首届ALICE实验与重离子物理讲习班

The 1st ALICE Experiment and Heavy-Ion Physics School

夸克-胶子等离子体五十年：过去、现在和未来（第四讲）

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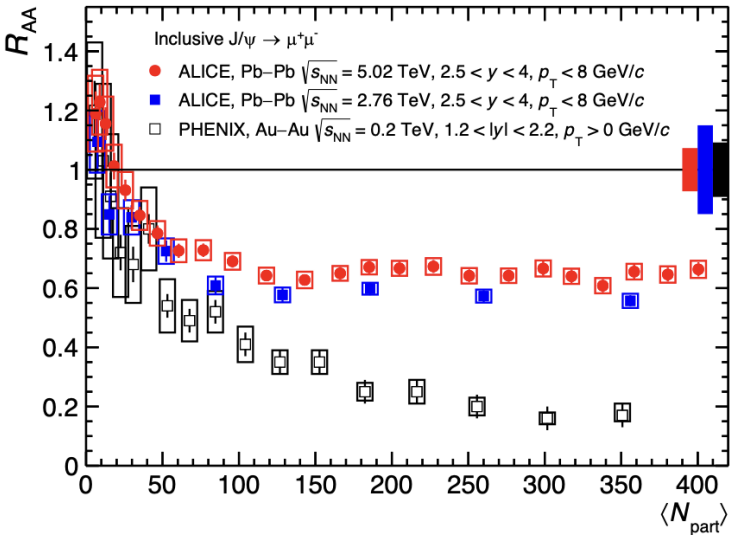
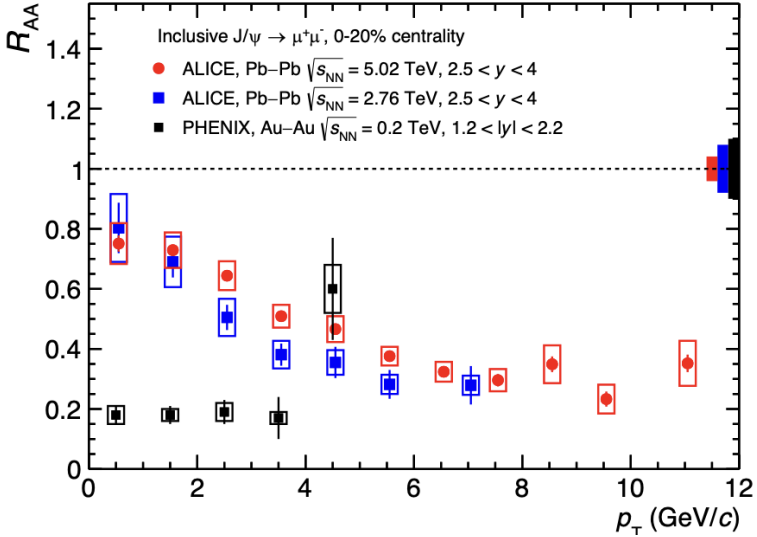
上海，复旦大学，2025年11月

昨天的图表：A new regime for J/ψ production!

- a remarkable change of behaviour from SPS/RHIC!

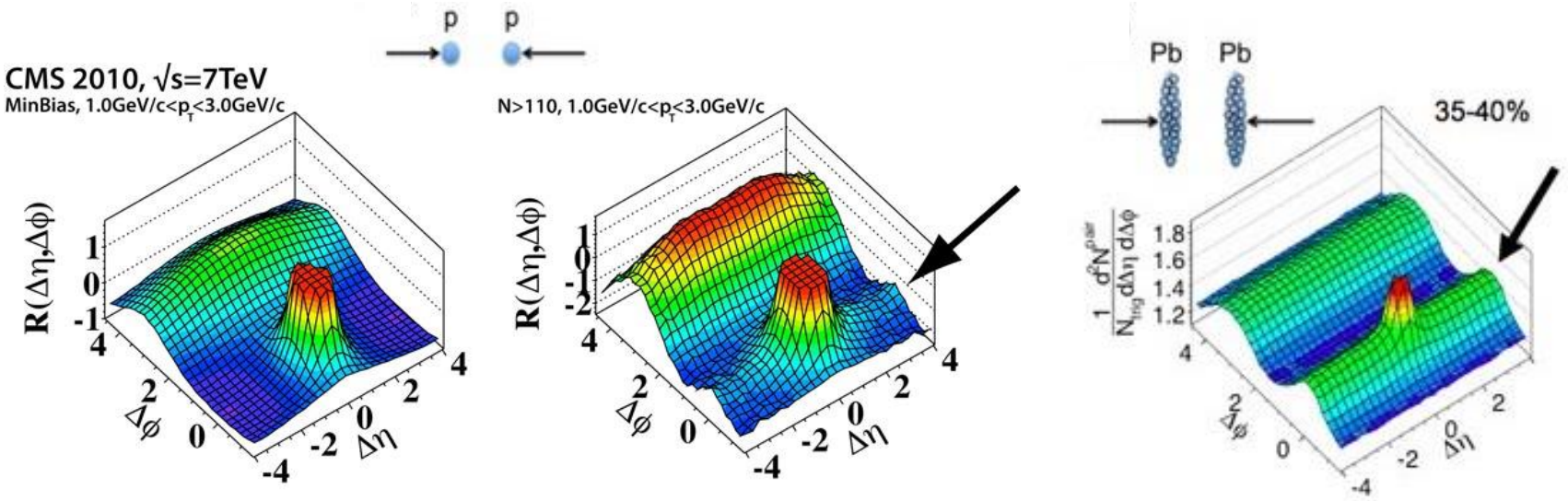




- in both the centrality and the p_T dependence
- evidence for production by recombination of exogamous $c\bar{c}$ pairs!

Small systems: a new frontier

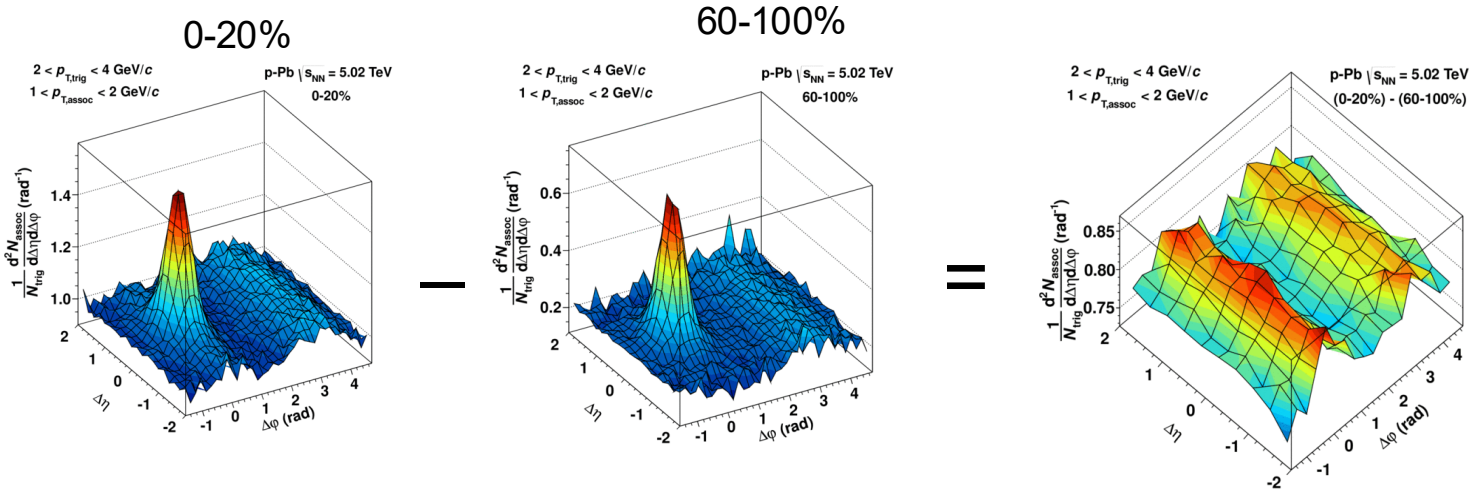
- long-range ridge on near side in high-multiplicity pp collisions at the LHC!
- very similar structure as in Pb-Pb collisions
  - where it is connected with v_2



CMS: JHEP 1009:091,2010

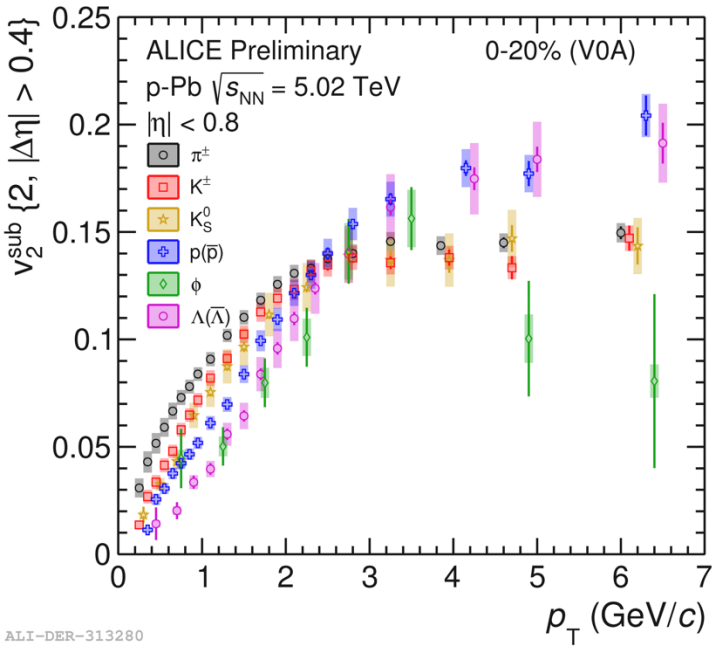
Near- and away-side ridge in p-Pb

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

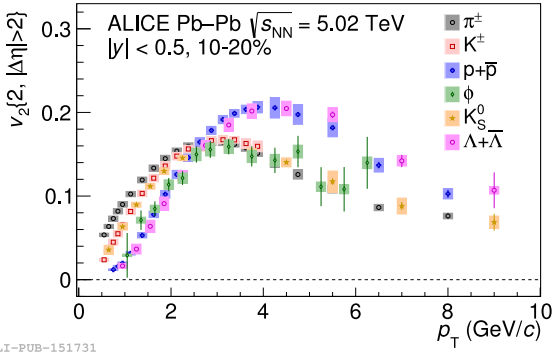


ALICE: Phys Lett B 719 (2013) 29

v2 for identified particles in p-Pb



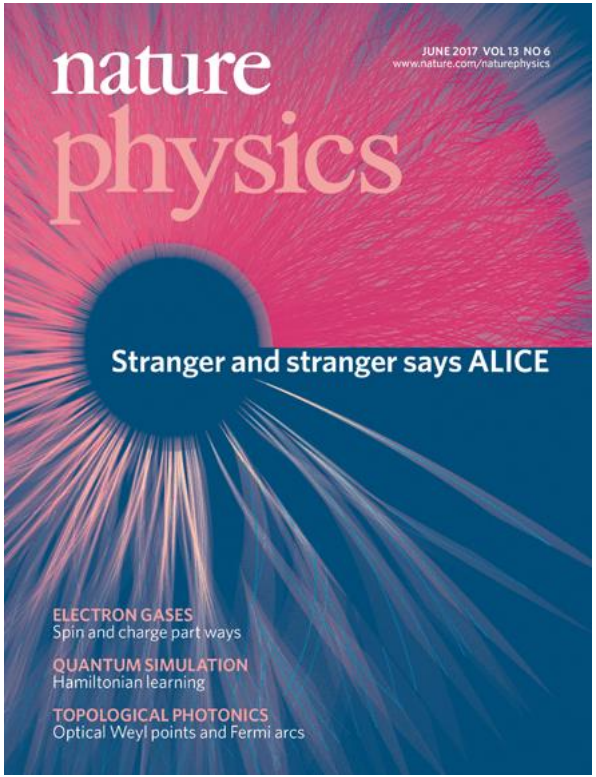
- clear mass ordering at high multiplicity
  - same as in Pb-Pb



- consistent with common velocity field

→ consistent with hydrodynamic expansion!

Strangeness enhancement in pp!



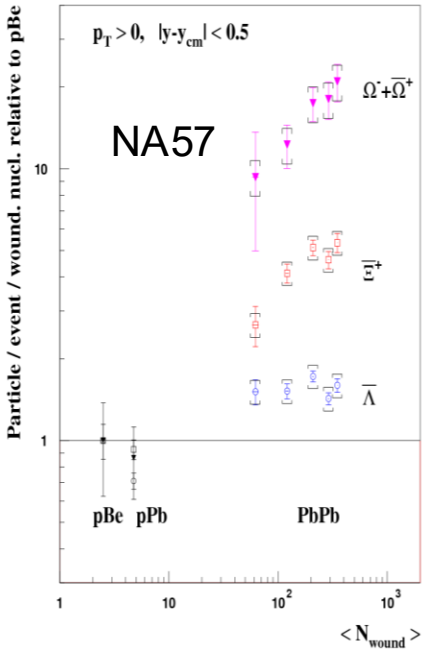
Nature Physics (2017) doi:10.1038/nphys4111

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

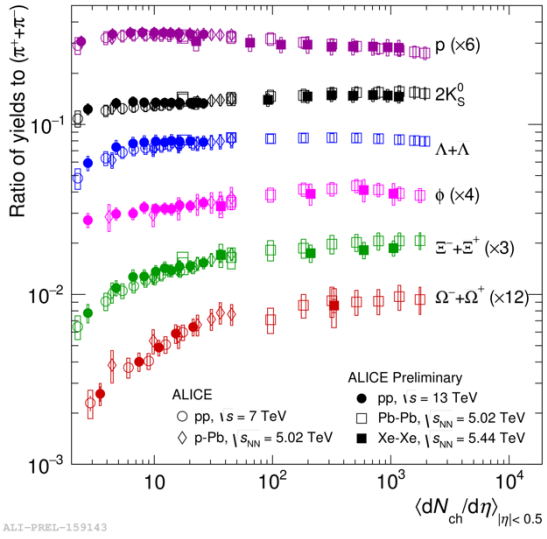
→ observed at SPS in the 90's
WA97, NA57, NA49

- 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



→ 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

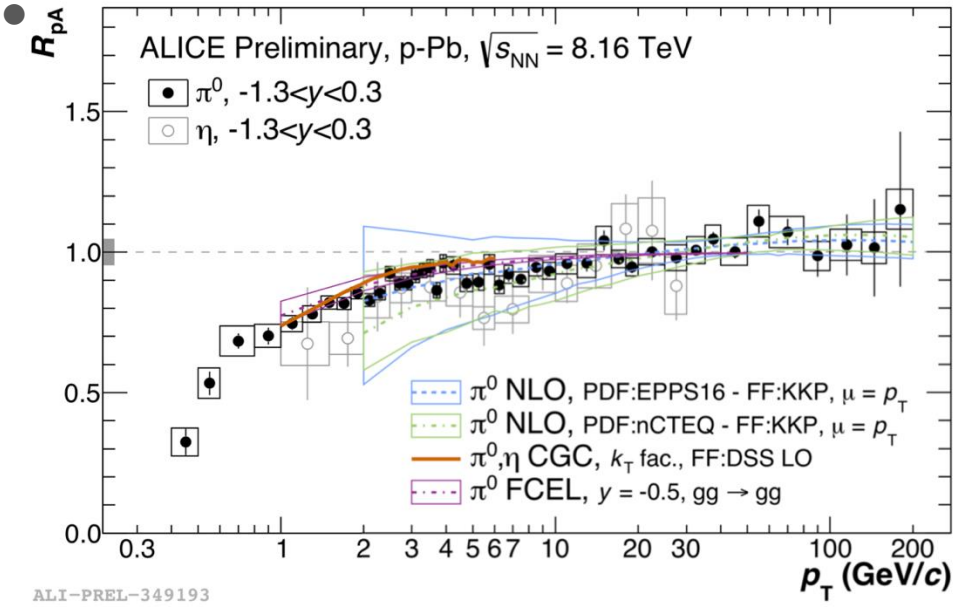
- strangeness enhancement vs size
  - smooth evolution vs event multiplicity
- challenge for pp event generators
  - e.g.: T Sjostrand at Quark Matter 2018

Summary and outlook

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.
- String close-packing likely to influence hadronization, before (shoving), during (ropes) and after (rescattering).
- Currently no known unique solution, so free to explore.
- Several recent & ongoing studies look promising, but much work and few active with pp generator outlook.
- Further experimental input crucial!

Whole new field of study opening up!

But no sign of quenching yet!

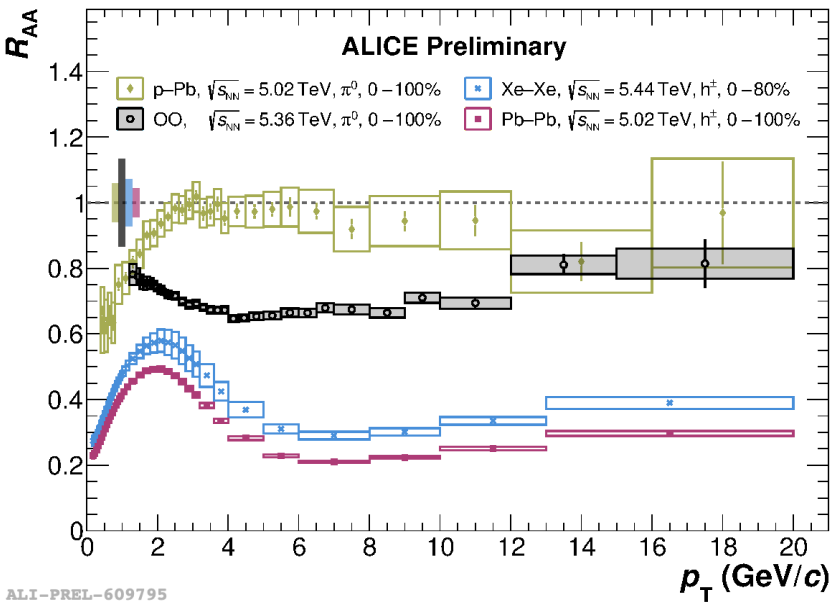


[ALICE: PLB 827 (2022) 136943]

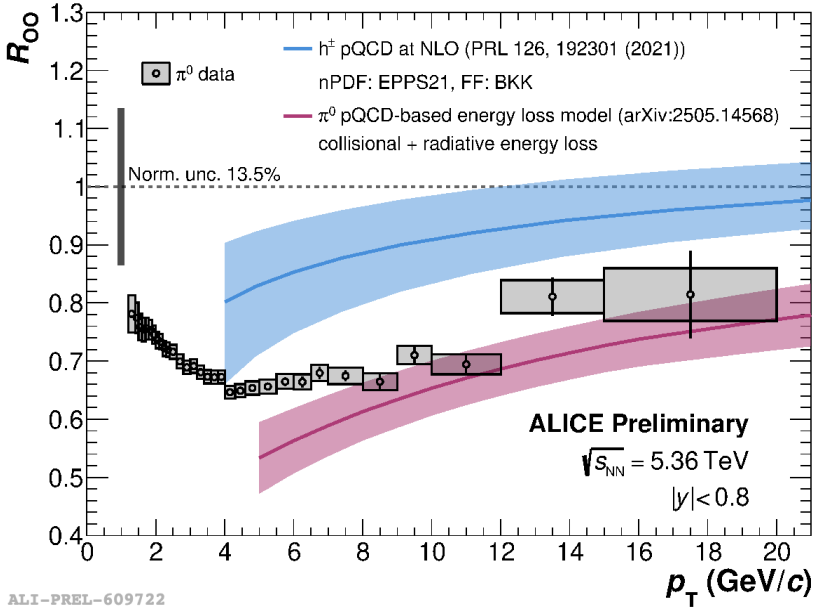
Light ions in the LHC!

OO, pO and Ne-Ne collisions in the LHC in July

- significant quenching observed!



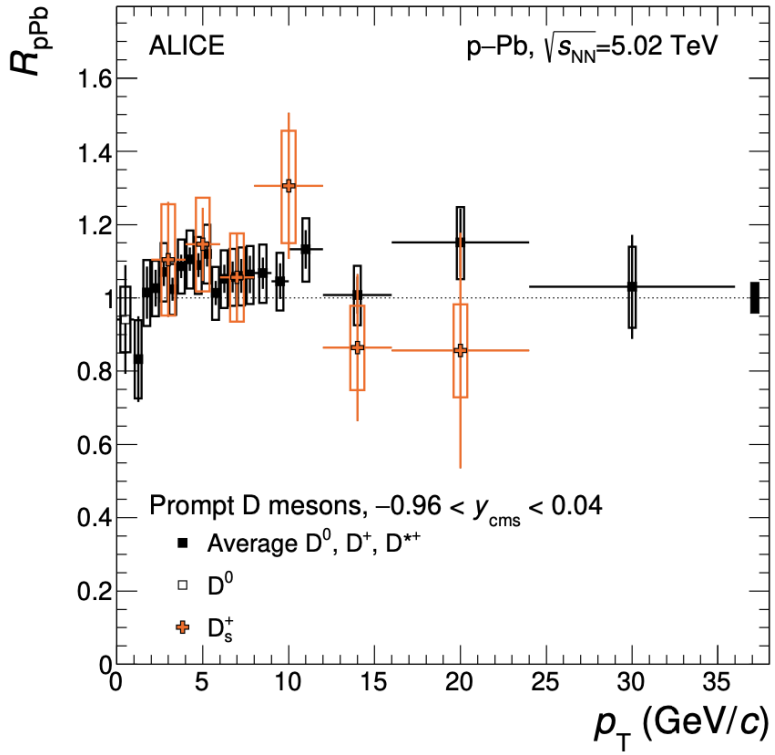
- beyond nPDF suppression



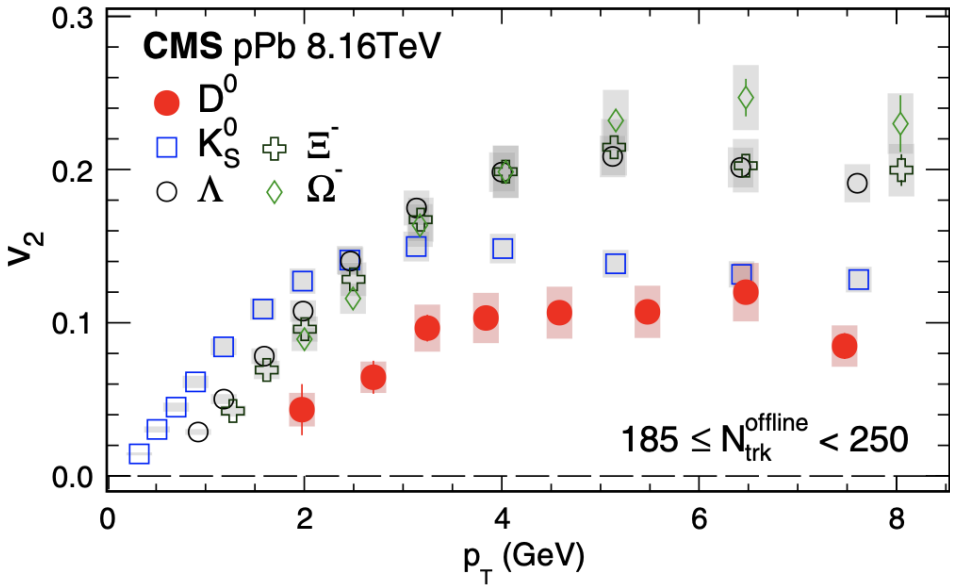
→ stay tuned!

How about heavy flavour in small systems?

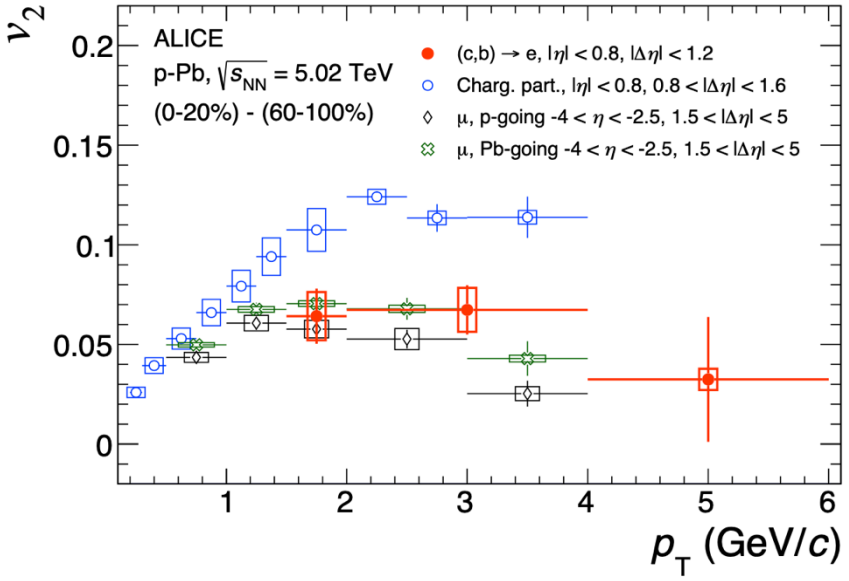
- no sign of quenching for charm (like for everything else...)



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



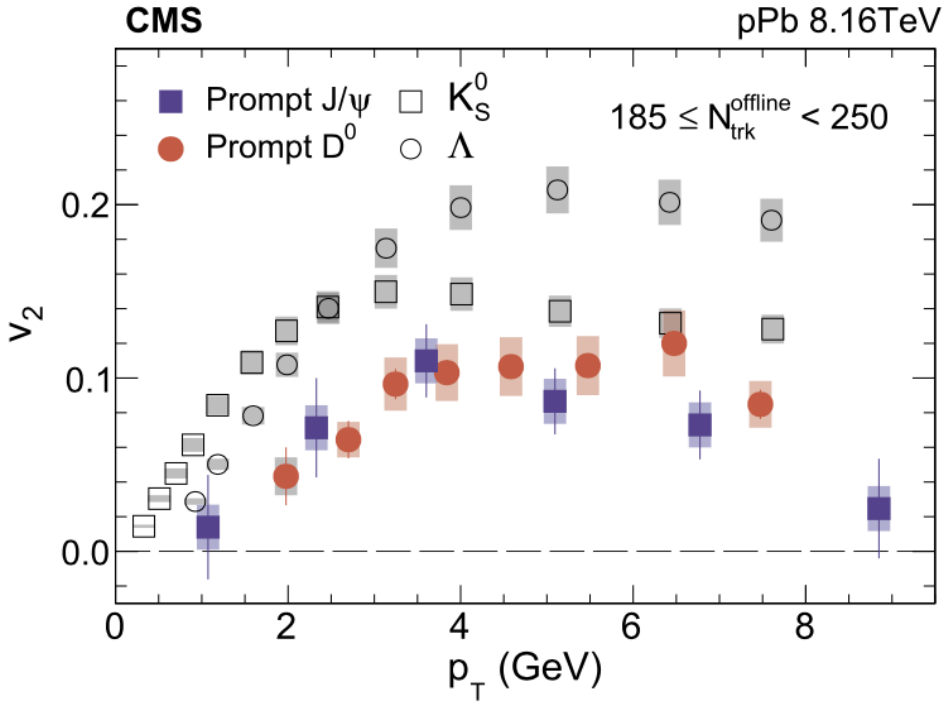
CMS: PRL 121 (2018) 082301



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...?

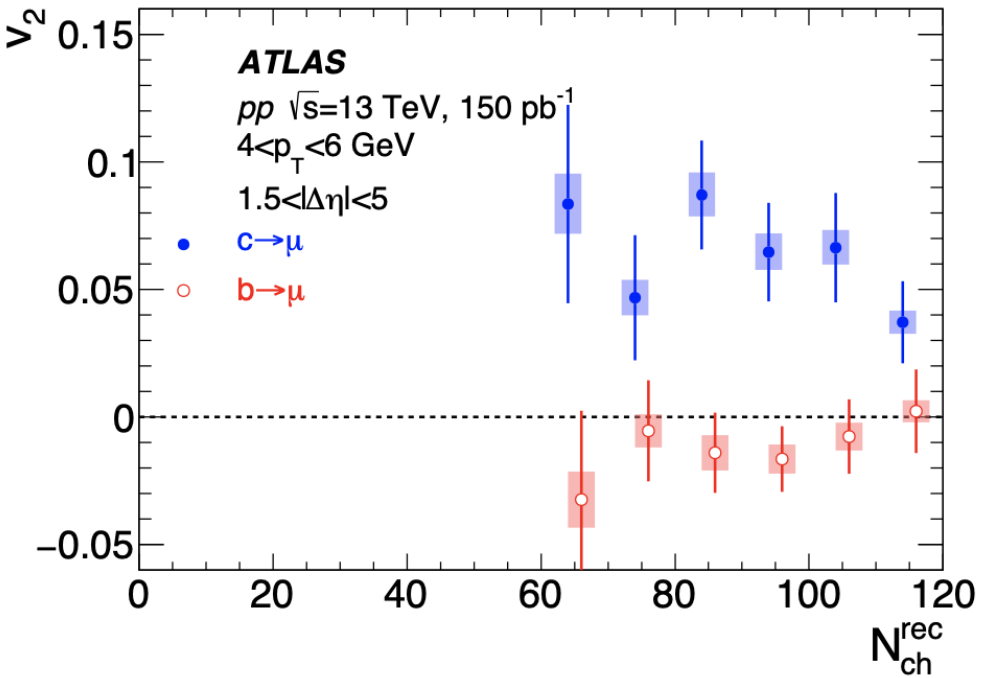
... also for prompt J/ψ...



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...

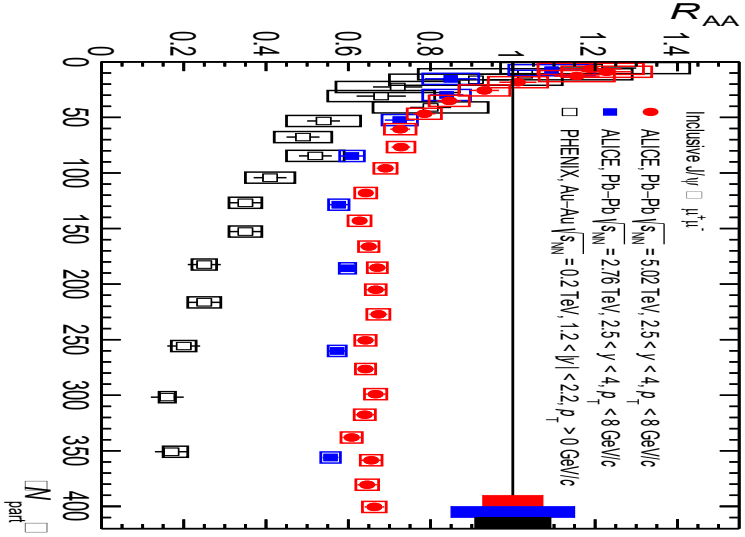


ATLAS: PRL 124 (2020) 082301

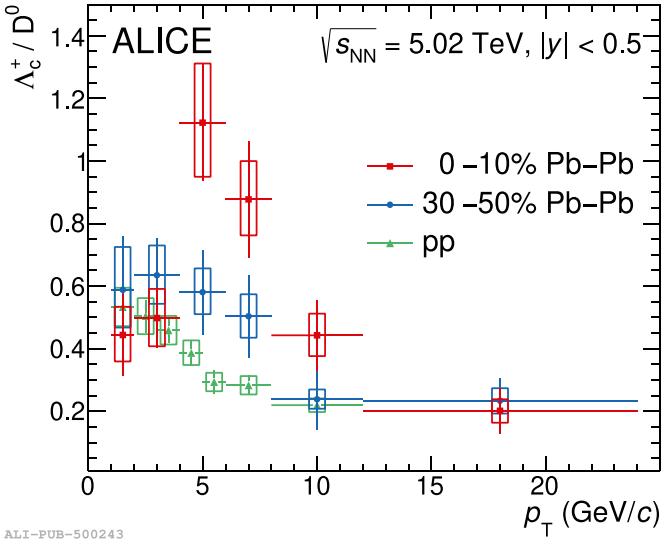
- another one of those beauty things...

In-medium hadronisation, a rich sector!

charmonium



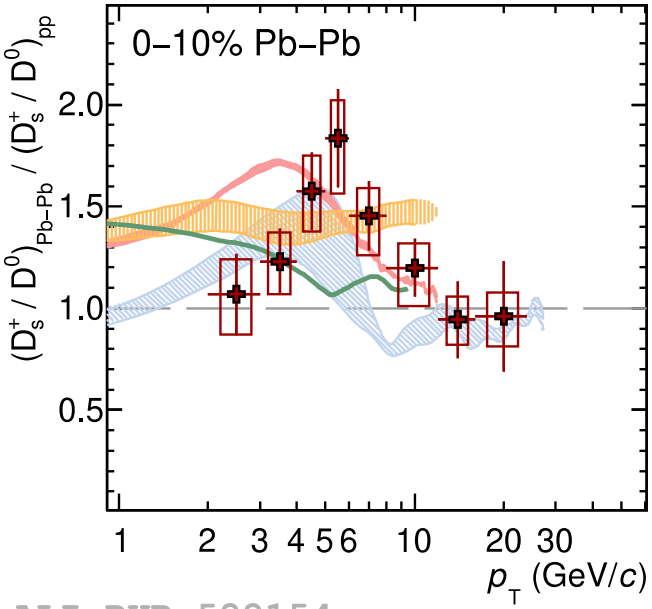
HF baryons



ALICE: arXiv:2112.08156

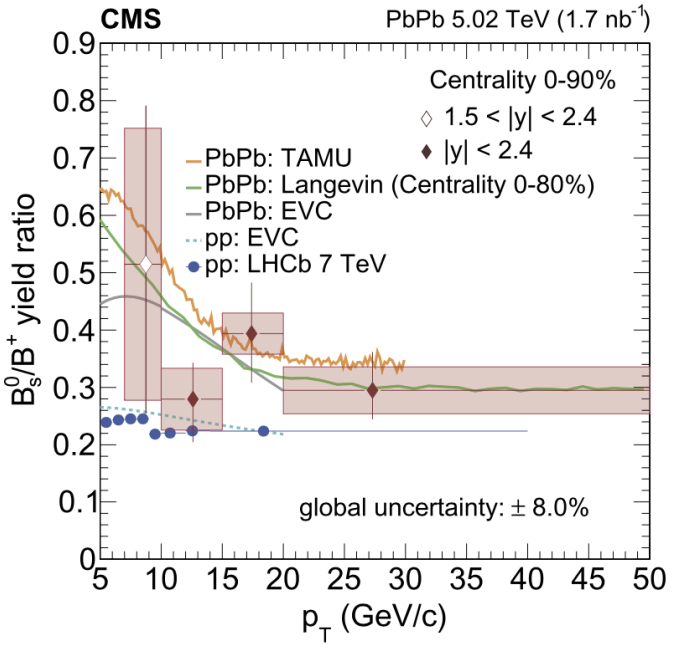
Strangeness enhancement in Pb-Pb!

D_s



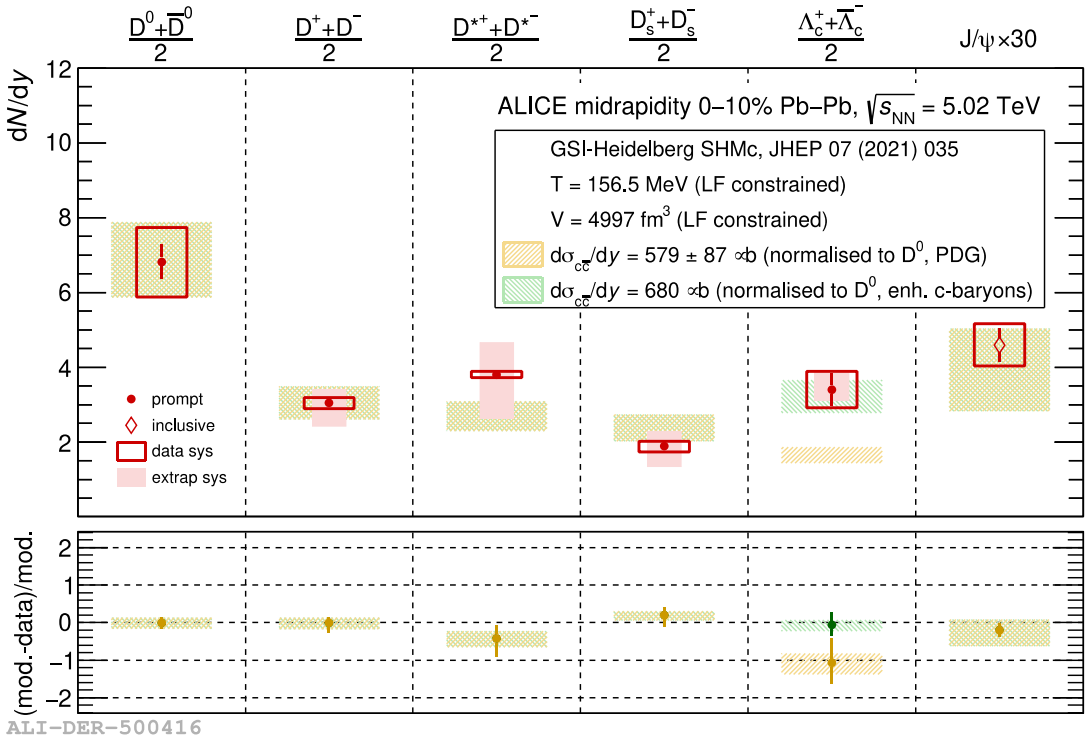
ALICE: PLB 827 (2022) 136986

B_s?

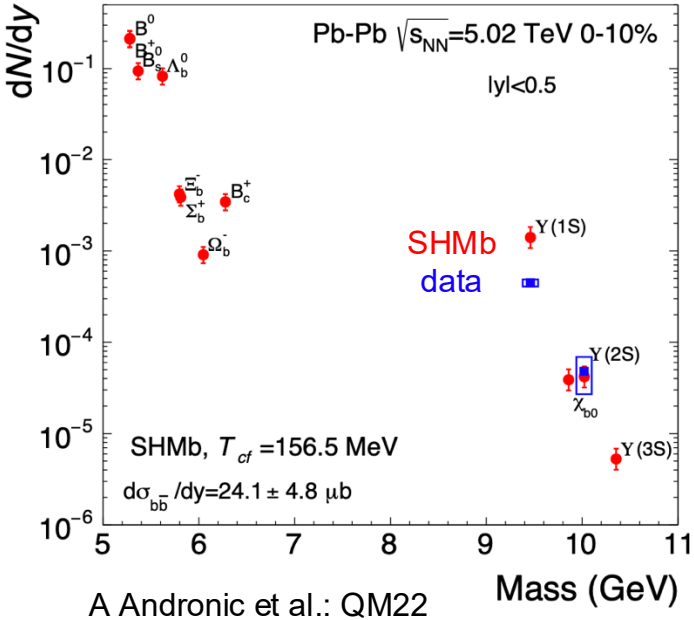


CMS: PLB 829 (2022) 137062

Chemical equilibrium for HF hadrons?



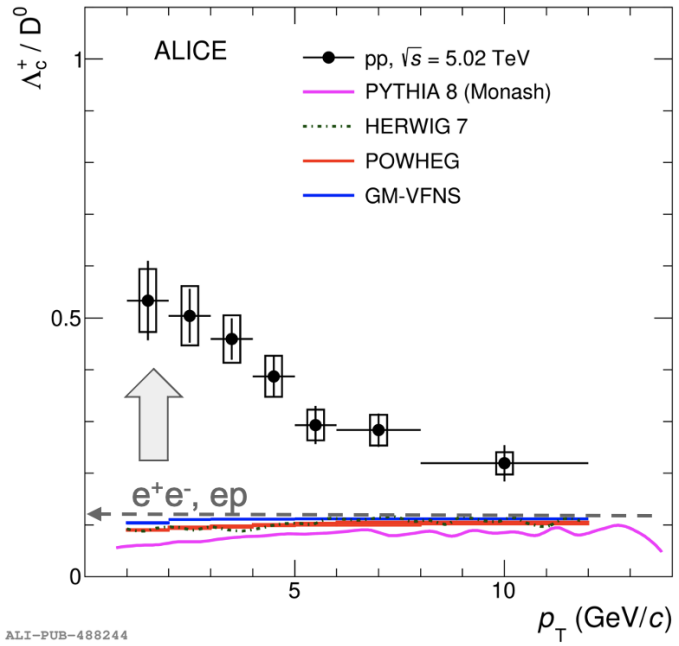
- for charm, looks like...
  - not for absolute σ, of course...
  - γ_c ~ 30 for 0-10%
- and, once again, b is different...
  - SHMb ~ 3 x data for Υ(1S)

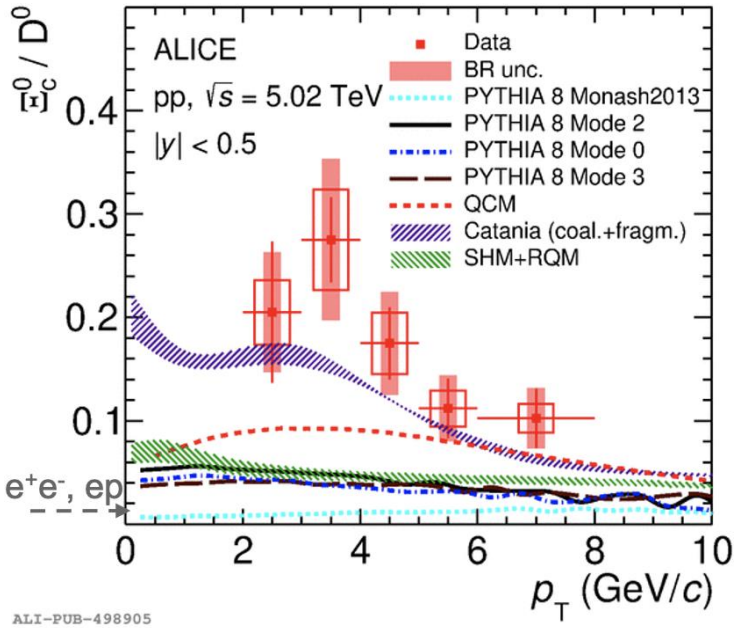


A Andronic et al.: QM22

Already in pp, p-Pb...

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

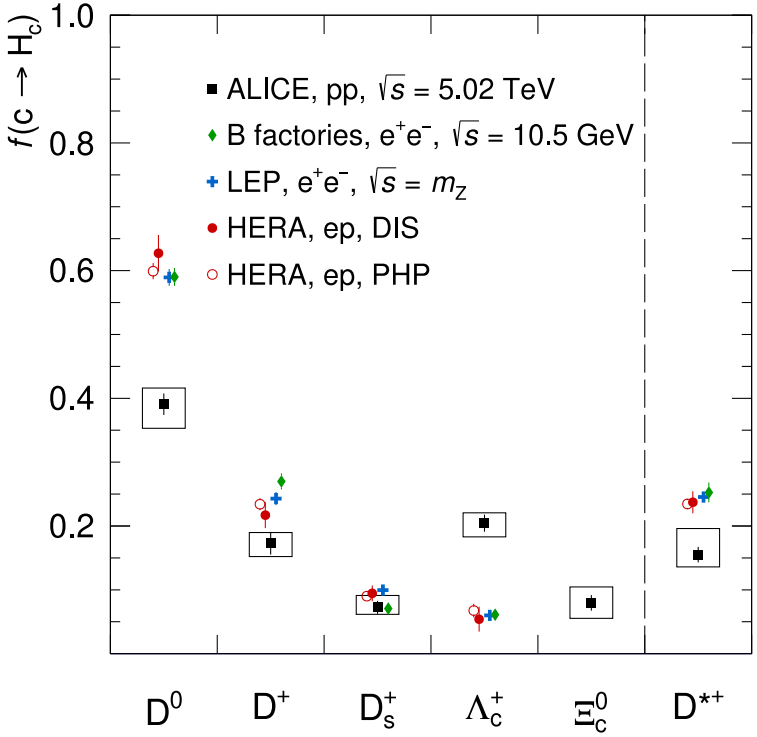




ALICE: PRL 127 (2021) 202301

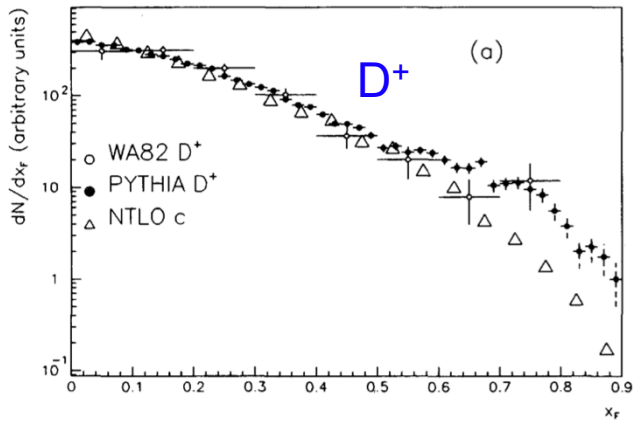
ALICE: JHEP 10 (2021) 159

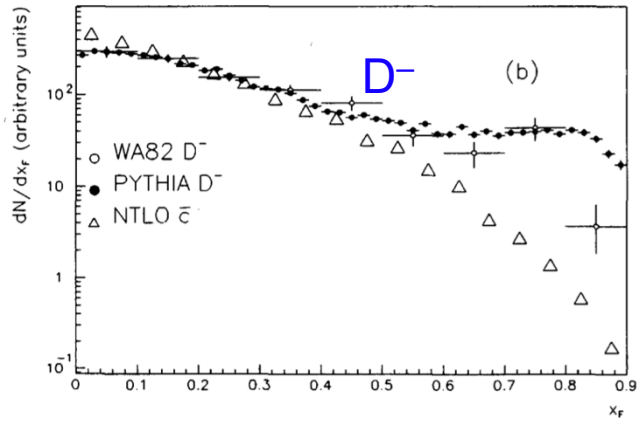
Fragmentation Fractions: pp ≠ e^+e^-



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

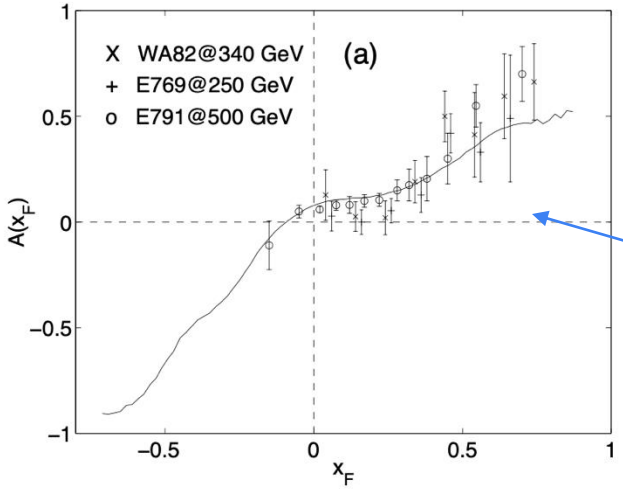
But already at the SPS... (my thesis 🙂!)





WA82: PLB 305 (1993) 402

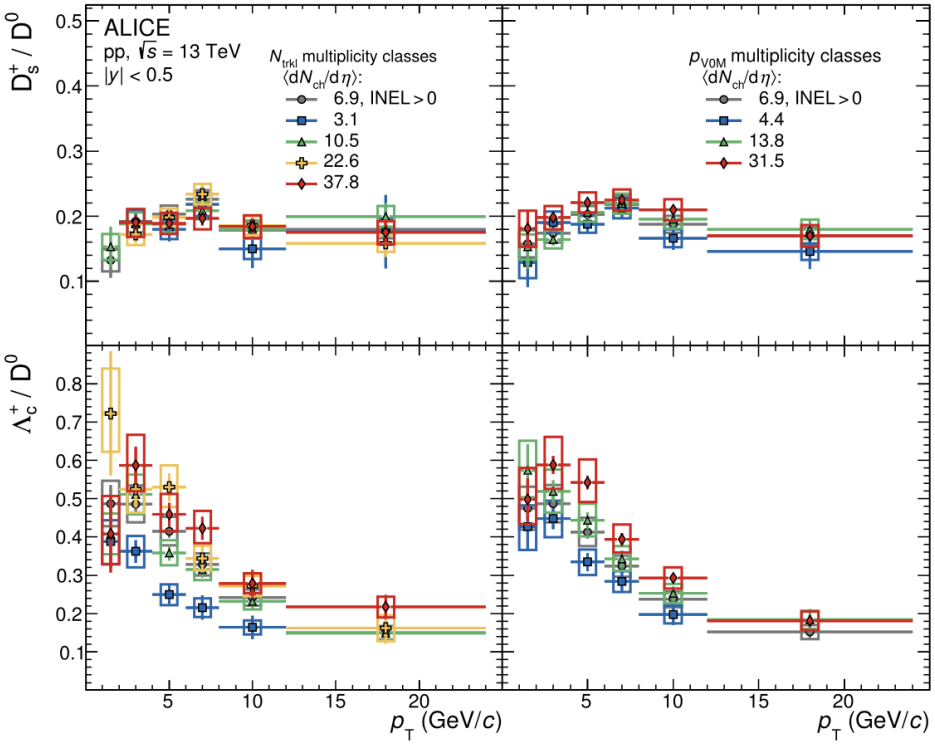
- WA82 (OMEGA): π^-A collisions
  - charm production in forward hemisphere
- beam valence: $d\bar{u}$ (π^-)
- excess of D⁻ ($\bar{c}d$) over D⁺ ($c\bar{d}$)
  - $D^-/D^+ = 1.34 \pm 0.13$
- particularly pronounced close to beam x_F
- (try and do this with Peterson's fragmentation...)
- modified PYTHIA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



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

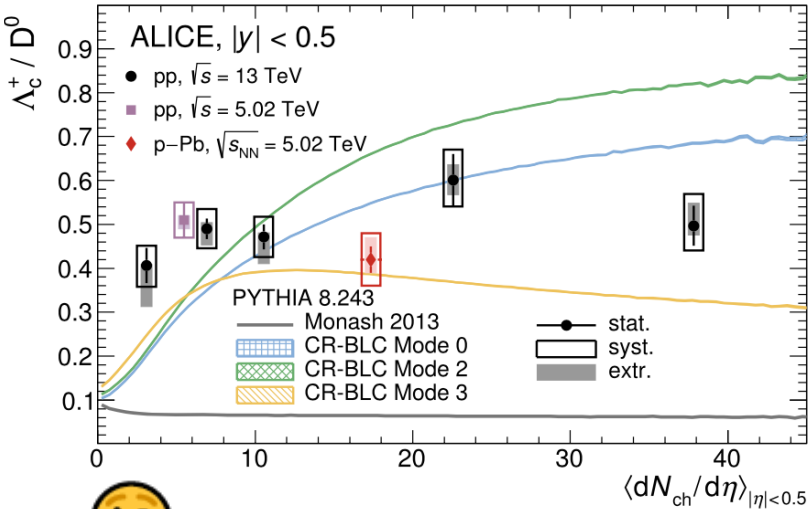
(asymmetry vs x_F)

Multiplicity evolution?



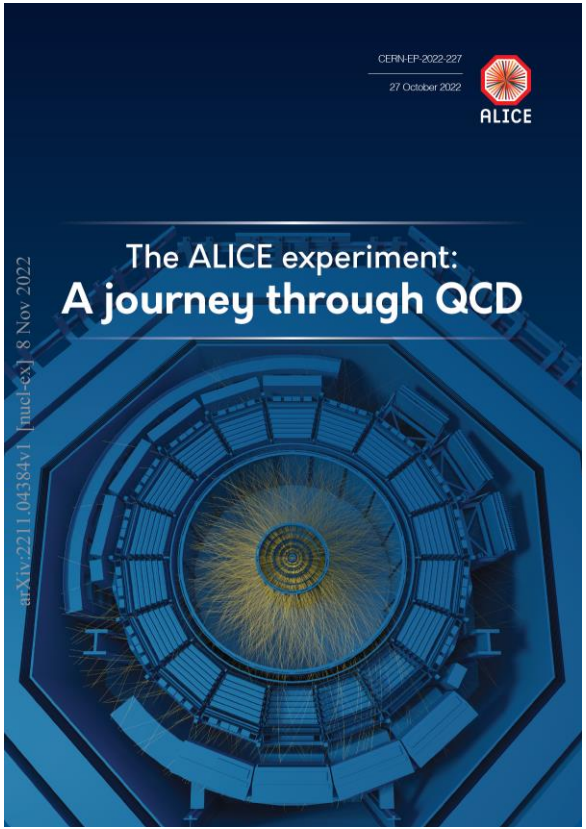
ALICE: PLB 829 (2022) 137065

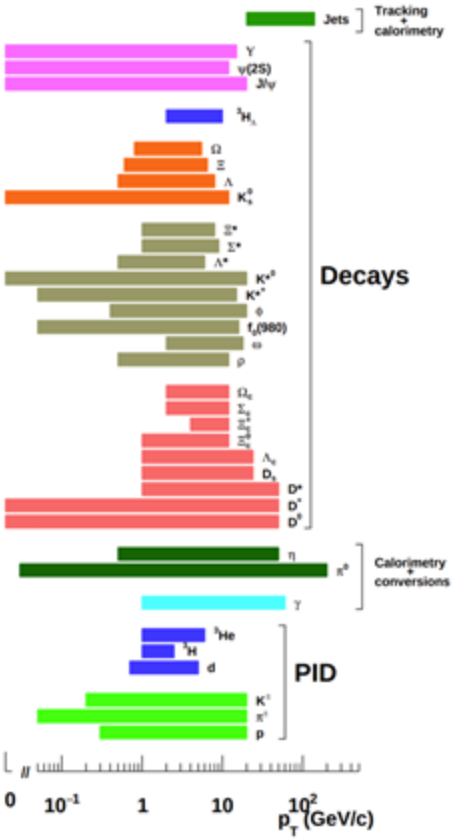
- clear evolution for Λ_c/D
  - (not so much for D_s/D...)
  - (wrt neither to cent nor to fwd mult'y)
- and not much for the integrated yields?



- 🤔 ...

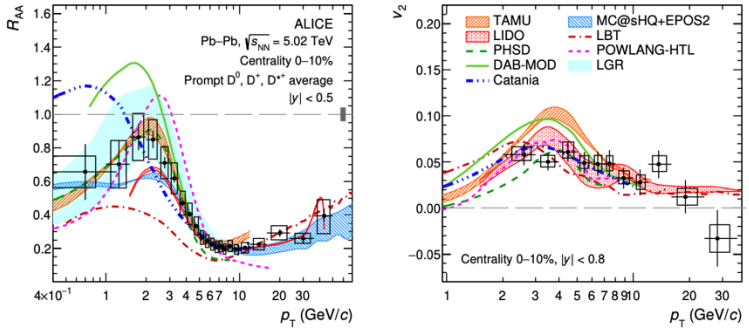
ALICE results from LHC Run 1, 2: full review

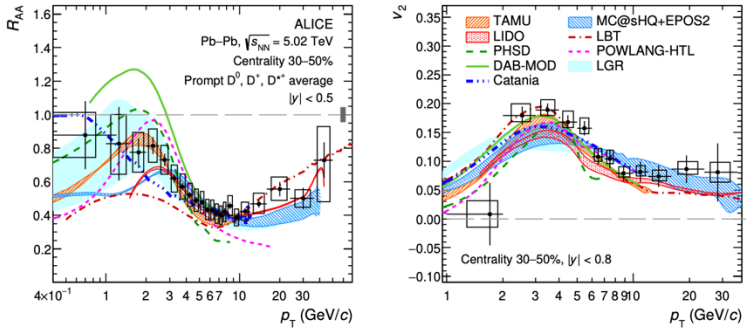


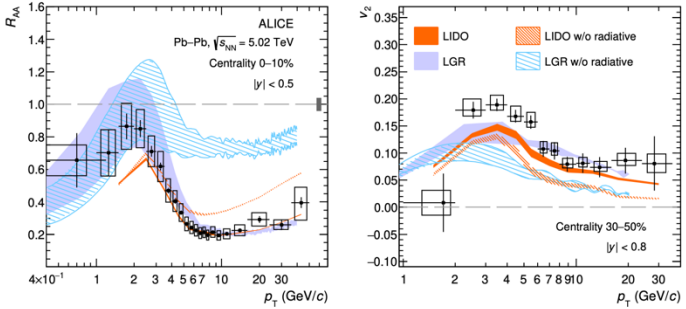


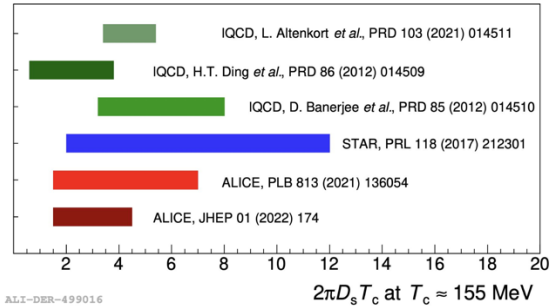
arXiv:2211.04384

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

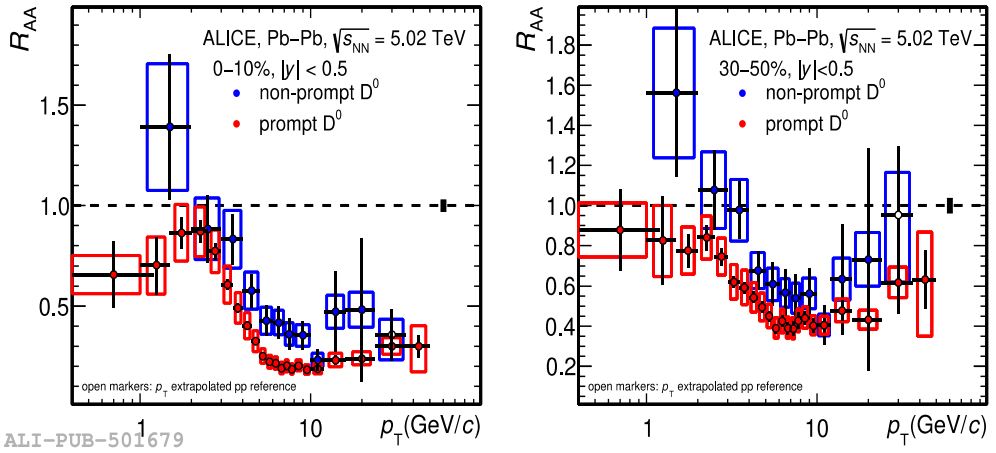
Low-p_T beauty!

- 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 $m_b \sim 3 m_c$)
  - 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...?

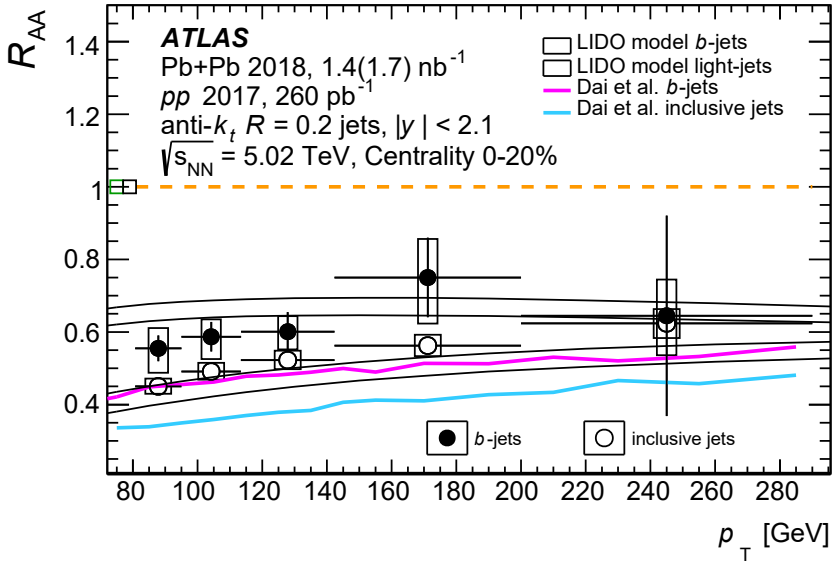


→ need high-precision b down to p_T=0

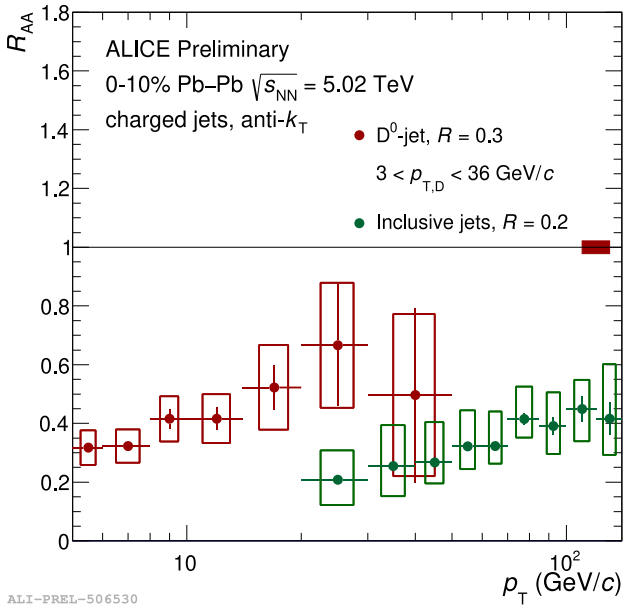
→ (and watch the hadrochemistry!)

Jets as quark proxy

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



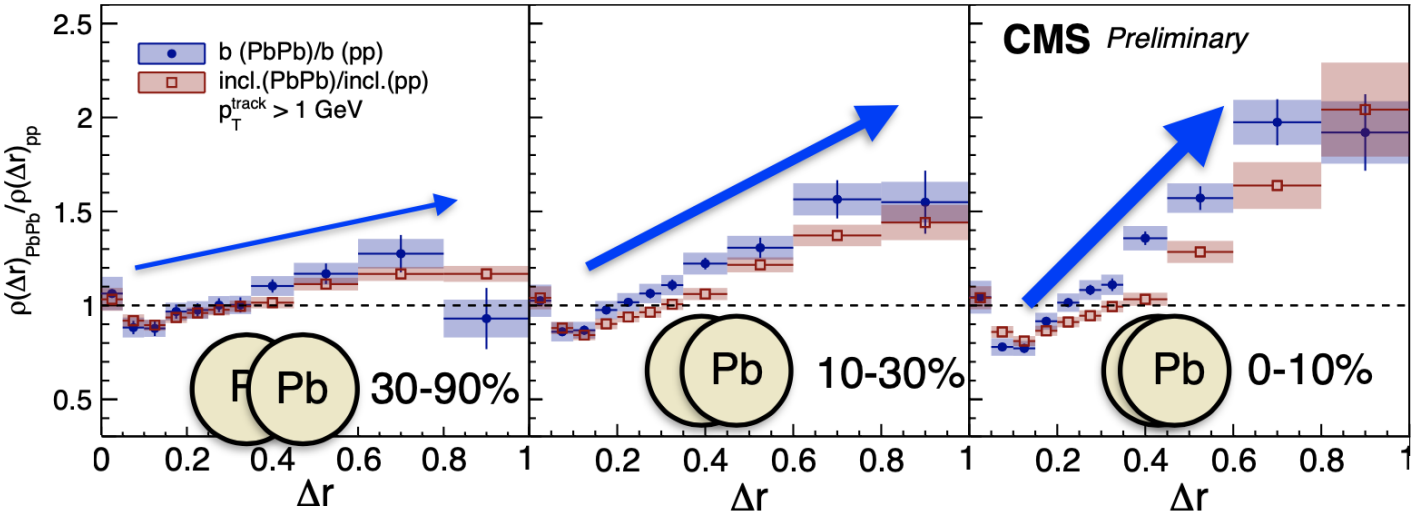
ATLAS: arXiv:2204.13530



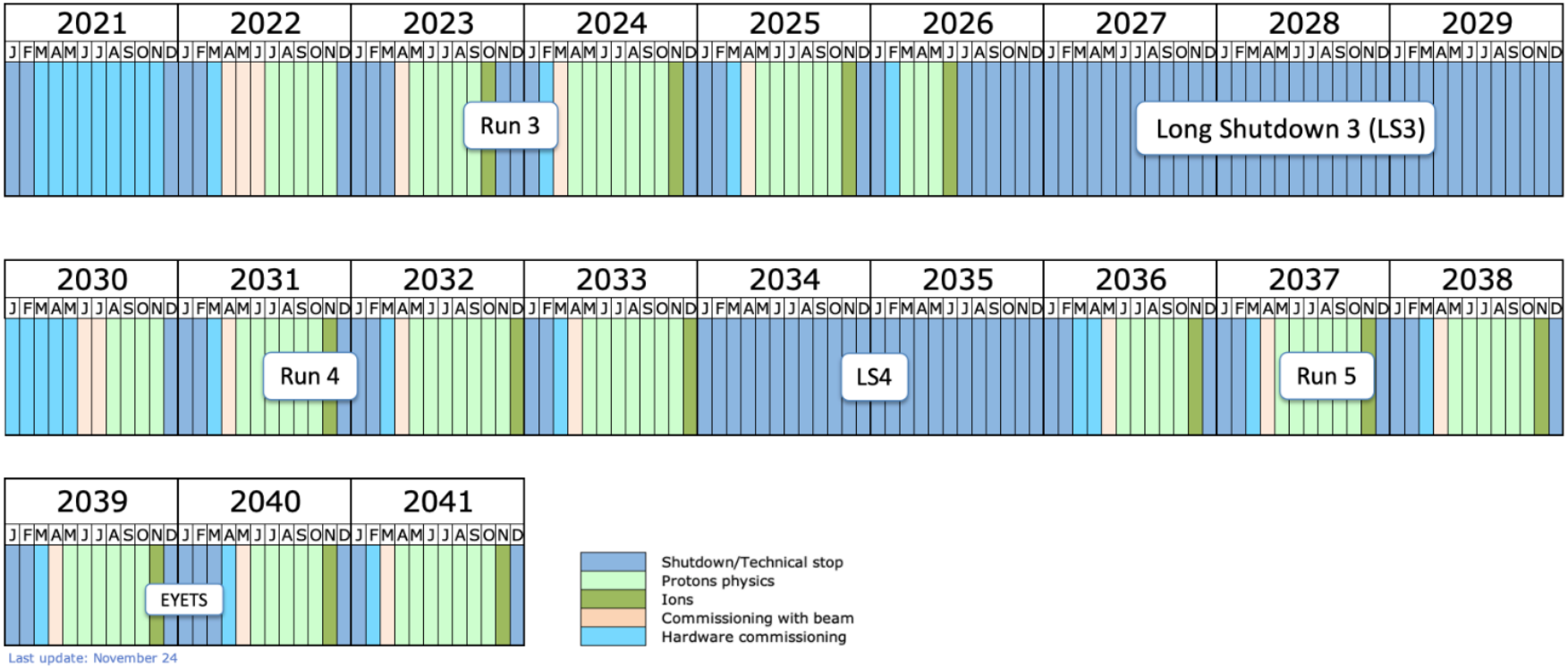
ALICE: SQM 2022

Jets as imaging of in-medium parton processes

- e.g.: jet broadening



Plans for LS3, LS4



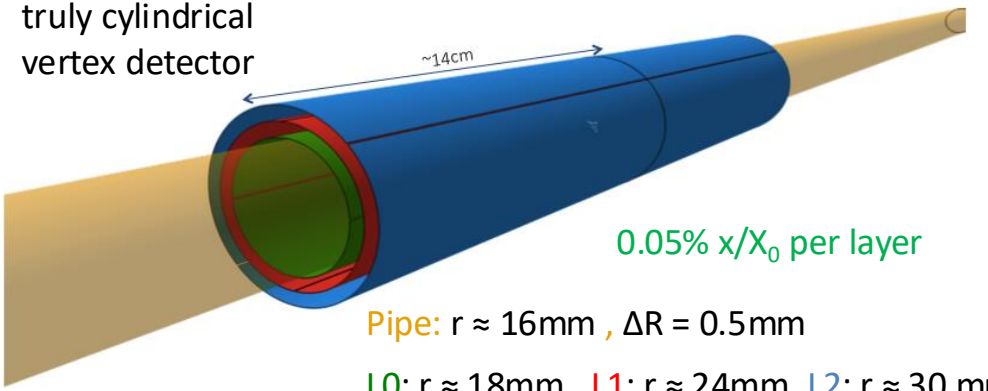
ITS3 Vertex detector (3 inner layers)

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)

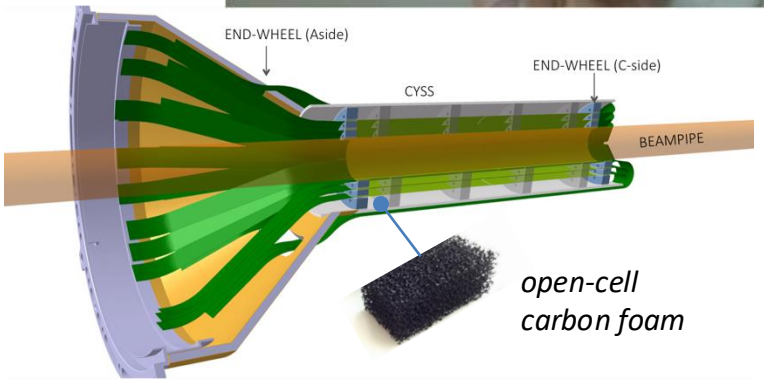
truly cylindrical
vertex detector



0.05% x/X_0 per layer

Pipe: r ≈ 16mm , ΔR = 0.5mm

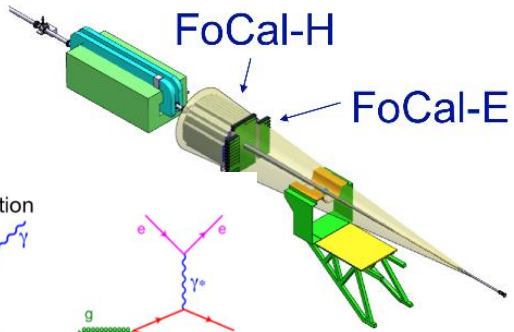
L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm

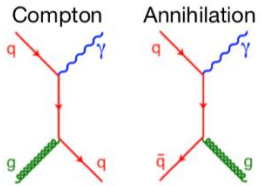


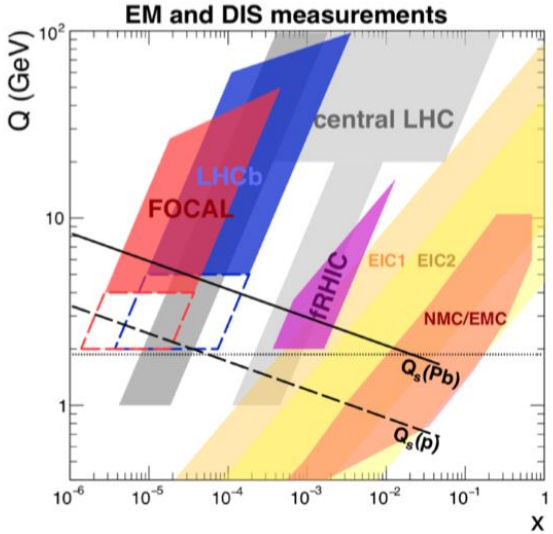
FoCal

- 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

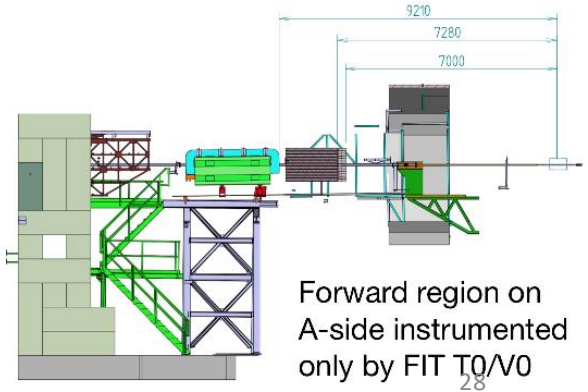
→ access to gluon parton distribution functions







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



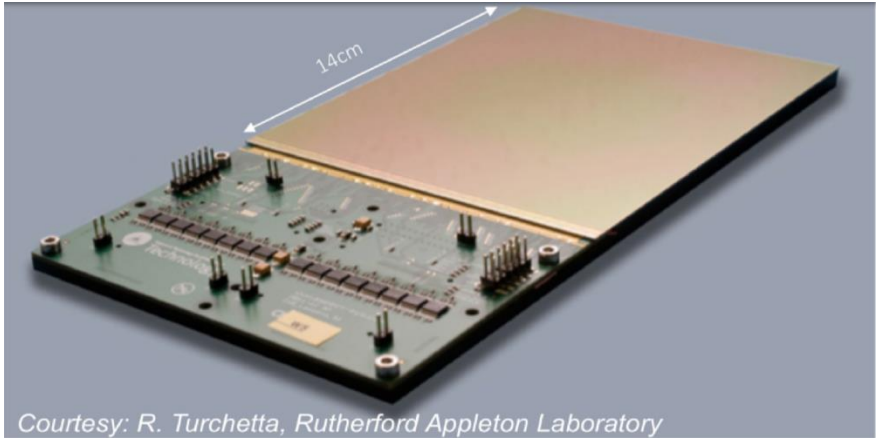
Forward region on A-side instrumented only by FIT T0/V0

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, …

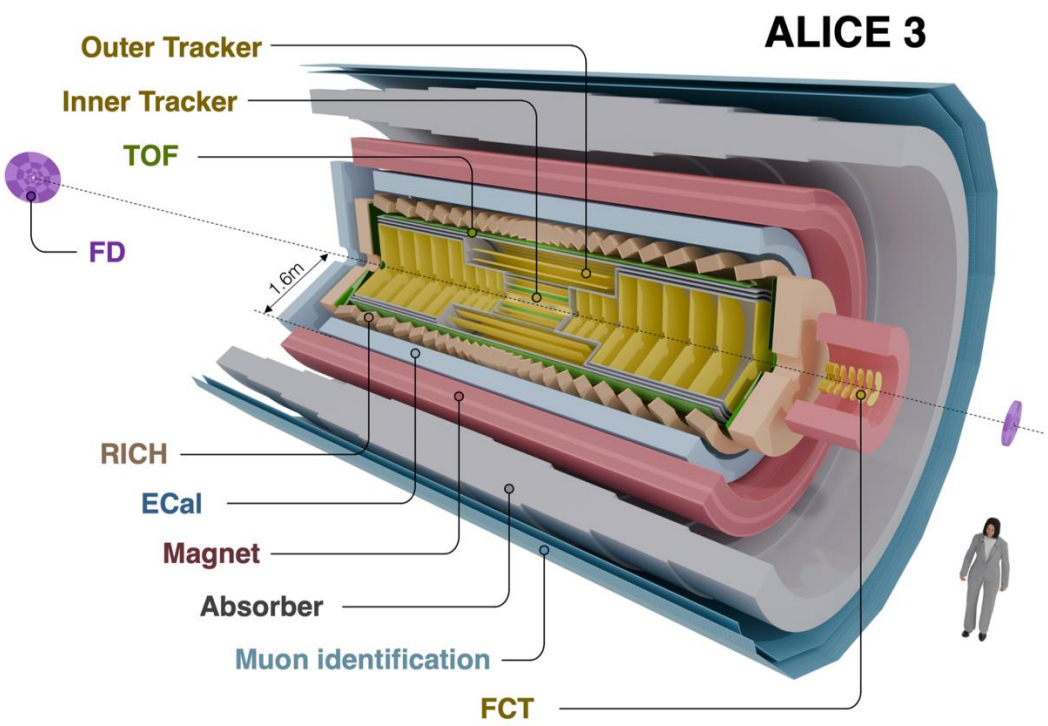
flexible wafers



wafer-size circuits (stitching)

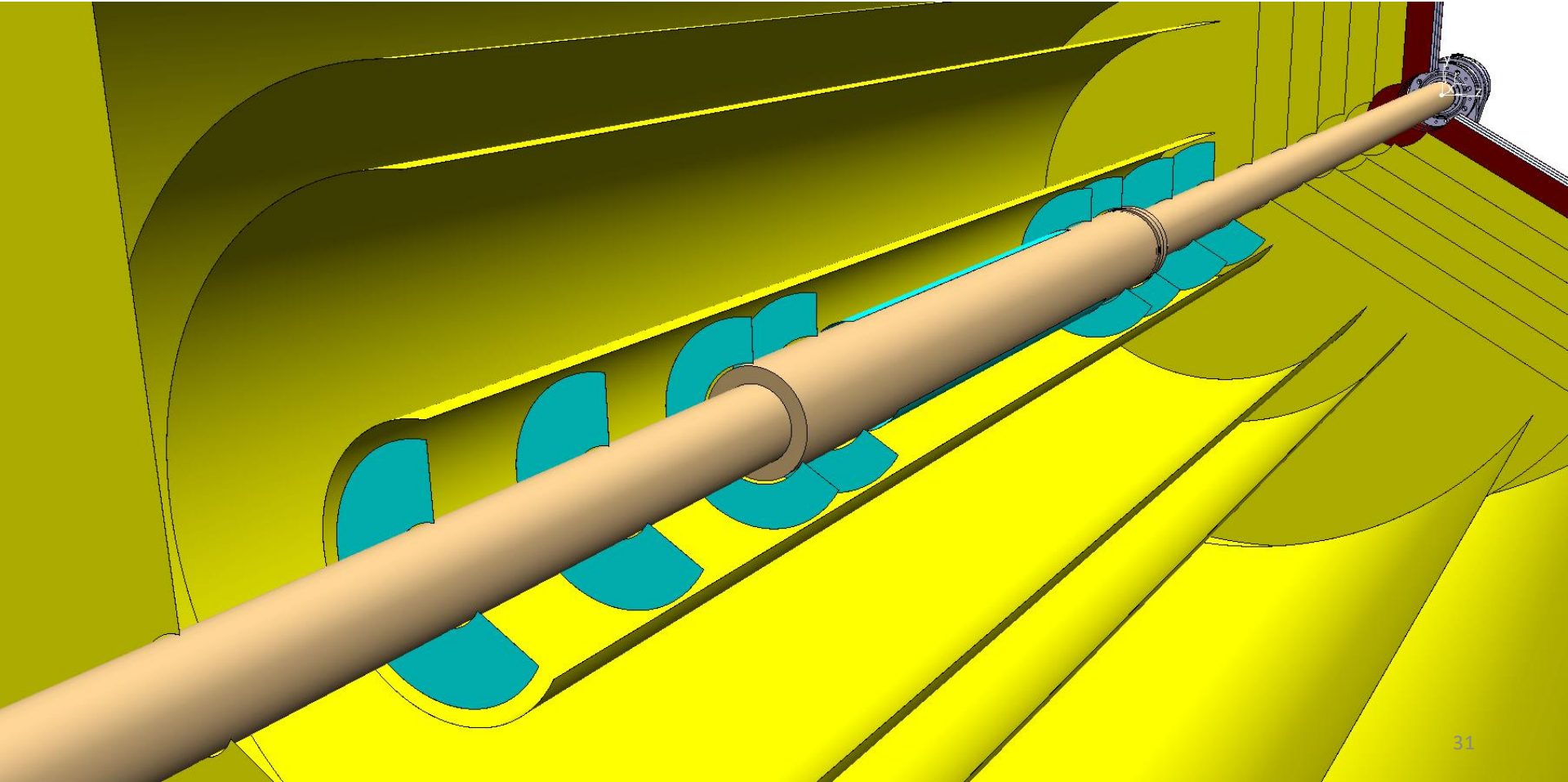
The new frontier: ALICE 3!

a next-generation heavy-ion experiment at the LHC

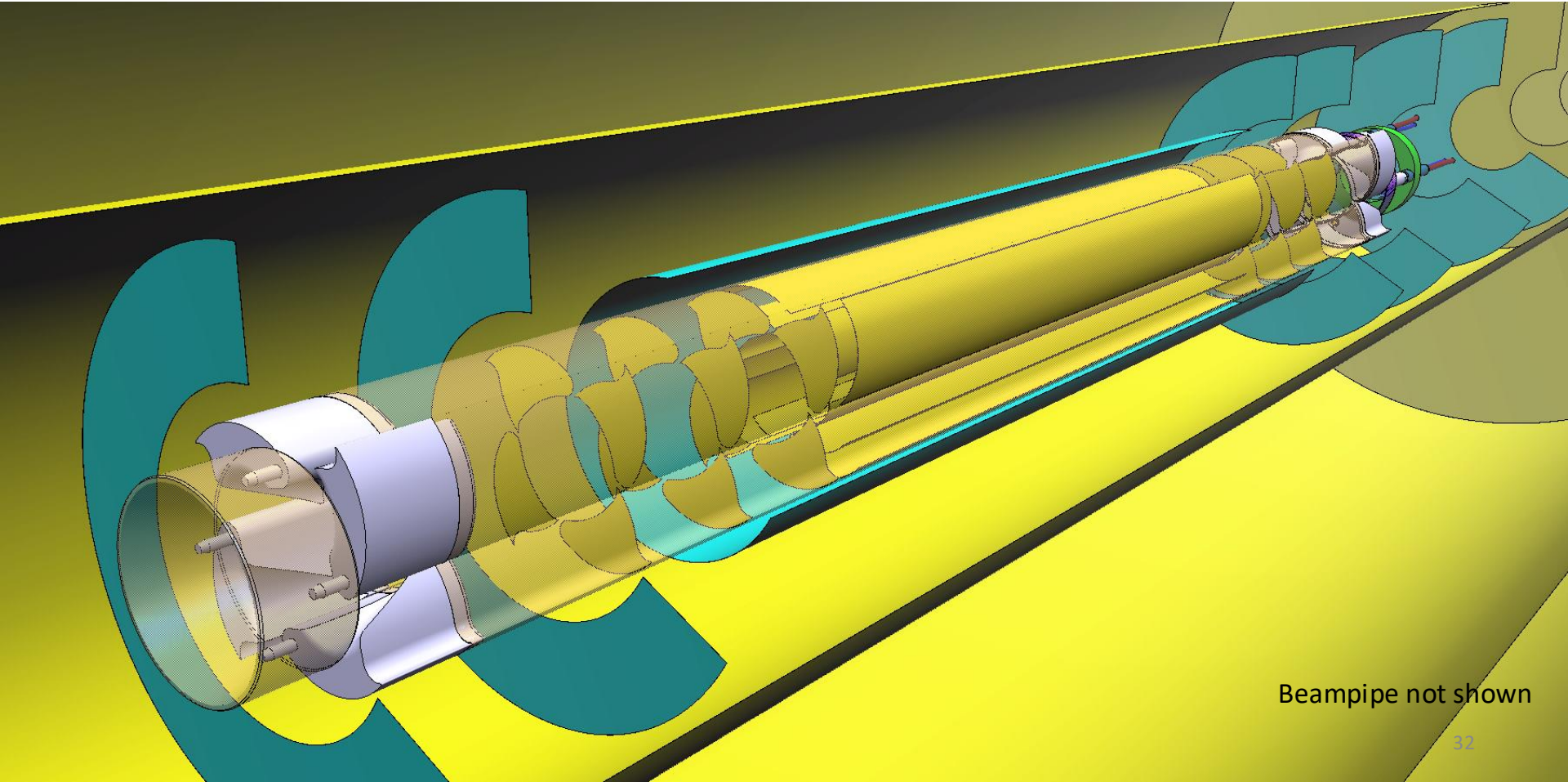


- compact, “all-silicon” tracker
- wide rapidity acceptance (8 units)
- high-resolution vertex detector
  - as close as possible to beams!
- superconducting magnet system
- hadron, muon, electron identification
- forward conversion tracker

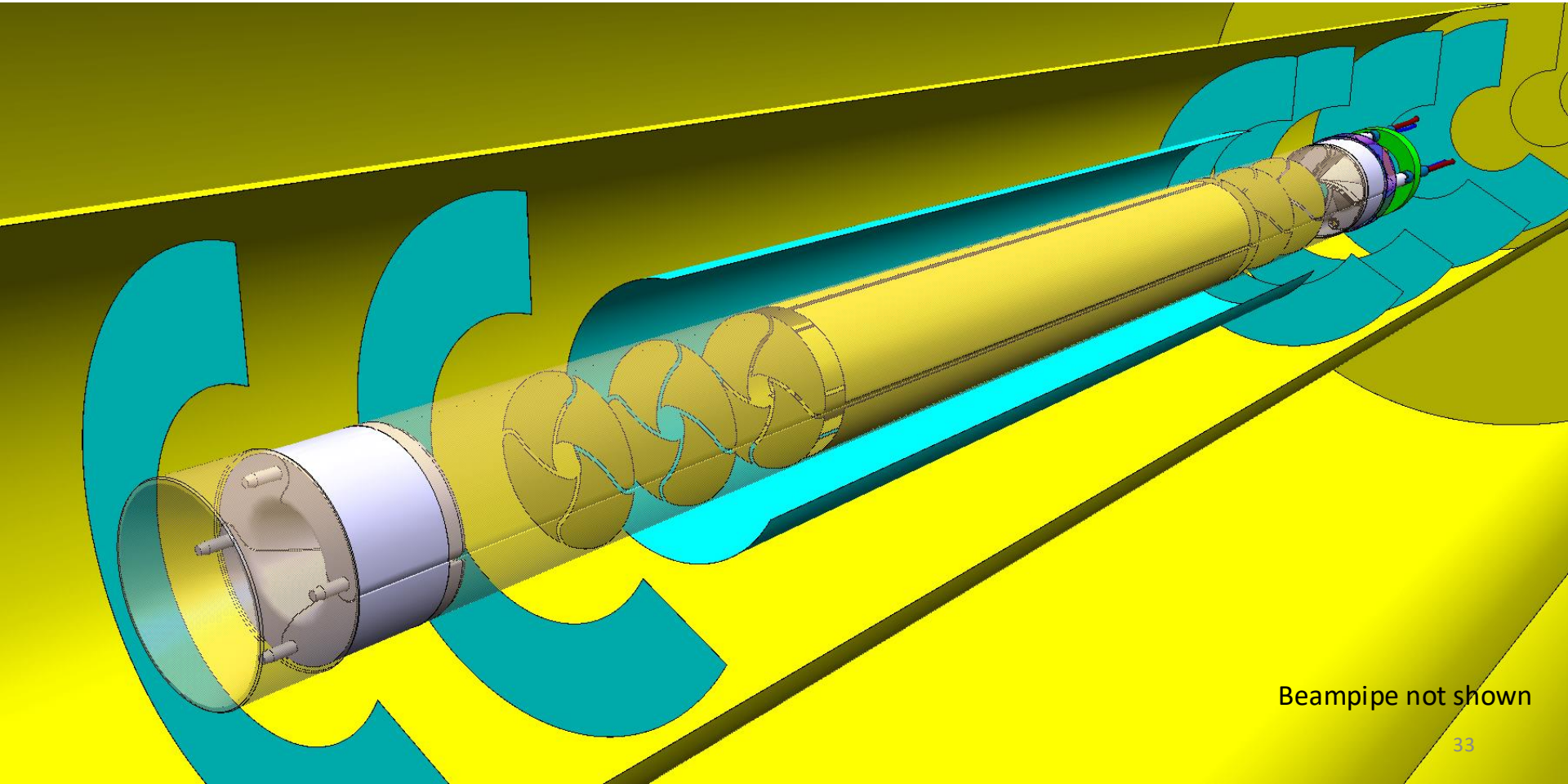
IRIS: inside the beam pipe



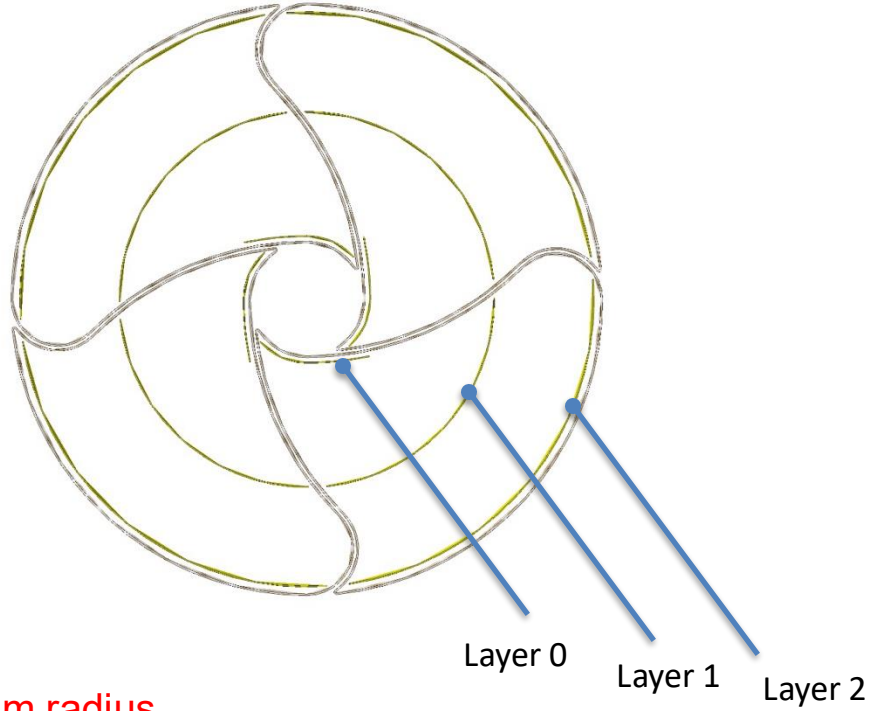
IRIS: inside the beam pipe



IRIS: inside the beam pipe



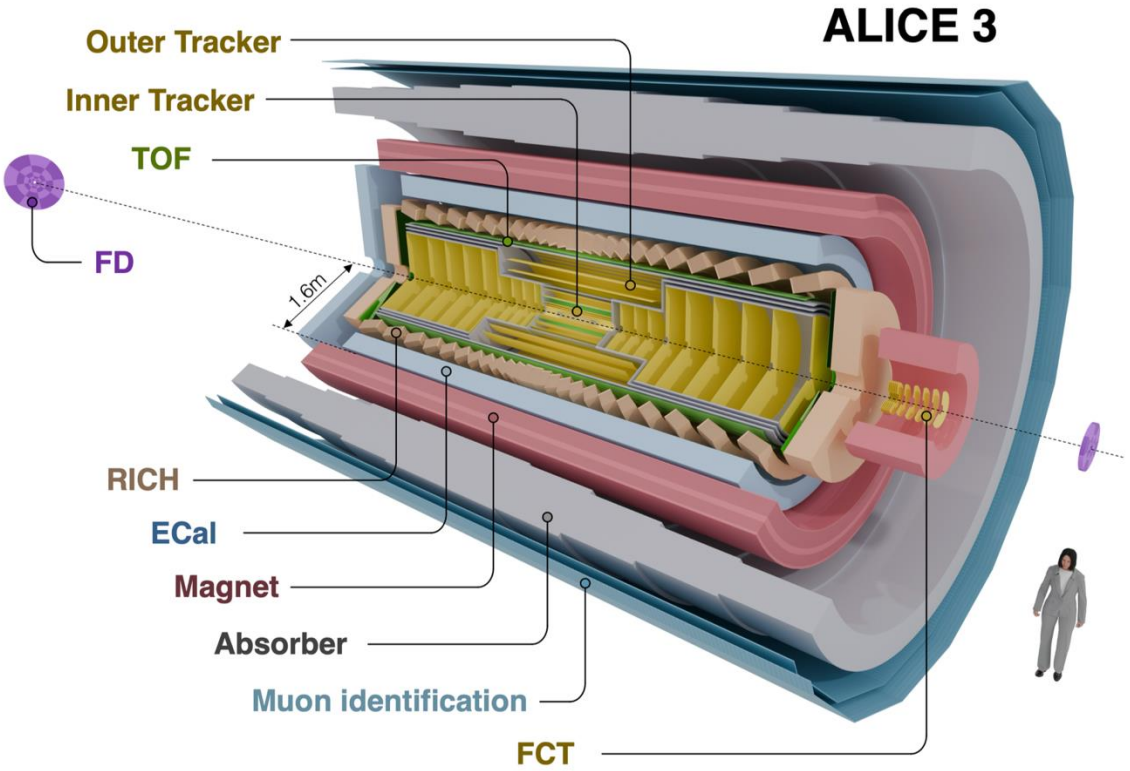
IRIS: aperture



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

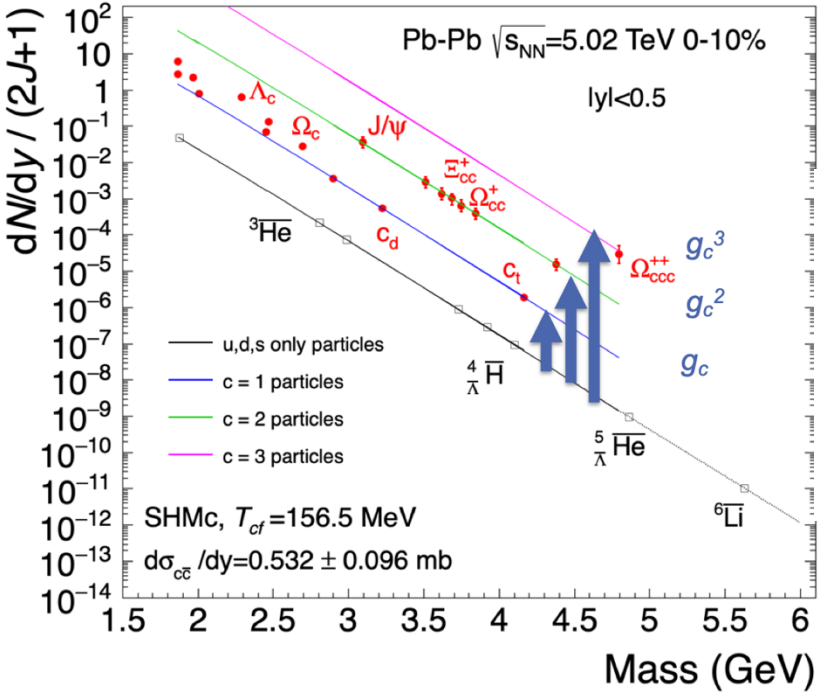
Physics potential

- some personal favourites…



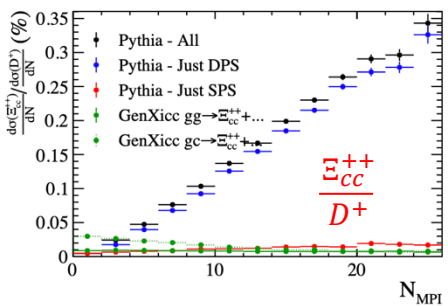
Multi-charm: the final frontier?

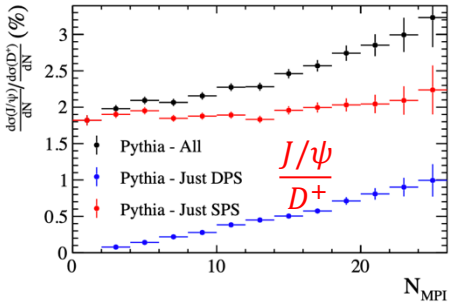
Statistical Hadronisation Model



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



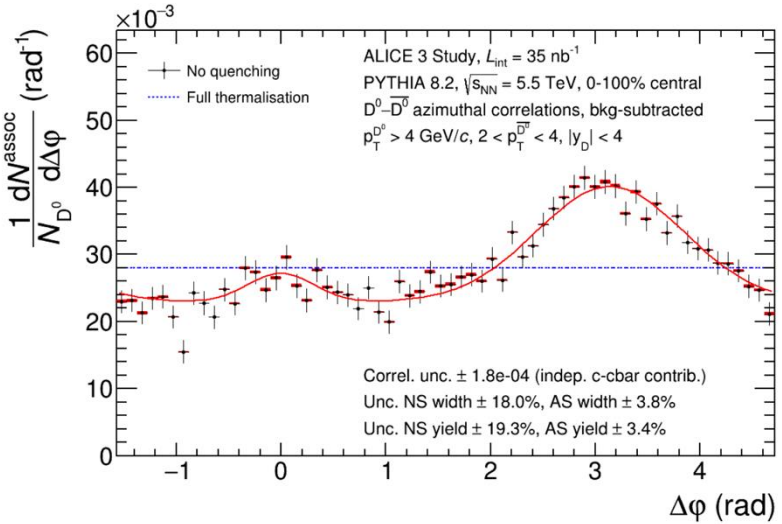


P Skands & C: arXiv:2205.15681

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

$D\overline{D}$ 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



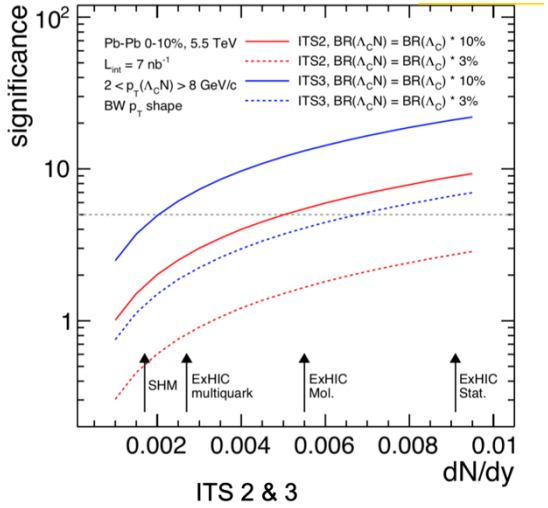
Charmed hypernuclei?

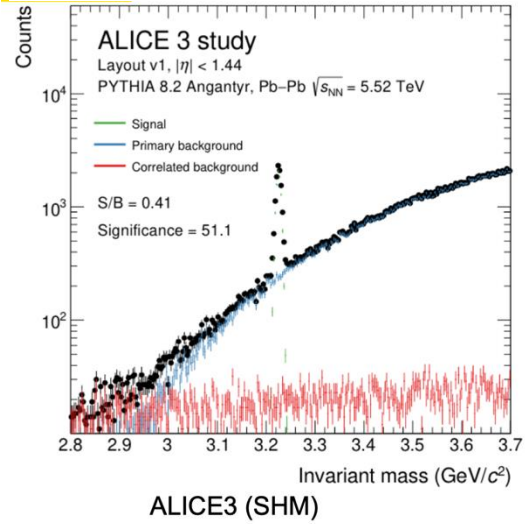
- nuclei containing a charm baryon
  - sometimes called *supernuclei*
- e.g.: c-deuteron ($\Lambda_c^+ n$), c-triton ($\Lambda_c^+ nn$)
- first suggested in the 70's
  - C B Dover and S H Kahana, PRL 39 (1977) 1506
- existence/stability debated ever since

- 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?





An old dream: thermal charm?

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

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.

- 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%

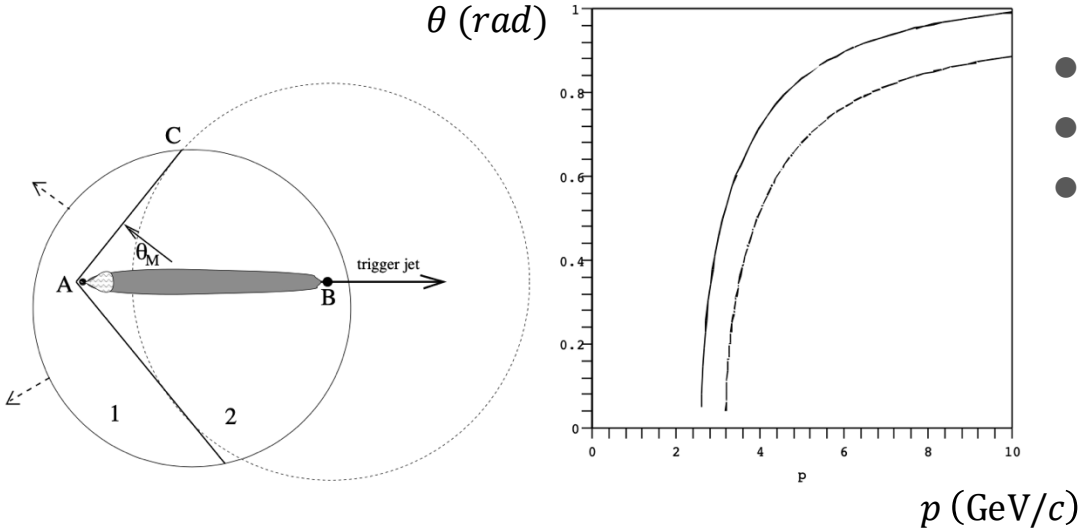
  - + centrality / A dependence different from initial component

→ 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...)

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

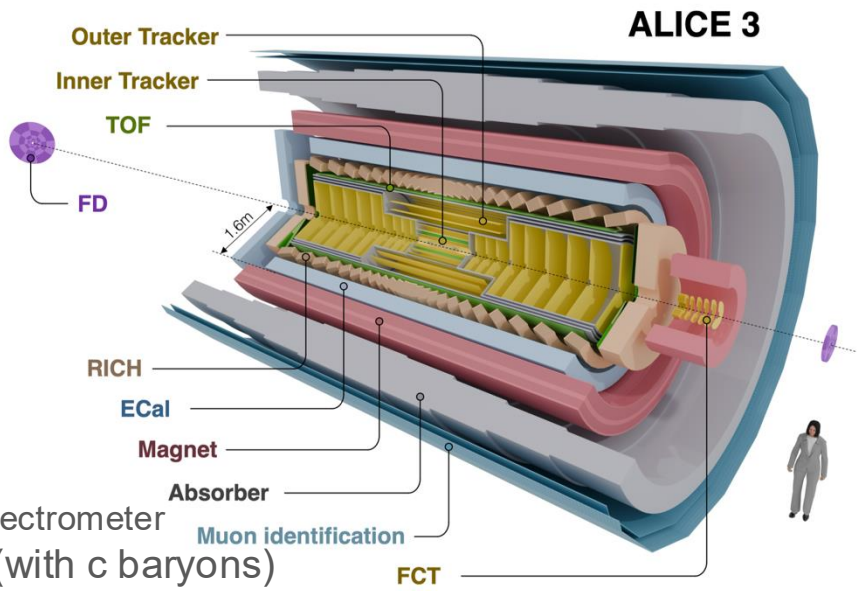


- taking $\overline{c_s} \sim 1/\sqrt{3}$ ... $1/2$
- b subsonic for $p < \sim 3$ GeV/c
- p-dependent wake in multi-GeV range?
  - ~ 40 º at 5 GeV, ~ 55º at 10 GeV!

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

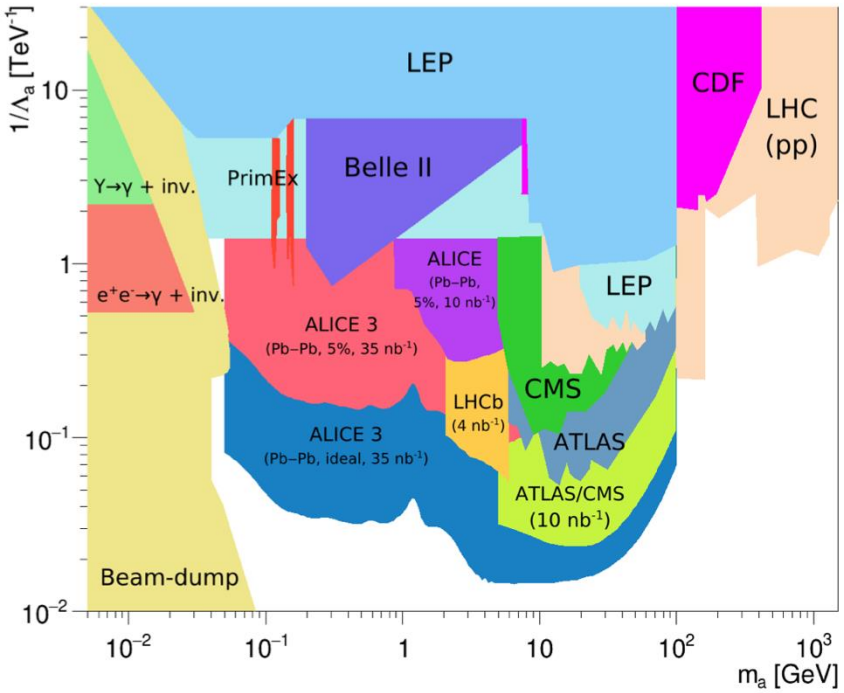
Physics potential (more examples)

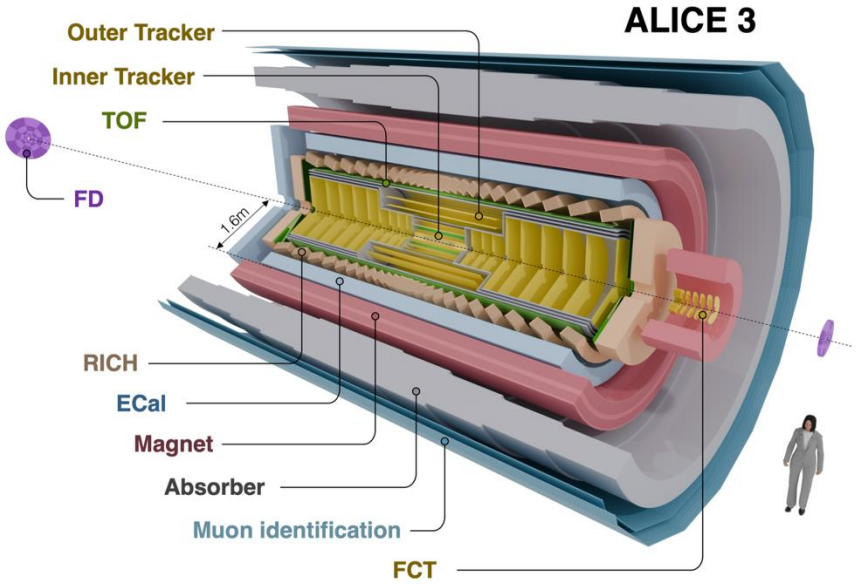
- heavy flavours, quarkonia
  - multi-heavy flavoured hadrons (Ξ_{cc}, Ω_{cc}, Ω_{ccc})
  - D D correlations
  - B mesons at low p_T
  - χ_c, X, Y, Z states and exotic hadrons
- low-mass dielectrons
  - chiral symmetry restoration
  - thermal continuum (virtual photons)
- fluctuations of conserved charges
  - 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

Axion-Like Particles (ALP) searches





Fresh off the press:
Physics Book online

The view of the national HEP communities

Summary talk (K. Jakobs)

- **Completing the full HL-LHC programme** is essential and must remain a high priority for CERN;

It is paramount to fully exploit the High-Luminosity LHC (HL-LHC) to maximise scientific returns

ALICE 3 supported and prioritised in several community inputs:

- NuPECC LRP
- …

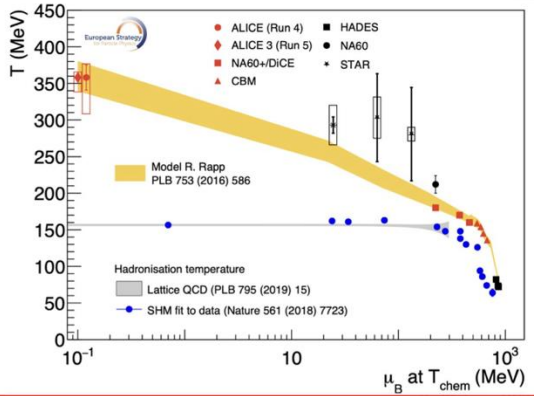
Hot and dense QCD and QCD connections

Summary talk (K. Jakobs)

- **HL-LHC:** rich physics programme in non-perturbative QCD
  (full exploitation already encouraged in 2020 strategy, ongoing)

  - **High-temperature QCD**
    → quark-gluon plasma equilibration with heavy quarks, temperature and its time evolution

  - Hadron nature (exotica) and interactions
    (very relevant for astro(particle) physics)



Conclusions

- we have come a long way!
  - from the realisation of the possible existence of deconfined matter in the 70's
  - to the first explorations of collective effects (AGS, SPS S beams)
  - through the discovery of deconfinement (SPS Pb beams)
  - through the evidence for strongly-coupled QGP (RHIC)
  - to the LHC harvest
    - parton-dependent energy loss
    - direct observation of QGP hadronisation
    - discovery of collectivity in small systems
    - quantitative access to QGP parameters
- today:
  - the plans of the community are being drawn for the next two decades
  - we are entering the next phase:

  → systematic exploration of the emergent properties of QCD condensed matter

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敬请期待！