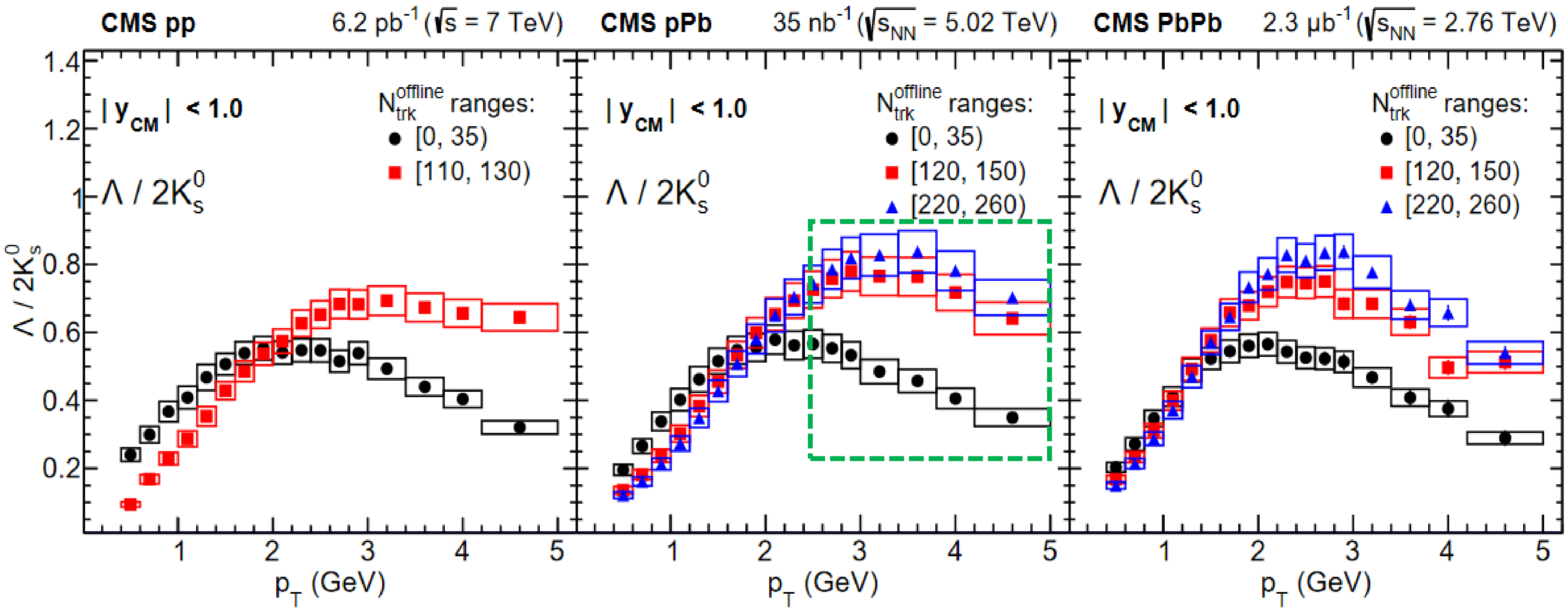




Hadron chemistry in small systems

- Thermal effects in small systems?
  - Large enhancement of baryon-to-meson ratios for strangeness
  - Similar for charm sectors?

Phys. Lett. B 768 (2017) 103

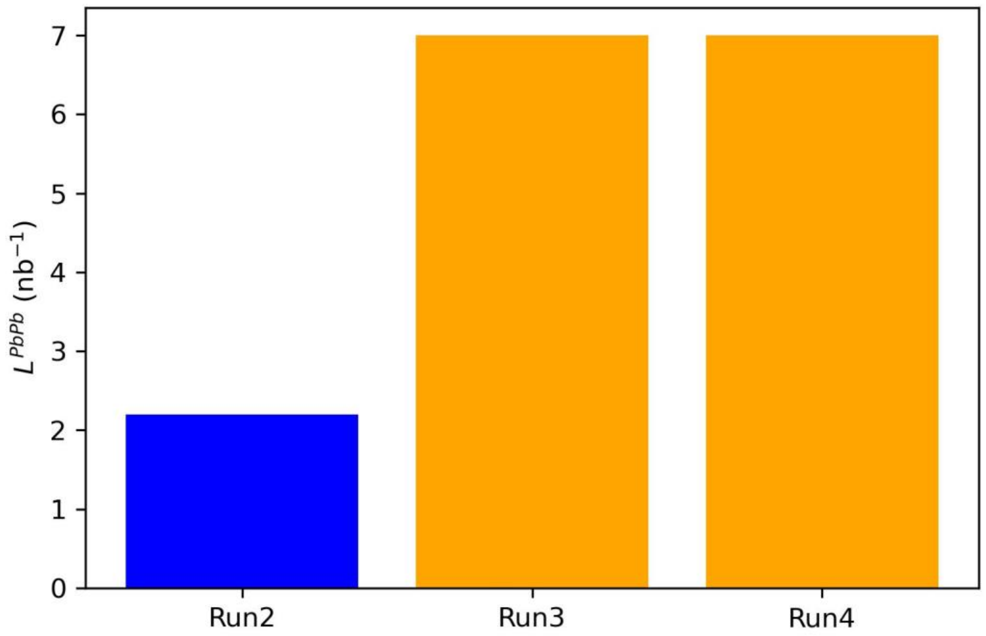


Future opportunities of heavy ion physics

- Run3 and beyond

Run 2	Run 3, ALICE 2	LS3, Upgrade	Run 4, CMS Phase 2	Run 5 (ALICE 3)
2015 – 2018	2022 – 2025	2026 – 2028	2029 – 2032	2033 – 2038

Collisions	Run2	Run3	Run4
Pb-Pb	2.2/nb	7/nb	7/nb
p-Pb	0.186/pb	0.5/pb	0.5/pb

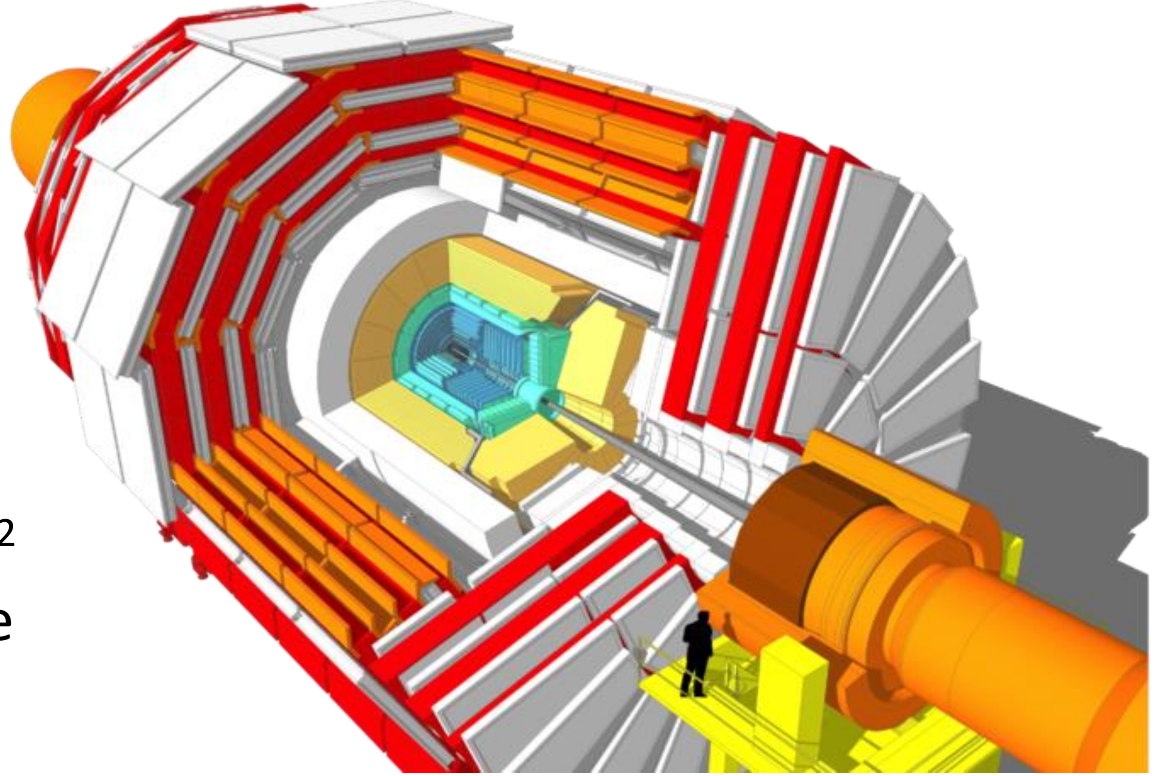


Opportunities

- Higher luminosity
- Detector upgrade

CMS Phase II upgrade

- Trigger and readout
  - L1 bandwidth: 100 kHz → 750 kHz
  - DAQ readout: 6GB/s → 51 GB/s
- High granularity Calorimeter
  - High granularity endcap with 5D info
- Tracker
  - Extend |η| from 2.4 to 4
  - pixel size: 100x150 um^2 → 50x50 um^2
  - Potential tracking trigger in hardware
- MIP timing detector
  - **Entirely new, resolution ~35ps**
  - **Large coverage, |η|<3**

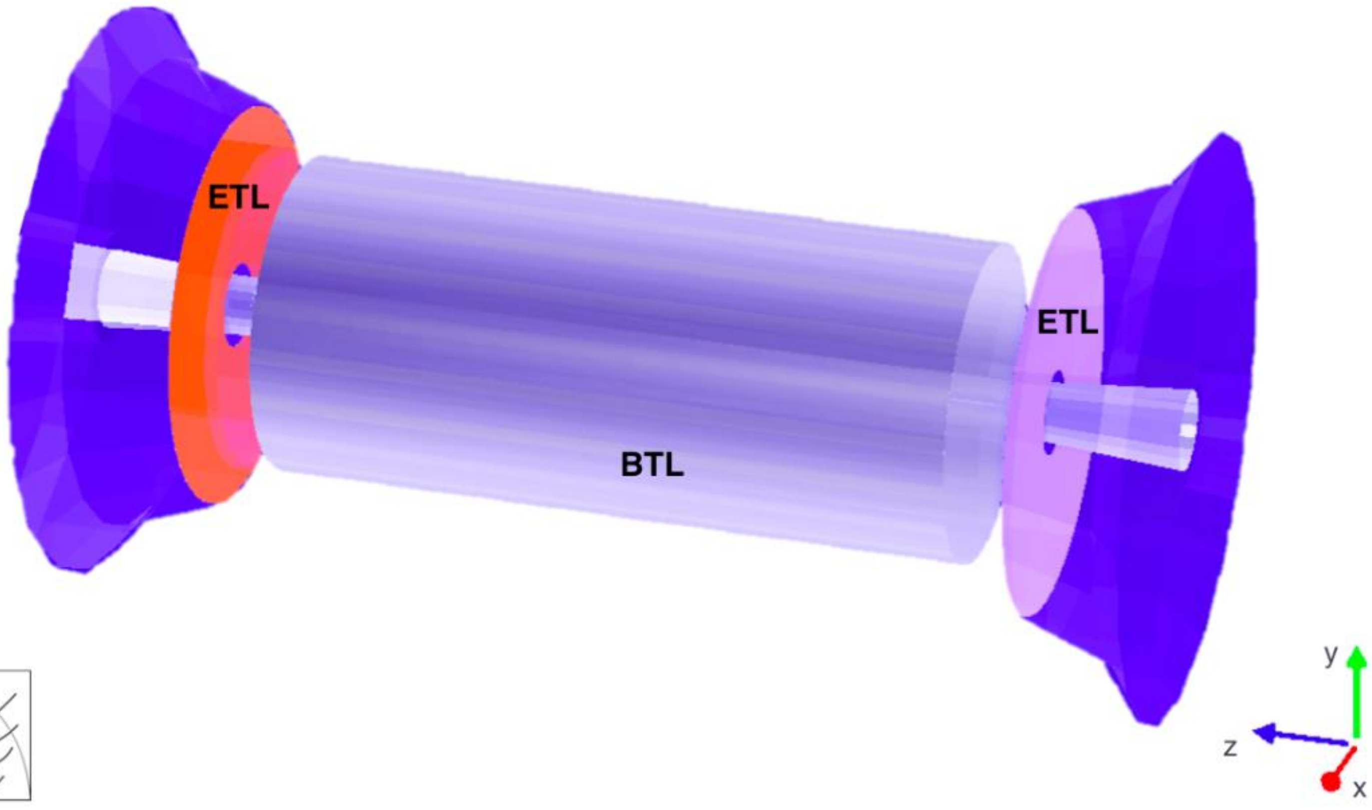


MIP timing detector

- MTD
  - Barrel timing layer
  - Endcap timing layer
- PID $\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$

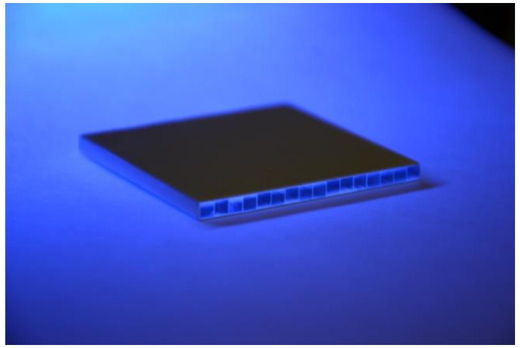
Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) (m $\times$ ps^{-1})
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

- Benefit
  - PU mitigations
  - Search for long-lived particles
  - …
  - ***Heavy-ion physics***

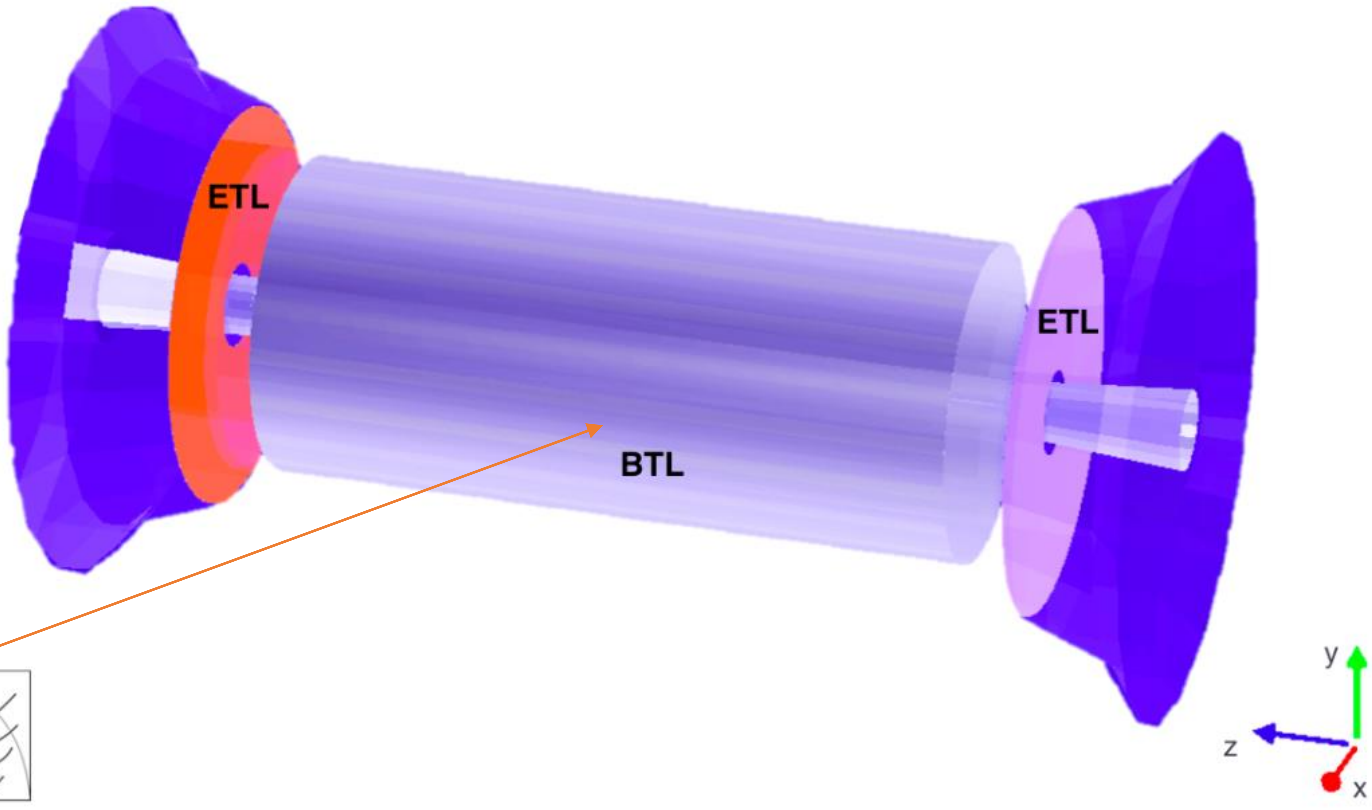


Barrel timing layer

- Barrel timing layer (BTL)
  - Fast rise time
  - Large coverage area
- General
  - LYSO bars + SiPM readout
  - $|\eta|<1.45$
  - Inner radius: 1148 mm (40mm tl
  - Length: +/- 2.6 m along z
  - Surface ~38 m^2; 332k channels

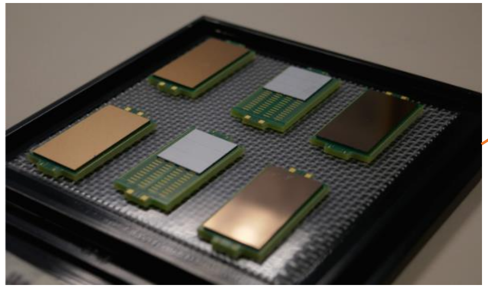


16x1 array of crystal bar

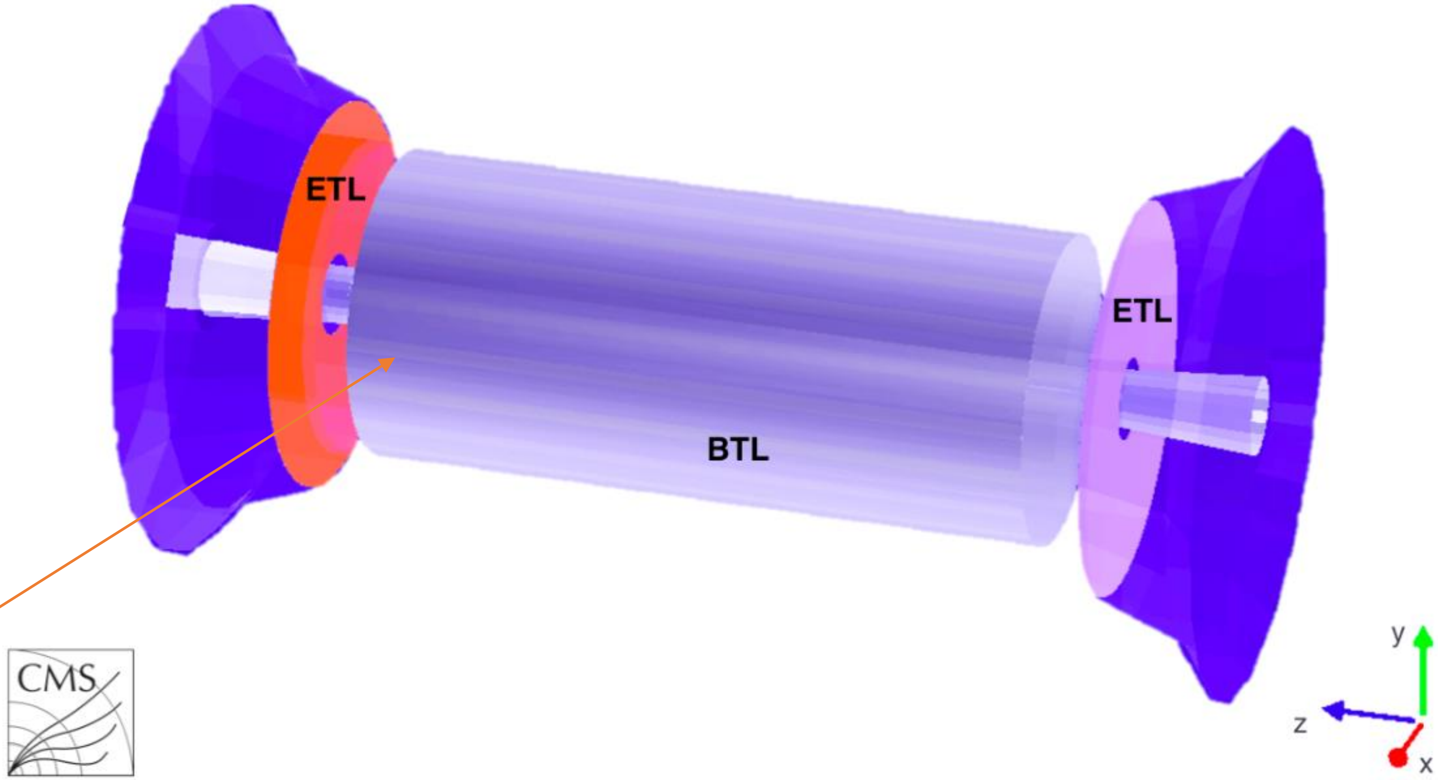


Endcap timing layer

- Endcap timing layer (ETL)
  - Good radiation tolerance
  - Low occupancy
  - High timing resolution
- General
  - Si with internal gain (LGAD)
  - 1.6 < | η | < 3.0
  - Radius: 315 < R < 1200 mm
  - Position in z: +/-3.0 m (45 mm thick)
  - Surface ~14 m^2; ~8.5M channels

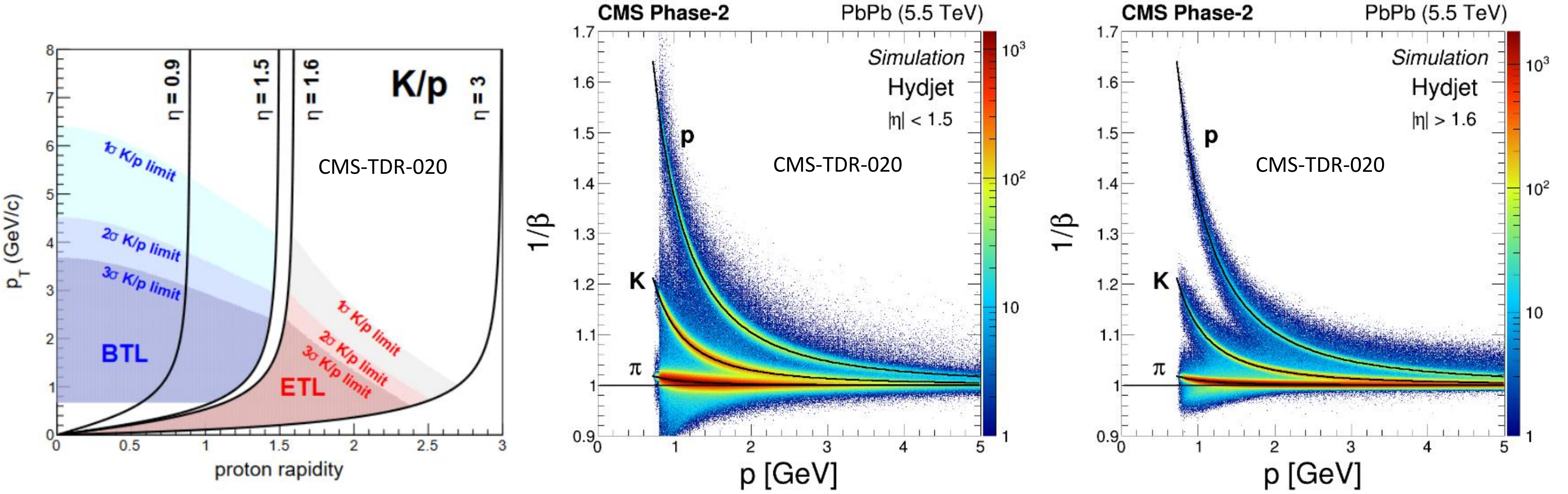


LGAD sensors on PCB



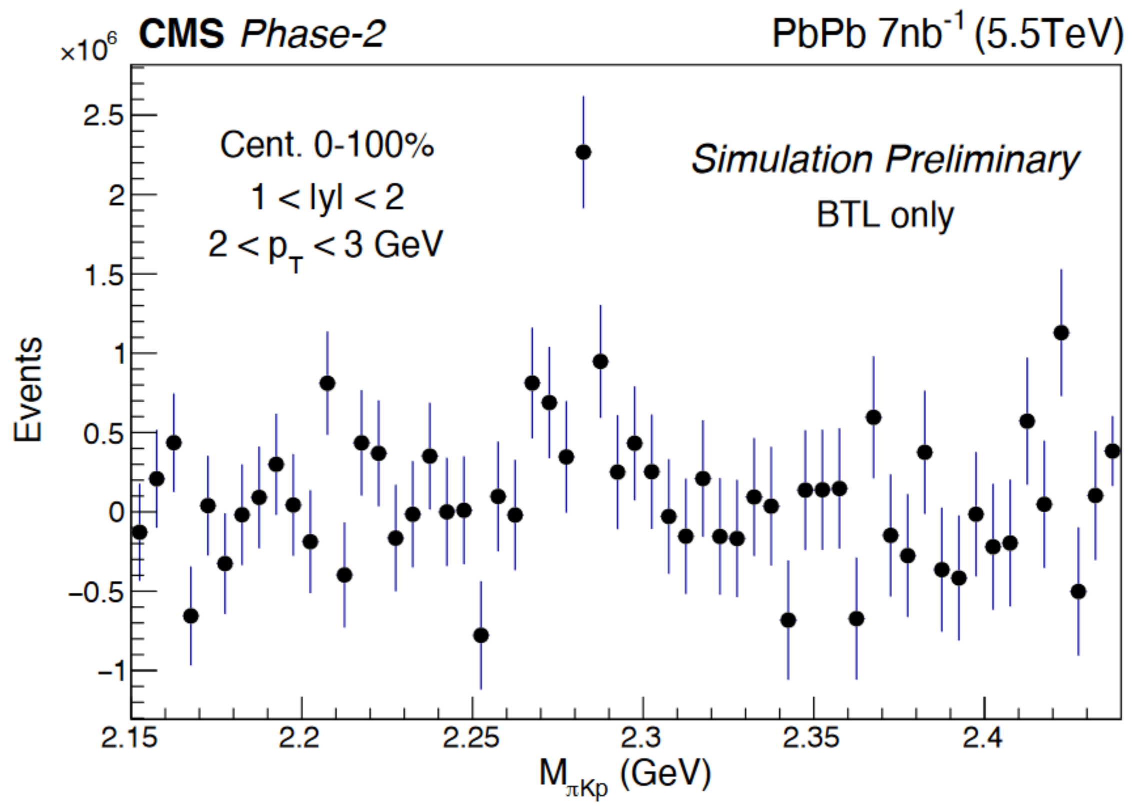
CMS-MTD and particle identification

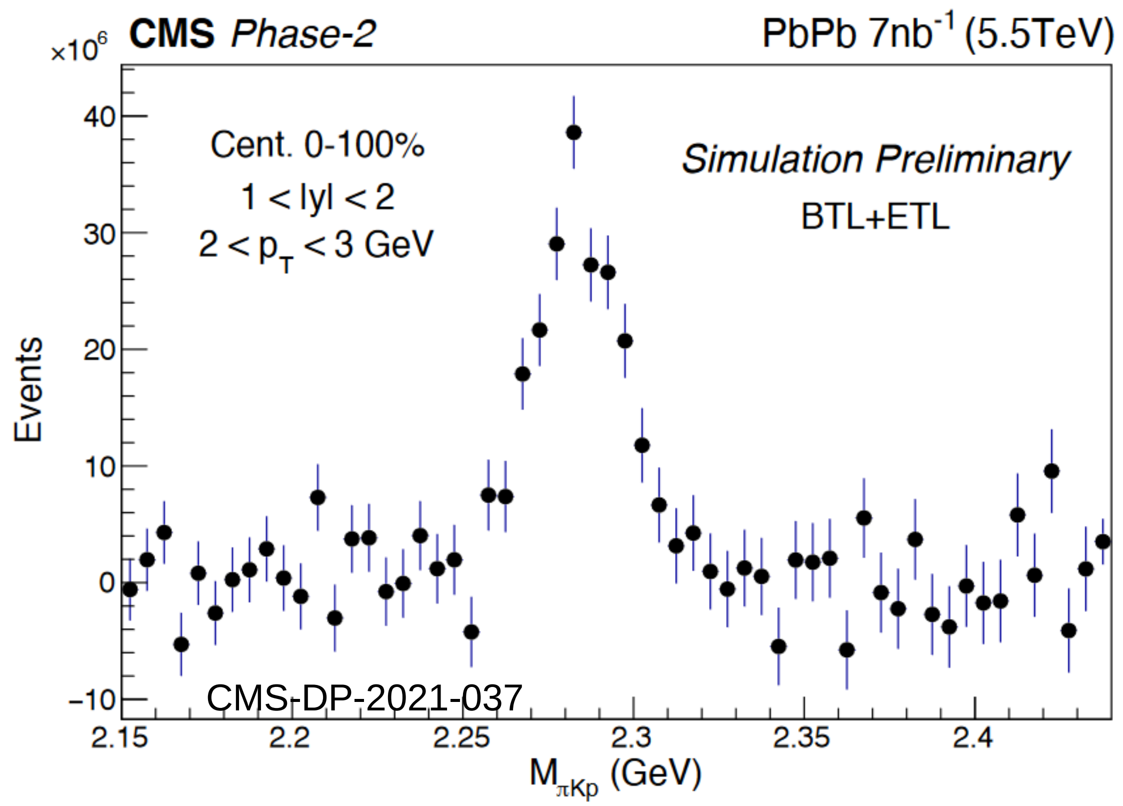
- Wide coverage up to 6 units of rapidity
- π/K separation up to 3 GeV
- K/p separation up to 5 GeV



Projections for Λ_c^+

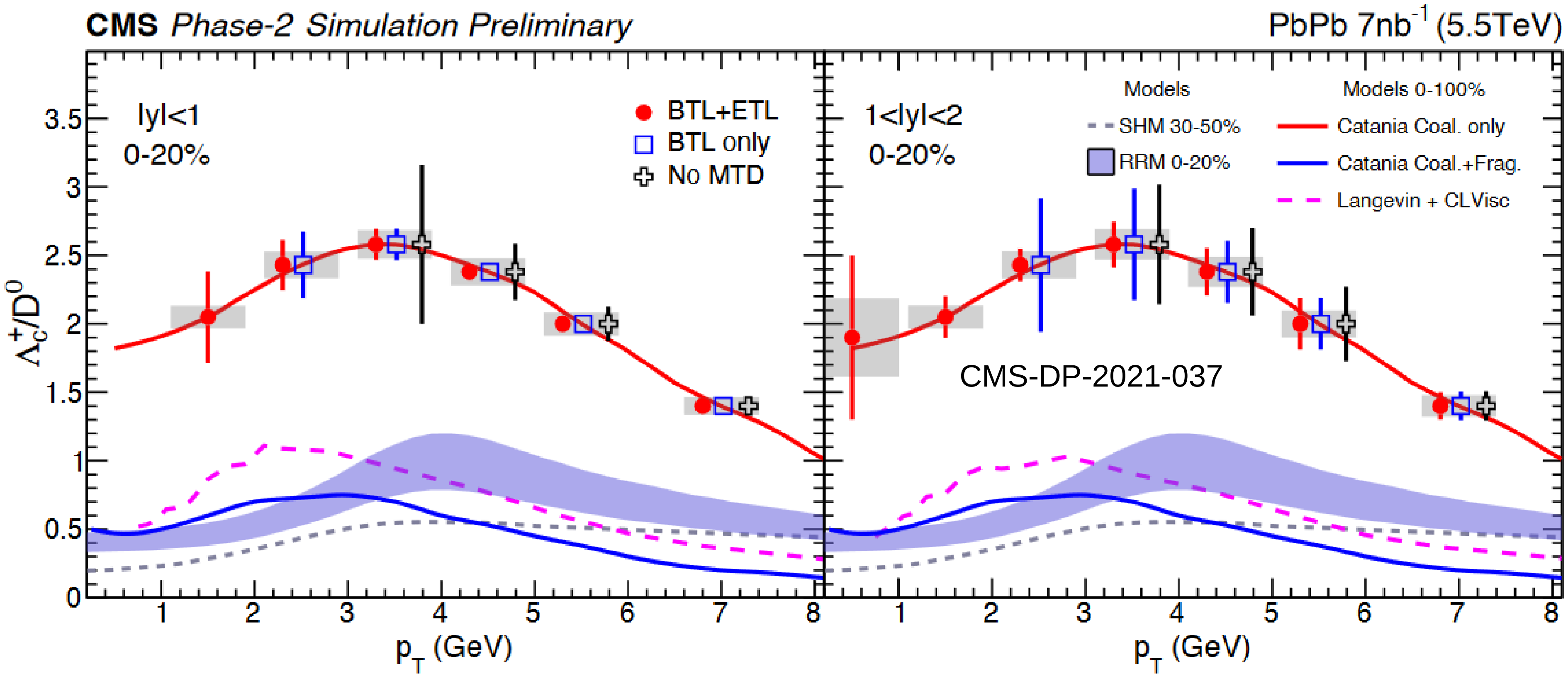
- Reconstruct Λ_c^+ in forward rapidity with ETL





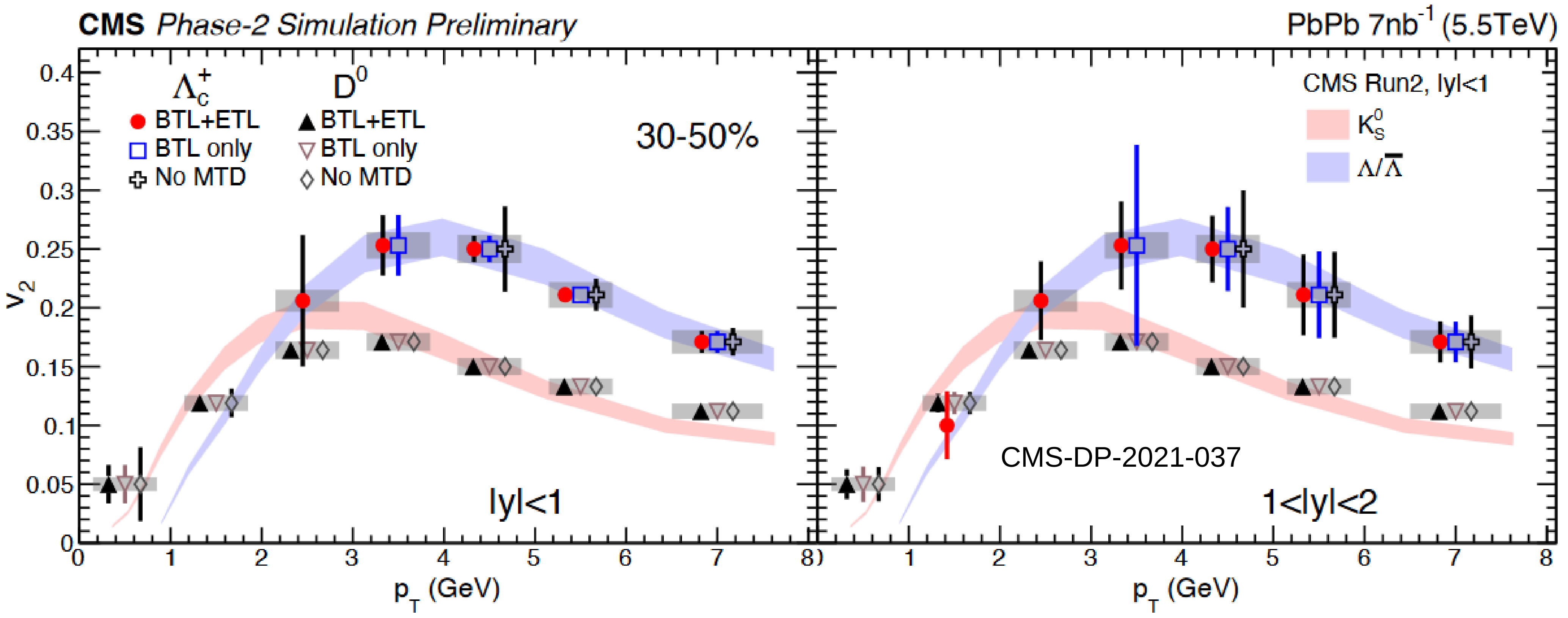
Coalescence effects of charm hadrons

- Access full p_T range of Λ_c^+ *with MTD*
  - Total charm cross section
  - CMS *unique* access over a rapidity range of ***up to 6 (4) units in MB (central)*** *events*

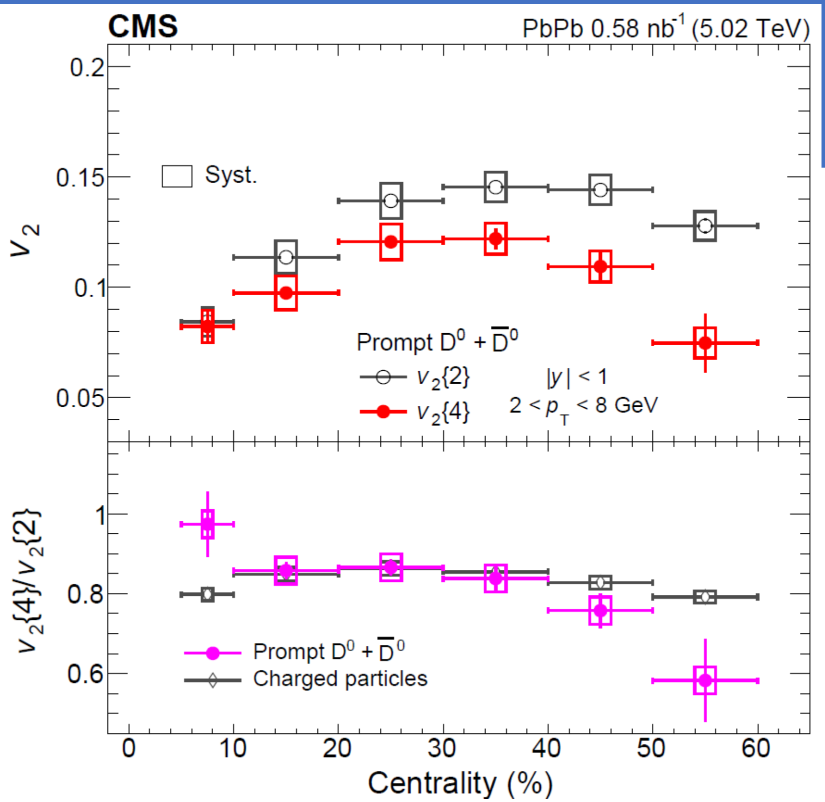


Coalescence effects of charm hadrons

- Precision measurements down to *low p_T with MTD*
- Number of constituent quark scaling – $v_2(\Lambda_c^+)/v_2(D^0) = 3/2$?



Summary



- Tremendous progress for heavy flavor flow in both large and small systems
  - Significant charm flow in large event activity
  - Mild bottom flow in large systems
- Future opportunities with the new era of LHC!