The beauty of heavy ion collisions

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23rd August 2017, GSI

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Outline:

- Introduction to heavy ion collisions
- hard probes
  - open heavy flavour: focus on beauty
- future
- summary

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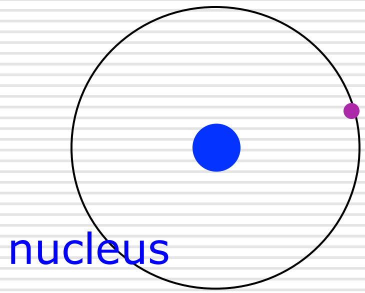
Confinement: a crucial feature of QCD

electron



neutral atom

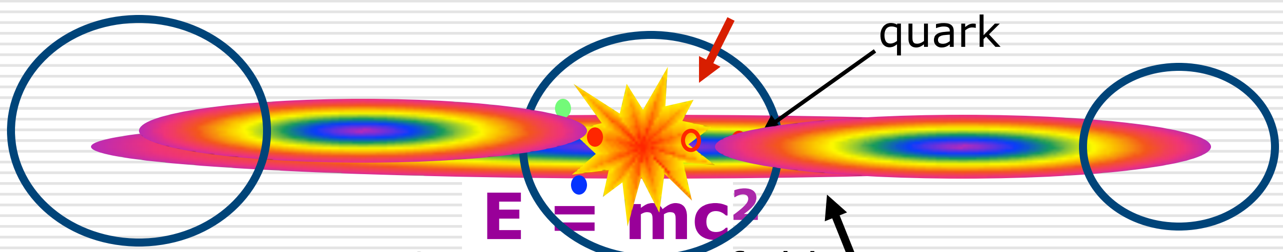
We can extract an electron from an atom by providing energy

But we cannot get free quarks out of hadrons: **"colour confinement"**

•

quark-antiquark pair
created from vacuum

quark



Strong **colour** field
Energy grows with separation!

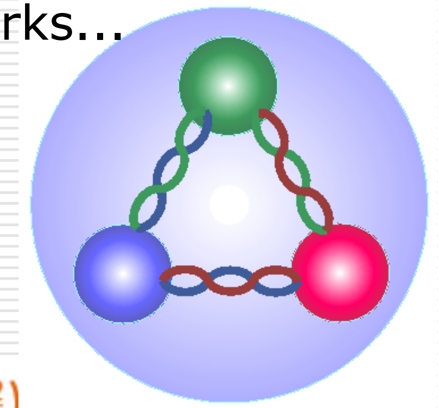
"white" proton
(confined quarks)

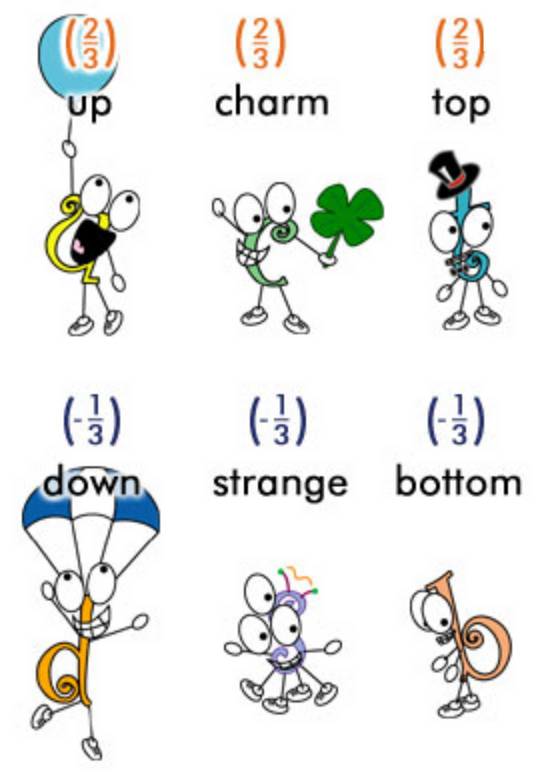
"white" π^0
(confined quarks)

"white" proton

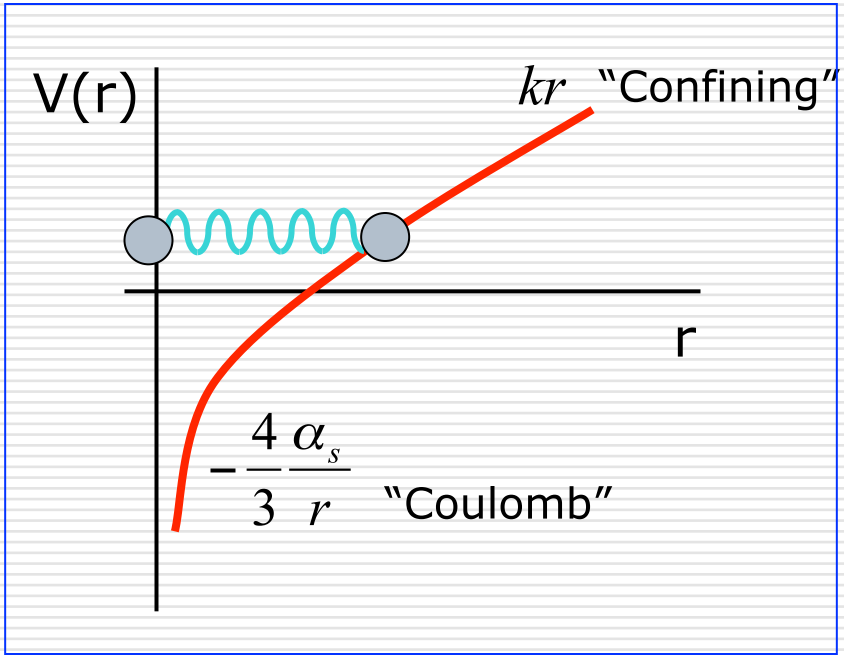
Confinement: a crucial feature of QCD

A proton is a composite object made of quarks... and gluons



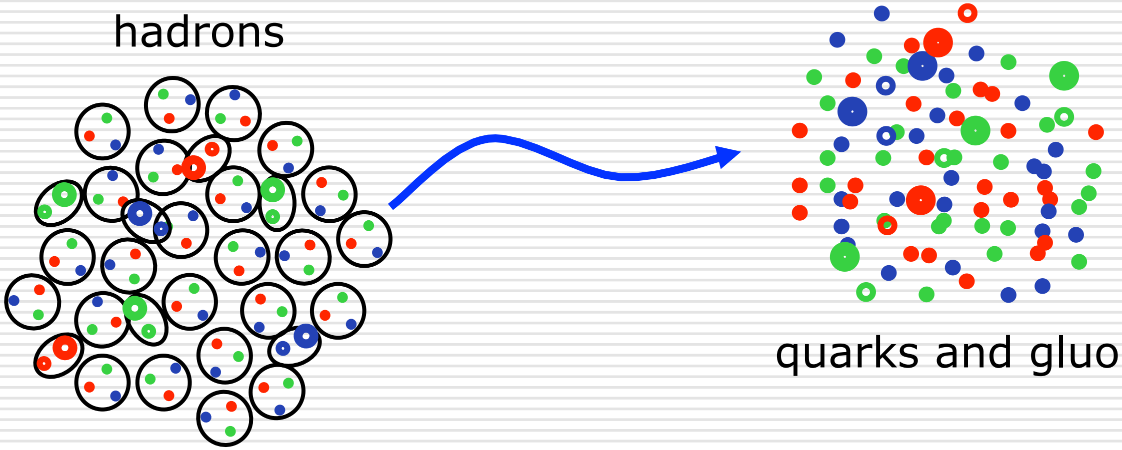


No one has ever seen a free quark; QCD is a "confining gauge theory"

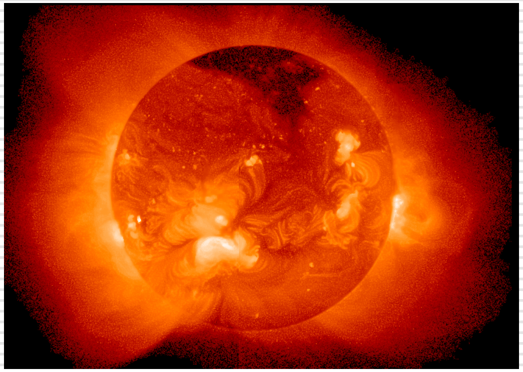


The QCD phase transition

Lattice QCD calculations indicate that, at a *critical* temperature around 170 MeV, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined into hadrons



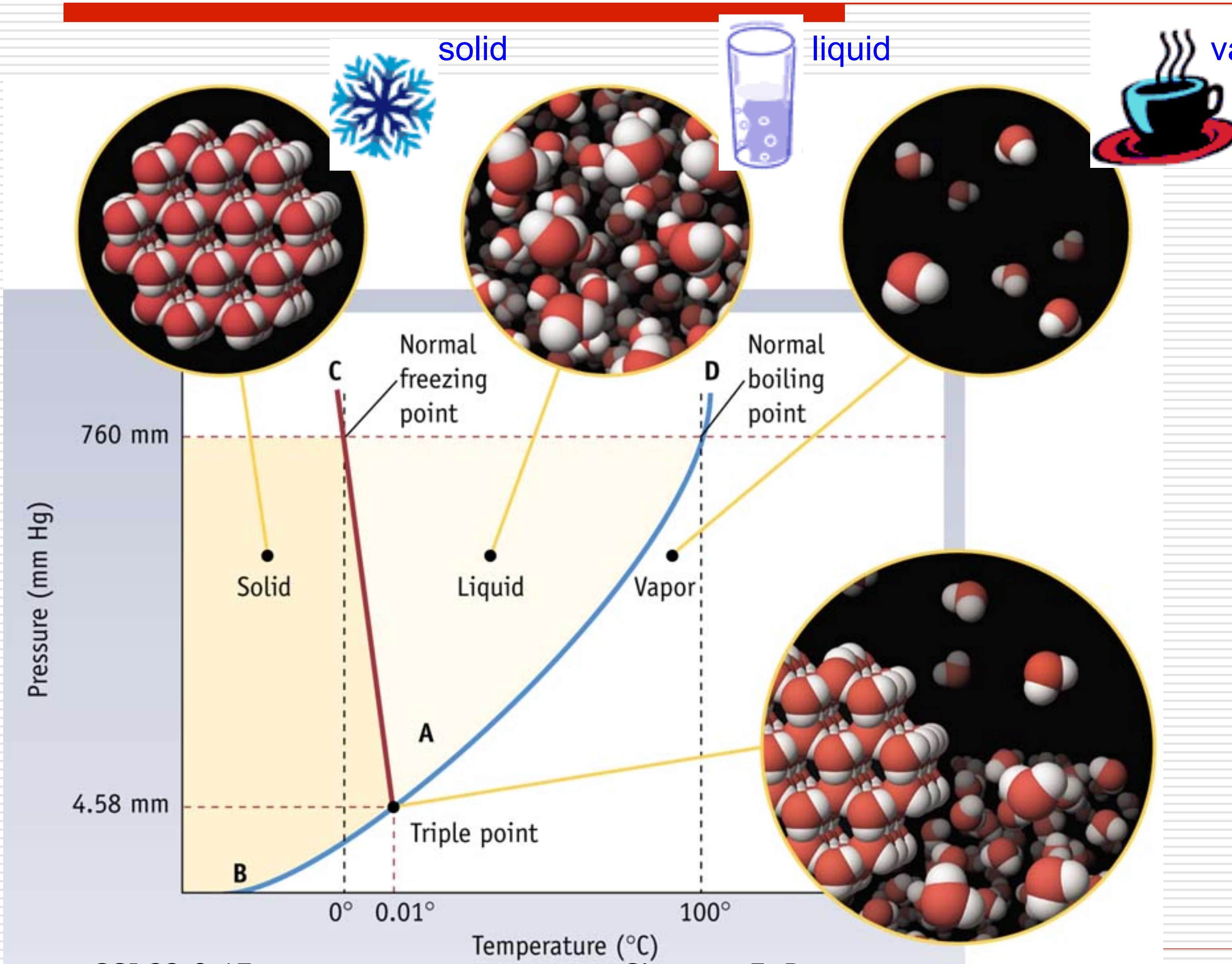
How hot is a medium of T ~ 170 MeV?



15 M °K

100,000 times hotter than the Sun core

The phase diagram of water



The phase diagram of QCD, in 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. Cabibbo and G. Parisi, Phys. Lett. B59 (1975) 67

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

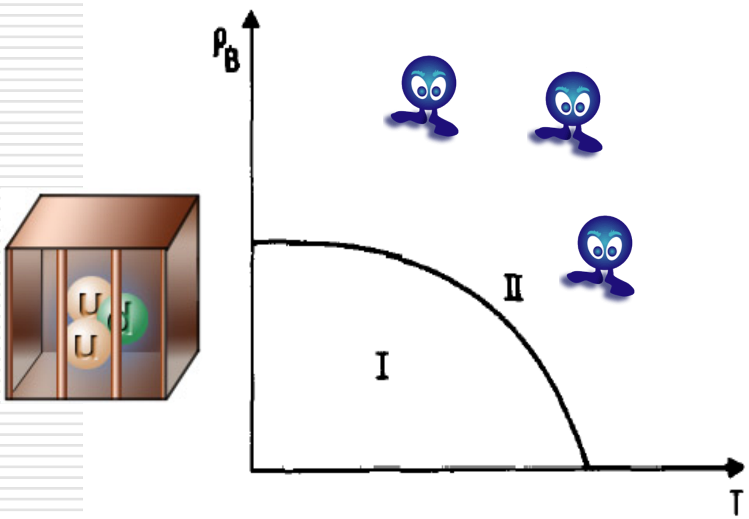
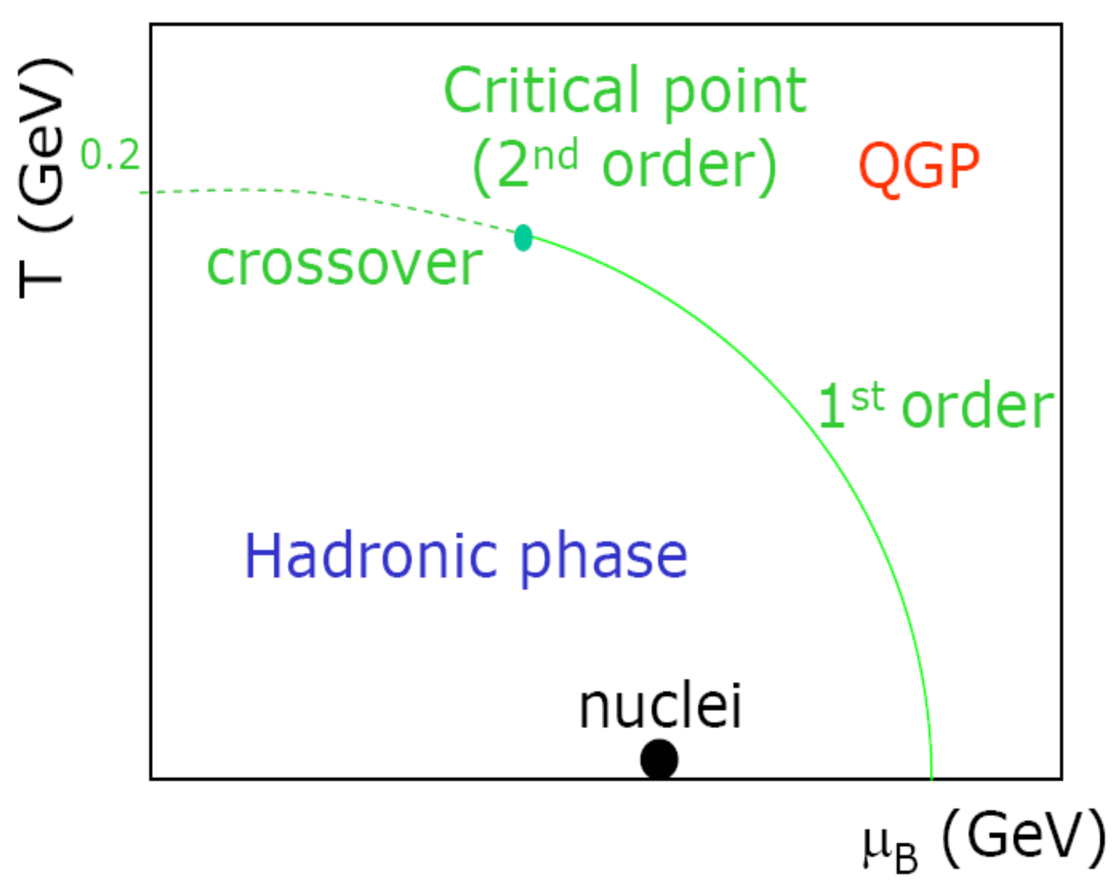


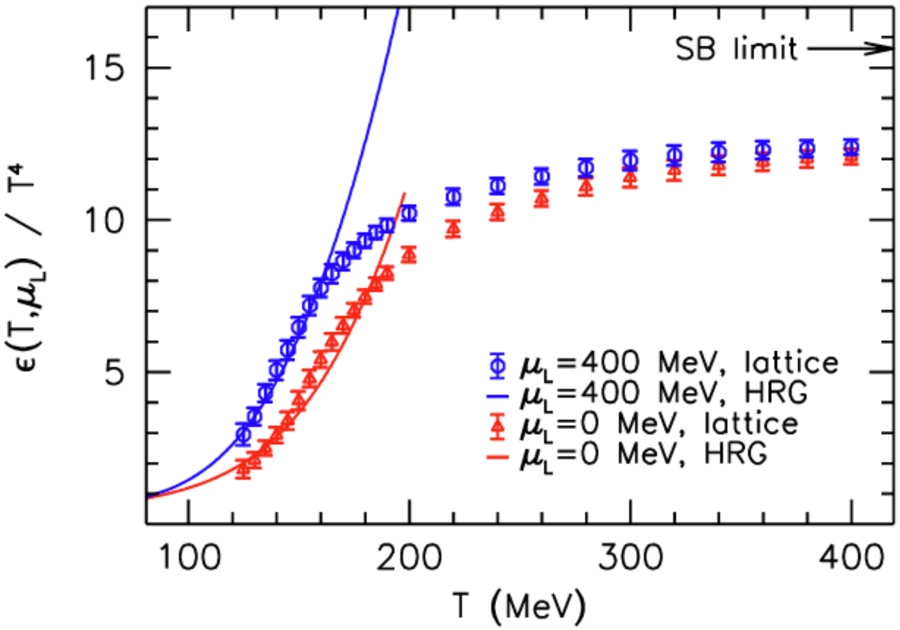
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

The phase diagram of QCD, today



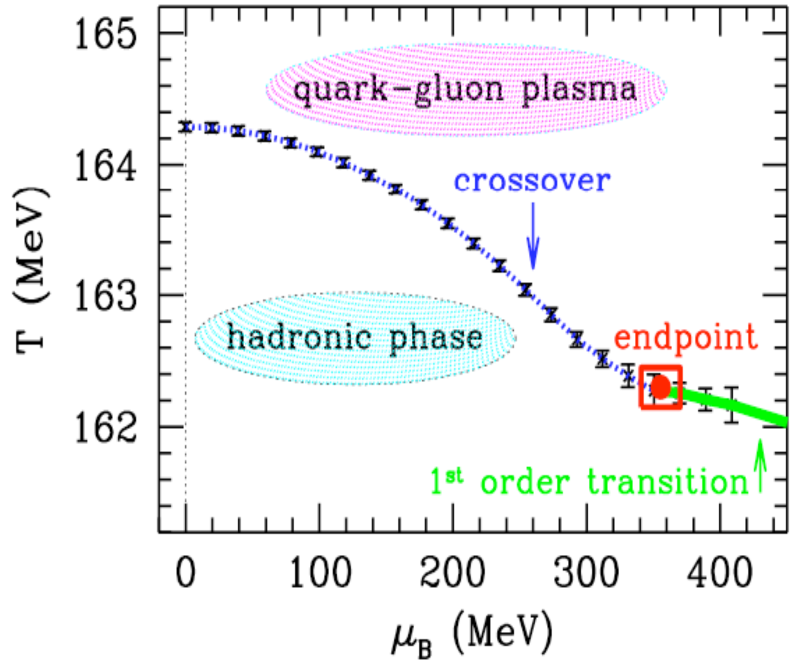
Lattice QCD: results

- Transition to QGP phase is a prediction of the lattice QCD
  - the order of the transition depends on μ_B



S. Borsanyi et al., JHEP (2012)

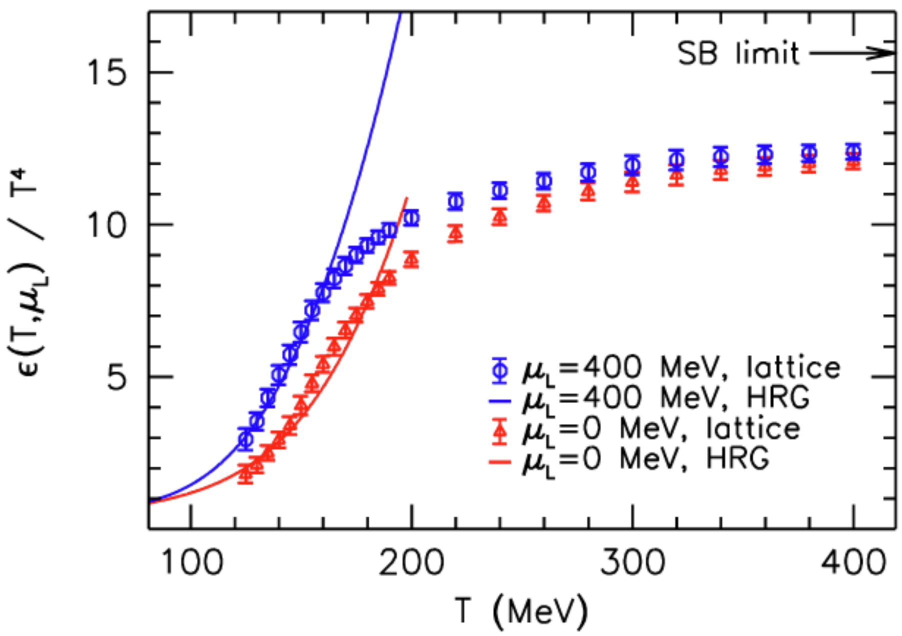
Z. Fodor, S. Katz, JHEP04 204 (2004)



"Most importantly one has to extrapolate to the continuum limit"

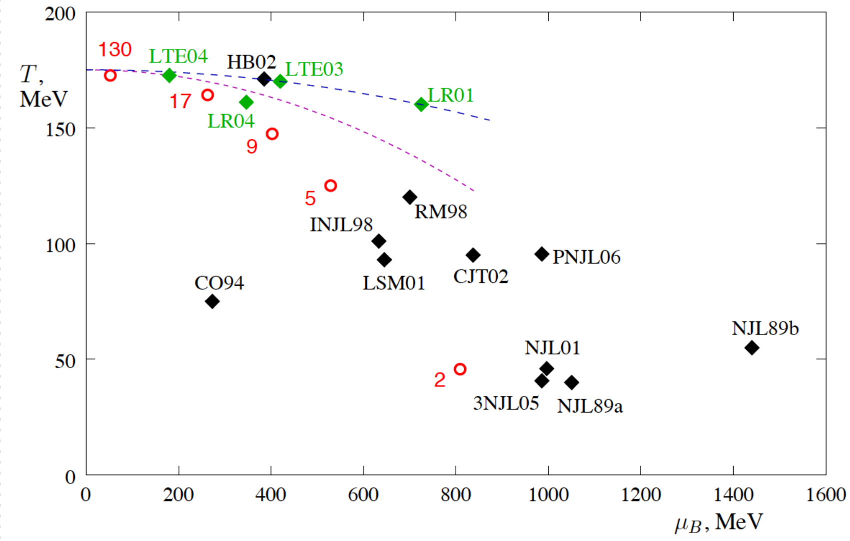
Lattice QCD: results

- Transition to QGP phase is a prediction of the lattice QCD
  - the order of the transition depends on μ_B



S. Borsanyi et al., JHEP (2012)

M. Stephanov, PoS LAT2006 (2006)

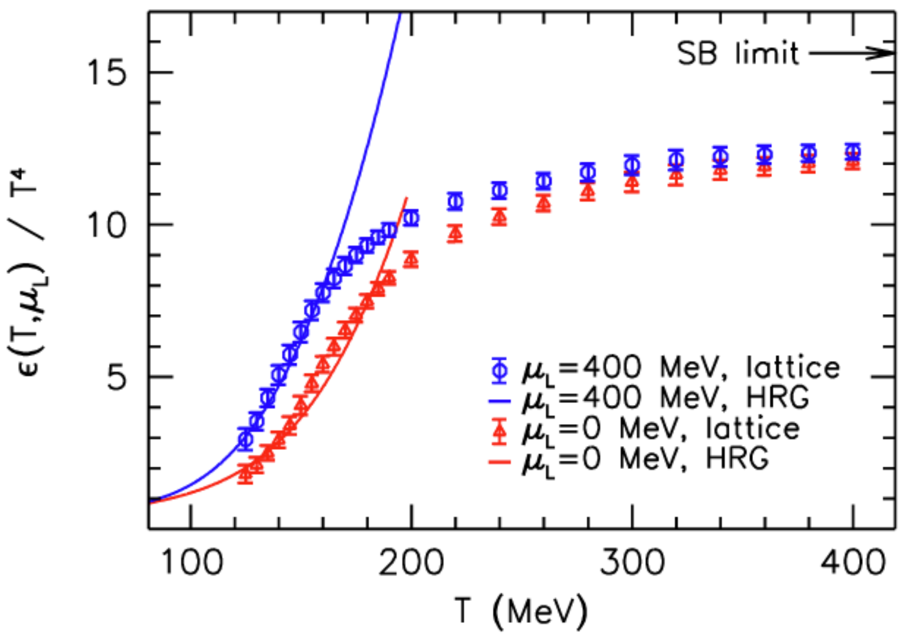


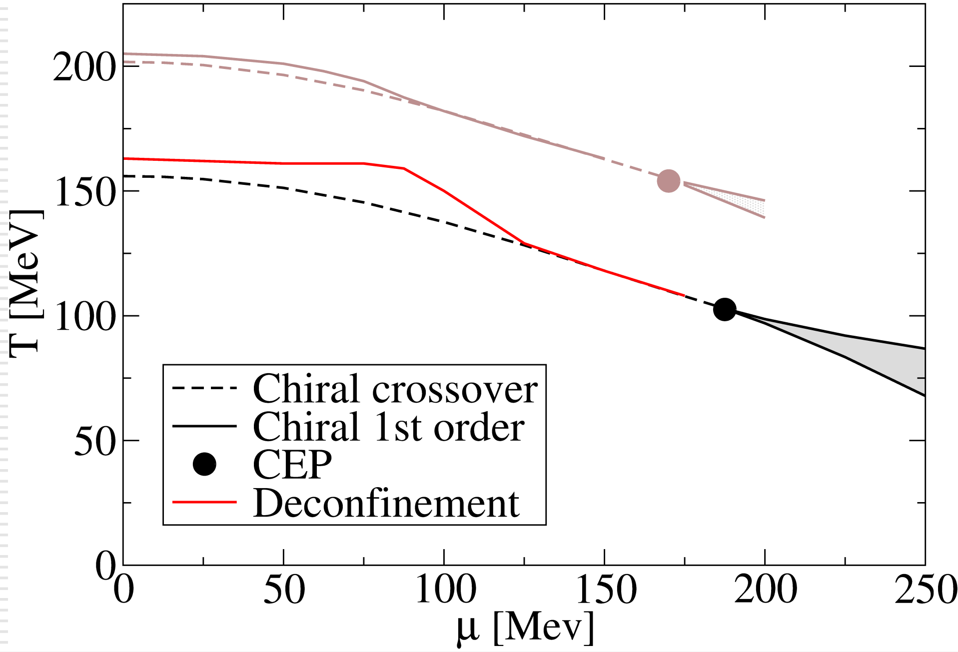
"... predictions for the location of the QCD critical point"

Lattice QCD: results

- Transition to QGP phase is a prediction of the lattice QCD
  - the order of the transition depends on μ_B

C. Fischer, J. Luecker, PLB718 (2013)



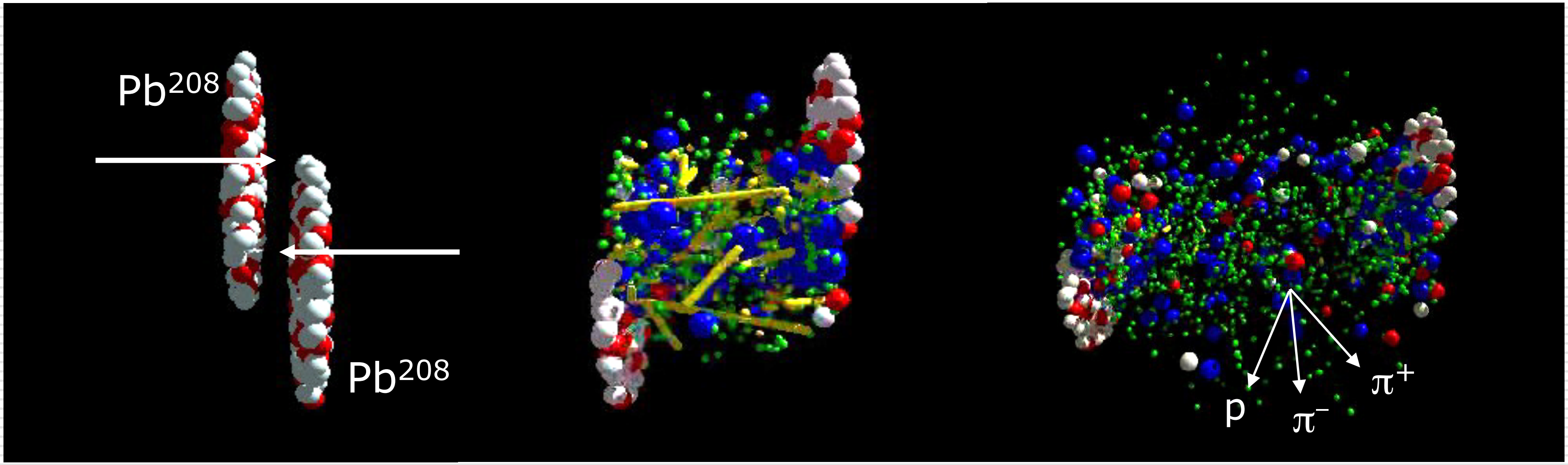


S. Borsanyi et al., JHEP (2012)

“We ... find a potential critical endpoint..."

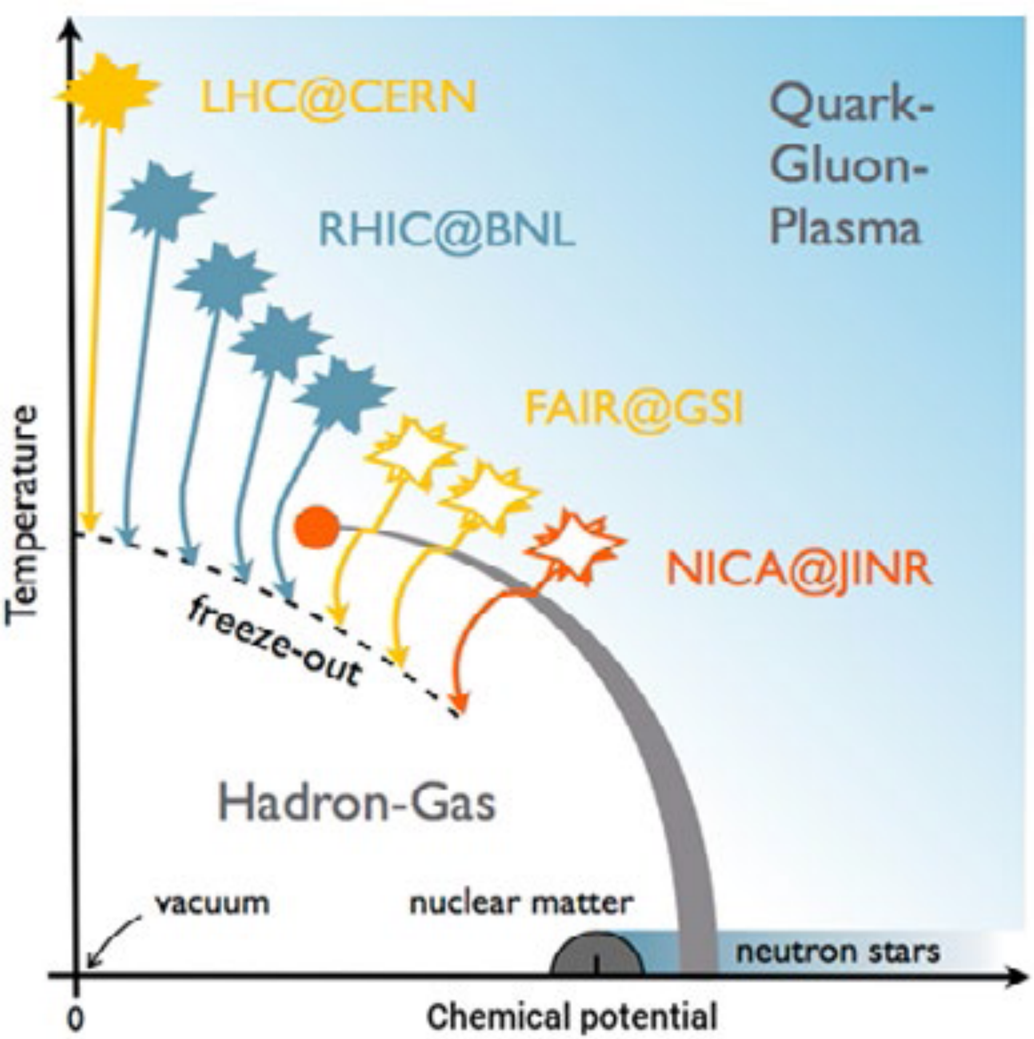
How do we study *bulk* QCD matter?

- We can heat and/or compress a large volume of QCD matter
- Done in the lab by colliding heavy nuclei at high energies

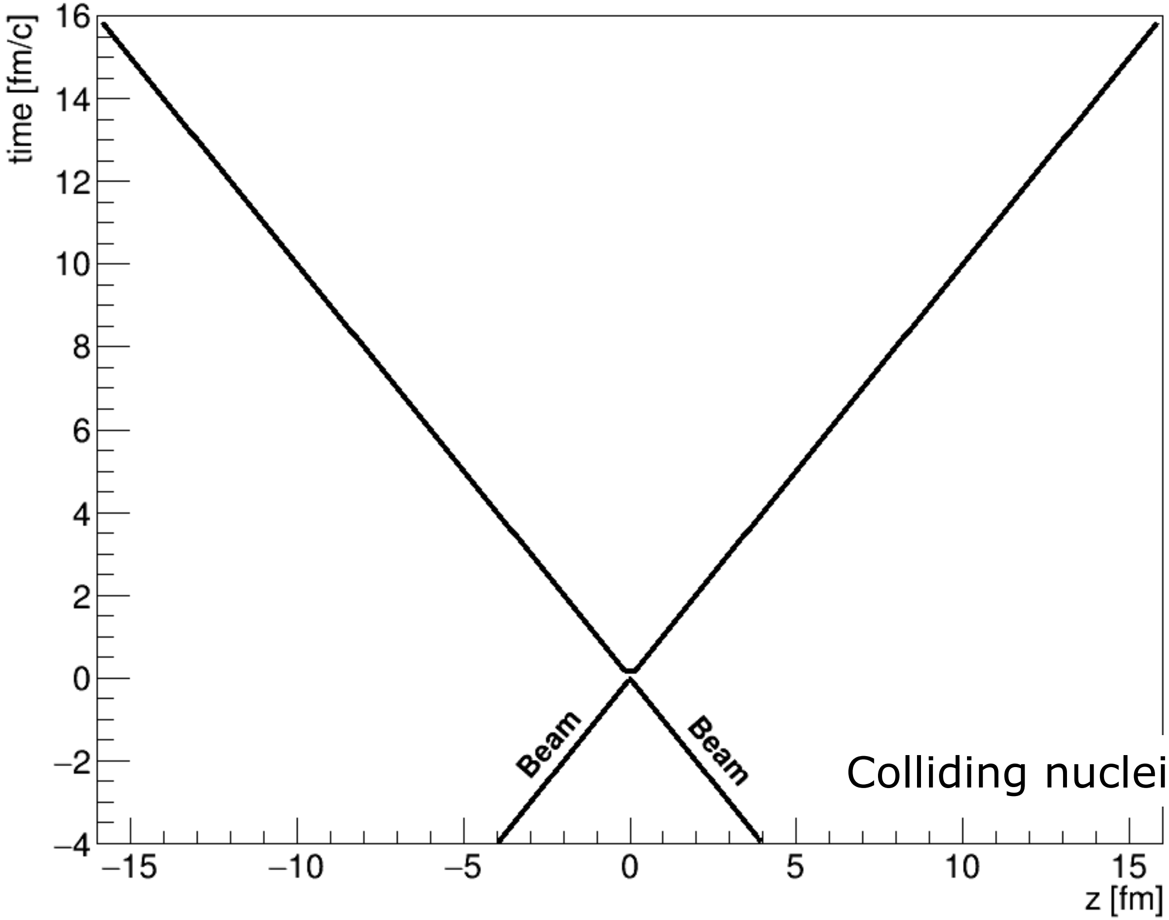


Exploring the QCD phase diagram

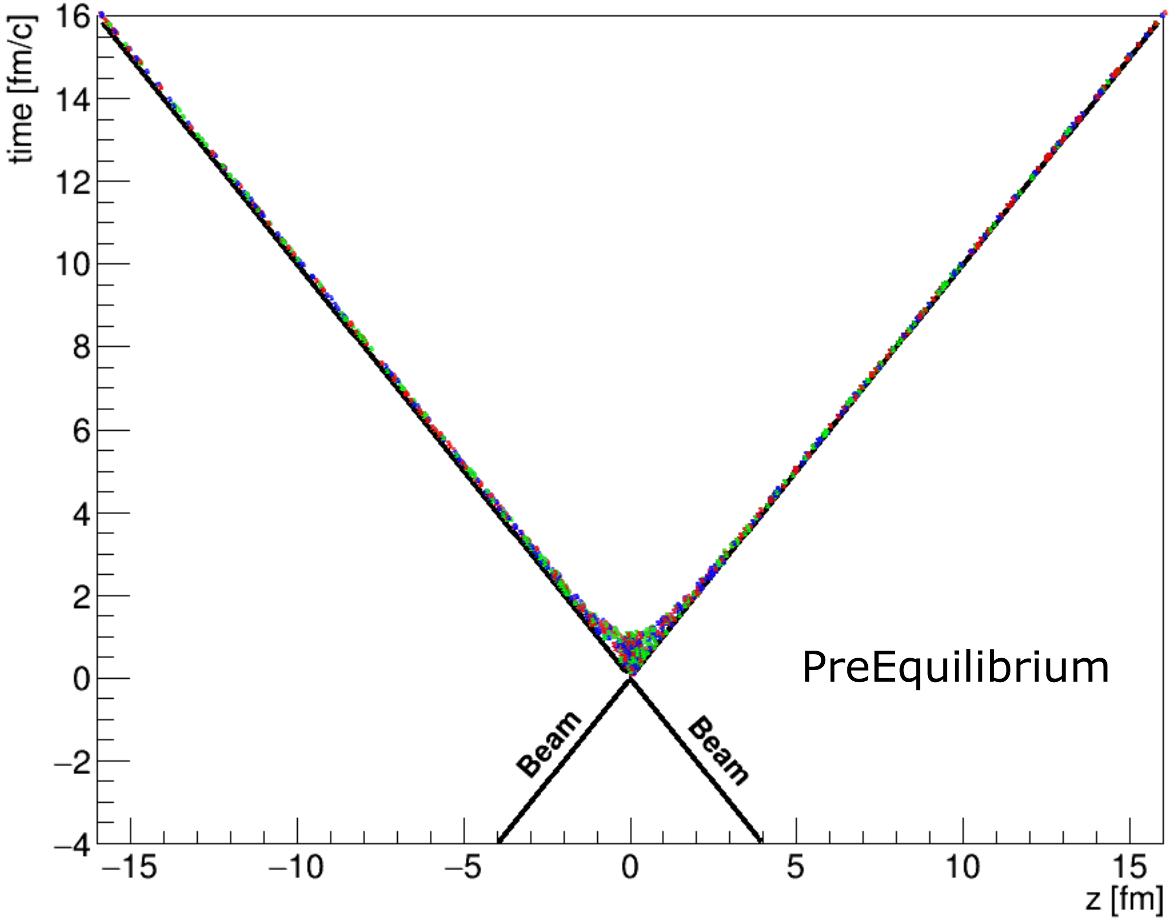
- regime of "transparency
  - very high T, $\mu_b \cong 0$
  - LHC and top RHIC energy
- high density regime:
  - partial stopping of the nucleons in collisions
  - physics of FAIR@GSI

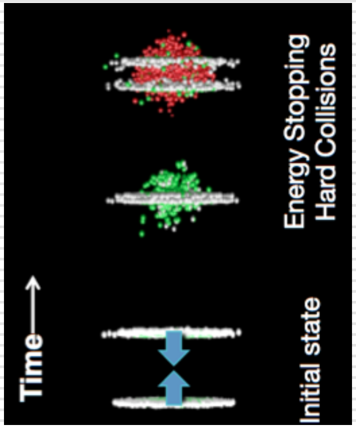


Space time evolution of A-A collision

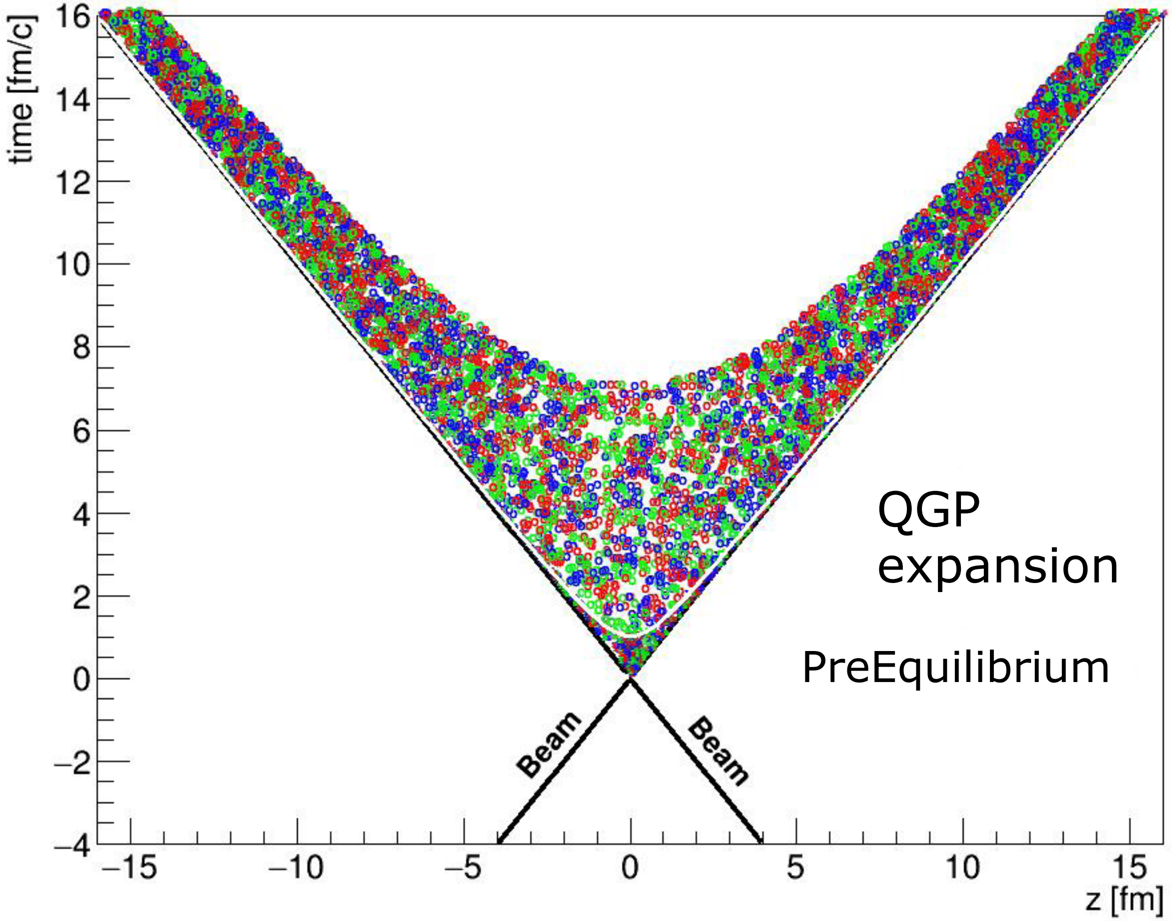


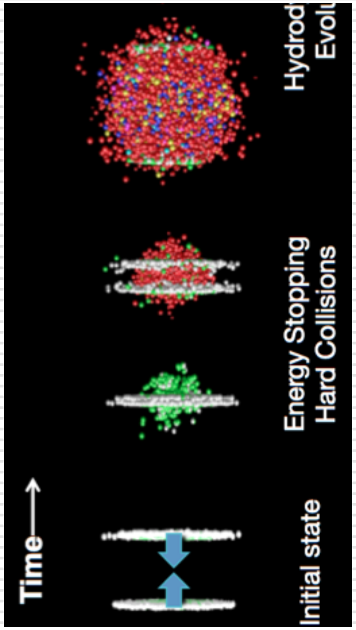
Space time evolution of A-A collision



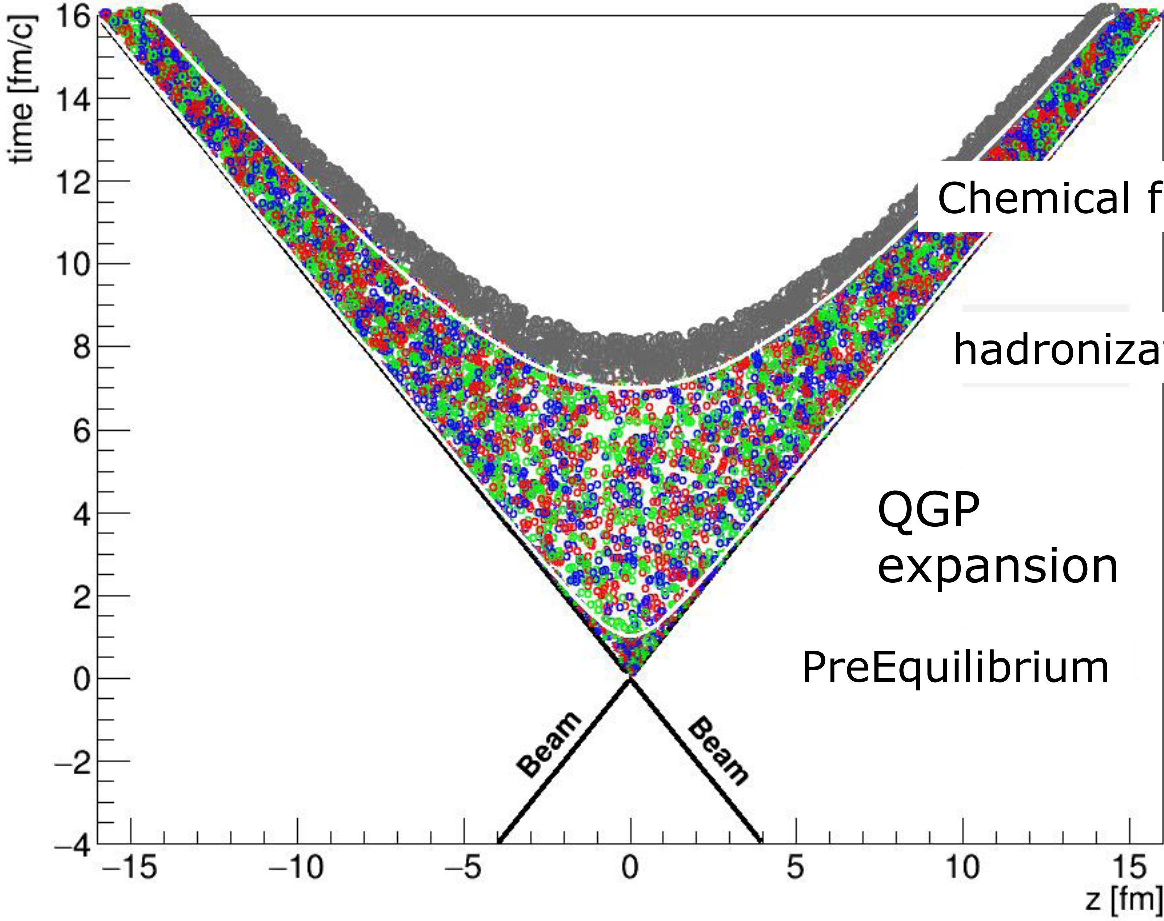


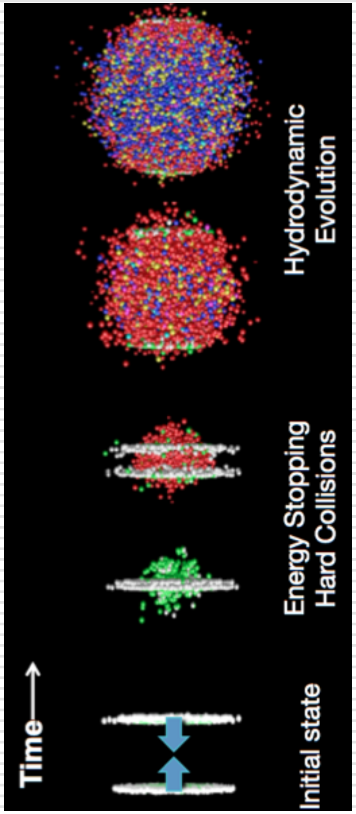
Space time evolution of A-A collision



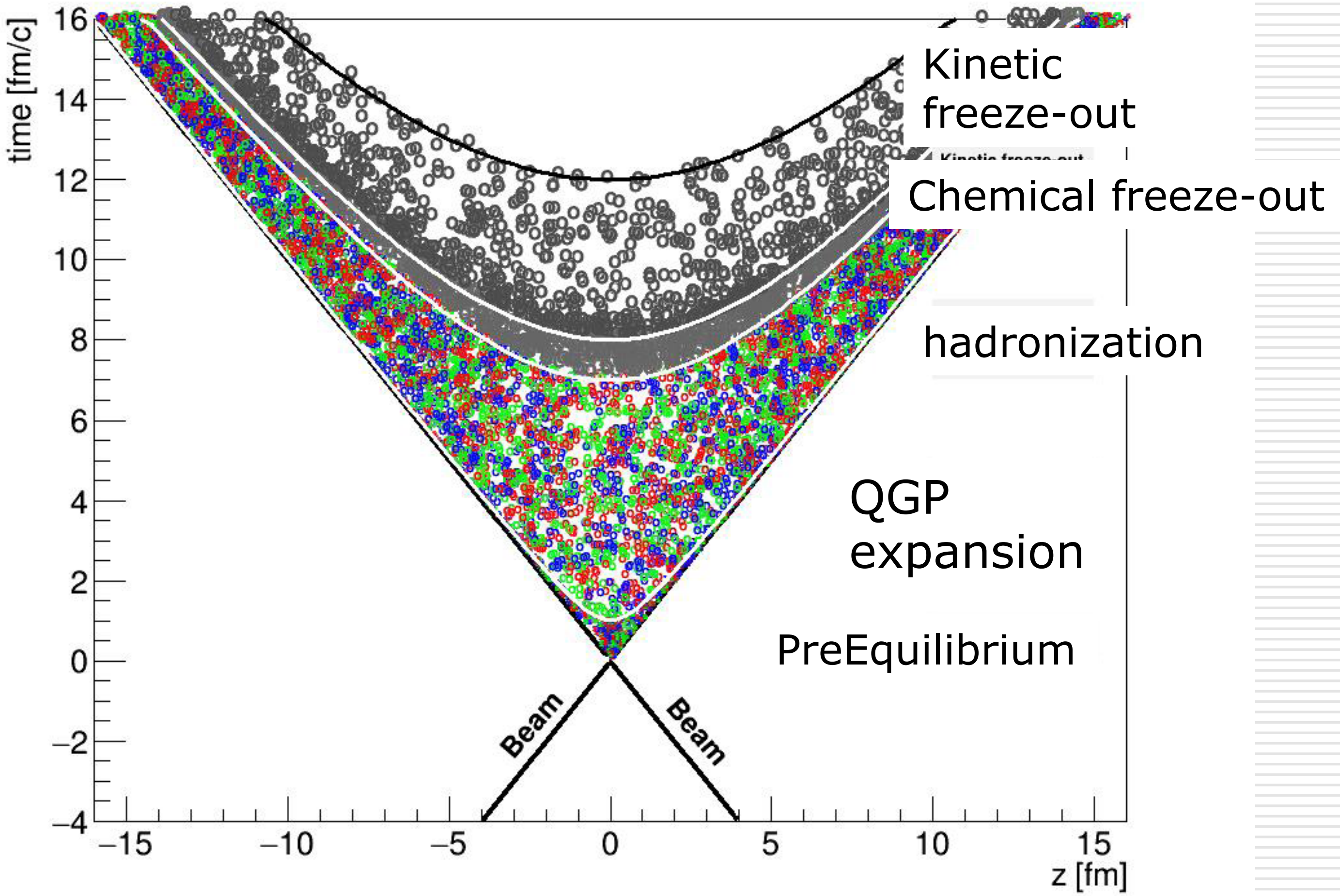


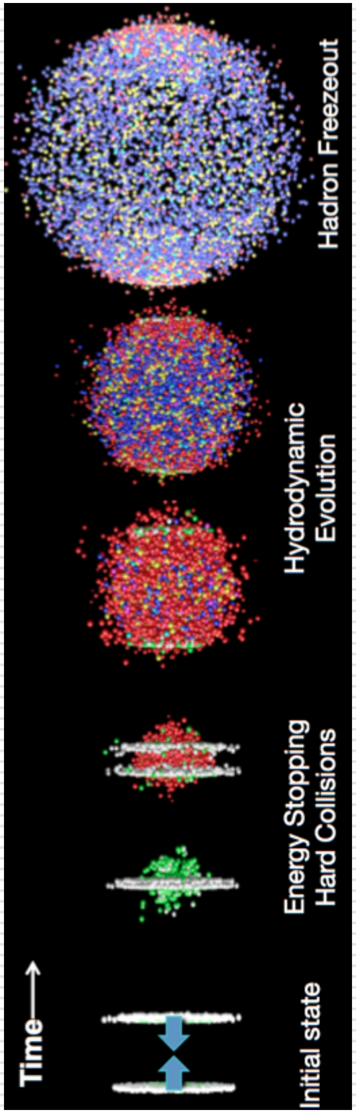
Space time evolution of A-A collision



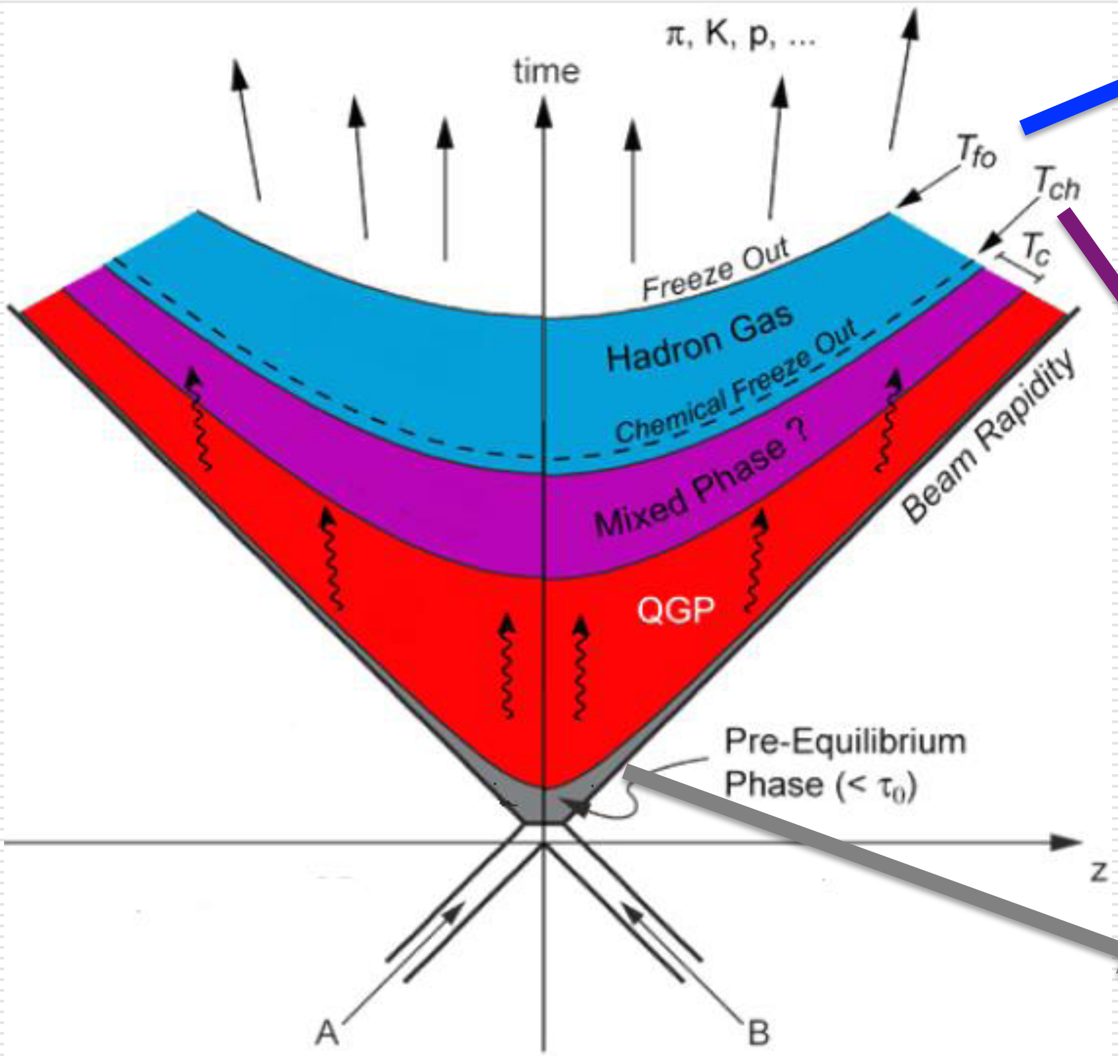


Space time evolution of A-A collision



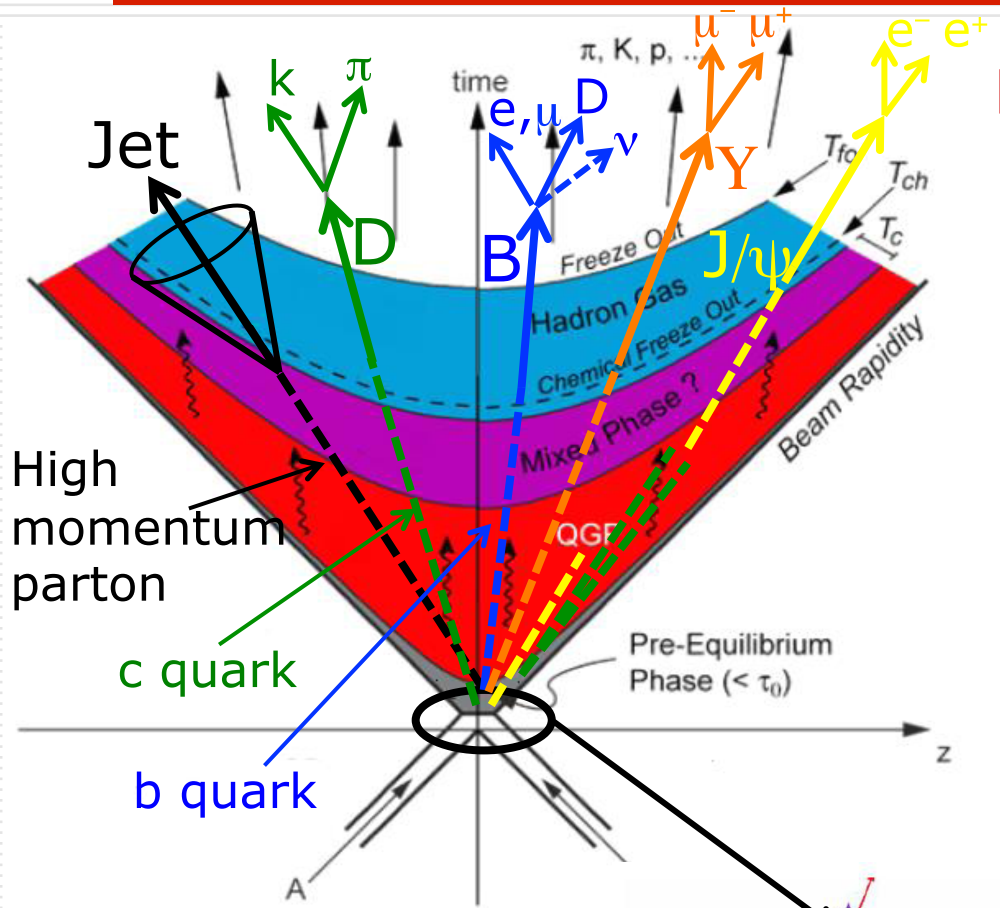


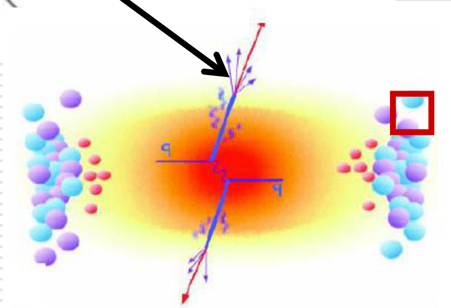
Space time evolution of A-A collision



- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 100 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 150 MeV
- Thermalization time
  - System reaches local equilibrium
  - τ_{eq} ~ 0.5 fm/c

Hard probes of A-A collision





$$\tau_f = \frac{\hbar}{m_T}$$

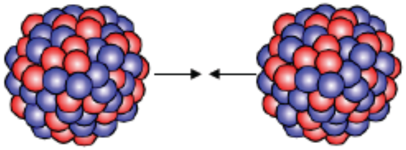
- Hard probes in nucleus-nucleus collisions:
  - produced at the very early stage of the collisions in partonic processes with large Q^2
  - traverse the hot and dense medium
  - can be used to probe the properties of the medium
  - no extra production at hadronization

→ probes of fragmentation

- e.g.: independent string fragmentation vs recombination

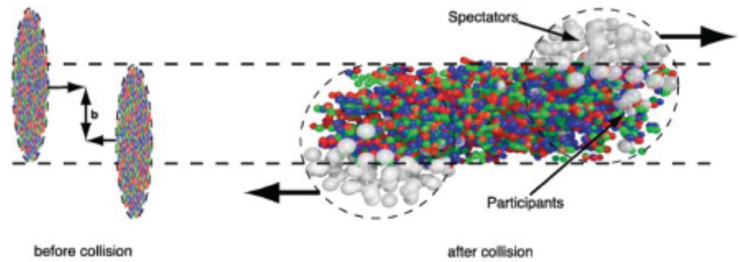
- In reference pp collisions
  - pQCD can be used to calculate cross sections

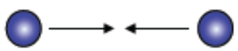
from pp to Pb-Pb collisions at LHC



Pb-Pb Collisions ($\sqrt{s_{NN}}$ = 2.76, 5 TeV)

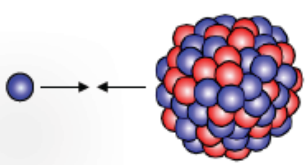
- Core business: create and characterize the QGP
- Centrality





pp Collisions ($\sqrt{s}$ = 0.9 –13 TeV)

- Reference data



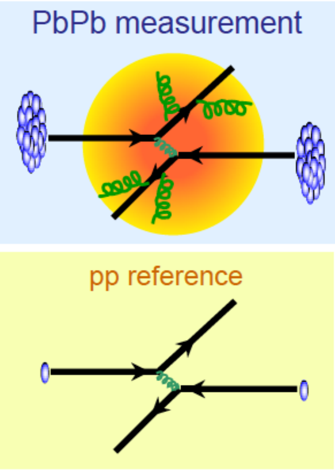
p-Pb Collisions ($\sqrt{s_{NN}}$ = 5, 8 TeV)

- Control experiment
- “Cold nuclear matter” effects (e.g. modifications to PDF)

Nuclear modification factor

- Without nuclear effects, the production of hard probes in A-A is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor**

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

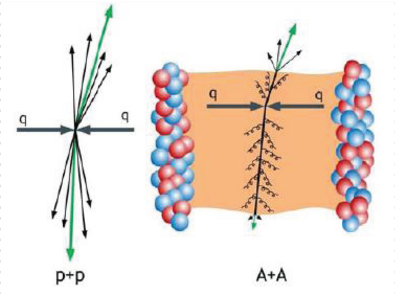


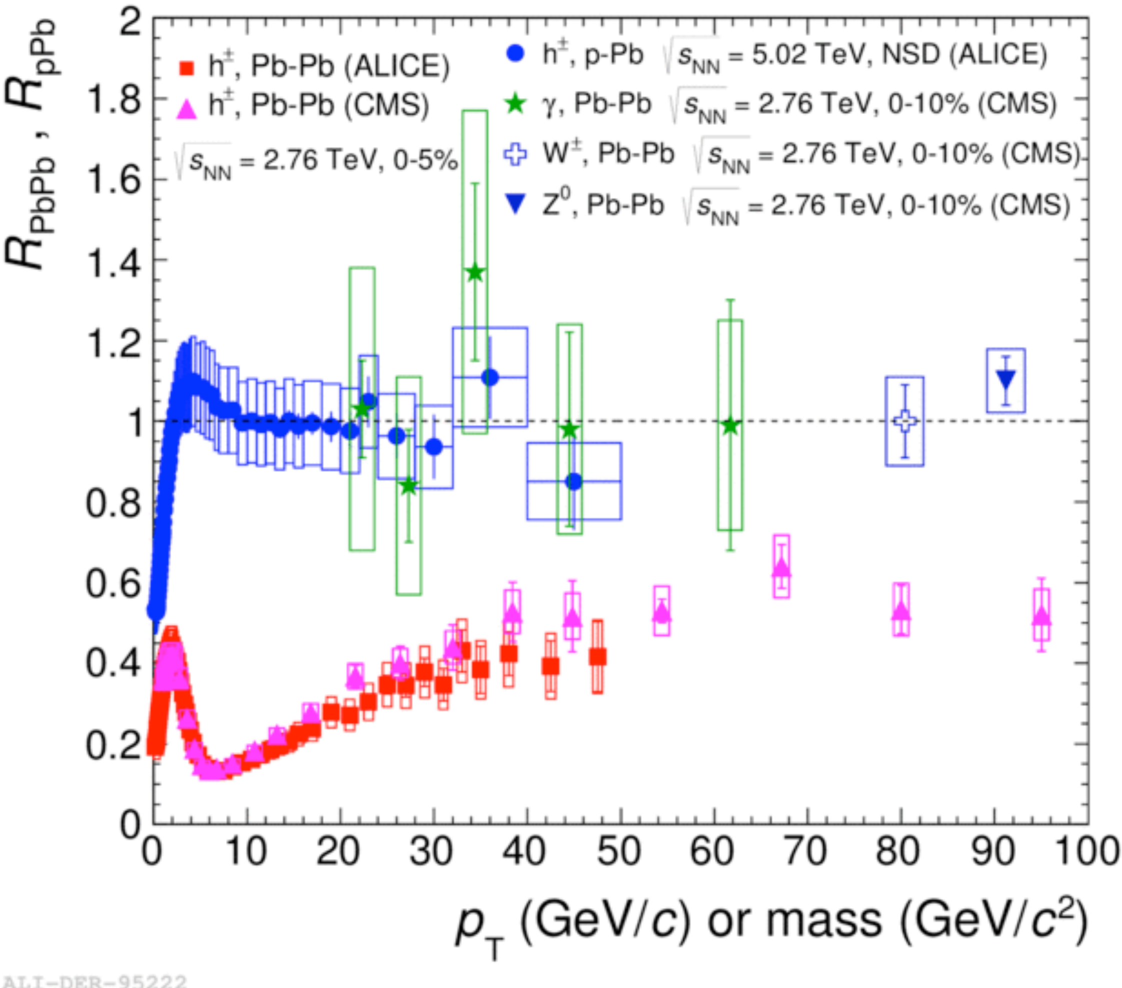
- If no nuclear effects are present → $R_{AA}=1$
- Effects from the hot and deconfined medium created in the collision → breakup of binary scaling → $R_{AA}\neq 1$
  - **Parton energy loss** via gluon radiation and collisions in the medium
- But also initial state effects (e.g. nuclear modification of PDFs) may lead to $R_{AA}\neq 1$
  - Need control experiments: p-A collisions + medium-blind probes (photons, W, Z)

Nuclear modification of unidentified particles

- The easiest way to study "jet quenching"

- physics interpretation:
  - scattered parton (high p_t) looses energy while traversing the medium
    - collisional energy loss
    - radiative energy loss (gluonstrahlung)

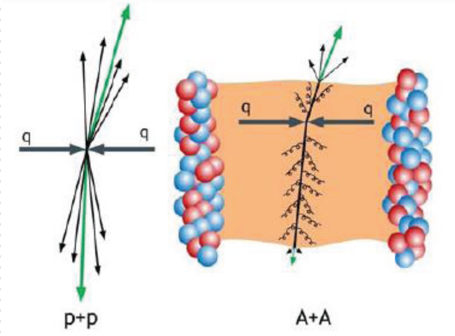




Nuclear modification of identified particles

light flavour vs. charm vs. beauty hadrons (or jets)

- quenching vs. colour charge of partons
  - heavy flavour hadron comes from quark (C_R = 4/3)
  - light flavour from (p_T-dep) mix of quark and gluon (C_R = 3) jets



- quenching vs. mass of partons
  - heavy flavour predicted to suffer less energy loss
    - gluonstrahlung (dead cone effect)
    - collisional loss
  - **beauty vs charm**

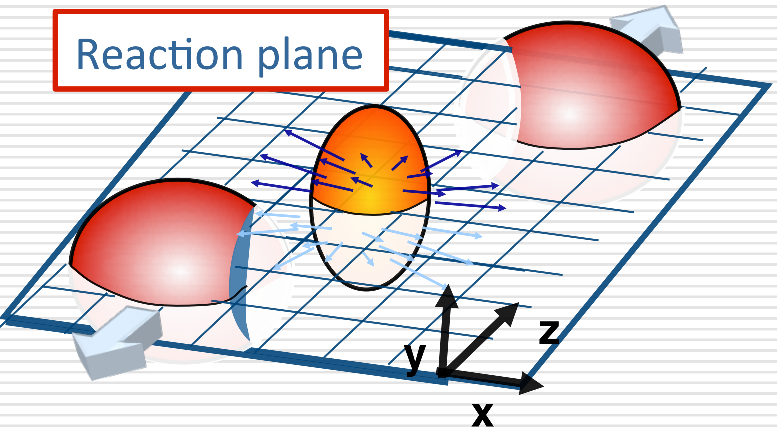
- Expectations: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow$

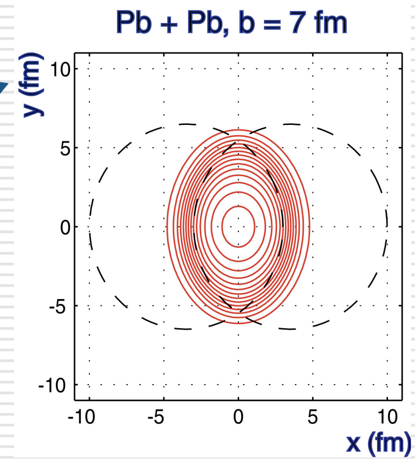
  naively: $R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$

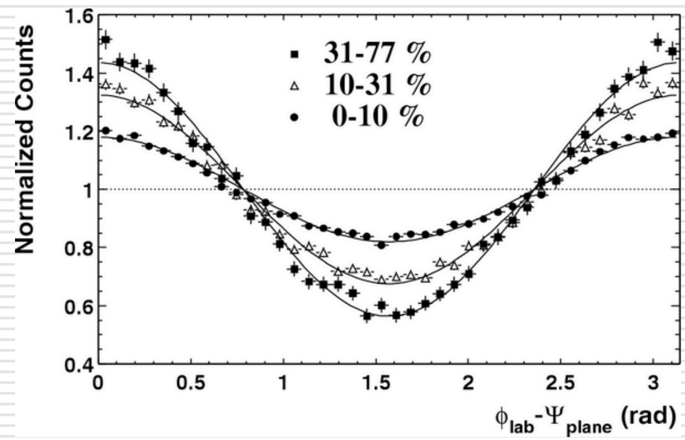
  considering different p_t distributions and fragmentations:

  $$\boldsymbol{R_{AA}^{h} \approx R_{AA}^{D} < R_{AA}^{B}}$$

Azimuthal anisotropy



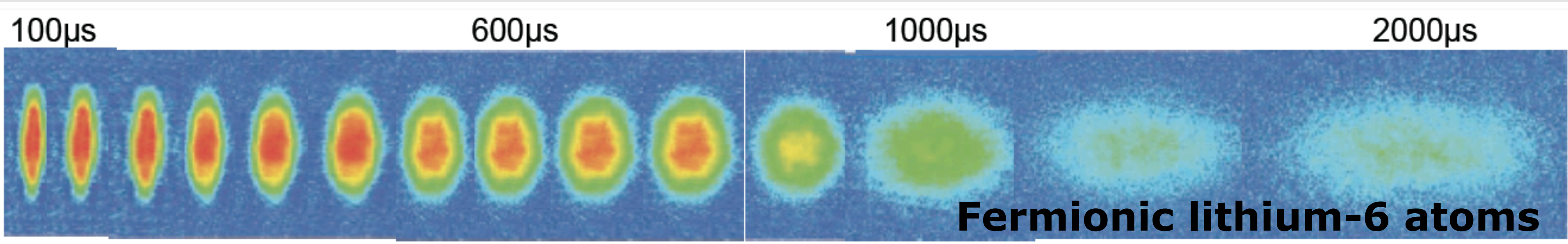




Almond shaped overlap region in geom. space → strong in-plane expansion due to pressure gradients → anisotropy in momentum space

$$\frac{dN}{d(\varphi-\psi_{RP})} \propto 1 + 2\sum_{n=1} v_n \cos\left(n[\varphi-\psi_{RP}]\right)$$

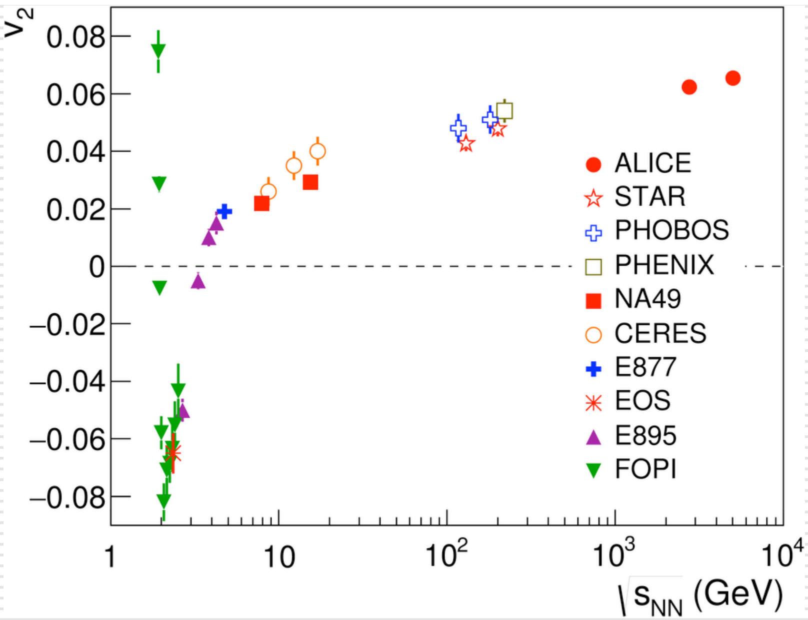
$$v_2 = \left\langle \cos\left[2(\varphi-\psi_{RP})\right]\right\rangle$$

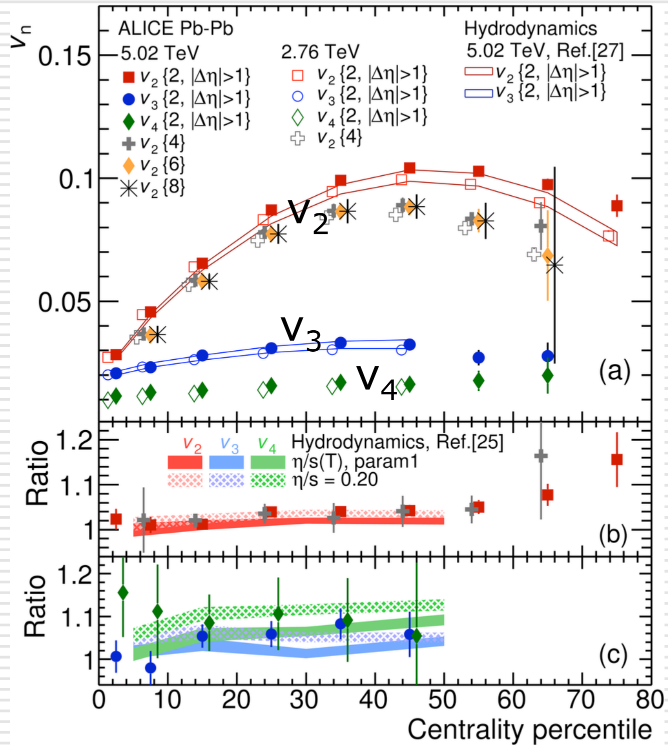


M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Flow of unidentified charged particles

PRL 105 25230 (2010) ; PRL 116, 132302 (2016)





- The flow increases by about 30% w.r.t. RHIC. The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)
  - constraints dependence of η/s versus temperature

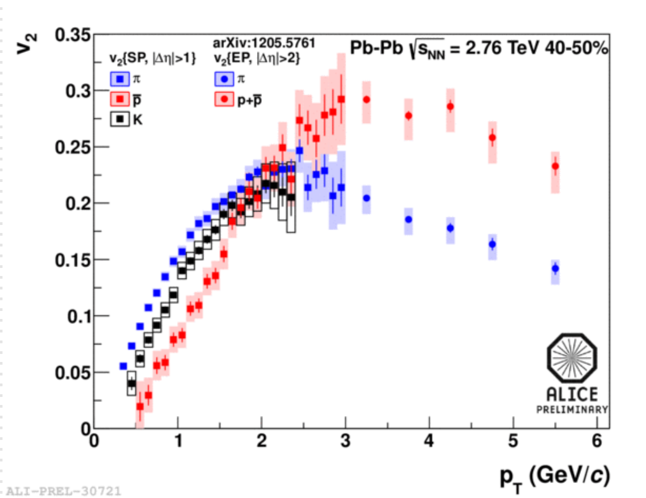
Heavy quark and the medium

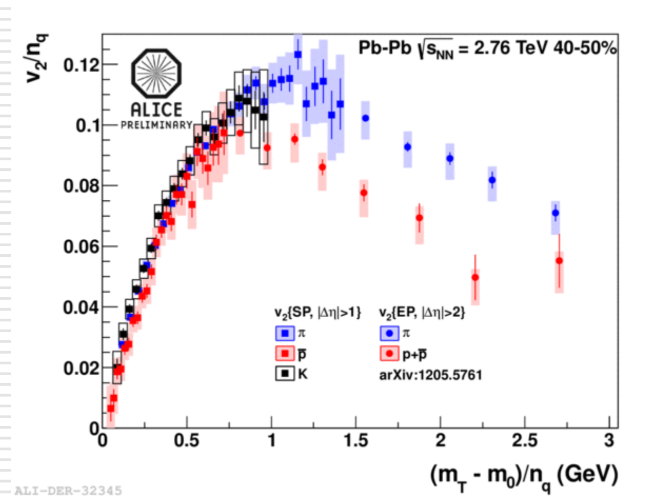
- Study the QGP thermalization and collectivity via heavy quark hadronization and flow
  - Are the quenched heavy quarks thermalized in the system ?
  - Do they carry “elliptic flow” ?
  - Do they hadronize via recombination ?

$v_2(q)=v_2(c)=v_2(b)$?

thermalization

- Indications of light quark thermalization:
  - constituent quark scaling of elliptic flow v2





hydro regime

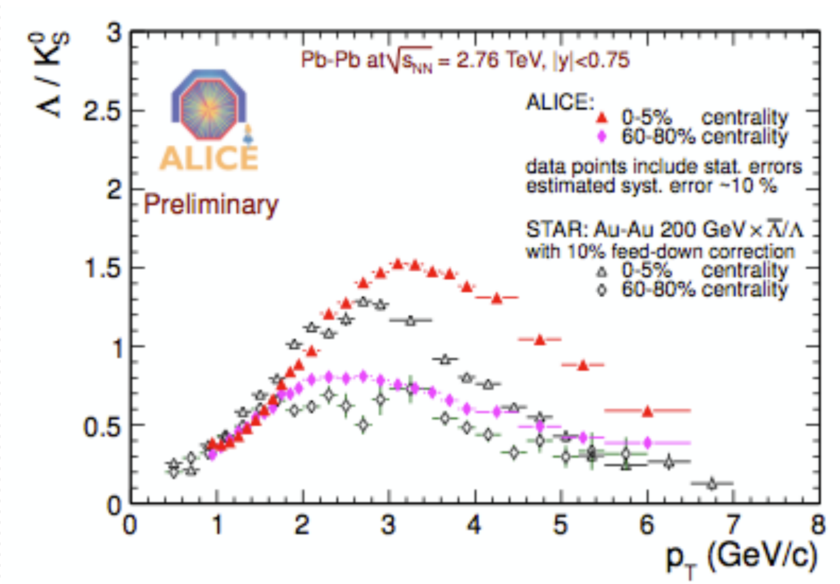
path length dependence
of energy loss

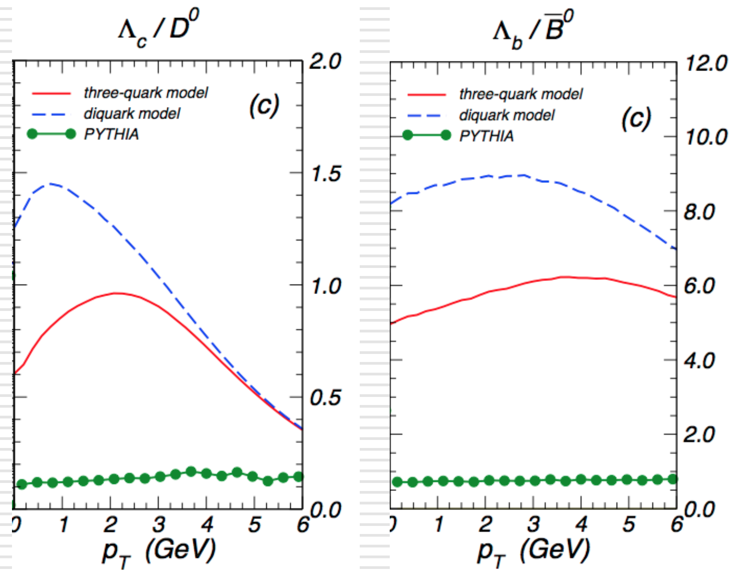
- Goal: measure this in the heavy quark sector
  - e.g. Λ_c and D flow starting from 2-3 GeV/c (splitting of baryon and meson)

recombination

- Indications of light quark recombination:
  - baryon / meson enhancement in central collisions (p/π, Λ/K)

(C.M.Ko et al. PRC79)



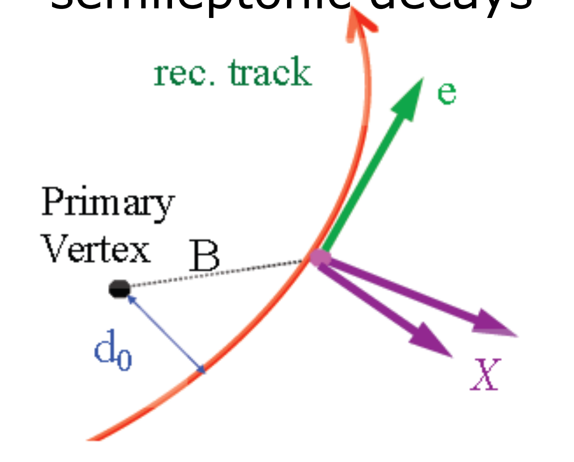


- Goal: measure this in the heavy quark sector
  - e.g. Λ_c/D starting below 3 GeV/c (maximum of Λ/K)

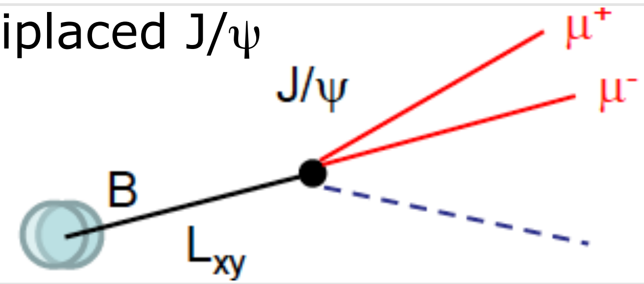
Open Heavy Flavour in Heavy Ion collisions

- How can we measure it ?

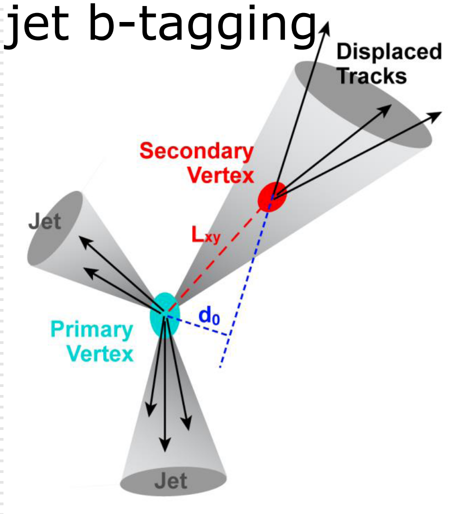
semileptonic decays



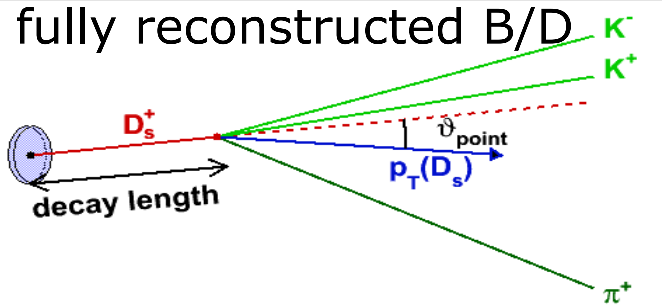
diplaced J/ψ

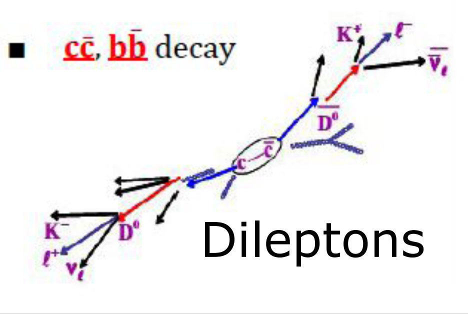


jet b-tagging

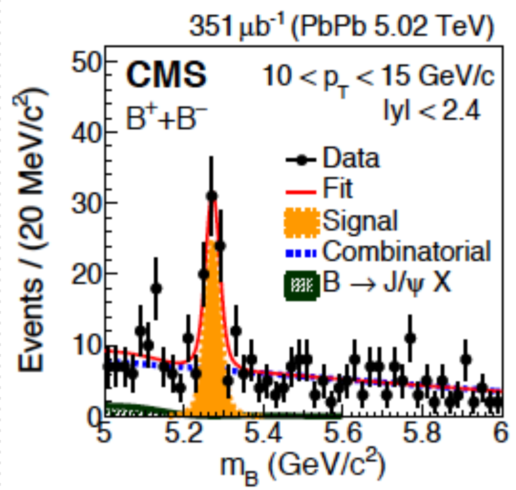


fully reconstructed B/D

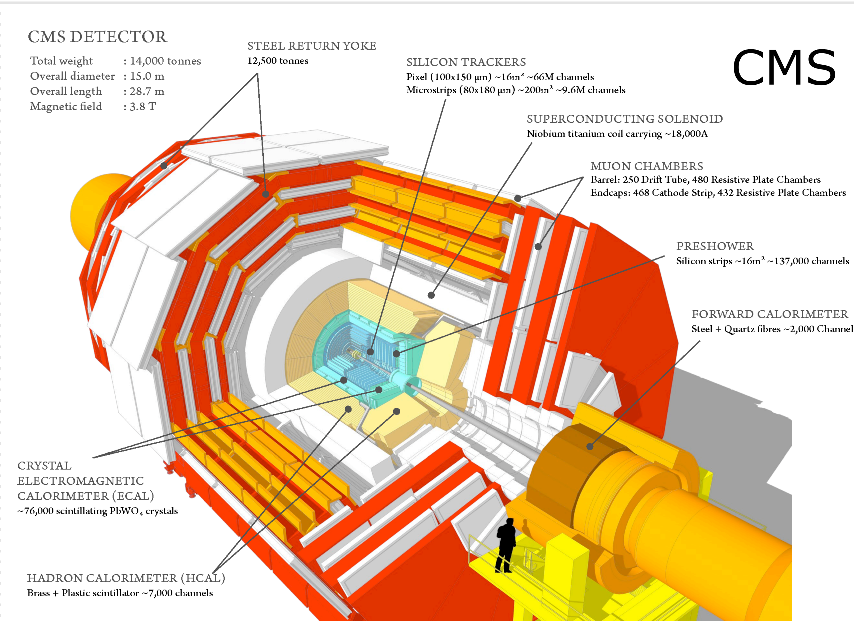


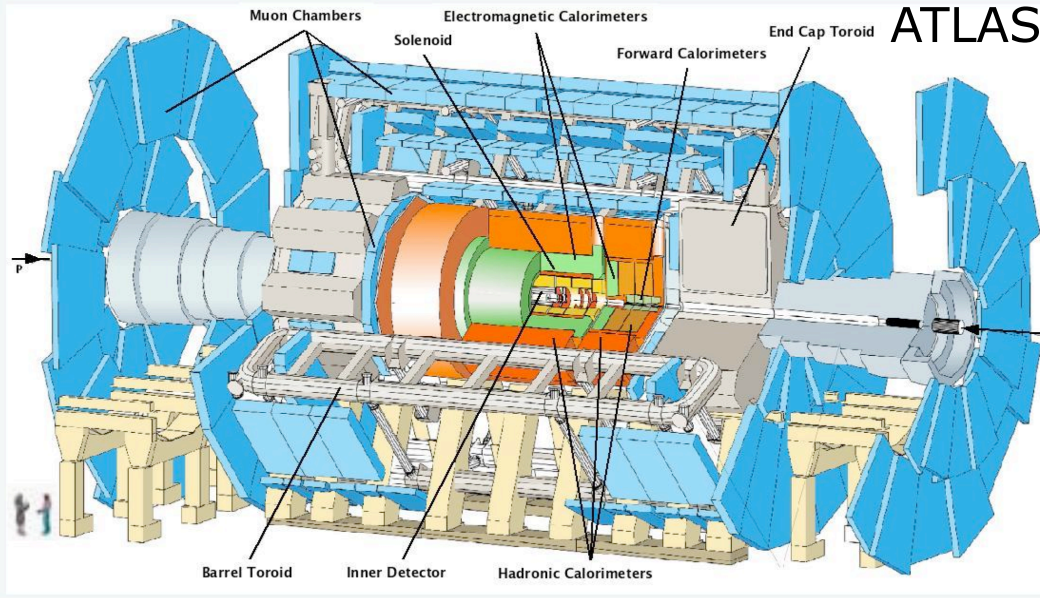


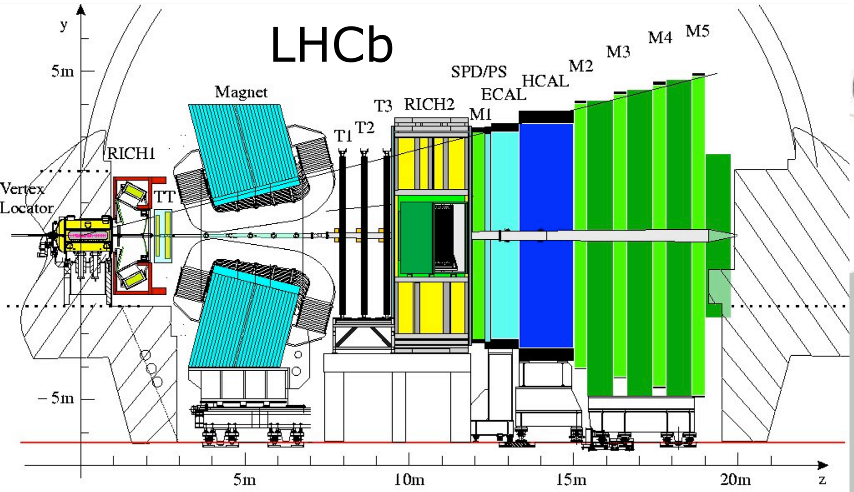
e.g.:
$B^+ \to J/\psi + K^+$
$B^+ \to D^0 K^+$

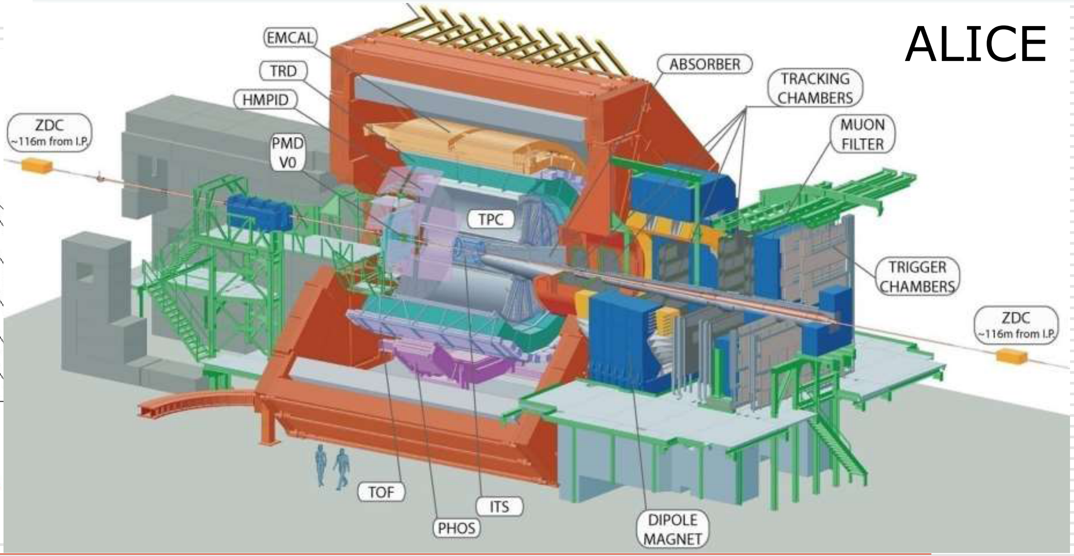


The four main LHC experiments









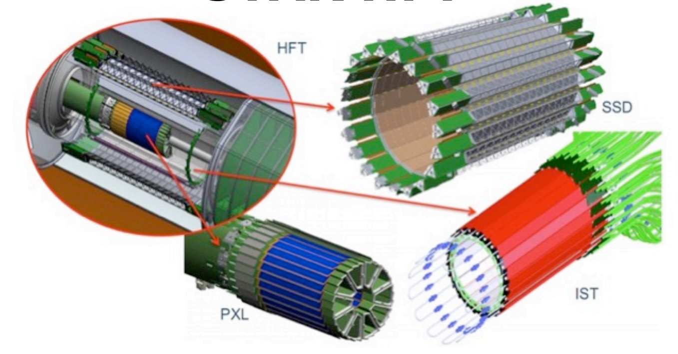
Open HF at the LHC

- peculiarities of the 4 LHC experiments
  - CMS and ATLAS
    - exploit great muon reconstruction capabilities
      - $B \rightarrow J/\psi + X$; $B \rightarrow J/\psi + K$ ($J/\psi \rightarrow \mu^+\mu^-$)
      - no pid (so far) for charged particle
      - very high B field: min p_t of about 7 -10 GeV/*c*
    - large acceptance calorimeters
      - well suited for b-jet physics
  - LHCb
    - excellent at forward rapidity
    - joined only recently the heavy ion programme
  - ALICE
    - PID with several detectors
    - very low material budget
    - low p_t coverage

STAR and PHENIX at RHIC

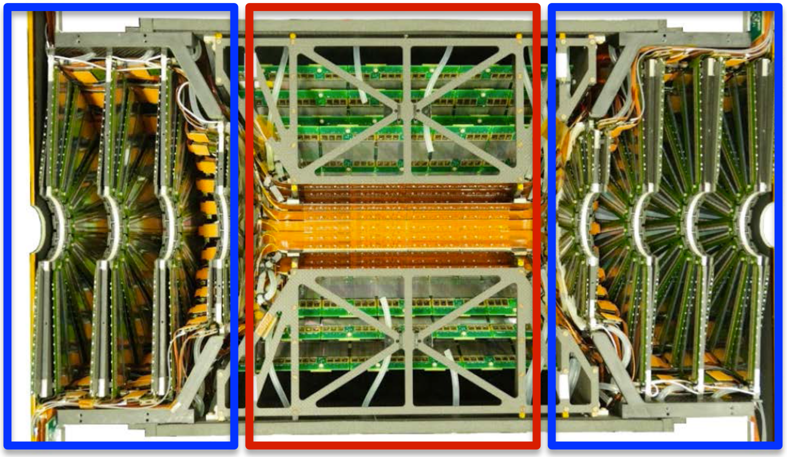
- since few years equipped with silicon micro-vertex detectors

STAR HFT



- STAR Pixel detector (since 2014) – first application of MAPS technology in collider experiments
  - ALICE upgrade, CBM, sPHENIX MVTX, EIC detector R&D, NA61?

PHENIX VTX / FVTX

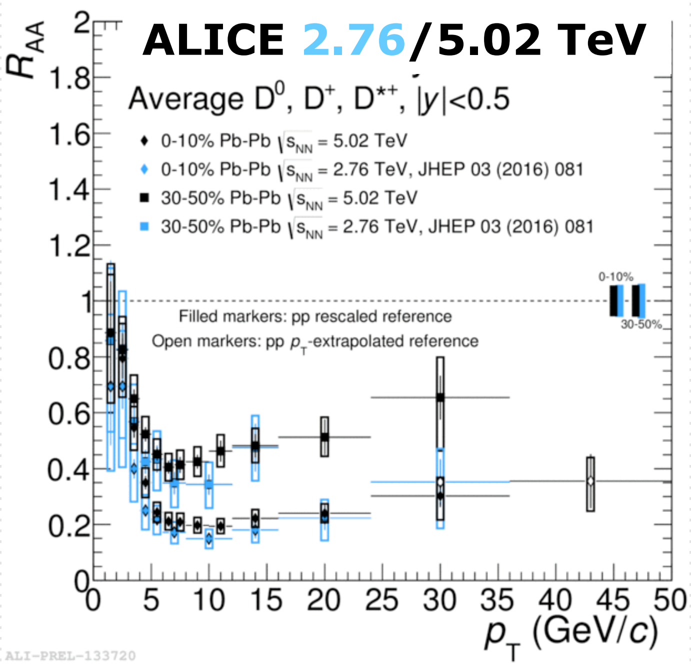


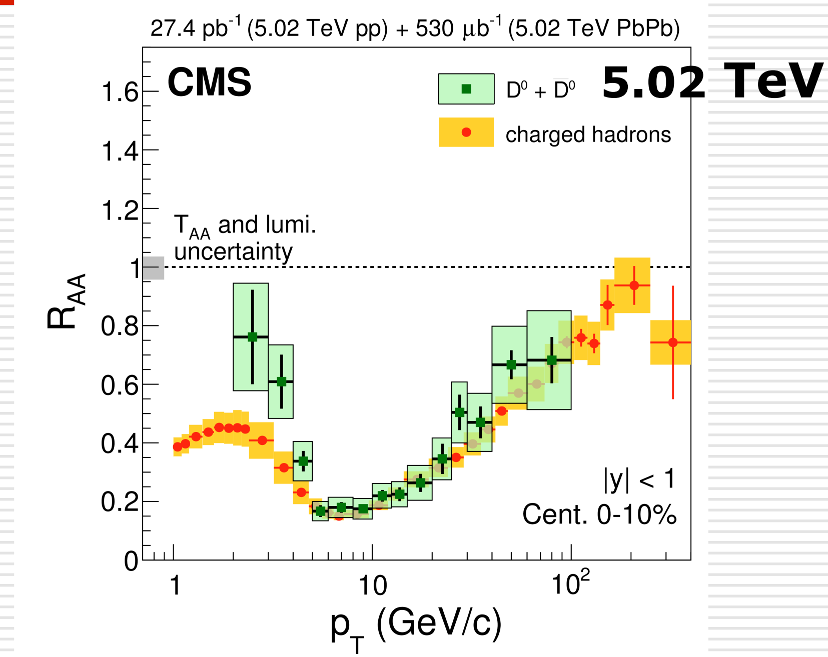
- **VTX** installed in 2011
  - |y|<1.2, φ~2π
  - 4 layers (2 pixels + 2 strips)
- **FVTX** installed in 2012
  - 1.2<|y|<2.2, φ=2π
  - 4 layers

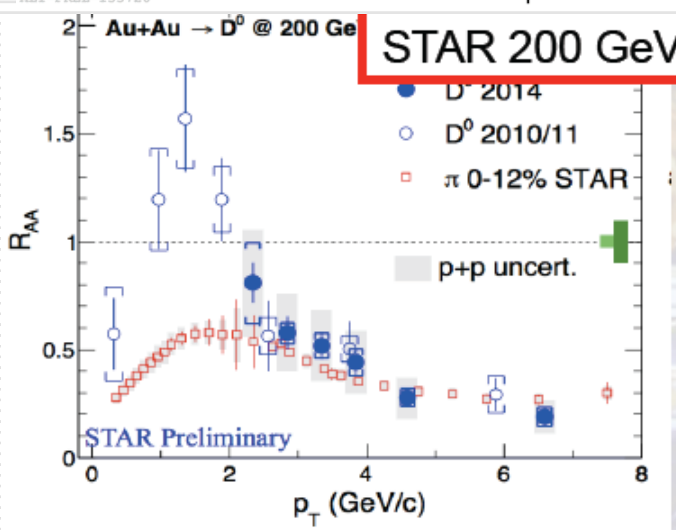
Key Instruments – Pixel Silicon Detector

	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	1%X_0	2 %X_0	2 %X_0	~1%X_0	1%X_0	**0.4%X_0**

Evidence of charm energy loss at LHC and RHIC

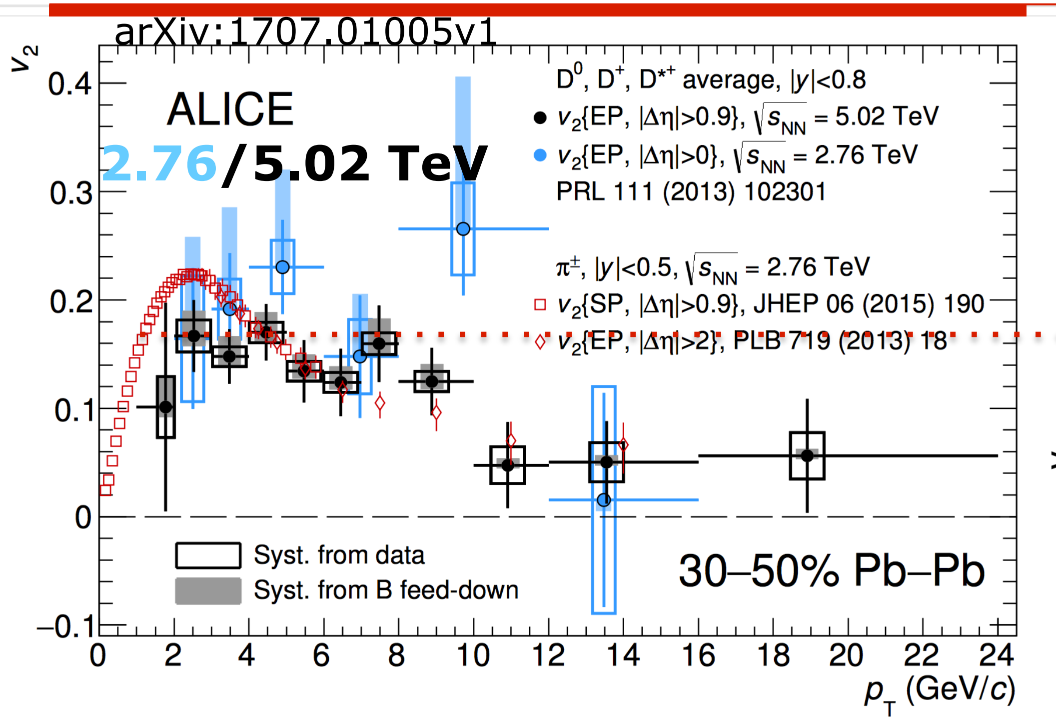


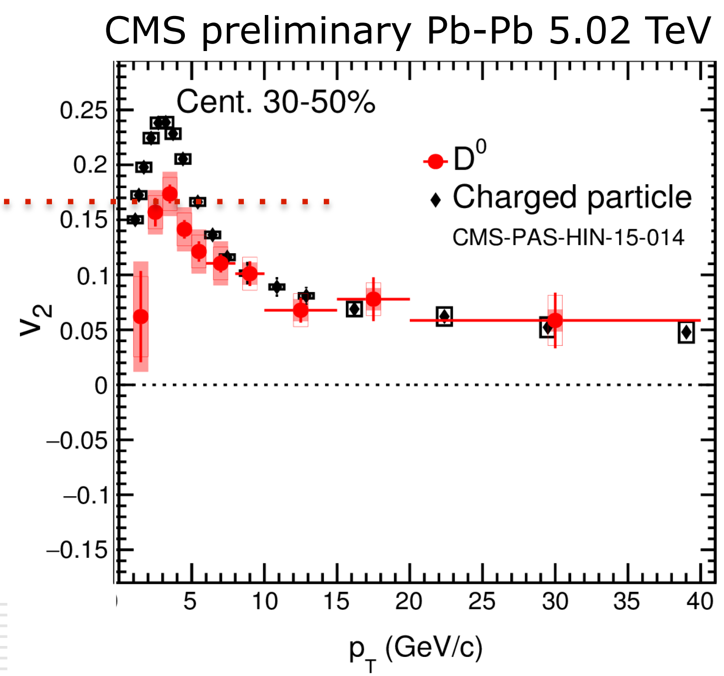




- $R_{AA}(D) \approx R_{AA}(\pi)$ at $p_t > 4$ GeV/c
  - strong interaction between charm and medium
- non-monotonic structure at low p_t at RHIC
  - coalescence + charm flow

Evidence of charm flowing with the medium at LHC

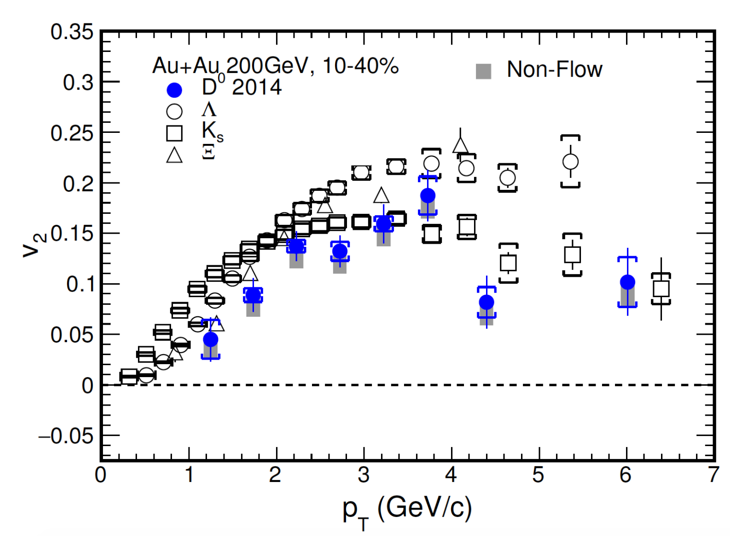


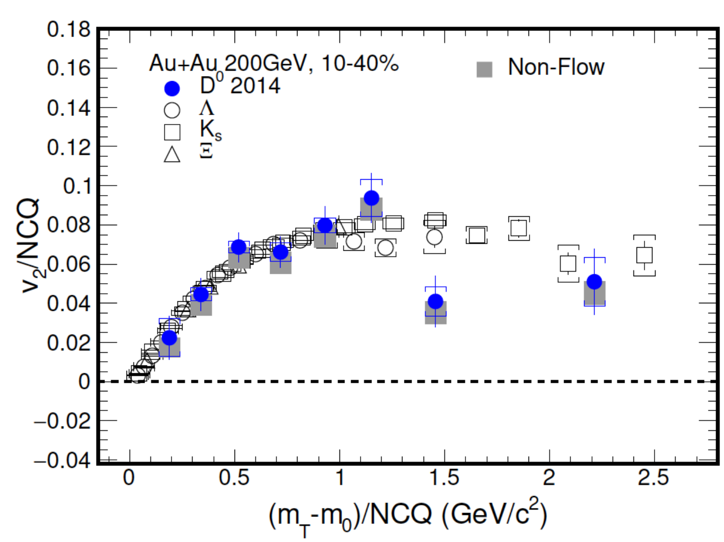


- final results from ALICE
  - much improved with respect to RUN2 data
- in agreement with CMS results (covering higher pt range)
- D^0 v_2 < charged particle v_2

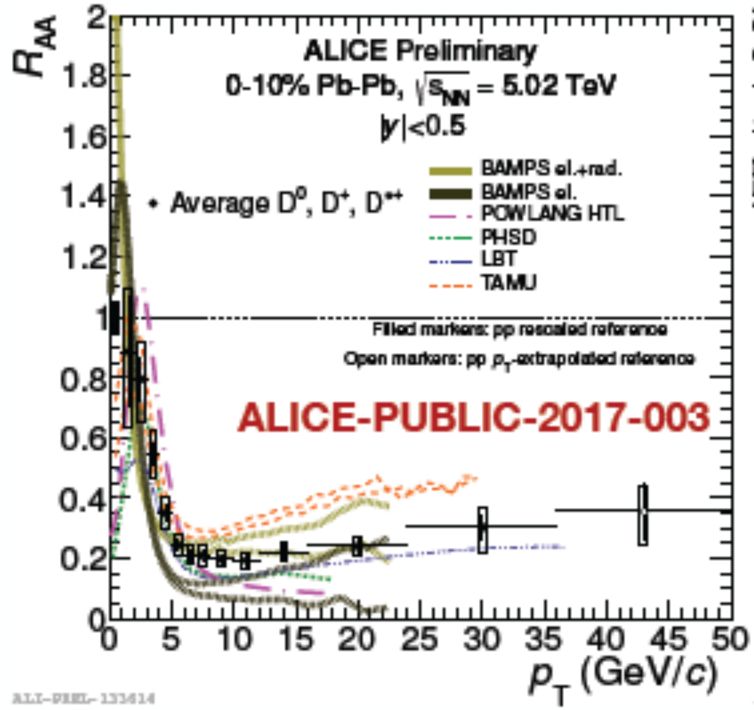
Evidence of charm flowing with the medium at LHC and RHIC

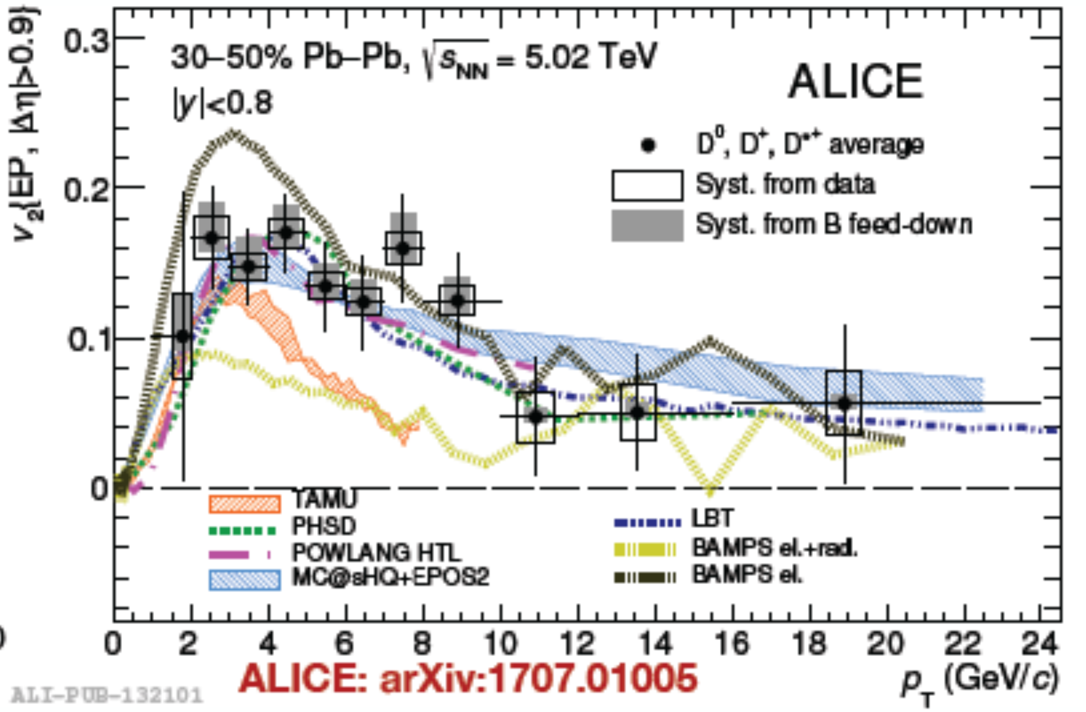
- Significant $v_2(D)>0$ at RHIC!
- Mass "ordering" and m_T-m_0 ordering suggest hydro-dynamic behavior!





Constraining the models in the charm sector





- stringent constraint to models aiming at describing both R_{AA} and v_2
  - strict interplay between radiative energy loss (e.g. needed to describe the high p_T region) and collisional one

Beauty

How ? so far:

- semi-inclusive channels
  - $B \rightarrow e+X$
  - $B \rightarrow J/\psi + X$
- exclusive channels (high p_t only)
- fully reconstructed b-jets

HF electrons (B→e+X)

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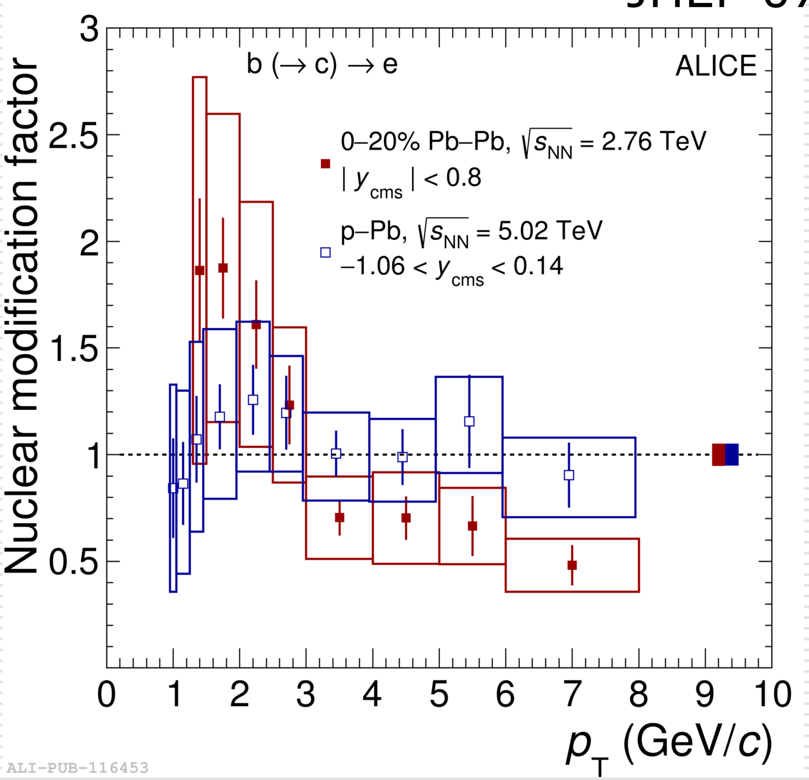
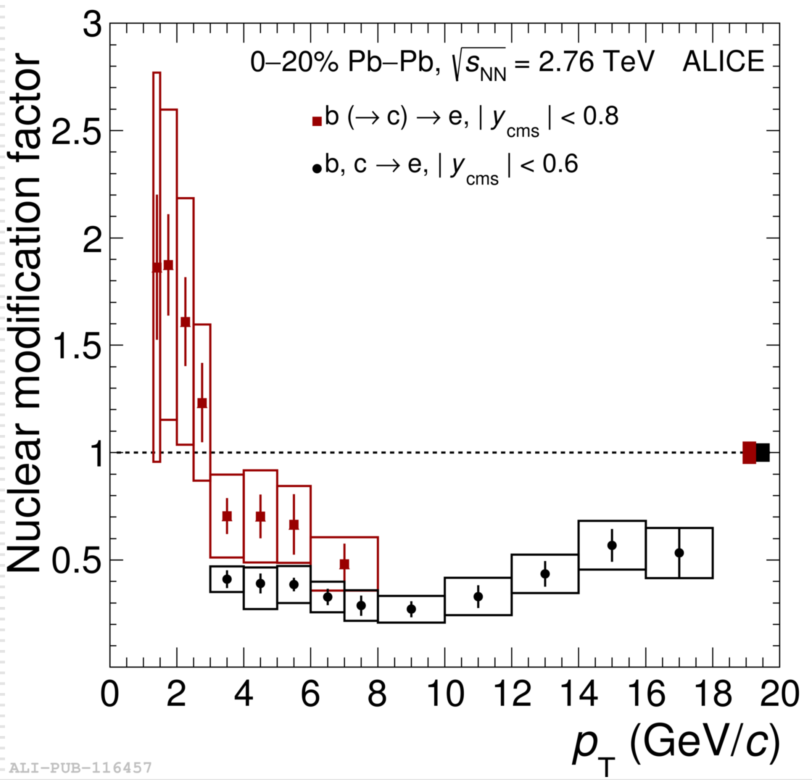
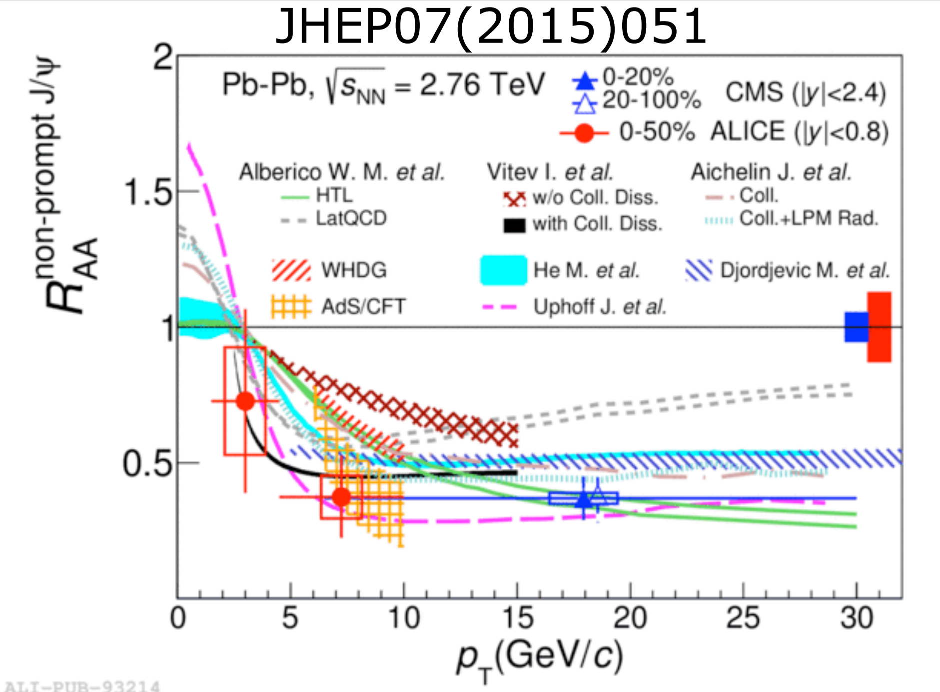
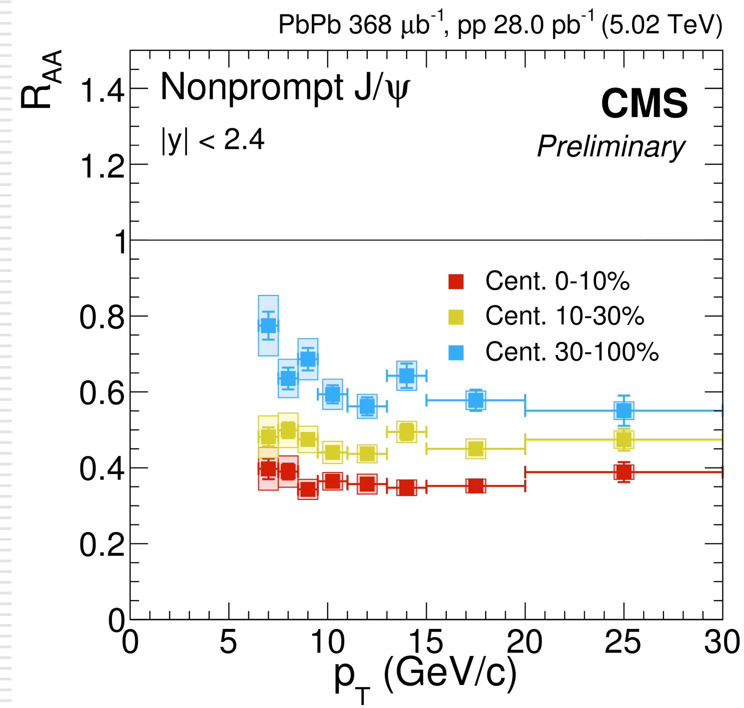




- hint of smaller suppression for electrons from beauty than electrons from charm

non –prompt J/ψ (B→J/ψ +X)





- ALICE Run1 data (2.76 TeV)
  - ample room for improvement with Run2 data !
- precise preliminary results from CMS with run2
  - min. p_t of ~ 7 GeV/*c*

beauty vs. charm (vs. pions)

- strongest evidence, so far, of the expected smaller suppression for beauty
  - further corroborated by Pb-Pb 5.02 TeV results

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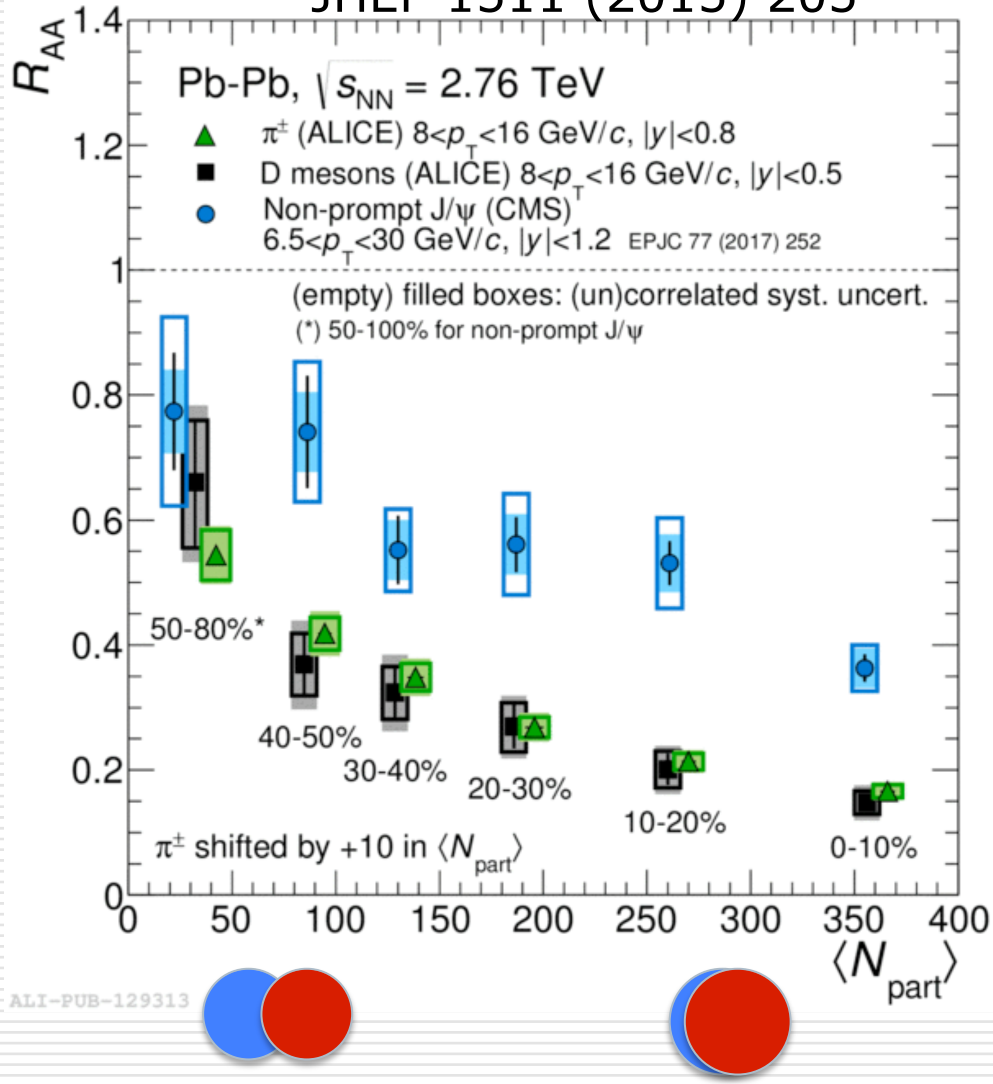

beauty vs. charm: models

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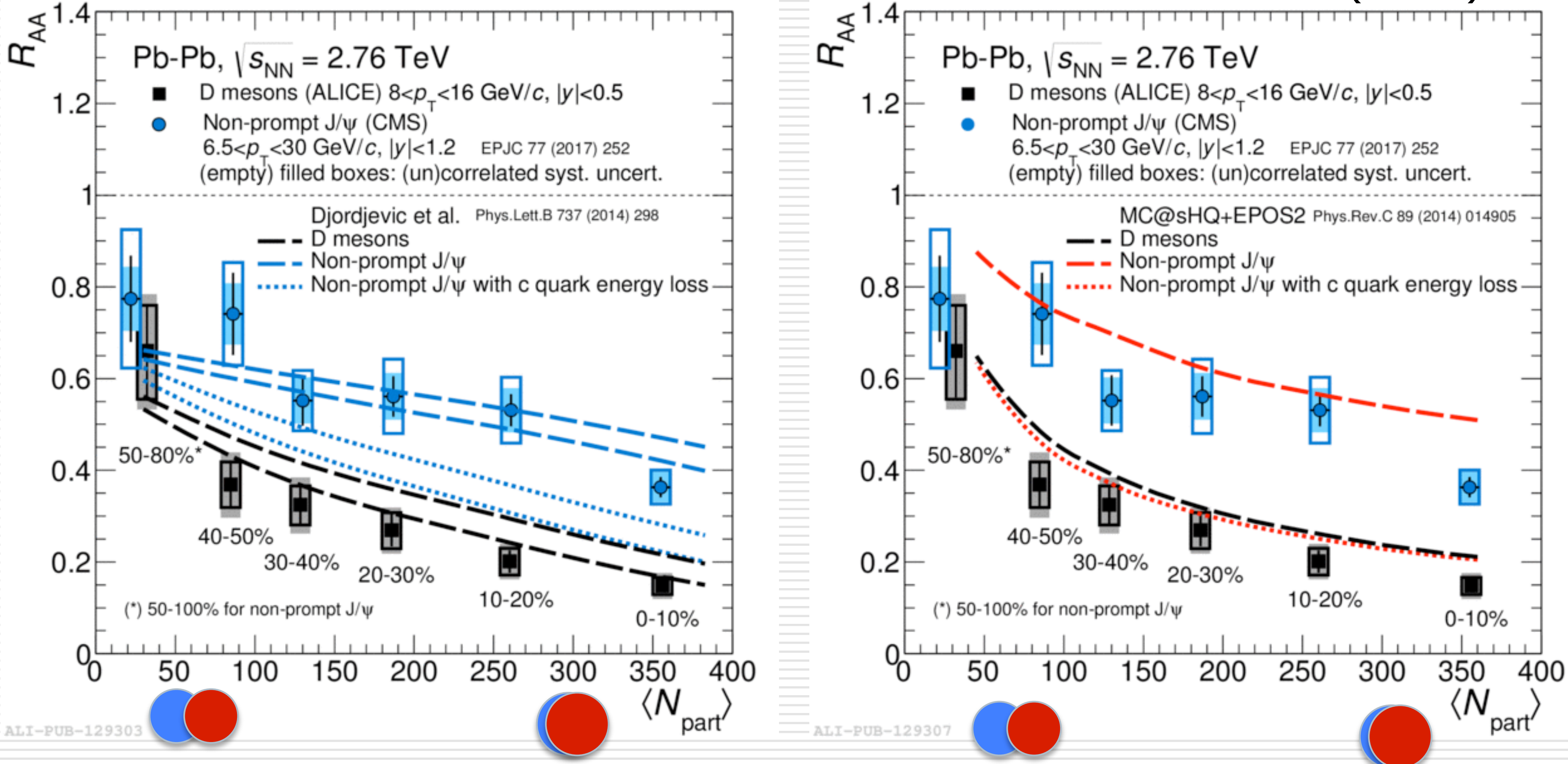
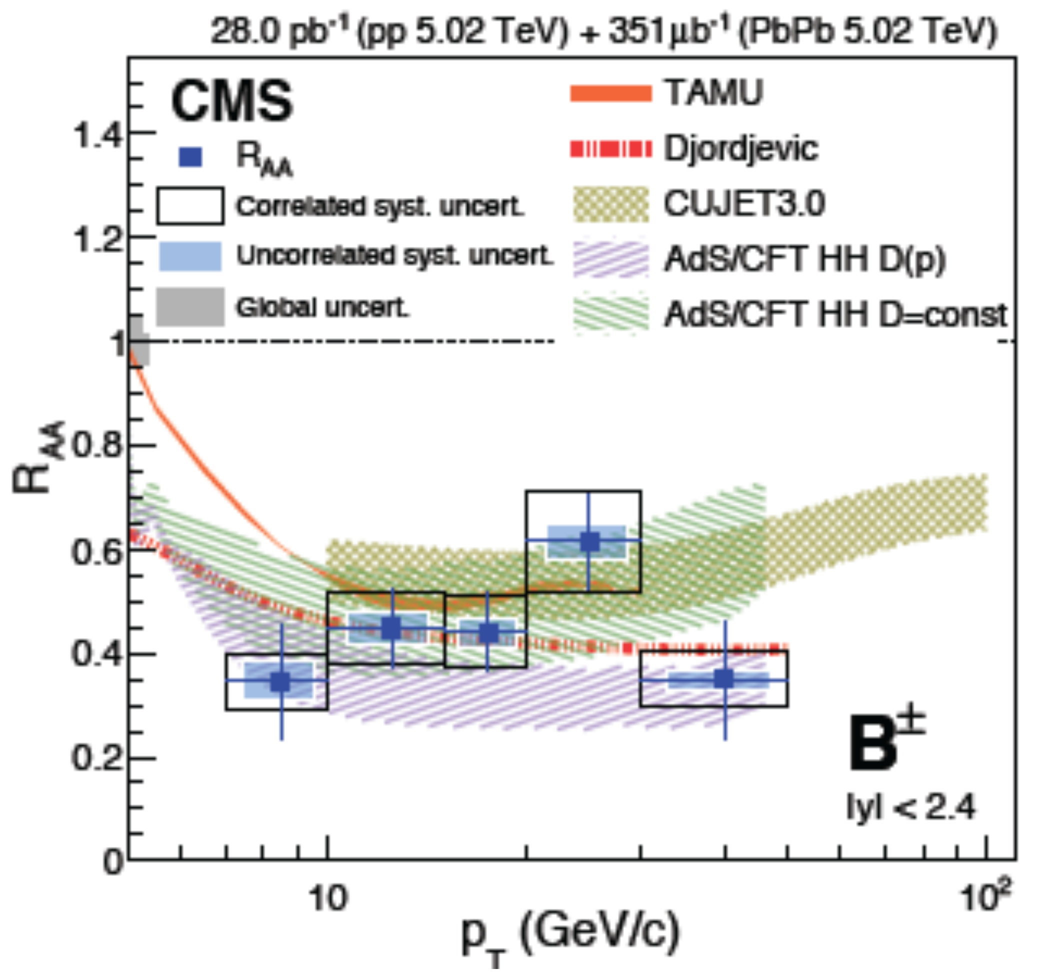


- Examples of 2 models describing the mass dependence of the energy loss in the QGP

Exclusive B^+ meson

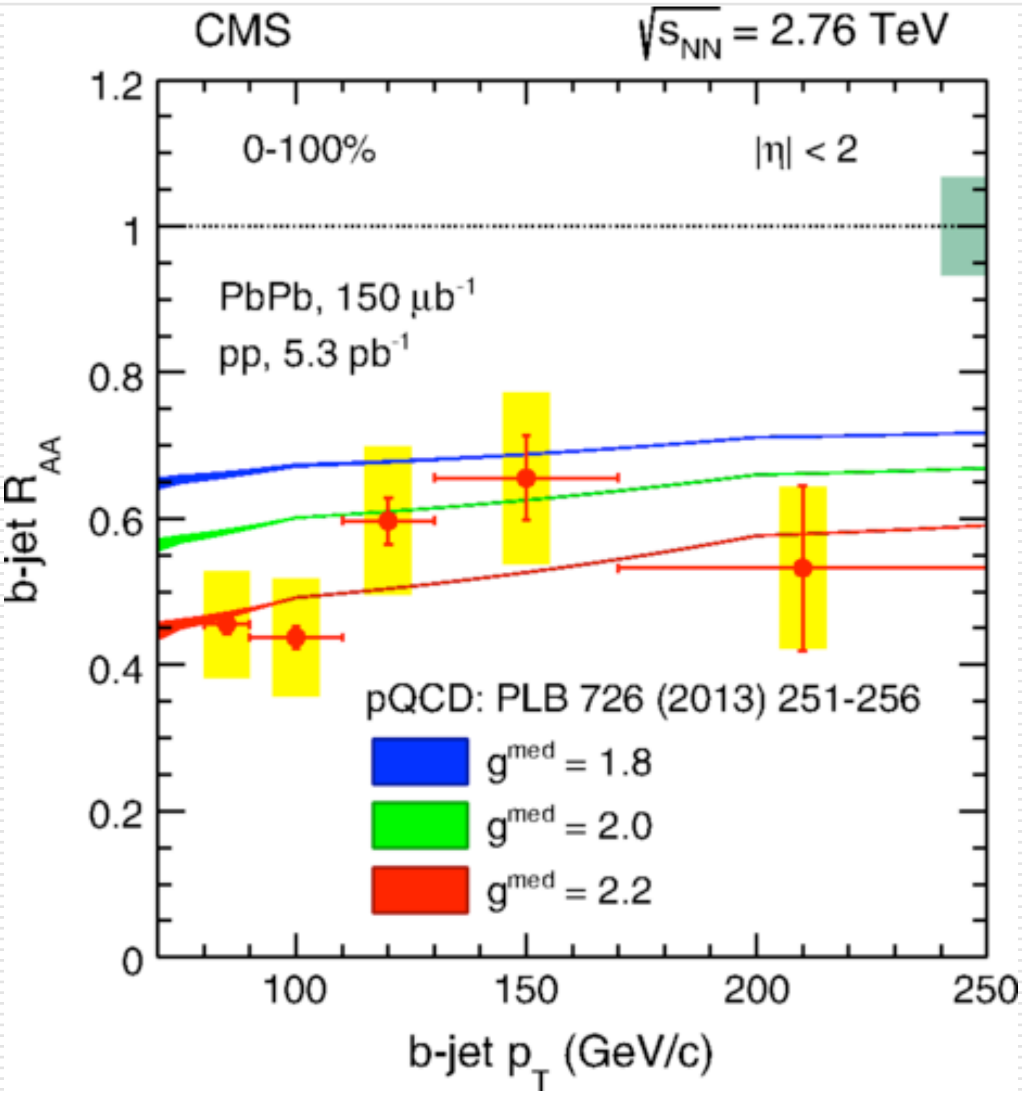
- first measurement ever in AA collisions
- Strong suppression (R_{AA}~0.4) observed in 0-100% Pb-Pb collision for p_T>7 GeV/*c*
  - Well described by theoretical calculations that include radiative energy loss



beauty jets

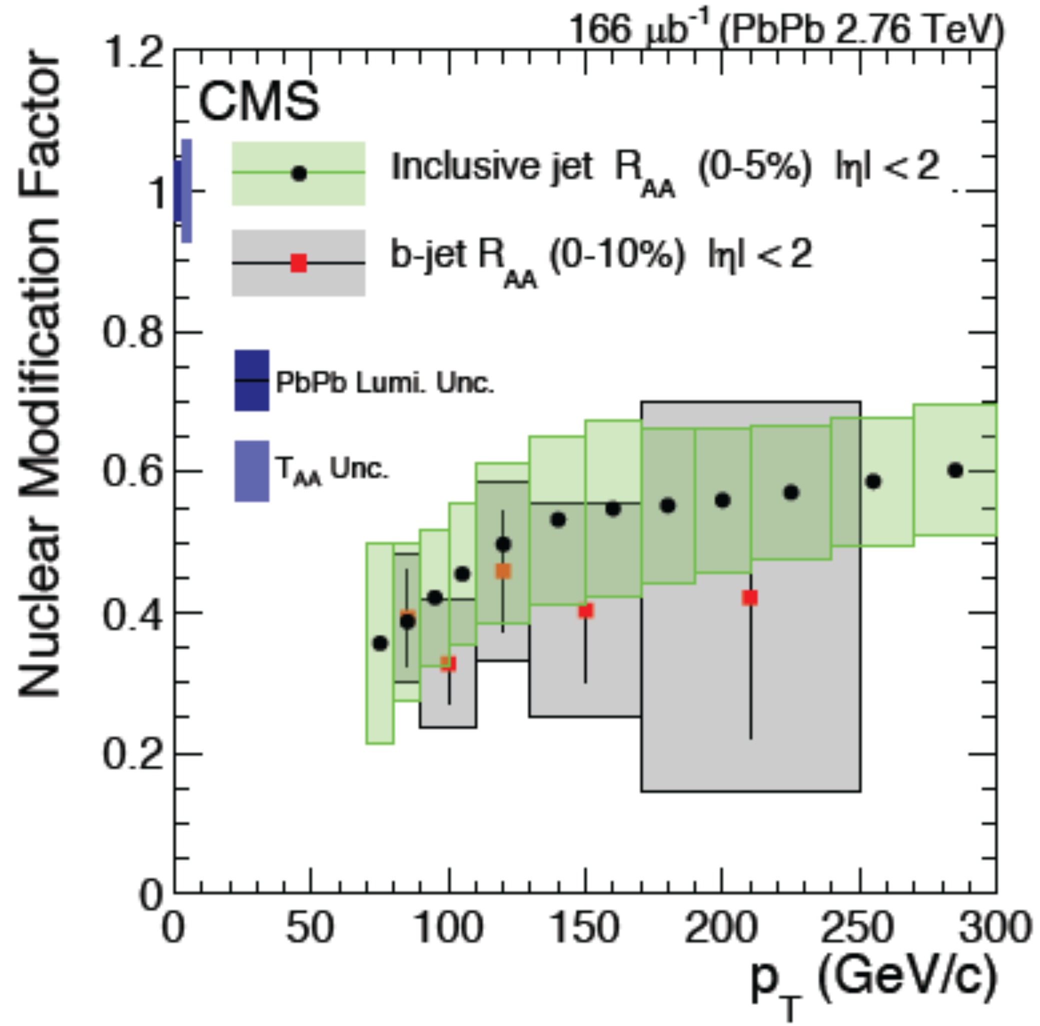
PRL 113, 132301 (2014)

- pQCD calculations with a jet-medium coupling (g^{med}) in the range of 1.8–2 describe data
  - similar value found for inclusive jets



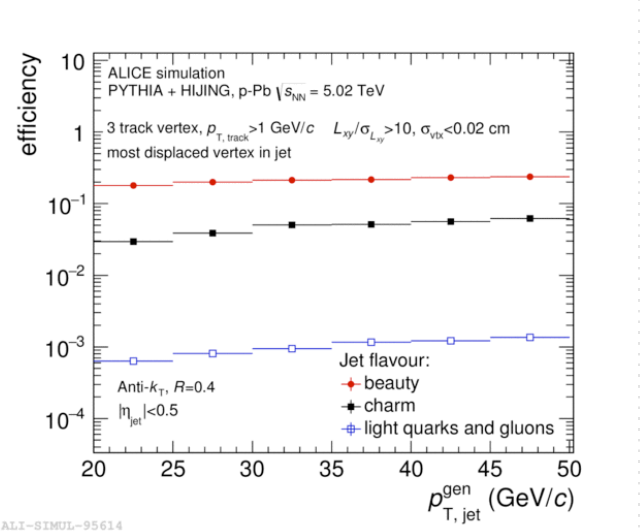
beauty jets

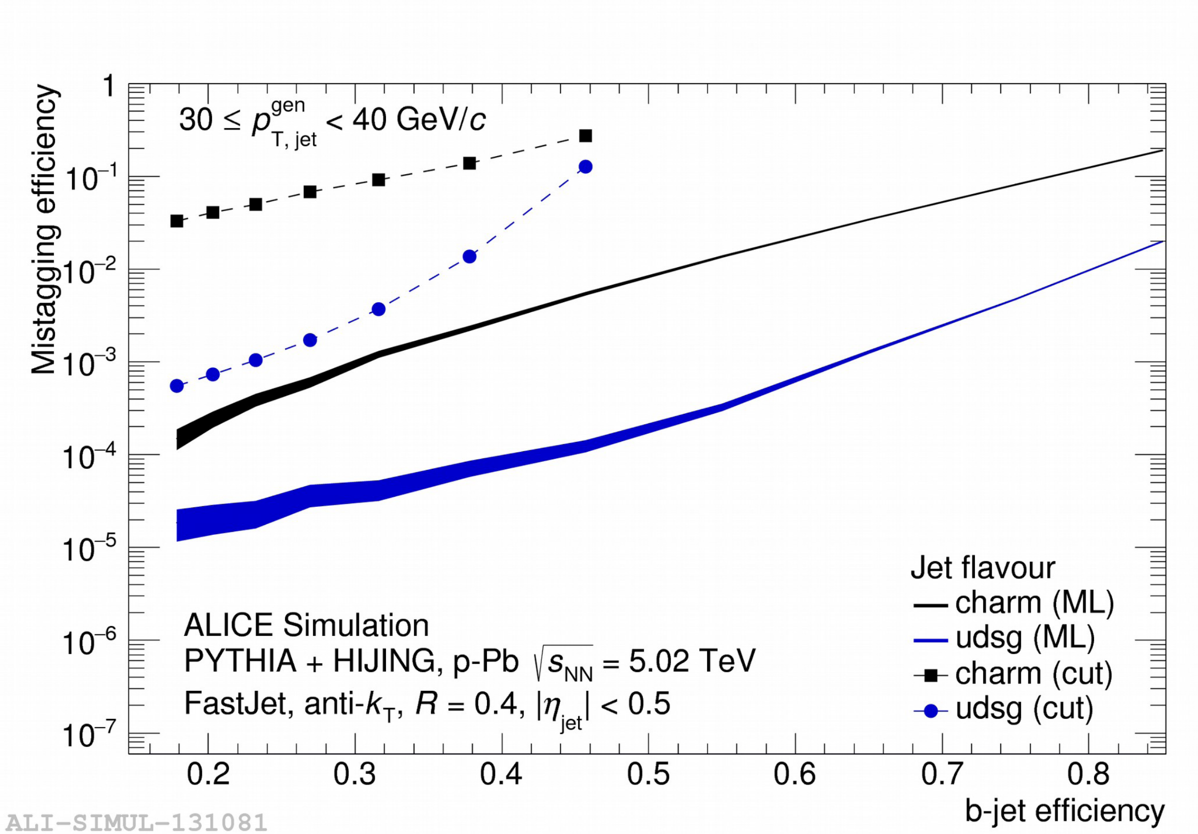
- pQCD calculations with a jet-medium coupling (g^{med}) in the range of 1.8–2 describe data
  - similar value found for inclusive jets
- in the explored p_t range, b-jet suppression is found to be qualitatively consistent with that of inclusive jets



beauty jets at lower pt

- ALICE has good potentials

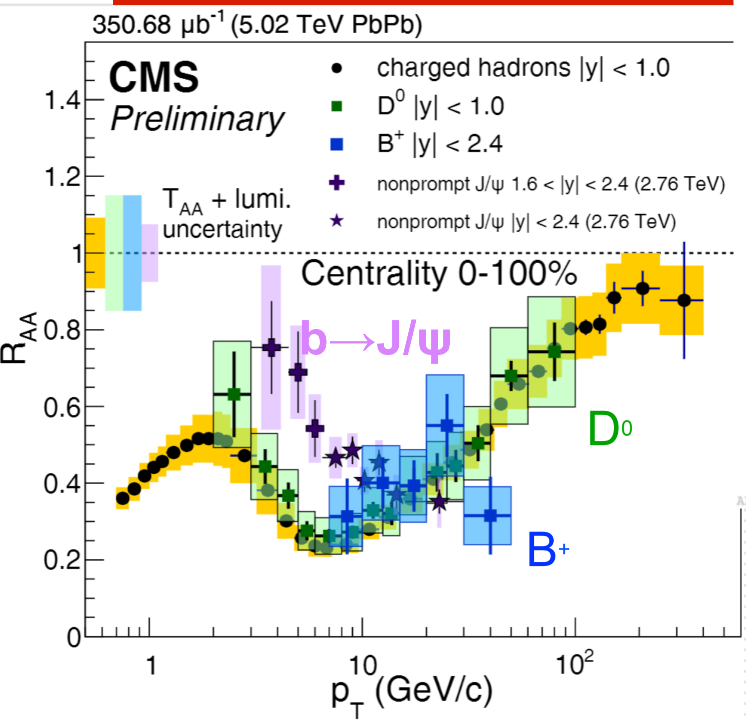


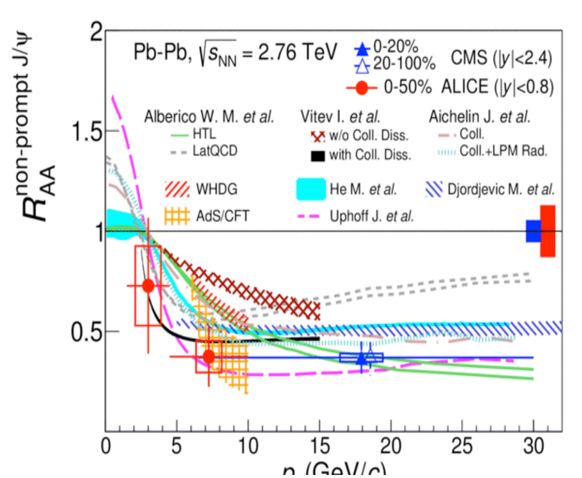


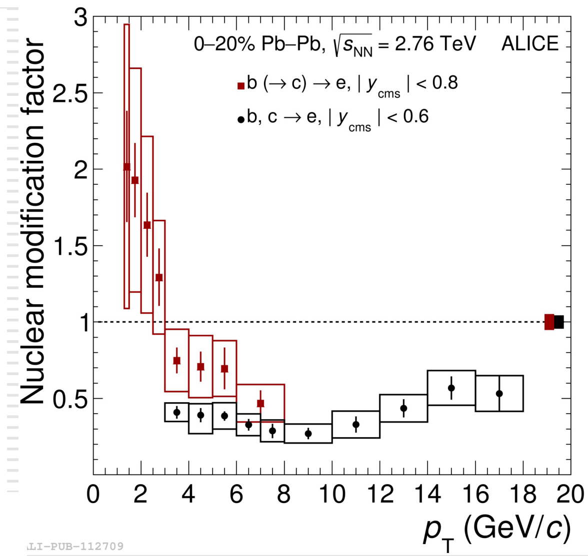
Solid lines:
ML-based method (statistical uncertainty only)

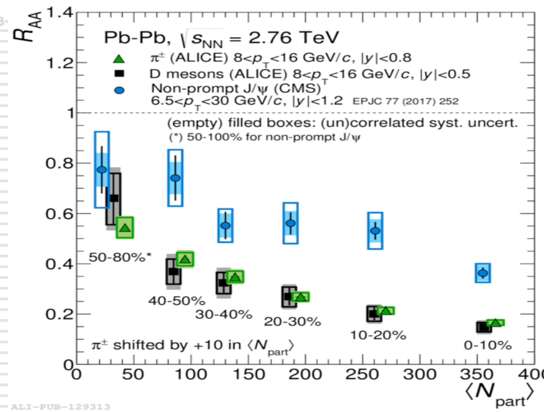
- **Dashed lines:**
Conventional, cut based method (arXiv: 1605.00143)

Beauty Energy loss at LHC: summary





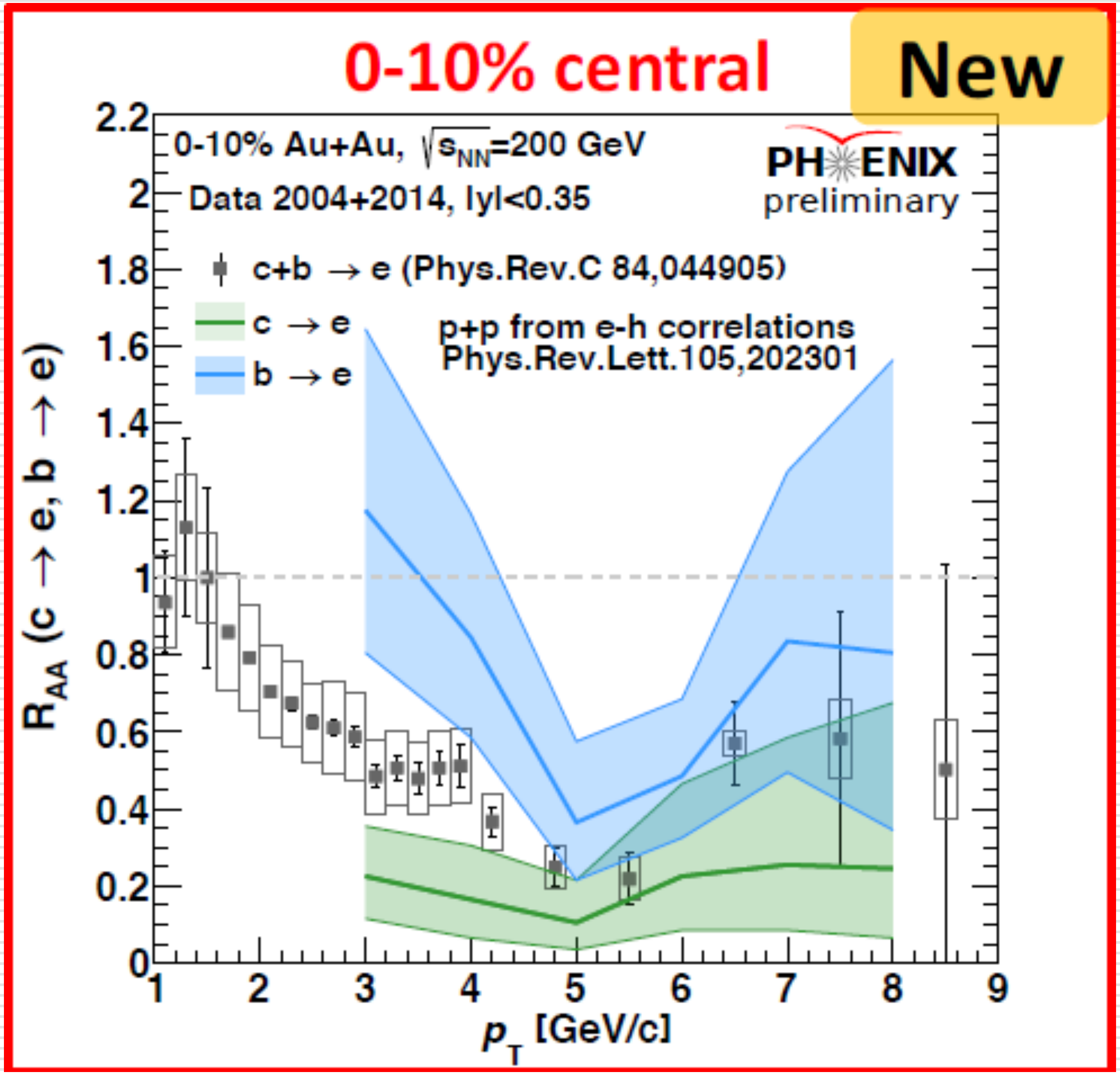




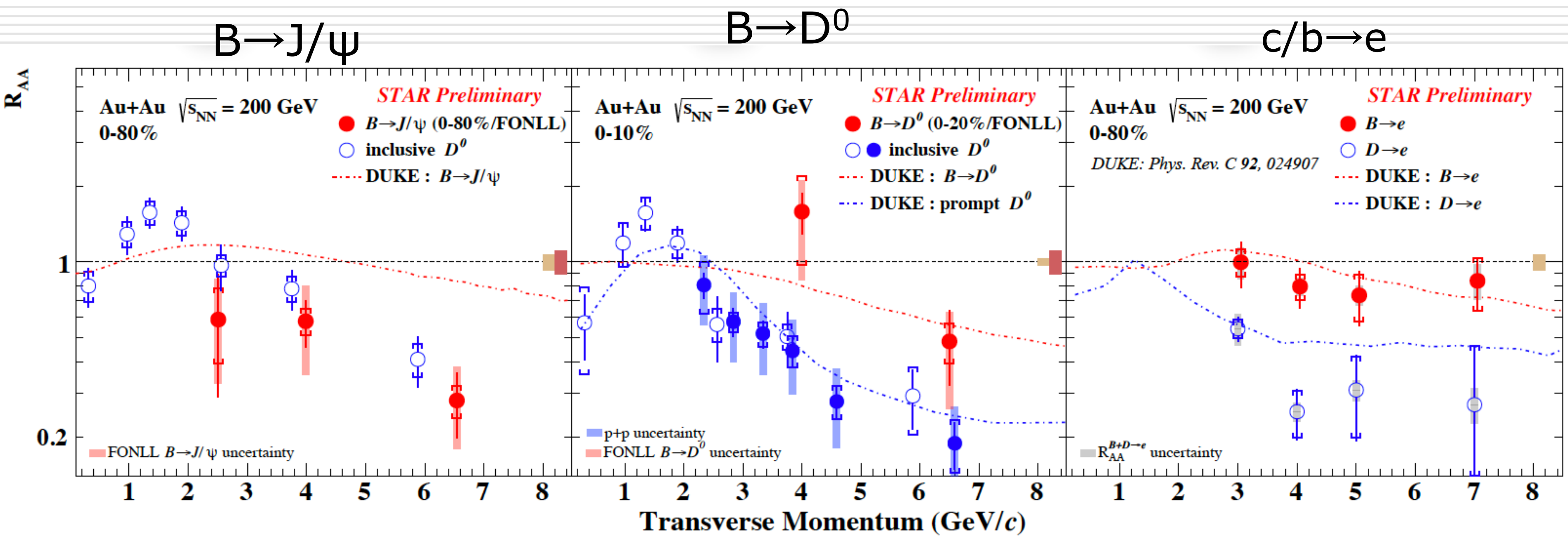
- first evidence/hints of mass effect in the energy loss in the intermediate p_t region (5-10 GeV/c)
- lowest p_t region still to be explored

PHENIX at RICH: e^{HF} with IP fit

- charm more suppressed in 0-10% than in MB collisions
- less suppression of beauty component at low p_t

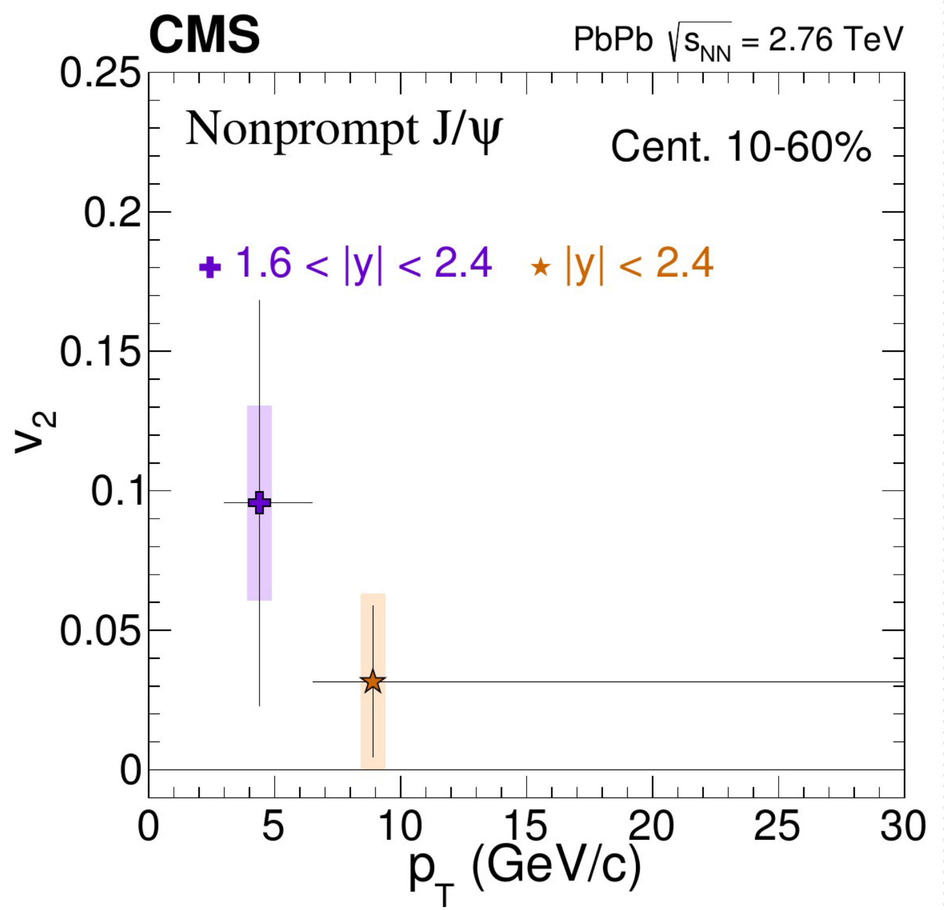


Beauty vs charm R_{AA} with STAR



- Beauty suppression using three different analyses techniques
- again hint of $R_{AA}(B)>R_{AA}(D)$
  - in two cases pp reference from theory (FONLL)

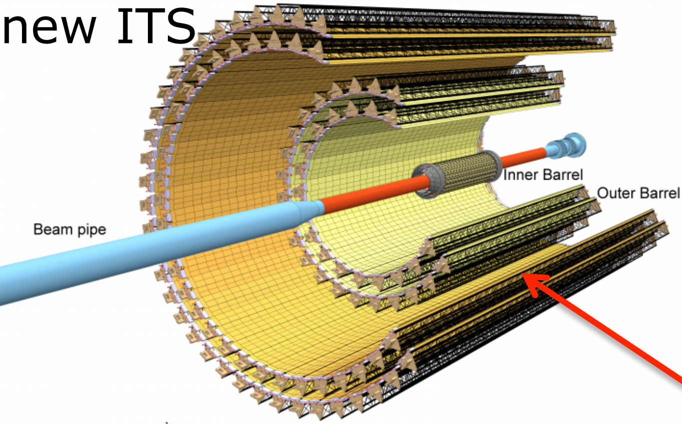
Collective behavior of beauty ?



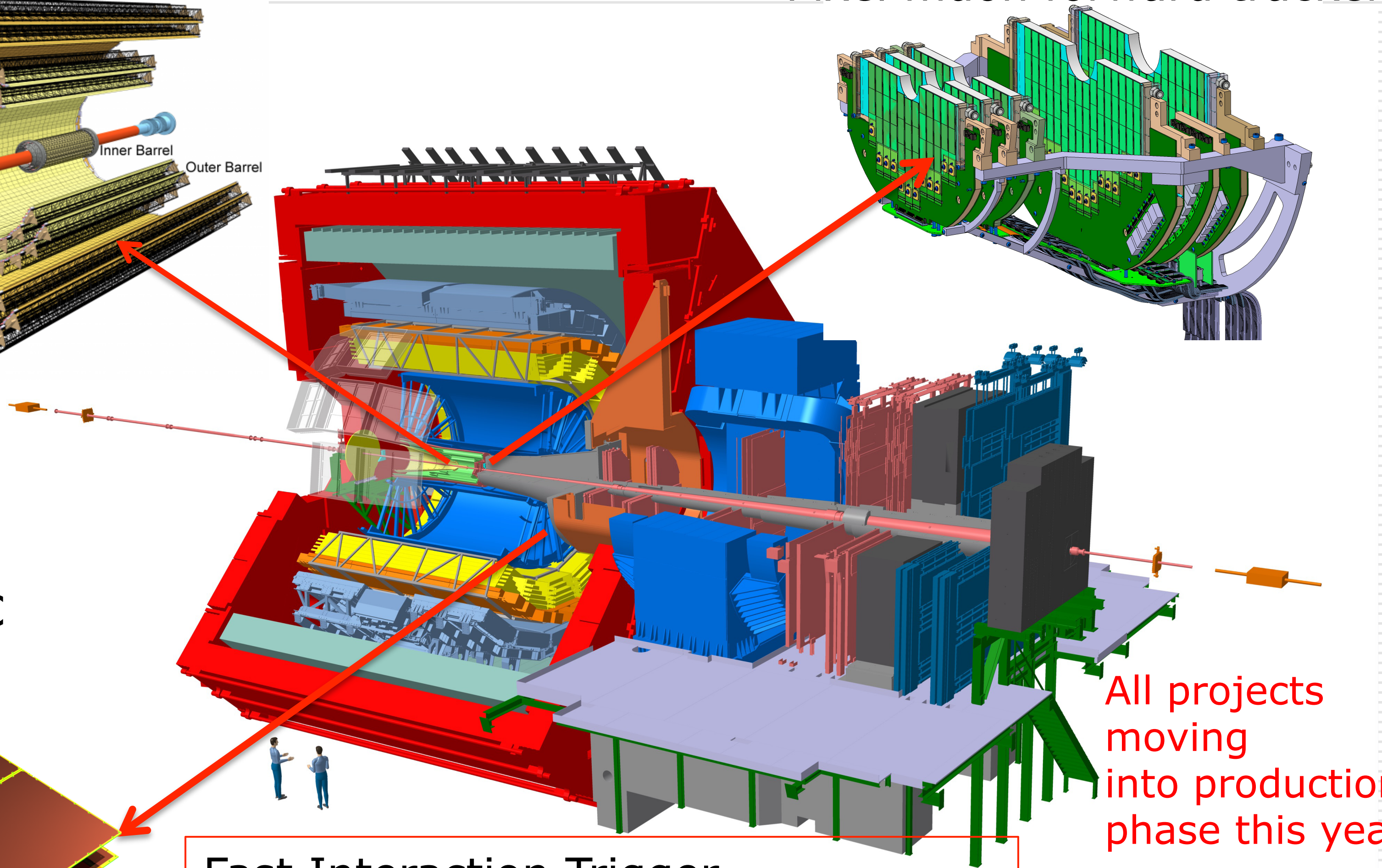
- quite likely only Run3 and Run4 of LHC could address this question

ALICE after Run-2

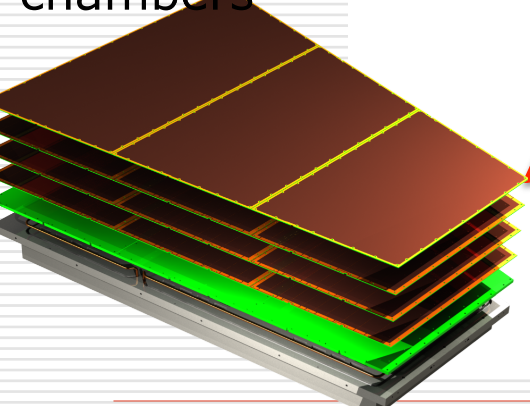
new ITS



Pixel muon forward tracker



GEM-based TPC chambers

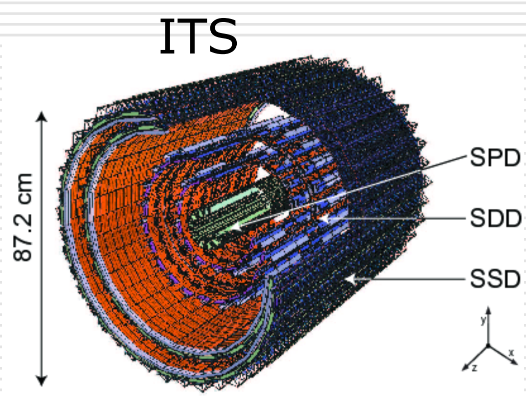


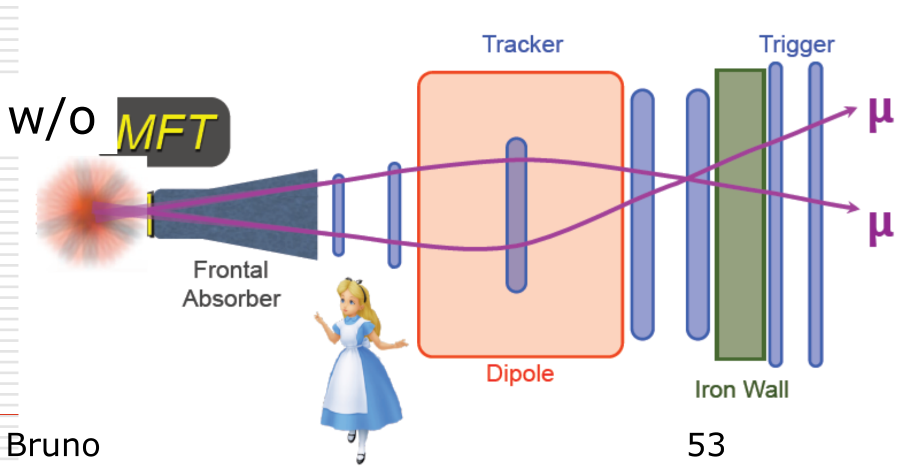
All projects moving into production phase this year

Fast Interaction Trigger
New Online-Offline system
Readout upgrade of other detectors

Key Instruments – Pixel Silicon Detector

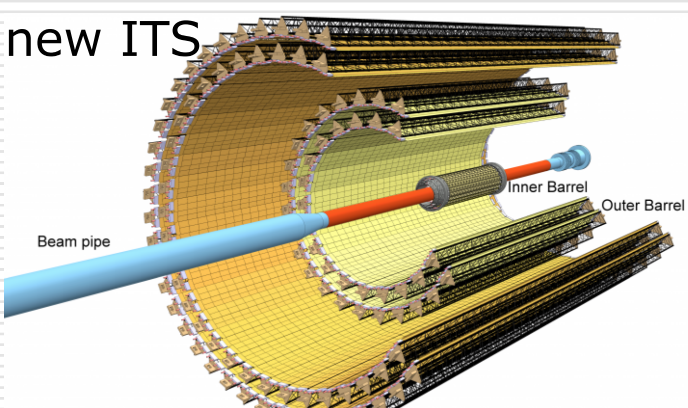
	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	$1\%X_0$	$2\%X_0$	$2\%X_0$	$\sim1\%X_0$	$1\%X_0$	**$0.4\%X_0$**

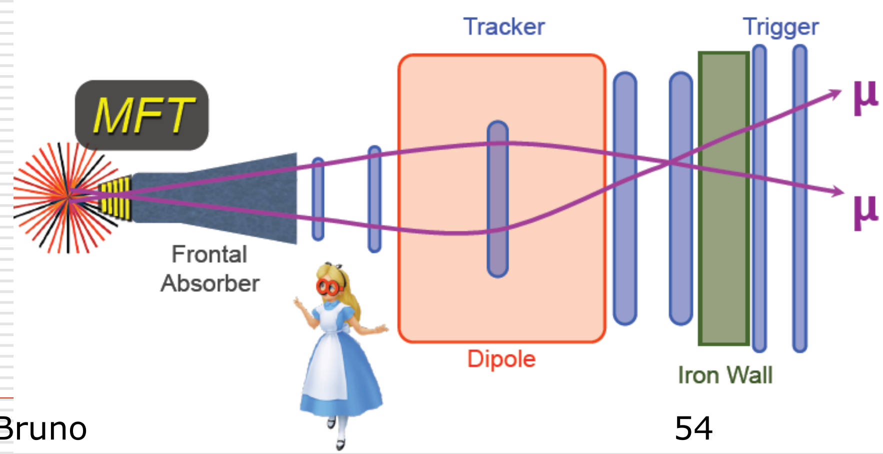




Key Instruments – Pixel Silicon Detector

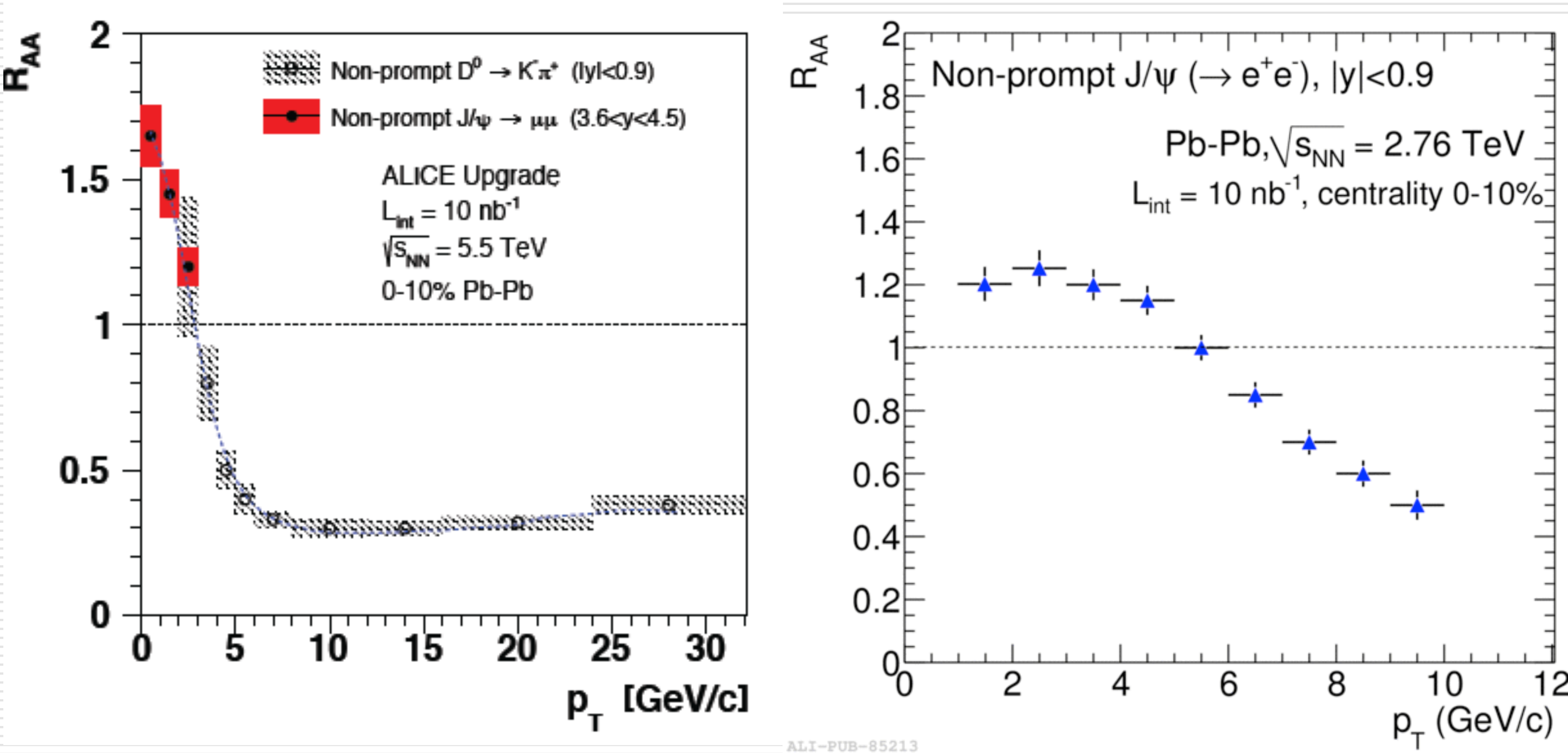
	ALICE UPGRADE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	MAPS	Hybrid	Hybrid	Hybrid	Hybrid	MAPS
Pitch size (μm^2)	15x30	50x400	100x150	200x200	50x425	20x20
Radius of first layer (cm)	2.2	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	0.3% X_0	2 %X_0	2 %X_0	~1%X_0	1%X_0	0.4%X_0





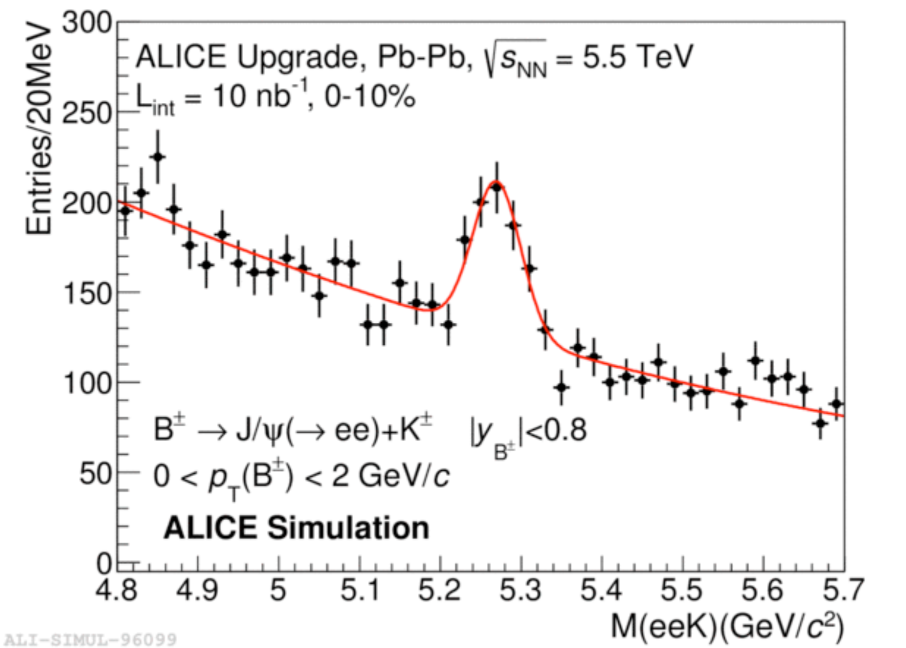
perspectives: ALICE upgrade

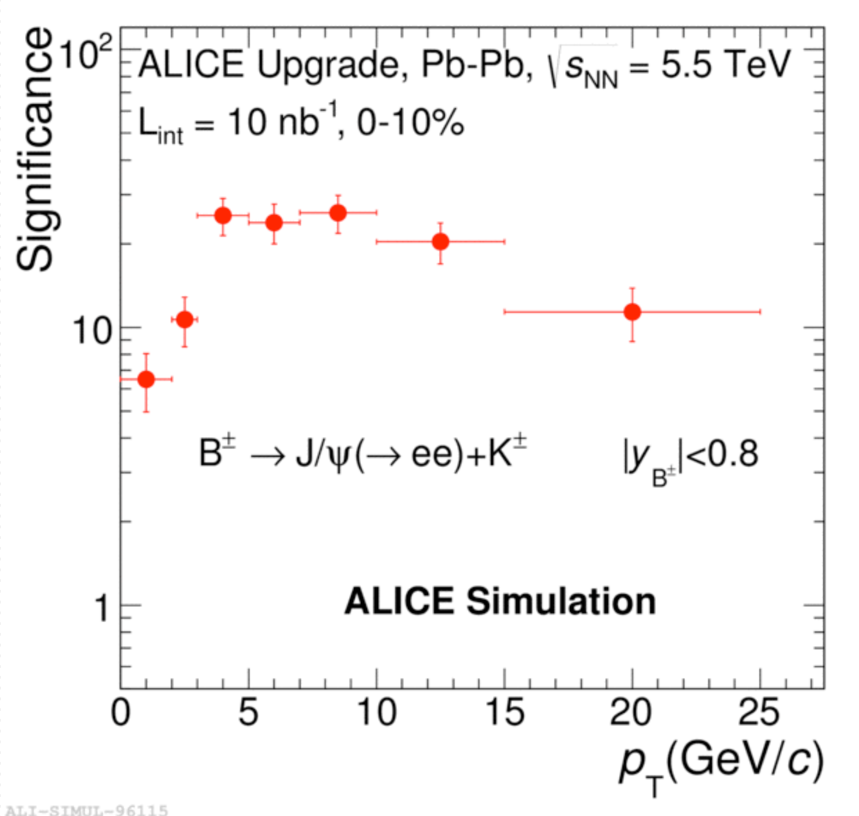
- $B \rightarrow D^0+X$ (barrel) and $B \rightarrow J/\psi+X$ (barrel & MFT)



perspectives: ALICE upgrade

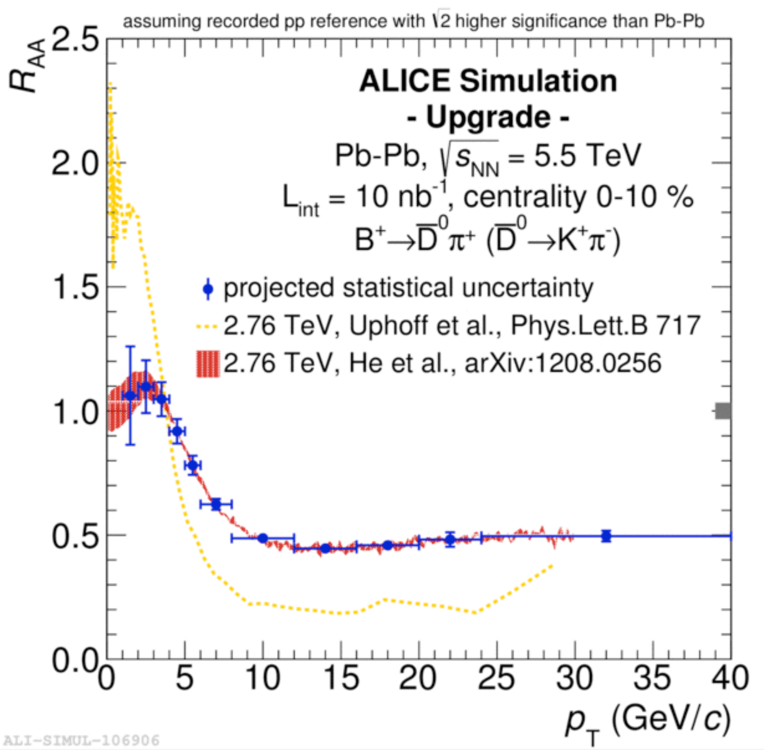
- fully reconstructed beauty mesons

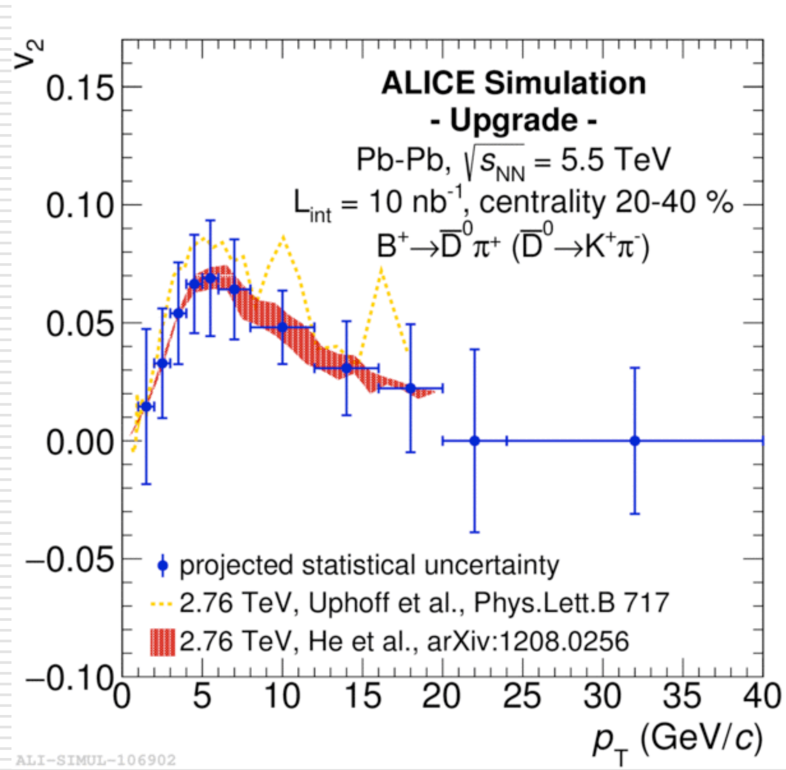




perspectives: ALICE upgrade

- fully reconstructed beauty mesons

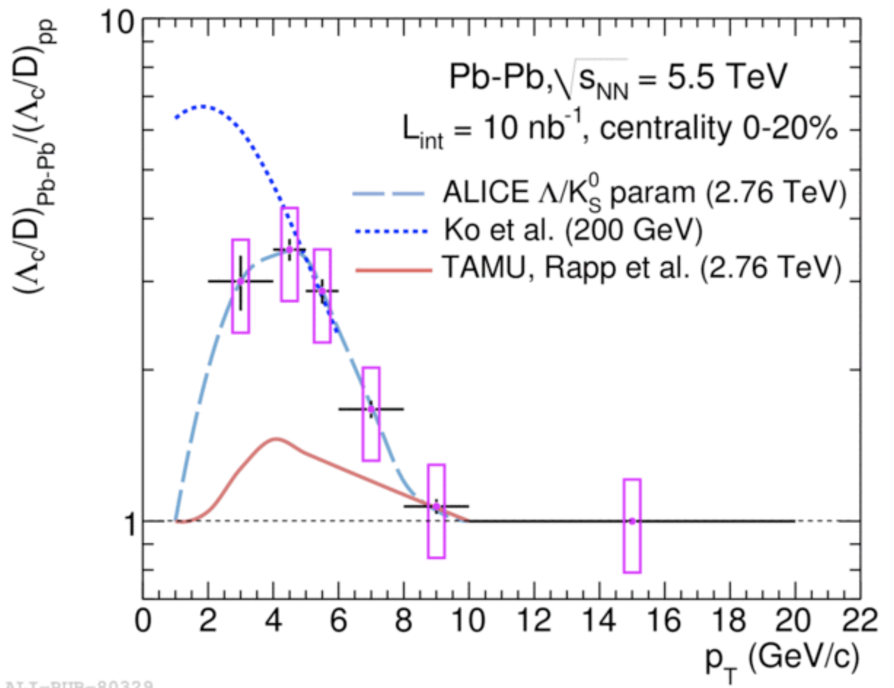




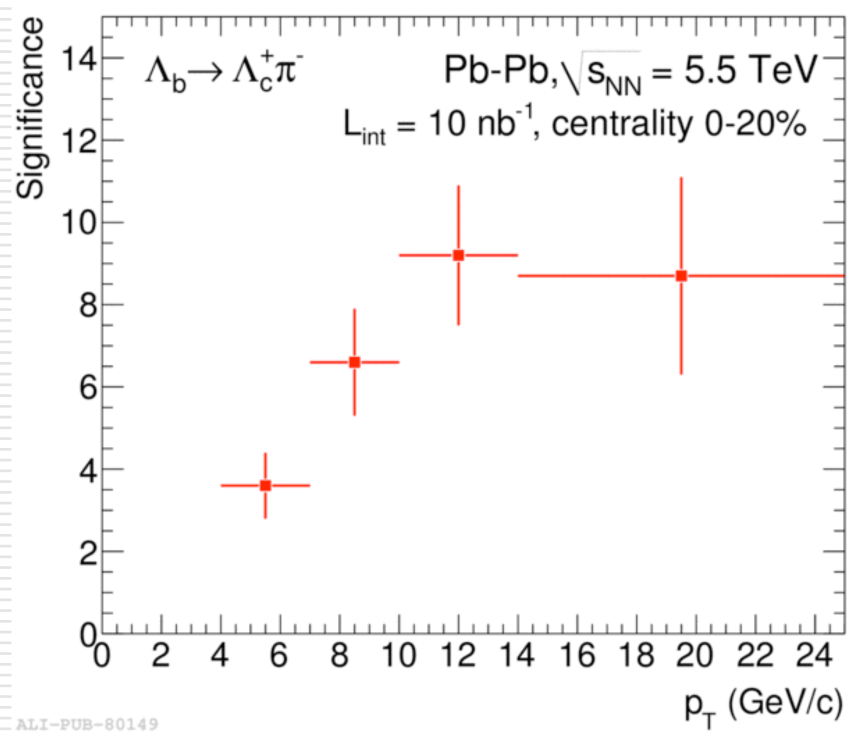
perspectives: ALICE upgrade

- HF baryons

charm



beauty



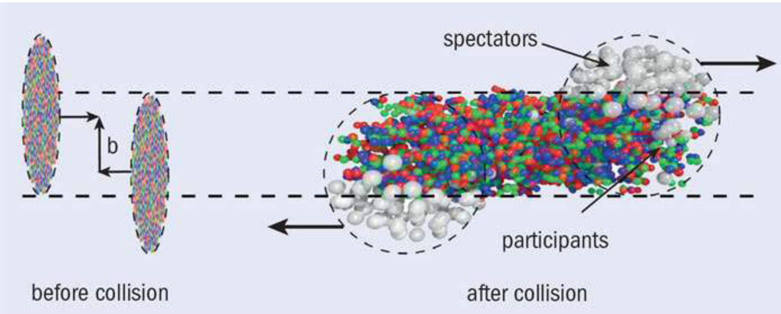
Summary

- LHC Run2 data and RHIC experiments with Silicon Microvertex detectors are providing precise measurements in the charm sector
  - stringent constraints on the models describing the properties of the system (e.g., transport coefficients, η/s) and its dynamical evolution
- Beauty
  - First evidences of mass dependence of energy loss
  - Run3 and Run4 of LHC will allow a detailed study in the beauty sector thanks to the detector upgrades

SPARES

Global characterization of the system

Centrality definition

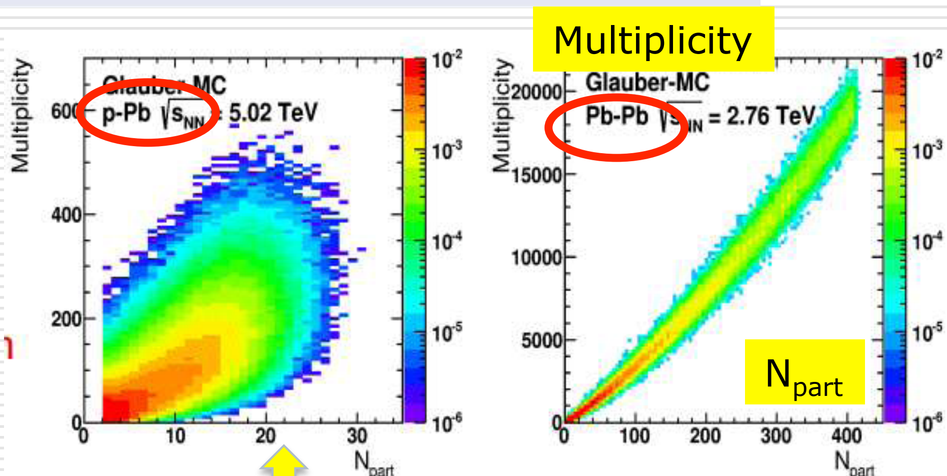


N_{part} :Number of nucleons participating to the collision

N_{coll} : Average number of binary collisions between nucleons

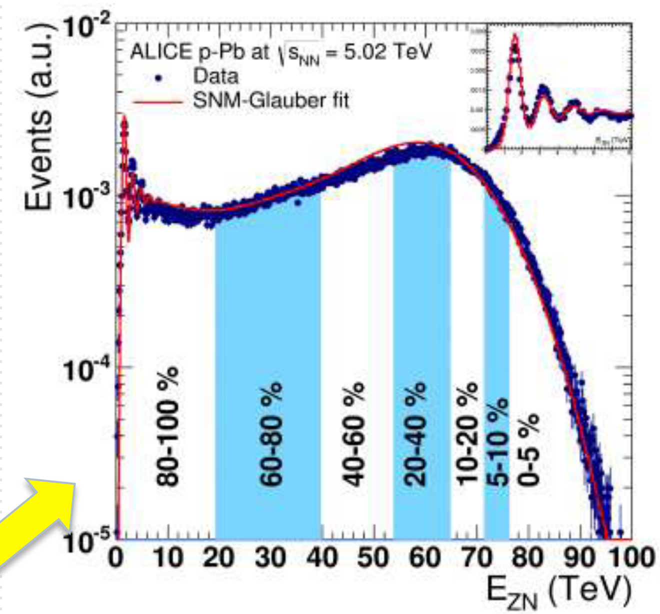
Example LHC:
Centrality 0-1%
Npar = 403
Ncoll = 1681

Centrality = fraction of σ_{PbPb}



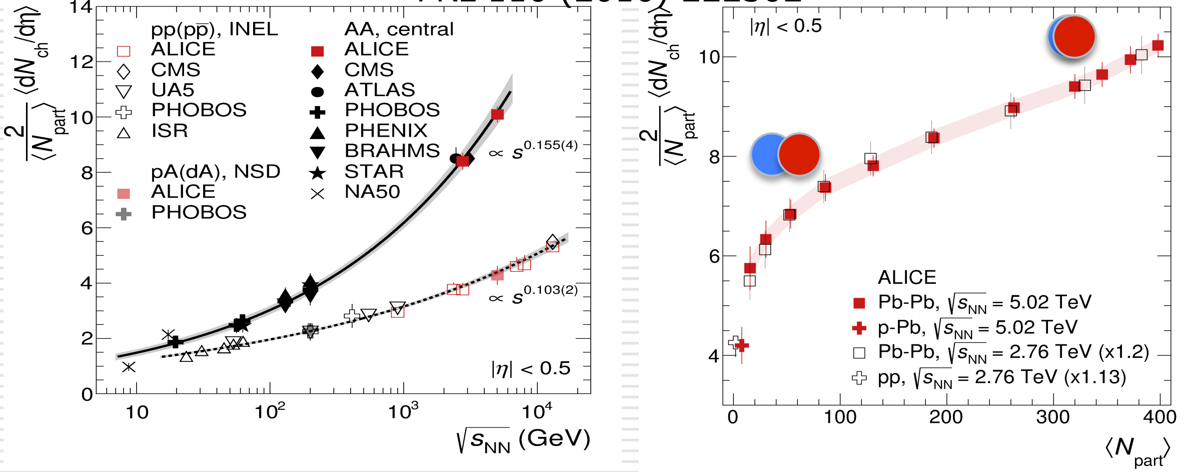
Centrality estimators

- Multiplicity : bias on the hardness of the pN collisions (quantified by the number of hard scatterings per pN collision).
- ZDC : expected to be insensitive to bias. Establish a geometry-related particle scaling with a better than 10% precision

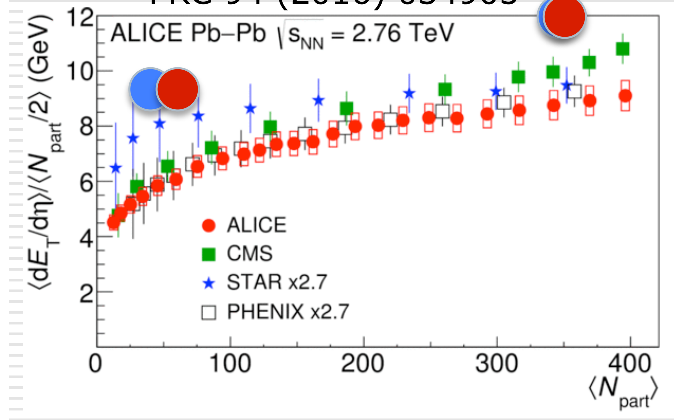


Charged multiplicity & energy density

PRL 116 (2016) 222302



PRC 94 (2016) 034903



- $dN_{ch}/d\eta$ / (N_{part}/2) increases with √s
  - pp: ~$s^{0.103}$ in
  - central A+A: ~ $s^{0.155}$
  - ~20% increase going from 2.76 to 5.02 TeV
- similar centrality dependence as at RHIC

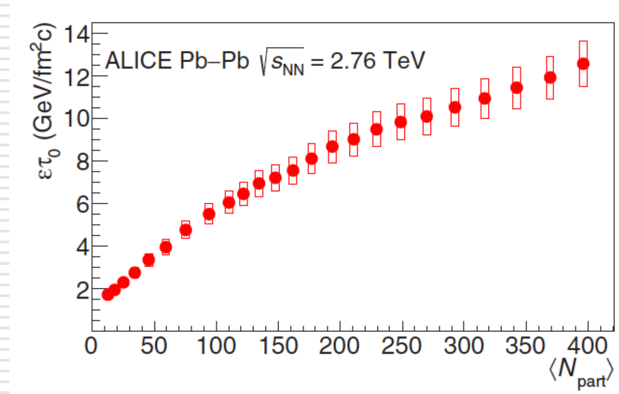
$$\varepsilon\tau_0 = \frac{J\langle dE_T / d\eta\rangle}{c\pi R^2}$$

J = 1.12 ±0.06

central collisions

$$\varepsilon\tau_0 \approx 12.5 \pm 1.0 \text{ GeV/fm}^2/c$$

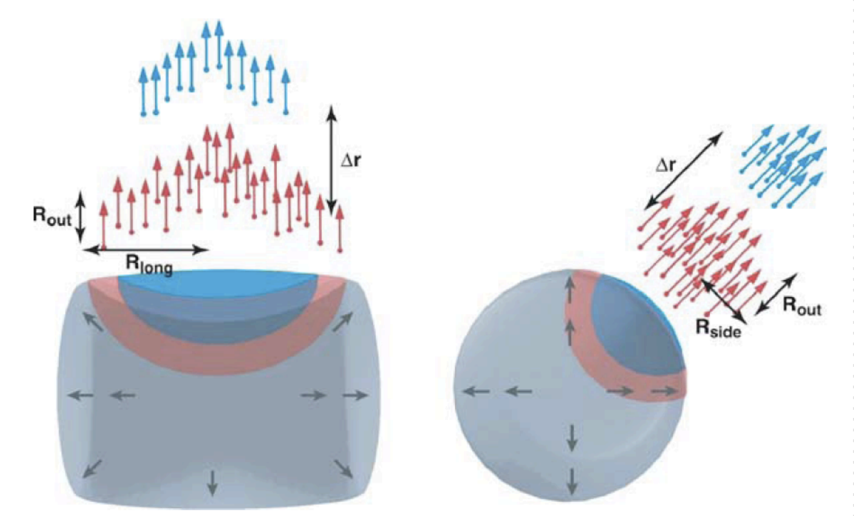
$$\varepsilon_c\tau_0 \approx 21 \pm 2 \text{ GeV/fm}^2/c$$

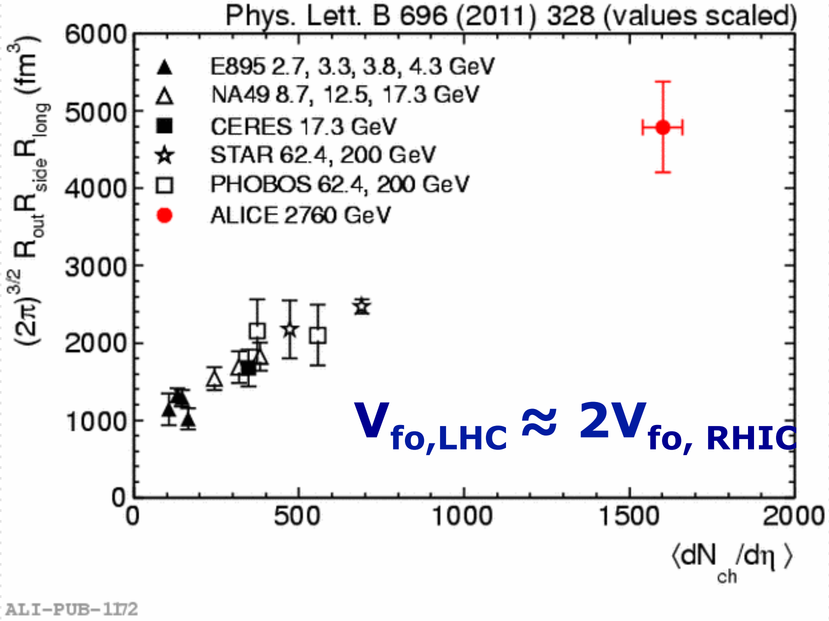


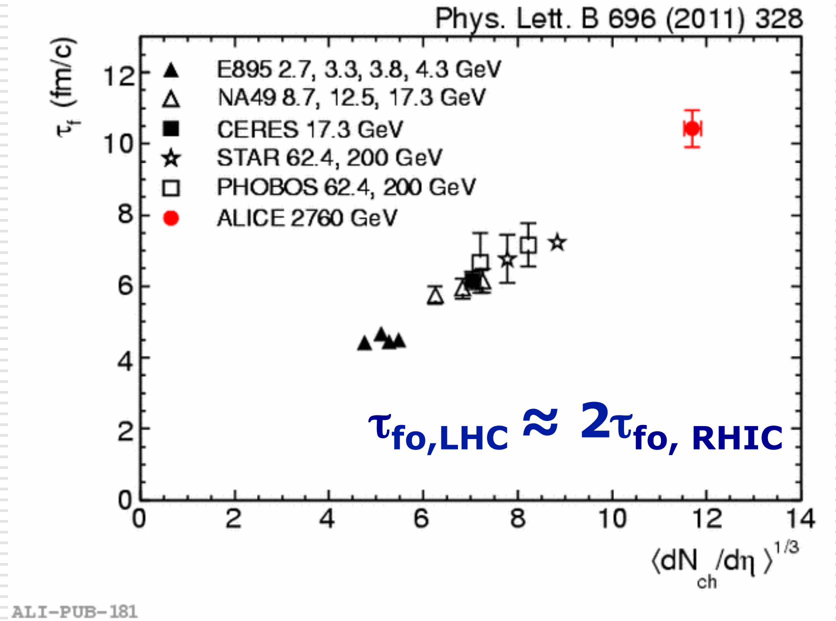
Initial energy density at LHC (and RHIC) well above $\varepsilon_{crit} \approx$ 0.5 GeV/fm^3

System size

- Space-time evolution of the system from two-pion Bose-Einstein Correlations (HBT)

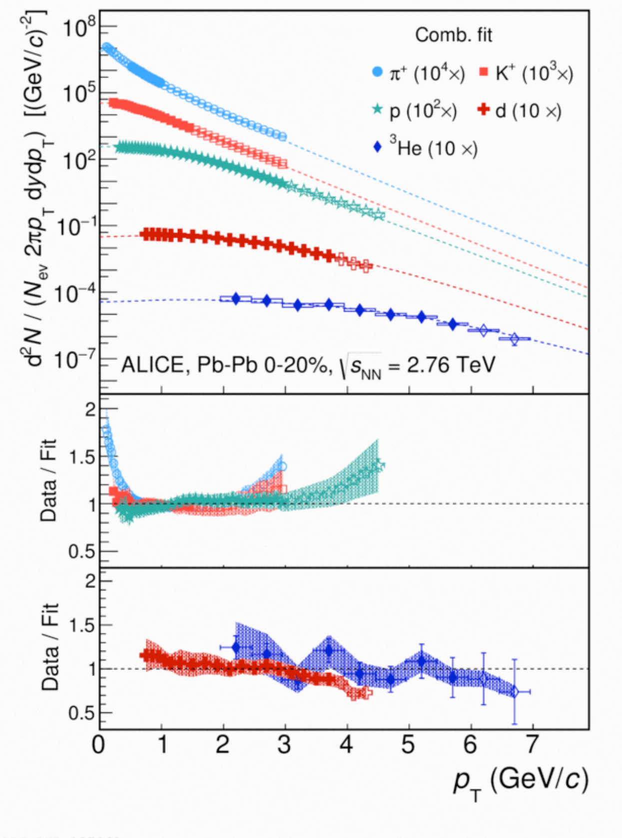




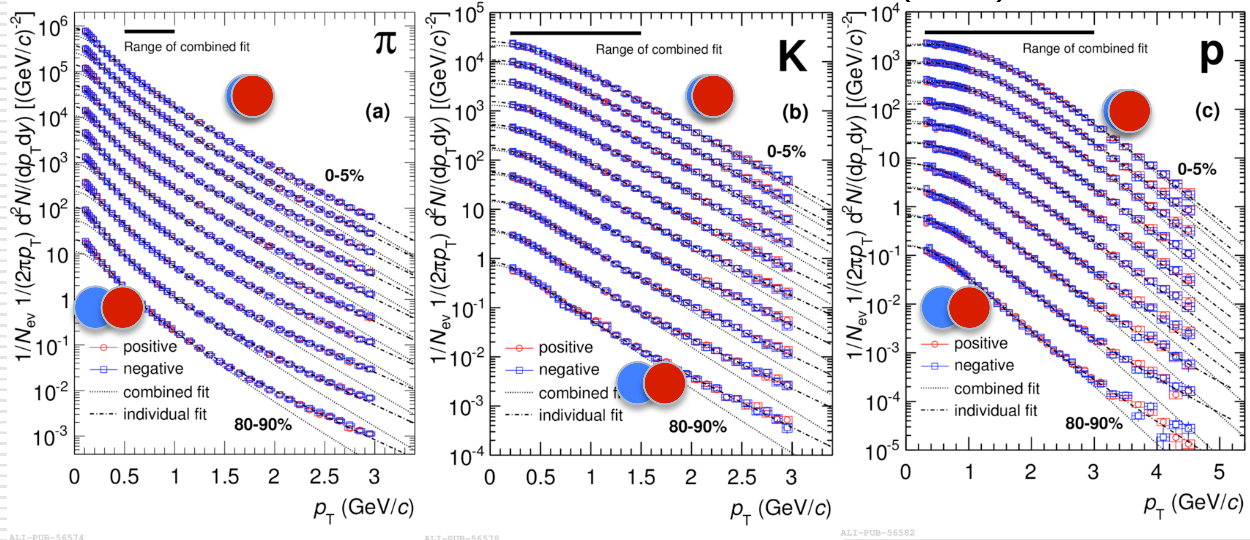


Identified particle spectra

PRC 93 (2015) 024917



PRC 88 044910 (2013)



- spectra get flatter for more central collisions
- stronger effect for heavier particles
- consistent with a hydrodynamic description
- even nuclei described by hydro

Collective Transverse Expansion

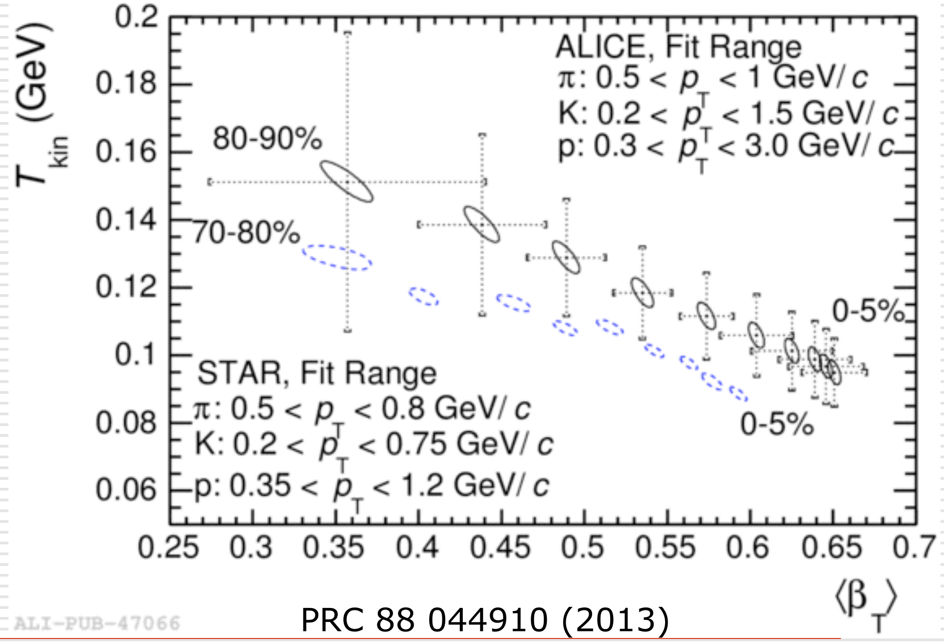
- p_T distributions described as combined result of thermal motion (**T**) and collective transverse expansion (**β_T**) at freeze-out

$$m_T = \sqrt{m^2 + p_T^2}$$

$$\frac{d^2 N_j}{m_T dy dm_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_T \cosh\rho}{T}\right) \cdot I_0\left(\frac{p_T \sinh\rho}{T}\right) r dr$$

$$\rho(r) = \tanh^{-1}\beta_\perp(r) \qquad \beta_\perp(r) = \beta_S \left[\frac{r}{R_G}\right]^{n(=1)} \qquad r \le R_G$$

Schnedermann, Sollfrank, Heinz, PRC48 (1993) 2462



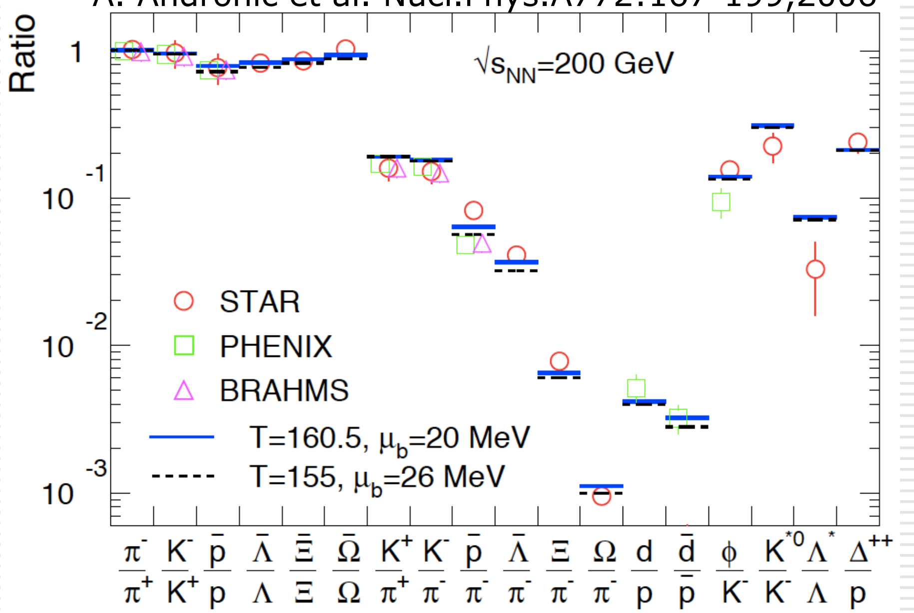
PRC 88 044910 (2013)

- Strong radial flow: $\beta \approx 0.65$ for most central collisions, 10% higher than at RHIC
- Freeze-out temperature of about 100 MeV

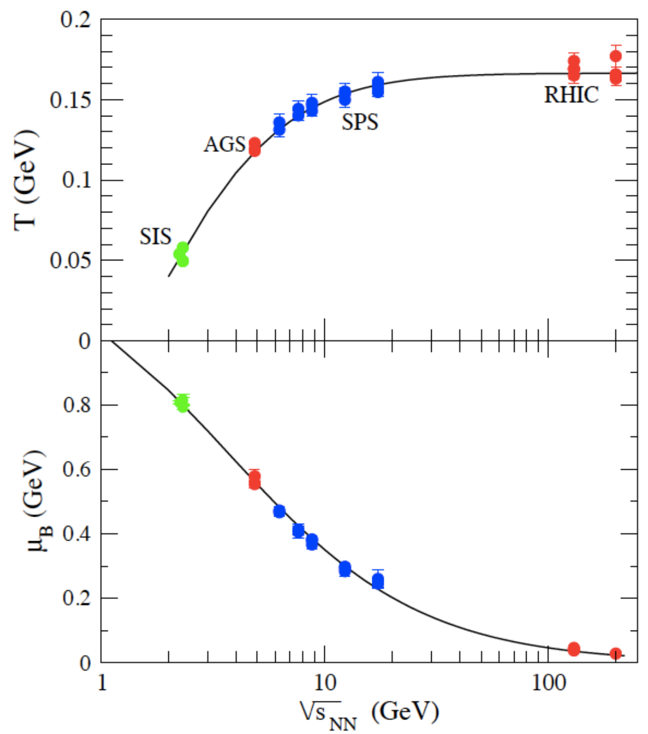
Hadro-chemistry

- relative abundances of hadron species can be described by statistical distributions

A. Andronic et al. Nucl.Phys.A772:167-199,2006



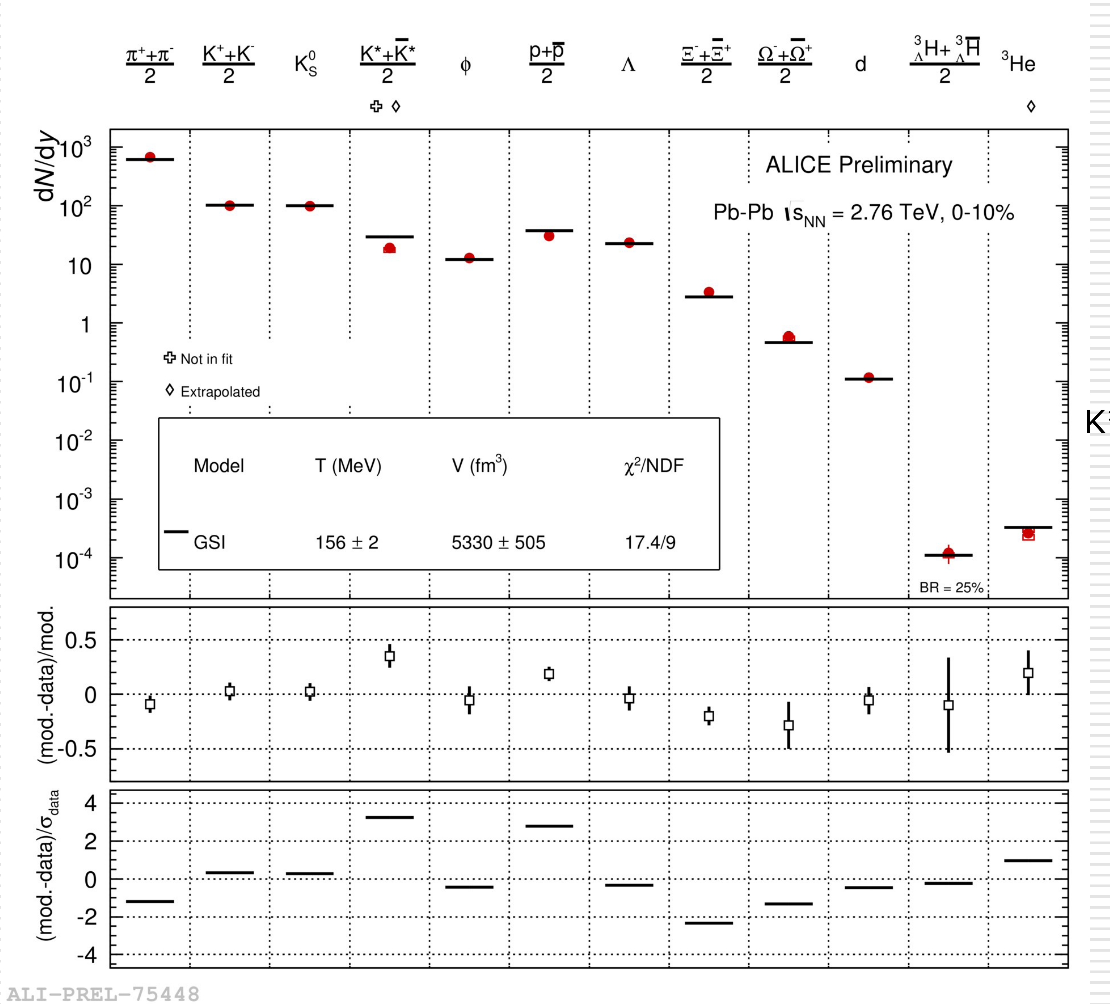
J. Cleymans et al. Phys.Rev.C73:034905,2006



- thermodynamic interpretation of model parameters in high energy A+A collisions:

$$T_{chem} = T_C$$

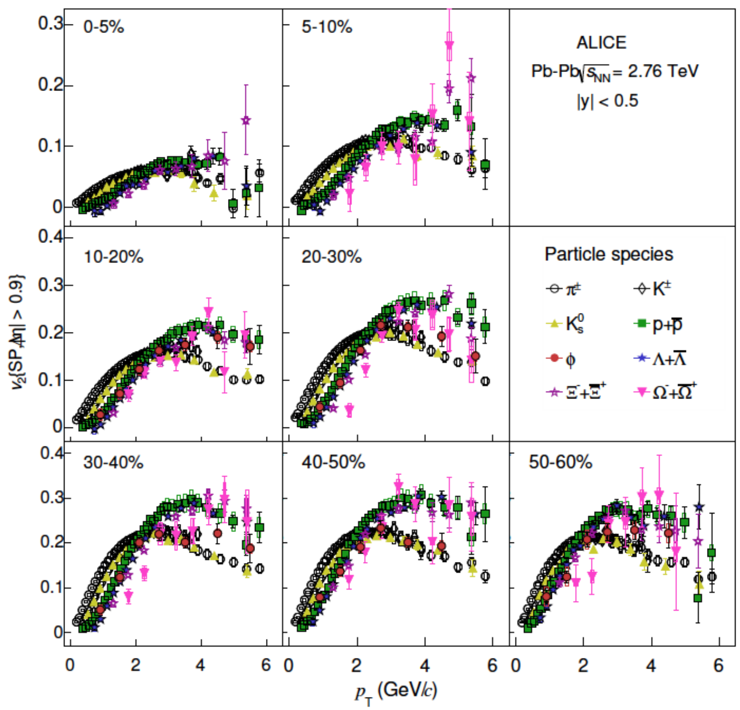
Chemical Equilibrium at LHC?

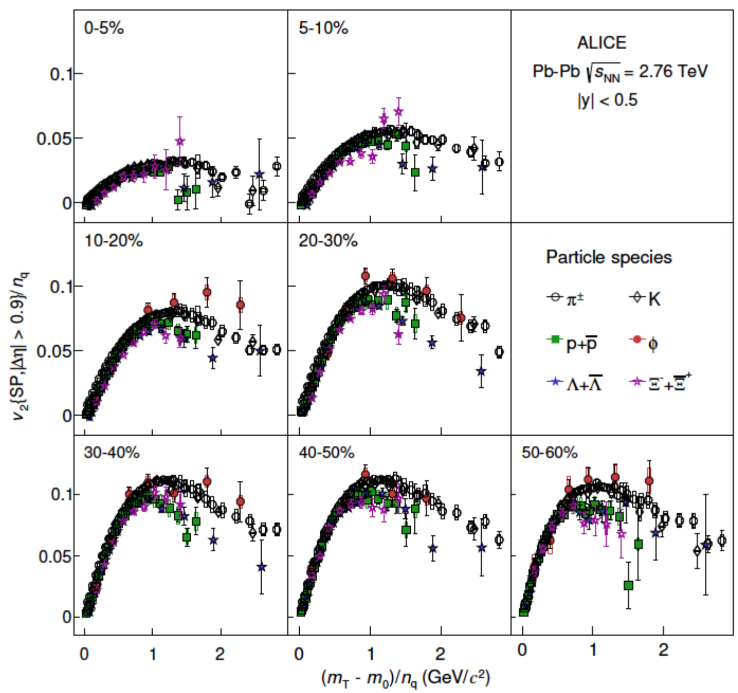


K* not include in the fit

- hadrons (including nuclei) are described with a common chemical freeze-out temperature
  - T_{ch} = 156 (2) MeV →T_{ch} (LHC) ~ T_{ch} (RHIC) ~ T_c

Elliptic flow of identified particles





- main scaling with constituent quark number
  - at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics
- pion, kaon (and strange baryons) v_2 are described rather well with hydrodynamic predictions
  - for protons hadronic cascade important

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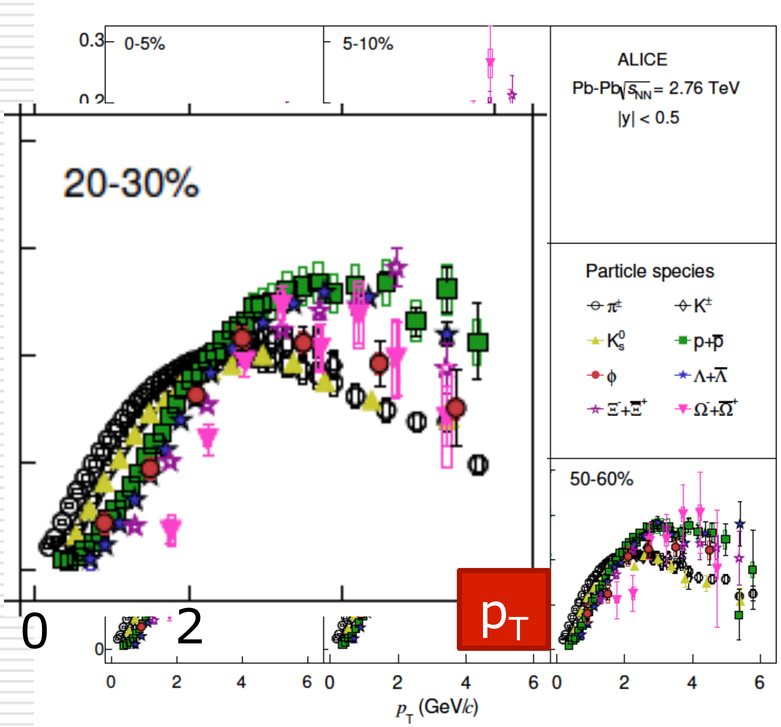

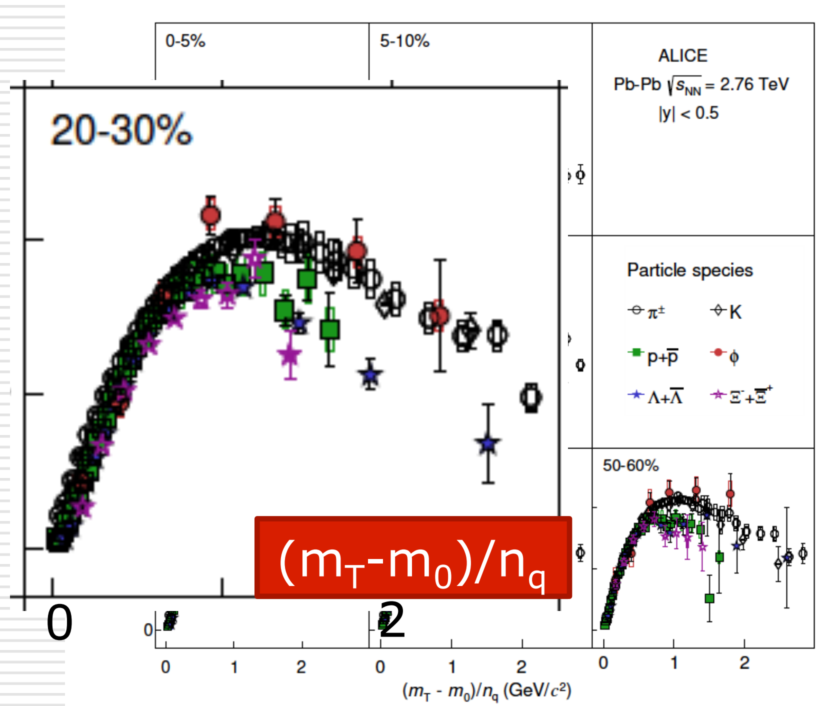

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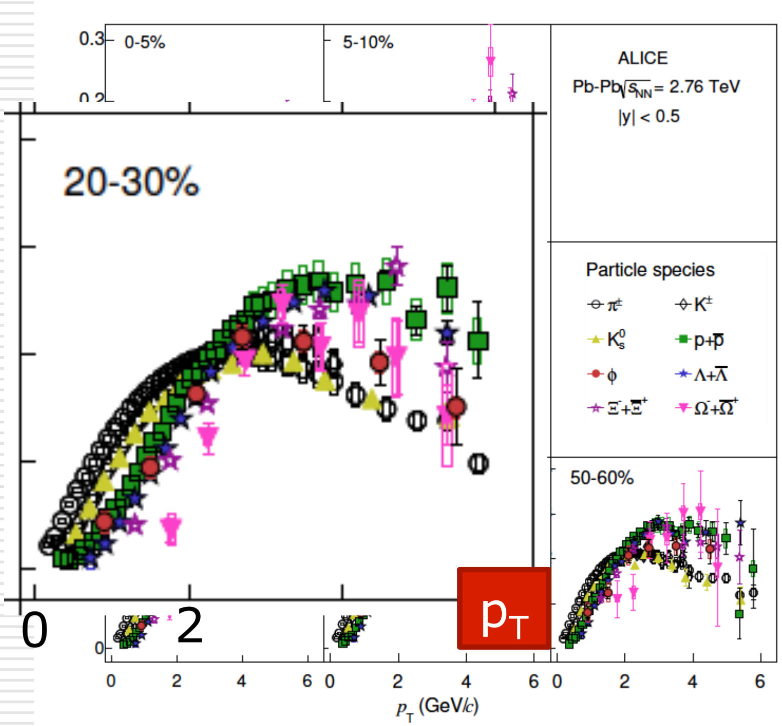

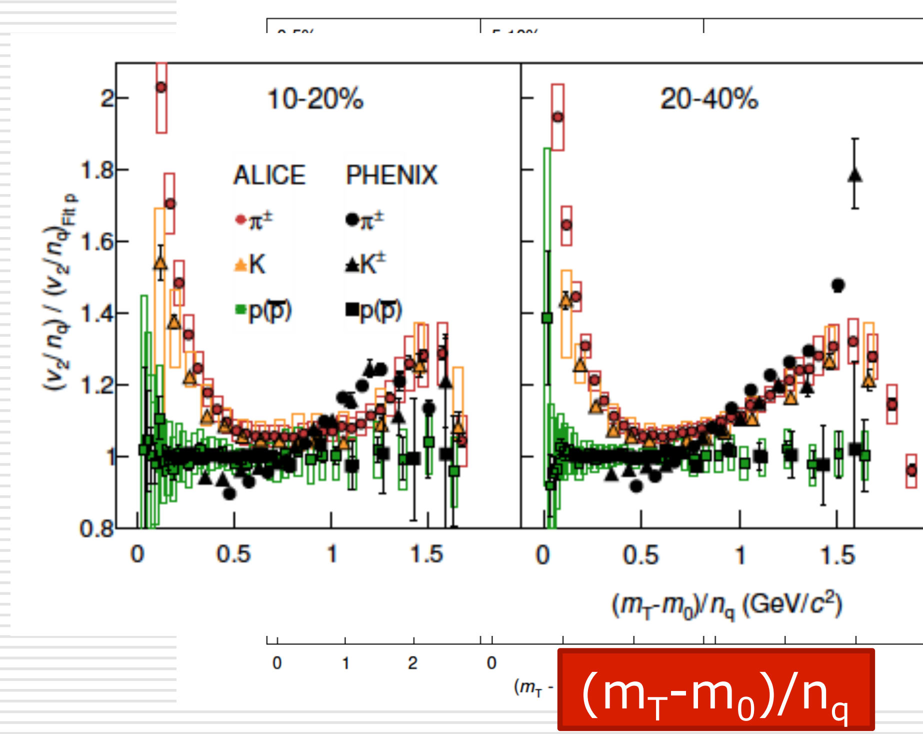

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The "Fireball" at LHC

- system created at LHC is consistently larger, denser, more excited than at lower energy (RHIC)
- multiplicity, transverse energy: "initial" energy density

$$\left(\varepsilon_i \cdot \tau_i\right)_{2.76\ \mathrm{TeV}} \approx 15\ \mathrm{GeV/fm^2}c \approx 3\left(\varepsilon_i \cdot \tau_i\right)_{0.2\ \mathrm{TeV}}$$

- pion interferometry: freeze-out size and lifetime

$$V_{fo}(2.76\ \mathrm{TeV}) \approx 2V_{fo}(0.2\ \mathrm{TeV})$$

$$\tau_{fo}(2.76\ \mathrm{TeV}) \approx 1.4\tau_{fo}(0.2\ \mathrm{TeV})$$

- identified transverse momentum spectra: transverse expansion

$$\left\langle \beta_{fo} \right\rangle_{2.76\ \mathrm{TeV}} \approx 1.15\left\langle \beta_{fo} \right\rangle_{0.2\ \mathrm{TeV}}$$

Heavy flavour

- From "discovery phase" to detailed characterization of the QGP properties

- ***Hard probes*** (jets, heavy-quarks, quarkonia)
  → "resolve" medium constituents

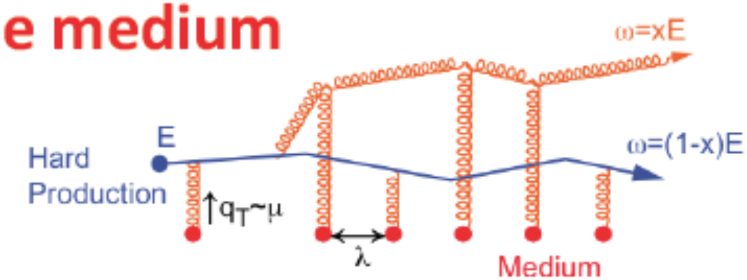
- **Microscopic description of the medium**

QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

at all p_T for charm and beauty (large masses >> Λ_{QCD})

⇨ **"Calibrated probes" of the medium**



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)

Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

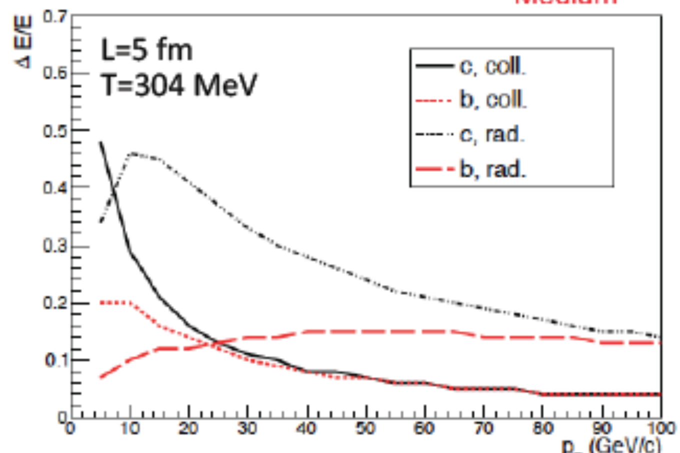


Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009),
Phys. Rev. C74 064907 (2006).

QGP tomography with heavy quarks

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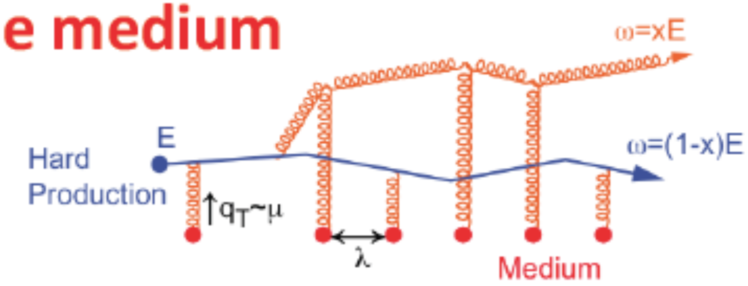

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$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

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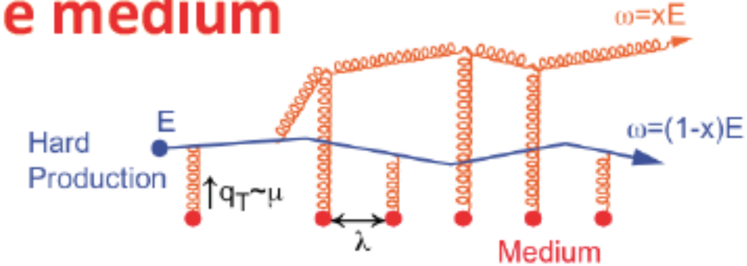

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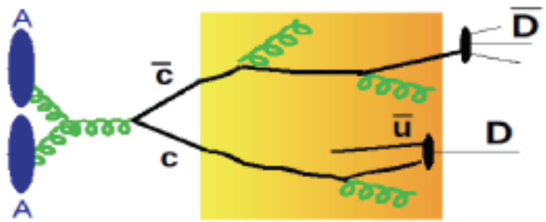
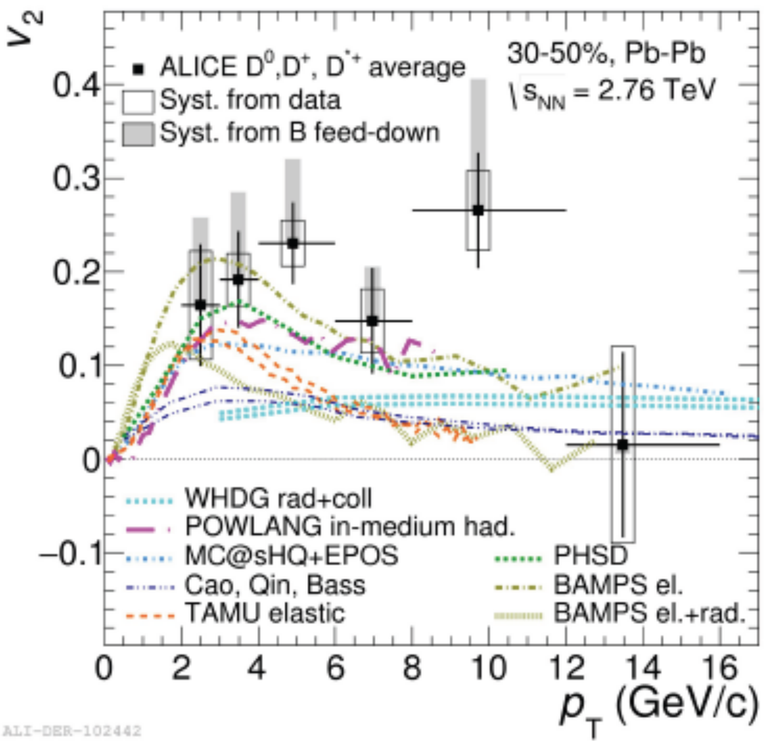


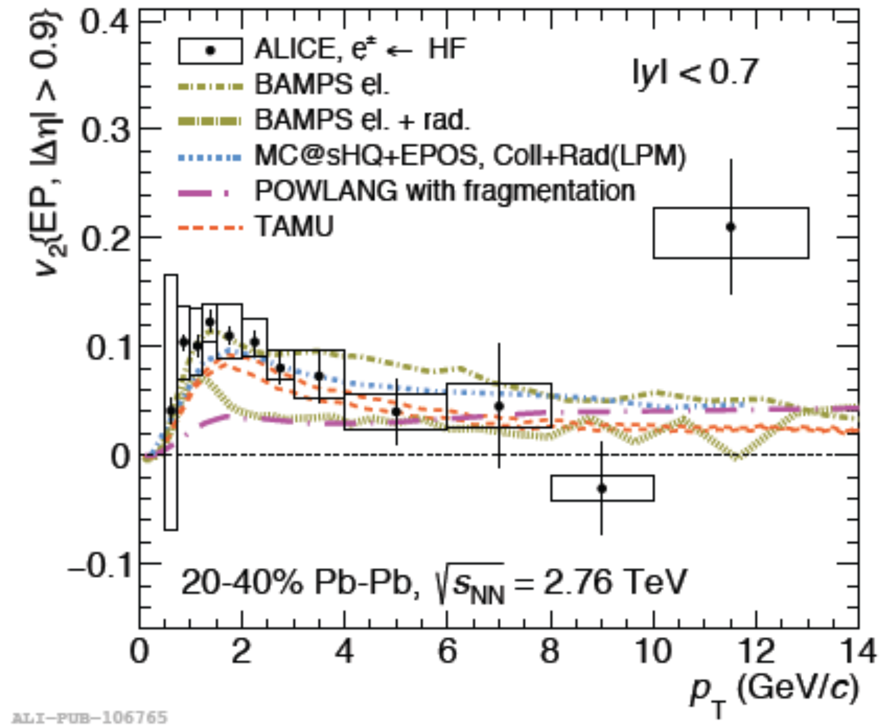
- medium **modification to HF hadron formation**
  - hadronization via quark coalescence

- participation in collective motion ➜ azimuthal anisotropy of produced particle

v_2: comparison with models

Model references in backup

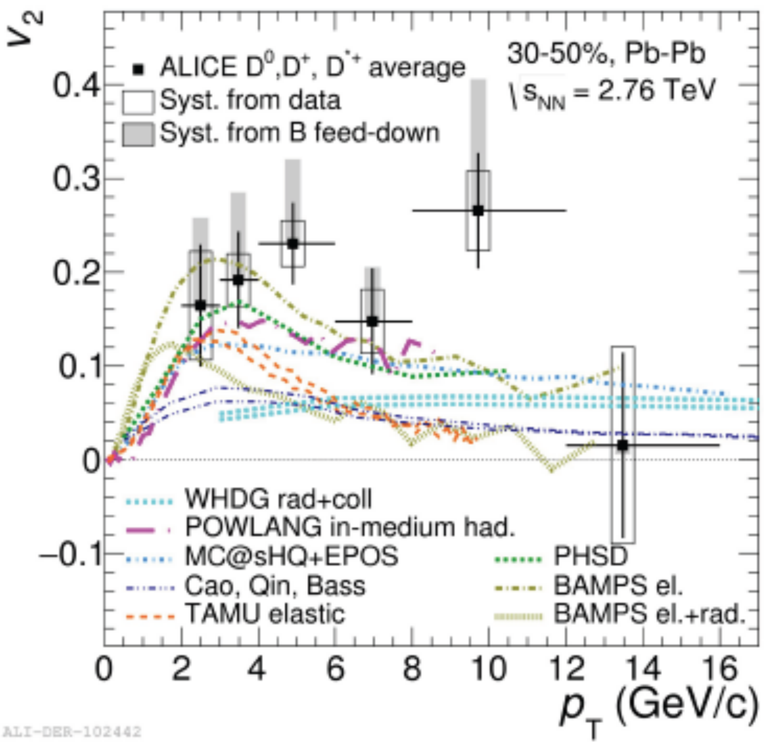


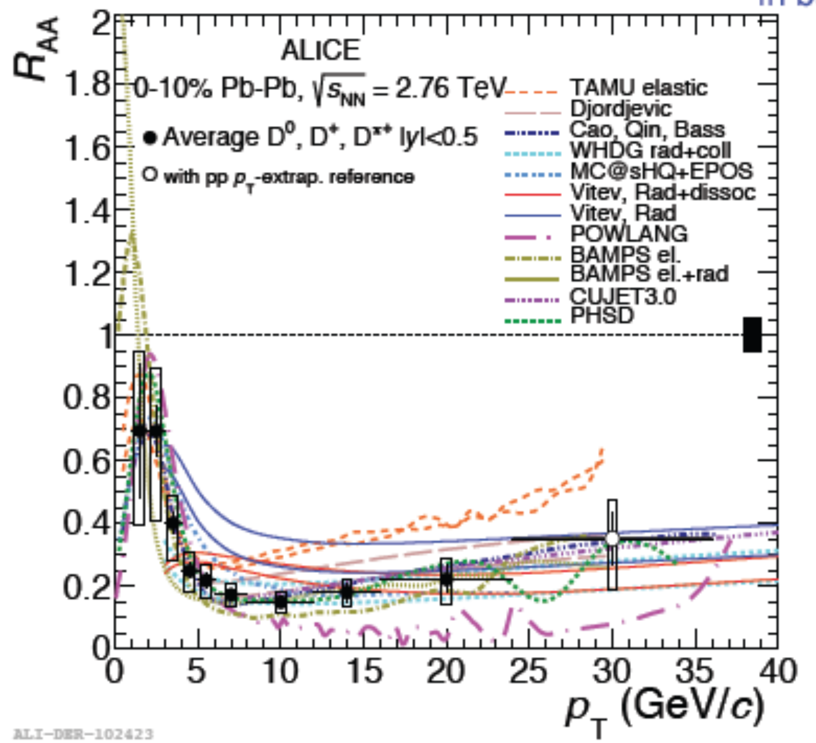


- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions

v_2 and R_{AA}: comparison with models

Model references in backup

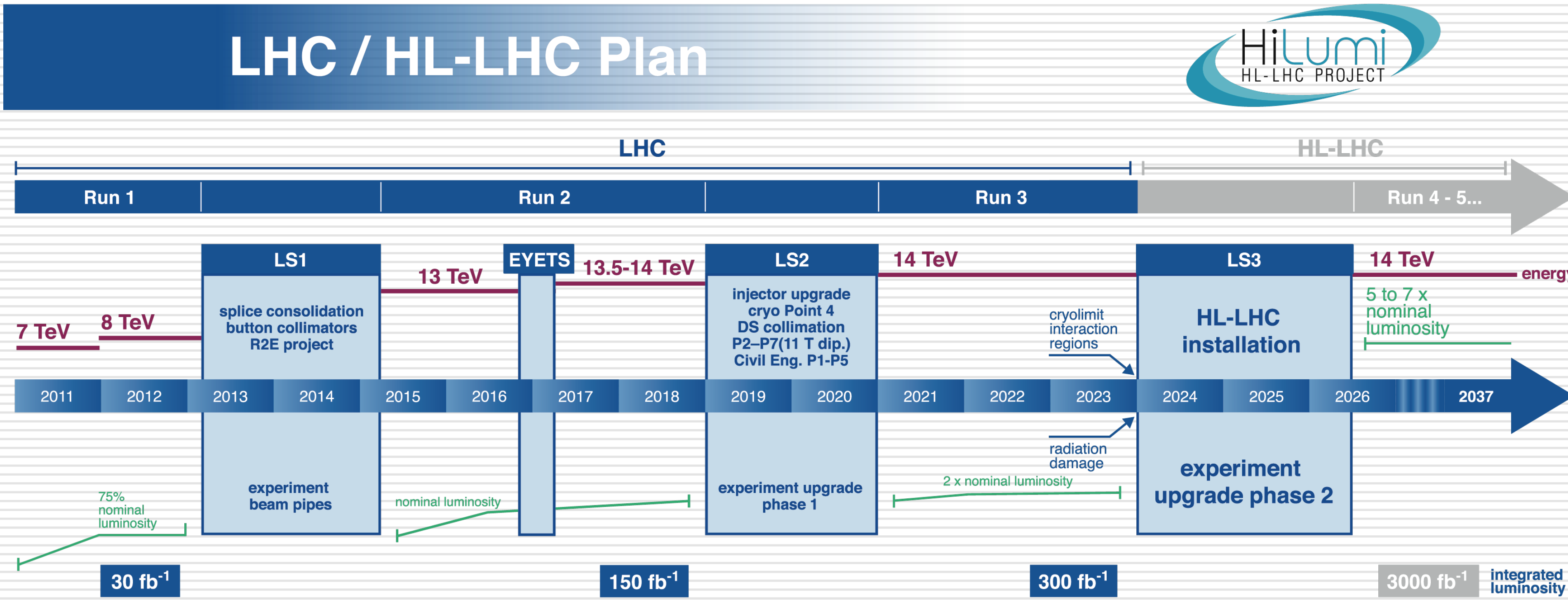




- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions
- v_2 and R_{AA} measurements over a wide p_T range can set stringent constraints to model

ALICE Upgrade

LHC / HL-LHC Plan

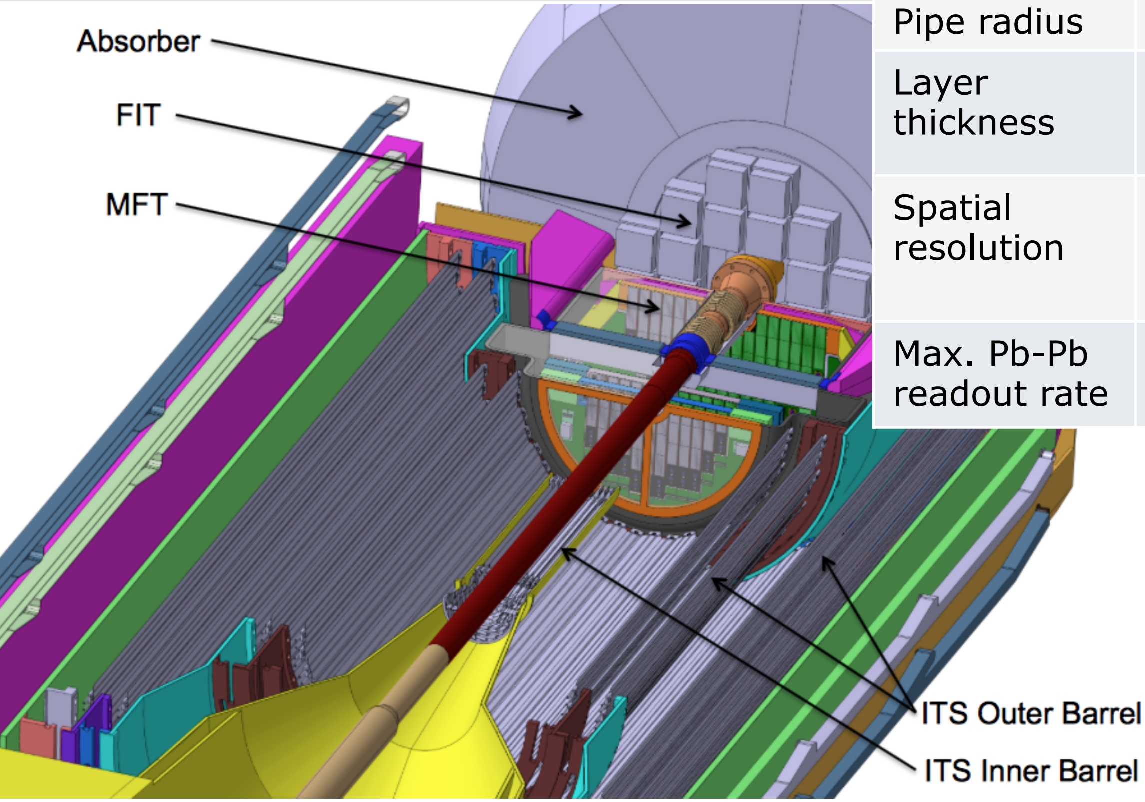


- Main upgrades relevant for the Heavy-Ion physics (LS2:2019-2020)
  - LHC collimator upgrades: target L ≈ $6x10^{27}$ cm^{-2} s^{-1} for Pb-Pb
  - Major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS

New all-pixel trackers: ITS and MFT

- Both trackers fully based on Monolithic Active Pixel Sensors (MAPS)

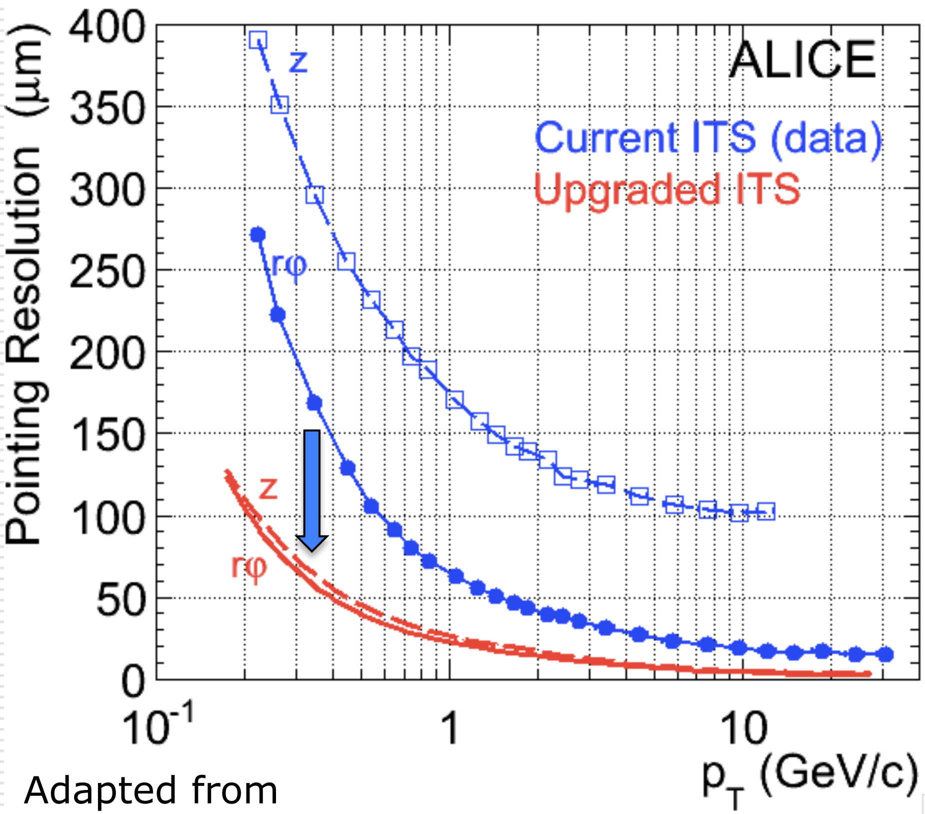
	Pres. ITS	New ITS	MFT
Acceptance	|η|<0.9	|η|<1.5	-3.6<η<-2.3
N Layers	6	7	5
Inner radius	3.9 cm	2.3 cm	/
Pipe radius	2.94 cm	1.86 cm	/
Layer thickness	~1.1%X_0	0.3-0.8% X_0	0.6%X_0
Spatial resolution	12x100 μm^2 35x20 μm^2 20x830 μm^2	~5x5 μm^2	~5x5 μm^2
Max. Pb-Pb readout rate	1 kHz	100 kHz	100kHz



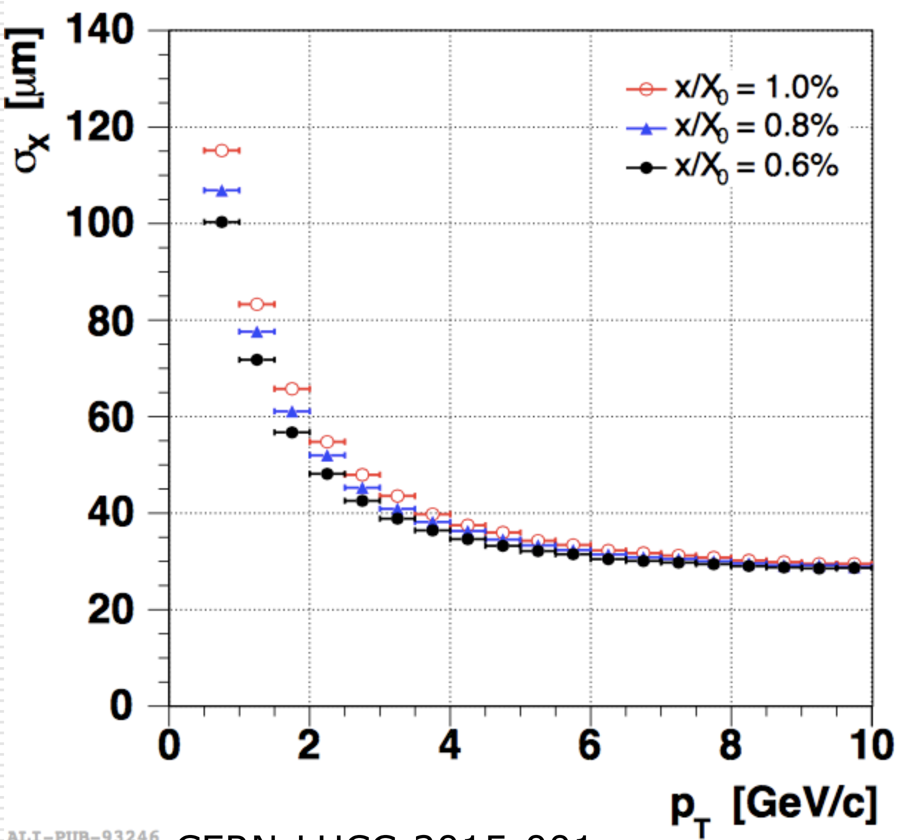
ITS: CERN-LHCC-2013-024
MFT: CERN-LHCC-2015-001

Tracking precision

- ITS: pointing resolution x3 better in transverse plane (x6 along beam)
- MFT: pointing resolution better than 100 μm for *p*T > 1 GeV/*c*



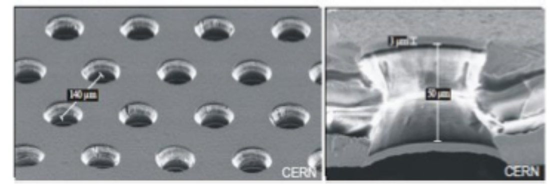
Adapted from CERN-LHCC-2013-024



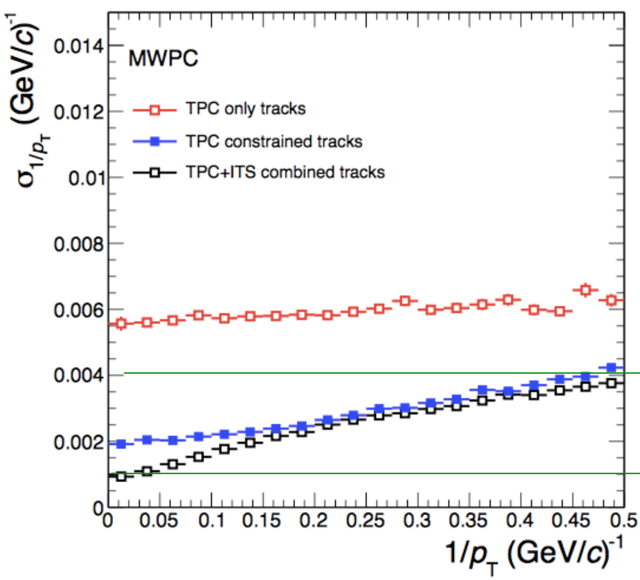
CERN-LHCC-2015-001

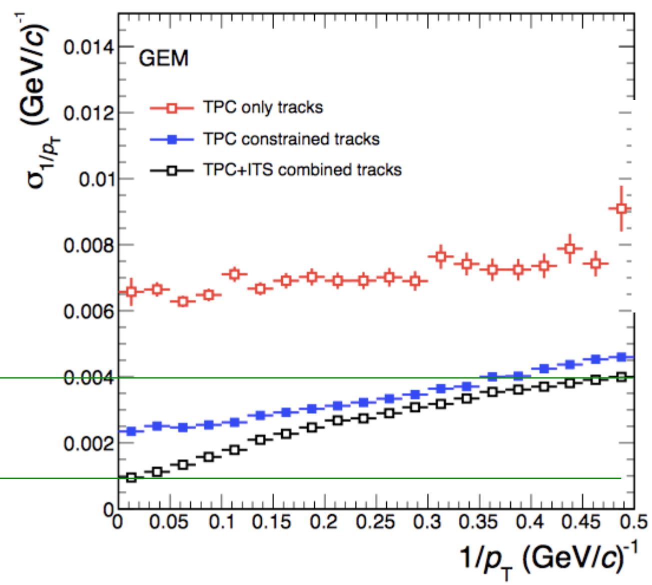
TPC with GEM readout chambers

- Current MWPC: readout limited by ion backflow
- New readout chambers (GEM): readout up to 50 kHz
  - preserve momentum resolution for TPC + ITS tracks
  - preserve particle identification via dE/dx

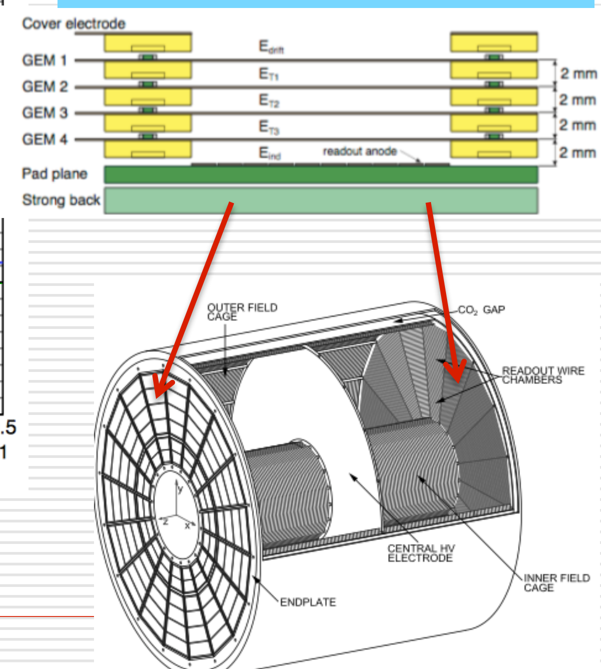


Electron microscope photograph of a GEM foil



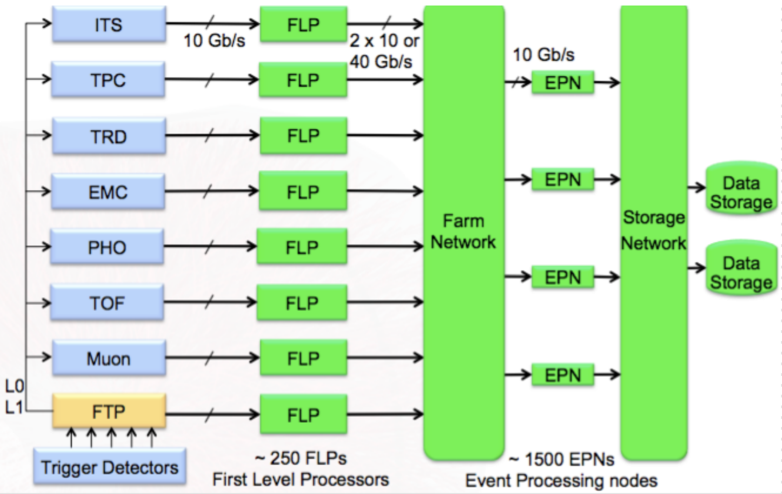


Stack of 4-GEM-foils



Online-Offline (O^2) System

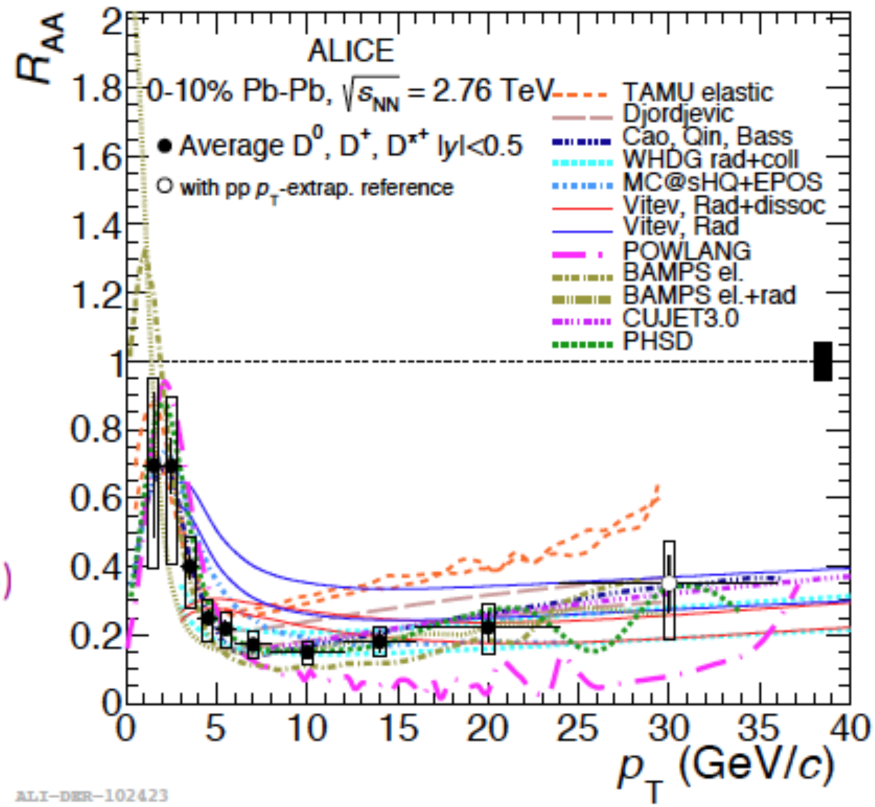
- Pb-Pb at 50 kHz → 1.1 TB/s of data (90% from the TPC)
- The O^2 will integrate in a single infrastructure the present DAQ, HLT and Offline (reconstruction) systems
- A large computing farm close to the detector will process the data online, calibrate the TPC, and reject detector noise
- The overall reduction factor is ~13 → ~85 GB/s to tape
  - Projection based on experience with present HLT system



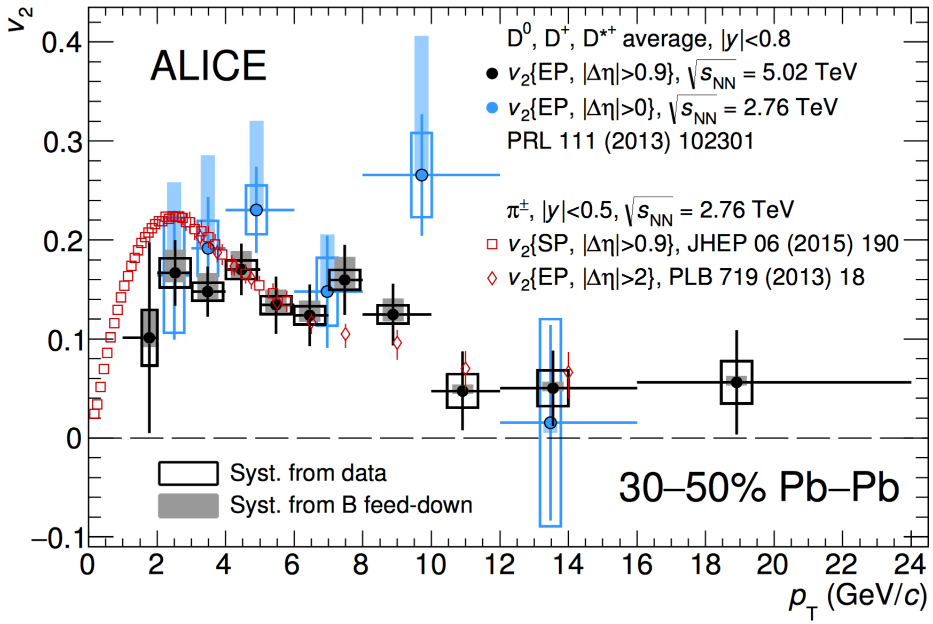
Detector	Data rate for Pb-Pb @ 50 kHz (GB/s)	Compressed data rate (GB/s)	Data reduction
TPC	1012	50	20.2
ITS	40	26 (8)	1.5 (5)
TRD	20	3	6.7
MFT	10	5	2
Total	**1082**	**84 (66)**	**12.9 (16.4)**

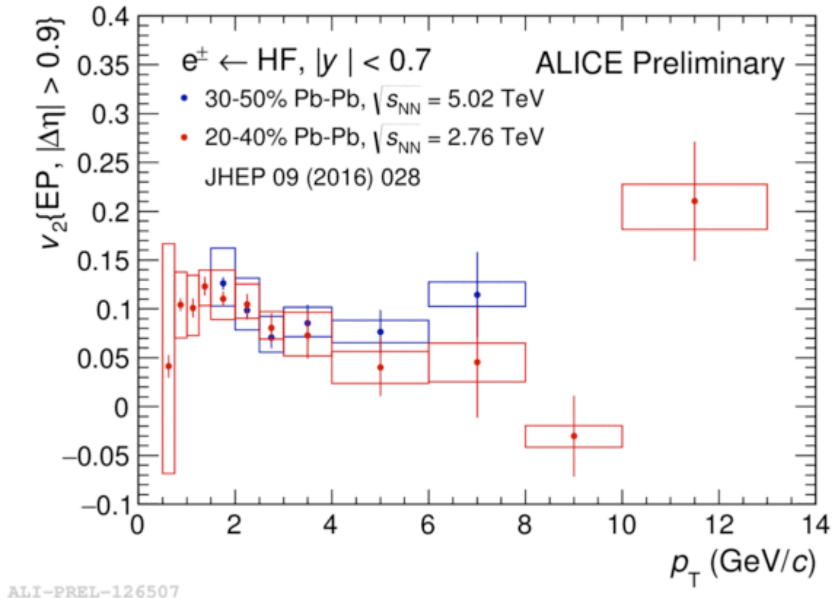
Model references

- POWLANG: EPJ C 75 (2015) 121;
- TAMU: arXiv:1401.3817;
- MC@HQ+EPOS: PRC 89 (2014) 014905;
- WHDG: Nucl. Phys. A 872 (2011) 256;
- BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];
- Cao,Quin, Bass: PRC 88 (2013);
- Vitev:: PRC 80 (2009) 054902;
- Djordjevic: PRL 737 (2014) 298
- CUJET 3.0: Chin. Phys. Lett. 32 no. 9, (2015) arXiv:1411.3673 [hep-ph].
- PHSD: arXiv:1512.00891

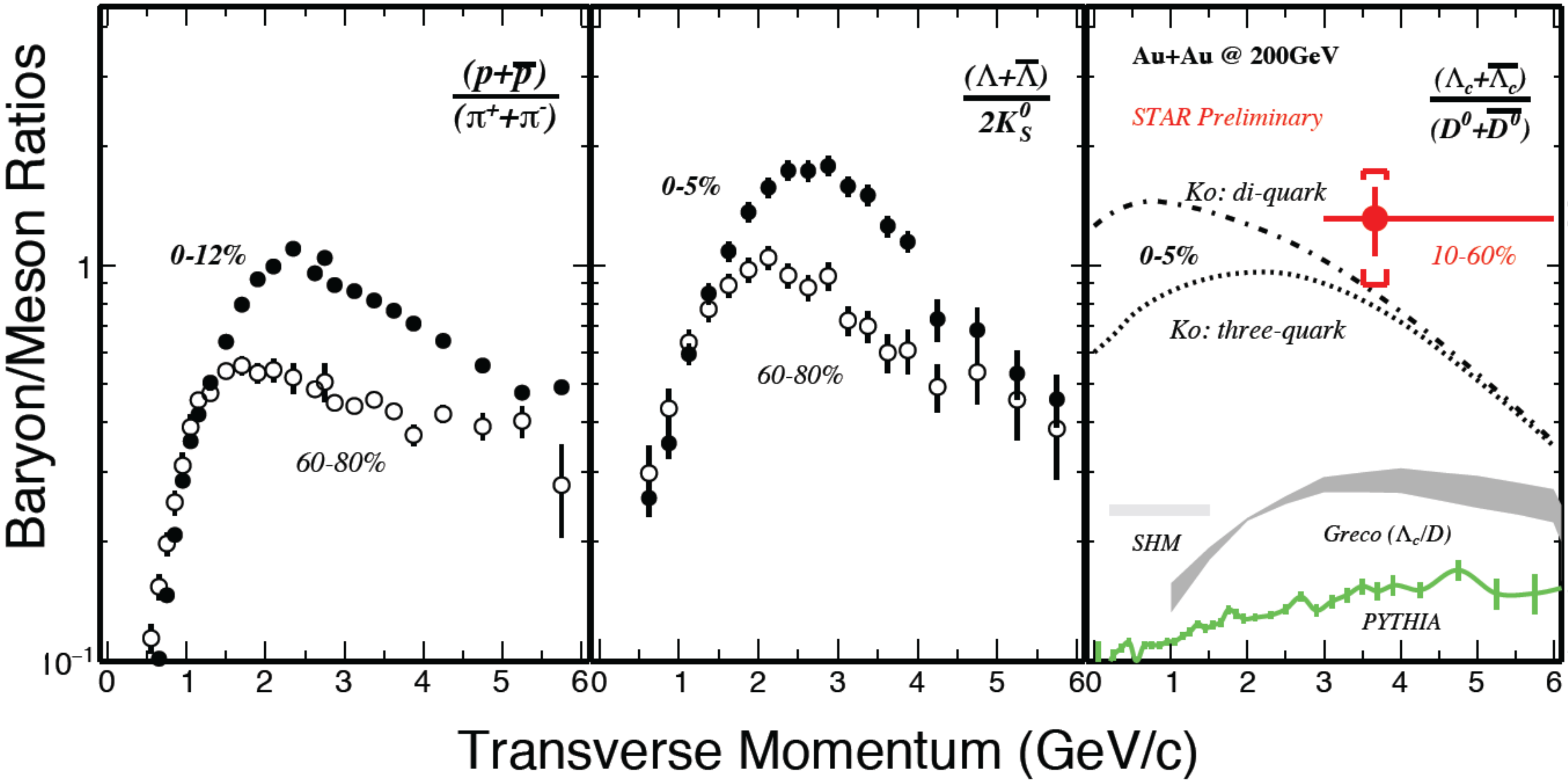


Evidence of charm flowing with the medium at LHC





Baryon to Meson Ratio



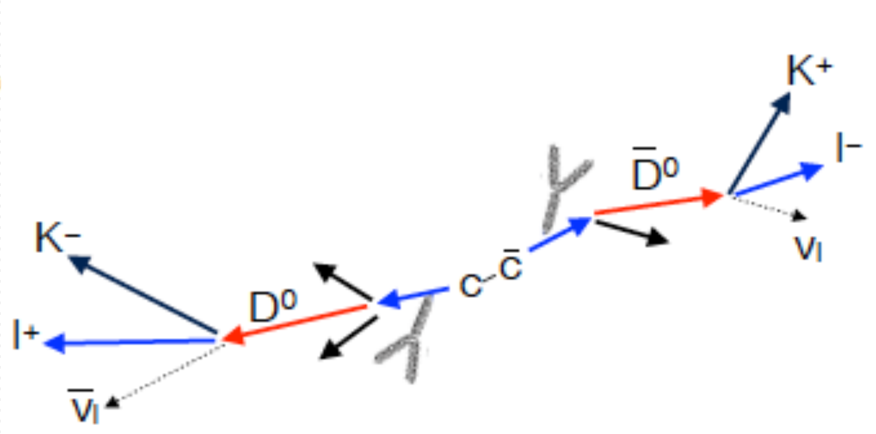
Refs:
[1] S. Ghosh et al., *PRD* 90 054018 (2014).
[2] Y. Oh et al., *PRC* 79 044905 (2009).
[3] S. Lee et al., *PRL* 100 22301 (2008).

- Enhancement of Λ_c/D^0 ratio compared to PYTHIA prediction
- The Λ_c/D^0 ratio is similar to that of light-flavor hadrons
- Coalescence model with thermalized charm quarks consistent with our data

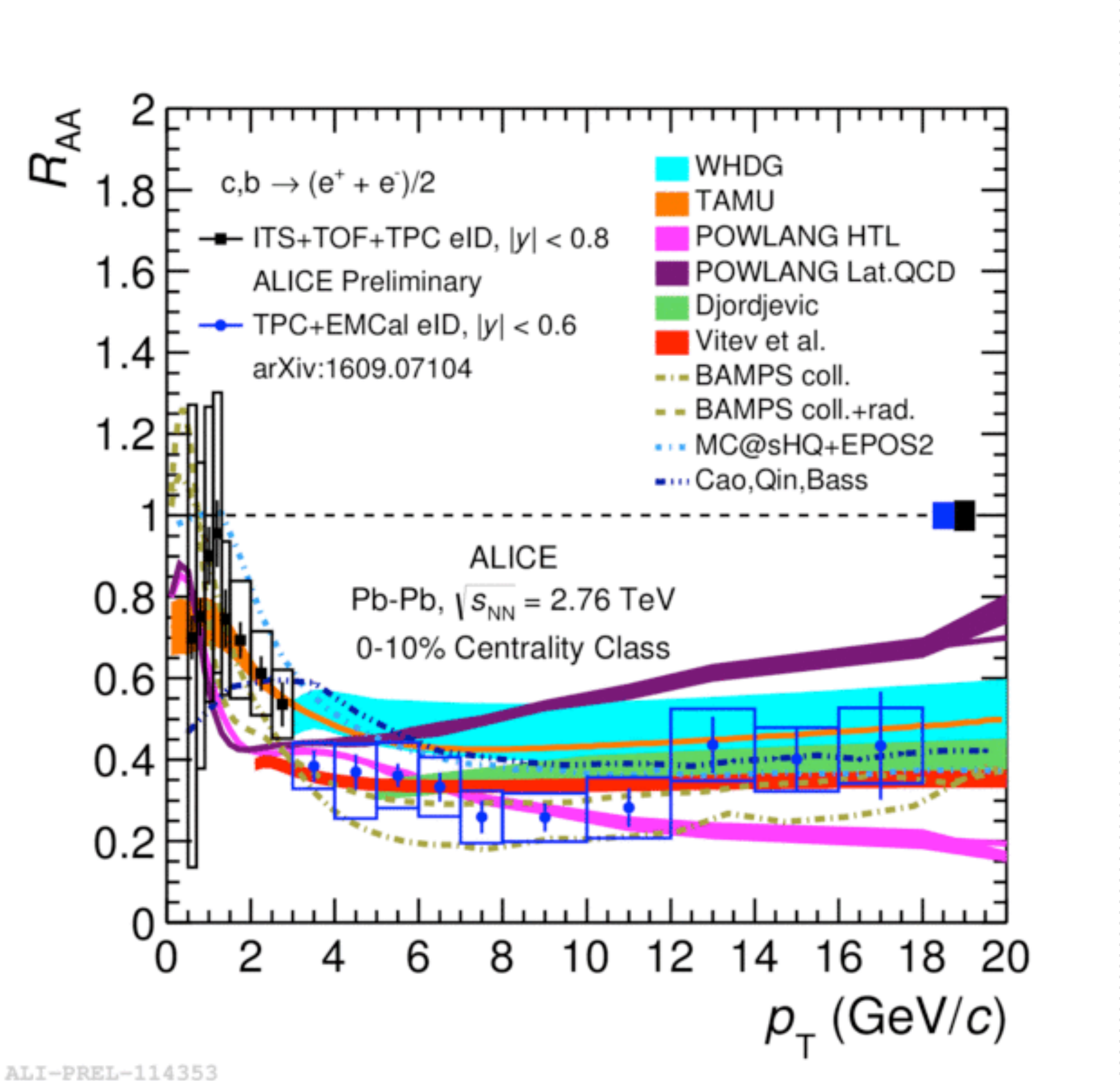
Outlook: In run 2016, collected 2 billion Au+Au events. We will study R_{cp} for the ratio of Λ_c/D^0.

cc and bb with dileptons

- dd



e^{HF} : model comparison



Azimuthal Anisotropy

- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) → coefficients $v_2, v_3, v_4, \ldots, v_n$
- Elliptic flow (v2): spatial anisotropy — pressure gradients leads to momentum anisotropy — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

$$\frac{dN}{d(\varphi - \psi_{RP})} \propto 1 + 2\sum_{n=1} v_n \cos\left(n[\varphi - \psi_{RP}]\right)$$

$$v_n = \langle \cos n(\varphi - \psi_{RP}) \rangle$$