Overview of recent ALICE results

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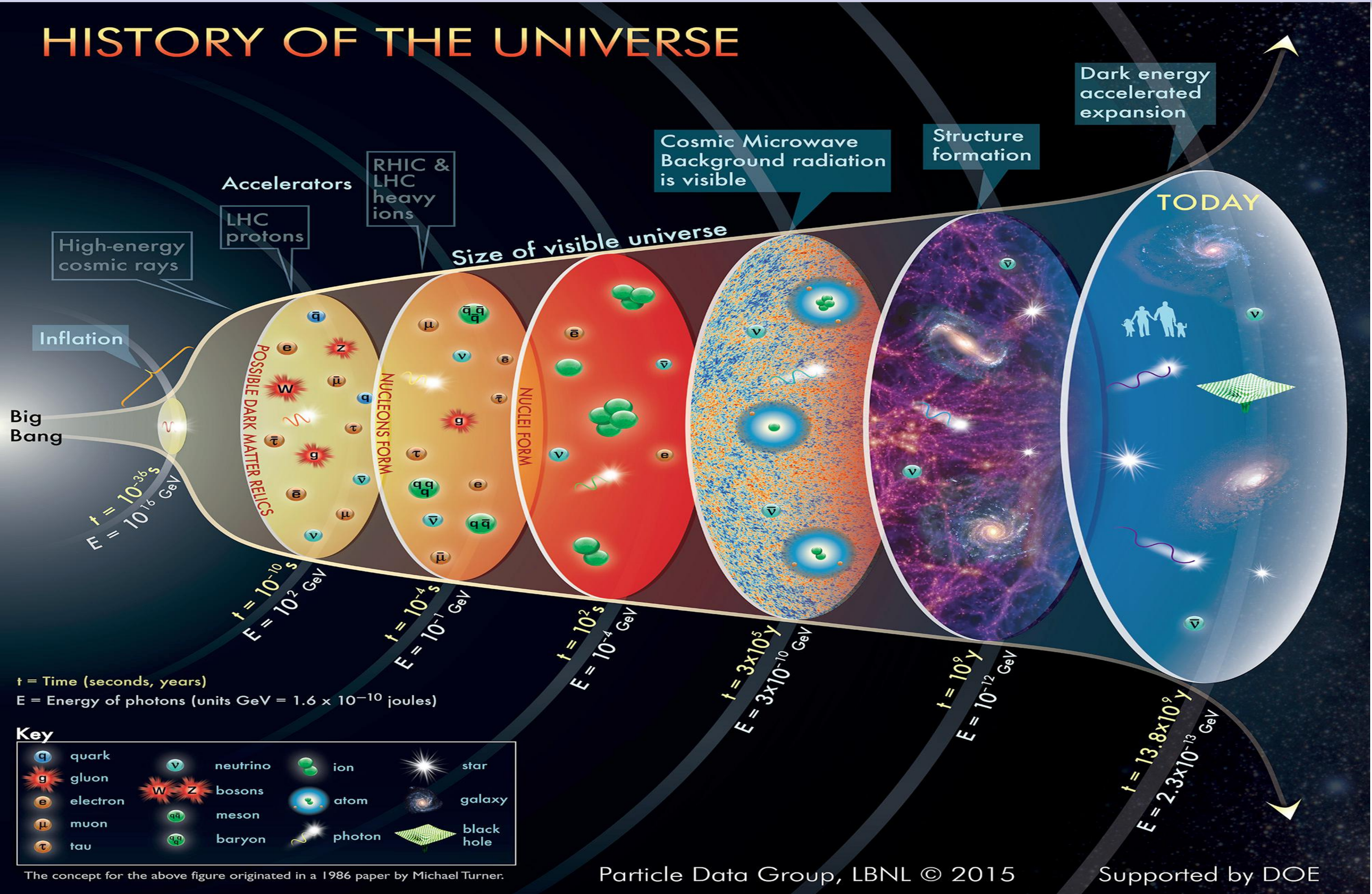
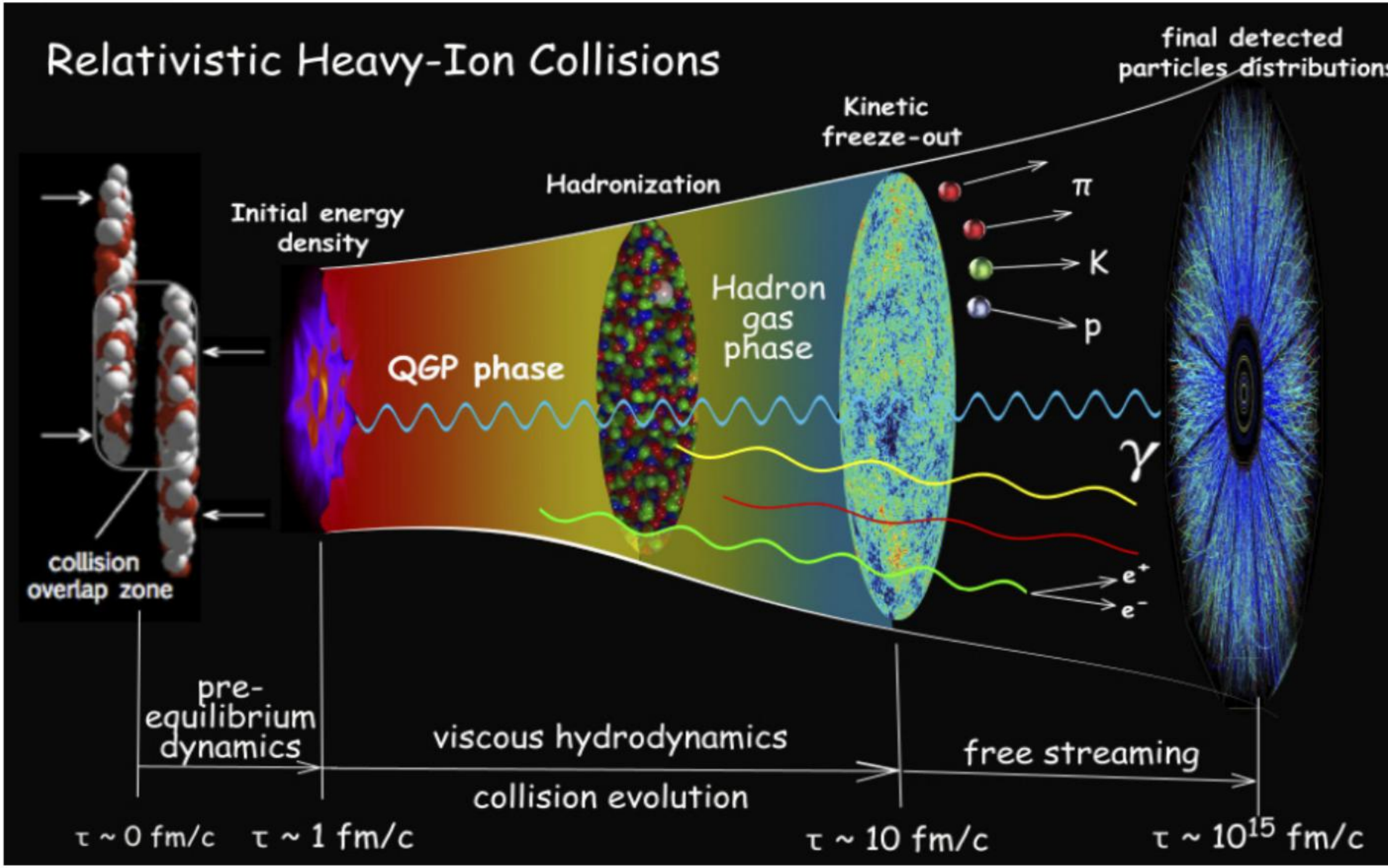
(for the ALICE collaboration)

This work has been supported by the Hungarian NKFIH/OTKA K 120660 grant and the János Bolyai scholarship of the Hungarian Academy of Sciences

It all started with a big bang...



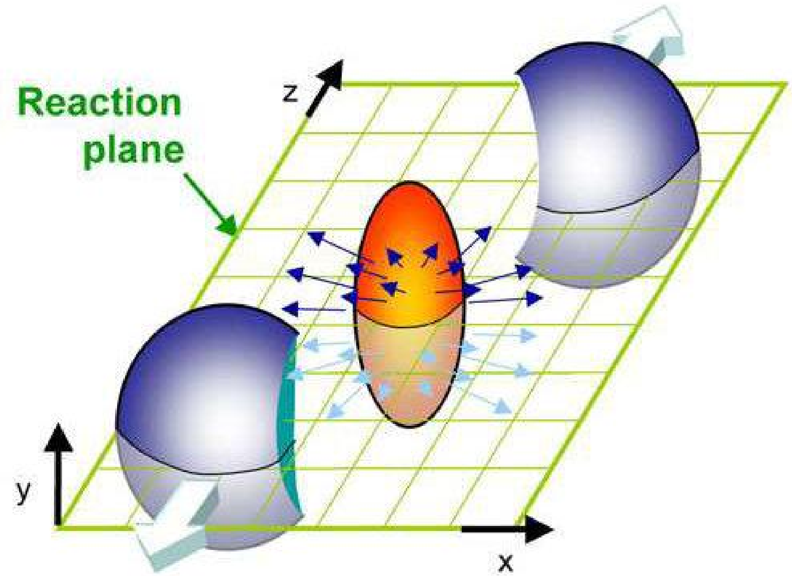
“Little bangs” in the laboratory



Courtesy of Paul Sorensen and Chun Shen

Probing the nuclear matter

- **"Soft" processes**
  - Bulk physics:
    many, low-momentum particles
  - From the later stages
  - **Thermal behavior**
  - **Collective dynamics ("flow")**



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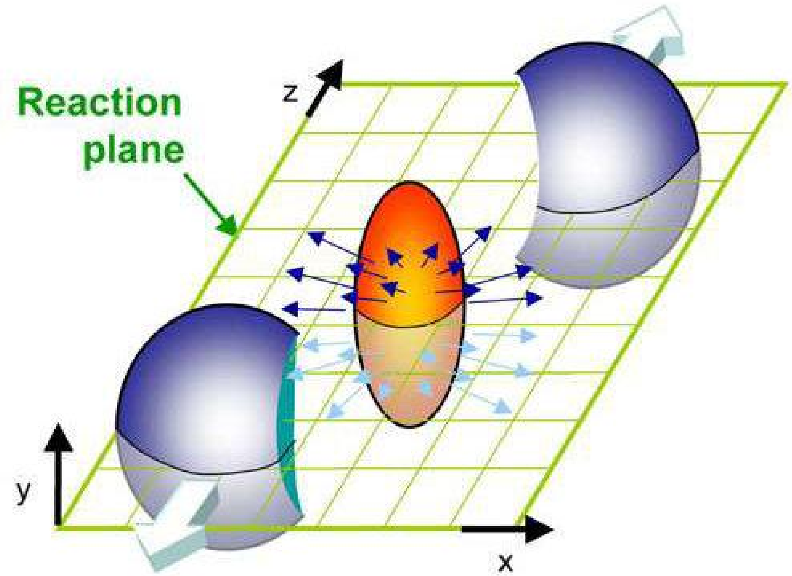
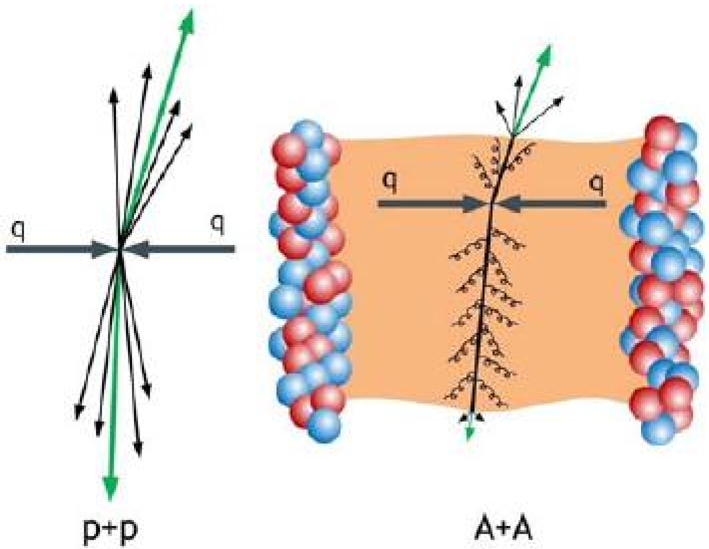
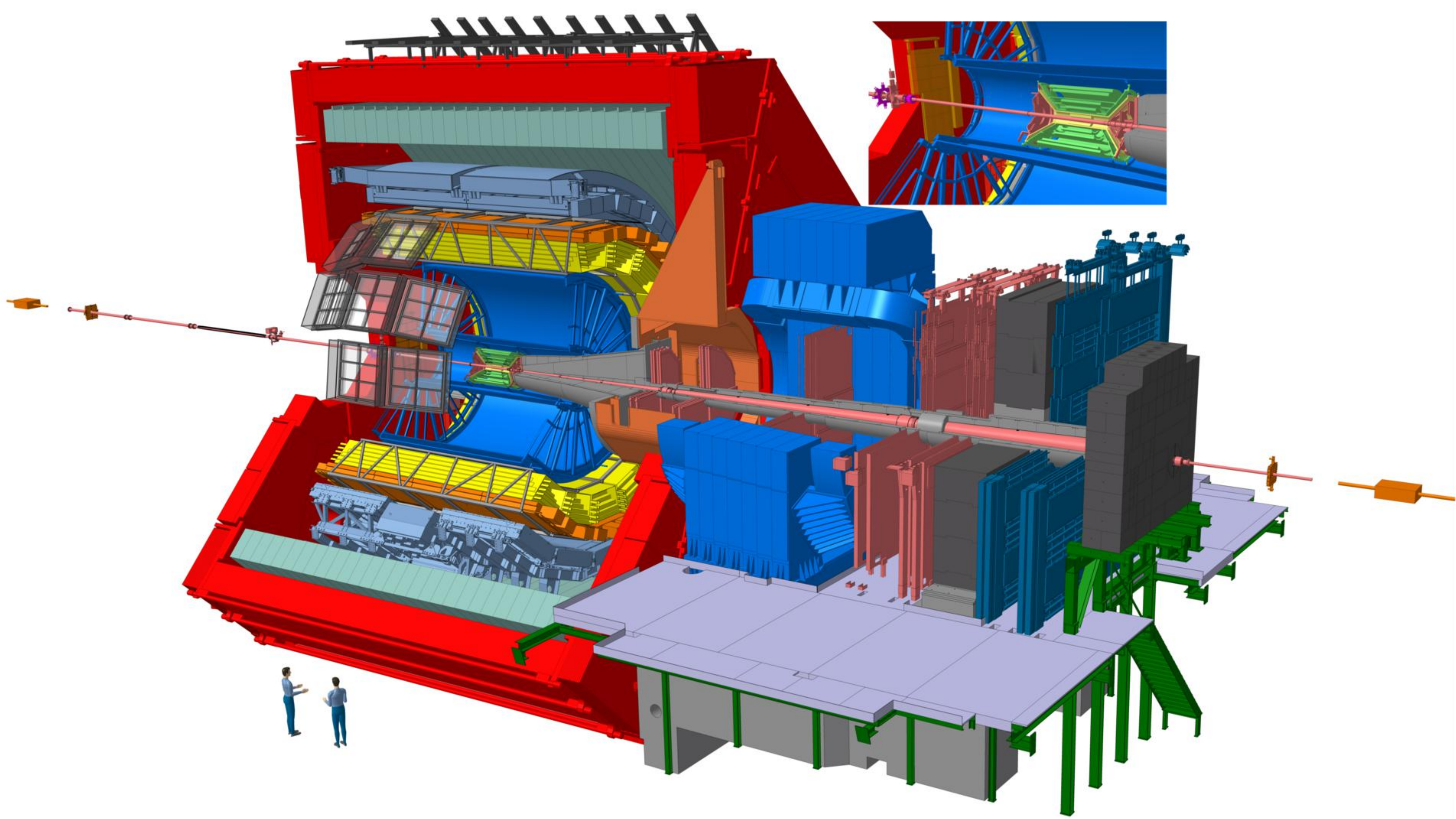




- **"Hard" processes**
  - Few, high-momentum particles
  - Early production in analytically calculable pQCD processes
  - Heavy flavor probes
  - **Tomography of the QGP, modification in the medium**

ALICE (Run-2)



A dedicated heavy-ion experiment at the LHC, excellent PID

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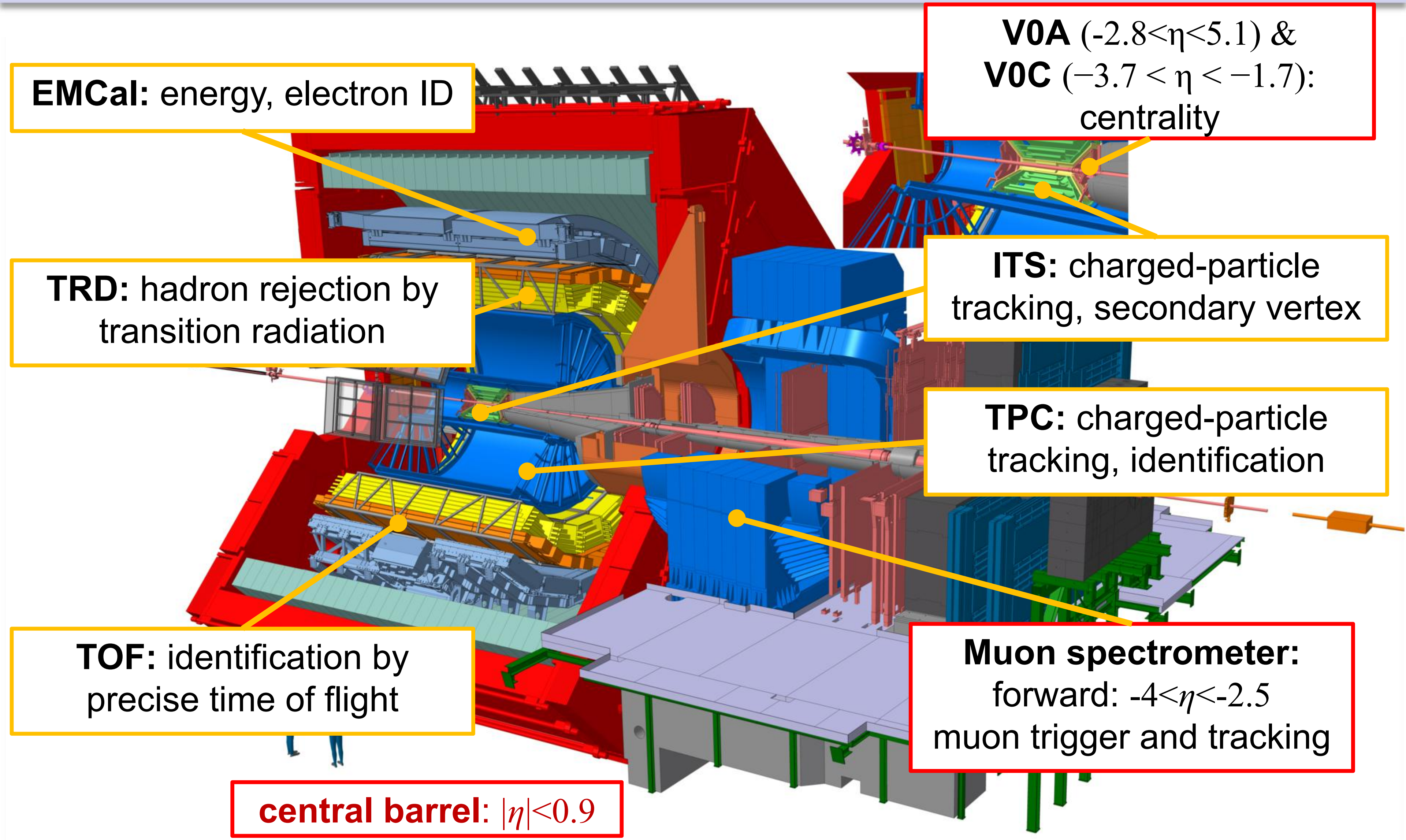

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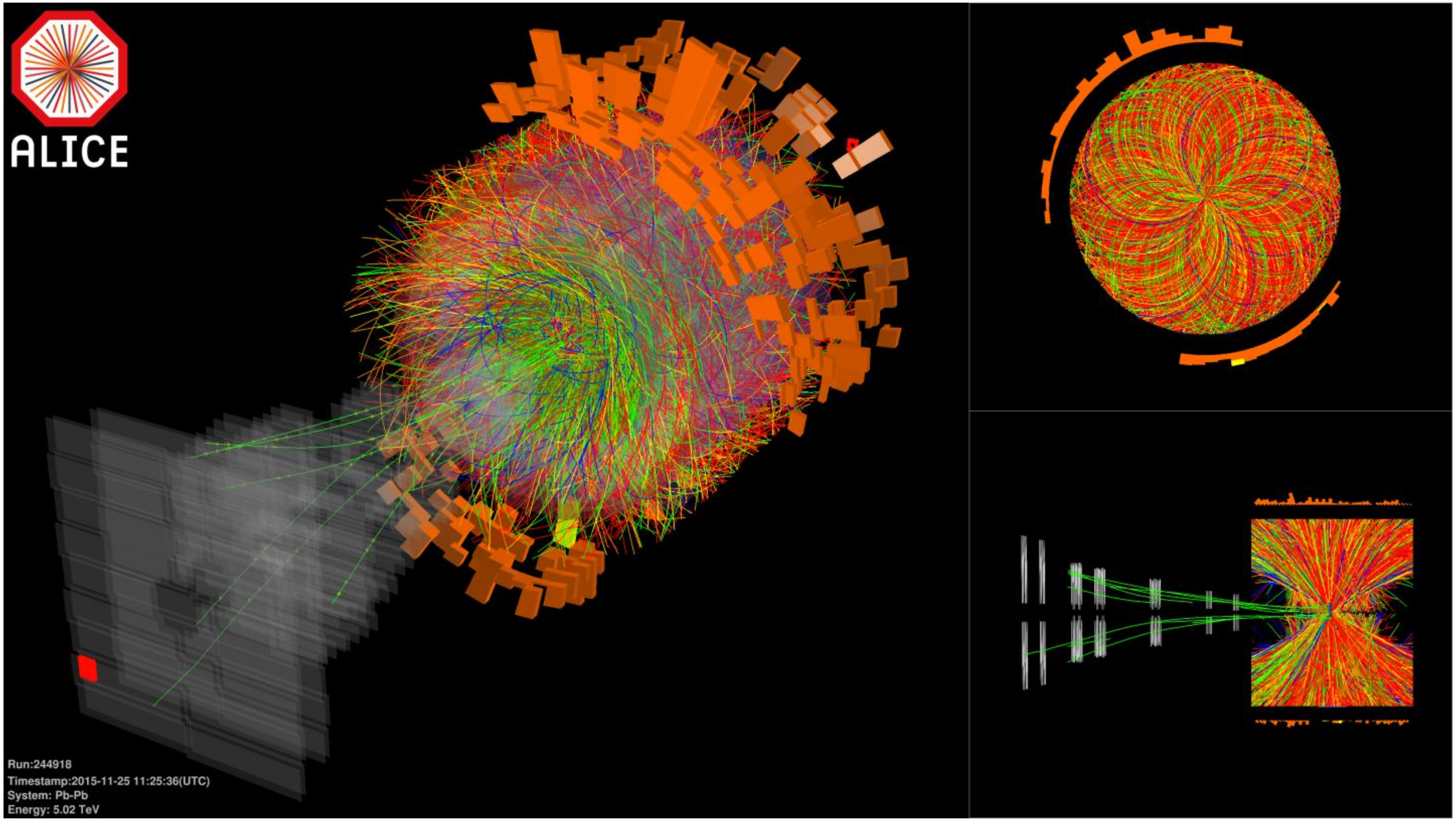
Reconstructed heavy-ion collision

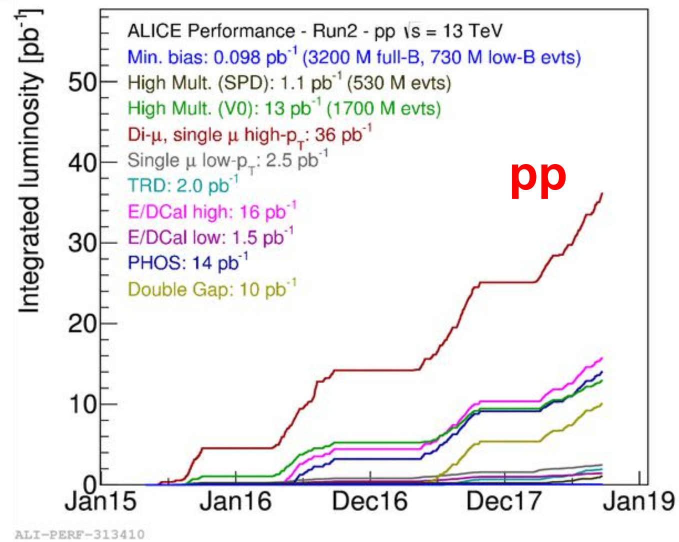


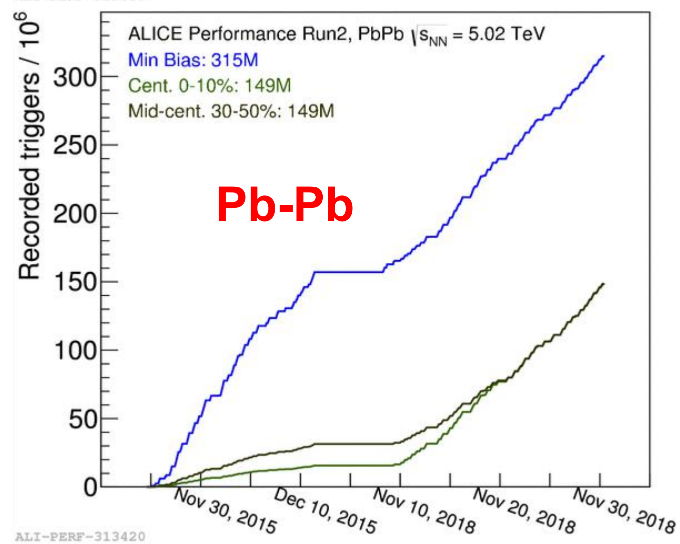
- Up to 600 million events per second
- Signals of up to thousands of particles to be identified, processed
- 2-4 GB data every second

ALICE data collected: Run-1 & Run-2

System	year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2013	0.9	~200 μb^{-1}
		2.76	~100 μb^{-1}
		7	~1.5 pb^{-1}
		8	~2.5 pb^{-1}
	2015-2018	5.02	~1.3 pb^{-1}
		13	~59 pb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02	~3 nb^{-1}
		8.16	~25 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	2018	5.02	0.9 nb^{-1}

- Small to large systems
- Several different collision energies





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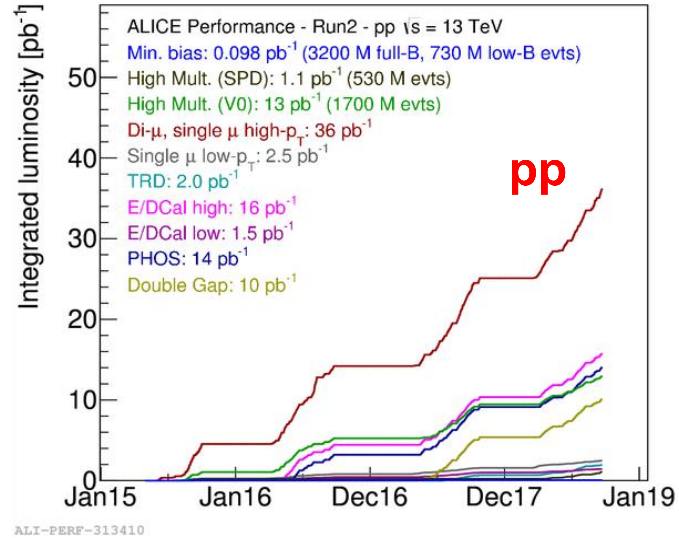
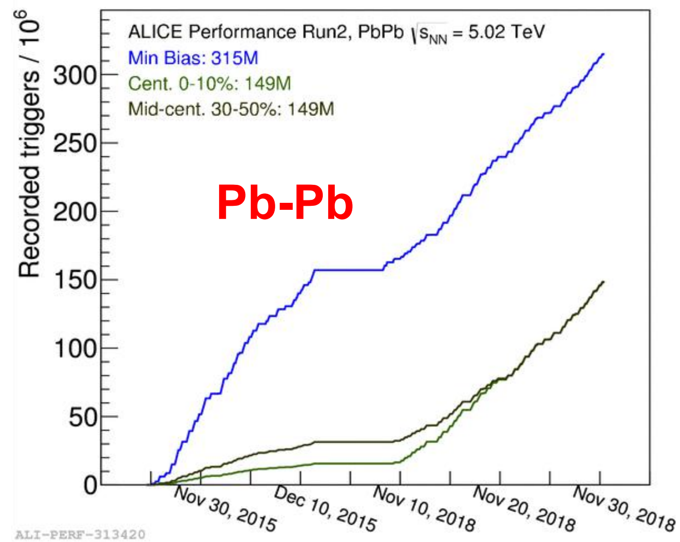
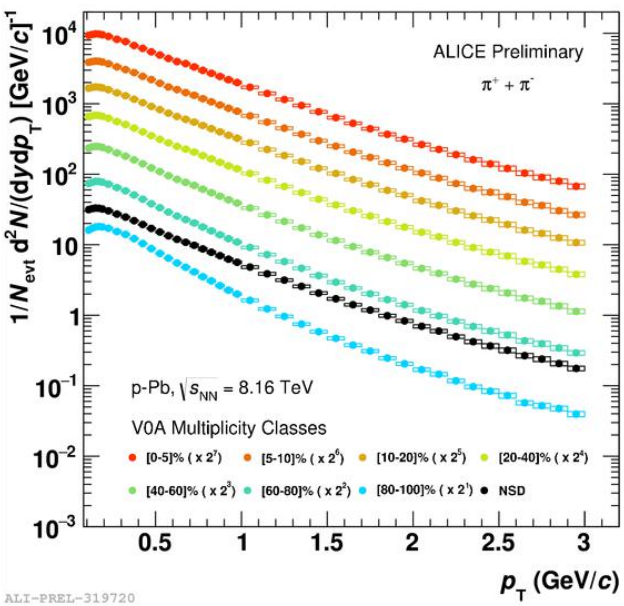


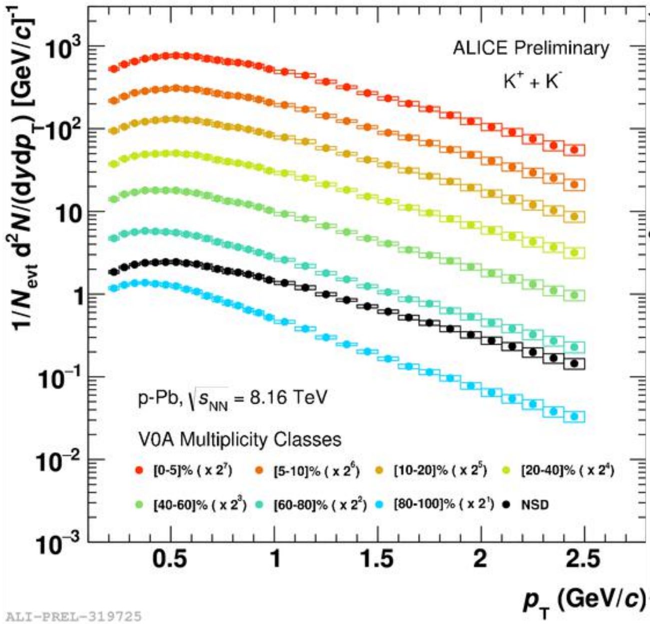


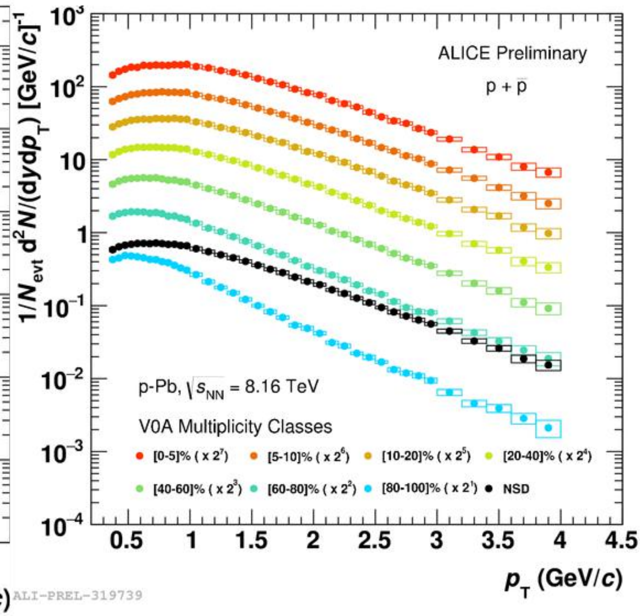
- Small to large systems
- Several different collision energies

=> Towards a comprehensive understanding of the strongly interacting nuclear matter

Spectra of identified particles (π, K, p)







- High-precision measurements of identified particles

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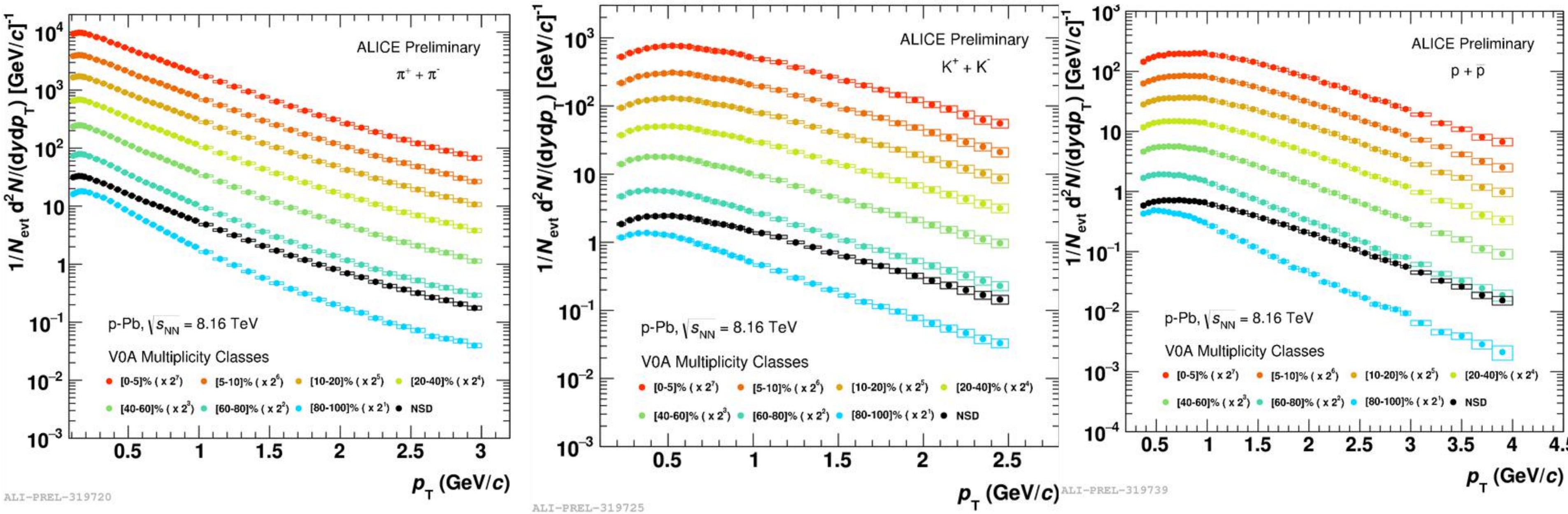


- High-precision measurements of identified particles
- Mass-dependent hardening of spectra with increasing multiplicity

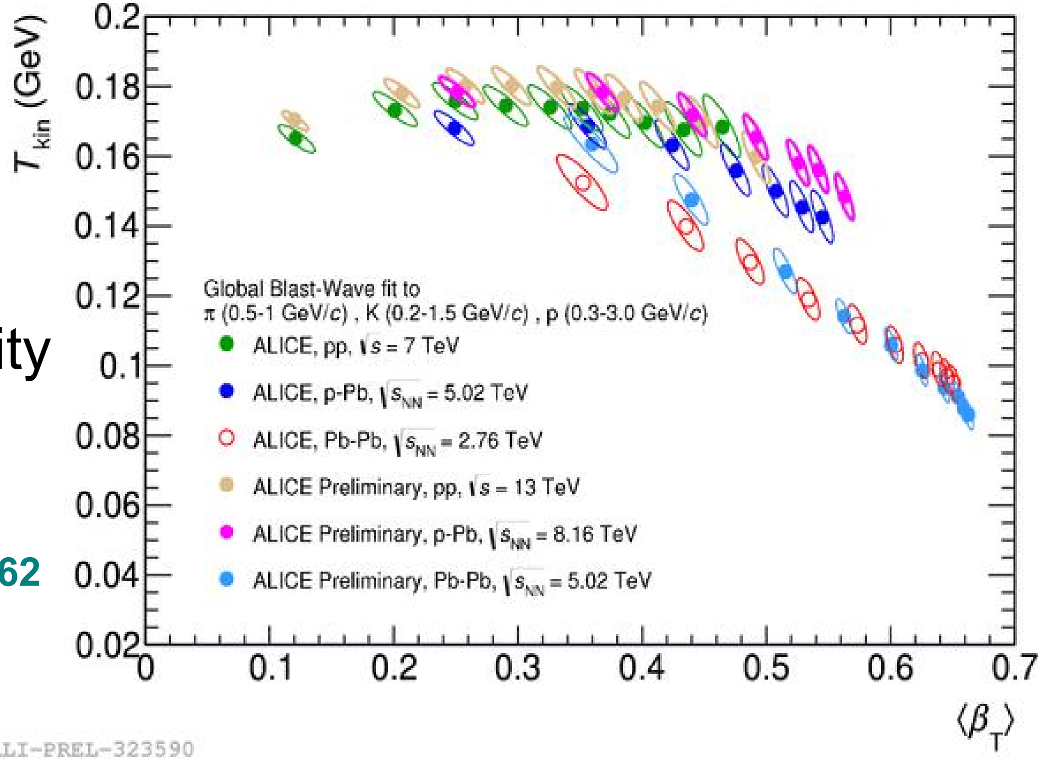
$$T_{eff} \sim T_{kin} + 1/2\, m\langle u_T\rangle^2 \quad \text{(at low } p_T\text{)}$$

==> **Collective radial expansion**

Kinetic freezeout via blast-wave fits

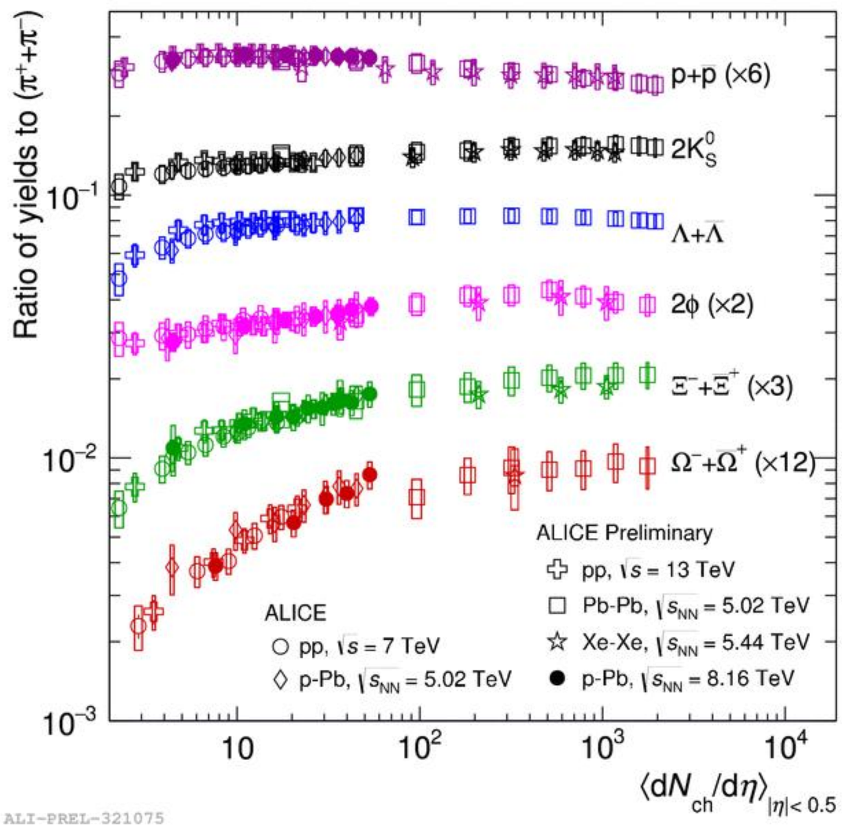
- Blast-Wave model
  - particle production from expanding hypersurface
  - β_T: radial expansion velocity
  - T_{kin} : kinetic freeze-out temperature

Schnedermann et al., PRC (1993) 48, 2462



- Simultaneous fits to π, K, p spectra in bins of multiplicity/centrality
- Similar trend observed in pp, p-Pb, Pb-Pb collisions
- Larger β_T in small systems at similar multiplicity

Particle production across systems



- Strangeness enhancement once considered as a sign of QGP
  Rafelski, Müller, PRL 48, 1066 (1986)
- Enhancement increases with strangeness content
- No significant energy and system dependence at given multiplicity
- Smooth evolution with system size

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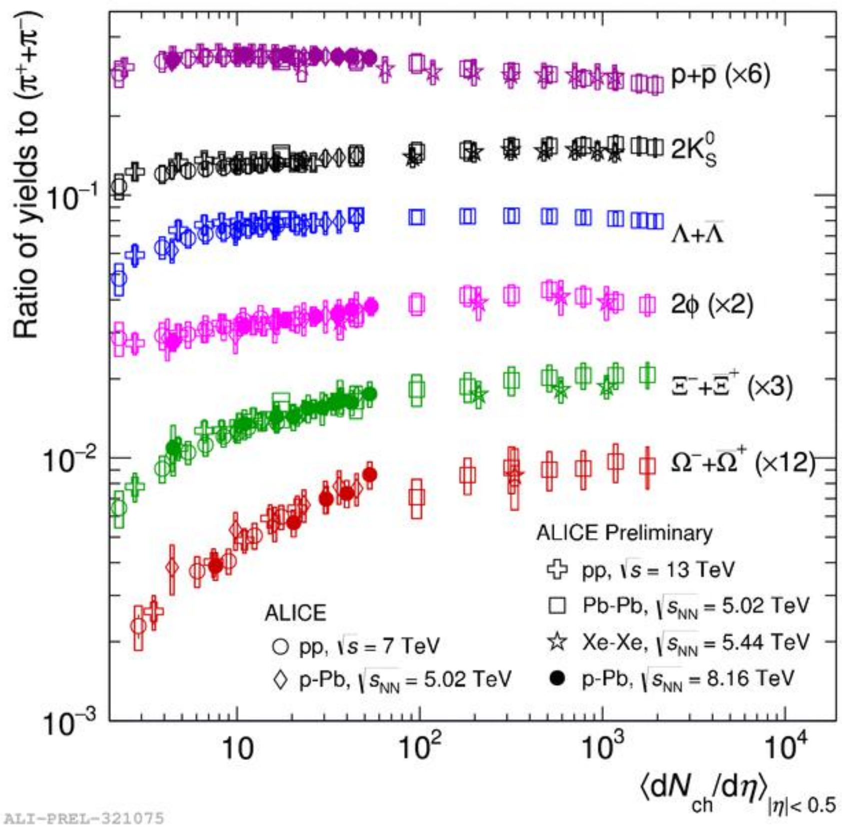

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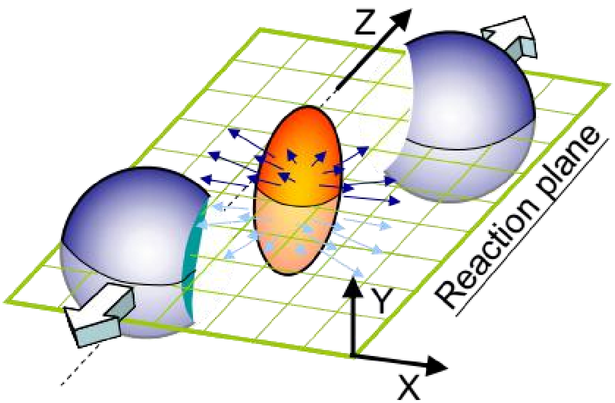
Production of light and strange particles are driven by the characteristics of the final state

Collectivity

- Azimuthal momentum anisotropy
  - parametrized by Fourier coefficients

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2 dy}\left[1 + 2v_1 \cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right]$$



  - v_1: Radial expansion
  - v_2: Azimuthal anisotropy (“elliptic flow”)

$$v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

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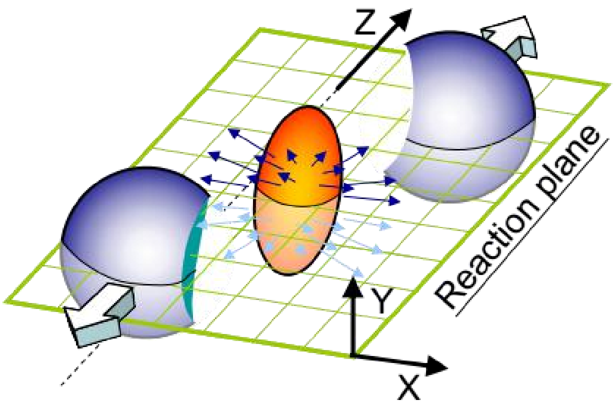
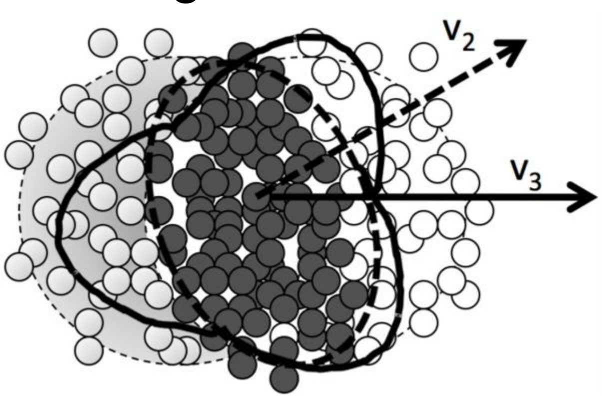


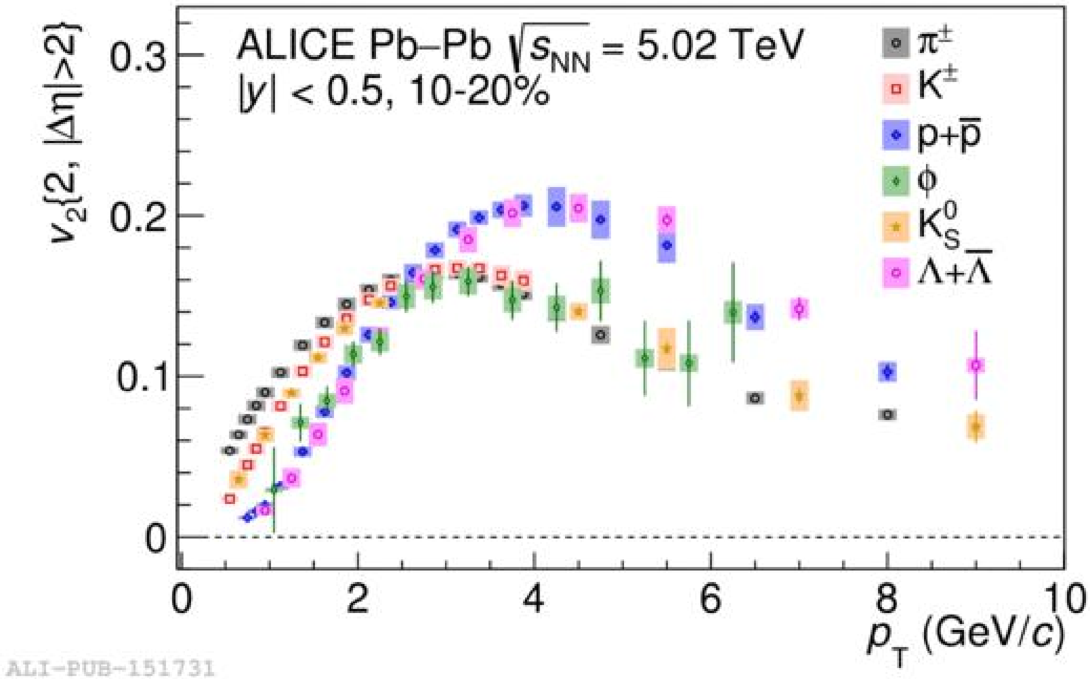
- Flow caused many surprises...

1. RHIC: **Substantial v_2, perfect hydro**, NCQ scaling
   -> **strongly coupled QGP**
2. **Higher harmonics are important** (v_2~v_3)
   -> **initial state fluctuations**
3. LHC: **Small systems "flow"**
   -> hydro description != QGP



Elliptic flow: light and strange particles

1805.04390



- v_n are sensitive to the full evolution of the system
  - initial conditions
  - QGP phase
  - hadronic phase

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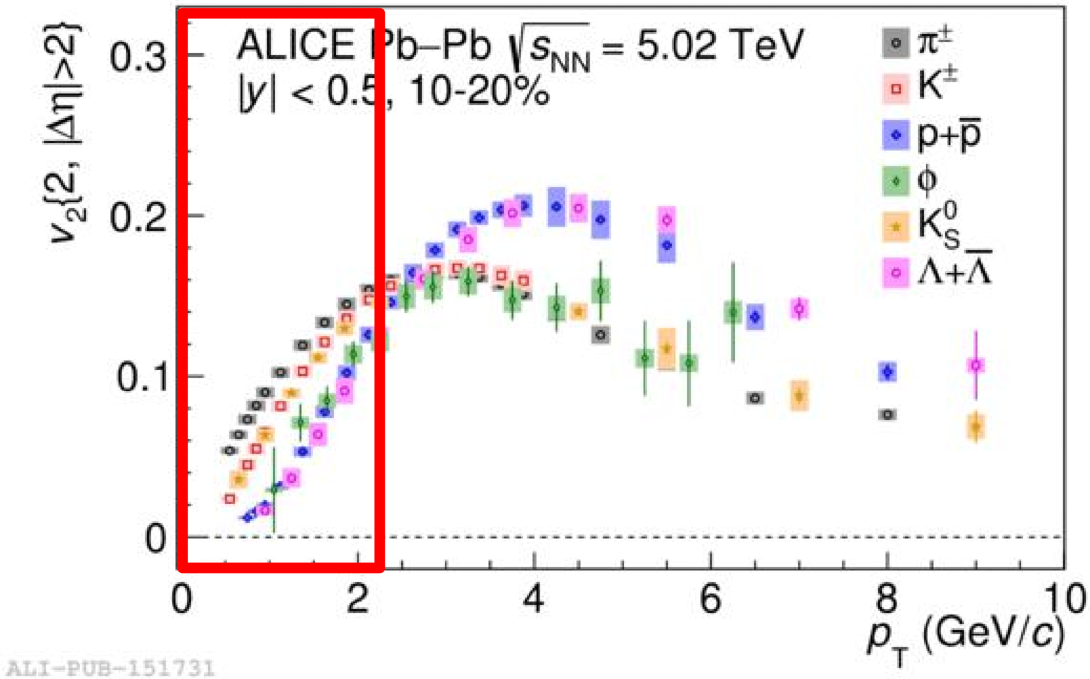

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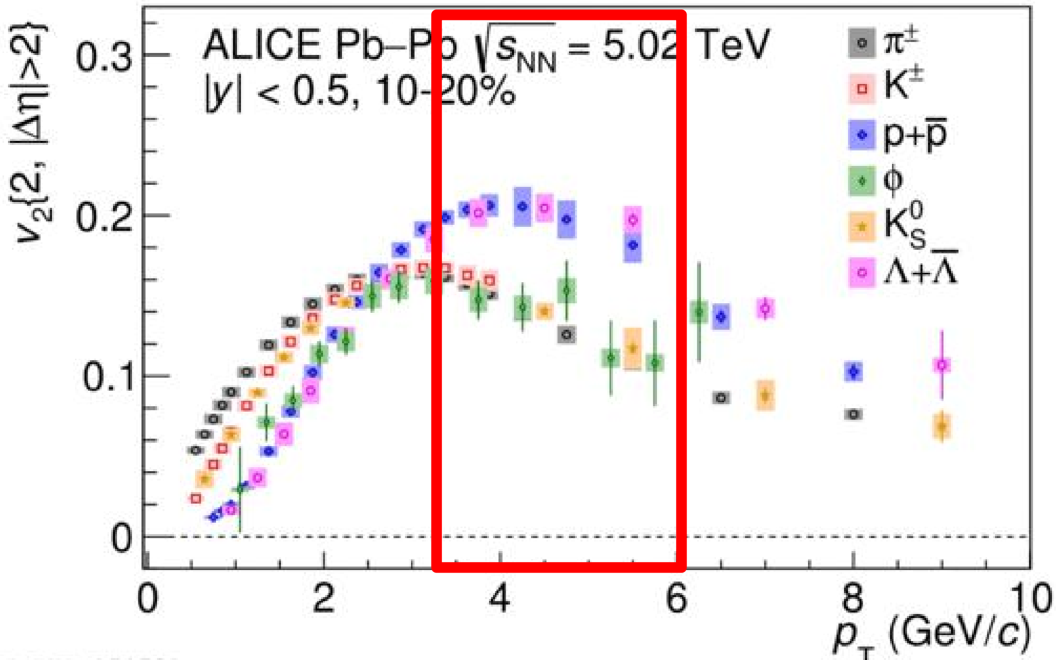

ALI-PUB-151731

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  - *φ meson: clearly determined by mass at low p_T and quark content at intermediate p_T*

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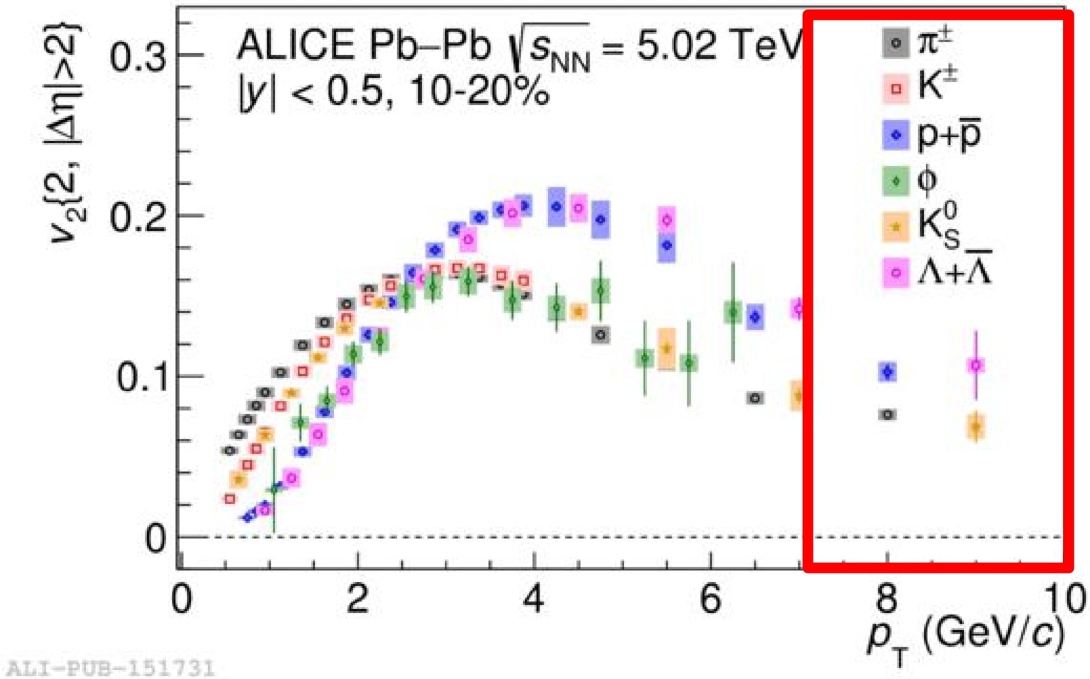

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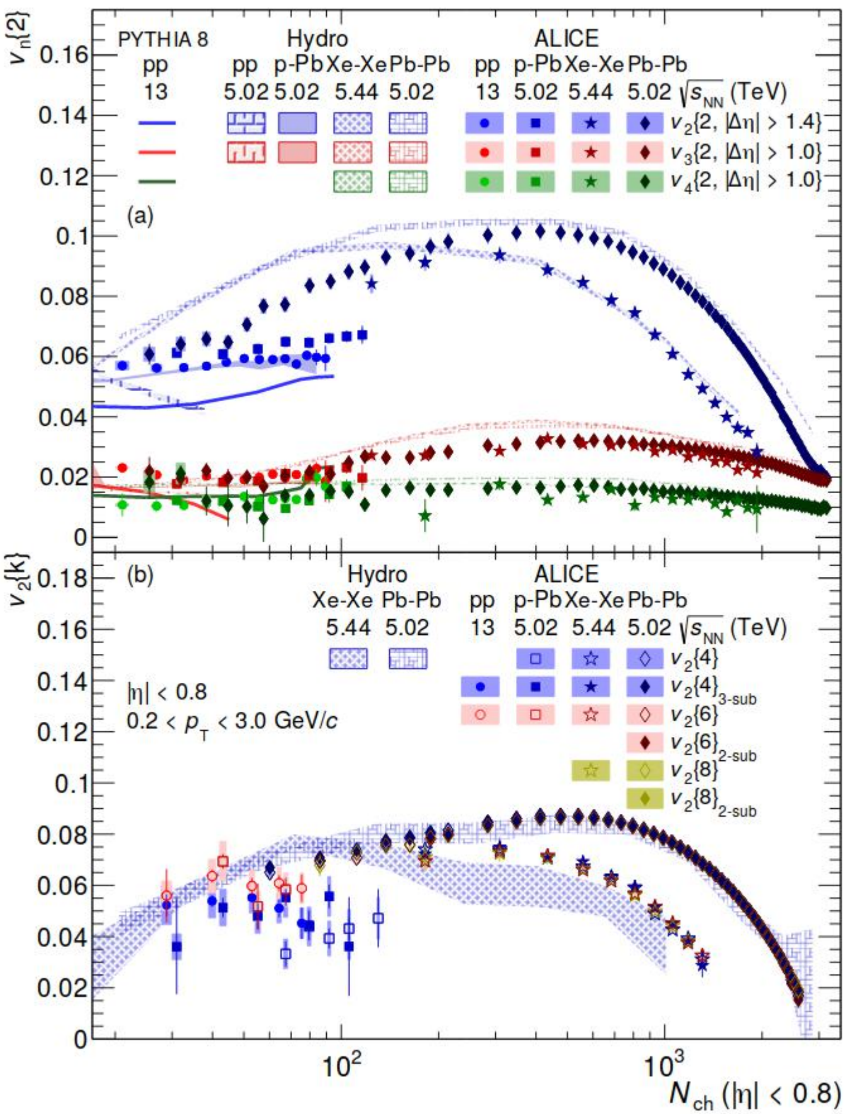
- High p_T: parton energy loss dominant

Flow harmonics across systems

1903.01790



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  - Two-particle, multi-particle and subevent methods are qualitatively the same

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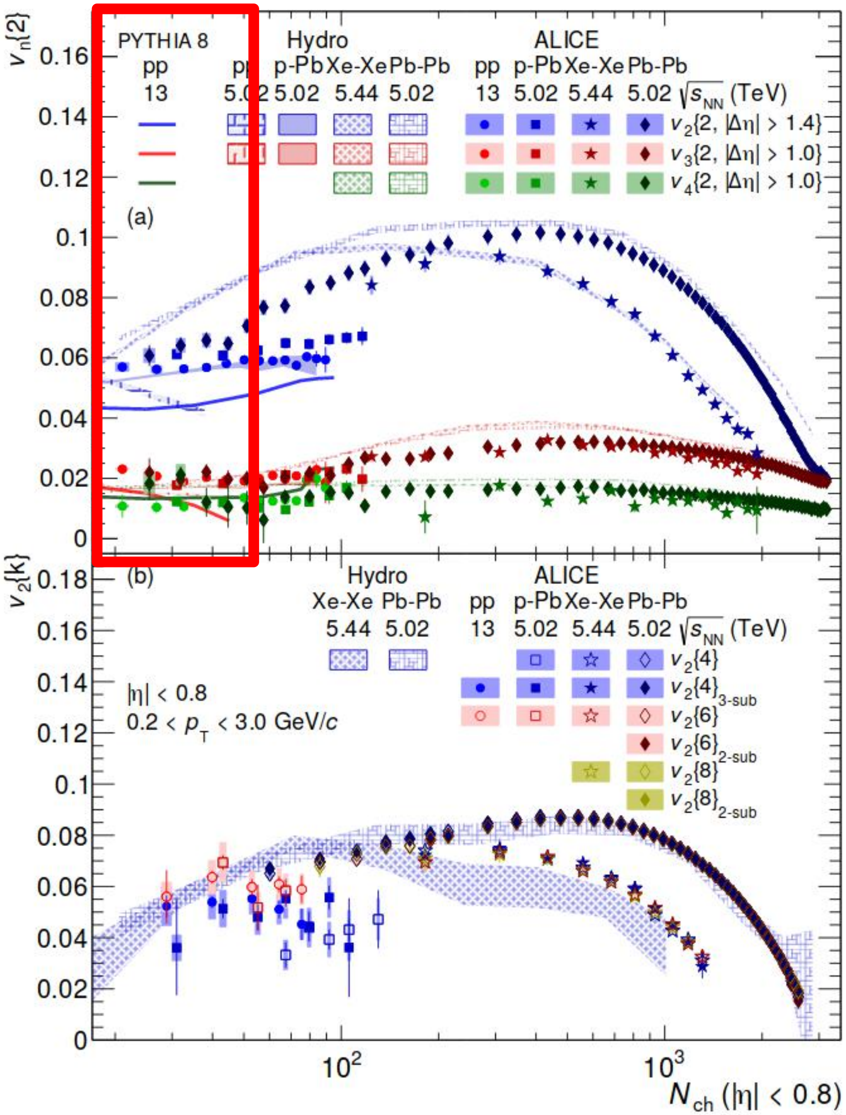

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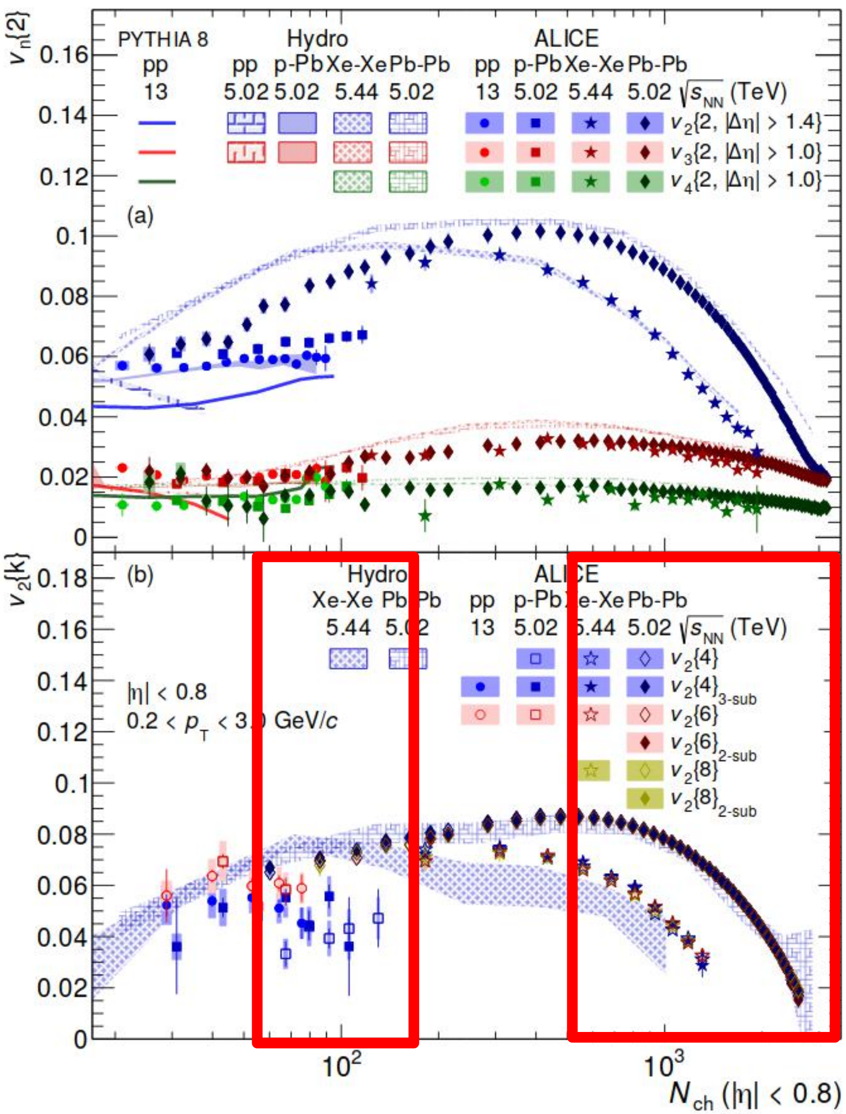

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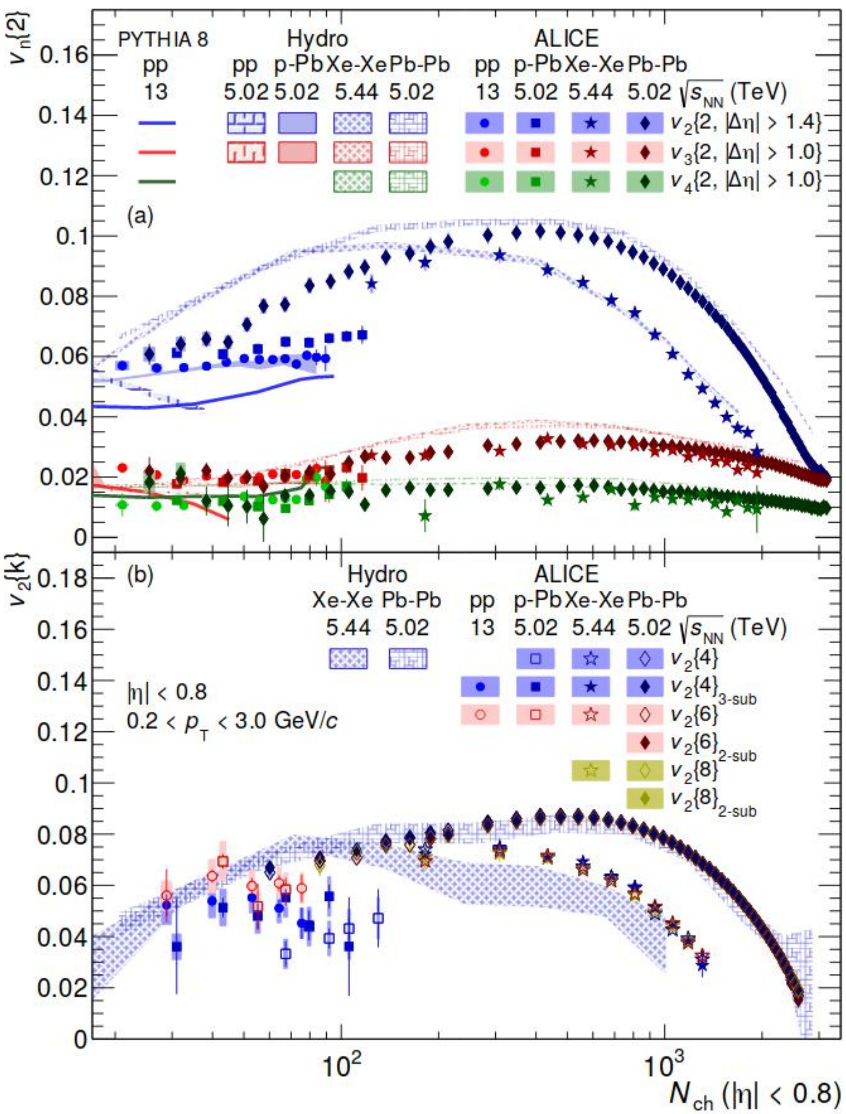

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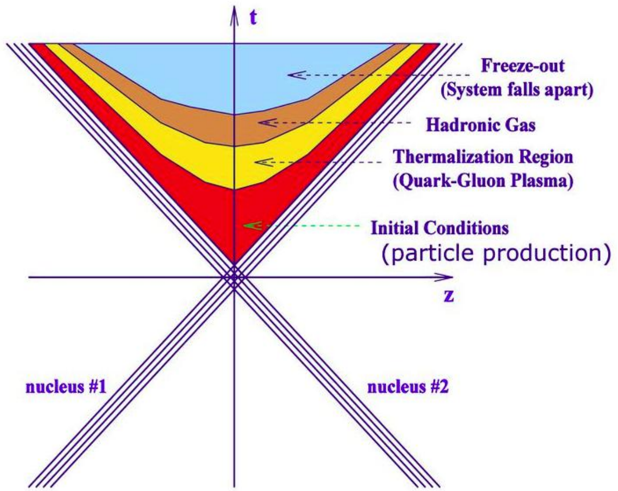
  - At higher values, v_2 does not scale with N_{ch}: **different initial geometries in small and large systems**
- Model description of pp and p-Pb data is not statisfactory (PYTHIA8, IP-Glasma+MUSIC+UrQMD)

Thermal photons: QGP temperature

- Direct photons are all photons except from hadron decays: Hard scattering, jet radiation, sQGP, hadron gas



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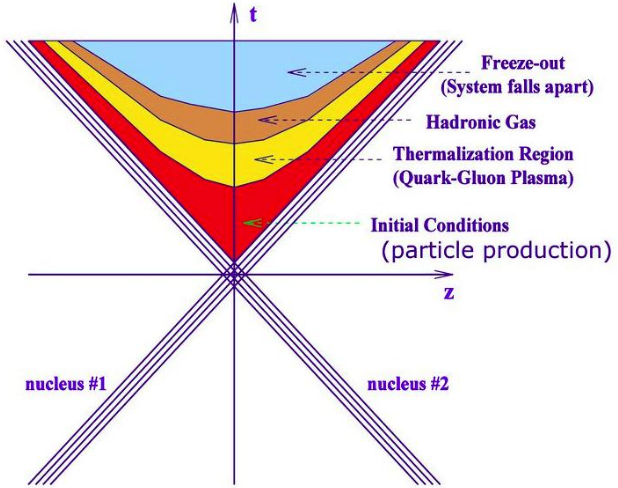
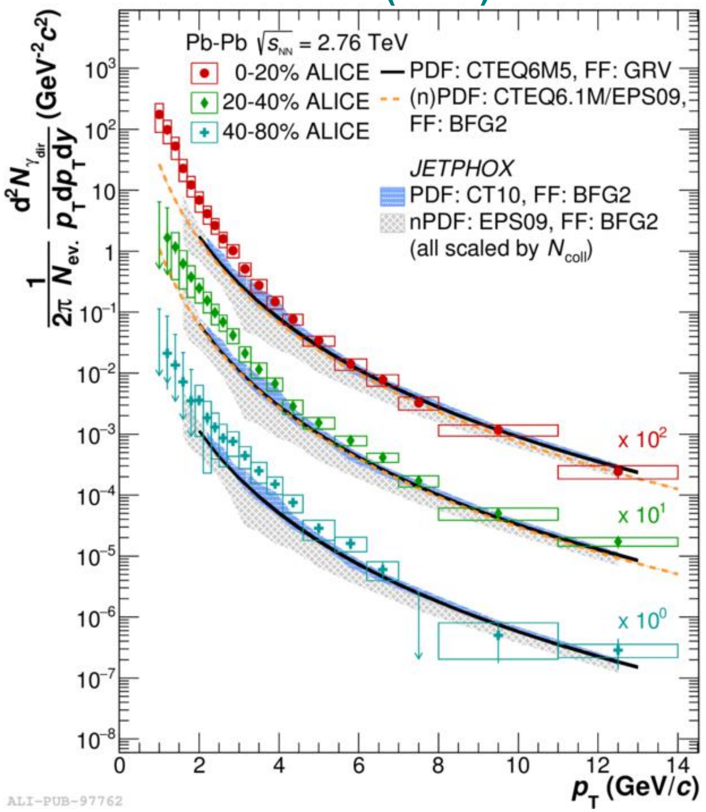


PLB 754 (2016) 235



- Excess in direct photon production over models and pp at low p_T
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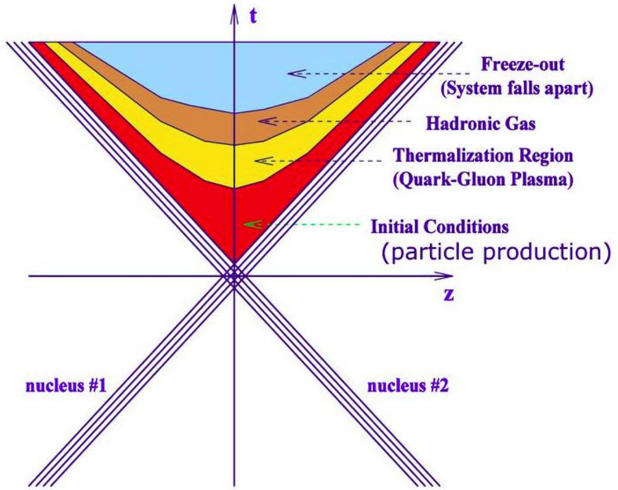

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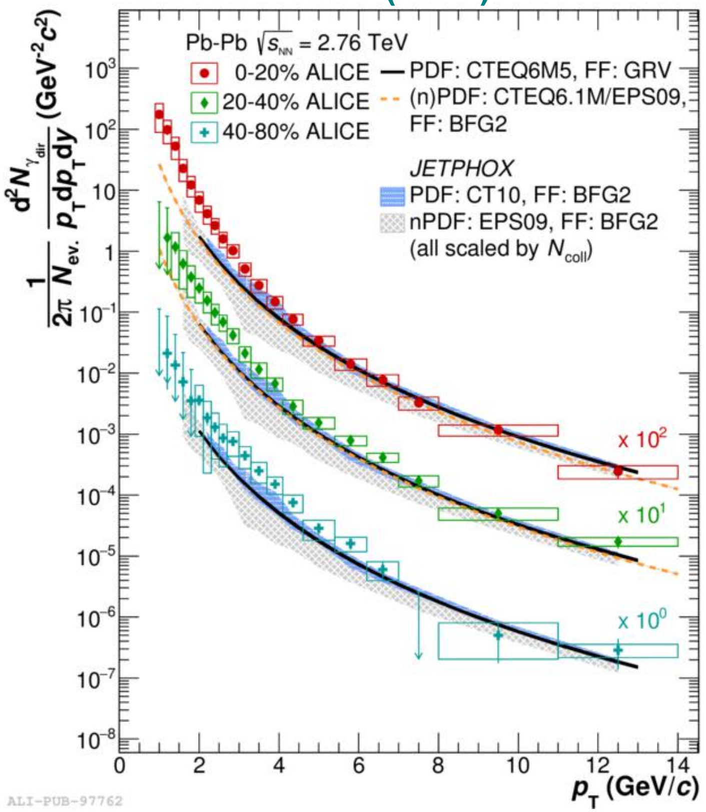


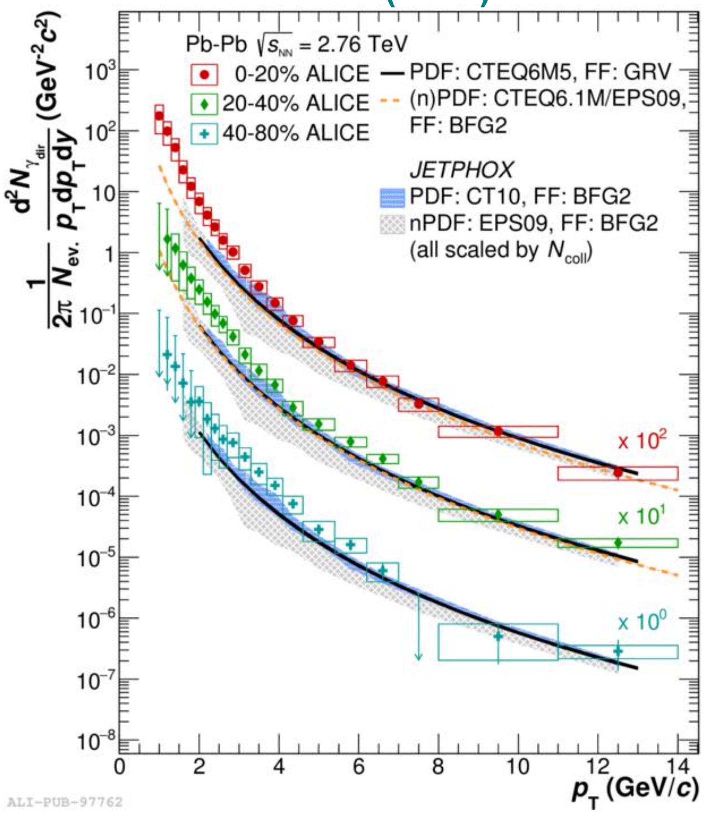
- Excess in direct photon production over models and pp at low p_T
  - Thermal radiation
- Effective ('average') temperature: $T_{eff} \approx 297 \pm 12(stat) \pm 41(syst)$ MeV much higher than $T_C \sim 170$ MeV

  => deconfined matter!
- $T_{ini} \sim 300 - 600$ MeV (via models)

Direct photons in p-Pb collisons

New!

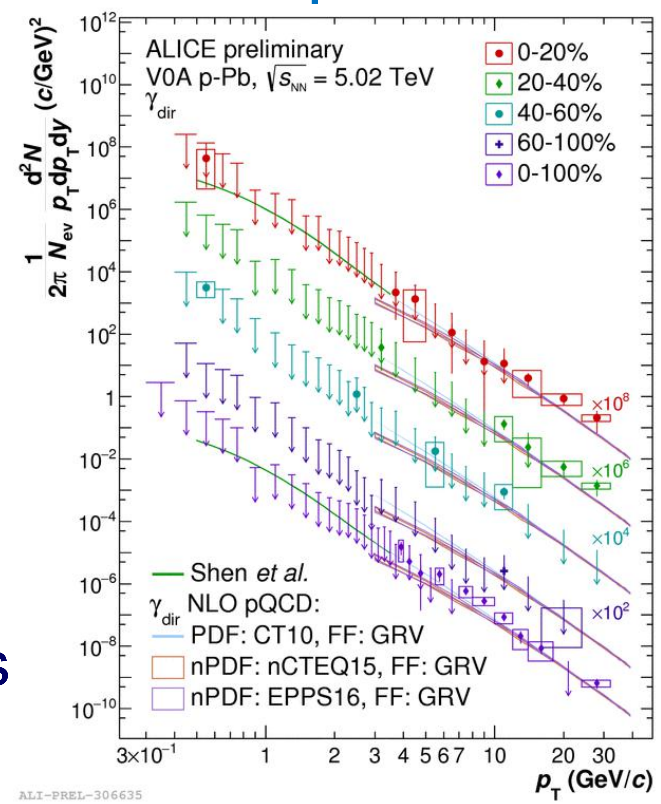
PLB 754 (2016) 235



Pb-Pb

- Excess in direct photon production over models and pp at low p_T
  - Thermal radiation

p-Pb

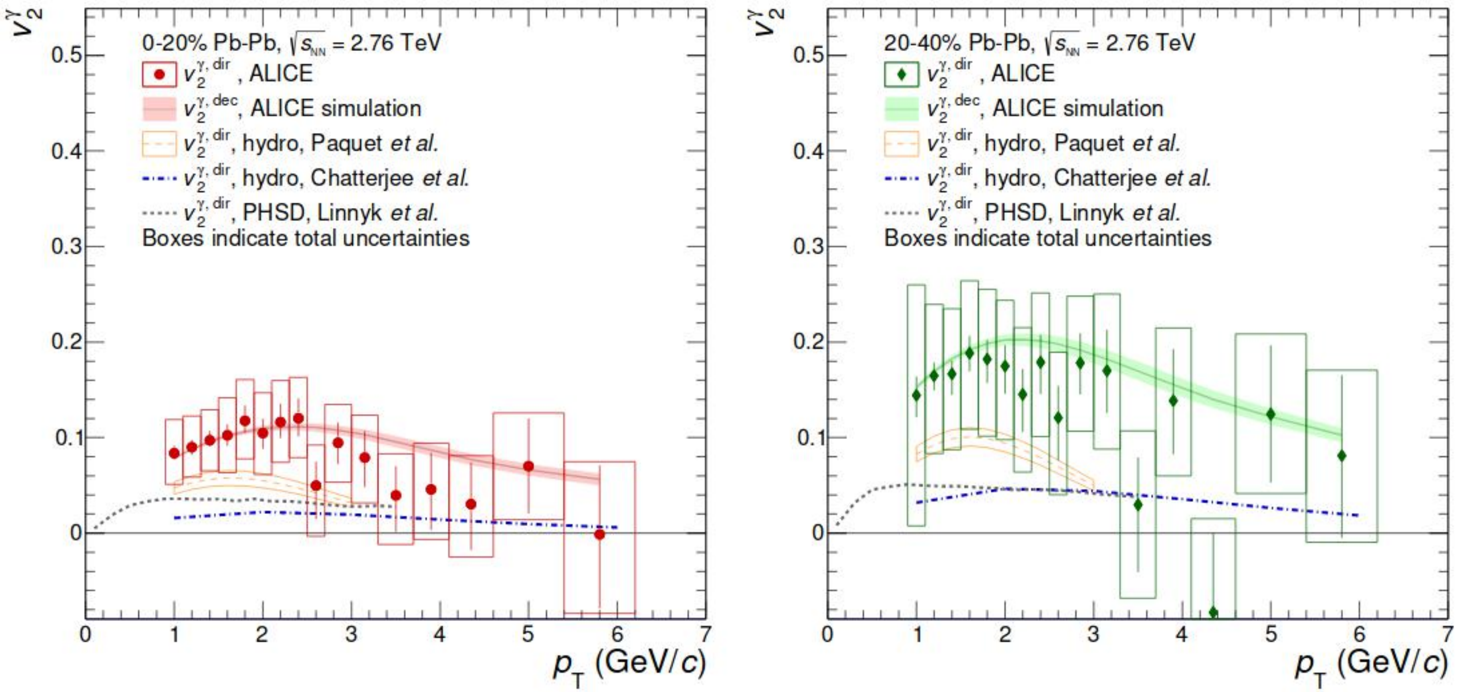


- No such excess seen in pPb collisions above model calculations

Flow of direct photons

New!

Phys. Lett. B 789 (2019) 308



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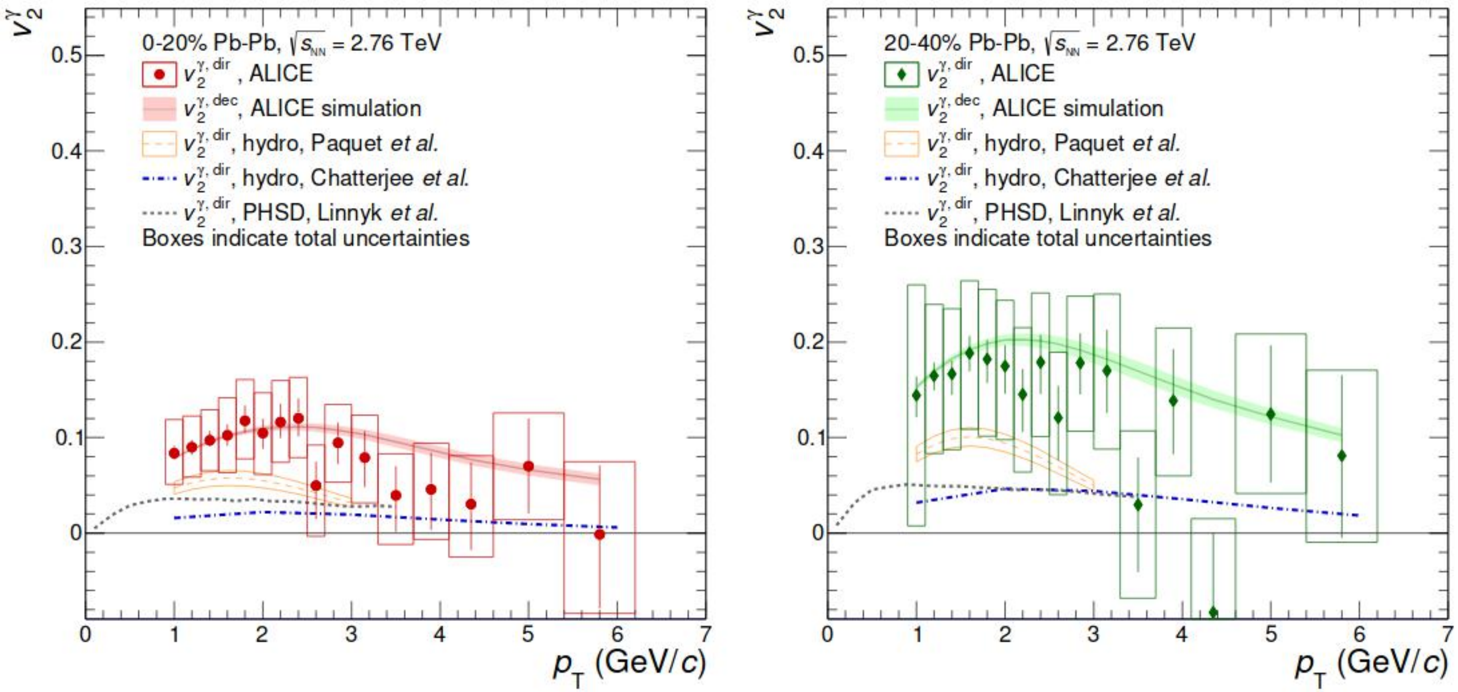
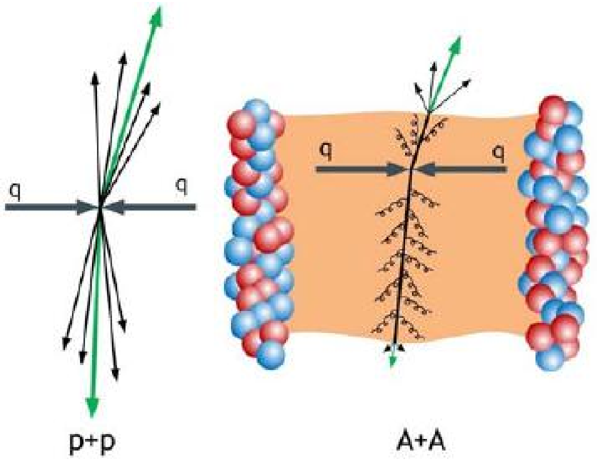
Phys. Lett. B 789 (2019) 308



- Direct photon flow is as large as decay photon flow (ie. final state)
- No role of earlier states at all?
- **These results question the current understanding of thermal photons!**

Penetrating probes of the medium

- **pp**: pQCD benchmark and reference for larger sytems
- **p-A**: cold nuclear matter effects
- **A-A**: hot nuclear matter effects



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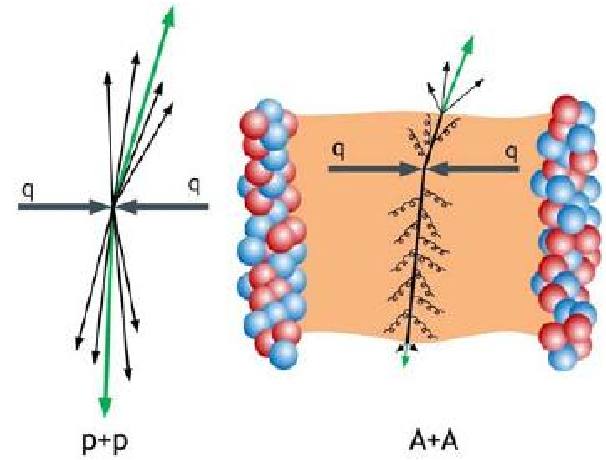
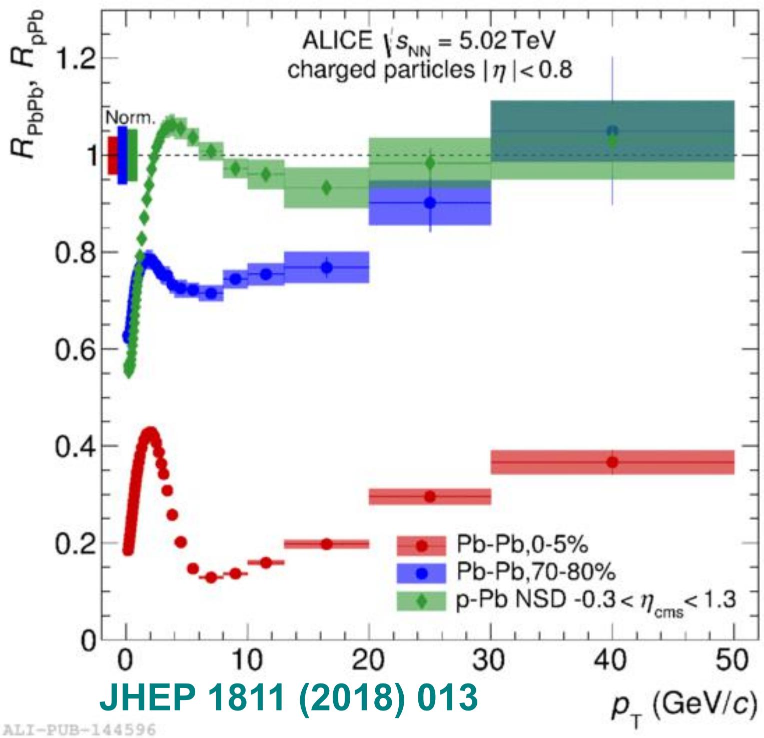


- Nuclear modification

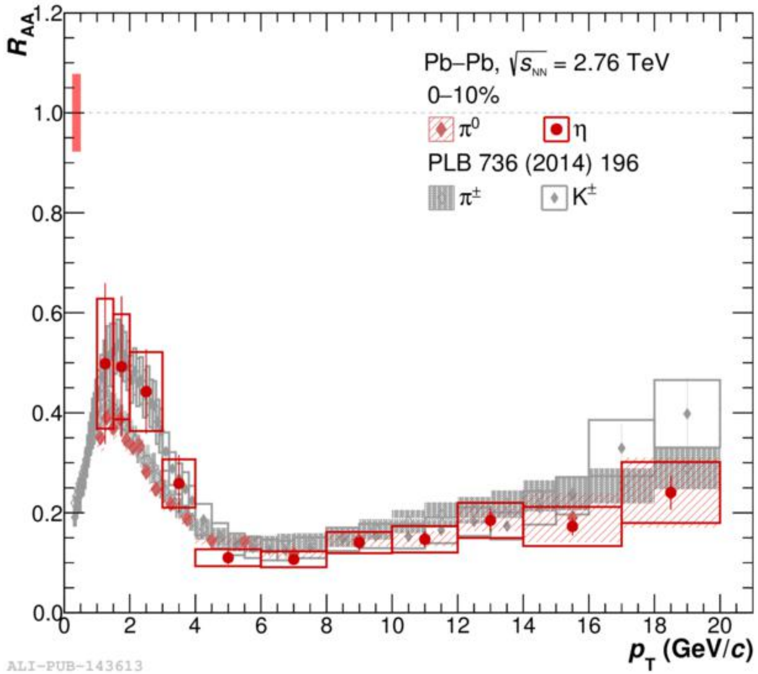
$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

  - Clearly an effect of the QGP in AA collisions

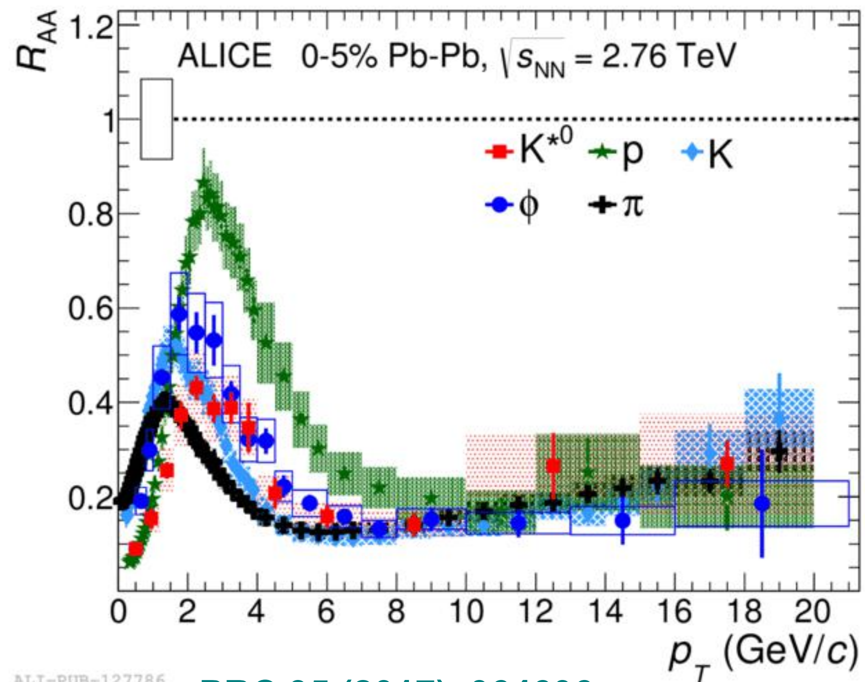


JHEP 1811 (2018) 013

Light and strange hadron energy loss



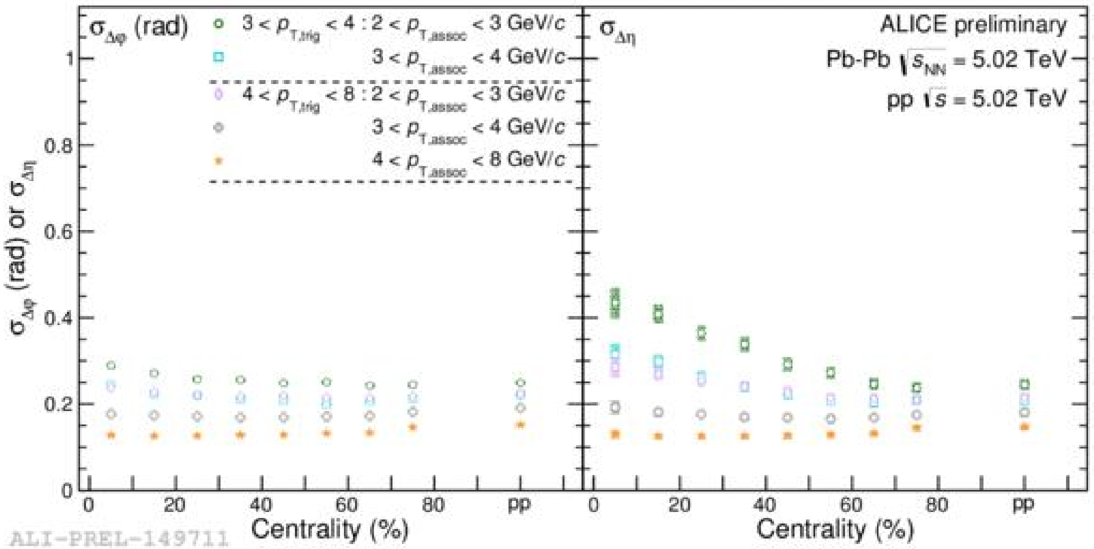
PRC 98 (2018), 044901

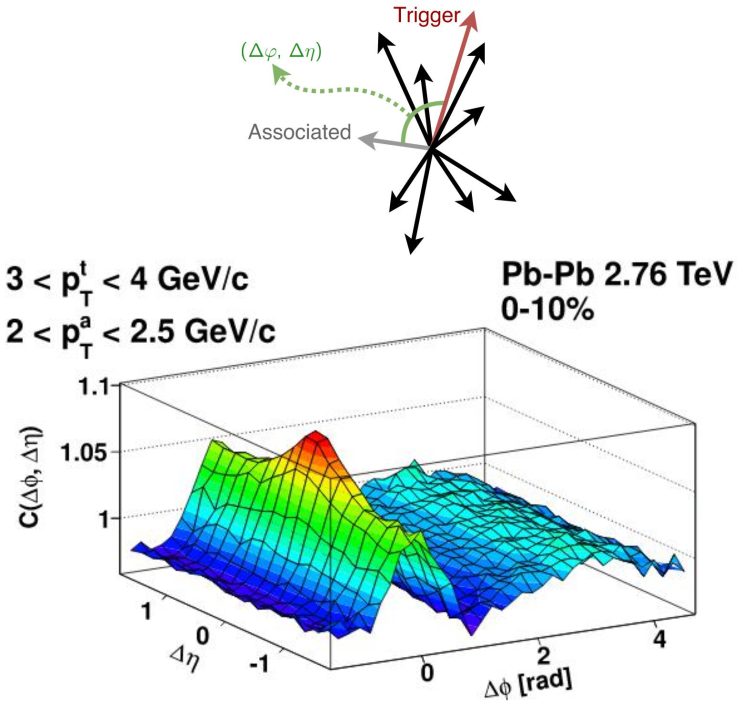


PRC 95 (2017), 064606

- **Universal, strong suppression at high-p_T**
  - Regardless of hadron types (light or strange)
- Sensitivity to radial flow, hadronization at low-p_T

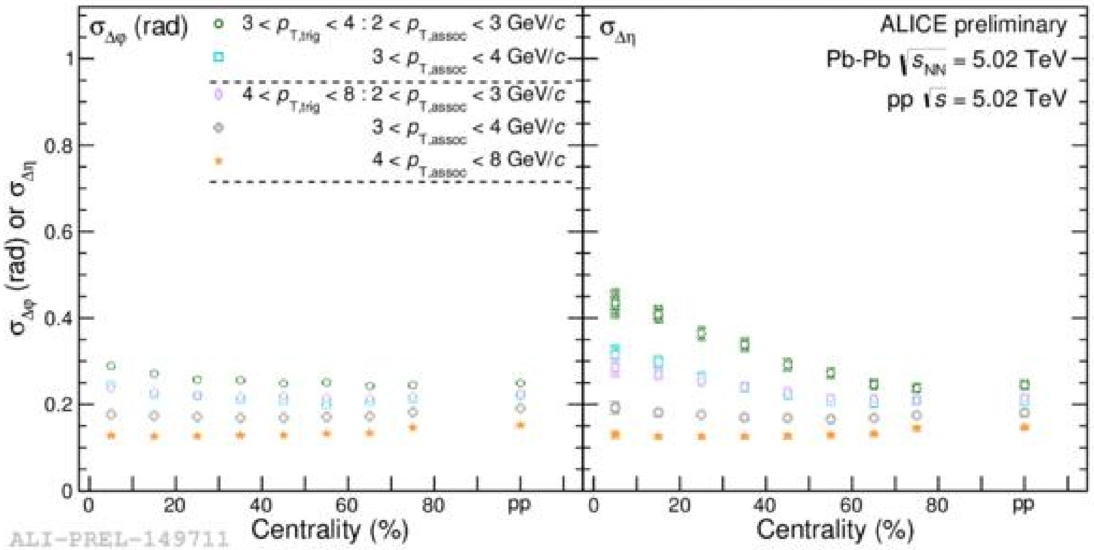
Jet-medium interactions

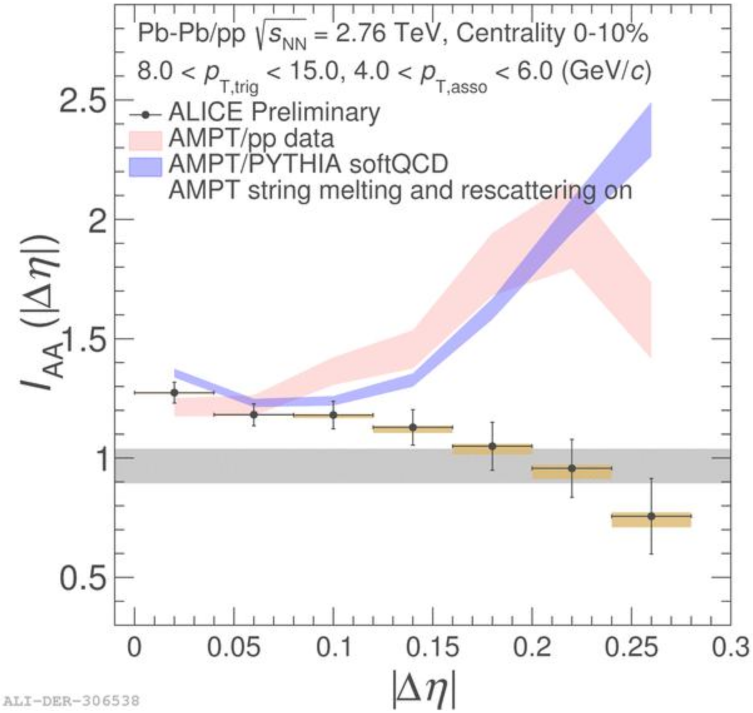




- **Low p_T**: Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of **central** angular correlation peaks in the **$\Delta\eta$** direction
  - Understanding: rescattering with radial flow (AMPT)

Jet-medium interactions

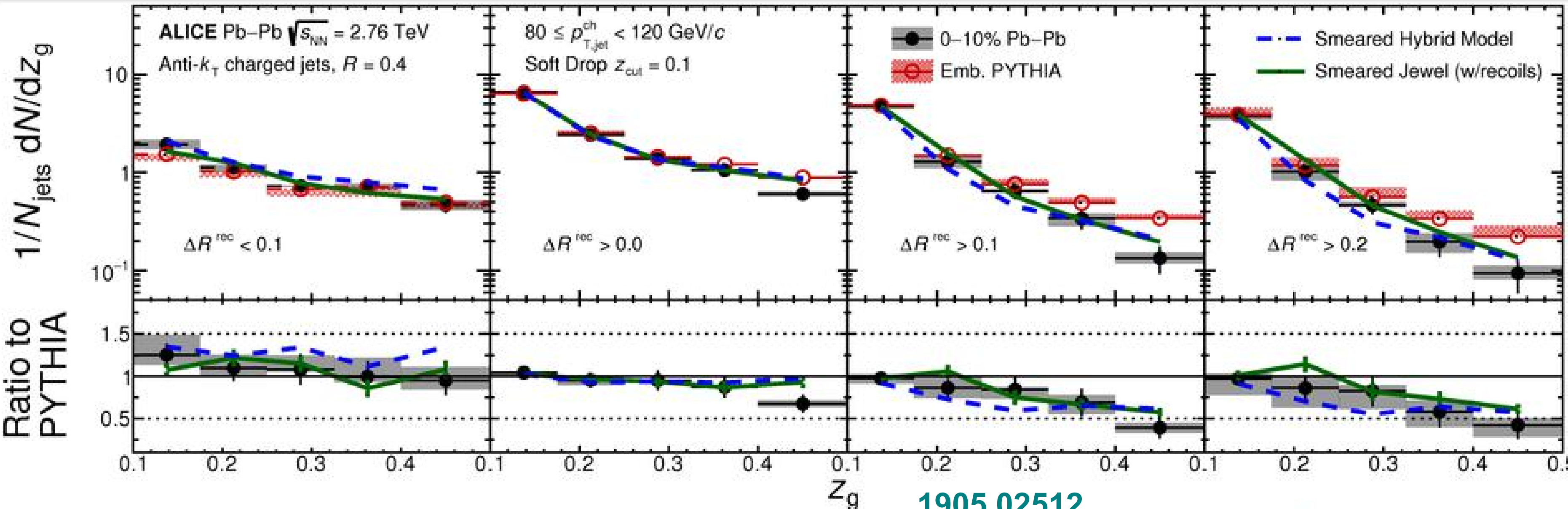




- **Low p_T**: Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of **central** angular correlation peaks in the **$\Delta\eta$** direction
  - Understanding: rescattering with radial flow (AMPT)
- **Higher p_T**: Azimuthal h-h correlations, $I_{AA} = Y_{AA}/Y_{pp}$
  - **Narrowing** of the peak in **central** events in the **$\Delta\eta$** direction
  - Jet structure modifications? No proper understanding by models.

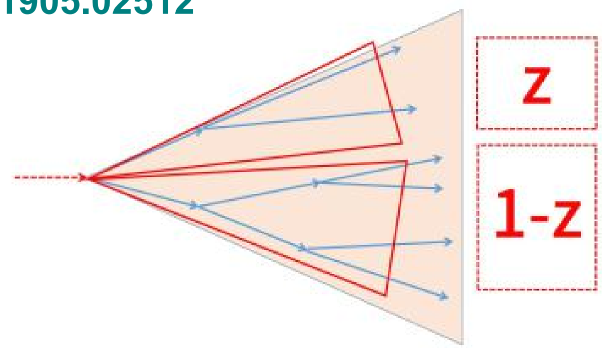
Jet Substructure

New!



1905.02512

- First intra-jet splitting z_g



$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Jet Substructure

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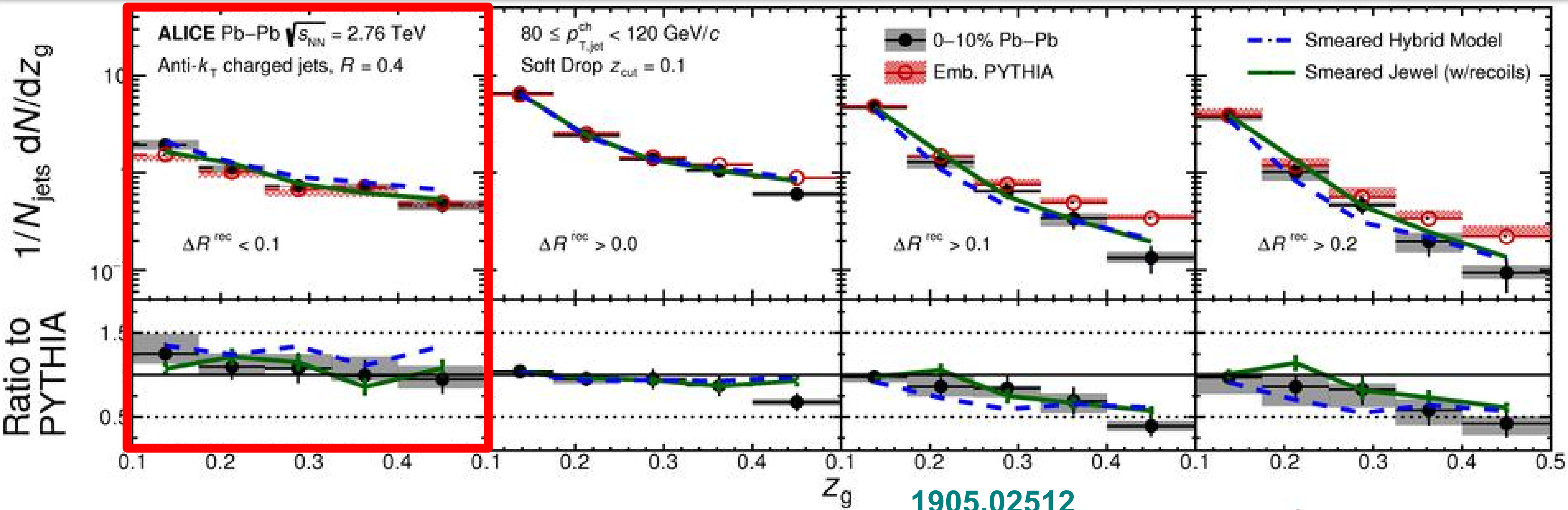
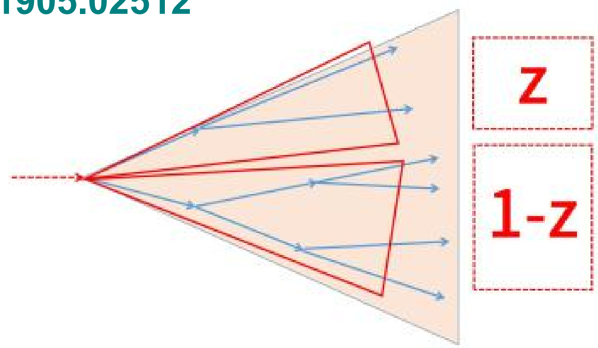


1905.02512

- First intra-jet splitting z_g
  - At small angles ($\Delta R < 0.1$): consistent z_g distributions in Pb-Pb and vacuum



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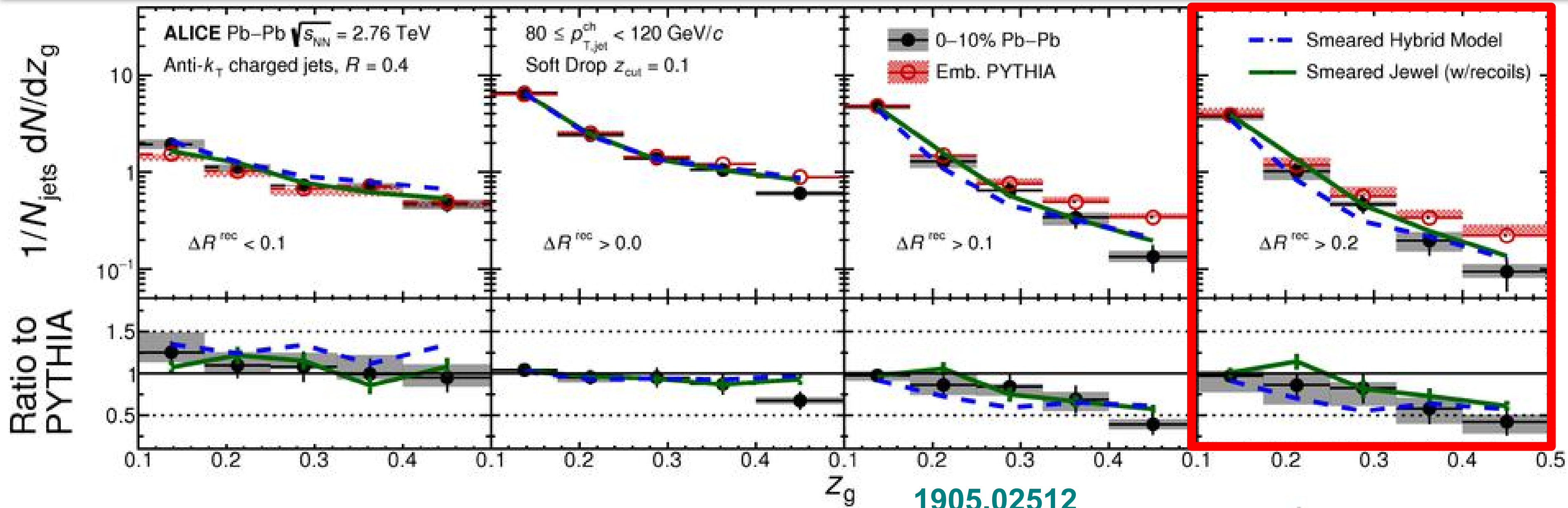
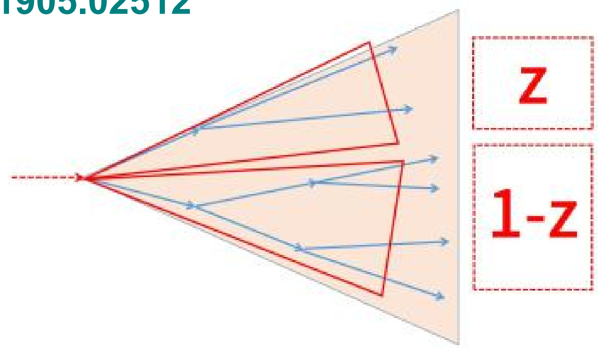


1905.02512

- First intra-jet splitting z_g
  - At small angles (ΔR < 0.1): consistent z_g distributions in Pb-Pb and vacuum
  - At large angles (ΔR > 0.2): z_g distributions are steeper in medium than in vacuum



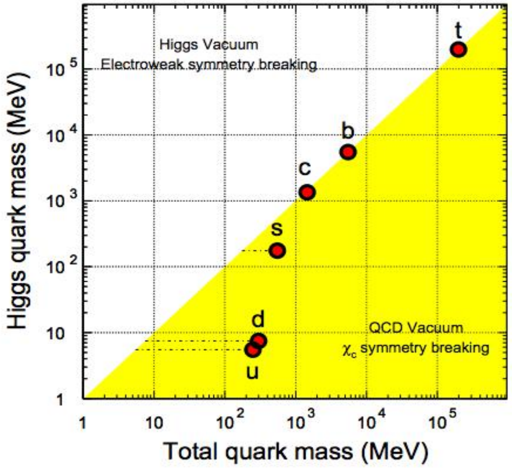
$$z = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- **Early jet development influenced by medium**

Probes with heavy flavor

- Heavy quarks are...
  - (Mostly) produced in early hard processes
    $\tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1$ fm << $\tau_{QGP} \sim$ 5-10 fm
  - Their numbers are (almost) conserved:
    No flavour changing, negligible thermal production
    → Very little production or destruction in the sQGP
    $m >> \Lambda$ (m_c~1.5 GeV, m_b~5 GeV)

X. Zhu et al, PLB 647 366 (2007)



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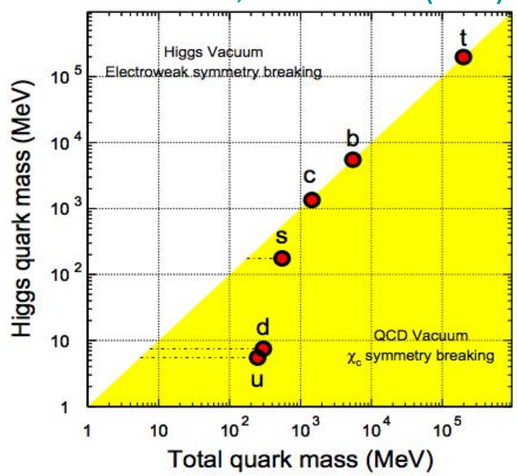
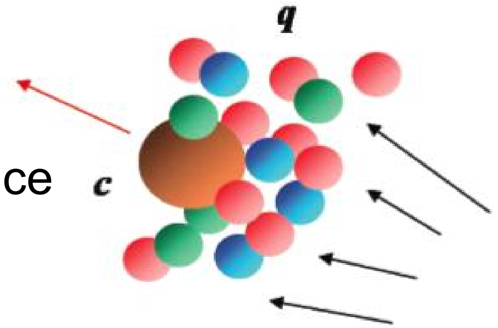


- **Open heavy flavor**: Transport through the whole system
  - Access to **transport properties** of the system
  - **Flavor-dependent hadronization**
    fragmentation: color charge effects, dead cone; coalescence
  - **Penetrating probes down to low momenta**



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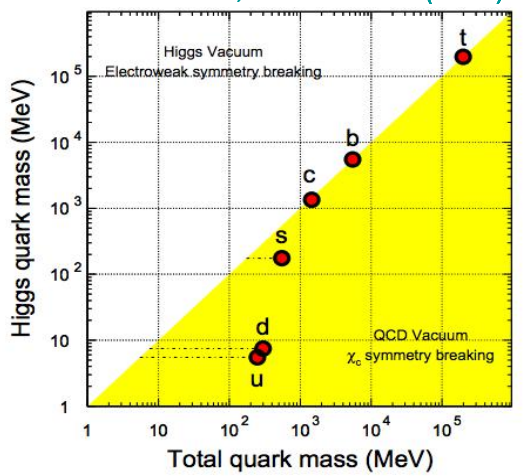

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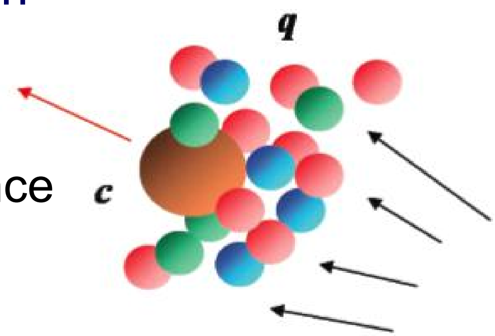


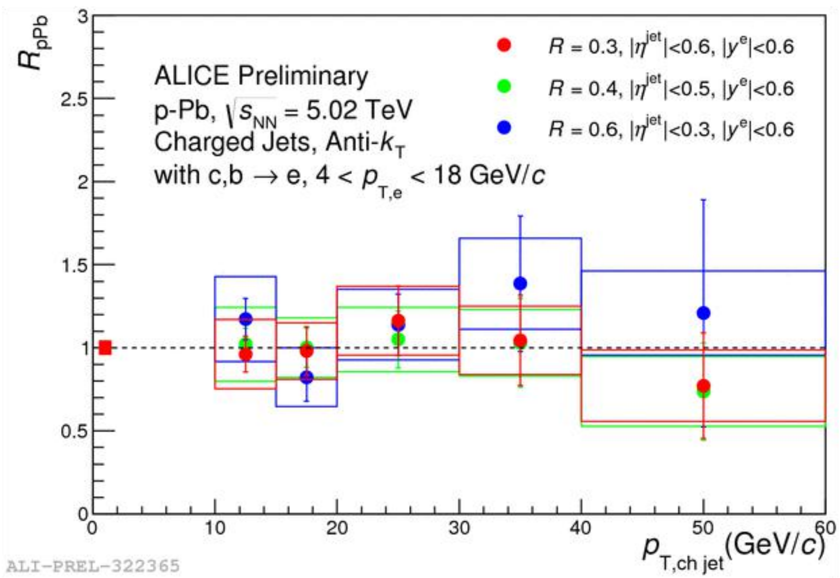
- **Quarkonia:** dissociation and regeneration in the QGP
  - Debye screening of the color charge
  - Sequential melting of different states

  => **QGP thermometer**
  - However: strong regeneration of charmonia at LHC!

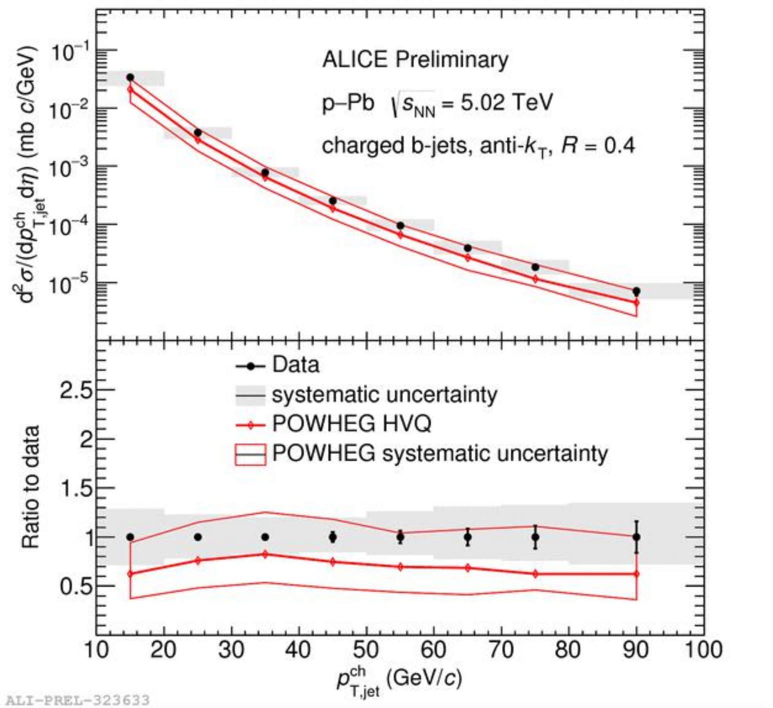
Heavy flavor jets in p-Pb

New!

jets with HFE

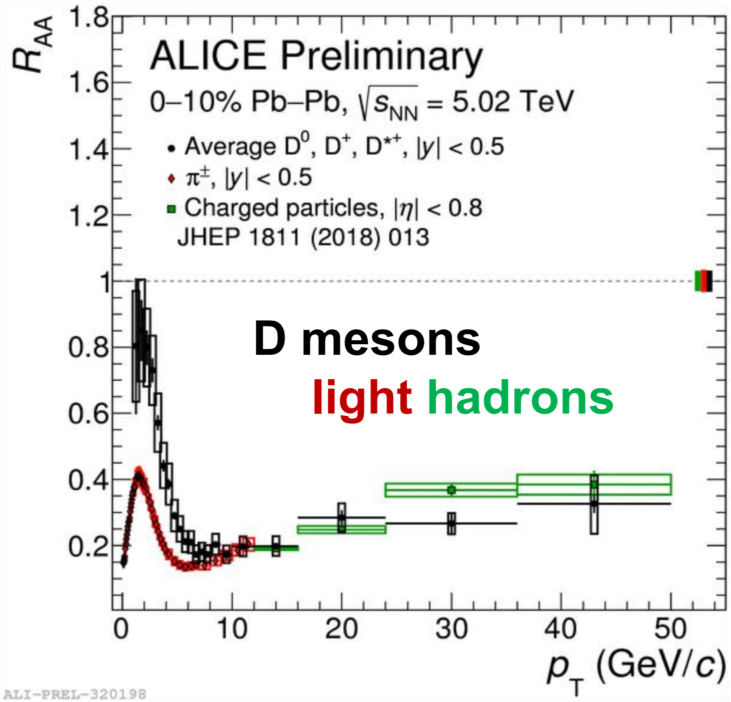


b-jets



- Heavy-flavor jets measured down to p_T = 10 GeV/c
- **No mid-rapidity nuclear modification of HFE jets** visible
  - Regardless of chosen jet resolution parameter
- Cross section of **beauty jets** tagged with displaced vertices also **described by POWHEG HVQ x A (pp)** within uncertainty

Pb-Pb - Heavy-flavor energy loss



$$R_{\rm AA}(p_{\rm T}) = \frac{1}{\langle N_{\rm coll}\rangle}\frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}}{{\rm d}N_{\rm pp}/{\rm d}p_{\rm T}}$$

- **Strong suppression at high-p_T**
  - **Charm is suppressed similarly to light and strange quarks**
  - No mass ordering (dead cone, color charge & fragmentation effects)
- Less suppression for **D** mesons at low-p_T

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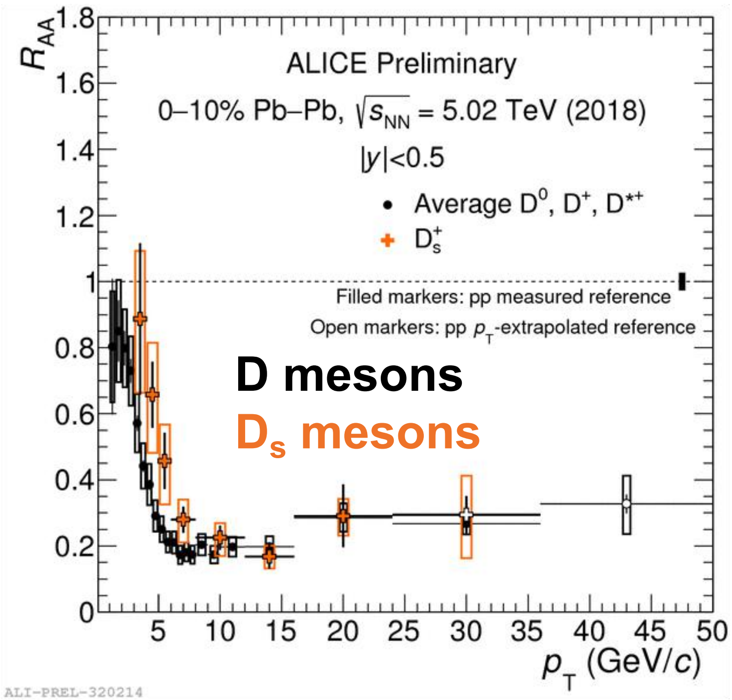

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

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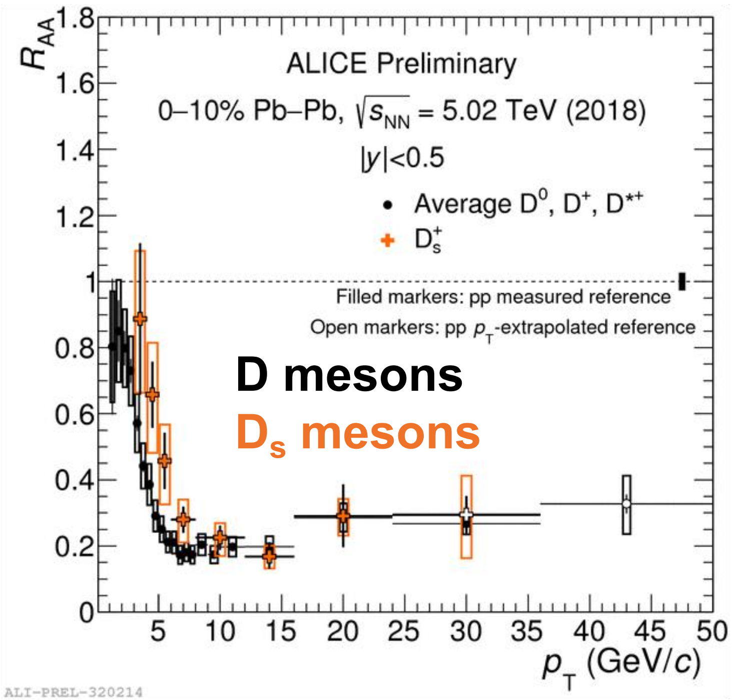

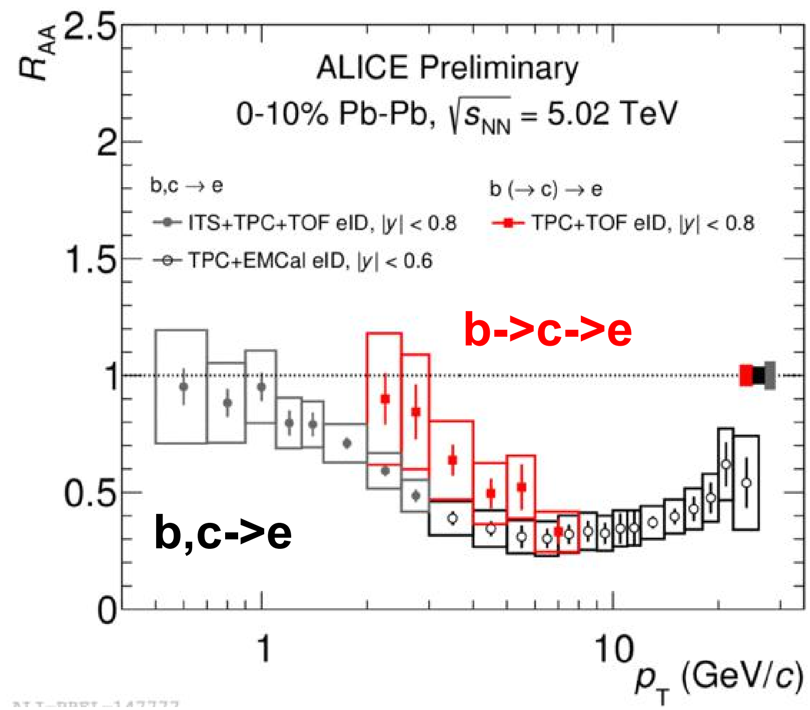

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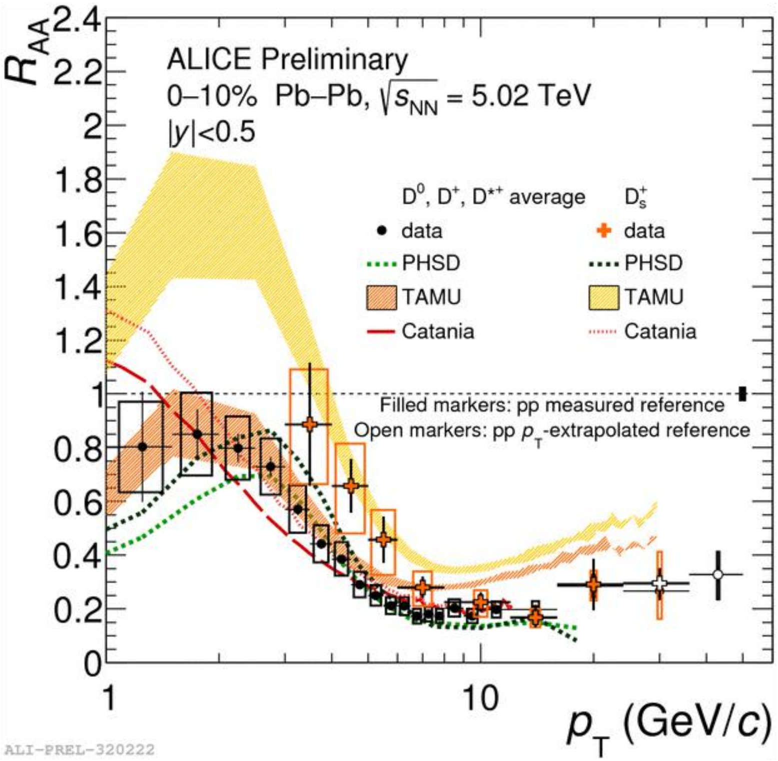
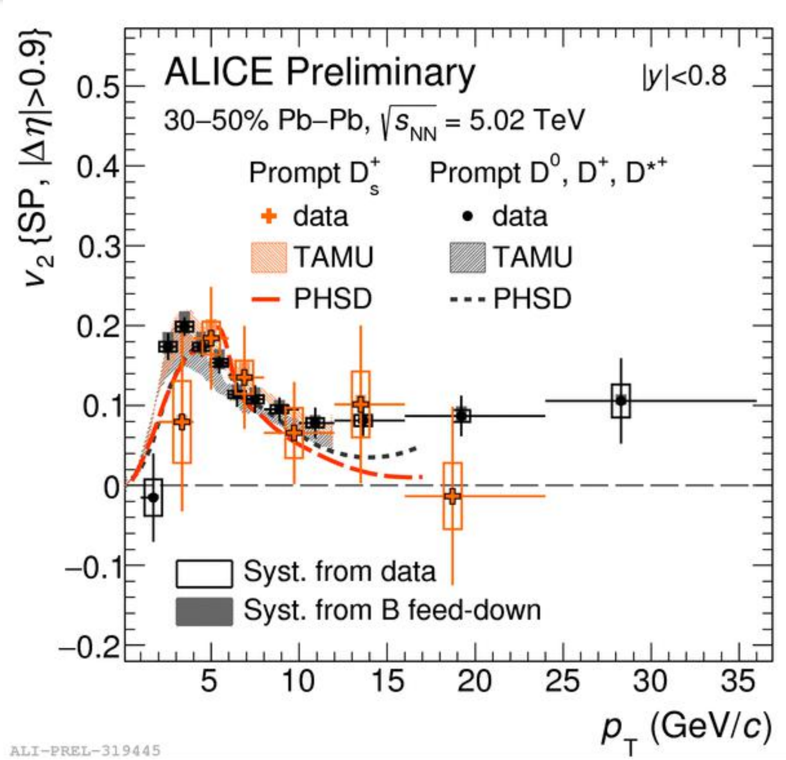
  - **Charm is suppressed similarly to light and strange quarks**
  - No mass ordering (dead cone, color charge & fragmentation effects)
- Less suppression for **D** and **D_s** mesons at low-p_T
- HFE: **beauty appears less suppressed than charm**
  - Mass ordering

Open charm and collectivity

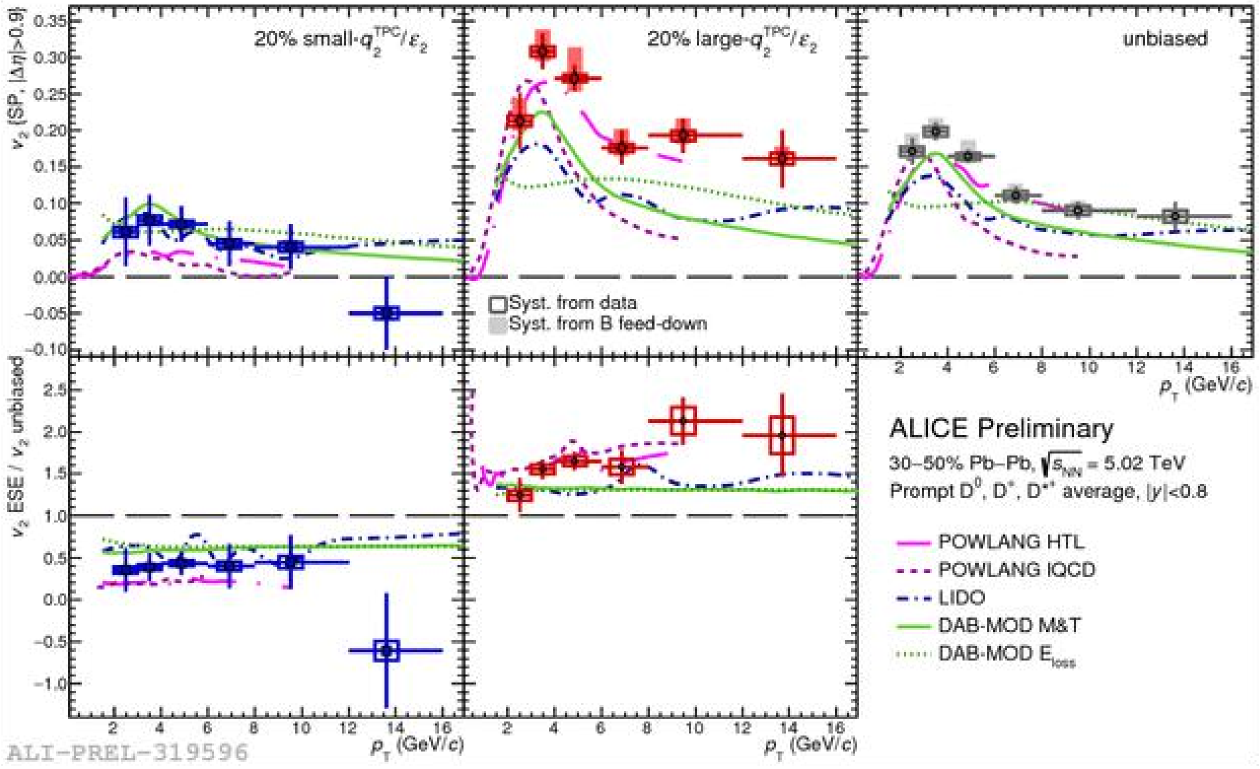




TAMU: PLB 735,445-450(2014)
PHSD: PRC 92, 014910 (2015)
Catania: EPJC (2018) 78, 348

- Precise data constrains models at low p_T
  - Simultaneous description of R_{AA} and v_2 for both **D** and **D_s**
  - **Charm - light quark coalescence** on top of shadowing and collisional/radiative energy loss

Open charm flow vs. event shapes



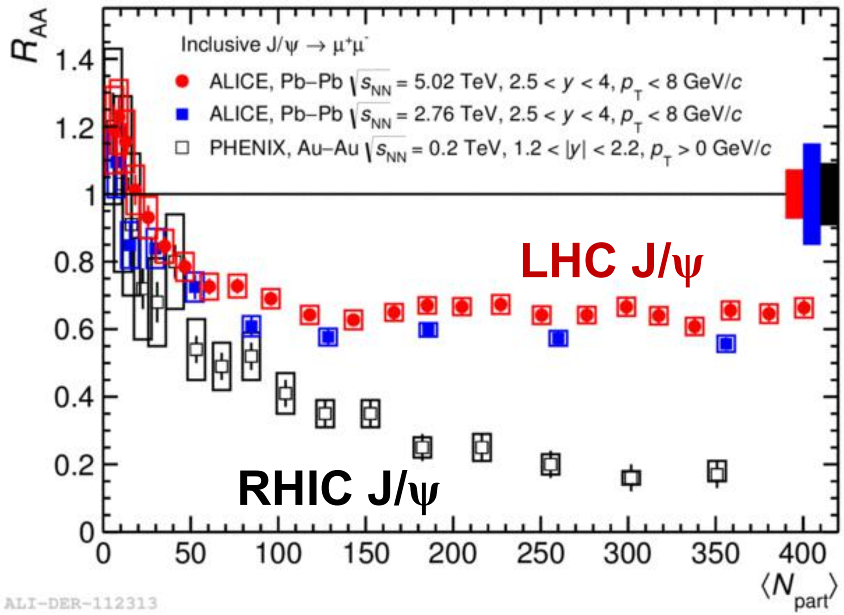
- Classification based on event shapes: 2nd order harmonic reduced flow vector

$$q_2 = |\boldsymbol{Q}_2|/\sqrt{M},$$

$$\boldsymbol{Q}_2 = \begin{pmatrix} \sum_{i=1}^{M} \cos(2\varphi_i) \\ \sum_{i=1}^{M} \sin(2\varphi_i) \end{pmatrix}$$

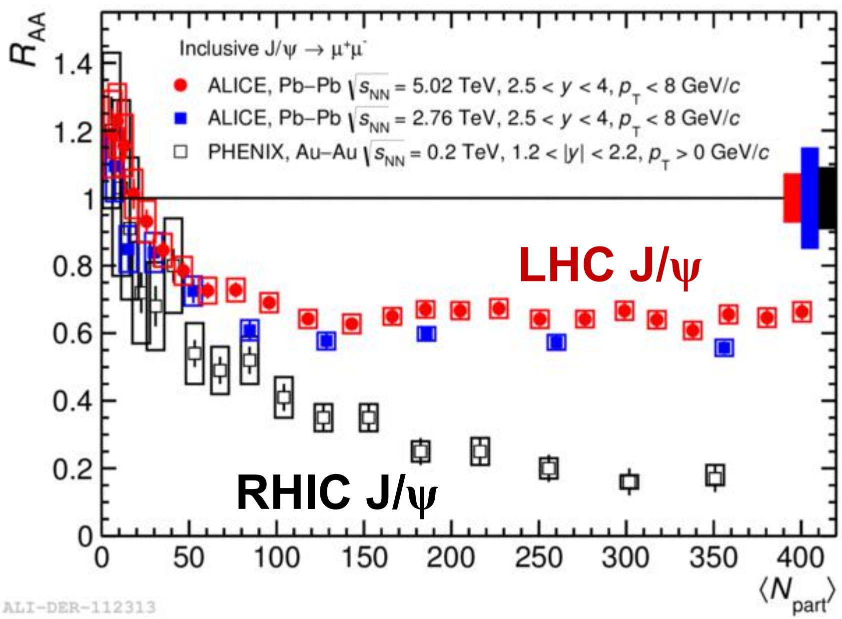
- Unbiased D-meson flow similar in magnitude to LF flow
- Small(large) q_2 corresponds to smaller(larger) D-meson flow
- Reasonable description by transport models

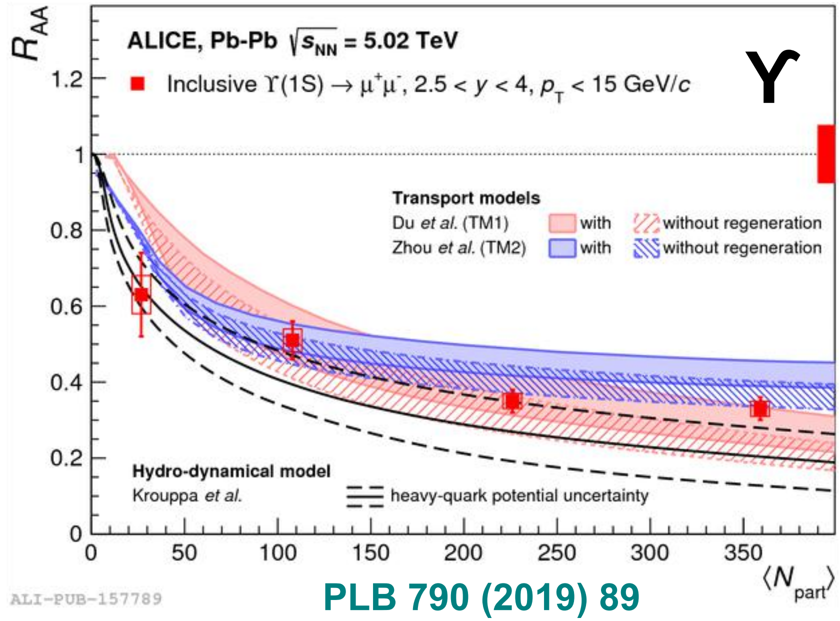
Quarkonia



- Quarkonium suppression due to **dissociation** of bound states in a colored medium (**Debye-screening** of qqbar potential)
- J/ψ: less suppression at **LHC** than at **RHIC**. "The J/ψ puzzle"
  - Understanding: later recombination of the c-cbar pairs

Quarkonia





PLB 790 (2019) 89

Du et al, PRC 96 (2017) 054901
Zhou et al., NPA 931 (2014) 654

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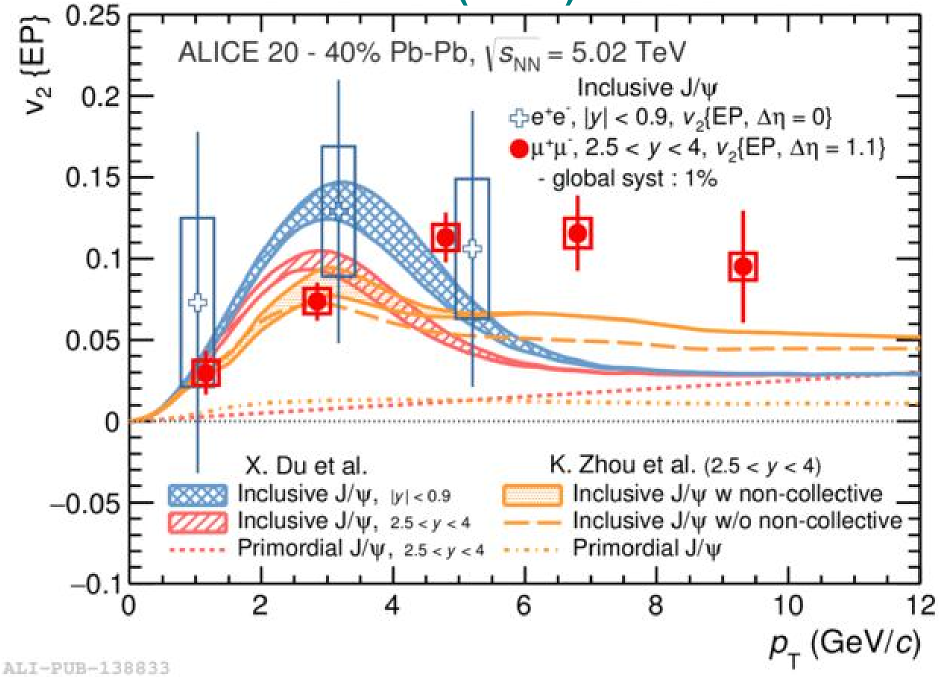
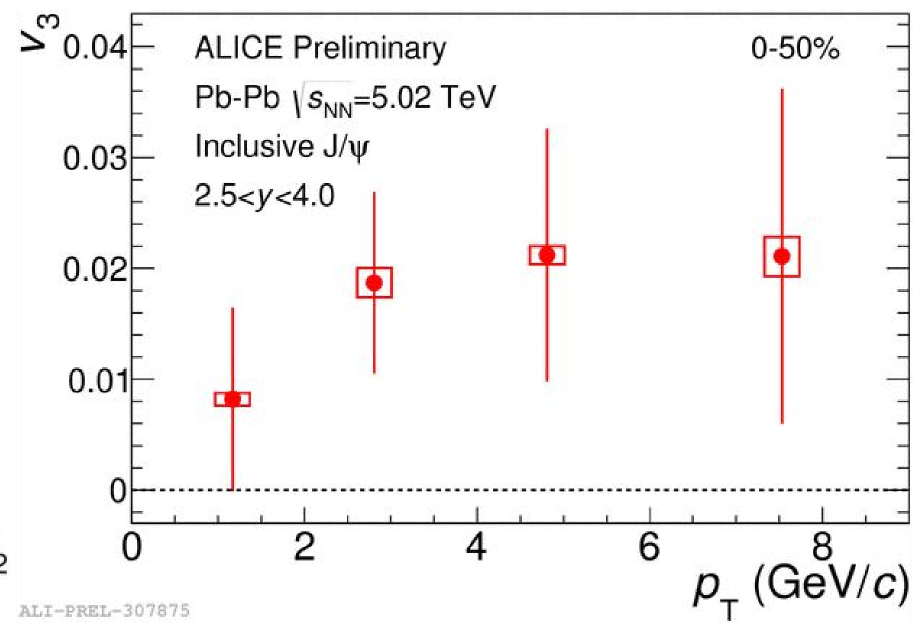
- J/ψ: less suppression at **LHC** than at **RHIC**. "The J/ψ puzzle"
  - Understanding: later recombination of the c-cbar pairs
- ϒ: strong suppression - regeneration effect is small
  - Models: T_{ini} ~ 520-750 MeV in $\sqrt{s_{NN}}$=5.02 TeV Pb-Pb collisions (consistent with thermal photon measurements)

Anisotropy of charmonium: J/ψ

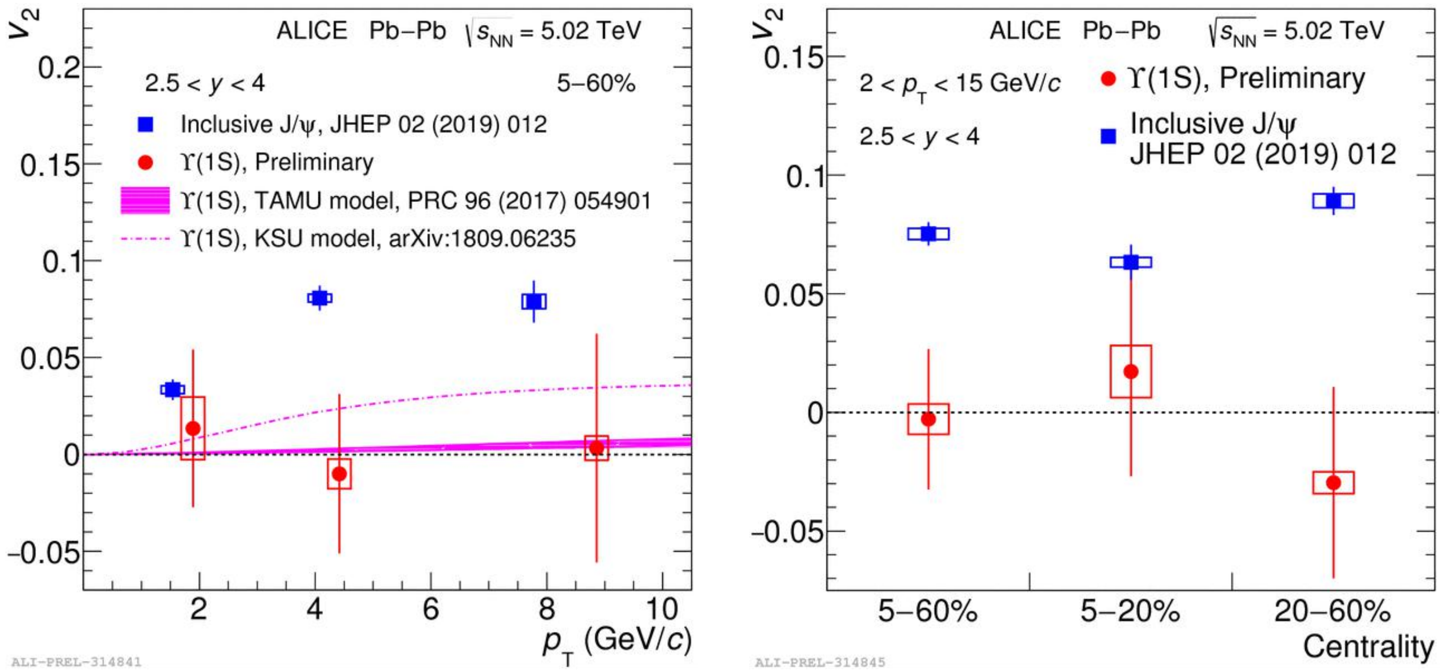
PRL 119 (2017) 242301





- Substantial J/ψ v_2 and v_3
  - RHIC: at low-p_T, flow is consistent with 0
  - LHC: Sizeable, less than LF or D
  - Consistent with strong charmonium recombination
  - Quantitative description challenging

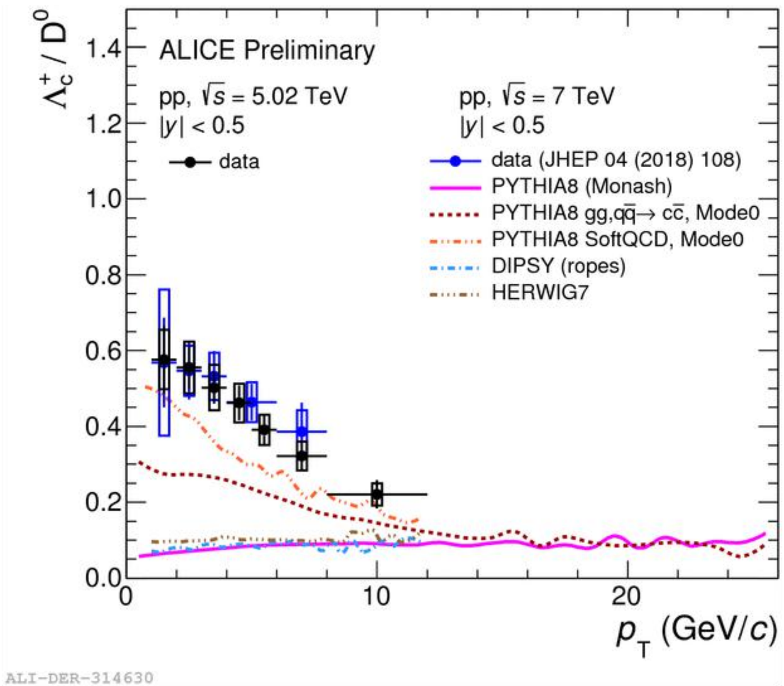
Anisotropy of bottomonium: ϒ(1S) New!



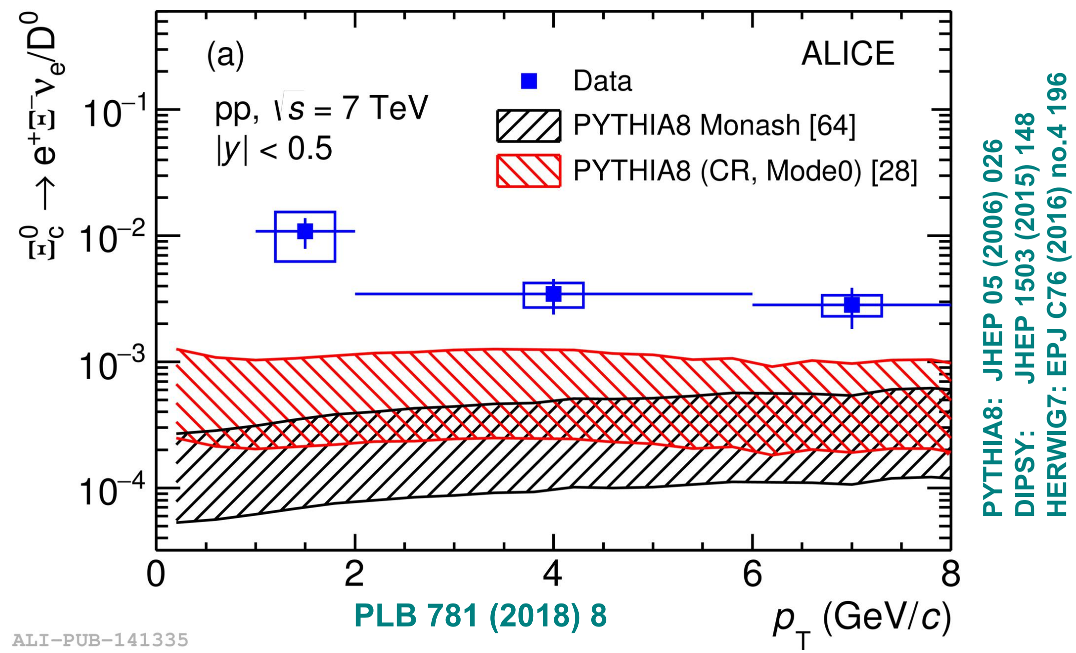
- First measurement
- v_2 consistent with 0 : **Only hadron at LHC**
  - Early production, decouples from medium
  - Later recombination is not strong (#b<<#c)

Charmed baryons in **pp**: Λ_c^+/D^0, Ξ_c^0/D^0

Λ_c^0/D



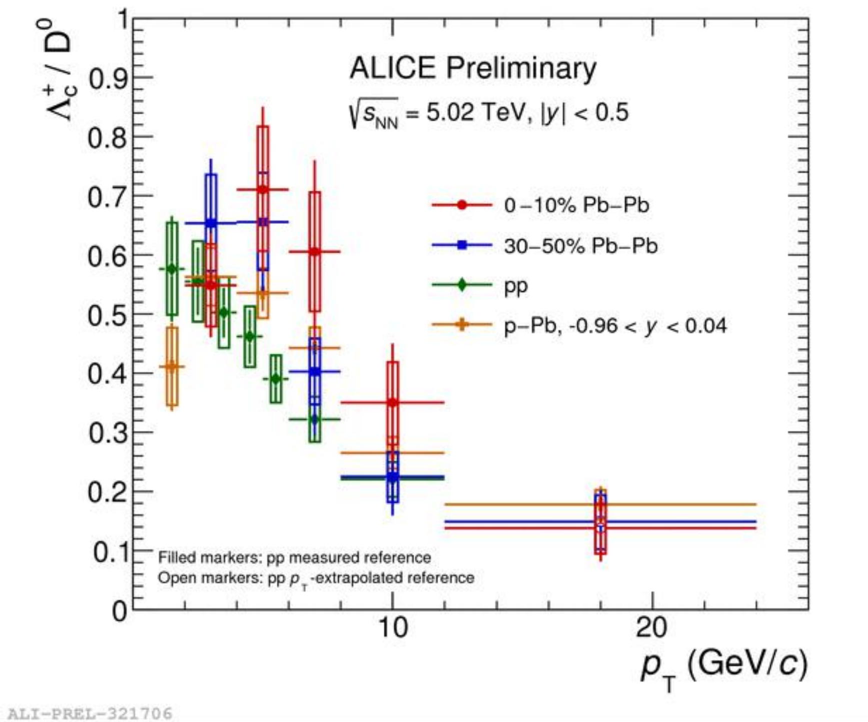
Ξ_c^0/D



- Ξ_c^0/D^0 as well as Λ_c^+/D^0 is underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889

Λ_c^0/D in p-Pb and Pb-Pb

New!



- A hint of higher Λ_c^+/D^0 ratio in central Pb-Pb collisions than in pp
  - Trend from pp through p-Pb to Pb-Pb is not clear by current precision

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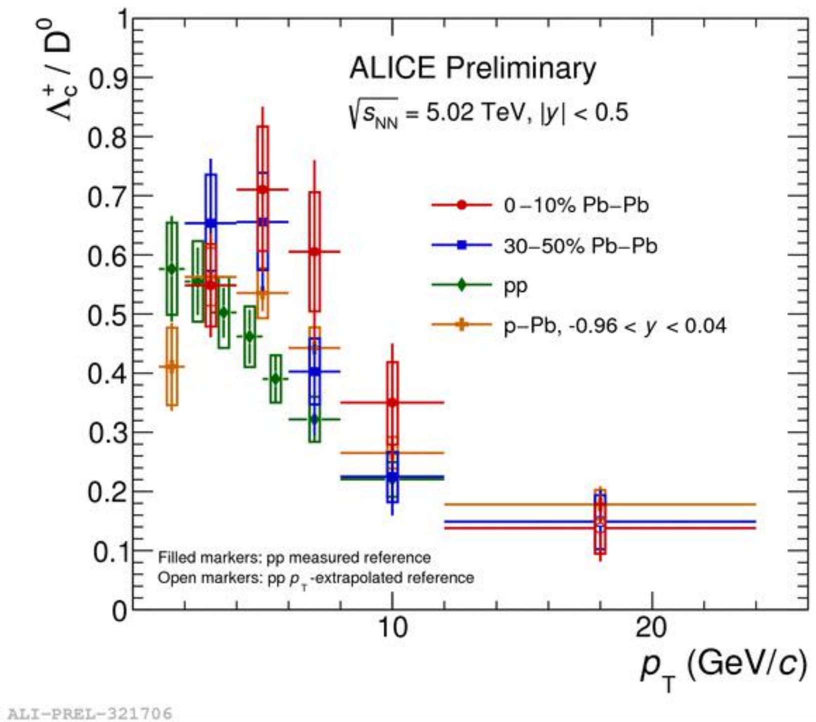
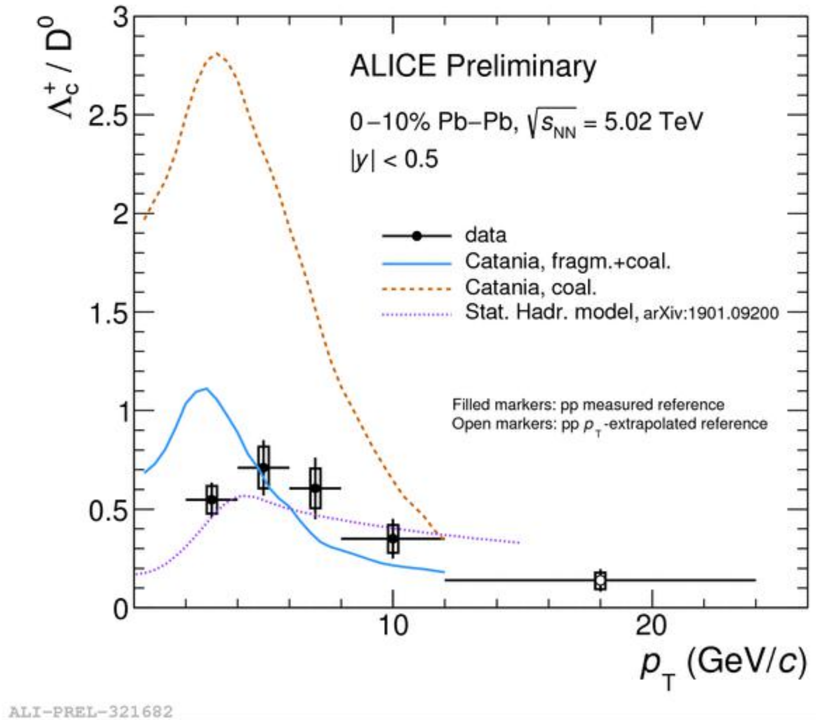
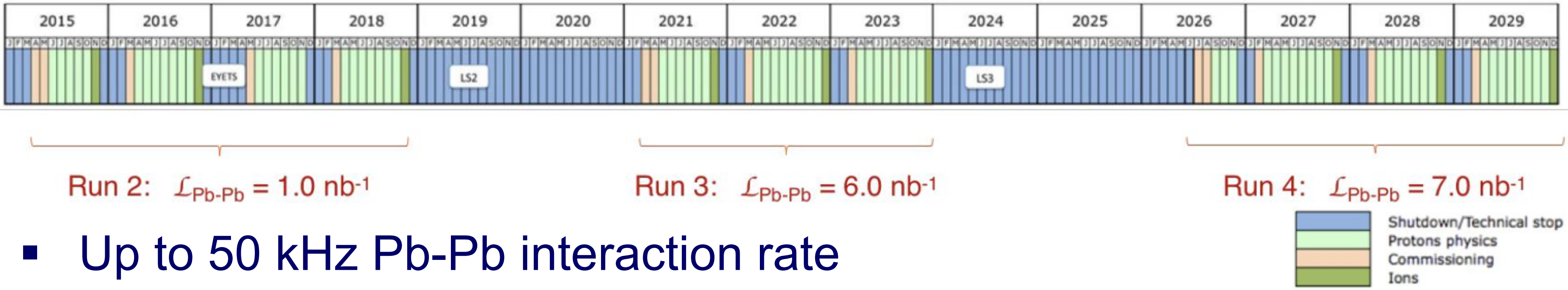




- A hint of higher Λ_c^+/D^0 ratio in central Pb-Pb collisions than in pp
  - Trend from pp through p-Pb to Pb-Pb is not clear by current precision
- Catania model including both coalescence and fragmentation describes the Λ_c^+/D^0 ratio in Pb-Pb collisions

ALICE Upgrade for Run-3 and Run-4



- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb-1 (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continouos readout

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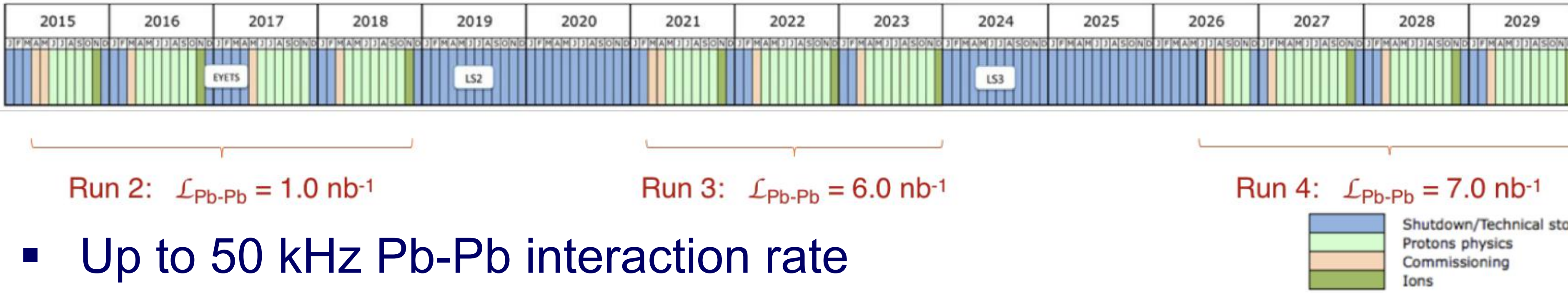

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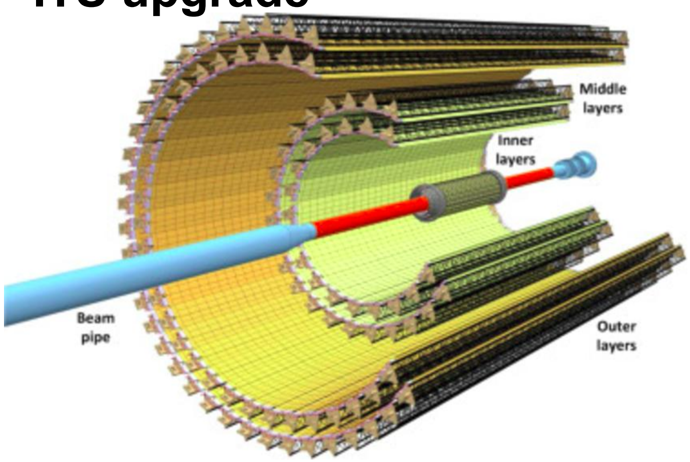
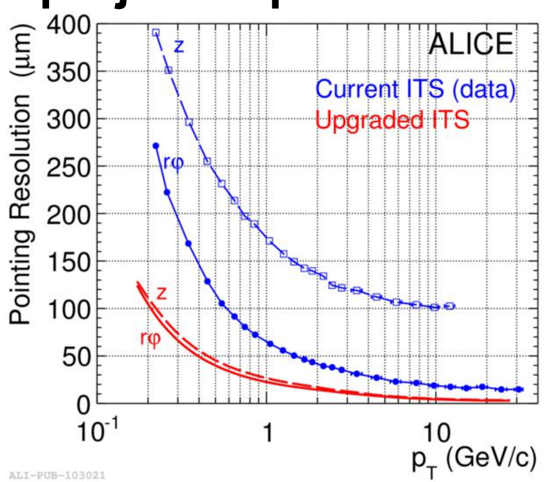
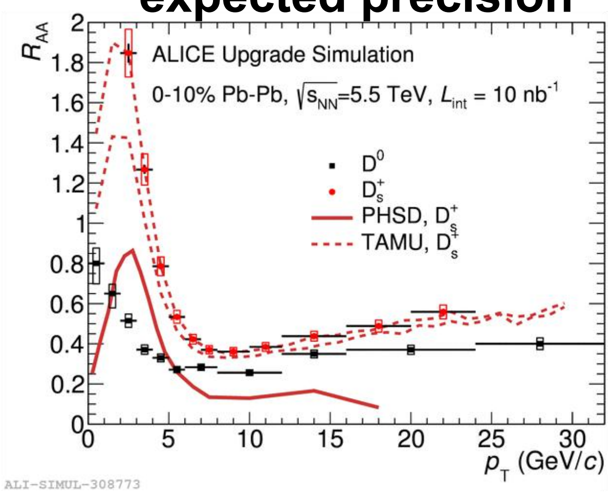
ITS upgrade



projected performance



expected precision



Summary and outlook

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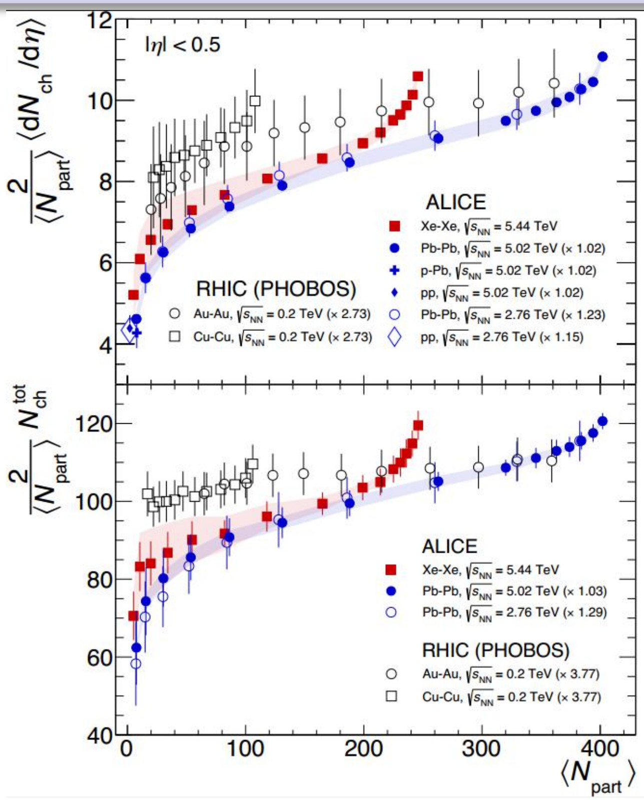
- Run-3 after LS2 (2021): improved luminosity, detectors
  - Precision measurements: charmed barions, beauty etc.
  - Jet structures, event shapes: understand soft-hard boundary

Thank you!

...and stay tuned for new great results

This work has been supported by the Hungarian NKFIH/OTKA K 120660 grant and the János Bolyai scholarship of the Hungarian Academy of Sciences

Multiplicities in pp, p-Pb, Xe-Xe, Pb-Pb



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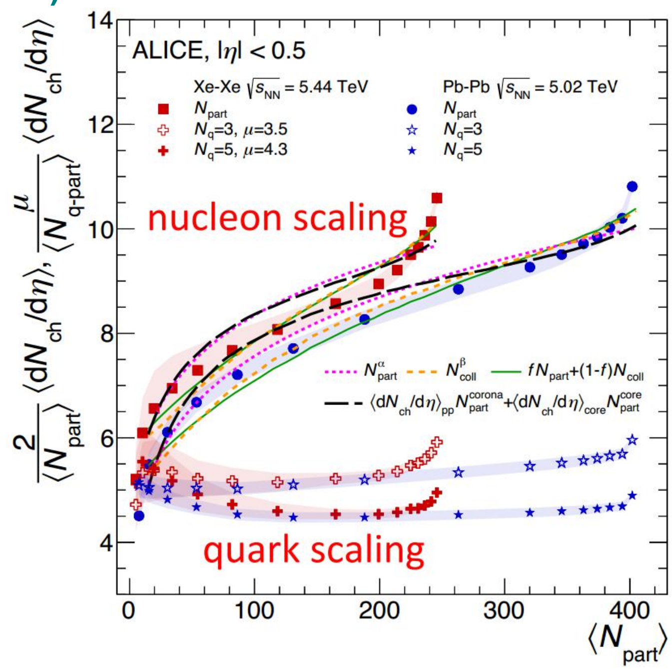
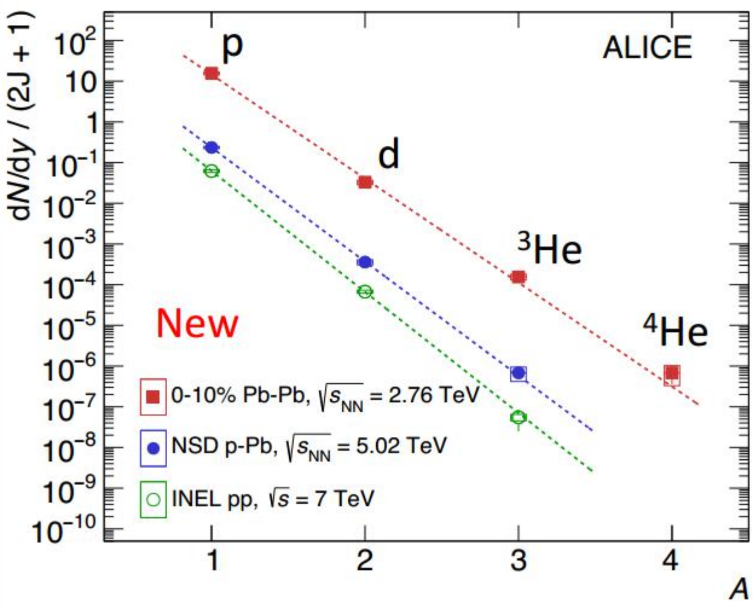
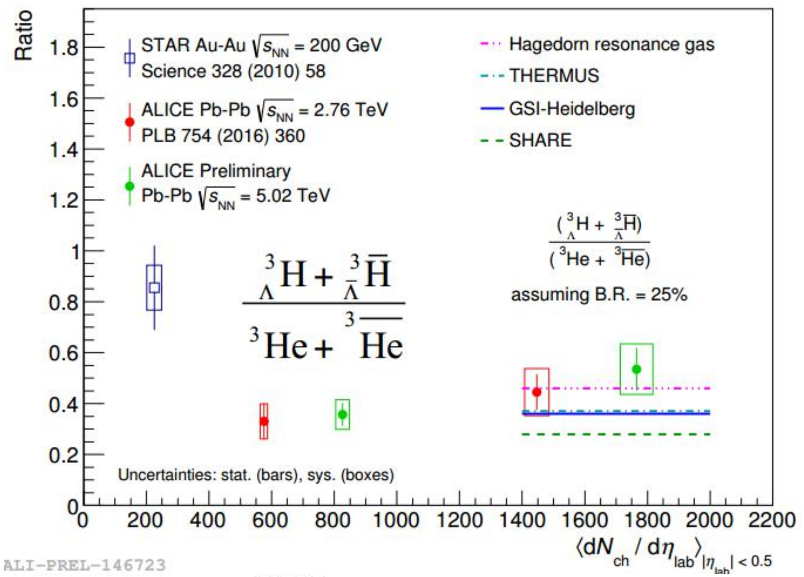


- Charged-particle multiplicity density and total multiplicity vs. centrality
  - Deviation from N_{part} scaling: Steeper rise in most central Xe-Xe and Pb-Pb collisions due to upward fluctuations
- Collision geometry plays an important role in particle production!

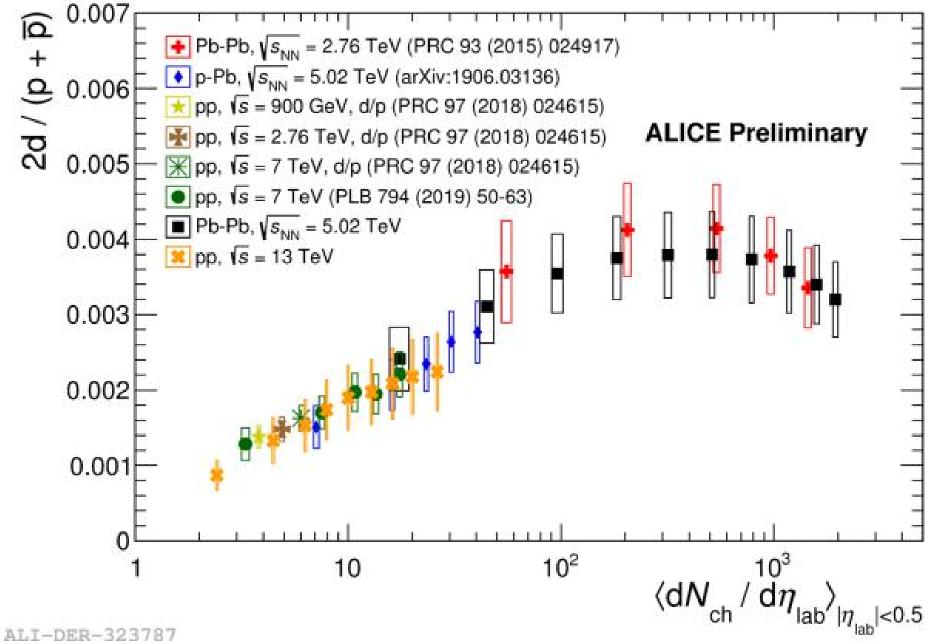
Production of nuclei





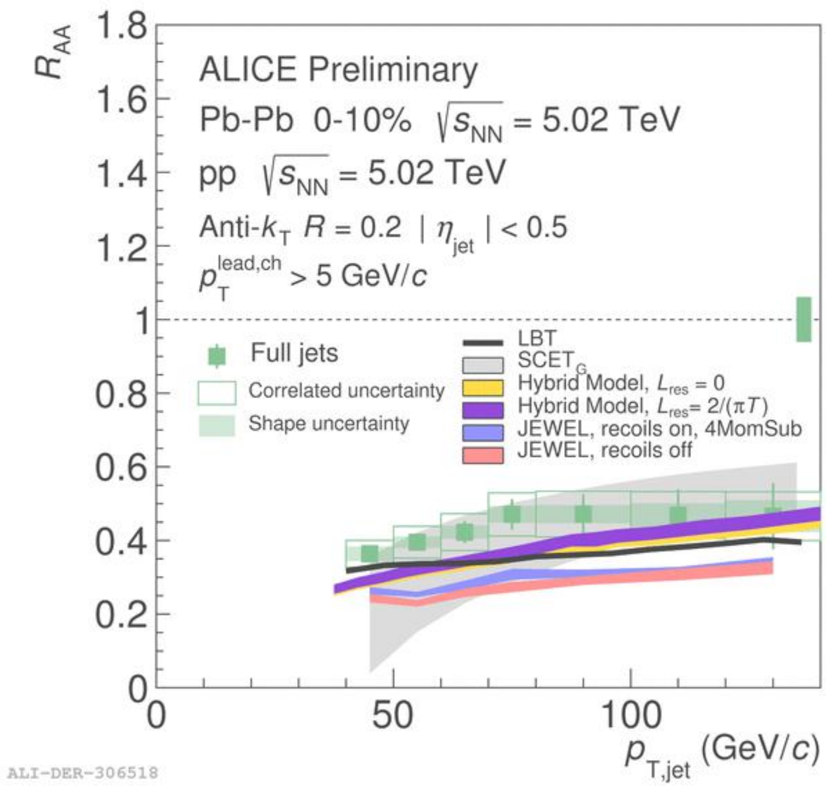
1906.03136

- Production of light nuclei is exponentially suppressed by A
- Production is consistent with thermal model
- d/p ratio depends on multiplicity
  - pp, p-Pb, Pb-Pb
  - 2.76 through 13 TeV

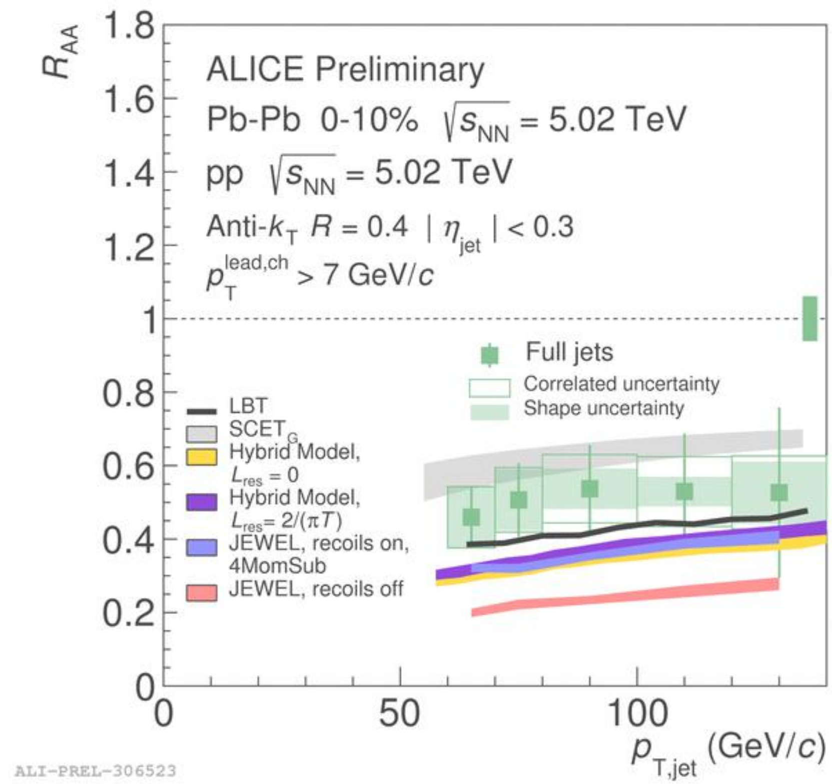


Jet suppression in Pb-Pb

narrow jets, R=0.2

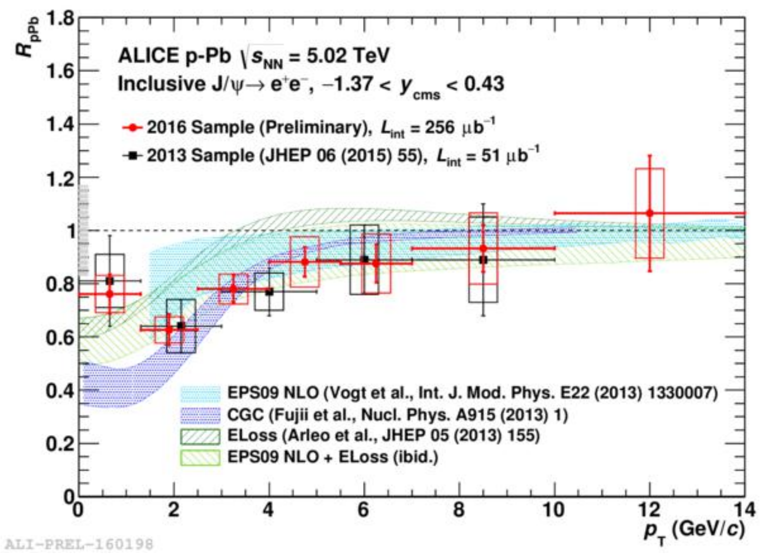


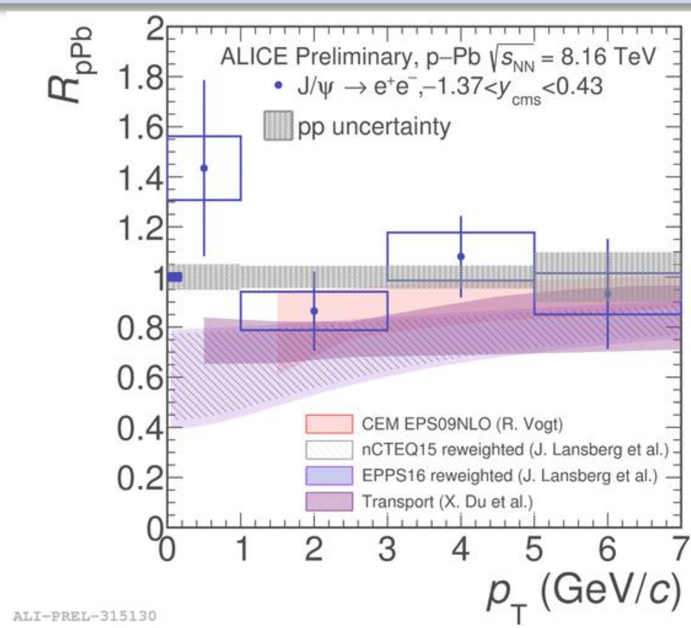
wide jets, R=0.4

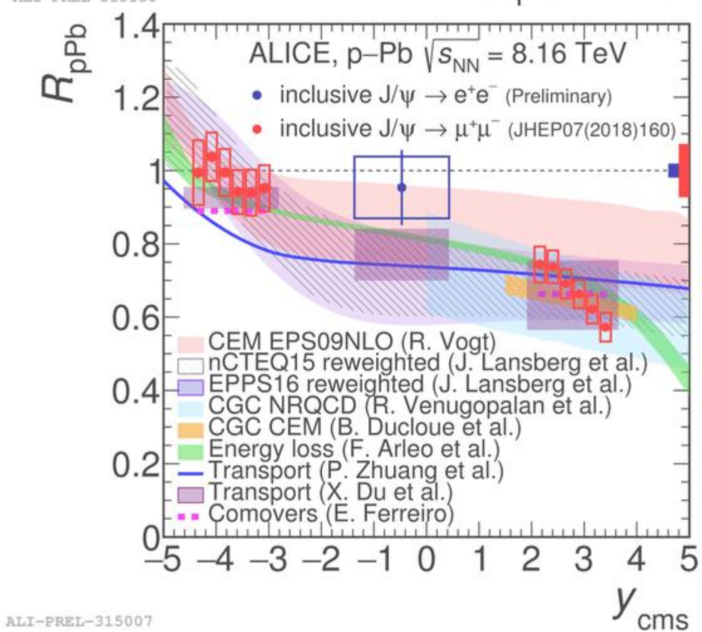


- Measurement down to p_T = 40 GeV/c => redistribution of energy
- Only weak dependence seen in data on jet resolution R
- Challenge to some models: stronger R dependence predicted than in data

Inclusive J/ψ in p-Pb collisions







- R_{pPb} of inclusive J/ψ at $\sqrt{s_{NN}}$ = 8.16 TeV and $\sqrt{s_{NN}}$ = 5.02 TeV are consistent within uncertainties
- Rapidity dependence for p_T>0 are described by models including CNM effects