



Acoplanarity: new angles on an old idea

Peter Jacobs, LBNL

*Jet Quenching In The Quark-Gluon Plasma
ECT* Trento
June 16, 2022*



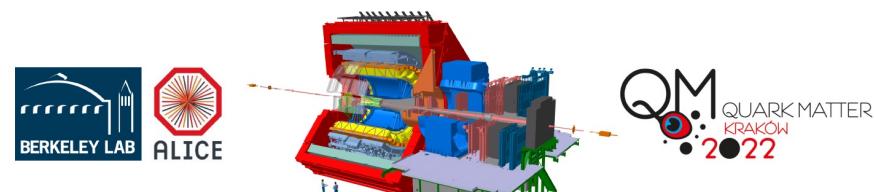
Measurement of medium-induced modification of $\gamma_{\text{dir}} + \text{jet}$ and $\pi^0 + \text{jet}$ yield and acoplanarity in $p+p$ and central $\text{Au}+\text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ by STAR

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Derek Anderson
Texas A&M University
For the STAR Collaboration

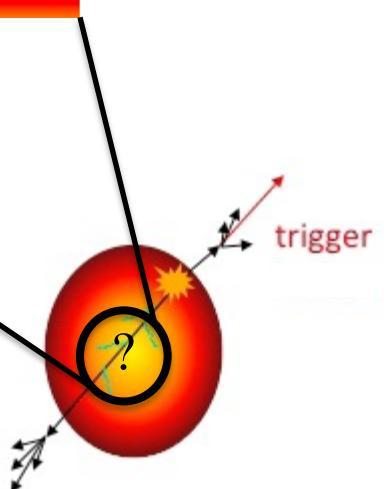
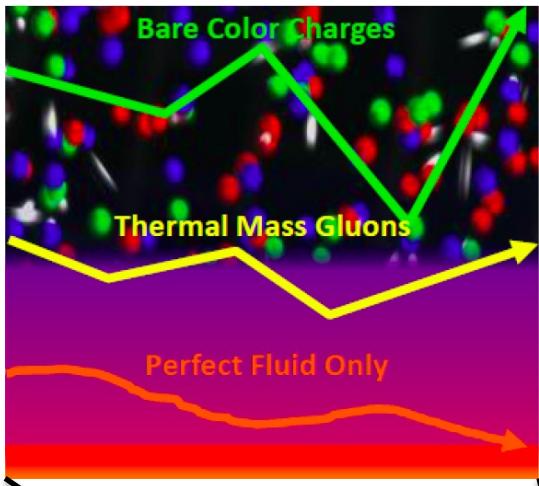
Jet acoplanarity and energy flow within jets in Pb-Pb and pp collisions with ALICE



Rey Cruz-Torres
reynier@lbl.gov
on behalf of the ALICE Collaboration
04/07/2022

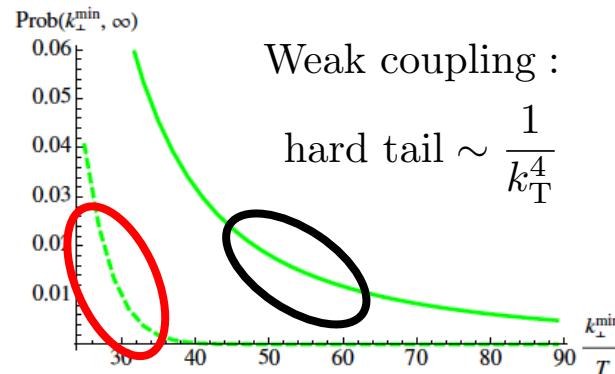
Jet acoplanarity: in-medium hard scattering ("Rutherford experiment")

Discrete scattering centers or
effectively continuous medium?



d'Eramo et al., JHEP 1305 (2013) 031

Distribution of momentum transfer k_T



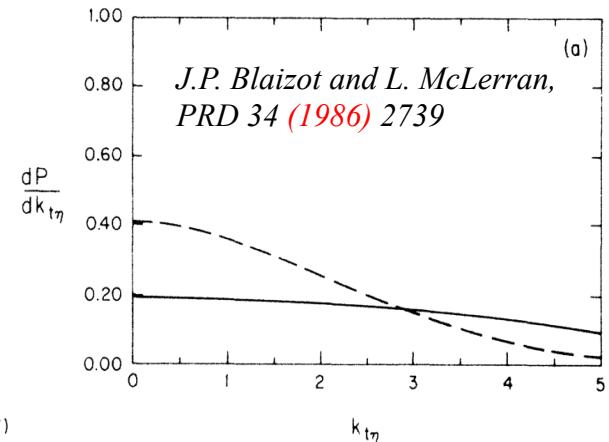
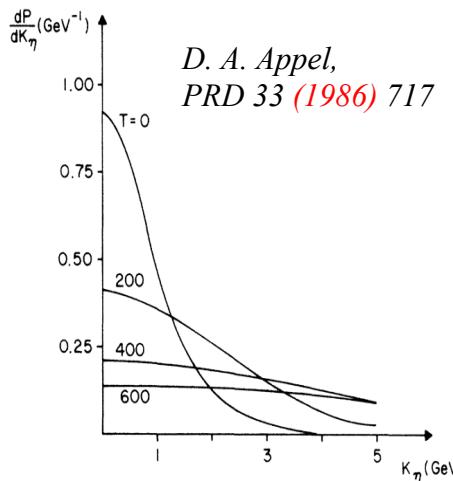
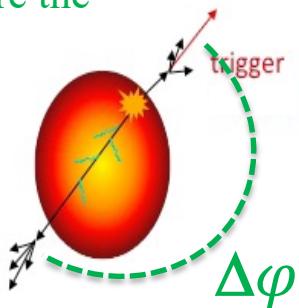
Strong coupling:
Gaussian distribution

What are the quasi-particles?

- high Q^2 : bare q and g
- low-ish Q^2 :
 - thermal-mass glue
 - magnetic monopoles
 - ...?

Jet acoplanarity: in-medium multiple scattering

Jet scattering to measure the QGP is an old idea



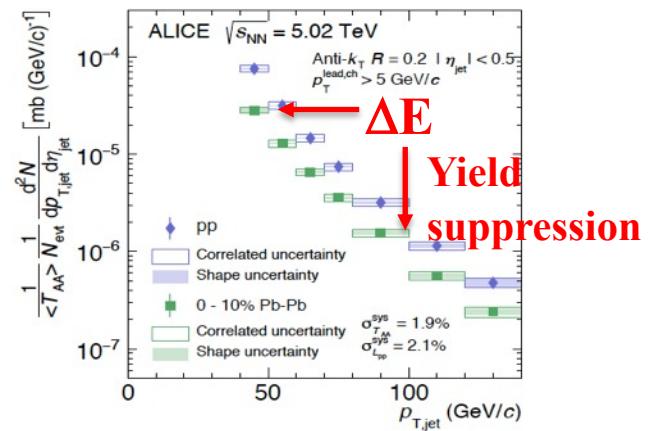
BDMPS: multiple soft scattering

Medium-induced jet energy loss:

$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

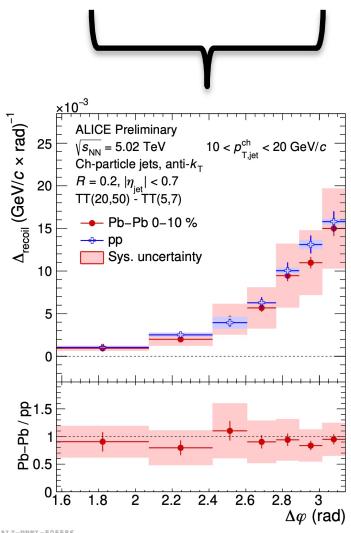
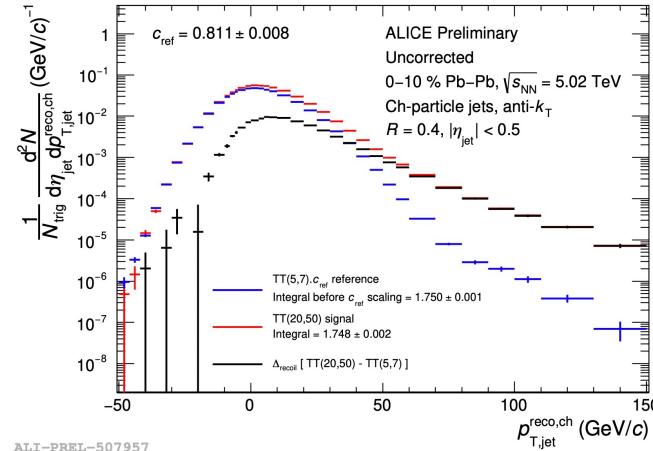
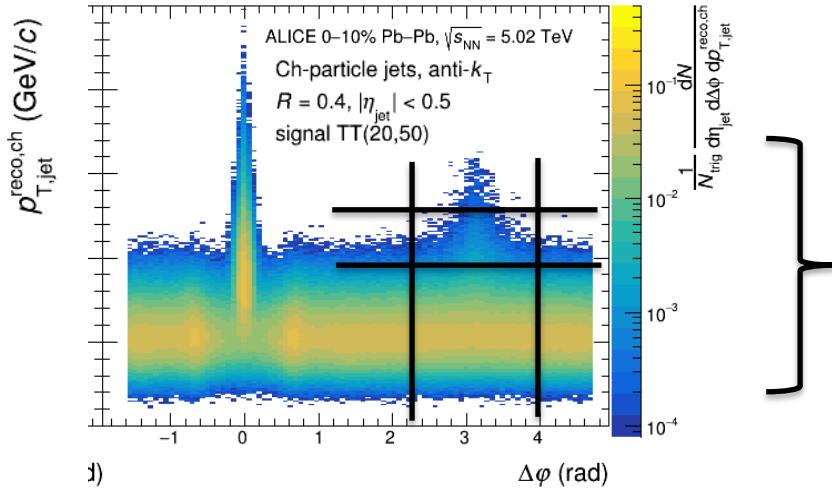
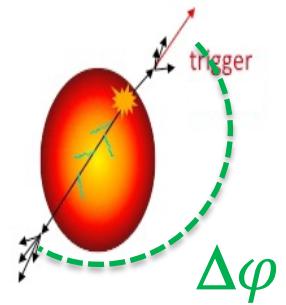
Medium-induced angular broadening:

$$\langle k_T^2 \rangle \sim \langle \Delta\varphi^2 \rangle \sim \alpha_s \hat{q} L$$



Expect largest acoplanarity at low p_T^{jet} → experimentally challenging

Semi-inclusive distributions



Select events based on cleanly-measured trigger:

- ch hadron, π^0 , γ_{dir}
- distributed “inclusively”

Count all recoil jets in acceptance (no rejection)

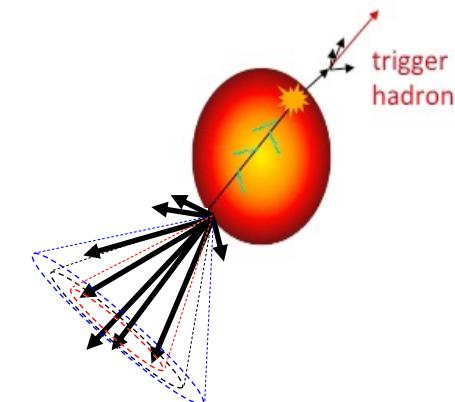
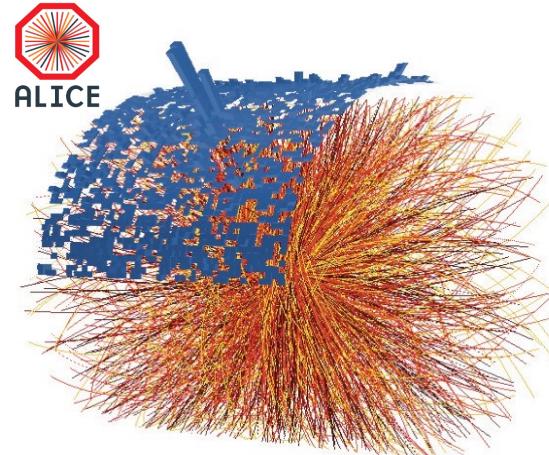
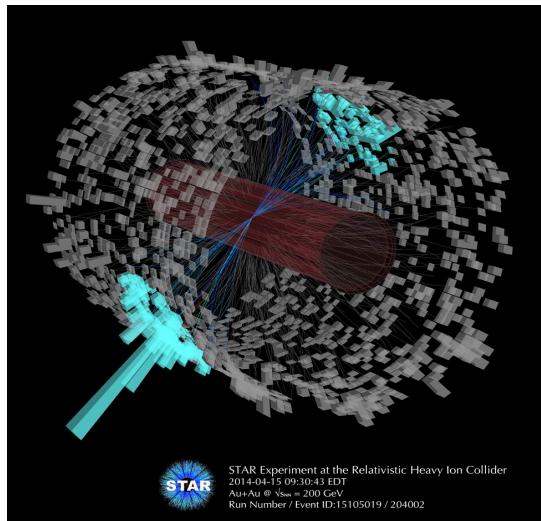
Normalize per trigger

Not equivalent:

- jet-wise rejection
- pair-wise normalization

New angles on acoplanarity

The heavy-ion jet measurement challenge: uncorrelated background



Pions do not come labelled “jet” or “background”:

- you cannot know with certainty whether any given hadron (or hadron cluster) arises from the same high- Q^2 process as the trigger
- “uncorrelated background” strictly has meaning only for ensemble-averaged distributions

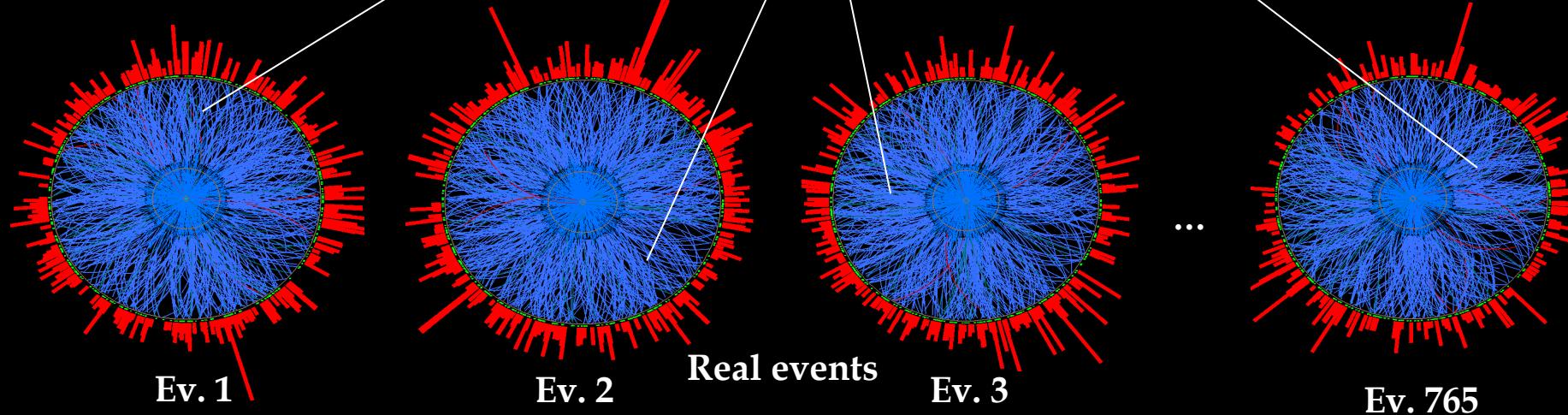
→ “Statistical” correction for uncorrelated background yield

Uncorrelated background: mixed events

STAR Collaboration,
Phys. Rev. C 96 (2017), 024905

Destroys all multi-hadronic correlations, including jets

Pick one random track per real event
→ add to mixed event



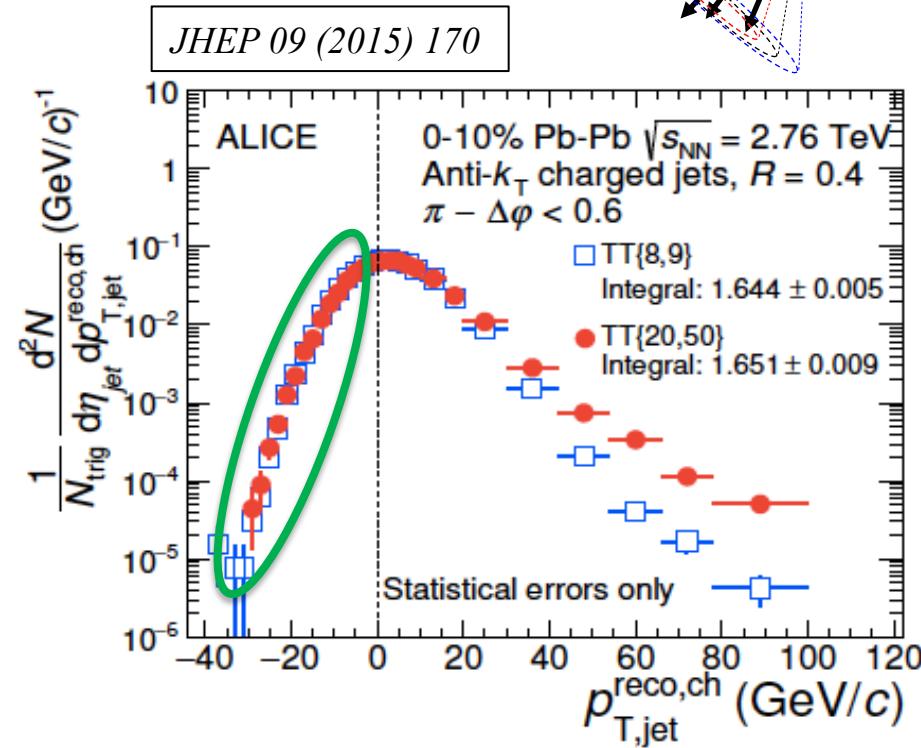
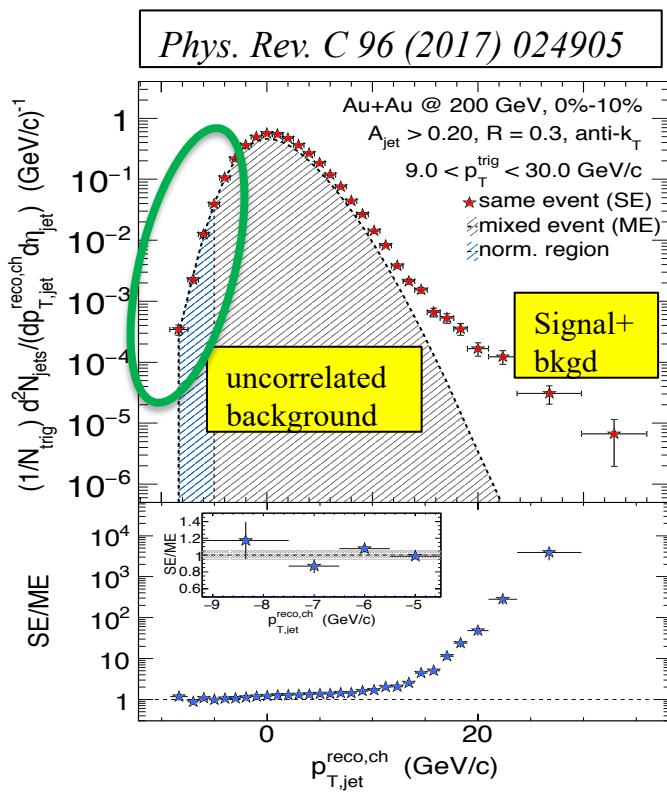
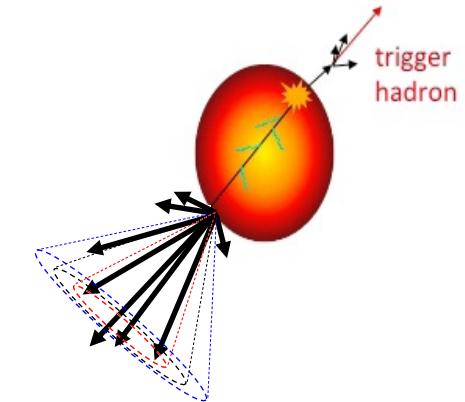
New angles on acoplanarity

Statistical uncorrelated background yield correction

Data-driven, no modeling

Two bkgd normalization constants (horiz, vert)

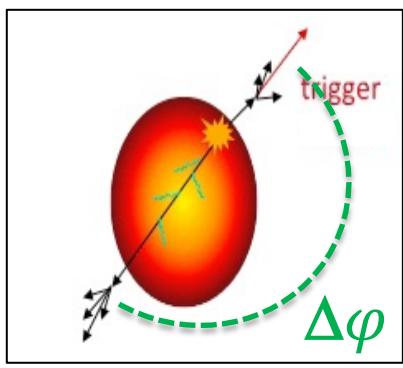
- extracted from data
- values within few percent of unity
- rel. uncertainties \sim per-mil



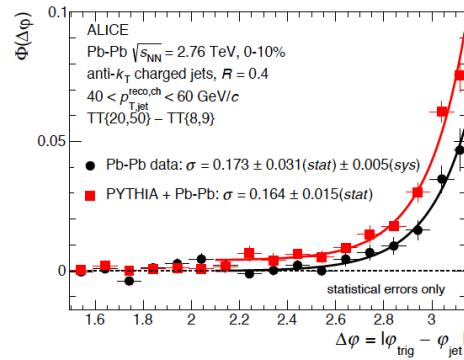
Unbiased correction for broad range of observables

- enables precise heavy-ion jet measurements at very low p_T^{jet} and large R

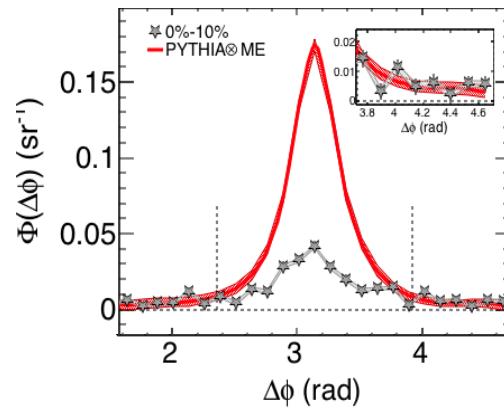
Jet acoplanarity: first measurements



ALICE, JHEP 09 (2015) 170

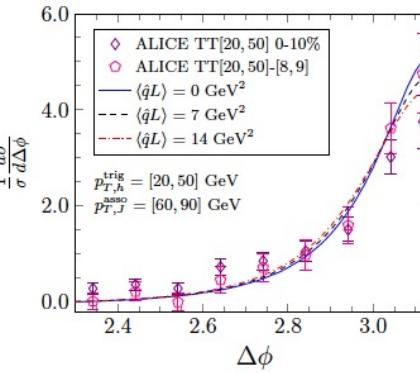
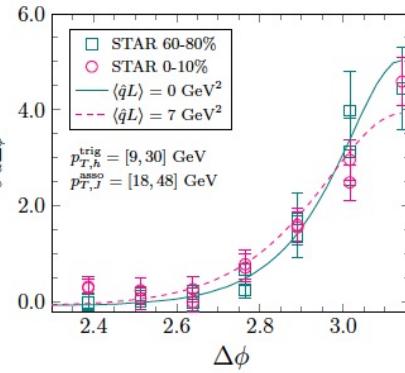
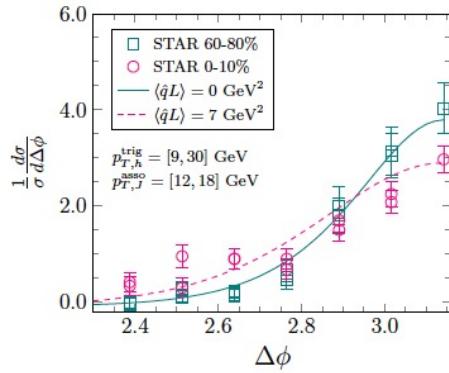


STAR, Phys Rev C96 (2017) 024905

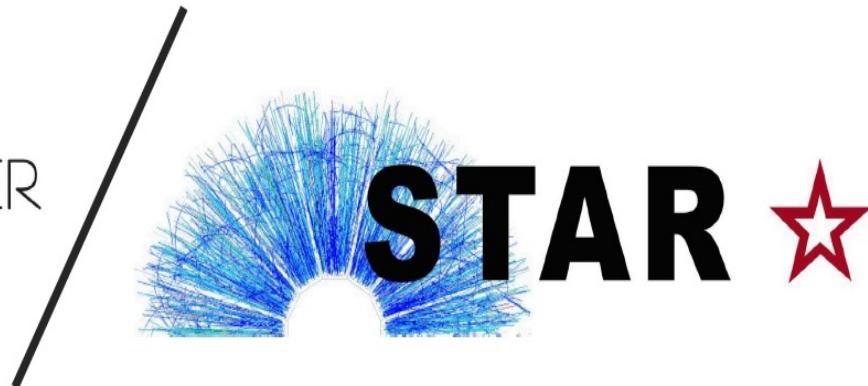


Significant background: vacuum (Sudakov) radiation

L. Chen et al., Phys.Lett.B 773 (2017) 672



First-generation ALICE+STAR measurements:
no medium-induced acoplanarity observed within uncertainties
In progress: second-generation measurements with greater precision...



Measurement of medium-induced modification of $\gamma_{\text{dir}} + \text{jet}$ and $\pi^0 + \text{jet}$ yield and acoplanarity in $p+p$ and central Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV by STAR

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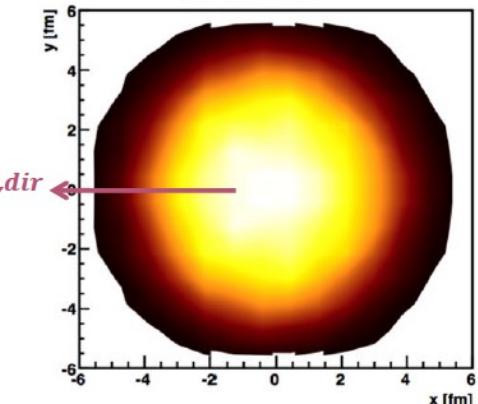
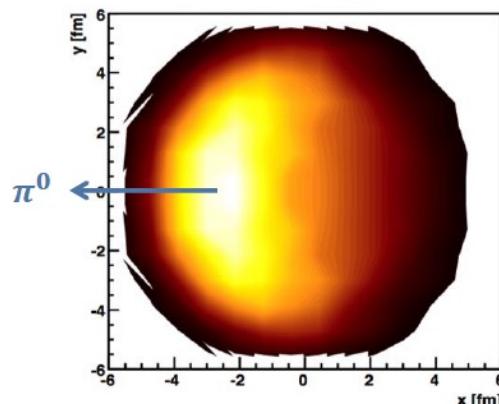
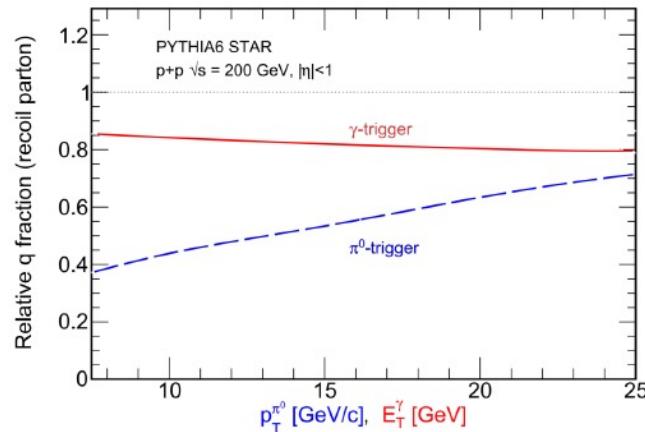
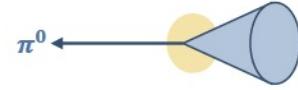
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$\gamma_{\text{dir}}/\pi^0 + \text{jet}$ as probes of the QGP



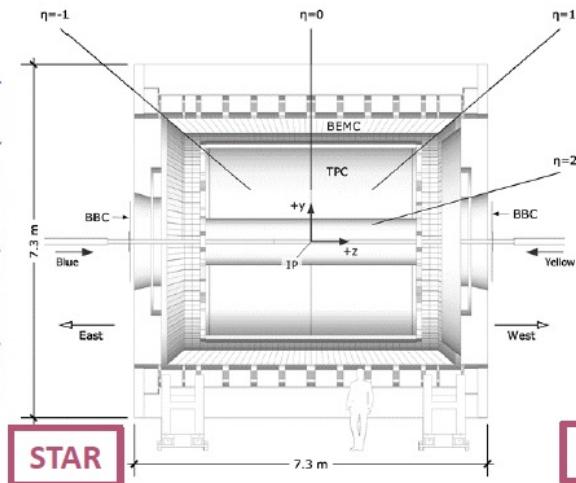
Adapted from
Renk, PRC **88**, 054902 (2013)

- Jets coincident with direct photons (γ_{dir}) are valuable probe to study in-medium modification (**jet quenching**)
 - γ_{dir} constrains kinematics of recoil jet
- Comparing $\gamma_{\text{dir}}/\pi^0$ triggers:
 - ⇒ **Different q/g fractions**
 - ⇒ **Different recoil path length distributions**



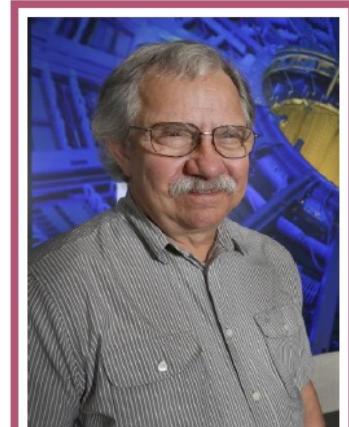
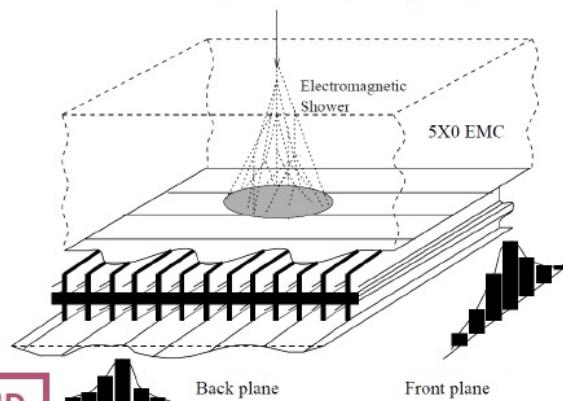
STAR subsystems and datasets

STAR, PRD 86, 032006 (2012)



BSMD

Beddo et al, NIM A499, 725 (2003)



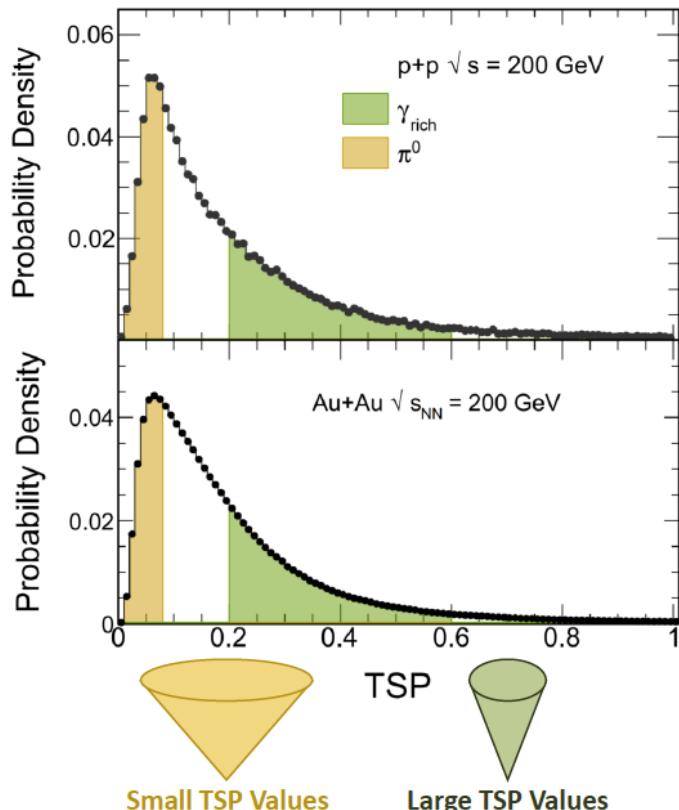
*In memoriam,
Tom Cormier*

- **Time Projection Chamber (TPC)**
 - charged particles ($|\eta| < 1$, full azimuth)
- **Barrel Electromagnetic Calorimeter (BEMC):**
 - trigger on energetic γ_{dir} or π^0
- **Barrel Shower Maximum Detector (BSMD):**
 - discriminates $\gamma_{\text{dir}}/\pi^0$ based on transverse shower profile

- **This analysis**
 - BEMC trigger ($E_T^{\text{tower}} \gtrsim 6 \text{ GeV}$)
 - **Au+Au:** 13 nb^{-1} (2014)
 - **p+p:** 23 pb^{-1} (2009)



$\gamma_{\text{dir}}/\pi^0$ identification



- Candidate $\pi^0/\gamma_{\text{dir}}$ triggers are clusters made of:
 - 1 or 2 BEMC towers, and
 - 15 η and 15 ϕ BSMD strips

- $\pi^0/\gamma_{\text{dir}}$ identified via **Transverse Shower Profile (TSP)**:

$$\text{TSP} \equiv \frac{E_{\text{cluster}}}{\sum_i e_i r_i^{1.5}}$$

- TSP used to split data into two samples:
 - i. 95% pure sample of π^0
 - ii. Sample with an enhanced fraction of γ_{dir} (γ_{rich})

- γ_{rich} background levels (B)
 - 33% ~ 16% ($Au+Au$)
 - 57% ~ 47% ($p+p$)

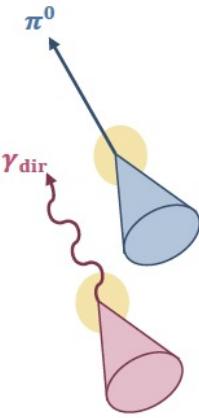
- Decay background in γ_{rich} removed via statistical subtraction

$$Y_{pp}^{\gamma_{\text{dir}}} = \frac{Y_{pp}^{\gamma_{\text{rich}}} - B \cdot Y_{pp}^{\pi^0}}{1 - B}$$

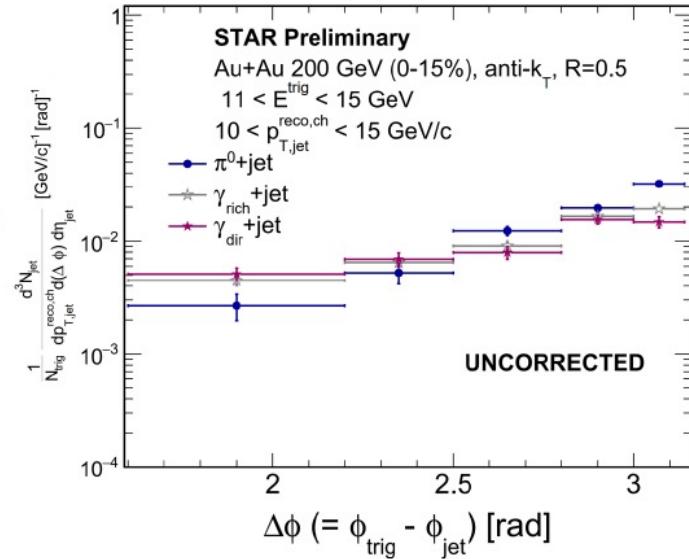
↗ Measured via near-side h^\pm yields
 ↗ Includes some fragmentation photons
 ↳ STAR, PRC 82, 034909 (2010)



Raw jet distributions

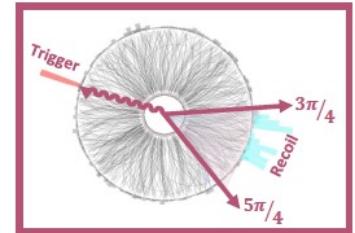
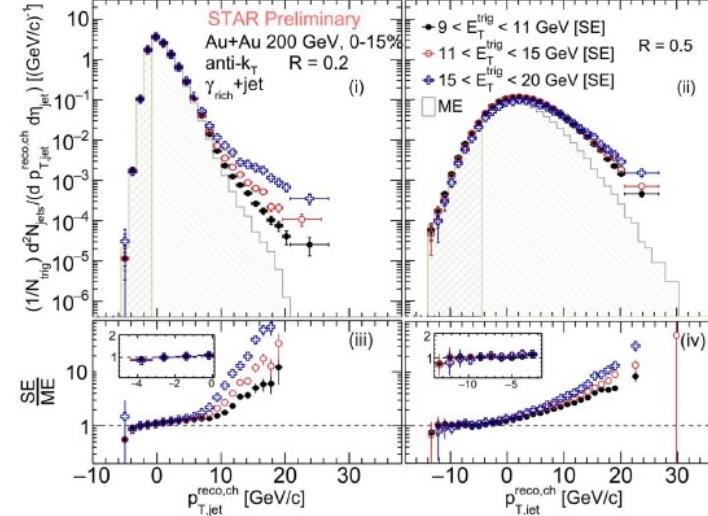


Nihar Sahoo poster [Wed T04_1]



- Jets reconstructed by clustering TPC tracks
 - anti- k_T ($R = 0.2, 0.5$)
 - › Cacciari et al, JHEP 04, 063 (2008)
 - $|\eta_{\text{jet}}| < 1 - R$

$\Delta\phi \in (3\pi/4, 5\pi/4)$



April 5th, 2022

Derek Anderson, QM 2022

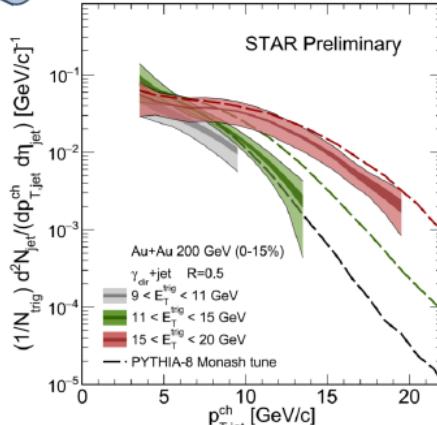
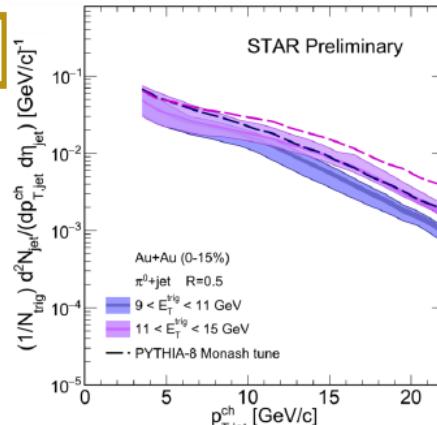
7/21



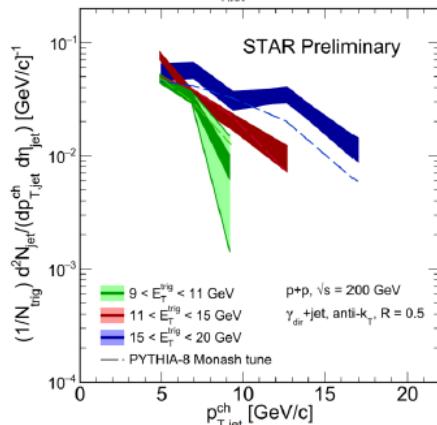
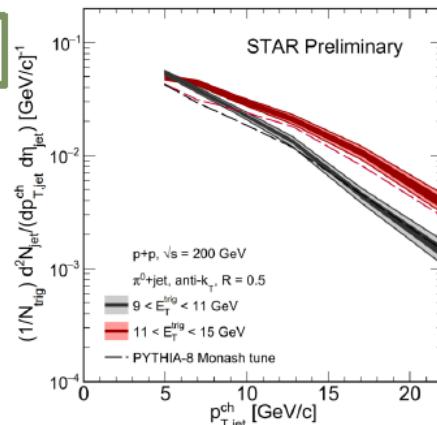
Corrected recoil jet distributions

- Semi-inclusive recoil jet $p_{T,\text{jet}}^{\text{ch}}$ distributions
 - $E_T^{\text{trig}}(\pi^0)$: [9, 11], [11, 15] GeV
 - $E_T^{\text{trig}}(\gamma_{\text{dir}})$: [9, 11], [11, 15], [15, 20] GeV
- **Dark band:** statistical errors
Light band: systematic uncertainties
- **Dominant systematic uncertainties:**
 - Tracking efficiency
 - Unfolding procedure
 - Purity (hadronic background subtraction)
- **Dashed line:** PYTHIA-8 (MONASH tune)
 - E_T^{trig} shifted and smeared to account for trigger energy scale/resolution

Au+Au



p+p



April 5th, 2022

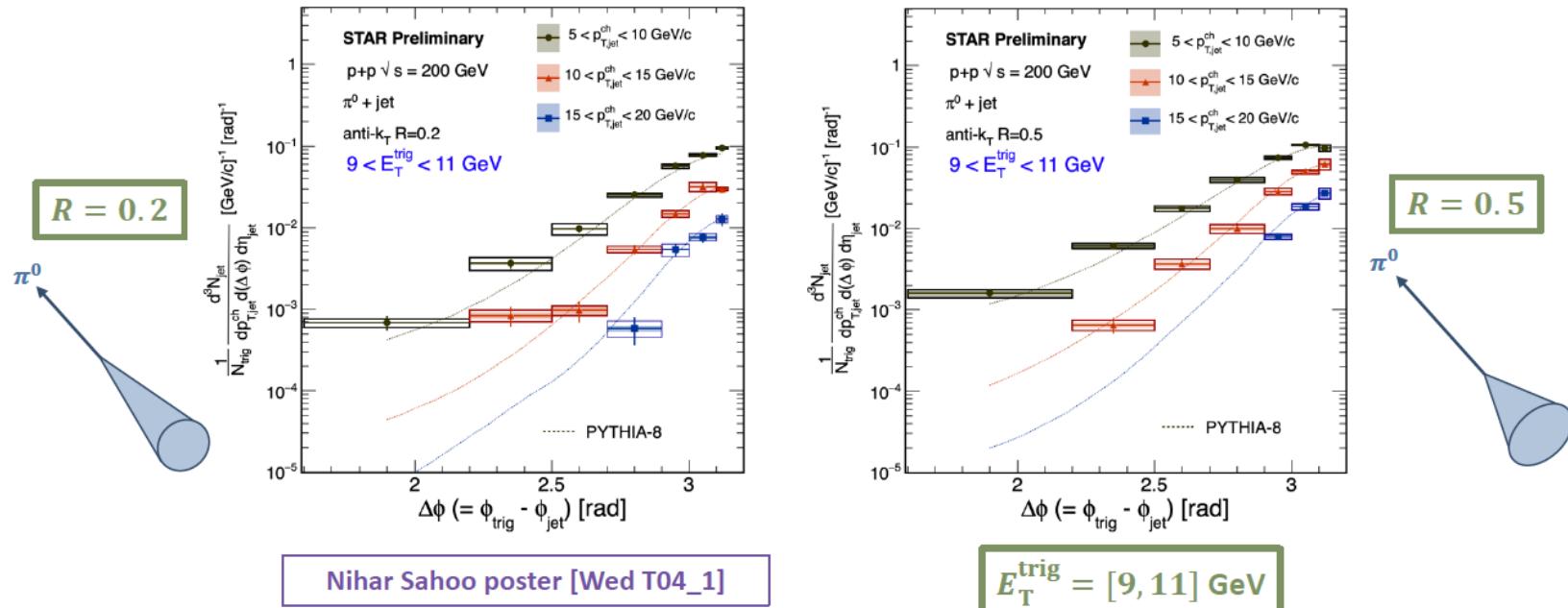
Derek Anderson, QM 2022

11/21

**Au+Au: 13 nb⁻¹
p+p: 23 pb⁻¹**



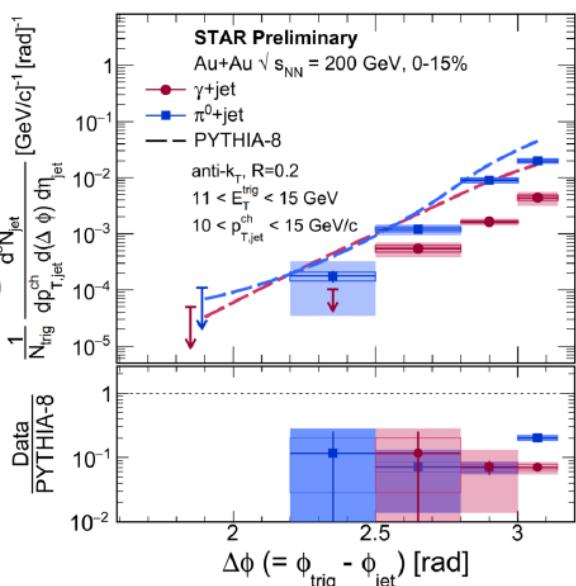
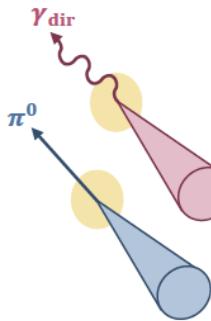
Corrected $\Delta\phi$ distributions in $p+p$ collisions



- Corrected $\Delta\phi$ spectra in $p+p$ compared against E_T^{trig} smeared PYTHIA-8
 - PYTHIA-8 consistent with Data
- PYTHIA-8 only LO+LL
 \therefore NLO calculations needed

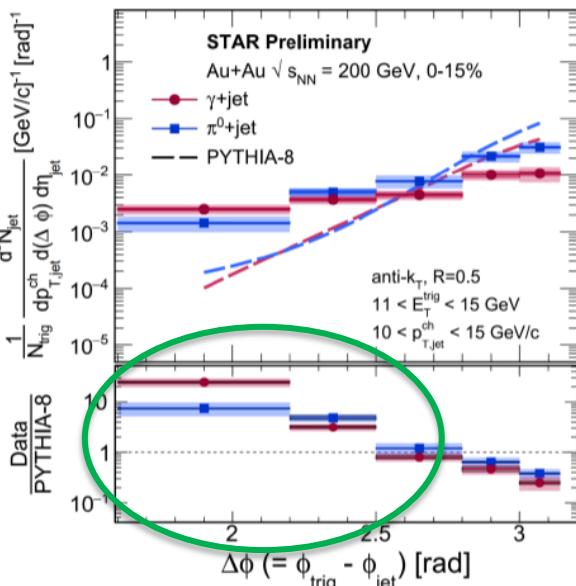
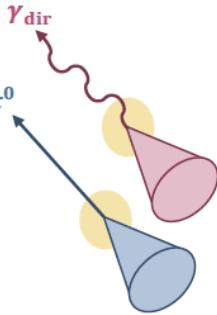
Corrected $\Delta\phi$ distributions in Au+Au collisions

$R = 0.2$



Nihar Sahoo poster
[Wed T04_1]

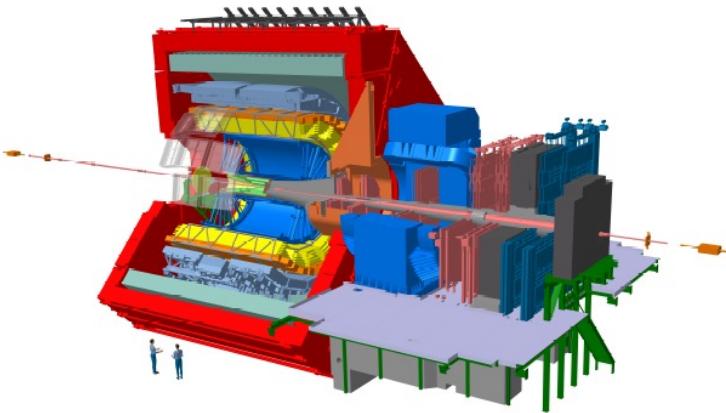
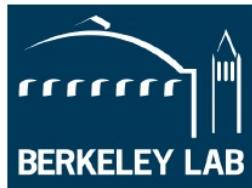
$R = 0.5$



$E_T^{\text{trig}} = [11, 15]$ GeV

- Corrected $\Delta\phi$ spectra in Au+Au compared against smeared PYTHIA-8
 ⇒ PYTHIA-8 validated against π^0 +jet $p+p$ data
- Note: $\Delta\phi$ integrated yield is I_{AA}
- Highly significant medium-induced broadening of acoplanarity for $R = 0.5$!
- ⇒ Medium effects include
 - Scattering off QGP quasi-particles
 - Multiple soft scatters

Jet acoplanarity and energy flow within jets in Pb-Pb and pp collisions with ALICE



Rey Cruz-Torres
reynier@lbl.gov
on behalf of the ALICE Collaboration
04/07/2022

Background yield: statistical correction

$$n \equiv \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^2 N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{ch}}^{\text{jet}} d\eta_{\text{jet}}}$$

Yield measured in two exclusive trigger track classes

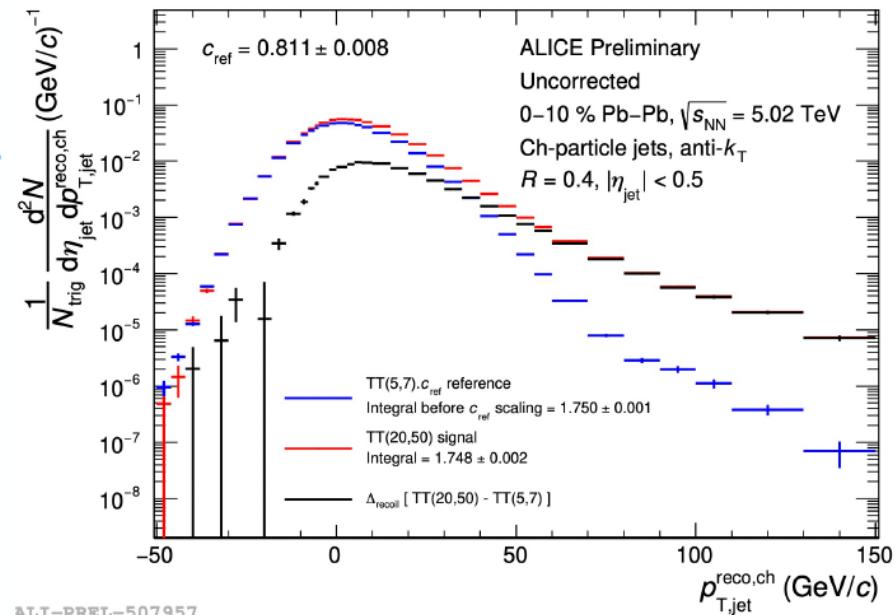
$\text{TT}_{\text{Sig}} : 20 < p_{T,\text{trig}} < 50 \text{ GeV}/c$

$\text{TT}_{\text{Ref}} : 5 < p_{T,\text{trig}} < 7 \text{ GeV}/c$

Data-driven subtraction of uncorrelated background (including MPI) by taking difference between signal and reference spectra

$$\Delta_{\text{recoil}} = n(\text{TT}_{\text{Sig}}) - c_{\text{Ref}} \cdot n(\text{TT}_{\text{Ref}})$$

c_{Ref} ≡ “alignment” constant extracted from data



Method allows for measurement down to low p_T and high R

Correction for (p_T , $\Delta\phi$) smearing due to instrumental effects and bkgd fluctuations: SVD/Bayesian unfolding

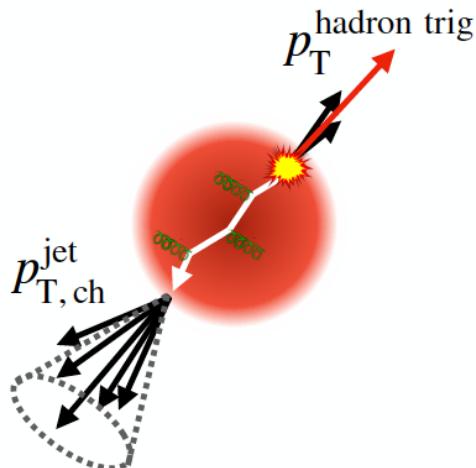
NEW

I_{AA} results - energy redistribution

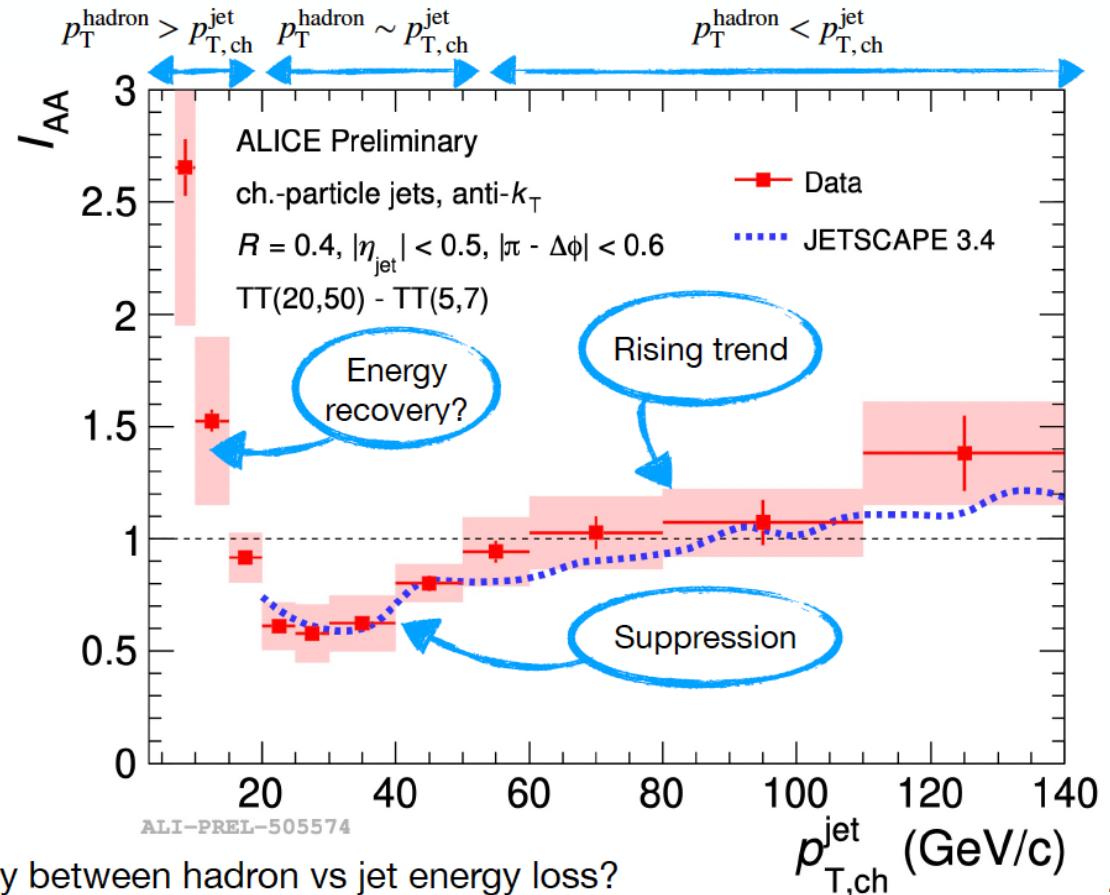


$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

JETSCAPE prediction in agreement with measurement



R. Cruz-Torres - QM22

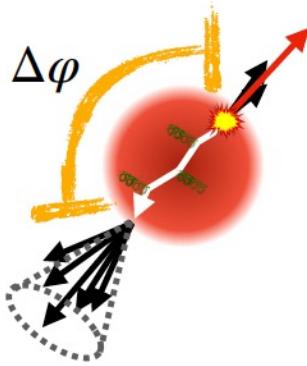


Interplay between hadron vs jet energy loss?

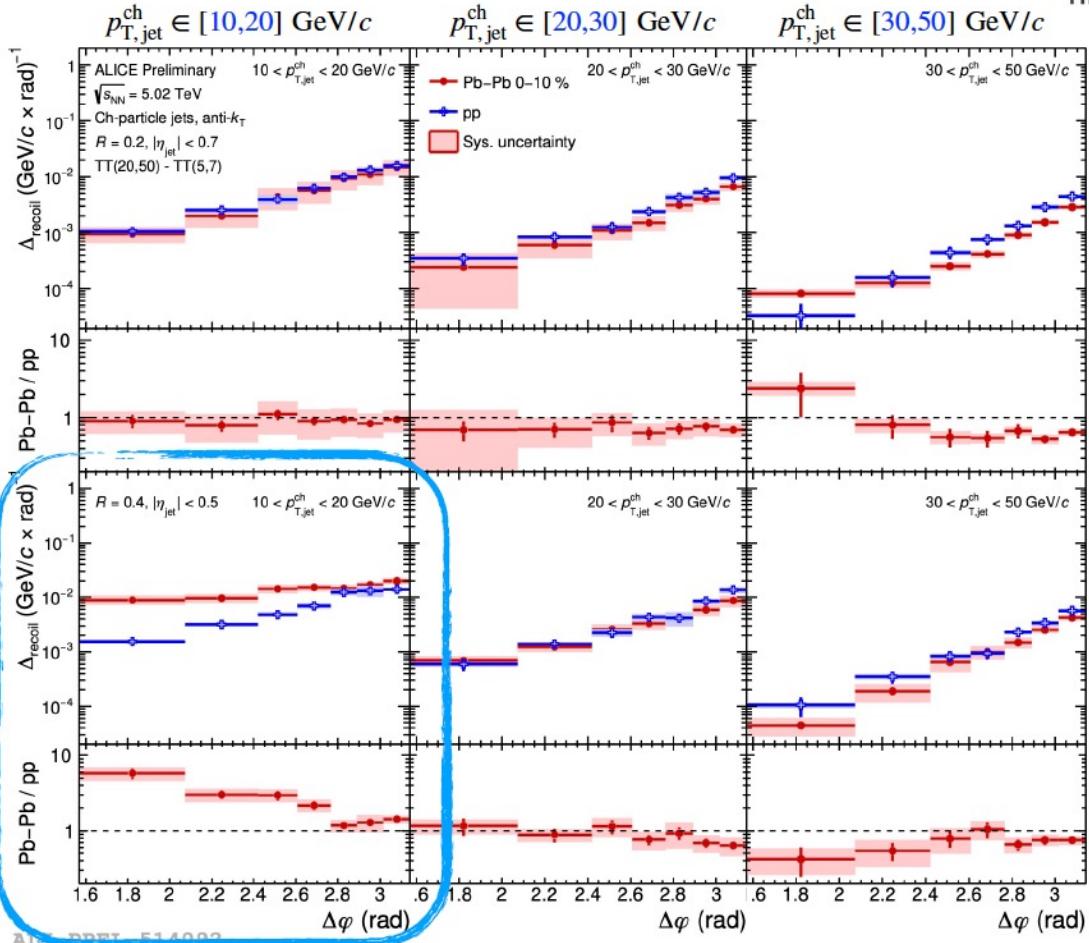
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NEW

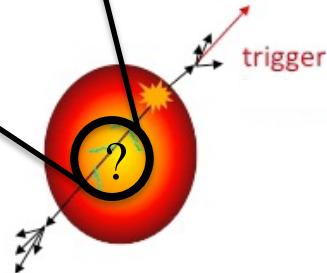
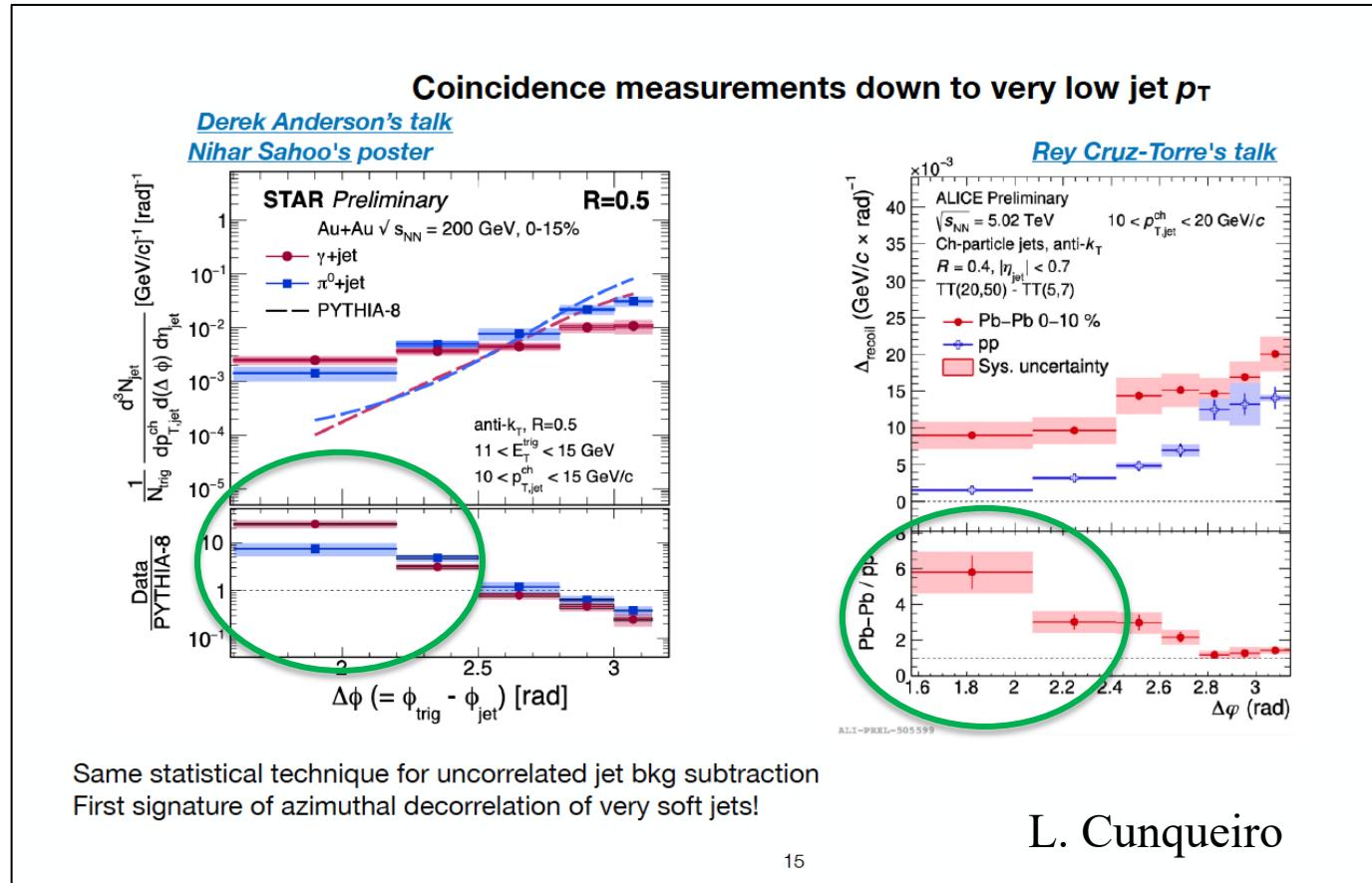
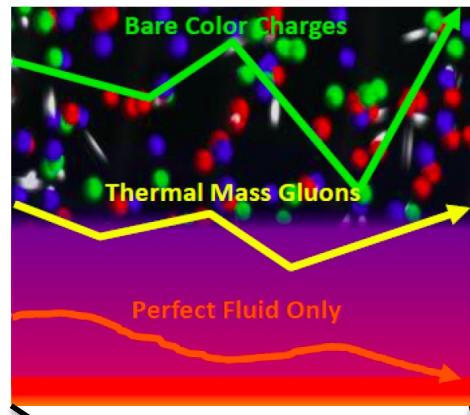
$\Delta\varphi$ results - angular deflections



$R = 0.2$

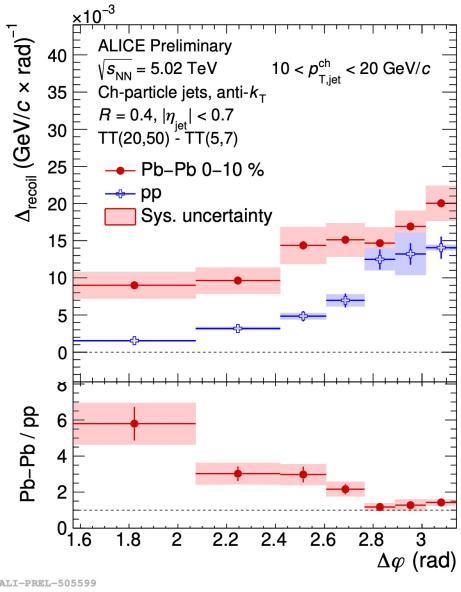
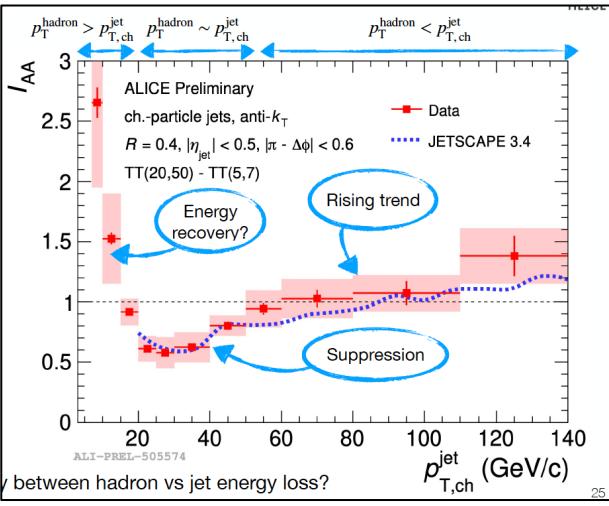


jet azimuthal broadening in QGP

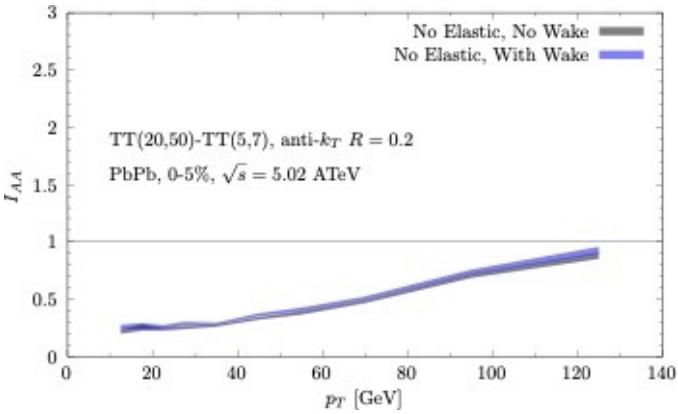


Discrete scattering centers?
Effectively continuous medium?

New angles on acoplanarity

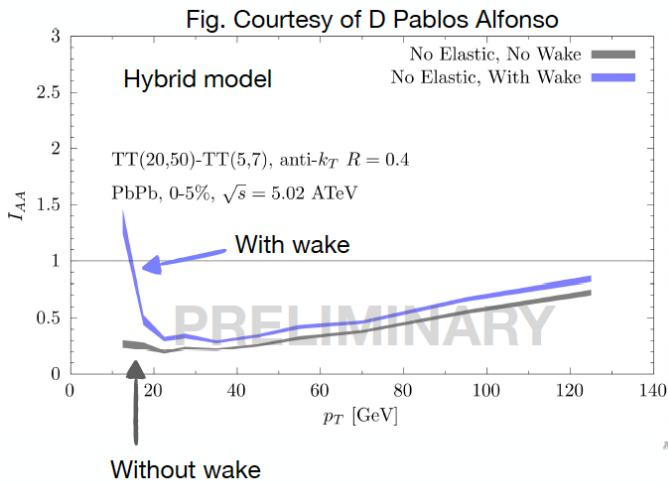
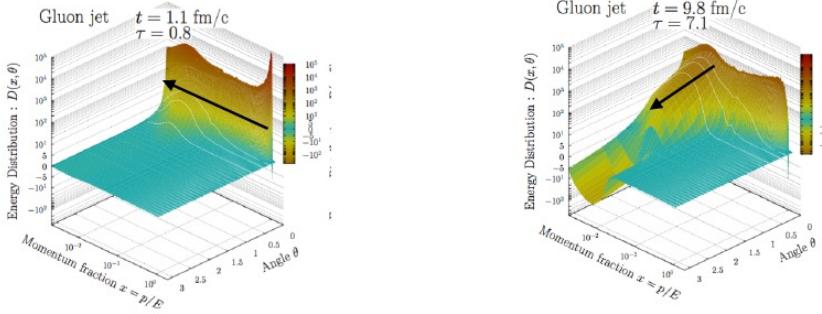


Hybrid model (Dani+Krishna)



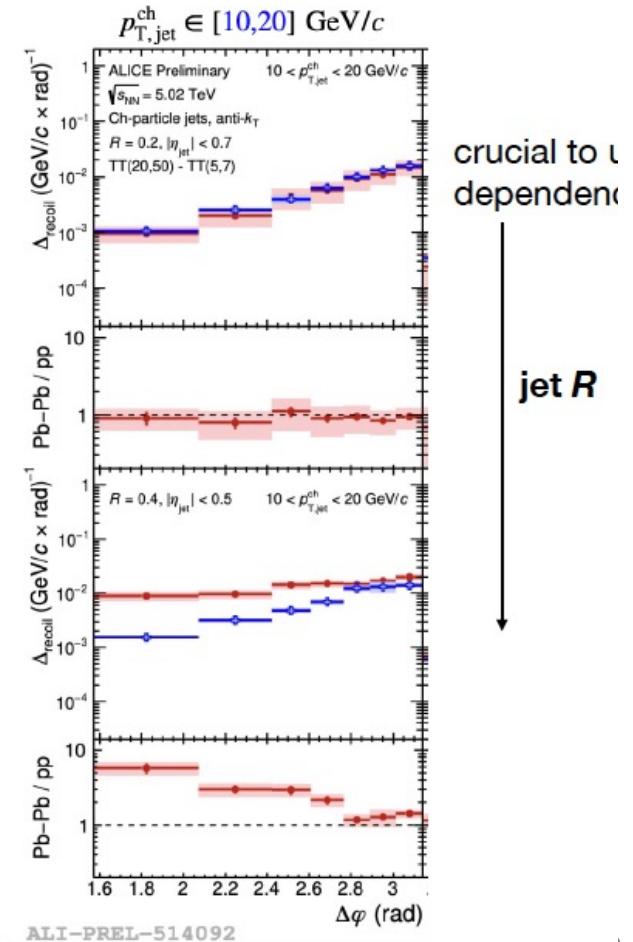
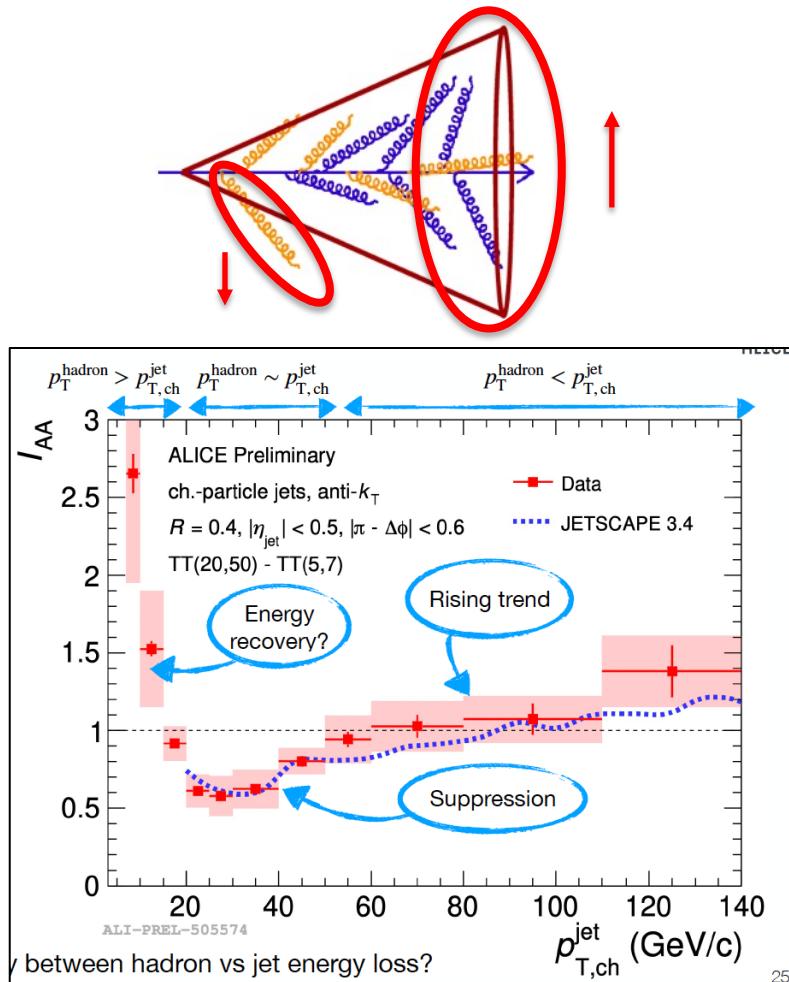
Jet thermalization (Soeren)

Out-of-cone energy loss and thermalization of highly energetic partons/jets governed by nearly collinear cascade + broadening of soft fragments



Alternative: quenched-jet fragments + energy conservation

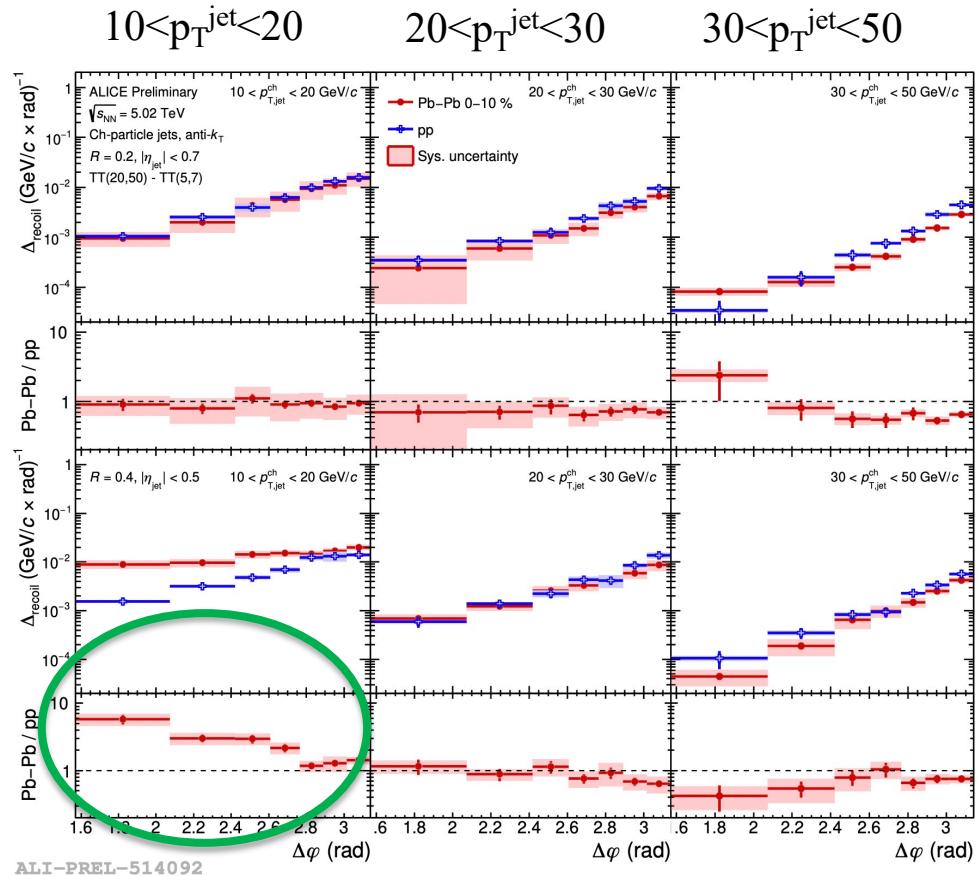
- enhancement at low p_T^{jet} and large angle are shower fragments stripped from higher energy jets (energy loss!)
- consistent with medium-induced narrowing of substructure at high p_T^{jet} ?



Next steps

Striking dependence on
R and p_T^{jet}

R=0.2



Conjecture: enhanced yield at low p_T^{jet} and large R us due to diffuse radiation

- Medium response, jet fragments,...

Then driving parameter to collect 10 GeV is R^2 , not R

→ measure jet profile/internal structure of this population

Extra slides