Heavy ion physics overview (Exp.)

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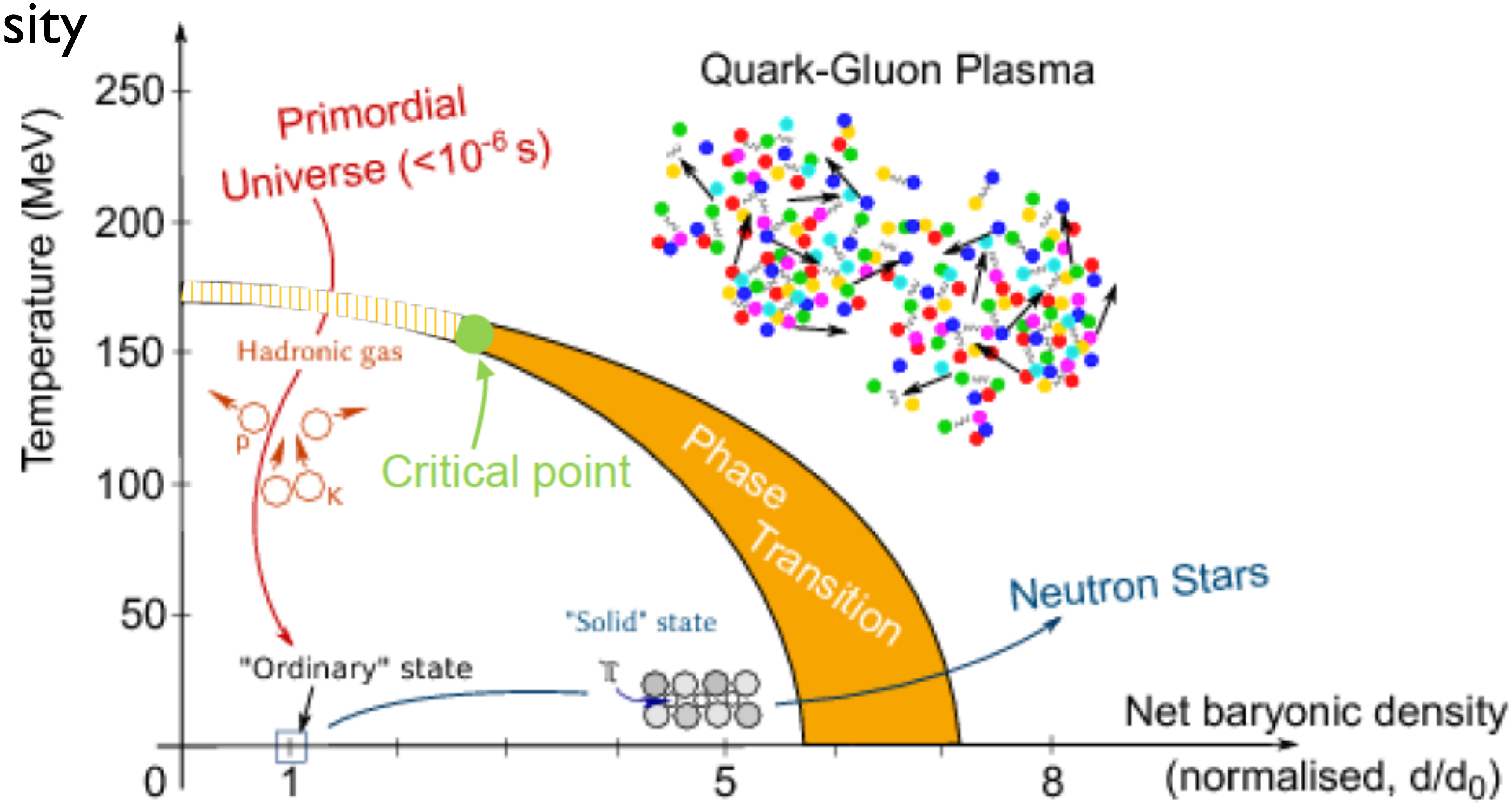
2017年12月23日

Heavy ions at the LHC

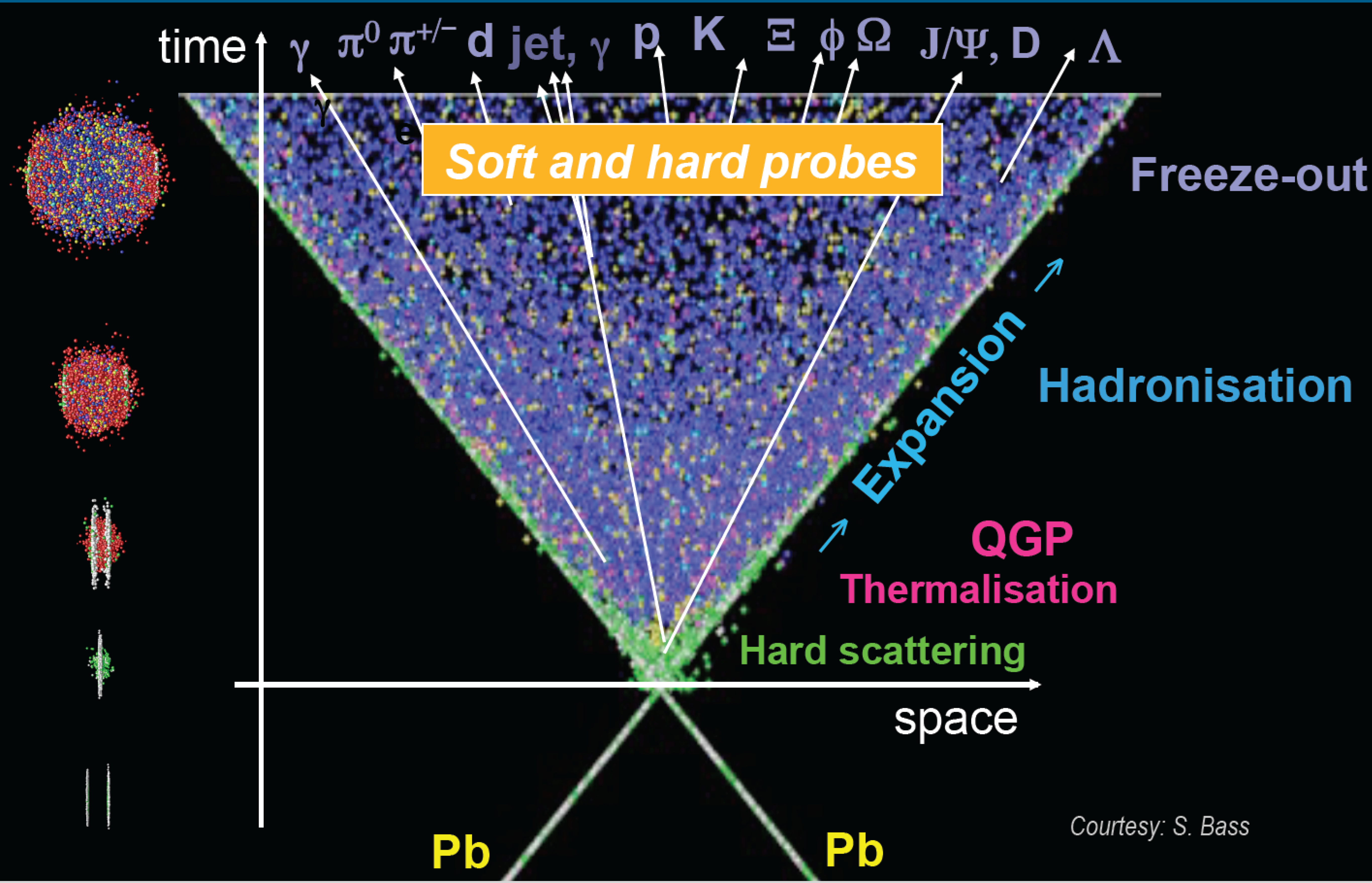
- Investigate the region of the phase diagram of strongly interacting matter corresponding to the highest possible temperature and the lowest net baryon density



- Recreate the first (and hottest!) liquid that ever existed and that gave rise to matter around us …

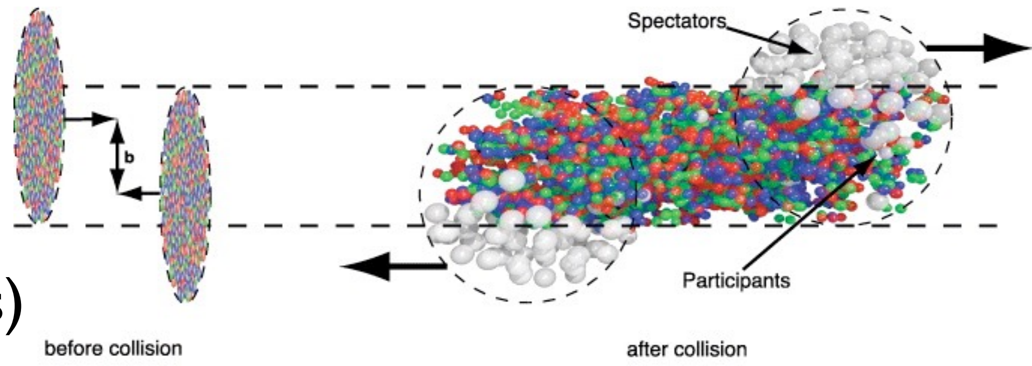
  … and study its properties in the laboratory

Space-time evolution of a heavy-ion collision

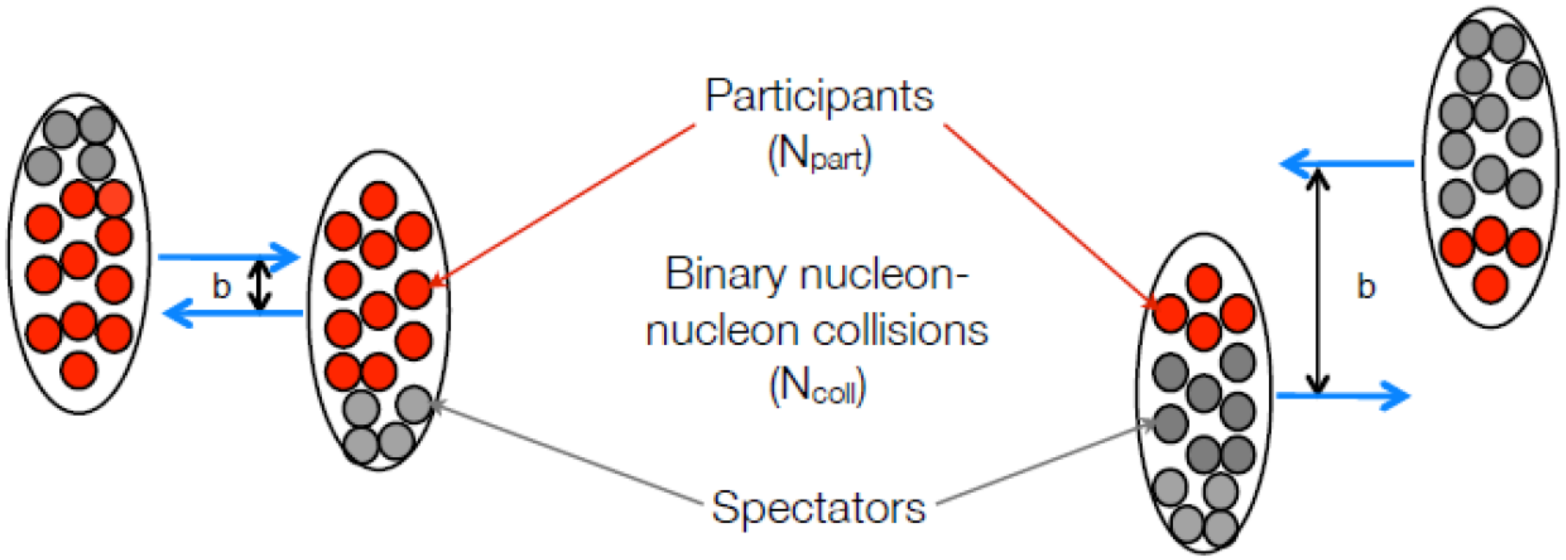


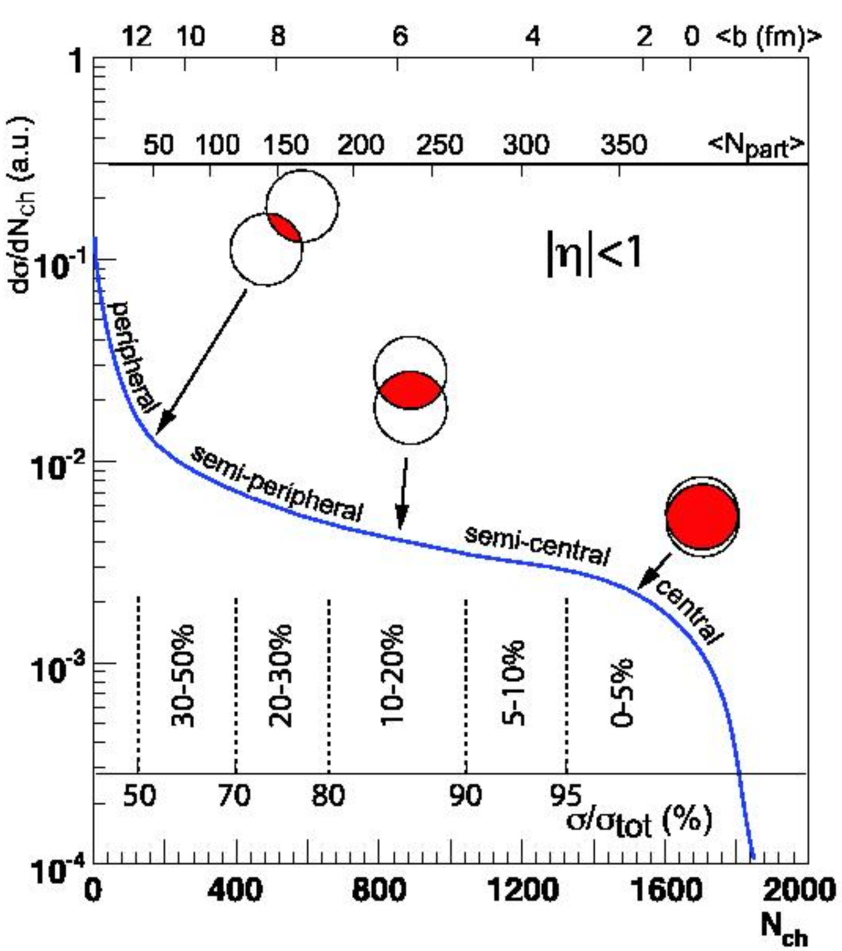
Collision centrality

- Nuclei are extended objects
- Geometry related to observables via Glauber Model
- Related to multiplicity or forward energy (spectators)



Central Peripheral

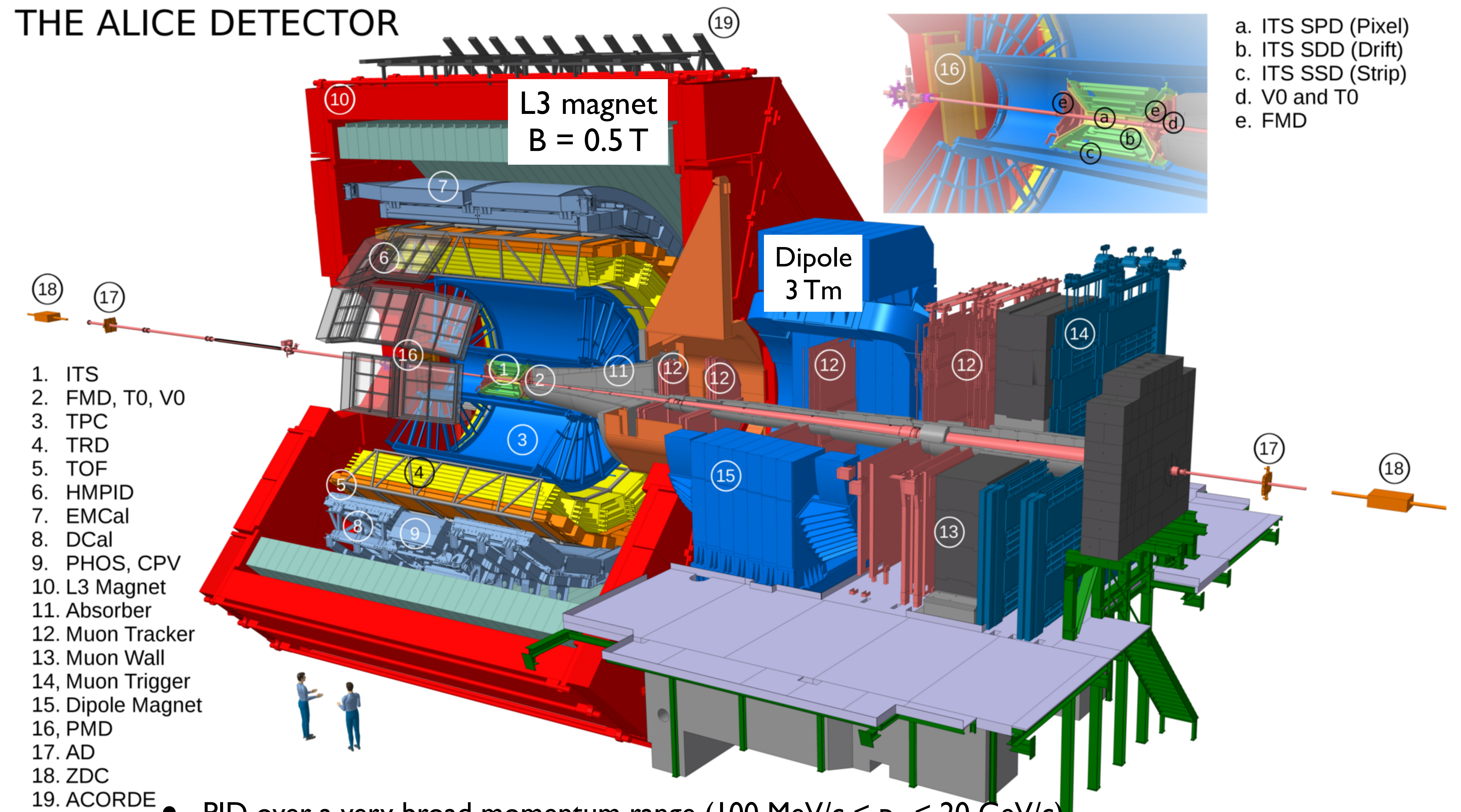




Soft processes: long timescale, large σ, $\sigma_{tot} \propto N_{part}$

Hard processes: short timescale, large σ, $\sigma_{tot} \propto N_{coll}$

A Large Ion Collider Experiment

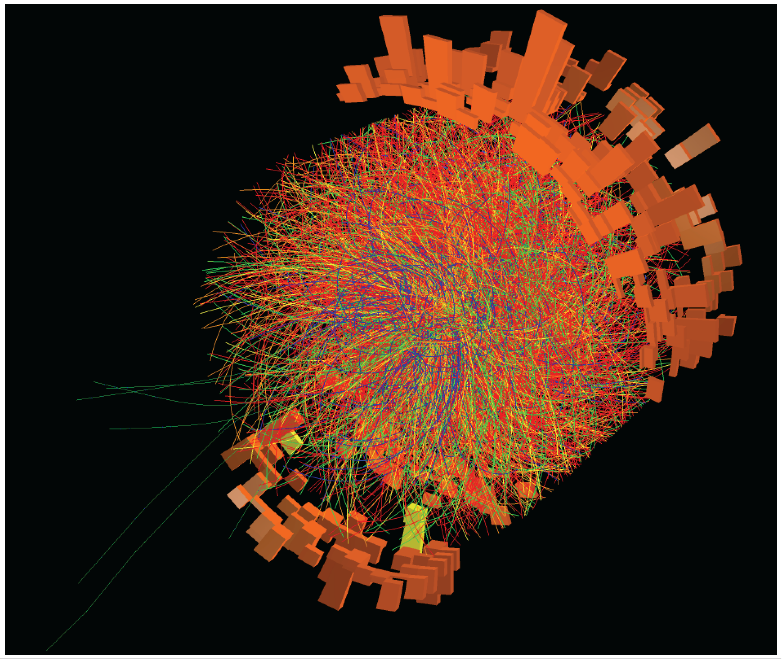


- PID over a very broad momentum range (100 MeV/c < p_T < 20 GeV/c)
- Large acceptance in azimuth
- Mid-rapidity coverage ($|\eta| < 0.9$) and $-4 < \eta < -2.5$ in forward region

ALICE data taking in Run-2

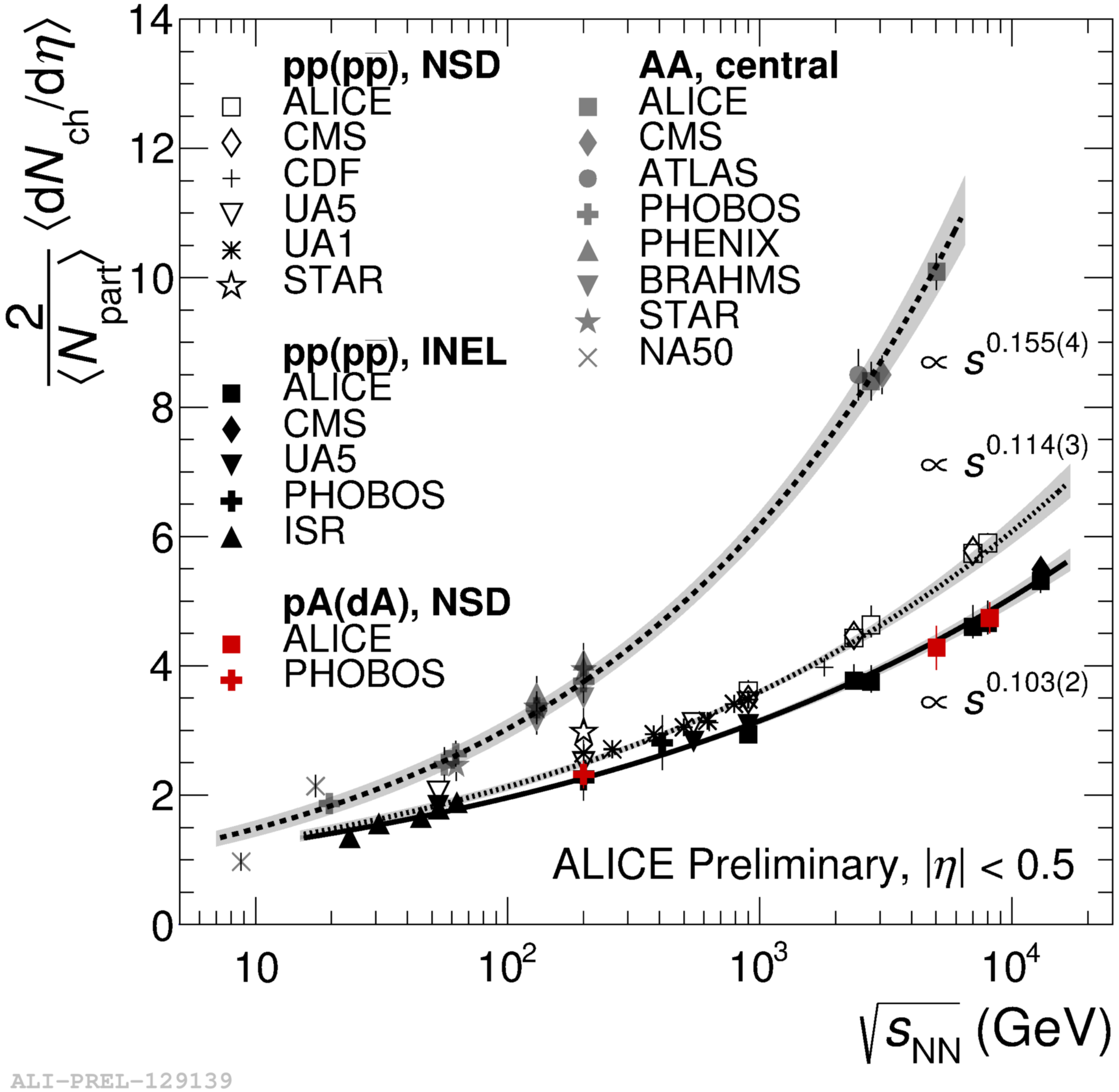
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2015-2017	13	~ 24 pb^{-1}
pp	2015, 2017	5.02	~ 600 nb^{-1}
p-Pb	2016	5.02	~ 3.4 nb^{-1}
p-Pb	2016	8.16	~ 20 nb^{-1}
Pb-p	2016	8.16	~ 20 nb^{-1}
Pb-Pb	2015	5.02	~ 0.4 nb^{-1}
Xe-Xe	2017	5.44	~ 300 mb^{-1}

- Goals for 2018 before LHC LS2
  - pp 13 TeV: reach 40/pb target
  - Pb-Pb 5.02 TeV: reach 1/nb target

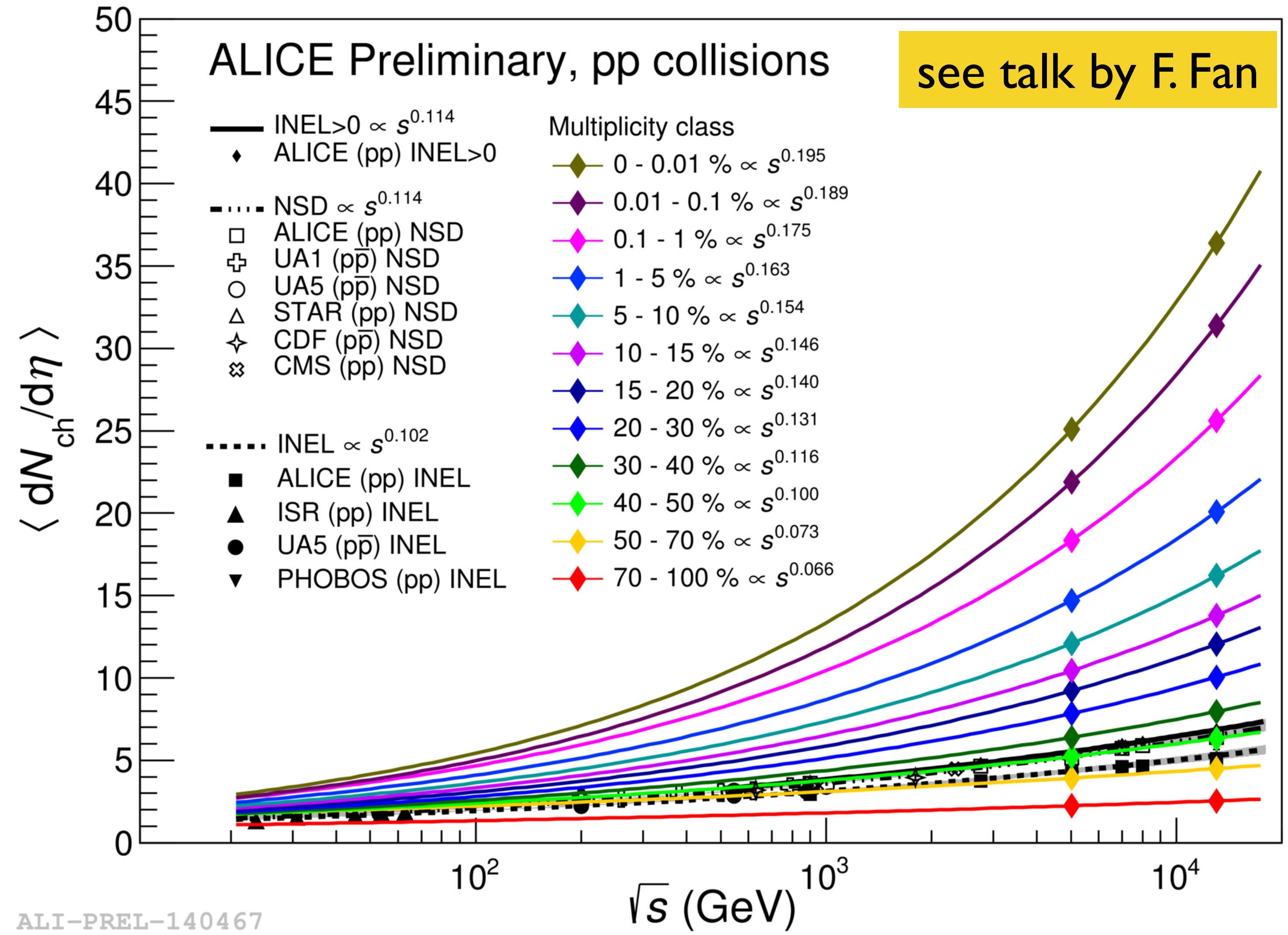


Charged particle multiplicity

different collision systems



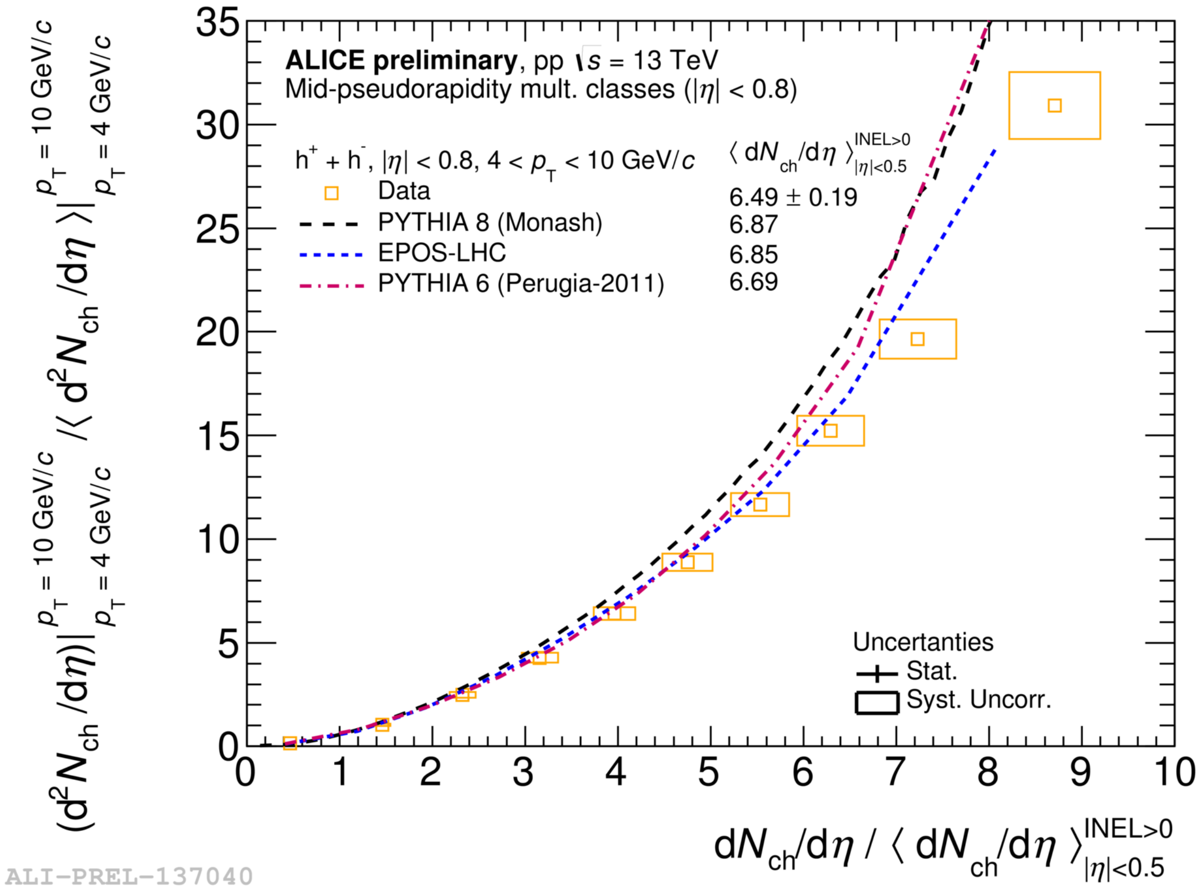
pp collisions



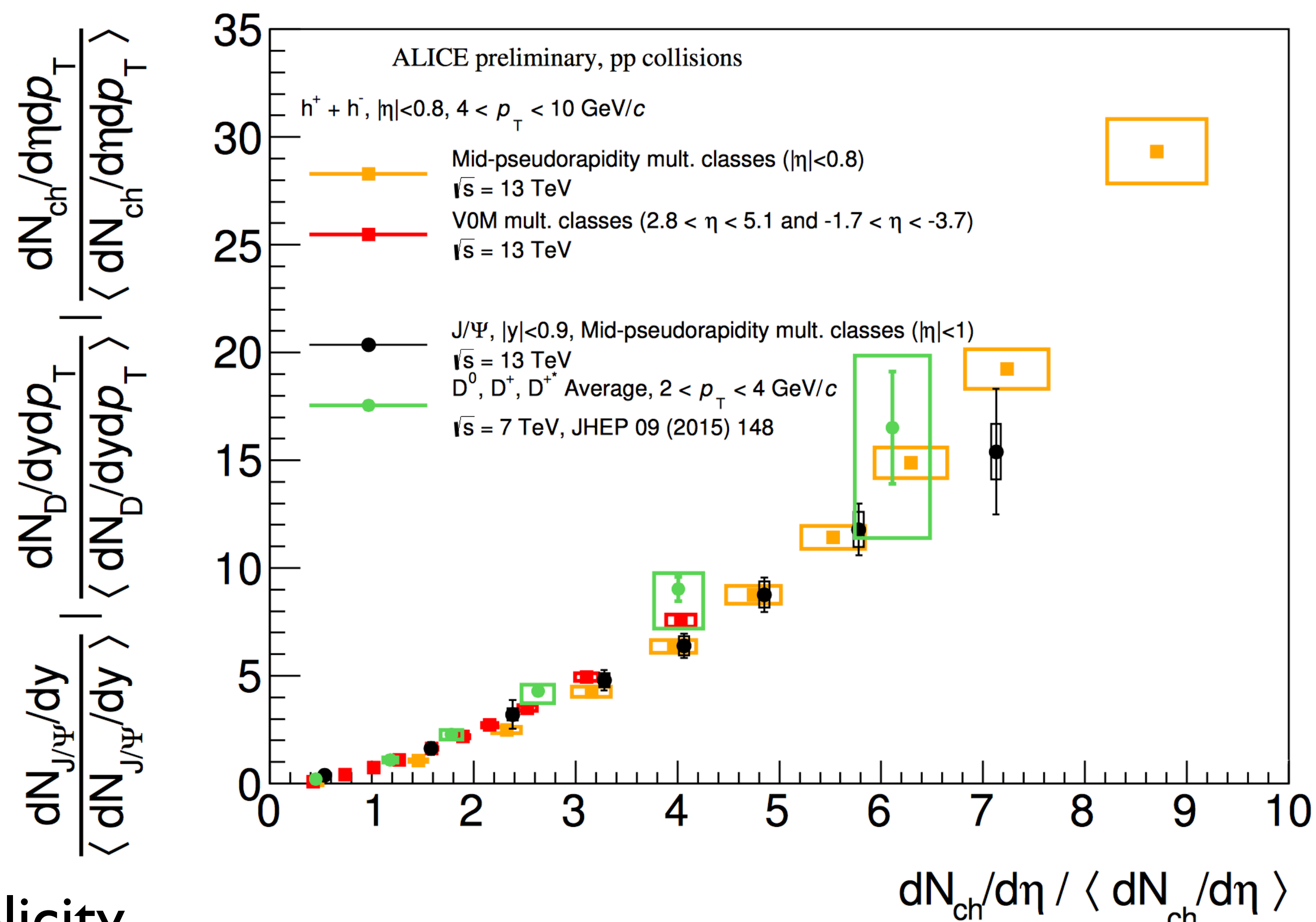
- ALICE: Pb-Pb at 5.02 TeV, highest energy reached so far → confirms trend from lower energies
- Power law dependence fits well and faster in Pb-Pb ($\sim s^{0.155}$) than in pp ($\sim s^{0.103}$)
- Rise in $\langle dN_{ch}/d\eta \rangle$ becomes more steeper for high multiplicity class

Multiplicity dependent particle yield

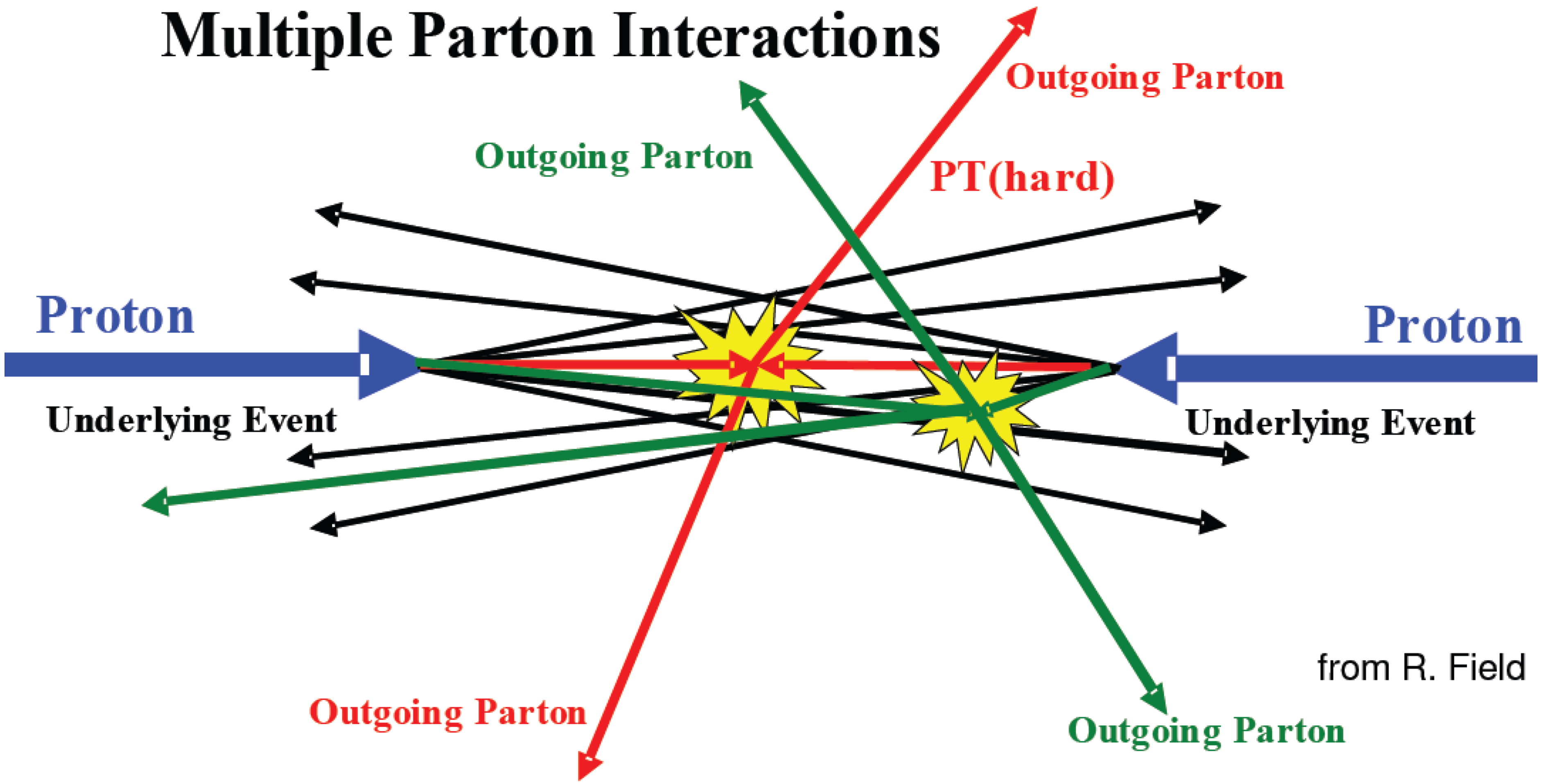
inclusive charged particle



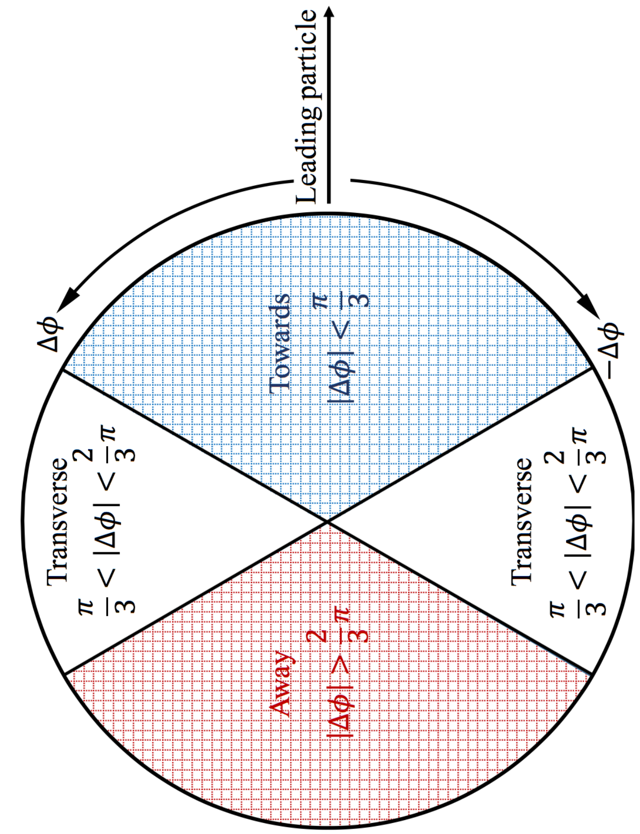
different particle species



- The yield increases with multiplicity
  - Yields grow faster than linear in multiplicity with respect to MB
  - Rising trend quite similar for light and heavy flavor particles
  - Described qualitatively by generators

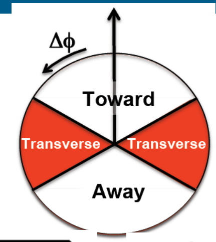


from R. Field

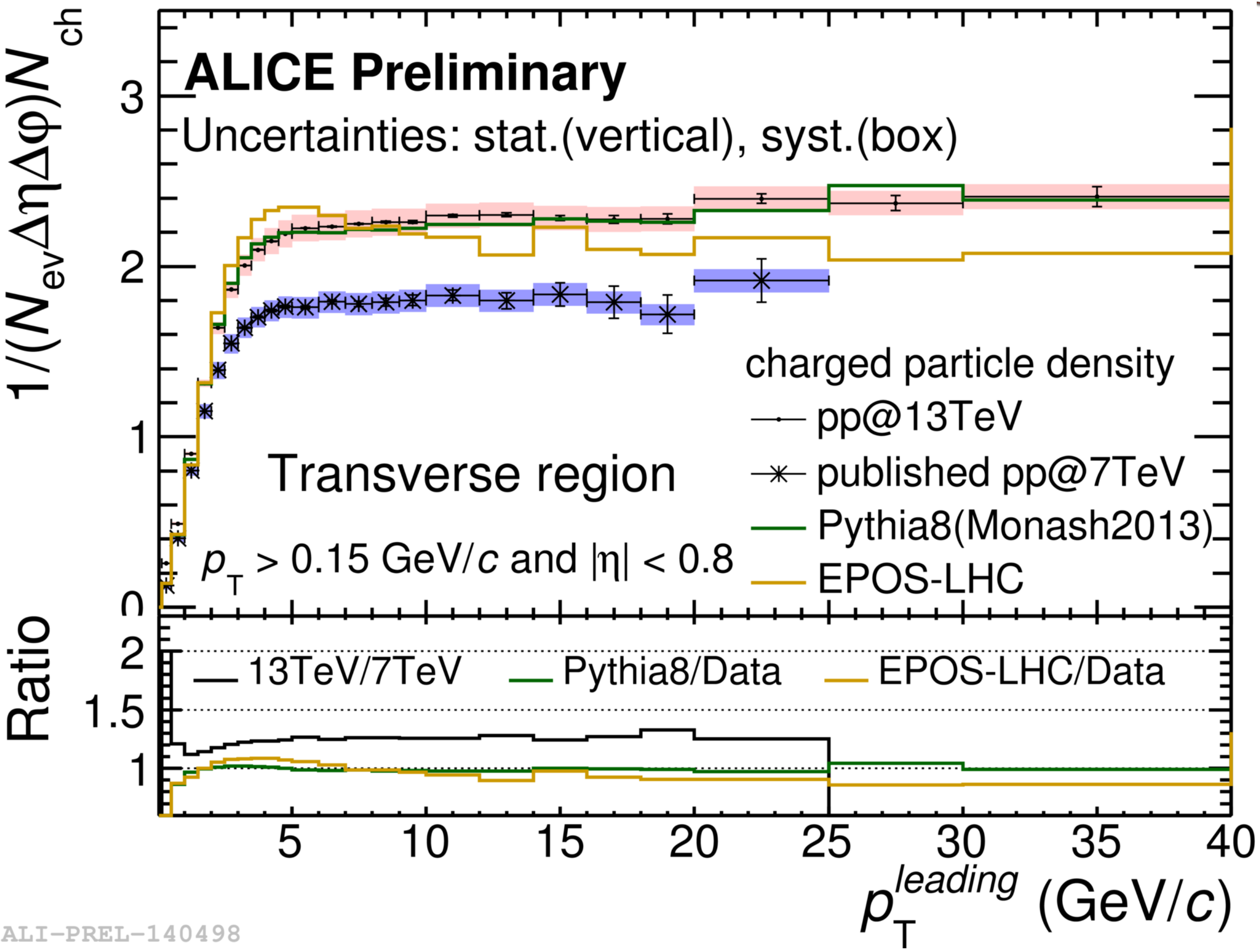


- What is the underlying event (UE)?
  - ➡ Everything, except the LO process we are currently interested in
    - parton showers
    - additional remnant - remnant interactions (multi-parton interactions, soft/hard)
  - ➡ Not pile-up events (luminosity dependent)
- Why UE?
  - basic step for event characterization process
  - good control of UE allows to access deep information of the hadronic structure, hard probes

Underlying event properties

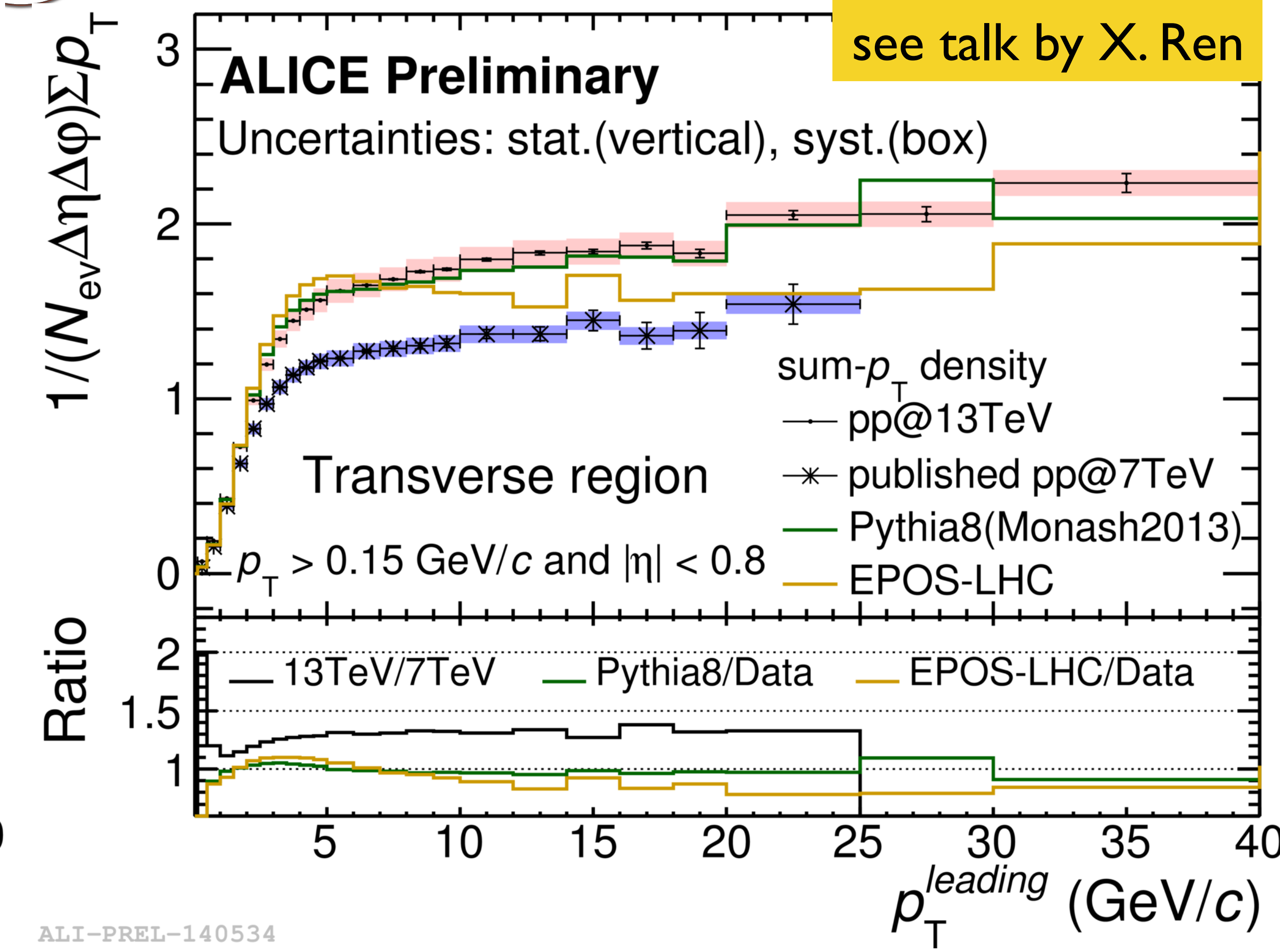


charged particle density



Σp_T density

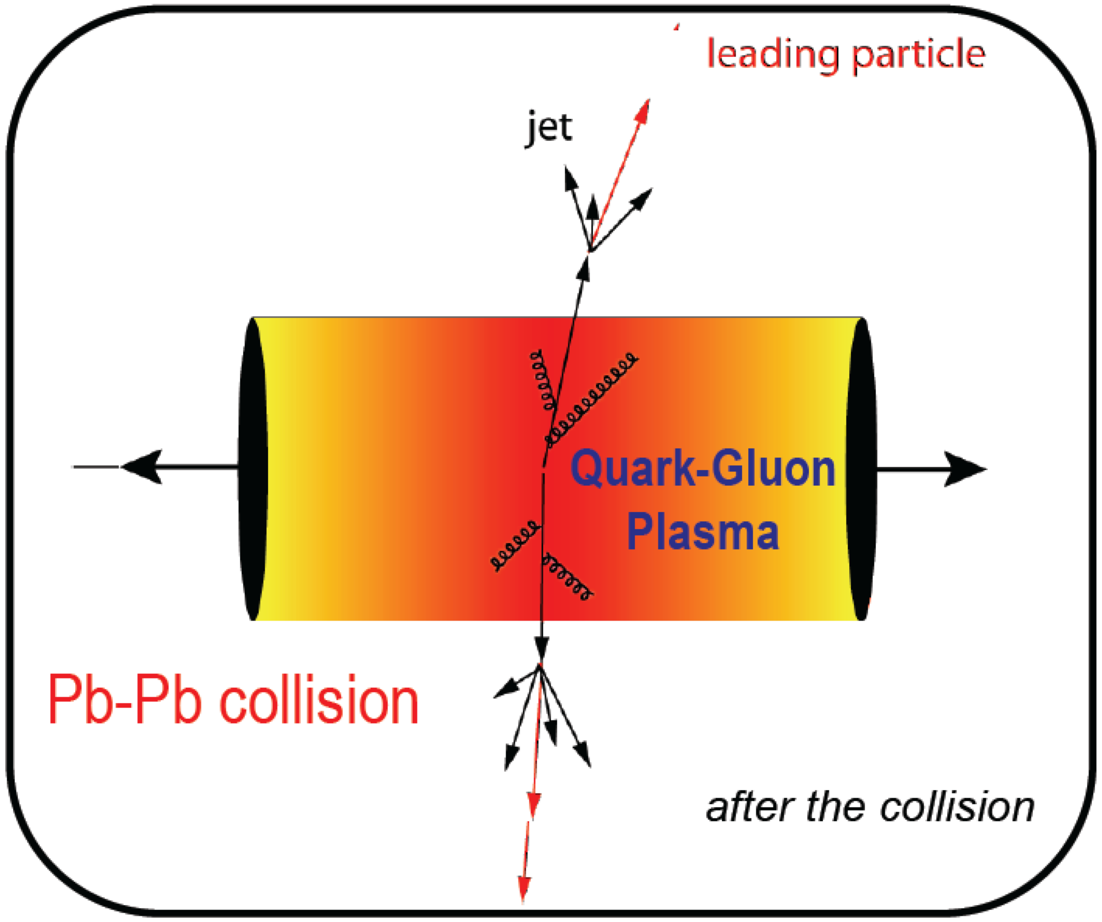
see talk by X. Ren

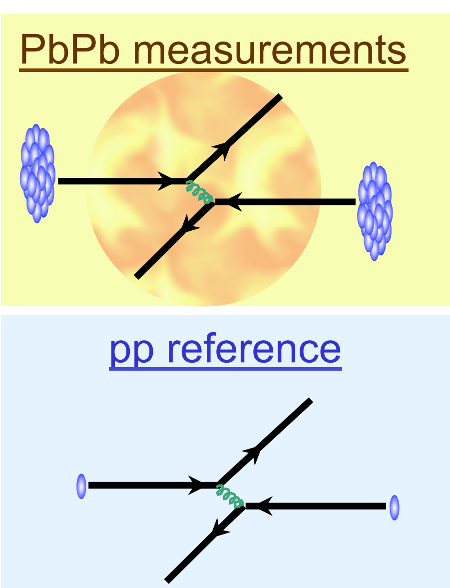


- Similarity of UE behavior at different collision energies
  - Fast rise for p_T < 5 GeV/c, mostly attributed to the increase of MPI rate, followed by a plateau-like region
  - Higher collision energy generates larger charged particle density
  - UE level can be simulated by PYTHIA8 generator

Probing hot QCD matter with hard probes

- Hard processes serve as calibrated probe (pQCD)
- Hard probes traverse through the medium and interact strongly in heavy ion collisions
- Suppression pattern provides density measurements
- General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents
- Quantify the medium effects with nuclear modification factor

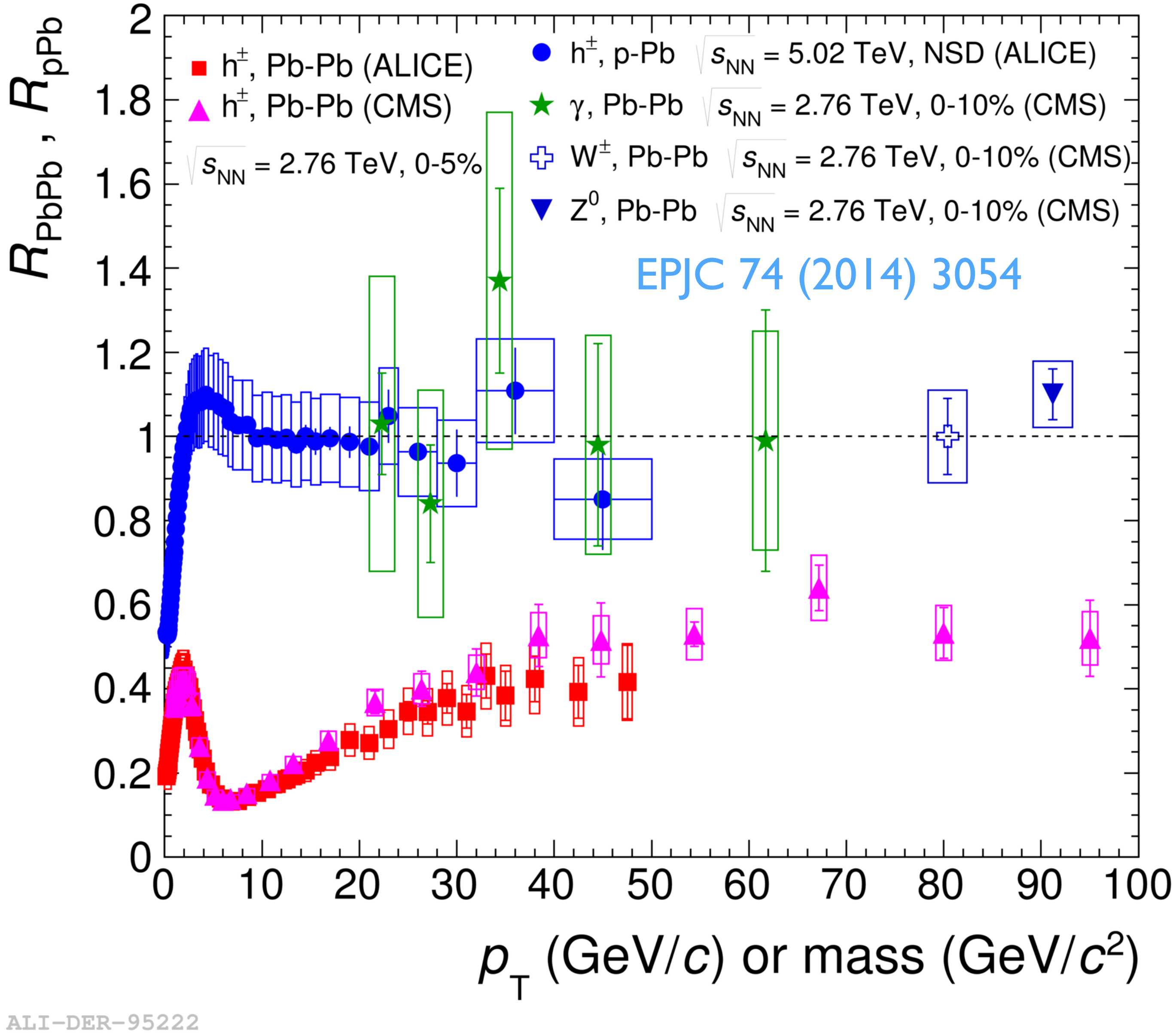


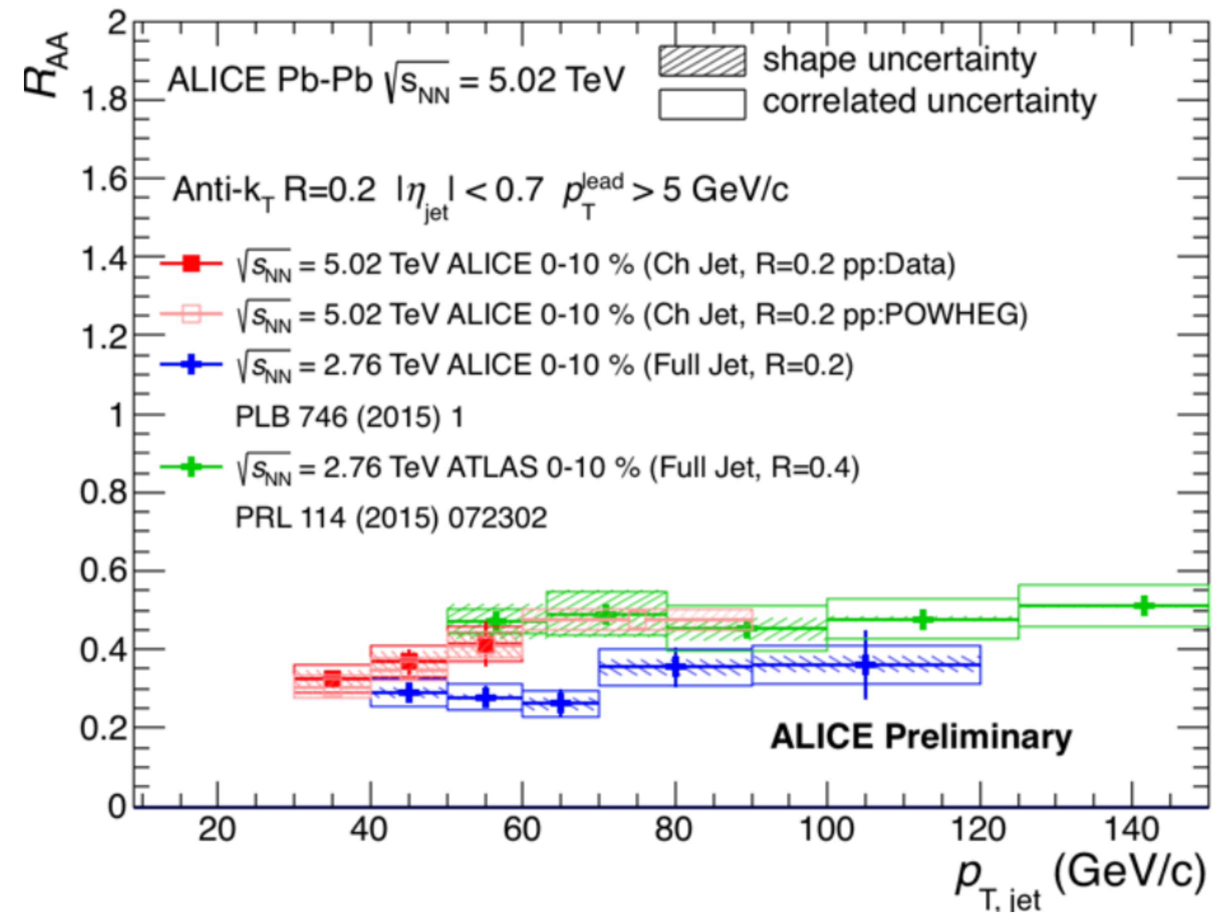


$$= \quad R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

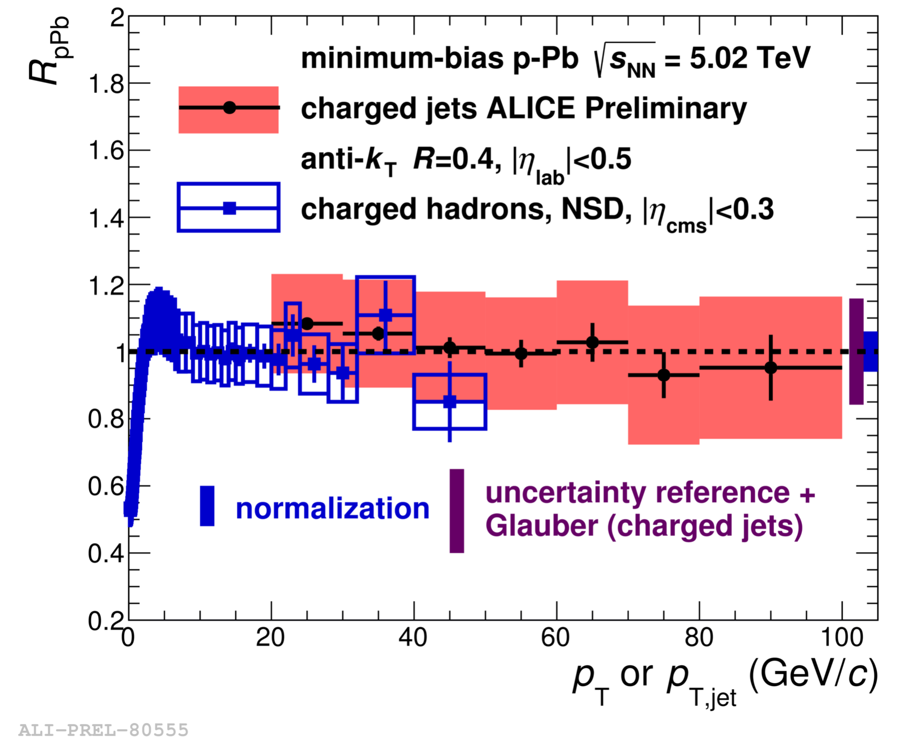
$R_{AA} > 1$ (enhancement)
$R_{AA} = 1$ (no medium effect)
$R_{AA} < 1$ (suppression)

High p_T particle and jet production

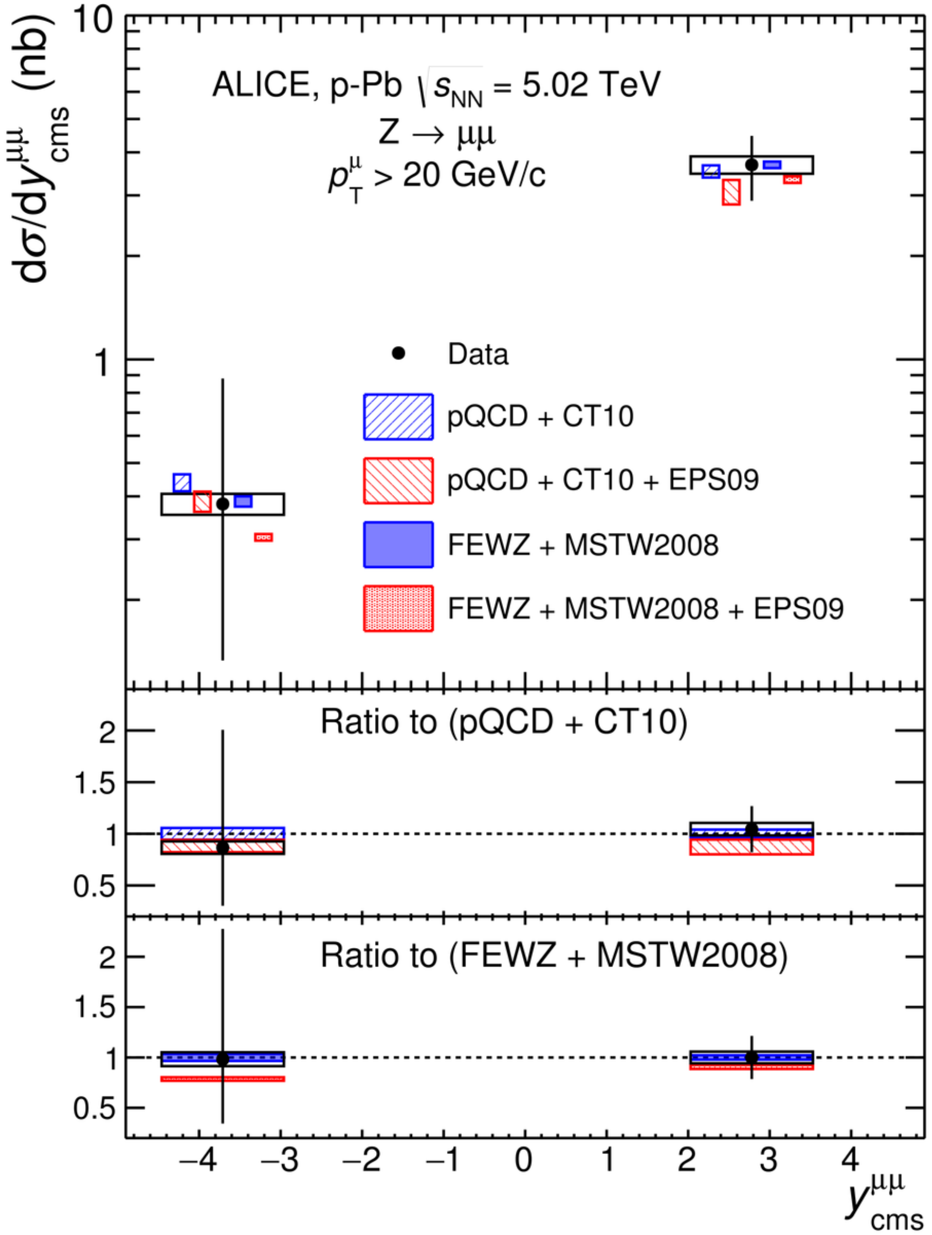


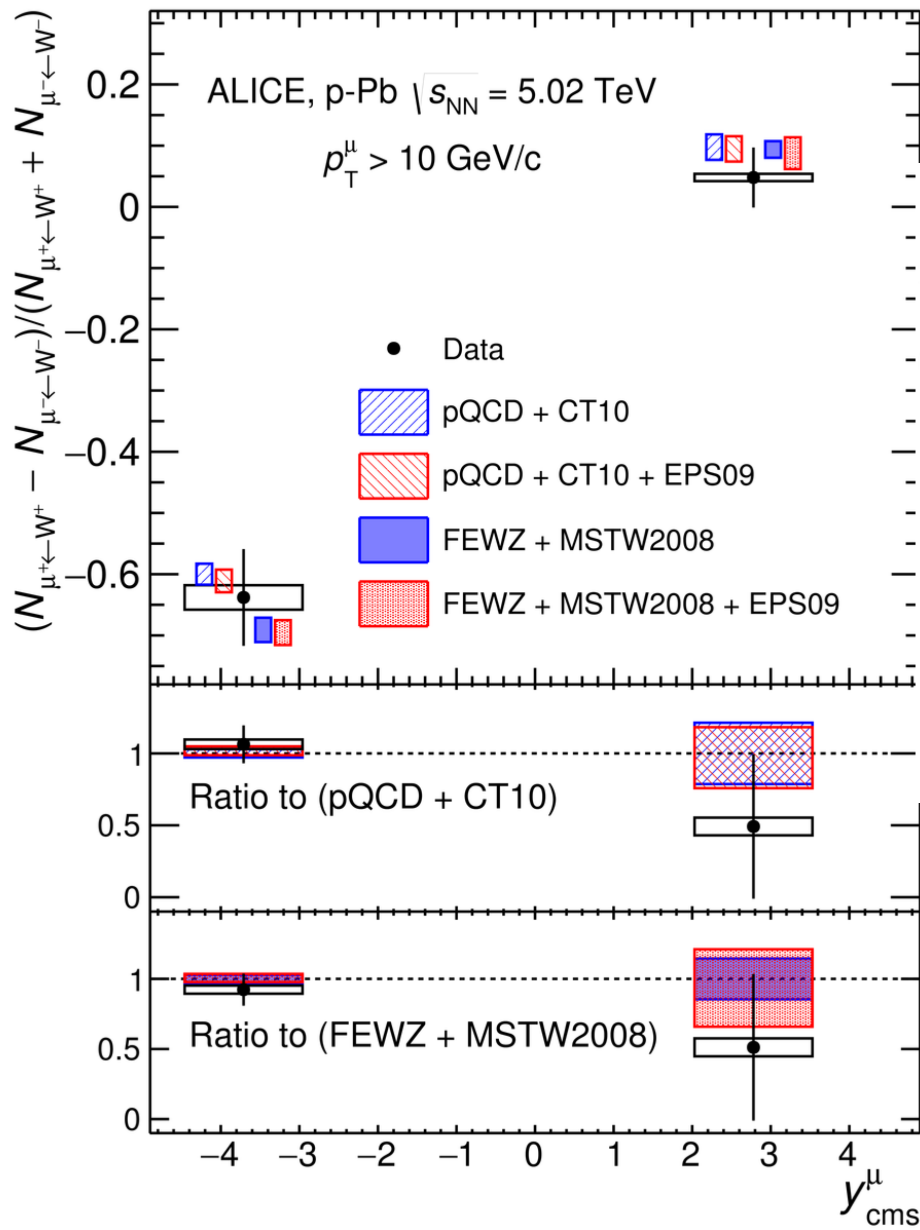


- Strong suppression for charged hadrons and jets observed in most central Pb-Pb collisions
  - final state effect due to hot and dense QCD matter
- Z,W and γ production in Pb-Pb consistent with N_{coll} scaling ($R_{AA} \approx 1$)
  - not sensitive to medium as expected; geometry (N_{coll}) under control
- Absence of nuclear modification in p-Pb collisions

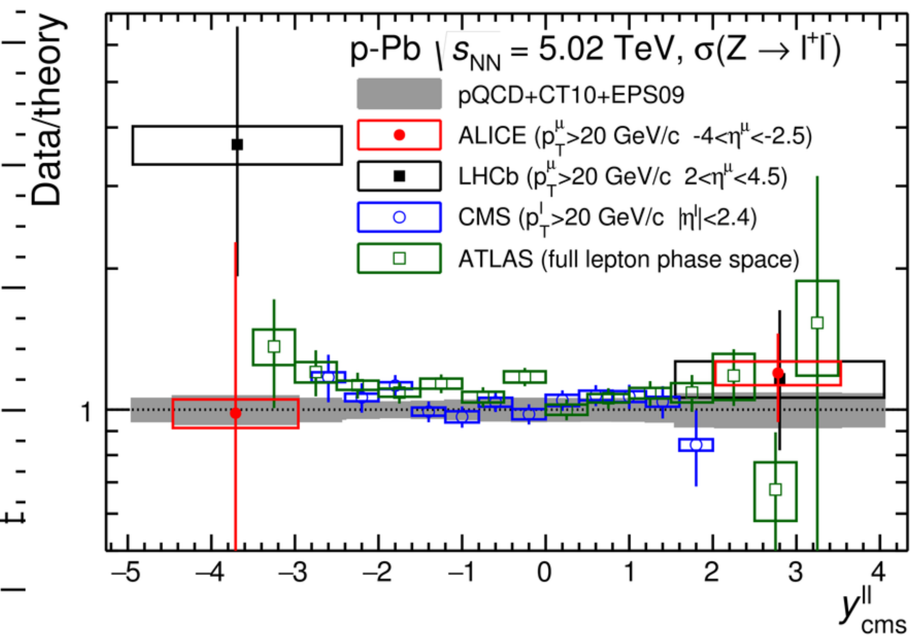


W/Z boson productions in p-Pb collisions





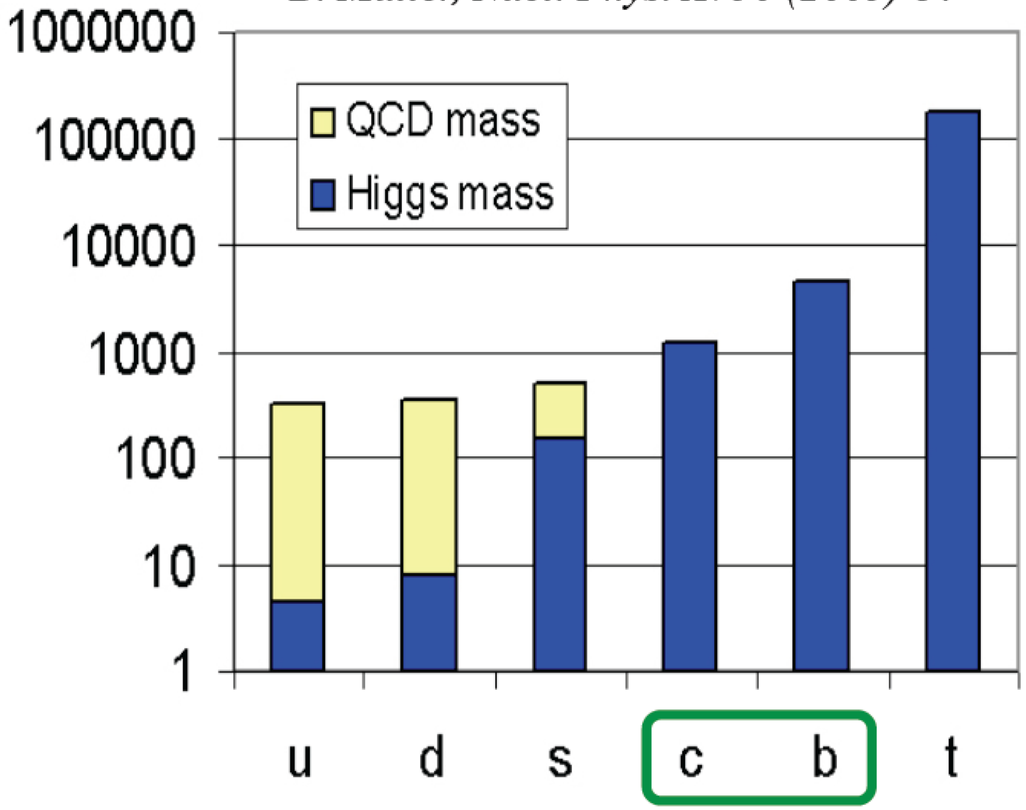
JHEP 02 (2017) 077

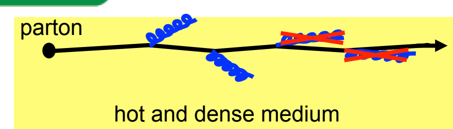


- Measurement of the W/Z production cross section in p-Pb collisions via the semi- leptonic decays of W bosons in the muon channel.
- Measured cross section well described by NLO pQCD calculation with CT10 PDF and EPS09 shadowing parameterization
- Different experiments have quite consistent cross section results, statistics needs to be improved to constrain theoretical models

Heavy quarks are ideal probes

B. Müller, Nucl. Phys. A750 (2005) 84

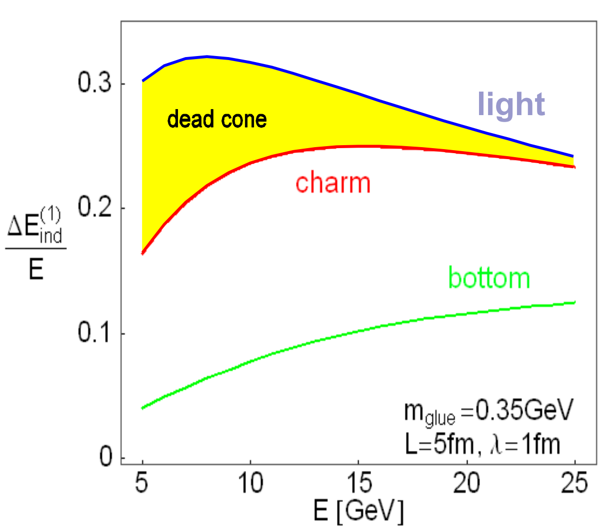




Formation time:

$\tau \sim 1/2m_Q \sim 0.1$ fm $<< \tau_{QGP} \sim 5\text{-}10$ fm

ENERGY LOSS

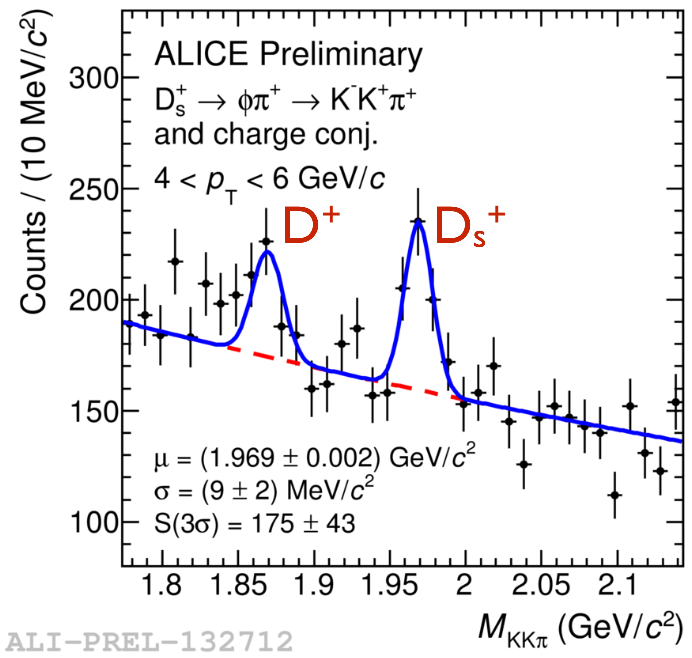


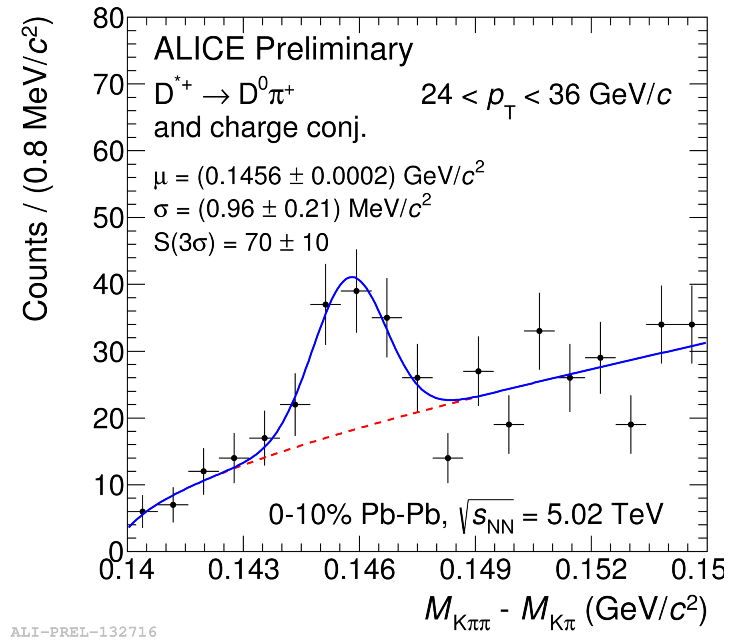
M.Djordjevic PRL 94 (2004)

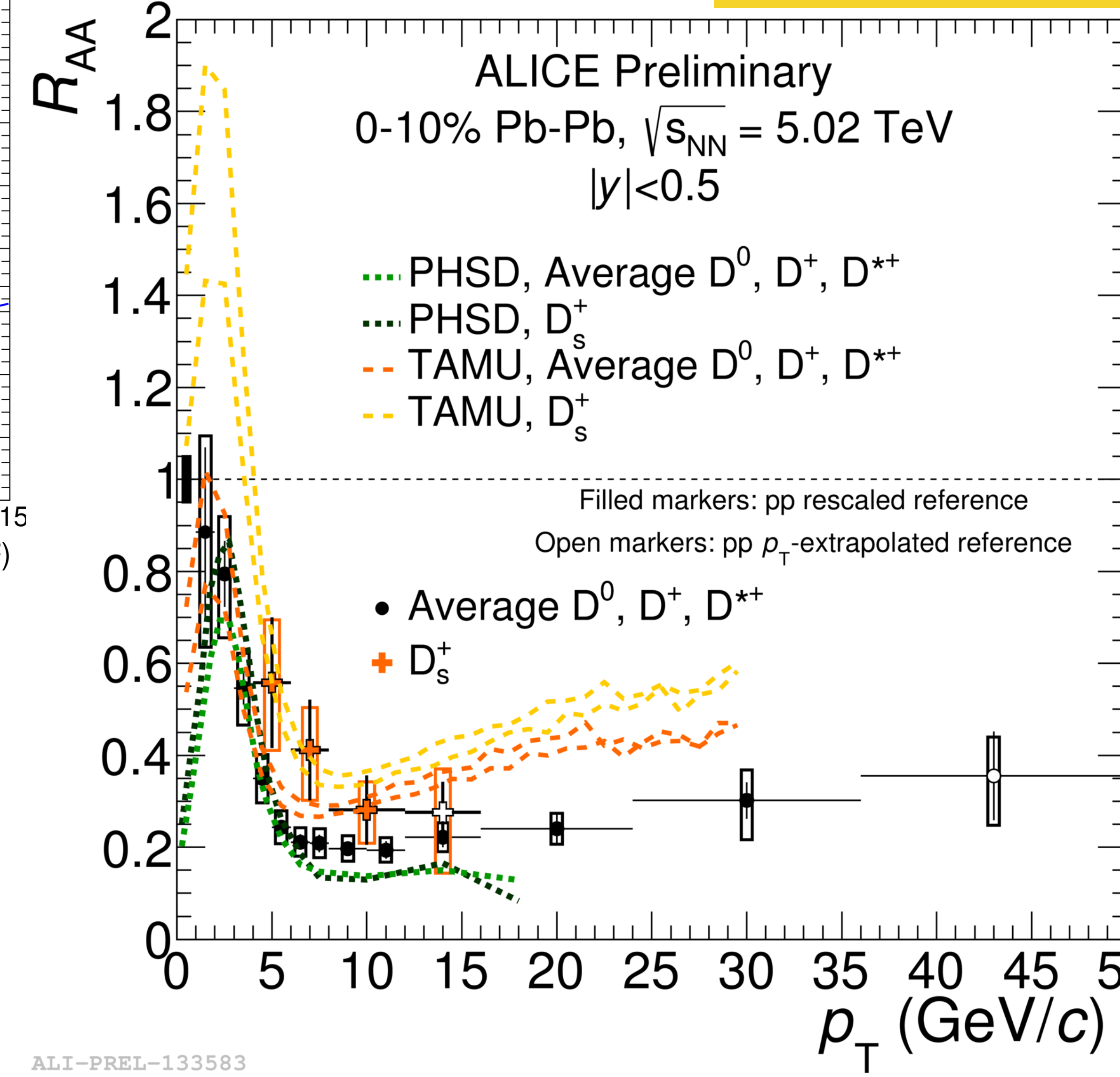
- Symmetry break
  - Higgs mass: electro-weak symmetry break → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass
- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP
- Test QCD at transition from perturbative to non-perturbative regime: charm and beauty quarks provide hard scale for QCD calculations
- Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)
  - Expectation: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$, $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

Prompt D-meson R_{AA} in Pb-Pb

see talk by X. Peng







$D^0 \to K^-\pi^+$, BR = (3.88±0.05)%, $c\tau$ = 123 μm

$D^+ \to K^-\pi^+\pi^+$, BR = (9.13±0.19)%, $c\tau$ = 312 μm

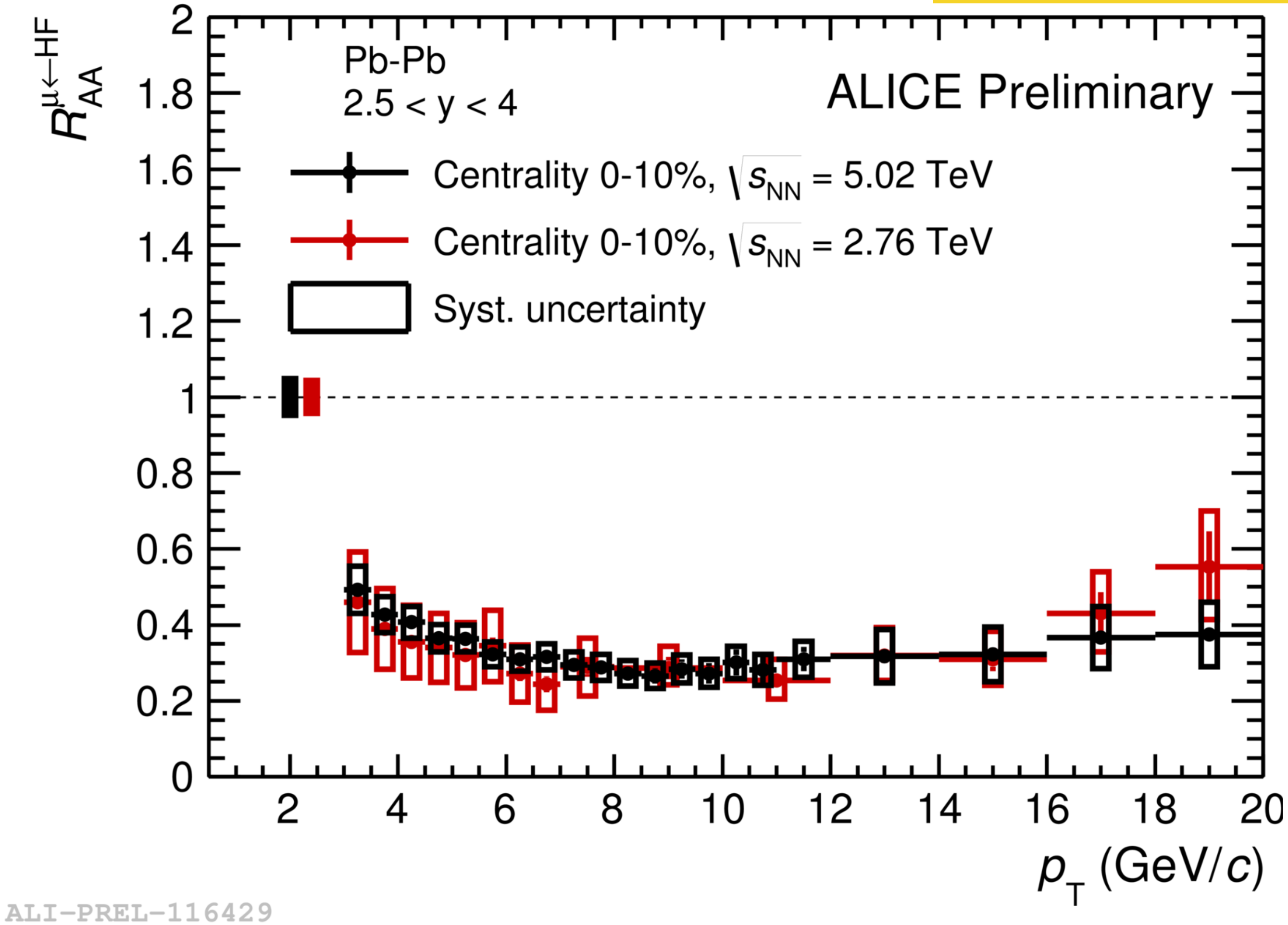
$D^{*+} \to D^0\pi^+$, BR = (67.7±0.5)%

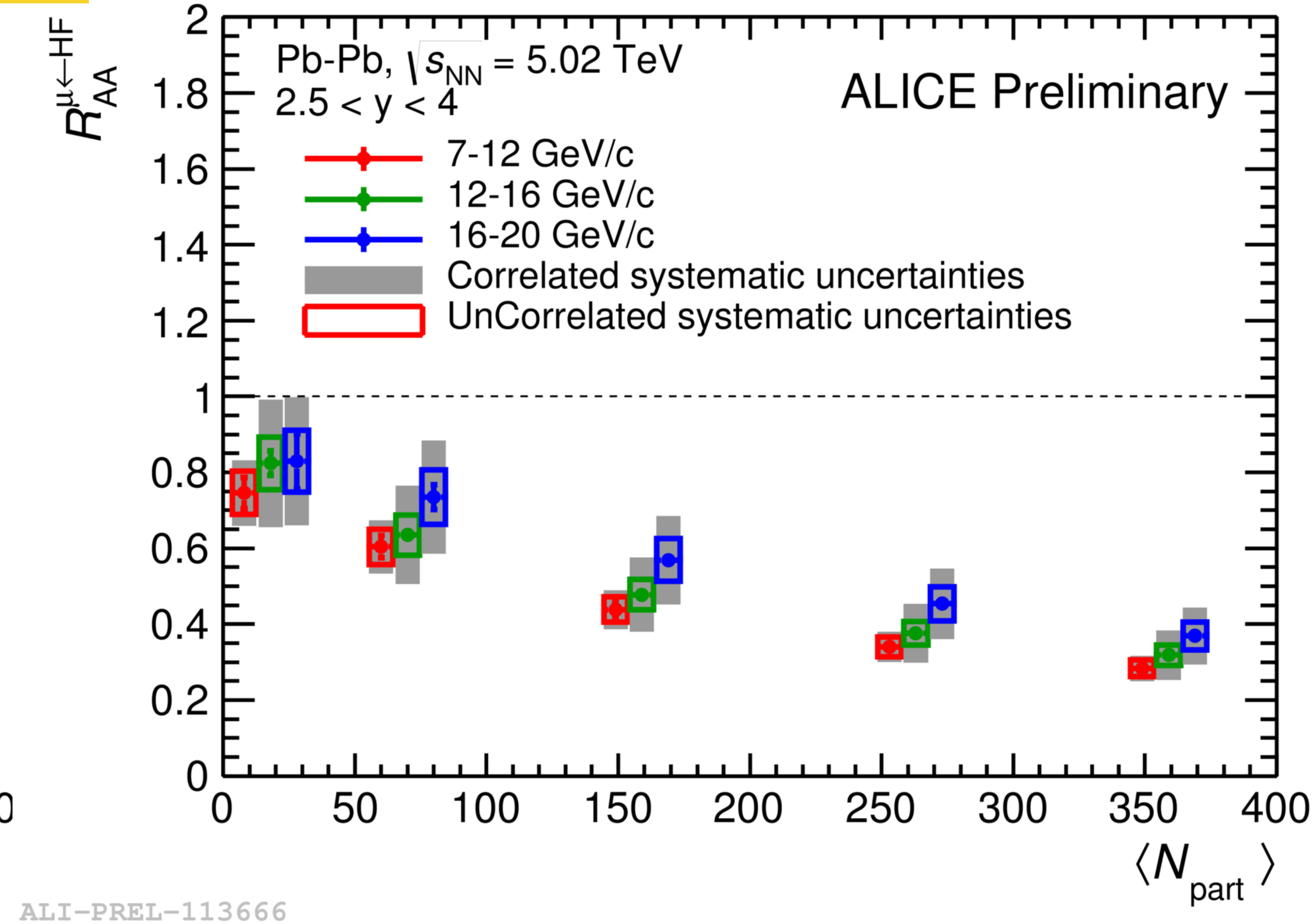
$D_s^0 \to K^+K^-\pi^+$, BR = (2.27±0.08)%

- Above 5 GeV/c strong suppression (factor 4-5) of D-meson yield in central Pb-Pb, compared to binary scaling from pp
- First D_s^+ (cs) measurement in heavy-ion collisions
- Expectation: enhancement of strange D-meson yield at intermediate p_T if charm hadronises via recombination in the medium

Heavy flavor decay muon R_{AA} in Pb-Pb

see talk by J. Zhu

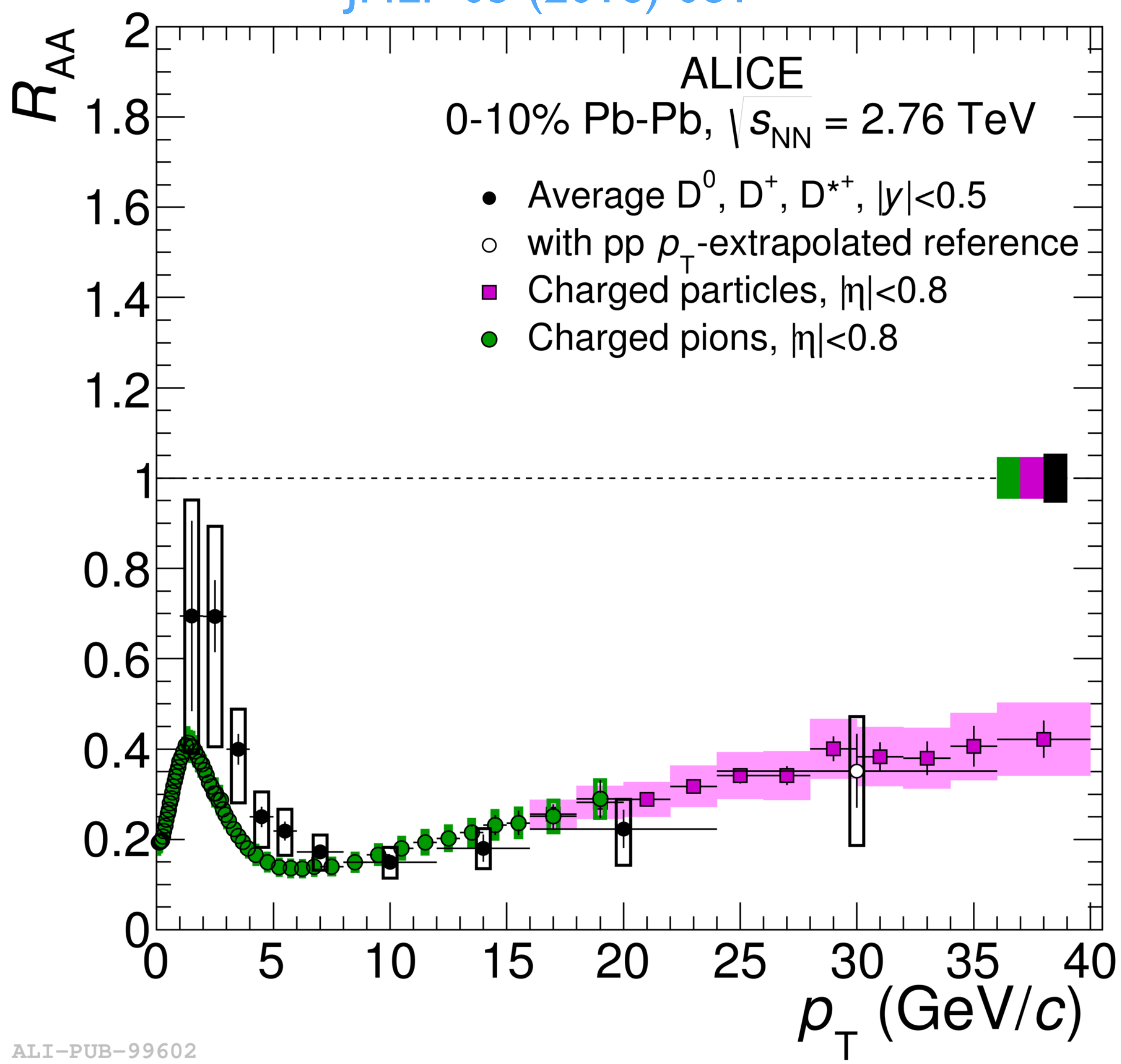


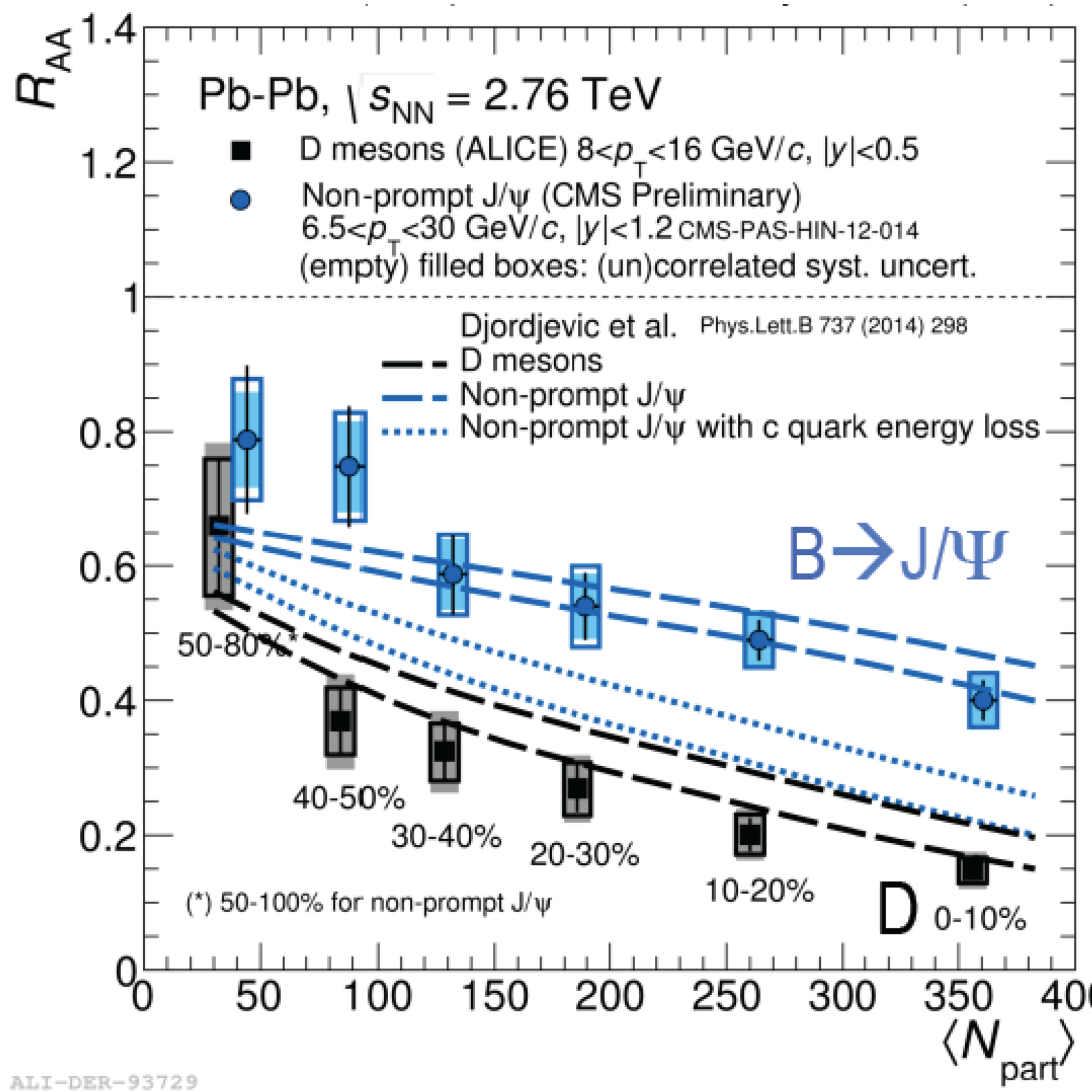


- Much better precision in Run-2 results
- Similar suppression at 5.02 TeV and 2.76 TeV for most central collisions within uncertainties
  - ➡ "compensation" between increasing suppression and modification of the shape of the spectra
- Suppression increases with collision centrality
- Small p_T dependent R_{AA}

Probe flavor and mass dependence

JHEP 03 (2016) 081





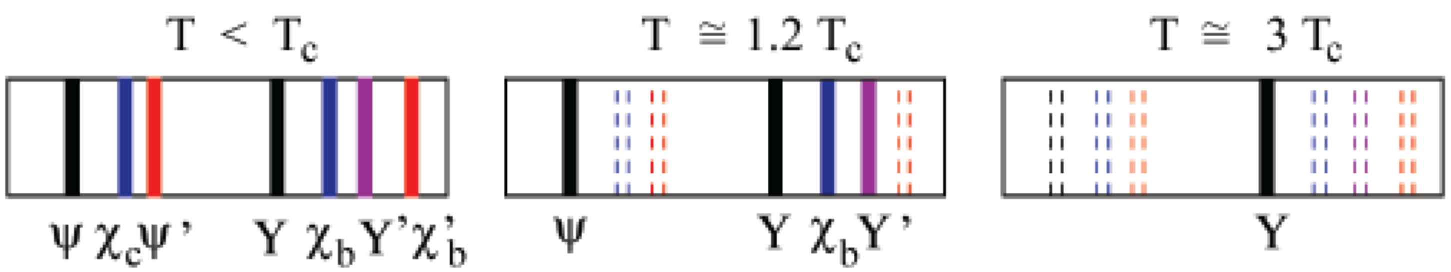
- Slight enhancement of D at low p_T for most central collisions
- Indication for rising R_{AA} (flavor and mass dependence?)
- Described by theoretical calculations including quark-mass dependent energy loss ($R_{AA}^D < R_{AA}^B$) in the studied p_T range

➡ Precise measurements down to low p_T can be pursued with upgraded detectors

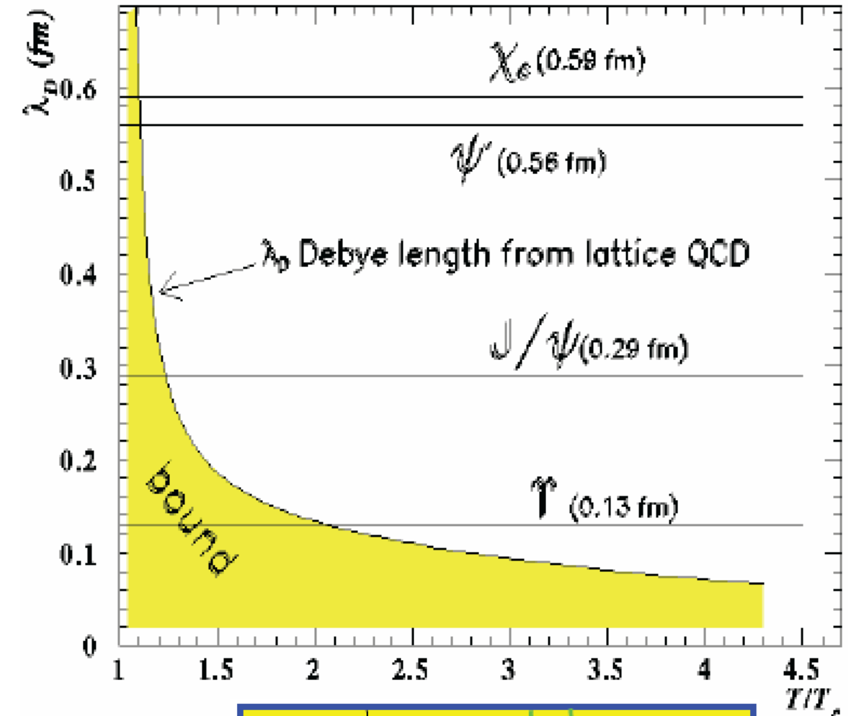
see talk by Y. Wang

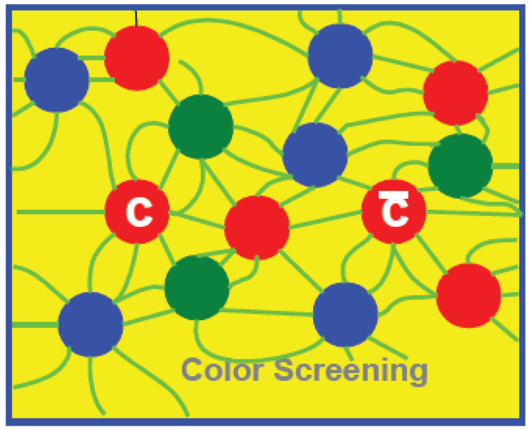
Quarkonia production in hot QCD matter

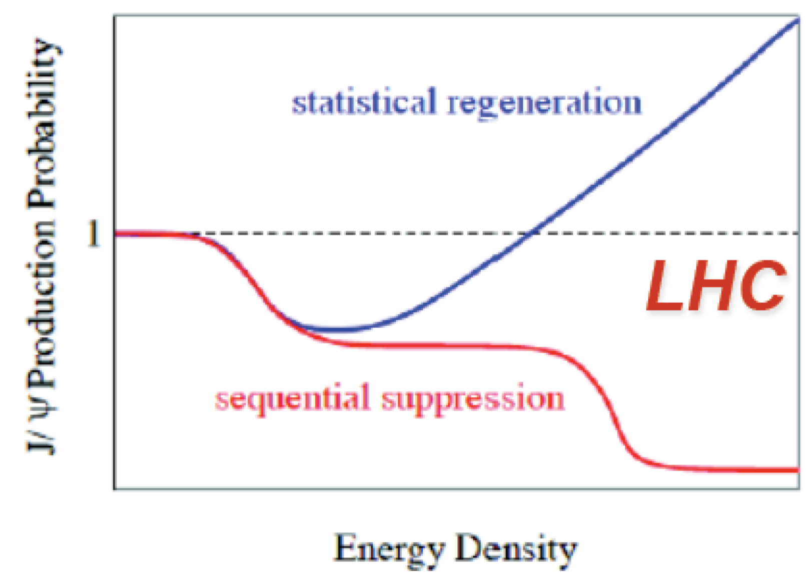
- Color screening length λ_D in the deconfined medium decreases with temperature
- Quarkonia "melt" when their binding distance becomes bigger than screening length → yields suppressed (one of the first QGP signatures, PLB 178 (1986) 416)
- Screening at different temperature for different states (binding energy) → sequential suppression of the quarkonium states →QCD thermometer (PRD 64 (2001) 094015)



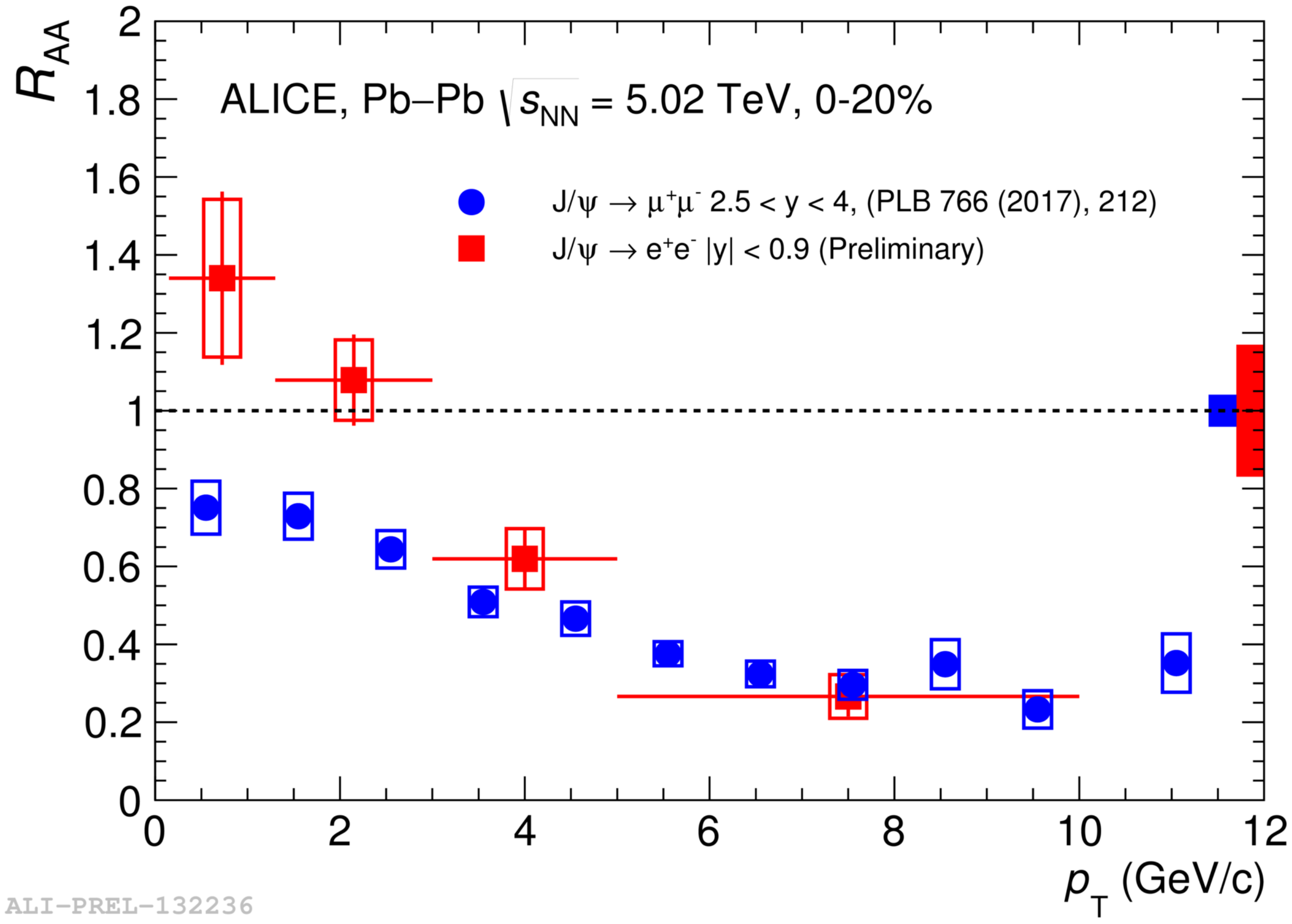
- Enhancement via (re-)generation of quarkonium due to large abundance of c quarks in the medium compensates suppression (PLB 571 (2003) 36)

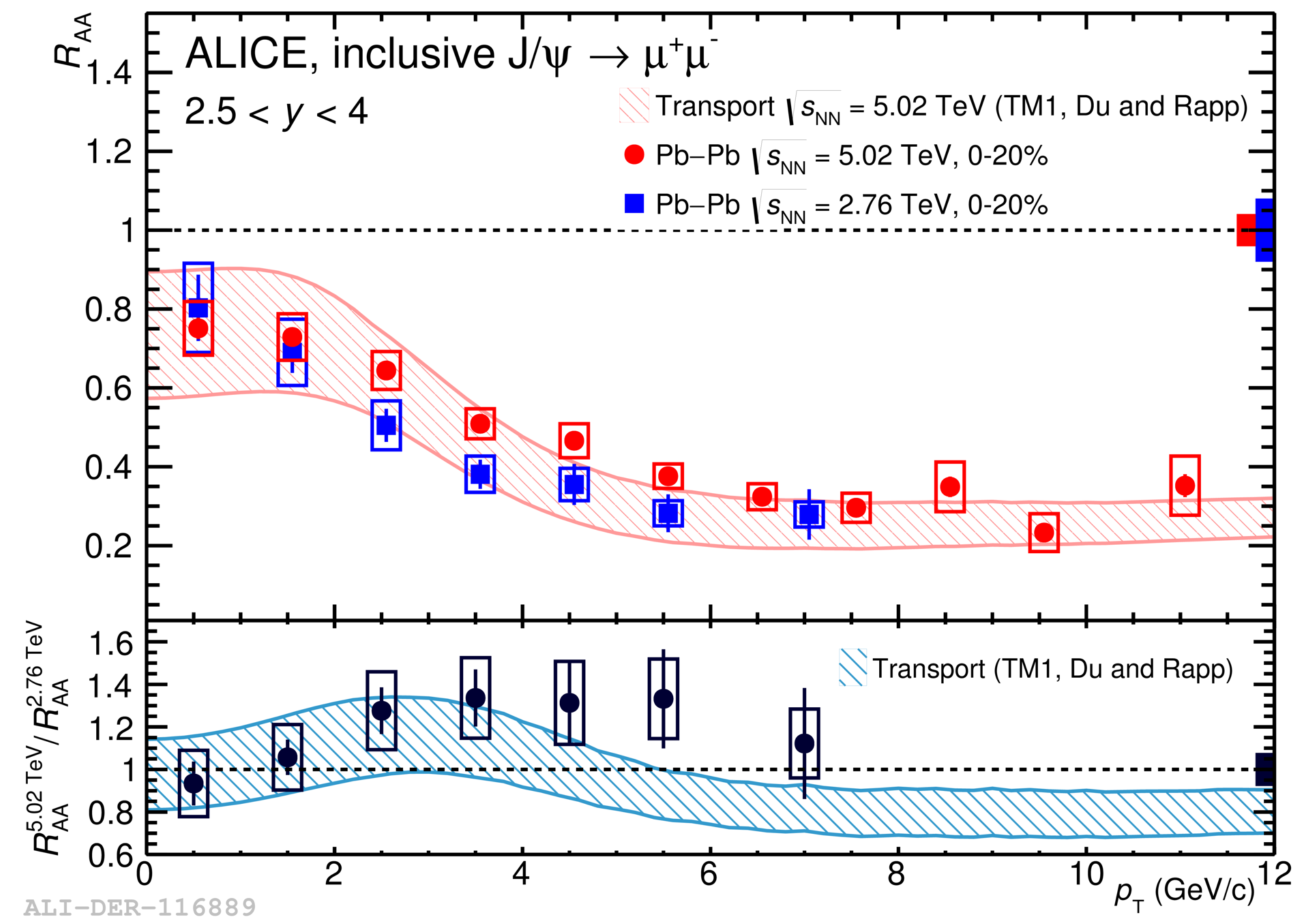






J/ψ production in 5.02 TeV Pb-Pb

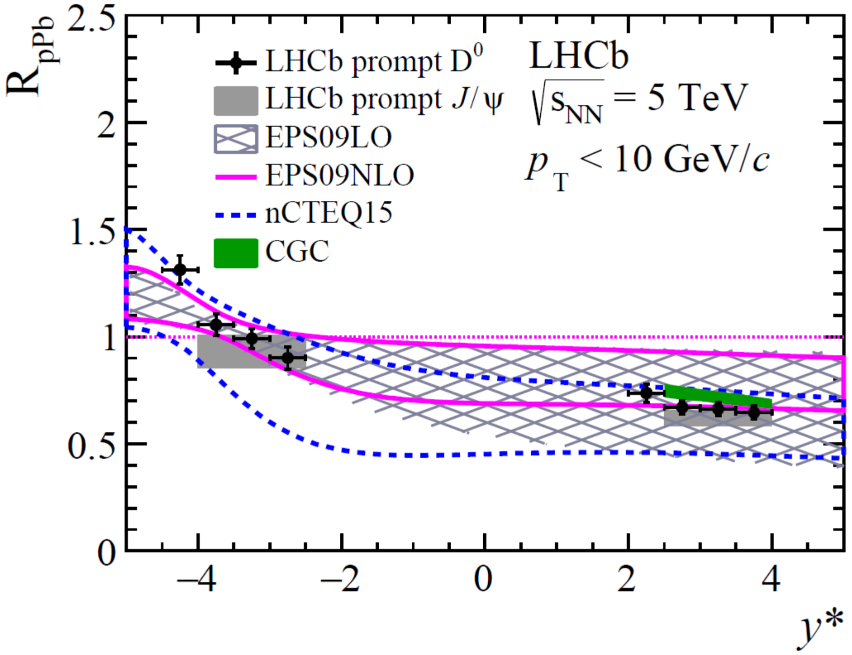




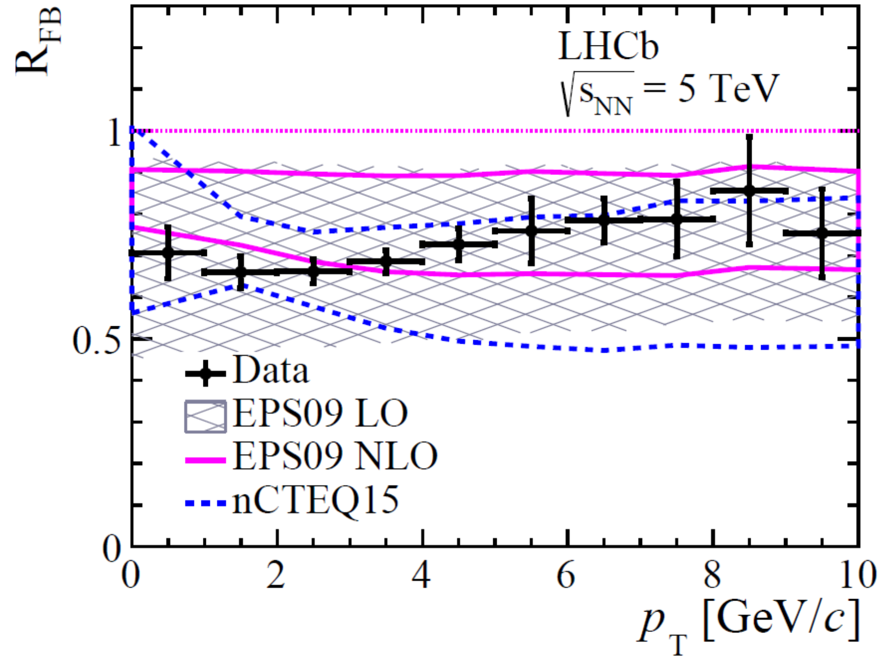
- Data indicate a smaller suppression at mid-rapidity than at forward rapidity in central collisions at low p_T
- Transport model with sizeable QGP regeneration component describes data within uncertainties; data on the upper side of the theory band

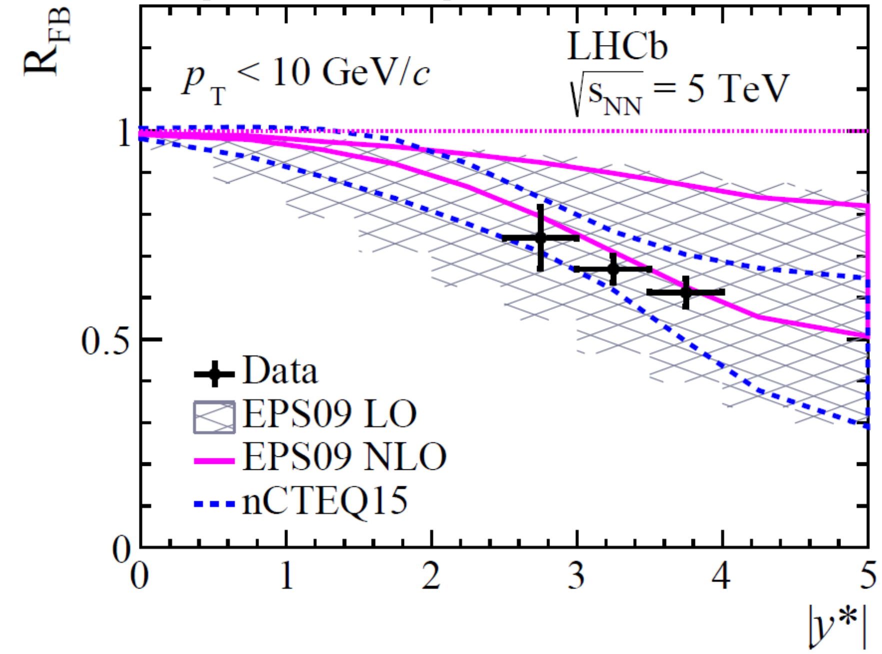
LHCb effort on heavy-ion physics

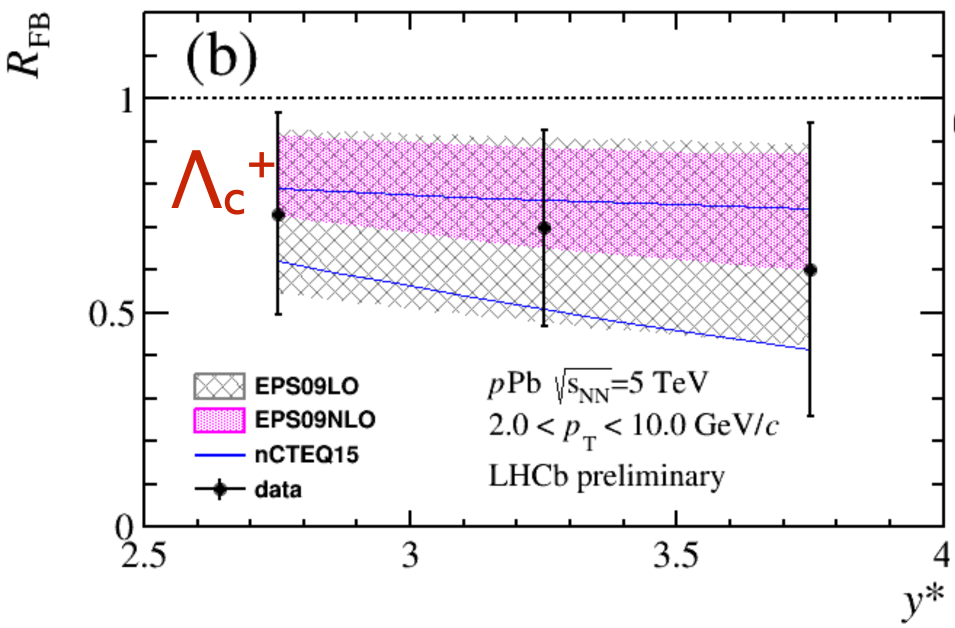
nuclear modification factor

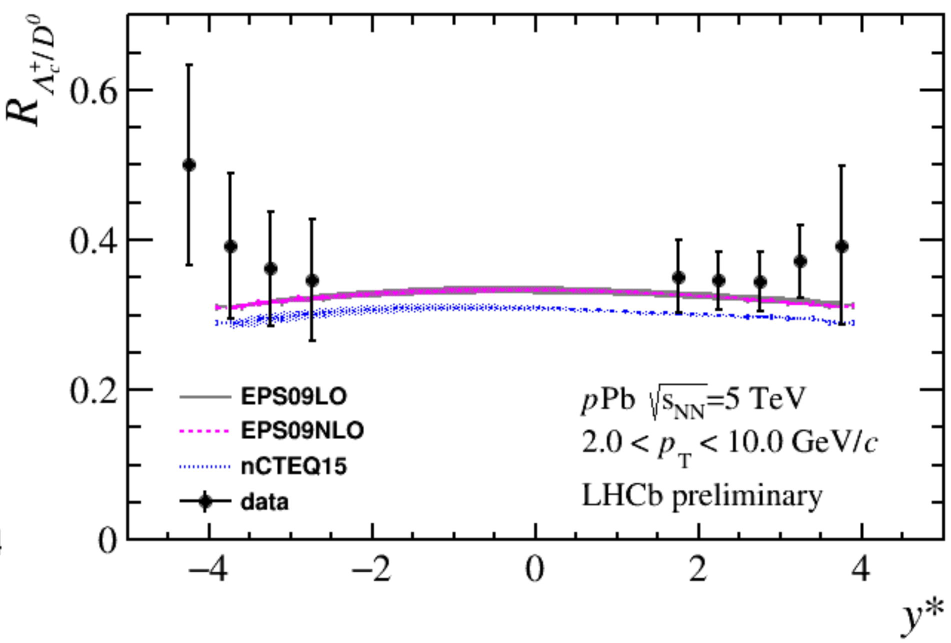


forward-backward asymmetry









$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A}\frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}$$

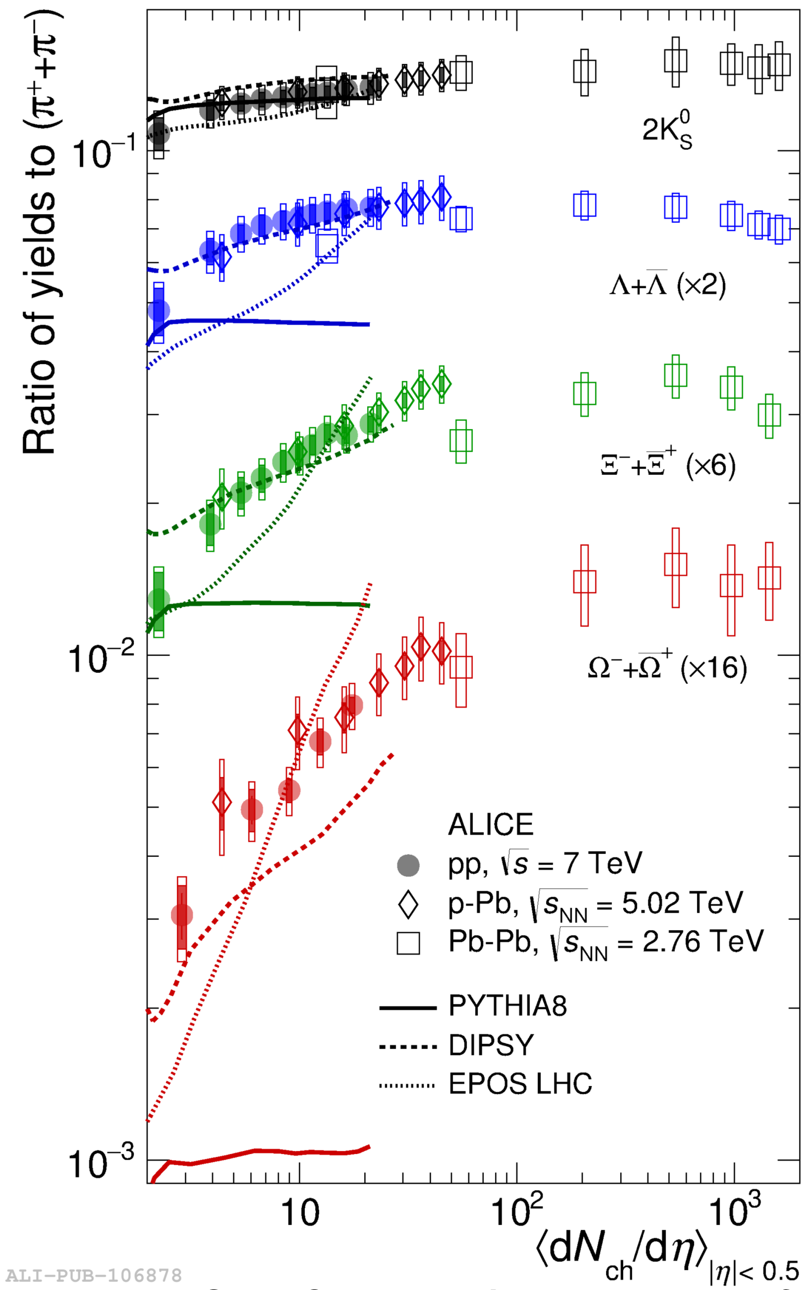
$$R_{FB}(p_T, y^*) \equiv \frac{d^2\sigma_{pPb}(p_T, +|y^*|)/dp_T dy^*}{d^2\sigma_{Pbp}(p_T, -|y^*|)/dp_T dy^*}$$

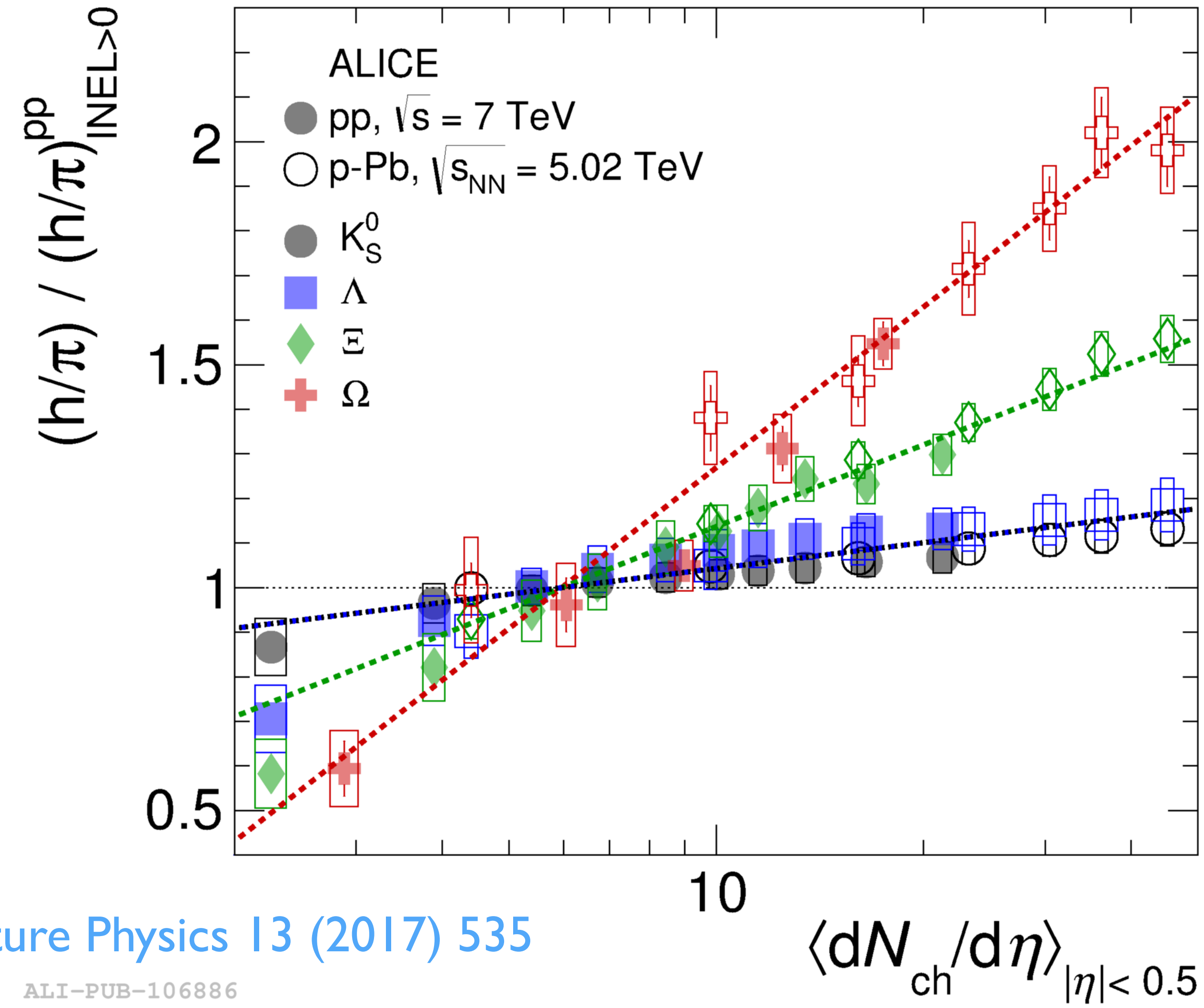
LHCb, JHEP 10 (2017) 090
LHCb-CONF-2017-005

see talk by J. Sun

- Backward R_{pPb} ~ 1 and forward R_{pPb} <1, consistent with theoretical calculations
- Forward-backward asymmetry R_{FB} measurements consistent with theory predictions

Multiplicity dependent strangeness production



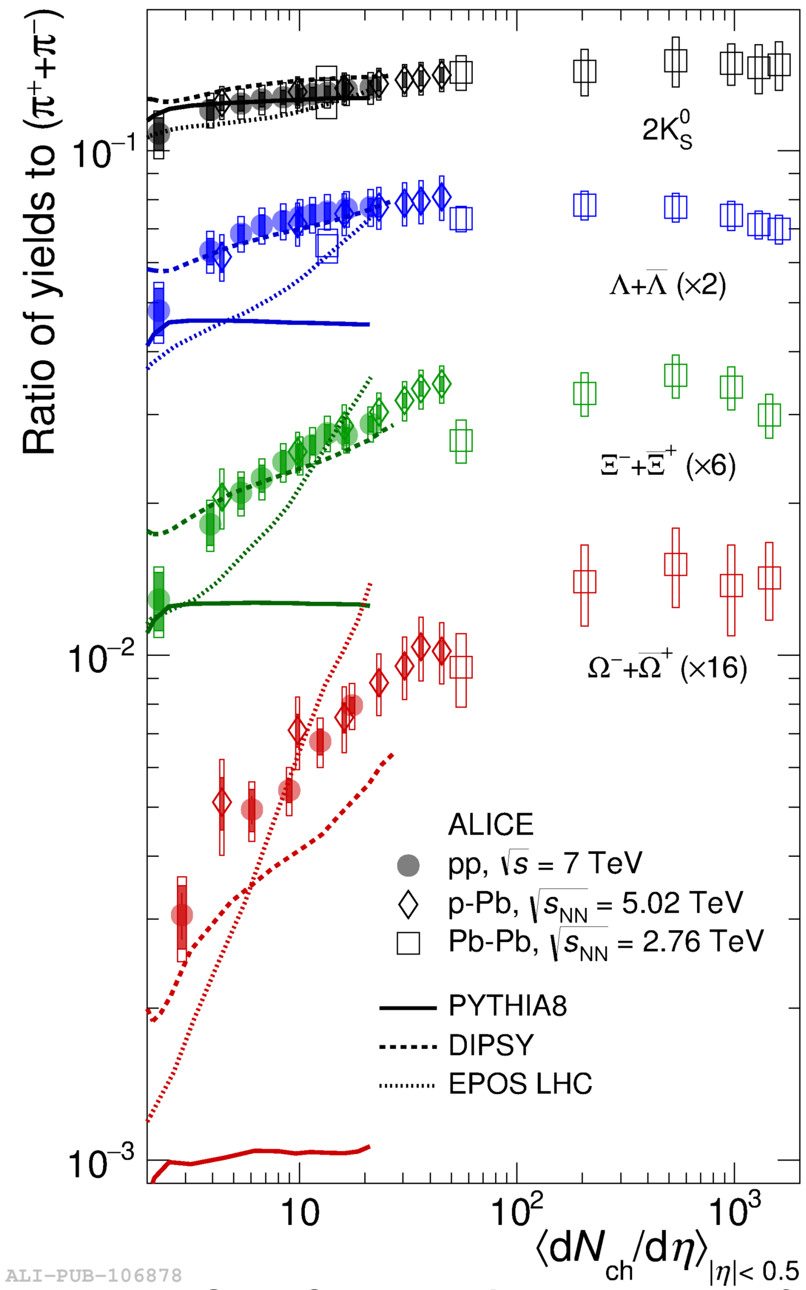


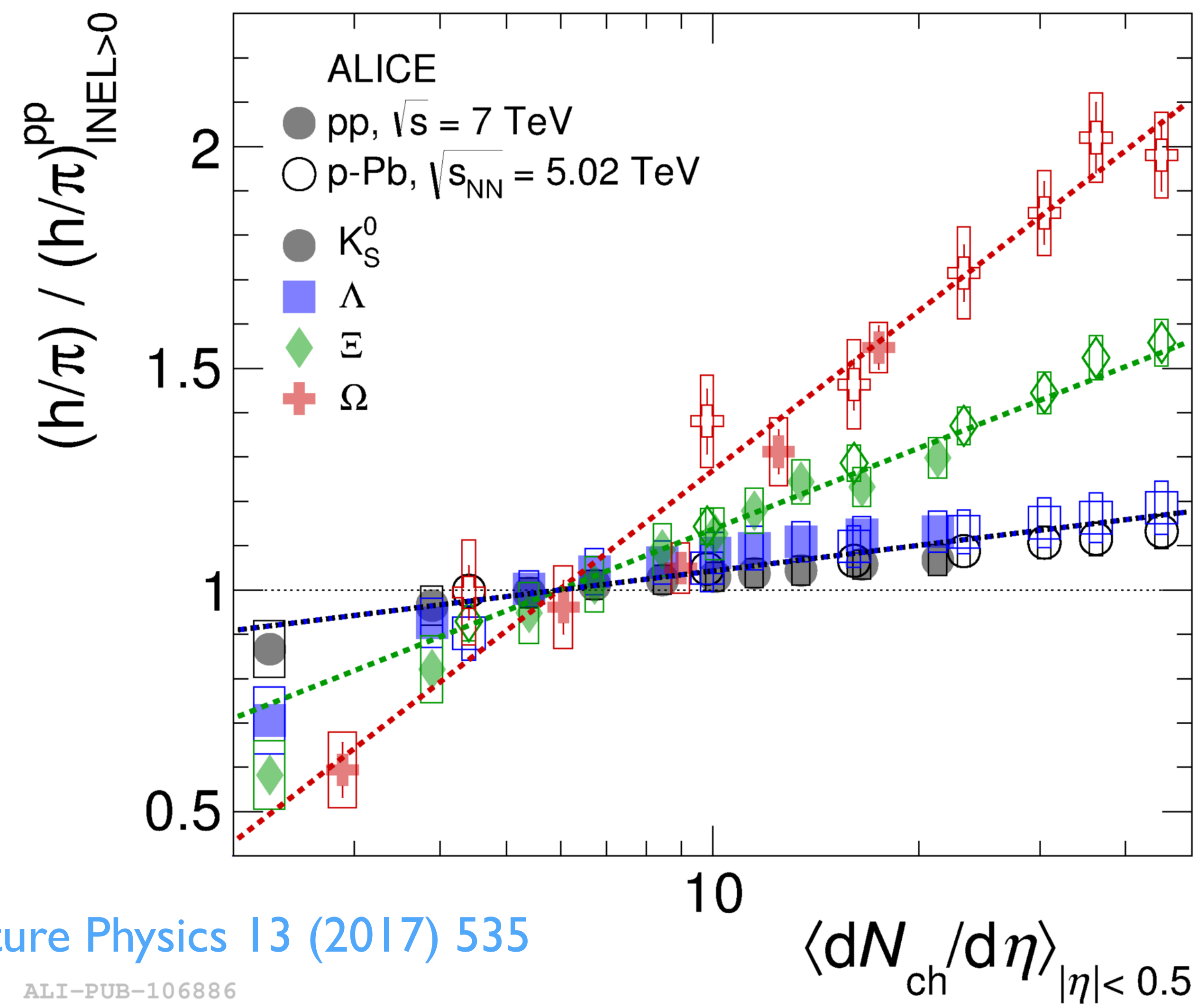
Nature Physics 13 (2017) 535

- Significant enhancement of strange and multi-strange particle production
- At high multiplicities, pp ratio reaches values value similar to the one in Pb-Pb
- No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy
- String hadronization models do not describe the data; only DIPSY gives a qualitative description

Multiplicity dependent strangeness production

see talk by X. Zhang





Nature Physics 13 (2017) 535

➡ Same mechanism in smaller system?

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- At high multiplicities, pp ratio reaches values value similar to the one in Pb-Pb
- No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy
- String hadronization models do not describe the data; only DIPSY gives a qualitative description

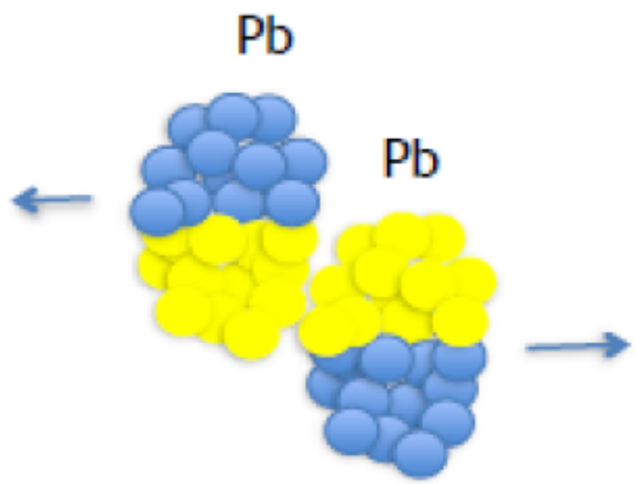
Conclusions

- LHC ideal for the study of the properties of the matter of the early Universe, the quark-gluon plasma
- Lots of exciting measurements from Pb-Pb collisions
  - Parton-medium interaction → parton energy loss
  - $R_{AA}(\pi) \sim R_{AA}$(D, single leptons) < R_{AA}(B) at low p_T
  - Quarkonia melting and regeneration
- p-Pb (and also pp) data: more than control measurements; mechanisms at work not fully understood
  - Indication for collective-like behavior in small systems, reminiscent of that observed in Pb-Pb collisions (→ next talk)
- Many more exciting results ahead of us
  - More institutes in China join in heavy-ion effort
  - After detector upgrades in 2019/2020

Thank you for your attention!

backup

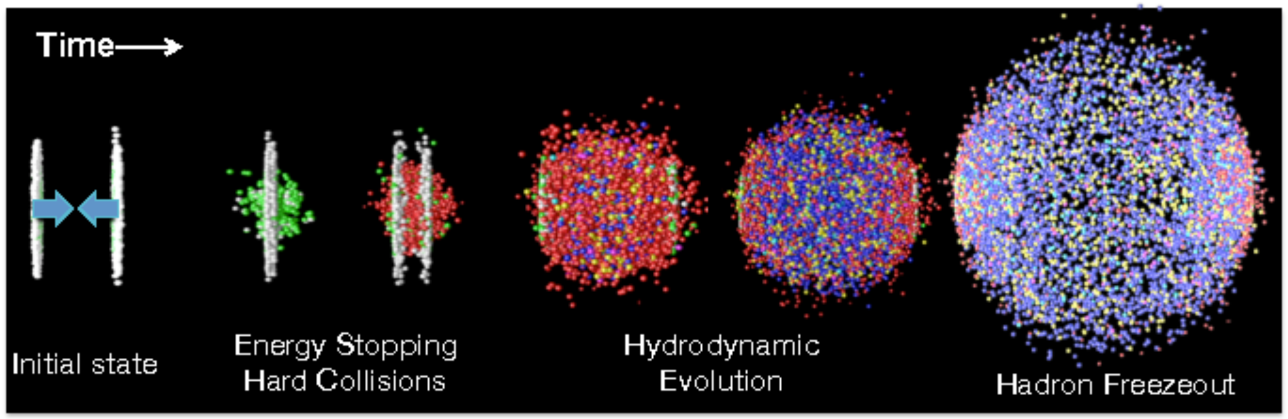
The collision systems

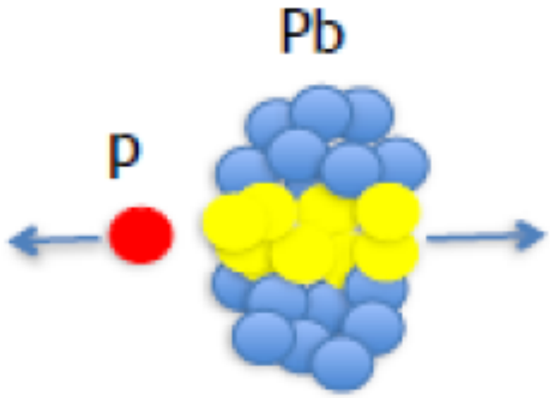


Pb-Pb collisions

Hot matter effects

Soft + hard probes





p-Pb collisions

Calibrate cold nuclear matter effects (CNM)

pp collisions

Reference for Pb-Pb collisions, QCD

Change of paradigm at LHC energies

High multiplicity p-Pb and pp collisions show intriguing signal of QGP-like effects

The energy frontier

- Evolution of (some) properties of the system with the collision energy (N. B. approximate values!)

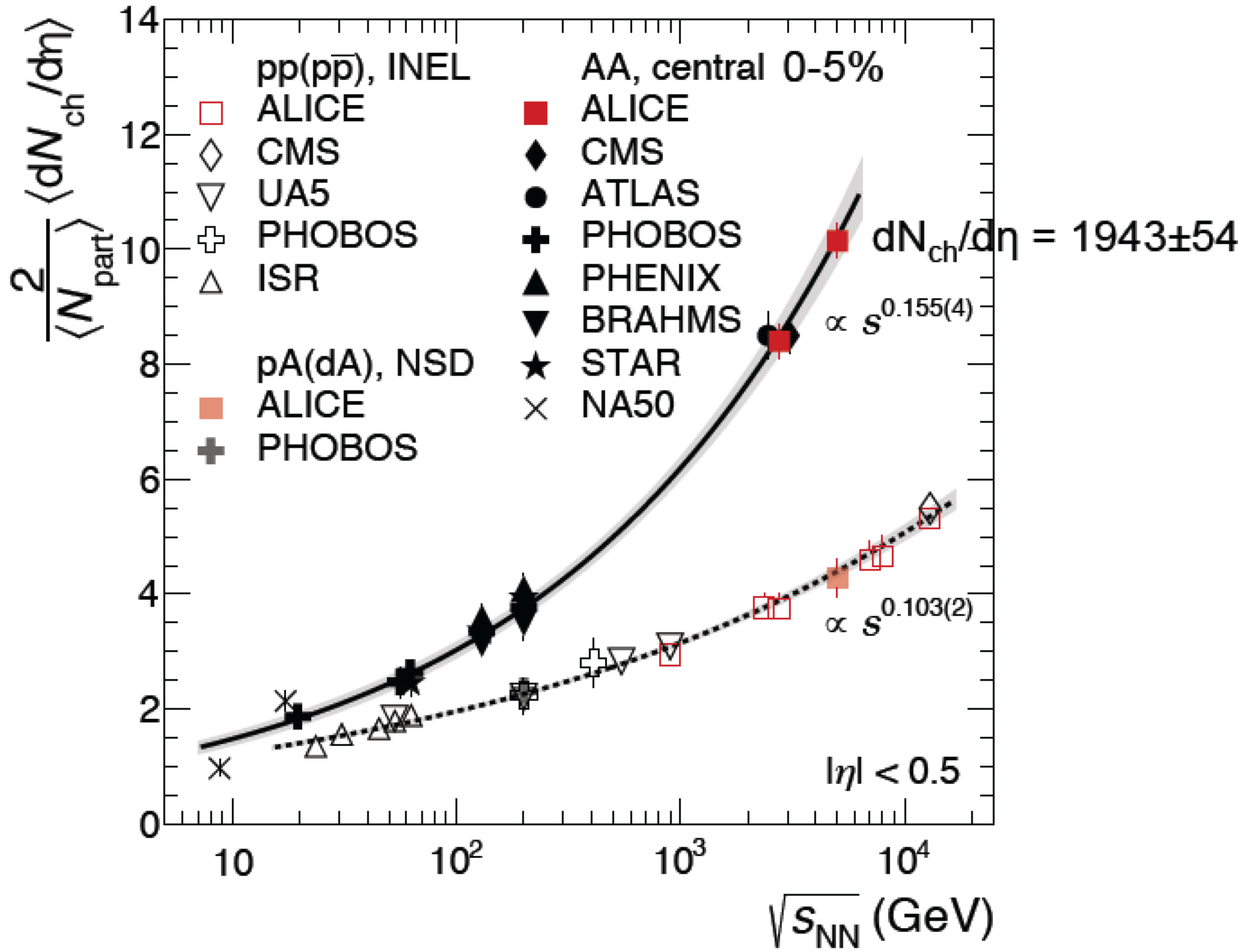
Central collisions	SPS	RHIC	LHC
$\sqrt{s}$ (GeV)	17	200	5000 (today)
dNch/dη (η = 0)	450	650	2000
Energy density (GeV/fm^3)	2.2-3.2	5.4	20
V (fm^3) - from HBT	120	160	300
Decoupling time (fm/c) - from HBT	6	7.5	10.5
Average QGP temperature (MeV) -photons, dileptons	190	240	300

LHC→ hotter, larger, and longer lived fireball!

Charged particle multiplicity

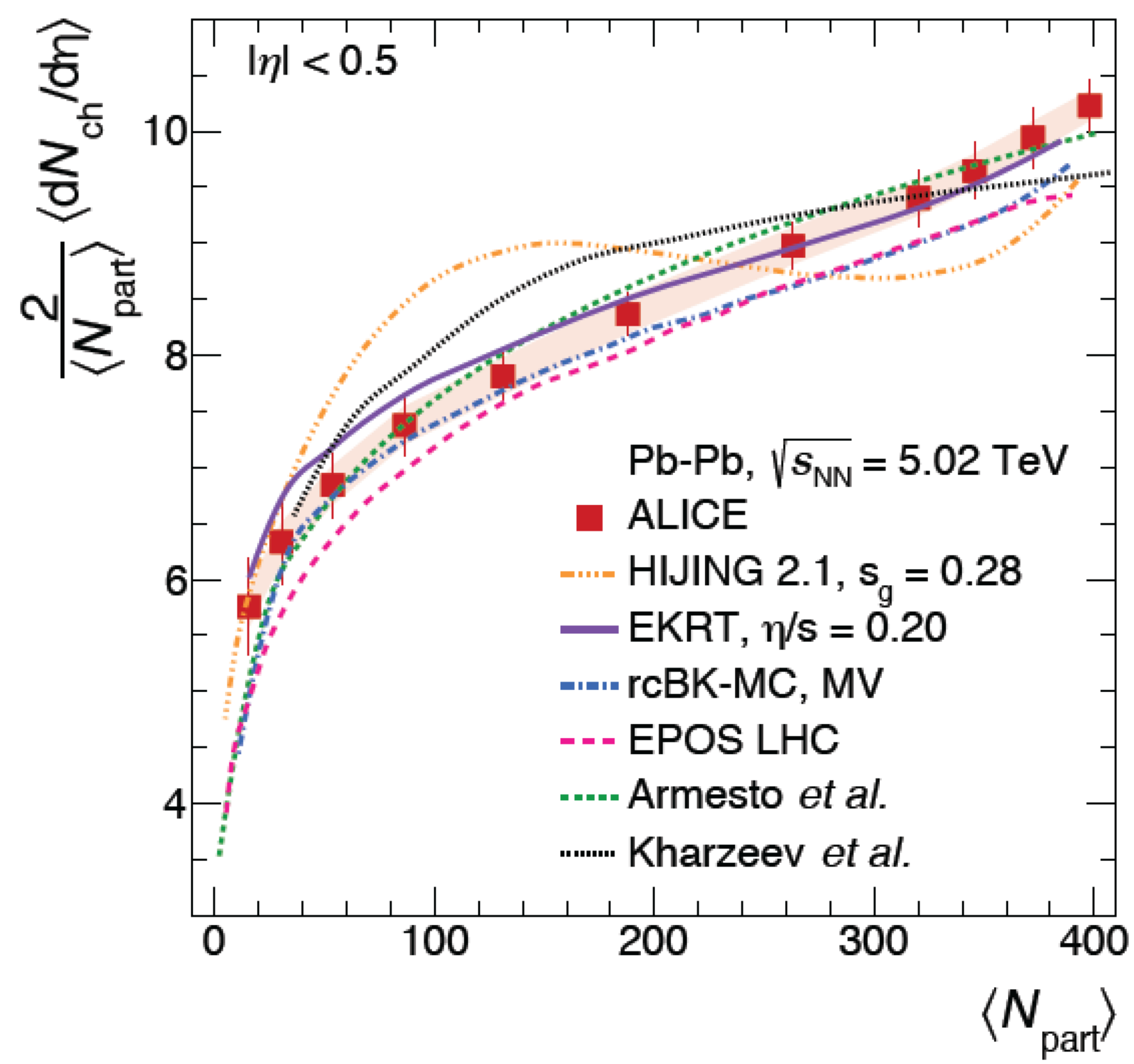
vs. cms energy

Phys. Rev. Lett. 116, 222302 (2016), Phys. Rev. Lett. 105, 252301 (2010)



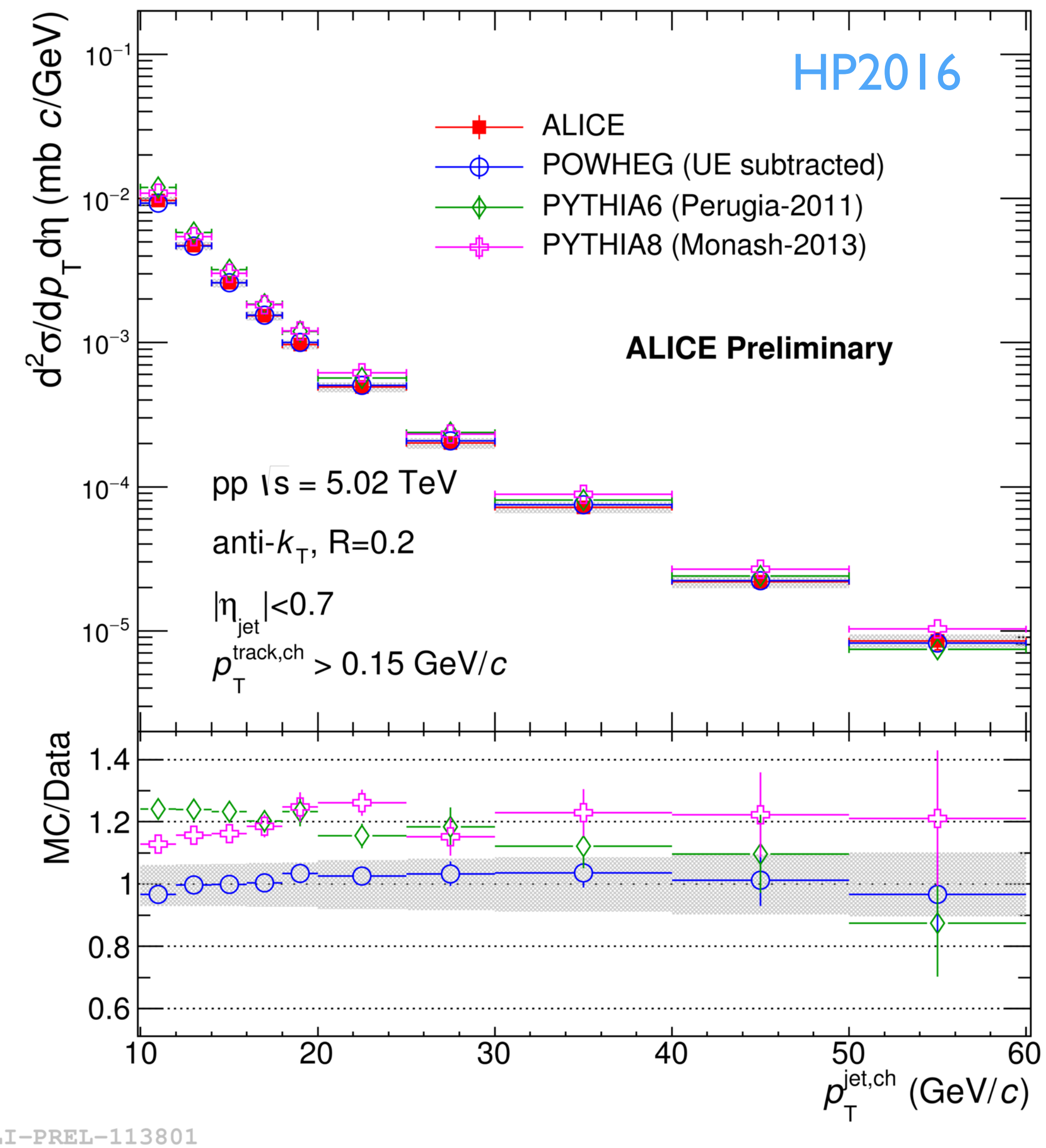
vs. number of participants

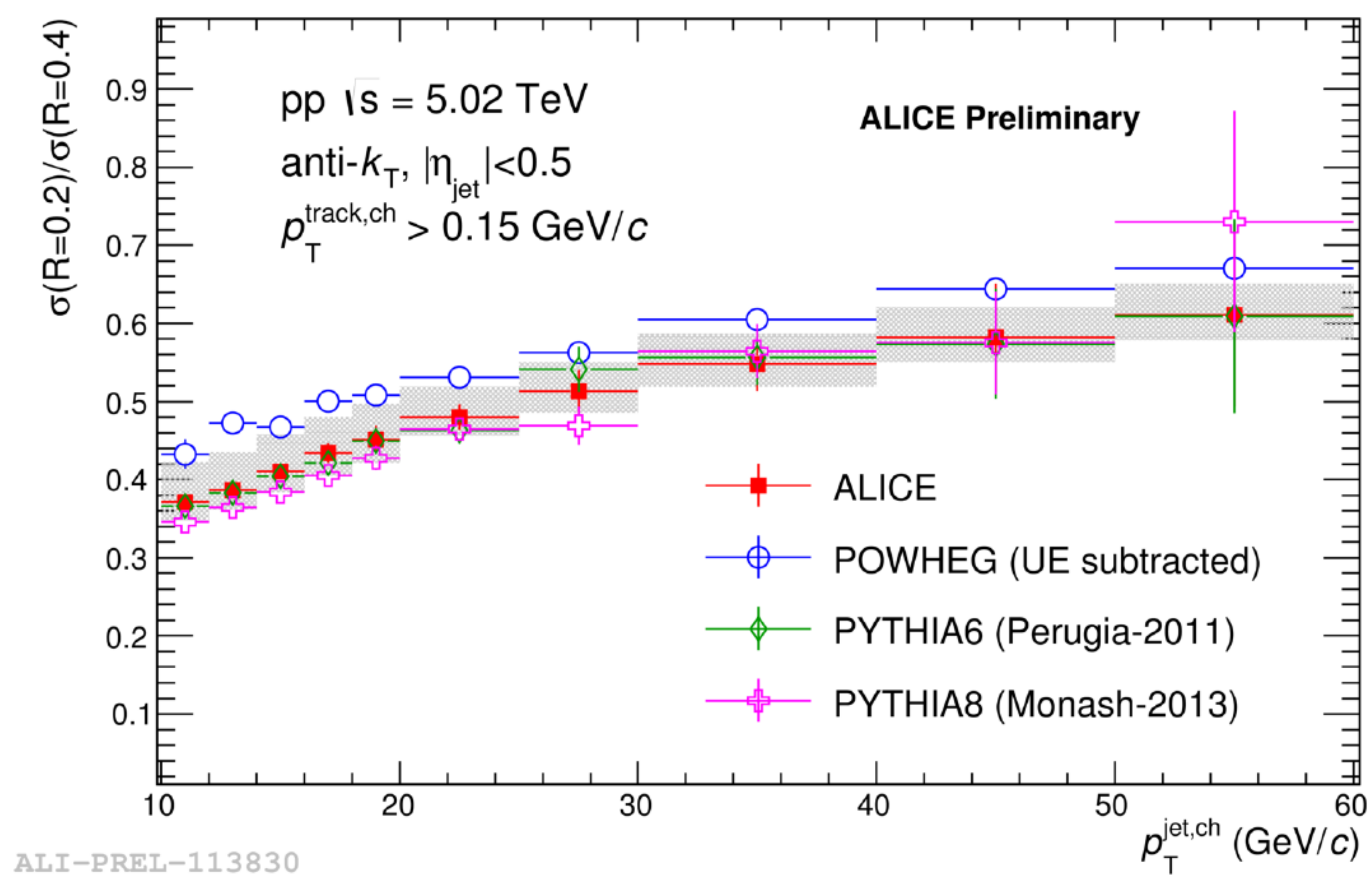
Phys. Rev. Lett. 106, 032301 (2011)



- ALICE: Pb-Pb at 5.02 TeV, highest energy reached so far → confirms trend from lower energies
- Power law dependence fits well and faster in Pb-Pb ($\sim s^{0.155}$) than in pp ($\sim s^{0.103}$)
- Provides further constraints for model

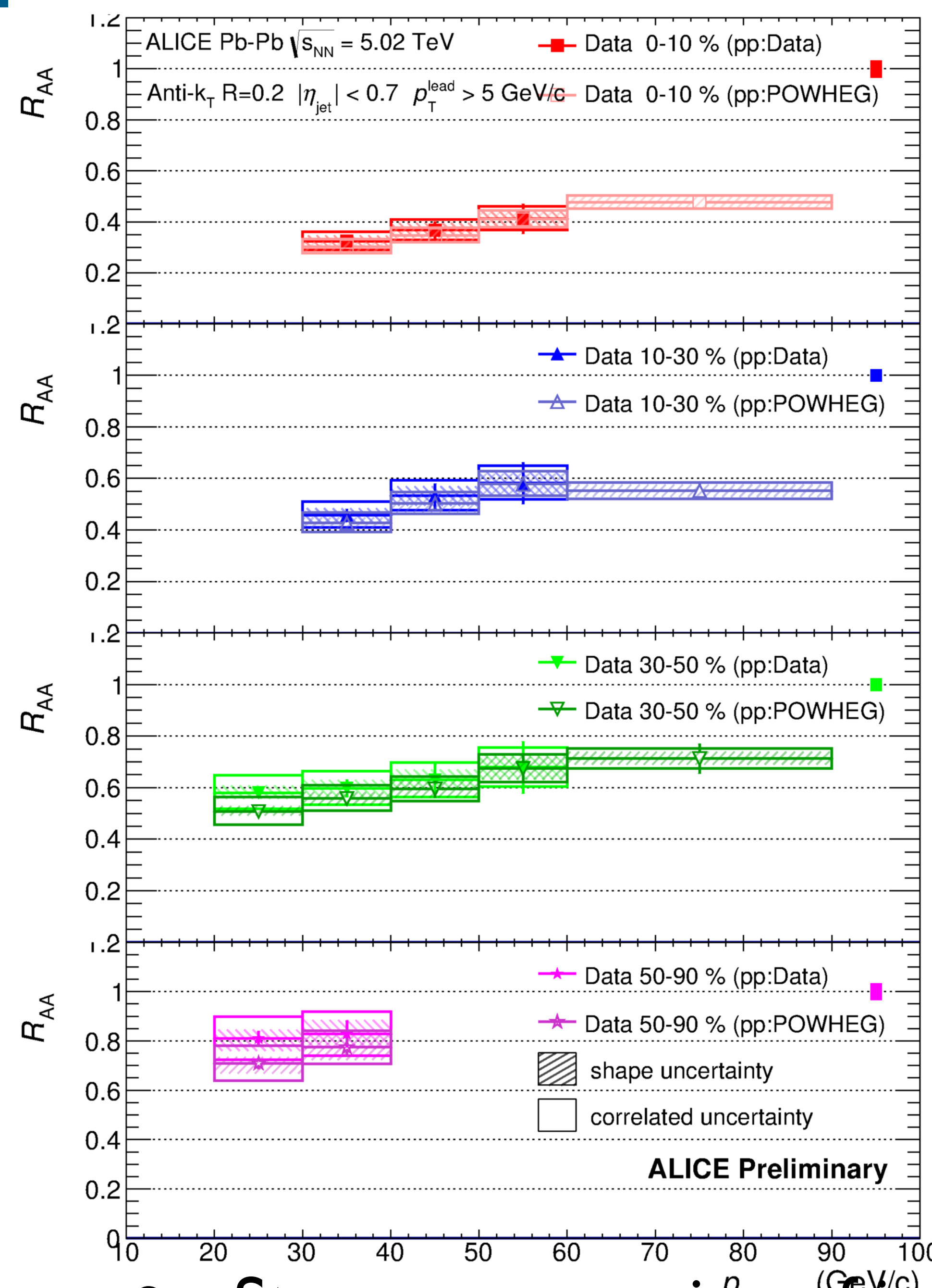
jet cross sections in pp at 5.02 TeV





- Jet cross section is well described by POWHEG NLO calculations within systematic uncertainties
- Cross section ratio between R = 0.2/R = 0.4 consistent with model calculations, slightly increasing with jet p_T → reflect jet collimation information info

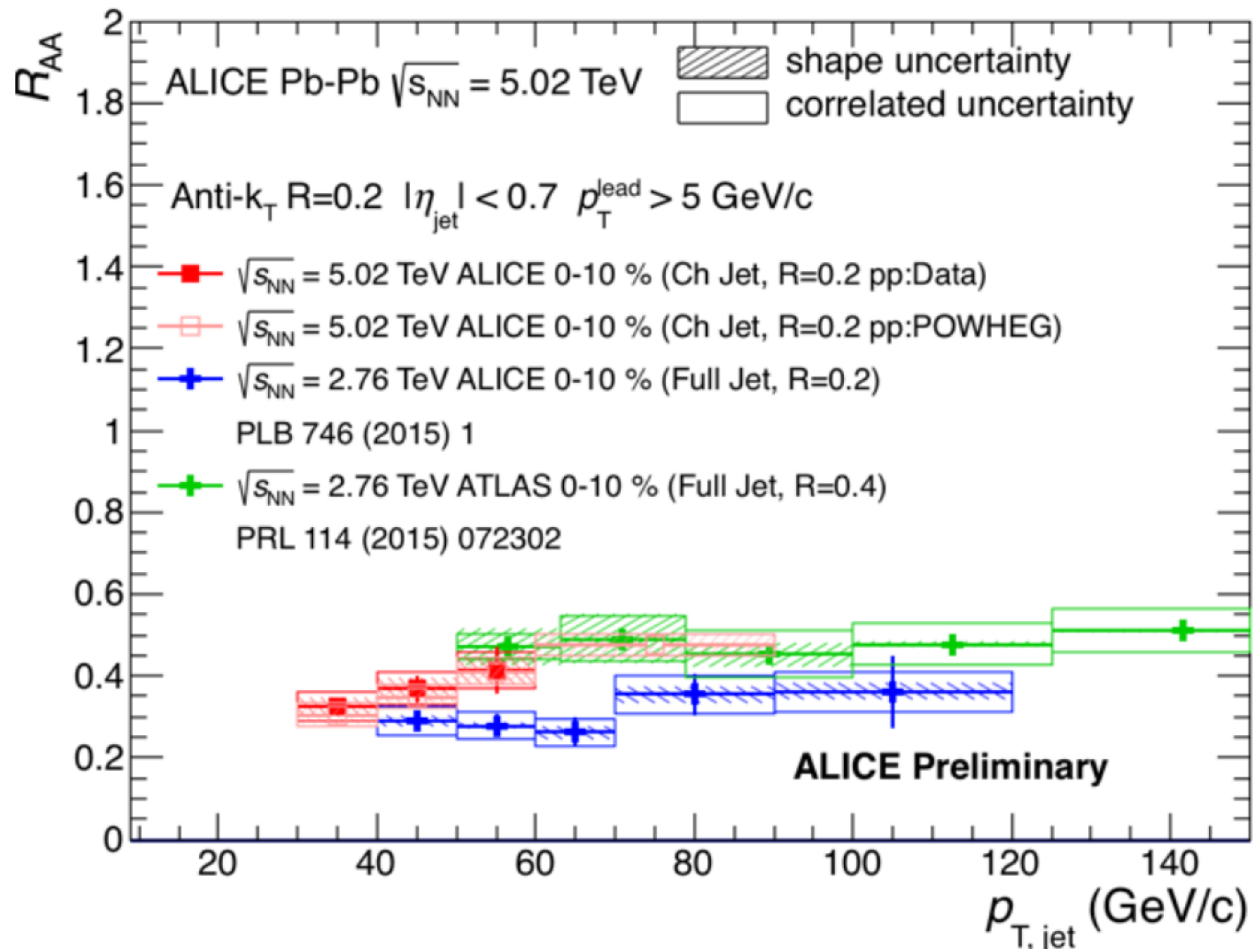
Jet nuclear modification factor R_{AA}



ALICE-PREL-113513

HP2016

$$R_{AA} = \frac{1}{<N_{coll}>} \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$



- Strong suppression of jet yield in most central collisions
- R_{AA} at 5.02 TeV similar to 2.76 TeV
  - ➡ "compensation" between increasing suppression and modification of the shape of the spectra

ALICE upgrade program (for Run3)

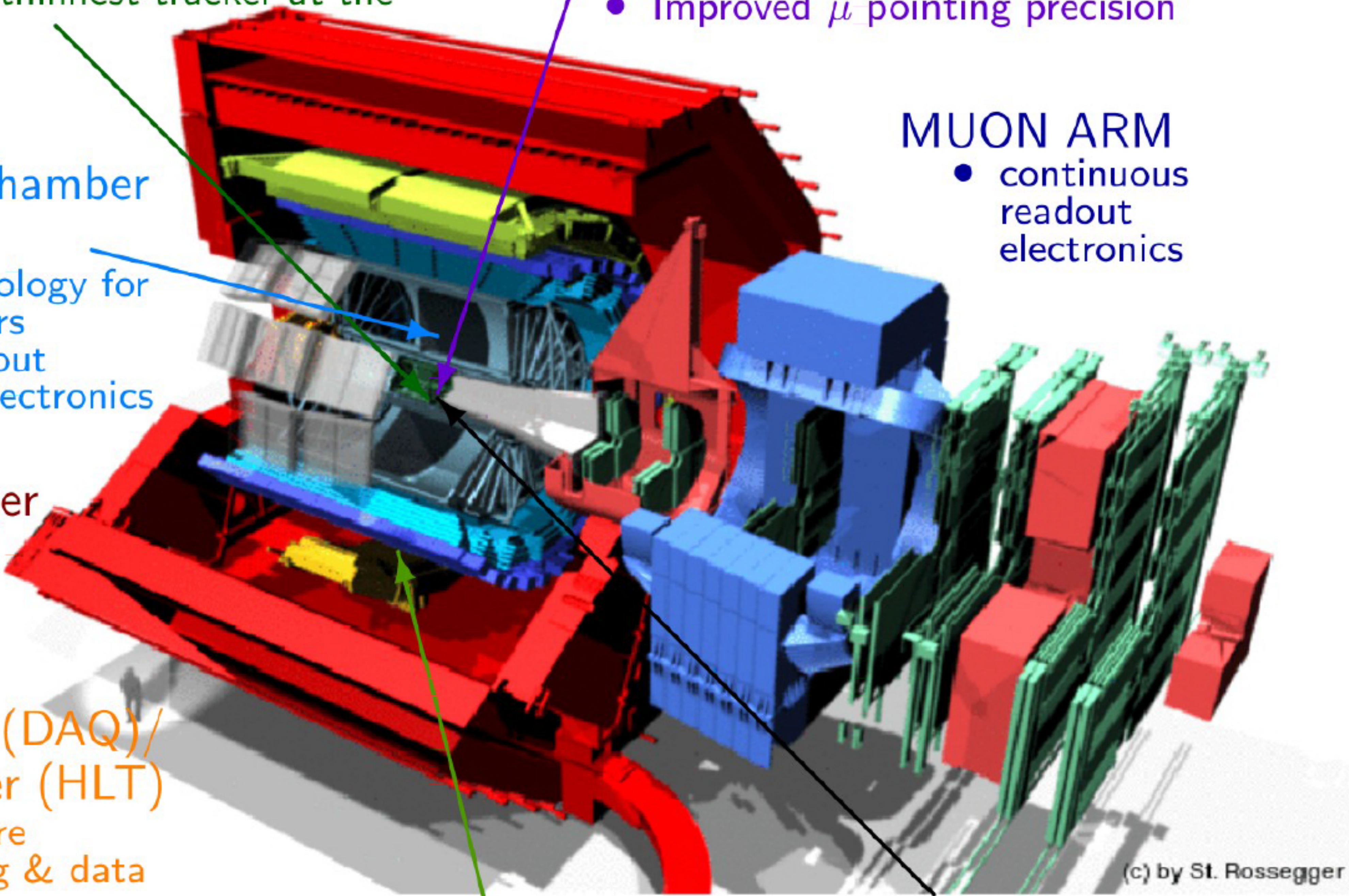
New Inner Tracking System (ITS)
- improved pointing precision
- less material → thinnest tracker at the LHC

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

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor (CTP)



Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

→ technical design reports in CDS