ALICE – Future Plans

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on behalf of the ALICE Collaboration

HI Community Town Meeting, CERN, 24 October 2018

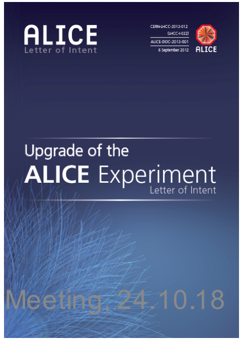
Outline

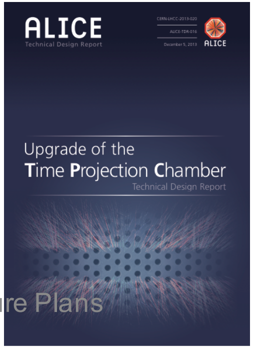
- ALICE LS2 upgrade: strategy and status
- Physics in Run-3 and Run-4
- LS3: a new inner tracker and other ideas
- A possible concept for physics in Run-5

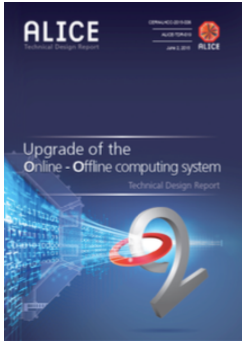
ALICE LS2 upgrade: driving physics goals (2012)

- Heavy-quark interactions in QCD medium
  - → Heavy-flavour dynamics and hadronisation at low p_T
- Quarkonium melting and regeneration in QGP
  - → Charmonium down to zero p_T
- QGP radiation and chiral symmetry restoration at μ_B=0
  - → Thermal di-leptons, photons, vector mesons
- Production of light nuclei in QGP
  - → High-precision measurement of light nuclei and hyper-nuclei

Vertexing
Low p_T
Hadron/e/μ ID
Low S/B







Upgrade strategy

ALICE

- Increase tracking granularity, reduce material thickness
- Speed-up main ALICE PID detectors
- No dedicated triggers possible
  → increase readout rate, reduce data size, write all Pb-Pb at 50 kHz

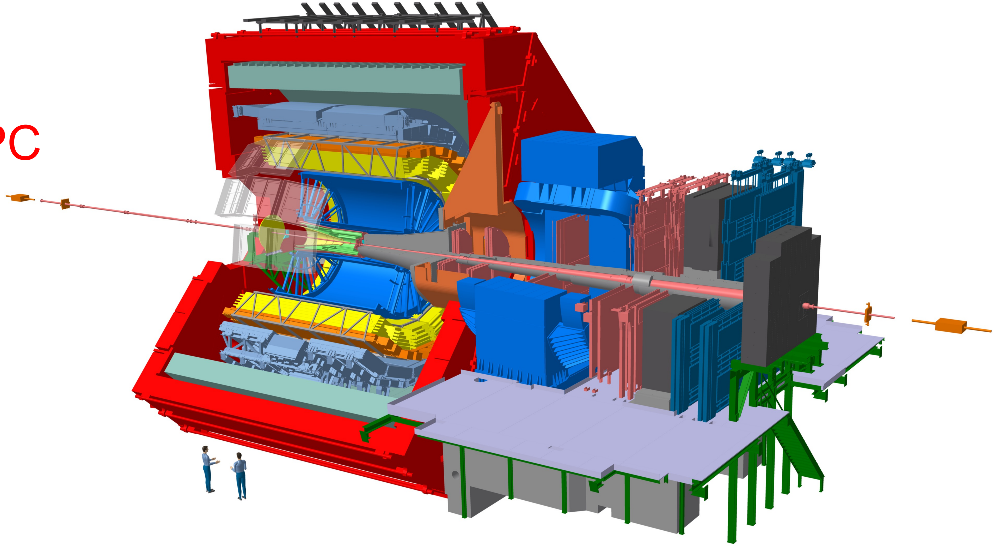
Vertexing
Low p_T
Hadron/e/μ ID
Low S/B

Run 3-4: increase of MB sample **x100** wrt Run 2

10/nb ~ 100 billion Pb-Pb events + 3/nb dedicated run at low B field (dielectrons)

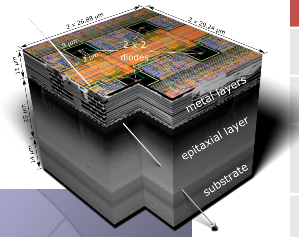
ALICE in 2021

- New Inner Tracking System (ITS)
- New Forward Muon Tracker (MFT)
- New GEM Readout Chambers for TPC
- New Online-Offline system (O^2)
- New trigger detector (FIT)
- Upgraded readout for TOF, TRD, MUON, ZDC, EMCal, PHOS

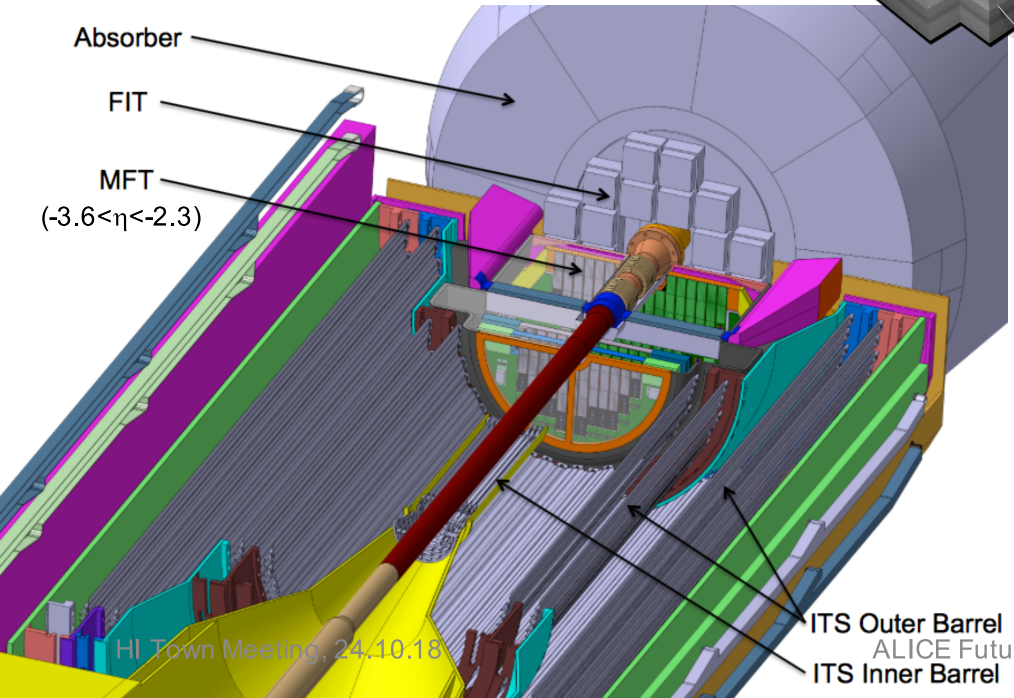


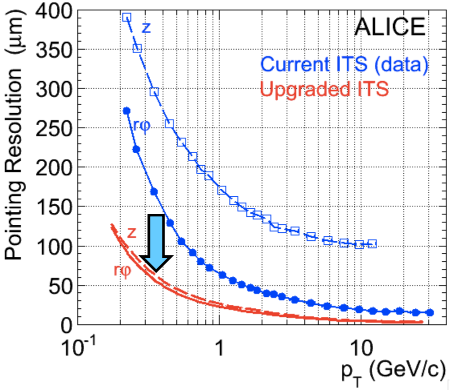
New all-pixel trackers: ITS2 and MFT

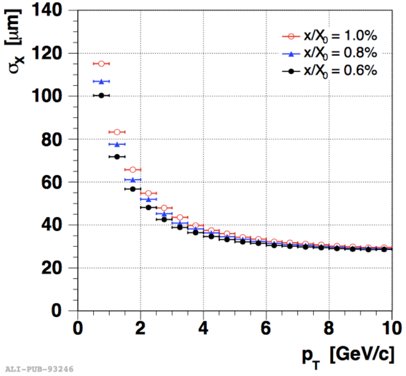
- Monolithic Active Pixel Sensors (MAPS)
  - Low resistivity, high efficiency, low thickness, low power consumption
  - Also chosen by sPHENIX and MPD@NICA



	Current ITS	New ITS2	MFT
N Layers	6	7	5
Inner radius	3.9 cm	2.3 cm	/
Layer thickness	~1.1% X_0	0.3-1.0% X_0	0.8% X_0
Spatial resolution	12x100 μm^2 35x20 μm^2 20x830 μm^2	~5x5 μm^2	~5x5 μm^2







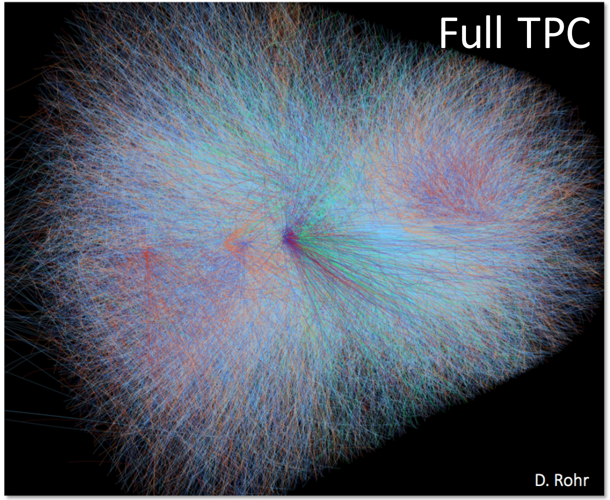
ITS2 tracking precision x3 better in rφ plane, <20 μm above 1 GeV/c

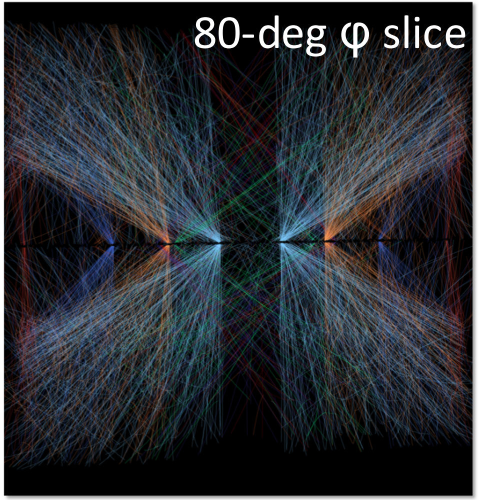
MFT: <100 μm above 1 GeV/c

CERN-LHCC-2013-024, CERN-LHCC-2015-001

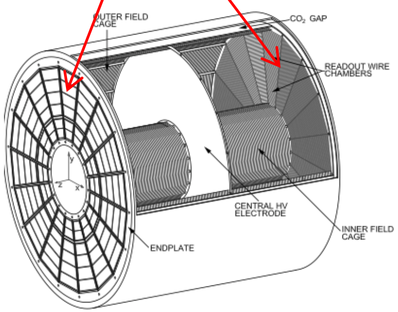
TPC with GEM readout for Pb-Pb at 50 kHz

- Current MWPC: readout rate limited by ion backflow
- New readout chambers (GEM): continuous readout of Pb-Pb at interaction rate of 50 kHz
  - preserve p_T and dE/dx resolution
- 5 interactions on average during TPC drift time (90 μs)
- Calibration and track-to-event assignment in O^2 system

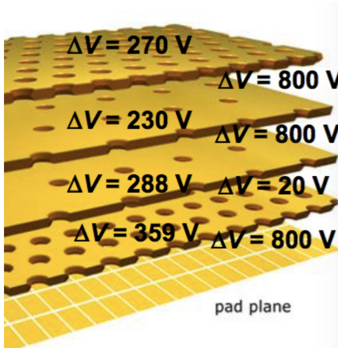


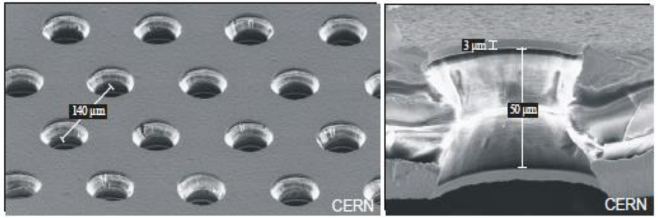


72 readout chambers



Stack of 4-GEM-foils



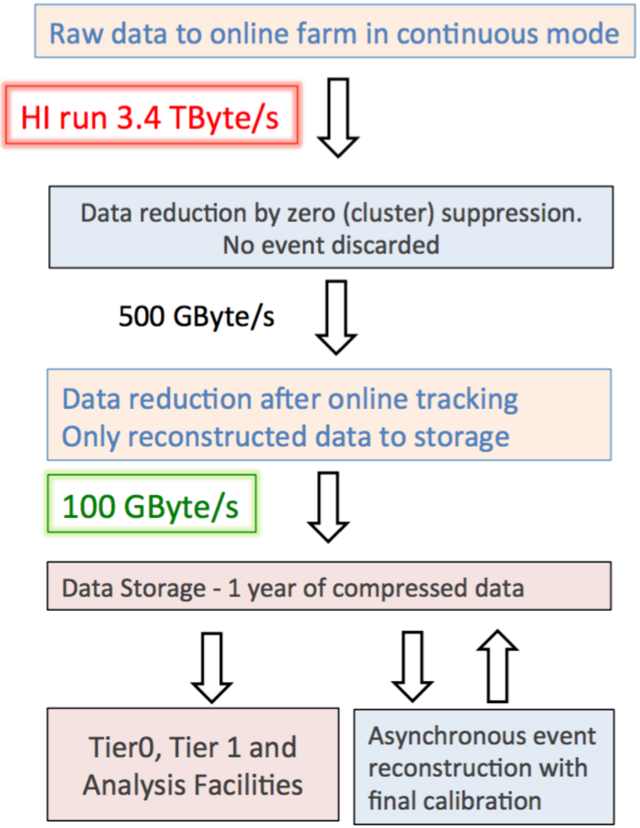


Electron microscope photograph of a GEM foil

CERN-LHCC-2013-020

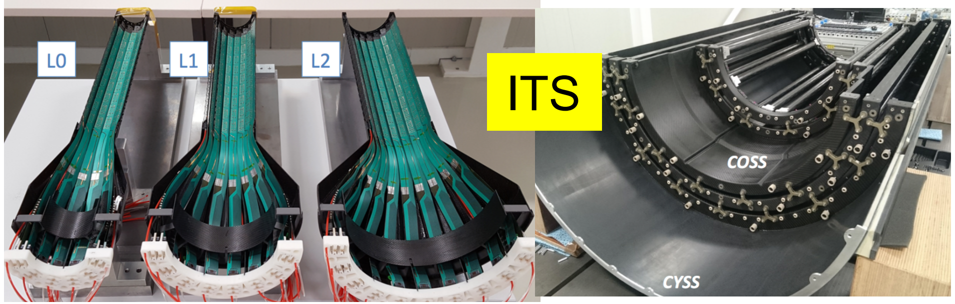
O^2 Online-Offline System

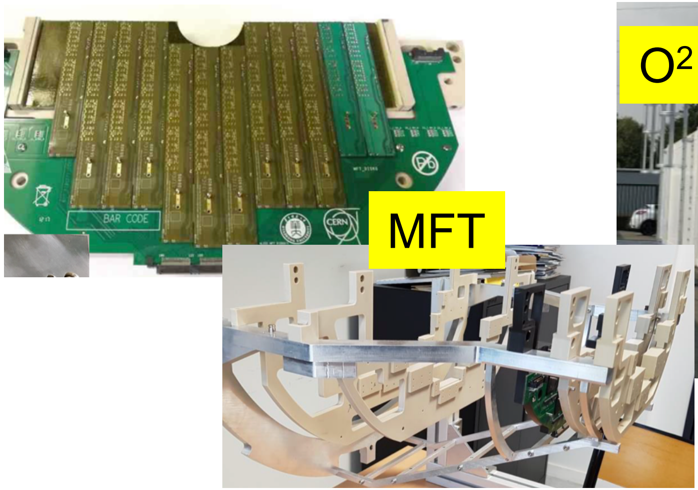
- O^2 will integrate the present DAQ, HLT and Offline systems
- A large computing farm will process the data online, calibrate the TPC, reject detector noise, and build events
- Data reduction factor >30 in Pb-Pb, without event rejection
  - 3.4 TB/s → 0.1 TB/s to tape

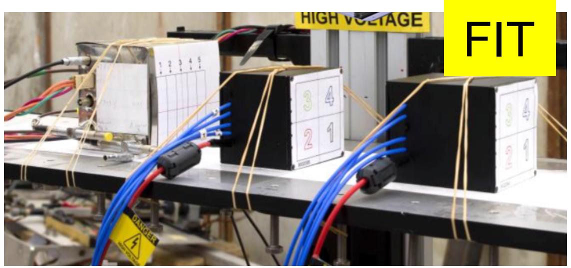


CERN-LHCC-2015-006

All this now coming together, and much more







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Physics of high-density QCD at LHC after LS2

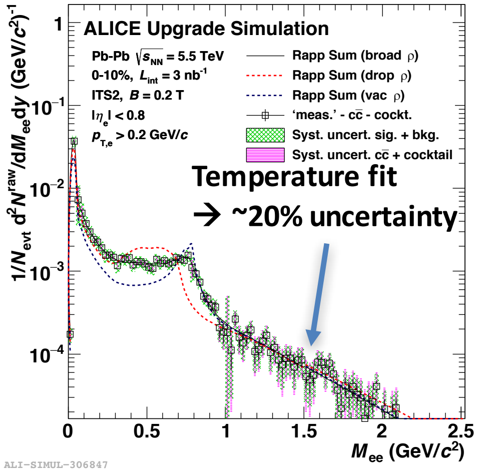
- Key priorities of the whole programme
  1. Macroscopic long-wavelength QGP properties with unprecedented precision
  2. Microscopic parton dynamics underlying QGP properties
  3. Parton densities in broad kinematic range and search for saturation
  4. Collectivity across colliding systems, hot medium in small systems?

- ALICE will provide unique insight on all four priorities
  - Only some examples given in the following
  - See also previous talk on WG5 HI

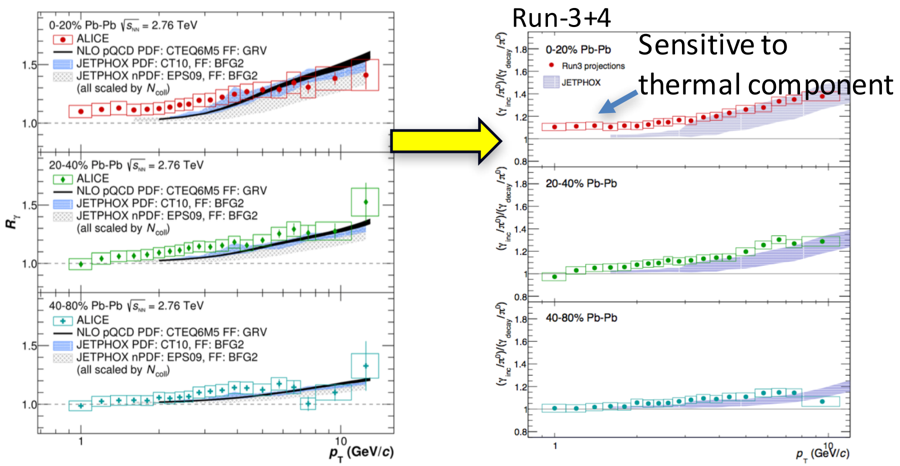
1. Macroscopic long-wavelength QGP properties

- **Temperature** → thermal radiation from real and virtual photons

Di-electrons (less material, better tracking, low-B run)



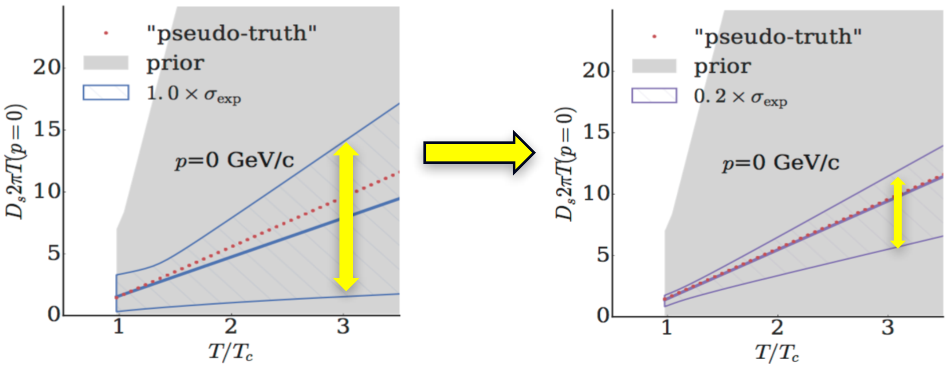
Real photons (less material, ITS with material calibration)



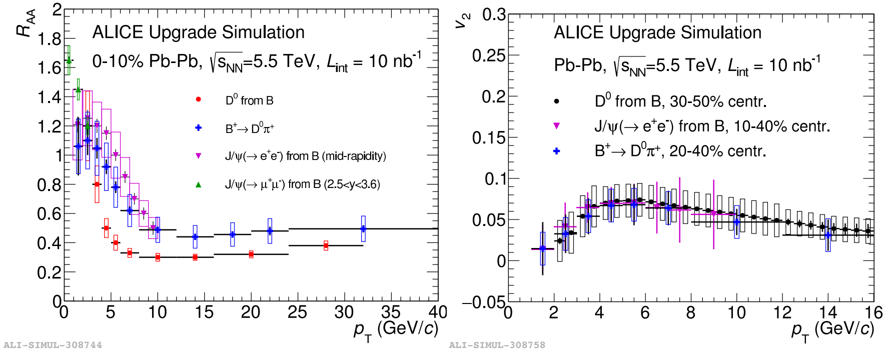
1. Macroscopic long-wavelength QGP properties

- **Temperature** → thermal radiation from real and virtual photons
- **Transport coefficients** → heavy-quark diffusion coefficients

Open heavy-flavour R_{AA} and v_2 down to p_T=0 → Precise determination of $2\pi TD_s$ vs. T



Bayesian analysis of D meson pseudo-data, S. Bass et al.

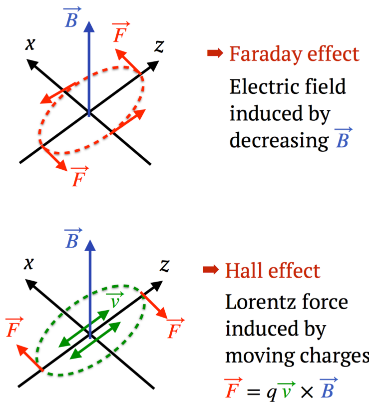


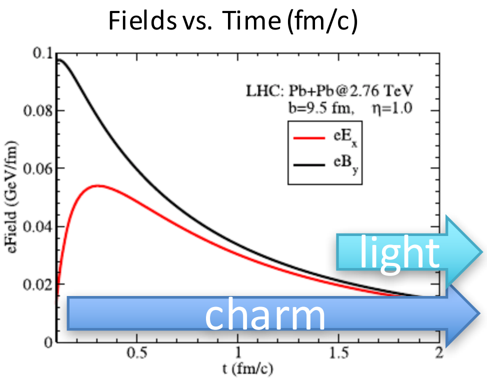
B meson R_{AA} and v_2

1. Macroscopic long-wavelength QGP properties

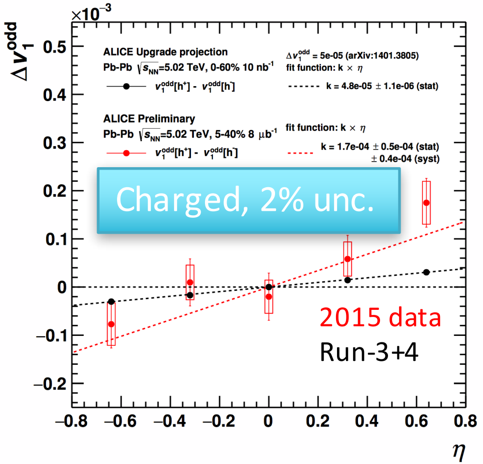
- **Temperature** → thermal radiation from real and virtual photons
- **Transport coefficients** → heavy-quark diffusion coefficients
- **Primordial E-M fields** → charge-dependent v_1 for light and heavy flavour

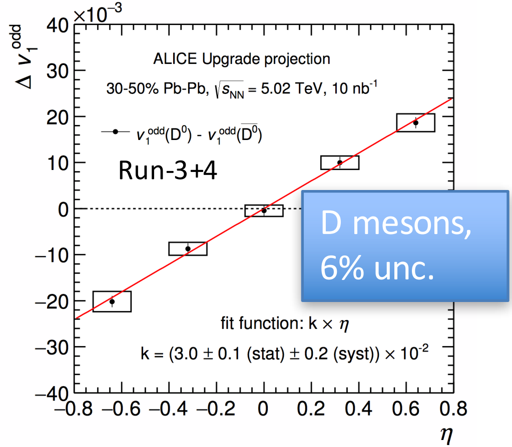
Δv_1^{odd} for charged particles and D mesons → role of E and M fields and their time evolution





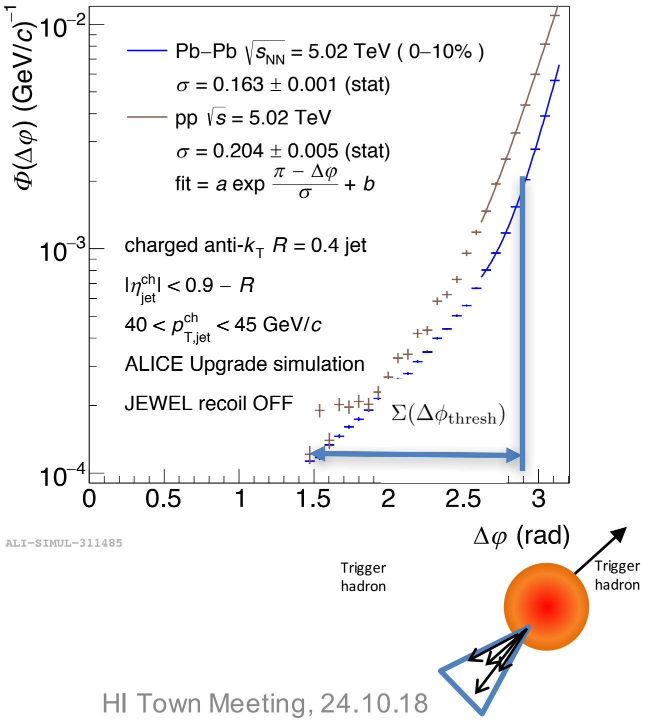
Das et al. PLB768(2017)

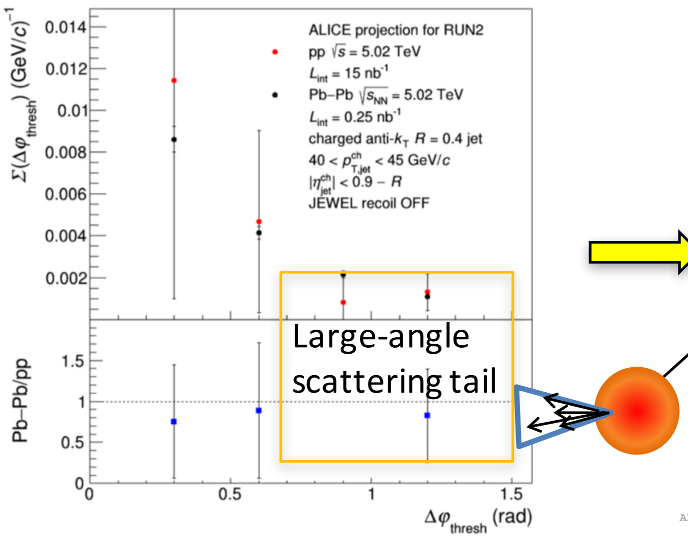


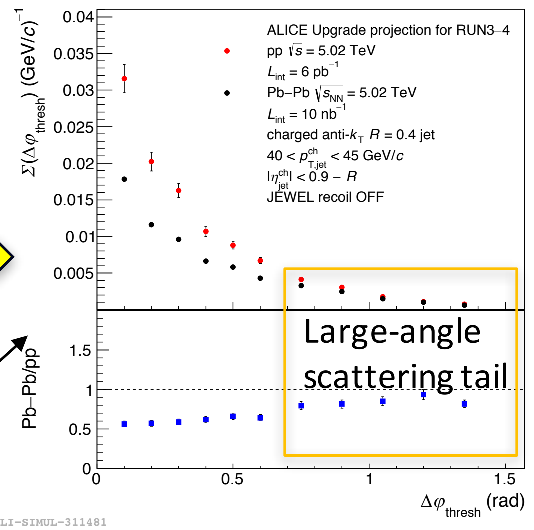


2. Microscopic QGP dynamics ("inner workings")

- **QGP substructure, quasi-particles?** → large-angle scattering with low-p_T h-jet





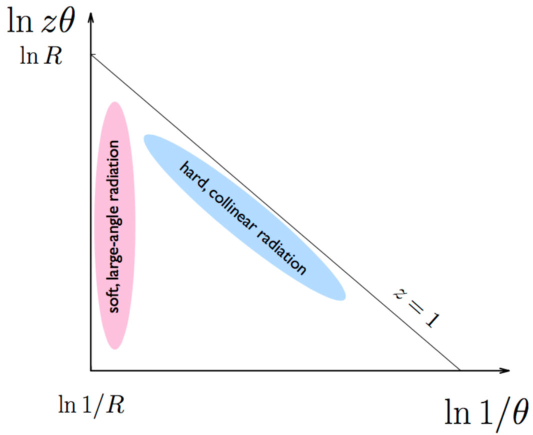


Run-2 ~50% unc.

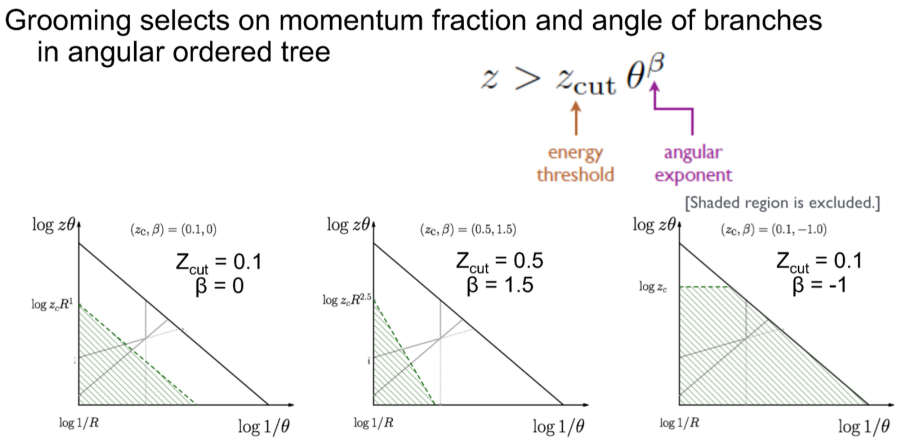
Run-3+4 ~5% unc.

2. Microscopic QGP dynamics (“inner workings”)

- **QGP substructure, quasi-particles?** → large-angle scattering with low-p_T h-jet
  → explore Lund diagram with jet substructure selections



H. Andrews et al., arXiv:1808.03689



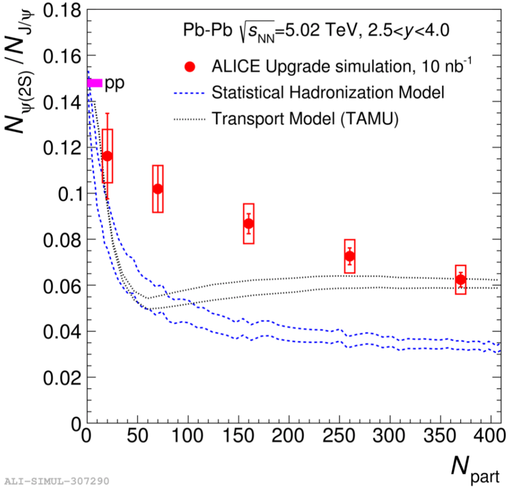
M. Verweij, HP2018

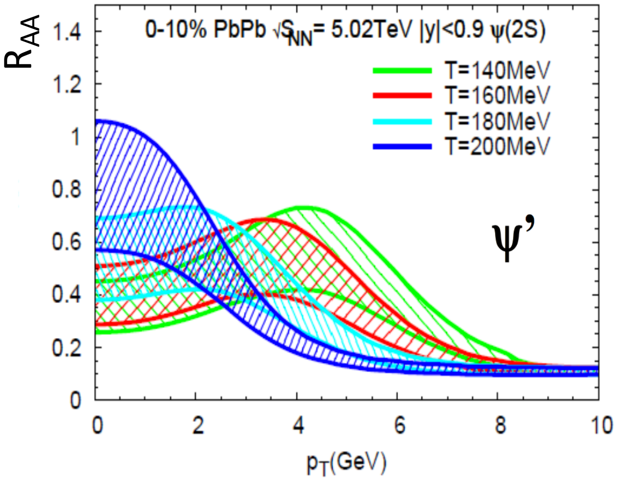
Large samples in Run-3+4 enable high-statistics coverage of substructure phase space

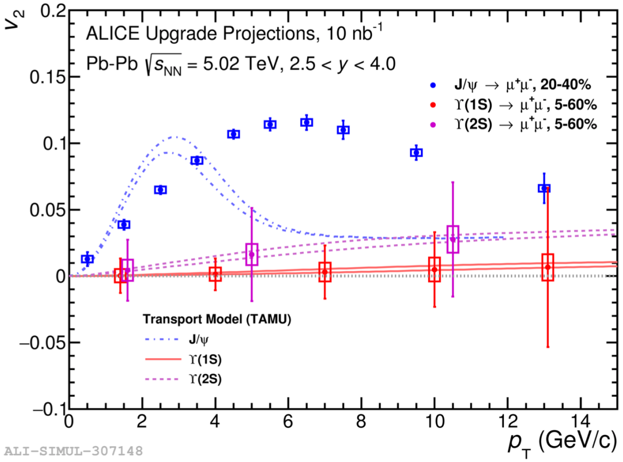
2. Microscopic QGP dynamics ("inner workings")

- **QGP substructure, quasi-particles? →** h-jet, jet substructure, Lund diagram
- **Charm quark in-medium potential and regeneration →** low-p_T charmonia

ψ(2S) / J/ψ sensitive to detailed dynamics of melting and regeneration, and to temperature
Precise v_2 and v_3 measurements will address the puzzle current data-model comparisons



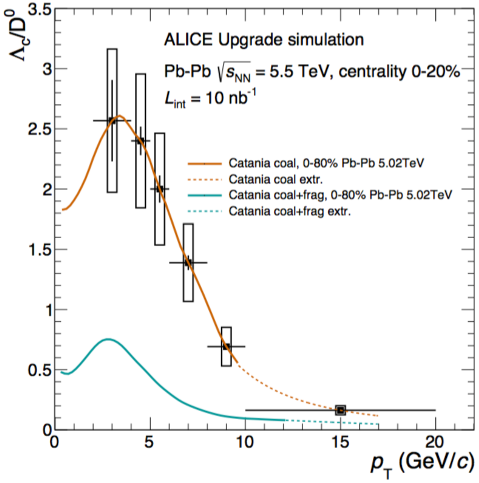


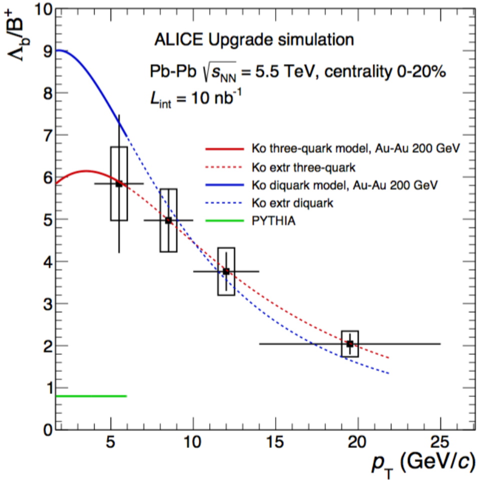


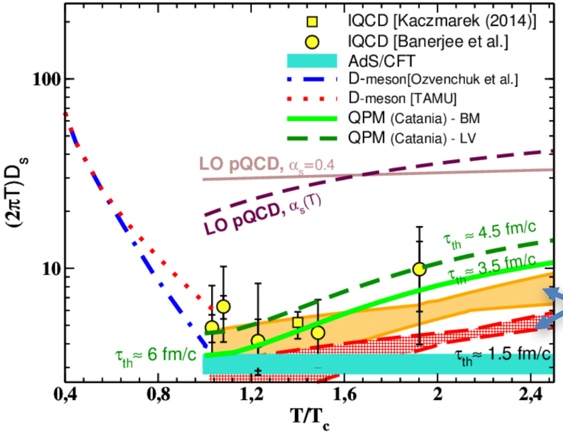
2. Microscopic QGP dynamics ("inner workings")

- **QGP substructure, quasi-particles?** → h-jet, jet substructure, Lund diagram
- **Charm quark in-medium potential and regeneration** → low-p_T charmonia
- **Heavy flavour recombination** → heavy-flavour hadrochemistry and baryons

D_s / D, Λ_c / D and Λ_b / B down to low-p_T → recombination vs radial flow, also crucial for diffusion coefficient





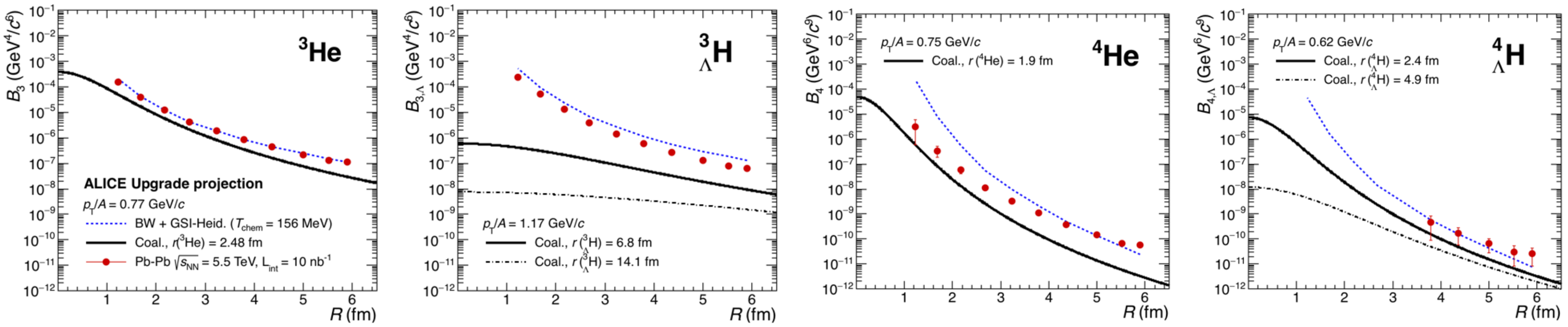


Different recombination scenarios

2. Microscopic QGP dynamics ("inner workings")

- **QGP substructure, quasi-particles?** → h-jet, jet substructure, Lund diagram
- **Charm quark in-medium potential and regeneration** → low-p_T charmonia
- **Heavy flavour recombination** → heavy-flavour hadrochemistry and baryons
- **Formation of large/fragile particles** → light and hyper-nuclei A=3, 4

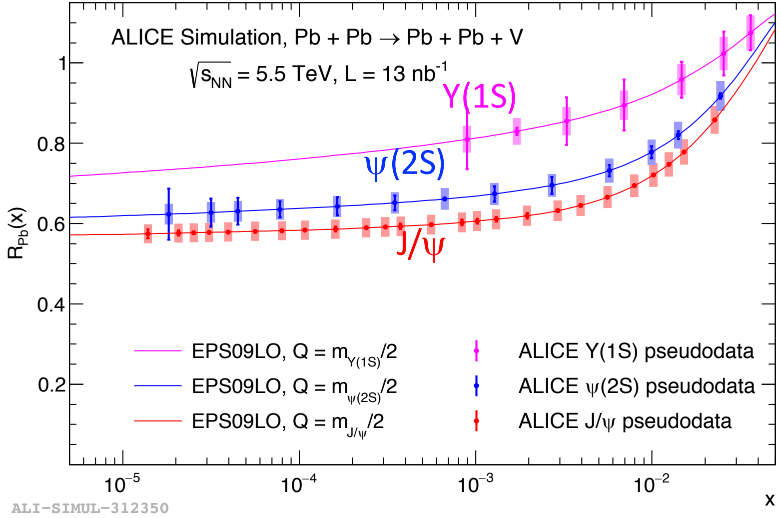
Coalescence parameters vs. centrality (system radius) discriminate among production scenarios



3. Initial-stage partonic state, search for saturation

- **Small-x studies** → Quarkonium production in Pb-Pb UPCs

Broad coverage $10^{-5}<x<10^{-2}$, directly sensitive to gluon nPDF/PDF $R_{Pb}(x)$



→ FoCal proposal to use cleanest probe, i.e. direct photons (will be discussed later in the talk)

4. Understanding collectivity across systems, hot medium in small systems?

- **High-precision multiplicity-dep. studies + cover Pb-Pb-like multiplicities also with pp collisions**

→ New extended programmes in small collision systems

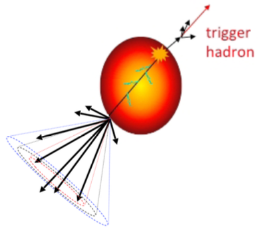
- **pp 14 TeV: 200 pb^{-1} with HM trigger in Run-3 → 15x$\langle N_{ch} \rangle$ ~60% Pb-Pb centrality**
  - + central diffractive events: x14 wrt Run-2 statistics
- **p-Pb 8.8 TeV: 0.5 pb^{-1} in Run-3 → increase x20 wrt Run-2 statistics**
  - A second p-Pb run after LS3, depending on FoCal study schedule
- **Support option for a short O-O campaign in Run-3 (onset of medium effects)**

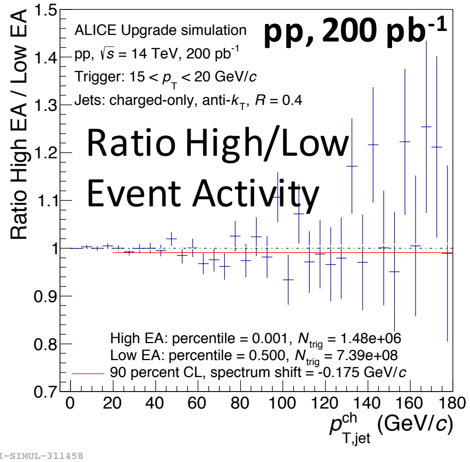
4. Understanding collectivity across systems, hot medium in small systems?

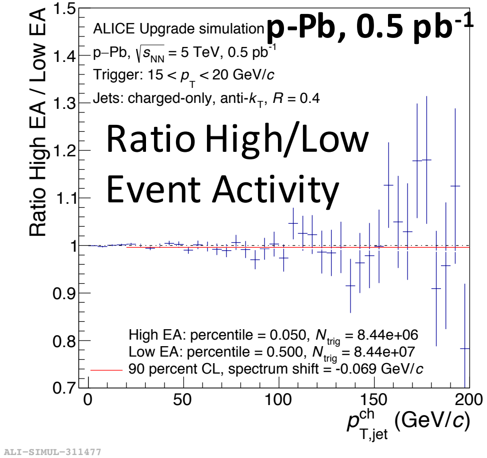
- **Search for energy loss →** hadron-jet recoil in pp and p-Pb vs Event Activity (EA)

Robust in small systems, no "centrality" determ. (N_{coll}) → Run-3: sensitive to ΔE > 200 MeV in pp, 70 in p-Pb

~ 100-times smaller than shift measured in Pb-Pb



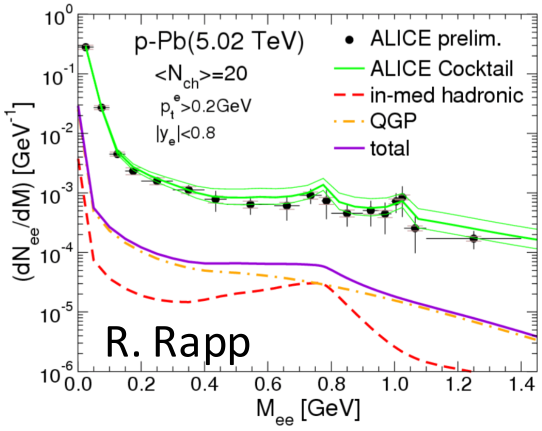


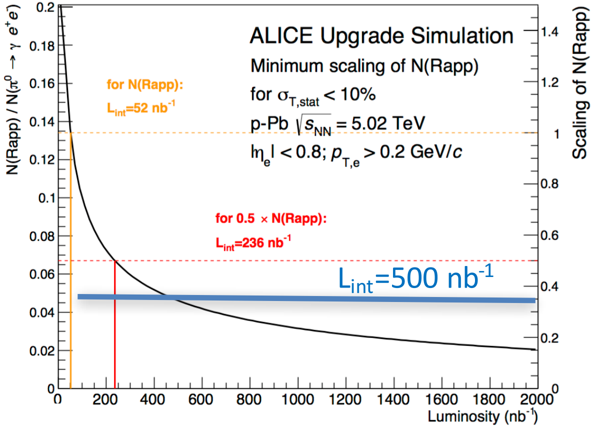


4. Understanding collectivity across systems, hot medium in small systems?

- **Search for energy loss** → hadron-jet recoil in pp and p-Pb
- **Search for thermal radiation** → real and virtual photons

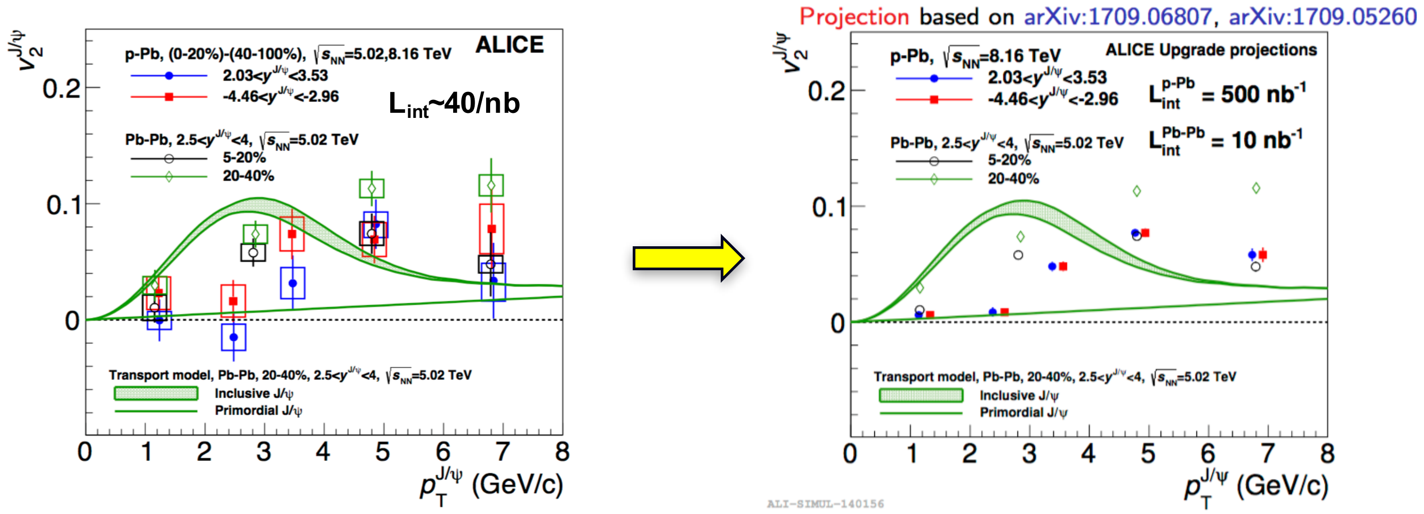
With 500 nb^{-1}, 10% stat. unc. on thermal spectrum slope, even with ~1/3 of predicted thermal signal (R. Rapp)





4. Understanding collectivity across systems, hot medium in small systems?

- **Search for energy loss** → hadron-jet recoil in pp and p-Pb
- **Search for thermal radiation** → real and virtual photons
- **Mass-dependence of collectivity** → Heavy quark and quarkonium flow in p-Pb



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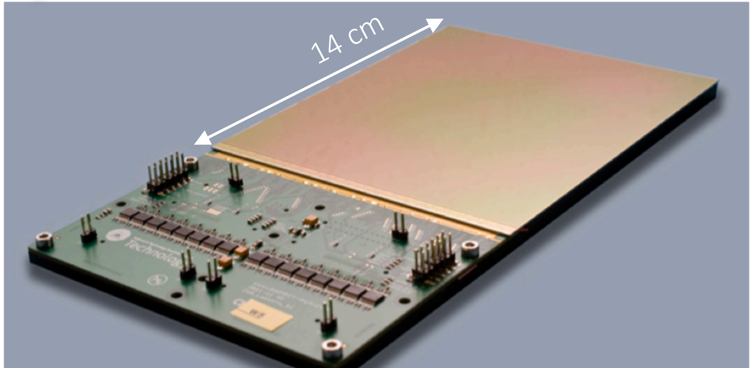
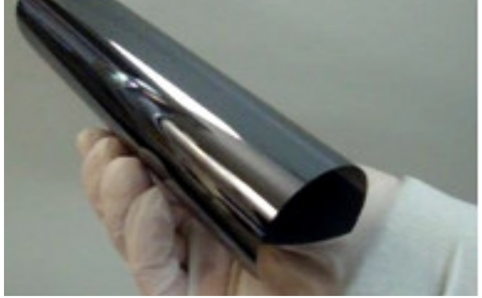
A new ultra-light inner barrel in LS3?

- Driving requirements of ITS upgrade
  - Reduce material budget
  - Move closer to beam-line
- can be pushed further using technologies that are quickly becoming mature
  - Silicon stitching allows fabrication of sensors of ~ 10x10 cm^2
  - Thinning to ~30 μm allows curved (cyl.) sensors

New Public Note with Expression of Interest: ALICE-PUBLIC-2018-013



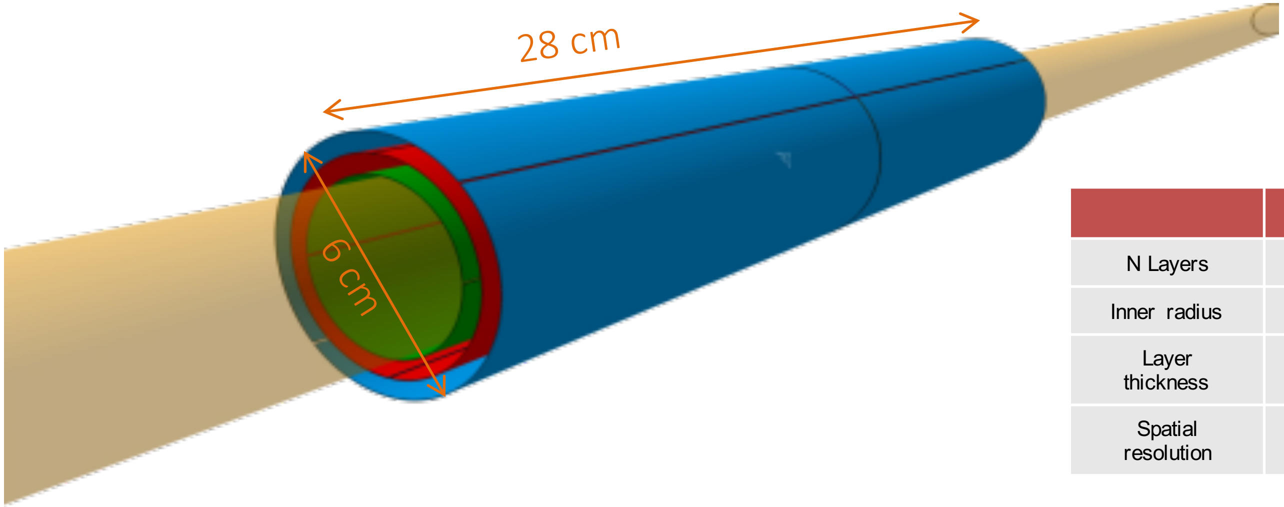
R. Turchetta, Rutherford Appleton Laboratory

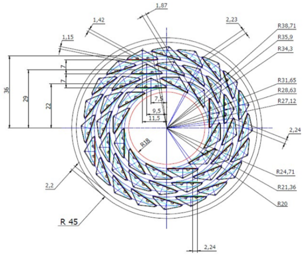


Silicon Genesis:
20 μm thinned wafer

A new ultra-light inner barrel in LS3: concept

- 3 truly cylindrical layers made of ~7x14 cm^2 sensors thinned to 20-40 μm
- Readout circuitry (power consumption) at periphery, outside acceptance
- No water cooling, minimal support structure in acceptance
- **Total material at R < 4 cm: ~1.3% → ~0.3%**

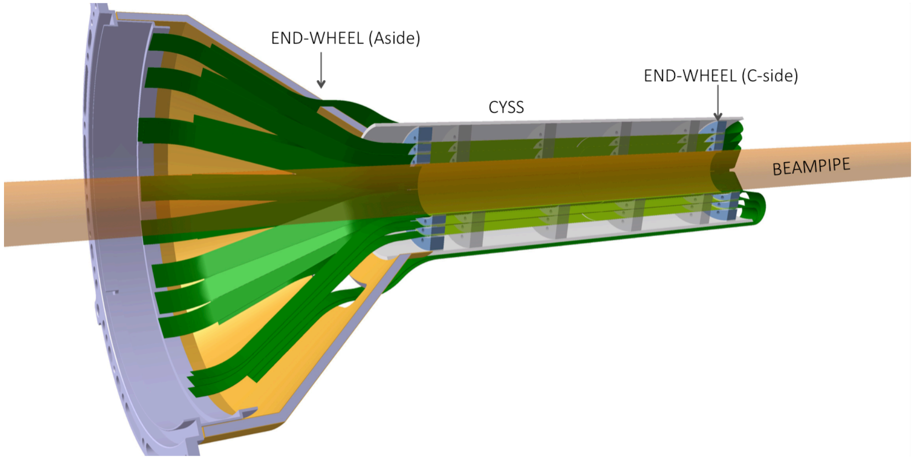


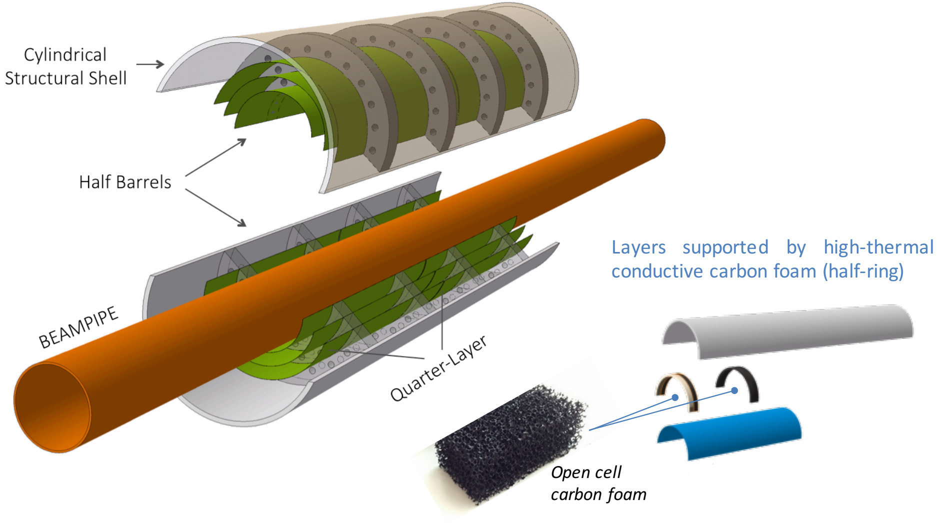


	ITS (inner)	ITS2 (inner)	ITS3 (inner)
N Layers	2	3	**3**
Inner radius	3.9 cm	2.3 cm	**1.8 cm**
Layer thickness	1.1% X_0	0.3% X_0	**0.05% X_0**
Spatial resolution	12x100 μm^2	~5x5 μm^2	**~5x5 μm^2**

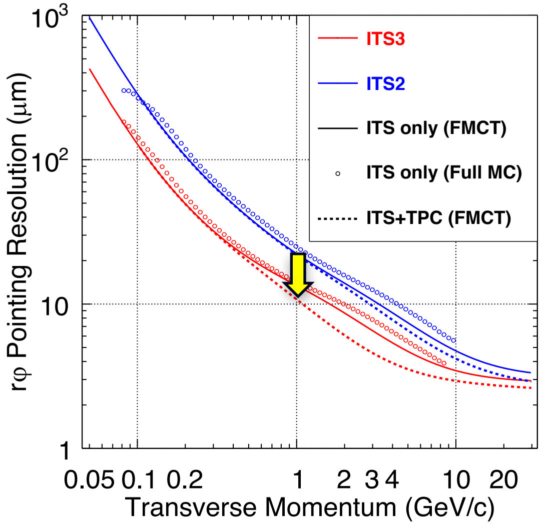
A new ultra-light inner barrel in LS3: design

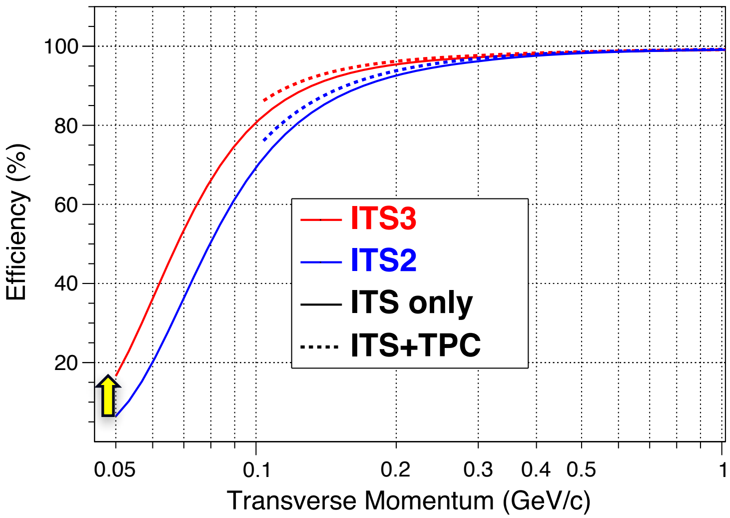
- Towards a conceptual design, including support and services
- Full integration with ITS outer barrels, MFT, FIT





A new ultra-light inner barrel in LS3: tracking



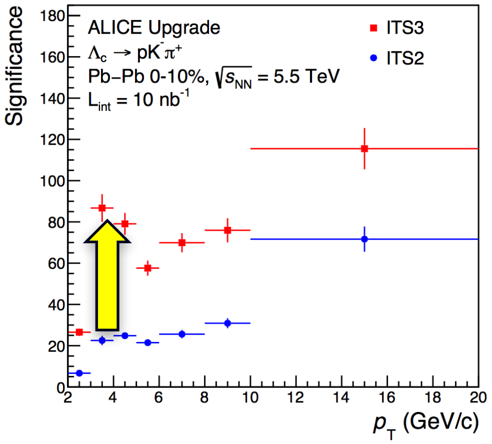


FMCT: semi-analytical, includes QED hits, but no energy loss fluctuations
Full MC: simplified ITS3 geometry, full MC simulation (GEANT3), Cellular Automaton ITS Tracker

- ITS3 vs. ITS2: resolution improved by factor 2 at all p_T's; tracking efficiency at low p_T (50-60 MeV/c) improved by factor 2

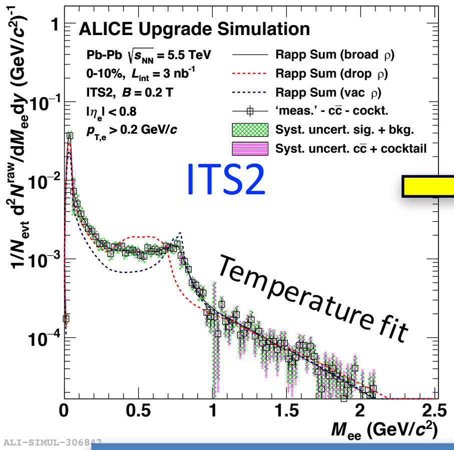
A new ultra-light inner barrel in LS3: physics

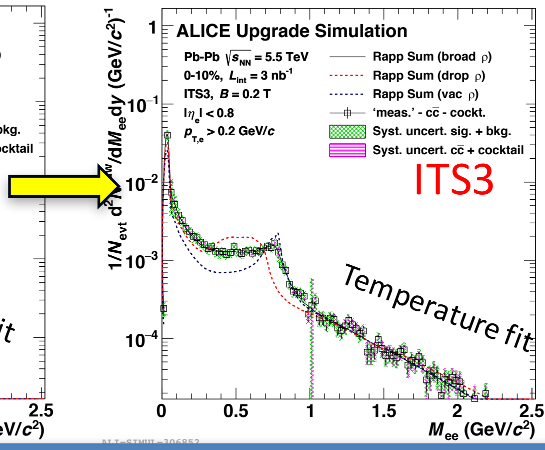
- Charm baryons (smallest cτ):
  - ✓ Vertexing precision



	S/B	Signif.
ITS3 / ITS2	10	4

- Low-mass dielectrons:
  - ✓ Vertexing (better charm rejection)
  - ✓ Lower material thickness (less conversions)
  - ✓ Higher low-p_T efficiency (better conversion rejection)

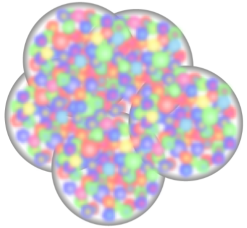


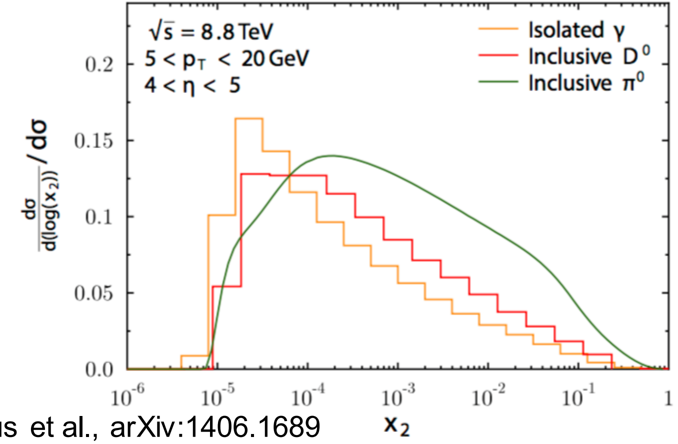


T (QGP)	Stat. error	Syst. (bkg)	Syst. (charm)
ITS3 / ITS2	1/1.3	1/2	1/2

In preparation: small-x physics with FoCal

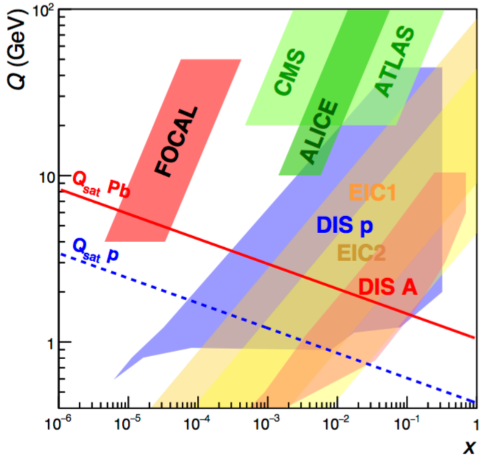
- R&D for a high-granularity Forward Calorimeter at $3 < \eta < 5$
  - Possible installation during or after LS3
- Main goal: direct photons in p-Pb ($x \sim 10^{-5}$)
  - Lower x than for open charm at same η
  - No final-state effects





Helenius et al., arXiv:1406.1689

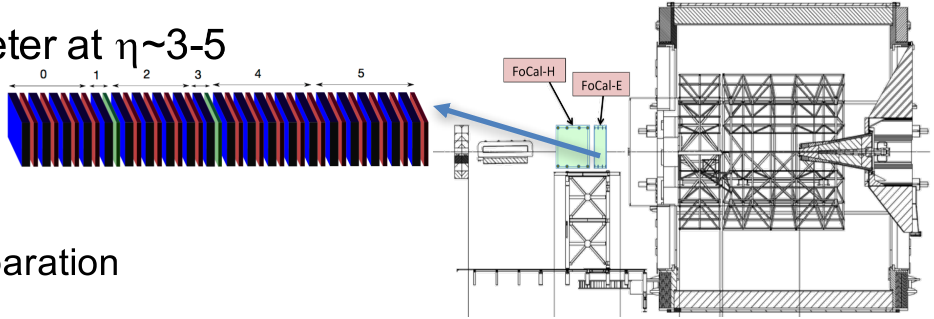
EM probes - kinematic coverage



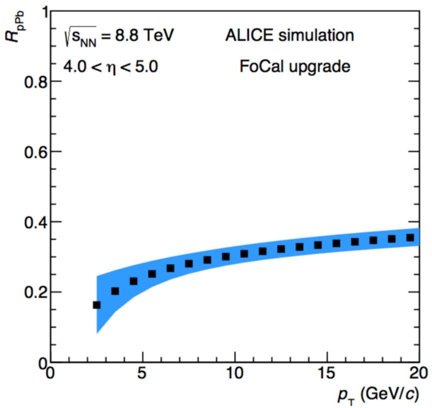
Note: LHCb DY possible similar coverage as FoCal

In preparation: small-x physics with FoCal

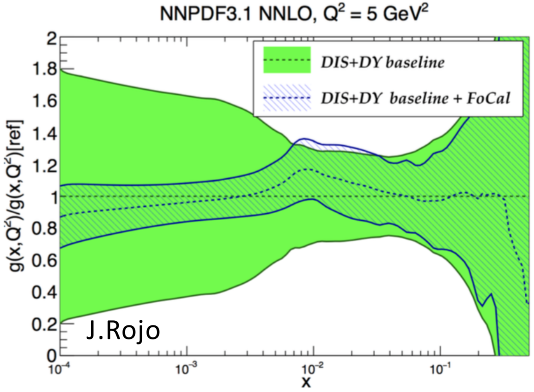
- R&D for a high-granularity Forward Calorimeter at η~3-5
  - Possible installation during or after LS3
- FoCal-E: hybrid design (2 types of sensors)
  - **Si-pads** (≈ 1 cm²): energy measurement
  - **CMOS pixels** (≈ 30x30 μm²): two-shower separation



Isolated γ R_{pPb}



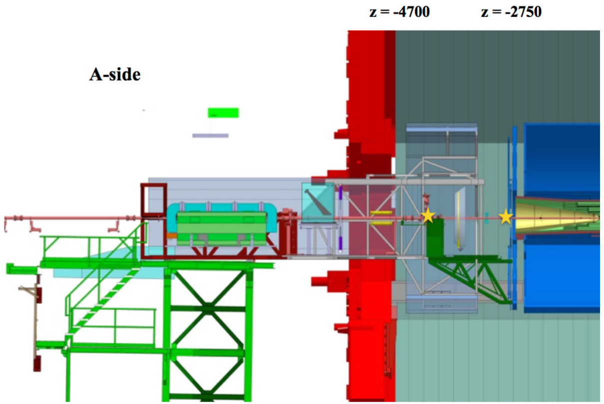
Impact on gluon nuclear PDF

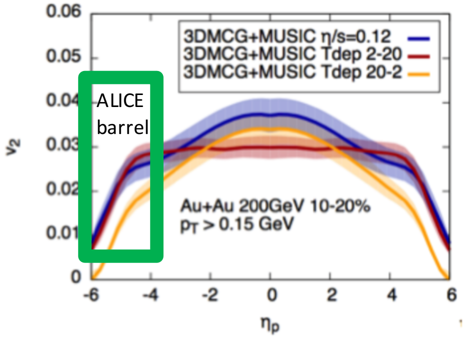


Under discussion: Fixed target in ALICE?

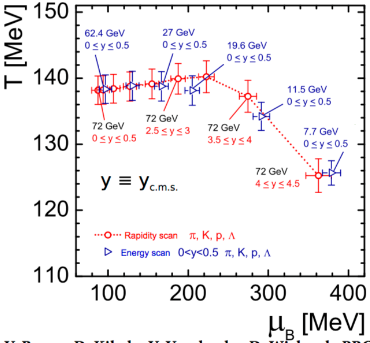
- Programme proposed within AFTER@LHC initiative
  - talk later today and arXiv:1807.00603
  - already started in LHCb with SMOG
- How in ALICE?
  - Extract beam halo with bent crystal (UA9)
  - Collide on solid target(s) inside beam pipe
- Integration / interferences to be studied

- Two main directions, for **studies at mid-y with muons and at backward-y with ID-hadrons**
  1. AA at $\sqrt{s_{NN}}$=72 GeV: flow at bkwd-y sensitive to $\eta/s(T)$; QGP with large μ_B at bkwd-y?
  2. pA+AA: open charm and quarkonia at mid-y sensitive to PDFs and nPDFs at x > 0.1





G.Denicol et al. PRL106 (2016)



V. Begun, D. Kikola, V. Vovchenko, D. Wielanek, PRC 98 (2018)

Outline

- ALICE LS2 upgrade: strategy and status
- Physics in Run-3 and Run-4
- LS3: a new inner tracker and other ideas
- A possible concept for physics in Run-5

Next major step forward: thin, precise, and fast

Extend ITS3 concept of ultra light and granular tracker to a very fast detector that can gain up to 2 orders of magnitude in statistics by exploiting higher luminosity with lighter ions

- Conceptual guidelines:
  - Very high rate capability (e.g. Ar-Ar projection ~ 10 MHz)
  - Low material to push down the p_T coverage and the vertexing precision
  - Hadron and electron identification
  - Extended rapidity acceptance (ideally $|\eta| < 4$)

Run-5: main physics goals

- Thermal radiation (dileptons and photons)
  - Dilepton multi-differential analysis vs. M_{ee} and $p_{T,ee}$
  - Higher flow harmonics
  - Photon femtoscopy
  - Electrical conductivity, sensitive to the strength of the coupling among constituents

→ Characterize T, size and shape of thermal source vs. time

- Heavy flavour, quarkonia
  - Multi-heavy-flavour: Ω_{cc}, Ω_{ccc}, B_c, XYZ states
  - $\chi_{c1,2}$
  - Ultimate precision on B mesons at low p_T

→ Detailed study of HQ recombination b-quark diffusion coefficient

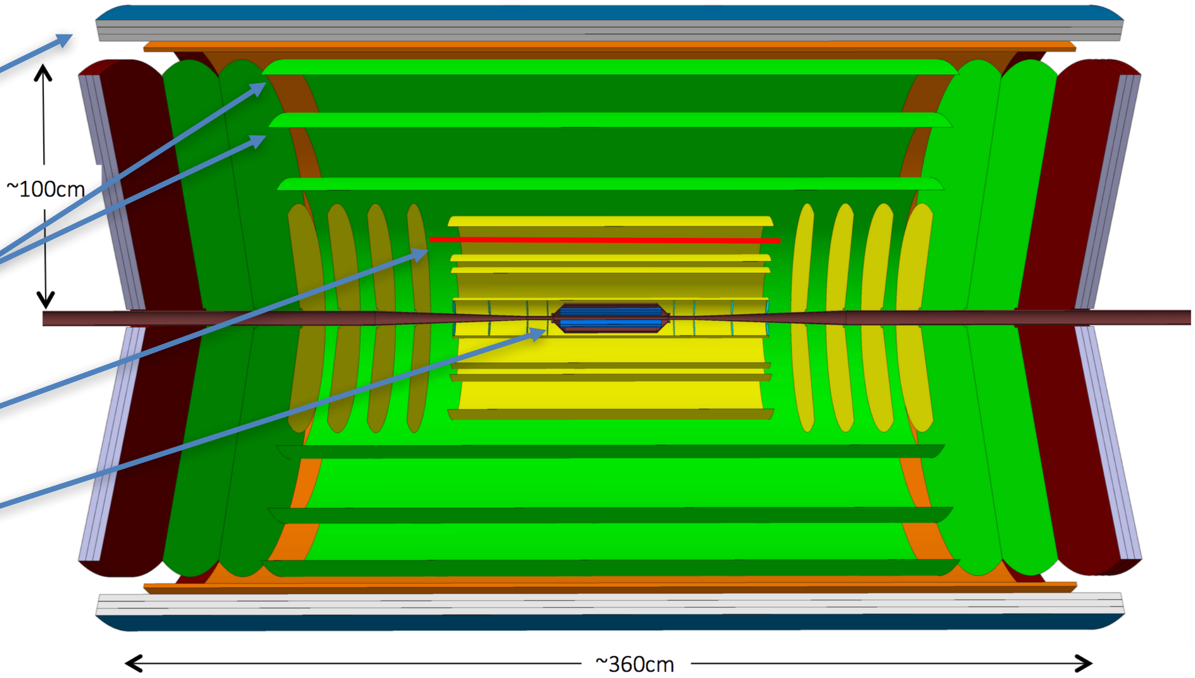
- Softest pions
  - Spectrum down to ~50 MeV
  - π^+/π^0 ratio

→ Coherent production? Bose-Einstein condensate? Disoriented chiral condensate?

- Other topics under study
  - A = 5, 6 light nuclei and hyper-nuclei
  - Fluctuations of conserved charges
  - Femtoscopy

Run-5: A possible detector concept

- All-pixel tracking and PID detector
- Pre-shower layers with W+pixels for ID high-*p* electrons
- Timing layers σ~25 ps for t.o.f. ID of hadrons and low-*p* electrons
- Insertable converter layer for photon detection
- Innermost layers inside the beam pipe



Conclusions

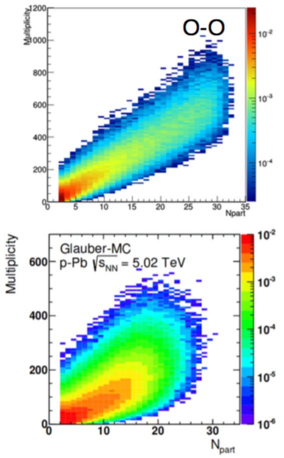
- LS2 upgrade well under way, major enterprise for the next 3 years
- Run-3/4 programme: several unique contributions to key priorities of the field, in particular QGP characterization at various length scales and understanding of physics underlying system-size dependence
- Lively discussion and preparation of next steps
  - New programmes? (small-x?, fixed target?)
  - Ultimate performance and precision → ultra-thin, high-speed

EXTRA SLIDES

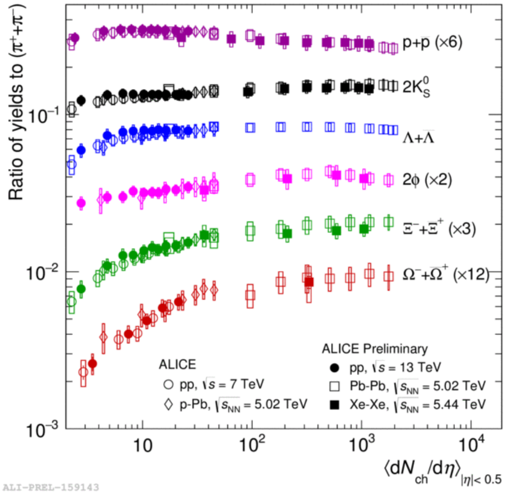
Short O-O run: onset of medium effects?

- Xe-Xe results raised interest in a possible O-O run in Run-3
  - Search for energy loss in small system with AA geometry but same N_{ch}, N_{part}, N_{coll} as p-Pb
    - 20% R_{AA} suppression in central O-O (N_{coll}~35) expected on the basis of Xe-Xe
  - Moreover: strangeness/pion, initial vs final state effects in flow
- ALICE supports proposal of a 1-2 days run (few 100/μb) to address these questions

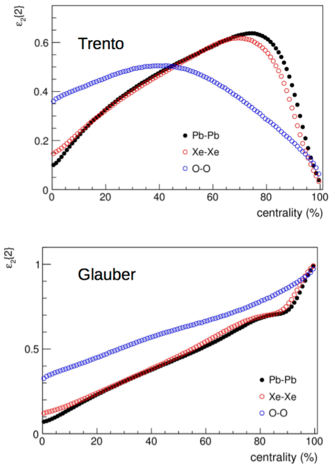
Mult. vs. N_{part}



Particle prod. vs. mult.



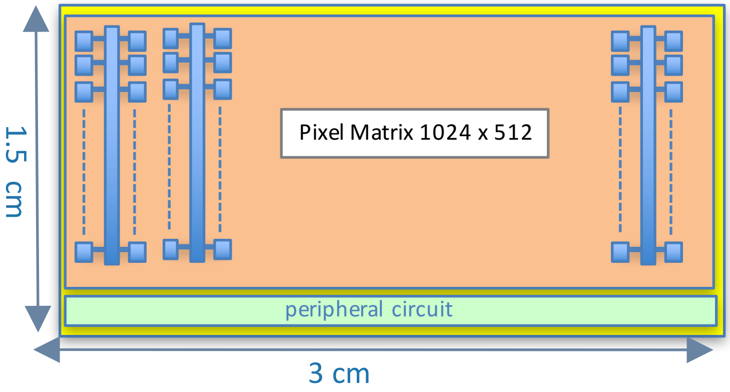
Initial conditions (ecc.)



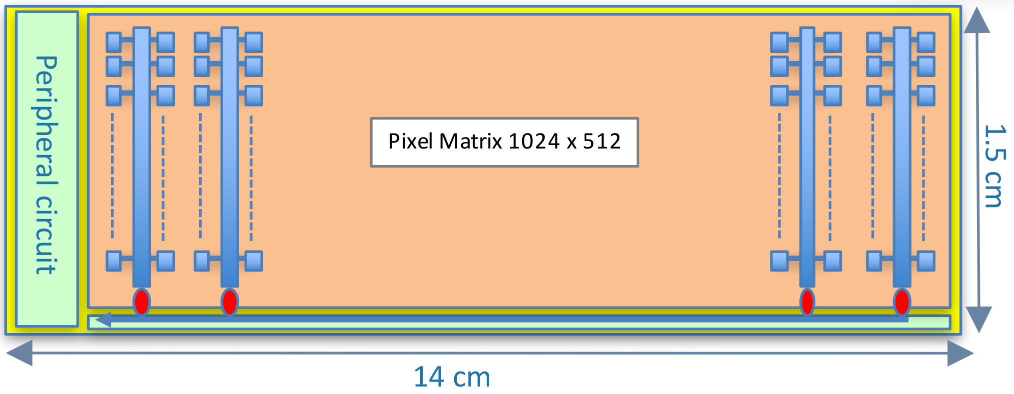
C.Loizides,
HL-LHC June WS

Stitching allows the fabrication of wafer scale sensors

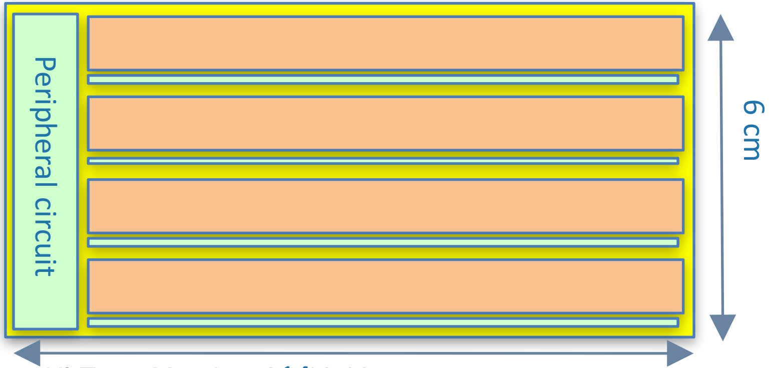
ALPIDE Chip



1D stitched sensor (z direction)



2D stitched sensor – wafer-scale



By instantiating multiple times the same circuits in the second dimension (ϕ) one can realize the sensors for the different layers. For example

- L0 = 14 cm x 6.0 cm
- L1 = 14 cm x 7.5 cm
- L2 = 14 cm x 9.0 cm

Particle Rates

Expected maximum particle density in the layers of the ITS Inner Barrel

	Particle density (cm^{-2})			
	LS2 Upgrade		LS3 Upgrade	
Layer	Hadronic[a]	QED electrons[b]	Hadronic[a]	QED electrons[b]
0	43	7	73	12
1	25	3	43	8
2	17	2	29	6

[a] *maximum particle density in central Pb-Pb collisions (including secondaries produced in material) for B = 0.2T*

[b] *for an integration time of 10μs, an L_{int} = 50 kHz and B = 0.2T*

Particle density at L0 increases by ≈ 70%

Sensor occupancy (fraction of pixel with a particle hit) ≈ 10^{-3} ⇨ no issues for the tracking

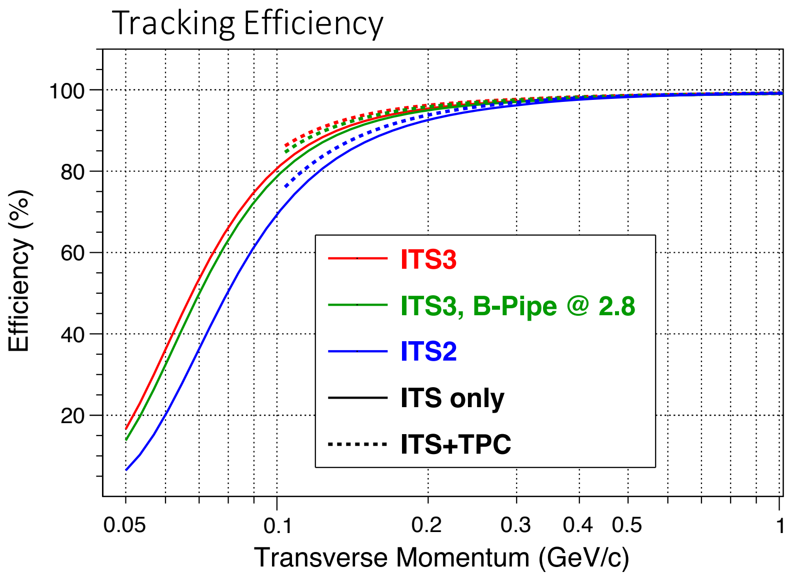
Particle flux (for 50 kHz Pb-Pb) < 4 MHz / cm^2 ⇨ well within the detector readout capabilities

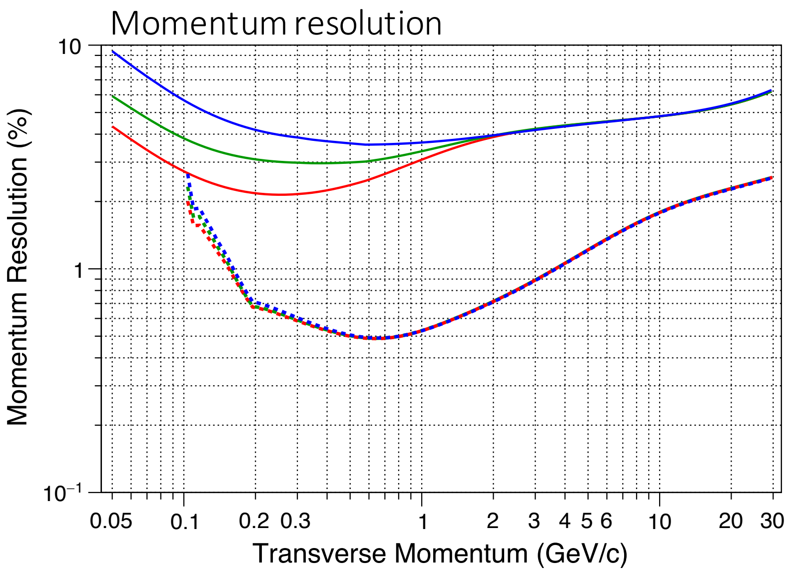
Radiation load increases by ≈ 70% ⇨ still well below the safety values

Tracking Performance

Tracking efficiency and momentum resolution

Pb-Pb, B=0.5T





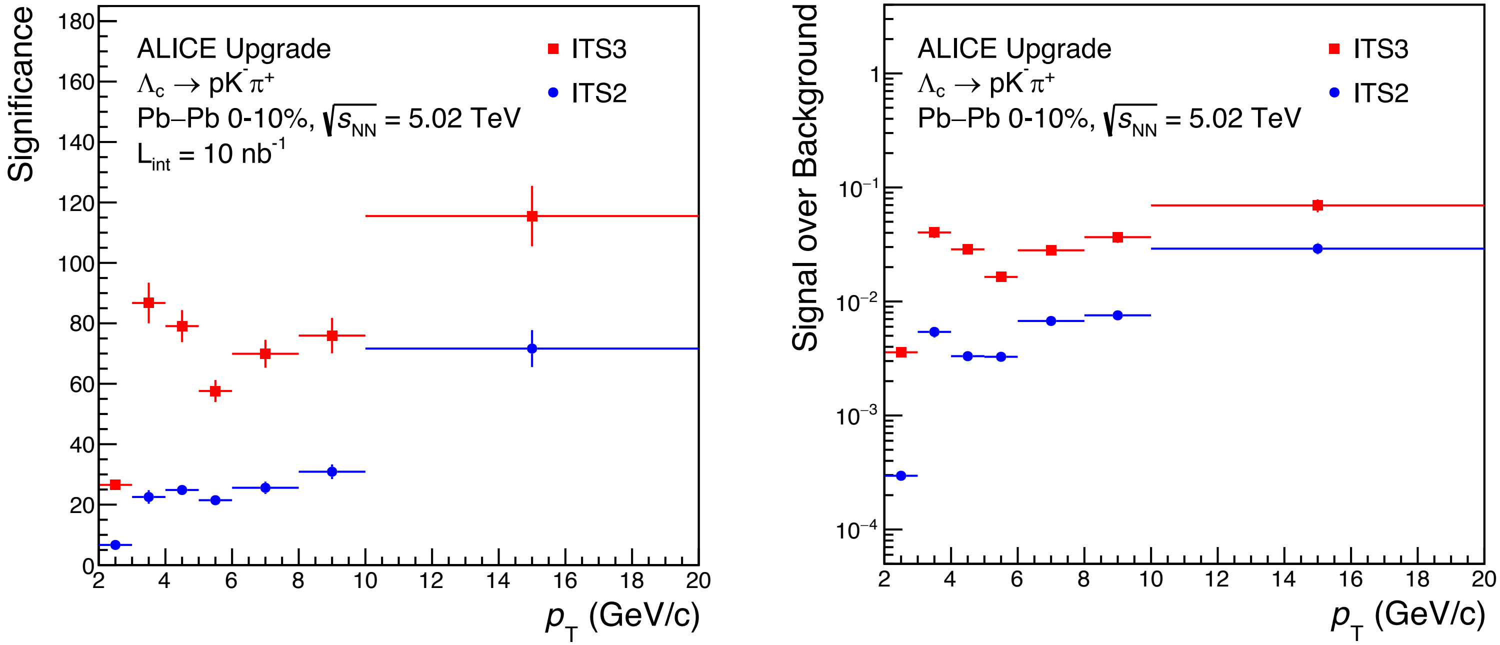
Efficiency increases factor 1.2 – 2, for pT < 100MeV

Standalone p_T resolution improvement ≈ 2

⇨ ITS standalone efficiency likely overestimated, due to lack of fluctuations

Physics Performance Studies – Λ_c

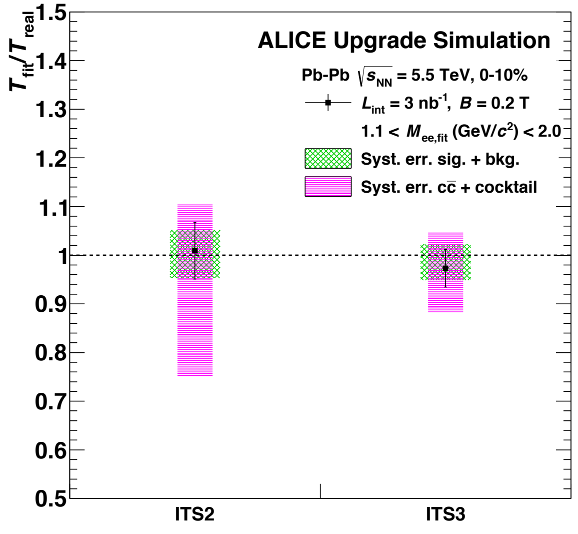
$\Lambda_c \rightarrow pK^-\pi^+$ in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV (Lint = 10 nb^{-1})



ITS 3 improvement: factor 4 (significance) and factor 10 (S/B)

Physics Performance Studies – Thermal Dielectrons

Temperature Extraction



T *extracted from an exponential fit to the invariant mass excess spectrum in* **1.2 < Mee < 2.5 Gev/c²**

Comparison ITS2 (LS2) and ITS2 (LS3 Upgrade)

ITS3 upgrade reduces

- *Statistical* uncertainty by a **factor 1.3**
- The systematic uncertainty from the subtraction of the *combinatorial background* by a **factor 1.5**
- The systematic uncertainty from the subtraction of the light-hadron and charm decay backgrounds by a **factor of 2**

T (QGP)	Stat. error	Syst. (BG)	Syst. (Charm)
ITS3 / ITS2	Factor 1.3	Factor 1.5	Factor 2

A new HI dedicated experiment beyond LS4?

Design guidelines

- Increase rate capabilities (factor 20 to 50 wrt to RUN4): $\langle L_{NN} \rangle$ ~ up to 10^{34} $cm^{-2}s^{-1}$
- Improve vertexing
  - Ultra-thin wafer-scale sensors with truly cylindrical shape, inside beampipe
  - spatial resolution ~ 1-3μm
  - material thickness < 0.05% X_0 /layer
- Improve tracking precision and efficiency
  - About 10 layers with a radial coverage of 1m
  - Spatial resolution of about 5μm up to 1m
  - whole tracker could be less than 6% X_0 in thickness (at mid-rapidity)
- Extended rapidity coverage (ideally up to 8 rapidity units)

Focus on relatively low p_T phenomena, $0.01 < p_T < 10$ GeV/*c*

Magnetic fields of < 0.5T would be sufficient but 1T (or higher) is to be considered

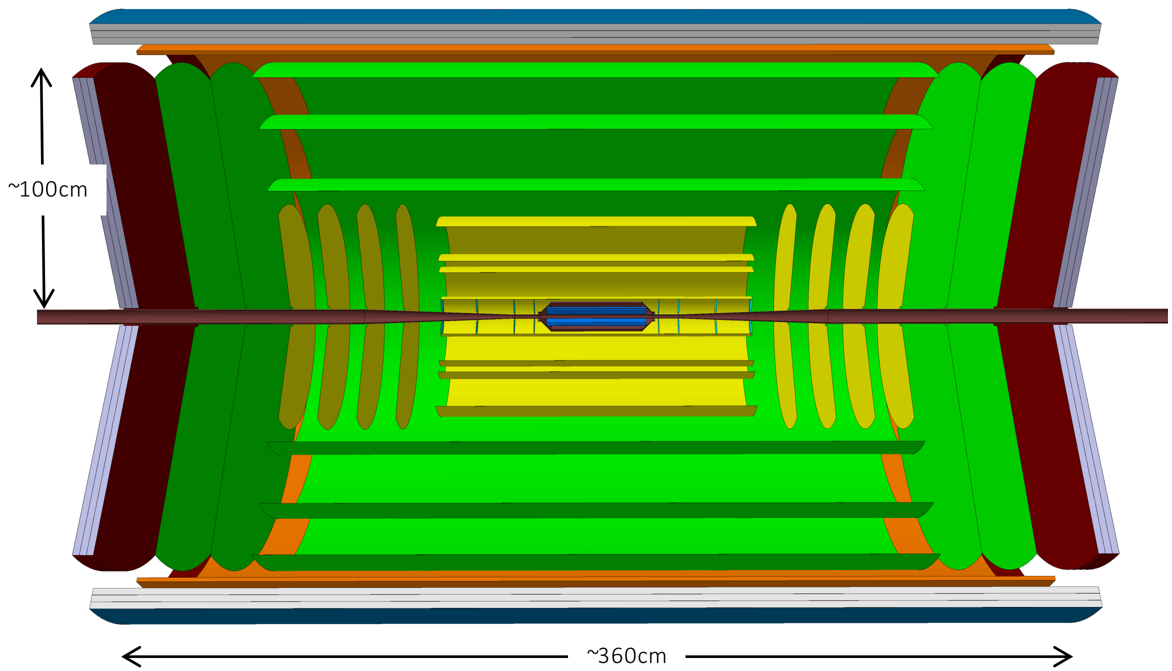
A new experiment based on a "all-silicon" detector

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Hadron ID: TOF with outer silicon layers (orange)

Electron ID: pre-shower (outermost blue layer)

Extended rapidity coverage: **up to 8 rapidity units**
+ FoCal?



Preliminary studies

Magnetic Field
- B = 0.5 or 1 T

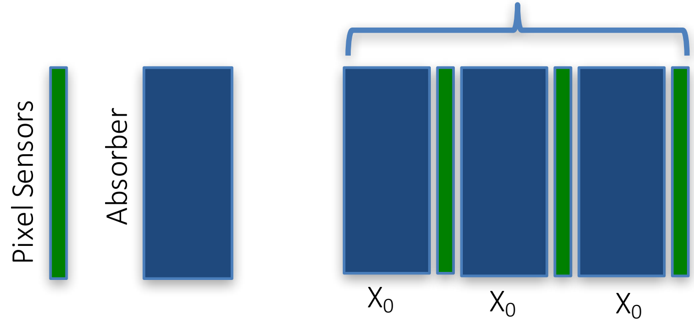
Spatial resolution
- Innermost 3 layers: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Time Measurement
Outermost layer integrates high precision time measurement (σ_t < 30ps)

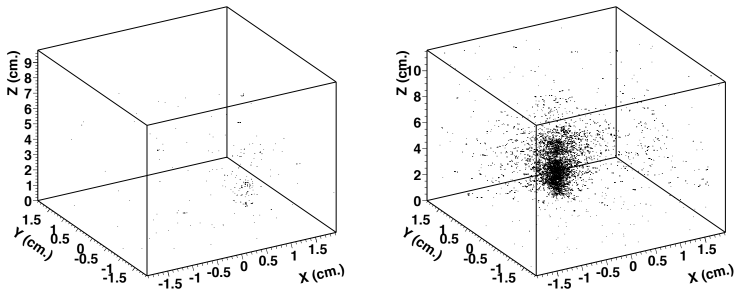
Particle Identification

Electron and hadron PID using dE/dx, TOF and pre-shower

- dE/dx in silicon (middle layers): PID at very low p_T (20 – 200 MeV)
- Time of Flight: $\sigma_{TOF} \approx$ 20-30ps, track length ~1m ⇨ good e/π separation < 500 MeV
- Pre-shower (2-3 X_0) based on high-granularity (CMOS pixels) digital calorimetry
  - great potential to identify electrons down to few hundred MeV by detailed imaging (particle counting, geometry) of the initial shower



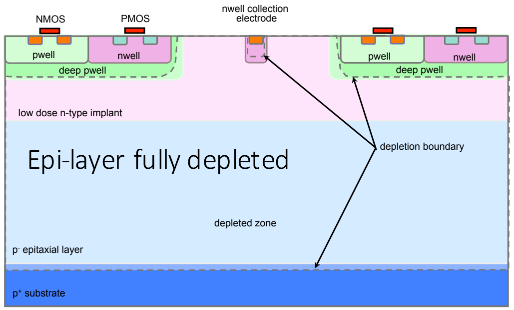
FoCal - R&D studies



2 GeV/c positrons   100 GeV/c positrons

Hadron ID with silicon TOF detector

Time resolution of a fully depleted CMOS pixel sensors a la "ALPIDE"



Modified process CERN/Tower

R&D for the ALICE upgrade: developed in collaboration with Tower a process modification that allows full depletion of the high resistivity silicon layer

- Reduces charge collection time (<1ns)
- Enhances radiation hardness (~10^{15} n / cm^2)

First order approximation $\sigma_t = c \frac{t_r}{SNR}$

t_r: amplifier rise time

c = 0.4 – 0.6

In ultra-thin O(10μm) fully depleted CMOS sensors (e.g. INVESTIGATOR or ALPIDE with CERN/TJ modified process) with 10V reverse bias

- Charge (e) collection time T ≈ 170ps
- Standard deviation of signal centroid time $\Delta_T \approx$ 15ps
- noise ≈ few electrons
- Signal on seed pixel ≈ 1000 electrons

- $\sigma_{TDC} \approx$ 15ps
- jitter ≈ 10ps
- $T_0 \approx$ 10ps

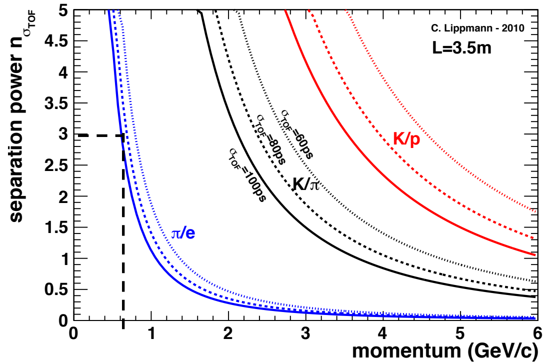
Single layer

$\sigma_t < 27 ps$

Time resolution might be further limited by signal shape fluctuations inside sensor

Electron ID

Time Of Flight



TOF PID – track length 3.5m

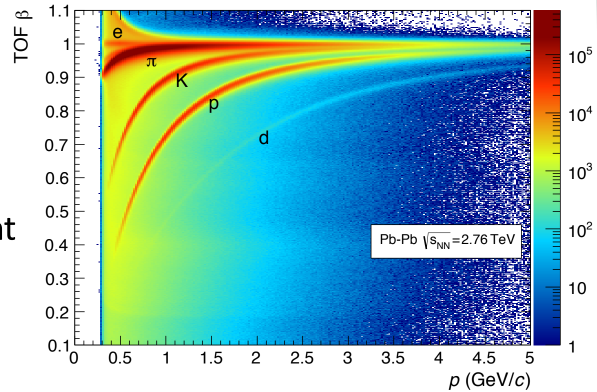
3 system time resolutions

60ps, 80ps , 100ps

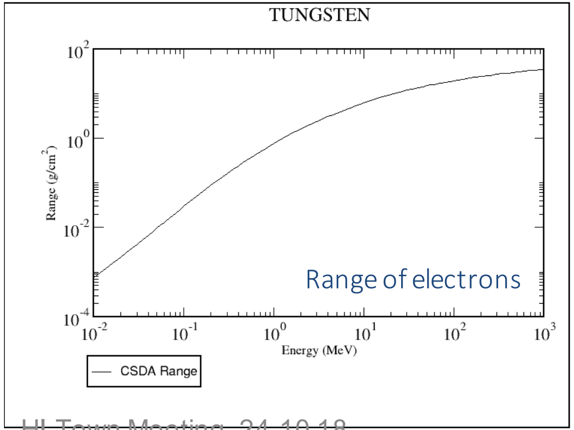
Ideal track length and p measurement

Good e/π separation < 600 MeV/c

ALICE TOF (current)



Range of electrons in W



Absorption of electrons in W

- X_0 = 0.35 cm
- ρ = 19.3 g/cm³

Range of e in W > 4.5X_0 for E> 500MeV

Energy (MeV)	10	50	100	200	500	1000
Range (cm)	0.33	0.79	1.02	1.26	1.58	1.81
Range (X_0)	0.92	2.27	2.90	3.60	4.52	5.18

Range of electrons in copper