Heavy Ion Requests at the HL-LHC

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on behalf of ALICE, ATLAS, CMS and LHCb

talk largely based on a similar talk by A. Dainese at the HL-LHC ECFA Meeting 2014

additional thanks to
J. Jia, B. Wyslouch and B. Schmidt

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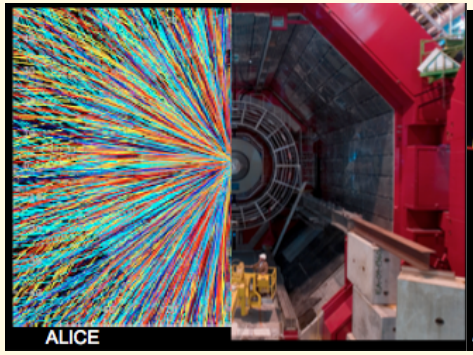
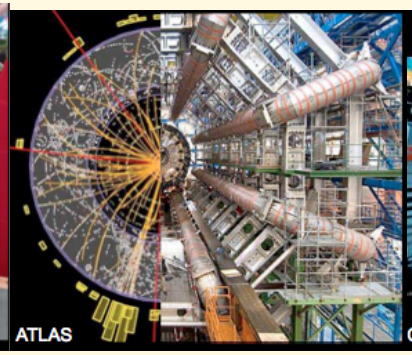
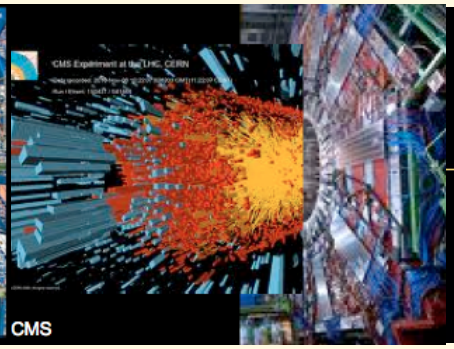
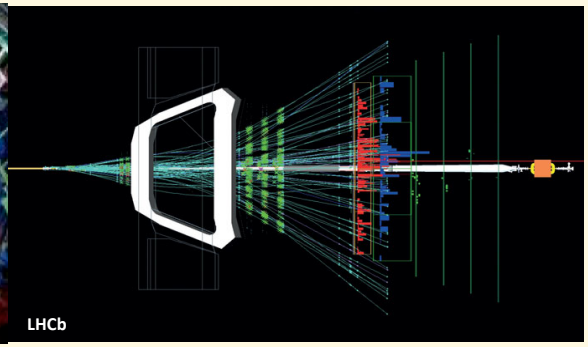
Outline

- Timeline of future HI running
- Pb-Pb physics program at HL-LHC
- Besides Pb-Pb: pPb, pp reference, light ions
- Experiment upgrades and strategies
- Selected performance studies









Timeline of future HI running at the LHC

- Run 2:
  - Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5 TeV
  - p-Pb (at increased luminosity)
  - pp reference at Pb-Pb energy (~ 5 TeV)
- LS2:

  full ALICE and LHCb upgrades (all TDRs have been approved!)
  upgrades relevant to HI also for ATLAS, CMS (LS2 and LS3)
  LHC collimator upgrades to cope with Pb-Pb interaction of 50 kHz
- Runs 3+4:
  - Experiments request **Pb-Pb: >10/nb** (eg. ALICE: 10/nb at 0.5 T + 3/nb at 0.2 T)
  - + other systems (see below)
  - HL-LHC HI physics focus on rare probes, their coupling with QGP medium and their (medium-modified) hadronization process

HL-LHC program (Pb-Pb)(I)

- **Jets:** characterization of 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 (focus of **ATLAS** and **CMS**)
  - Flavor-dependent in-medium fragmentation functions (focus of **ALICE**)
- **Heavy Flavor**: characterization of mass dependence of energy loss, HQ 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 (focus of **ALICE** and **LHCb**)
  - B and b-jets (focus of **ATLAS**, **CMS** and **LHCb**)

HL-LHC program (Pb-Pb) (II)

- **Quarkonium:** precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-p_T charmonia and elliptic flow (focus of **ALICE** and **LHCb**)
  - Multi-differential studies of Y states (focus of **ATLAS**,**CMS** and **LHCb**)
- **Low-mass di-leptons:** thermal radiation γ (→ e^+e^-) to map temperature during system evolution; modification of ρ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)
- **Heavy nuclear states:** use excellent PID to study production of exotic objects in Pb-Pb
  - Anti-nuclei, light multi-Λ hyper-nuclei, di-baryons (**ALICE**)

Besides Pb-Pb: pp reference, pPb, (lighter nuclei)

- pp reference at 5 TeV required
  - ALICE / LHCb (for HF and charmonia needs): **~10/pb** (cf. CERN-LHCC-2012-012)
  - ATLAS / CMS: match Pb-Pb yields for high-p_T process, **~300/pb**
- p-Pb at high luminosity has two-fold interest:
  - Explore partonic structure of high-energy nuclei → also needed as "control experiment" for the QGP studies
  - Study development of collective effects in high-particle-density collisions

  → **Requested by all experiments** (**ALICE**, **ATLAS**, **CMS** and **LHCb**)
- Lighter nuclei (e.g. Ar): still under consideration after LS2
  - Study system size dependence and onset of QGP effects
  - Larger instantaneous luminosity compensates the reduced yields for hard processes (which scale with A^2, e.g. Ar-Ar/Pb-Pb = 1/27)

Focus of the upgrades (I)

ALICE

- Detector specificities (preserved / strengthened with the upgrades): hadron and lepton ID, light-weight and precise trackers, low magnetic field
- Main focus on "untriggerable" signals (extremely low S/B)

→ Trigger approach: write all events at up to 50 kHz in Pb-Pb (now 0.5 kHz)

~1 TB/s → HLT/DAQ (O^2) → **~20 GB/s**

→ HL-LHC: increase of minimum-bias sample **x100** wrt Run 2

ATLAS and CMS

- Detector specificities (strengthened with the upgrades): muon ID, precise tracker, calorimetry
- Main focus on muons, jets, displaced track triggers

→ Trigger/DAQ approach: strong data reduction

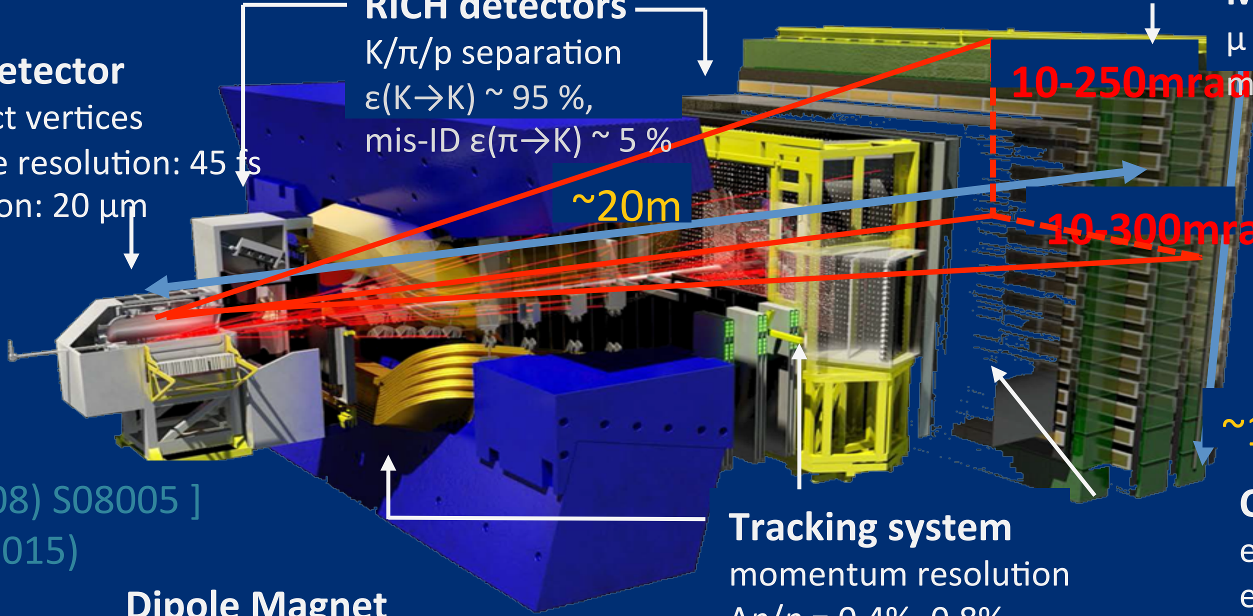
50 kHz → L1 → **~ few kHz** → HLT → **~ 100 Hz**

→ HL-LHC: increase of minimum-bias sample **x10** wrt Run 2

Focus of the upgrades (II)

LHCb

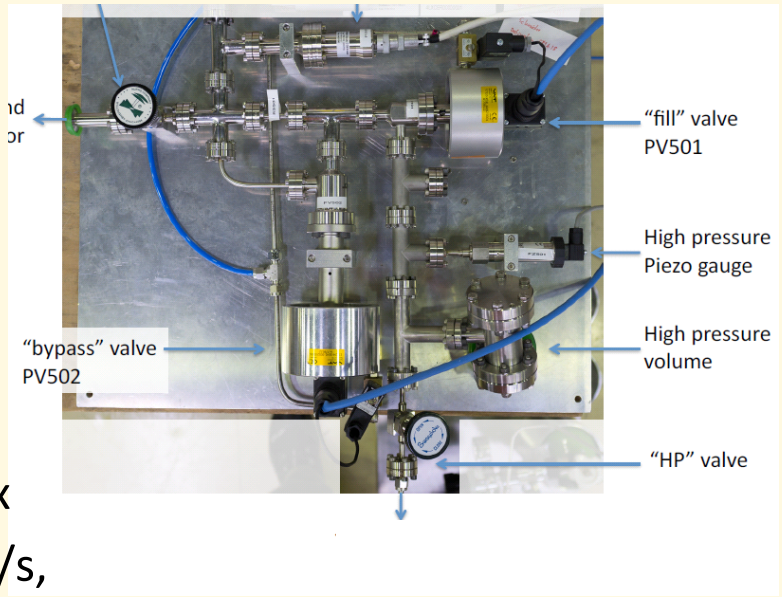
- LHCb will upgrade its detector in LS2 to operate at a 5 x higher luminosity and detector occupancy, while retaining the excellent detector performance
- This will remove the present limitation to reconstruct high centrality events
  - **Improved granularity will enhance capabilities for heavy ion physics**
- LHCb will read out all collisions, using a pure software trigger for event selection



[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

Fixed target physics at the LHCb

- Based on **SMOG** : **S**ystem for **M**easuring the **O**verlap with **G**as
  - Injection of low density noble gas into the LHCb Vertex Locator
  - Successful data-taking in 2015 with He, Ne and Ar gas
    - no decrease of LHC performances observed
    - plans for Pb-Ar data-taking in Nov/Dec 2015
    - Assuming a pressure of 10^{-9} bar, a proton flux of 3.5 x 10^{18} p/s and a Pb flux of 4.5 x 10^{14} Pb/s, one can obtain luminosities of **10/μb/s for p-Gas and 1/mb/s in Pb-Gas**



- Test factorization of cold nuclear matter (CNM) effects
  - measure Drell Yan in pA and pB to predict A+B and compare with high statistics measurement
- In **FT** mode access to **the high Feynman x_F** domain ($x_F = p_z/p_{zmax}$), and probing of energy densities between those probed at the SPS and RHIC

➢ **The gap between the SPS and RHIC can be bridged by a single experiment**

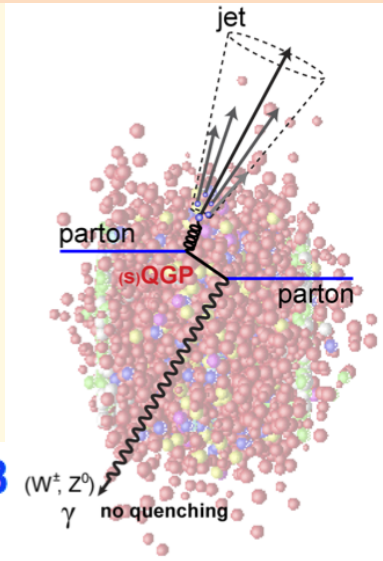
Outline

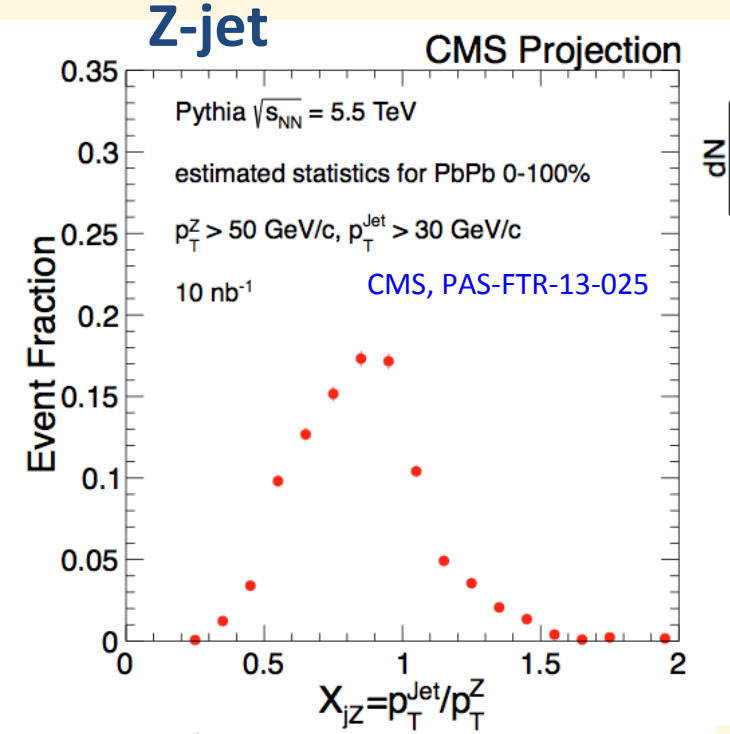
- Timeline of HI running
- Pb-Pb physics programme at HL-LHC
- Besides Pb-Pb: pPb, pp reference, light ions
- Experiment upgrades most relevant for HI measurements
- Selected performance studies
- Summary

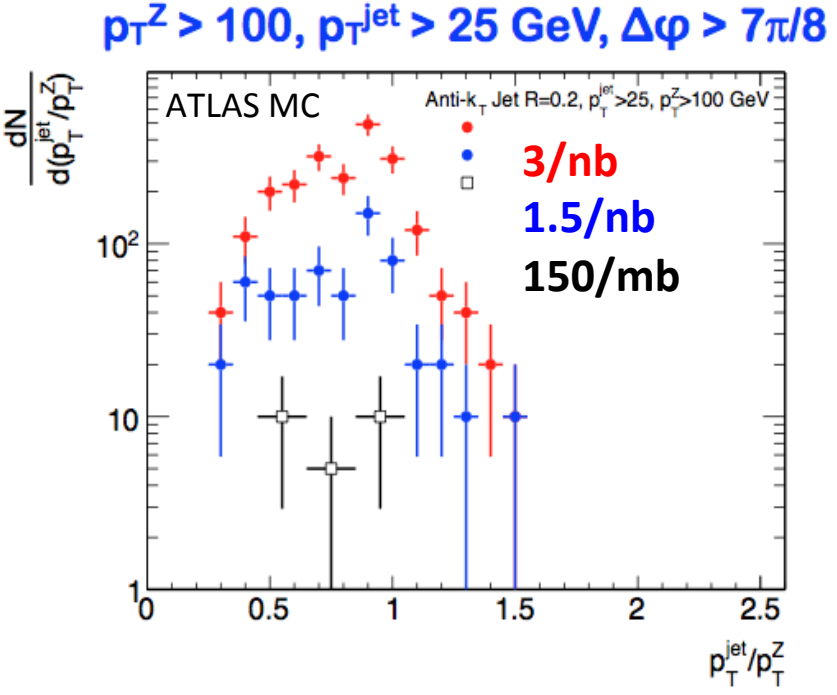
More can be found here:
https://indico.cern.ch/event/252045/session/4/contribution/12/material/slides/0.pdf

Jet quenching: performance

- High precision γ-jet, Z-jet ($E^{\gamma/Z} = E^{\text{jet}}$!), di-jets, also with b-jets. E.g.:
  - 10M di-jets with $p_{T,1}$>120 GeV/c (CMS, 10/nb)
  - 140k b-jets with p_T > 120 GeV/c (CMS, 10/nb)
- Understand medium response and energy radiation details, map path-*L*ength dependence (e.g. radiative ~L^2, collisional ~L)







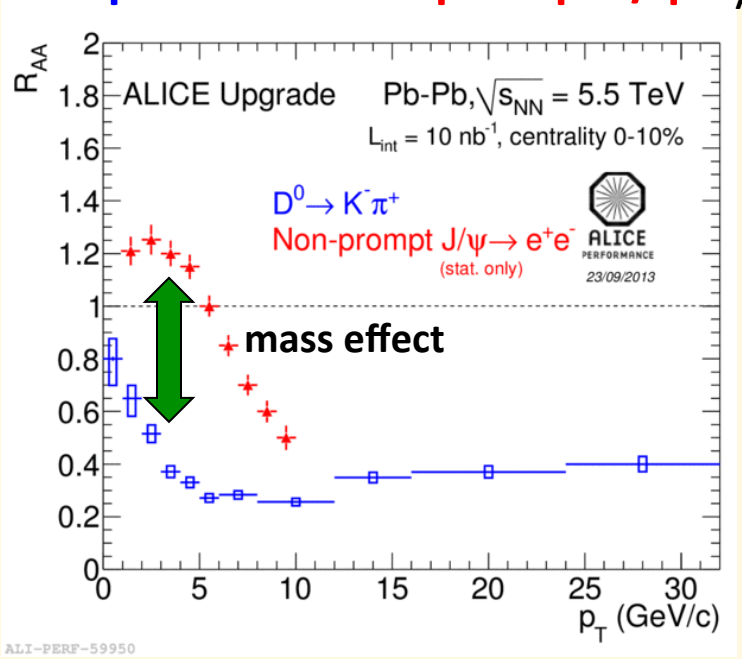
HF central rapidity: performance

HL-LHC → exploit the potential of HQ as probes for the in-medium interaction and their thermalization

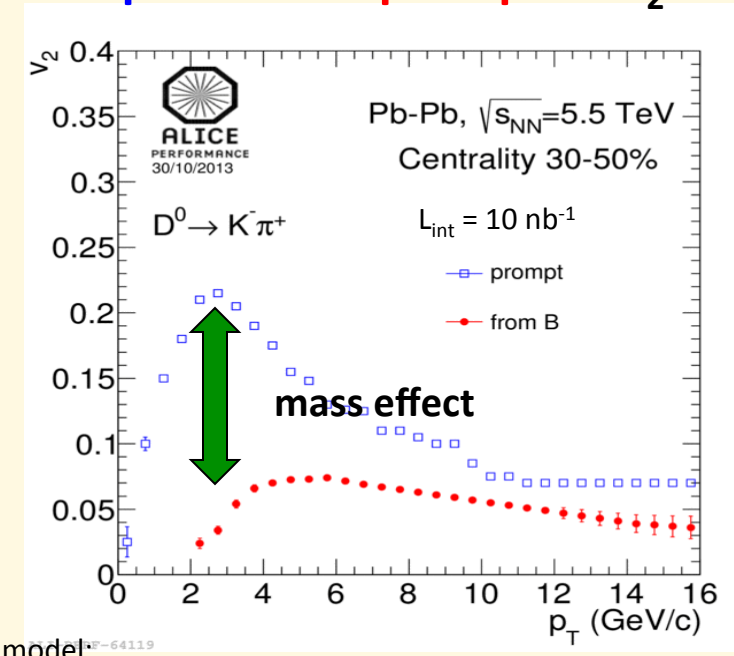
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

→ R_{AA} and v_2 of D and B over a wide p_T range

Prompt D^0 and Non-prompt J/ψ R_{AA}



Prompt and non-prompt D^0 v_2

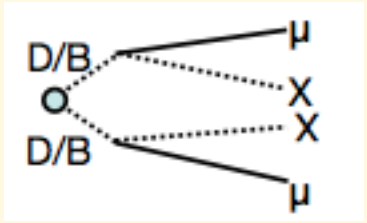


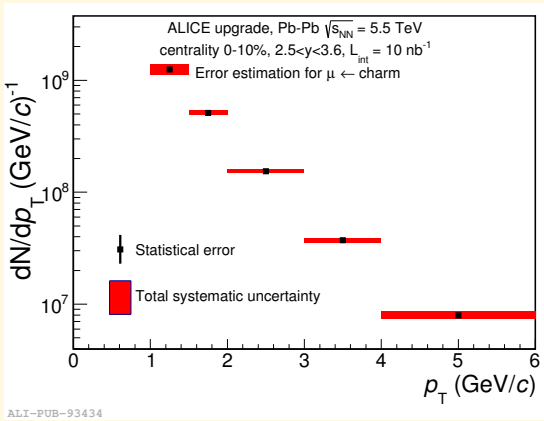
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

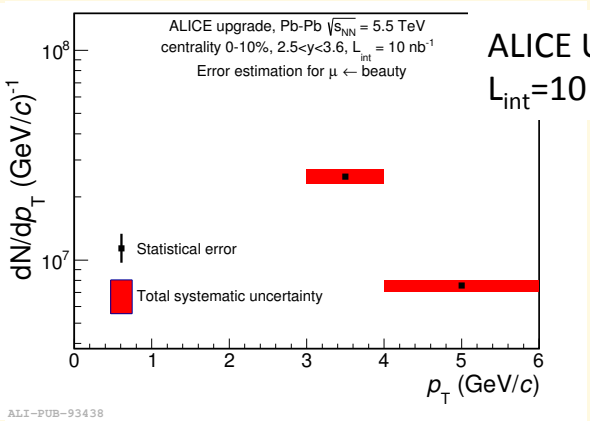
ALICE, CERN-LHCC-2013-024

HF forward rapidity: performance

- ALICE Muon Forward Tracker: pixel tracker (2.5<η<3.5) in front of the muon spectrometer; enables separation of beauty decay vertices;
  also excellent coverage in LHCb (2 <|y|< 5)
- Open Heavy Flavour down to p_T~0:
  - Single muons via offset at primary vertex (charm, beauty)

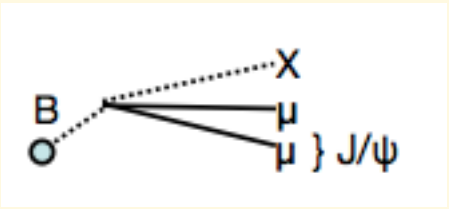


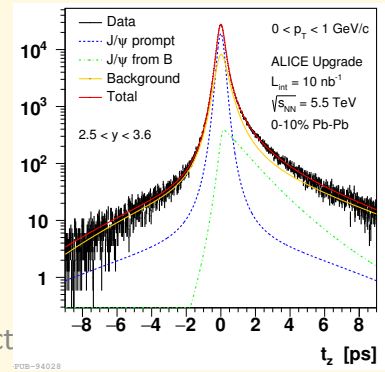


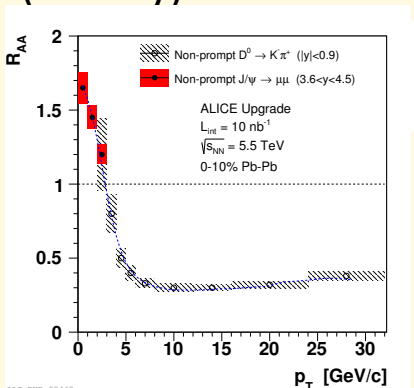


ALICE Upgrade
L_{int}=10 nb^{-1}

  - Displaced J/ψ via pseudo-proper decay length (beauty)



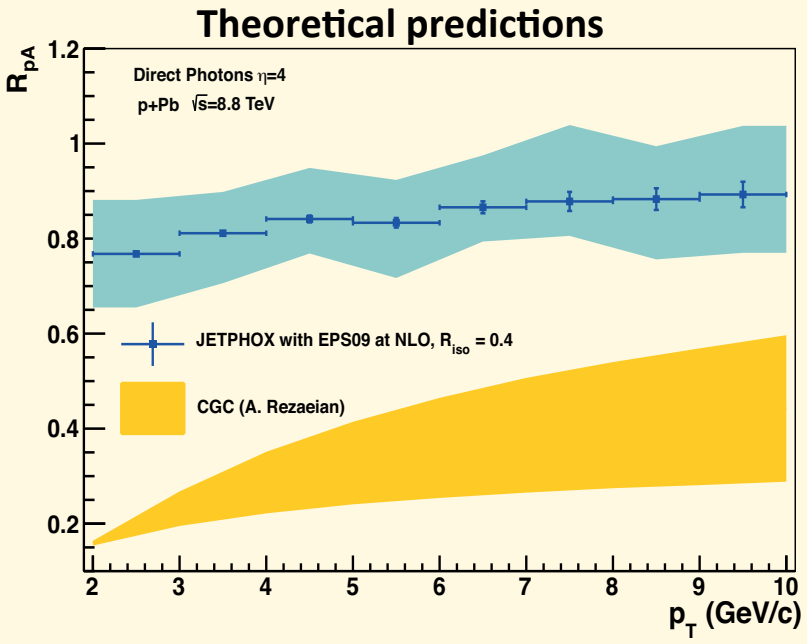


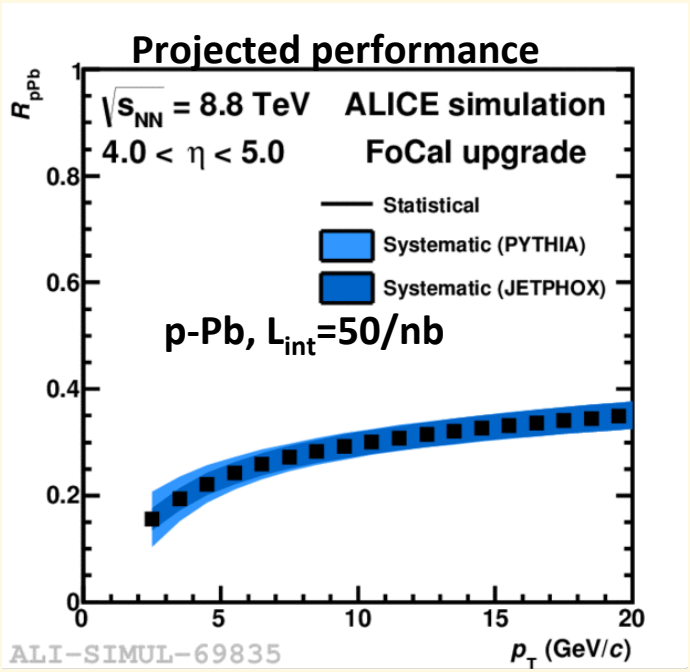


ALICE Upgrade
L_{int}=10 nb^{-1}

Forward photons in p-Pb: performance

- **FoCal in ALICE**: possible minor addition in LS3 high-granularity calorimeter at η~3-5 main focus on saturation physics studies
- Photons at $4 < \eta < 5$ are sensitive to Bjorken-x $< 10^{-5}$





- Signature of gluon saturation in high-energy nuclei: strong suppression of forward R_{pA} = p-Pb/(N_{coll}-scaled-pp), not described within collinear factorization (NLO pQCD) + PDF shadowing

Summary

- "HL-HI-LHC" (Runs 3+4) will fully exploit the potential of the machine as a high-luminosity **HI** collider
- Rich physics program geared at precision measurements of the properties of the QGP
  - Upgraded detectors, very large statistics, diverse trigger approaches, complementary strengths of the experiments
- Needs:
  - Pb-Pb >10/nb → x10 integrated luminosity wrt Run 2
    → x100 for minimum bias wrt Run 2 (ALICE)
  - pp reference at Pb-Pb energy
  - p-Pb
  - possibly light ions

Backup

ALICE LS2 upgrades

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

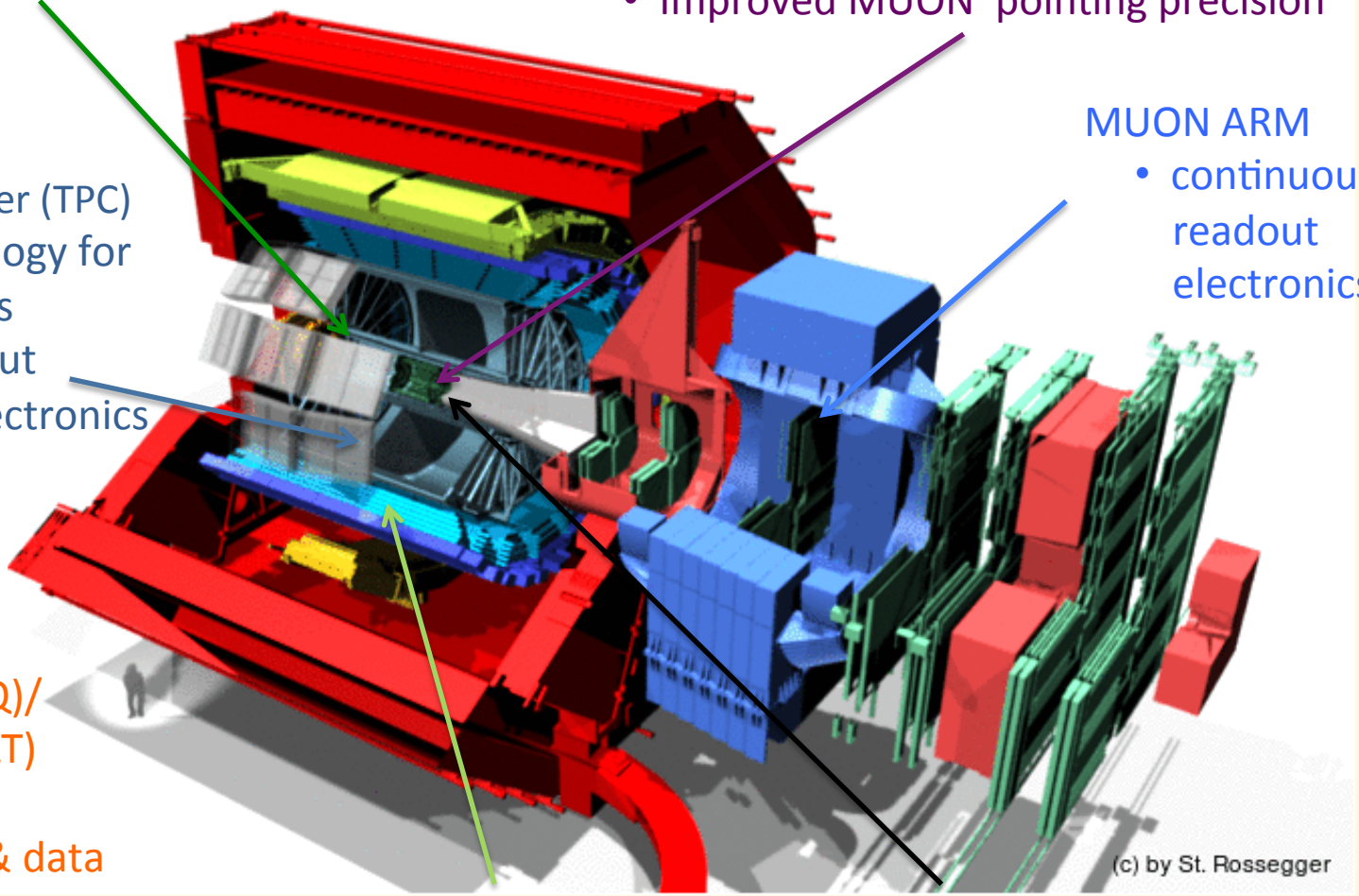
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

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 Pbb event rate



TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

Ion operating conditions outlined in ALICE LoI

The plan is to run at a maximum interaction rate of 50 kHz in Pb-Pb.

In the LoI we assume: peak luminosity of $6x10^{27}$ $cm^{-2}s^{-1}$ and an average luminosity of $2.4x10^{27}$ $cm^{-2}s^{-1}$.

The upgrade program assumes:

- integrated luminosity of 10 nb^{-1} in PbPb at full magnetic field and top energy
- one special PbPb run at reduced magnetic field for low-mass dileptons (O~ 3 nb^{-1})
- one p-Pb run with about 50 nb^{-1}
- pp reference run at 82/208 * top energy

time horizon: to be completed by LS4 under the basic assumption of about one month LHC heavy ion operation per year.

Scheduling scenario after LS2

Tentative plan (modulo start of Run3) as stated in the LoI of the upgrade (CERN-LHCC-2012-012)

Possible running scenario after upgrade:

2021 – Pb–Pb 2.85 nb^{-1}

2022 – Pb–Pb 2.85 nb^{-1} (low magnetic field)

2023 – pp reference run (low luminosity, small μ)

2024 - 2026 – LS3

2027 – Pb–Pb 2.85 nb^{-1}

2028 – ½ Pb–Pb 1.5 nb^{-1} + ½ p–Pb 50 nb^{-1}

2029 – Pb–Pb 2.85 nb^{-1}