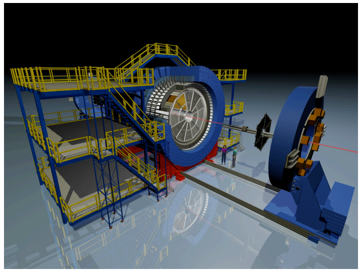
Jet quenching at RHIC and the LHC:
a status report

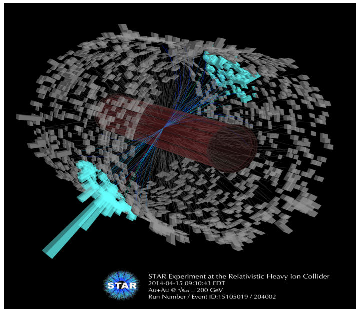
biased

Peter Jacobs

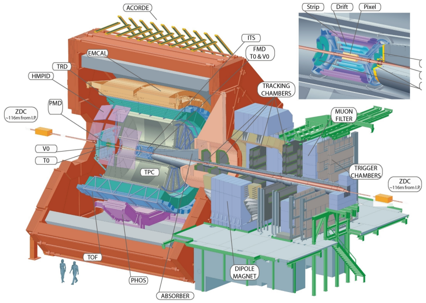
Lawrence Berkeley National Laboratory

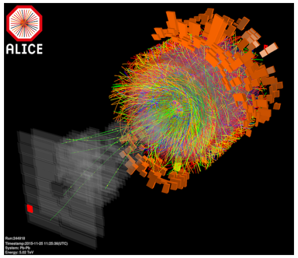
STAR@RHIC



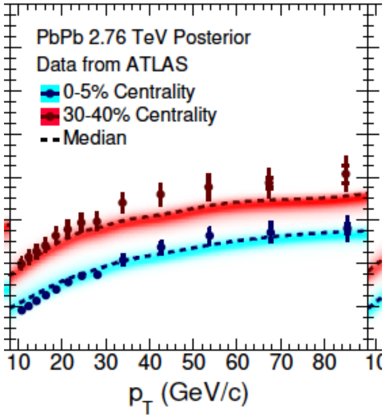

STAR Experiment at the Relativistic Heavy Ion Collider
2014-04-15 09:30:43 EDT
Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
Run Number / Event ID:15105019 / 204002

ALICE@LHC



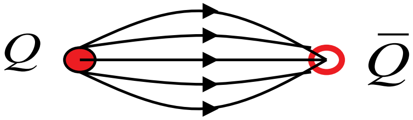


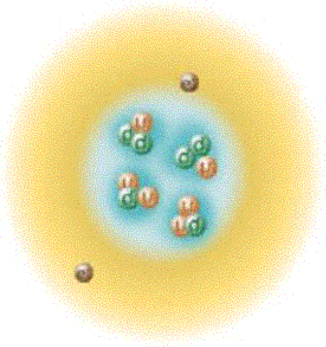
JETSCAPE



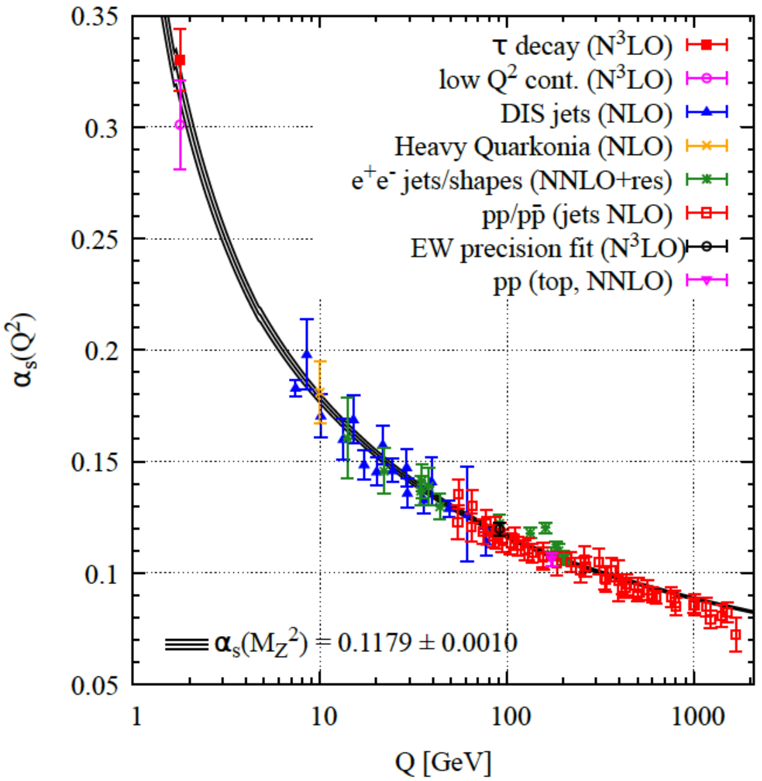
Hallmark of QCD: running of α_s

Confinement





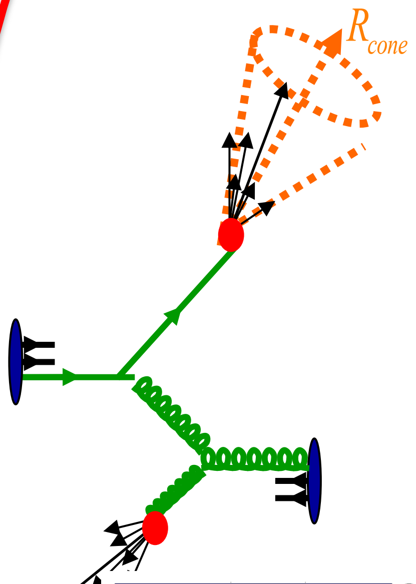
PDG2020

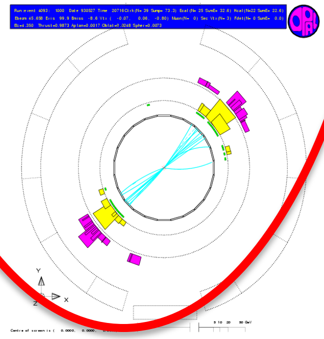


Low momentum

High momentum

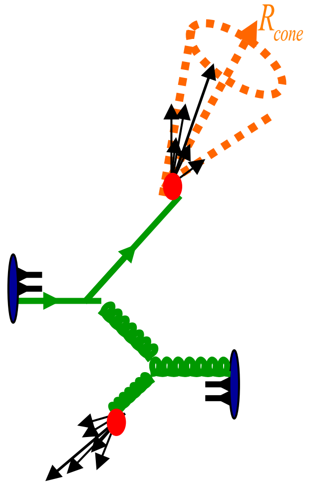
Asymptotic Freedom



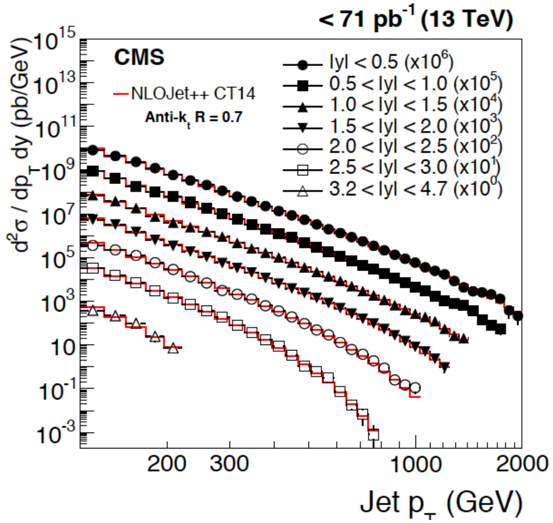


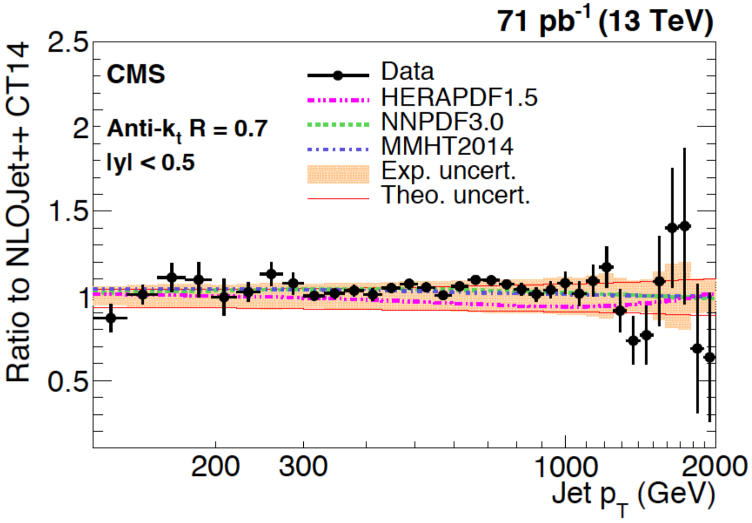
Scattering of energetic quarks and gluons → jets

Testing perturbative QCD: inclusive jet production in p+p collisions



CMS, Eur. Phys. J C76 (2016) 451





Magnificent achievement of QCD

- needed 30 years of development in theory, experiment, and algorithms to connect the two

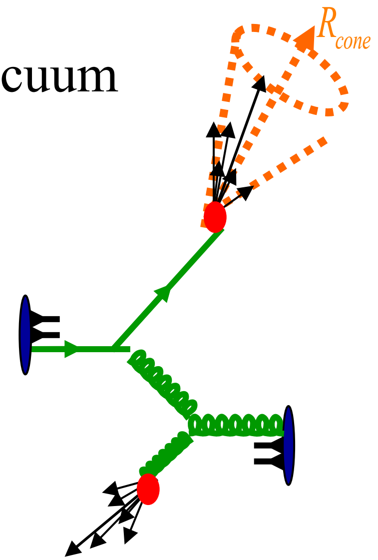
Infrared and collinear-safe (IRC-safe) jet reconstruction algorithms:

- Integrate out all hadron degrees of freedom
- Same procedures applied to pQCD theory and experiment
- Enables direct, precise and improvable comparison of theory/experiment

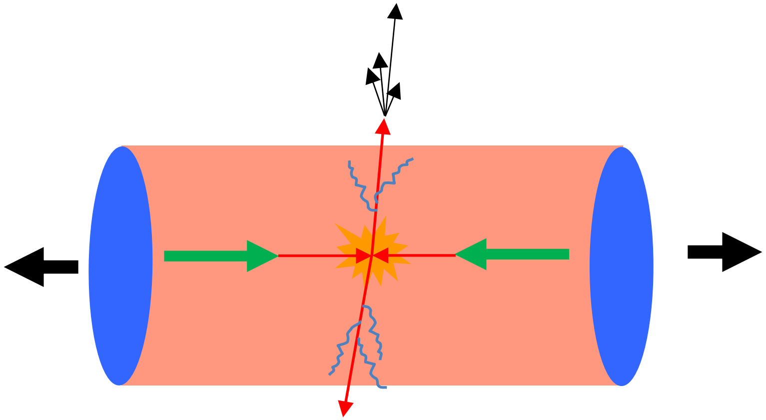
➔ jets measure partons

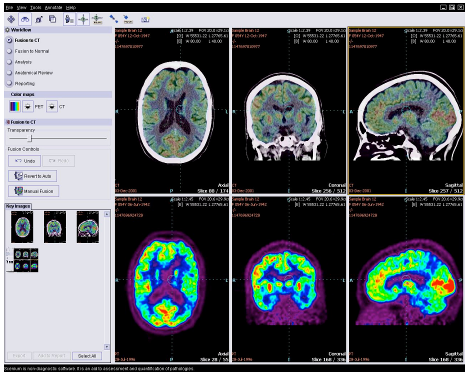
Jets in QCD matter

Jets in vacuum

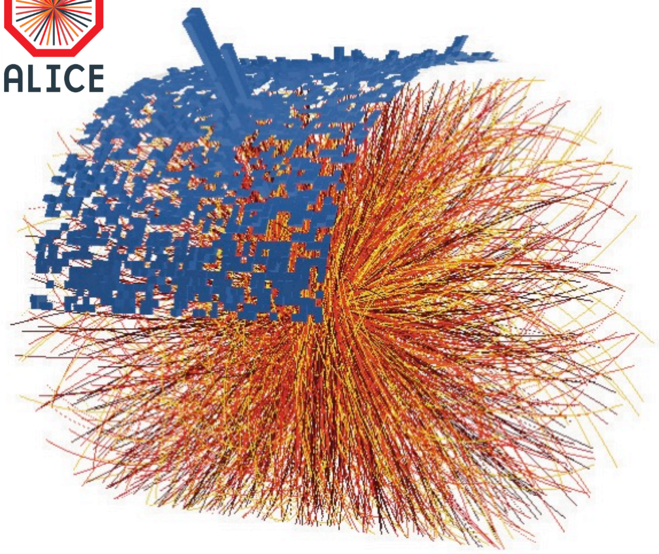


Jets in nuclear collisions





ALICE



Energy loss in QED

Fractional energy loss of an (on-shell) electron or positron in Lead

http://pdg.lbl.gov/2017/reviews/rpp2016-rev-passage-particles-matter.pdf

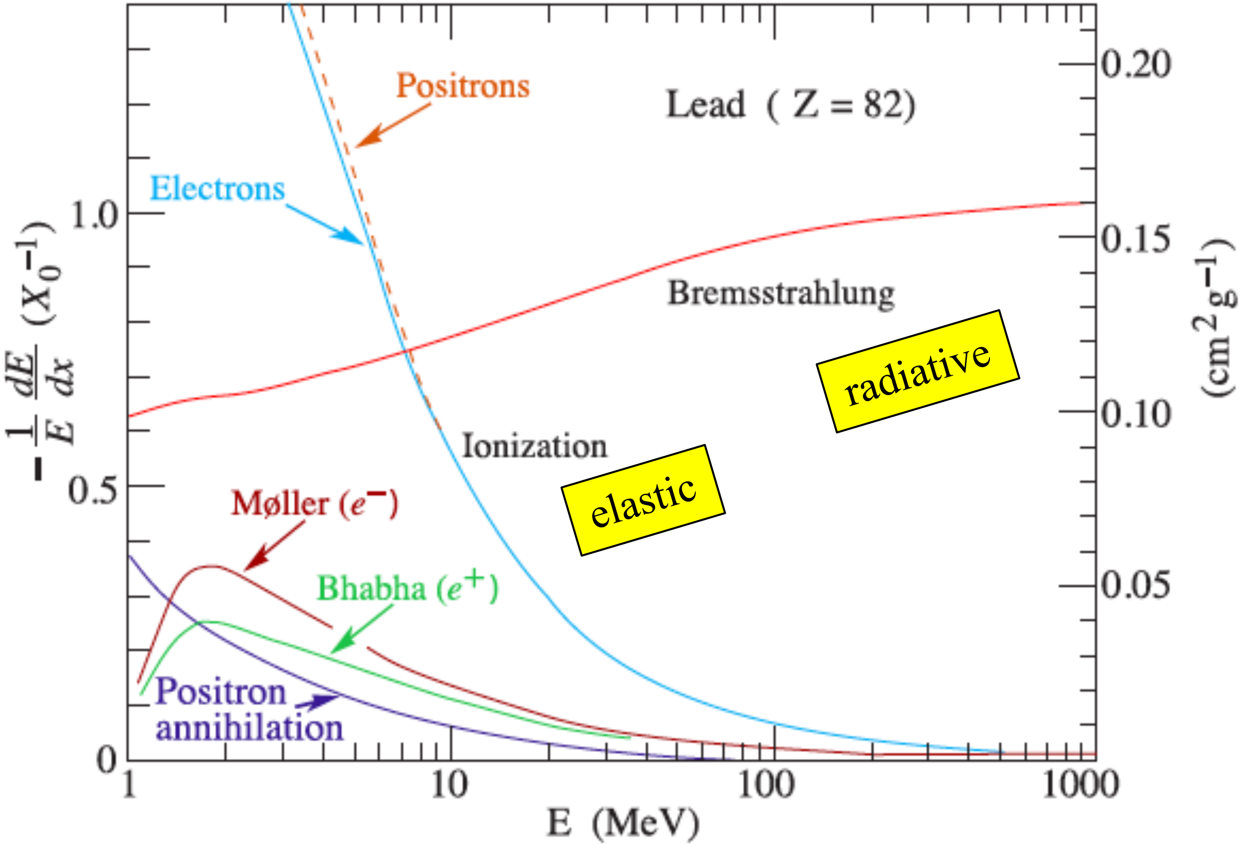


Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

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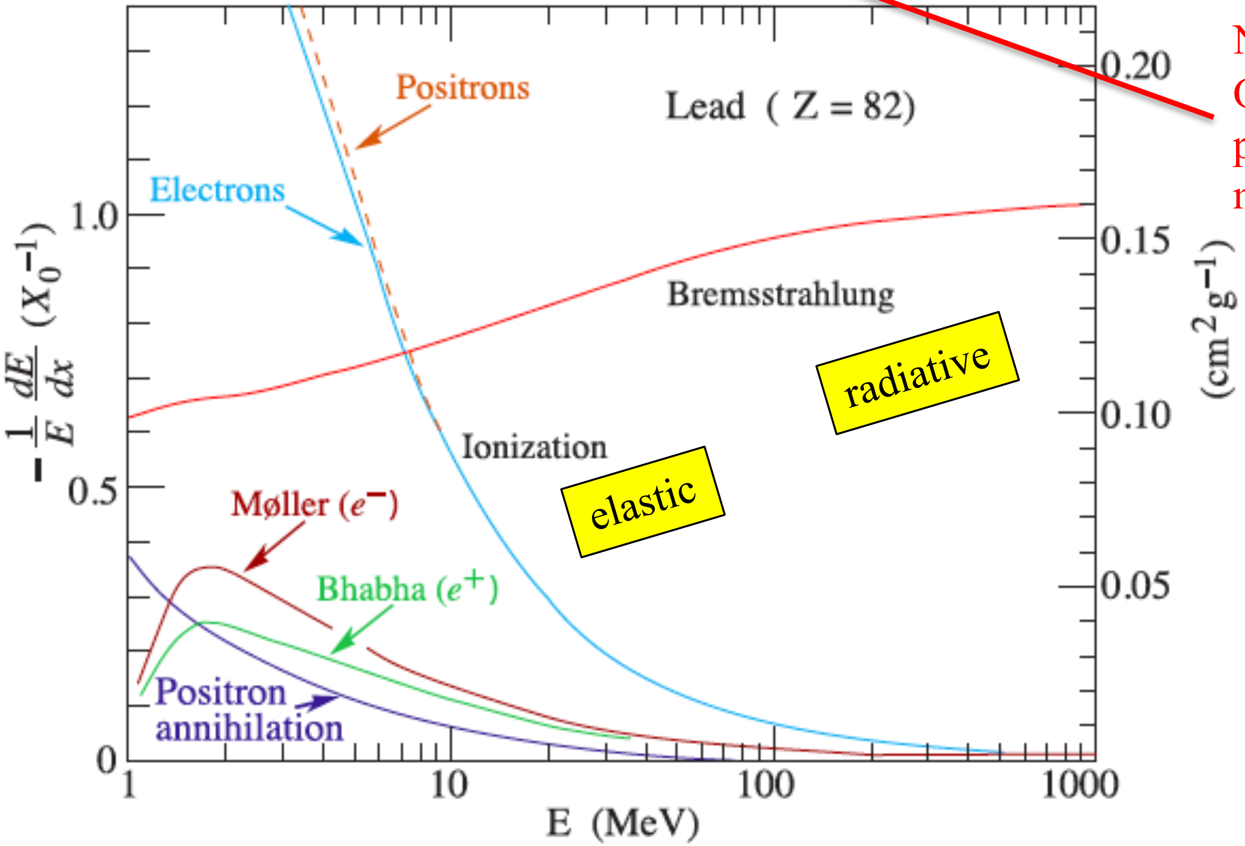
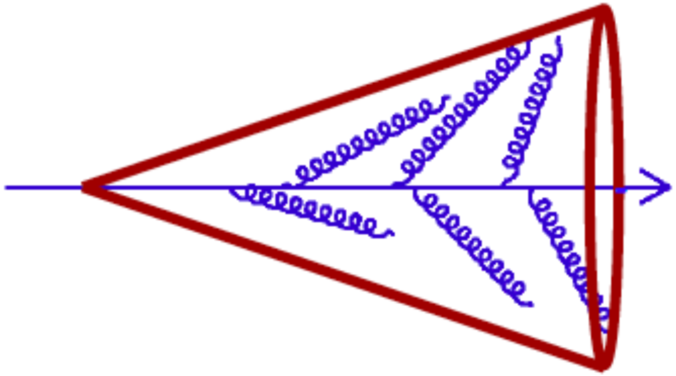


Not the case for QCD jets propagating in matter

Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

Jet quenching in one slide

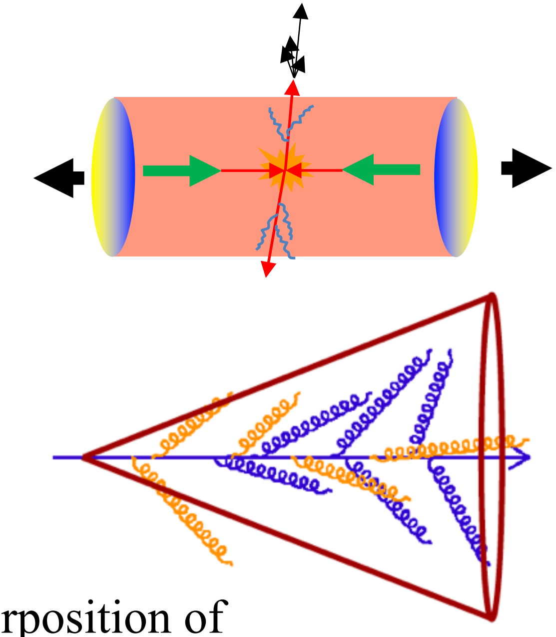
Jet shower in vacuum



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



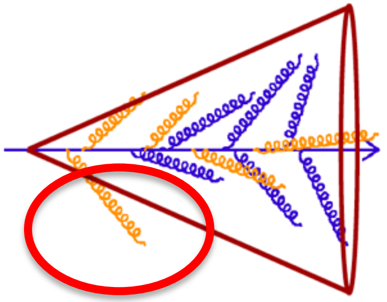
Superposition of
- vacuum shower
- medium-induced gluon emission

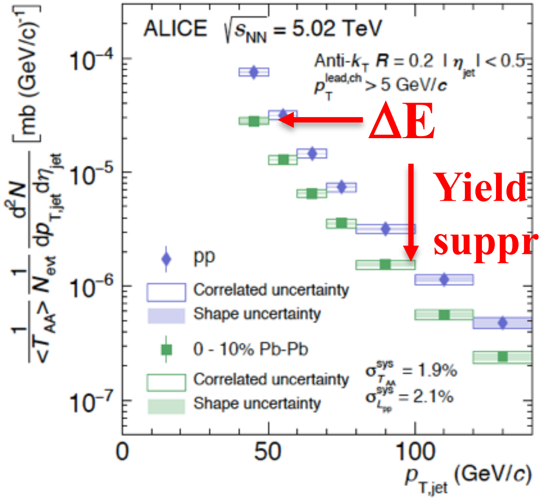
These processes happen simultaneously and interfere

Angle-ordering is modified or destroyed

Jet quenching: observable consequences I

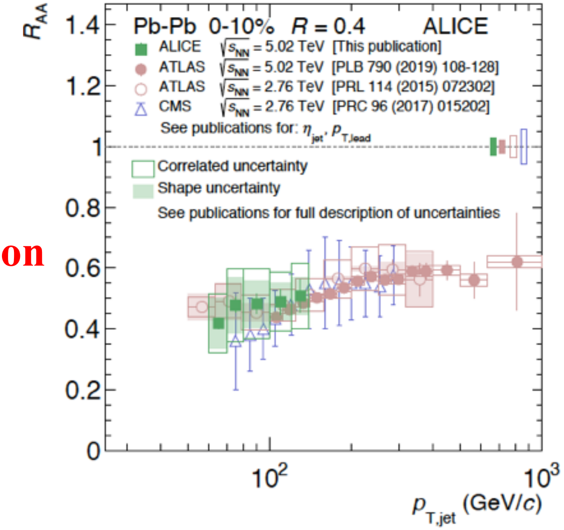
1. Energy loss



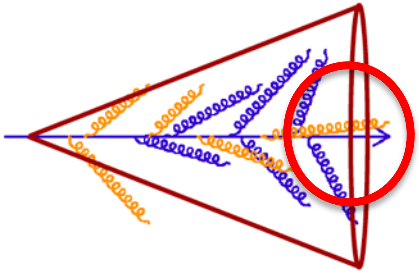


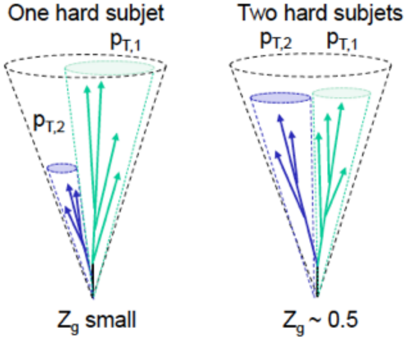
ΔE

Yield suppression

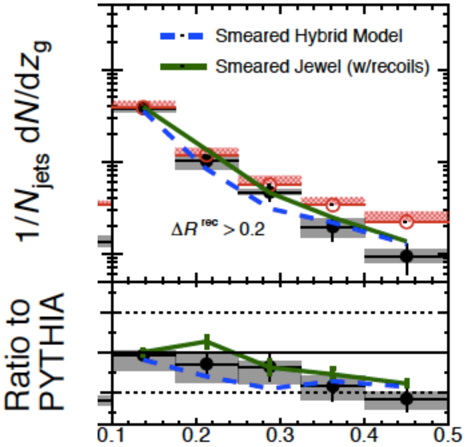


2. Modification of jet substructure



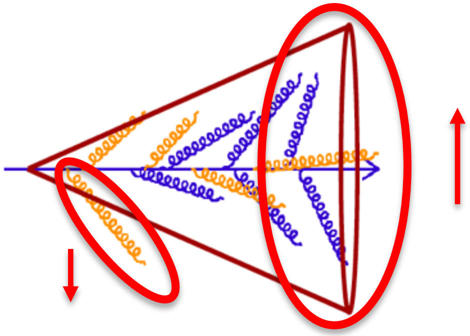


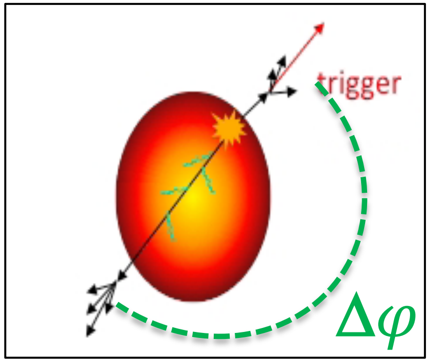
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

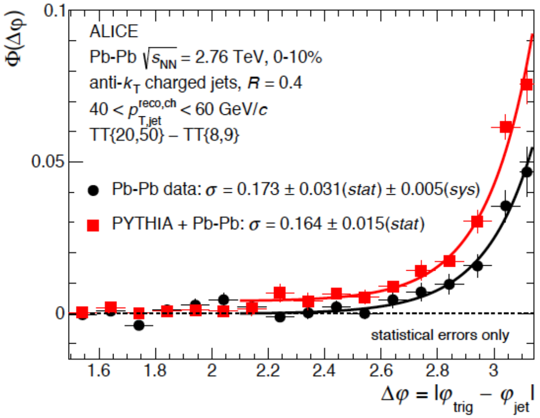


Jet quenching: observable consequences II

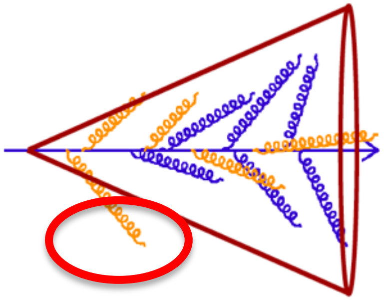
3. Jet deflection

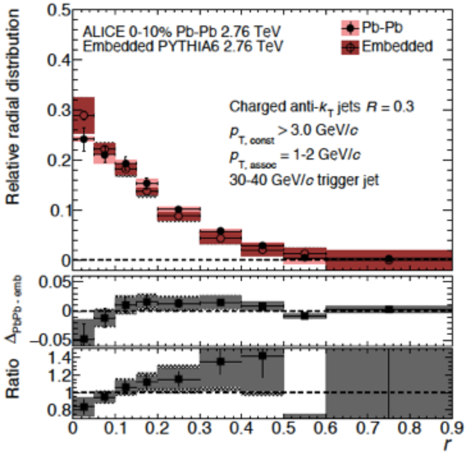


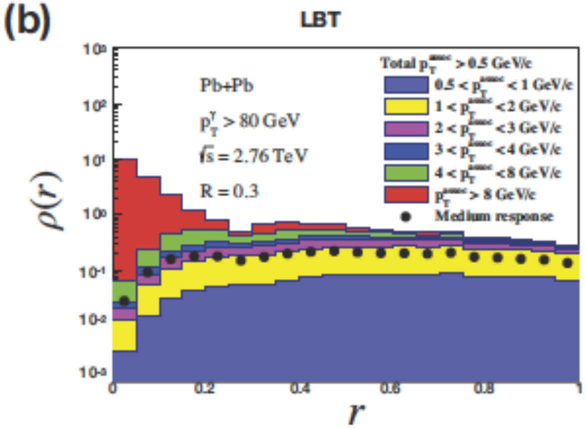




4. Recovery of large-angle radiation







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

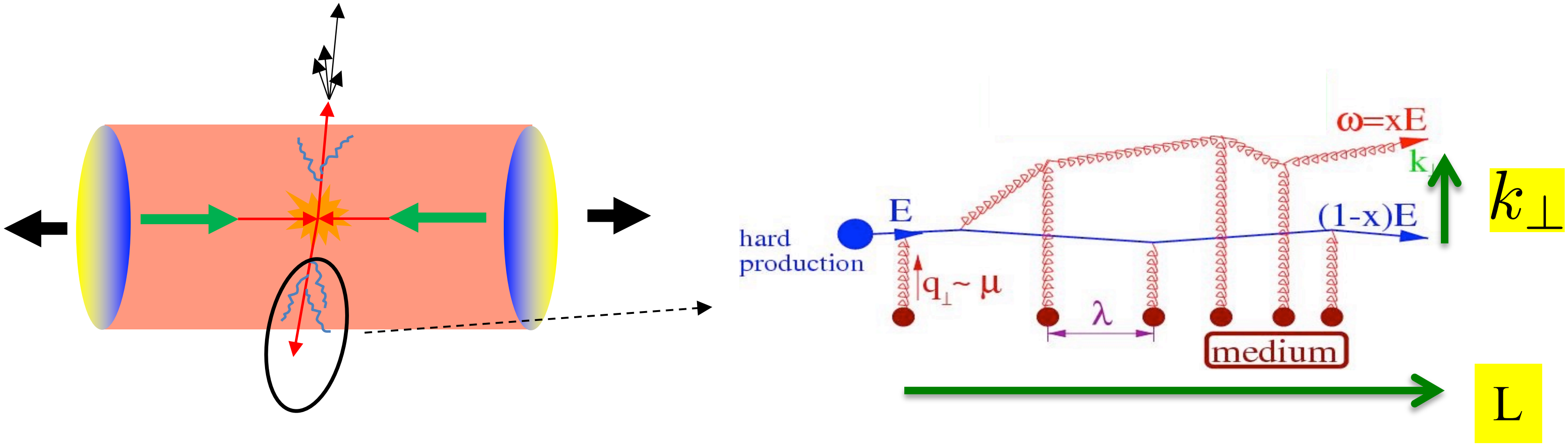
- All must occur if any of them does
- Probe different aspects of jet quenching
- Different experimental systematics as fn of kinematics and collision system
- Different theoretical sensitivity as fn of kinematics and collision system

This is an opportunity:

Measure the same physics multiple ways and require consistency

→ needs a theoretical framework…

Radiative energy loss in QCD



Thermal field theory:

$$C(\mathbf{q}) = \frac{g_s^2 m_D^2 T}{\mathbf{q}^2 (\mathbf{q}^2 + m_D^2)}$$

$$m_D^2 = 3 g_s^2 T^2 / 2$$

$C(\mathbf{q})$ = Scattering kernel

$\mathbf{q}$ = Momentum transfer

T = Temperature

m_D = Debye mass

QGP properties

$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} \sim \frac{1}{L} \int d\mathbf{q}^2 \mathbf{q}^2 C(\mathbf{q})$$

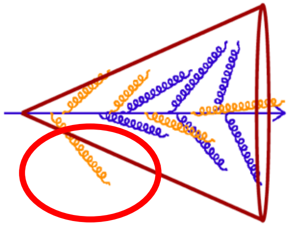
Connecting qhat to measurements

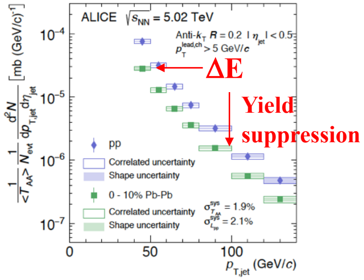
Useful example: BDMPS

- multiple soft scattering approximation
- gives insight into parametric dependencies
- connection to more complete approaches must be checked

Medium-induced jet energy loss:

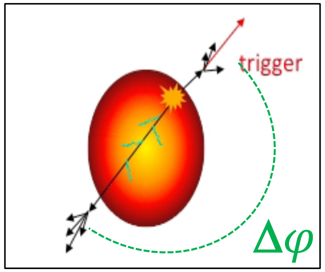
$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

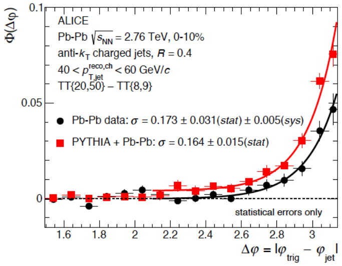




Medium-induced angular broadening:

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



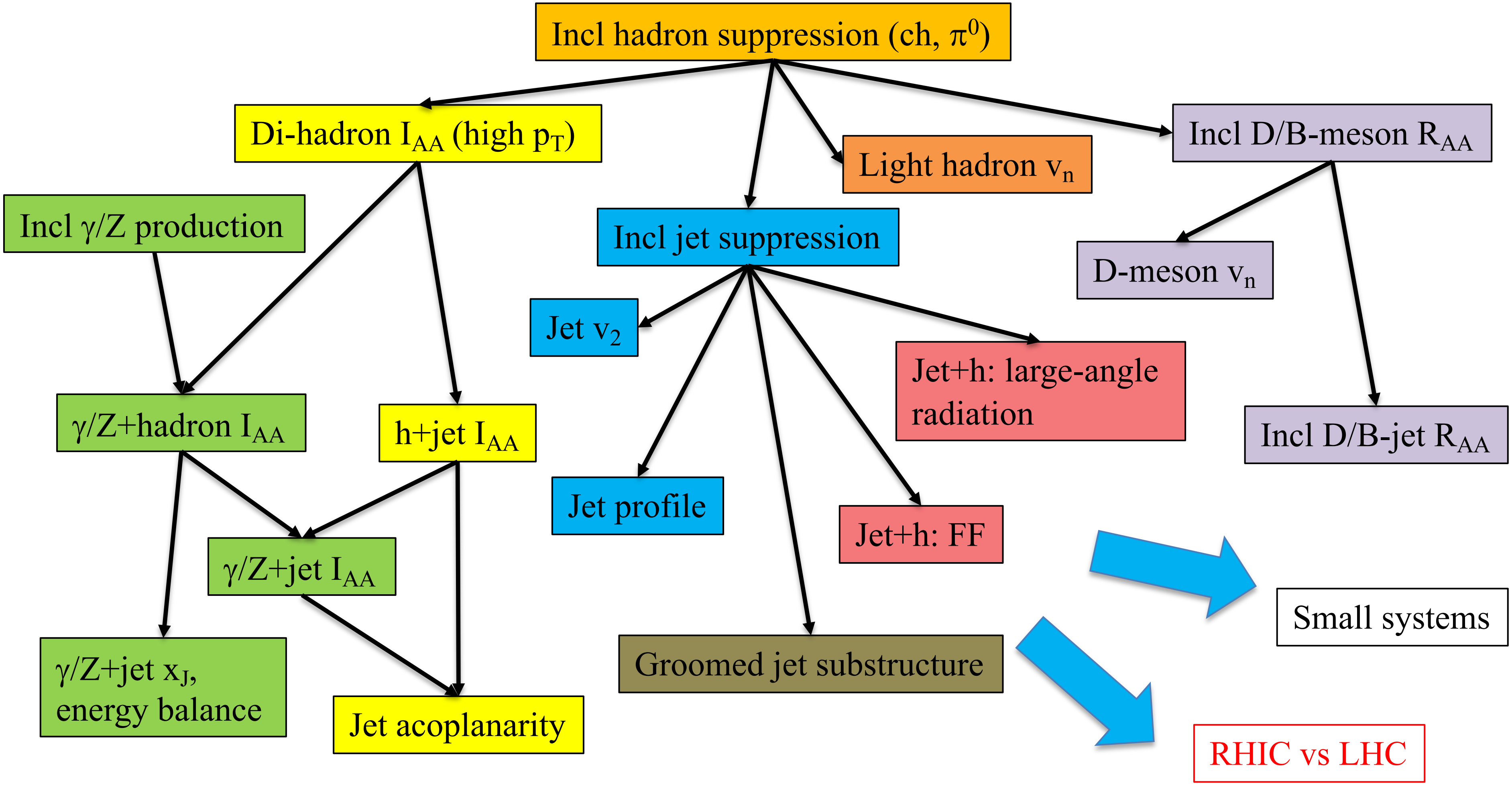


Taxonomy of current jet quenching measurements

Map driven by experimental considerations:

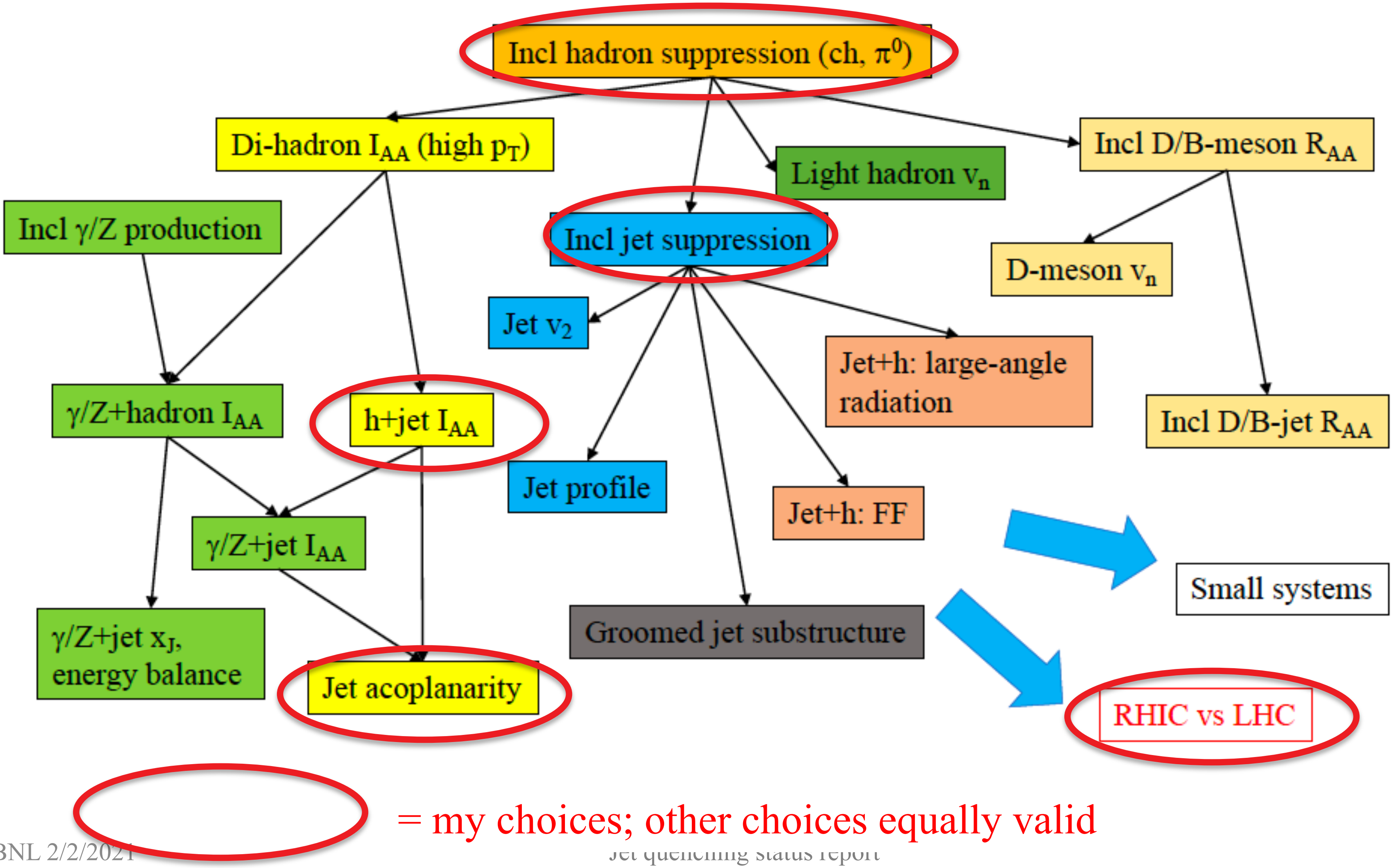
- arrows connect observables with just one thing changed

How do these map onto theory?



Confusing! How to make sense of so many observables?

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



Incl hadron suppression (ch, π^0)

Di-hadron I_{AA} (high p_T)

Light hadron v_n

Incl D/B-meson R_{AA}

Incl γ/Z production

Incl jet suppression

D-meson v_n

Jet v_2

Jet+h: large-angle radiation

γ/Z+hadron I_{AA}

h+jet I_{AA}

Incl D/B-jet R_{AA}

Jet profile

Jet+h: FF

γ/Z+jet I_{AA}

Small systems

Groomed jet substructure

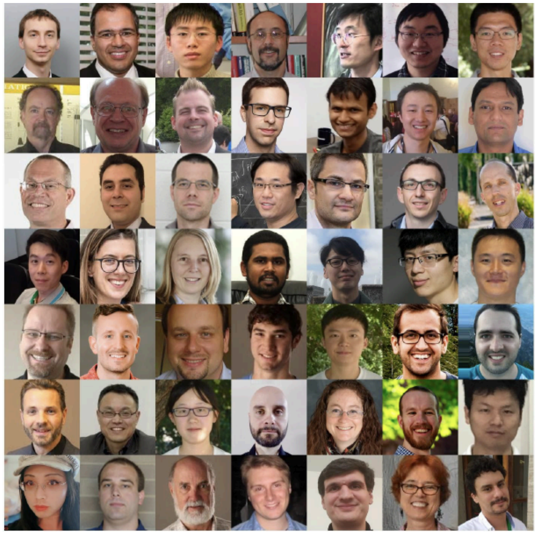
γ/Z+jet x_J, energy balance

Jet acoplanarity

RHIC vs LHC

= my choices; other choices equally valid

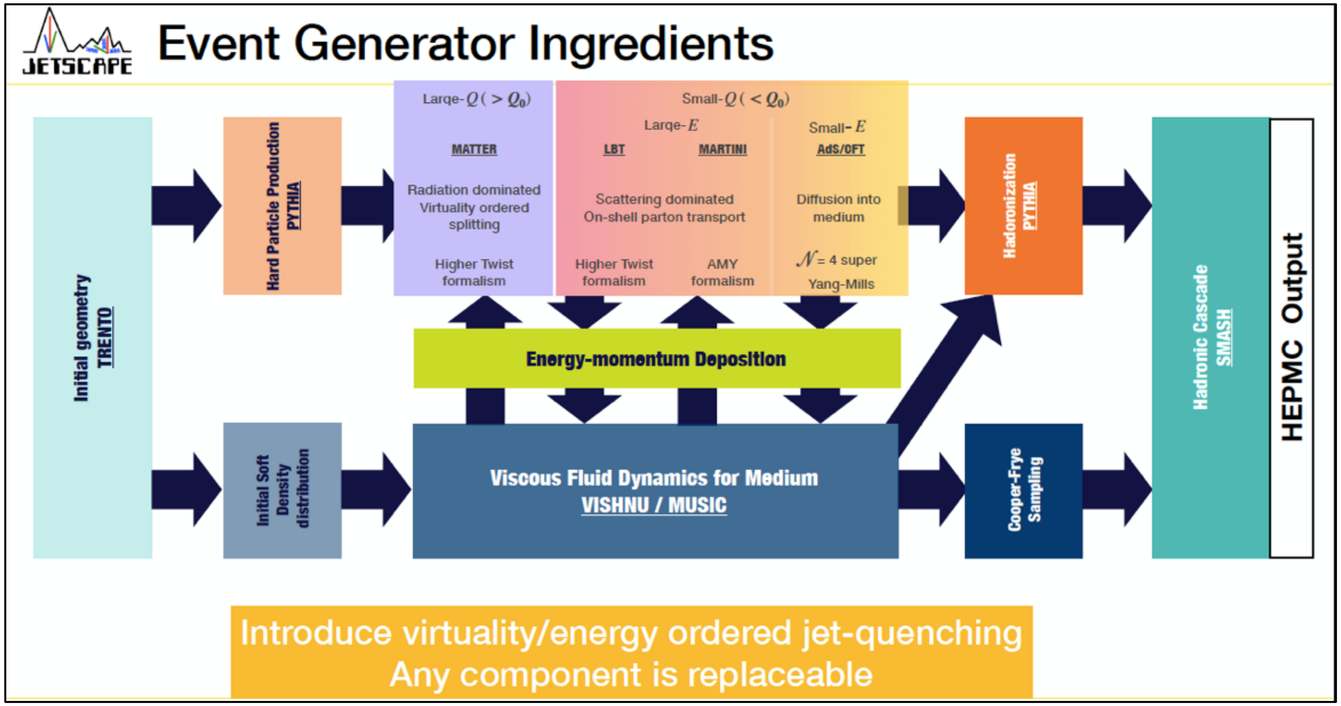
Connecting experiment and theory…



Modular framework: multi-stage jet quenching calculations

Parameter extraction via Bayesian Inference

Goal: general tool for entire HI community



Event Generator Ingredients

Large-Q ($> Q_0$)

MATTER

Radiation dominated
Virtuality ordered
splitting

Higher Twist
formalism

Small-Q ($< Q_0$)

Large-E

LBT

MARTINI

Scattering dominated
On-shell parton transport

Higher Twist
formalism

AMY
formalism

Small-E

AdS/CFT

Diffusion into
medium

$\mathcal{N}$ = 4 super
Yang-Mills

Initial geometry
TRENTO

Hard Particle Production
PYTHIA

Initial Soft Density distribution

Energy-momentum Deposition

Viscous Fluid Dynamics for Medium
VISHNU / MUSIC

Hadronization
PYTHIA

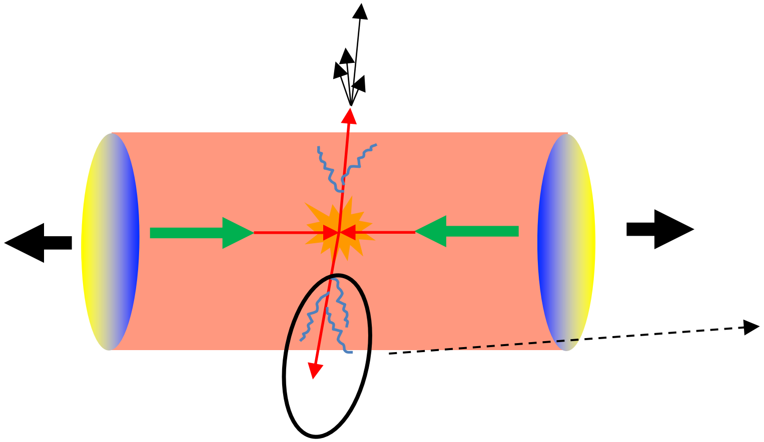
Cooper-Frye Sampling

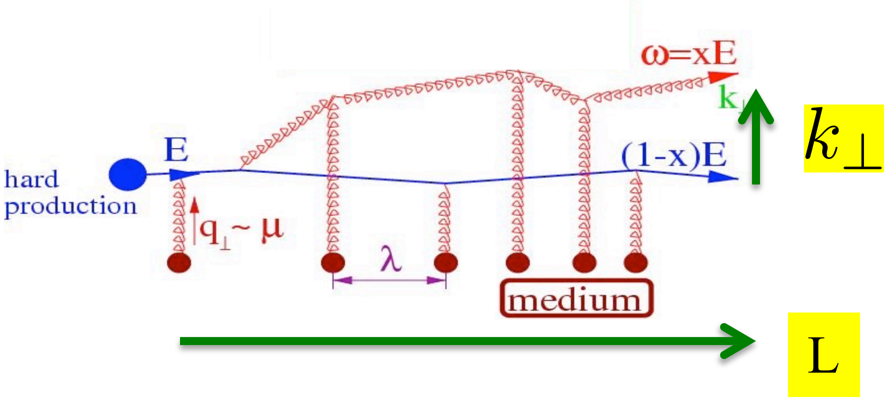
Hadronic Cascade
SMASH

HEPMC Output

Introduce virtuality/energy ordered jet-quenching
Any component is replaceable

JETSCAPE: measuring $\hat{q}$ using incl hadrons





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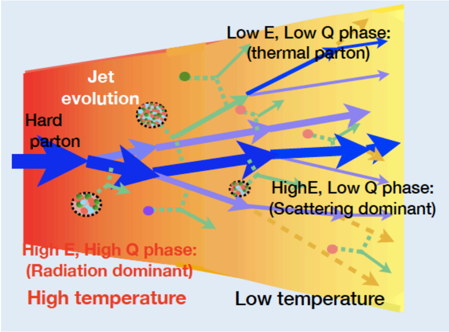
JETSCAPE parametrization



High jet virtuality
Q>>T

Low jet virtuality Q~T
(sensitive to thermal medium)

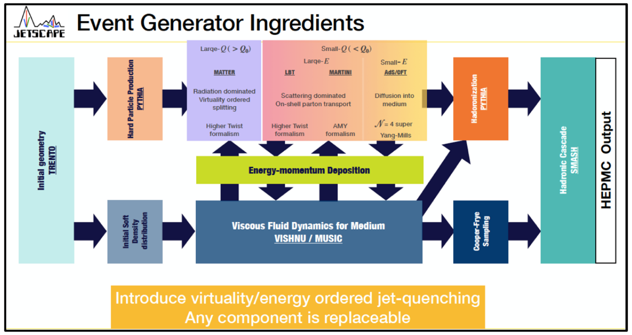
$$\frac{\hat{q}\left(E,T\right)|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}$$

Bayesian inference: inclusive hadrons

paper in preparation

$$\frac{\hat{q}\,(E,T)\,|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}$$

+



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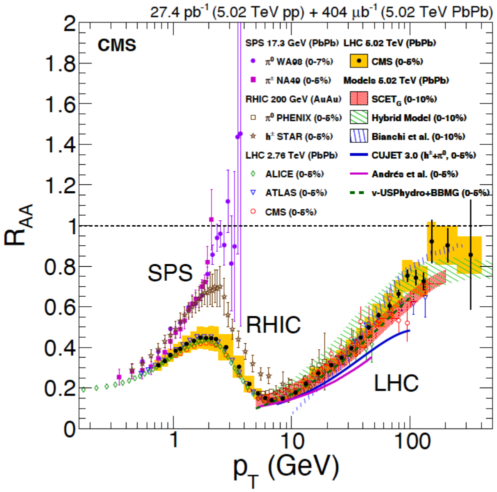

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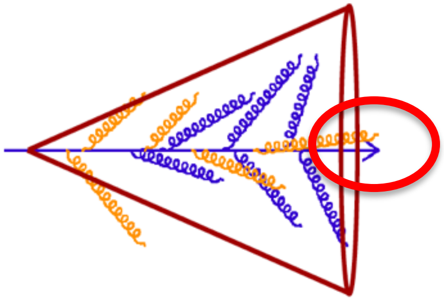
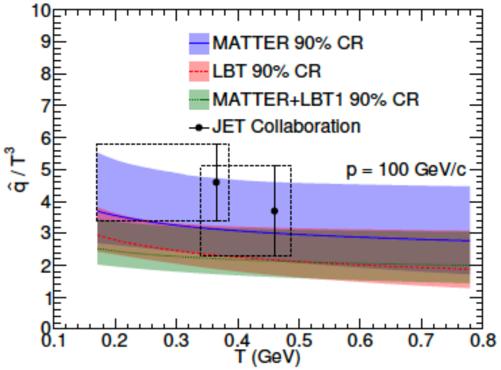
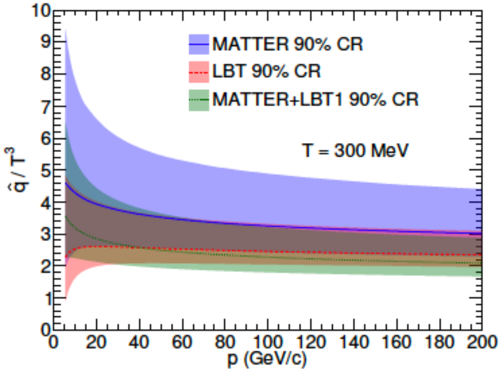
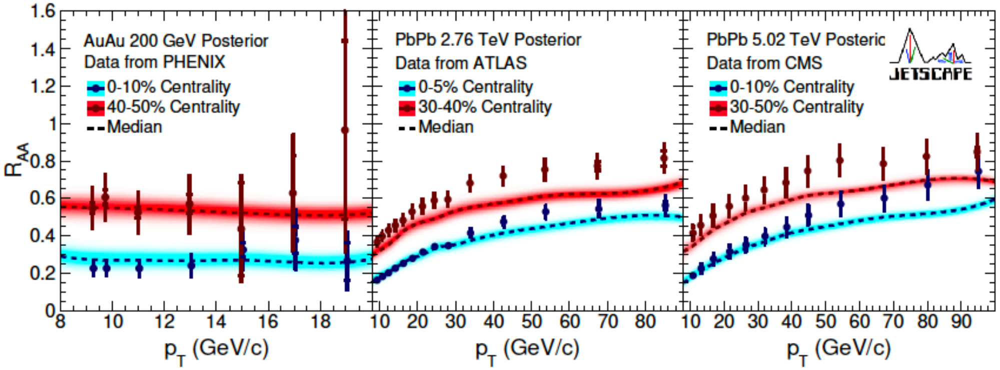
Rigorous quantitative determination of $\hat{q}$







Posterior distributions



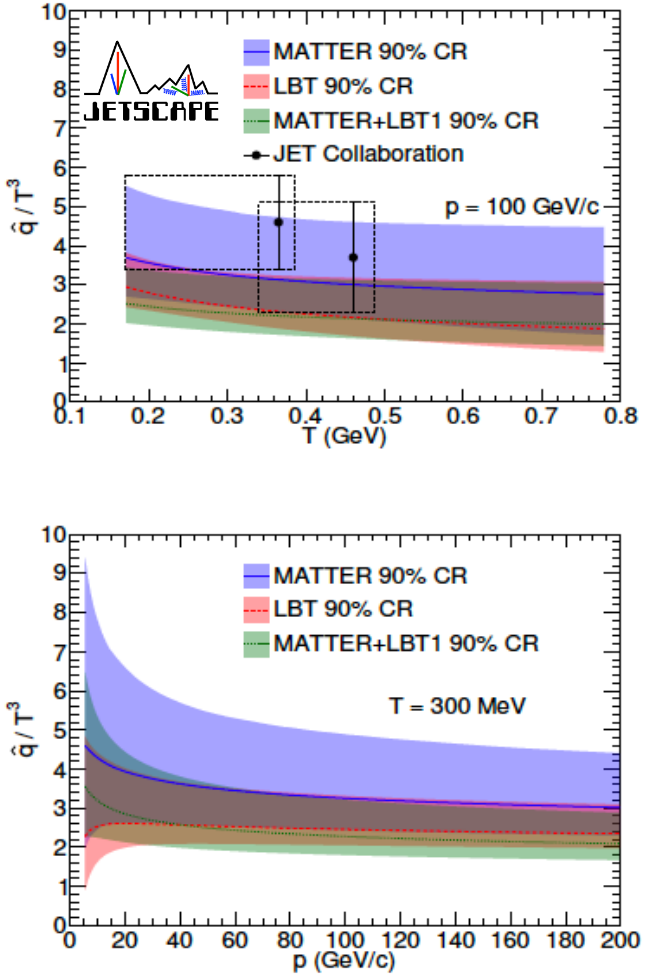
JETSCAPE determination of qhat using inclusive hadron R_{AA}:

Current state-of-the-art quantitative analysis of jet quenching

Are we done?

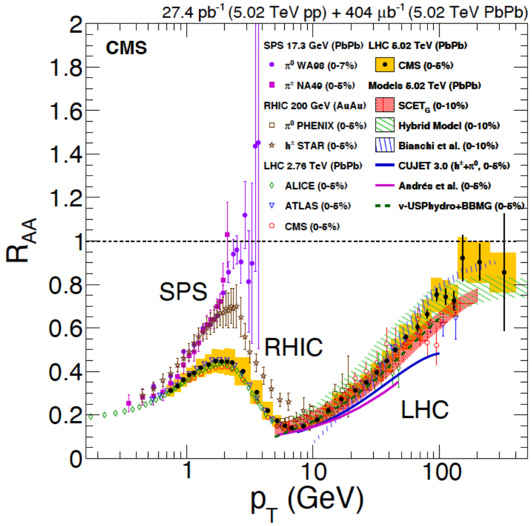
→ real progress, but hardly the complete story

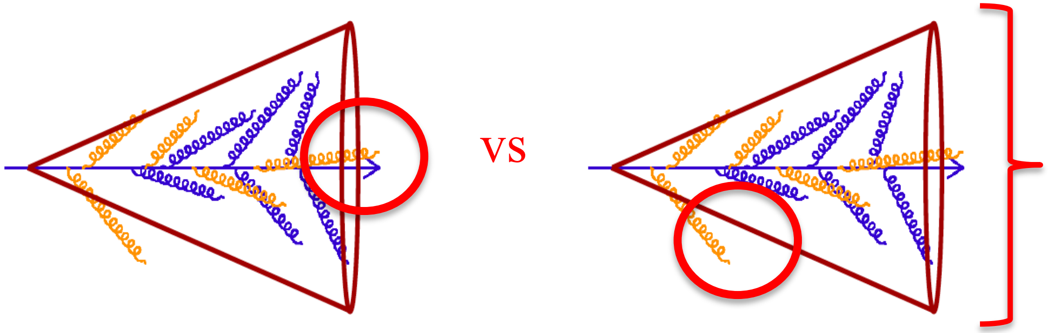
paper in preparation



Consider some next steps….

Inclusive hadron vs inclusive jet suppression



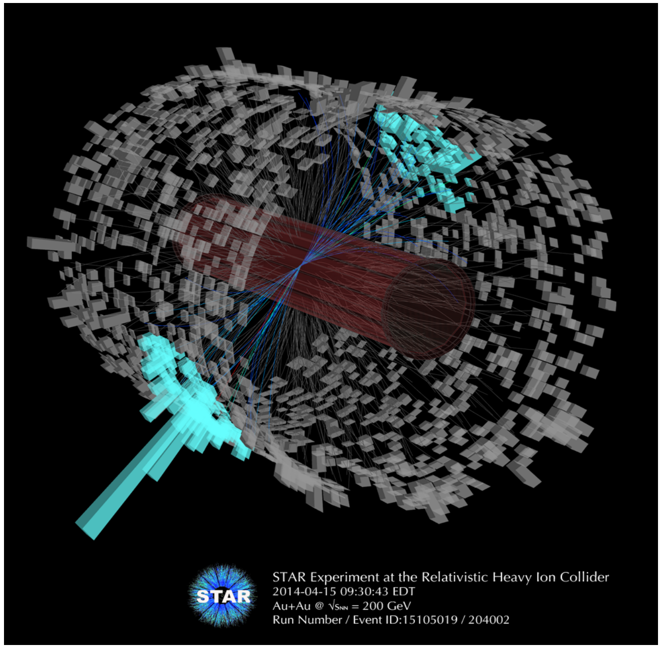


Inclusive hadron suppression driven by energy transport away from the hardest branch in the jet

- Insensitive to specific mechanisms of energy transport

More comprehensive: reconstructed jets

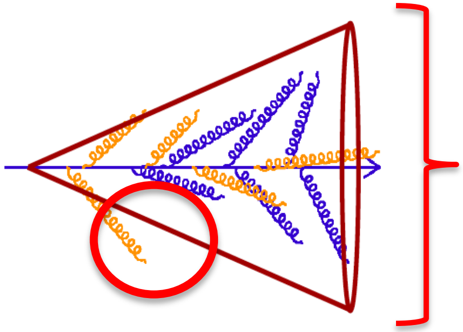
- very challenging due to large backgrounds, especially at RHIC
- but problem has been solved

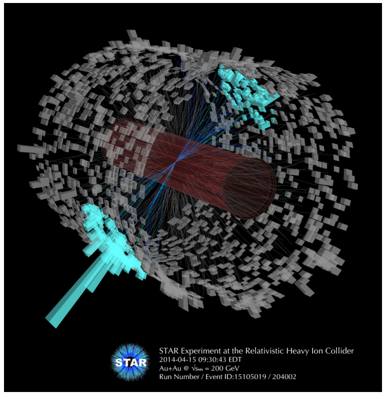


Inclusive jets in A+A: spectra

RHIC

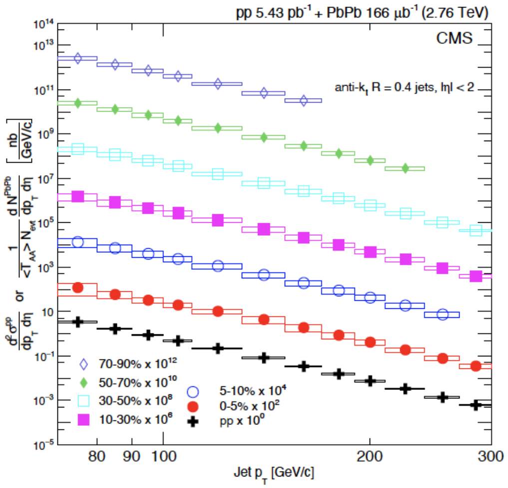
?

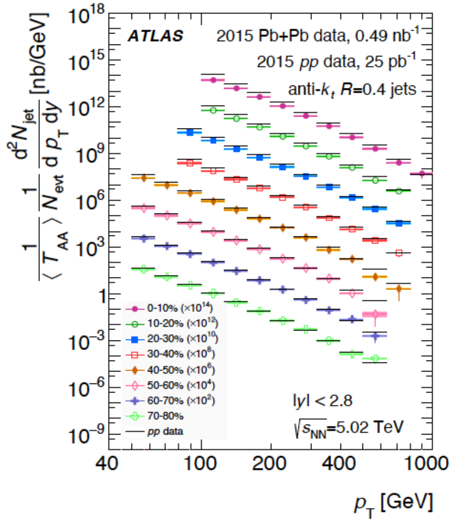


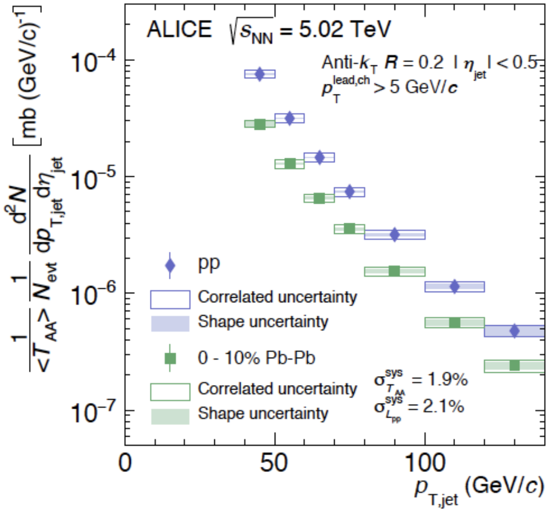


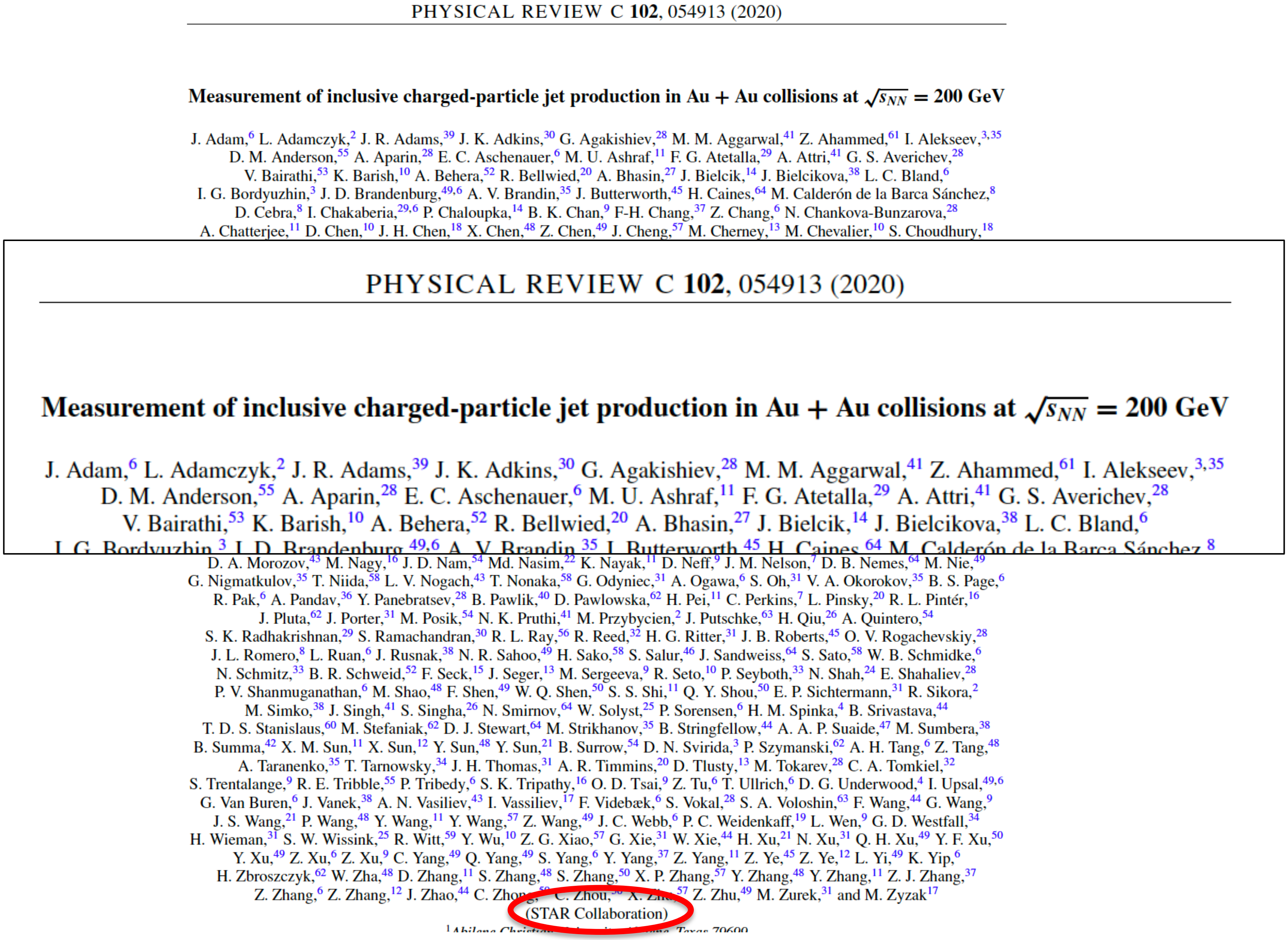
High-quality data over a vast kinematic range

LHC









PHYSICAL REVIEW C **102**, 054913 (2020)

Measurement of inclusive charged-particle jet production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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A. Chatterjee,[11] D. Chen,[10] J. H. Chen,[18] X. Chen,[48] Z. Chen,[49] J. Cheng,[57] M. Cherney,[13] M. Chevalier,[10] S. Choudhury,[18]

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D. A. Morozov,[43] M. Nagy,[16] J. D. Nam,[54] Md. Nasim,[22] K. Nayak,[11] D. Neff,[9] J. M. Nelson,[7] D. B. Nemes,[64] M. Nie,[49]
G. Nigmatkulov,[35] T. Niida,[58] L. V. Nogach,[43] T. Nonaka,[58] G. Odyniec,[31] A. Ogawa,[6] S. Oh,[31] V. A. Okorokov,[35] B. S. Page,[6]
R. Pak,[6] A. Pandav,[36] Y. Panebratsev,[28] B. Pawlik,[40] D. Pawlowska,[62] H. Pei,[11] C. Perkins,[7] L. Pinsky,[20] R. L. Pintér,[16]
J. Pluta,[62] J. Porter,[31] M. Posik,[54] N. K. Pruthi,[41] M. Przybycien,[2] J. Putschke,[63] H. Qiu,[26] A. Quintero,[54]
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P. V. Shanmuganathan,[6] M. Shao,[48] F. Shen,[49] W. Q. Shen,[50] S. S. Shi,[11] Q. Y. Shou,[50] E. P. Sichtermann,[31] R. Sikora,[2]
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(STAR Collaboration)

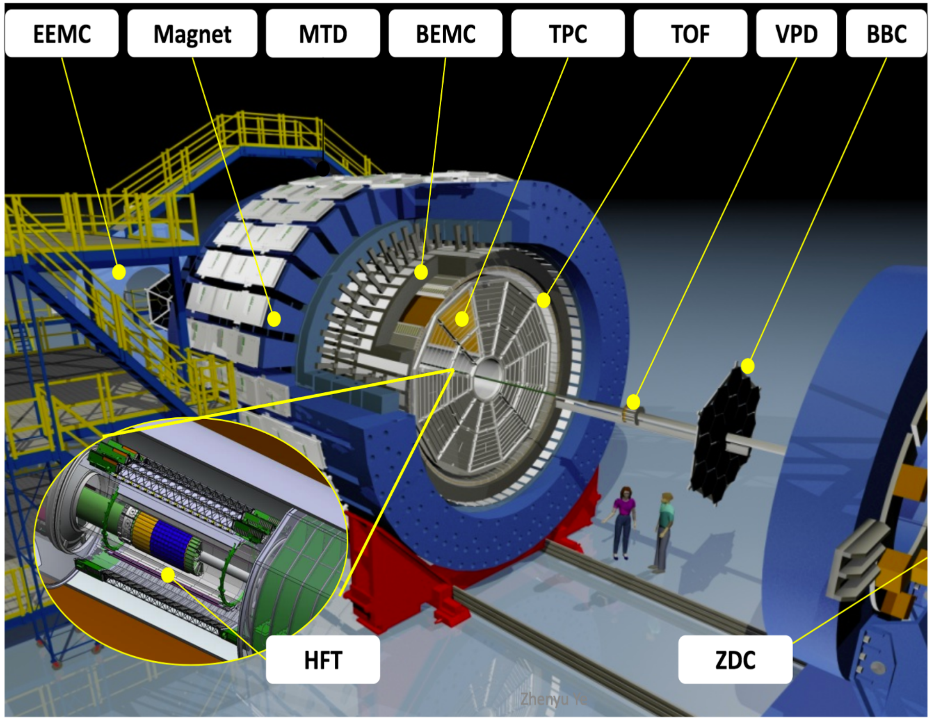
STAR heavy ion jet measurements: subsystems and datasets

Charged-particle jets (this paper):

- Time Projection Chamber (TPC)
- Vertex Position Detector (VPD)

Calorimetric jets (in progress)

- + Barrel EM Calorimeter (BEMC)



Dataset: Au+Au, $\sqrt{s_{NN}}$=200 GeV

- 2011 minimum bias, L_{int}=6 μb^{-1}
- 2014 minimum bias; BEMC-triggered, L_{int}=5.2 nb^{-1}

Centrality selection:

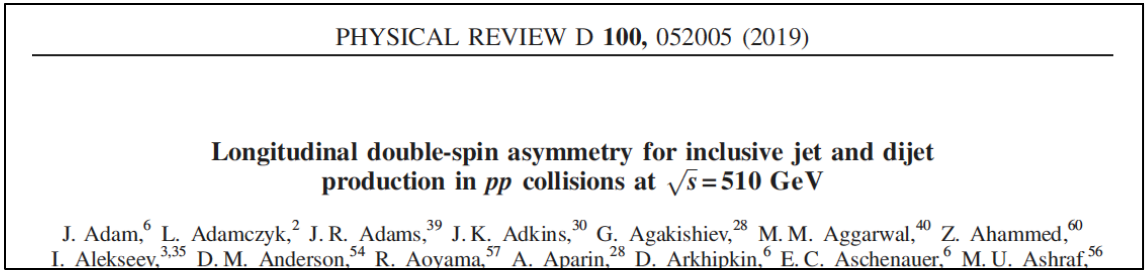
- charged-track multiplicity, $|\eta| < 0.5$
- central: 0-10%
- peripheral: 60-80%

Charged-jet reference: 200 GeV pp collisions

Charged jets: cannot trigger, need MB pp

- But insufficient MB pp @ 200 GeV

→ PYTHIA 6.428 Perugia 2012, STAR tune

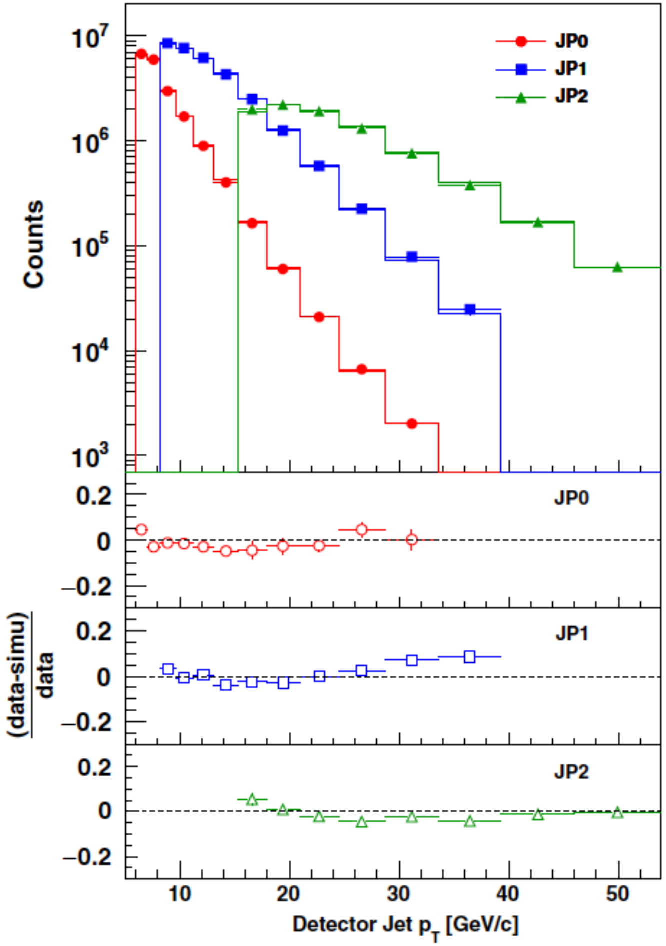


PHYSICAL REVIEW D **100,** 052005 (2019)

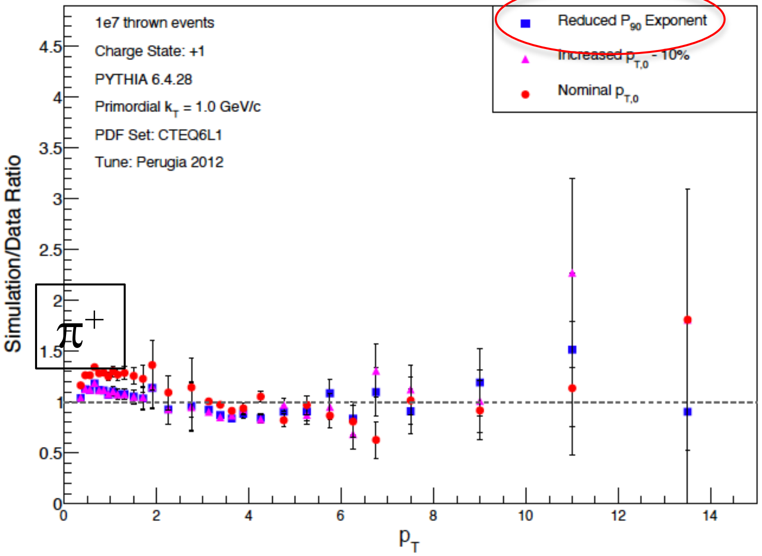
Longitudinal double-spin asymmetry for inclusive jet and dijet production in *pp* collisions at $\sqrt{s} = 510$ GeV

J. Adam,[6] L. Adamczyk,[2] J. R. Adams,[39] J. K. Adkins,[30] G. Agakishiev,[28] M. M. Aggarwal,[40] Z. Ahammed,[60] I. Alekseev,[3,35] D. M. Anderson,[54] R. Aoyama,[57] A. Aparin,[28] D. Arkhipkin,[6] E. C. Aschenauer,[6] M. U. Ashraf,[56]

PYTHIA STAR tune vs STAR data: detector-level jets



K. Adkins, PhD Thesis, U. Kentucky



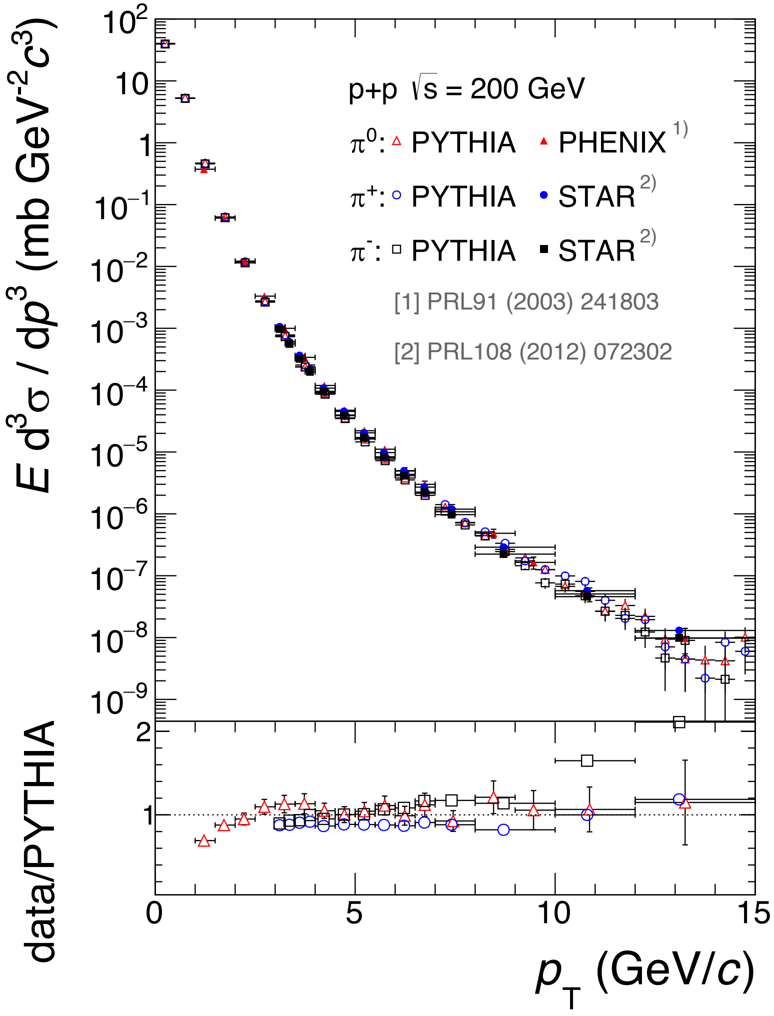
IR regularization scale for MPIs, tuned to LHC 7 TeV pp:

$$p^2_{T,0}(s) = p^2_{T,0}(s_{ref})\left(\frac{s}{s_{ref}}\right)^{P_{90}}$$

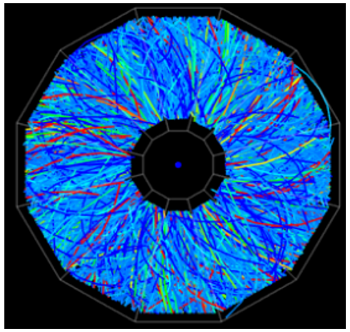
PYTHIA STAR tune: additional check

Compare inclusive pion yield

Phys. Rev. C102, 054913 (this paper)

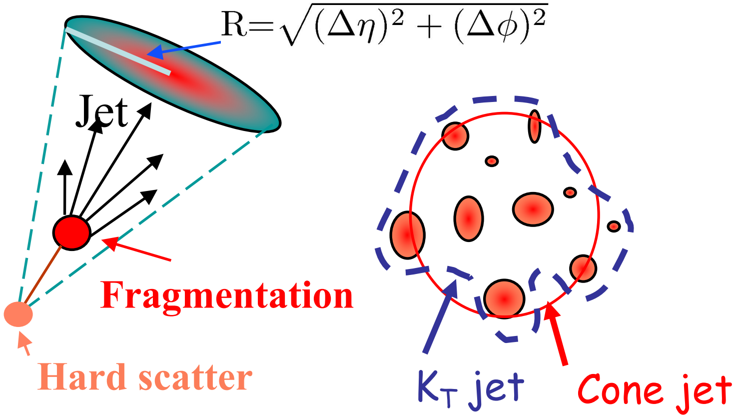


Jet reconstruction



Charged jets:
- all ch. tracks $|\eta|<1$
- $0.2 < p_T < 30$ GeV/c

Jet reconstruction:
- Anti-k_T, R=0.2, 0.3, 0.4
- Recombination: boost-invariant p_T (3-vec)
- Jet centroid acceptance: $|\eta|<1-R$



This gives a population of jet candidates that is a combination of
- Jets from hard (high Q^2) processes with p_T smeared by complex uncorrelated event 👍
- Combinatorial “jets” from random combination of hadrons from soft (low Q^2) processes 👎

High: $Q^2 > \sim (\text{few GeV})^2$, somewhat arbitrary
- need an operational procedure to discriminate in measurement

Analysis strategy: uncorrelated background suppression

G. De Barros et al., arXiv:1208.1518

Correction via unfolding is a linear transformation:

measured *truth*

$$\mathbf{m} = \mathbf{R}\mathbf{t} \qquad \mathrm{R}_{ij} = \Pr\left(\text{measure } i \middle| \text{truth is } j\right)$$

Response matrix

Regularized inversion:

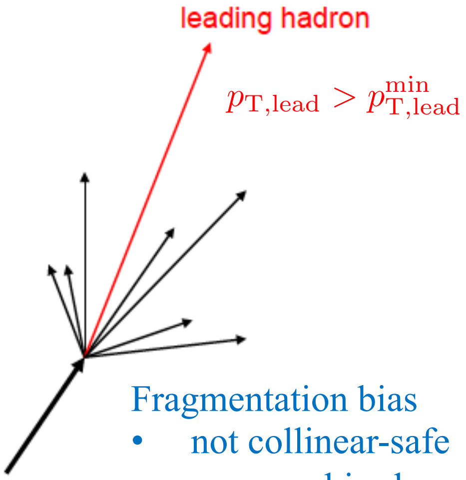
$$\mathbf{t}' = \widetilde{\mathbf{R}^{-1}}\mathbf{m}$$

Solution: bias signal jet population by requiring a hard leading hadron

If jet population contains significant non-jet background yield

- "Response" not meaningful
- Unfolding fails: doesn't know where to put the counts

→ need to suppress non-jet bkgd prior to unfolding



Fragmentation bias

- not collinear-safe
- measure bias by varying cut

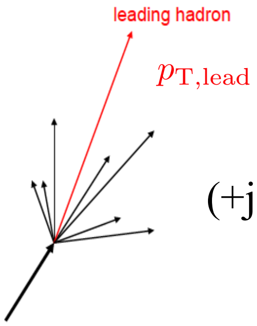
But: no cut on p_T^{jet}

- unique to this analysis (for incl. jets)
- enables measurement to low p_T^{jet}, large R

Cuts and corrections

Event-wise:

Yield correction ("vertical")



$p_{\mathrm{T,lead}} > p^{\mathrm{min}}_{\mathrm{T,lead}}$

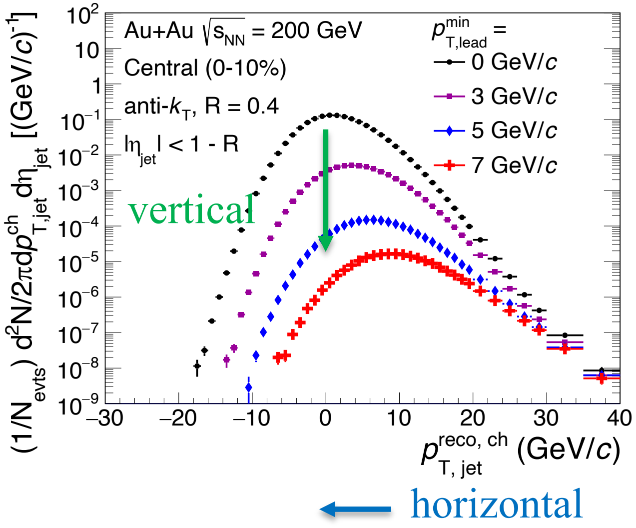
(+jet area cut)

p_{T}-shift for UE ("horizontal")

Standard Fastjet procedure:

$$\rho = \mathrm{median}\left\{\frac{p^{\mathrm{raw},i}_{T,\mathrm{jet}}}{A^i_{\mathrm{jet}}}\right\}$$

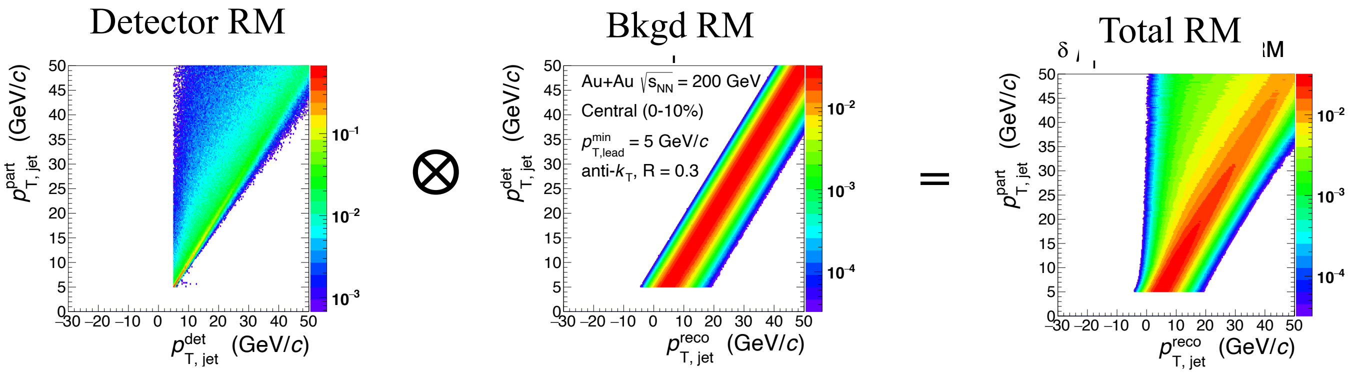
$$p^{\mathrm{reco},i}_{T,\mathrm{jet}} = p^{\mathrm{raw},i}_{T,\mathrm{jet}} - \rho A^i_{\mathrm{jet}}$$



Ensemble-averaged distribution:

Unfolding $\mathbf{t}' = \widetilde{\mathbf{R}^{-1}}\mathbf{m}$

$\mathbf{R}$ = Detector effects $\otimes$ Bkgd fluctuations



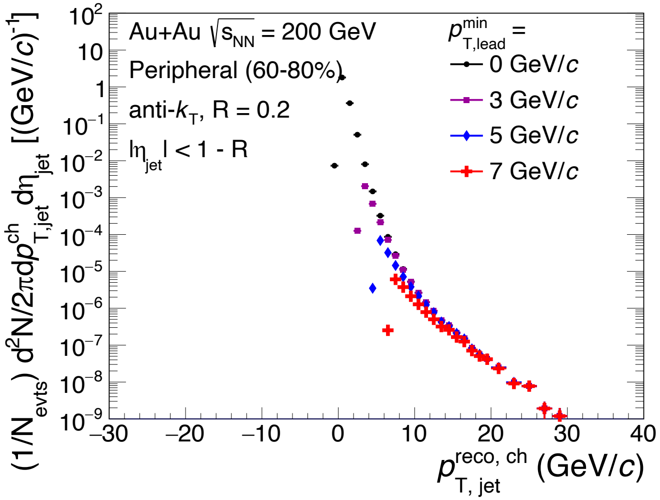
Syst. Uncert.
details in backup
slides

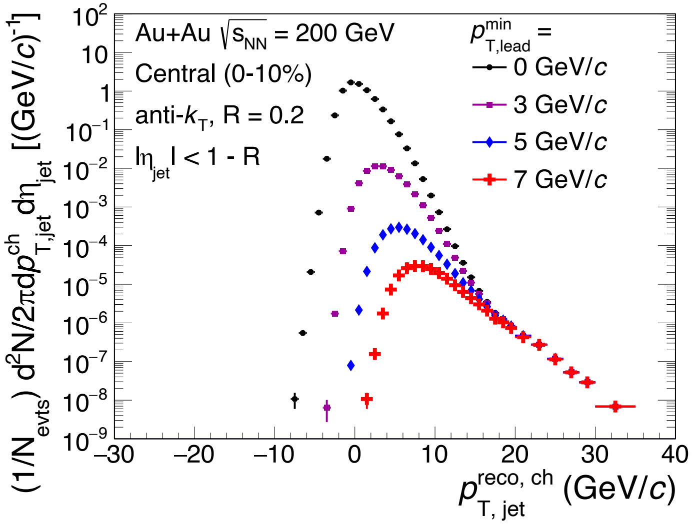
Inclusive charged jets: raw data

Peripheral Au+Au

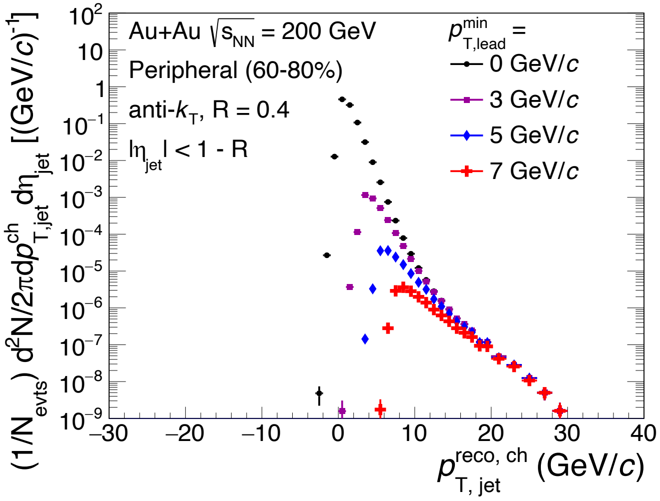
Central Au+Au

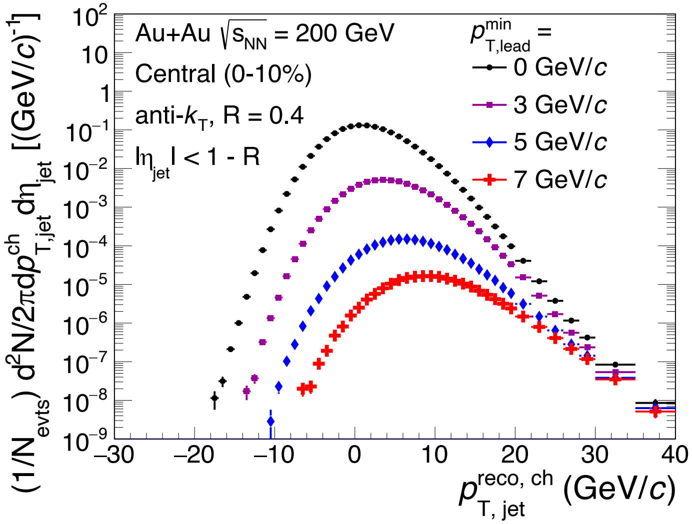
R=0.2





R=0.4



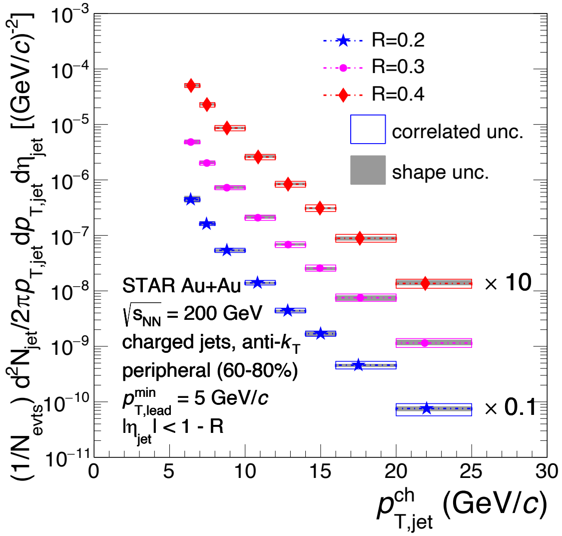


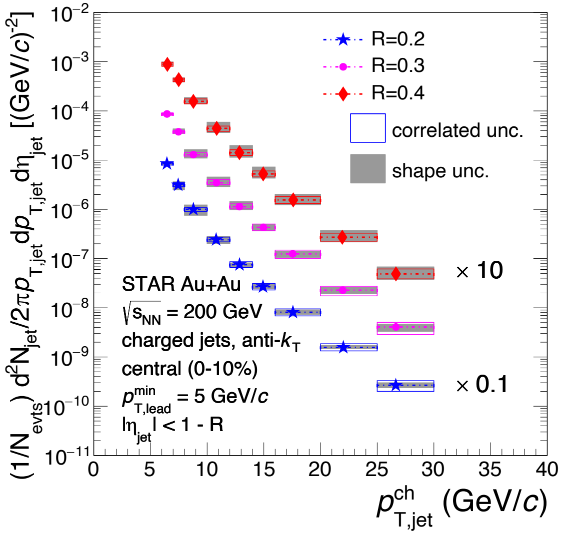
Inclusive charged jets: corrected spectra

Peripheral Au+Au

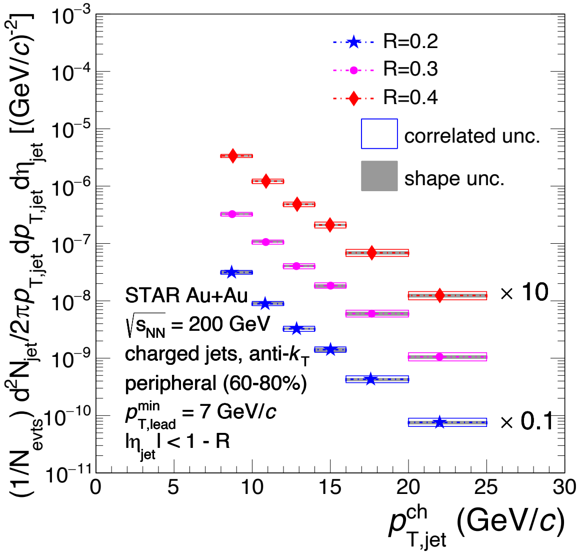
Central Au+Au

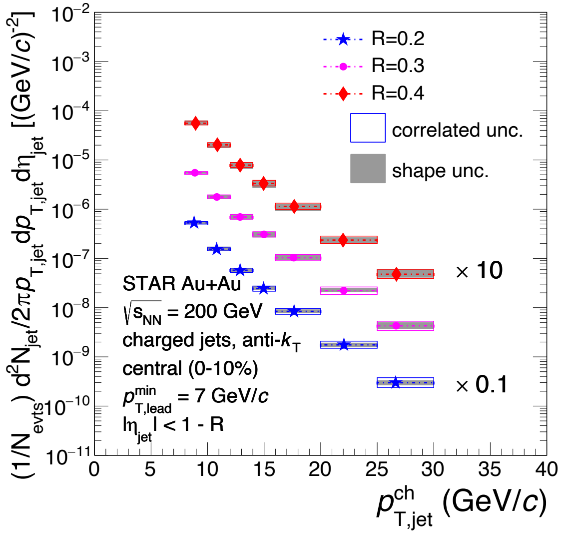
$p_{\mathrm{T,lead}}^{\mathrm{min}} = 5\ \mathrm{GeV/c}$





$p_{\mathrm{T,lead}}^{\mathrm{min}} = 7\ \mathrm{GeV/c}$





Closure Test

Full analysis on simulated data

- answer is known
- close the circle and check consistency

Parametrized model

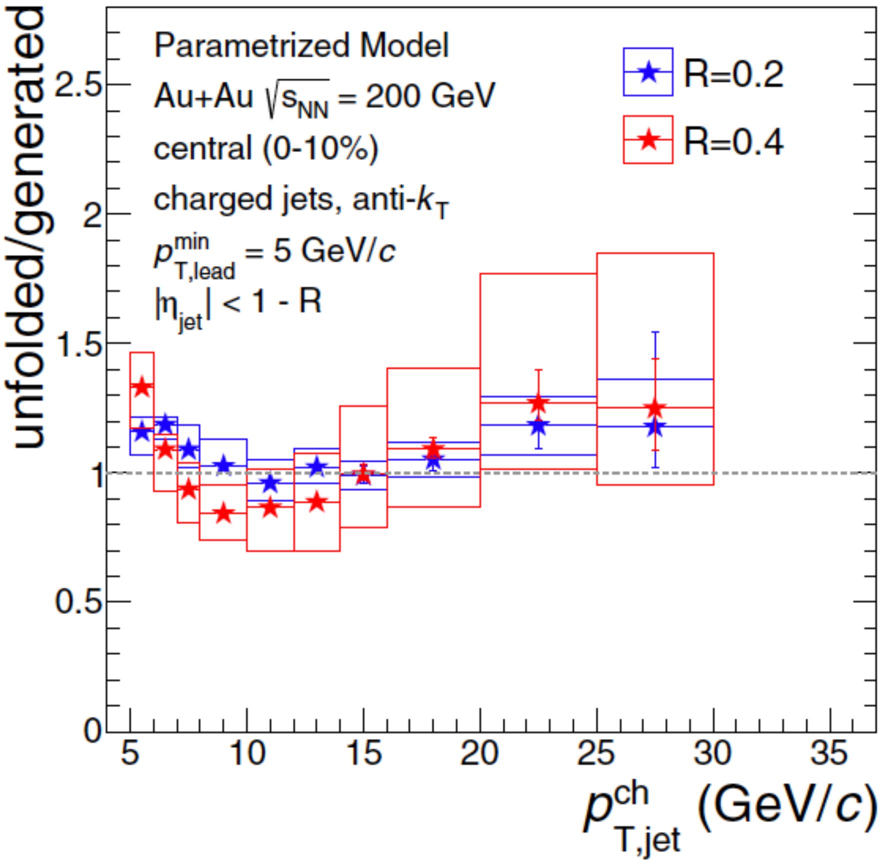
- “thermal” bkgd + PYTHIA jets + yield suppression
- good agreement with real data distributions (backup slides)

Event generation

- similar statistical precision as real dataset

Complete analysis chain

- including syst. uncert.



→ no evidence of bias beyond sys uncert band 👍

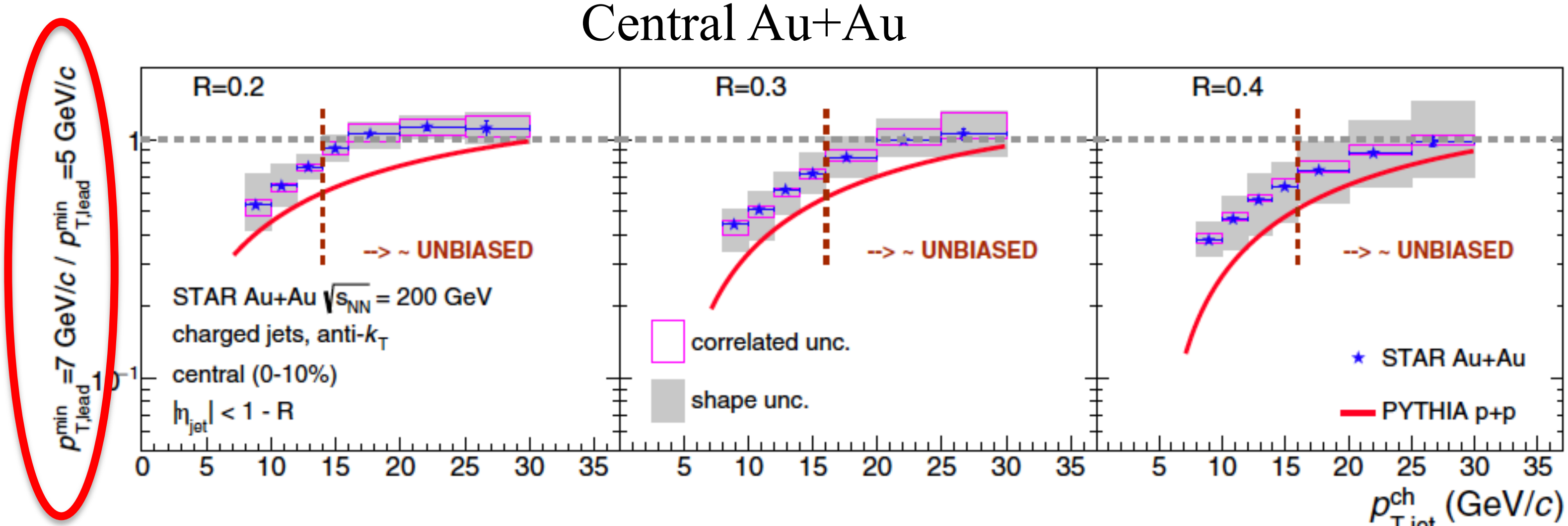
Measure bias due to $p_{T,lead}{}^{min}$

Assertion: larger $p_{T,lead}{}^{min}$ → larger bias

Compare $p_{T,lead}{}^{min}$ = 5 and 7 GeV/c

- ratio ~ unity within uncert. → bias is negligible

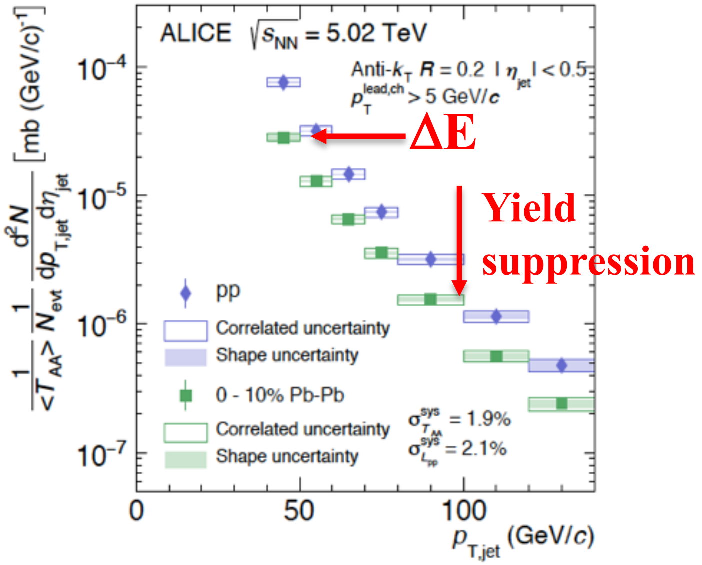
Central Au+Au



Curious fact: bias is smaller in central Au+Au than in PYTHIA p+p….?

- non-trivial fragmentation+quenching physics
- explore with next-generation calorimetric measurement, TBD

Measuring jet energy loss

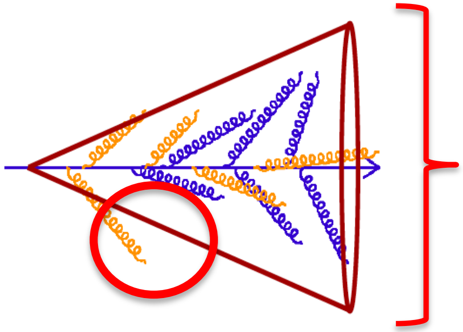


ΔE

Yield suppression

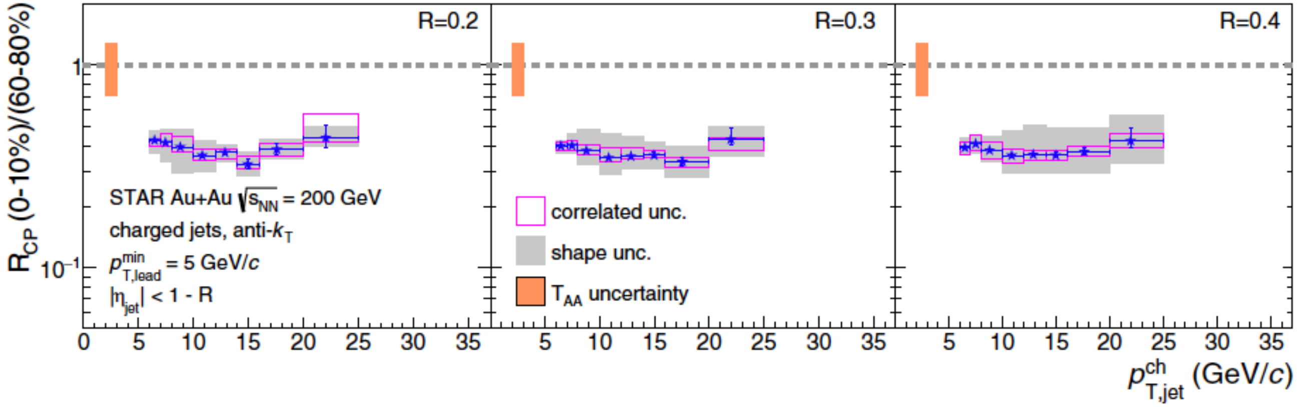
$$R_{AA} = \frac{\text{Rate in central A + A}}{\text{Rate in p + p} \otimes \text{geometry}}$$

$$R_{CP} = \frac{\text{Rate in central AA}}{\text{Rate in periph AA} \otimes \text{geometry}}$$

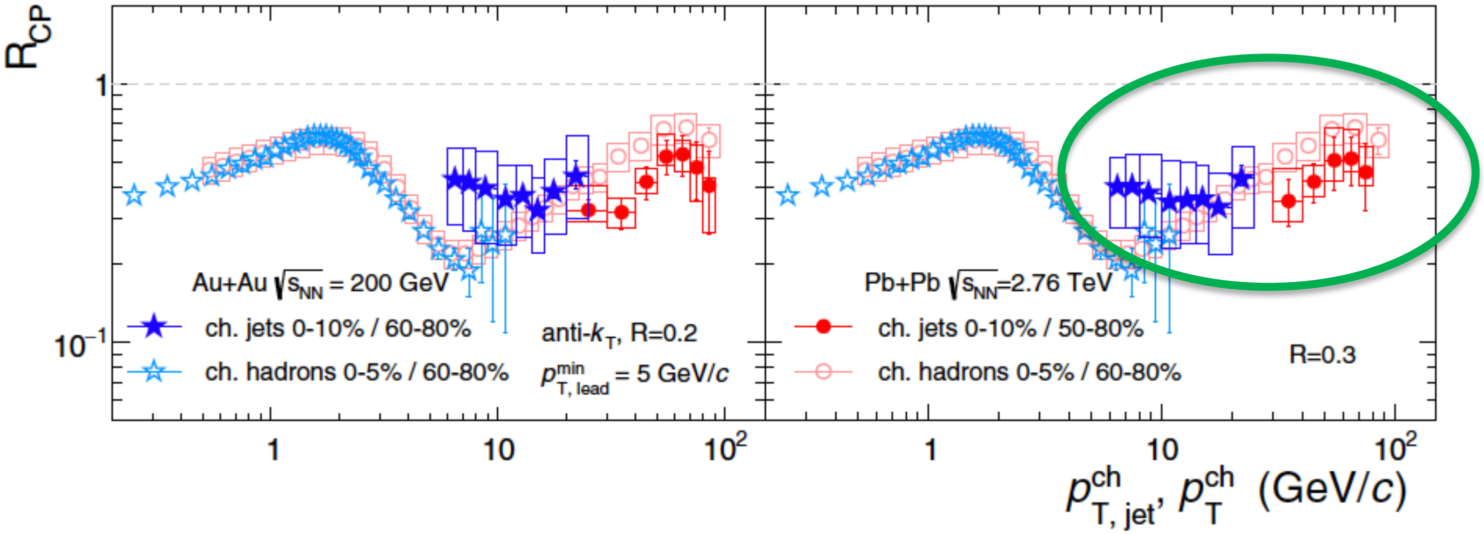


Jet energy loss: R_{CP}

$p_{T,lead}^{\text{min bias}}$ ~cancels in ratio, show full p_T range



Compare to charged hadrons & LHC charged jets



STAR

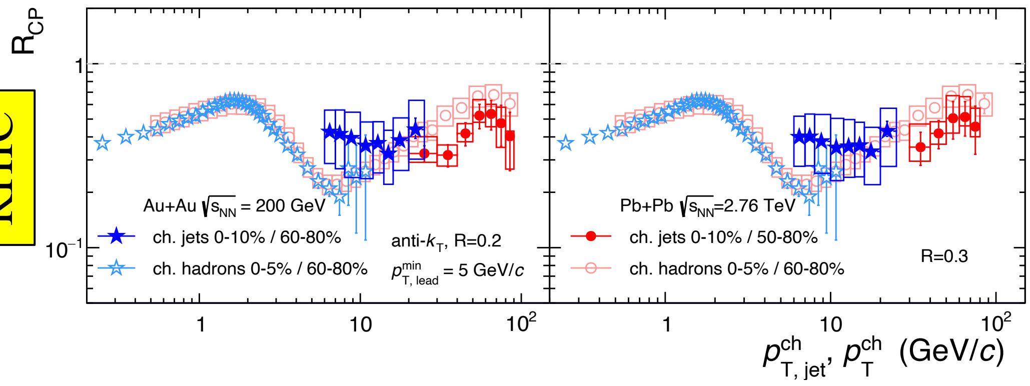
ALICE

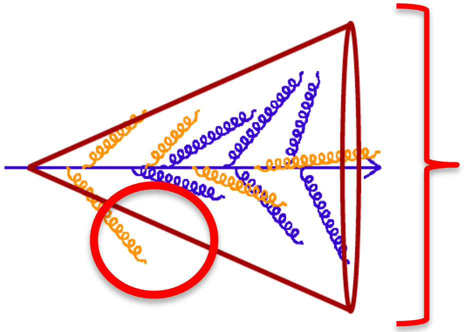
Similar suppression w/ different spectrum shapes…??

Jet suppression RHIC vs LHC: additional comparisons

Charged jet R_{CP}

RHIC

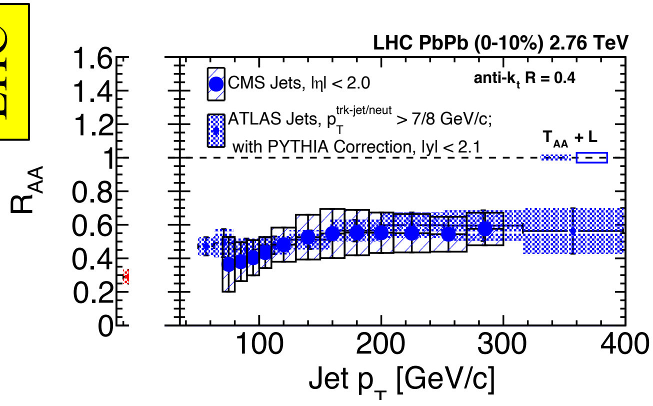


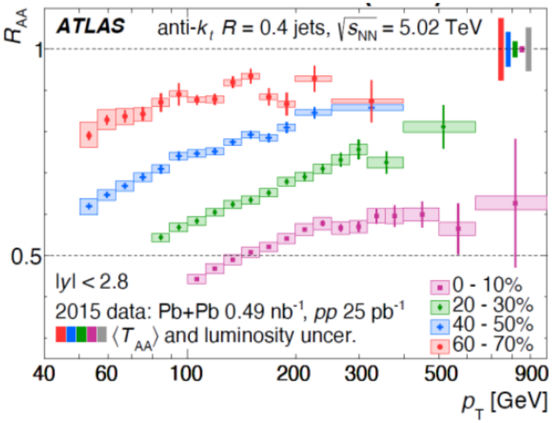


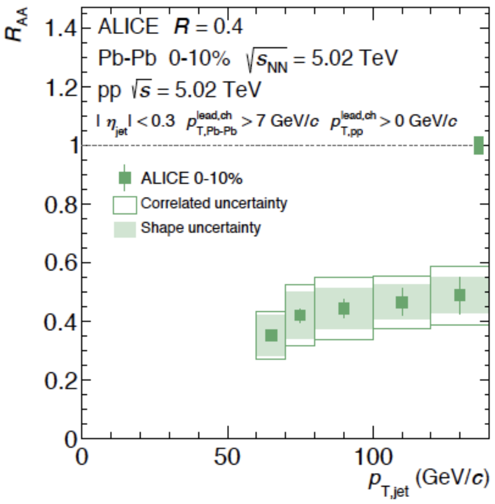
- Strong jet yield suppression
- Suppression ~ similar magnitude at RHIC and LHC…?

Calorimetric jet R_{AA}

LHC

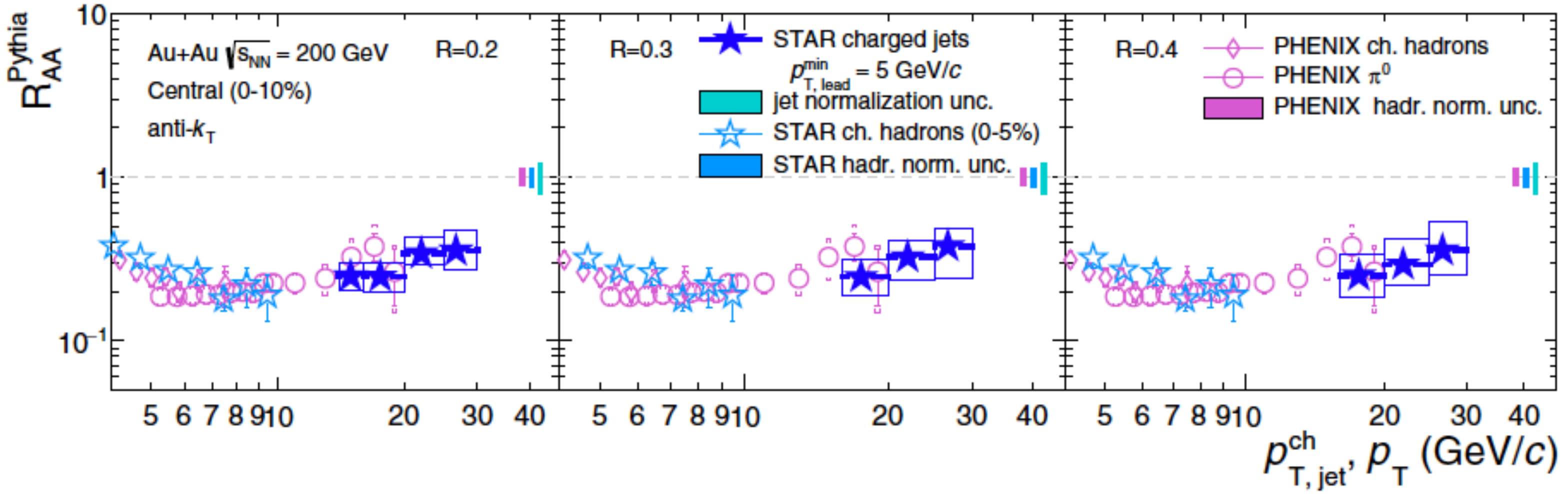




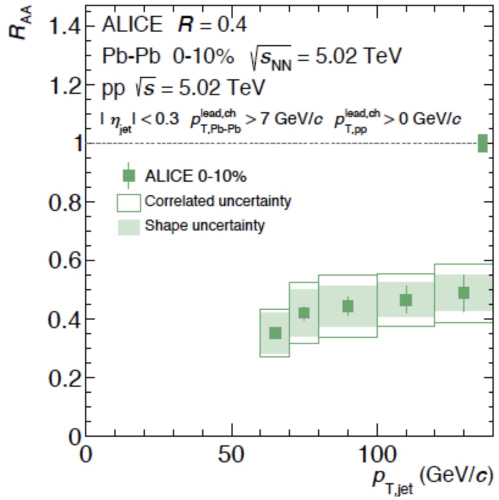


Jet energy loss: R_{AA}

pp reference: PYTHIA STAR tune

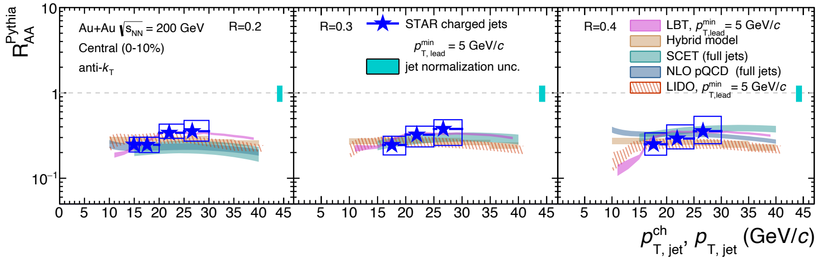


Similar picture to R_{CP}

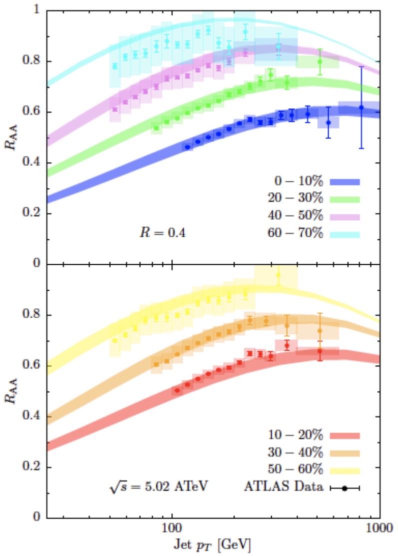


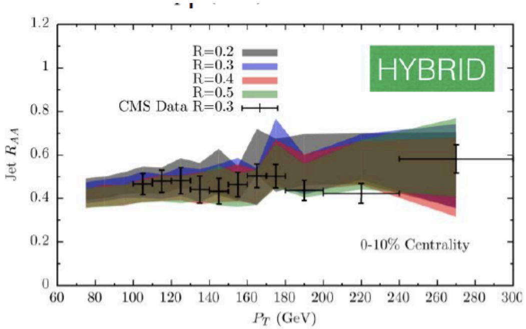
Inclusive jet R_{AA}: comparison to models

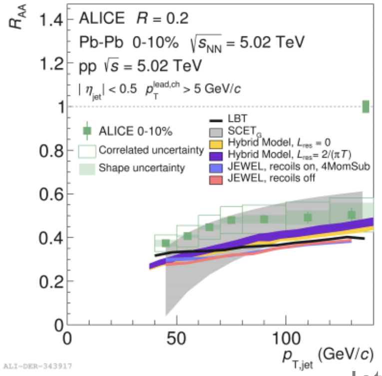
Diverse jet quenching calculations based on pQCD
+ various approximations for jet+medium interaction



arXiv:2101.01742







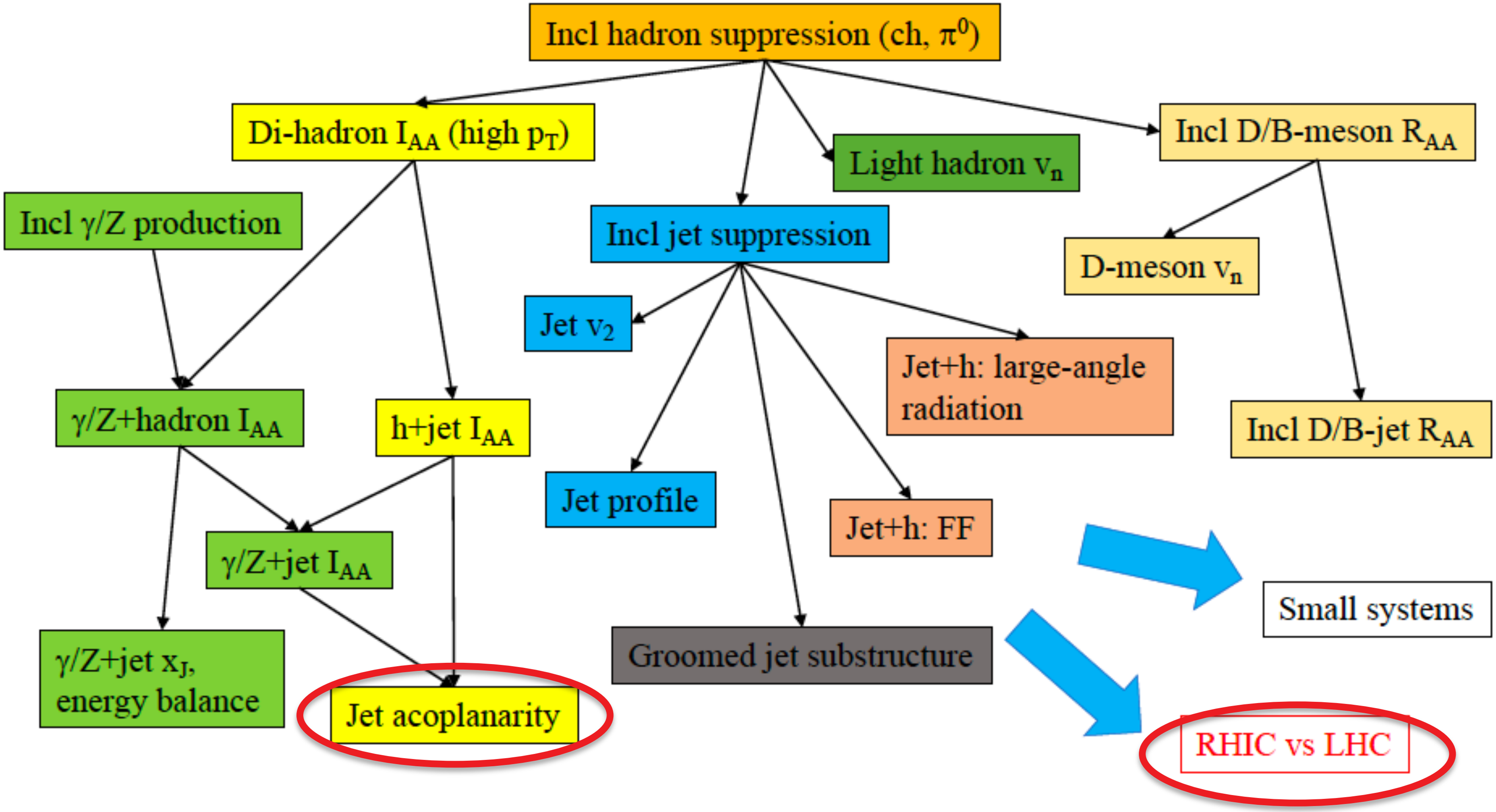
Current models work well over a wide range

Data relatively featureless, do not discriminate

How to make progress?

1. JETSCAPE: go beyond current formulation of qhat to capture full dynamics of jet-medium interaction → global fits to hadron&jet data

2. Other observables with orthogonal parametric dependencies



Incl hadron suppression (ch, π^0)

Di-hadron I_{AA} (high p_T)

Light hadron v_n

Incl D/B-meson R_{AA}

Incl γ/Z production

Incl jet suppression

D-meson v_n

Jet v_2

Jet+h: large-angle radiation

γ/Z+hadron I_{AA}

h+jet I_{AA}

Incl D/B-jet R_{AA}

Jet profile

Jet+h: FF

γ/Z+jet I_{AA}

Small systems

γ/Z+jet x_J, energy balance

Jet acoplanarity

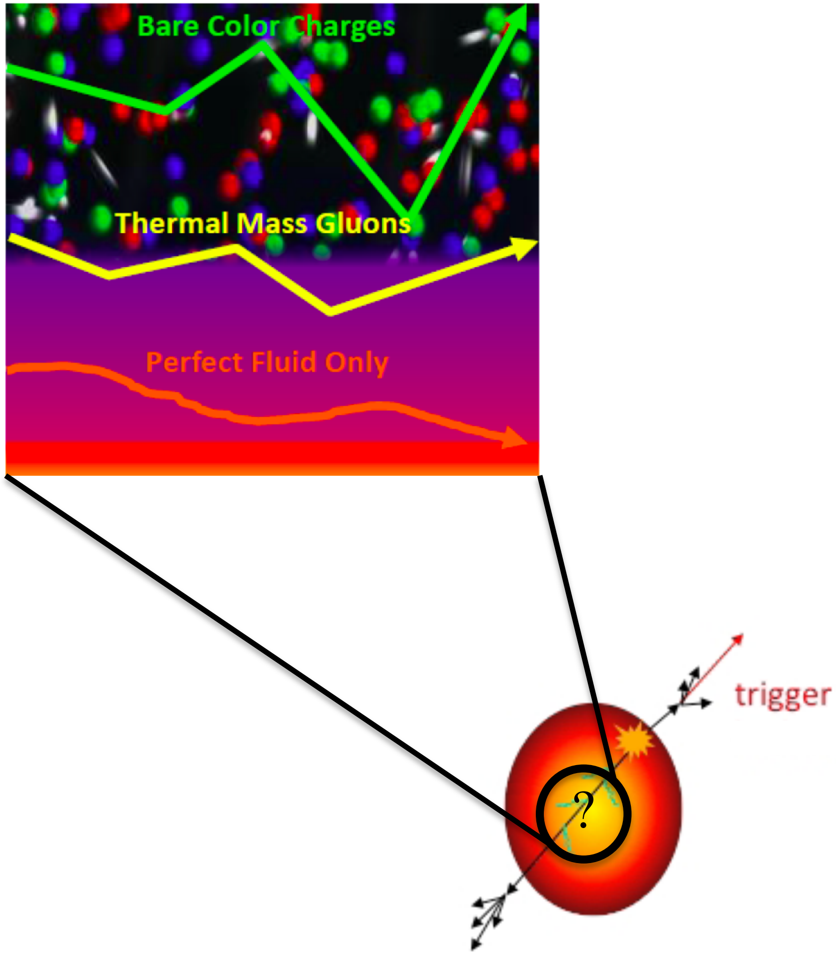
Groomed jet substructure

RHIC vs LHC

Jet acoplanarity: in-medium hard scattering

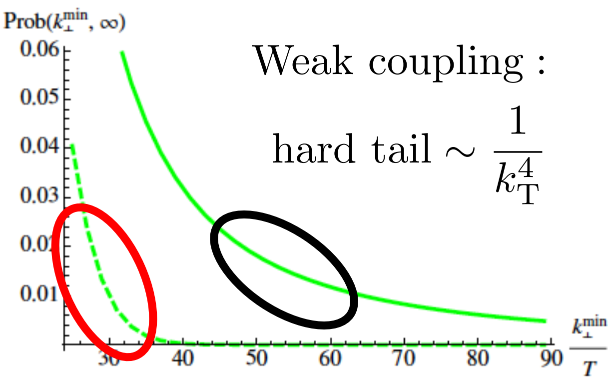
(“Rutherford experiment”)

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?

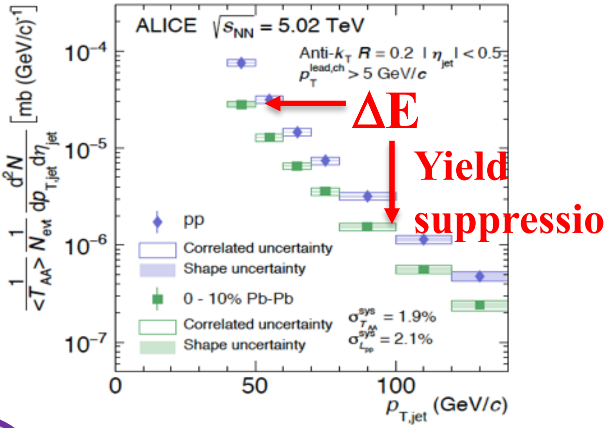
- high Q^2: bare q and g
- low-ish Q^2:
  - thermal-mass glue
  - magnetic monopoles
  - …?

Jet acoplanarity: in-medium soft deflection

For intuition use BDMPS theory: multiple soft scattering approximation

Medium-induced jet energy loss:

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

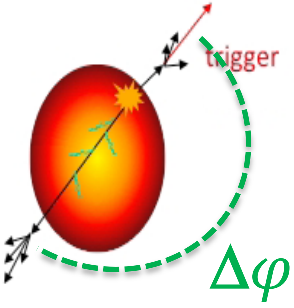


ΔE

Yield suppression

Medium-induced angular broadening:

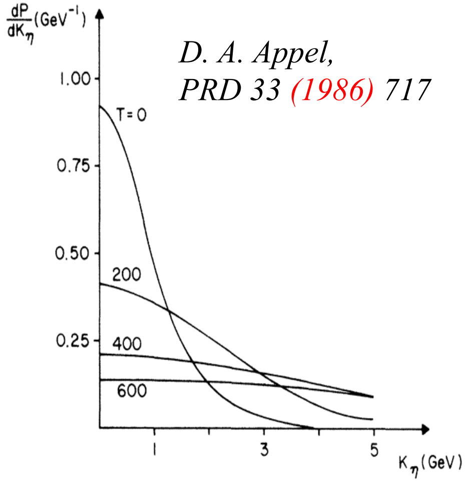
$$\langle k_T^2 \rangle \sim \langle \Delta\varphi^2 \rangle \sim \alpha_s \hat{q} L$$



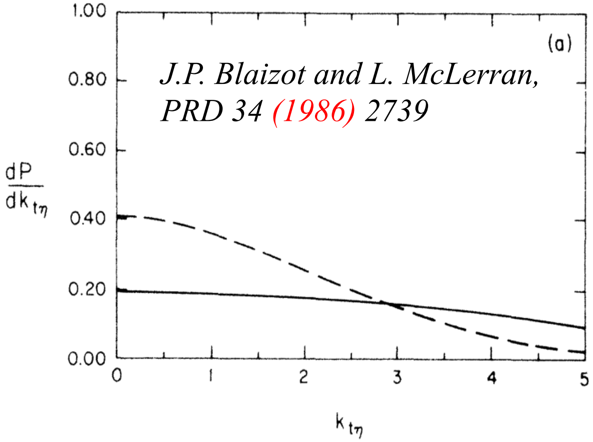
Different parametric dependencies → better model discrimination?

Side note: using jet scattering to measure the QGP is an old idea but experimentally very challenging

- techniques now in place

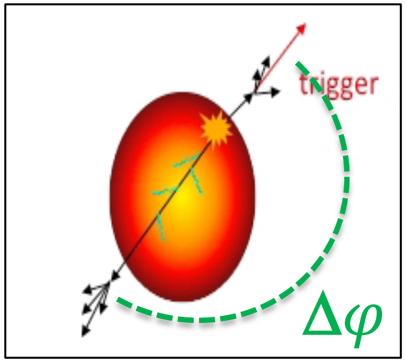


D. A. Appel, PRD 33 (1986) 717

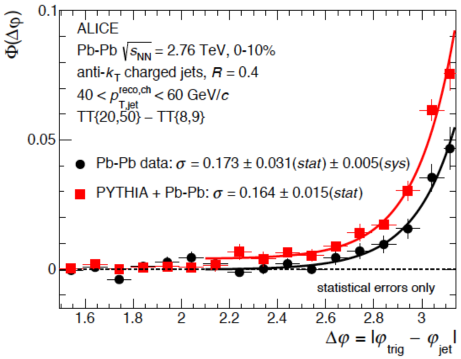


J.P. Blaizot and L. McLerran, PRD 34 (1986) 2739

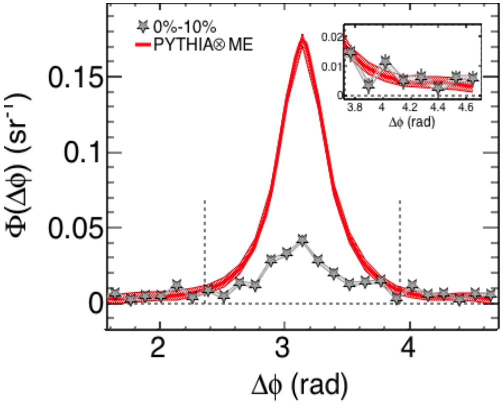
Jet acoplanarity: data



ALICE, JHEP 09 (2015) 170

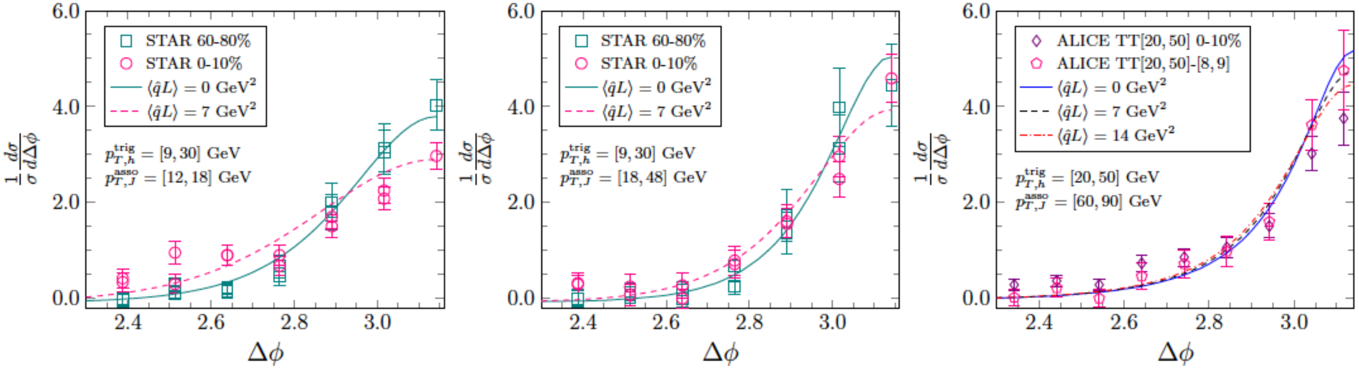


STAR,Phys Rev C96 (2017) 024905



Significant background: Initial-state (Sudakov) radiation

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

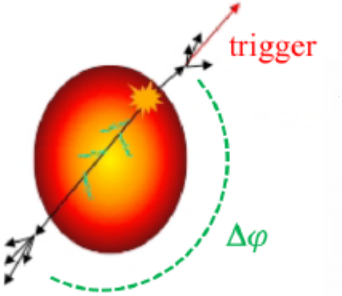


First- generation ALICE+STAR measurements:

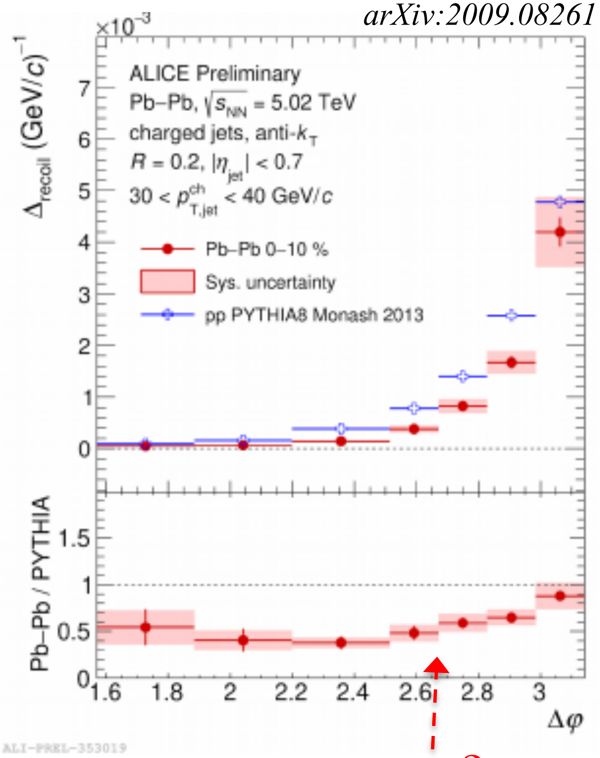
no medium-induced acoplanarity observed above background

Second-generation measurements with greater precision in progress….

Jet acoplanarity: ALICE Run 2



arXiv:2009.08261



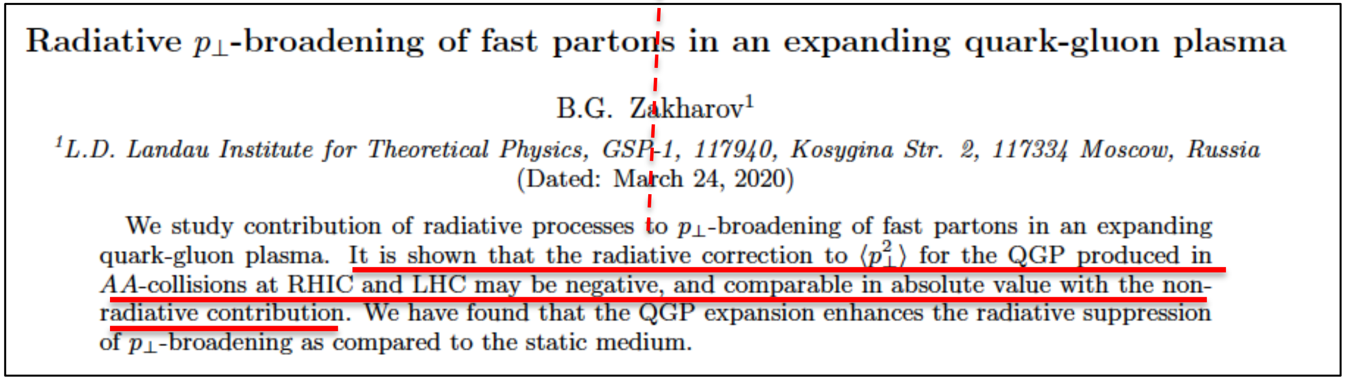
Work in progress:

- larger R, lower p_T^{jet}
- measured p+p reference

Narrowing due to radiative corrections…?

?

arXiv:2003.10182



Radiative $p_\perp$-broadening of fast partons in an expanding quark-gluon plasma

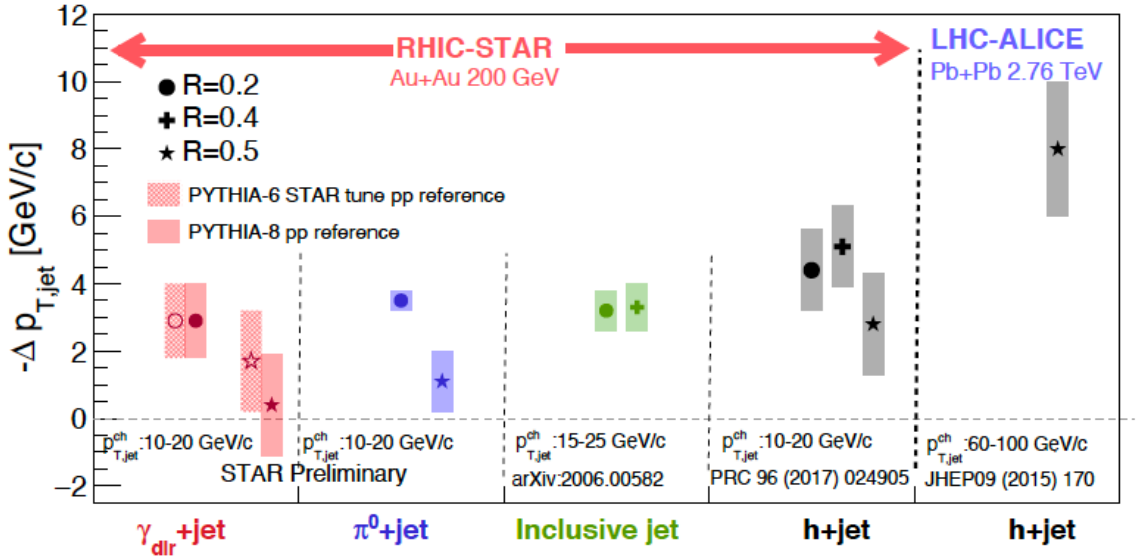
B.G. Zakharov[1]

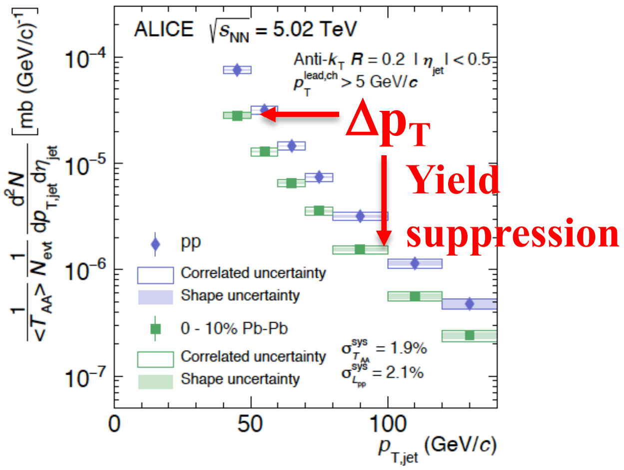
[1]*L.D. Landau Institute for Theoretical Physics, GSP-1, 117940, Kosygina Str. 2, 117334 Moscow, Russia*
(Dated: March 24, 2020)

We study contribution of radiative processes to $p_\perp$-broadening of fast partons in an expanding quark-gluon plasma. It is shown that the radiative correction to $\langle p_\perp^2\rangle$ for the QGP produced in AA-collisions at RHIC and LHC may be negative, and comparable in absolute value with the non-radiative contribution. We have found that the QGP expansion enhances the radiative suppression of $p_\perp$-broadening as compared to the static medium.

Phenomenology: in-medium energy loss measured via jet spectrum shift

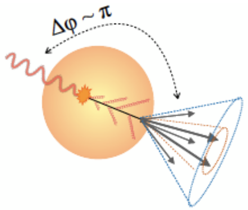
Inclusive jet and X+jet measurements

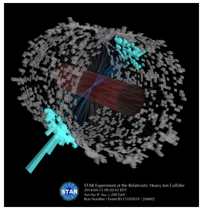


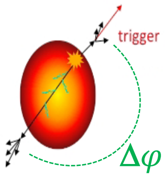


Δp_T

Yield suppression







RHIC: energy loss similar for different probes

- possible R-dependence

LHC: energy loss larger than RHIC

Confrontation with theory calculations TBD

Jet quenching: Outlook

LHC
- Run 3 starts early 2022; factor ~10 luminosity increase
- ALICE: essentially a new detector with vastly improved capabilities
- ATLAS/CMS moderate improvements (major upgrades ~2025 for Run 4)
- Through Run 4 (2029): Pb+Pb @10 nb $^{-1}$

RHIC
- New detector focused on jet physics: sPHENIX
- Upgraded STAR
- Through 2025: STAR Au+Au@110 nb $^{-1}$; sPHENIX Au+Au @23 nb $^{-1}$

→ At both facilities: factor ~10 increase in data, much improved instrumentation

But experimental advances alone are not sufficient for quantitative understanding of jet quenching and the QGP

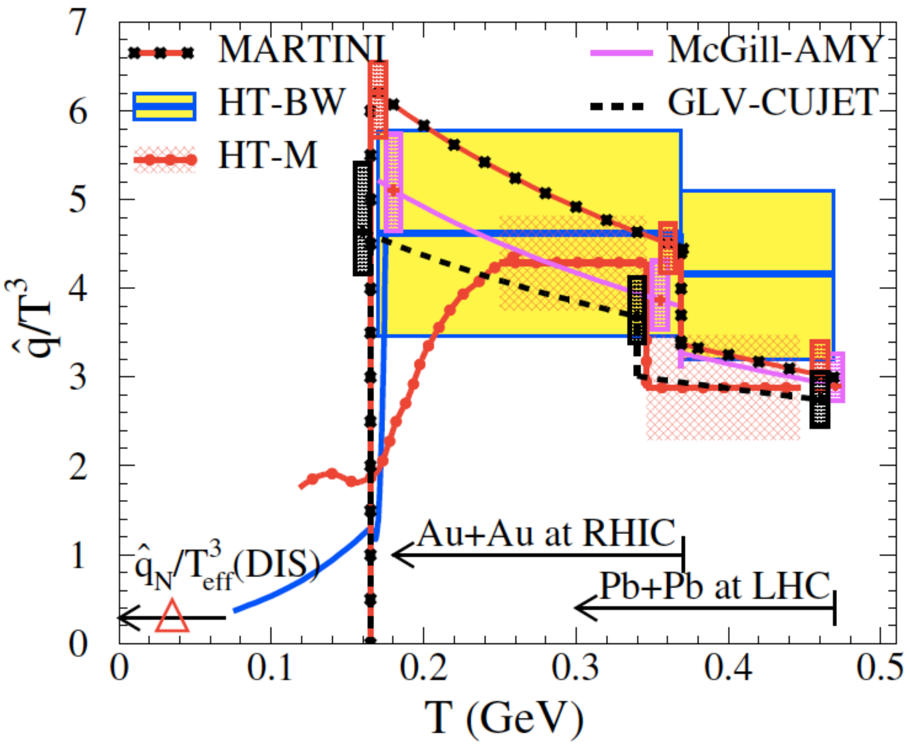
Theory and modelling:
- Conceptual and calculational advances in modelling of in-medium jet modification
- Rigorous-large scale global fits to a wide range of judiciously chosen jet and hadron data

→ Bayesian inference using JETSCAPE

Jet quenching was discovered 20 years ago; still compelling, not yet solved…

Extra slides

Measuring $\hat{q}$: inclusive hadron suppression



JET Collaboration
Phys.Rev. C90 (2014) 1, 014909

Fit pQCD-based models to **single-hadron suppression** data at RHIC and LHC

For a 10 GeV light quark at time 0.6 fm/c:

$$\text{RHIC}: \ \hat{q} \approx 1.2 \pm 0.3 \ \text{GeV}^2/\text{fm}$$

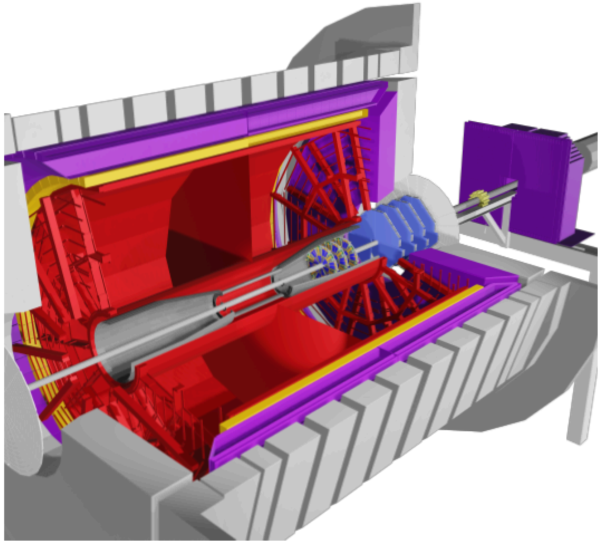
$$\text{LHC}: \ \hat{q} \approx 1.9 \pm 0.7 \ \text{GeV}^2/\text{fm}$$

Reasonable and improvable precision

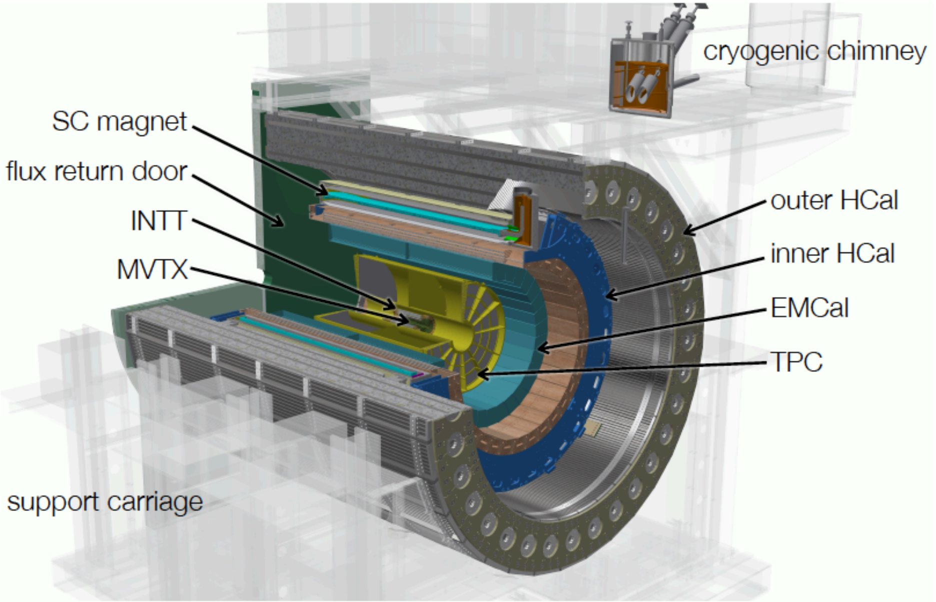
Cold matter (e+A at HERA): $\hat{q} \approx 0.02 \ \text{GeV}^2/\text{fm}$

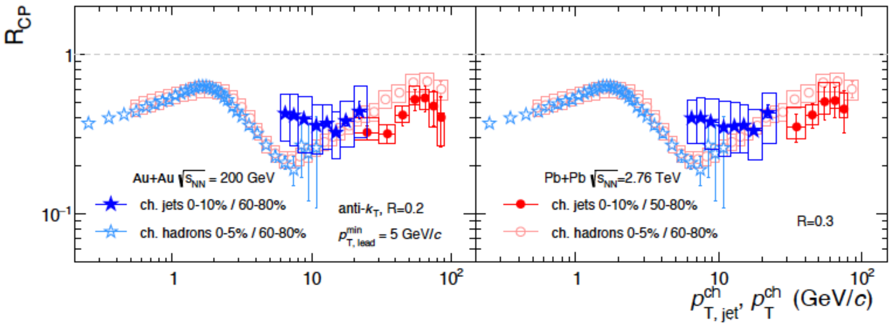
RHIC && LHC: the present

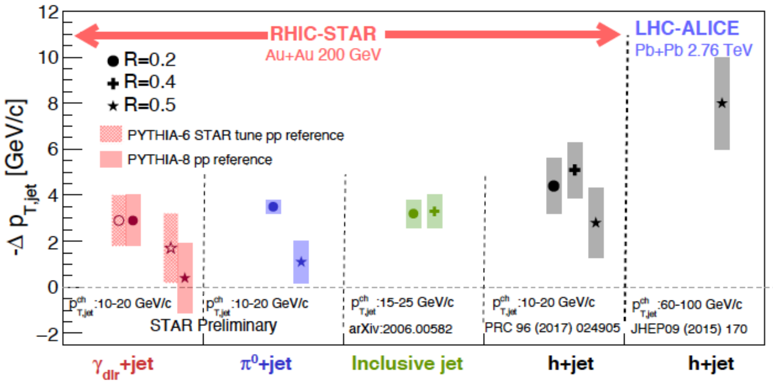
STAR



sPHENIX (under construction)







RHIC: the future

Beam Use Request to RHIC PAC, Sept 2020

STAR

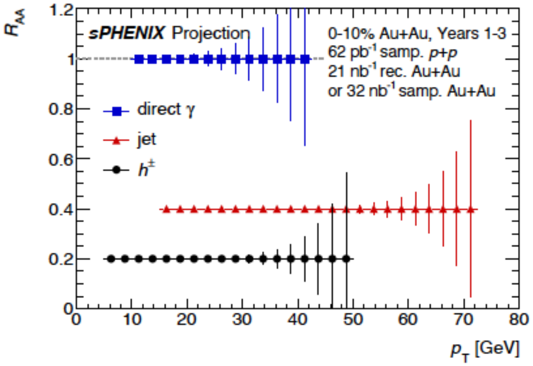
year	minimum bias $[\times 10^9$ events$]$	high-p_T int. luminosity $[\mathrm{nb}^{-1}]$		
		all vz	$\vert vz\vert<70$cm	$\vert vz\vert<30$cm
2014 2016	2	26.5	19.1	15.7
2023	10	43	38	32
2025	10	58	52	43

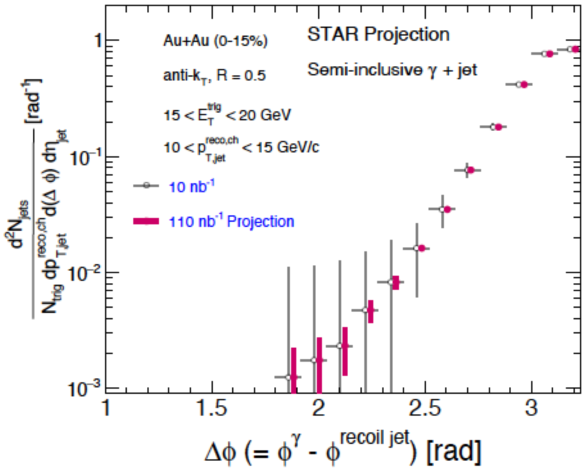
sPHENIX

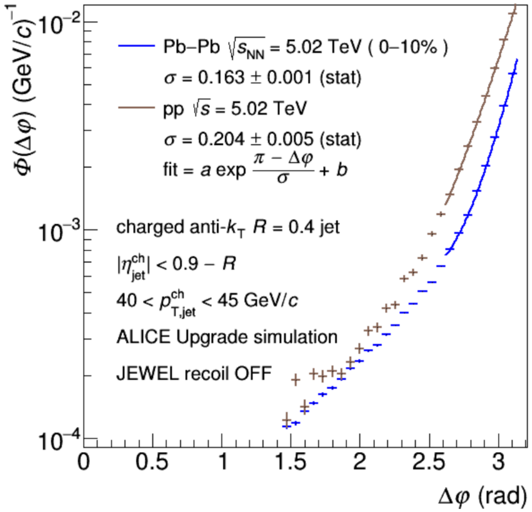
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\vert z\vert<10$ cm	Samp. Lum. $\vert z\vert<10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^\uparrow p^\uparrow$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^\uparrow$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Au+Au total int lumi through 2025:

- STAR: 110 nb^{-1}
- sPHENIX: 23 nb^{-1}

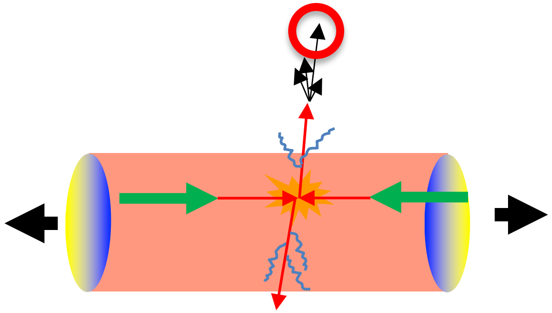


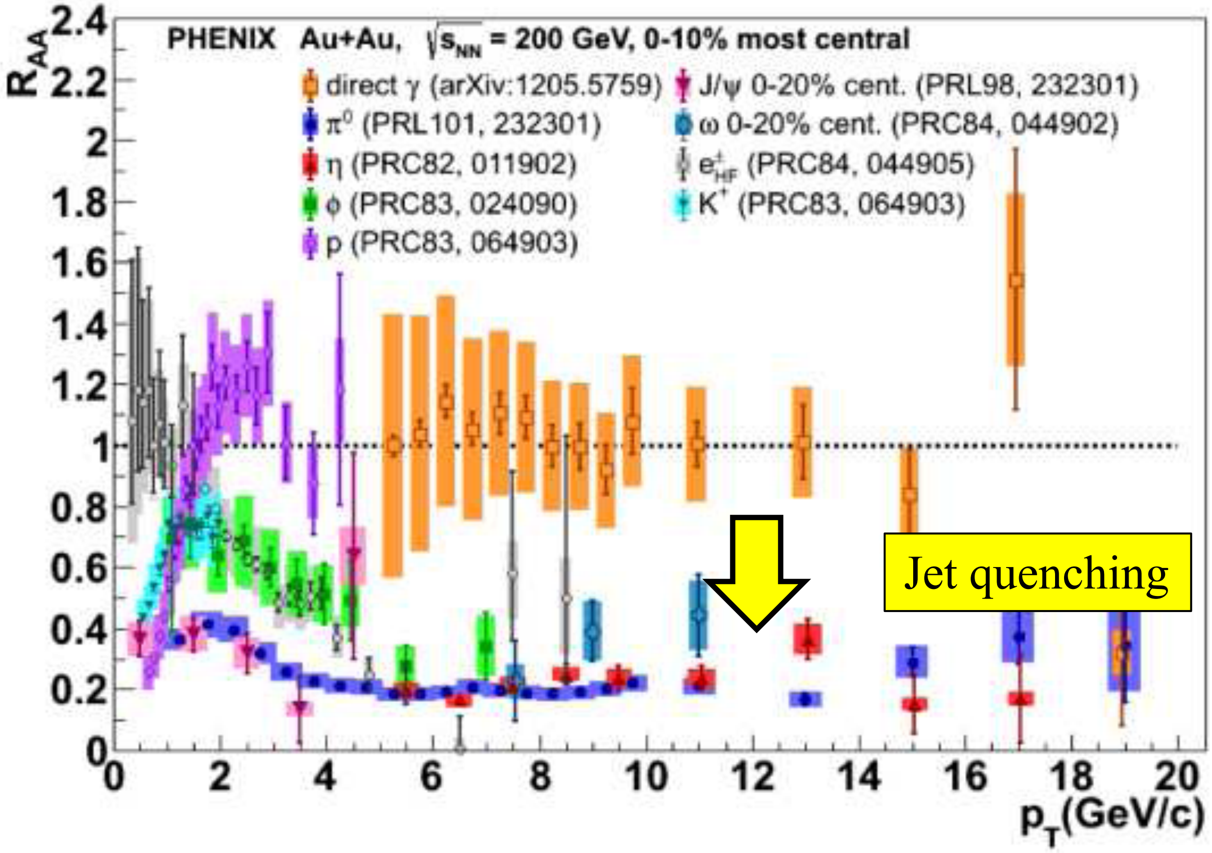




Jet quenching via high p_T hadrons

$$R_{AA} = \frac{\text{Observed rate in AA}}{\text{Expected rate from pp} \otimes \text{geometry}}$$





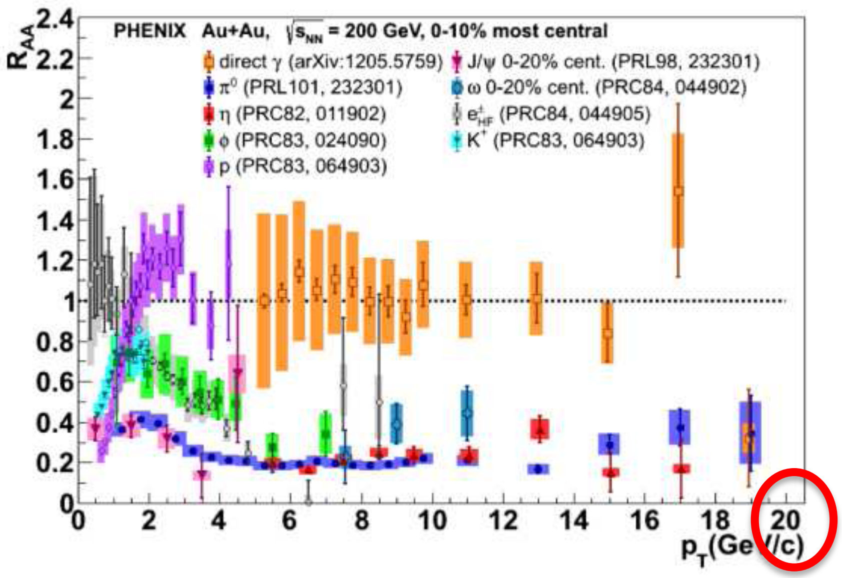
Jet quenching

Photons (color-neutral)

Jet fragments (color-charged)

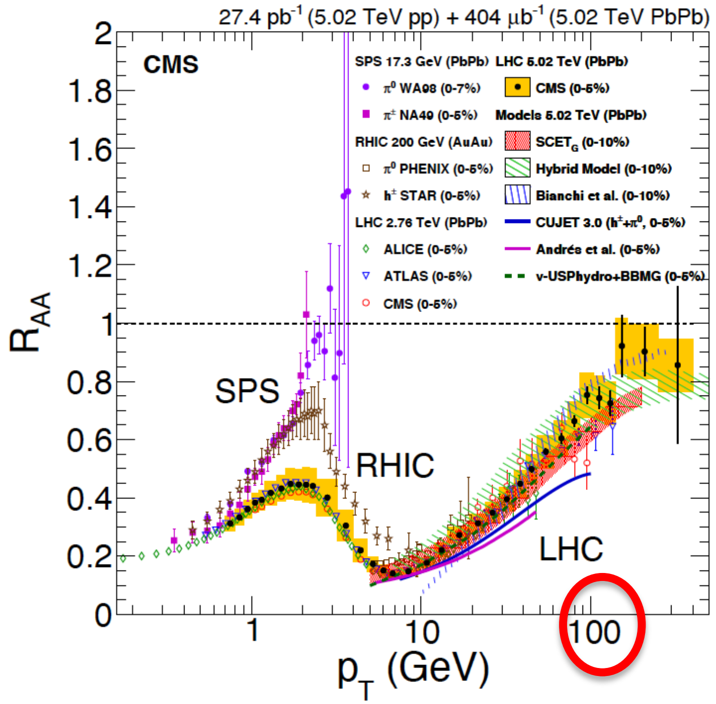
Inclusive hadron suppression: RHIC vs LHC

RHIC



LHC

JHEP 04 (2017) 039



RHIC/LHC: Qualitatively similar, quantitatively different

- interplay between energy loss (~matter density) and spectrum shape

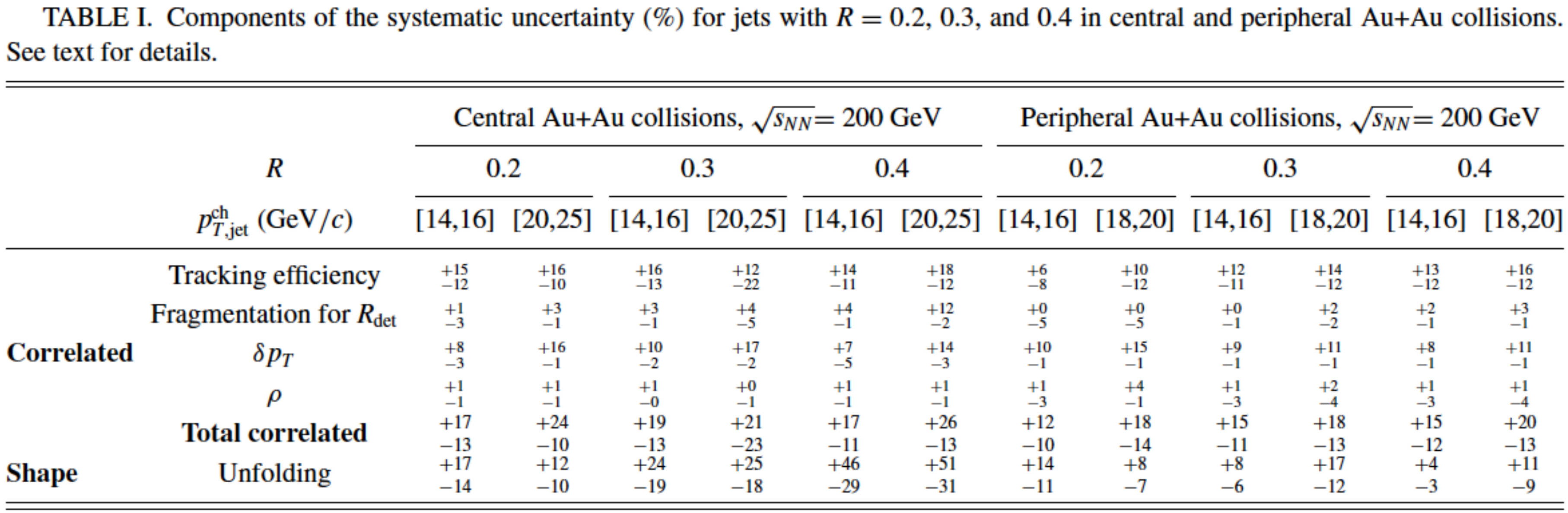


TABLE I. Components of the systematic uncertainty (%) for jets with $R = 0.2$, 0.3, and 0.4 in central and peripheral Au+Au collisions. See text for details.

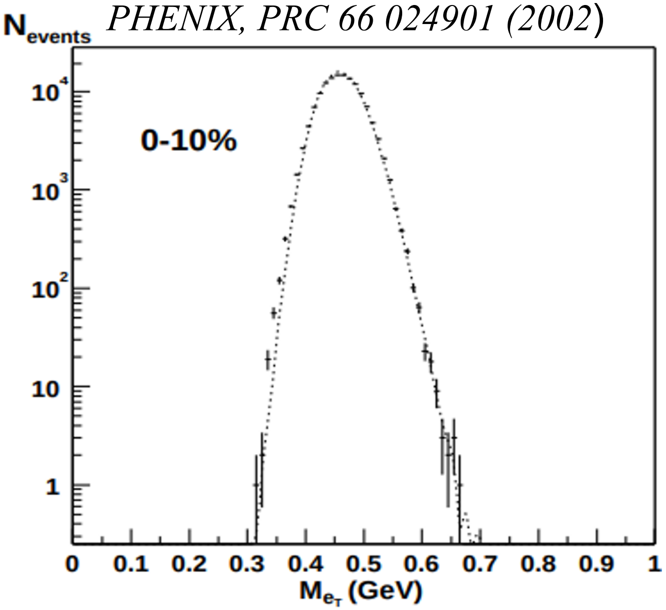
		Central Au+Au collisions, $\sqrt{s_{NN}}$= 200 GeV						Peripheral Au+Au collisions, $\sqrt{s_{NN}}$= 200 GeV					
	R	0.2		0.3		0.4		0.2		0.3		0.4	
	$p_{T,\mathrm{jet}}^{\mathrm{ch}}$ (GeV/c)	[14,16]	[20,25]	[14,16]	[20,25]	[14,16]	[20,25]	[14,16]	[18,20]	[14,16]	[18,20]	[14,16]	[18,20]
Correlated	Tracking efficiency	$^{+15}_{-12}$	$^{+16}_{-10}$	$^{+16}_{-13}$	$^{+12}_{-22}$	$^{+14}_{-11}$	$^{+18}_{-12}$	$^{+6}_{-8}$	$^{+10}_{-12}$	$^{+12}_{-11}$	$^{+14}_{-12}$	$^{+13}_{-12}$	$^{+16}_{-12}$
	Fragmentation for R_{det}	$^{+1}_{-3}$	$^{+3}_{-1}$	$^{+3}_{-1}$	$^{+4}_{-5}$	$^{+4}_{-1}$	$^{+12}_{-2}$	$^{+0}_{-5}$	$^{+0}_{-5}$	$^{+0}_{-1}$	$^{+2}_{-2}$	$^{+2}_{-1}$	$^{+3}_{-1}$
	δp_T	$^{+8}_{-3}$	$^{+16}_{-1}$	$^{+10}_{-2}$	$^{+17}_{-2}$	$^{+7}_{-5}$	$^{+14}_{-3}$	$^{+10}_{-1}$	$^{+15}_{-1}$	$^{+9}_{-1}$	$^{+11}_{-1}$	$^{+8}_{-1}$	$^{+11}_{-1}$
	ρ	$^{+1}_{-1}$	$^{+1}_{-1}$	$^{+1}_{-0}$	$^{+0}_{-1}$	$^{+1}_{-1}$	$^{+1}_{-1}$	$^{+1}_{-3}$	$^{+4}_{-1}$	$^{+1}_{-3}$	$^{+2}_{-4}$	$^{+1}_{-3}$	$^{+1}_{-4}$
	Total correlated	$^{+17}_{-13}$	$^{+24}_{-10}$	$^{+19}_{-13}$	$^{+21}_{-23}$	$^{+17}_{-11}$	$^{+26}_{-13}$	$^{+12}_{-10}$	$^{+18}_{-14}$	$^{+15}_{-11}$	$^{+18}_{-13}$	$^{+15}_{-12}$	$^{+20}_{-13}$
Shape	Unfolding	$^{+17}_{-14}$	$^{+12}_{-10}$	$^{+24}_{-19}$	$^{+25}_{-18}$	$^{+46}_{-29}$	$^{+51}_{-31}$	$^{+14}_{-11}$	$^{+8}_{-7}$	$^{+8}_{-6}$	$^{+17}_{-12}$	$^{+4}_{-3}$	$^{+11}_{-9}$

Background Description - Parametrized Model

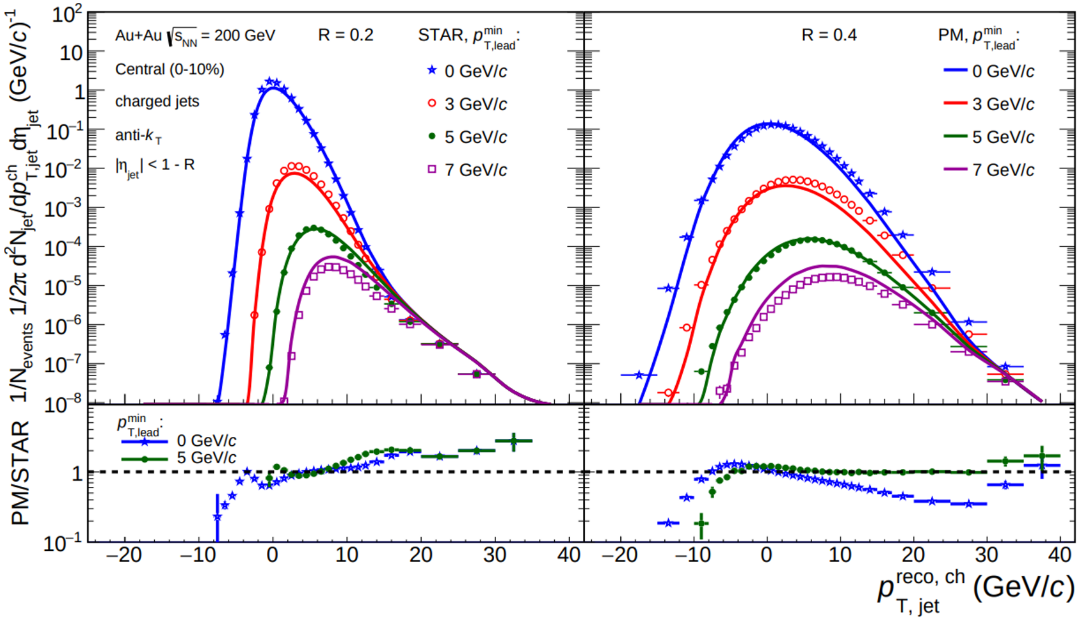
Closure test utilizes simple model for background: Boltzmann-distributed independent emission with hard jet fragmentation based on PYTHIA p+p calculation

E-by-e ET fluctuations well-described by Boltzmann indep. emission

PHENIX, PRC 66 024901 (2002)



Also works well for jet measurements



Picture consistent with good description of jet background by Mixed Events (STAR h+jet)

Heavy-ion jet measurement background strongly dominated by statistical phase space
Contrary to conventional wisdom: the problem is simple!

Jet broadening: R=0.2/R=0.4