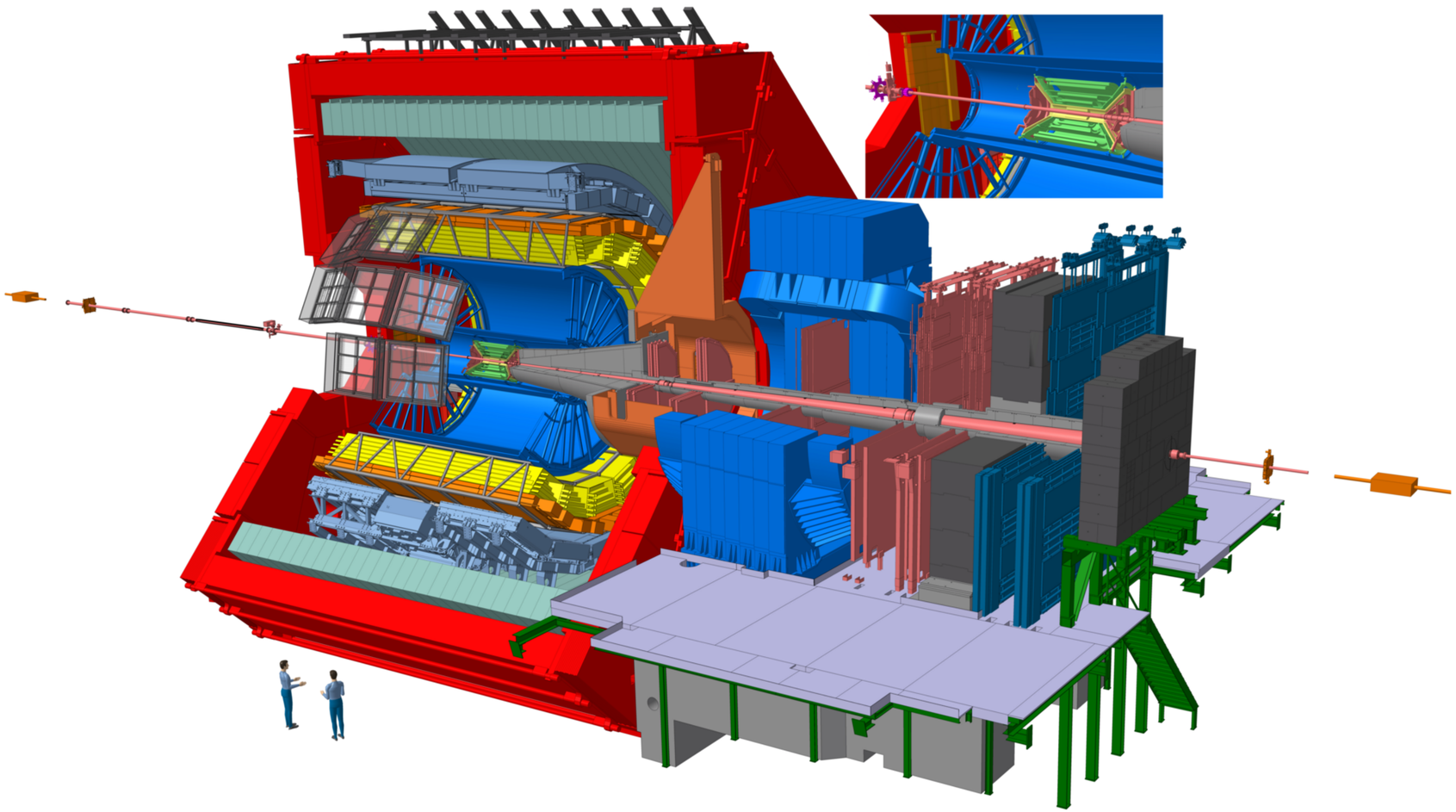
ALICE Overview

– Torsten Dahms –
Excellence Cluster Universe - Technische Universität München
(on behalf of the ALICE Collaboration)

Hard Probes 2018
October 1st, 2018

Outline

- **Electromagnetic Probes**
  - low mass dielectrons
  - photons
- **Jets**
  - γ–jet correlations
  - jet quenching & structure
- **Heavy Flavour**
  - heavy-flavour jets
  - baryons
  - directed flow
- **Quarkonia**
  - new pp reference
  - flow
  - in small systems



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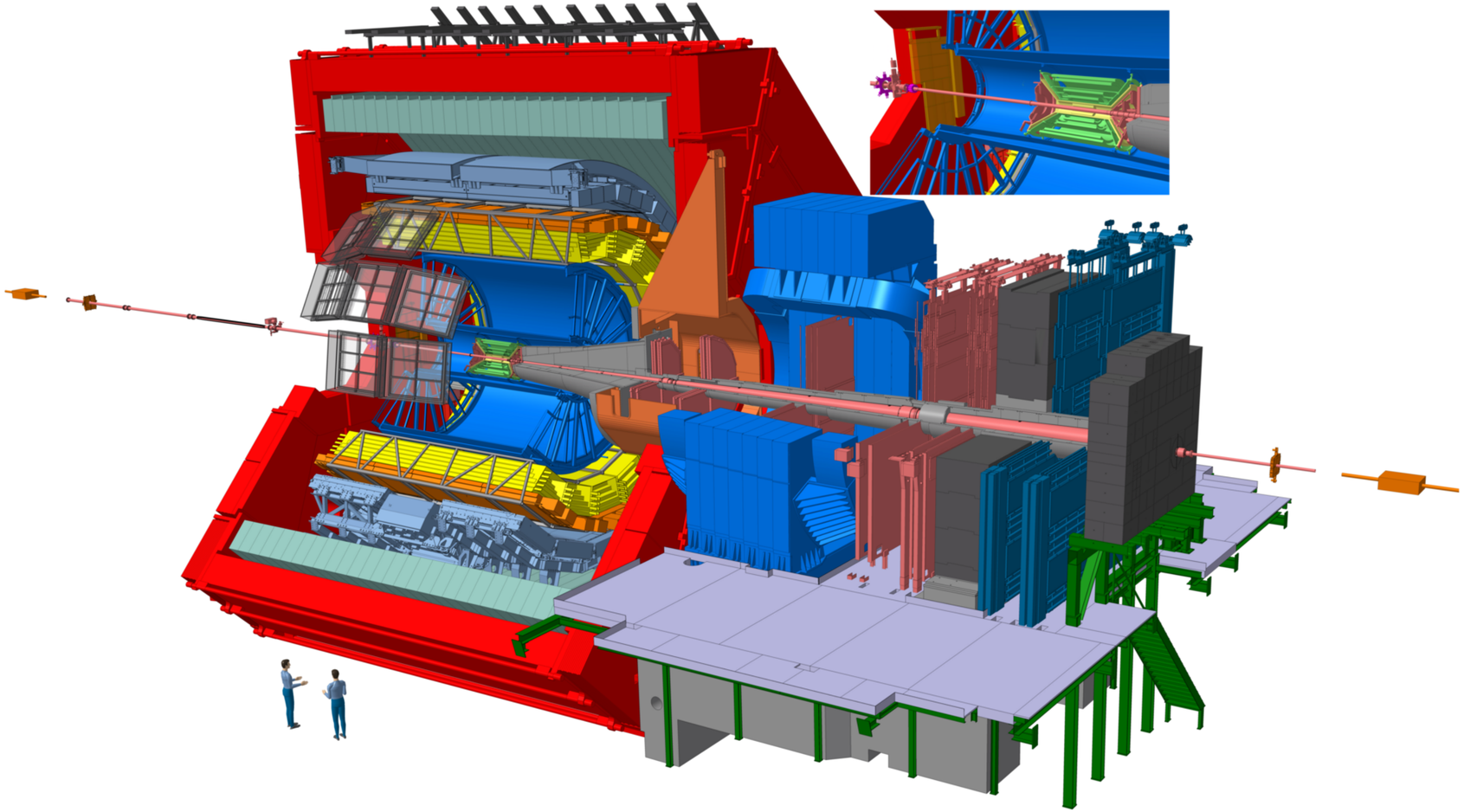
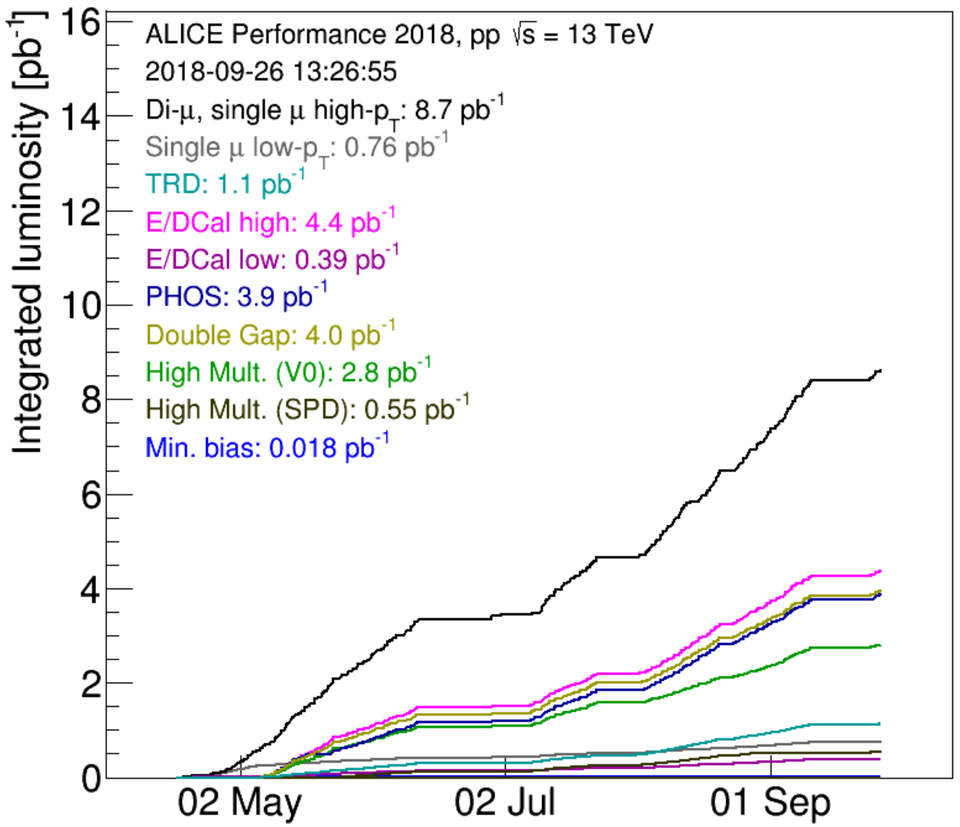
New result!

New reference!
Run-2 pp at $\sqrt{s}$ = 5 TeV



ALICE Data

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb–Pb	2010–2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	upcoming: 2018	**5.02**	**~750 μb^{-1}**
Xe–Xe	2017	5.44	~0.3 μb^{-1}
p–Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009–2013	0.9, 2.76	~200 μb^{-1}, ~100 nb^{-1}
		7, 8	~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015, **2017**	**5.02**	**~1.3 pb^{-1}**
	2015–2018	13	~35 pb^{-1}

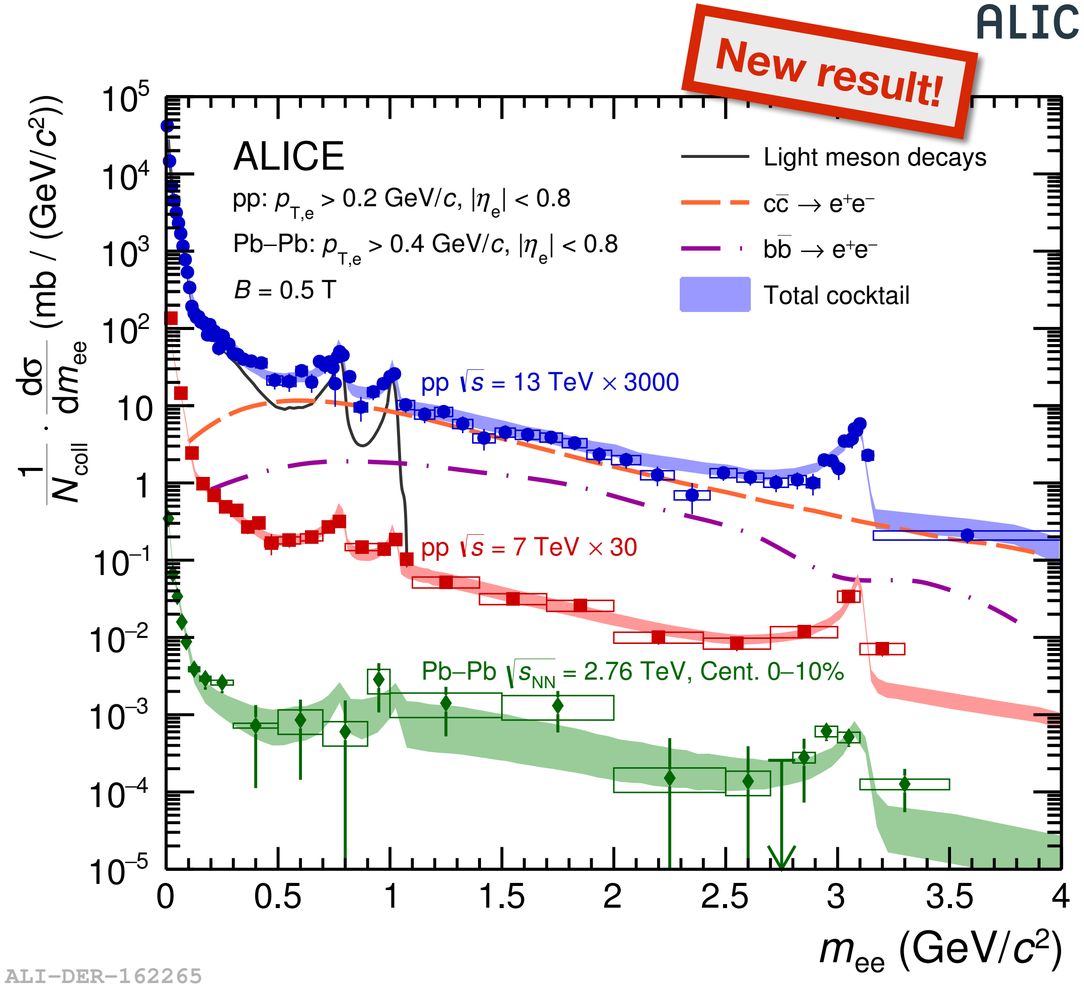


- LHC Run-2 nearing completion
- **One month from now: last Pb–Pb campaign of Run 2, aiming at total L_{int} ~1 nb^{-1}**
- **Last year: sizeable pp reference sample at $\sqrt{s}$ = 5 TeV → improved R_{AA} for hard probes**
- **Significant detector upgrades during LS2**

Electromagnetic Probes

Low-Mass Dielectrons

- Emitted from all stages of the collisions w/o strong final-state interactions
  - **search for signals of thermal radiation and chiral-symmetry restoration (ρ modification)**
  - hidden behind ordinary signal from hadron decays (not to mention combinatorial background)
- **Published results in pp at $\sqrt{s}$ = 7 and 13 TeV and Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV**
- Data consistent with cocktail expectation
- Measure charm and beauty cross sections in pp
  - major background for any low-mass measurement
- **Not yet sensitive to quantify the presence of an enhancement in Pb–Pb**
- **New results in Pb–Pb at $\sqrt{s_{NN}}$ = 5 TeV**
  - charm is not described by PYTHIA×N_{coll}
  - improved description when adding shadowing (EPPS16)



A. Caliva, Wed, 12h05

ALICE, JHEP 09 (2018) 64
arXiv:1805.04407 (submitted to PLB),
arXiv:1807.00923 (submitted to PRC)

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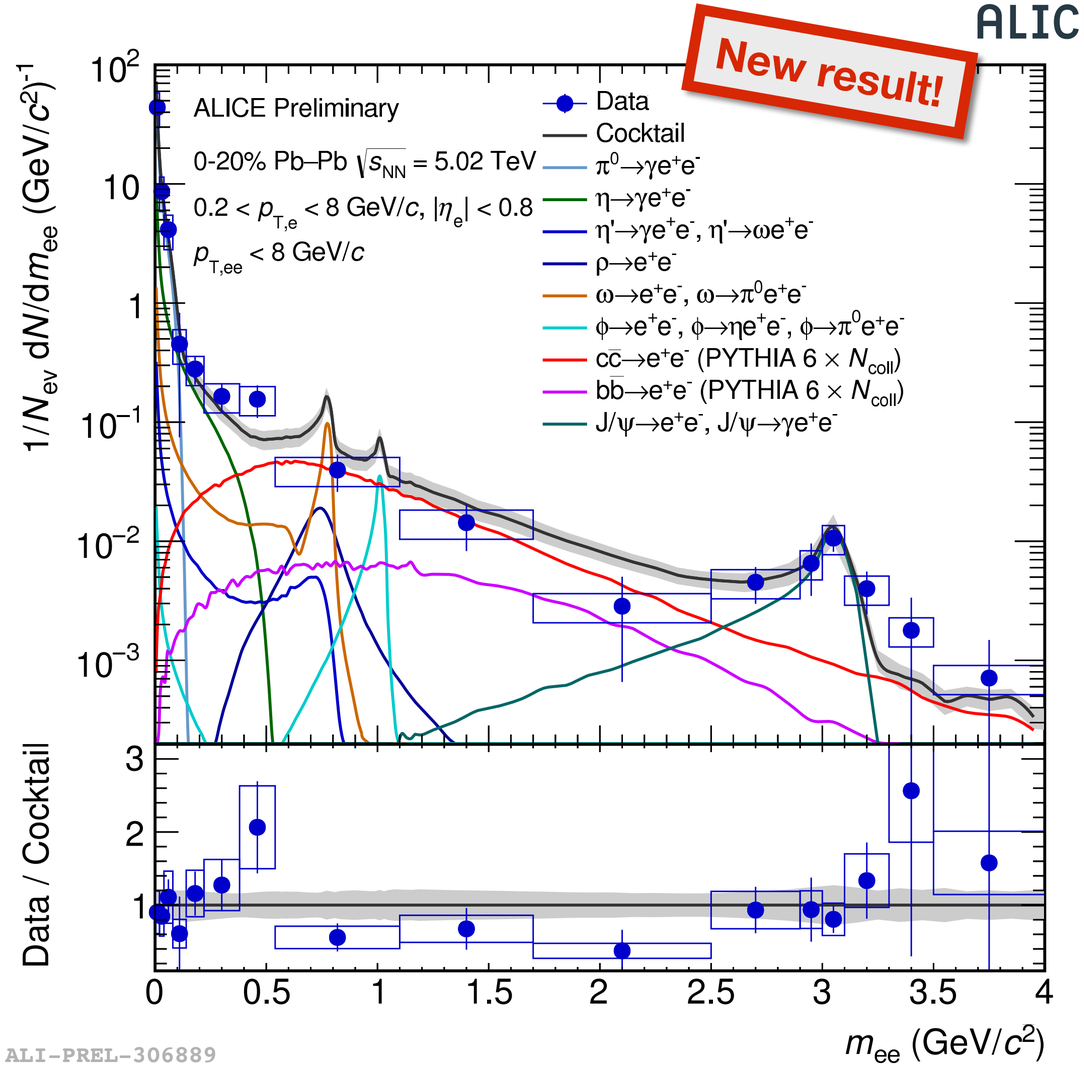

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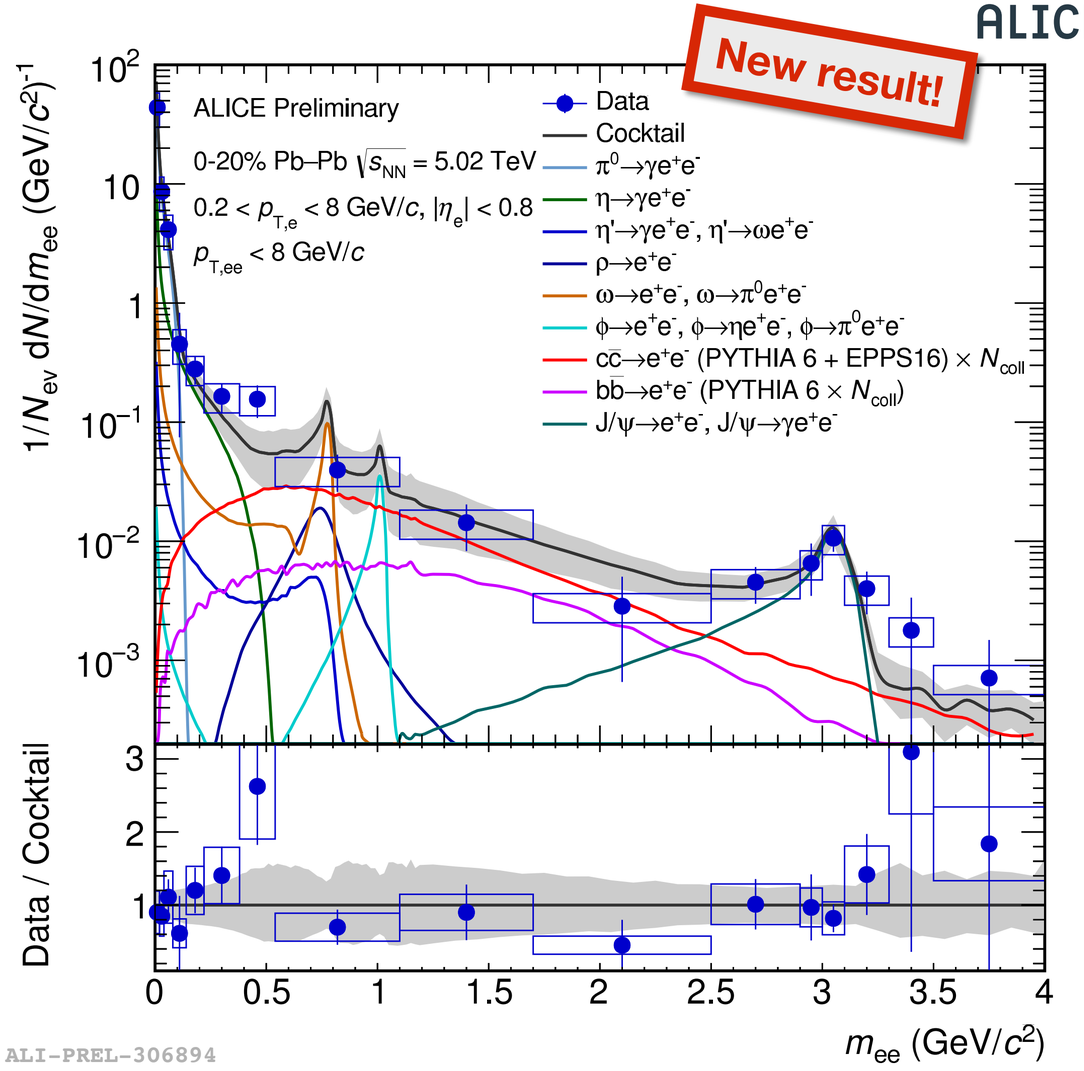

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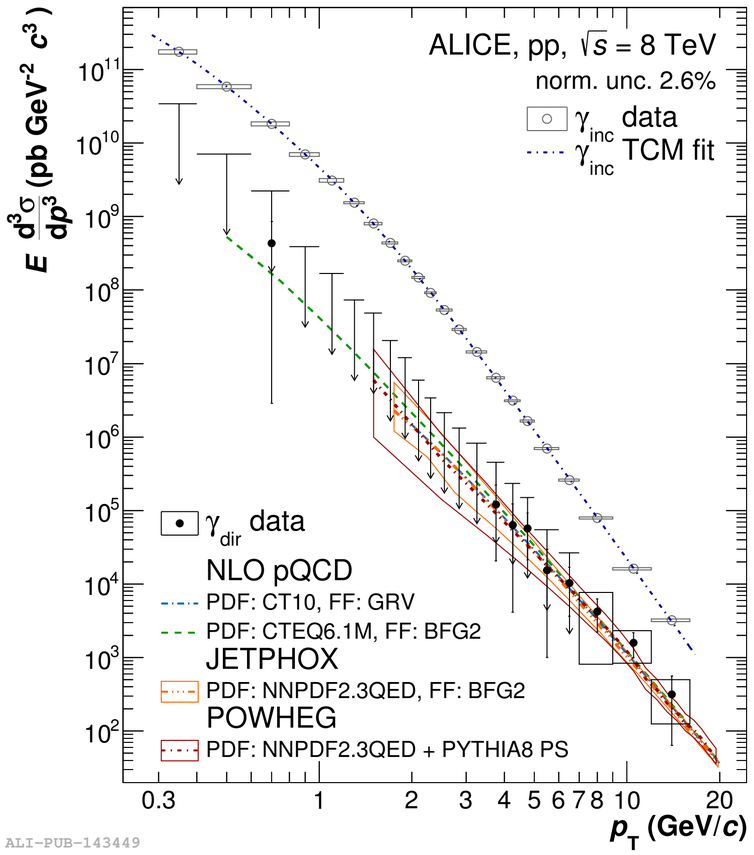
Direct Photons in pp and p–Pb

- Average of three independent measurements
  - EMCal, PHOS, Photon Conversions
- Systematics limited
- Large uncertainties from hadron-decay background



ALICE, arXiv:1803.09857 (submitted to PRC)

N. Schmidt, Wed, 10h

Direct Photons in pp and p–Pb

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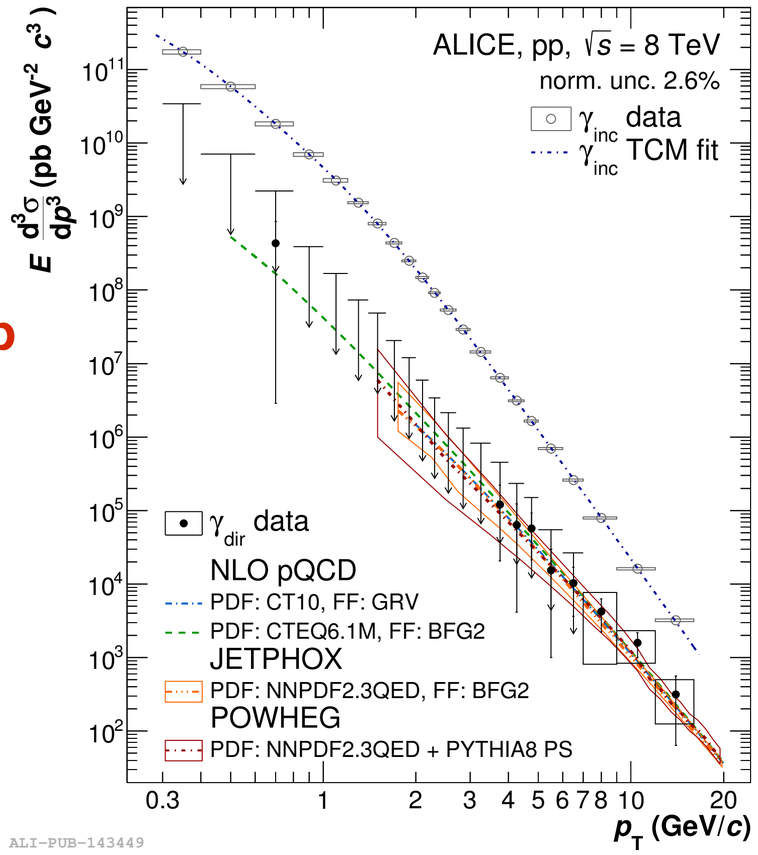
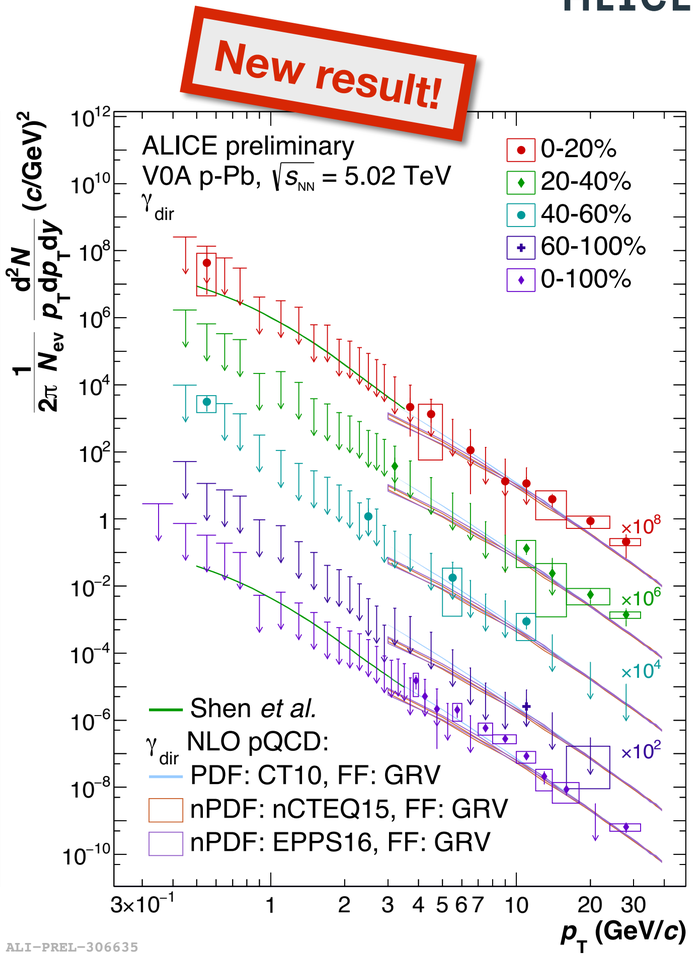
- Systematics limited
- Large uncertainties from hadron-decay background
- **New: multiplicity dependence in p–Pb**
- Limits consistent with NLO pQCD in pp and p–Pb
  - pQCD scaled by N_{coll}
  - p–Pb data not yet sensitive to nPDF effects





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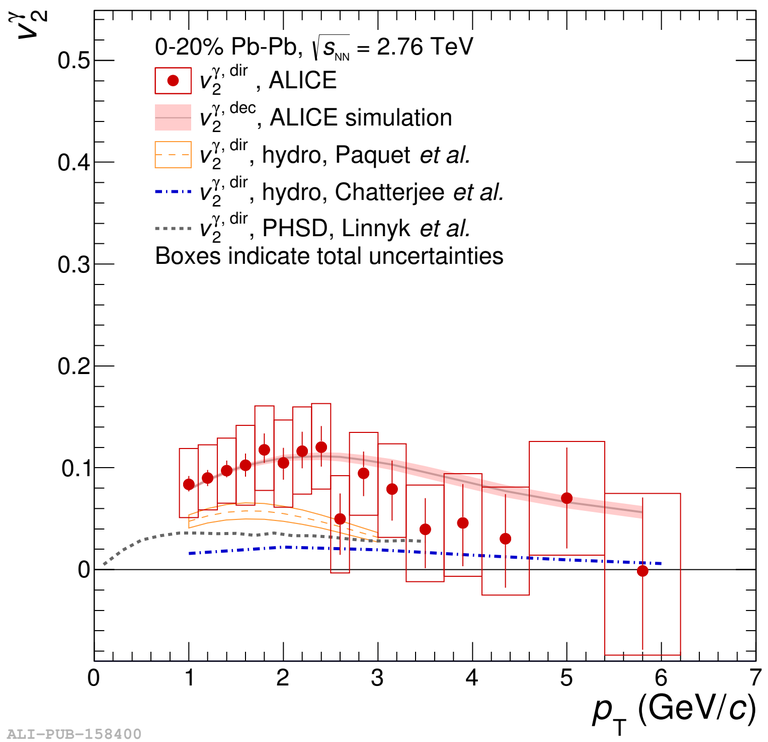
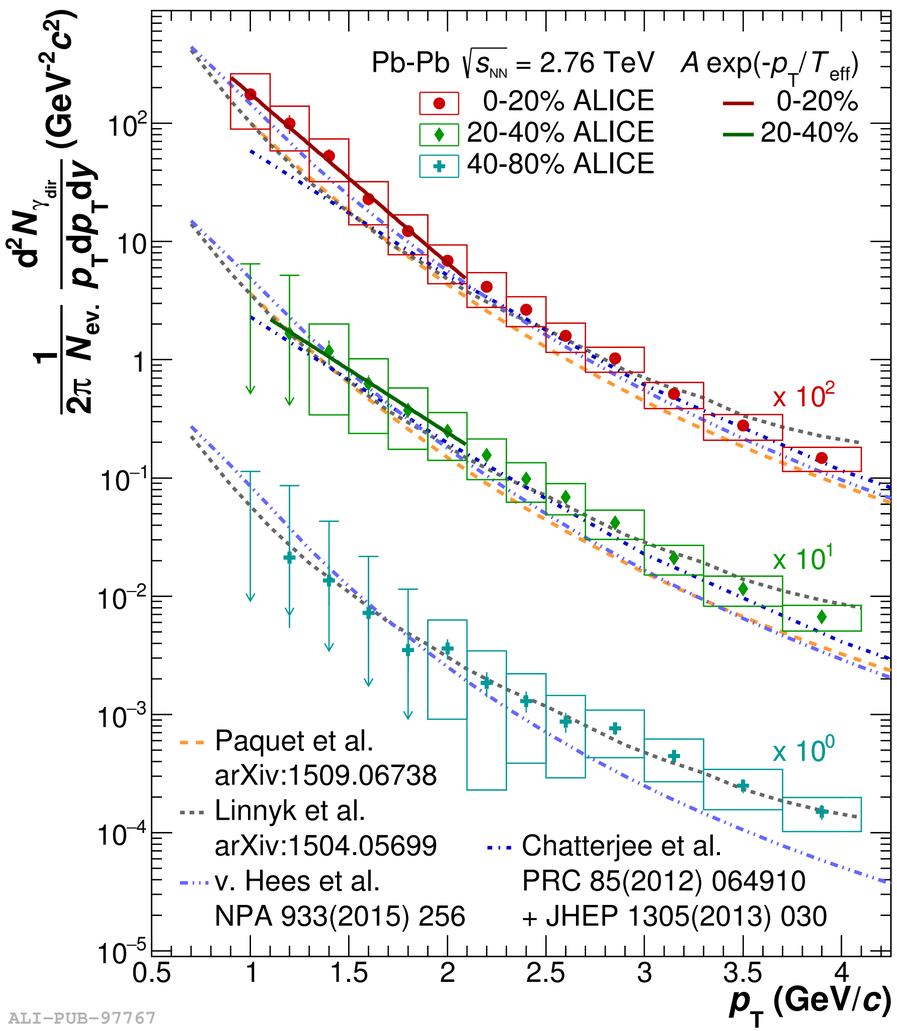
N. Schmidt, Wed, 10h

Direct Photons in Pb–Pb

- Clear direct photon signal in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- Consistent with models of thermal radiation from QGP
- Large uncertainties on v_2
  → **no direct-photon puzzle at the LHC (yet?)**



ALICE, arXiv:1805.04403 (submitted to PLB)



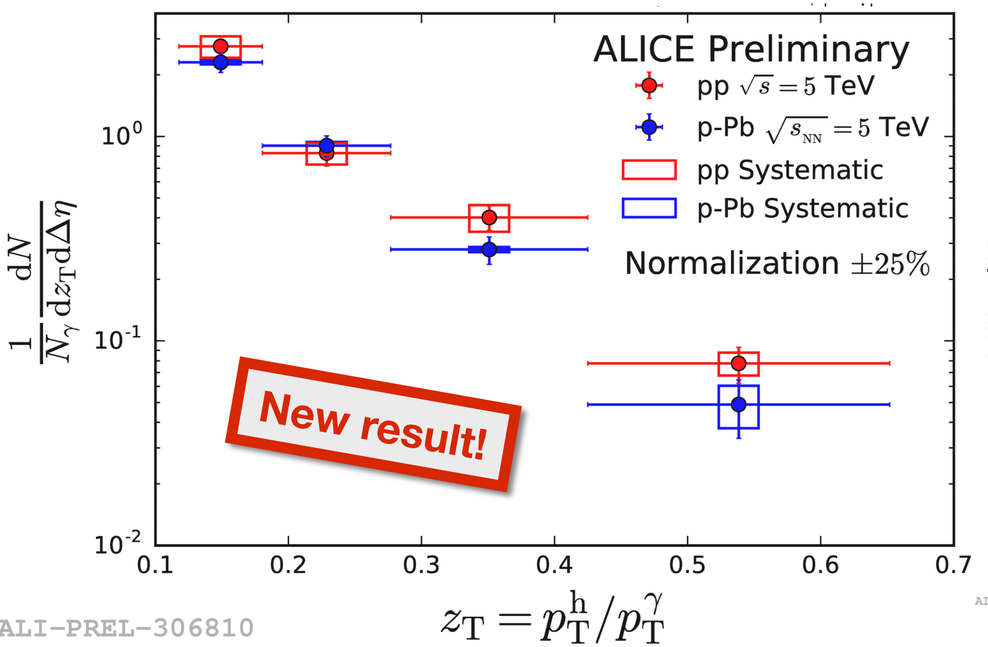
ALICE, PLB 754 (2016) 235

N. Schmidt, Wed, 10h

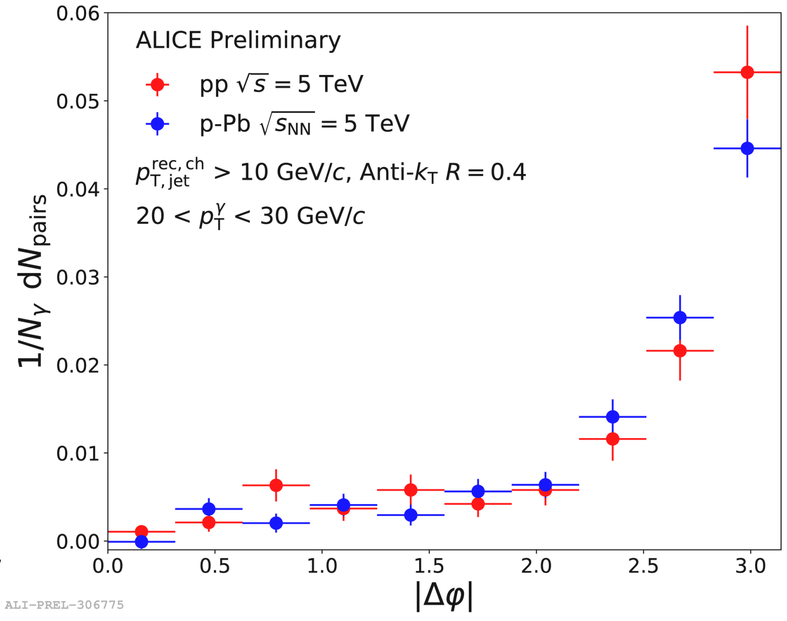
Jets

γ–Jet Correlations in pp and p–Pb at $\sqrt{s_{NN}}$ = 5 TeV

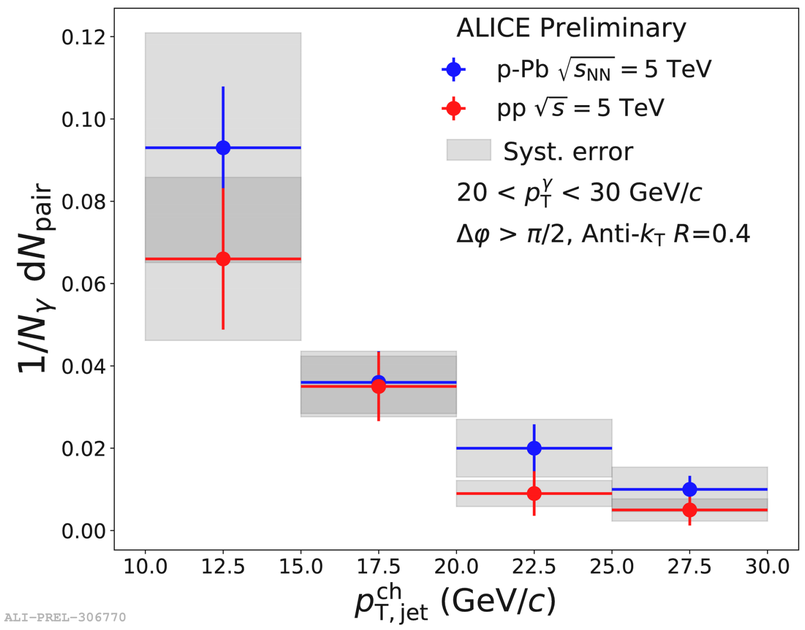
Fragmentation Function



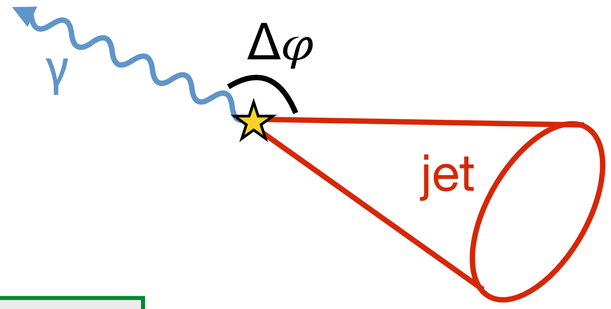
Azimuthal Correlation



Per-trigger Jet Yield

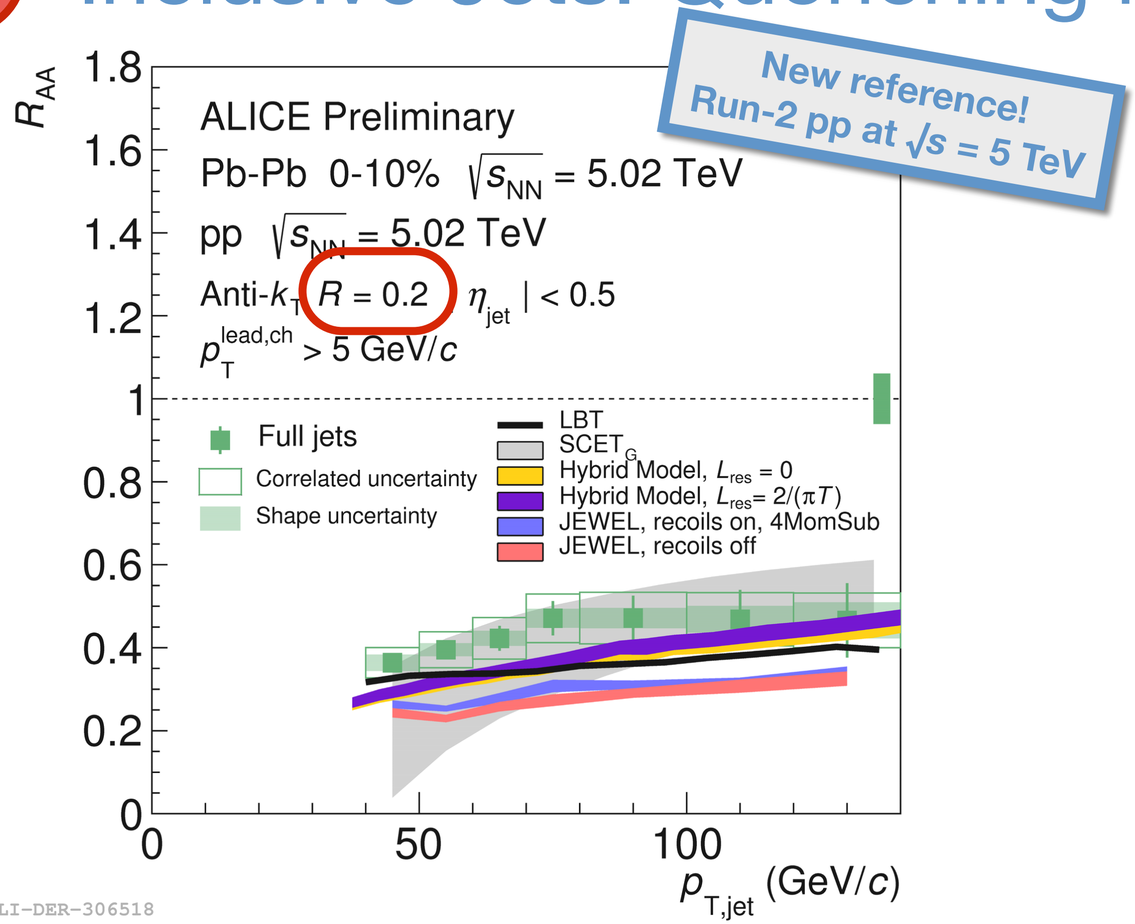


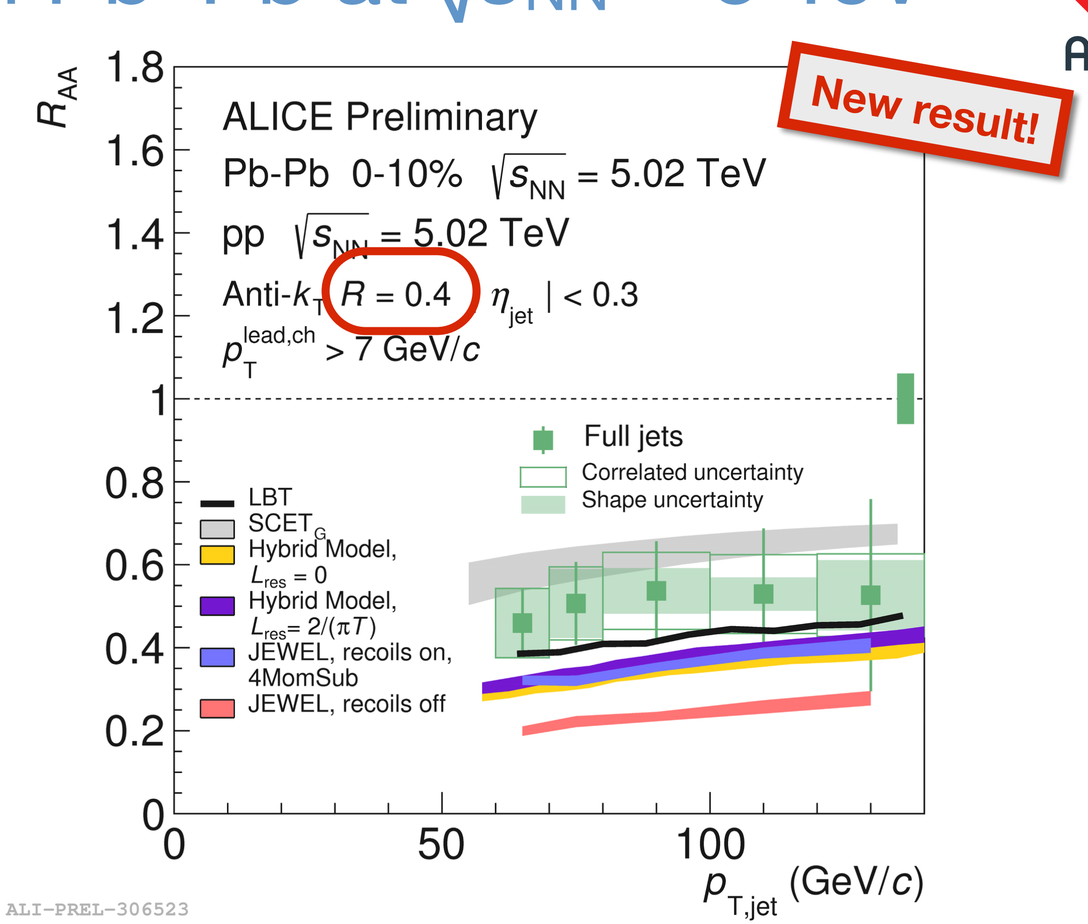
- Unique access to low-Q^2 and low-x_{Bj} region
- **As expected: no significant differences between pp and p–Pb in**
  - fragmentation function
  - angular correlations
  - jet yield
- Reference for Pb-Pb measurement



M. Arratia, Tue, 16h25

Inclusive Jets: Quenching in Pb–Pb at $\sqrt{s_{NN}}$ = 5 TeV





- Jet quenching measured down to $p_{T,jet}$ = 40 GeV/c
- **New: measured with jet radii up to R = 0.4**
- ***R* dependence probes the angular distribution of medium-induced radiation**
  - Hint of tension with most models at low p_T

J. Mulligan, Wed, 11h05

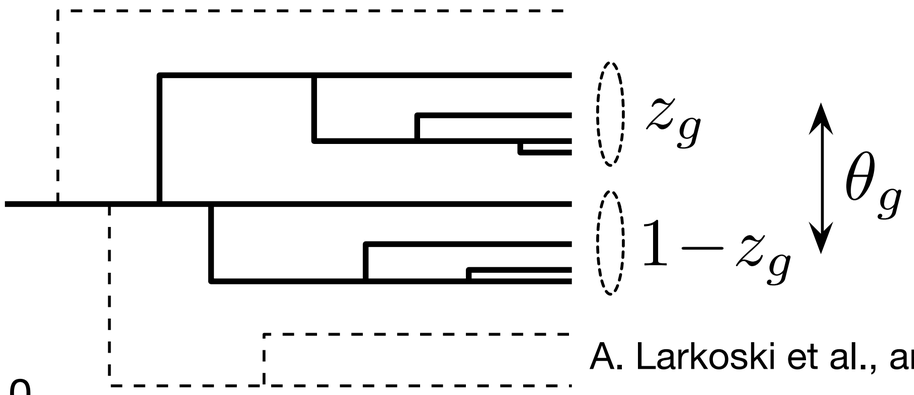
(model references in backup)

Jet Structure: Splitting Function

- **Study QCD 1→2 splitting function in pp**
  - momentum fraction z_g carried hard jet component after removing soft jets with momentum fraction z

$$z = \frac{\min(p_{\mathrm{T},1};\, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

here: $z_{\mathrm{cut}} = 0.1$, $\beta = 0$

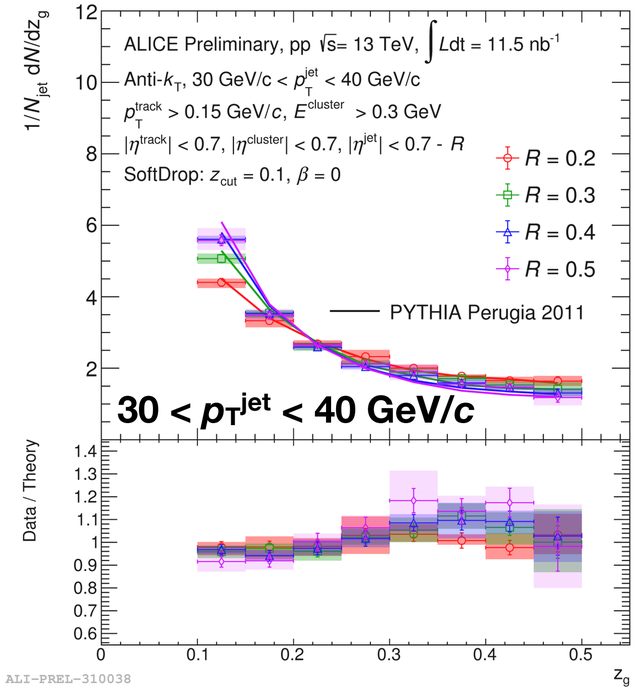


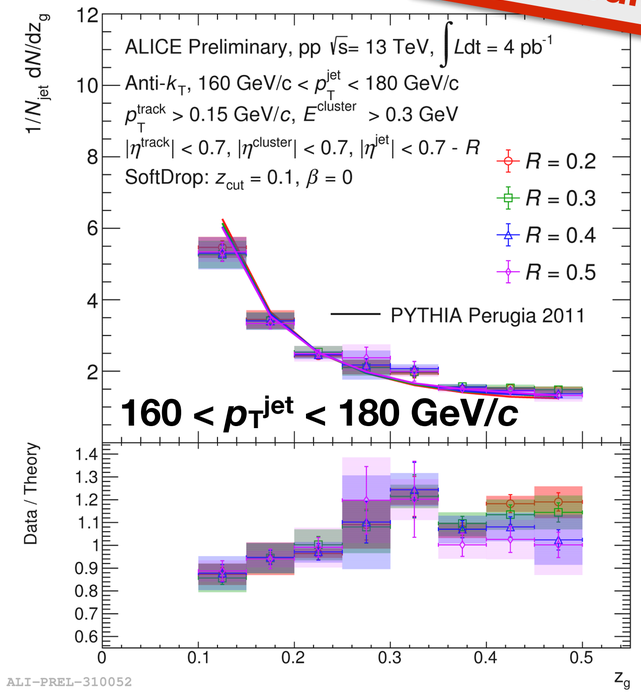
A. Larkoski et al., arXiv:1704.05066

- **No dependence on jet p_T (as expected)**
  - probe now high-p_T jets (180 GeV/c)
- **Depends on jet cone radius at low p_T → points to non-perturbative effects**
- Studied out to $R = 0.5$

M. Fasel, Wed, 9h40

New result!





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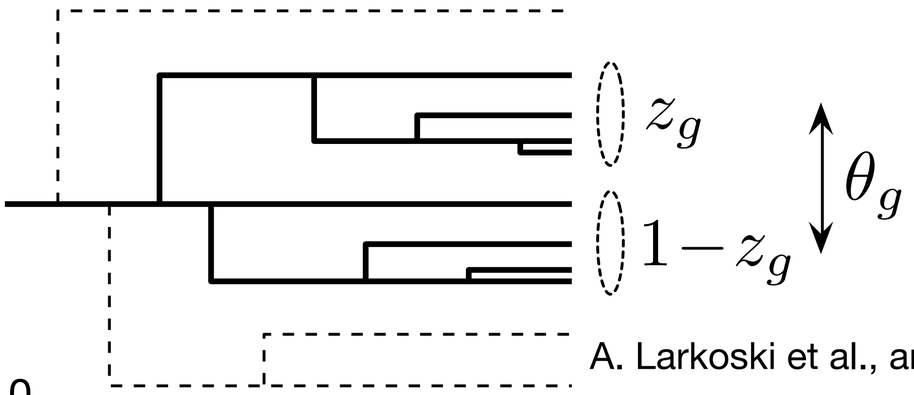

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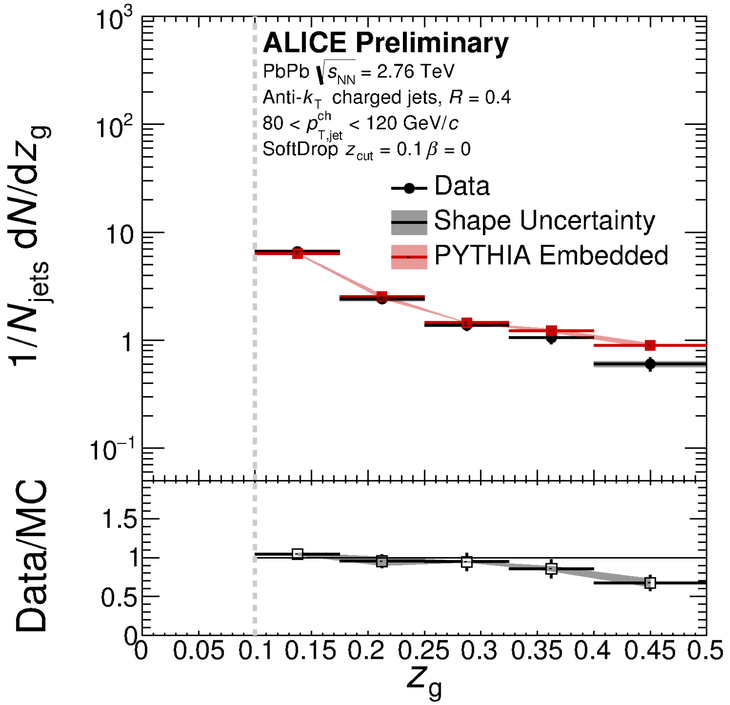


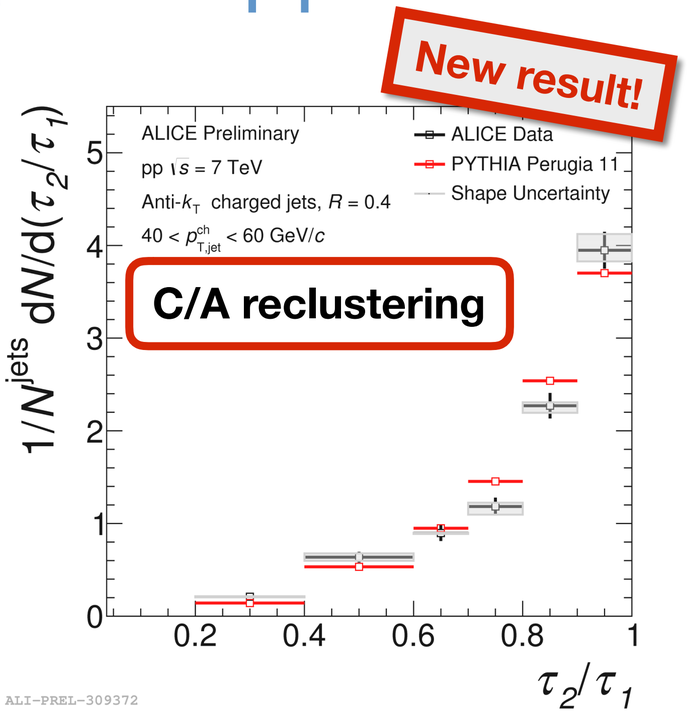
M. Fasel, Wed, 9h40

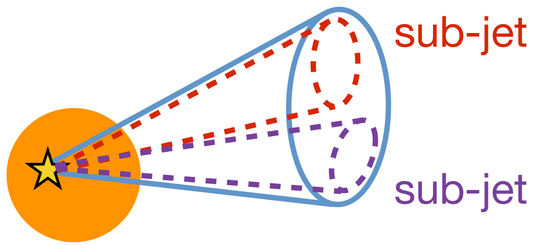
Jet Structure: Sub-jets in pp and Pb–Pb

- Study number of sub-jets within jets
  - Quantify how pronounced *N* prongs are in a jet

$$\tau_N = \frac{\sum_i p_{\mathrm{T},i} \min(\Delta R_{1,i},\, \Delta R_{2,i}, \ldots \Delta R_{N,i})}{R \sum_i p_{\mathrm{T},i}}$$

  - $\tau_N \rightarrow 0$: *N* or less cores
  - $\tau_N \rightarrow 1$: at least *N*+1 cores
  - $\tau_2/\tau_1 \rightarrow 0$: jet has 2 prongs





N. Zardoshti, Thu, 14h40

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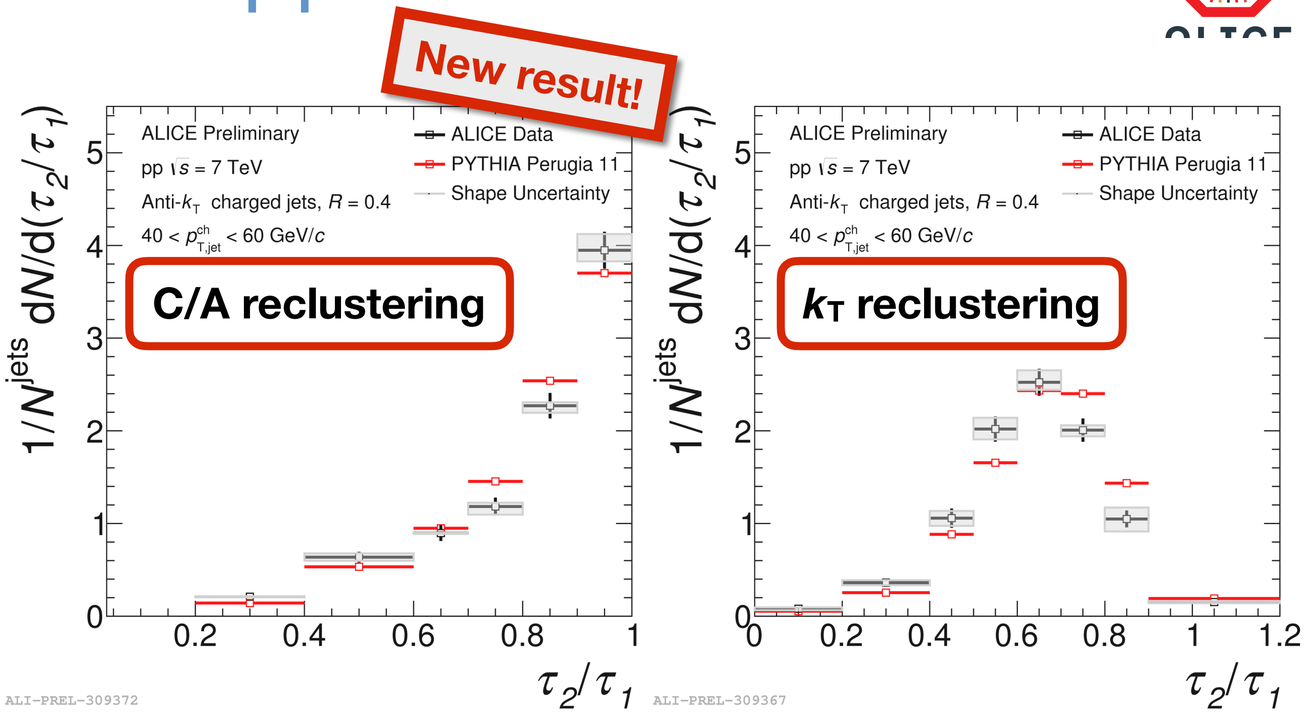
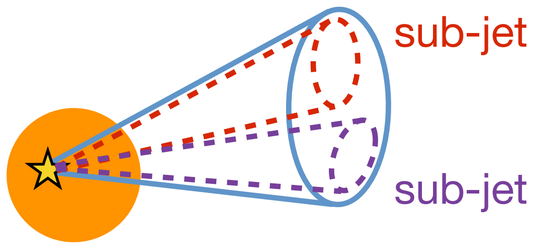
- **Splitting of sub-jets in pp described by PYTHIA**
  - use PYTHIA for energy extrapolation: 7 TeV → 2.76 TeV





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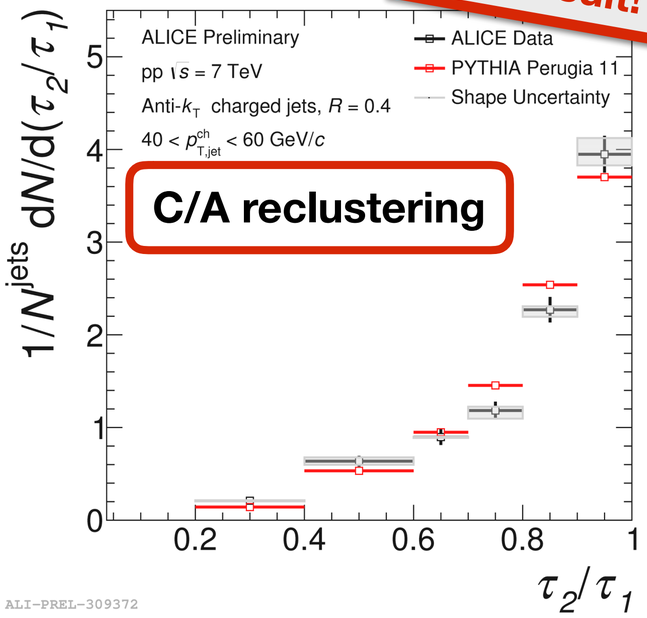
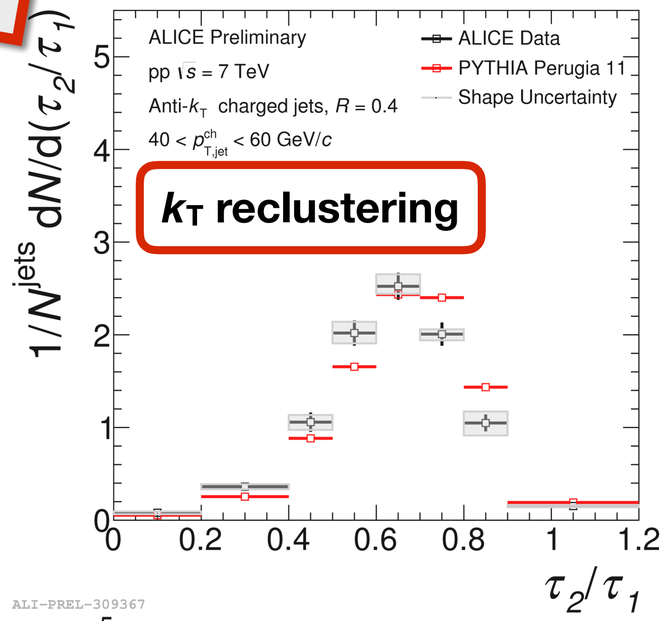
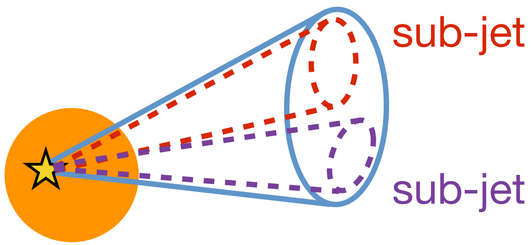
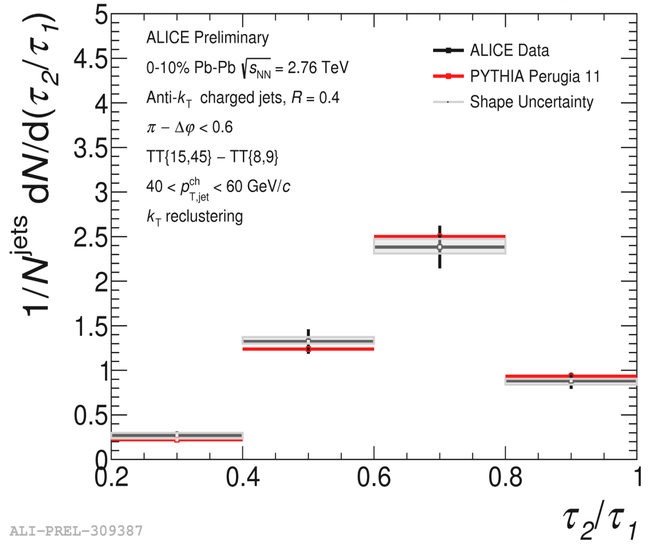
  - use PYTHIA for energy extrapolation: 7 TeV → 2.76 TeV
- **Very similar sub-jet structure in Pb–Pb → In-medium jet core remains vacuum-like**
  - more pp data needed to quantify

New result!









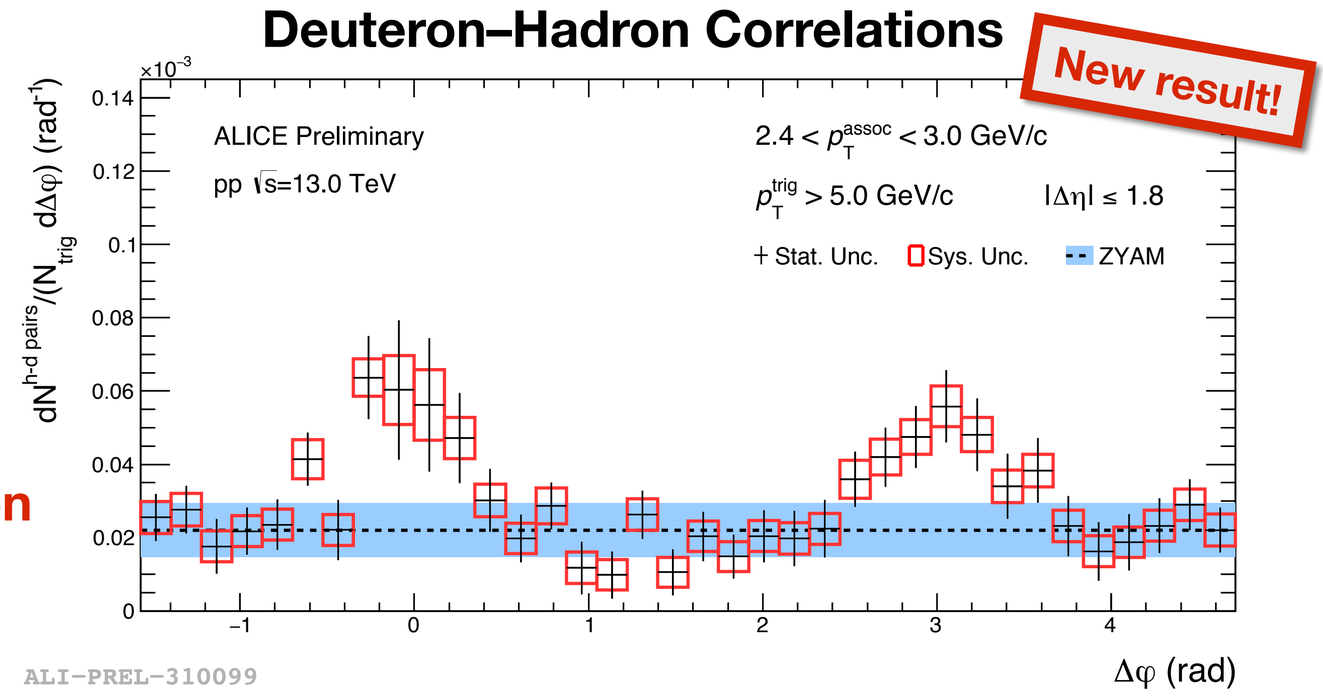
N. Zardoshti, Thu, 14h40

Particle ID in Jets: Deuterons

- **Are deuterons created in jets?**
  - e.g. by coalescence of protons and neutrons
  - **directly linked to baryon production in jets**

- If yes, should observe a correlation of deuterons with other hadrons in jet

- **High-p_T deuterons show angular correlation with high-p_T hadrons in pp at $\sqrt{s}$ = 13 TeV**
  - indication that deuterons are also produced in jets (and not only non-composite hadrons)

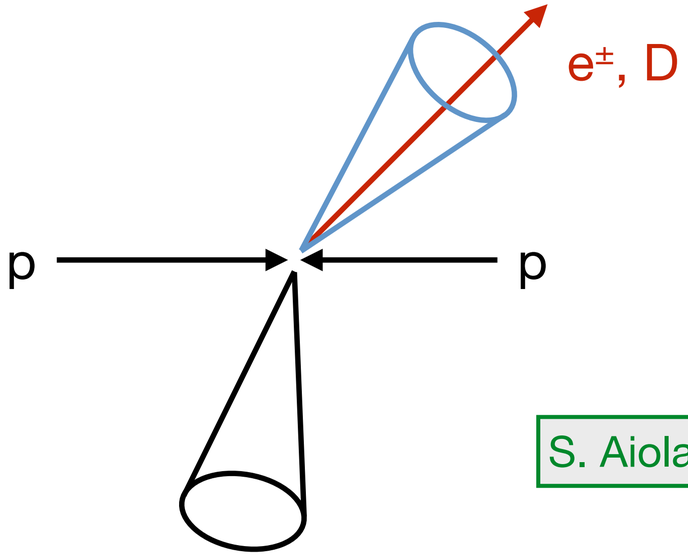


B. Schaefer, Tue, 12h05

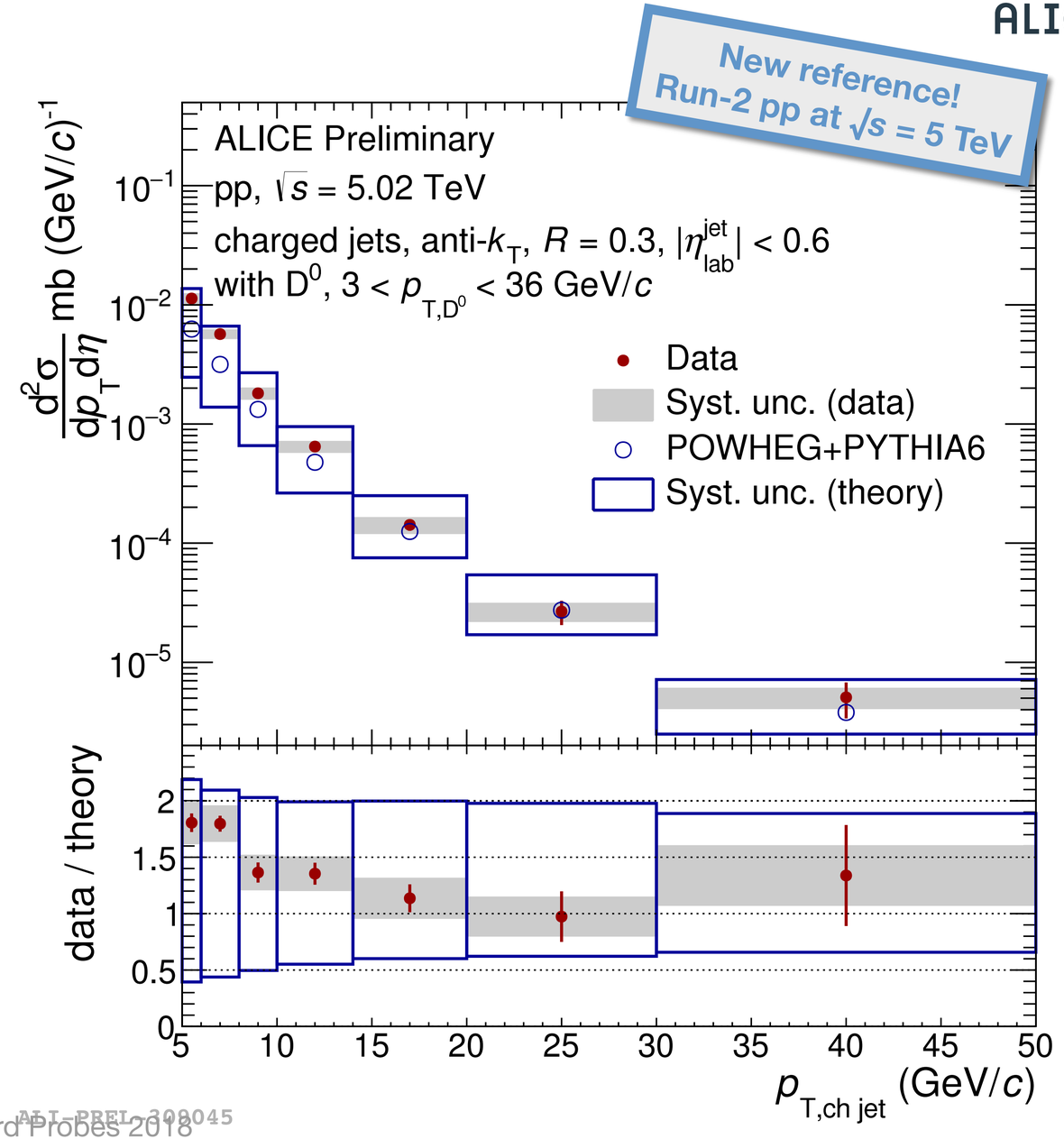
Heavy Flavour

Particle ID in Jets: Heavy Flavour

- Identify heavy flavour jets via:
  - electrons from semileptonic HF decays
  - fully reconstructed D^0 meson
- Charged HF jets well reproduced by POWHEG (NLO event generator)



S. Aiola, Thu, 11h45



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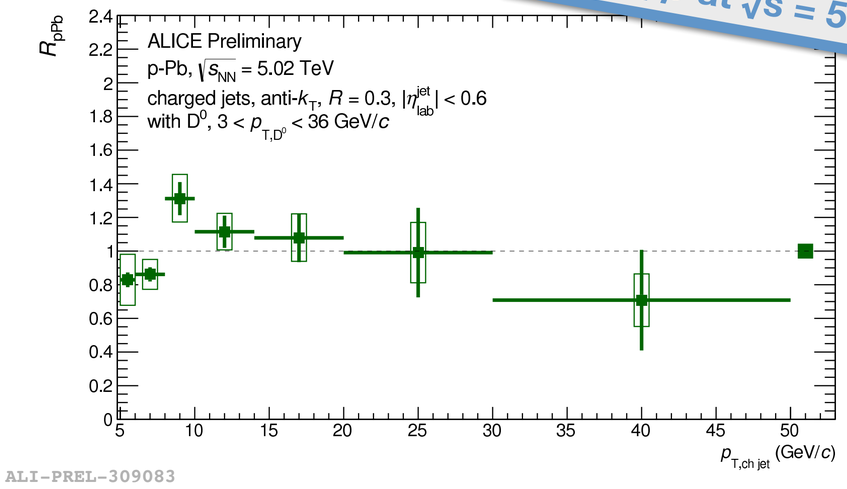

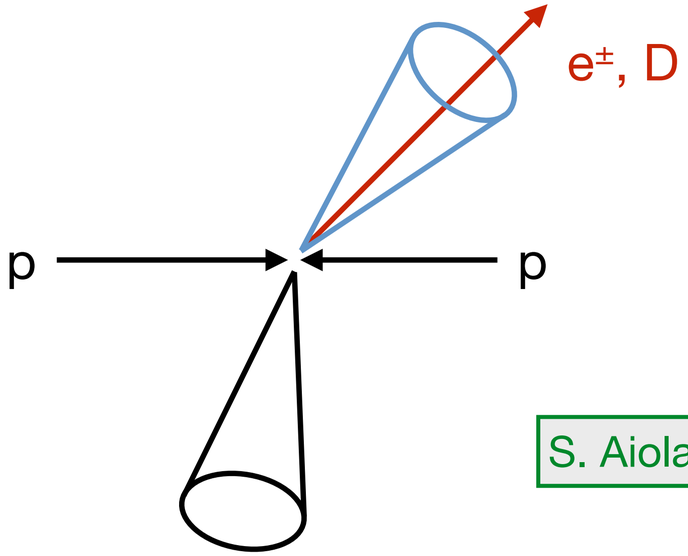

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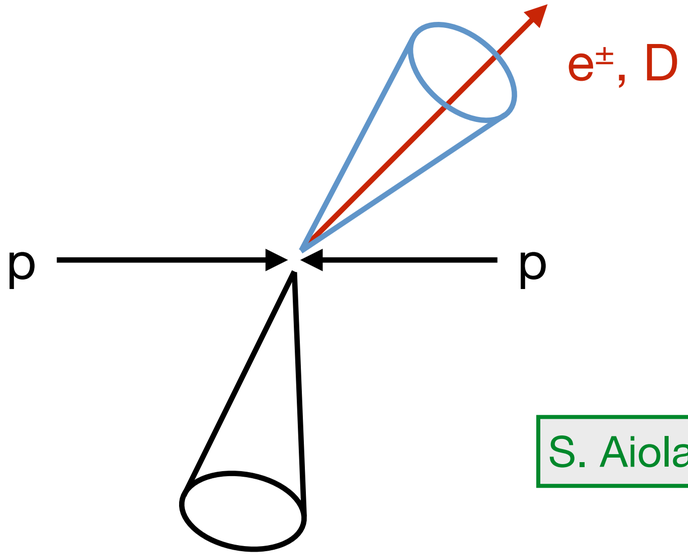
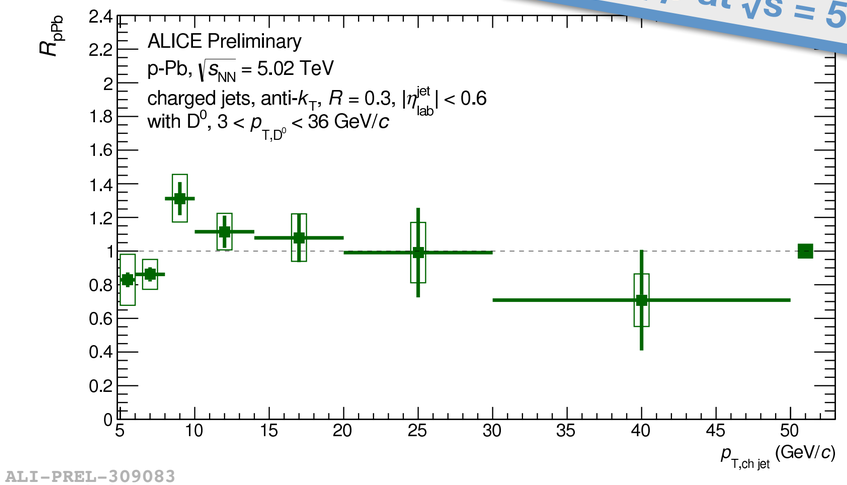
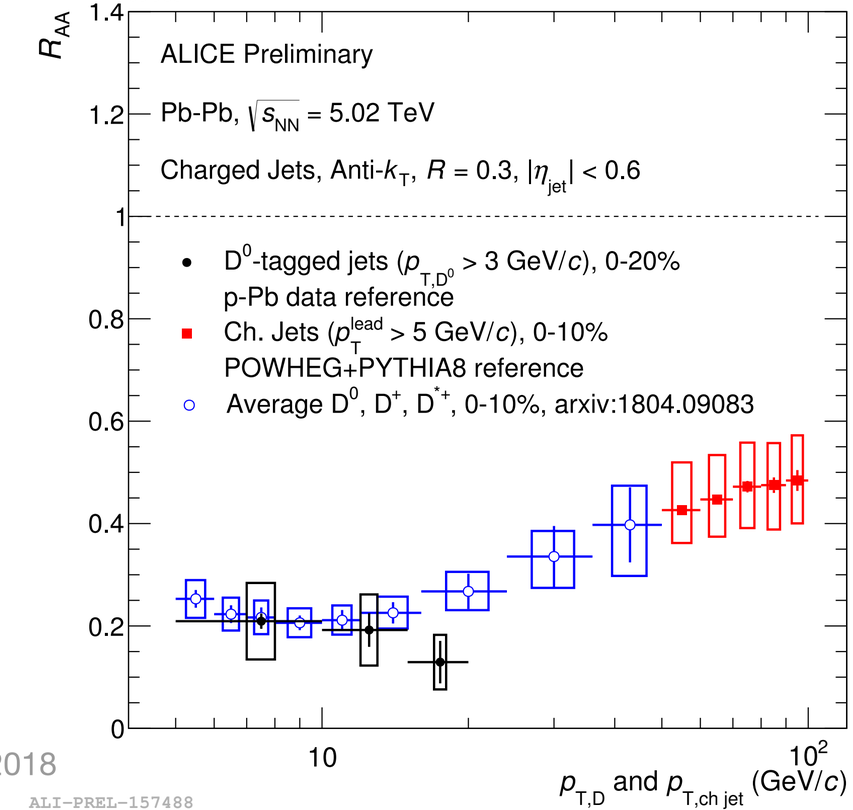
- **No suppression of D-tagged jets in p–Pb**
- **Clear suppression of D-tagged jets in Pb–Pb**
  - comparable to D-meson suppression



S. Aiola, Thu, 11h45

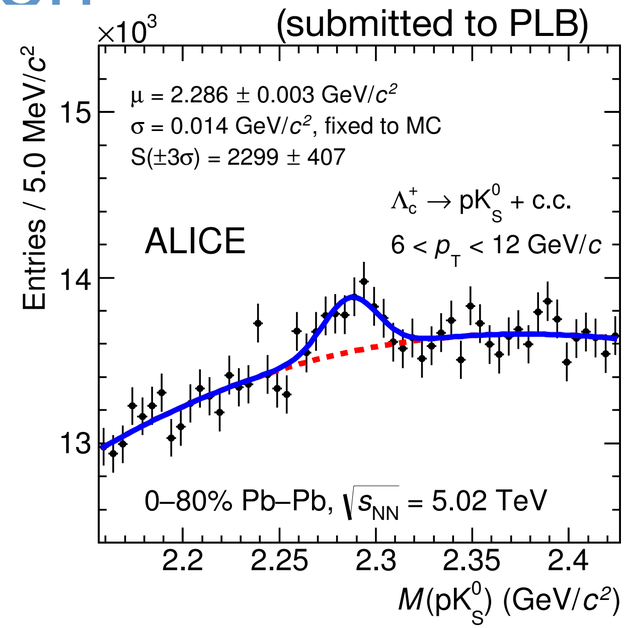


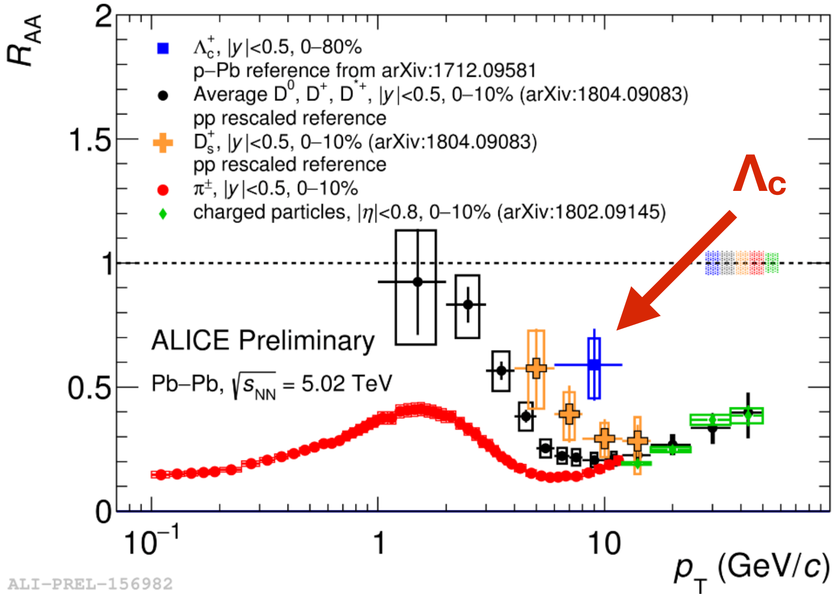


Charm Baryon Production

- **Pb–Pb: indication of Λ_c/D larger than in pp**
  - suggests coalescence contributes to hadronisation in Pb–Pb

ALICE, arXiv:1809.10922
(submitted to PLB)





E. Meninno, Thu, 11h05

Charm Baryon Production

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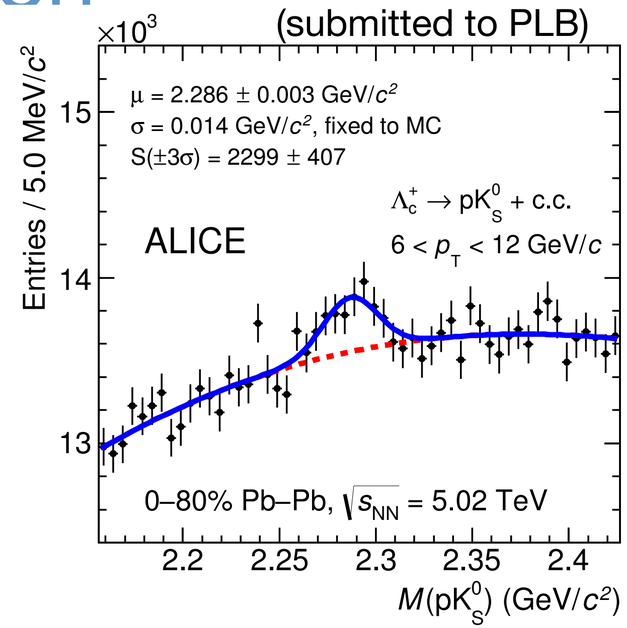
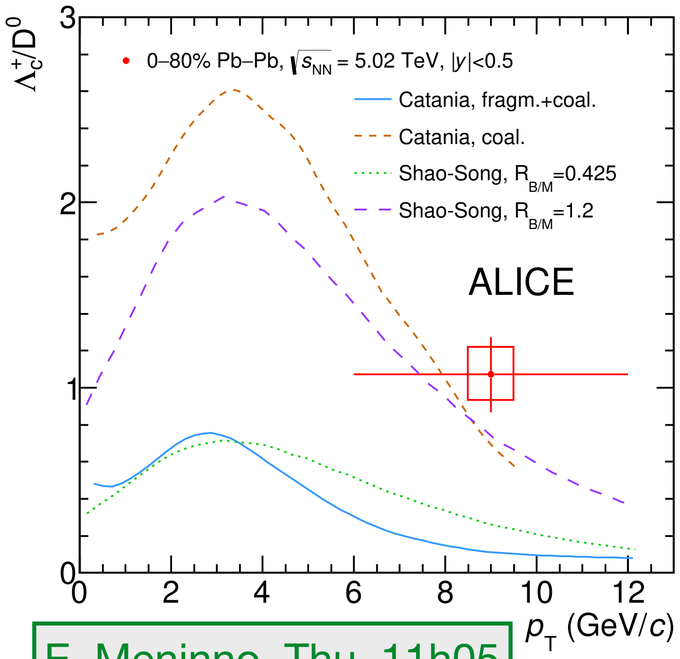
ALICE, arXiv:1809.10922
(submitted to PLB)





E. Meninno, Thu, 11h05

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ALICE, arXiv:1809.10922
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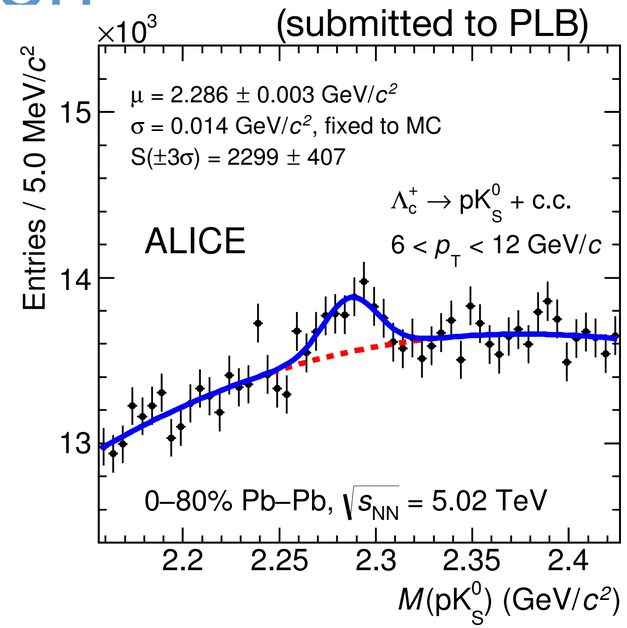
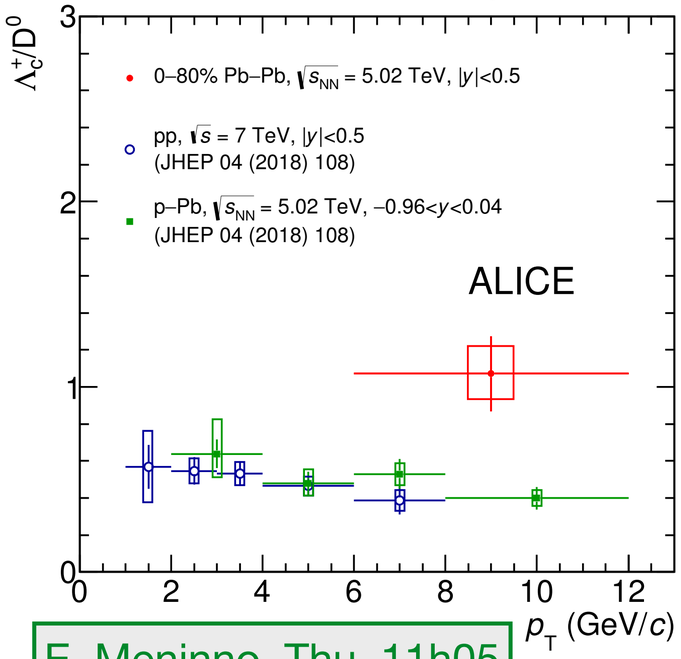


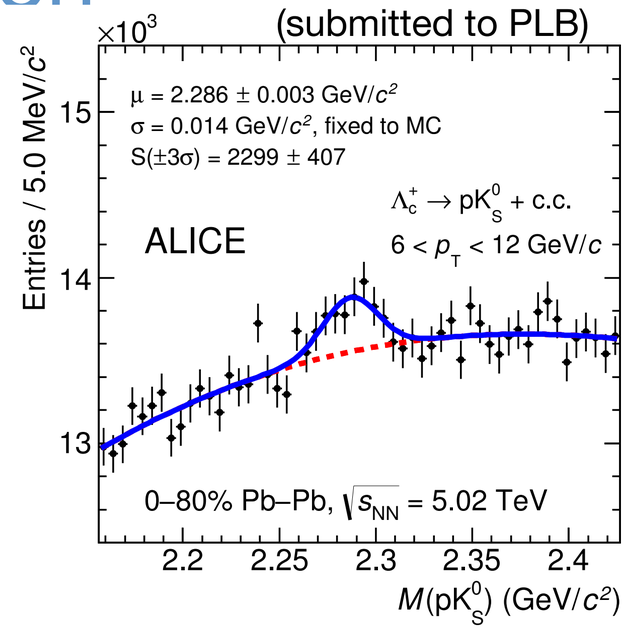


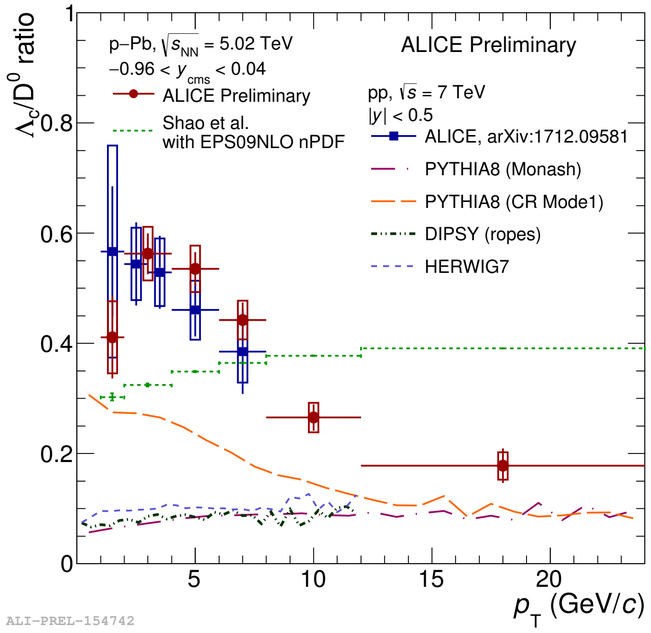
E. Meninno, Thu, 11h05

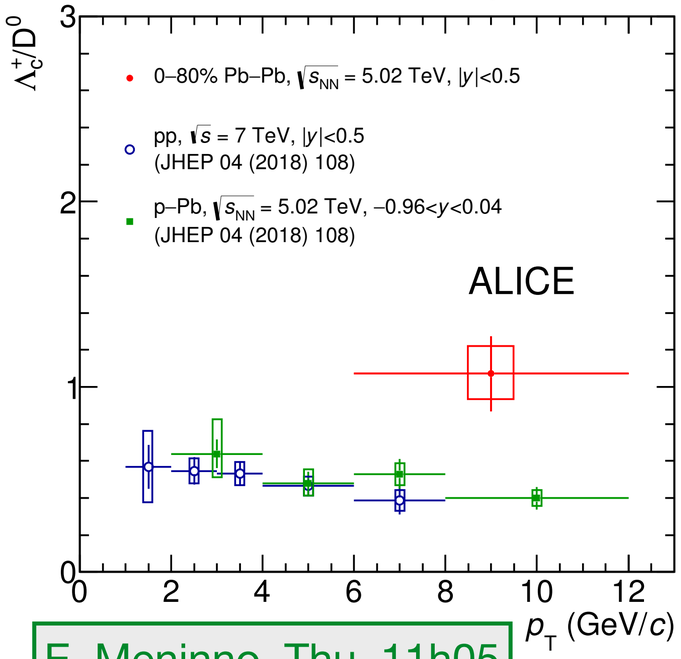
Charm Baryon Production

- **Pb–Pb: indication of Λ_c/D larger than in pp**
  - suggests coalescence contributes to hadronisation in Pb–Pb
- **pp: Λ_c (and Ξ_c) productions higher than expected (based on e^+e^- data from LEP)**
  - p–Pb: no significant difference to pp for Λ_c/D
  - **impact on total charm cross section estimates**

ALICE, arXiv:1809.10922 (submitted to PLB)





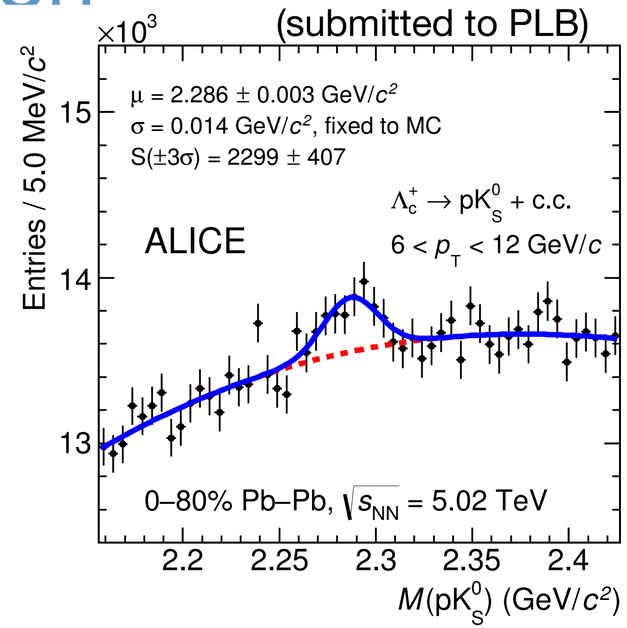


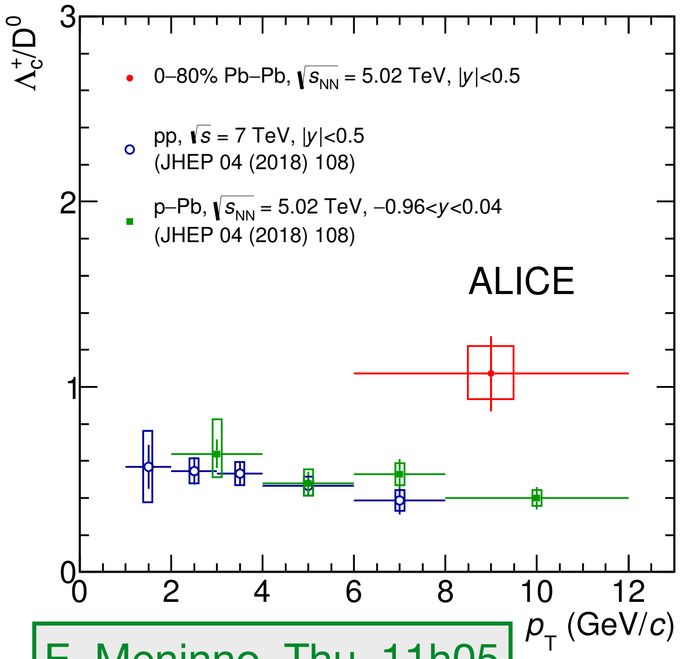
E. Meninno, Thu, 11h05

Charm Baryon Production

- **Pb–Pb: indication of Λ_c/D larger than in pp**
  - suggests coalescence contributes to hadronisation in Pb–Pb
- **pp: Λ_c (and Ξ_c) productions higher than expected (based on e^+e^- data from LEP)**
  - p–Pb: no significant difference to pp for Λ_c/D
  - **impact on total charm cross section estimates**
  - new pp data at $\sqrt{s}$ = 5 TeV with improved precision
  - similar effect as observed for light hadrons

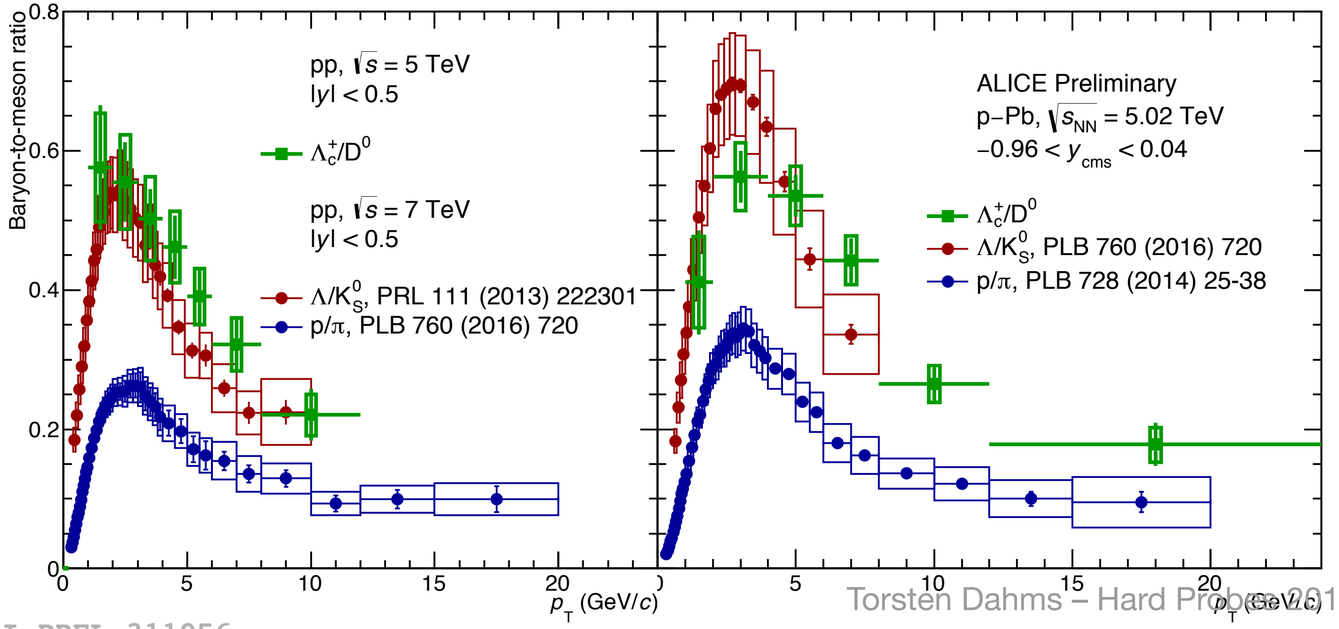
ALICE, arXiv:1809.10922 (submitted to PLB)





E. Meninno, Thu, 11h05

New reference!
Run-2 pp at $\sqrt{s}$ = 5 TeV

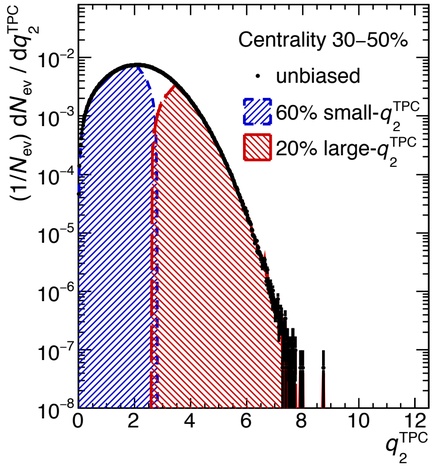


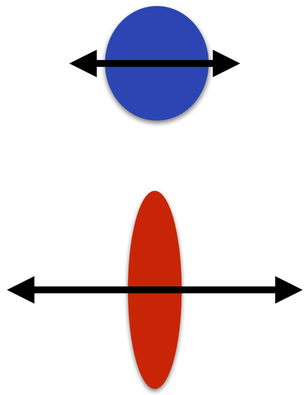
ALI-PREL-311056

D Mesons & Event-Shape-Engineering

- ESE to distinguish different initial state geometries for same impact parameter
  - second-harmonic reduced flow vector

$$q_2 = |\overrightarrow{Q_2}|/\sqrt{M}, \quad \overrightarrow{Q_2} = \sum_{j=1}^{M} e^{i2\phi_j}$$



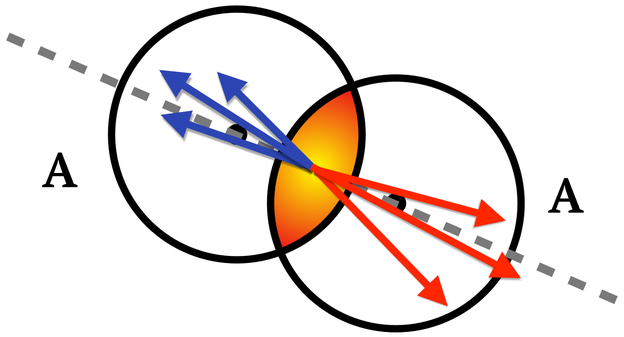


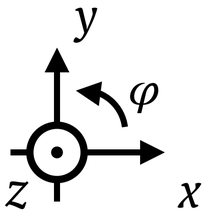
60% smallest q_2^{TPC}

$\langle v_2 \rangle_{\text{small}-q_2} < \langle v_2 \rangle_{\text{unb}}$

20% largest q_2^{TPC}

$\langle v_2 \rangle_{\text{large}-q_2} > \langle v_2 \rangle_{\text{unb}}$





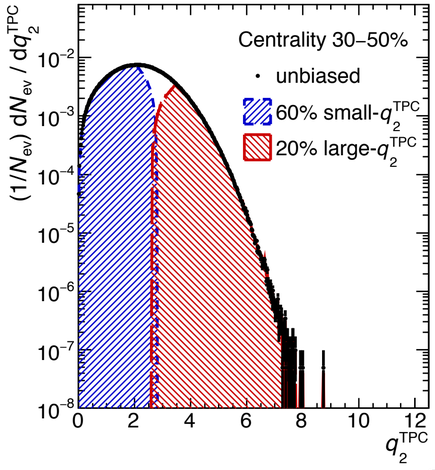
Reaction plane Ψ_{RP}

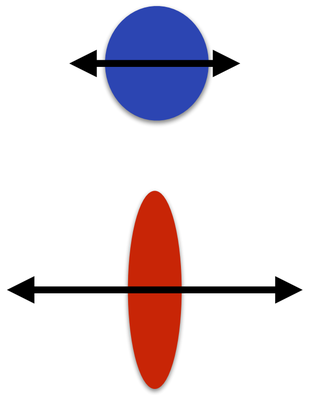
F. Grosa, Tue, 11h25

D Mesons & Event-Shape-Engineering

- ESE to distinguish different initial state geometries for same impact parameter
  - second-harmonic reduced flow vector

$$q_2 = |\overrightarrow{Q_2}|/\sqrt{M}, \quad \overrightarrow{Q_2} = \sum_{j=1}^{M} e^{i2\phi_j}$$





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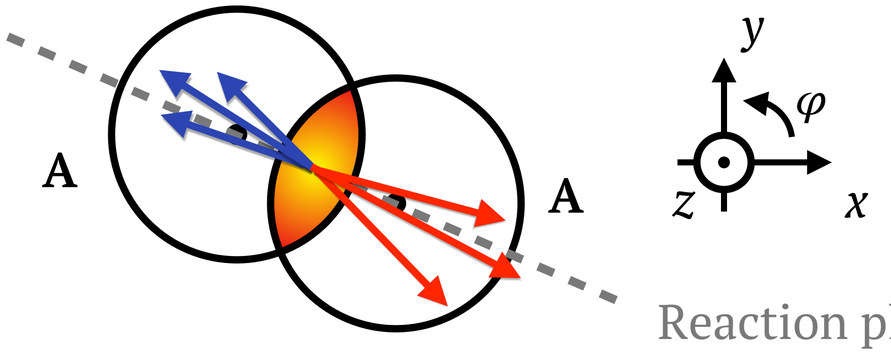
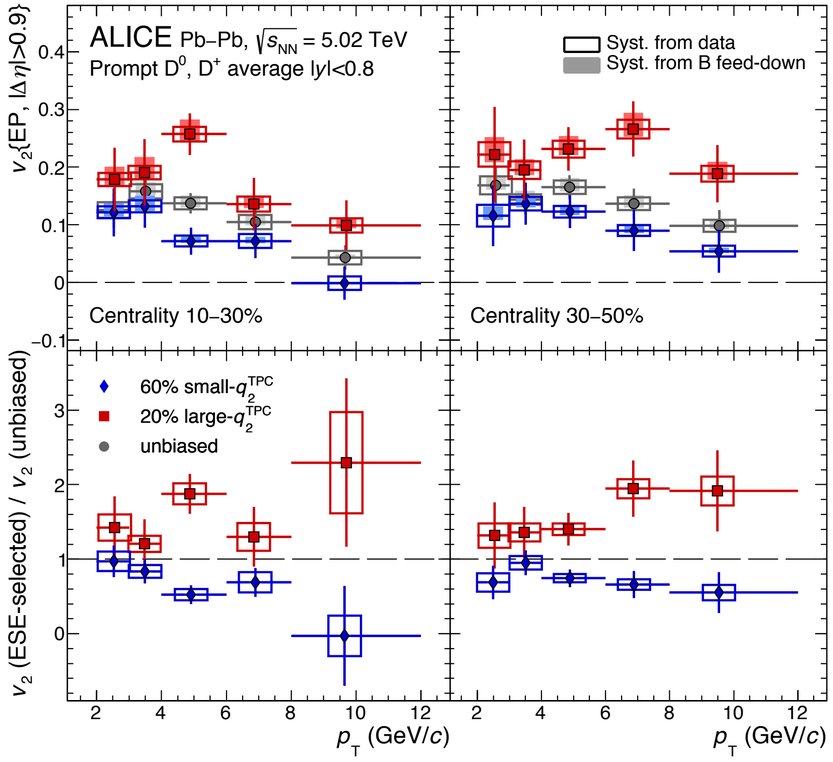




- **Ordering of D v_2 with q_2 in Pb–Pb at $\sqrt{s_{NN}}$ = 5 TeV heavy flavour v_2 follows shape fluctuations**

F. Grosa, Tue, 11h25

ALICE, arXiv:1809.09371
(submitted to JHEP)

D-Meson Directed Flow

“International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions”

D-Meson Directed Flow

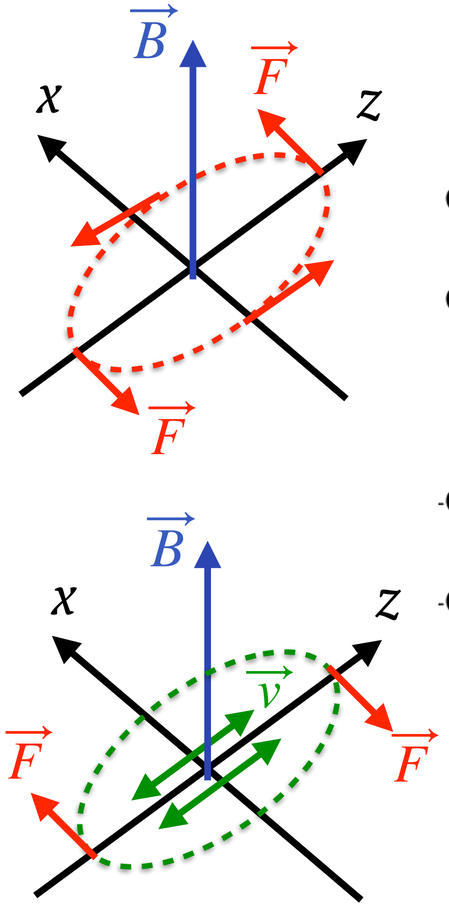
“International Conference on Hard Probes of Electromagnetism in High-Energy Nuclear Collisions”

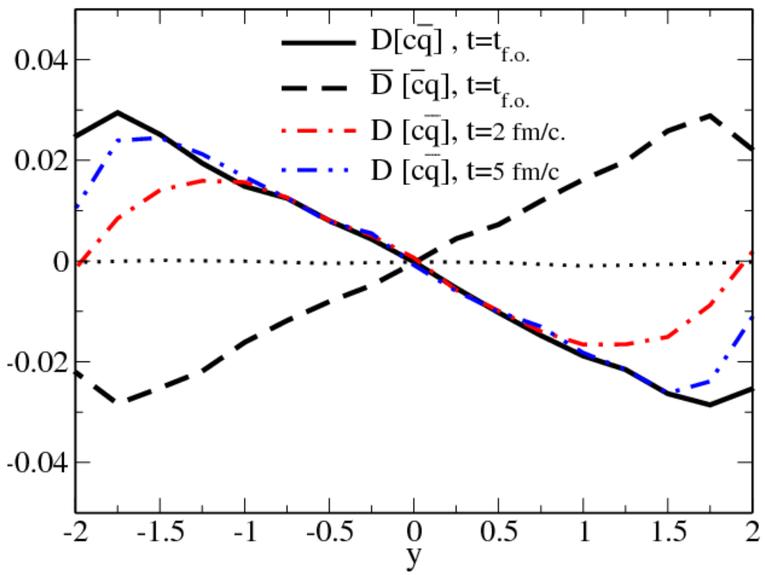
D-Meson Directed Flow

"International Conference on Hard Probes of Electromagnetism in High-Energy Nuclear Collisions"

- Strong magnetic field created by passing charged nuclei
- Charm quarks produced at time of max. B field
- Charm quark relaxation time comparable to QGP life time
  - much larger than that of light quarks

- ***B* field induces C-odd directed flow v_1**
- **Two effects: *B* and *E* fields with opposite signs**
  - time order of maxima of *B* and *E* is important
  - prediction: *B* field effect dominates



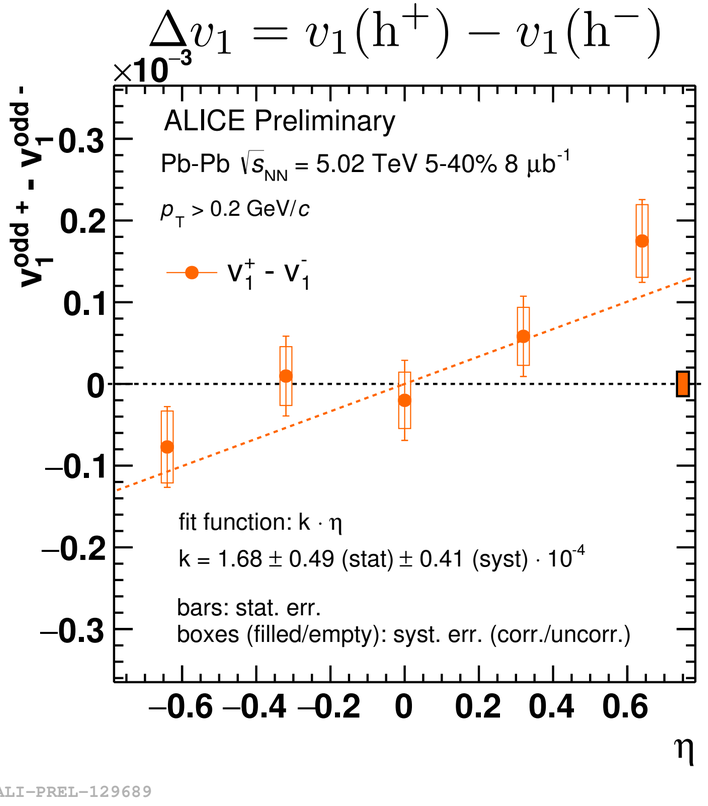


S. Das et al., PLB 768 (2017) 260

D-Meson Directed Flow

- Light hadrons: observe positive slope of Δv_1

F. Grosa, Tue, 11h25



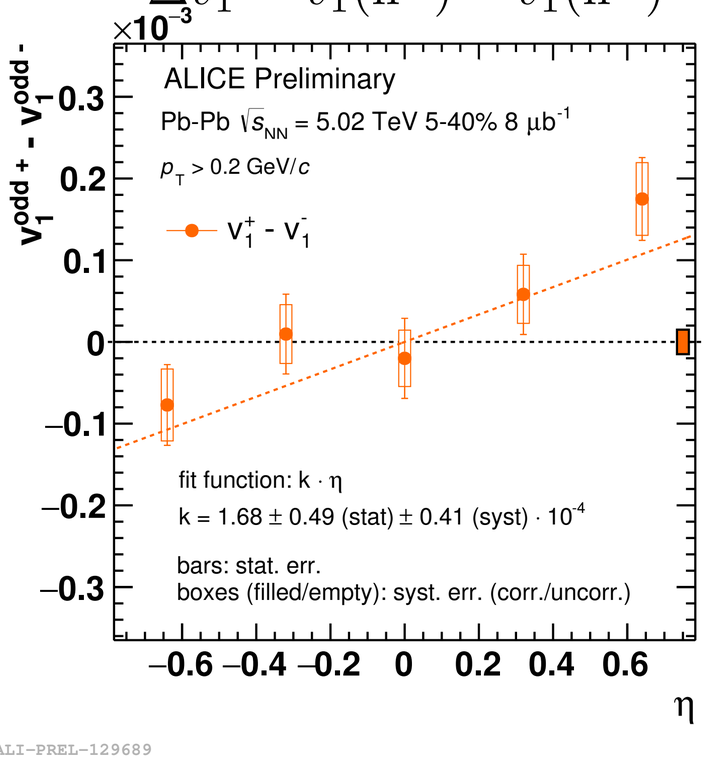
D-Meson Directed Flow

- Light hadrons: observe positive slope of Δv_1
- **Indication of positive slope of Δv_1 with rapidity (significance of 2.7σ)**

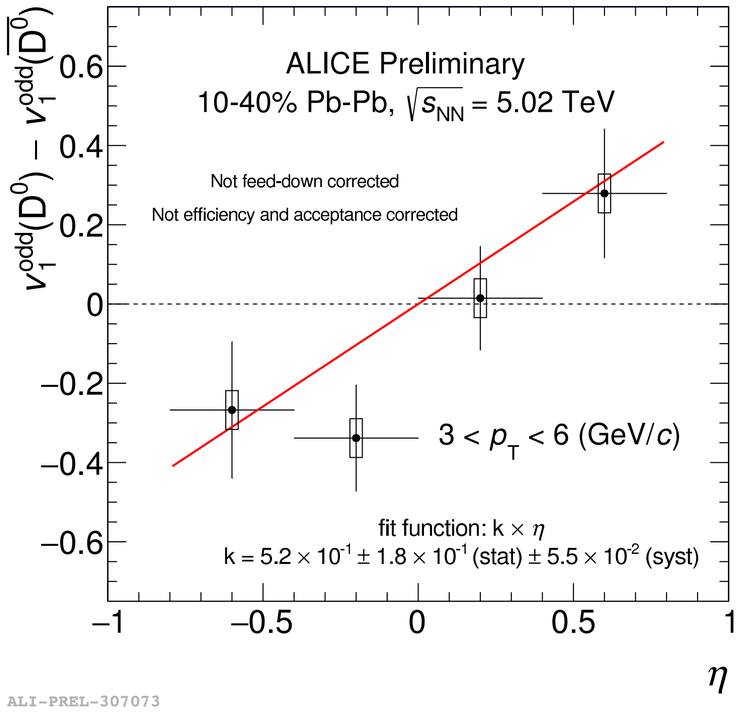
F. Grosa, Tue, 11h25

New result!

$$\Delta v_1 = v_1(\mathrm{h}^+) - v_1(\mathrm{h}^-)$$



$$\Delta v_1 = v_1(\mathrm{D}^0) - v_1(\overline{\mathrm{D}}^0)$$

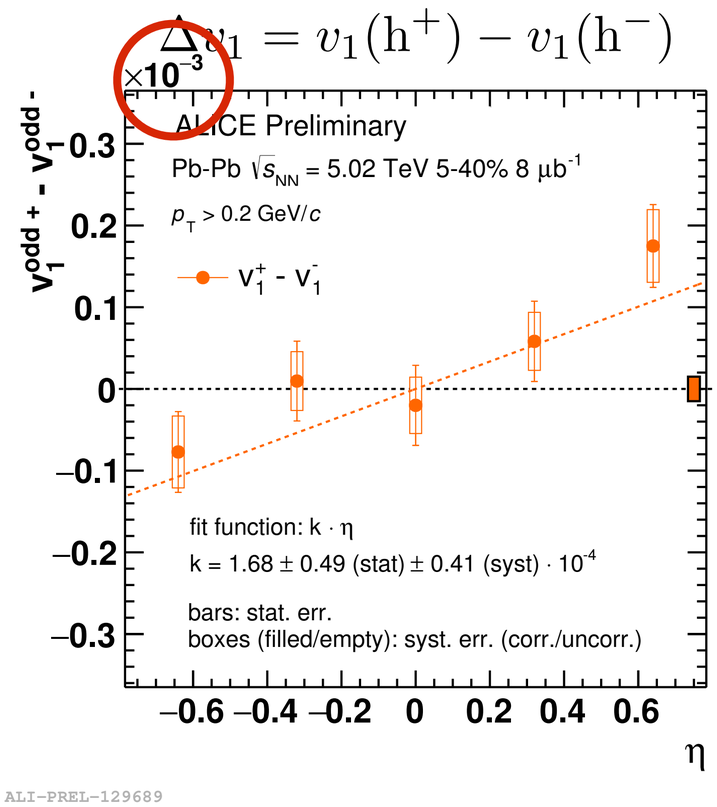


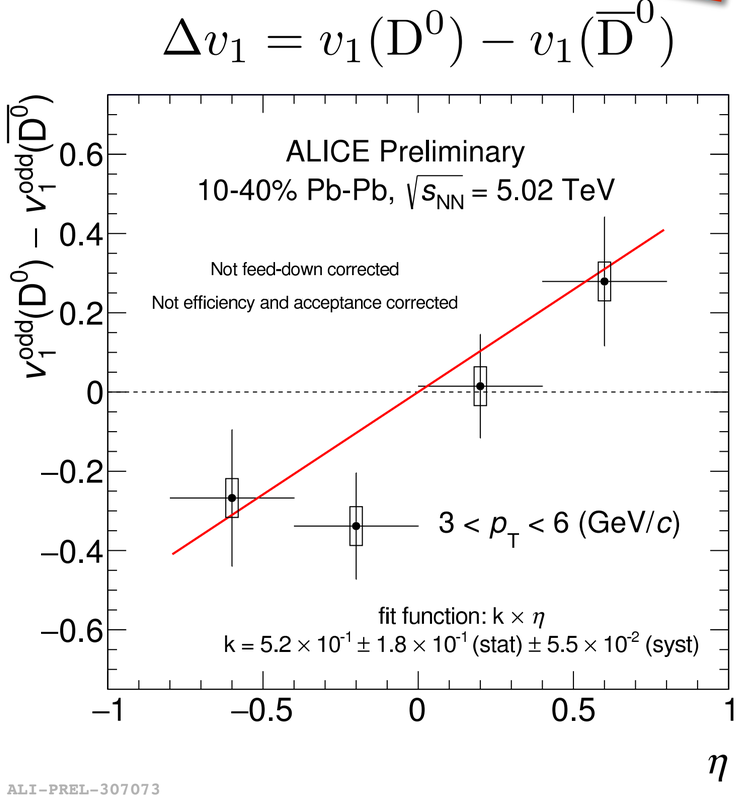
D-Meson Directed Flow

- Light hadrons: observe positive slope of Δv_1
- **Indication of positive slope of Δv_1 with rapidity (significance of 2.7σ)**
- Same trend as for light hadrons but $O(10^3)\times$ stronger

F. Grosa, Tue, 11h25

New result!





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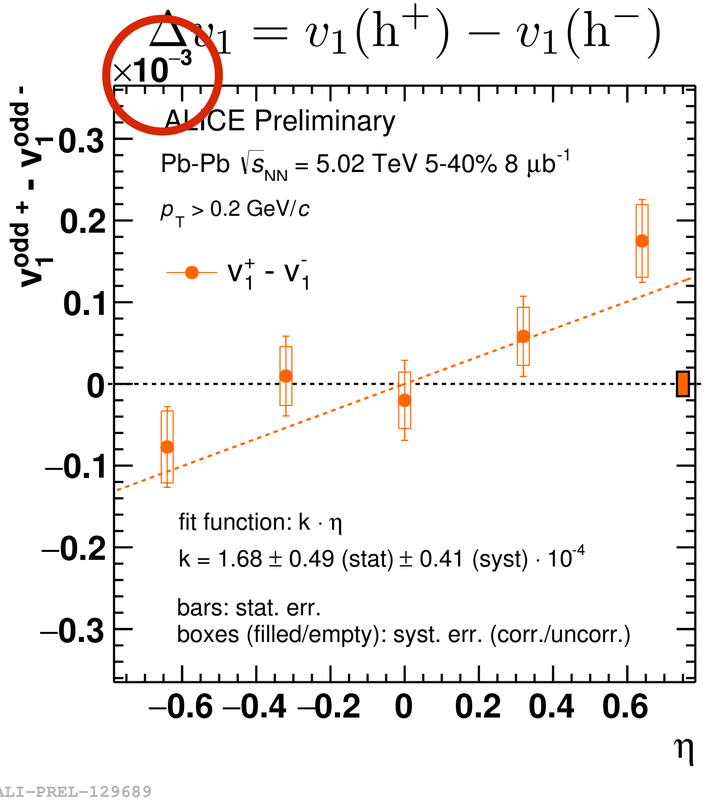
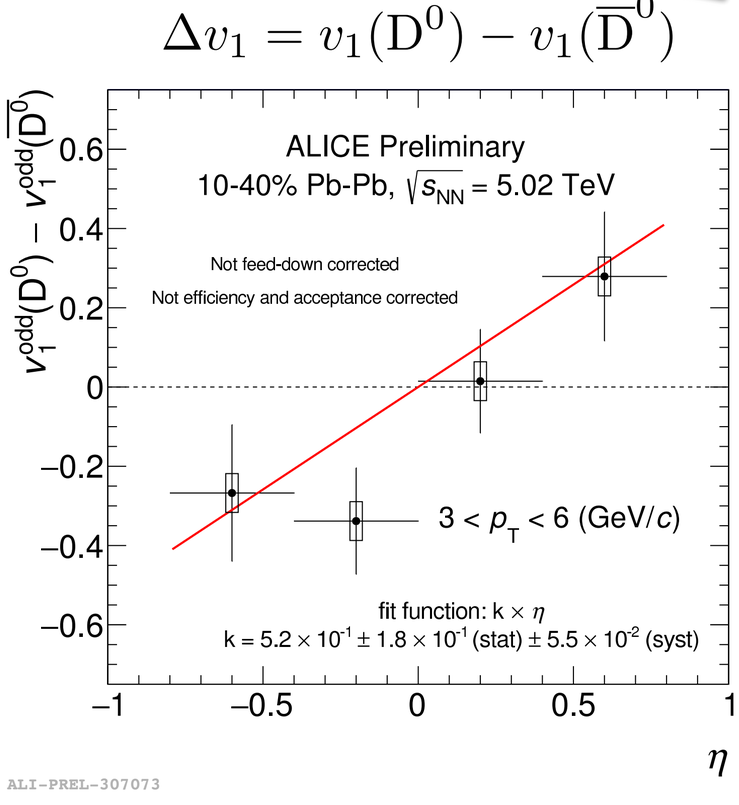
F. Grosa, Tue, 11h25

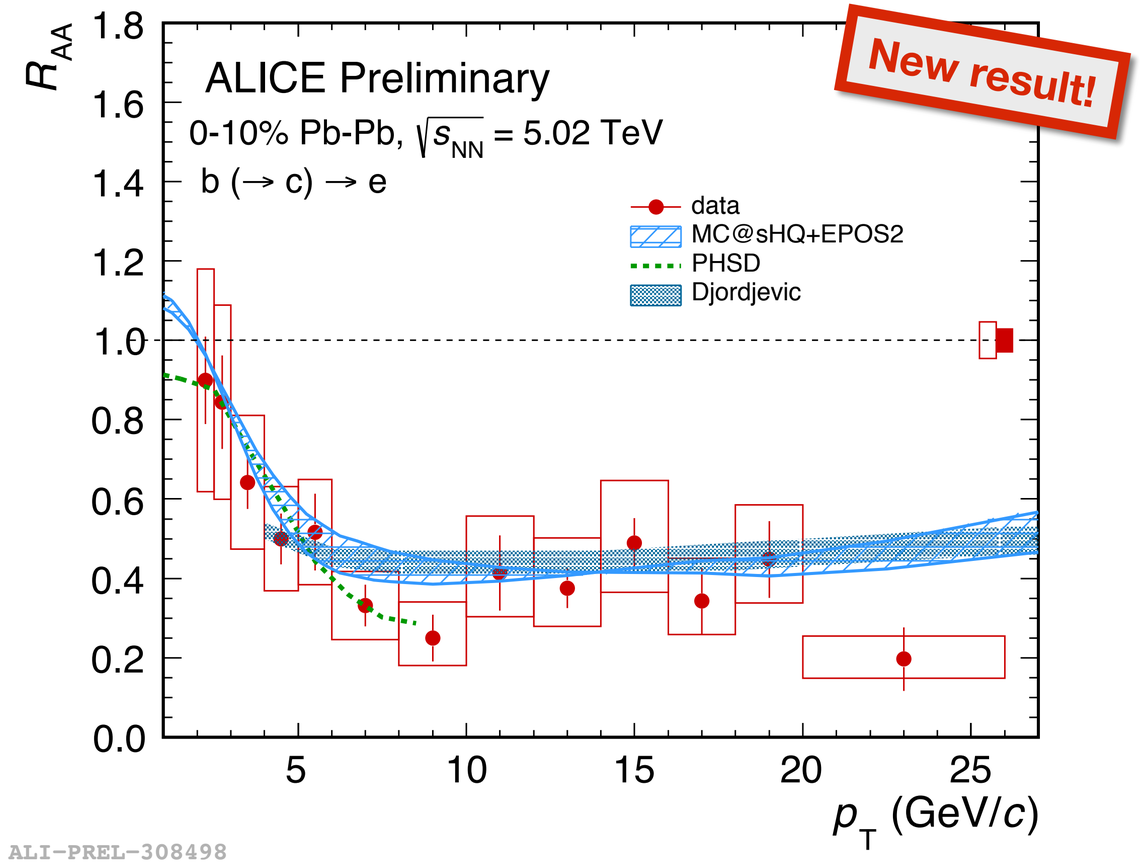
New result!

- **Opposite from theory expectation → is charm produced when induced *E* field dominates over *B* field?**
- More data this year will help to confirm effect





Beauty Suppression in Pb–Pb



Z. Zhang, Tue, 15h

- **New: electrons from beauty decays out to p_T = 26 GeV/c**
  - separation from light and charm hadrons decays via template fit of impact parameter
- Suppression well described by models that include mass dependent energy loss

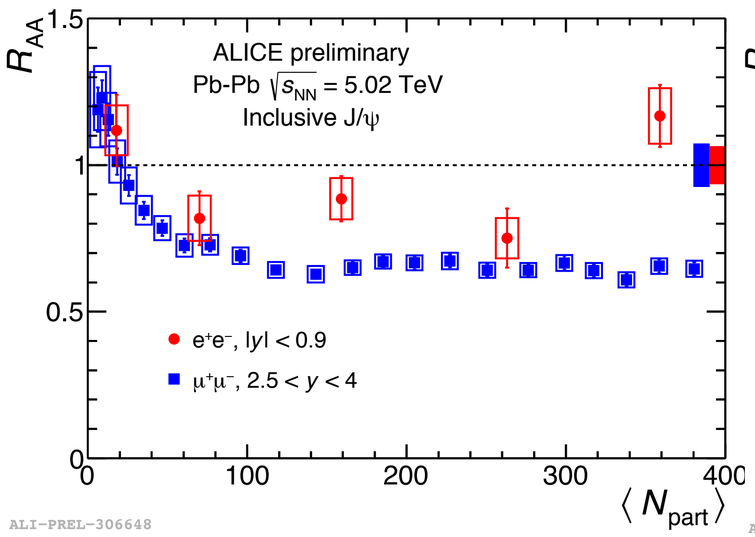
Quarkonia

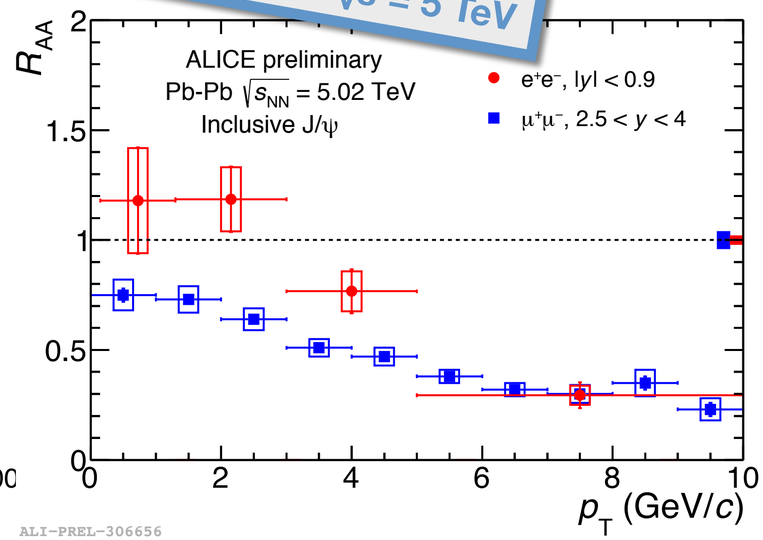
J/ψ R_{AA} and Elliptic Flow

- Updated R_{AA} at midrapidity based on measured pp reference at $\sqrt{s}$ = 5 TeV

- **Clear signs of (re)generation:**
  - in central collisions: J/ψ at midrapidity less suppressed than at forward rapidity
  - low-p_T J/ψ less suppressed than high p_T

New reference!
Run-2 pp at $\sqrt{s}$ = 5 TeV





ALICE, PRL 119 (2017) 242301

M. Köhler, Wed, 9h20

J/ψ R_{AA} and Elliptic Flow

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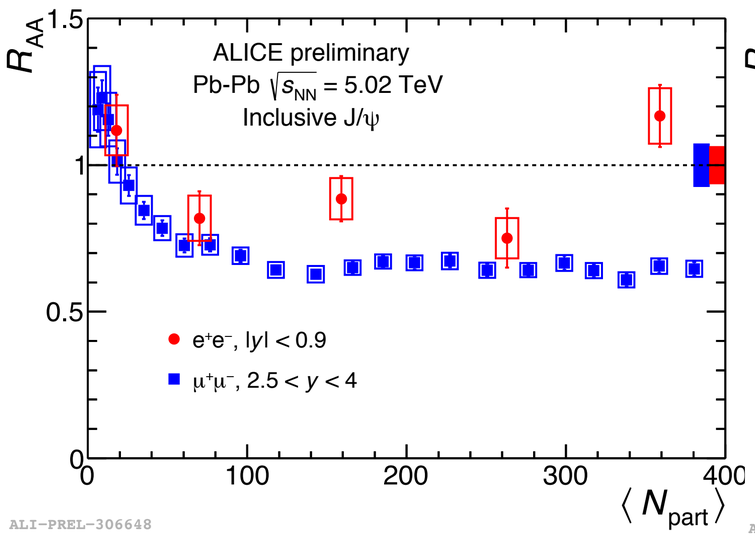
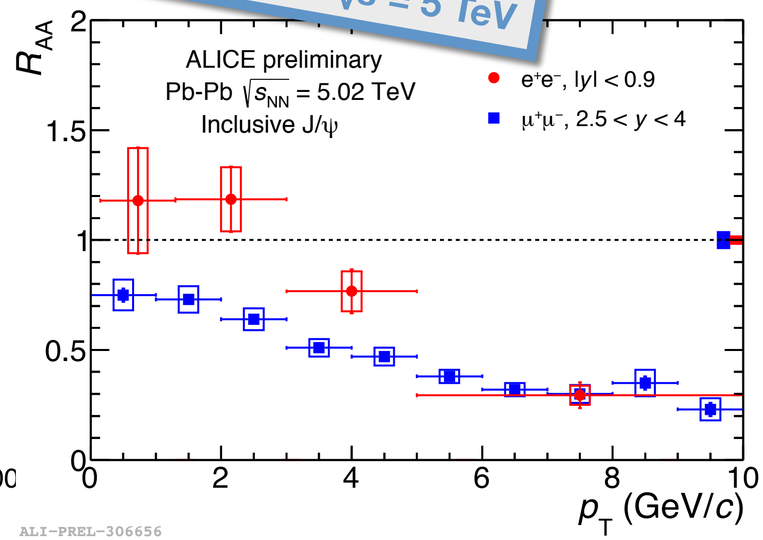
Run-2 pp at $\sqrt{s}$ = 5 TeV





- **Clear signs of (re)generation:**
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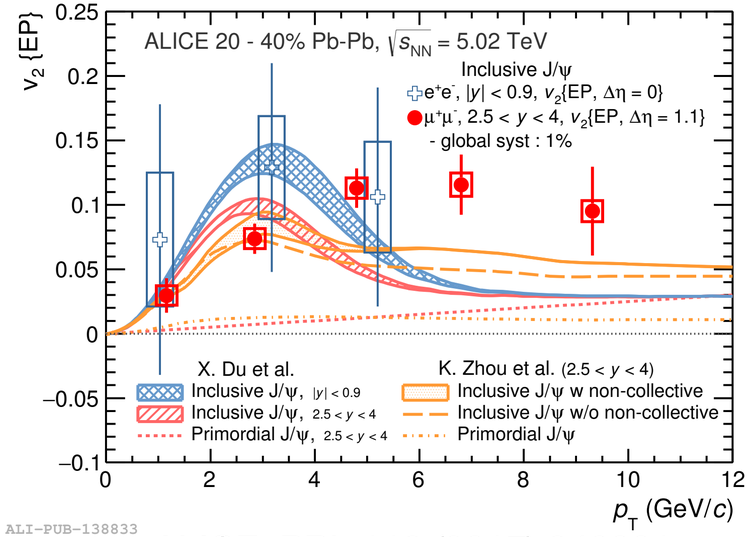
  - low-p_T J/ψ less suppressed than high p_T

- **Sizeable J/ψ v_2**



ALICE, PRL 119 (2017) 242301

M. Köhler, Wed, 9h20

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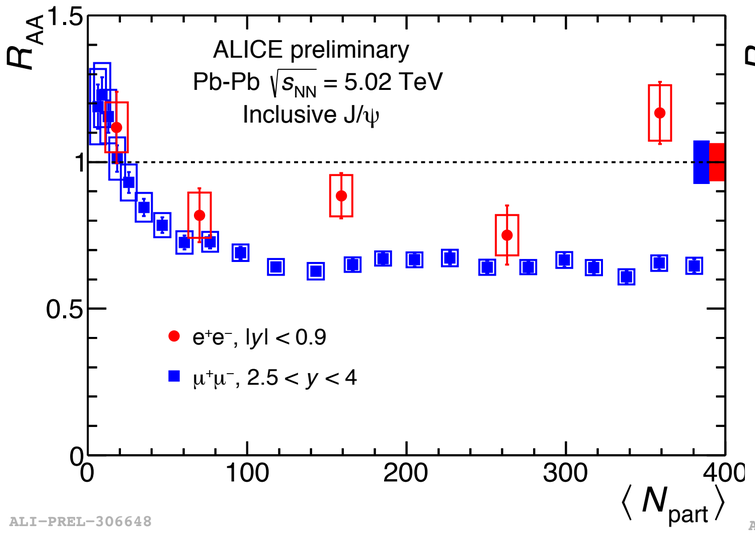
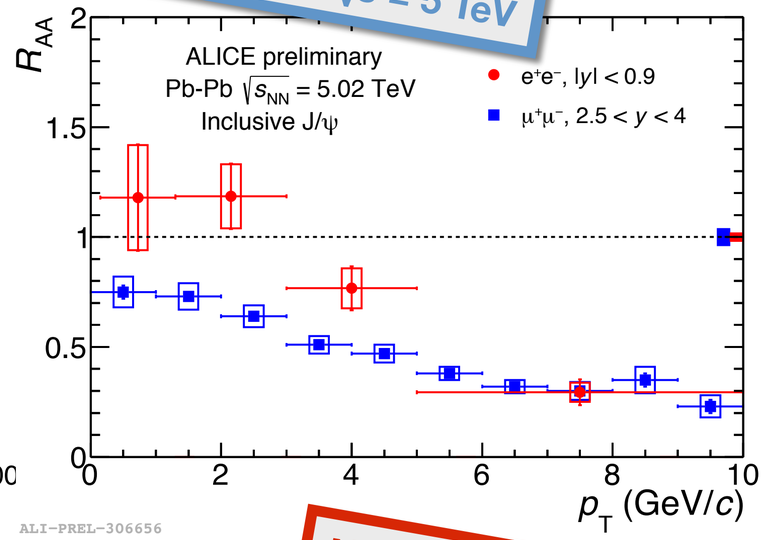
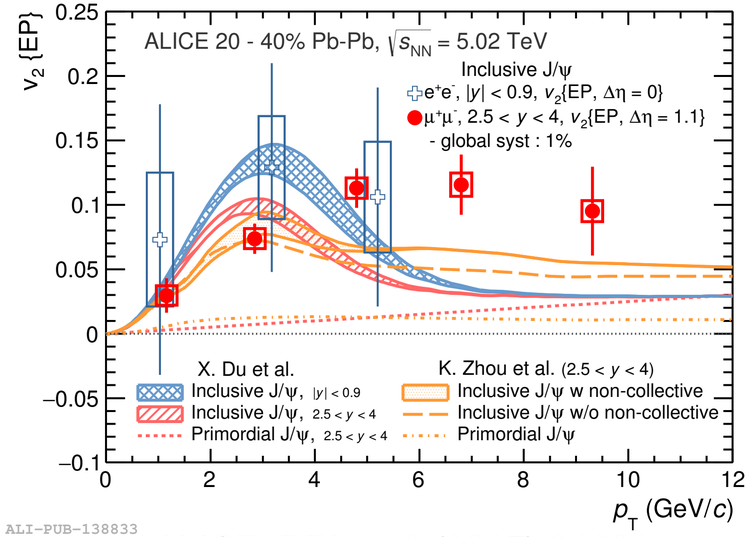


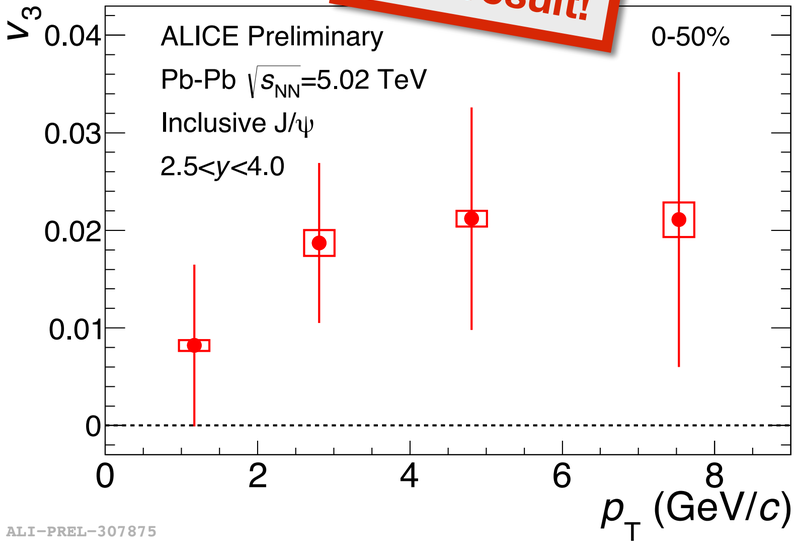
New reference! Run-2 pp at $\sqrt{s}$ = 5 TeV



- **Sizeable J/ψ v_2**
- **First evidence for v_3 > 0!**
  - p_T-integrated significance 3.7σ
  - ordering: v_3/v_2(J/ψ) < v_3/v_2(h±)
- Further corroborates the significant contribution of (re)generation as source of J/ψ production in Pb–Pb



New result!



ALICE, PRL 119 (2017) 242301

M. Köhler, Wed, 9h20

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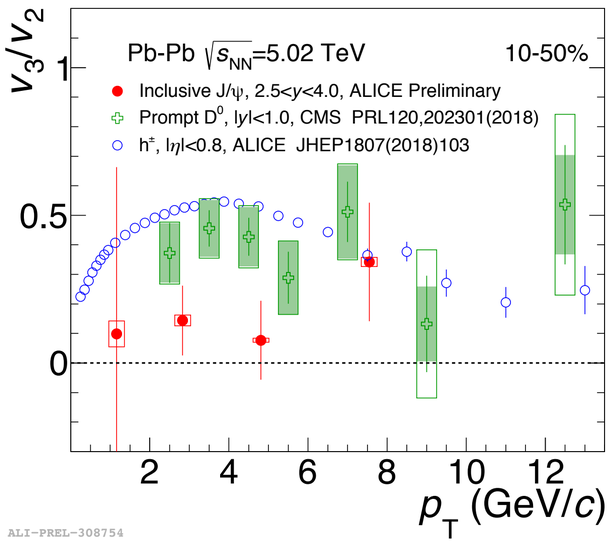

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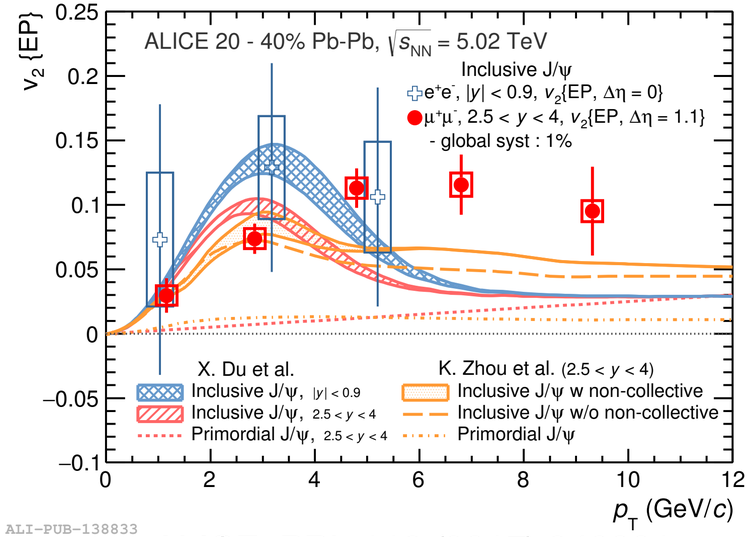
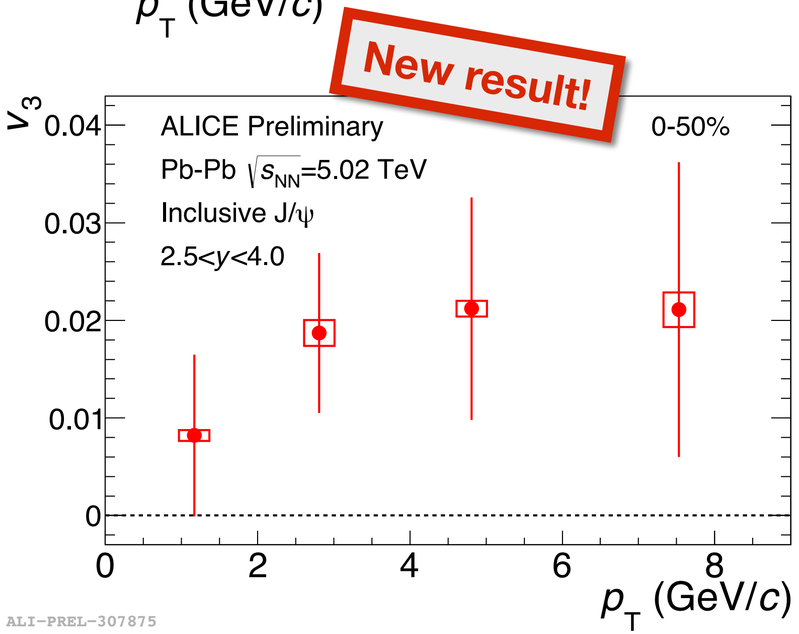
- Further corroborates the significant contribution of (re)generation as source of J/ψ production in Pb–Pb



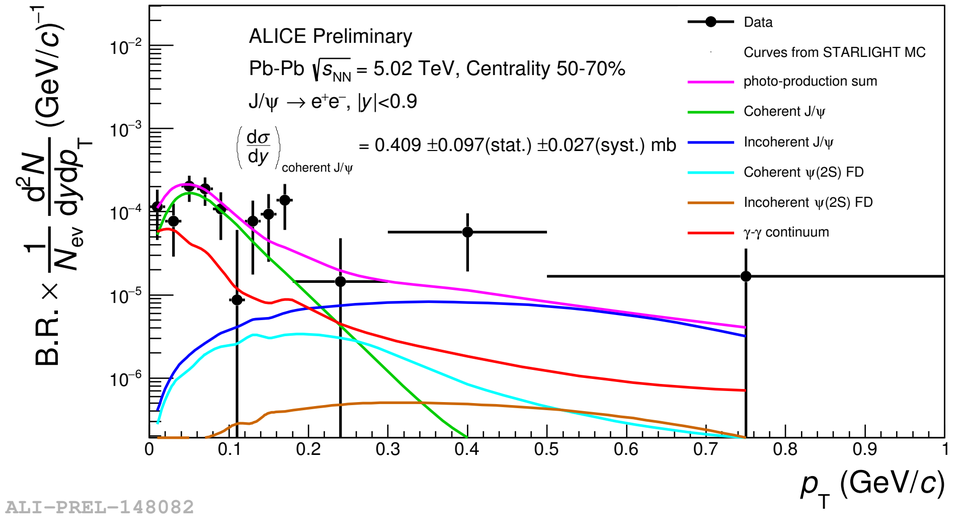


ALICE, PRL 119 (2017) 242301

M. Köhler, Wed, 9h20

Photoproduction of J/ψ in peripheral Pb–Pb collisions

- Low-p_T excess of J/ψ in peripheral Pb–Pb collisions with nuclear overlap, so far seen at
  - forward rapidity at $\sqrt{s_{NN}}$ = 2.76 TeV
  - midrapidity at $\sqrt{s_{NN}}$ = 5 TeV
  - consistent with calculations of J/ψ photoproduction



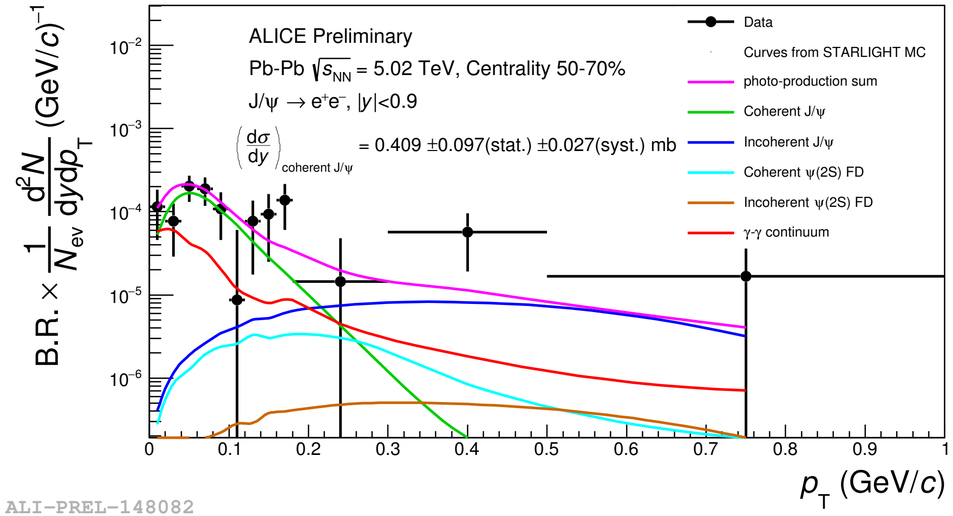
L. Massacrier, Tue, 9h40

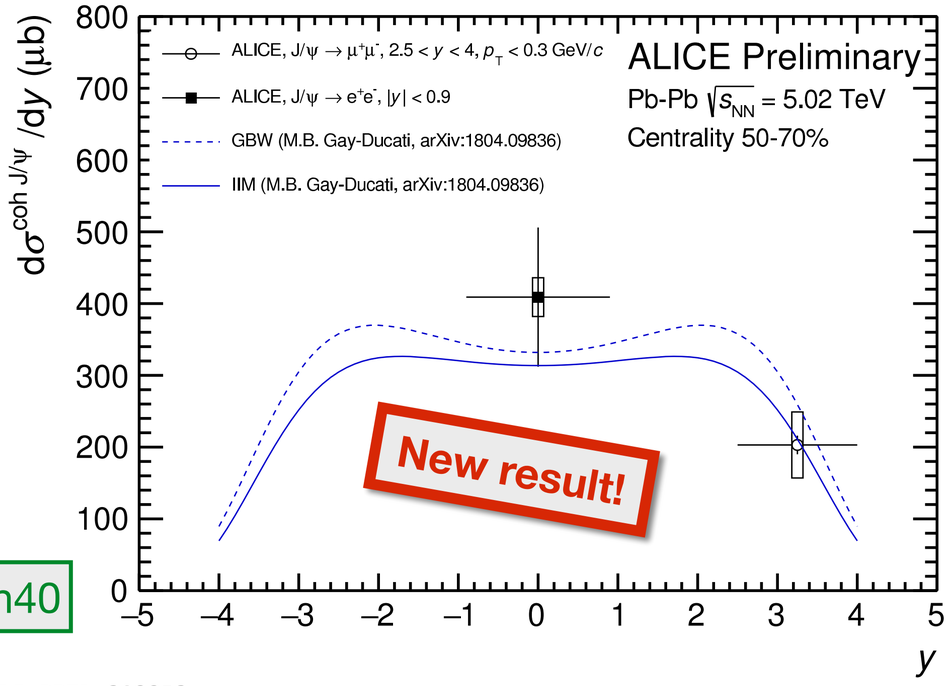
Photoproduction of J/ψ in peripheral Pb–Pb collisions

- Low-p_T excess of J/ψ in peripheral Pb–Pb collisions with nuclear overlap, so far seen at
  - forward rapidity at $\sqrt{s_{NN}}$ = 2.76 TeV
  - midrapidity at $\sqrt{s_{NN}}$ = 5 TeV
  - consistent with calculations of J/ψ photoproduction

- **New results at forward rapidity at $\sqrt{s_{NN}}$ = 5 TeV**
  - also described by model calculations of photoproduction

- **A new probe for colour screening in QGP?**
  - formed very early in the collision
  - passes through the QGP
  - (re)generation insignificant at very low p_T

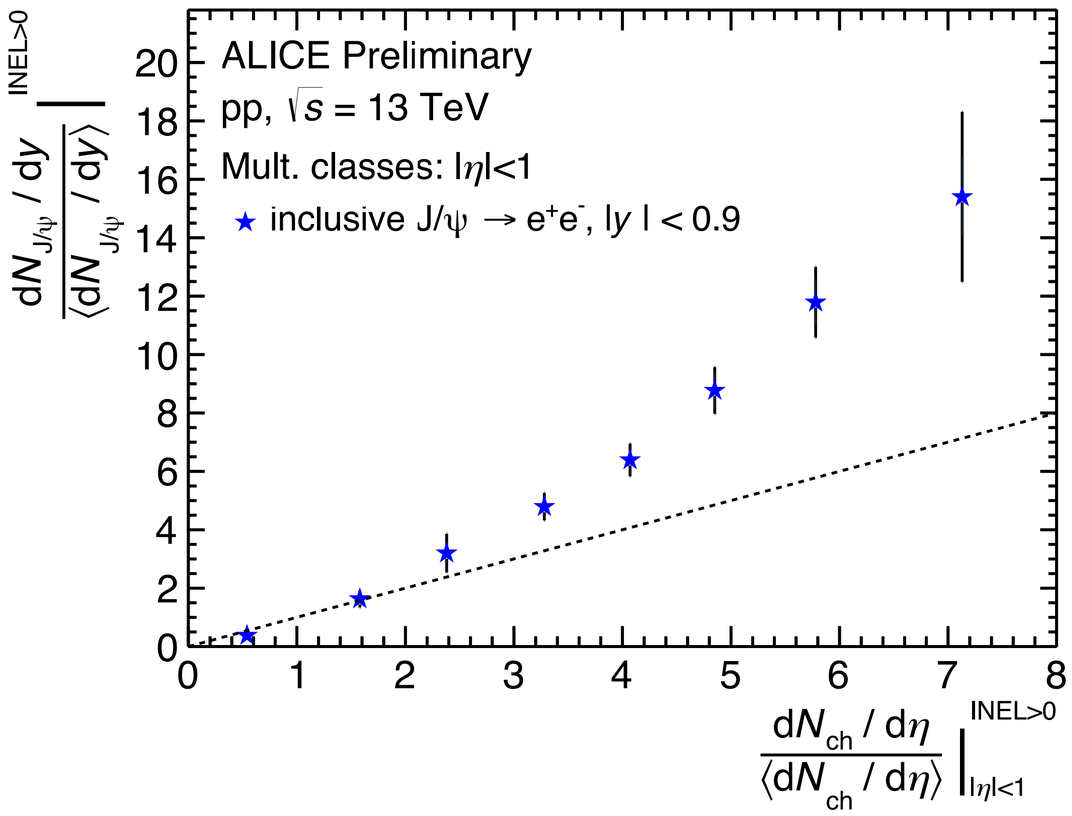


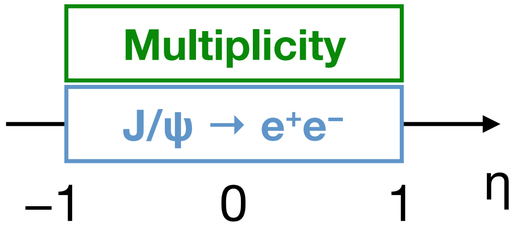


L. Massacrier, Tue, 9h40

Quarkonia in small systems

- **Faster than linear scaling with multiplicity for J/ψ at midrapidity in pp at √s = 13 TeV**
  - i.e. w/o rapidity gap between signal and multiplicity estimator





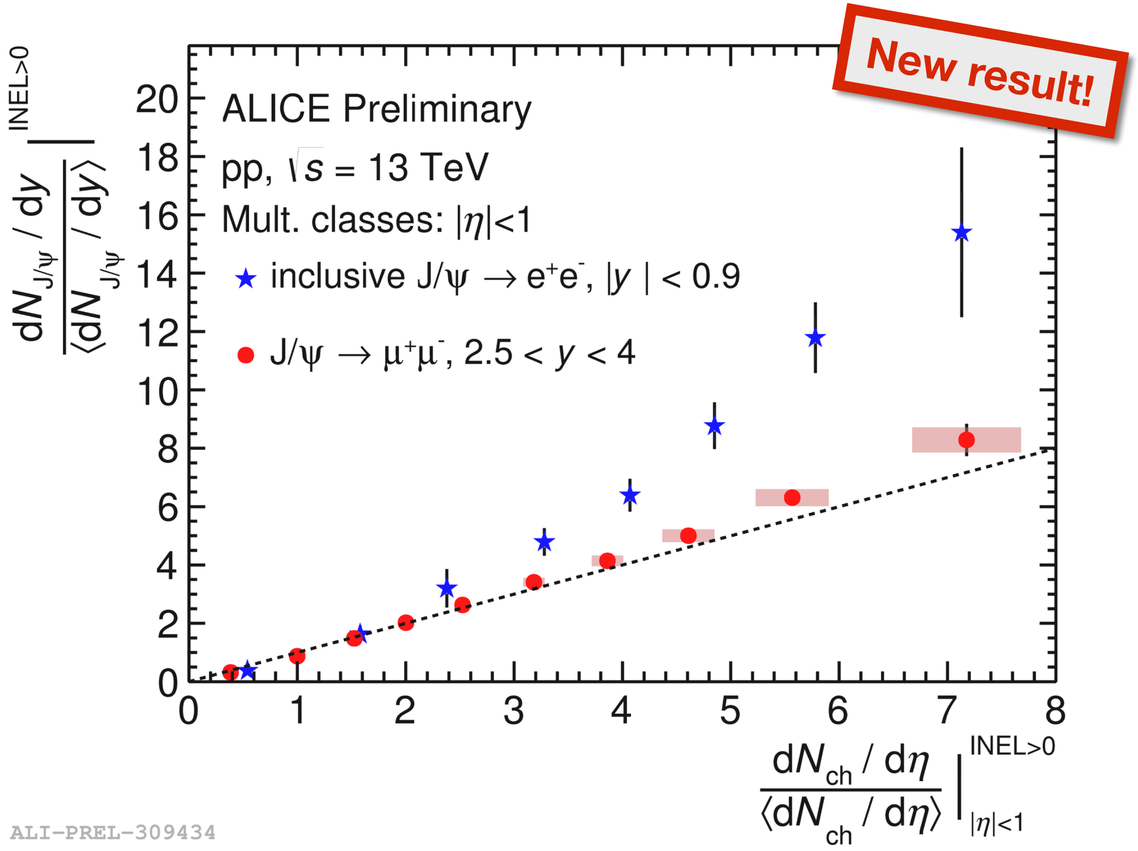
D. Thakur, Tue, 16h45

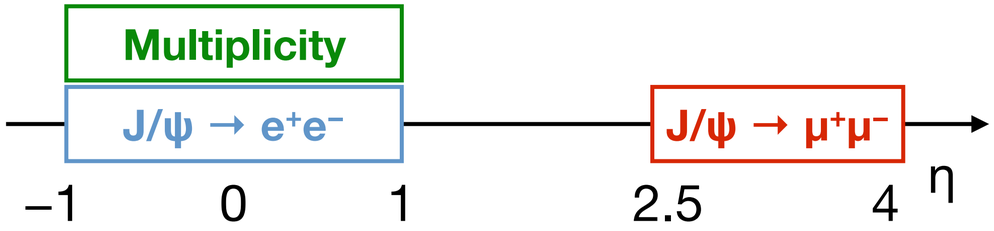
Quarkonia in small systems

- **Faster than linear scaling with multiplicity for J/ψ at midrapidity in pp at √s = 13 TeV**
  - i.e. w/o rapidity gap between signal and multiplicity estimator

- **Introducing a rapidity gap: significantly reduces deviation from linear multiplicity scaling**

- **Sign of autocorrelation (e.g. jet bias) w/o rapidity gap between signal and multiplicity estimator**





D. Thakur, Tue, 16h45

Quarkonia in small systems

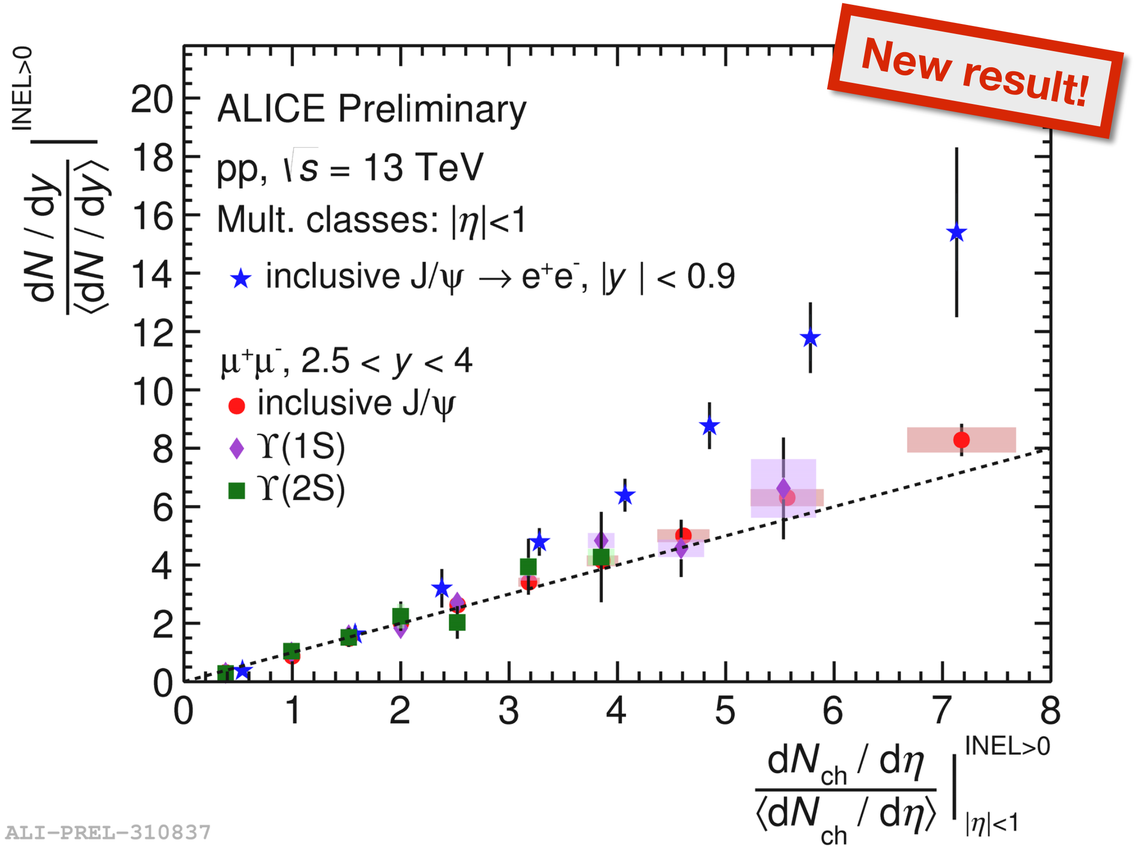
- **Faster than linear scaling with multiplicity for J/ψ at midrapidity in pp at √s = 13 TeV**
  - i.e. w/o rapidity gap between signal and multiplicity estimator

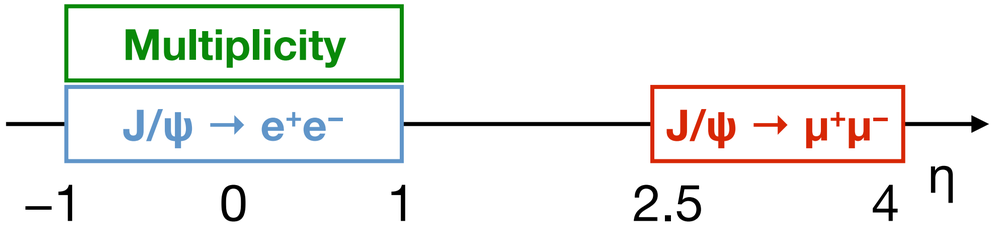
- **Introducing a rapidity gap: significantly reduces deviation from linear multiplicity scaling**

- **Sign of autocorrelation (e.g. jet bias) w/o rapidity gap between signal and multiplicity estimator**

- Also measured ϒ(1S) and ϒ(2S) vs multiplicity

D. Thakur, Tue, 16h45

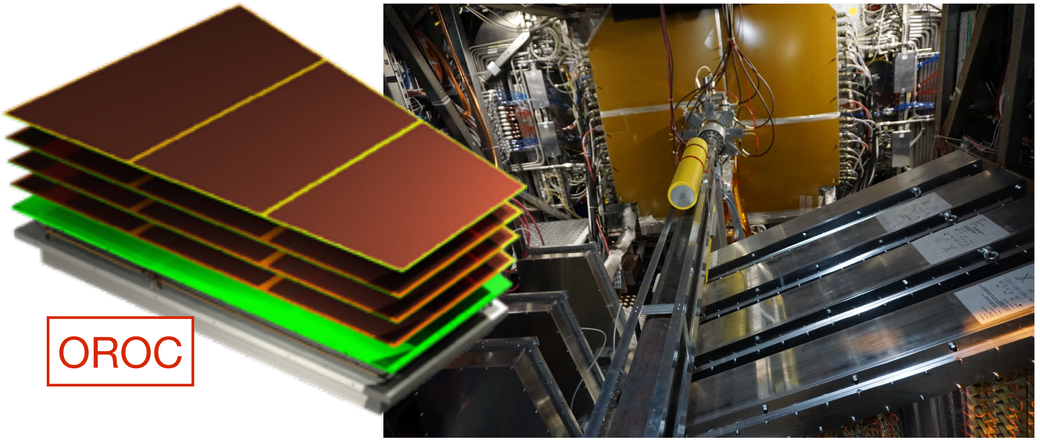




Upgrades

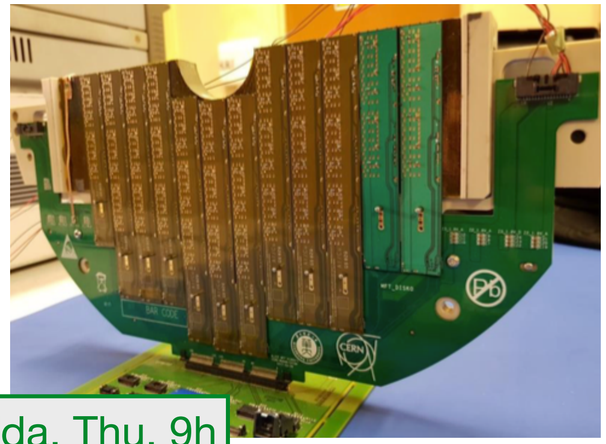
ALICE Upgrades: Run-3 and beyond

GEM-TPC

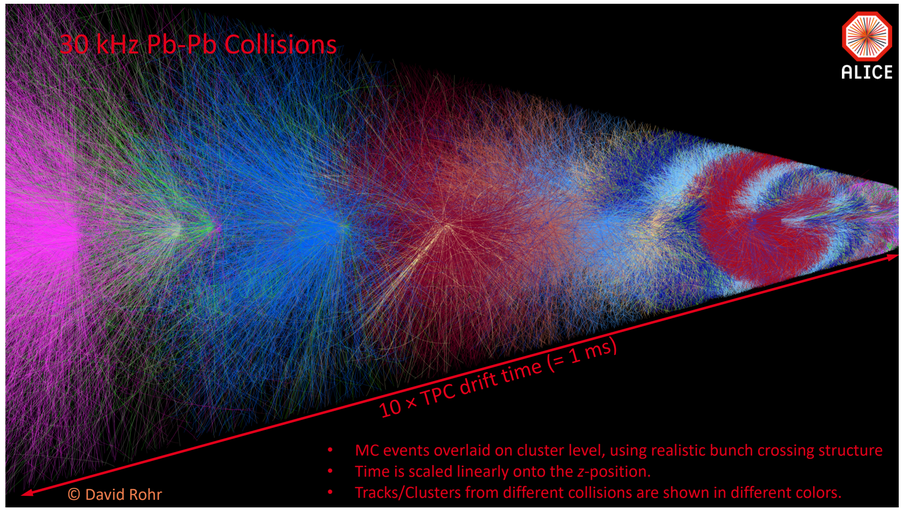


ITS

MFT



C. Bedda, Thu, 9h



- Major detector upgrades during the LHC Long Shutdown 2
  - **Focus on low-p_T and non-triggerable probes, e.g. low-mass dielectrons → continuous readout of 50 kHz Pb–Pb collisions: TPC, Muon arm, Fast Interaction Trigger**
  - **Improve low-p_T tracking and vertexing for e.g. Λ_c: Inner Tracking System (ALPIDE: pixels based on CMOS MAPS technology)**
  - **Secondary-vertex reconstruction at forward rapidity: Muon Forward Tracker**
- And beyond: FOCAL…

Th. Peitzmann, Tue, 11h05

ALICE Talks

Tuesday

1. **Jack Otwinowski:** “ALICE results on the production of charged particles in pp, p-Pb, Xe-Xe and Pb-Pb collisions at the LHC”, Tue, 9h00
2. **Laure Massacrier:** “Coherent J/psi photo-production in Pb–Pb collisions with nuclear overlap with ALICE at the LHC”, Tue, 9h40
3. **Dmitry Peresunko:** “Neutral-meson production in ALICE”, Tue, 10h45
4. **Thomas Peitzmann:** “Forward photon measurements with ALICE at the LHC as a probe for low-x gluons”, Tue, 11h05
5. **Fabrizio Grosa:** “Measurement of D-meson nuclear modification factor and flow in Pb-Pb collisions with ALICE at the LHC”, Tue, 11h25
6. **Shreyasi Acharya:** “Event-multiplicity and event-shape dependence of open heavy-flavour production in pp collisions with ALICE at the LHC” Tue, 12h05
7. **Brennan Schaefer:** “Jet Associated Deuteron Production in pp collisions at 13 TeV with ALICE at the LHC”, Tue, 12h05
8. **Zuman Zhang:** “Measurements of heavy-flavour decay leptons production in Pb–Pb and Xe–Xe collisions with ALICE at the LHC”, Tue, 15h00
9. **Antoine Lardeux:** “ALICE results on quarkonium production in p-Pb collisions”, Tue, 15h40
10. **Miguel Arratia:** “Isolated photon + hadron and jet correlation in p–Pb and pp collisions with ALICE”, Tue, 16h25
11. **Dhananjaya Thakur:** “Quarkonium production as a function of charged particle multiplicity in pp and p-Pb collisions measured by ALICE at the LHC”, Tue, 16h45
12. **Cristina Terrevoli:** “Open-heavy-flavour production and elliptic flow in p–Pb collisions at the LHC with ALICE”, Tue, 17h05
13. **Jaime Norman:** “hadron+jet measurements in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE”, Tue, 17h25
14. **Hyeonjoong Kim:** “Using di-hadron correlations to investigate jet modifications in Pb–Pb collisions with ALICE”, Tue, 17h45

Wednesday

15. **Markus Köhler:** “Quarkonium production in Pb–Pb and Xe–Xe collisions with ALICE at the LHC”, Wed, 9h20
16. **Markus Fasel:** “Jet substructure measurements in pp collisions at $\sqrt{s}$ = 13 TeV with ALICE”, Wed, 9h40
17. **Amal Sarkar:** “Measuring electroweak boson production in p–Pb and Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE at LHC”, Wed, 9h40
18. **Nicolas Schmidt:** “Direct photon production and flow at low transverse momenta in pp, p–Pb and Pb–Pb collisions”, Wed, 10h00
19. **James Mulligan:** “Inclusive jet measurements in pp and Pb-Pb collisions with ALICE”, Wed, 11h05
20. **Alberto Caliva:** “Low-mass dilepton measurements with ALICE at the LHC”, Wed, 12h05
21. **Sandeep Dudi:** “Identified particle production in p-Pb collisions at 8.16 TeV with ALICE at the LHC”, Wed, 12h05

Thursday

22. **Cristina Bedda:** “Enhanced hard-probes measurements in the 2020s with the ALICE Upgrade”, Thu, 9h00
23. **Elisa Meninno:** “Charm baryon production in pp, p–Pb and Pb–Pb collisions with ALICE at the LHC”, Thu, 11h05
24. **Salvatore Aiola:** “Measurements of heavy-flavour correlations and jets with ALICE at the LHC”, Thu, 11h45
25. **Nima Zardoshti:** “Exploring the phase space of jet splittings at ALICE in pp and Pb–Pb collisions using jet shapes and grooming techniques”, Thu, 14h40

Posters

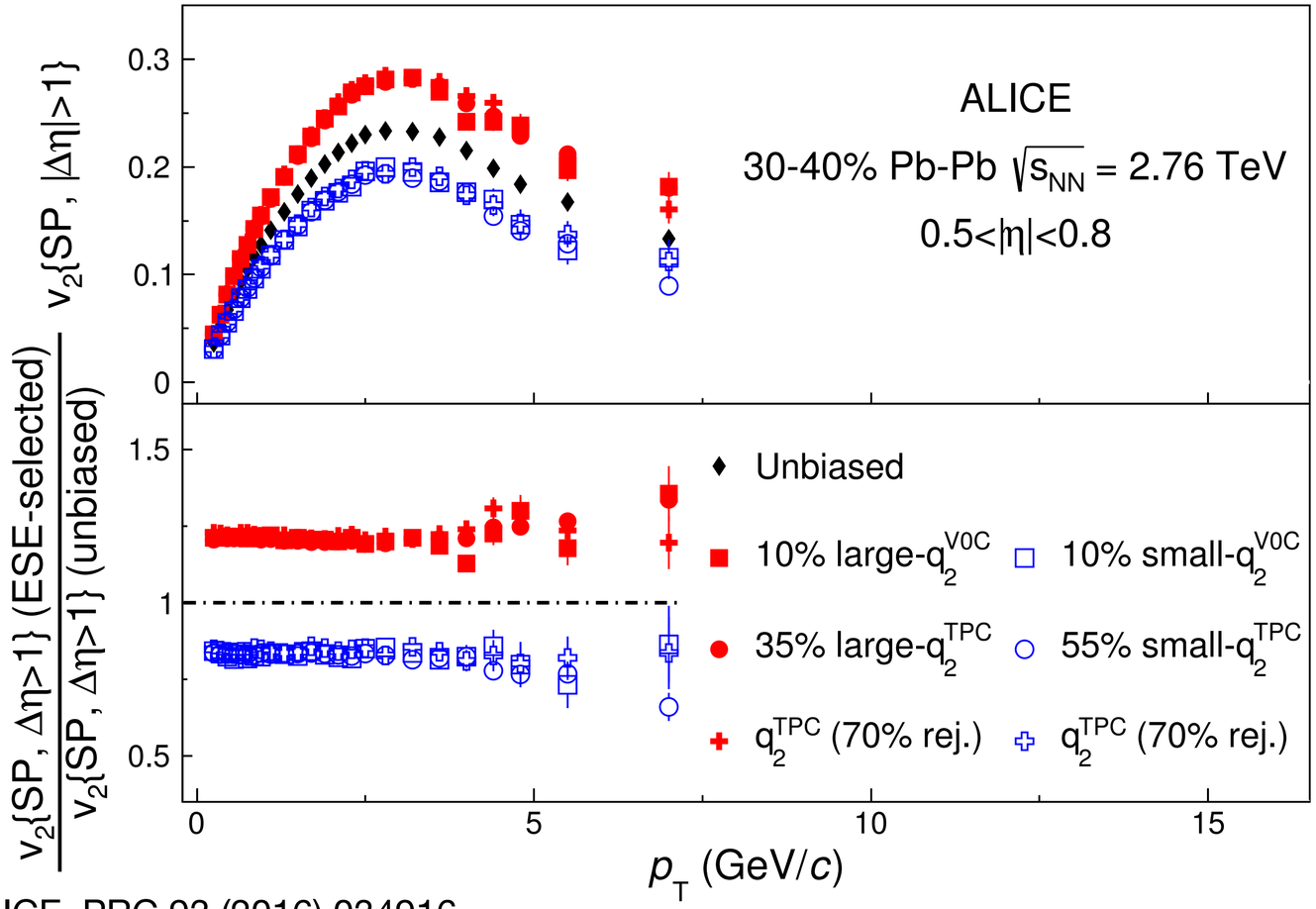
1. **Sebastian Scheid:** “Direct-photon and heavy-flavour production in proton--proton collisions at $\sqrt{s}$ = 7 TeV” (ID 188)
2. **Erin Gauger:** “Nuclear modification factor of beauty-decay electrons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE” (ID 192)
3. **Alexander Borissov:** “Σ^0 and Σ^0 production in pp Collisions at $\sqrt{s}$ =7 TeV” (ID 207)
4. **Antonio Uras:** “Low-mass dimuon measurements in pp and Pb-Pb collisions with ALICE at the LHC” (ID 231)
5. **Rathijit Biswas:** “Measurement of charged jet cross-section and properties in proton–proton collisions at 2.76 TeV with ALICE” (ID 289)
6. **Andrea Dubla:** “Magnetic fields and directed flow of D mesons in heavy-ion collisions with the ALICE detector” (ID 290)
7. **Marcelo Munhoz:** “Measurement of electrons from heavy-flavour hadron decays as a function of centrality in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV” (ID 305)
8. **Patrick Huhn:** “Data-driven particle composition correction of tracking efficiency for charged particles with ALICE” (ID 323)
9. **Ran Xu:** “Isolated photon–charged hadron correlation in pp collisions at 13 TeV” (ID 348)
10. **Yongzhen Hou:** “Multiplicity dependent charged jet production in pp collisions at 13 TeV with ALICE” (ID 349)
11. **Ritsuya Hosokawa:** “Measurement of jet radial profile through jet-hadron correlation in Pb–Pb collisions at 5.02 TeV” (ID 375)
12. **Artem Isakov:** “Performance of b jet-tagging algorithm in ALICE” (ID 596)

Summary

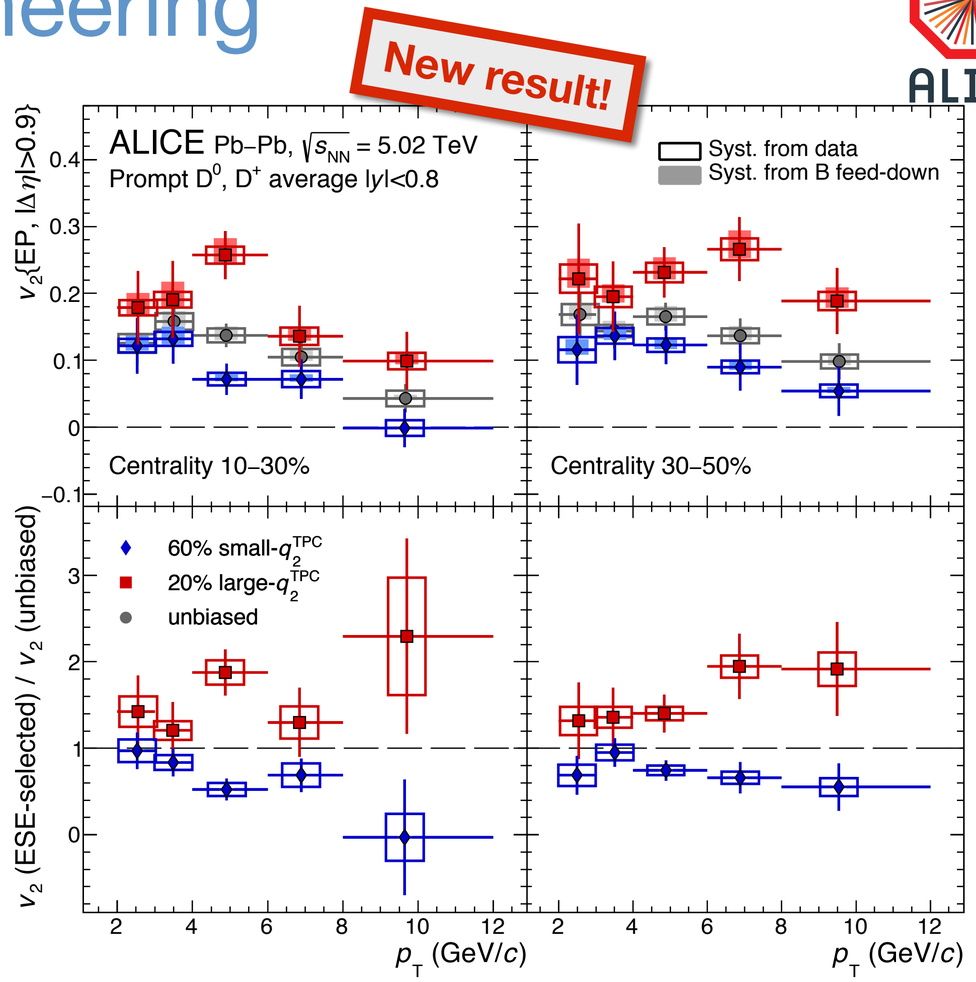
- New results on hard and electromagnetic probes in heavy-ion collisions
- Benefitting from high-statistics pp reference at $\sqrt{s}$ = 5 TeV
- **Moving towards connecting hard and soft probes**
  - jet structure and ID
  - heavy-flavour baryon production
  - event-shape-engineering with open and hidden heavy flavour
  - J/ψ v_3
  - quarkonia vs multiplicity in small systems
  - first look at low-mass dielectrons, more in Run 3

Backup

Event Shape Engineering



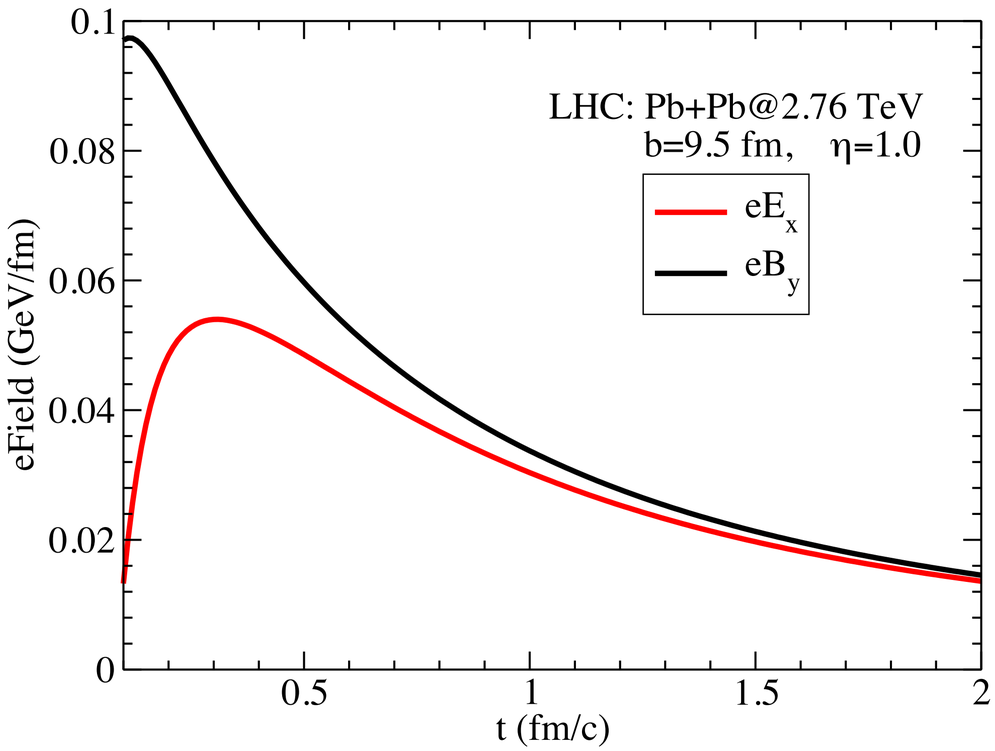
ALICE, PRC 93 (2016) 034916

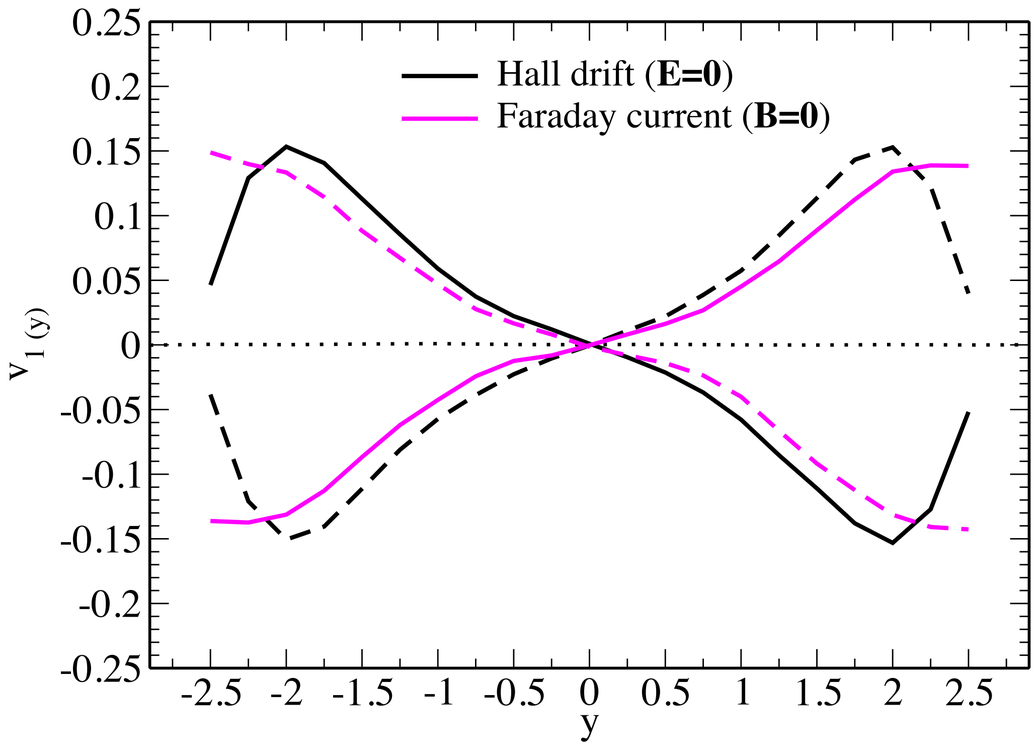


ALICE, arXiv:1809.09371

- Comparison of v_2 with event shape engineering for light and heavy flavour

Heavy Flavour Directed Flow





S. Das et al., PLB 768 (2017) 260

References for Jet-R_{AA} Models

- LBT: Y. He et al.,in arXiv:1809.02525 and PRC 91 (2015) 054908
- SCETG: H. Li et al., arXiv:1801.00008 and Z.-B. Kang, PLB 769 (2017) 242
- Hybrid: J. Casalderrey-Solana et al., JHEP 10 (2014) 19; JHEP 03 (2016) 53; JHEP 03 (2017) 135 and D. Pablos et al., JHEP 03 (2018) 10
- JEWEL (generated internally, R. Hosokawa): K. Zapp et al. JHEP 03 (2013) 80; JHEP 07 (2017) 141 and EPJ C 76 (2016) 695