Jet quenching at RHIC and the LHC: a status report

Peter Jacobs

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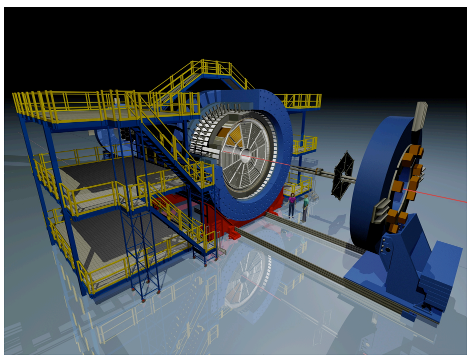
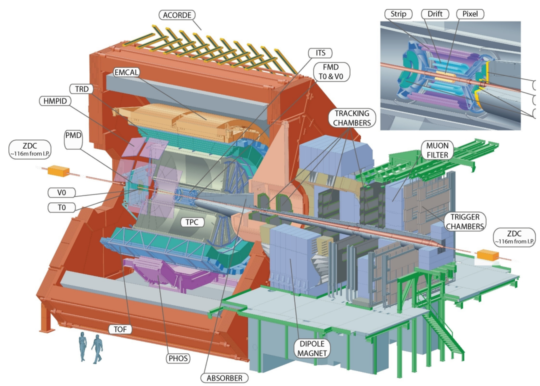
STAR@RHIC

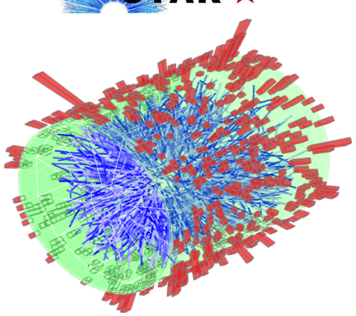
ALICE@LHC

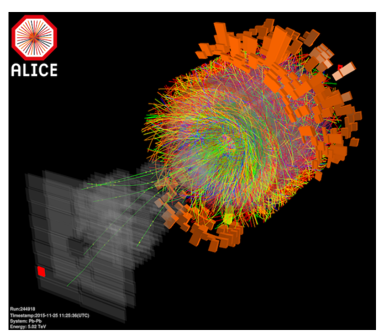


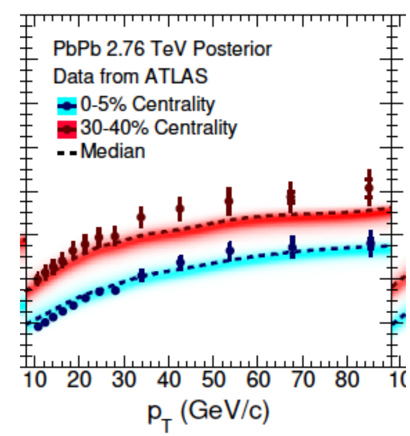


JETSCAPE

STAR

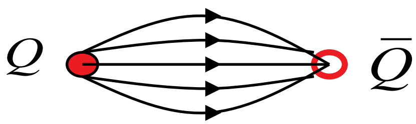


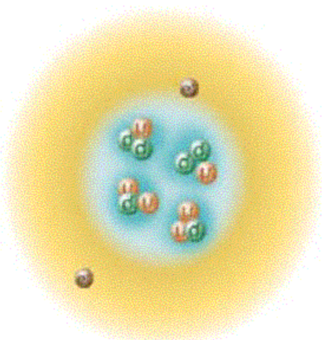


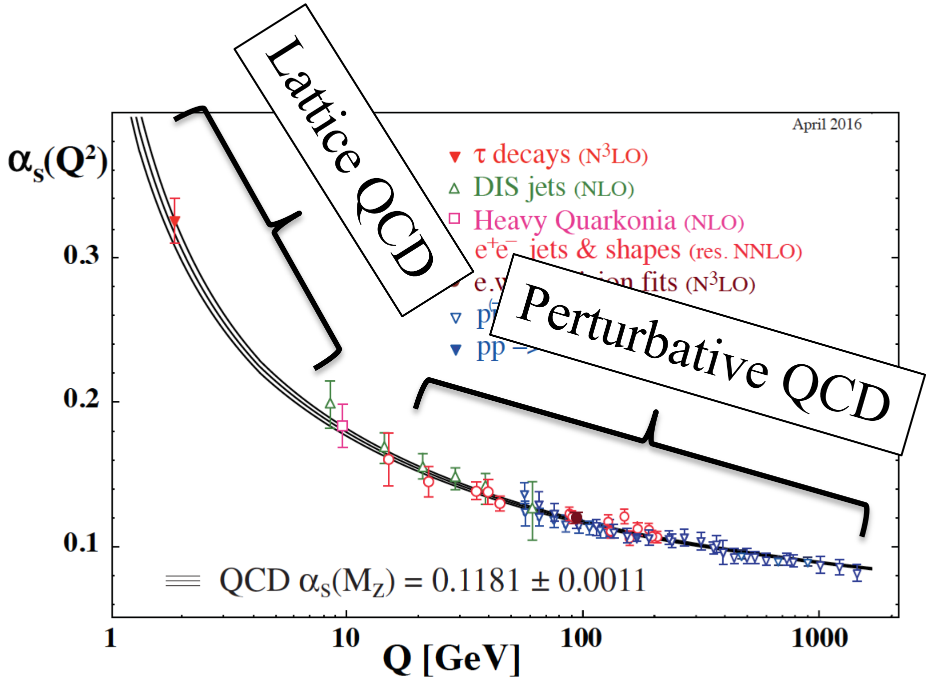


Hallmark of QCD: running of the coupling

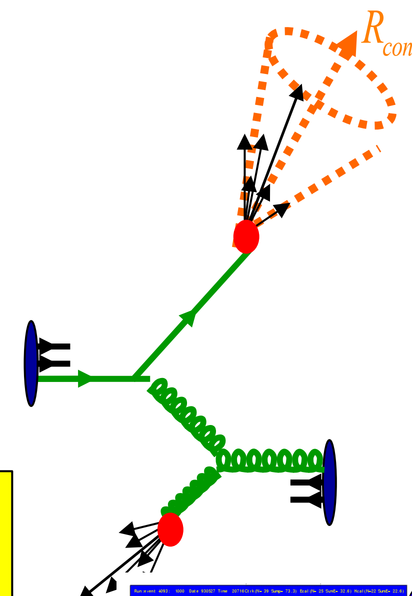
Confinement

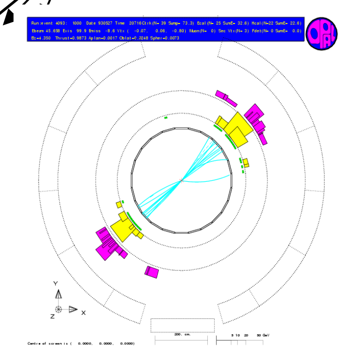






Asymptotic Freedom





Low momentum

High momentum

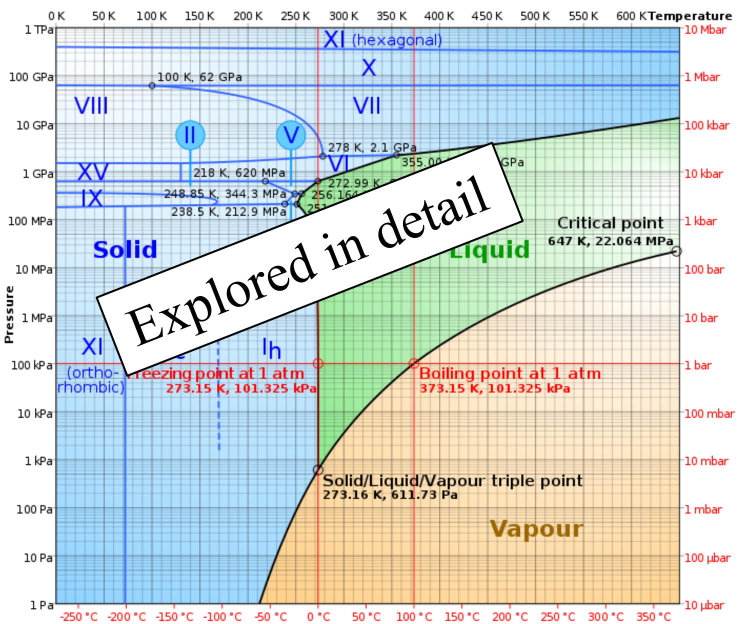
Gross Politzer Wilczek

Now consider "matter"

When many particles interact, complex new things happen
➔ emergent phenomena

Phase diagram of water

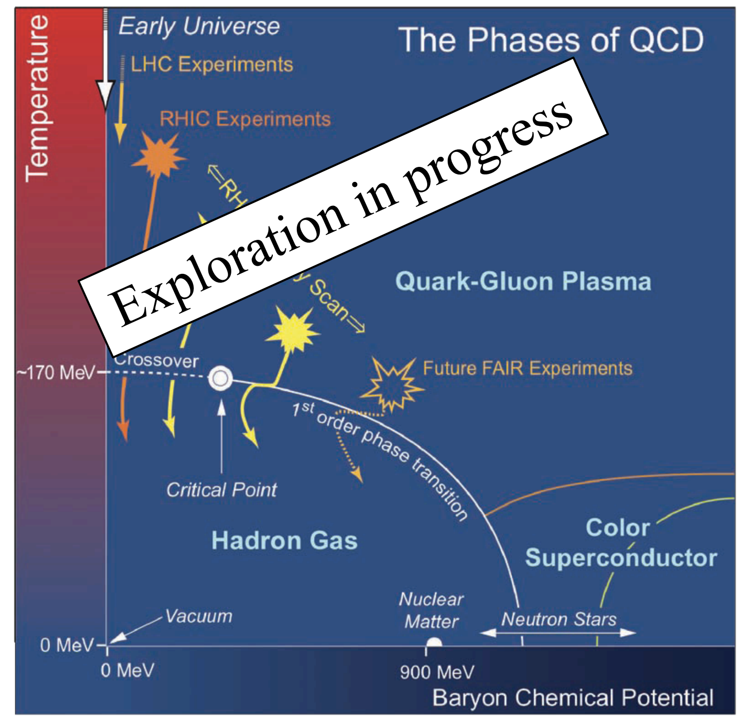
compress ➔



heat ➔

Phase diagram of QCD matter

heat ➔



compress ➔

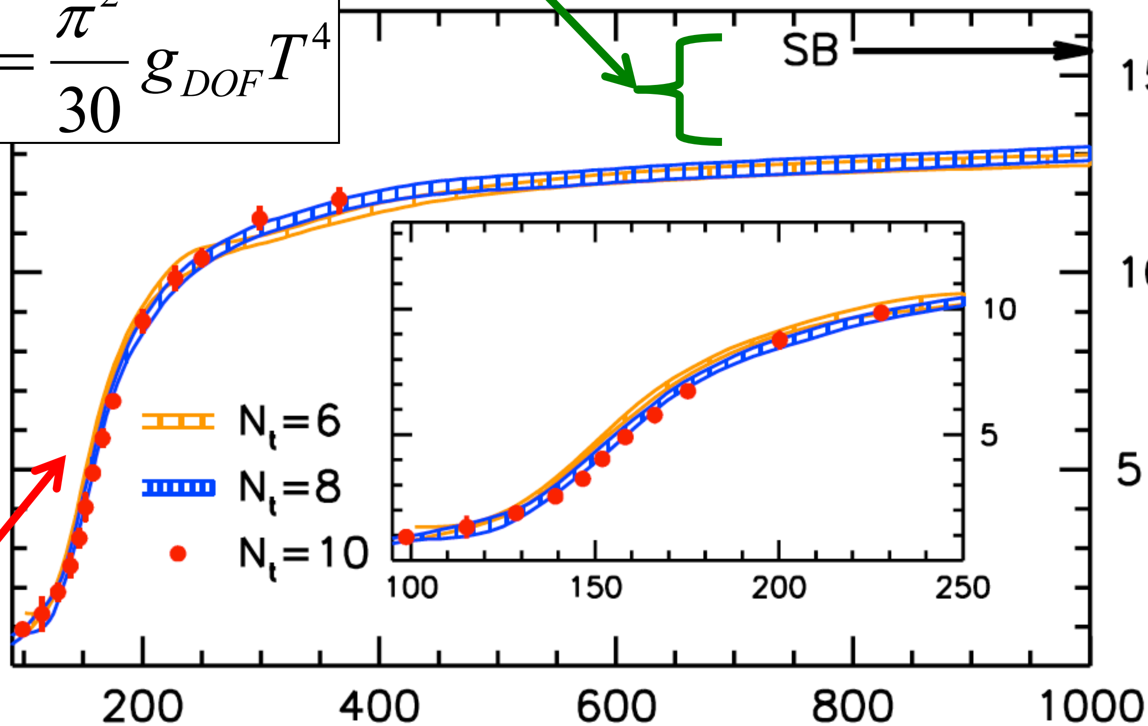
Finite Temperature QCD on the lattice (μ_B=0)

Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? “strongly-coupled” plasma?

Energy density

$$\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$$

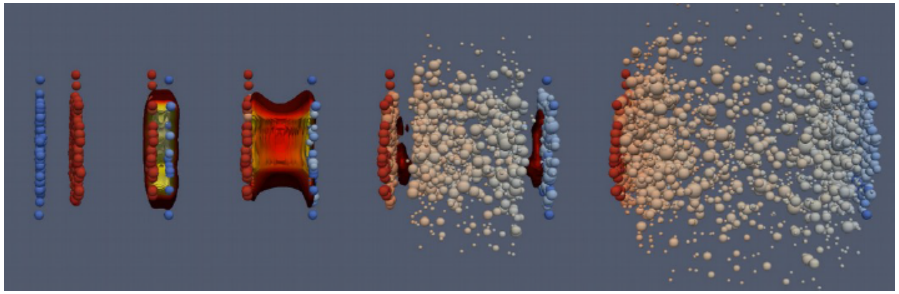
$$\frac{\varepsilon}{T^4}$$



S. Borsanyi et al., JHEP 1011, 077 (2010)

Temperature [MeV]

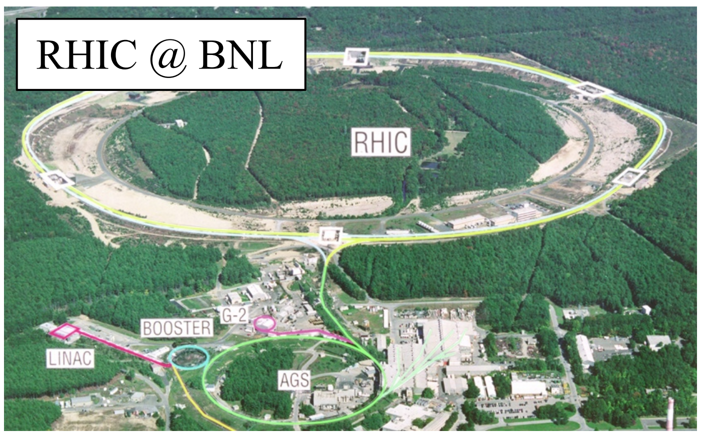
Cross-over, not sharp phase transition
(like ionization of atomic plasma)



Hot QCD in the laboratory

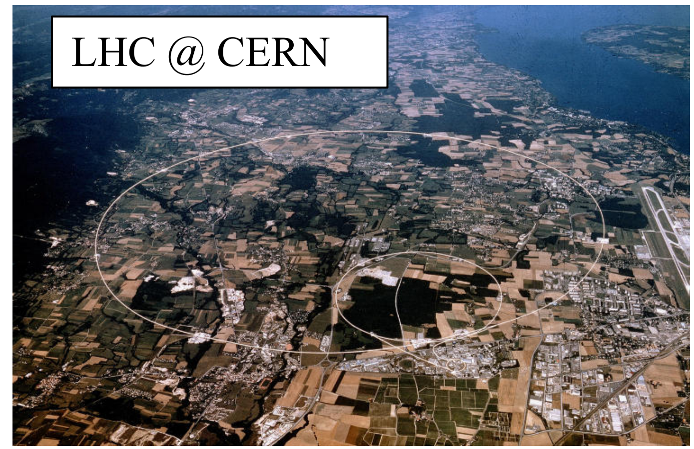
Au+Au $\sqrt{s_{NN}}$=200 GeV

RHIC @ BNL

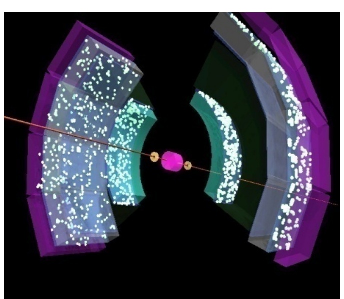


Pb+Pb $\sqrt{s_{NN}}$= 5 TeV

LHC @ CERN



PHENIX



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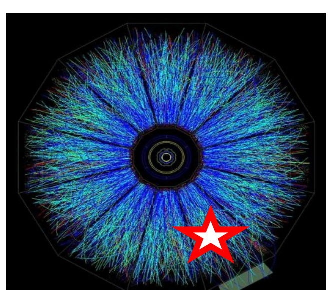
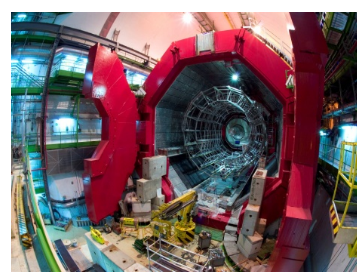
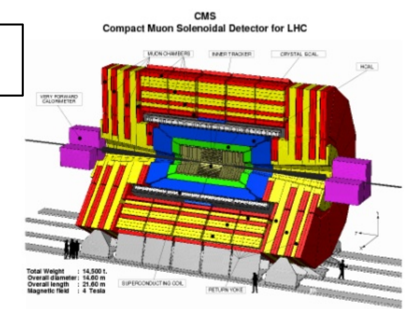


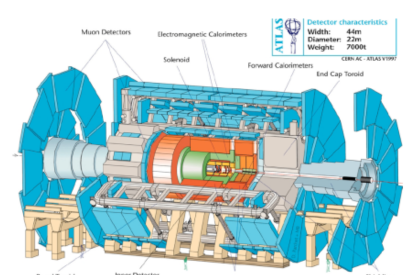
ALICE



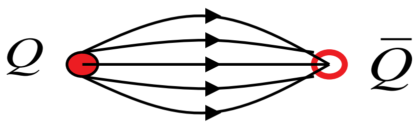
CMS

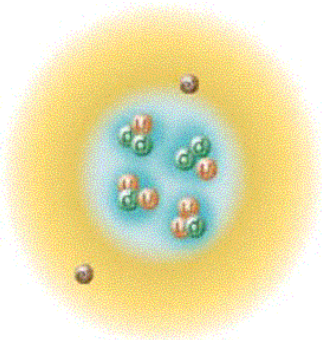


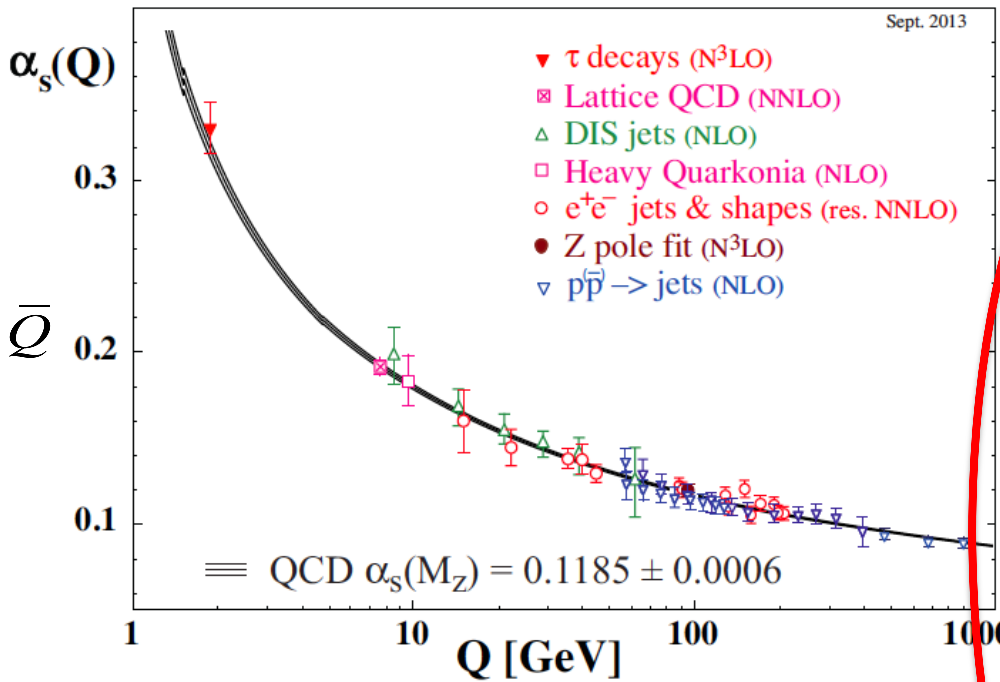
ATLAS



Confinement







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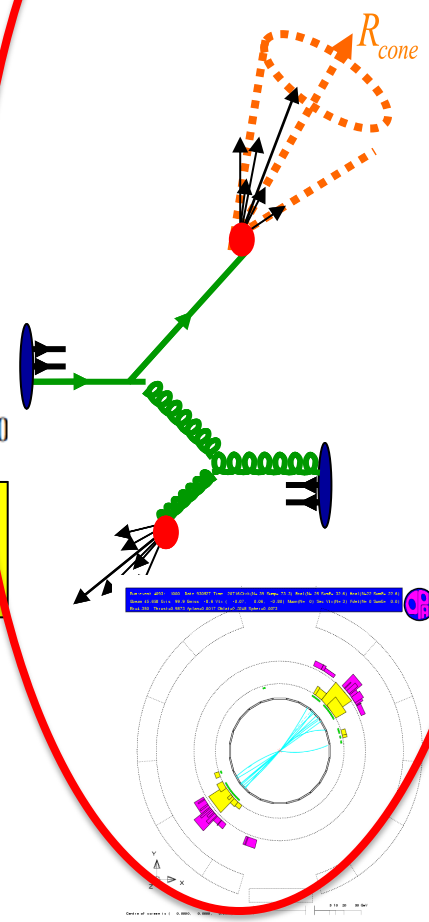
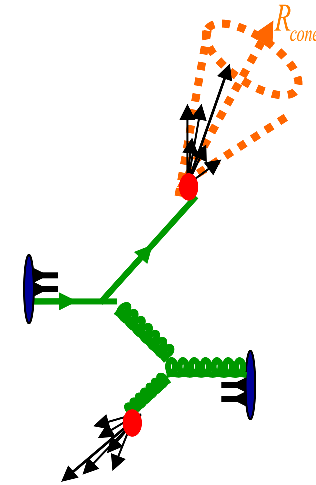
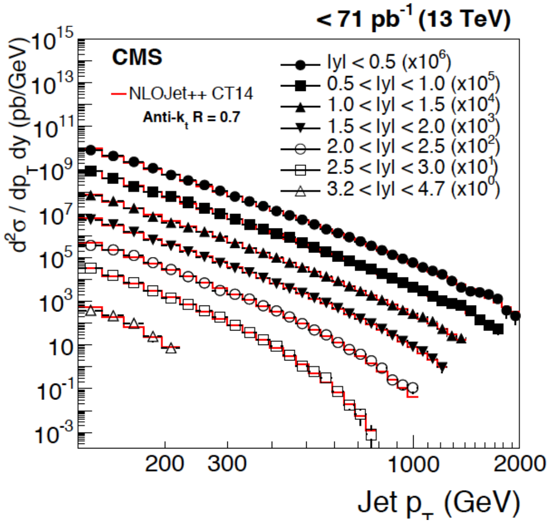


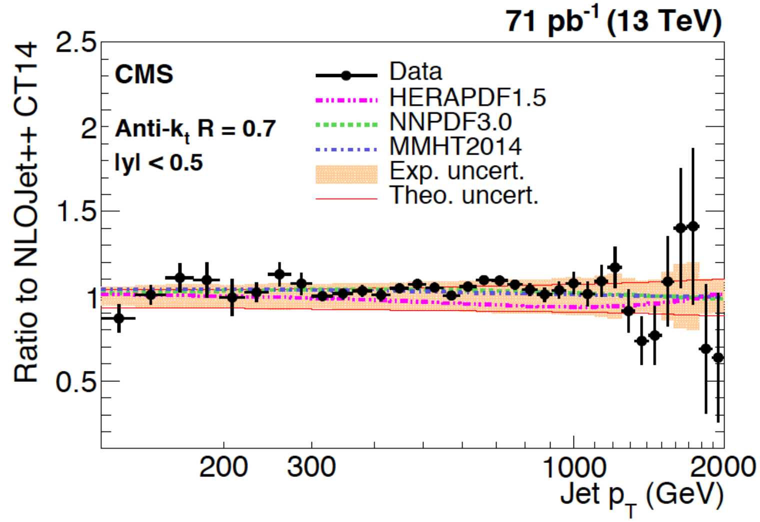
Scattering of energetic quarks and gluons → jets

Testing perturbative QCD at the LHC: 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

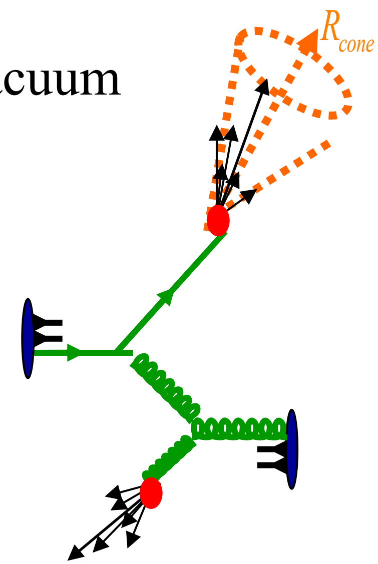
Infrared and collinear-safe (IRC-safe) jet reconstruction algorithms:

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

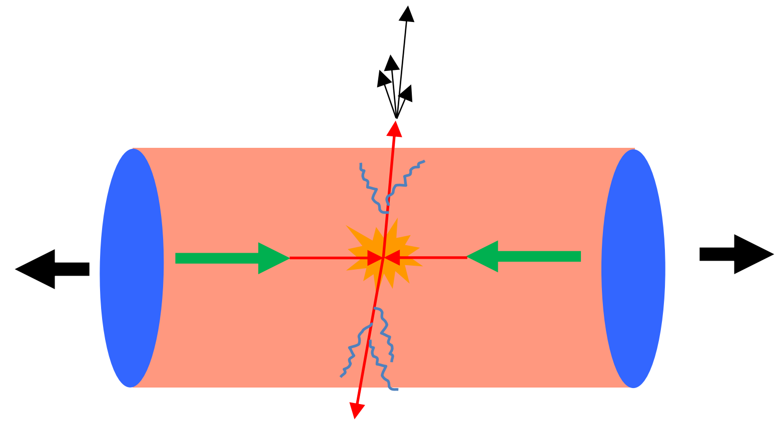
➔ jets measure partons

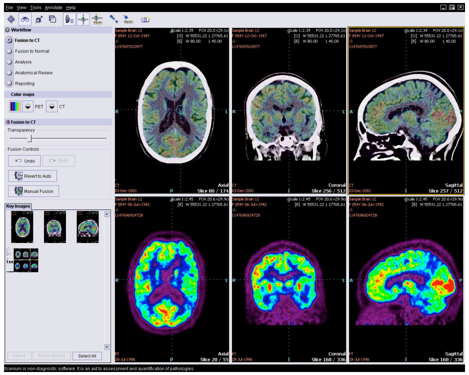
Jets in QCD matter

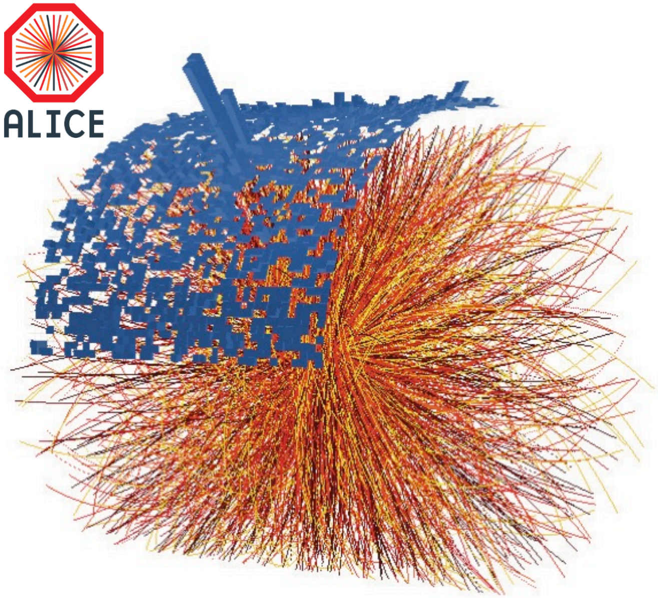
Jets in vacuum



Jets in nuclear collisions







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

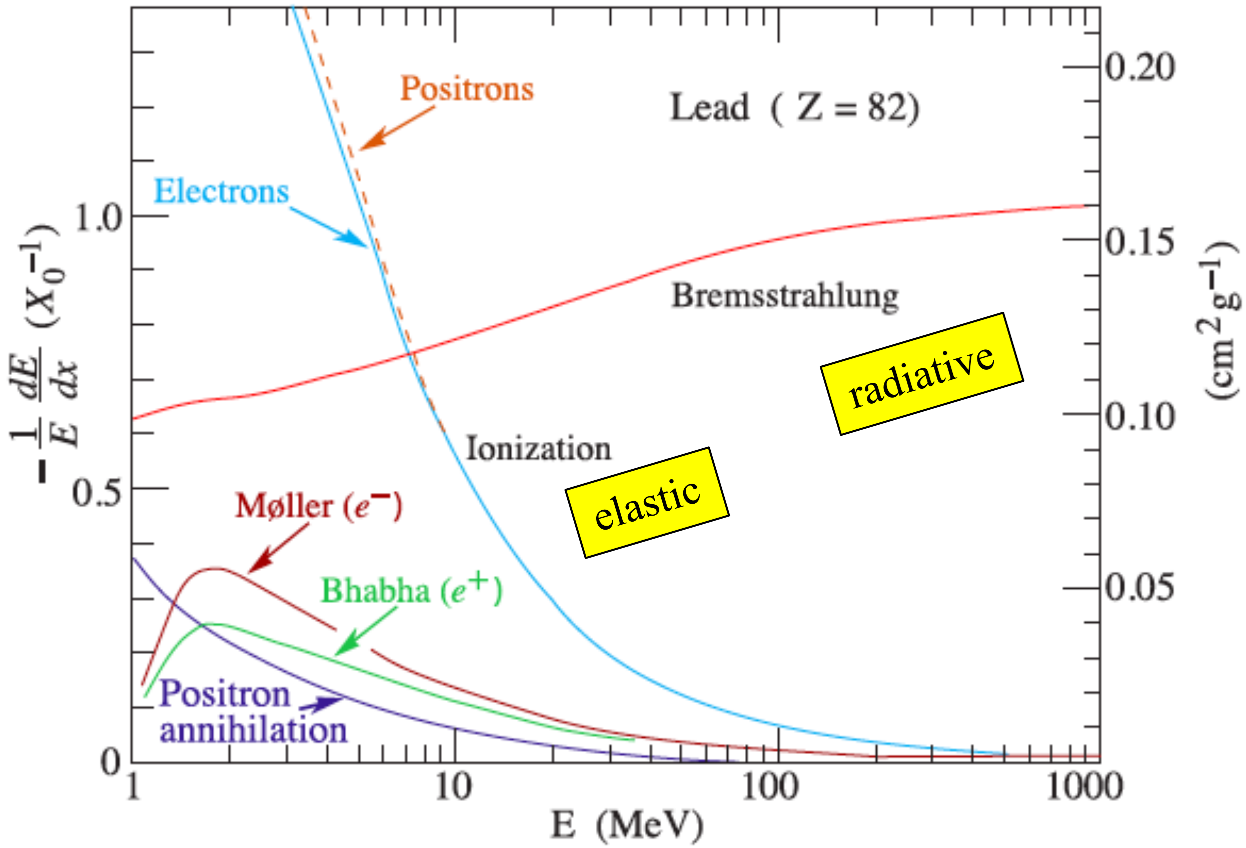


Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

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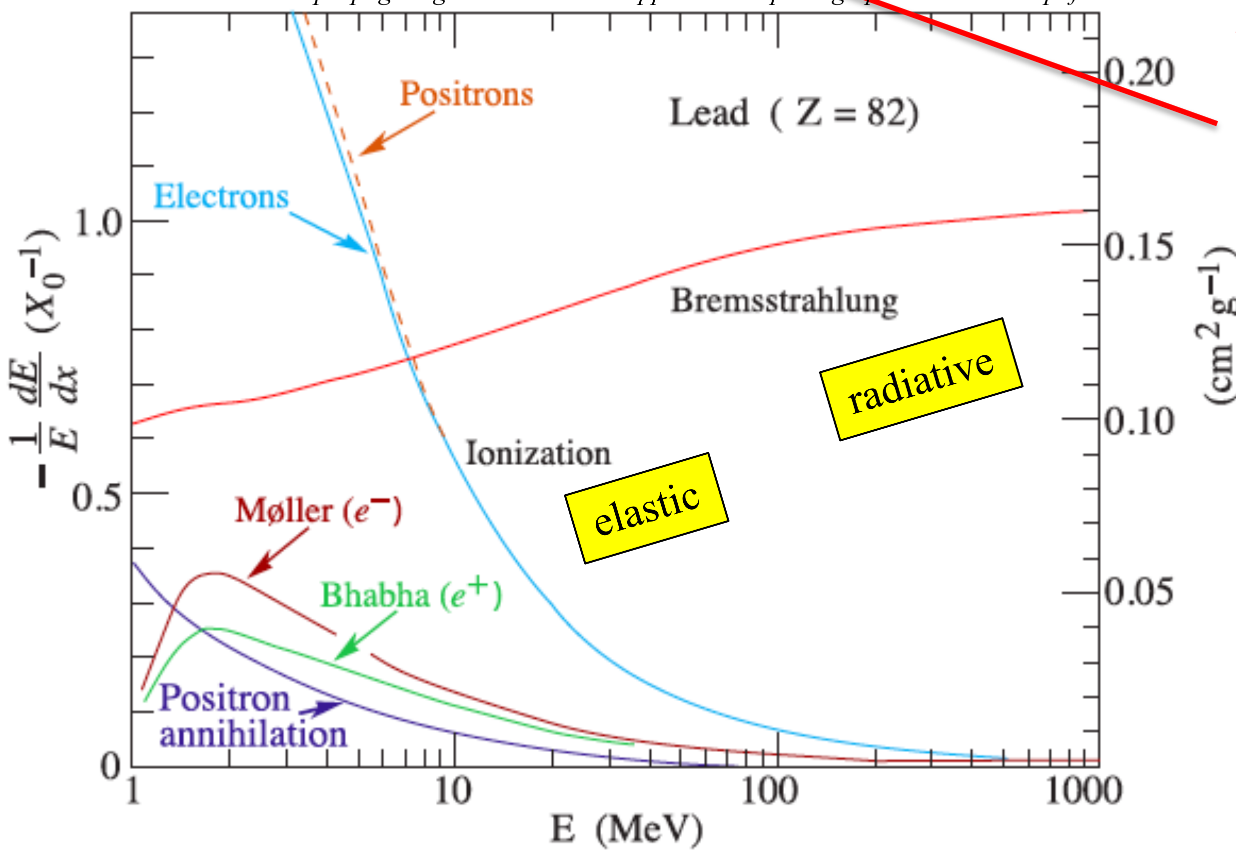
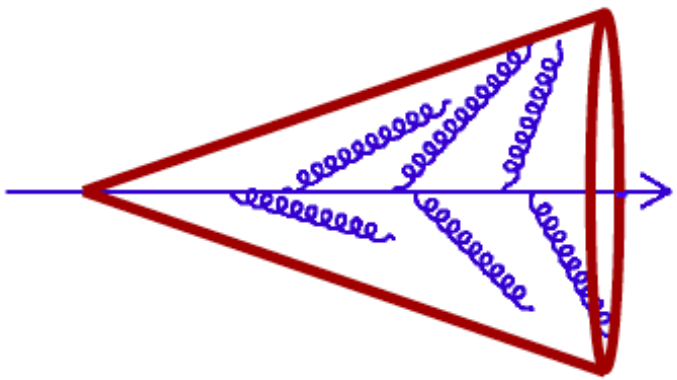


Not the case for QCD jets propagating in matter

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

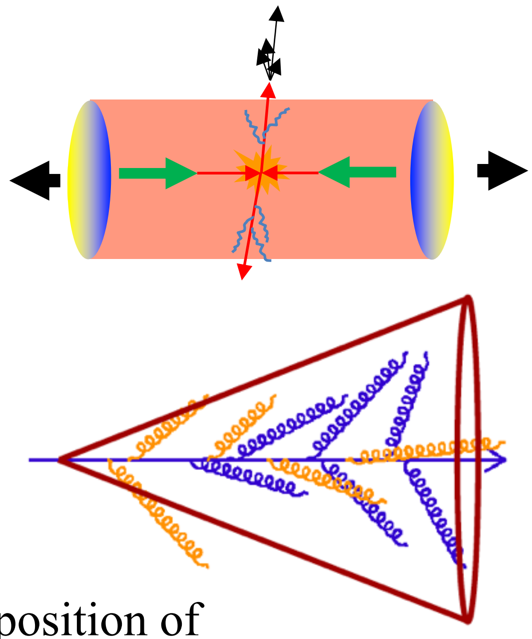


Evolution of highly virtual parton via gluon radiation

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

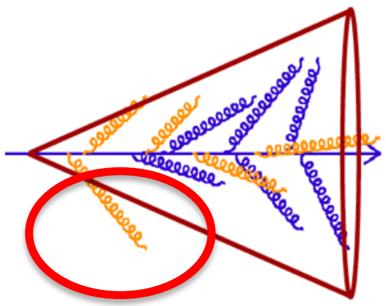
- vacuum shower
- medium-induced gluon emission

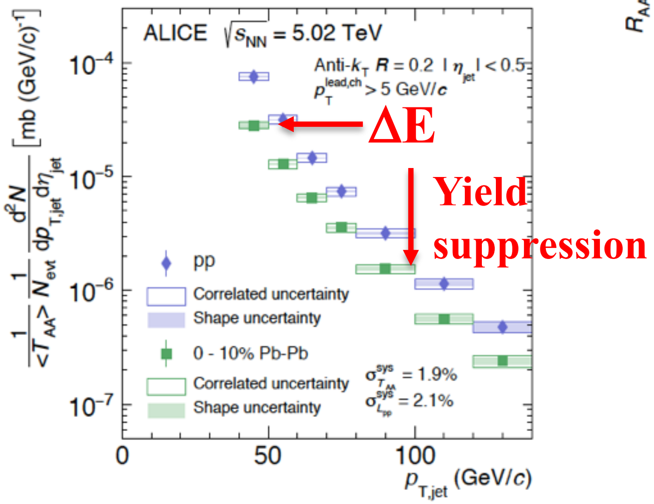
These processes happen simultaneously and interfere

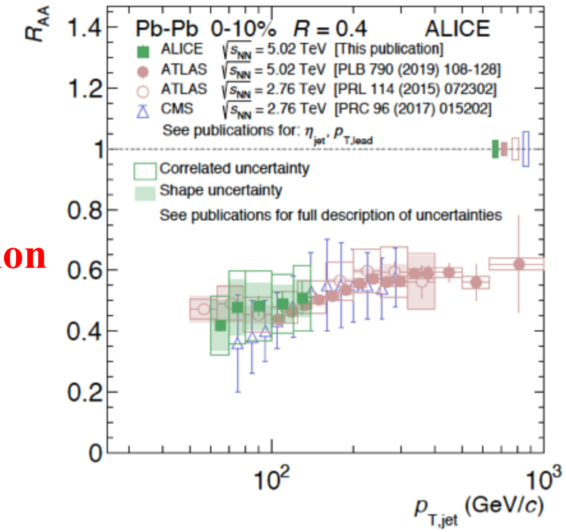
Angle-ordering is modified or destroyed

Jet quenching: observable consequences I

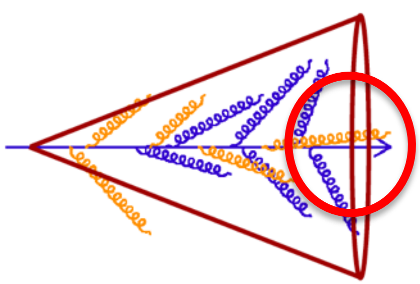
1. Energy loss

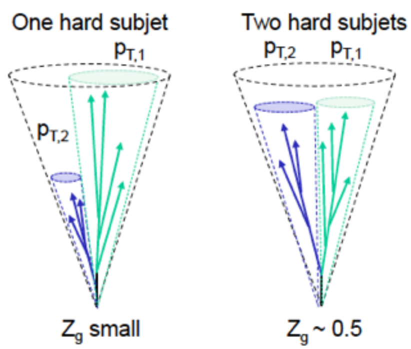




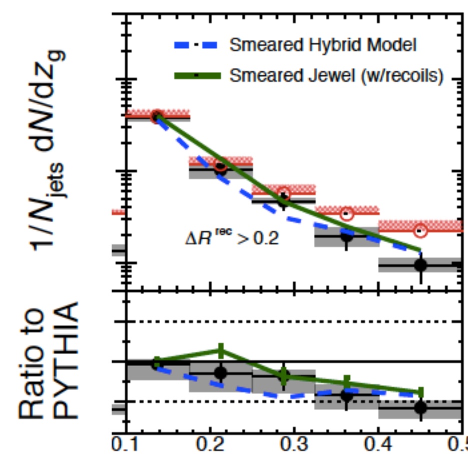


2. Modification of jet substructure



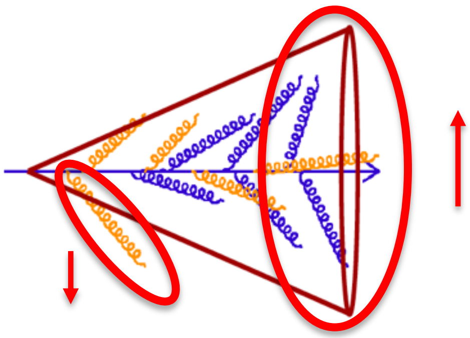


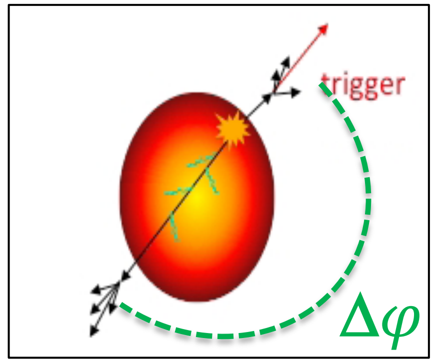
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

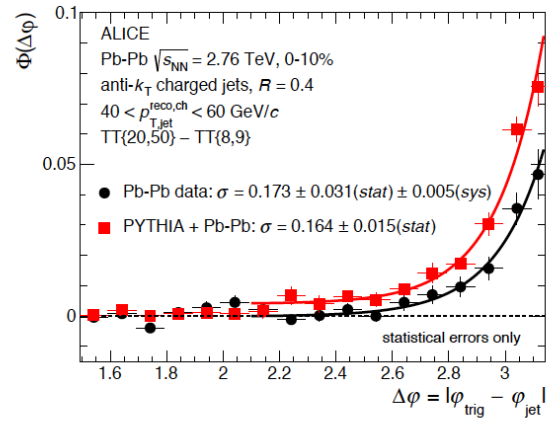


Jet quenching: observable consequences II

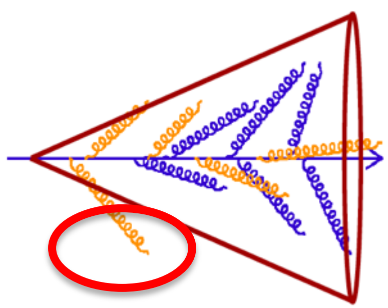
3. Jet deflection

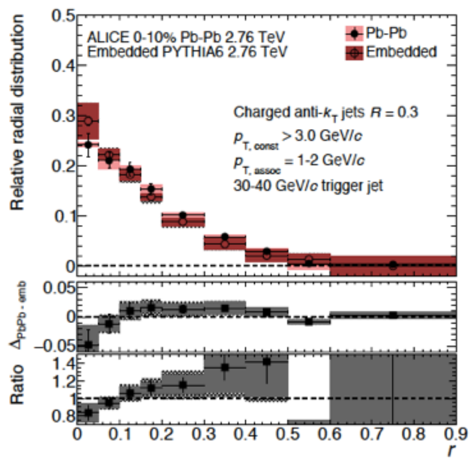


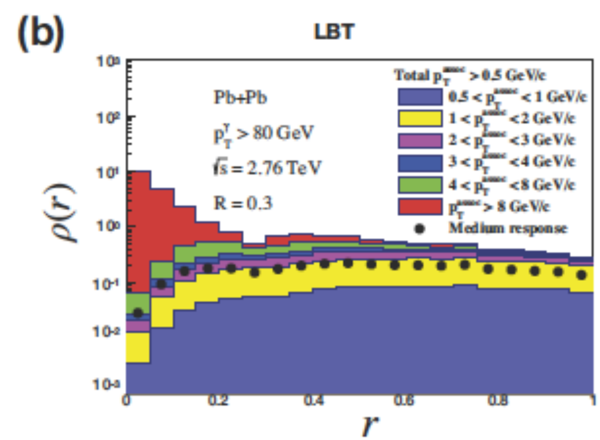




4. Recovery of large-angle radiation







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

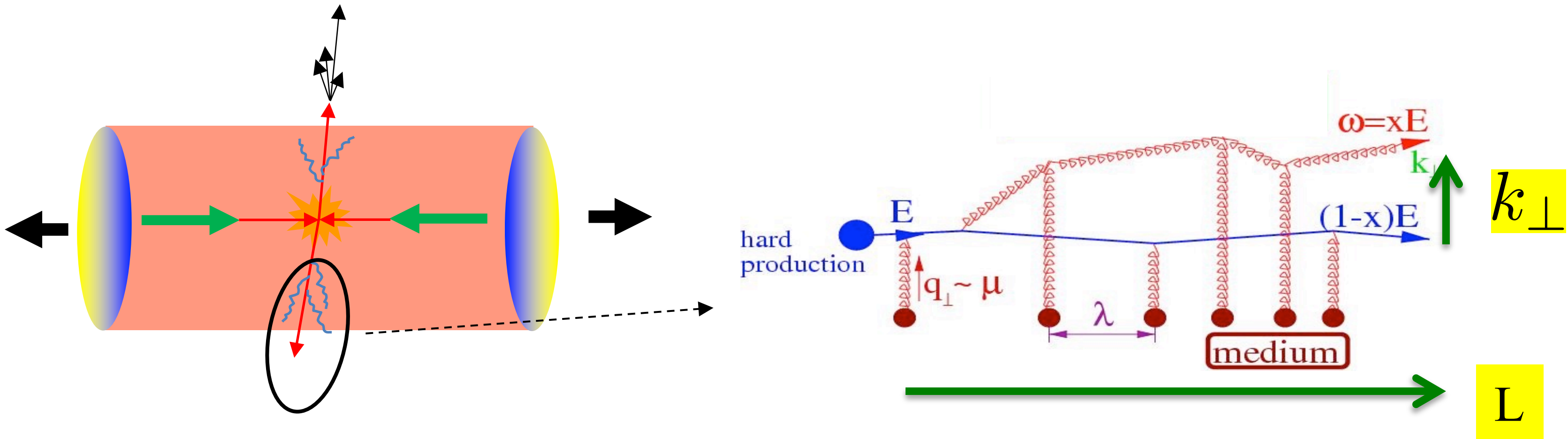
- All must occur if any of them does
- Probe different aspects of jet quenching
- Different experimental systematics as fn of kinematics and collision system
- Different theoretical sensitivity as fn of kinematics and collision system

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:

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

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

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

$\mathbf{q}$ = Momentum transfer

T = Temperature

m_D = Debye mass

} QGP properties

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

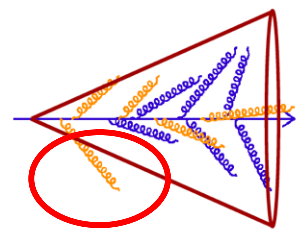
Connecting qhat to measurements

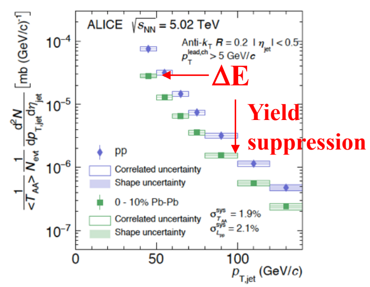
BDMPS: multiple soft scattering approximation

- Gives simple and intuitive formulas
- Connection to other approaches must be checked

Medium-induced jet energy loss:

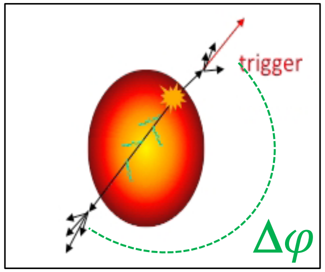
$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

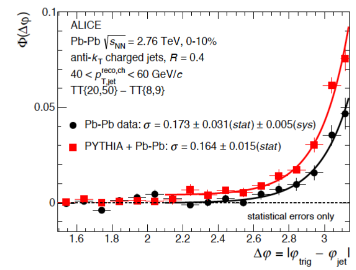




Medium-induced angular broadening:

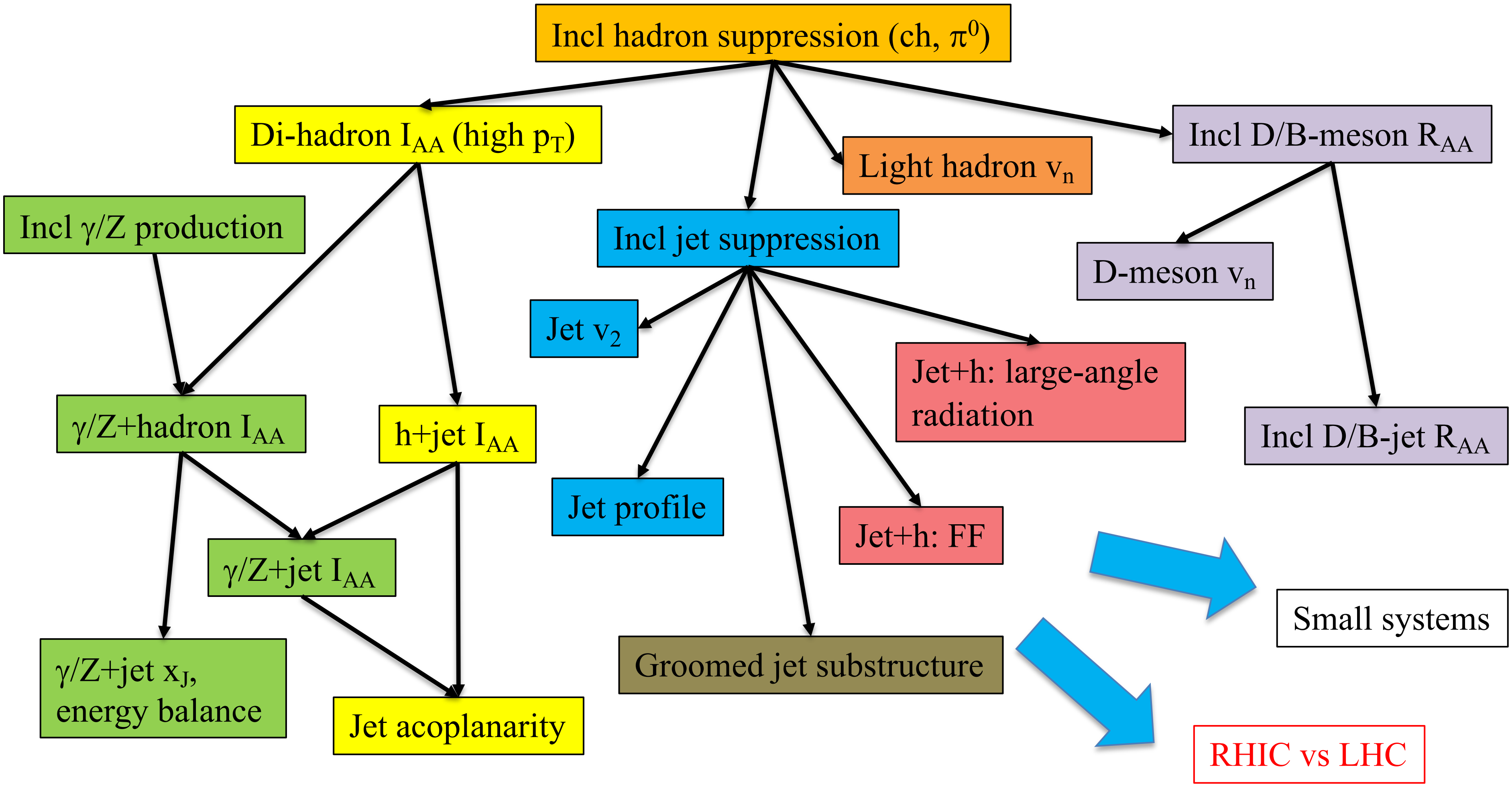
$$\langle k_T^2 \rangle \sim \langle \Delta\varphi^2 \rangle \sim \alpha_s \hat{q} L$$





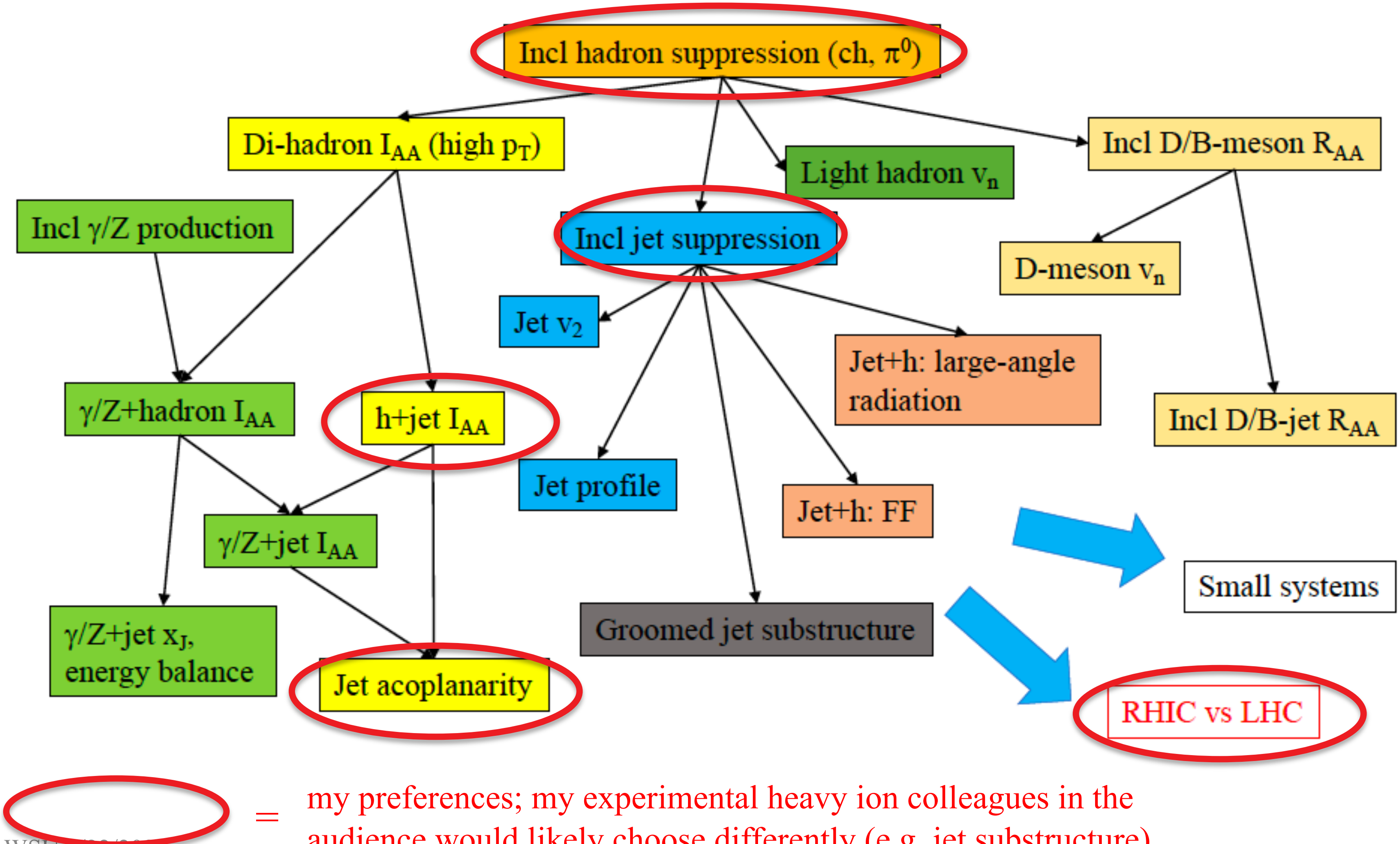
Taxonomy of current jet quenching measurements

- Driven by experimental considerations: arrows connect observables with just one thing changed
- How do these map onto theory?



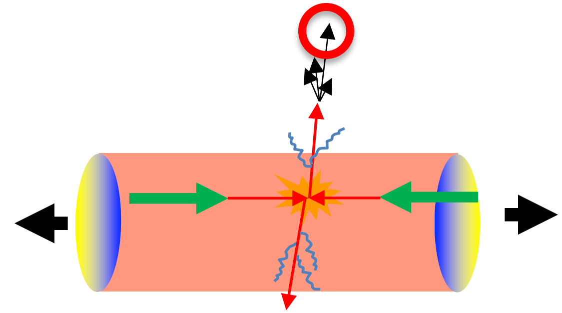
Confusing! How to make sense of so many observables?

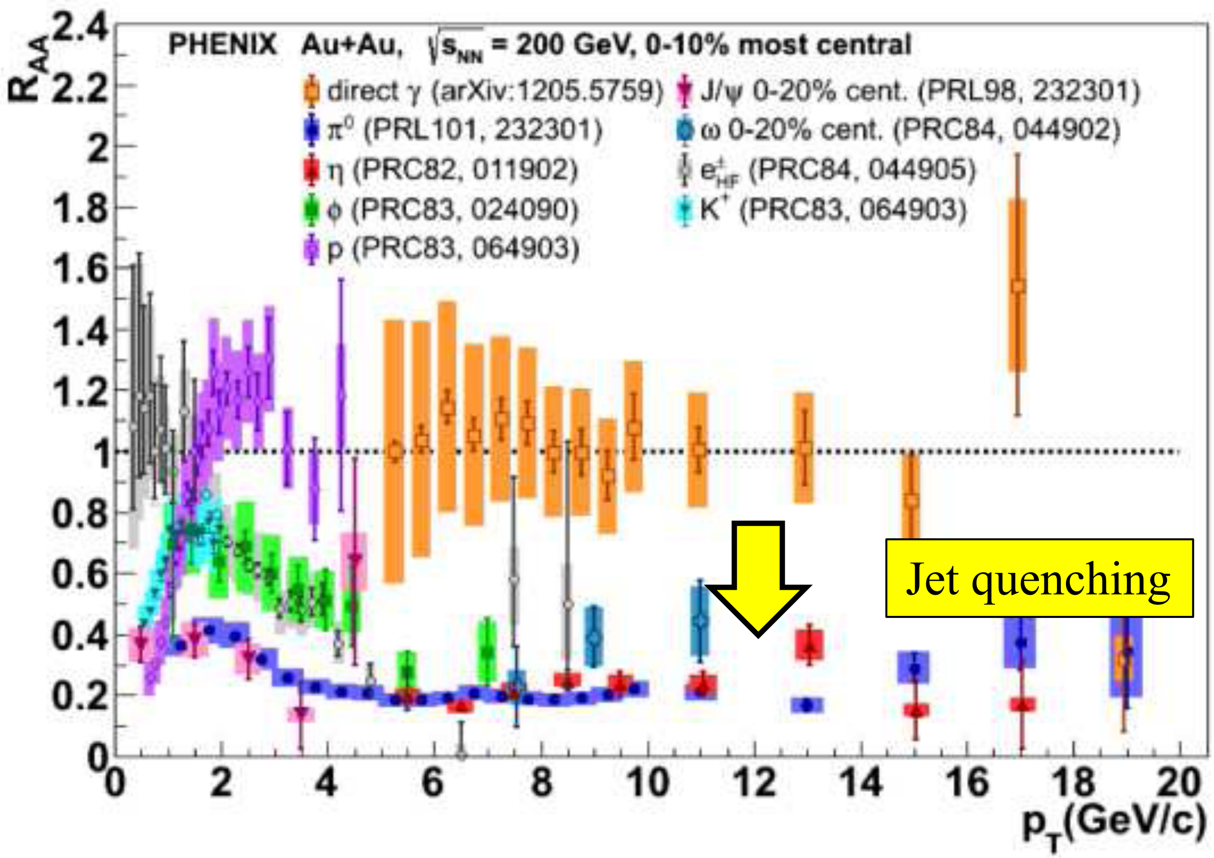
Go systematically: start with a few key measurements and build up the picture…



Jet quenching via high p_T hadrons

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



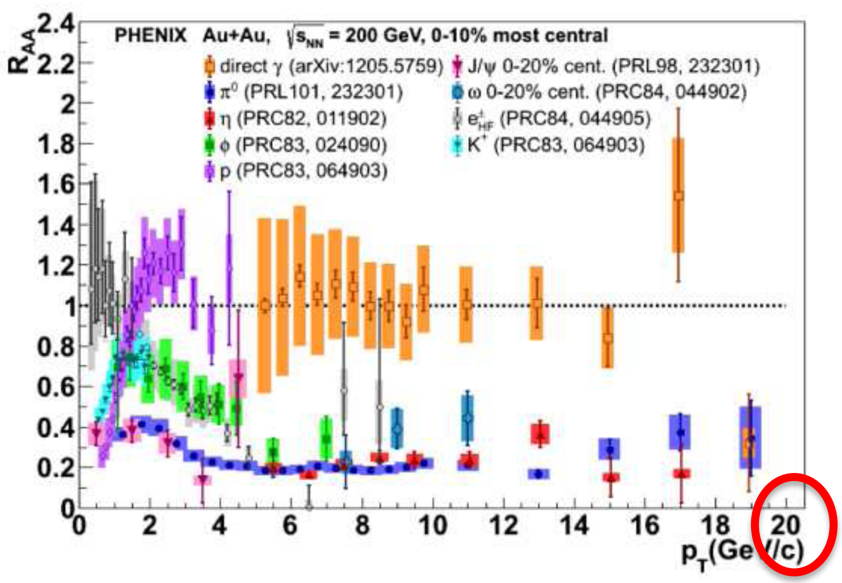


Photons (color-neutral)

Jet fragments (color-charged)

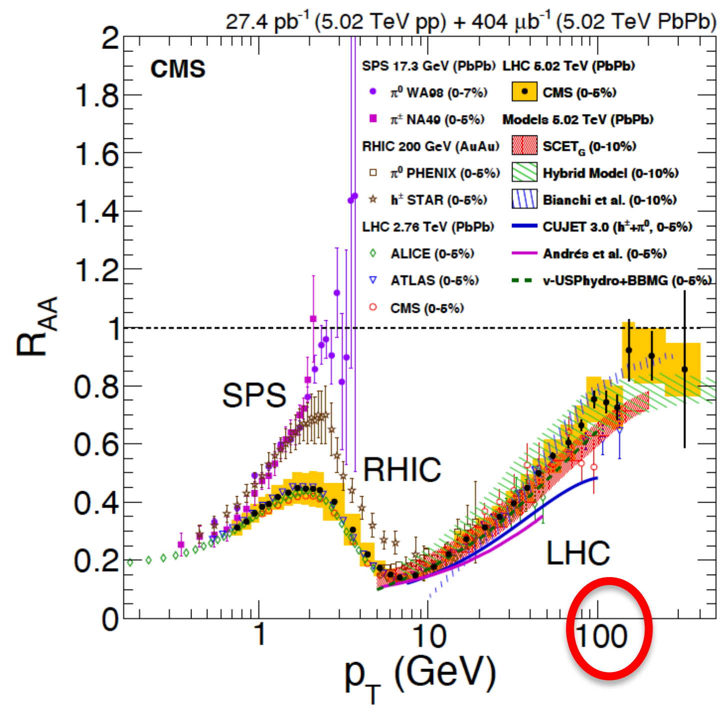
Inclusive hadron suppression: RHIC vs LHC

RHIC



LHC

JHEP 04 (2017) 039



RHIC/LHC: Qualitatively similar, quantitatively different

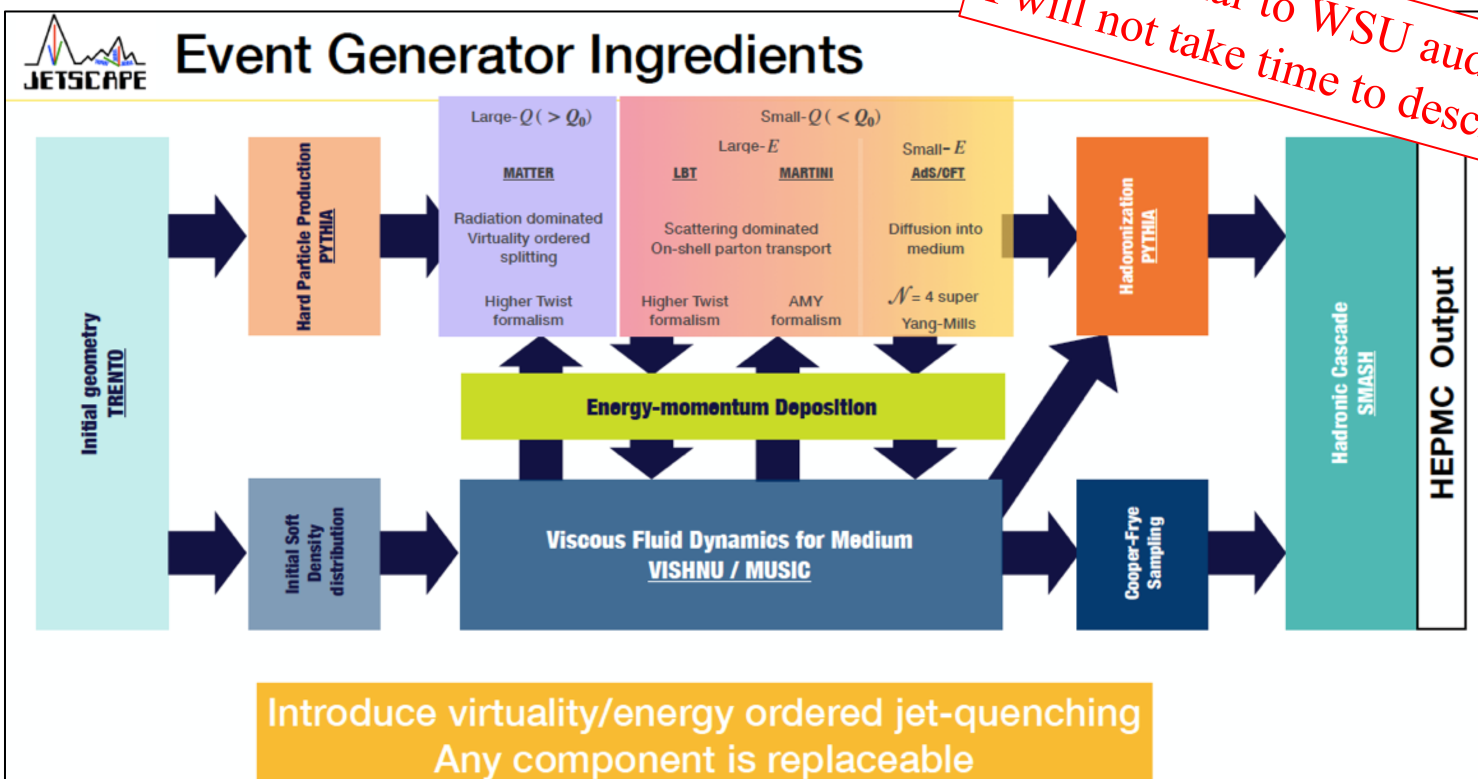
- interplay between energy loss (~matter density) and spectrum shape

Connecting experiment and theory…

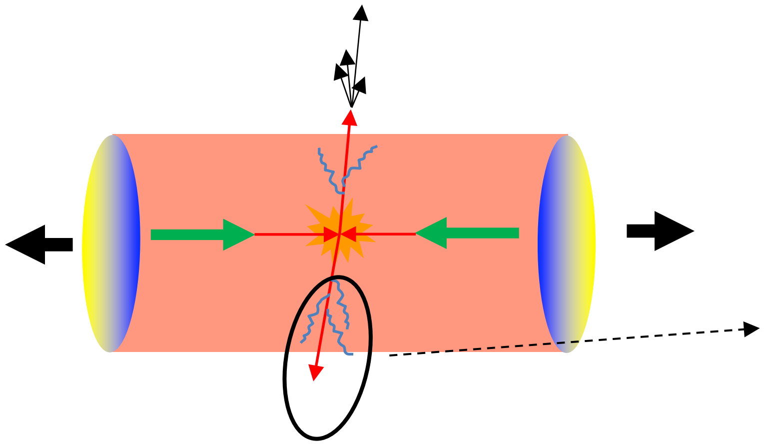
Modular framework: multi-stage jet quenching calculations

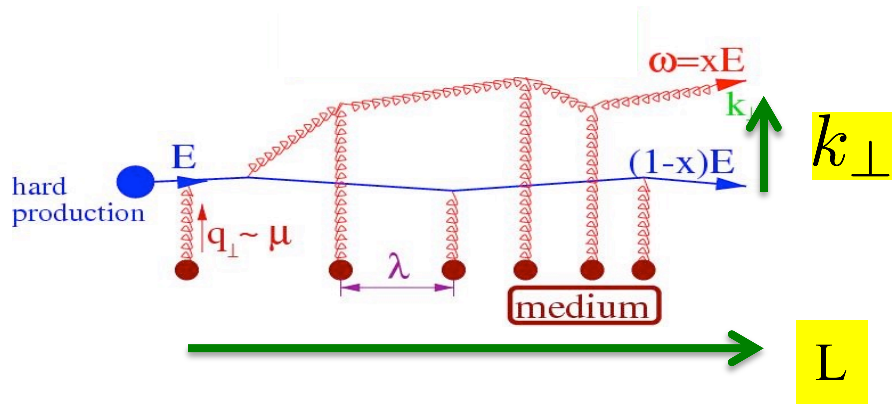
Goal: general tool for entire HI community

Very familiar to WSU audiences!
I will not take time to describe it



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





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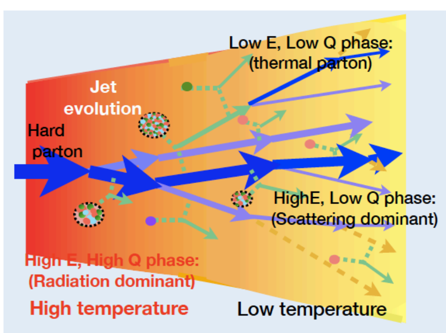
T = Temperature

m_D = Debye mass

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

JETSCAPE parametrization



High jet virtuality Q>>T

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

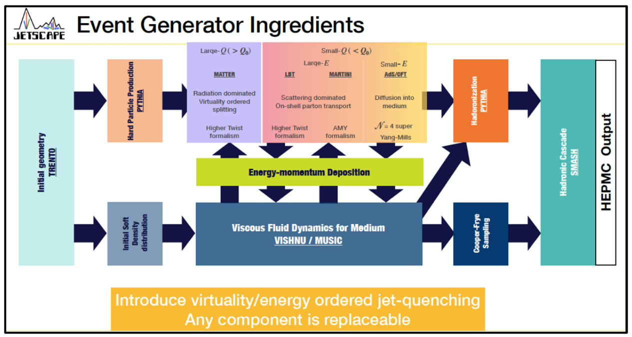
$$\frac{\hat{q}(E,T)|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi} \left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}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

Bayesian inference: inclusive hadrons

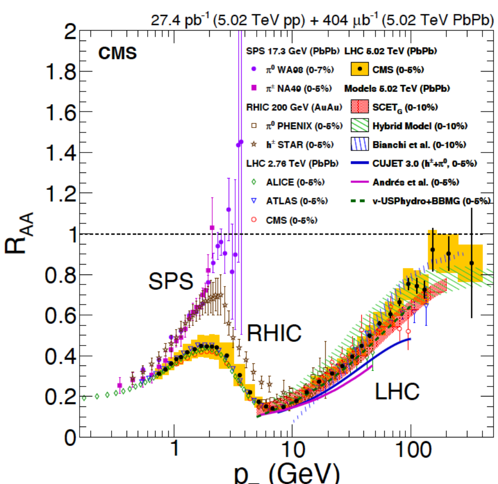
paper in preparation

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

+

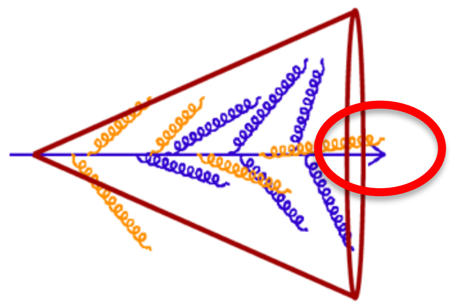


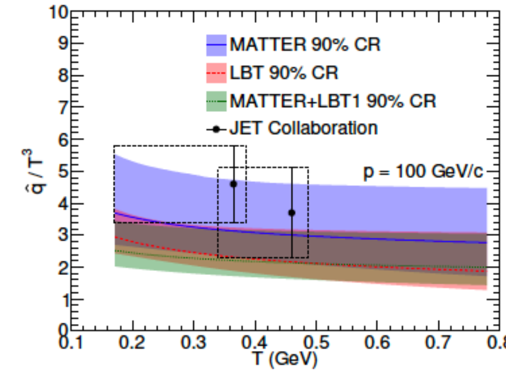
+

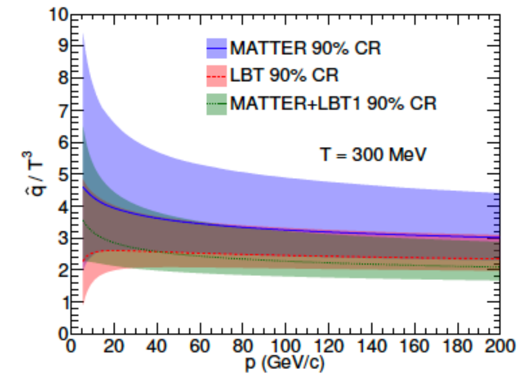


=

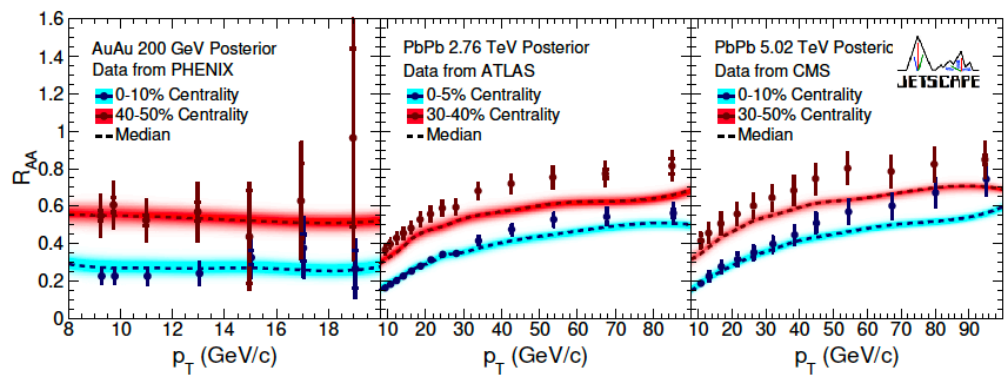
Rigorous quantitative determination of $\hat{q}$







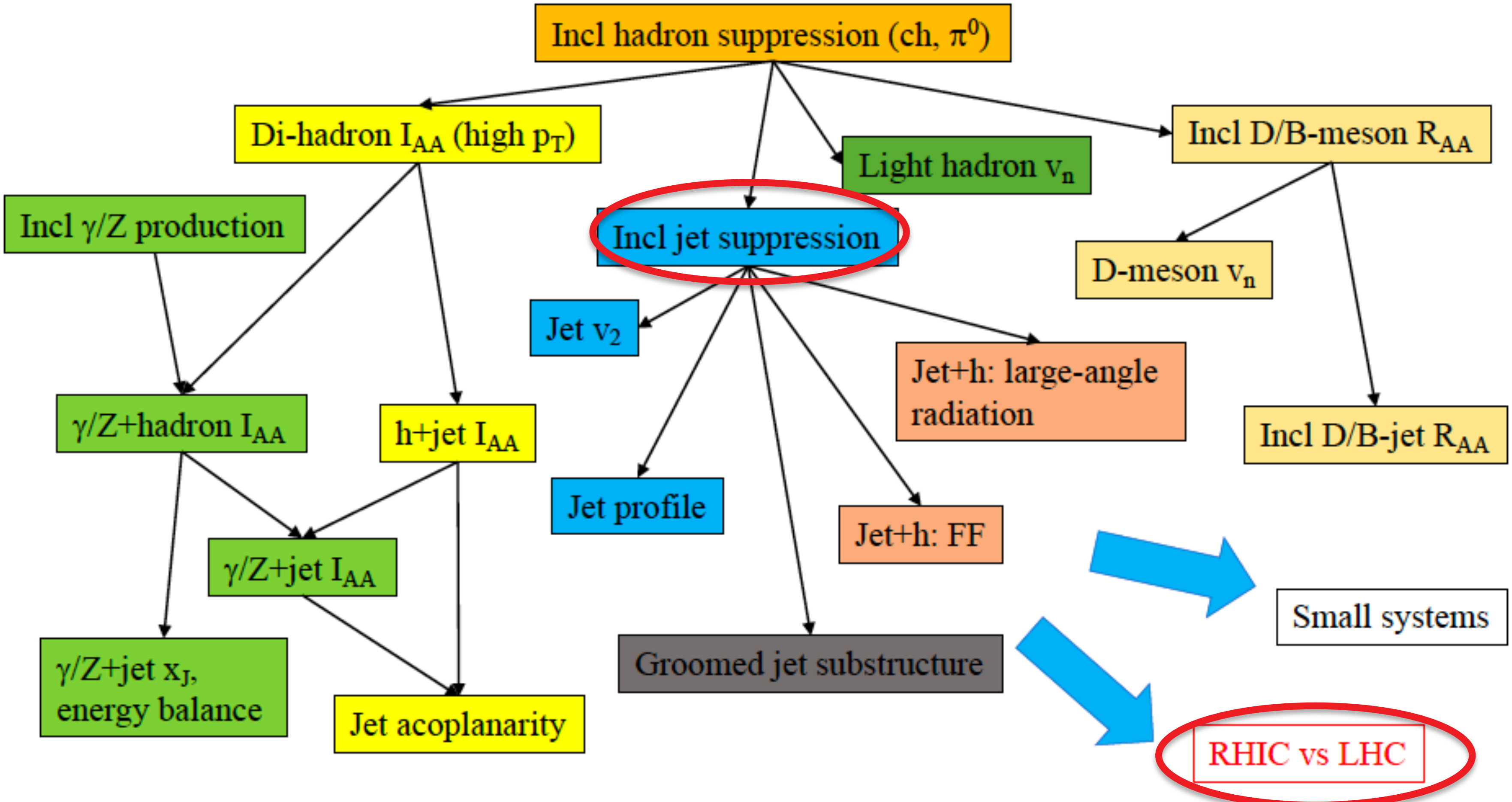
Posterior distributions



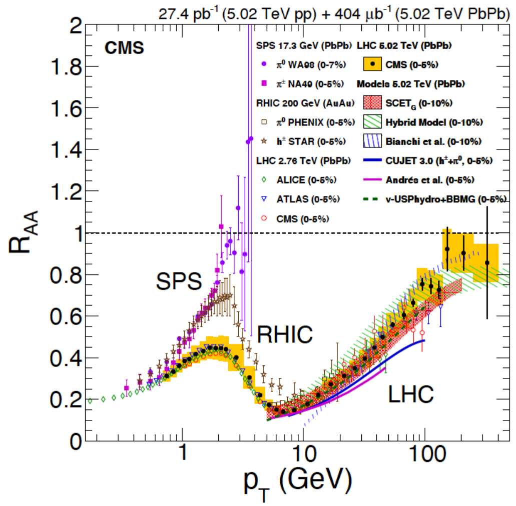
This is the end of the quantitative part of the talk

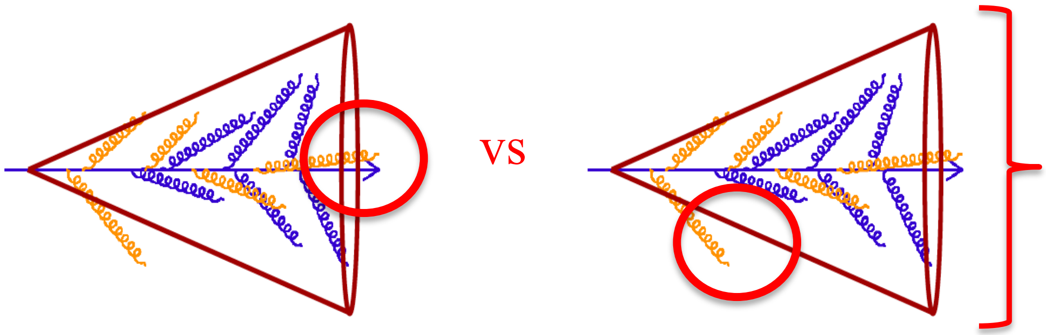
Remainder of talk is work-in-progress

Key issue: theory-experiment connection


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
Groomed jet substructure
Jet acoplanarity
RHIC vs LHC

Inclusive hadron vs inclusive jet suppression



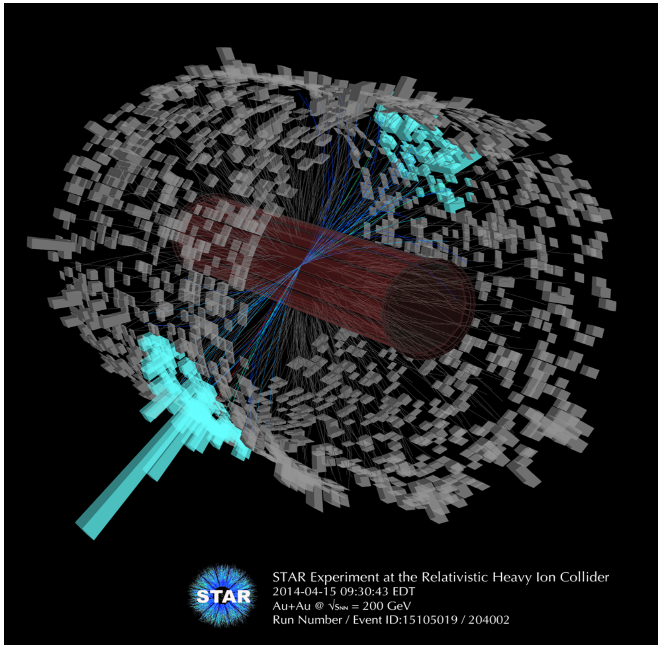


Inclusive hadron suppression driven by energy transport away from the hardest branch in the jet

- Insensitive to specific mechanisms of energy transport

More comprehensive: reconstructed jets

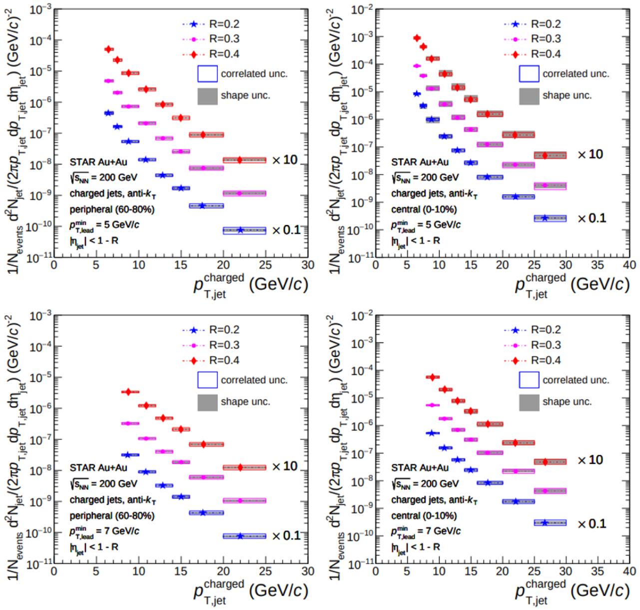
- very challenging due to large backgrounds, especially at RHIC
- but problem has been solved

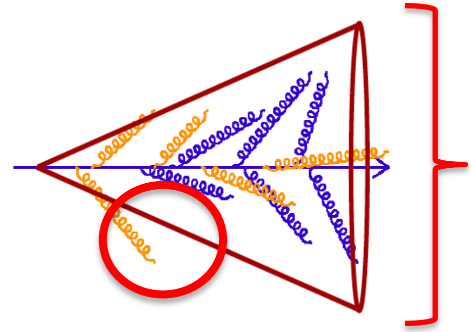


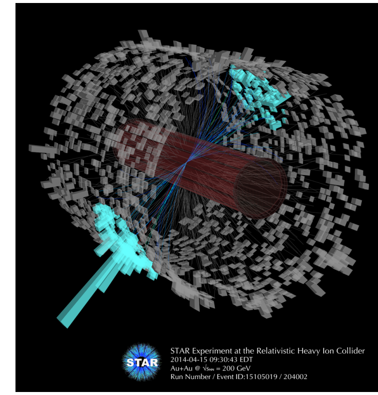
Inclusive jets in A+A: spectra

STAR *PhysRevC 102, 054913*

RHIC

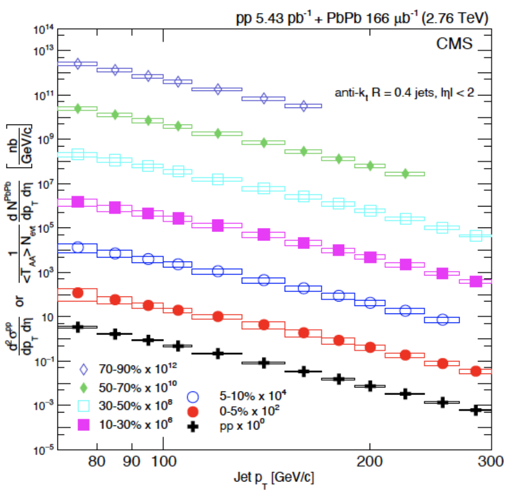


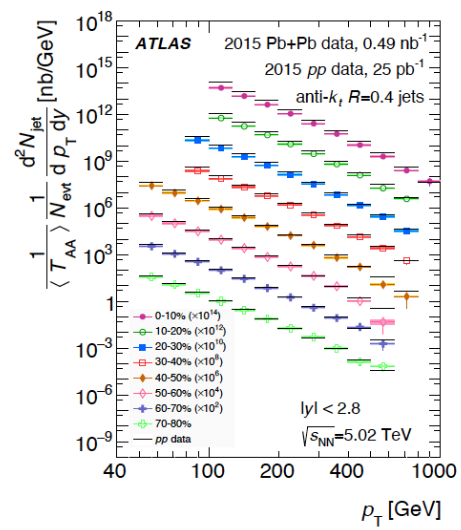


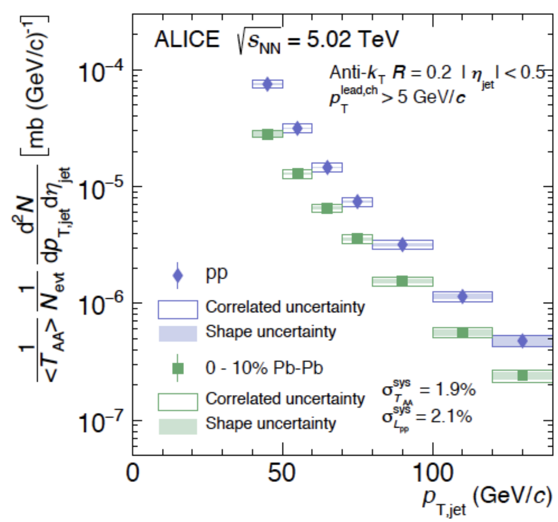


High-quality data over a vast kinematic range

LHC

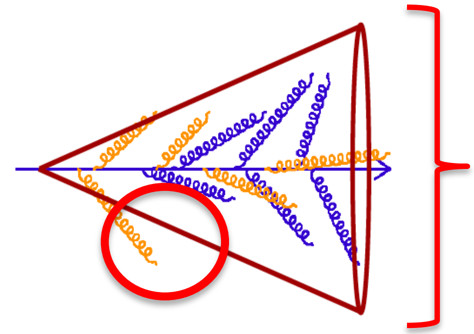






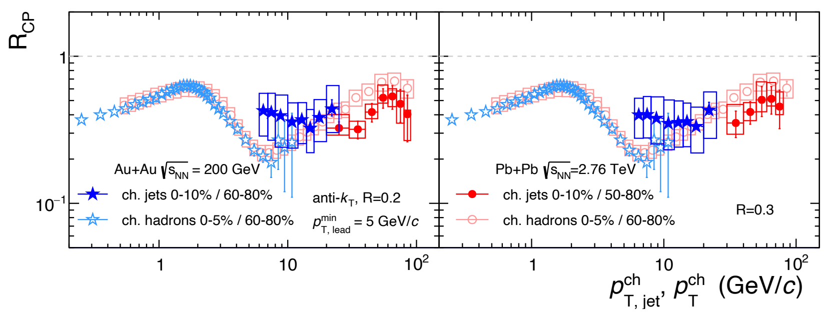
Inclusive jets in A+A: R_{AA}

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



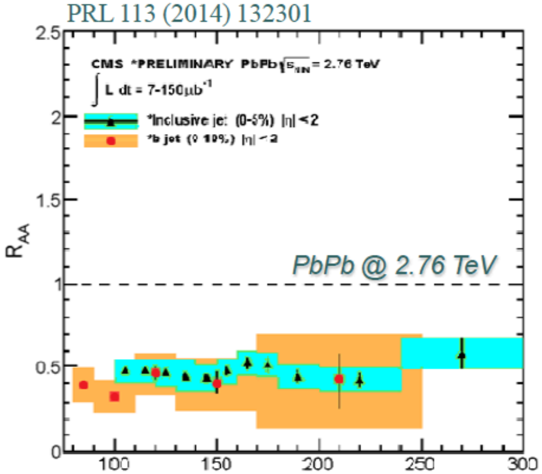
- Strong jet yield suppression
- Suppression ~ similar magnitude at RHIC and LHC…?

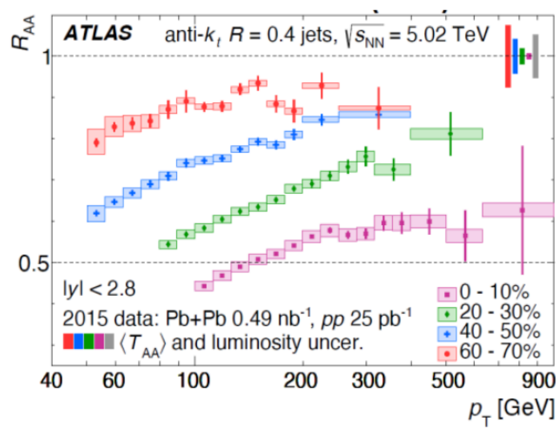
RHIC

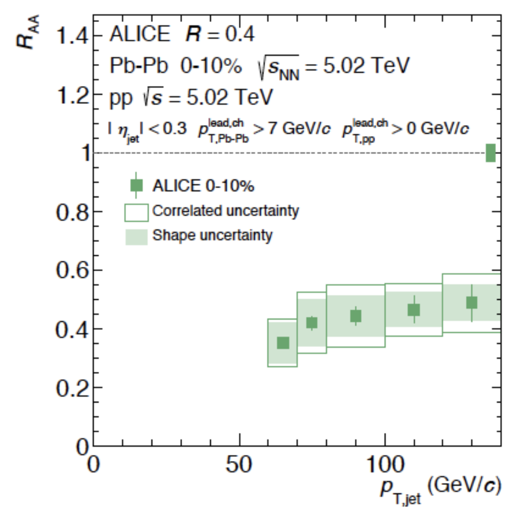


LHC

PRL 113 (2014) 132301

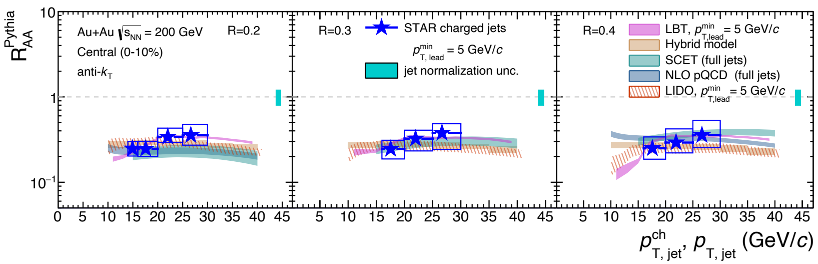




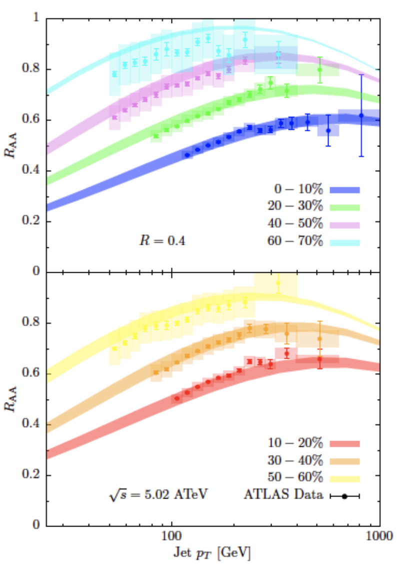


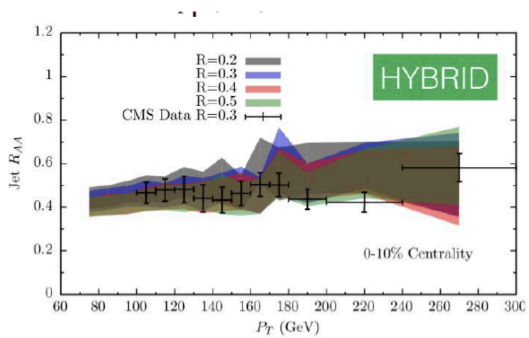
Inclusive jet R_{AA}: comparison to models

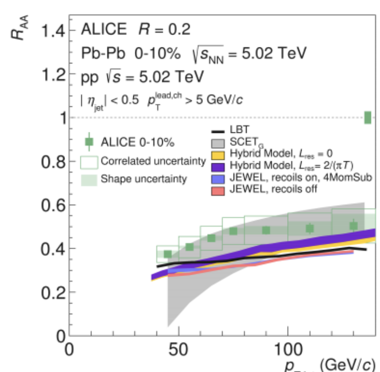
Diverse jet quenching calculations based on pQCD
+ various approximations for jet+medium interaction



arXiv:2101.01742







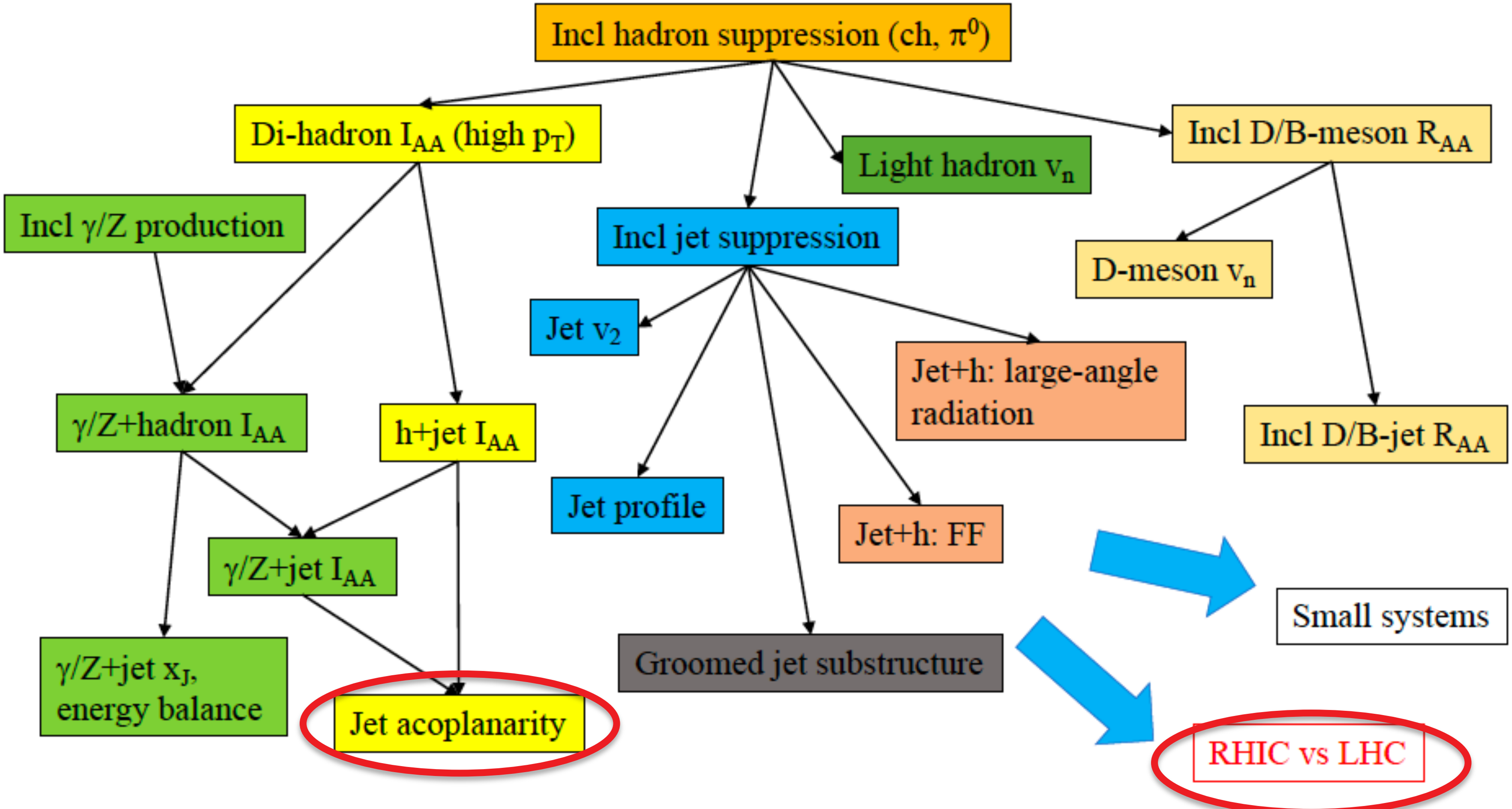
Current models work well over a wide range

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
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Jet+h: large-angle radiation
γ/Z+hadron I_{AA}
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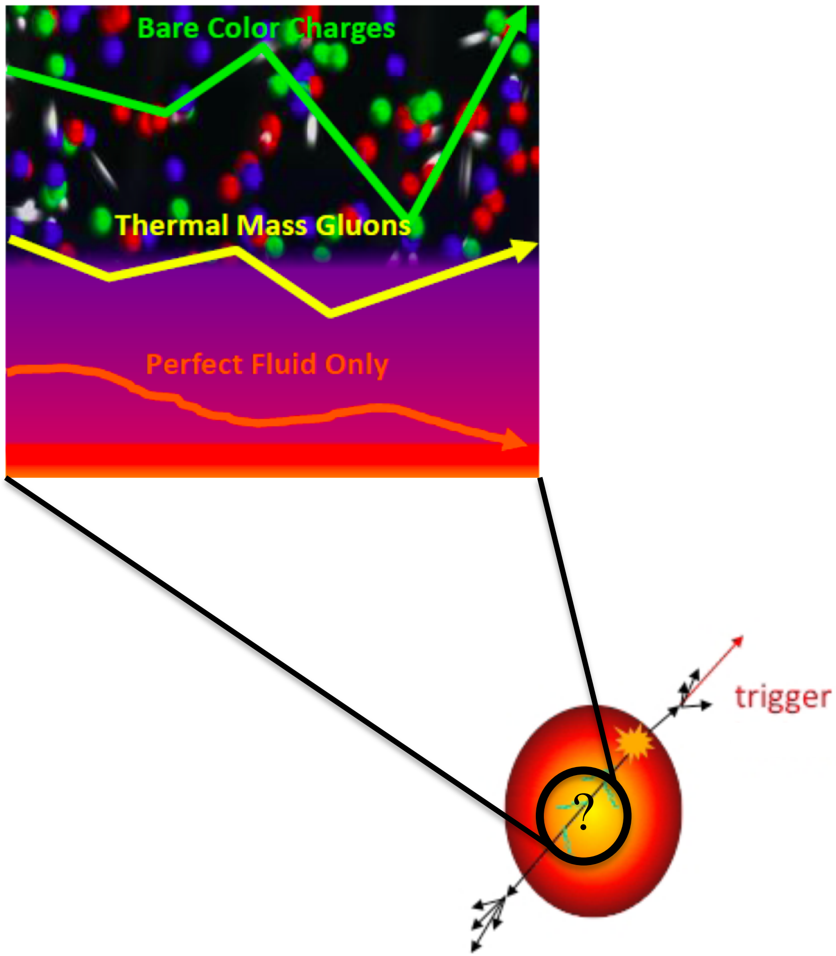
Incl D/B-jet R_{AA}
Jet profile
Jet+h: FF
γ/Z+jet I_{AA}
Small systems
γ/Z+jet x_J, energy balance
Jet acoplanarity
Groomed jet substructure
RHIC vs LHC

Jet acoplanarity: in-medium hard scattering

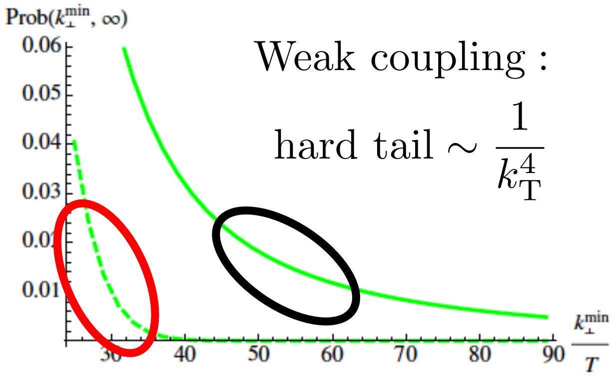
("Rutherford experiment")

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?

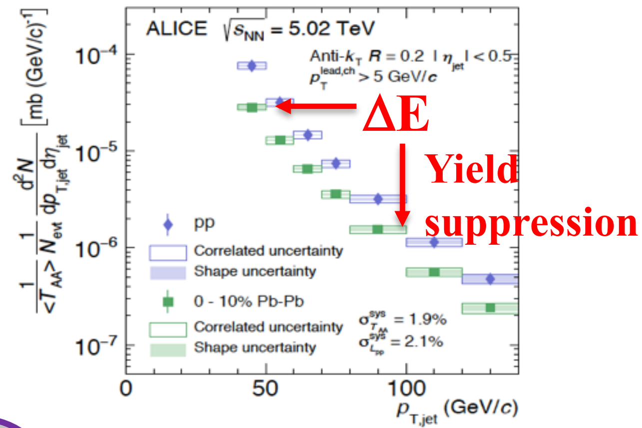
- high Q^2: bare q and g
- low-ish Q^2:
  - thermal-mass glue
  - magnetic monopoles
  - …?

Jet acoplanarity: in-medium soft deflection

For intuition use BDMPS theory: multiple soft scattering approximation

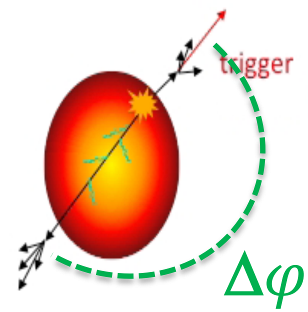
Medium-induced jet energy loss:

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



Medium-induced angular broadening:

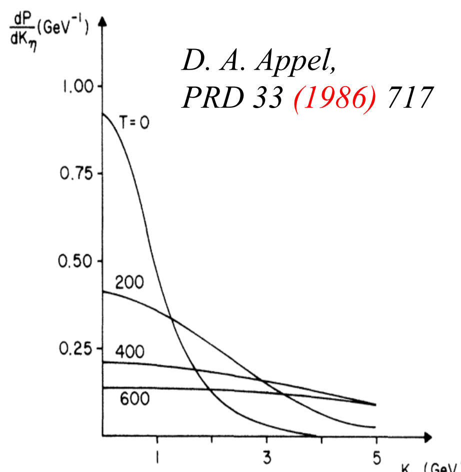
$$\langle k_T^2 \rangle \sim \langle \Delta\varphi^2 \rangle \sim \alpha_s \hat{q} L$$

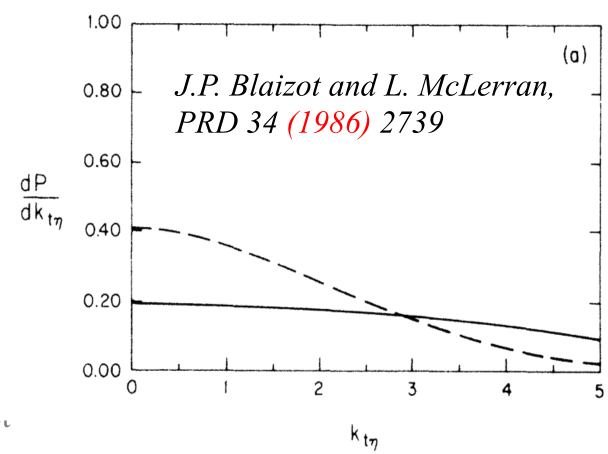


Different parametric dependencies! Better model discrimination…?

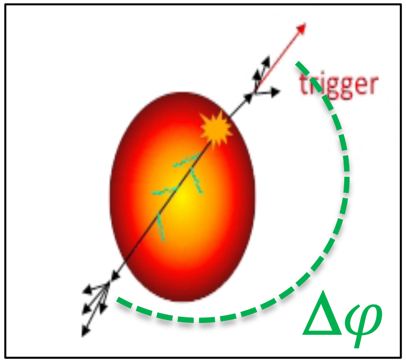
Side note: using jet scattering to measure the QGP is an old idea but experimentally very challenging

- techniques now in place

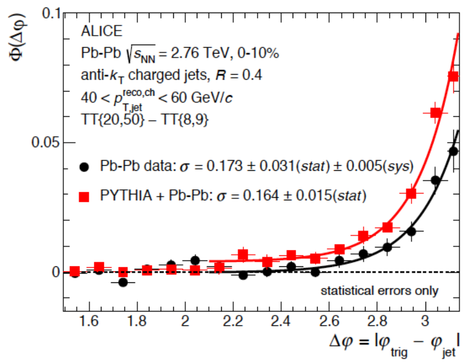




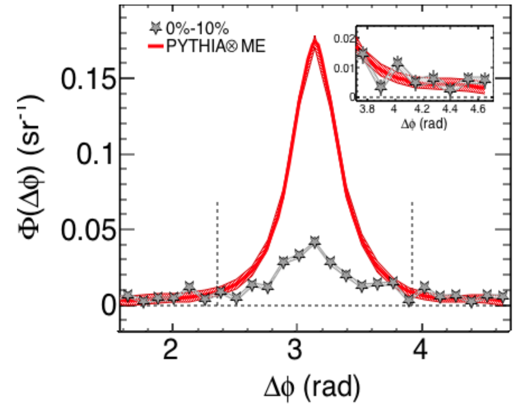
Jet acoplanarity: data



ALICE, JHEP 09 (2015) 170

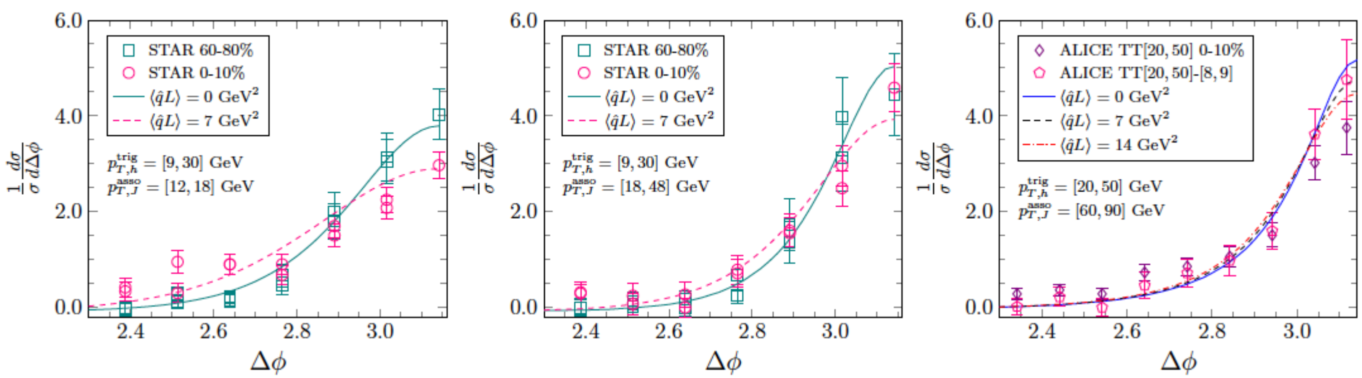


STAR,Phys Rev C96 (2017) 024905



Significant background: Initial-state (Sudakov) radiation

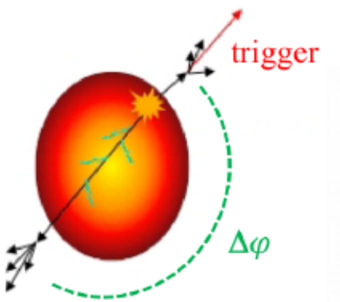
L. Chen et al., Phys.Lett.B 773 (2017) 672



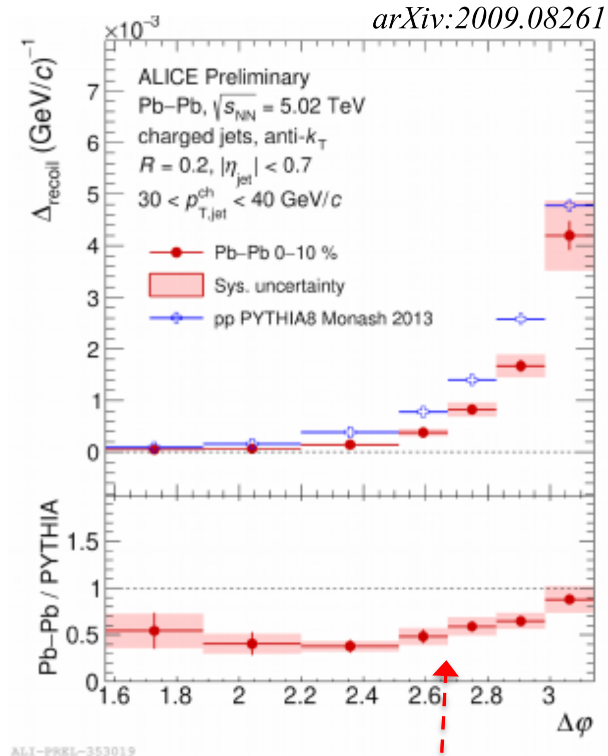
First- generation ALICE+STAR measurements:
no medium-induced acoplanarity observed above background

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

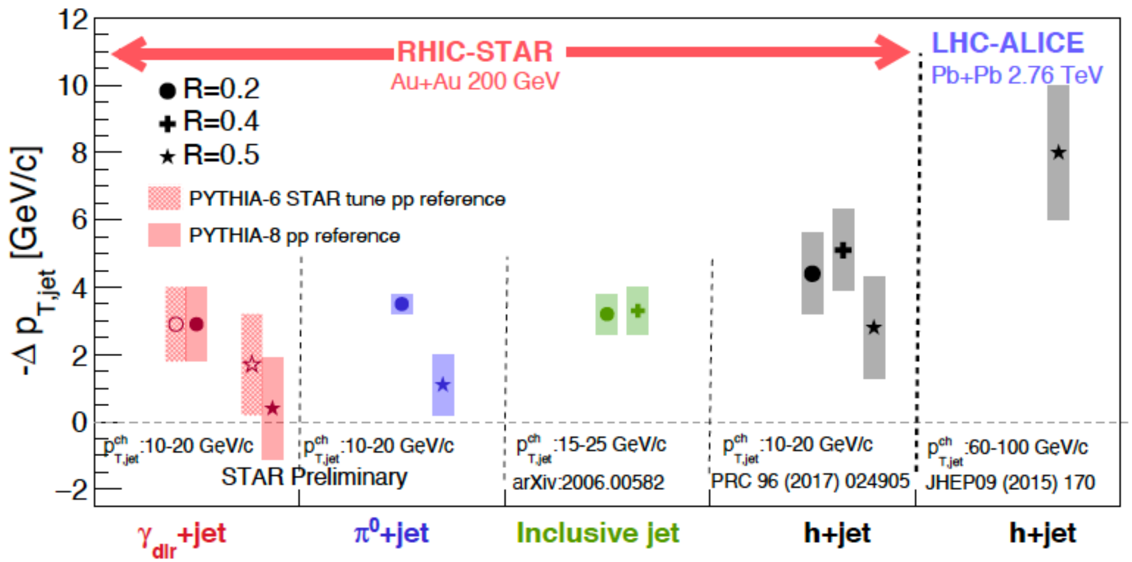
B.G. Zakharov[1]

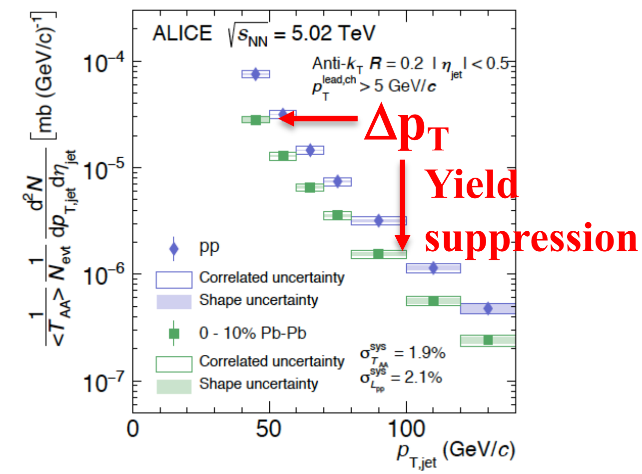
[1]*L.D. Landau Institute for Theoretical Physics, GSP-1, 117940, Kosygina Str. 2, 117334 Moscow, Russia*
(Dated: March 24, 2020)

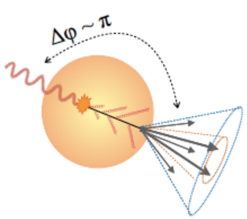
We study contribution of radiative processes to $p_\perp$-broadening of fast partons in an expanding quark-gluon plasma. It is shown that the radiative correction to $\langle p_\perp^2 \rangle$ for the QGP produced in AA-collisions at RHIC and LHC may be negative, and comparable in absolute value with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

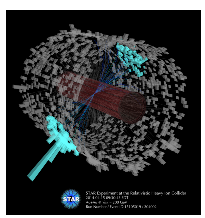
Phenomenology: in-medium energy loss measured via jet spectrum shift

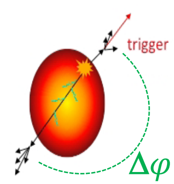
Inclusive jet and X+jet measurements











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 this year (?); factor ~10 luminosity increase
- ALICE: essentially a new detector with vastly improved capabilities
- ATLAS/CMS moderate improvements (major upgrades 2025)
- 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:

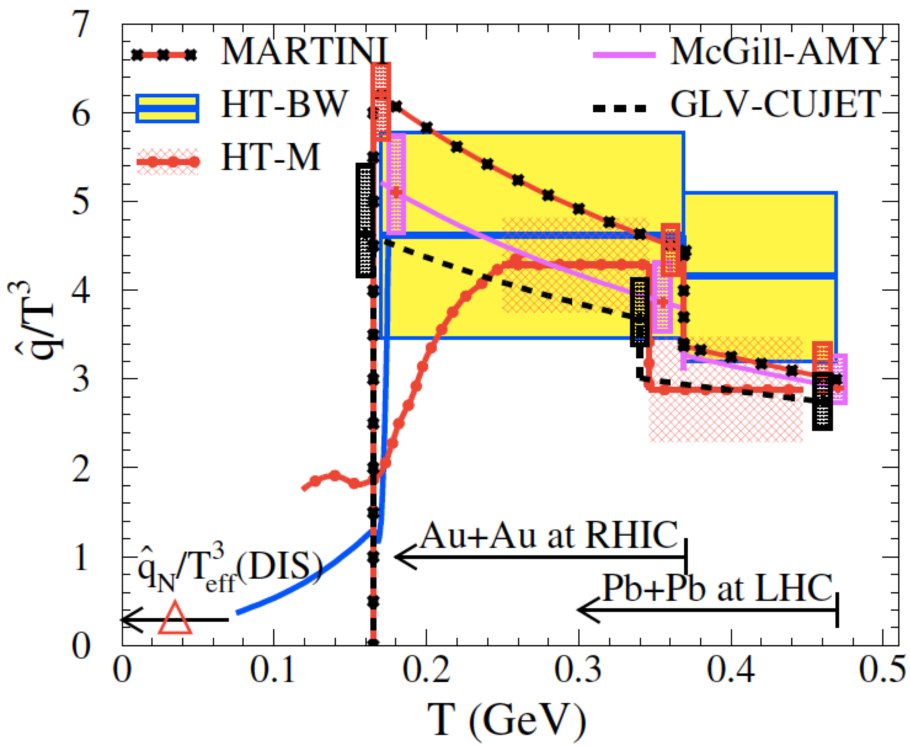
- Conceptual and calculational advances in modelling of in-medium jet modification
- Rigorous-large scale global fits to a wide range of judiciously chosen jet and hadron data

→ Bayesian inference using JETSCAPE

Much more to come!

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:

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

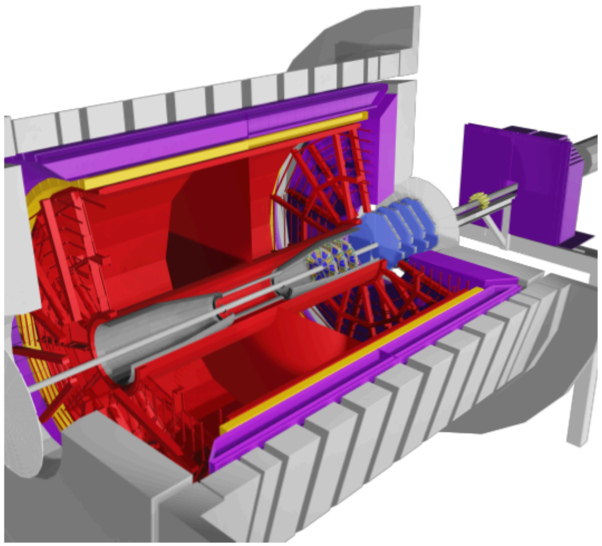
$$\text{LHC}: \quad \hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm}$$

Reasonable and improvable precision

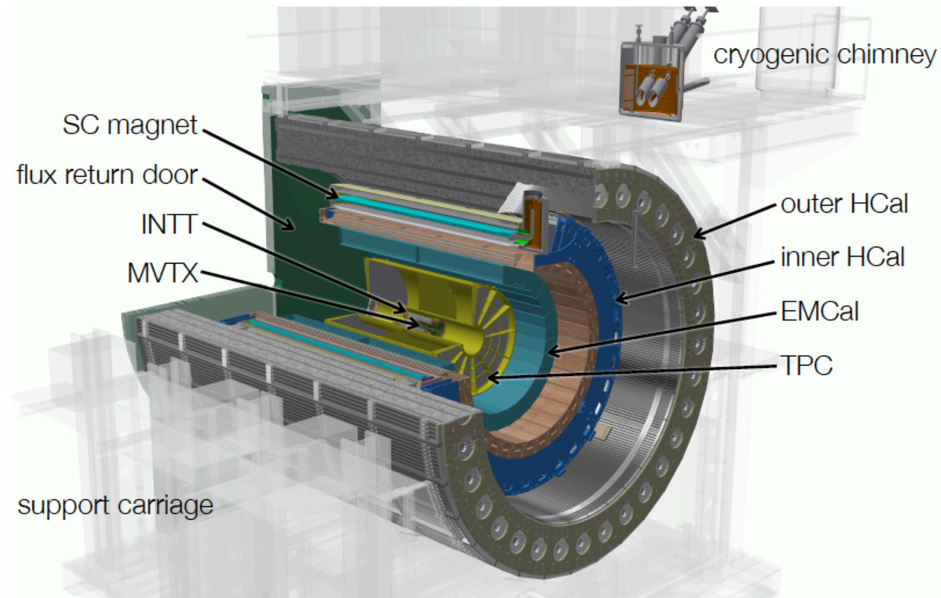
Cold matter (e+A at HERA): $\hat{q} \approx 0.02 \text{ GeV}^2/\text{fm}$

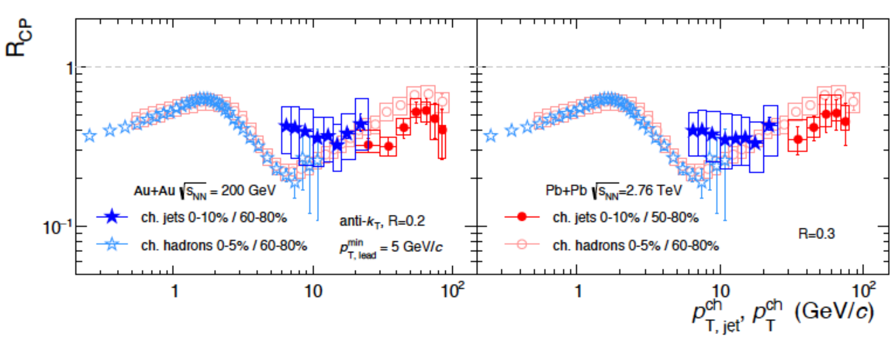
RHIC && LHC: the present

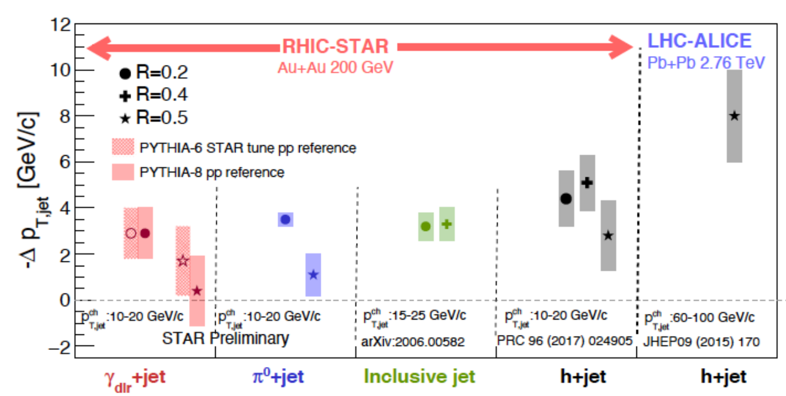
STAR



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 [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}