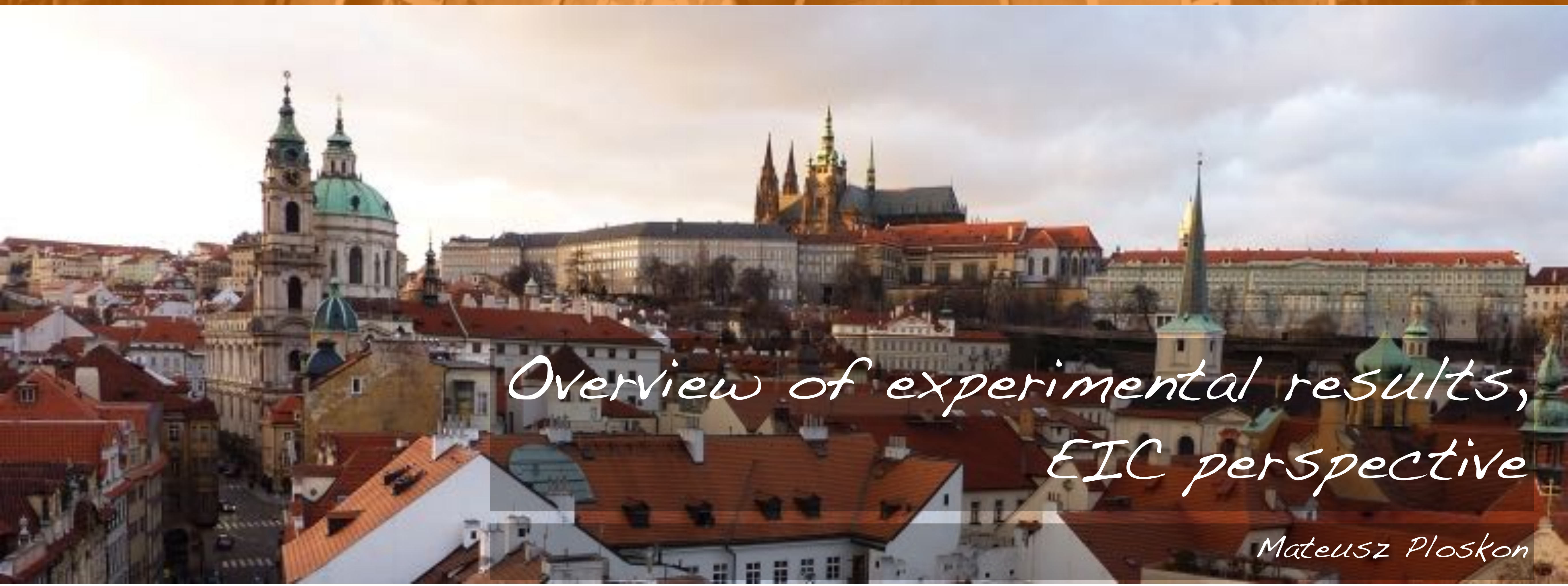
30th Indian-summer School of Physics

Phenomenology of Hot and Dense Matter for Future Accelerators

September 3–7, 2018, Prague, Czech Republic



Overview of experimental results, EIC perspective

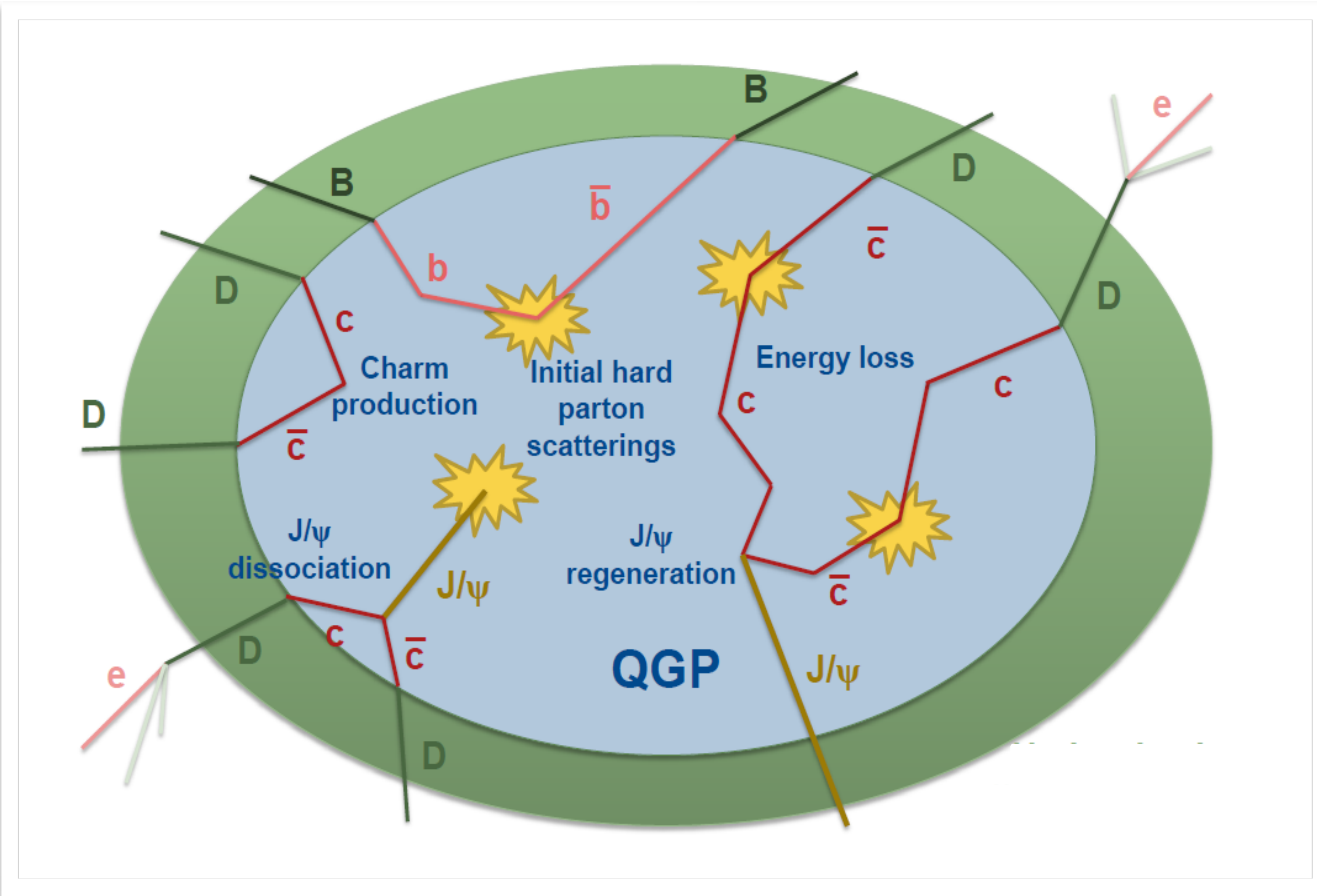
Mateusz Ploskon

Lecture #4

until now...

- Heavy-ion collisions: high-T, high energy density, size, lifetime, Tch > Tkin
- QGP: v2 > 0, vn > 0 - hydrodynamical description with small **η**/s; Trouble: hydrodynamics describes any system with same/similar parameters ...
- High-energy partons interact within QGP <=> high-pT particles suppressed (with respect to vacuum reference); jets are modified (jet quenching) - constant fractional energy loss - jet collimation and enhancement of soft components; ; subjets (elements of hard splitting) with larger **Δ**R interact as independent sources; large angle parton-parton scatterings (parton-plasma) - homogeneity of the medium

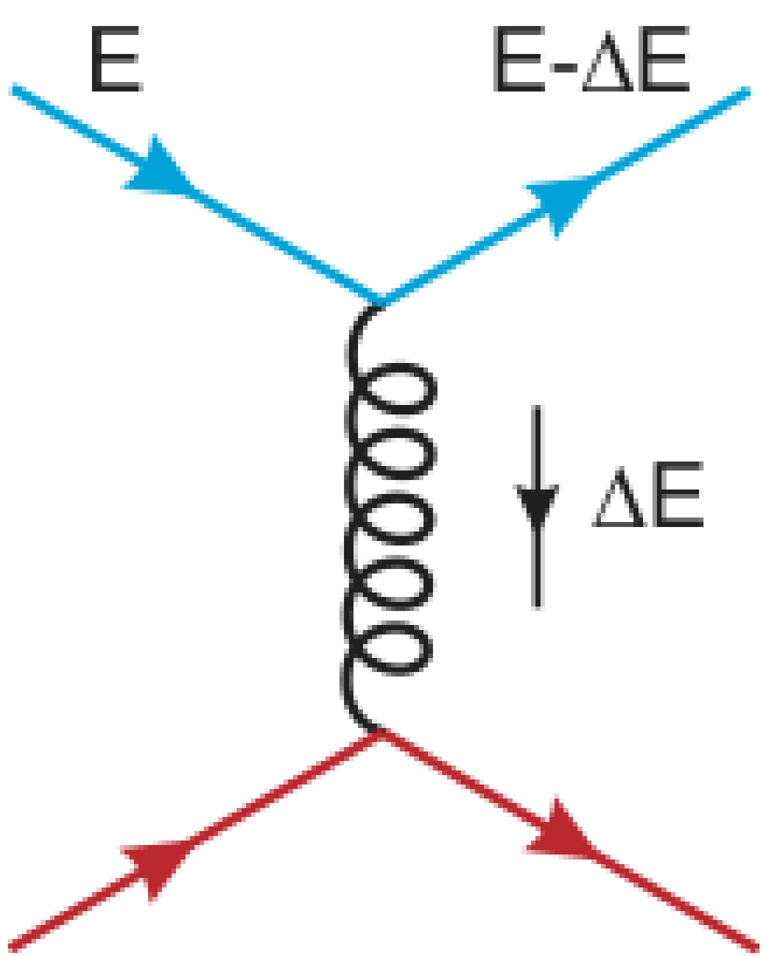
Heavy-flavor in medium



Parton in-medium energy loss: elastic (collisional) and inelastic (radiative)...

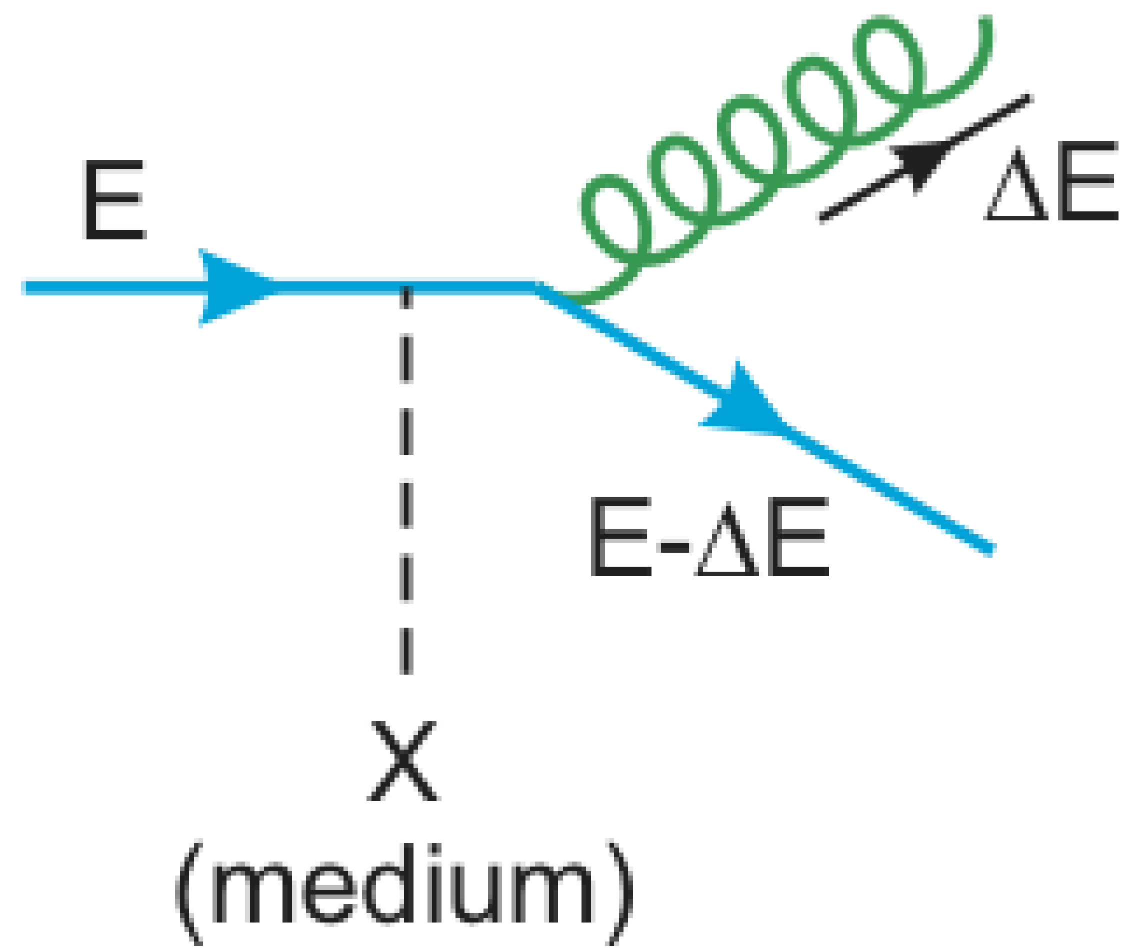
Longitudinal drag coef. (collisional)

$\hat{e}$



p_T diffusion (radiative)

$\hat{q}$



Reminder: at high-E radiative processes dominate...

R_{AA} for different particle type

Is parton energy loss different
for gluons, light-quarks and heavy-quarks?

Expectation: $\Delta E_g > \Delta E_{light\text{-}q} > \Delta E_{heavy\text{-}q}$

$\Delta E \propto \alpha_S C_R \hat{q} L^2$
CR = 4/3 for quarks, 3 for gluons

Casimir (color factor)
- gluons "glue" better to the medium than quarks

"Dead-cone" effect:
mass of the parent quark

=> radiation for angles $\theta < m/E$ is suppressed

=> $R_{AA}^{pions} < R_{AA}^{D\text{-}mesons} < R_{AA}^{B\text{-}mesons}$

Reminder: at high-E radiative processes dominate...

Parton energy-loss: gluons vs. quarks

$$\Delta E \propto \alpha_s C_R \hat{q} L^2$$

- Energy loss depends on parton:
  - Casimir factor (C_R=3 for gluons and 4/3 for quarks)
  - Mass of the quark (**dead cone** effect): radiation suppressed for angles $\theta < m/E$

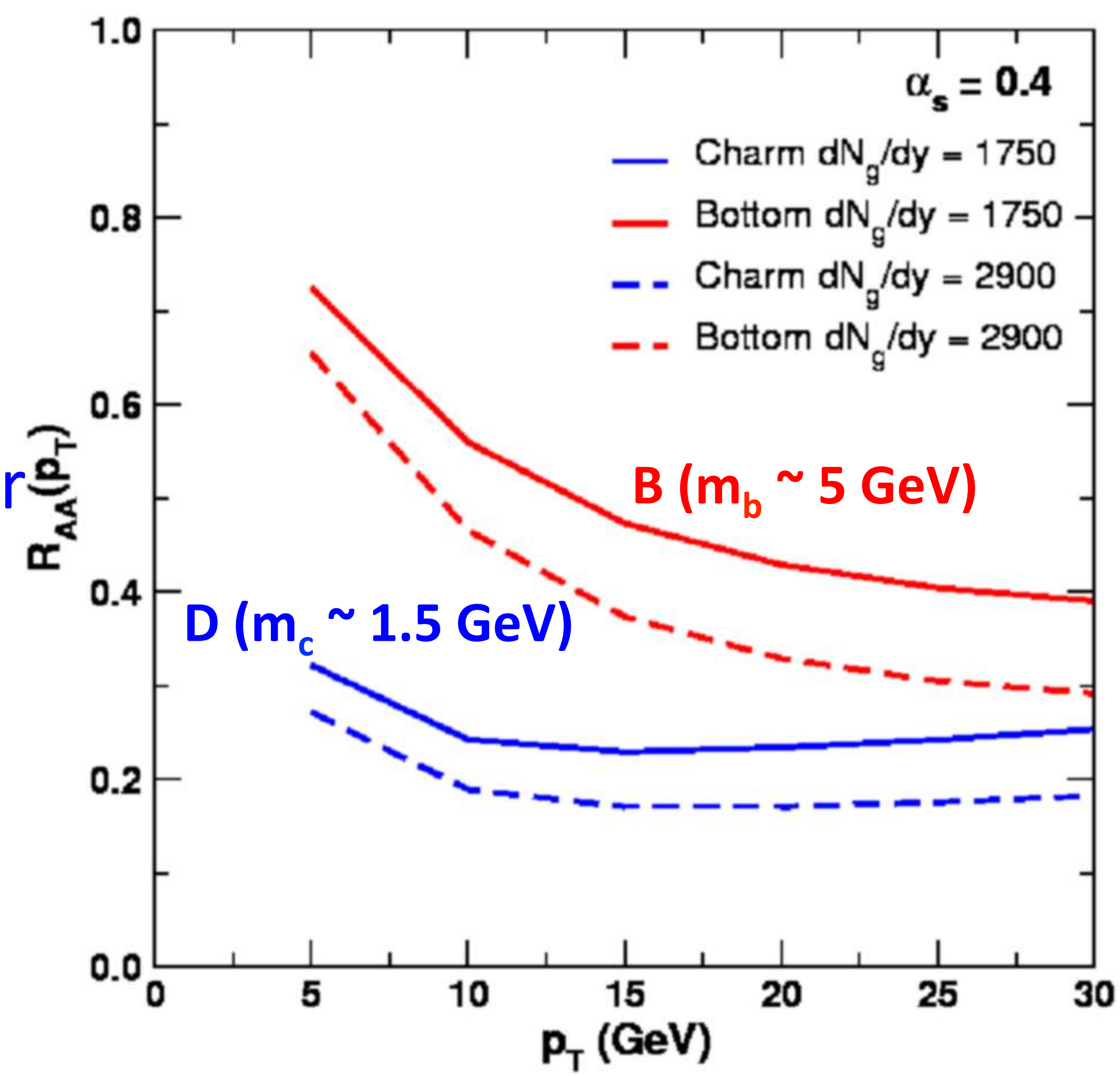
$$\Delta E_{gluon} > \Delta E_{quark}$$
$$\Delta E_{light-q} > \Delta E_{heavy-q}$$

- Does it persist at low-p_T as:

$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

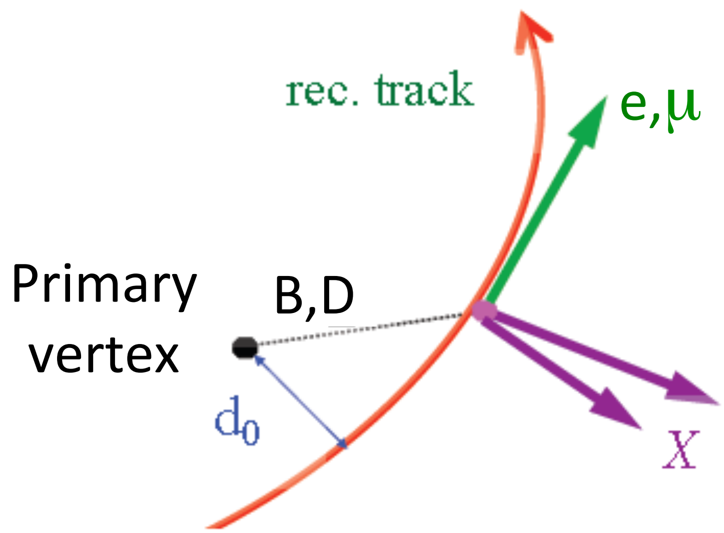
Prediction!

Wicks, Gyulassy, Last Call for LHC predictions

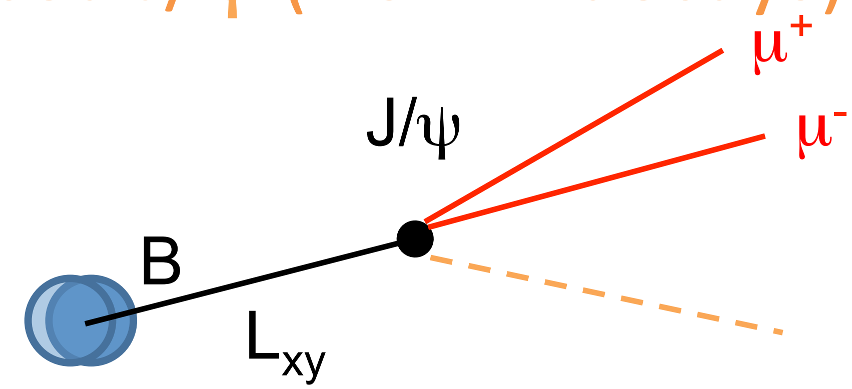


Heavy-flavor reconstruction

Semi-leptonic decays (c,b)



Displaced J/ψ (from B decays)



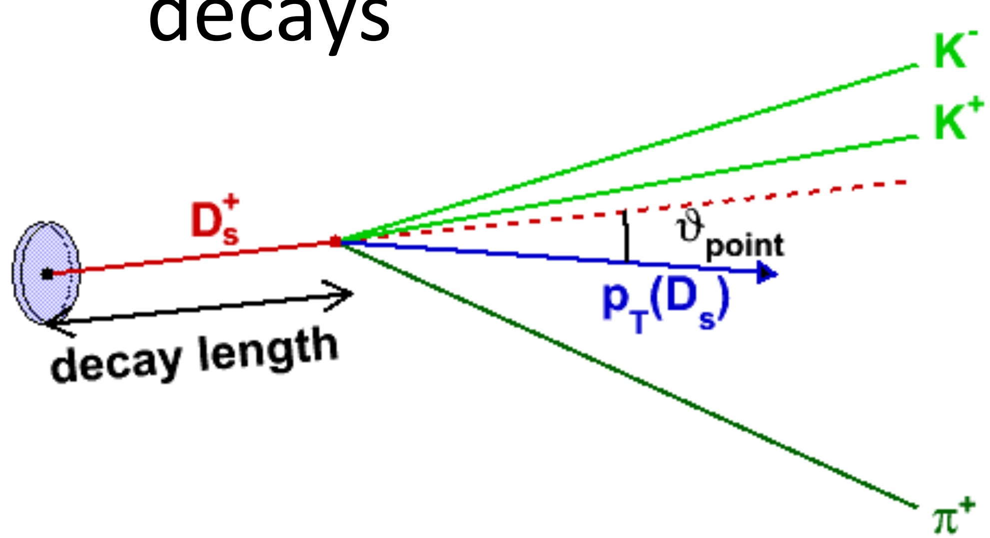
Full reconstruction of D meson hadronic decays

$D^0 \rightarrow K^- \pi^+$

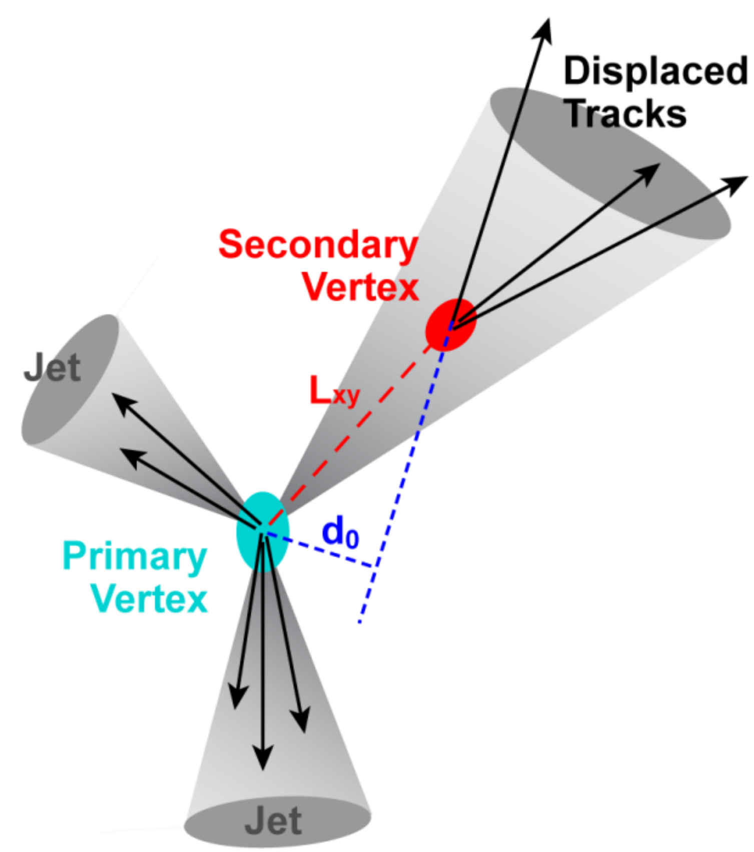
$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow K^- K^+ \pi^+$



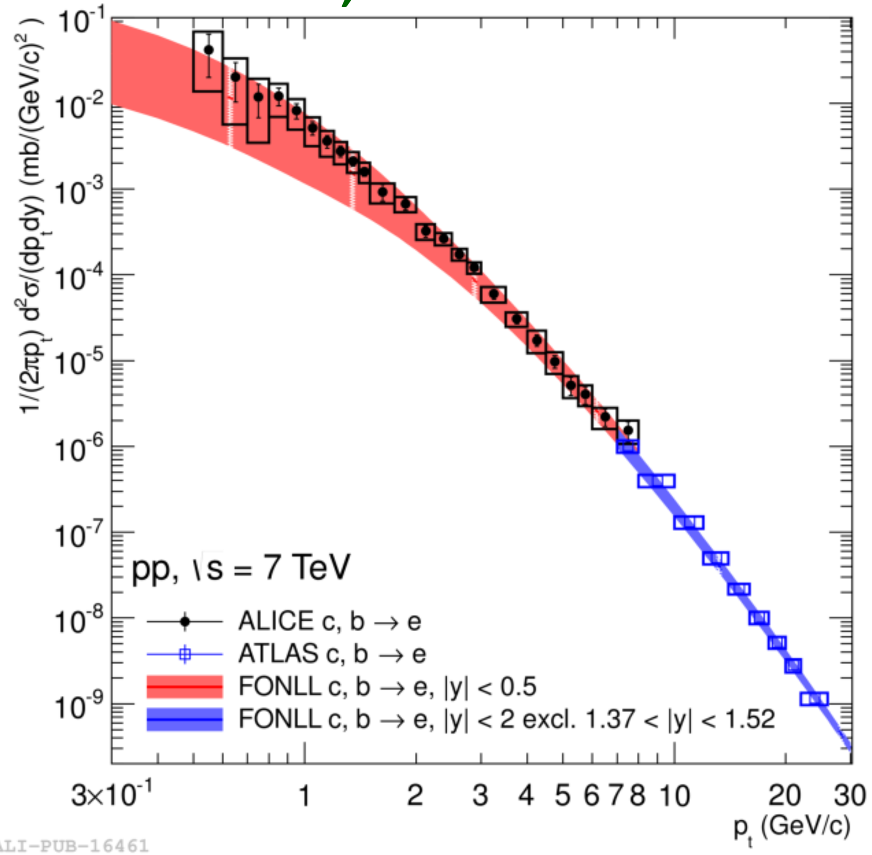
jet b-tagging



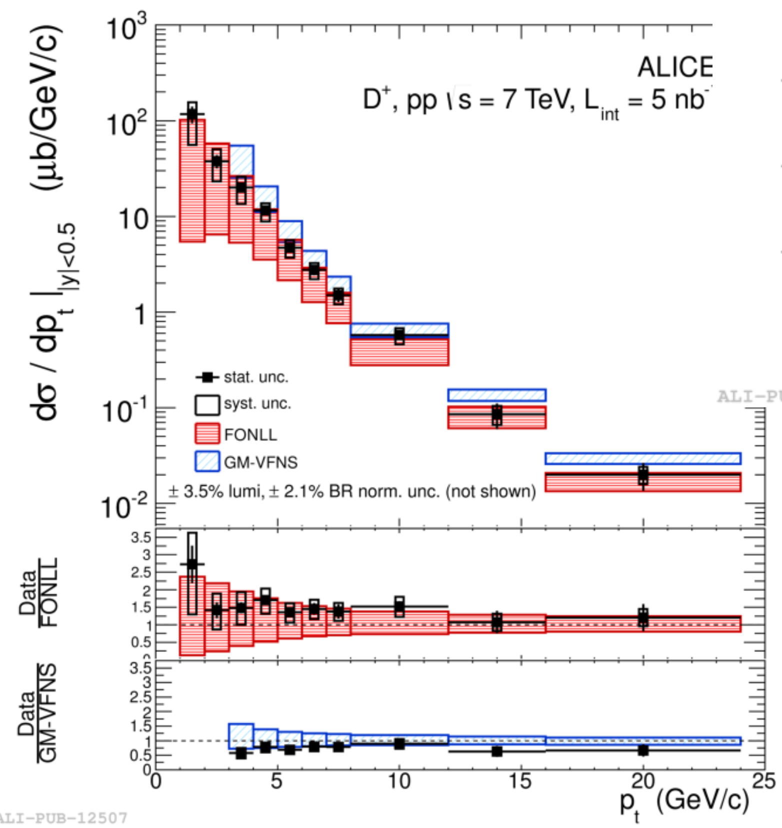
Heavy-flavor – calibrated probes?

Production in p-p

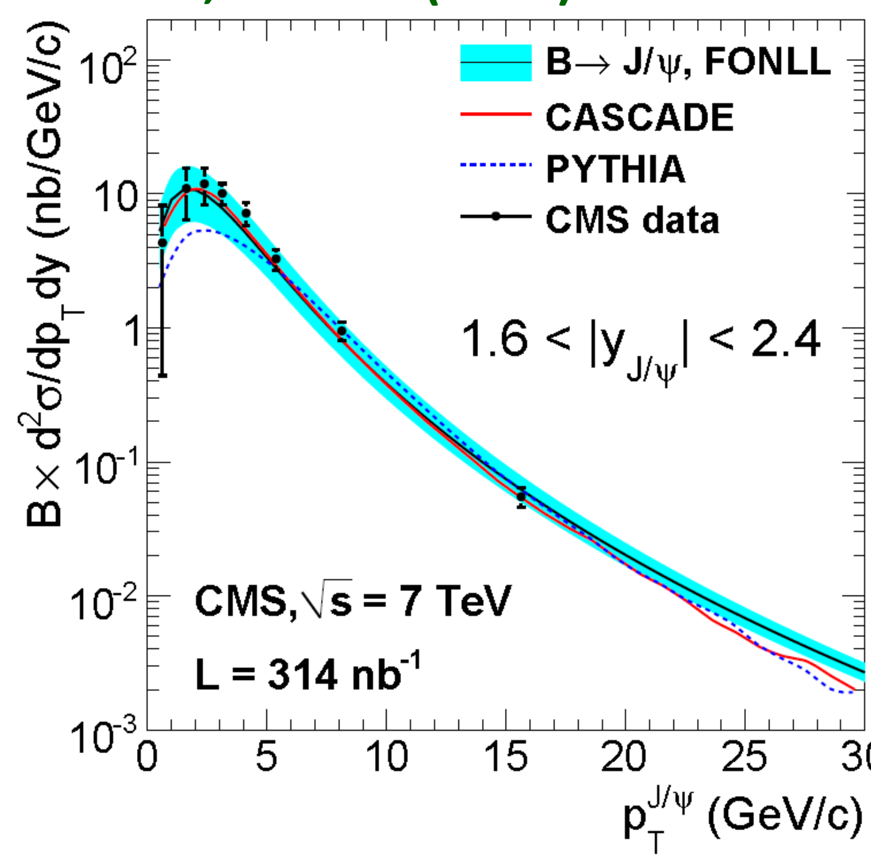
ALICE, arXiv:1205.5423



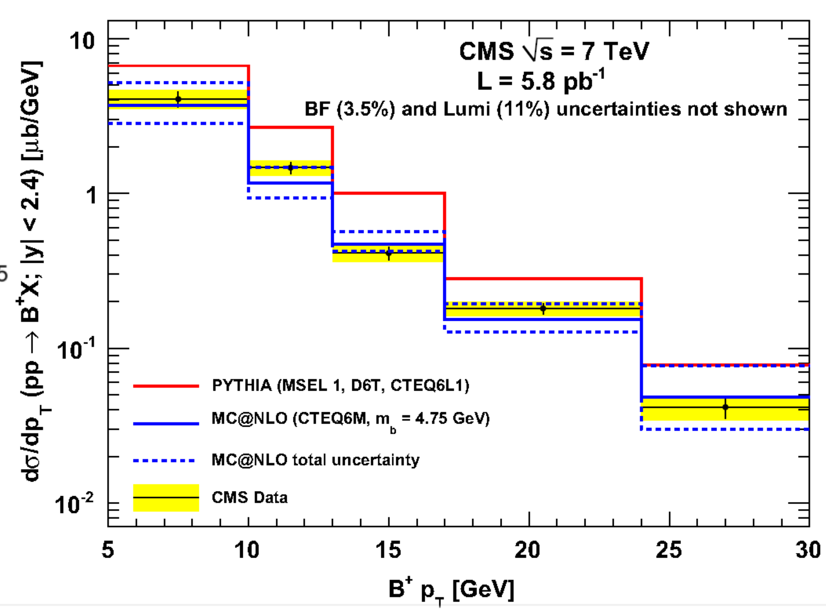
ALICE, JHEP 1201 (2012)



CMS, EPJC 71 (2011) 1575

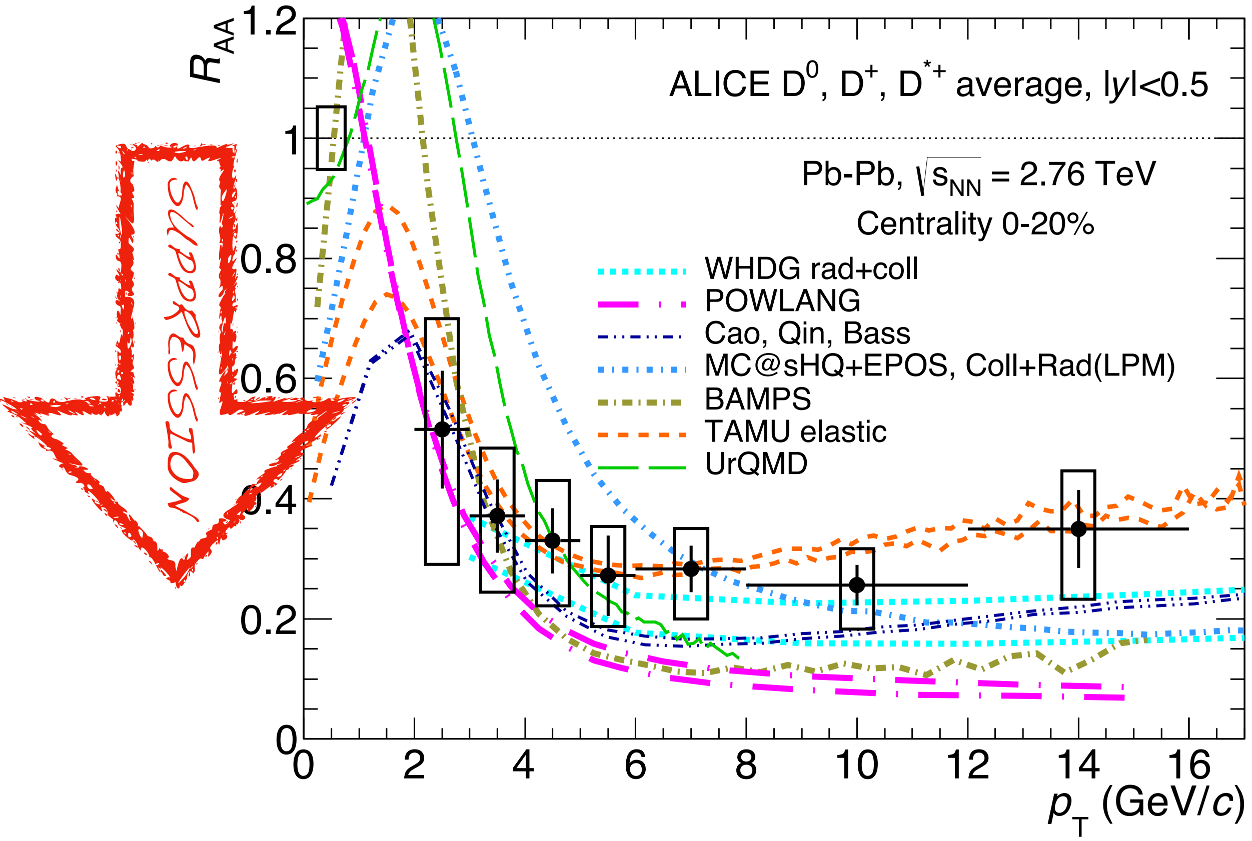


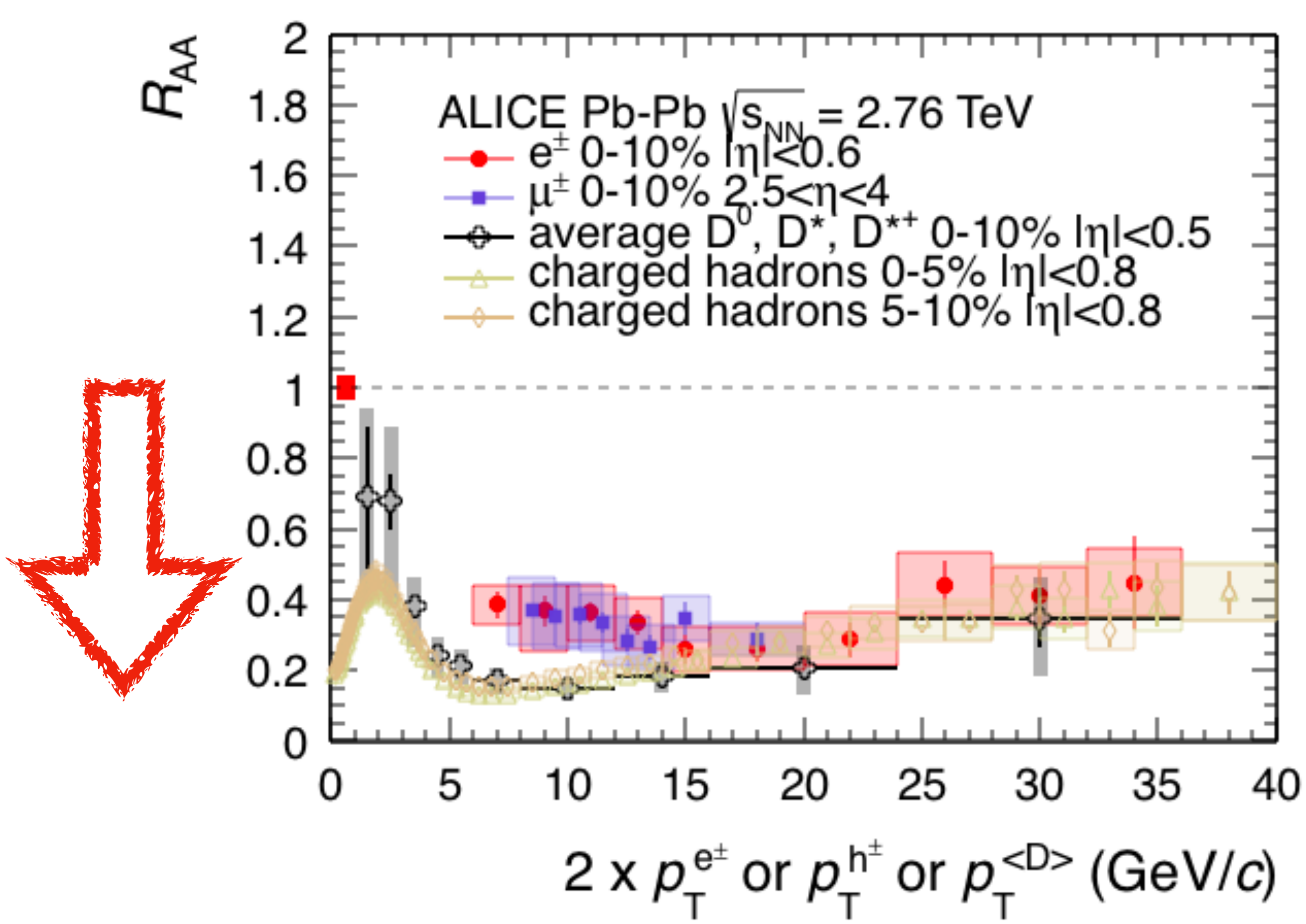
CMS, PRL 106 (2011) 112001



pQCD agree with data within uncertainties

Heavy-flavor suppression in QGP





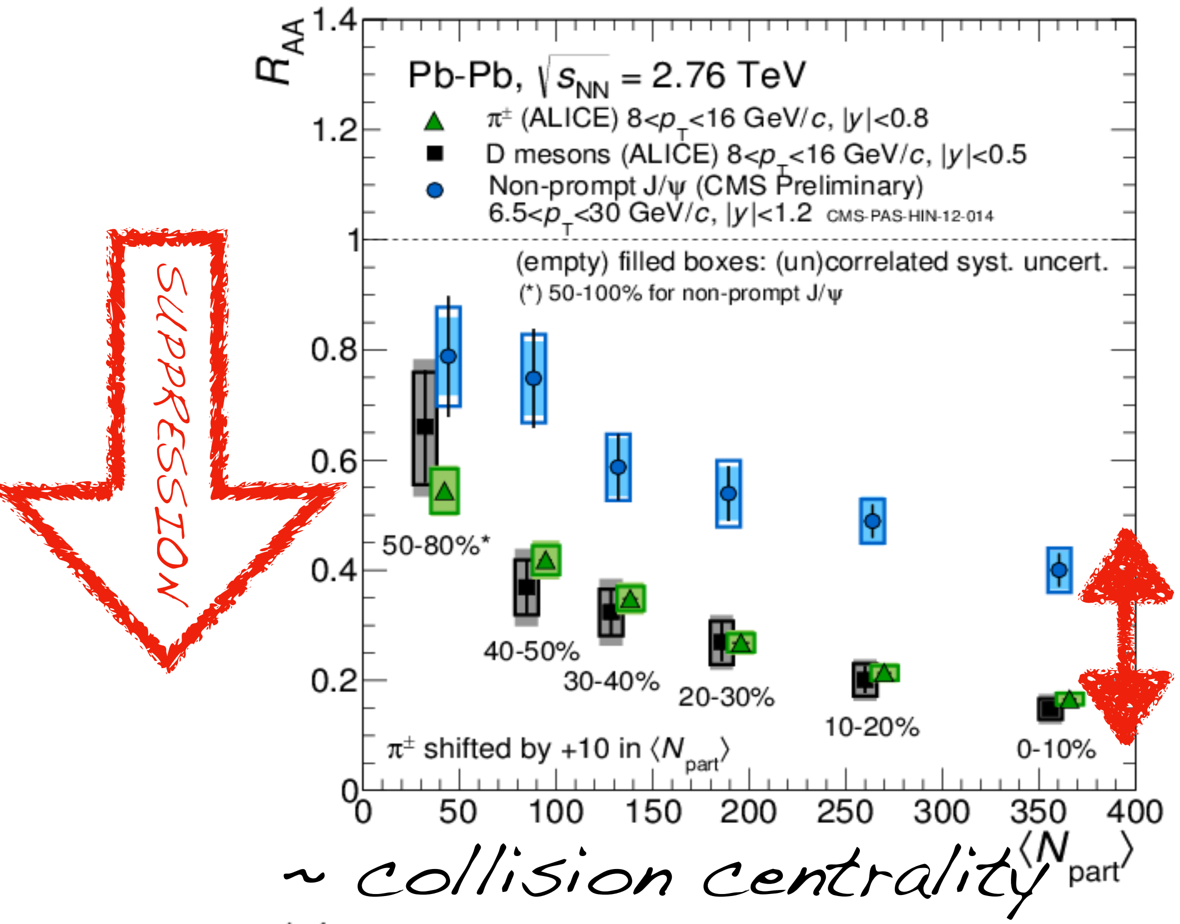
Open charm and HF-electrons suppressed (RAA<<1)

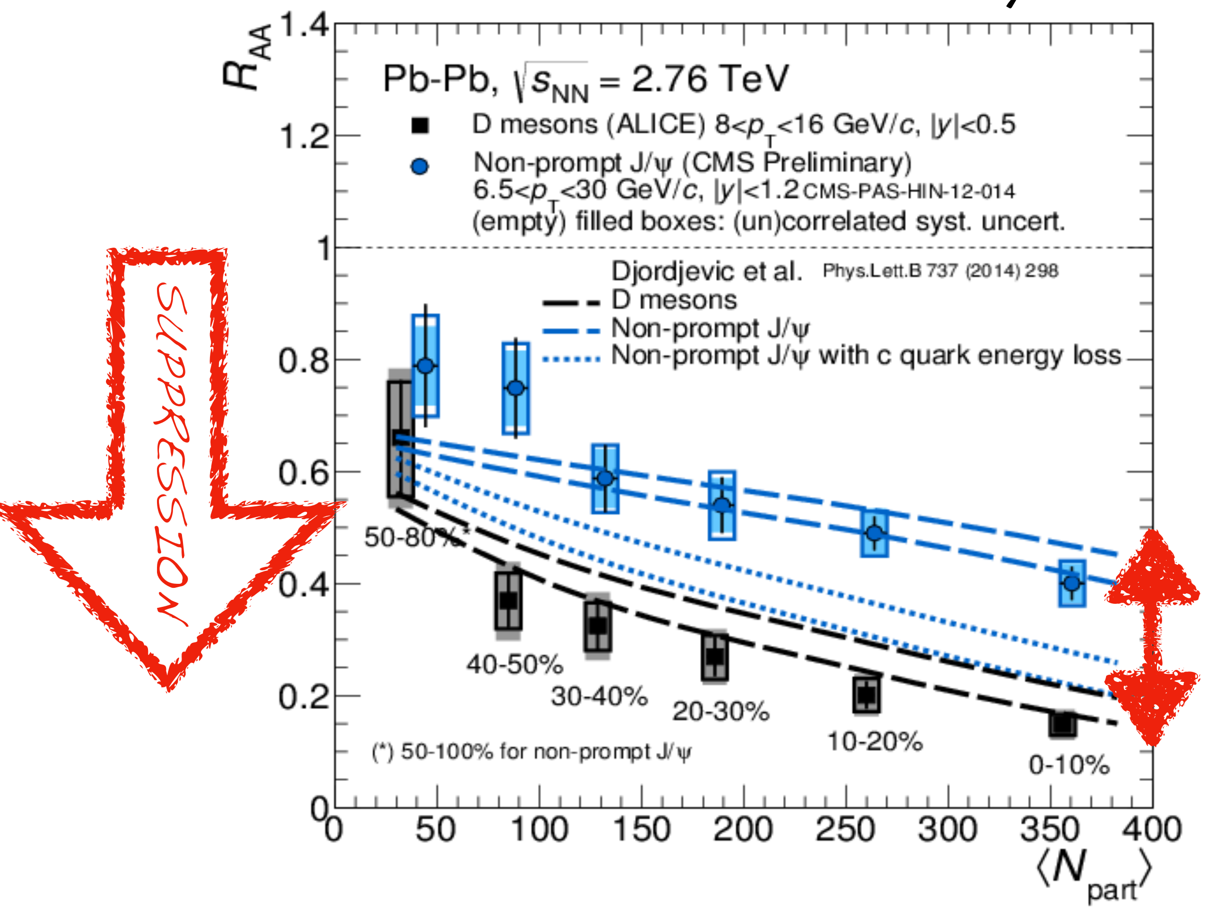
Number of models explain the data qualitatively - need for better precision in data

Energy loss for charm similar to light flavor? Caveat: gluon splitting within parton shower

Some indication for parton mass dependent in-medium energy loss (relatively low-pT electrons [yet b-dominated] compared to pion R_{AA}) - also see next slide...

Heavy-flavor suppression in QGP



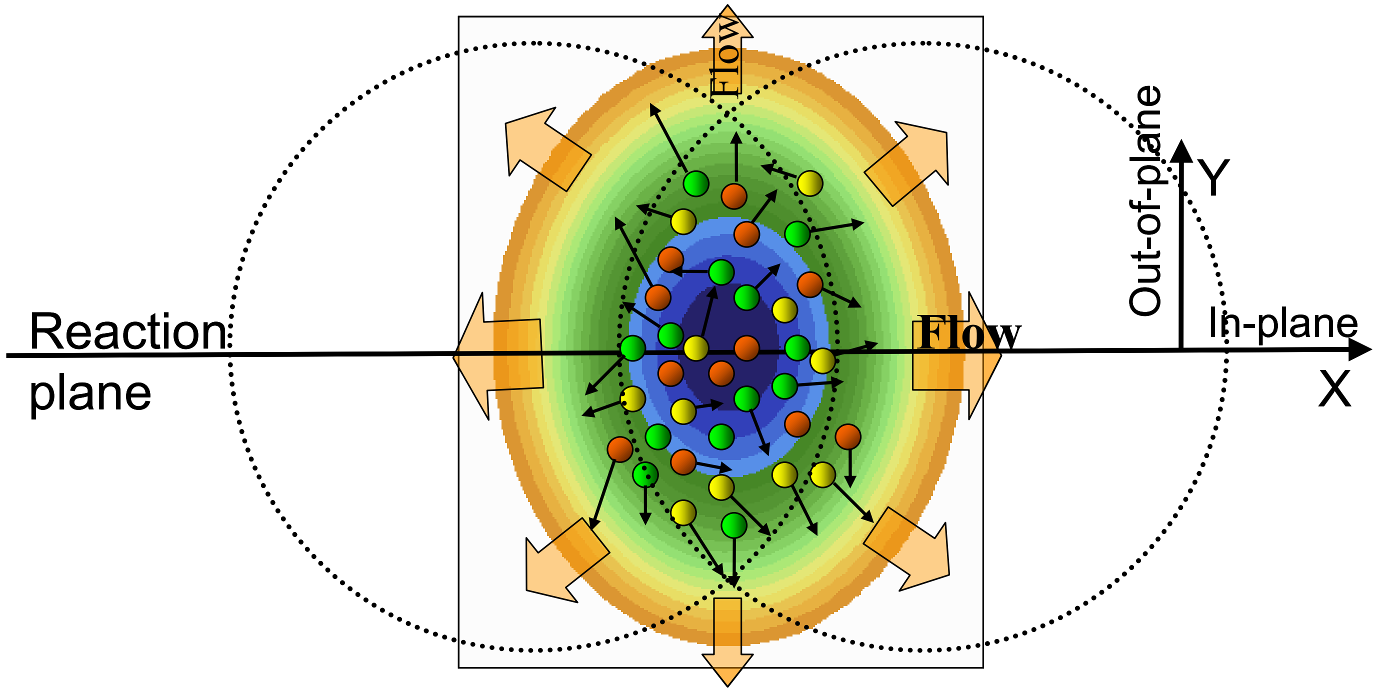


Integrated (p_T)
$R_{AA} << 1$

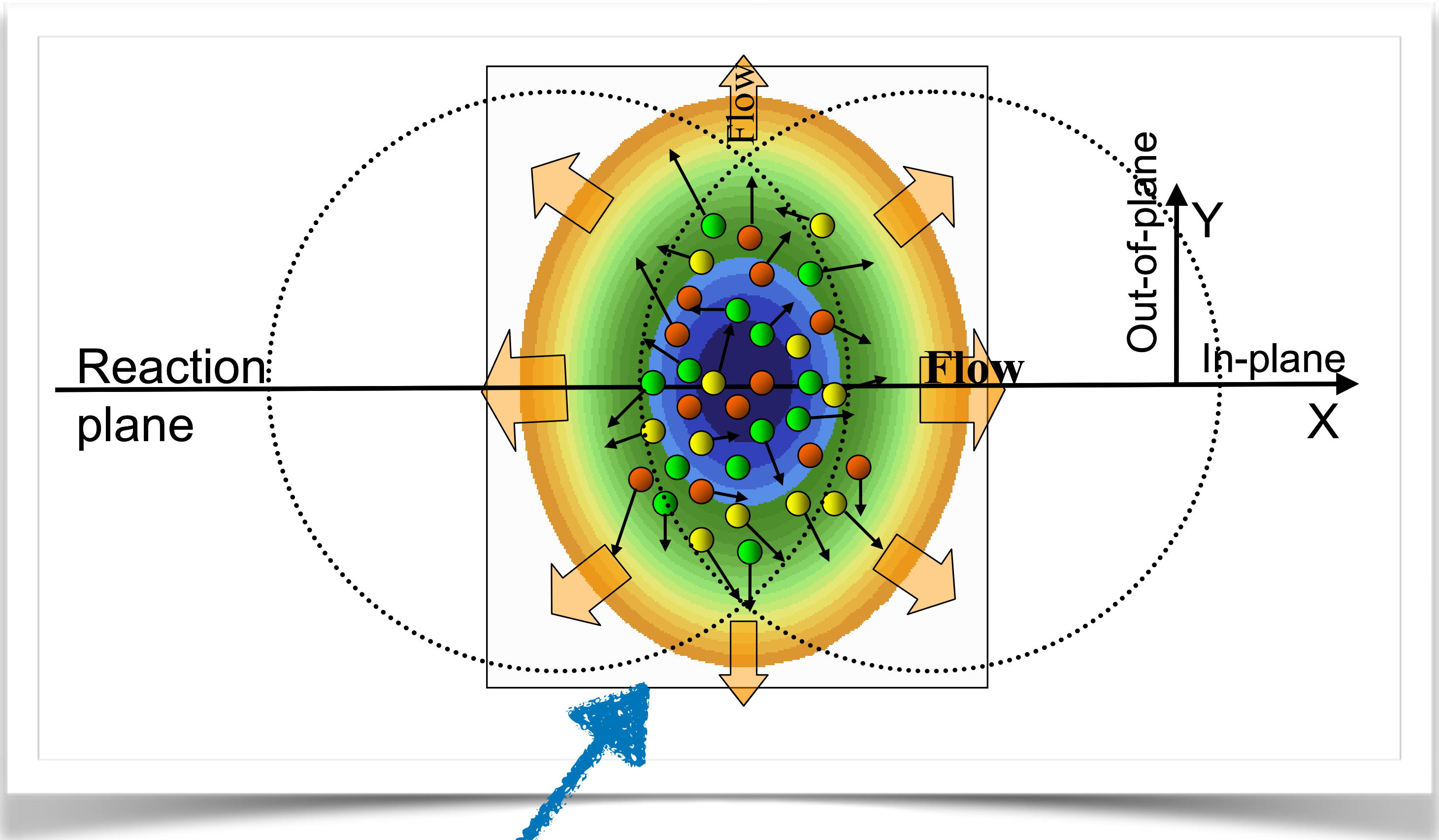
Comparison of prompt D-mesons (charm) with non-prompt J/ψ (proxy for beauty) consistent with mass dependent in-medium energy loss

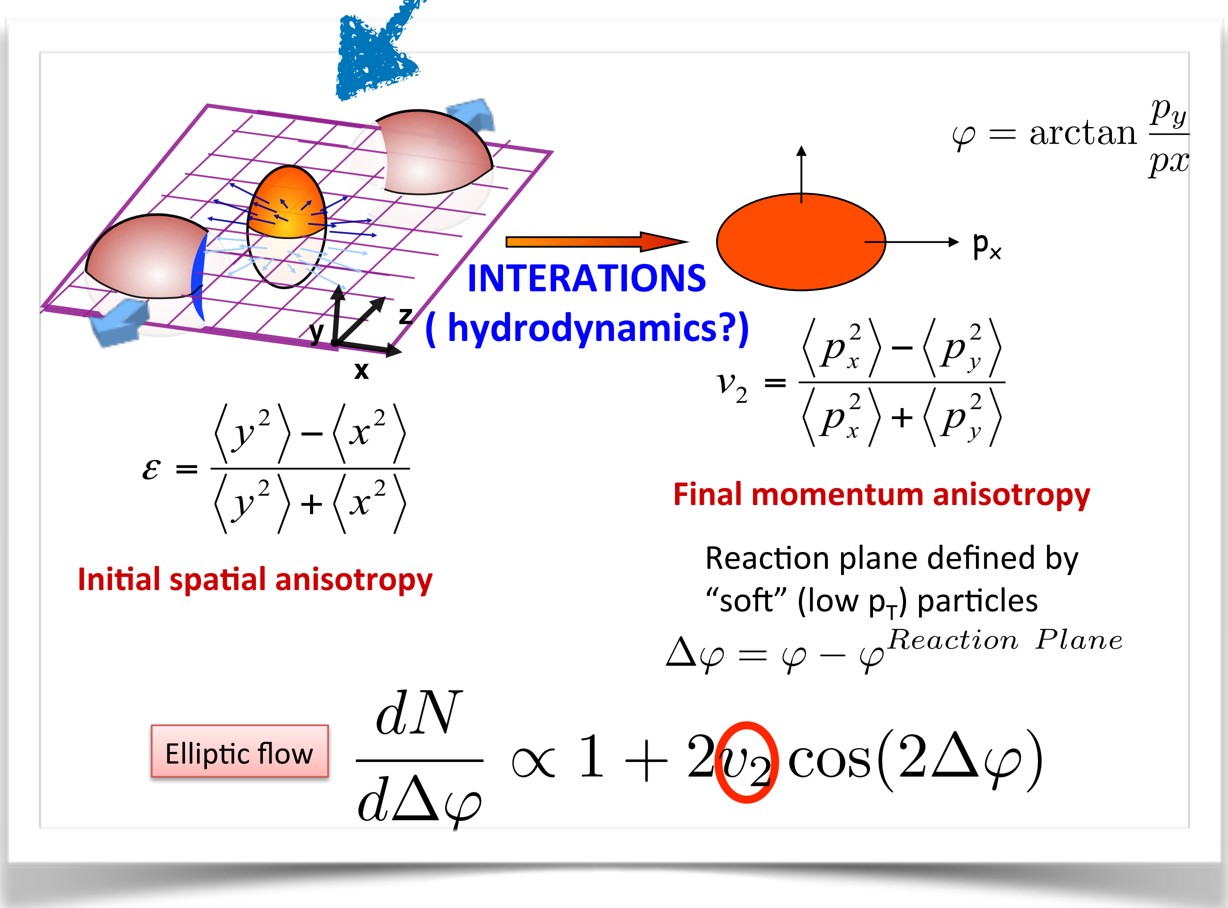
Heavy-flavor - azimuthal anisotropy

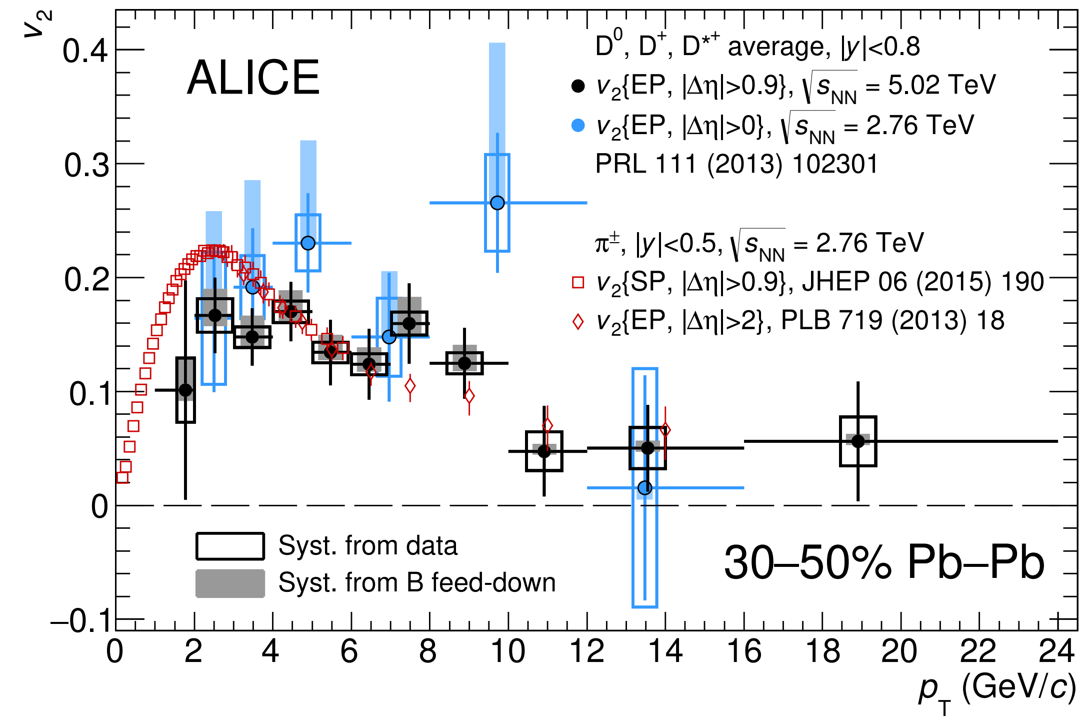
- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
  - Transported through the full system evolution

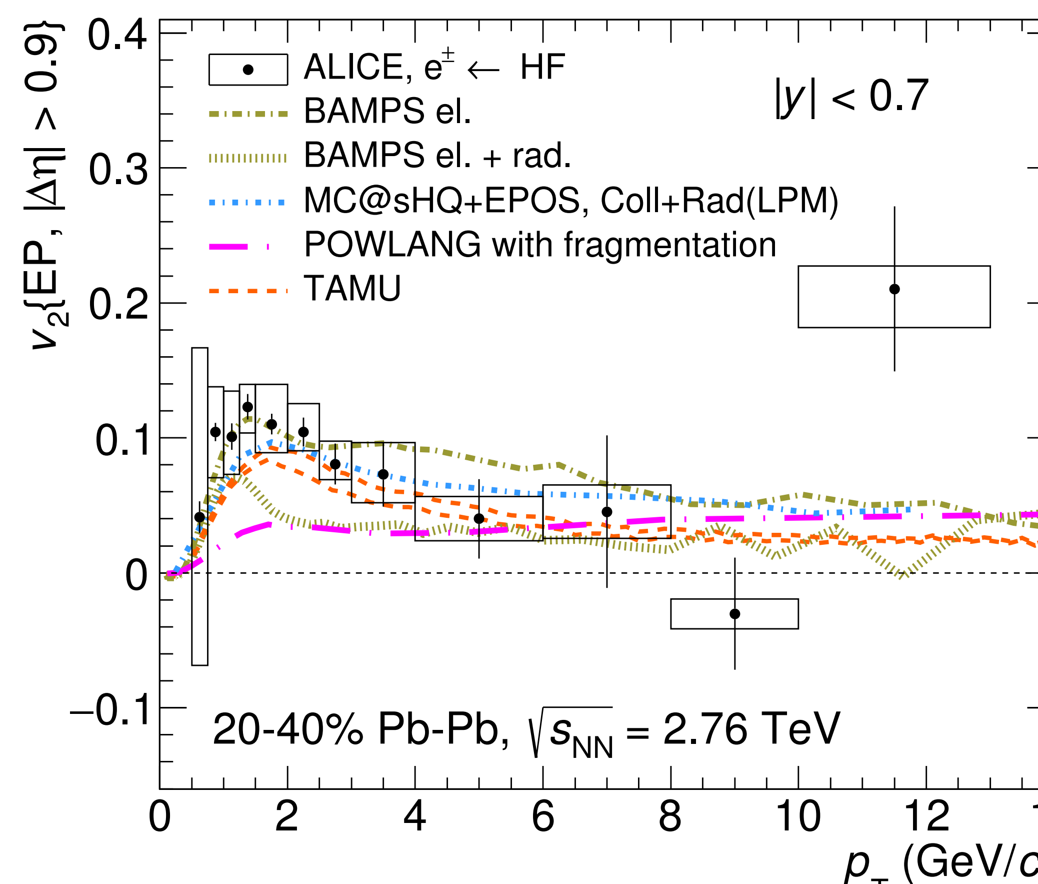


Heavy-flavor flows with the medium

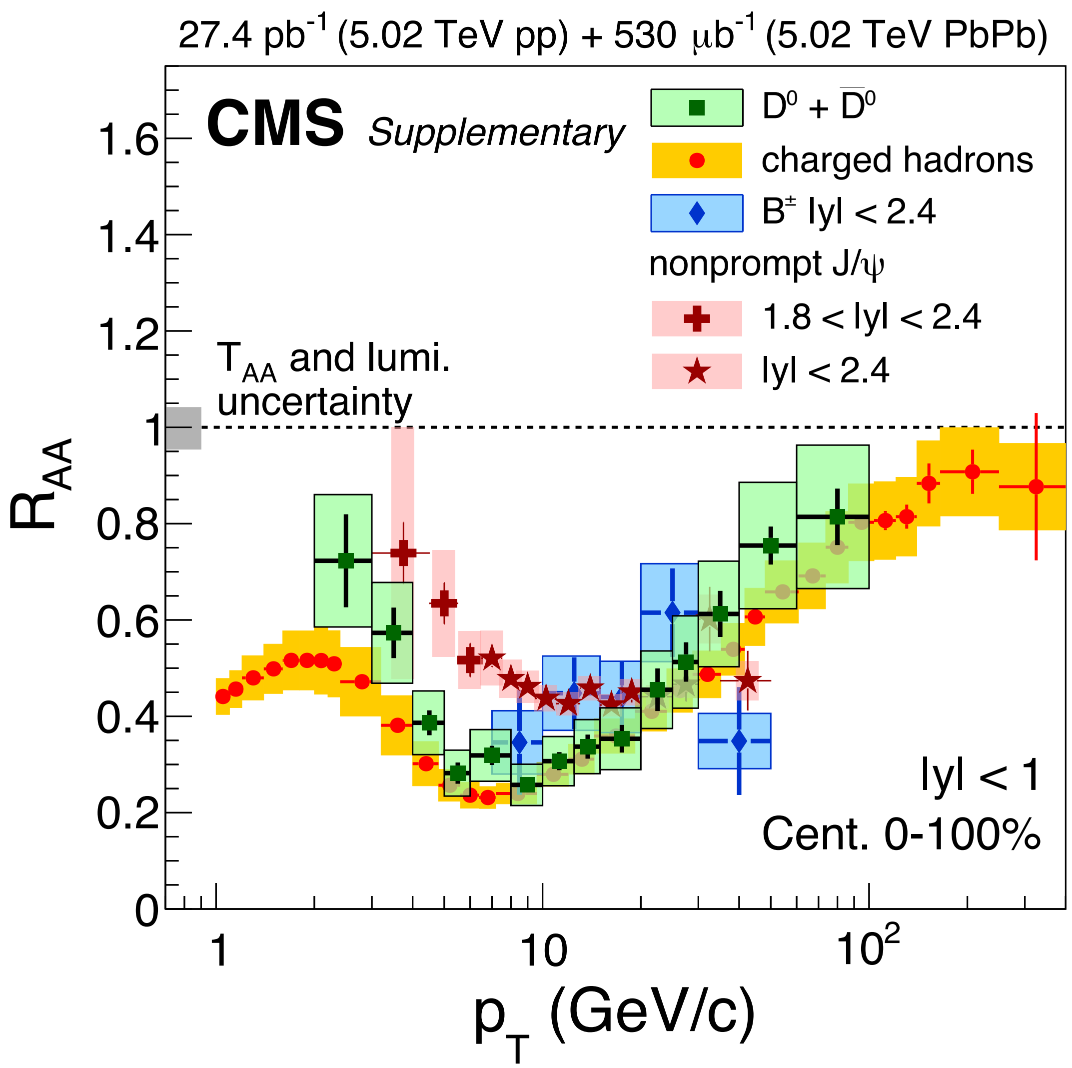


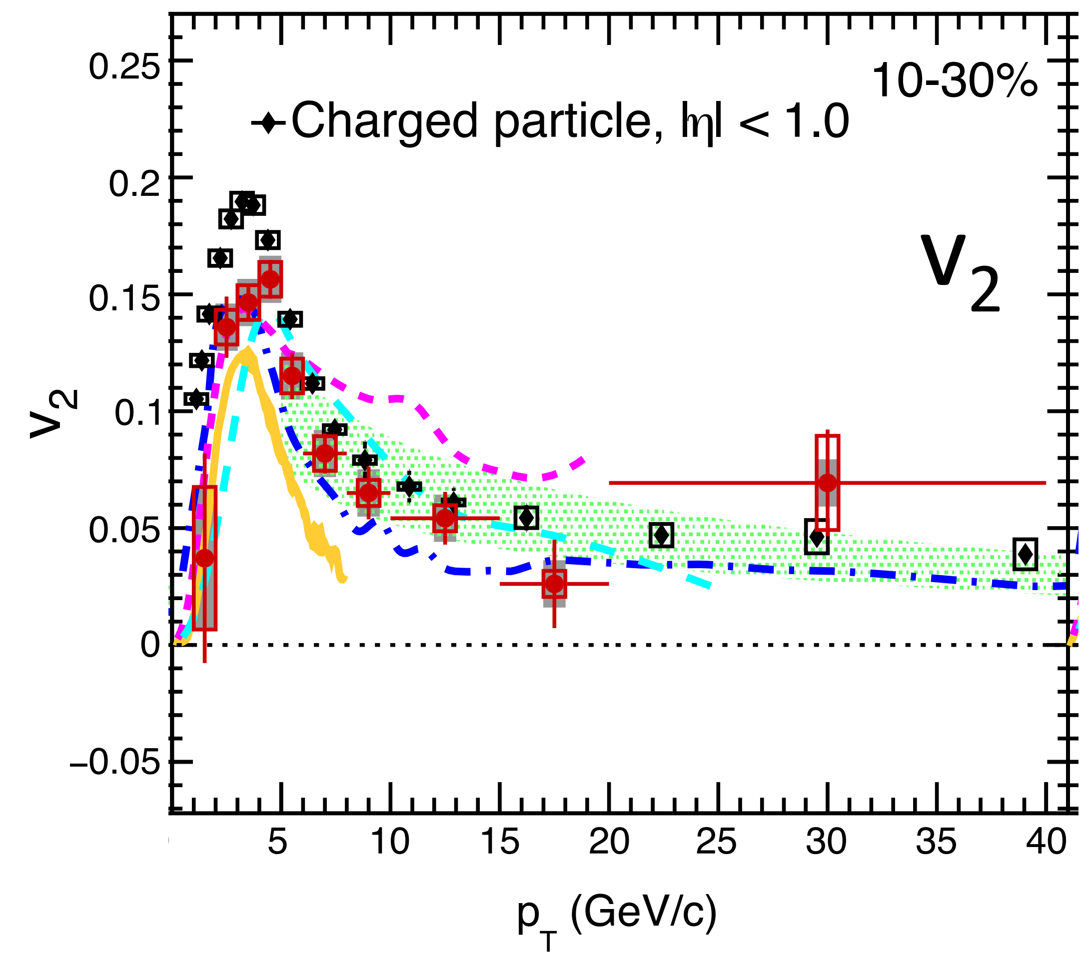






Case study: HF sensitivity to the in-medium energy loss





Two regions (a qualitative selection) - light vs. heavy(charm)-flavor

Lower p_T : below 5 GeV (parton energy ~ 10 GeV?) => different v_2 & different R_{AA} (coll. E-loss)

Higher p_T : above 5 GeV (parton energy > 10 GeV) => similar R_{AA} => radiative E-loss

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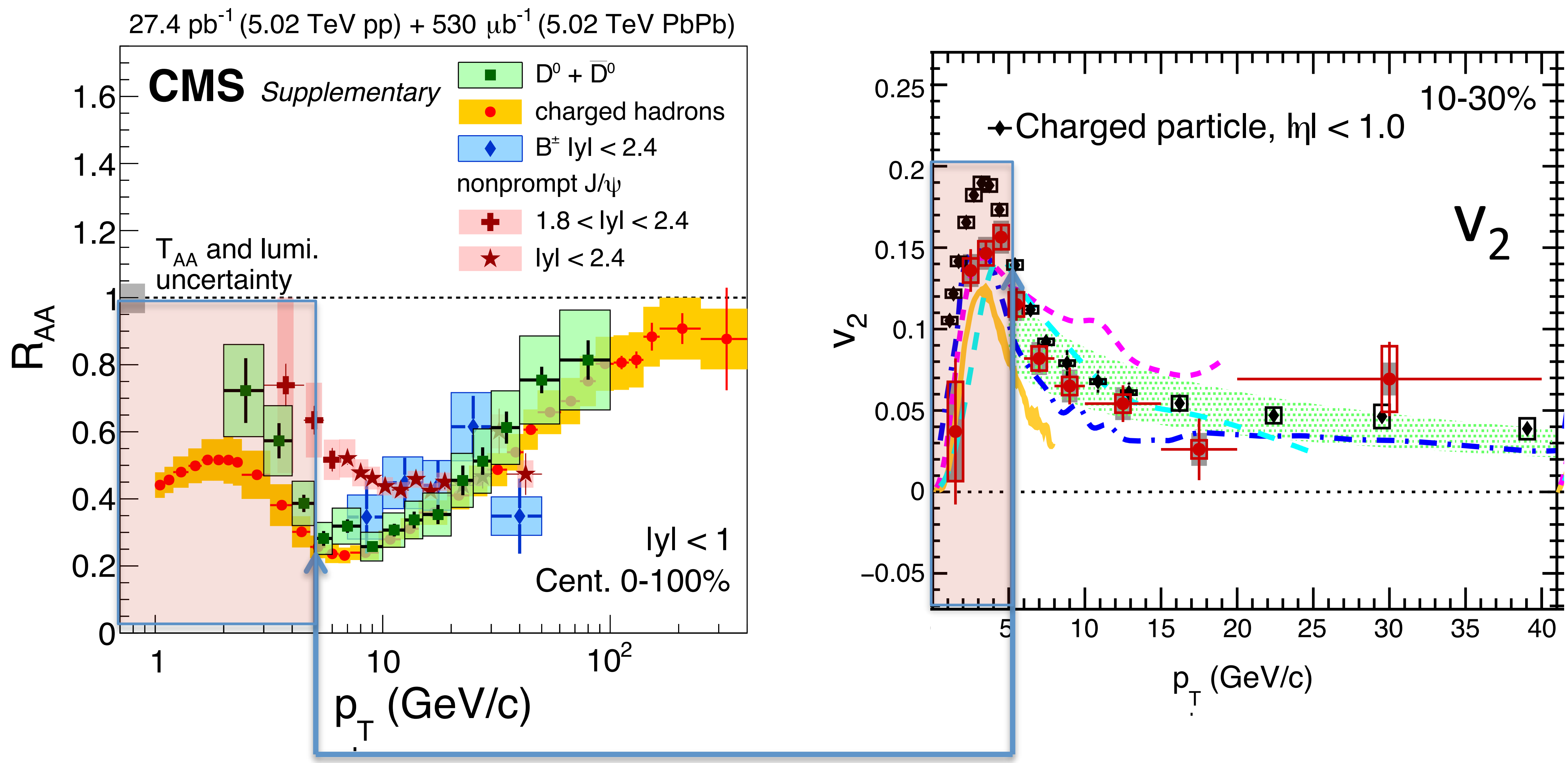

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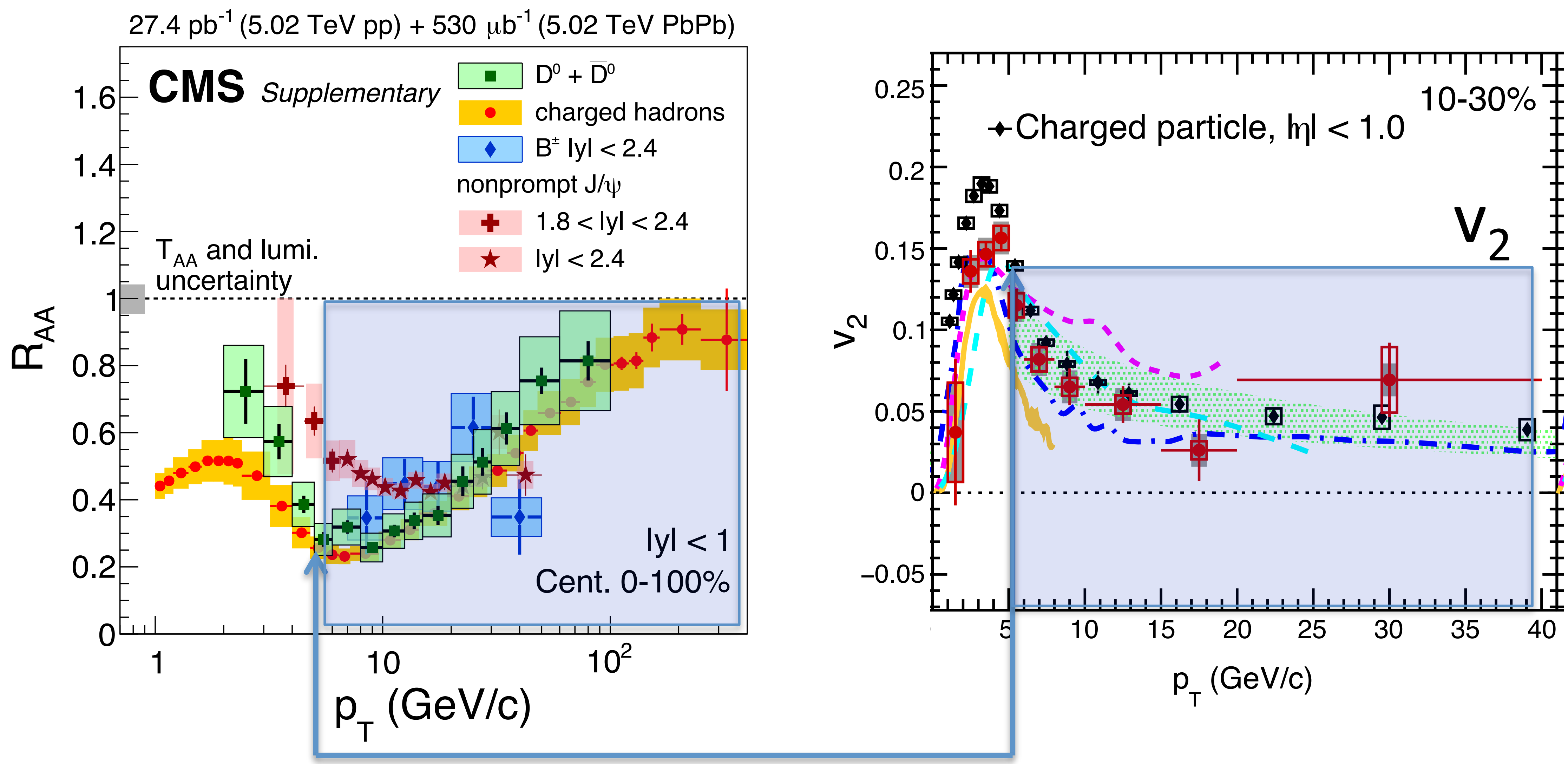

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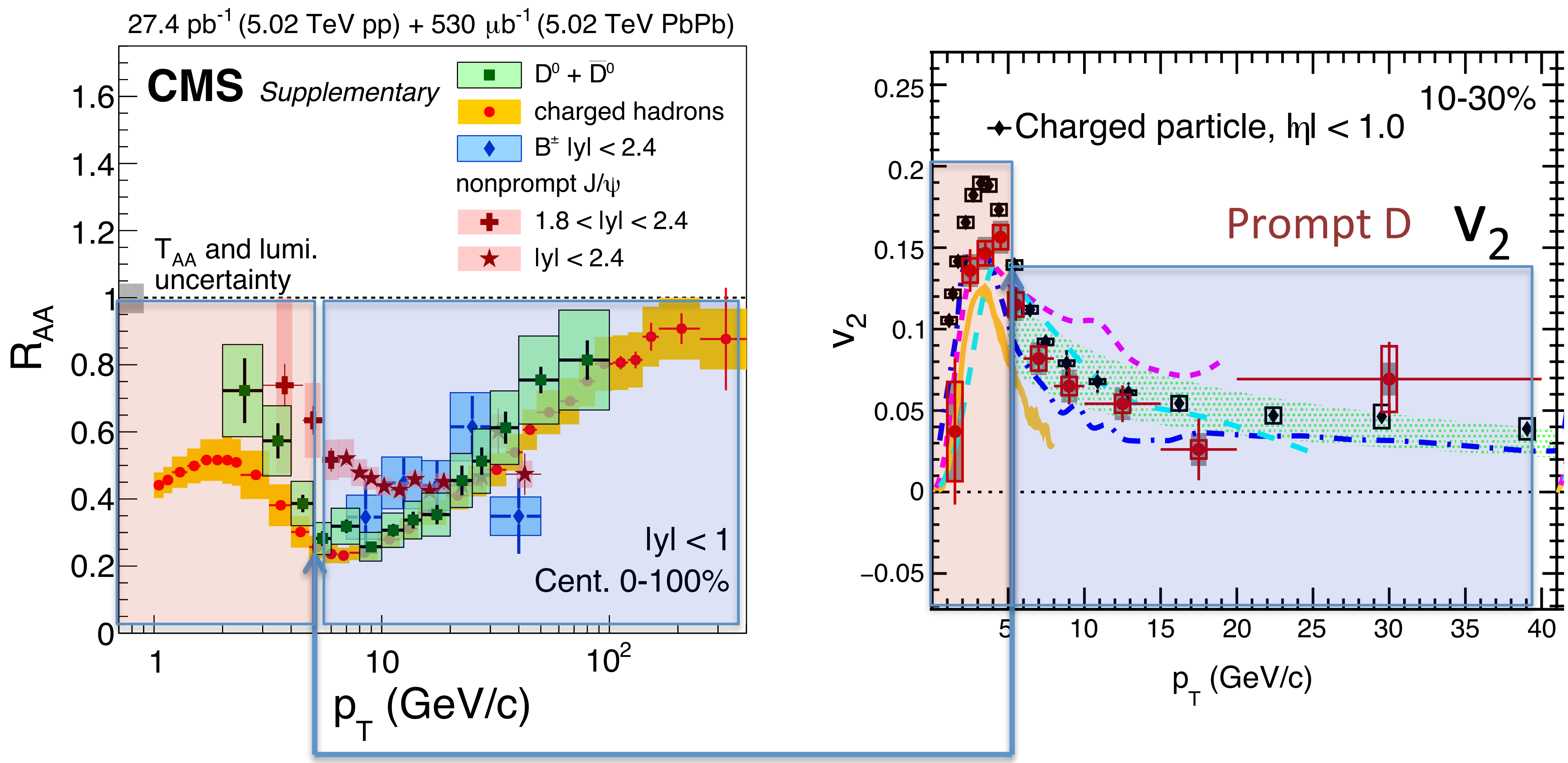

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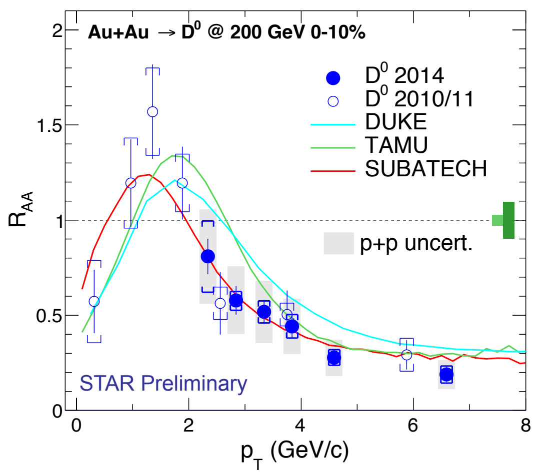
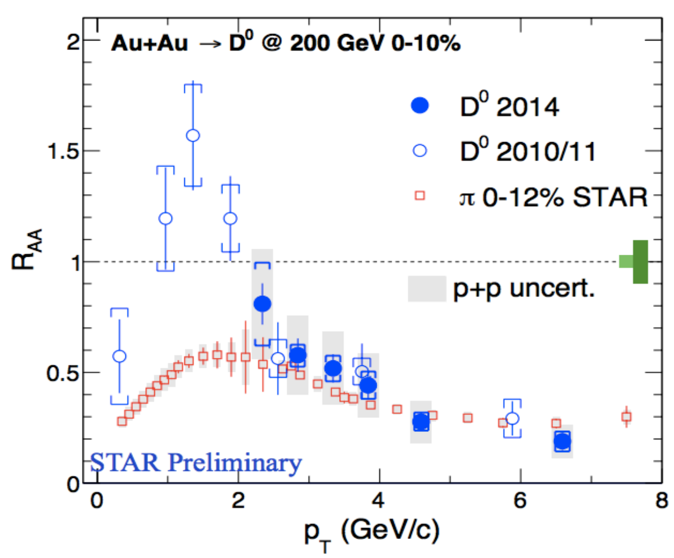
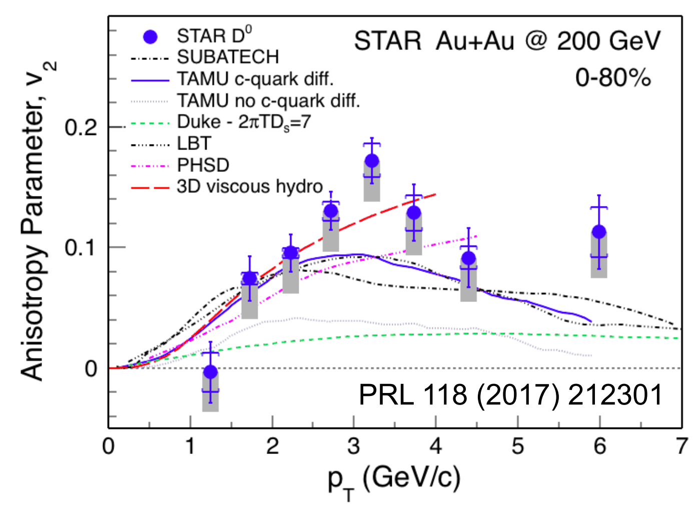
HF results from RHIC

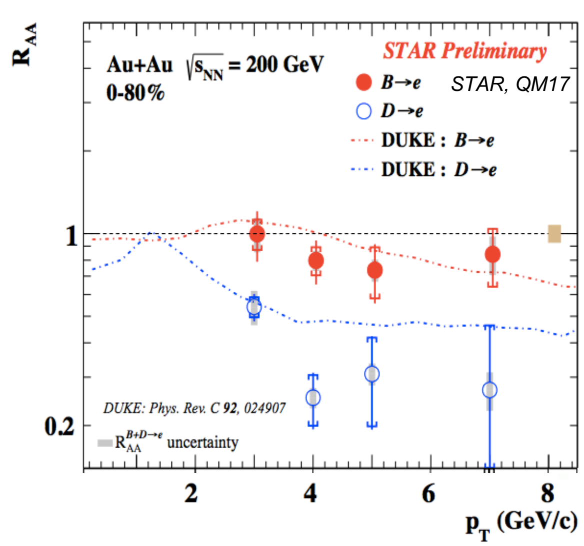


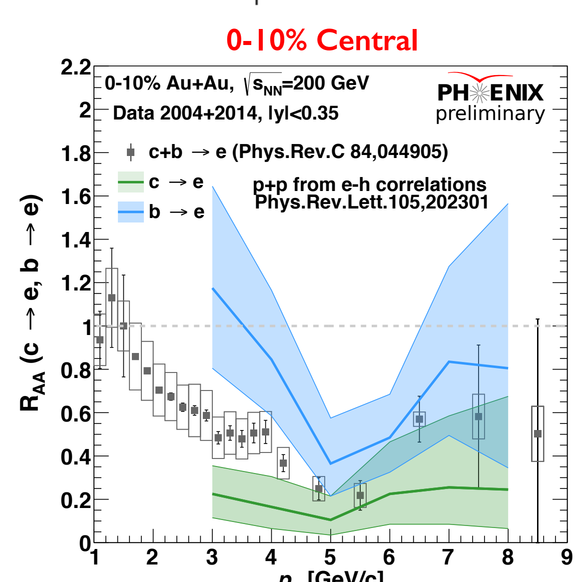
Despite vastly different centrality selections – a similar picture at RHIC:
R_{AA} of D at high-p_T similar to light-hadrons
D flows within the medium (similar to strange-hadrons) – mass scaling





Spatial diffusion within QGP needed to describe the data





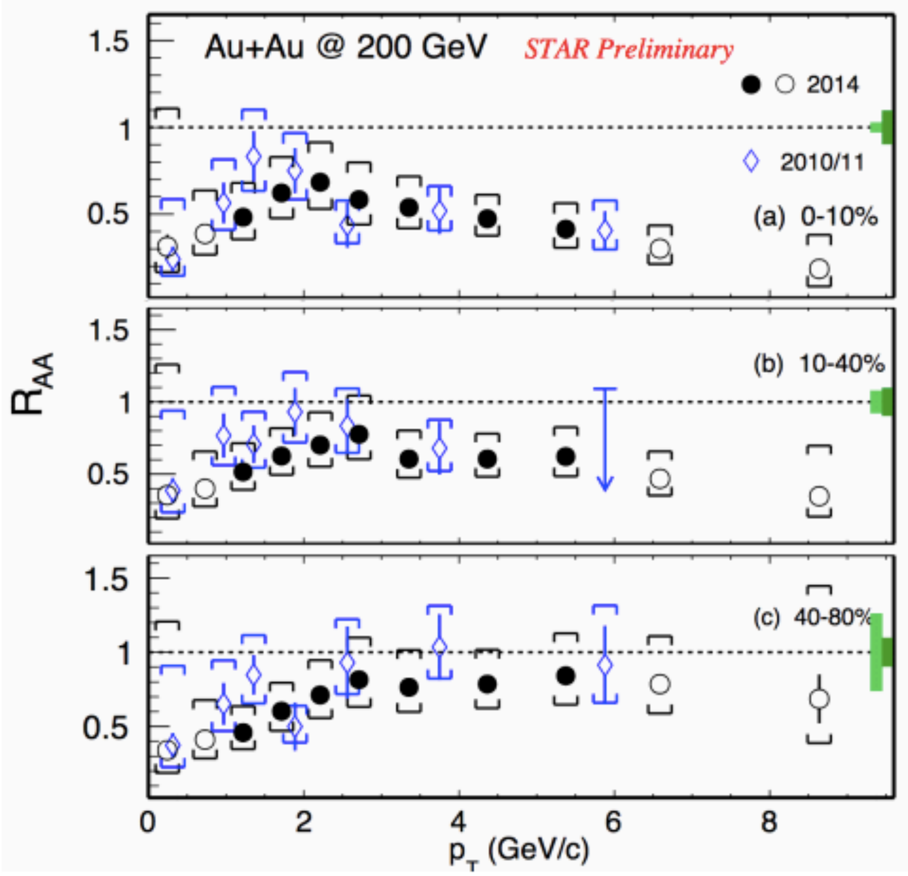
Electrons from B-hadrons => beauty less suppressed than charm (low-pT < 5)

- **Needs better precision(!)**

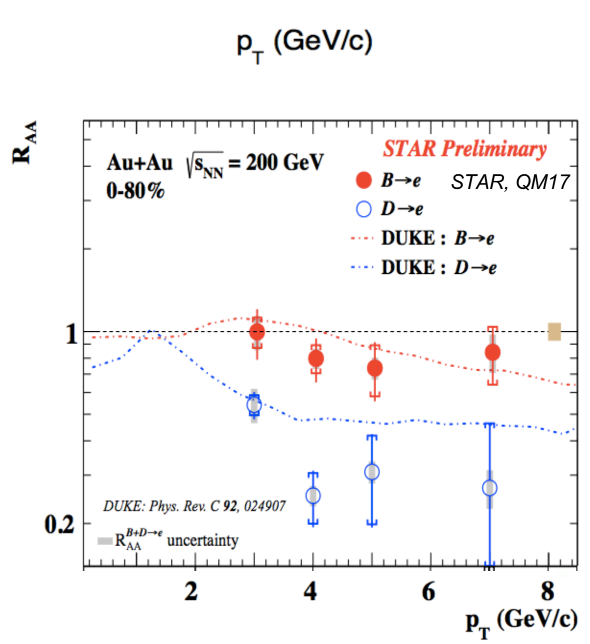
…more measurements: non-prompt J/y; di-leptons

HF results from RHIC

New D meson RAA



Updated results: R_{AA} < 1 at all p_T



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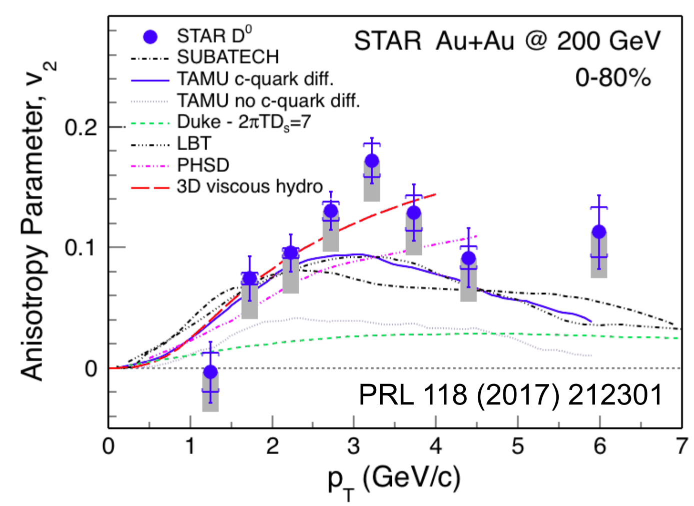
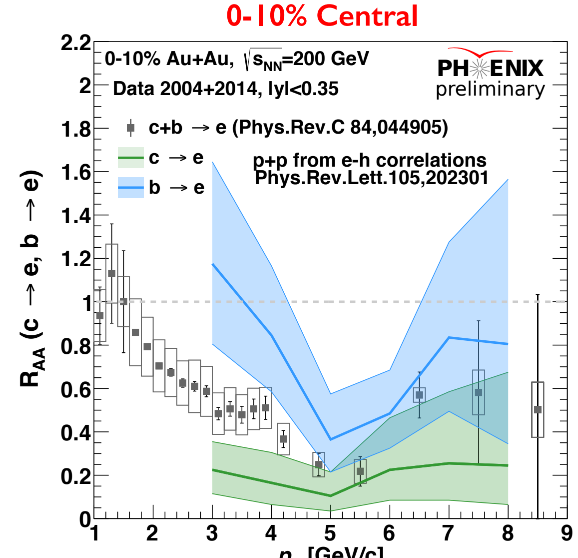


Spatial diffusion within QGP needed to describe the data

0-10% Central



Electrons from B-hadrons => beauty less suppressed than charm (low-pT < 5)

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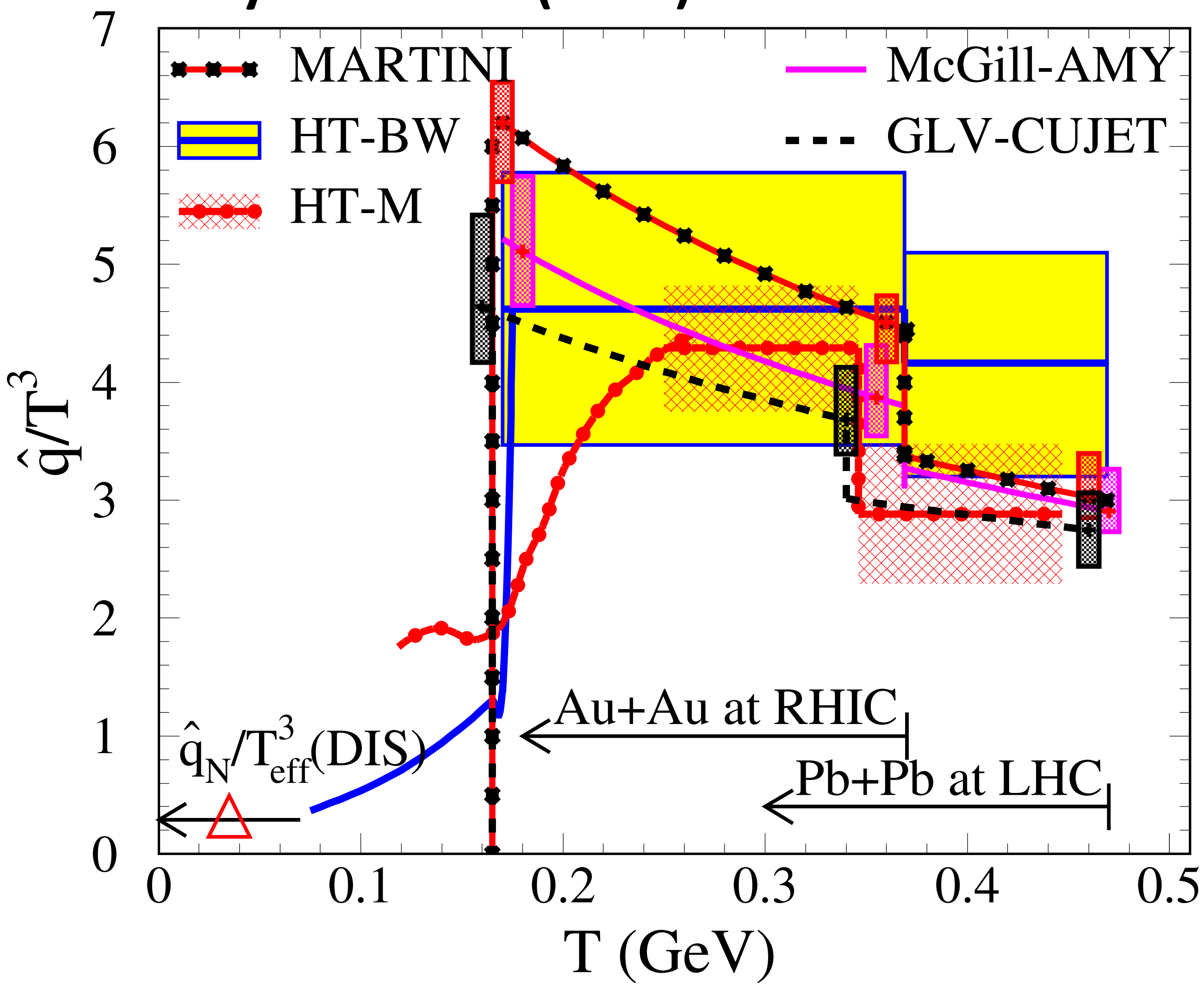
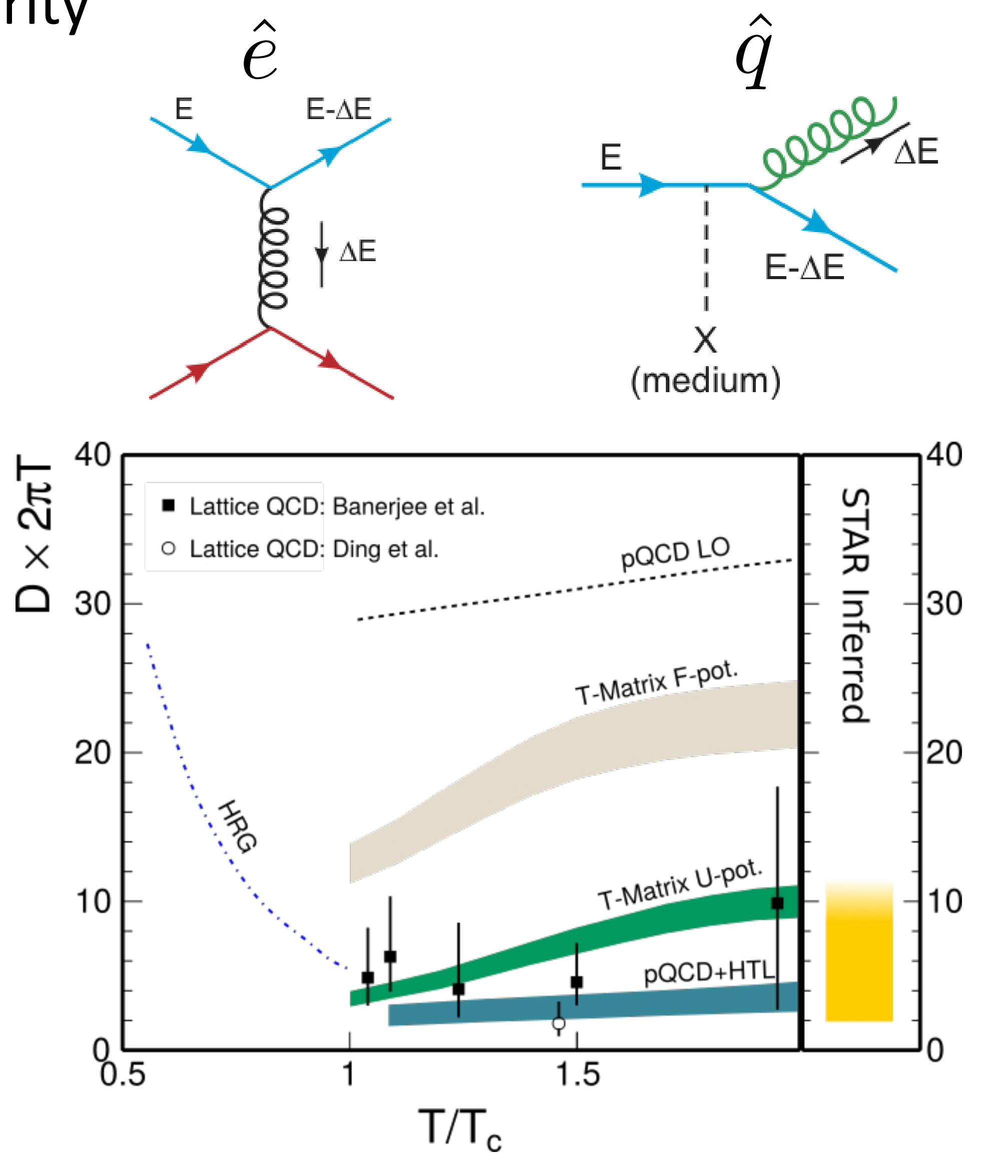
…more measurements: non-prompt J/y; di-leptons

Transverse & longitudinal diffusion
- consistent picture
- temperature and/or density dependence?

RHIC ⇔ LHC complementarity

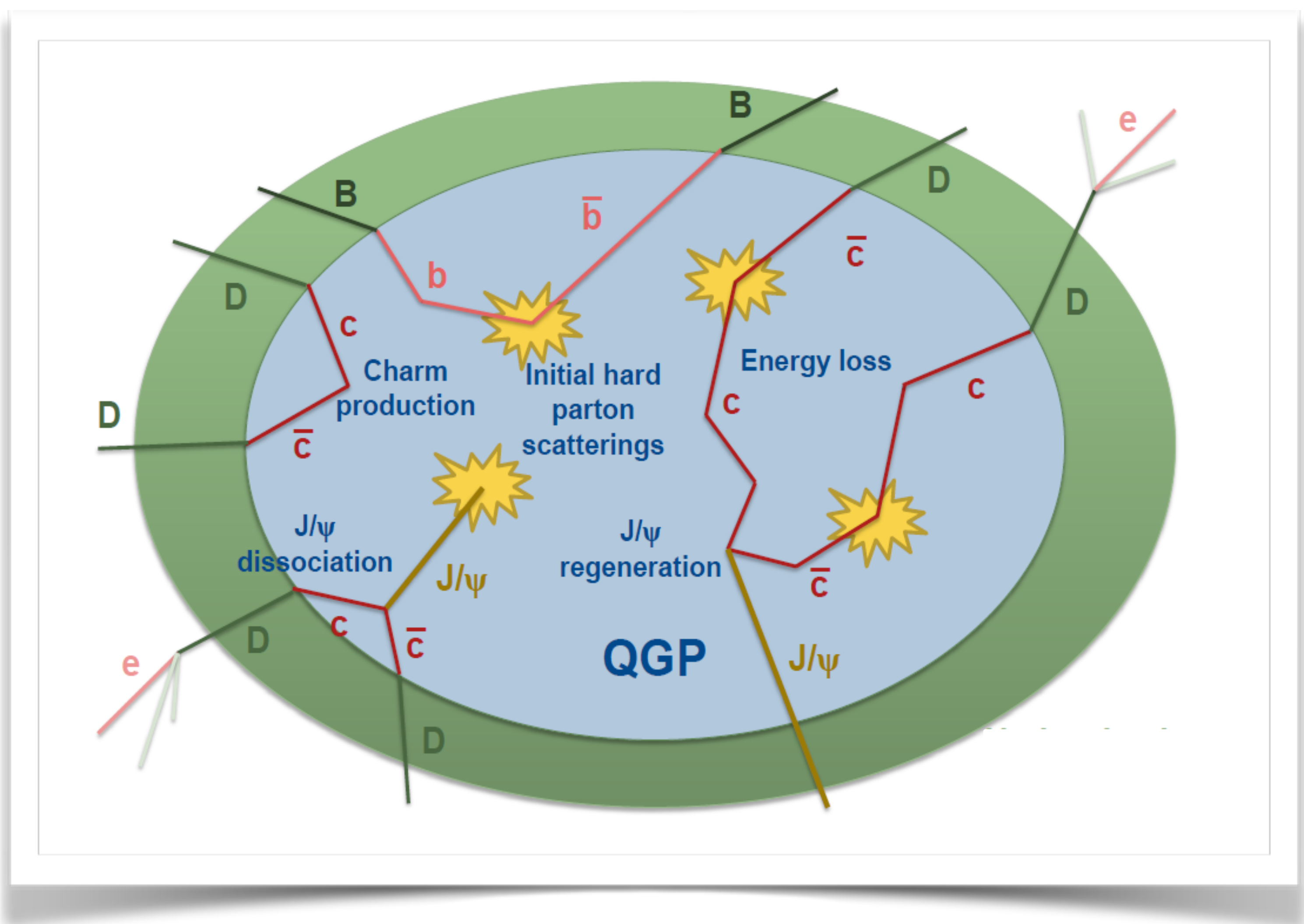
Phys.Rev. C90 (2014) 014909





Work in progress: complete parton shower in-(dynamic) medium evolution; inclusion of heavy-quarks (theory community - JETSCAPE Collaboration for example)

Quarkonia: q-qbar in medium

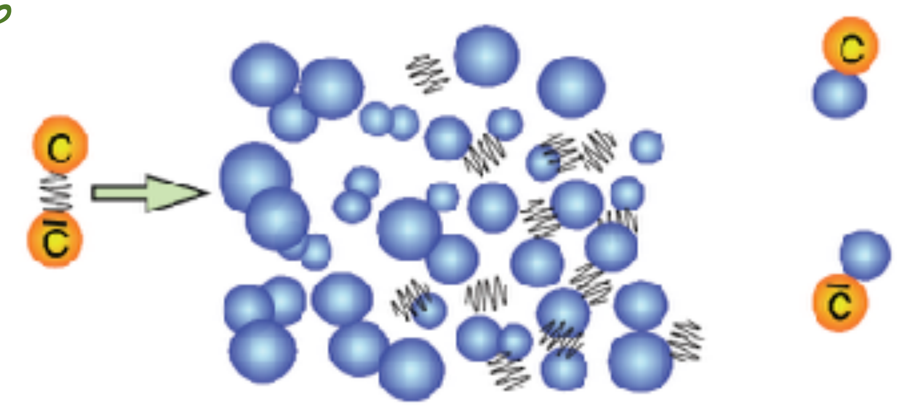


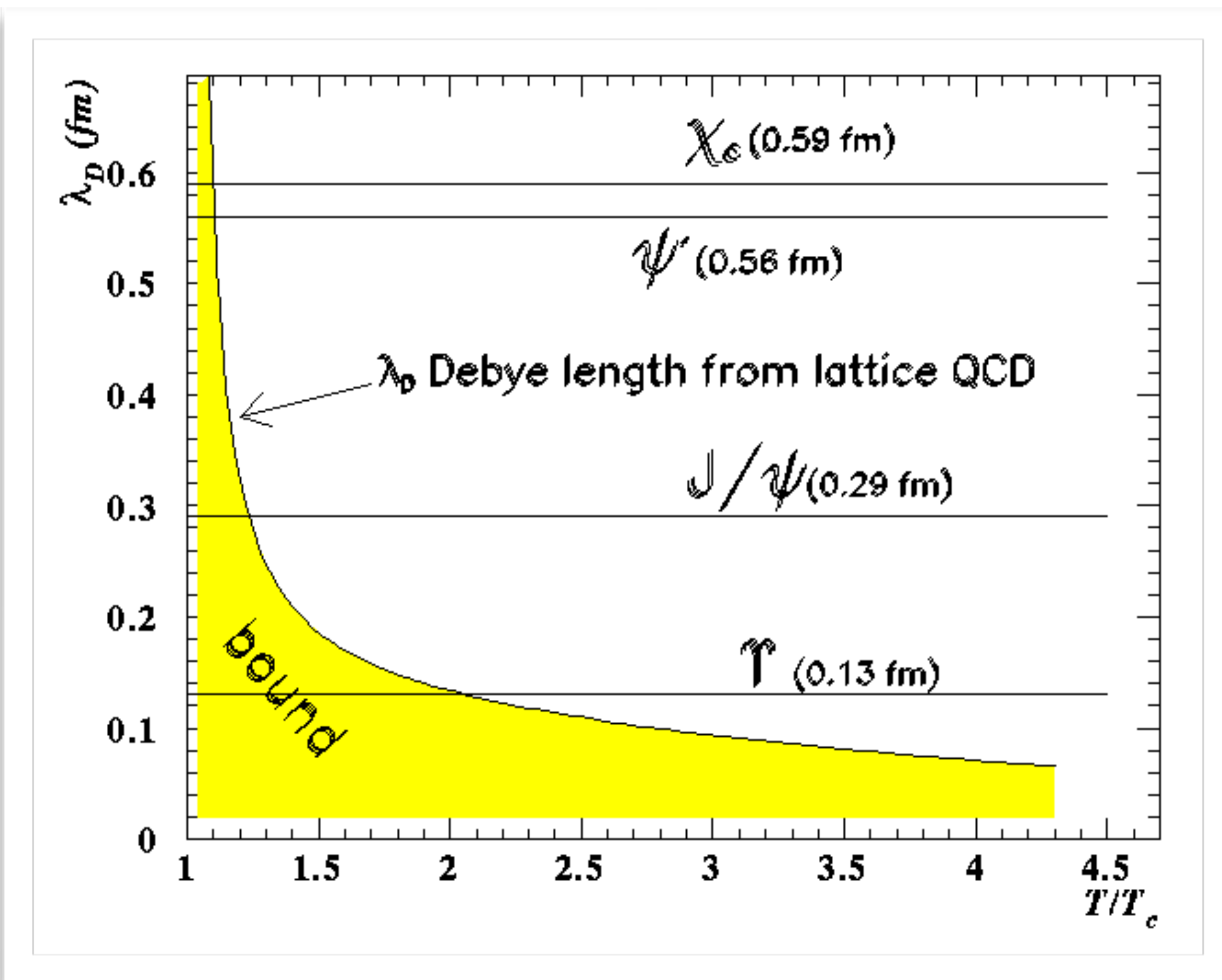
Charmonium suppression

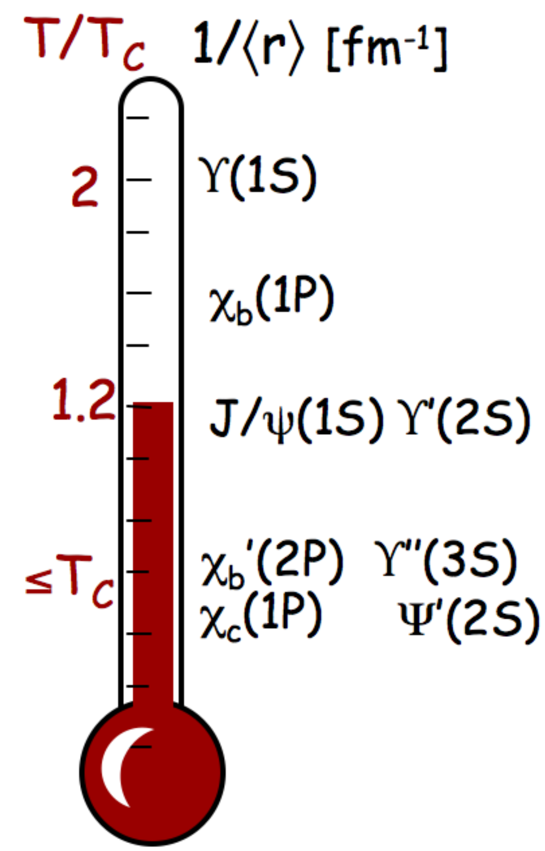
QGP signature proposed by Matsui and Satz, 1986

In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):

Charmonium(cc) and bottonium(bb) states with $r > \lambda_D$ will not bind; their production will be suppressed (qqbar states will "melt")

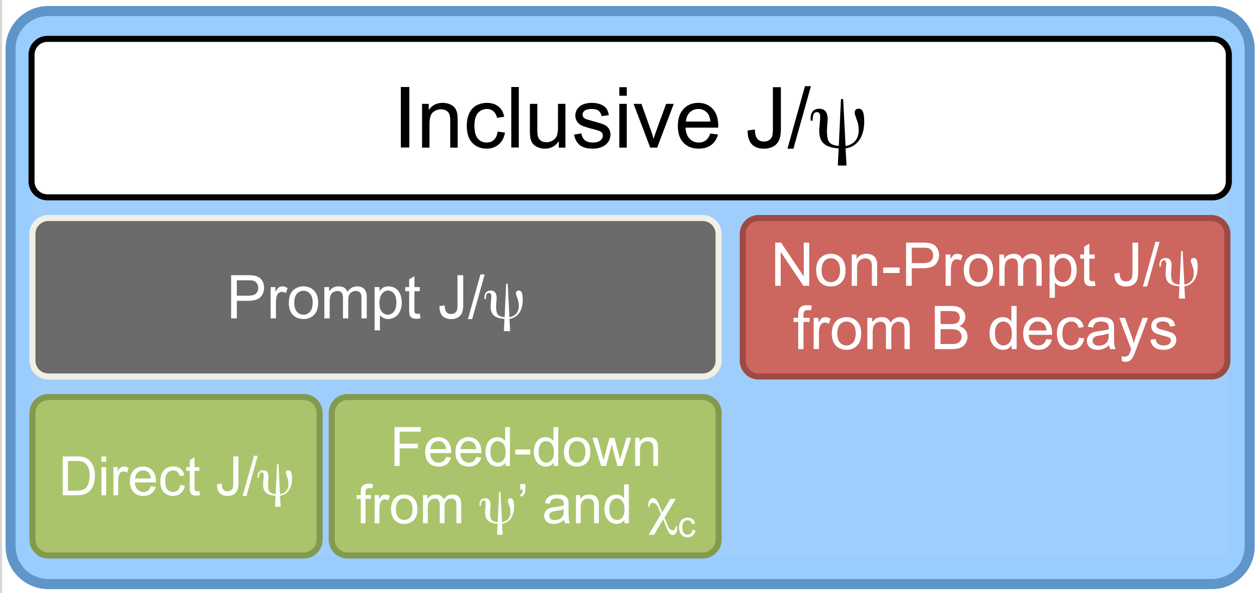






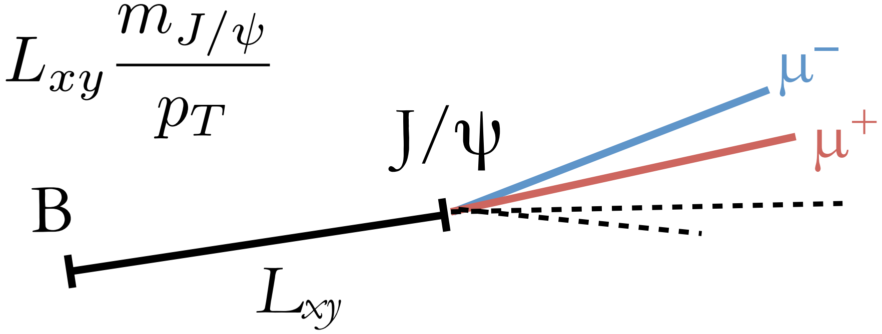
Mocsy, EPJ C 61 (2009) 705

J/ψ in heavy-ion collisions

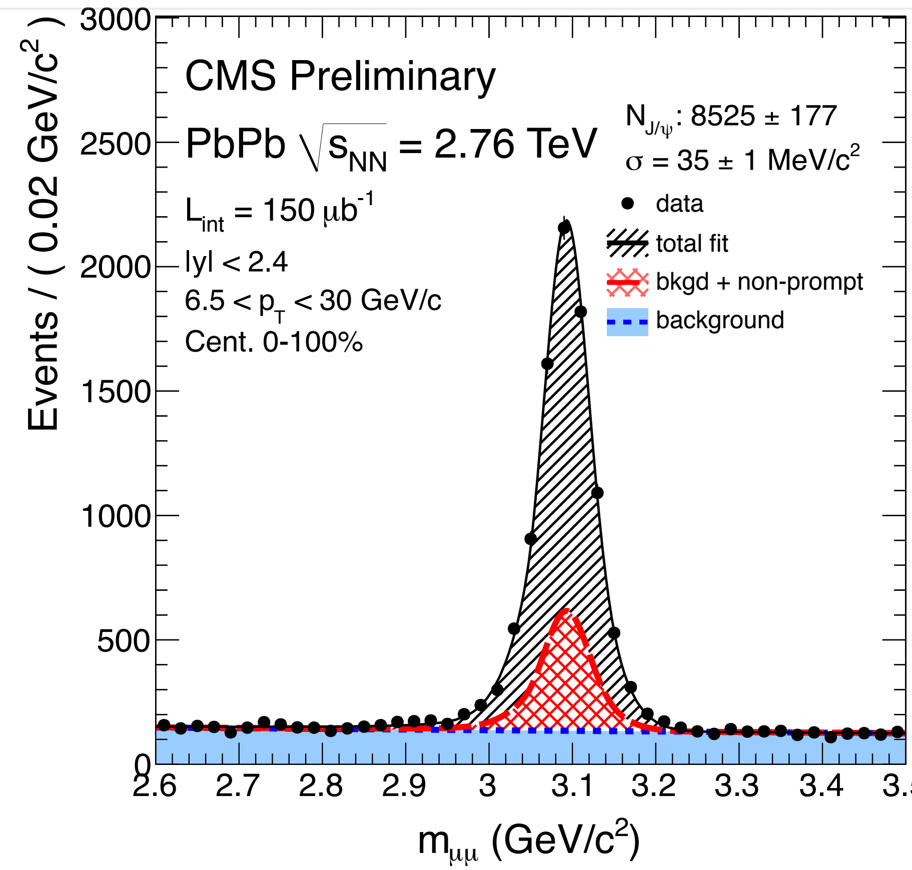


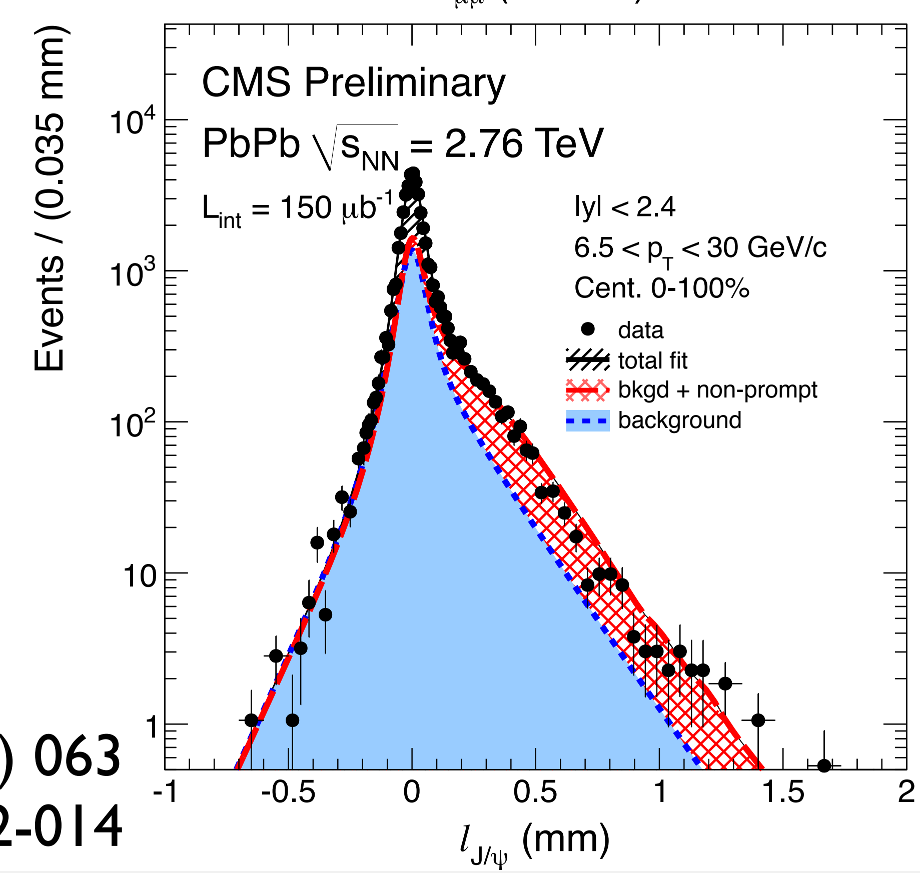
- Non-prompt J/ψ become significant towards higher p_T (20–30%)!
- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



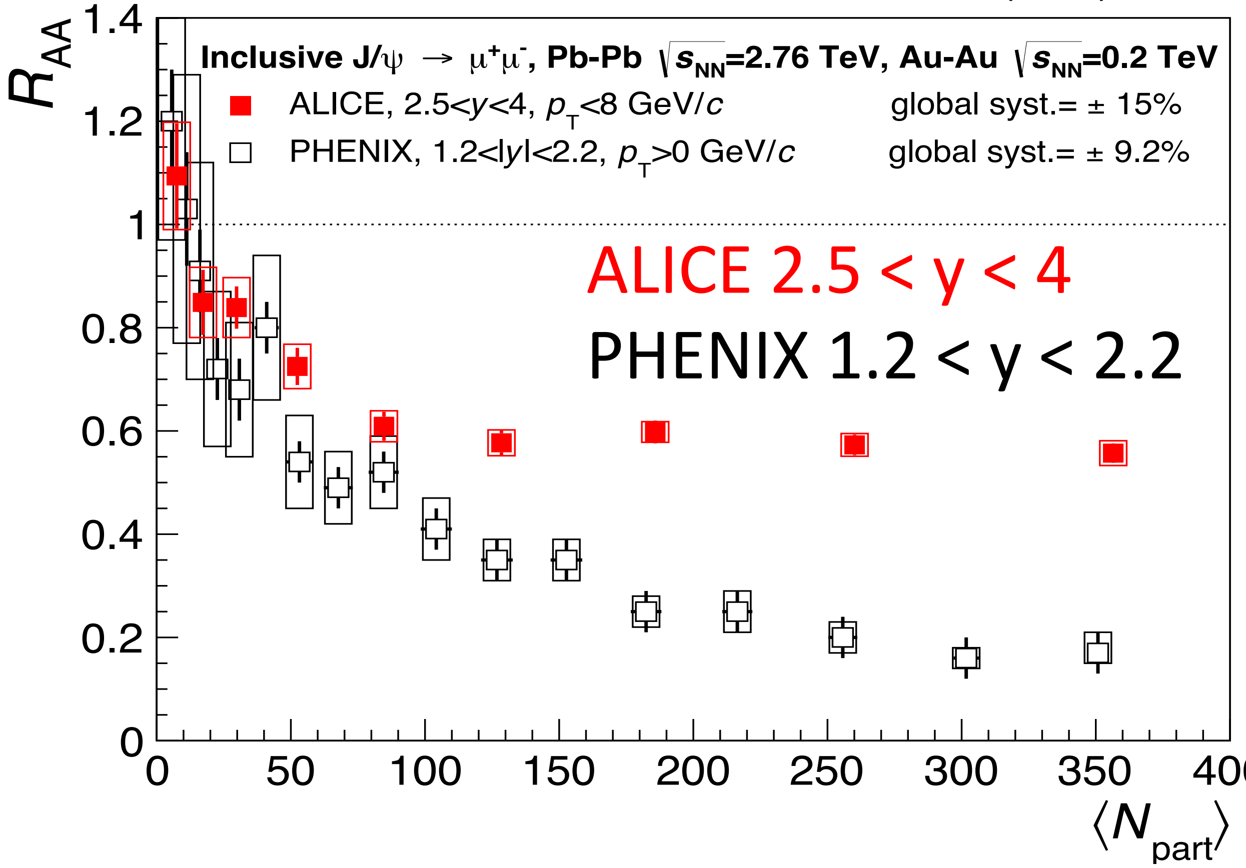
2010 data: JHEP 1205 (2012) 063
2011 data: CMS PAS HIN-12-014

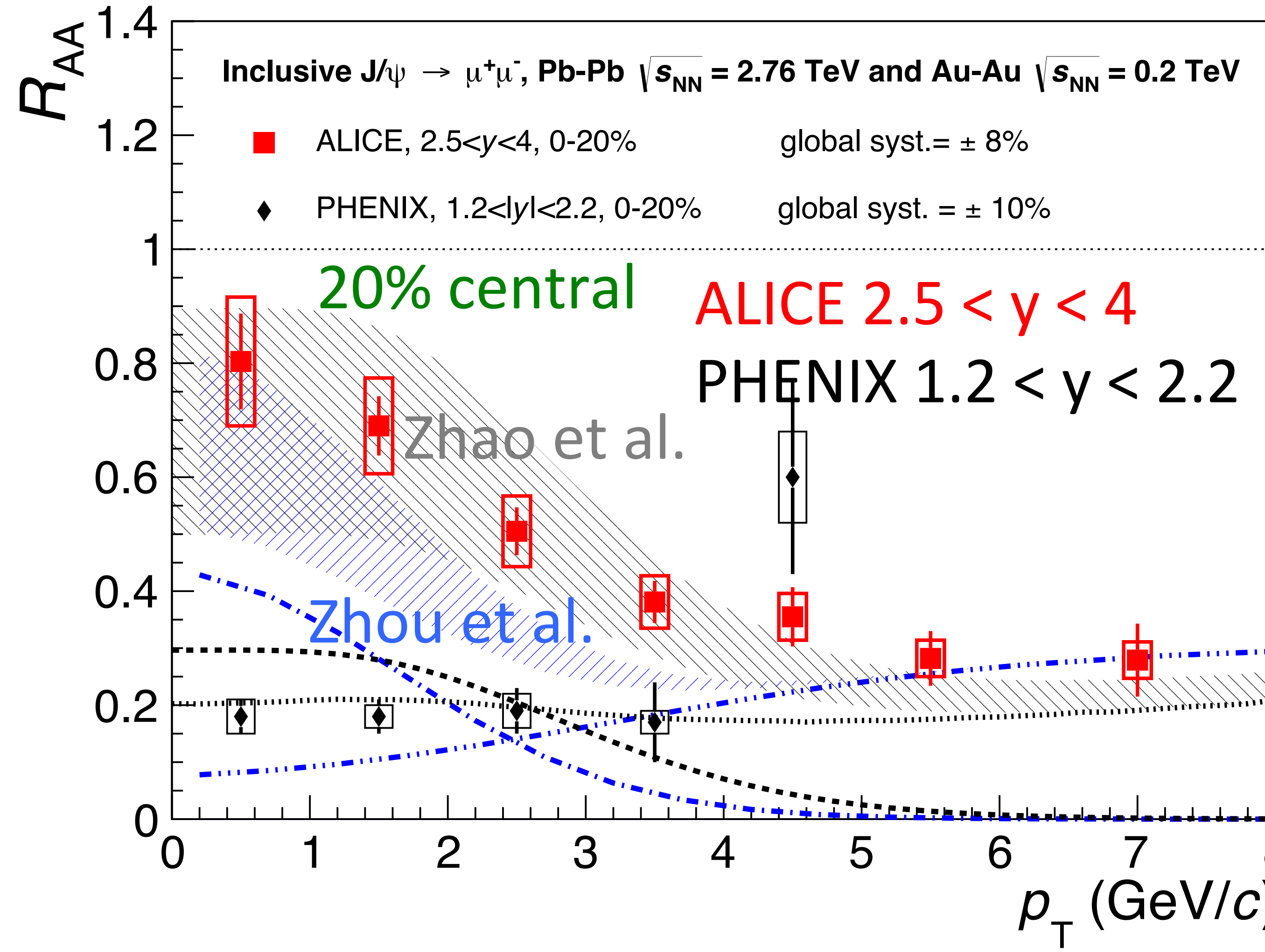


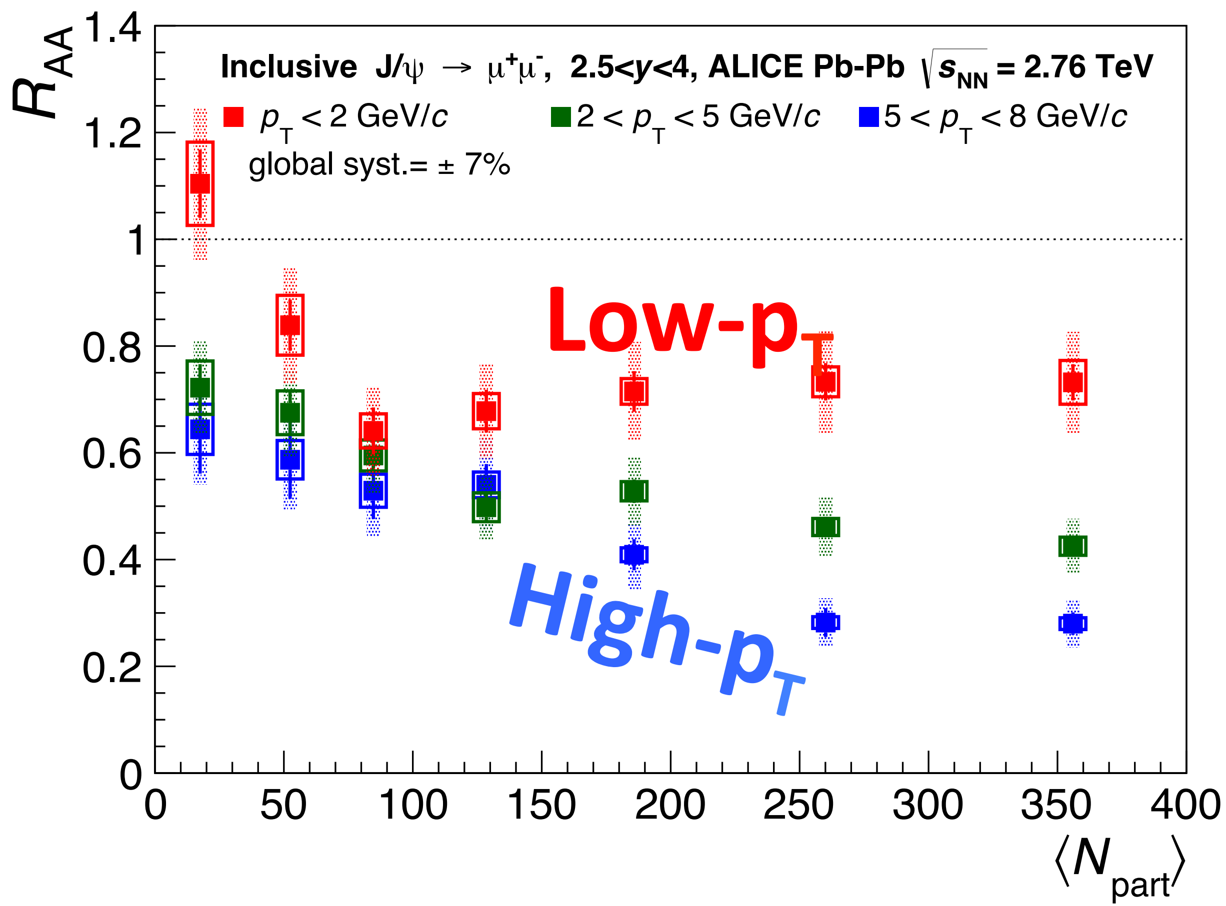


J/ψ suppression

ALICE Coll. PLB 734 (2014) 314







Recombination needed
to explain R_{AA} at the LHC

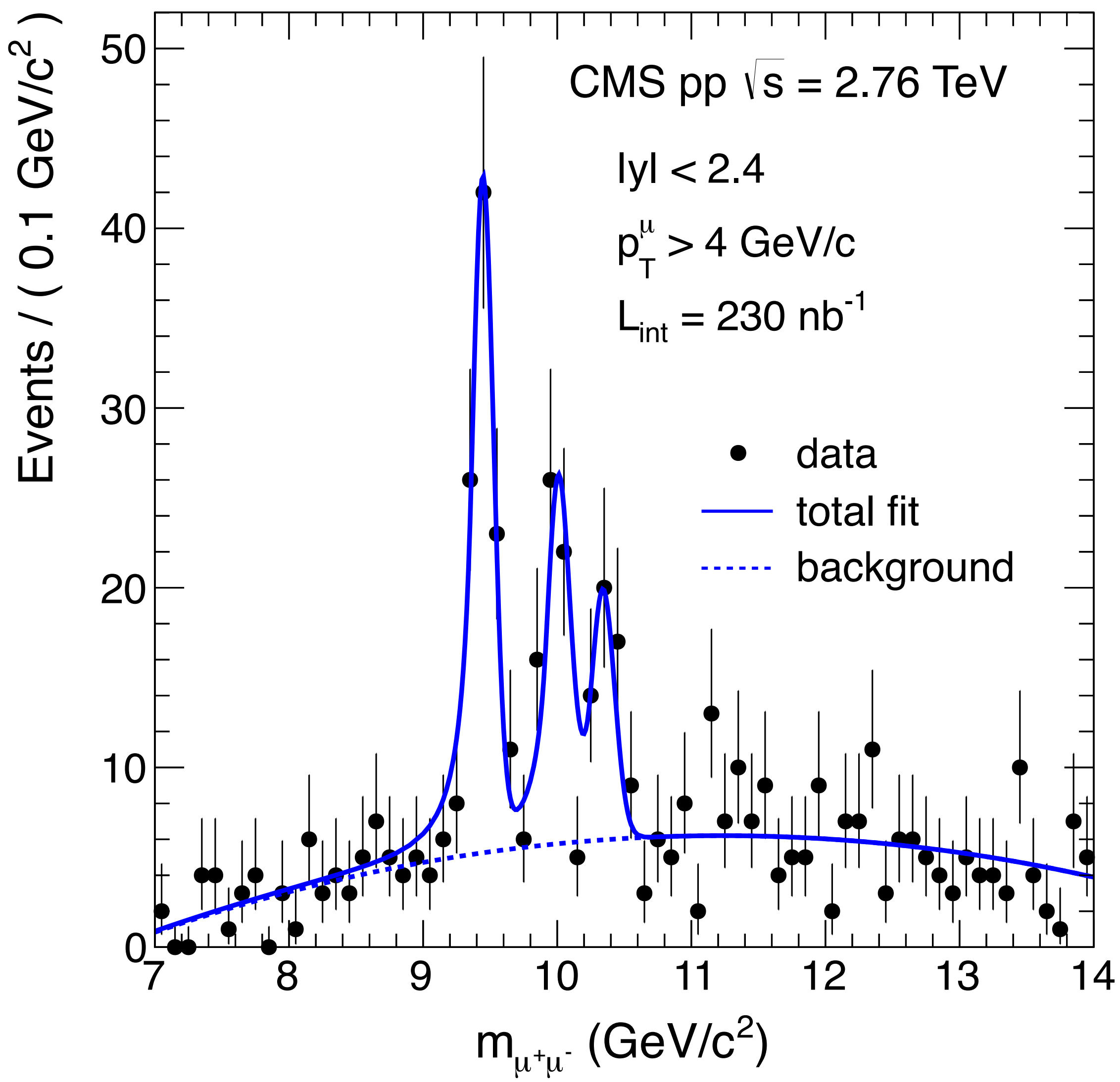
J/ψ enhanced/re-generated at low-p_T

High-p_T J/ψ suppressed (similar
magnitude at LHC & RHIC)

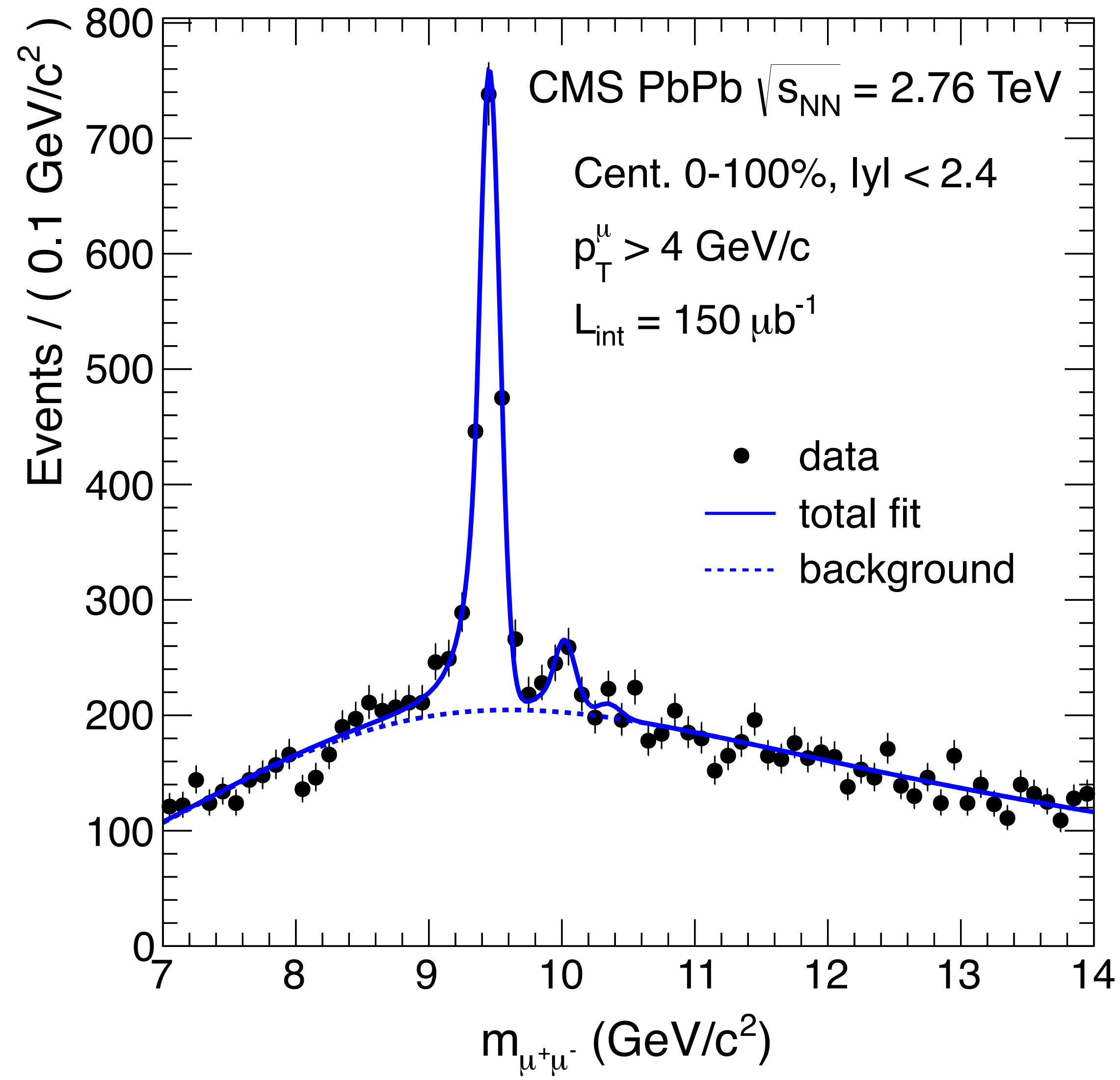
Strong suppression in central as
compared to peripheral collisions

Υ(nS)/Υ(1S) Single Ratios

pp



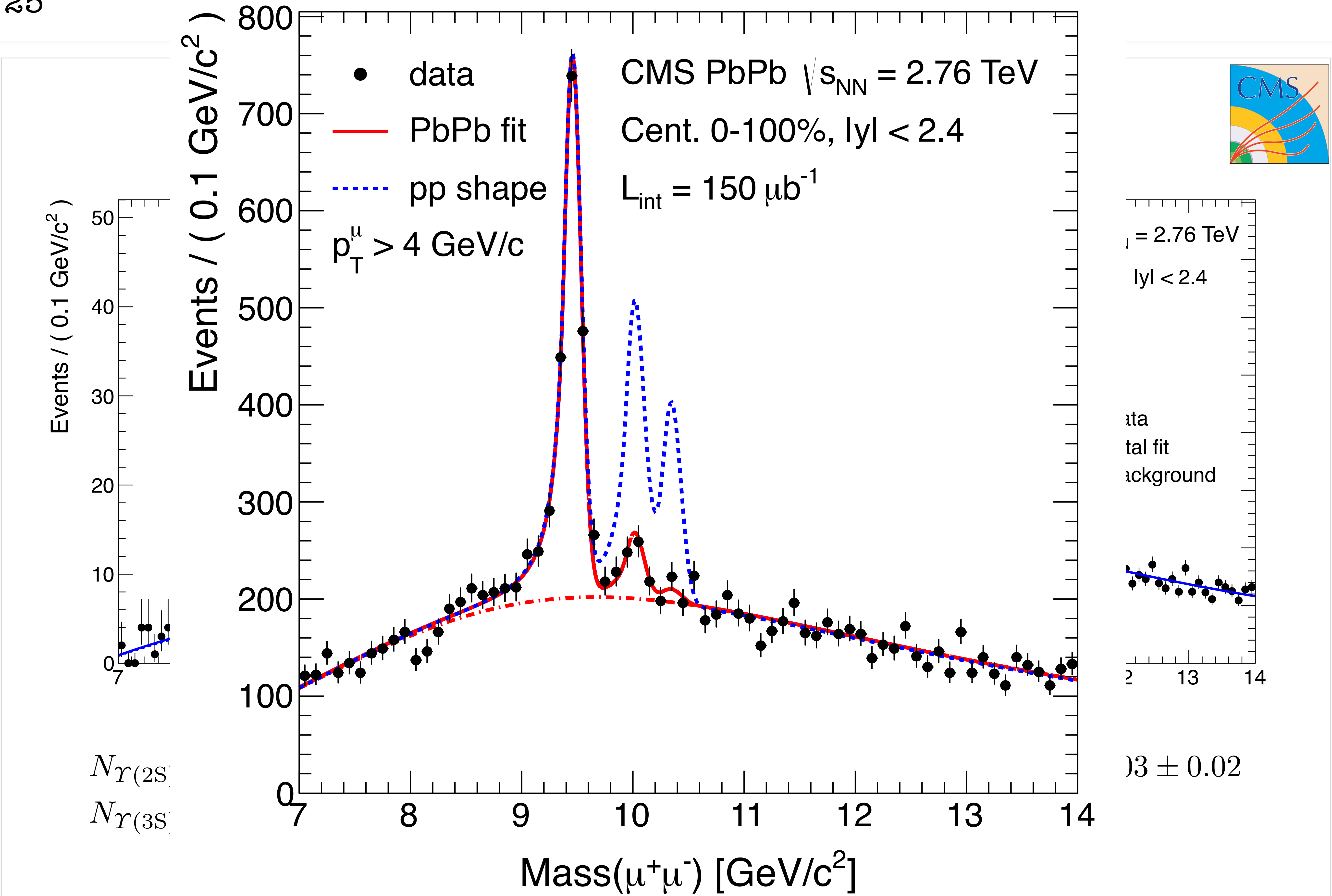
PbPb



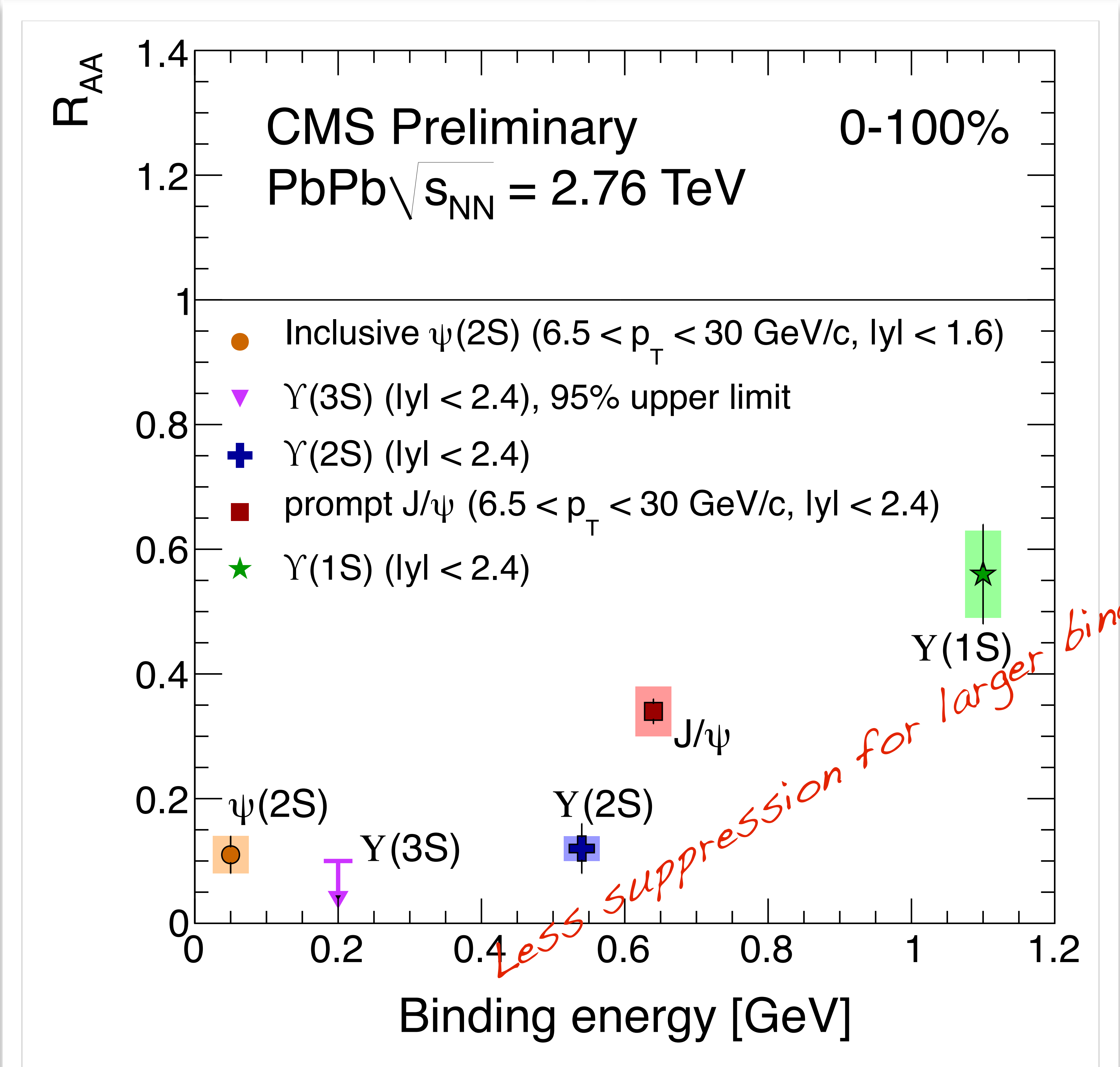
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.41 \pm 0.11 \pm 0.04$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency


data
PbPb fit
pp shape
$p_T^{\mu} > 4$ GeV/c
CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Cent. 0-100%, |y| < 2.4
L_{int} = 150 μb^{-1}
Events / (0.1 GeV/c^2)
Mass($\mu^+\mu^-$) [GeV/c^2]
0
100
200
300
400
500
600
700
800
7
8
9
10
11
12
13
14

Quarkonia suppression at the LHC

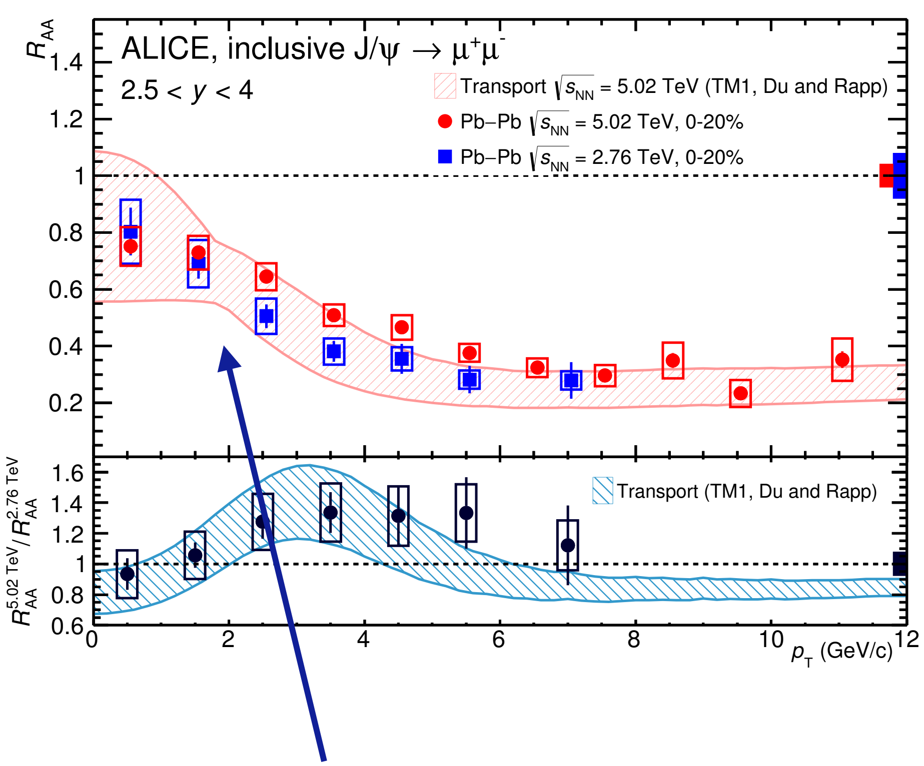


Recent results

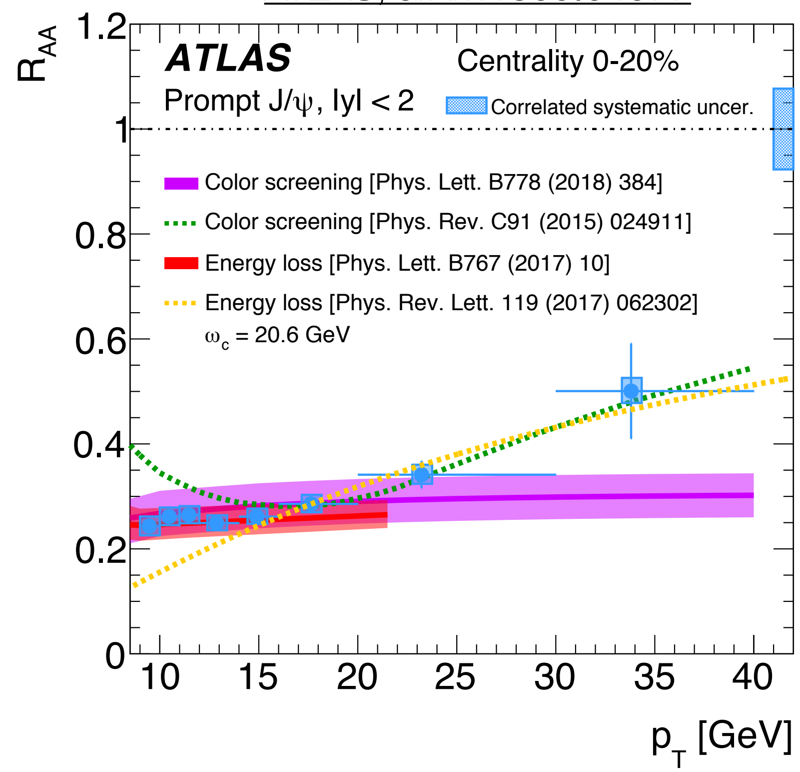
High-pT j/psi

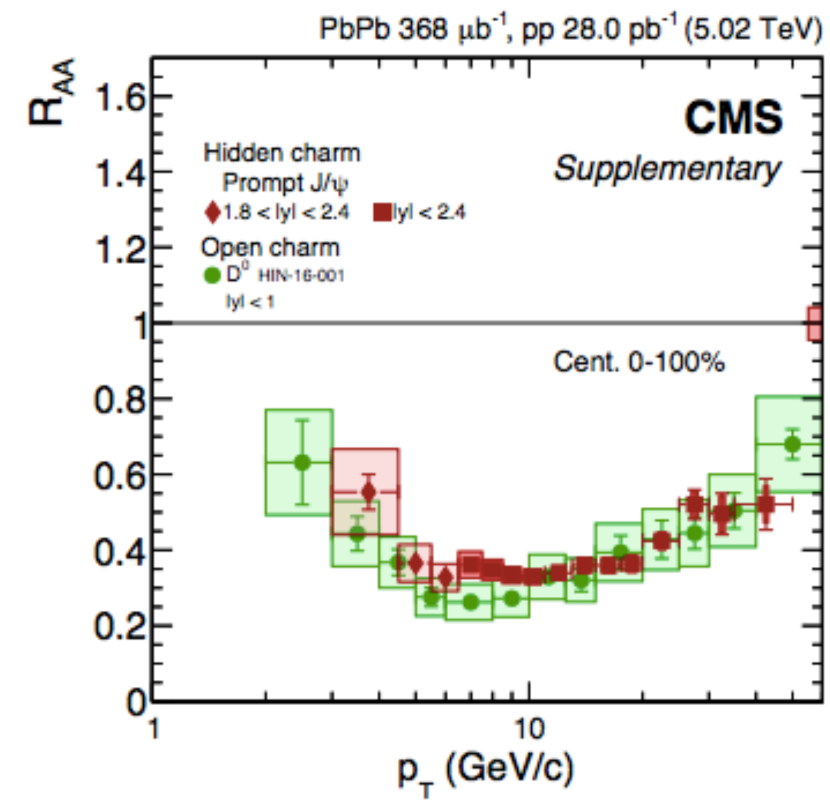
Open charm and prompt J/ψ

ALICE, PLB 766, 212



ATLAS, arXiv:1805.04077





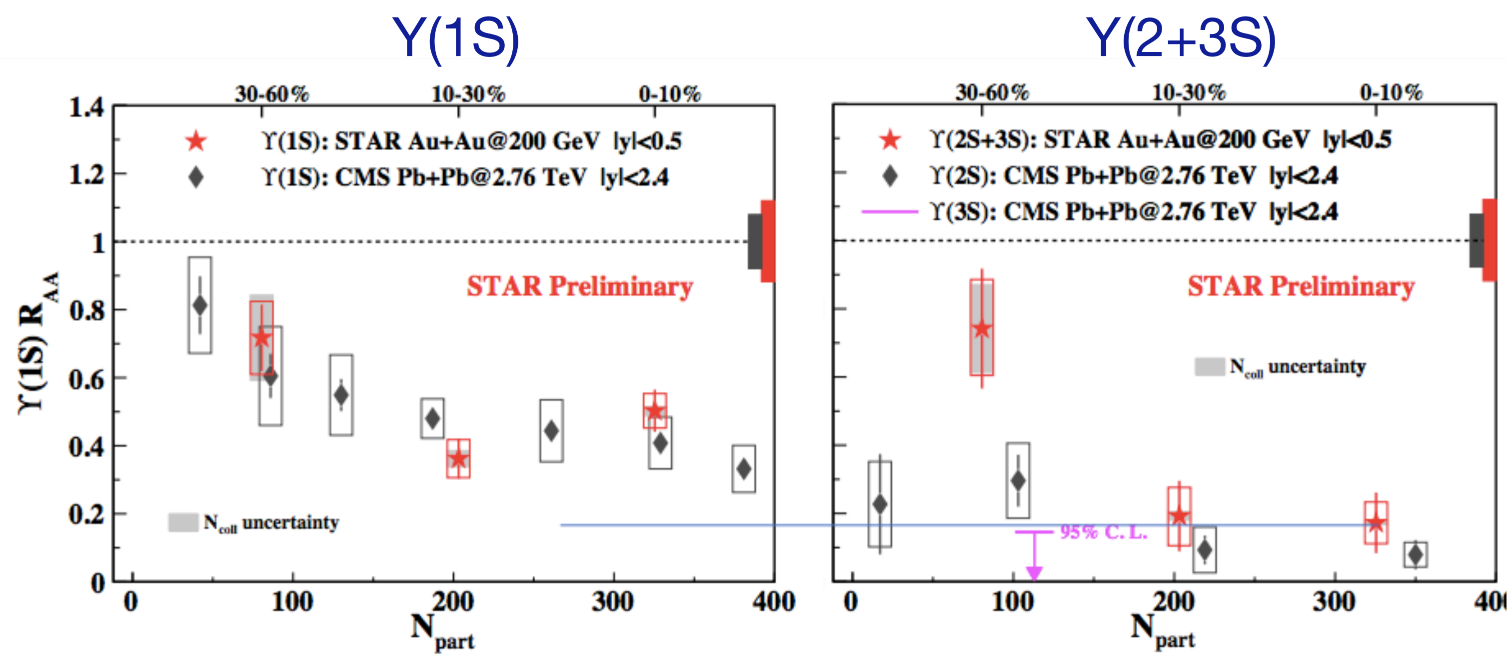
Low p_T: coalescence/recombination important

High p_T: open and hidden charm R_{AA} similar

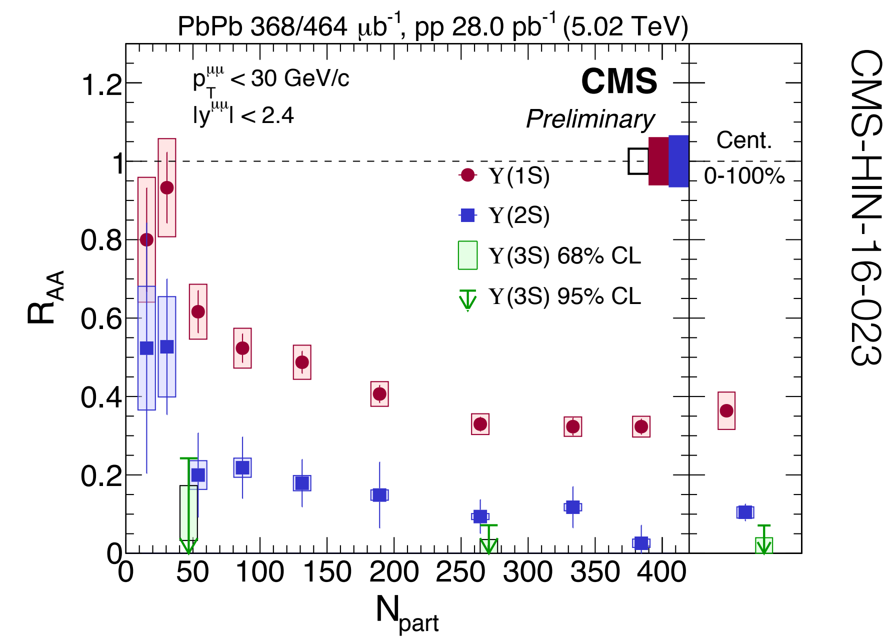
J/ψ suppression at high p_T driven by parton energy loss?

M. van Leeuwen

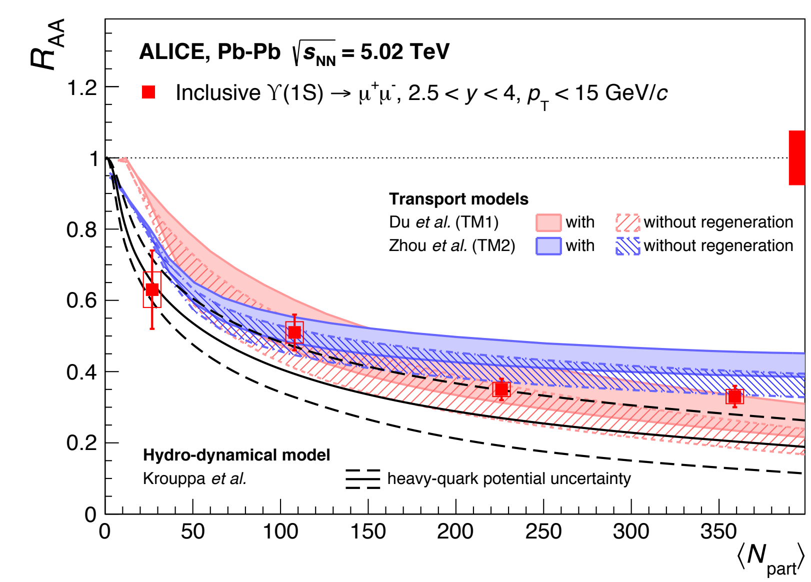
More recent results - bottomonium



CMS PLB 04, 031 (2017)



ALICE, arXiv:1805.04387



TAMU, X. Du et al PRC 96, 054901

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	500	240	190

B. Krouppa, et al PRD 97, 016017

	Υ(1S)	Υ(2S)	Υ(3S)
T_{disso}(MeV)	600	230	170

Clear hierarchy of suppression, but no sudden turn-on

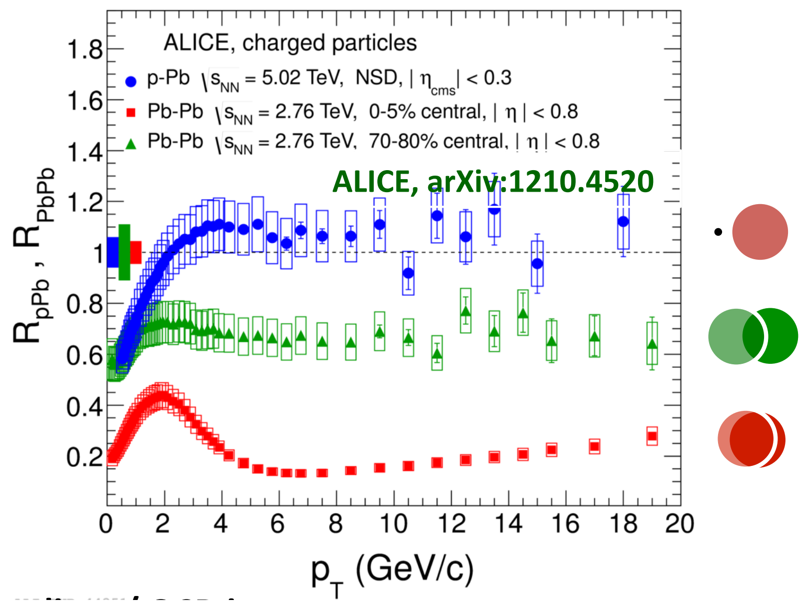
- T does not change rapidly with centrality
- Average over system
- Melting sets in for $T < T_m$

M. van Leeuwen

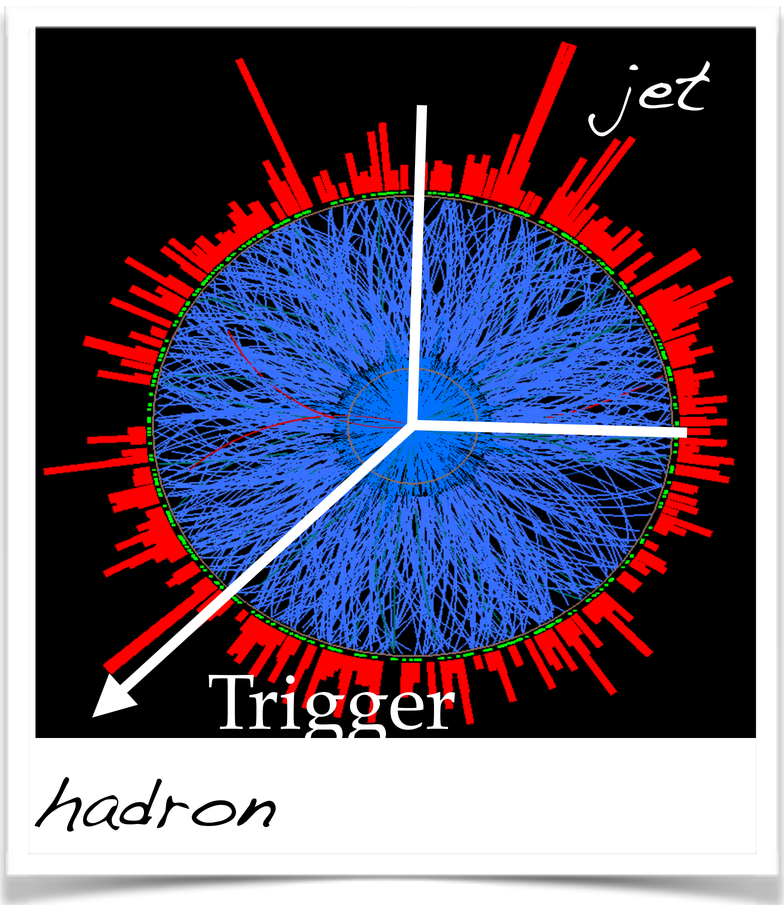
Hard sector in low-multiplicity collisions (p-Pb, pp)

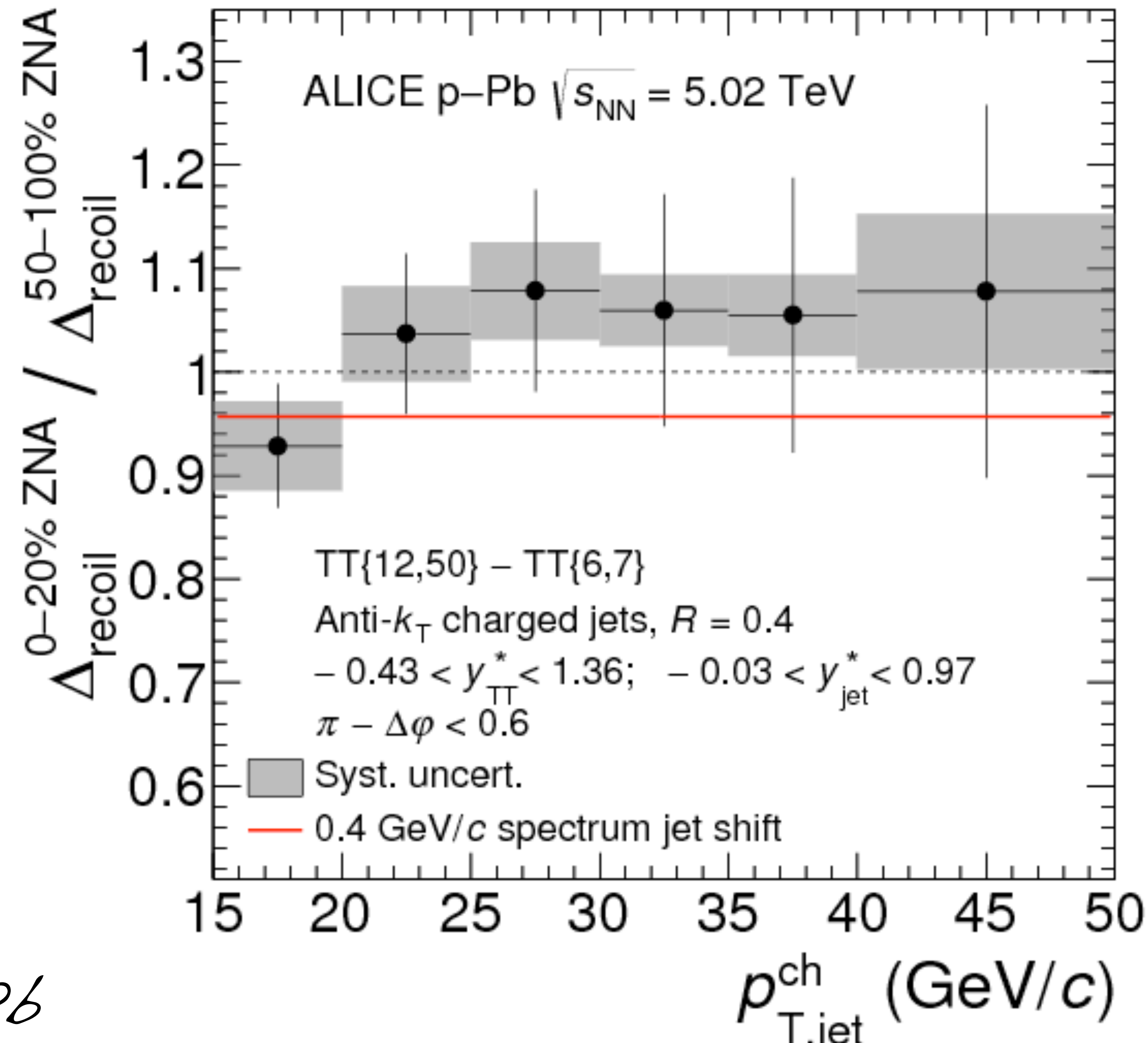
selected topics

pPb - no jet quenching



Constraints on jet quenching in p-Pb collisions measured by the event-activity dependence of semi-inclusive hadron-jet distributions (Phys.Lett. B783 (2018) 95-113)





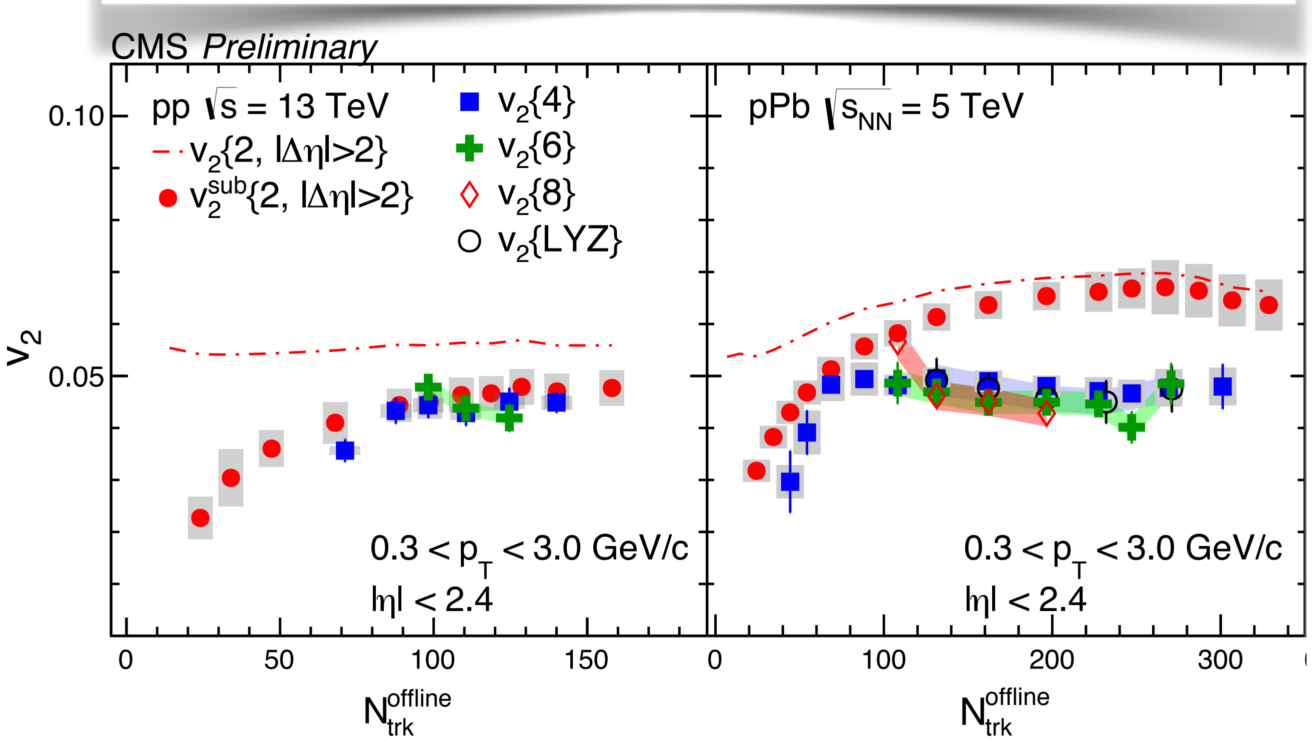
Limit on jet quenching in pPb

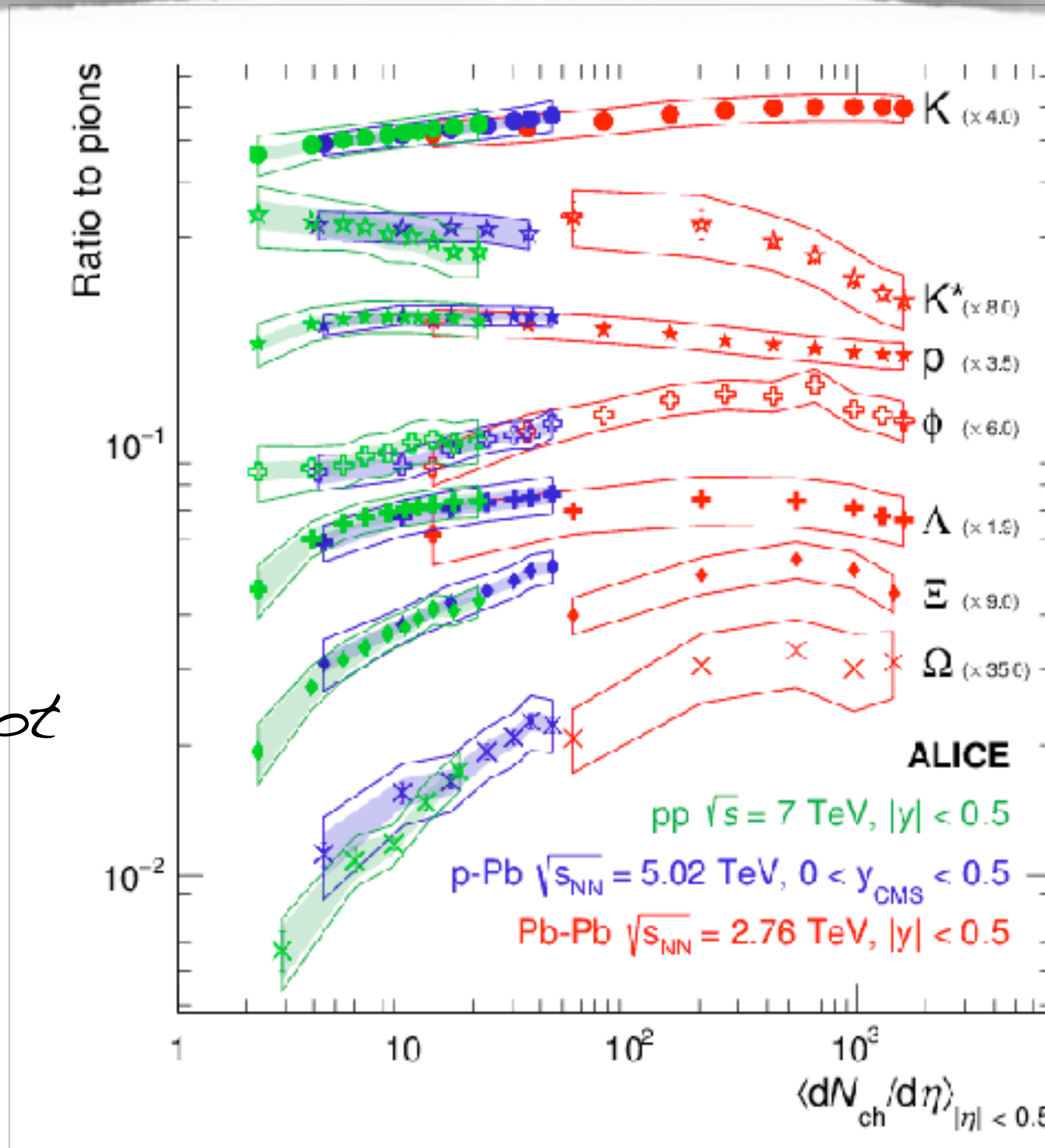
$\Delta E < 0.04$

Particle production as a function of multiplicity

Multi-particle correlations - similarities in pA and AA

Strangeness - striking continuous evolution with event multiplicity from pp to AA 1807.11321





All this while jet quenching is not present in pPb collisions...

Limit obtained using hadron-jet correlations ($\Delta E < 0.04$)

pPb - no jet quenching however, signal for collectivity ($v_2 > 0$) for heavy-quarks and j/psi

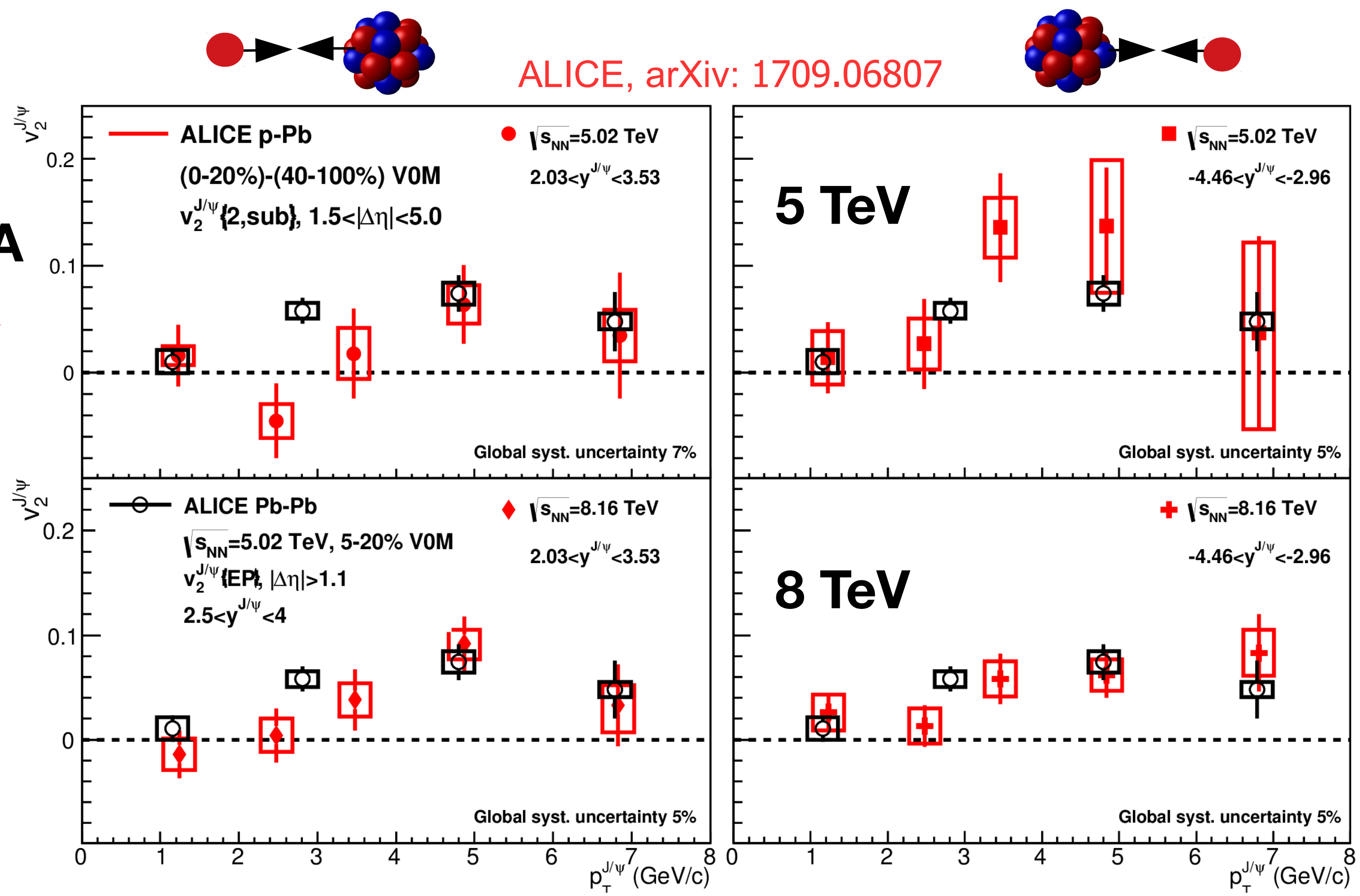
Collectivity - j/psi

Recently new result from pPb...

J/Ψ v_2

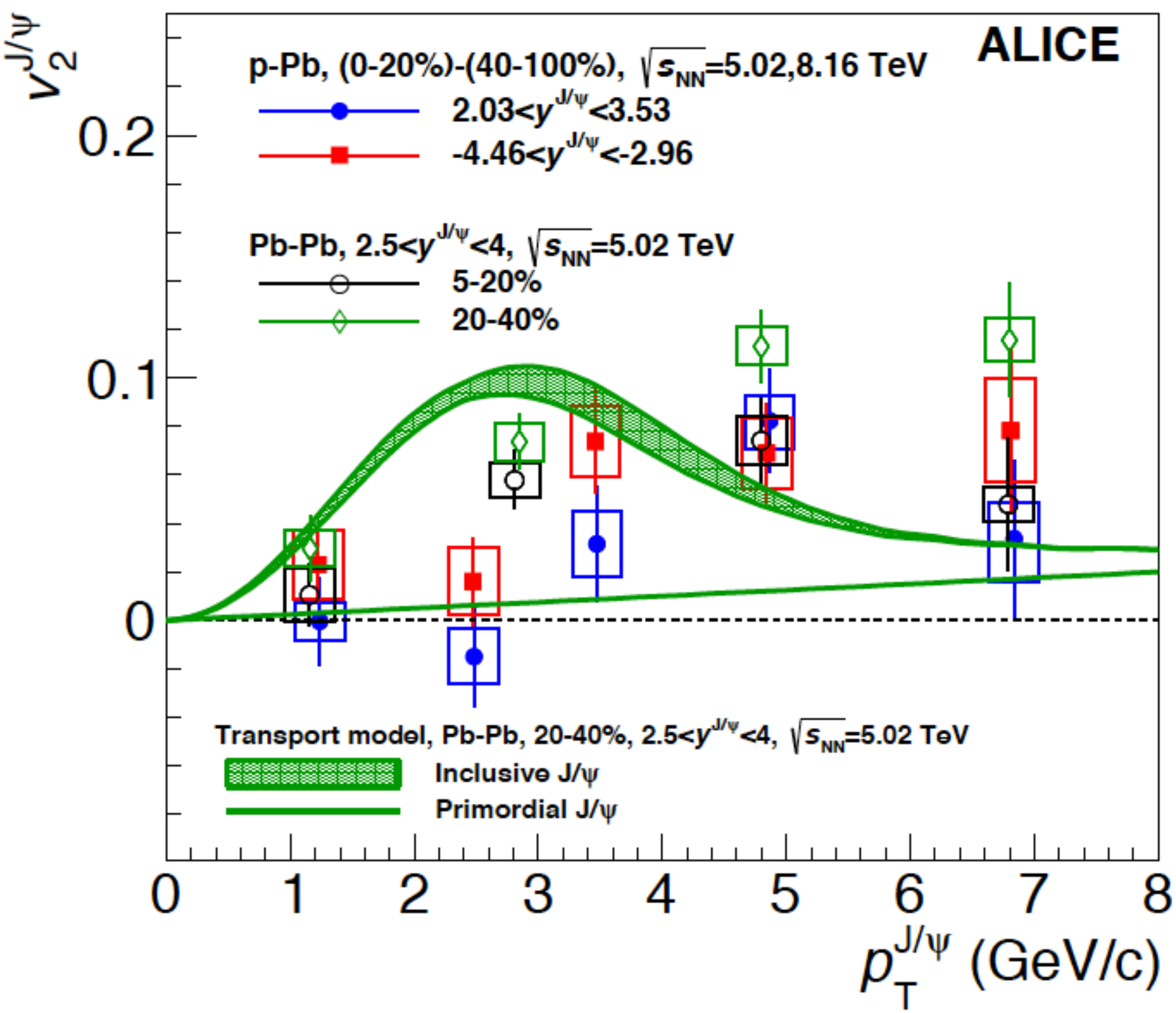
Black: AA

Red: pA



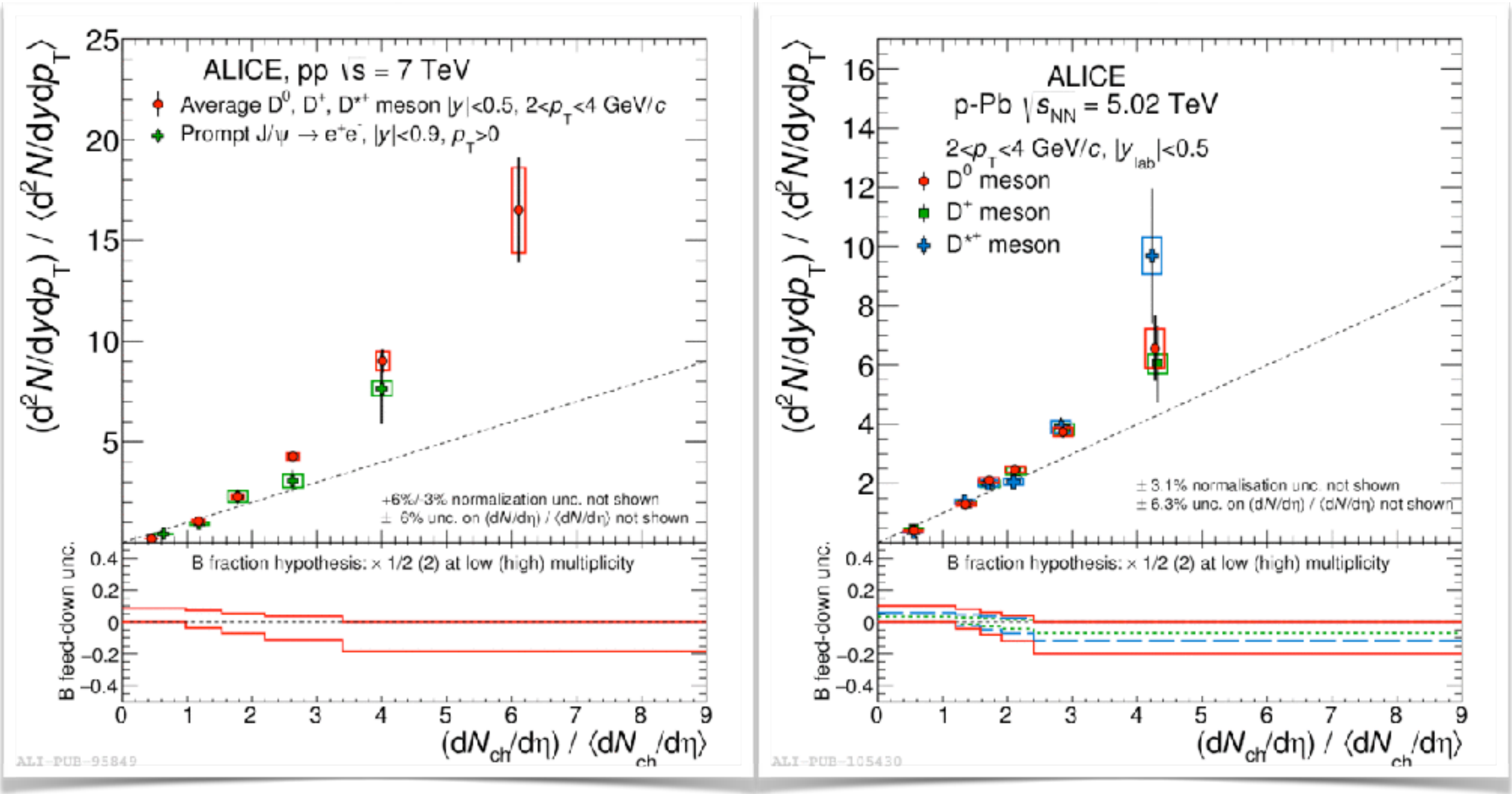
- v_2 for p_T<3 GeV/c is compatible with zero
- v_2 in 3<p_T<6 GeV/c is positive with a total significance of 5σ
  - Comparable to values from central Pb-Pb collisions

Collectivity - j/psi



J/ψ flow similar in magnitude in p-Pb as compared to PbPb
Similar mechanism? MPI dominance in high-multiplicity collisions ?

Rise of heavy-quark production with multiplicity of the events <=> multiple parton interactions



v2>0 and no jet-quenching - some theory developments

Some time last year...

Collectivity from Interference

Urs Achim Wiedemann
CERN TH Department

Solutions to the "Flow w/o quenching" puzzle in pp / pA

- 1. Quantitative Explanation: maintain that v_n result from final state interactions
  - ➡ **small jet quenching effects must be seen in pp/pA**
    for techniques to detect them, see e.g. **Mangano, Nachman arXiv:1708.08369**
  - Theory improvements needed to relate jet quenching and v_n signals.
- 2. High-density Scenario: azimuthal correlations from a **saturated initial state ("CGC")**
  Altinoluk, Armesto, Beuf, Dumitru, Gotsman, Jalilian-Marian, Iancu, Kovner, Lappi, Levin, Lublinsky, McLerran, Skokov, Schlichting, Venugopalan, ….
  - ➡ UE (underlying event) physics in pp multi-purpose MC event generators based on dilute system of up to O(10) MPIs (multi parton interactions)
  - If saturated initial state needed to describe pp UE, then dramatic implications: **Torbjorn go home.**
  - **One needs to understand whether initial density effects are necessary for azimuthal correlations.**

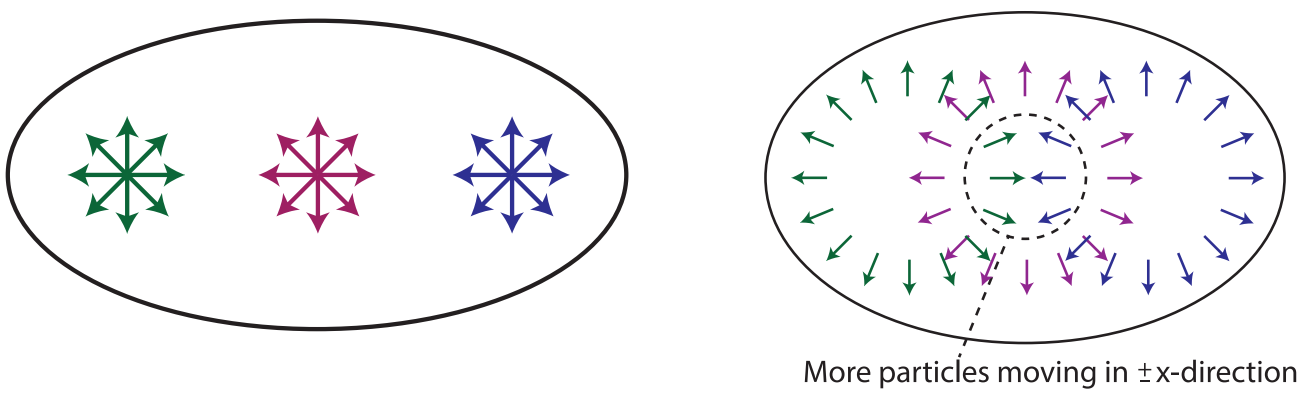
… solutions to the "Flow w/o quenching" puzzle, cont'd...

- 3. High-density Scenario: **strongly coupled fluid paradigm** (à la AdS/CFT) for pp/pA
  - ➡ **small jet quenching effects must be seen in pp/pA**
  - **UE model radically different from that in MC generators**
- 4. Low-density Scenario: fluid dynamics negligible, **azimuthal correlations from escape mechanism**
  Liang He et al., Phys. Lett. B753 (2016) 506-510; AMTP
  - mechanism to be understood quantitatively outside a MC code
  - ➡ **small jet quenching effects must be seen in pp/pA**
  - mild extension of UE model of multi-purpose MC generators
- 5. Low-density Scenario: **Collectivity from interference**
  B.Blok, C. Jäkel, M. Strikman, UAW, arXiv:1708.08241
  - No initial density and no initial asymmetry, no final state interactions
  - Contribution to v_n from QM interference & color correlations?
  - ➡ **does not imply jet quenching in pp/pA**
  - natural extension of UE model of multi-purpose MC generators

This Talk

v2>0 and no jet-quenching - some theory developments

Can you have flow with a few scatterings?
'anisotropic escape' mechanism



Initially isotropic momentum distribution

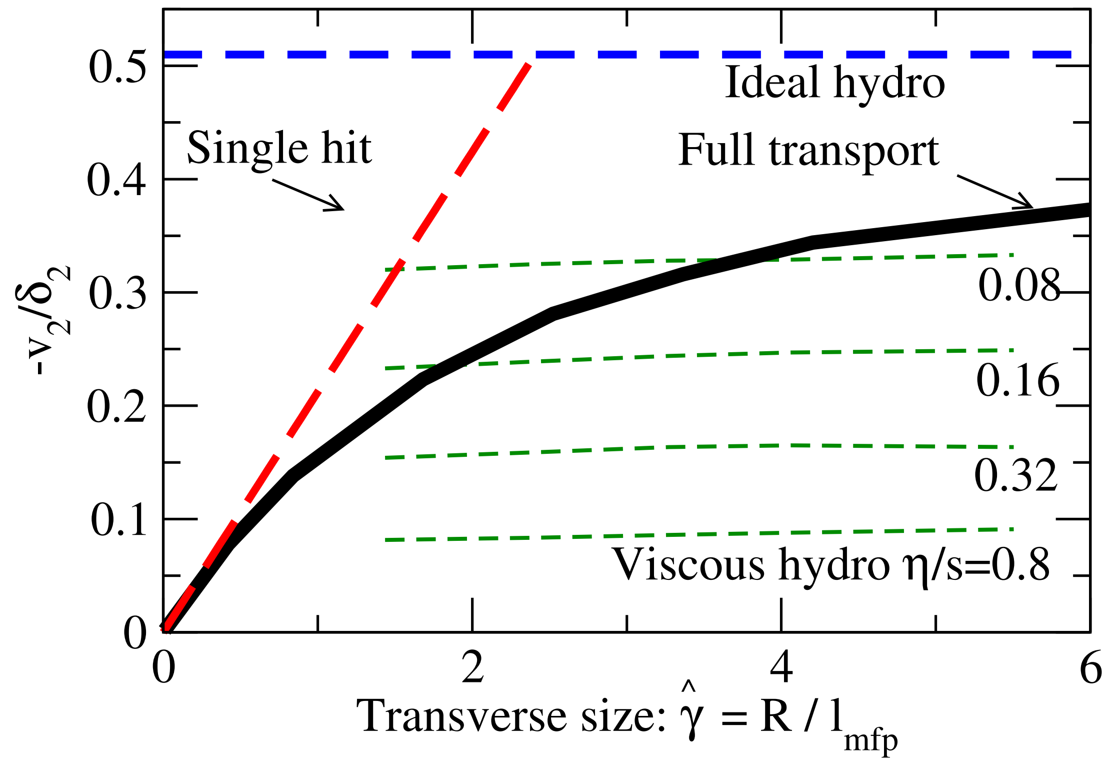
Kurkela, Wiedemann, Wu, arXiv:1803.02072

Scattering randomises directions; more scatterings to 'out-of-plane'

Anisotropic density converted into anisotropic momentum distribution by few scatterings

2018

Kurkela, Wiedemann, Wu, arXiv:1805.04031

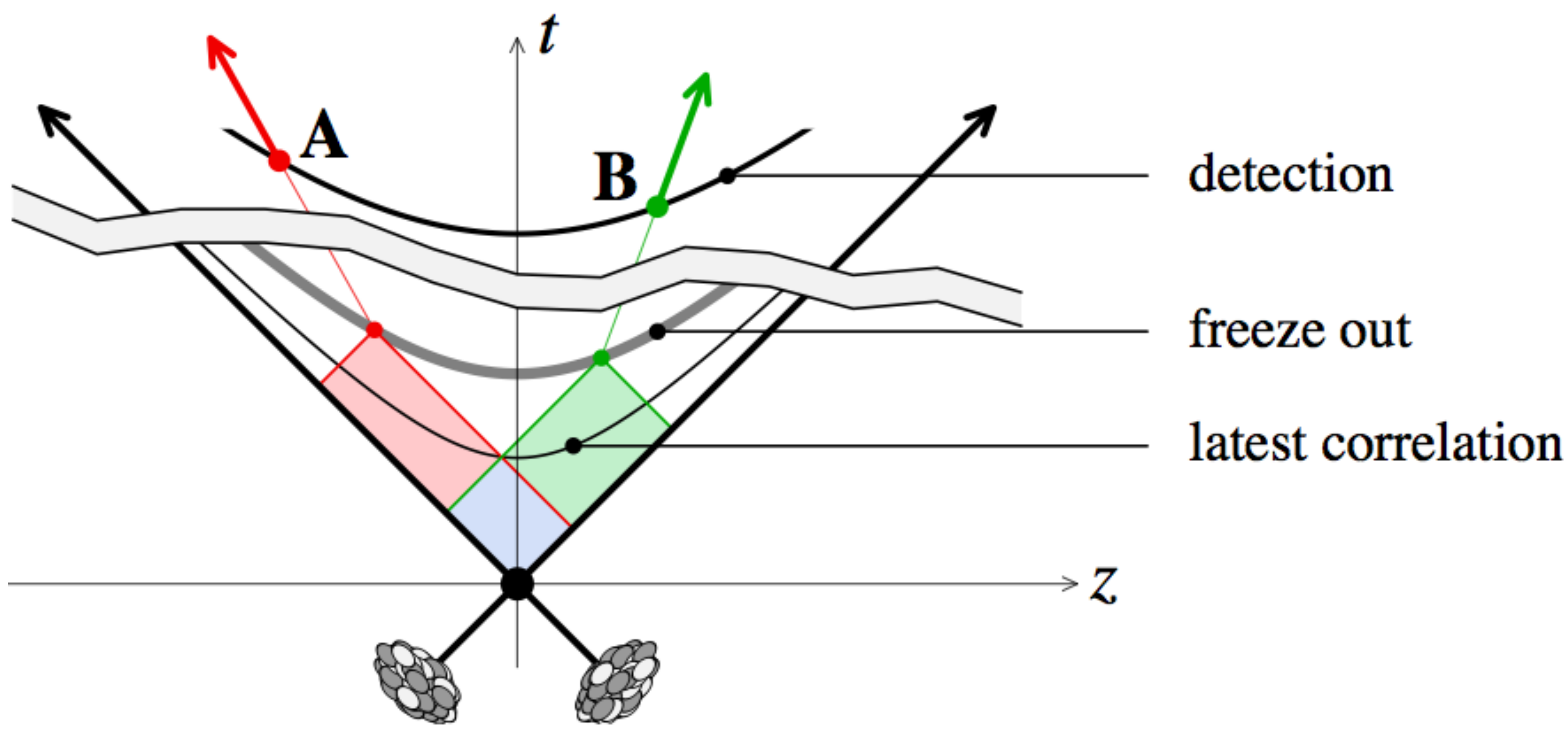


Small systems: 'single hit' kinetic transport equal to full hydro

... by a few scatterings (no liquid)
=> possibly a very small effect for high energy partons
=> no/small jet quenching

Raju Venugopalan

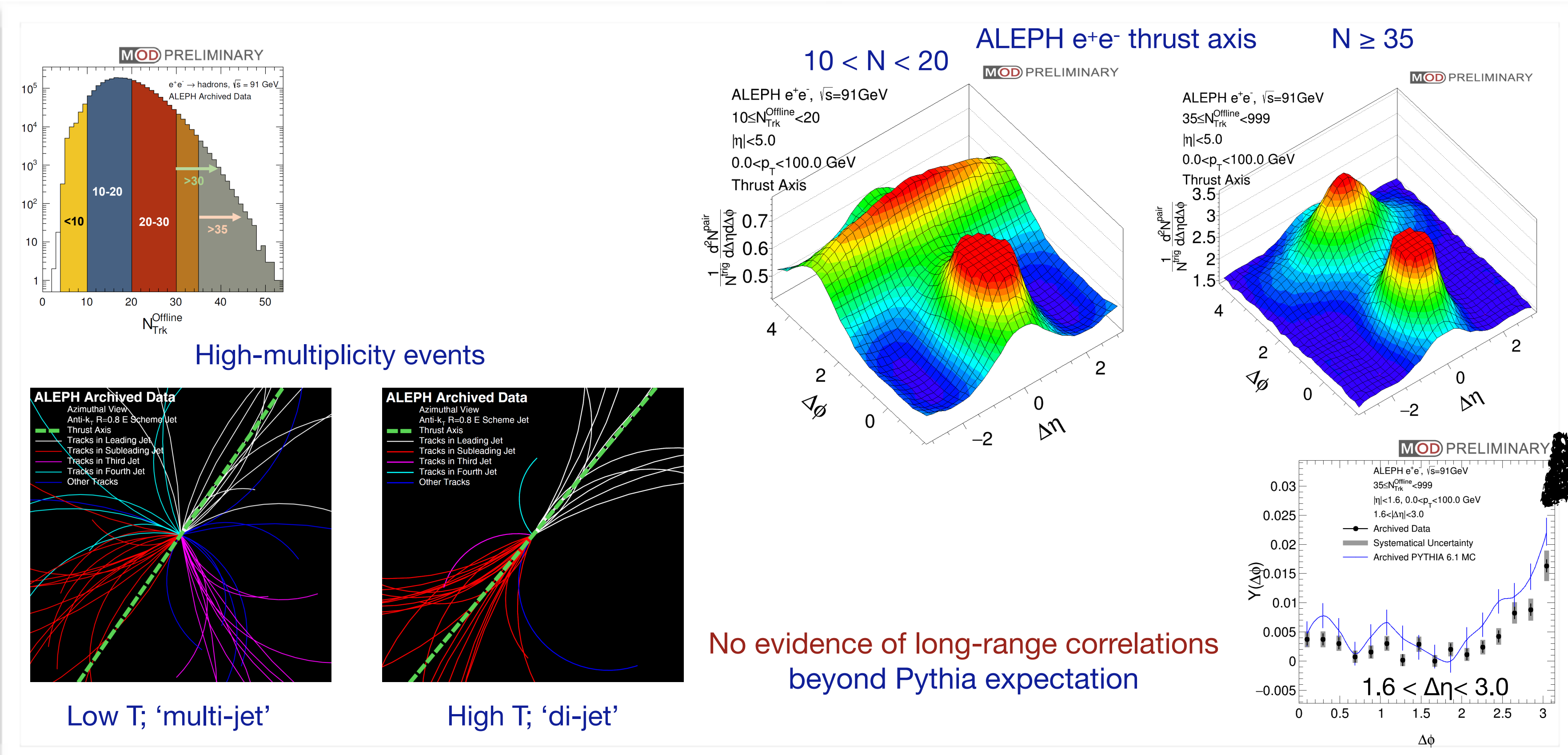
Long range rapidity correlations are a chronometer



$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

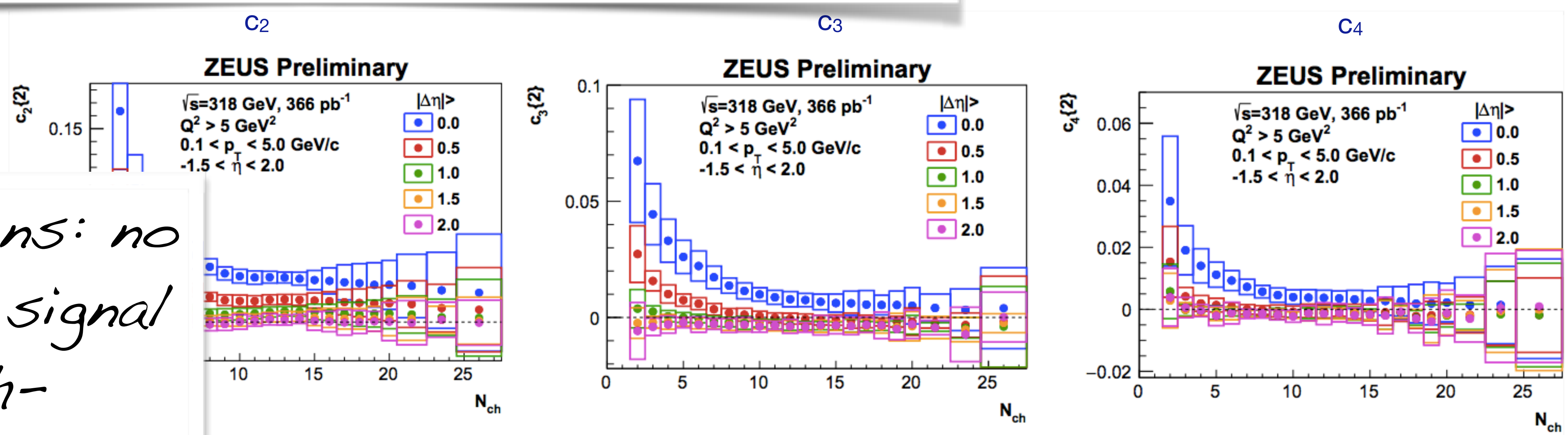
Long range correlations sensitive to very early time (fractions of a femtometer ~ 10^{-24} seconds) dynamics in collisions

v2 in more elementary collisions?



e+e- collisions: no extra correlations (beyond known MC / physics)

Quark Matter 2018, M. van Leeuwen



ep collisions: no collective signal in high-multiplicity events

Familiar behaviour: non-flow dominates at small multiplicity and without eta-gap

No flow-like signal seen in high-multiplicity, large eta gap for c_2, c_3, c_4

No flow with 'single string' ⇒ Need multiple interactions to set up initial geometry

Putting a few things together

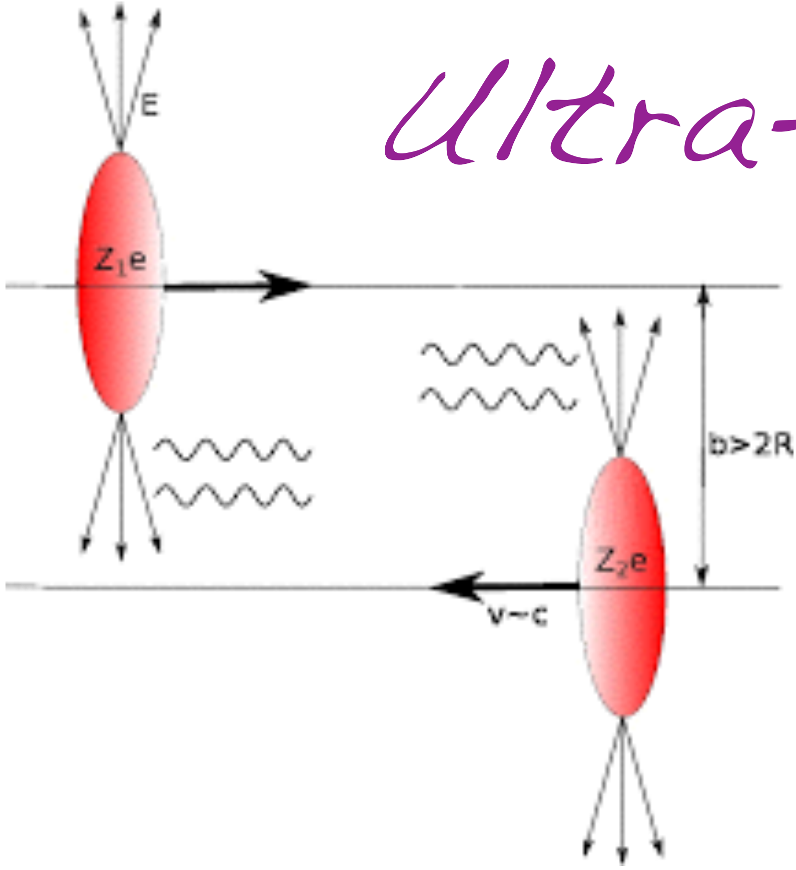
- AA at high energy:
  - collective behavior ($v_2>0$)
  - parton-medium interactions: light and heavy-flavor suppression; jet quenching
- pp, pPb at high energy:
  - collective behavior ($v_2>0$) - even for heavy-flavor
  - parton-medium interaction: (hydrodynamics works...) droplets of QGP? vs. few scatterings kinetic effect vs. string melting; there is no (measurable Today) suppression - no "medium" in hot QGP sense...
- Any system at high-energy: look forward to eIC!?
  - collectivity signal ($v_2>0$) - hydrodynamics 'works' (possibly "everywhere" where collective effects present - not in ep & ee)
  - particle production: part of a smooth evolution with particle multiplicity (number of sources, MPIs)

Ultra-peripheral collisions

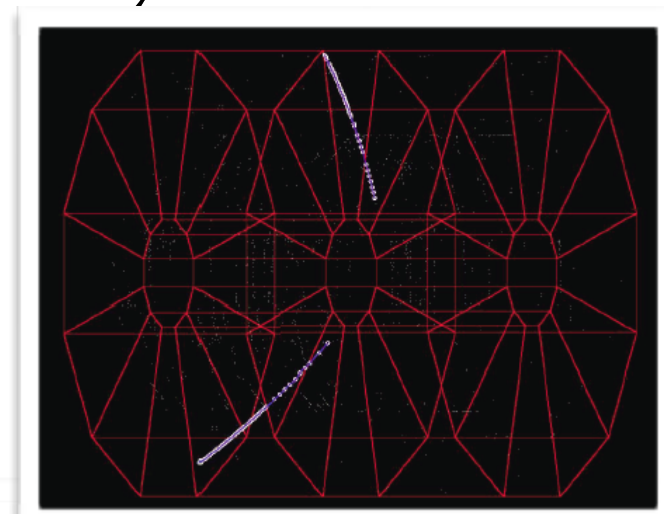
selected topics

Ultra-peripheral collisions

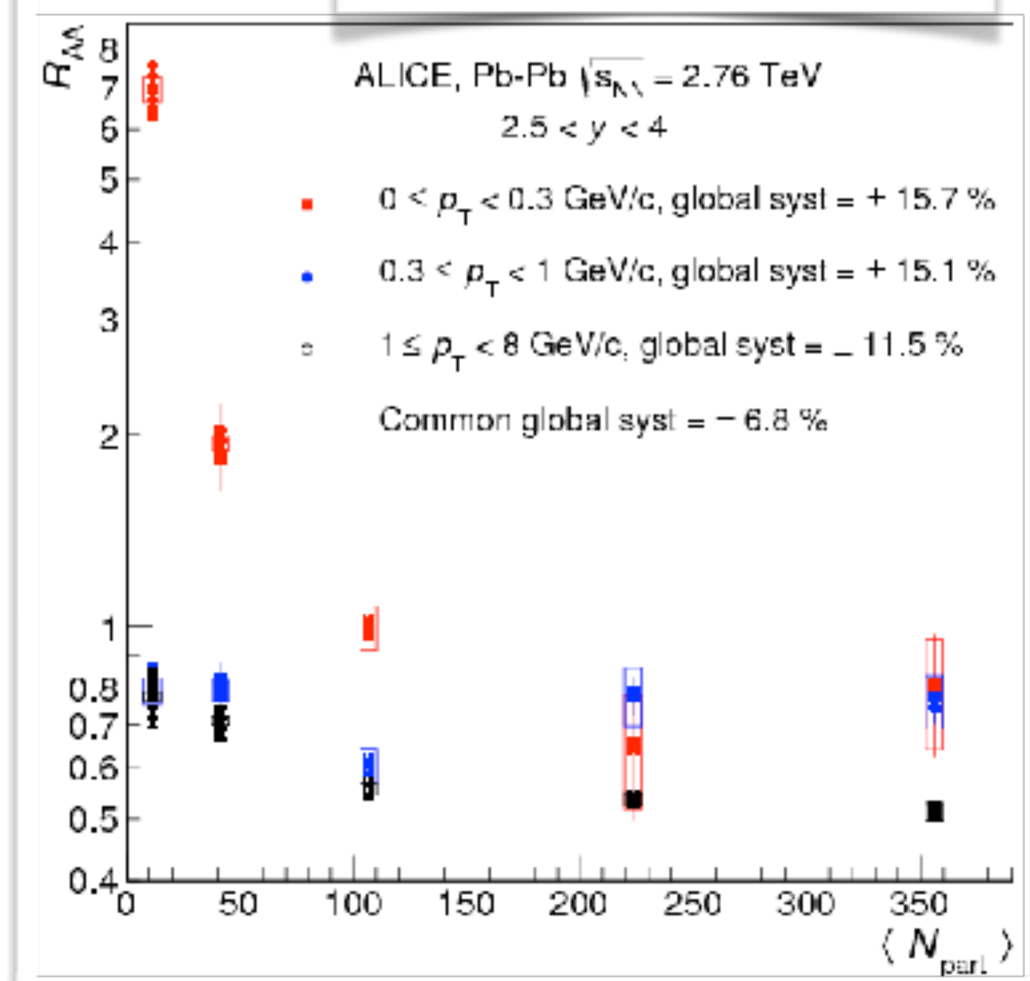
S. Klein, QM2017, https://indico.cern.ch/event/433345/contributions/2321627/



UPCs: heavy nuclei carry strong electric and magnetic fields
- fields are perpendicular => nearly-real virtual photons $E_{max}=\gamma c h/b$
- photo nuclear reactions
- two-photon interactions

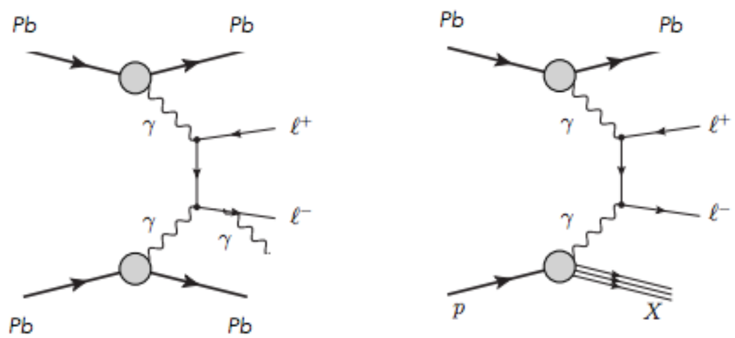


- The energy frontier for electromagnetic probes
  - Maximum CM energy $W_{\gamma p}$ ~ 3 TeV for pp at the LHC
    - ~ 10 times higher in energy than HERA
  - Probe parton distributions in proton and heavy-ions down to
    - Bjorken-x down to a few 10^{-6} at moderate Q^2
- Electromagnetic probes have α_{EM} ~ 1/137, so are less affected by multiple interactions than hadronic interactions
  - "Precision" measurements,
  - Exclusive interactions
- Two-photon physics & couplings at the energy frontier
  - New particle searches (axions), $\gamma\gamma$->W^+W^-, etc.

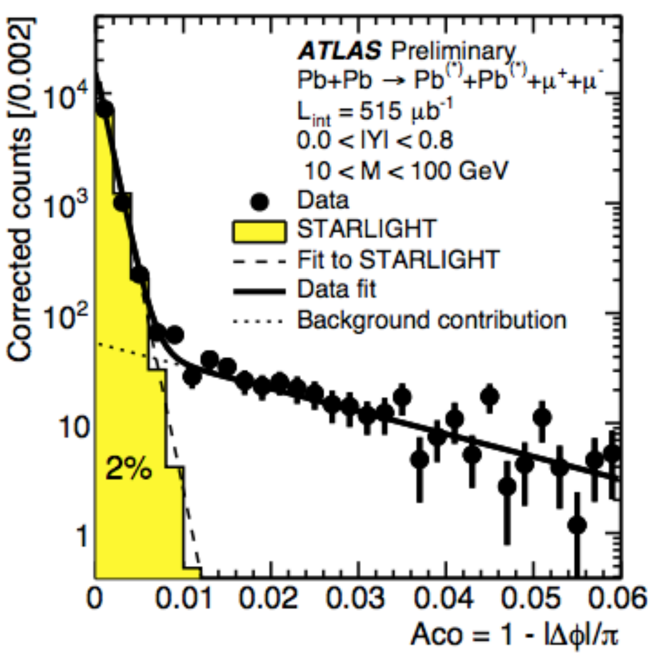


Energy	AuAu	pp RHIC	PbPb LHC	pp LHC
Photon energy	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max gg	6 GeV	~100	200 GeV	~1400 GeV

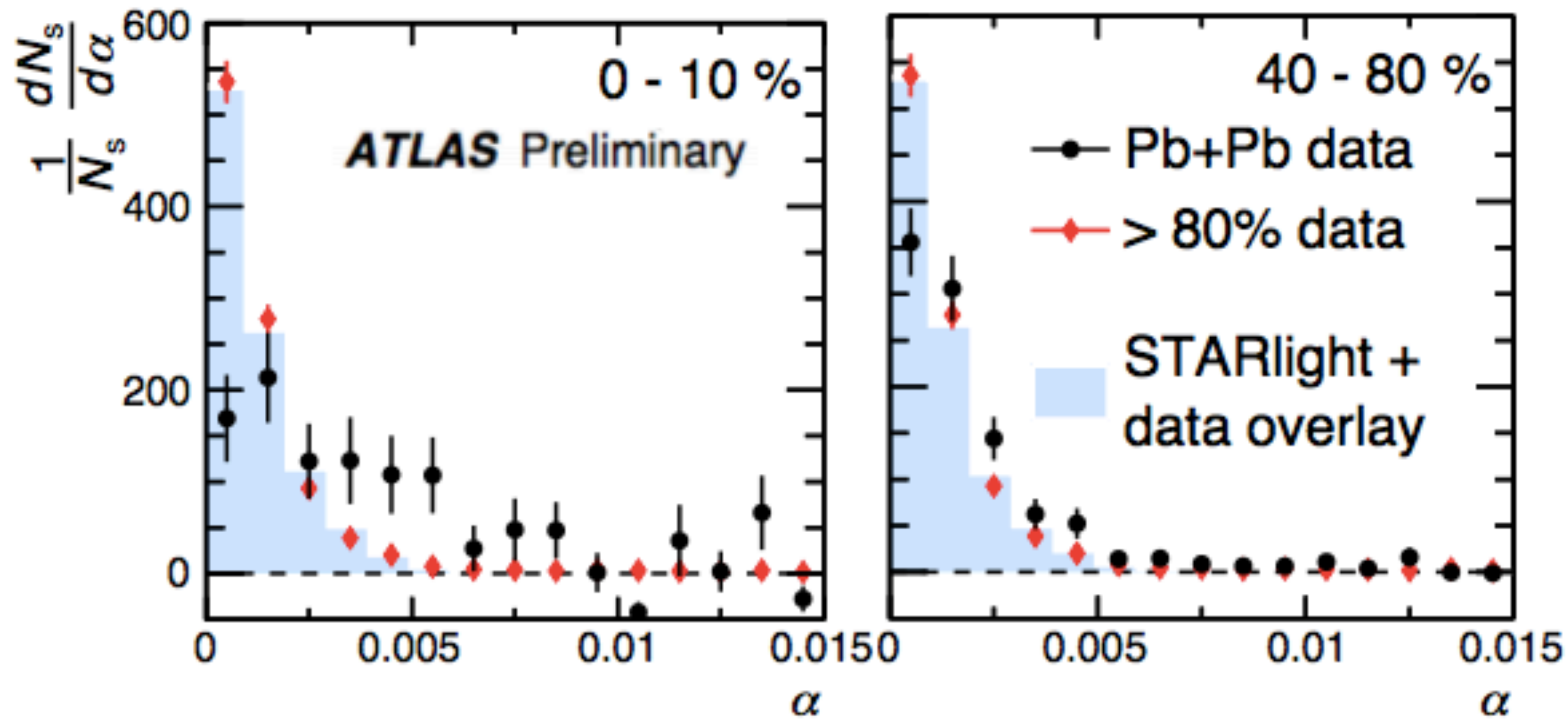
Ultra-peripheral collisions



UPC process:
gg -> m m

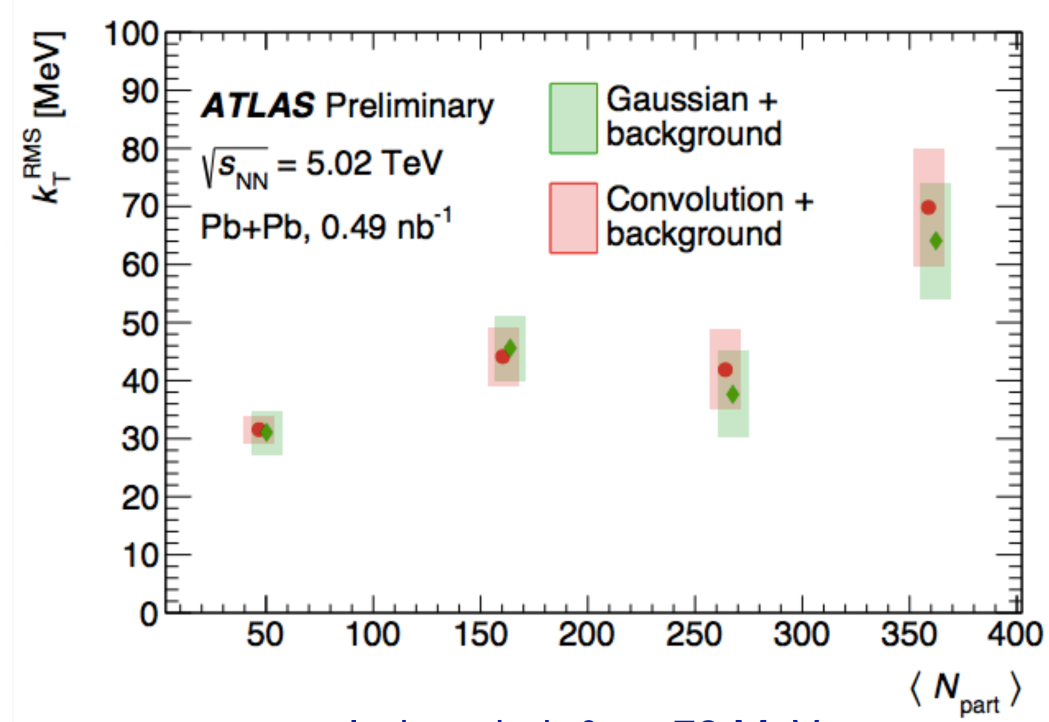


$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$



Heavy flavour background subtracted with DCA, momentum balance

Acoplanarity

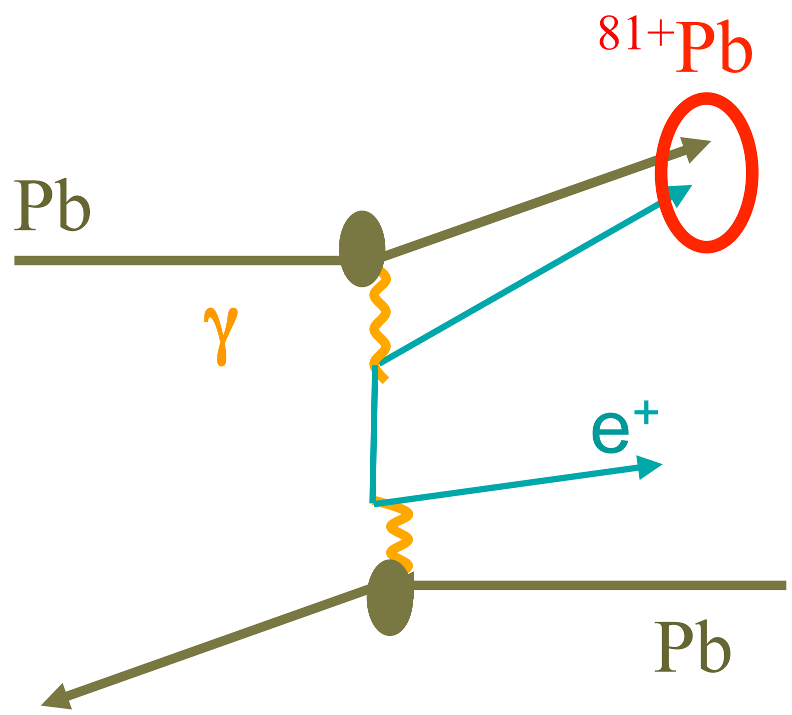


Induced $\langle k_T^2 \rangle \approx 70$ MeV

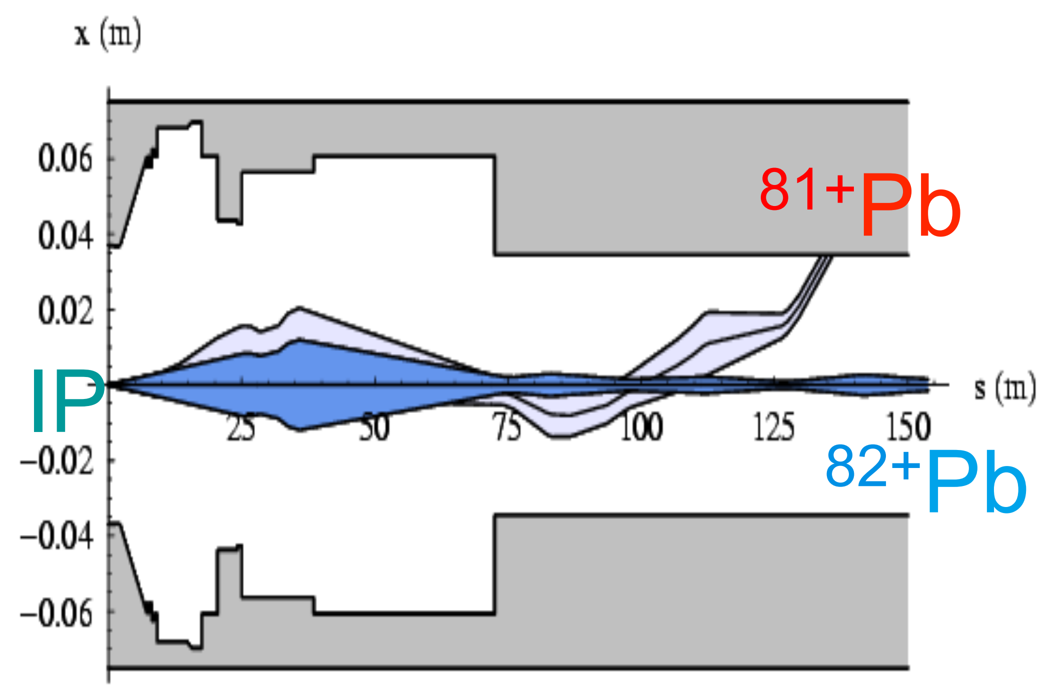
Back to back muon pairs with small accoplanarity
=> as a function of centrality of AA collisions(!)

UPCs and LHC Luminosity

S. Klein, QM2017, https://indico.cern.ch/event/433345/contributions/2321627/



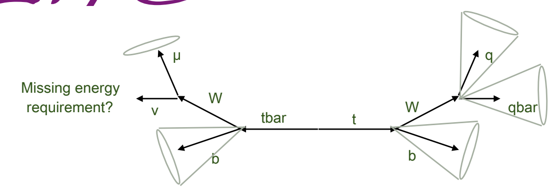
- σ[PbPb($\gamma\gamma$) -> (Pbe^-) Pb e^+] ~ 280 b @ LHC
- Single-electron lead has charge:mass ratio reduced by 1/82
- The (Pbe^-) beam strikes the beampipe 135 m downstream from the magnet
  - At $L = 10^{27}/cm^2/s$, the beam deposits 23 Watts
- LHC magnet quench from BFPP demonstrated!
  - $L_{max}=2.3*10^{27}/cm^2/s$
- Luminosity limit for LHC & potentially FCC
  - Some mitigation possible by orbit bumps.



Looking forward...

An appetizer… Heavy-ion perspective on FCC but also high-luminosity LHC

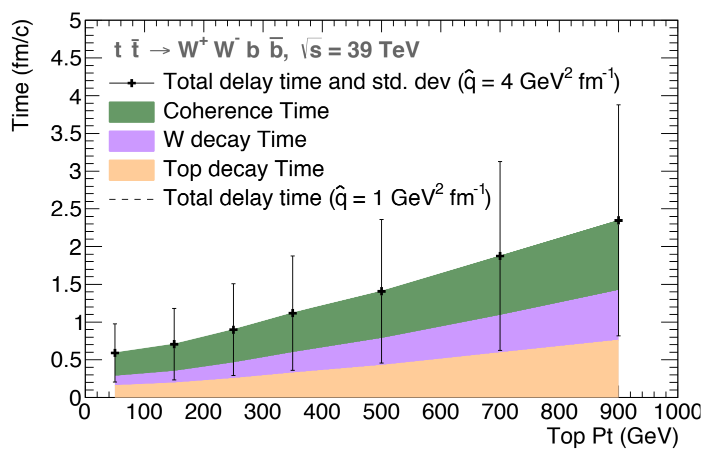
"Time" tomography of the medium with boosted tops (accessible at sLHC but also some at high-luminosity LHC)

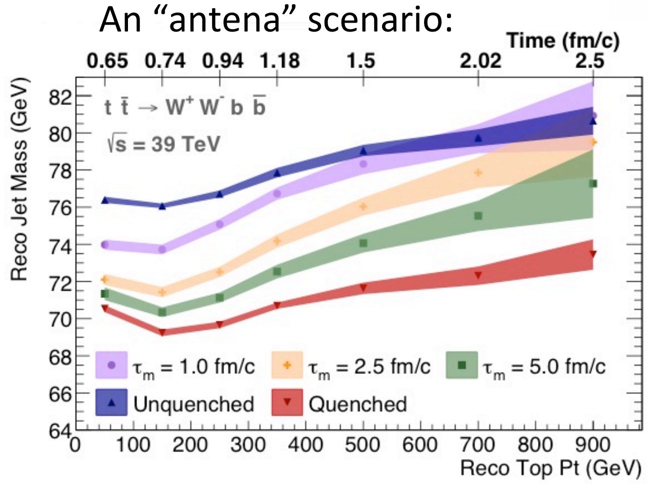


$$t\bar{t} \rightarrow b\bar{b} + \ell + 2\,jets + E_T$$

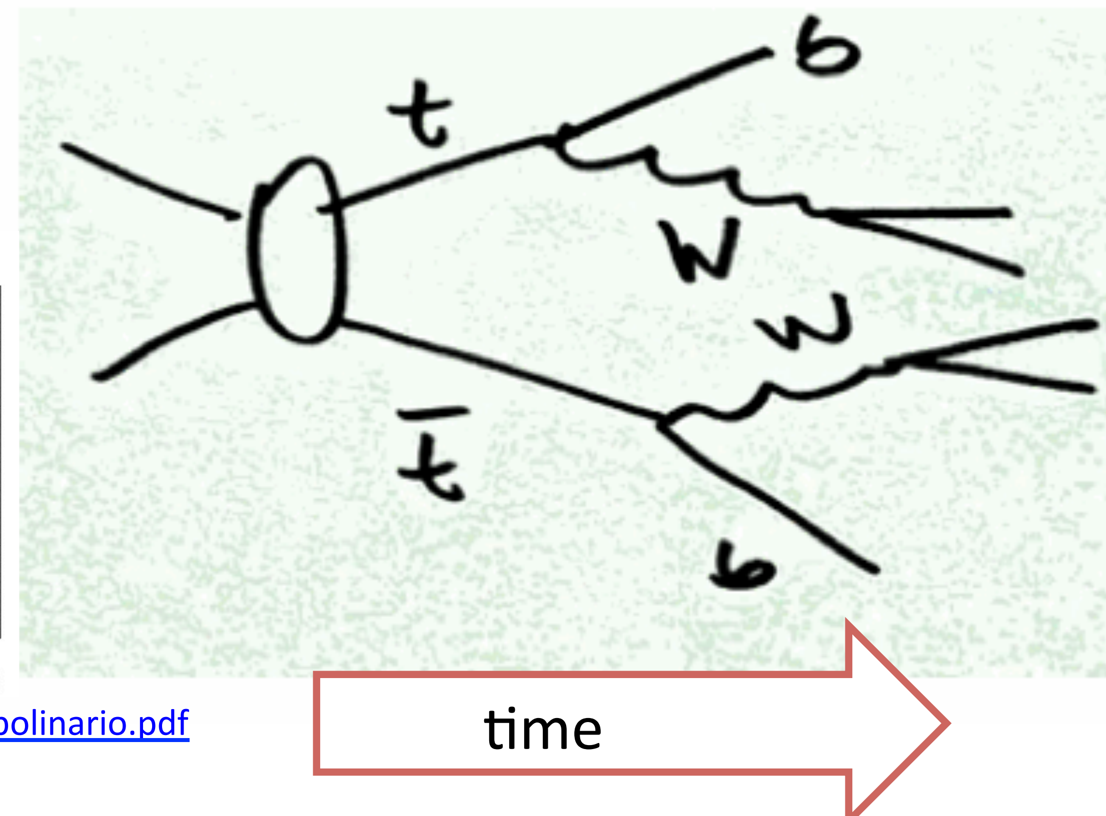
$\sigma_{ttbar \rightarrow qqbar + \mu\nu}$ ~ 10 pb (LHC) and 1 nb (FCC)

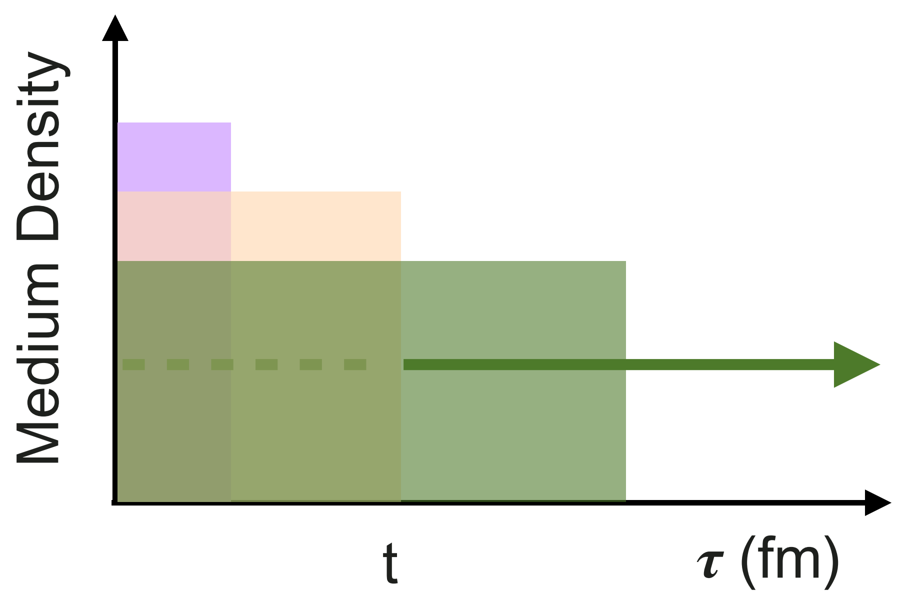
An "antena" scenario:





http://www.int.washington.edu/talks/WorkShops/int_17_1b/People/Apolinario_L/Apolinario.pdf





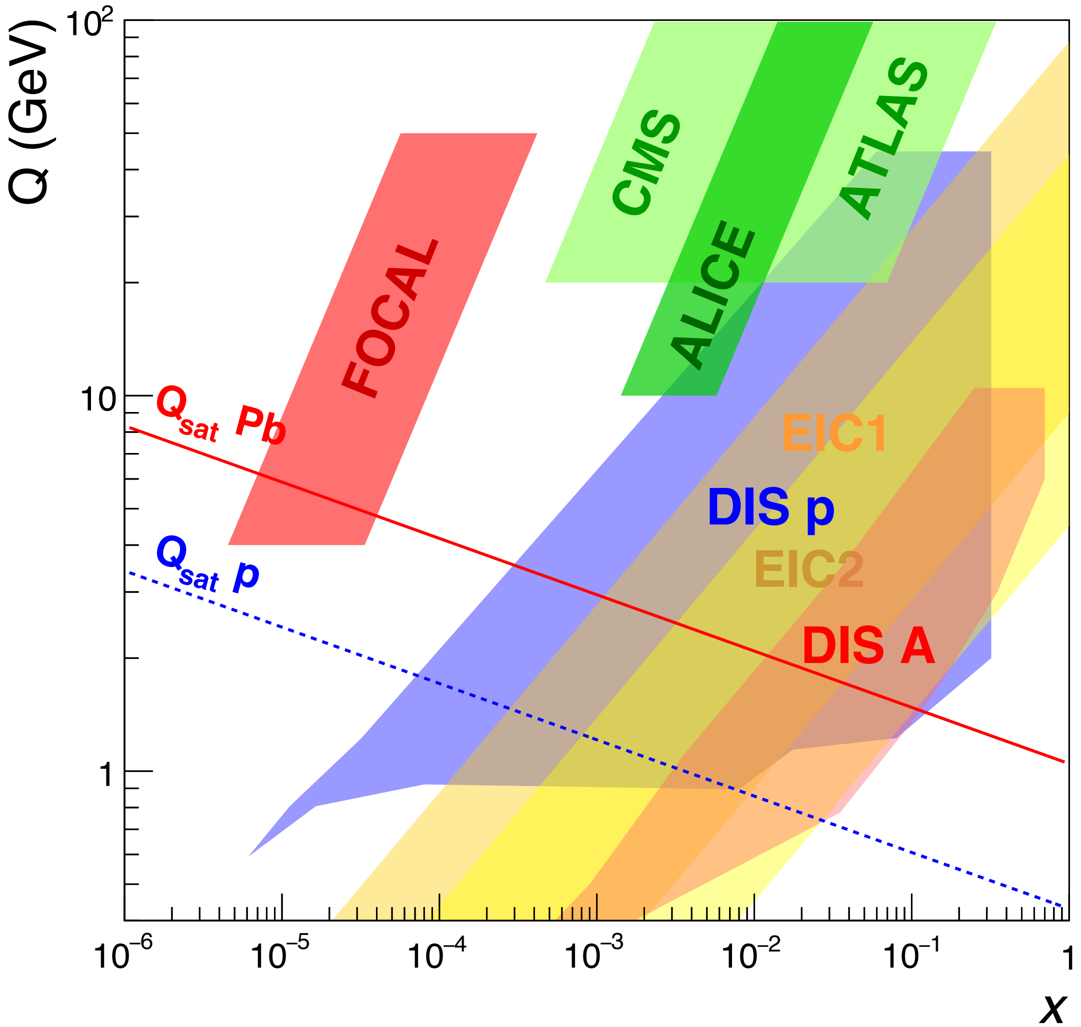
time

	Pt=1 TeV	Pt=500 GeV
ttbat produced	0 fm/c	0 fm/c
top → W+b	1 fm/c	0.5 fm/c
W decay	1.6 fm/c	0.8 fm/c
qqbar in singlet	2.3 fm/c	1.3 fm/c

L. Apolinário, G. Salam (CERN), C. A. Salgado (USC) (IST), G. Milhano (IST and CERN),

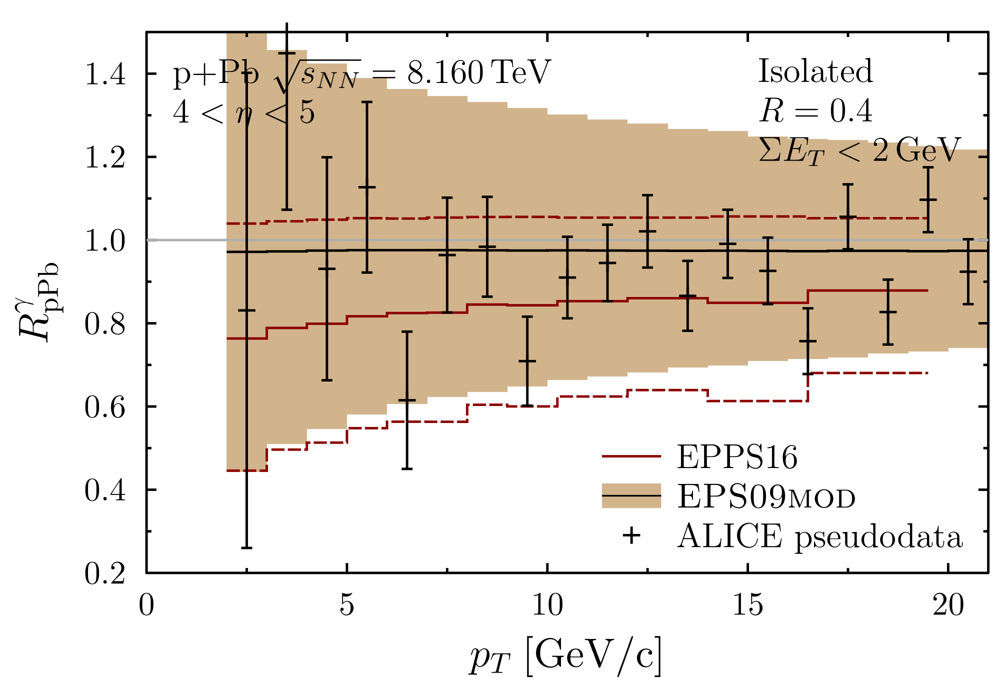
LHC: new instrumentation for saturation physics

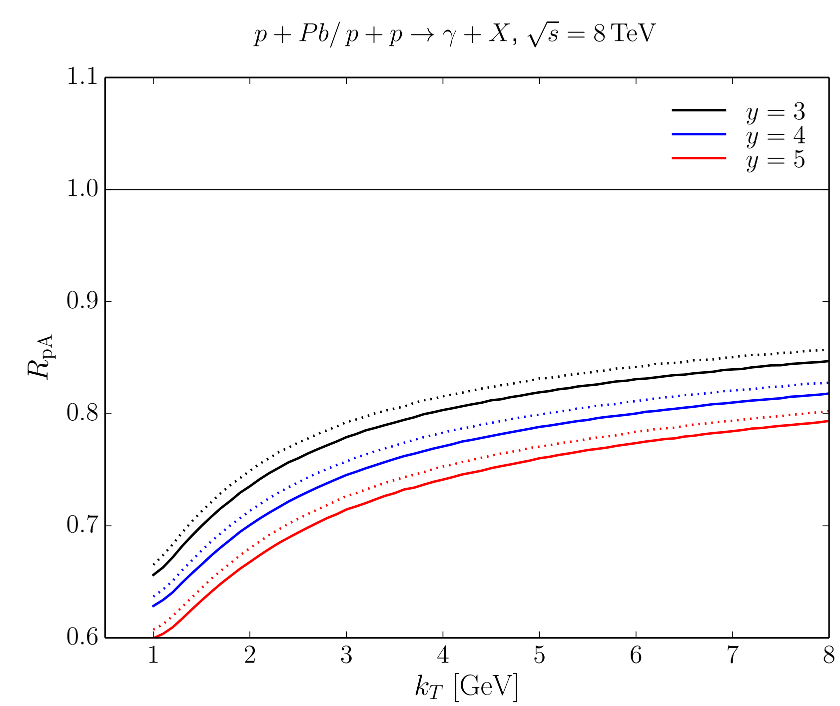
ALICE Forward Calorimeter (proposal & R&D)



1. prove or refute gluon saturation
   - compare saturation models with linear QCD
   - depends on saturation model implementation and flexibility of PDF analytical shape
2. show invalidity of linear QCD at low *x*
   - can all potential measurement outcomes be absorbed in a modified PDF?
3. constrain the PDFs at low x
   - nuclei, also protons

- main observable: nuclear modification factor R_{pA} of direct photons
  - saturation stronger in nuclei
  - possibly non-existent in protons (calculation of reference in models?)





CGC Calculation:
Ducloué, Lappi, Mäntysaari,

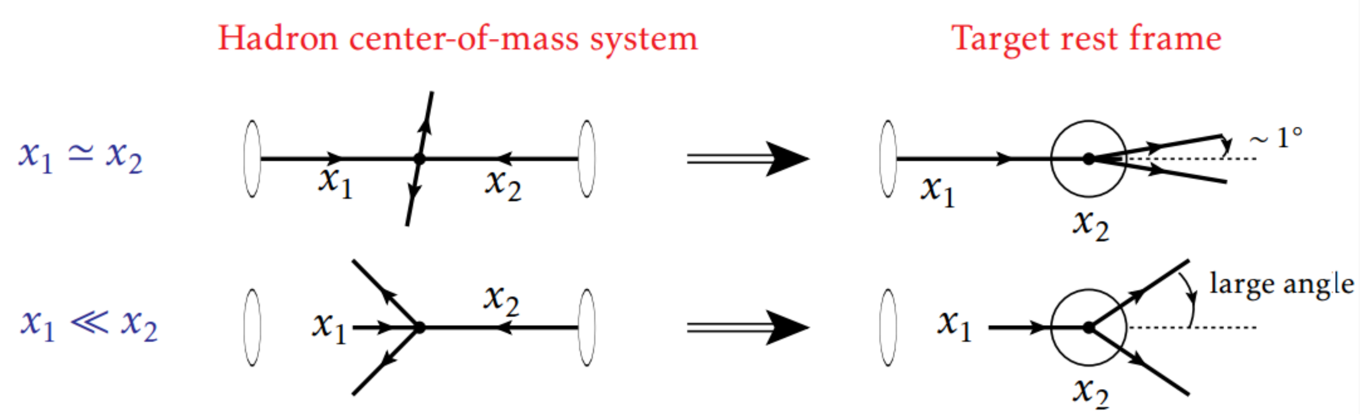
LHC: fixed target experiment

http://after.in2p3.fr/after/index.php/Talks#Talks_on_AFTER

Why a fixed-target experiment at the LHC?

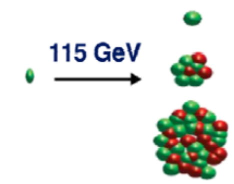
- High luminosities → access to rare probes (heavy quarks)
- High precision Heavy-Ion program between SPS and RHIC top energy
- Access to high Feynman x_F domain ($|x_F| = |p_z|/p_{z\,max} \rightarrow 1$)
- Variety of atomic mass of the target,
- Large kinematic coverage
- Polarization of the target → spin physics at the LHC

Boost effect → access to backward physics



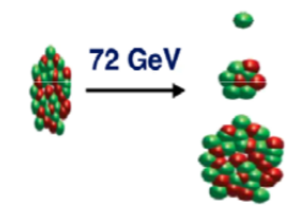
backward physics = large-x_2 physics ($x_F < 0 \rightarrow$ large x_2)

- p+p or p+A with a 7 TeV p on a fixed target



$$\sqrt{s} = \sqrt{2 m_N E_p} \approx 115\,GeV$$
$$y_{CMS} = 0 \rightarrow y_{Lab} = 4.8$$

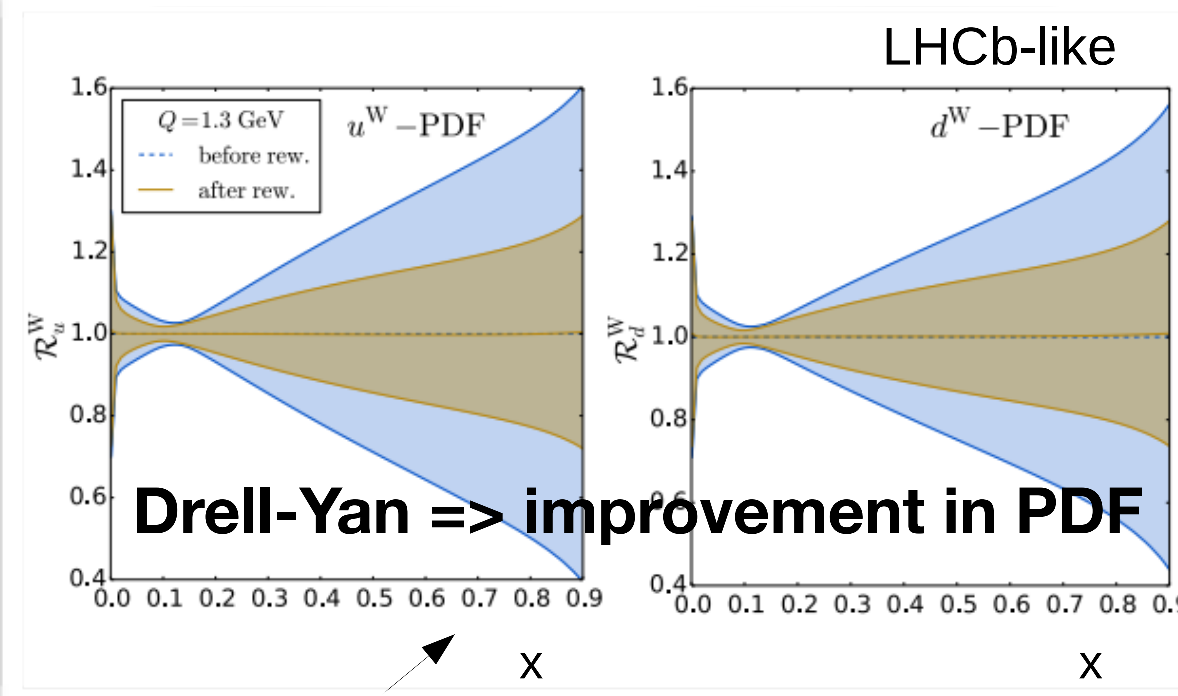
- A+A collisions with a 2.76 TeV Pb beam



$$\sqrt{s} \approx 72\,GeV$$
$$y_{CMS} = 0 \rightarrow y_{Lab} = 4.3$$

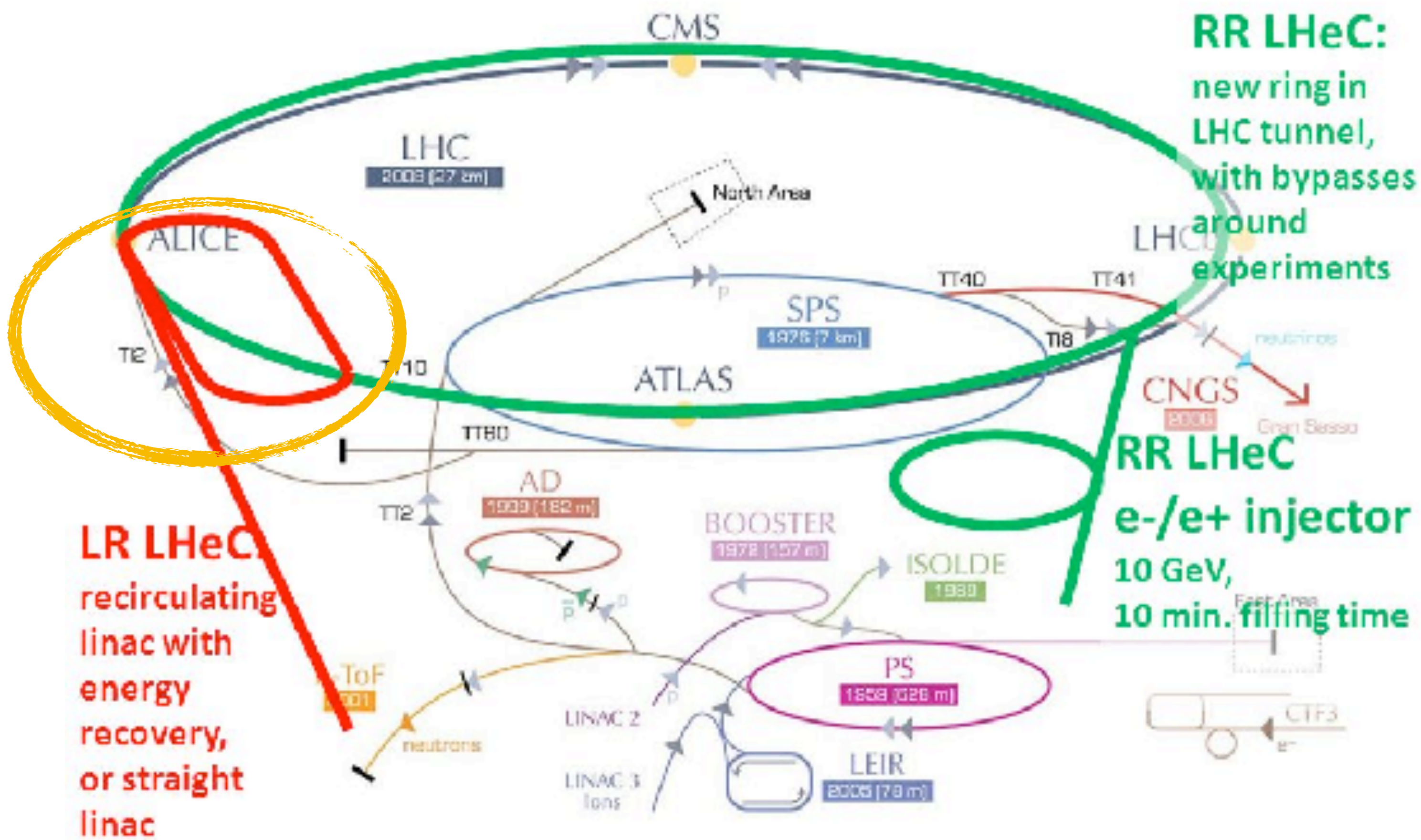
How to make fixed-target collisions with the LHC beams?

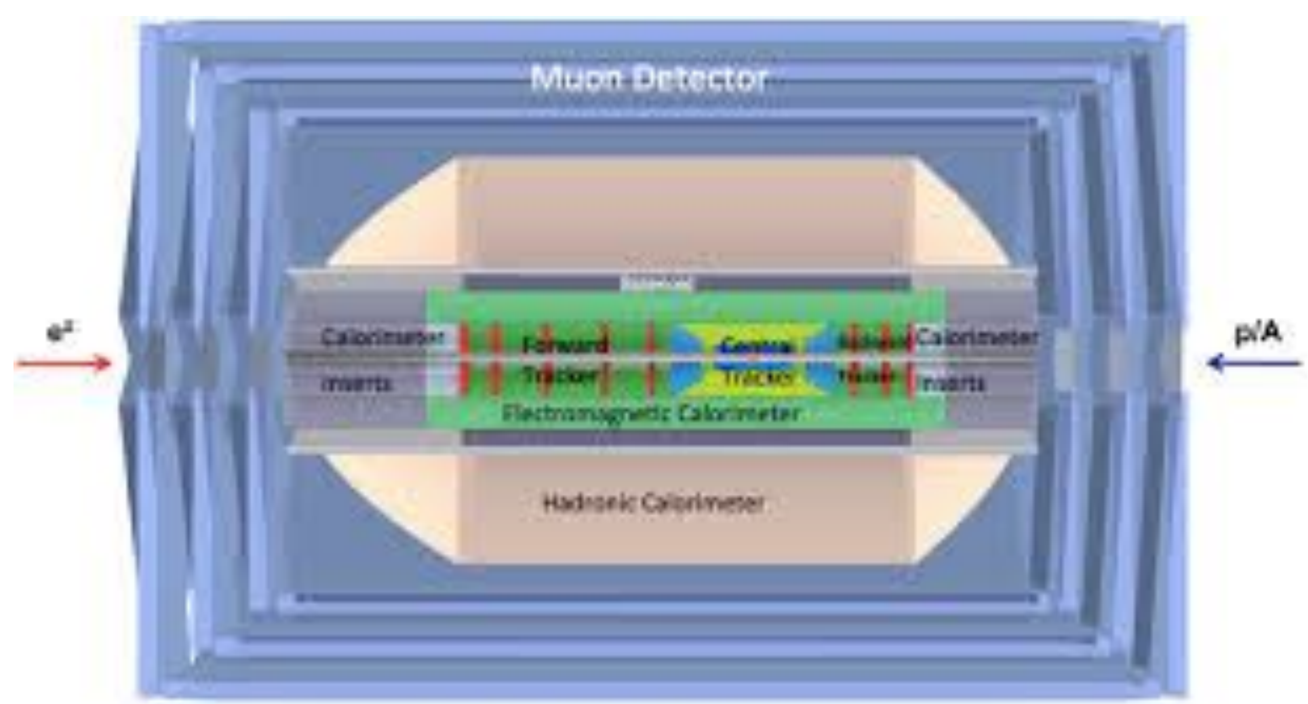
- Internal (solid or gas) target + existing detector
  - gas target (unpolarized/polarized) and full LHC beam
  - beam splitting by bent-crystal + internal (solid, pol.?) target
  - internal Wire/Foil target (directly in the beam halo)
- Beam extraction by bent-crystal
  - new beam line + new experiment



electron-ion collider(s)?

LHeC – several options





electron-ion collider(s)?

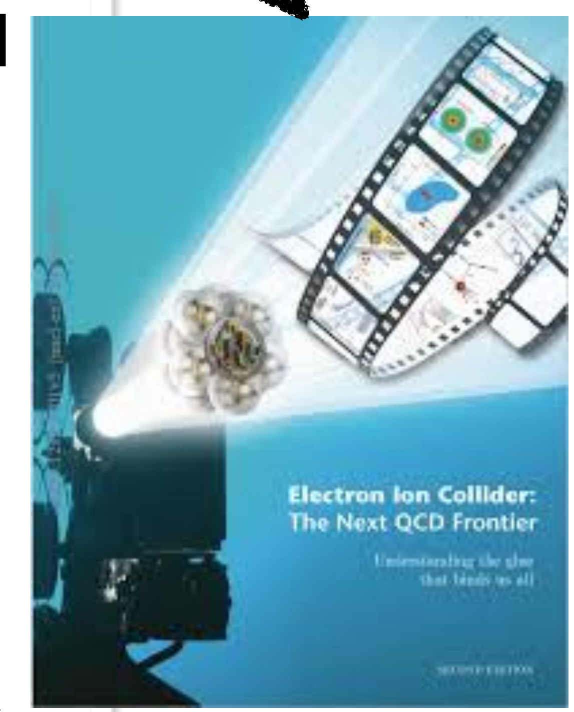
White Paper documents the physics case of an EIC
Eur.Phys.J. A52 (2016), 268; arXiv:1212.1701

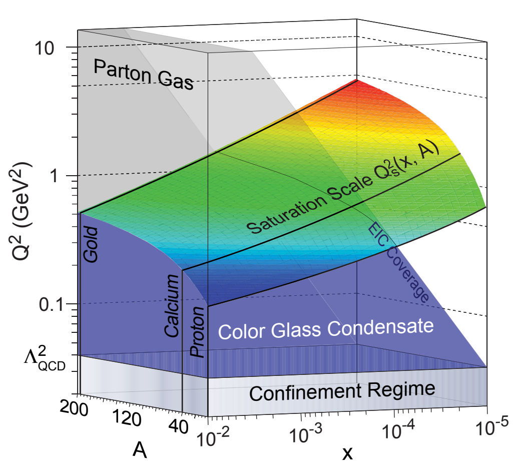
Electron-Ion Collider: Goals

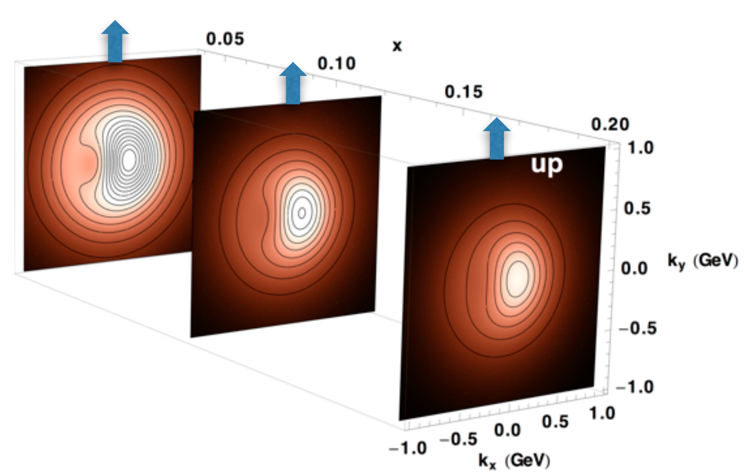
Investigate with precision universal dynamics of gluons

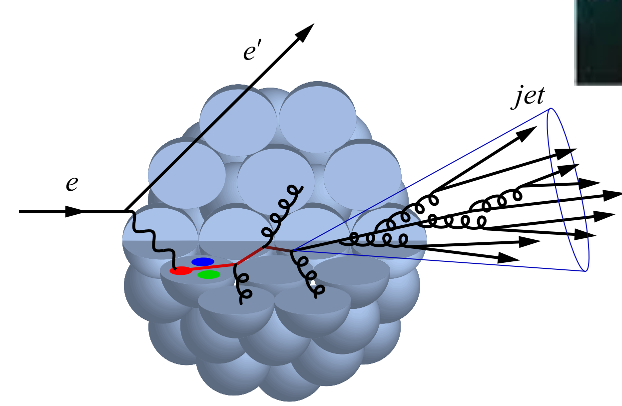
Central themes:

- Probing the momentum-dependence of gluon densities and the onset of saturation in nucleons and nuclei
- Mapping the transverse spatial and spin distributions (imaging) of partons in the gluon-dominated regime
- Provide novel insight into propagation, attenuation and hadronization of colored probes









T. Ullrich

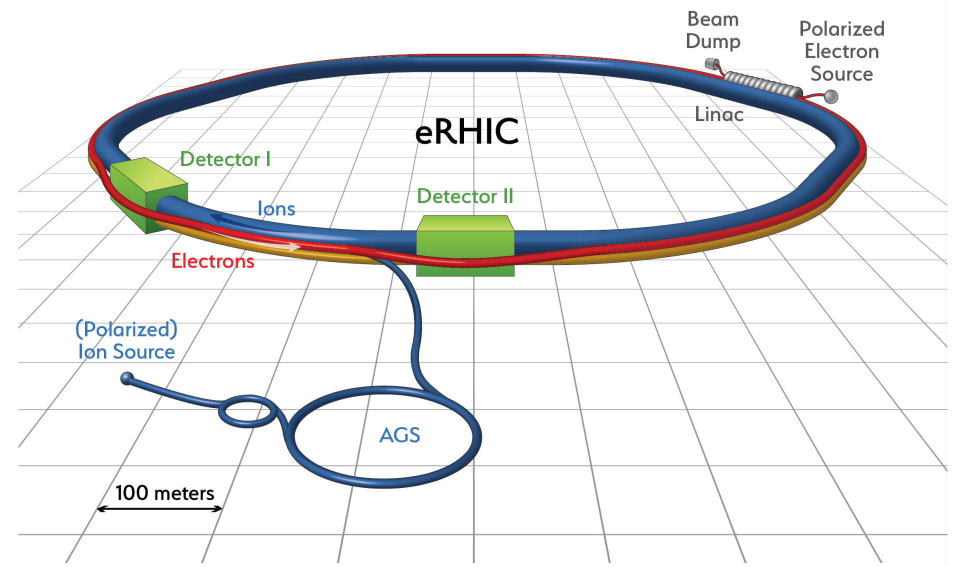
electron-ion collider(s)?

White Paper documents the physics case of an EIC: Eur.Phys.J. A52 (2016), 268; arXiv:1212.1701

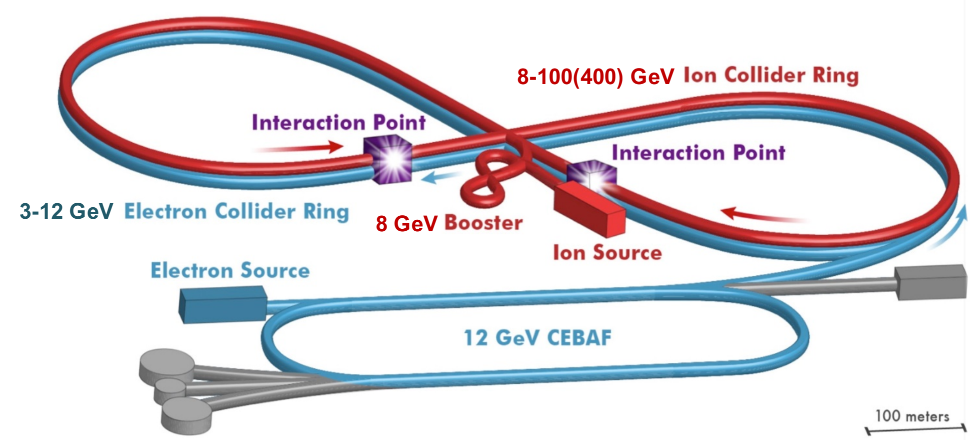
US Electron Collider: Realization

T. Ullrich

- **eRHIC (BNL)**
  - Add e Rings to RHIC facility: Ring-Ring (alt. recirculating Linac-Ring)
  - Electrons up to 18 GeV
  - Protons up to 275 GeV
  - $\sqrt{s}$=30-140 $\sqrt{(Z/A)}$ GeV
  - L ≈ 1×10^{34} $cm^{-2}s^{-1}$ at $\sqrt{s}$=105 GeV



- **JLEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF as injector
  - Electrons 3-10 GeV
  - Protons 20-100 GeV
  - e+A up to $\sqrt{s}$=40 GeV/u
  - e+p up to $\sqrt{s}$= 64 GeV
  - L ≈ 2×10^{34} cm^{-2} s^{-1} at $\sqrt{s}$=45 GeV

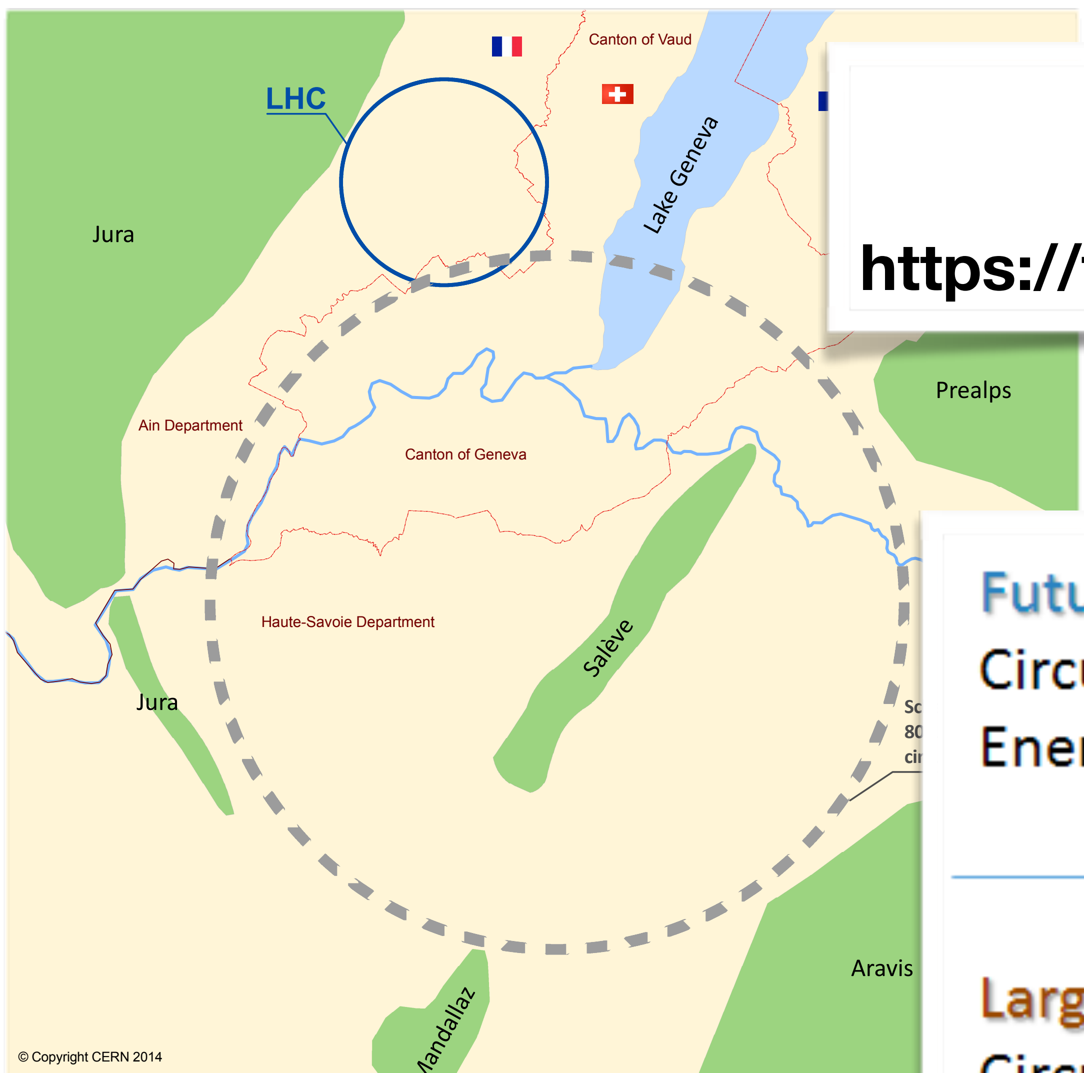


eRHIC: arXiv:1409.1633, JLEIC: arXiv:1504.07961

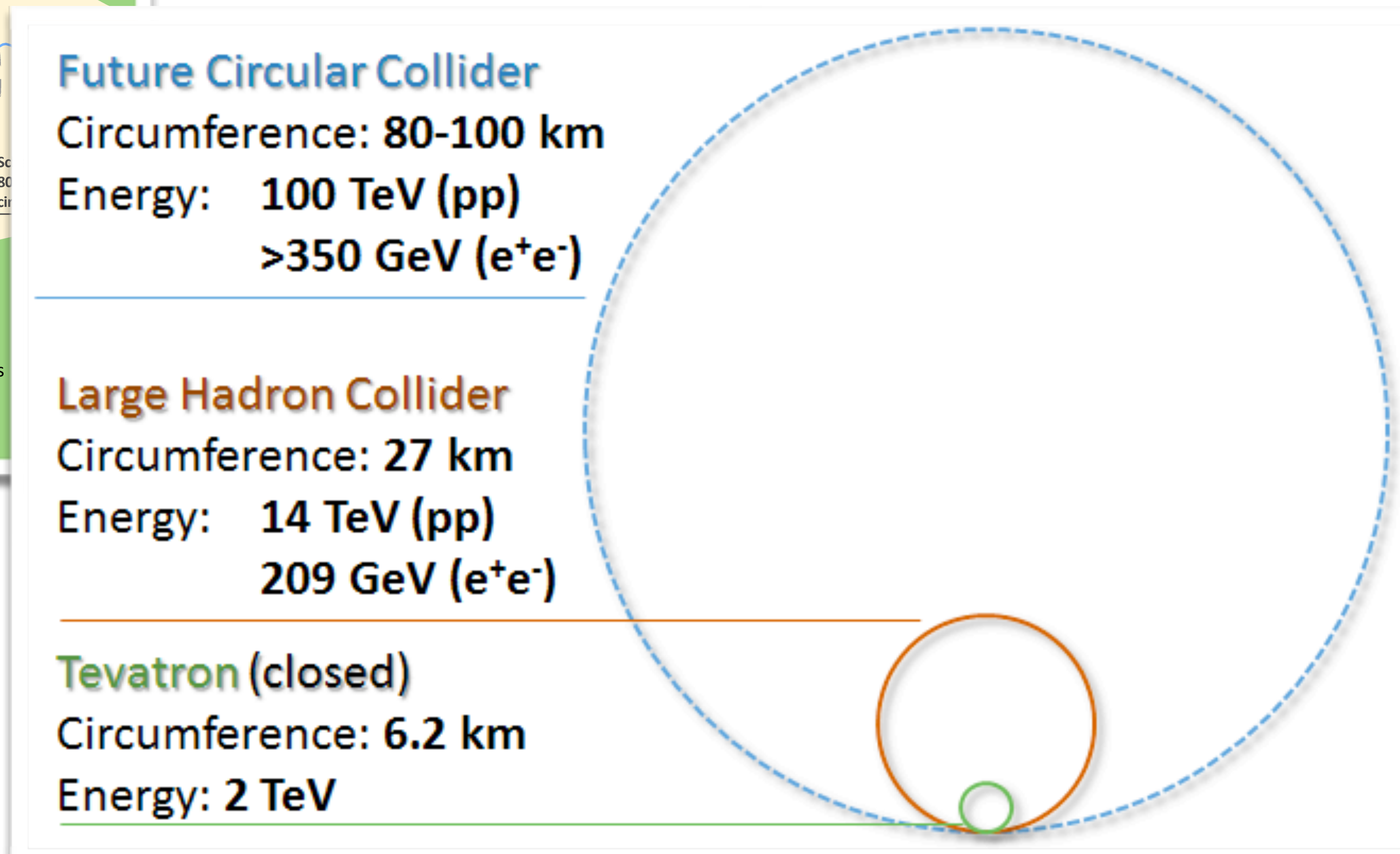
- EIC PID needs are more demanding then your 'normal' collider detector
- EIC needs absolute particle numbers at high purity and low contamination

Future Circular Collider

https://fcc.web.cern.ch/Pages/default.aspx



Heavy-ions at FCC:
https://arxiv.org/abs/1605.01389
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons



Notes on the future

- LHC Run-3 (Run-2 ends 2019)
  - 10/nb AA data (10^{11} events!)
  - Potentially another pPb run (202X?)
- RHIC: new sPHENIX experiment
  - Continued Beam Energy Scan
  - High rate jet detector (high statistics jets)
- Electron-Ion collider?
  - A USA based machine (RHIC? JLAB?)
    - Construction 2025++ (significantly beyond 2025)
  - LHeC - conceptual work ongoing
- Future Circular Collider?
  - 40TeV PbPb Collisions (100 TeV pp machine)

What we did NOT talk about?

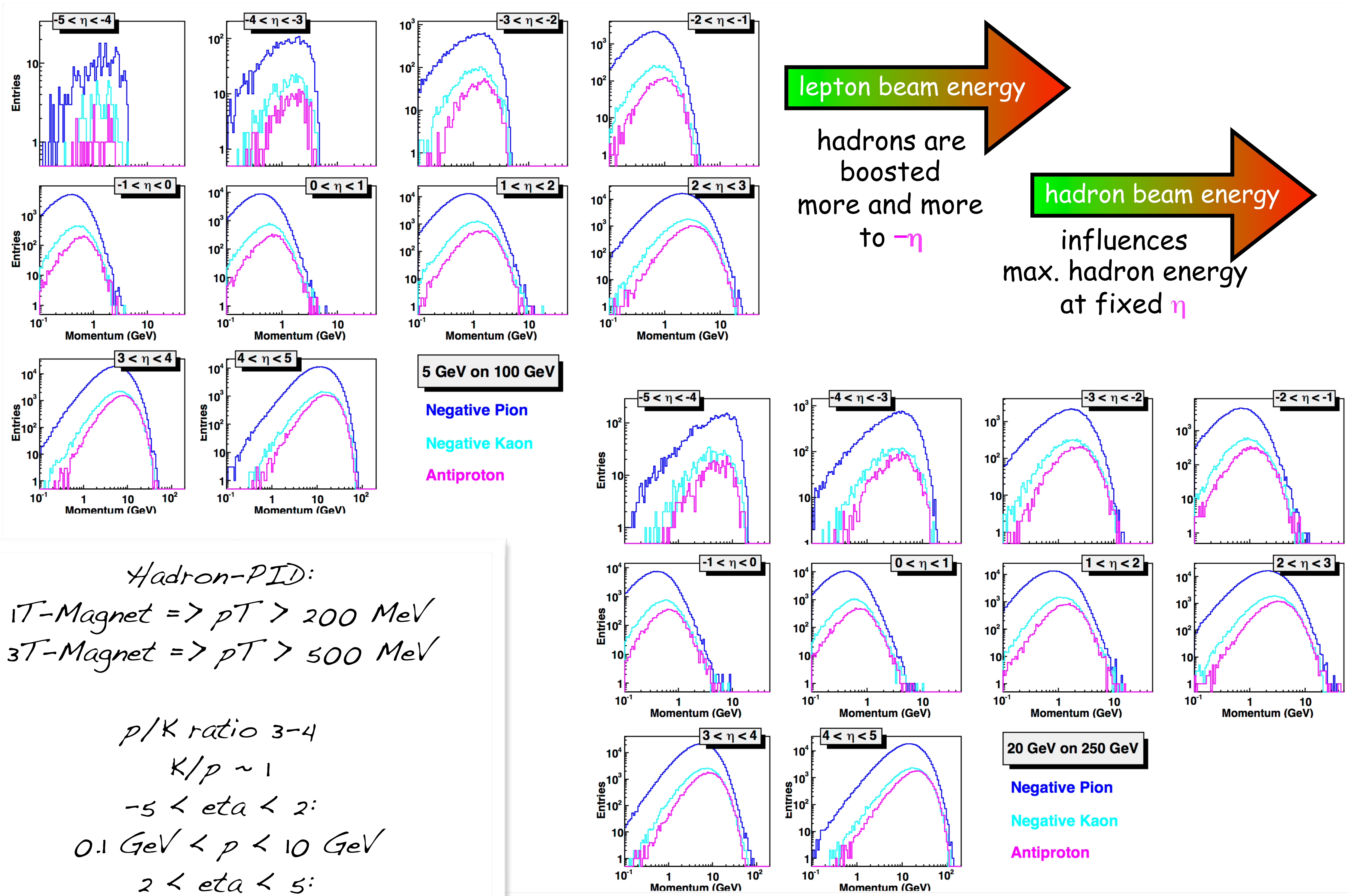
- Beam energy scan at RHIC: looking for critical point on QCD phase diagram; physics of finite baryon density programs (NA61, FAIR, …)
- Di-lepton measurements in AA collisions: messengers of the dynamics; signals for chiral symmetry restoration
- Search for Chiral Magnetic Effect, vorticity in HIC, balance functions, jet hadrochemistry, details of the so-called underlying event - soft-QCD, …
- Novel work on HIC and QGP
- Extraction of QGP parameters with a Bayesian analysis
- Machine learning - quickly developing for HIC:
  - hydrodynamical evolution
  - jets and jet quenching quenching

Thank you!

Drop me an email in case of questions: mploskon@lbl.gov

Additional Slides

Detector requirements from physics - an EIC example



Hadron-PID:

1T-Magnet => pT > 200 MeV

3T-Magnet => pT > 500 MeV

p/K ratio 3-4

K/p ~ 1

-5 < eta < 2:

0.1 GeV < p < 10 GeV

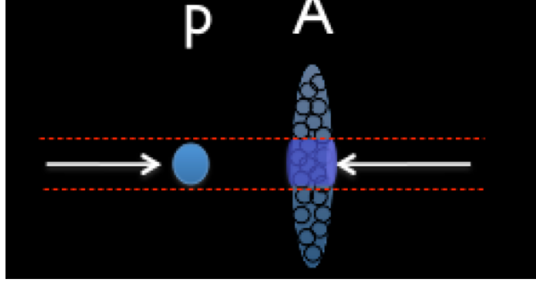
2 < eta < 5:

0.1 GeV < p < 100 GeV

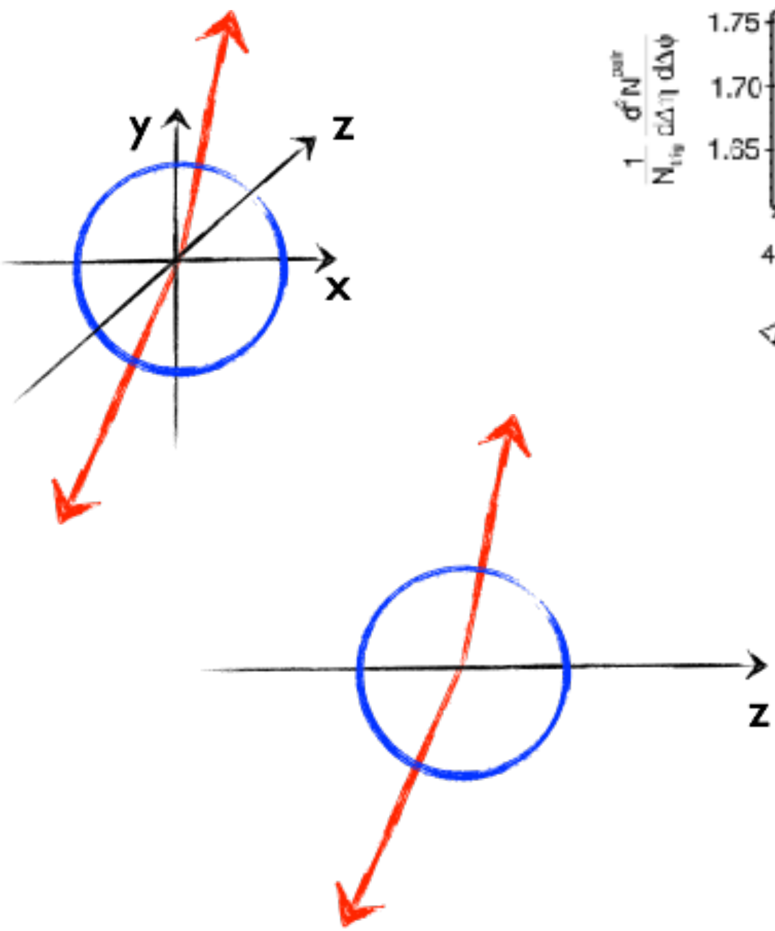
=> impact on choice of technology

Unexpected novel effects...

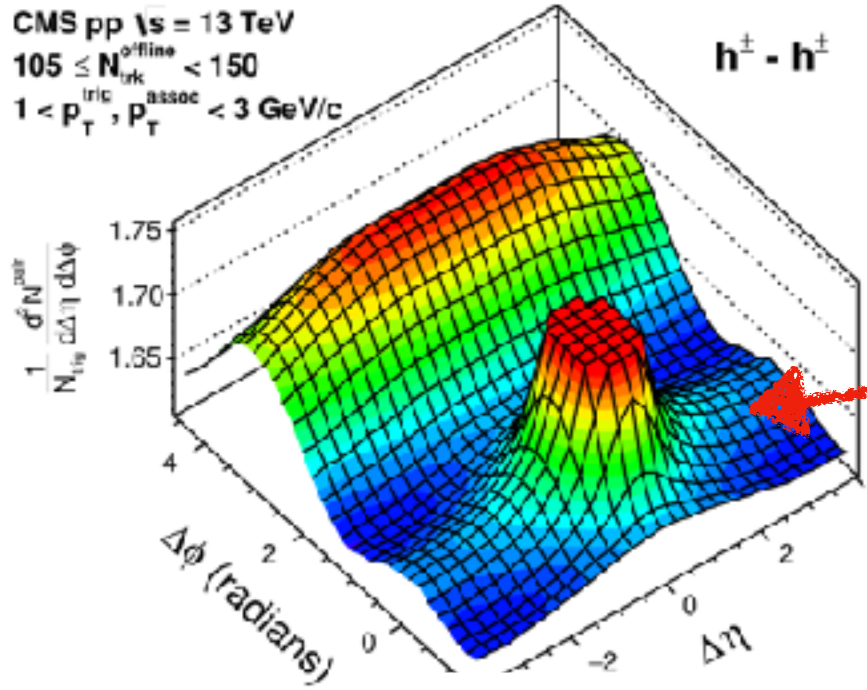
Quem mandou isso?



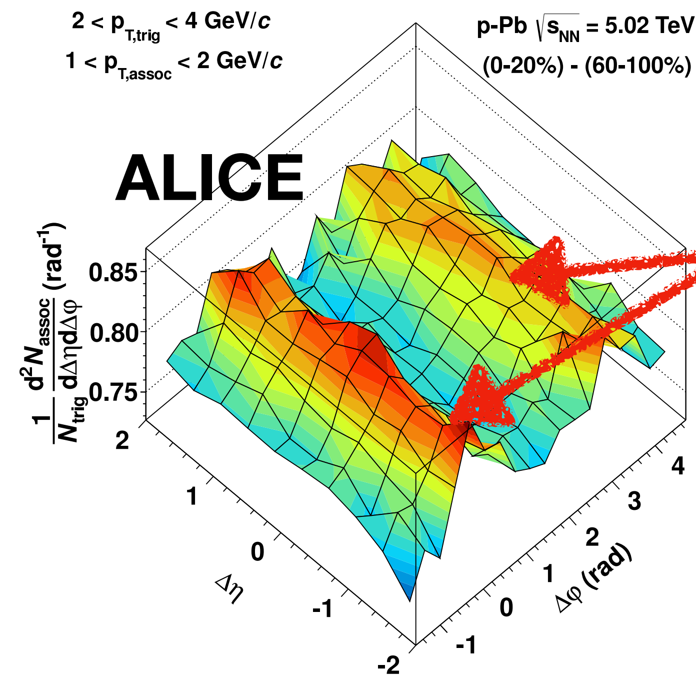
Δφ azimuthal angle difference
- angle in the transverse plane



Δη - longitudinal - pseudo-rapidity distance



Long-range correlation structure in high-multiplicity pp collisions

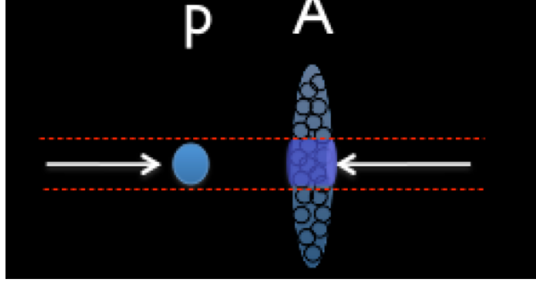


Long-range correlation double structure in high-multiplicity pPb collisions

Similar observations made by ATLAS & LHCb

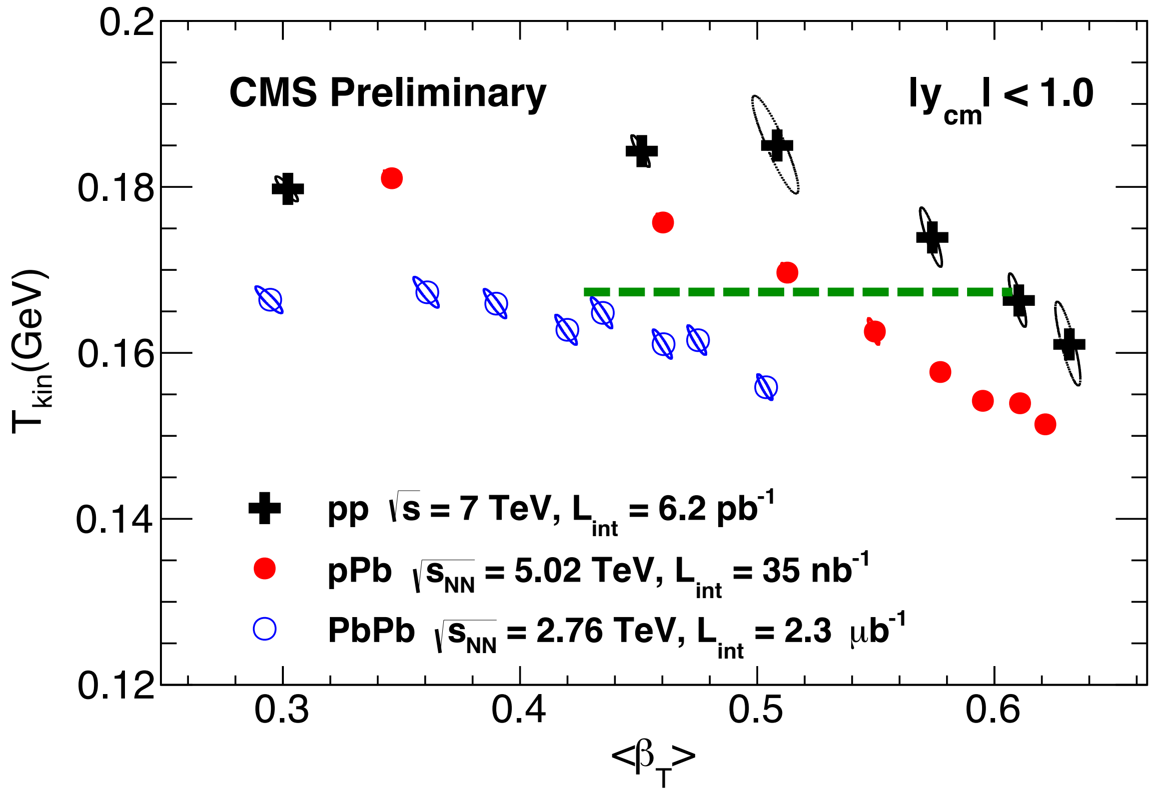
Long range correlations are intimately related to initial stages - early times - ~10^{-24}s.
Do we fully understand initial stages of nuclear collisions? - No (!).
ALICE: + (not shown) indication of v_2>HF (?) in p-Pb collisions (muon-hadron correlations)

Quem mandou isso?

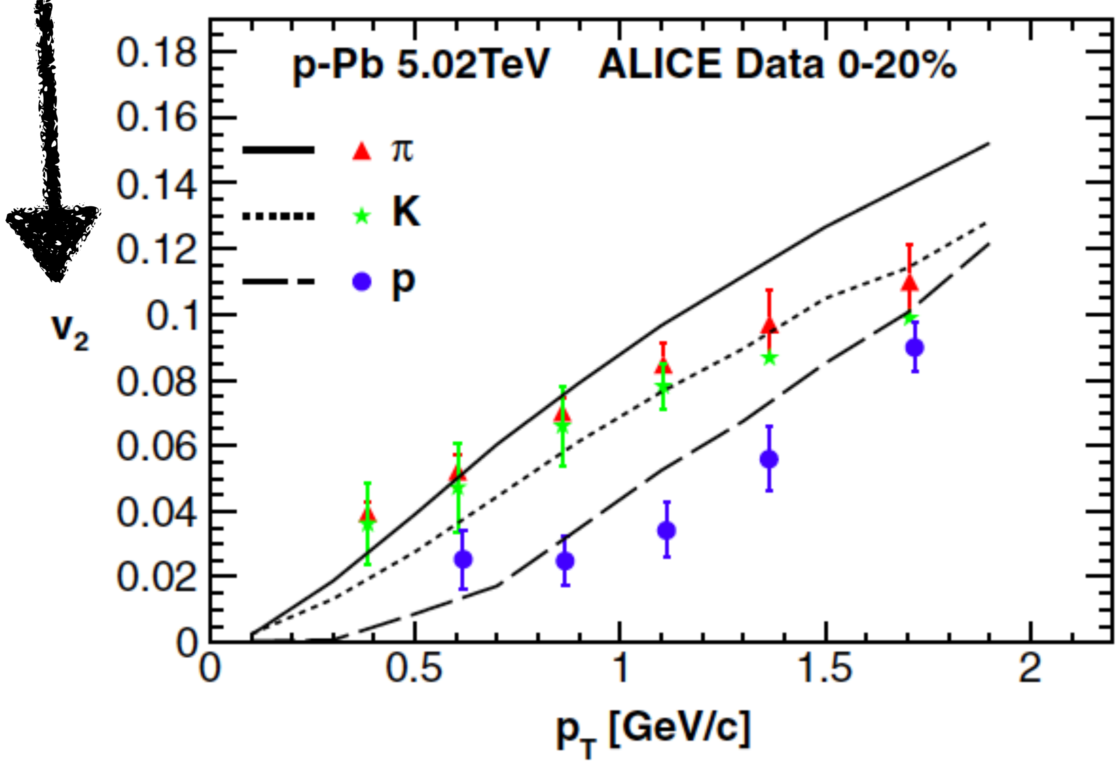


Blast-wave fits - different freeze-out among systems (50.5 caveat); however, events with similar T_{kin} need further understanding/investigation

Hydrodynamics?: mass splitting
However: also qualitatively reproduced in UrQMD (non-flow)



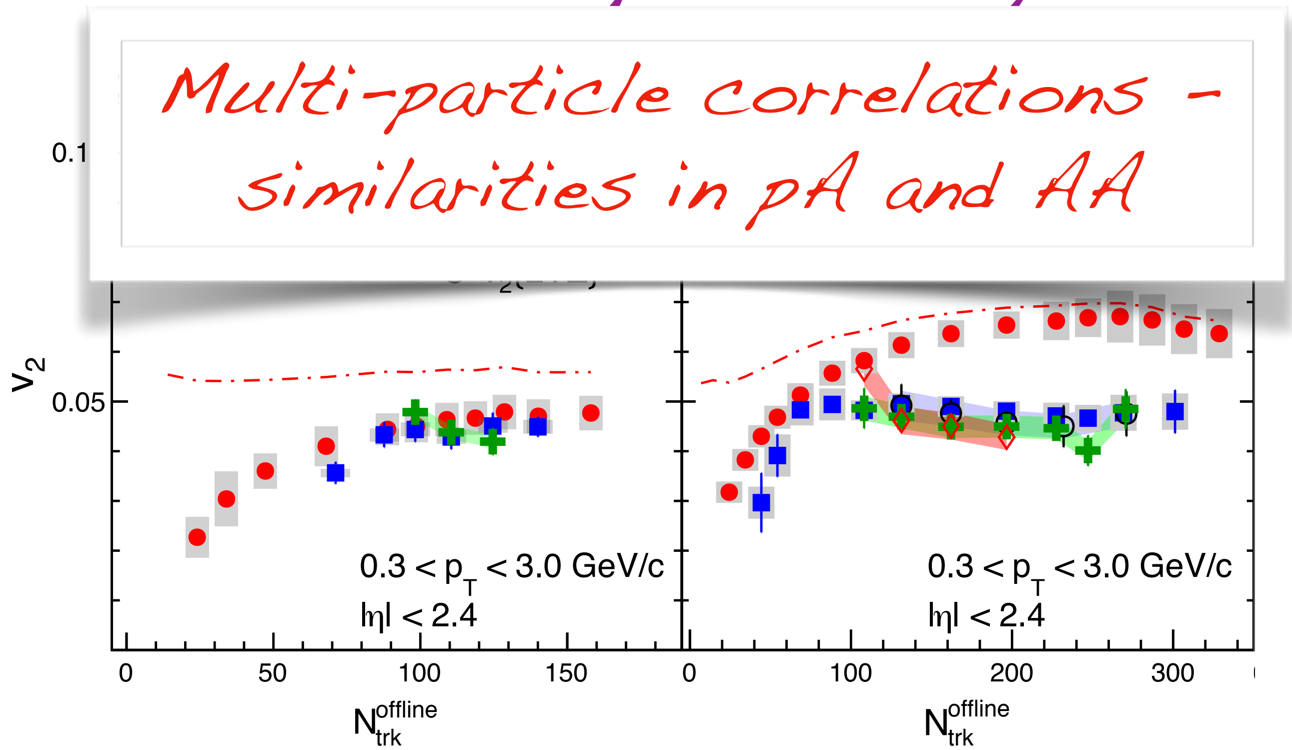
P. Bozek et al., Phys Rev Lett 111, 172303

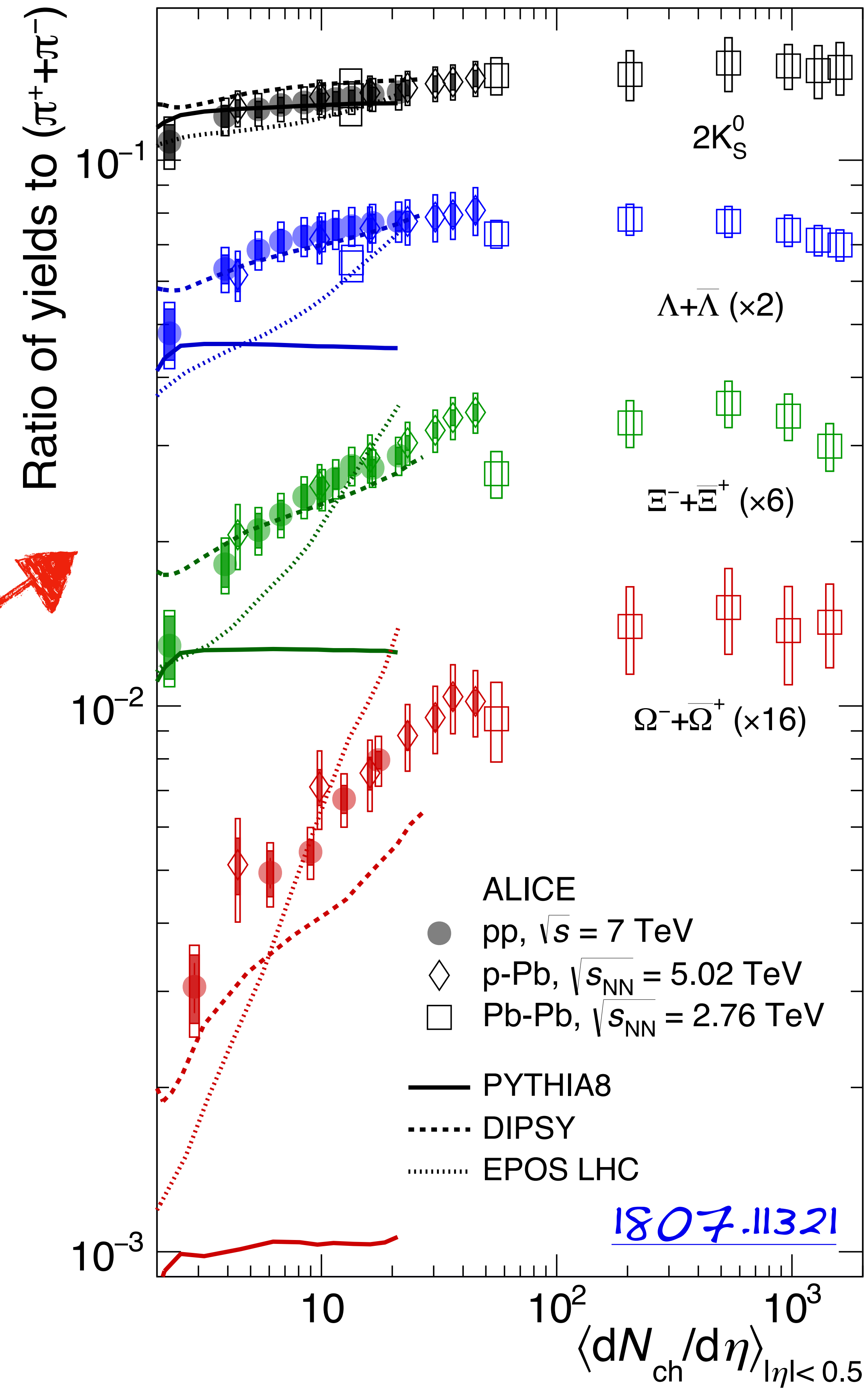


Long range correlations are intimately related to initial stages - early times - ~10^{-24}s.
Do we fully understand initial stages of nuclear collisions? - No (!).
ALICE: + (not shown) indication of v_2>HF (?) in p-Pb collisions (muon-hadron correlations)

Particle production as a function of multiplicity

Multi-particle correlations - similarities in pA and AA

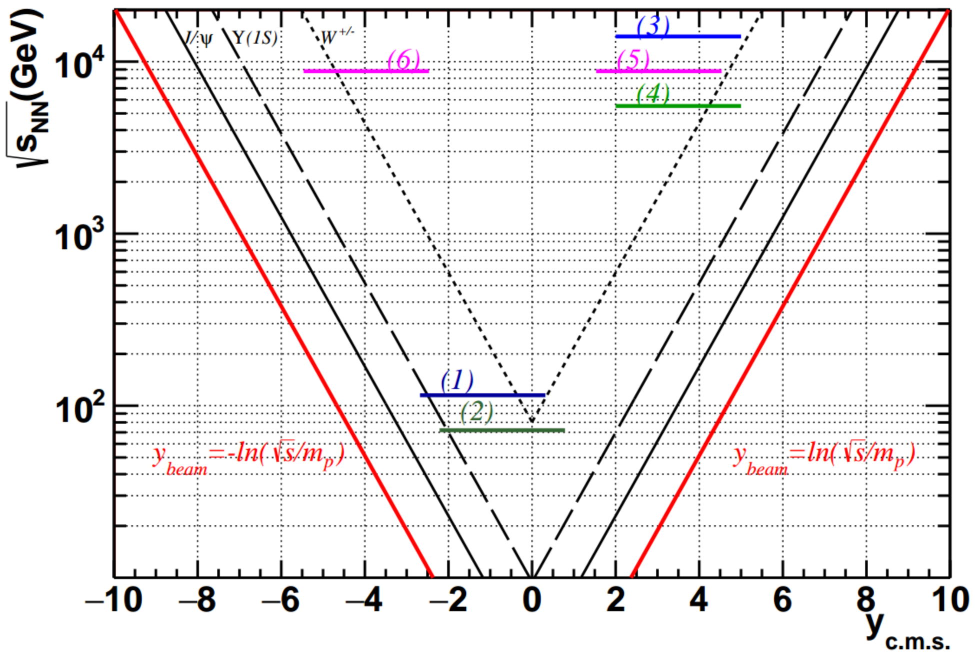




Strangeness - striking continuous evolution with event multiplicity from pp to AA

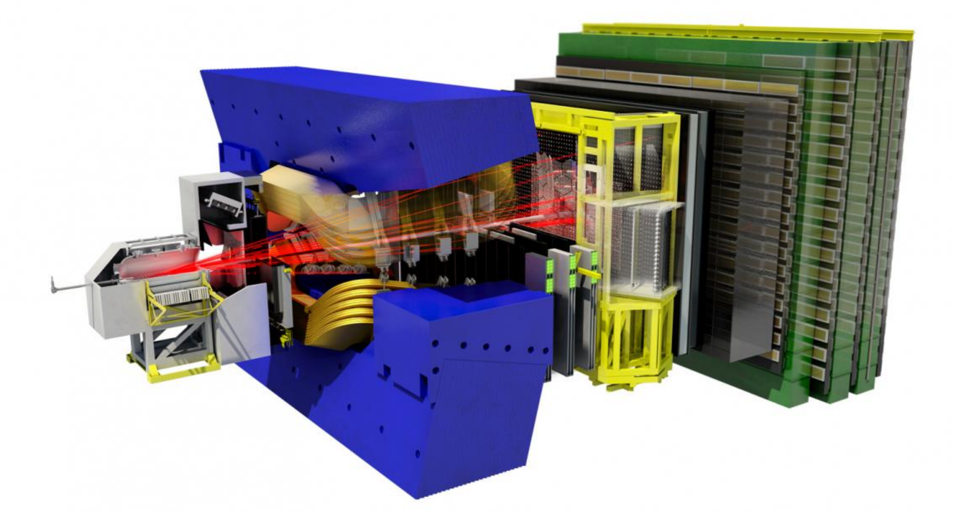
All this while jet quenching is not present in pPb collisions...
Limit obtained using hadron-jet correlations ($\Delta E < 0.04$)

Kinematic coverage: collider vs fixed target



LHCb: $2 < \eta^{lab} < 5$

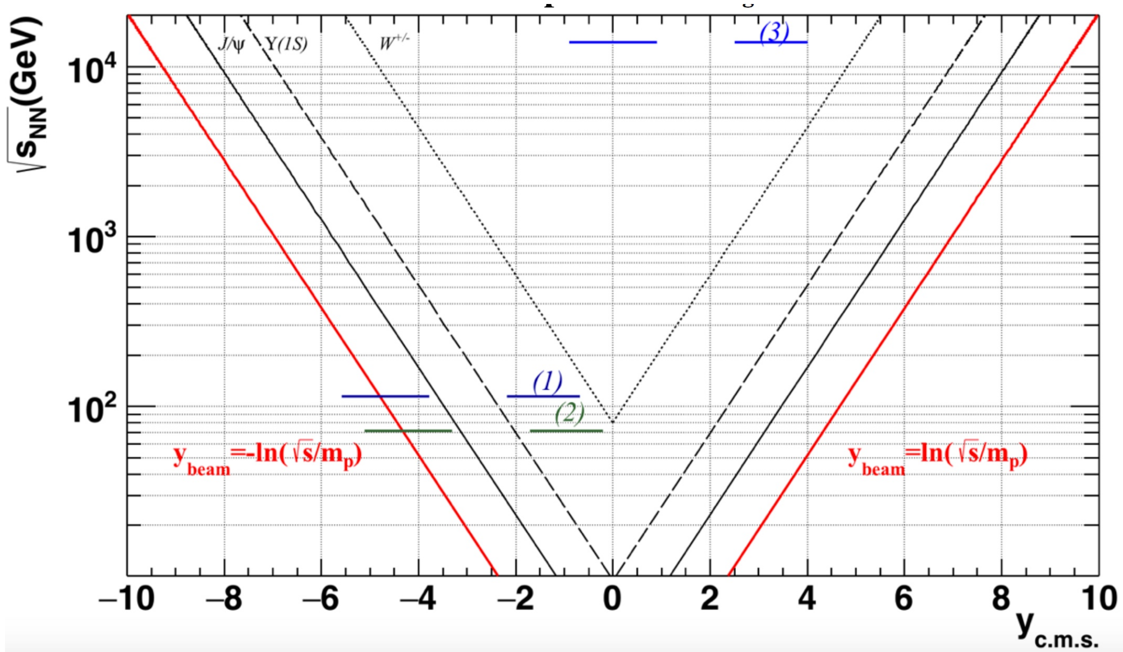
LHCb detector



https://lhcb.web.cern.ch/lhcb

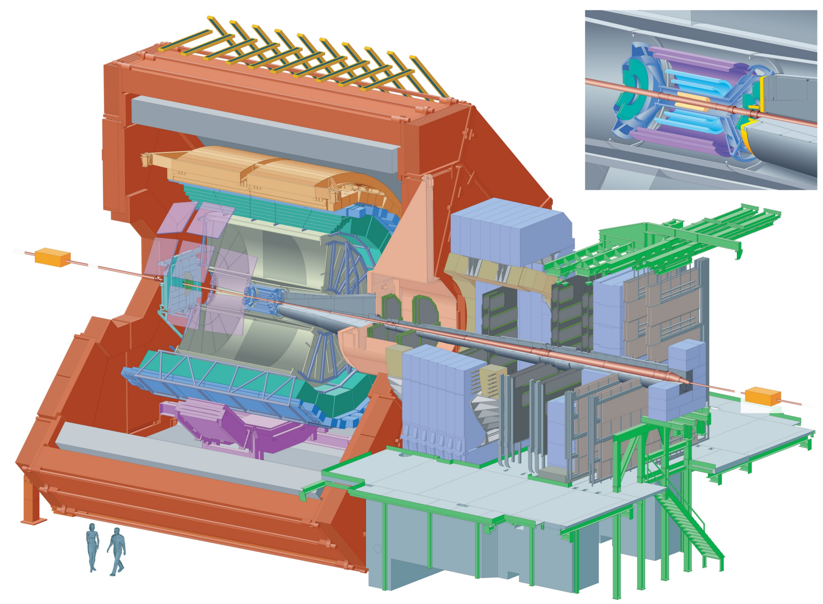
(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV; (2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;
(3) collider mode, $\sqrt{s}$ = 14 TeV; (4) collider mode, $\sqrt{s_{NN}}$ = 5.5 TeV, (5),(6) $\sqrt{s_{NN}}$ = 8.8 TeV

Kinematic coverage: collider vs fixed target



ALICE: Muon Det.: $2.5 < \eta^{lab} < 4$,
TPC: $|\eta^{lab}| < 0.9$

ALICE detector



http://aliceinfo.cern.ch

(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV; (2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;
(3) collider mode, $\sqrt{s}$ = 14 TeV;

for Z_{target} ~ 0