Prospects on Heavy Ion Physics at the HL-LHC

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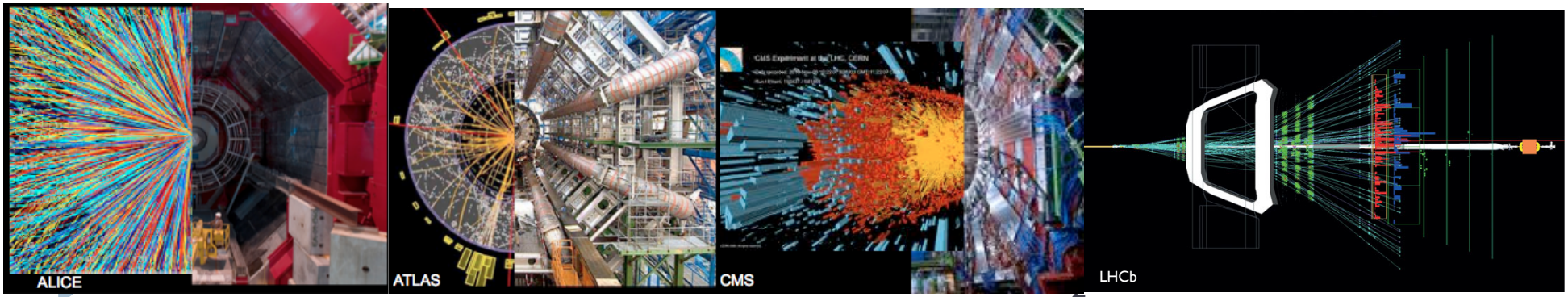
for the ALICE, ATLAS, CMS, LHCb Collaborations

thanks to: J. Jowett (LHC), J. Jia & A. Trzupek (ATLAS),
A. Dainese (ALICE), M. Nguyen & J. Lee (CMS), G. Manca (LHCb)

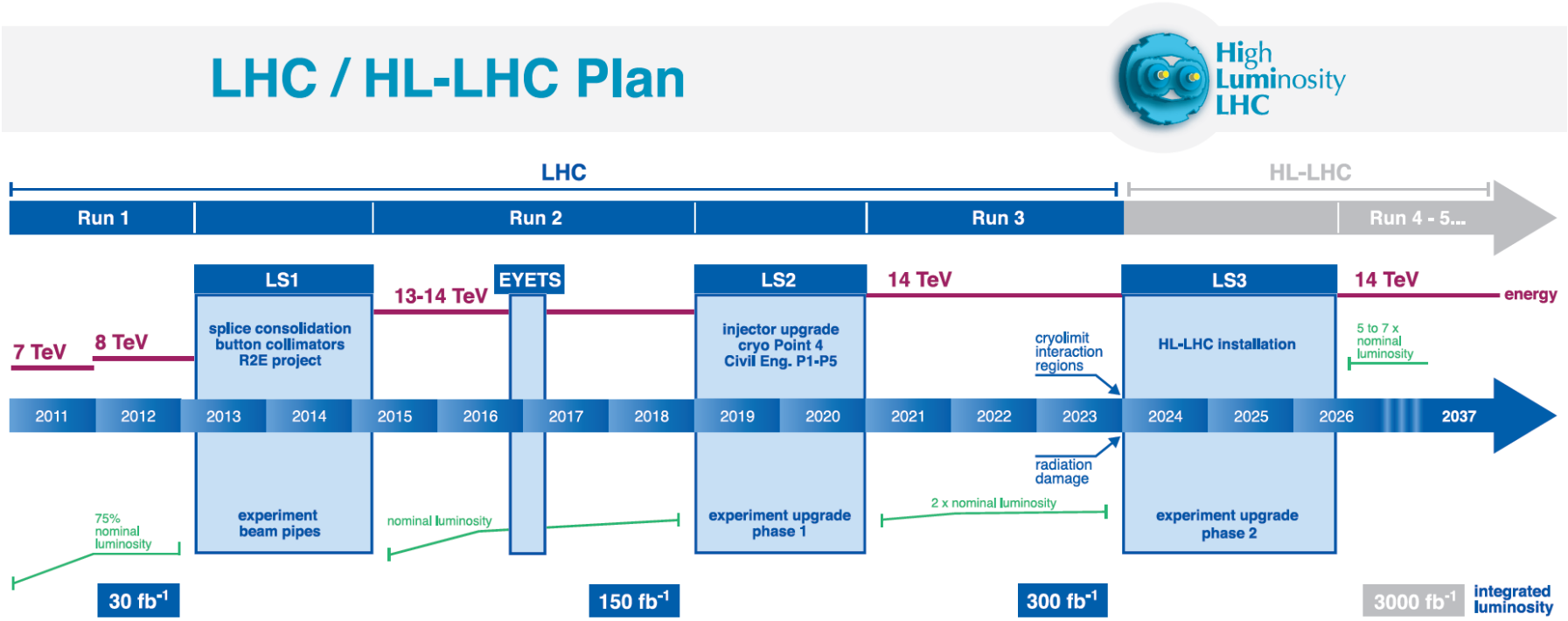
Outline

- LHC Luminosity evolution and HI running timeline
- Heavy ion physics programme at HL-LHC
- Experiment upgrades and strategies
- Discussion of selected performance studies
- Summary

More details on Saturday Upgrades Plenary session



LHC Luminosity evolution



https://hilumilhc.web.cern.ch/about/hl-lhc-project

Main upgrades relevant for HI (2018-2019)

- LHC collimator upgrades: target L~6x10^{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

Timeline of future HI running at the LHC

- Run 2:
  - Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5.1 TeV
  - p-Pb probably in 2016 and probably at 5.02 TeV (ALICE request). Still not clear a possible luminosity improvement
  - pp reference at Pb-Pb energy (5.1 TeV)

- Runs 3+4 **["HL-HI-LHC"]**:
  - Experiments request for **Pb-Pb: >10/nb** (ALICE LoI: 10/nb at 0.5T + 3/nb at 0.2T)
    - x100 larger min. bias sample for ALICE wrt Run 2
    - x10 larger rare trigger sample for ATLAS/CMS wrt Run 2
  - + pp reference, pA, lighter nuclei

HL-LHC Programme (AA)

(A selection of topics!)

- **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**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)

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  - Low-p_T production and elliptic flow of several HF hadron species (focus of **ALICE**)
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LHCP2015

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- **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**)

Besides Pb-Pb: pp reference, pA, lighter nuclei

- pp reference at 5.5 TeV required
  - ALICE (for HF and charmonia needs): ~**10/pb** (see 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 4 experiments

- Lighter nuclei:
  - 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)
  - to be considered for schedule after LS2

ALICE strategy

- Detector specificities (strengthened with the upgrades):
  - hadron and lepton identification
  - 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 **~10 GB/s**

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

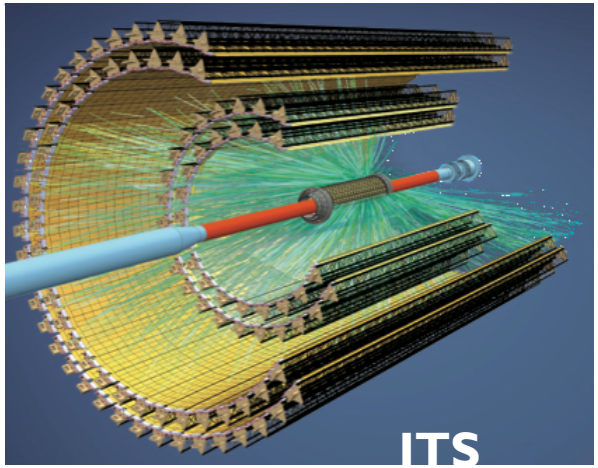
- Main observables:
  - Low-p_T Heavy Flavour
  - Low-p_T Charmonia
  - (Very) low-p_T and low-mass di-leptons

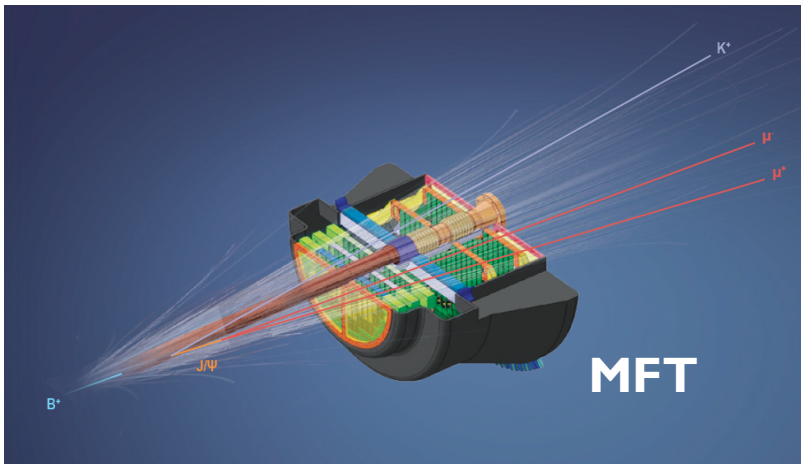
ALICE strategy

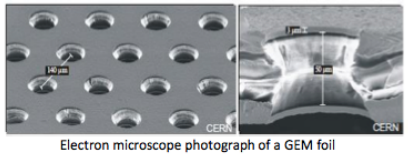
Detailed presentation on Saturday morning session by R. Tieulent

LHCP2015

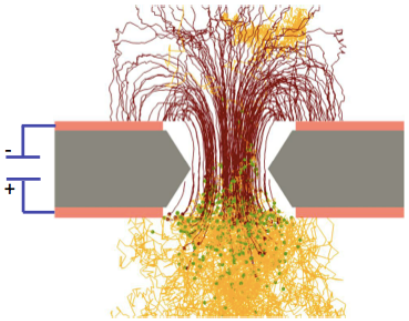
- New Inner Tracking System (ITS)
  - Improved resolution, Smaller material budget, Faster readout
- New Forward Muon Tracker (MFT)
  - Heavy flavour vertices also at forward rapidity
- TPC Upgrade:
  - replace the MWPC-based readout chambers by detectors employing GEMs to allow TPC operation in continuous 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)






Electron microscope photograph of a GEM foil

GEM-based TPC readout



CMS and ATLAS strategy (most relevant for HI)

LHCP2015

- CMS
  - A lighter silicon tracker with extended coverage out to η =4
  - GEM muon stations matching the eta coverage of the tracker
  - New high granularity calorimeter endcaps that together with the tracker will enable particle-flow reconstruction at large rapidity (recently approved)

- ATLAS
  - All new Tracking Detector
  - Level-I track trigger
  - Calorimeter electronics upgrades
  - Upgrade muon trigger system

Detailed presentations on Saturday morning session:
- A. Canepa for ATLAS
- L. Silvestris for CMS

Main focus on muon, jet, displaced track triggers

→ Trigger/DAQ approach: strong data reduction

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

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

LHCb strategy

Detailed presentation on Saturday morning session by R. Jacobsson

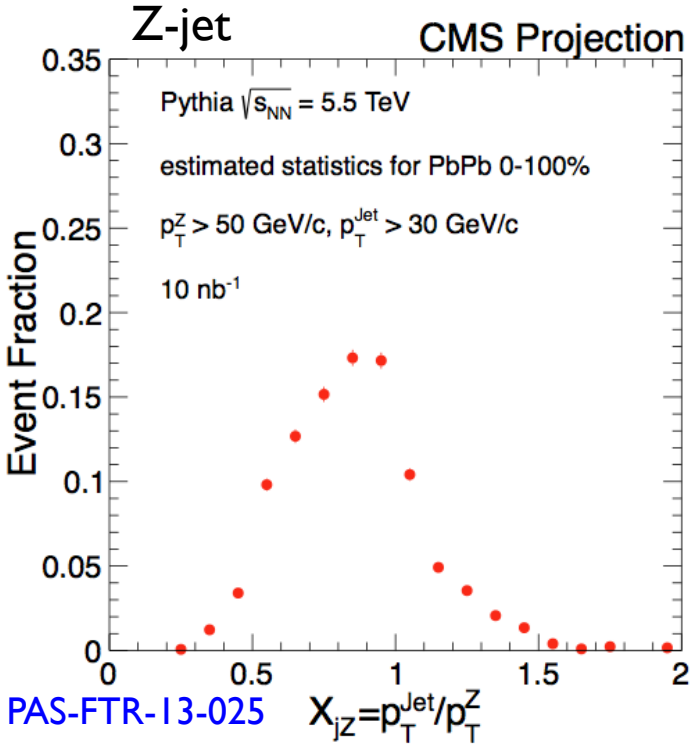
LHCP2015

- LHCb participation to the 2013 p-Pb run very successful
- Exploration of LHCb unique features: forward, vertexing, PID
  - Cold nuclear matter effects on prompt and non-prompt J/ψ, and Υ(1S) JHEP 07 (2014) 094
  - First observation of Z production in p-Pb
- Participation to next Pb-Pb and p-Pb runs
- Use of SMOG as a fix target
  - Various gases could be injected
- Upgrades (LS2) most relevant to HI:
  - New trackers (pixel, strip, scintillating fiber)
  - Readout upgrade: up 40 MHz (pp) → will allow to exploit full delivered p-Pb luminosity

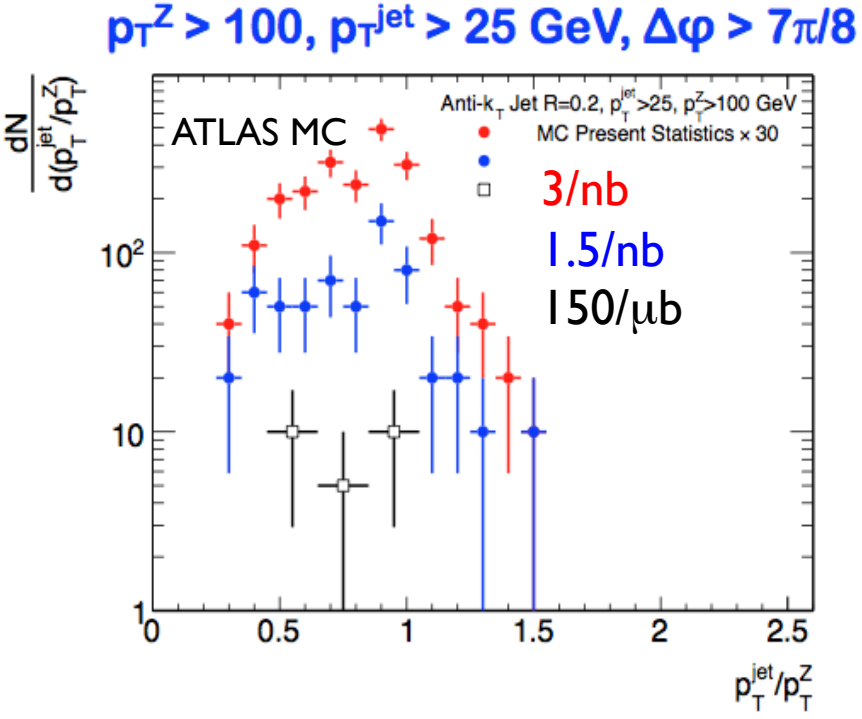
Jet quenching: performance (ATLAS, CMS)

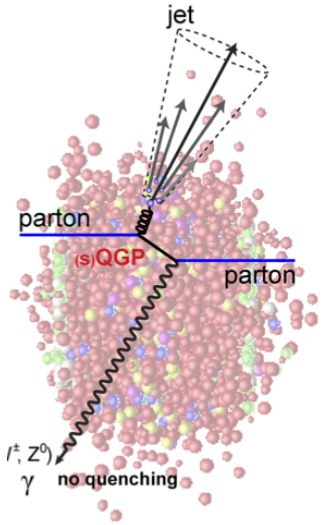
LHCP2015

- High precision γ-jet, Z-jet ($E^{\gamma/Z} = E^{jet}$!), 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)



CMS, PAS-FTR-13-025





HF central rapidity: performance (ALICE)

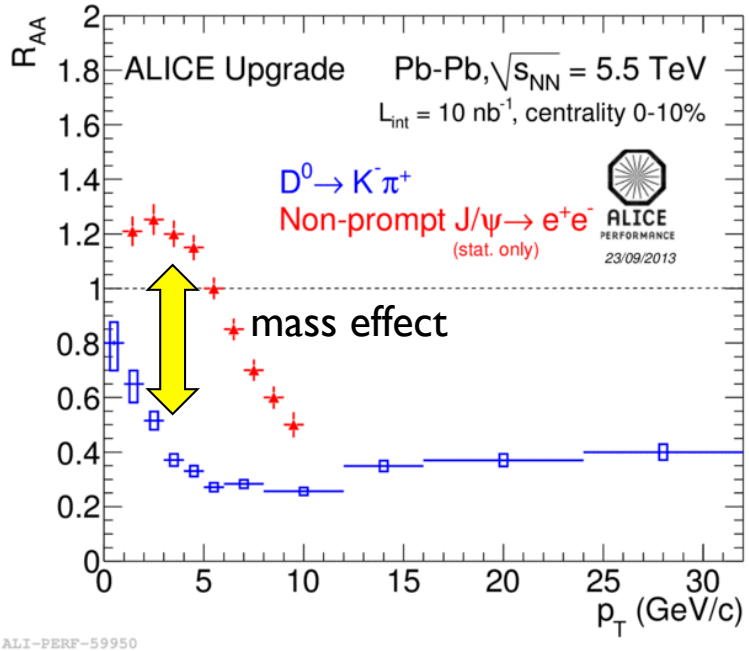
LHCP2015

HL-LHC → HQ as probes the in-medium interactions and of its thermalization

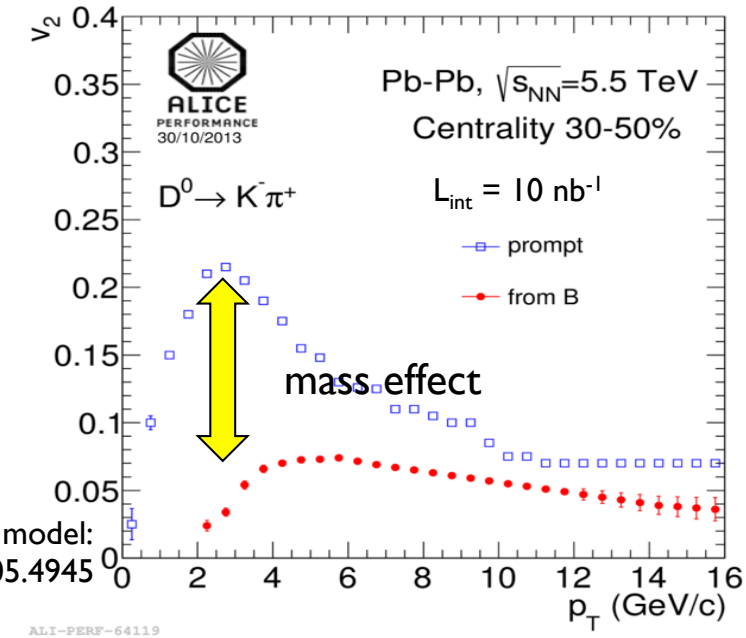
- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

→ R_{AA} and v_2 of D and B in 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

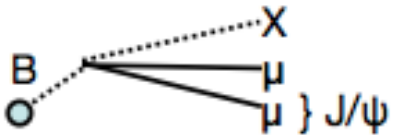
HF forward rapidity: performance (ALICE)

LHCP2015

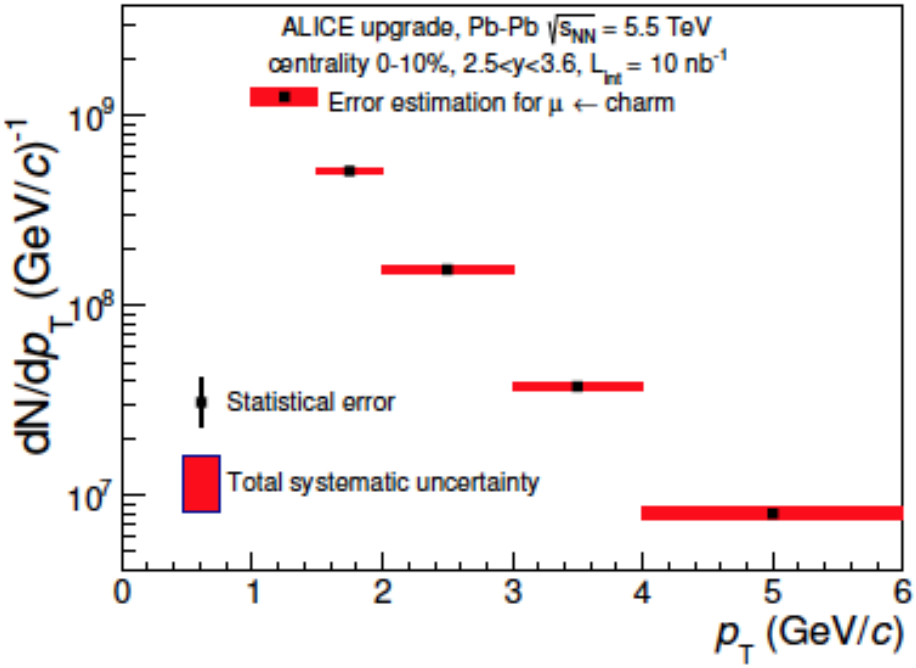
- ALICE Muon Forward Tracker: pixel tracker ($2.5<\eta<3.5$) in front of the muon spectrometer; enables separation of beauty decay vertices
- Open Heavy Flavour down to $p_T \sim 0$:

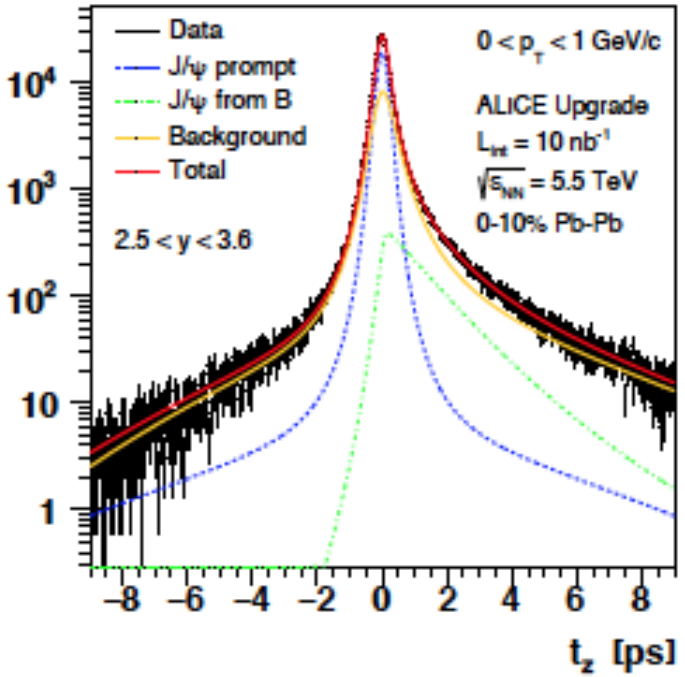
ALICE Upgrade
$L_{int}=10\ nb^{-1}$

Single muons via offset at primary vertex (charm, beauty)



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

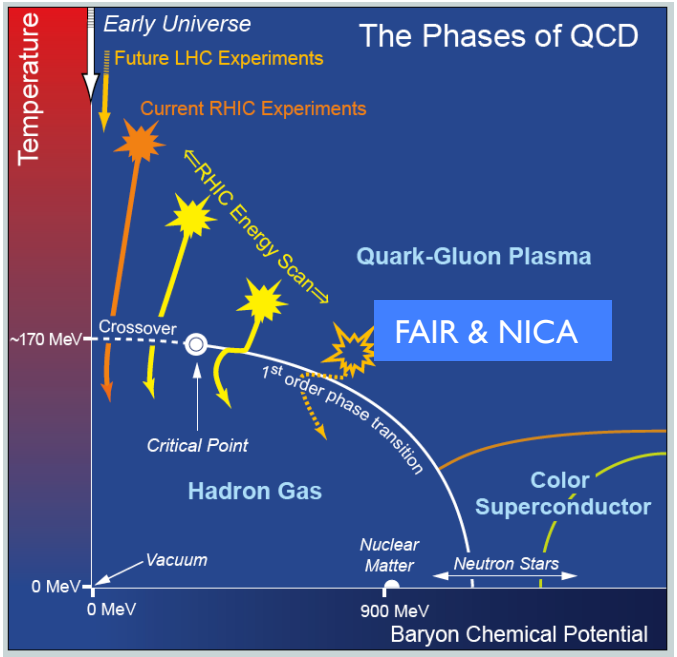




CERN-LHCC-2015-001

Future facilities - NICA/FAIR

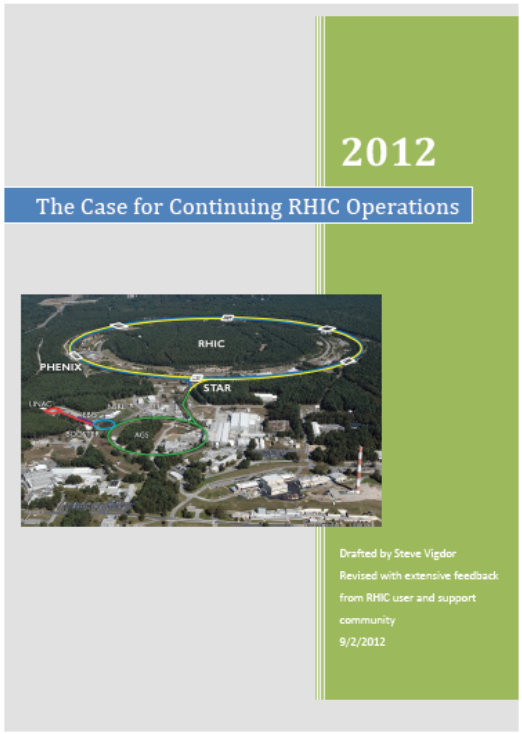
- **QCD matter at NICA** ($\sqrt{s_{NN}}$=4-11 GeV) **and FAIR/SIS100** ($\sqrt{s_{NN}}$= 4.7-7.5 GeV)
  - Highest net baryon density
  - Energy range covers onset of deconfinement
  - Complementary to the RHIC/BES, FAIR and CERN experimental programs



- **Bulk properties, EOS**
  - ***particle yields & spectra, ratios, femtoscopy, flow***
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high ρB**
  - ***enhanced strangeness production***
- **QCD Critical Point**
  - ***event-by-event fluctuations & correlations***
- **Strangeness in nuclear matter - *hypernuclei***

Synergies: the future RHIC program

- RHIC community formulated their wish to continue operation for one more decade
  - Beam energy scan, (BES) II
  - Luminosity increase x10, low cost
  - Different ion species (U-U, Cu-Au) @ 200 GeV



- Physics program (examples)
  - Search of onset of deconfinement and critical point
  - Study of temperature dependence of QGP transport parameters
  - Transition from strong coupling to asymptotic freedom
  - Study origin of initial density fluctuations

→implies machine and experiment upgrades

→complementary to LHC programme

Summary

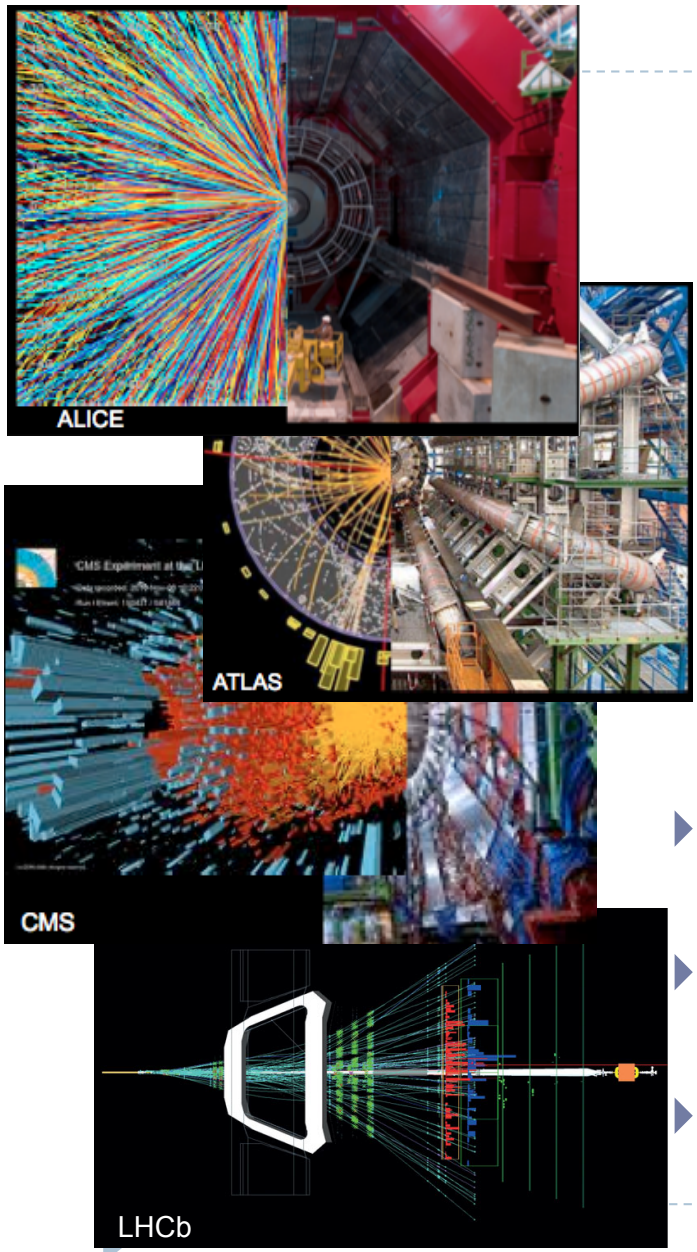
- "HL-HI-LHC" (Runs 3+4): fully exploit the potential of the machine as a high-luminosity HI collider
  - Pb-Pb >10/nb → x10 wrt Run 2, x100 for minimum bias (ALICE)
  - pp reference at Pb-Pb energy; p-Pb; possibly light ions
- Rich physics programme prepared by the experiments
  - Upgraded detectors, very large statistics, diverse trigger approaches, complementary strengths of the experiments
- Future facilities: NICA and FAIR are complementary to the RHIC/ BES and CERN experimental programs
- Synergies and complementarities with the future RHIC program

Backup slides

Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade TDR: CERN-LHCC-2013-024
- CMS HI HL-LHC projections: CMS-PAS-FTR-13-025
- Presentations at the Heavy Ion Town Meeting (June 2012):
  - http://indico.cern.ch/event/HItownmeeting
- Inputs by ALICE, ATLAS, CMS to the ESPG meeting Cracow (Sep 2012)
  - http://indico.cern.ch/confId=182232
  - HI community presentation (H. Appelshaeueser) http://indico.cern.ch/getFile.py/access?contribId=16&sessionId=2&resId=0&materialId=slides&confId=182232

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}

- 2011 Pb-Pb run: $5x10^{26}$! already above nominal luminosity
- First, very successful, p-Pb run (with all four large exp!)
- Two short pp reference runs at Pb-Pb $\sqrt{s}$

Heavy Ions at the LHC: Run 2

- Run 2 (LS1→LS2):
  - Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5.1 TeV
  - p-Pb
  - pp reference at Pb-Pb energy (5.1 TeV)

- Goals (in short):
  - > x10 times larger statistics: improve precision of current measurements, explore new observables
  - Extend Run 1 measurements to ~5 TeV (energy dependence)
  - But several measurements require detector upgrades and much larger luminosity

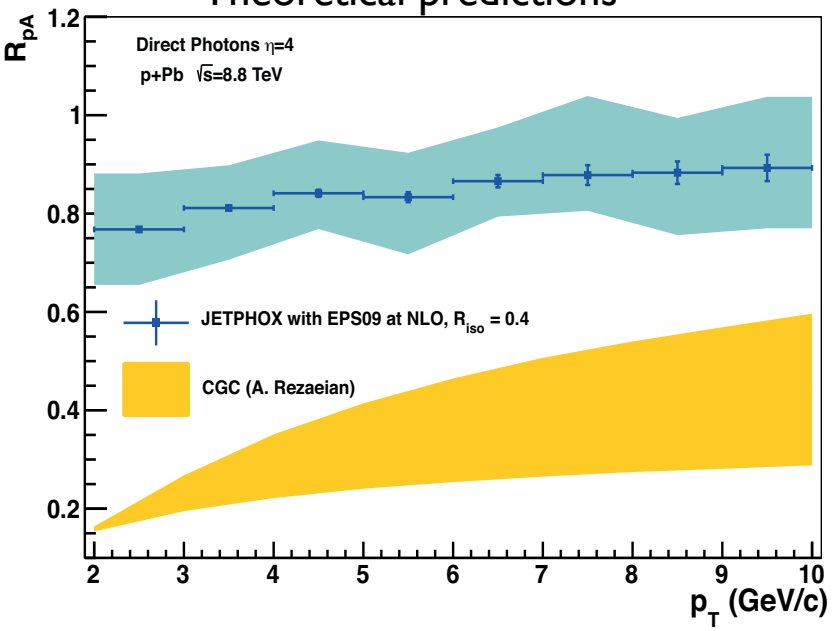
Upgrades most relevant to HI

- ALICE (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel muon tracker: precise tracking and vertexing for μ
  - New TPC readout chambers, upgraded readout for other detectors and new integrated Online-Offline: x100 faster readout (up to 50 kHz for Pb-Pb)
- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- CMS
  - Upgrade of trigger and DAQ, L1 calorimeter trigger (LS1): enables L1 rejection at 95%, e.g. (after LS2) from 50 kHz to <3 kHz (HLT input)
  - New pixel tracker (YES15-16), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade forward calorimeter (LS3): forward jets in HI
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

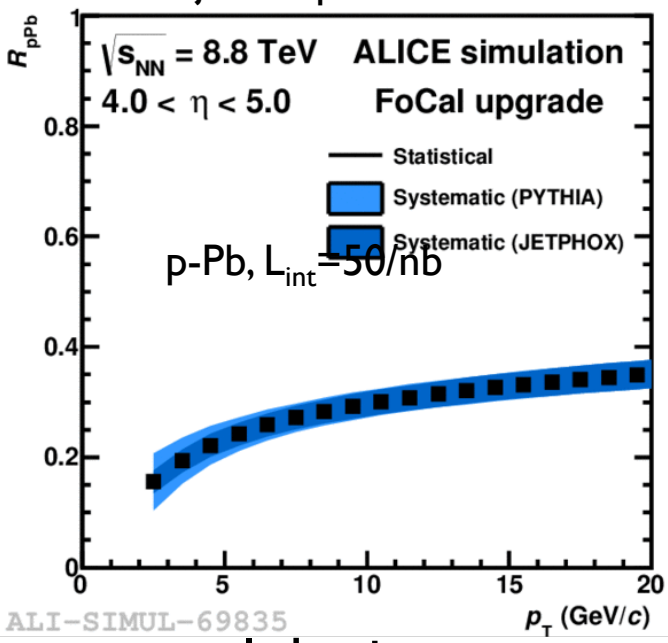
Forward photons in p-Pb: performance

- FoCal in ALICE: R&D for a new high-granularity calorimeter at η~3-5, with main focus on saturation physics studies
- Photons at $4 < \eta < 5$ are sensitive to Bjorken-x $< 10^{-5}$

Theoretical predictions



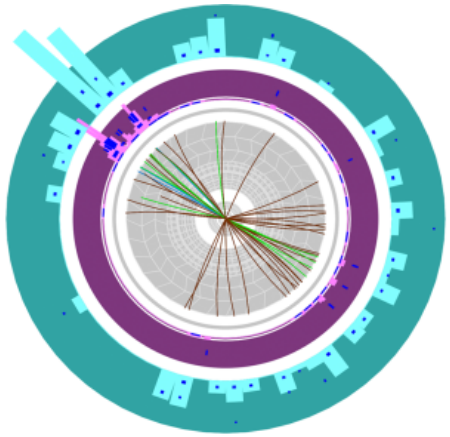
Projected performance

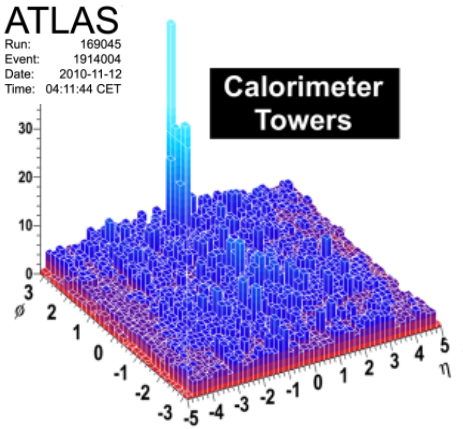


- Signature of gluon saturation in high-energy nuclei: strong suppression of forward R_{pA} = p-Pb/(N_{coll}-scaled-pp), not described within collinear factorization (NLO pQCD) + PDF shadowing

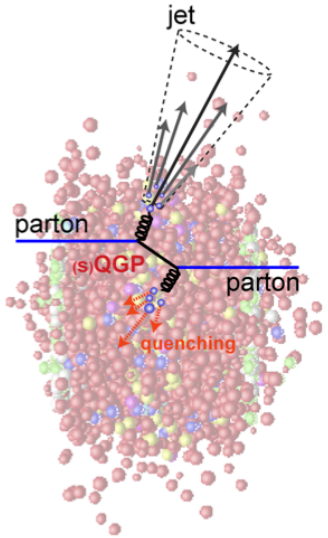
Jet quenching

- Pb-Pb events with large di-jet imbalance





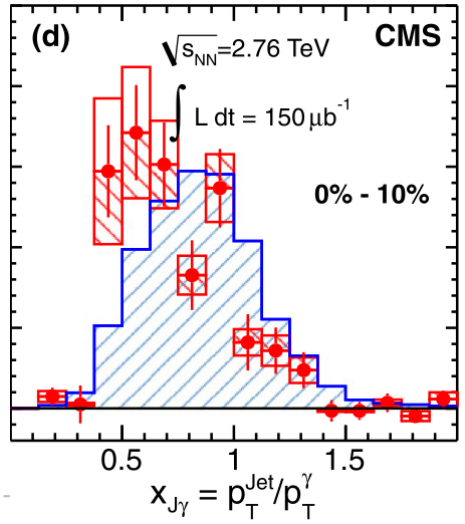
Direct observation of in-medium parton energy loss

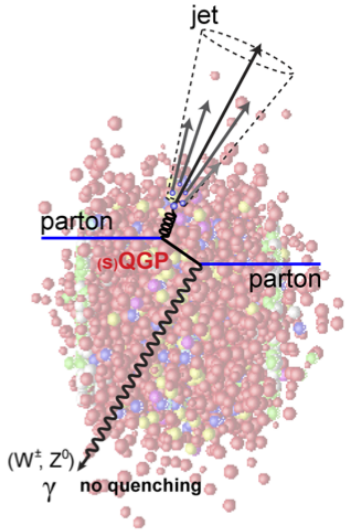


ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176

- A powerful tool: γ/Z-jet correlations
  - $E^{\gamma/Z} = E^{jet}$!
  - First measurement of γ-jet

    p_T imbalance p_T^{Jet}/p_T^{γ}

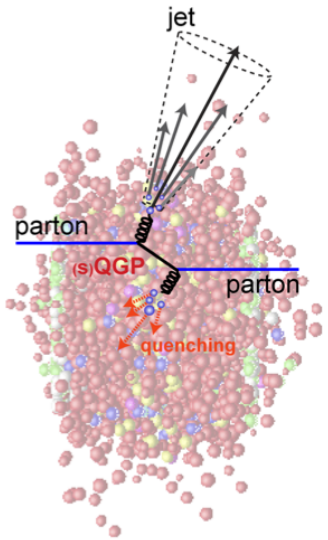


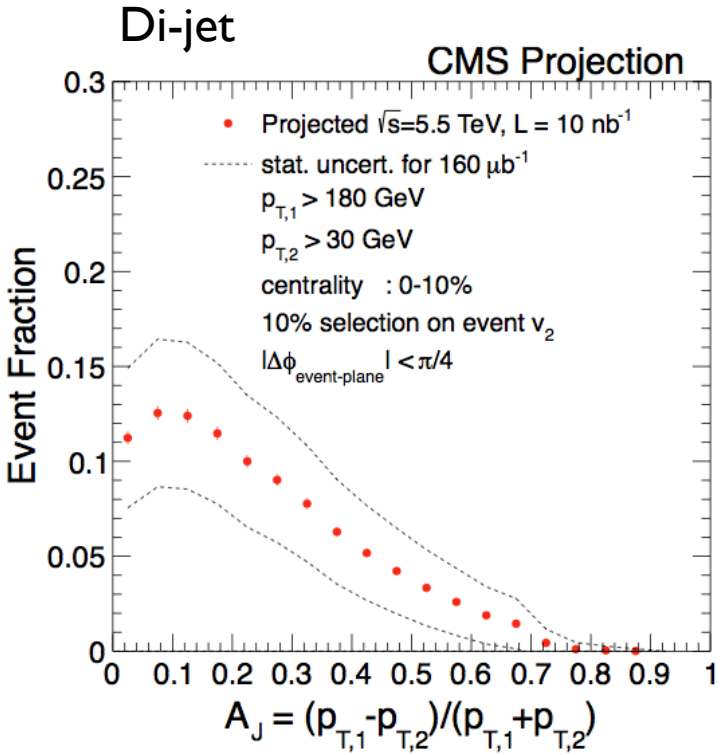


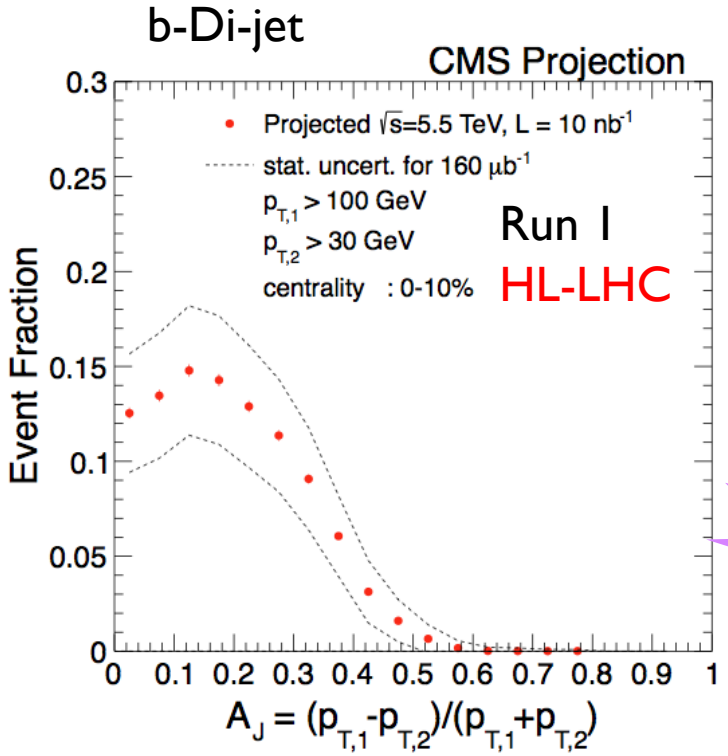
CMS, PLB718 (2013) 773

Jets: performance

- High precision γ-jet, Z-jet, di-jet correlations, 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)





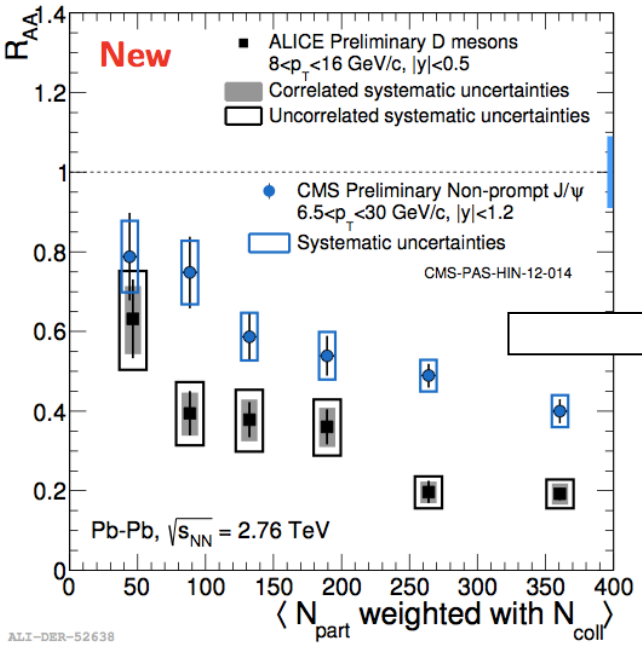


CMS, PAS-FTR-13-025

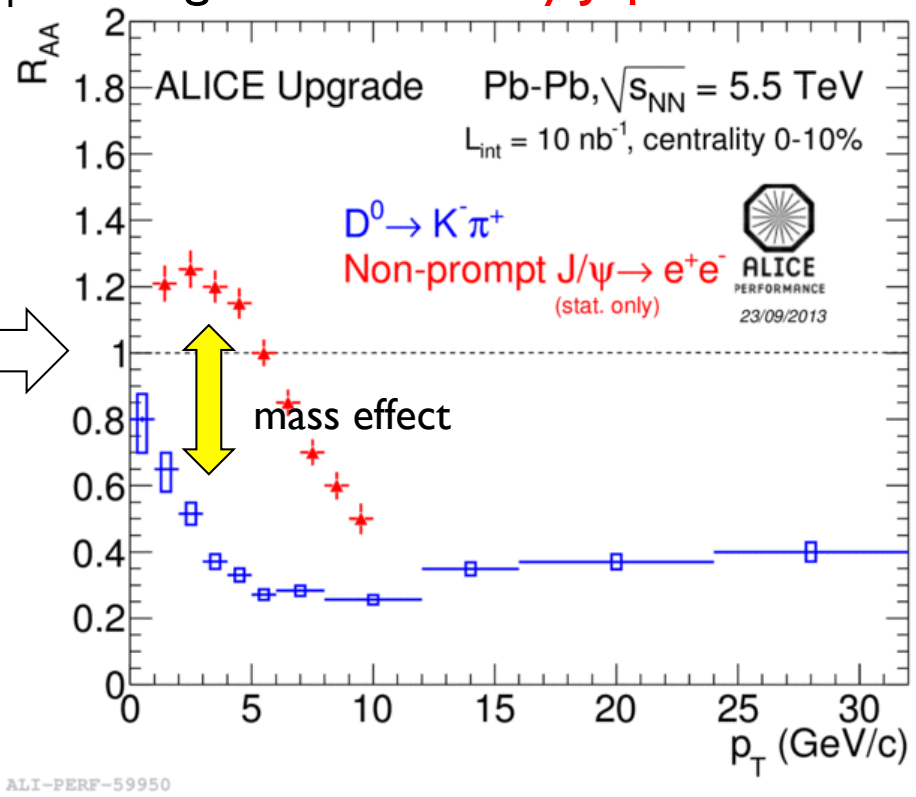
HL-HI-LHC Performance

Heavy flavour R_{AA}: Upgrade

Present data at p_T~10 GeV



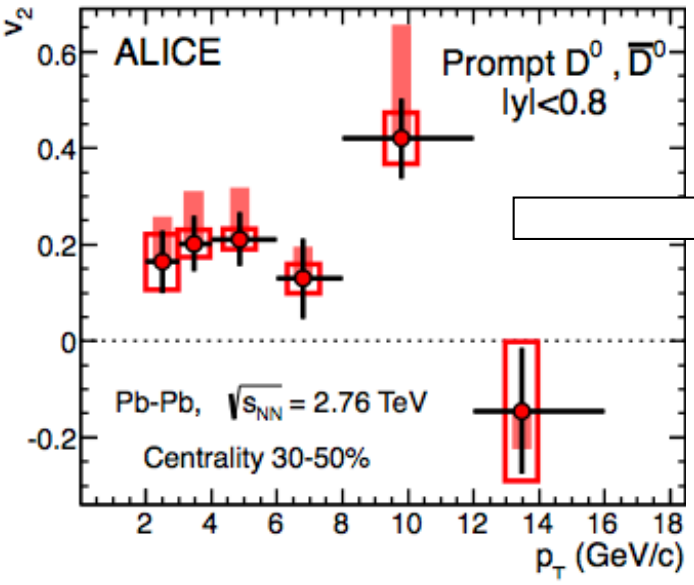
Upgrade: Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ



ALICE, CERN-LHCC-2013-024

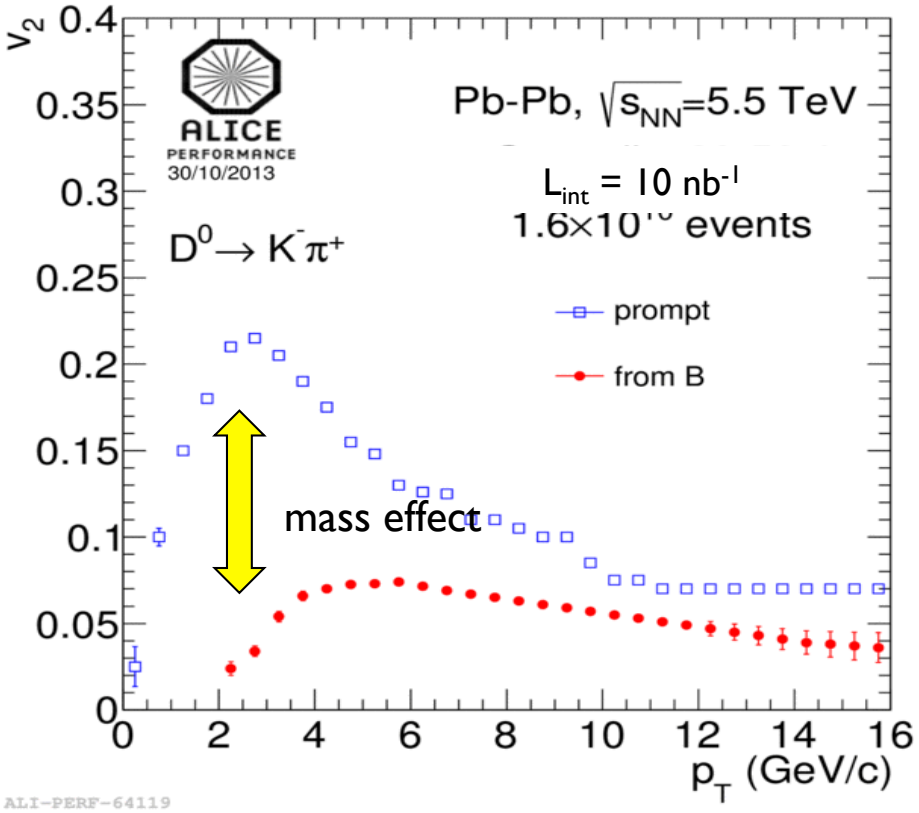
Heavy flavour flow: Upgrade

Present data on charm v_2



ALICE, PRL 111 (2013) 102301

Upgrade: Charm and beauty v_2 down to p_T~0 using prompt and B-decay D^0



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

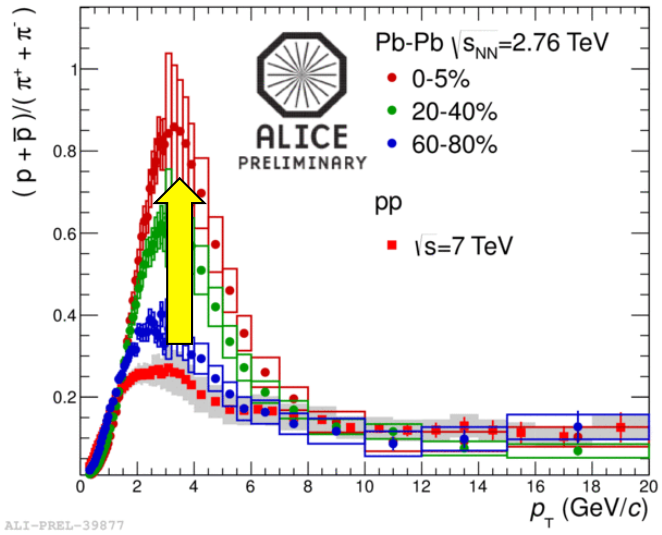
ALICE, CERN-LHCC-2013-024

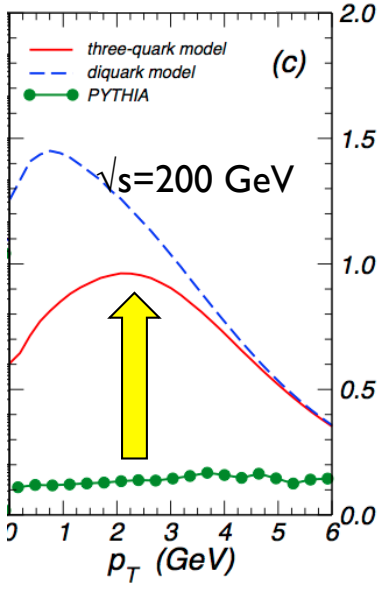
Heavy flavour in-medium hadronization?

- Baryon/meson enhancement and strange-enh. → most direct indication of light-quark hadronization in a partonic system

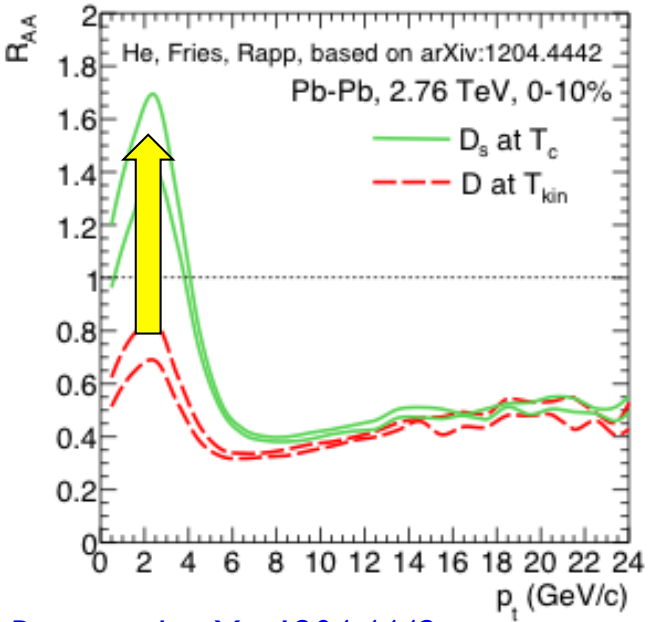
→ Measure this in the HF sector! Does it hold for charm?

→ Charm baryons (Λ_c) and charm-strange mesons (D_s)





Ko et al. PRC79

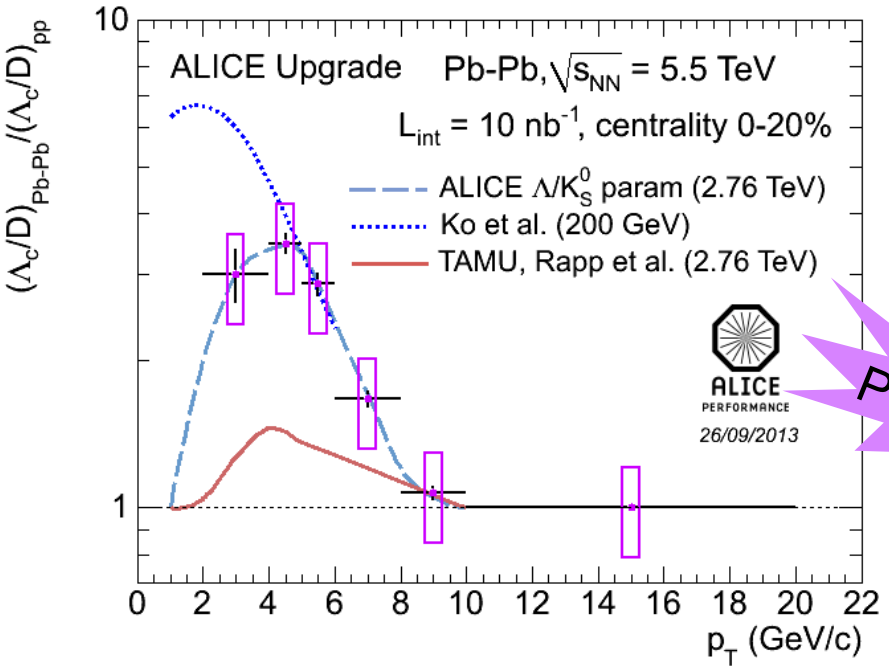


Rapp et al. arXiv:1204.4442

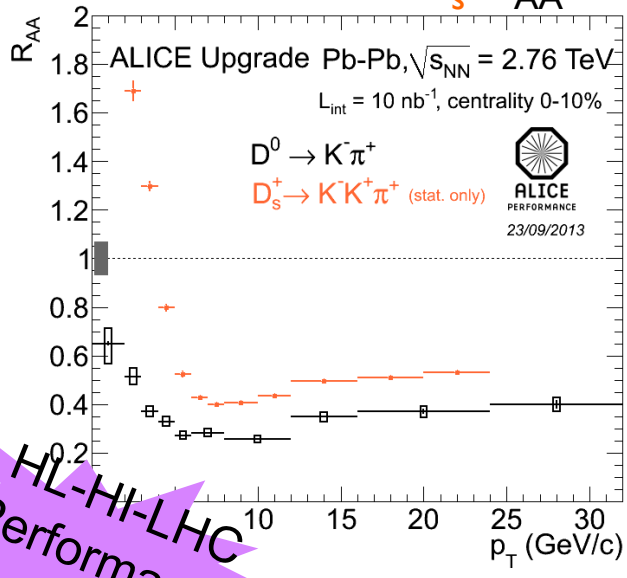
Low-p_T charm: performance

- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau$=60 and 150 μm) measured with good precision in ALICE with upgrades and 10/nb

Λ_c/D enhancement
(full detector sim.)

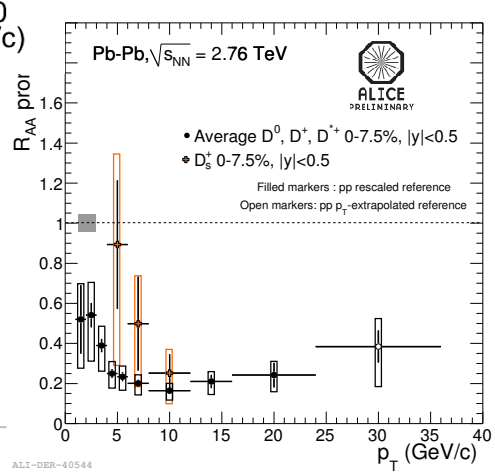


D^0 and D_s R_{AA}



HL-HI-LHC Performance

2011 data



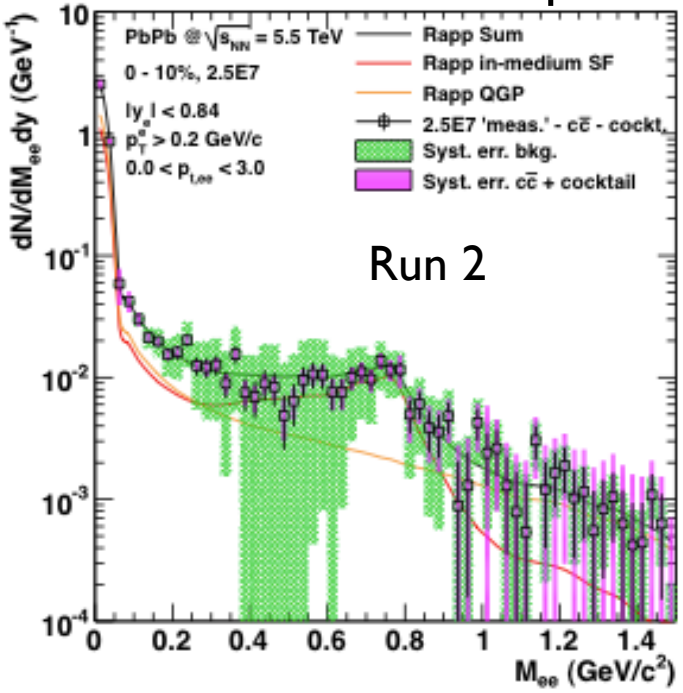
Needs minimum-bias trigger (low S/B) → HL-LHC = 100x Run2 stat.

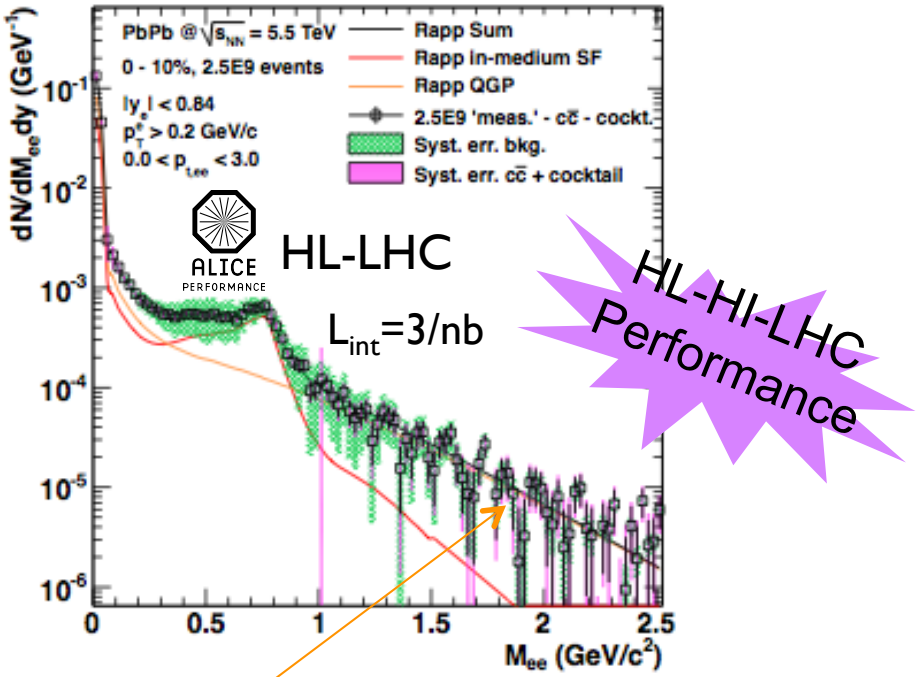
Low-mass di-leptons: performance

- ALICE: new inner tracker **+ dedicated run at 0.2 T (+3/nb)**
  → electron acceptance down to p_T = 50 MeV/c

Needs minimum-bias trigger (low S/B) → HL-LHC = 100x Run2 stat.

Di-electron mass spectrum after bkg subtraction:

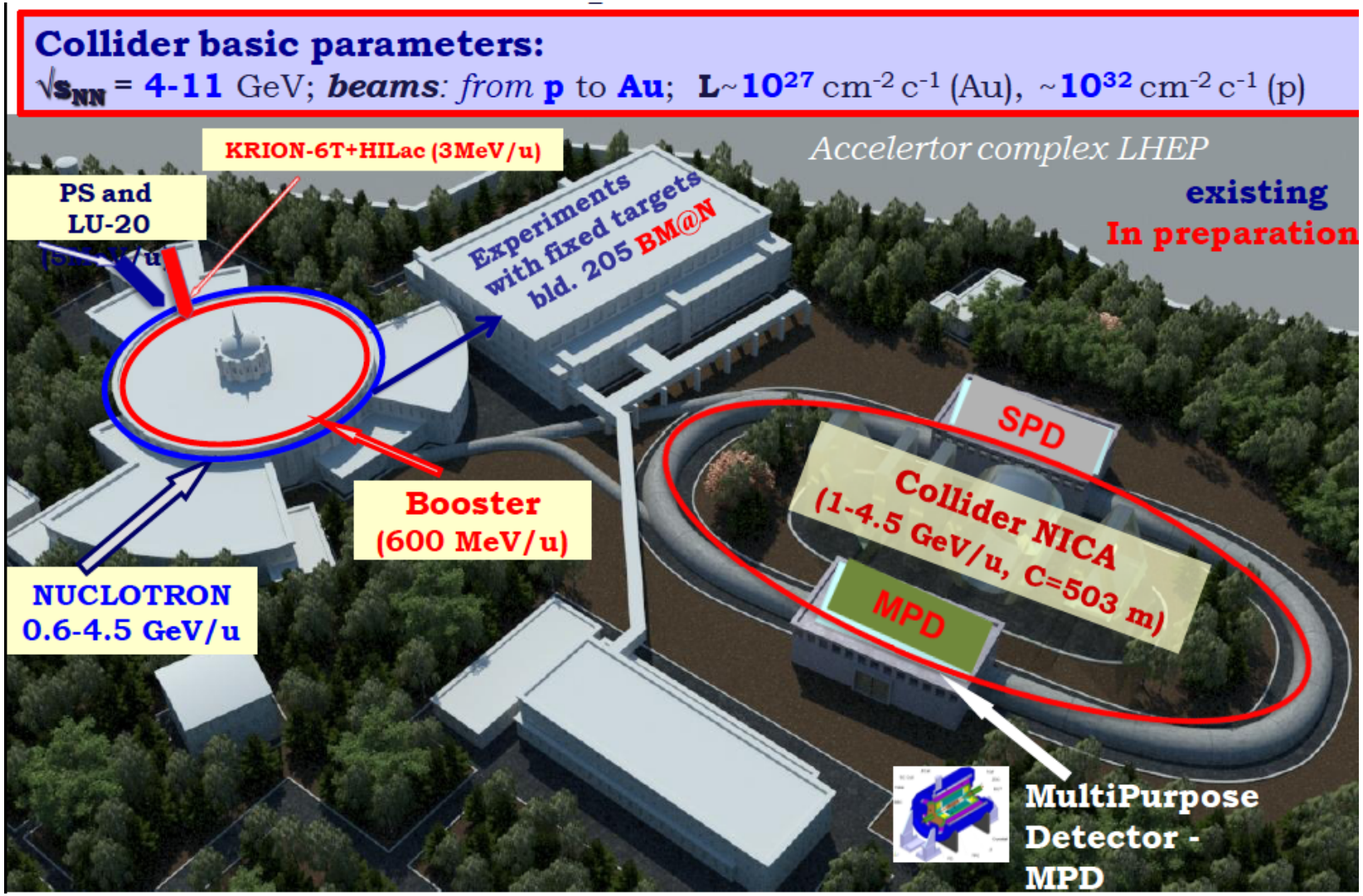




ALICE, CERN-LHCC-2012-012

Precision of ~10% on the inverse slope → T

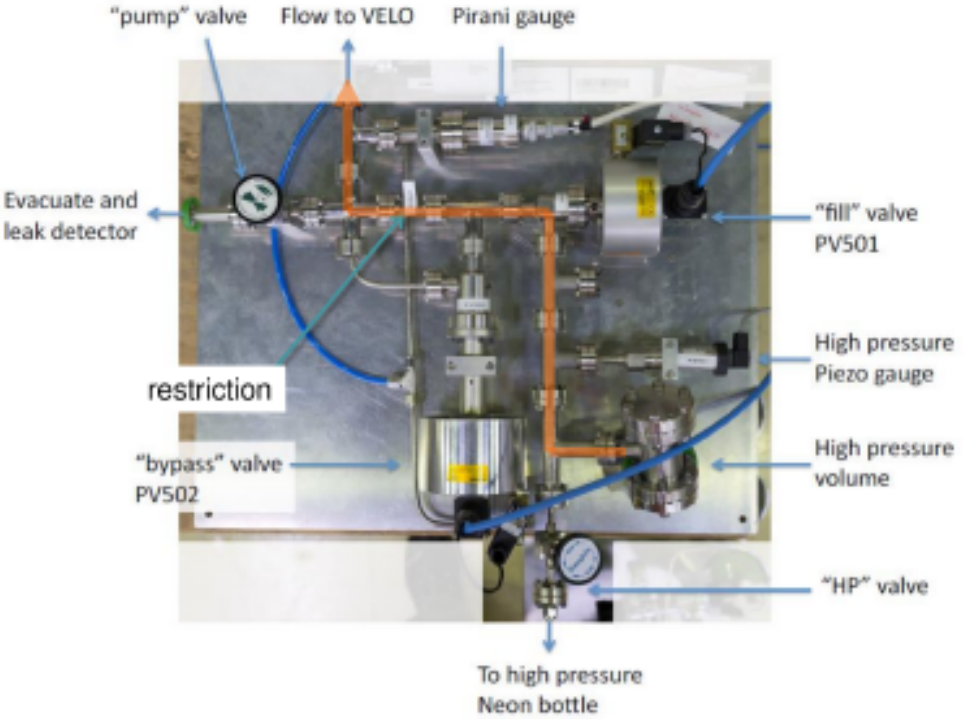
NICA


Collider basic parameters:
√sNN = 4-11 GeV; beams: from p to Au; L~10^27 cm^-2 c^-1 (Au), ~10^32 cm^-2 c^-1 (p)
KRION-6T+HILac (3MeV/u)
PS and LU-20
Experiments with fixed targets bld. 205 BM@N
Accelertor complex LHEP
existing
In preparation
SPD
Collider NICA (1-4.5 GeV/u, C=503 m)
MPD
Booster (600 MeV/u)
NUCLOTRON 0.6-4.5 GeV/u
MultiPurpose Detector - MPD

LHCb – SMOG test

- SMOG (System from Measuring the Overlap with Gas) used to inject gas into the VELO to perform a measurement of the luminosity based on Beam-Gas imaging method
- Test of readout chain including L0, HLT1 and HLT2 trigger

Test was successful.
Gas injection is working and trigger for luminosity and calibration ready



- At least, LHCb could be an ideal pilot experiment for future fixed target programs