XXXIV International School "Francesco Romano"
on Nuclear, Subnuclear and Astroparticle Physics

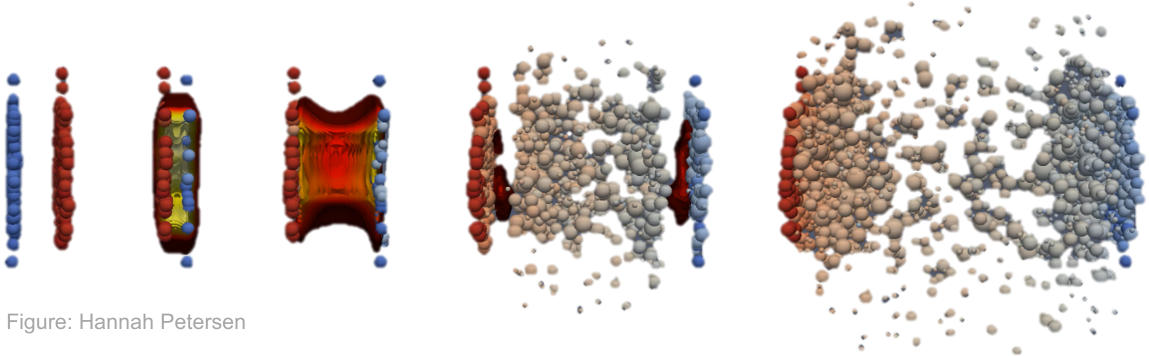


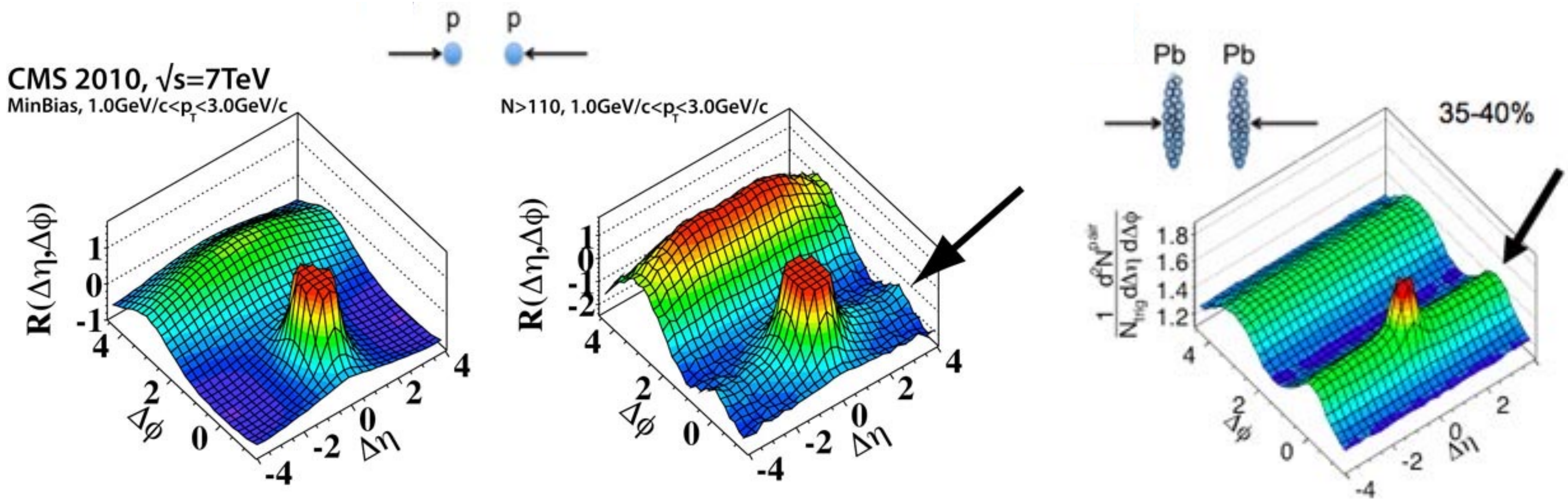
Figure: Hannah Petersen

Introduction to Ultrarelativistic Nuclear Collisions (3)

Federico Antinori
(INFN, Padova, Italy)

Small systems: a new frontier

- long-range ridge on near side in high-multiplicity pp collisions at the LHC!
- very similar structure as in Pb-Pb collisions
  - where it is connected with v_2



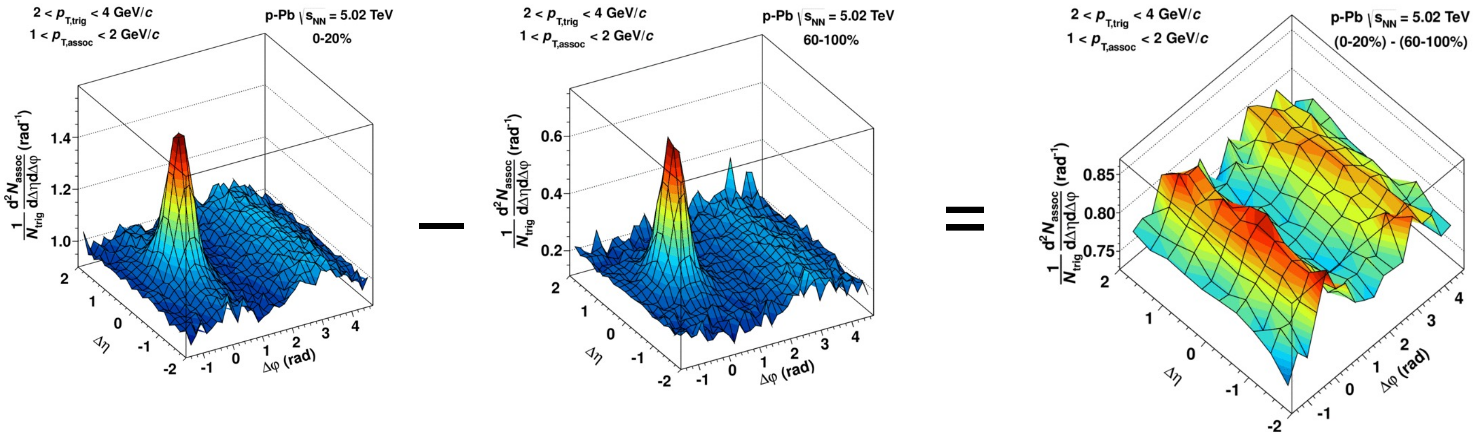
CMS: JHEP 1009:091,2010

Near- and away-side ridge in p-Pb

- evidence for collective behaviour in high-multiplicity p-Pb,
  - e.g. symmetric double-ridge when subtracting low from high mult’y p-Pb

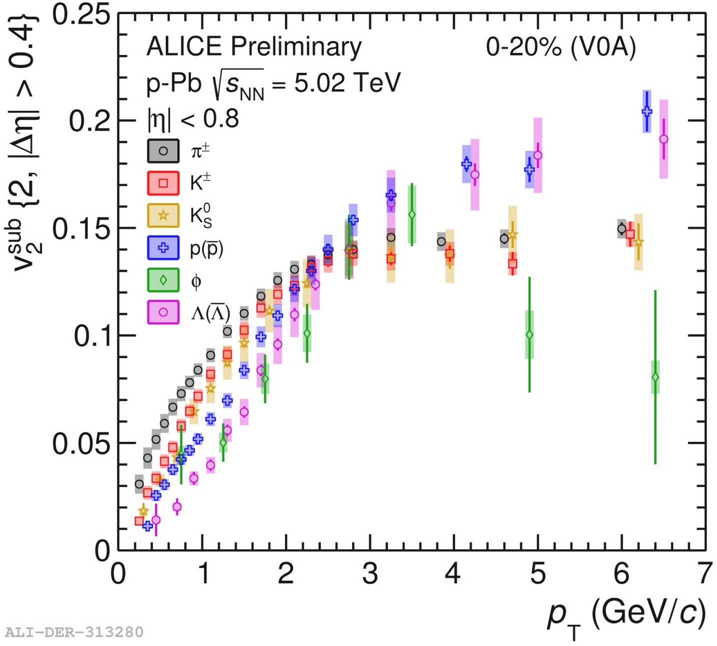
0-20%

60-100%

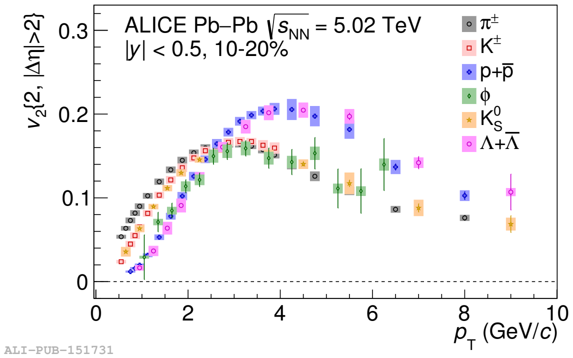


ALICE: Phys Lett B 719 (2013) 29

v2 for identified particles in p-Pb



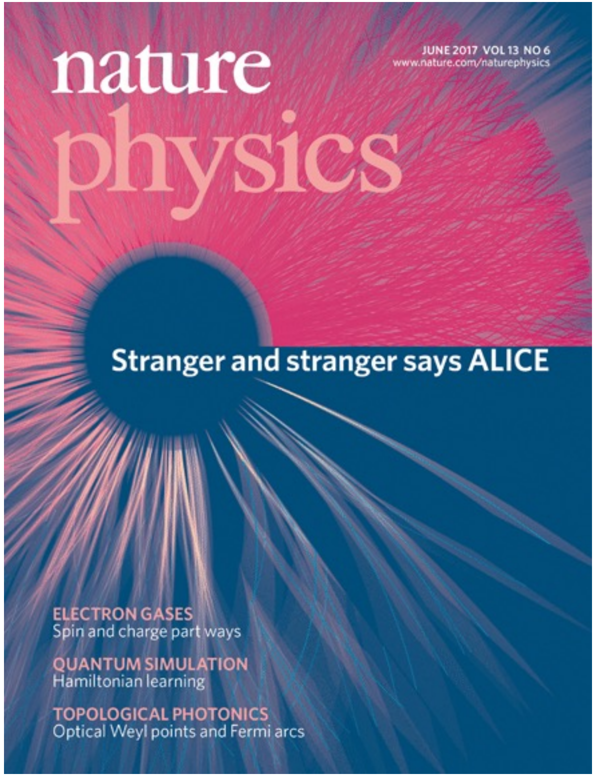
- clear mass ordering at high multiplicity
  - same as in Pb-Pb



- consistent with common velocity field

→ consistent with hydrodynamic expansion!

Strangeness enhancement in pp!



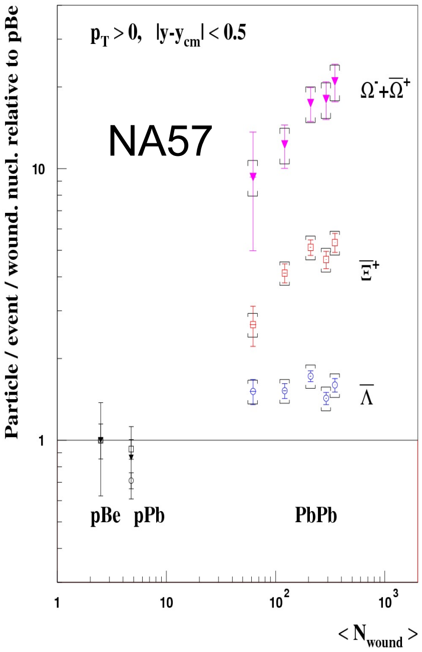
Nature Physics (2017) doi:10.1038/nphys4111

- one of the hallmarks of QGP
- predicted in 1982
  J Rafelski & B Müller, PRL 48 (1982) 1066

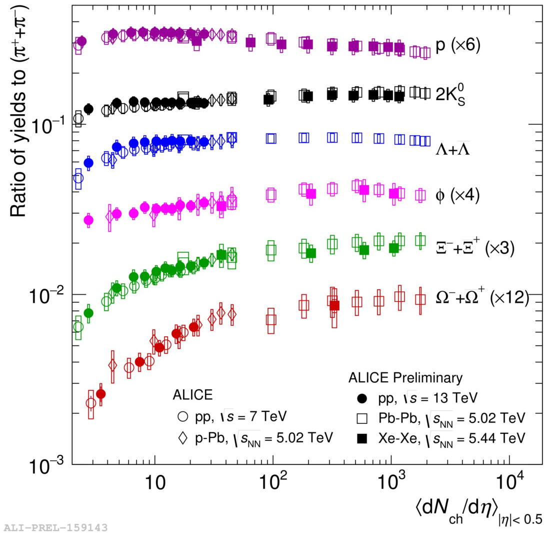
→ observed at SPS in the 90's
  WA97, NA57, NA49

- now observed in high-mult pp!
  - not reproduced by models
- a precursor phenomenon?
- QGP in high-mult pp???

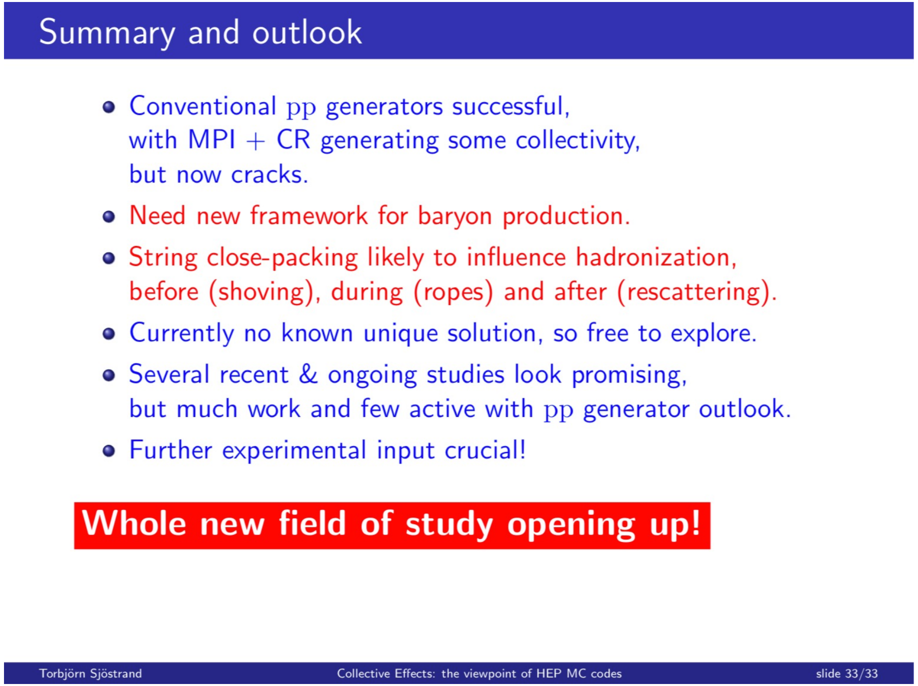
→ new directions for research!
  - study effects turn-on, evolution
  - new weapon: pp generators!



Hadron chemistry vs system size



- strangeness enhancement vs size
  - smooth evolution vs event multiplicity
- challenge for pp event generators
  - e.g.: T Sjostrand at Quark Matter 2018

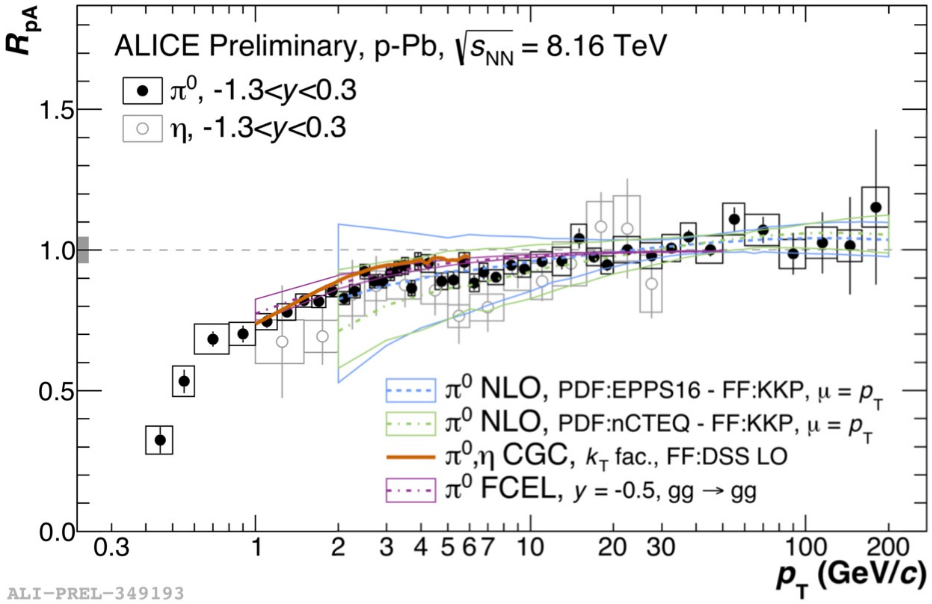


→ new avenue to microscopic understanding of buildup of collectivity!

→ could help resolve muon puzzle in cosmic rays?

T Pierog et al, UHECR 2018, EPJ Web Conf
S Baur et al, arXiv:1902.09265
T Pierog, ESPP Symposium, Granada
T Pierog, ICRC 2019, Madison

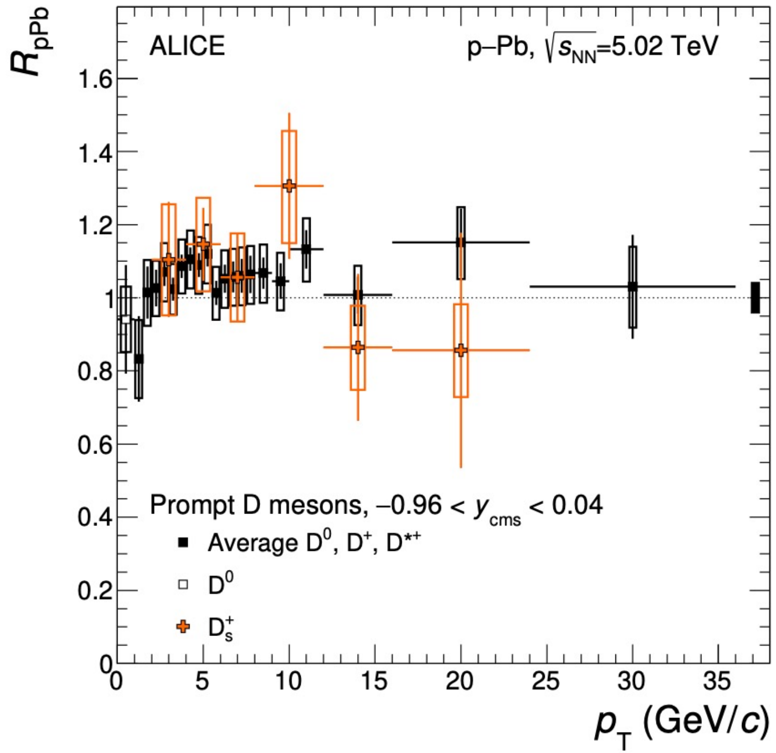
But no sign of quenching yet!

- 

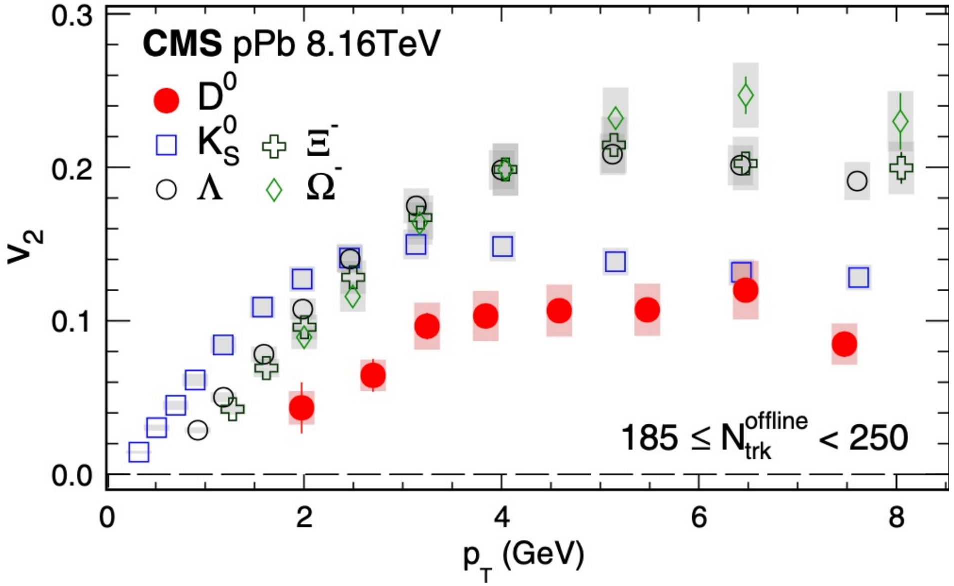
[ALICE: PLB 827 (2022) 136943]

How about heavy flavour in small systems?

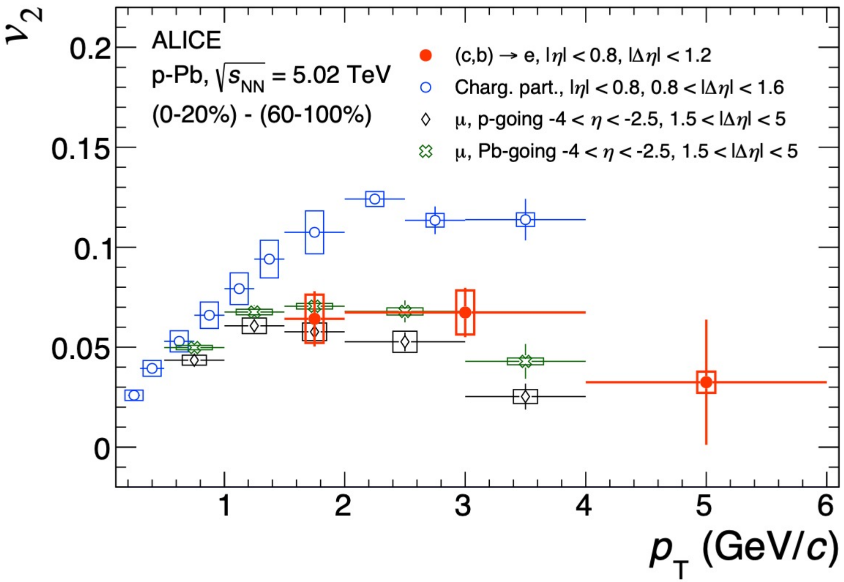
- no sign of quenching for charm (like for everything else...)



...but flow seems to be there...!



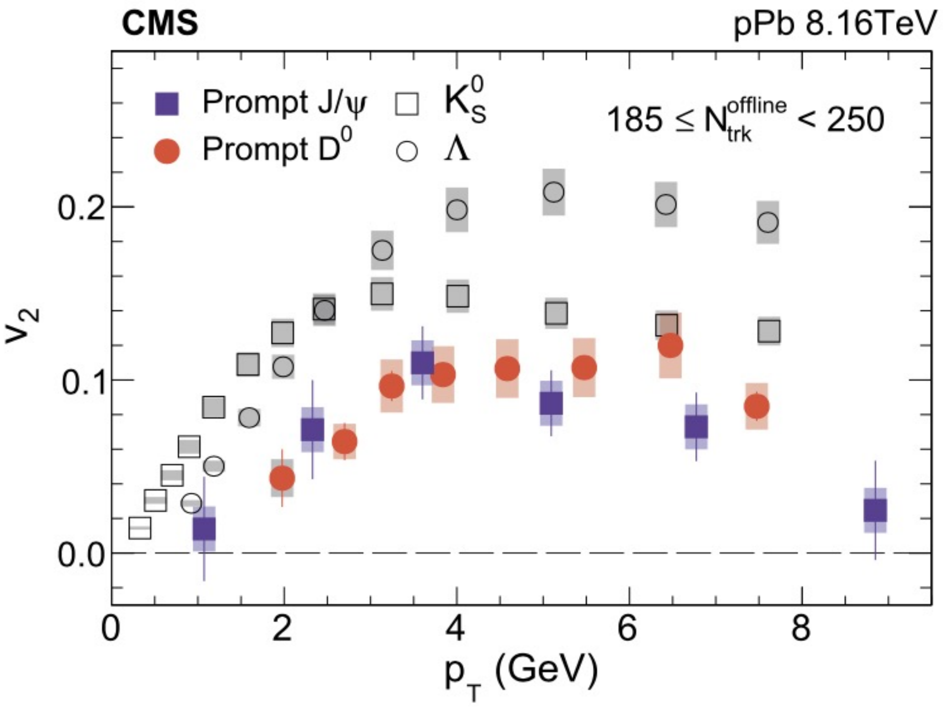
CMS: PRL 121 (2018) 082301



ALICE: PRL 122 (2019) 072301

- ... what's this??? (isn't charm produced isotropically in initial parton-parton scattering?)
  - a sign of azimuthally-dependent energy loss??? 🤔...
- could it just be the light quarks...?

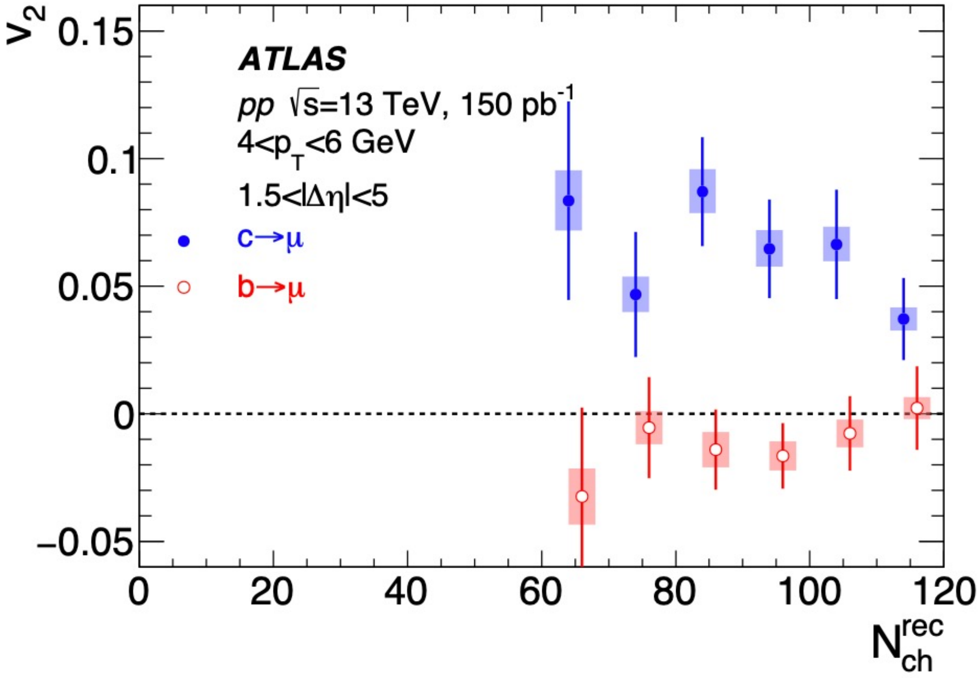
... also for prompt J/ψ...



CMS: PLB 791 (2019) 172

- ... no, it's not just the light quarks...
  - it seems to be the c themselves...
- consistent with R_{pPb} measurements?
- these are supposed to be mostly pair-produced $c\bar{c}$, propagating together... right? 🤔...
- if v_2 is due to energy loss, does its amount carry information about octet v singlet?

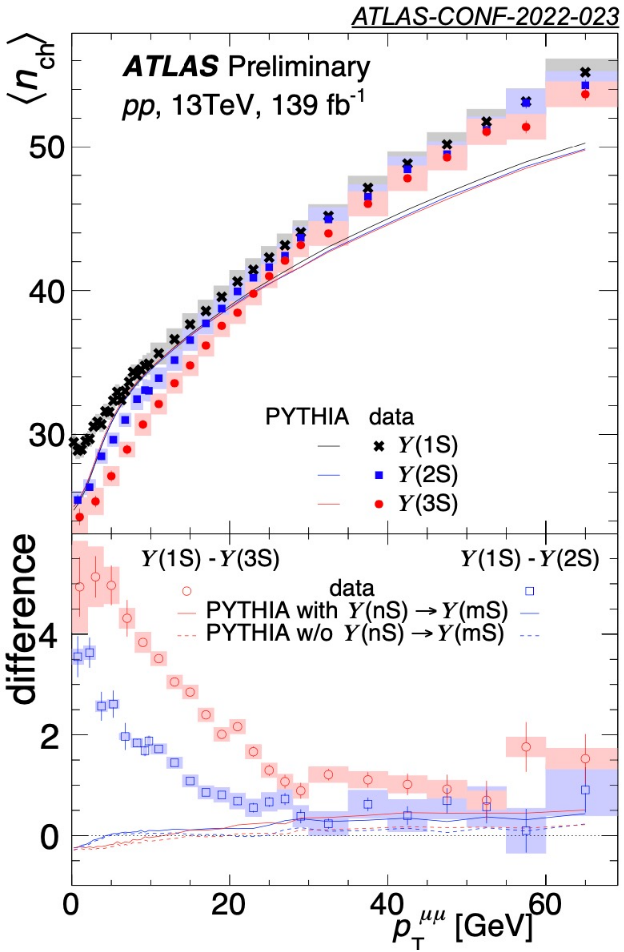
... but not for beauty...



ATLAS: PRL 124 (2020) 082301

- another one of those beauty things...

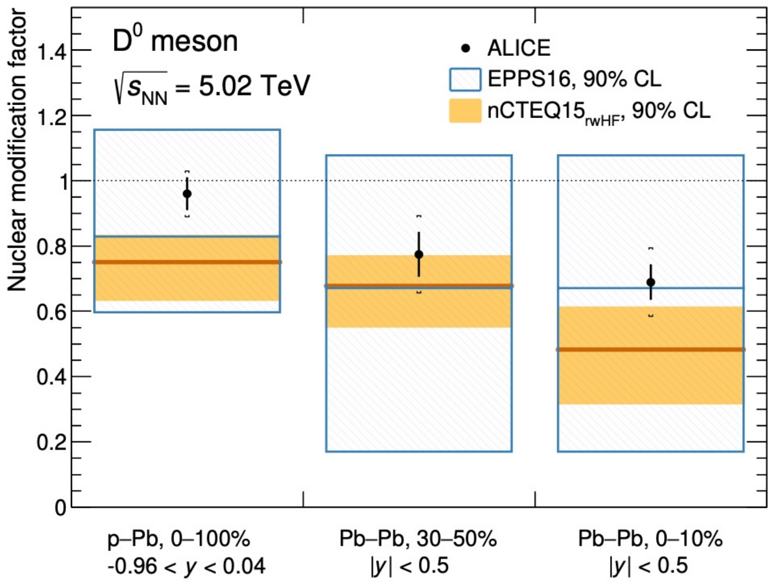
... a sign of life...?



- ATLAS @ QM 2022
- multiplicity of underlying event for ϒ events
- a hierarchy at low p_T...
- ... or just an MPI bias not reproduced in PYTHIA?

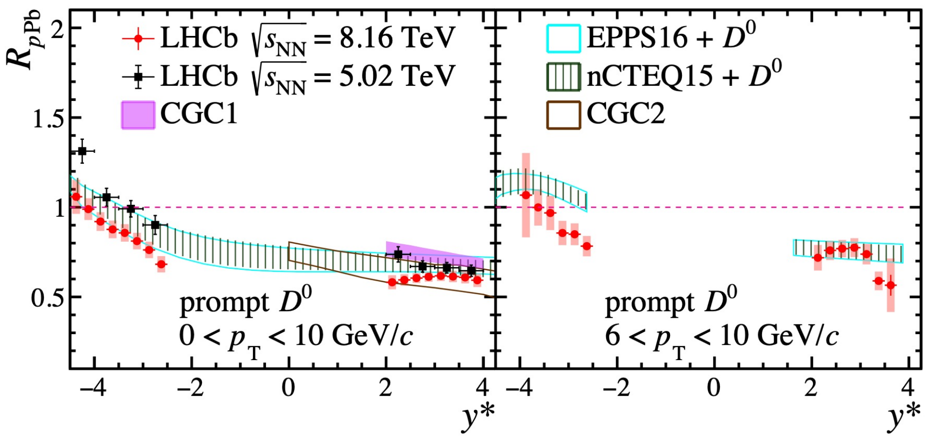
By the way: nPDFs seem to be doing not too bad...

p_T-integrated D^0 R_{pPb} R_{PbPb}



ALICE: JHEP01 (2022) 174

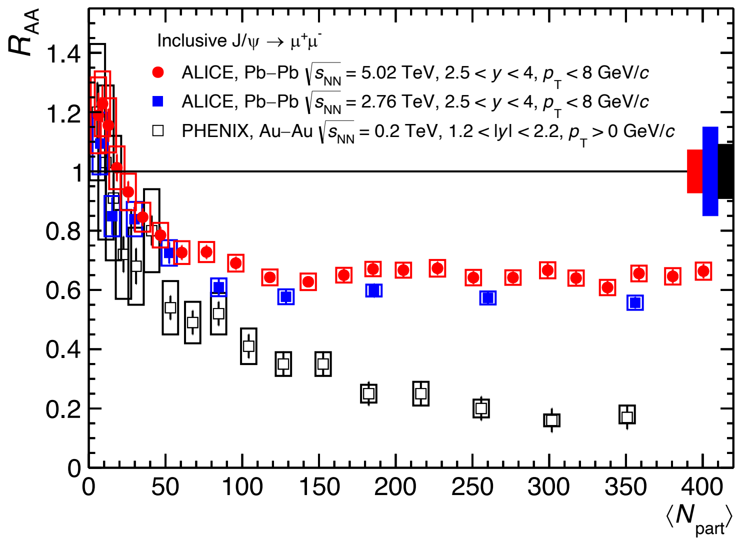
D^0 R_{pPb} vs y



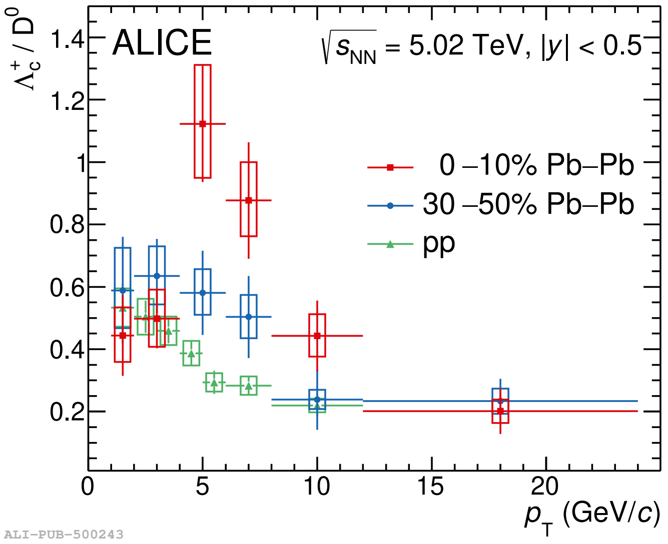
LHCb: arXiv:2205.03936

In-medium hadronisation, a rich sector!

charmonium



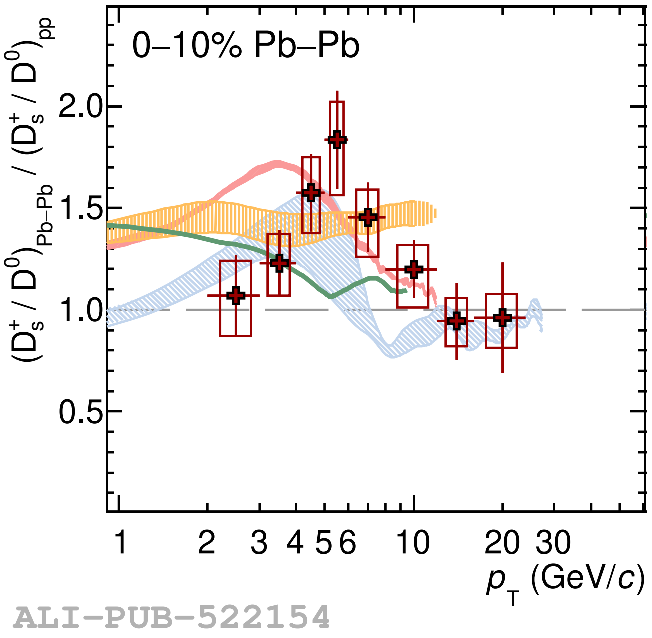
HF baryons



ALICE: arXiv:2112.08156

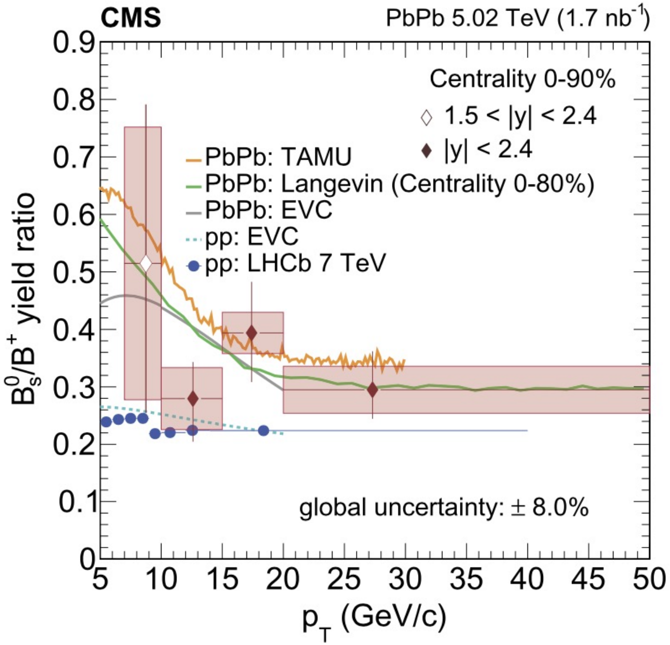
Strangeness enhancement in Pb-Pb!

D_s



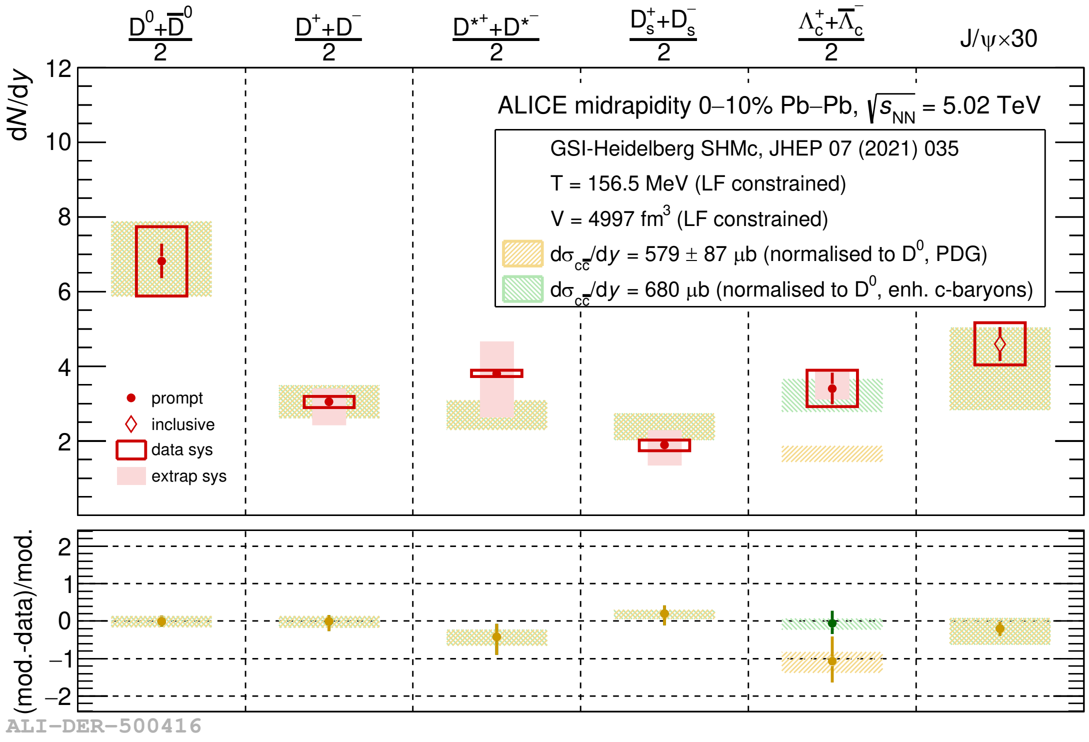
ALICE: PLB 827 (2022) 136986

B_s?

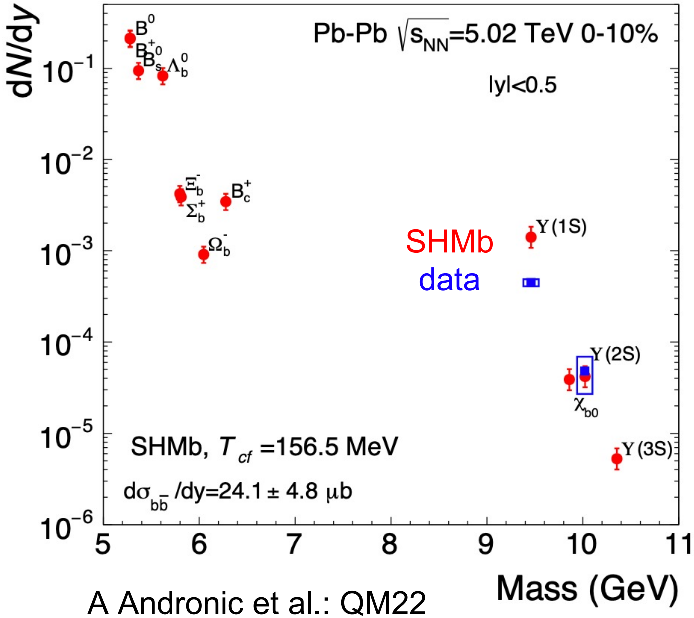


CMS: PLB 829 (2022) 137062

Chemical equilibrium for HF hadrons?



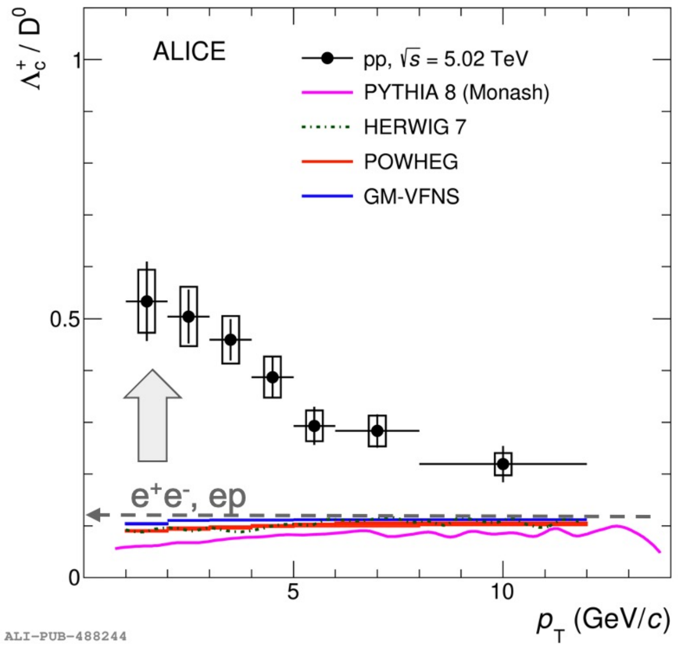
- for charm, looks like...
  - not for absolute σ, of course...
  - γ_c ~ 30 for 0-10%
- and, once again, b is different...
  - SHMb ~ 3 x data for Υ(1S)



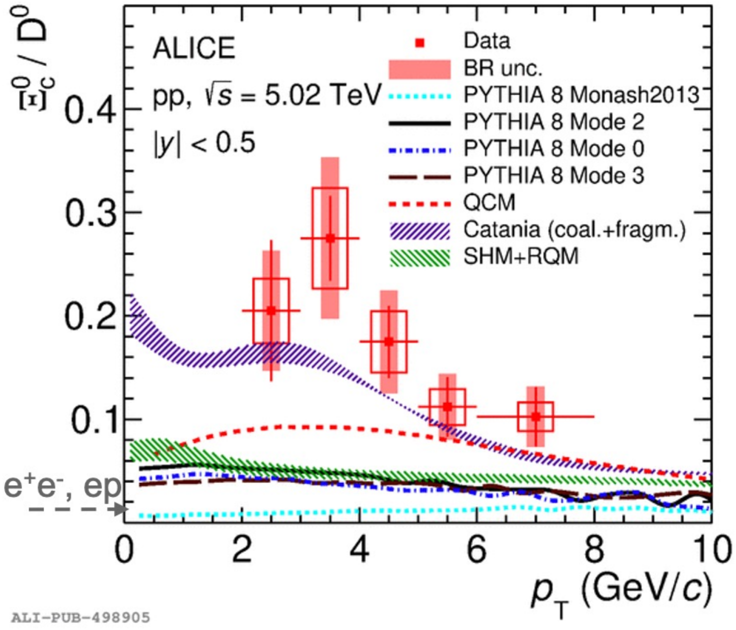
A Andronic et al.: QM22

Already in pp, p-Pb...

- HF baryon/meson enhanced wrt e^+e^- (especially at low p_T)

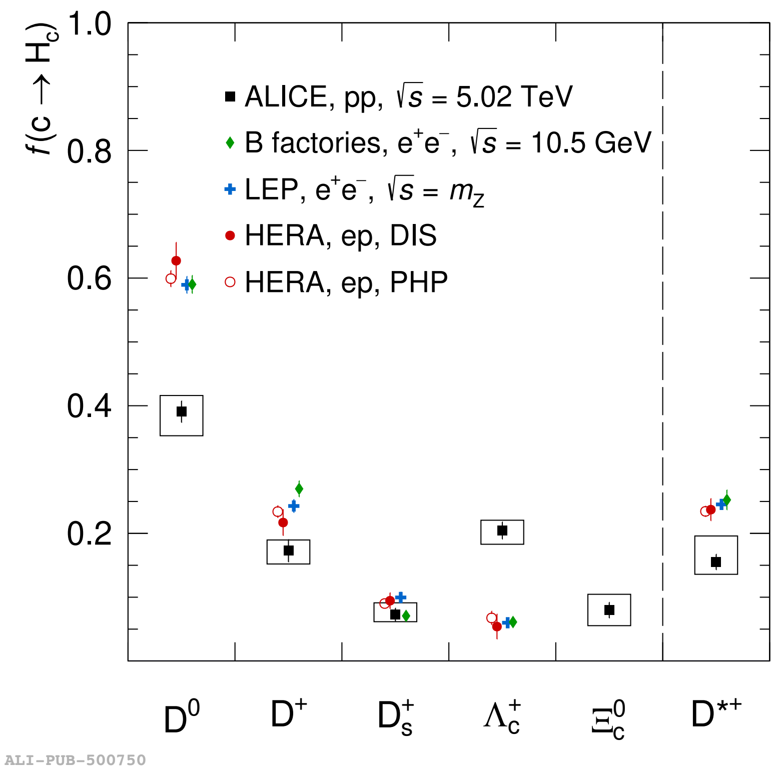


ALICE: PRL 127 (2021) 202301



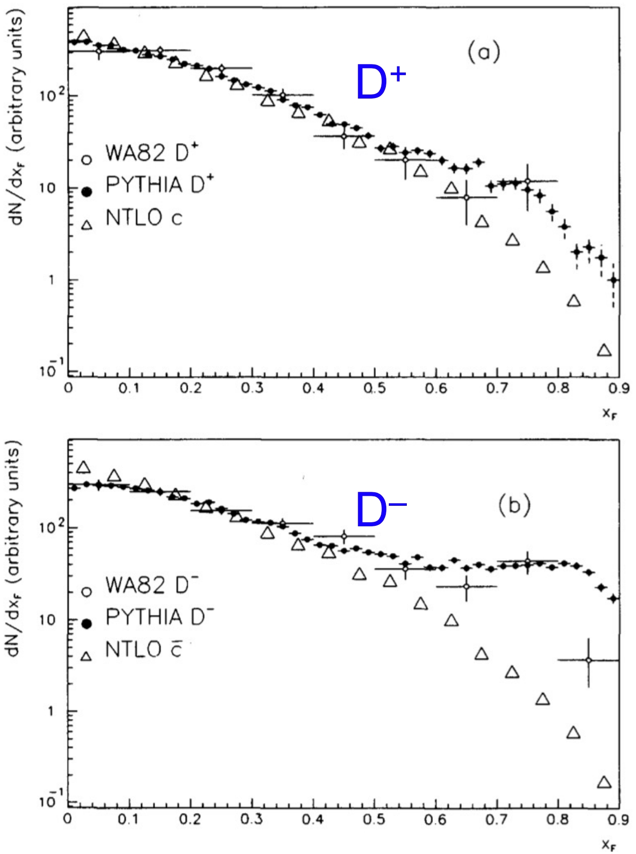
ALICE: JHEP 10 (2021) 159

Fragmentation Fractions: pp ≠ e^+e^-



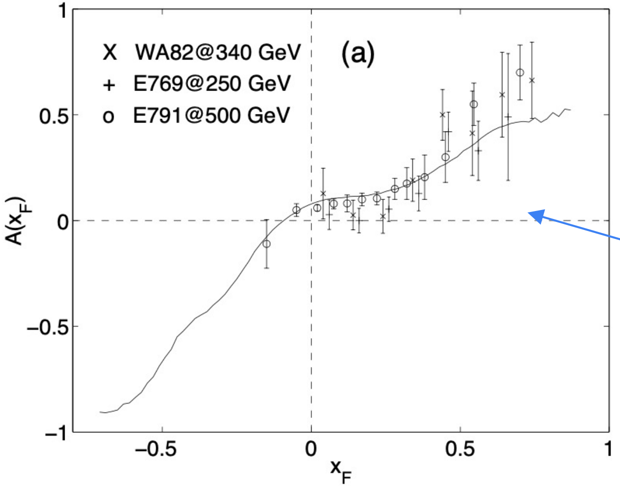
- fragmentation factorisation is violated
  - already in pp
- hadronisation in hadronic environments is a different game than in e^+e^-

But already at the SPS... (my thesis 🙂!)



WA82: PLB 305 (1993) 402

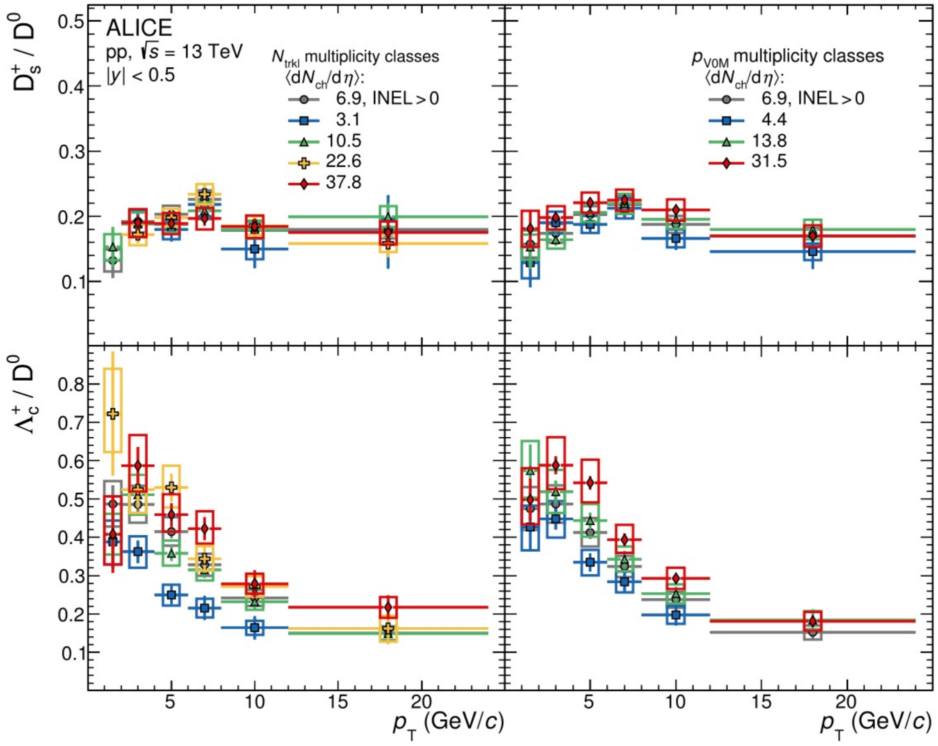
- WA82 (OMEGA): π^{-}A collisions
  - charm production in forward hemisphere
- beam valence: $d\bar{u}$ (π^{-})
- excess of D⁻ $(\bar{c}d)$ over D⁺ $(c\bar{d})$
  - D⁻/D⁺ = 1.34 $\pm$ 0.13
- particularly pronounced close to beam x_F
- (try and do this with Peterson's fragmentation...)
- modified PYTHIA tune:



E Norrbin and T Sjöstrand: PLB 442 (1998) 407

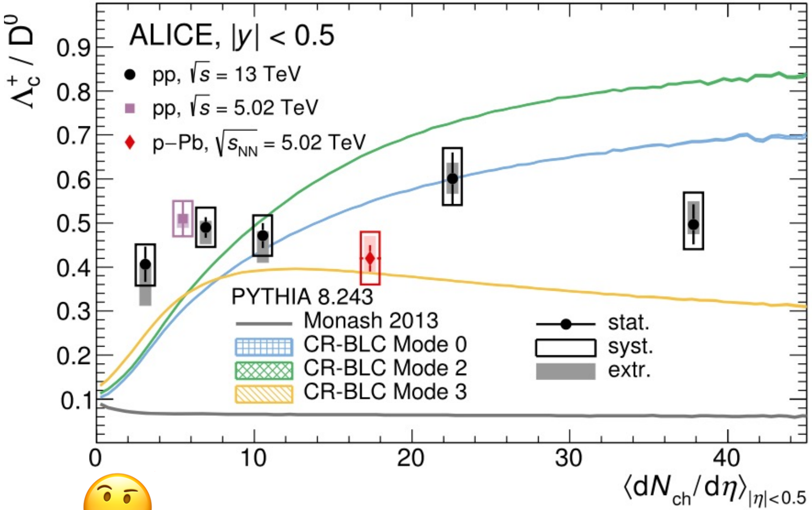
(asymmetry vs x_F)

Multiplicity evolution?



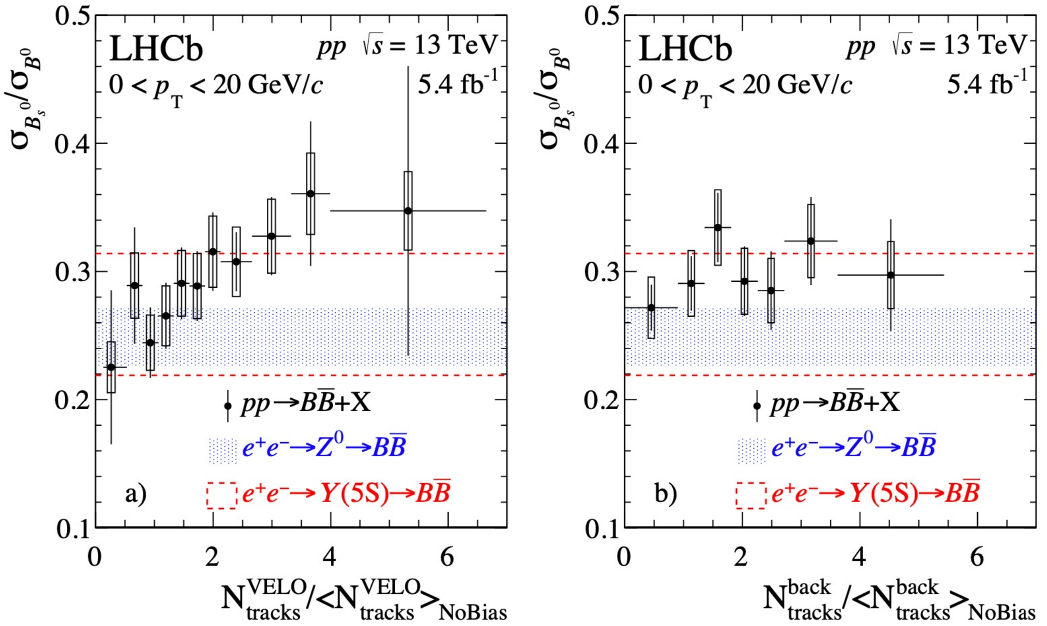
ALICE: PLB 829 (2022) 137065

- clear evolution for Λ_c/D
  - (not so much for D_s/D...)
  - (wrt neither to cent nor to fwd mult'y)
- and not much for the integrated yields?



- 🤔...

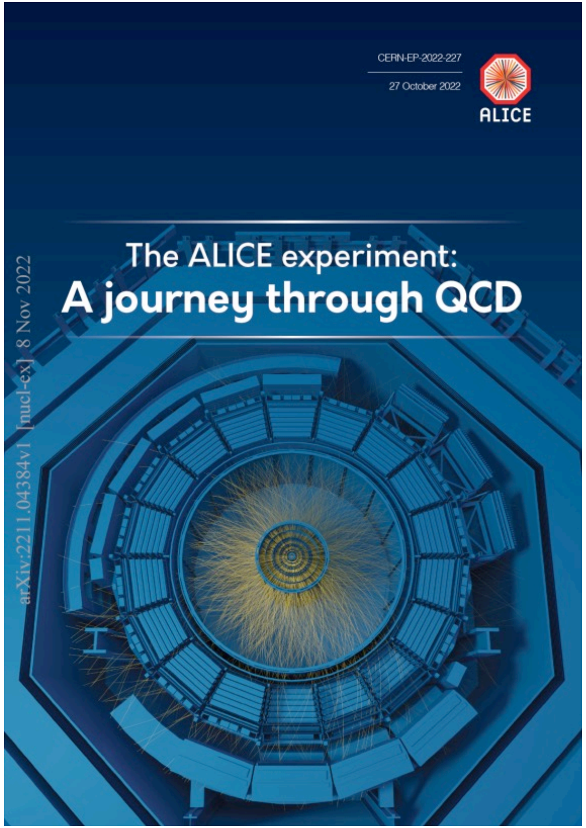
By the way: for B_s...



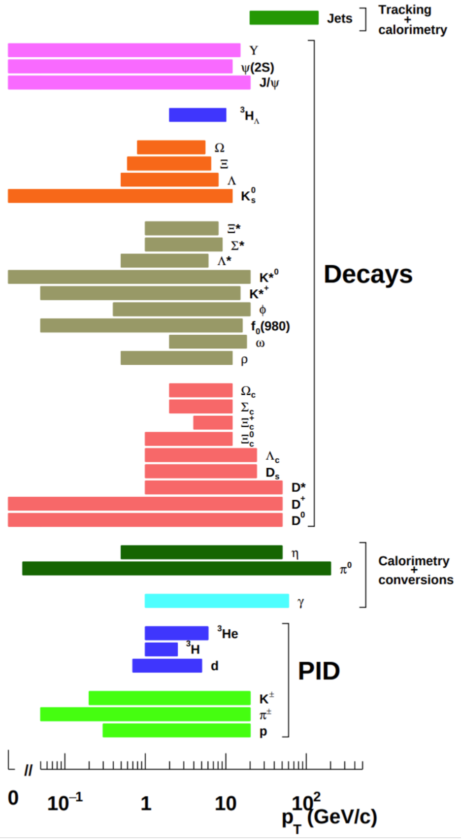
LHCb: arXiv:2204.13042

- evolution with local mult'y (VELO)
  - unlike for D_s...?!
  - 🤔...
- not much with backward mult'y

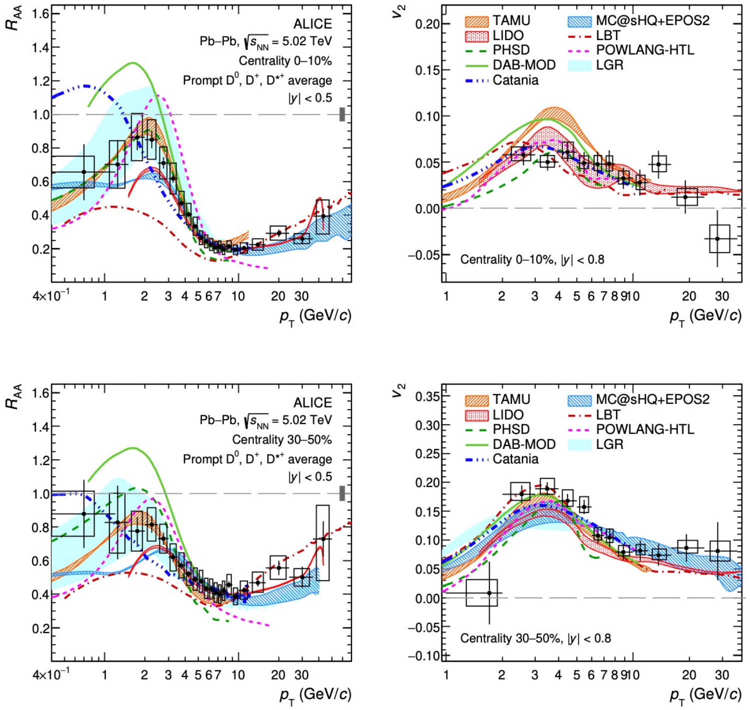
ALICE results from LHC Run 1, 2: full review

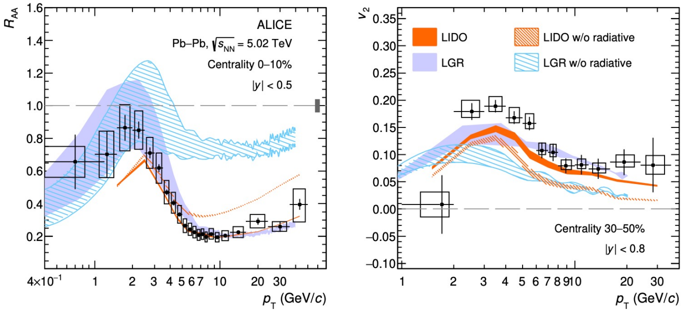


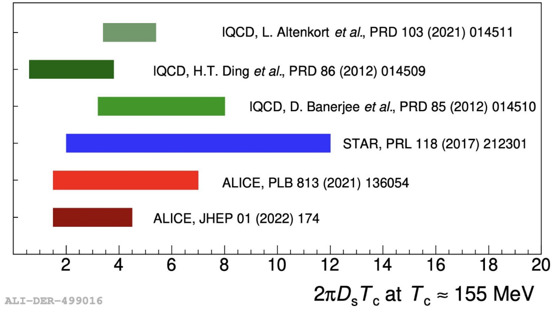
arXiv:2211.04384



Where do we go from here...?







- 10-100 x expected from Run 3, 4 → entering high-precision era!

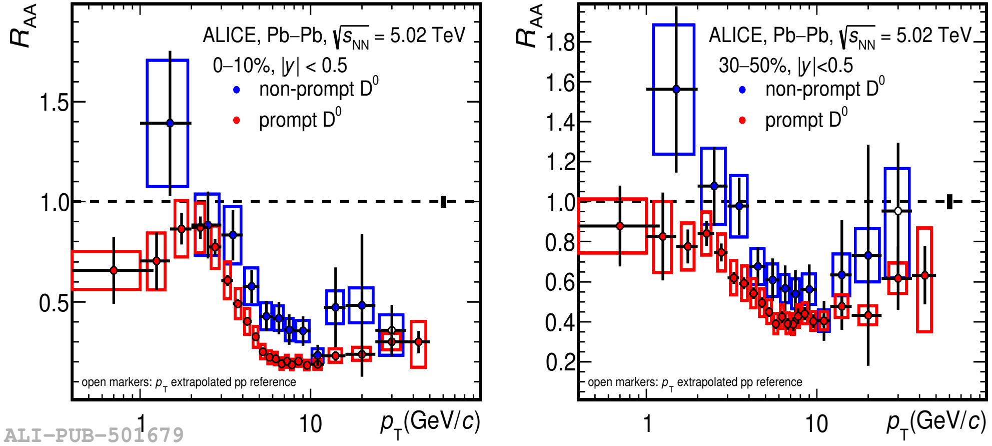
→ in the following: a few of my personal favourites

Low-p_T beauty!

- beauty not fully equilibrated?
  - less suppression than for charm
  - less flow than for charm
  - SHM seems to fail
- relaxation ~ 3 times slower than charm
  - $\tau_Q = \left(\frac{m_Q}{T}\right) D_s$ (with $m_b \sim 3m_c$)
  - of course this does not imply that b cannot fully equilibrate...
    - given enough volume/time...
  - ....but experimentally it looks like it doesn't...

→ b mass just at the right spot?

- to see equilibration on the move...?

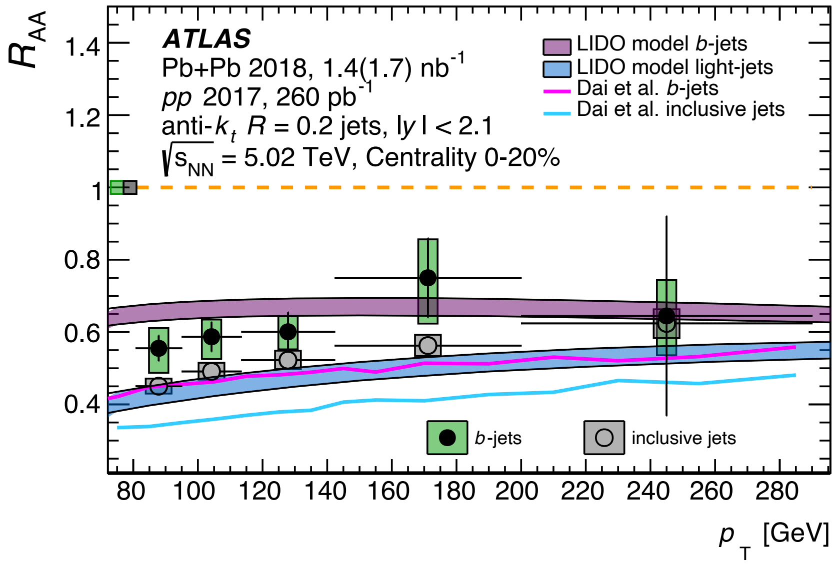


→ need high-precision b down to p_T=0

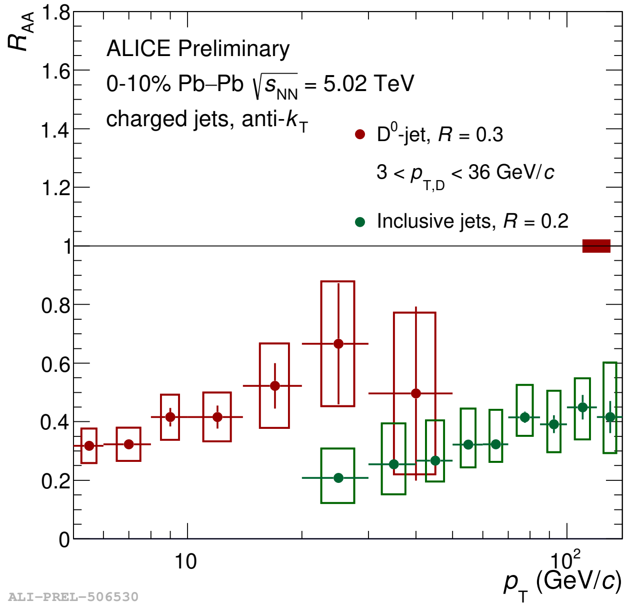
→ (and watch the hadrochemistry!)

Jets as quark proxy

- direct access to parton (ideally, at least...)

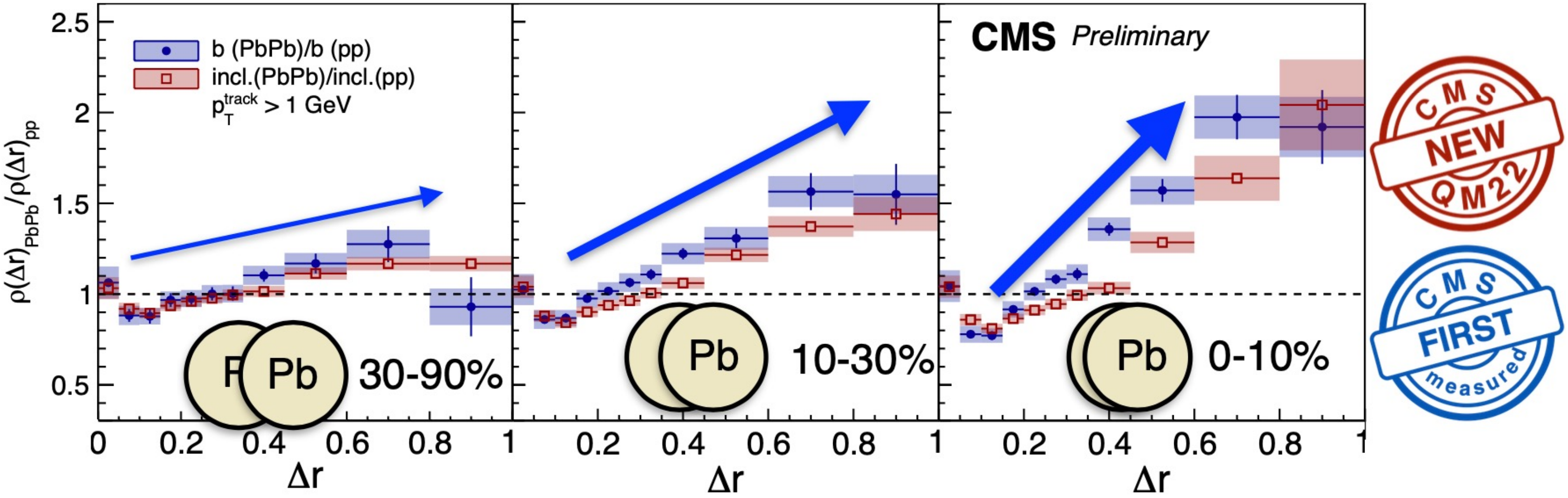


ATLAS: arXiv:2204.13530



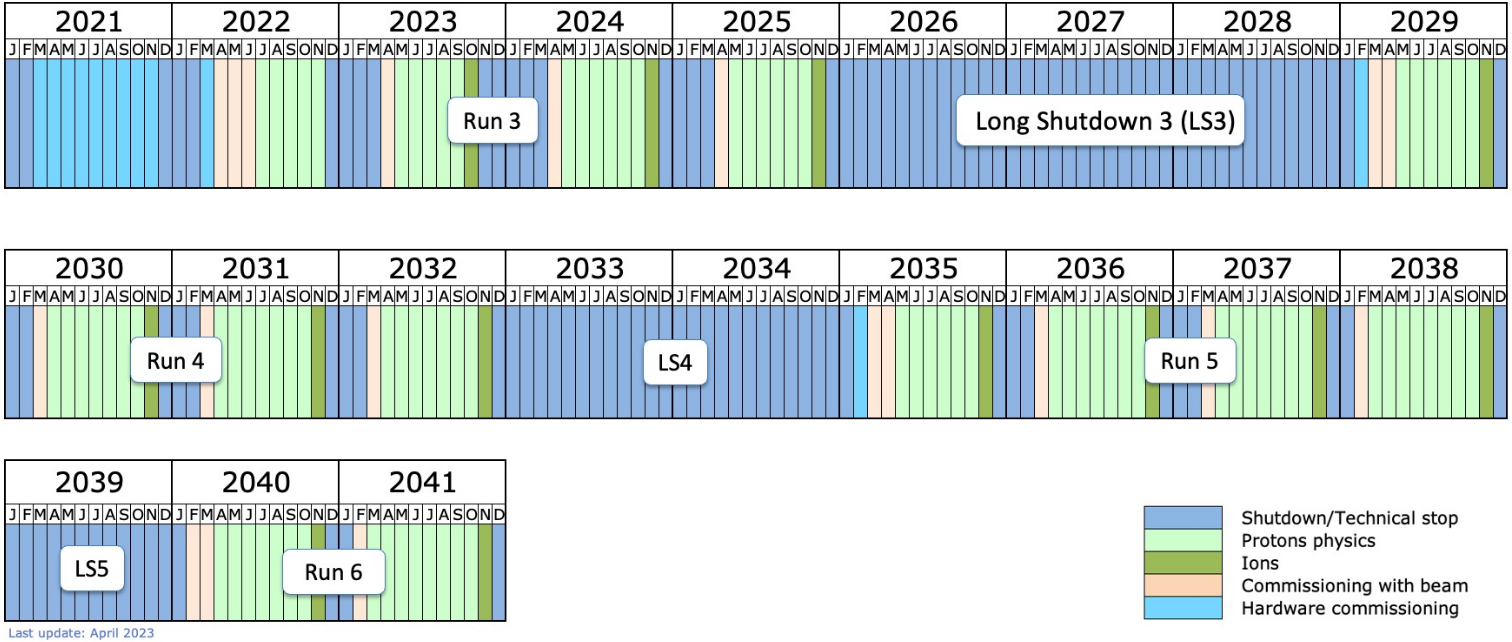
ALICE: SQM 2022

Jets as imaging of in-medium parton processes



LHC timeline

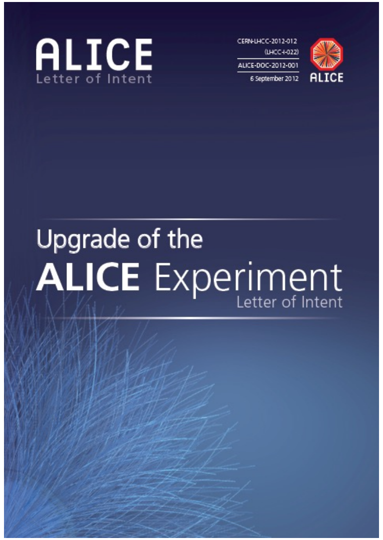
- during LS2:
  - LHC injector upgrades, Pb-Pb rate → 50 kHz (now ~10 kHz)
  - major ALICE upgrades campaign (vertexing, data collection speed)
- aim for > 13/nb Pb-Pb collisions (Run 3 + Run 4)

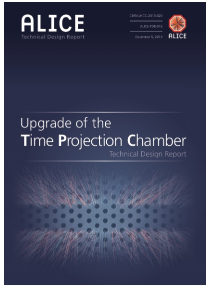


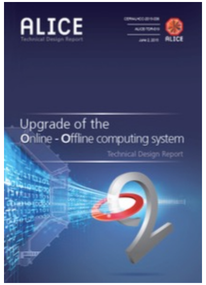
ALICE LS2 upgrades

Main physics goals

- study heavy quark interaction in QCD medium
  → heavy flavour dynamics and hadronisation at low p_T
- study charmonium regeneration in QGP
  → charmonium down to zero p_T
- chiral symmetry restoration and QGP radiation
  → vector mesons and virtual thermal photons (di-leptons)
- production of nuclei in QGP
  → high-precision measurement



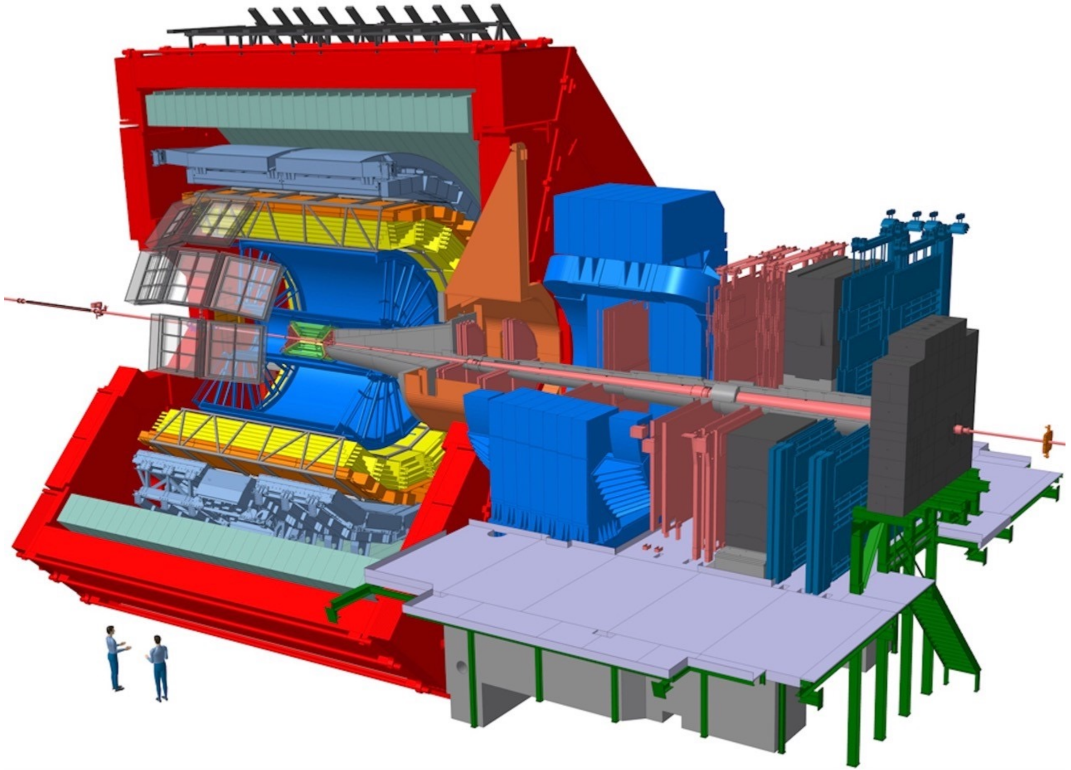




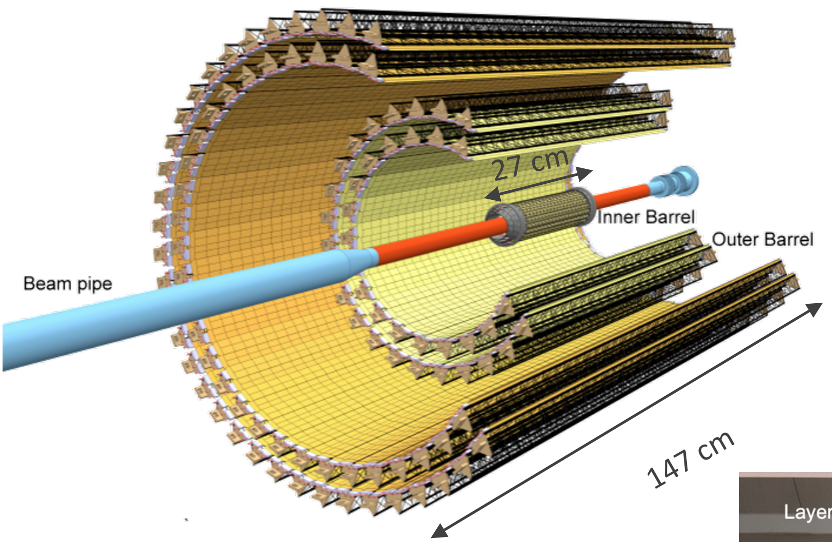
ALICE LS2 upgrades

Layout

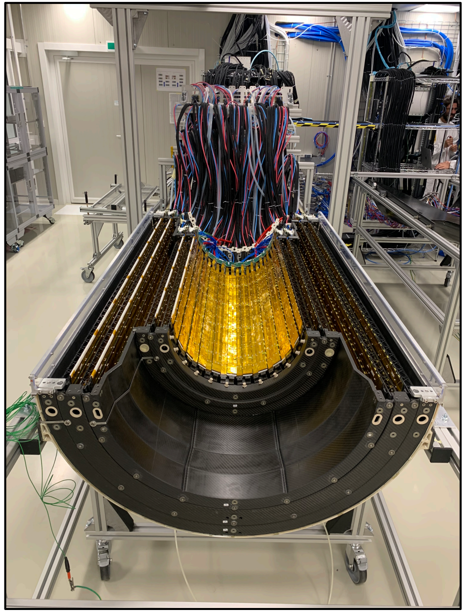
- New Inner Tracking System (ITS)
  - MAPS: improved resolution, less material, faster readout
- New Muon Forward Tracker (MFT)
  - vertex tracker at forward rapidity
- New TPC Readout Chambers
  - 4-GEM detectors → continuous r/o
- New forward trigger detectors (FIT)
  - centrality, event plane
- Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS, new Online-Offline system (O^2)
  - record minimum-bias Pb-Pb data at 50 kHz (currently <1 kHz)

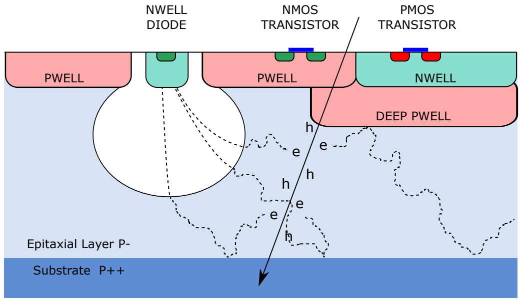


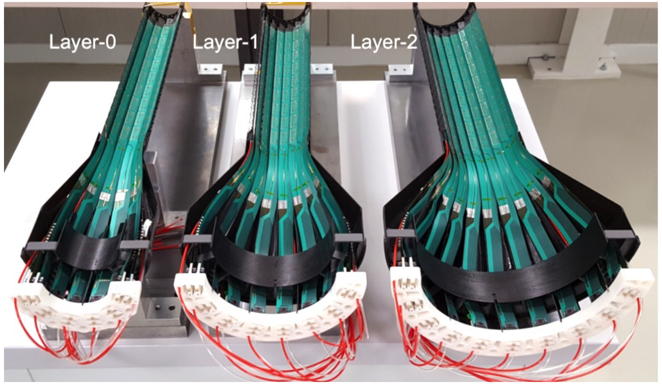
ITS upgrade: Monolithic Active Pixel Sensors



- 7-layer geometry (23 – 400mm, $|\eta| \leq 1.5$)
- 10 m^2 active silicon area (12.5 G-pixels)
- Pixel pitch 28 x 28 μm^2
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Material thickness: ~0.3% / layer (IB)
- Max particle rate: 100 MHz / cm^2





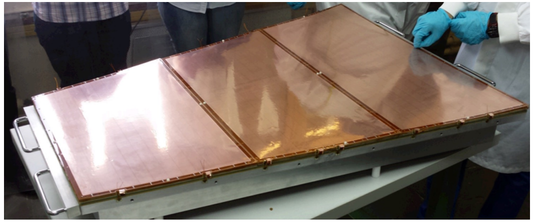


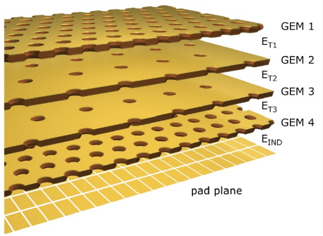
TPC upgrade: GEM readout

- with current MWPC r/o rate < kHz (Pb-Pb)
  - limited by ion backflow, gating grid

- GEM: ion backflow suppressed to < 1%

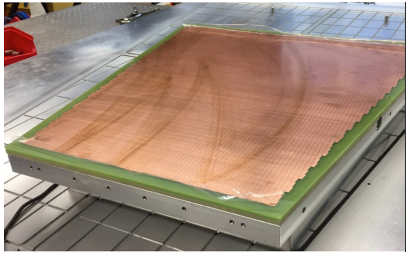
→ replace MWPC with 4-GEM stacks

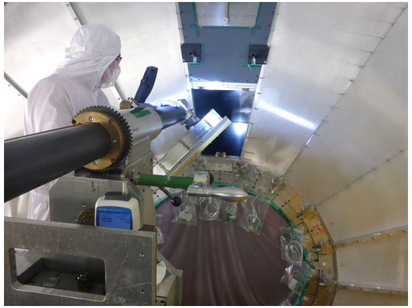




- 100 m^2 single-mask GEM foils
- 524 000 pads
- continuous readout at 50 kHz (Pb-Pb)

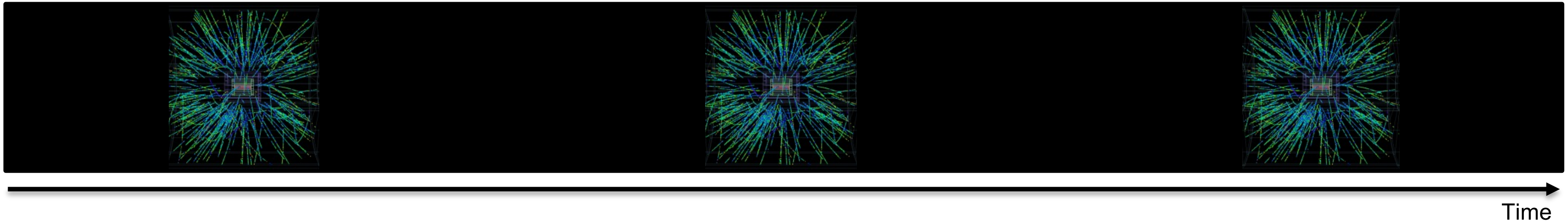
→ 3.4 TB/s!



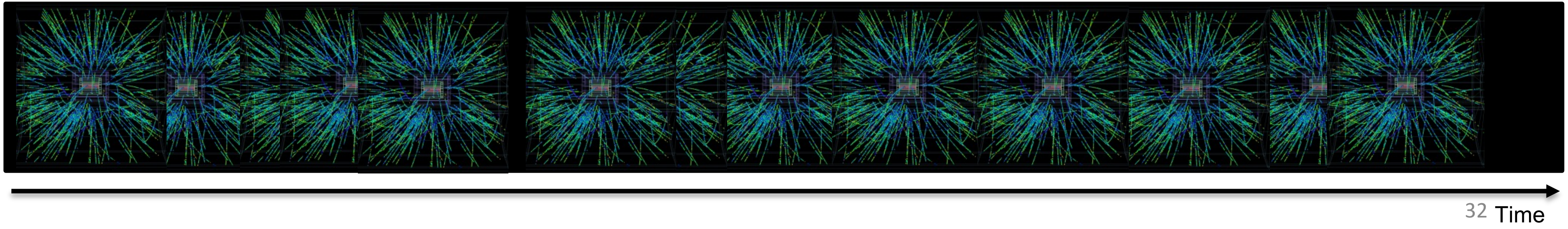


TPC at 50 kHz

- Run1, Run2: average time between collisions ~125 μs ~ TPC drift time
  - 1 event in TPC at any given time → triggerable



- after upgrade: average time between collision ~ 20 μs << TPC drift time
  - 5 events in TPC at any given time → continuous readout



O^2 System

Requirements

1. LHC min bias Pb-Pb at 50 kHz
2. very small signal over background
   → triggering not possible
3. support for continuous read-out

New computing system

- ➔ read-out the data of all interactions
- ➔ compress data intelligently
  → online reconstruction
- ➔ common online-offline computing system
  → O^2
- ➔ 2.2 MW Computer Centre on site

<u>Unmodified raw data of all interactions shipped from detector to online farm in triggerless continuous mode</u>

HI run 3.4 TByte/s ⇩

Baseline correction and zero suppression
Data volume reduction by zero cluster finder.
<u>No event discarded.</u>
Average compression factor 6.6

500 GByte/s ⇩

<u>Data volume reduction by online tracking.</u>
<u>Only reconstructed data to data storage.</u>
Average compression factor 5

100 GByte/s ⇩

Data Storage
1 year of compressed data

120 GB/s ⇩ ⇧

Tier 0, Tiers 1 and Analysis Facilities

200 GB/s ⇩ 20 GB/s ⇧

Asynchronous (hours) event reconstruction with final calibration

---

Detector Electronics
9000 GBTs links

⇩

270 First-Level Processors
Hw acc: FPGAs

⇩

Switching Network

⇩

1500 Event Processing nodes
Hw acc: GPUs

⇳

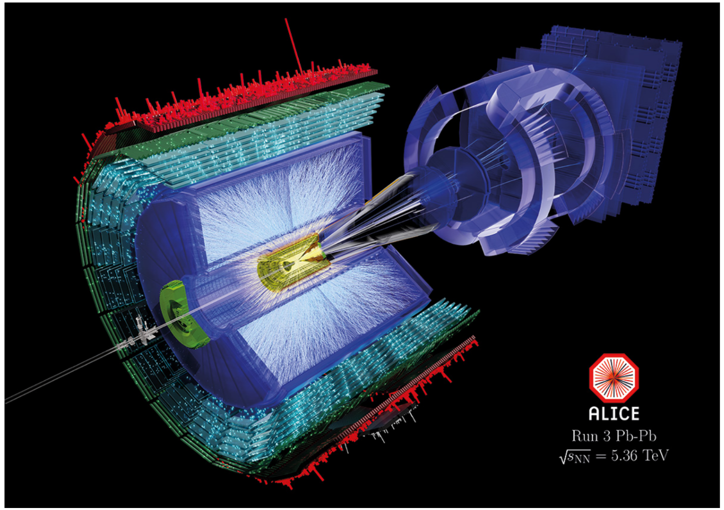
Switching Network

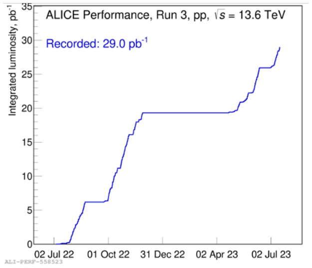
⇳

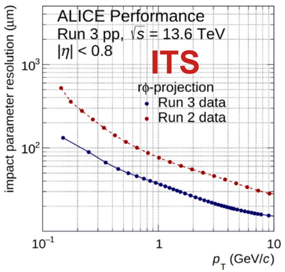
Data storage
Wr 120 GB/s Rd 320 GB/s
Capacity: 60 PB

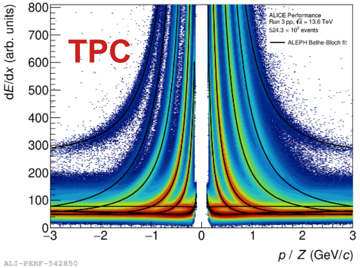
Run 3 is here!

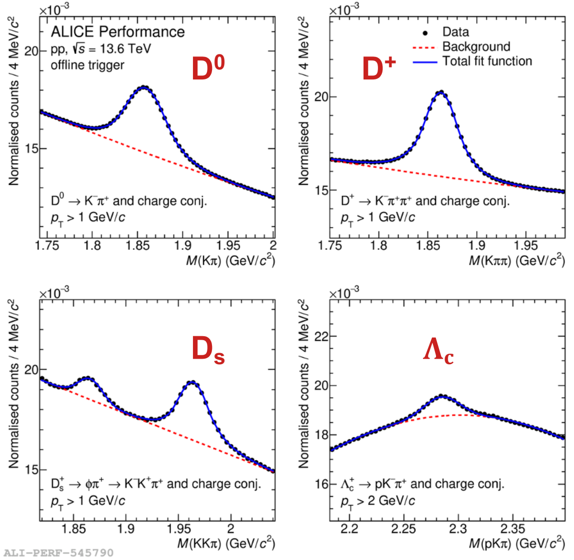
- huge increase in statistics
  - Pb-Pb x 100
  - pp, p-Pb x 1000
- analysis-level event selection
  - 10^4 compression factor

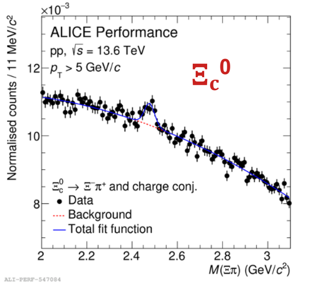


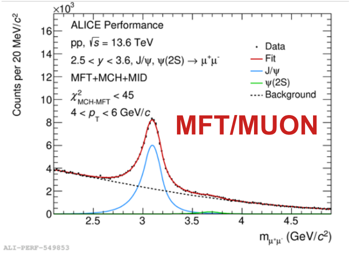




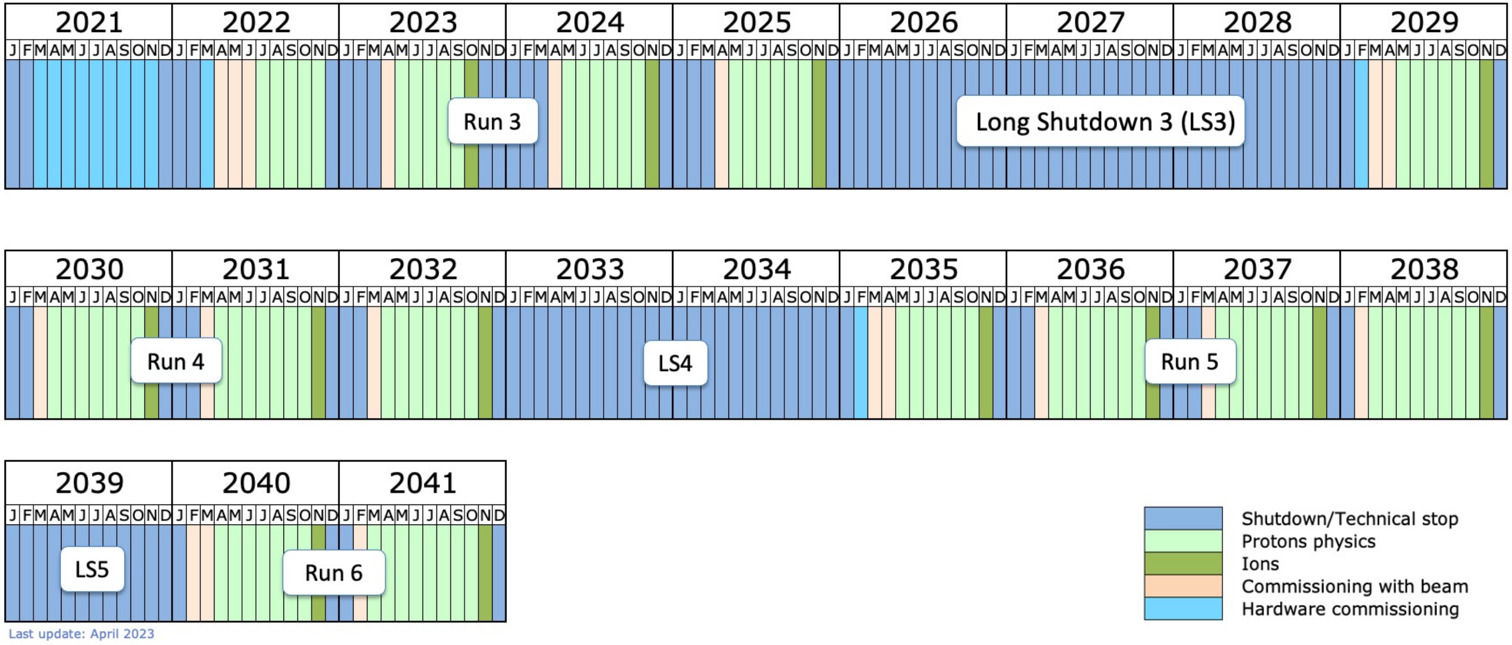






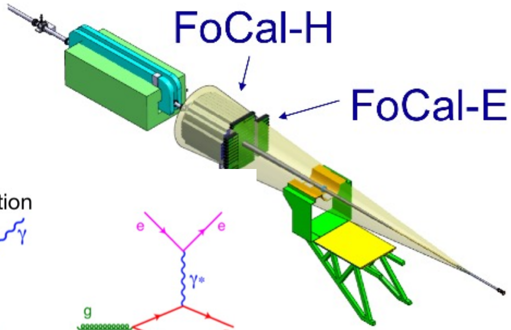


Plans for LS3, LS4

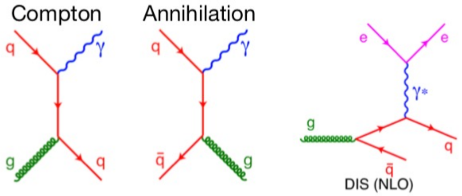


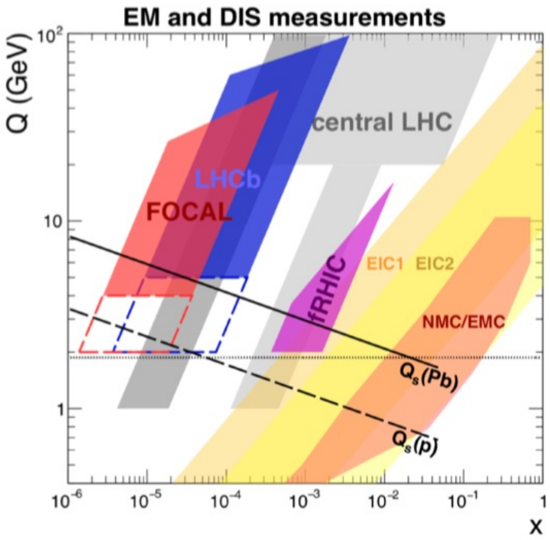
FoCal

- proposal to instrument ALICE with a Forward Calorimeter in LS3 ALICE-PUBLIC-2019-005
  - FoCal-E: high-granularity Si-W sampling calorimeter
    - photons, π^0
  - FoCal-H: sampling hadronic calorimeter
    - photon isolation, jets

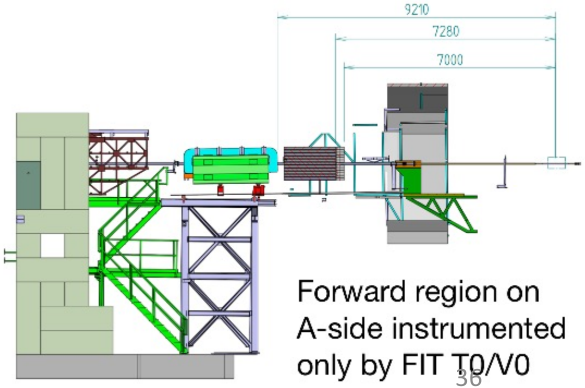


→ access to gluon parton distribution functions





+ other observables
- π^0
- jets (and di-jets)
- J/ψ, Υ in UPC
- W, Z
- event plane and centrality
- …



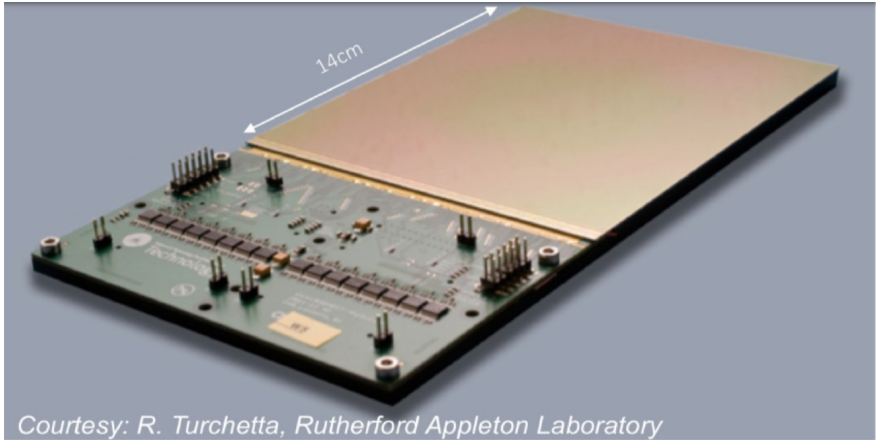
Forward region on A-side instrumented only by FIT T0/V0

Beyond LS4

- ongoing upgrade will bring us to maximum rate for a TPC spectrometer
  - @ 50 kHz: space-charge distortions ~ 10 cm, track density ~ 40% (inner region)

- advances in CMOS technology open new opportunities
  - vertexing, tracking, calorimetry, …

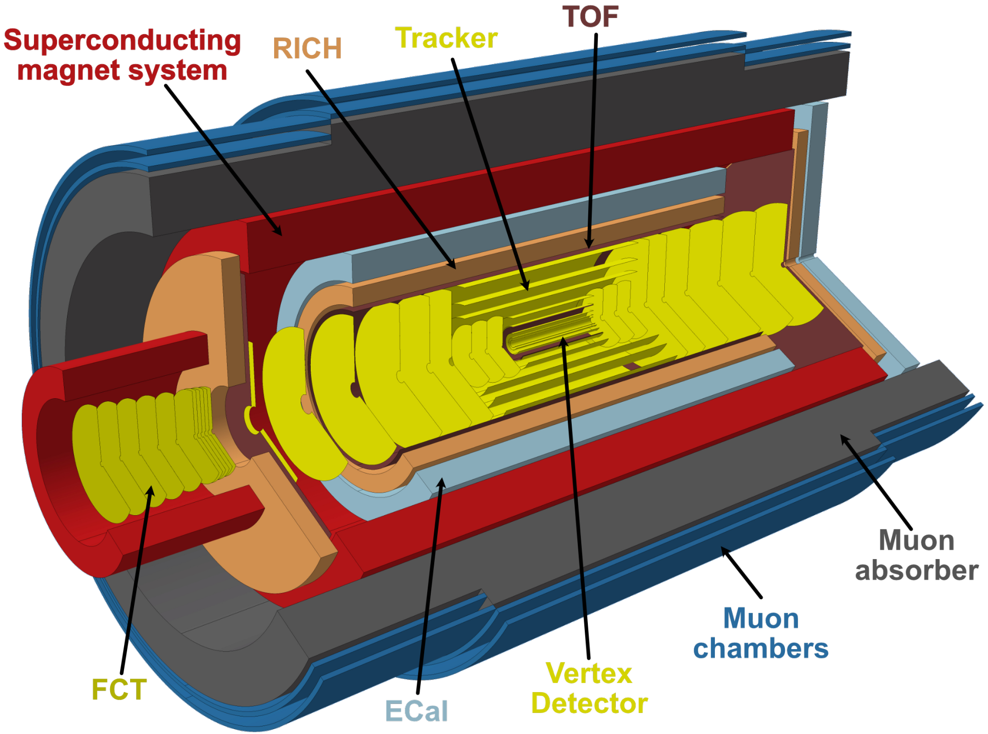
flexible wafers



wafer-size circuits (stitching)

A new dream: ALICE 3!

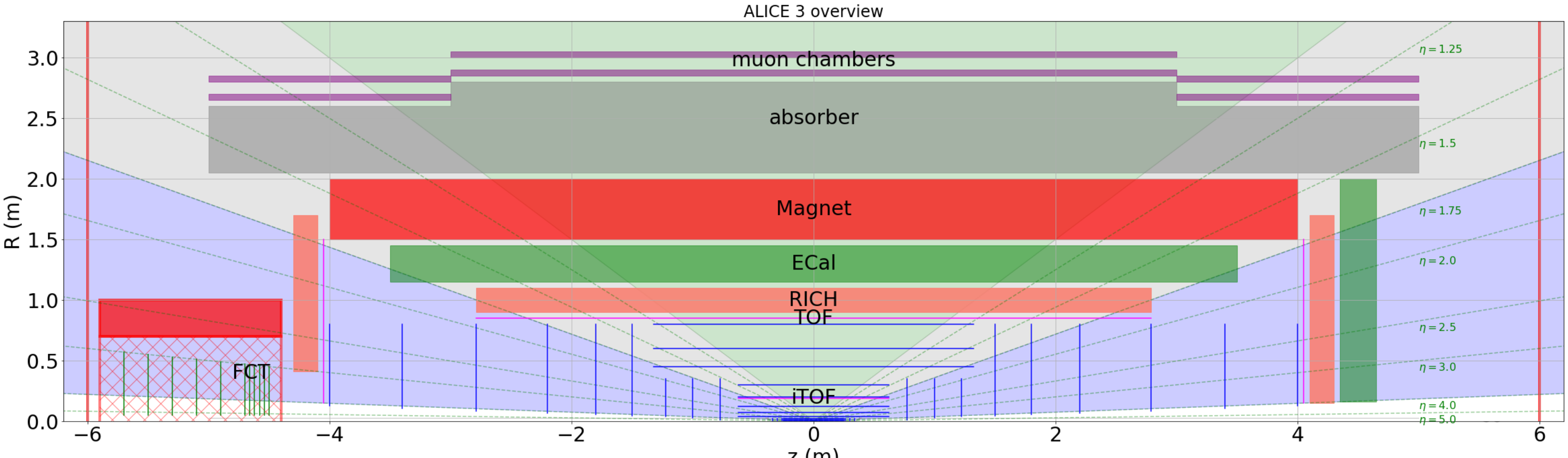
a next-generation heavy-ion experiment at the LHC



- compact, “all-silicon” tracker
- wide rapidity acceptance (8 units)
- high-resolution vertex detector
  - as close as possible to beams!
- superconducting magnet system
- hadron, muon, electron identification
- electromagnetic calorimeter
- forward conversion tracker

Observables

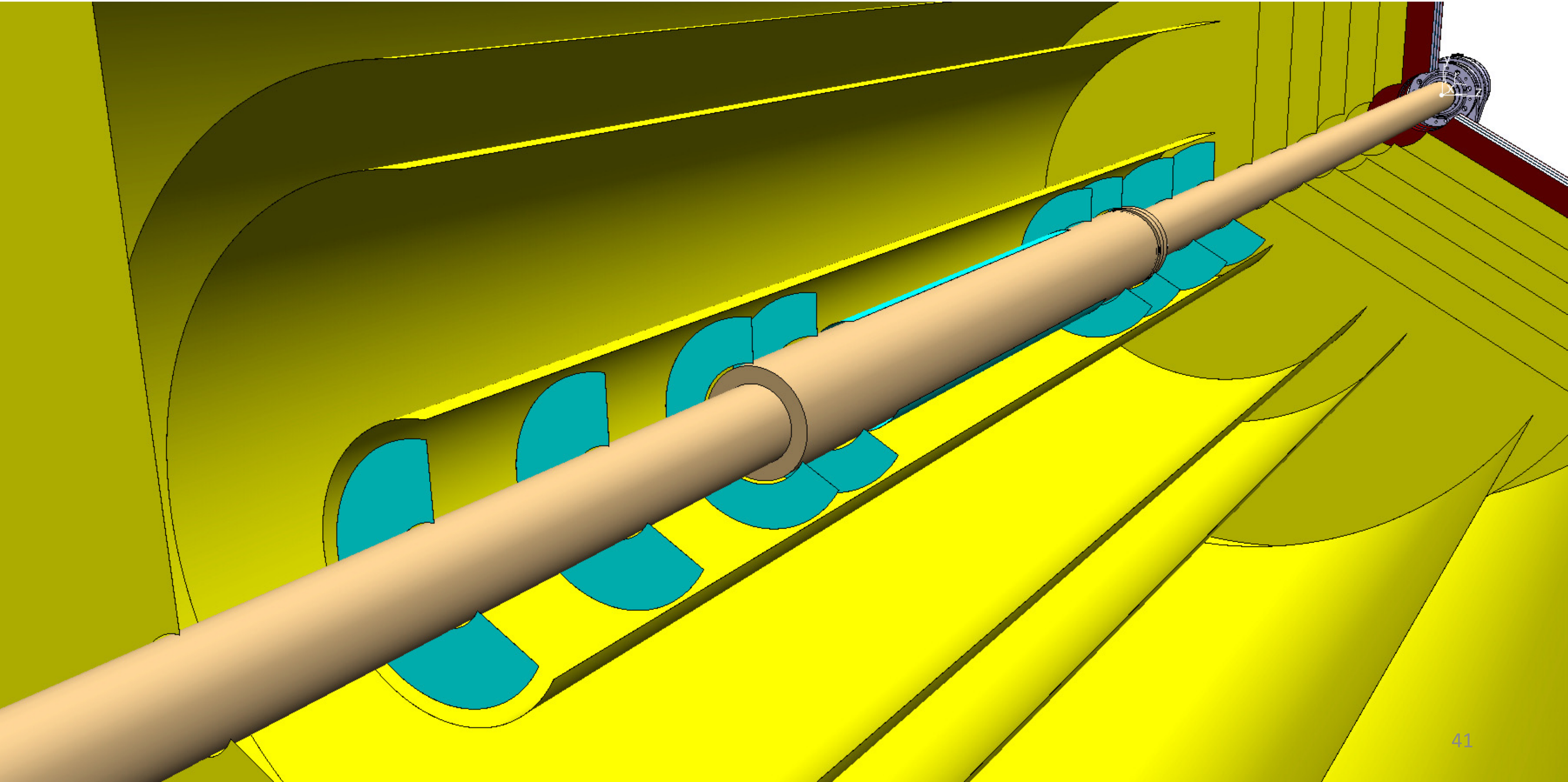
- heavy-flavour hadrons ($p_T \rightarrow 0$, wide η range)
  - → vertexing, tracking, hadron id
- dileptons ($p_T \sim 0.1$ - 3 GeV/c, $M_{ee} \sim 0.1$ - 4 GeV/c^2)
  - → vertexing, tracking, lepton id
- photons (100 MeV/c - 50 GeV/c, wide η range)
  - → electromagnetic calorimetry
- quarkonia and exotica ($p_T \rightarrow 0$)
  - → muon id
- jets
  - → tracking and calorimetry, hadron id
- ultrasoft photons ($p_T \sim 1$ - 50 MeV/c)
  - → dedicated forward detector
- nuclei
  - → identification of z > 1 particles



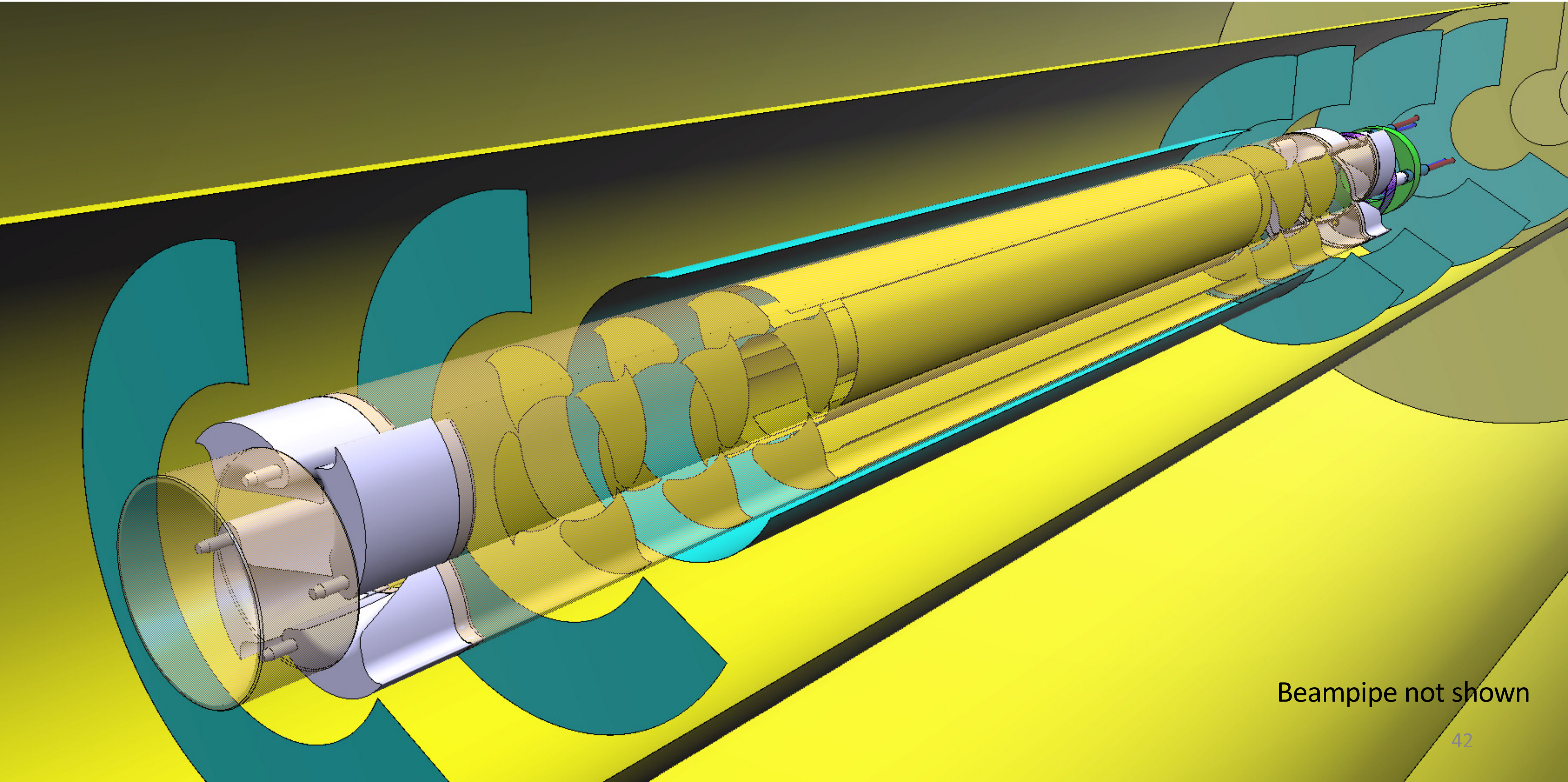
Detector requirements

Component	Observables	$\lvert\eta\rvert < 1.75$ (barrel)	$1.75 < \lvert\eta\rvert < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ µm at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ µm at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ µm, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ µm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer
Hadron ID	Multi-charm baryons	**π/K/p separation up to a few GeV/*c***		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to ~2 - 3 GeV/*c*		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad possibly preshower detector
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*		steel absorber: $L \approx 70$ cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/*c*	Forward Conversion Tracker based on silicon pixel sensors

IRIS: inside the beam pipe

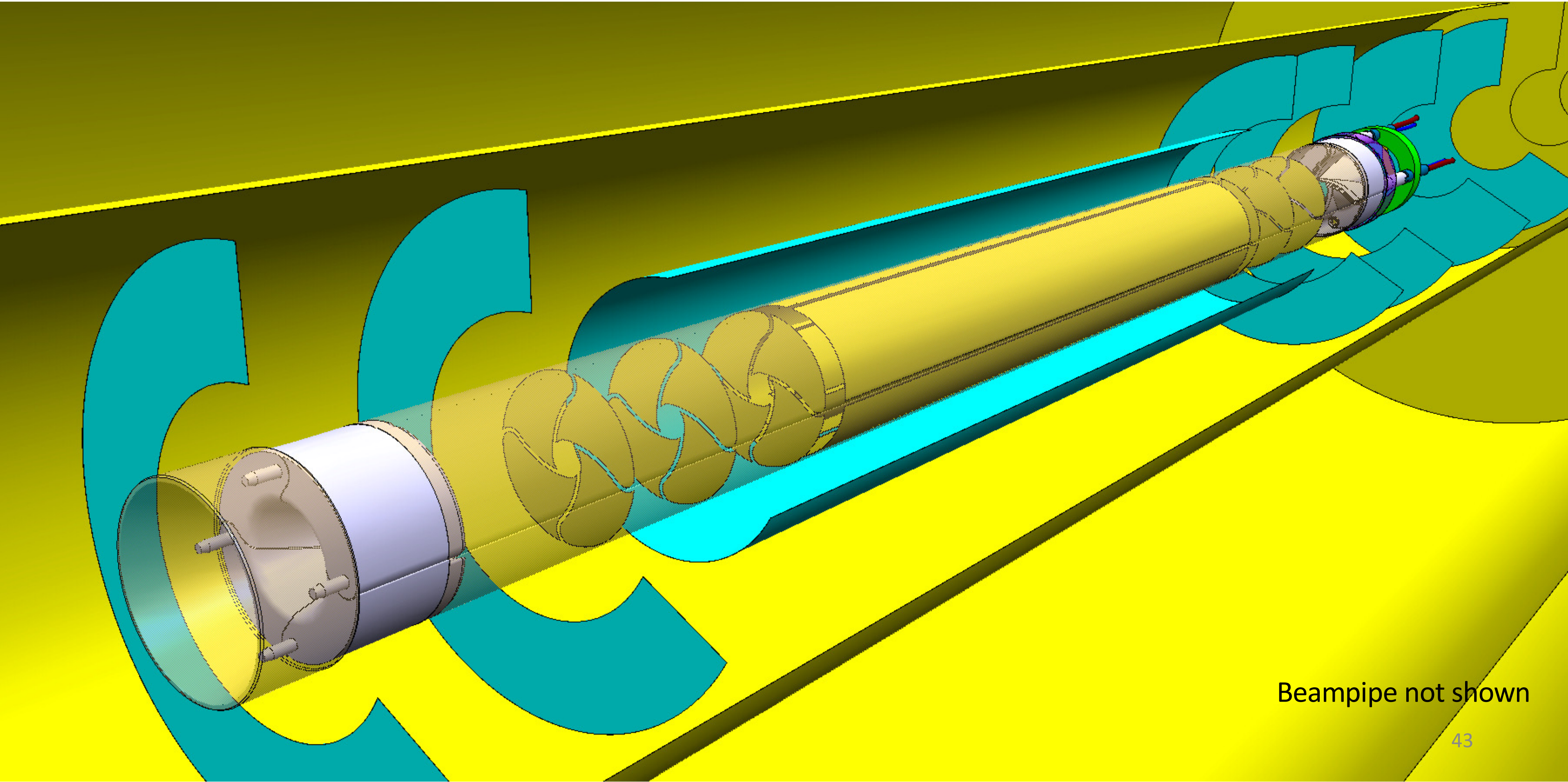


IRIS: inside the beam pipe



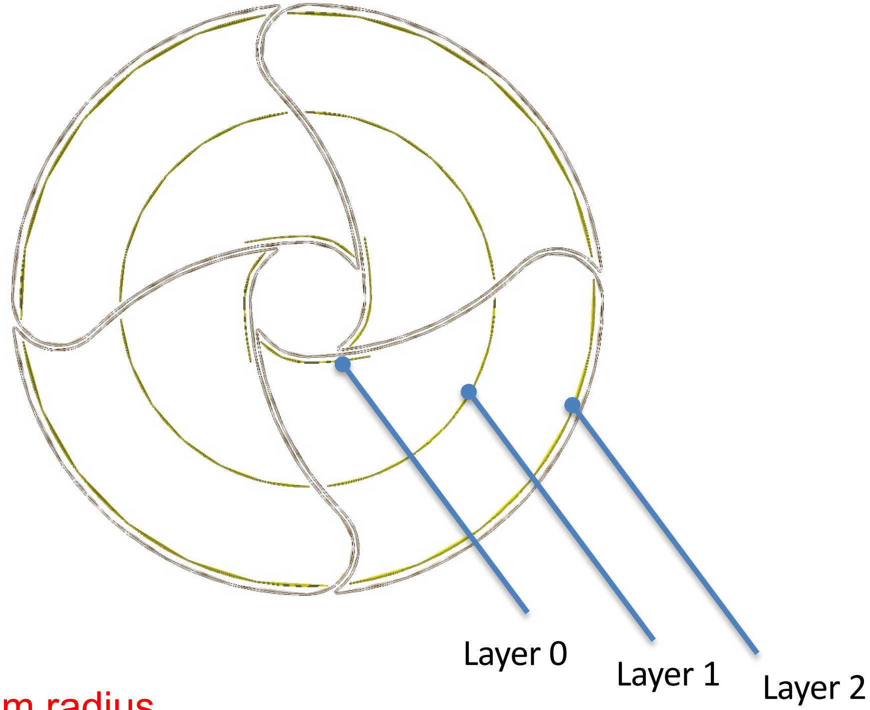
Beampipe not shown

IRIS: inside the beam pipe



Beampipe not shown

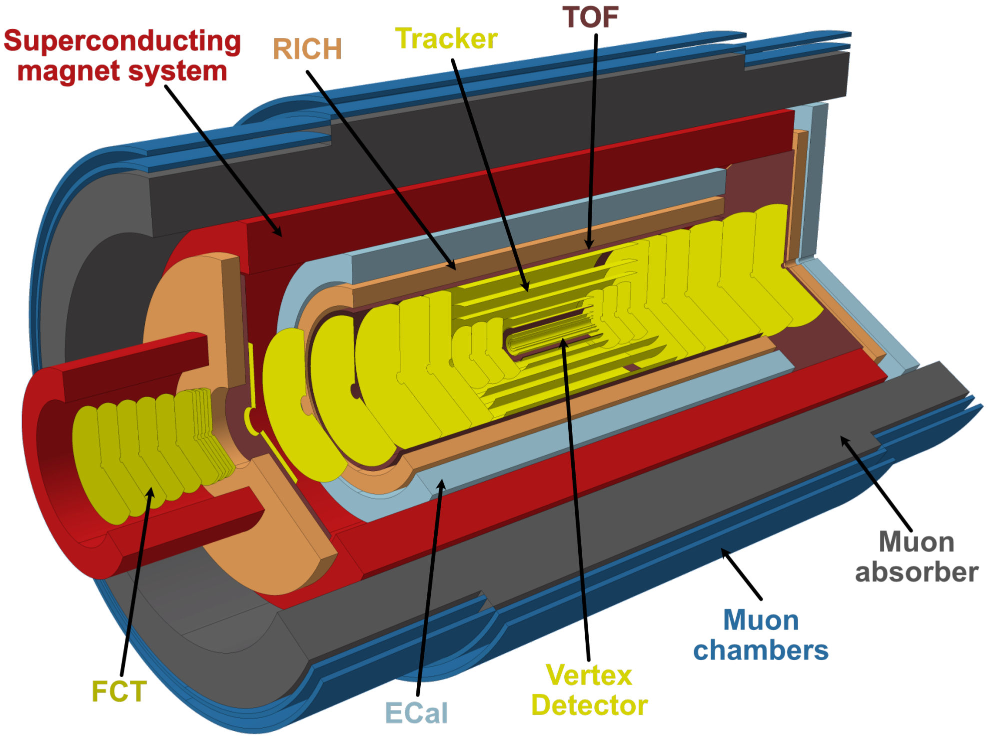
IRIS: aperture



Minimum aperture at injection: 16mm radius
Closes to 5mm radius during operation

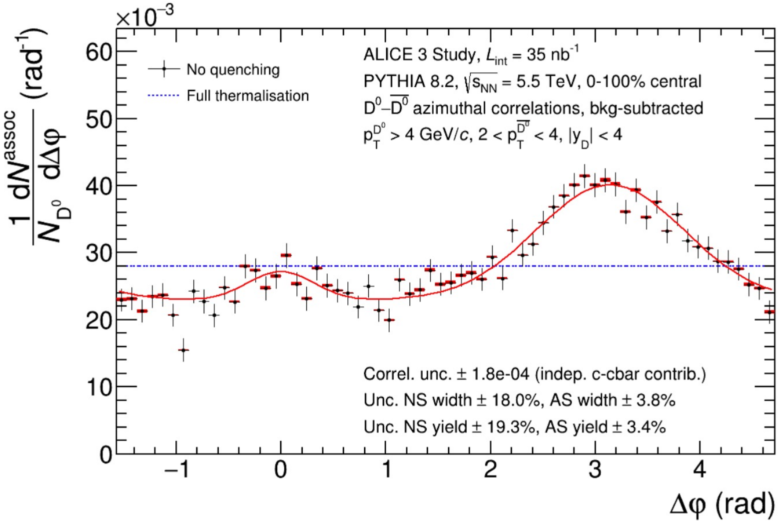
Physics potential

- some personal favourites…



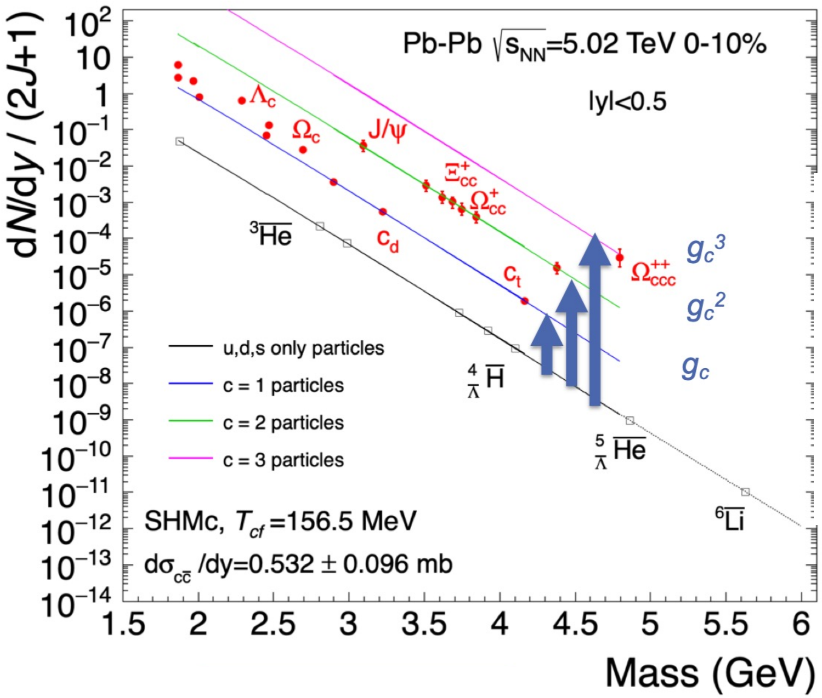
$D\bar{D}$ correlations

- ~ Rutherford experiment on QGP!
- constrain energy loss and angular decorrelation simultaneously
- collisional vs radiative eloss vs momentum scale
- full isotropisation at low p_T?
- e.g.: ALICE 3 LoI



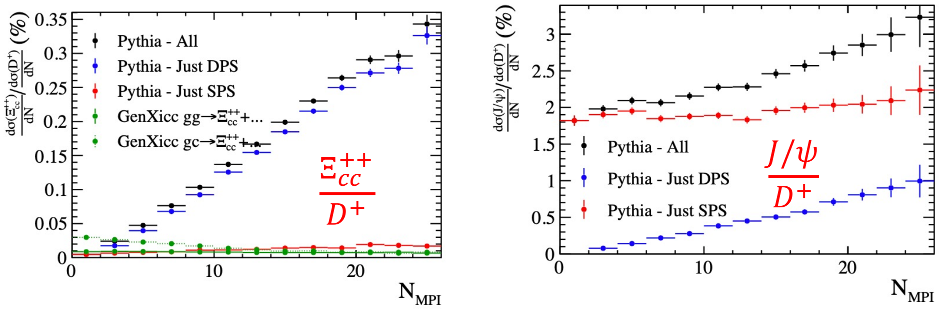
Multi-charm: the final frontier?

Statistical Hadronisation Model



A Andronic et al.: JHEP 07 (2021) 035

- huge enhancements predicted
  - up to 10^3 wrt pQCD for the Ω_{ccc}!
- negligible production in Single-Parton Scattering
  - unlike J/ψ



P Skands & C: arXiv:2205.15681

- only "exogamous" production
  - unlike J/ψ
- <u>ultimate sensitivity to degree of c thermalisation!</u>

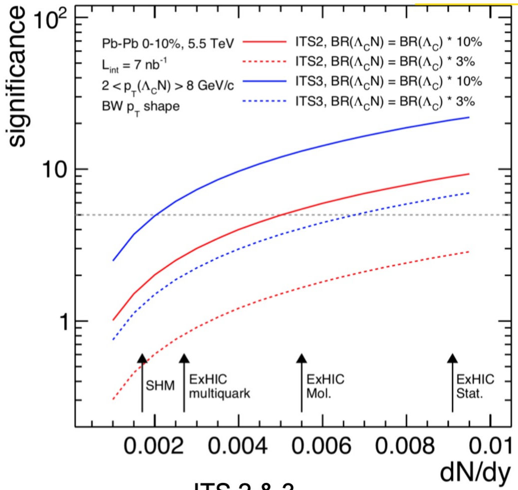
Charmed hypernuclei?

- nuclei containing a charm baryon
  - sometimes called *supernuclei*
- e.g.: c-deuteron ($\Lambda_c^+ n$), c-triton ($\Lambda_c^+ nn$)
- first suggested in the 70's
  - C B Dover and S H Kahana, PRL 39 (1977) 1506
- existence/stability debated ever since

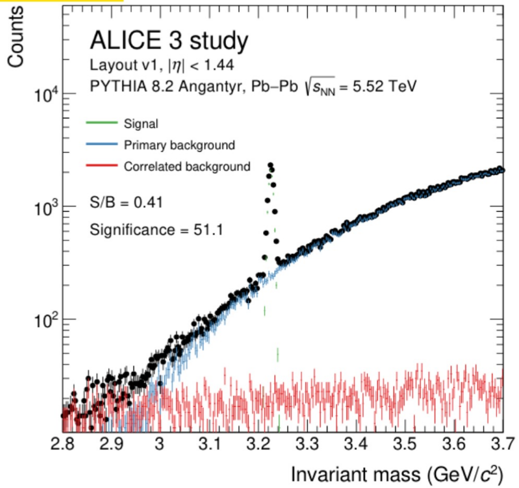
- at SHM abundances → expected to come into view at LHC
- if full equilibration confirmed both for c and for nuclear states...

→ discover or exclude existence!

- + direct study of Λ_c^+-N potential via femtoscopy?



ITS 2 & 3



ALICE3 (SHM)

An old dream: thermal charm?

ЯДЕРНАЯ ФИЗИКА
JOURNAL OF NUCLEAR PHYSICS
т. 28, вып. 3(9), 1978

- γ_c ~ 30 → thermal component only ~ 3%
- but that's for central Pb-Pb...

- initial production: $Y_{in}(c\bar{c}) \propto A^{4/3}$
- thermal production: $Y_{th}(c\bar{c}) \propto A$

- $\gamma_c \propto \frac{Y_{in}}{Y_{th}} \propto A^{1/3}$
- e.g. for central Ar-Ar (or ~ 60% Pb-Pb) γ_c ~ 15

→ thermal component already 6%
  - + centrality / A dependence different from initial component

→ can it be separated from other centrality-dependent effects with very-large stats?

- btw: already in our minds at time of ALICE TP
  - (but theory predictions were overestimated...)

E V Shuryak: Yadernaya Fizika 28 (1978) 403

КВАРК-ГЛЮОННАЯ ПЛАЗМА И РОЖДЕНИЕ ЛЕПТОНОВ, ФОТОНОВ И ПСИОНОВ В АДРОННЫХ СОУДАРЕНИЯХ

Э. В. ШУРЯК

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

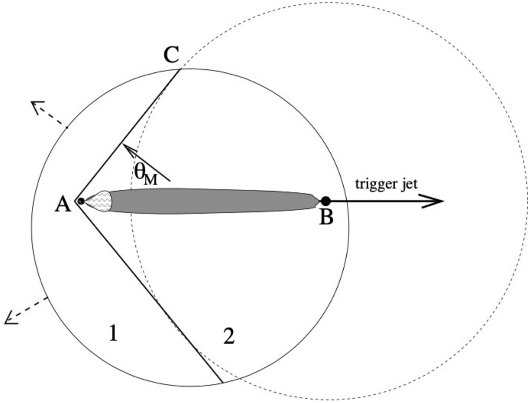
(Поступила в редакцию 14 марта 1978 г.)

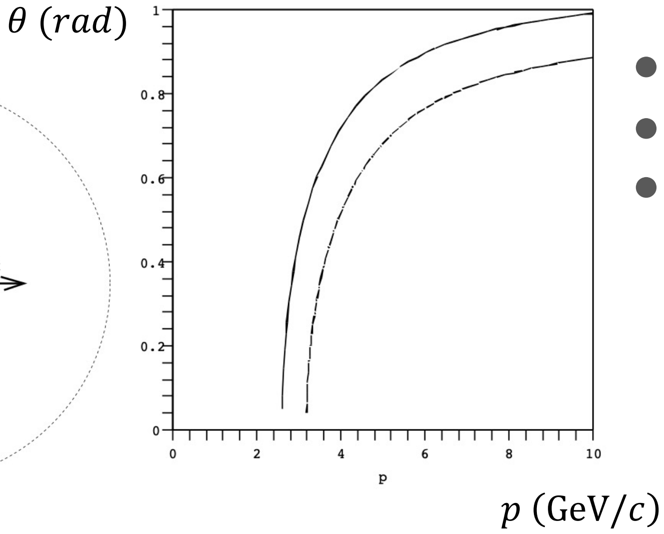
Предлагается теория явлений, связанных с массами M и поперечными импульсами $p_\perp$, такими, что 1 *Гэв* $\lesssim M$, $p_\perp \ll \sqrt{s}$. Для их описания применяется модель локально-равновесной кварк-глюонной плазмы, разлетающейся по определенному закону. Применение квантовой хромодинамики для вычисления скоростей ряда реакций в такой плазме позволяет вычислить спектры масс дилептонов, распределение по $p_\perp$ лептонов, фотонов, пионов и адронных струй, сечения рождения пар очарованных кварков и различных состояний чармония (псионов): J/ψ-, χ-, ψ'-мезонов. Результаты согласуются с экспериментальными данными.

An old dream: beauty shock waves?

- low momentum b quarks are slow! (e.g.: at 10 GeV $\beta \sim 0.9$)

→ angle of shock wave emitted by propagating b quark should depend on p





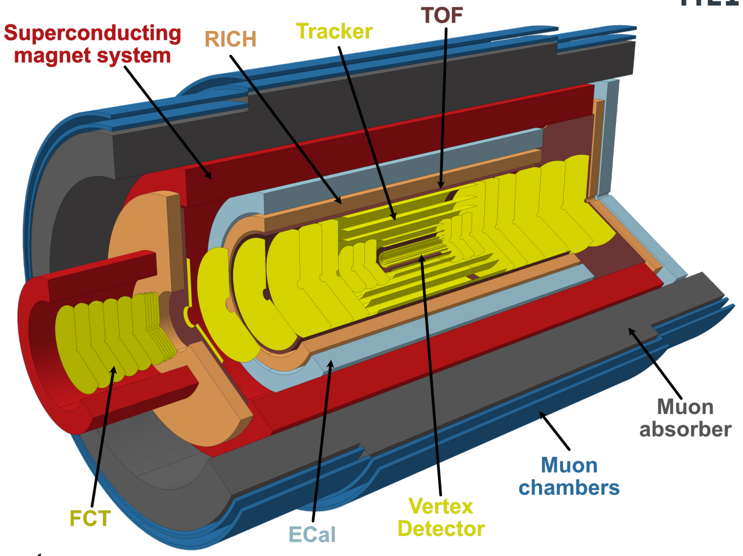
- taking $\overline{c_s}$ ~ $1/\sqrt{3}$ ... $1/2$
- b subsonic for $p <\sim$ 3 GeV/c
- p-dependent wake in multi-GeV range?
  - ~ 40 º at 5 GeV, ~ 55º at 10 GeV!

F Antinori, E V Shuryak: J.Phys. G31 (2005) L19

ALICE

Physics potential (examples)

- heavy flavours, quarkonia
  - multi-heavy flavoured hadrons (Ξ_{cc}, Ω_{cc}, Ω_{ccc})
  - D D correlations
  - B mesons at low p_T
  - χ_c , X, Y, Z states and exotic hadrons
- low-mass dielectrons
  - chiral symmetry restoration
  - thermal continuum (virtual photons)
- fluctuations of conserved charges
  - over wide rapidity range
- ultra-soft photons
  - down to MeV scale with dedicated forward spectrometer
- nuclei, hyper-nuclei, search for super-nuclei (with c baryons)
- BSM searches
  - dark photons
  - axion-like particles
  - …



Letter of Intent: https://cds.cern.ch/record/2803563

ITS3 Vertex detector (3 inner layers)

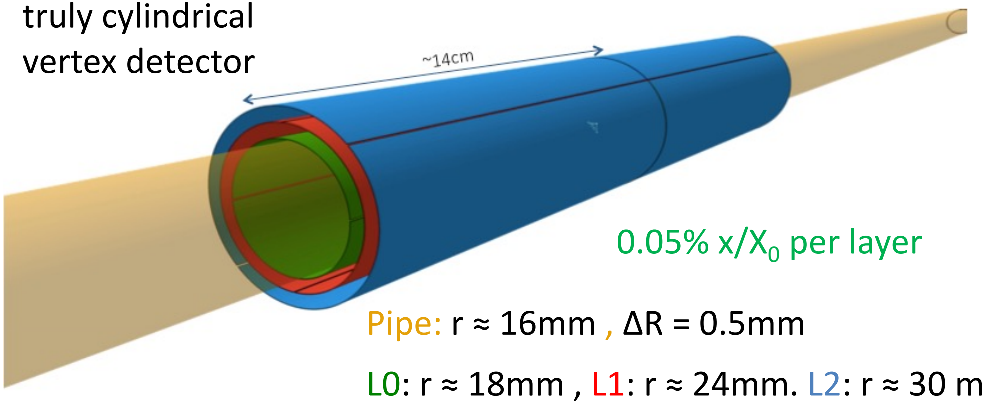
a new, ultra-light Inner Barrel in LS3

Letter of Intent https://cds.cern.ch/record/2703140

- advances in Silicon technology: ultra-thin, wafer-scale sensors
  - eliminate active cooling (for power < 20 mW/cm^2)
  - eliminate electrical substrate (if sensor convers full stave length)
  - perfectly cylindrical geometry

    (30 µm thick can be curved to 10-20 mm radius)

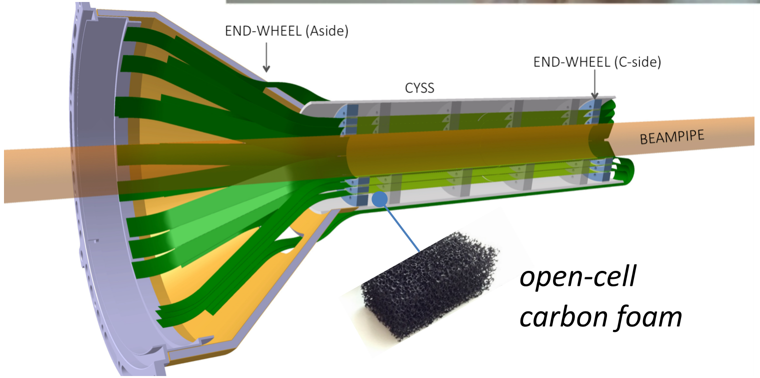
truly cylindrical
vertex detector



0.05% x/X_0 per layer

Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm



open-cell carbon foam

Conclusions

- in this brief course, we could only go through a limited choice of subjects

- I concentrated on some of the most representative ones
  - there is of course much more that we could not discuss...

- I hope you have enjoyed the lectures
  - and have learned something new!

- this is a very rich, dynamic, experiment-driven field

Conclusions

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- I concentrated on some of the most representative ones
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