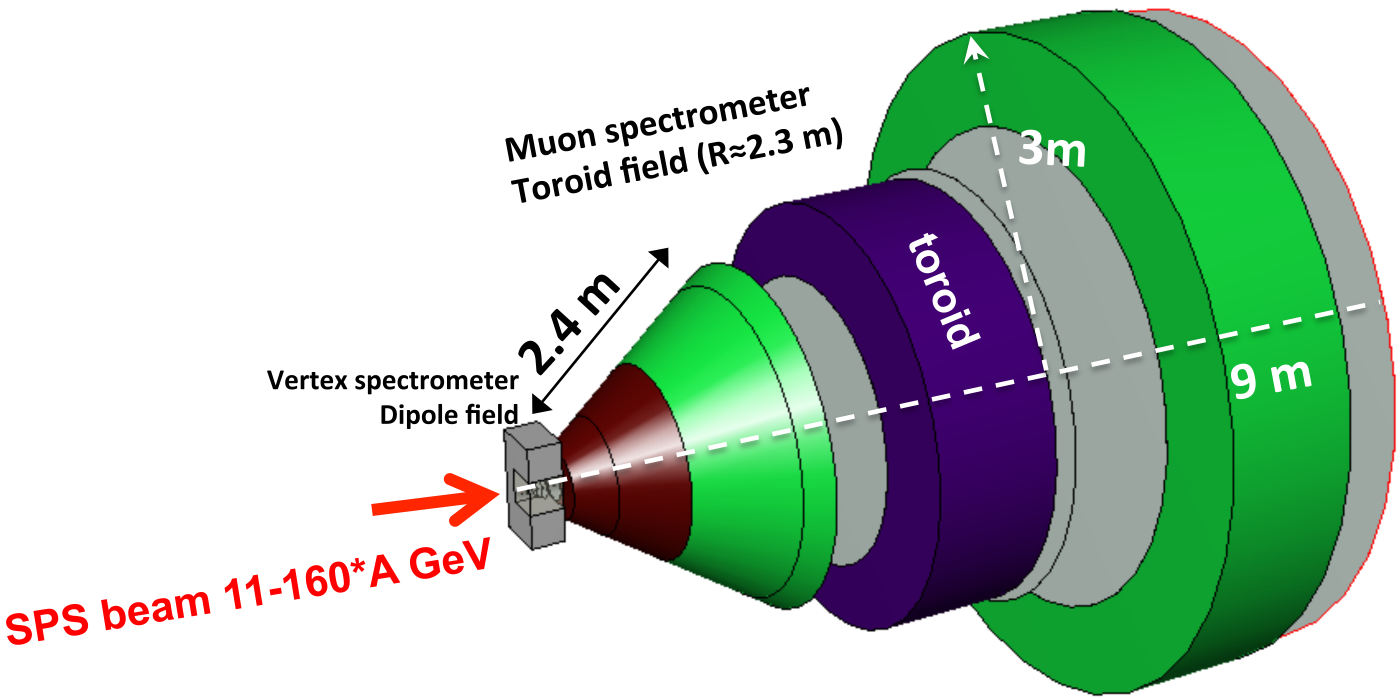
ADDITIONAL MATERIAL

EXTRA SLIDES
FIXED TARGET

WHAT ELSE ?

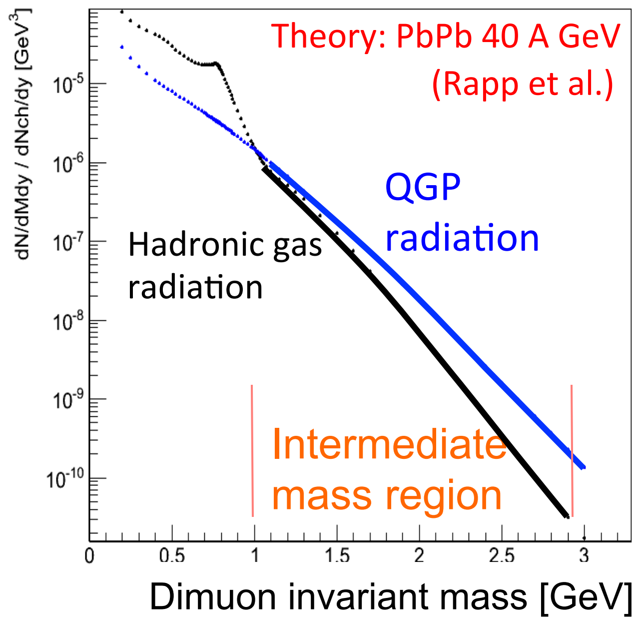
New experiment at SPS?

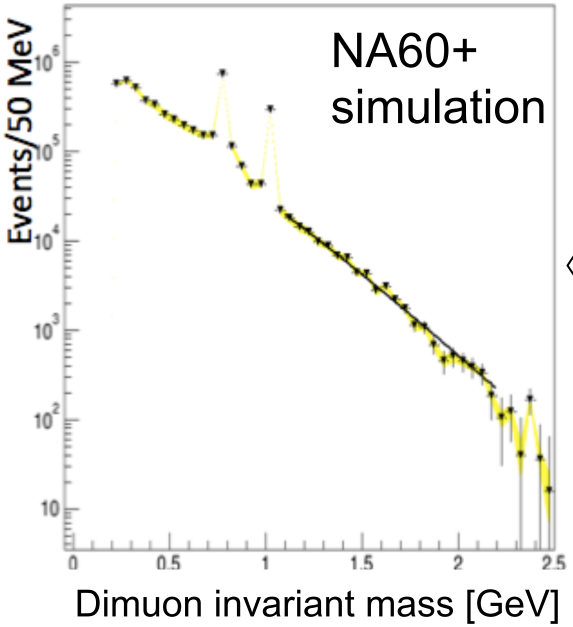
- Precise measurement of electromagnetic radiation and charmonium over full SPS energy range $11 < E_{beam} < 160$ GeV/nucleon and with different nuclei
  - Onset of deconfinement and first order phase transition
  - Chiral symmetry restoration
- Successor of NA60 (2001-2004), similar detector concept (dimuon spectrometer with pixel tracker)
  - First simulation studies carried out (G. Usai, PRIN2009)



Onset of deconfinement: thermal radiation $\gamma^* \rightarrow \mu^+\mu^-$

- $\mu\mu$ mass distribution in intermediate region has contributions from radiation by the QGP and radiation by the hot hadronic gas
- Their relevance depends on how far the system reaches beyond phase transition line
  - Can be varied with beam energy scan
- Onset of deconfiment: QGP radiation dominant





Example observable: slope of mass spectrum dN/dM → temperature T of the source with few MeV precision

E_{Beam} scan → T scan around T_c~150 MeV

Onset of deconfinement: thermal radiation $\gamma^* \rightarrow \mu^+\mu^-$

- $\mu\mu$ mass distribution in intermediate region has contributions from radiation by the QGP and radiation by the hot hadronic gas
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  - Can be varied with beam energy scan
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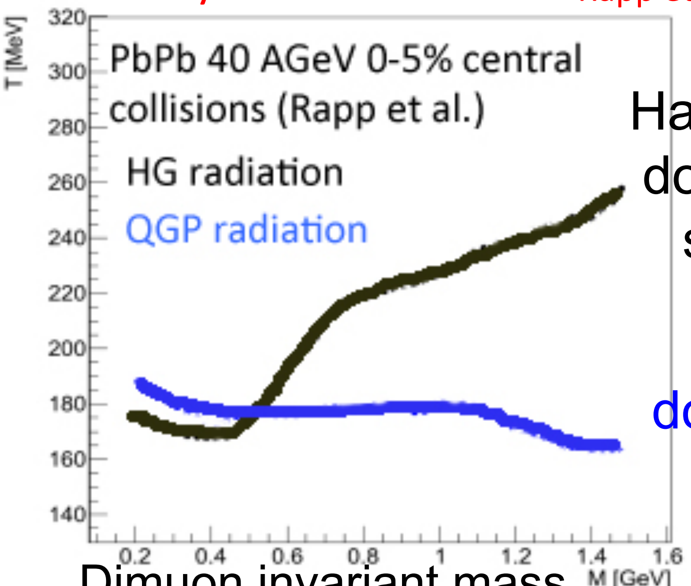
Theory: PbPb 40 A GeV Rapp et al.



Dimuon invariant mass

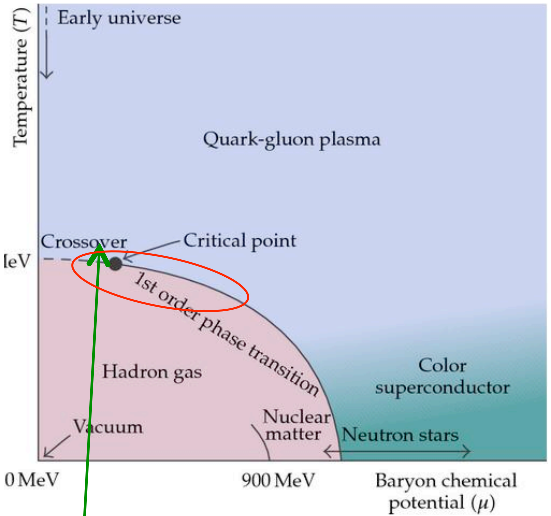
Hadron gas dominated system

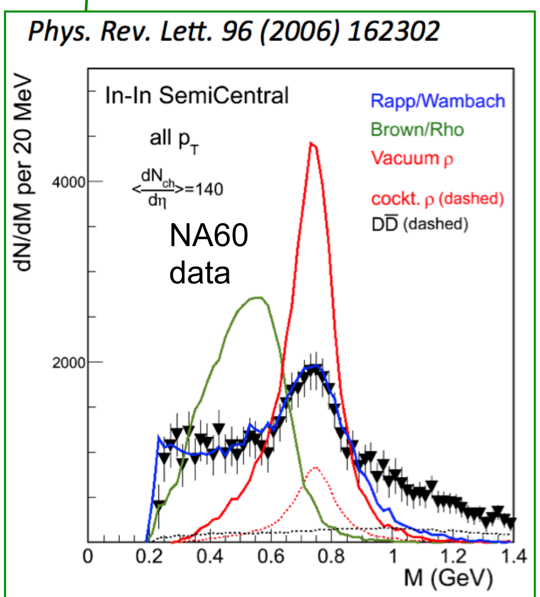
QGP dominated system

2nd observable: slope of p_T spectrum in bins of dimuon M → effective temperature T_{eff}, sensitive to QGP vs. hadronic source

E_{Beam} scan → onset of QGP dominance

Chiral symmetry restoration: ρ spectral function

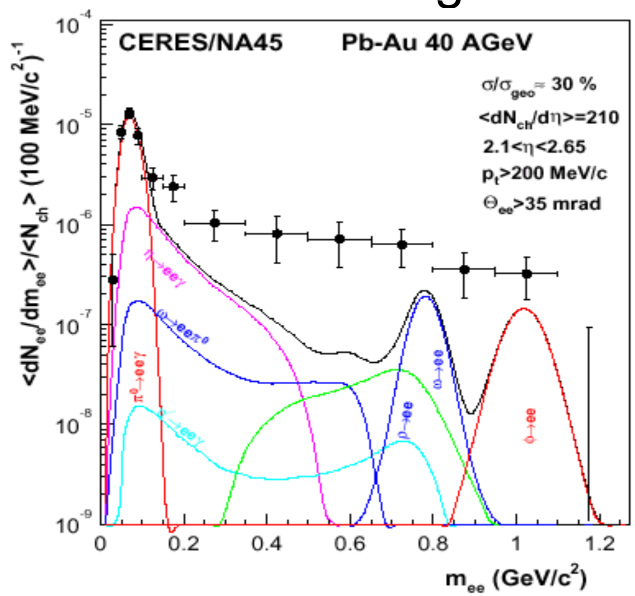




- NA60 data at top SPS energy: broadening of the ρ spectral function interpreted as manifestation of chiral symmetry restoration
- NA60+: measurements vs. beam energy

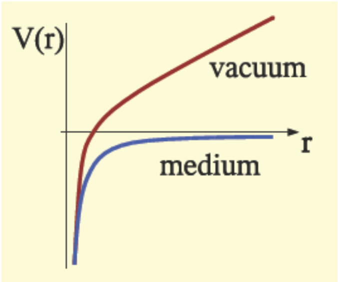
  → Chiral symmetry restoration as a function of μ_B

  - ρ broadening expected to be driven by μ_B → measure at lower energy, where baryon density gets maximal
- No precise measurement existing at low energy:

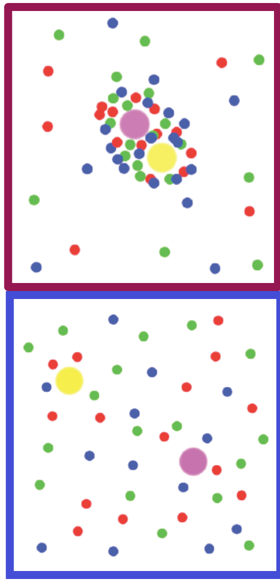


Onset of deconfinement: charmonium melting

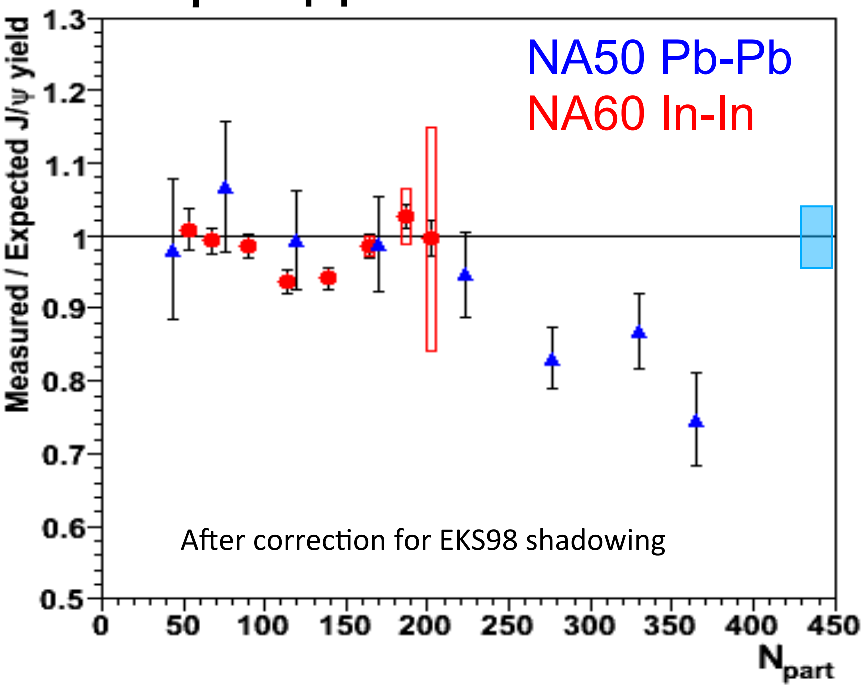
- In the deconfined phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):
- Quarkonium states with $r > \lambda_D$ are melted



Matsui, Satz, PLB178 (1986) 416



J/ψ suppression at SPS:



- What happens at lower energy?
- Is there a threshold? Onset of deconfinement?
- NA60+ could make precise study vs. beam energy and measure the onset of J/ψ suppression

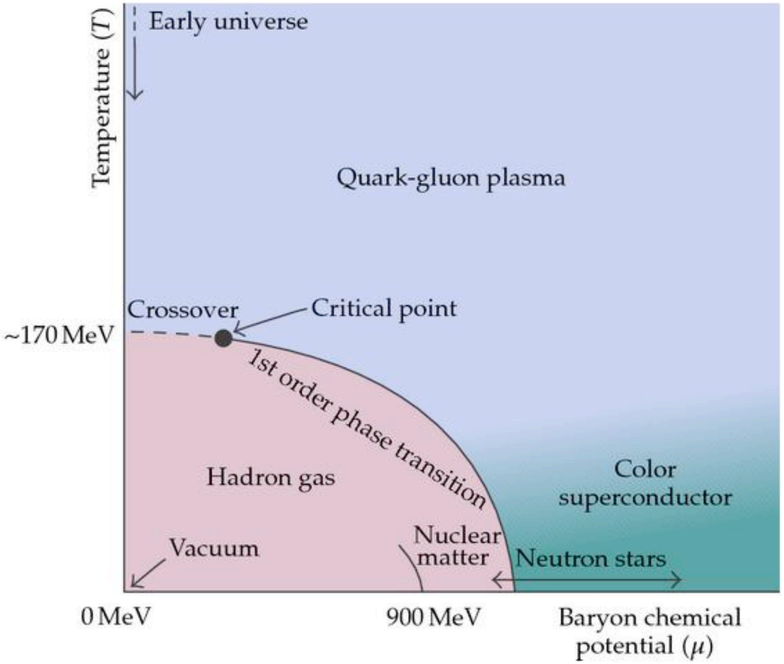
Beam conditions: SPS vs. SIS@FAIR

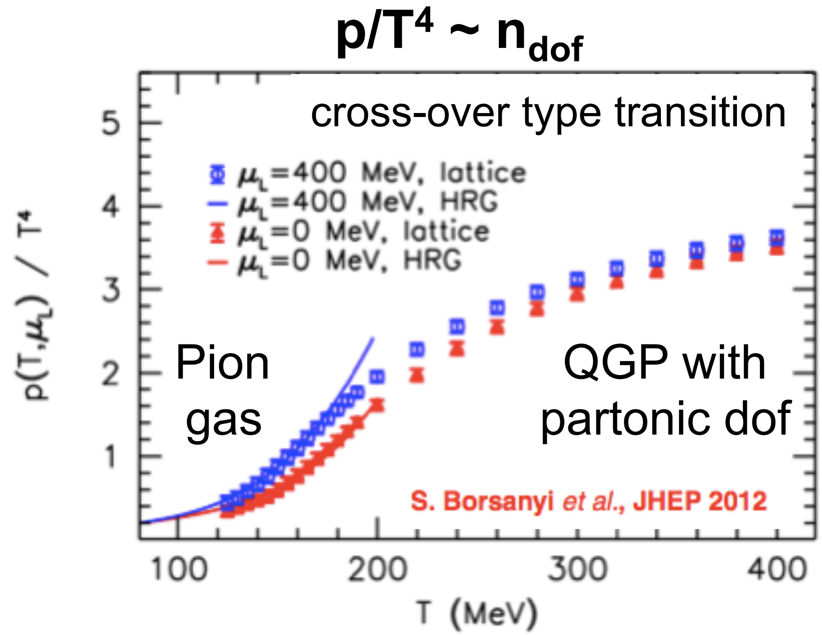
	SPS			SIS100/300
Beam energy range: [GeV]	10 – 158			< 11 – 35 (45)
	beam intensity [Hz]	target thickness [λ_i]	interaction rate [Hz]	interaction rate [Hz]
NA60 (2003)	2.5×10^6	20%	5×10^5	
new injection scheme	10^8 10^8	10% 1%	**10^7** **10^6**	**10^5 - 10^7**
LHC AA			5×10^4	

Luminosity at the SPS comparable to that of SIS100/300

EXTRA SLIDES
QGP PHYSICS

Calculating the phase diagram: lattice QCD





- Type of the phase transition:
  - First order at high μ_b (discontinuity in energy density)
  - Cross-over at low μ_b (no discontinuity in energy density)
- Challenges for lattice QCD theory:
  - Map phase line on (μ_B, T) plane
  - Predict position of critical point (from 1st order transition to cross-over)

Ultra-relativistic heavy-ion accelerators

- **BNL-AGS**, early '90s, Au-Au up to $\sqrt{s_{NN}} = 5\ \mathrm{GeV}$
  - Below critical energy density
- **CERN-SPS**, from 1994, Pb-Pb up to $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$
  - Estimated energy density ~ 1 × critical value ε_c
  - First QGP signatures (strangeness enhanc., J/ψ suppression)
- **BNL-RHIC**, from 2000, Au-Au $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$
  - Estimated energy density ~ 10 × critical value ε_c
  - First qualitative QGP properties: high opacity, looks like a low-viscosity liquid (rather than a gas)
- **CERN-LHC**, from 2010, Pb-Pb $\sqrt{s_{NN}} = 2.76 - 5.5\ \mathrm{TeV}$
  - Estimated energy density ~ 15-30 × critical value ε_c
  - (Ongoing) Precise characterization of the QGP, new probes available: jet quenching, energy loss properties, quarkonium suppression and regeneration

EXTRA SLIDES
LHC (>2020)

(not discussed in detail)

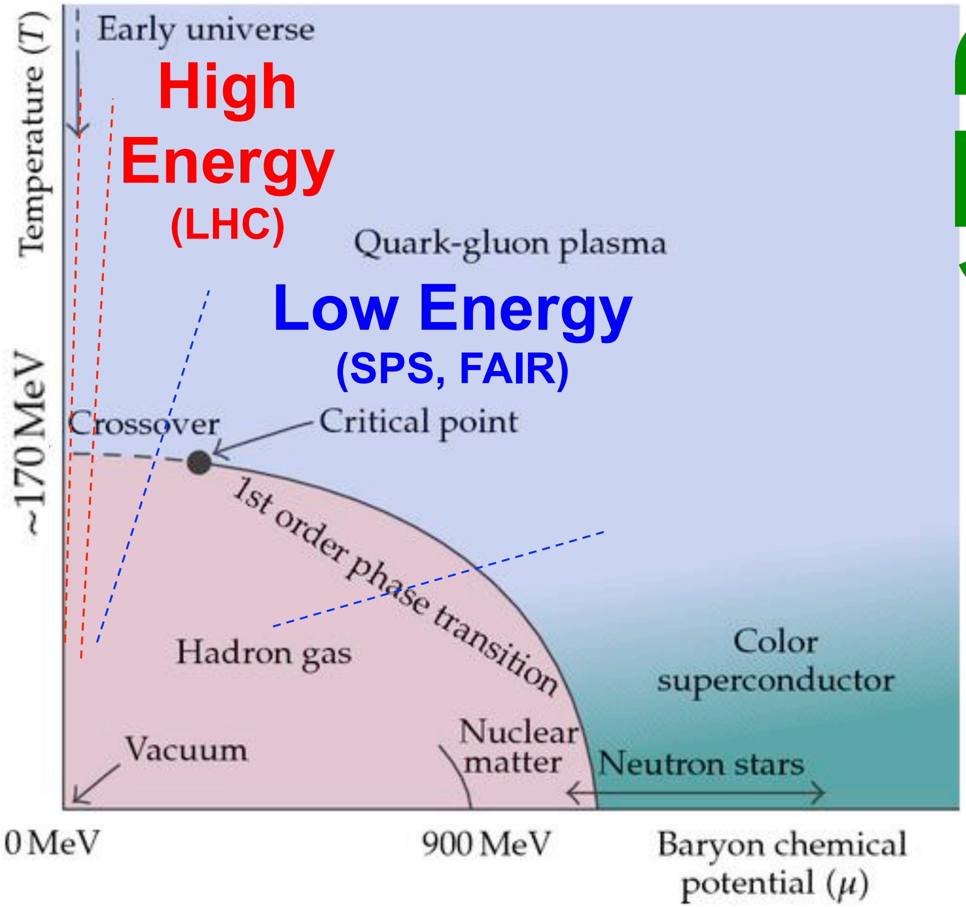
HL-LHC Programme

- **Heavy flavour:** mass dependence of energy loss, HQ in-medium thermalization and hadronization, probe of the medium transport properties
  - Low-p_T production and elliptic flow of several HF hadron species (focus of **ALICE**)
  - B and b-jets (focus of **ATLAS** and **CMS**)
- **Quarkonium:** quarkonium dissociation pattern and regeneration, probe of deconfinement and of the medium temperature
  - Low-p_T charmonia and elliptic flow (focus of **ALICE**)
  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)
- **Low-mass di-leptons:** thermal radiation to map temperature during system evolution; chiral symmetry restoration (modification of ρ meson spectral function)
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)
- **Jets:** parton energy loss mechanism as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (focus of **ATLAS** and **CMS**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)

Experiment upgrades most relevant to HI

- ALICE (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel muon tracker: precise tracking and vertexing for μ
  - New TPC readout chambers, upgraded readout for other detectors and new DAQ-HLT: x100 faster readout
- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- CMS
  - New pixel tracker (LS2), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade of trigger and DAQ (LS2): HI-specific development to reach necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT)
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Open questions



High energy heavy ion (e.g. RHIC, LHC):

- QGP temperature and its evolution?
- Properties of QGP fluid: viscosity? opacity? transport properties?
- Chiral symmetry restoration at μ_B~0

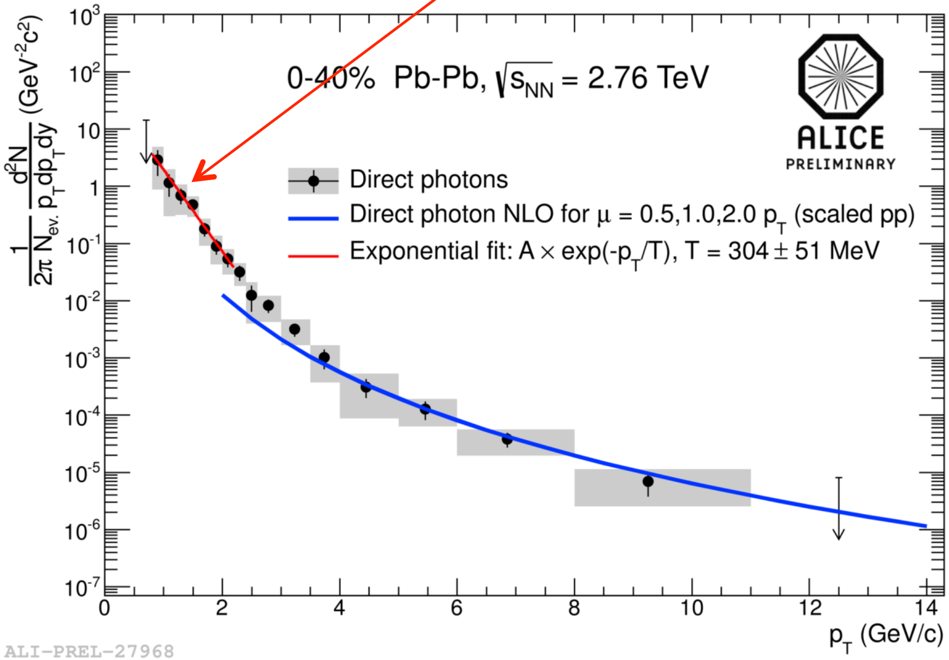
Low energy heavy ion (e.g. SPS, FAIR):

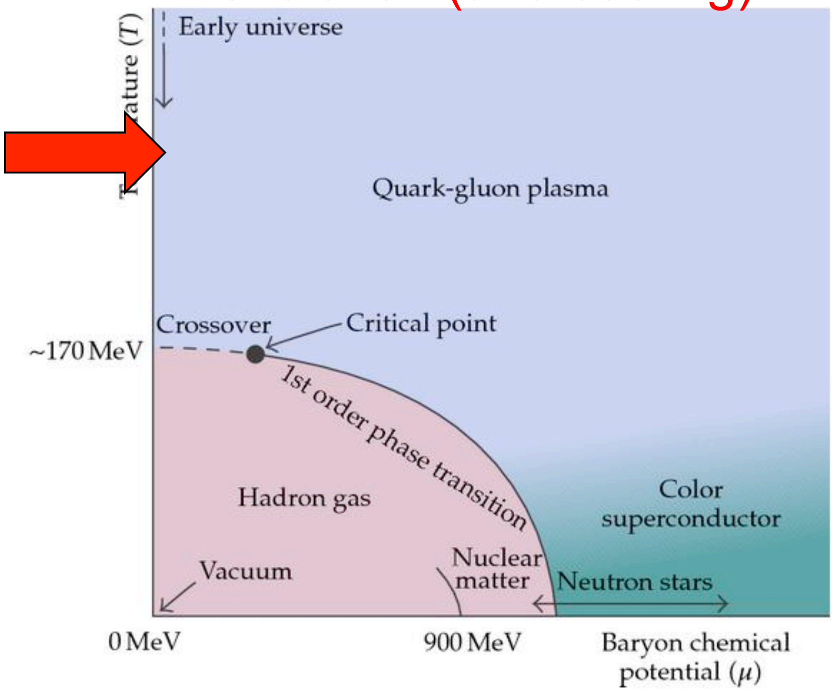
- Search for the critical point
- Chiral symmetry restoration at high μ_B
- QGP properties at high baryon density, new phases (color superconductor?)

What is the QGP temperature?

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

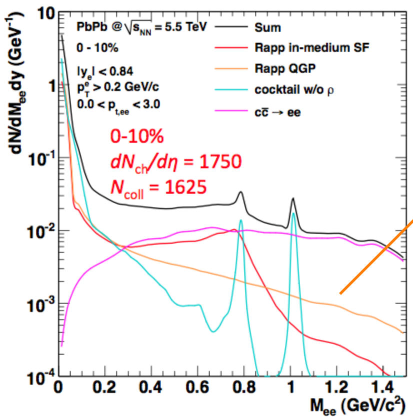
An effective temperature, averaged over system evolution (and cooling)



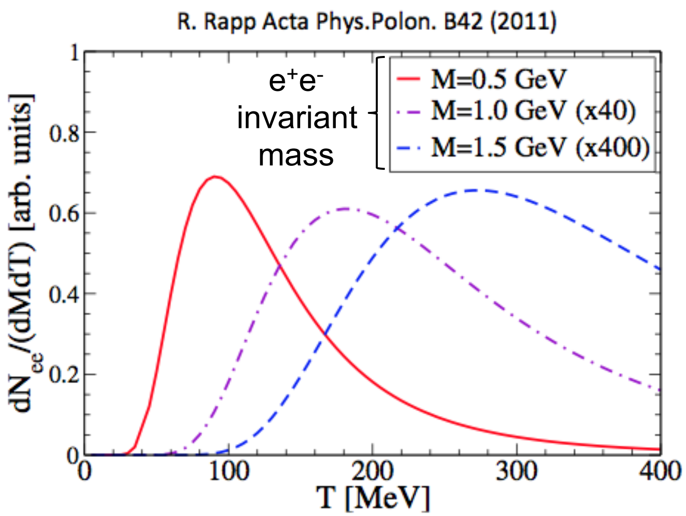


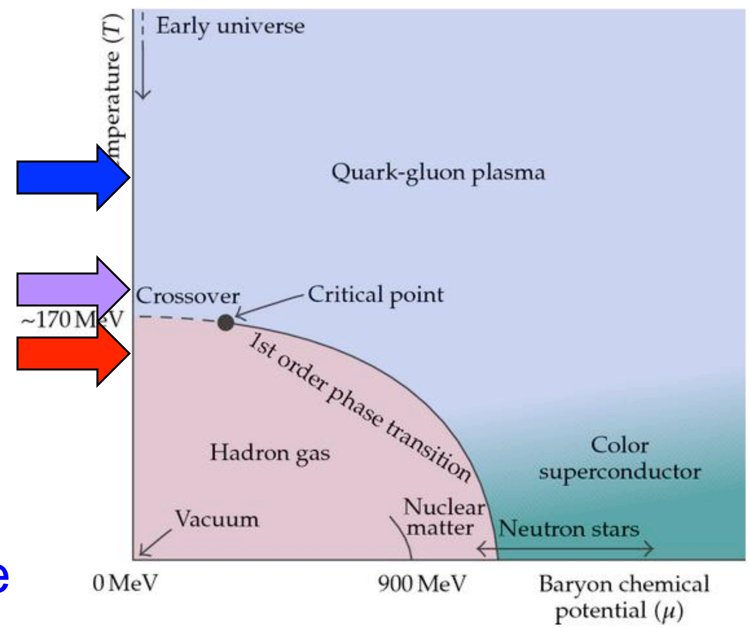
Temperature evolution: low-mass di-electrons

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



Di-leptons from virtual photons $\gamma^* \to e^+e^-$





High masses → high T, early stage

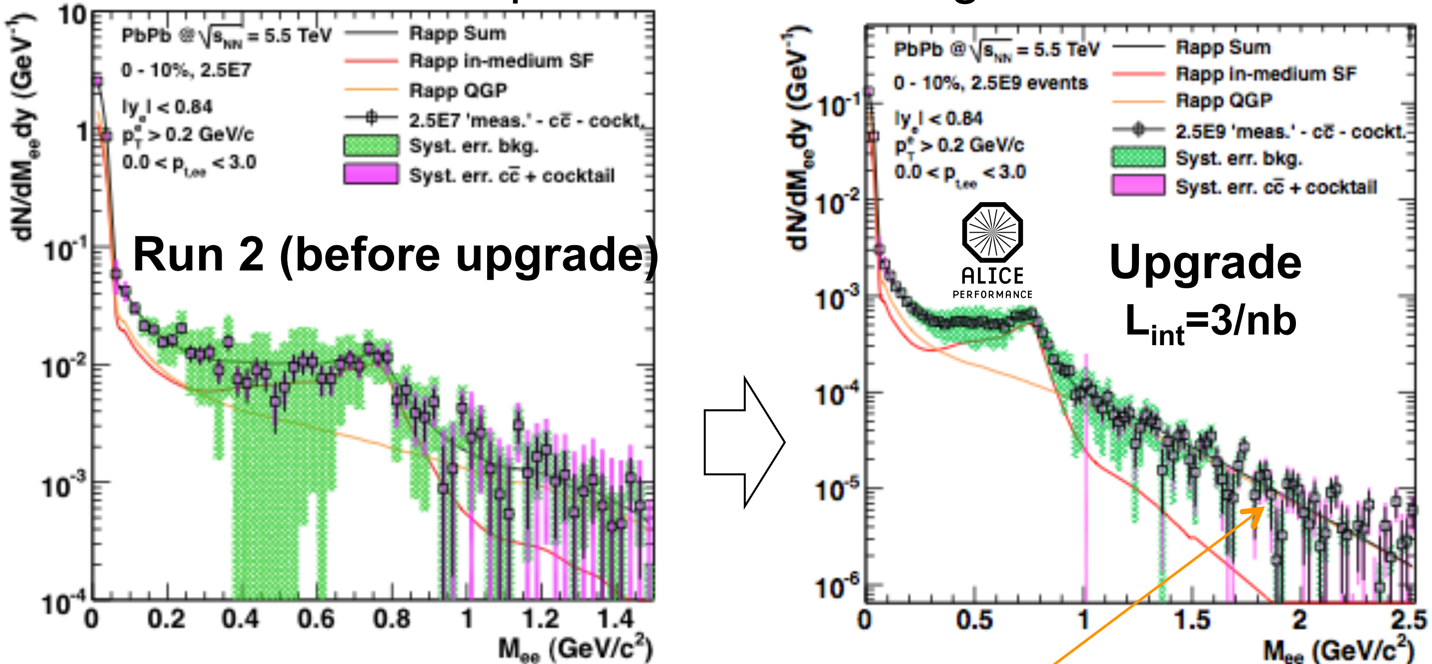
Intermediate masses

Low masses → low T, late stage

ALICE upgrade: low-mass di-electrons

- ALICE: new inner tracker + high-rate readout upgrade
  → electron acceptance down to p_T = 50 MeV/c

Di-electron mass spectrum after background subtraction:



Precision of ~10% on the inverse slope → T

ALICE, CERN-LHCC-2012-012

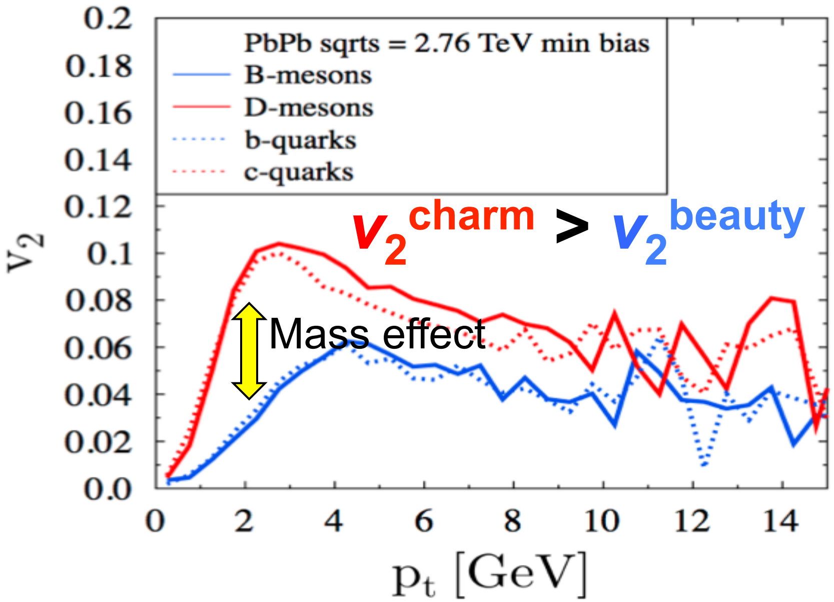
QGP viscosity via Heavy Flavour dynamics

- Heavy quarks: large mass → produced at the initial stage of the collision
- Interact with QGP constituents during system expansion and cooling
- HF kinematics sensitive to QGP viscosity and interaction mechanism
- Example: Langevin equation gives momentum (**p**) evolution vs. time (*t*):

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

Loss term → energy loss

Gain term → "flow" (radial, elliptic)
D is related to the QGP viscosity



v_2: elliptic flow coefficient, measures azimuthal modulation induced by interactions in non-central collisions

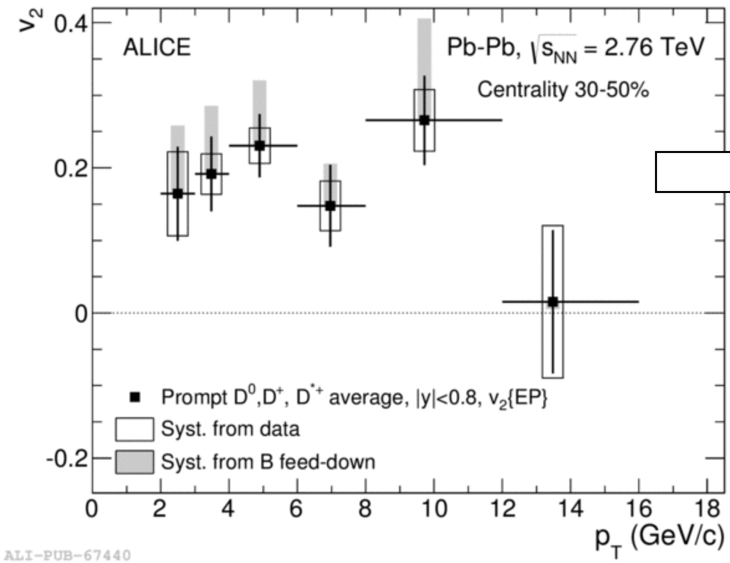
Predictions of large v_2 for charm and significant mass effect in charm vs. beauty

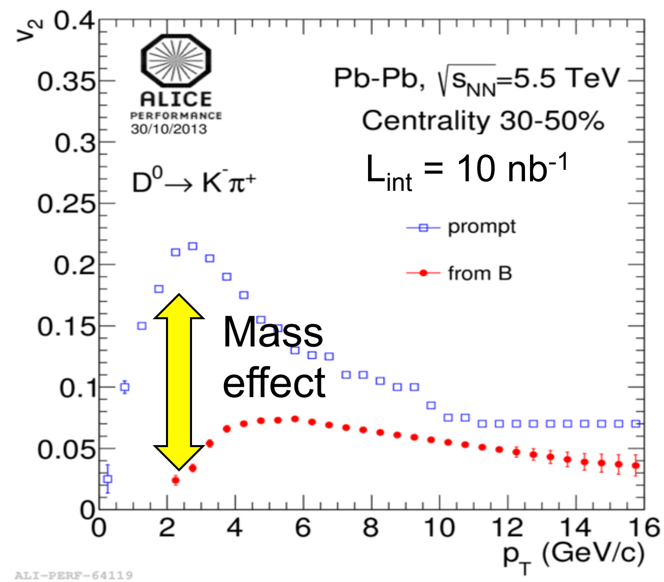
For illustration: J. Aichelin et al. in arXiv:1201.4192

ALICE upgrade: heavy flavour flow

Present data on charm v_2

Upgrade: high precision on charm and beauty v_2 down to p_T~0





ALICE, PRL 111 (2013) 102301

ALICE, CERN-LHCC-2013-024

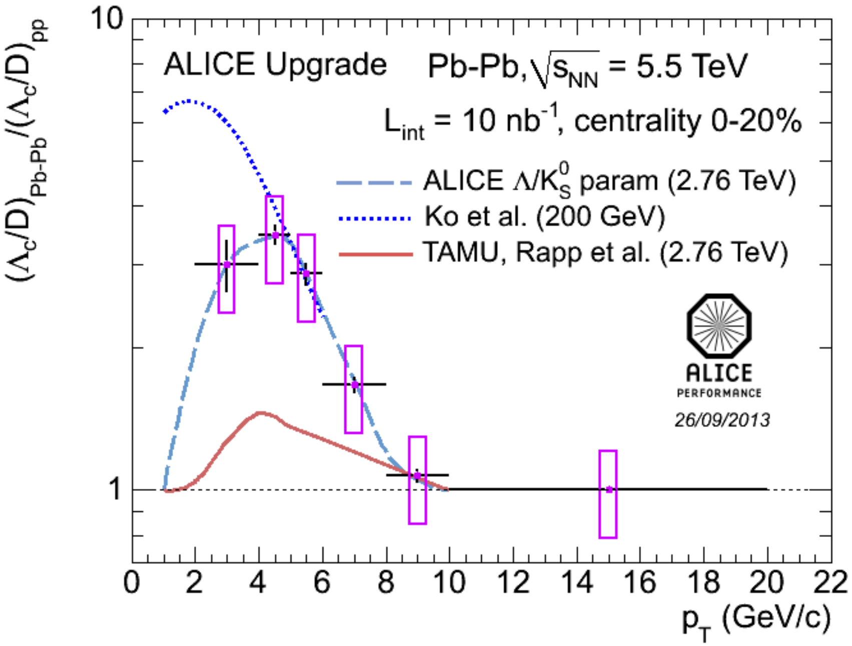
First measurement at LHC, sizeable uncertainties for charm and no direct measurement for beauty

Within 10 years: high precision measurement; relation with lattice QCD calculations (e.g. for diffusion); requires also advancement of theory framework

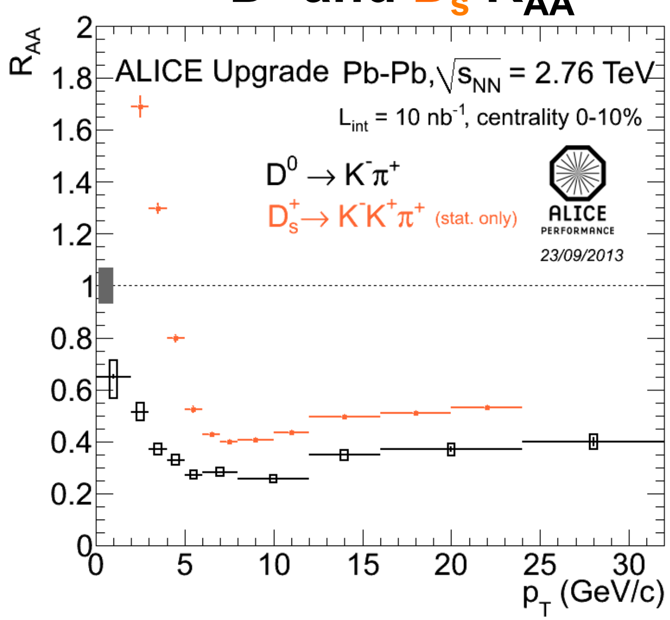
Heavy flavour hadronization?

- Baryon/meson enhancement and strange-enh. → most direct indication of light-quark hadronization in a partonic system
  - Measure this in the HF sector! Does it hold for charm?
  - Charm baryons (Λ_c) and charm-strange mesons (D_s)

Λ_c/D enhancement
(full detector sim.)



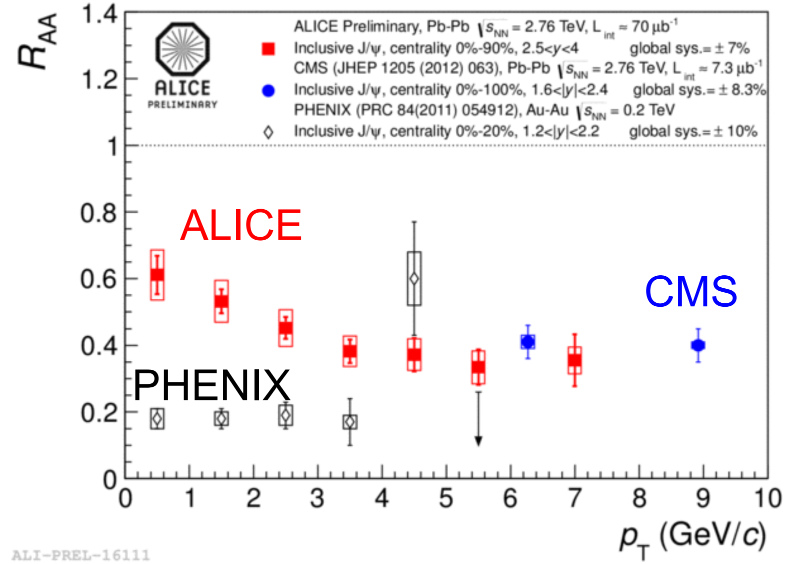
D^0 and D_s R_{AA}



Low-p_T charmonium: performance

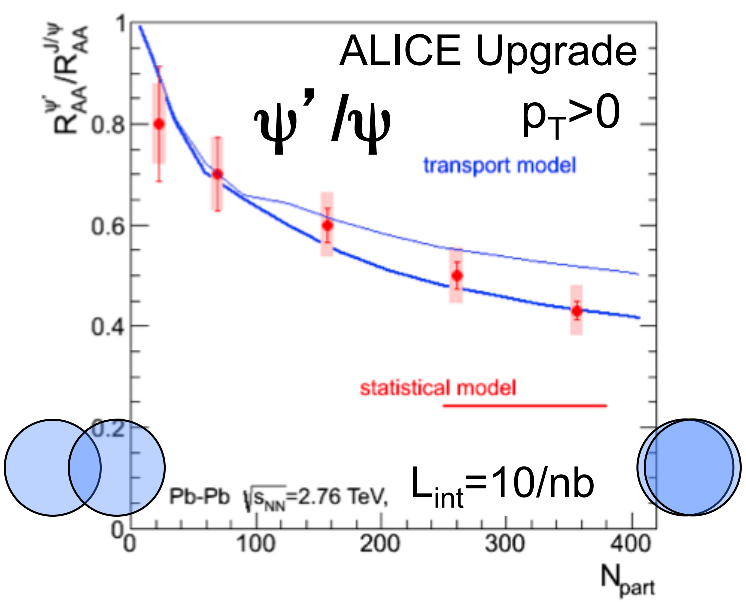
- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\overline{c}$ in a deconfined medium?

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



High statistics → explore this "new" probe of deconfinement

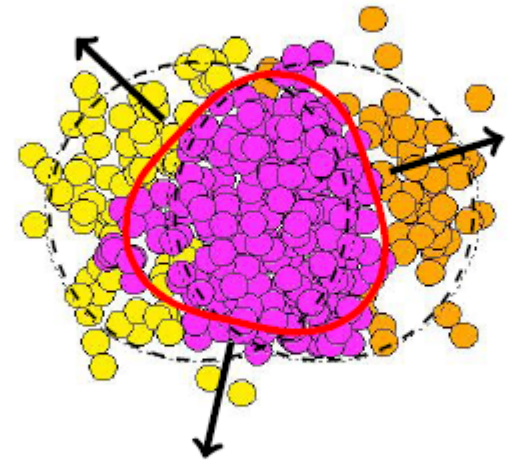
- Understand the underlying mechanism that binds deconfined heavy quark pairs
- Add information! E.g. low-p_T ψ' /ψ discriminates between models



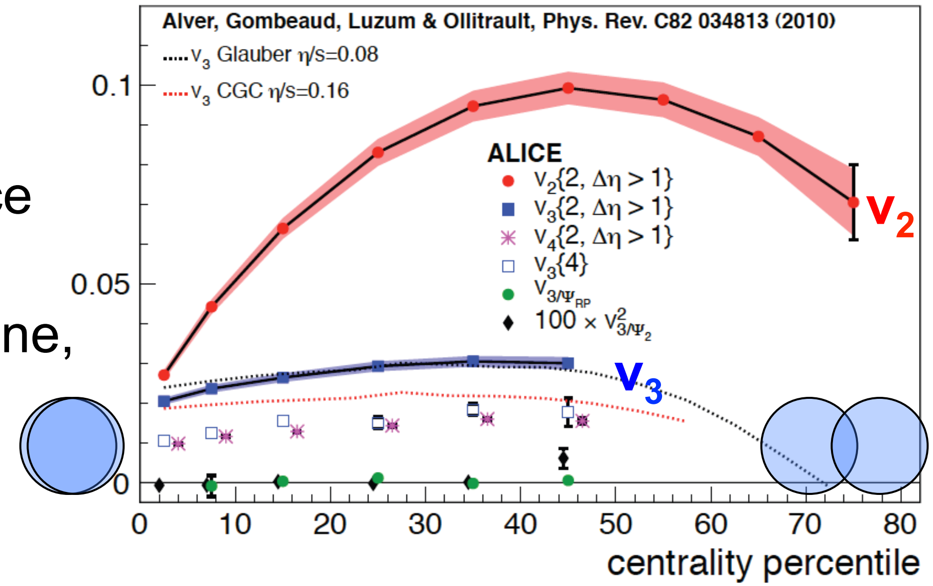
ALICE, CERN-LHCC-2013-014

Higher harmonics

- “Ideal” shape of nuclear overlap is elliptic
  - no odd harmonics expected (v_3, v_5, …)
- but fluctuations in initial conditions:
  - participants plane $\psi_2 \neq$ reaction plane Ψ_{RP}
  - → v_3 (“triangular”) harmonic appears [B Alver & G Roland, PRC81 (2010) 054905]



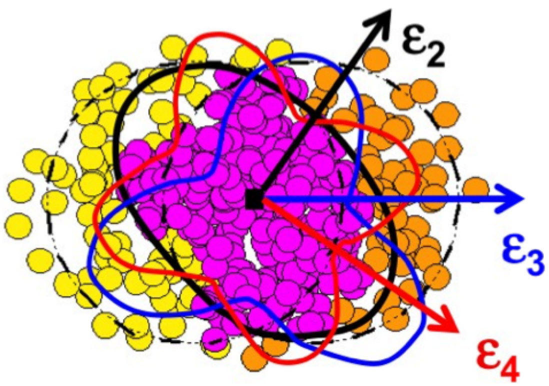
- and indeed, **v_3 > 0** !
- **v_3** has weaker centrality dependence than **v_2**
- when calculated wrt participants plane, **v_3** vanishes
  - as expected, if due to fluctuations…

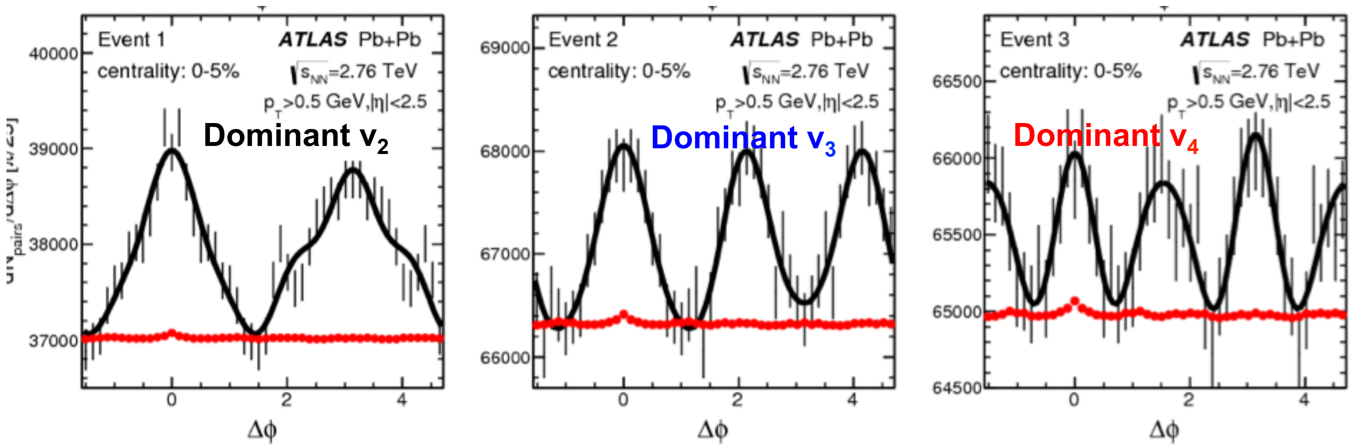


ALICE: PRL 107 (2011) 032301

Event-by-event shapes at the LHC

- And not only v_3 (triangular events), also v_4, v_5, …
- At LHC, multiplicity large enough to "see" event-by-event shapes





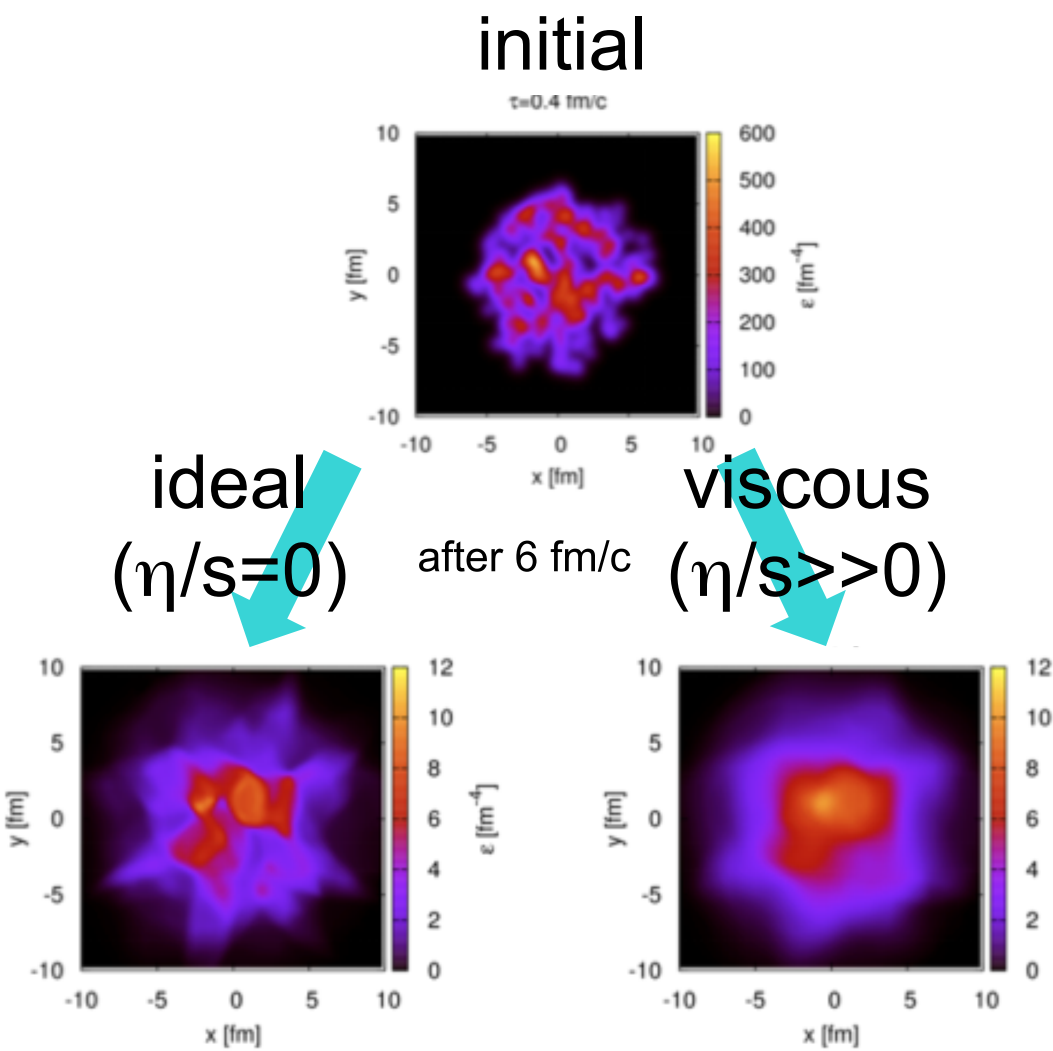
Initial conditions and viscosity of the QGP

- Medium viscosity: one of its fundamental properties
- η/s: shear viscosity / entropy ratio

- Large viscosity washes out the details of the initial-state

→ Final state fluctuations can give information on viscosity

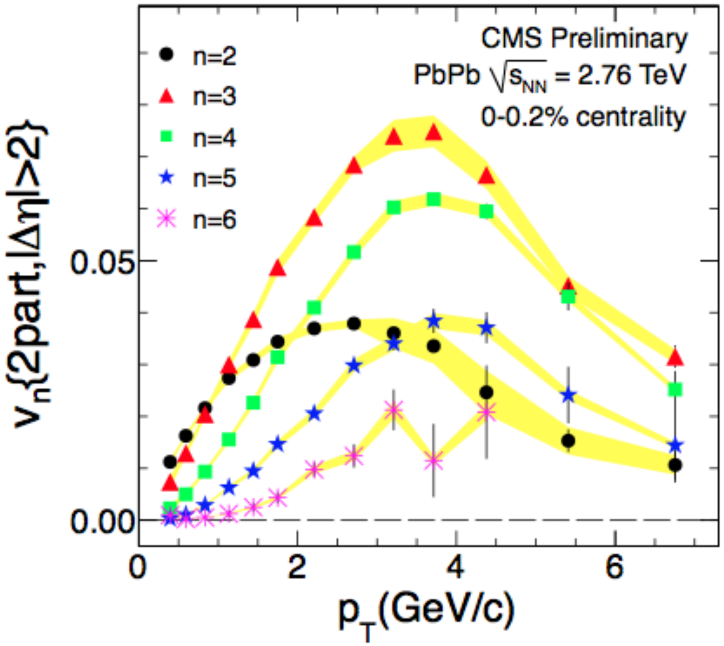
Energy density profile in the transverse plane:



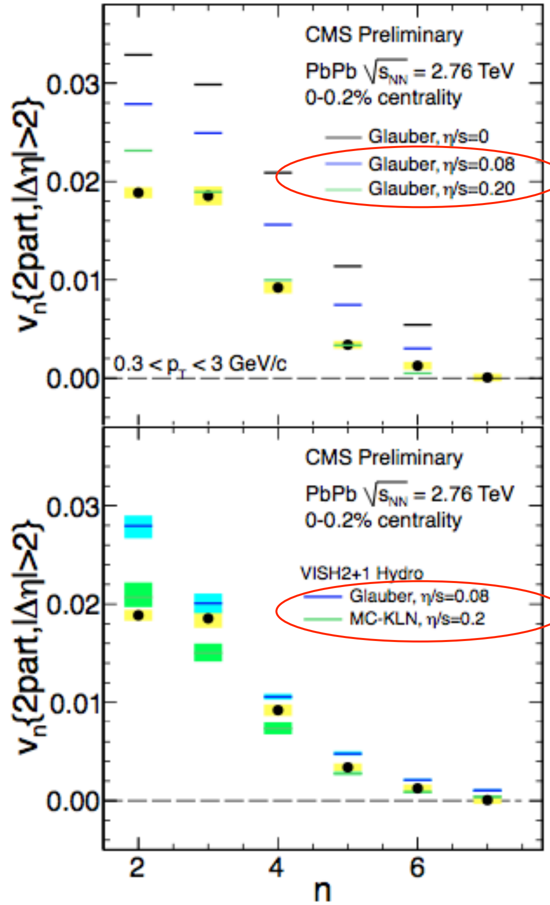
S Jeon et al, QM 2012, B. Schenke, et al. PRL106, 042301 (2011)

Addressing the QGP viscosity

Example:



Disentangle initial conditions and transport coefficients



CMS-HIN-12-011

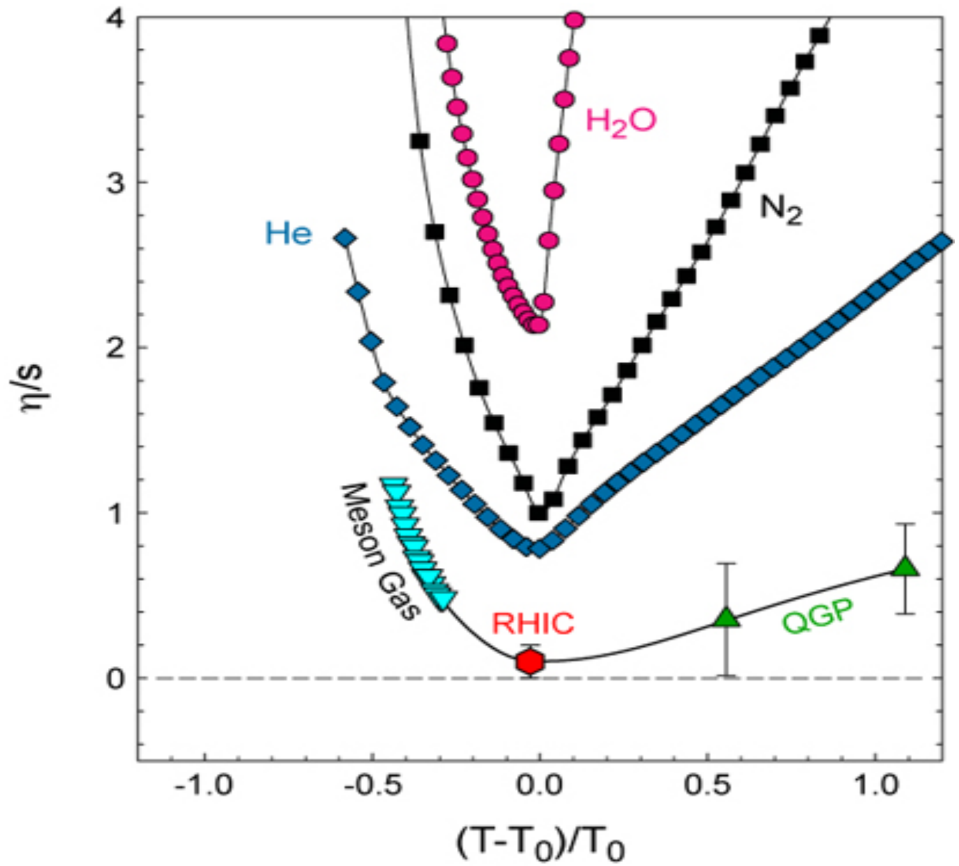
\+ comparison to many other measurements at RHIC and LHC

→ Data prefer values of $\eta/s \sim 0.08\text{-}0.40$

See e.g. Luzum QM2012

The lowest viscosity liquid?

- η/s has a minimum at the phase transition (T_0) for all fluids
- Current estimates for QCD matter: η/s 10 times smaller than water and >5 times smaller than Helium



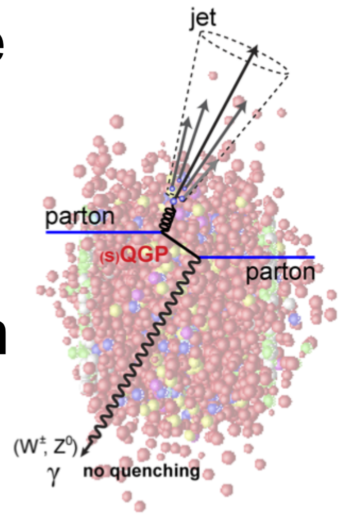
Still far from a precise measurement of this fundamental property
→ Need to combine many observables, studied with % accuracy

Lacey et. al, PRL98:092301

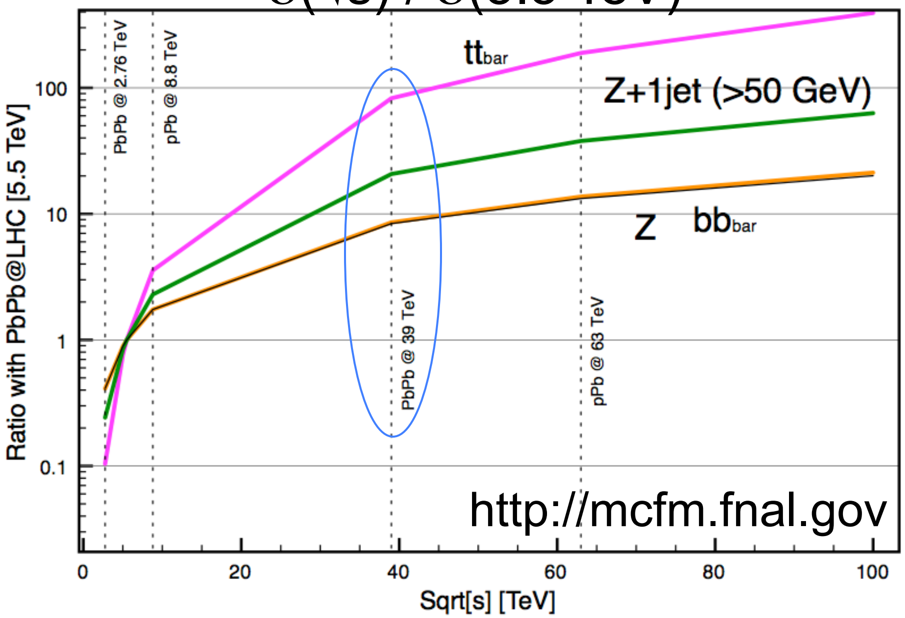
EXTRA SLIDES
FCC

A new set of Hard Probes

- LHC heavy-ion programme shows that it is possible to reconstruct HEP-like observables in HI collisions
  - Jets, b-jets, Z^0, W, γ-jet correlations …
- Large $\sqrt{s}$ and $\mathscr{L}$ of the FCC will make new probes abundantly available, for the study of the interaction mechanisms, of the medium density and its time evolution



$\sigma(\sqrt{s}) / \sigma(5.5\text{ TeV})$



- Larger increases for larger masses:
  - 80x for top
  - 20x for Z^0 + 1 Jet(p_T>50 GeV)
  - 8x for bottom or Z^0

High-density QCD in the initial state: Saturation at low x

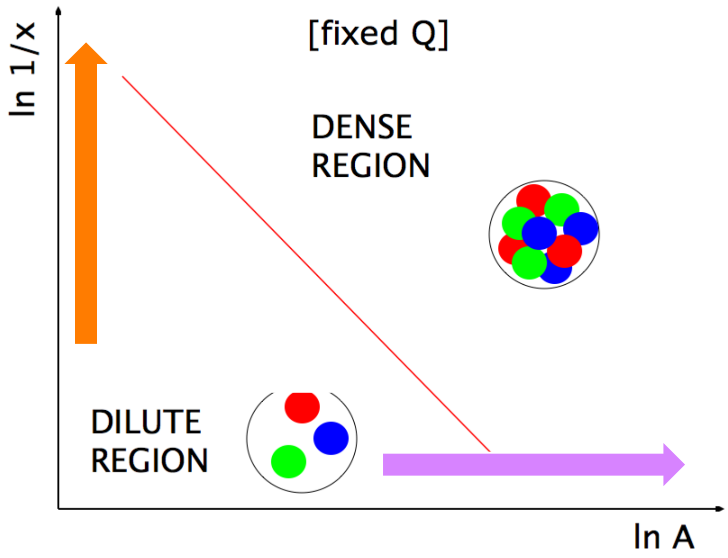
- Explore new unknown regime of QCD: when gluons are numerous enough (low-x) & extended enough (low-Q^2) to overlap → *Saturation, Non-linear PDF evolution*

Enhanced in nuclei: more gluons per unit transverse area

Saturation scale:

$$Q_S^2 \sim \frac{A g(x, Q_S^2)}{\pi A^{2/3}} \sim A^{1/3} g(x, Q_S^2) \sim A^{1/3} \frac{1}{x^\lambda} \sim A^{1/3} \left(\sqrt{s}\, e^y\right)^\lambda$$

(λ~0.3)



Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

→ **decrease *x* (larger √s, larger *y*)**

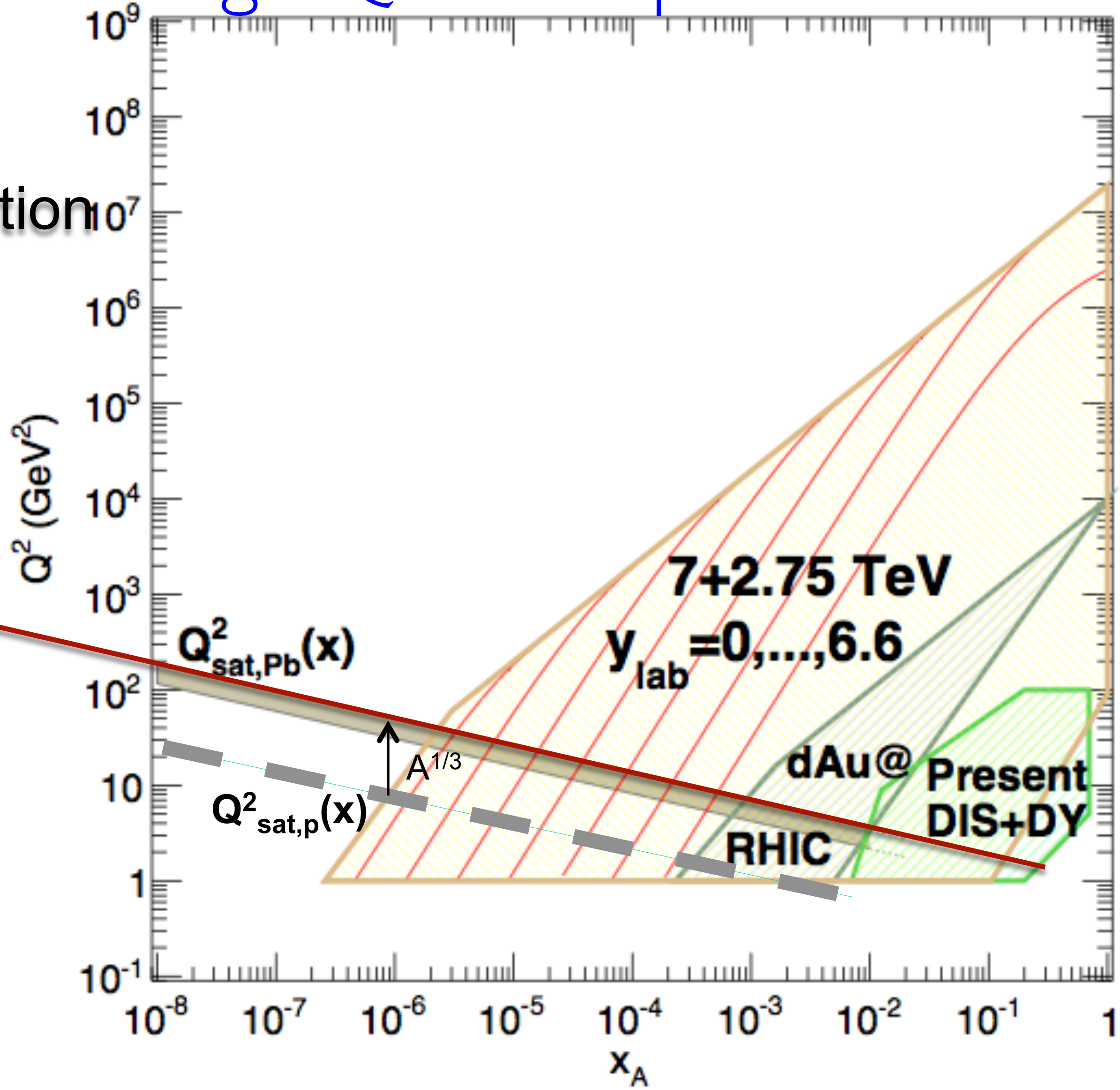
→ **increase A**

Kinematic coverage Q^2 vs. x: pA LHC

Goals:

- determine Q^2_S
- test non-linear evolution

Saturation region for $Q^2 < Q^2_S$



Kinematic coverage Q^2 vs. x: pA FCC

Goals:
- determine Q^2_S
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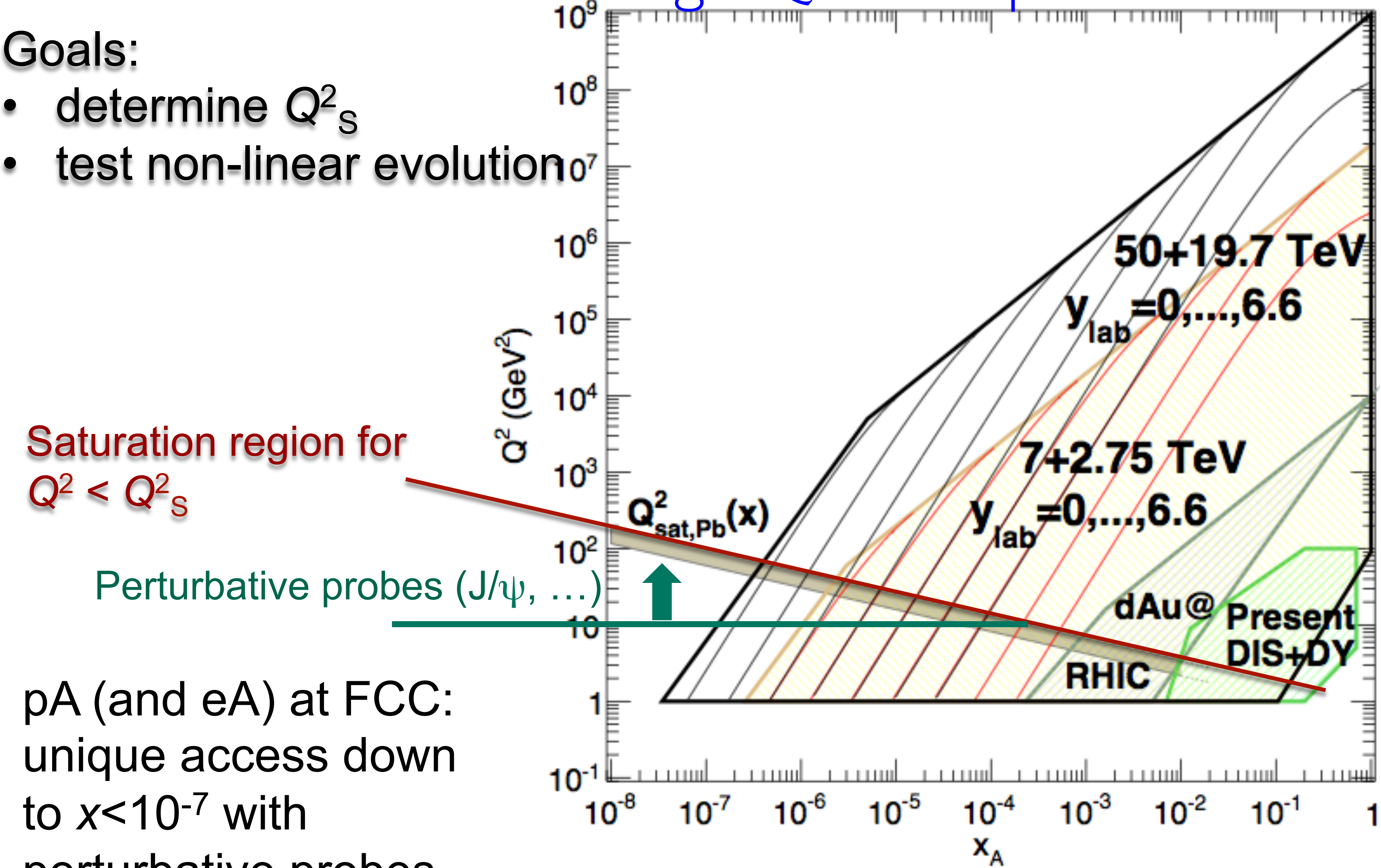
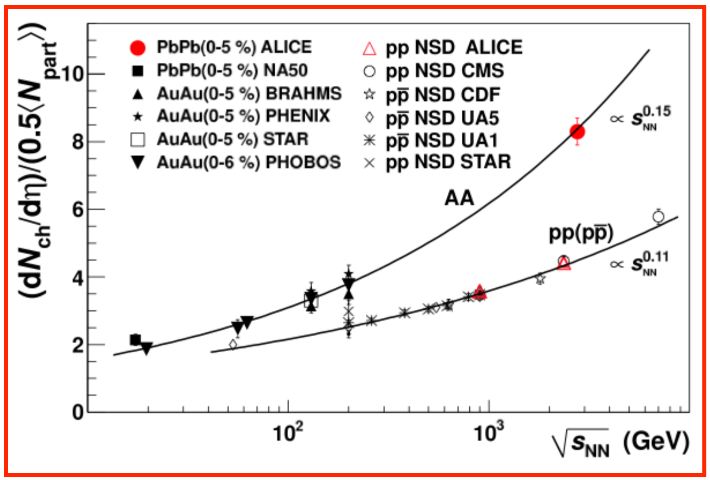


pA (and eA) at FCC: unique access down to $x<10^{-7}$ with perturbative probes

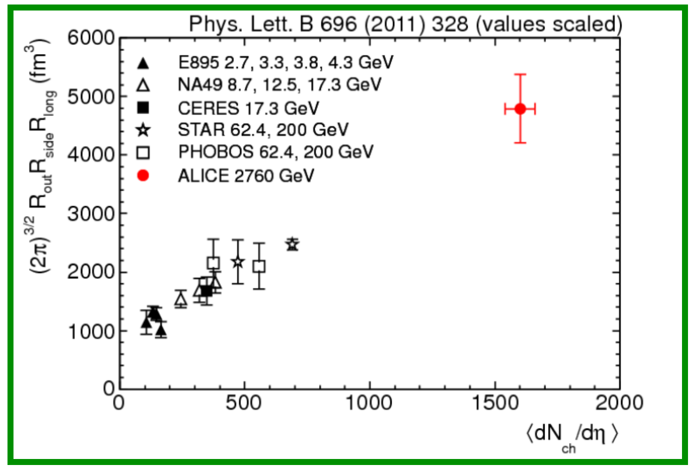
QGP studies at the FCC: global properties

- Extrapolation to 39 TeV: increase wrt LHC 5.5 TeV

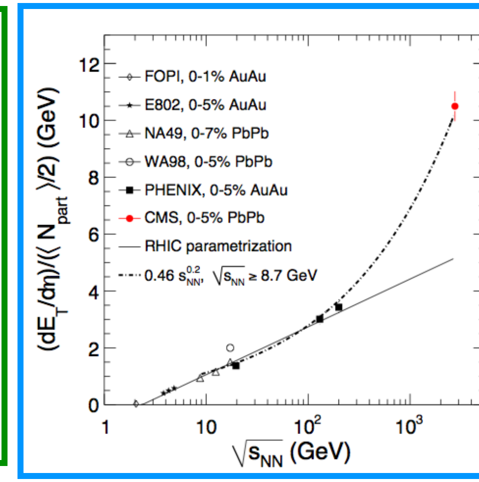
$dN_{ch}/d\eta$ x 1.8



Volume x1.8



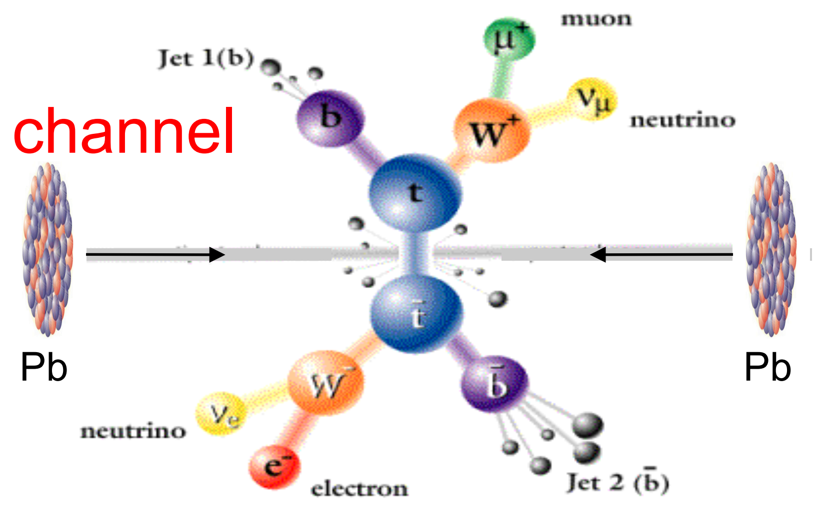
$dE_T/d\eta$ x2.2



Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

Top quarks in Pb-Pb at HL-LHC and FCC

- $t\bar{t}$ decay channels:
  - 10% $b\bar{b}+\ell\ell+\not{E}_T$ observation channel
  - 44% $b\bar{b}+\ell+2\,jets+\not{E}_T$
  - 46% $b\bar{b}+4\,jets$



- Estimate for observation channel in CMS (CMS PAS-FTR-2013-025)

→ **~500 events for 10 nb^{-1} Pb-Pb 5.5 TeV ("HL-LHC")**

- FCC: with 100 nb^{-1}, x800 more wrt HL-LHC

→ **FCC** with CMS-like setup, **~4x10^5** for "observation channel"
  - could be 4-5x more in the other channels (but higher background)

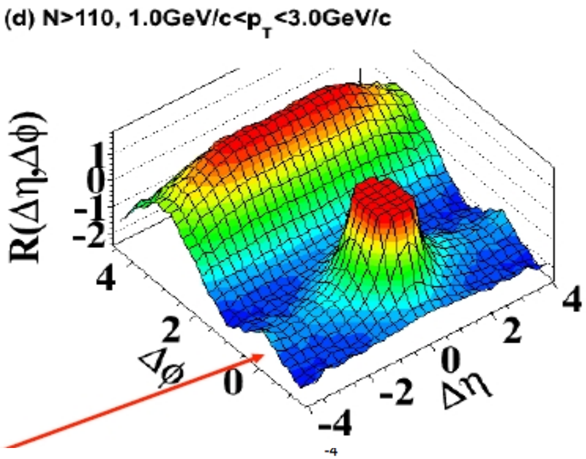
→ few 10^3 with p_T > 0.5 TeV

→ few 10^2 with p_T > 1 TeV

High-multiplicity events in small systems

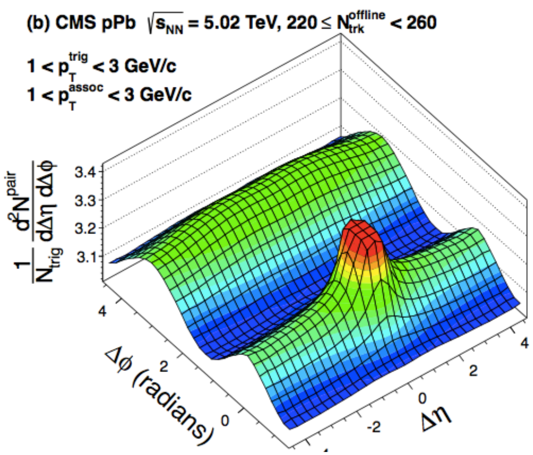
- One of the most interesting findings of the LHC HI programme: similarity of long-range correlations (ridge) in high-mult pp, pPb as in Pb-Pb collisions
- Similar mechanism? Collectivity in small high-density systems? Initial or final state collectivity?

pp, high mult



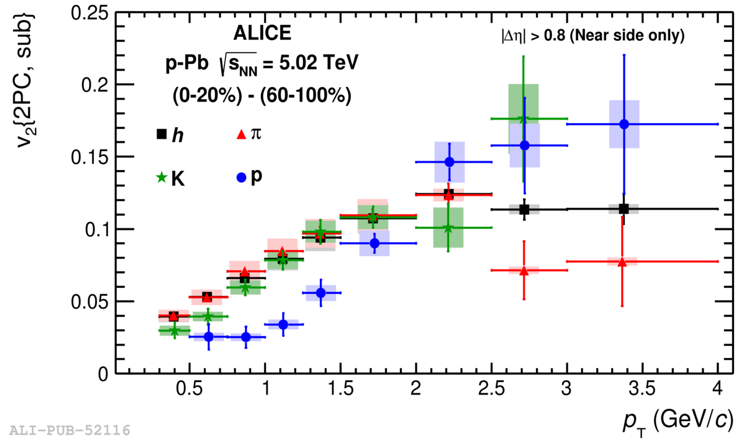
CMS, JHEP 1009 (2010) 091

pPb, high mult



CMS, PLB 724 (2013) 213

pPb, high mult



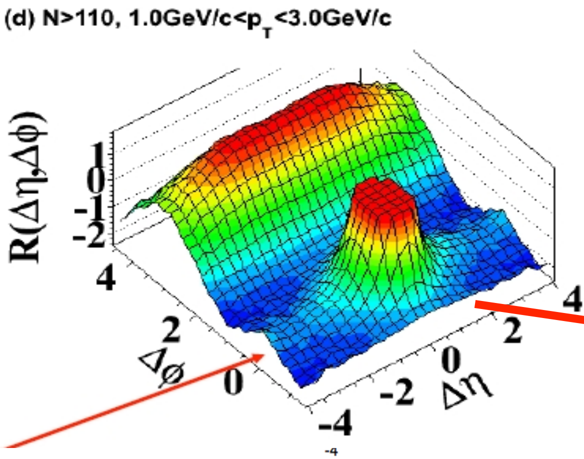
ALICE, PLB726 (2013) 164

- Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity

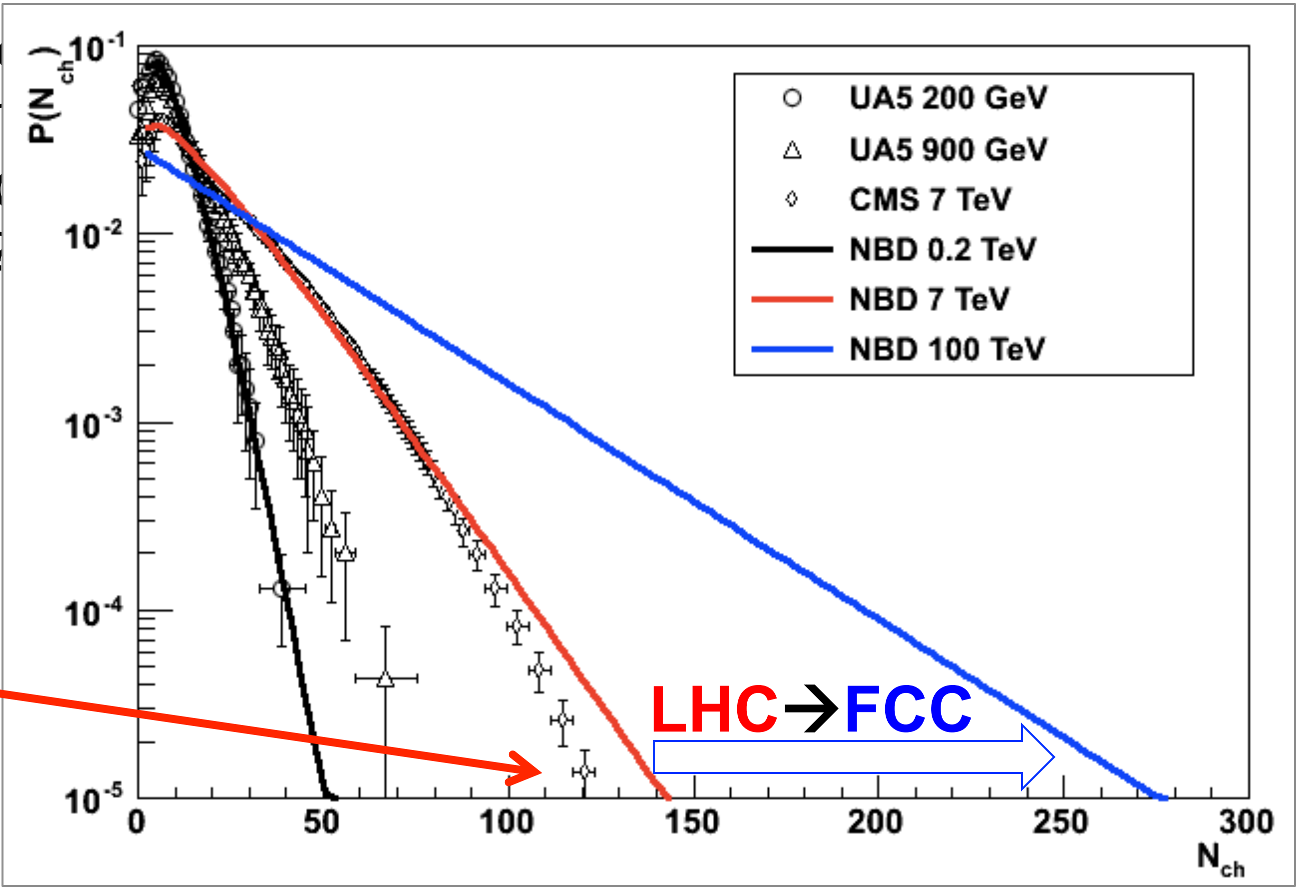
High-multiplicity events in small systems

- One of the most inter
long-range correlation
- Similar mechanism? (
final state collectivity?

pp, high mult



CMS, JHEP 1009 (2010) 091

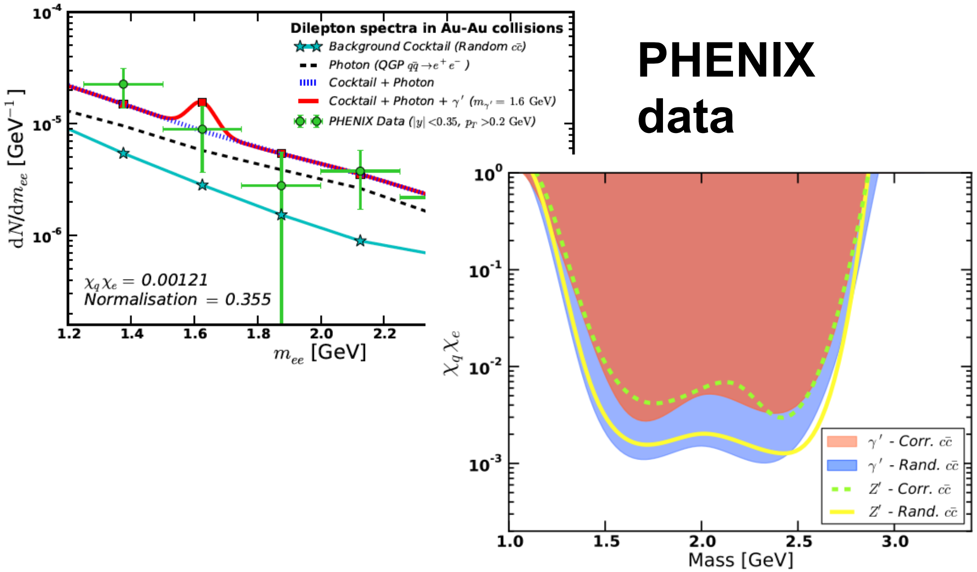


- Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity

EXTRA SLIDES
“EXOTICA”

Dark photons from the QGP?

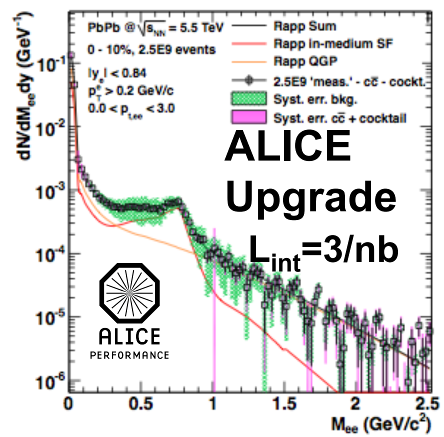
- Example: search in dielectron mass distribution measured in Au-Au by PHENIX at RHIC

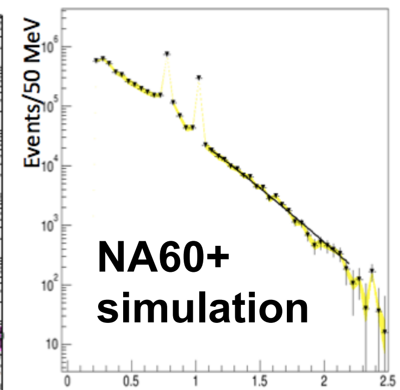


- In the invariant mass range 1.2-2.6 GeV, Davis et al. bounded product of coupling to quarks and leptons to be $\chi_q\ \chi_e < 10^{-3}$ at 95% CL

Davis et al. arXiv:1306.3653

- Search possible with much finer mass binning at LHC and with possible new dimuon experiment at SPS

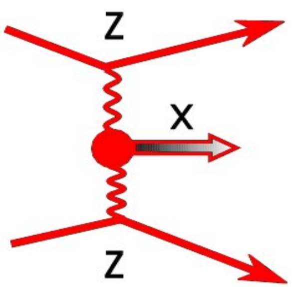




- Possible complementarity in high mass region (~GeV) with JLab programmes (ee, eA)

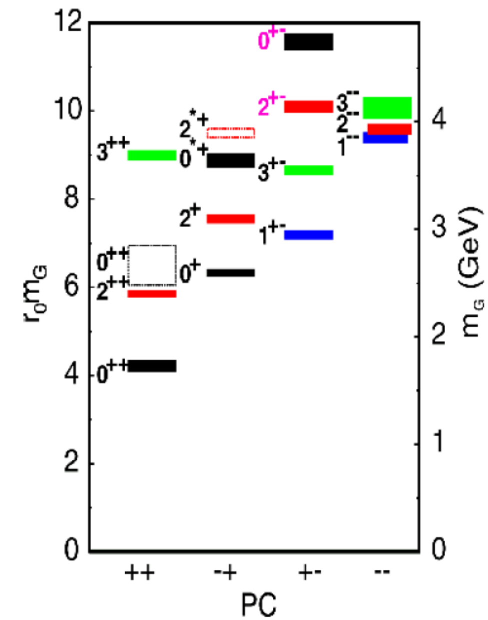
Glueballs and other “exotica”

- Glueballs: basic prediction of QCD (self-interaction of gluons)
- Nucleus-nucleus collisions provide large advantage for the $\gamma\gamma \rightarrow G$ production process
- $\gamma\gamma$ cross section in ultra-peripheral collisions scales with Z^4 (10^7 for Pb-Pb)



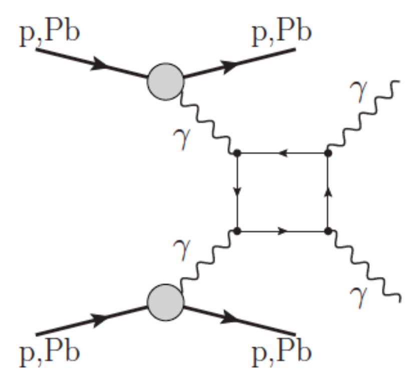
Glueball Candidate	$\Gamma_{\gamma\gamma}$ [eV]	RHIC [nb]	LHC [μb]
$f_0\,(1500)$	0.77	14-9.3	0.7-1.3
$f_0\,(1710)$	7.03	60-43	3.8-8.6
$X\,(1835)$	0.021	0.11-0.09	0.01-0.02

Machado and Da Silva, PRCC83 (2011)



Mathieu et al, arxiv:0810.4453

- Another possibly interesting channel: $\gamma\gamma \rightarrow \gamma\gamma$ cross section sensitive to exotica that couple with the photon (SUSY, monopoles, …)



D’Enterria and Silveria, PRL111 (2013)