Heavy-Flavor Measurements in Heavy-Ion Collisions in LHC Run3+4

Beauty 2019

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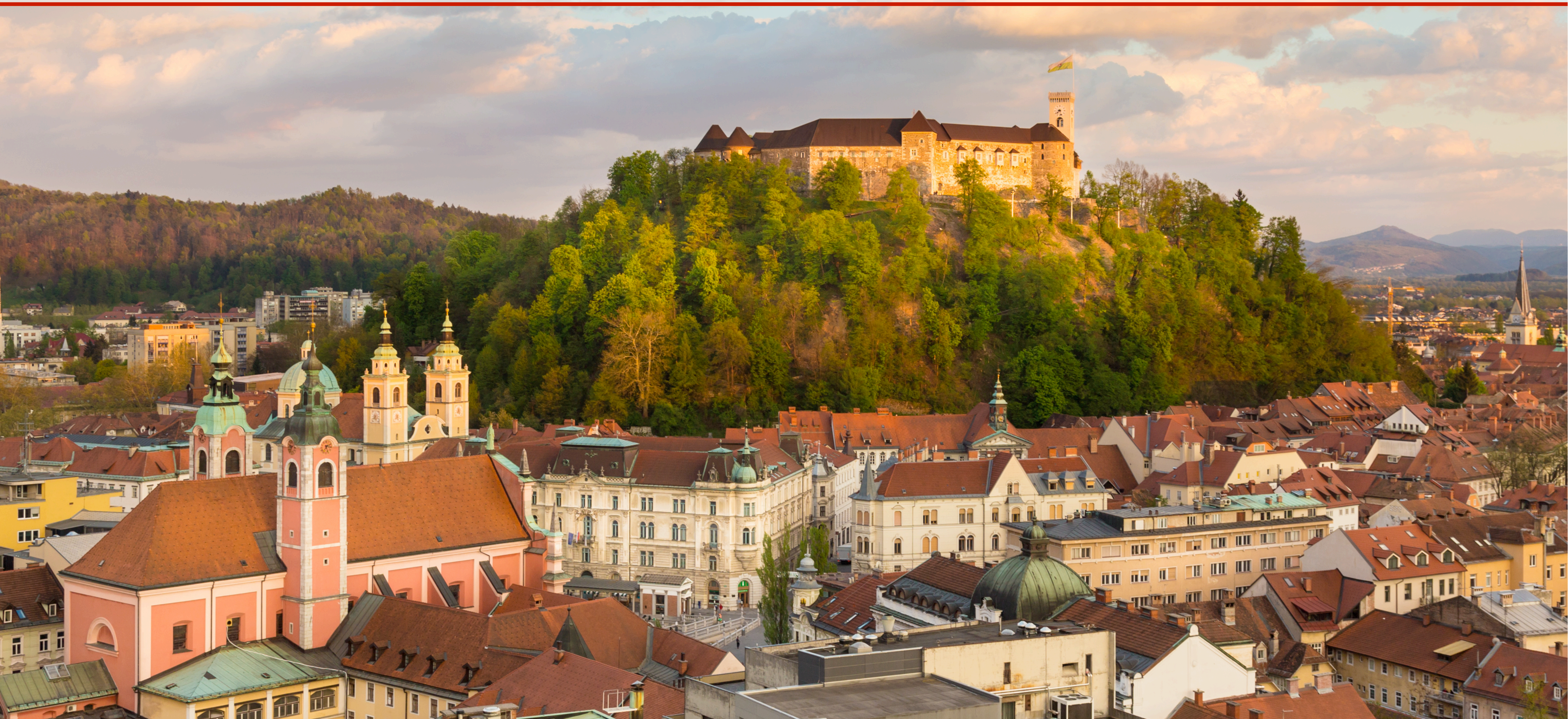
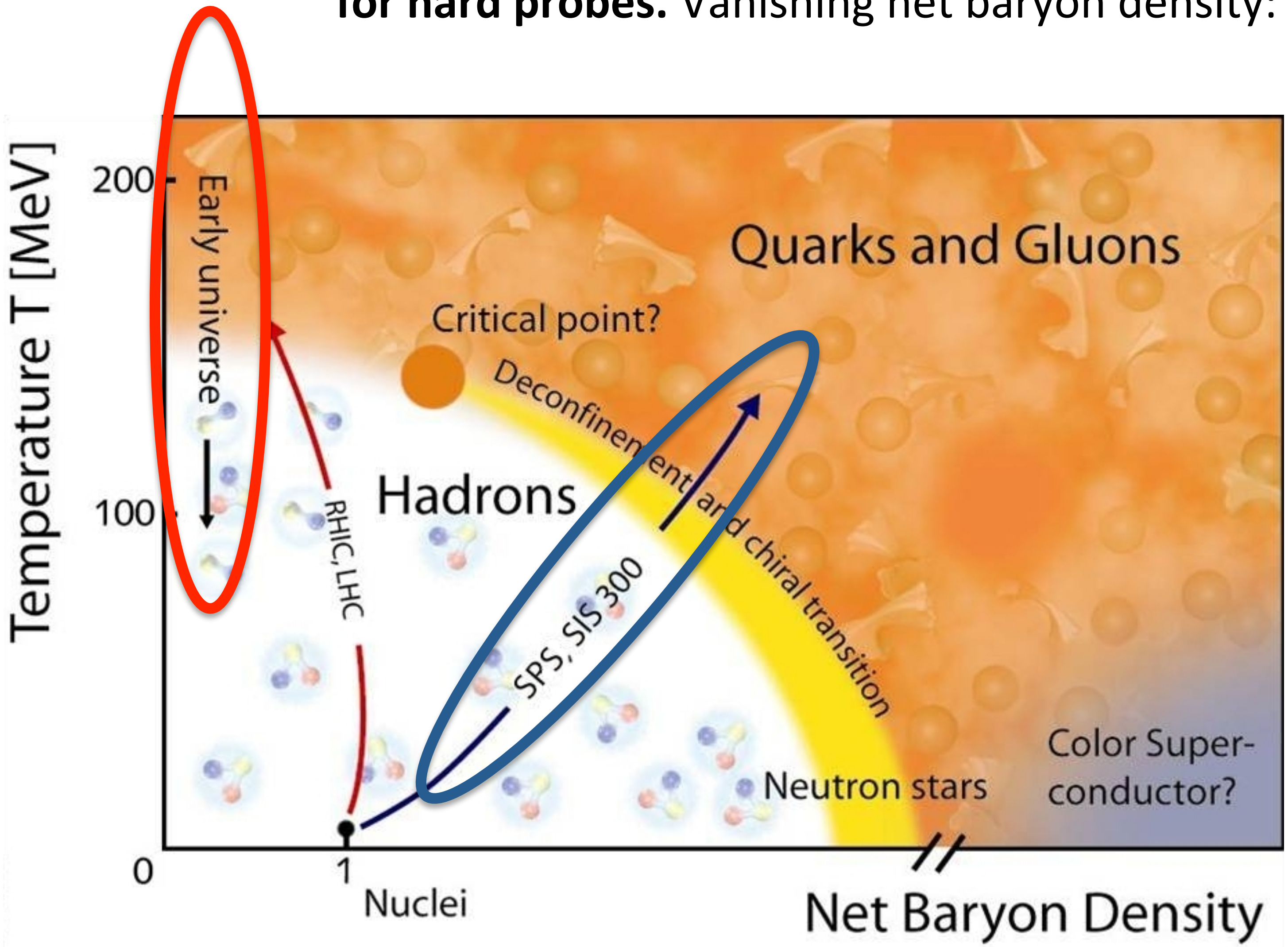
IP2I - Lyon – CNRS/IN2P3



❖ **The high-energy frontier: large and long-living QGP, large cross-sections for hard probes.** Vanishing net baryon density: Early Universe conditions

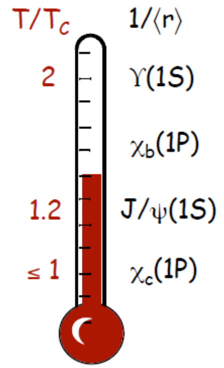


❖ **The low-energy frontier:** focus on bulk observables. Energy scan: search of the critical point and characterization of the phase transition

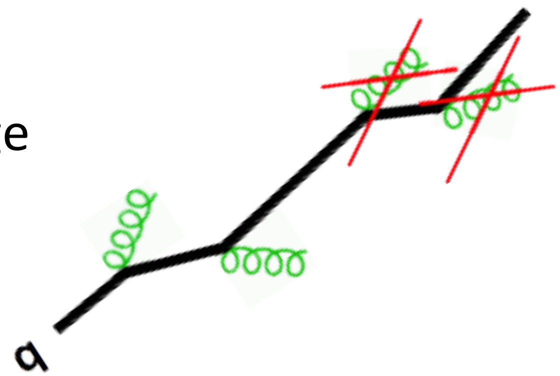
Which Heavy-Flavor Physics in Heavy-Ions?

(see talk by E. Scomparin for a complete overview)

- **Direct probe of medium deconfinement and temperature** through the study of quarkonium states dissociation of via color-screening



- **Direct probe of QCD interaction dynamics over extended systems:**
  - **Mass-dependence of parton energy loss (dead cone) →** in-medium gluon radiation increasing with the color-charge of the emitting particle, and decreasing with its mass
  - **Anisotropic flow of heavy quarks →** direct probe of their (possibly thermal) coupling with the bulk



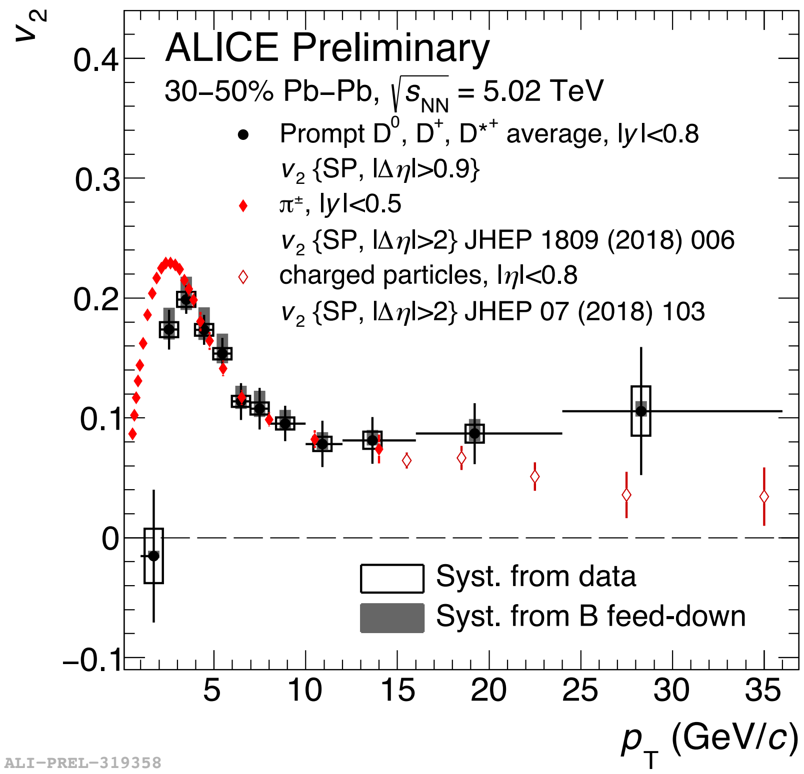
- **Direct probe of hadronization mechanisms of heavy quarks in a deconfined medium** through the study of baryon/meson ratios for different families of HF hadrons

HF Physics in Heavy-Ions: What's Missing?

❖ **Physics program for LHC Run3+4: moving from an exploratory phase to a precision-measurement phase**

➡ Quantitative leap in the precision of the experimental observations

- ✓ Flow measurements: limited precision, especially for the beauty sector
- ✓ Still challenging to see expected hierarchy in energy loss: comparison between b/c energy loss is limited to high p_T
- ✓ Limited or no access in Pb-Pb to charm and beauty baryons: no precise baryon/meson ratio measurements for heavy flavors
- ✓ Room for more differential measurements on quarkonium states



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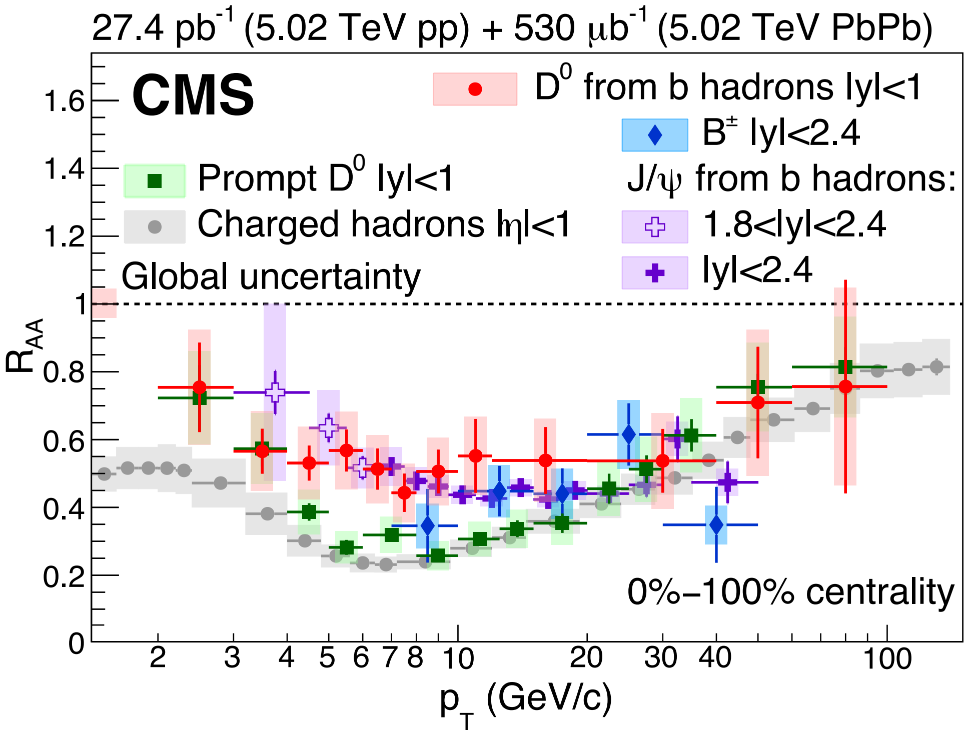

CMS, Phys. Rev. Lett. 123, 022001 (2019)

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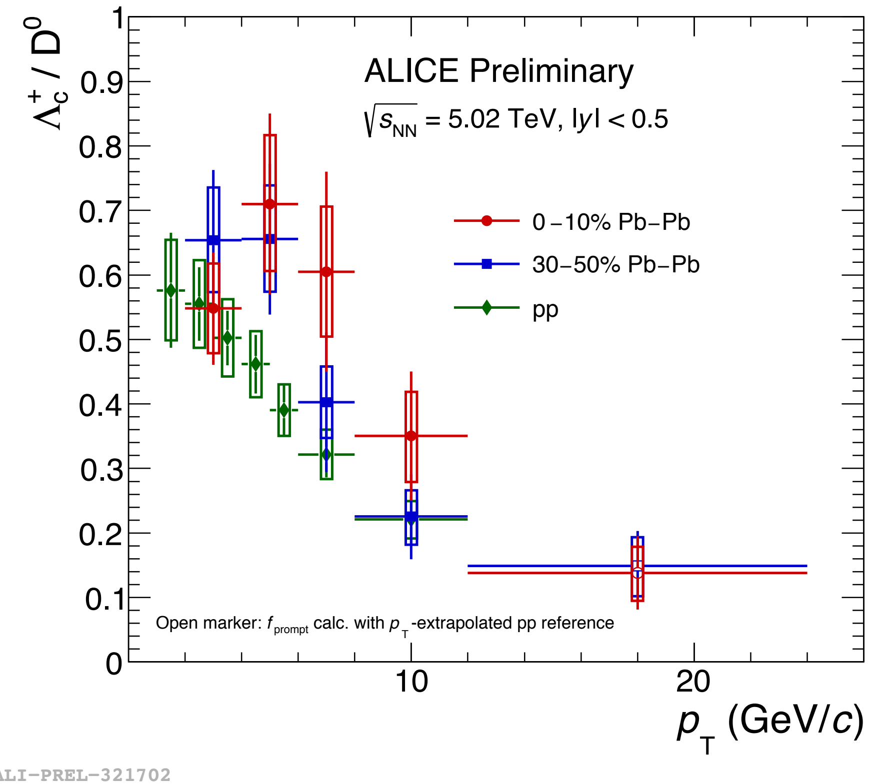

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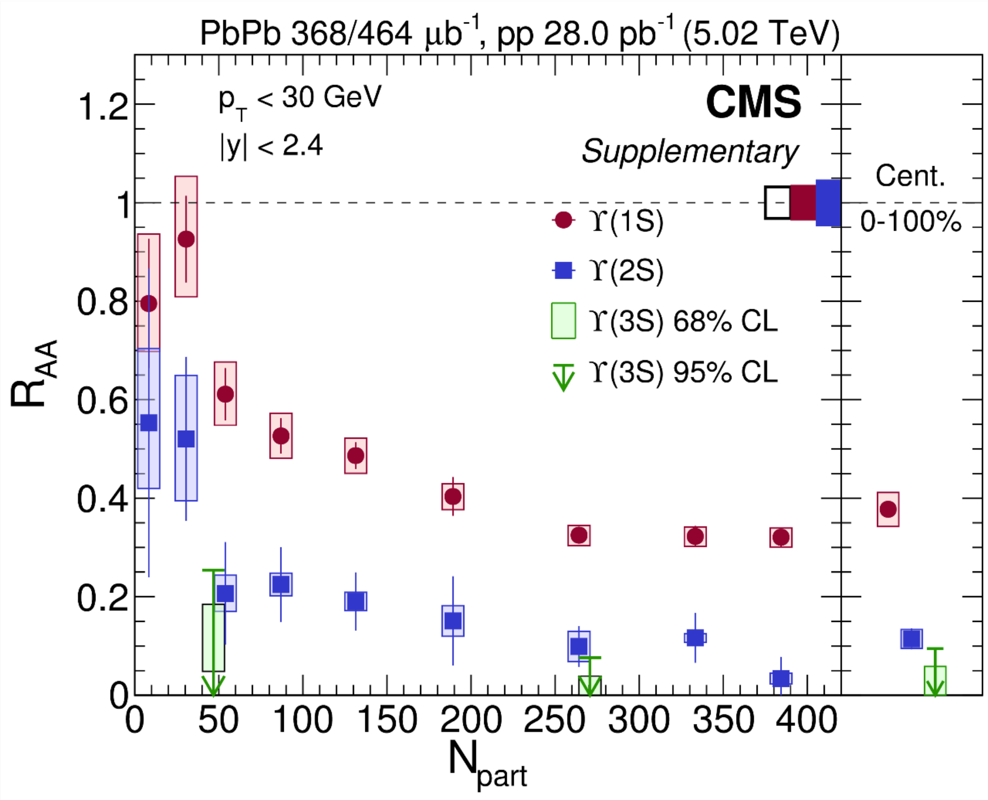
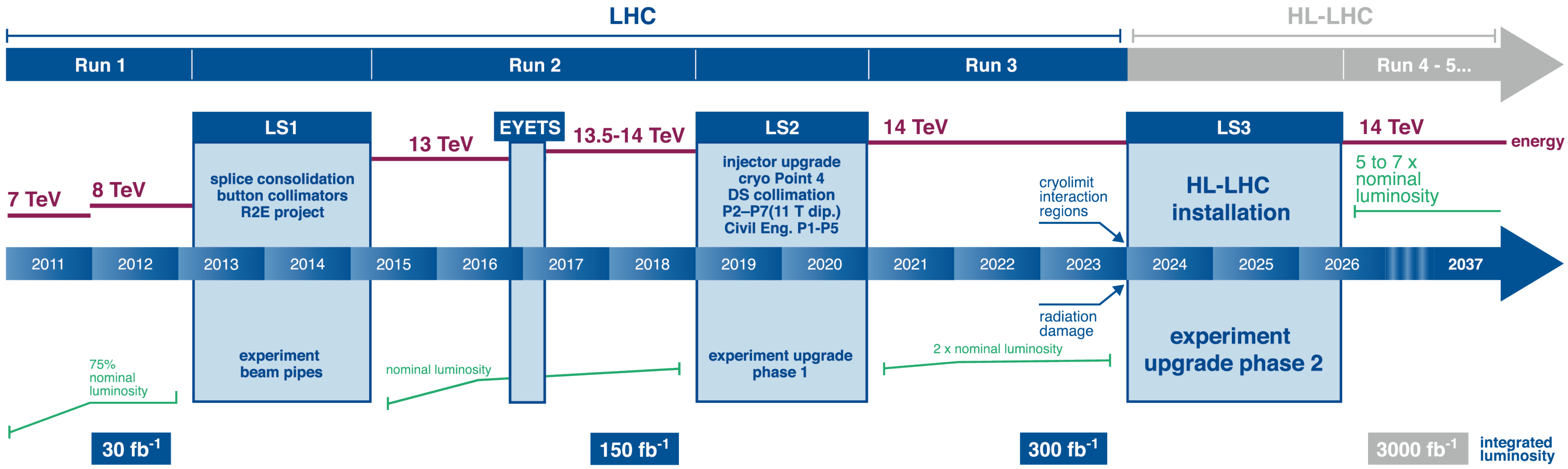


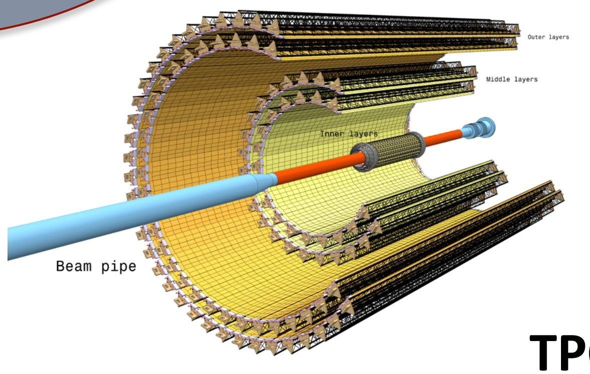
CMS, Phys. Lett. B790 (2019) 270



Main upgrades relevant for the Heavy-Ion physics (LS2: 2019-2020)

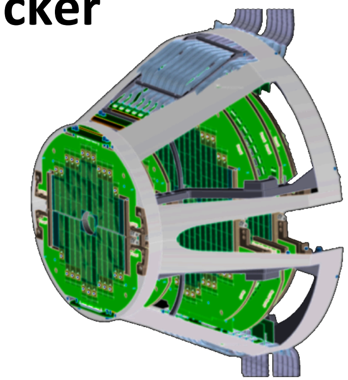
- LHC collimator upgrades: target $L \approx 6\times10^{27}$ cm^{-2} s^{-1} for Pb-Pb (i.e. 50 kHz int. rate)
- Major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS
- Focus on rare probes, their coupling with QGP medium and (medium-modified) hadronization

ALICE Upgrade Strategy: LS2



New Inner Tracking System + Muon Forward Tracker

- New pixel technology: higher granularity, reduced material budget → improved resolution for heavy-flavor vertices



TPC Upgrade:

- Replacement of the MWPC-based readout by detectors employing GEMs to allow TPC operation in continuous mode

Upgraded read-out for many detectors, new integrated Online-Offline, new Fast Interaction Trigger detector

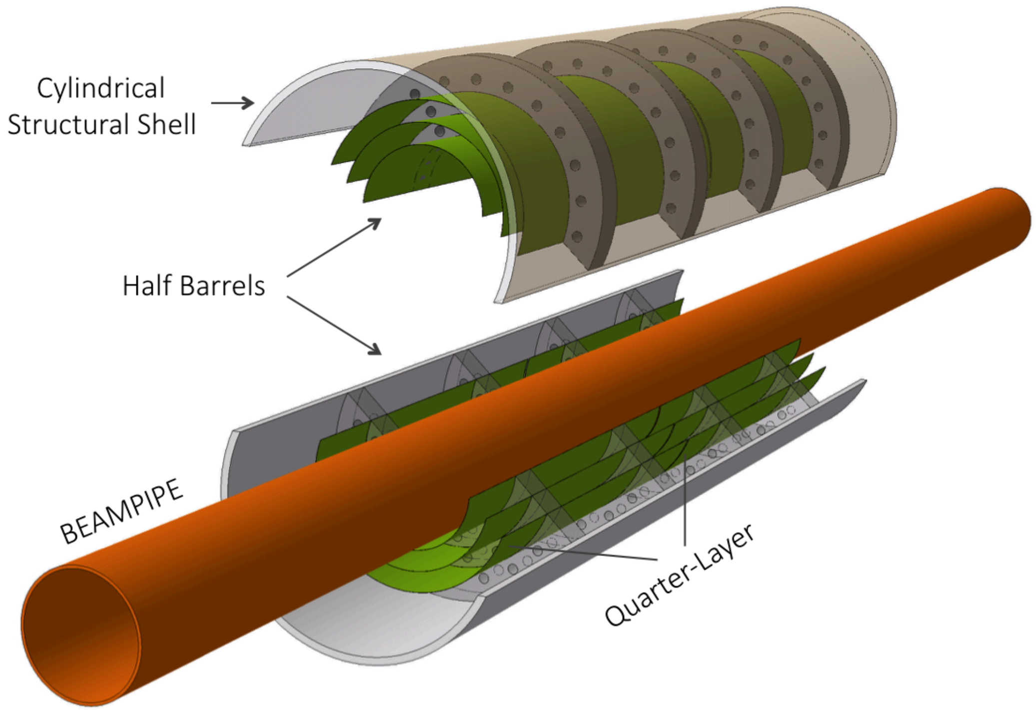
- Record all events at up to 50 kHz in Pb-Pb (1 kHz during Run2): data reduction from 1 TB/s to 85 GB/s via online reconstruction
- Run3+4: increase of minimum-bias sample ×50-100 w.r.t. Run1+2

Preserve and strengthen detector specificities: hadron and lepton identification, light-weight and precise trackers, low magnetic field

ALICE Upgrade Strategy: LS3 Proposal

Proposal for a further upgrade of the innermost part of the inner tracking system:

- New beam pipe with IR = 16mm, DR = 0.5mm
- Three truly cylindrical layers based on curved ultra-thin sensors ($x/X_0 < 0.02 - 0.04\%$ per layer)

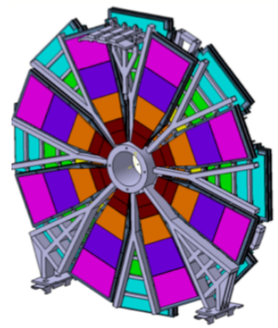


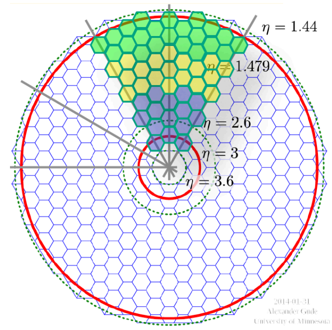
- **The three layers would replace the innermost three layers of ITS in LS3**, with the innermost layer at R = 18 mm
- New design → **material budget** reduced to the bare minimum for a Silicon tracker, large improvement of the **tracking precision and efficiency at low p_T**

CMS/ATLAS Upgrades (LS3) Relevant for Heavy-Ions

- **CMS detector**
  - Lighter silicon tracker with extended coverage out to η = 4
  - GEM muon stations matching the η coverage of the tracker
  - New high granularity calorimeter endcaps that together with the tracker will enable particle-flow reconstruction at large rapidity

- **ATLAS detector**
  - Complete replacement of the internal tracker
  - Level-I track trigger
  - Upgraded calorimeter electronics and muon trigger system





- **Timing detectors in ATLAS and CMS (pile-up rejection)** should allow for π/K/p separation by time-of-flight measurement in the range 0.7 - 2 GeV/*c*

Main focus on triggerable signals (complementary strategy w.r.t. ALICE): muon, jet, displaced track triggers

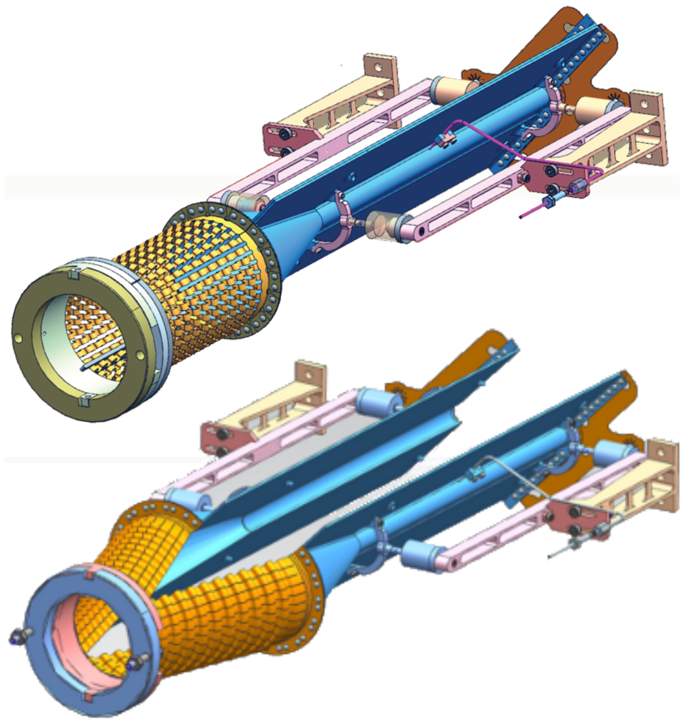
- Trigger/DAQ approach: strong event recording reduction from 50 to 0.1 kHz
- HL-LHC: increase of sample ×10 w.r.t. Run 2

LHCb as a Heavy-Ion Detector

- **Very successful participation in p-Pb and Pb-Pb runs of LHC Run2**
  - Current limitations in detector performance in the most central heavy-ion collisions (collider mode) due to the large multiplicity

- **Run3+4: exploitation of LHCb unique features: forward acceptance, vertexing, PID, calorimetry**

- **SMOG system: LHCb data taking in fixed-target mode (currently unique at the LHC)**
  - Various gases can be injected. $\sqrt{s_{\mathrm{NN}}}$ up to ~100 GeV
  - To be continued after LS2 with more noble gas species



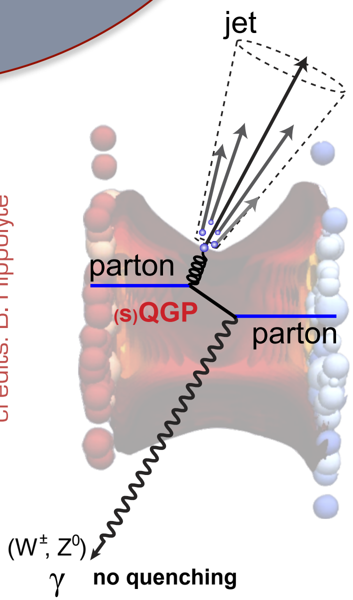
- **Upgrades (LS2) most relevant to Heavy-Ions:**
  - New trackers (pixel, strip, scintillating fiber)
  - Readout upgrade: exploiting full delivered p-Pb L_{int}

Heavy-Flavor Heavy-Ion Physics in LHC Run3+4

- **Open heavy flavors: mass dependence of energy loss, study of in-medium thermalization and hadronization as a probe of the medium transport properties**
  - Low-p_T production and elliptic flow of several HF hadron species, with first measurements of beauty at forward rapidity down to zero p_T (main focus of ALICE)
  - B hadrons and b-jets (main focus of ATLAS and CMS)

- **Quarkonium: precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature**
  - Low-p_T charmonium production and its elliptic flow (main focus of ALICE)
  - Multi-differential studies of Υ states (main focus of ATLAS and CMS)
  - LHCb: performance in the most central collisions to be assessed

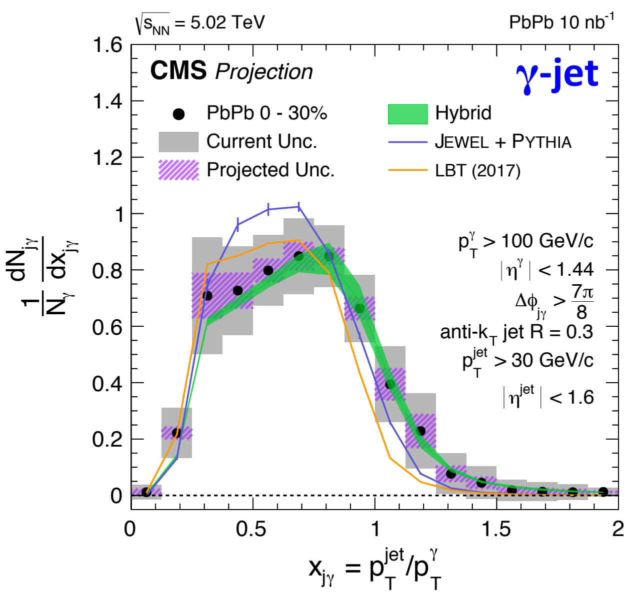
b-Jets (Quenching) in ATLAS and CMS

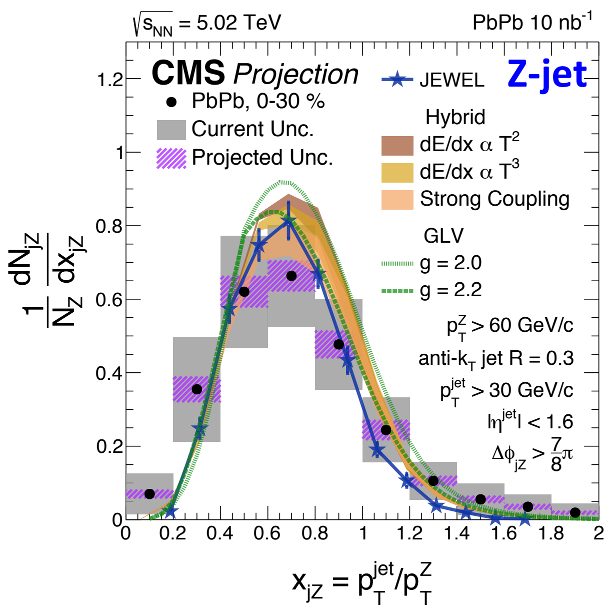


credits: B. Hippolyte

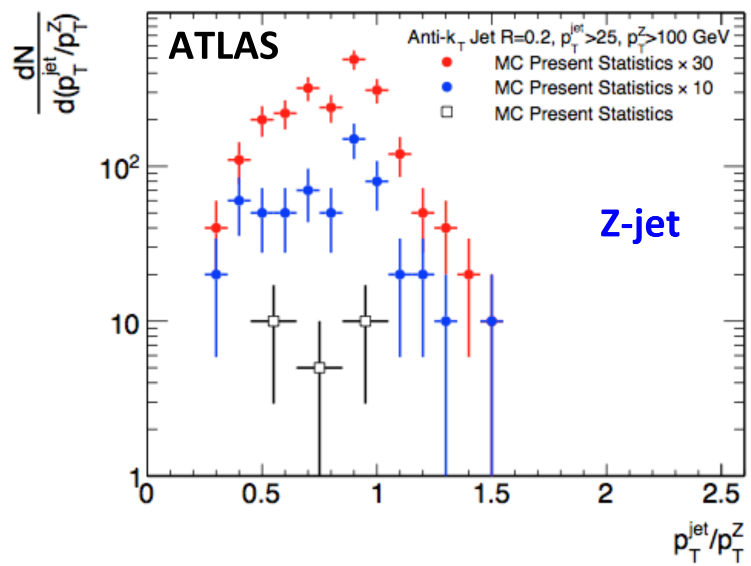
- **High precision γ-jet, Z-jet correlations ($E^{\gamma/Z} = E^{jet}$ before medium effects), di-jets, with dedicated b-jet triggering**
  - 10M di-jets with $p_{T,1}$ > 120 GeV/c (CMS, 10 nb^{-1})
  - 140k b-jets with p_T > 120 GeV/c (CMS, 10 nb^{-1})
- **Understand medium response and energy radiation details, map path-length dependence (radiative ~L^2, collisional ~L)**

CMS Proj. : CMS-PAS-FTR-17-002





p_T^Z > 100, p_T^{jet} > 25 GeV, Δφ > 7π/8



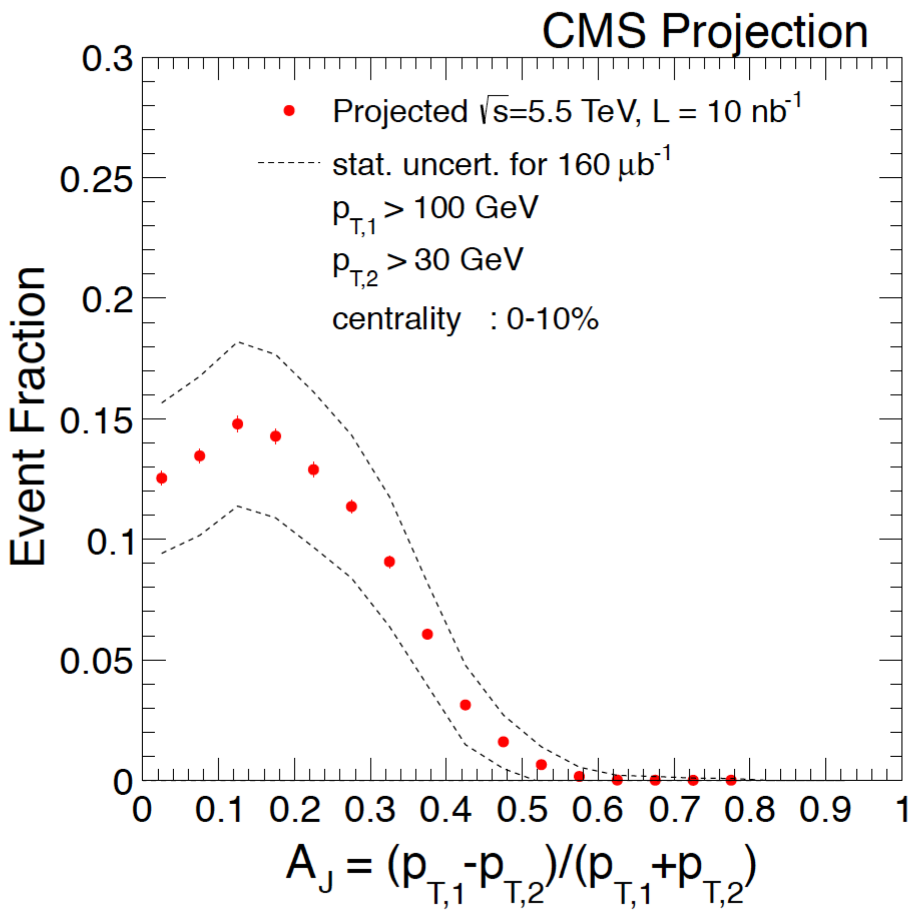
b-Jets (Quenching) in ATLAS and CMS

- **b-jets profit from efficient tagging algorithm**, thanks to the large decay length of the beauty hadrons

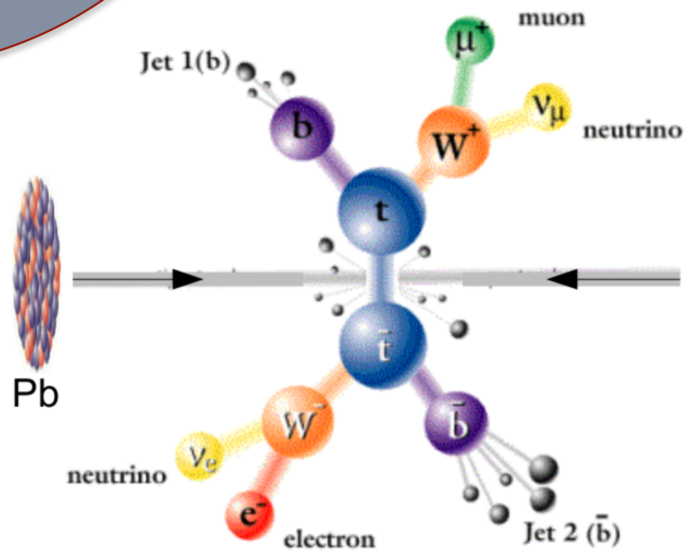
- Of the order of 140k b-jets with $p_T > 120$ GeV/c are expected with 10 nb^{-1} of Pb-Pb collisions at 5.5 TeV

- Experimental channels with the smallest systematic uncertainties:
  - **γ/Z-jet**
  - **Double b-jets**

Main observables: energy or p_T imbalance. Predictions from theory?



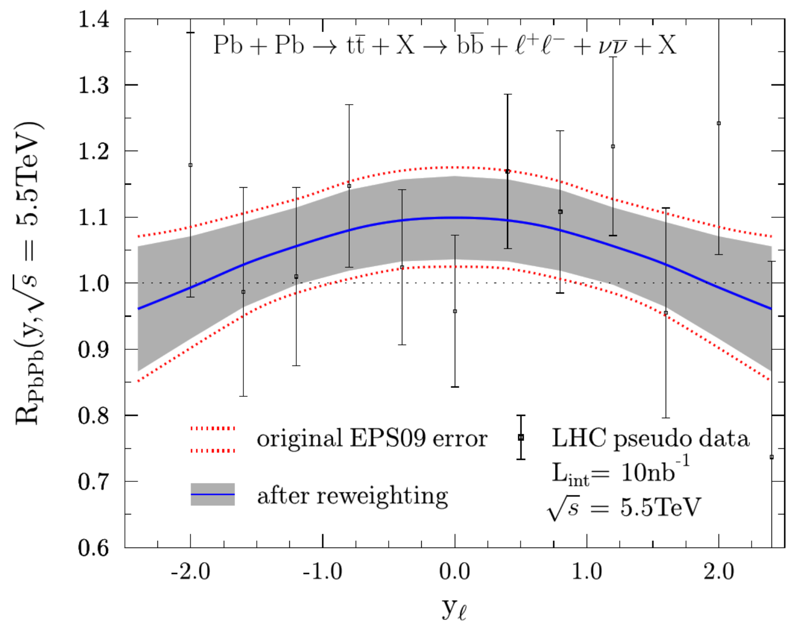
Double t-jets at the LHC?



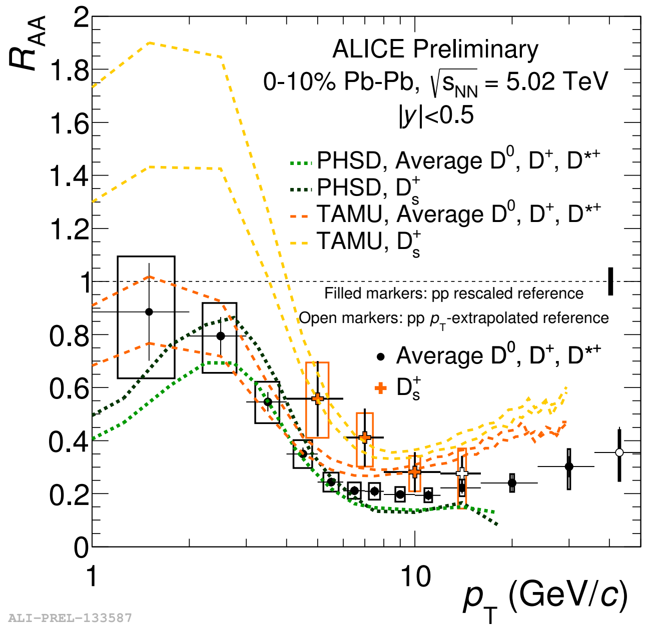
- Production of the top quark was never observed in heavy-ion collisions
- Due to the large mass, probe of the **nuclear Parton Distribution Functions** in an unexplored x region
- **Short decay time: decay happens typically before QGP formation…**

https://indico.cern.ch/event/698005/contributions/2906348/attachments/1611768/2559610/dde_ttbar_hl_lhc_ions_march18.pdf

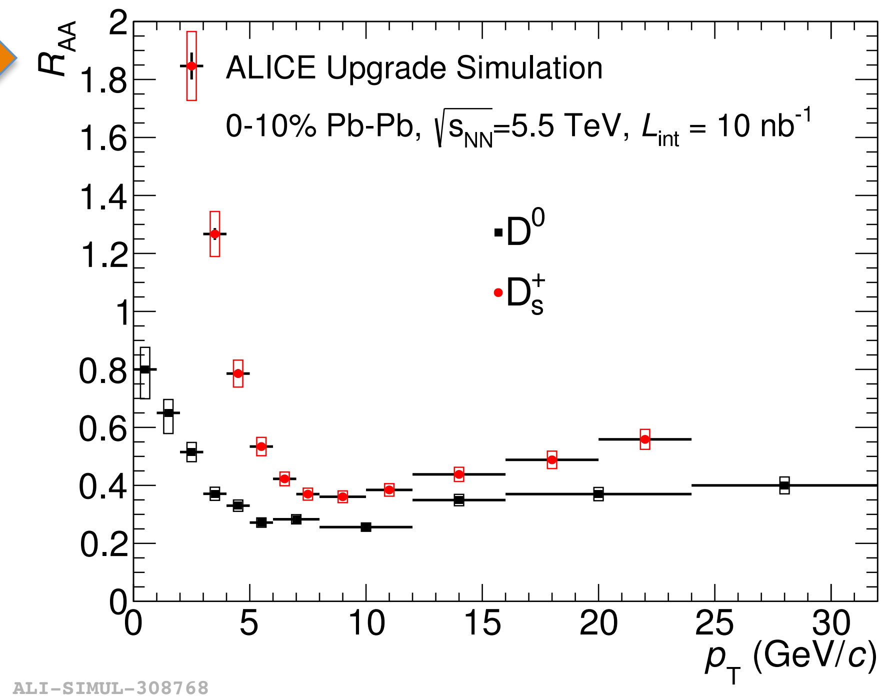
- … however, by selecting **high-momentum t pairs** one can select a sample of tt pairs spending a fraction of their lifetime inside the QGP: energy loss measurement could be afforded
- Nearly 35 000 tt pairs expected for 10 nb^{-1} Pb-Pb collisions at 5.5 TeV, with ≈ 450 reconstructed pairs in the l^+l^- + bb + MET channel



Charmed Mesons in ALICE



- **D^0: standard candle for charm measurements.** Total uncertainties with the new ITS below 10% down to zero p_T thanks to:
  - **Easier signal extraction** (background down by a factor 5-10)
  - **Precise prompt component isolation**

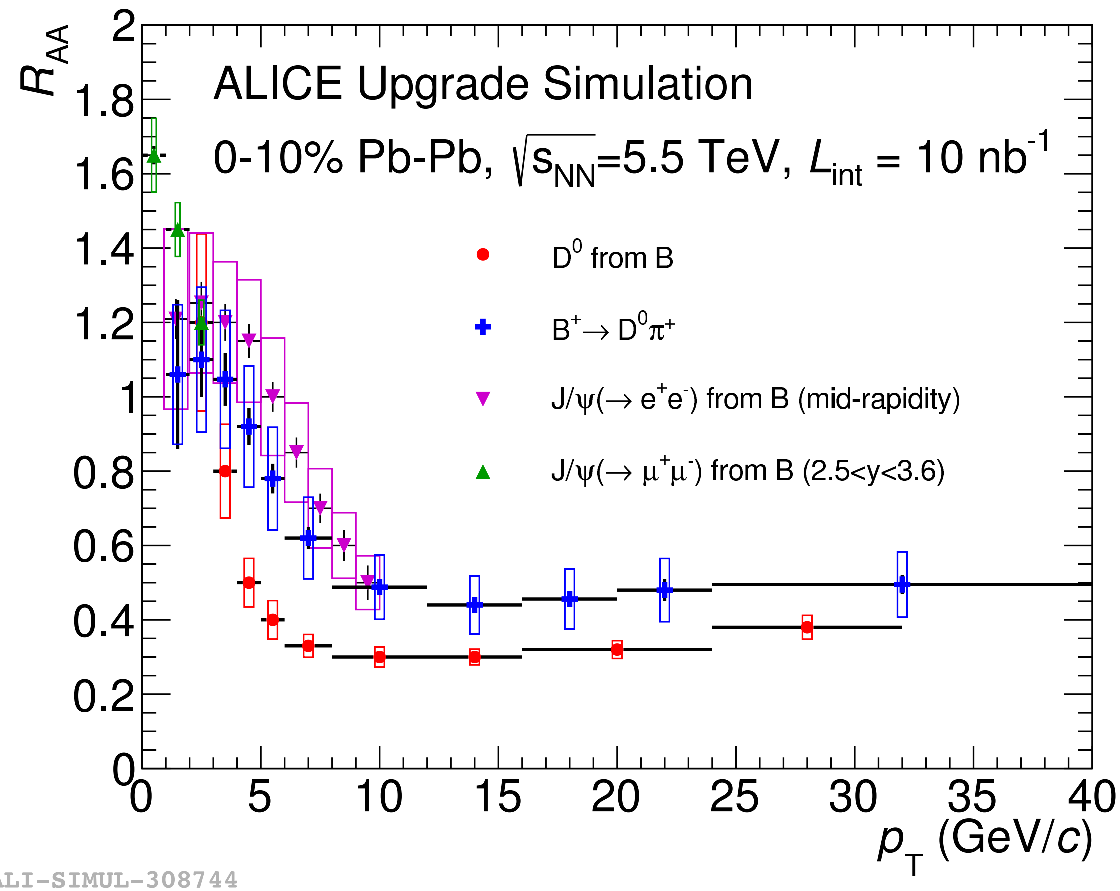


- **D_s also accessible down to low p_T:** comparison of different D mesons reveals the hadronization mechanisms of charm quarks in the QGP

ALICE upgrade performace:
CERN-LPCC-2018-07 arXiv:1812.06772 & ALICE-PUBLIC-2019-001

Beauty Measurements with ALICE

- **ALICE upgrade strategy foresees a combination of beauty measurements at mid- and forward-rapidity, down to vanishing p_T,** to better constrain theoretical models



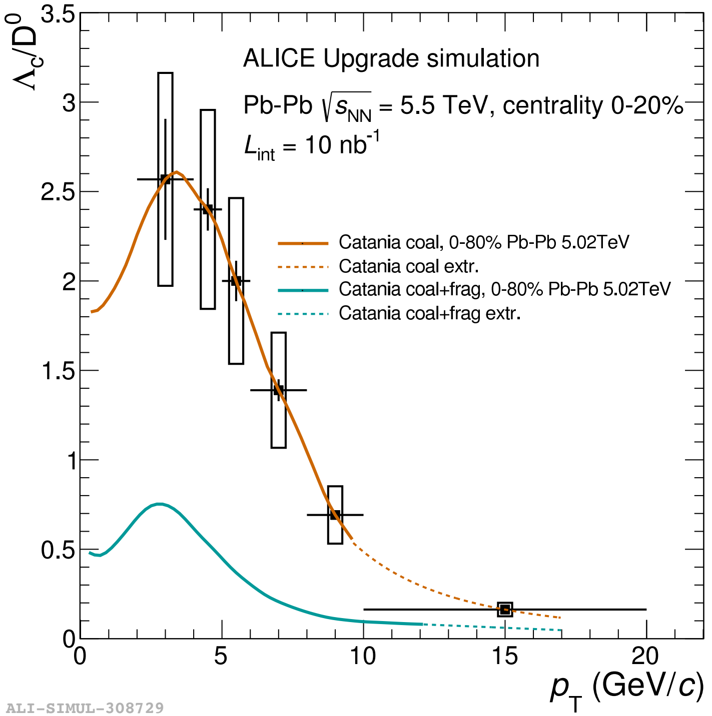
ALI-SIMUL-308744

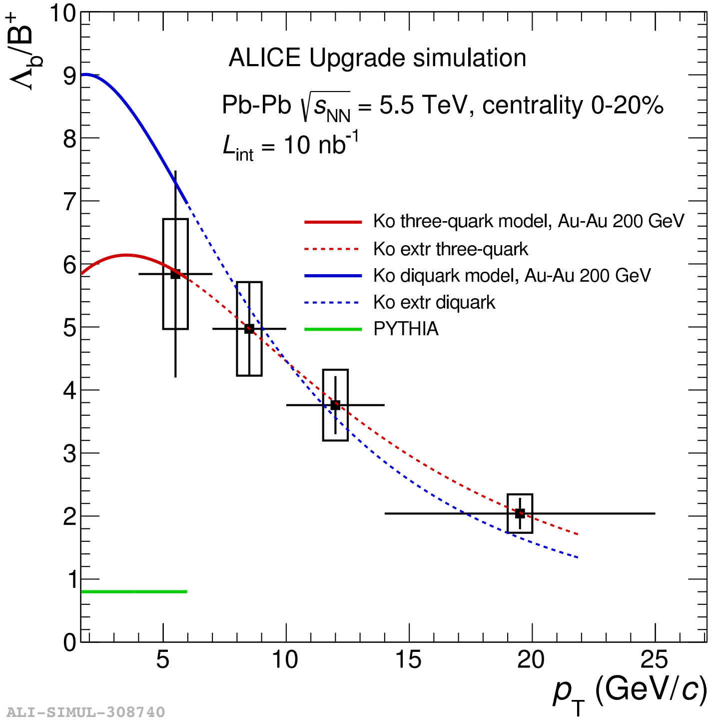
- Fully-reconstructed B mesons and displaced D^0 mesons at mid-rapidity
- Displaced J/ψ both at mid- and forward rapidity

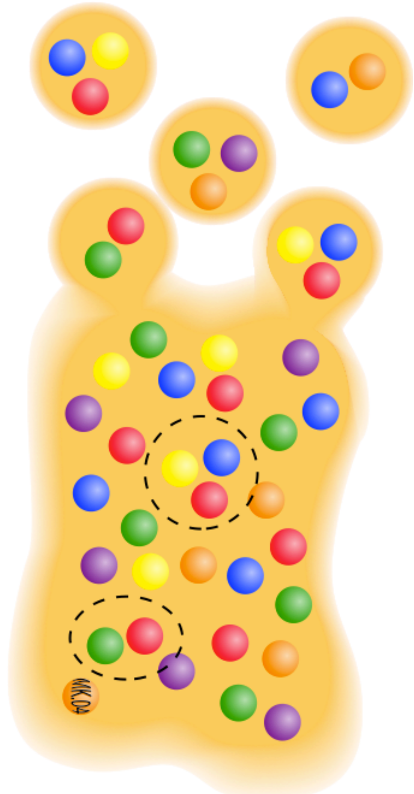
- **Goal:** transverse momentum, flavour and mass dependence of heavy-quark energy loss

Baryon/meson ratio for charm and beauty thanks to the cleaner vertex resolution for Λ_c and Λ_b baryons (Λ_c production measurable down to p_T = 2 GeV/c)

- Insight into the hadronization mechanisms of heavy quarks in the QGP





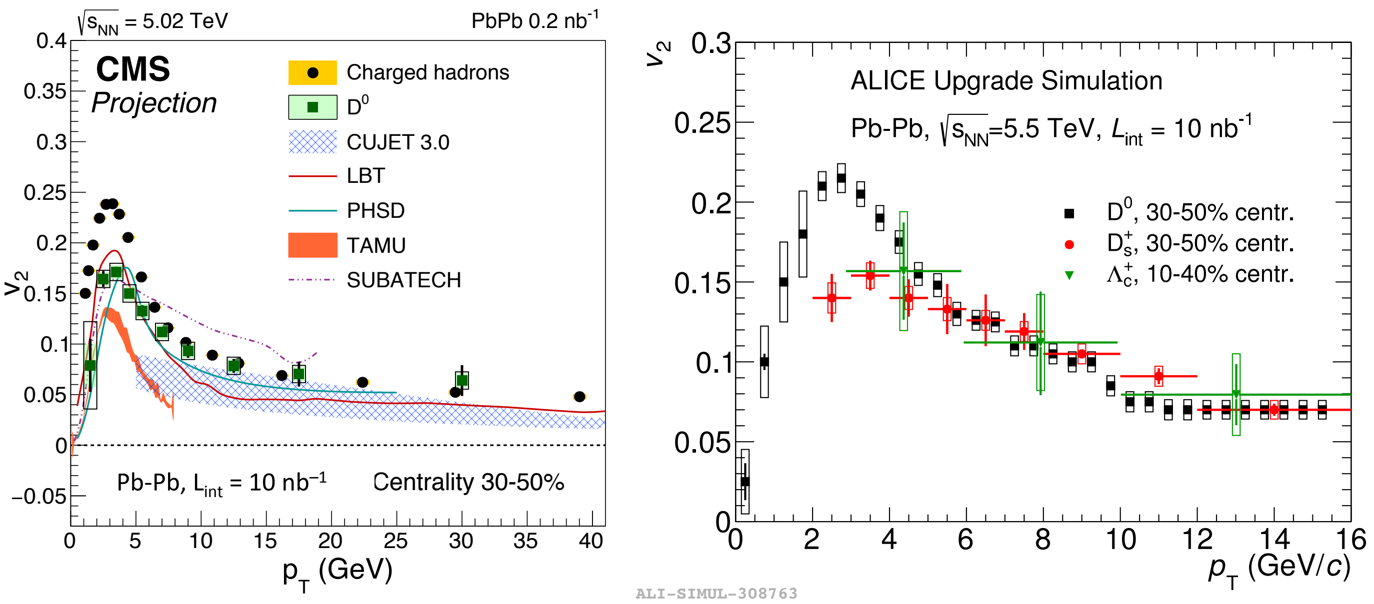


Elliptic Flow of Charm and Beauty

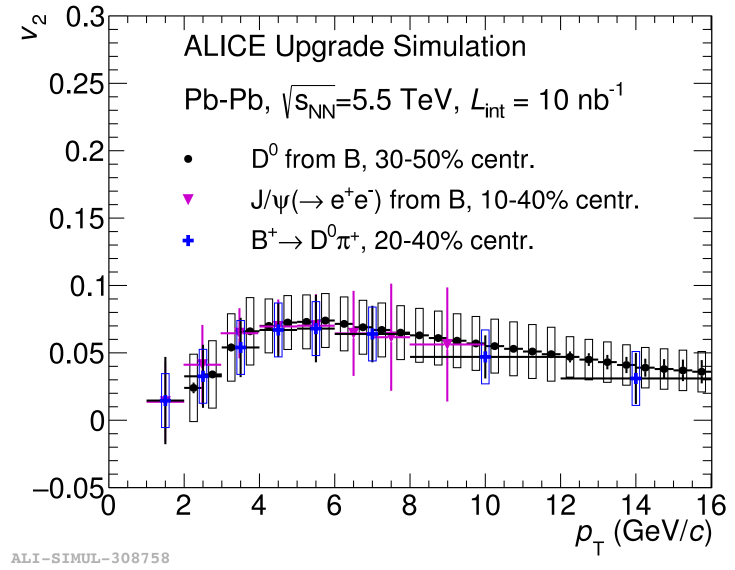
- **Heavy-quark v_2** gives insight into the interactions with the light quarks of the medium and the hadronization processes. The simultaneous description of R_{AA} and v_2 for heavy-flavor hadrons is still challenging for most of the theoretical models

- **Elliptic-flow measurement** will be addressed by ALICE both at mid- and forward-rapidity for both charm and beauty sectors. CMS will also perform precise measurements of the charm elliptic flow at mid-rapidity

charm



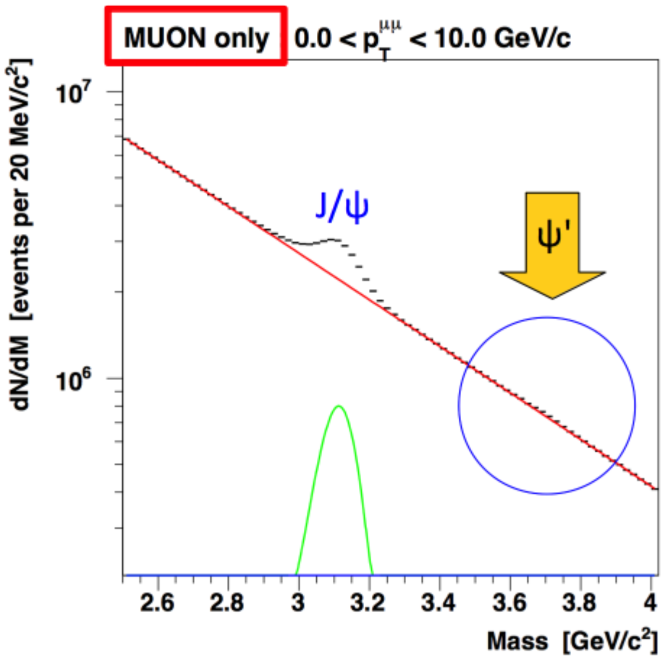
beauty

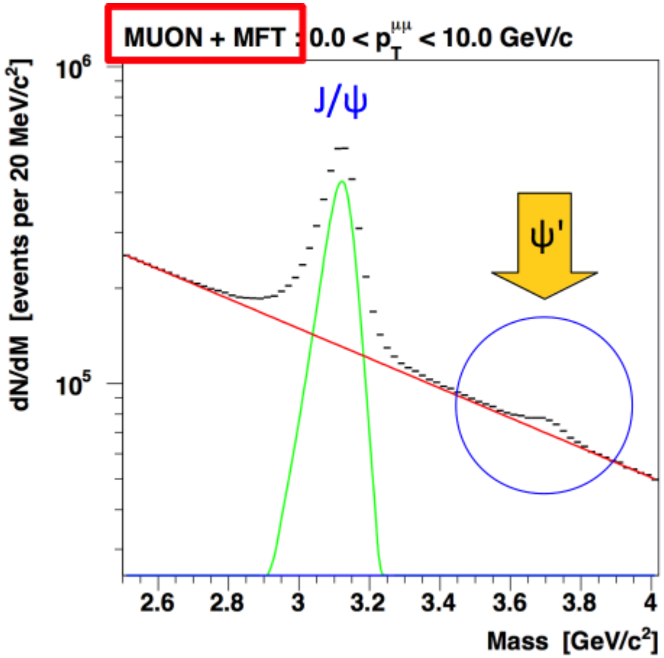


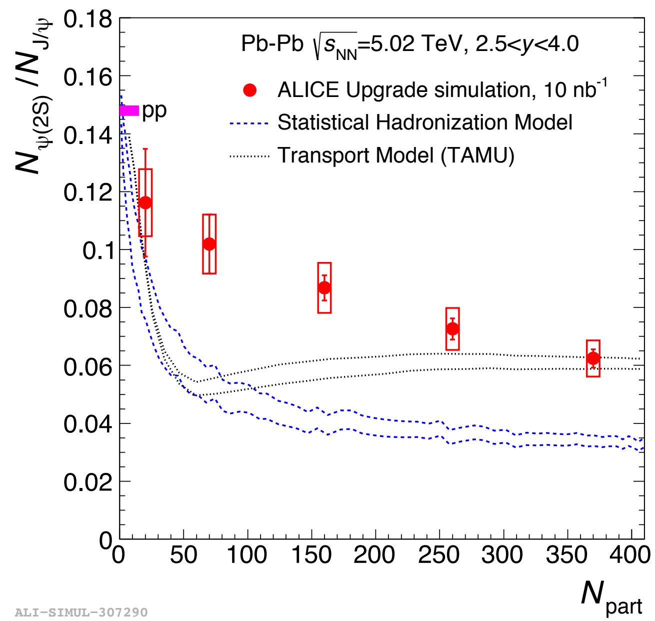
Improved Quarkonium Measurements in ALICE

Improved discrimination of prompt/displaced dileptons thanks to the upgraded ITS (central dielectrons) and MFT (forward dimuons)

- **Prompt J/ψ separation** achievable at forward rapidity
- Improved signal/background for **ψ(2S)**: test for charmonium production and recombination models at forward rapidity

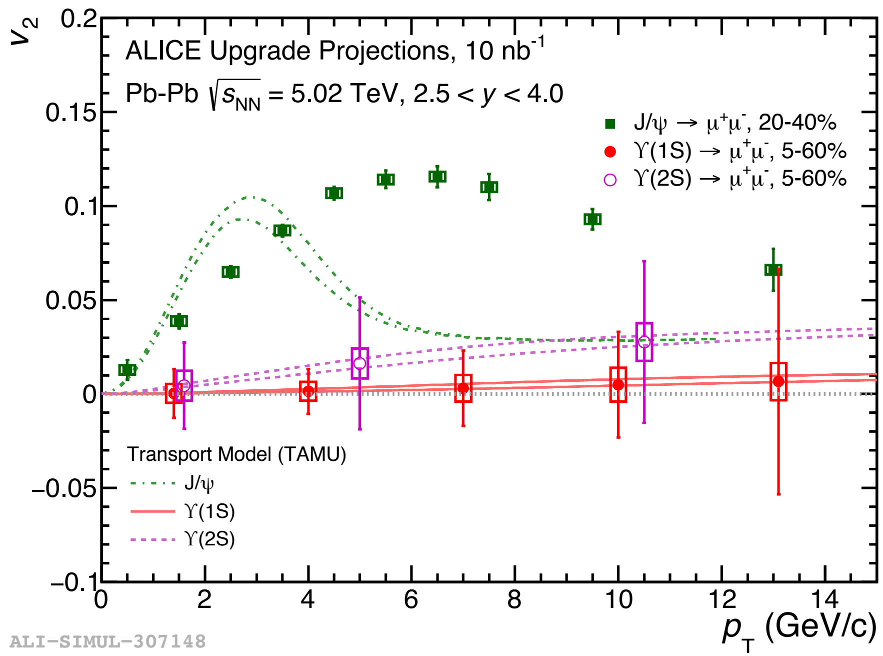


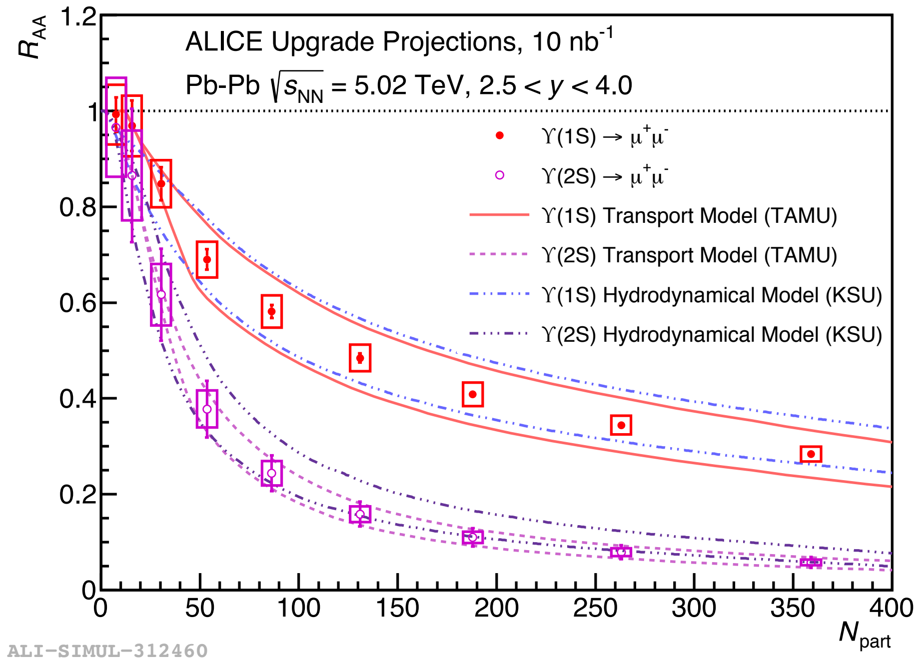




Improved discrimination of prompt/displaced dileptons thanks to the upgraded ITS (central dielectrons) and MFT (forward dimuons)

- Precise comparison of charmonium and bottomonium states: **mass/flavour dependence of heavy-quark flow**
- Precise centrality dependence of bottomonium R_{AA} at forward rapidity





Summary

- **Heavy-Ion physics in LHC Runs 3+4: fully exploit the potential of the machine as a high-luminosity Heavy-Ion collider**

- **Rich heavy-flavor physics program being prepared by the experiments**
  - Untriggerable probes (low-p_T) accessible by recording all events after online data volume reduction
  - Triggerable probes (high-p_T, jets) targeted with L1 and High-Level Triggers to reduce the rate of recorded events

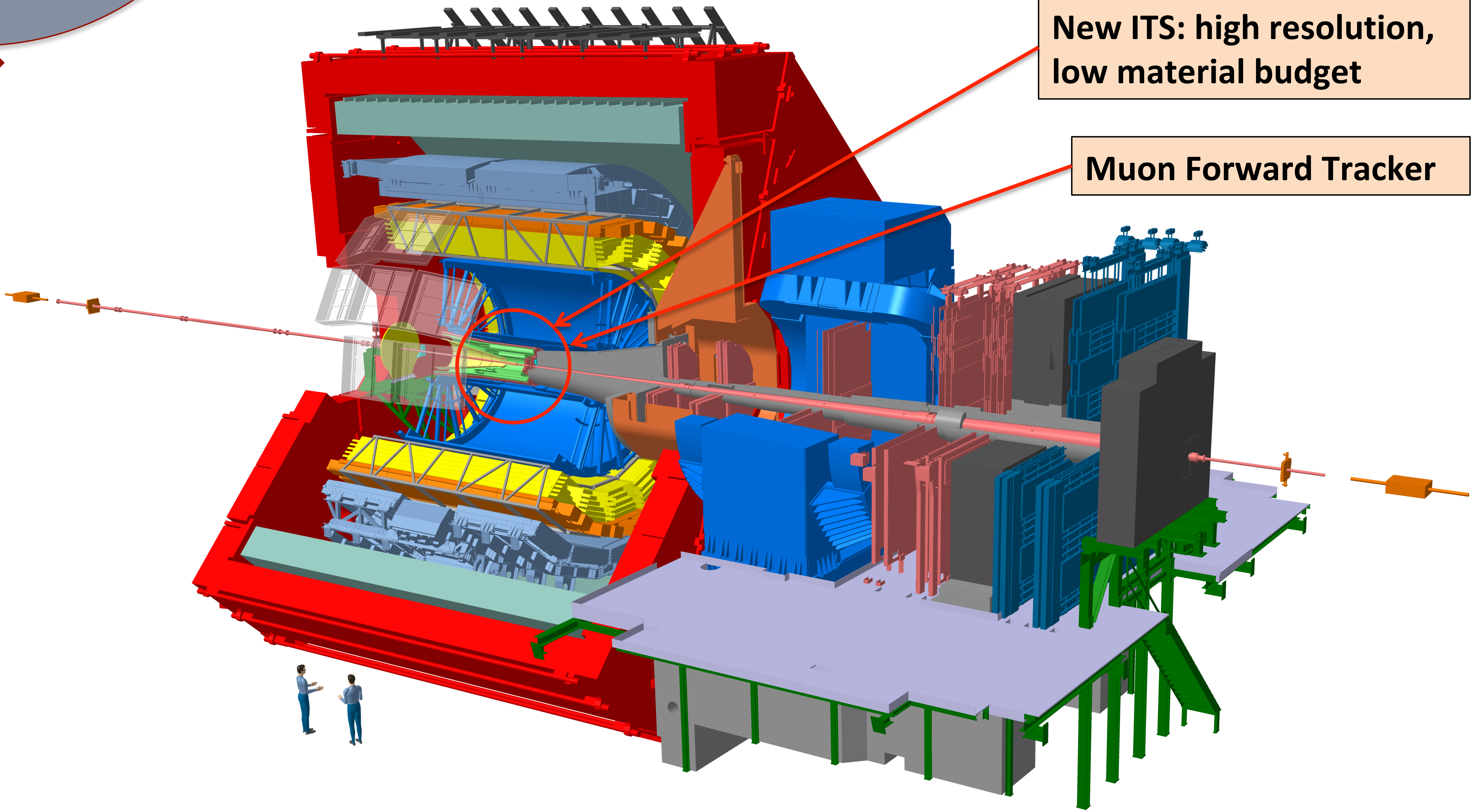
- **Mass-dependence of parton energy loss:** more precise measurements of R_{AA} for charm and beauty hadrons, down to vanishing p_T

- **Study of the (possibly thermal) coupling of heavy quarks with the bulk:** improved precision on the measurement of anisotropic flow

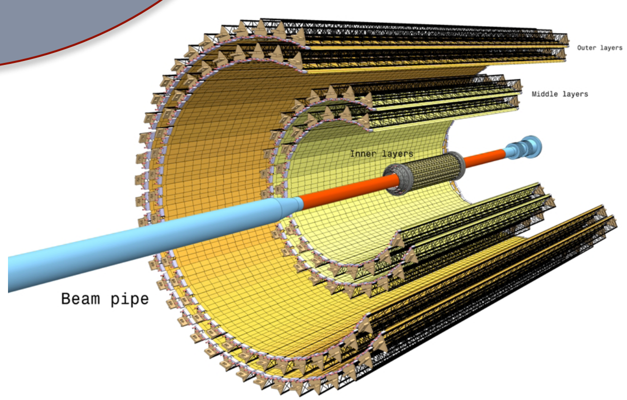
- **Hadronization, dissociation and recombination mechanisms** of heavy quarks in the medium: baryon/meson ratios, more differential quarkonium measurements

Backup Slides

ALICE Upgrade Strategy



ALICE Upgrade Strategy



New Inner Tracking System (ITS)

- New pixel technology: improved granularity and resolution, reduced material budget

New Forward Muon Tracker (MFT)

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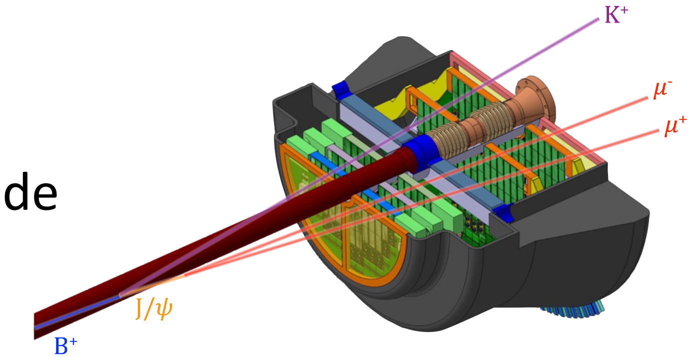
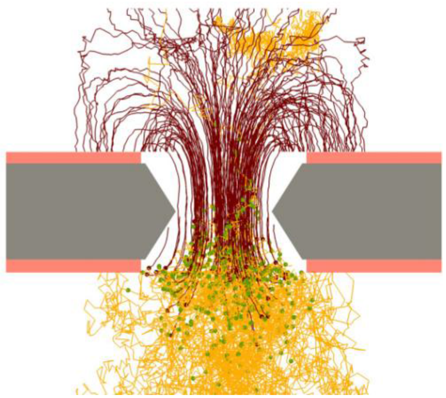


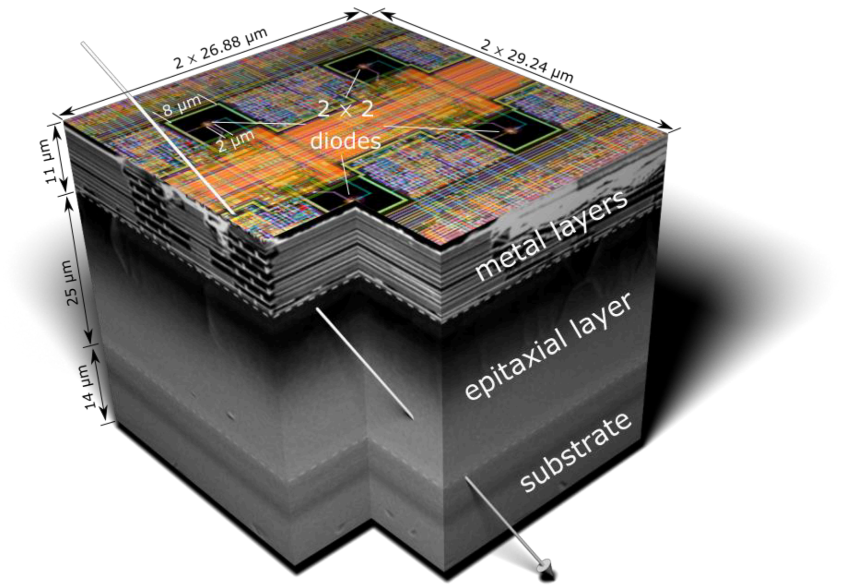


Upgraded read-out for many detectors, new integrated Online-Offline (O^2), new Fast Interaction Trigger detector

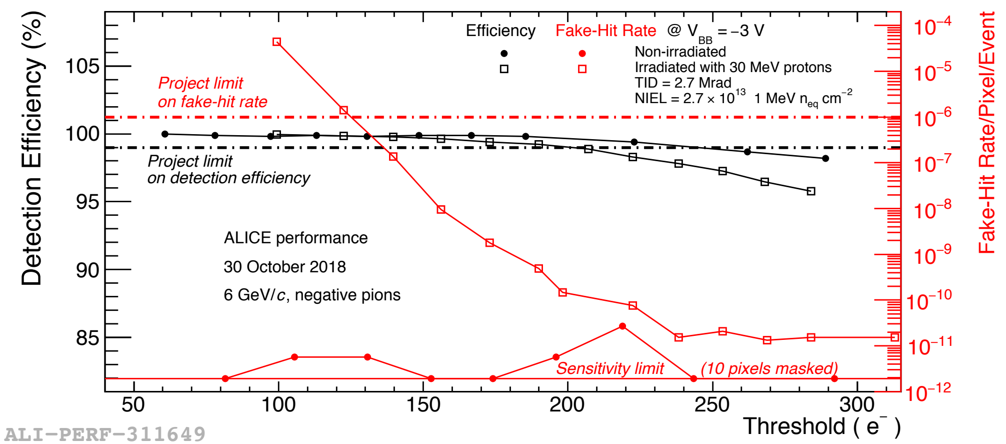
- Upgraded ALICE will record Pb-Pb data at 50 kHz (1 kHz in Run 2)

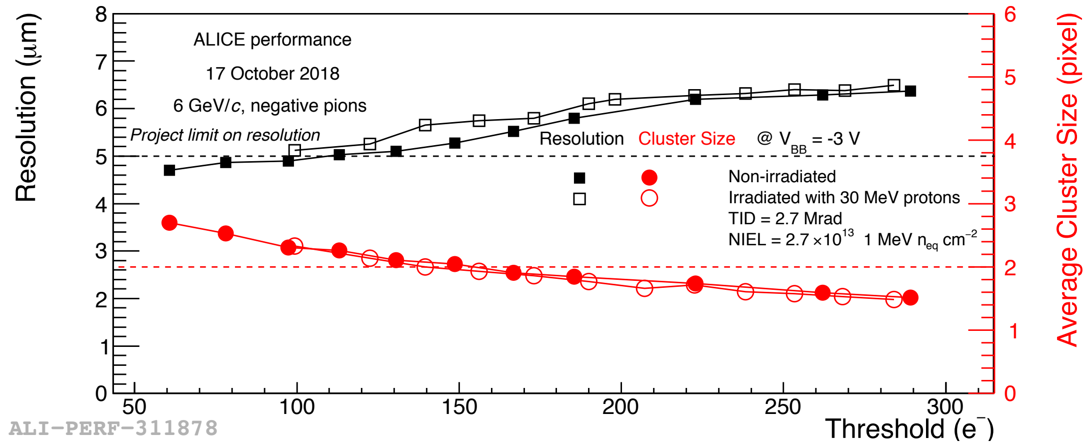
ALICE Upgrade Strategy: the ALPIDE Chip

CMOS Monolithic Active Sensors (MAPS), TowerJazz 0.18 µm technology

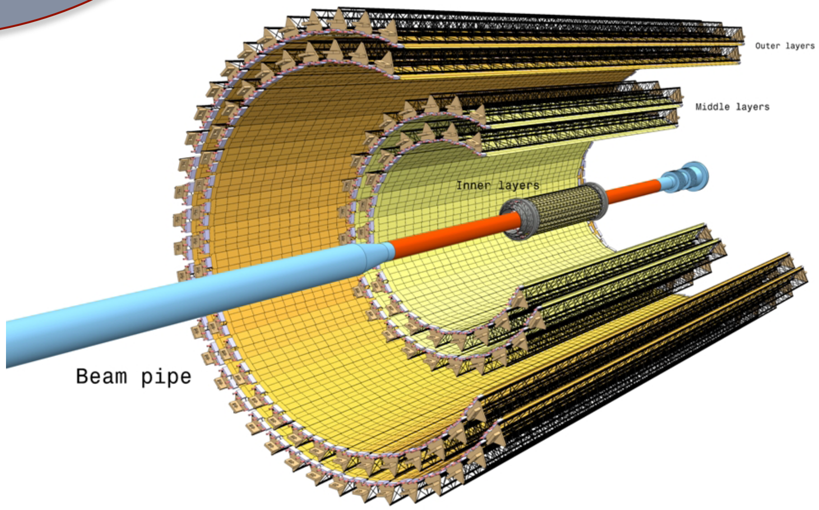


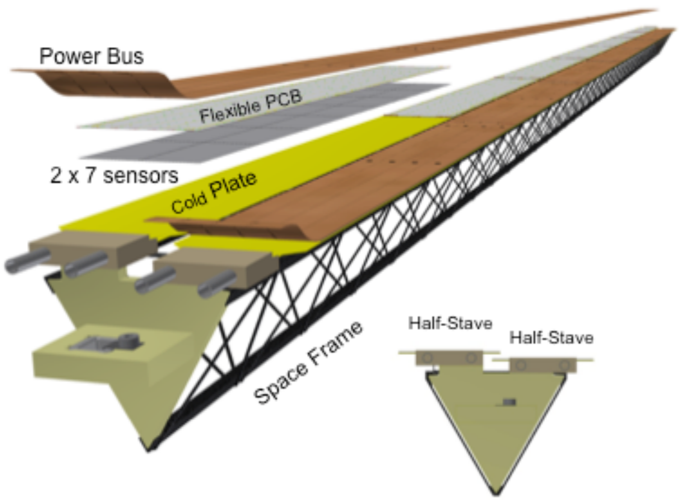
- **Sensor size:** 15 mm x 30 mm
- **Pixel size:** 29 µm x 27 µm
- **Detection efficiency:** > 99%
- **Event time resolution:** < 4 µs
- **Space resolution:** 5 µm
- **Power consumption:** ≈ 40 mW/cm^2
- **Radiation dose (Run3+Run4):** < 300 krad, < 2.0×10^{12} 1MeV n_{eq}/cm^2





ALICE Upgrade Strategy: ITS Upgrade

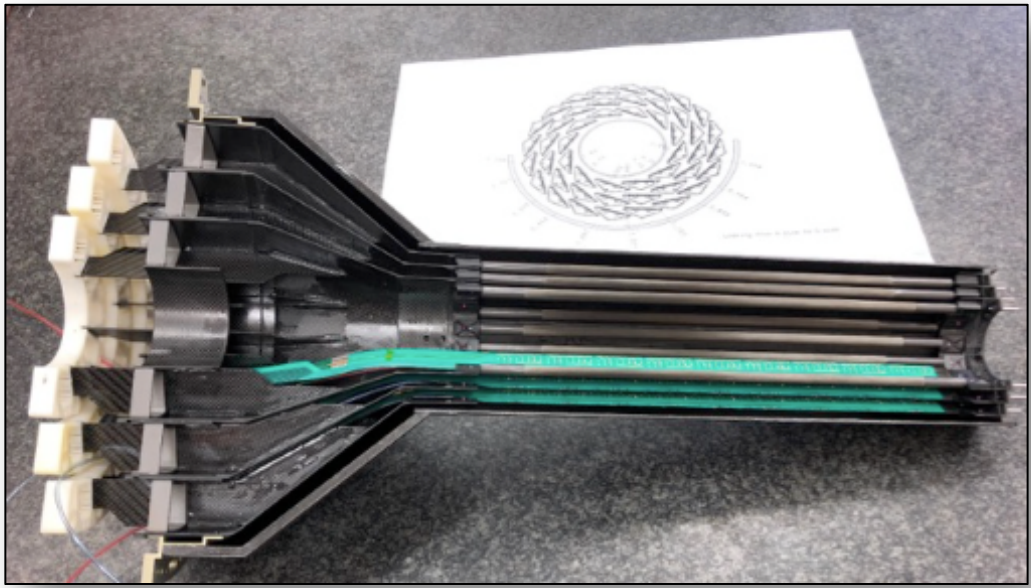


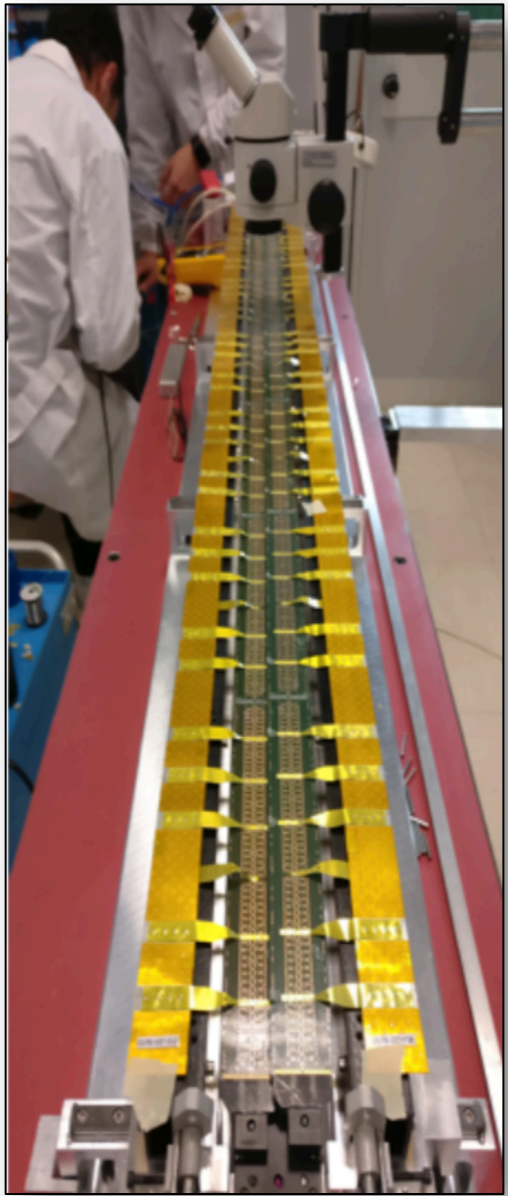


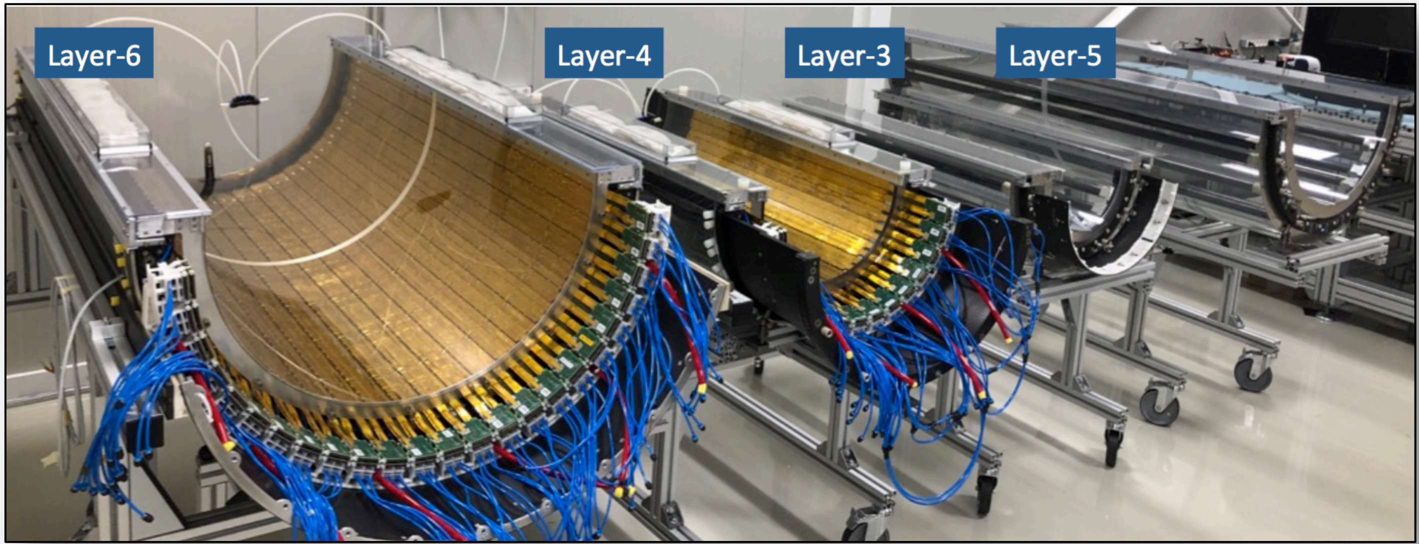
Main goal: improving tracking performance, namely at low p_T

- Large area (10 m²) silicon pixel (MAPS) sensor tracker ($|\eta| < 1.22$)
- 24'000 pixel chips, 12.5 Gigapixels (binary readout)
- 7 layers from R = 22 mm to R = 400 mm: Inner Barrel, Outer Barrel (Middle layer & Outer layer)
- Spatial resolution *o*(5 µm).
- First layer closer to IP (smaller beam pipe radius)
- 0.3% X_0 per layer in the inner most 3 layers (light mechanical structure)

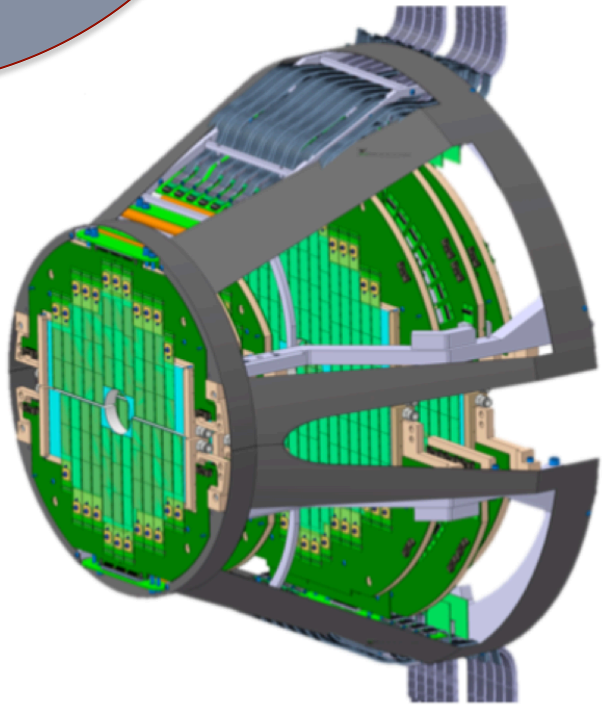
ALICE Upgrade Strategy: ITS Upgrade



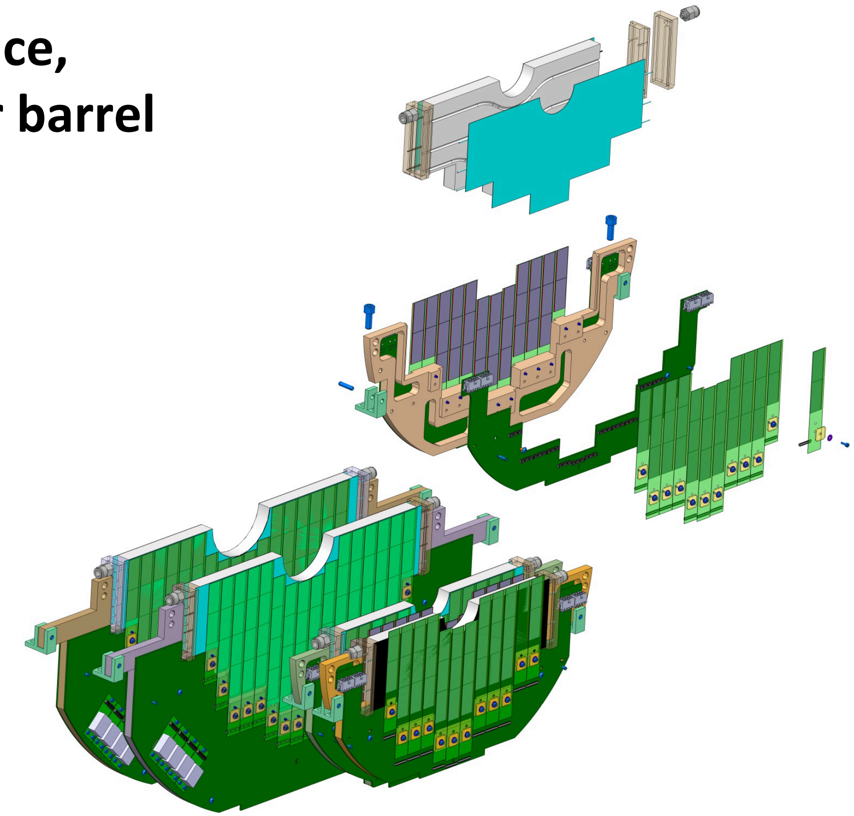




ALICE Upgrade Strategy: MFT Upgrade

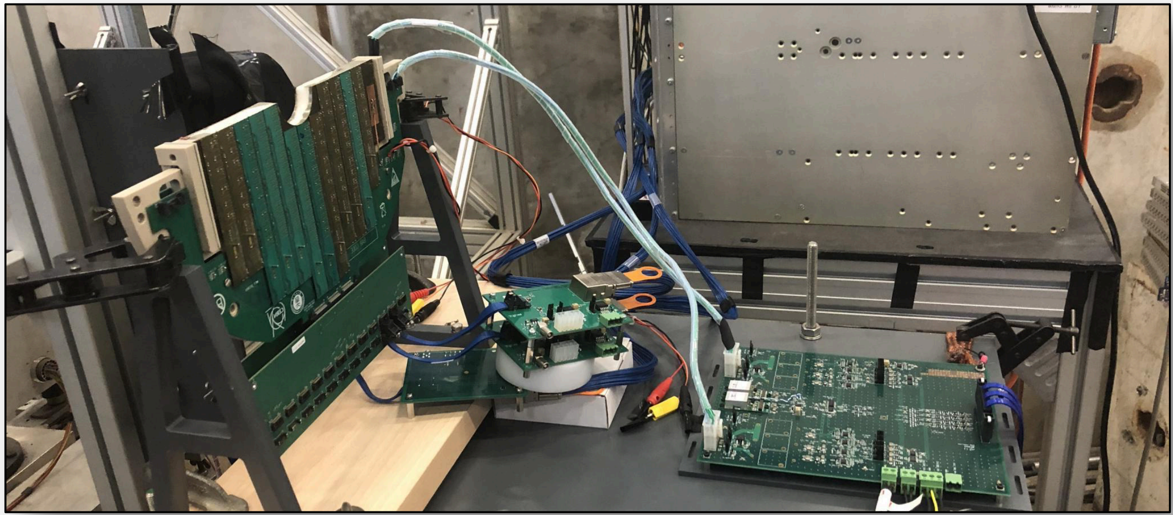


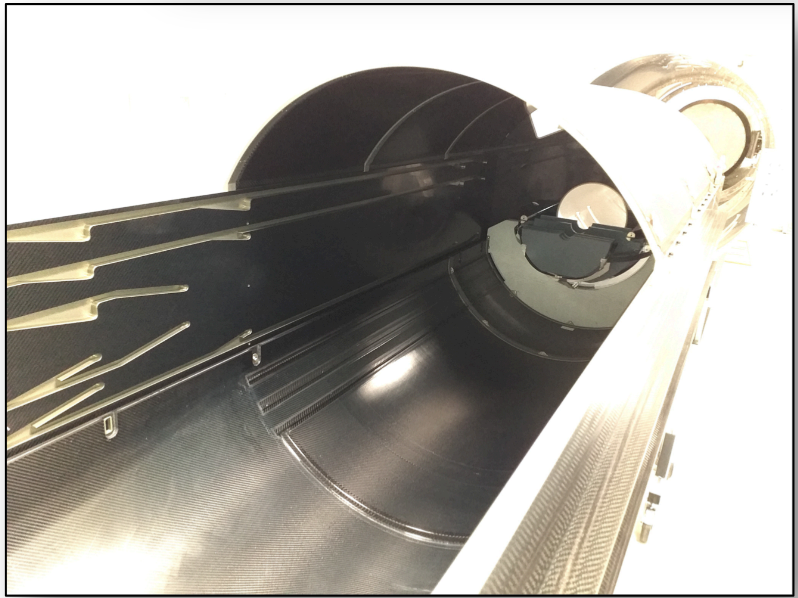
- **920 silicon pixel sensors (0.4 m^2)** in 280 ladders of 2 to 5 sensors each
- **10 half-disks, 0.7% x/X_0 and 2 detection planes each**
- **5% of the ITS surface, twice the ITS inner barrel**



- **Nominal acceptance:**
  - $2.5 < \eta < 3.6$
  - Full azimuth
- **Inner radius limited by the beam pipe**. Combined MFT+MUON acceptance will be 0.4 unity of rapidity smaller than current MUON one

ALICE Upgrade Strategy: MFT Upgrade





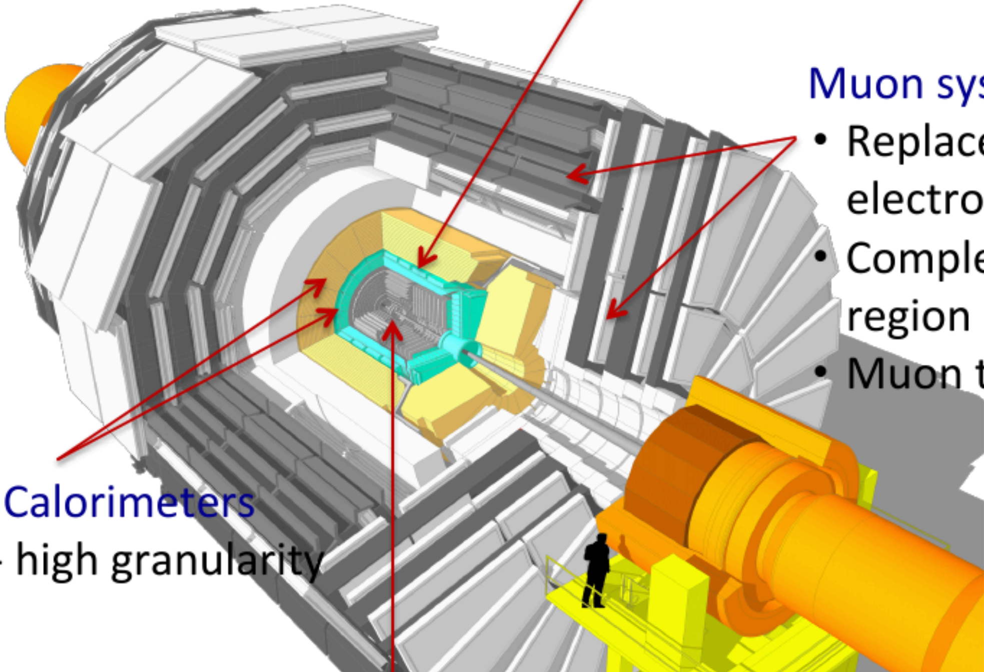
CMS Upgrades Relevant for Heavy-Ions

Installation during LHC LS3 (2024-26)

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘)

Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

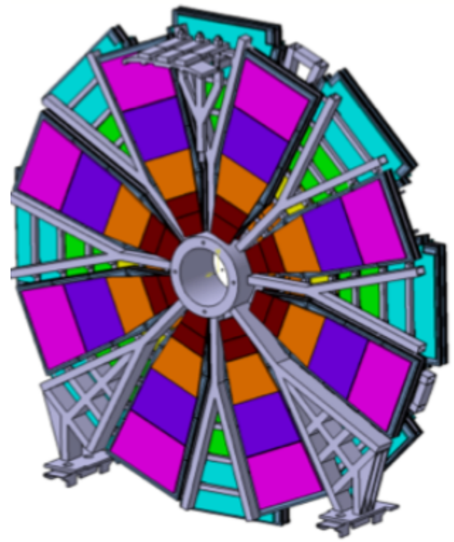
Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout ($P_t \geq 2$ GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

ATLAS Upgrades Relevant for Heavy-Ions

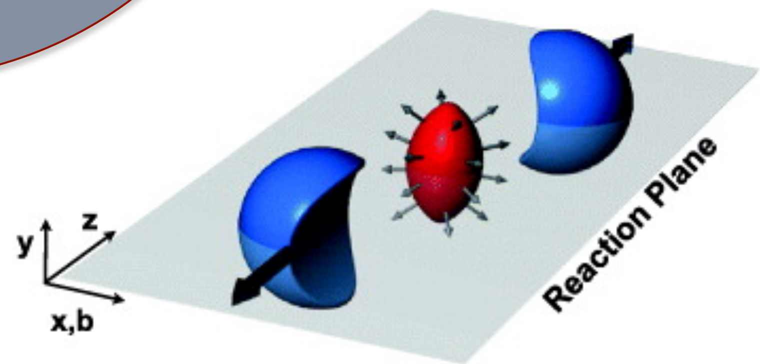
- **ATLAS detector Phase 1 Upgrade (before Run 3)**
  - Level-I trigger based on hardware track reconstruction and fitting: extra resources will be available in L2 trigger for more advanced selection algorithms (b-tagging, lepton identification…)
  - Calorimeter electronics upgrades: improved segmentation
  - New forward muon detectors with better performance at high occupancy

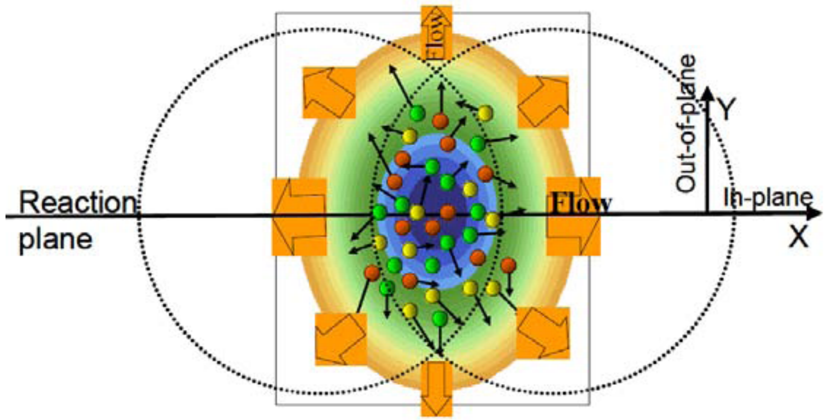
- **ATLAS detector Phase 2 Upgrade (before Run 4)**
  - Complete replacement of the ATLAS inner detector with silicon pixel and strip detector with substantially reduced material budget

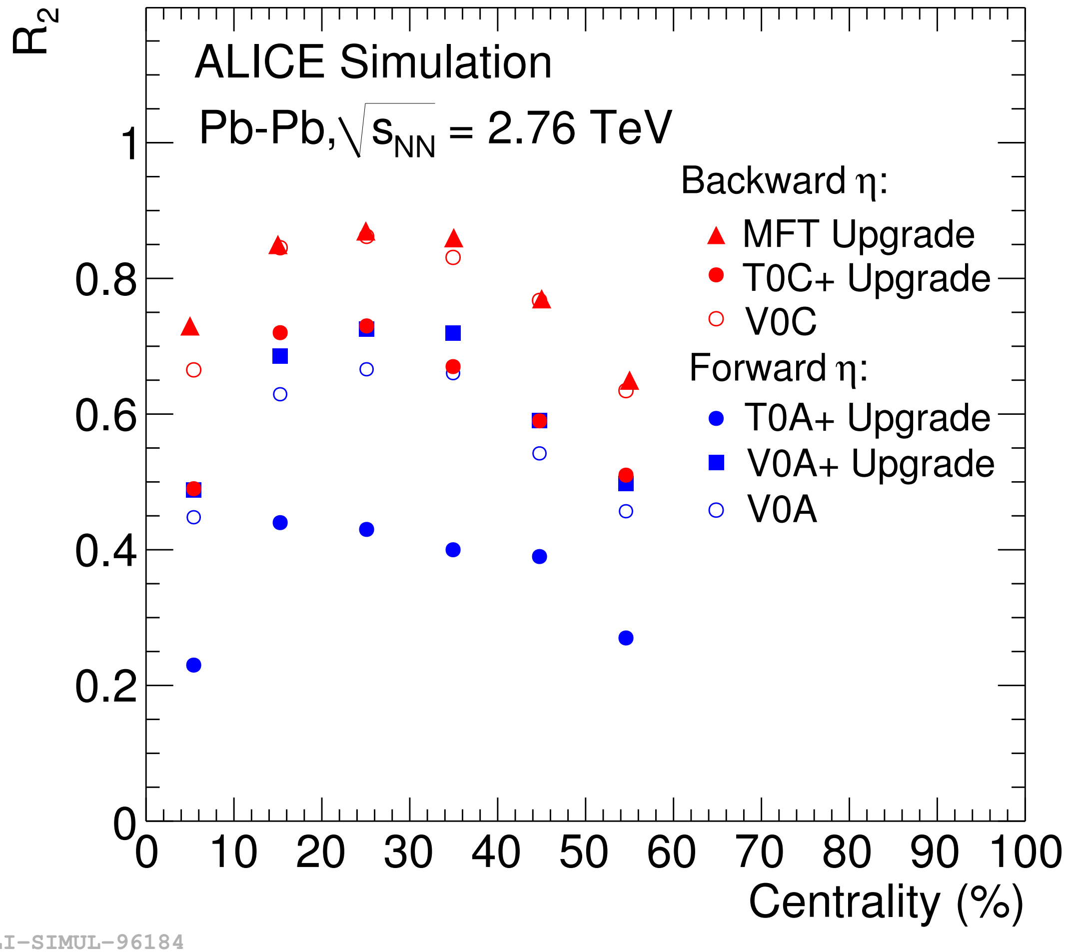
- **Main benefits:**
  - Better pattern recognition in Pb-Pb (reduced multiple scattering, rates for photon conversion and electron bremsstrahlung)
  - Improved mass resolution for the Υ states
  - Improved background rejection for γ/Z-jet events



Reaction Plane Measurement







- **Excellent reaction plane resolution**, thanks to the high-granularity and the possibility to perform a standalone tracking (excluding contaminations from noisy clusters)

Low-Mass Drell-Yan Measurement

Low-mass (< 10 GeV/c^2) Drell-Yan lepton-pair production at forward rapidity: important source of information on the partonic structure of protons

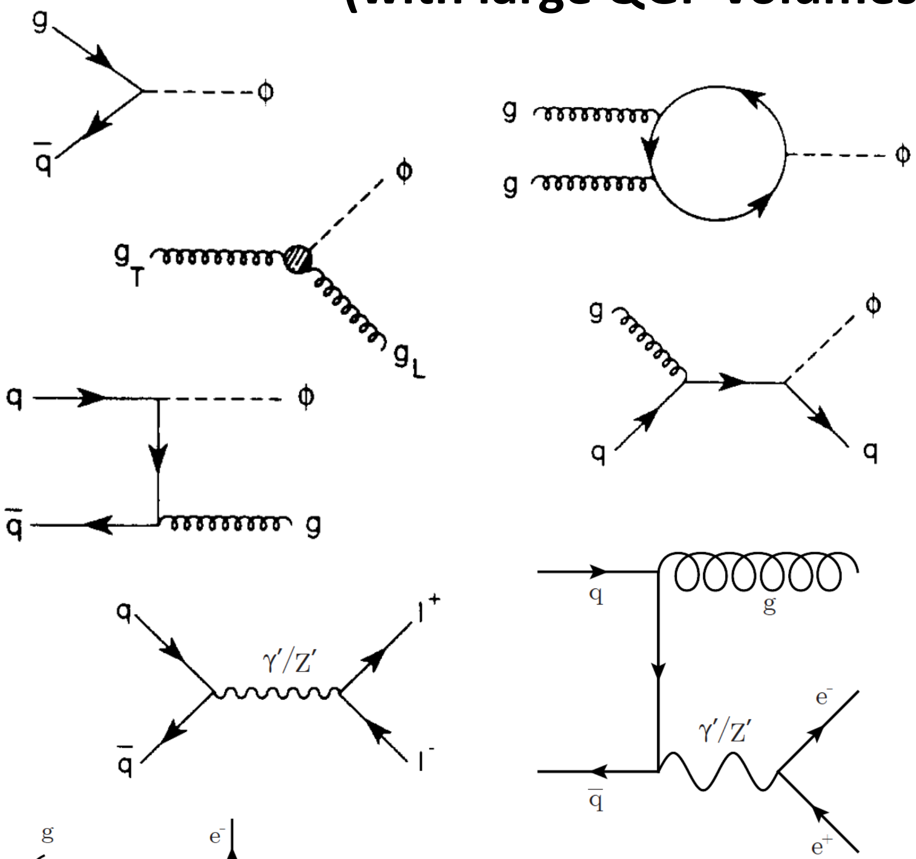
- Constraints on the gluon distribution and its nuclear dependence through the transverse momentum distributions
- Information about the onset of (gluon) saturation at small-x

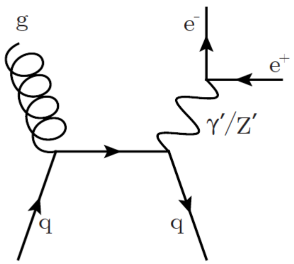
Drell-Yan: main source of prompt dimuons between J/ψ and ϒ at the LHC

- Easily identifiable with a mass-offset combined fit on MFT-matched dimuons
- Due to the relatively large mass, a strong single-μ p_T cut (p_T > 2 GeV/c) can be imposed to improve the quality of the sample

Light BSM Bosons from QGP: a Case for HL-LHC?

Light scalar or vector BSM bosons could be observed in **high-energy (with large QGP volumes produced), high-luminosity nuclear collisions**





J. Ellis & P. Salati, Nuclear Physics B342 (1990)
J. Davis & C. Böhm, arXiv:1306.3653

- **Resonance in the thermal dilepton production from the QGP** for masses up to 3 GeV/c^2: dilepton measurements in ALICE could set limits on quark- and lepton-couplings of light BSM bosons

- **Heavier bosons** would mainly decay into multiparticle states involving cc and ττ pairs, and are **no longer detectable in the ee or μμ channels**

- **ALICE: feasibility studies on dark photons of mass < 100 MeV/c^2**

  http://www.ge.infn.it/~ldma2015/presentations/wednesday-morning/05_gunji.pdf