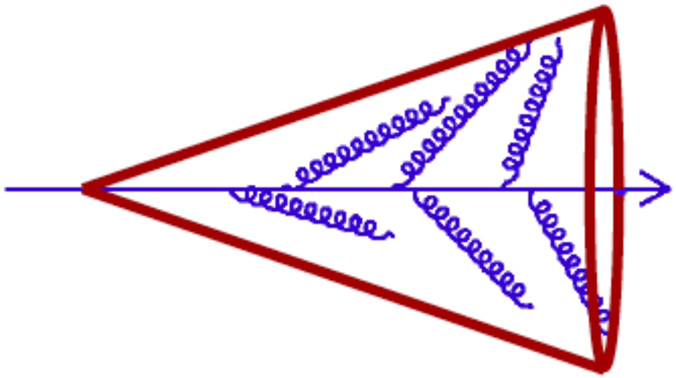
News from the jet quenching front

Peter J.
RNC Group Meeting, Nov. 3

Jet quenching in one slide

Jet shower in vacuum

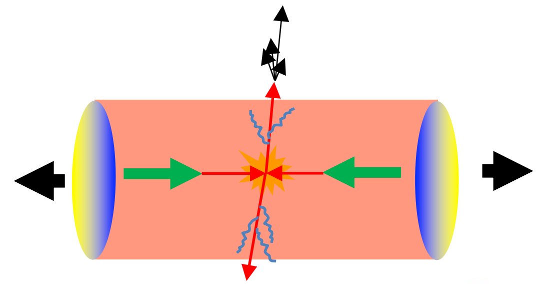


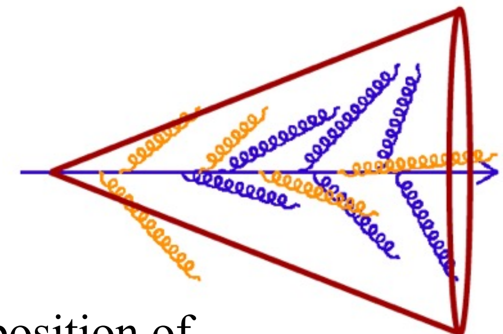
Evolution of highly virtual parton via gluon radiation

Quantum interference → angle-ordering

- hardest radiation is most collinear with jet axis
- Precise understanding in pQCD
- Accurately calculable with QCD-based Monte Carlo models

Jet shower in-medium





Superposition of

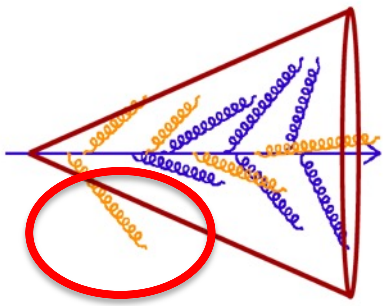
- vacuum shower
- medium-induced gluon emission

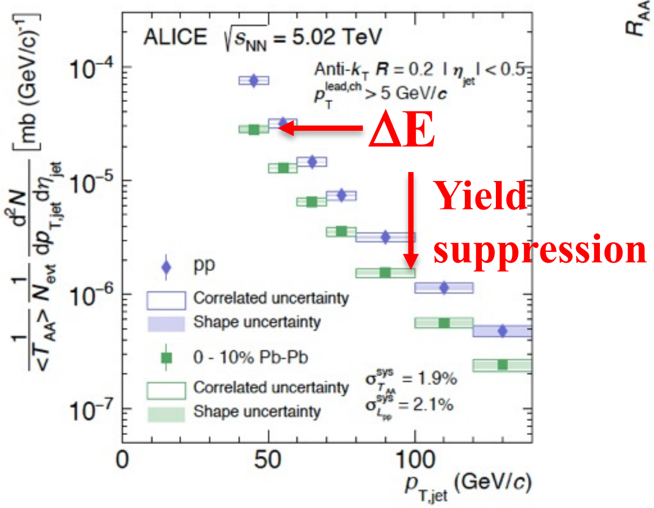
These processes happen simultaneously and interfere

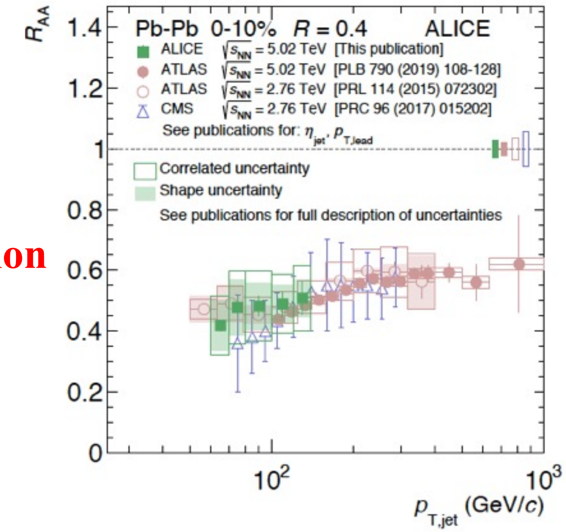
Angle-ordering is modified or destroyed

Jet quenching: observable consequences I

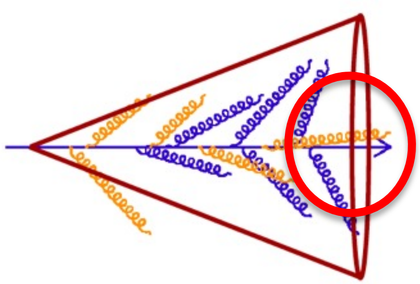
1. Energy loss

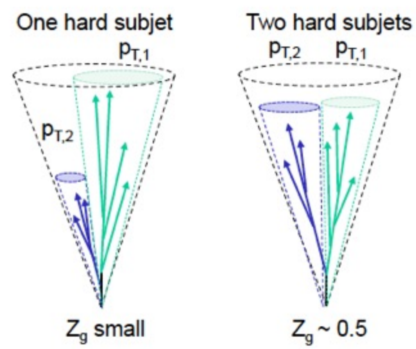




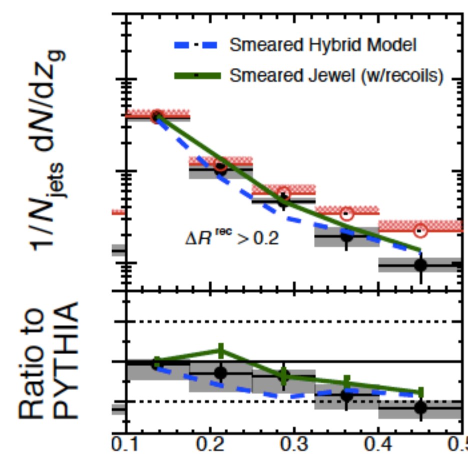


2. Modification of jet substructure



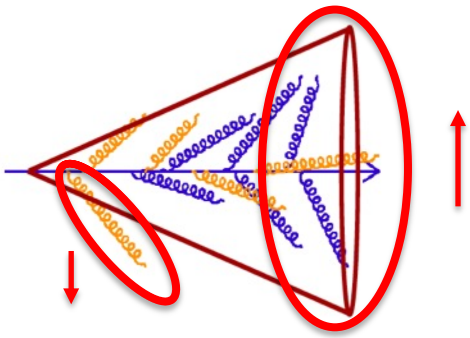


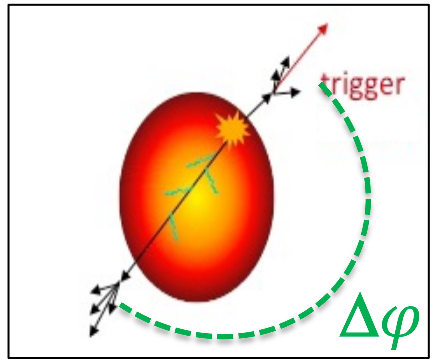
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

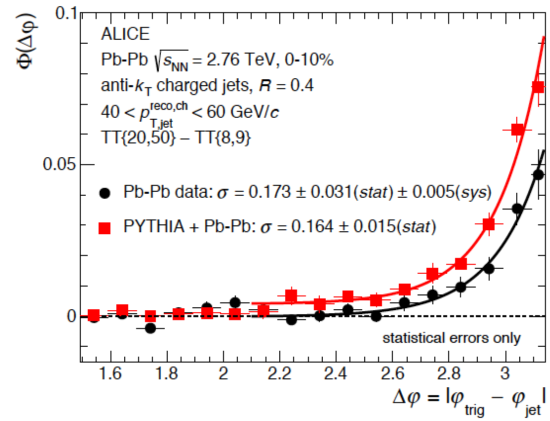


Jet quenching: observable consequences II

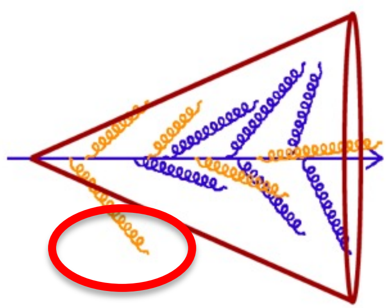
3. Jet deflection

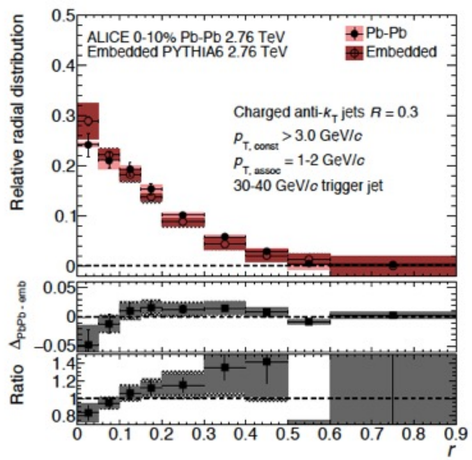


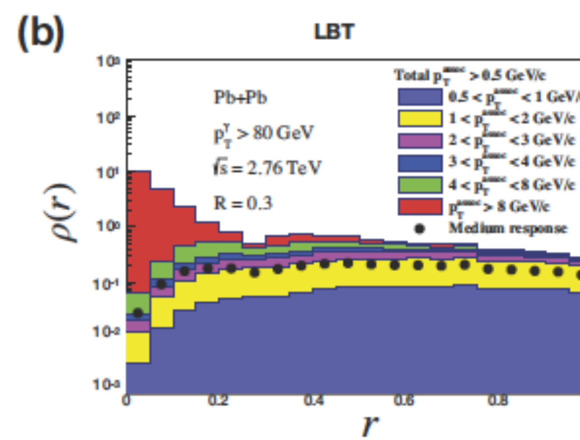




4. Recovery of large-angle radiation







Jet quenching: observable consequences III

Four distinct manifestations of jet quenching:

- Jet energy loss
- Jet substructure modification
- Jet deflection
- Large-angle radiation

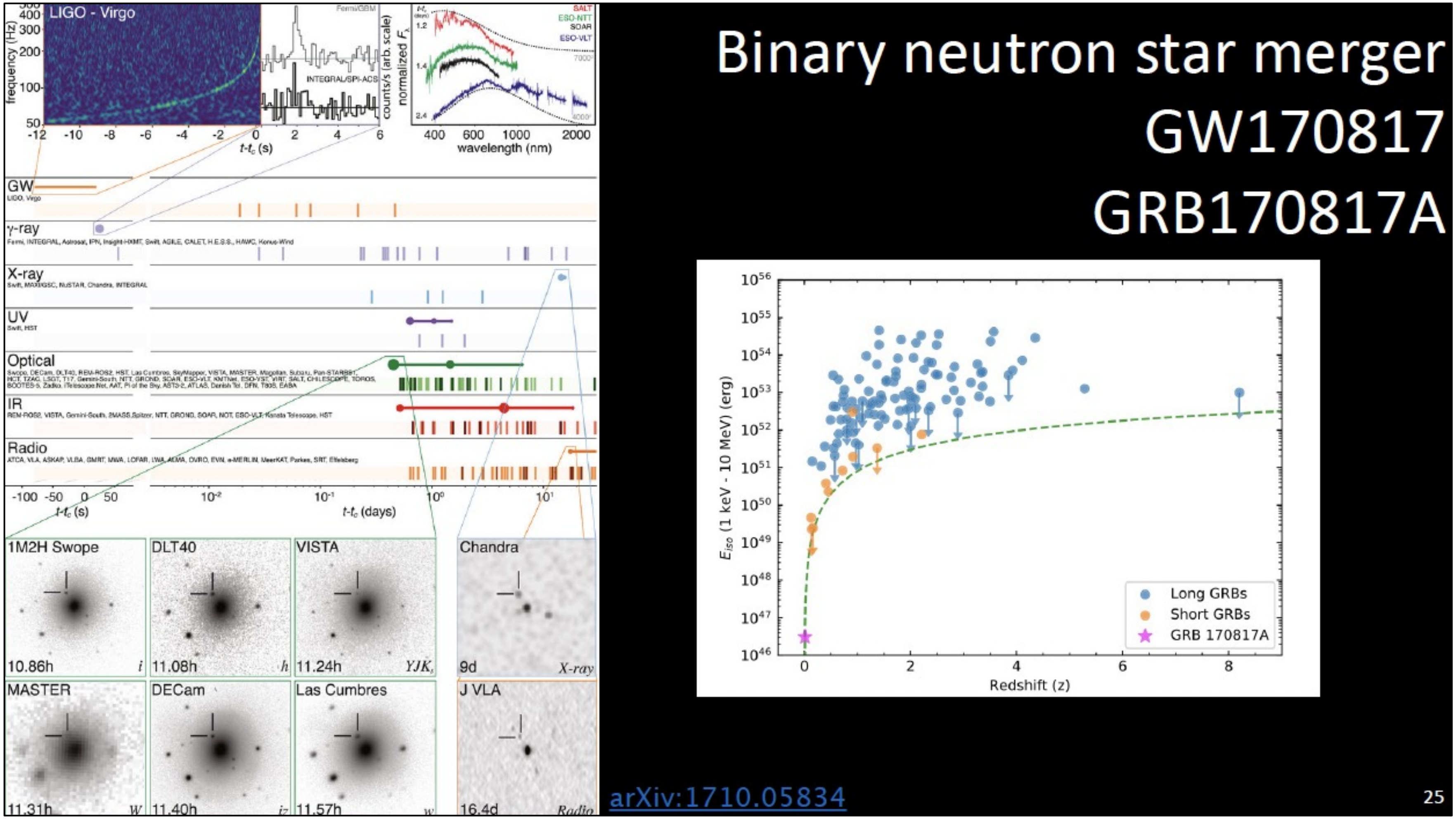
Different manifestations of same underlying physics

- All must occur if any of them does
- Probe different aspects of jet quenching
- Different experimental systematics as fn of kinematics and collision system
- Different theoretical sensitivity as fn of kinematics and collision system

Multi-messenger physics!
Measure the same physics multiple ways and require consistency

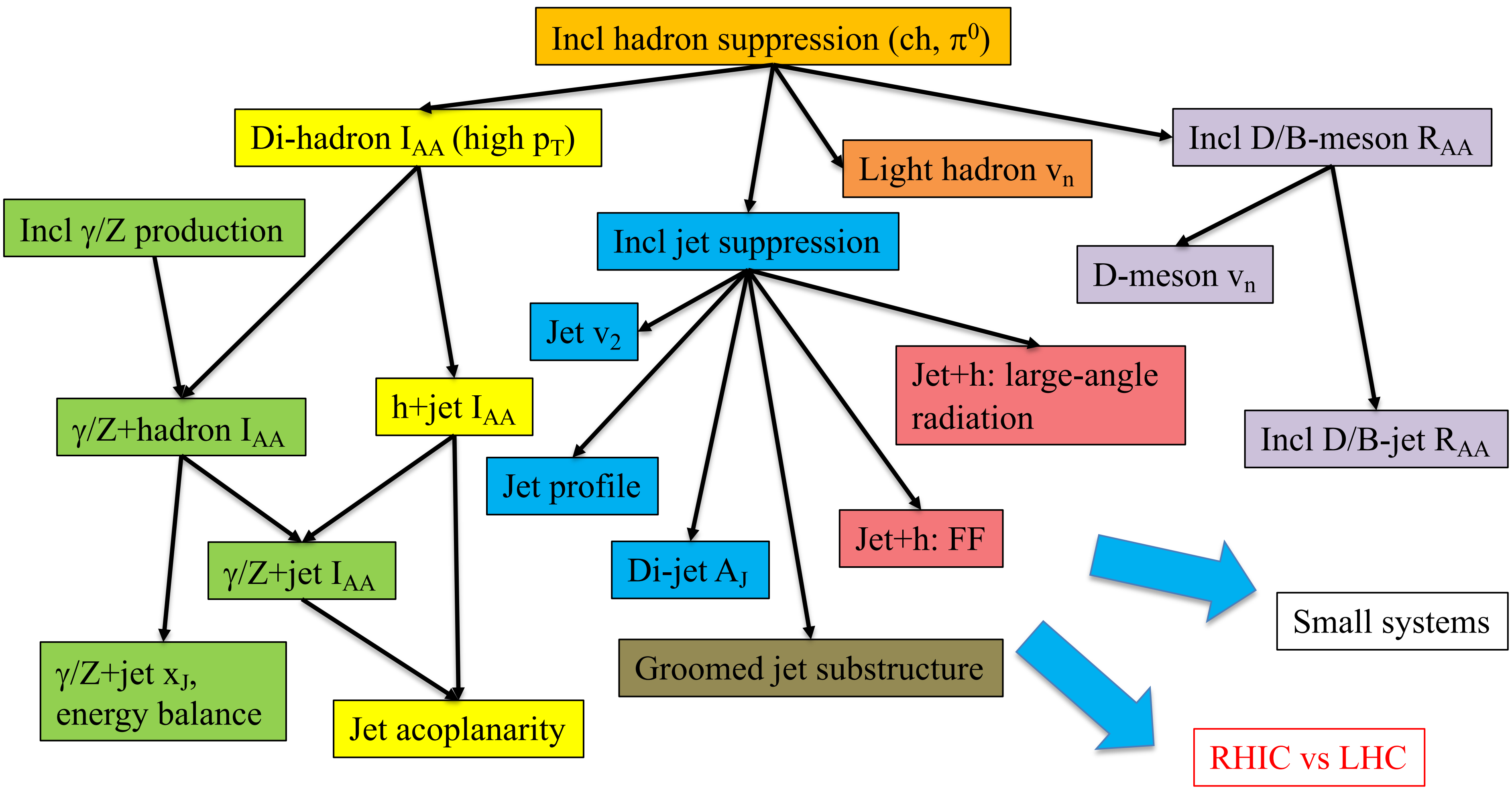
Multi-messenger physics: another example

G. De Wasseige, ICHEP 2022



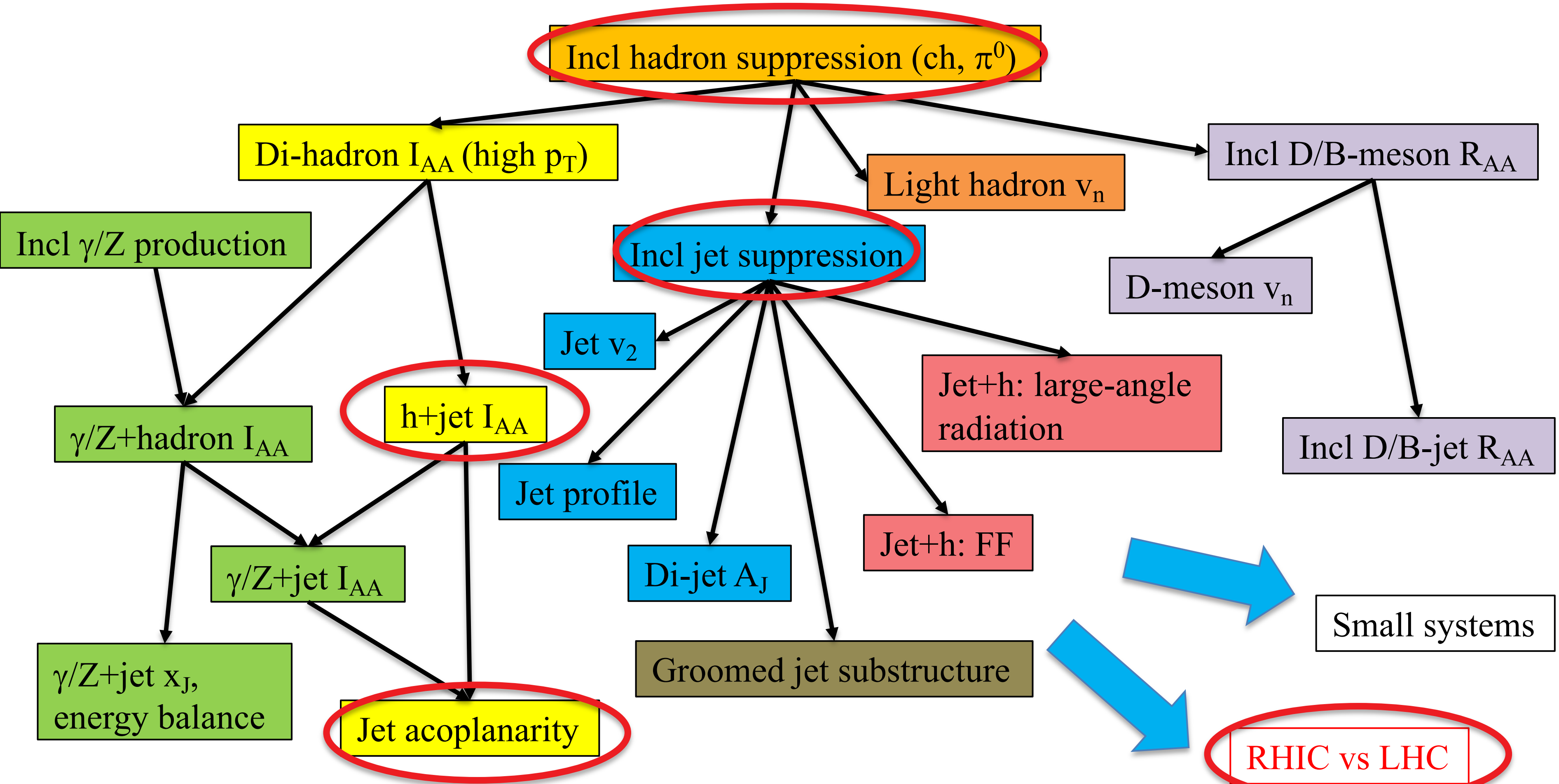
Taxonomy of current jet quenching measurements

Driven by experimental considerations: arrows connect observables with just one thing changed



Too many messengers - confusing!
How to make sense of so many observables?

Go systematically: start with a few key measurements and build up the picture…



= my preferences; others may choose differently (e.g. jet substructure)

QUARK MATTER KRAKÓW 2022 / STAR

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

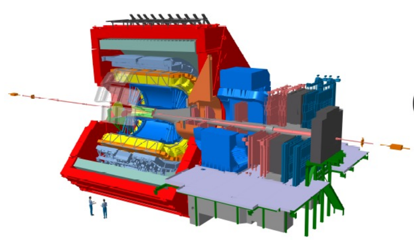
Supported in part by:
U.S. DEPARTMENT OF ENERGY | Office of Science

Texas A&M University

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

BERKELEY LAB | ALICE



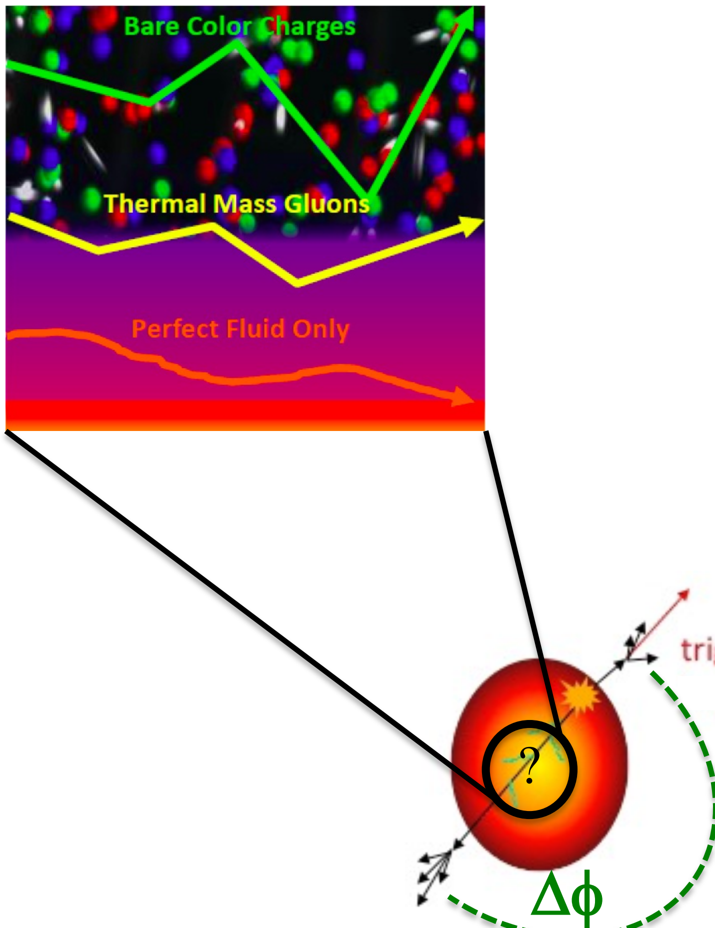
QUARK MATTER KRAKÓW 2022

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

Jet acoplanarity: in-medium hard scattering

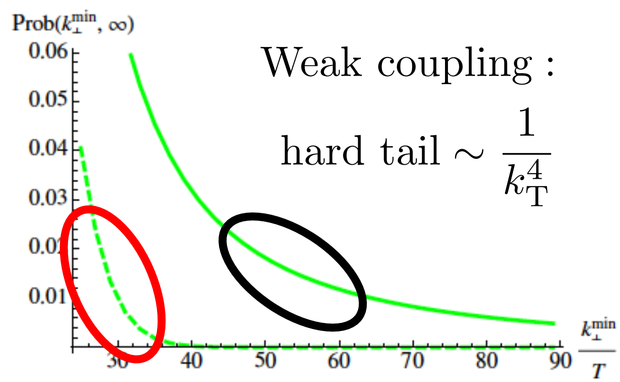
("Rutherford experiment")

Discrete scattering centers or effectively continuous medium?



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

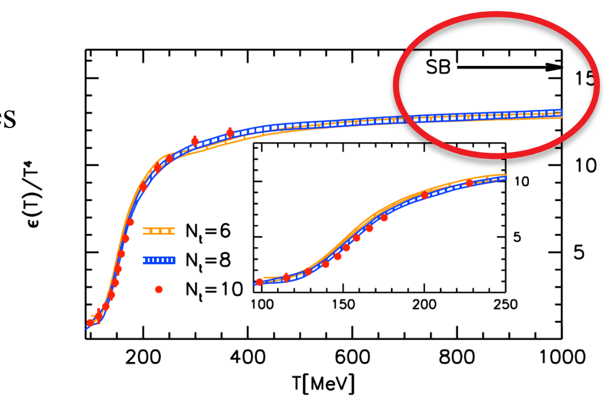
Distribution of momentum transfer k_T



Strong coupling:
Gaussian distribution

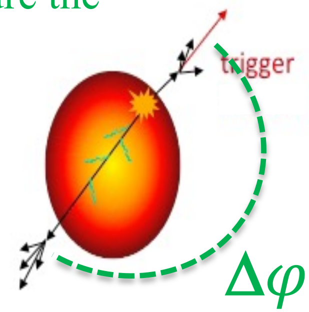
What are the quasi-particles?

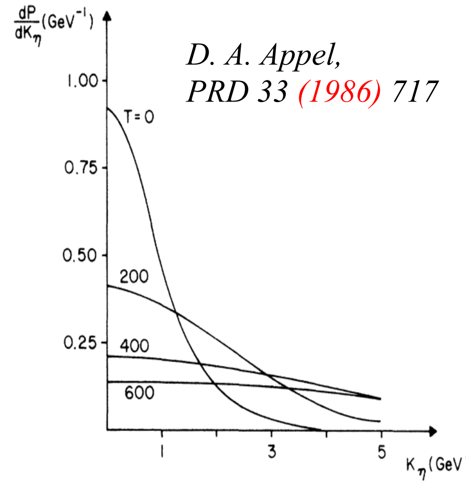
- high Q^2: bare q and g
- low-ish Q^2:
  - thermal-mass glue
  - magnetic monopoles
  - …?

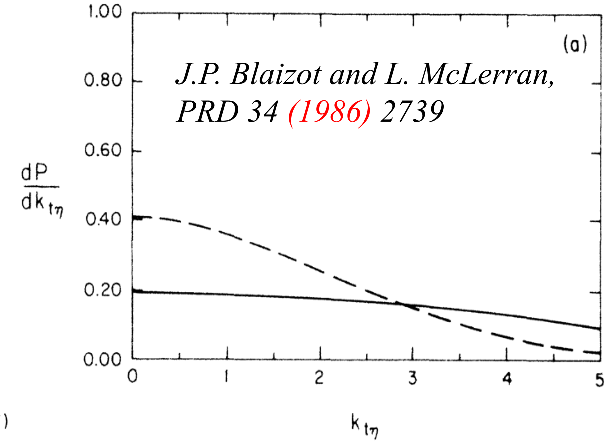


Jet acoplanarity: in-medium multiple scattering

Jet scattering to measure the QGP is an old idea







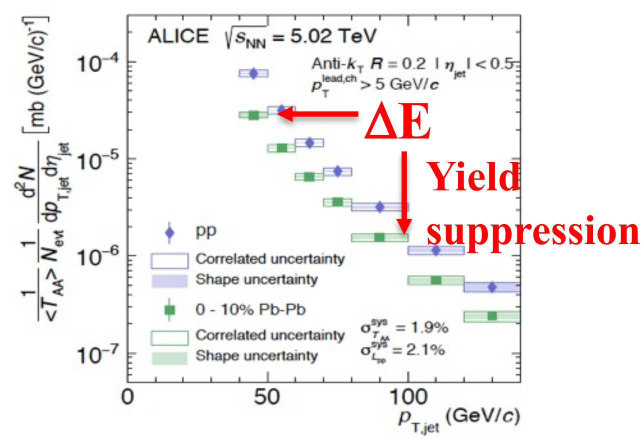
BDMPS: multiple soft scattering

Medium-induced jet energy loss:

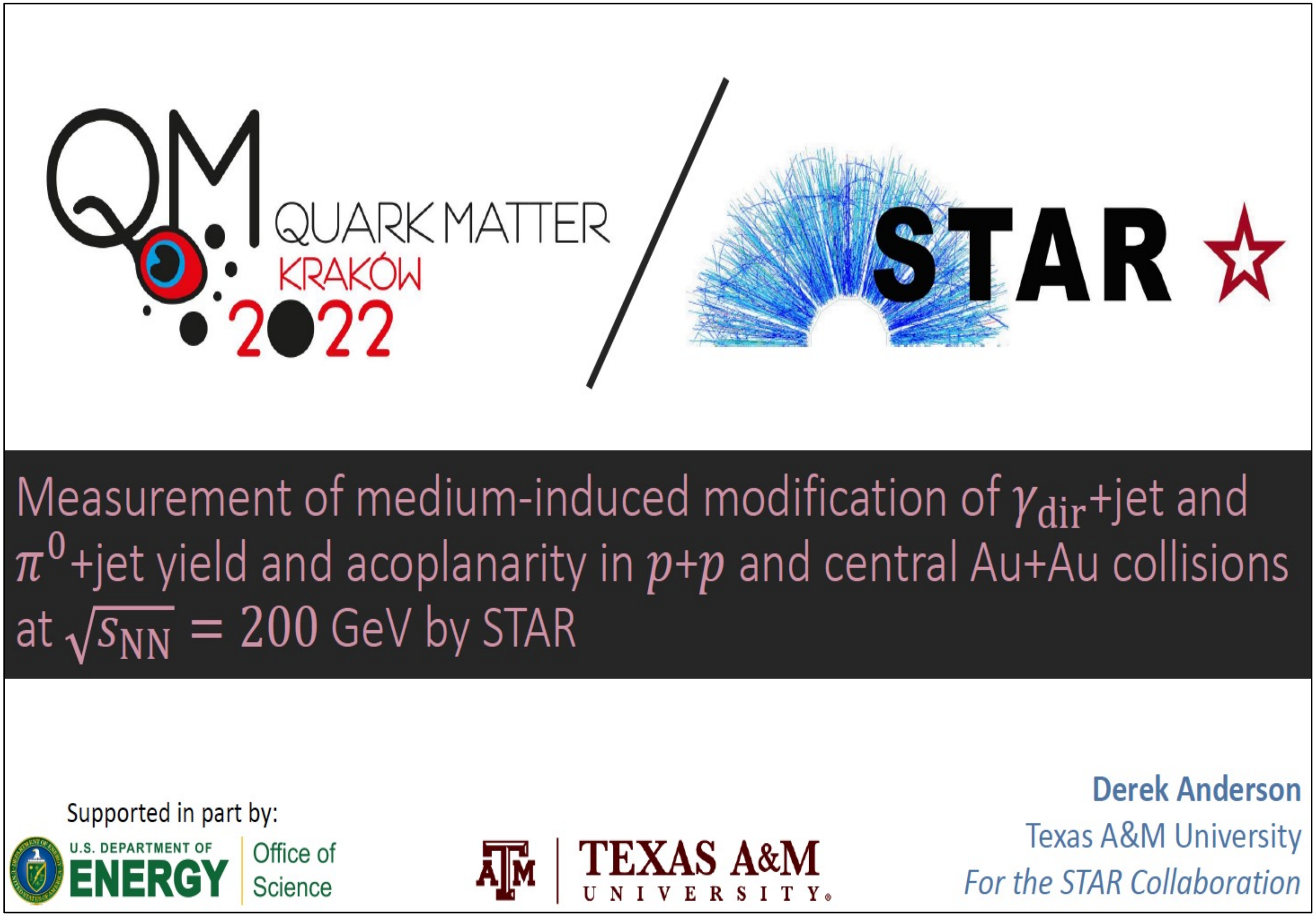
$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

Medium-induced angular broadening:

$$\langle k_{\mathrm{T}}^2 \rangle \sim \langle \Delta\varphi^2 \rangle \sim \alpha_s \hat{q} L$$

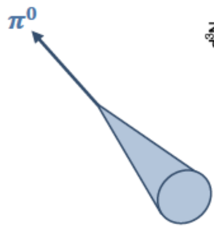


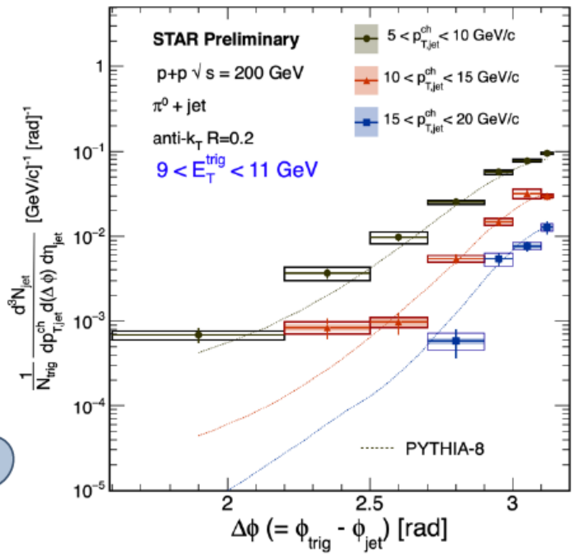
Expect largest acoplanarity at low p_T^{jet} → experimentally challenging

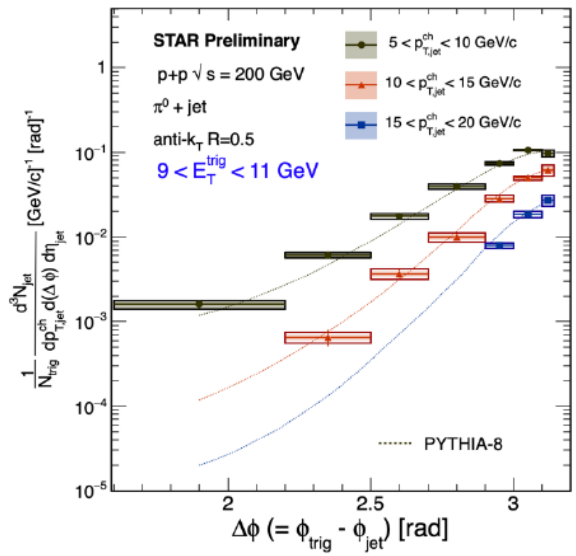

QM
QUARK MATTER
KRAKÓW
2022
STAR
Measurement of medium-induced modification of γ_{dir}+jet and π^0+jet yield and acoplanarity in p+p and central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by STAR
Supported in part by:
U.S. DEPARTMENT OF ENERGY
Office of Science
TEXAS A&M UNIVERSITY
Derek Anderson
Texas A&M University
For the STAR Collaboration

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

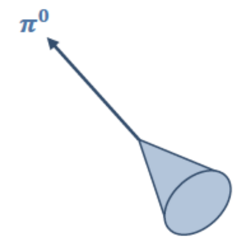
$R = 0.2$







$R = 0.5$



Nihar Sahoo poster [Wed T04_1]

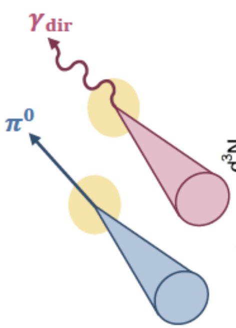
$E_T^{trig} = [9, 11]$ **GeV**

- 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
  - ∴ **NLO calculations needed**

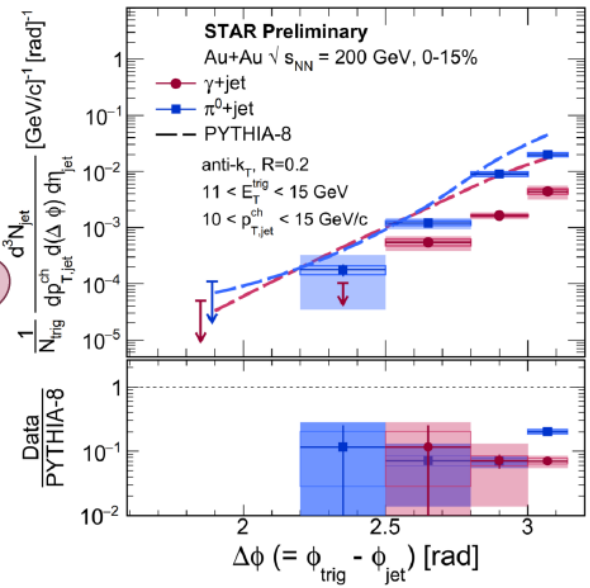
April 5th, 2022 Derek Anderson, QM 2022 18/21

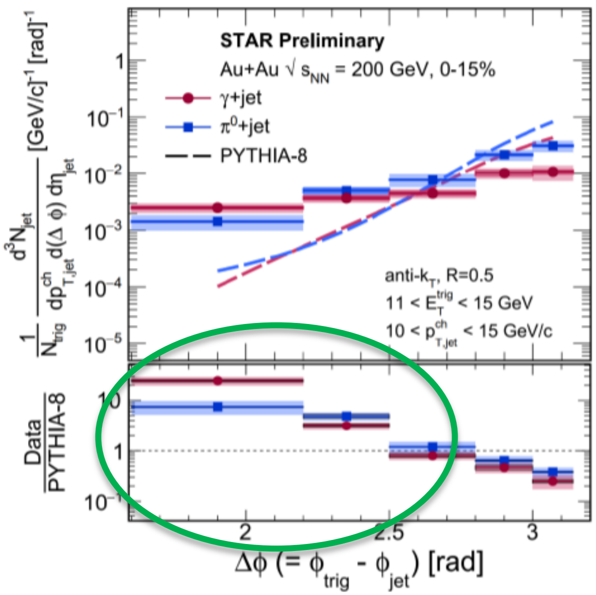
Corrected $\Delta\phi$ distributions in Au+Au collisions

$R = 0.2$

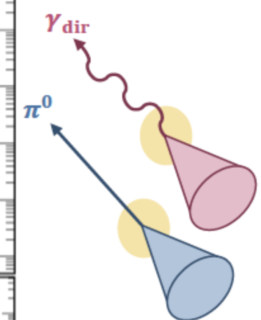


Nihar Sahoo poster [Wed T04_1]





$R = 0.5$



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

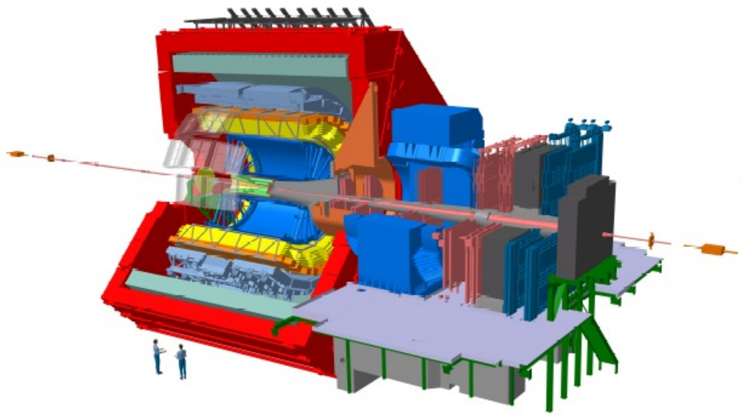
a) Scattering off QGP quasi-particles

b) Multiple soft scatters

April 5th, 2022 Derek Anderson, QM 2022 19/21

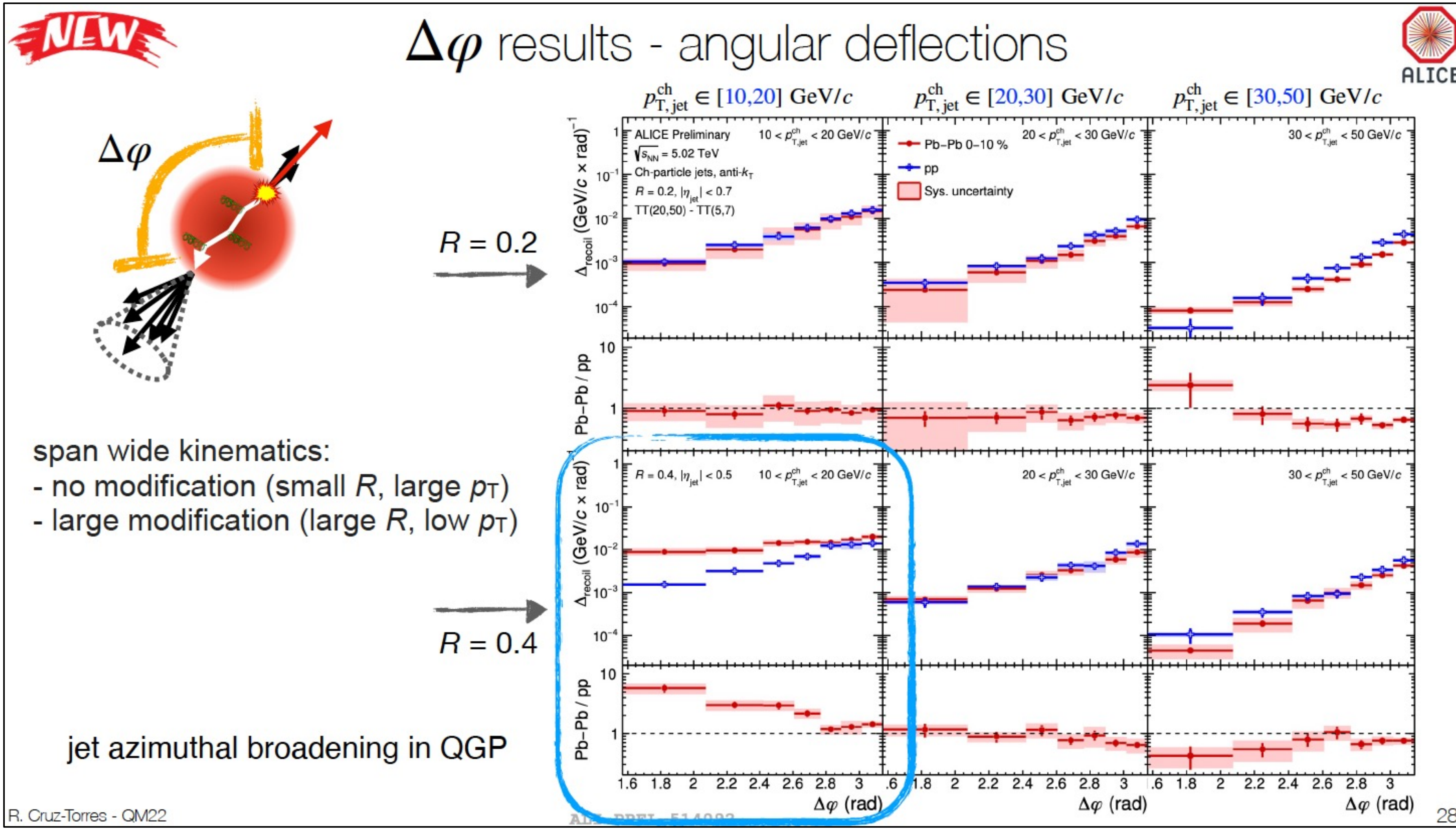
Jet acoplanarity and energy flow within jets in Pb-Pb and pp collisions with ALICE

BERKELEY LAB ALICE



QM QUARK MATTER KRAKÓW 2022

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


NEW
Δφ results - angular deflections
ALICE
Δφ
R = 0.2
R = 0.4
span wide kinematics:
- no modification (small R, large pT)
- large modification (large R, low pT)
jet azimuthal broadening in QGP
R. Cruz-Torres - QM22
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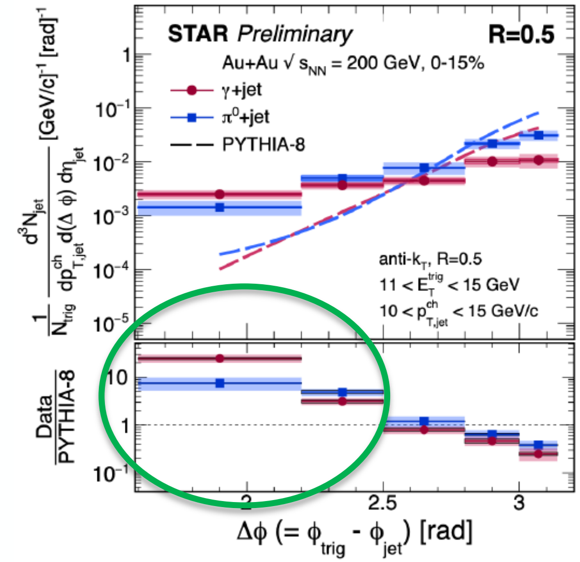
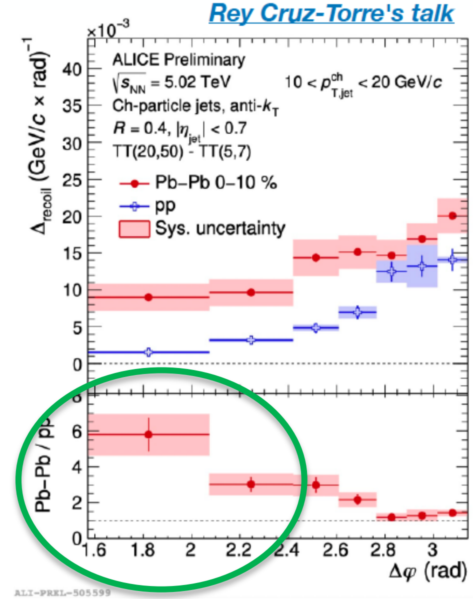
p^ch_T,jet ∈ [10,20] GeV/c
p^ch_T,jet ∈ [20,30] GeV/c
p^ch_T,jet ∈ [30,50] GeV/c
ALICE Preliminary
√sNN = 5.02 TeV
Ch-particle jets, anti-kT
R = 0.2, |ηjet| < 0.7
TT(20,50) - TT(5,7)
R = 0.4, |ηjet| < 0.5
10 < p^ch_T,jet < 20 GeV/c
20 < p^ch_T,jet < 30 GeV/c
30 < p^ch_T,jet < 50 GeV/c
Pb–Pb 0–10 %
pp
Sys. uncertainty
Δrecoil (GeV/c × rad)^-1
Pb–Pb / pp
Δφ (rad)

Coincidence measurements down to very low jet p_T

Derek Anderson's talk
Nihar Sahoo's poster

Rey Cruz-Torre's talk





Same statistical technique for uncorrelated jet bkg subtraction
First signature of azimuthal decorrelation of very soft jets!

L. Cunqueiro

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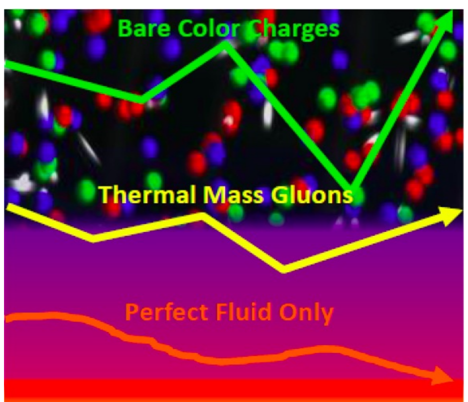
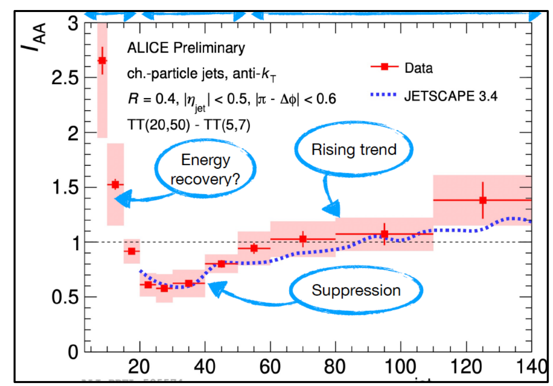
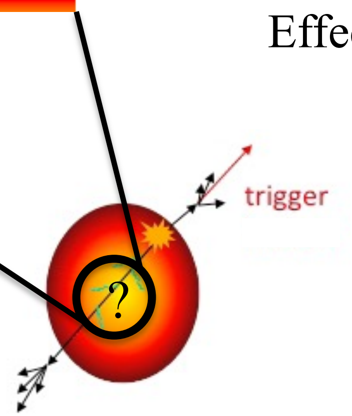


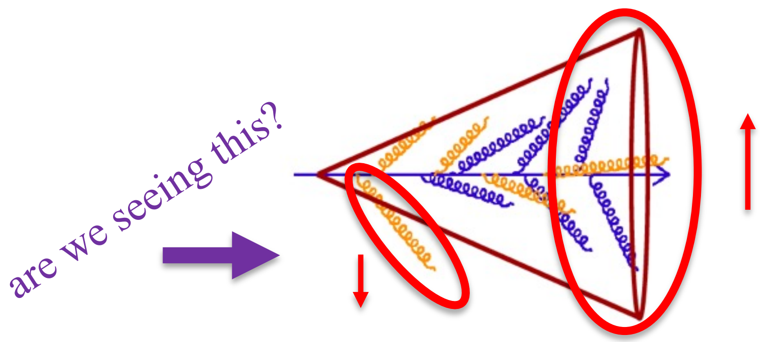
Discrete scattering centers?
Effectively continuous medium?

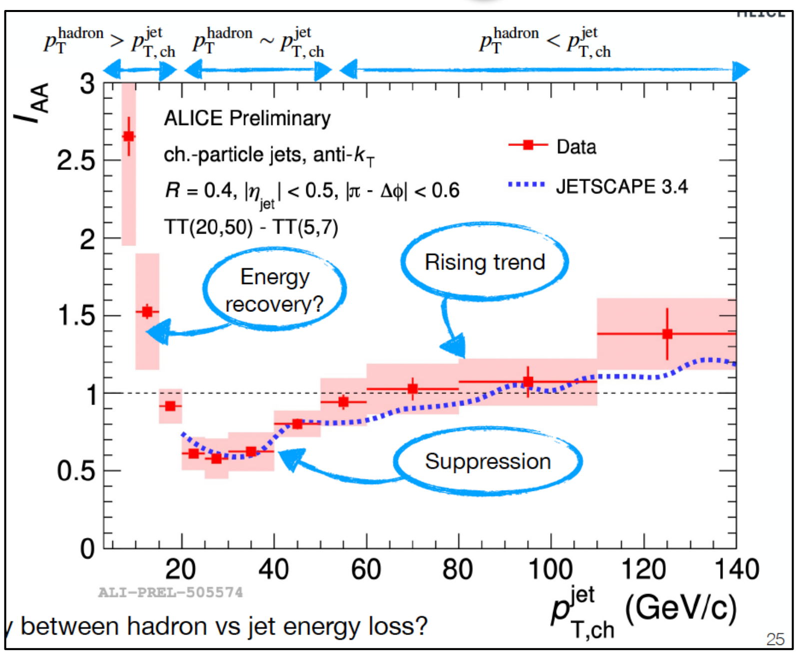


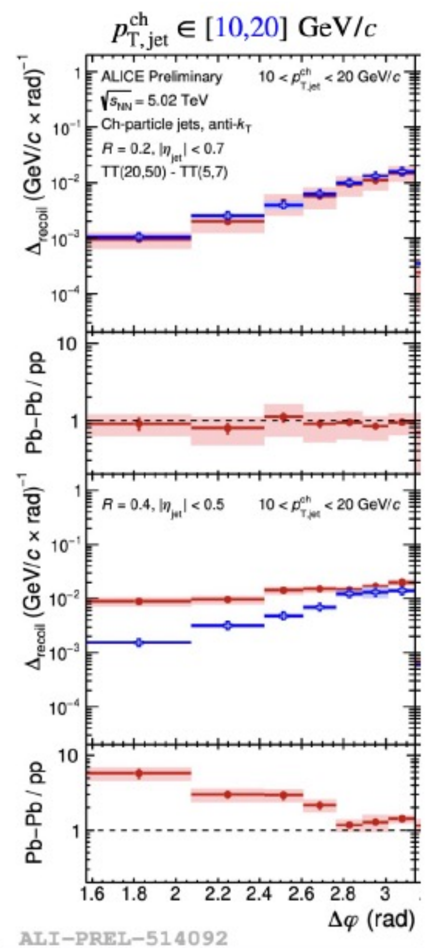


Alternative: quenched-jet fragments + energy conservation

- Recovery of lost energy: yield enhancement at low p_T^{jet} and large angle are shower fragments stripped from higher energy jets
- consistent with medium-induced narrowing of substructure at high p_T^{jet}?

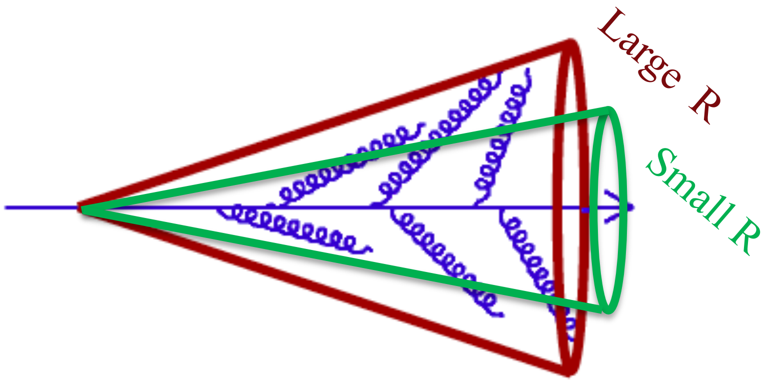






crucial to u
dependen
jet R

Jet shape in pp: inclusive jets

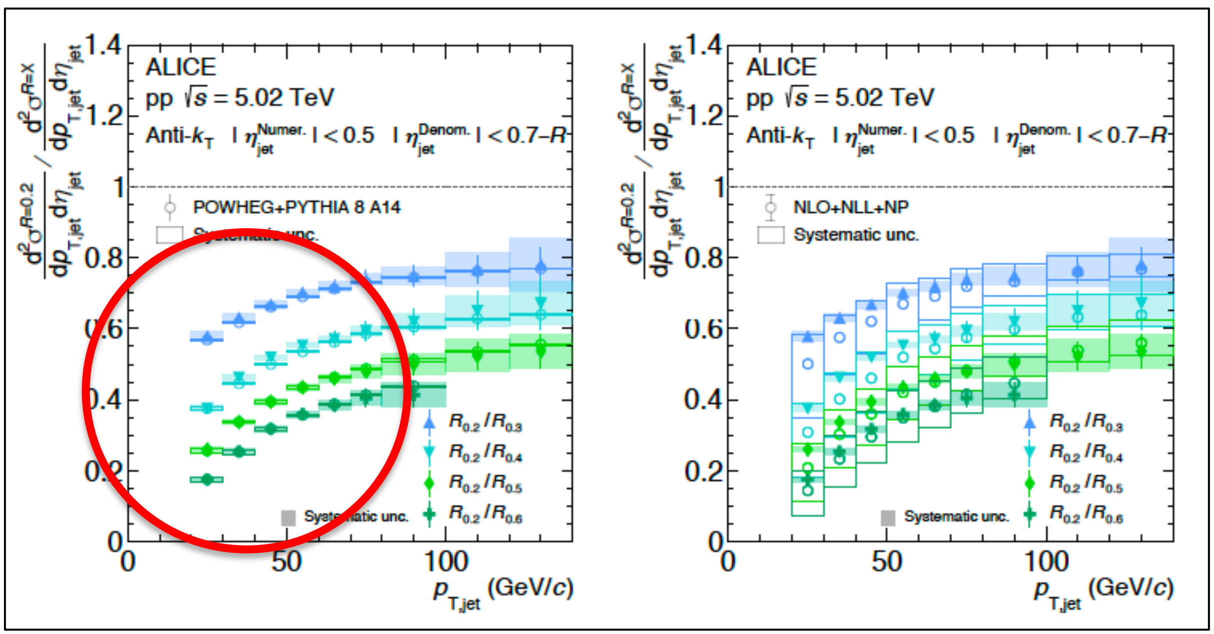


Average jet transverse profile in vacuum:

- peaked near jet axis
- Long tail to large angles
- Low-p_T jets are wider

Observable: incl jet cross section ratio
small-R/large-R

Phys.Rev.C 101 (2020) 034911

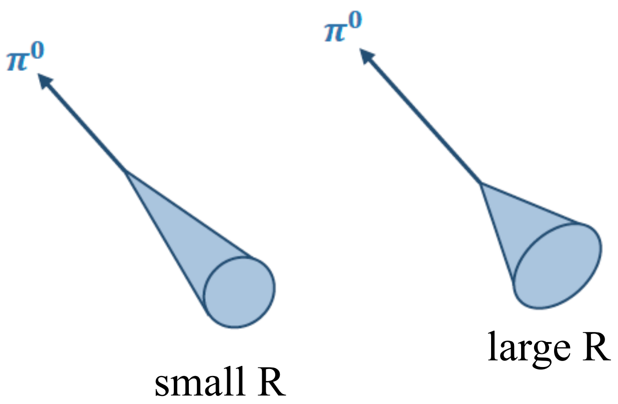


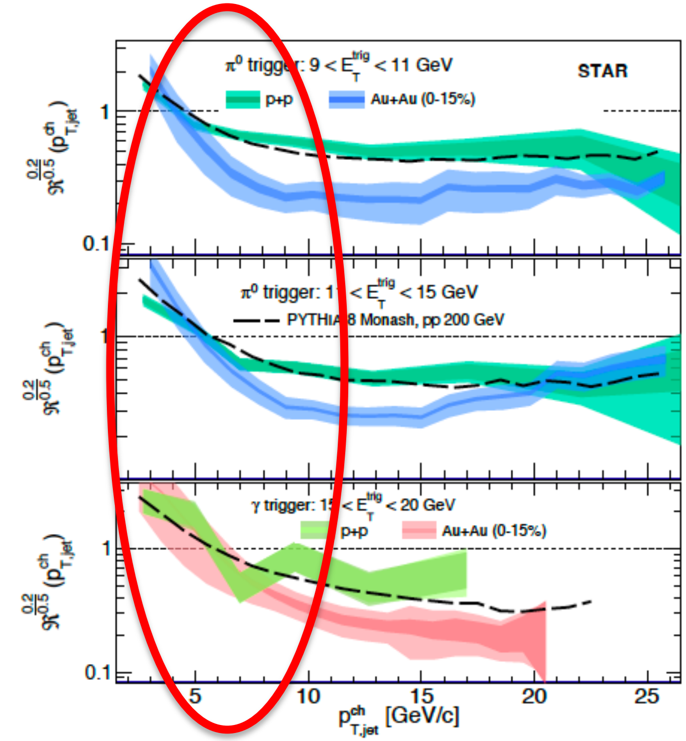
James's thesis analysis!

Ratio<1 and decreasing to lower p_T: agrees with above picture

Both features well-described by QCD calculations

Jet shape in pp: coincidence channels

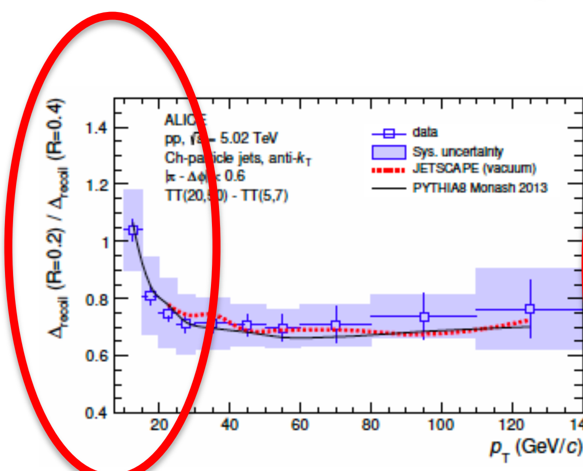


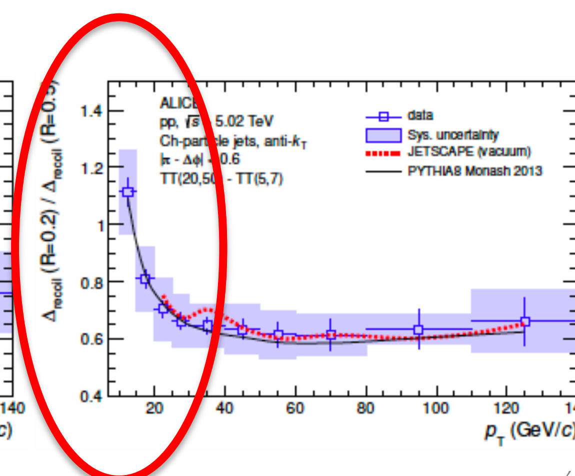


Take ratio of trigger-normalized recoil yield small-R/large-R

Opposite behavior at low p_T!

- seen in both STAR and ALICE pp measurements
- Well-described by PYTHIA





What's going on?

Jet production at LO:
- 2→2 process
- Jets are back-to-back and balanced in p_T

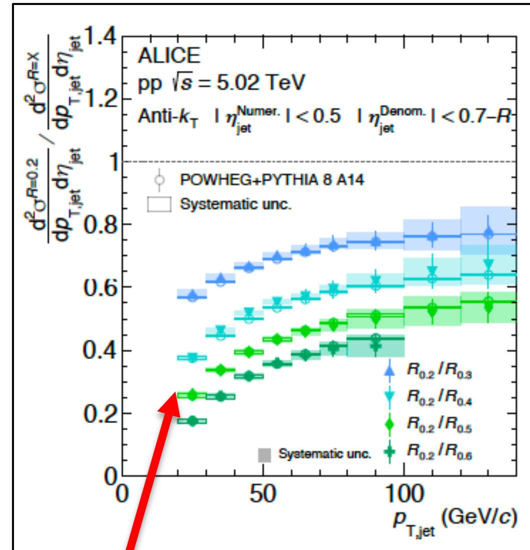
Triggered correlation
- trigger: h, π^0, γ
- trigger has p_T threshold
- LO: recoil jet p_T must exceed threshold

Define: $\tilde{z} = \dfrac{p_{\mathrm{T,jet}}^{\mathrm{recoil}}}{p_{\mathrm{T,trig}}}$

$\tilde{z} < 1$: LO suppressed!

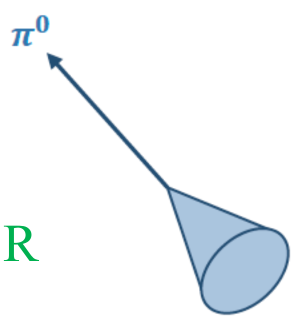
Large-angle gluon radiation → small R more often sees two jets

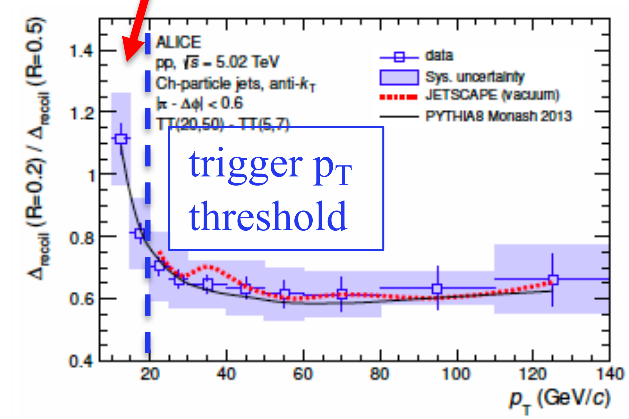
inclusive



?

coincidence





Dial up threshold: new trick to generate a population of "fat jets" ? (Krishna et al.)

Next steps

Both ALICE and STAR analyses are proceeding towards publication
- Since QM: finalizing analysis, new theory calculations

STAR:
- Long PRC paper detailing analysis
- PRL: IAA, R-dependence of yields
- PRL: acoplanarity (systematics not yet complete)

ALICE:
- Long PRC paper detailing analysis
- PRL: IAA, R-dependence of yields, acoplanarity

Entirely by chance: both sets of papers will start GPC/IRC within the next ~2 weeks
- On arXiv before HP? Fingers crossed…

For the record: I do not recommend writing five papers at the same time ;-(

Other jet quenching analyses in progress

STAR:

- Inclusive jet RAA with fully reconstructed jets
  - w/ Robert L. and Jana; Robert will be visiting again in December

- Novel approach to prompt photons + correlations in pp and Au+Au
  - w/ Hanseul and Rongrong; HP timescale

ALICE

- Search for jet quenching in pp@13 TeV via acoplanarity
  - w/ Prague group; paper in preparation

- ME a la STAR for incl and coincidence obseravbles
  - Incl Jet RAA down to pTjet~10 GeV
  - w/ Alex + Heidelberg student; HP timescale

- Quasi-particle search using substructure
  - Raymond is driving; paper in preparation

qhat from inclusive hadron and jet R_{AA}

Include new theory developments (coherence effects at high virtuality, arXiv:2204.01163)

Expanded dataset

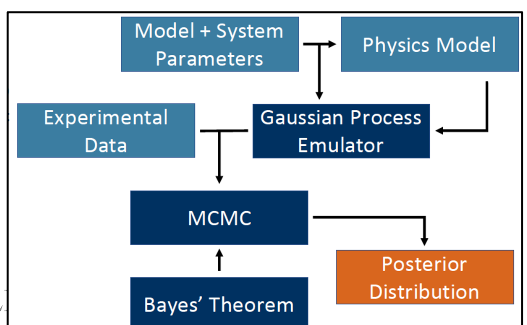
Experiment	$\sqrt{s_{NN}}$	Inclusive R_{AA} observables
STAR	200	jets $R = 0.2, 0.4$
PHENIX	200	π_0 R_{AA}
ALICE	2.76, 5.02	jets $R = 0.2, 0.4$
ATLAS	2.76, 5.02	hadron, jets $R = 0.4$
CMS	2.76, 5.02	hadron, jets $R = 0.2$-0.4

Huge calculational campaign

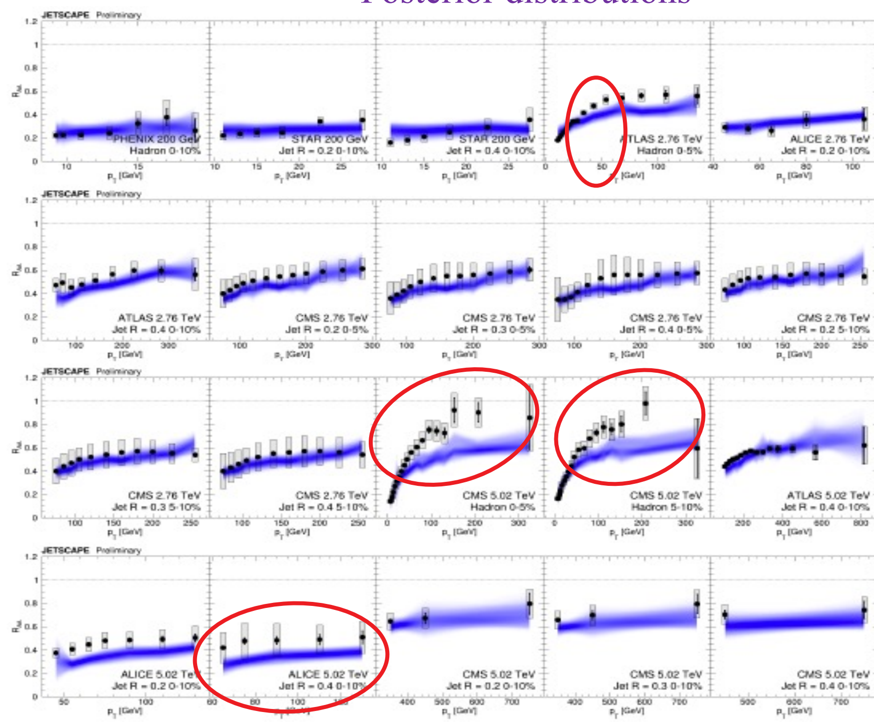
- 5-6 model parameters;
- 200 sample points in parameter space with high statistical precision
- Very large cpu needs; large data volumes
- Utilized several US HPC centers
- Complex facility and data management

Eventually took on the character of a collider run of an experiment

- Start to finish: took 18 months
- Being completed now; will generate multiple papers



Posterior distributions



First look:

- tension in some observables → model is still incomplete
- that's good! it's what we want to learn