ALICE overview

highlights from Run 1 & 2

—

upgrades for Run 3

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for the ALICE Collaboration

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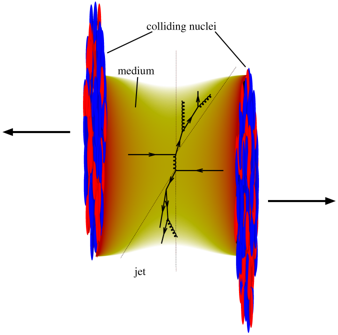
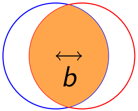
LHCP 2019
Puebla (Mexico)
May 20 - 25, 2019

high density/temperature QCD

- heavy ions to produce hot and dense QCD matter
  → exp. access to non-perturbative QCD features
- **particle production**
  - integrated particle yields
  - recombination/coalescence
  - dielectrons
- **medium evolution**
  - radial flow
  - azimuthal anisotropy
- **medium interaction**
  - quenching
  - jet modification





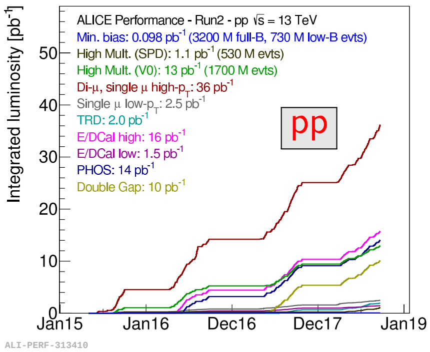
understand evolution of bulk matter
and interaction of hard probes

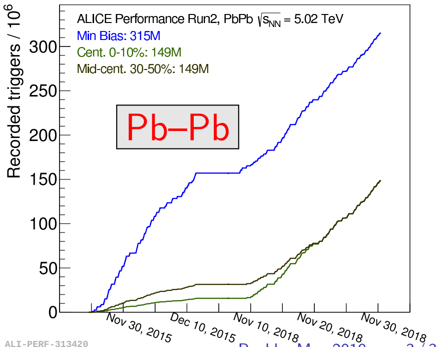
datasets from Run 1 & 2

- Run 2 data taking concluded

system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	0.9	$\sim 200\ \mu b^{-1}$
	2.76	$\sim 100\ nb^{-1}$
	5.02	$\sim 1.3\ pb^{-1}$
	7	$\sim 1.5\ pb^{-1}$
	8	$\sim 2.5\ pb^{-1}$
	13	$\sim 25\ pb^{-1}$
p–Pb	5.02	$\sim 15 + 3\ nb^{-1}$
	8.16	$\sim 25\ nb^{-1}$
Xe–Xe	5.44	$\sim 0.3\ \mu b^{-1}$
Pb–Pb	2.76	$\sim 75\ \mu b^{-1}$
	5.02	$\sim 0.25 + 1\ nb^{-1}$

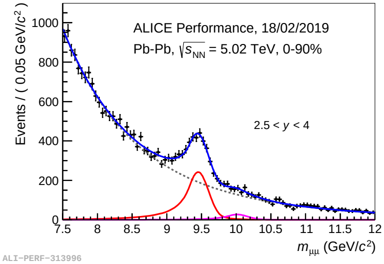
system and energy dependence at LHC



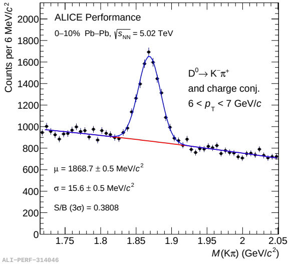


Pb–Pb run 2018

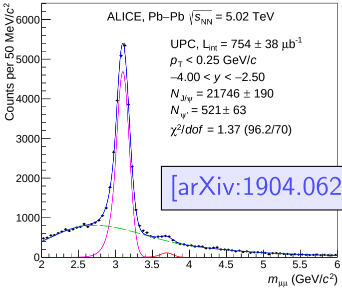
$\Upsilon(1S)$



D^0



J/ψ (UPC)



[arXiv:1904.06272]

- fast reconstruction for muon spectrometer and calorimeters synchronous with data taking
- fully calibrated reconstruction including central barrel done (second pass to be done for improved performance)
- improved data quality w.r.t. 2015 Pb–Pb run (reduced space charge distortions in TPC)

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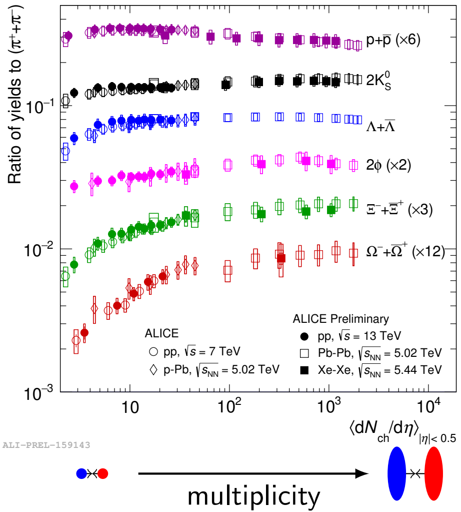
analyses of full run 2 statistics on-going ⇝ more results for summer conferences

particle production

hadro-chemistry, hadronisation dynamics

particle production

yields normalized to pions



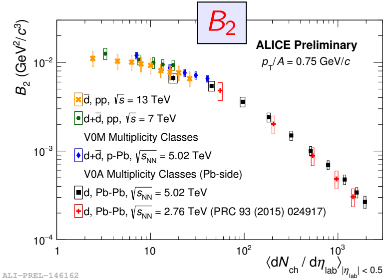
■ Xe–Xe (new!)

- particle identification capabilities down to low p_{T} $\rightsquigarrow$ integrated particle yields
- fully characterized by thermal model:
  - baryon chemical potential $\beta \simeq 0$
  - temperature $T \simeq 153$ MeV
  - volume $V \simeq 7000$ fm^3

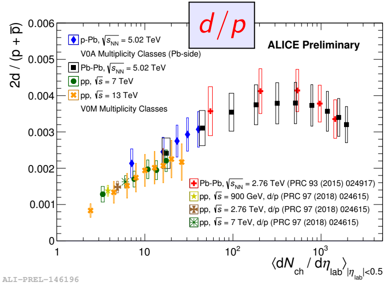
  (for Pb–Pb $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV)
- thermodynamic description $\leftrightarrow$ microscopic fundamental interactions
- particle ratios as function of multiplicity show **smooth evolution from pp to Pb–Pb collisions**, transition between different mechanisms?

$\rightarrow$ C. Jahnke, Thu 11:50

formation of (light) nuclei: (anti-)deuterons



multiplicity



- coalescence of nucleons close in phase space:

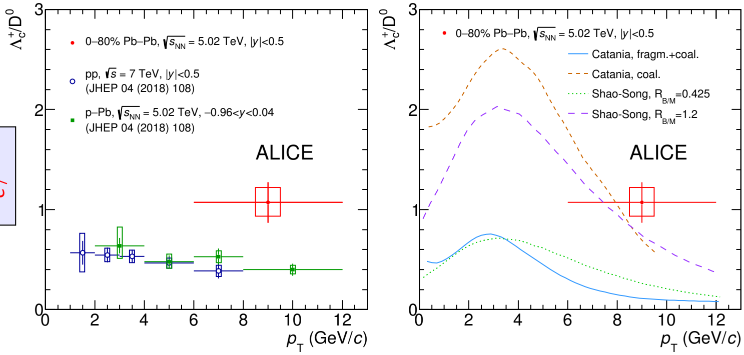
$$E_\mathrm{d} \frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{d}^3} = B_2 \cdot \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^2$$

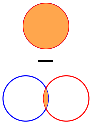
- B_2 vs multiplicity:
  - for small systems: weak dependence on N_ch (no dependence on p_T)
  - for large systems: decrease with source volume
- d/p ratio vs multiplicity:
  - increase for small systems (expected for $d \propto p^2$)
  - roughly constant for large systems (fixed by thermal yield)

[arXiv:1902.09290] → R. Lea, Wed 10:36

recombination: Λ_c

Λ_c/D^0



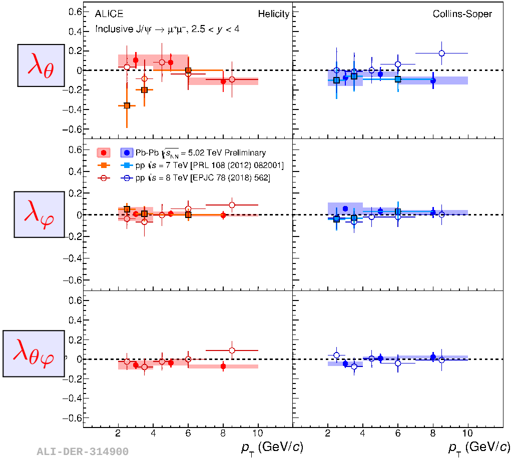


- Λ_c composed of *udc*
  (heavy quarks produced early in the collision)
- Λ_c/D^0 increases considerably from pp/p–Pb to Pb–Pb
  $\rightarrow$ favours recombination from quarks in the medium (instead of primordial production)
- similar effect seen for J/ψ

[arXiv:1809.10922] $\rightarrow$ R. Hosokawa, Tue 12:30

J/ψ polarisation

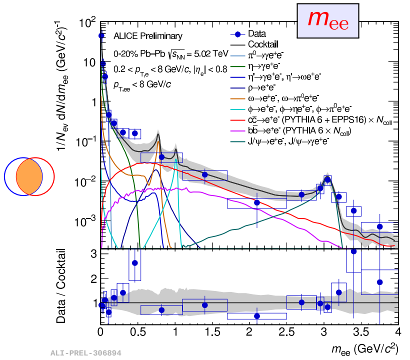
helicity Collins-Soper

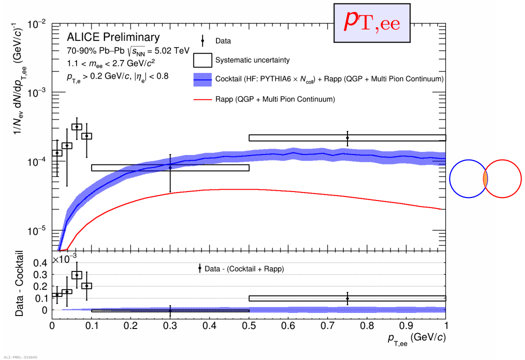


○ pp ■ pp • Pb–Pb

- non-perturbative formation of J/ψ from $c\bar{c}$
- polarisation sensitive to production mechanism:
  - transverse (LO NRQCD)
  - longitudinal (NLO color singlet model)
- pp results consistent with no polarisation (feed-down from higher charmonium states)
- first measurement of non-polarisation in Pb–Pb probing interaction with and formation from medium
- feed-down fraction changed in Pb–Pb: suggests no polarisation for J/ψ and $\psi(2S)$

dielectron production





- probe production of various sources:
  - light flavour mesons
  - heavy-flavour mesons
  - thermal radiation
  - photoproduction
- hadronic cocktail describes m_{ee} spectrum when accounting for cold nuclear effects

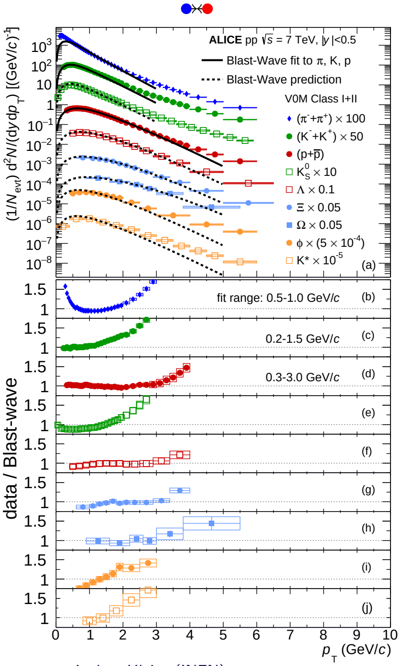
- low-p_T range most sensitive to photo production
  - no excess in 0-40 %
  - 3.7σ excess in 70-90 % (also seen by STAR)

→ S. Lehner, Thu 14:52

medium evolution

radial flow, azimuthal anisotropy

radial expansion



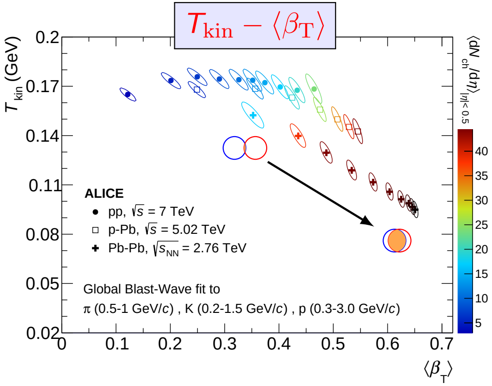
- velocity becomes common variable:
  $\Rightarrow$ mass-dependent hardening of spectra
  (**radial flow**)
- analytical model of collective expansion with:
  - expansion velocity β_T
  - common freeze-out temperature T_{kin}

  $\rightsquigarrow$ Boltzmann-Gibbs blast-wave model
  Schnedermann et al., PRC (1993) 48, 2462
- simultaneous fit to π, K, p spectra
- applied to all measured systems
  in bins of multiplicity/centrality
  (better agreement in Pb–Pb)

Phys. Rev. C (2019) 99, 024906

$\rightarrow$ N. Jacazio, Wed 11:55

radial expansion



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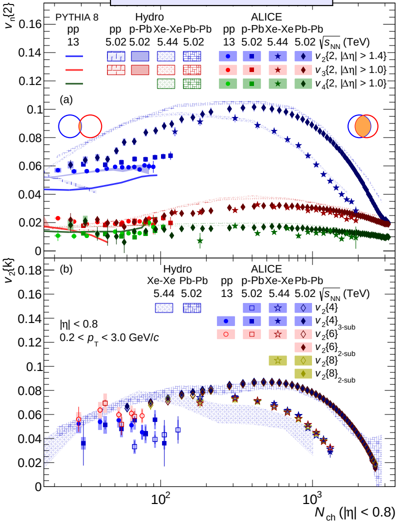
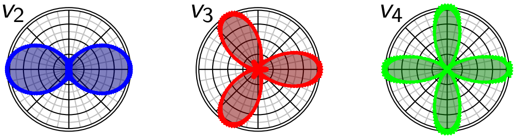
anisotropic expansion

v_n vs multiplicity



- quantify azimuthal anistropy by Fourier coefficients:



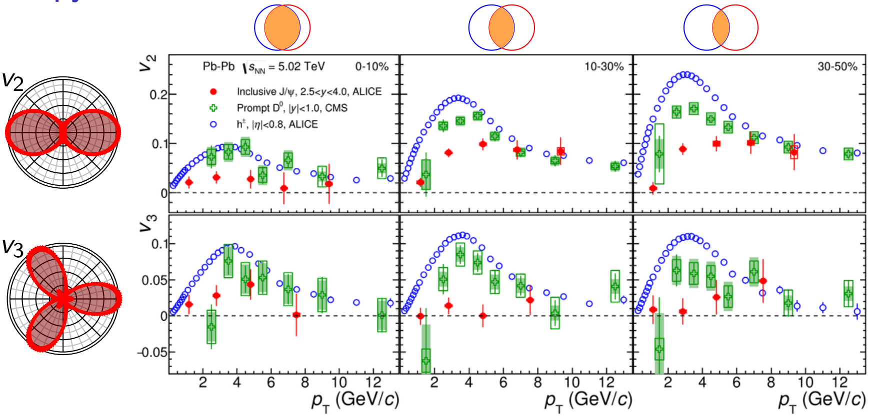
. . .

- v_2 mostly driven by overlap geometry
- higher orders mostly driven by fluctuations
  (odd harmonics non-existent in average geometry)
- compare different systems
  using multiplicity as scaling variable
  - finite v_n in pp:
    similar values as peripheral Pb–Pb/Xe–Xe
  - different geometry at given multiplicity:
    $\rightarrow$ v_2 does not scale with multiplicity

[arXiv:1903.01790]

$\rightarrow$ A. Ortiz, Wed 9:24

J/ψ anisotropy

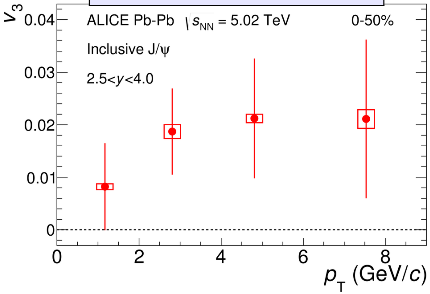


- J/ψ flows $\Rightarrow$ coupling to medium (consistent with recombination)
- ordering: $v_2(J/\psi) < v_2(D^0) < v_2(h^{\pm})$
- v_3/v_2 significantly smaller for J/ψ

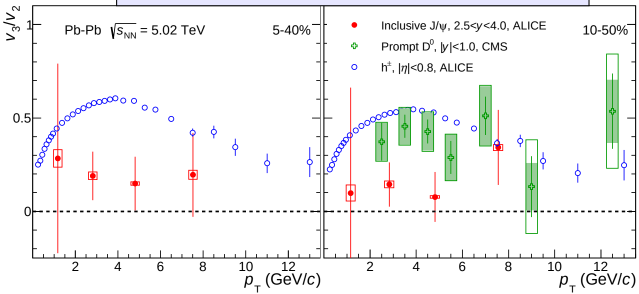
[arXiv:1811.12727] → R. Hosokawa, Tue 12:30

J/ψ anisotropy

v_3 (0-50 % integrated)



v_3/v_2: 5-40 % (left), 10-50 % (right)



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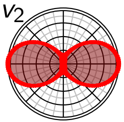
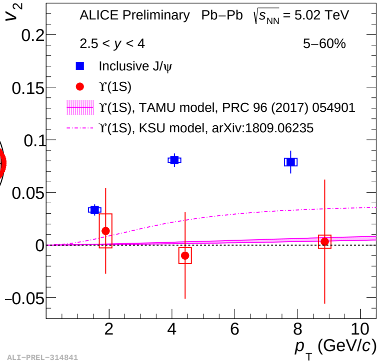
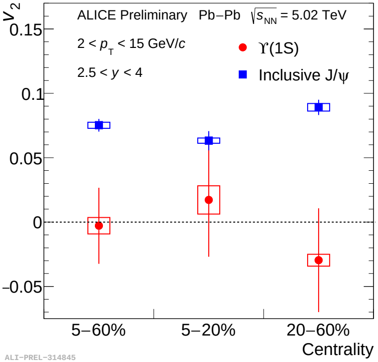
Υ anisotropy – **Pb–Pb 2018!**

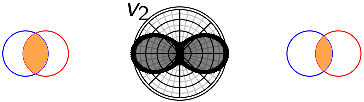


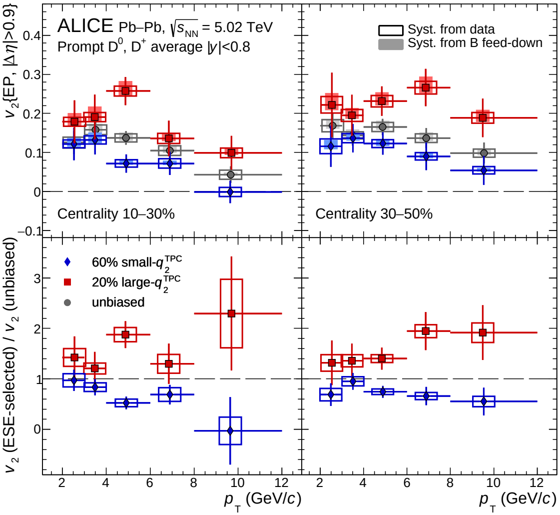




- first measurement of v_2 for Υ: consistent with 0
  first particle measured not to have flow!
- not dragged along by flow of medium,
  not produced by recombination

D^0 anisotropy





- D^0 mesons exhibit $v_2 > 0$
- classificy events according to flow for charged hadrons
  - 60 % small q_2: $v_2(D^0)$ reduced
  - 20 % large q_2: $v_2(D^0)$ increased
- $v_2(D^0)$ follows selection
  ⇝ originates from same underlying ellipticity

[arXiv:1809.09371]

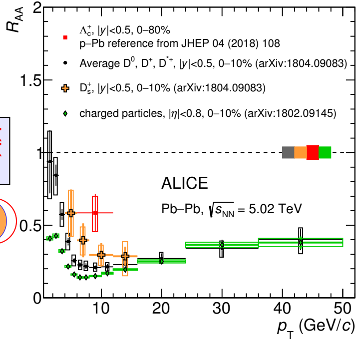
→ R. Hosokawa, Wed 12:30

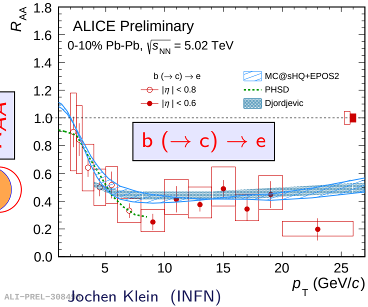
medium interaction

energy loss, quenching, jet evolution

energy loss (identified particles)

ALICE





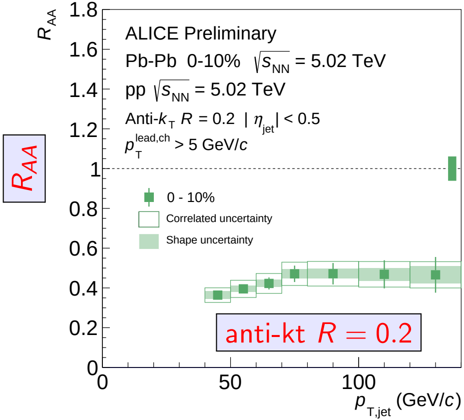
- compare Pb–Pb collision with incoherent pp superposition

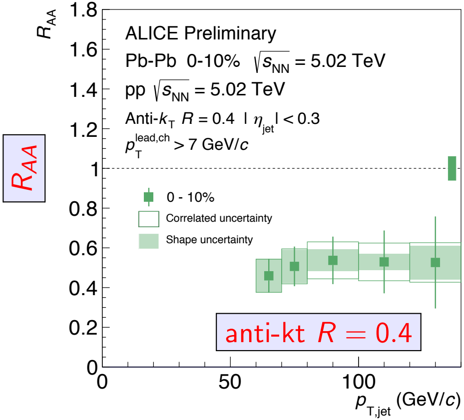
$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle \, dN^{pp}/dp_T}$$

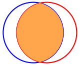
- **significant suppression** w.r.t. pp, hint of ordering:
  - charged hadrons
  - D mesons
  - D_s
  - b (→ c) → e (bottom)
  - Λ_c
- described by models implementing **mass-dependent energy loss** and recombination (for Λ_c)

→ R. Hosokawa, Wed 12:30

energy loss (jets)



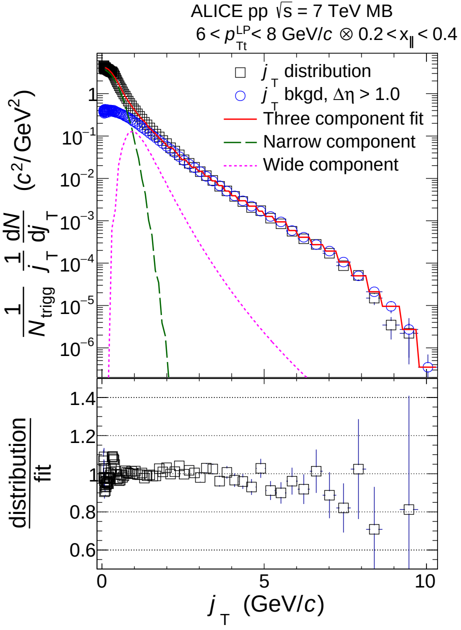


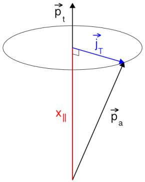


- also jets are strongly suppressed in medium
- excellent tool to study medium interaction

look in more detail than just suppression
$\rightsquigarrow$ fragmentation and substructure

jet fragmentation



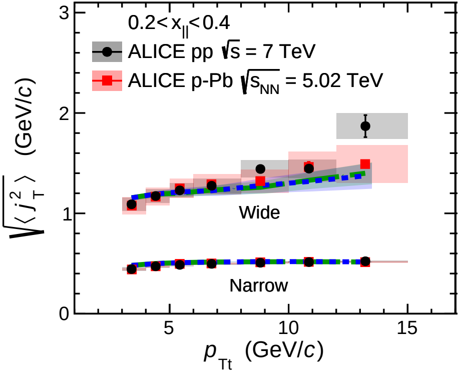


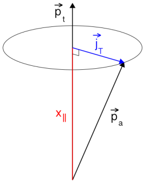
- reconstruct j_T substructure of jets using leading charged particle as proxy
- substract background (using η gap)
- distribution described by two compone
  - hadronization
    $\rightarrow$ narrow component
  - showering
    $\rightarrow$ wide component
- narrow component depends weakly on p_T
  $\rightsquigarrow$ universality of hadronization
- wide component increases with p_T
  $\rightsquigarrow$ increase in splitting

[arXiv:1811.09742]

$\rightarrow$ M. Fasel, Wed 12:24

jet fragmentation





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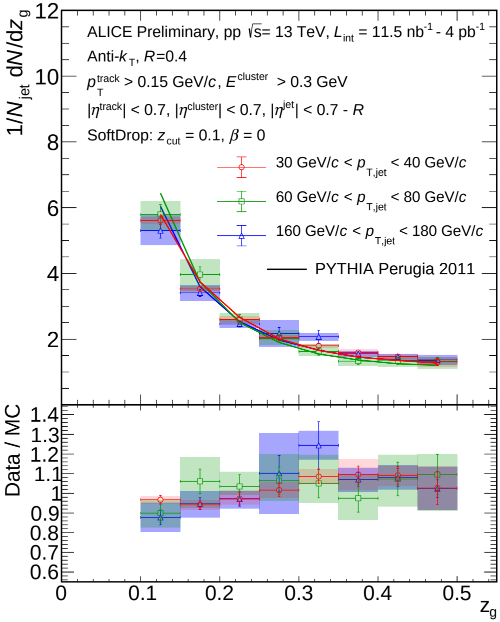
[arXiv:1811.09742]

$\rightarrow$ M. Fasel, Wed 12:24

jet substructure



- grooming procedure
  - recluster jet (using C/A algorithm)
  - remove softer branch until

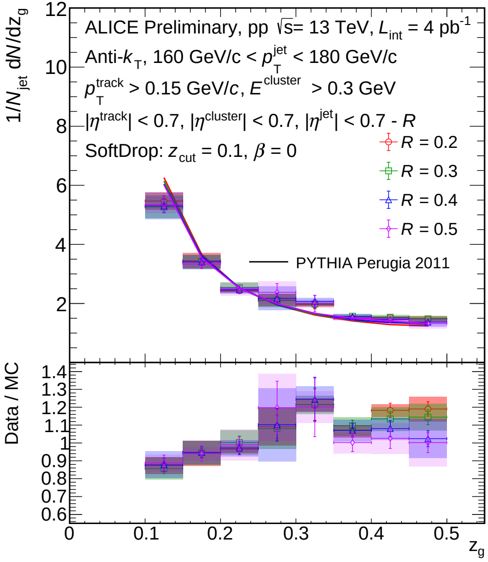
$$z_g = \frac{\min\left(p_T^1, p_T^2\right)}{p_T^1 + p_T^2} > z_{\text{cut}}$$

to identify hard splittings

- no p_T dependence (for large R)
- no R dependence (for large p_T^{jet})
- in line with expectation
  - z_g maps splitting function
  - hadronisation effects small at high p_T

→ M. Fasel, Wed 12:24

jet substructure



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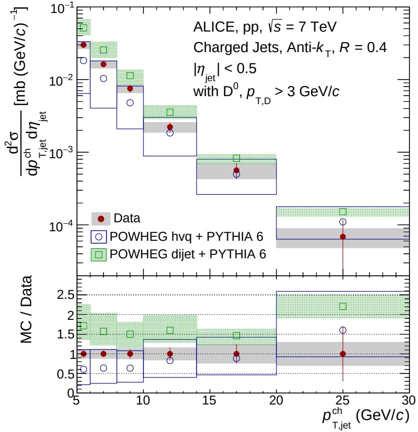
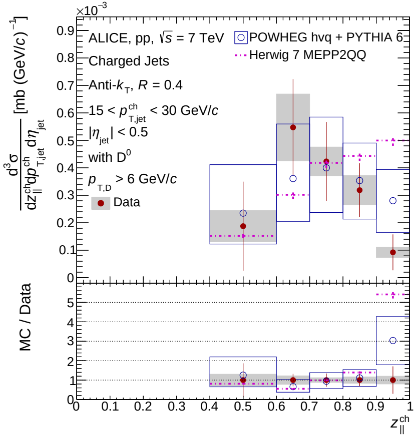
→ M. Fasel, Wed 12:24

heavy-flavour jets

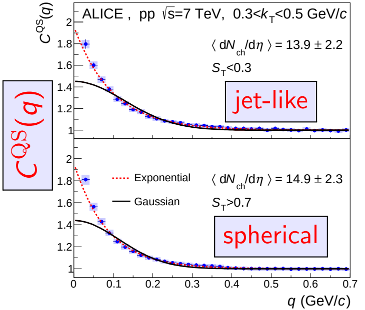


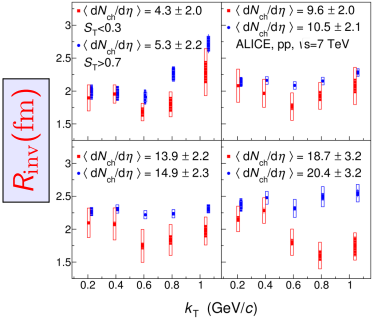


- charged anti-kt jets ($R = 0.4$) containing a D^0
- cross section in good agreement with POWHEG hvq + PYTHIA
- fragmentation function tends to be softer than predicted

→ Y. Pachmayer, Mon 18:06

event-shape and mult. dependence of freeze-out radii





- exploit quantum correlations of identical pions:

$$C^{QS}(q) = 1 + \lambda \cdot e^{-R_{inv} \cdot q}, \quad q = \sqrt{(p_1 - p_2)^i (p_1 - p_2)_i}$$

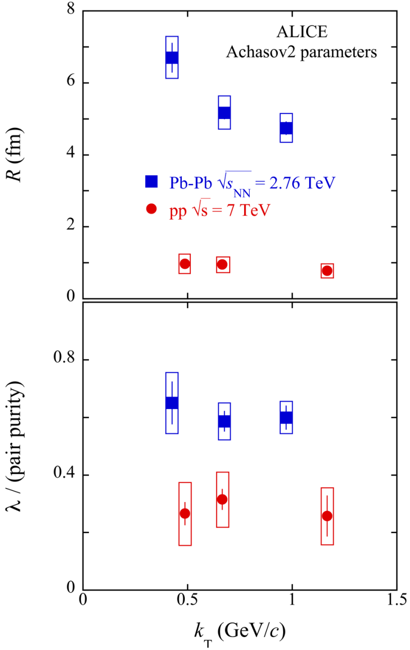
  to measure freeze-out radius R_{inv}

- reach in $k_T = \frac{1}{2}|\mathbf{p}_1 + \mathbf{p}_2|$ limited by influence of mini-jets
- mitigate by using transverse sphericity to select
  - spherical events ($S_T > 0.7$)
  - jet-like events ($S_T < 0.3$)
- spherical events show weak k_T dependence across multiplicity bins

[arXiv:1901.05518]

→ G. Simatović, Thu 12:07

hadronic interactions



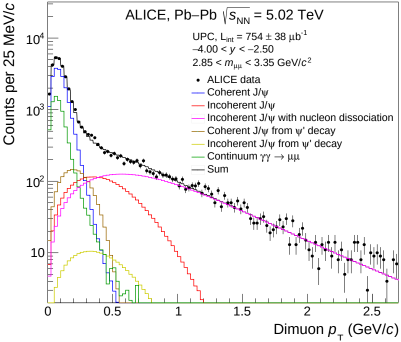
- measure quantum correlation of K^0_S and $K^\pm$ caused by final state interaction via:

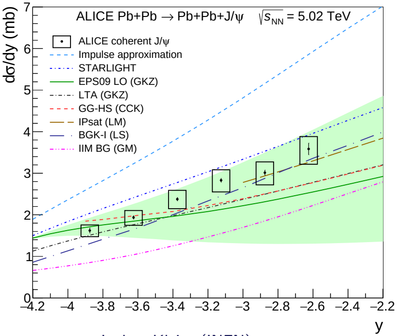
$$K^0_S K^- \leftrightarrow a_0^-(980)$$

- favours interpretation of $a_0(980)$ as tetraquark state
- method gives access to more final state interactions, e.g. attractive interaction between proton and Ξ [arXiv:1904.12198]

[arXiv:1809.07899]

coherent J/ψ production – **Pb–Pb 2018!**





last but first (publication from Pb–Pb run 2018):

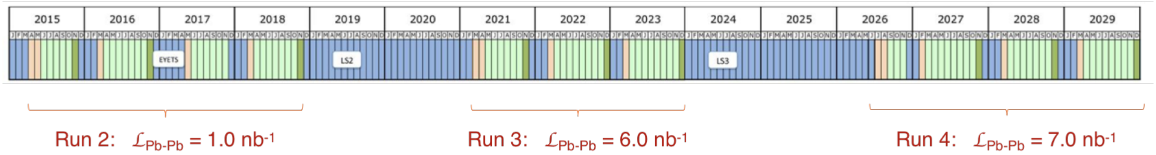
- select ultra-peripheral events:
  $b > R_{\mathrm{Pb}}$
- reconstruct J/ψ, ψ' in $\mu\mu$ channel
- separate production off nucleon and nucleus using p_{T} spectra
- photoproduction off nucleus indicates importance of gluon shadowing

[arXiv:1904.06272]

→ D. Horak, Fri 15:10

future physics goals

- **precision measurements** of
  - heavy flavour and quarkonia
  - jets
  - low-mass dileptons
  - light (hyper-)nuclei
- Run 3/4 to increase Pb–Pb statistics by an order of magnitude



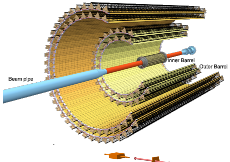
→ M. Winn, Sat 09:00

LS2 upgrades

objective: operation at high interaction rates (50 kHz of Pb–Pb collisions)

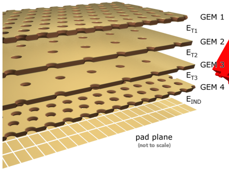
$\Rightarrow$ continuous (i.e. untriggered) read-out for core detectors

Inner Tracking System

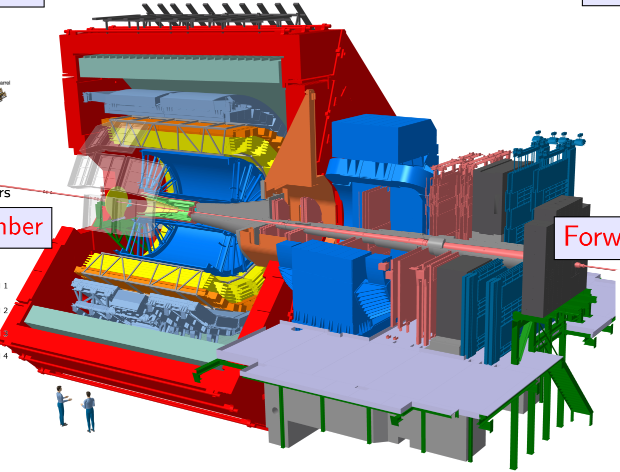


Monolithic Active Pixel Sensors

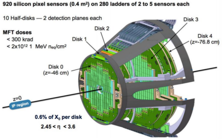
Time Projection Chamber



GEM readout chambers

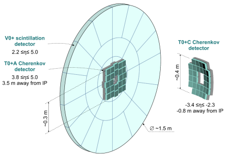


Muon Forward Tracker



MAPS-based forward tracker

Forward Interaction Trigger

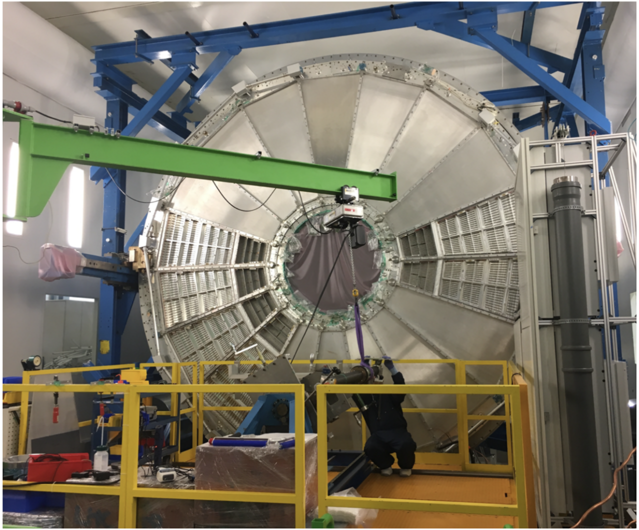


Cherenkov + scintillator

$\rightarrow$ J. Norman, Thu 15:42

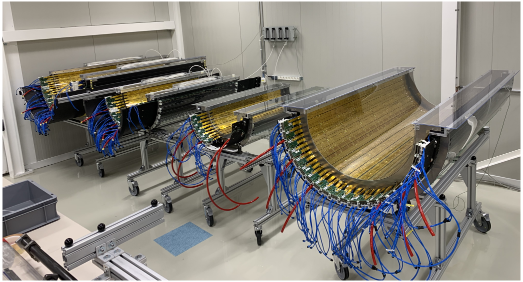
construction & commissioning

TPC



→ E. Hellbär, Fri 12:24

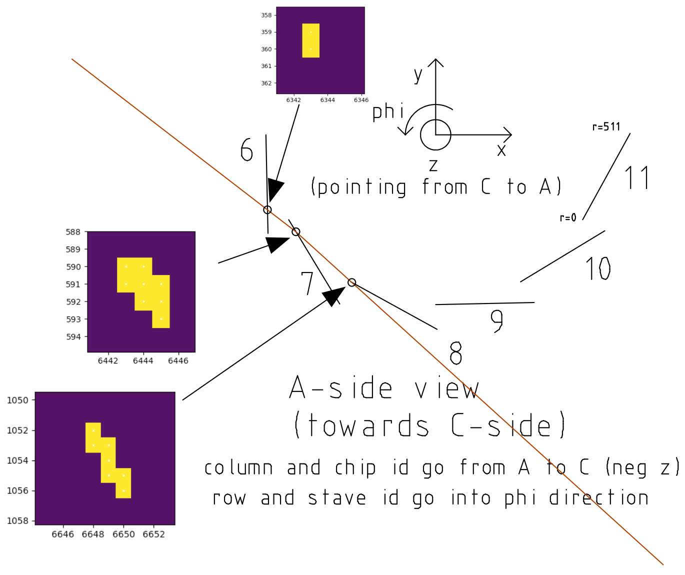
ITS Inner/Outer Barrel

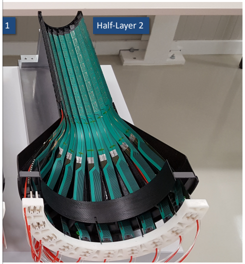


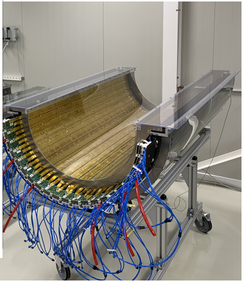
construction & commissioning

ter Barrel

first cosmic in inner-most layer





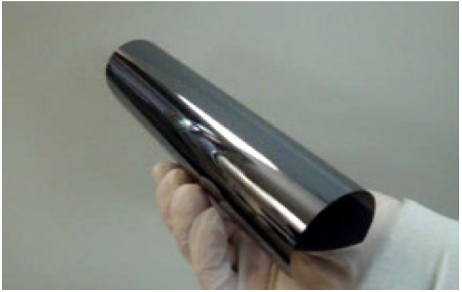


→ E. Hellbär, Fri 12:24

beyond LS2

ALICE

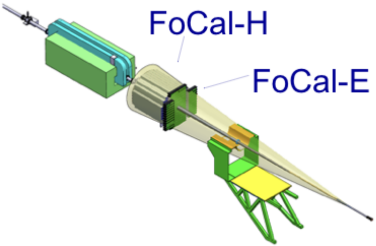
ITS3



- wafer-sized sensors
- on-chip power distribution
- cooling by forced air flow
- significant reduction of material budget

→ M. Keil, Fri 11:45

FoCal



- forward region so far uninstrumented
- FoCal-E: photons and π^0s
- FoCal-H: photon isolation and jets
- constrain gluon PDFs at low x

→ N. Novitzky, Fri 14:48

More from ALICE ...

- broad physics programme from pp to Pb–Pb
- analyses using full Run-2 statistics on-going
- upgrades progressing well

new results

- Quarkonia and open heavy-flavour measurements with ALICE (G. Luparello, Tue 11:52)
- Recent results on hard probes in heavy-ion collisions from ALICE and LHCb (R. Hosokawa, Tue 12:30)
- Heavy-flavour jet measurements with ALICE (M. Mazzilli, Tue 15:26)
- Recent results on collective effects and soft particle production in heavy-ion collisions from ALICE (N. Jacazio, Wed 11:55)
- Measurements of jet fragmentation and jet substructure with ALICE (M. Fasel, Wed 12:24)
- Particle production vs. multiplicity in pp collisions with ALICE (C. Jahnke, Thu 11:50)
- Event-shape studies in pp collisions with ALICE (G. Simatović, Thu 12:07)
- Low-mass dielectron measurements in pp, p–Pb, and Pb–Pb collissions with ALICE (S. Lehner, Thu 14:52)
- Recent ALICE results on ultra-peripheral collisions (D. Horak, Fri 15:10)

plenaries

- HF production and spectroscopy (Y. Pachmayer, Mon 18:06)
- Particle production vs. multiplicity, small systems (A. Ortiz, Wed 9:24)
- Probes of hadronization (R. Lea, Wed 10:36)
- Future of heavy-ion and ALICE (M. Winn, Sat 9:00)

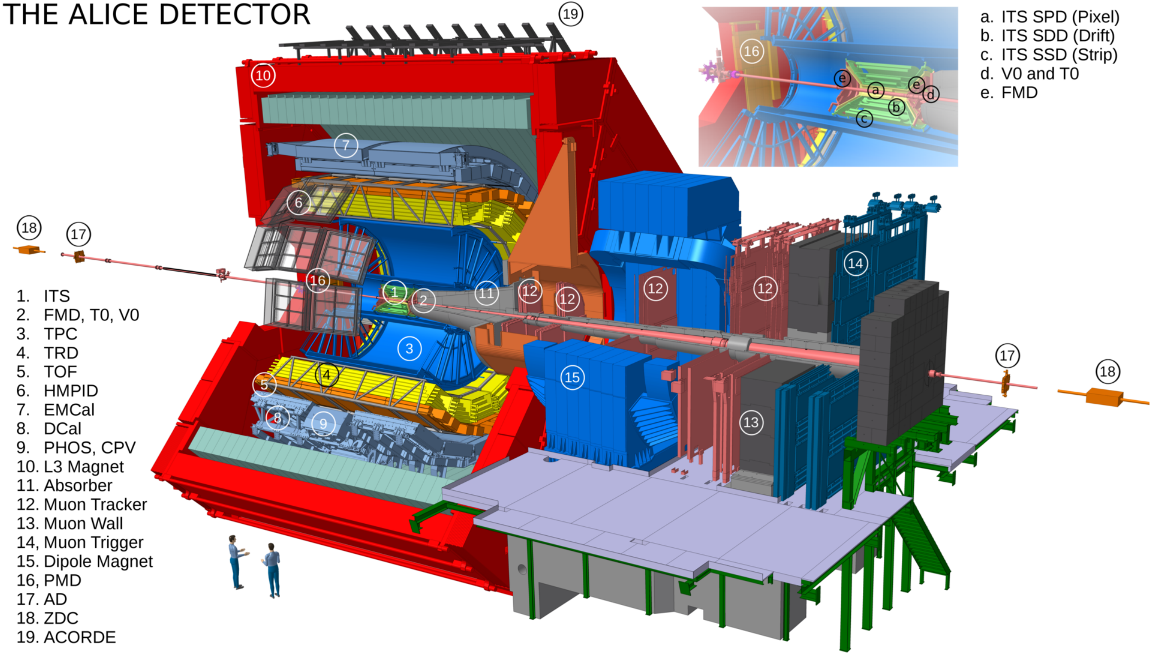
performance & upgrades

- Muon spectrometry at forward rapidities with ALICE (M. Marchisone, Mon 14:30)
- Using ML techniques for Data Quality Monitoring in CMS and ALICE (K. Deja, Thu 12:36)
- ALICE LS2 upgrade – commissioning and physics projection (J. Norman, Thu 15:42)
- ALICE LS3 upgrade – a fully cylcindrical inner tracking system (M. Keil, Fri 11:45)
- The ALICE TPC: optimization of the performance in Run 2 and developments for the future (E. Hellbär, Fri 12:24)
- ALICE Forward Calorimeter (FOCal) – detector design and physics reach (N. Novitzky, Fri 14:48)

Backup

ALICE in Run 2

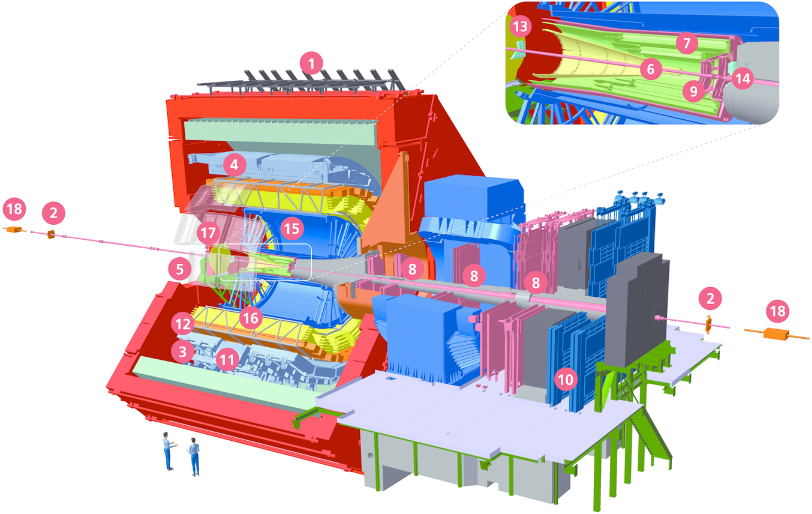
THE ALICE DETECTOR



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

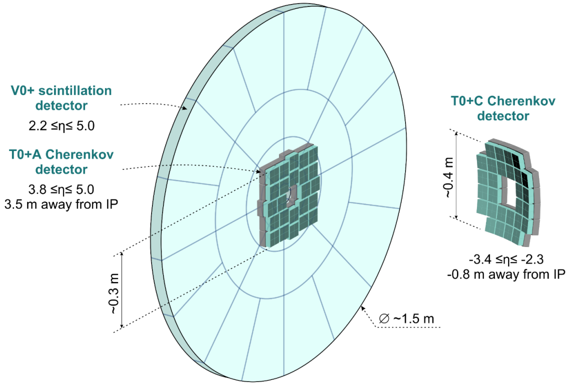
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

ALICE in Run 3



1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

Forward Interaction Trigger (FIT)

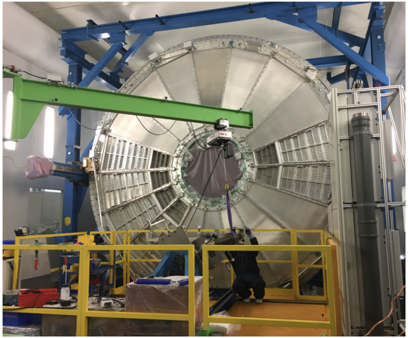


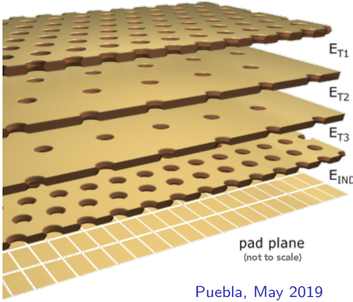
- Cherenkov array (T0+)
  - installed on both sides of the IP
  - excellent timing resolution
  - used for triggering
- Scintillator ring (V0+)
  - installed on A-side
  - used for triggering
  - centrality measurement

Time Projection Chamber (TPC)

- operation with Ne-CO_2-N_2:
  electron drift time $\sim 100\ \mu s$
- MultiWire Proportional Chambers being replaced with **Gas Electron Multipliers** to avoid gating grid and allow high rate
- conservative operation limits
  - $\mathrm{IBF} < 1\ \%$
  - energy resolution better than 12 % (for ^{55}Fe measurements)
- space charge distortions up to 20 cm

$\rightsquigarrow$ talk by E. Hellbär





Inner Tracking System (ITS)

- barrel with 7 (3 + 2 + 2) layers

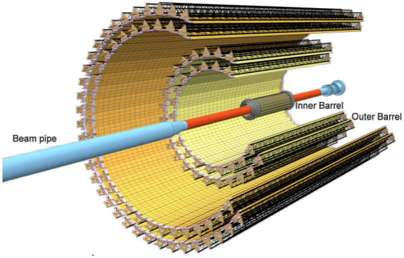
  distance to beam (innermost layer):
  39 $\rightarrow$ 23 mm

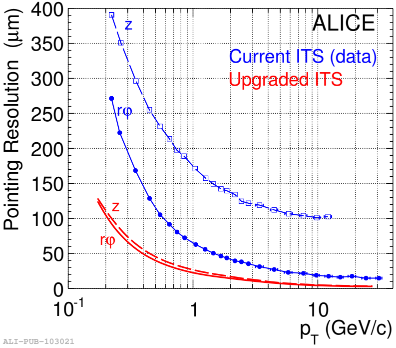
- $\sim 0.38X_0$ for inner layers

- ALice PIxel DEtector (ALPIDE):

  monotlithic active pixel sensor,
  binary read-out

- 24'000 chips $\rightsquigarrow$ 10 m^2 coverage,
  12.5 billion pixels,
  pointing resolution 5 $\mu\mathrm{m}$





$\rightsquigarrow$ talk by J. Norman

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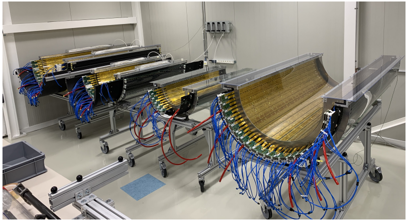
Inner Barrel

Outer Barrel

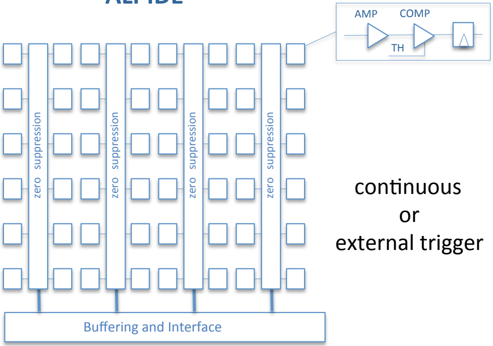


$\rightsquigarrow$ talk by J. Norman

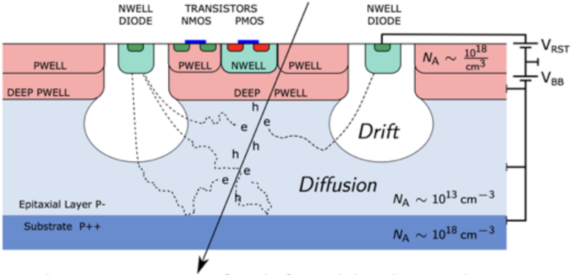
ALice PIxel DEtector (ALPIDE)

- charge collection by drift and diffusion
- binary read-out
- detection efficiency above 99 %
- fake rate below $10^{-6}/\mathrm{ev}/\mathrm{px}$

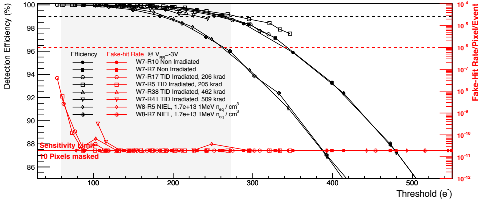
ALPIDE



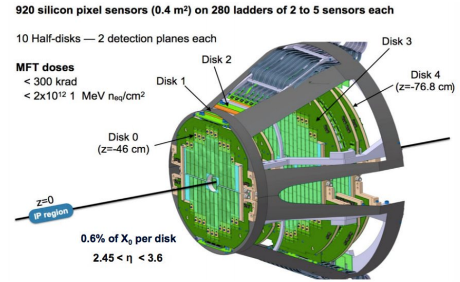
continuous
or
external trigger

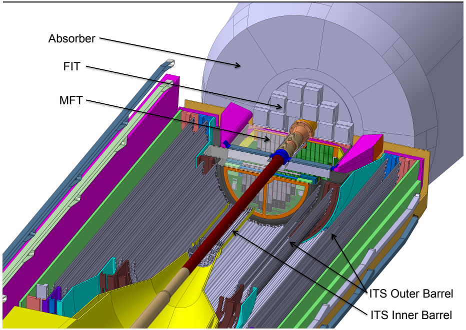


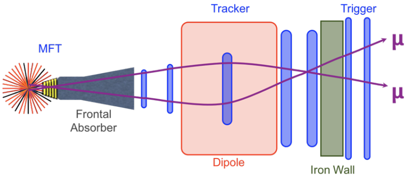
schematic cross section of pixel of monolithic silicon pixel sensor



Muon Forward Tracker (MFT)



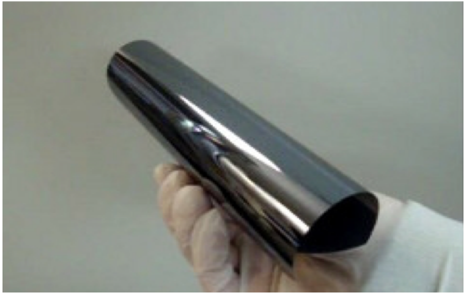


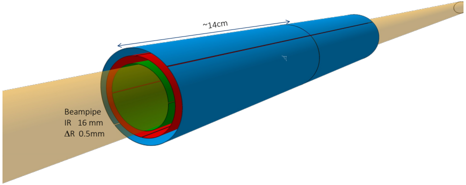


- also based on ALPIDE (same as ITS)
- improved pointing resolution to primary vertex
  ⇝ secondary vertexing

⇝ talk by J. Norman

beyond LS2: ITS3

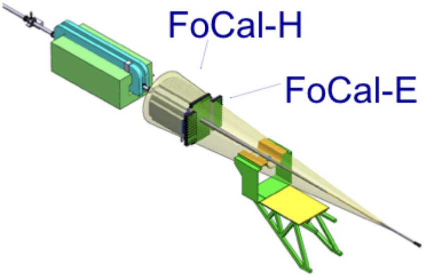


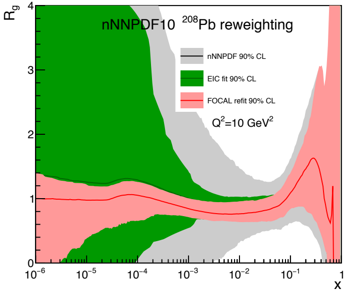


- exploit stitching
  $\Rightarrow$ wafer-sized sensors
- exploit flexibility of thin silicon ($< 50\ \mu\mathrm{m}$):
  $\Rightarrow$ fully cylindrical silicon tracker
- all electrial connections in chip,
  cooled by forced air flow
  $\Rightarrow$ severely reduced material budget
- very close to the beam pipe ($R = 16$ mm):
  $R_0 = 18$ mm, $R_1 = 24$ mm, $R_2 = 30$ mm
- significant improvement of measurements of
  low-p_T charmed hadrons and low-mass dielectrons

$\Rightarrow$ **reduced multiple scattering, improved momentum resolution**

beyond LS2: FoCal





- high-granularity Si-W calorimeter for photons and π^0
- hadronic calorimeter for photon isolation and jets
- forward region not instrumented $\Rightarrow$ "unobstructed" view of interaction point
- strong constraints over large x-range ($x < 10^{-2}$ not constrained by DIS)

$\rightsquigarrow$ talk by N. Novitzky

thermal model