CERN Heavy Ion Physics

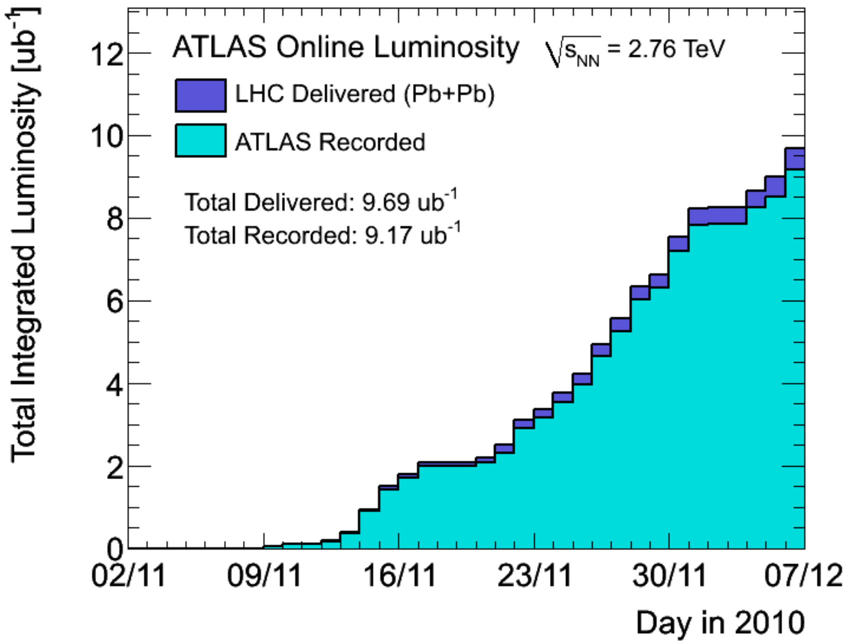
Urs Achim Wiedemann
CERN PH-TH

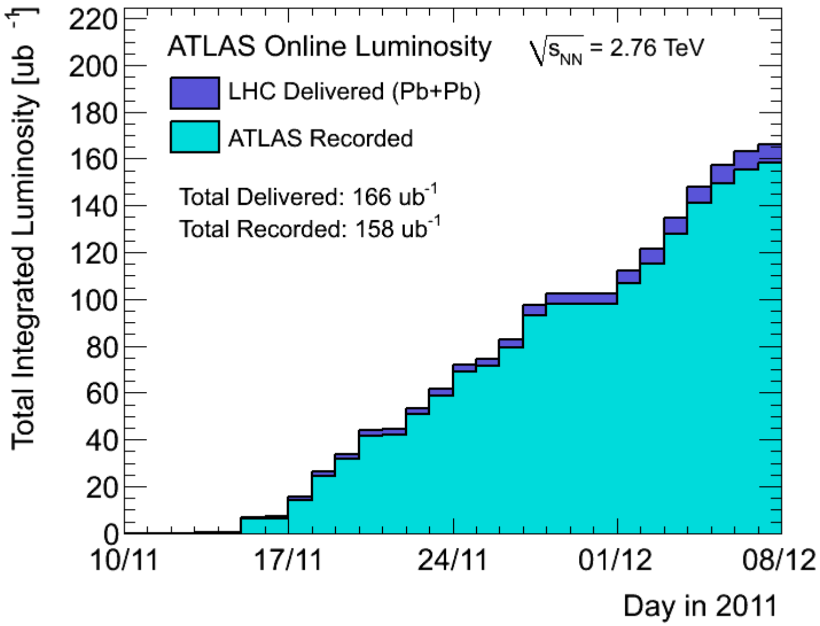
Contribution to:
Prospects and Challenges for Future Experiments in
Heavy Ion Collisions
15-16 February 2013

First three-year LHC running period reaches a conclusion

Geneva 14 February 2012. At 7.24am, the shift crew in the CERN Control Centre extracted the beams from the Large Hadron Collider, bringing the machine's first three-year running period to a successful conclusion…
(from CERN Press Release)

- Two Pb-Pb runs in fall of 2011 and 2012





- First p-Pb run just finished on Su, 10 Feb
- Few days p-p comparison data at 2.76 TeV

LHC Heavy Ion Programme - highlights

- QGP Hydrodynamics
  towards era of precision
  (quantitative comparisons of TH and EXP)
  => transport coefficients

- Parton energy loss
  how probes propagate and dissipate in QGP?
  => access to microscopic structure of QGP
  and the dynamics of equilibration

- Quarkonium physics
  characterizing the QGP at varying length scales
  => access to screening of the color force

Dissipative fluid dynamic description

- Based on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- Sensitive to properties of matter that are

calculated from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

AdS/CFT =>

EOS: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

transport coefficients: shear η, bulk ξ viscosity, conductivities …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

relaxation times: τ_π, τ_Π, …

Initial fluctuations propagated by fluid

Alver&Roland 2009, Sorensen, Moczy, ….

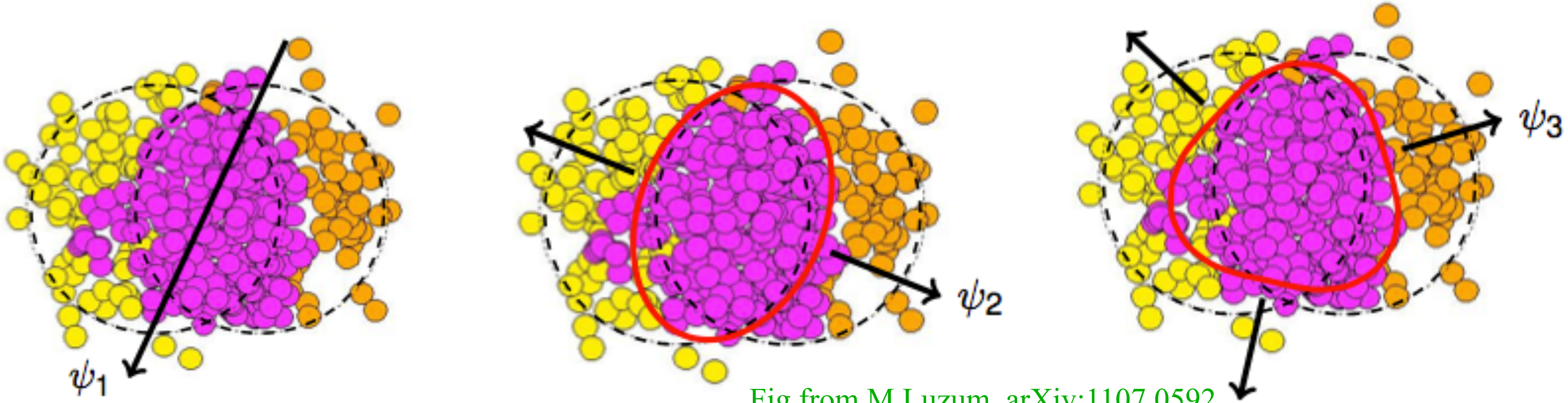
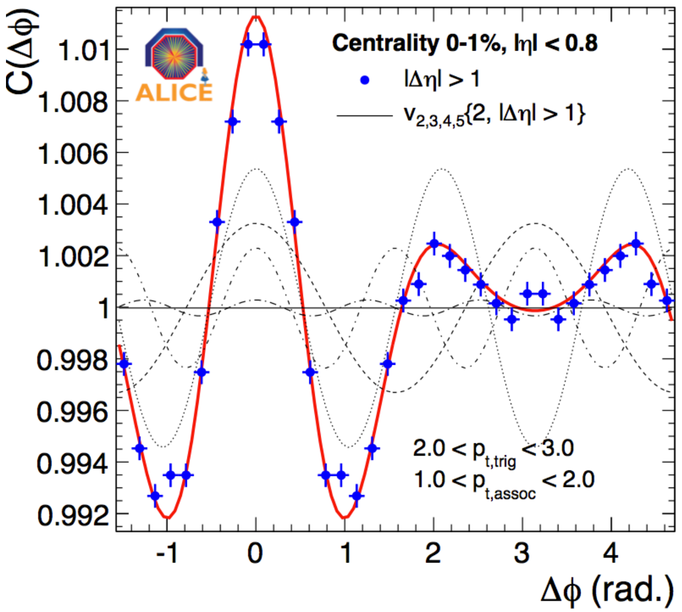
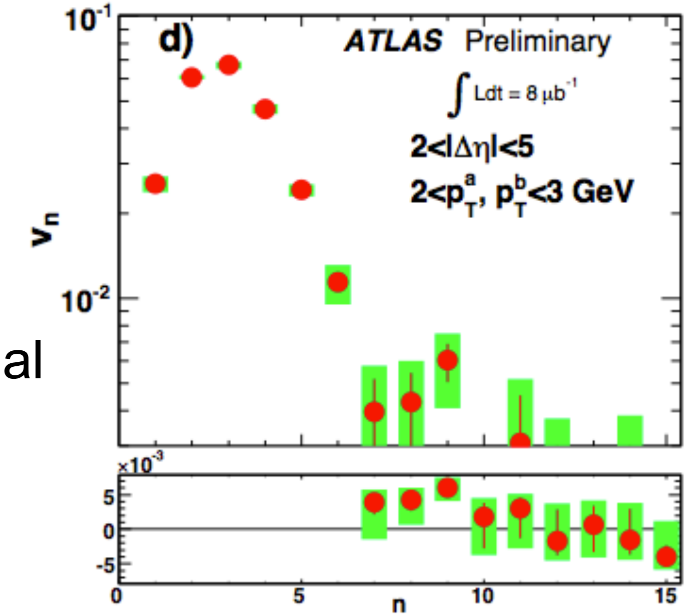


Fig from M.Luzum, arXiv:1107.0592



$$v_n \propto \varepsilon_n$$

Approximately linear relation between spatial and momentum azimuthal anisotropy

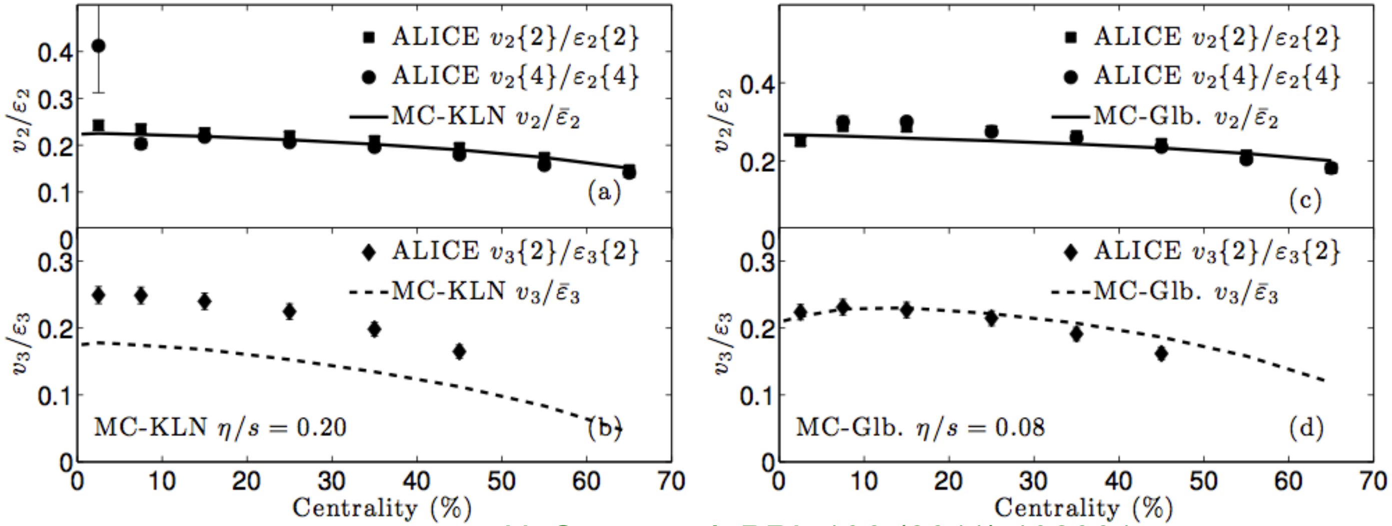


Fluid dynamics – towards precision

- Recent data & recent analyses yield tight constraints

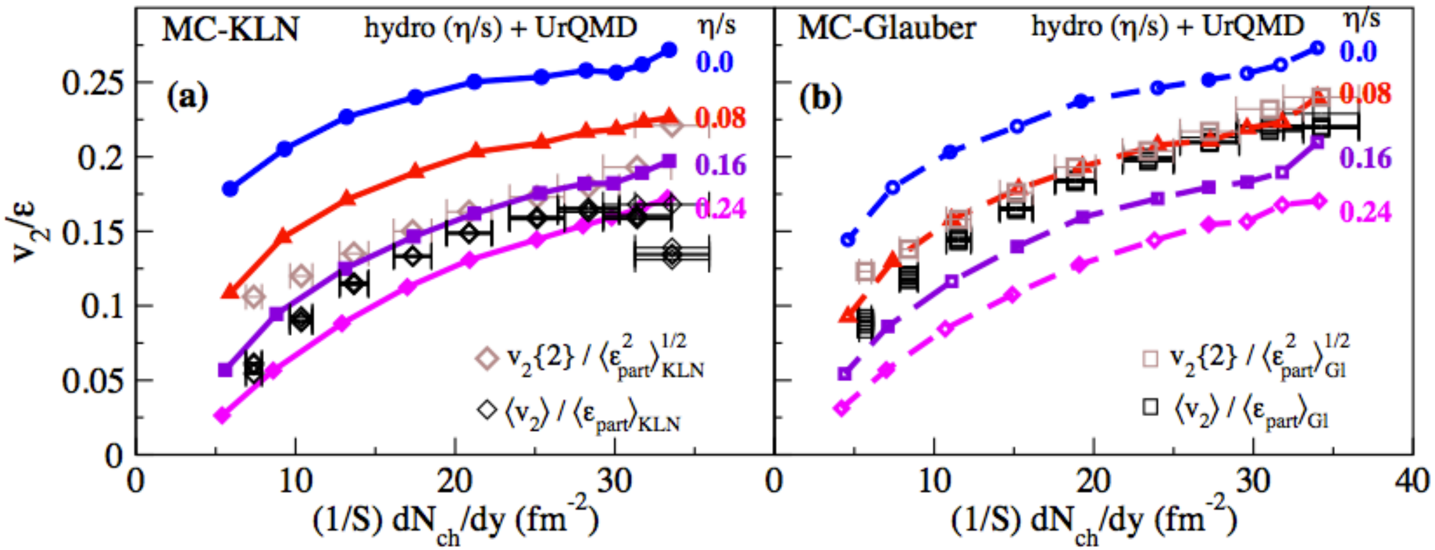
$$1 \le 4\pi\left(\eta/s\right) \le 2$$

LHC



H. Song et al. PRL 106 (2011) 192301
Z. Qiu et al., Phys.Lett.B 707 (2012) 151

RHIC



Main TH conclusions from current analysis

- Value of shear viscosity minimal,
  => perfect liquid, strongly coupled plasma

- Fluid dynamics applies at $\tau_0 < 1\,fm$
  In perturbative scenario: hydro valid if

  but $\underbrace{\alpha_s^2 T_0}_{collision\ rate} >> \underbrace{1/\tau_0}_{espansion\ rate}$

  => non-perturbative thermalization

  $\alpha_s >> 1 \quad \Rightarrow 0.65 \le \tau_0 T_0$

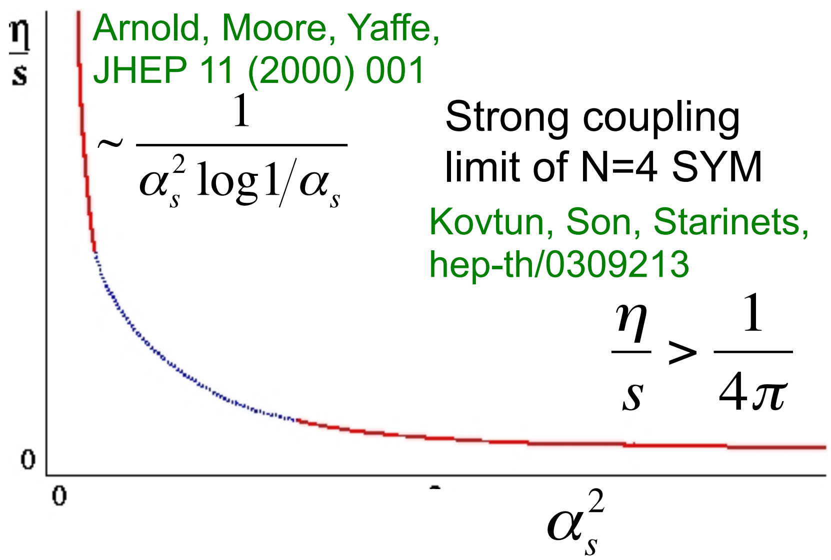
  Heller, Janik Witaszczyk, PRL 108 (2012) 201602
  Chesler, Yaffe, PRL 102 (2009) 211601

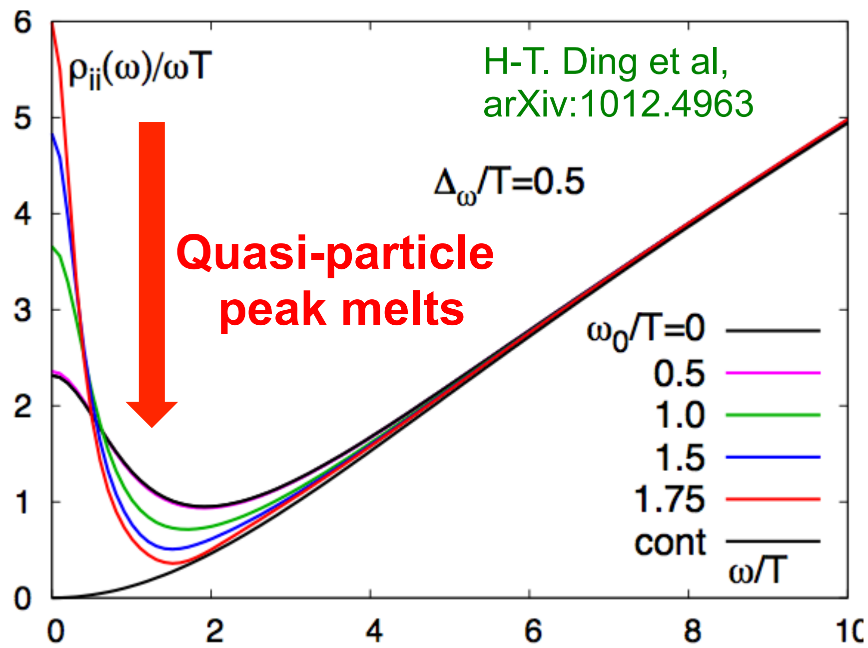
- Perturbatively require $\tau_{quasi} \sim \frac{1}{\alpha_s^2 T} >> \frac{1}{T}$

  but $\tau_{quasi} \approx \frac{const}{T} \frac{\eta}{s}$

  Such a plasma is unique in that it does **not carry quasi-particle excitations**

One driver for future EXP&TH: test this conjecture





The future use of minimal viscosity

A perfect liquid is maximally transparent to fluctuations.

- Precision how? Event-by-event fluctuations far from fully explored. Fluctuation damping controlled by sound attenuation length $\Gamma_s = \frac{\eta}{sT}$

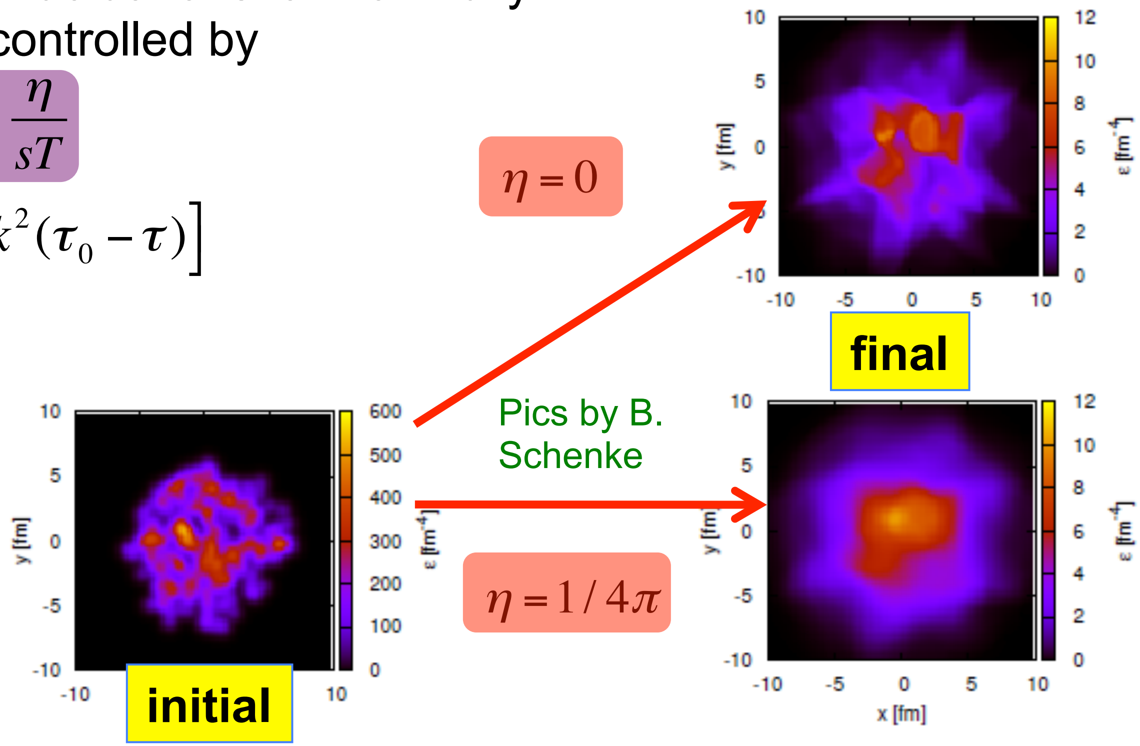
$$\delta v(\tau,k) = \delta v(\tau_0,k)\left(\frac{\tau_0}{\tau}\right)^* \exp\left[-\Gamma_s k^2(\tau_0-\tau)\right]$$

Much to be learnt from varying scale of fluctuation

e.g. $\tau_{1/e}(k) = \frac{1}{\Gamma_s k^2}$

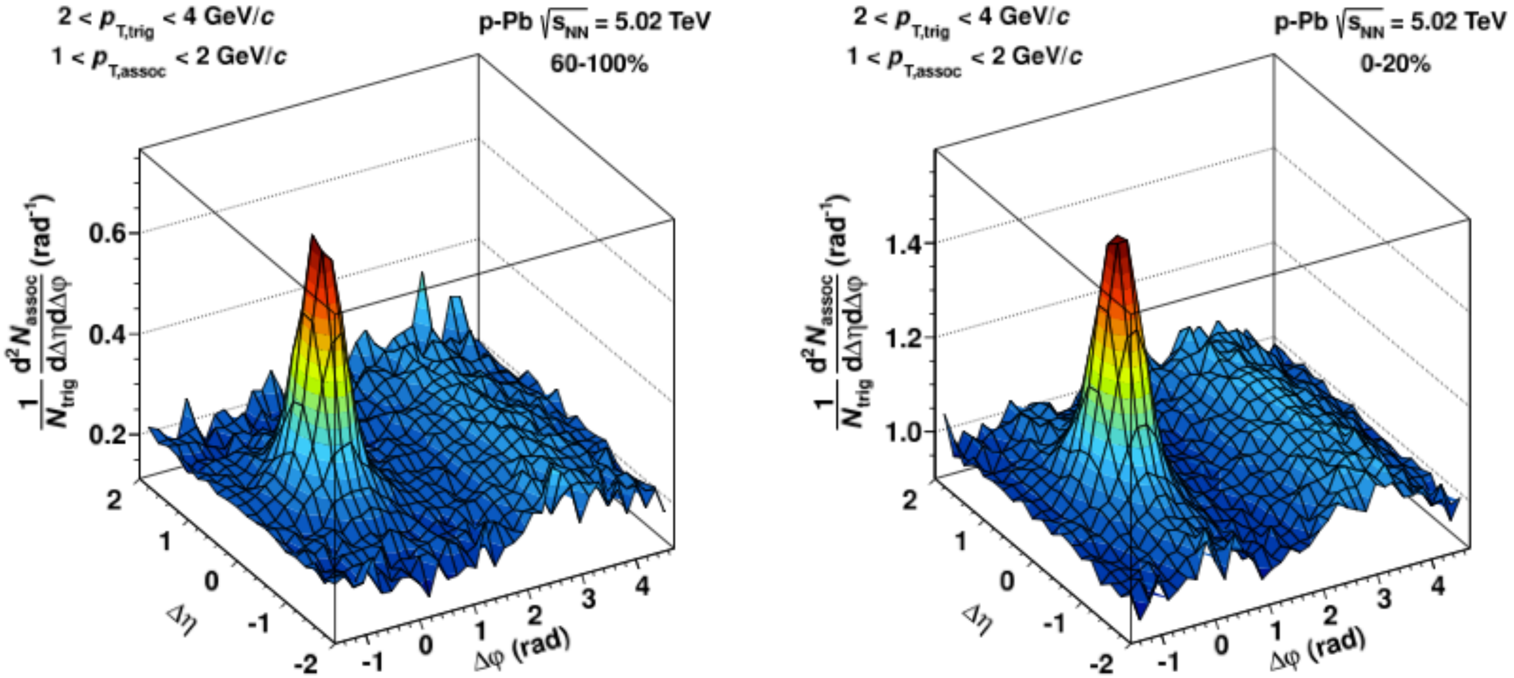
$$\tau_{1/e}(k = 1\,fm^{-1}) \approx 10-20\,fm$$

$$\tau_{1/e}\left(k = (0.5\,fm)^{-1}\right) \approx 2.5-5\,fm$$

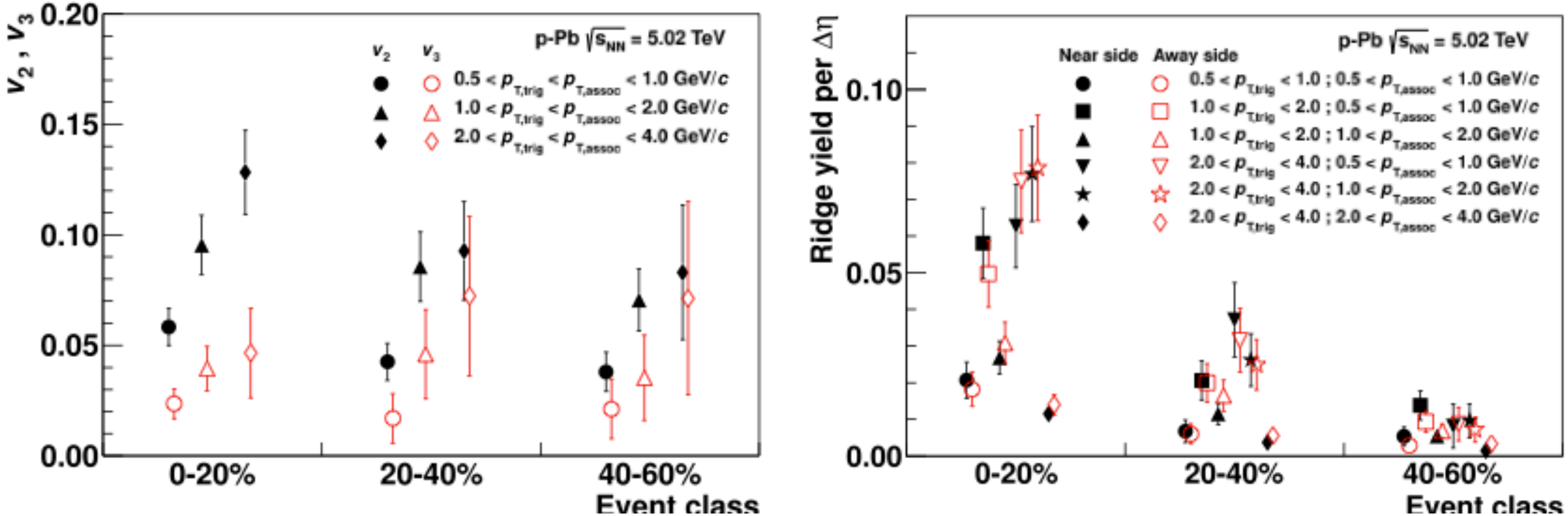


- Questions:
  - are all low-pt fluctuation measures of fluid dynamic origin?
  - what are the limitations of a CMB-like fluctuation analysis?

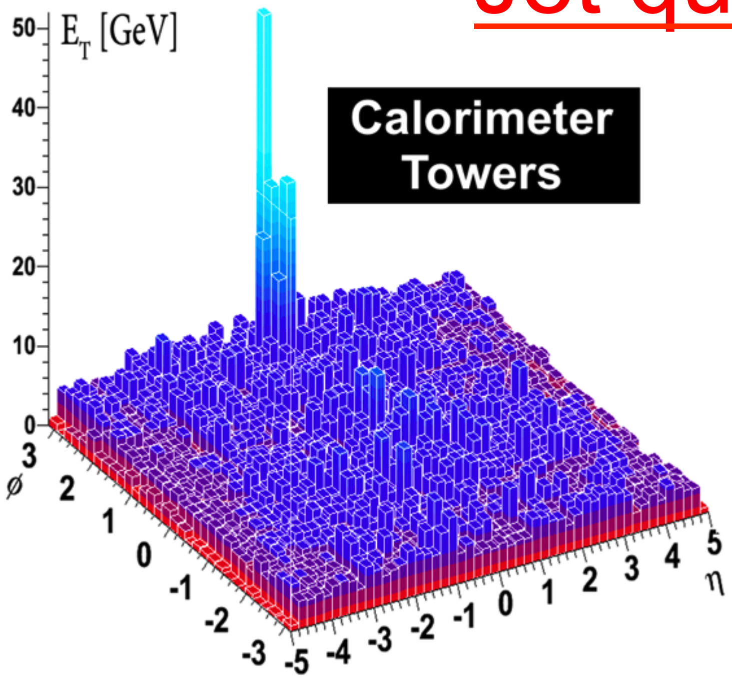
pA – extending or challenging the fluid dynamic picture

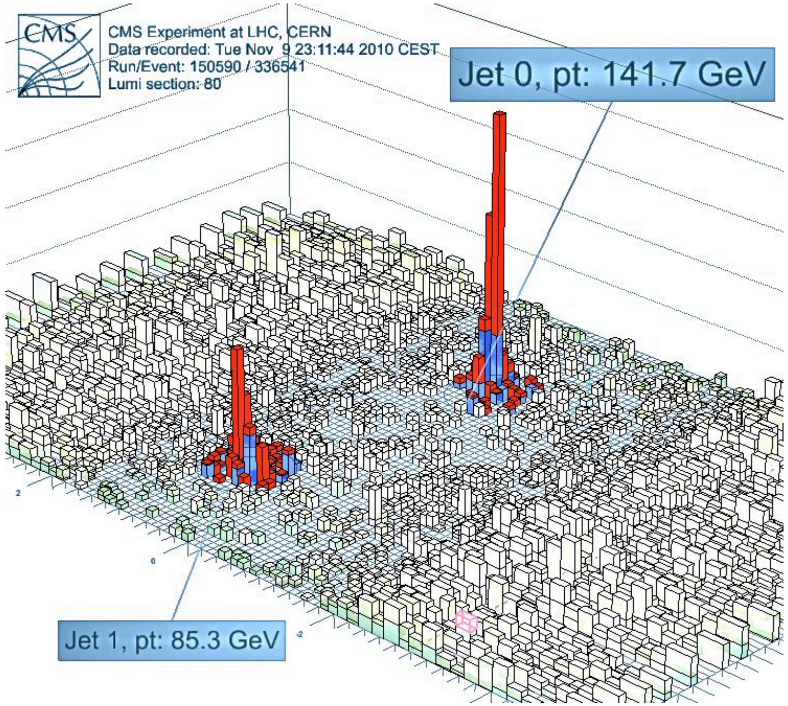


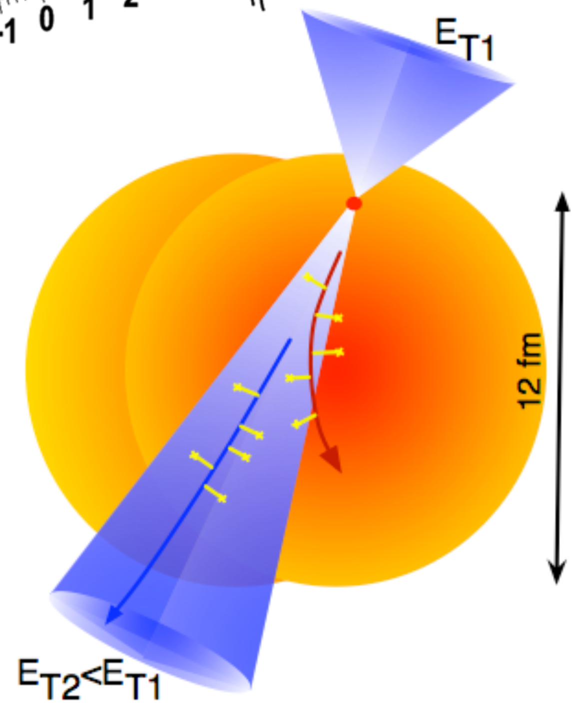
ALICE, arXiv:1212.2001, PLB719 (2013) 29-41



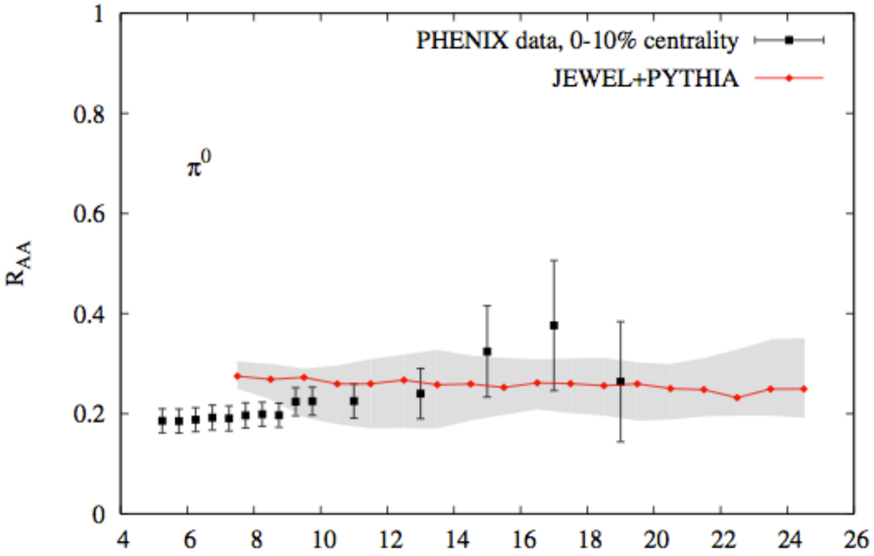
Jet quenching @ LHC

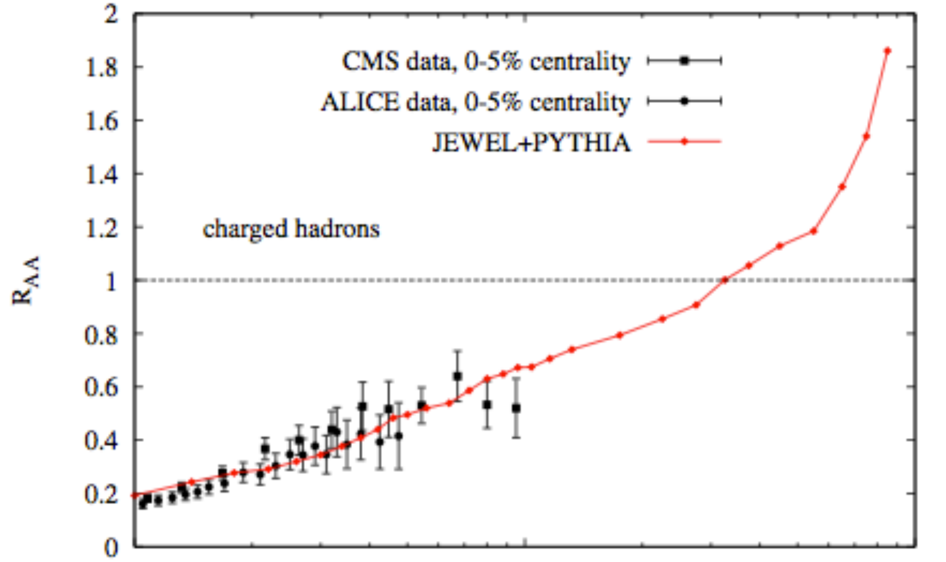




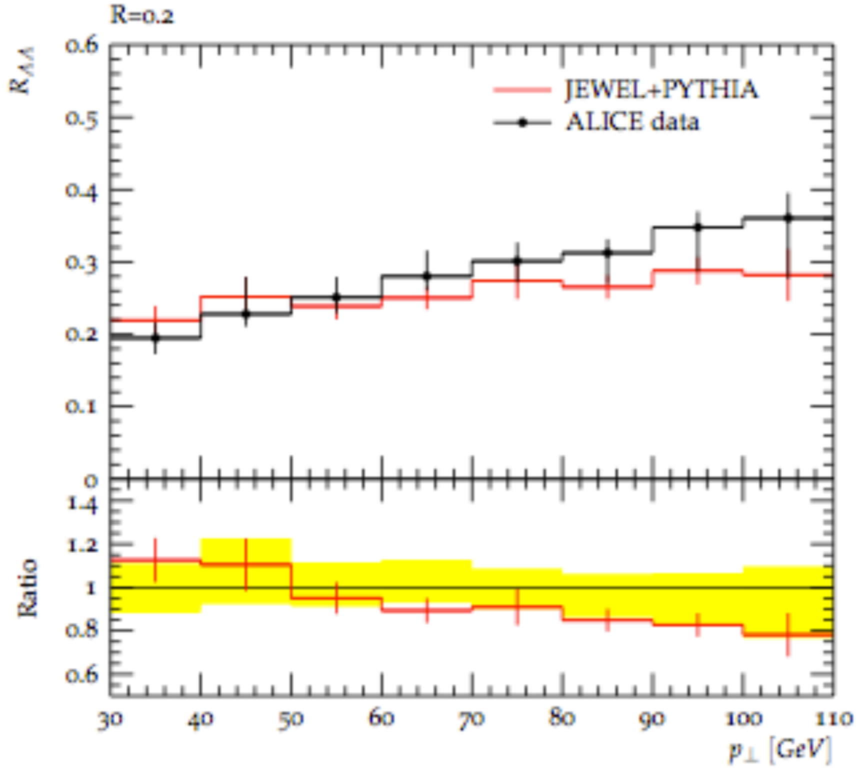


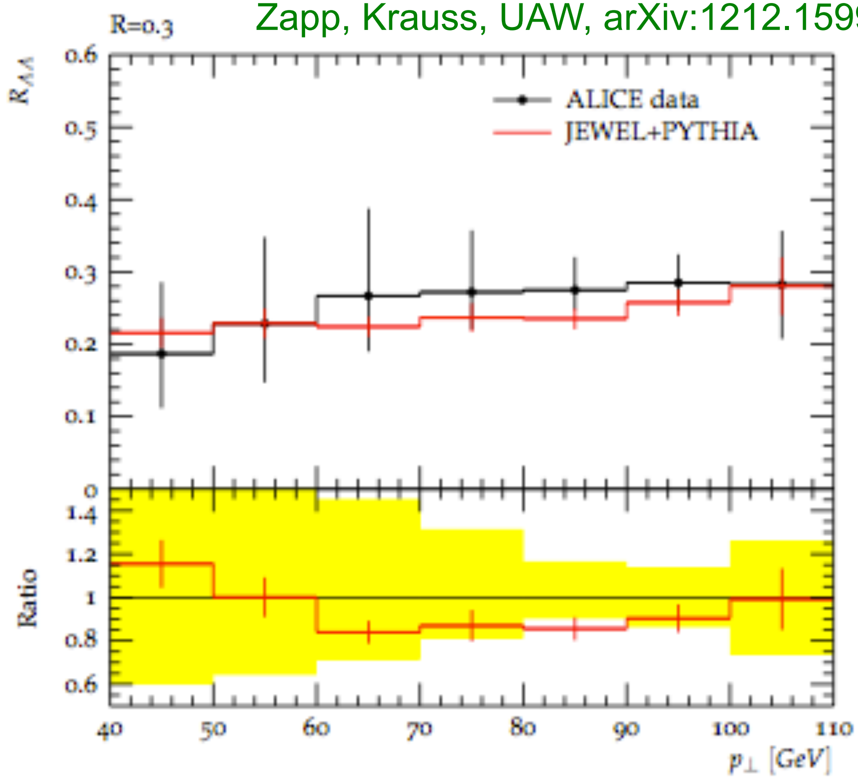
From Discovery via Precision to Dynamical Understanding





Zapp, Krauss, UAW, arXiv:1212.1599





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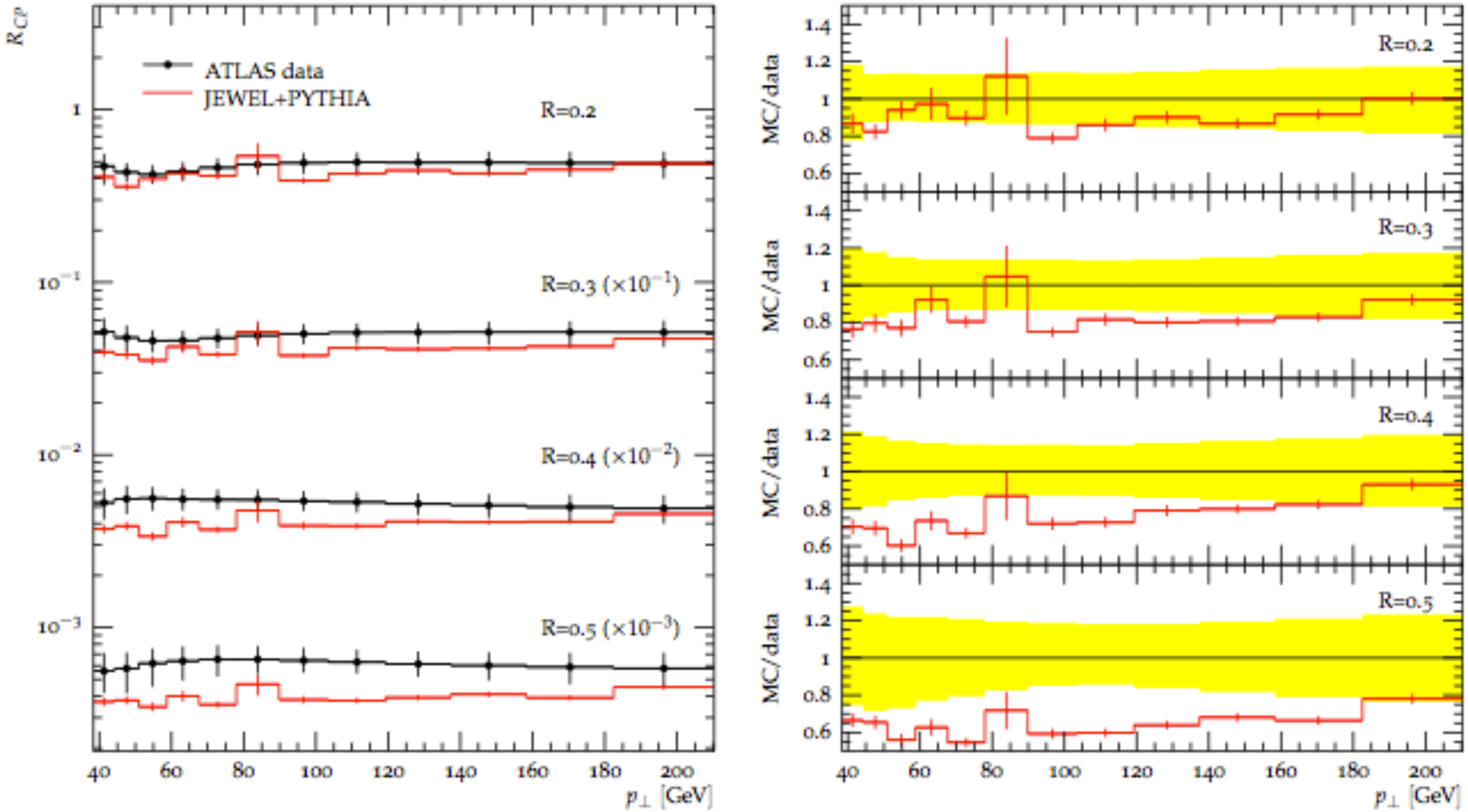

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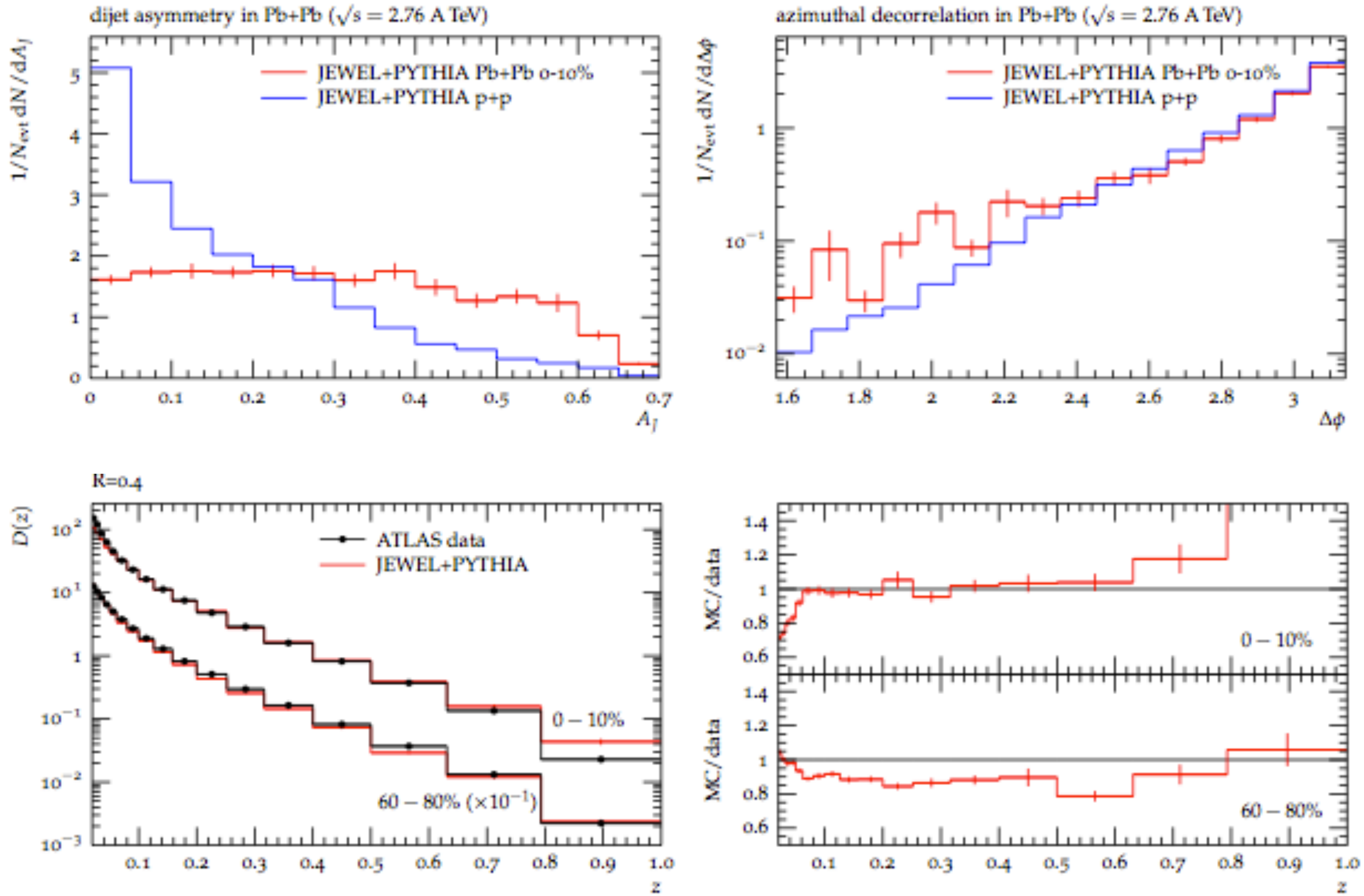

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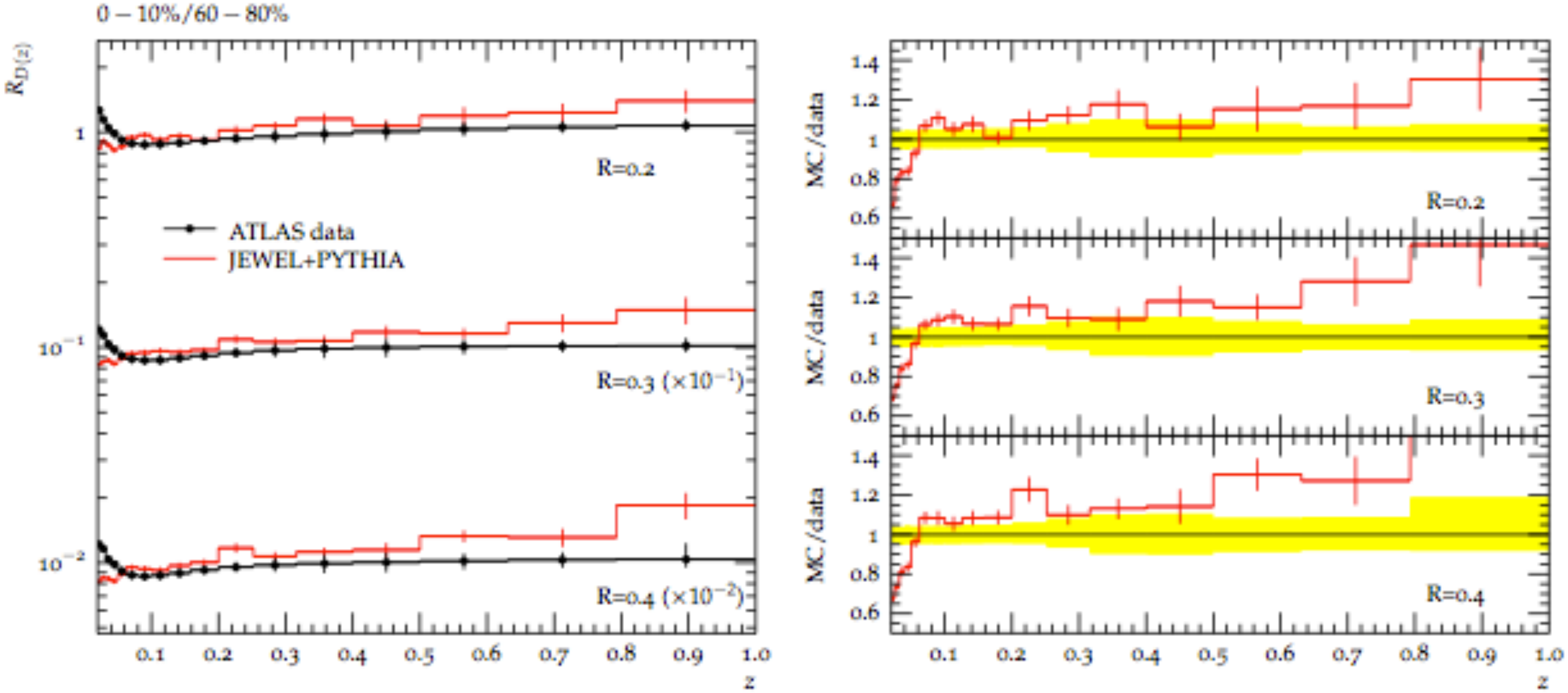


We start to confront wealth of precision data with models.

Hard Probes

- Light high-momentum hadrons
  $\pi, K, p, \Lambda, \ldots$
- Heavy flavors
  $D^0, D^+, D^{*+}, \ldots$
- Quarkonia
  $J/\psi, \psi', \Upsilon(1s), \Upsilon(2s)\ldots$
- Jets,

▪ created at $\tau_{init} \approx 1/Q_{hard} << 1\,fm$

▪ propagate up to $\tau_{final} \approx 10\,fm$

➡ Hard probes test the conjecture that the plasma does not carry quasi-particle excitations.

Impossible to cover all the versatile physics of hard probes in 20 min, here only one example … pto

Open heavy flavor at low pt

- 'No-quasiparticle conjecture' implies that light low-momentum dressed quarks do not exist (i.e. do not propagate beyond $L \approx 1/T$)

  In contrast, charm & bottom propagate (consequence of flavor conservation). How?

- At low pt, Langevin dynamics determines how charm & beauty quarks move: The perfect liquid is source of **random forces**

$$\frac{dp_L}{dt} = \xi_L(t) - \mu(p_L)p_L, \qquad \langle \xi_L(t)\xi_L(t') \rangle \equiv \kappa_L(p_L)\,\delta(t-t')$$

$$\frac{dp_T}{dt} = \xi_L(t) \qquad \langle \xi_{Ti}(t)\xi_{Tj}(t') \rangle \equiv \kappa_T(p_L)\,\delta_{ij}\delta(t-t')$$

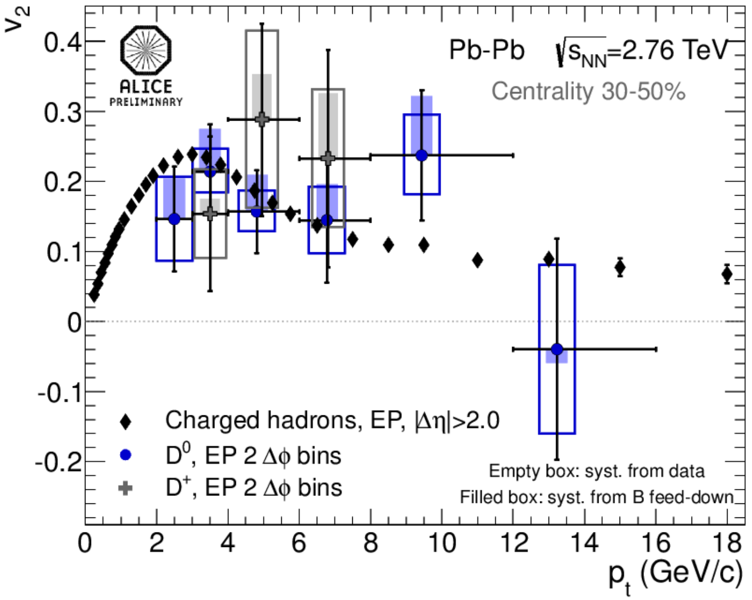
calculable from 1st principles in quantum field theory, e.g. in strong coupling limit:

$$\kappa_T = \pi\sqrt{\lambda}T^3\sqrt{\gamma} \qquad \kappa_L = \pi\sqrt{\lambda}T^3\gamma^{5/2}$$

- This hard probe is unique in that we know already that it is moved by the flow.

  In coming years: establish T-dependence and separate flow of b and c to constrain κ_T, κ_L, μ

  RHIC&LHC needed



LHC Heavy-Ion Program up to 2022

Approved plan after 1st long shutdown (LS1) is

John Jowett, CERN Beam Department
Submission to Cracow Open Symposium of European Strategy Preparatory Group,
https://indico.cern.ch/contributionDisplay.py?contribId=164&confId=175067

Year	Colliding species	Remarks
2015-16	**Pb-Pb**	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling if required.
2017	**p-Pb *or* Pb-Pb**	p-Pb to enhance 2015-16 data. Pb-Pb if luminosity still needed
2018		LS2: install DS collimators around ALICE to protect magnets, injector upgrades* (ALICE upgrade for 6 × design luminosity)
2019	**Pb-Pb**	2-3×design luminosity in ALICE (or more with, eg, reduced bunch spacing*).
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target and collimation requirements.
2022		LS3, Possible upgrades such as cooling systems.

Table 1: LHC heavy ion programme from the end of Long Shutdown 1 to the start of Long Shutdown

Recommendations of town meeting

Conclusions from the Town Meeting on Relativistic Heavy Ion Physics
Submission to European Strategy Preparatory Group,
https://indico.cern.ch/userAbstracts.py?confId=175067

1. *The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.*

2. **At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.**

3. **The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.**

4. **Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.**

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3. The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.

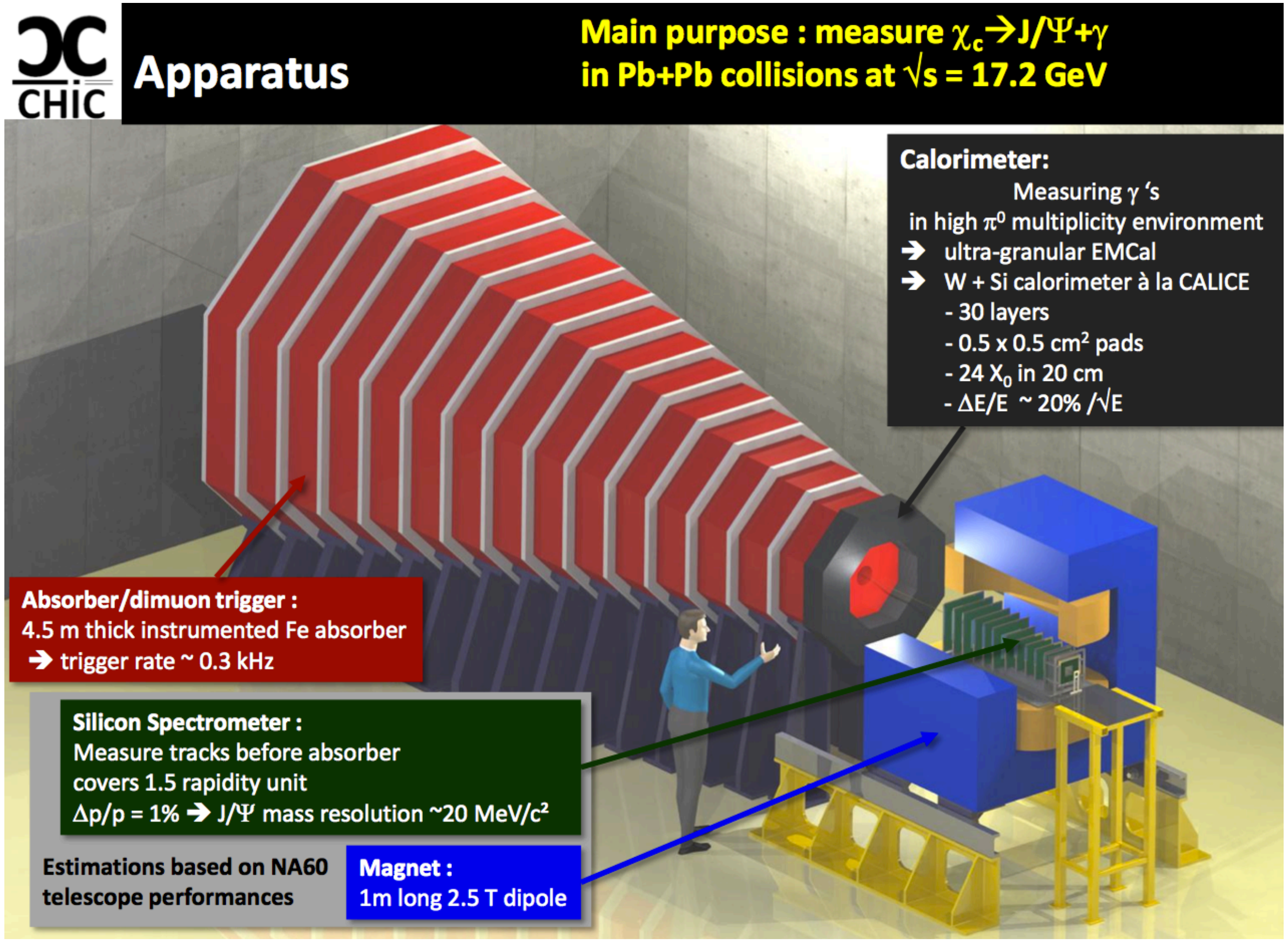
4. Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.

One heavy ion experiment (NA61/SHINE) is currently studying the region of highest baryon densities at the CERN SPS.

At least within this decade, the CERN SPS provides a unique opportunity for future heavy ion fixed target experiments at beam energies above ~ 8 GeV/nucleon.

CHIC – one idea for a future CERN SPS experiment

- Expression of interest submitted to CERN-SPSC-2012-031
- Still a long way to a (proto)collaboration, but several such concepts are discussed
- Central topics (dileptons, charmonium / open charm, critical point) could be addressed.



CERN Heavy Ion Programme

- LHC programme
  - a decade of scheduled experimentation
  - upgrades that respond to emerging opportunities

- CERN SPS fixed target programme
  - a standing invitation to the worldwide HI community