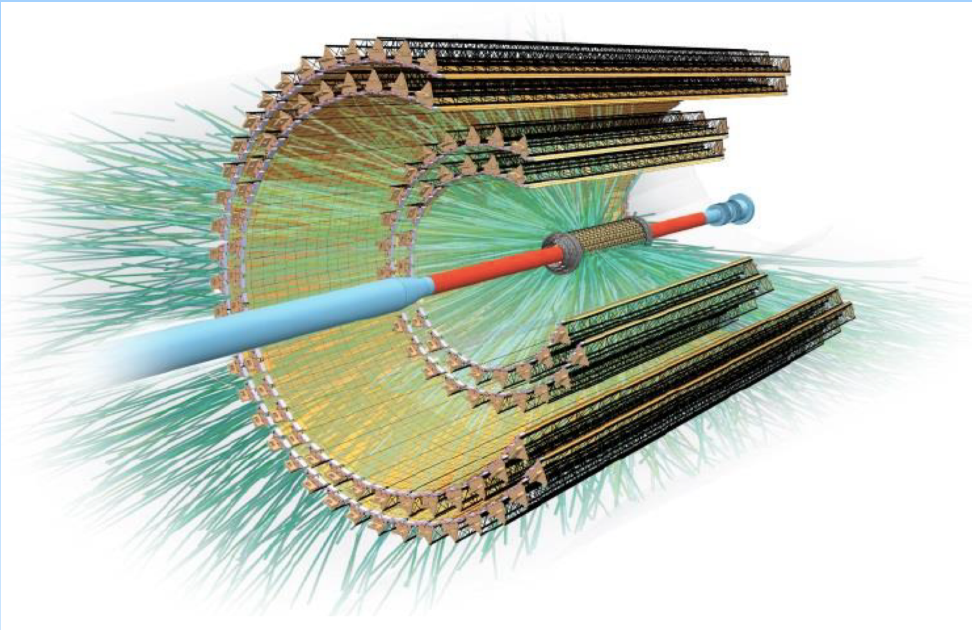
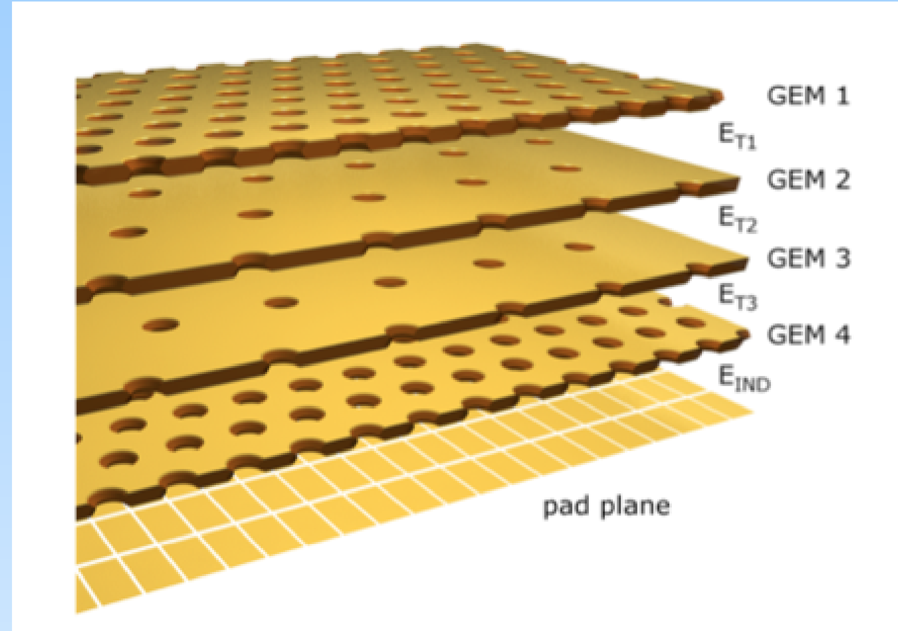




The ALICE upgrade program

Silvia Masciocchi, GSI

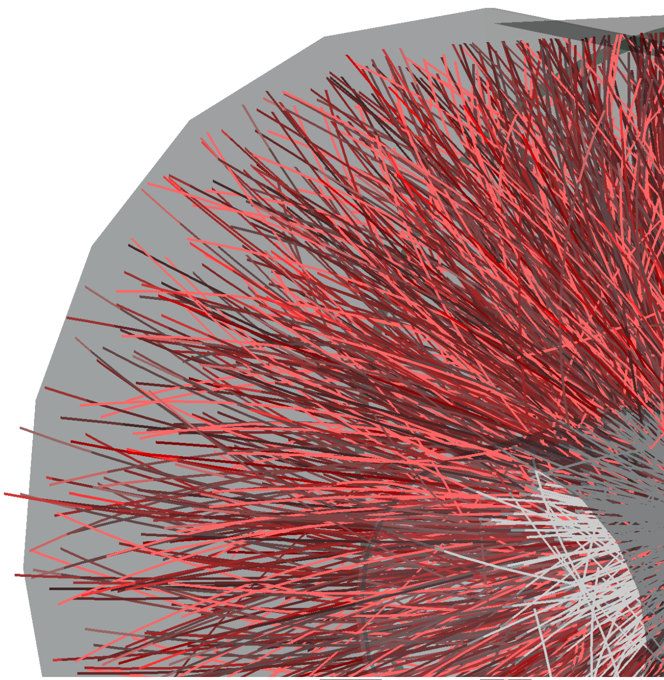
EMMI NQM seminar,
GSI, November 16, 2016

Outline

- What comes after what ALICE measured with run 1 data and what is being recorded during run 2?

- Heavy-ion collisions at the LHC in runs 3 and 4
- Upgrades to the experiment
- ALICE physics program

- Summary



Heavy ions at the LHC: run 1

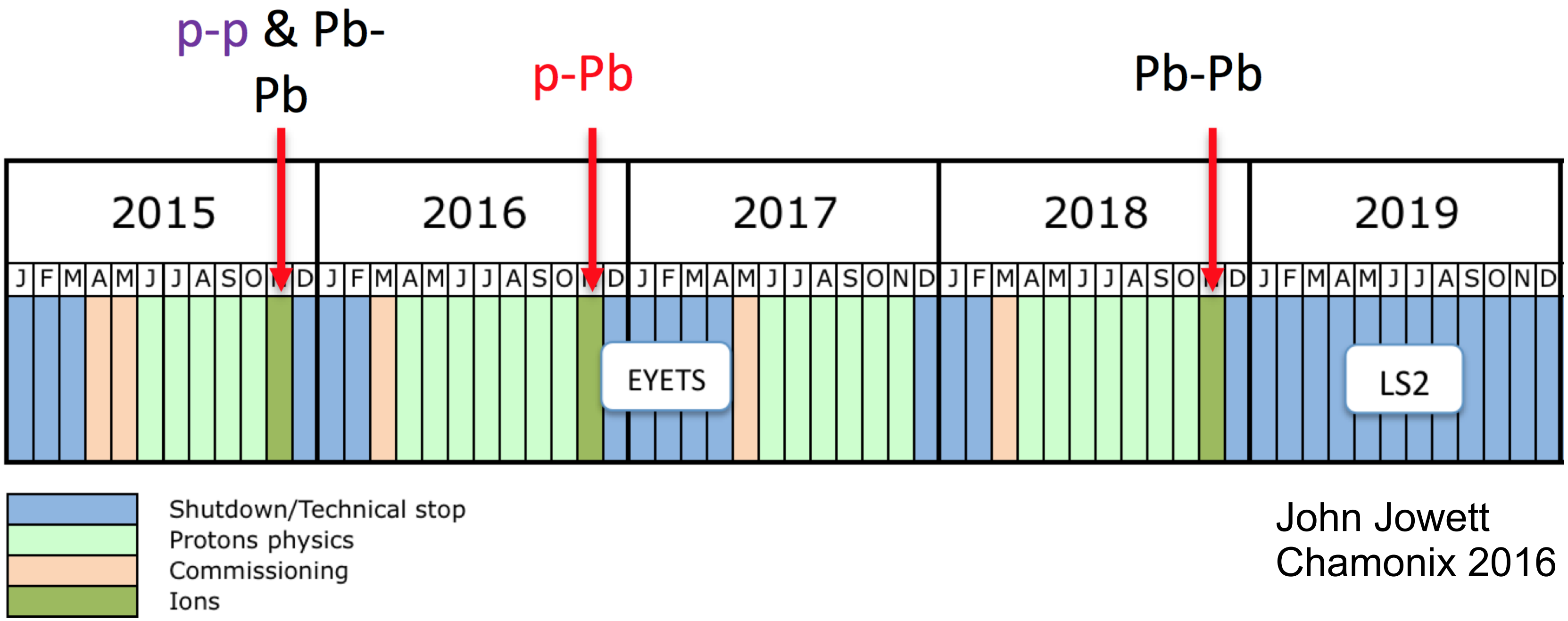
year	system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**Pb-Pb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 250 nb^{-1}
2011	**Pb-Pb**	**2.76**	**~ 150 μb^{-1}**
2013	p-Pb	5.02	~ 30 nb^{-1}
2013	pp	2.76	~ 5 pb^{-1}

In 2011, LHC already reached the nominal Pb-Pb luminosity: 5×10^{26} $cm^{-2}s^{-1}$ (interaction rates around 5-6 kHz)

Heavy ions at the LHC: run 2

Higher collision energy: Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV and 8 TeV



John Jowett
Chamonix 2016

Goal of run 2 for ALICE: **~ 1-2 nb^{-1} integrated luminosity (Pb-Pb)**

x 10 wrt run 1

Including rare triggers

2015 Pb-Pb run at the LHC

- **AMAZING PERFORMANCE!**

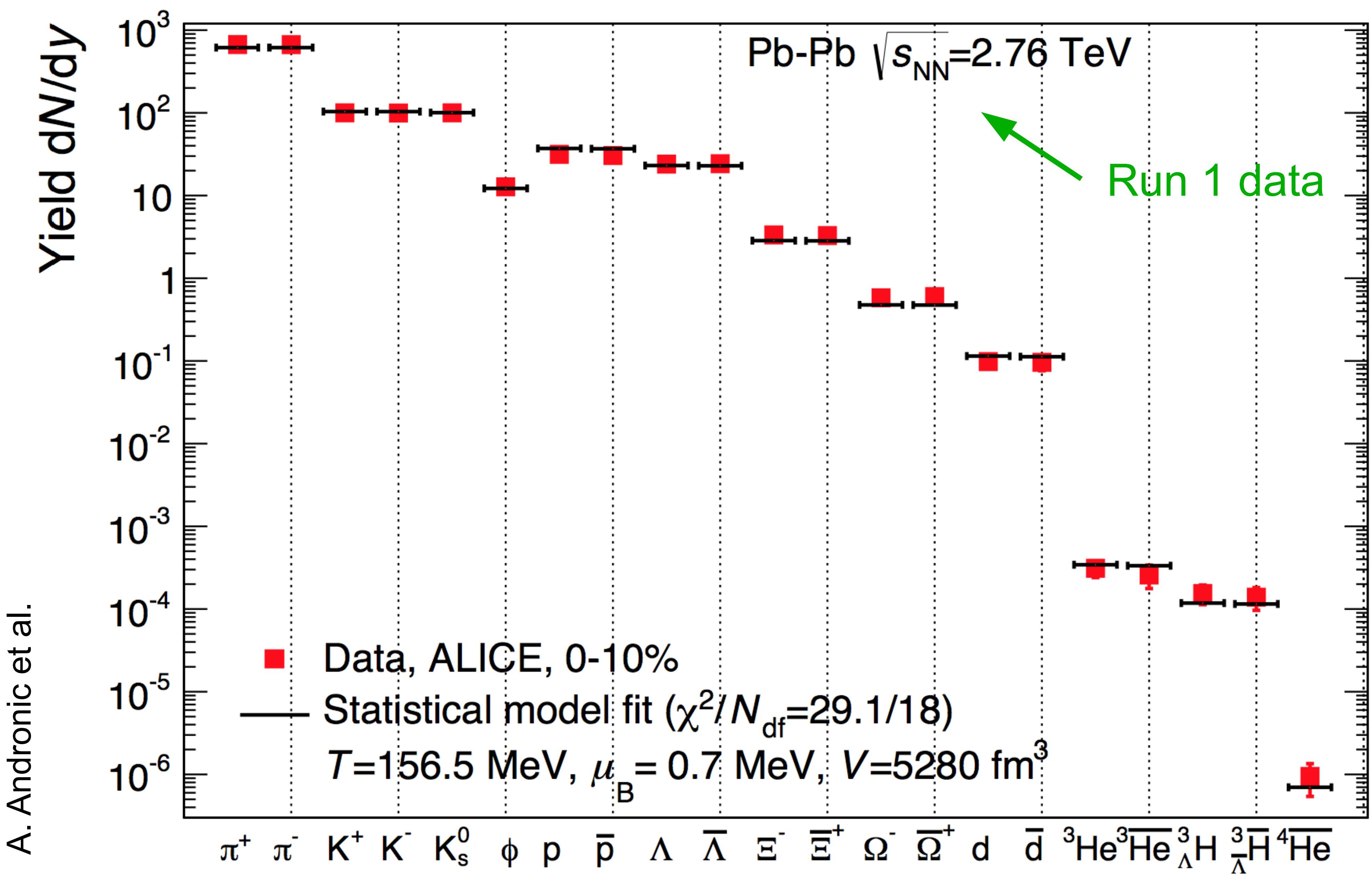
- In 2015, luminosity exceeded the design value:
  - First it reached 10^{27} $cm^{-2}s^{-1}$ (2 x design) using the highest achieved intensity of ions in the 426 bunches filled from the injectors (PS and SPS)
  - Then reached 3 x design having up to 518 bunches in the LHC (thanks to the reduced rise time of the SPS injection kicker array)
  - Many important limits of LHC with heavy ions tested!!

- Machine already running at (safety) limits

- Luminosity leveling used at ALICE in 2015

Why beyond the planned 1 nb^{-1}?

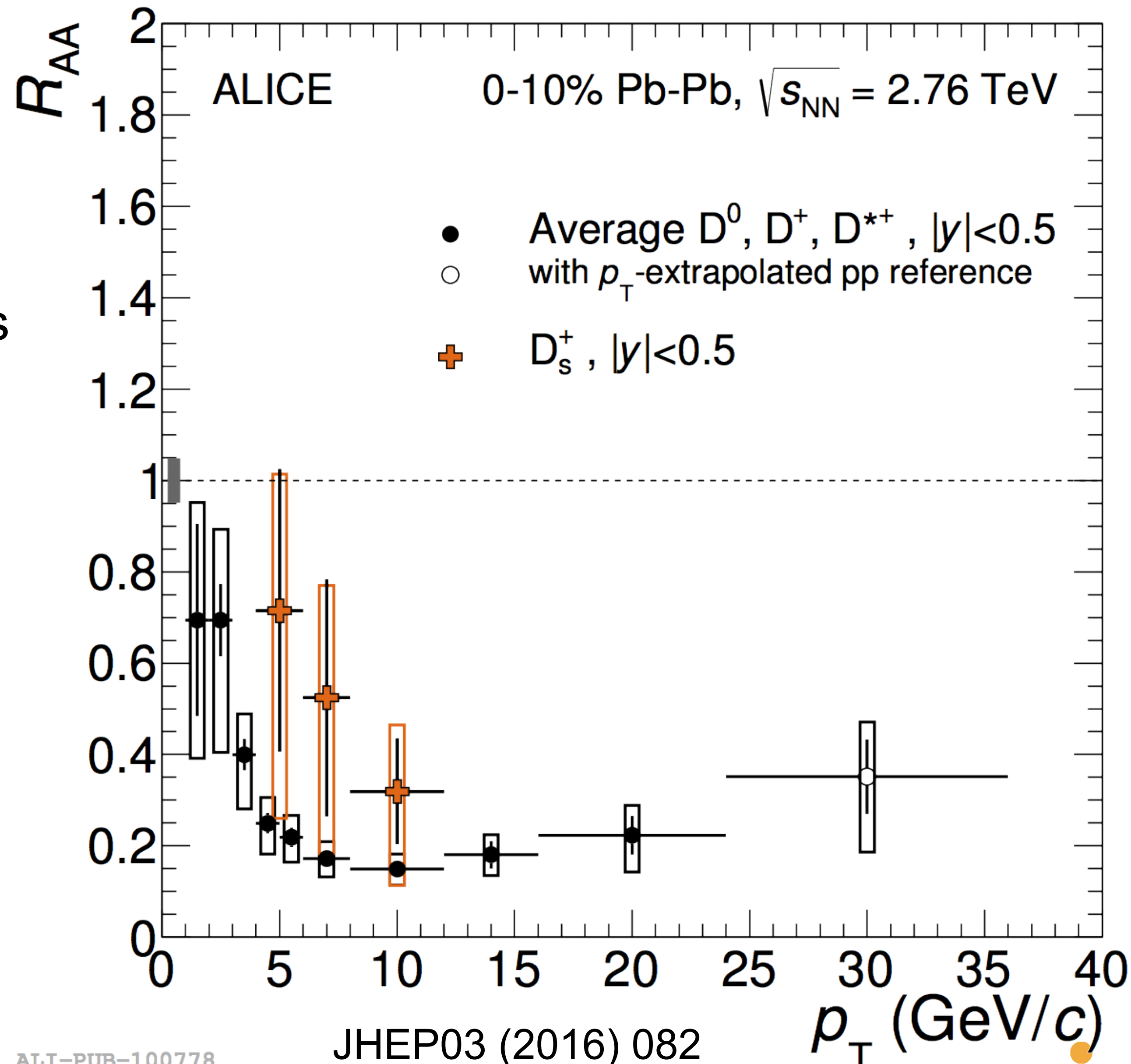
HI at the LHC: the precision era



More statistics is needed: example 1

- D_s^+ ($c\bar{s}$) compared to average of $\mathbf{D^{0,+,*+}}$
- Sensitive to strangeness production
- and to the hadronization mechanism of charm quarks

- Need statistics and precision
- Reach 0 p_T



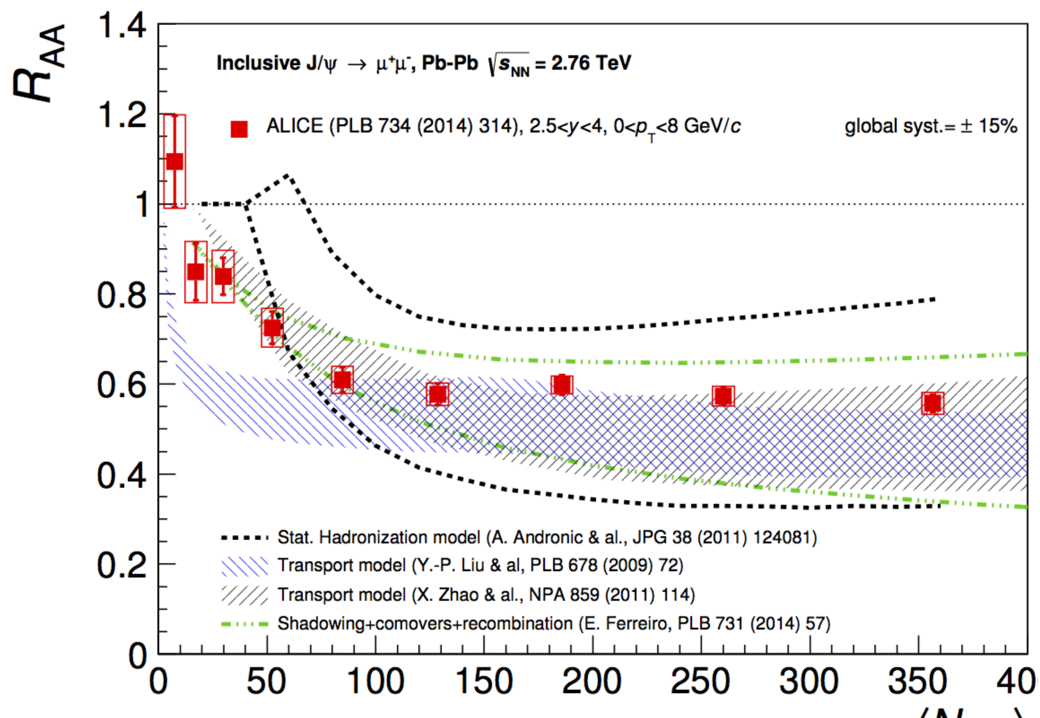
JHEP03 (2016) 082

More statistics is needed: example 2

J/ψ nuclear modification factor versus centrality, run 1 data

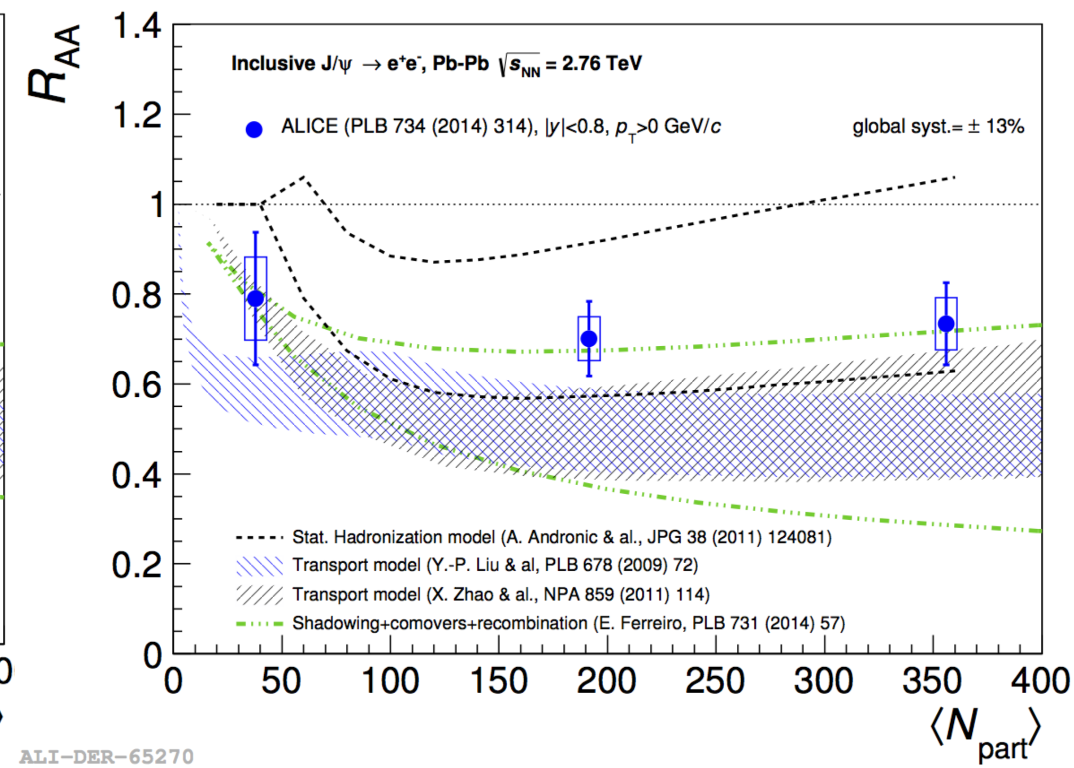
Comparison to statistical hadronization and two transport models

Forward rapidity



PLB 734 (2014) 314

Mid rapidity



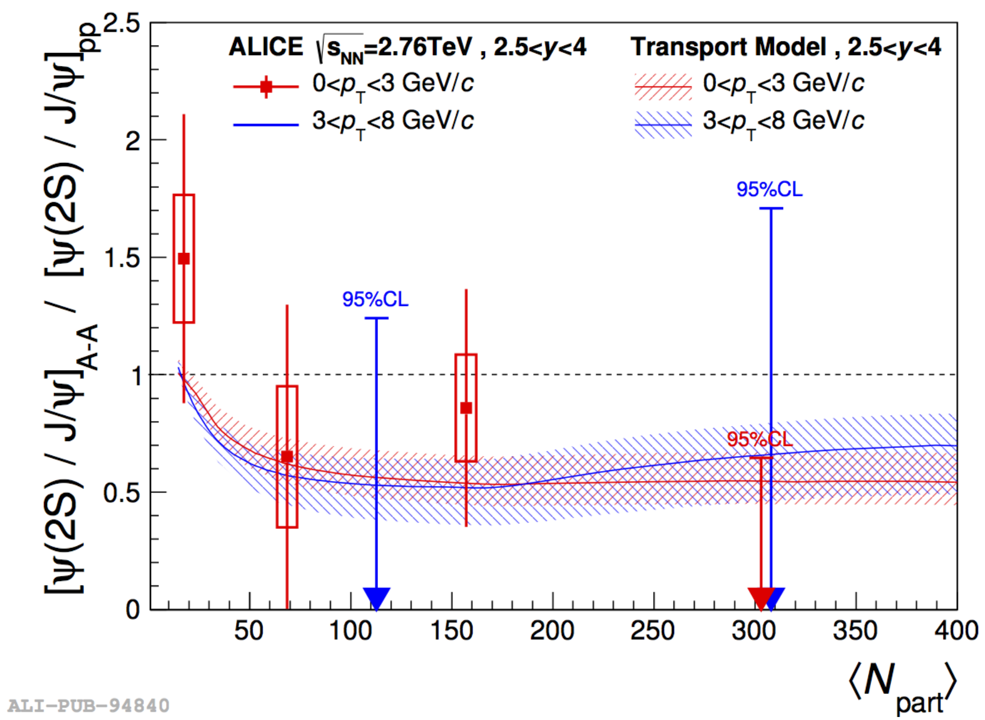
Charm production cross section needed with good precision!

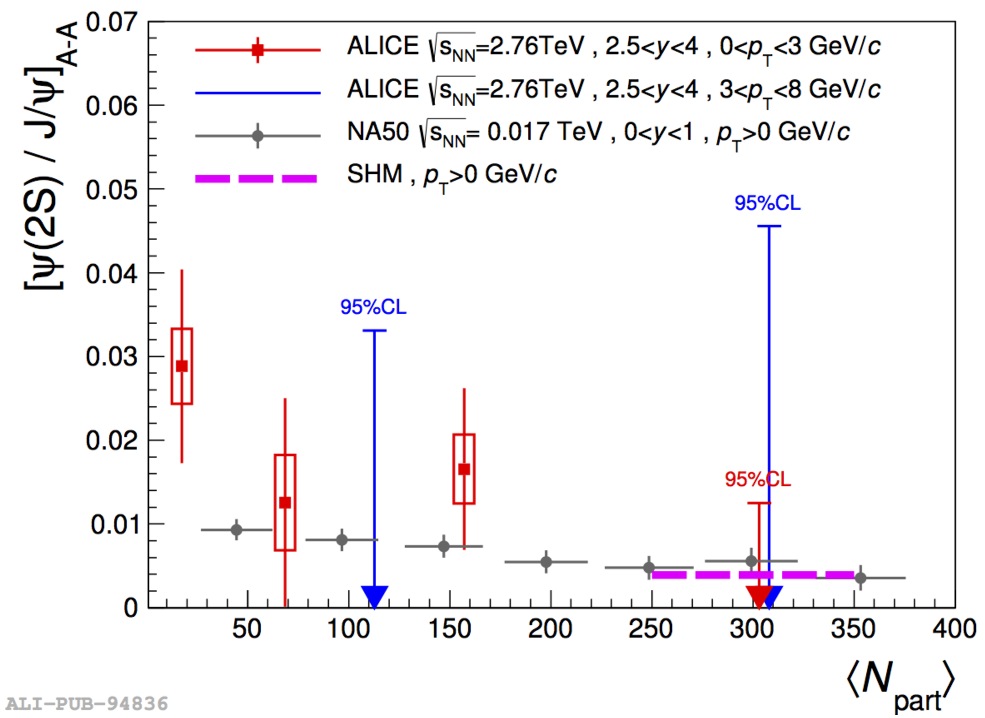
More statistics is needed: example 2

Discrimination between different charmonium production mechanisms:

- Transport models: in-medium destruction and generation
- Statistical hadronization: generation at phase boundary

will be possible with high statistics ψ(2S) measurements





limited statistics, no central collisions

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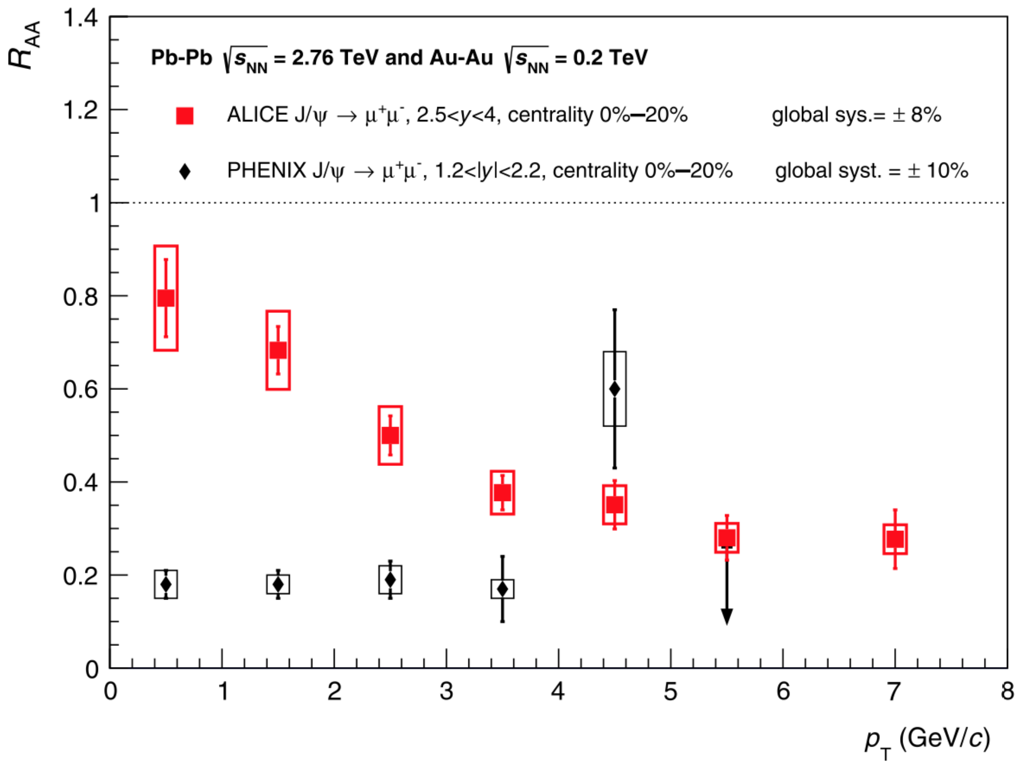
Focus on low transverse momentum

… the place where most of the interesting action takes place



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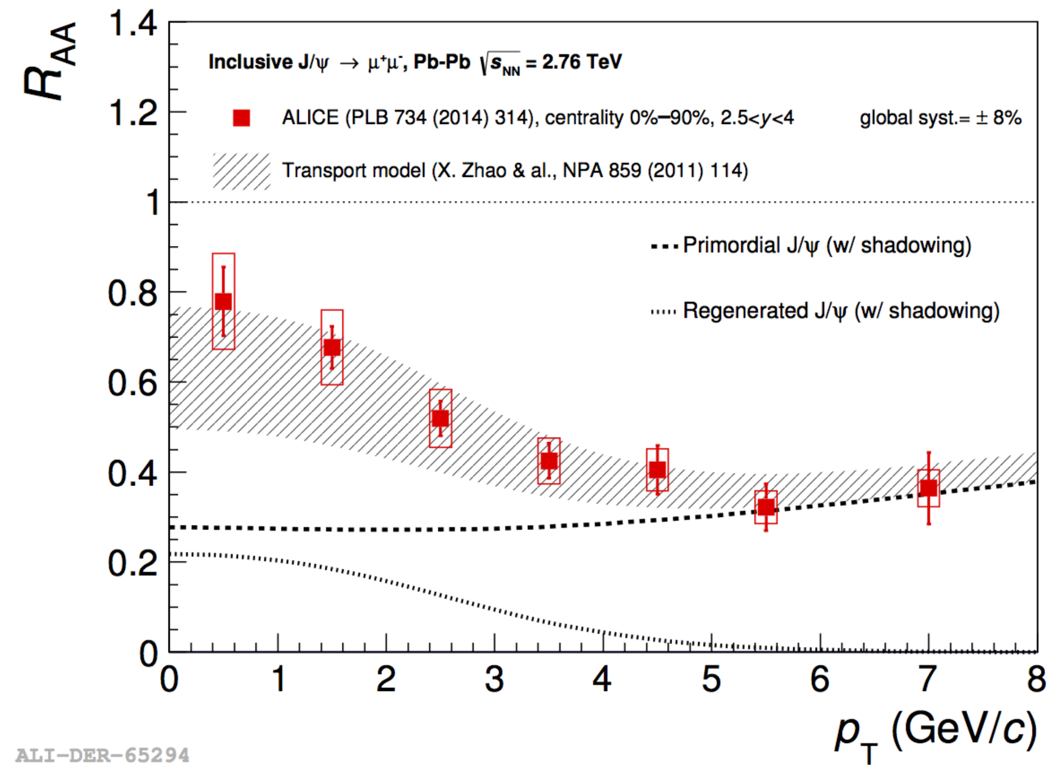


What do we need next

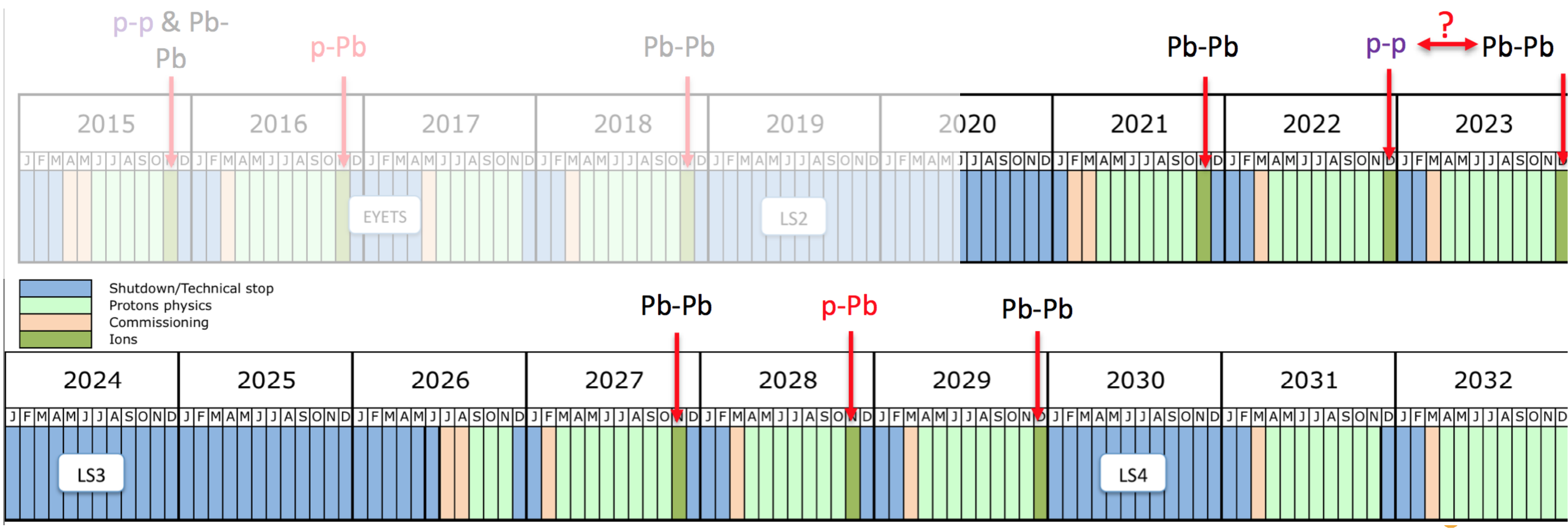
- Significantly higher integrated luminosity
  → possibly a factor 100 more than run 2 (n. events)
- Interest focused on soft probes and hard probes down to 0 p_T
  → only possible with minimum bias data

How can this be achieved?

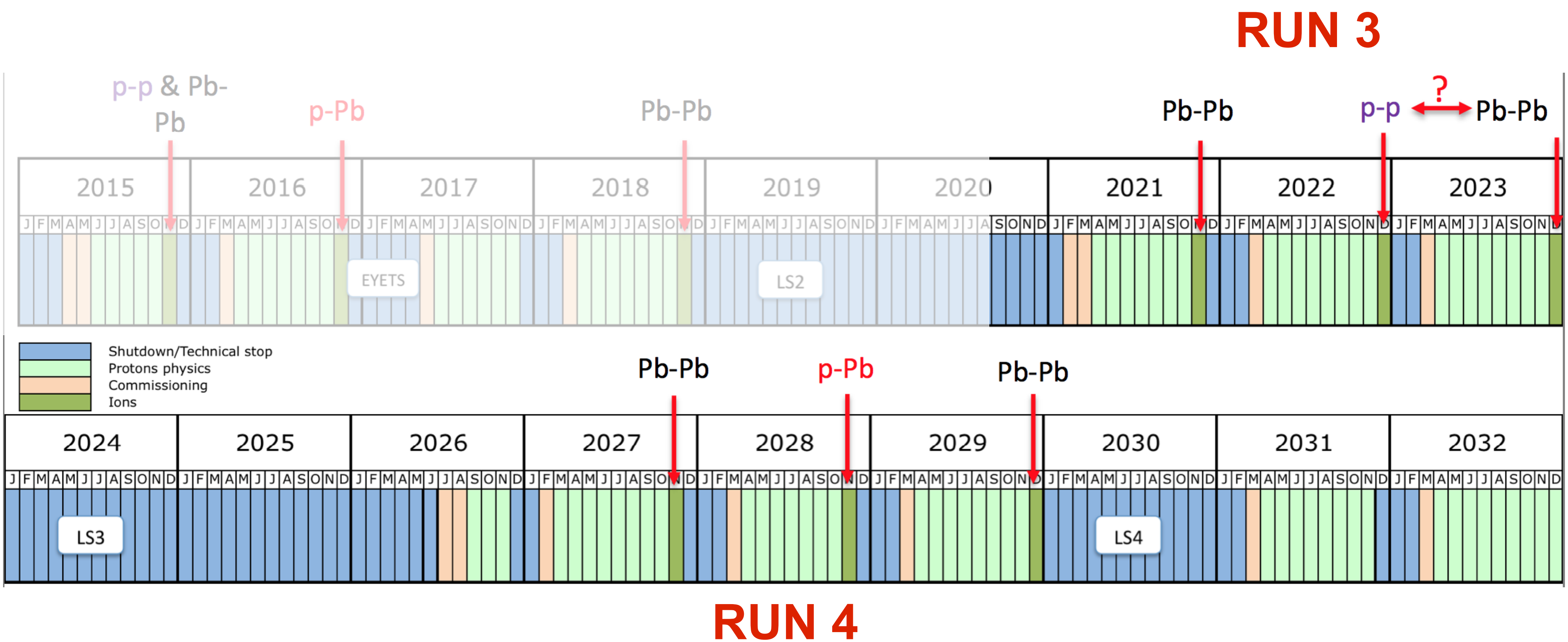
- Higher interaction rates of heavy ions at the LHC: 50 kHz after LS2
- Minimum bias data
- Adapt detectors and data processing to allow recording of all interactions (continuous readout, online data reduction, etc)
- Optimize experimental setup for high resolution at low p_T

LHC heavy-ion beams from 2021 on

- Increase total number of lead nuclei stored in the LHC
  - Reducing bunch spacing at the PS
  - Decreasing the SPS kicker rise time
- Upgrade of LHC collimators
- Peak luminosity exceeding 6×10^{27} $cm^{-2}s^{-1}$ (→ 50 kHz int. rate)
- Foreseen integrated luminosity of 2.85 nb^{-1} per year



LHC heavy-ion beams from 2021 on



Goal for run 3 and 4 (2021 – 2029):

- 4 heavy-ion periods → 10 – 13 nb^{-1} integrated luminosity
- Minimum bias → $8x10^9$ events
- Reference pp and p-Pb runs

Upgrade program: an overview

- Full replacement of the Inner Tracking System (ITS) with 7 layers of monolithic active pixels (MAPS)

  → higher resolution in all coordinates, lower material budget, higher precision in tracking and vertexing

- Replacement of the beam pipe (smaller radius)

  → lower material budget, higher precision

- Addition of a Muon Forward Tracker (MFT, pixels as ITS)

  → augment the muon spectrometer with vertexing, to strengthen all aspects of heavy-flavor physics

- Replacement of the TPC MWPC (+ gating grid) with GEM chambers and new readout electronics

  → continuous readout

- Upgrade of readout systems of all detectors

  → higher readout speed

- Development of a new online + offline system O^2

  → data compression, online processing, allow 50 kHz “minimum bias”

- New trigger detectors

The LS2 ALICE upgrades

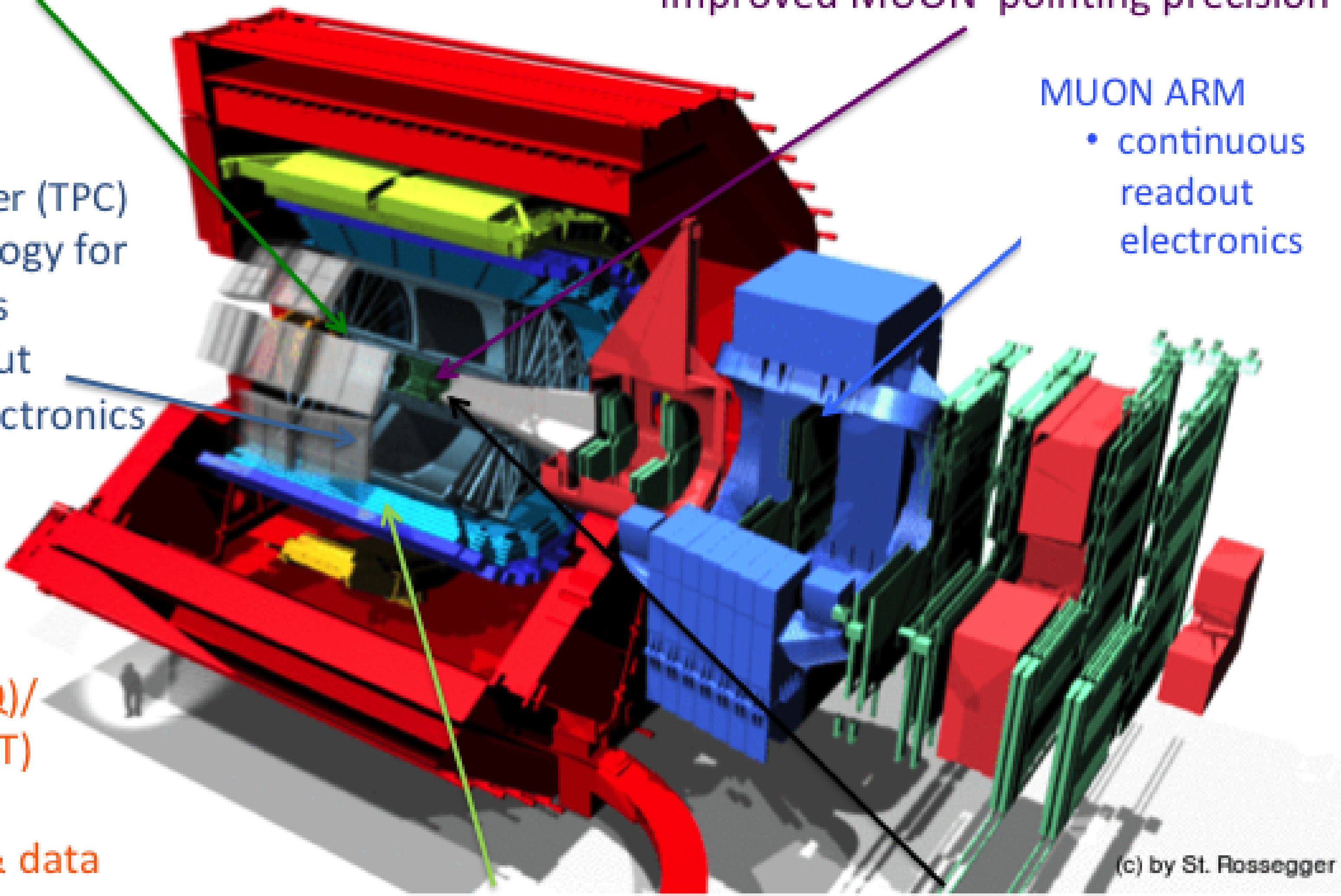
ALICE

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics



New Central Trigger Processor

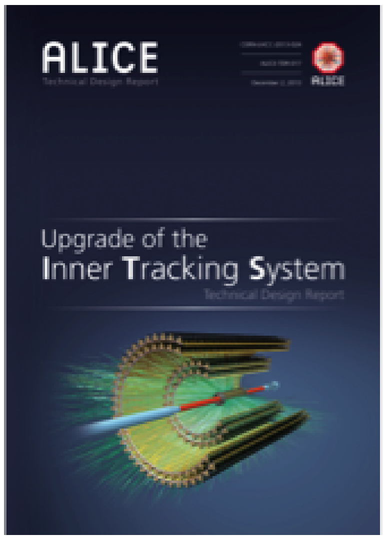
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz PbPb event rate

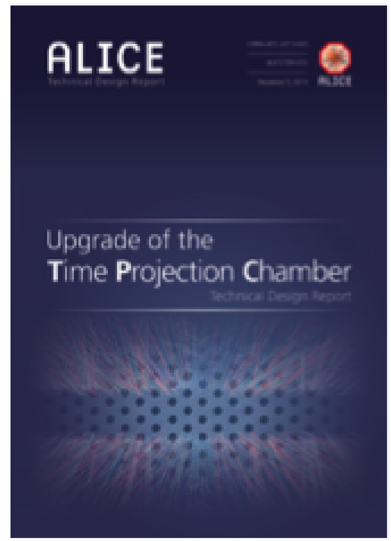
TOF, TRD, ZDC
- Faster readout

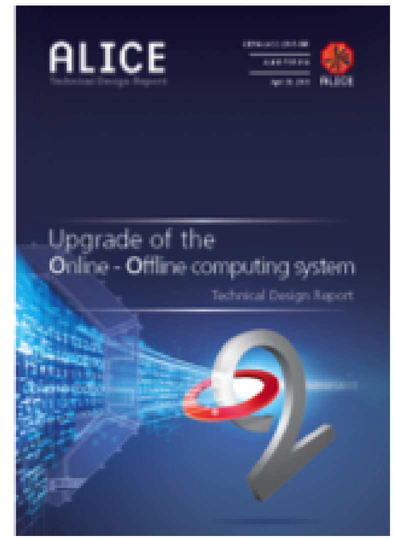
New Trigger Detectors (FIT)

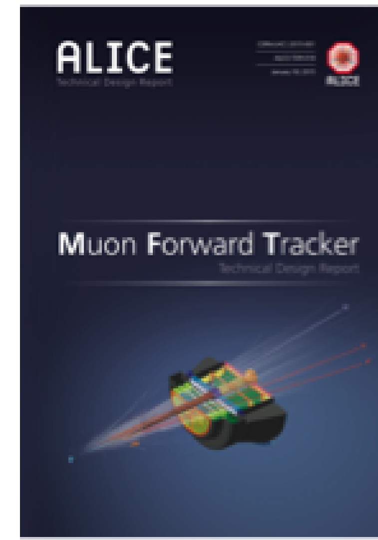
TDRs, UCG, RB ...

- 5 Technical Design Reports





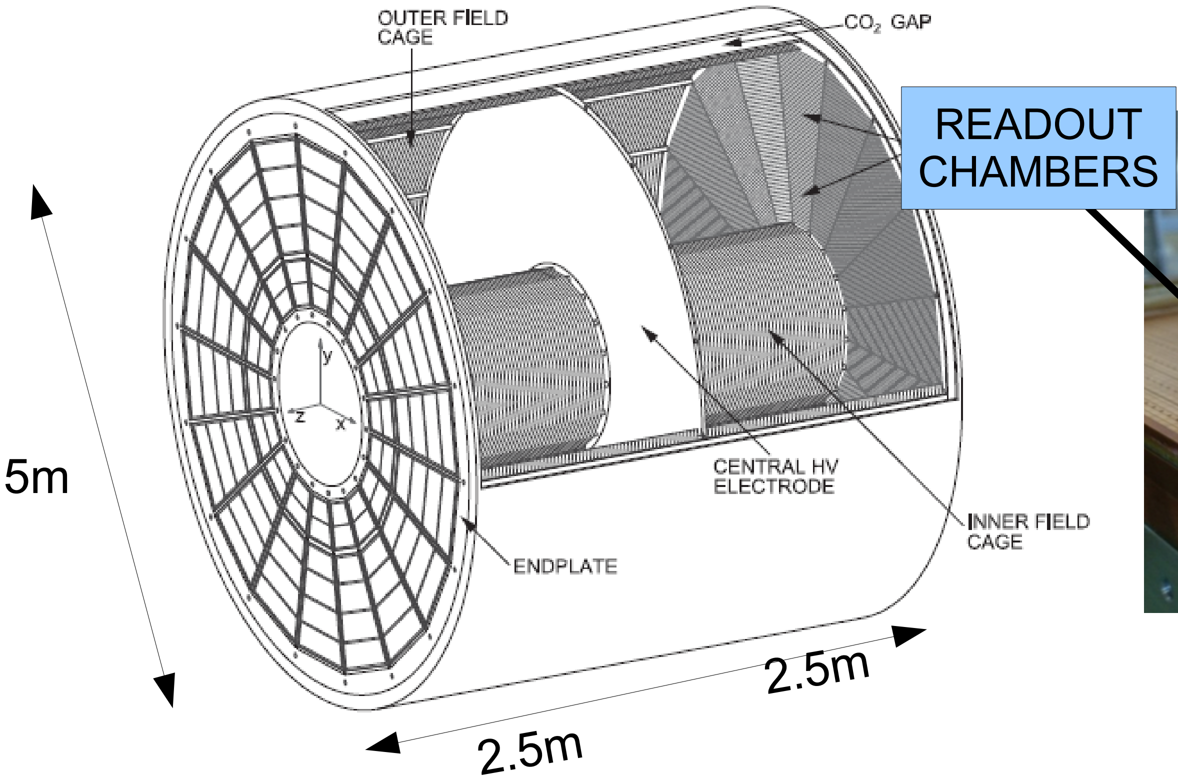




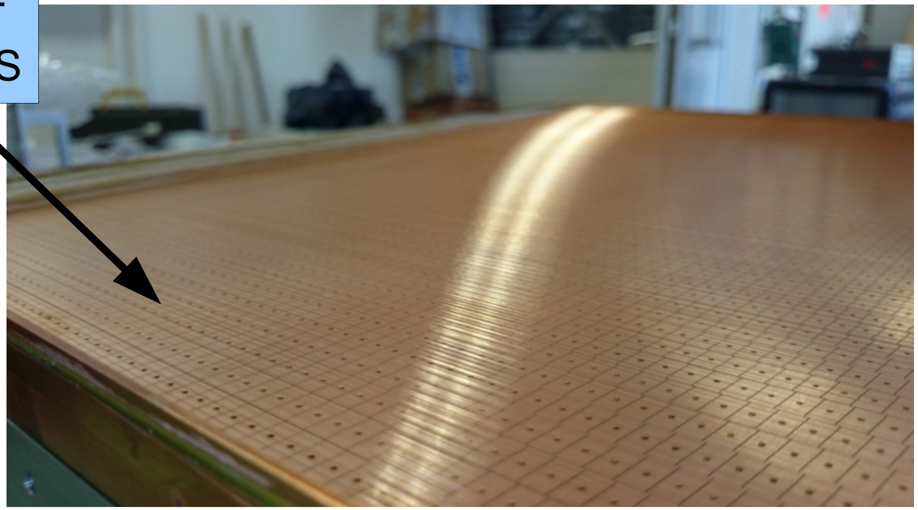
- Approved by the LHCC, the Upgrade Cost Group, the Research Board
- 4 of 5 Memorandum of Understandings signed
  (GSI: Readout and Trigger, TPC, O^2 coming soon)

ALL PROJECTS ON THE WAY

The ALICE Time Projection Chamber

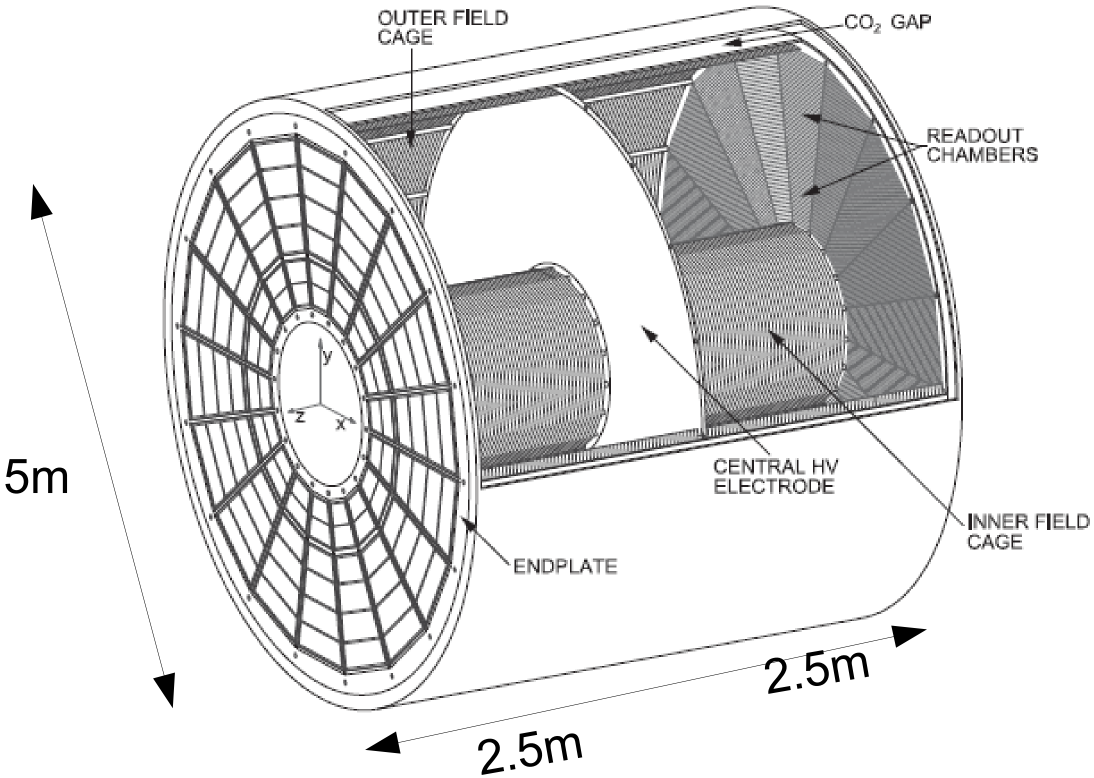


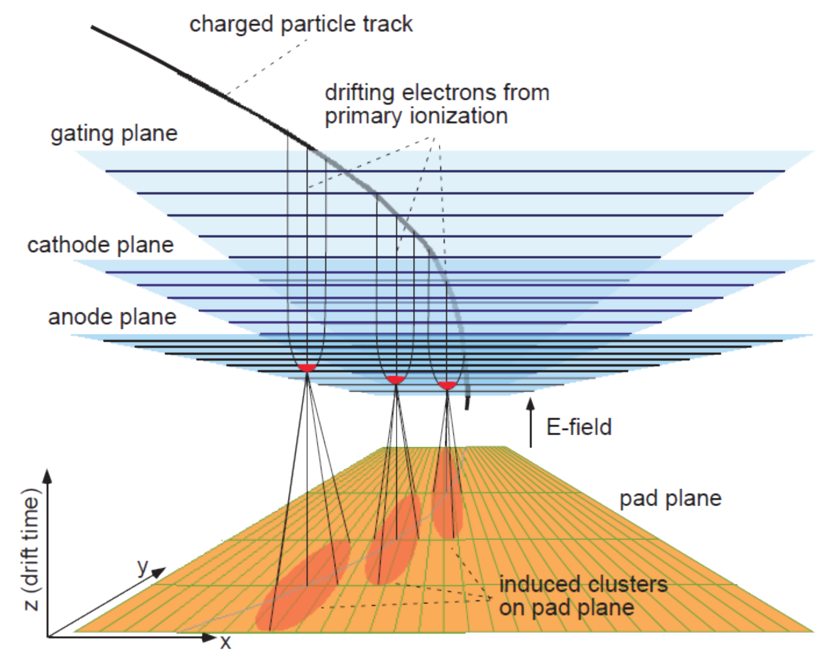
Multi-Wire Proportional Chamber



- ~ 90 m^3 gas volume ($Ne\text{-}CO_2(\text{-}N_2) \rightarrow Ar\text{-}CO_2$), equipped with **MWPC**
- Half a million readout pads
- Ions from the amplification region are prevented from reaching the drift volume by a gating grid
- Full readout time ~(100+200) μs → maximum readout rate of 3 kHz

The ALICE Time Projection Chamber





- ~ 90 m^3 gas volume (Ne-CO_2(-N_2) → Ar-CO_2), equipped with **MWPC**
- Half a million readout pads
- Ions from the amplification region are prevented from reaching the drift volume by a gating grid
- Full readout time ~(100+200) μs → maximum readout rate of 3 kHz

TPC upgrade

CERN-LHCC-2013-20

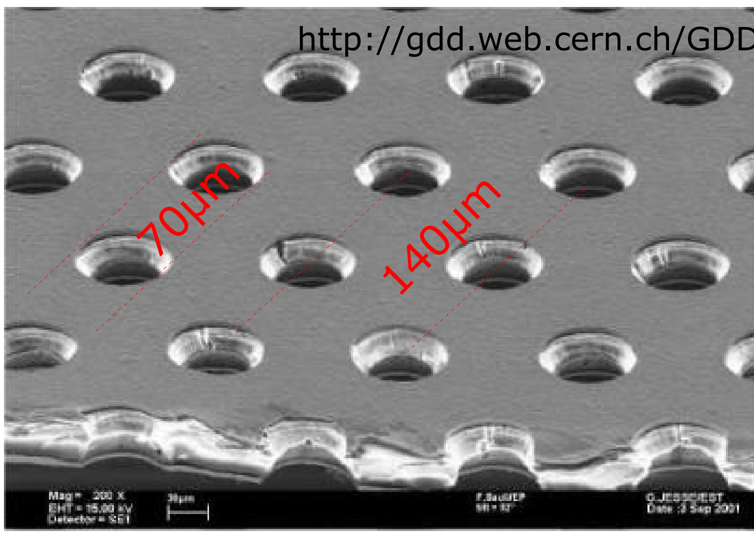
- **Continuous readout** to cope with the 50 kHz Pb-Pb interaction rate and record all minimum bias events

- New **readout** electronics: FE ASIC SAMPA:
  - direct readout mode (continuous, can be triggered)
- Signal processing at CRU – Common Readout Unit:
  - Common mode correction, zero suppression, etc
- 5 MHz ADC sampling frequency → **1-3 TBytes/s**
- Significant data compression required!

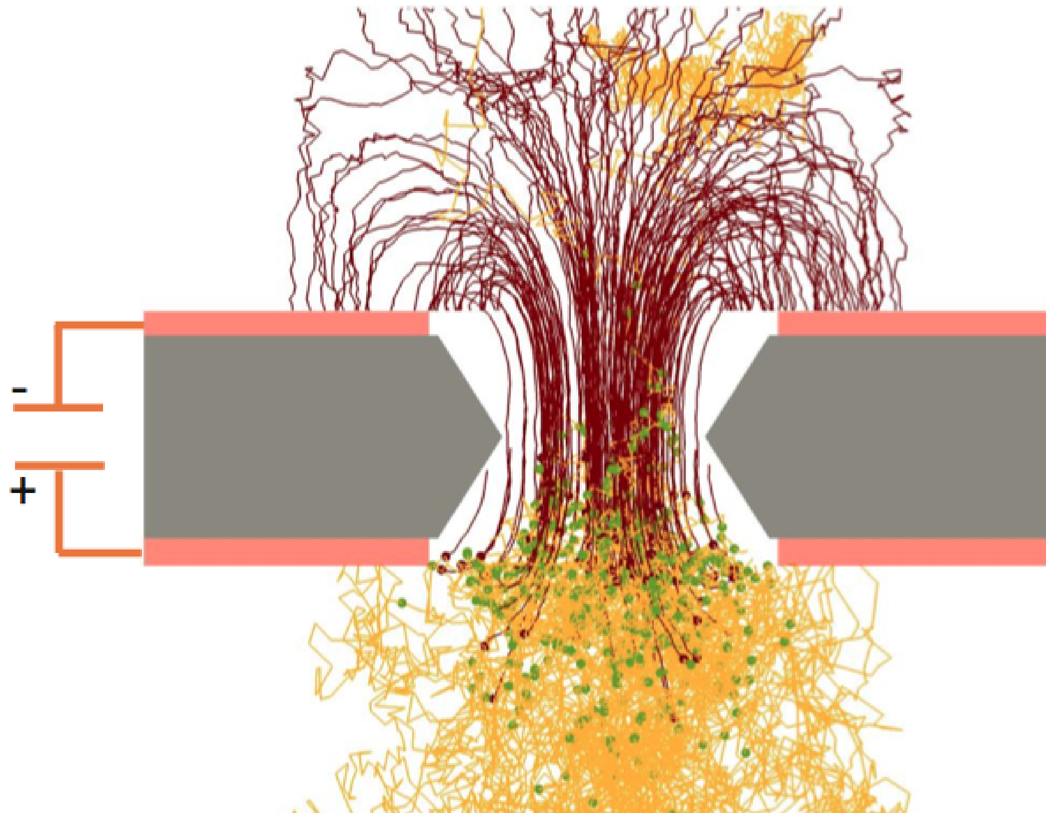
TPC upgrade

CERN-LHCC-2013-20

- **Continuous readout** to cope with the 50 kHz Pb-Pb interaction rate and record all minimum bias events
  → New readout chambers, no gating grid
  GEM: Gas Electron Multiplier foils. Offer opportunity to reach low ion back-flow (IBF) in multiple GEM stacks

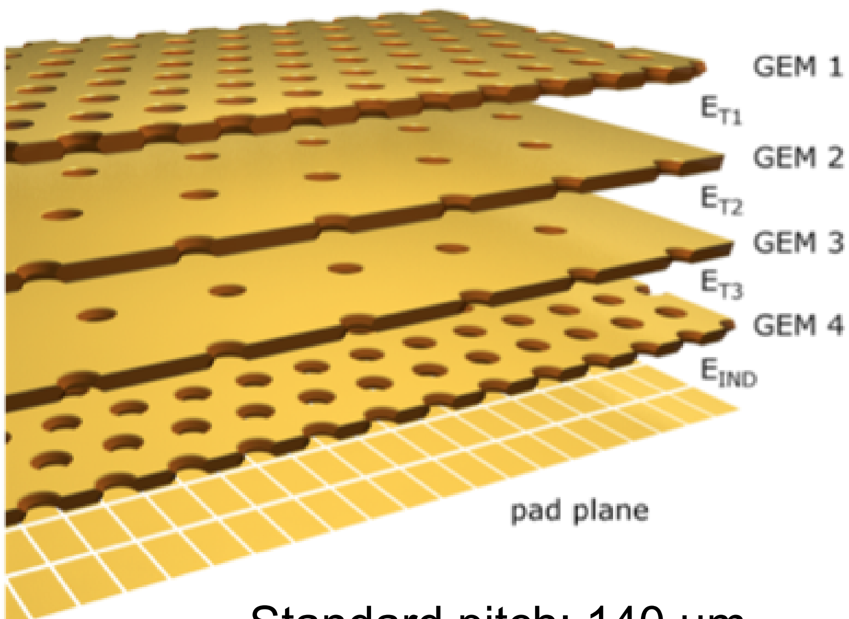


Copper coated kapton foils (50 μm)
ΔU=500V → ~ 100kV/cm

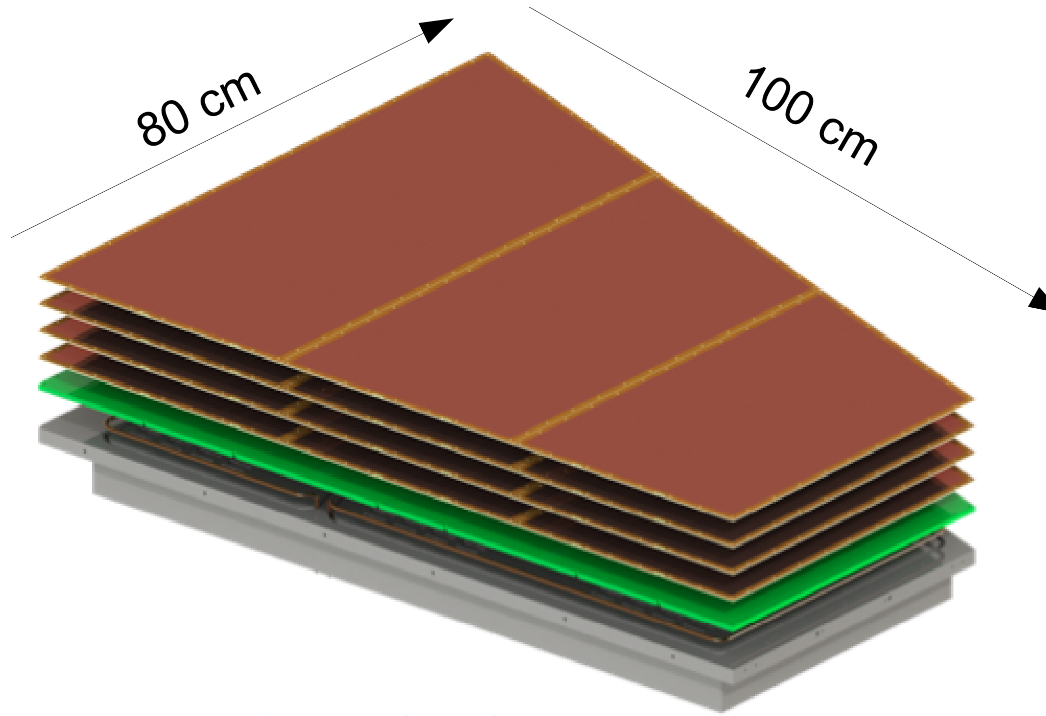


TPC upgrade: GEM chambers

- Low IBF (<1%) is achieved combined 4 GEM foil
- Momentum resolution and particle identification performance is preserved: dE/dx resolution <12%

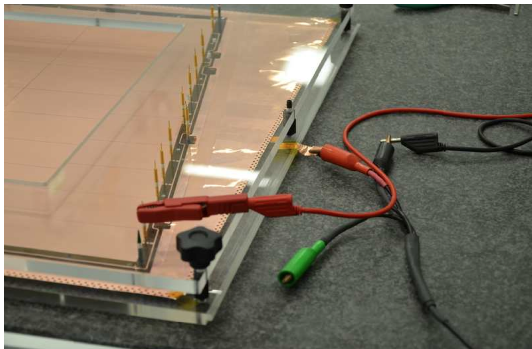


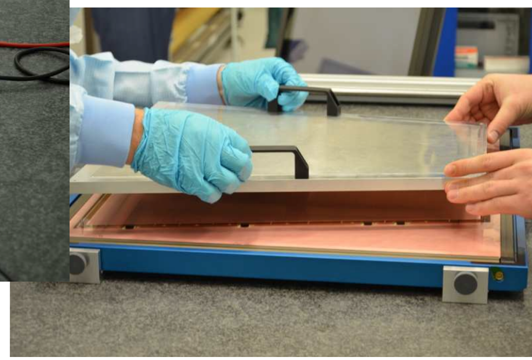
Standard pitch: 140 μm
Large pitch: 280 μm

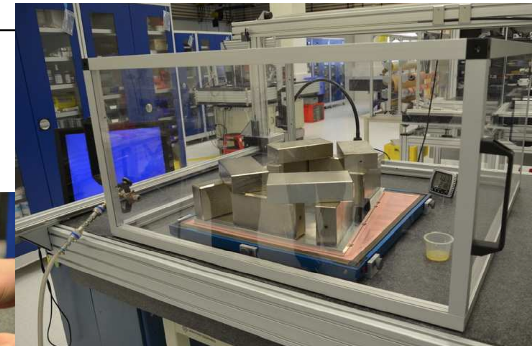


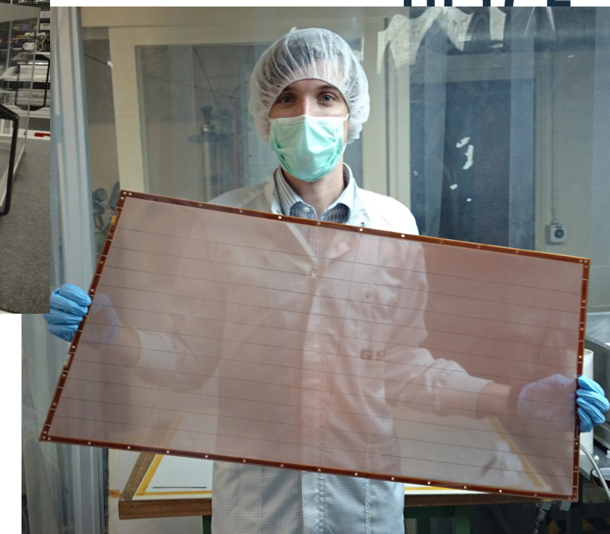
Outer Read-Out Chamber

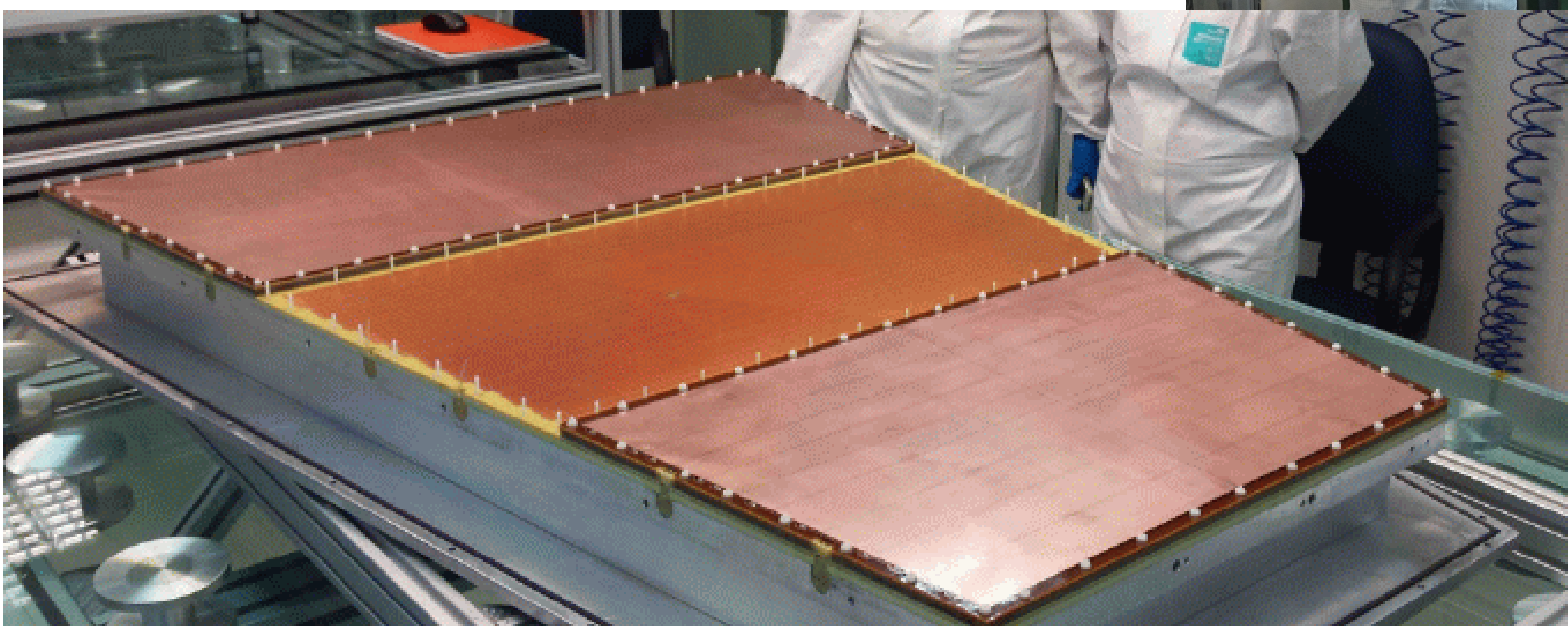
TPC upgrade







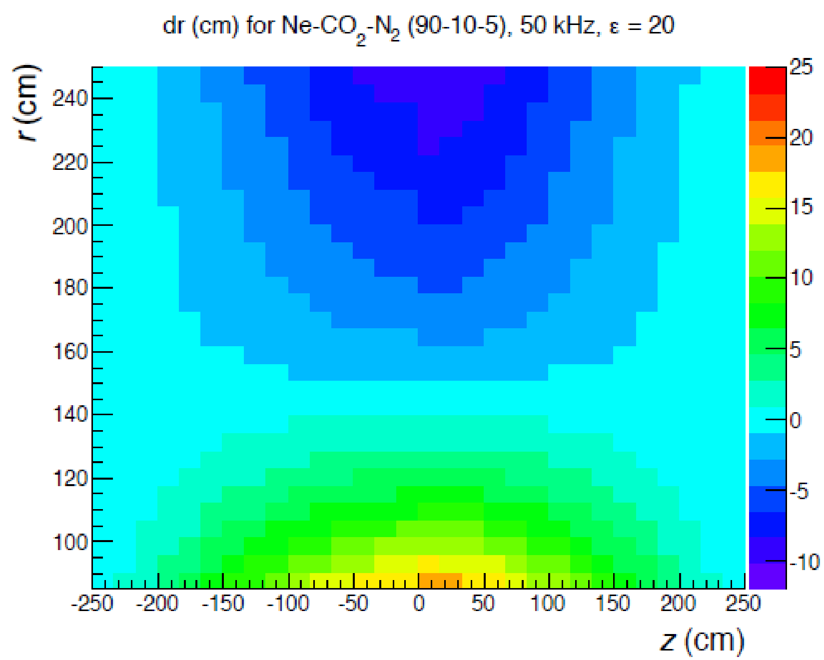




TPC upgrade: performance

- Pad Response Function optimized for MWPC: narrower for GEMs, help by diffusion → only slightly worse overall resolution (space point)
- Slightly worse for TPC only tracks, restored for ITS-TPC tracks
- @50 kHz Pb-Pb → on average 5 overlapping events
- Track reconstruction efficiency and momentum resolution preserved
- Only moderate worsening of dE/dx resolution

- Space-charge density from IBF produce distortions: electric field (Poisson) → space points (Langevin)
- Distortions up to dr ≈ 20cm and drφ ≈ 8cm
- Fluctuations at the 3% level, dominated by event and multiplicity fluctuations
- Online calibration of distortions. Update interval O(5ms)
- Strategy in place restores full performance (2nd stage)

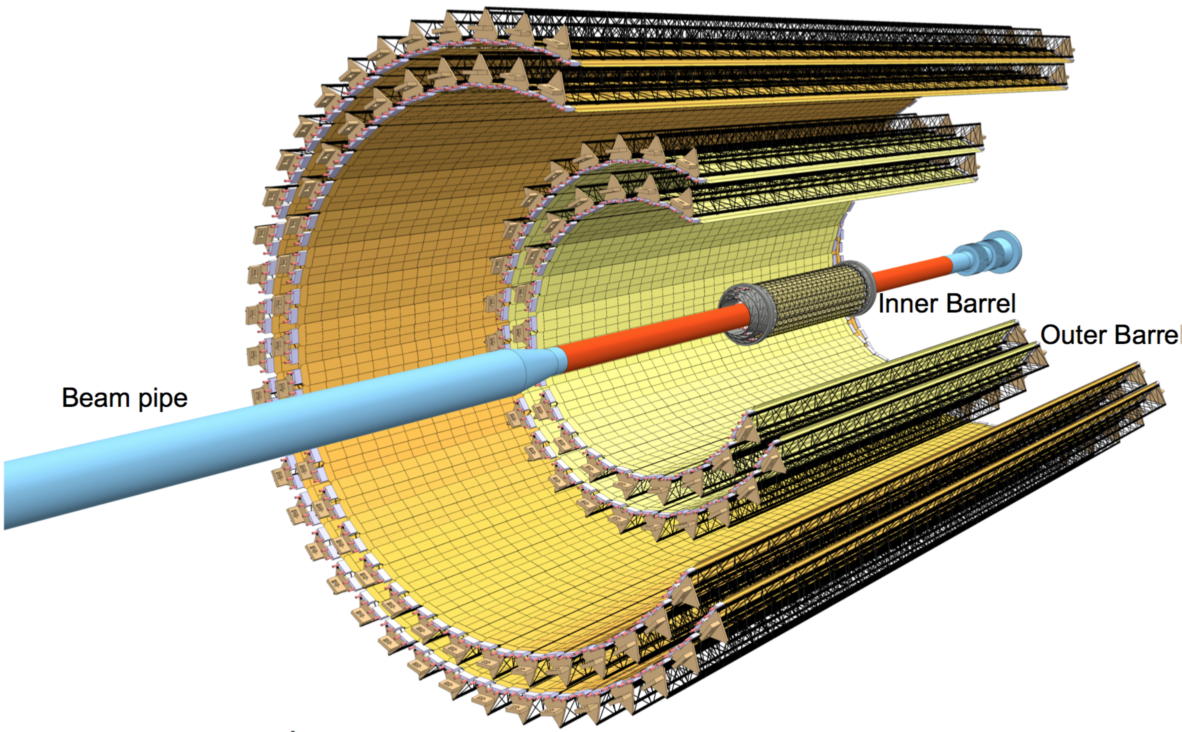


New Inner Tracking System

- 7-layer barrel geometry based on CMOS sensors:
  ~10 m^2, 12.5 G-pixel
- ALPIDE pixel chip

- Radius: 23 – 400 mm (smaller beam pipe radius)
- 3 Inner Barrel layers (IB)
  4 Outer Barrel layers (OB)
- $|\eta| < 1.22$ for tracks from 90% most luminous region

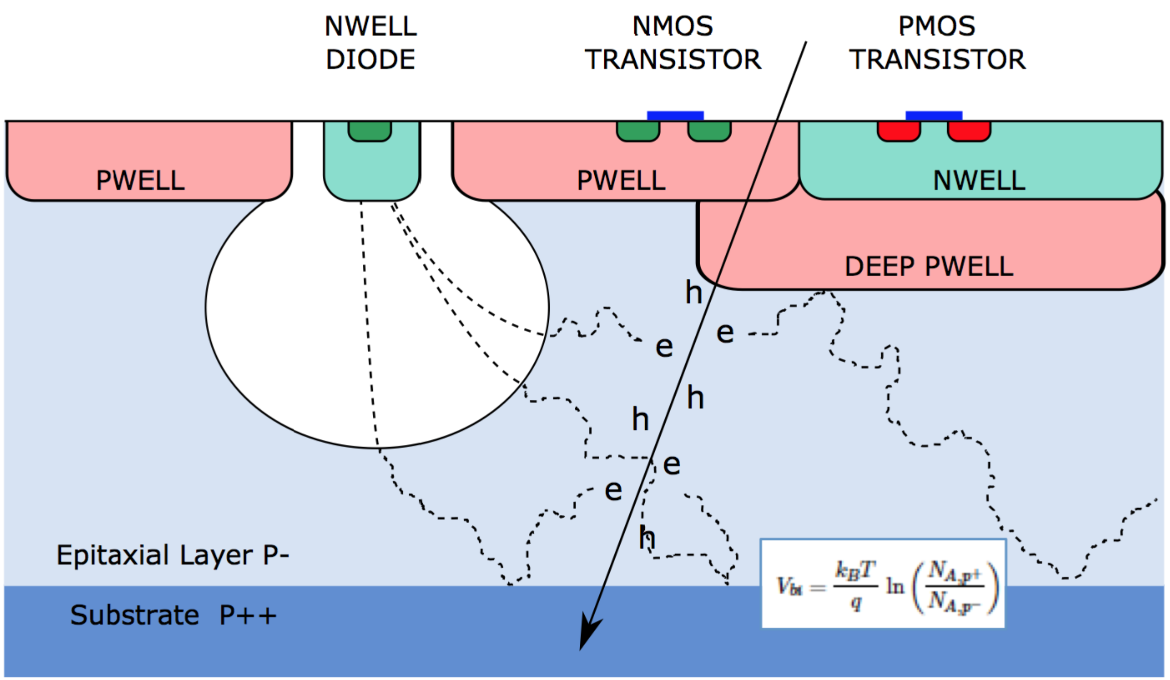
- Radiation load:
  TID: ~ 2.7 Mrad
  NIEL: ~1.7×10^{13} 1MeV n_{eq} / cm^2



Ultra-light vertex detector:
material / layer:
0.3 % X_0 (IB)
1 % X_0 (OB)

ITS upgrade: ALPIDE pixel chip

CMOS pixel sensor: TowerJazz 0.18 μm CMOS image processing

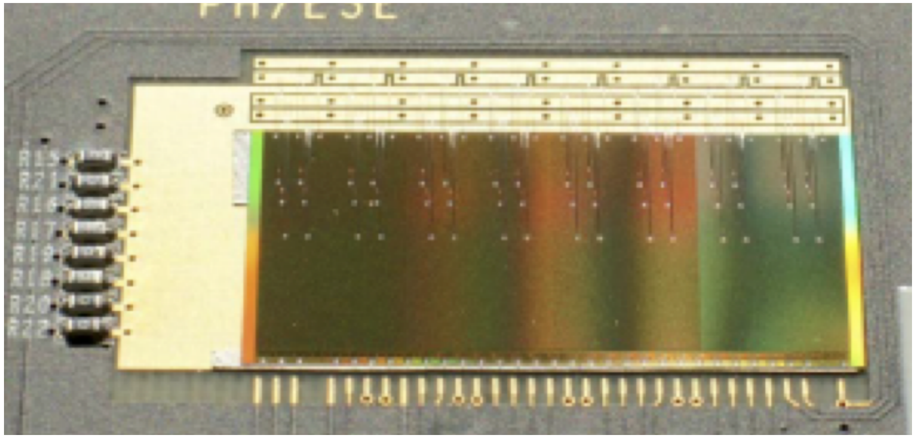


- High-resistivity (>1 kΩ cm) p-type epitaxial layer (18-30 μm), on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel → low capacitance
- (moderate) reverse bias to substrate to increase depletion zone around n-well diode
- Deep p-well shields n-well of PMOS transistor to allow for full CMOS circuitry within active area

ITS upgrade: details and sources

Monolithic Active Pixel Sensors (MAPS)

- ALPIDE chip: 30 mm x 15 mm
- Pixel matrix: 1024 col x 512 rows
- Pixel pitch: 29 μm x 27 μm
- Ultra-low power: ~30 mW/cm^2



ITSU Conceptual Design Report: CERN-LHCC-2012-013

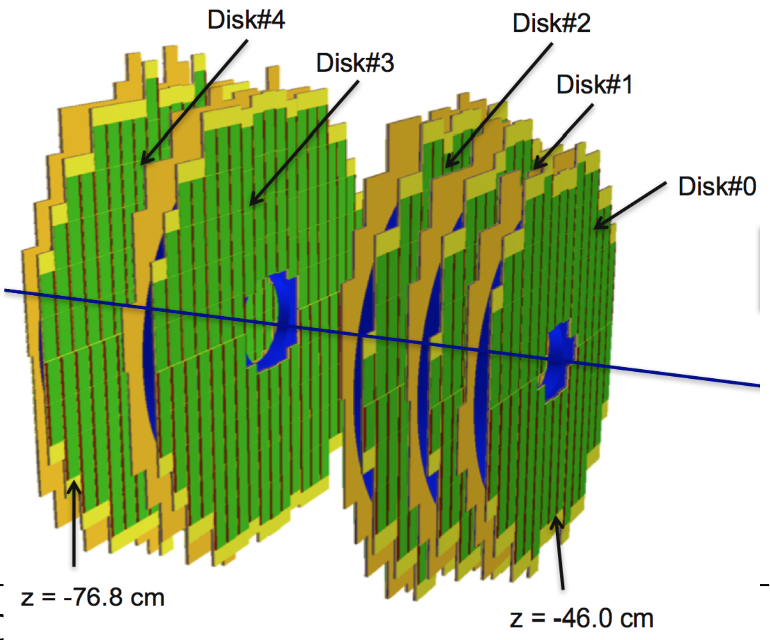
ITSU Technical Design Report: CERN-LHCC-2013-024

Muon Forward Tracker (MFT)

5 layers before muon absorber

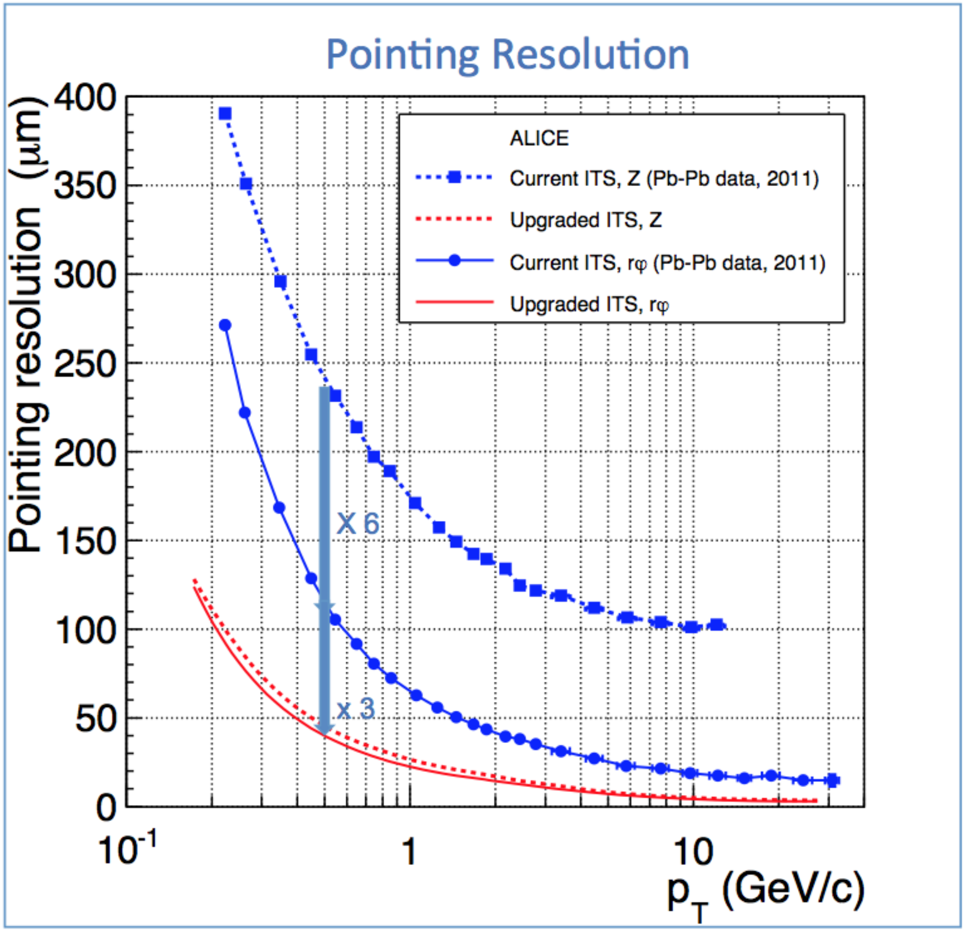
same pixel sensors (0.4 m^2, 5% of ITS)

CERN-LHCC-2015-001

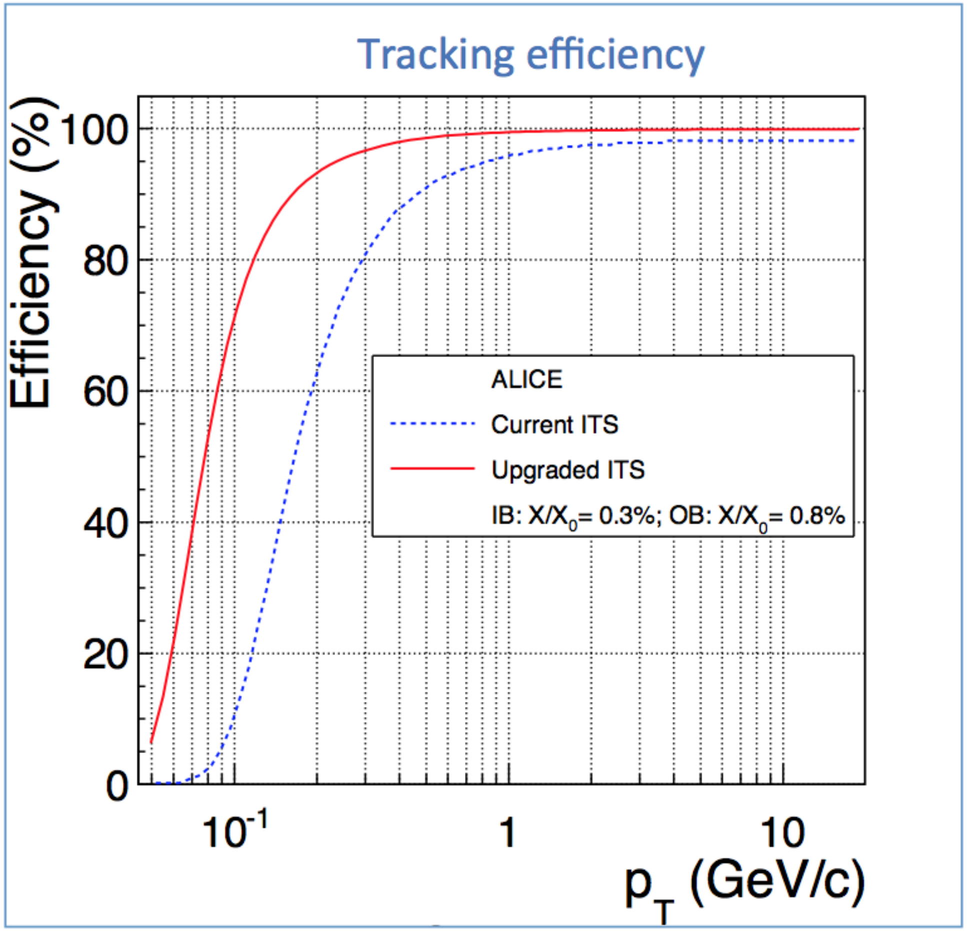


ITS: projected performance

Impact parameter resolution

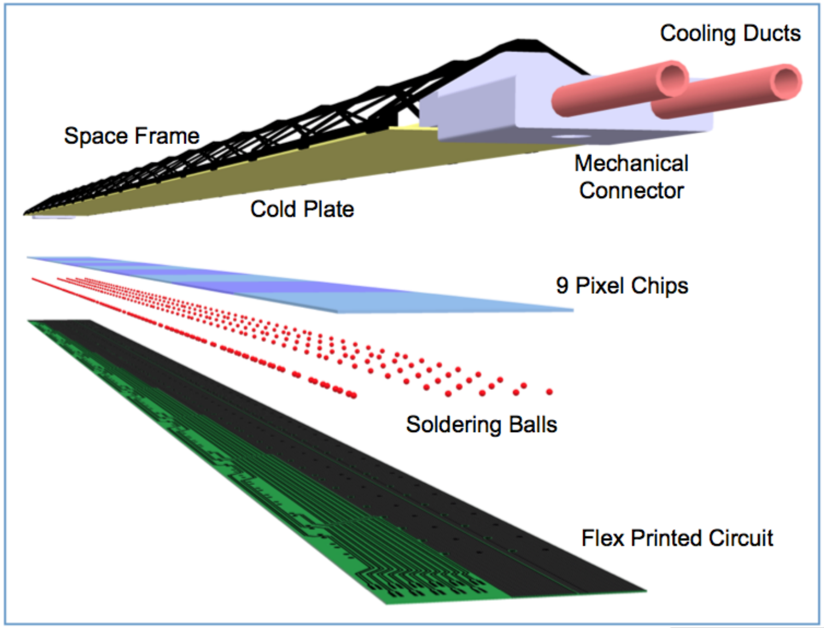


Tracking efficiency (ITS standalone)



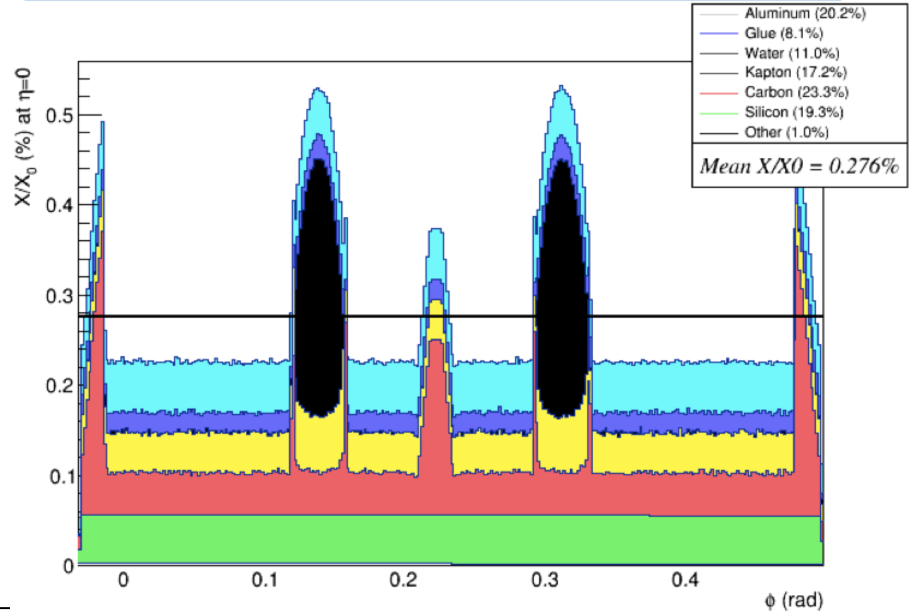
~ 40 μm at p_T = 500 MeV/c

ITS ultra-light



Silicon sensor + readout electronics:
Only 20% of the total material budget

Active cooling



Physics program

- **Open heavy flavors**

  high precision measurements of R_{AA} and v_n of charm and beauty, with exclusive decay reconstruction, to study the dynamics of heavy quarks in the medium

- **Charmonium**

  understand the production mechanism, infer properties of the phase transition

- **Light nuclei and exotic states**

  hadronization mechanism, production of heavy and loosely bound states, search for exotica

- **Di-lepton spectrum**

  thermal radiation, temperature of the medium, chiral symmetry, heavy-flavor cross section

Open heavy flavors

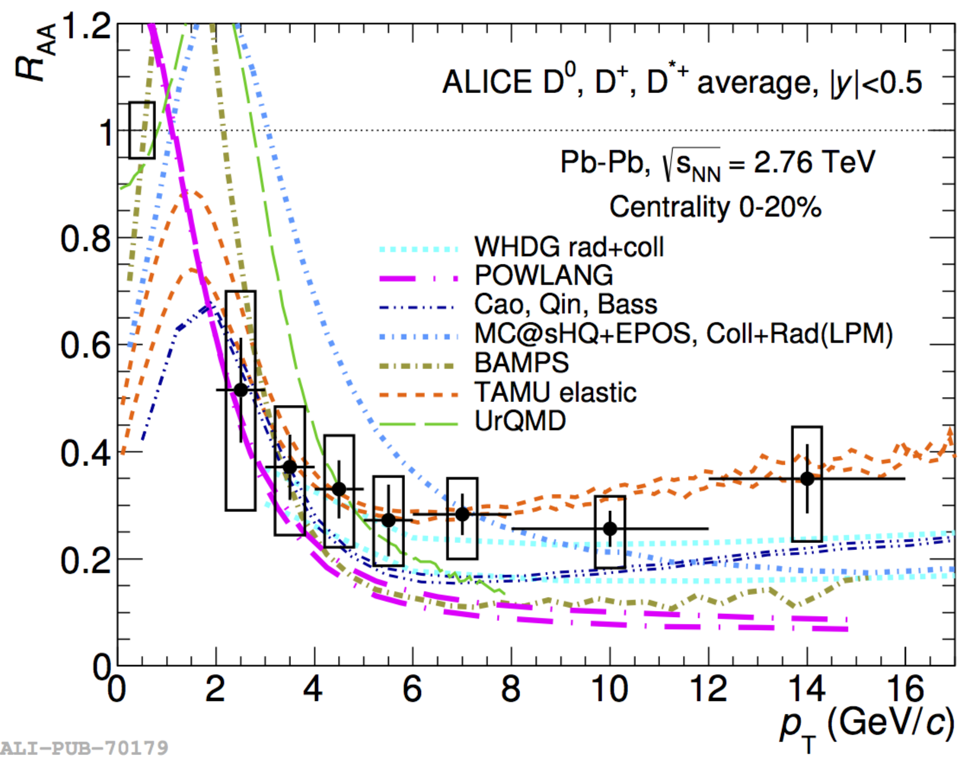
Open heavy flavor: current results

Charm

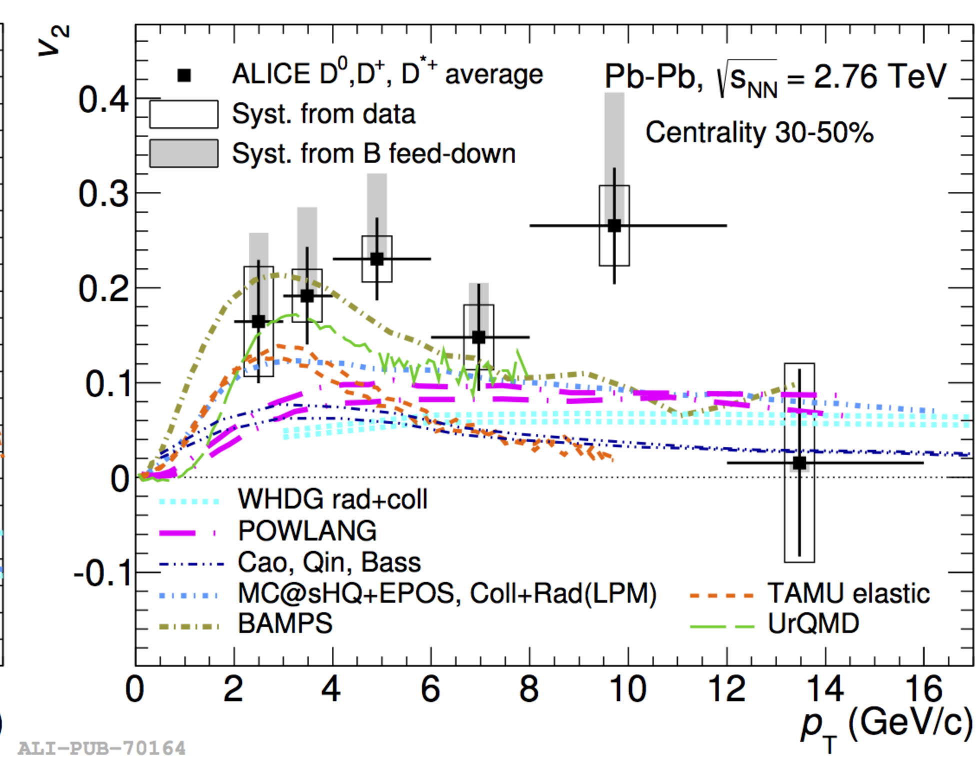
Exclusive reconstruction of hadronic decays of D mesons

$D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, $D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^- \pi^+$

Nuclear modification factor R_{AA}



Elliptic flow coefficient v_2



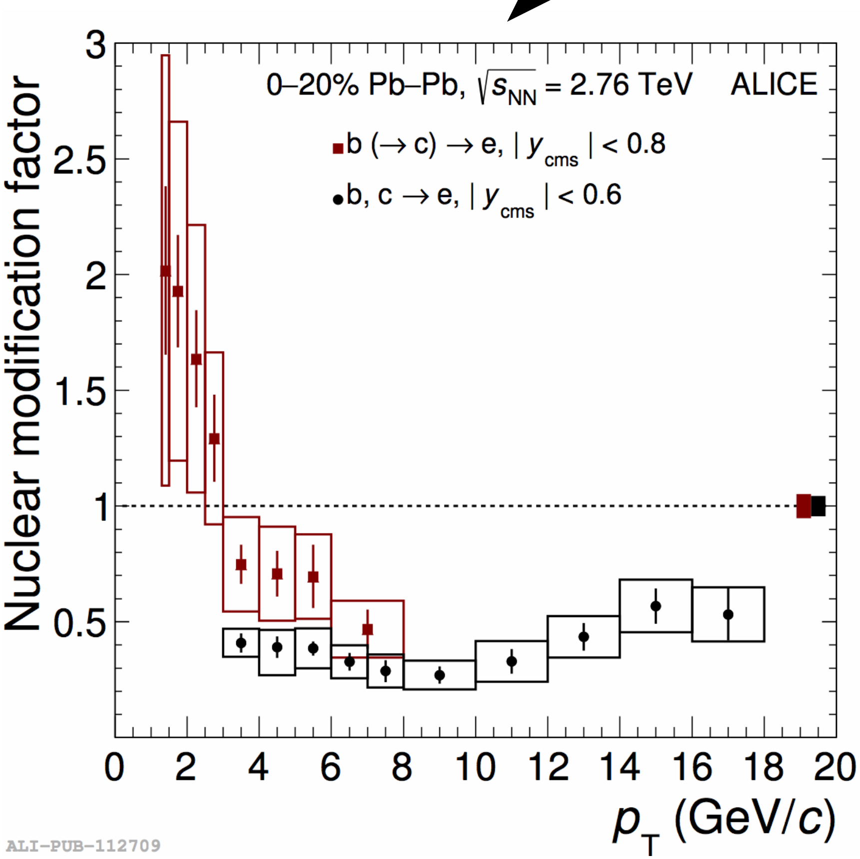
PRL 111(2013)102301
PRC90(2014)034904
JHEP03 (2016) 082

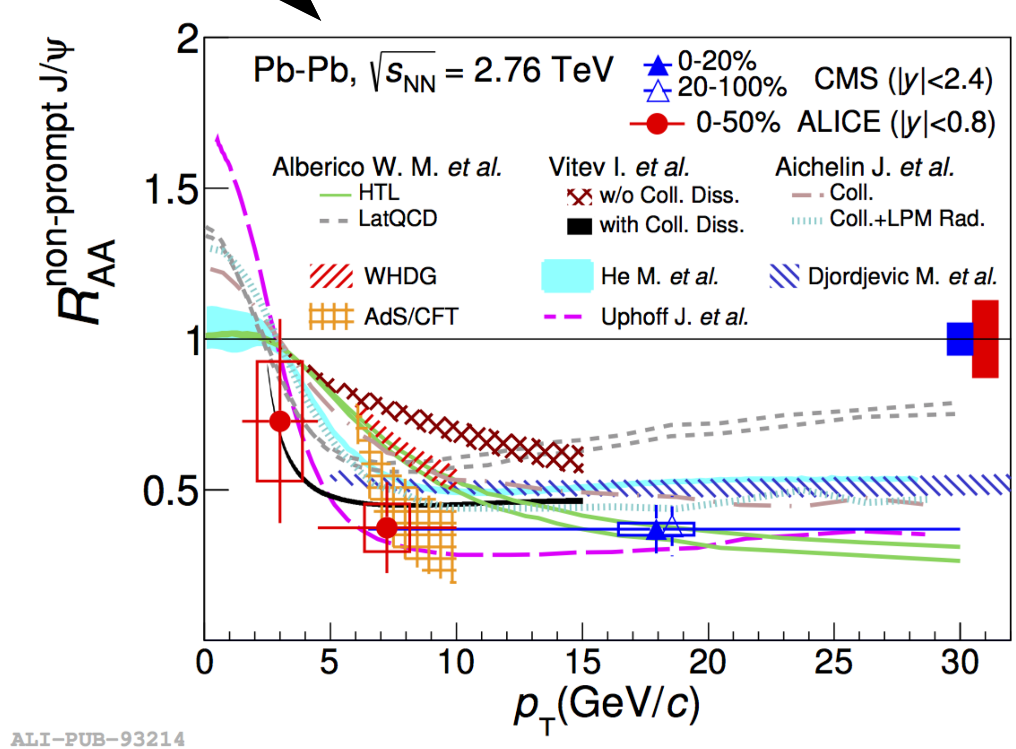
Open heavy flavor: current results

Beauty: nuclear modification factor R_{AA}

Semi-leptonic decays: electrons from beauty hadrons at mid-rapidity

and non-prompt J/ψ from beauty hadron decays





arXiv:1609.03898

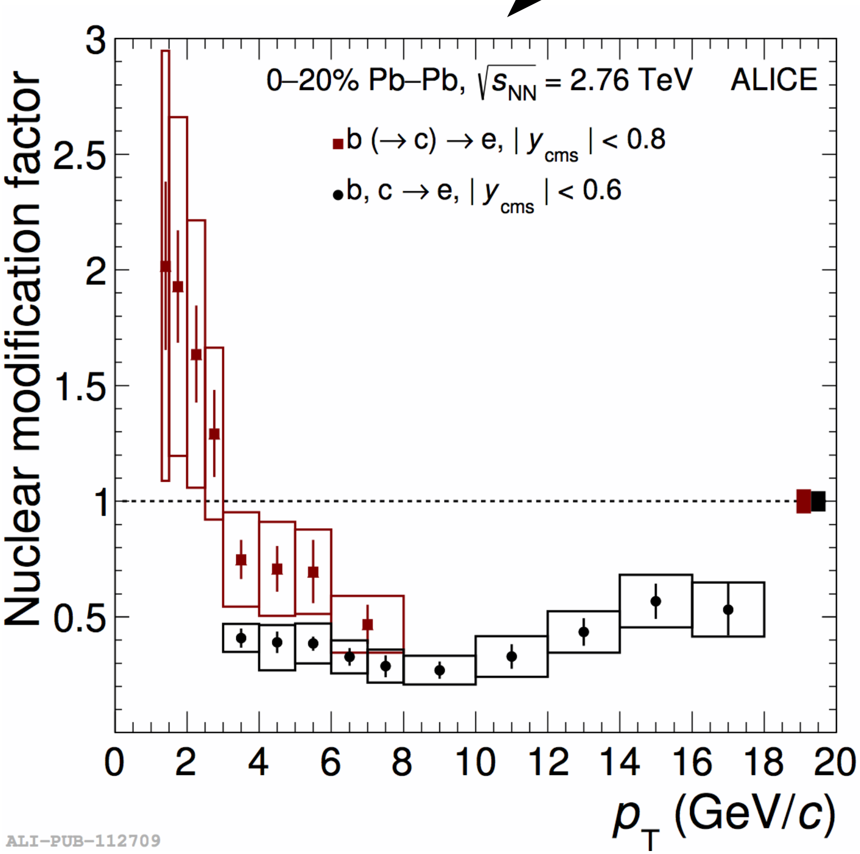
JHEP 1507 (2015) 051

Open heavy-flavor: current results

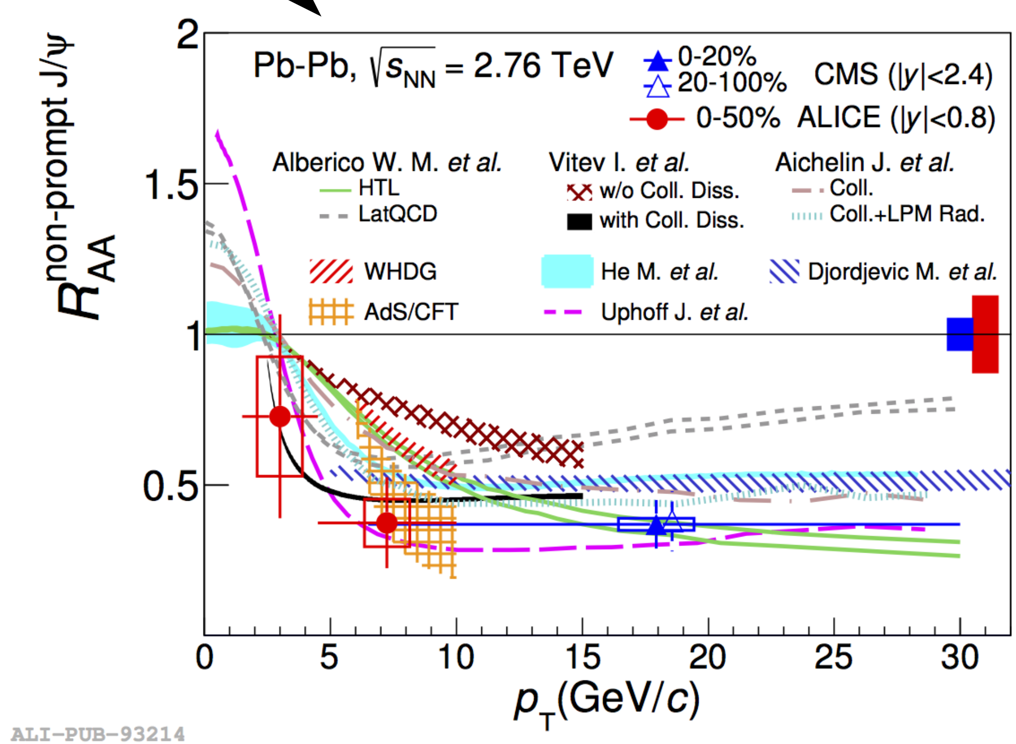
Beauty: nuclear modification factor R_{AA} No v_2

Semi-leptonic decays: electrons from beauty hadrons at mid-rapidity

and non-prompt J/ψ from beauty hadron decays



arXiv:1609.03898



JHEP 1507 (2015) 051

Open heavy-flavor: goals

Study:

- Parton mass and color-charge dependence of in-medium energy loss
  - p_T and centrality dependence of R_{AA} for D and B mesons separately
- Thermalization of heavy quarks in the medium
  - Azimuthal-flow anisotropy of charm and beauty hadrons
  - Determination of the baryon-to-meson ratio for charm and beauty hadrons

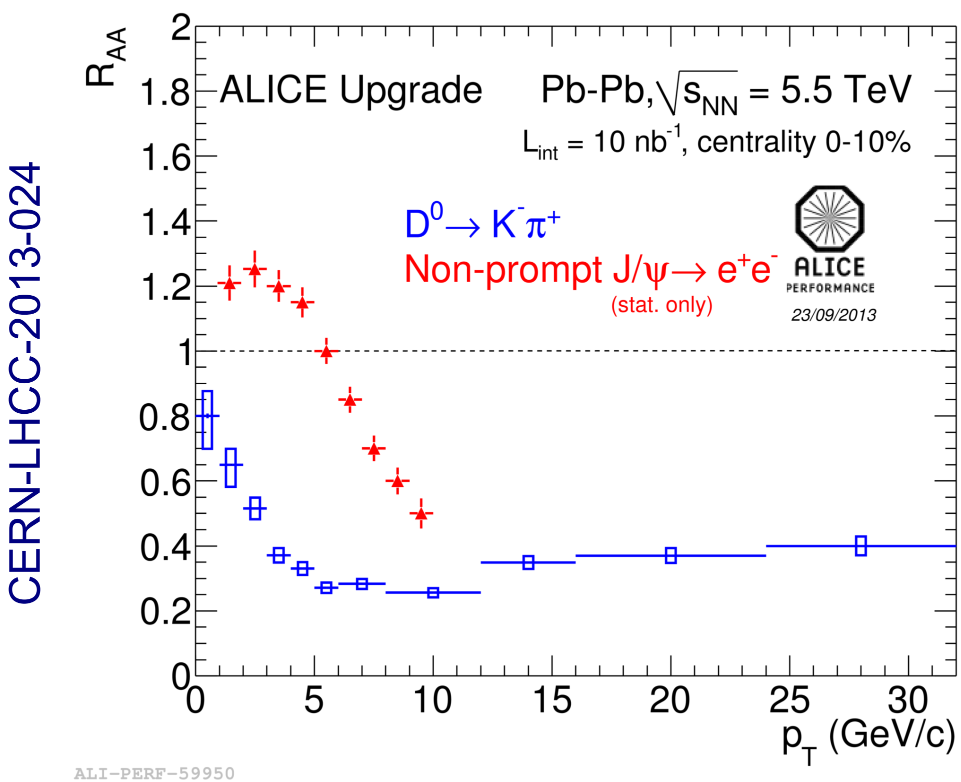
Higher precision and statistics make new channels accessible:

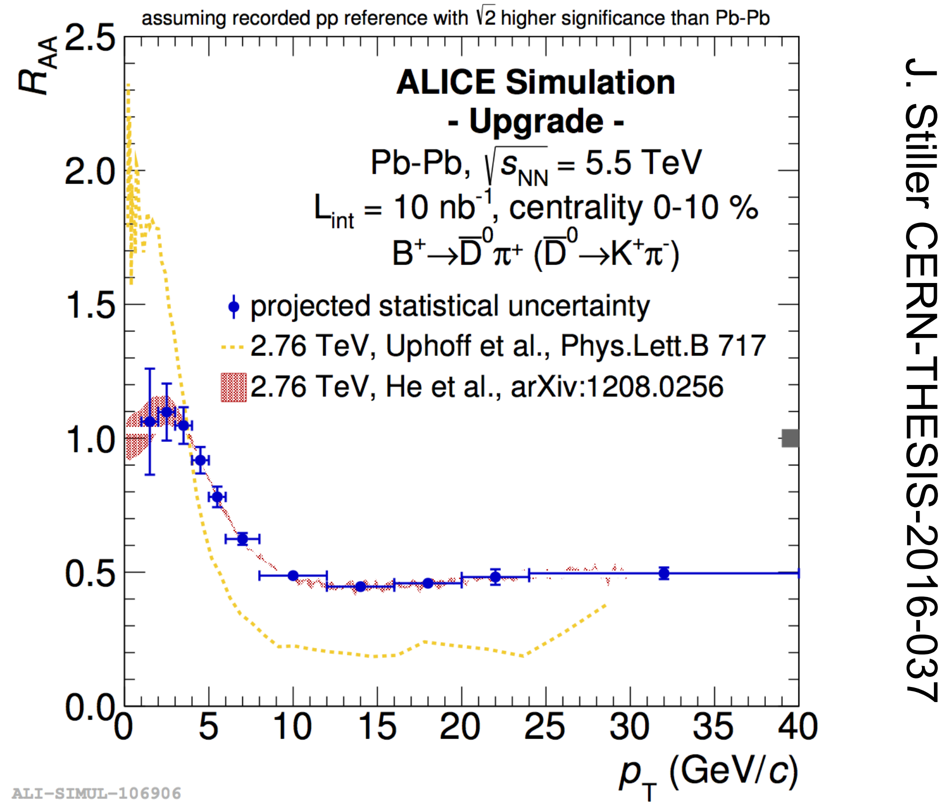
- $B \rightarrow D^0 + X$, $B^+ \rightarrow D^0 + \pi^+$
- $B \rightarrow J/\psi\ (ee,\mu\mu) + X$
- $B \rightarrow e/\mu + X$

- $\Lambda_c \rightarrow p\, K\, \pi$
- $\Lambda_b \rightarrow \Lambda_c\, \pi$

Nuclear modification factor: projections

- Integrated luminosity 10 nb^{-1} $\rightarrow$ 8.5 x 10^{9} events
- Projected statistical uncertainty of the measurement of R_{AA}





- Reach p_T=0, more precision in centrality dependence
- Mass dependence

Elliptic flow: projections

- Integrated luminosity 10 nb^{-1} → 8.5 x 10^9 events

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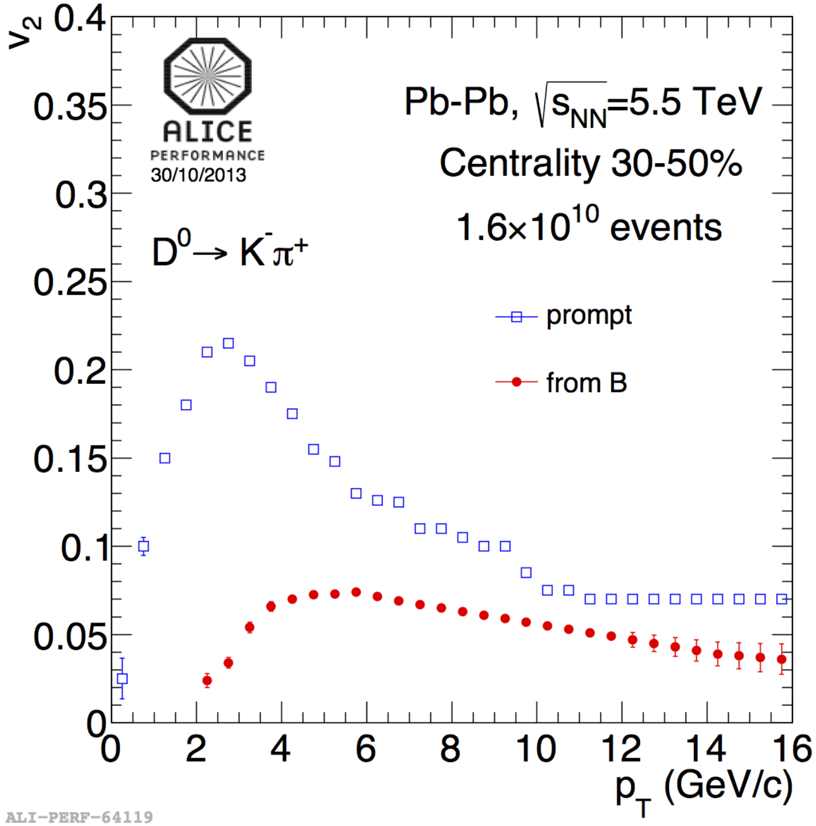
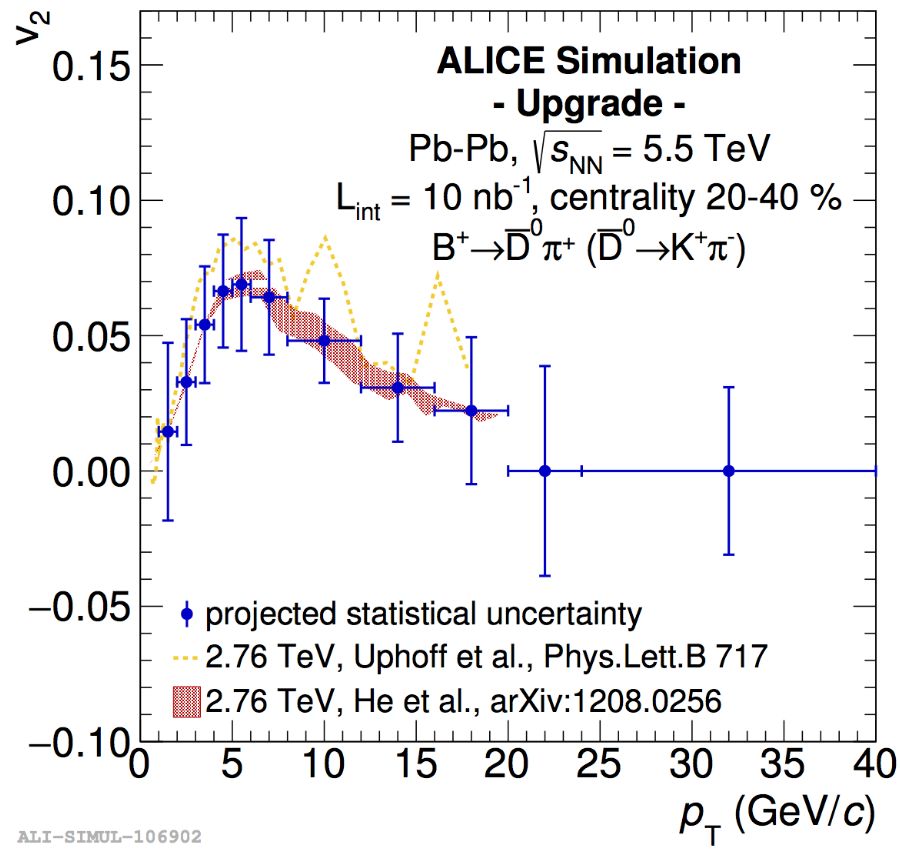




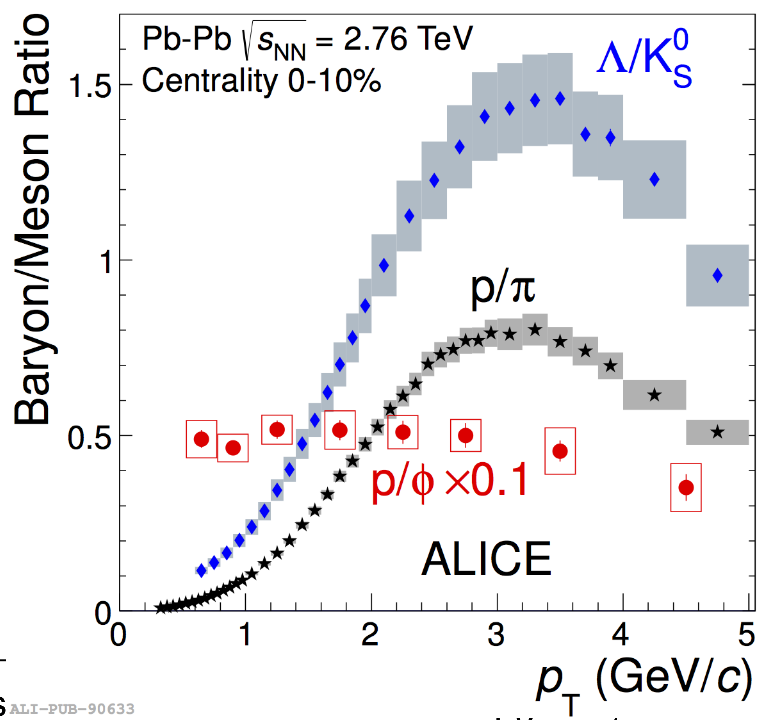
J. Stiller CERN-THESIS-2016-037

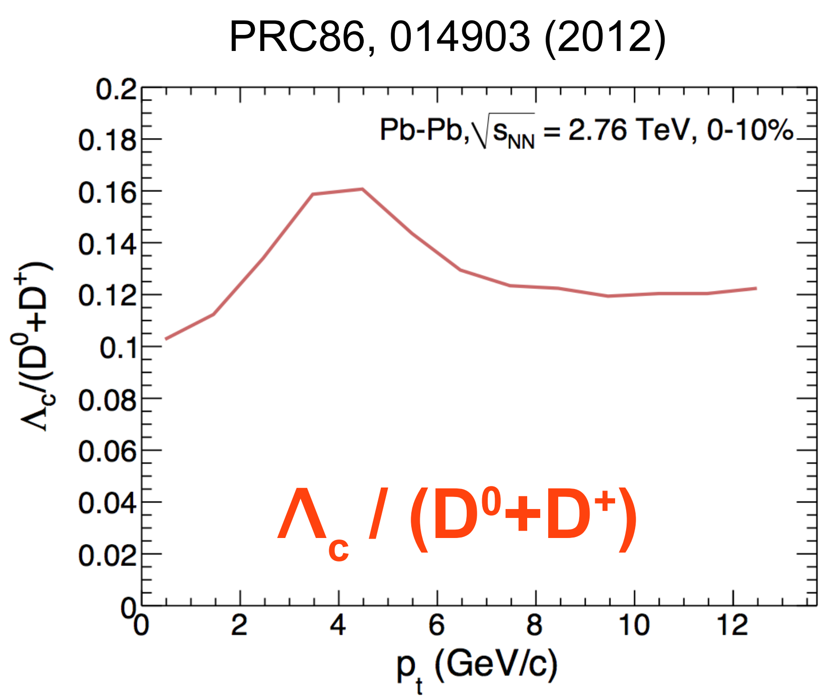
- Reach 0 (low) p_T for c (b ← new!)
- Hadronization mechanism

Hadronization

- Current hints that charm might recombine in-medium:
  - D v_2 (LHC) and D R_{AA} (RHIC) better described with recombination?
  - D_s R_{AA} larger than D R_{AA}?
  - J/ψ production at low p_T?
- Can be studied via precise measurements of D_s vs D, and baryons vs mesons

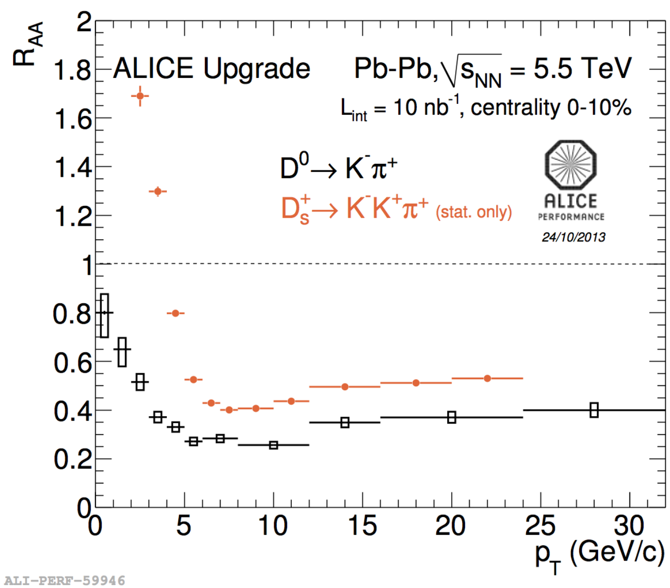
Light flavors → Heavy: theory predictions

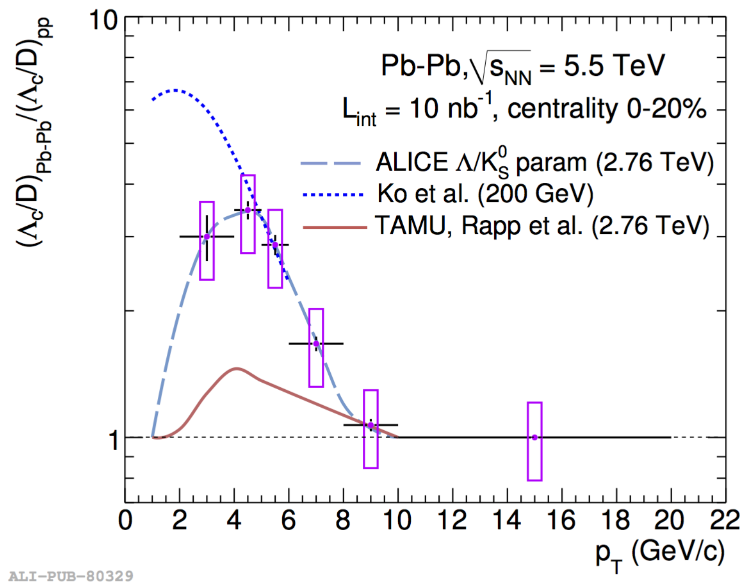


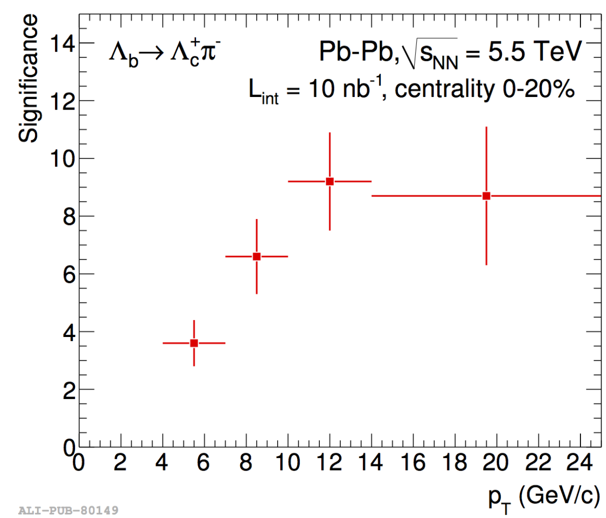


D_s, Λ_c, Λ_b: projections

$D_s \rightarrow KK\pi$	$\Lambda_c \rightarrow pK\pi$	$\Lambda_b \rightarrow \Lambda_c\pi$
Good precision for $p_T > 2$ GeV/c	Good precision for $p_T > 2$ GeV/c	Accessible for $p_T > 7$ GeV/c
R_{AA}	**Λ_c / D**	**Λ_b significance**







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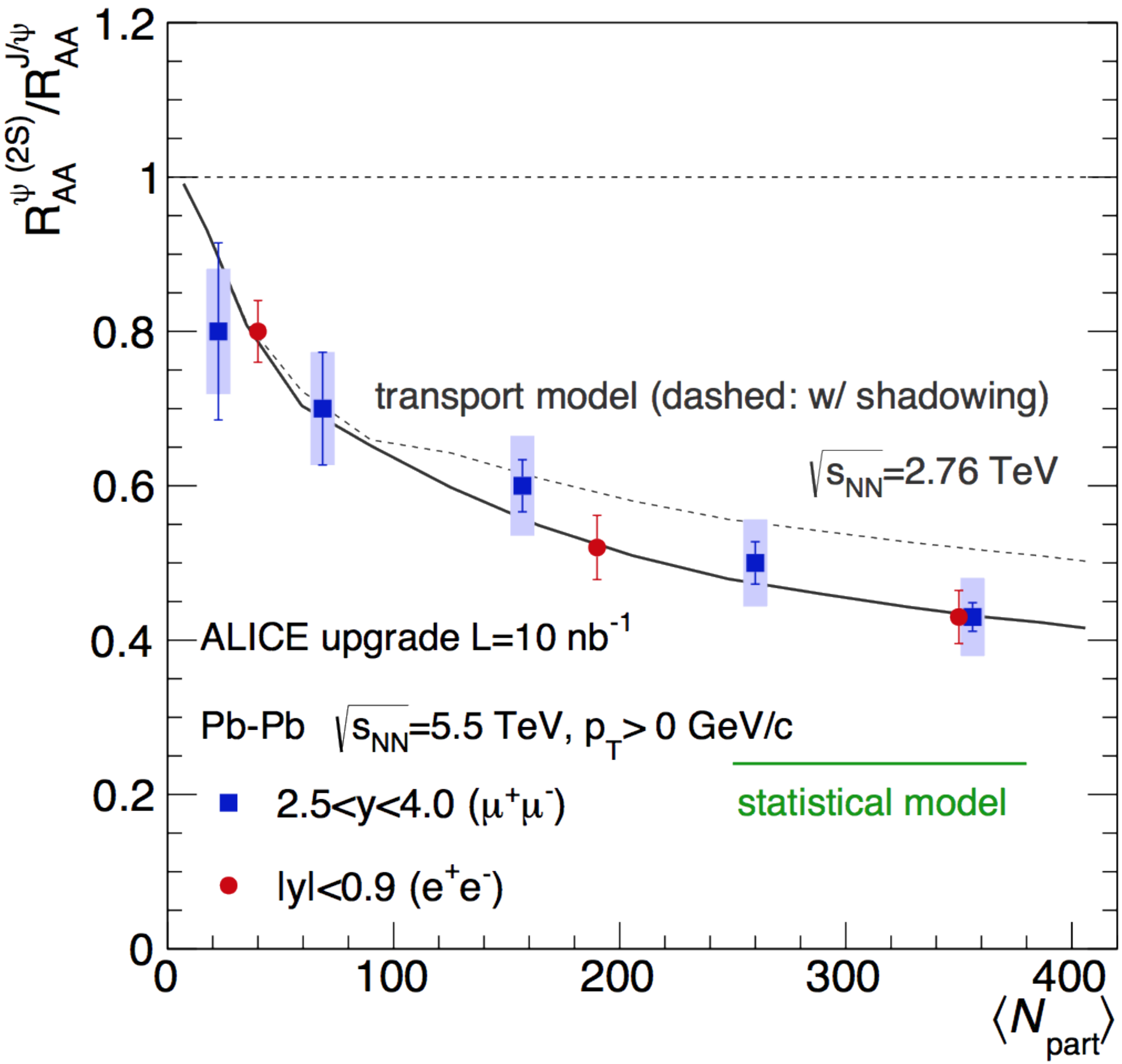
Charmonium

Charmonium: production mechanism

Discrimination between different charmonium production mechanisms (models) will be possible with high statistics ψ(2S) measurements



J.Phys. G41 (2014) 087001
LHCC-I-022-ADD-1
EPJ C76 (2016) 3, 107

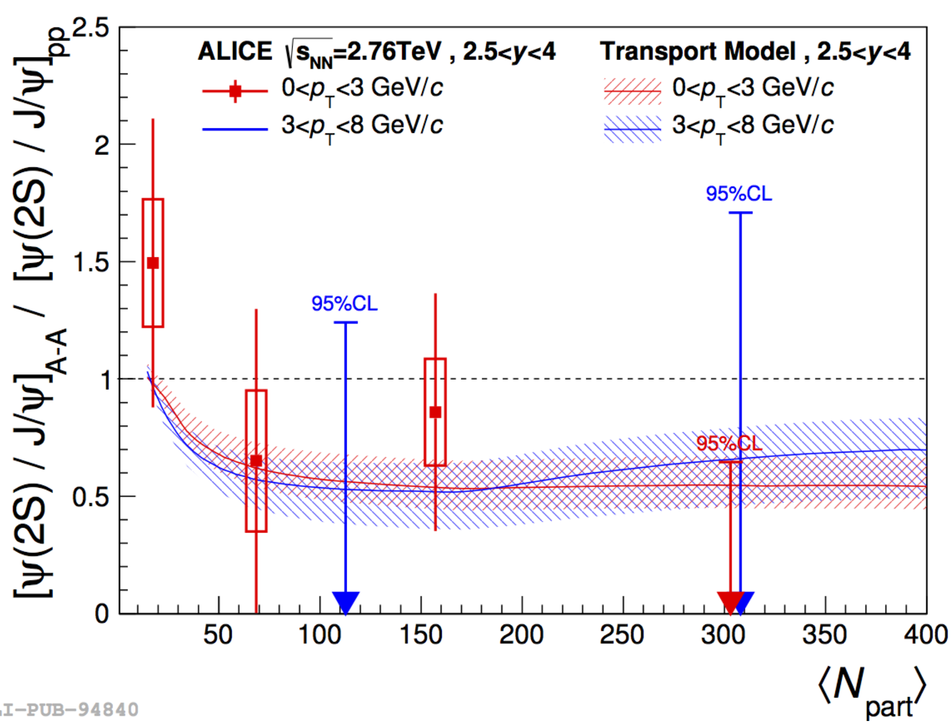
Mor REMINDER mple 2

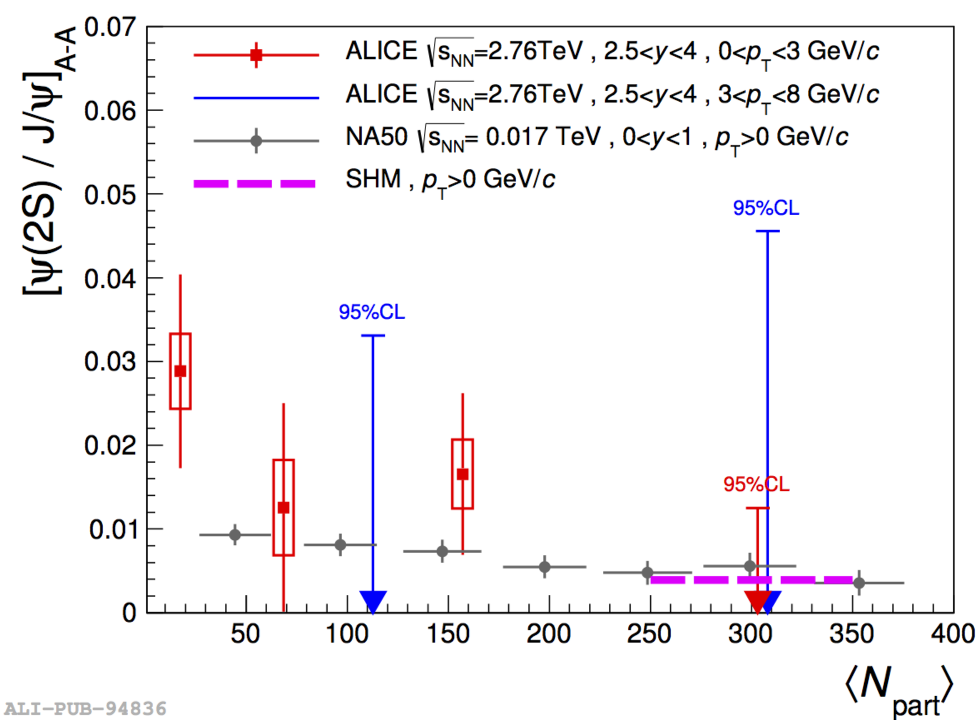
REMINDER

Discrimination between different charmonium production mechanisms:

- Transport models: in-medium destruction and generation
- Statistical hadronization: generation at phase boundary

will be possible with high statistics ψ(2S) measurements



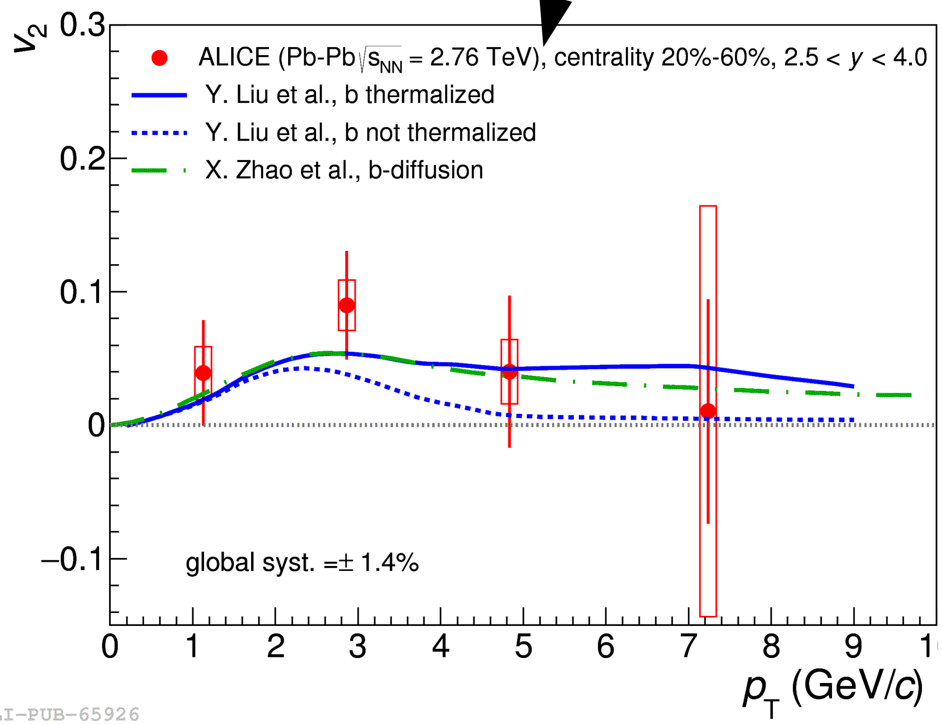


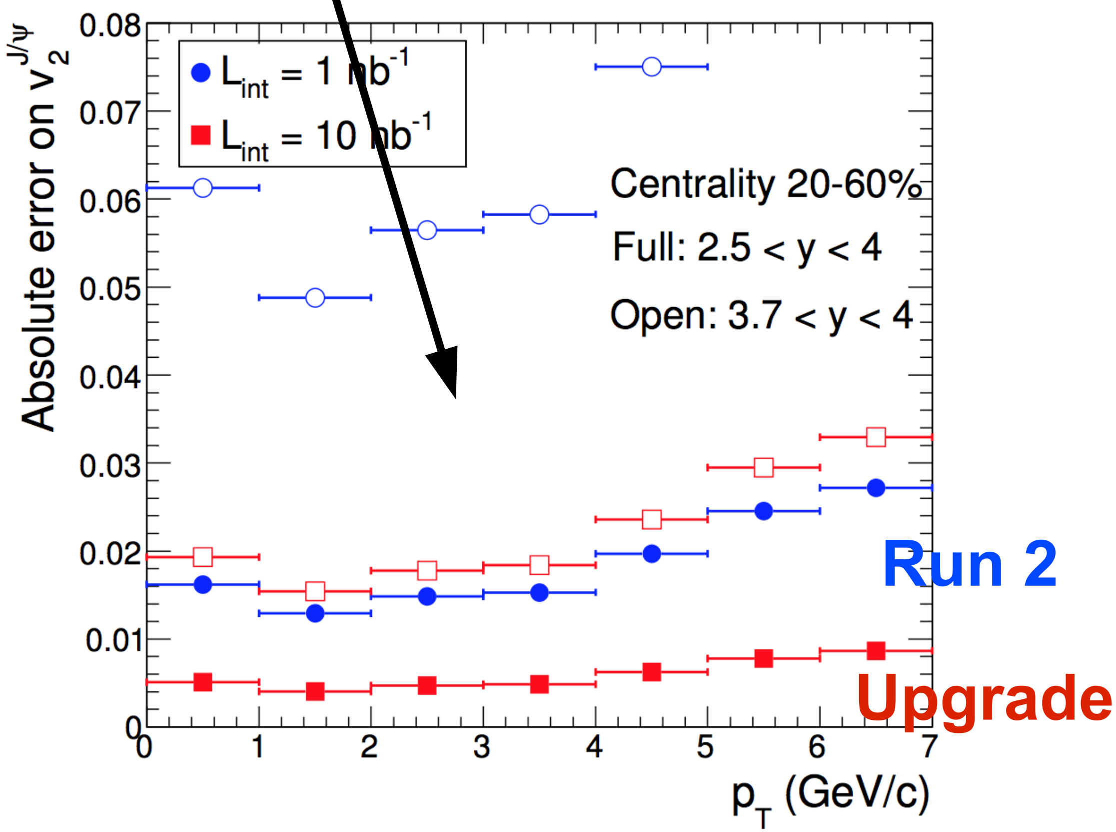
limited statistics, no central collisions

JHEP 1605 (2016) 179

J/ψ elliptic flow

- Crucial observable to test the regeneration scenario
- Limited precision in run 1 → 10 times better precision with upgrade!





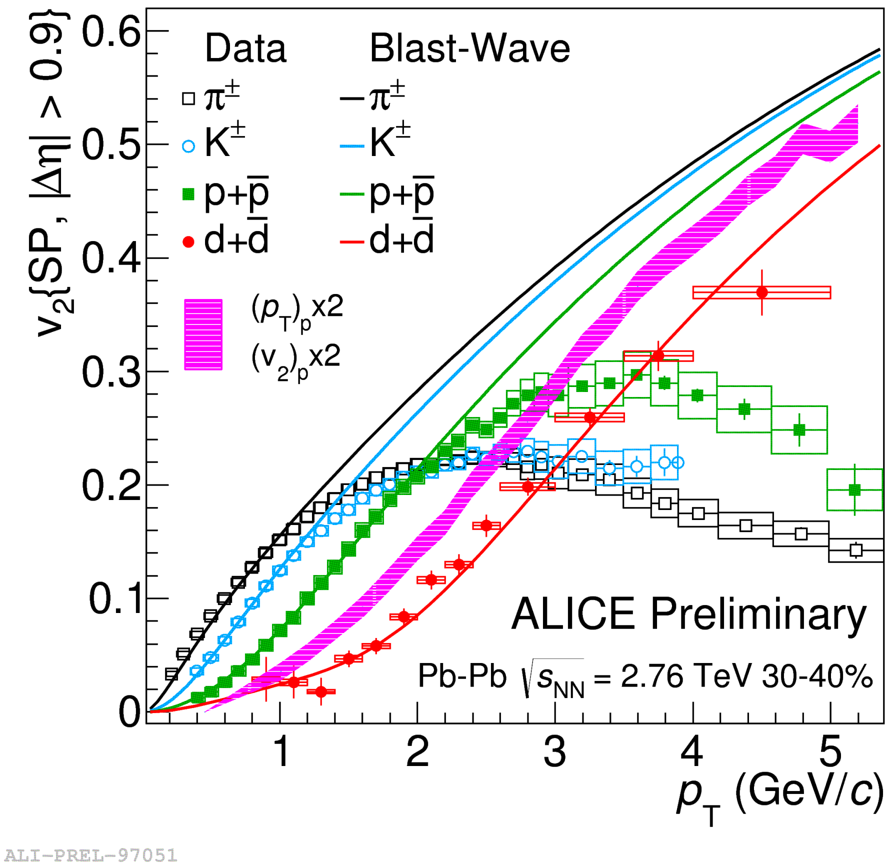
PRL 111 (2013) 162301

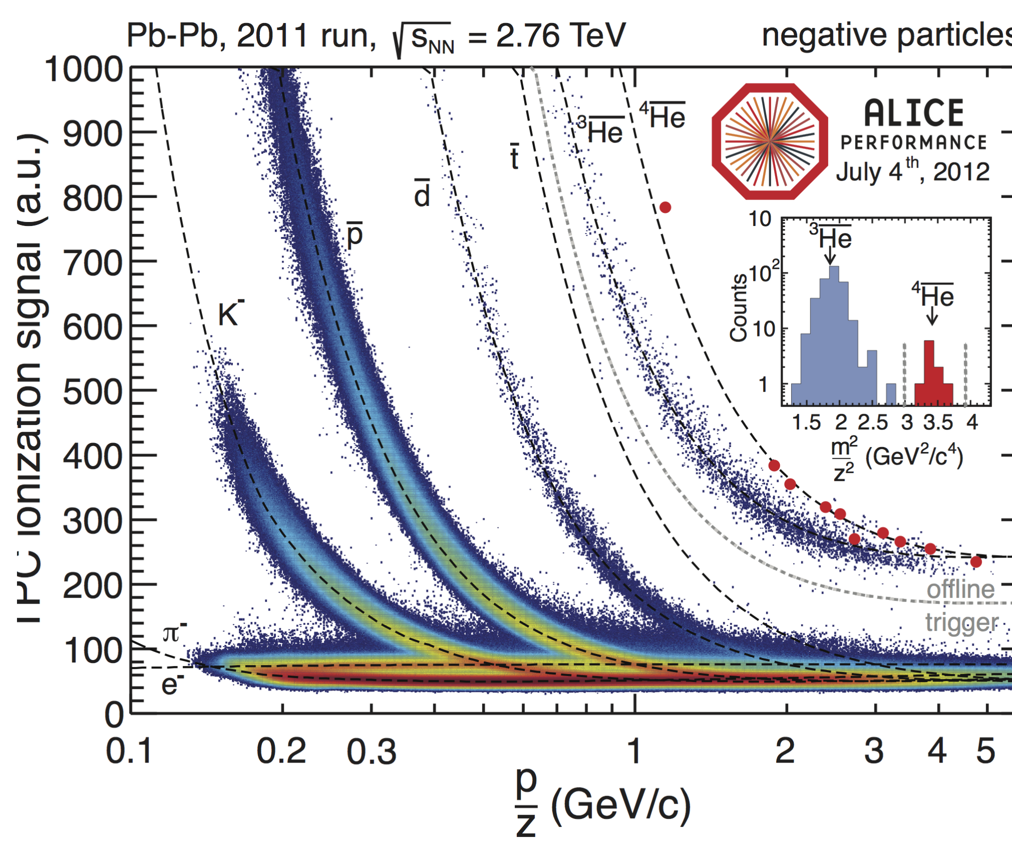
CERN-LHCC-2012-012

(Hyper-)nuclei, exotica

Nuclei: goals and current status

- Test production mechanisms, e.g. statistical hadronization versus coalescence
- Implications of low binding energy of these extended objects
- Explore QCD and QCD-inspired models predicting multi-baryon states

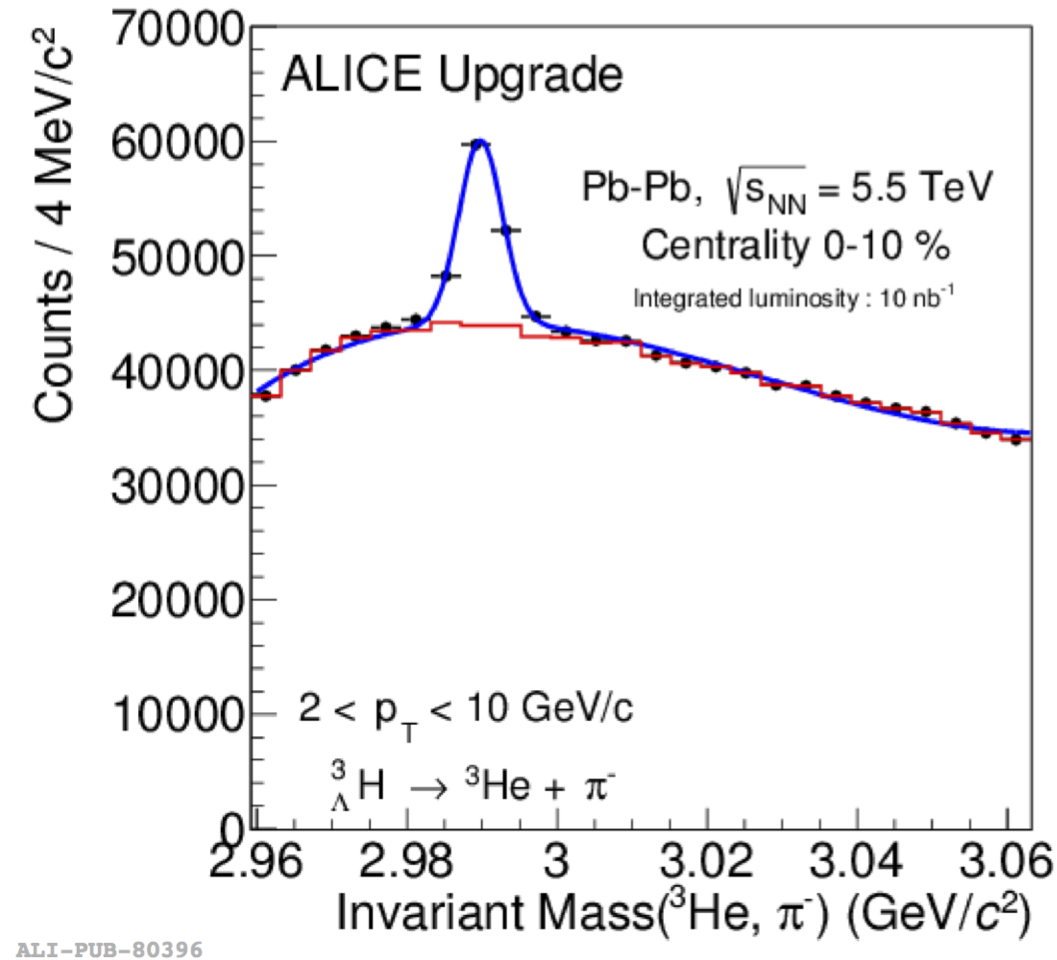




Hyper-nuclei: projections

Higher statistics and resolution will allow precision measurements for hyper-triton including:

- Lifetime
- Branching ratios



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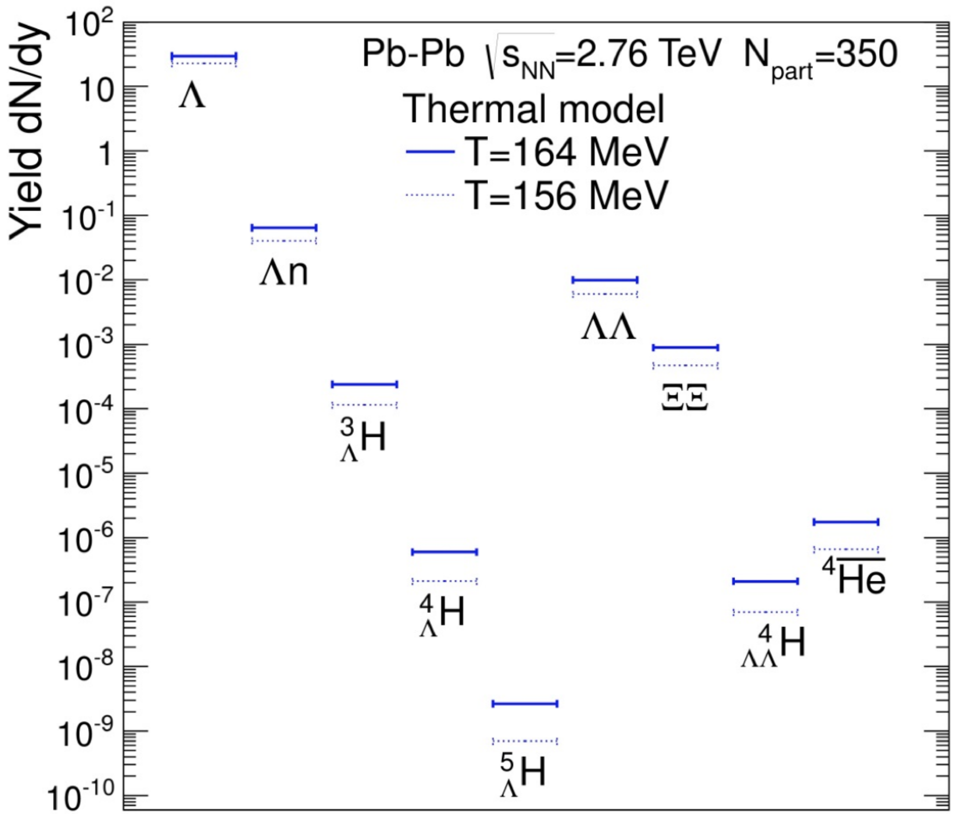
Nuclei: projections

The physics we can now do for A=2 and A=3 will become possible for

A=4

State	dN/dy [82]	B.R.	$\langle Acc \times \varepsilon \rangle$	Yield
$^{3}_{\Lambda}H$	1×10^{-4}	25 % [83]	11 %	44000
$^{4}_{\Lambda}H$	2×10^{-7}	50 % [83]	7 %	110
$^{4}_{\Lambda}He$	2×10^{-7}	32 % [84]	8 %	130

Continue exploration of multi-baryon states, including exotic, unknown ones

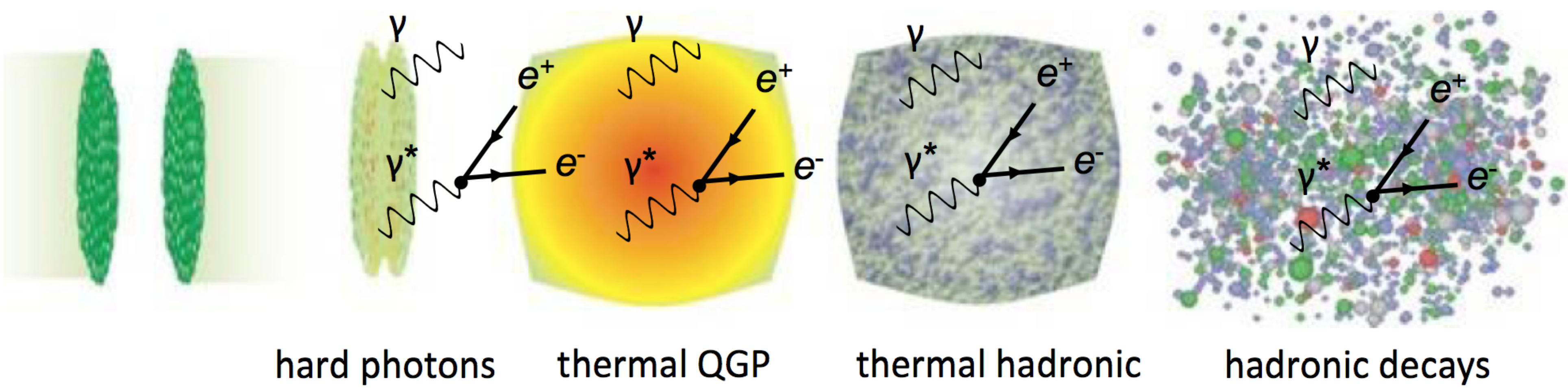


A. Andronic, priv. comm.

Di-lepton spectrum

Photons and di-leptons

- Electromagnetic **thermal radiation spectrum** of hot QCD matter
- Produced at **all stages** of the collisions
- Leave the system without Final State Interactions

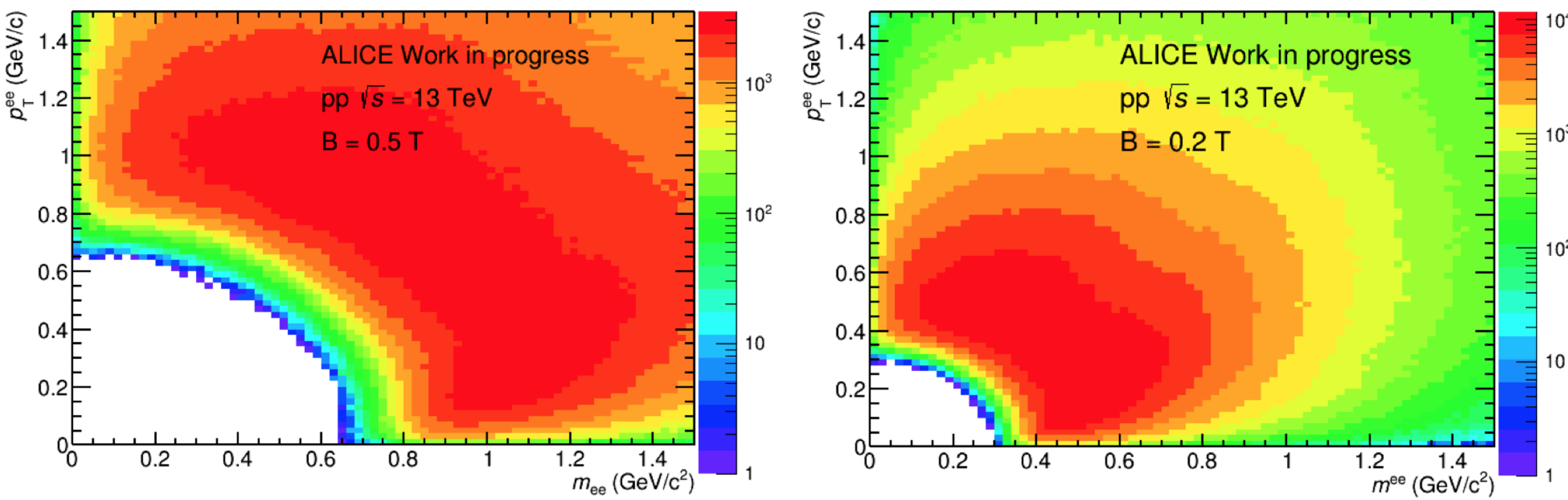


- QGP temperature
- Generation of hadron masses, chiral symmetry restoration
- Space-time evolution of the system
- Heavy-flavor production cross section

Di-leptons in run 3-4

- Significantly reduced material in **ITS:** fewer conversions and mult. scat.
- Higher resolution and efficiency at **low p_T**
- Plan for 3 nb^{-1} recorded at ALICE **B=0.2 T** (vs 0.5 T)

Much improved pair acceptance



O. Vazquez Doce

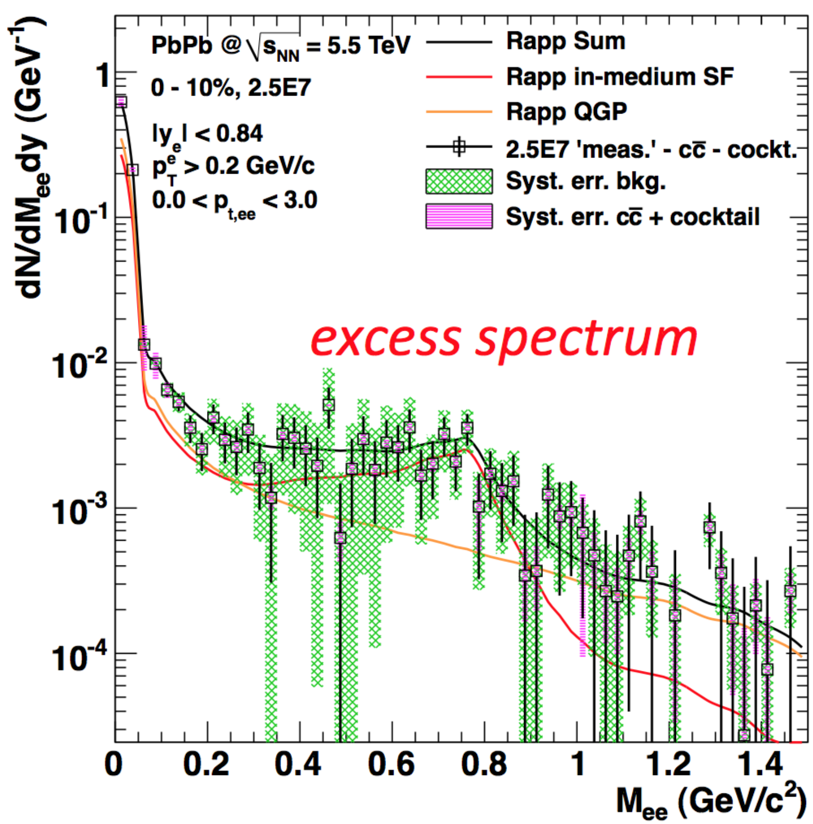
Di-leptons in run 3-4

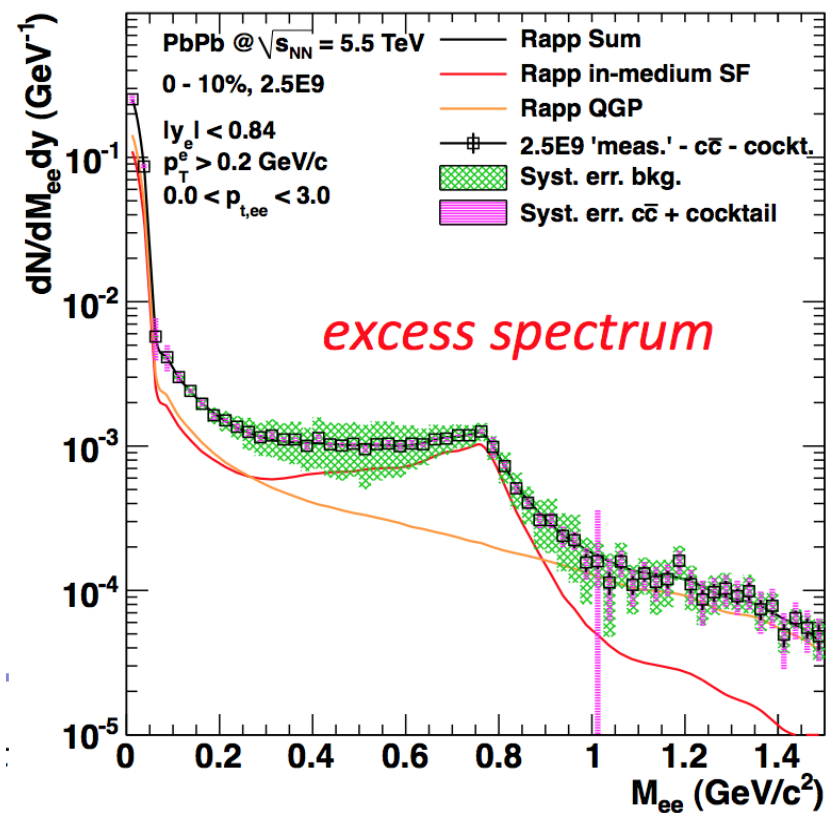
- High rate: increase statistical significance by factor 10 (continuous readout)
- Spatial resolution: reject charm via DCA cuts

ITS, TPC

- Projection: current detectors → upgraded detectors: ITS, TPC

2.5 x 10^7 ev   2.5 x 10^9 ev





CERN-LHCC-2013-024

Physics program: summary

- 50 kHz Pb-Pb collisions at the LHC (≥ 2021)
- New ITS and GEM TPC → continuous readout, improved spatial resolution and vertexing, comparable PID
- Faster readout and new Online-Offline system (O^2)

will provide 100 times the Pb-Pb statistics of run 2 (10+3 nb^{-1} integrated luminosity) with we will study properties of the QGP via:

- Heavy flavors
- Charmonium
- Nuclei
- Di-leptons

I did not discuss

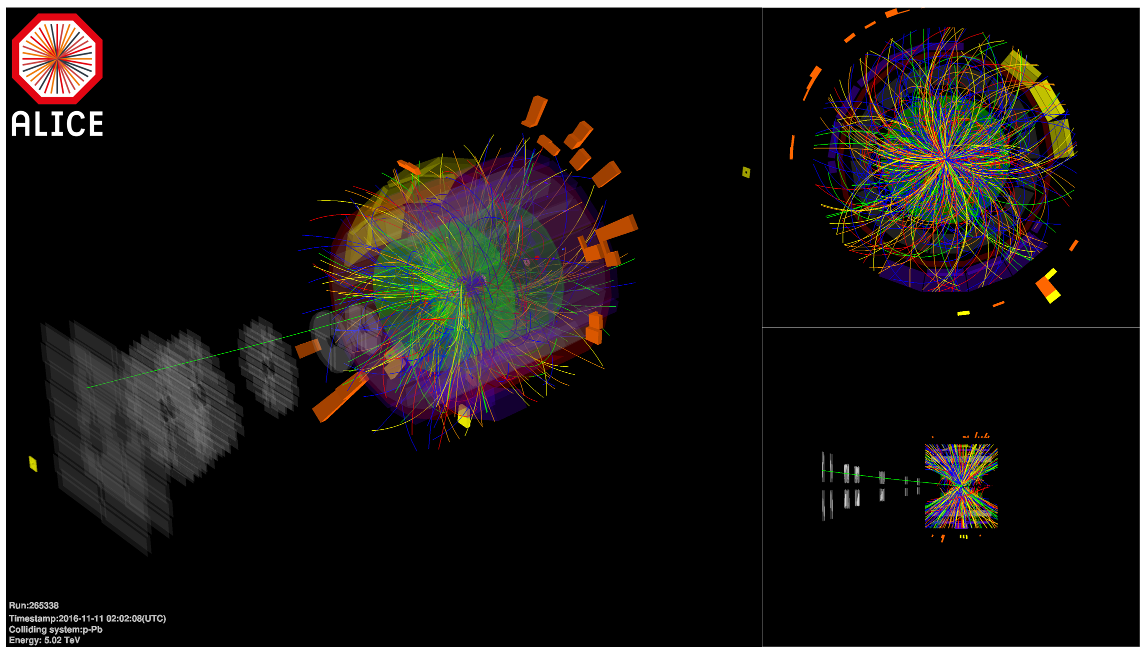
- Muon forward tracker MFT CERN-LHCC-2015-001
- Readout & trigger system CERN-LHCC-2013-019
    - New trigger detectors FIT
    - New, faster readout electronics
- Online-Offline system O^2 CERN-LHCC-2015-006

- FOCAL
- related jet physics program

Outlook

ALICE Collaboration is SUPER BUSY:

- Still publishing from run 1 data
- Full immersion in run 2 (2015-2018): data taking and preparation, analysis
- Construction of new detectors (Production Readiness Reports, test beams, etc.)

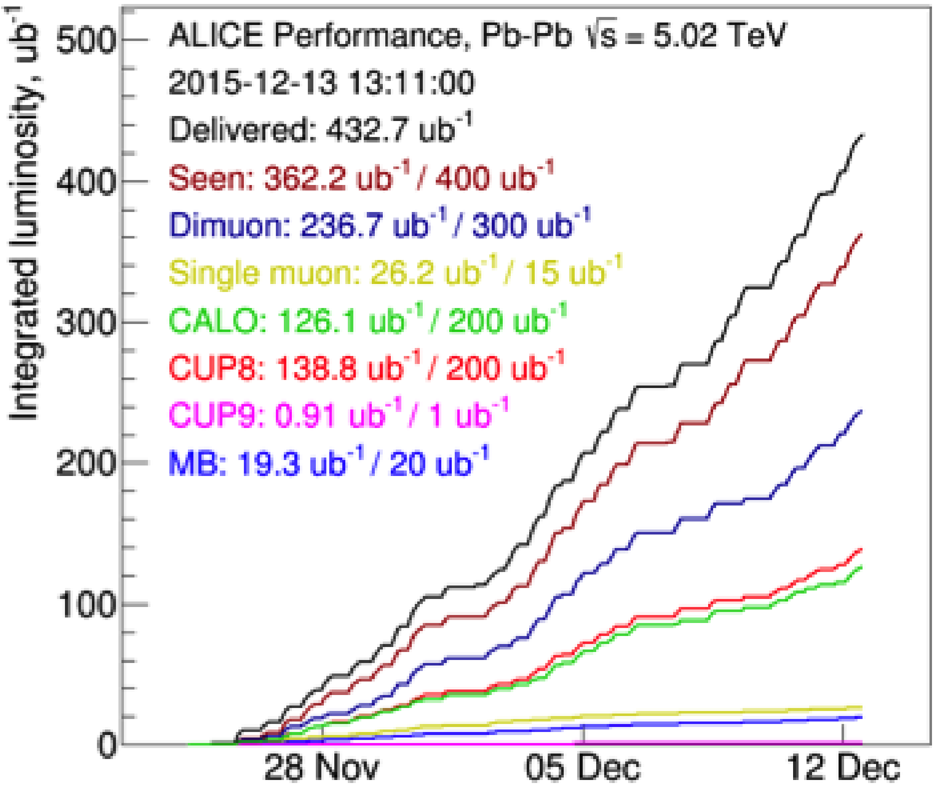


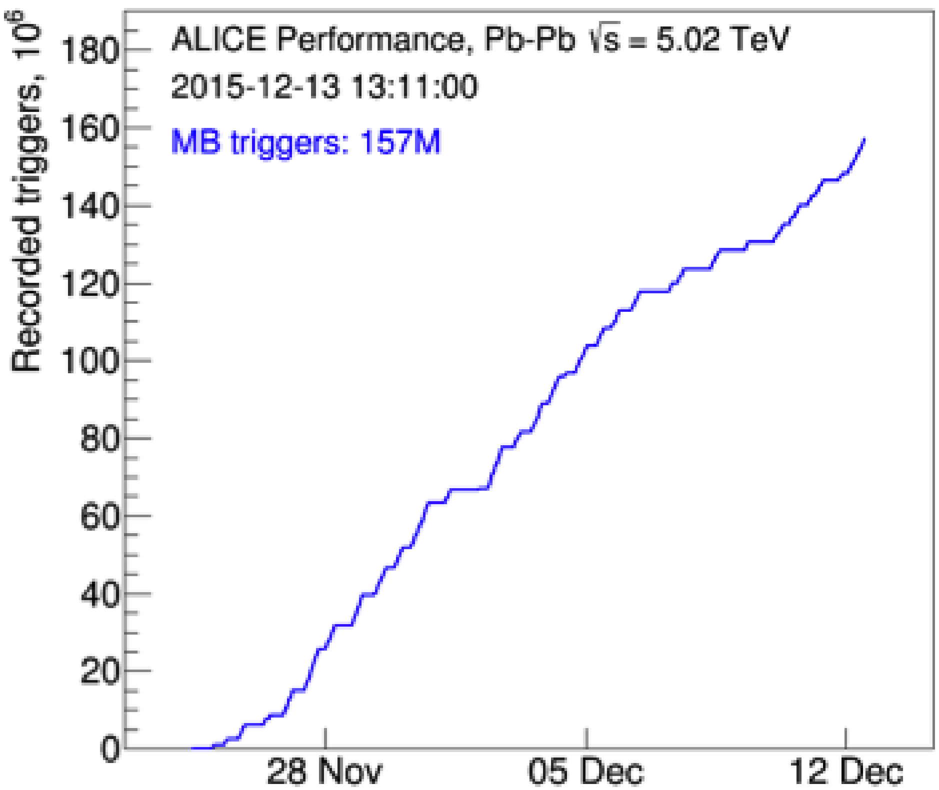
p-Pb
Nov 2016
$\sqrt{s_{NN}}$ = 5.02 TeV

Fantastic potential for current and future physics program

Spares

Pb-Pb 2015 ALICE





Pb-Pb 2015 LHC (J. Jowett)

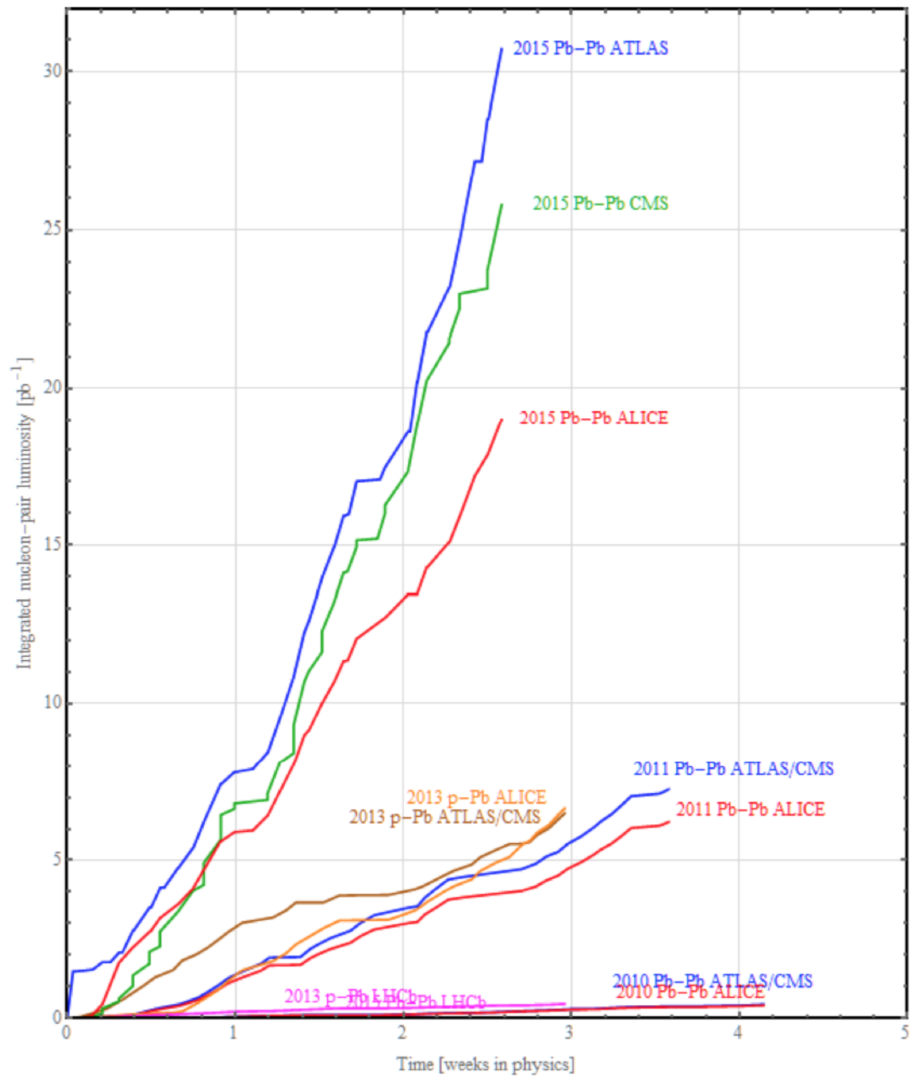
Expect to achieve LHC "first 10-year" baseline Pb-Pb luminosity goal of 1 AA nb^{-1} = 43 NN pb^{-1} in Run 2 (=2015+2018)

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

$$\Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4\ Z \text{ TeV} & \text{in p-Pb} \end{cases}$$

But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.

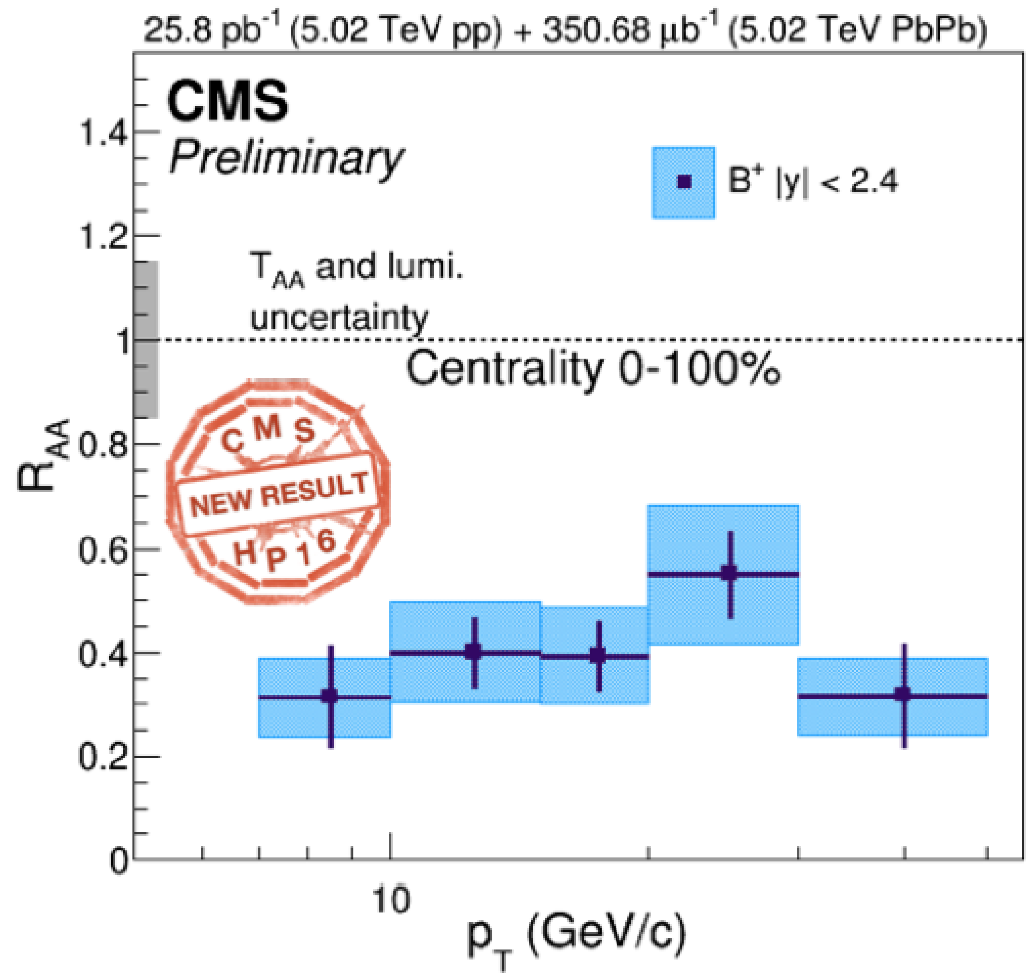


2012 pilot p-Pb run not shown (1 fill but major physics output)

J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016

Nuclear modification factor

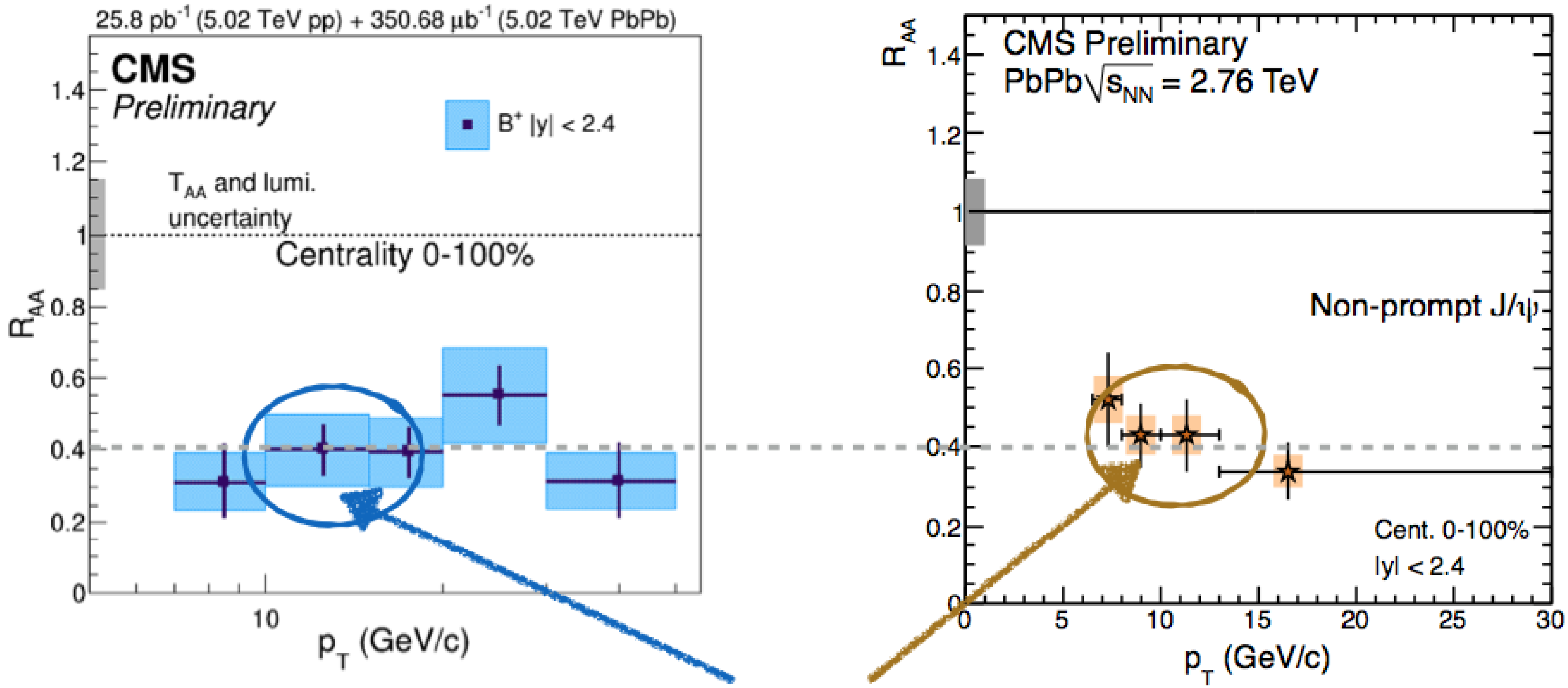
- Result derived in 5 B^+ p_T bins, from 7 to 50 GeV in |y| < 2.4 inclusive centrality (0~100%)
- Suppression of B meson production rate is observed in PbPb collision
- B meson R_{AA} ~ 0.3 to 0.6 with no obvious trend observed within statistical and systematic uncertainty



CMS-PAS-HIN-16-011

Nuclear modification factor

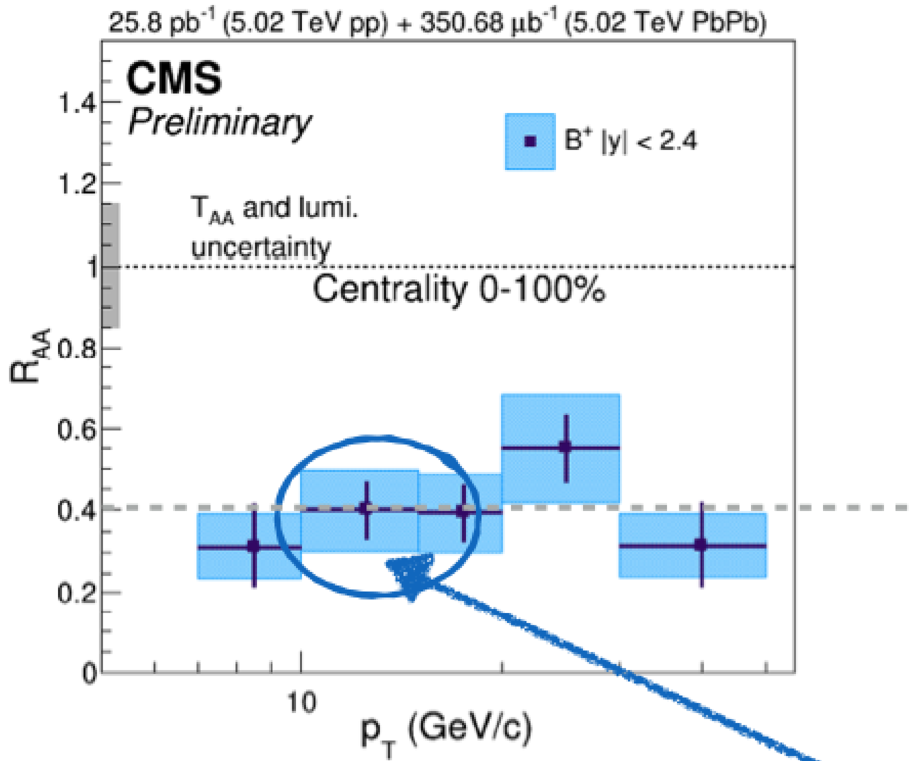
CMS-PAS-HIN-12-014

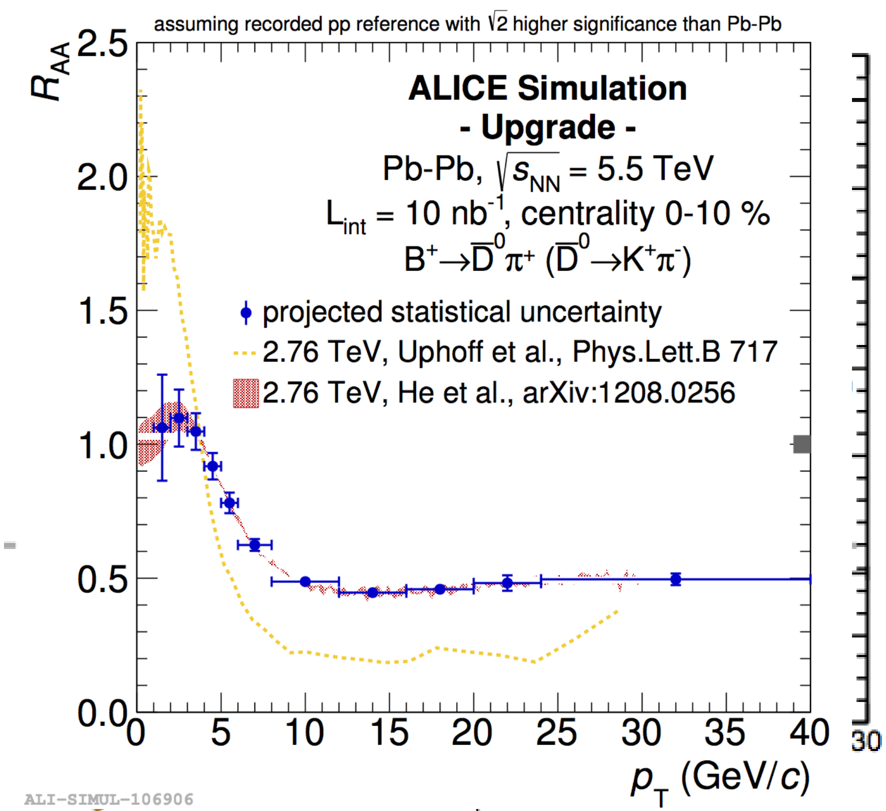


- B^{+} p_T 10~15 GeV → J/ψ p_T 8~10 GeV
- Results compatible with each other within uncertainty

Nuclear modification factor

CMS-PAS-HIN-12-014

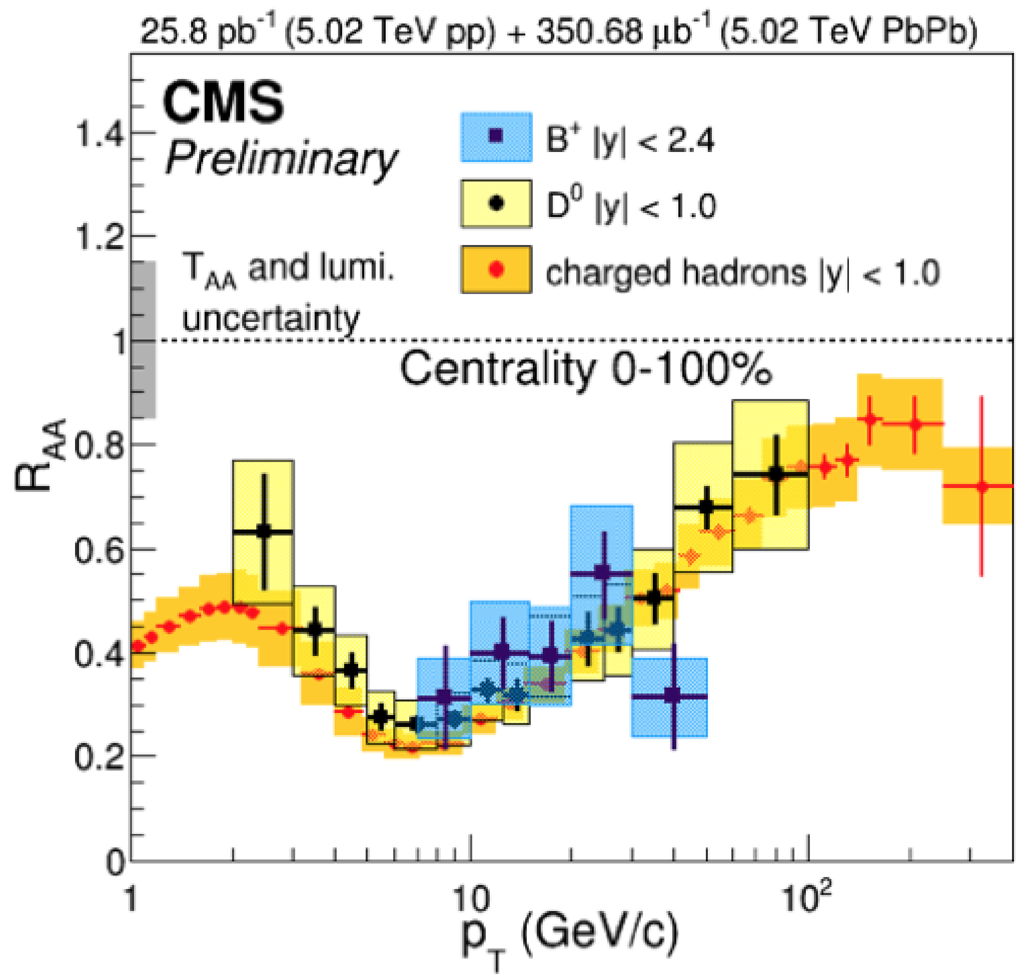




- B^+ p_T 10~15 GeV → J/ψ p_T 8~10 GeV
- Results compatible with each other within uncertainty

Nuclear modification factor

- Comparison with the D^0 meson [1] and charge hadron [2] R_{AA}



[1] CMS-PAS-HIN-16-001

[2] CMS-PAS-HIN-15-015