Future directions for precision studies of the QCD phase diagram

- Large community: about 150 physicists (>2500 worldwide)

- Several meetings (joint theory+experiment) were held

- Good occasion for a constructive discussion inside our community, between theory and experiment
  - → single out the most promising directions for our field
  - → Decision to prepare a "white paper" to analyze the expected developments in the next decade and the role of the INFN community (editors: A. Dainese, E. Scomparin, G. Usai)

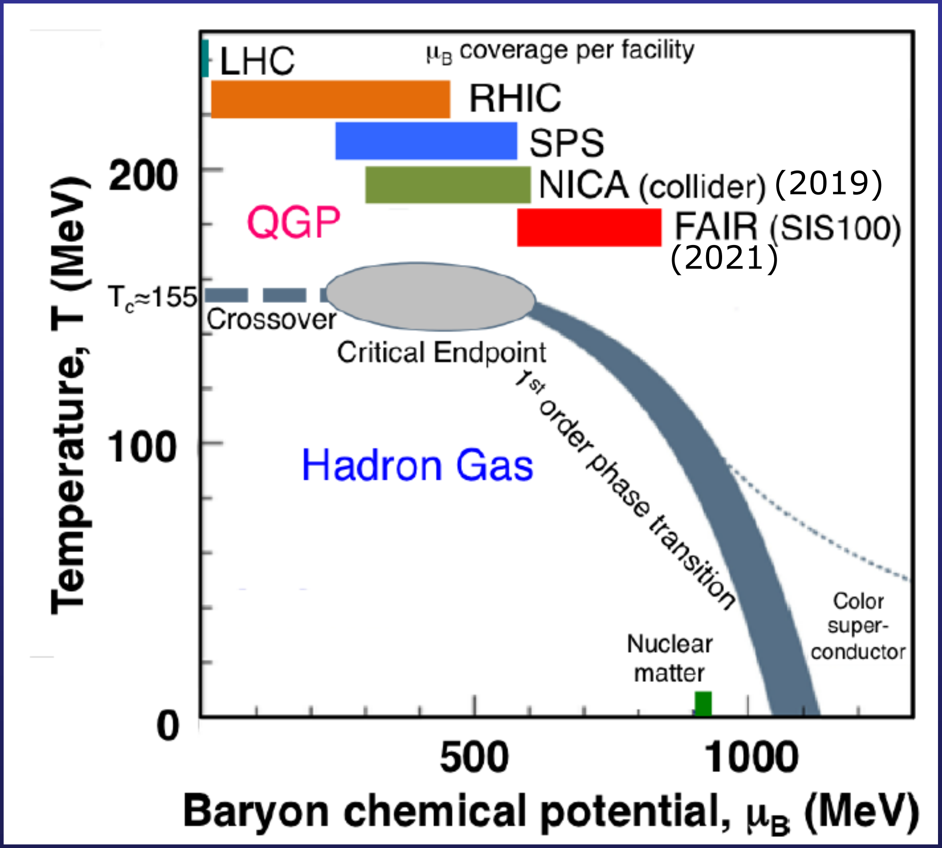
→ February 15, 2016 → arXiv submission (arXiv:1602.04120)

Precision studies of the QCD phase diagram

Study of the cross-over region at $\mu_B \sim 0$

↓

Existing high-energy RHIC/LHC experiments



Study of the QCD critical point and chiral symmetry restoration

↓

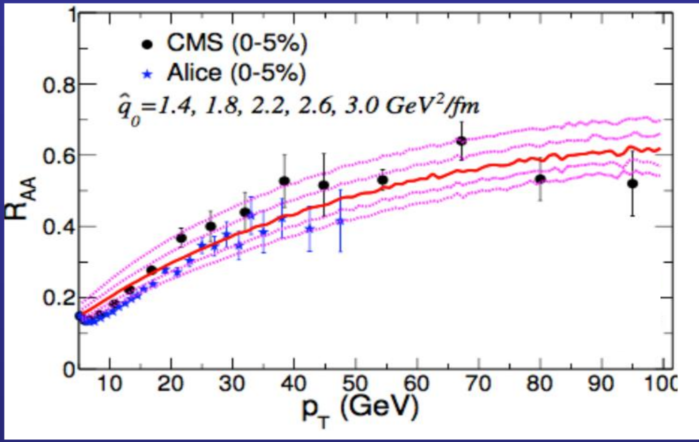
Forthcoming low energy experiments

RHIC energy scan
SPS, FAIR

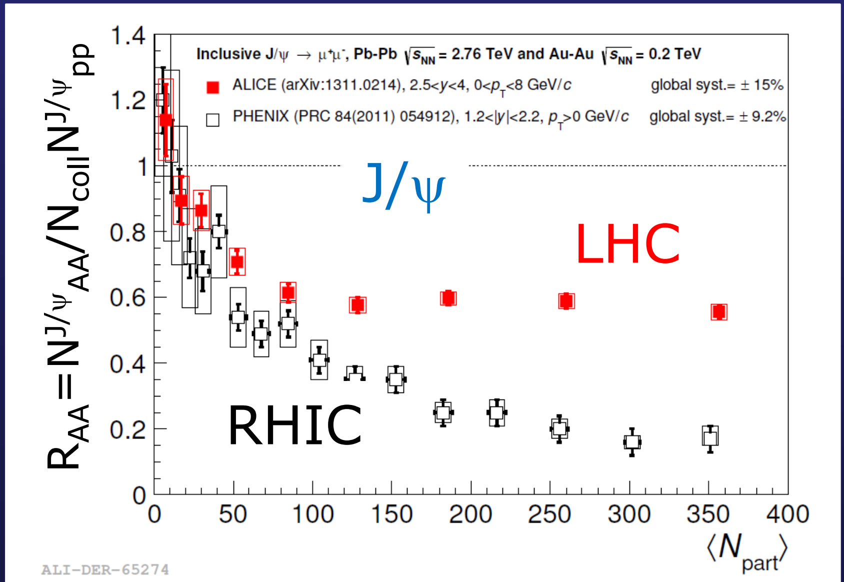
Considering the best approach to achieve strong impact on both domains

High-energy frontier: status

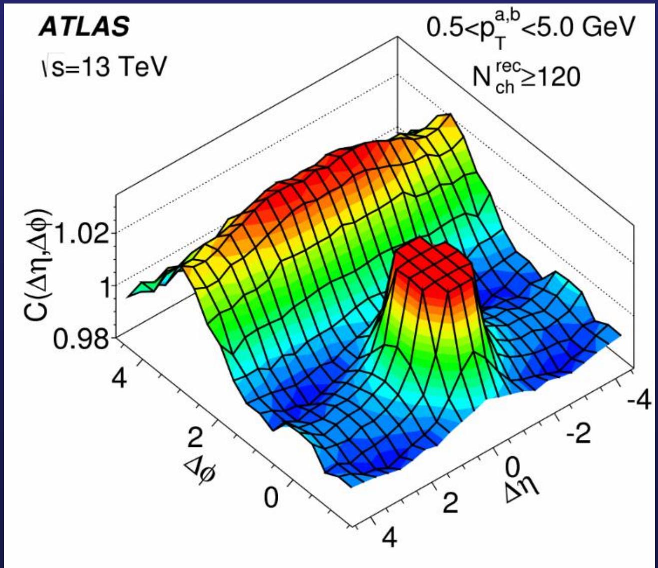
- Quantitative studies of QGP features → **PbPb collisions LHC run1**
  - Average temperature (photons) T = (297 ± 12 ± 41) MeV ~ 1.4 x T_{RHIC}
  - Energy density (E_T) ε = 15 GeV/fm^3 ~ 3 x ε_{RHIC}
  - Lifetime (femto) τ_f ~ 10 fm/c ~ 1.4 x $\tau_{f\ RHIC}$
  - Volume (femto) V~5000 fm^3 ~ 2 x V_{RHIC}
  - Viscosity/entropy (flow) $\eta/s \rightarrow 1/4\pi$ (ideal fluid)
  - Transport coefficient $\hat{q}_0$: 35% uncertainty



- Highlights/unexpected observations
  - $c\bar{c}$ re-combination to form J/ψ in the QGP
  - Collective effects observed in small systems (p-Pb, high mult. pp)



arXiv:1311.0214



arXiv:1509.04776

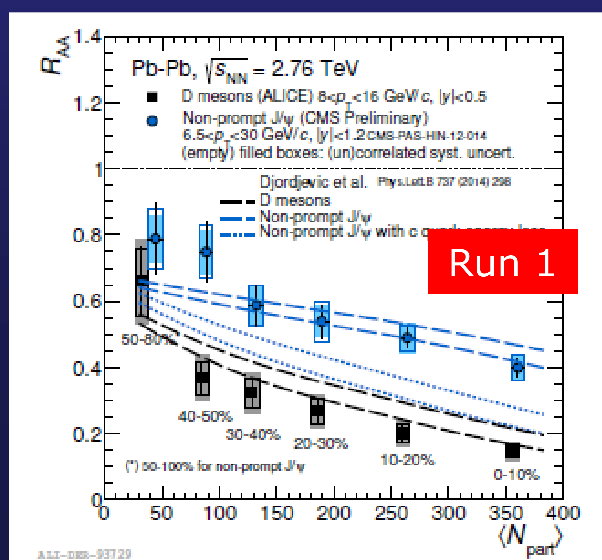
High-energy frontier: prospects

run3 – run4: High-precision measurements, detailed QGP characterization

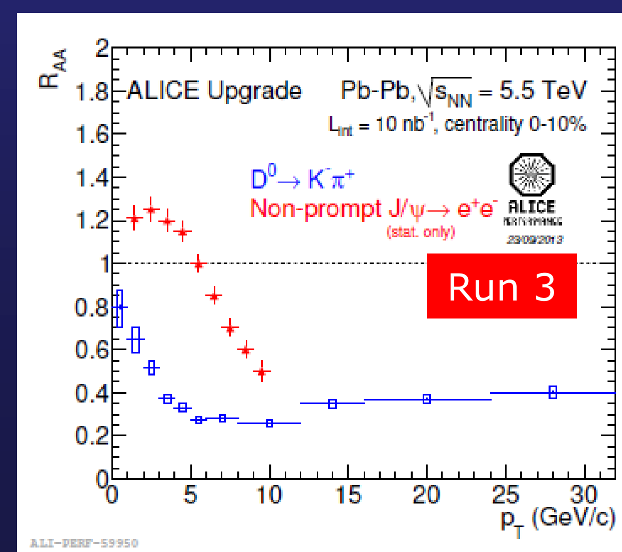
- ALICE: collect $L_{3\text{-}4} \sim 10 L_{1\text{-}2}$ (factor 100 min. bias!) with a strongly upgraded apparatus (new ITS, r/o TOF, MUON, ZDC)
- ATLAS, CMS, LHCb participate in ion runs

- ALICE main physics goals
  - Compare transport parameters for heavy quarks with first-principle theory (lattice-QCD)
  - Complete characterization of jet shapes, tagged jets (Z+jet,…)
  - Investigate regeneration processes in QGP (J/ψ flow, ψ(2S))
  - Light nuclei/antinuclei/hypernuclei

Example: performance on heavy quarks



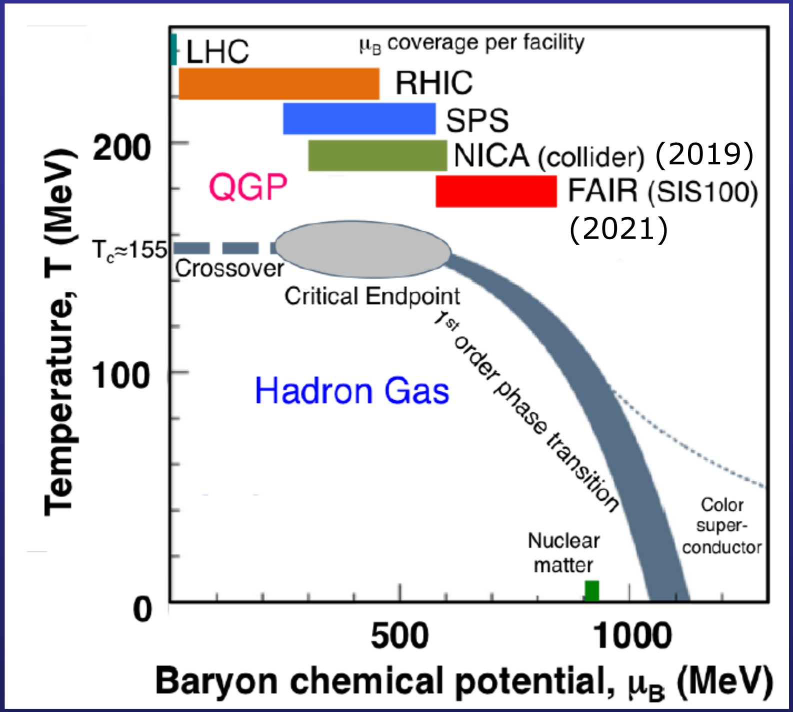
ALICE, arXiv:1506.06604, CMS-PAS-HIN12-014



TDR ITS, JPG41(2014)087002

Critical point/onset of deconfinement

- Various facilities can in principle investigate the high μ_B region of the QCD phase diagram



- High interaction rates (>1 MHz) can be reached at the CERN SPS ($\sqrt{s}$ = 4.5 – 17.3 GeV)
- Forthcoming FAIR facility at GSI: complementary region $\sqrt{s}$ = 2-4.5 GeV (possibly too limited for onset of deconfinement)
- Collider facilities (NICA, RHIC): interaction rates lower by 2-3 order of magnitudes

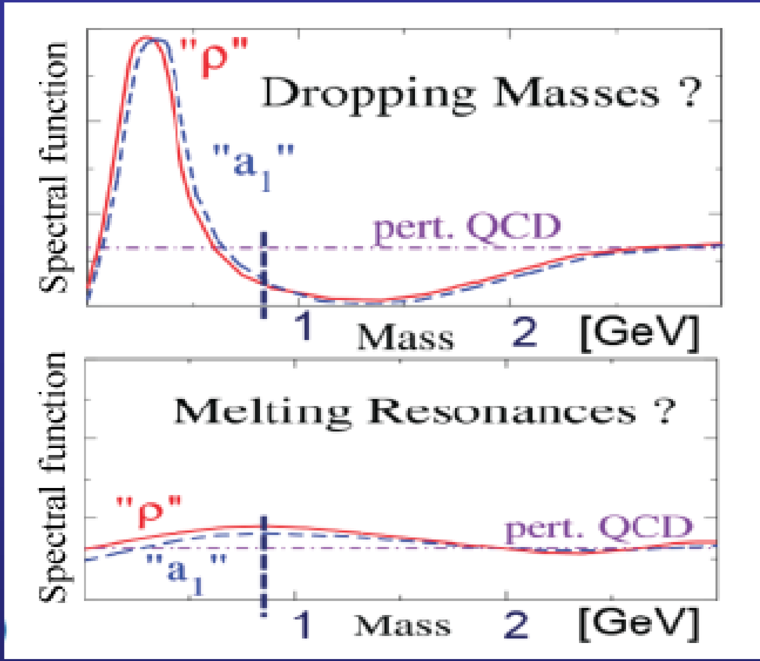
Most promising direction for a new INFN initiative with high scientific impact, to take place in the next decade

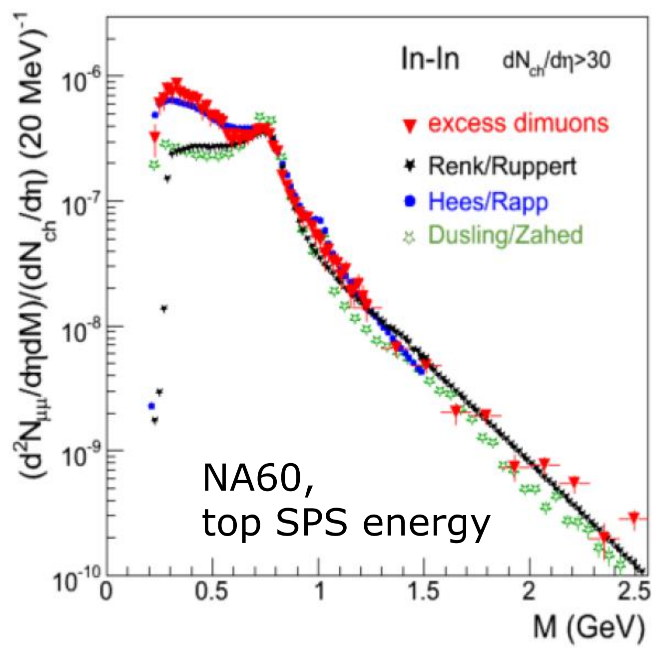
NA60+ → Study of the dimuon spectrum via a beam energy scan with a dedicated experimental set-up at the CERN SPS
(follow-up of the NA60 experiment, 2002/2003, with p and In beams)

NA60+: physics observables

❑ **Chiral symmetry restoration**

- ❑ Chiral symmetry responsible for the largest fraction of hadron masses
- ❑ $\langle q\bar{q} \rangle \to 0$ at phase transition
- ❑ Vector and axial-vector mesons degenerate (mixing ρ-a_1)
  → dropping mass or melting scenarios
- ❑ $D\bar{D}$ threshold enhancement



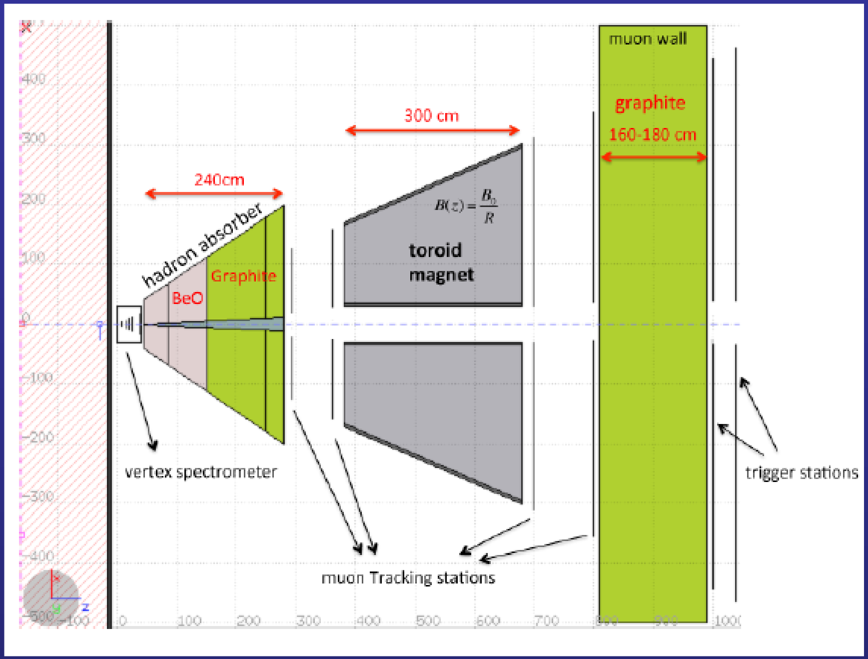


❑ **Onset of deconfinement/critical point**

- ❑ Measure a caloric curve (temperature vs energy density) via thermal dimuons
  → pin down 1st order phase transition
- ❑ Look for appearance of J/ψ suppression
  → onset of deconfinement

NA60, arXiv:1011.0615

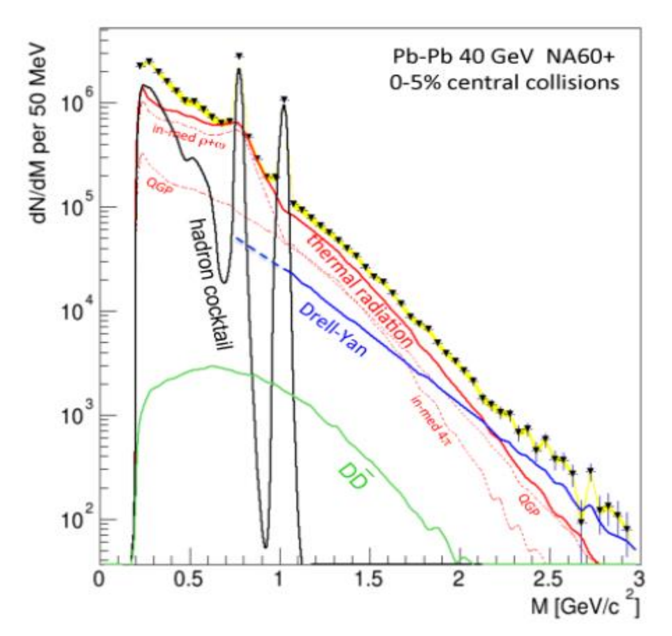
Experimental set-up, performance



- Detector concept
  - Muon spectrometer
    (tracking detectors (GEM?), trigger stations, toroidal magnet)
  - Vertex spectrometer
    (5 planes of hybrid or monolithic pixel sensors, dipole field)

Goal:
- $\sigma_{\omega,\varphi}$~10 MeV
- Factor 100 statistics wrt NA60

- ρ and a_1 modifications in medium
  → $\rho \to \mu\mu$, $a_1\pi \to \mu\mu$ ($1.1<m_{\mu\mu}<1.5$ GeV)
- Measure T of thermal dimuons (few MeV unc.)
  → $\mu\mu$ continuum ($1.5<m_{\mu\mu}<2.5$ GeV)
- Charmonium suppression
  → ~10^4 J/ψ for each incident energy
- D-mesons
  → hadronic and semi-leptonic decays



Tag the onset of deconfinement and investigate chiral symmetry restoration

Longer-term interesting opportunities

- **FCC** (2035-2040)
  - Design studies include heavy-ions (see e.g. NPA931(2014)1163)

Quantity	pp	Pb–Pb	p–Pb
Beam energy [TeV/A]	50	19.5	50/19.5
$\sqrt{s_{\mathrm{NN}}}$ [TeV]	100	39	63
$\mathcal{L}_{\mathrm{peak}}$ [10^{27} cm^{-2}s^{-1}]	5.6×10^7	7.3	1192
$L_{\mathrm{int,run}}$ [nb^{-1}]	–	8.3	1784

- wrt LHC
  - Increase energy density by a factor ~2
  - Thermalization time much smaller than at LHC → T_0 ~ 800 MeV
  - Secondary charm production sizeable and very senstitive to T_0
  - New rare hard probes (boosted top quarks…)

- Fixed target collisions with LHC beams → **AFTER** experiment (timeline under definition, after run-4)

  (Phys. Rept. 522 (2013)239)

- Use bent crystals to extract the halo of the LHC beam
  → UA9, LUA9 (CERN-LHCC-2011-007)

- QCD- and QGP-related studies at $\sqrt{s}$=115 GeV (pp), $\sqrt{s_{NN}}$ =72 GeV (PbPb)
- Detailed studies of the target fragmentation region ($x_F \to -1$) in pPb
- Spin physics with polarized targets
- EoI under preparation

Conclusions

Two directions for the study of the QCD phase diagram in the next decade

- **High-energy experiments (already approved program!)**
  - Upgrade of the ALICE detector (ITS, MUON, TOF and ZDC)
  - Collect/analyze data from run3 (2021-2023), run-4 (2026-2029)
  - Decisive improvements on quarkonium/HF studies
  - Contribution of ATLAS/CMS/LHCb important on these topics

- **Low-energy experiments (WhatNext!)**
  - New fixed-target experiment at SPS (NA60+)
  - Study onset of deconfinement/chiral symmetry/critical point
  - Discussions ongoing to form an international collaboration in view of a Letter of Intent (by 2018)

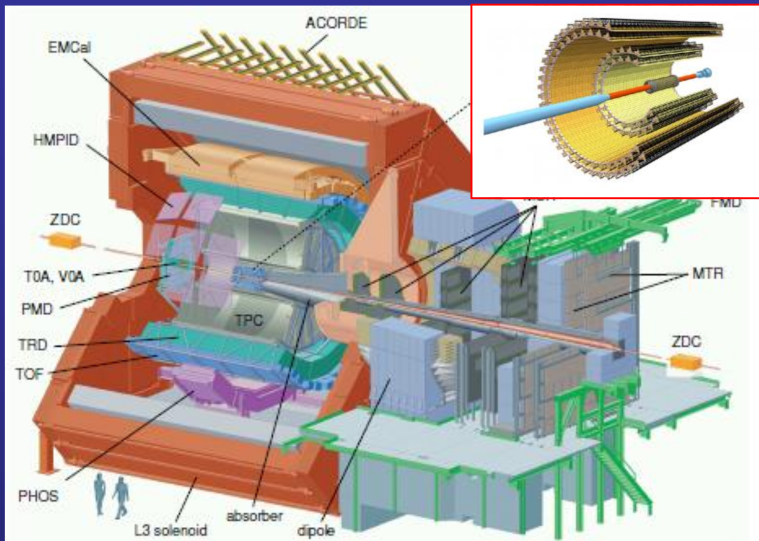
- Other medium-long term options followed with interest (AFTER,FCC)

- Interactions/Collaborations between the Italian experimental and theory community are very fruitful and must be further strengthened

Outcome of WhatNext discussions → see arXiv:1602.04120

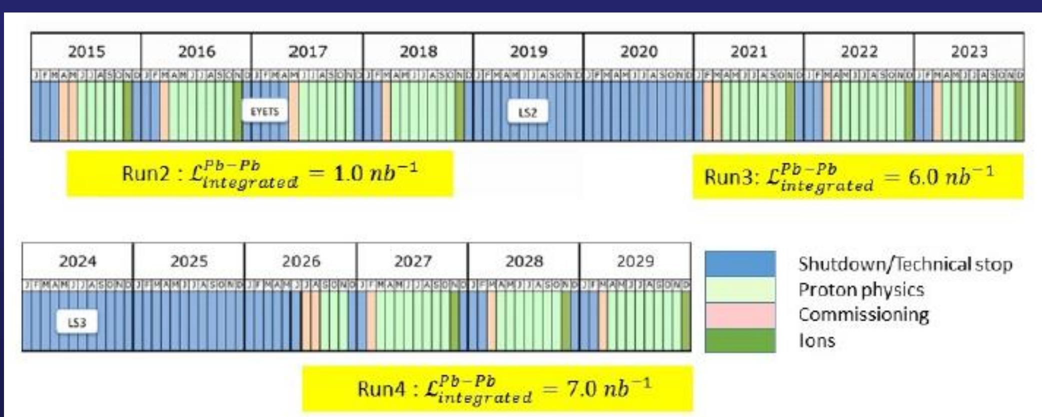
Backup

ALICE upgrades for run3-run4



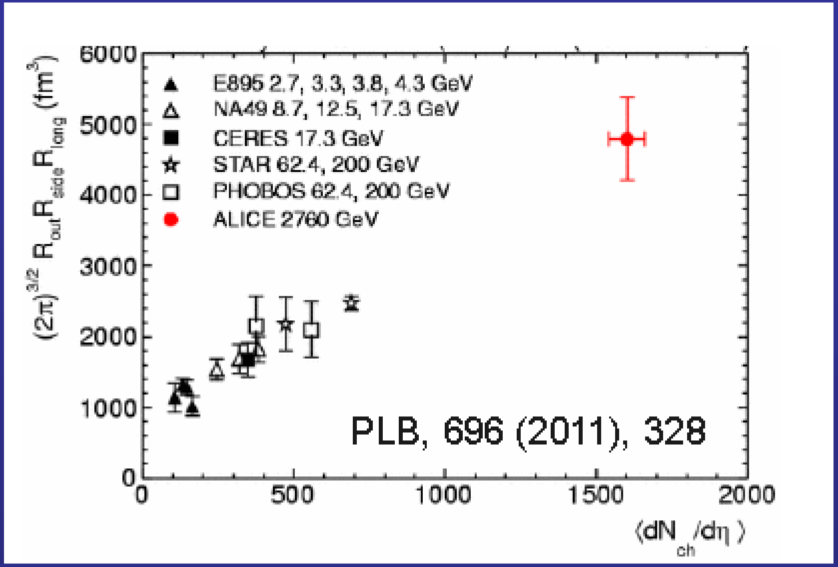
- ❑ Major upgrade of the Inner Tracking system
- ❑ New Muon Forward Tracker
- ❑ New read-out chambers for TPC
- ❑ R/O upgrade of MUON, TOF, ZDC
- ❑ New integrated O^2 system

↳ Improve track reco performance
Event R/O rate to 50 kHz Pb-Pb

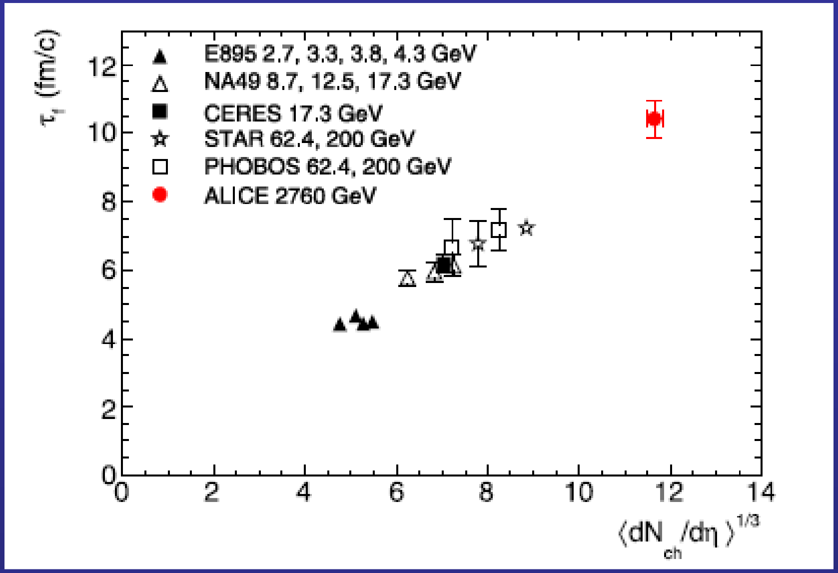


Run3–Run4: collect $L_{3-4} \sim 10 L_{1-2}$
(factor 100 min. bias!)
with a significantly
upgraded ALICE apparatus

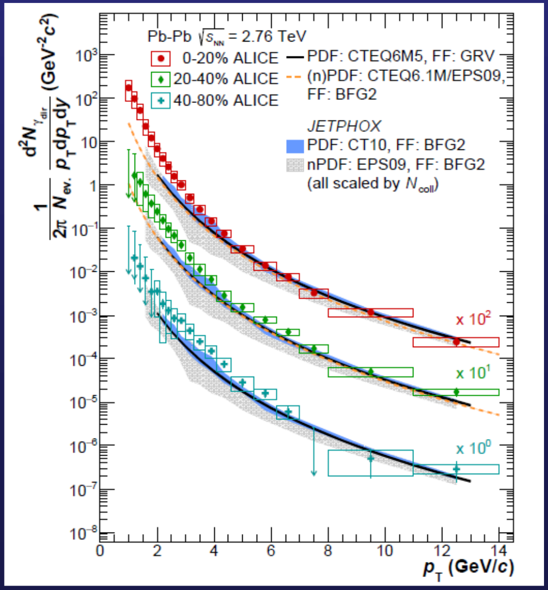
Global properties: LHC vs RHIC

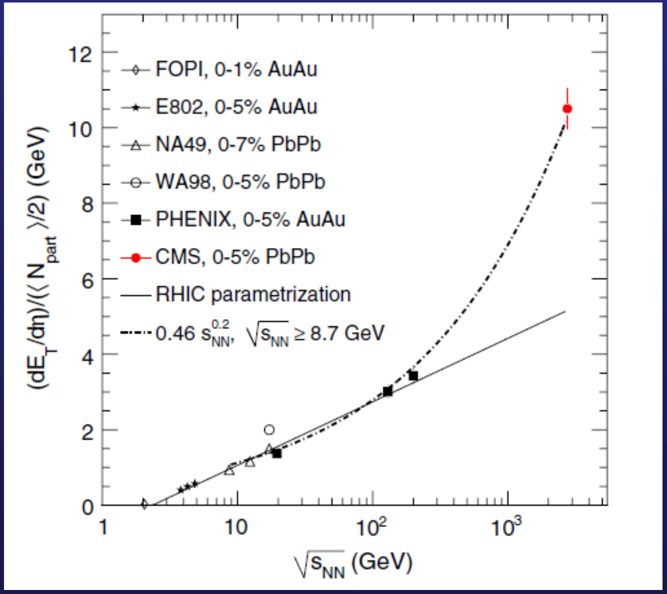


Freeze-out volume LHC~ 2 x V_{RHIC}



Lifetime LHC~ 40% larger than RHIC

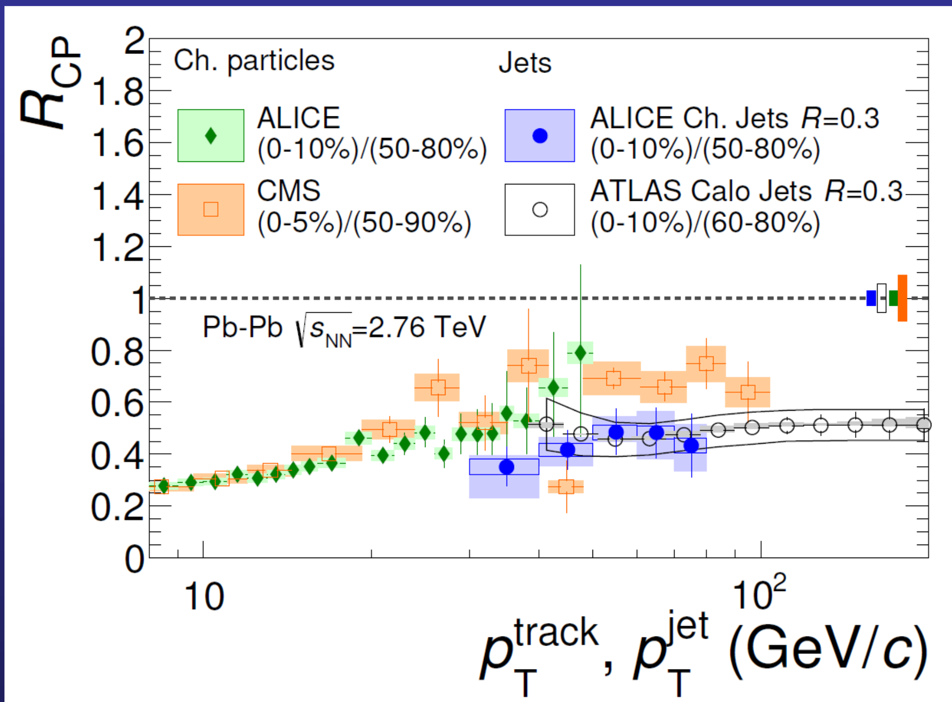


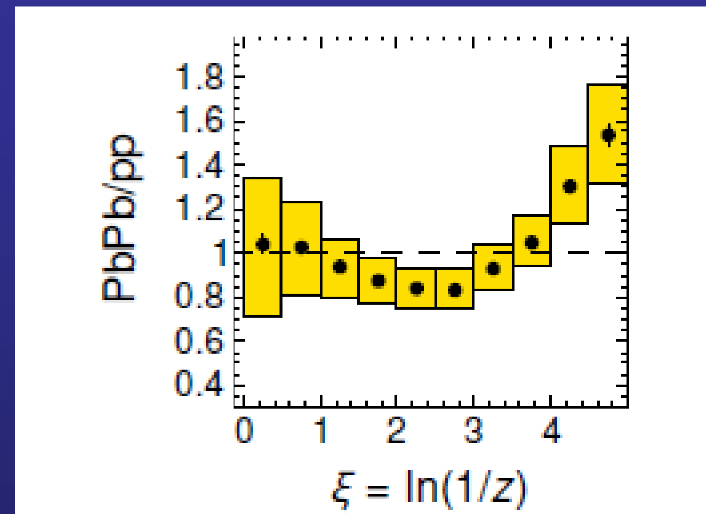


T = 297 ± 12 ± 41vMeV ~ 1.4 x T_{RHIC} Energy density=15GeV/fm^3 ~ 3 x ε_{RHIC}

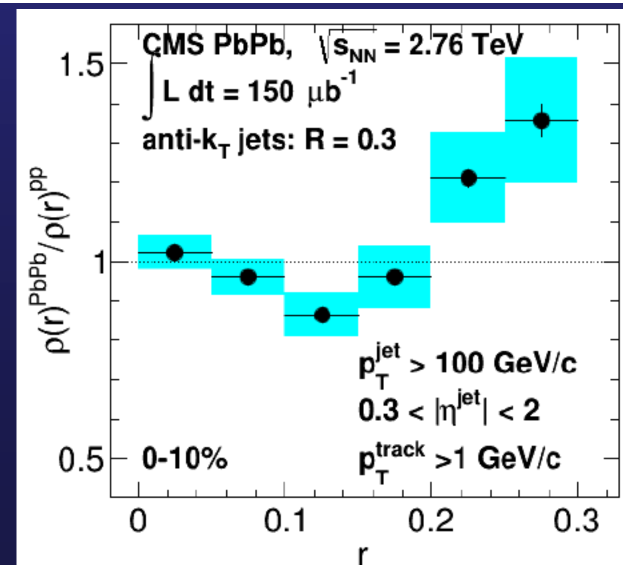
Jet production

- Jet production in Pb-Pb is suppressed at LHC energy
- Study how the energy lost in the QGP by fast partons is re-distributed inside/outside the jet cone → constrain energy loss mechanism





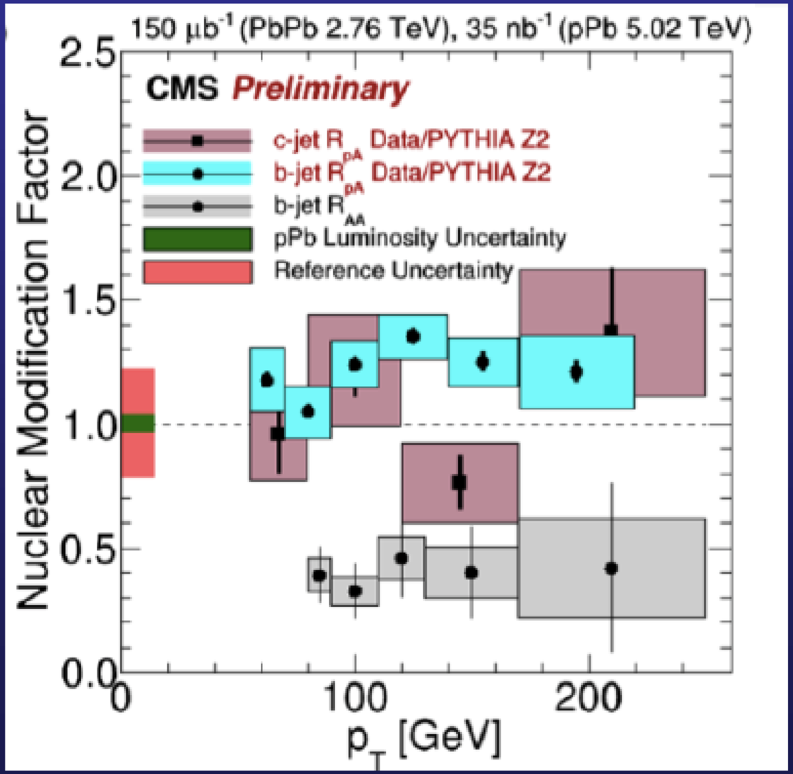
CMS



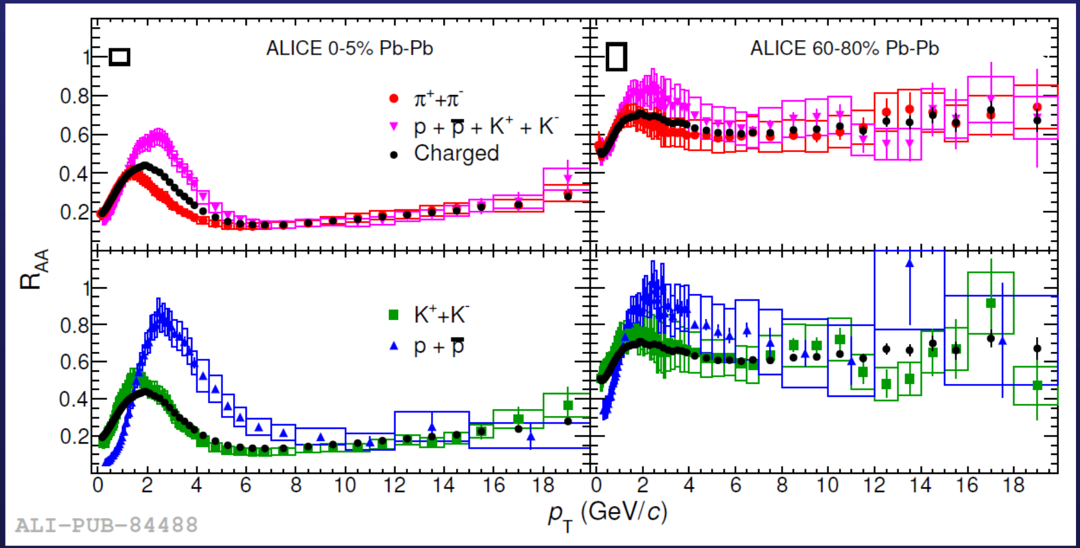
- Little change at small r, high p_T
- Narrowing/depletion at intermediate r, pT
- Broadening/excess at large r, low p_T

Jet production

- ❑ Run 3-4
- ❑ Investigate in detail
  - ❑ Tagged jets (Z+jet, photon-jet, HF-jets)
  - ❑ Complete characterization of final state
    - ❑ Jet-track correlation in-cone and out-of-cone
    - ❑ Jet shapes

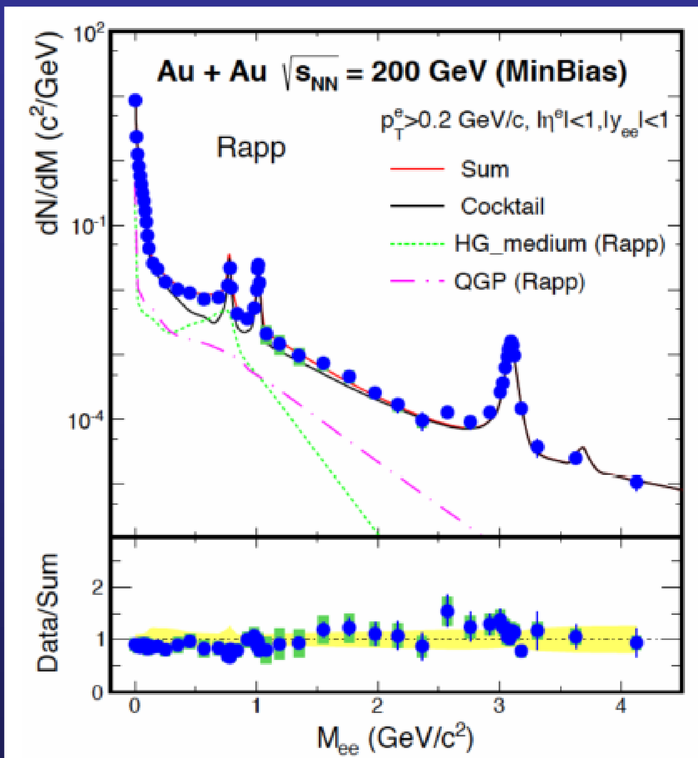


- ❑ On ALICE side
  - → push HF jets to low p_T (thanks to high-precision tracking)
  - → hadrochemistry studies (thanks to refined precision)



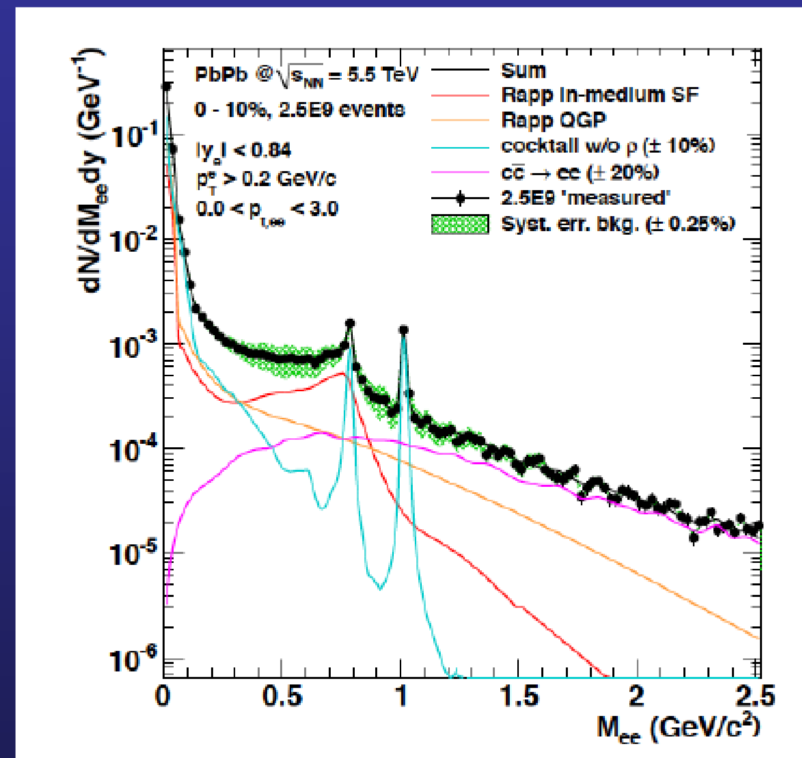
Dilepton production

- E.M. probes → not sensitive to final state
- Chiral symmetry restoration and hadron masses
- Temperature of the emitting medium



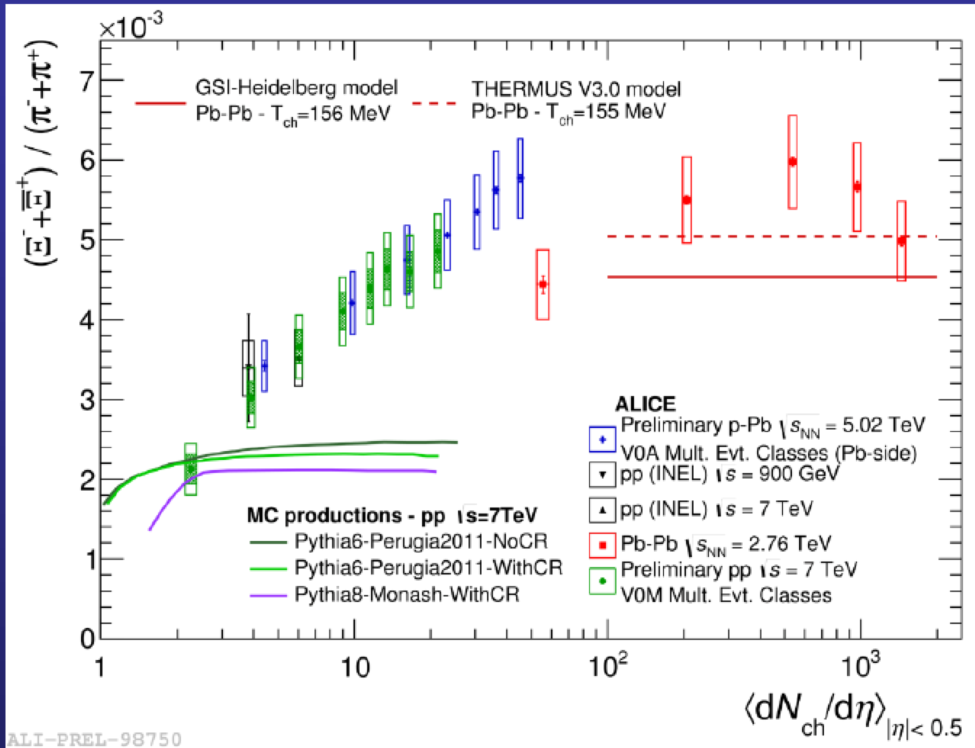
← RHIC

LHC run 3 prospects (ALICE)



- Good agreement between theory calculations and SPS (NA60) and RHIC (PHENIX+STAR) results
- No LHC run-1 (and possibly) run-2 results
- Goal @run-3: measure T with 10% stat (20% syst.) uncertainties

Bulk hadron production



- Increase of strangeness production from pp to Pb-Pb (SPS, RHIC)

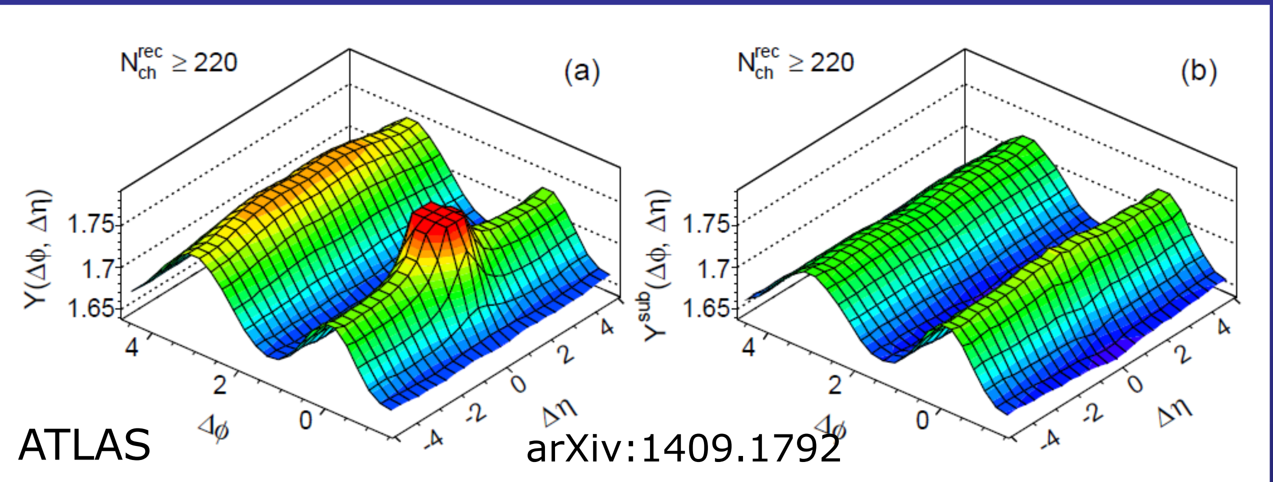
- LHC run-1
  → Observe increase also in high-mult. p-Pb events
  → Recently observed also in pp vs multiplicity!

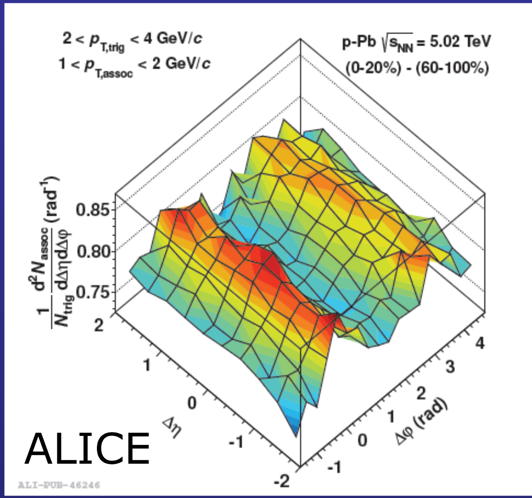
- Saturation to grand-canonical value of the ratio for intermediate size systems ?

- run2 - run-3
  - Large increase of statistics → multiplicity classes overlapping between p-Pb and Pb-Pb. Do ratios saturate at the same value ?
  - Also: freeze-out QGP temperatures different for u/d vs s ? Lattice predicts earlier freeze-out (higher T) for s quark
    → reflected in particle ratios

Collective effects in "small" systems

- Two-particle angular correlations ($\Delta\eta$,$\Delta\varphi$) give evidence of collective behavior (also) in high multiplicity pp and p-Pb interactions





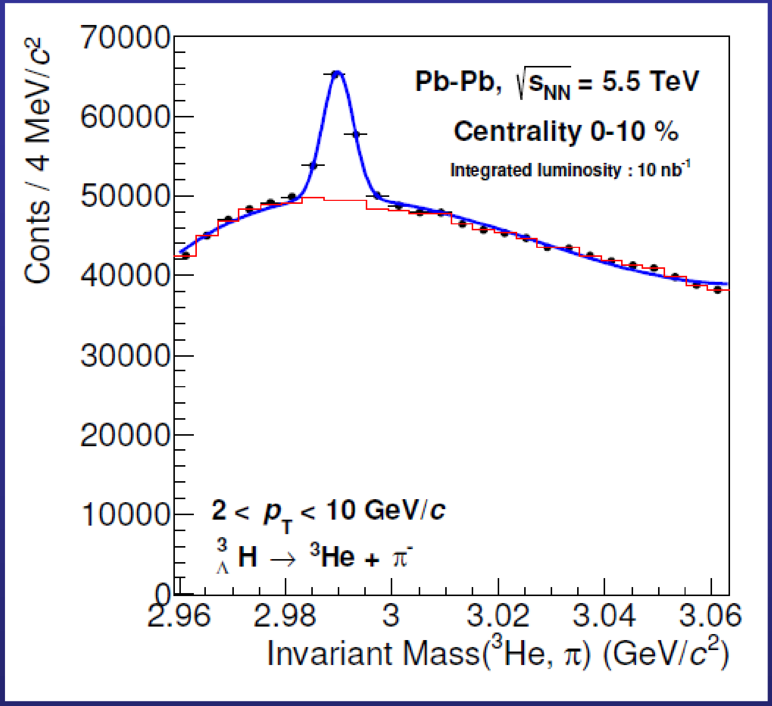
- First observed in A-A, attributed to QGP formation with collective flow
  - Hot expanding medium formed also in more elementary collisions?
  - No appreciable effect on jets and hard probes
  - Two explanations for correlations in light systems
    - initial state local partonic interactions
    - Hydrodynamic flow due to local anisotropies in the final state

- Run 3
  - ALICE extends $\Delta\eta$ range, studies 2-particle correlation with HQ (collective effects should depend on quark mass in hydro scenario)
  - Lighter ion-ion or p-lighter ion collisions

Nuclei, hypernuclei, exotic hadrons

Expected yields in ALICE for 10 nb^{-1}
Copious production!

State	dN/dy	B.R.	$\langle Acc. \times \epsilon \rangle$	Yield
d (TPC)	5×10^{-2}		0.63	3.09×10^{8}
d (TPC+TOF)	5×10^{-2}		0.34	1.36×10^{8}
^{3}He (TOF)	3.5×10^{-4}		0.77	2.16×10^{6}
^{4}He (TPC+TOF)	7.0×10^{-7}		0.26	1.46×10^{3}
$^{3}_{\Lambda}$H	3.5×10^{-4}	0.25	0.15	3.11×10^{4}
$^{4}_{\Lambda}$H	2.0×10^{-7}	0.50	0.13	1.06×10^{2}
$^{4}_{\Lambda}$He	2.0×10^{-7}	0.54	0.11	9.40×10^{1}
Λn	3.0×10^{-2}	0.35	0.17	1.44×10^{7}
$\Lambda\Lambda$	5.0×10^{-3}	0.064	0.04	9.51×10^{4}
$\Lambda\Lambda$	5.0×10^{-3}	0.41	0.04	6.09×10^{5}



- ❑ Nuclei-antinuclei
  - ❑ Precision test of CPT → difference in the interaction of N and $\overline{N}$
  - ❑ Production model: spectator fragmentation vs coalescence
- ❑ Run-1 → behavior governed by chemical freeze-out + hydro expansion

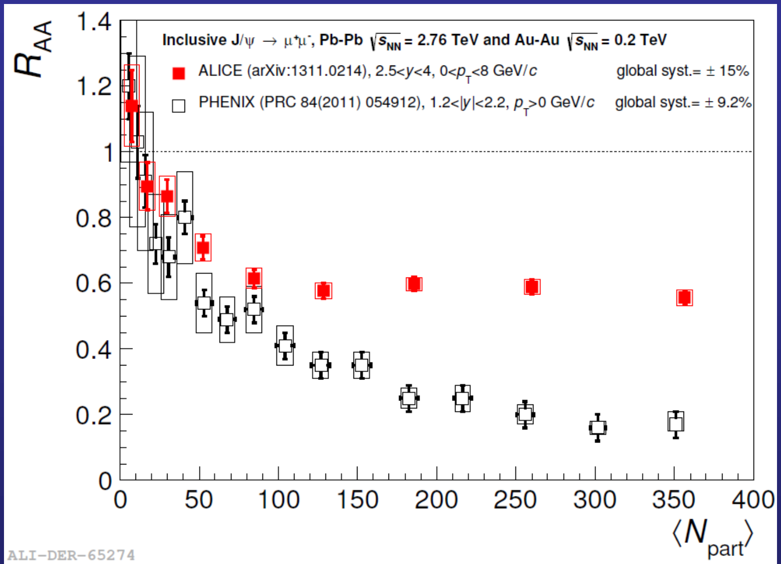
- ❑ Hyperons: weakly bound, sensitive to final stages of the collision
- ❑ Investigate strong interaction of strange hadrons

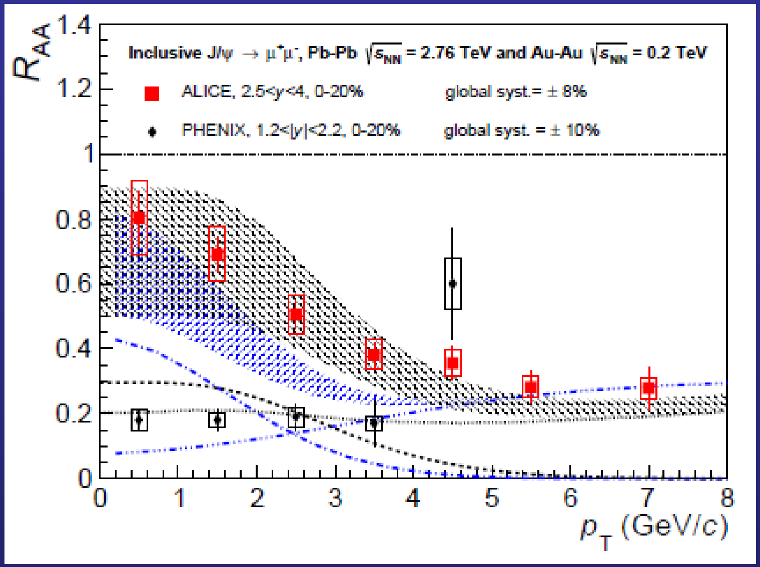
→ implications for description of dense matter (collapsed stellar core)

Quarkonia (charmonium)

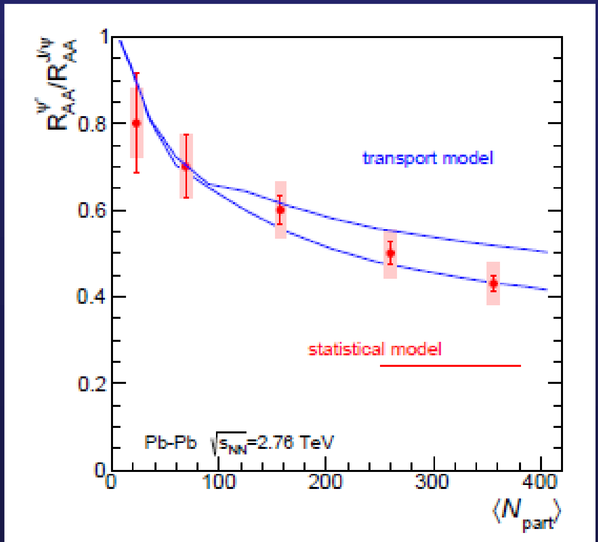
- ❑ LHC run-1 discovery
- ❑ J/ψ suppression less strong than at RHIC
  less strong at low p_T

Evidence for recombination of charm quarks in the QGP!





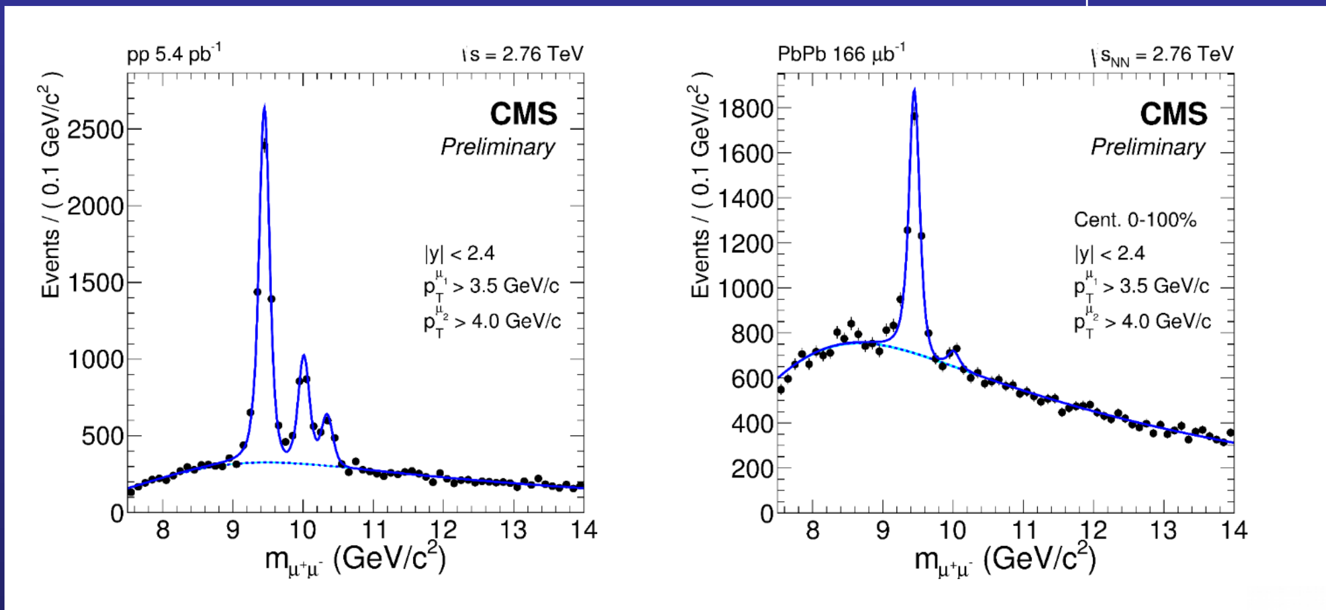
- ❑ Main prospects for run 3-4
  → High-statistics measurements of J/ψ flow and ψ(2S) state (not possible up to now)
- ❑ Discriminate between regeneration models → charmonia regeneration/dissociation in the QGP or at hadronization?



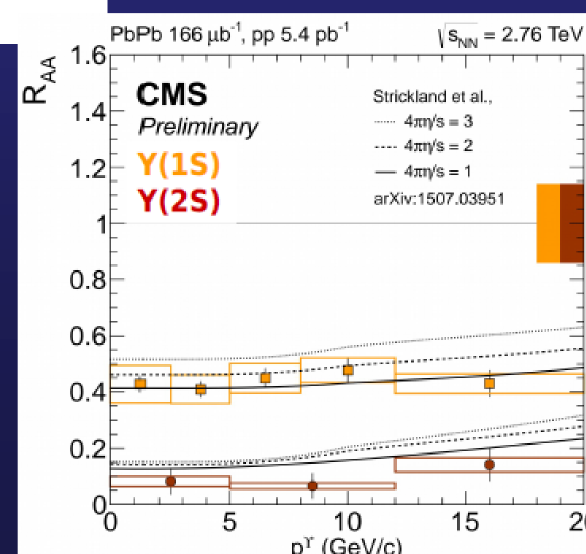
Quarkonia (bottomonium)

- LHC run-1 discovery
- Sequential suppression of the Υ states

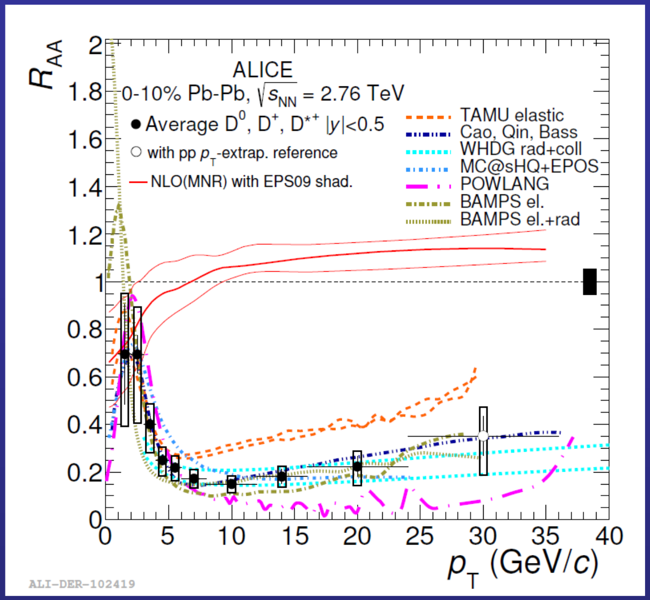
High-temperature QGP formed at LHC energy

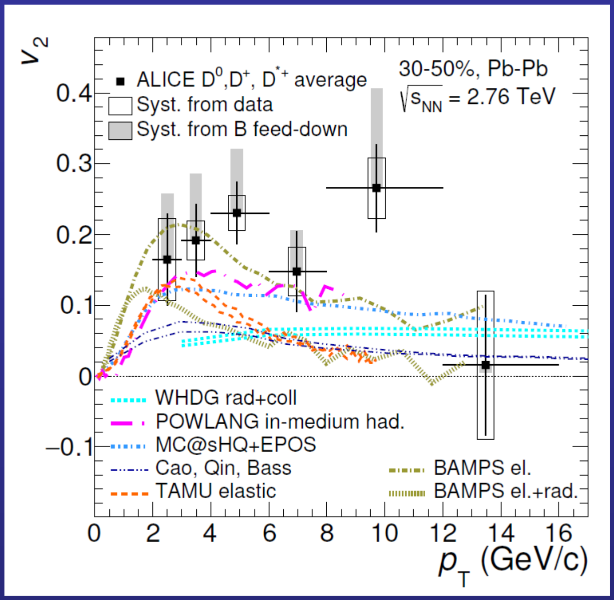


- Main prospects
- Increase significantly the statistics for the less bound states (2S,3S)
- Go differential in p_T, y and centrality



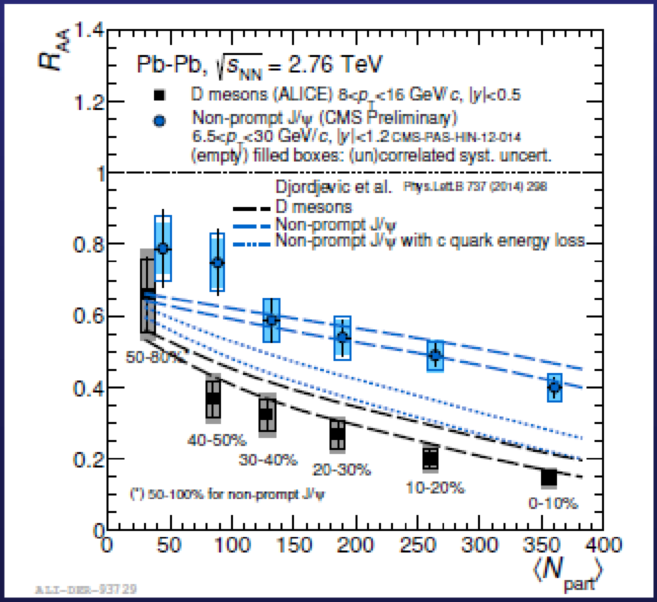
Open charm/beauty





- LHC run 1: first accurate study of R_{AA} and v_2 for charm
  → Still problematic for theory to reproduce BOTH observables

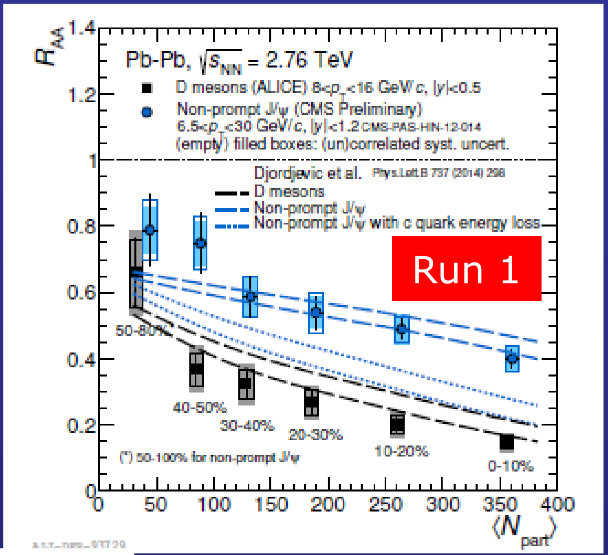
- Clear indication for a quark mass dependence of partonic energy loss

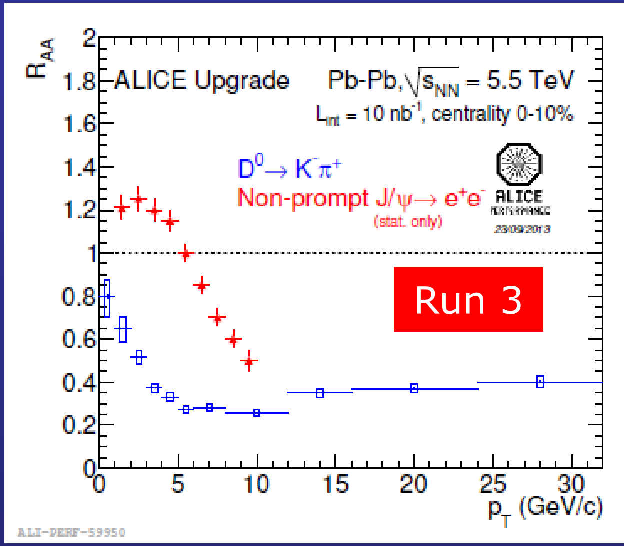


Open charm/beauty

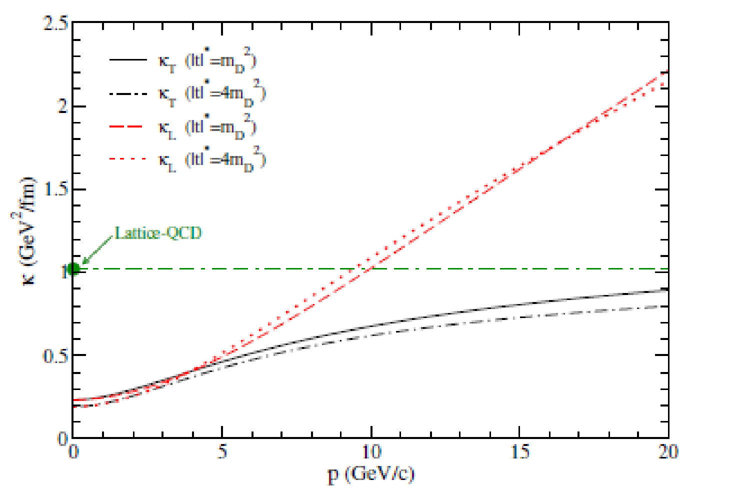
ALICE, arXiv:1506.06604, CMS-PAS-HIN12-014

- ❑ Open HF: flavor dependence of energy loss of hard partons in the QGP
- ❑ Run 3-4: quantitative description





upgrade TDR ITS, JPG41(2014)087002



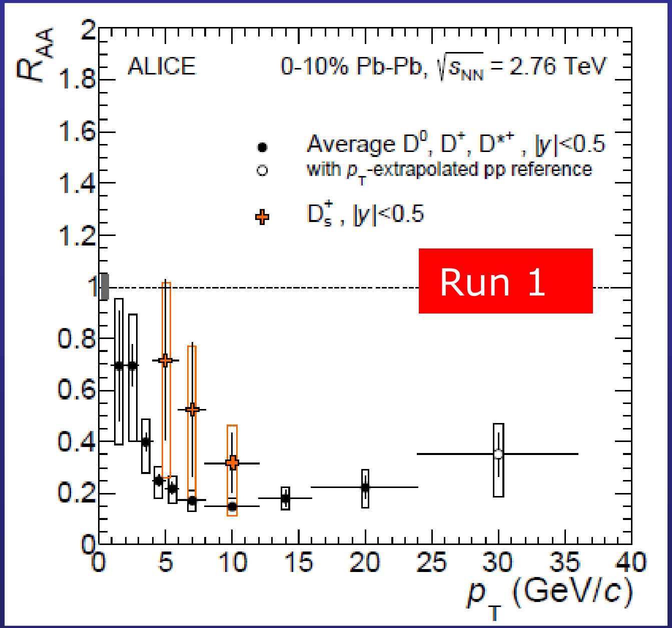
- ❑ Beauty (plot) and charm **transport coefficients** → Measurements at low p_T to compare with theory
- ❑ Complementary to **ATLAS/CMS** → HF hadrons and jets at high p_T

- ❑ Theory: lattice calculation of transport coefficients only available at low p_T
- ❑ Accuracy of the low p_T data still limited up to now

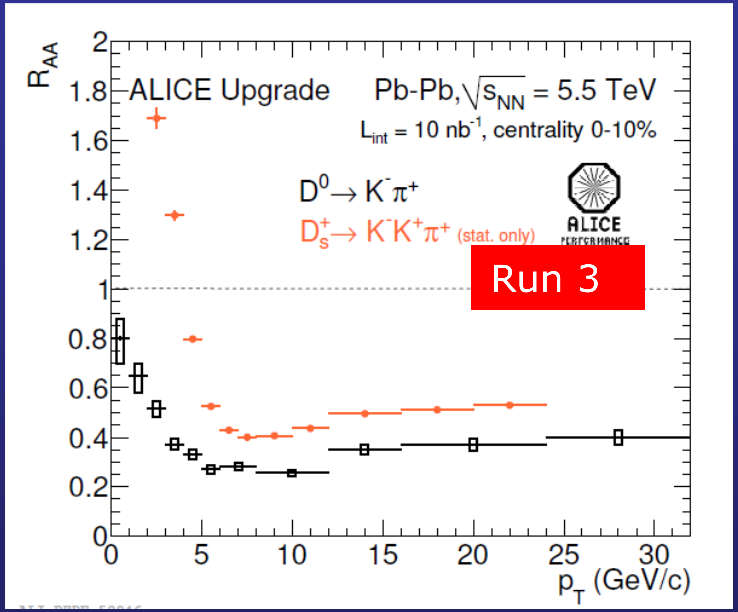
Strange charmed mesons

- Comparison strange vs non-strange mesons hardly possible now

ALICE, arXiv:1509.07287



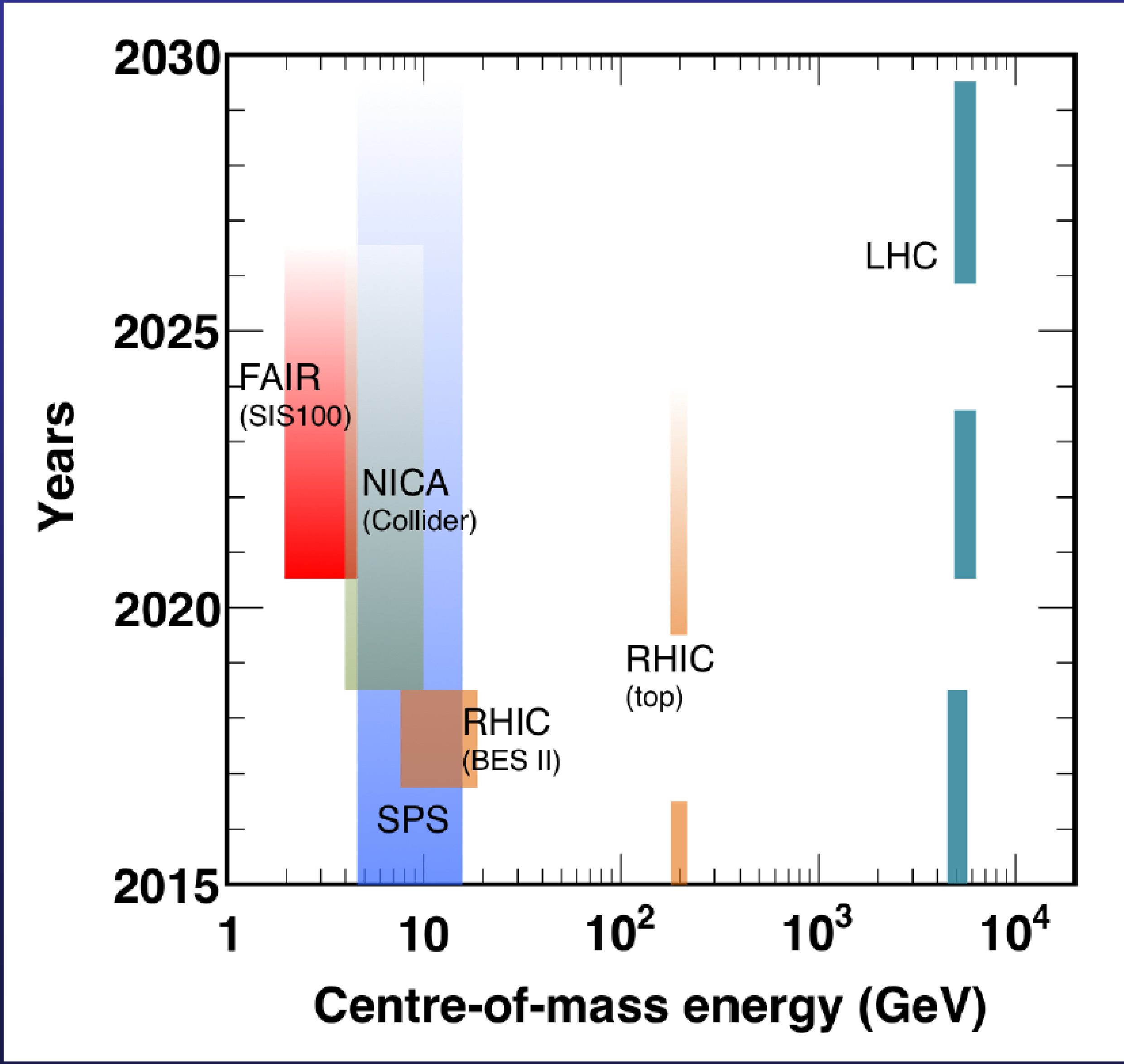
upgrade TDR ITS, JPG41(2014)087002



- Prediction of an enhancement of D_S/D
→ Coalescence mechanism in a medium rich of s quarks

- To be tested with ALICE upgrade

HI-related facilities



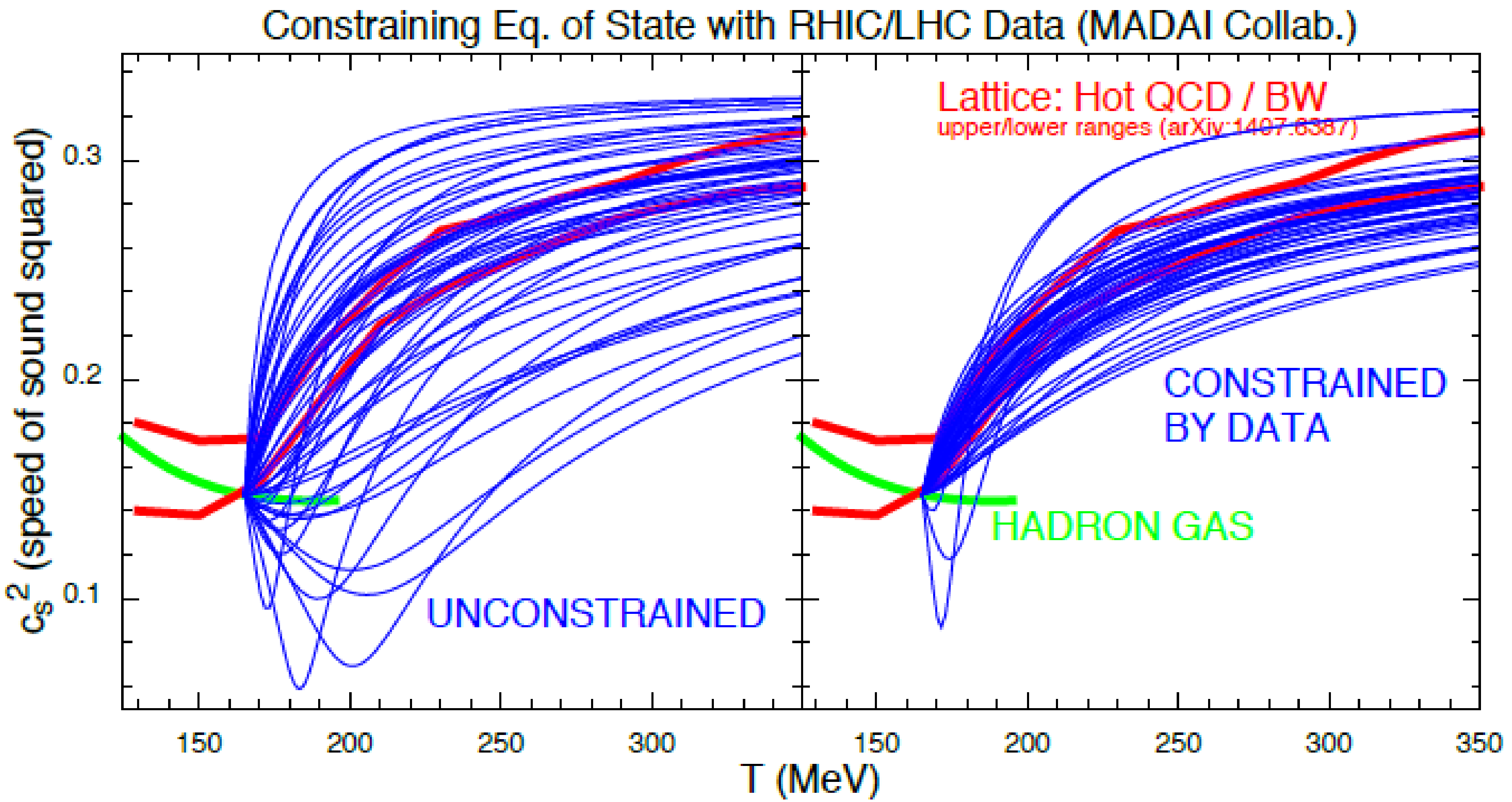
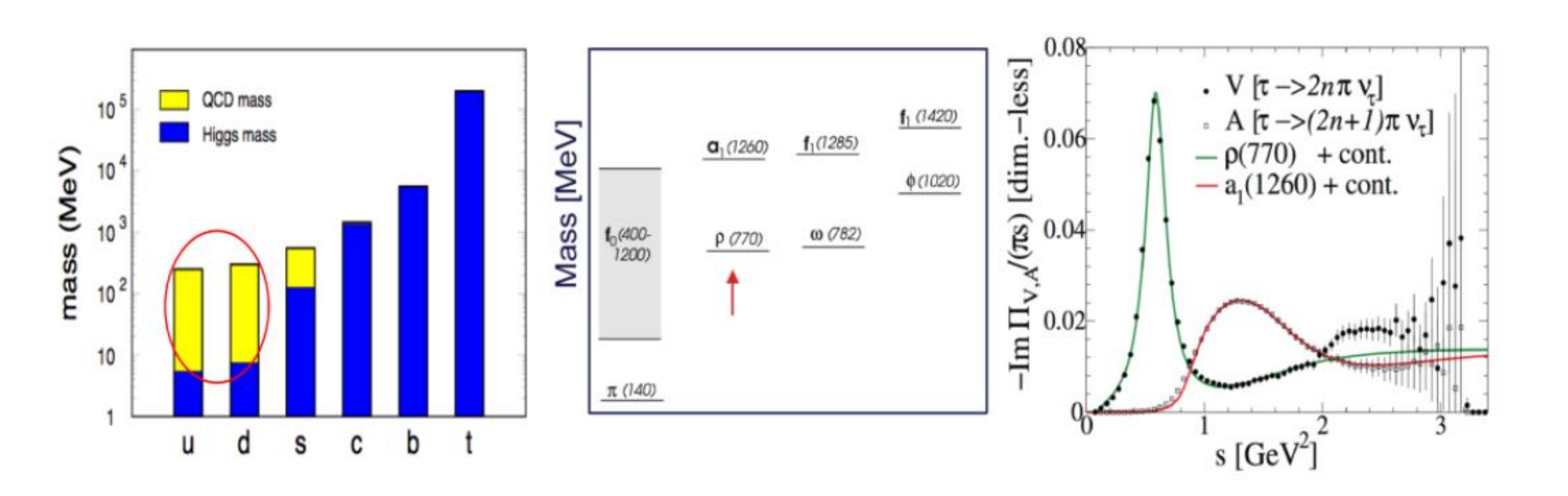


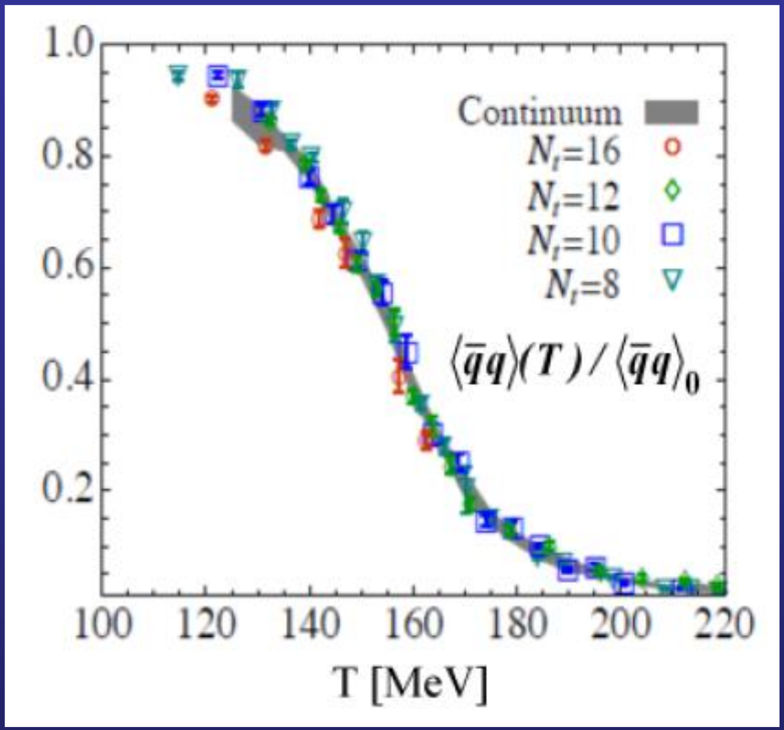
Figure 6: Studies of the QCD equation of state from Lattice QCD calculations and from models constrained by data from RHIC and the LHC [80]. The right panel shows that data prefer an equation of state consistent with lattice QCD demonstrating that our model of the collision dynamics is good enough to allow us to study the emergent properties of QCD.

Chiral symmetry

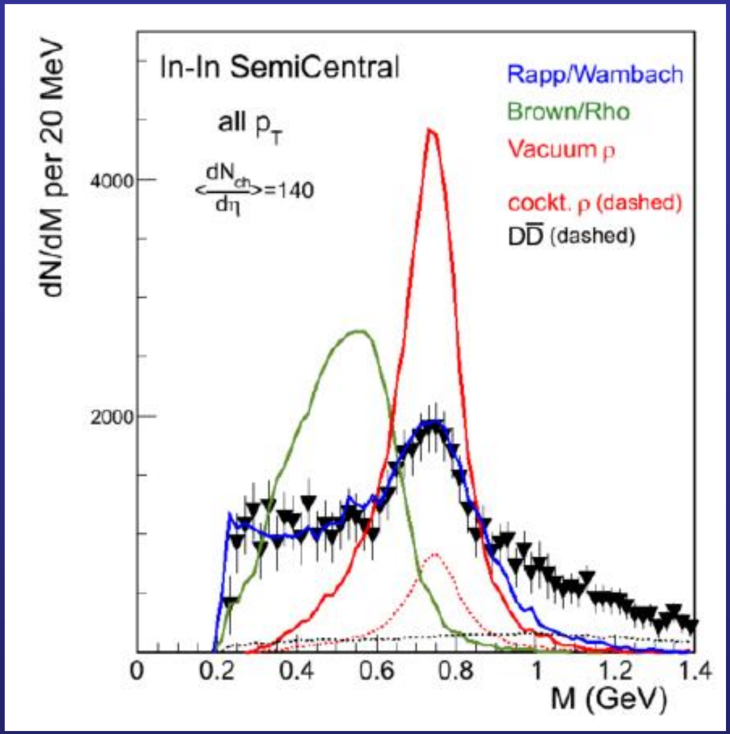


- ❑ Contribution to quark masses from chiral symmetry breaking is dominant for light quarks/hadrons
- ❑ Chiral symmetry removes degeneracy in the low-mass meson spectral function

Approach chiral symmetry restoration



Evolution of chiral condensate with T at $\mu_B=0$



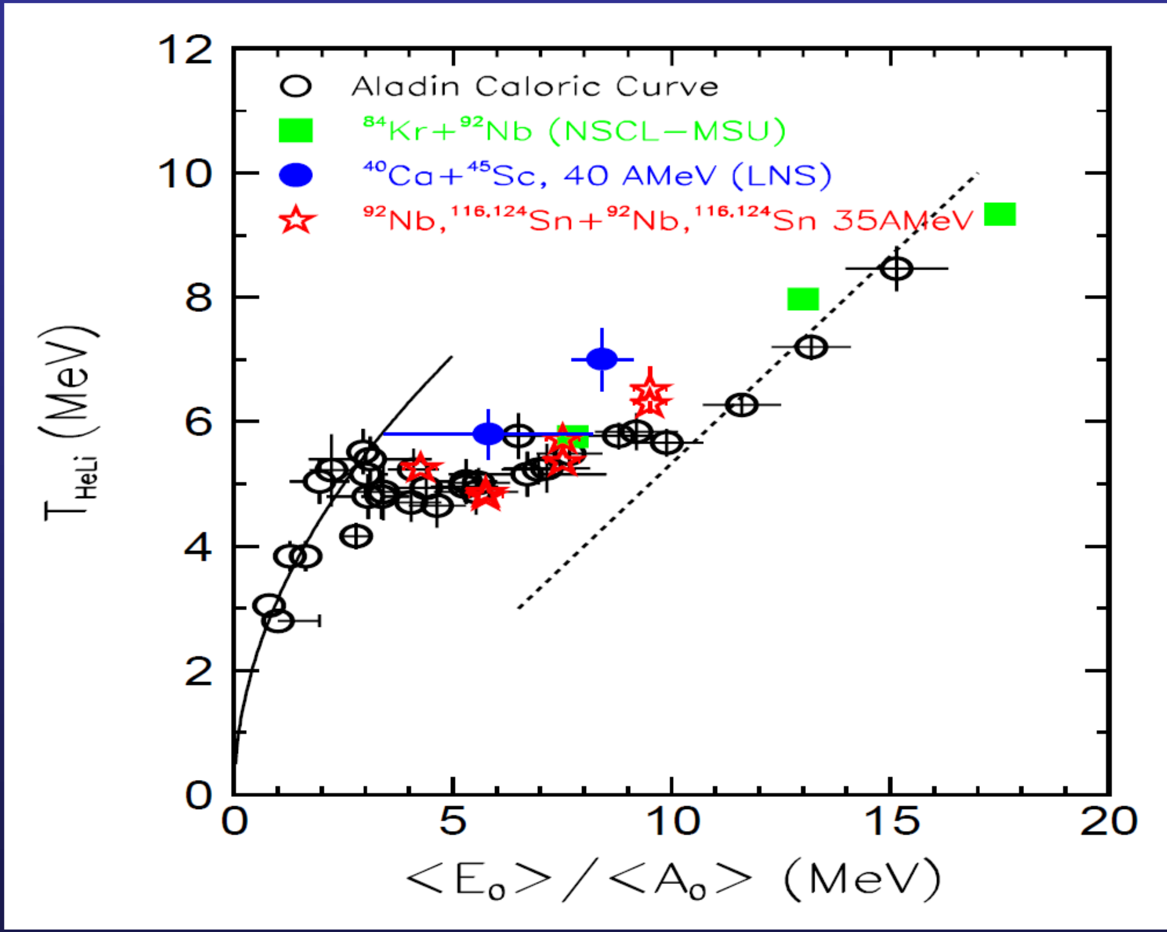
NA60

ρ-meson modifications

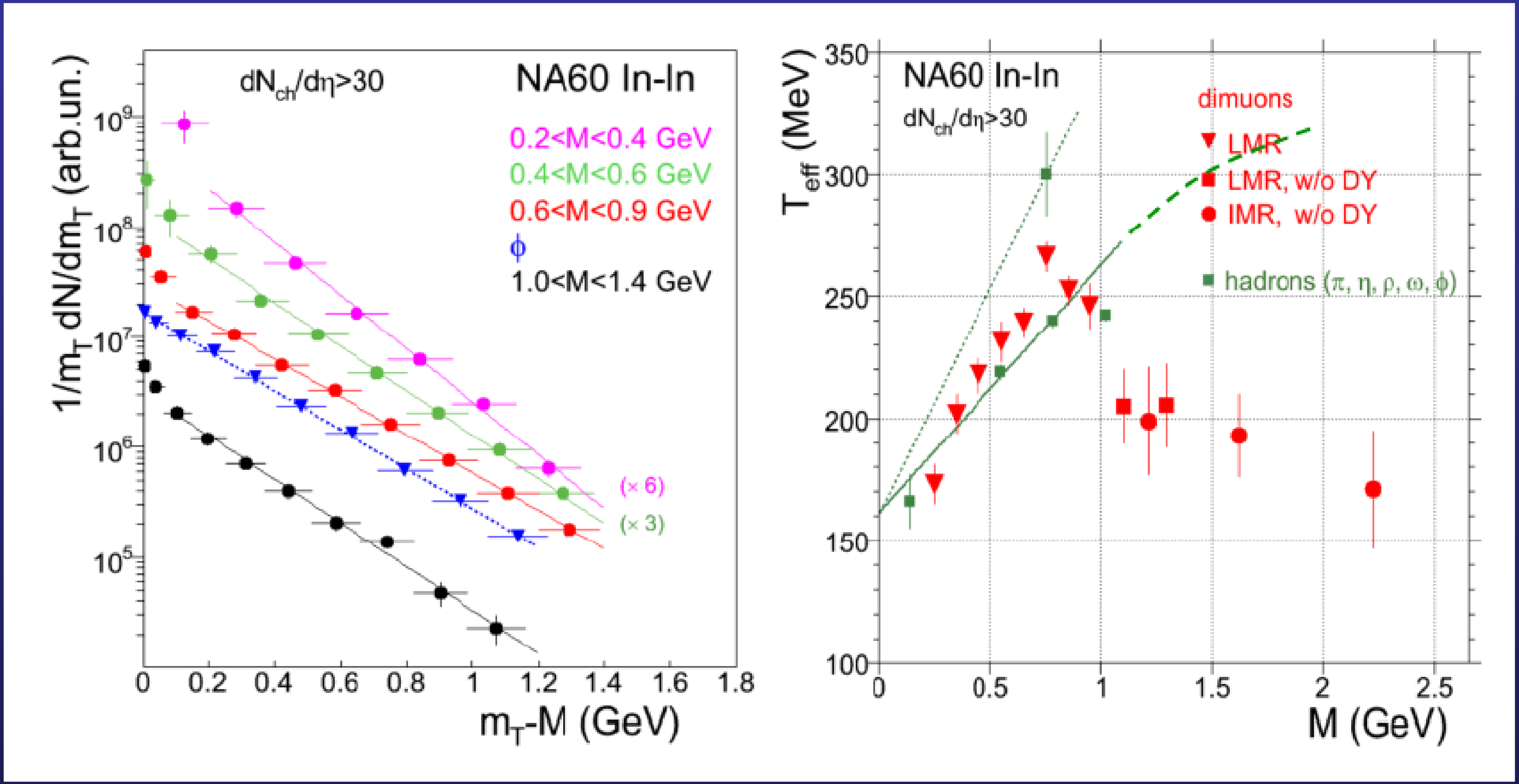
↓

Broadening with no mass shift

Liquid-gas phase transition of nuclear matter



NA60: from hadronic to partonic emission

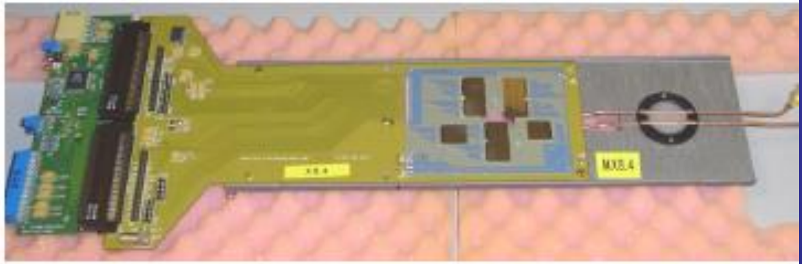


- Rise of T_{eff} at low masses → dominated by late ρ flow
- Drop at large masses → production dominated by a process of partonic origin (no time to build-up flow)

Options for Si tracker

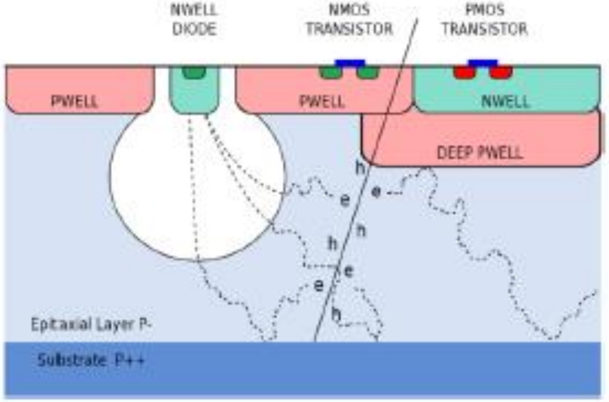
- Baseline option from NA60 experience: detector based on hybrid pixels
  - Pitch 40-50 μm
  - pixel station material budget ≈ 0.5-1% X_0

NA60 pixel plane based on ALICE hybrids

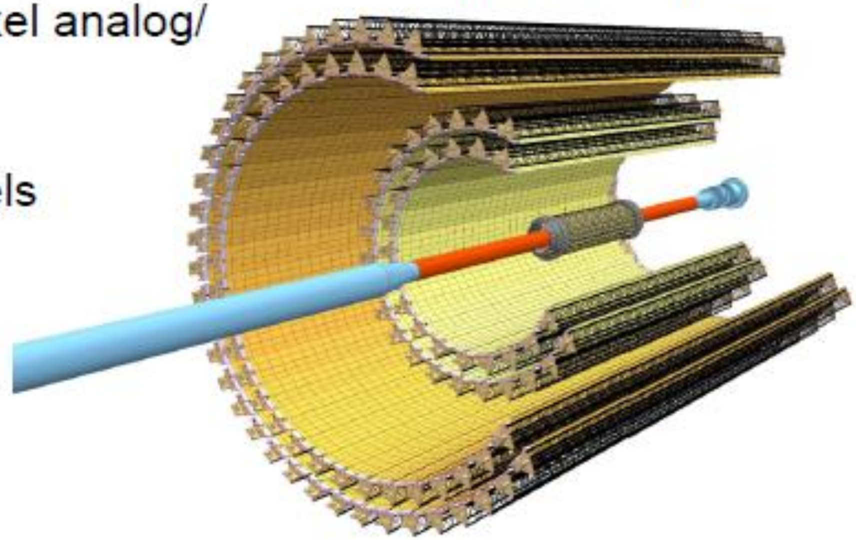


- New monolithic pixels: a break-through for high luminosity experiments might be almost within reach (interaction rates > 500 kHz)

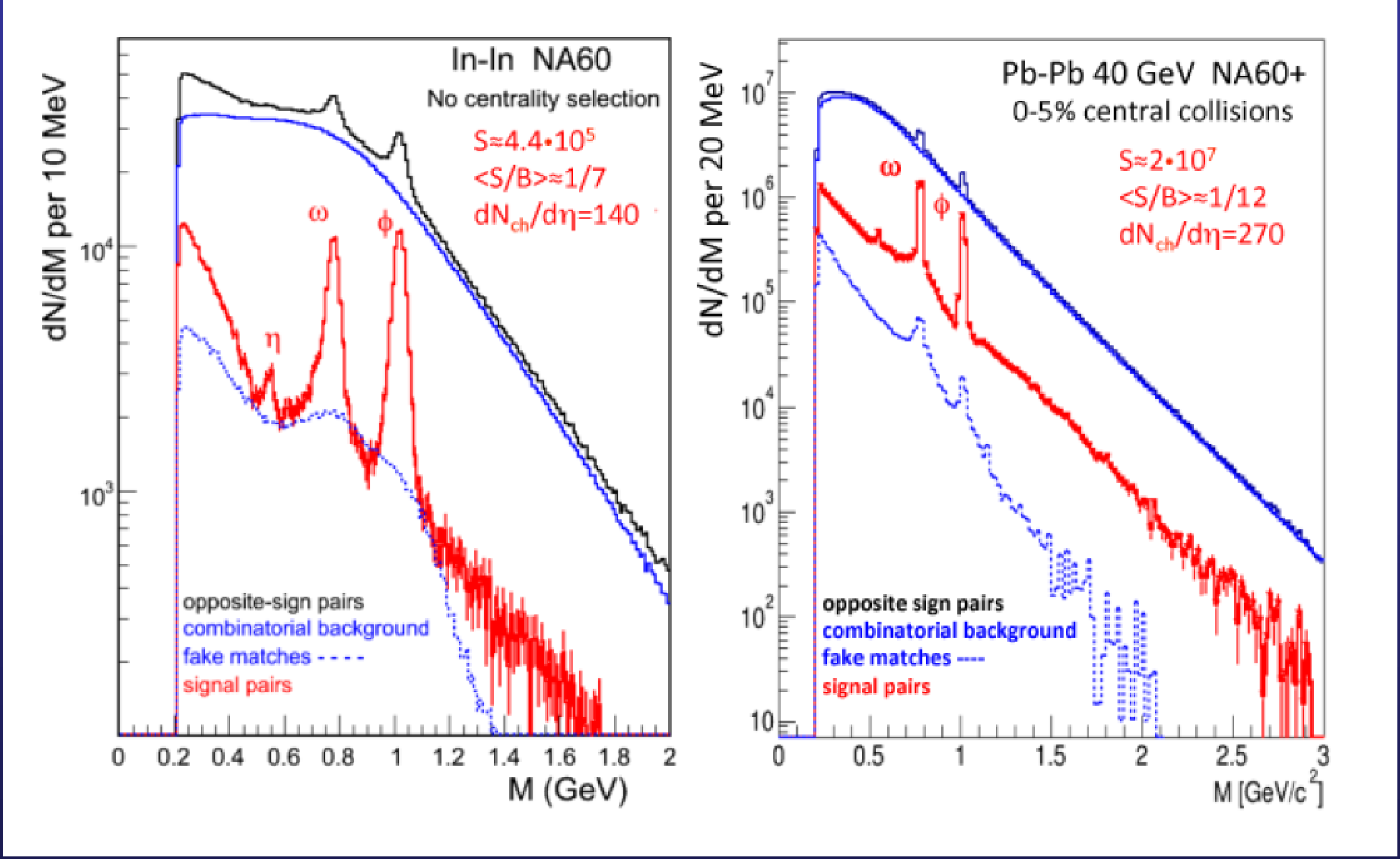
- New very innovative technology:
  - Deep pwell implant allows complex in-pixel analog/ digital front-end
  - Common strobe issued to matrix pixels
  - Address-encoder to readout only hit pixels



New ALICE ITS

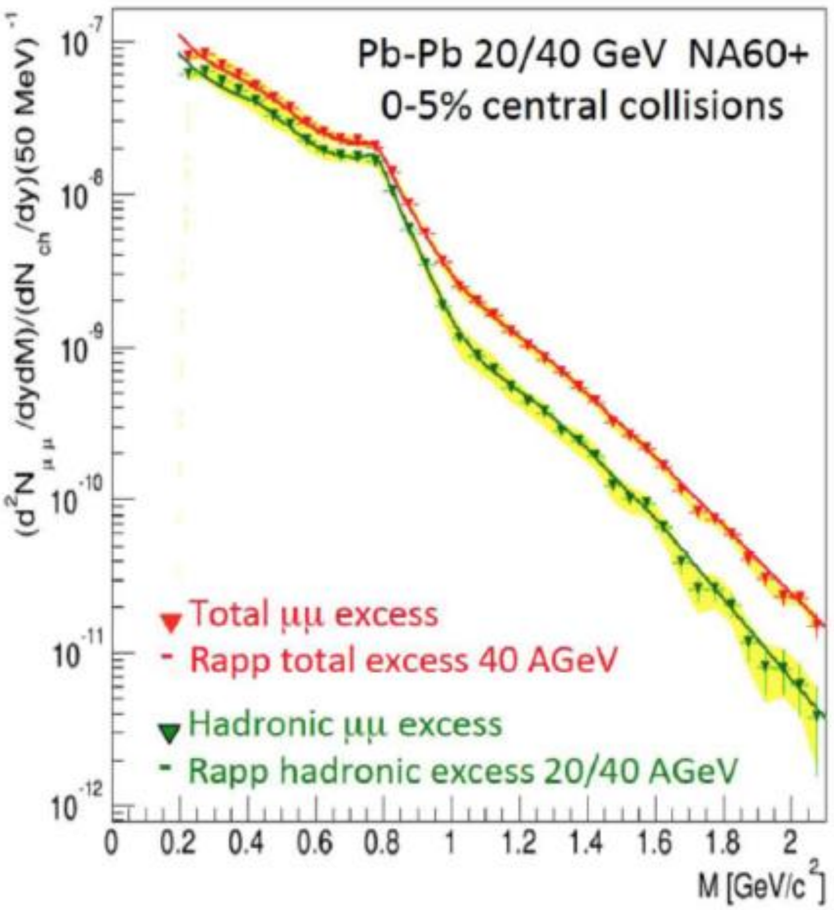


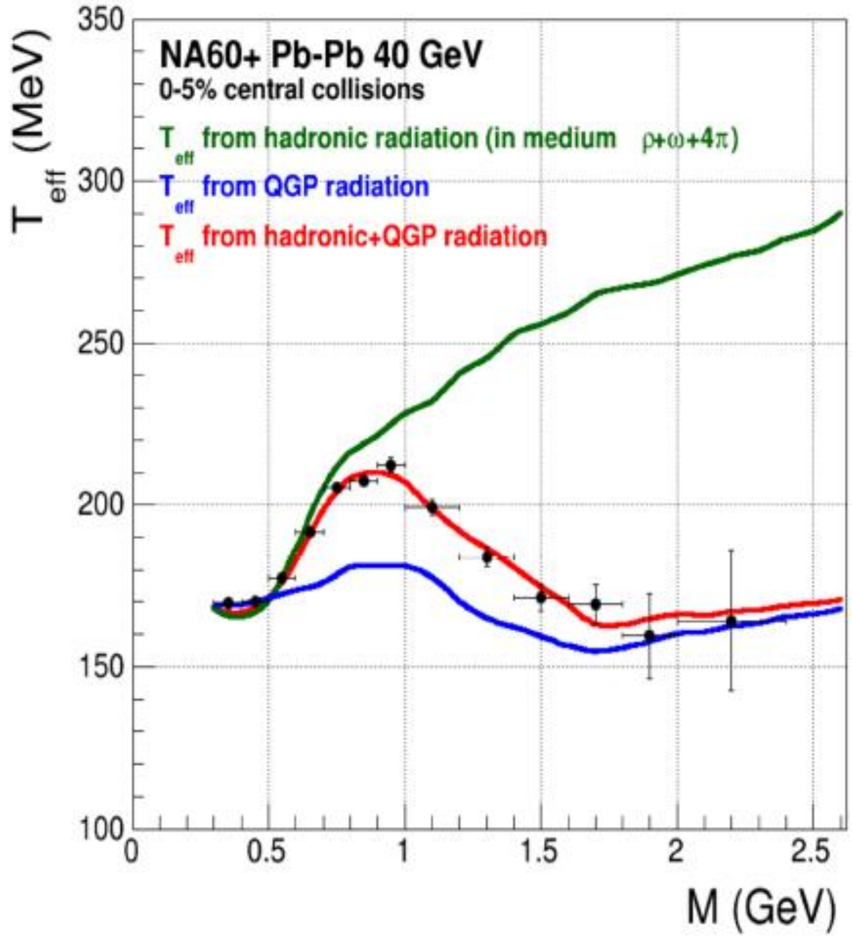
NA60 vs NA60+



In-In NA60
No centrality selection
S≈4.4•10^5
<S/B>≈1/7
dN_ch/dη=140
η
ω
ϕ
dN/dM per 10 MeV
M (GeV)
opposite-sign pairs
combinatorial background
fake matches - - - -
signal pairs
Pb-Pb 40 GeV NA60+
0-5% central collisions
S≈2•10^7
<S/B>≈1/12
dN_ch/dη=270
dN/dM per 20 MeV
M [GeV/c^2]
opposite sign pairs
combinatorial background
fake matches ----
signal pairs

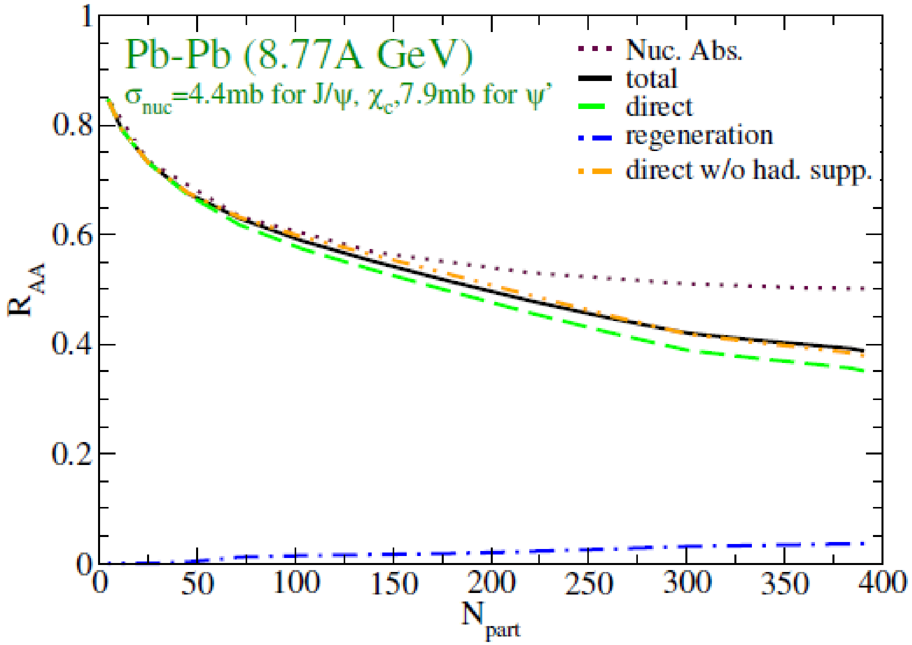
Thermal dimuons – QGP vs hadronic

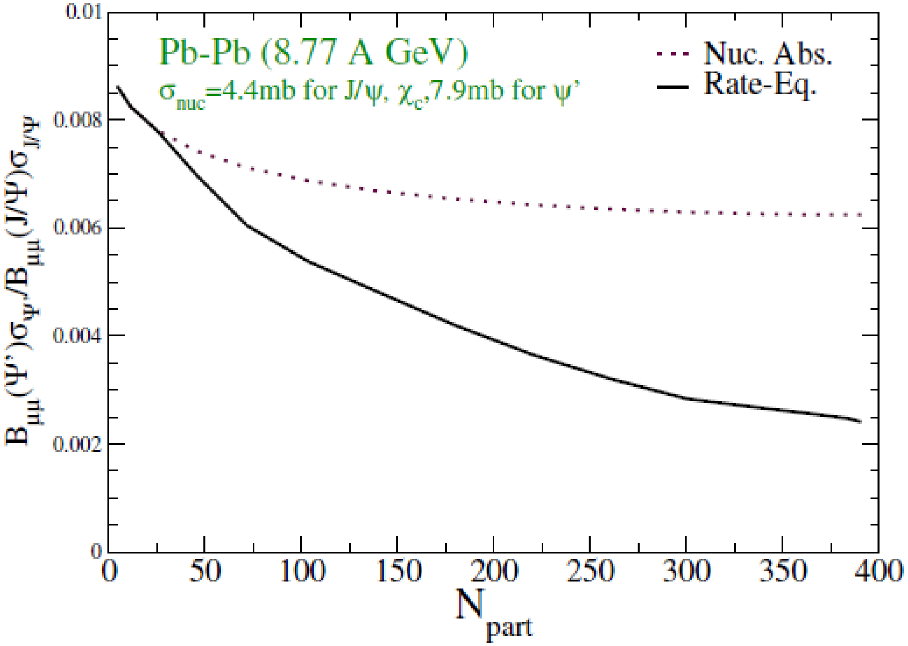


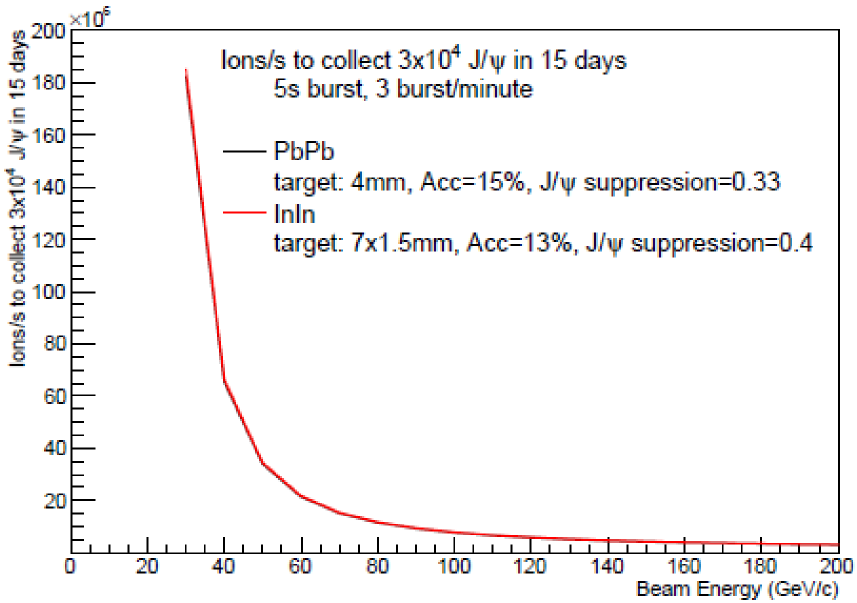


- Evolution of T vs M → drop related to deconfined matter

J/ψ and ψ(2S) suppression







- Goal for J/ψ suppression
  → collect $3\ 10^4$ J/ψ in O(1month)
- Feasible at SPS down to
  E_{Pb}~50 GeV/nucleons

NA60+: SWAT analysis

Internal		External	
Strengths	**Weaknesses**	**Opportunities**	**Threats**
Dilepton physics: strong Italian leadership (experimental) in the international community Experience from NA60 experiment: led by italian teams (Cagliari, Torino) Expertise on pixel detectors (hybrids and MAPS)	Available man-power in the short-time range	Unique measurement of thermal radiation: chiral symmetry restoration, onset of deconfinement SPS: existing facility – unique in years to come to explore the QCD phase diagram NA60+ detector concept: already proven very succesfully (NA60) Focused experiment: relatively low cost (15-20 Meuro) Small collaboration required (50-100 people)	

Decisive parameters for data quality

Luminosity → Effective Luminosity; Luminosity → Overall precision

Signal/Background ratio → Effective Luminosity; Signal/Background ratio → Overall precision

Interaction Rates I_R (Luminosity × σ_{int})

- Fixed target (SPS, SIS100/300): 10^6-10^7/s (NA60 5×10^5)
- Colliders (LHC upgrade): 5×10^4/s

Signal/Background ratio S/B (B - combinatorial background)

- range of B/S for different experiments: 20 - 1000 → B/S >>1
- effective signal size: $S_{eff} \sim I_R \times S/B$ reduction by factors of 20-1000 !

Overall precision

- systematics due to S/B: $\delta S_{eff}/S_{eff} = \delta B/B \times B/S$ $\delta B/B = 2 \ldots 5 \times 10^{-3}$

Combinatorial background/signal in dilepton experiments

Reference: hadron cocktail at masses of 0.5-0.6 GeV

Experiment	Centrality	Lepton flavor	B/S as meas. or simul.	B/S rescaled to $dN_{ch}/dy=300$
HADES-SIS100	semicentr	e^+e^-	20	60
CERES DR	semicentr	e^+e^-	80	100
CERES SR/TPC	central	e^+e^-	110	100
PHENIX with HBD	central	e^+e^-	250	100
PHENIX w/o HBD	central	e^+e^-	1300	600
STAR	central	e^+e^-	400	200
ALICE Upg ITS	central	e^+e^-	1200	200
CBM-SIS100	central	e^+e^-	80	100
CBM-SIS300	central	e^+e^-	100	100
NA60 (InIn)	semicentr	$\mu^+\mu^-$	35	80
NA60+	central	$\mu^+\mu^-$	90	110
CBM-SIS300	central	$\mu^+\mu^-$	100	100

data / simulations PbPb

BEAM EXTRACTION : THE PARASITIC MODE

- From standard collimation, to crystal-based collimation … and to **beam extraction**

today	SPS (UA9)	CRYSBEAM (SPS then LHC)
	LHC (LUA9)	AFTER (LHC)

- UA9 : a complete crystal collimation prototype is installed in the SPS
  - ✓ **Multi-turn channeling efficiency : 70÷80% for protons, 50÷70% for ions**
  - ✓ Loss reduction rate at crystal : 20× for protons, 7× for ions
  - ✓ Off-momentum loss reduction : 6× for protons, 7× for ions (currently, LHC is limited by dispersion losses)
- LUA9 : approved by the LHCC
  - ✓ 2 crystals already installed in the LHC beam pipe
  - ✓ **first tests with beam possibly in 2015/2016**

[S. Montesano, Joint LUA9-AFTER meeting, Nov. 2013]

LUMINOSITIES

$\sqrt{s}$ = 115 GeV

Estimates based on :

- extraction eff. (multi pass) ~**50% LHC beam loss** $\Rightarrow$ **5.10^8 p$^+$/s extracted**
- 1 year = 10^7 s for p$^+$ beam

✓ AFTER@LHC : outstanding luminosities $\Rightarrow$ precision studies

	Target	Luminosity / year fb^{-1}	yield / unit of rapidity at y=0 J/ψ	Υ
p-H	10 cm solid H	2.6	5.2 10^7	1.0 10^5
p-H	10 cm liquid H	2.0	4.0 10^7	8.0 10^4
p-H	10 cm liquid D	2.4	9.6 10^7	1.9 10^5
p-A	1 cm Be	0.62	1.1 10^8	2.2 10^5
p-A	1 cm Cu	0.42	5.3 10^8	1.1 10^6
p-A	1 cm W	0.31	1.1 10^9	2.3 10^6
p-A	1 cm Pb	0.16	6.7 10^8	1.3 10^6

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

Compare to :

- LHC 2012 Run (4 TeV p+ beam), delivered luminosity at **LHCb 2.115 fb^{-1}**
- **RHIC** expected luminosity (PHENIX decadal plan) in 2014
  pp @ 200 GeV **1.2 10^{-2} fb^{-1}**, dAu @ 200 GeV **1.5 10^{-4} fb^{-1}**

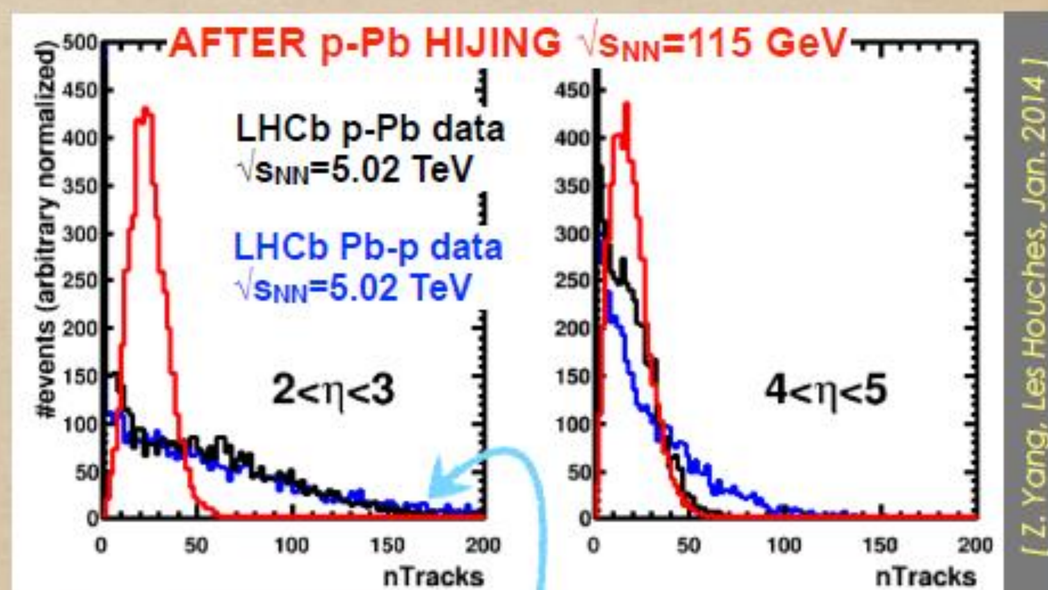
TOWARDS A FORWARD DETECTOR

- Focus on ($y_{CM}<0$) i.e. « large » angles ($\theta>1°$) but still forward angles in the Lab.
- What needs to be improved w.r.t. known detector performances ?

- for e.g. a LHCb-like detector : $2 < \eta < 5$

✓ Track multiplicity : cope with the boost

Despite the boost, the track multiplicity is lower in the fixed target mode than in the collider mode



highest multiplicity/event ever experienced so far by LHCb

TOWARDS A FORWARD DETECTOR

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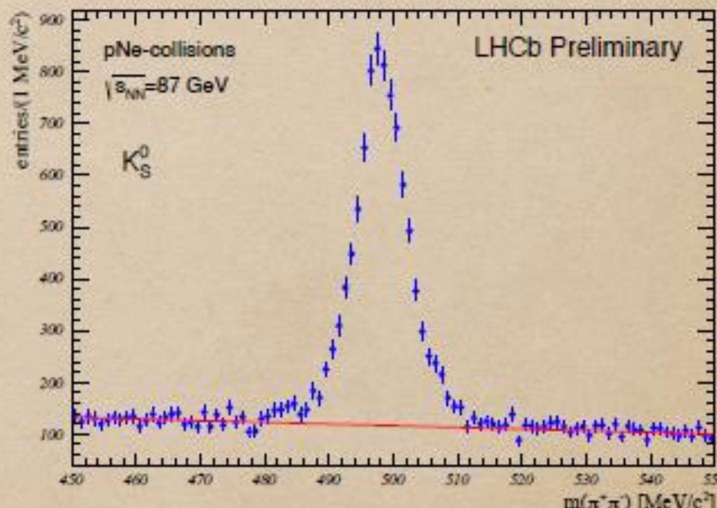
✓ Track multiplicity : cope with the boost

✓ SMOG pilot run : a proof of principle

System for Measuring Overlap with Gas

[M. Schmelling, Les Houches, Jan. 2014]

Inject rare gas (Ne) in the VELO, for luminosity measurements ⟹ **LHCb taking data in fixed-target mode, with gaseous target**



[LHCb-Conf-2012-034]

Strangeness production (for .e.g K^0_s)
4 TeV proton beam on gaseous Ne target

TOWARDS A FORWARD DETECTOR

- Focus on (y_{CM}<0) i.e. « large » angles (θ>1°) but still forward angles in the Lab.
- What needs to be improved w.r.t. known detector performances ?

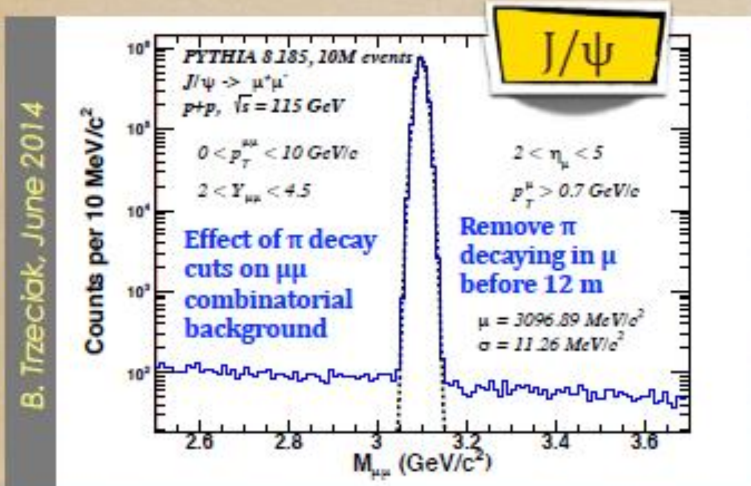
- for e.g. a LHCb-like detector : 2 < η <5

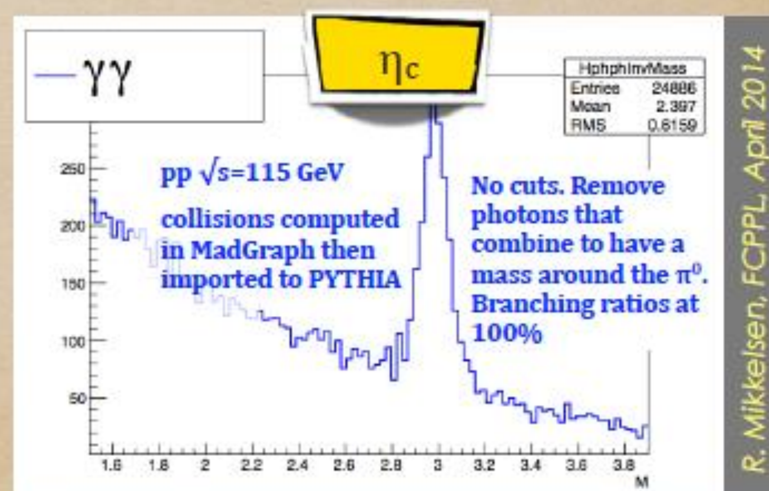
✓ Track multiplicity : cope with the boost

✓ SMOG pilot run : a proof of principle

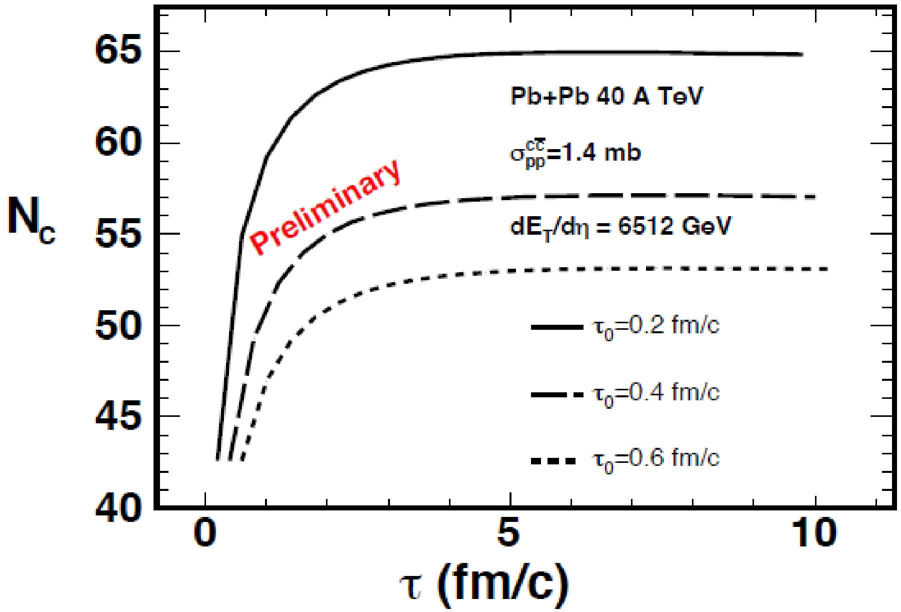
✓ Fast simulations : first look at the background for quarkonium

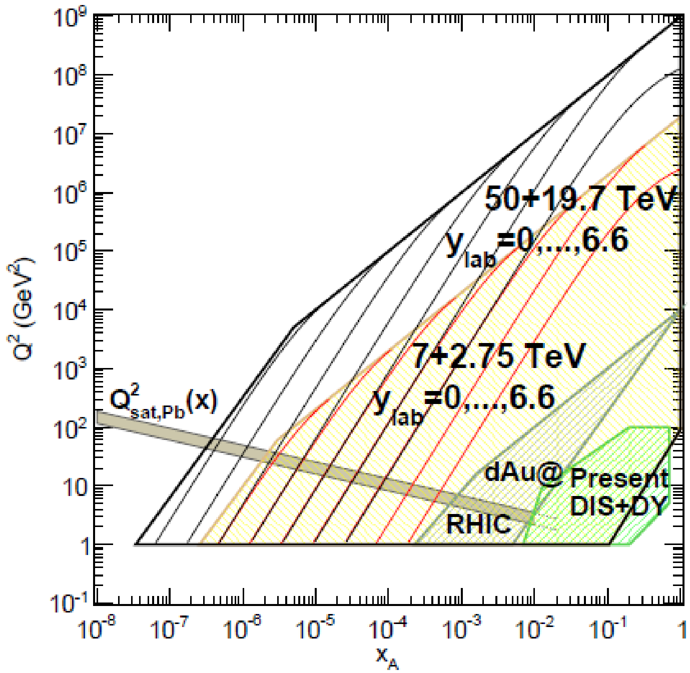
Using η coverage, photon ΔE/E, muon Δp/p of LHCb detector, + their usual cuts on muon p_T to improve the S/B ratio





Heavy-ions at FCC





Evolution of charm production, central Pb-Pb collisions
→ Sensitive to initial temperature and its evolution during QGP phase

Kinematic coverage

Ions at FCC

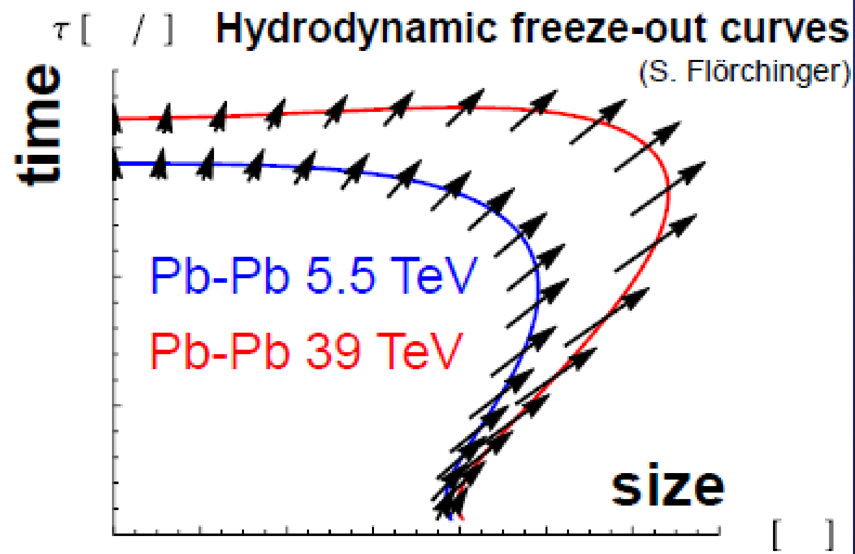
- Centre-of-mass energy per nucleon-nucleon collision:

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}} \Rightarrow \begin{array}{l} \sqrt{s_{PbPb}} = 39\ TeV \\ \sqrt{s_{pPb}} = 63\ TeV \end{array} \text{ for } \sqrt{s_{pp}} = 100\ TeV$$

- First (conservative) estimates of luminosity (in comparison with LHC): x8 larger L_{int} per month of running
- Could aim for programme of 100/nb (LHC x10)

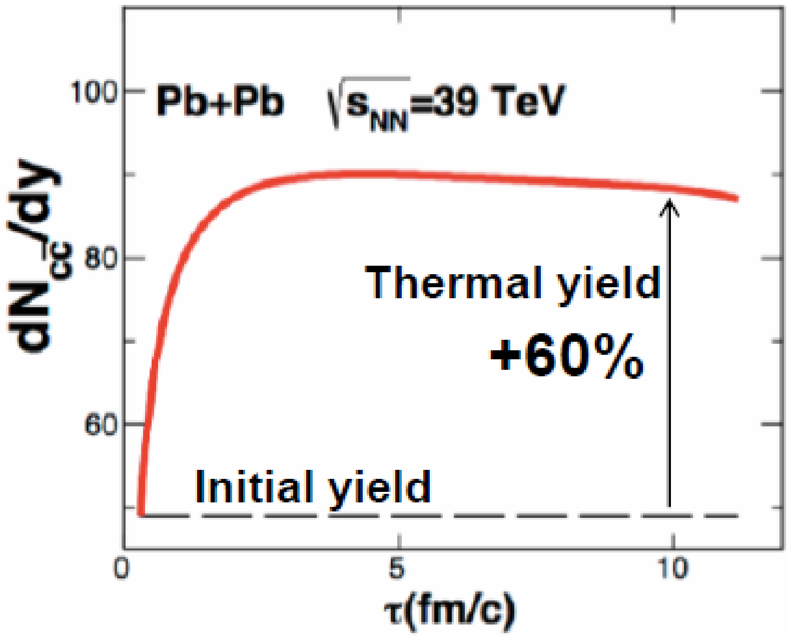
QGP properties:

- Saturated initial state (small-*x*)
- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced
- Initial temperature higher
- Abundant production of rare hard probes (Z+jets, top…)



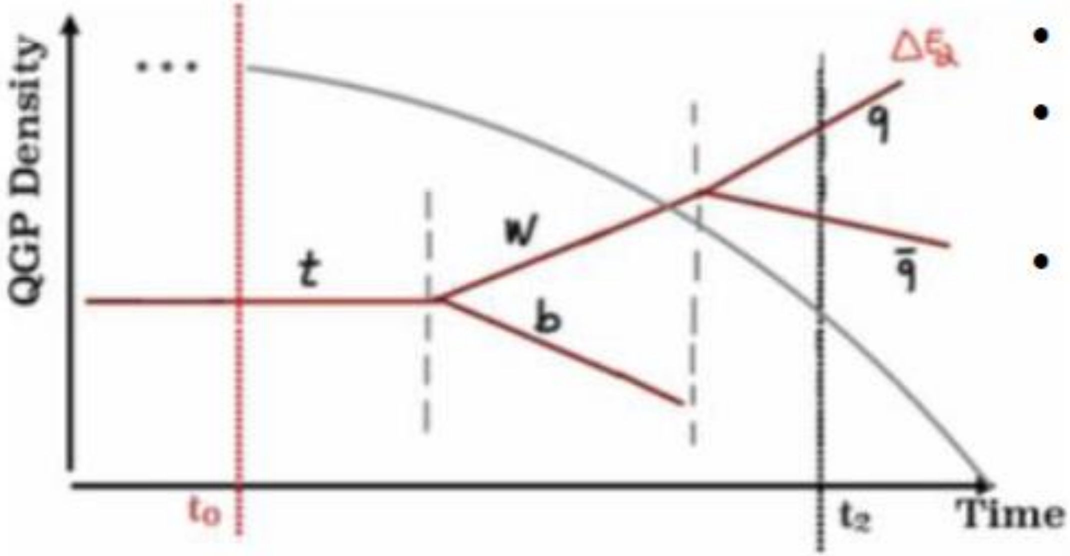
FCC-ion physics: thermal charm

- Significantly larger initial temperature (could reach close to 1 GeV) implies abundant "thermal" production of c-cbar pairs in the QGP
  - Sensitive to QGP temperature and its time evolution
  - ccbar recombination can lead to J/ψ $R_{AA}>1$



K. Zhou, Z. Chen, C. Greiner, and P. Zhuang, arXiv:1602.01667

FCC-ion physics: boosted top



- QGP forms at t_0
- q-qbar pair probes the QGP at $t > t_2$
- t_2 can be "varied" by selecting on top p_T

- Objective: study jet quenching as a function of time during QGP evolution
- Reconstruct t-tbar events with final state $b\bar{b} + \ell + 2\,jets + \not{E}_T$
- Measure the energy loss of the *2 jets* (from light q-qbar pair) as a function of the top quark boost (p_T)

N. Armesto et al., arXiv:1601.02963
L. Apolinario, G. Milhano, C. Salgado, in preparation