Incontro Nazionale di Fisica Nucleare
Padova, 24-26 marzo 2014

L’upgrade di ALICE: una visione ancora più dettagliata del QGP

Andrea Dainese
(INFN Padova, Italy)
on behalf of the ALICE Collaboration

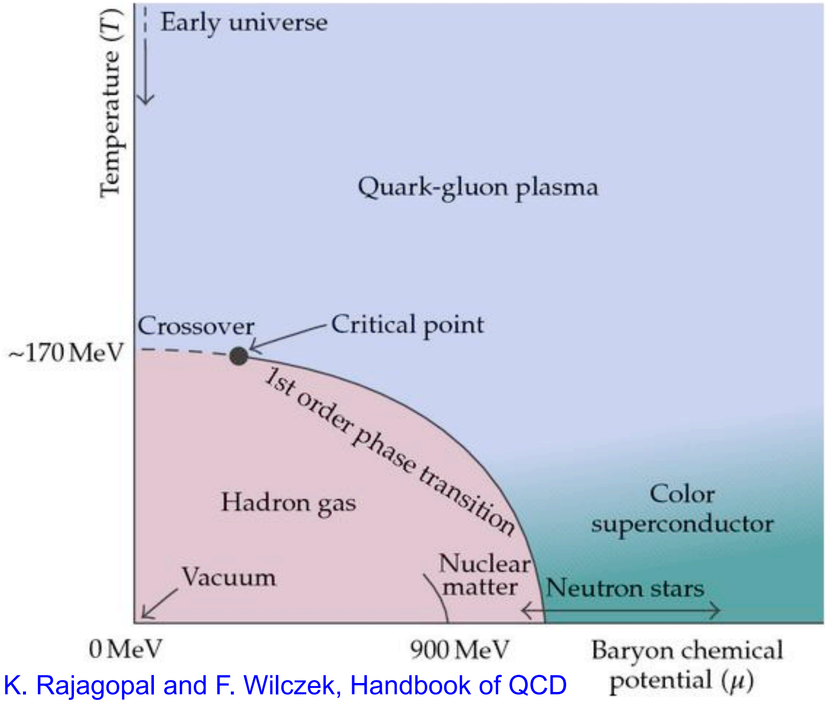
Outline

- Introduction
- Status and future of the LHC heavy ion programme
- The ALICE detector
- ALICE upgrade goals and strategy
- Brief overview of detector upgrades
- Selected aspects of the QGP: present view and prospects with upgrade
- Summary

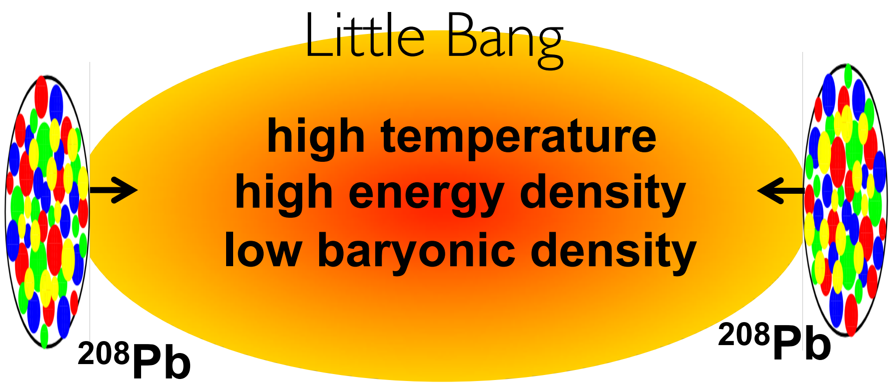
The Big Picture: ALICE and the Little Bang

- Explore the deconfined phase of QCD matter
- **High-energy nucleus-nucleus → large energy density** (~15 GeV/fm^3 at LHC) over a **large volume** (~ 5000 fm^3 at LHC)

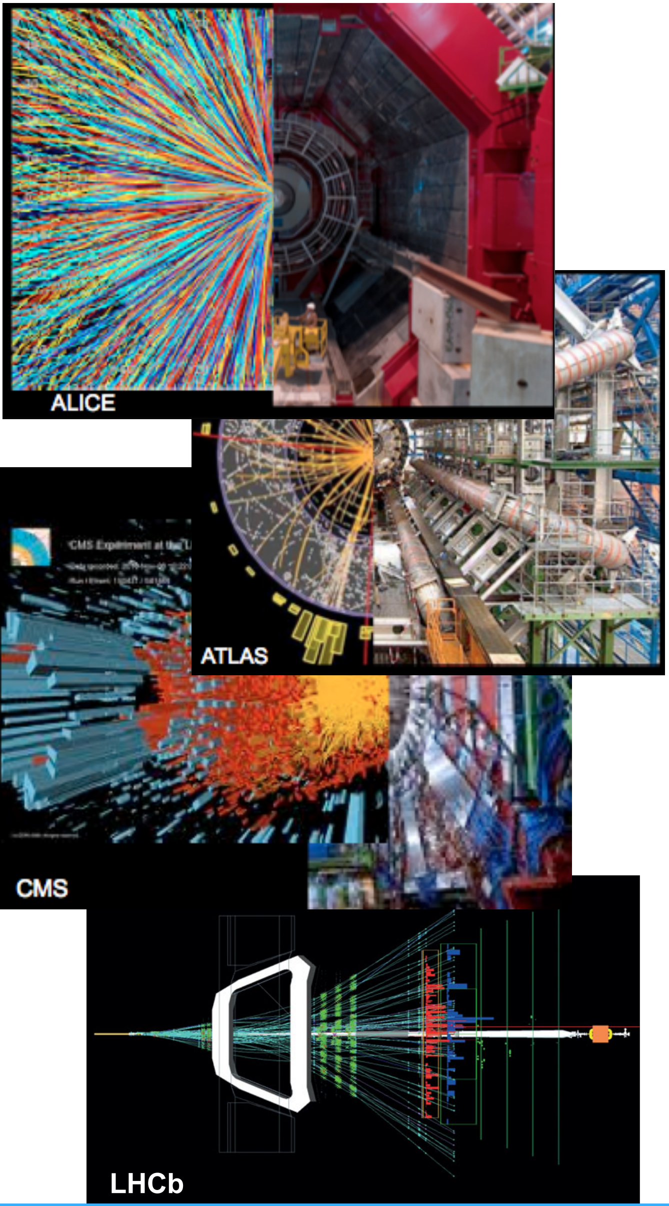
QCD Phase Diagram



K. Rajagopal and F. Wilczek, Handbook of QCD



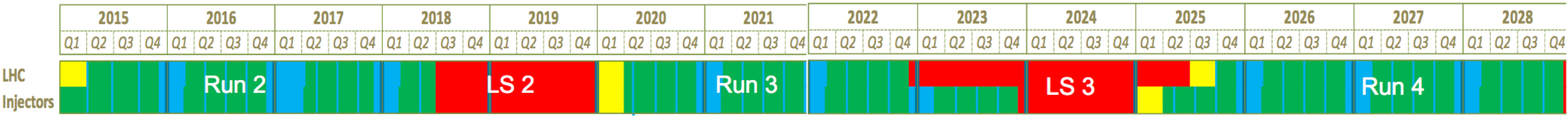
Heavy Ions at the LHC: Run 1



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

- 2011 Pb-Pb run: 5×10^{26} $cm^{-2}s^{-1}$! already above nominal luminosity
- First, very successful, p-Pb run (with all four large exp!)

Timeline of future HI running at the LHC



~0.3-1.5 nb^{-1} PbPb LS2 ~2-4 nb^{-1} PbPb LS3 ~10 nb^{-1} PbPb

Experiments request/goal:

Also corresponding pp reference

PbPb 5.1TeV	PbPb 5.1TeV	pPb? 8.2TeV

Also corresponding pp reference

ArAr pPb PbPb
5-8 TeV

PbPb pp (?)
5.5 TeV

- Run 2 (LS1→LS2): Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5.1 TeV
- LS2: ALICE upgrade, LHC lumi upgrade for ions (collimators)
- Run 3 + Run 4: Pb-Pb >10/nb, at $\sqrt{s_{NN}}$ ~ 5.5 TeV

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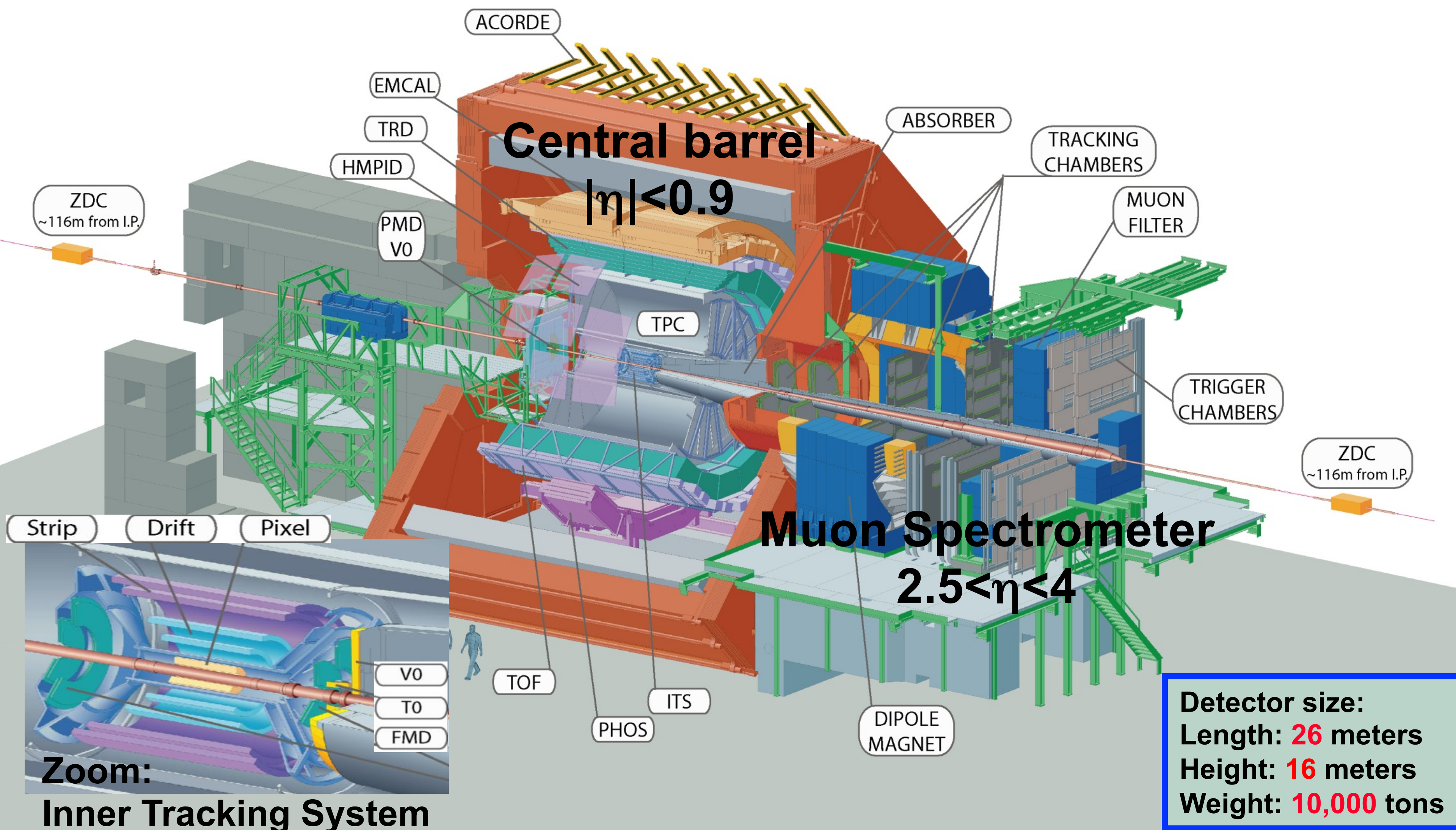
The ALICE detector



Detector size:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

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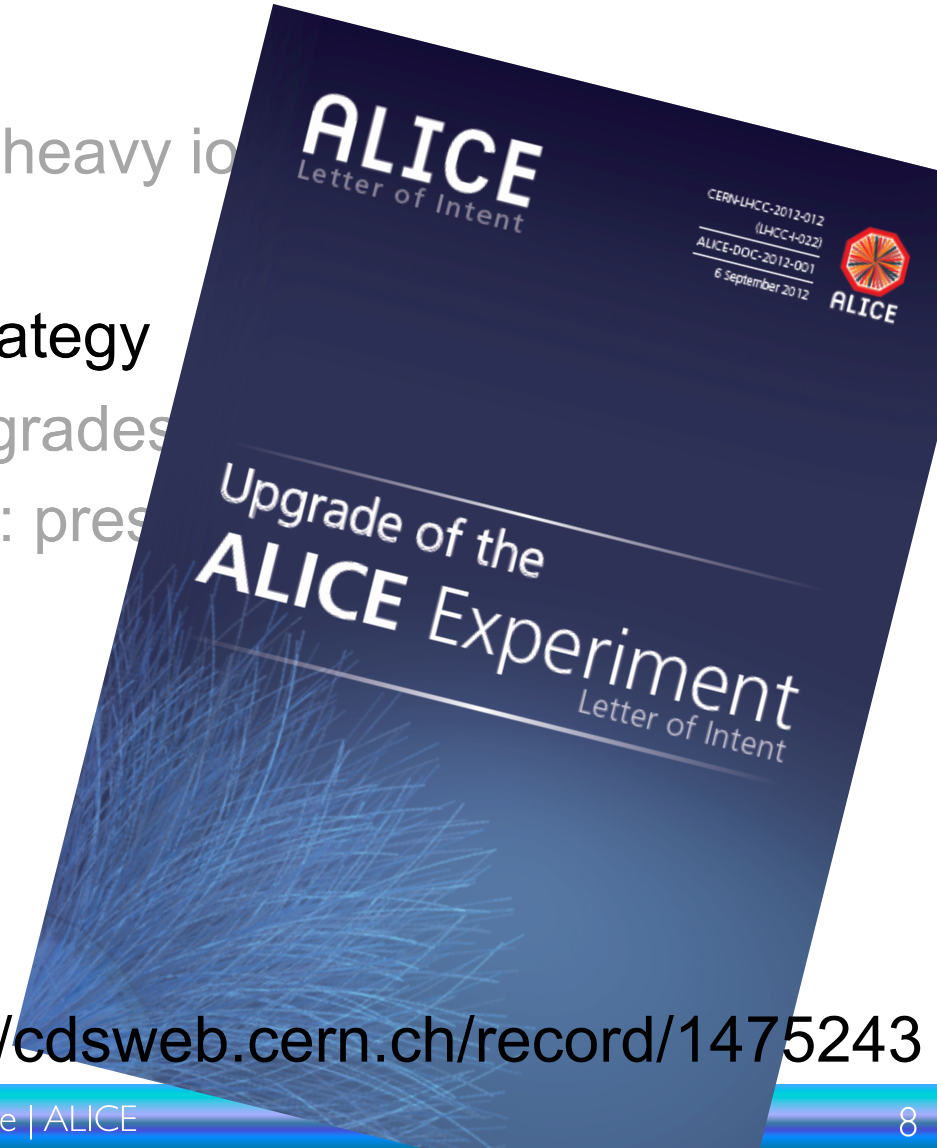


http://cdsweb.cern.ch/record/1475243

ALICE Upgrade: (main) physics questions & observables

1. **What are the mechanisms of the quark-medium (QGP) interaction? Understand QCD interactions in a multi-particle macroscopic system**

   → **Heavy flavour (charm and beauty) dynamics and hadronization at low p_T**

2. **How are the suppression and regeneration of quarkonia related to deconfinement and the QGP temperature?**

   → **Charmonia down to zero p_T**

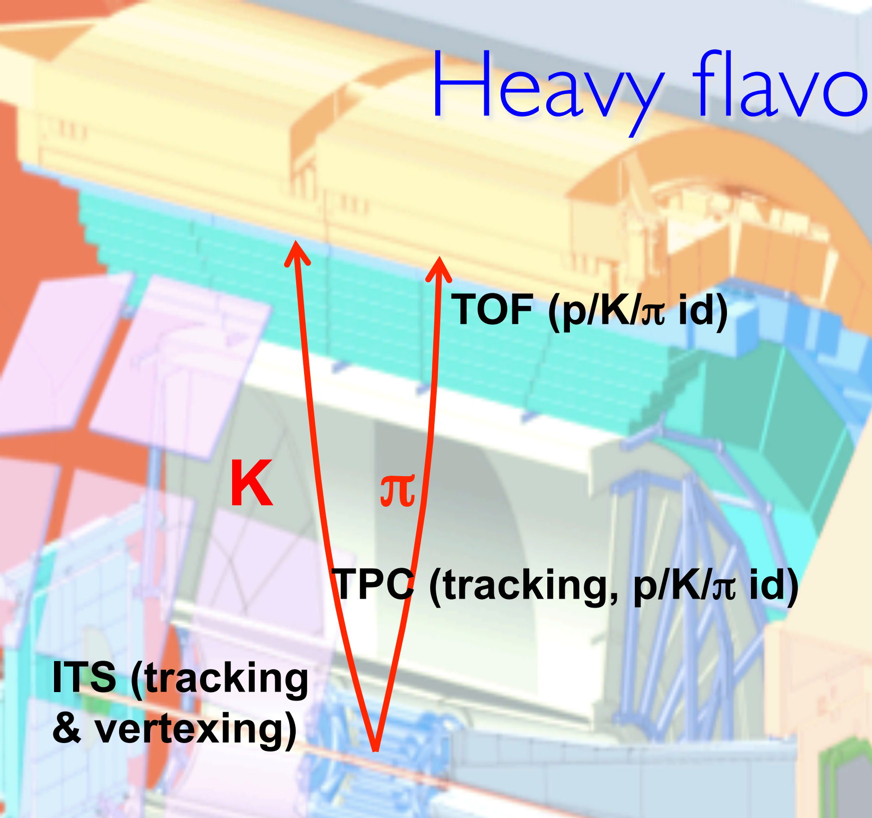
3. **What is the temperature evolution of the QGP medium?**

   → **Virtual thermal photons via the di-electron mass distribution**

More details in the following …

ALICE Upgrade LOI, CERN-LHCC-2012-012

Heavy flavour: requirements

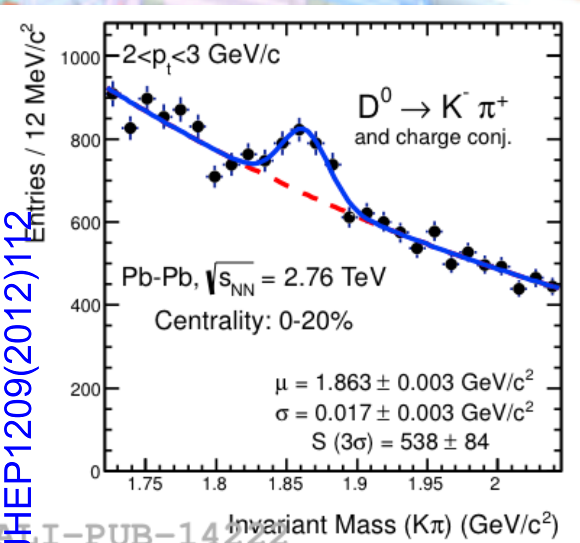


Currently, in Pb-Pb:
$D^0 \rightarrow K\pi$
$D^+ \rightarrow K\pi\pi$
$D^* \rightarrow D^0\pi$
$D_s \rightarrow KK\pi$
Goals for upgrade:
$B \rightarrow D^0+X$
$B \rightarrow J/\psi+X$
$B \rightarrow D^0\pi$
$B \rightarrow e/\mu +X$
$\Lambda_c \rightarrow pK\pi$
$\Lambda_b \rightarrow \Lambda_c\pi$

General features:

Decay at few 100 μm from interaction point

Large combinatorial background → low signal/background → no dedicated trigger



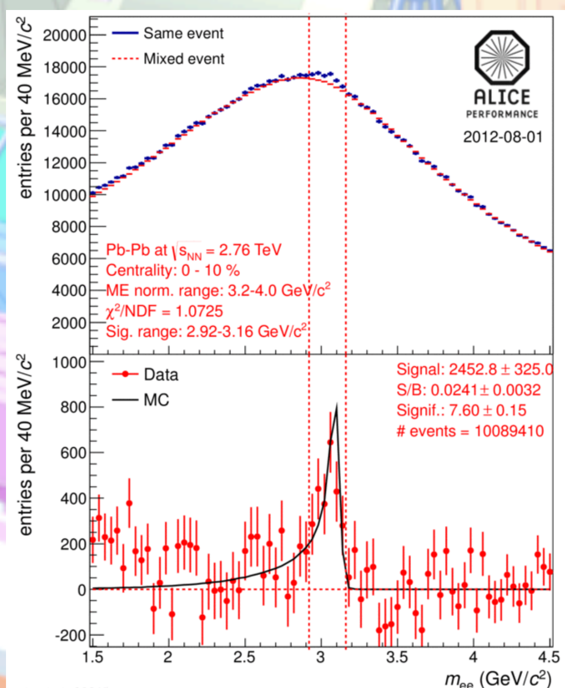
JHEP1209(2012)112

Requirements:

- **Vertexing resolution**
- **Preserve particle identification**
- **Large statistics (no dedicated trigger)**

Charmonium: requirements

e
e
ITS, TPC (tracking)
TPC, TRD, TOF (id)
μ
μ
MUON (tracking,id)



Currently, in Pb-Pb:
Incl. J/ψ → μμ
Incl. J/ψ → ee
ψ' → μμ
Goals for upgrade:
ψ' → ee
Direct J/ψ
B → J/ψ+X

General features:

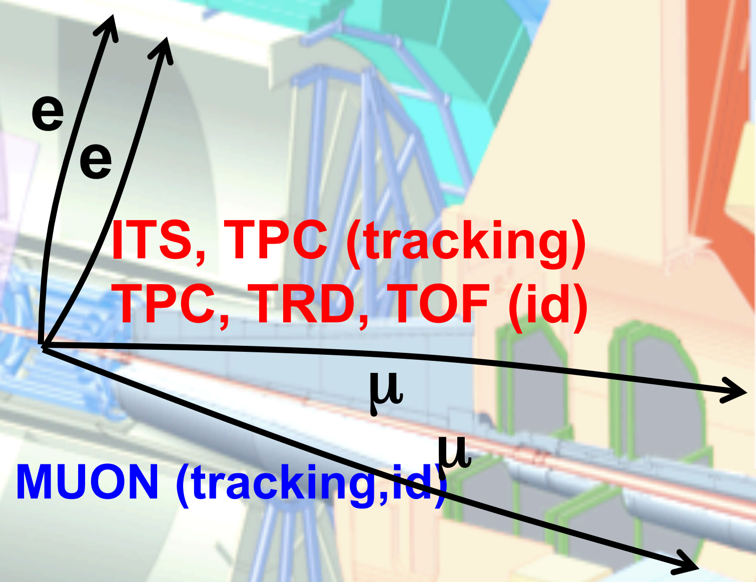
B decay few 100 μm from interaction point

Large combinatorial background in ee channel → low signal/background → no dedicated trigger

Requirements:

- **Vertexing resolution**
- **Preserve particle identification**
- **Large statistics (no dedicated trigger)**

Low-mass di-leptons: requirements



Currently, in Pb-Pb: not enough statistics

Goals for upgrade:
$\gamma^* \rightarrow ee$
$\gamma^* \rightarrow \mu\mu$

General features:

Electrons and muons with very low momentum

Large background from heavy flavour decays

Large combinatorial background → low signal/background → no dedicated trigger

Requirements:

- **Tracking efficiency at low p_T**
- **Vertexing resolution**
- **Preserve particle identification**
- **Large statistics (no dedicated trigger)**

ALICE Upgrade: summary of requirements

- Tracking efficiency and resolution at low p_T
  → increase tracking granularity, reduce material thickness

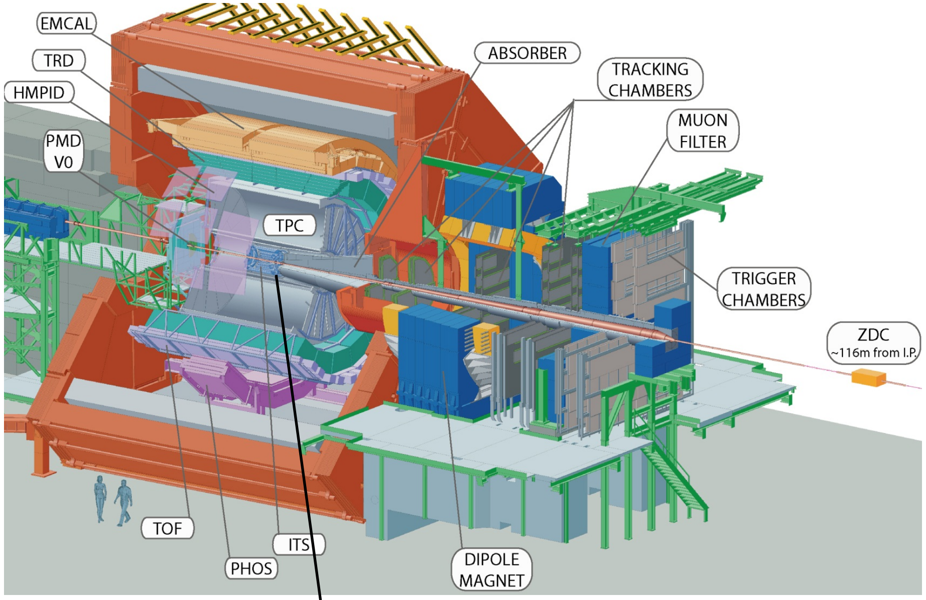
- Large statistics (no dedicated trigger)
  → increase readout rate, reduce data size (compression)

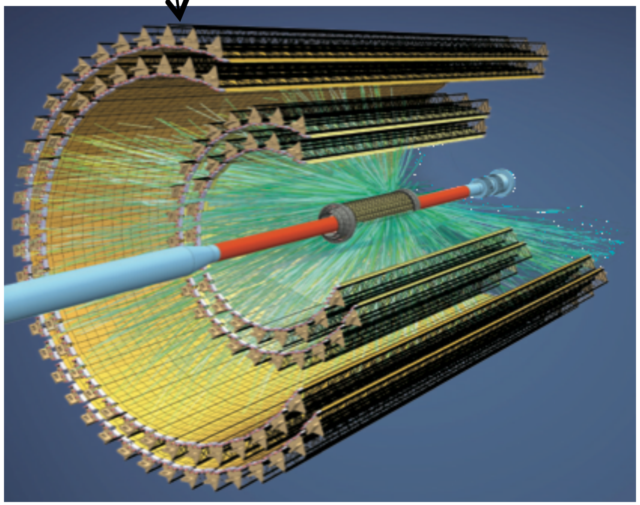
- Preserve particle identification
  → consolidate ALICE PID detectors (TPC, TOF, TRD, …)

ALICE Upgrade: strategy

→ New Inner Tracking System (ITS)

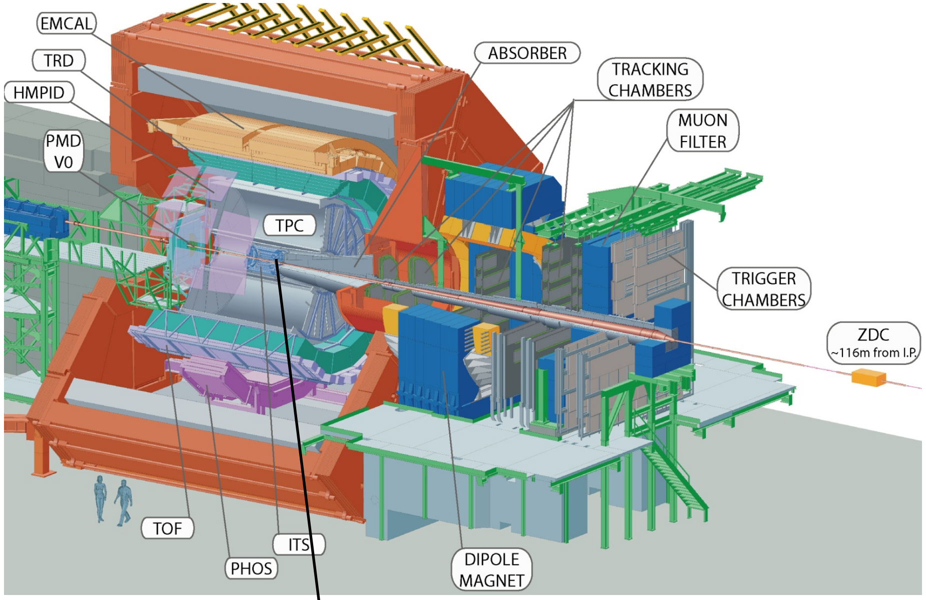
- Improved resolution, Smaller material budget, Faster readout

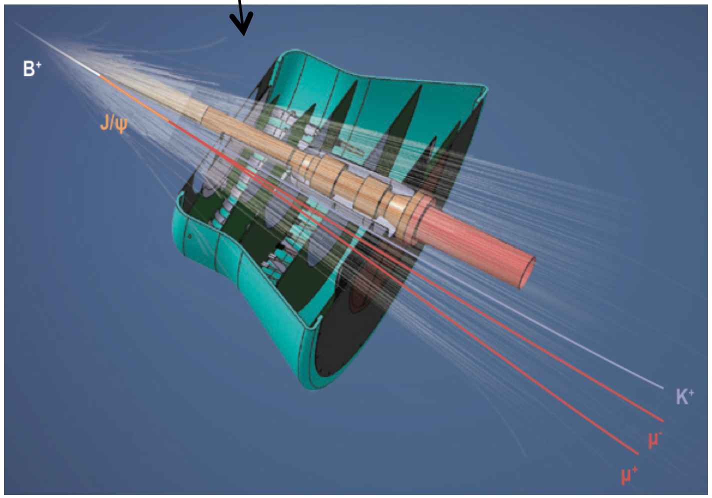




ALICE Upgrade: strategy

- → New Inner Tracking System (ITS)
  - Improved resolution, Smaller material budget, Faster readout
- → New Forward Muon Tracker (MFT)
  - Heavy flavour vertices also at forward rapidity



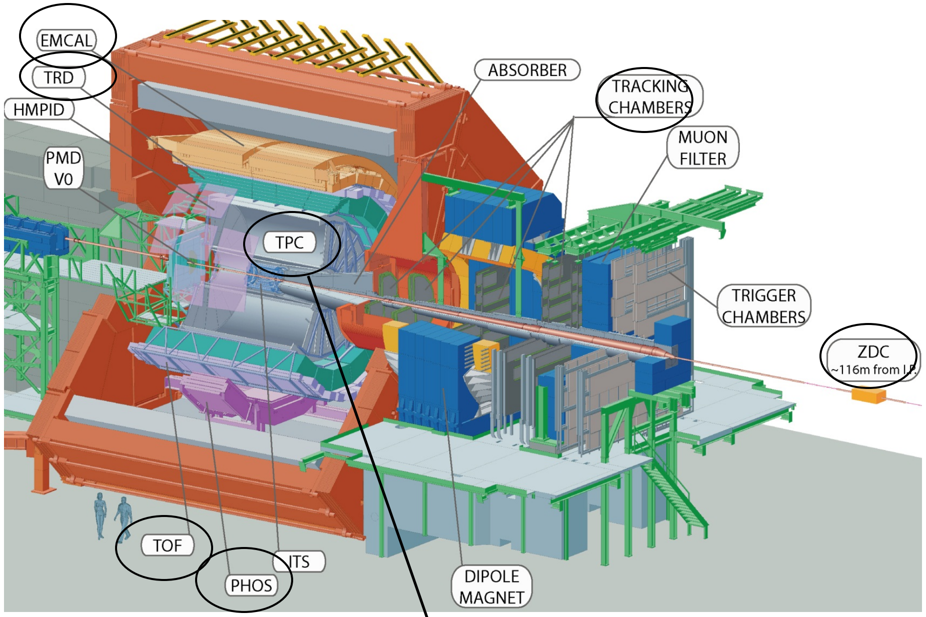


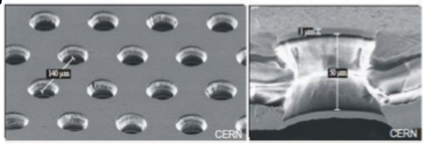
ALICE Upgrade: strategy

→ New Inner Tracking System (ITS)
- Improved resolution, Smaller material budget, Faster readout

→ New Forward Muon Tracker (MFT)
- Heavy flavour vertices also at forward rapidity

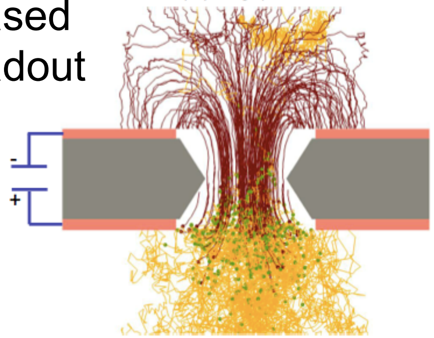
→ Upgraded read-out for TPC (GEM), TOF, TRD, PHOS, EMCAL, MUON, ZDC, Upgraded DAQ/HLT/Offline, new Fast Interaction Trigger detector
- Target LHC Pb-Pb luminosity after LS2 (~6×10^{27} $cm^{-2}s^{-1}$= 10 x current)
- Upgraded ALICE records Pb-Pb data at 50 kHz (currently <0.5 kHz)
- Integrate L_{int}=10 nb^{-1} after LS2 (~10^{11} minimum-bias Pb-Pb events)





Electron microscope photograph of a GEM foil

GEM-based TPC readout



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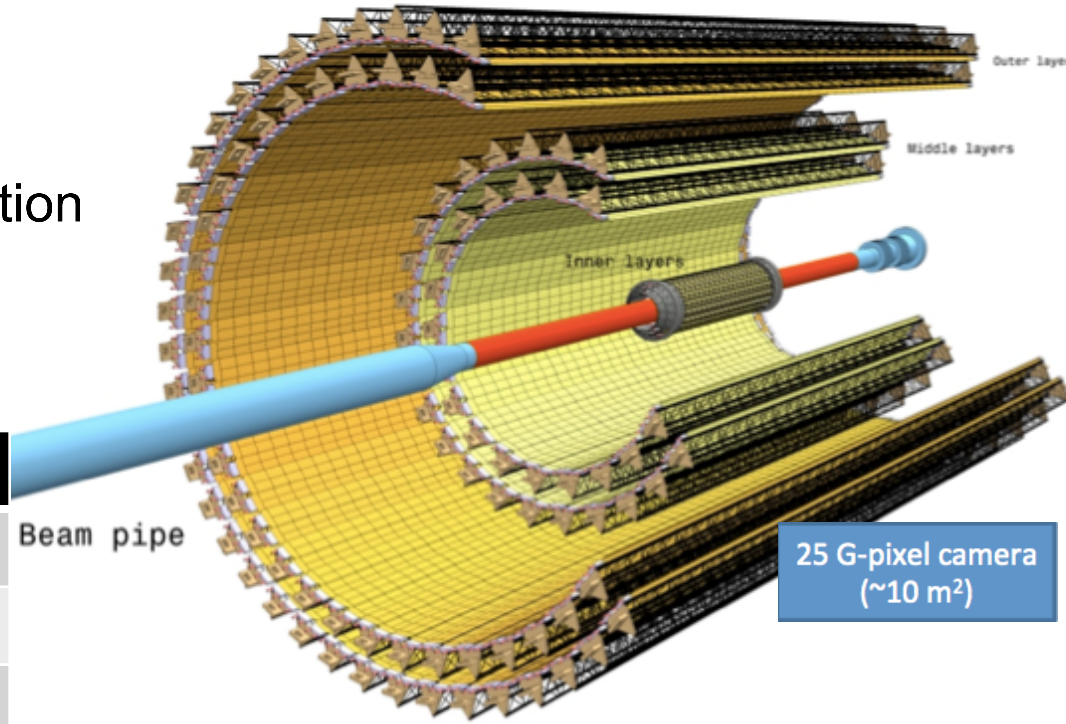
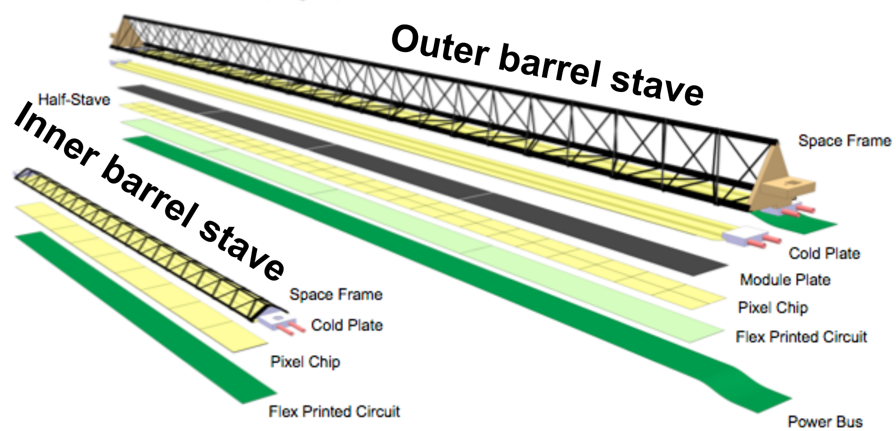
New Inner Tracking System (ITS)

- The new ITS design goals:
  - Improve vertex resolution
  - High efficiency and p_T resolution
  - Fast readout
- The new ITS features:

	Curr. ITS	New ITS
Layers	6	7
Inner radius	3.9 cm	2.3 cm
Pipe radius	2.9 cm	1.9 cm
Innermost layer thickness	1.14% X_0	0.3% X_0
Innermost layer pixel size	50x425 μm^2	20x30 μm^2
Max. Pb-Pb readout	1 kHz	100 kHz

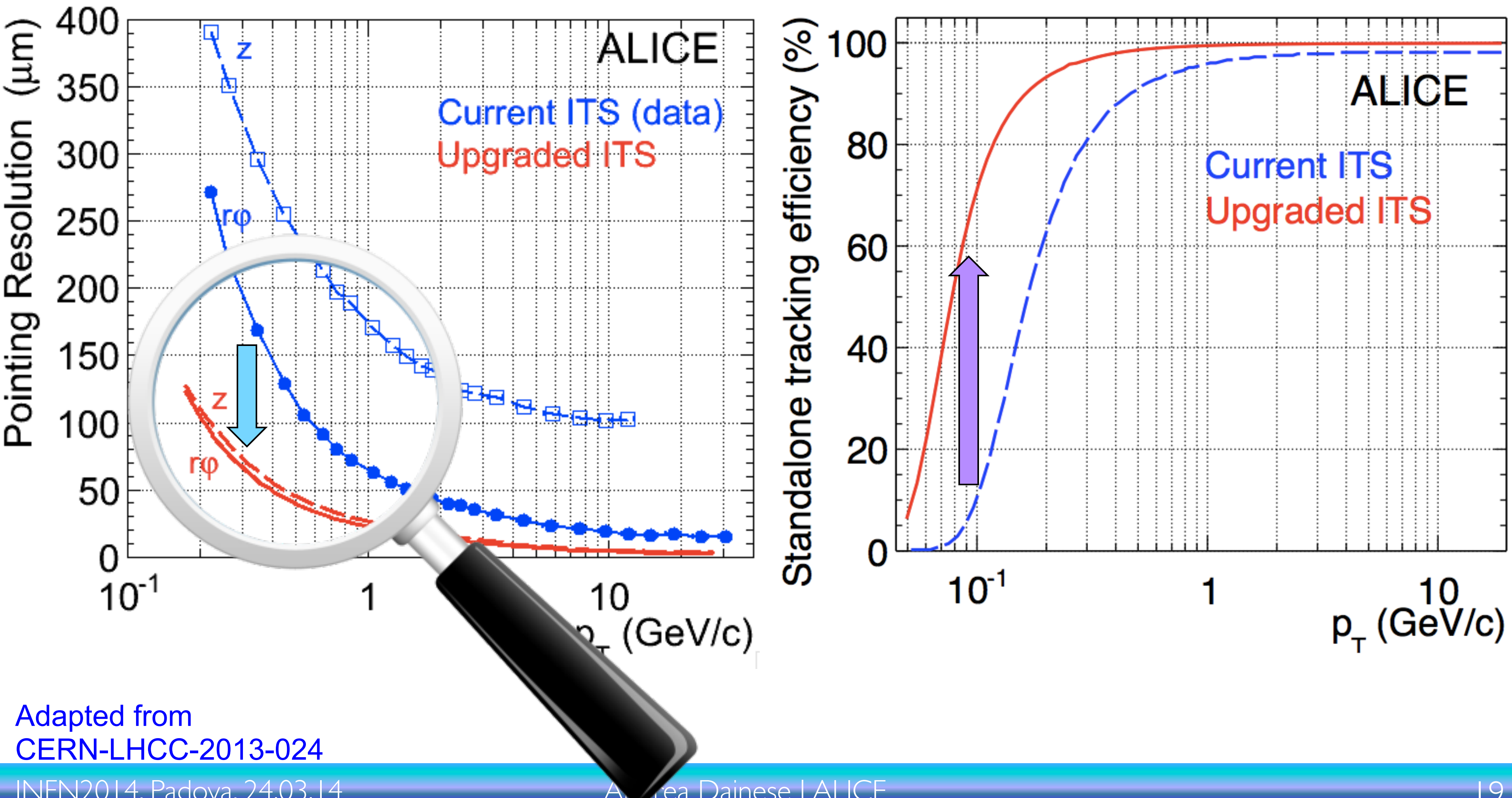
CERN-LHCC-2013-024





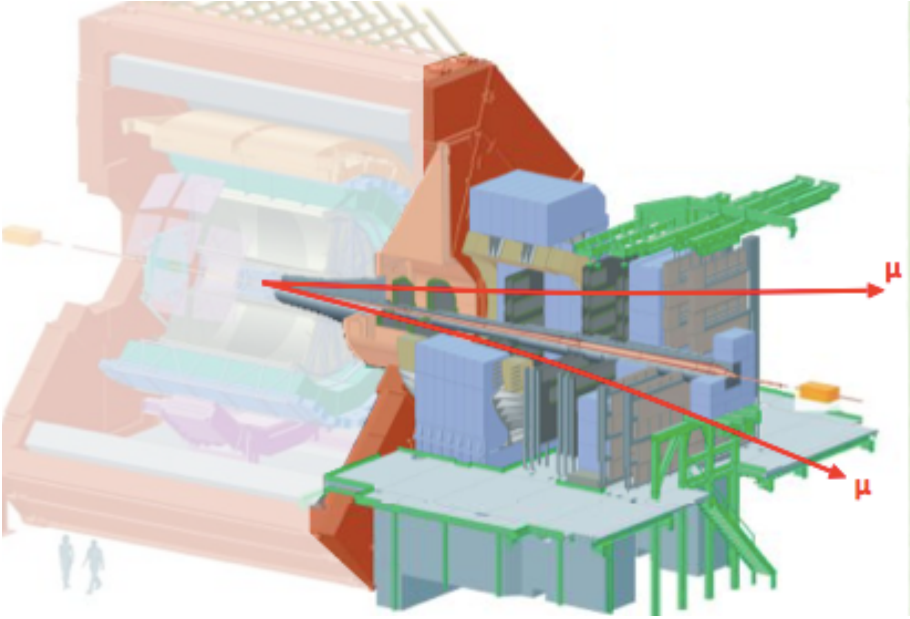
New ITS tracking performance

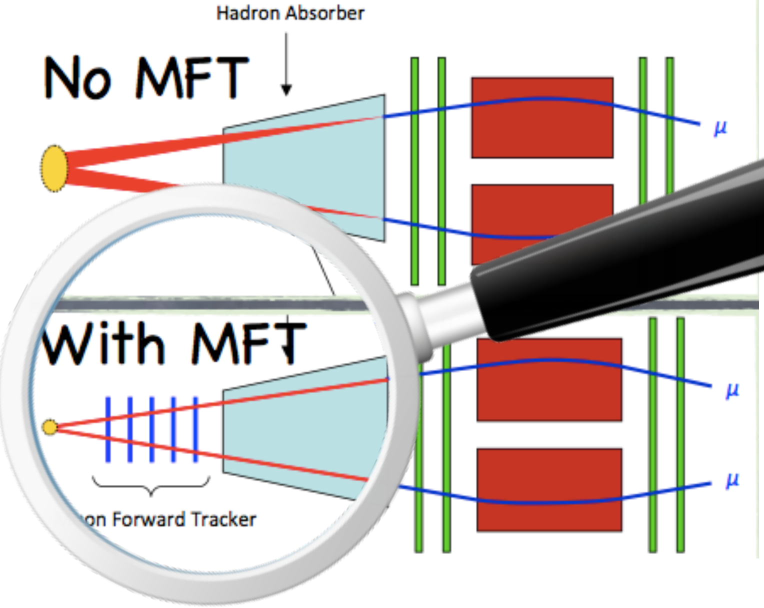
- Pointing resolution x3 better in transverse plane (x6 along beam)
- Tracking efficiency x10 better at low p_T

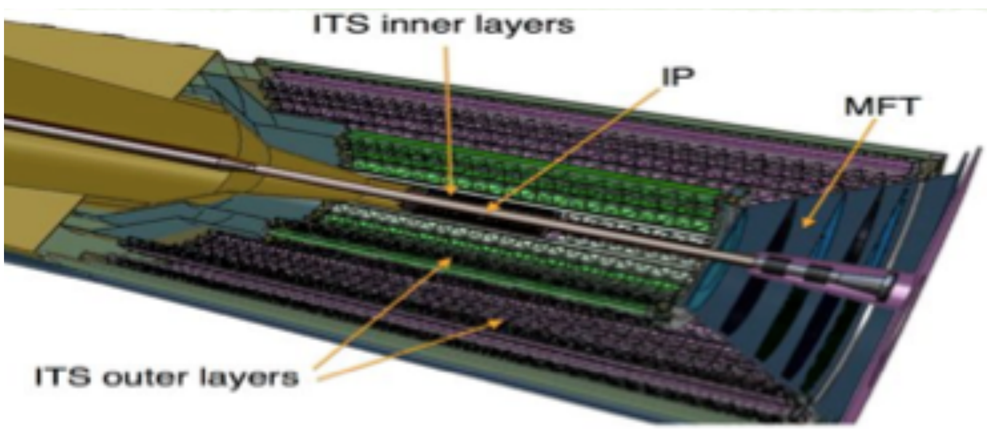


Adapted from
CERN-LHCC-2013-024

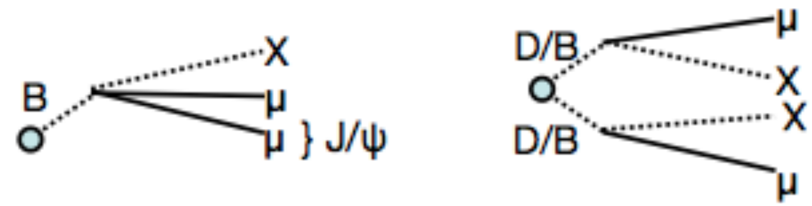
Muon Forward Tracker (MFT)







- Silicon pixel tracker in front of the muon spectrometer
- Enables separation of beauty decay vertices:



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ALICE Upgrade: physics questions & observables

1. **What are the mechanisms of the quark-medium (QGP) interaction? Understand QCD interactions in a multi-particle macroscopic system**

   → **Heavy flavour dynamics and hadronization**

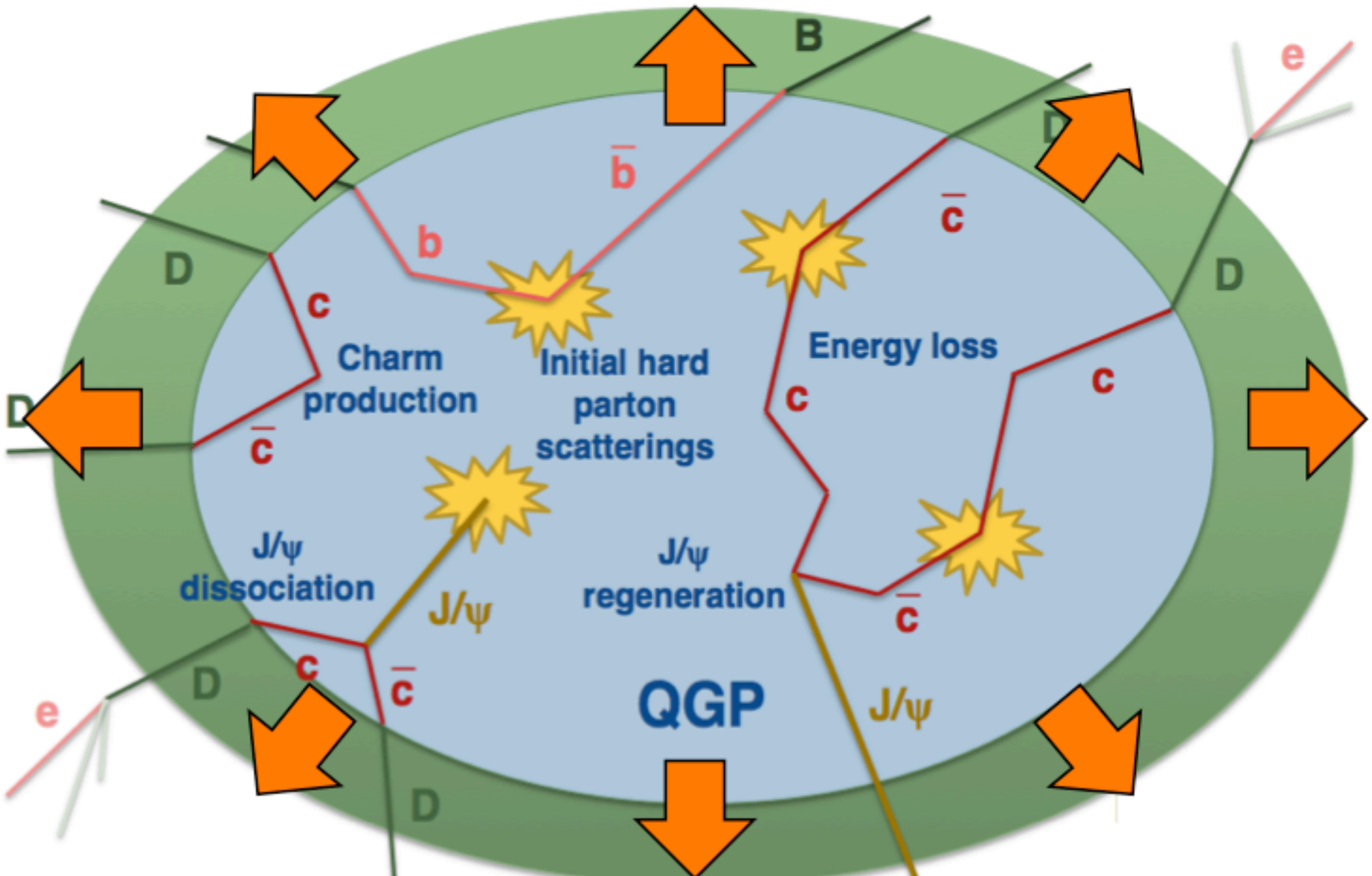
What's special about heavy quarks

- Large mass (m_c~1.5 GeV, m_b~5 GeV) → produced in large virtuality (Q^2) processes at the initial stage of the collision with short formation time $\Delta t > 1 / 2m_c \sim 0.1$ fm << $\tau_{QGP} \sim$ 5-10 fm
- Characteristic flavour, conserved in strong interactions
  - Production in the QGP is subdominant
  - Interactions with QGP don't change flavour identity
- Uniqueness of heavy quarks: cannot be "destroyed/created" in the medium → transported through the full system evolution

  → "Brownian motion markers of the medium" (*)

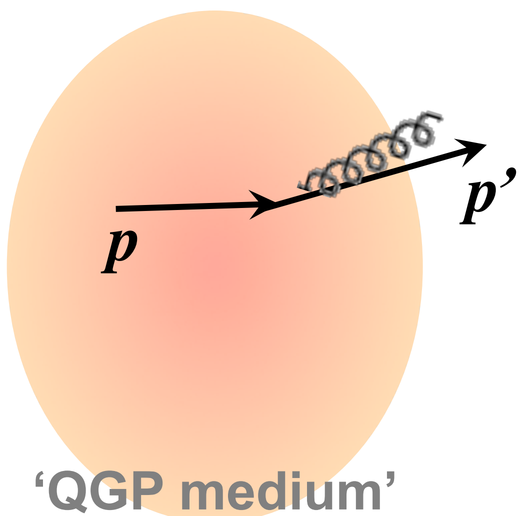
(*) Ralf Rapp

What's special about heavy quarks



graphics courtesy J. Uphoff

Parton energy loss



Parton Energy Loss by

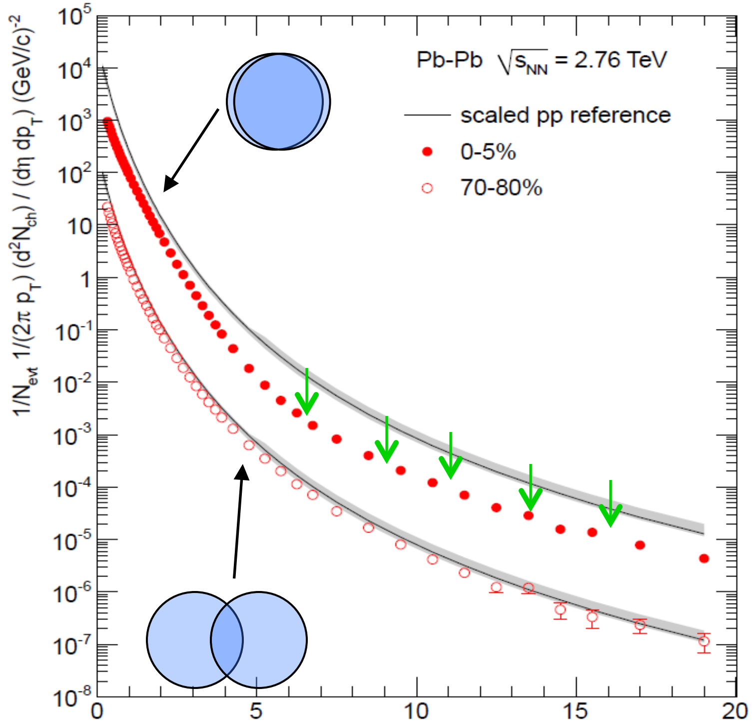
- medium-induced gluon radiation
- collisions with medium gluons

$$p' = p - \Delta E(\varepsilon_{medium})$$

Nuclear modification factor:

$$dN_{AA}/dp_T < \langle N_{coll} \rangle dN_{pp}/dp_T$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} < 1$$



ALICE, PLB 696, 30 (2011)

Heavy Flavour energy loss

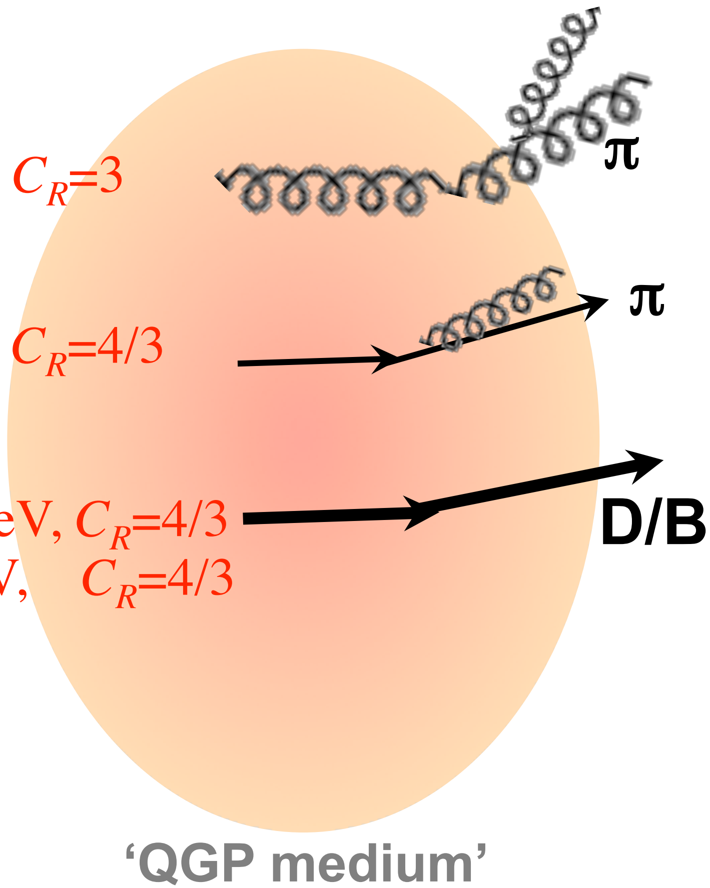
Heavy Quarks (charm and beauty): a tool to characterize the properties of the parton-medium interaction

g: $m=0,\ C_R=3$

u,d,s: $m\sim 0,\ C_R=4/3$

c: $m\sim 1.5$ GeV, $C_R=4/3$

b: $m\sim 5$ GeV, $C_R=4/3$



Parton Energy Loss predicted to depend on:

- Color charge C_R (larger for gluons)
- Mass m (larger for heavy quarks)

$$\Delta E(\varepsilon_{medium}; C_R, m)$$

pred: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

→ $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$

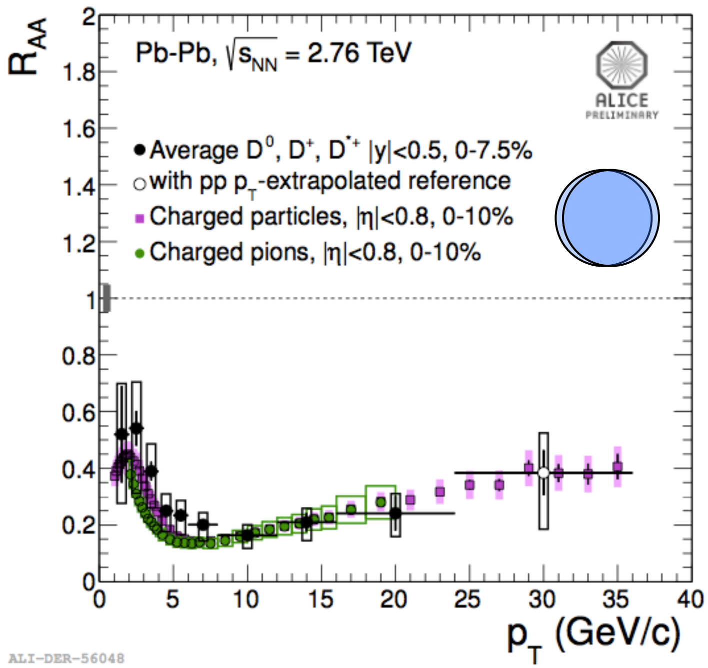
Reminder:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

See e.g.:
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

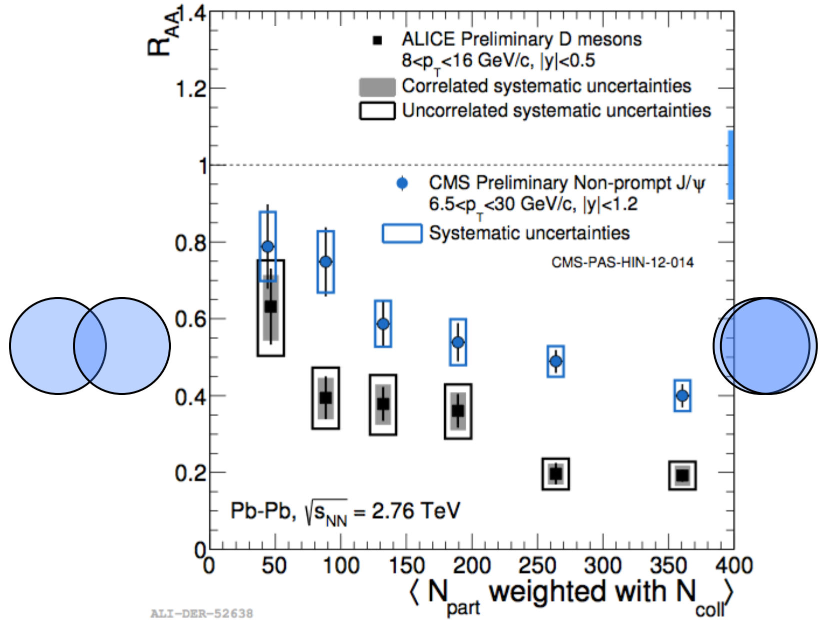
Heavy flavour R_{AA}: status from Run I

- D consistent with pions within uncertainties



Need to improve precision and accuracy to conclude on D vs π

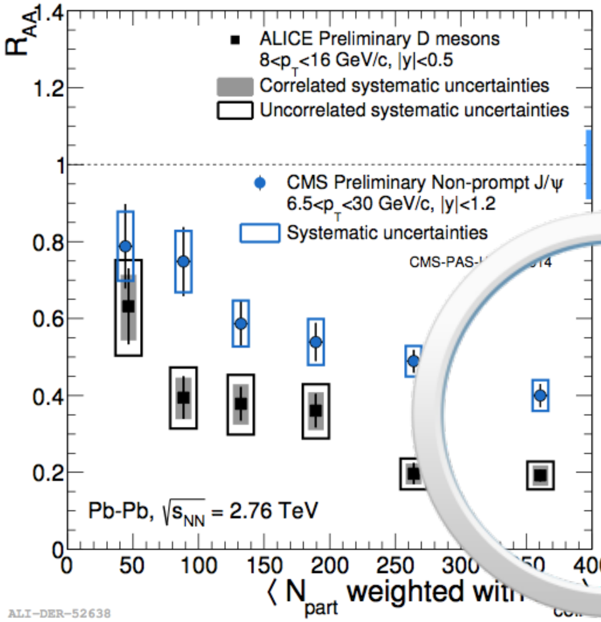
- First indication of mass dependence of energy loss: R_{AA}^B (CMS) > R_{AA}^D (ALICE)



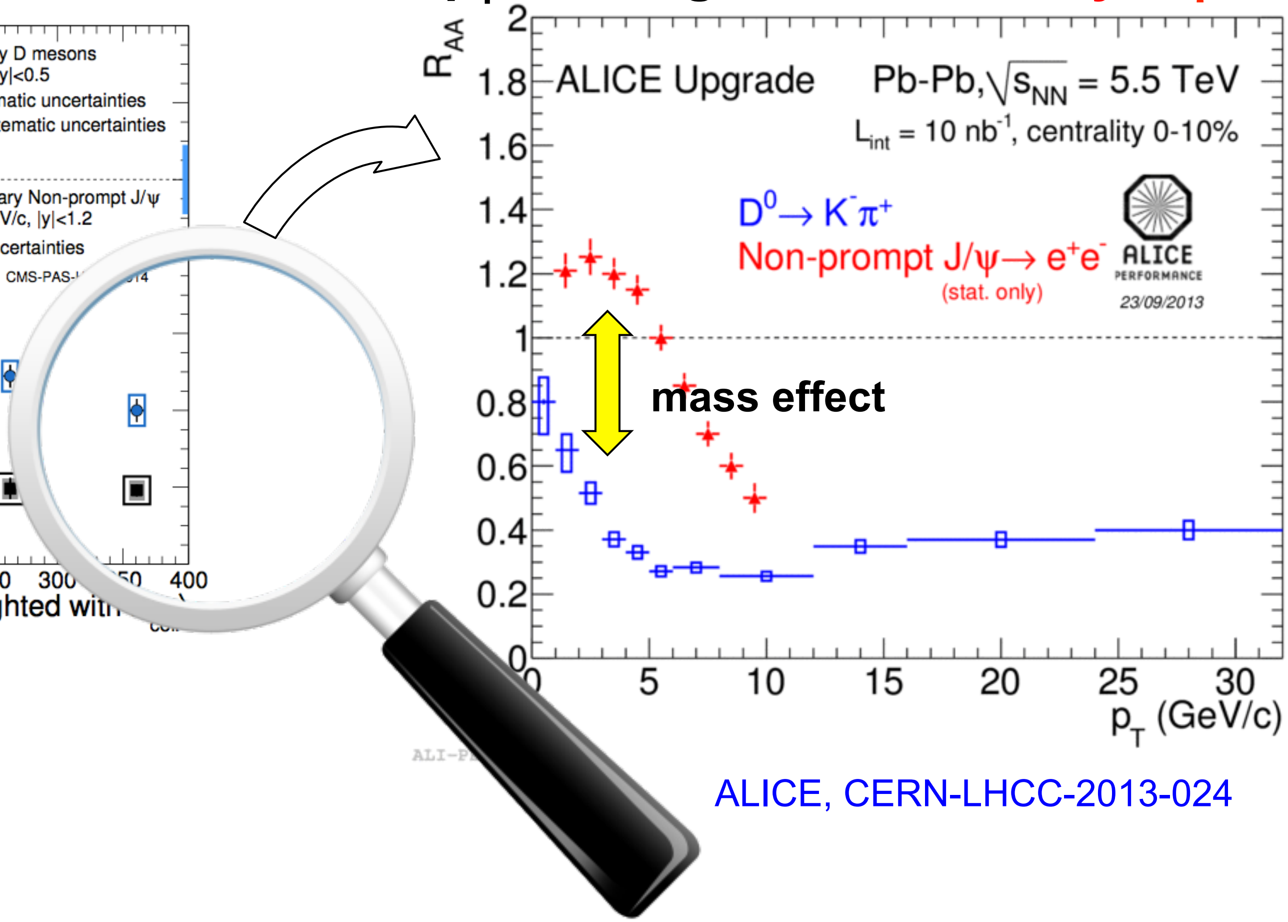
Limited to high p_T (~10 GeV) and large uncertainties in centrality dependence

Heavy flavour R_{AA}: Upgrade

Present data at p_T~10 GeV

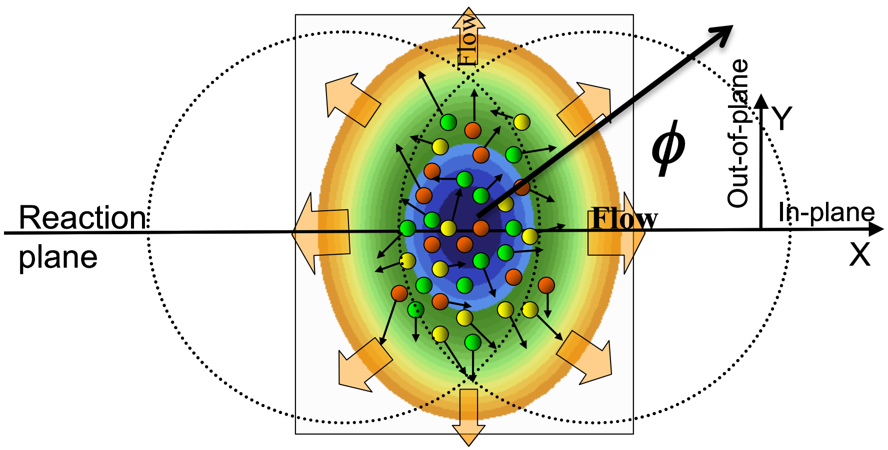


Upgrade: Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ



ALICE, CERN-LHCC-2013-024

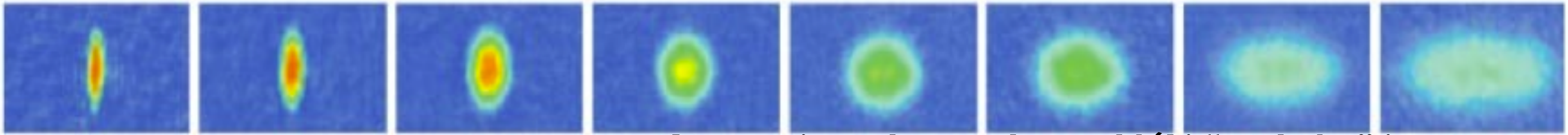
Azimuthal anisotropy: collective flow



- System geometry asymmetric in non-central collisions
- Expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- Measured by the elliptic flow parameter $v_2(p_T)$

$$\frac{dN}{N d\phi} \sim 1 + 2 v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

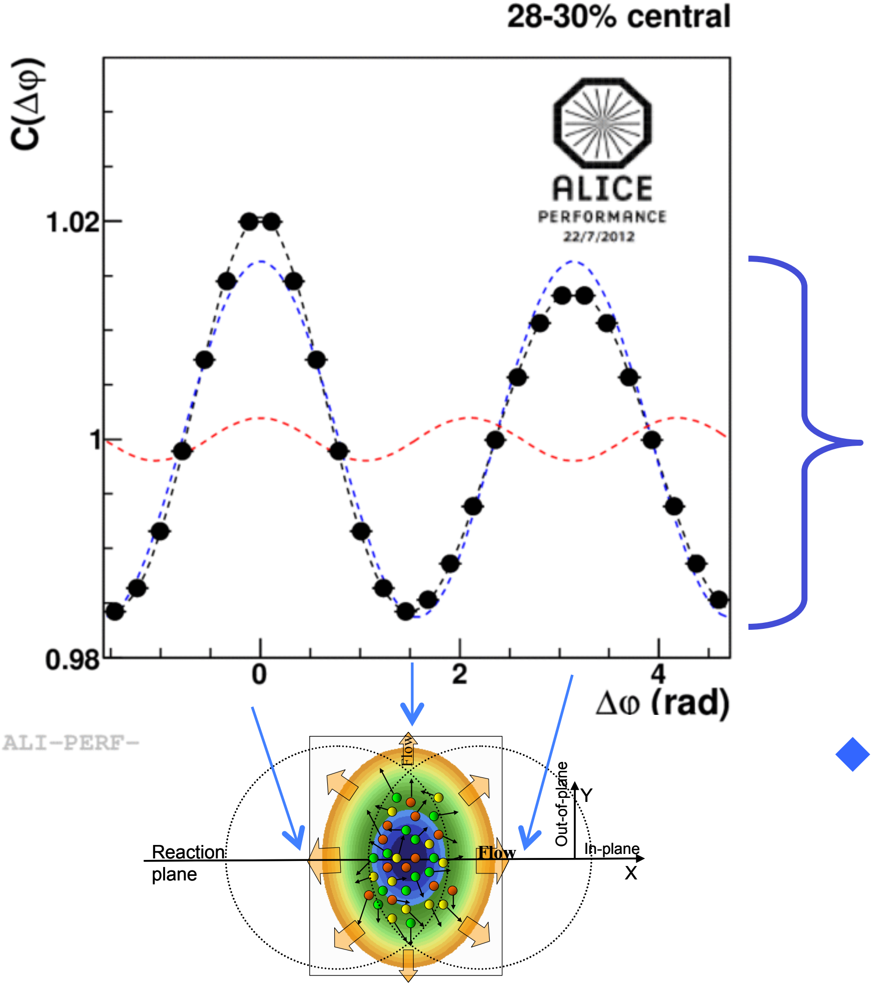
- v_2 of "bulk" (low p_T) provides a measure of strength of collectivity (mean free path of outgoing partons)
  - Higher harmonics understood in terms of initial state fluctuations



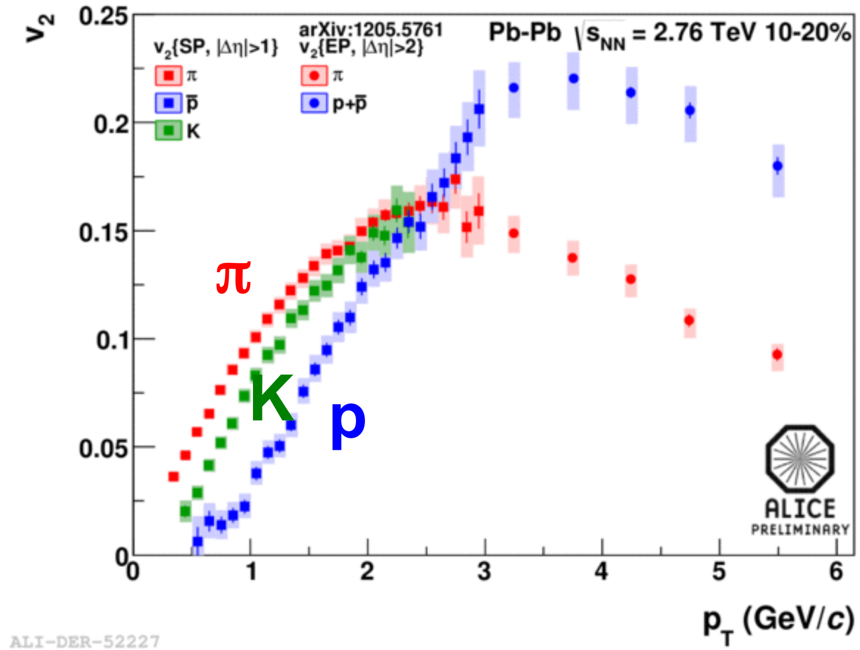
An atomic analogue: ultra-cold ^{6}Li "explodes" in vacuum

Two-particle Δϕ correlations and azimuthal anisotropy in Pb-Pb

Example of azimuthal modulation:



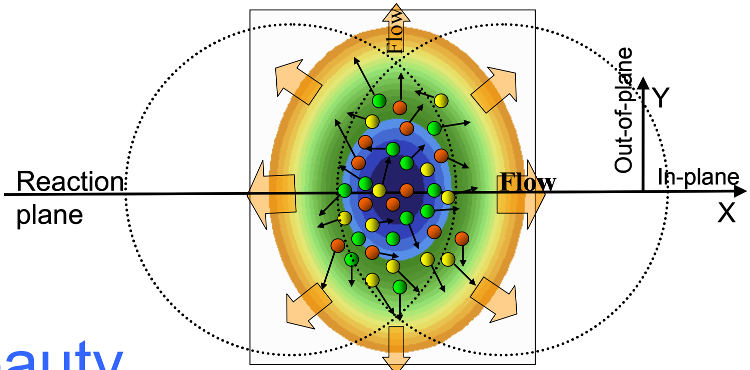
v_2: amplitude of 2[nd] order (elliptic) modulation

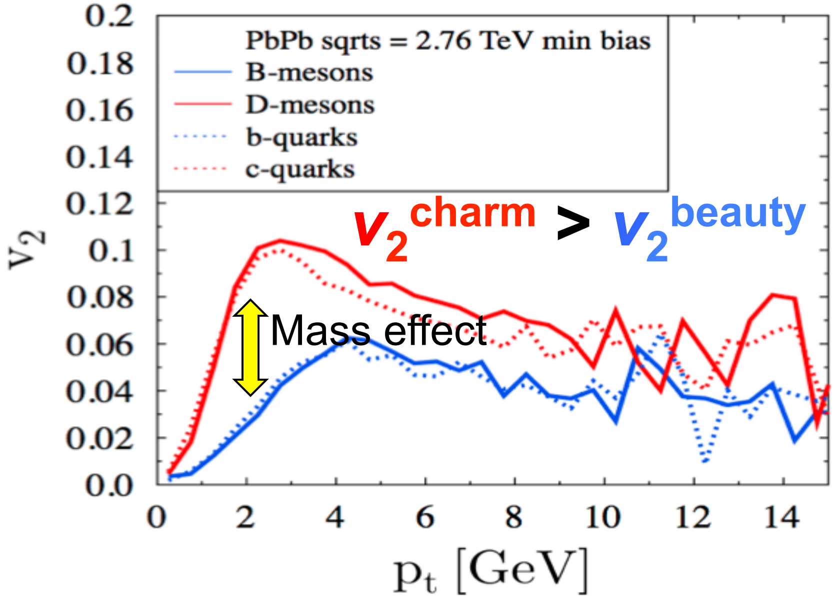


- Particle-species and p_T dependence follow expectations from hydrodynamical models, in which v_2 is built from collective expansion

Heavy Flavour elliptic flow (v_2)

- To what extent do heavy quarks take part in the collective expansions?
  - Probe of the interaction mechanism
  - Sensitive to medium viscosity
- Models predict large v_2 for charm and significant mass effect in charm vs. beauty

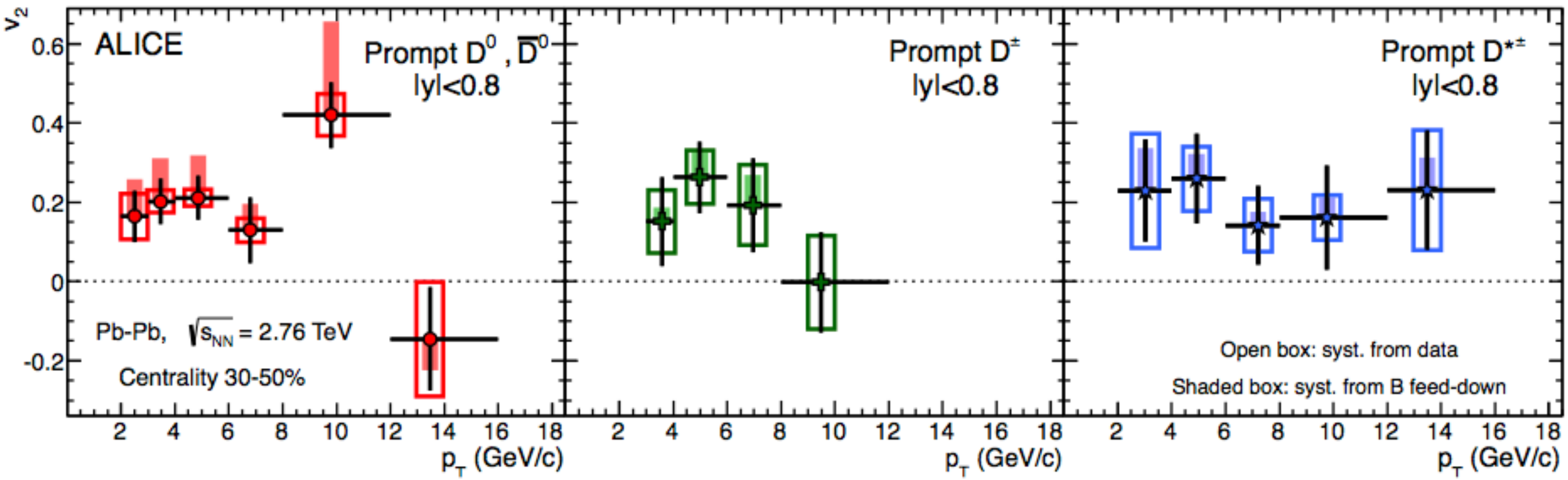




J. Aichelin et al. in arXiv:1201.4192

Heavy flavour flow: status from Run I

- Charm hadrons have v_2>0, comparable to light hadrons
- Heavy quark collective flow?

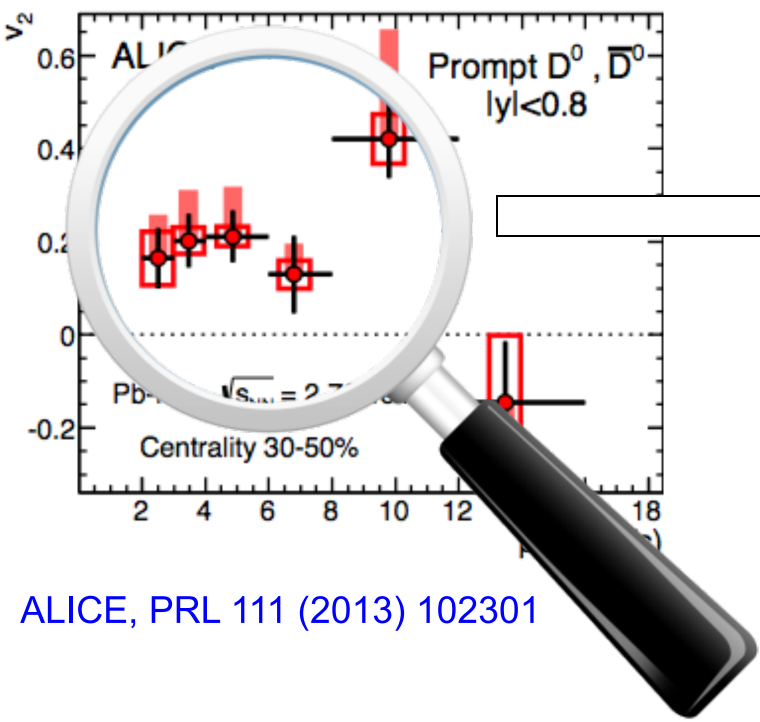


ALICE, PRL 111 (2013) 102301

Still quite qualitative, sizeable uncertainties for charm and no measurement for beauty

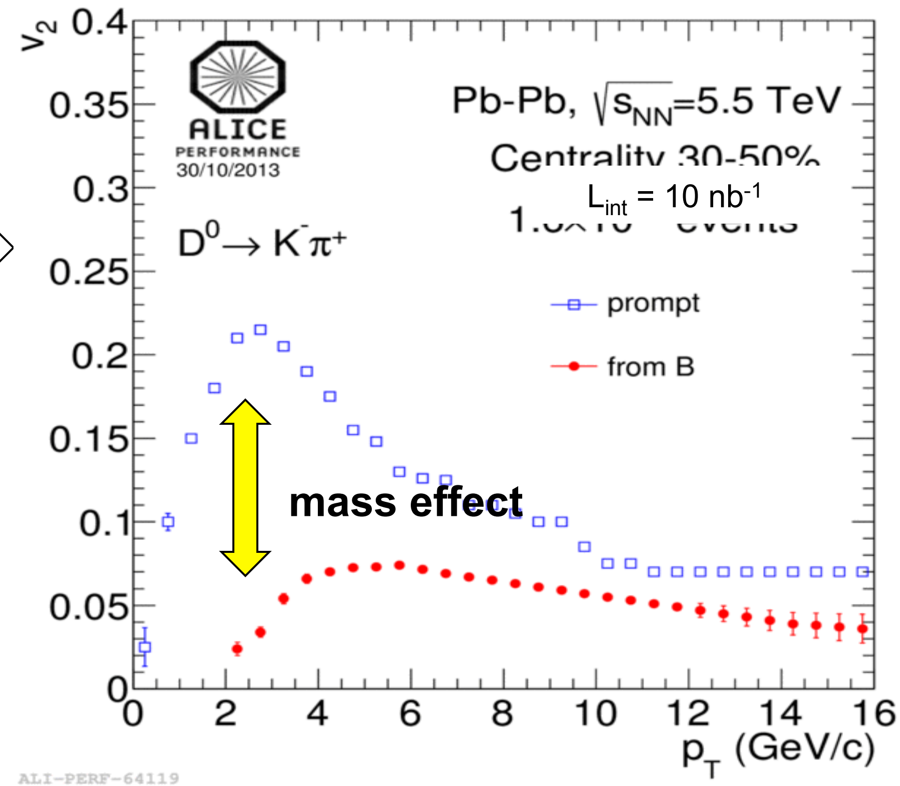
Heavy flavour flow: Upgrade

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

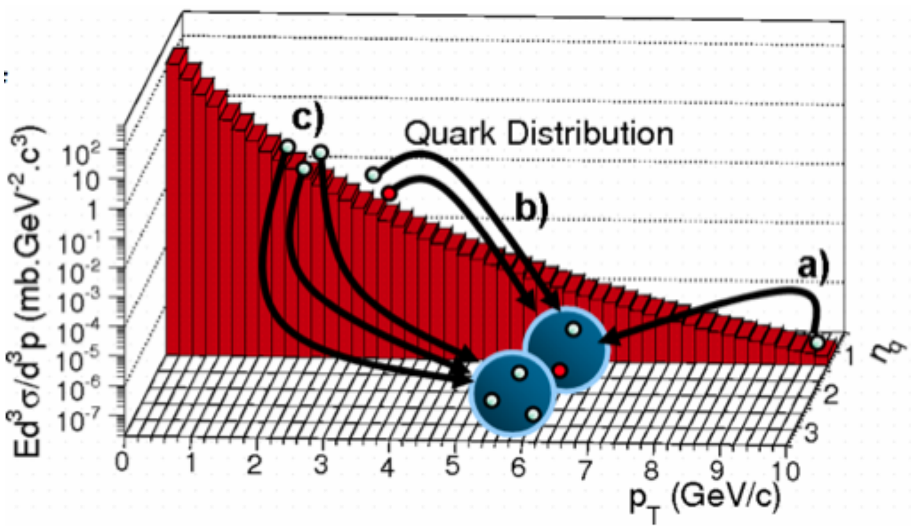


ALICE, CERN-LHCC-2013-024

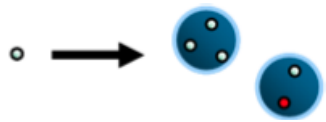
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

What is the QGP hadronization mechanism?

- When QGP cools down (freeze out), hadrons could be formed by recombination of quarks present in the system
- If this hadronization mechanism dominates over in-vacuum fragmentation in some momentum range, it should have visible effects on hadron p_T spectra → easier to form baryons

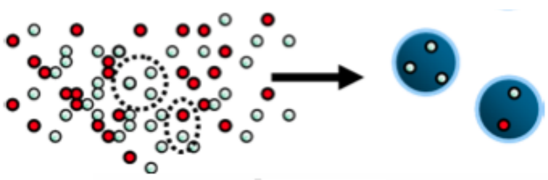


Fragmentation:



$$p_T^{hadron} = z \cdot p_T^{parton}$$

Recombination:

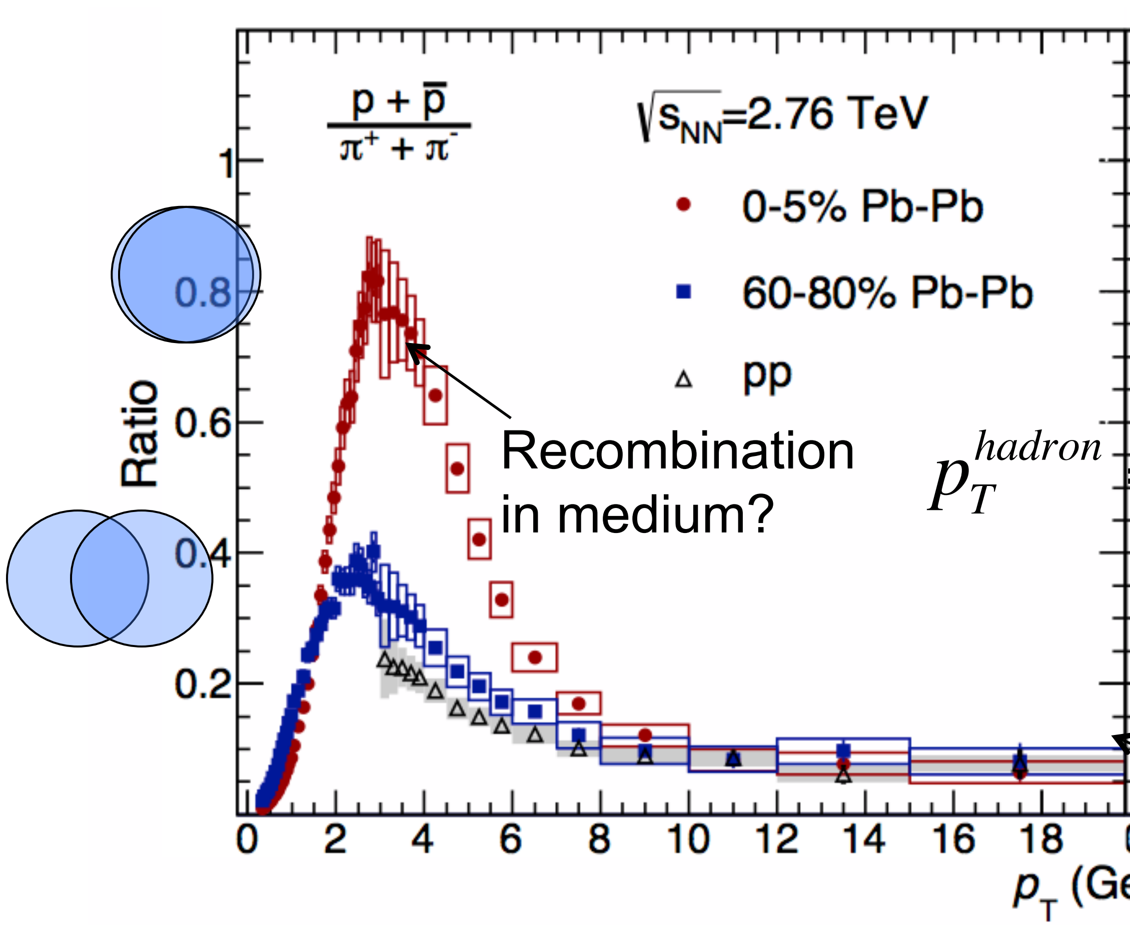


$$p_T^{hadron} = n_q \cdot p_T^{parton}$$

a) 6 GeV/c pion from 1x 10 GeV/c quark fragmentation
b) 6 GeV/c pion from 2x 3 GeV/c quark recombination
c) 6 GeV/c proton from 3x 2 GeV/c quark recombination

Recombination at play? Baryon/Meson

- Compare Baryon and Meson p_T spectra: p/π
  - Also measured for Λ/K



$$p_T^{hadron} = n_q \cdot p_T^{parton}$$

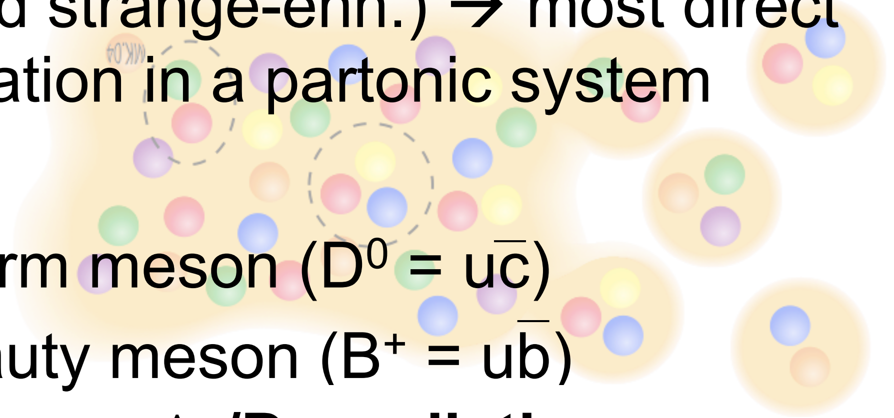
Fragmentation
in vacuum

$$p_T^{hadron} = z \cdot p_T^{parton}$$

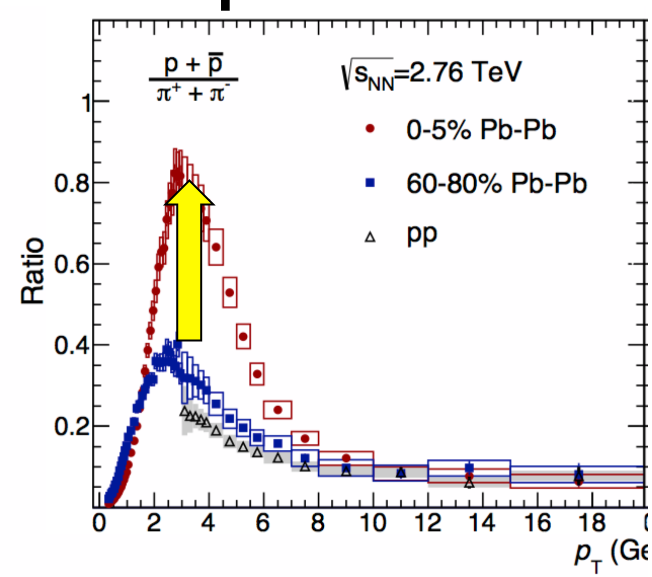
ALICE, arXiv:1401.1250

Heavy flavour hadronization mechanism?

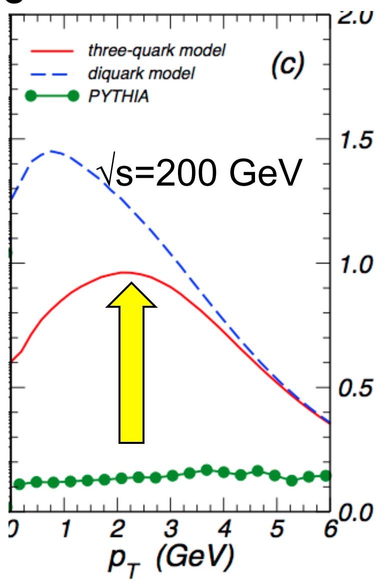
- Baryon/meson enhancement (and strange-enh.) → most direct indication of light-quark hadronization in a partonic system
  - Measure this in the HF sector!
  - Charm baryon (Λ_c = ucd) / Charm meson ($D^0 = u\bar{c}$)
  - Beauty baryon (Λ_b = ubd) / Beauty meson ($B^+ = u\bar{b}$)



p/π data



Λ_c/D prediction

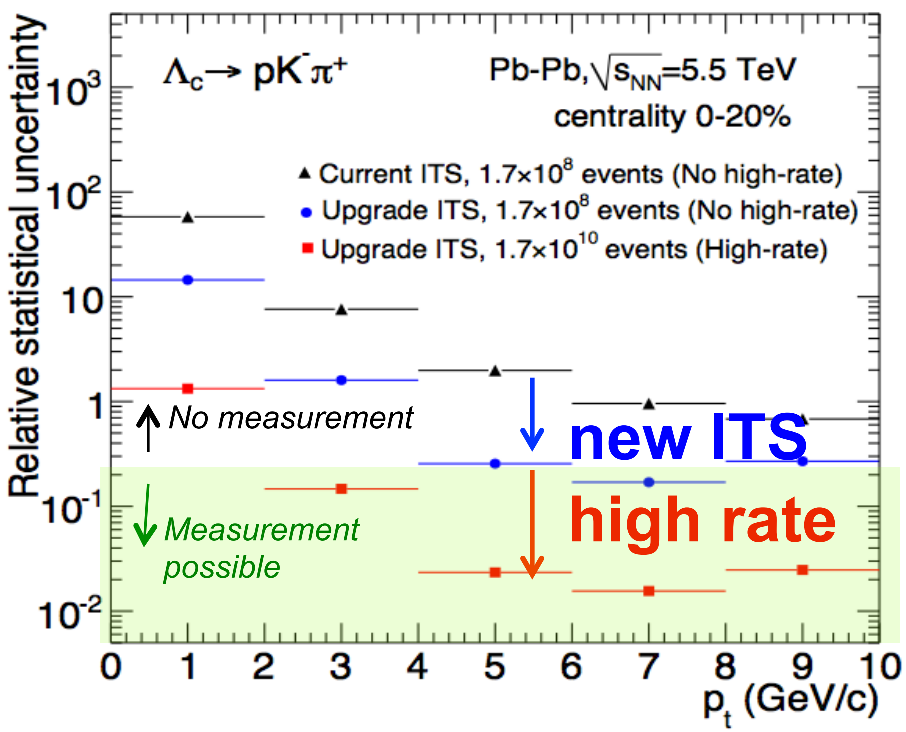


Ko et al. PRC79

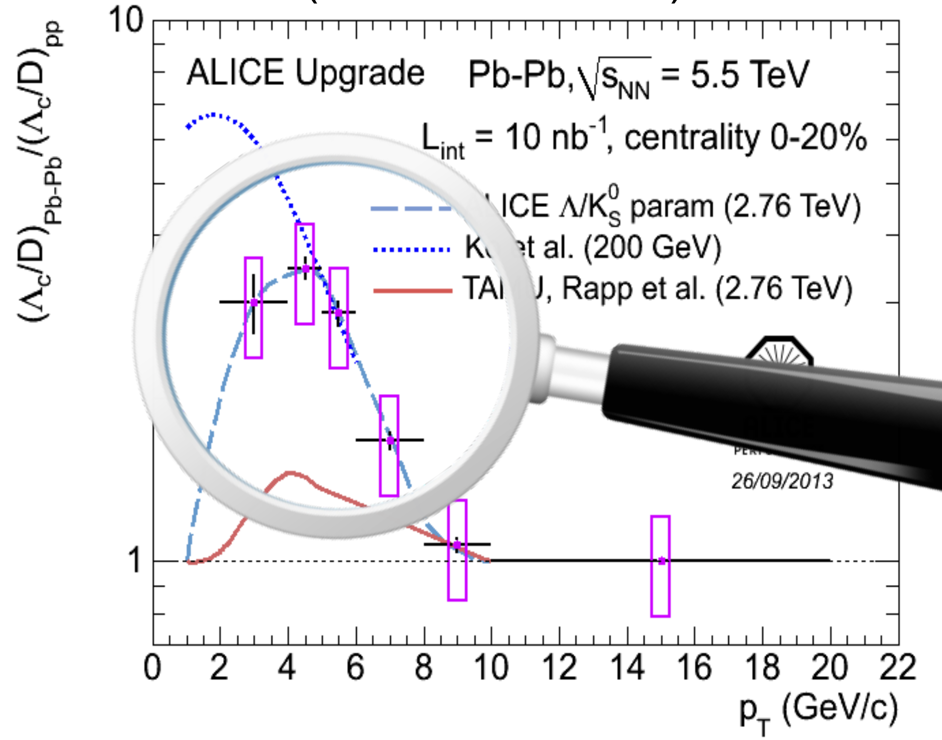
ALICE Upgrade: HF "hadrochemistry"

- $\Lambda_c \rightarrow pK\pi$ ($c\tau$=60 μm!) can be measured with good precision in ALICE with new ITS and L_{int}=10/nb
  - <10% precision also for $D_s \rightarrow KK\pi$ (not shown)

Λ_c statistical precision: break-down of improvement



Λ_c/D enhancement (full detector sim.)



ALICE, CERN-LHCC-2013-024

ALICE Upgrade: physics questions & observables

1. What are the mechanisms of the quark-medium (QGP) interaction? Understand QCD interactions in a multi-particle macroscopic system

   → Heavy flavour dynamics and hadronization

2. **How are the suppression and regeneration of quarkonia related to deconfinement and the QGP temperature?**

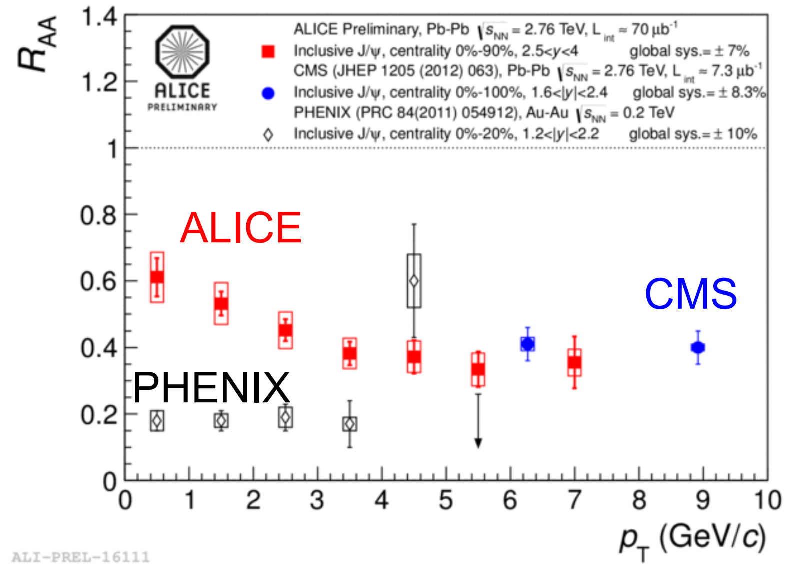
   → **Charmonia down to zero p_T**

Low-p_T charmonium

→ talk R. Arnaldi

- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\bar{c}$ in a deconfined medium?

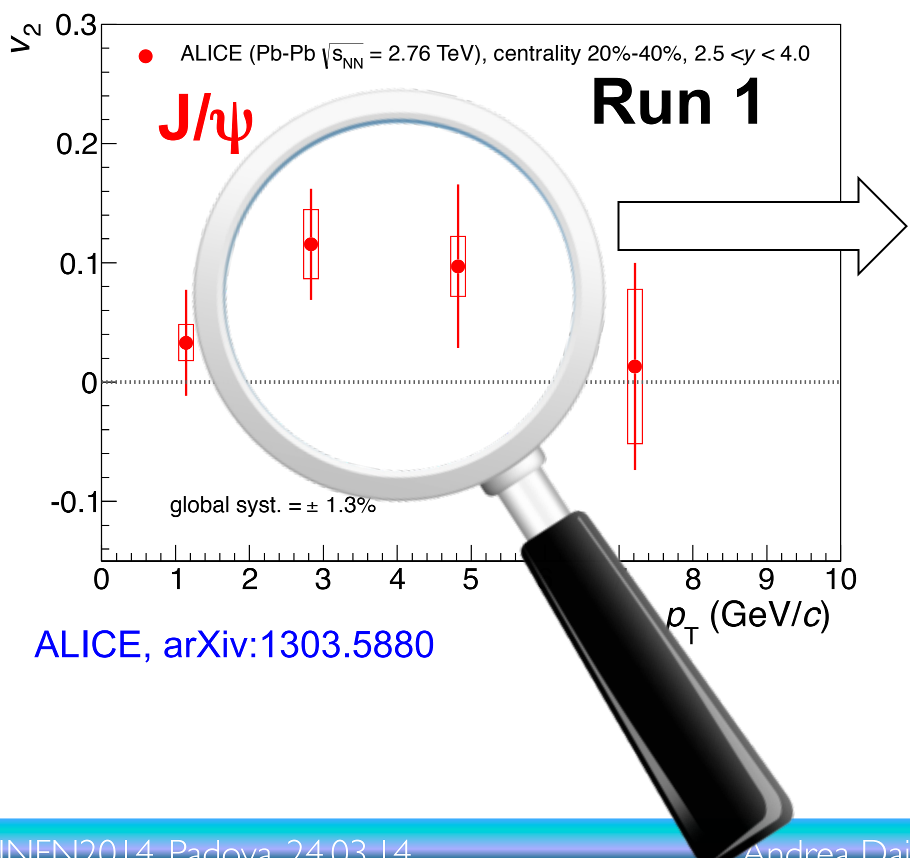
Braun-Muzinger and Stachel, PLB490(2000) 196
Thews et al, PRC63 (2001) 054905



ALICE Upgrade: low-p_T charmonium

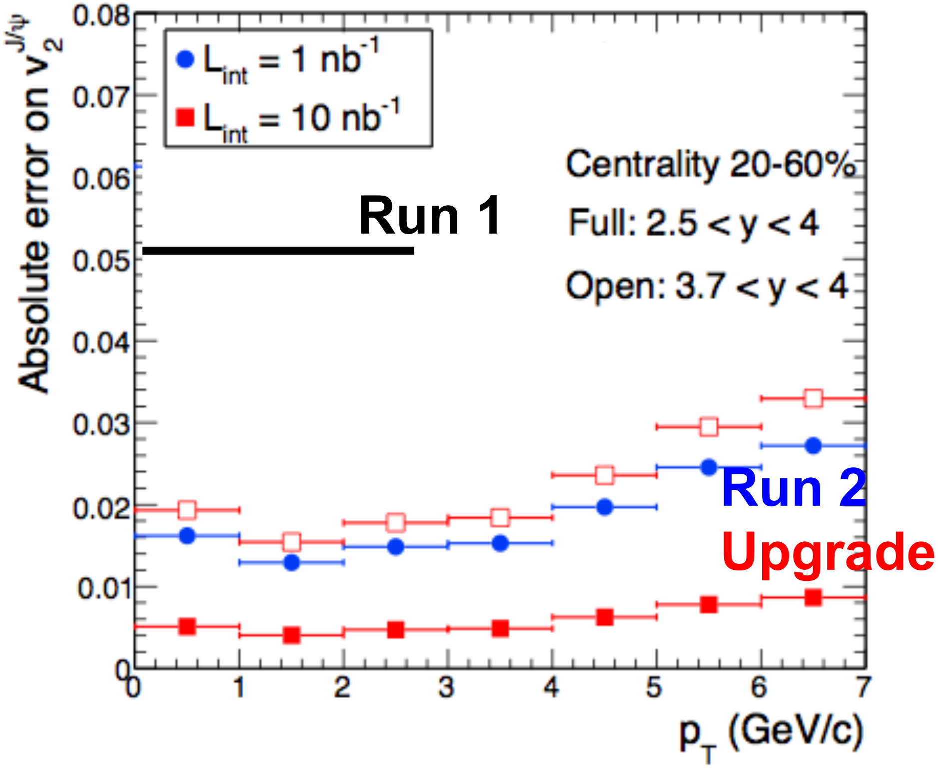
- This regeneration mechanisms provides an additional handle to study the thermalization of charm quarks in the QGP
- For example, regenerated J/ψ should inherit charm quark flow

Run 1: hint of v_2>0



ALICE, arXiv:1303.5880

Upgrade: x10 better precision



CERN-LHCC-2012-012

ALICE Upgrade: physics questions & observables

1. What are the mechanisms of the quark-medium (QGP) interaction? Understand QCD interactions in a multi-particle macroscopic system

   → Heavy flavour dynamics and hadronization

2. How are the suppression and regeneration of quarkonia related to deconfinement and the QGP temperature?

   → Charmonia down to zero p_T

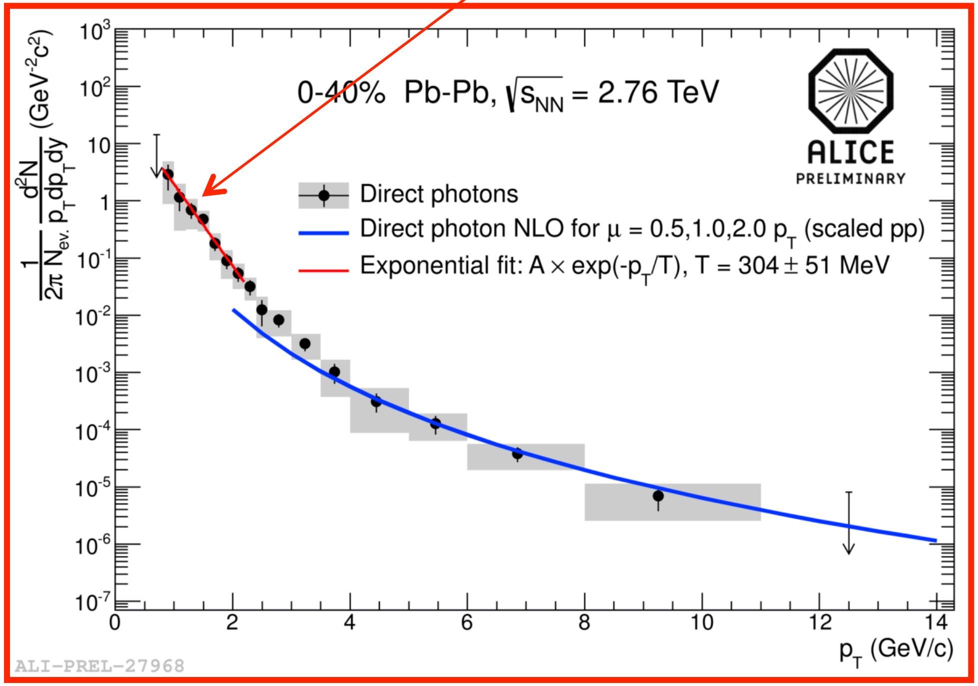
3. **What is the temperature evolution of the QGP medium?**

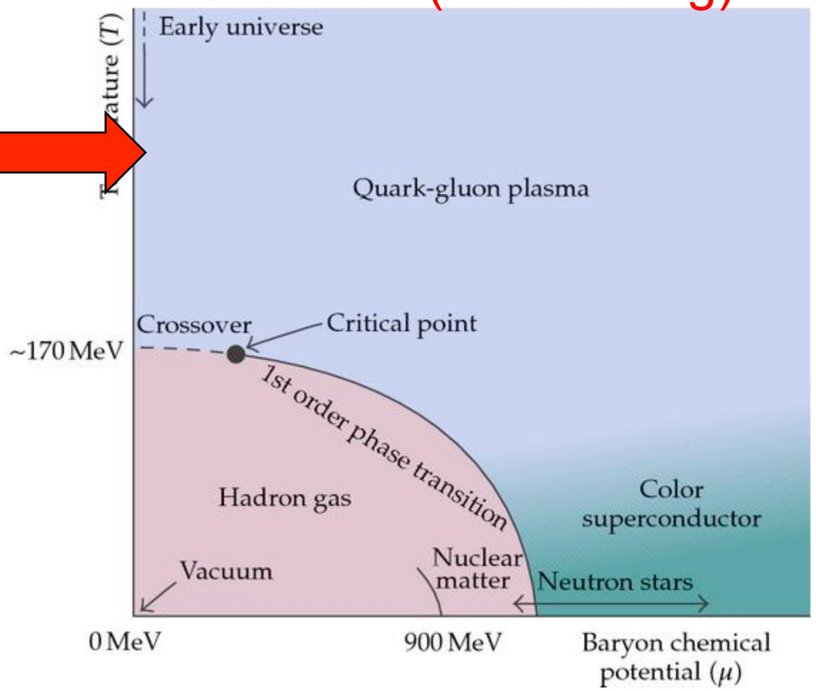
   → **Virtual thermal photons via the di-electron mass distribution**

What is the QGP temperature?

- Measure thermal radiation (black body photons)
- First measurement at LHC from soft exponential component of photon p_T spectrum: ***T* ≈ 300 MeV**

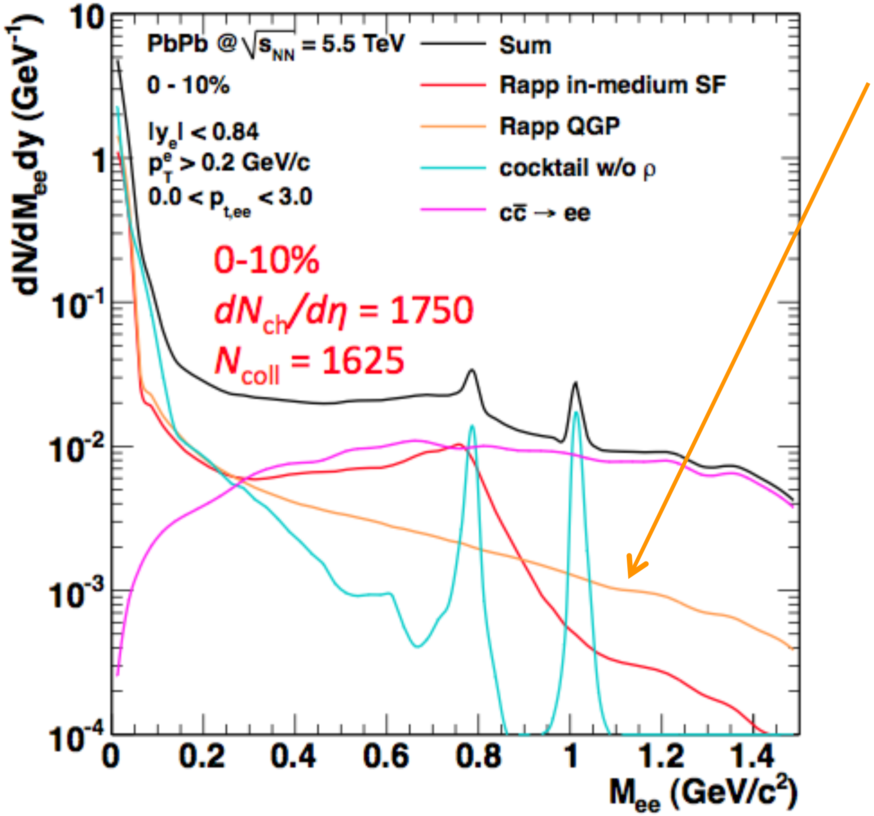
An effective temperature, averaged over system evolution (and cooling)





Temperature evolution: low-mass di-electrons

- Measurement of low-mass di-electrons allows to map the temperature during the system evolution

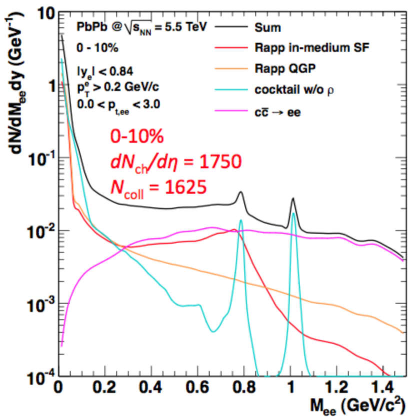


Di-leptons from real and virtual photons $\gamma \rightarrow e^+e^-$

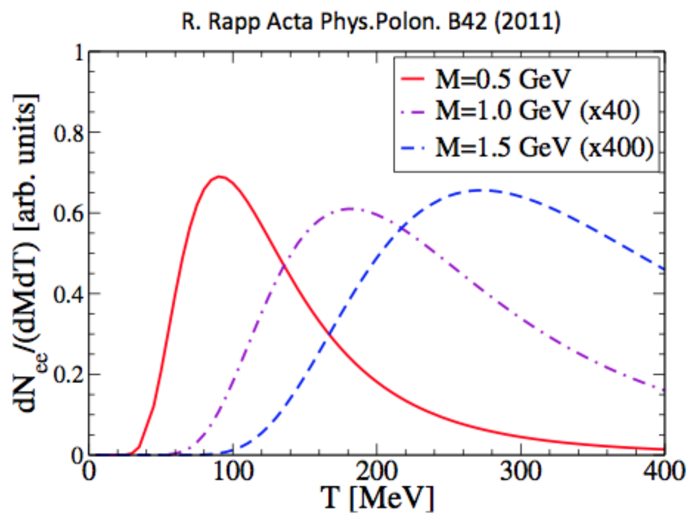
Complex measurement: need to disentangle all di-electron sources

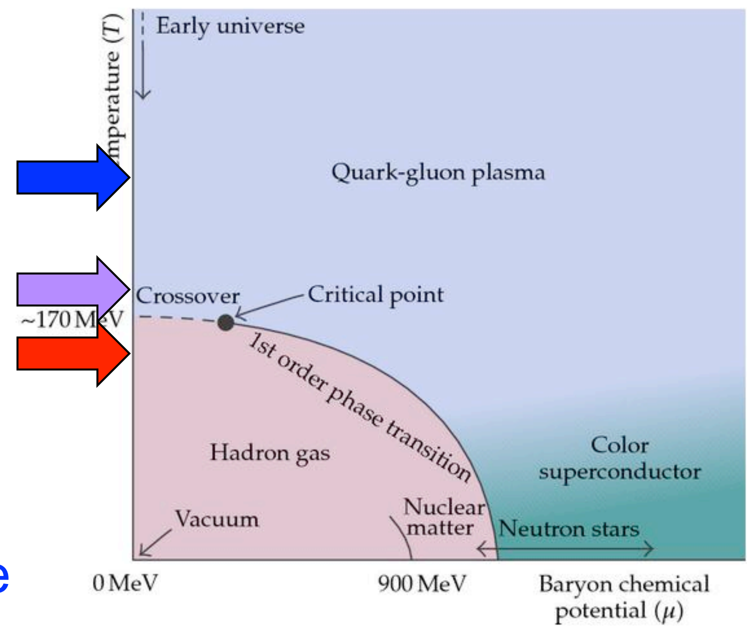
Temperature evolution: low-mass di-electrons

- Measurement of low-mass di-electrons allows to map the temperature during the system evolution



Di-leptons from real and virtual photons $\gamma \rightarrow e^+e^-$





High masses → high T, early stage

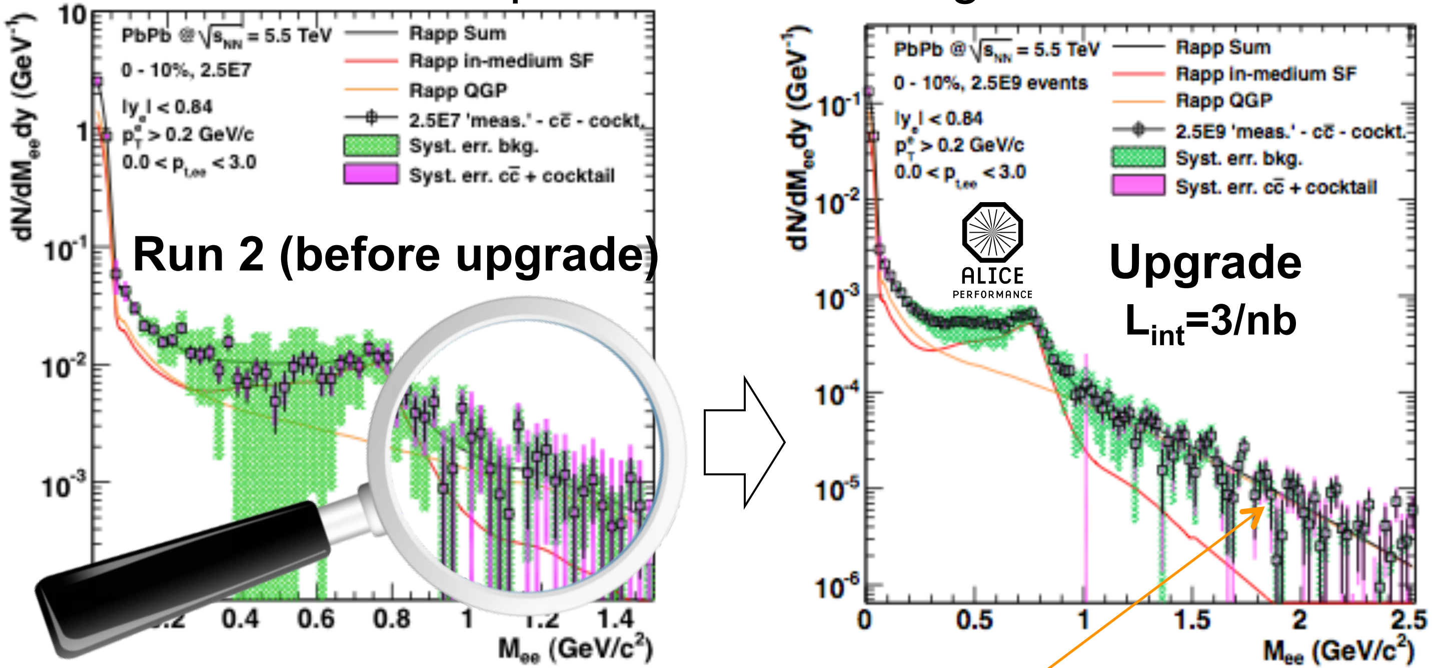
Intermediate masses

Low masses → low T, late stage

ALICE Upgrade: low-mass di-electrons

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

Di-electron mass spectrum after background subtraction:



Precision of ~10% on the inverse slope → T

ALICE, CERN-LHCC-2012-012

Summary

- Major ALICE upgrade in 2018
- Unique programme extending to the late 2020s
- Focus on rare probes and their interaction with the

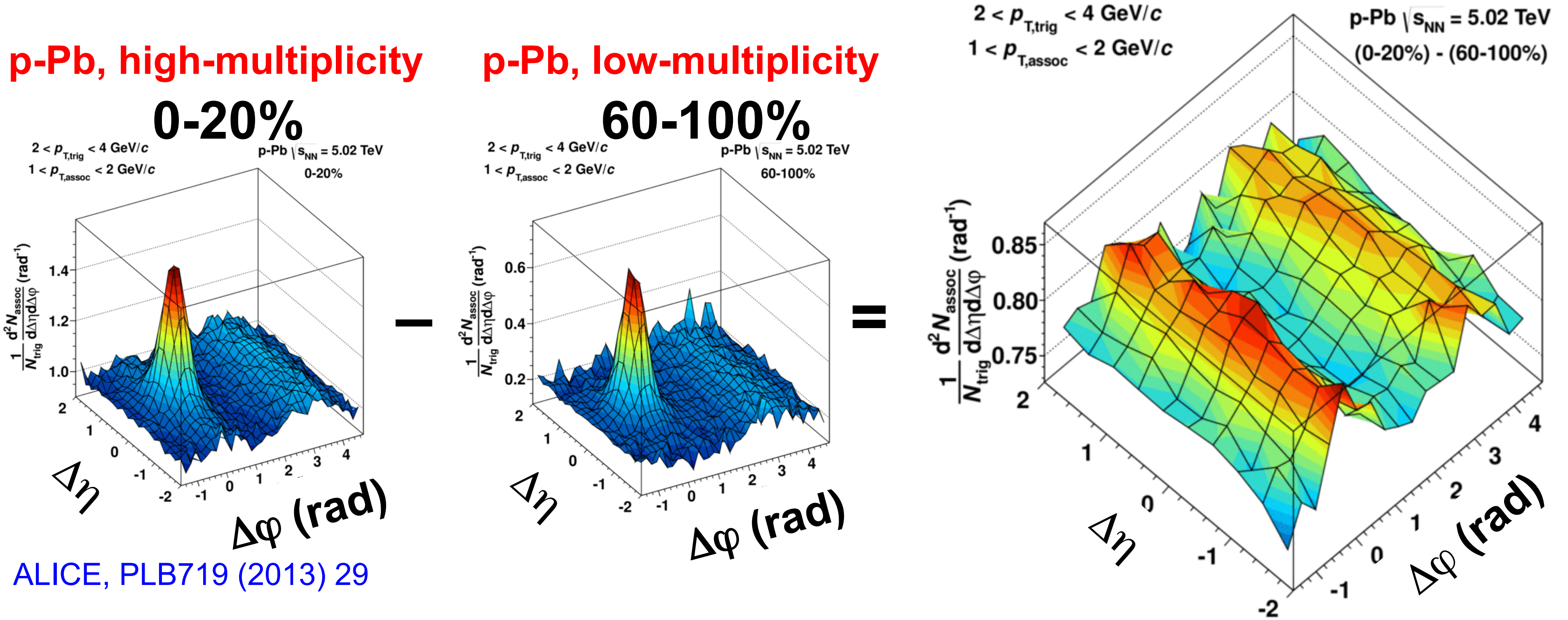
The TDR family is growing

Original LOI

EXTRA SLIDES

Correlations and anisotropy in p-Pb

- Two-particle (Δη,Δφ) correlations lead to first observation of an underlying azimuthal anisotropy in high-multiplicity p-Pb

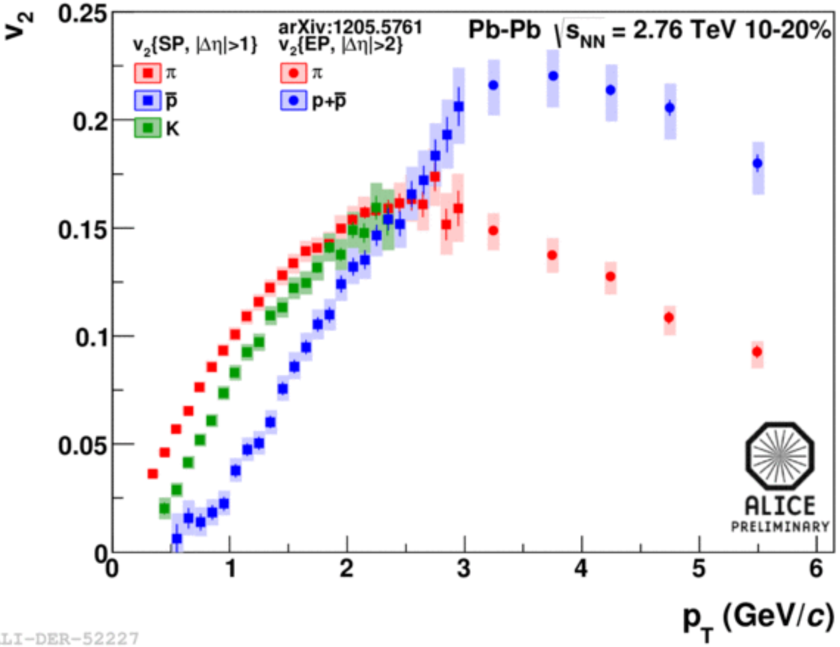


ALICE, PLB719 (2013) 29

- Resembles the v_2 modulation –attributed to flow in Pb-Pb

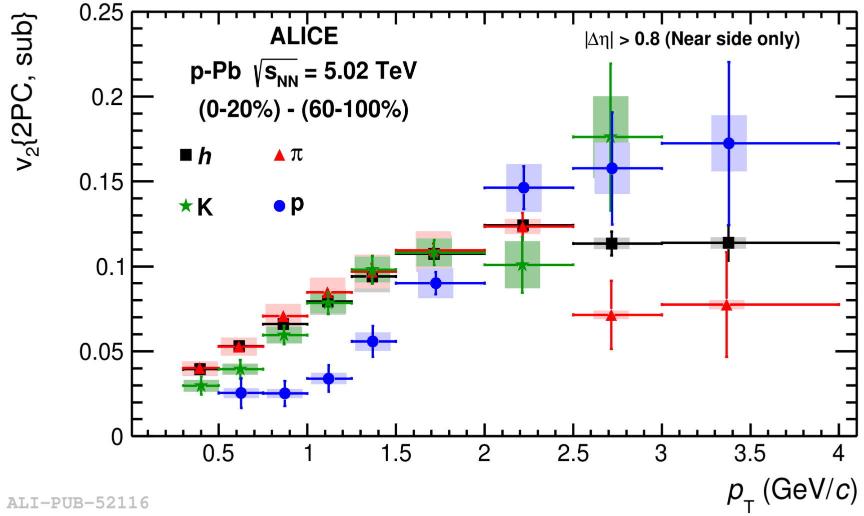
Is it *flow* in p-Pb? Look at identified particles

Pb-Pb



- Mass ordering, interpreted in terms of collective radial and elliptic flow

p-Pb, high-multiplicity



ALICE, arXiv:1307.3237

- Clear indication for mass ordering in p-Pb
- Resembles Pb-Pb and supports "flow" picture

HL-LHC Programme

(not exhaustive!)

- **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**)
- **Heavy flavour:** 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**)
  - B and b-jets (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 charmonia and elliptic flow (focus of **ALICE**)
  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)
- **Low-mass di-leptons:** thermal radiation γ ($\rightarrow$ 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**)

pp reference, pA, light nuclei

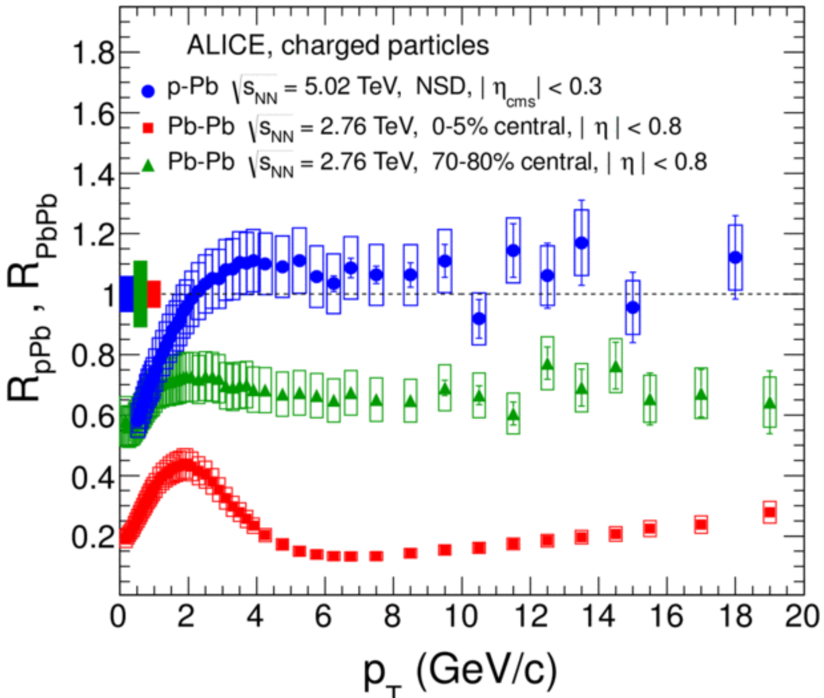
- pp reference at 5.5 TeV required
  - ALICE (for HF and charmonia needs): **~10/pb** (see CERN-LHCC-2012-012)
  - ATLAS / CMS: match Pb-Pb yields for high-p_T process, **~300/pb**
- p-Pb run at high luminosity (exploit upgraded detectors)
  - Requested by ALICE, ATLAS, CMS and LHCb
- p-Ar and Ar-Ar: a possibility to be considered for schedule after LS2, with priority that will be defined based on the outcome of the future data analysis (high statistics Pb-Pb and p-Pb from Run 2)

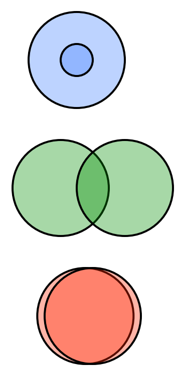
Experiment upgrades most relevant to HI

- 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 DAQ-HLT: x100 faster readout
- 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
  - New pixel tracker (LS2), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade of trigger and DAQ (LS2): HI-specific development to reach necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT)
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Nuclear modification factor: Pb-Pb, and p-Pb "control"

- Large suppression in central Pb-Pb: factor 7 at ~8 GeV/*c*
- No suppression wrt N_{coll}-scaled pp, in p-Pb for p_T>2 GeV/*c*





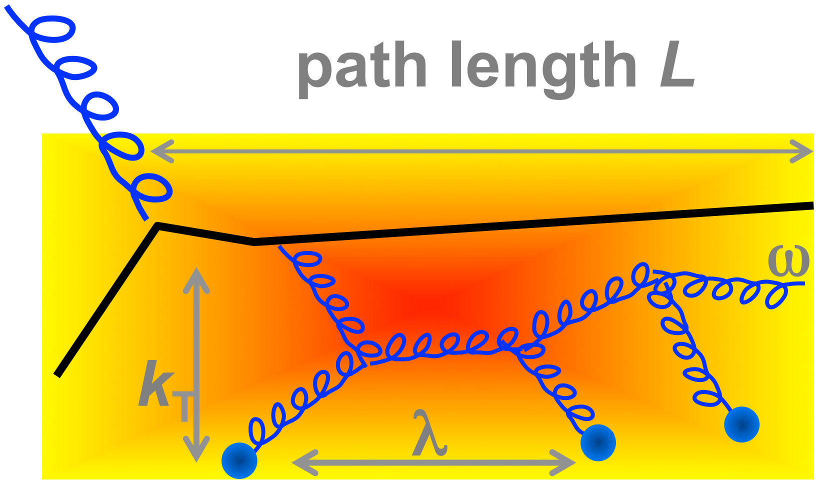
$$R_{pA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pA} / dp_T}{dN_{pp} / dp_T}$$

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

⇨ *The large suppression observed in central Pb-Pb is due to the formation of the hot medium*

ALICE, PRL110 (2013) 082302

Radiative energy loss: colour charge dependence …



Example: BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q}L^2}{\omega}}$$

C_R = Casimir coupling factor: 4/3 for q, 3 for g

→ Colour charge dependence of radiative energy loss

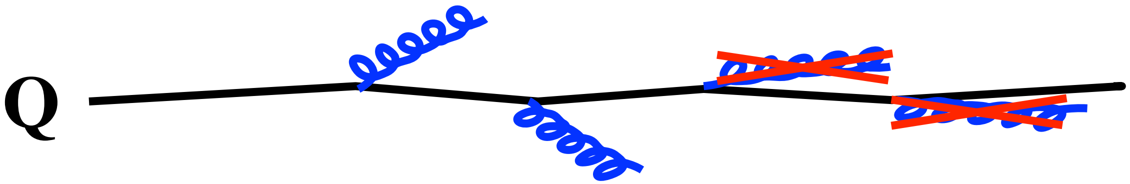
$$\Delta E_g > \Delta E_{c \approx q}$$

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

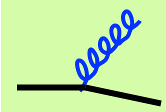
… and mass dependence

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

  $\rightarrow$ "dead cone" effect



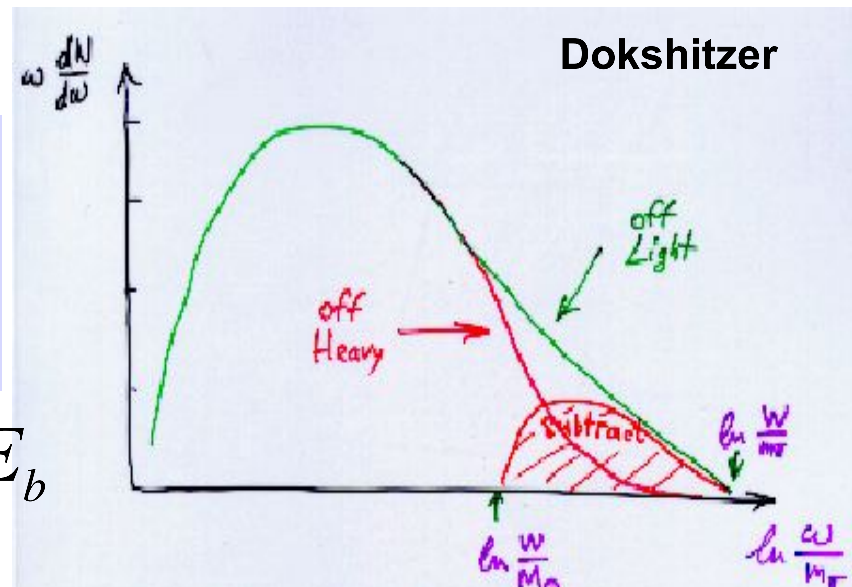
Gluonsstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppresses high-ω tail

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$



$$\Delta E_c > \Delta E_b$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Mass dependence in collisional energy loss

Example: Langevin formalism

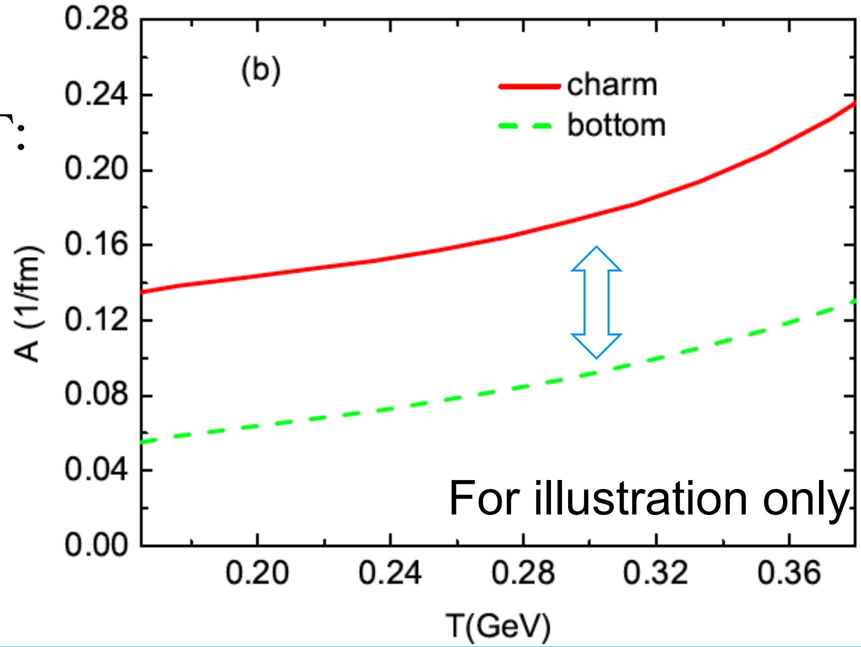
- Langevin equation gives momentum (**p**) evolution vs. time (*t*):

$$d\mathbf{p} = -\Gamma(p)\ \mathbf{p}\ dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\ \rho$$

Loss term → energy loss   Gain term → flow (radial, elliptic)

- Both Γ (drag) and *D* (diffusion) ~ $1/m_Q$

Thermal relaxation rate A ~ Γ:



$$\Delta E_c > \Delta E_b$$

He, Rapp, Fries, PRC86 (2012) 014903

New TPC GEM readout chambers

- Current readout chambers (MWPC): readout limited to 3.5 kHz
- New readout chambers (GEM): readout up to 50 kHz
  - preserve momentum resolution for TPC + ITS tracks
  - preserve particle identification via dE/dx