LHCP 2016
13-18 June
Lund, Sweden

Antonio Uras – IPN Lyon (France)

for the ALICE, ATLAS, CMS
and LHCb Collaborations

Heavy Ions at HL-LHC

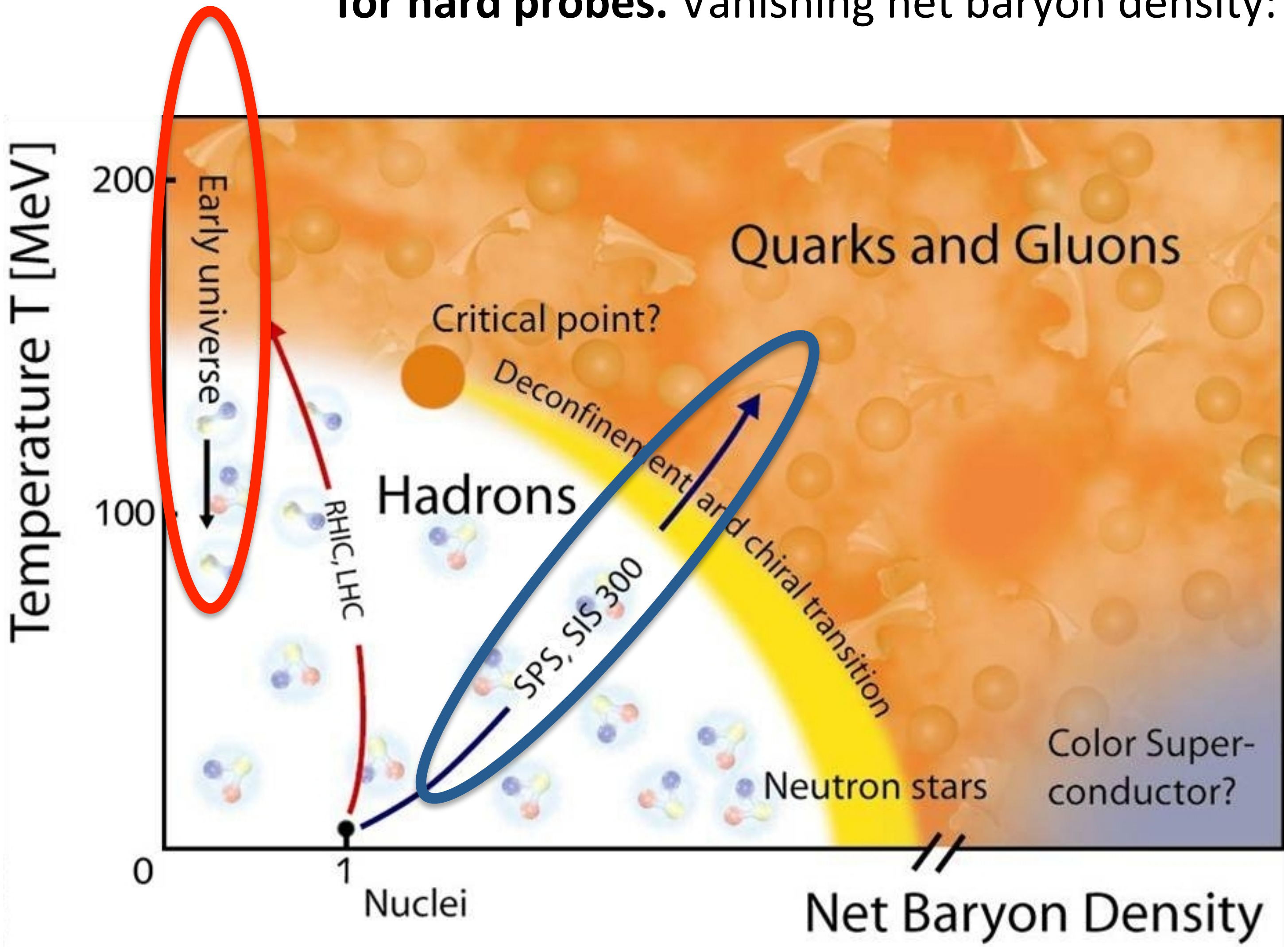
Thanks to: J. Jowett (LHC), J. Jia & A. Trzupek (ATLAS), A. Dainese (ALICE), M. Nguyen & Y-J. Lee (CMS), G. Manca & L. Massacrier (LHCb)

Outline

- LHC Luminosity evolution and Heavy-Ion running timeline
- Heavy ion physics program at HL-LHC
- Experiment upgrades and strategies
- A selection of performance studies

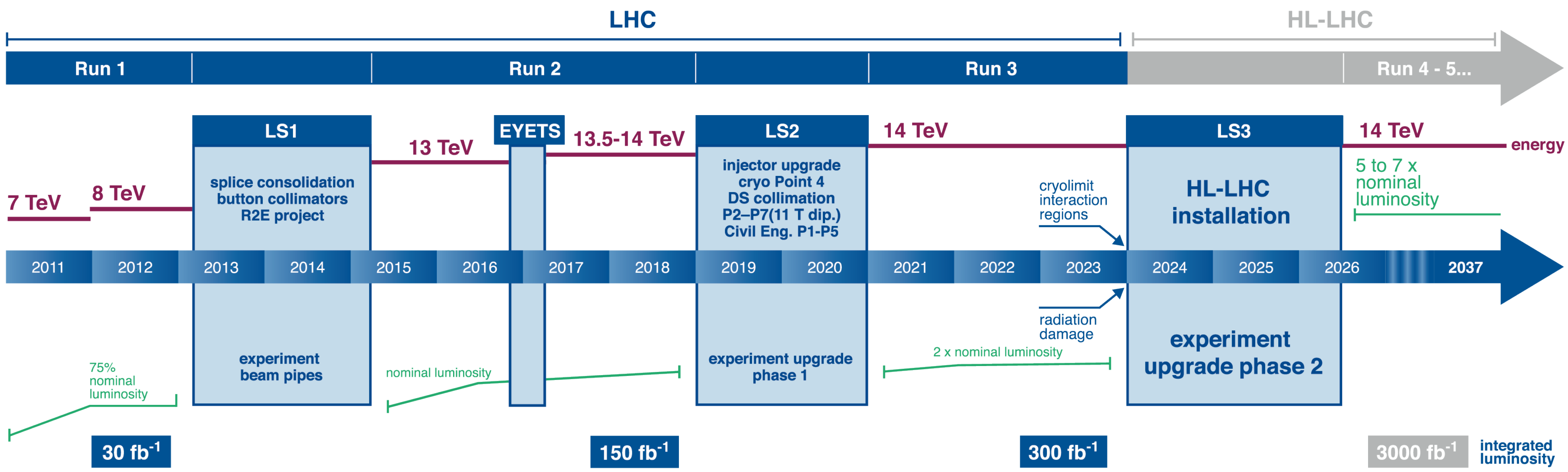
Heavy-Ion Physics: Why at the LHC?

❖ **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

LHC/HL-LHC Plan [https://hilumilhc.web.cern.ch/about/hl-lhc-project]



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

- LHC collimator upgrades: target L ≈ 6×10^{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

Heavy-Ion Running Conditions at the LHC

Heavy-Ions in LHC Run 2 (2015): [J.M. Jowett, M. Schaumann – IPAC2016, Busan, Korea]

- Pb-Pb collisions at 5.02 TeV per nucleon pair (c.m. energy of the 2013 p-Pb run)
- 18 days of operation for physics, design luminosity surpassed by a factor of 3.6
- Integrated luminosity of up to 0.7 nb^{-1} per experiment
- Specific bunch patterns providing Pb-Pb collisions in LHCb, for the first time

Heavy-Ions in LHC Runs 3+4 (2021 ➔):

- Experiments request for Pb-Pb: $L_{int} > 10\ nb^{-1}$ (ALICE LoI: 10 nb^{-1} with nominal solenoidal field + 3 nb^{-1} with reduced solenoidal field)
  - ×100 larger min. bias sample for ALICE w.r.t. Run 2
  - ×10 larger rare trigger sample for ATLAS/CMS w.r.t. Run 2
- pp reference, p-A. Investigating feasibility for lighter nuclei collisions

Heavy-Ion Physics at the HL-HI-LHC (I)

- **Jets: characterization of the energy loss mechanism, both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density**
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (main focus of ATLAS and CMS)
  - Flavor-dependent in-medium fragmentation functions (main focus of ALICE)

- **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)
  - LHCb: performance under investigation

Heavy-Ion Physics at the HL-HI-LHC (II)

- **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 under investigation

- **Prompt dilepton production: (i) thermal radiation** to map temperature during system evolution; **(ii) modification of ρ meson spectral function** as a probe of the chiral symmetry restoration; **(iii) analysis of the continuum** to study low-mass Drell-Yan production and put limits on low-mass dark γ'/Z' boson production
  - Improved background rejection for prompt dielectrons and dimuons down to low-p_T (ALICE)

ALICE Upgrade Strategy (I)

- **Detector specificities (strengthened with the upgrades):**
  - Hadron and lepton identification
  - Light-weight and precise trackers
  - Low magnetic field

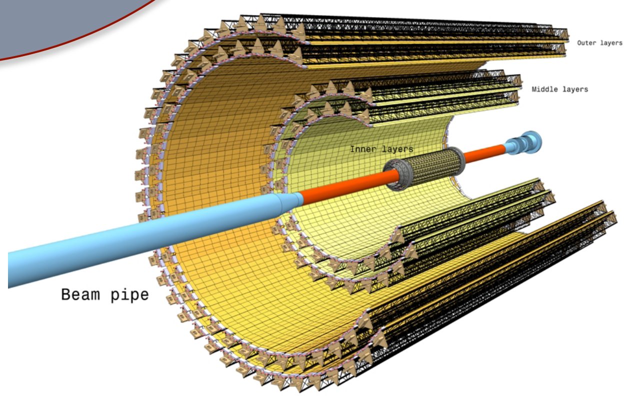
Talk by P. Antonioli
Saturday 8:30

- **Main observables…**
  - Low-p_T Heavy Flavors
  - Low-p_T Charmonium
  - Prompt dileptons down to low-mass and low-p_T

ALICE Upgrade LOI + addendum: CERN-LHCC-2012-012, CERN-LHCC-2013-014
ALICE TPC Upgrade TDR: CERN-LHCC-2013-020
ALICE ITS Upgrade TDR: CERN-LHCC-2013-024
ALICE MFT TDR: CERN-LHCC-2015-001
ALICE Online-Offline Upgrade TDR: CERN-LHCC-2015-006

- **… are based on "untriggerable" signals!**
  - Record all events at up to 50 kHz in Pb-Pb (currently 0.5 kHz): strong data reduction needed (from 1 TB/s to 50 GB/s via online reconstruction)
  - HL-HI-LHC: increase of minimum-bias sample ×100 w.r.t. Run 2

ALICE Upgrade Strategy (II)



New Inner Tracking System (ITS)

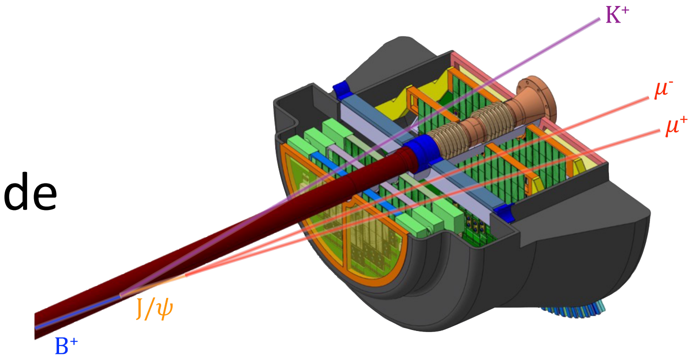
- New pixel technology: improved granularity and resolution, reduced material budget

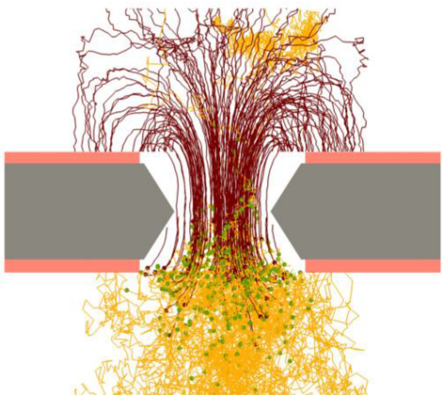
New Forward Muon Tracker (MFT)

- Vertex tracker for the forward muon spectrometer: heavy flavor vertices, prompt/displaced muon discrimination

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 (O^2), new Fast Interaction Trigger detector

- Upgraded ALICE records Pb-Pb data at 50 kHz (< 0.5 kHz in Run I)

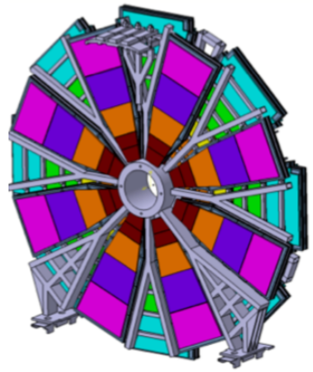
CMS/ATLAS Upgrades Relevant for Heavy-Ions

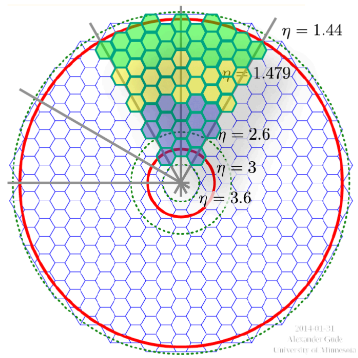
CMS detector

- 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
- Calorimeter electronics upgrades
- Upgraded muon trigger system



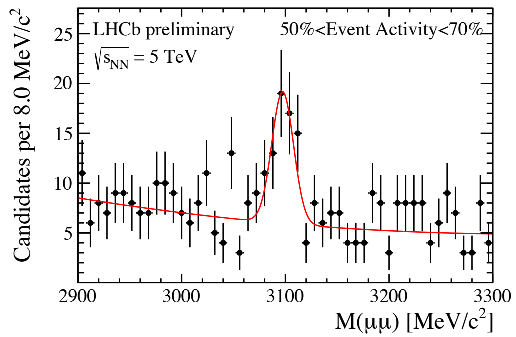


Main focus on triggerable signals (complementary strategy w.r.t. ALICE): muon, jet, displaced track triggers

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

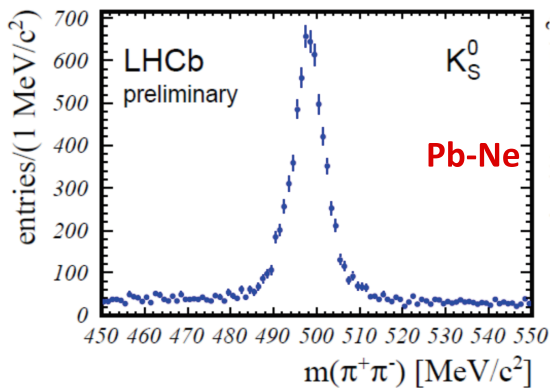
LHCb as a Heavy-Ion Detector

- **Very successful participation to the 2013 p-Pb run. First Pb-Pb run in 2015!**
  - Detector performance and potential in heavy-ion (collider mode) will be clear after the analysis of the 2015 data



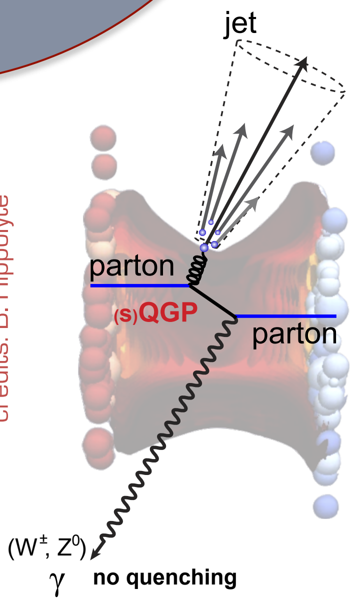
- **Exploration of LHCb unique features: forward acceptance, vertexing, PID, calorimetry**
  - Cold nuclear matter effects on prompt/non-prompt quarkonia and open HF down to zero p_T
  - First observation of Z production in p-Pb

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



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

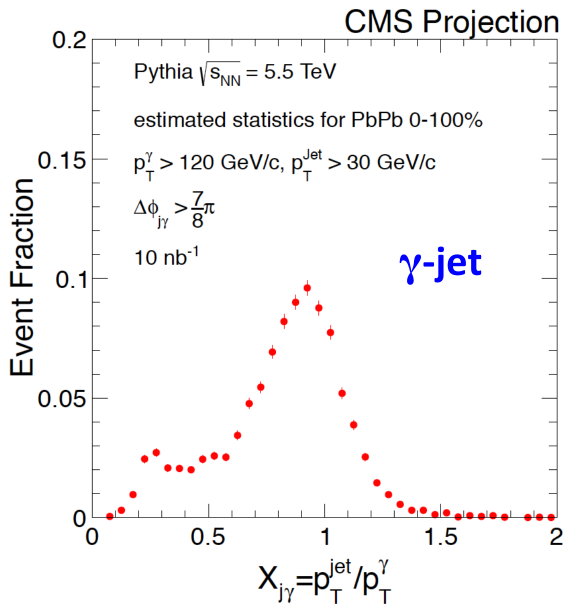
Jet Quenching in ATLAS and CMS

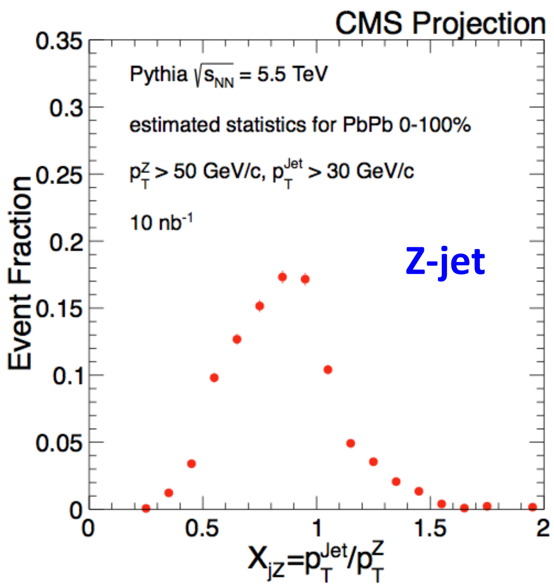


credits: B. Hippolyte

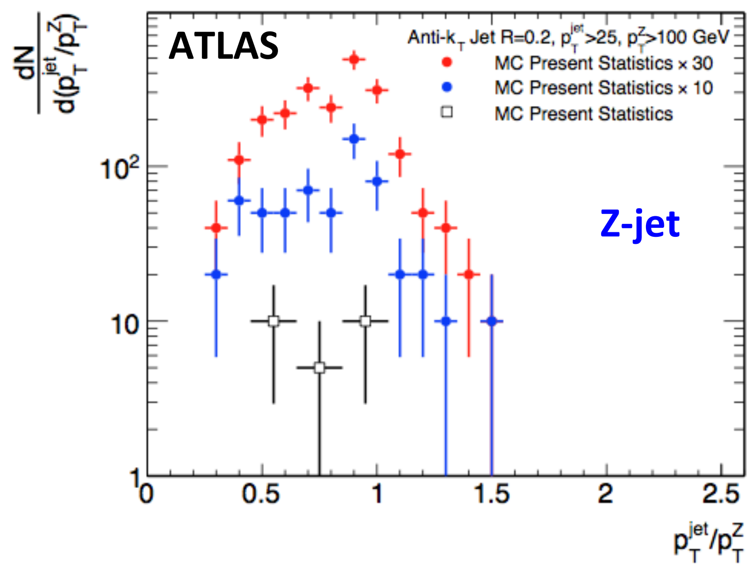
- **High precision γ-jet, Z-jet correlations ($E^{\gamma/Z} = E^{jet}$ before medium effects), di-jets, with dedicated b-jet triggering**
  - 10M di-jets with $p_{T,1} > 120$ GeV/c (CMS, 10 nb^{-1})
  - 140k b-jets with $p_T > 120$ GeV/c (CMS, 10 nb^{-1})
- **Understand medium response and energy radiation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

CMS Projection: CMS-PAS-FTR-13-025



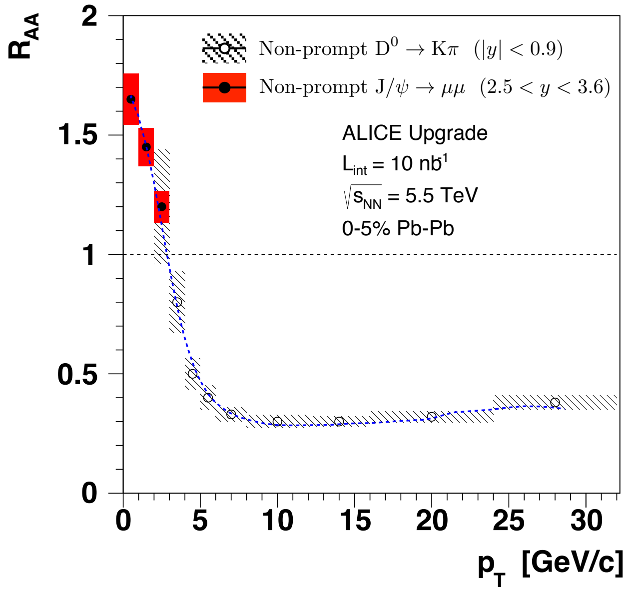


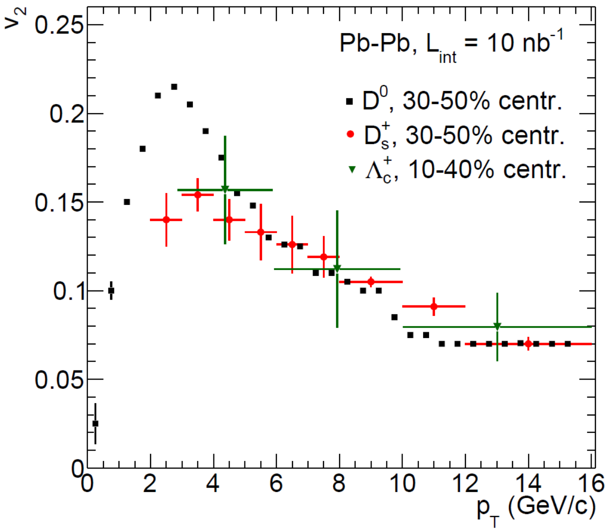
$p_T^Z > 100$, $p_T^{jet} > 25$ GeV, $\Delta\varphi > 7\pi/8$

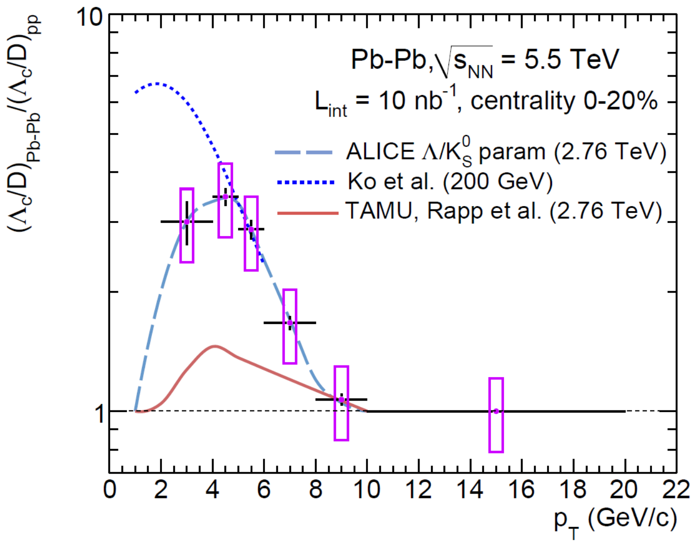


Low-p_T Heavy-Flavors in ALICE

- **Yield and elliptic flow in Heavy-Ion collisions** accessible at mid- and forward-rapidity for both charm and beauty sectors:
  - **Central barrel:** prompt charm mesons/baryons; D mesons and J/ψ from B + full B reconstruction
  - **Muon arm:** single muons from D; J/ψ from B + single muons from B





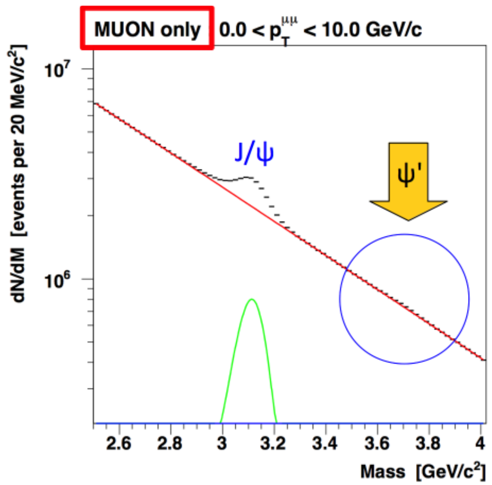


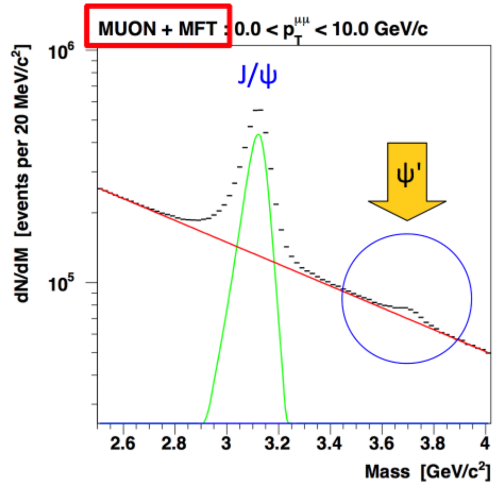
- **Baryon/meson ratio:** only available at mid-rapidity thanks to the upgraded ITS (upgrade especially needed for $\Lambda_c \to pK\pi$ with $c\tau \approx 60$ μm)

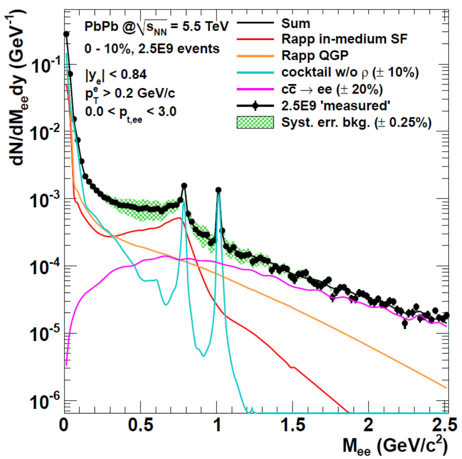
Charmonium and Low-mass Dileptons in ALICE

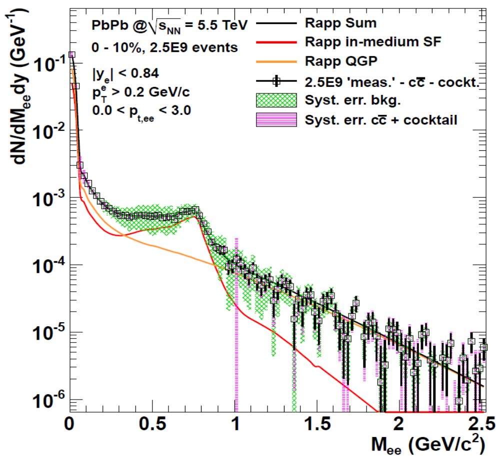
Improved discrimination of prompt/displaced dileptons thanks to the upgraded ITS (central dielectrons) and MFT (forward dimuons)

- **Isolation of forward prompt J/ψ** (not possible without the MFT)
- **S/B improvement for ψ(2S)** in central Pb-Pb (dimuon channel) by a factor 6-7





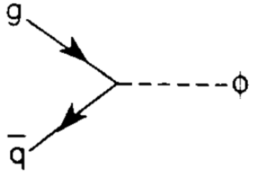


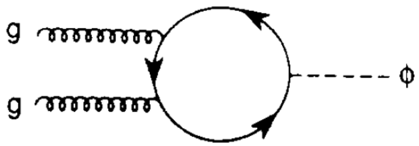


- **Isolation of medium-modified ρ; thermal radiation from QGP**
- **Excellent performance in the dielectron channel** with a dedicated low magnetic field (low-p_T acceptance)

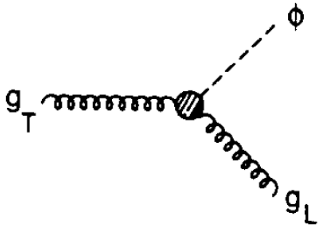
Light BSM Bosons from QGP: a Case for HL-LHC?

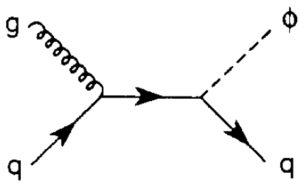
Light scalar or vector BSM bosons could be observed in **high-energy (with large QGP volumes produced), high-luminosity nuclear collisions**

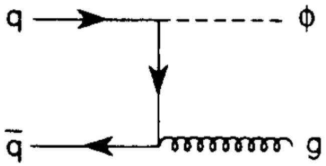




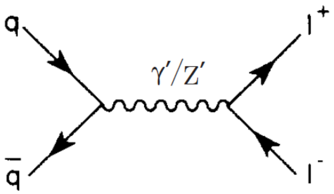
J. Ellis & P. Salati, Nuclear Physics B342 (1990)
J. Davis & C. Böhm, arXiv:1306.3653

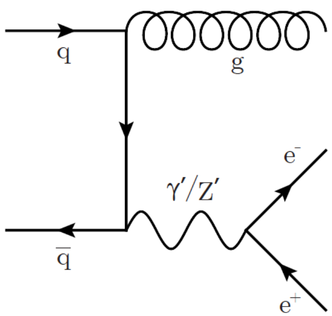




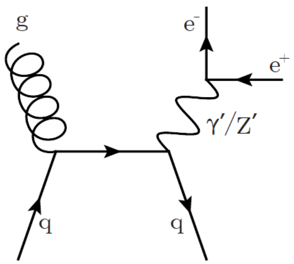


- **Resonance in the thermal dilepton production from the QGP** for masses up to 3 GeV/c^2: dilepton measurements in ALICE could set limits on quark- and lepton-couplings of light BSM bosons





- **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

Conclusions

- **"HL-HI-LHC" (Heavy-Ions in LHC Runs 3+4): fully exploit the potential of the machine as a high-luminosity HI collider**
  - Pb-Pb > $10nb^{-1}$: rare triggers ×10 w.r.t. Run 2 (CMS, ATLAS), ×100 for minimum bias (ALICE)
  - pp reference at Pb-Pb energy; p-Pb; possibly light ions

- **Rich physics program being prepared by the experiments**
  - Upgraded detectors and data acquisition systems to cope with the high interaction rate
  - **ALICE:** focus on untriggerable probes by recording all events after online data volume reduction
  - **CMS/ATLAS:** focus on triggerable probes with L1 and High-Level Triggers to reduce the rate of recorded events
  - **LHCb:** potential for the HL-HI-LHC will be clear once the results of the 2015 Pb-Pb run are available

Backup Slides

ALICE Muon Physics: Current Items

- **Low-mass dimuons.** Non-perturbative aspects of QCD through Dalitz and 2-body decays of light narrow resonances close to freeze-out. (Hidden) strangeness production. Thermal emission mediated by the broad vector meson ρ in the form $\pi^+\pi^- \longrightarrow \rho \longrightarrow \mu^+\mu^-$

- **Quarkonium states.** Dissociation/recombination in the QGP phase (and in smaller systems?). Thermal charm production at low p_T. Test of perturbative QCD hadro-production mechanisms in pp collisions. Photo-production in ultra-peripheral heavy-ion "collisions"

- **Heavy-flavor single muons.** Energy loss and coupling of charm and beauty quarks with the deconfined medium

- **Single muons and dimuons from W/Z bosons.** Standard candle reference for in-medium effects. Probes of nucleons and nuclei parton structure

ALICE Upgrade Strategy

- **ALICE will run at 50 kHz in Pb-Pb** (i.e. L = 6×10^{27} cm^{-1} s^{-1}) with minimum bias (pipeline) readout (max readout with present ALICE set-up: ≈ 0.5 kHz)
  - Gain a factor of 100 in statistics over current program: **×10** from the integrated luminosity (1 nb^{-1} → 10 nb^{-1}) and **×10** from the pipelined readout allowing inspection of all collisions. Inspect $o(10^{10})$ central collisions instead of $o(10^{8})$

- **Improve vertexing and tracking at low p_T:** better spatial resolution is needed on track reconstruction to improve secondary vertex reconstruction

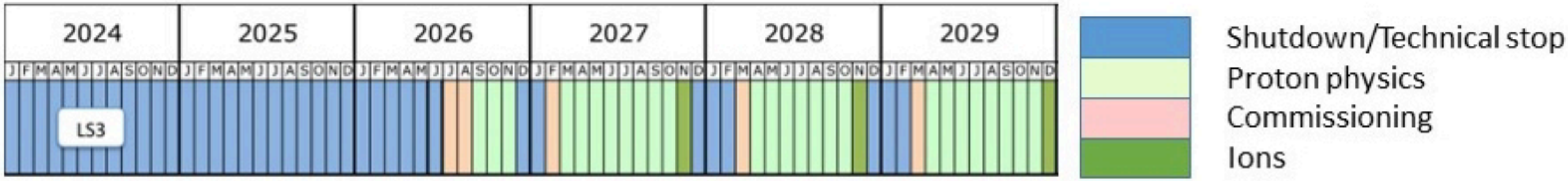
- **This entails a major upgrade of the whole apparatus:**
  - New, smaller radius beam pipe
  - New inner tracking system: upgraded ITS + MFT
  - High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ/HLT, Muons and Trigger detectors

ALICE Upgrade Strategy

LHC roadmap: ion runs

Run2 : $\mathcal{L}_{integrated}^{Pb-Pb} = 1.0\ nb^{-1}$

Run3: $\mathcal{L}_{integrated}^{Pb-Pb} = 6.0\ nb^{-1}$

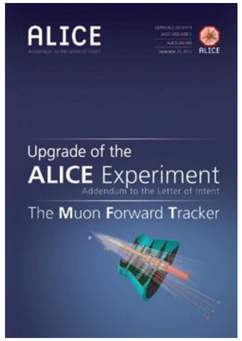


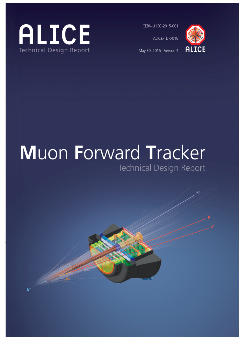
Run4 : $\mathcal{L}_{integrated}^{Pb-Pb} = 7.0\ nb^{-1}$

MFT Upgrade Physics Program

As a vertex tracker for the Muon Spectrometer, the MFT will have a major impact on several items of the ALICE muon physics

- **Open heavy flavors**
  - Charm measurement down to p_T = 1 GeV/c in the single muon channel
  - Beauty measurement down to p_T = 0 in the non-prompt J/ψ channel
- **Prompt Charmonium production**
  - Prompt/non-prompt J/ψ separation down to p_T = 0
  - ψ(2S) measurement in central Pb-Pb collisions, down to p_T = 0
- **Low-mass dimuons**
  - Improved mass resolution for resonances
  - Sensitivity to prompt continuum

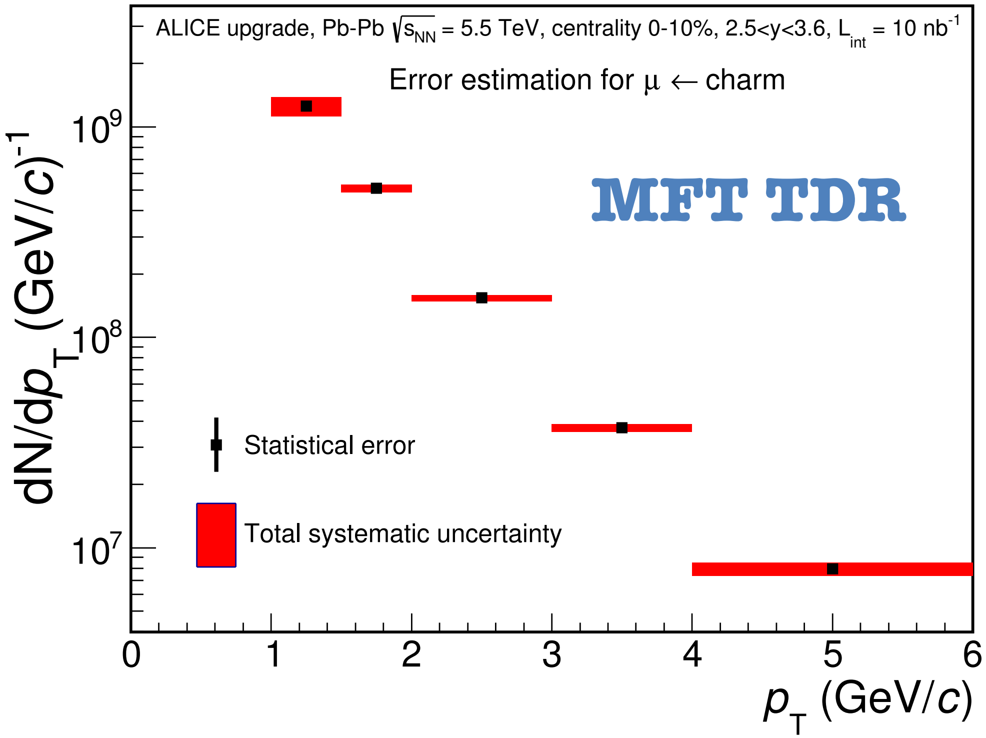




- **And also:**
  - Event plane measurement and azimuthal correlations at forward rapidity
  - Isolation of any prompt signal involving p_T > 1 GeV/c (Drell-Yan, limits on light BSM bosons?)

Charm Measurement with Single Muons

- **Systematic sources considered:**
  - Residual MFT-ITS misalignment
  - MC assumption for the p_T distributions of HF muons
  - Systematics on the description of the MFT response



- **Charm yield** accessible starting from $p_T(\mu)$ = 1 GeV/c (at least)
- **Important baseline** for charmonium measurements

Beauty Measurement with non-prompt J/ψ

- **Prompt/displaced J/ψ discriminating variable:** longitudinal projection of the primary-secondary vertex distance considered for the analysis

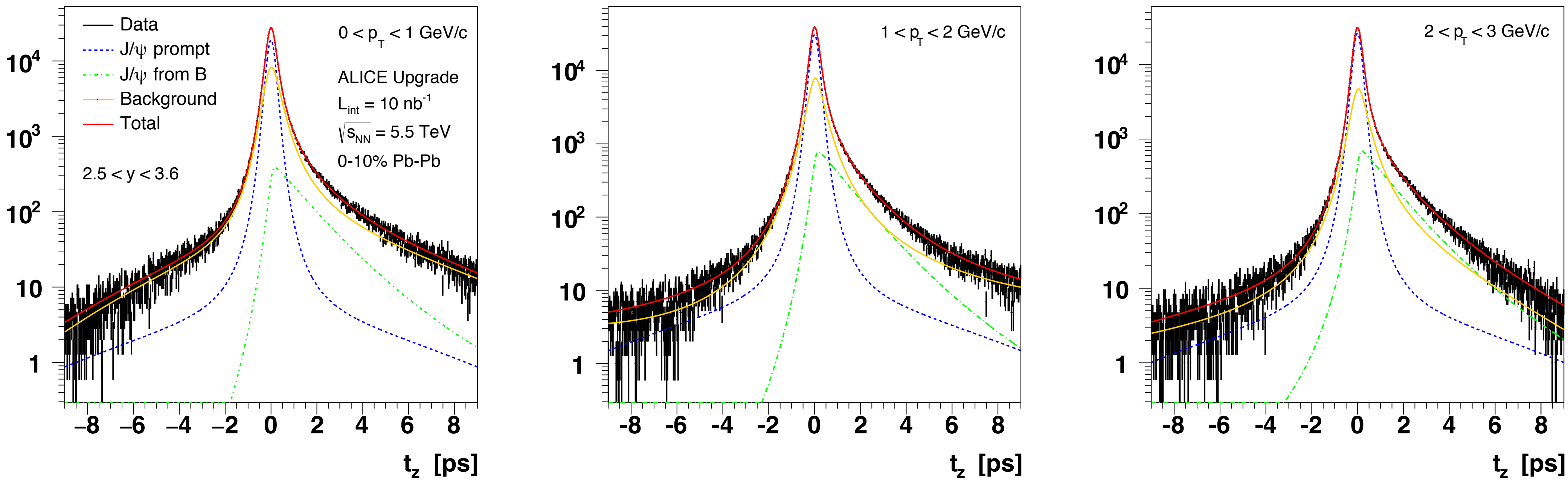
$$t_z = \frac{\left(z_{J/\psi} - z_{\mathrm{vtx}}\right) \cdot M_{J/\psi}}{p_z}$$

- **Analysis Strategy: double (possibly simultaneous) fit** on the dimuon invariant mass spectrum and the t_z distribution of the dimuons falling within the chosen J/ψ mass window
  - **The fit on the invariant mass spectrum** fixes the normalization of the background and the inclusive J/ψ signal. **The fit on the t_z distribution** then separates the two J/ψ contributions

Non-prompt J/ψ: t_z Template Fits

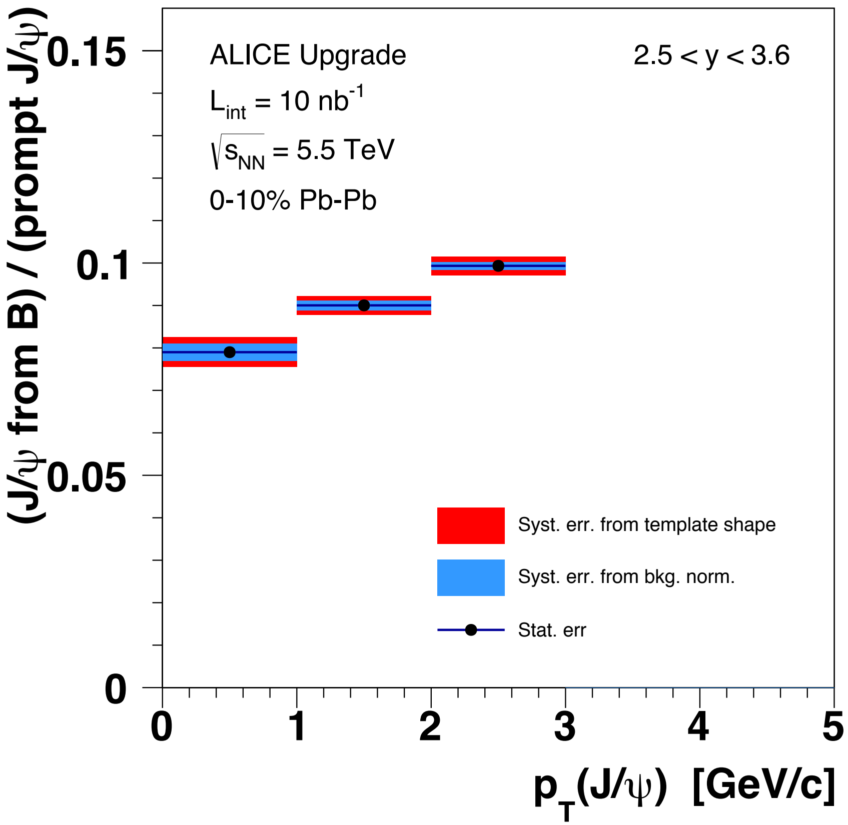
- **Weak p_T dependence of the t_z templates:** prompt/non-prompt J/ψ effective down to zero p_T

- **Background template:** cross-check possible between mixed event technique and data-driven side-band method. Normalization fixed by the fit on the invariant mass spectrum

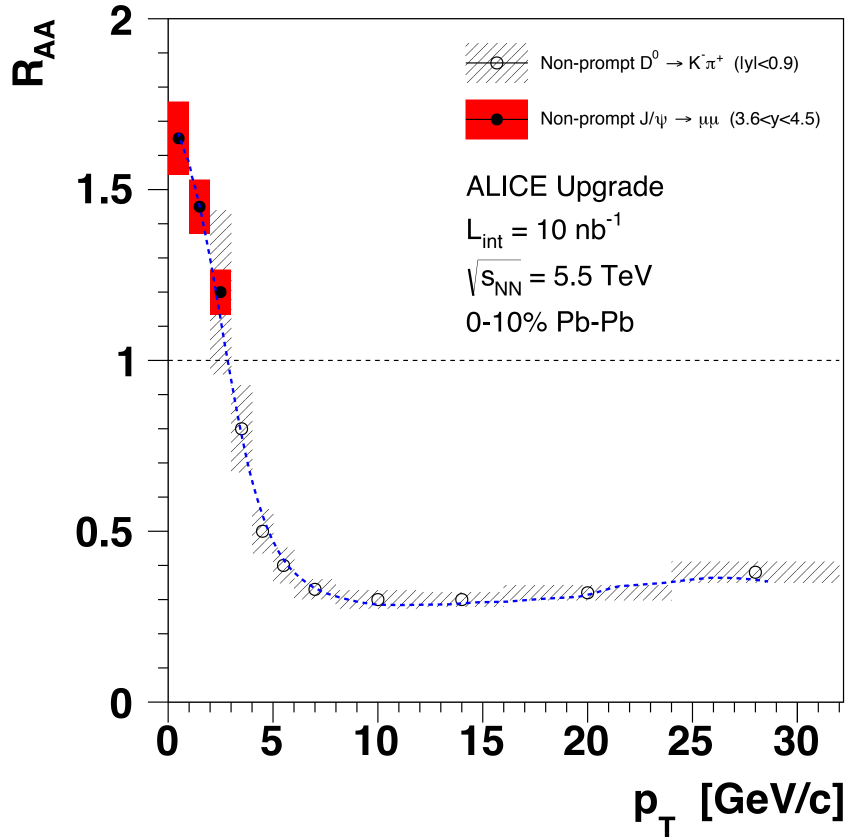


Beauty Measurement with non-prompt J/ψ

- **Displaced/prompt separation** possible down to zero $p_T(J/\psi)$ within 5% stat + syst uncertainties
- **Beauty R_{AA} measurement** possible down to zero $p_T(J/\psi)$ within 7% stat + syst uncertainties even in central Pb-Pb



MFT TDR



Prompt Charmonia: J/ψ and ψ'

- **Precision measurement for J/ψ at forward rapidity already in LHC Run 2, but:**
  - No insight on ψ' physics in central Pb-Pb
  - Only inclusive measurement available at forward rapidity

MFT

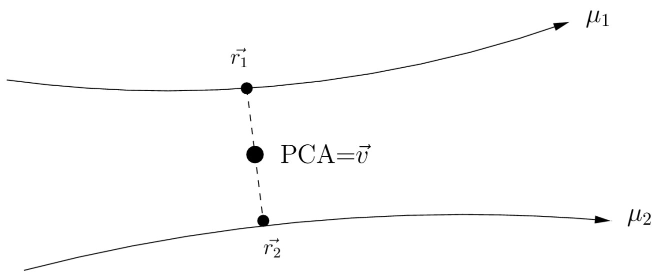
PCA: Point of Closest Approach between two muon tracks

PCA Quality: Estimates the probability that both muons are coming from the PCA

Powerful tool to improve the S/B when the tracks have $p_T > 1$ GeV/c

$$f_i(\vec{v}) = \exp\left[-0.5(\vec{v}-\vec{r_i})^T V_i^{-1}(\vec{v}-\vec{r_i})\right]$$

where $\vec{r_i}$ is the point of closest approach of track i to the point $\vec{v}$. V_i is the covariance matrix of the track i at $\vec{r_i}$

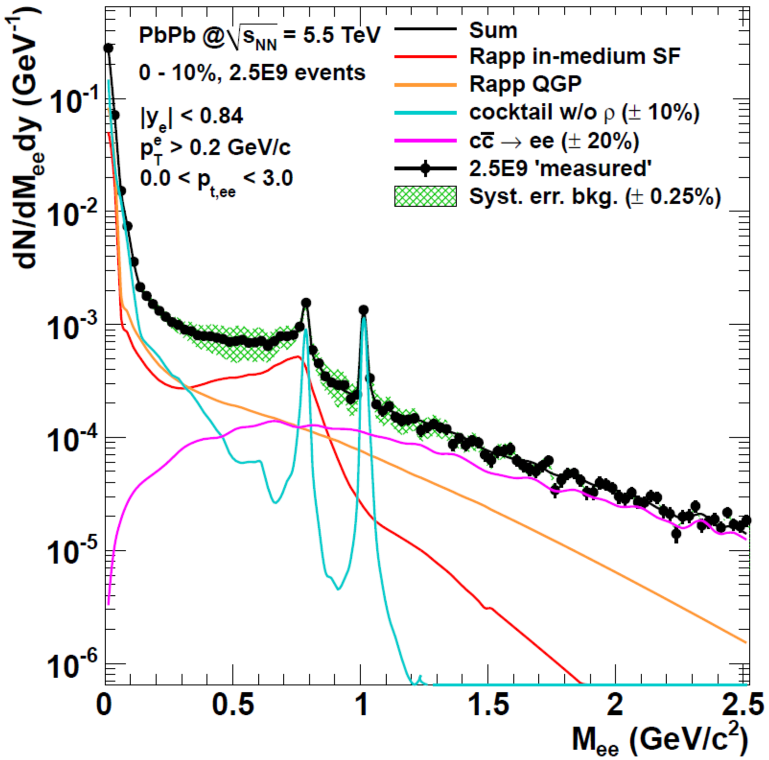


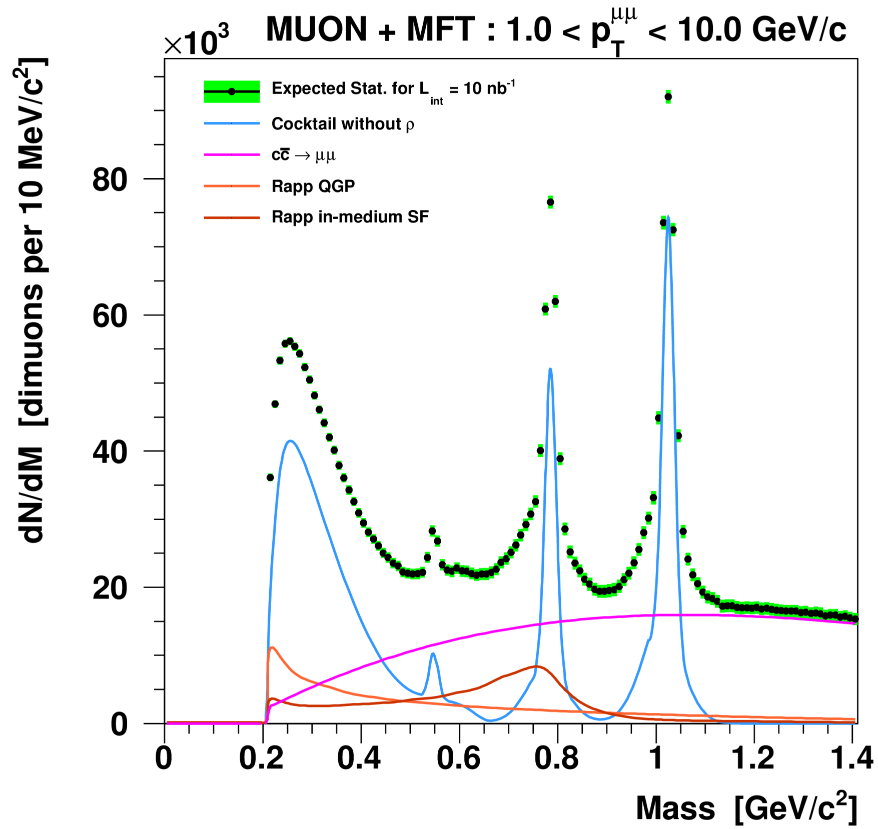
Probability that the two tracks come from the same vertex $\vec{v}$

$$P(\vec{v}) = \frac{2 f_1(\vec{v}) f_2(\vec{v})}{f_1(\vec{v}) + f_2(\vec{v})}$$

Low Mass & Continuum Dileptons

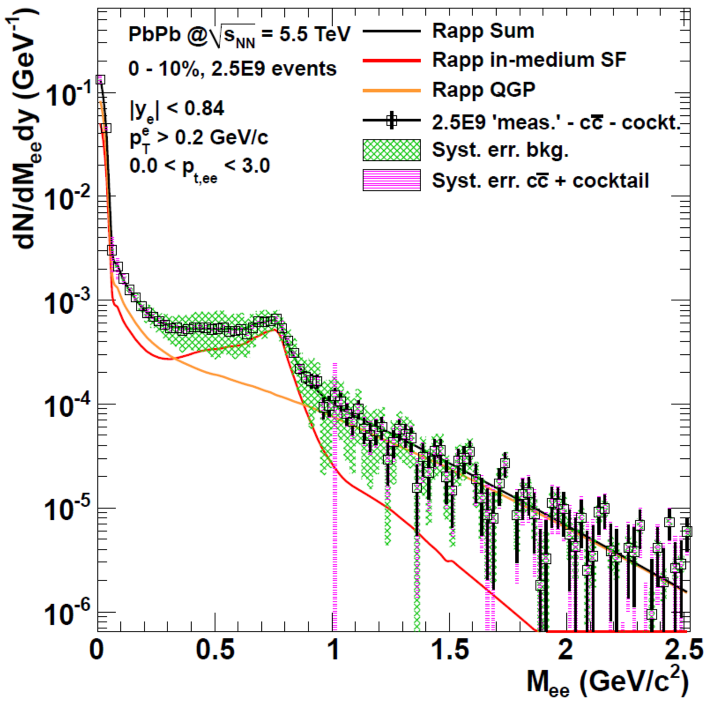
- **Low and intermediate mass dileptons** both in the dielectron (mid rapidity) and dimuon (forward rapidity) channels
- Isolation of prompt sources needs **precise measurement of dilepton offset**
- In addition, **MFT will improve the mass resolution** for light resonances in dimuons

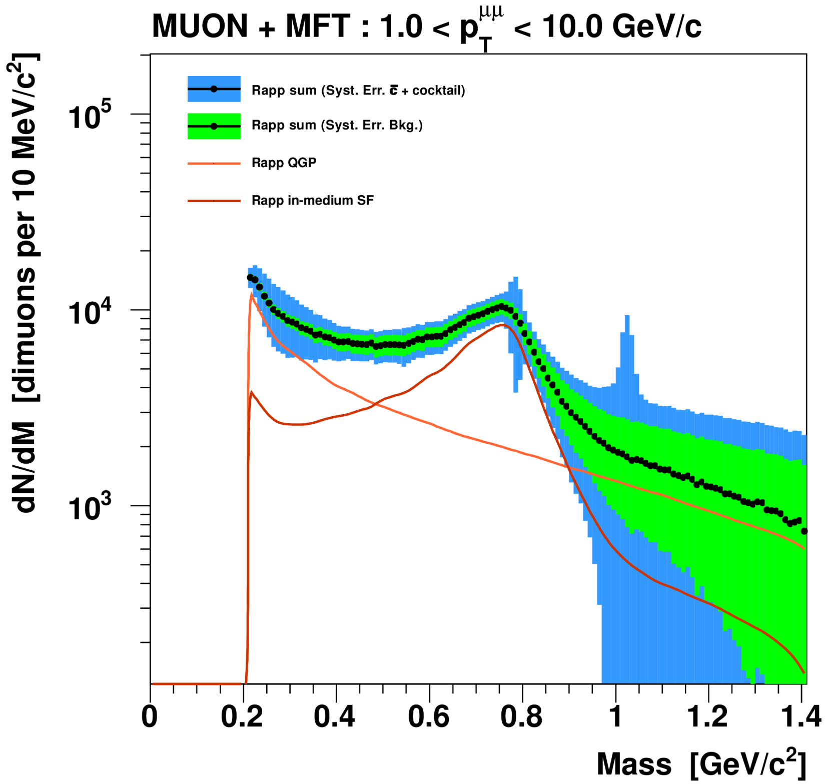




Low Mass & Continuum Dileptons

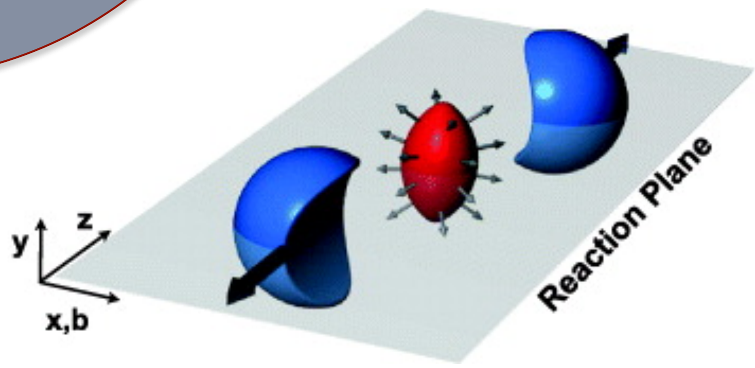
- **Precise measurement of dilepton offset** to remove charm and π/K continuum
- **Dielectron channel advantaged** thanks to the excellent offset resolution of the upgraded ITS, but dedicated low magnetic field needed for low p_T acceptance
- Charm rejection strategy for the MFT must e optimized for the intermediate masses

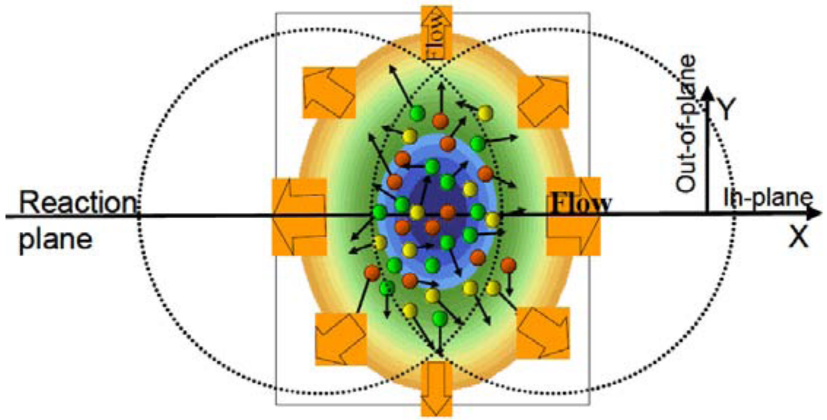


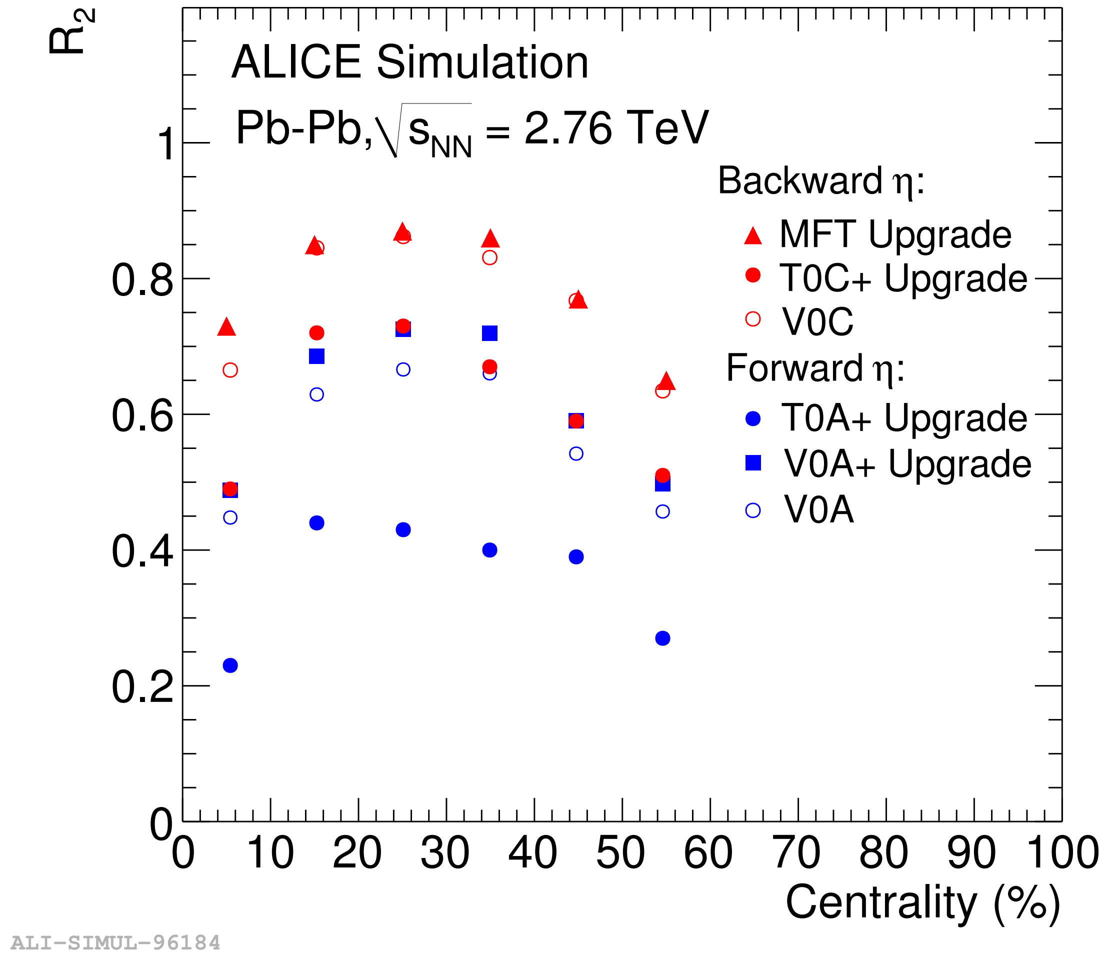


Other Items & Outlook

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

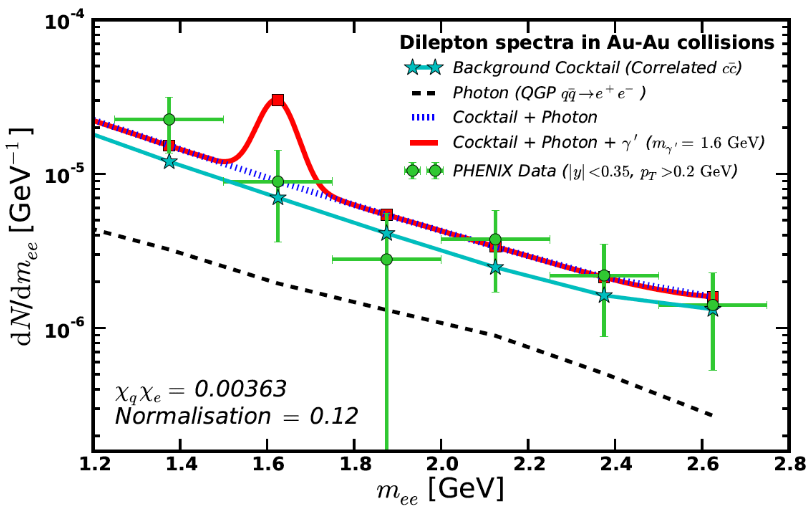
Drell-Yan: main source of prompt dimuons between J/ψ and ϒ at the LHC

- 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

Beyond Standard Model Searches?

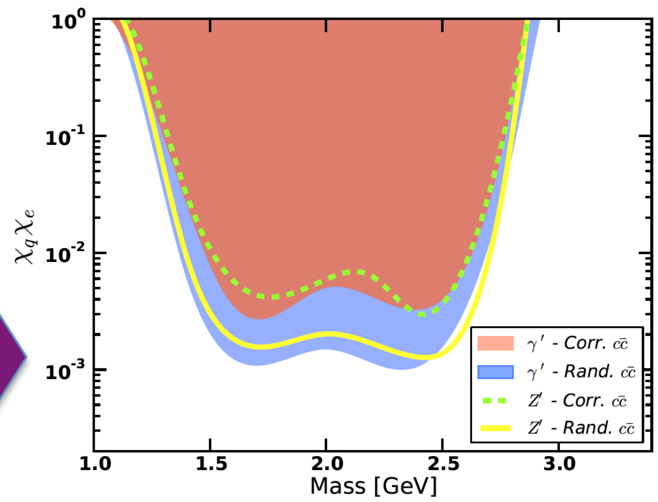
- **A low-mass dark γ' or Z' will generate a resonant enhancement** of the di-lepton spectrum produced thermally by the QGP, at an energy corresponding to the dark gauge boson mass.

- **Analysis recently proposed by D. Pagano on the Run2 data:** feasibility studies will start in the next weeks. First attempt in arXiv:1306.3653 on the PHENIX data. ALICE already studies limits on light dark photon production below 100 MeV/c^2



As a positive signal would appear

Exclusion plot for the q-l coupling



- **With the MFT:** rejection of non-prompt background (single-μ cut at 1.5 GeV/c should be affordable) and better mass resolution