Introductory jet physics and jet-quenching in heavy-ion collision

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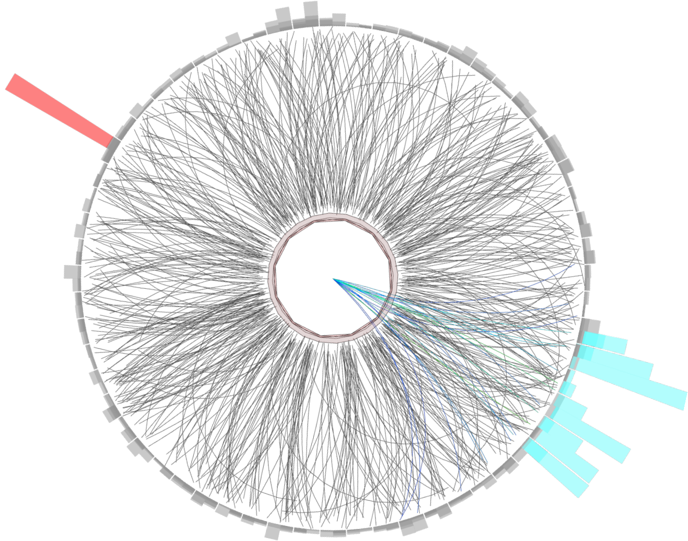
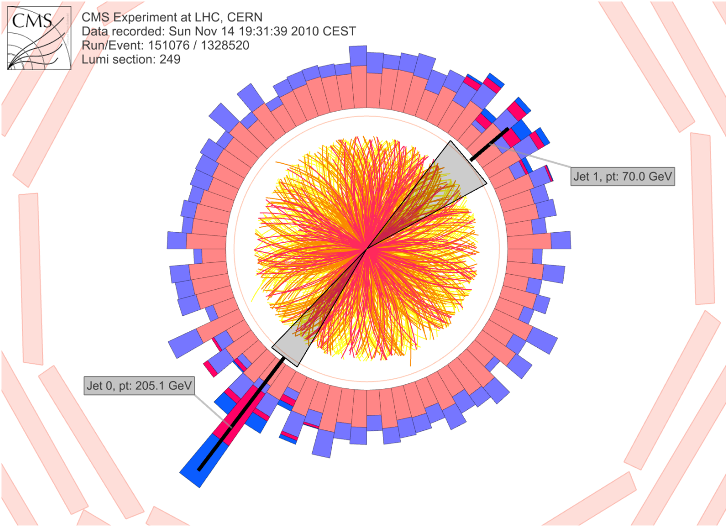




Outline

2 Lectures: 4 Nov. 2022
2.30-3.30 PM and 4.30-5.30 PM

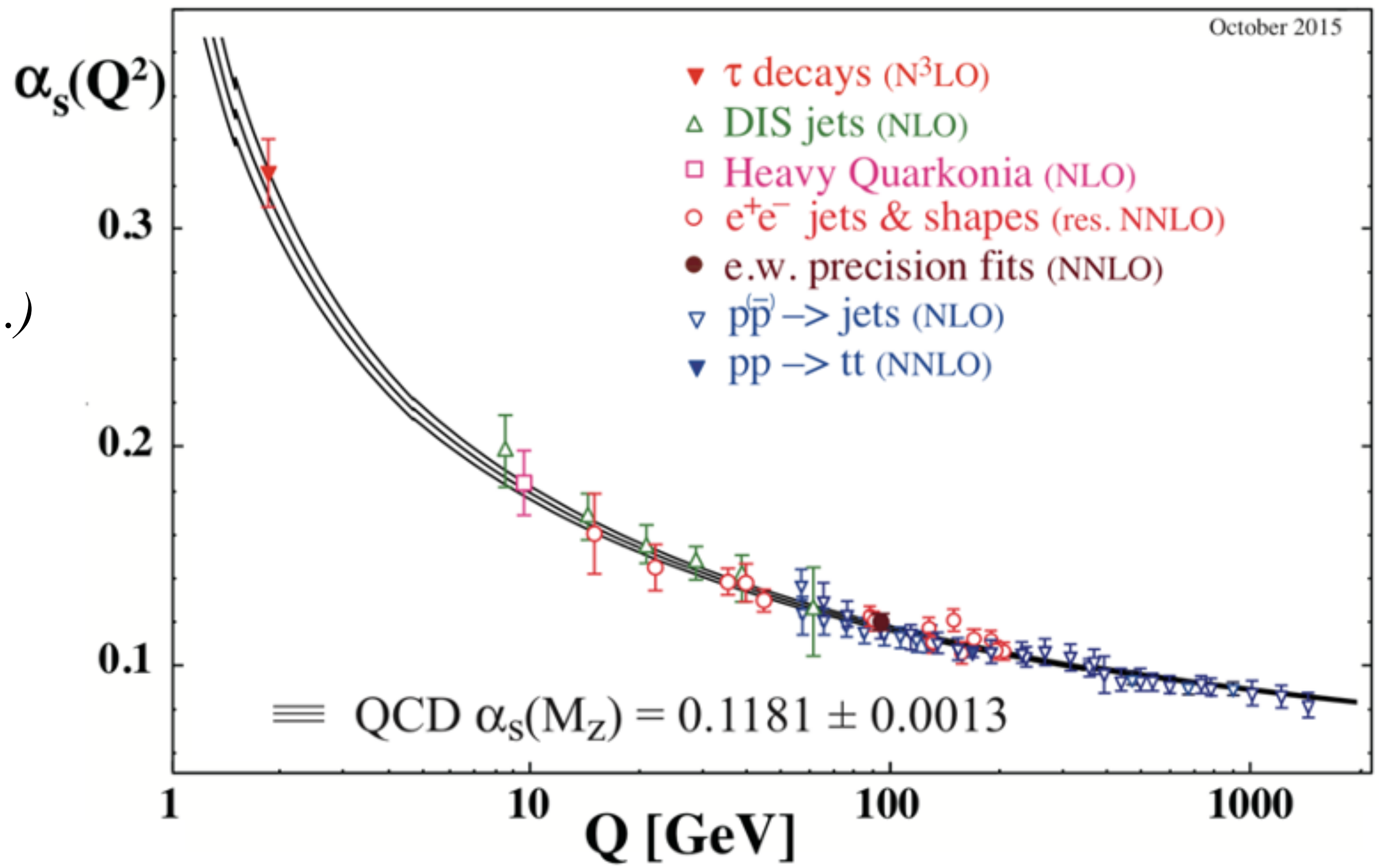
- Introduction to QCD jet
  - QCD in a nutshell
  - Early measurements and jet definition
  - Jet reconstruction in experiment and its challenges
  - Jet observables

- Jet-quenching in heavy-ion collisions
  - Introduction to QGP
  - Evidences of jet quenching in heavy-ion collisions
  - Consequences of jet-quenching
    - Observables and their physics interpretation
  - What have we learned about the properties of QGP (a finite temperature QCD) using jet as a probe?
  - Open questions and future measurements

QCD in a nutshell

Confinement

(Hadronization…)



Asymptotic freedom

(Jet , Quark-gluon plasma,…)

QCD in a nutshell

Gluon self-interaction

$F^A_{\mu\nu} = \partial_\mu A^A_\nu - \partial_\nu A^A_\mu - g_s f^{ABC} A^B_\mu A^C_\nu$

- Quarks and gluons → color objects
- Hadrons → colorless objects
- QED analogy, in QCD additional "color factor"

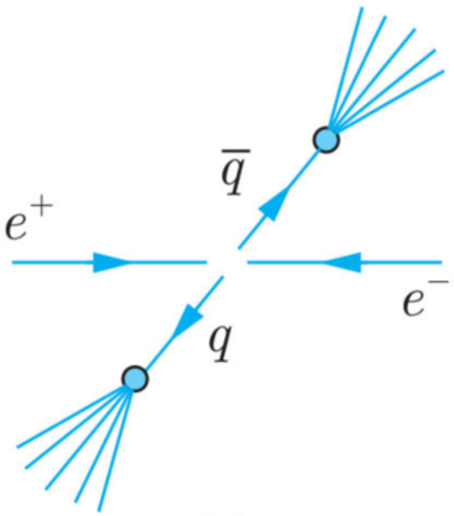
$$C(ik \to jl) \equiv \frac{1}{4} \sum_{a=1}^{8} \lambda^a_{ji} \lambda^a_{lk}$$

$\lambda_{ji} \to$ Gell-Mann SU(3) matrice

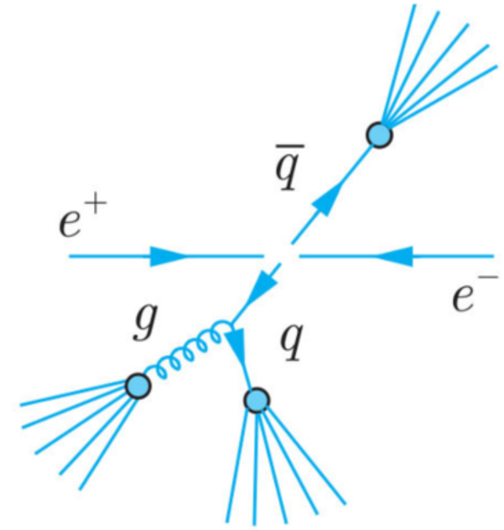
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Early measurements on *jet*…

$e^+ + e^-$ collisions (during 1970s)

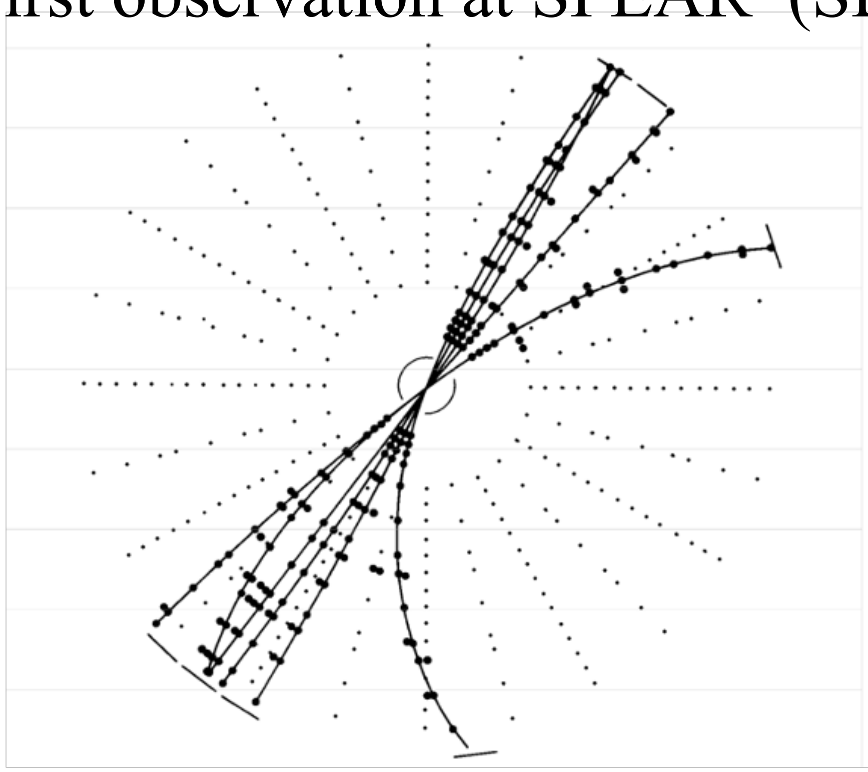


$e^+e^- \rightarrow q\bar{q} \rightarrow$ 2jets



$e^+e^- \rightarrow q\bar{q}g \rightarrow$ 3jets

First observation at SPEAR (SLAC)



Quark spin-1/2 confirmation

PRL 35, 1609 (1975); PRD 26, 991 (1982)

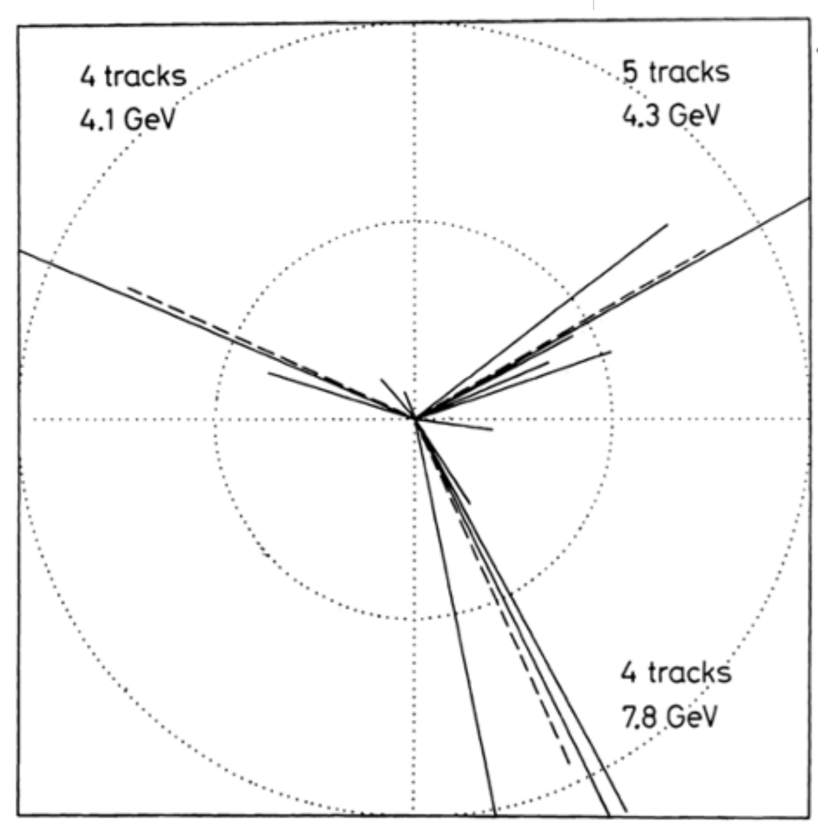


Fig.20g Another 3-jet event projected into the event plane.

TASSO

- First observation: TASSO expt. at PETRA accelerator (at DESY)
- 30 GeV c.o.m

Torquato Tasso
16th Century
Italian poet

B. H. Wiik , Bergen 1979

Not isotopically distributed…

Jet definition…

George Sterman and Steven Weinberg dijet definition

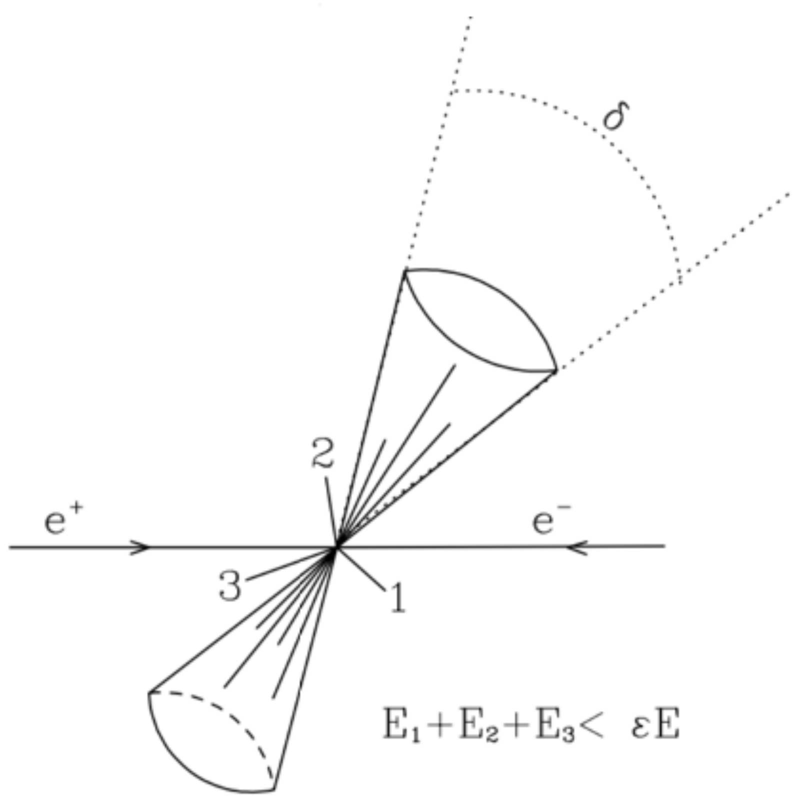
VOLUME 39, NUMBER 23 PHYSICAL REVIEW LETTERS 5 DECEMBER 1977

Jets from Quantum Chromodynamics

George Sterman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

and

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 26 July 1977)

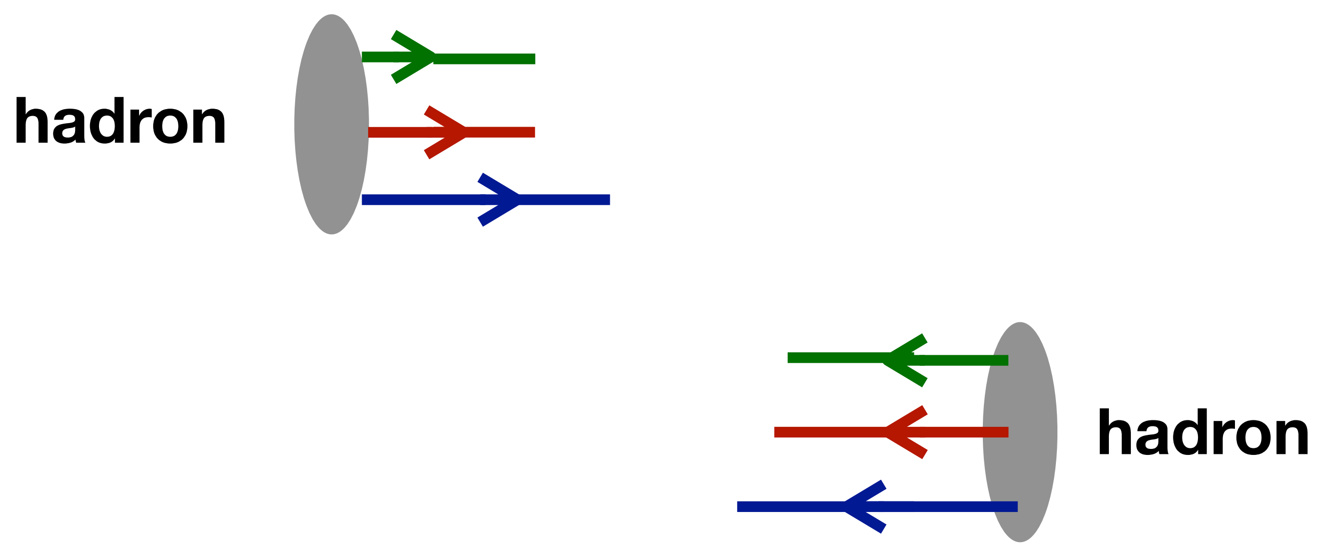


In an event

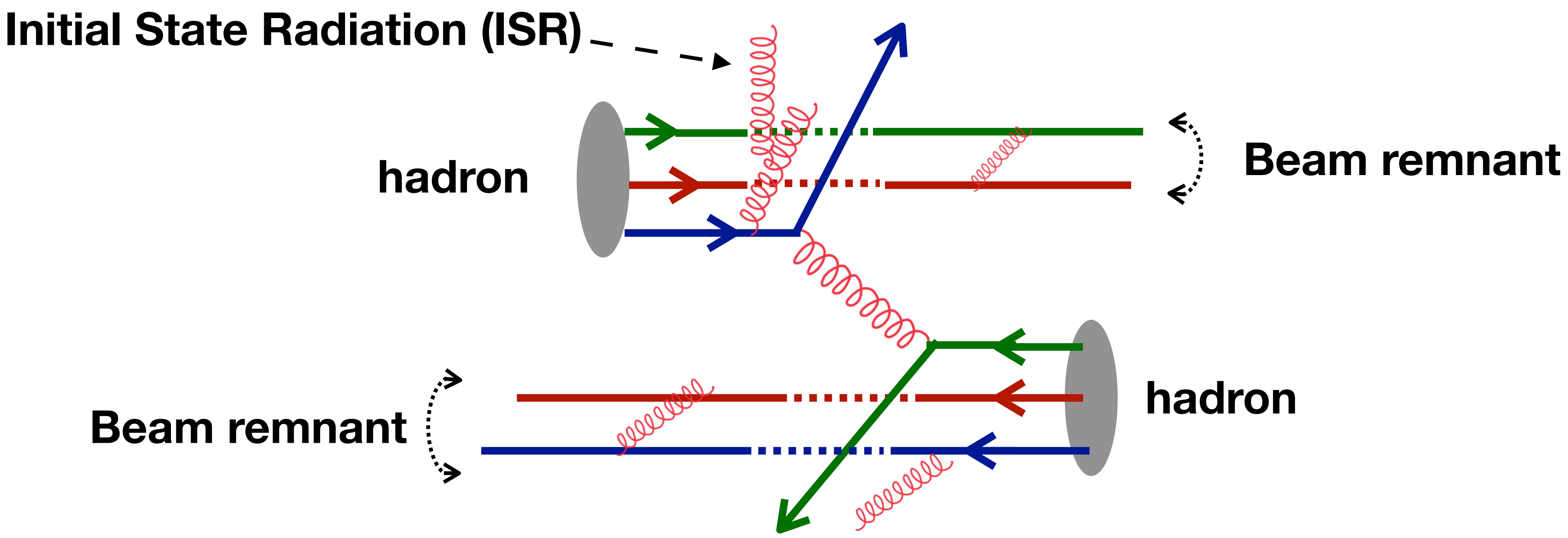
- Two 'cones' of opening angle δ containing all of the energy of that event
- Excluding a fraction ε of the total energy

Idea of jet as a cone begins…

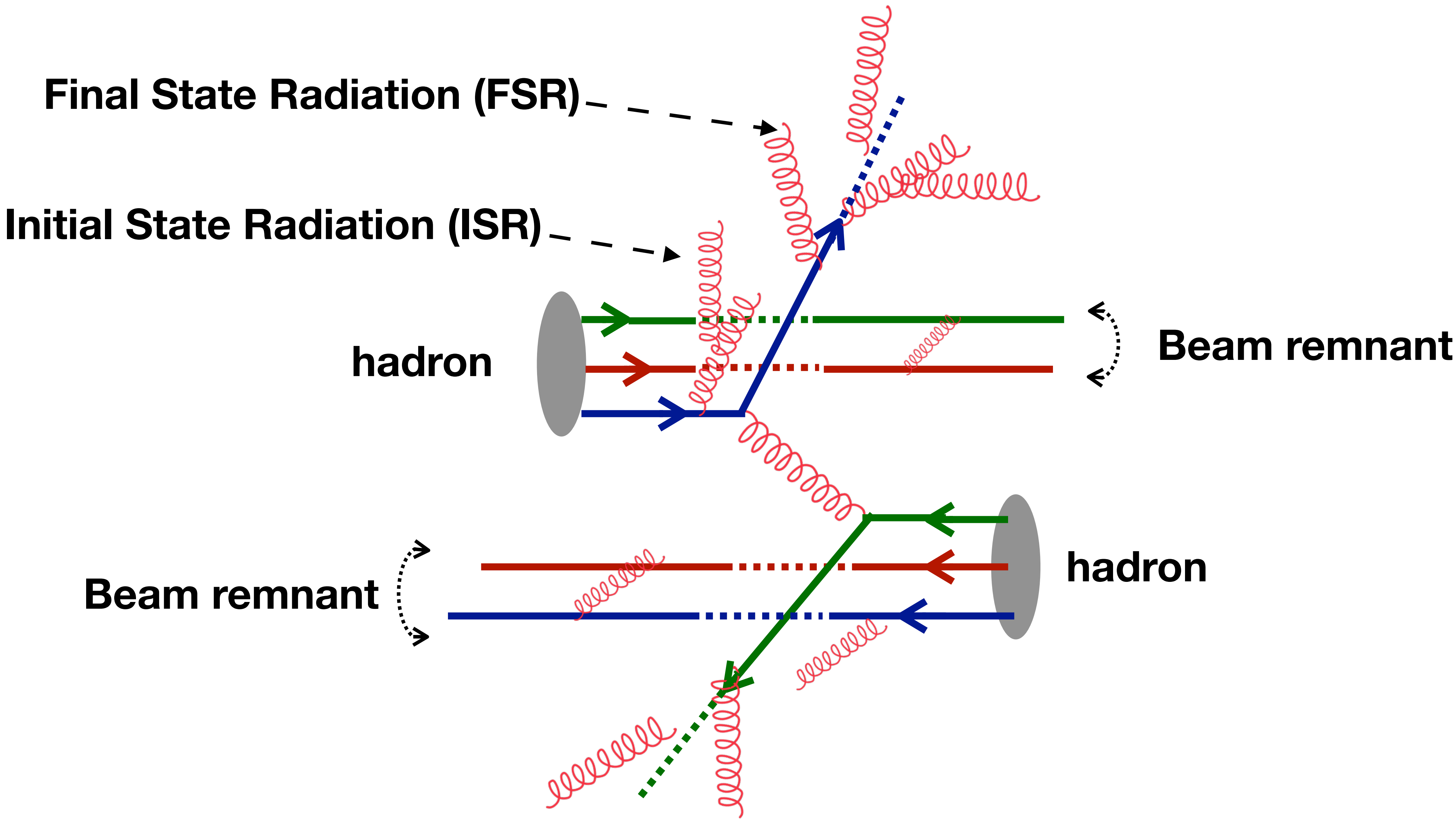
Jets in hadron-hadron collisions



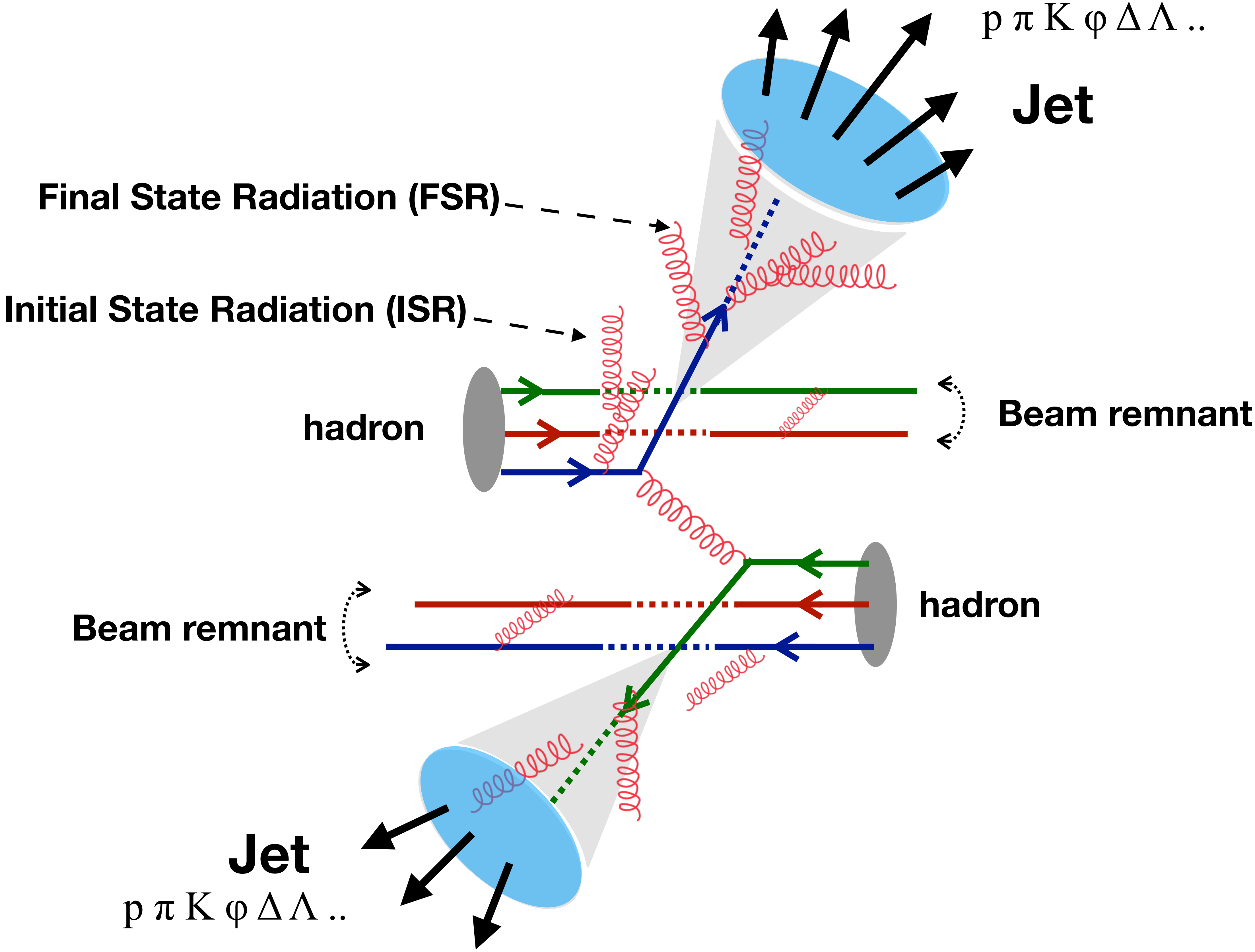
Jets in hadron-hadron collisions



Jets in hadron-hadron collisions

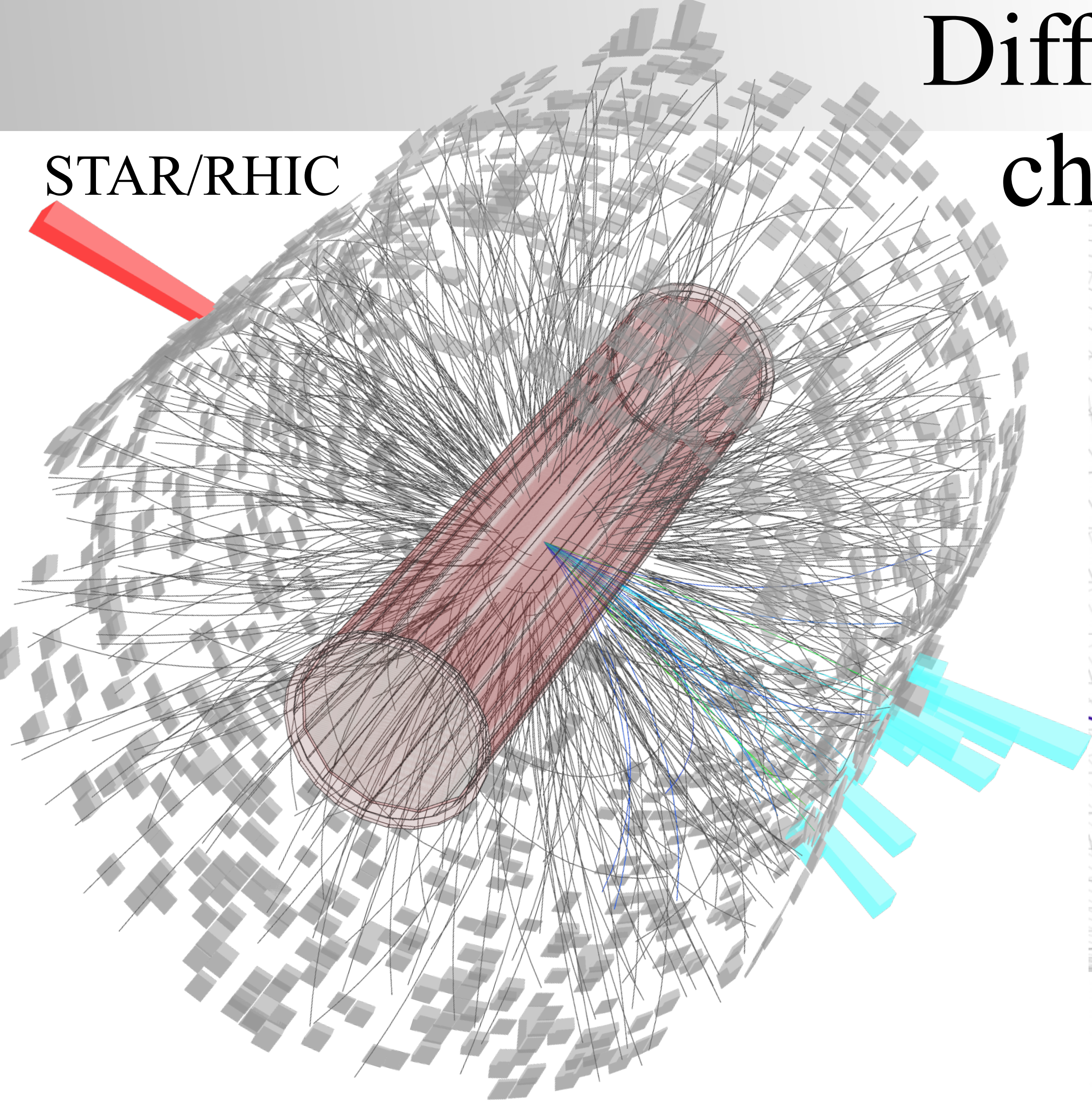


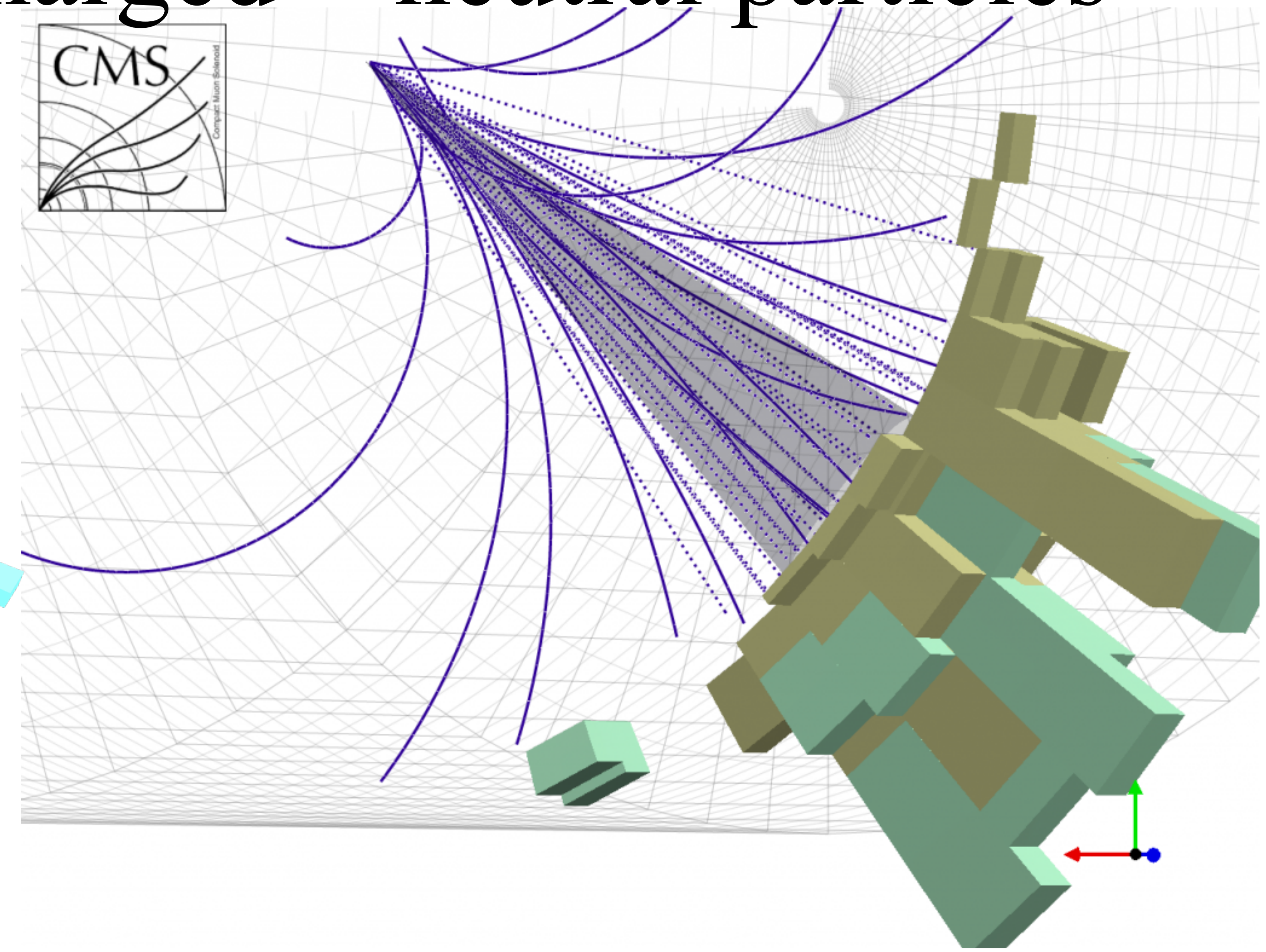
Jets in hadron-hadron collisions



Different detectors to measure charged + neutral particles

STAR/RHIC





- Detection of final state charged hadrons (π,k,p): using tracking detectors and hadronic calorimeter
- Neutral particles (EM): electromagnetic calorimeter

To reconstruct jet → 4-momentum (E, p_x, p_y, p_z)

QCD processes and jet terminology

Inclusive jet: $p + p \rightarrow \text{jet} + X$

Dijet: $p + p \rightarrow \text{jet} + \text{jet} + X$

hadron+jet: $p + p \rightarrow h + \text{jet} + X$

$q+\bar{q} \rightarrow g+g$
$q+q \rightarrow q+q$
$q+\bar{q} \rightarrow q+\bar{q}$
$q+g \rightarrow q+g$
$g+g \rightarrow g+g$
$g+g \rightarrow q+\bar{q}$

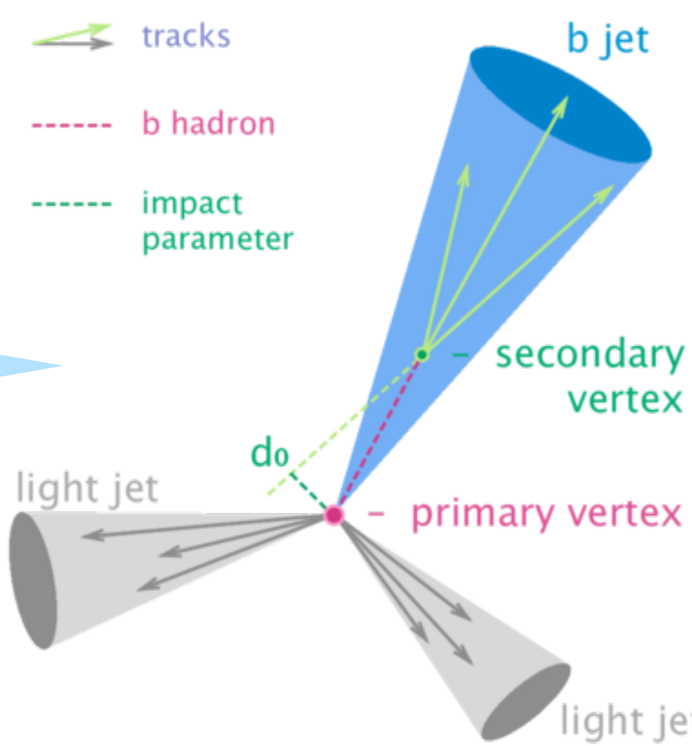
γ + jet:

$p + p \rightarrow \gamma + \text{jet} + X$

$q+g \rightarrow q+\gamma$ (QCD Compton)
$q+\bar{q} \rightarrow g+\gamma$ (Pair annihilation)

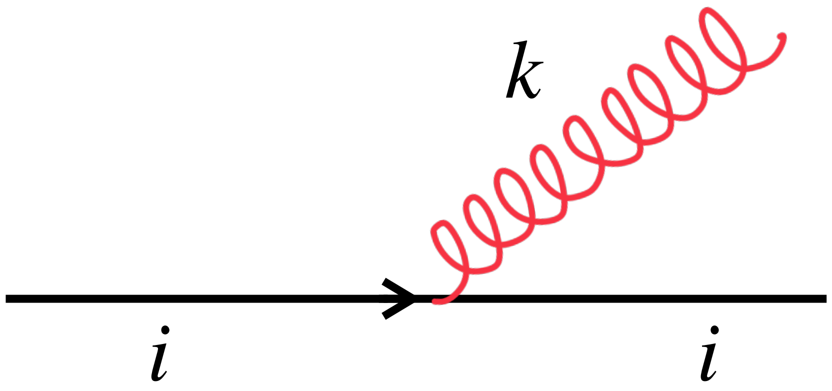
Heavy flavor-tagged jet
(Flavor tagging jet)

$p + p \rightarrow f + X$, where f → **jet**



Widely used in p+p and A+A collisions…

Soft and collinear emission and divergence



Splitting probability:

$$dP_{i\to ik} \sim \alpha_s C_F \frac{dE}{E} \frac{d\theta}{\theta}$$

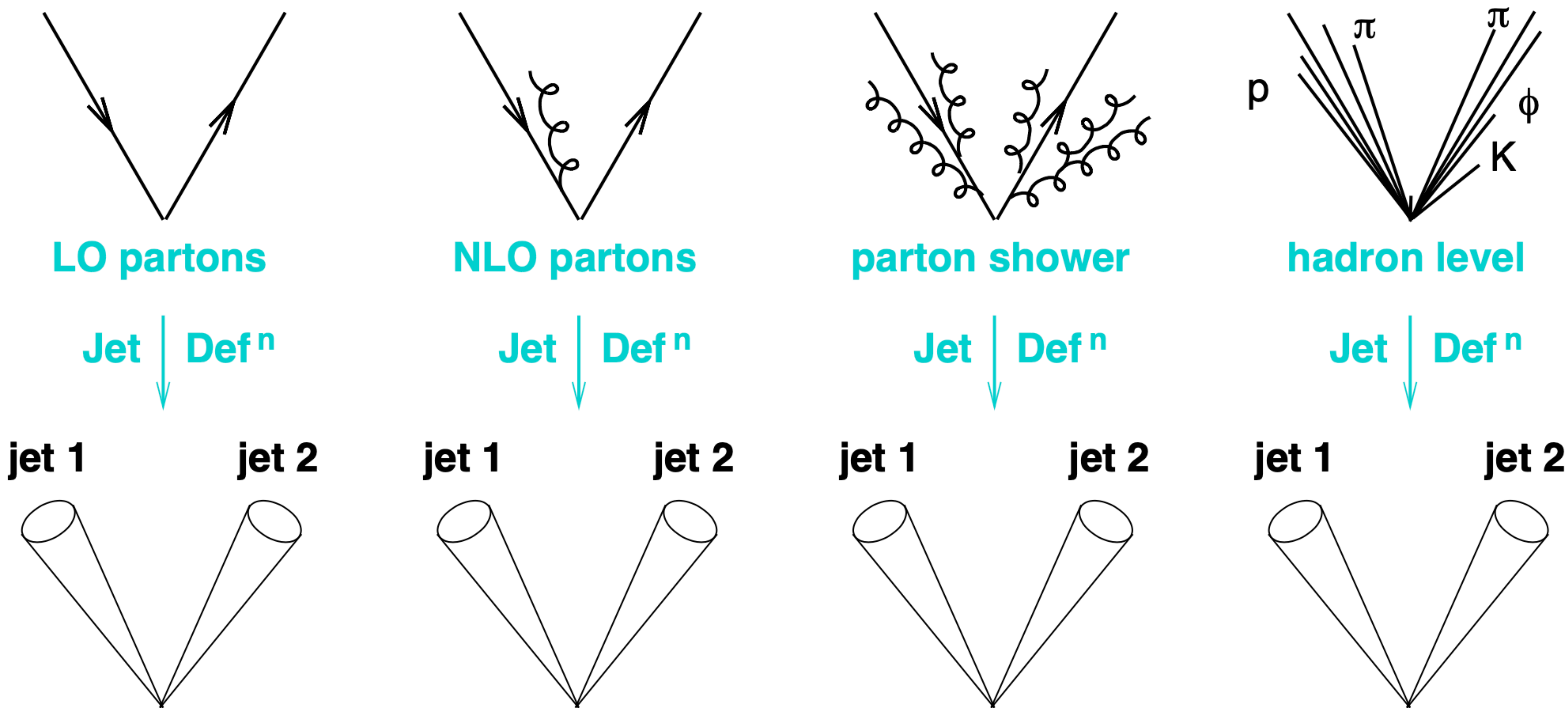
Divergences:

$E \to 0$: Infrared (IR) divergence

$\theta \to 0$ (or π) : Collinear (C)divergence

Jet calculation/measurement needs to avoid **IRC** divergence

Jet measurement: resilient to QCD effects



Projection to jets should be resilient to QCD effects

G. Salam, QCD Lectures

Jet reconstruction algorithms in hadron-hadron collisions

Experiment:

4-momentum $[p_i^{\text{track}}] \rightarrow [p^{\text{jet}}]_k$

Jet algorithms:

IRC safe: widely used *sequential recombination* jet algorithms

- k_T algorithm $[p = 1]$
- Cambridge and Aachen (C/A) algorithm $[p = 0]$
- anti-k_T algorithm $[p = -1]$

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{ti}^{2p}$$

$R \rightarrow$ Radius of cone/Jet resolution parameter

FastJet package:http://fastjet.fr/all-releases.html

Jet reconstruction algorithms in hadron-hadron collisions

Two input parameters: R and $p_{\mathrm{t,min}}$

Jet algorithms:

IRC safe: widely used *sequential recombination* jet algorithms

- k_T algorithm [$p = 1$] → Clustering involves soft particles
- Cambridge and Aachen (C/A) algorithm [$p = 0$] → angular ordering
- anti-k_T algorithm [$p = -1$]→ Clustering involves hard particles

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

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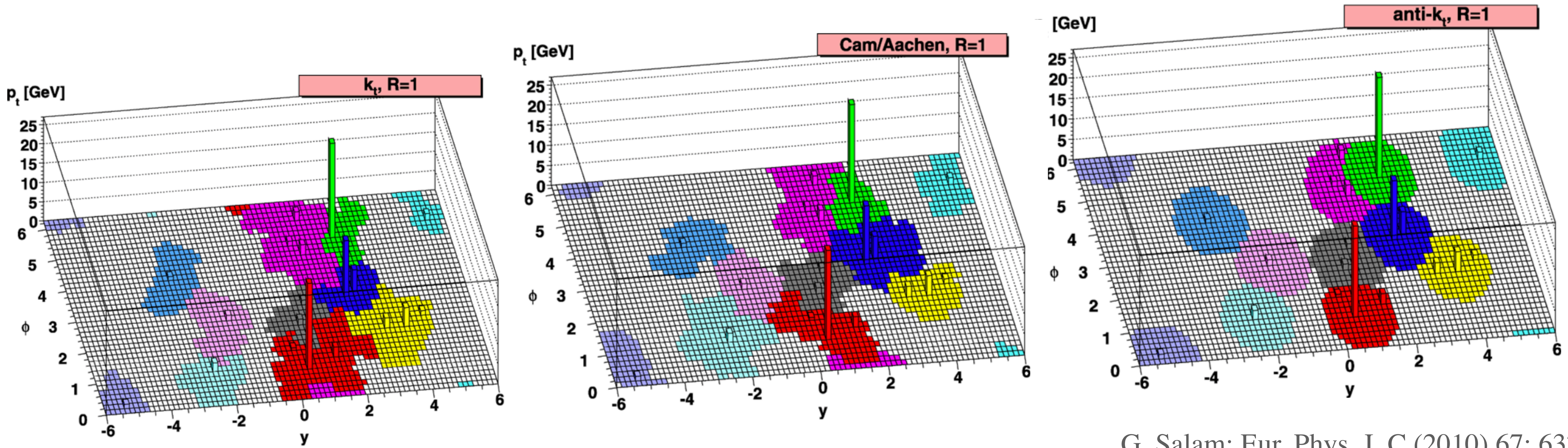
Jet reconstruction algorithms in hadron-hadron collisions

k_T C/A anti-k_T



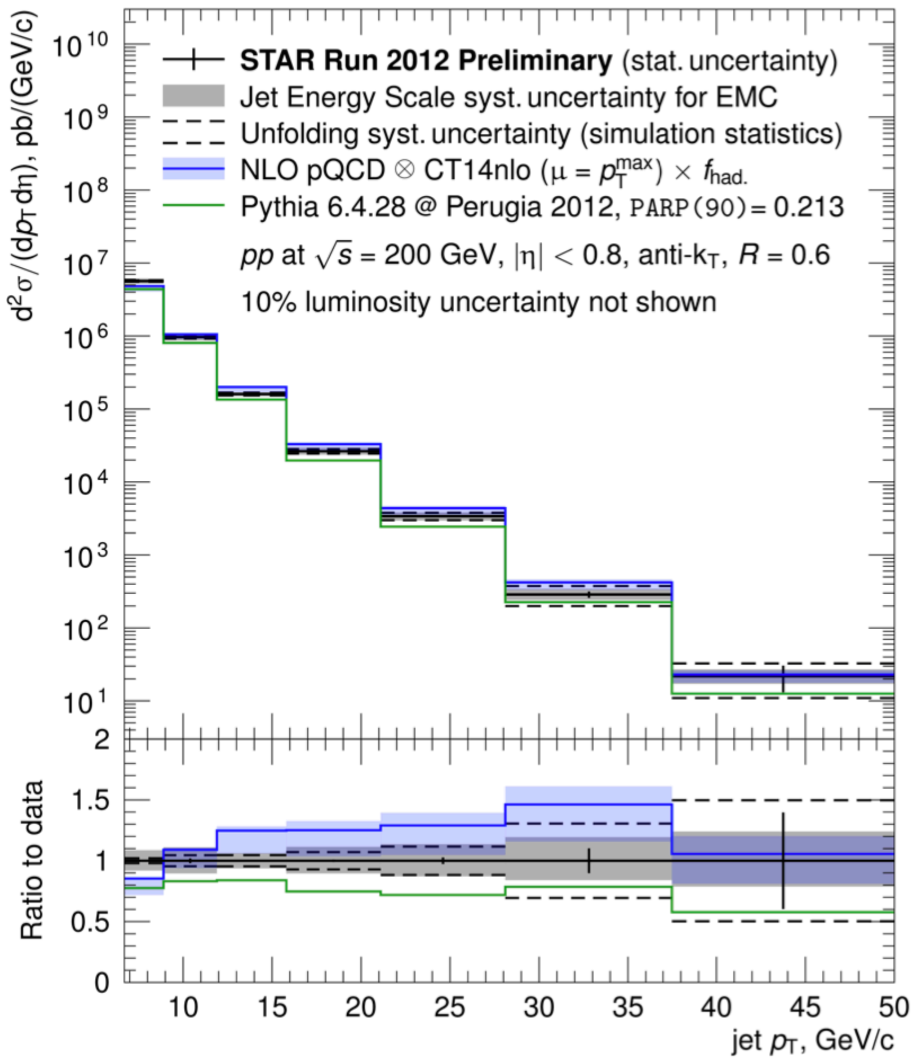
G. Salam: Eur. Phys. J. C (2010) 67: 637

- anti-k_T gives circular hard jets
- k_T and C/A give irregular jet structures

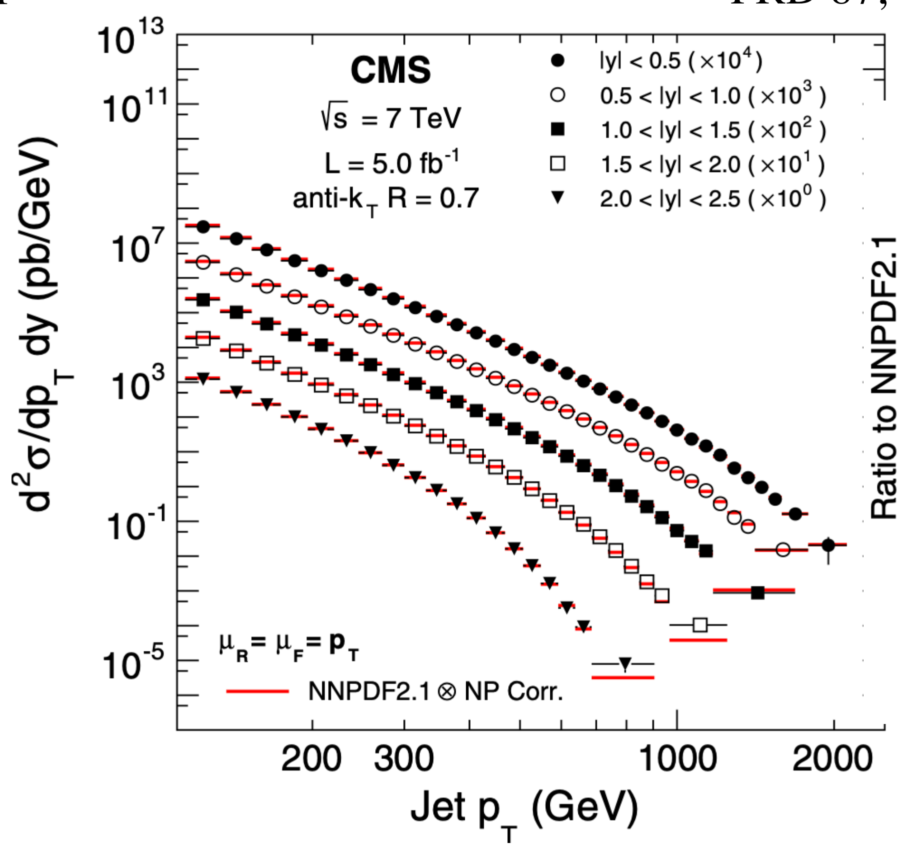
QCD: experiment and theory

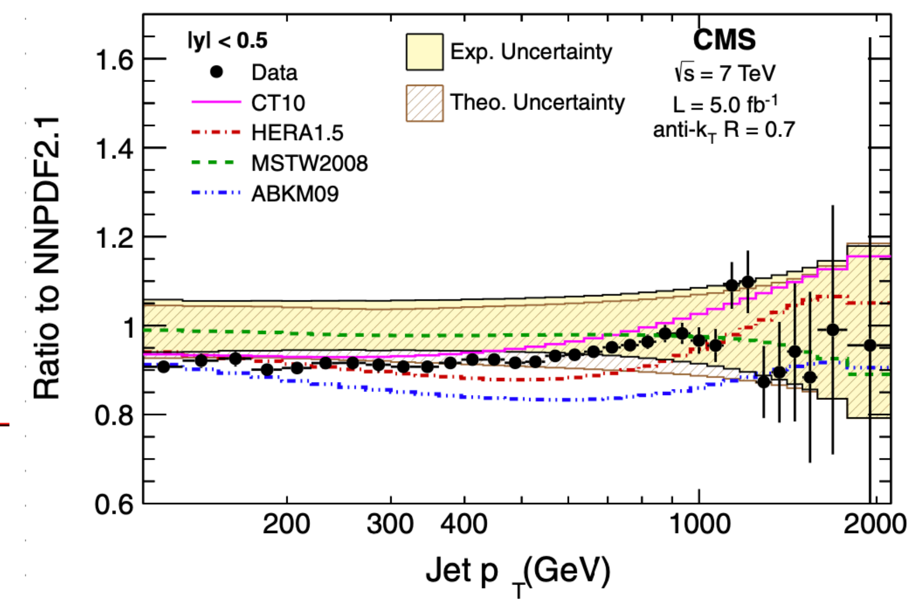
Inclusive jet measurement: $p + p \rightarrow \text{jet} + X$

STAR/RHIC: pp $\sqrt{s}$ = 200 GeV — Z. Chang, PANIC 2021



CMS/LHC: pp $\sqrt{s}$ = 7 GeV — PRD 87, 112002 (2013)

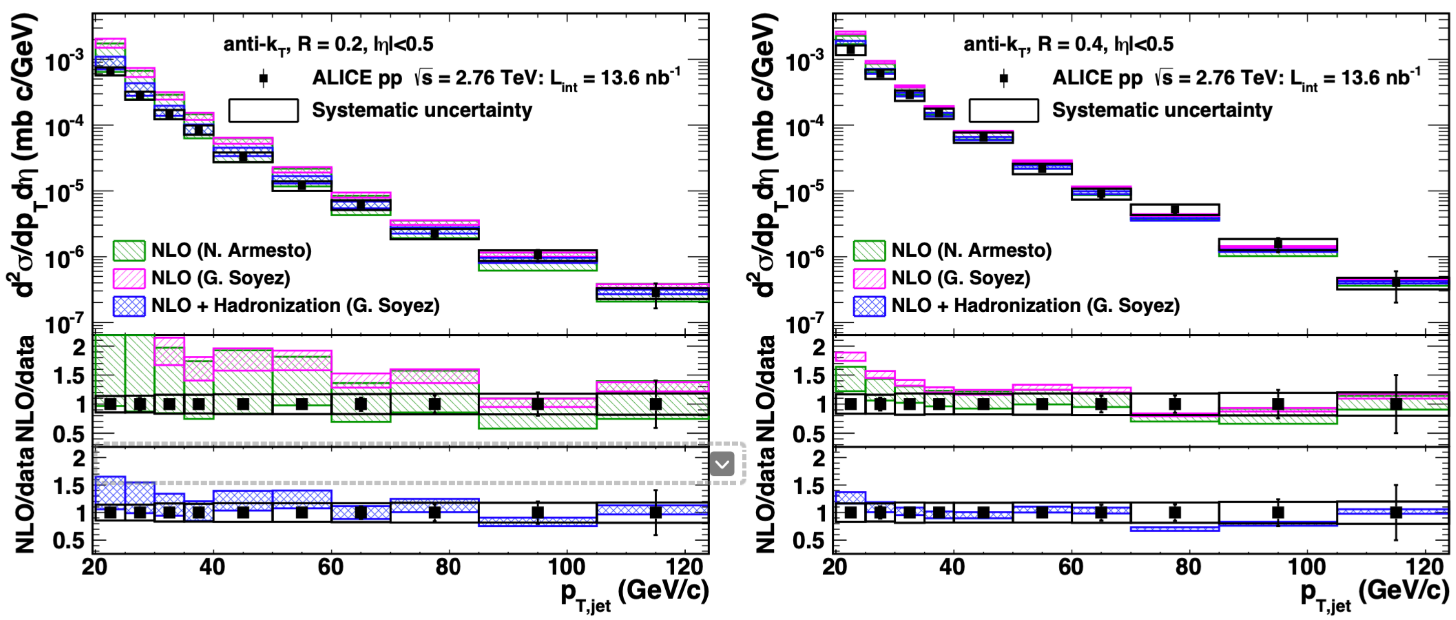




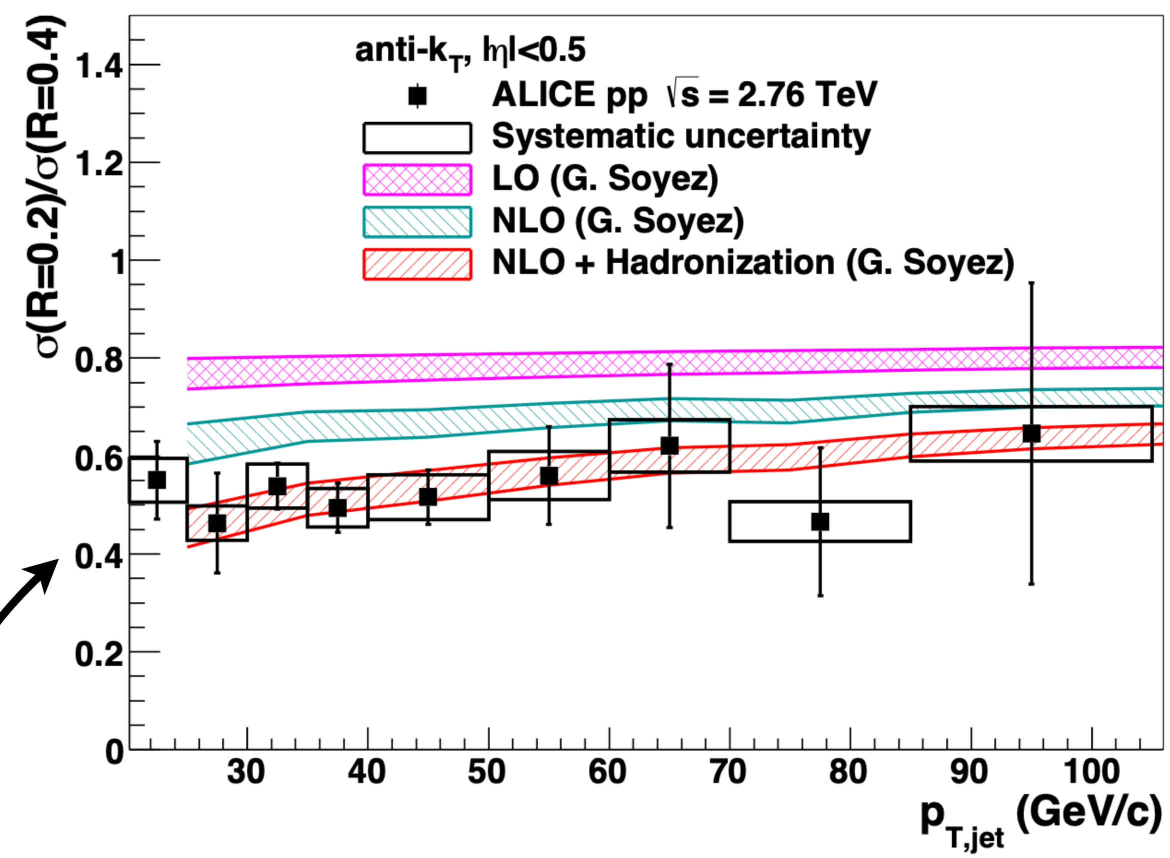
- Significant achievement in the development of QCD: theory and experiment
- We can measure partons as jets in experiment and study them

Jet cone size (shape) vs parton shower

Jet R = 0.2 Jet R = 0.4



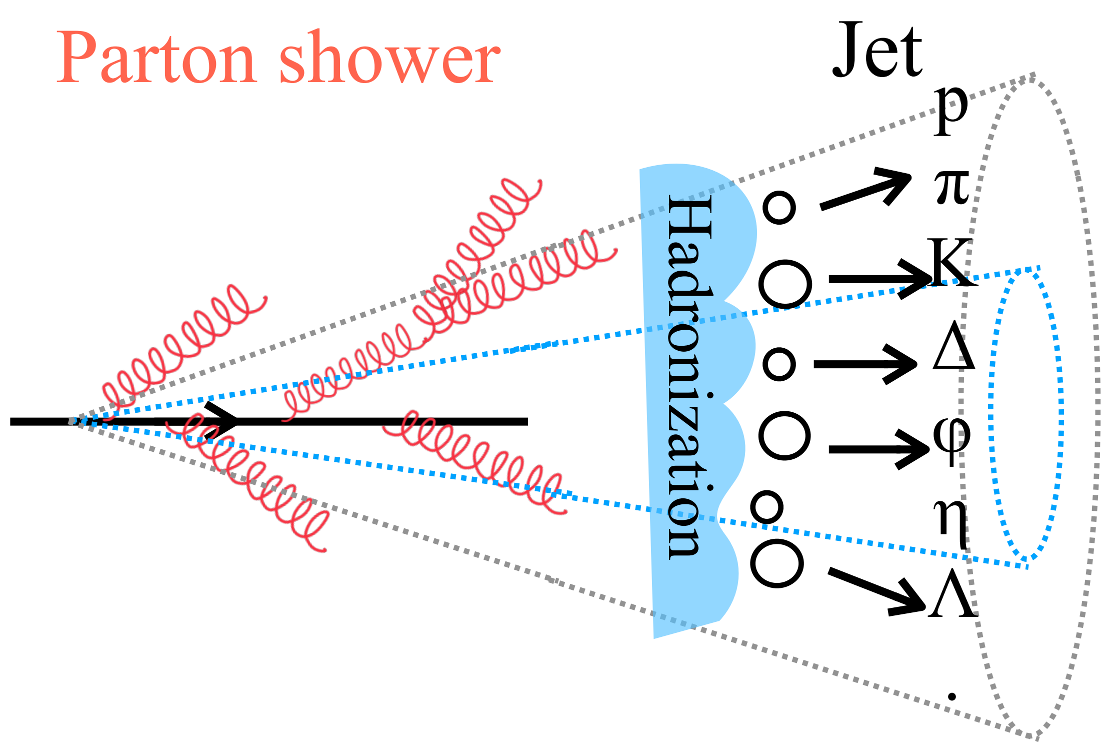
ALICE: Phys. Lett. B **722**, 262 (2013)



Jet cone size → varying jet R

$$\frac{\sigma(R=0.2)}{\sigma(R=0.4)}$$

Parton shower



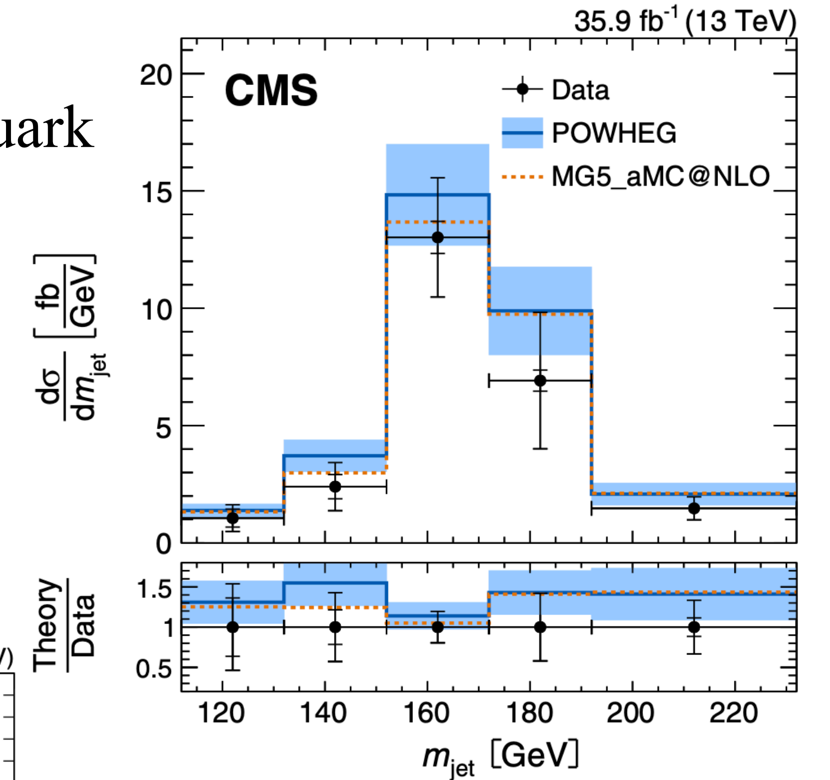
NLO pQCD + hadronization important to study jet shape

Jet mass and charge measurement

Jet observables are:

- Jet Mass: $M_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}$

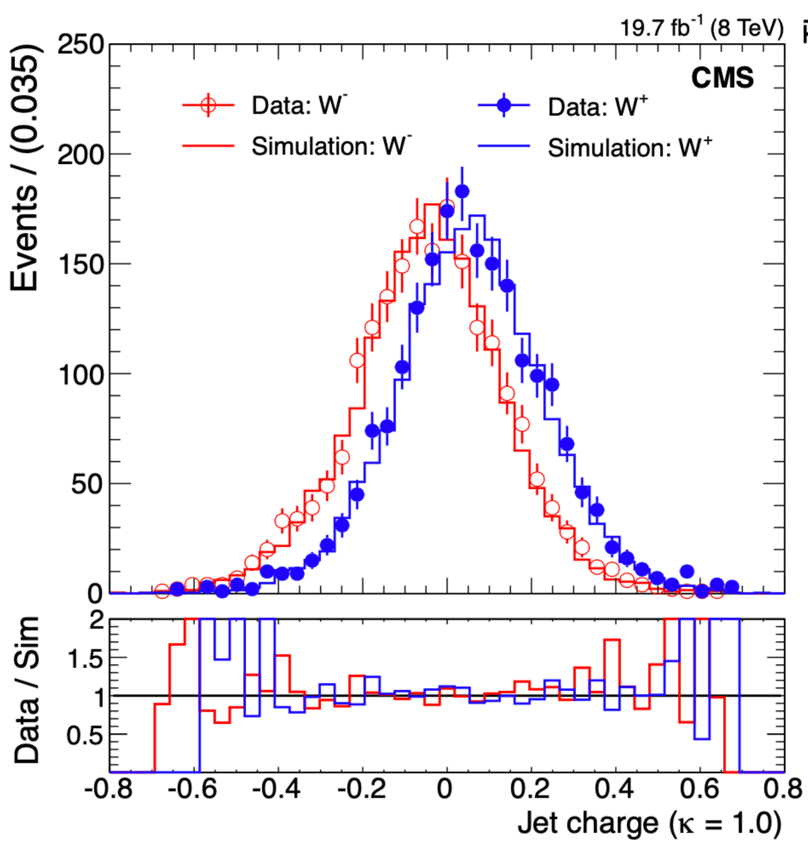
top quark



CMS: PRL 124, 202001 (2020)

- Jet charge (p_T-weighted sum)

$$Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_i Q_i (p_T^i)^\kappa$$



CMS: JHEP12 (2014) 017

Many measurements are ongoing at RHIC and LHC in this direction

For such measurement pp baseline is important for heavy-ion collisions

- QCD calculations can predict the jet observables in collider experiment
- Important to connect theory (parton) with experiment (jet)

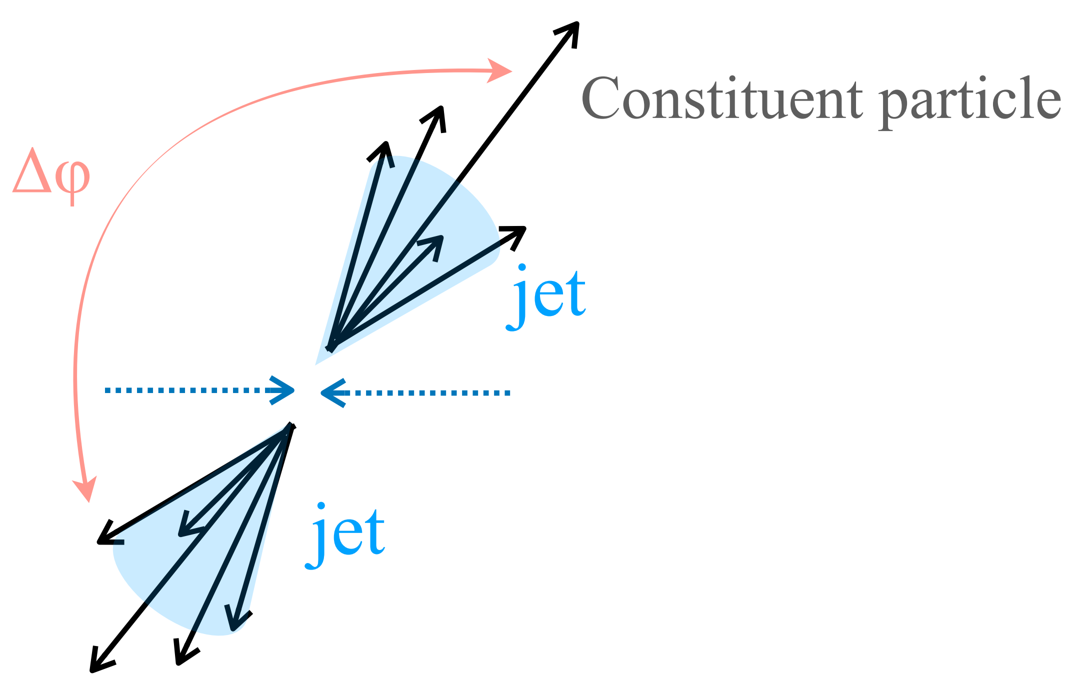
Jet can be used to study the properties of Quark-Gluon Plasma in heavy-ion collisions …

Jet measurements in heavy-ion collisions…

Jet and jet-like measurements in collider experiments

- Jet reconstruction using different algorithms
  - Effective in less uncorrelated background event: UE, heavy-ion collision, etc
  - Partons are jets
  - …
- Jet-like measurements

  In large background events



Jet and jet-like measurements in collider experiments

- Jet reconstruction using different algorithms (already discussed)
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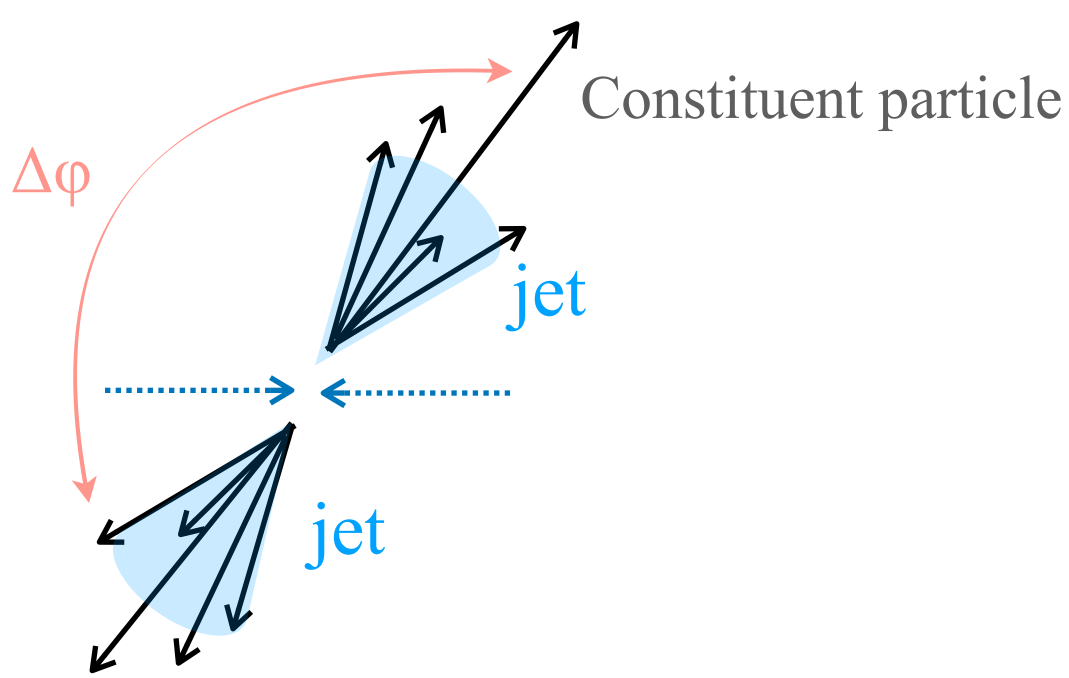
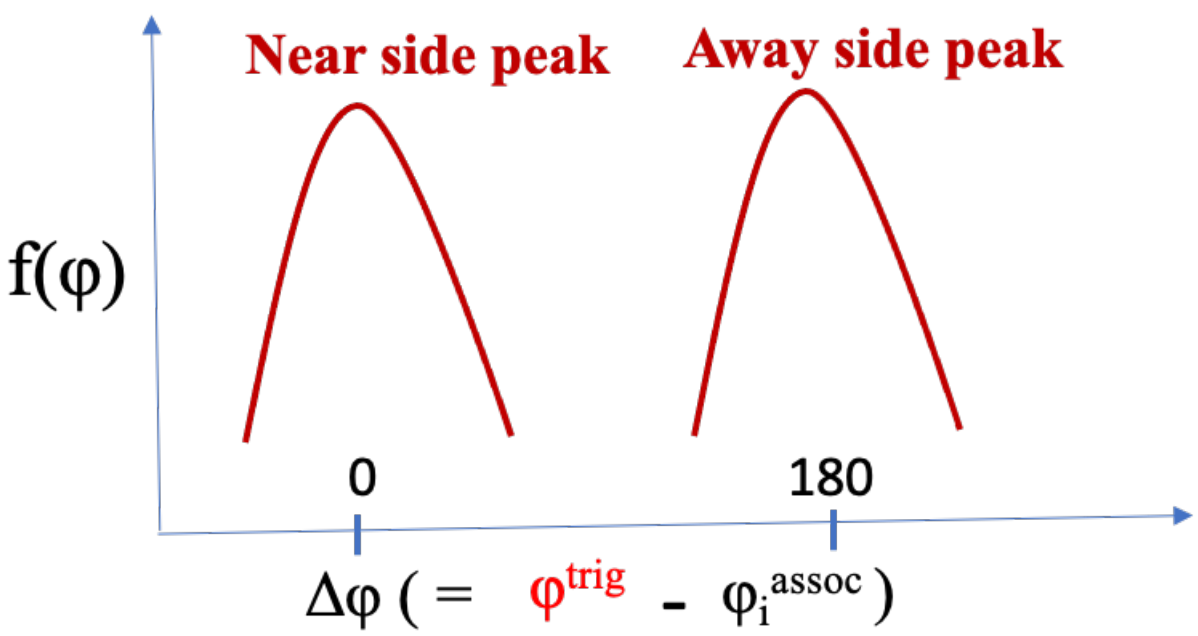
  In large background events

Di-hadron correlation measurement





Jet and jet-like measurements in collider experiments

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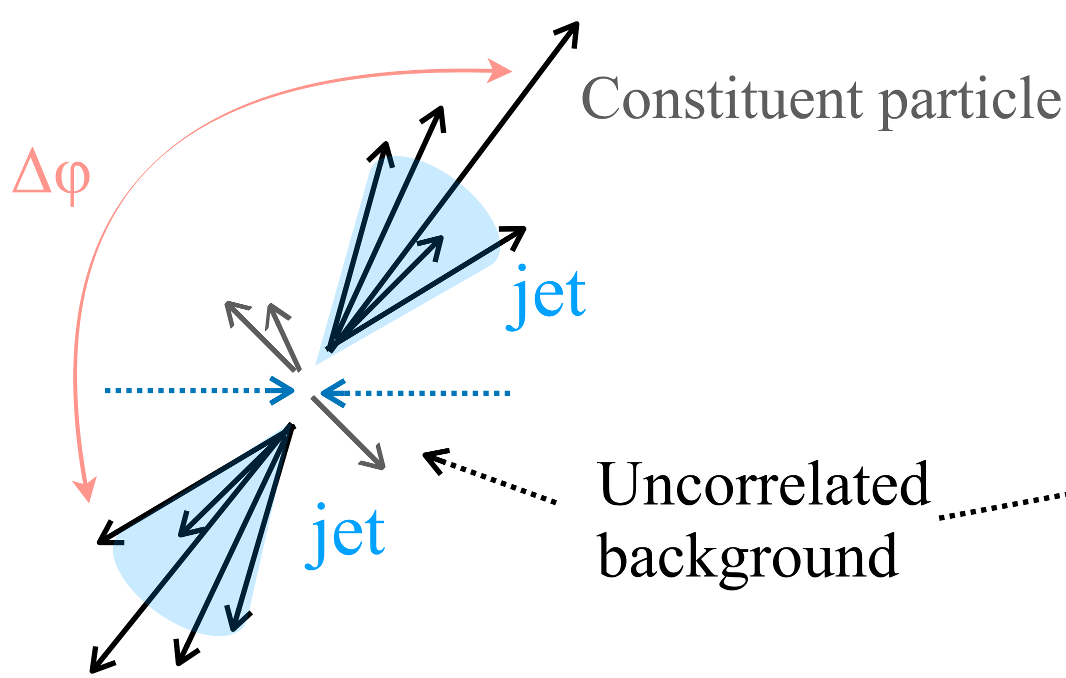
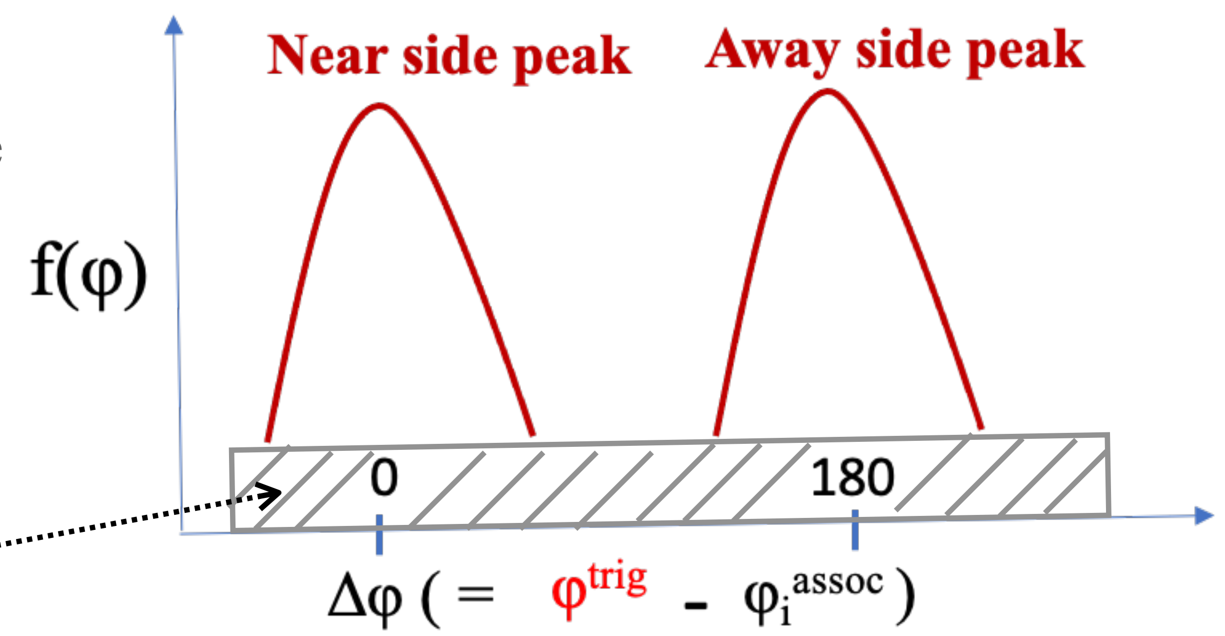
Di-hadron correlation measurement





In heavy-ion collisions, background appears with different modulation
ZYAM (Zero yield at minimum) useful to normalize the background

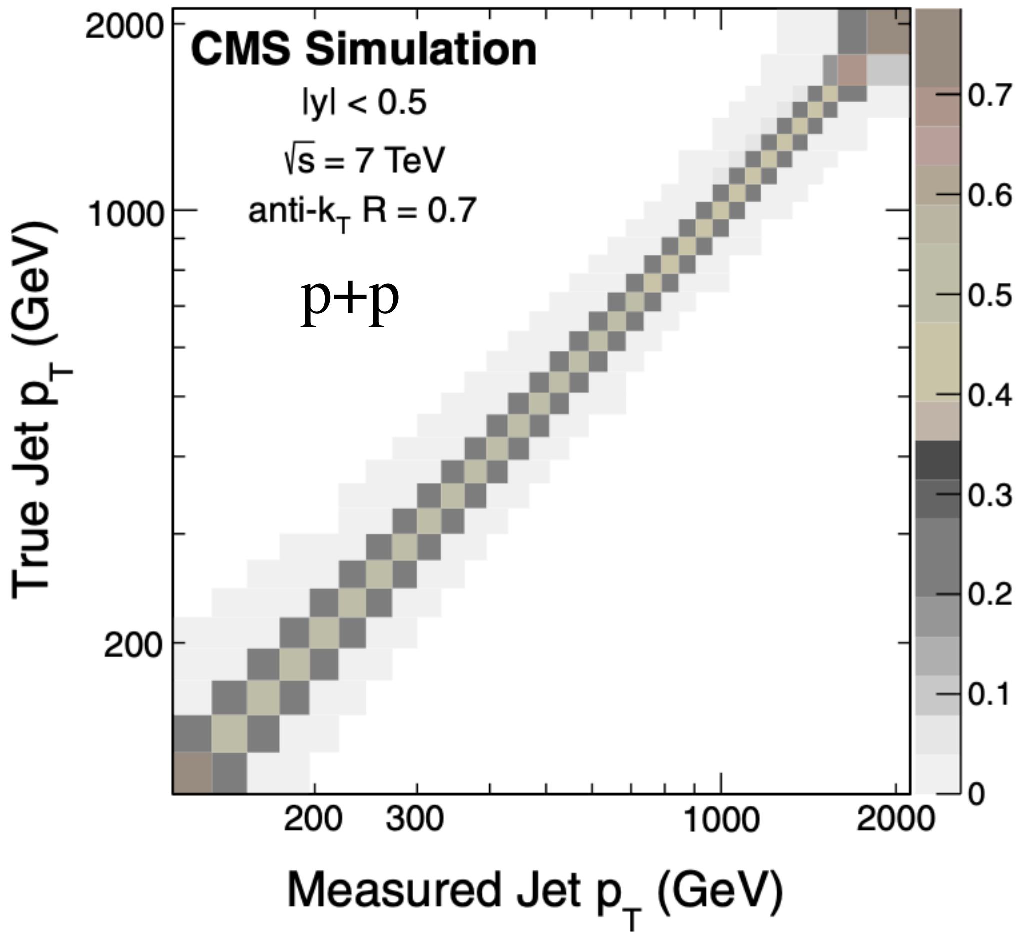
Jet measurements: Experimental challenges

Different corrections applied in jet (jet-like) measurements

- Detector effects
  - Detector efficiency
  - pT-resolution (Tracking detectors)
  - Energy resolution (Calorimeter)
  - Different Unfolding techniques (RooUnfold, OmniFold,..)

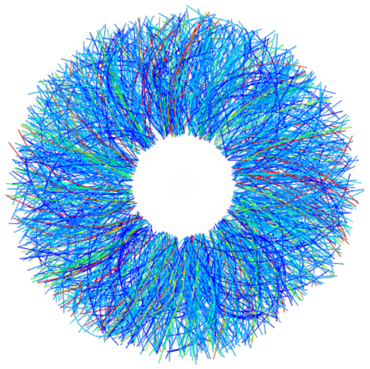
For example

PRD 87, 112002 (2013)



- Trigger efficiency of a detector
  - mainly for cross-section calculation

- Uncorrelated jet background
  - Combinatorial jet contribution



Various techniques are used in different experiments to correct all these effects

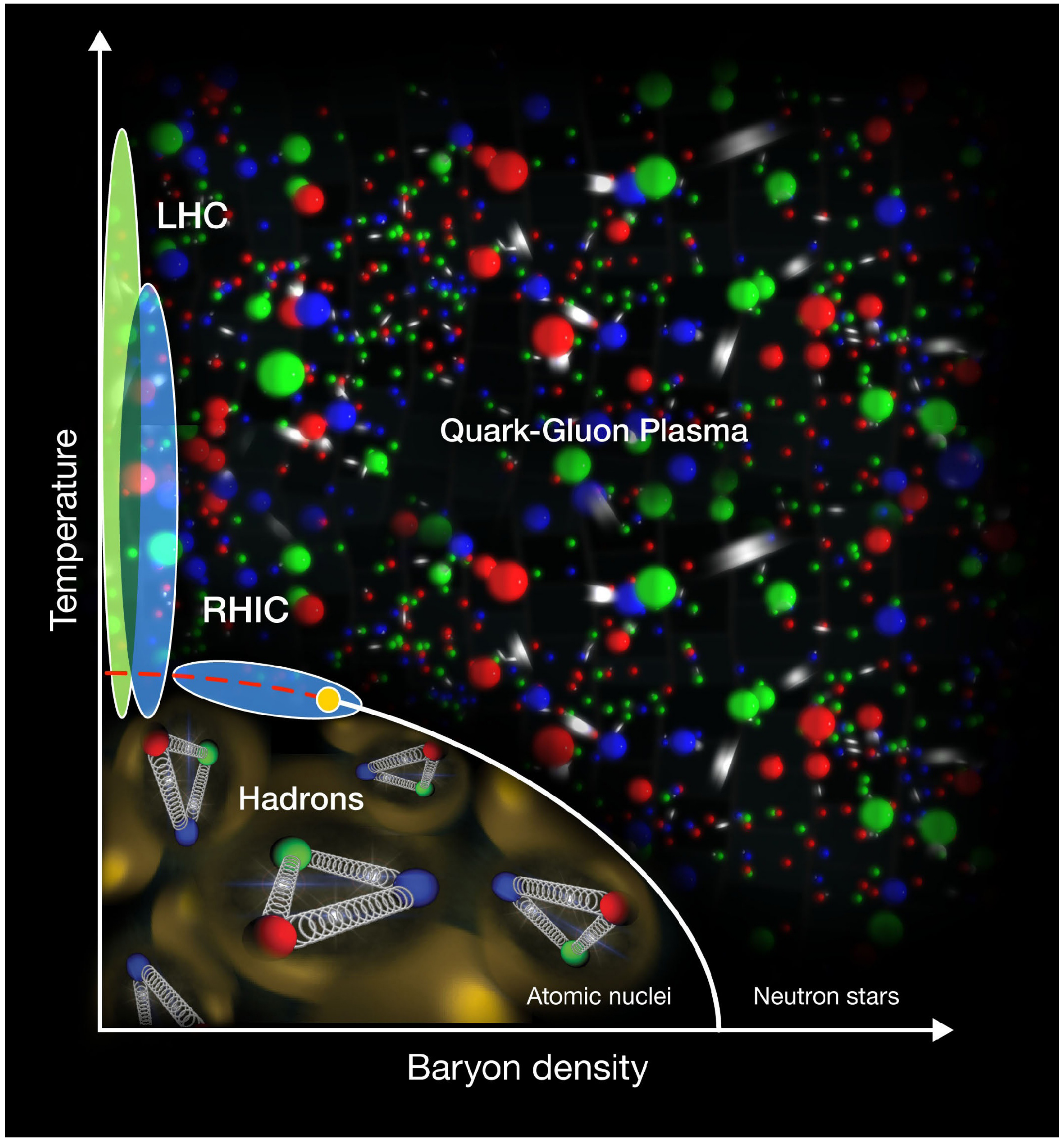
- Based on their detector setup and requirements
- And also certain bias …


TIME FOR TEA

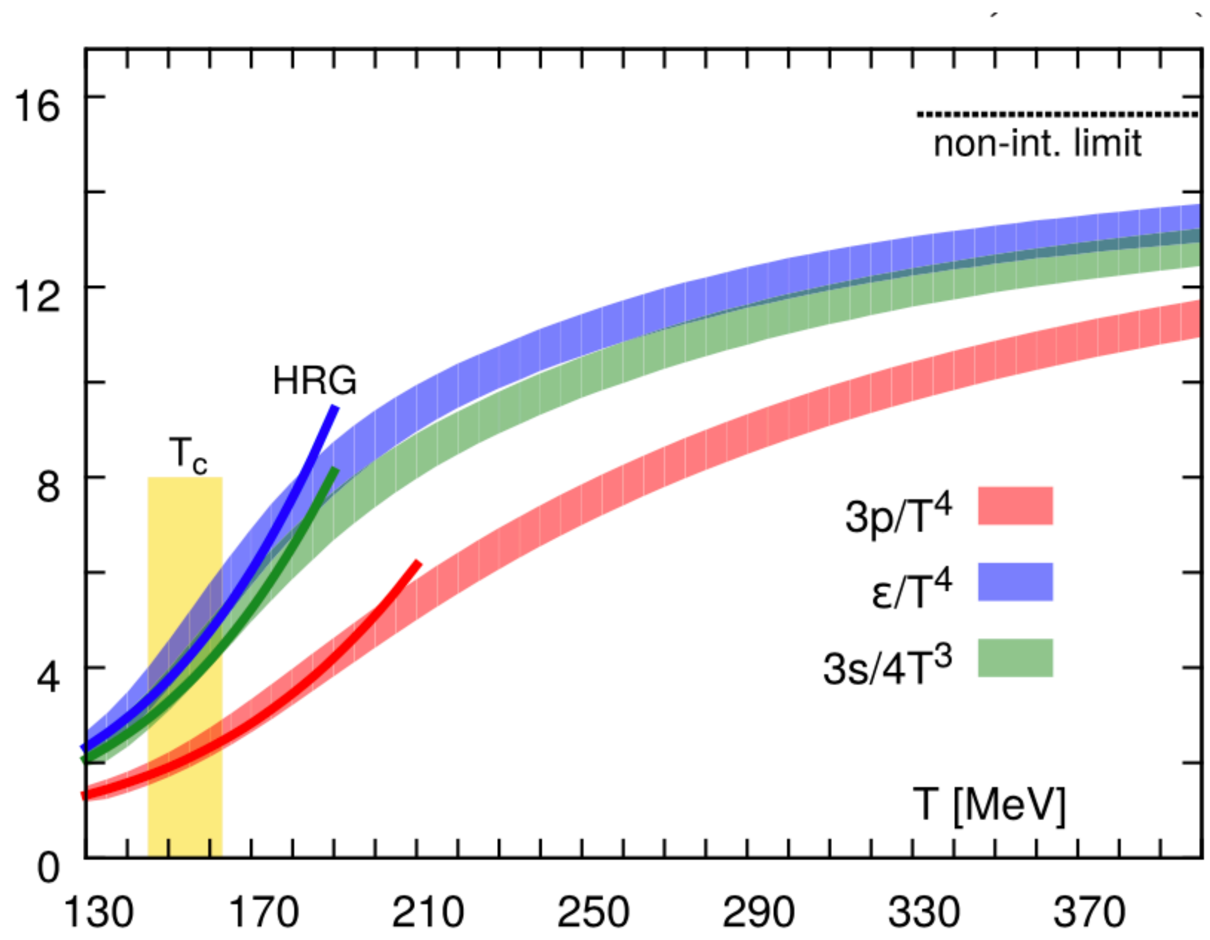
Jet in heavy-ion collisions and jet-quenching…

- Jet-quenching in heavy-ion collisions
  - Introduction to QGP
  - Evidences of jet quenching in heavy-ion collisions
  - Consequences of jet-quenching
    - Observables and their physics interpretation
  - What we have learned about the properties of QGP (a finite temperature QCD) using jet as a probe?
  - Open questions and future measurements

Quark-gluon plasma (QGP) in a nutshell



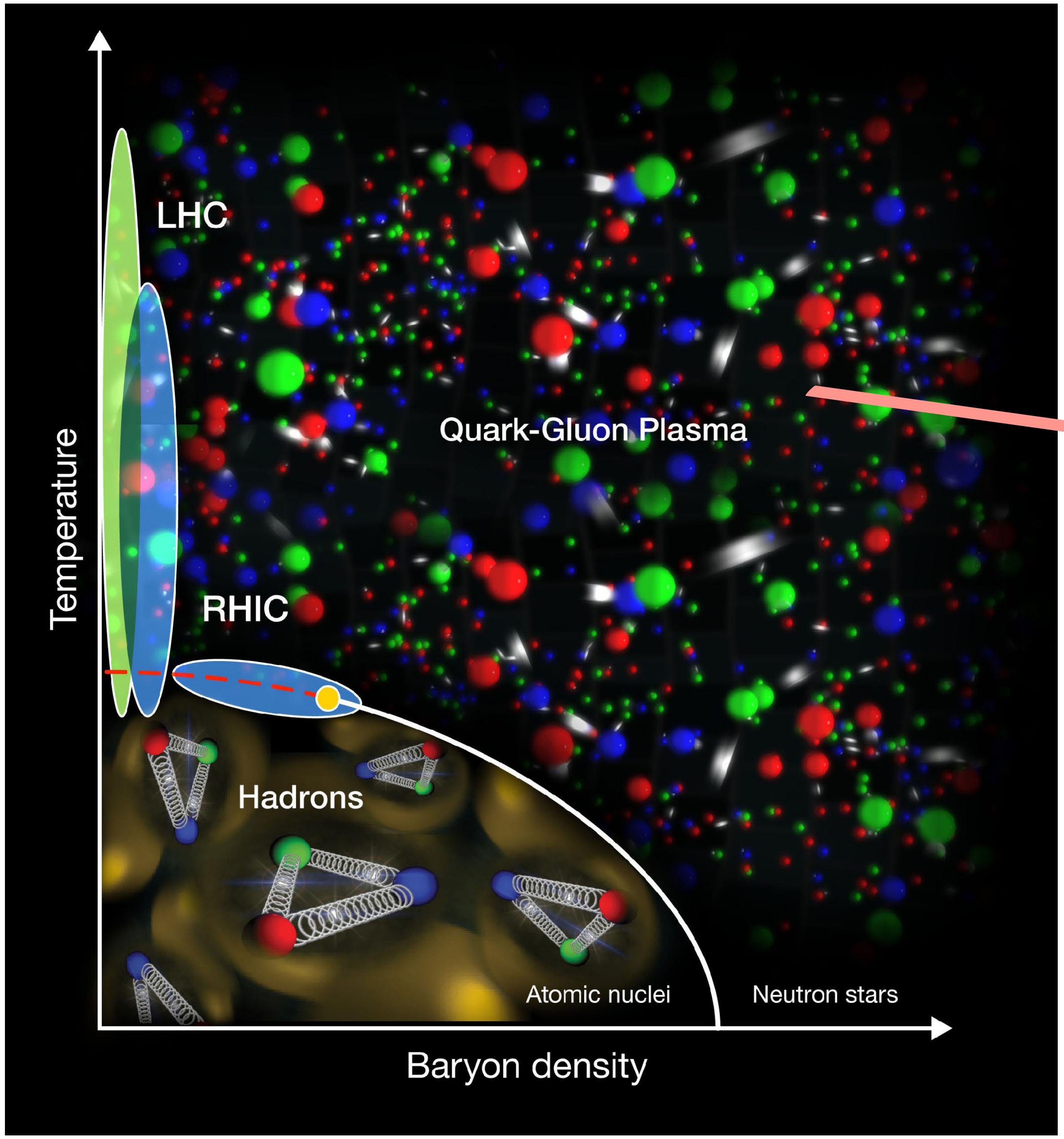
Equation of state



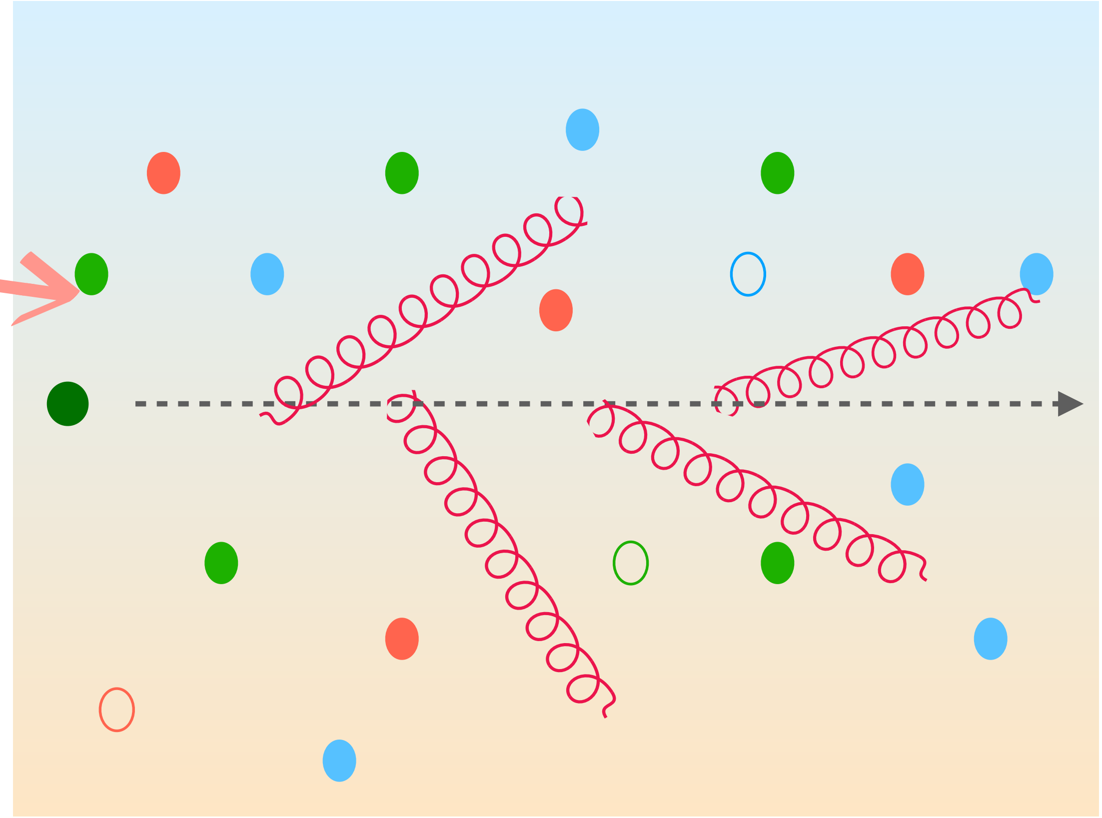
PRD 90, 094503 (2014)

QGPE lectures by Partha Pratim Bhaduri
QGPT lectures by Sandeep Chatterjee

Quark-gluon plasma (QGP) in a nutshell

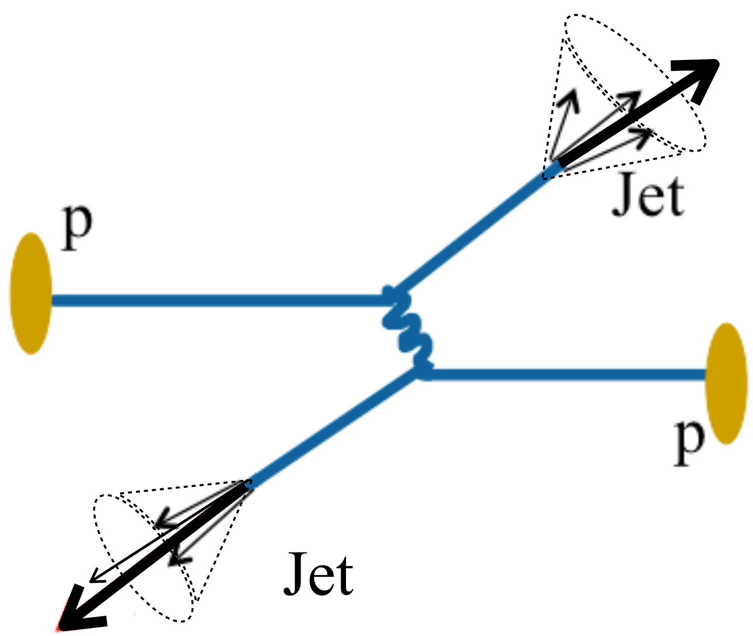


a finite temperature QCD

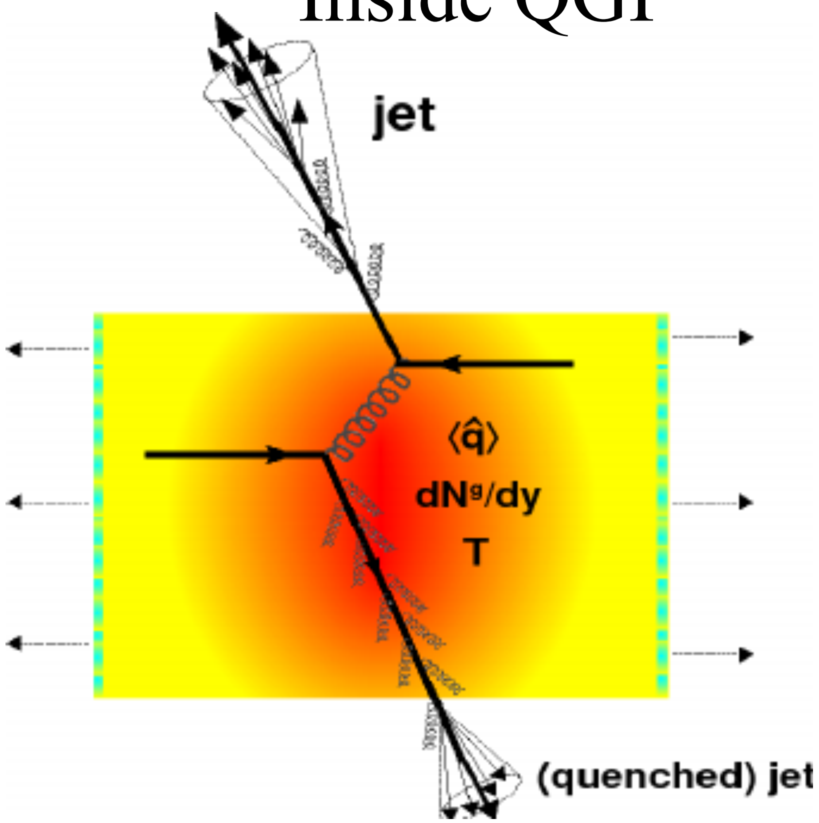


How does an energetic quark/gluon interact with the finite temperature QCD medium?

In vacuum



Inside QGP

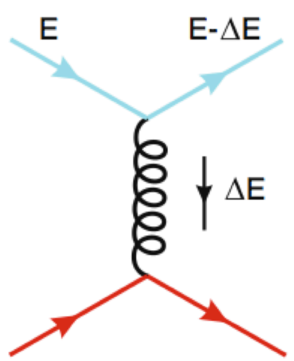


Modification of jet in heavy-ion collision (A+A) relative to in vacuum (p+p)

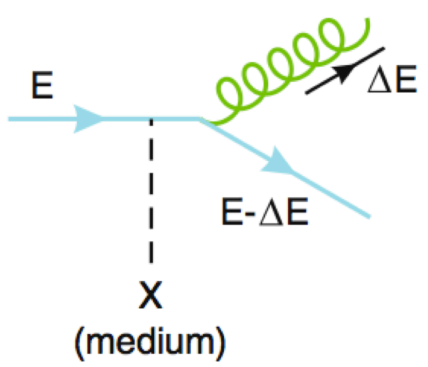
- Jets are produced at initial stage of the collision
- Production rate calculable using pQCD

Energy loss:

Collisional



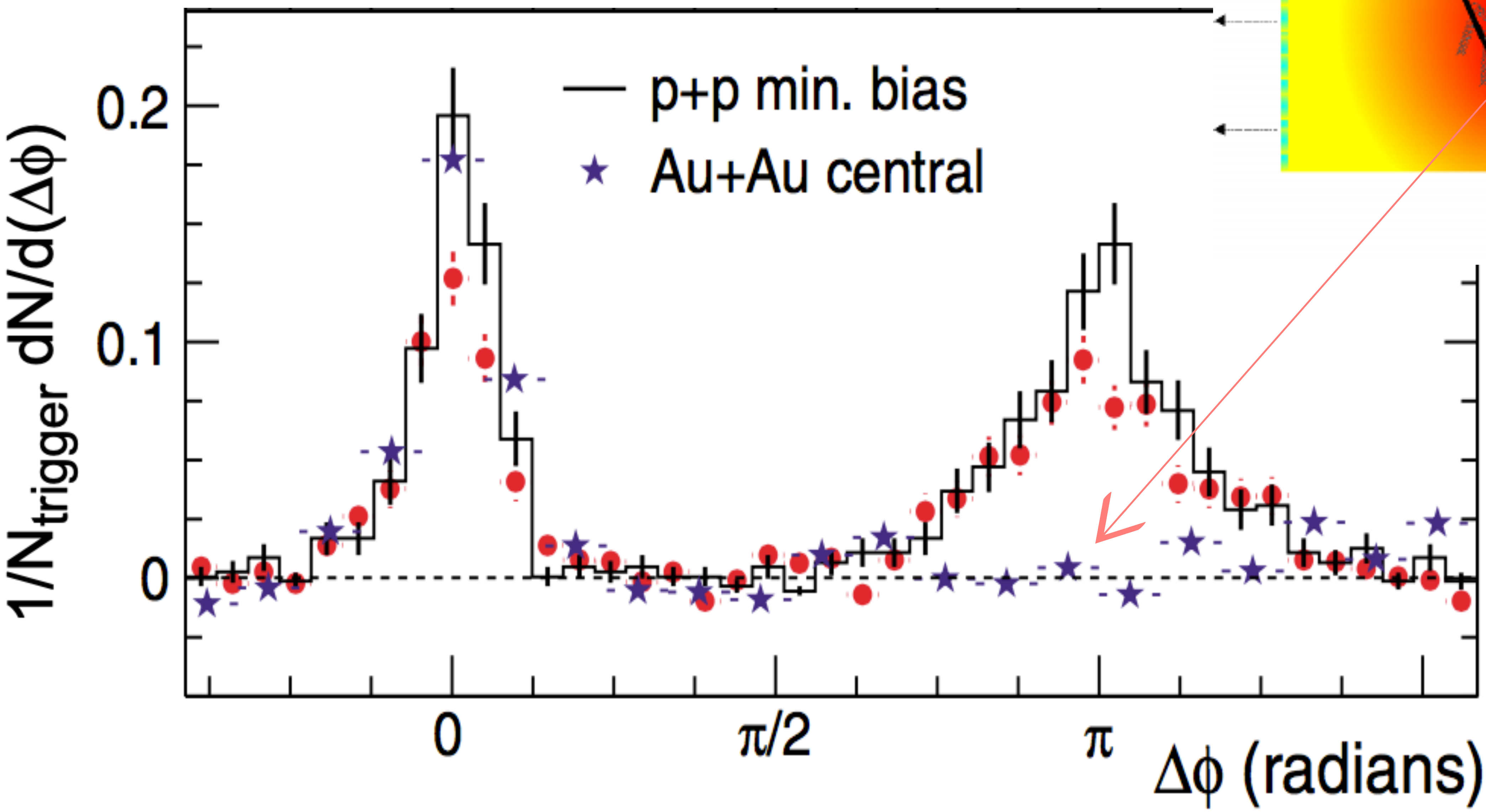
Radiative

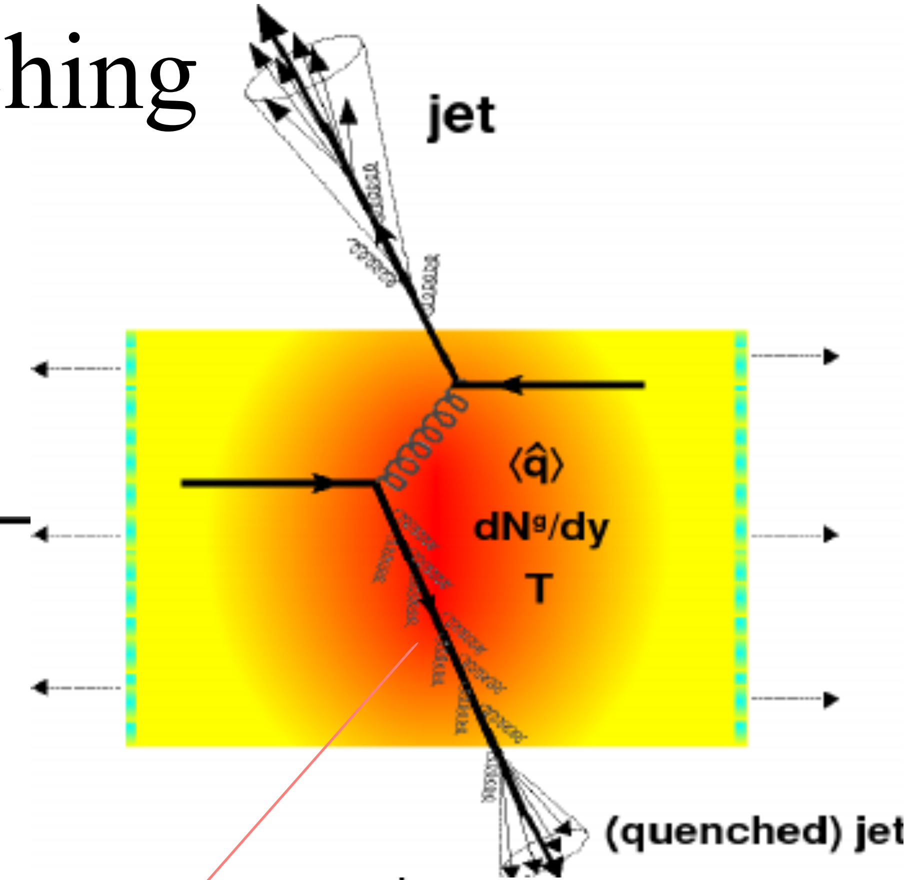


First evidence of jet-quenching

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

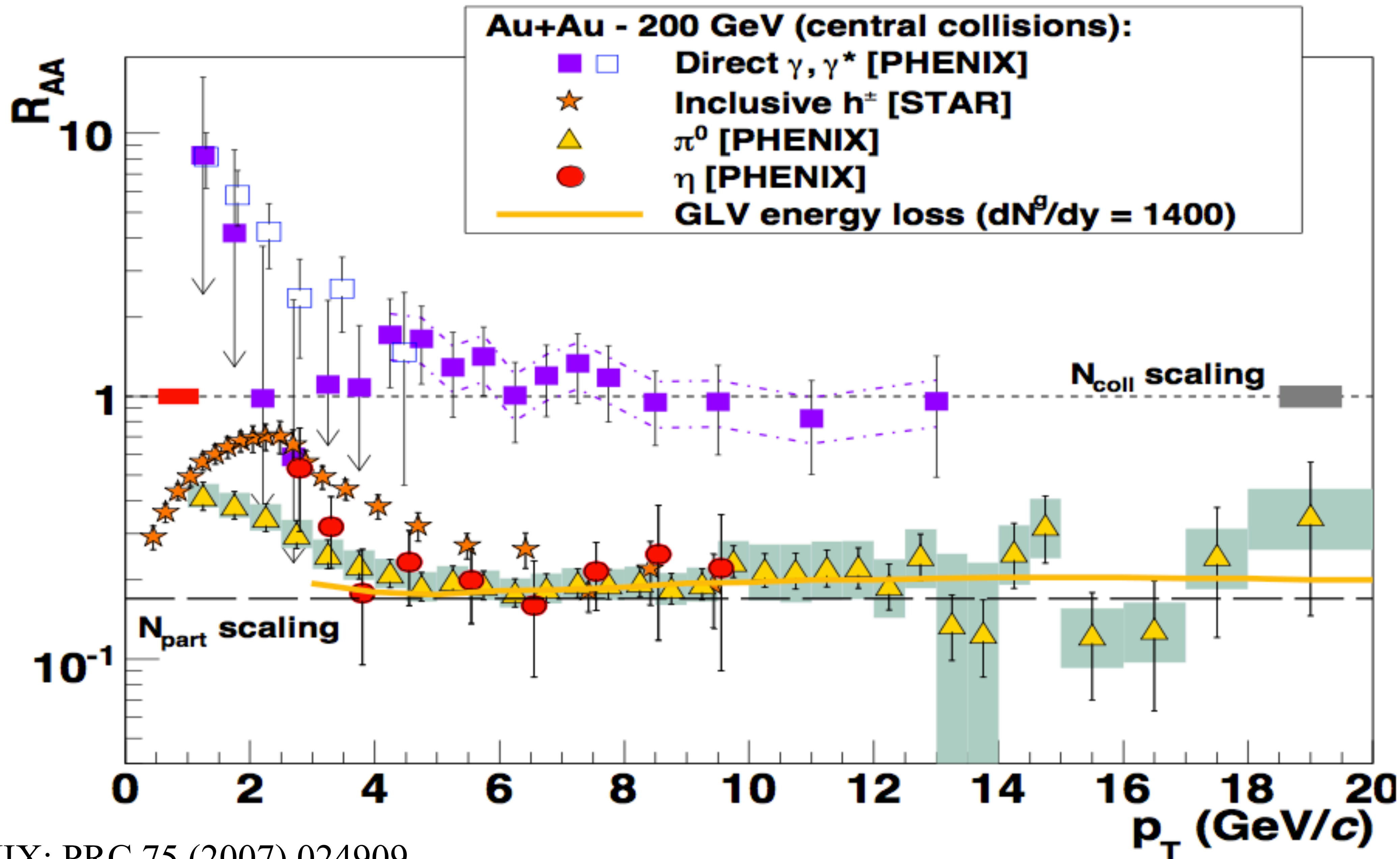
STAR: PRL 91, 072304 (2003)





Away-side jet suppression

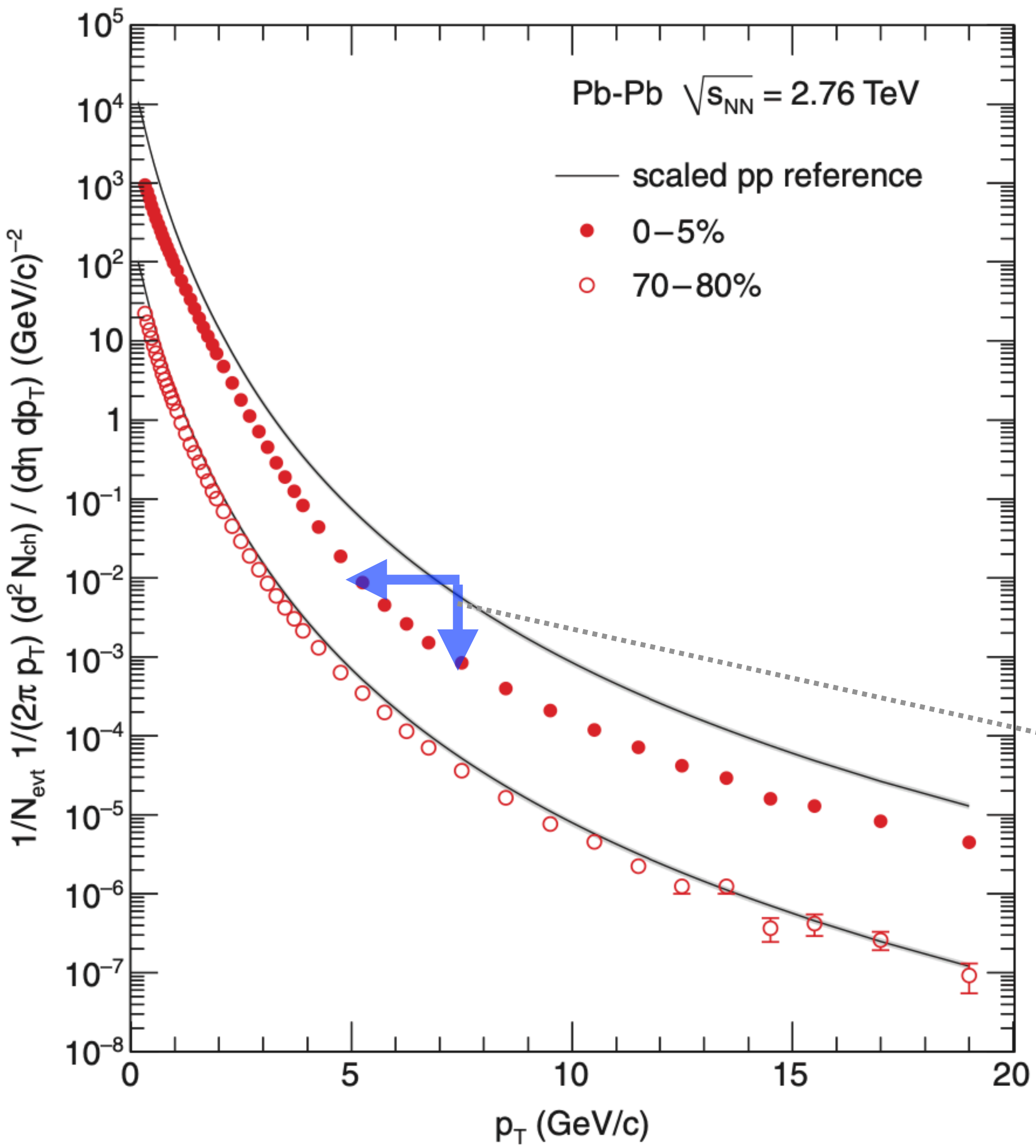
First evidence of jet-quenching



PHENIX: PRC 75 (2007) 024909

Let's understand first, what is R_{AA} ?

what is R_{AA} ?



Ansatz:

$$\frac{1}{T_{AA}}\frac{d^2N_{AA}}{dp_T d\eta} = \frac{d^2\sigma_{pp}}{dp_T d\eta}$$

Nuclear geometry

$$T_{AA} = \frac{<N_{\text{bin}}>}{\sigma_{\text{inel}}^{pp}}$$

$$R_{AA}(p_T) = \frac{\frac{d^2N}{dp_T d\eta}}{T_{AA}\frac{d^2\sigma^{pp}}{dp_T d\eta}}$$

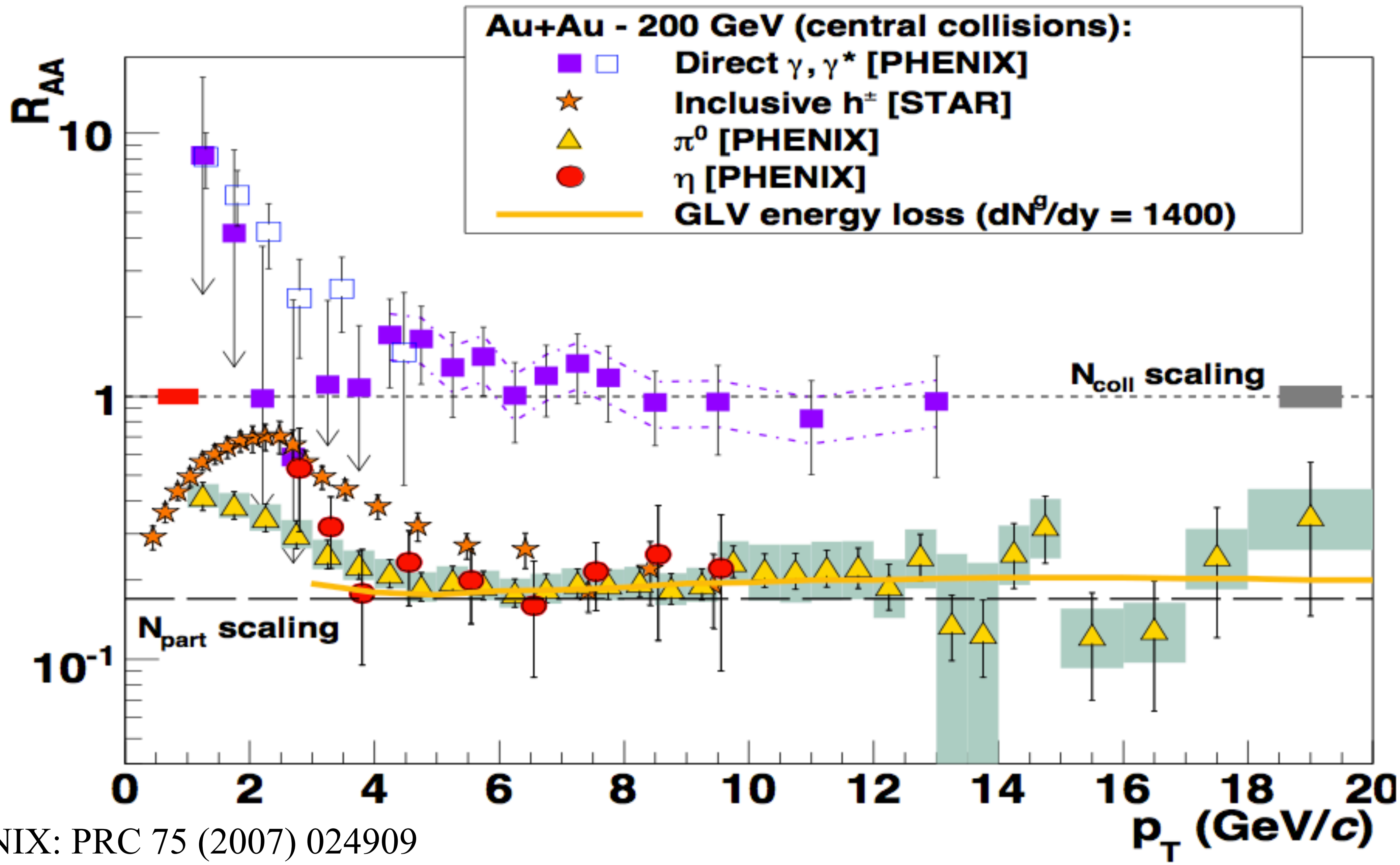
$R_{AA}(p_T) = 1 \rightarrow$ No medium effect

$> 1 \rightarrow$ Initial state effect

$< 1 \rightarrow$ Final state effect

- Initial state: shadowing, Cronin, gluon saturation
- Final state: hot-dense QCD medium

First evidence of jet-quenching



PHENIX: PRC 75 (2007) 024909

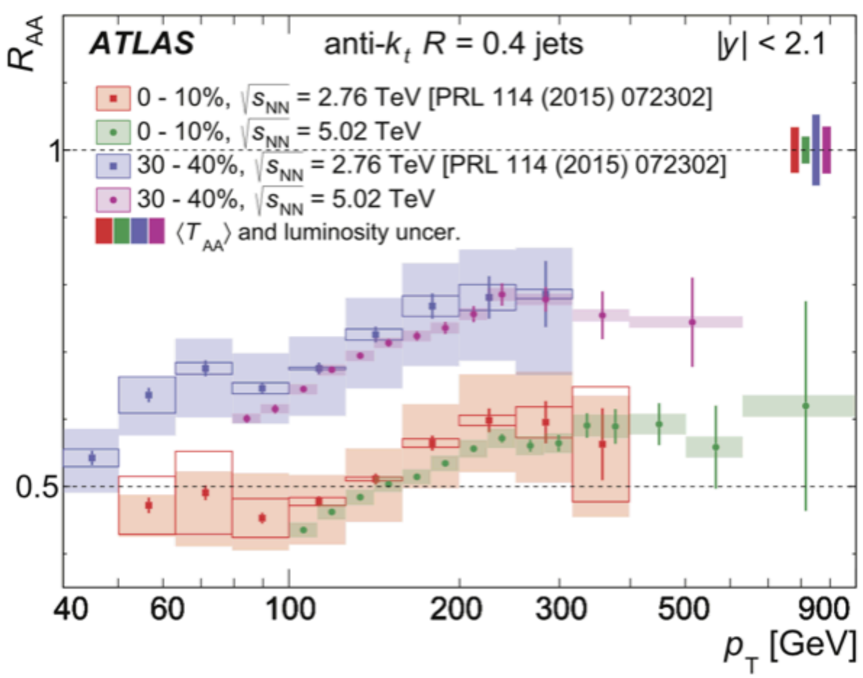
- Suppression of inclusive charged/neutral hadrons at high-p_T
- No suppression of vector boson (γ) $\rightarrow$ T_{AA} scaling holds

Evidence of jet-quenching at LHC

Inclusive jet measurement

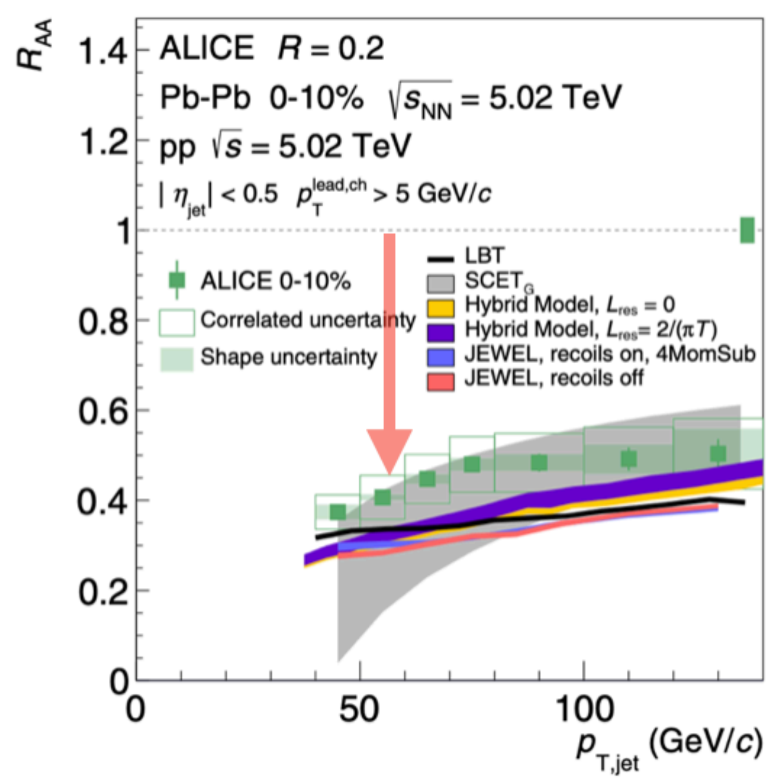
ATLAS

ATLAS: PLB 790 (2019)



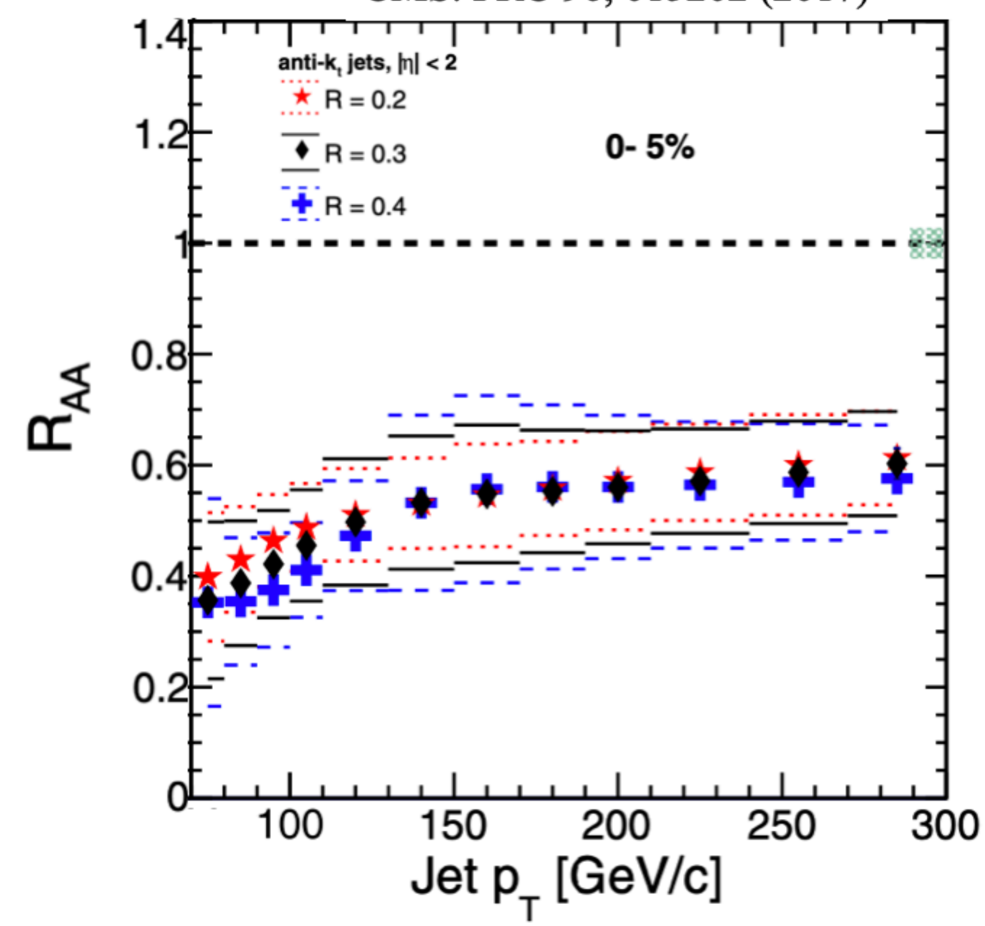
ALICE

ALICE: PRC 101, 034911 (2020)



CMS

CMS: PRC 96, 015202 (2017)



$$R_{AA}(p_{\mathrm{T,jet}}) = \frac{\dfrac{d^2N_{jet}}{dp_{\mathrm{T,jet}}d\eta}}{T_{AA}\dfrac{d^2\sigma^{pp}}{dp_{\mathrm{T,jet}}d\eta}}$$

Strong jet suppression at LHC

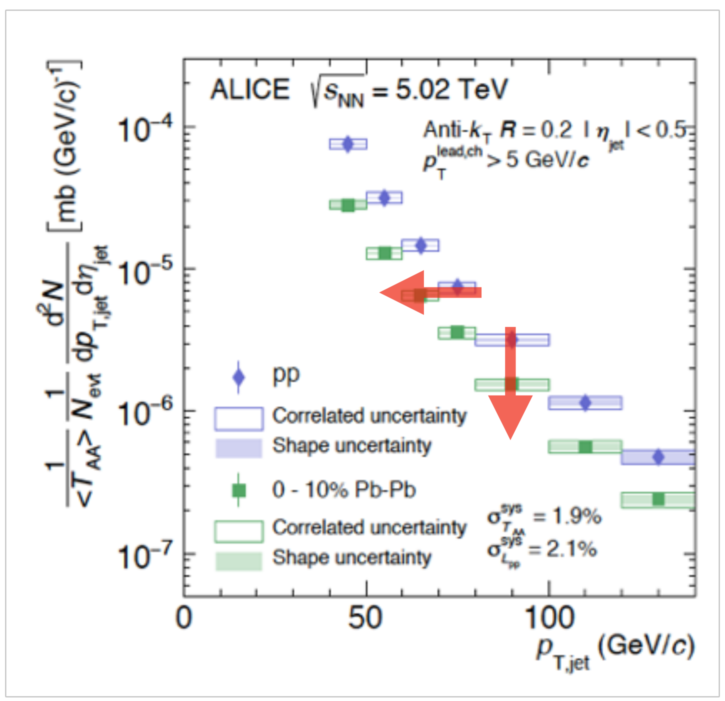
Unequivocal in observing jet-quenching in heavy-ion collisions

Signature of hot-dense QCD medium,
known as Quark-Gluon Plasma.

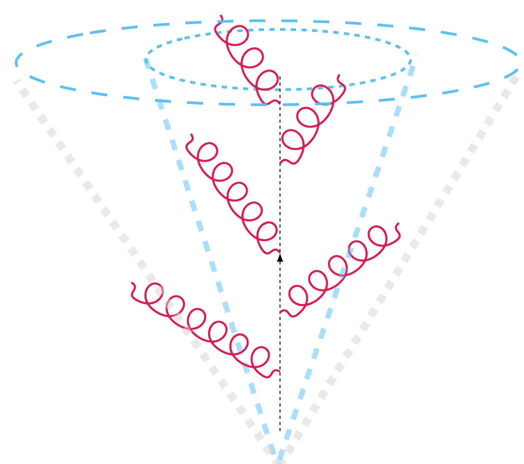
What are the consequences of jet-quenching?

Consequences of jet quenching

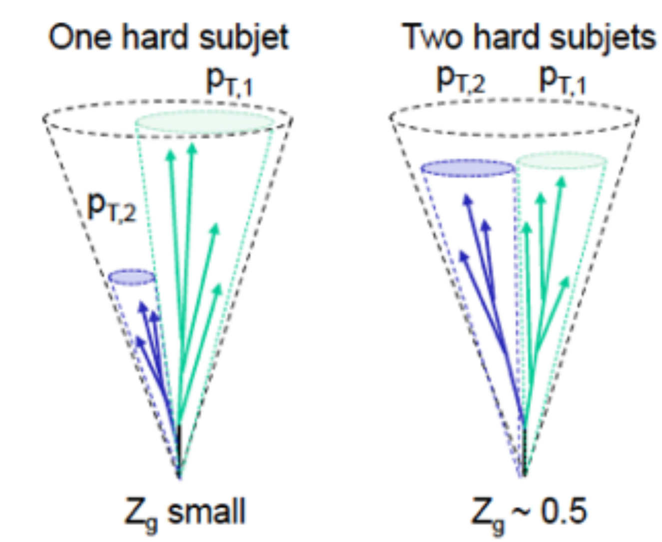
Energy loss



Jet shape

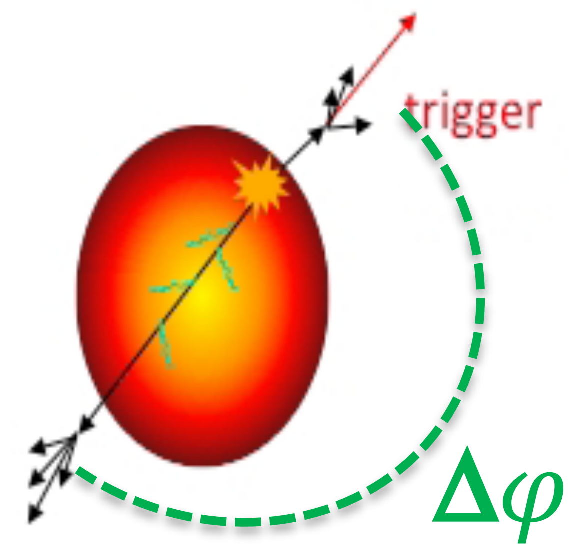


Modification of jet substructure



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

Jet deflection



Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

1. Jet energy loss
2. Jet shape modification
3. Jet substructure modification
4. Jet acoplanarity

Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

1. **Jet energy loss**
2. Jet shape modification
3. Jet substructure modification
4. Jet acoplanarity

Jet modifications: 1) energy loss

Measure of jet energy loss:

1) Nuclear modification factor: $R_{AA}\,(p_T)$ and $I_{AA}\,(p_T)$ [discussed already]

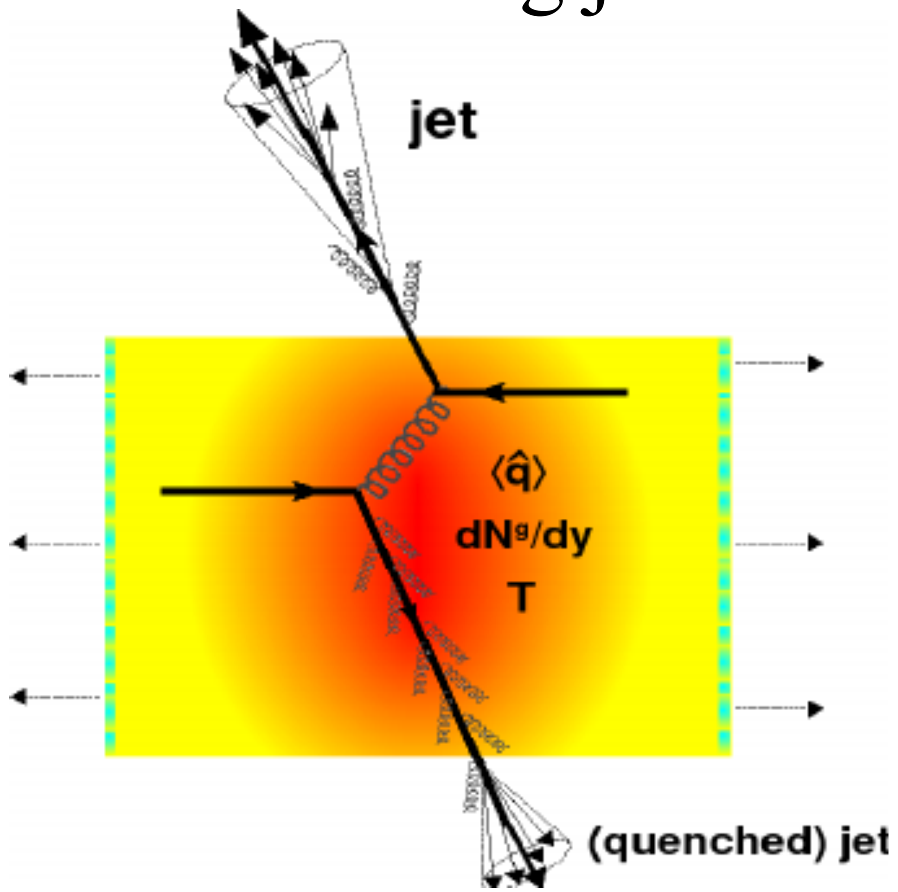
2) Jet imbalance:

$$A_J = \frac{p_{T,jet}^{Led} - p_{T,jet}^{SubLed}}{p_{T,jet}^{Led} + p_{T,jet}^{SubLed}}$$

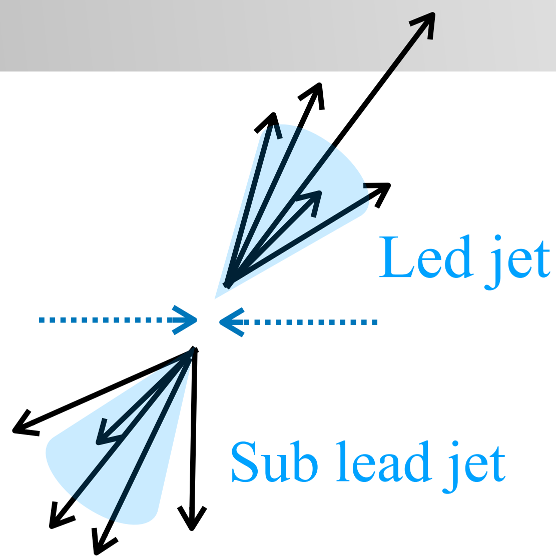
Or,

$$x_J = \frac{p_{T,jet}^{recoil}}{p_{T,jet}^{Trg}}$$

Leading jet



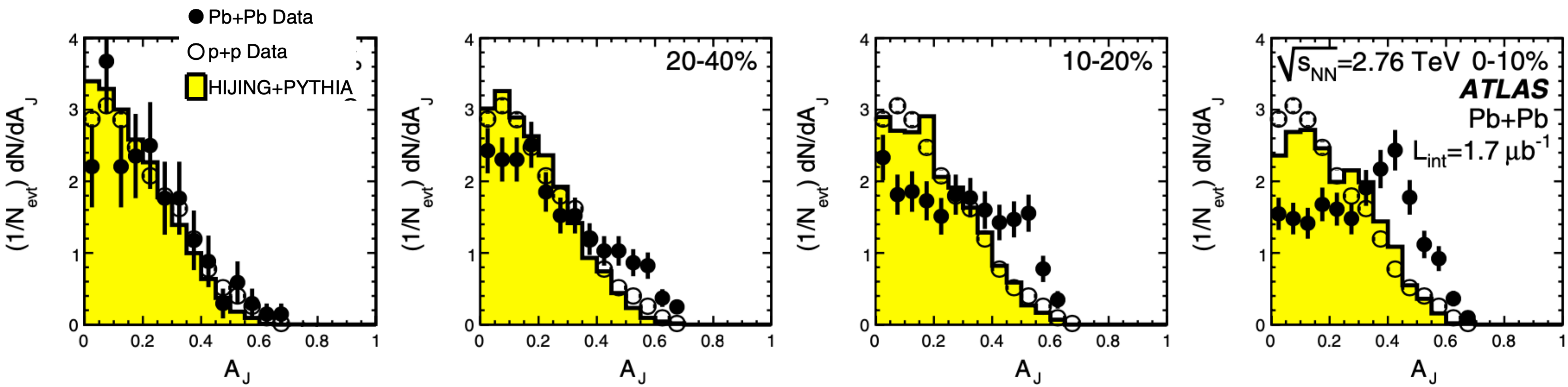
Sub-leading jet



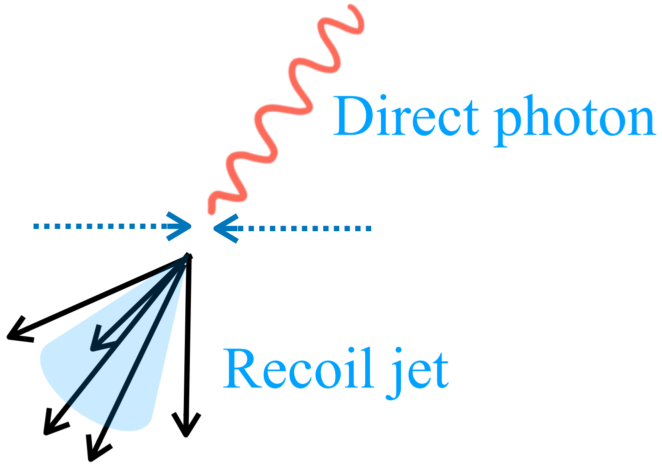
ATLAS: PRL 105, 252303 (2010)

Dijet imbalance at LHC

$$A_J = \frac{p_{T,jet}^{Led} - p_{T,jet}^{SubLed}}{p_{T,jet}^{Led} + p_{T,jet}^{SubLed}}$$



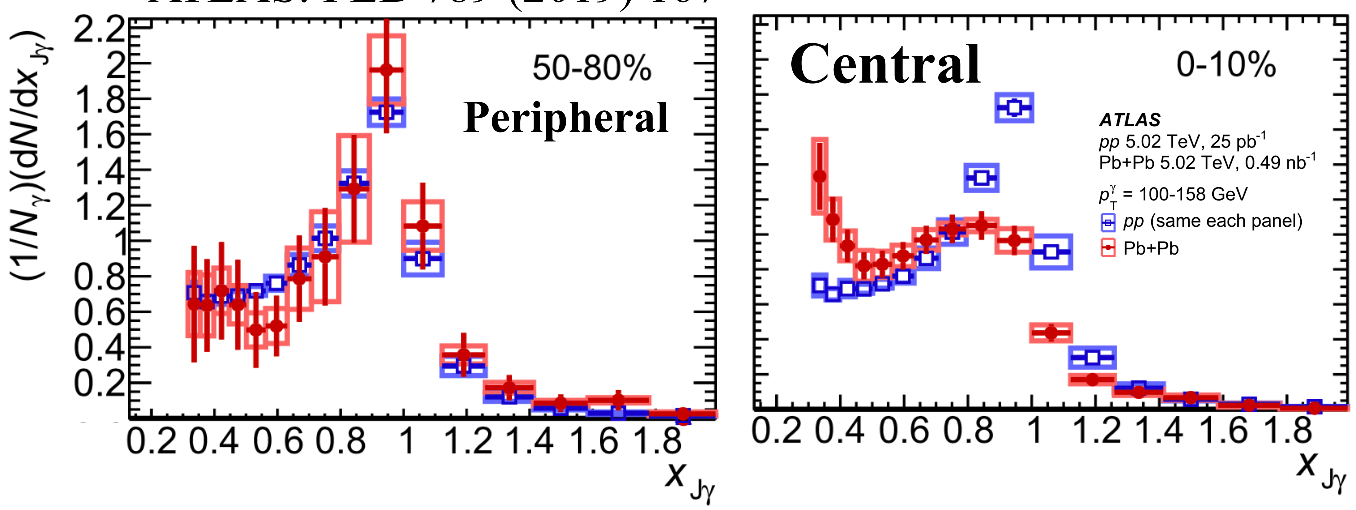
Jet modifications: 1) energy loss



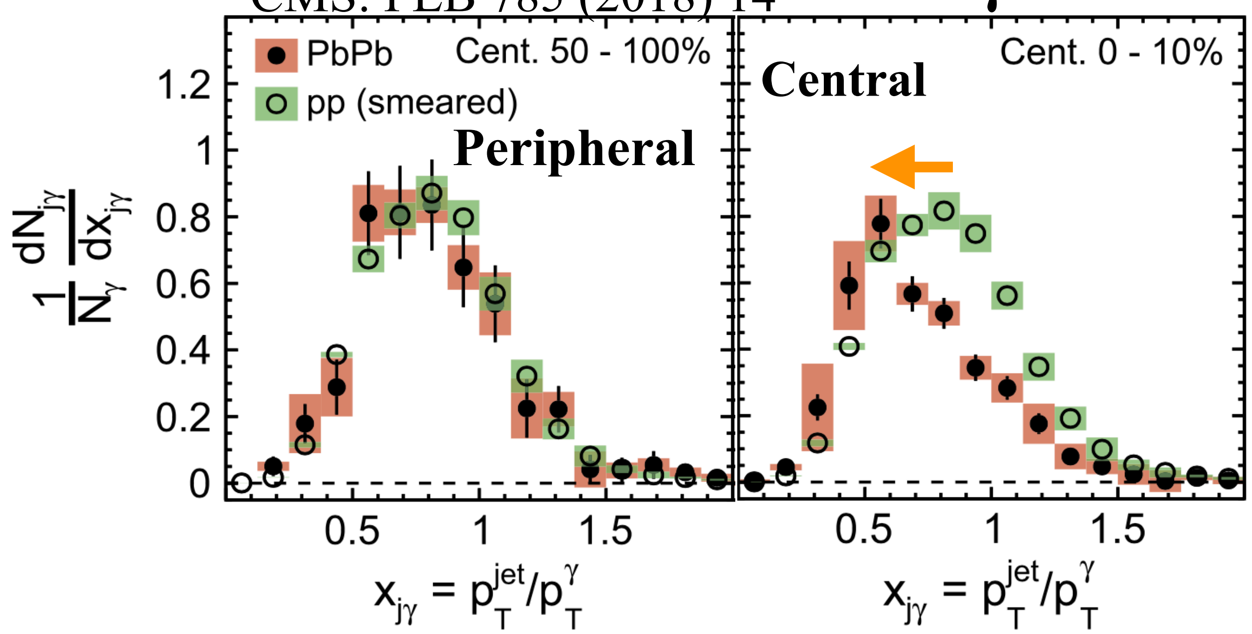
γ+jet imbalance at LHC

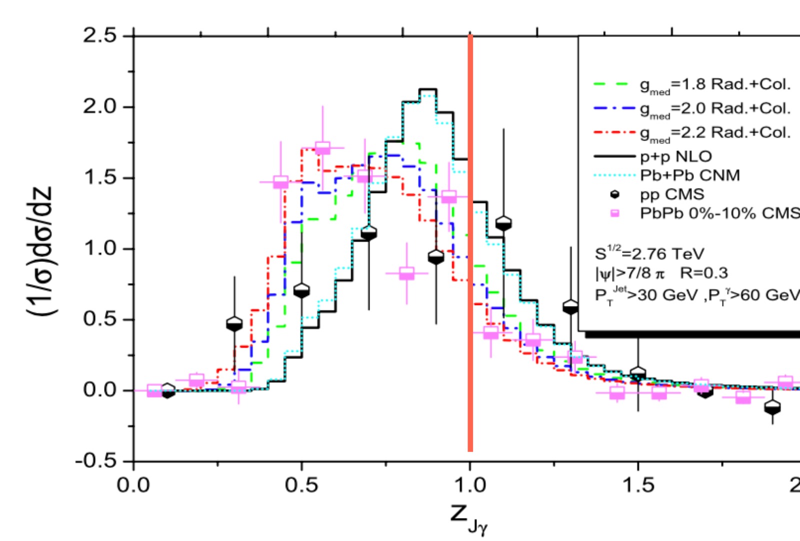
$$x_J = \frac{p_{T,jet}^{recoil}}{p_{T,jet}^{Trg}}$$

ATLAS: PLB 789 (2019) 167



CMS: PLB 785 (2018) 14





[Dai, Vitev, and Zhang, PRL 110, 142001 (2013)]

In p+p, $x_{j\gamma}$ is approximately unity (NLO effects)

In Pb+Pb, $x_{j\gamma}$ is asymmetry in central collisions

strong asymmetry in PbPb relative to pp events

Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

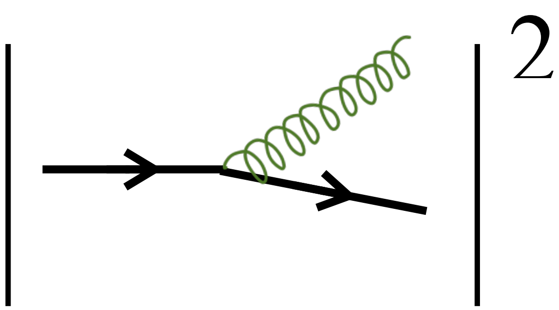
1. **Jet energy loss**
2. Jet shape modification
3. Jet substructure modification
4. Jet acoplanarity

Color factor
and
path length
dependence, etc.

Color factor dependence of energy loss

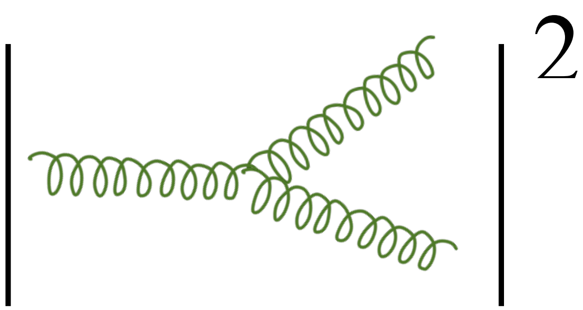
What is Color (Casimir) factor?

$$C(ik \to jl) \equiv \frac{1}{4} \sum_{a=1}^{8} \lambda_{ji}^{a} \lambda_{lk}^{a}$$



$q \to qg$

$\sim C_F = \frac{4}{3}$



$g \to gg$

$\sim C_A = 3$

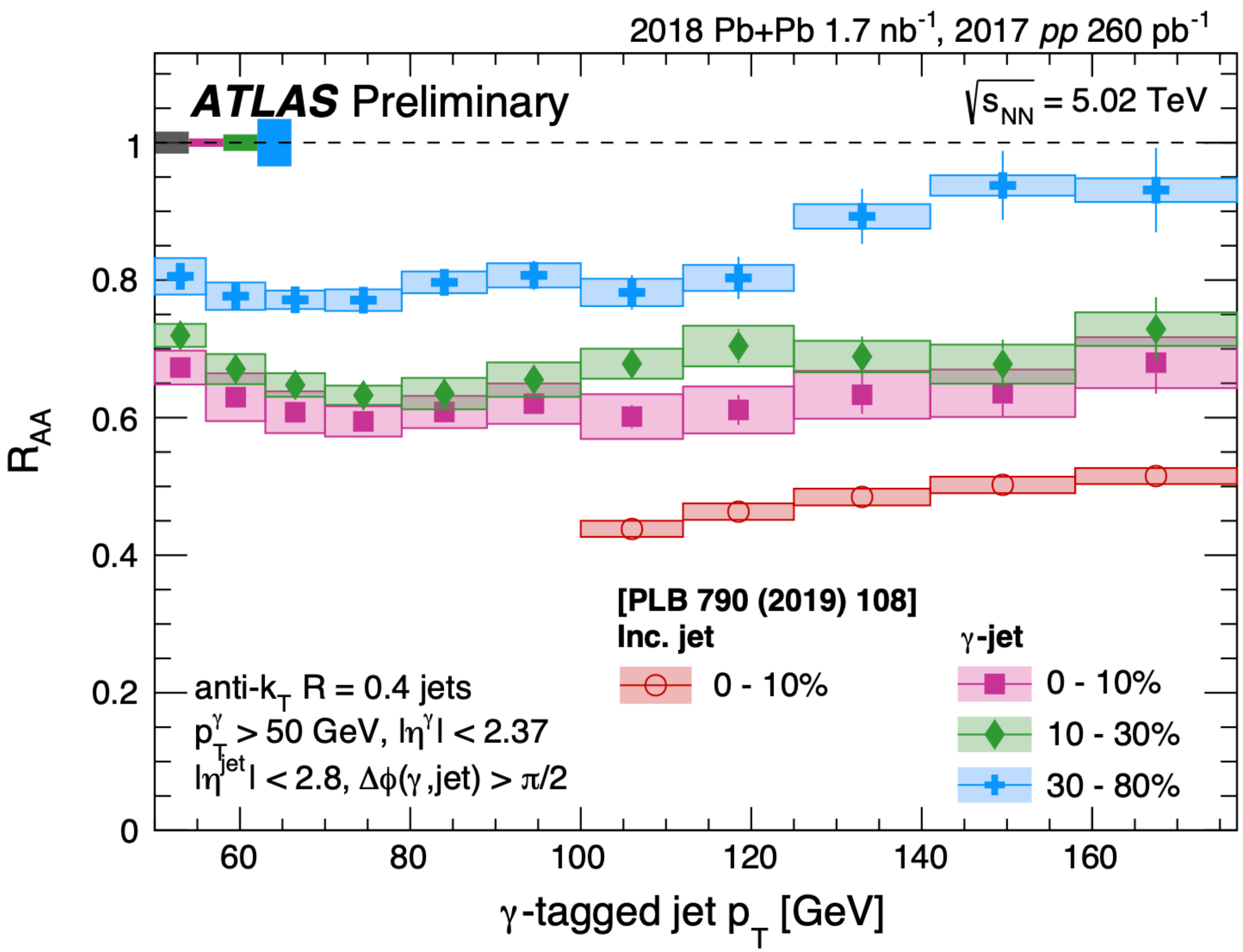
Probability of radiating gluon
by a gluon over a quark

$$\frac{C_A}{C_F} = \frac{9}{4}$$

Jet originated by gluon loses more energy than that by quark
→ gluon originated jet suppressed more than quark jet

Color factor dependence of energy loss

Inclusive jet vs γ+jet in Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV



Inclusive jet:

- Combination of both q- and g-originated jets
- But at LHC, g-jet dominates

For example: $q+q \rightarrow q+q$

$q+g \rightarrow q+g$

$g+g \rightarrow g+g$

γ+jet:

- Dominating process: QCD Compton

$q+g \rightarrow q+\gamma$

$q+\bar{q} \rightarrow g+\gamma$

ATLAS preliminary results show inclusive jets strongly suppressed relative to γ+jet

Detailed study ongoing in other experiments (RHIC/LHC)…

Consequences of jet quenching

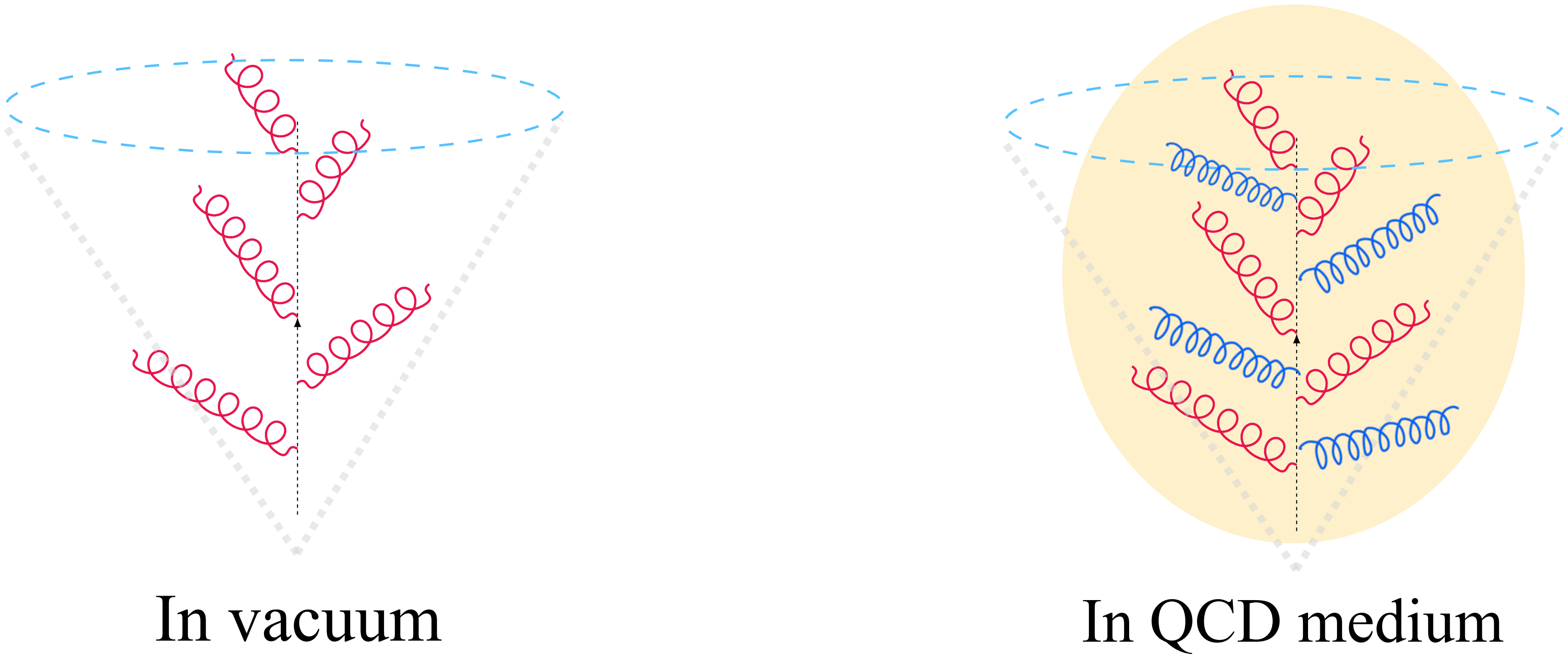
Experimental evidence at RHIC and LHC

Jet quenching consequences:

1. Jet energy loss
2. **Jet shape modification**
3. Jet substructure modification
4. Jet acoplanarity

Jet modifications: 1) Jet shape

Modification of jet internal structure due to medium-induced radiations

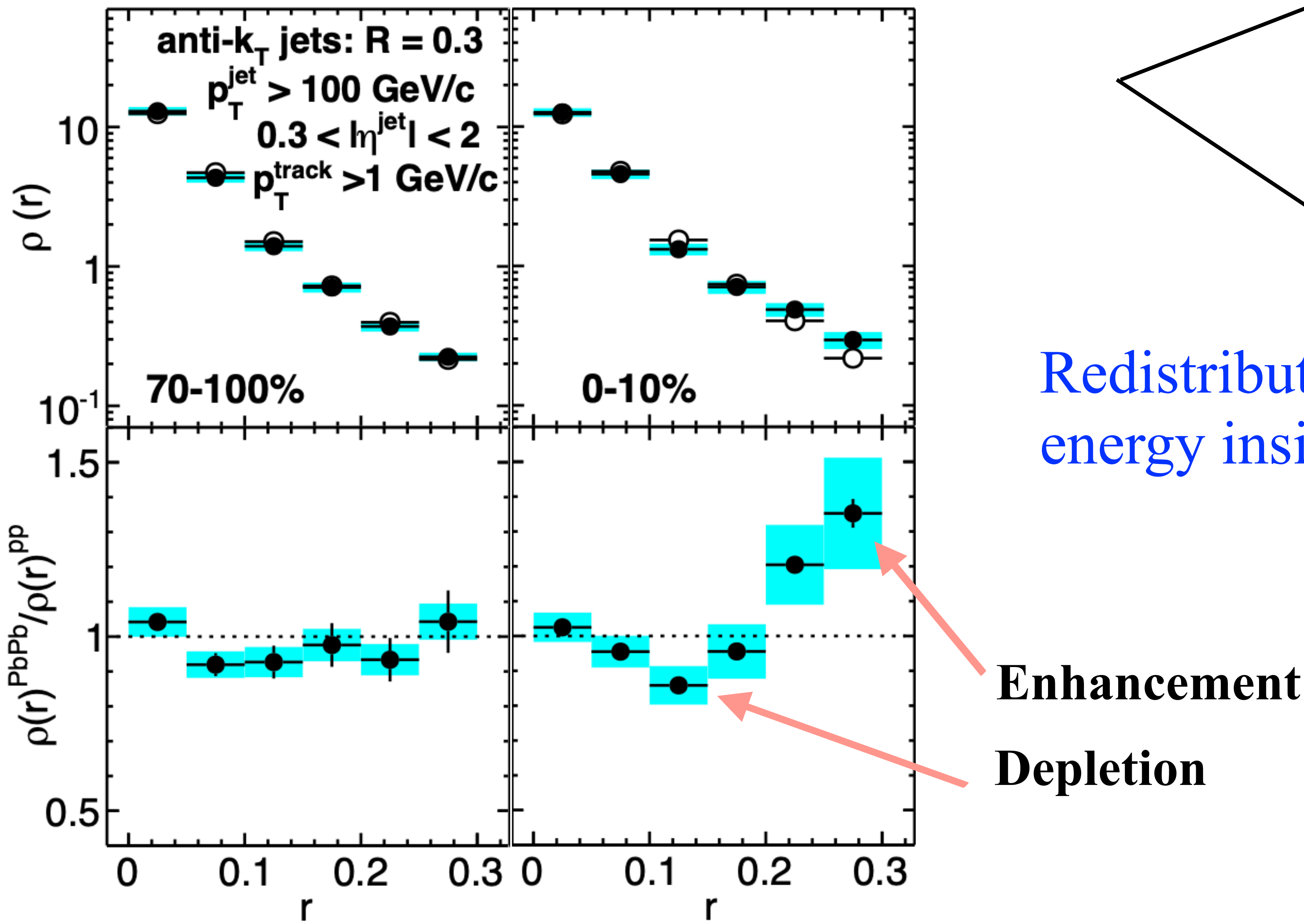


Jet shape observables:

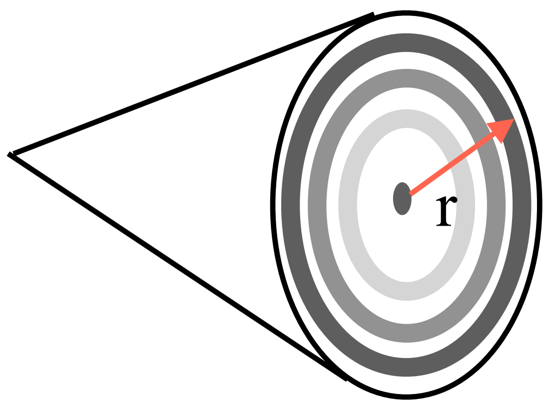
1) jet radial profile $\rho(r)$
2) Intra-jet broadening

Modification inside a jet

PbPb $\sqrt{s_{NN}}$ = 2.76 TeV



$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\in[r_a,\, r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$

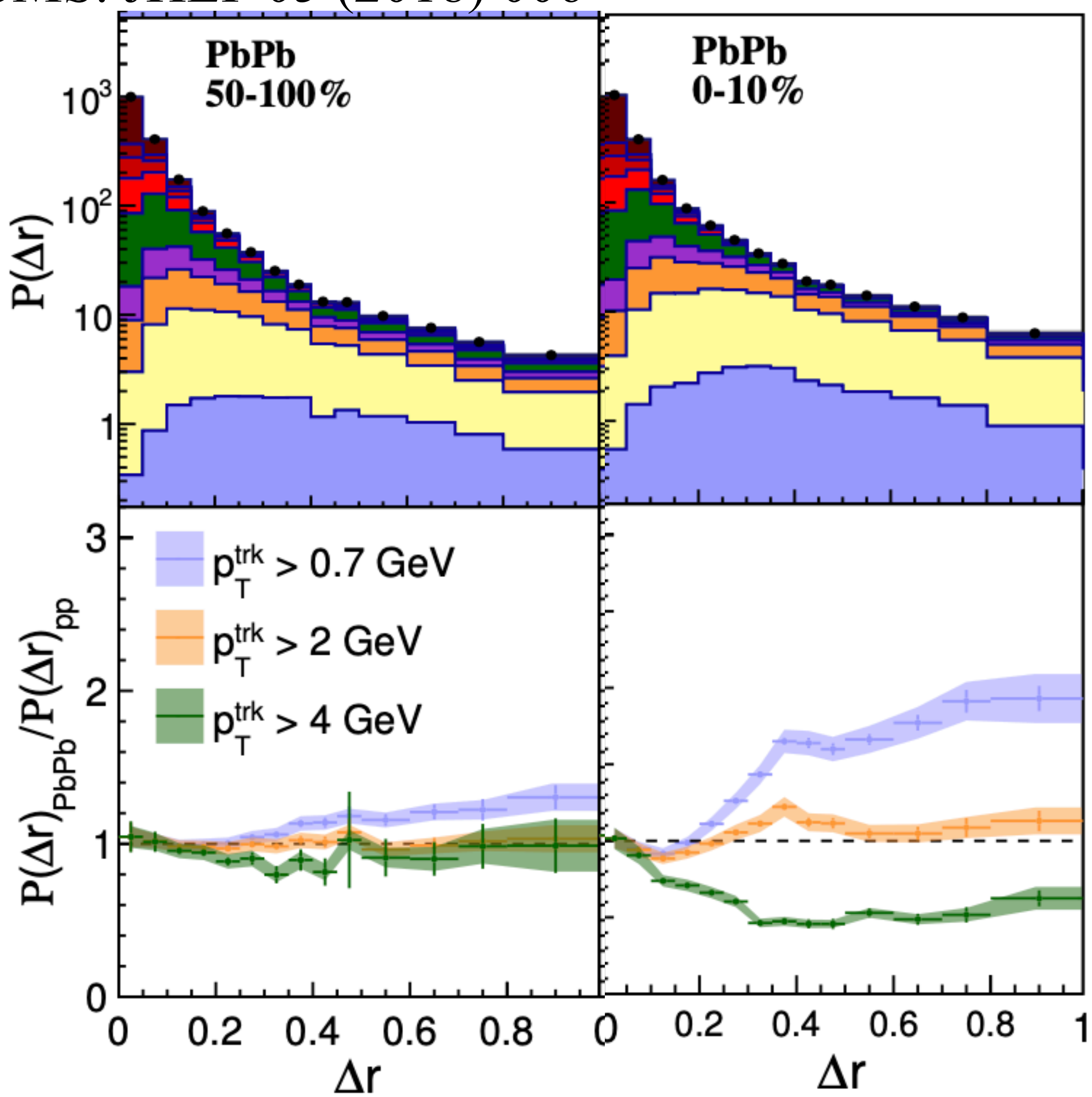


Redistribution of jet energy inside the cone

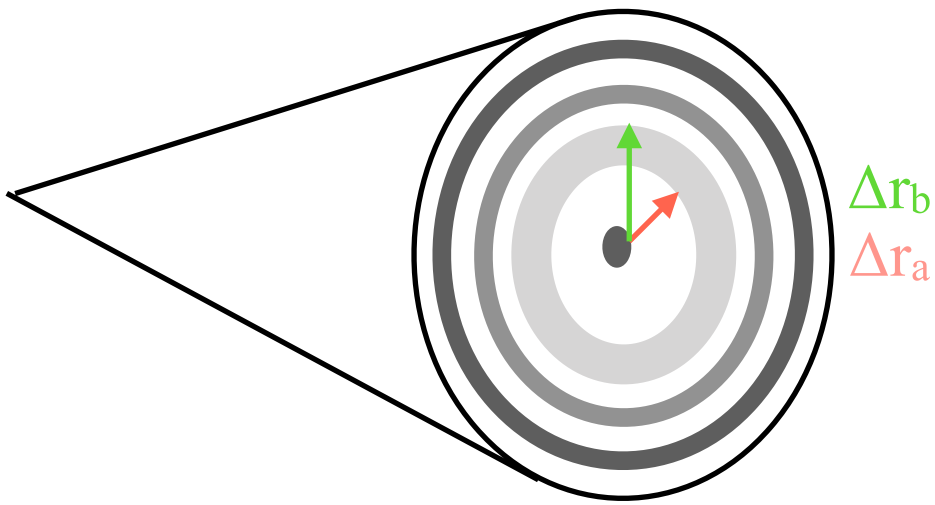
Modification inside a jet

PbPb $\sqrt{s_{NN}}$ = 5.02 TeV

CMS: JHEP 05 (2018) 006



transverse momentum profile



$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\Sigma_{tracks\in(\Delta r_a,\Delta r_b)}p_T^{trk},\ \Delta r < 1$$

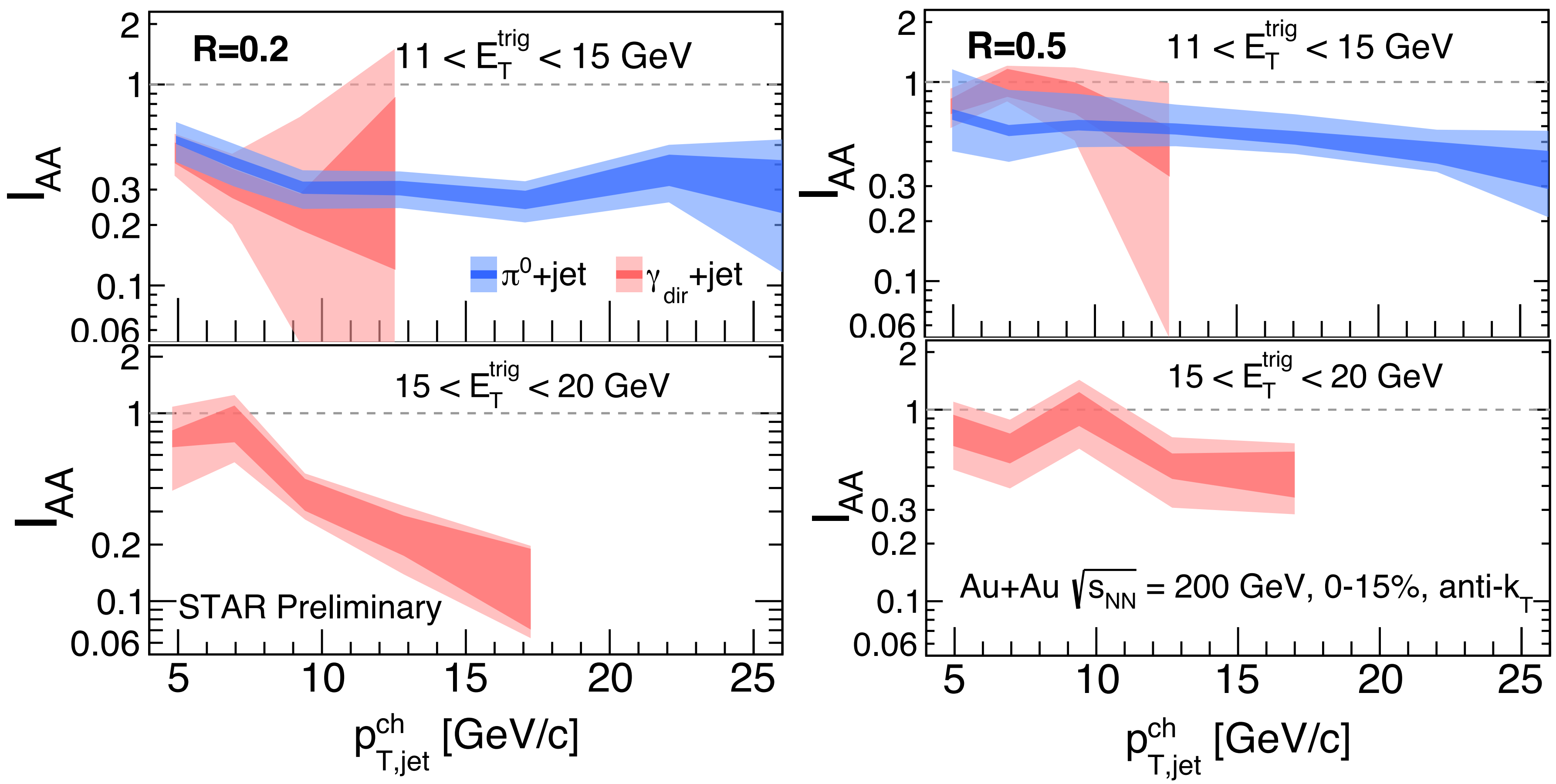
Enhancement of low-pT

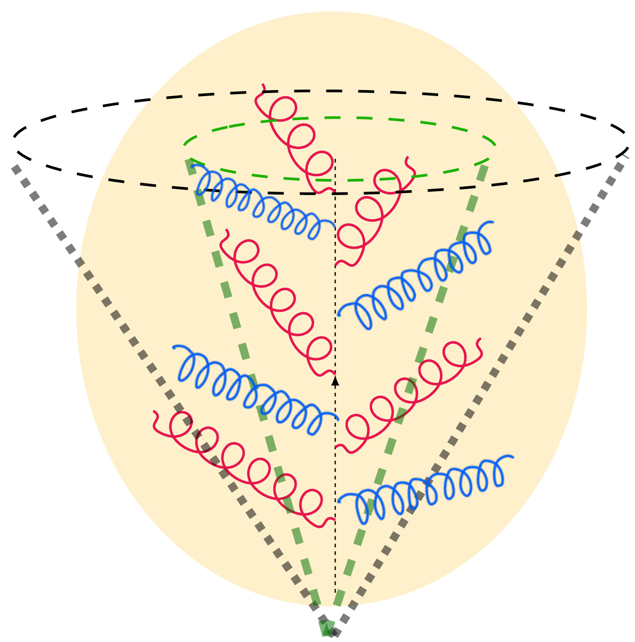
Depletion of high-pT

Modification of jet internal structure due to medium-induced radiations

Do we need larger jet R to contain energy loss?

RHIC/STAR : AuAu $\sqrt{s_{NN}}$ = 200 GeV





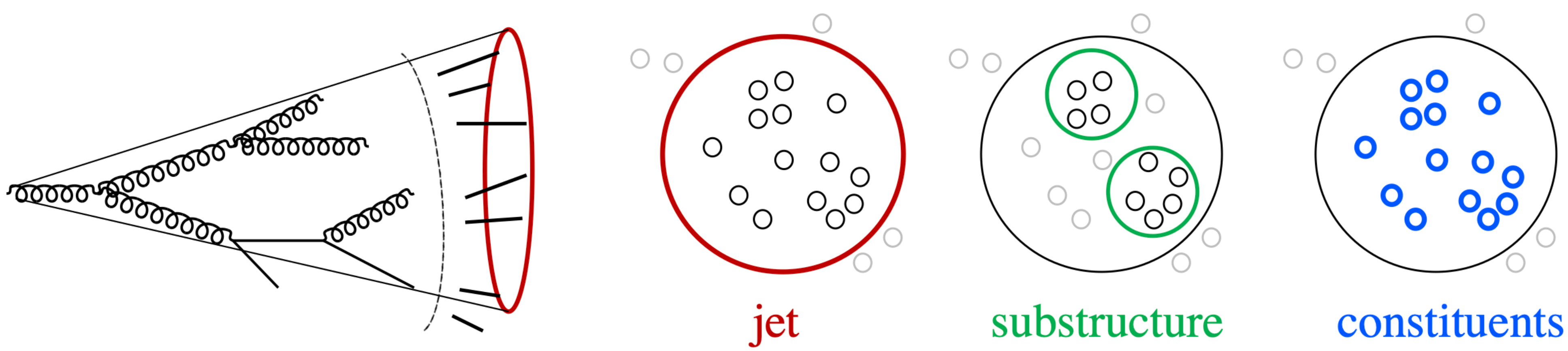
In QCD medium

Smaller R jet strongly suppressed than larger R

Experimental evidence at RHIC and LHC

Jet quenching consequences:

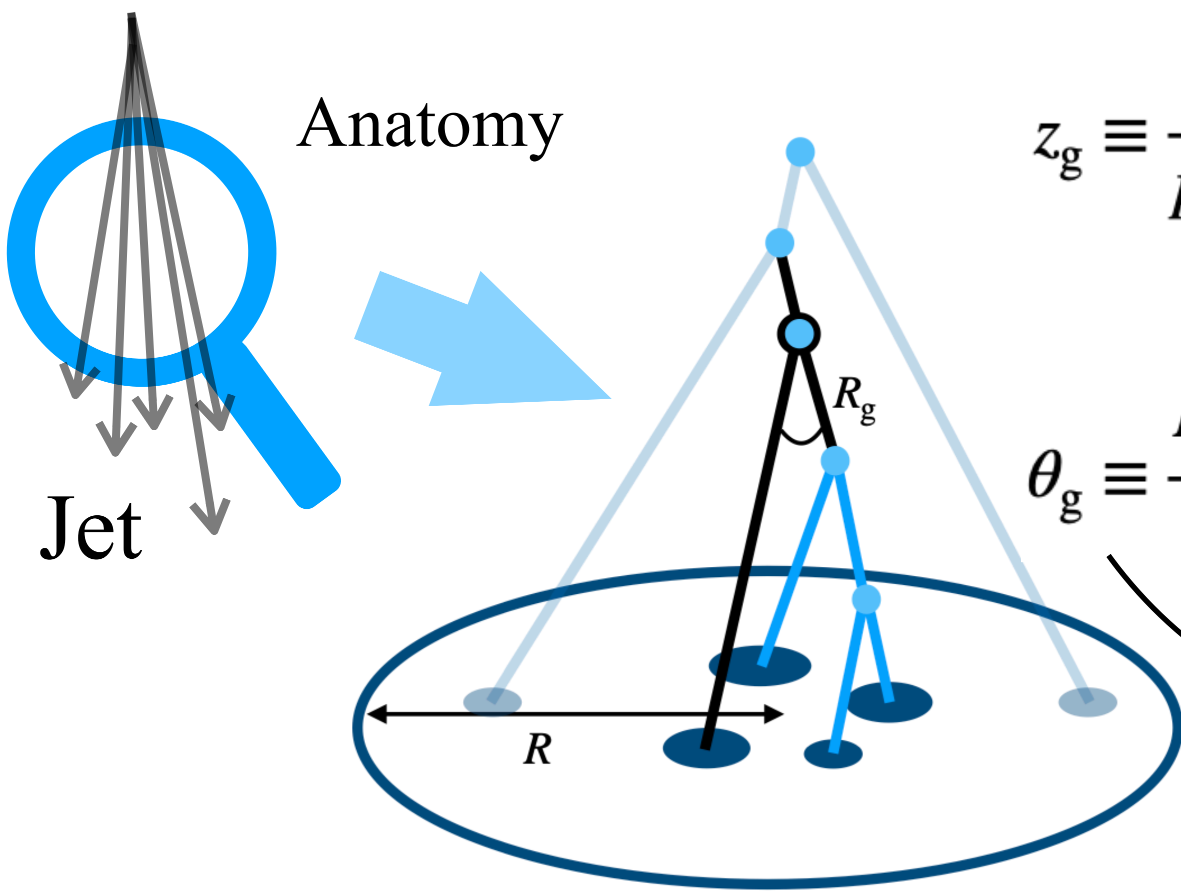
1. Jet energy loss
2. Jet shape modification
3. **Jet substructure modification**
4. Jet acoplanarity



Graphic: Yi Chen QM'19

SoftDrop grooming technique

- First apply anti-k$_T$ algorithm
- Recluster constituent of the jet using C/A algorithm (angular ordering)
- Select the splitting with condition $z > z_{\text{cut}}\theta^{\beta}$



Two kinematic observables

$$z_g \equiv \frac{p_{\text{T,subleading}}}{p_{\text{T,leading}} + p_{\text{T,subleading}}}$$

Groomed momentum fraction

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

Groomed jet radius

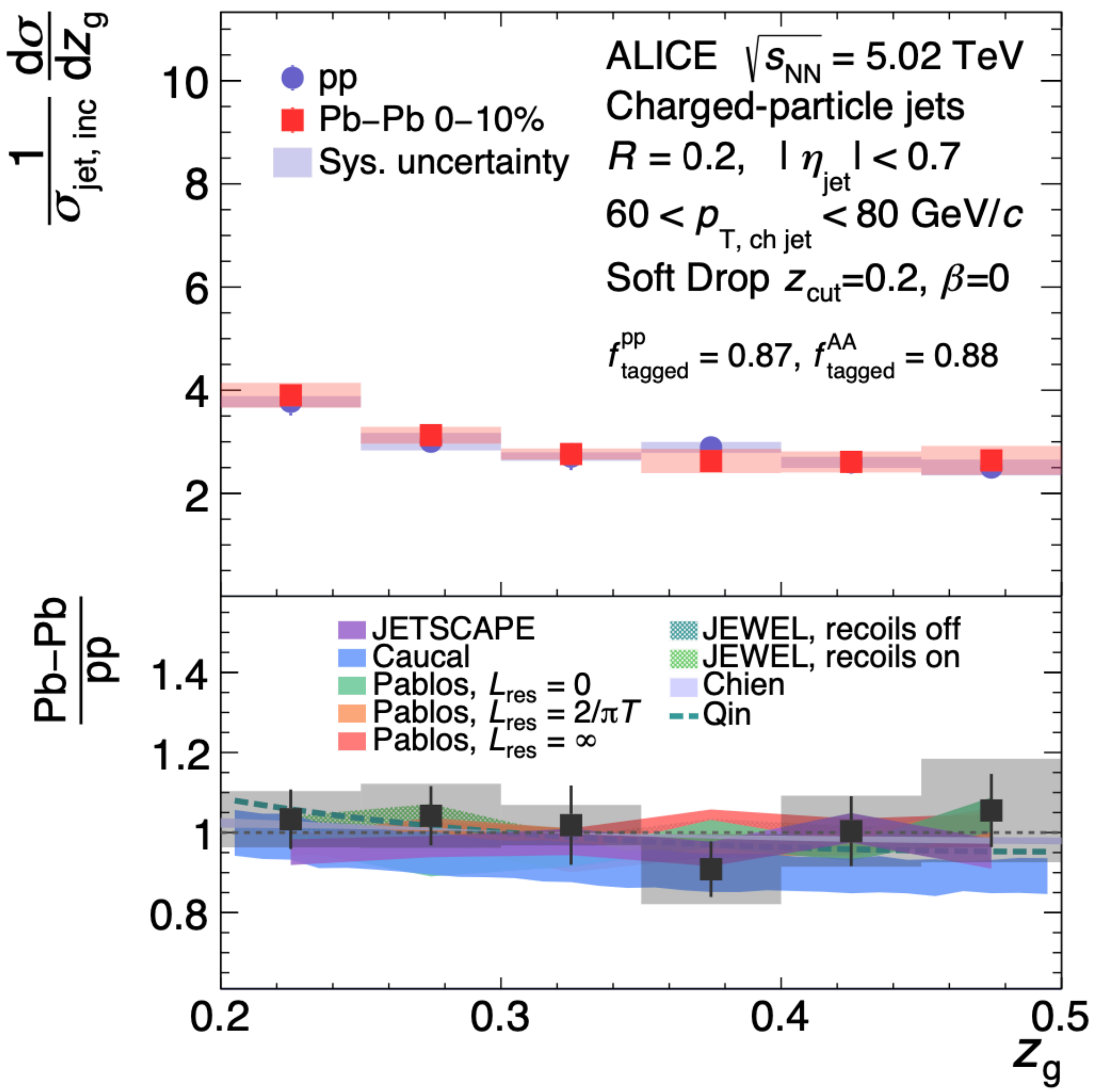
Formation time of splitting

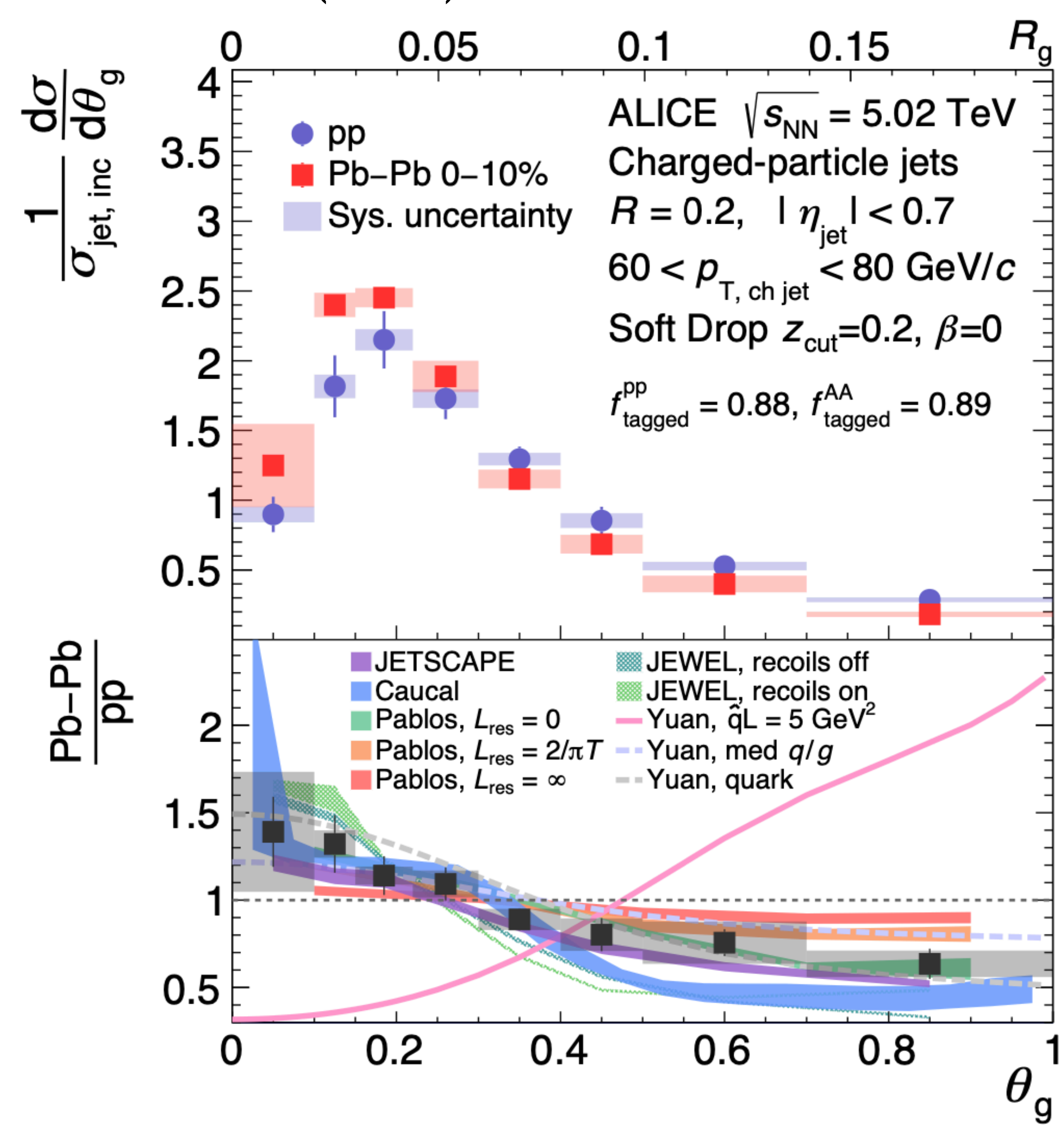
$$t_f \sim \frac{1}{\theta_g^2}$$

Measuring these observables, jet quenching mechanism can be well understood

Jet modifications: 3) Jet substructure

ALICE: PRL 128 (2022) 102001





z_g : No modification observed

θ_g : Modification observed in PbPb w.r.t pp

→ θ_g dist. narrower in PbPb than in pp

→ Modification of angular scale of groomed jet in the medium

Jet modifications: 3) Jet substructure

Many measurements are ongoing at RHIC and LHC in this direction

Other jet substructure observables are:

- Jet Mass: Both groomed and ungroomed jet mass
    - Ungroomed Jet mass: $M = |\sum_{i \in \text{jet}} p_i|$
    - Groomed jet mass: $M_g = |\sum_{i \in \text{jet}} p_g|$
- Jet charge (p_T-weighted sum) $Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_i Q_i (p_T^i)^\kappa$

For such measurement pp baseline is important for heavy-ion collisions

Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

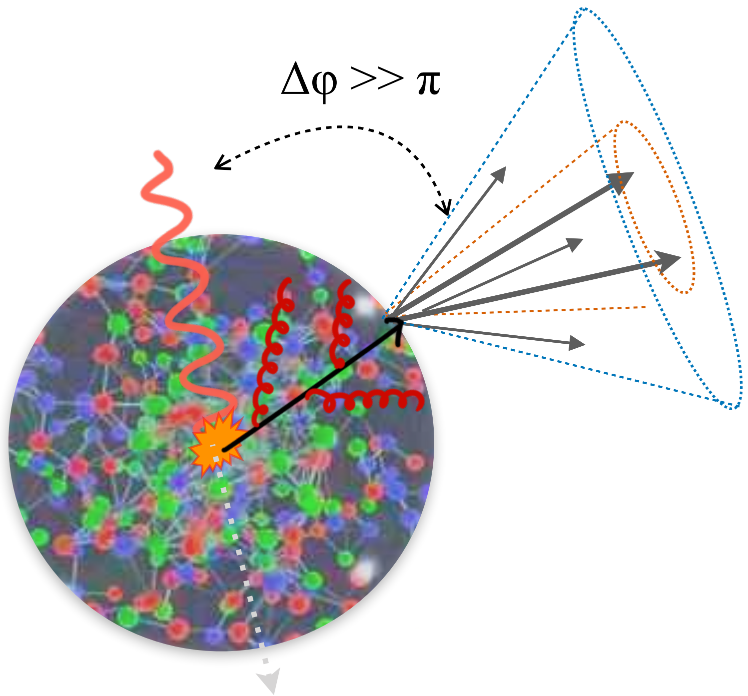
1. Jet energy loss
2. Jet shape modification
3. Jet substructure modification
4. **Jet acoplanarity**

Physics mechanisms for jet acoplanarity in heavy-ion collisions

- Rutherford Scattering: Energetic parton resolves microstructure of QGP

  Large-angle deflection of hard partons off quasi-particles

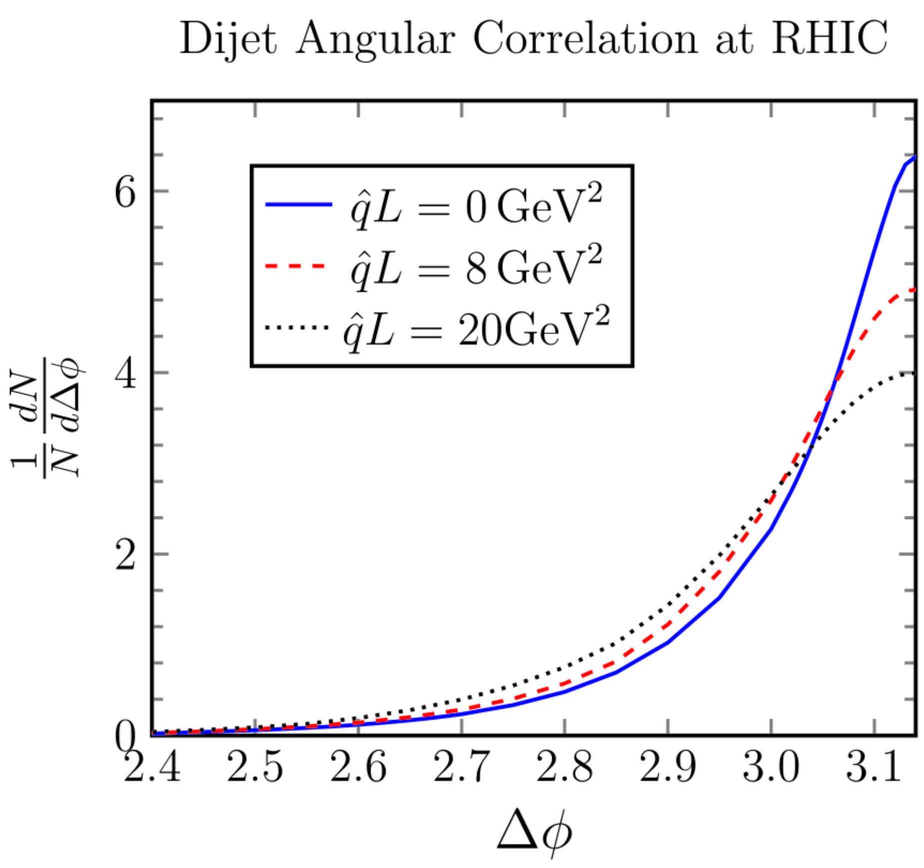
  D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172;
  D'Eramo, et. All, JHEP 05 (2013) 031



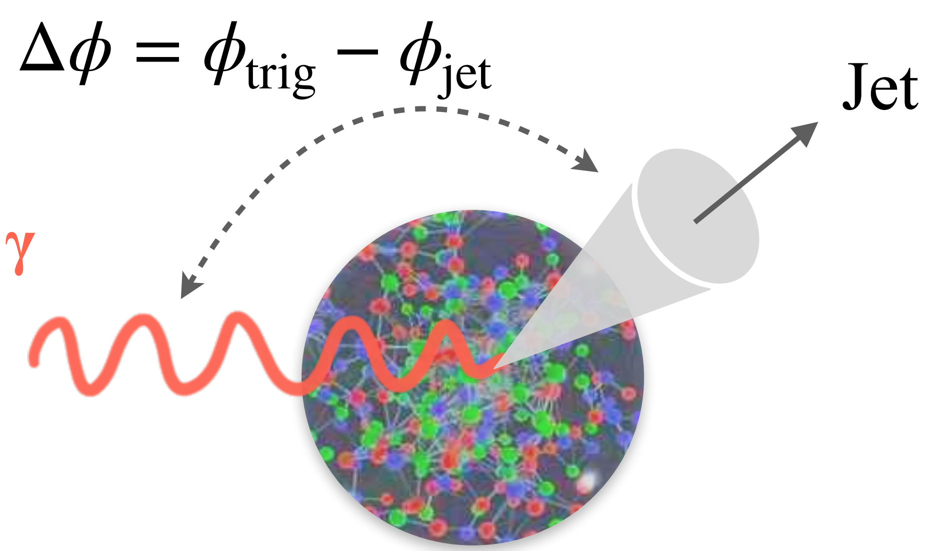
- Vacuum soft gluon radiation

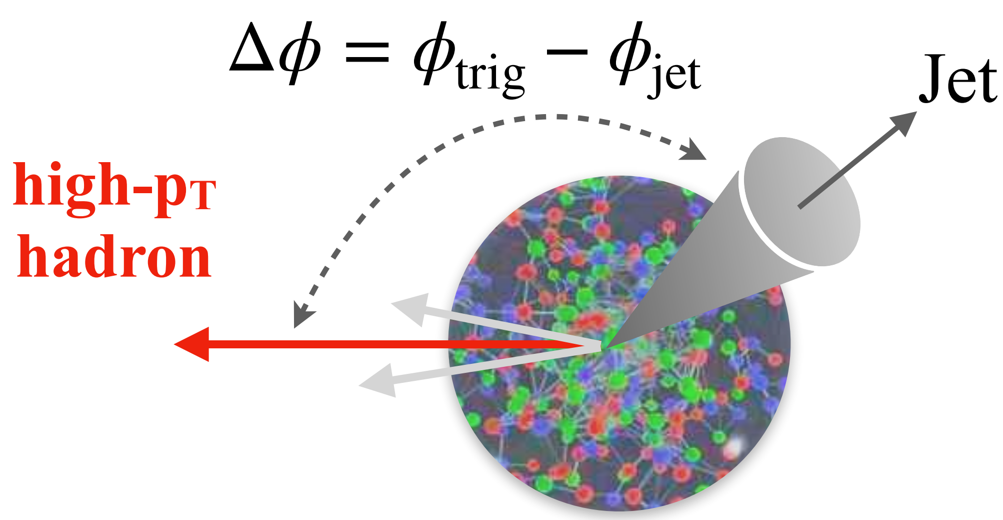
- Medium effect: multiple scattering and medium induced gluon radiation

A. Mueller et al, PLB 763 (2016) 208

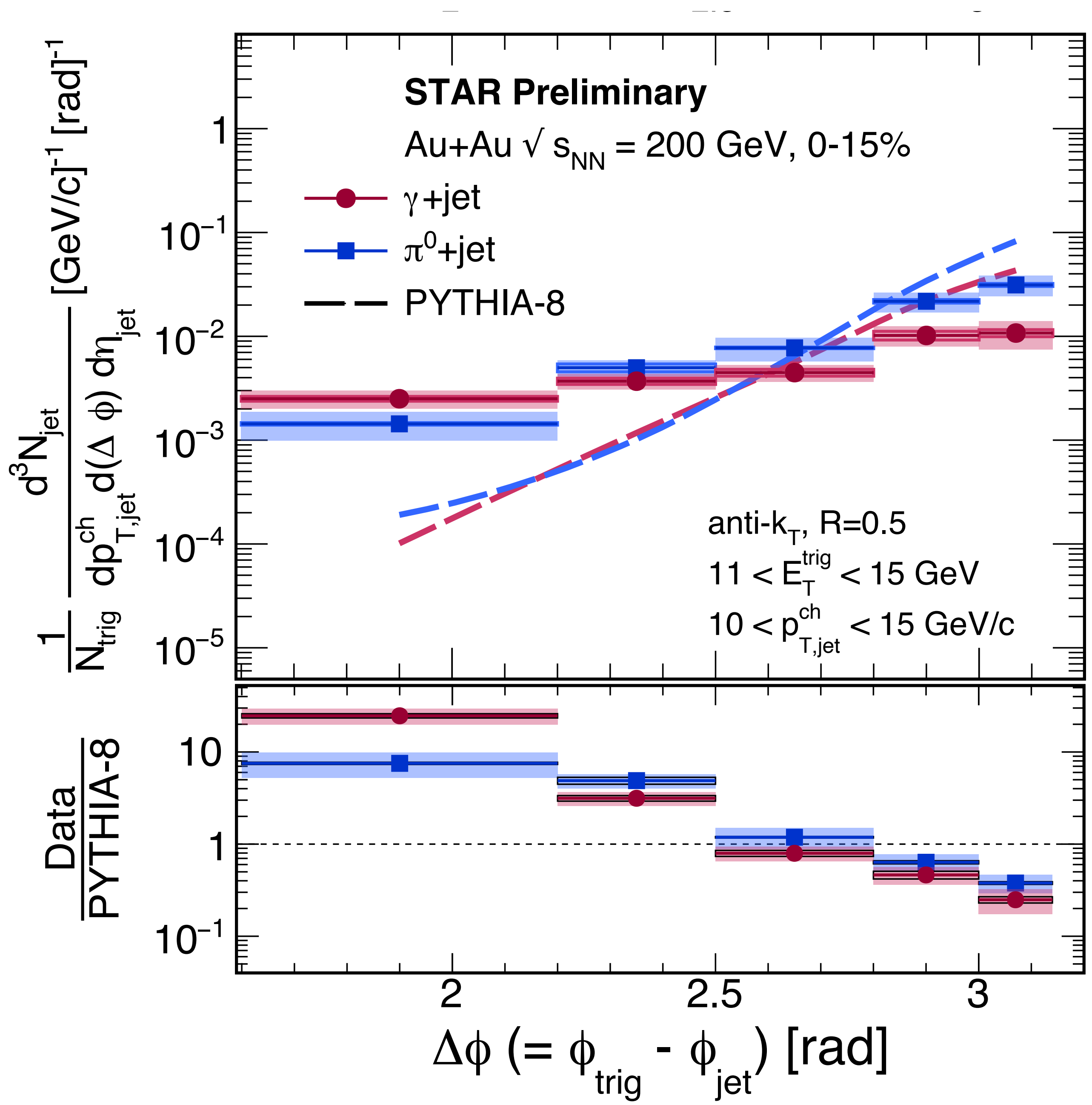


Azimuthal correlations between trigger particle and recoil jet



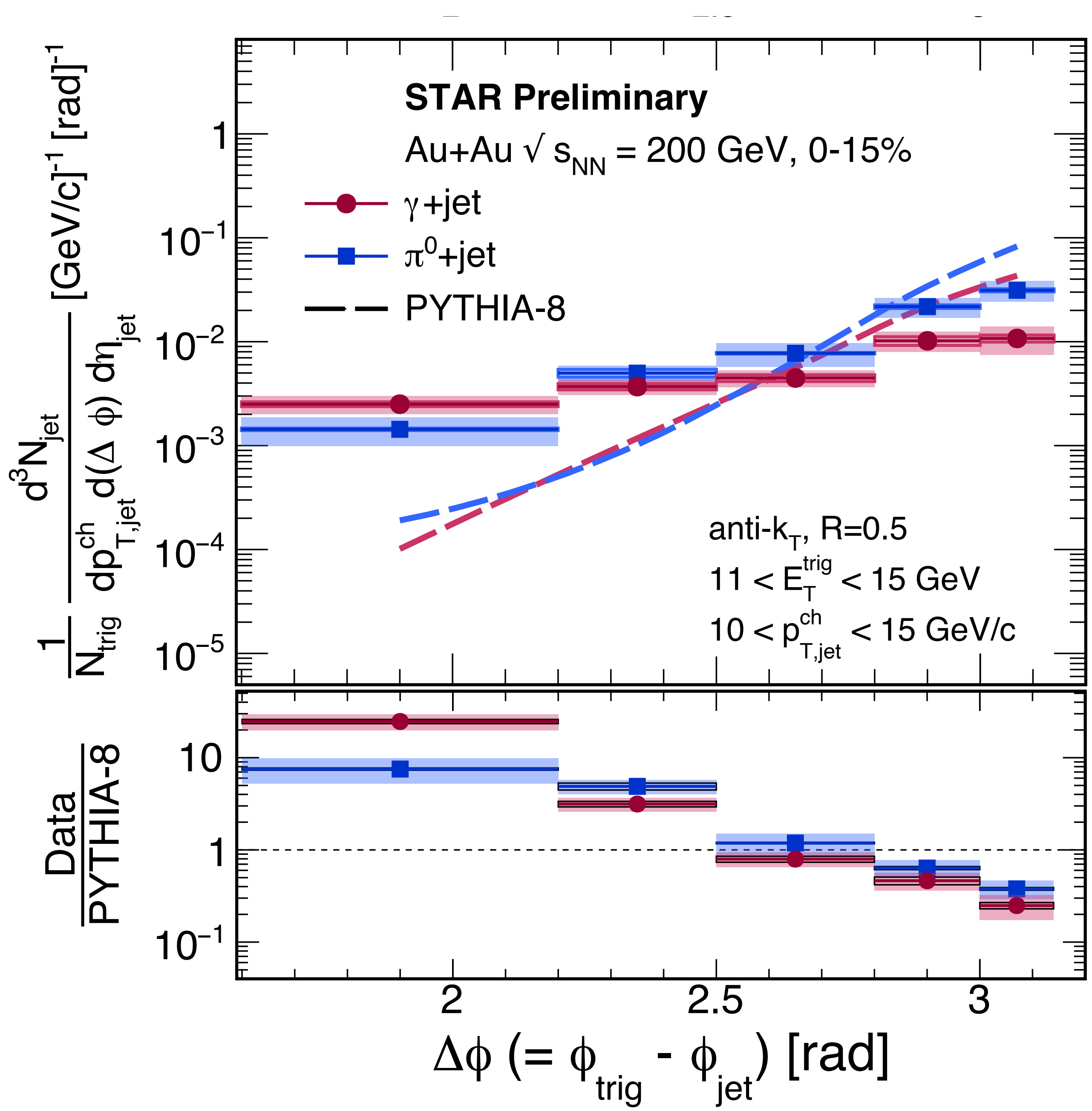


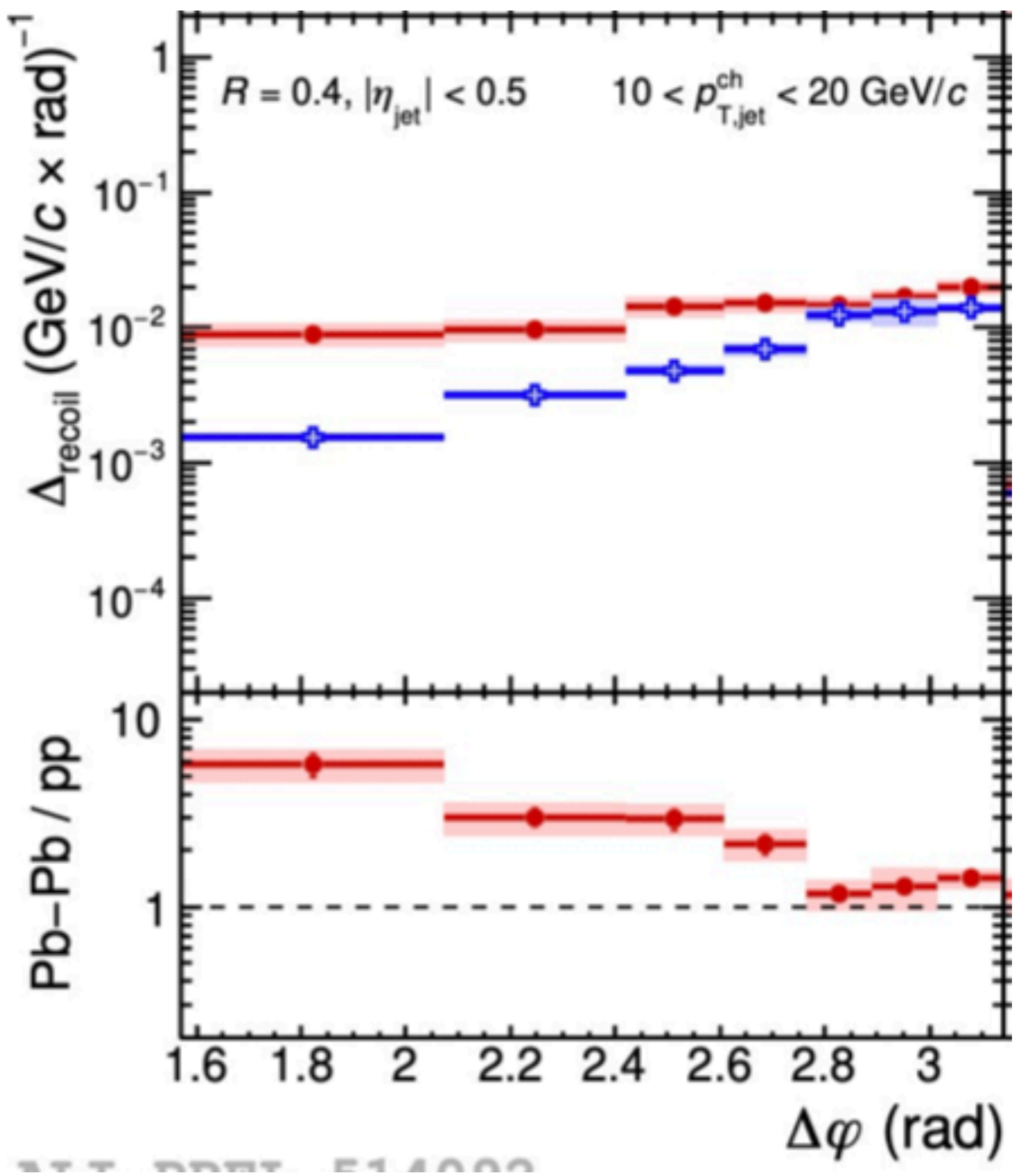
At RHIC: γ+jet and h+jet



Evidence of significant medium-induced jet acoplanarity in QGP

At RHIC: γ+jet and h+jet





Evidence of significant medium-induced jet acoplanarity in QGP

Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

1. Jet energy loss
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Consequences of jet quenching

Experimental evidence at RHIC and LHC

Jet quenching consequences:

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We discussed experimental results…
There significant progress has been made in theory side to understand jet-quenching mechanism…

One of such work is JETSCAPE collaboration…

Phenomenology work jet-medium interaction

Jet-thermal parton interaction/Jet-medium interaction

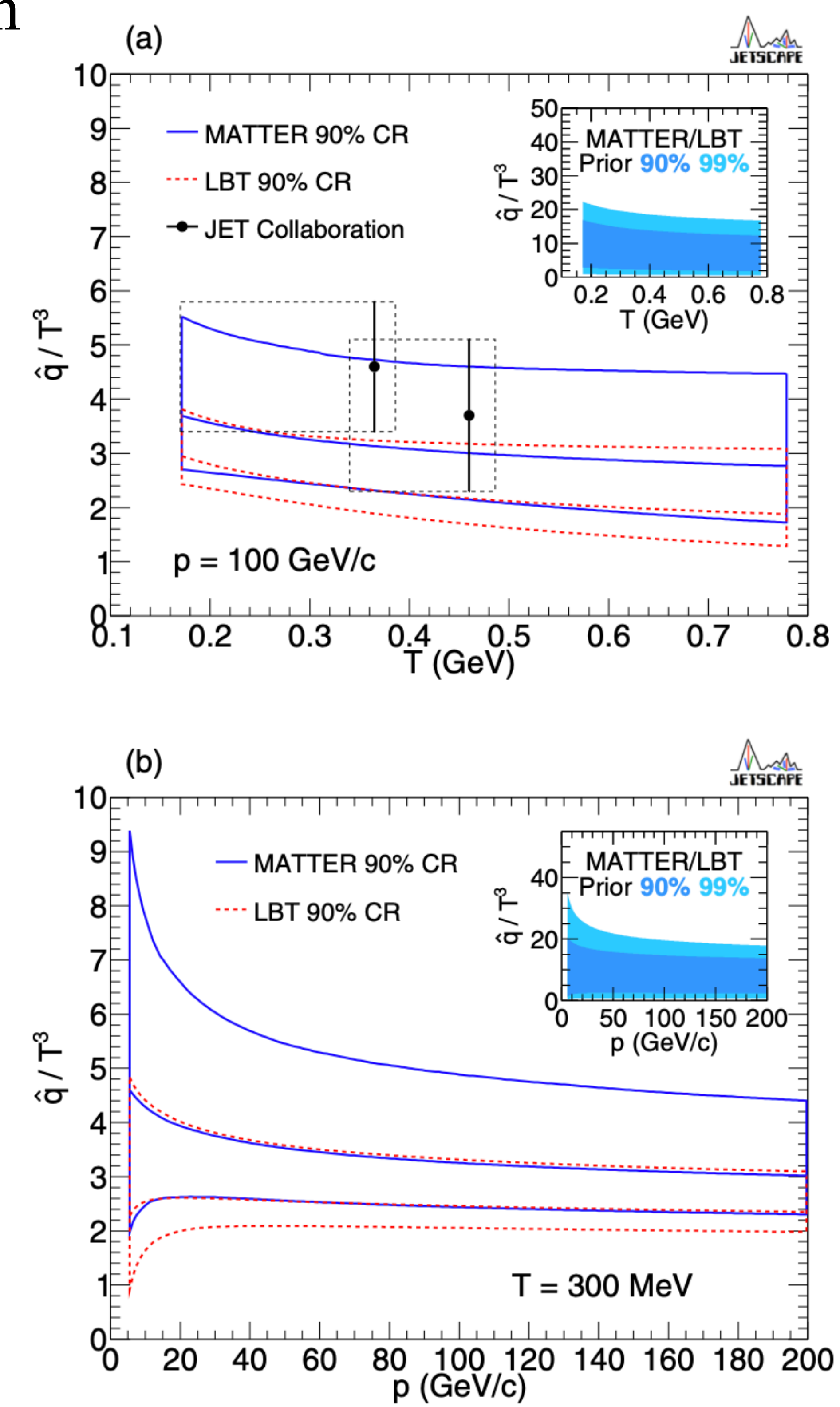
Transport coefficient:

$$\hat{q} \equiv \frac{d < k_T^2 >}{dL}$$

(Momentum transfer between the hard-parton with the thermal medium per unit length)

- Phenomenological work comparing data (R_{AA} from LHC to RHIC)
- Using Bayesian inference
- Weak dependence on medium temperature

JETSCAPE: PRC 104, 024905 (2021)



Open questions

- How does energetic parton interact with the QGP medium?
  - Color charge, mass, path length dependence…
- Can we probe the QGP at short distance scale so that quasi-particle picture can emerge?
  - Large angle scattering due to quasi-particle
  - In-medium broadening competing factor?
- Can jet substructure probe different regimes of QGP evolution?
- Is there any interplay between thermalization/hydrodynamic evolution of QGP and jet-quenching?

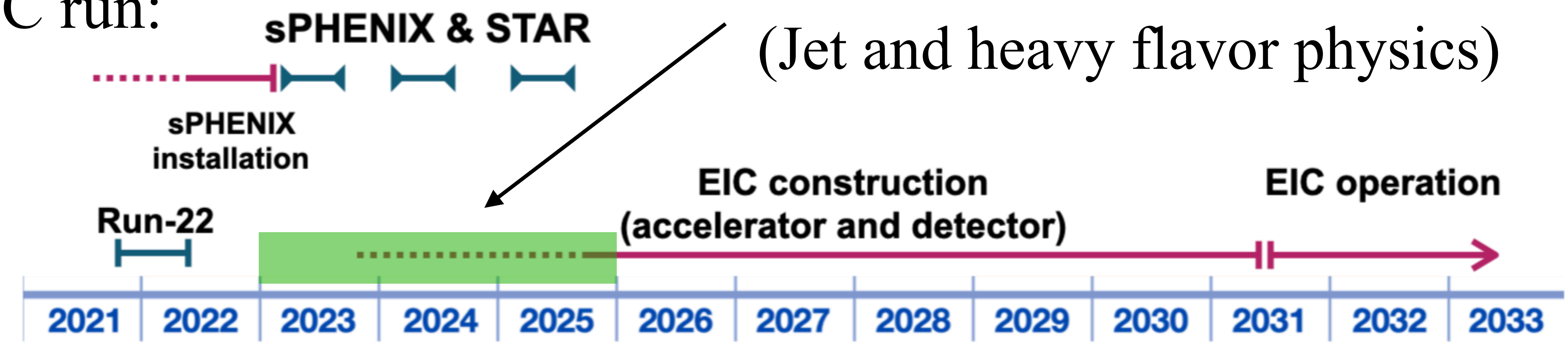
…

Lots of work ongoing at LHC and RHIC
And also from theory community…

Ongoing and upcoming measurements

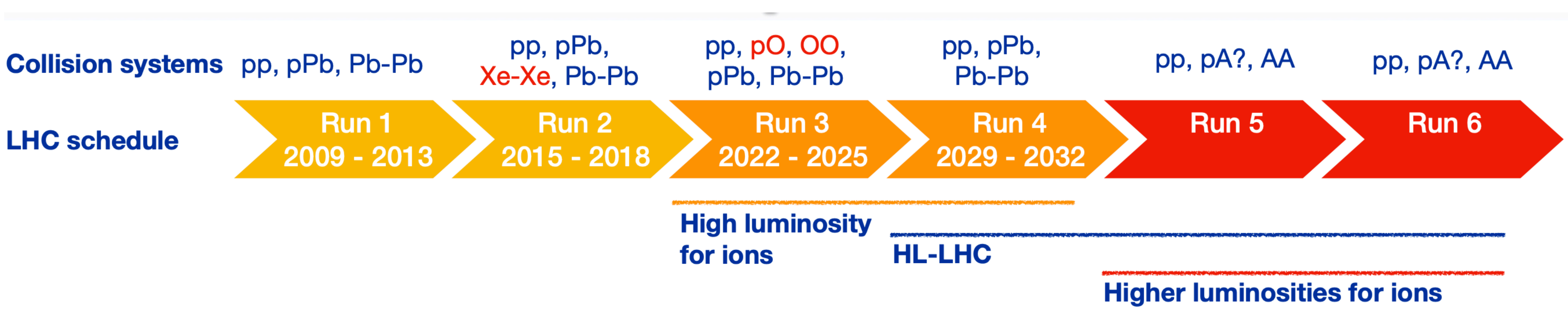
RHIC run:

Hard probes
(Jet and heavy flavor physics)



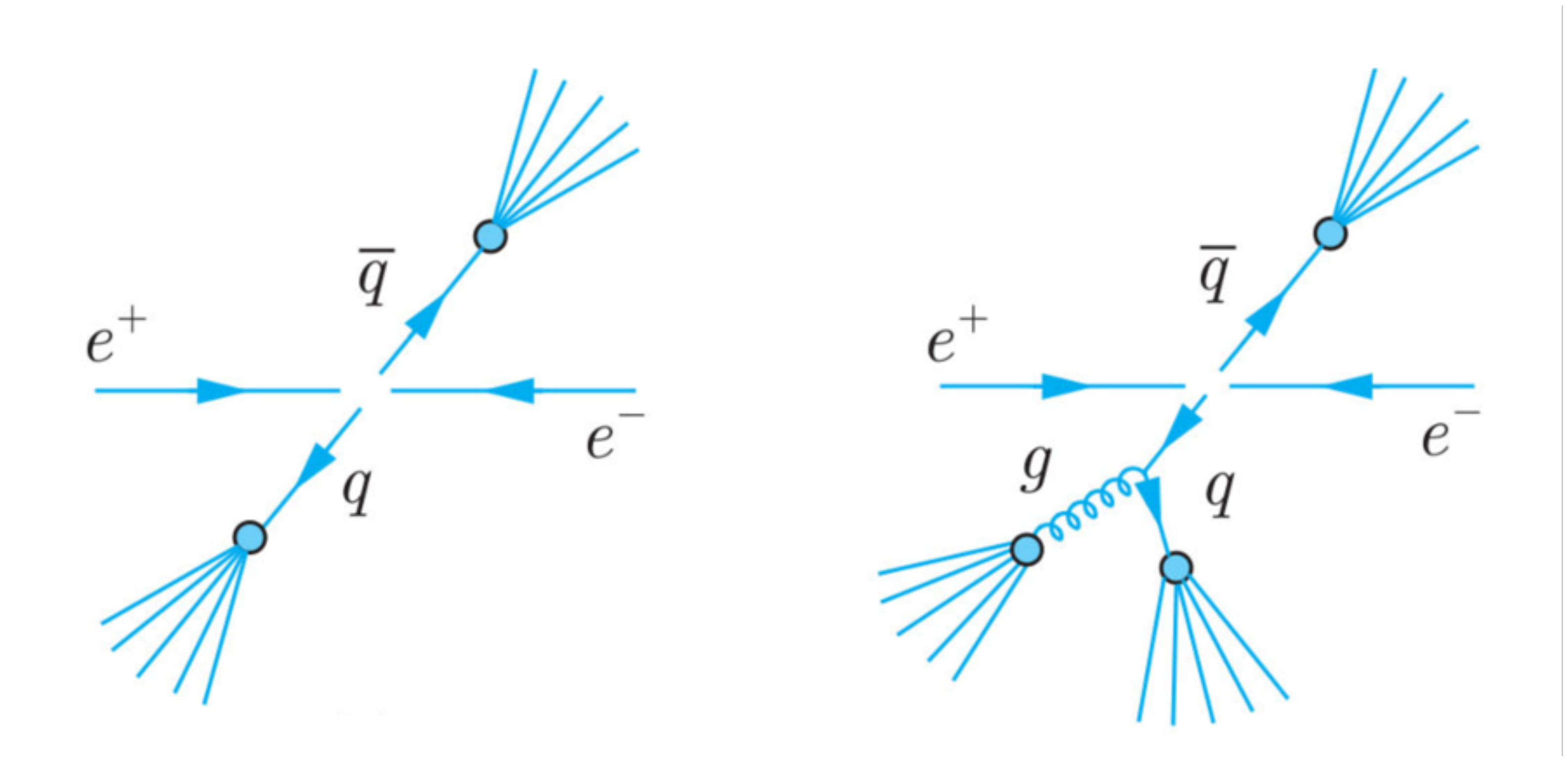
David Morrison, QM2022

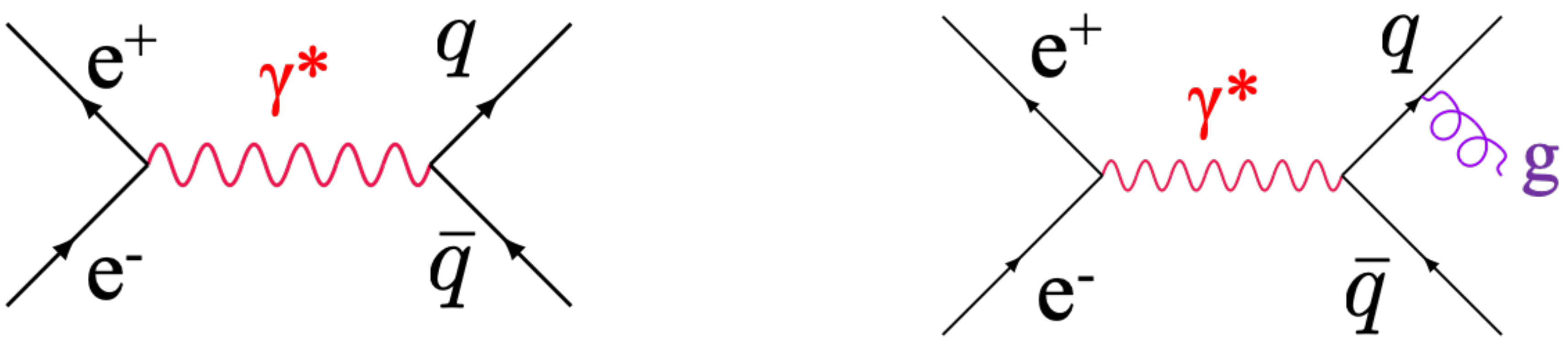
LHC run: ALICE/CMS/ATLAS/LHCb



Jochen Klein, QM2022

Backup





$e^+ + e^-$ annihilation to hadrons

From parton to spray of hadrons (jet)

E-scheme, or 4-vector recombination scheme

$$E_{t,\mathrm{jet}} = \sum_i E_{ti} \, ,$$

$$\eta_{\mathrm{jet}} = \frac{1}{E_{t,\mathrm{jet}}} \sum_i E_{ti} \eta_i \, ,$$

$$\phi_{\mathrm{jet}} = \frac{1}{E_{t,\mathrm{jet}}} \sum_i E_{ti} \phi_i \, ,$$

Considering jet as a massless object