Charged-hadron production in p+Pb, Pb+Pb, and Xe+Xe collisions measured with the ATLAS detector

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introduction

- quark-gluon plasma is created in heavy-ion (HI) collisions
- partons traversing through this matter lose their energy
- charged-hadron spectra in heavy-ion collisions are driven by the mechanism of energy loss and also by other effects

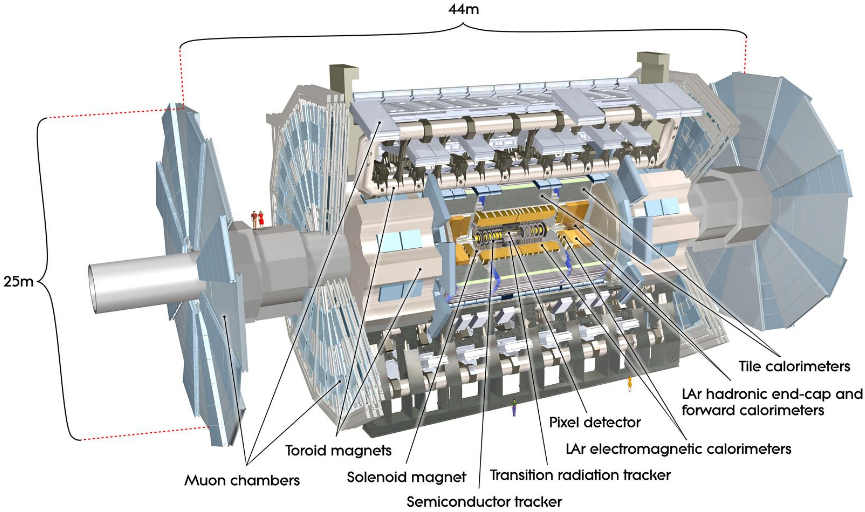
- nuclear modification factor R_{AA} quantifies the difference between the HI and pp spectra:

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{1/N_{\mathrm{evt}}\ \mathrm{d}^2 N_{\mathrm{A+A}}/\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$$

- both HI and pp collisions must be at the same center-of-mass energy

- what are the differences between Pb+Pb and Xe+Xe collisions?
- what are the differences between those and p+Pb collisions where no QGP is created?

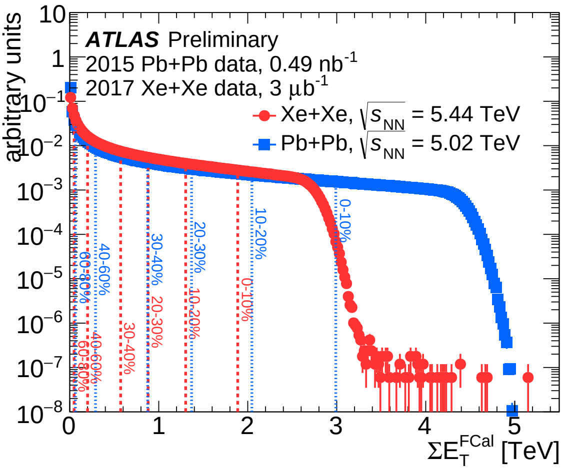
ATLAS detector



- Inner detector – 2 T magnetic field
- Forward Calorimeter (FCal) – used for the determination of centrality

centrality in Pb+Pb and Xe+Xe

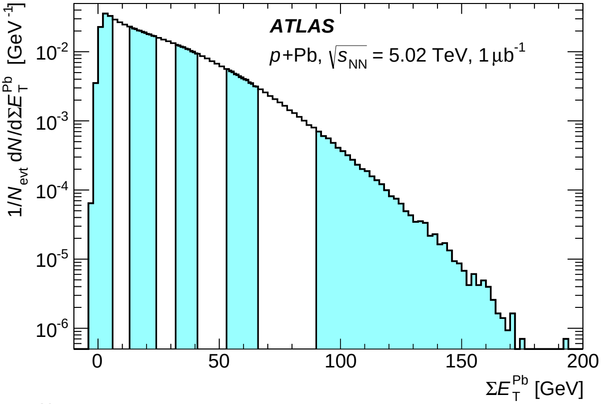
- centrality based on energy deposited in both sides of the Forward Calorimeter ($3.1 < |\eta| < 4.9$)
- pile-up events in heavy-ion collisions are removed from the analysis
- $\langle N_{\mathrm{part}} \rangle$ – number of participating nucleons
- $\langle N_{\mathrm{coll}} \rangle$ – number of binary nucleon–nucleon collisions
- $\langle T_{\mathrm{AA}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{NN}$



ATLAS-CONF-2018-007

centrality in p+Pb

- centrality based on energy deposited in Pb-going side of the Forward Calorimeter ($-4.9 < \eta < -3.1$)
- pile-up events in heavy-ion collisions are removed from the analysis



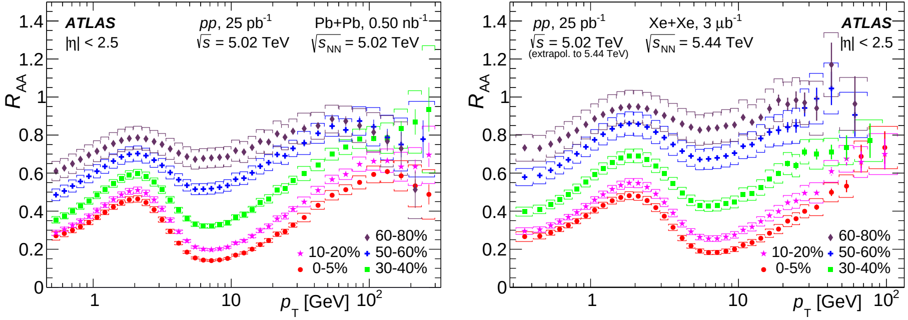
EPJC 76 (2016) 4:199, arXiv: 1508.00848

analysis overview

- the distributions are always corrected to the particle-level, i.e. independent on the detector acceptance
  - easy for theorists to compare with their models
  - easy for experimentalists to compare with other collaborations
  - tricky for experimentalists to work out all the corrections
- using several data sets:
  - pp, $\sqrt{s_{NN}} = 5.02$TeV, 25pb^{-1}
  - p+Pb, $\sqrt{s_{NN}} = 5.02$TeV, 28nb^{-1}
  - Pb+Pb, $\sqrt{s_{NN}} = 5.02$TeV, 0.50nb^{-1}
  - Xe+Xe, $\sqrt{s_{NN}} = 5.44$TeV, 3μb^{-1}
- to get particle-level distributions, we correct for:
  - fake and secondary tracks
  - p_{T} and η resolutions
  - track reconstruction efficiency
  - extrapolation to the same $\sqrt{s_{NN}}$ (for Xe+Xe reference only)

charged hadron R_{AA}: Pb+Pb and Xe+Xe

- larger suppression in more central collisions
- milder suppression in more peripheral collisions
- *"shouldn't there be no suppression when the collisions are peripheral enough?"*
  - good question, uncertain answer
  - problem with peripheral collisions is that it's not clear what is an inelastic nucleus–nucleus collision and what is not



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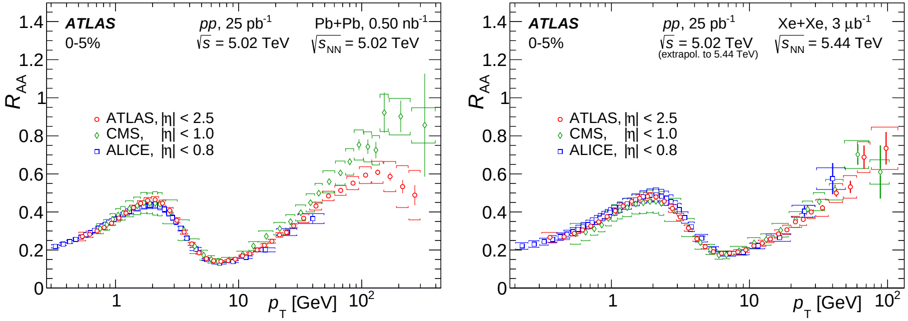
charged hadron R_{AA}: Pb+Pb and Xe+Xe

- all 3 experiments are consistent
- anything else would be worrisome
- all of them use the same definition for primary particles, correct to particle-level, ... etc.
- different $|\eta|$ ranges but R_{AA} doesn't have any strong $|\eta|$-dependence



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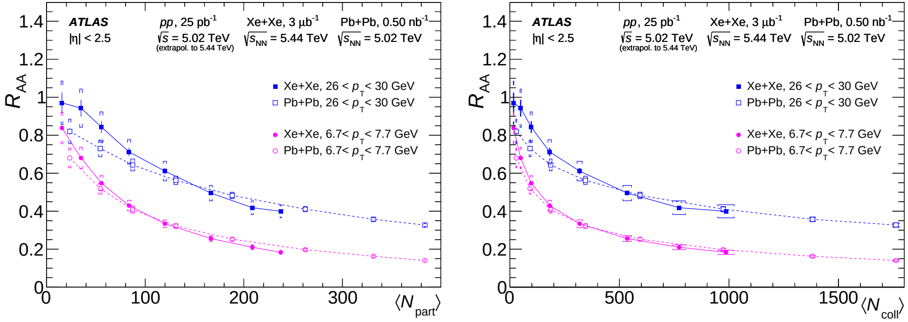
charged hadron R_{AA}: Pb+Pb and Xe+Xe

- can compare suppression in Pb+Pb and Xe+Xe
- both follow the same trend but the magnitude is different
- size of the fireball is not enough to describe the system, something else matters as well



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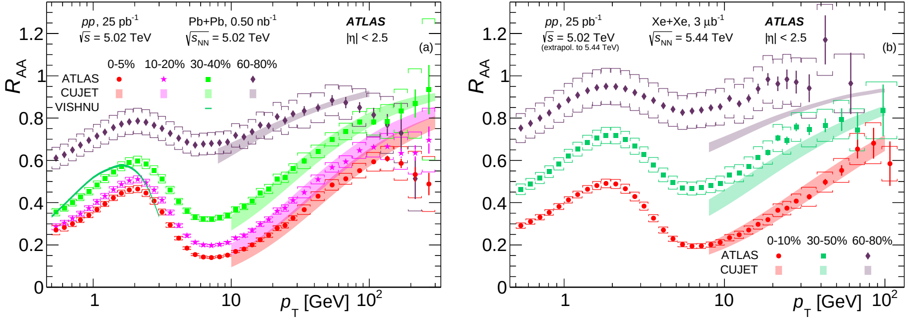
charged hadron R_{AA}: Pb+Pb and Xe+Xe

- CIBJET framework; arXiv:1808.05461
  - VISHNU is a (2+1)D relativistic viscous hydrodynamic model
  - CUJET describes high-p_T energy loss



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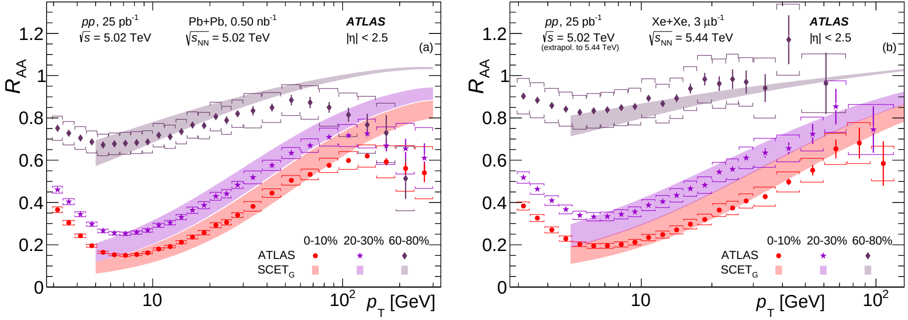
charged hadron R_{AA}: Pb+Pb and Xe+Xe

- Soft Collinear Effective Theory; SCET$_G$, arXiv:1509.02936
  - uses modified splitting functions and generalized DGLAP evolution
  - partons lose energy via soft gluon emissions
  - describes formation of showers in the medium



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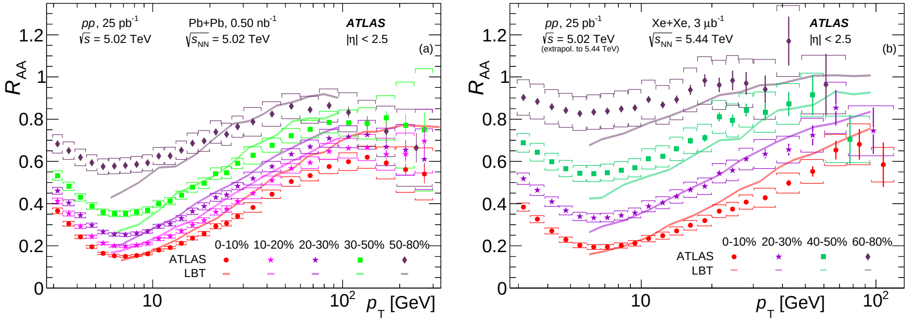
charged hadron R_{AA}: Pb+Pb and Xe+Xe

- Linear Boltzmann Transport model; LBT, arXiv:1503.0331
  - kinetic description of parton propagation
  - hydrodynamic description of the medium evolution
  - also keeps track of thermal recoil partons from each scattering and their further propagation in the medium



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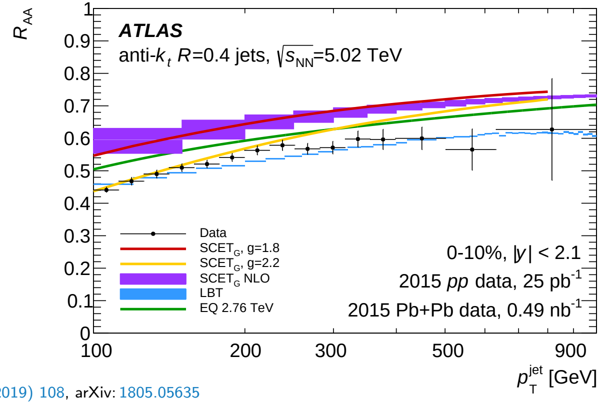
jet R_{AA}: Pb+Pb and Xe+Xe

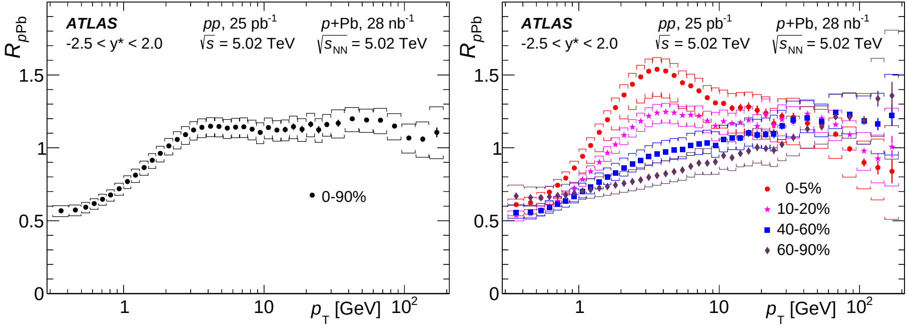
- definition of jet R_{AA} is analogical to charged hadron R_{AA}
- some models can describe both charged hadron production and jet production
- others focus only on jets (e.g. Effective Quenching)



Phys. Lett. B 790 (2019) 108, arXiv: 1805.05635

charged hadron R_{AA}: p+Pb

- no QGP in p+Pb collisions
- "just" effects of cold nuclear matter



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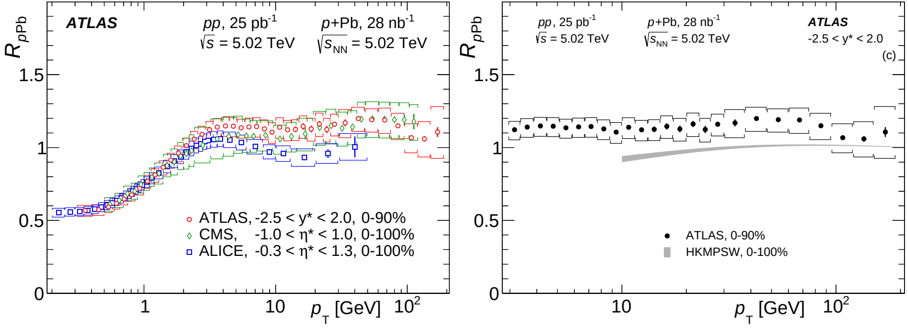
- interestingly, jet suppression is observed in p+Pb
- *apparent* jet suppression: ATLAS-CONF-2023-011

charged hadron R_{AA}: p+Pb

- comparisons available only for inclusive centrality
- ATLAS measurement consistent with CMS and ALICE
- HKMPSW model; arXiv:1808.05461



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summary

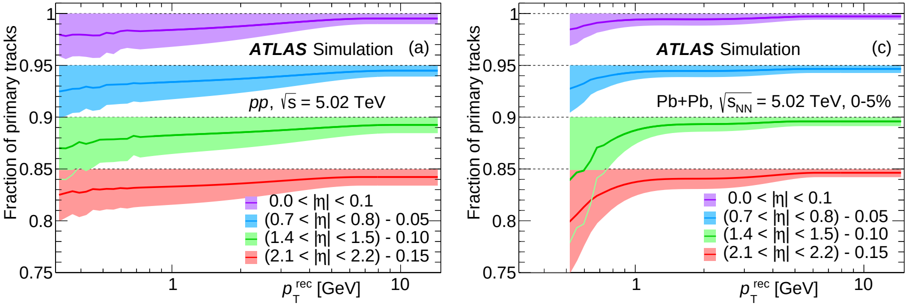
- quark-gluon plasma affects partons traversing it
- the energy loss of partons and partons' interactions with QGP are well substantiated
- all these affect production of jets, hadrons, ...
- there are still many unknowns:
  - is there a suppression even for the most peripheral collisions?
  - at very high p_{T}, is there some saturation of R_{AA} at values lower than 1 or will it eventually reach unity?
  - what is the nature of apparent jet suppression in p+Pb?
  - can the same apparent suppression be observed in Pb+Pb and Xe+Xe?
  - can the models describe low-p_{T} R_{AA} and azimuthal asymmetry (v_n) at the same time?
  - can they describe the intermediate p_{T} where both hydrodynamics and hard-scattering can't be neglected?
- with the new data from Run 3, we may resolve at least some of these

bonus slides

a.k.a. back-up slides

fake and secondary tracks correction

- some reconstructed tracks are better than others
- tracks may be linked to:
  - primary particles (our interest, $\tau > 0.3 \times 10^{-10}$ s)
  - secondary particles, from decays of Σ, Ξ, ... (not our interest)
  - no particles, just a spurious combination of hits (not our interest)



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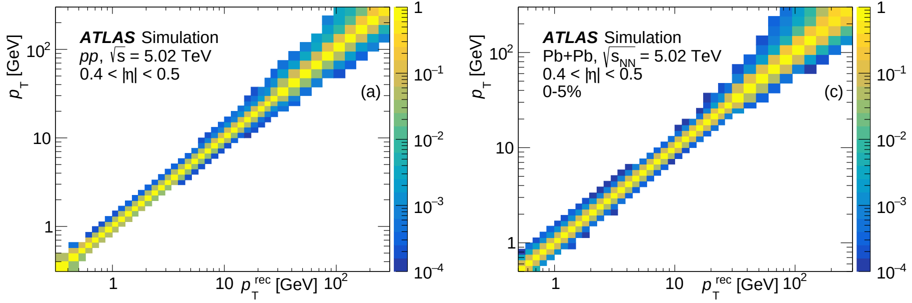
p_{T} and η resolution correction

- measured p_{T} is not the real p_{T}
- $\sigma_{p_{\mathrm{T}}} \approx c_0 + c_1 \cdot p_{\mathrm{T}}$
- migration to other p_{T} bin is very common
- problem more pronounced at higher p_{T}
- corrected for by Bayesian unfolding



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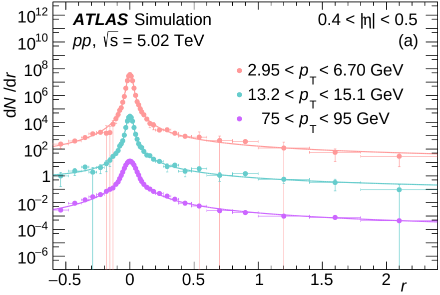
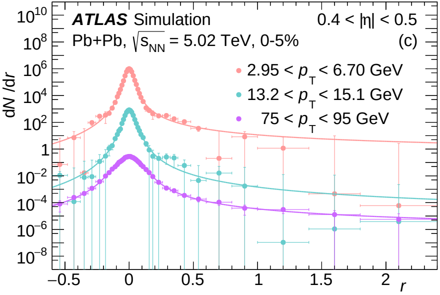
- analogically for η resolution, although it's more diagonal

p_{T} resolution

- off-diagonal elements susceptible to statistical fluctuations
- first, the distributions of resolution is fitted:

$$r = (p_{\mathrm{T}}/p_{\mathrm{T}}^{rec}) - 1$$





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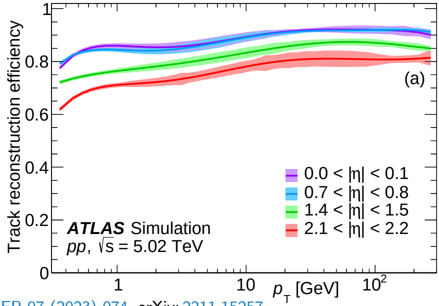
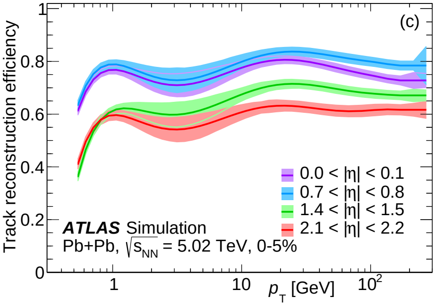
- the fits are used to fill the migration matrices for the Bayesian unfolding

⇒ this approach lead to a large reduction of systematic uncertainties

track reconstruction efficiency

- some particles pass through the detector undetected
- the reconstruction efficiency depends on the type of a particle
  - π, K, p
    - ★ reconstructed from low p_{T}; small differences
  - strange baryons (Σ, Ξ, Ω)
    - ★ at low p_{T}, decay before reaching the detector $\rightarrow$ truly unsportsmanlike
    - ★ possible to reconstruct only at $p_{\mathrm{T}} \gtrsim 10\mathrm{GeV}$
  - simulations reweighted to reflect the particle composition as in data
  - at p_{T} 3-4GeV, there is a "bitter spot" where it hurts the most





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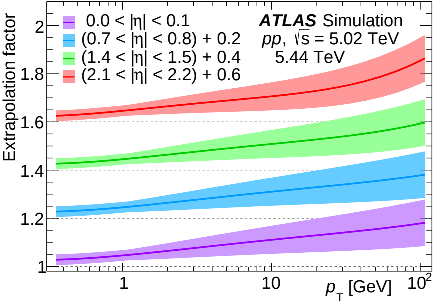
extrapolation to the same $\sqrt{s_{NN}}$

- to eliminate differences between samples due to different $\sqrt{s_{NN}}$
- pp cross-section measured only at $\sqrt{s} = 5.02\text{TeV}$
- to use it for comparison of Xe+Xe collisions, using Pythia for extrapolation to $\sqrt{s} = 5.44\text{TeV}$



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