Jets and jet structure In heavy ion collisions

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Summer student lectures @ Prague
26-28 June 2022

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The basics

What are ‘jets’ and ‘substructure’?

Why do we study JSS?

How does one experimentally measure JSS?

Physics with jets

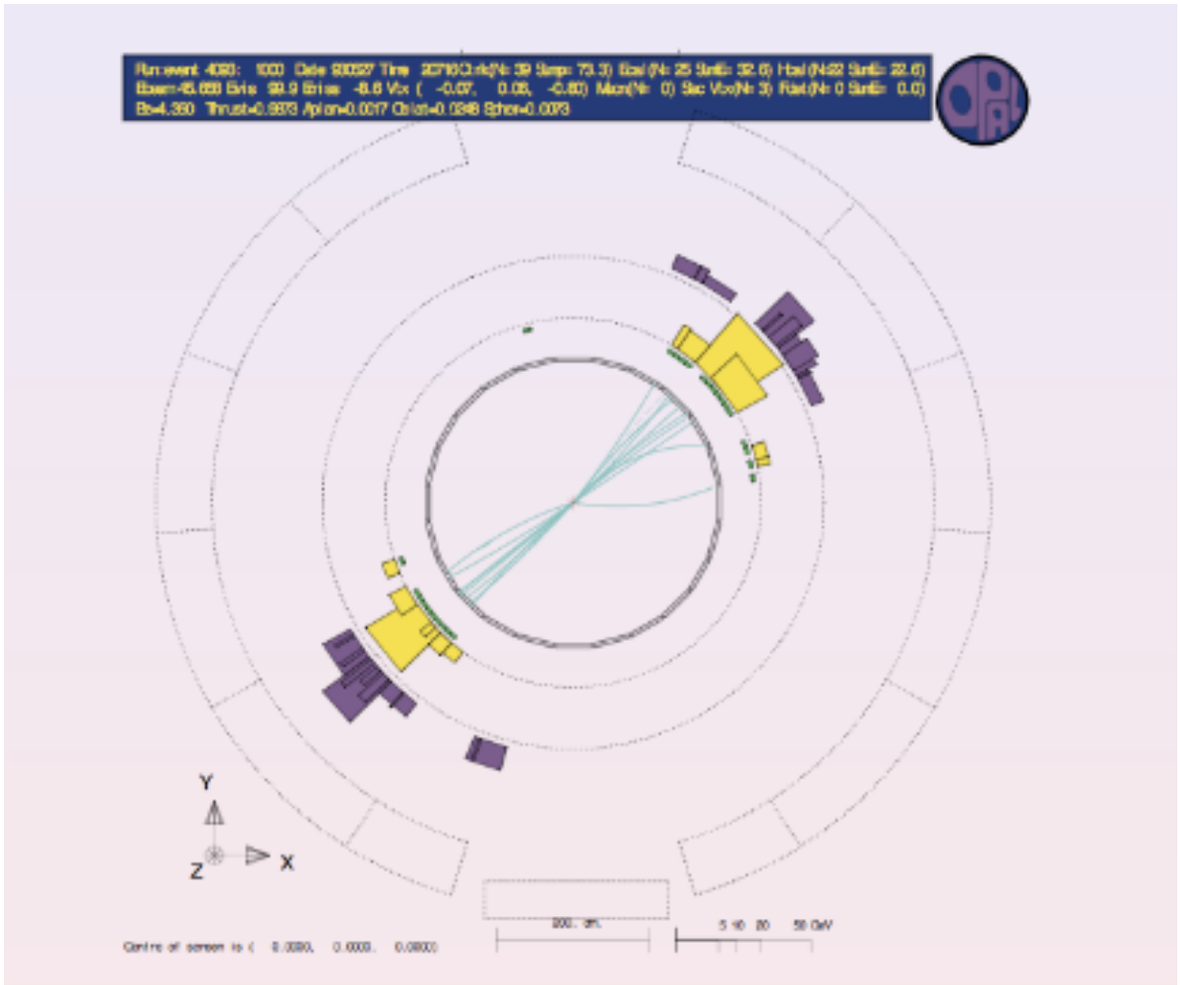
Fundamental Quantum ChromoDynamics

Studying transport properties of the Quark-Gluon Plasma

What are Jets?

These jets

OPAL Phys. Lett, B 265 462-474 (1991)



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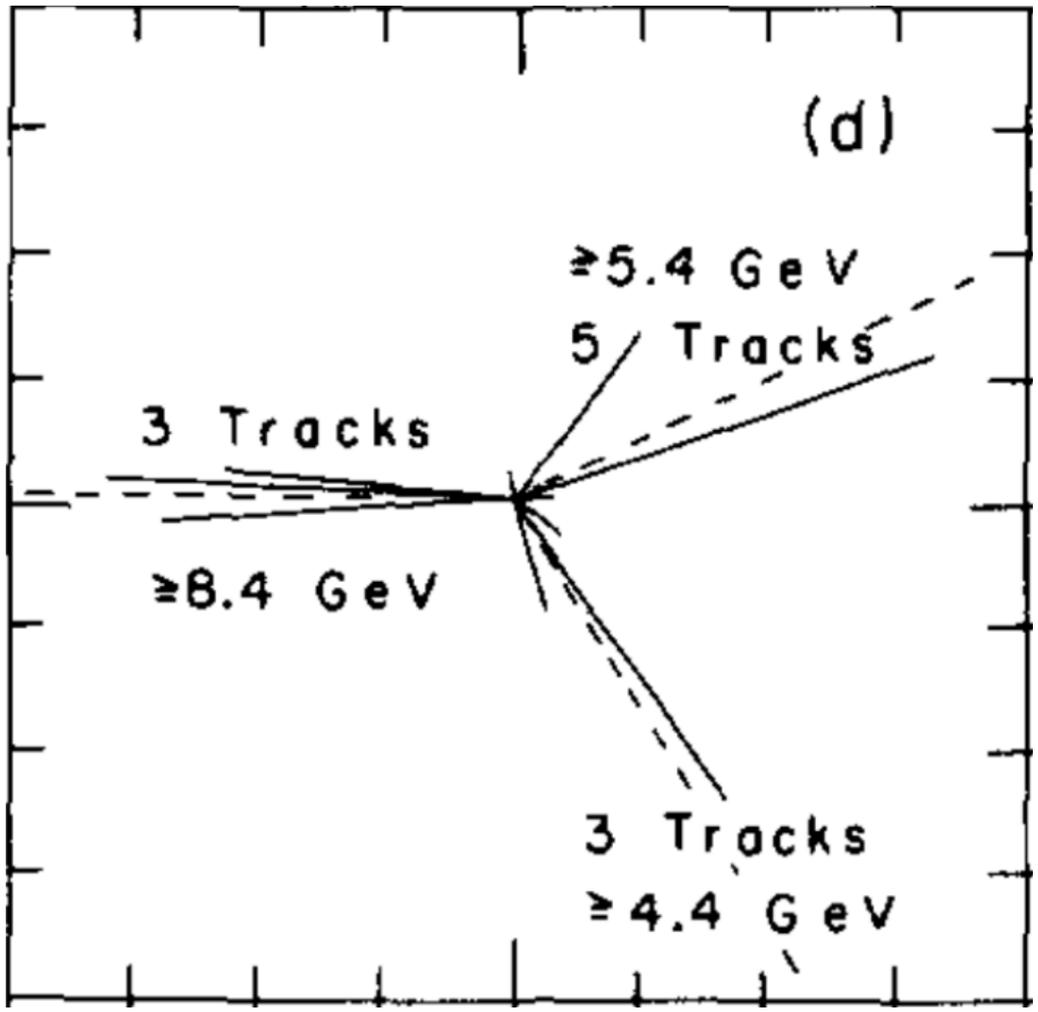
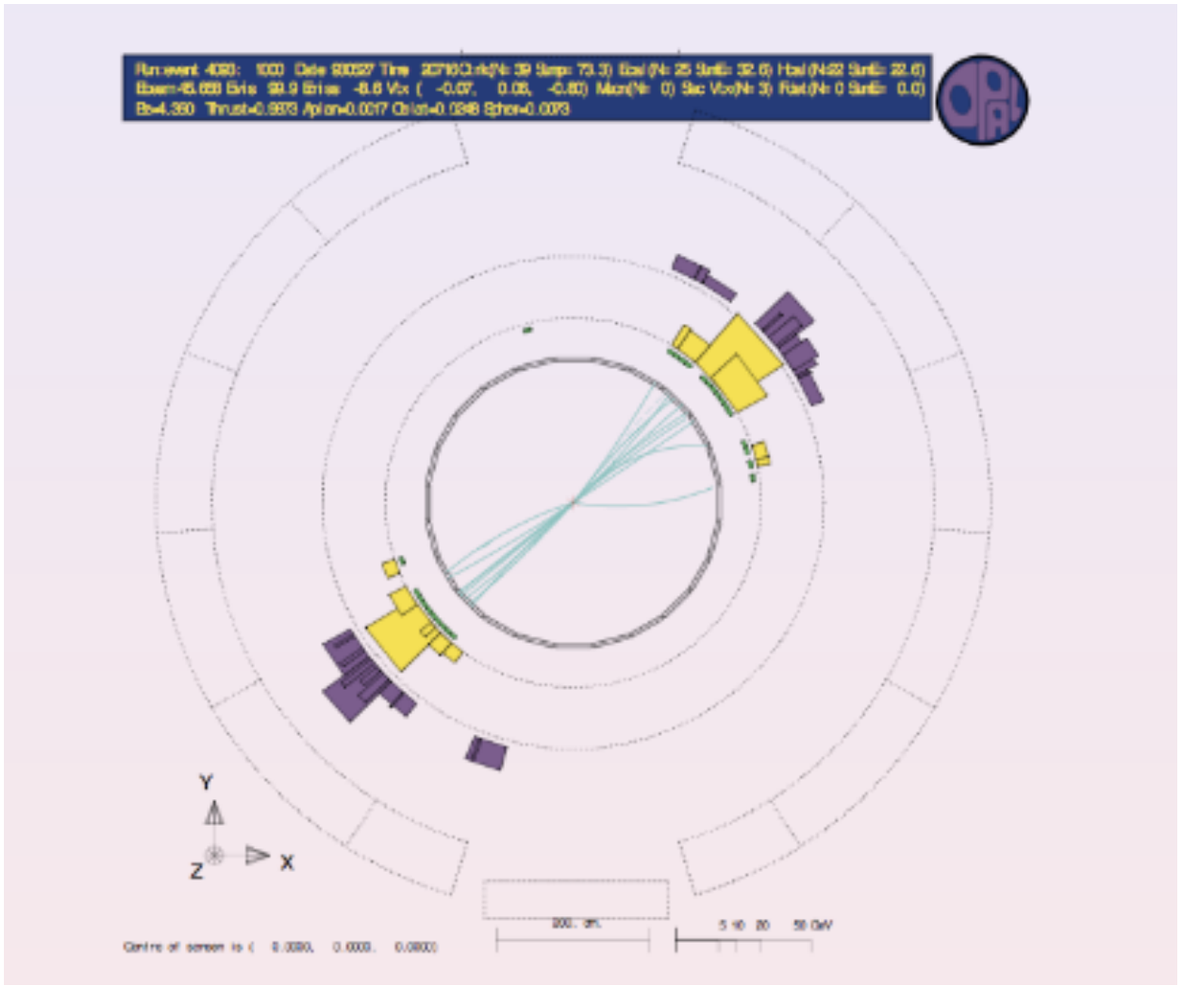


where are the jets?

These jets

OPAL Phys. Lett, B 265 462-474 (1991)



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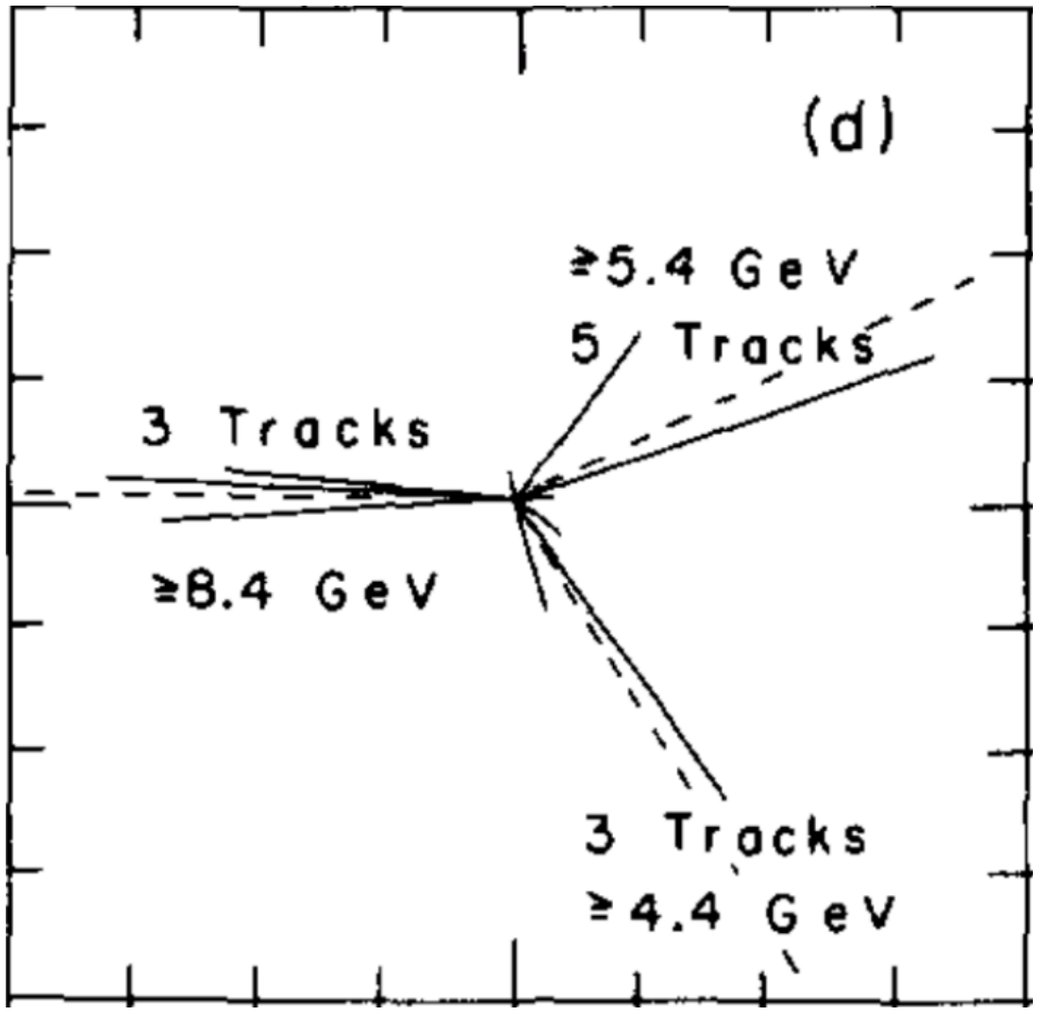
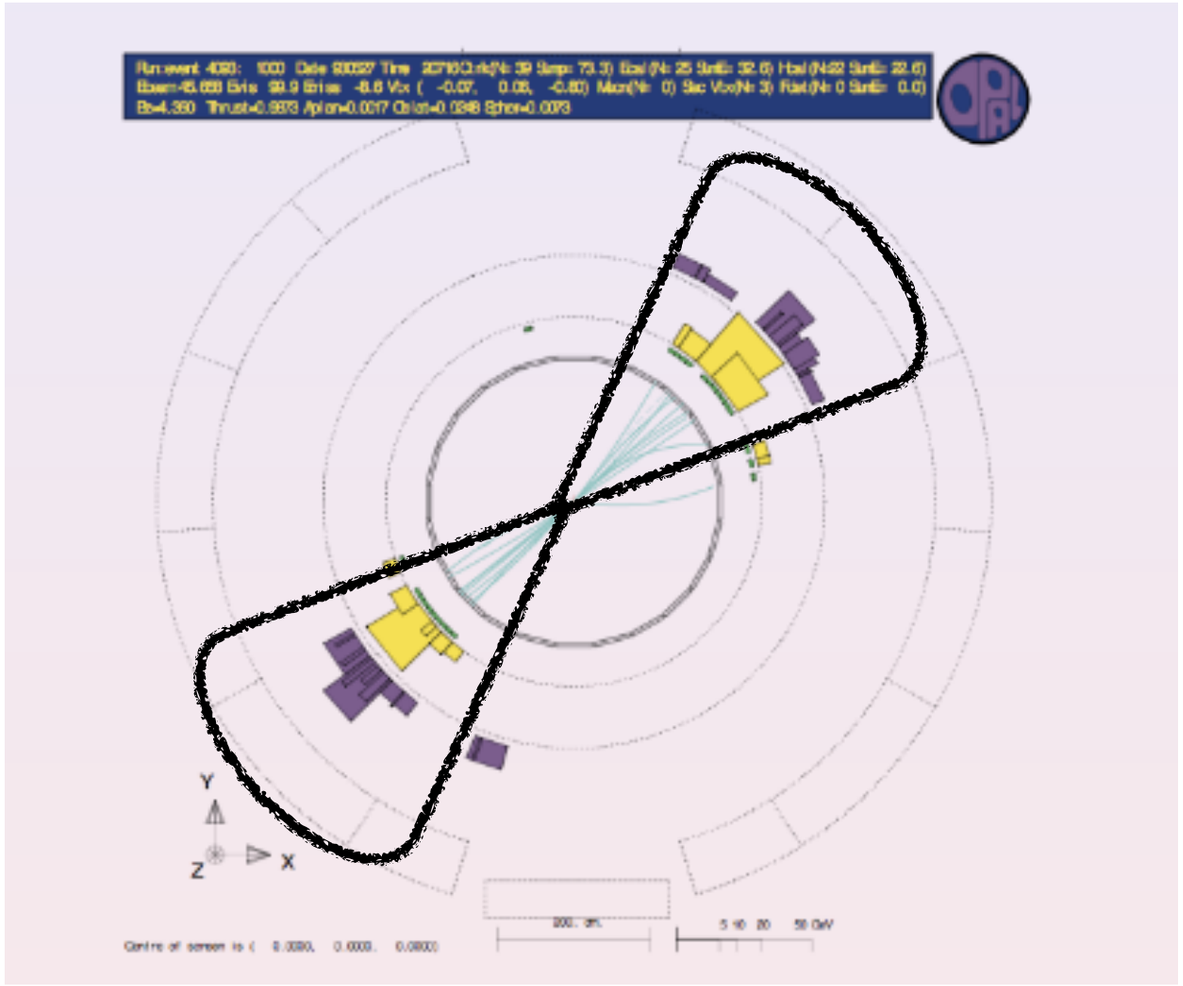


- Jets - collection of objects detected in an experiment

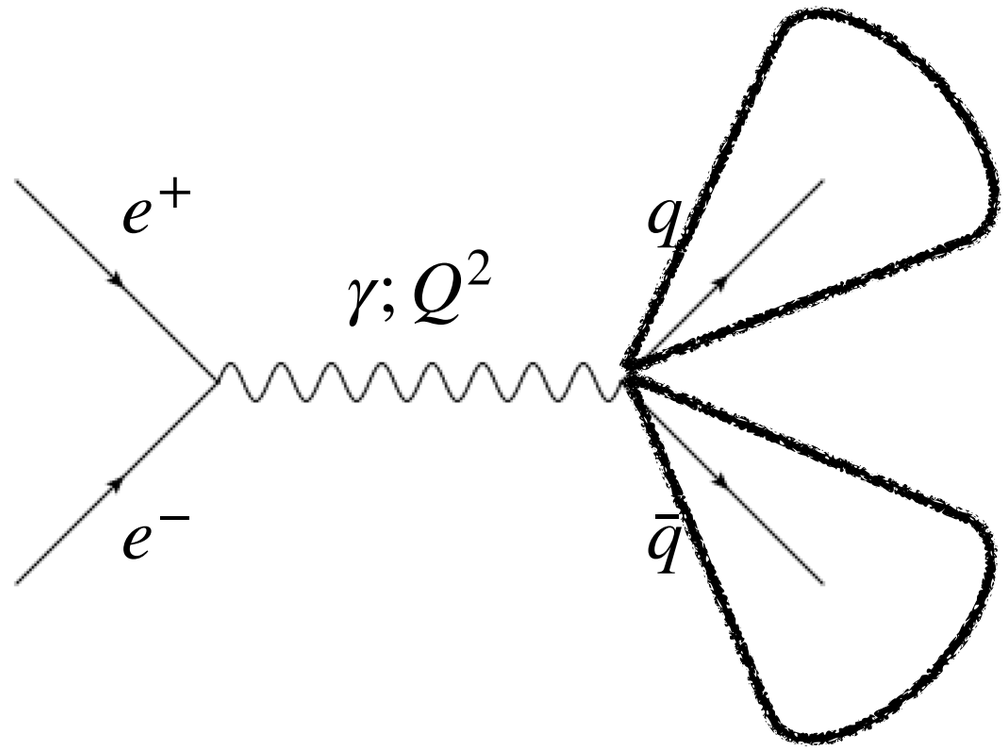
In order to define our jets,
we need to know where they come from

Where did these jets come from?



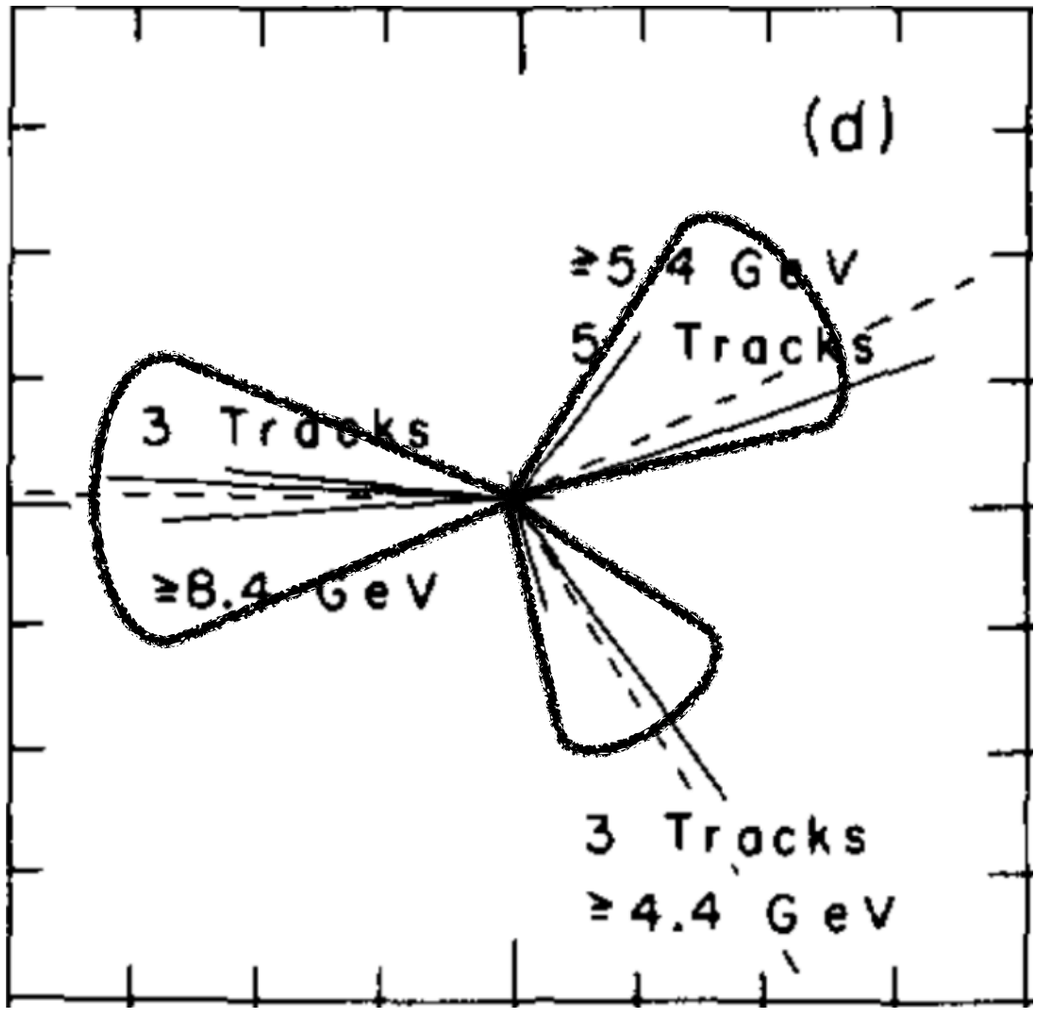
$$\sqrt{s} \approx 91 \text{ GeV}$$

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



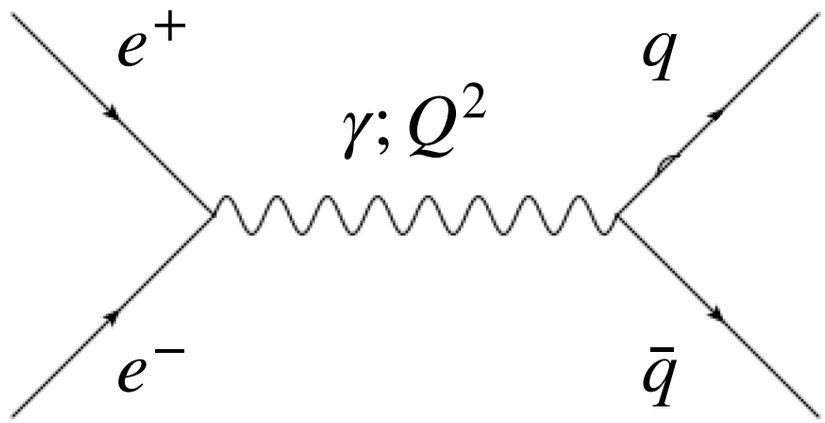
- Electron positron scattering results in a virtual photon - very clean and simple event to study

Where did these jets come from?



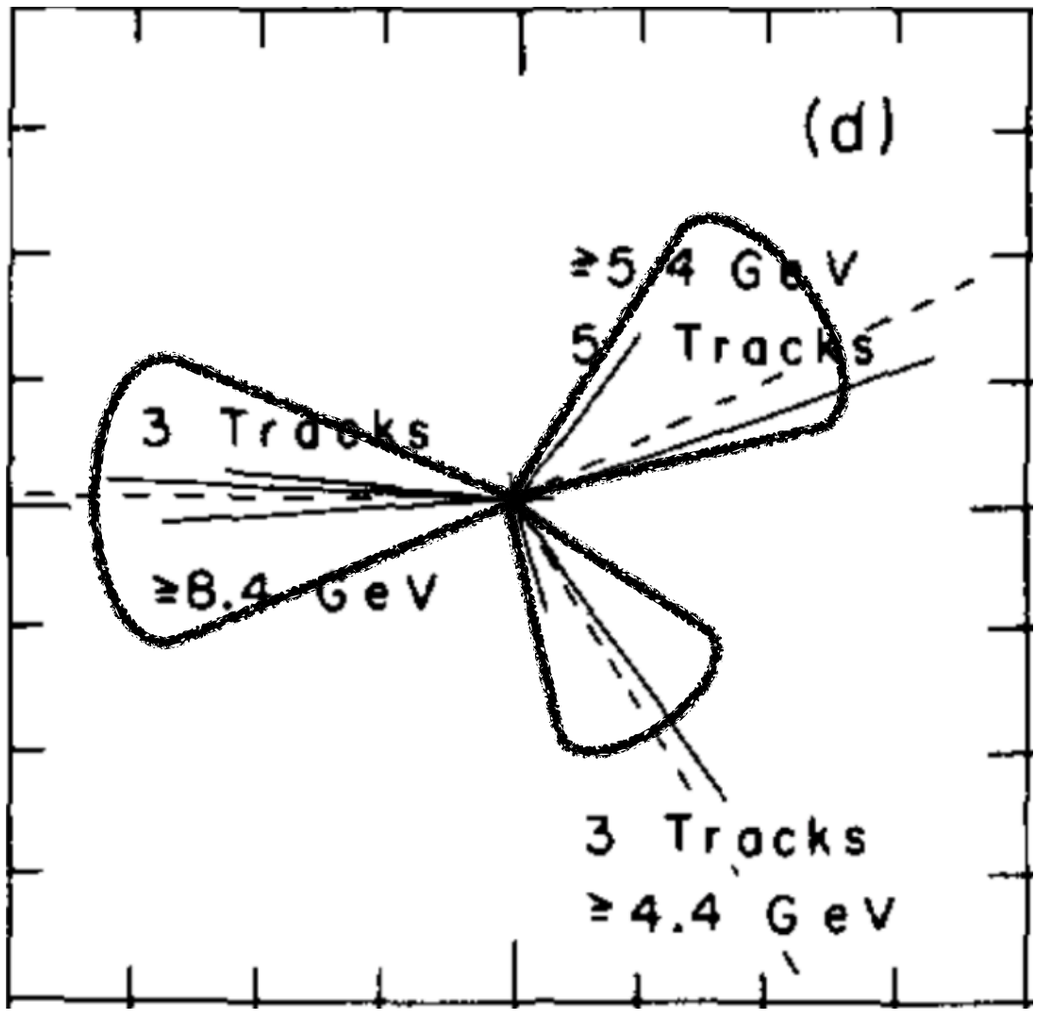
$$\sqrt{s} \approx 20 \text{ GeV}$$

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



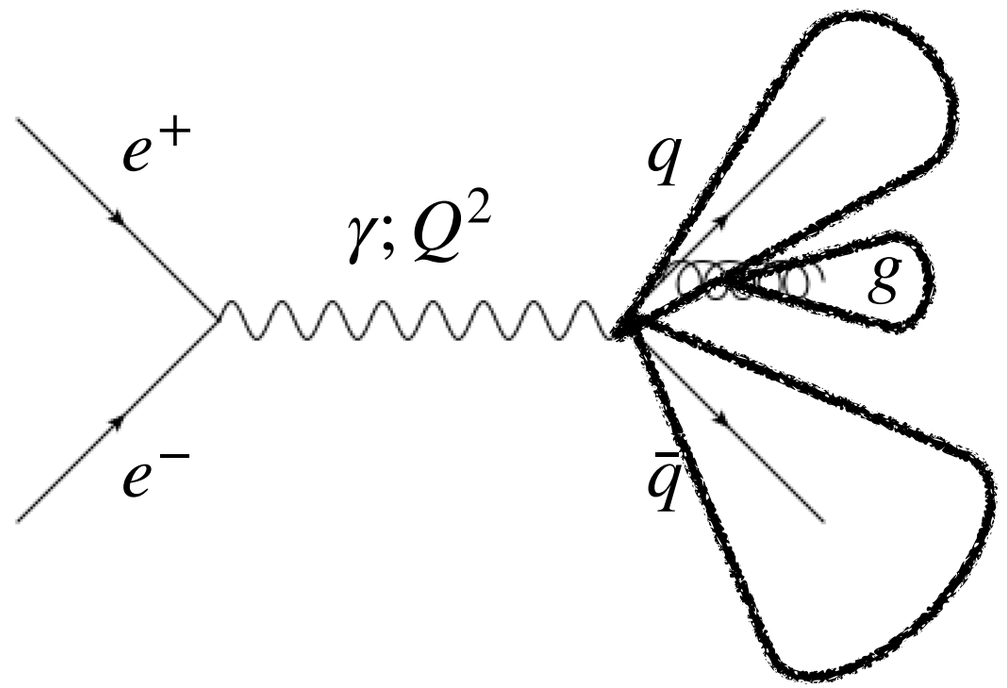
whats the third jet here?

Where did these jets come from?



$$\sqrt{s} \approx 20 \text{ GeV}$$

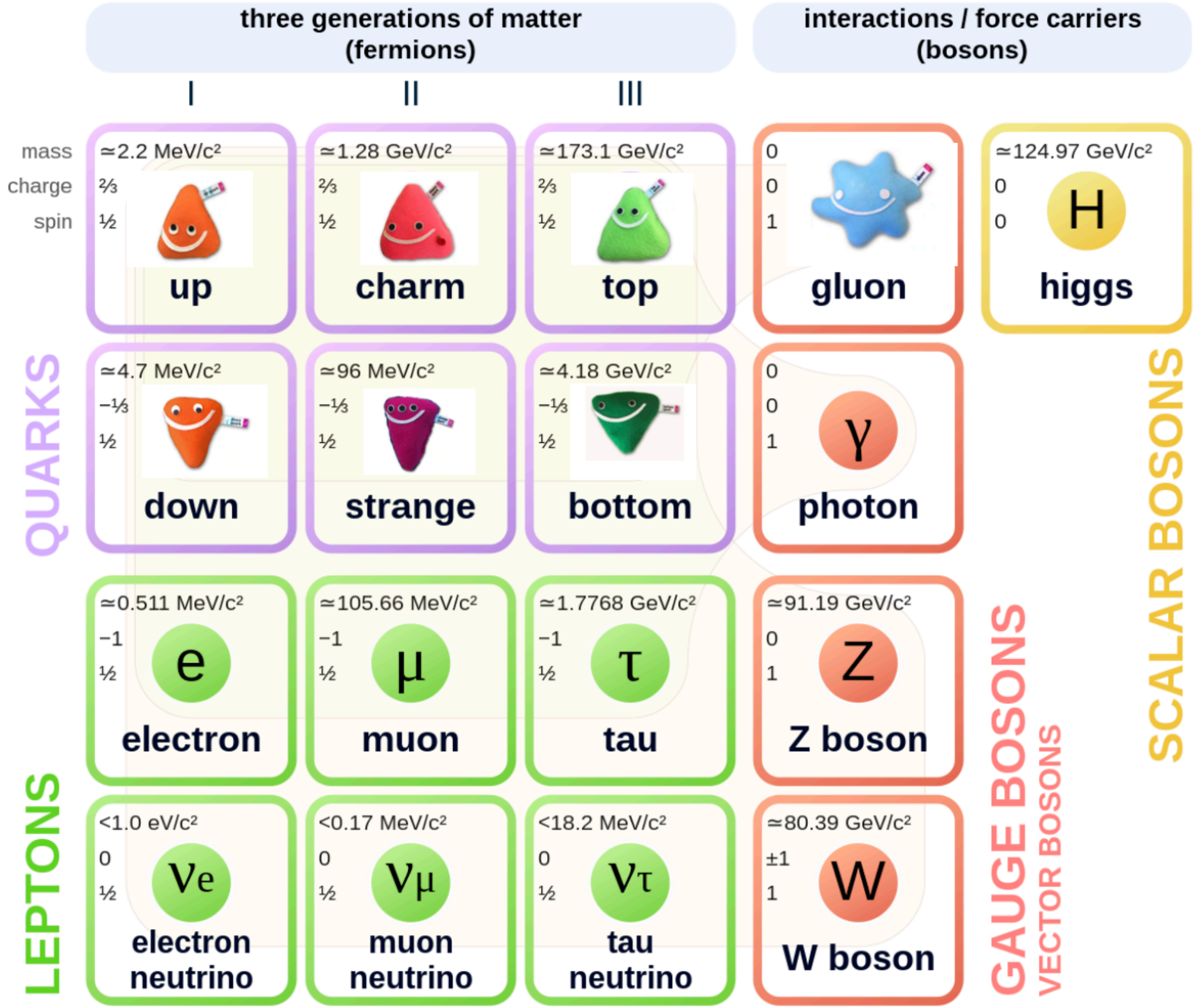
$$e^+ + e^- \rightarrow q + \bar{q} + g$$



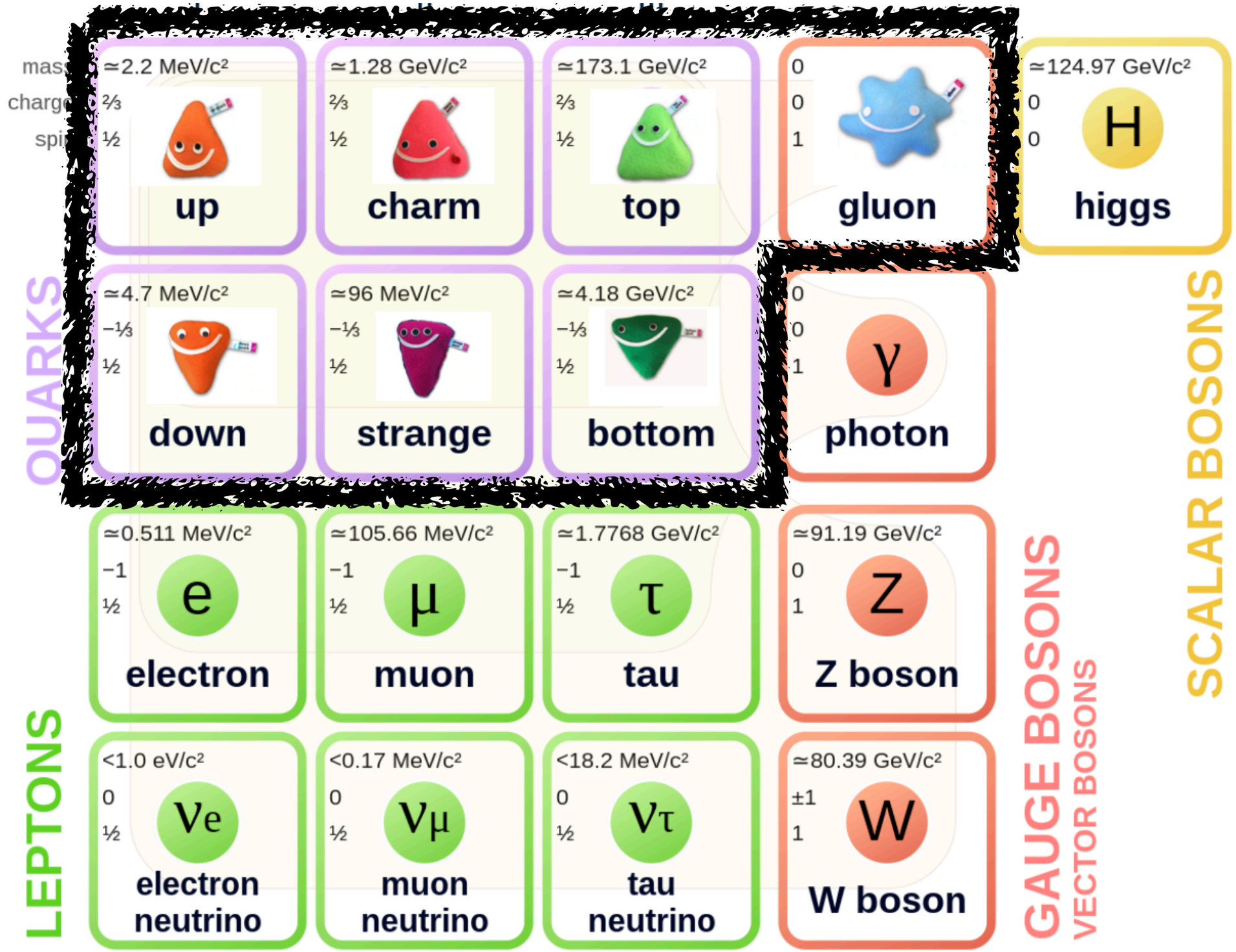
- Discovery of the gluon! (Which one is it on the left?)

Jets are parton proxies!

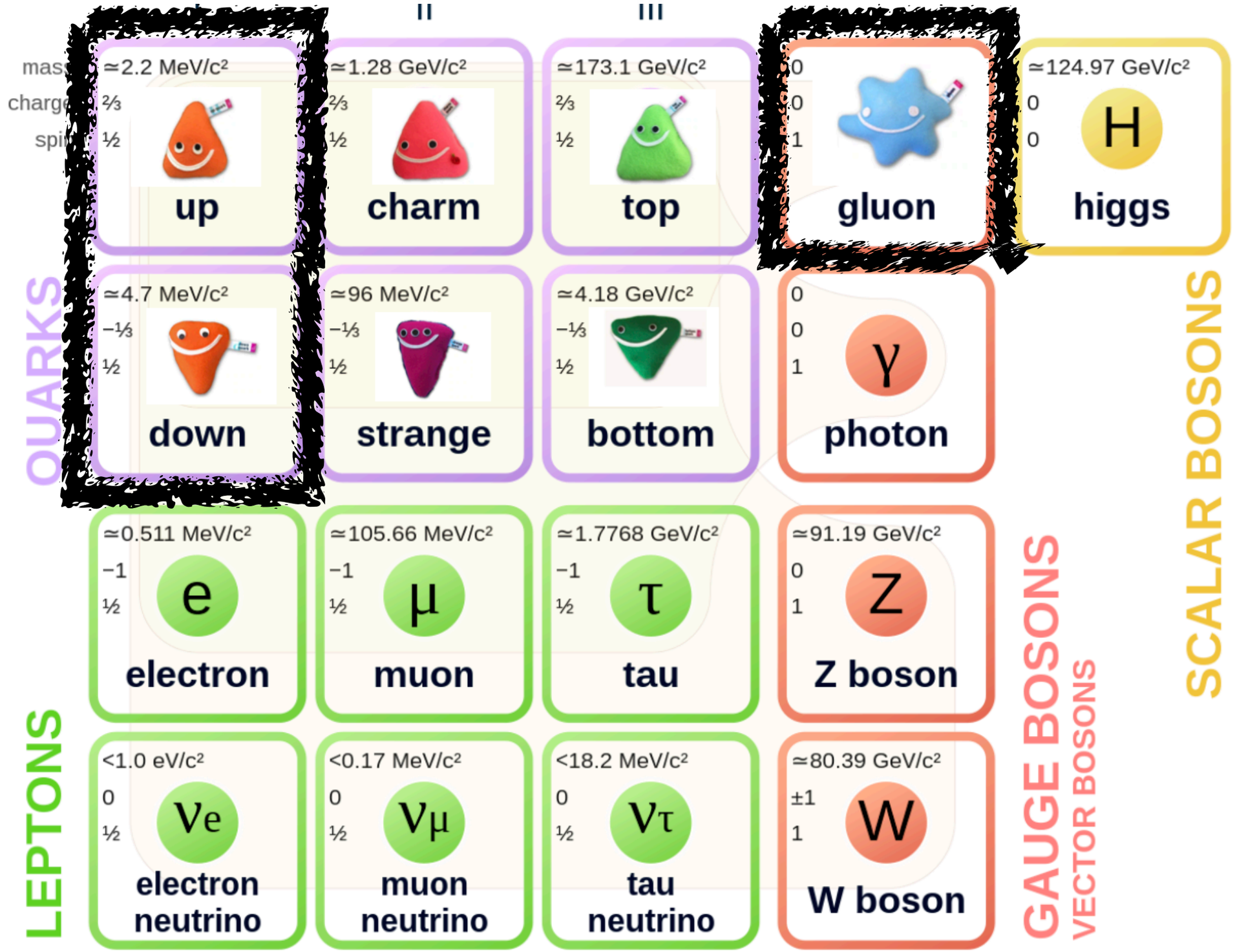
Standard Model of Elementary Particles



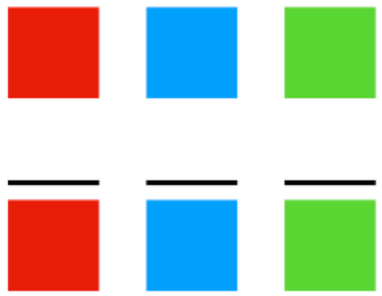
Jet producing partons

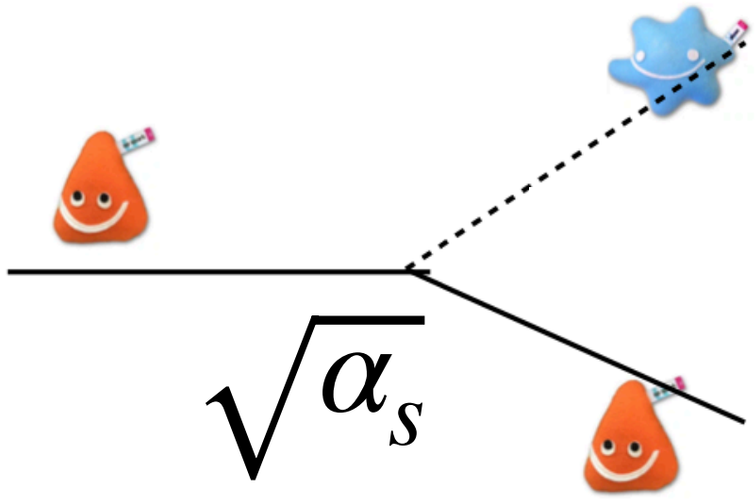


Today's partons!



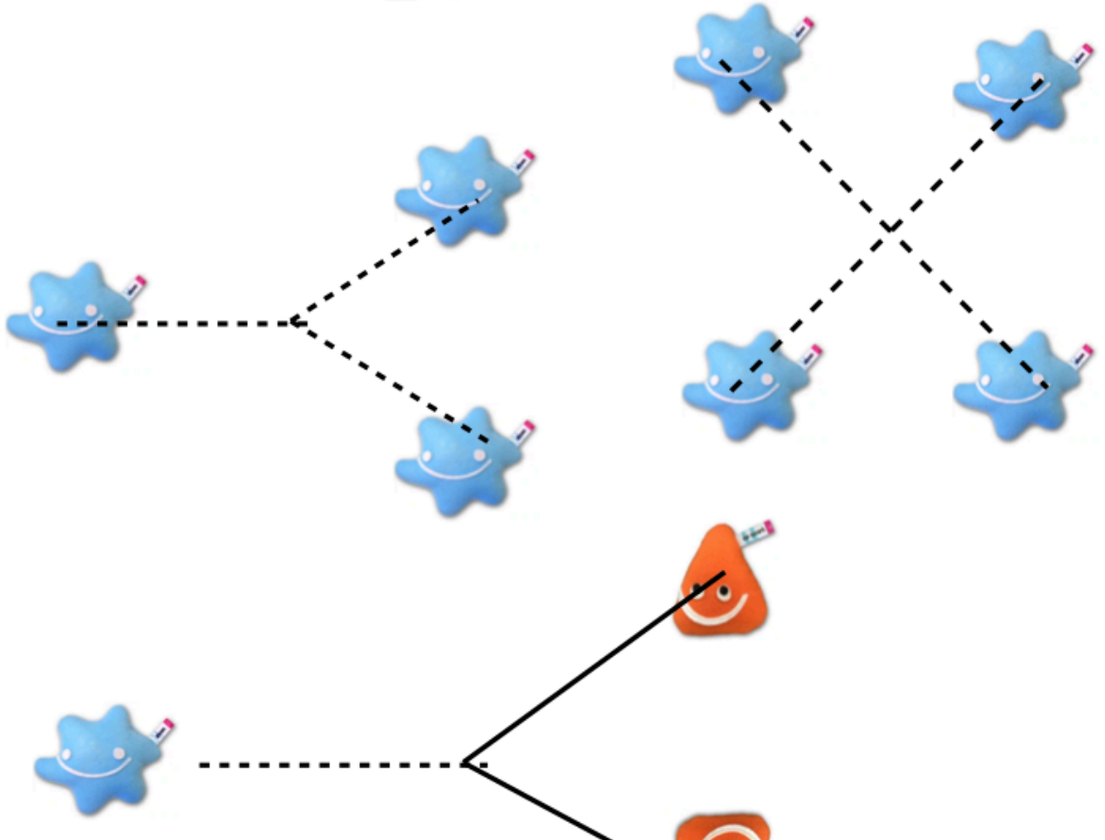
Quantum ChromoDynamics (QCD)
Interactions with color



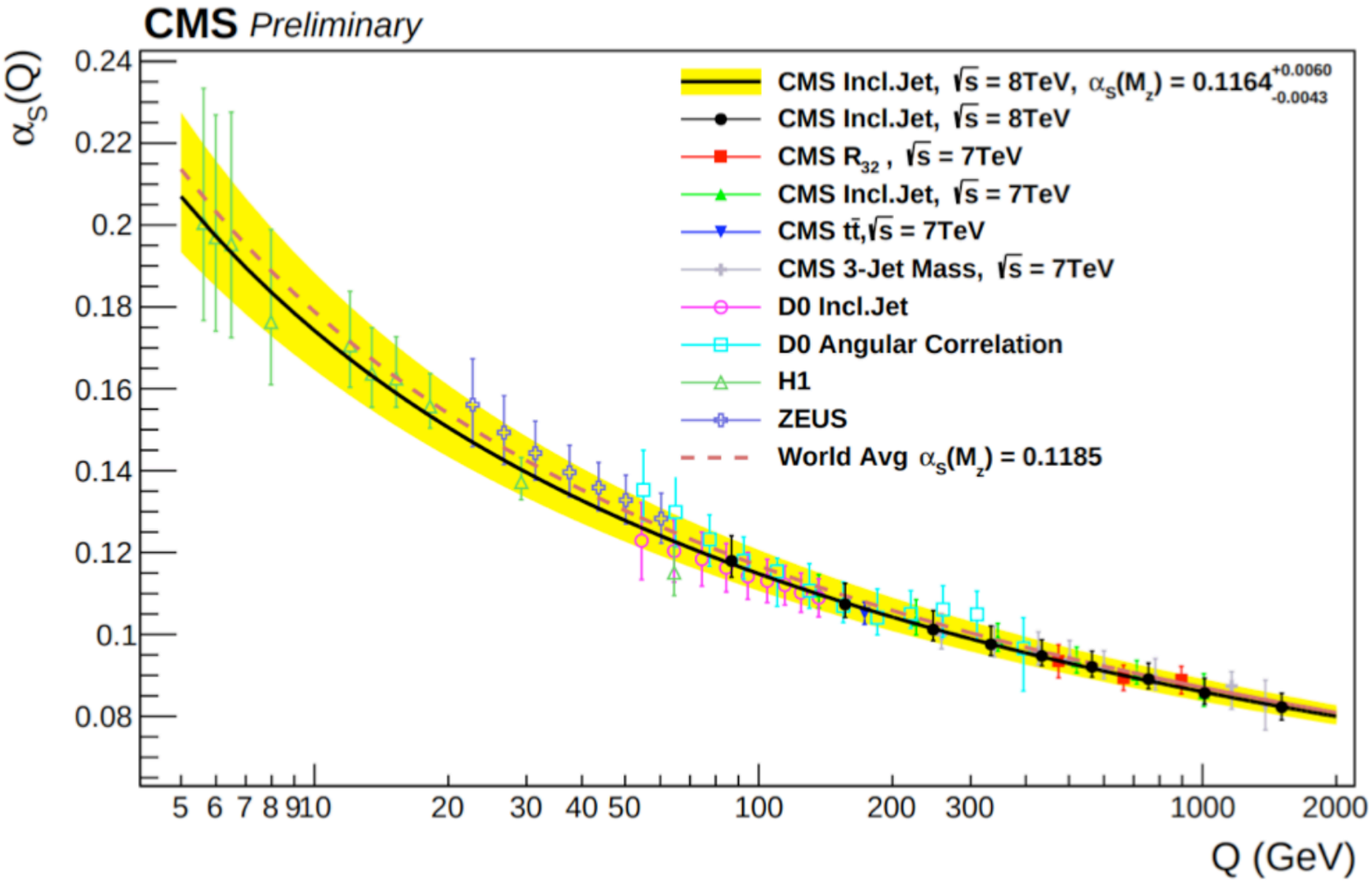


$$\frac{1}{\sqrt{2}}\left(\quad - \quad\right)$$

$$\frac{1}{\sqrt{12}}\left(\quad + \quad - 2\ \right)$$



Unique features of QCD

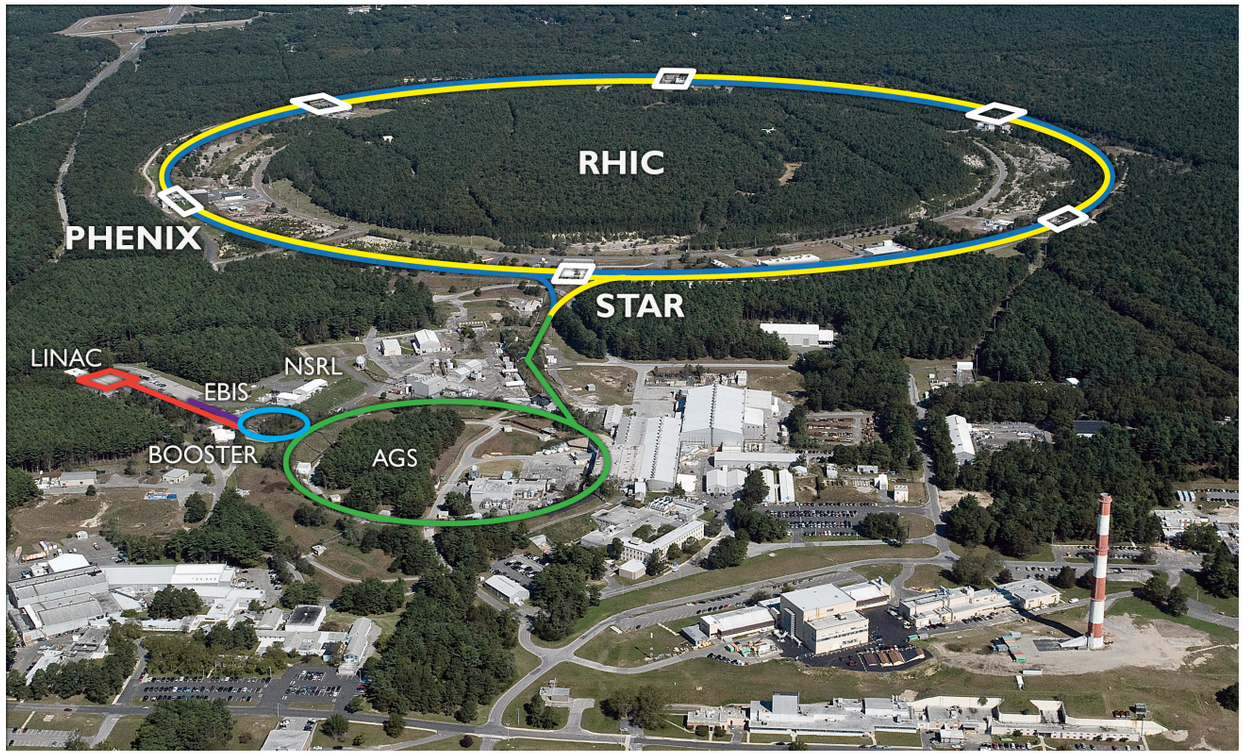


Small energy scales - large value of coupling constant leads to non-perturbative corrections and **confinement/hadronization**

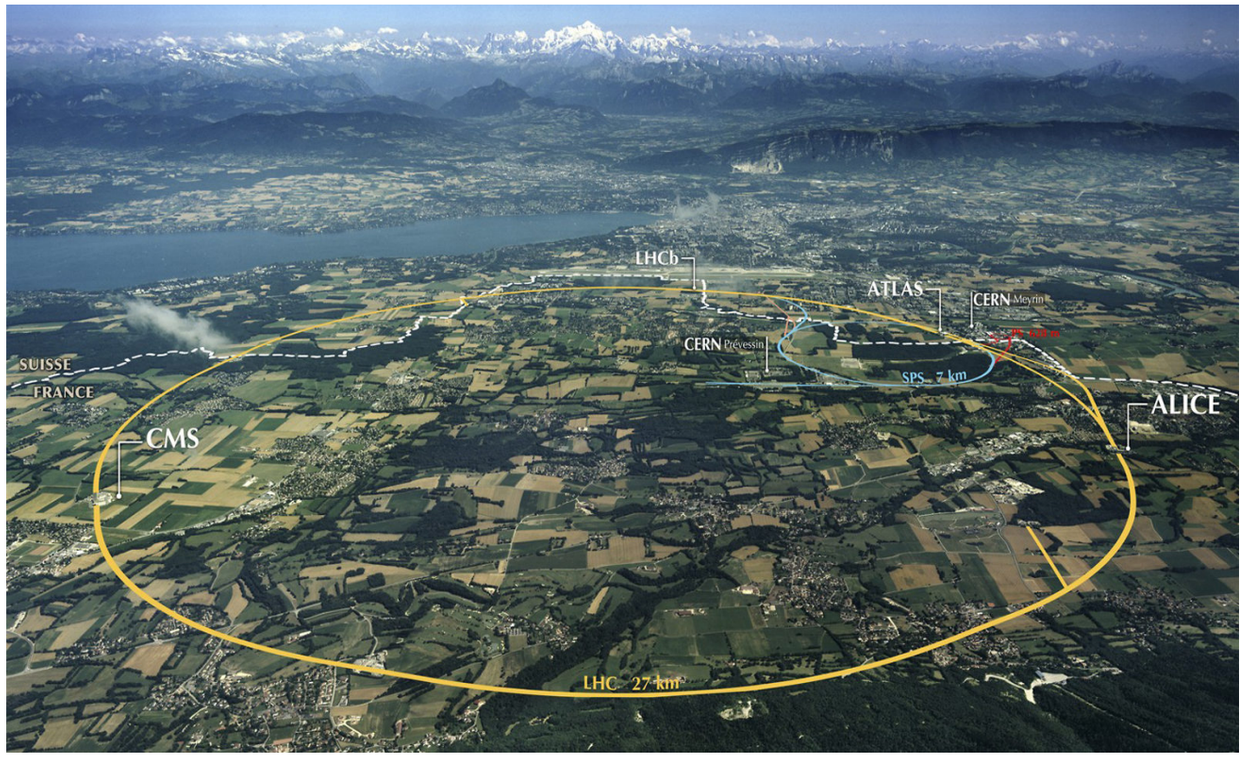
2004

Large energy scales - small values of coupling leads to perturbative calculations - **asymptotic freedom**

Current accelerators

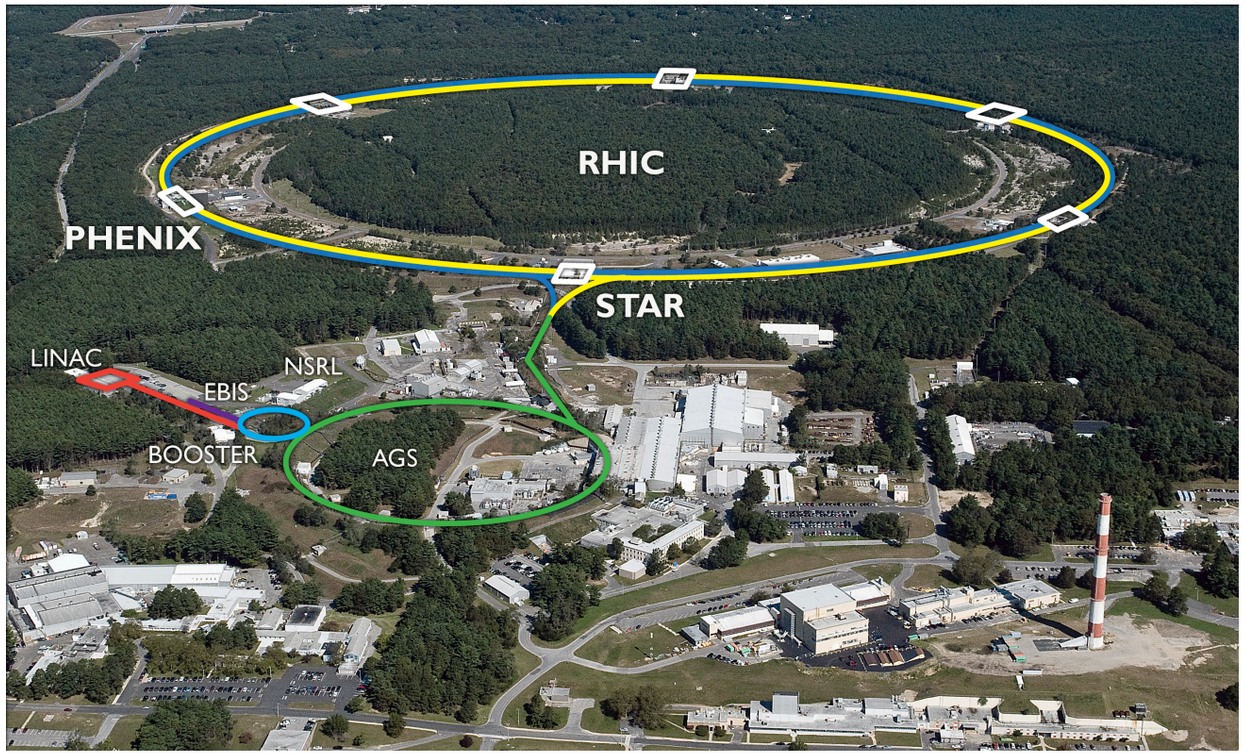


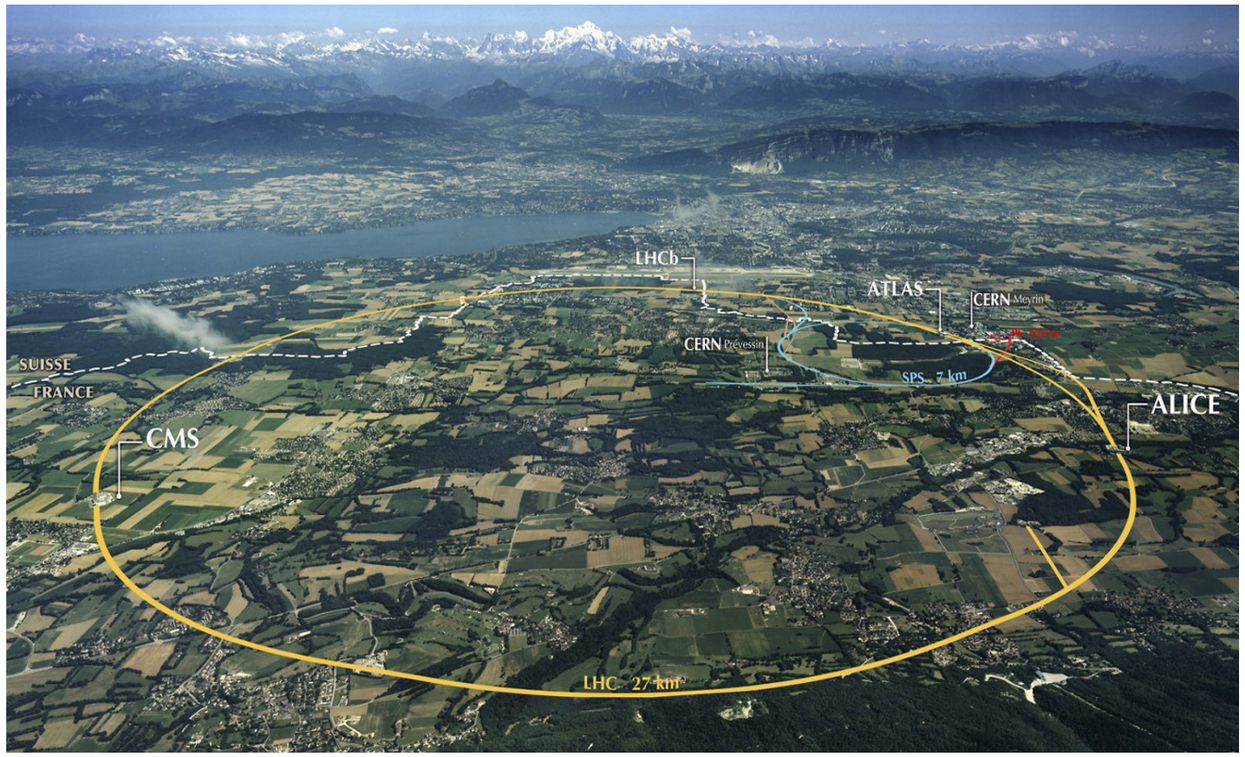
- Relativistic Heavy Ion Collider
- $\sqrt{s_{NN}} = 7.7 - 200$ GeV
- Particle Species - p+p, p+Au, d+Au, Au+Au, Cu+Au, Ur+Ur, etc…



- Large Hadron Collider
- $\sqrt{s_{NN}} = 2.76,\ 5.02$ TeV
- Particle Species - p+p, p+Pb, Pb+Pb, Ar+Ar

Current accelerators





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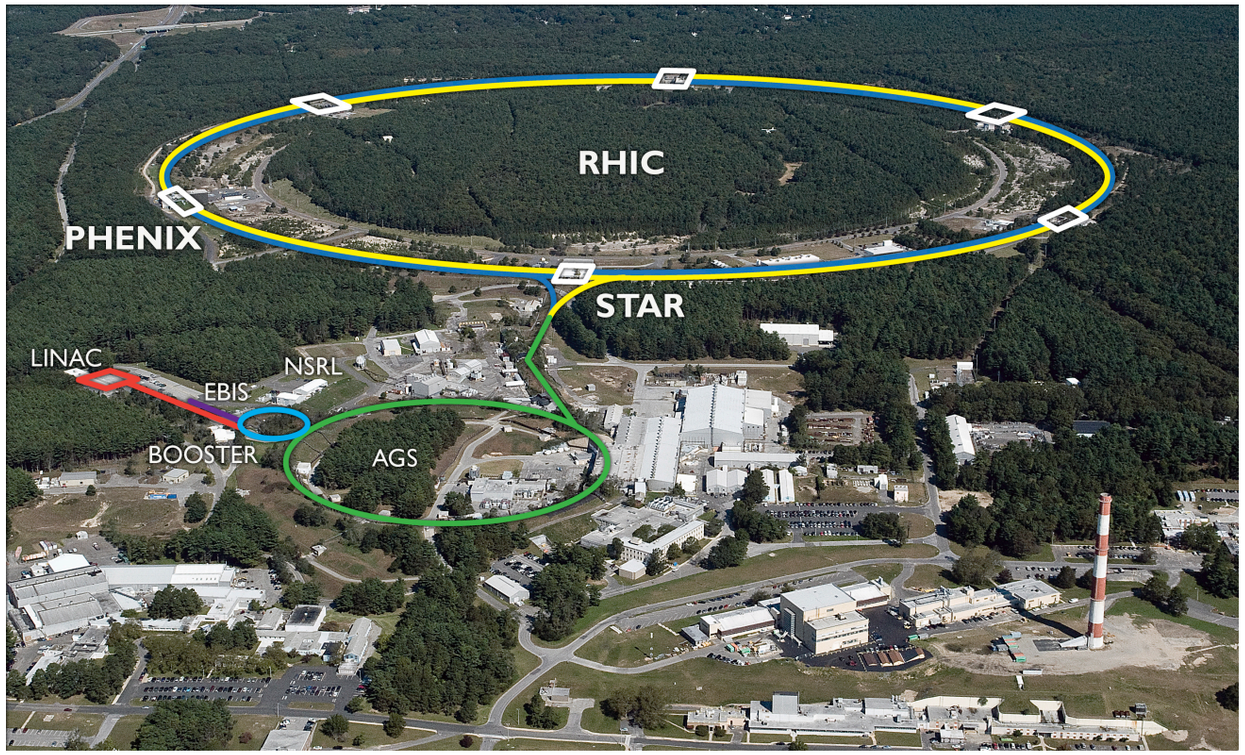

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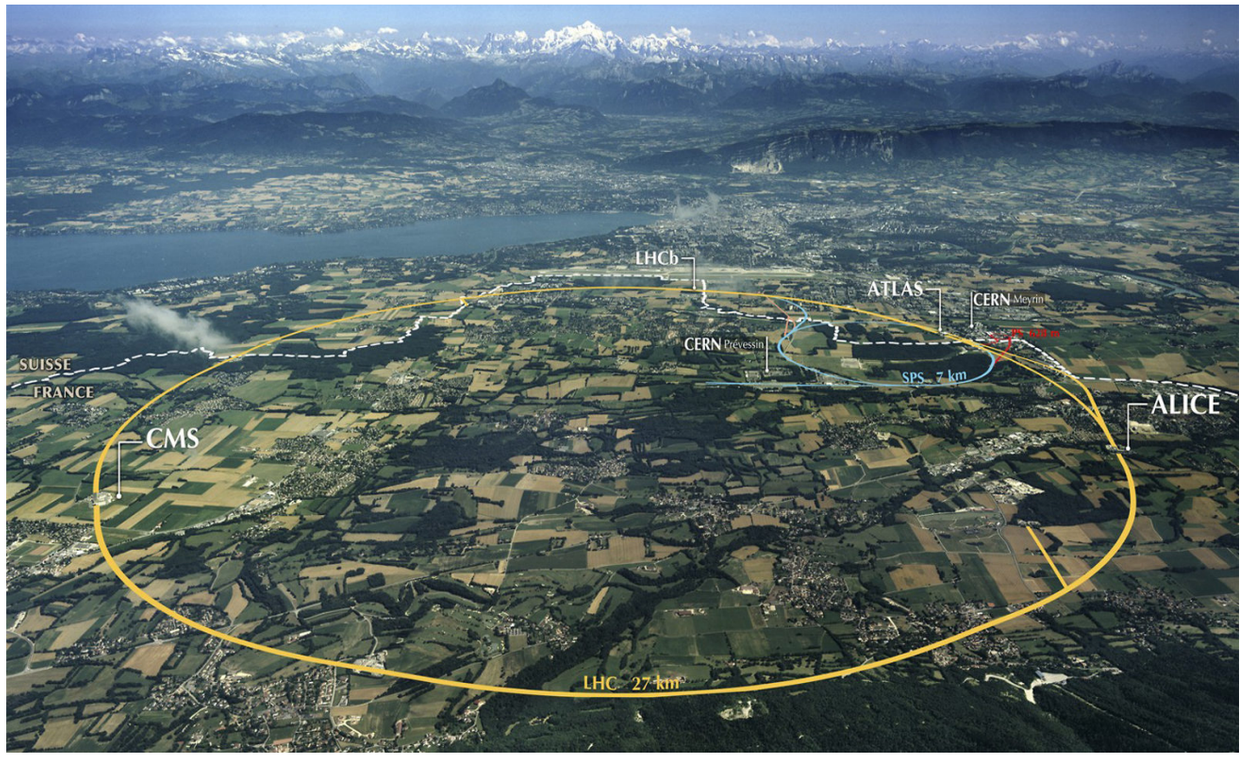

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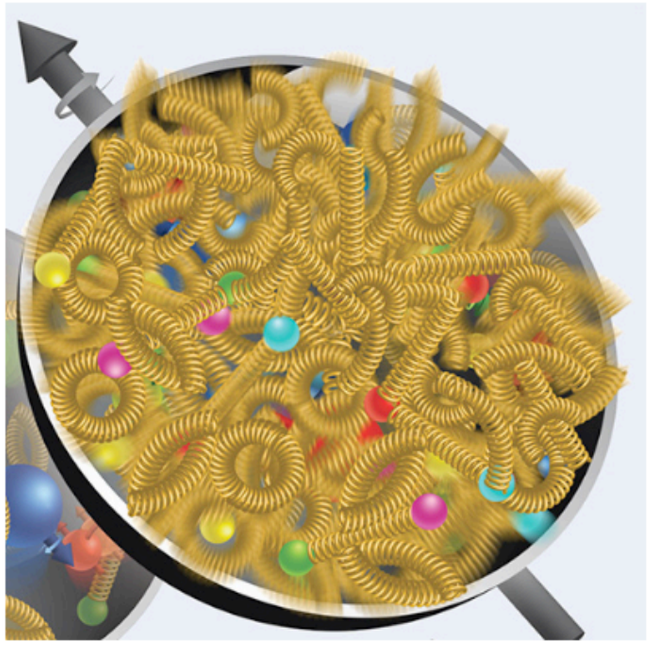
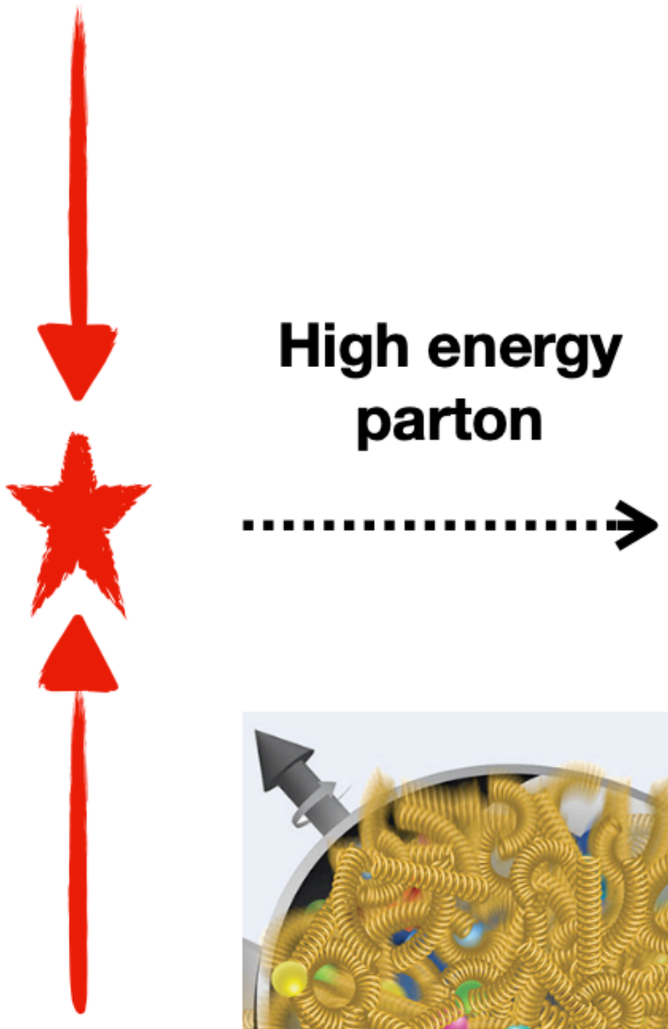
Observing quarks/gluons

High energy parton

High energy (hard) scattering of valence quarks, sea quarks or gluons



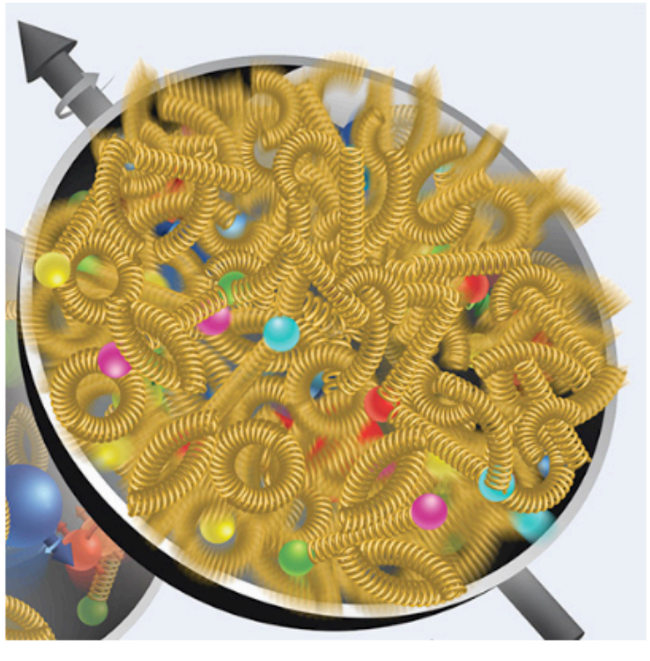
Observing quarks/gluons



High energy parton

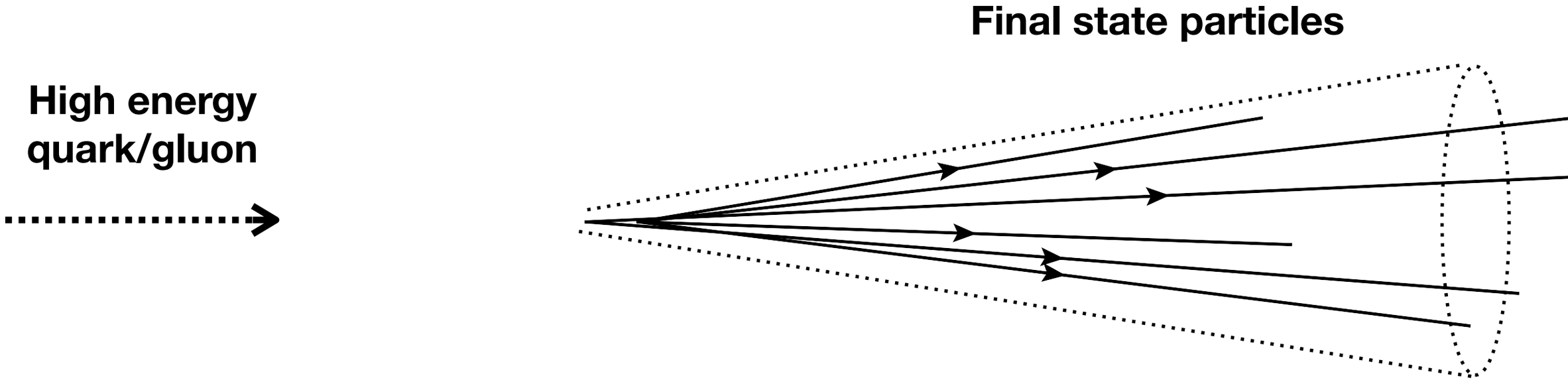
High energy (hard) scattering of valence quarks, sea quarks or gluons

What do we **see** in the experiment?



You already know the answer :)

Observing quarks/gluons in nature - Jets



Collimated collection of hadrons resulting from the '***metamorphosis***' of partons due to fragmentation and hadronization

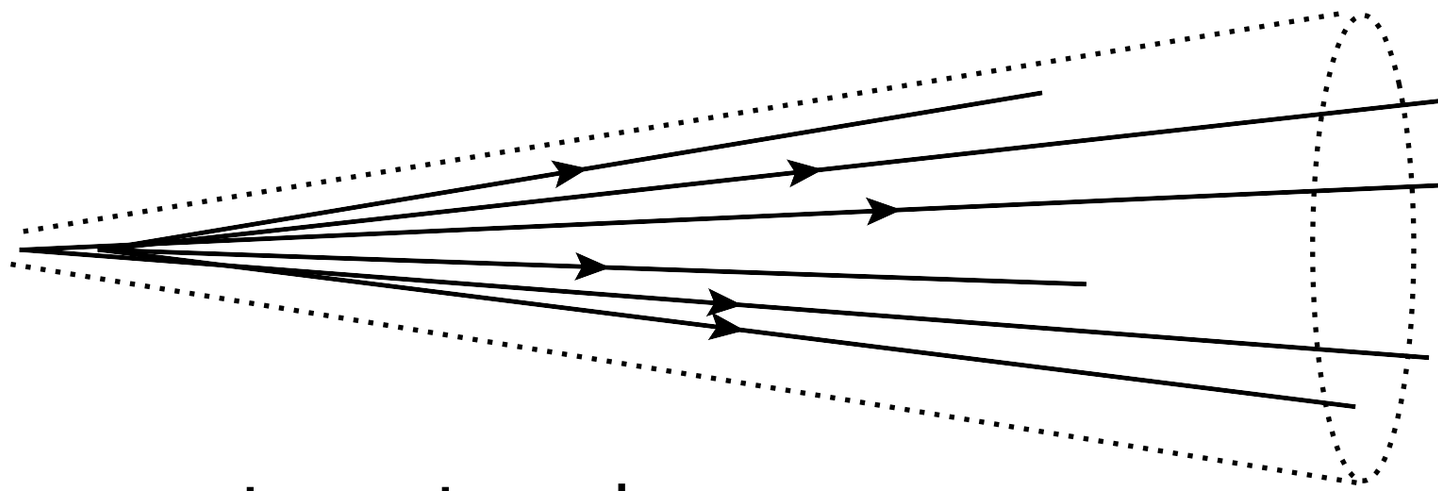
Gaillard et. al, Nucl. Phys. B111 (1976) 253-271

Metamorphosis

- How do we go from

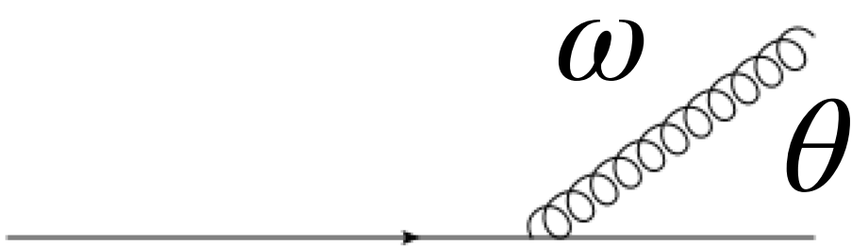
High energy quark/gluon

Final state particles



- Simplified version - there are two steps here
- Parton shower followed by hadronization
- What is a parton shower?

- Lets start with the basics of QCD - splitting functions



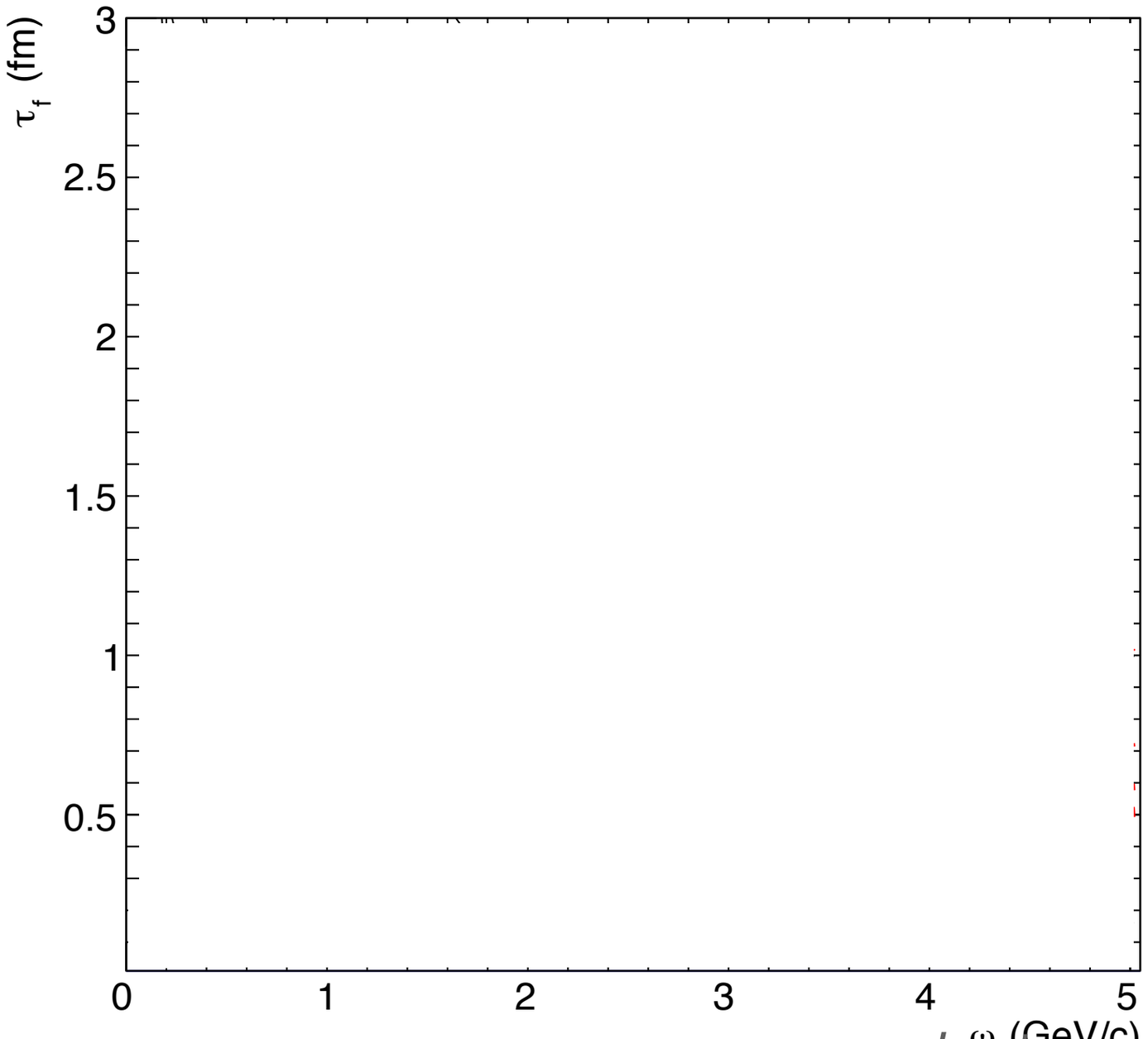
$$q \rightarrow q + g$$

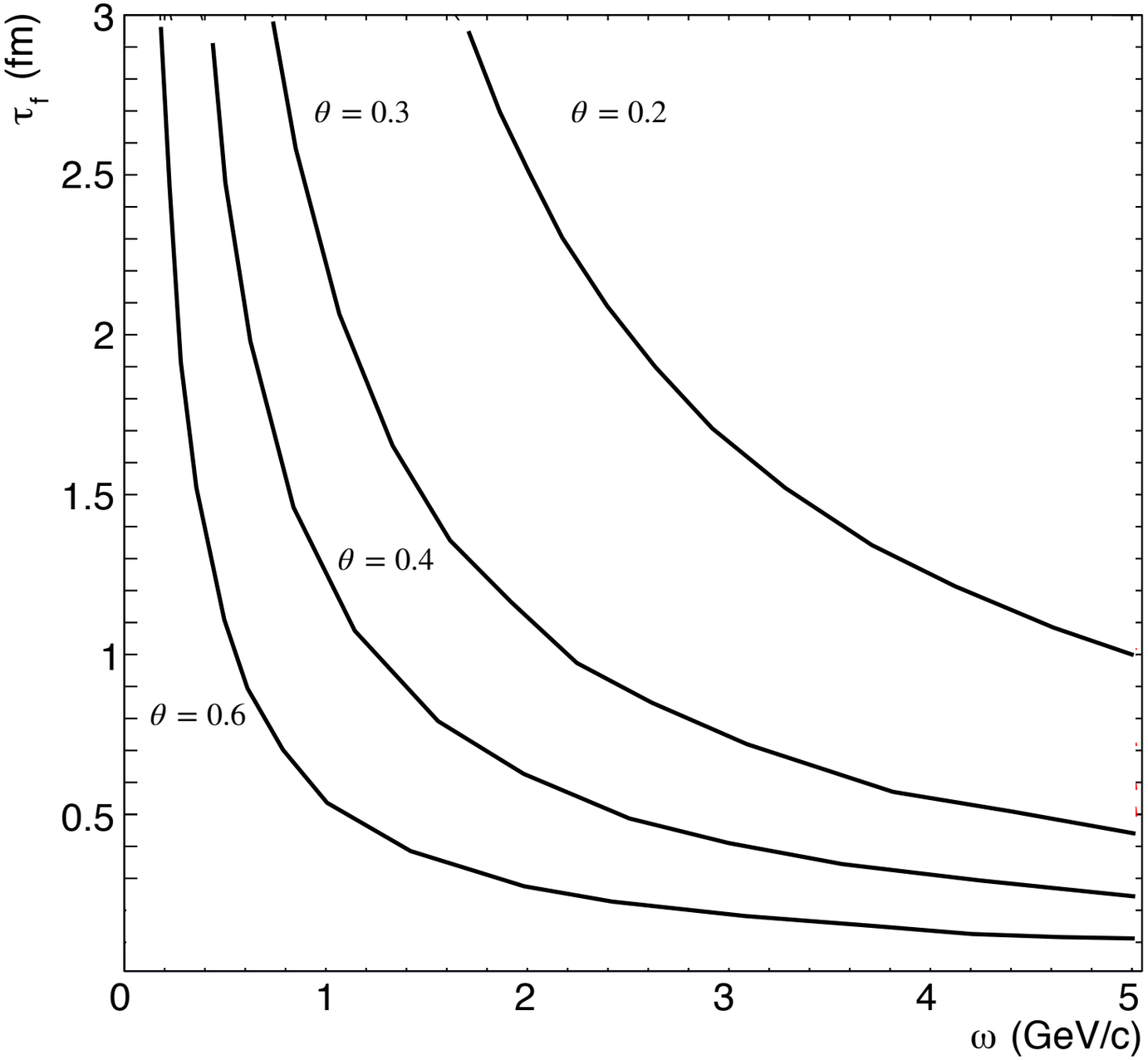
Splitting probabilities

$$dP \approx \frac{d\theta}{\theta}\frac{d\omega}{\omega}$$

formation times

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$





$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

Narrow emissions

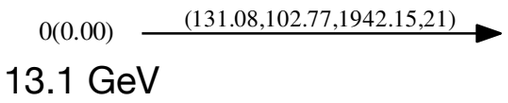
→

Later times

Wider emissions

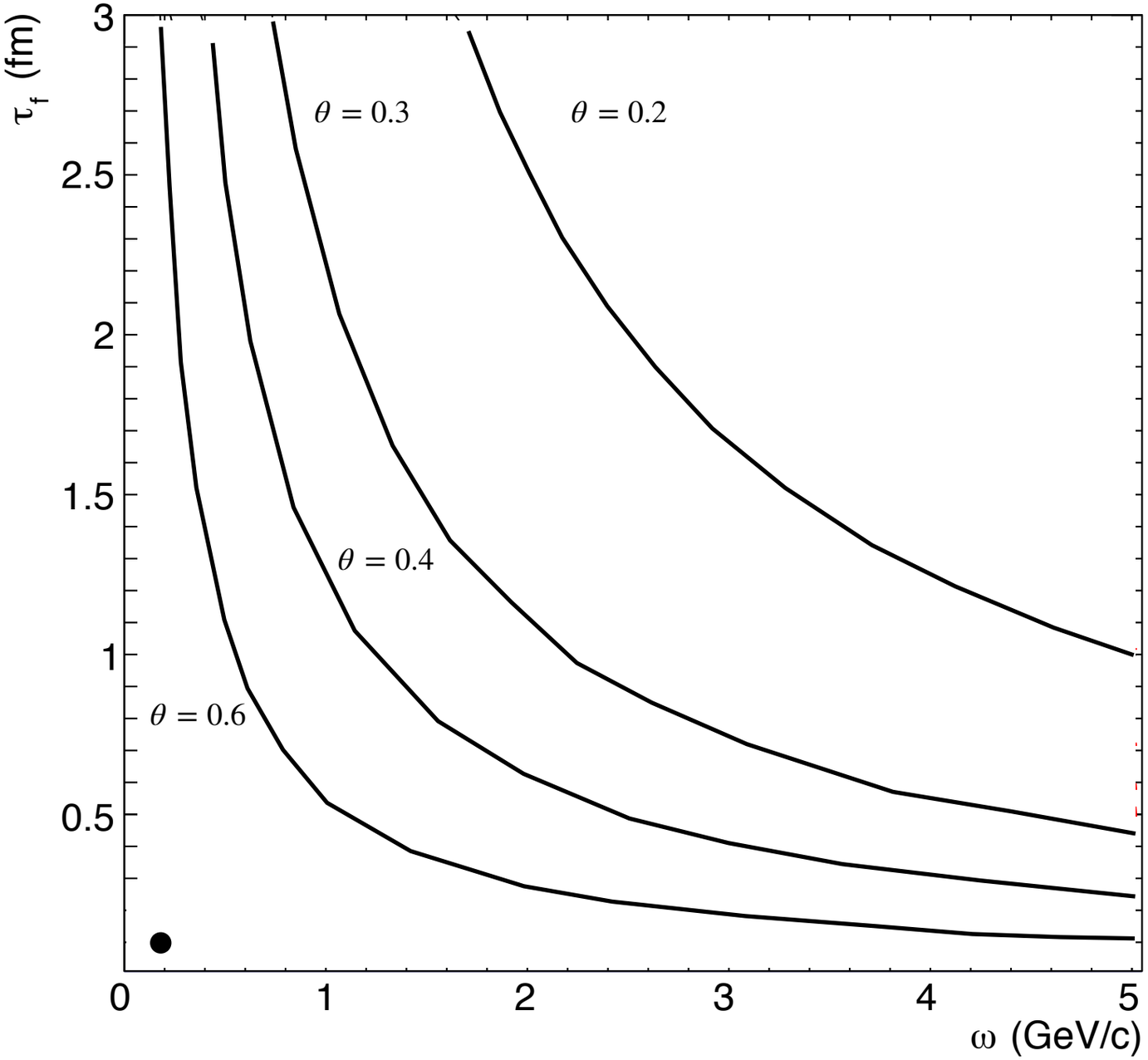
→

earlier times



Gluon jet

Particle Gun in PYTHIA 8
Parton Shower



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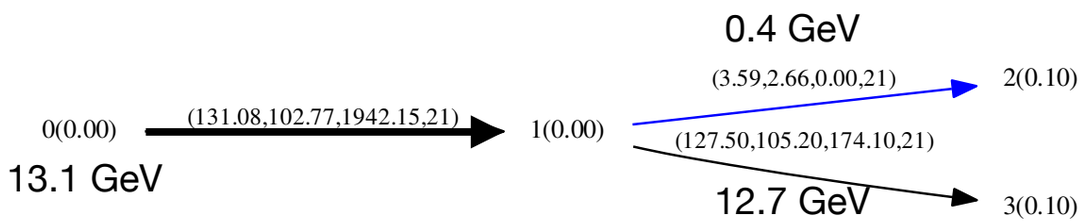
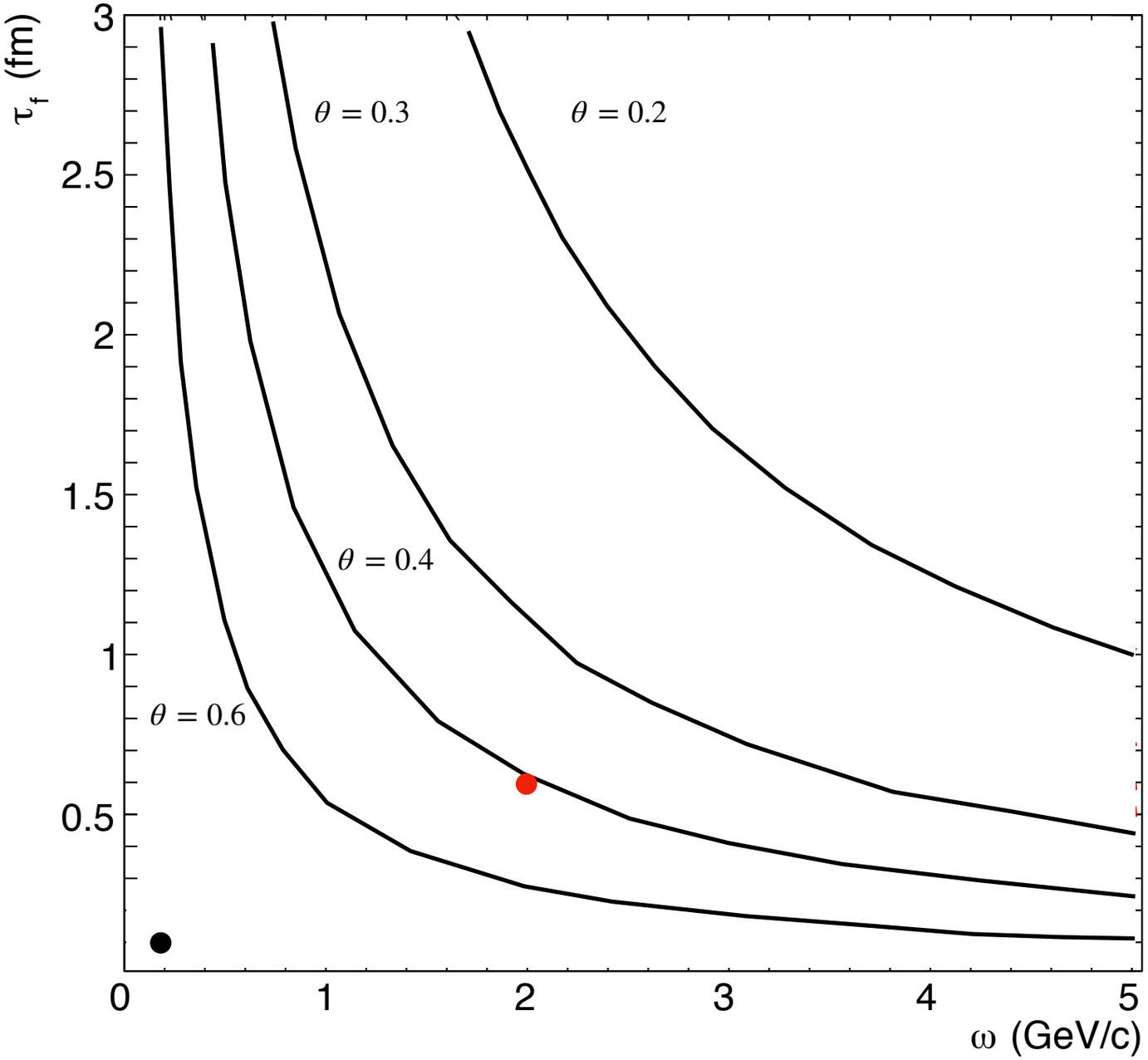


Gluon jet $g \rightarrow g + g$



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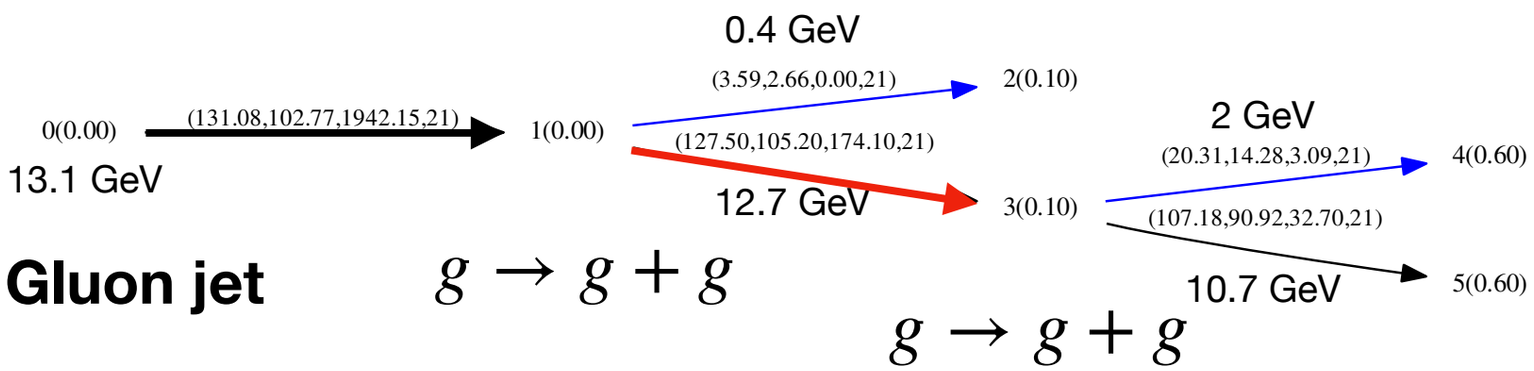
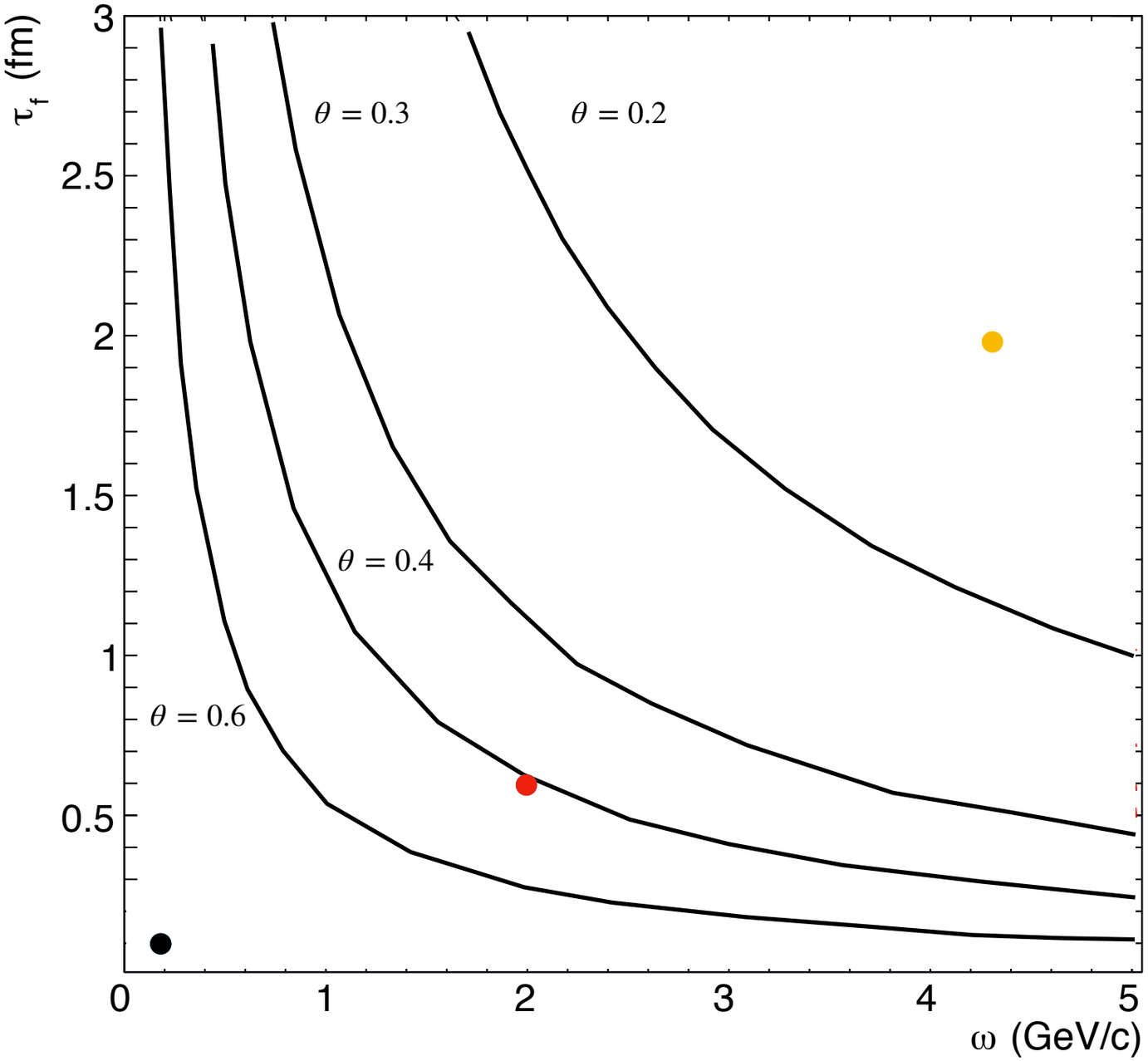


Gluon jet $g \to g + g$

$g \to g + g$

Particle Gun in PYTHIA 8

Parton Shower



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Narrow emissions

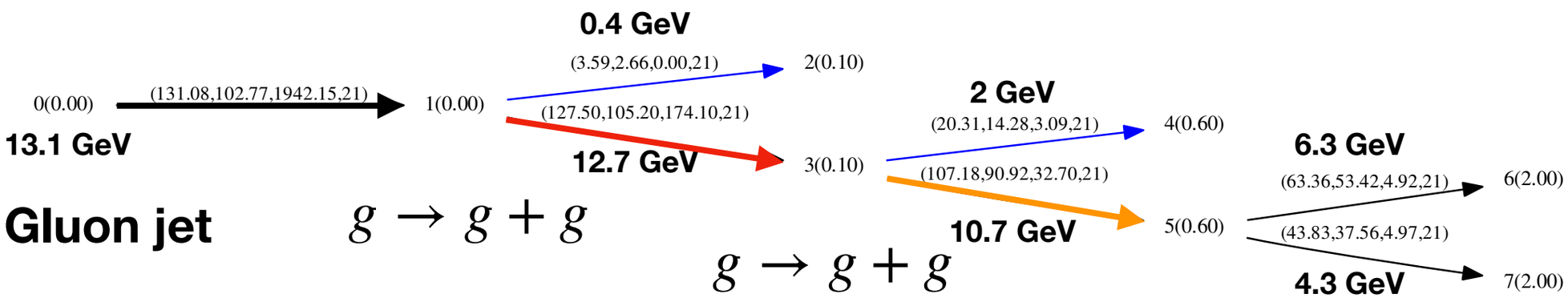
→

Later times

Wider emissions

→

earlier times



Gluon jet $g \to g + g$

$g \to g + g$

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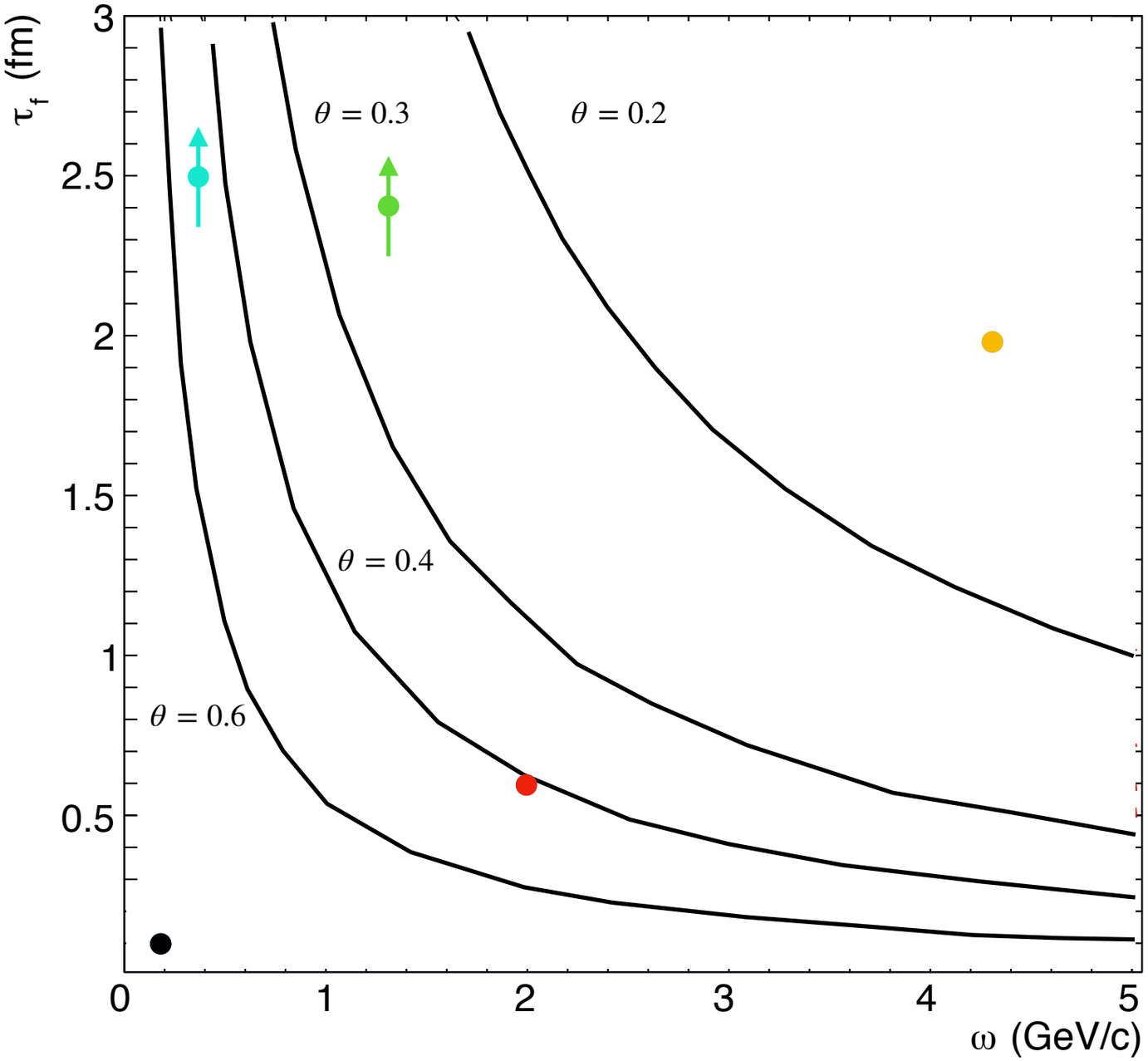
Particle Gun in PYTHIA 8

Parton Shower



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Narrow emissions

→

Later times

Wider emissions

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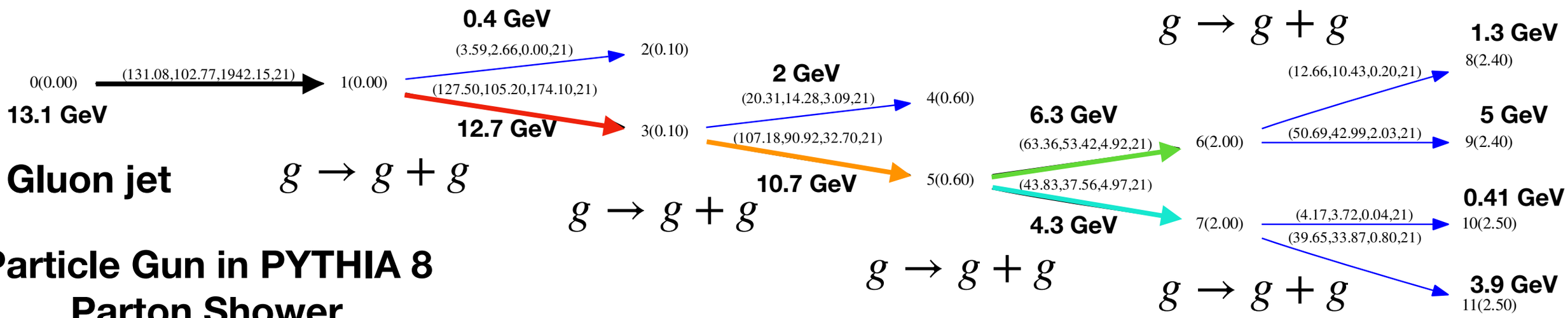
earlier times



Gluon jet

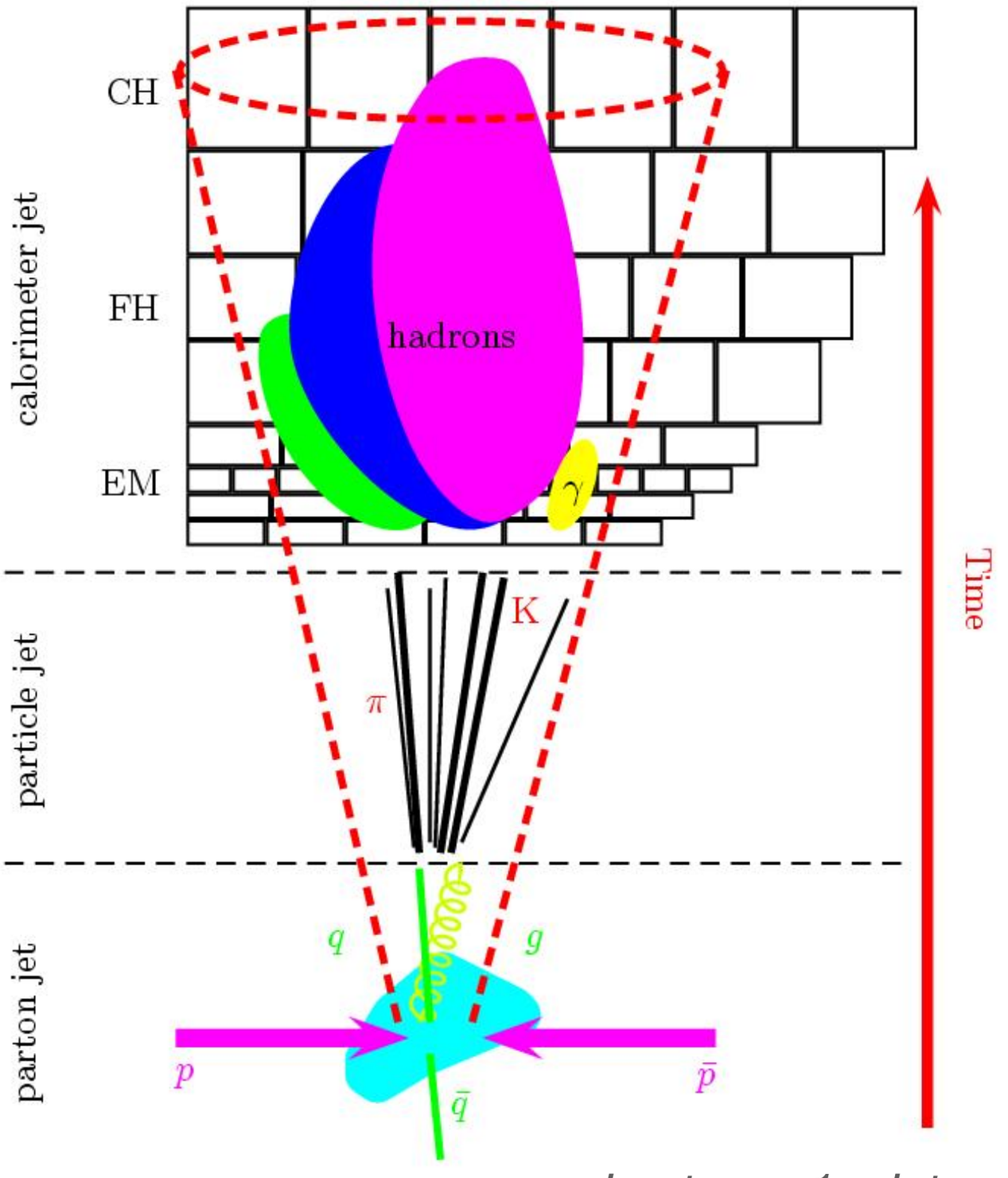
Particle Gun in PYTHIA 8

Parton Shower

Jets in experiment

- Jets are defined by a clustering algorithm, **characteristic angular scale** (Jet R) and their **momentum** (p_T)
- Jets can also have an **inherent angular scale (θ)** and a **momentum fraction (z)** due to vacuum splitting

$$dP \approx \frac{dz}{z}\frac{d\theta}{\theta}$$

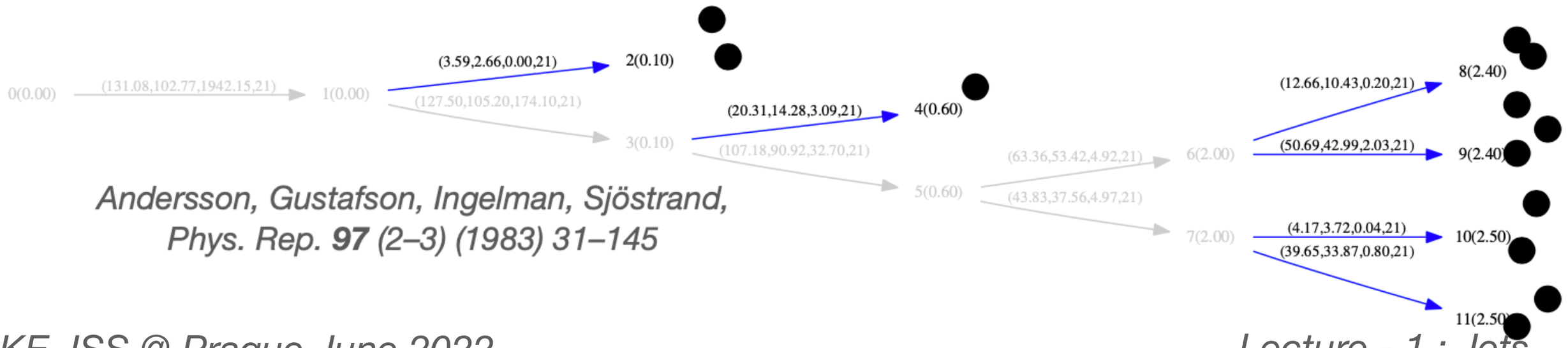


What do we want to measure?

- We want to translate an *intrinsic* (and unmeasurable) parton shower to **experimentally accessible** observable(s)

- We start with the hadronized remnants of the parton shower

Lund string model decided that the 6 partons converted into 12 final-state particles



*Andersson, Gustafson, Ingelman, Sjöstrand, Phys. Rep. **97** (2–3) (1983) 31–145*

What do we want to measure?

- We want to translate an *intrinsic* (and unmeasurable) parton shower to **experimentally accessible** observable(s)

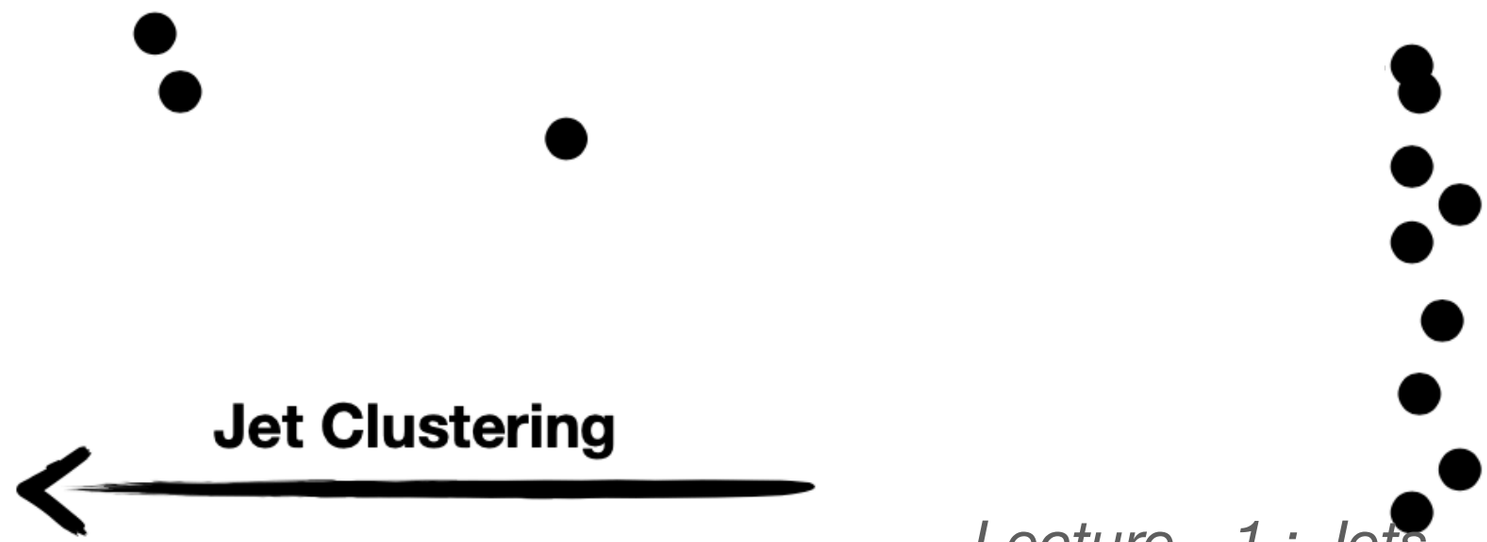
- Run jet clustering algorithms staring from the final state hadrons based on momentum weighted distance criterion

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

FastJet 3.3.4

Cacciari, Salam, Soyez,
Eur. Phys. J. C 72 (2012) 1896

Cacciari, Salam,
Phys. Lett. B 641 (2006) 57



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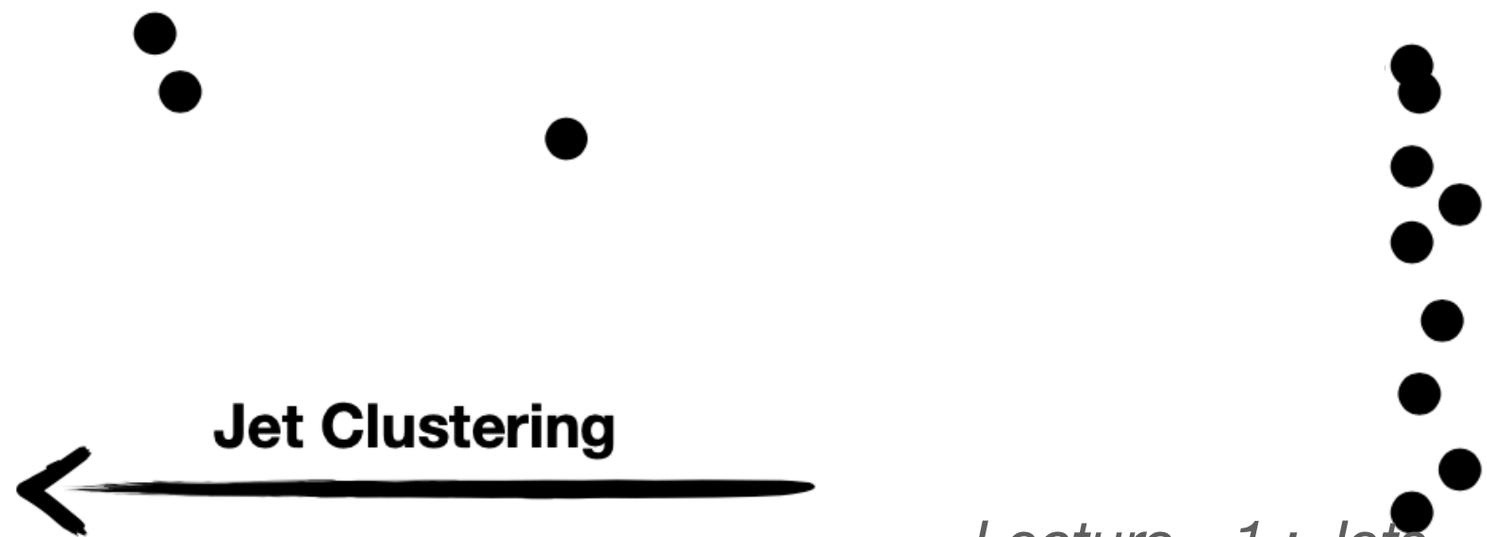
$$\min(p_{ti}^{2p}, p_{tj}^{2p})\,\Delta R_{ij}^2/R^2$$

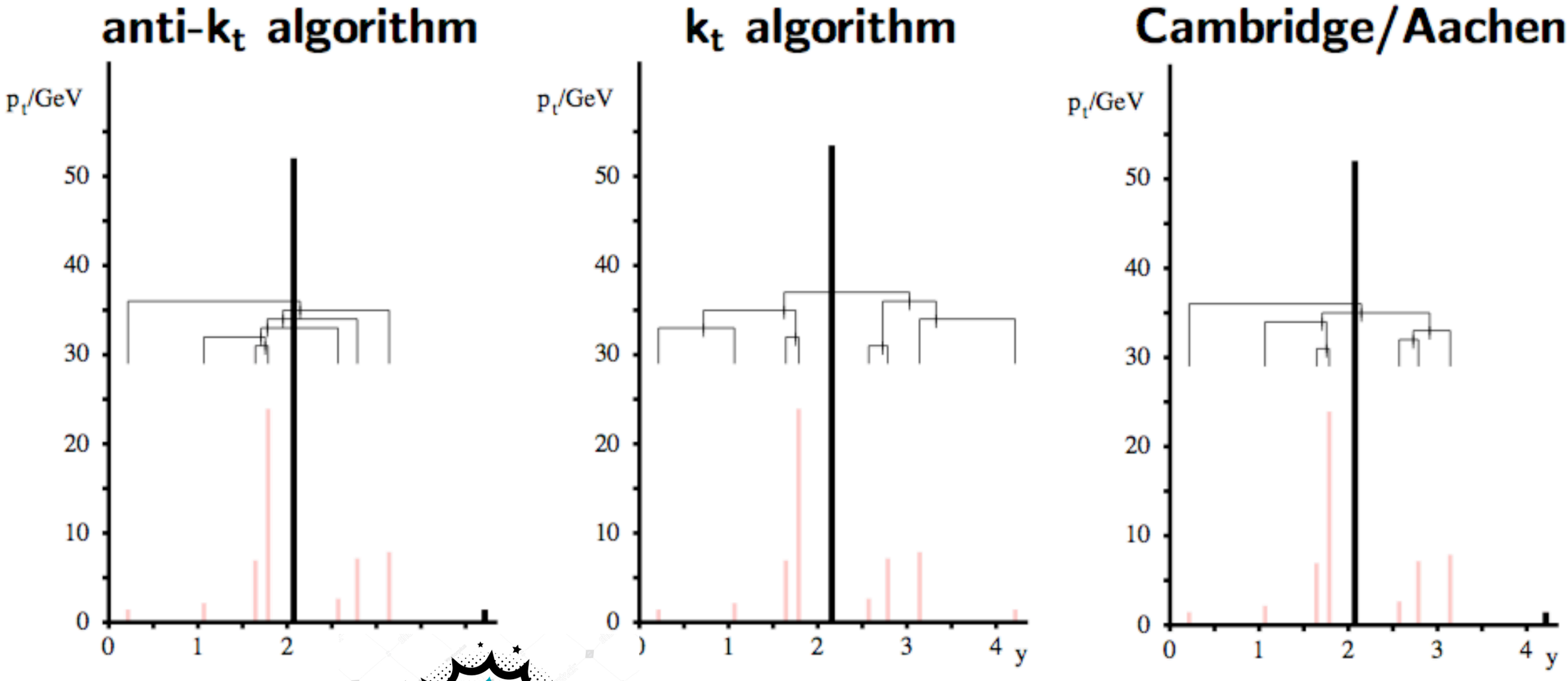
$p = 1$ k_T

$p = 0$ C/A

$p = -1$ anti-k_T



Clustering algorithms



Which of the clustering trees is ‘realistic’?

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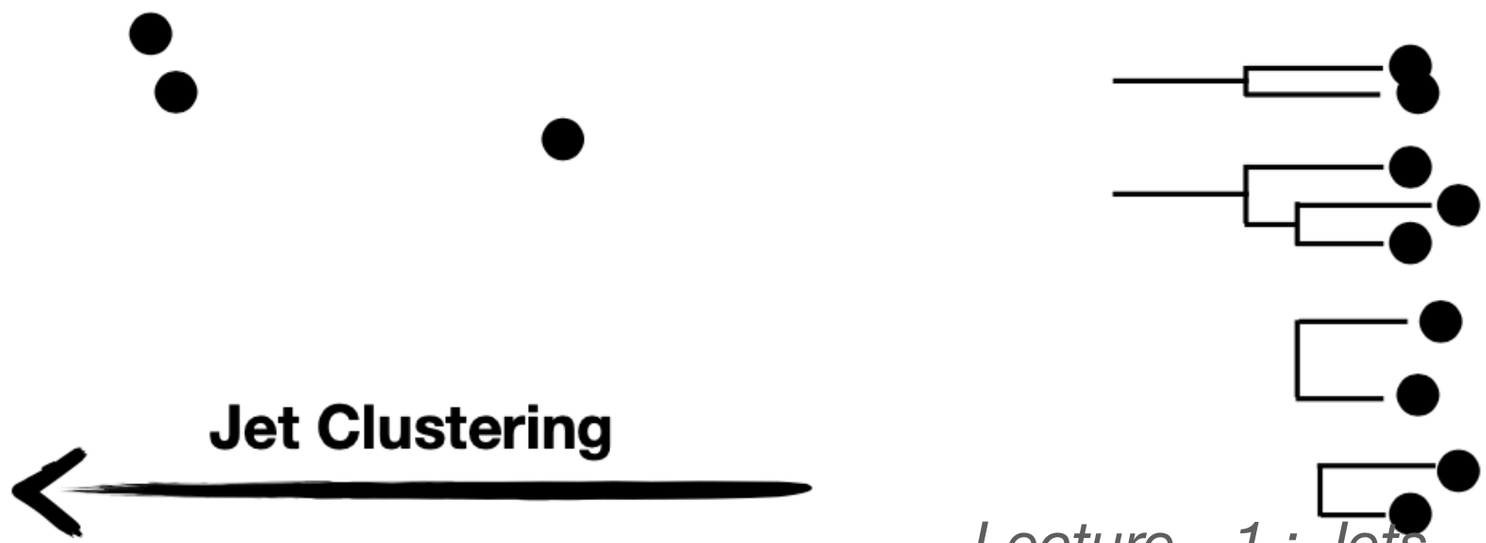
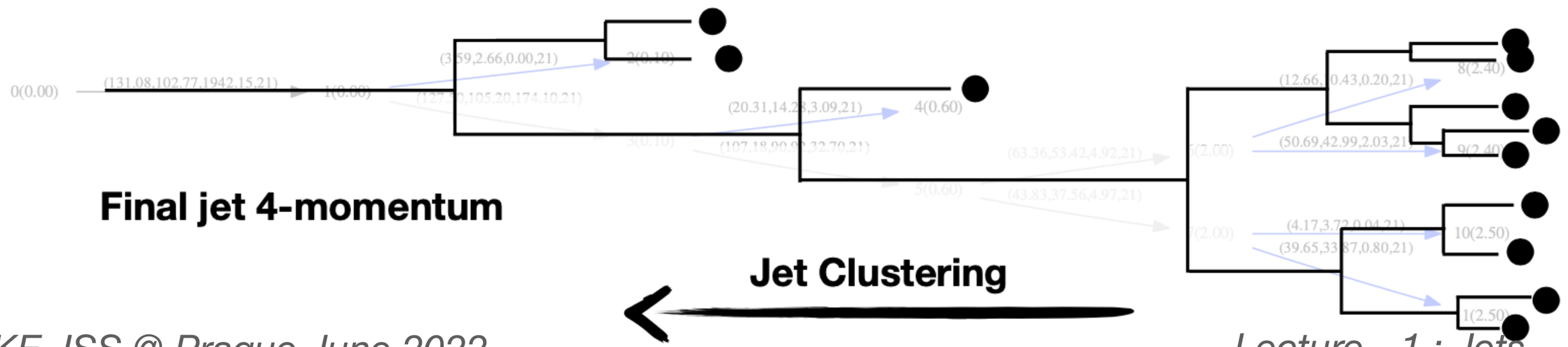


What do we want to measure?

- We want to translate an *intrinsic* (and unmeasurable) parton shower to **experimentally accessible** observable(s)

- Run jet clustering algorithms staring from the final state hadrons based on momentum weighted distance criterion

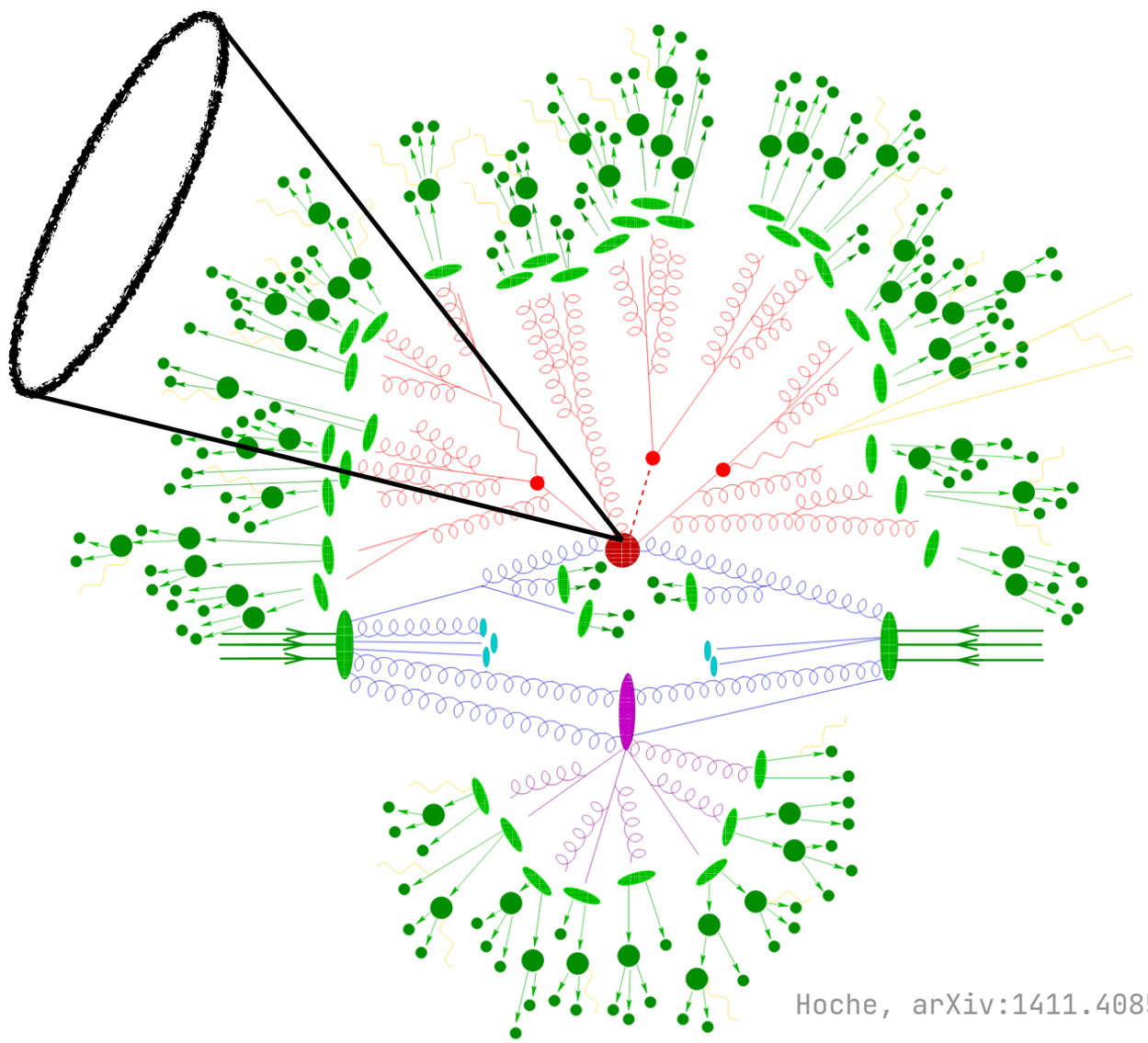


Recap - 1

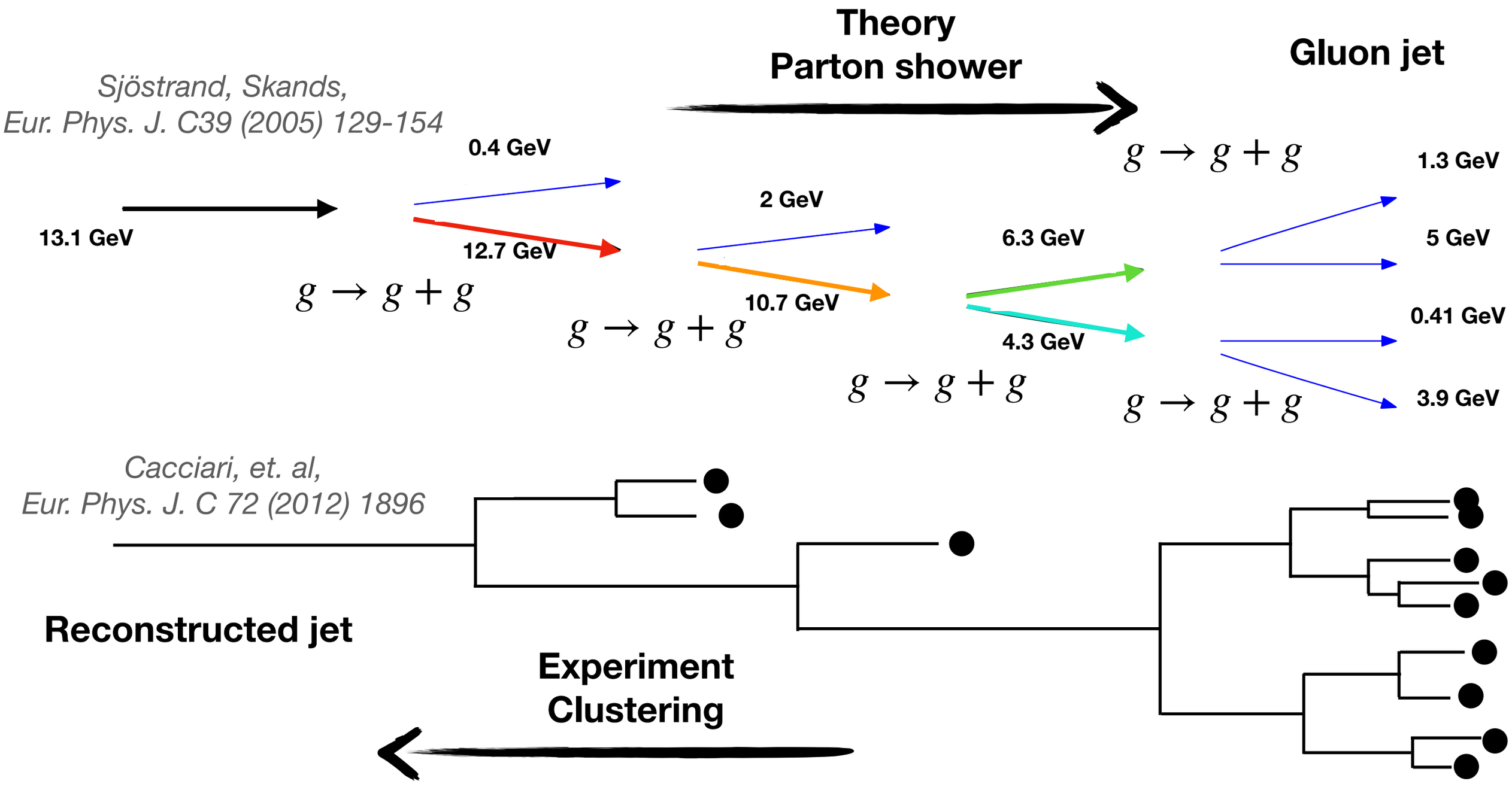
- Jet — Collection of particles grouped by an iterative algorithm

- With an appropriate jet radius and constituent momentum threshold, you hope to recover the originating parton

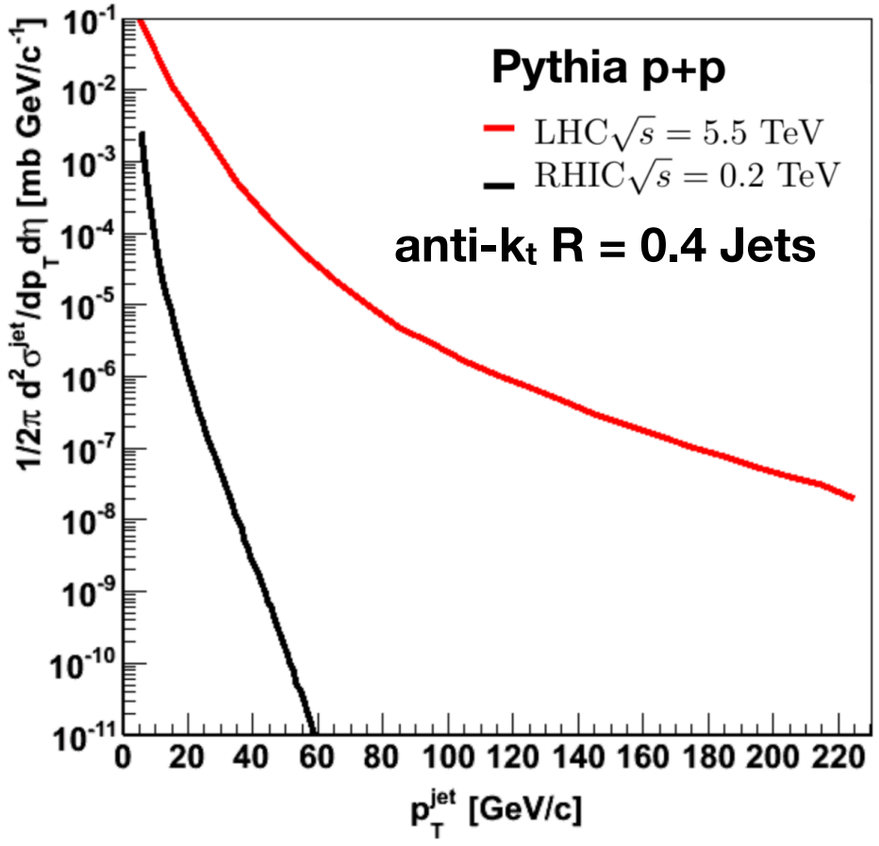
- Jets work as proxy to hard scattered q/g



Jet correspondence



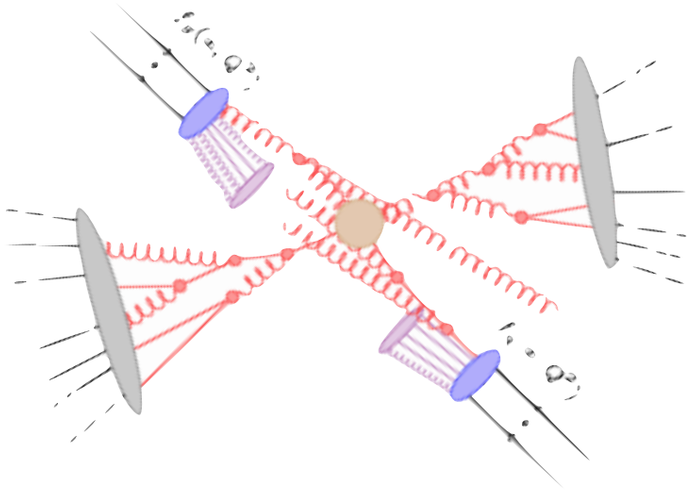
Ingredients in calculating jet spectra



- Calculable via QCD factorization
- Steeper cross-section at RHIC compared to the LHC

Jet production in high energy collisions of hadrons can be described in terms of following ingredients:

- *Initial state of hadrons*
- *Hard collision of partons*
- *Parton Shower*
- *Underlying Event (UE)*
- *Hadronization*

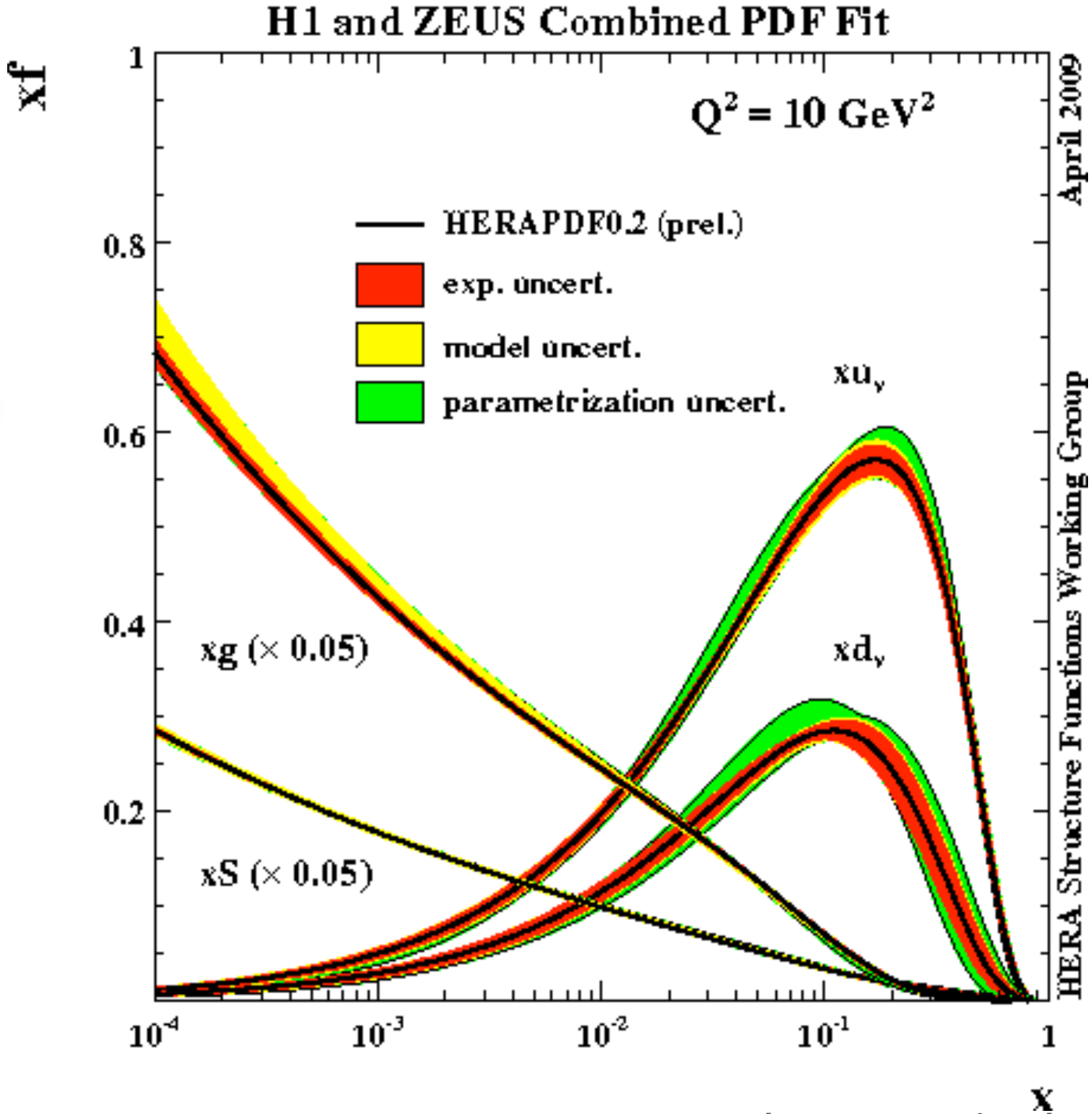


$$d\sigma_{pp\to jet+X}(Q^2) = \sum_{a,b} \int \underbrace{f_a(x_1,Q^2) f_b(x_2,Q^2)}_{\text{proton structure}} \underbrace{d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2)}_{\text{hard process+PS+Had.}} dx_1 dx_2$$

$$d\sigma_{pp\to jet+X}(Q^2) = \sum_{a,b} \int \underbrace{f_a(x_1,Q^2) f_b(x_2,Q^2)}_{\text{proton structure}} \underbrace{d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2)}_{\text{hard process+PS+Had.}} dx_1 dx_2$$

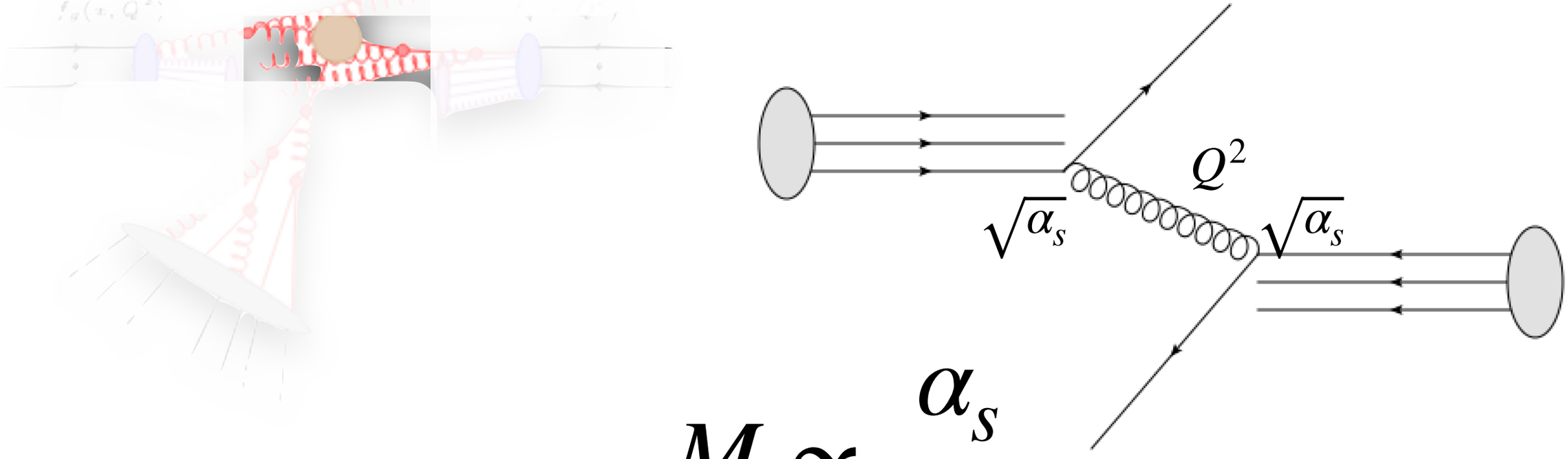
Parton Distribution Functions

$$f_a(x,Q^2)$$



$$d\sigma_{pp\to jet+X}(Q^2) = \sum_{a,b} \int \underbrace{f_a(x_1,Q^2) f_b(x_2,Q^2)}_{\text{proton structure}} \underbrace{d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2)}_{\text{hard process+PS+Had.}} dx_1 dx_2$$

Hard process - matrix element calculation



$$M \propto \frac{\alpha_s}{Q^2}$$

$$d\sigma_{pp\to jet+X}(Q^2) = \sum_{a,b} \int \underbrace{f_a(x_1,Q^2) f_b(x_2,Q^2)}_{\text{proton structure}} \underbrace{d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2)}_{\text{hard process}} dx_1 dx_2 \otimes \underbrace{\text{PS}}_{\text{+PS}} \otimes \underbrace{\text{Had.}}_{\text{+Had.}}$$

Parton Shower

$$\frac{d}{d\ln Q^2}\begin{pmatrix} q \\ g \end{pmatrix} = \begin{pmatrix} P_{q\leftarrow q} & P_{q\leftarrow g} \\ P_{g\leftarrow q} & P_{g\leftarrow g} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

Splitting functions are:

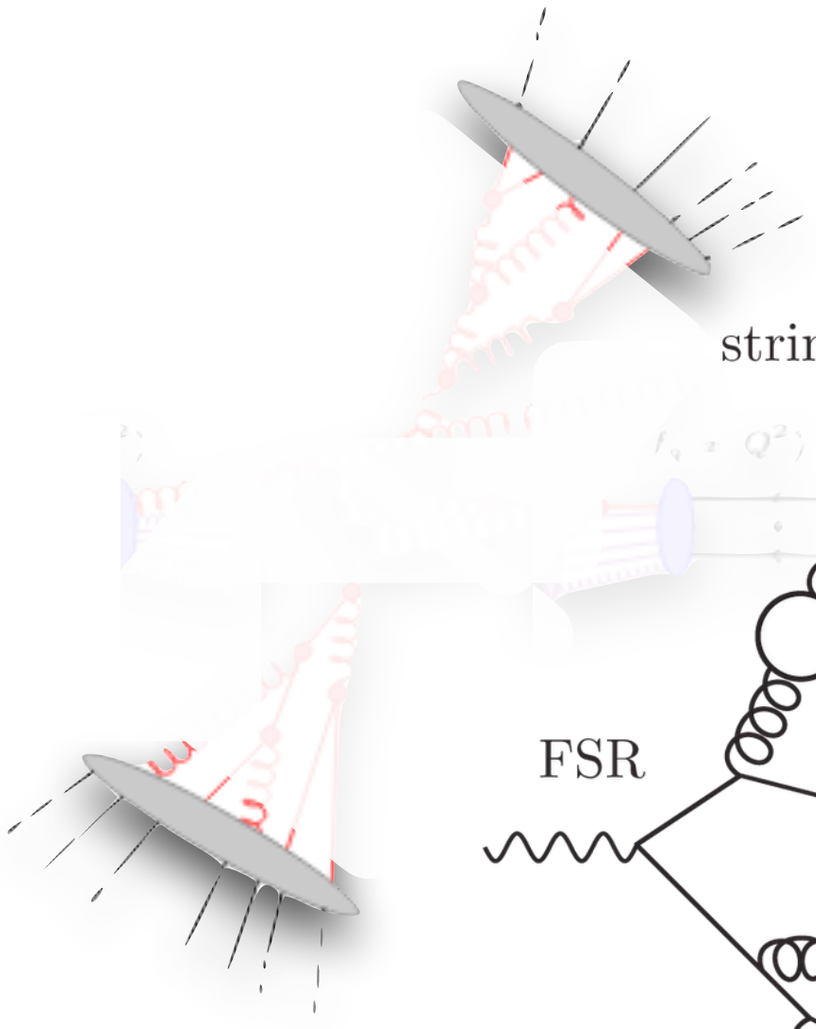
$$P_{qg}(z) = T_R\left[z^2 + (1-z)^2\right],$$

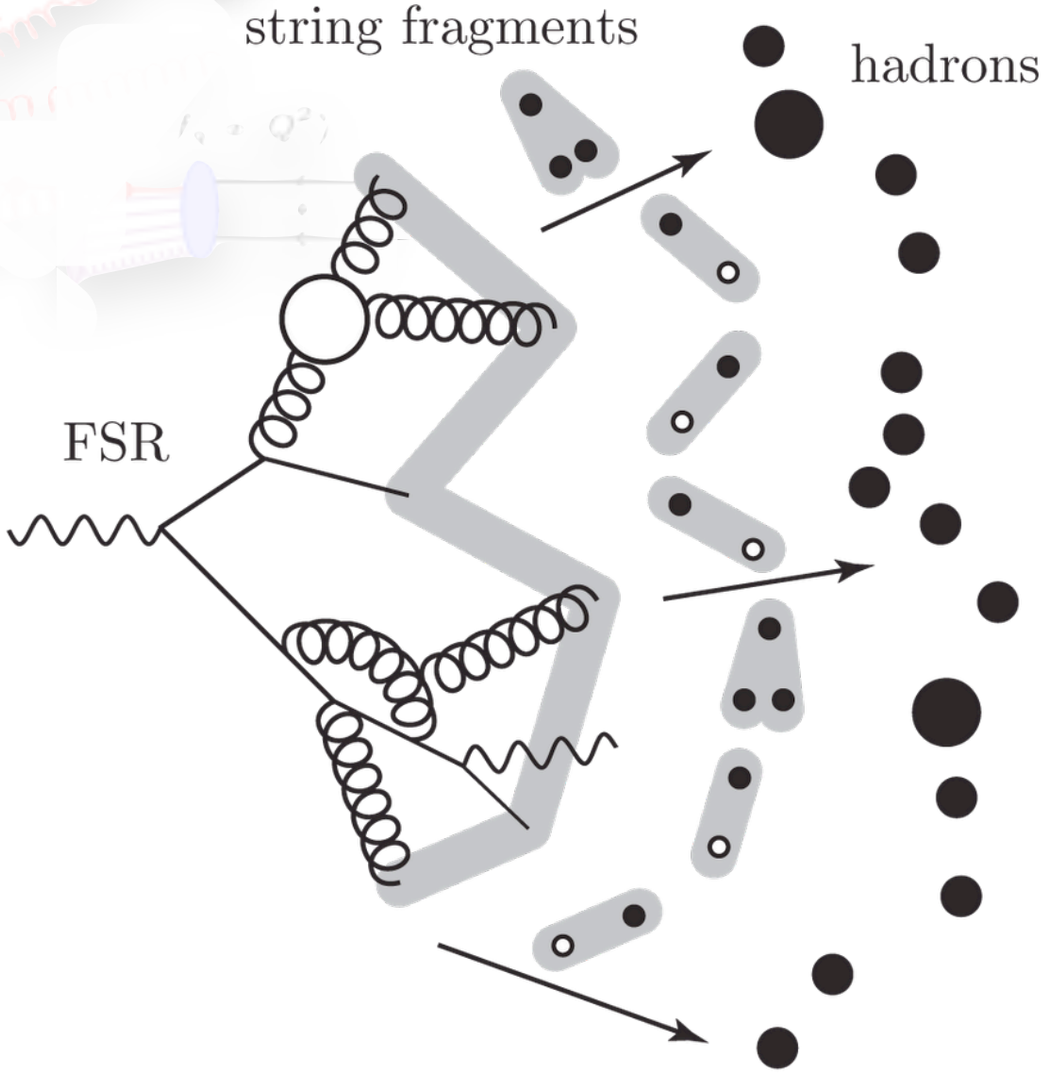
$$P_{gg}(z) = 2C_A\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z)\right] + \delta(1-z)\frac{(11C_A - 4n_f T_R)}{6}.$$

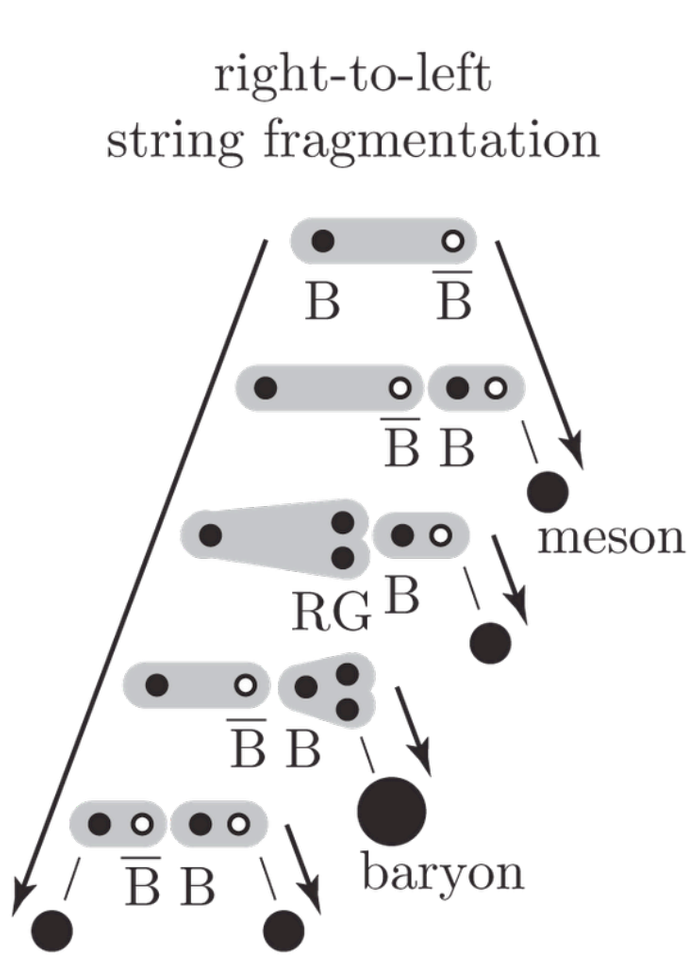
$$P_{gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right]$$

$$d\sigma_{pp\to jet+X}(Q^2) = \sum_{a,b} \int \underbrace{f_a(x_1,Q^2) f_b(x_2,Q^2)}_{\text{proton structure}} \underbrace{d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2)}_{\text{hard process+PS+Had.}} dx_1 dx_2$$

Hadronization

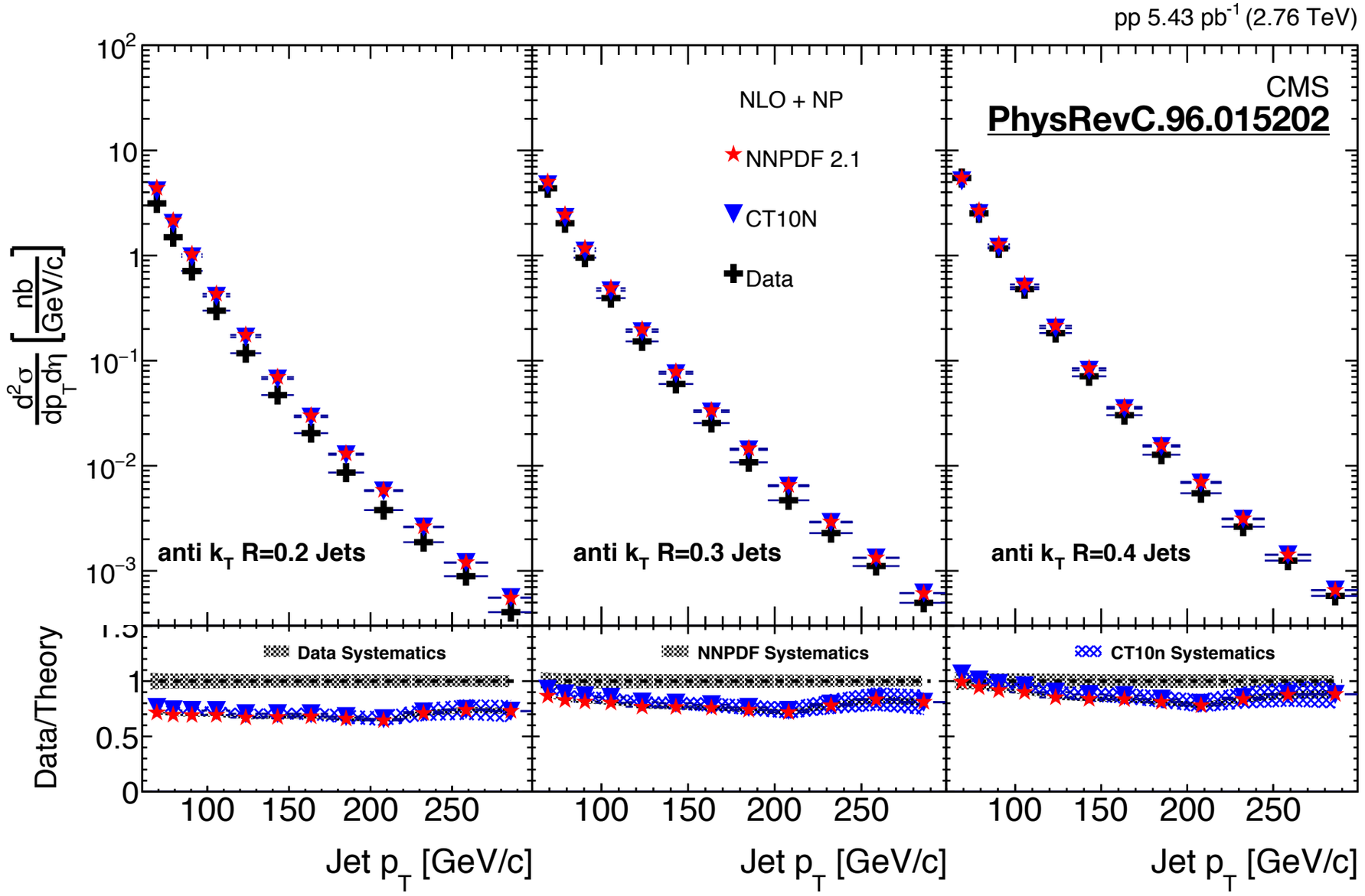




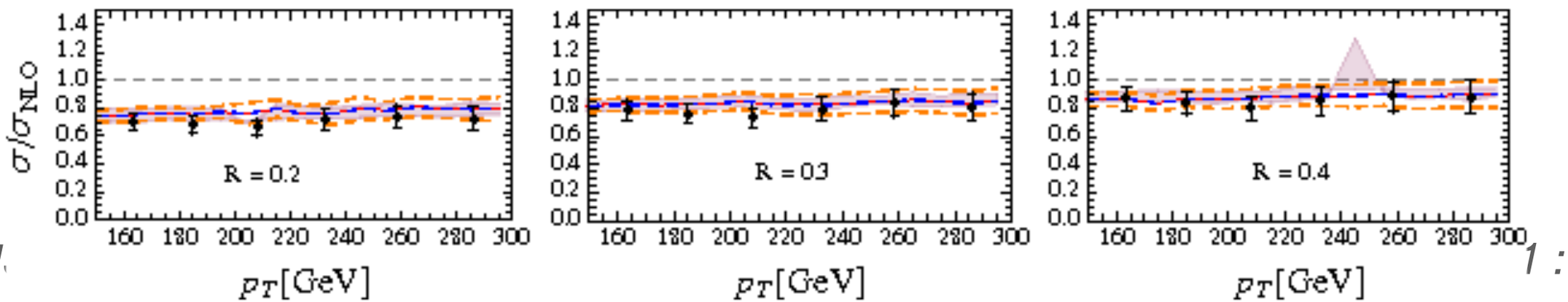


pp jet Spectra @ LHC

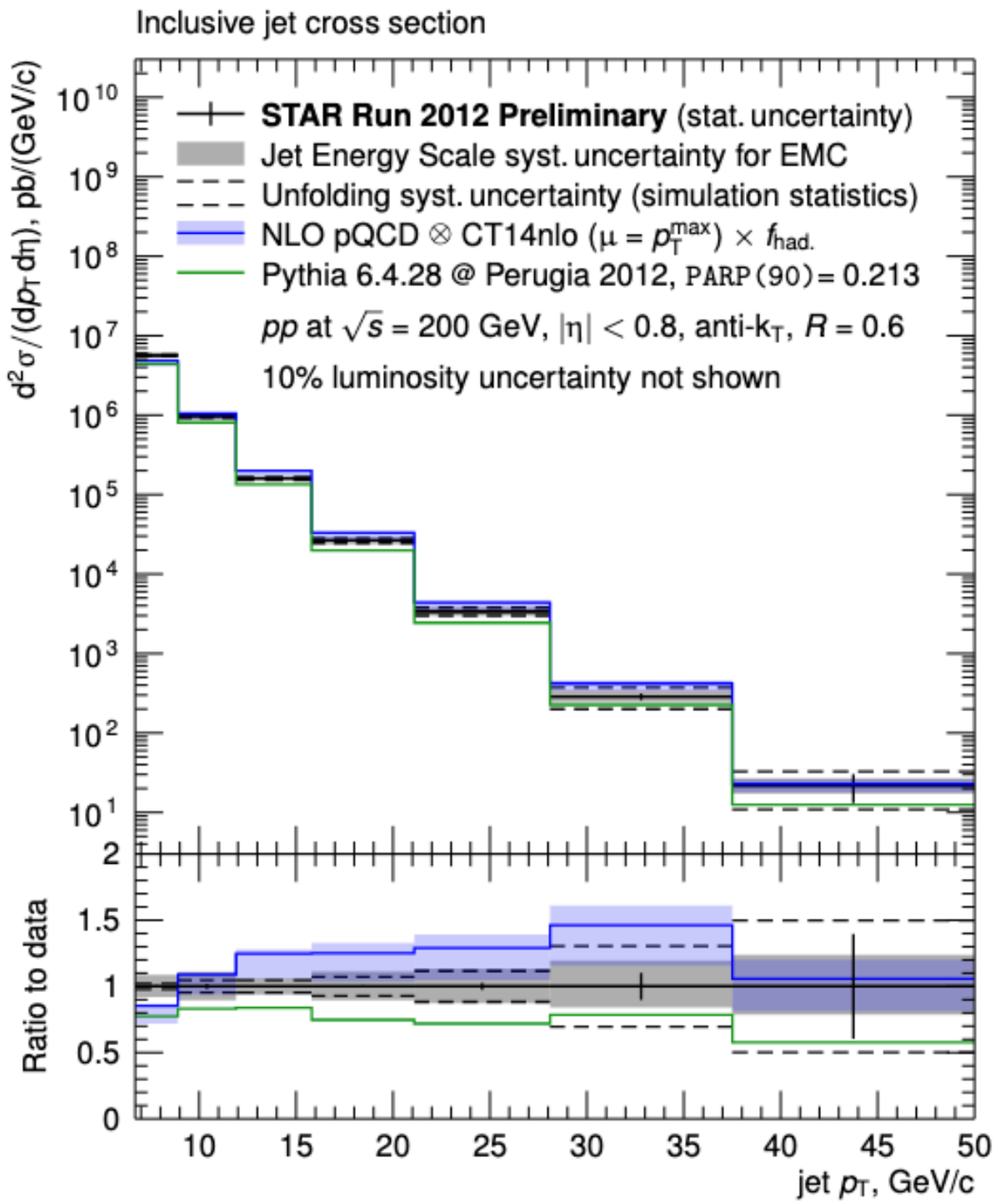
- Unfolded Jet Cross section overestimated by NLO+NP
- Resummations in ln r vital
- At NNLO these corrections are quite significant

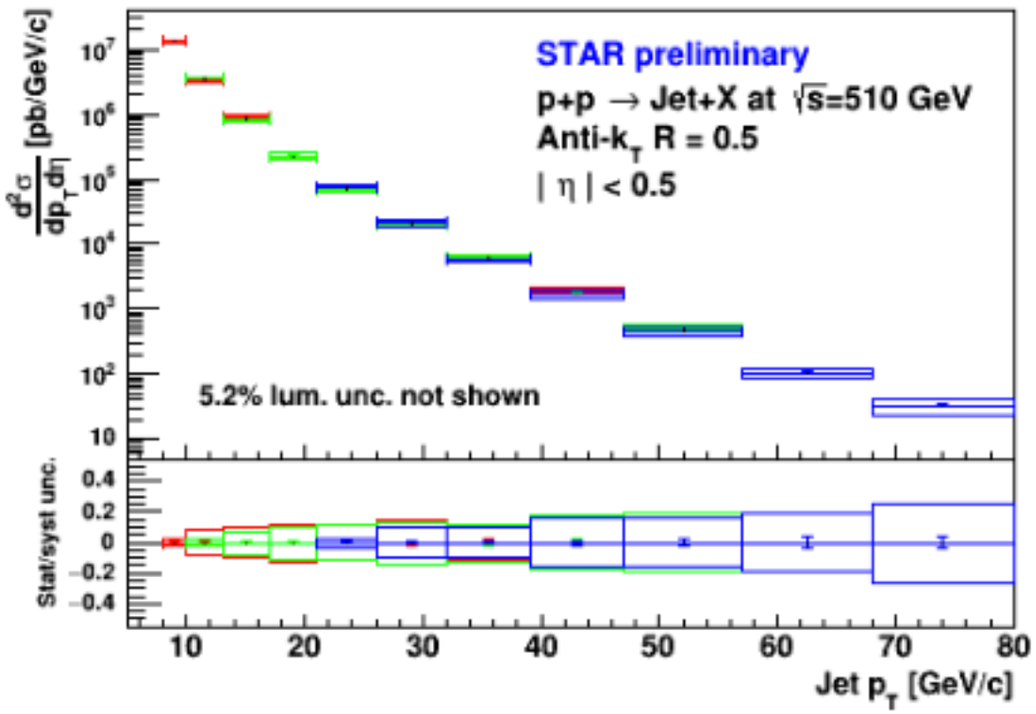


Xiaohui Liu et.al PRL 119 212001



pp jet spectra @ RHIC

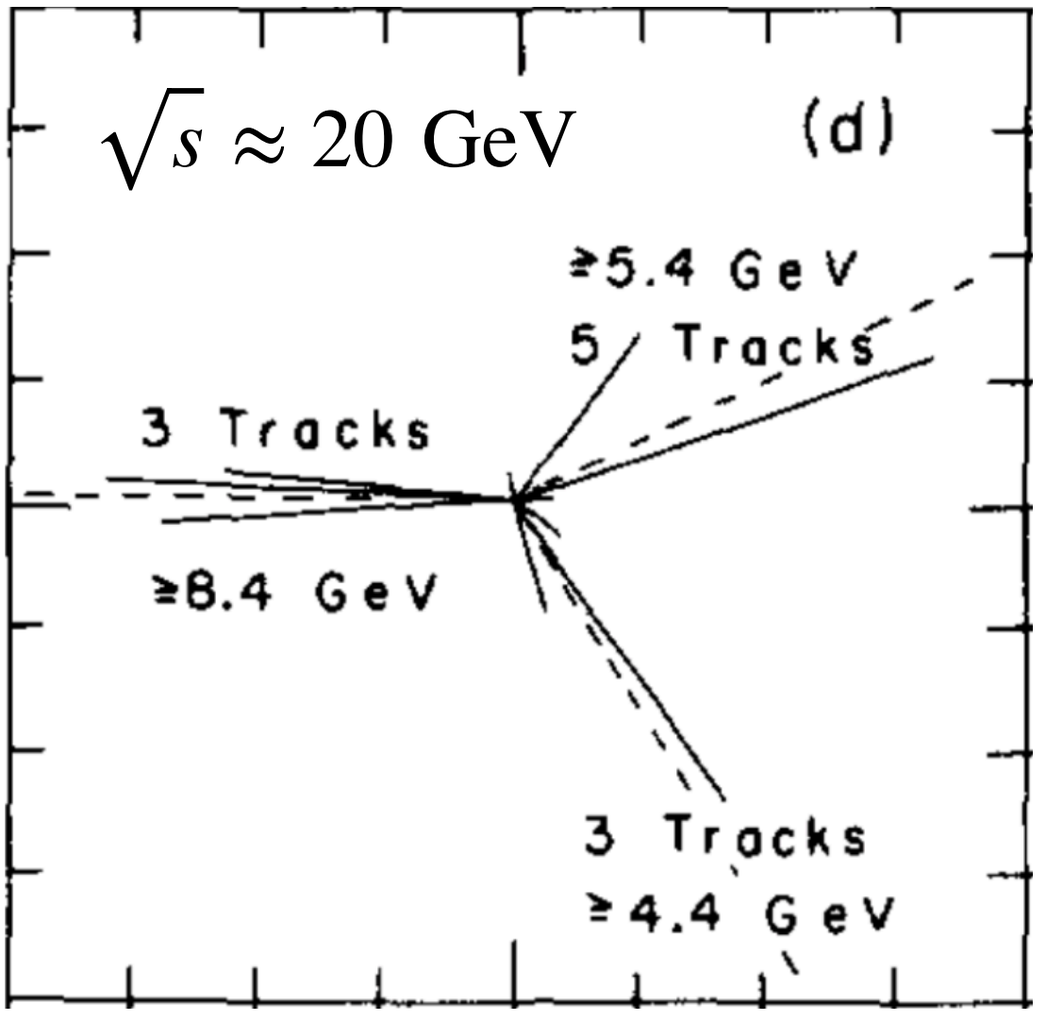




- Steeper spectra also consistent with NLO but highlighting regions tension
- Measurements at varying $\sqrt{s}$ will provide insights into energy dependence of various MC parameters

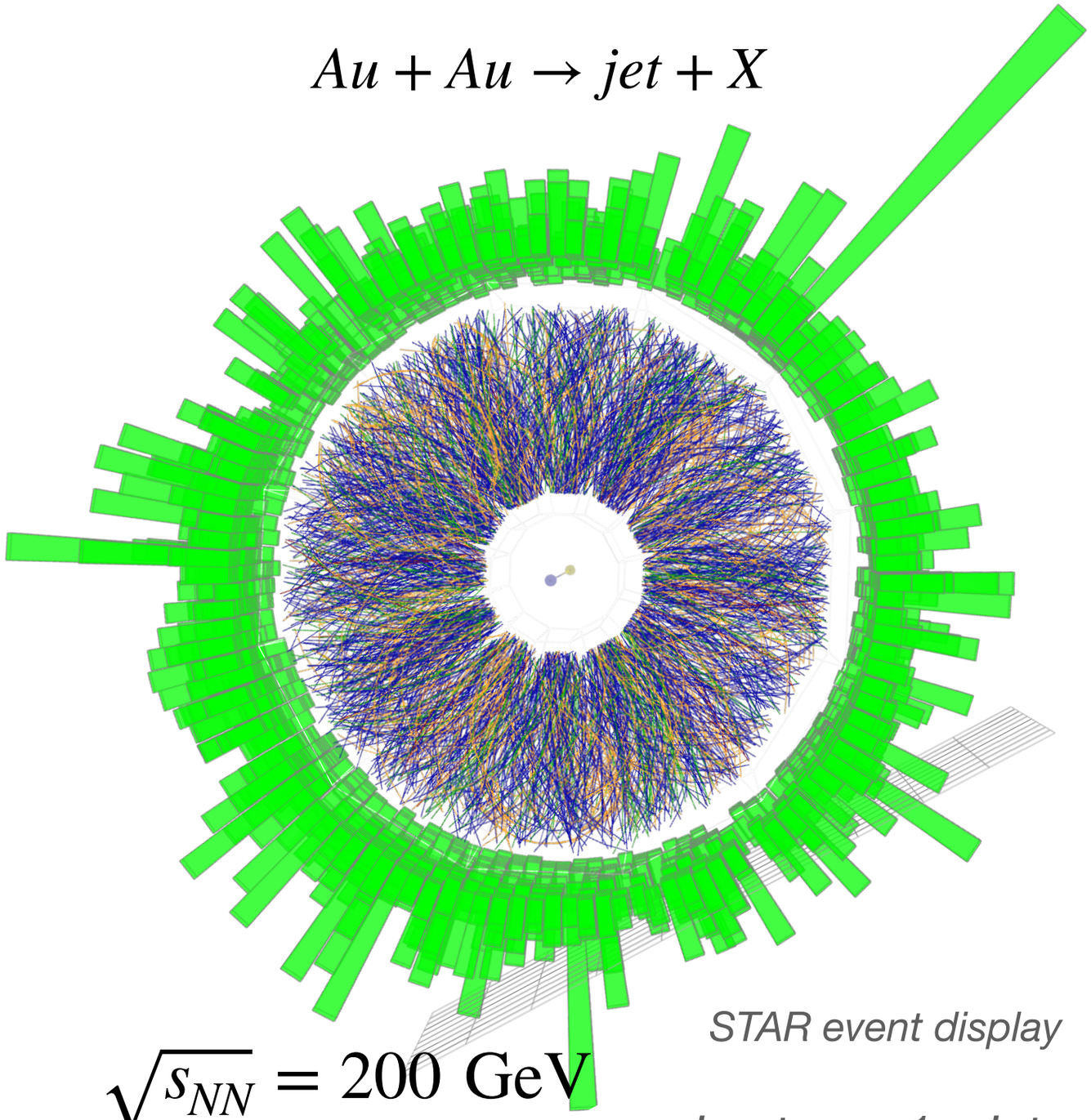
Observing quarks/gluons in nature - Jets

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



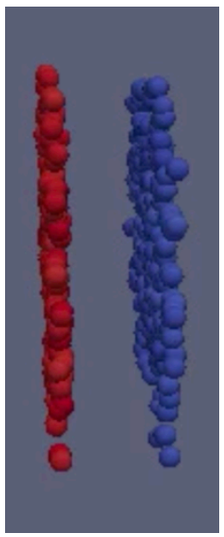
TASSO Phys. Lett, V 86B number 2 (1979)

$Au + Au \rightarrow jet + X$



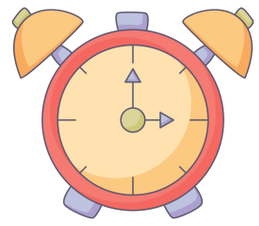
STAR event display

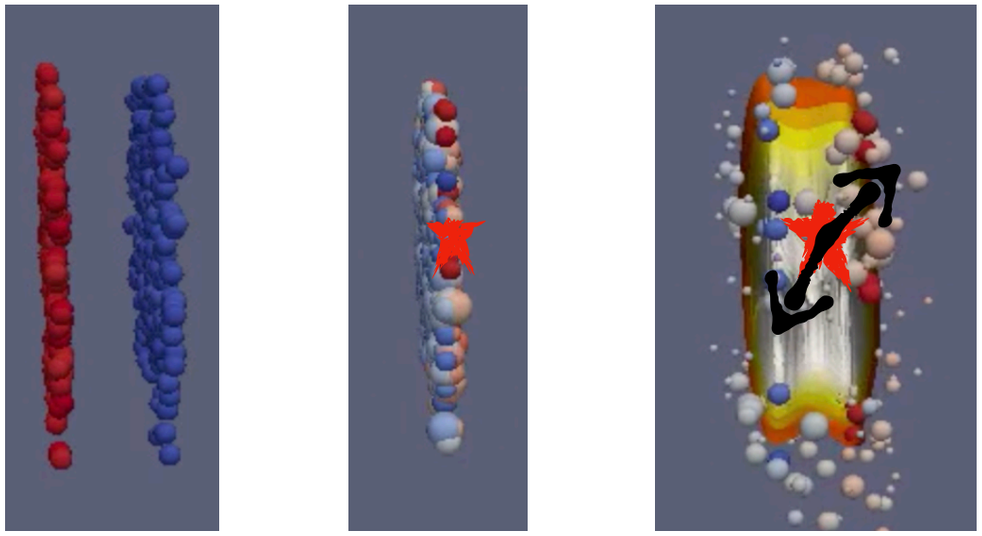
$\sqrt{s_{NN}} = 200$ GeV



MADAI Collaboration

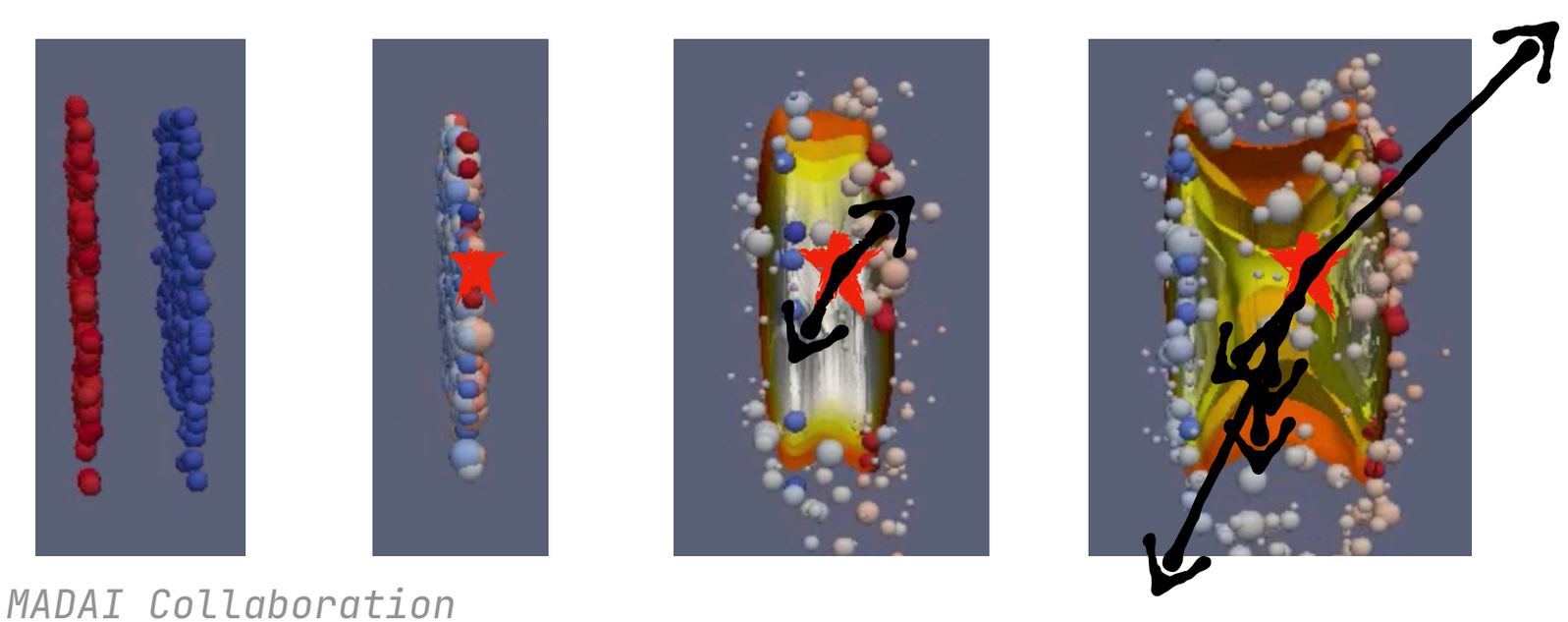
Time

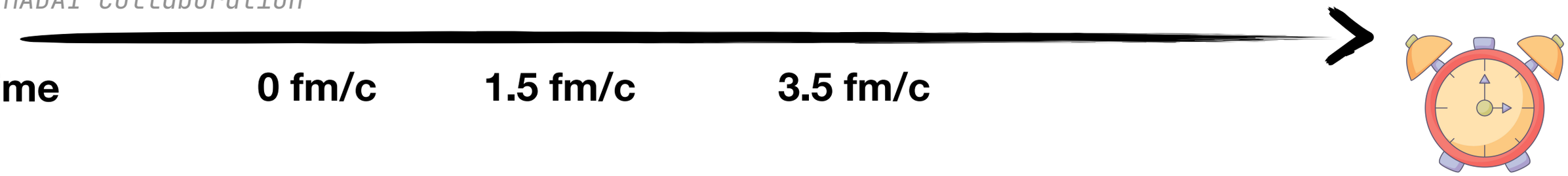




0 fm/c Jets are created nearly instantaneously

0.4 fm/c QGP is formed and starts to expand/cool

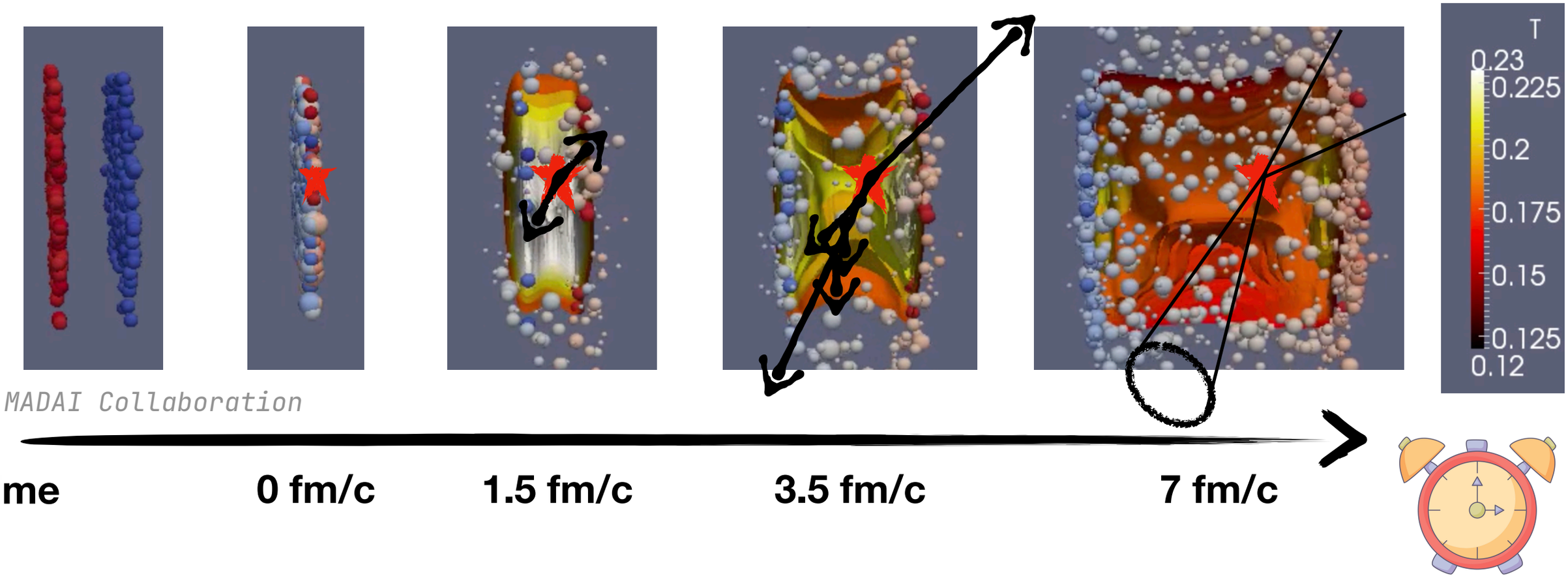




0 - 5 fm/c

Concurrent evolution of jet shower and QGP

Jets and the QGP



> 10 fm/c

Resulting modification to jet observables offers clue to medium properties

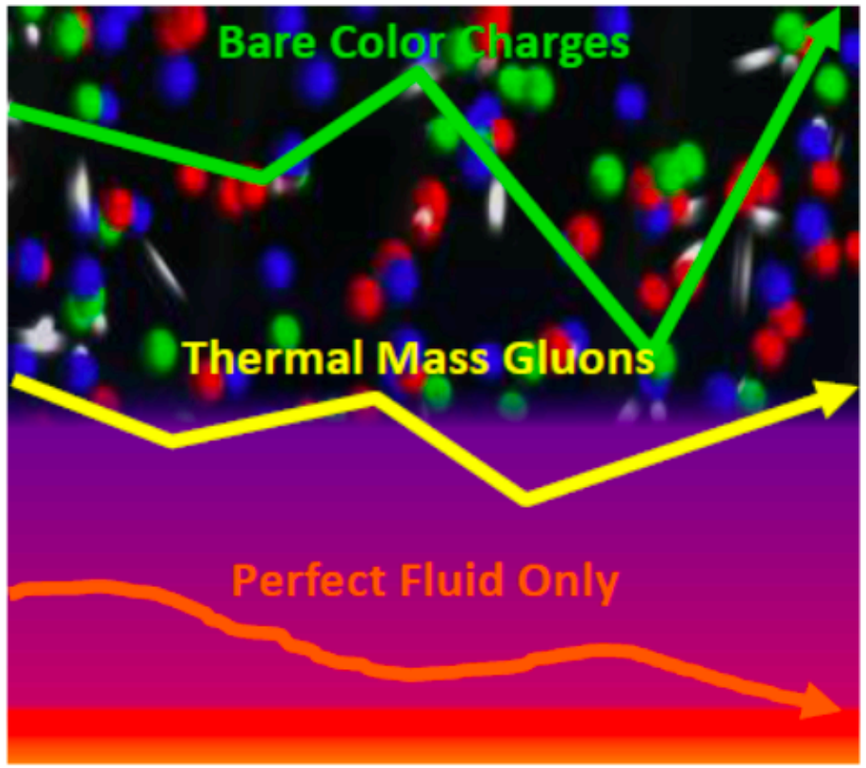
Jets in Heavy Ions - What to expect?

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J.D.Bjorken, FERMILAB-Pub-82/59-THY

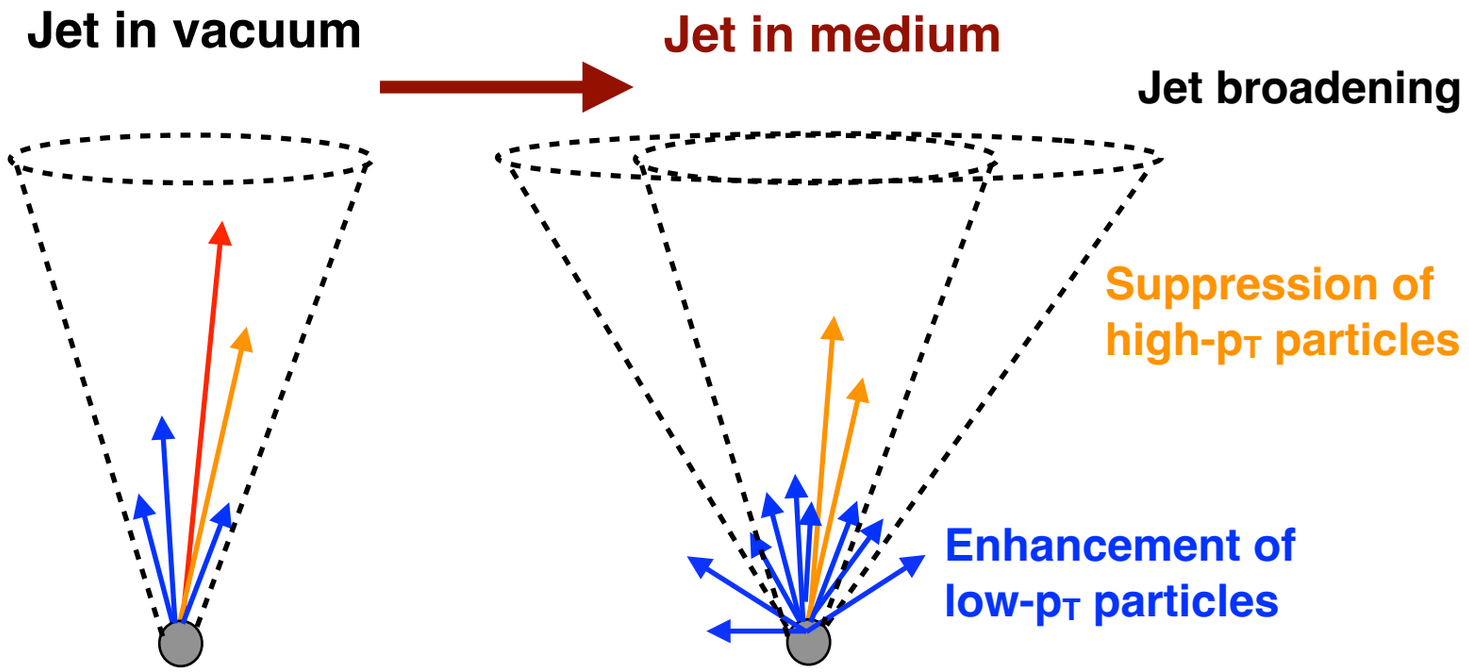
hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

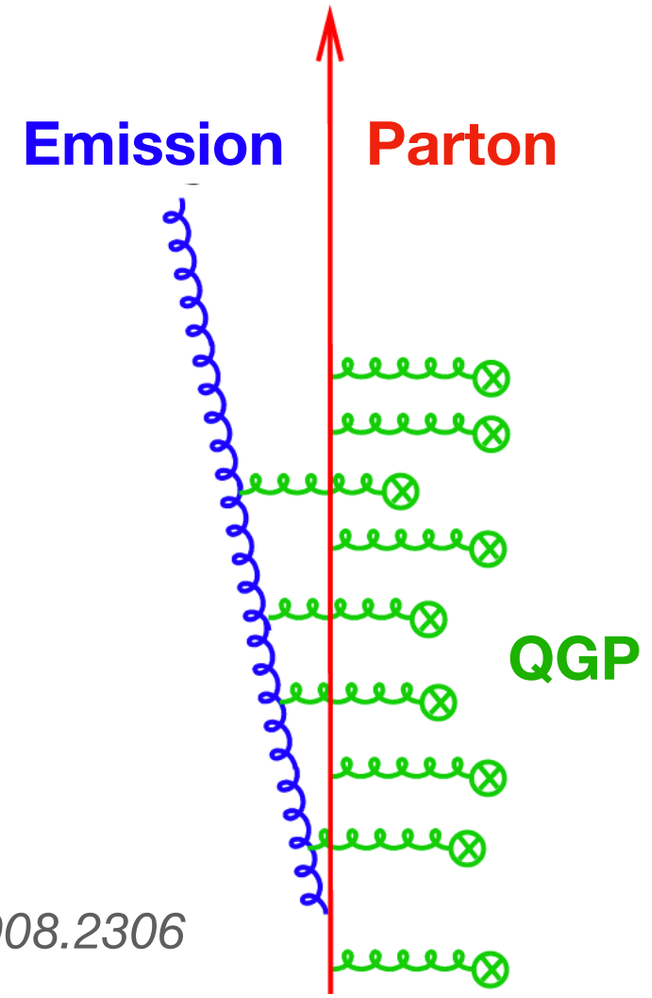
Image credit - 2015 LRP



- High pT particle/jet yield suppressed and energy loss
- Modification of the hard scattered partons due to scatterings in the medium - could affect both jet axis and distributions of jet constituents

Mechanisms of energy loss

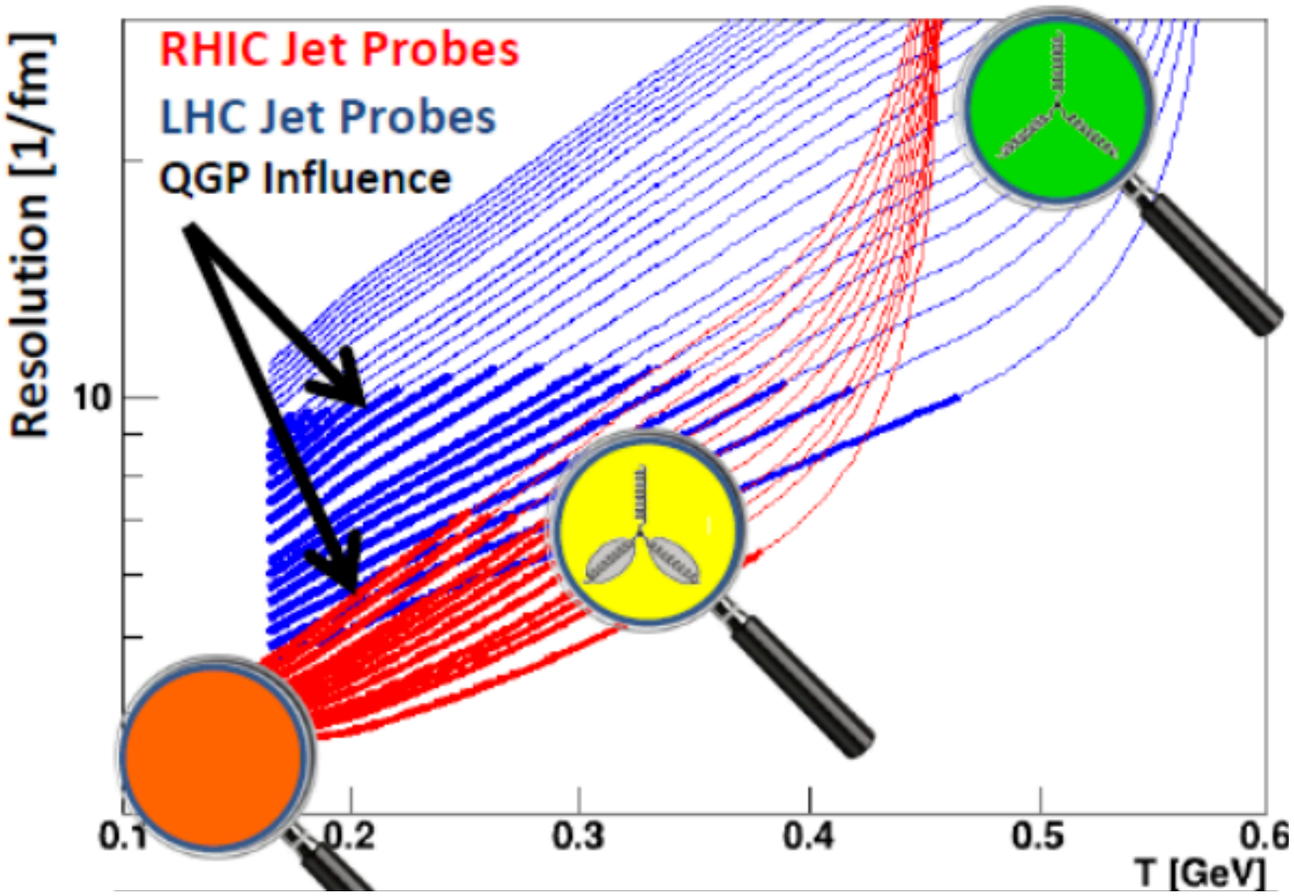




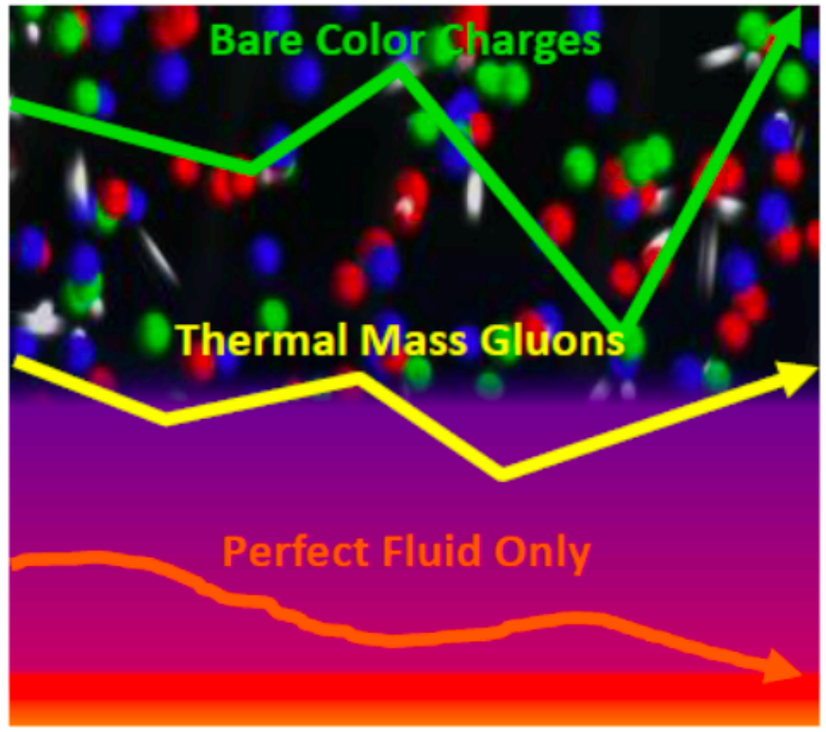
- pQCD-like multiple gluon radiations *Weidemann 0908.2306*
- medium induced scatterings (inelastic), *Zapp et al. JHEP 03 (2013) 080*
- AdS/CFT energy loss, *Liu et al. Phys. Rev. Lett. 97 (2006) 182301*
- color coherence/decoherence, *Solano et al. JHEP 10 (2014) 019*
- modified partonic splitting functions etc…

Qin, Wang,
Int. J. Mod. Phys. E 24 (2015) 11, 1530014

Jets in Heavy Ions - probe of parton energy loss



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



Microscopic properties of the QGP Medium
- structure at varying scales

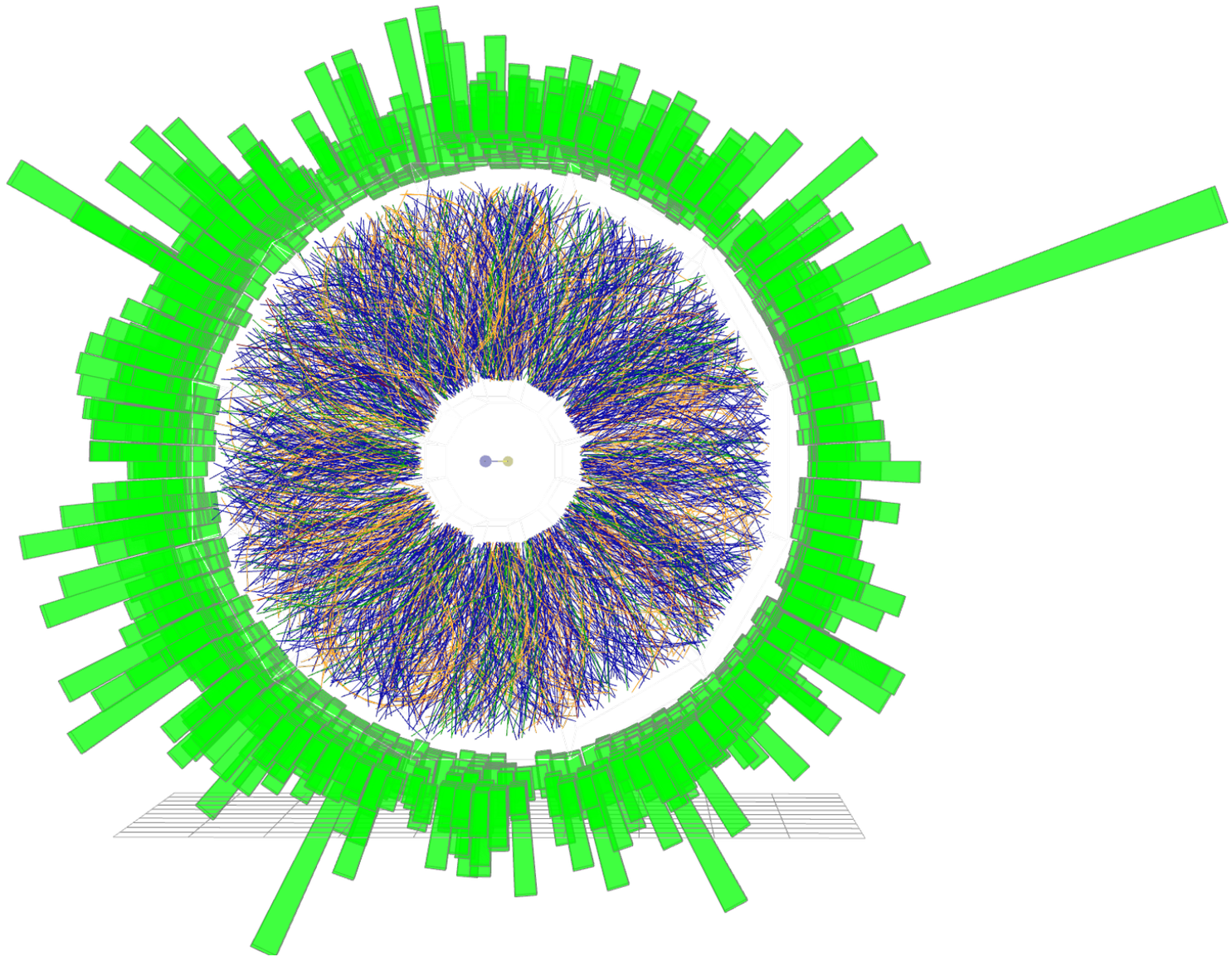
This is inherently a two step process that is not mutually exclusive

Understand jet energy loss → Extract medium properties

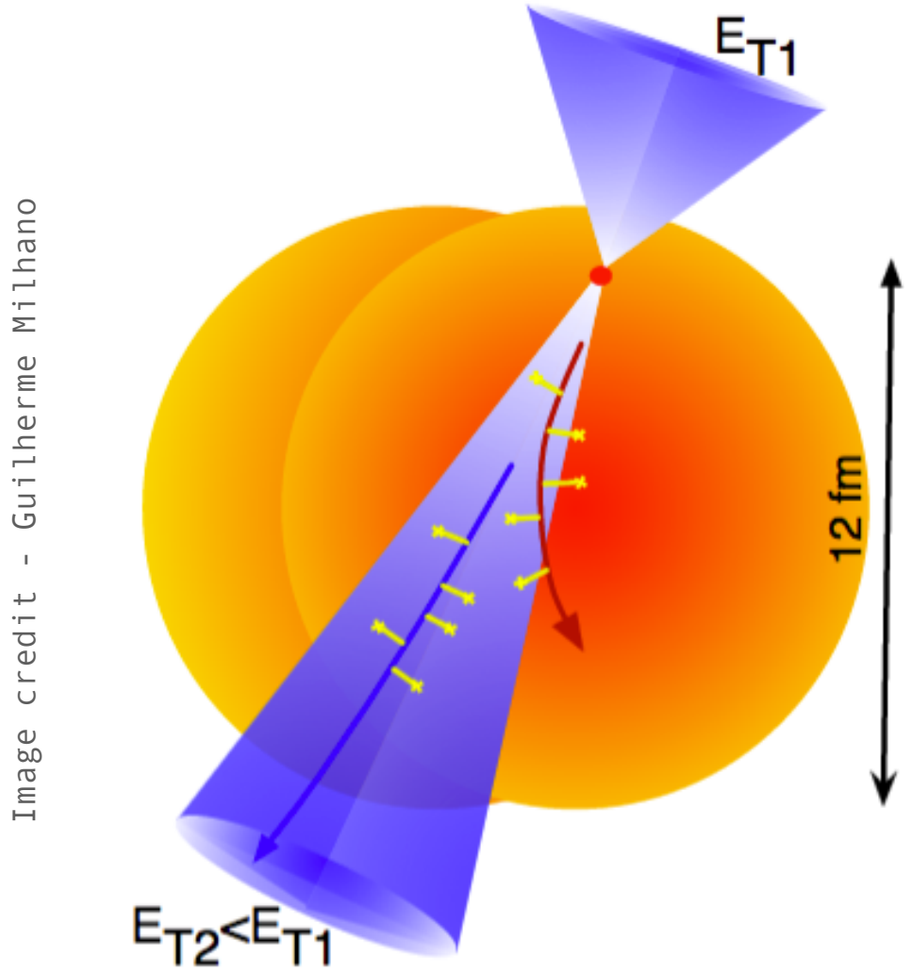
What makes jet measurements in heavy-ion collisions hard?

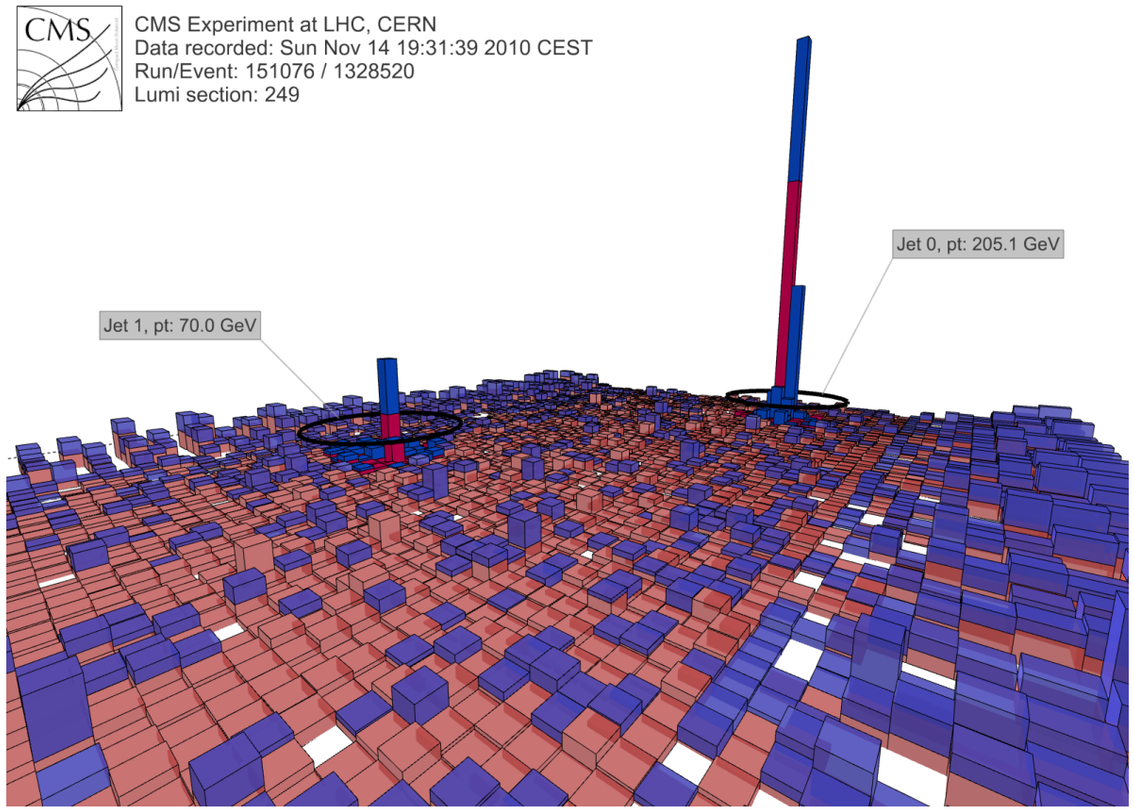
What makes jet measurements in heavy-ion collisions hard?

Where are the jets here?



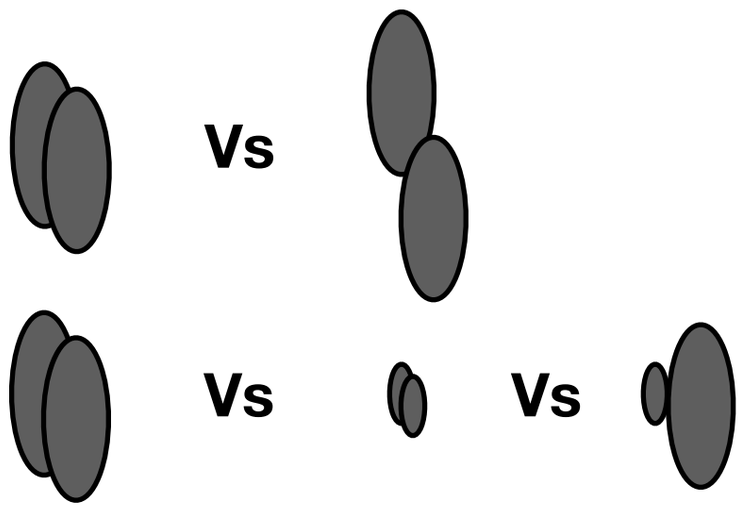
Experimentally measuring Jet Quenching





In comparisons of jet observables to a reference

- Central vs Peripheral collisions
- A+A vs p+p or p+A (with the assumption that medium induced modifications are weaker or non-existent in the latter systems)



Recap - 2

- Jets are calculable via QCD factorization and thus heralded as calibrated probes

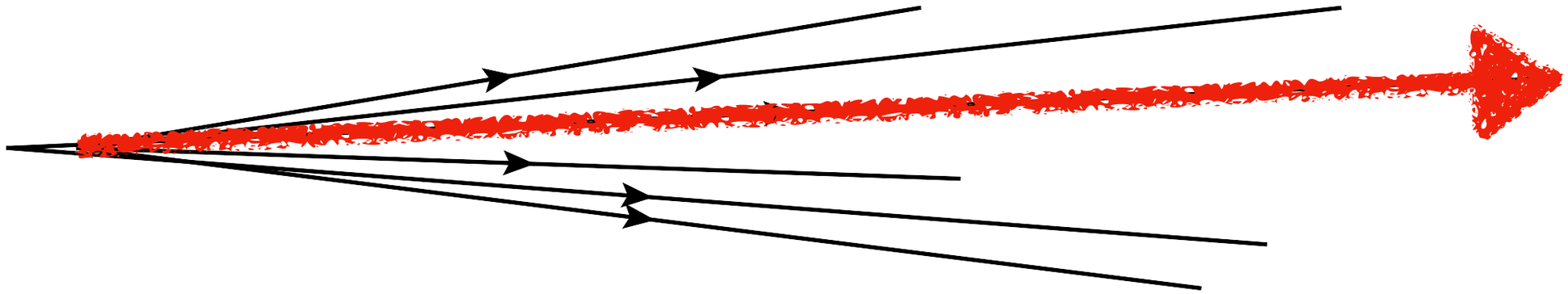
- Produced early in the collisions and traverse the QGP lifetime

- Expect parton jets to lose energy in the medium due to potential scatterings and radiations

- Need to reconstruct and compare jet properties to reverse engineer medium impact

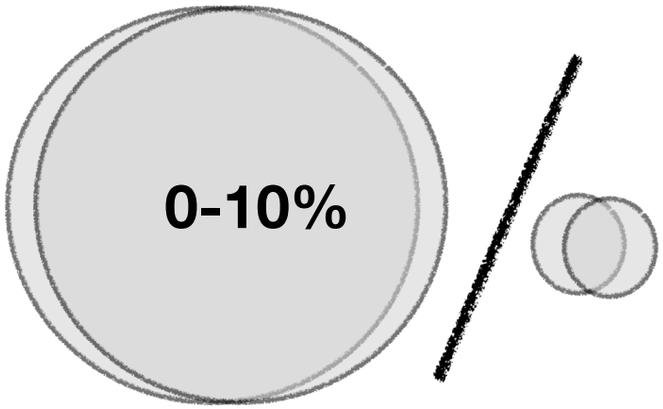
- Extracting jets from background is an issue

0th generation Jet Measurements

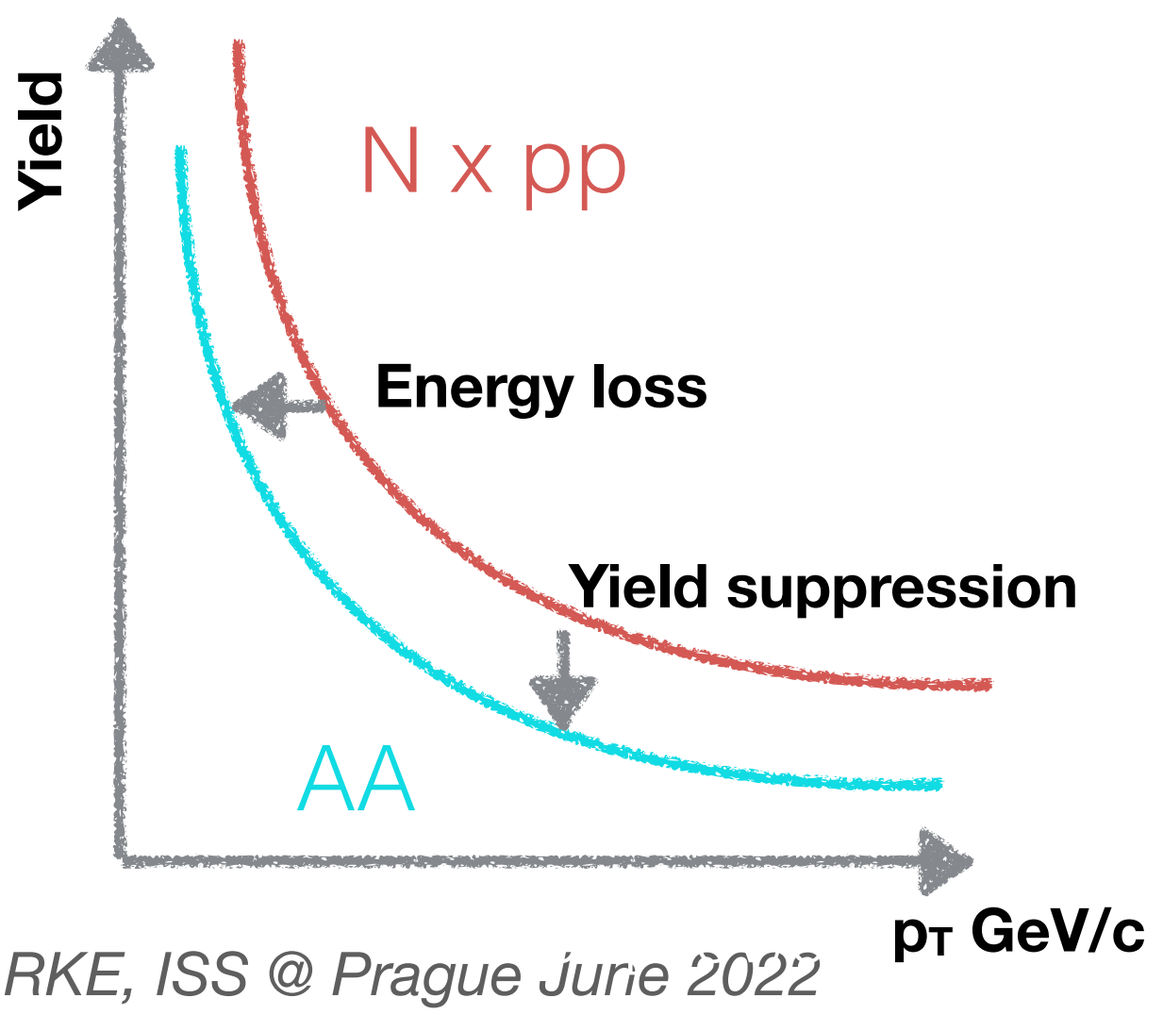


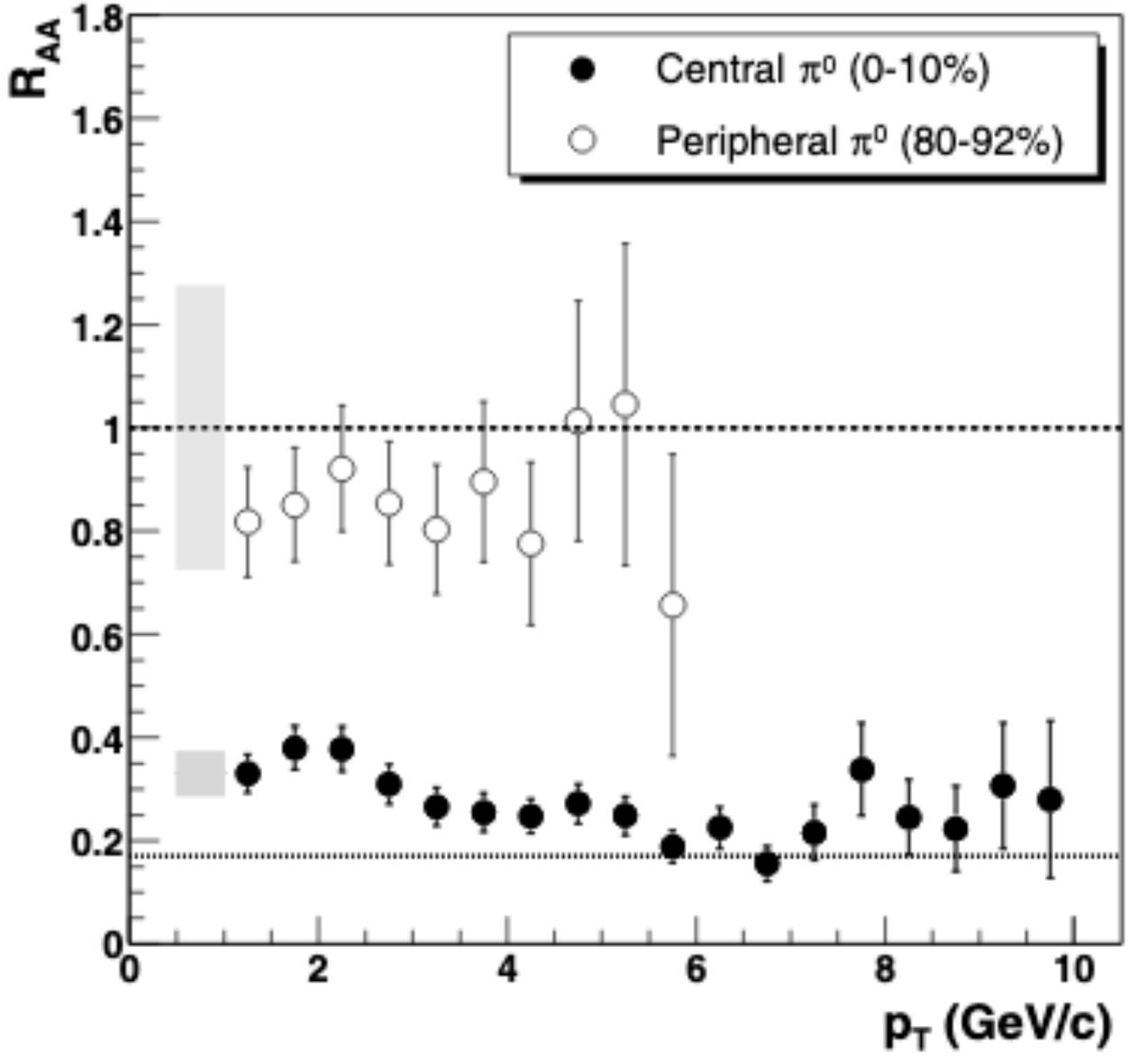
High momentum hadron as proxy for jet

Signature of energy loss and evidence for QGP formation

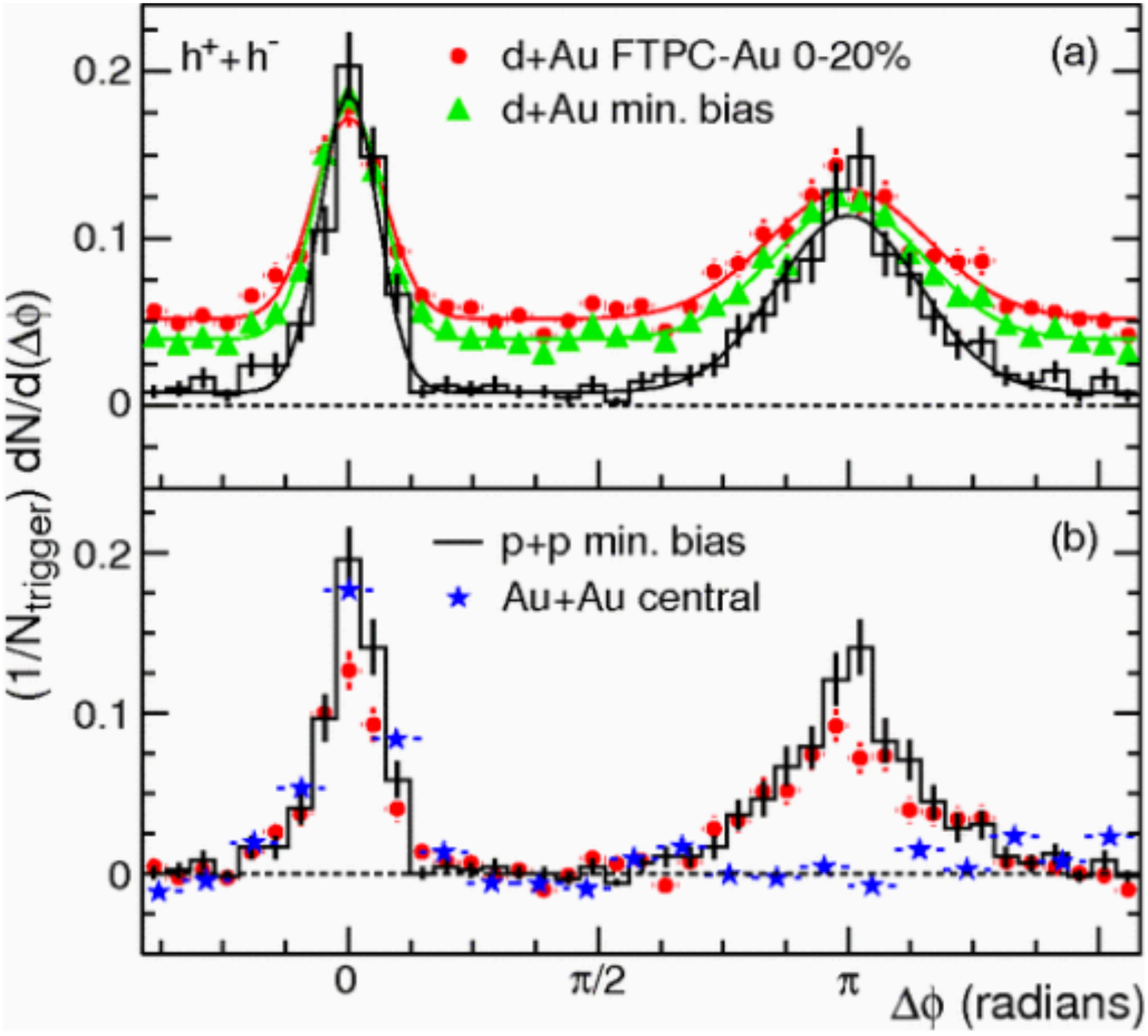


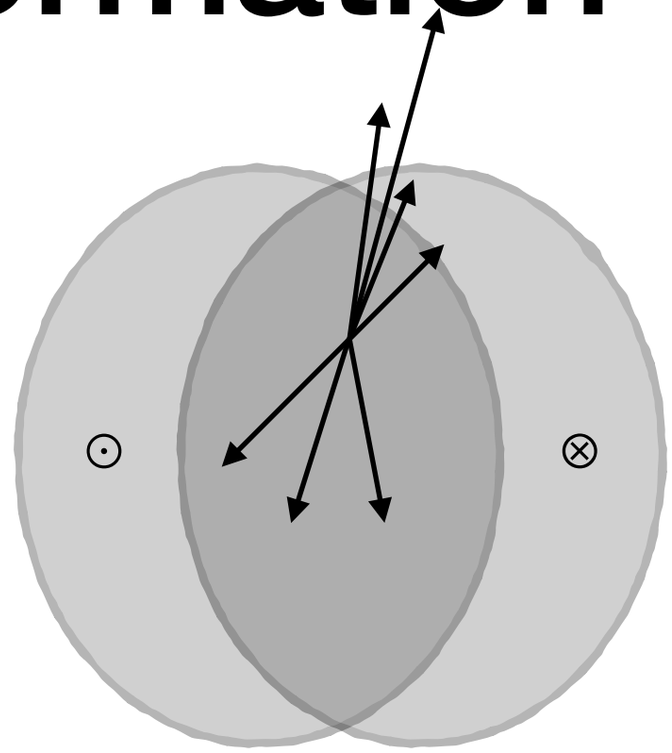
Number of × binary collisions





Signature of energy loss and evidence for QGP formation





- Disappearance of the away-side jet particles!

0th gen - what did we learn?

- High momentum hadron production is **significantly suppressed** in central heavy ion collisions

- **Disappearance of back-to-back production**, i.e. away-side yield in 2-particle correlations

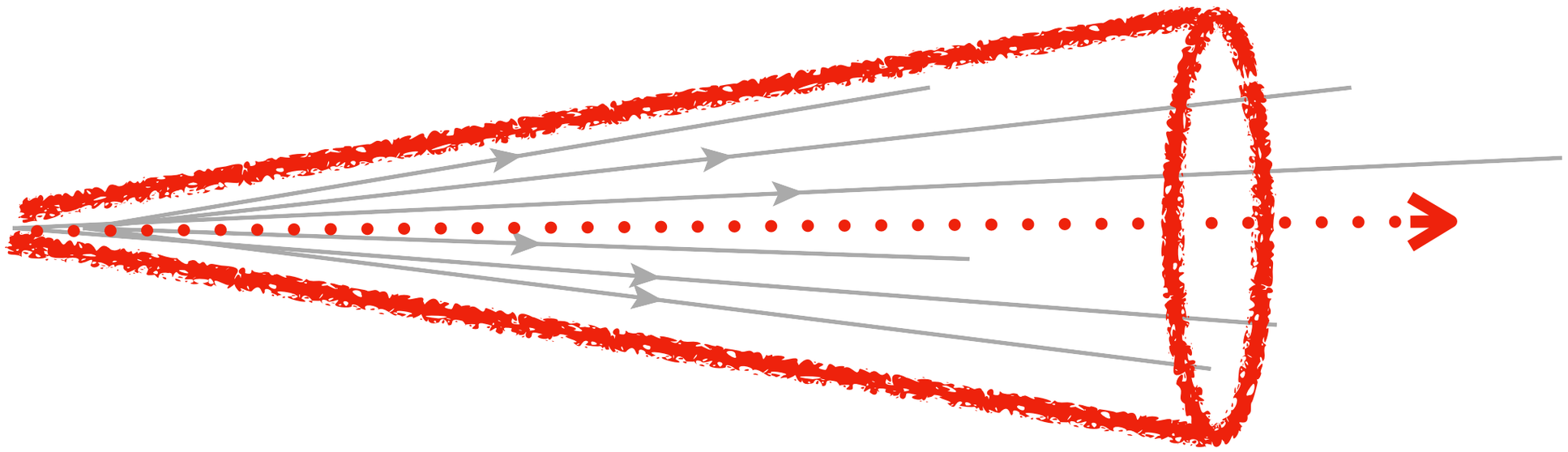
- Signature of quenching - but not learning much about jets or parton energy loss - need to reconstruct jets!

ATLAS Heavy Ion Publications
ALICE Heavy Ion Publications

CMS Heavy Ion Publications

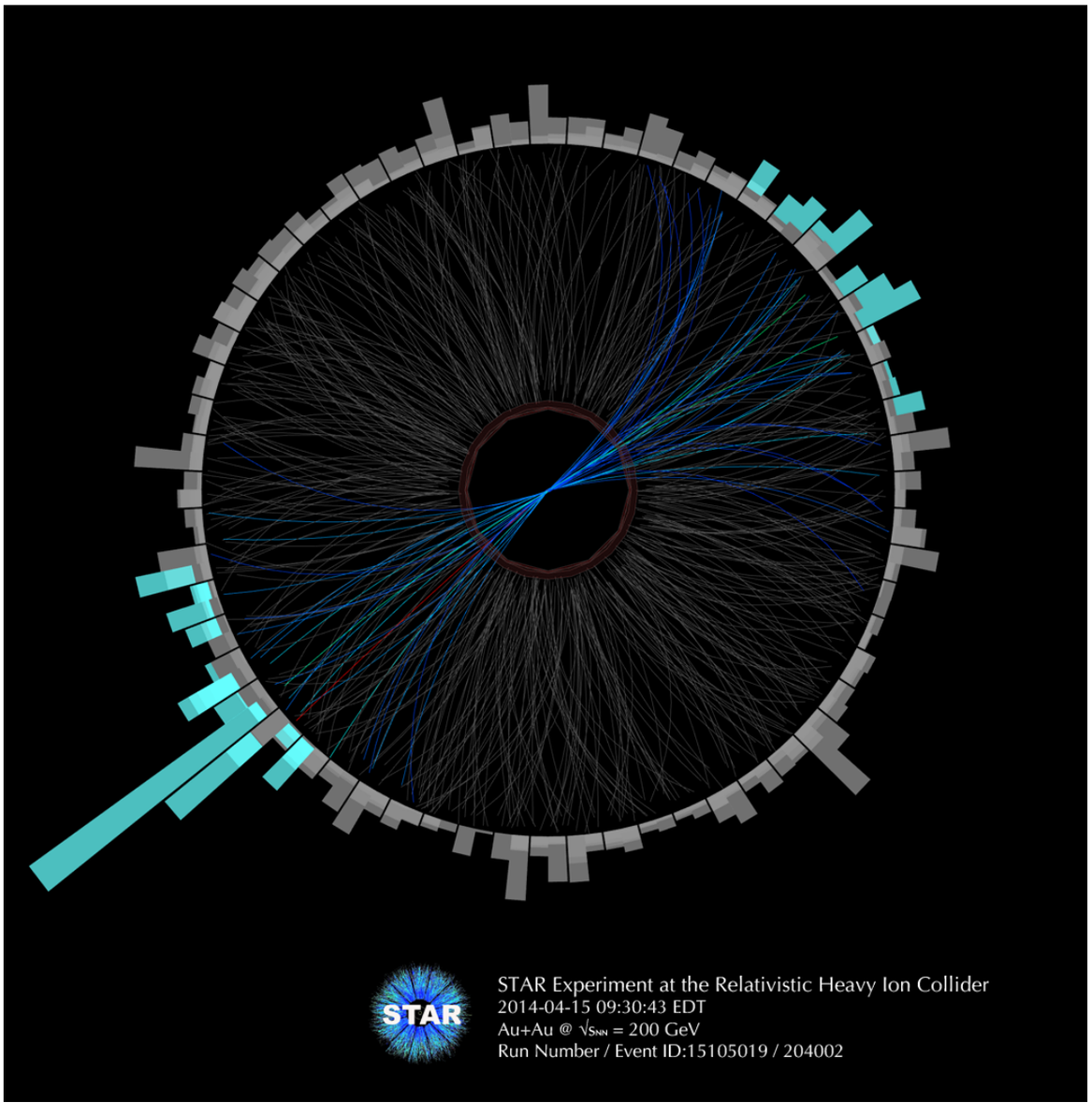
STAR Publications
PHENIX Publications

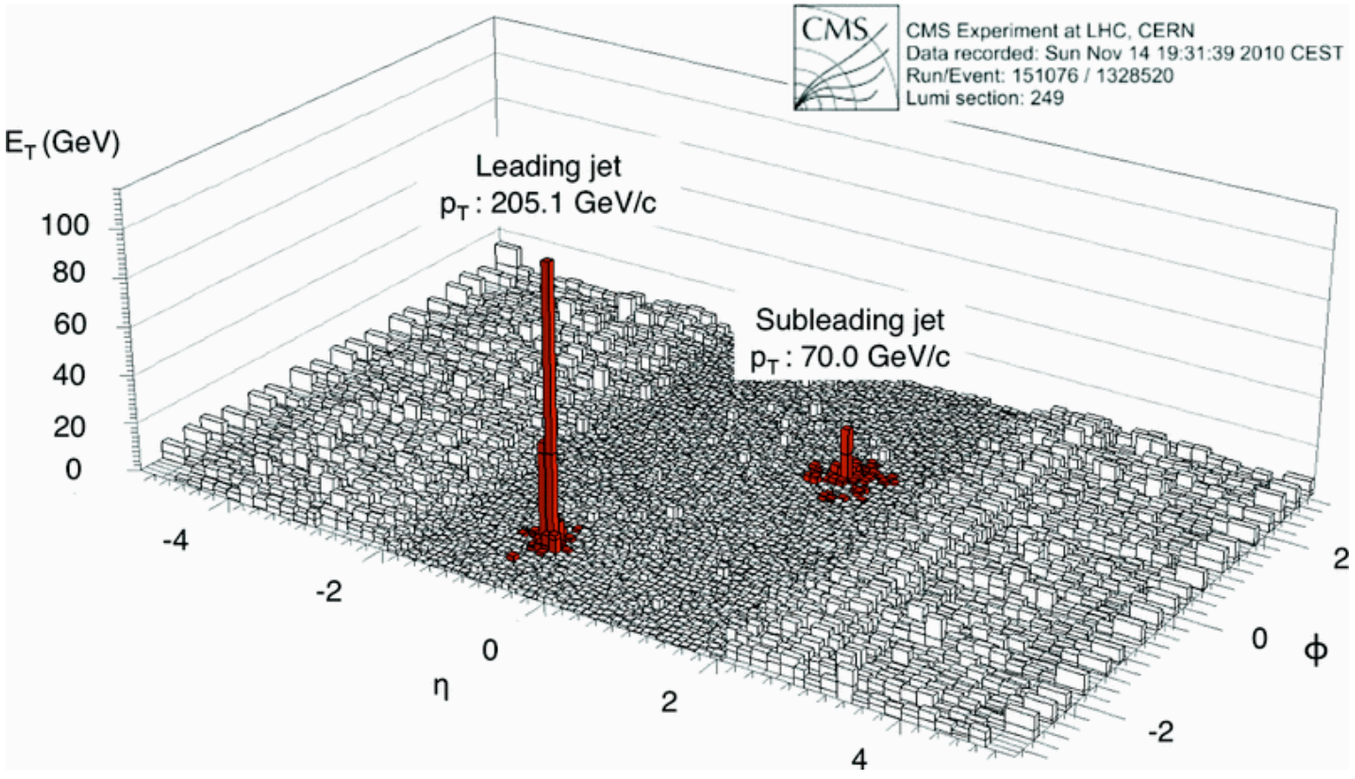
1st generation Jet Measurements



Fully reconstructed jets as proxies for hard scattered partons

Visually observing jet quenching

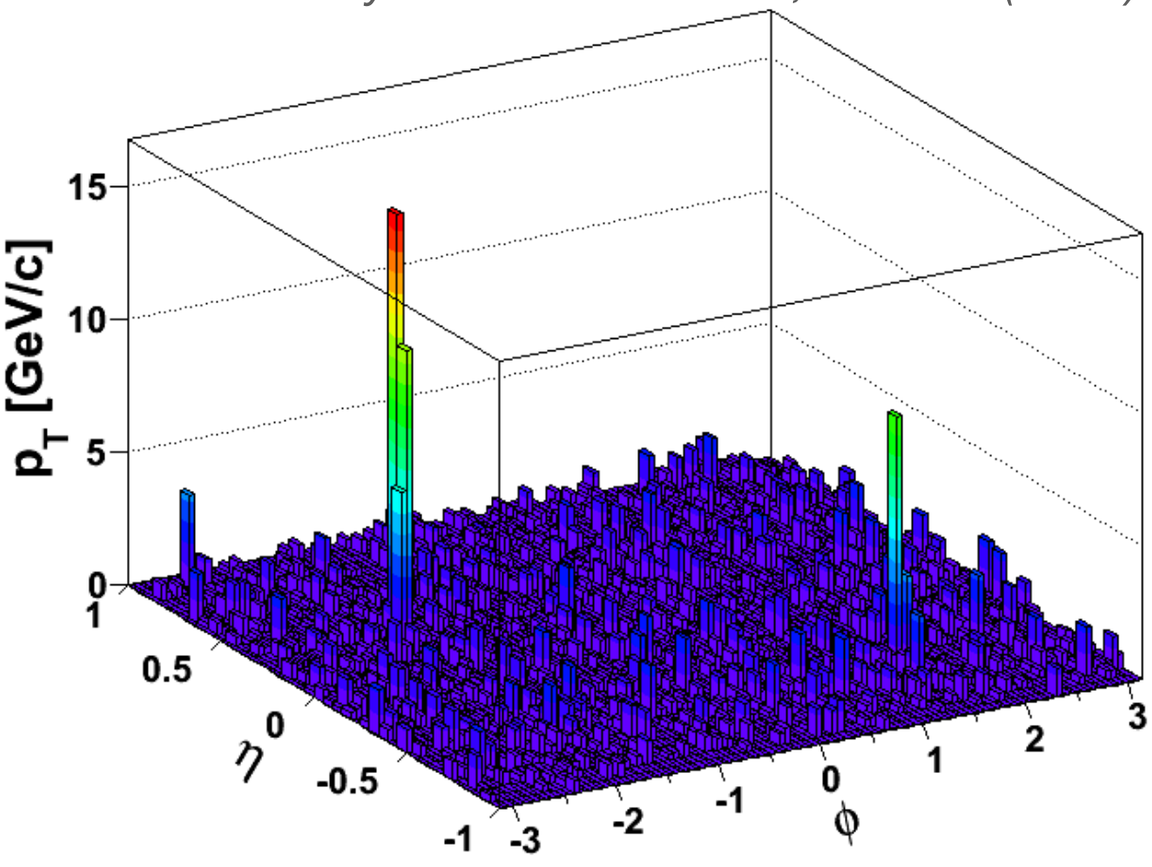




- Dijet-Balancing is a useful tool to ‘see’ jet quenching

Selecting a di-jet sample at STAR

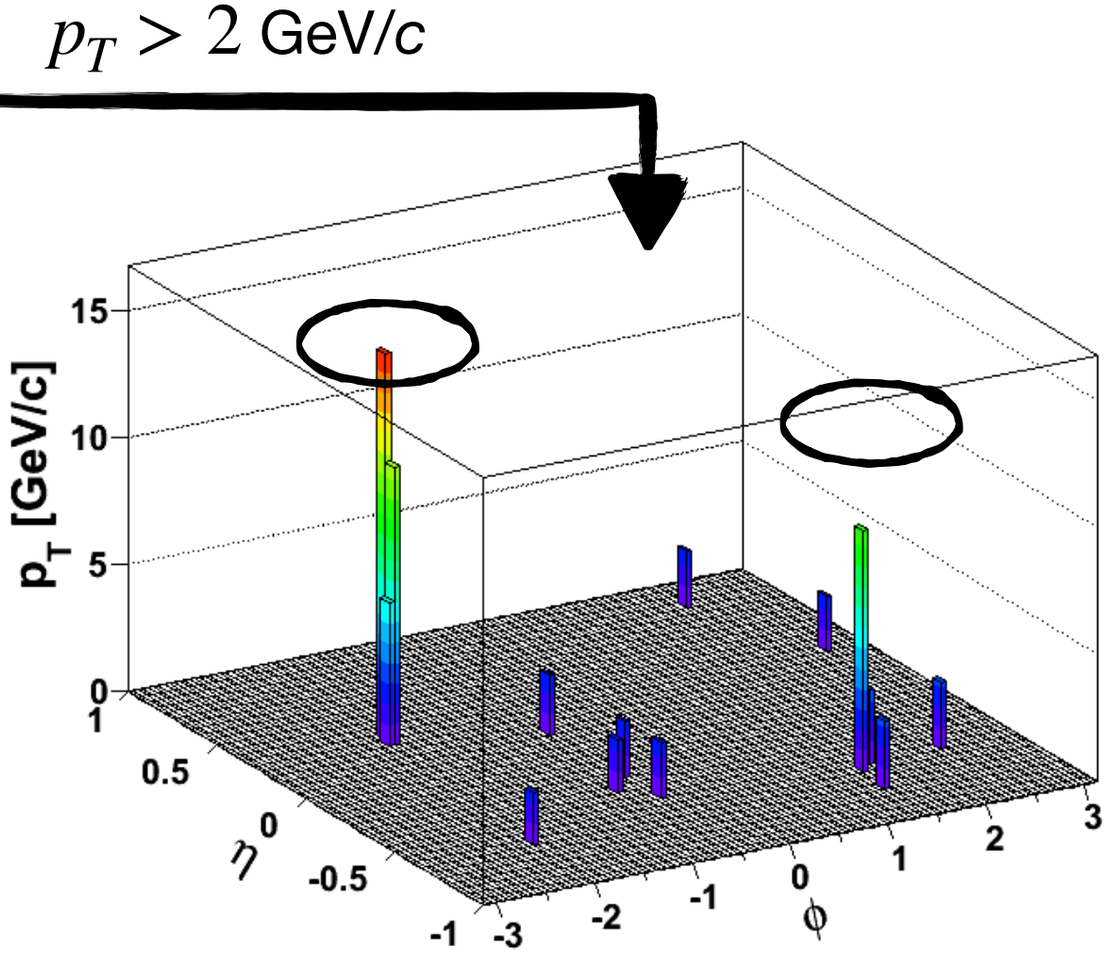
STAR Phys. Rev. Lett. 119 6, 062301 (2017)



- Resulting di-jets free of combinatorial jets and background

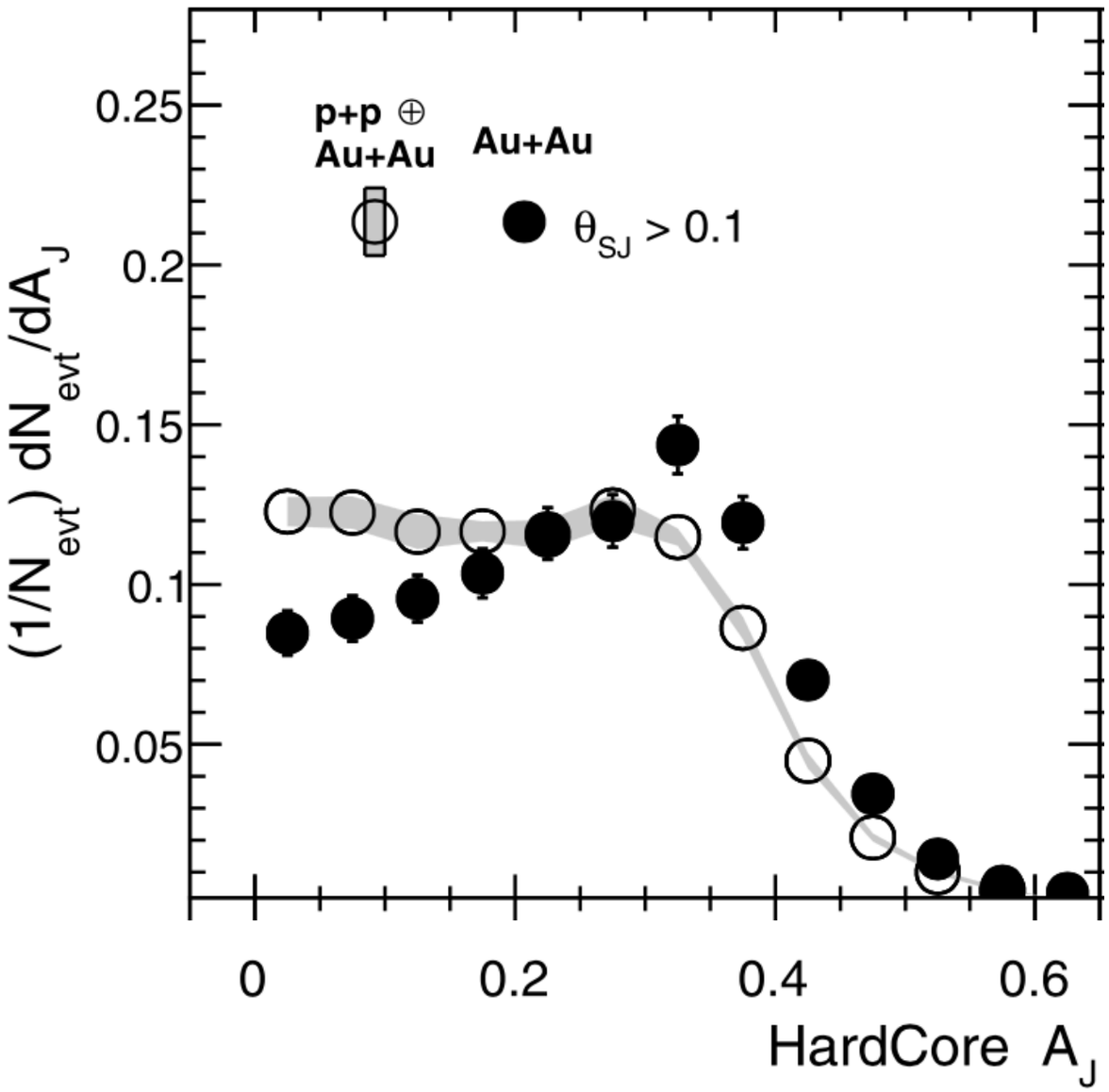
HardCore Selection

$p_T > 2$ GeV/c



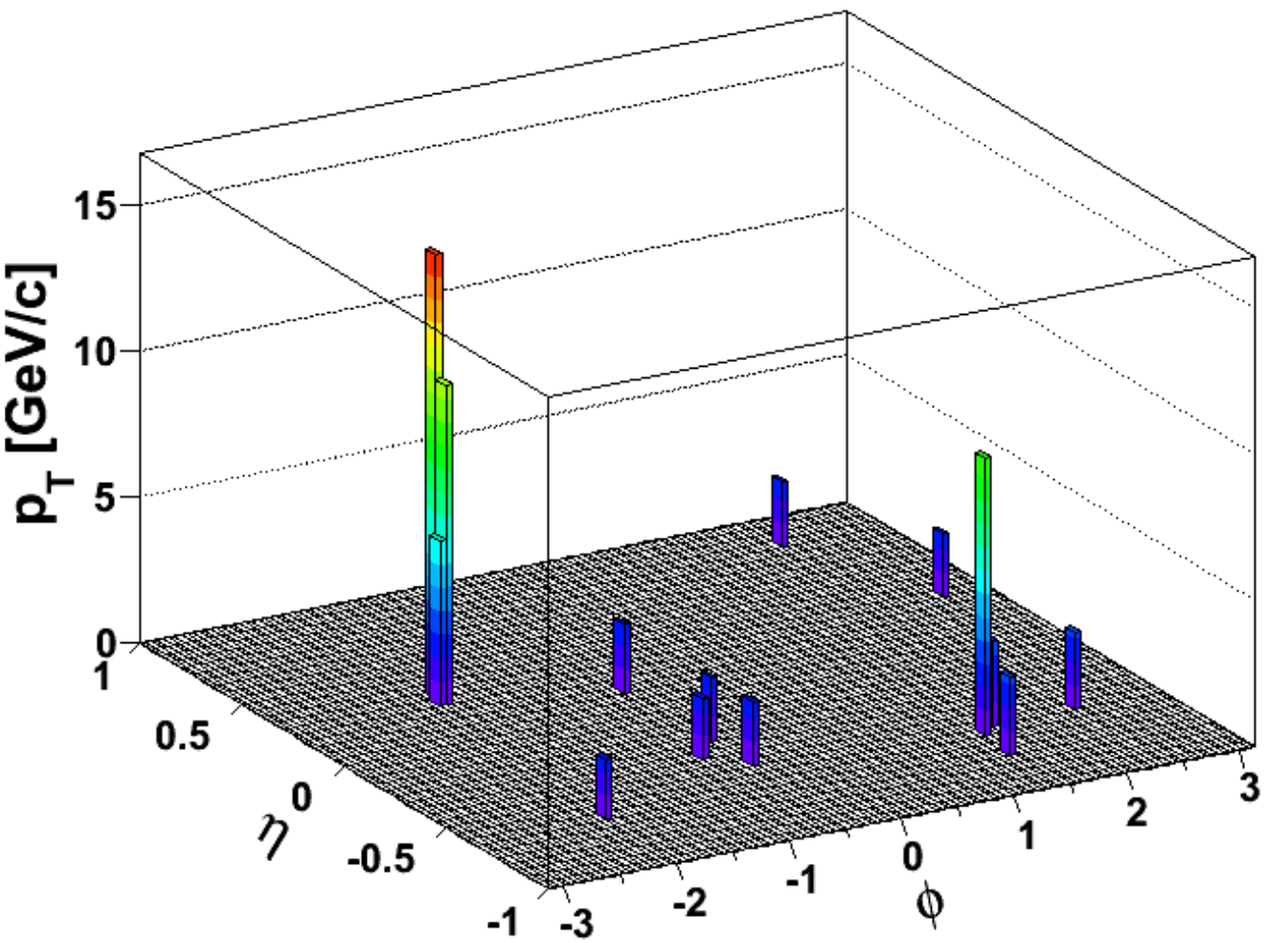
- Significant bias in jet fragmentation but lets utilize the bias to our advantage!

$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$



- HardCore Dijets in Au+Au are imbalanced compared to p+p ⊕ Au+Au

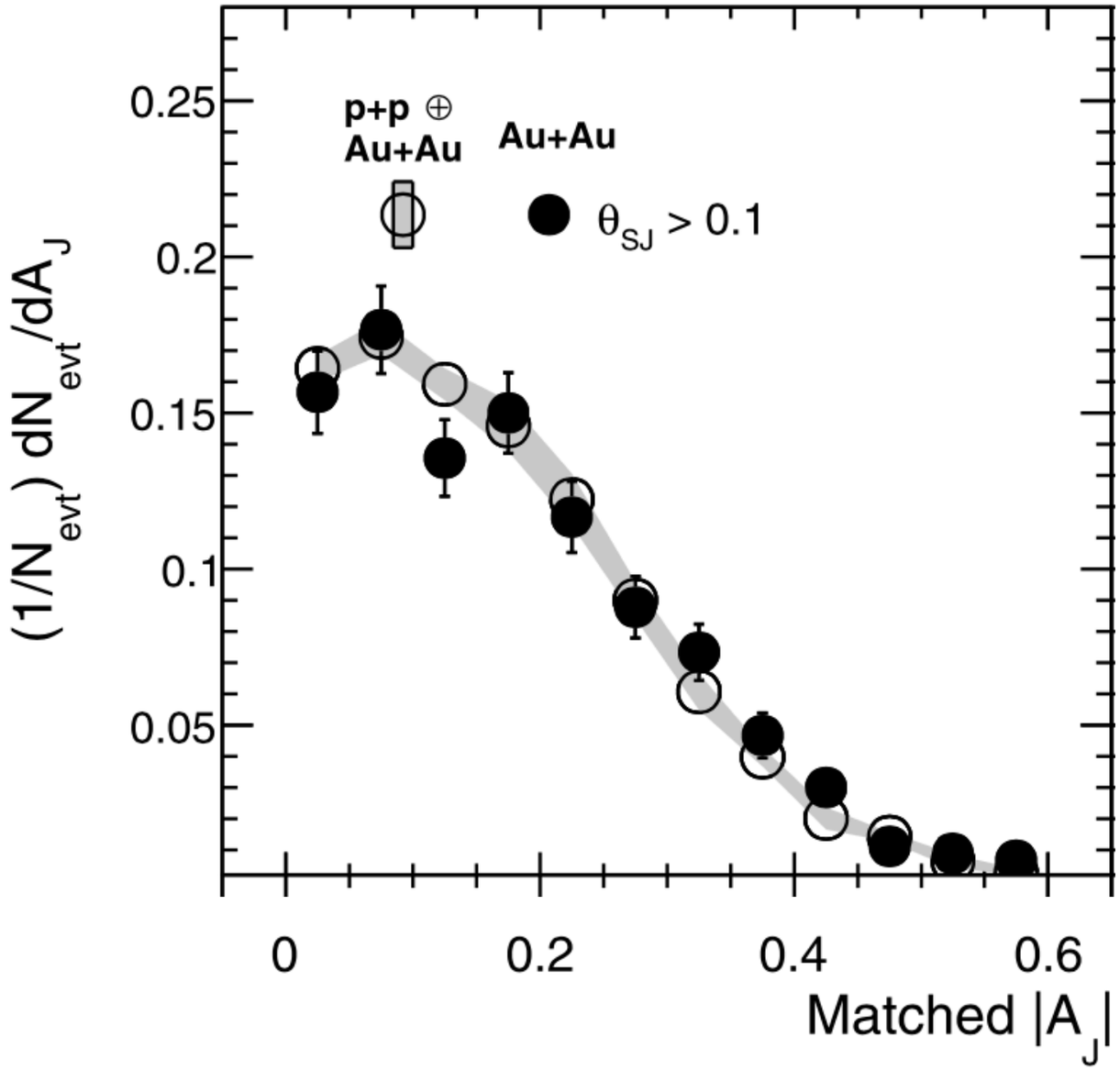
- High p_T particles ($p_T > 2$ GeV) lose energy in the medium

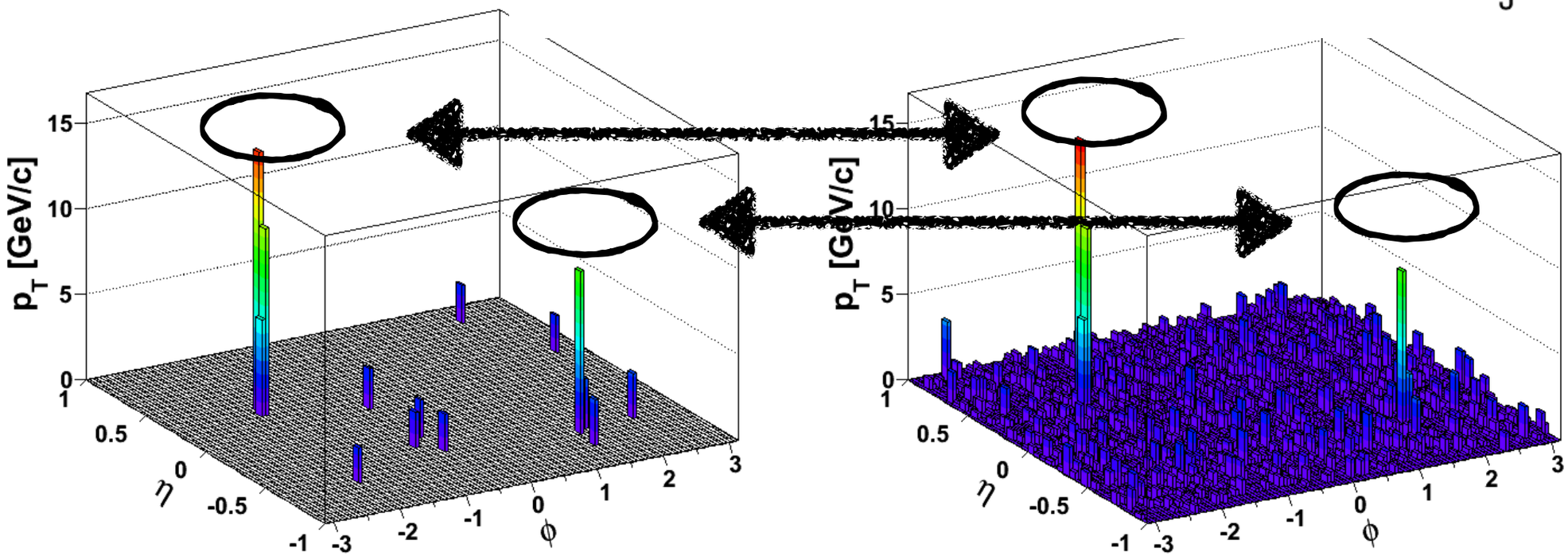


- Where is the quenched energy?

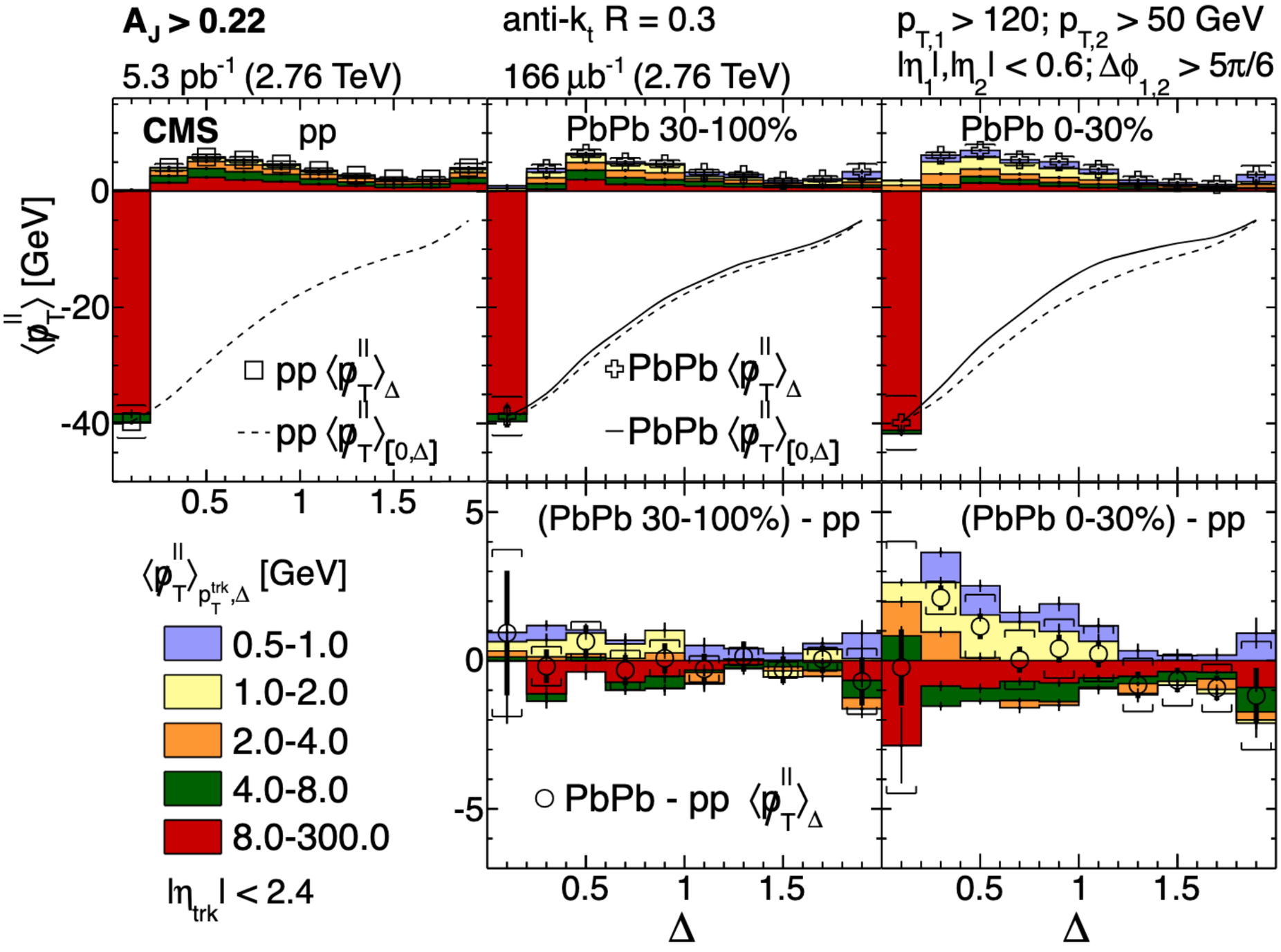
$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

- Matched jets recover the lost energy ($0.2 < p_T < 2$ GeV) within the jet cone (R = 0.4)!





At the LHC?



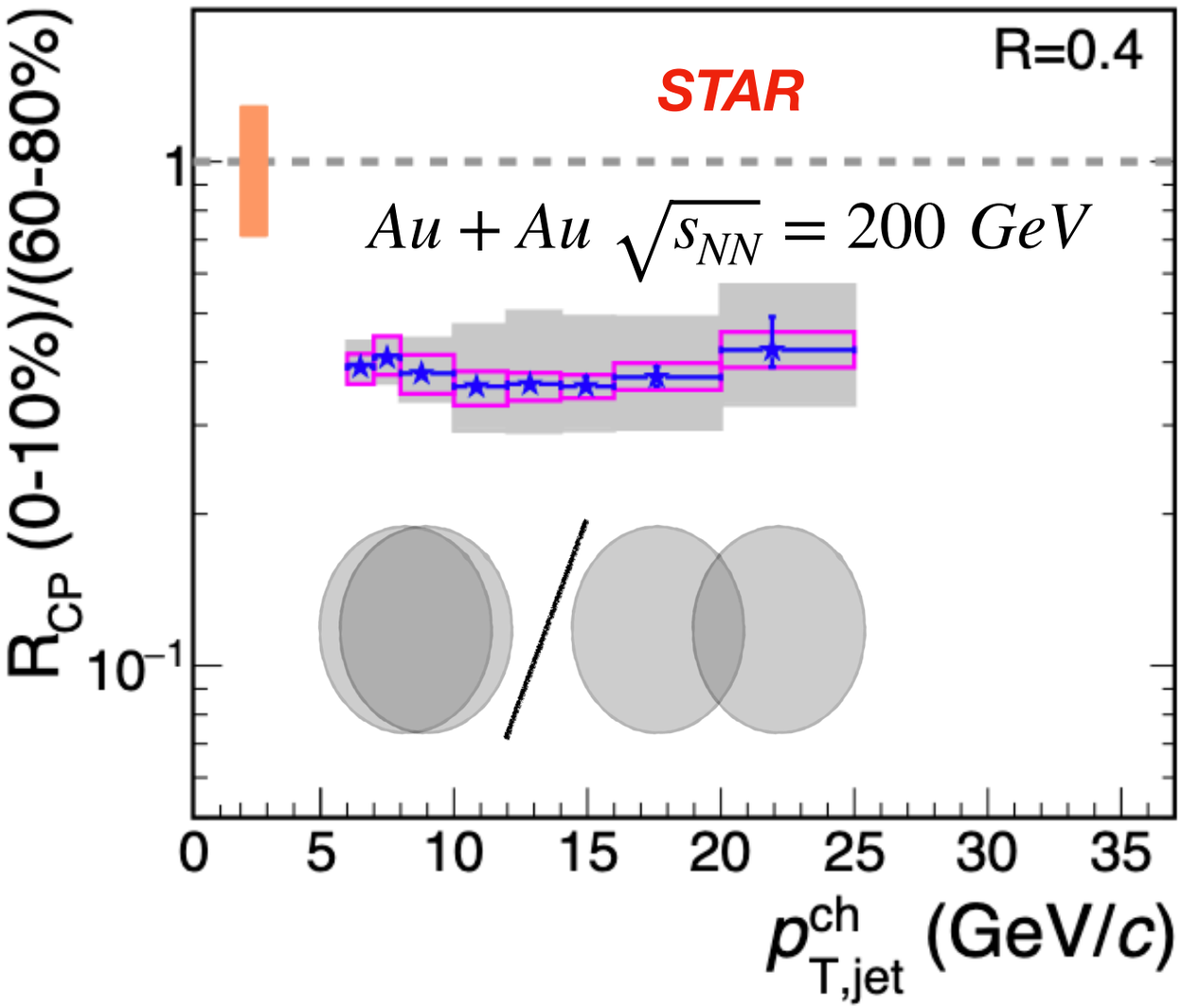
CMS JHEP 01 (2016) 006

Balancing only occurs much further after from the jet axis $\Delta R \approx 2$ the entire hemisphere!

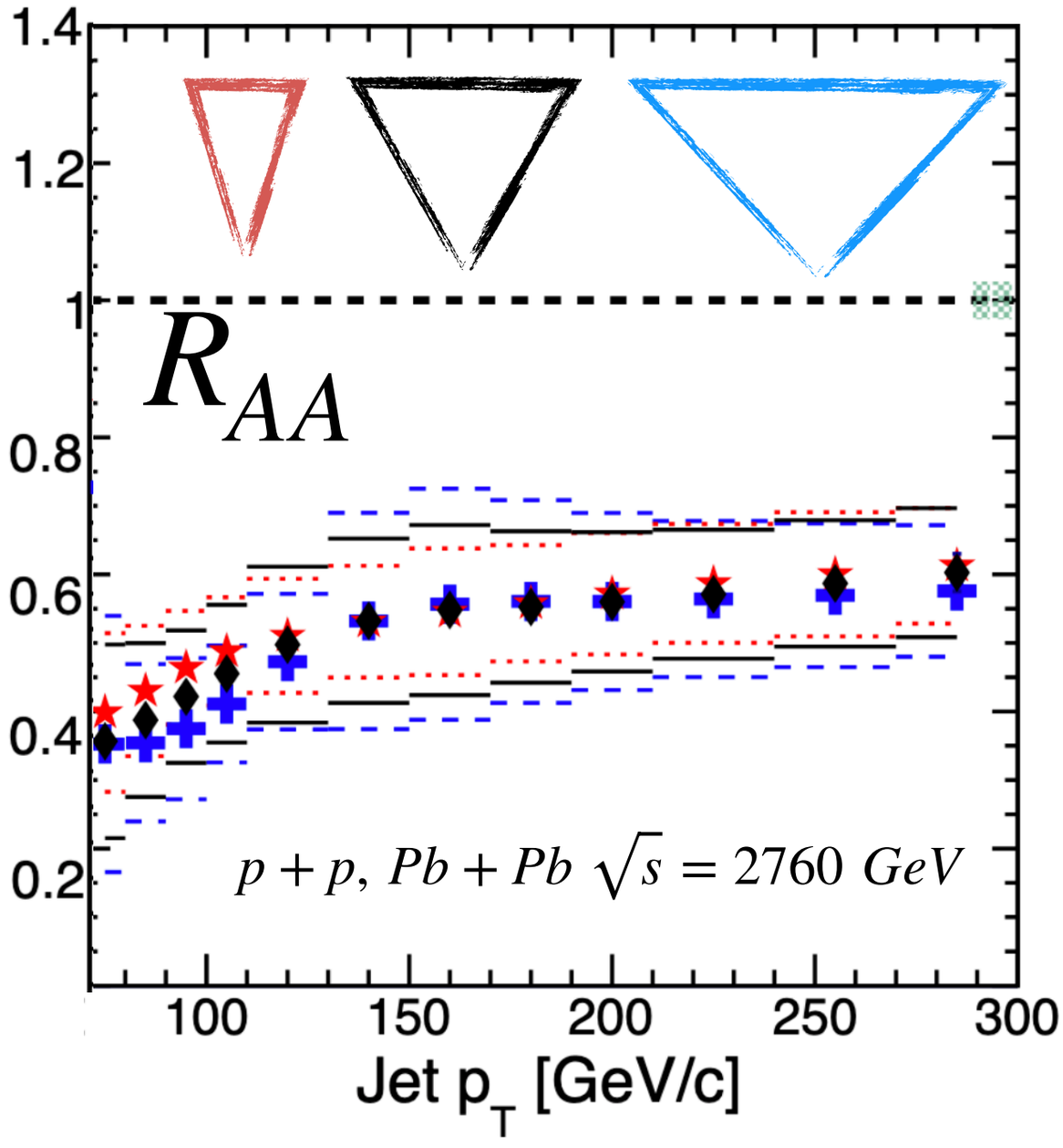
Enhancement of particles in heavy ions around the jet cone

Inclusive jets @ RHIC and LHC

STAR Phys. Rev. C 102 5, 054913 (2020)



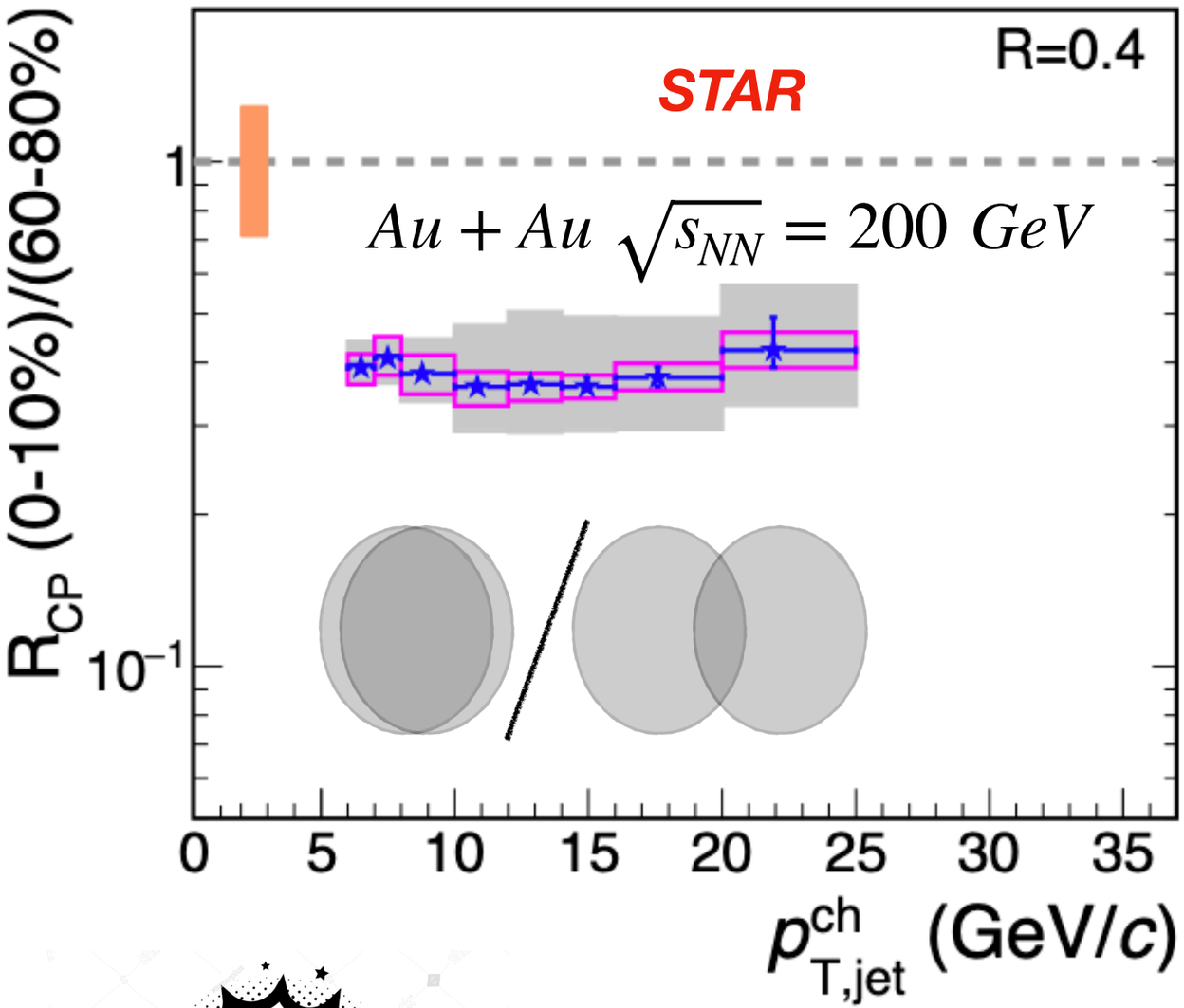
CMS Phys. Rev. C 96 (2017) 015202



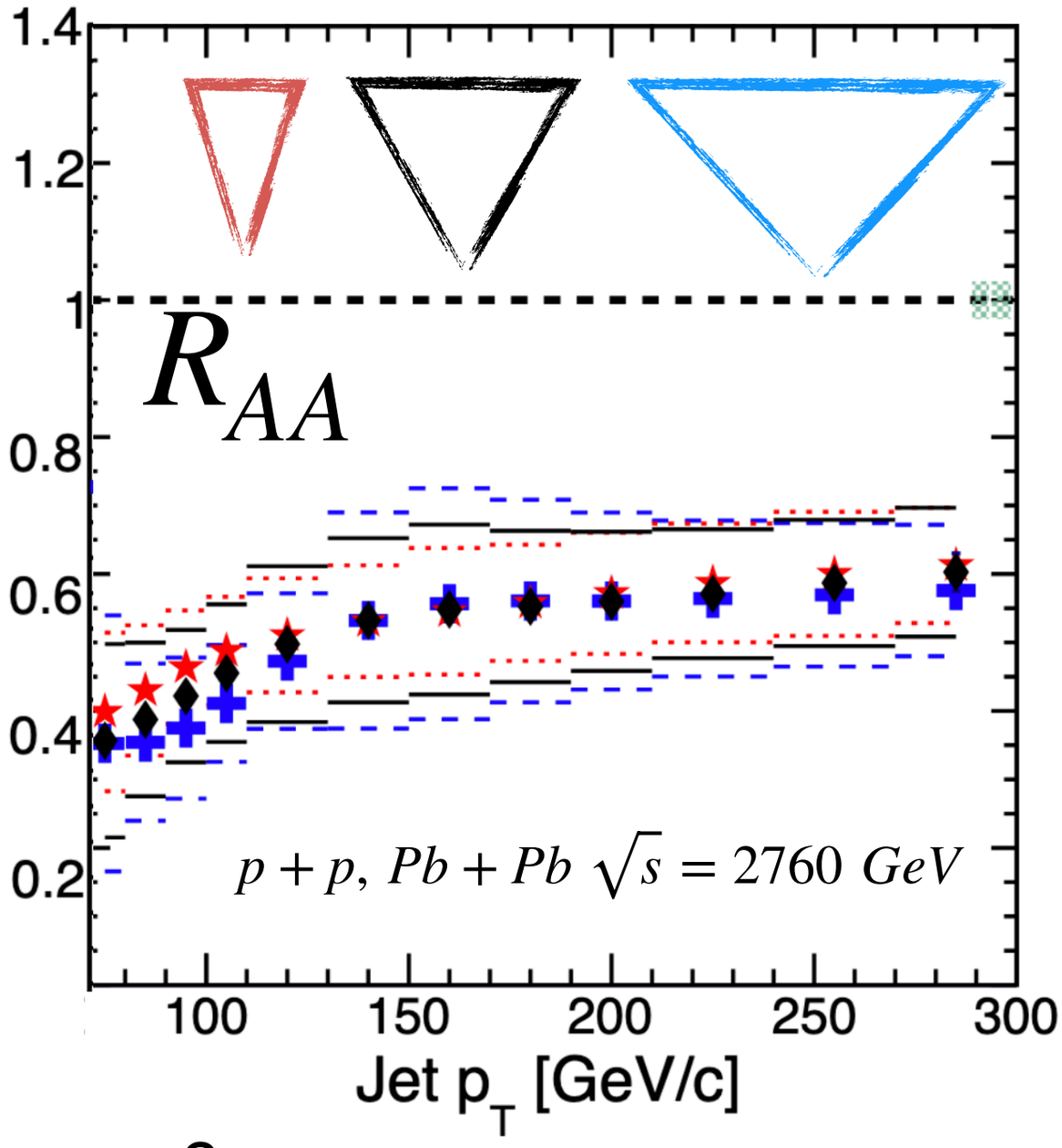
- Similar levels of suppression RAA (RCP) ~ 0.4-0.6

Inclusive jets @ RHIC and LHC

STAR Phys. Rev. C 102 5, 054913 (2020)

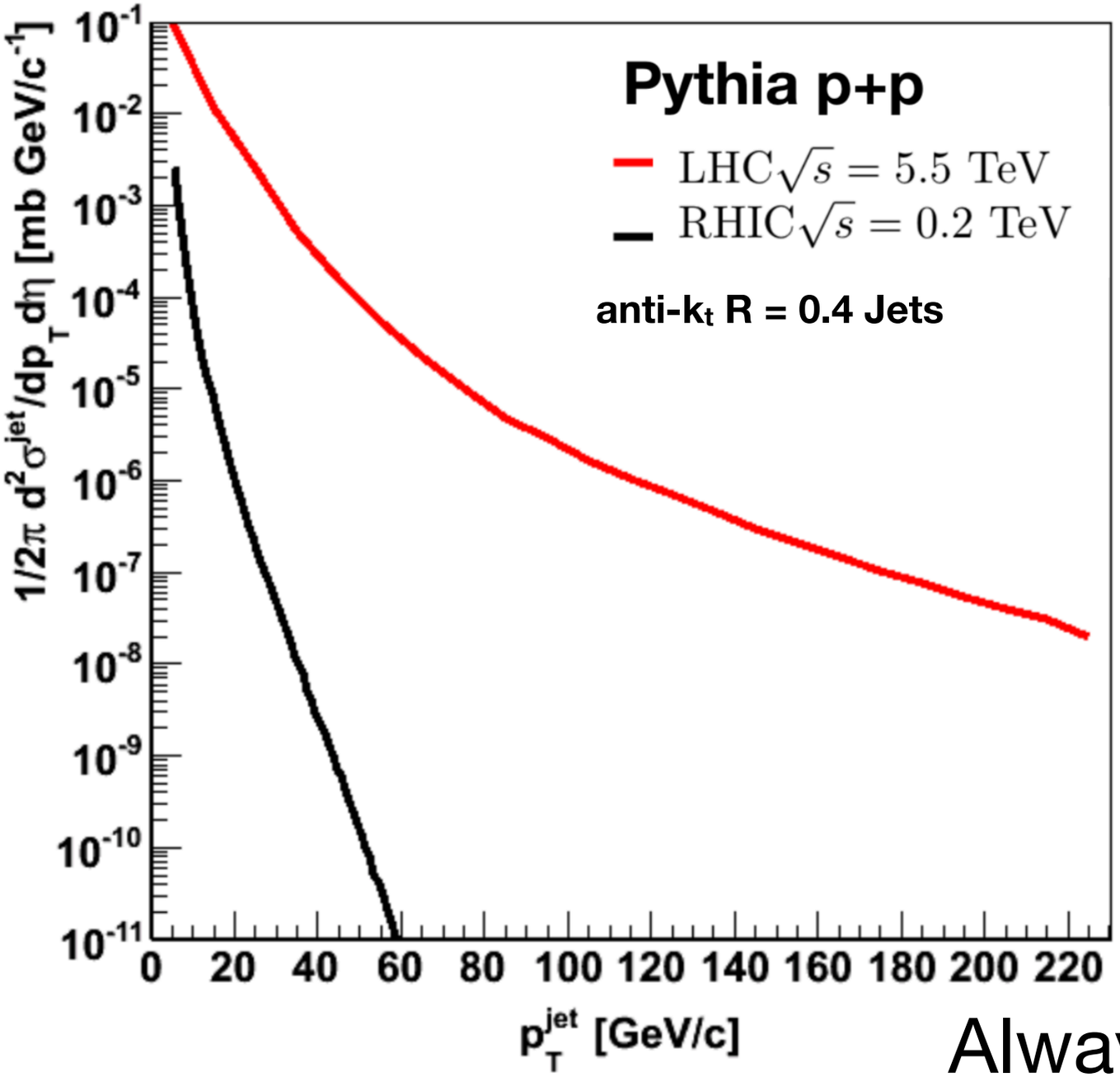


CMS Phys. Rev. C 96 (2017) 015202



Is the energy loss the same?

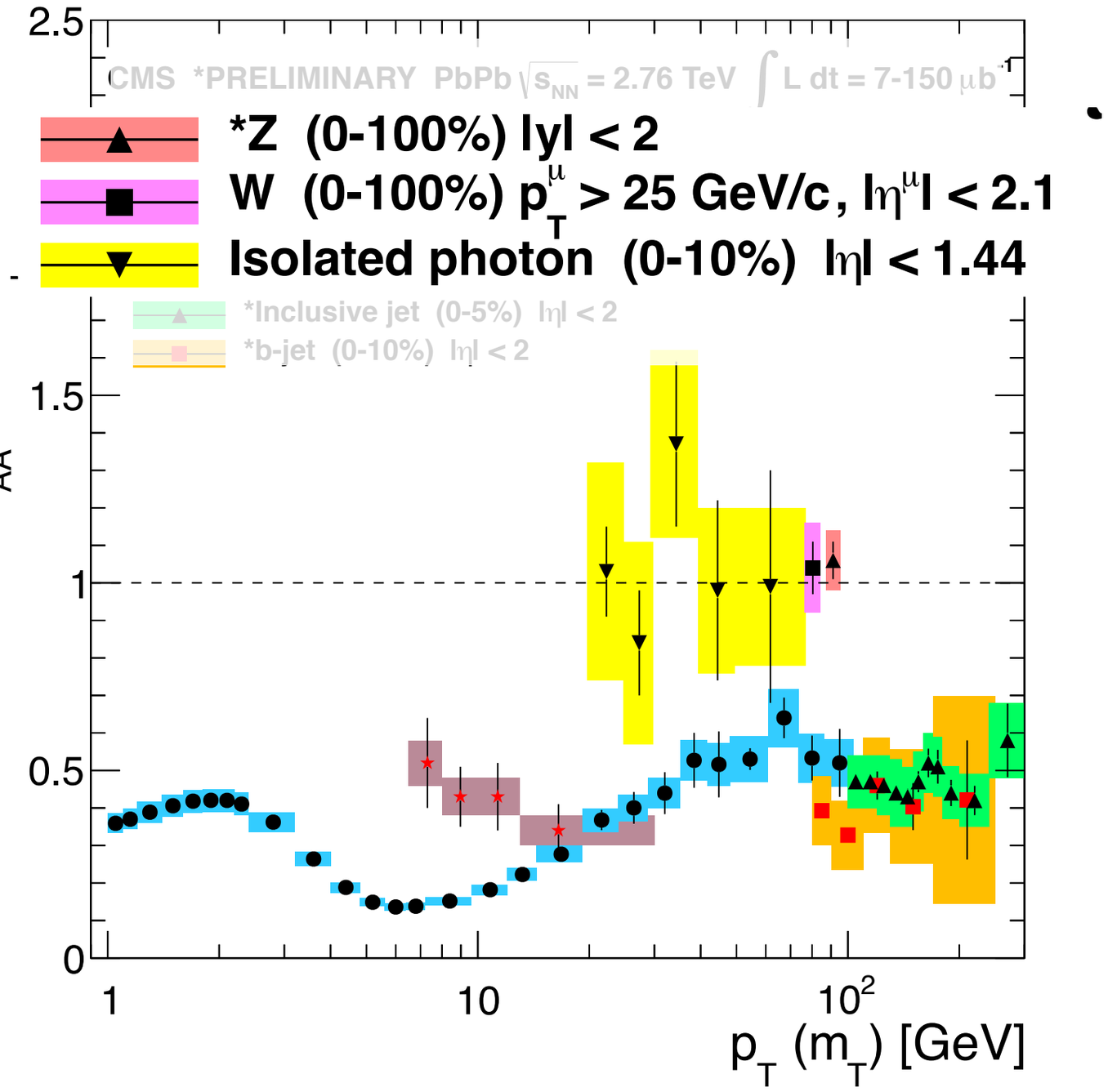
Lets hold on a second



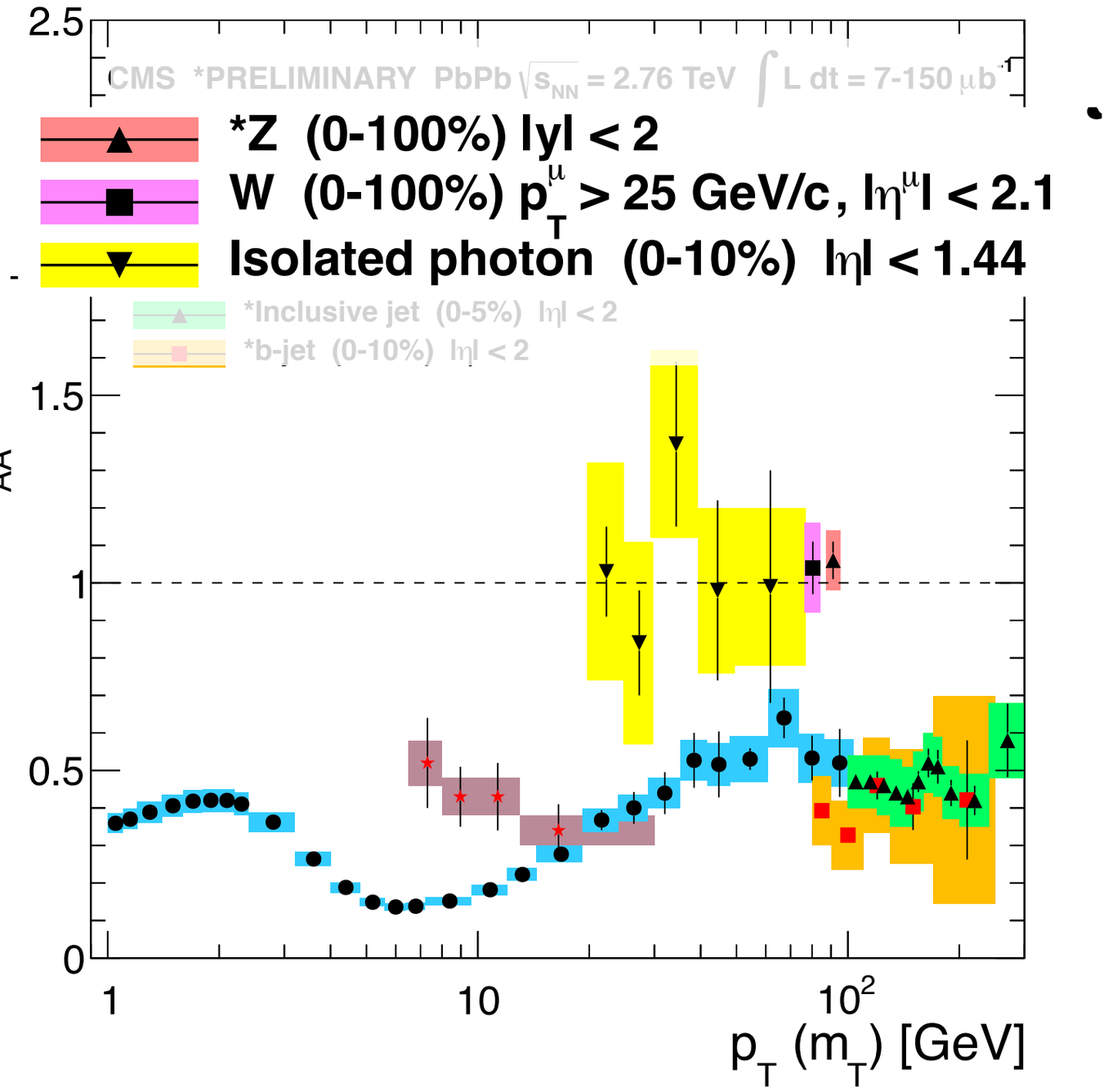
- Energy loss effects shifts the spectrum left
- Similar levels of RAA for a steeper spectrum implies what?
- At fixed jet p_T - do jets at RHIC or LHC lose more fractional energy?

Always keep the underlying spectrum in mind!

Lets hold on another second, why do we trust RAA?

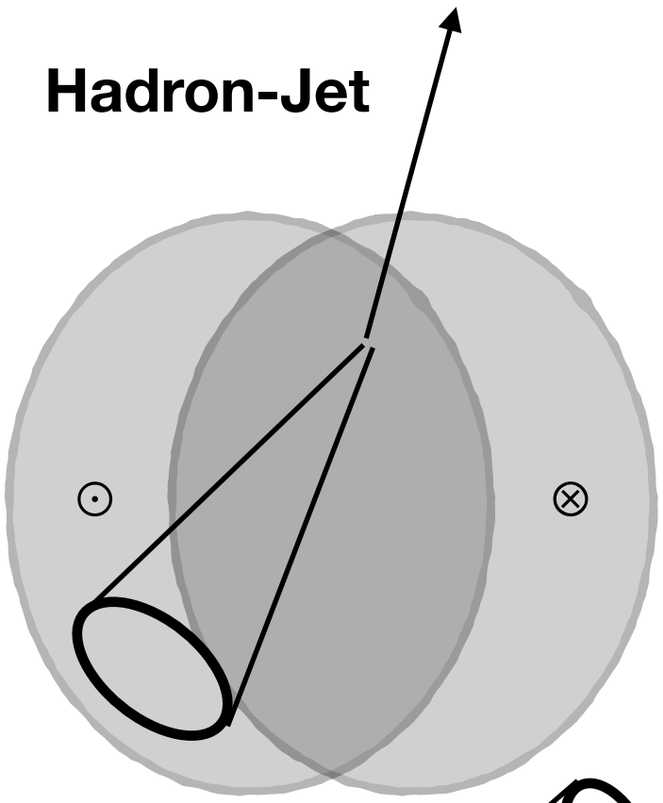


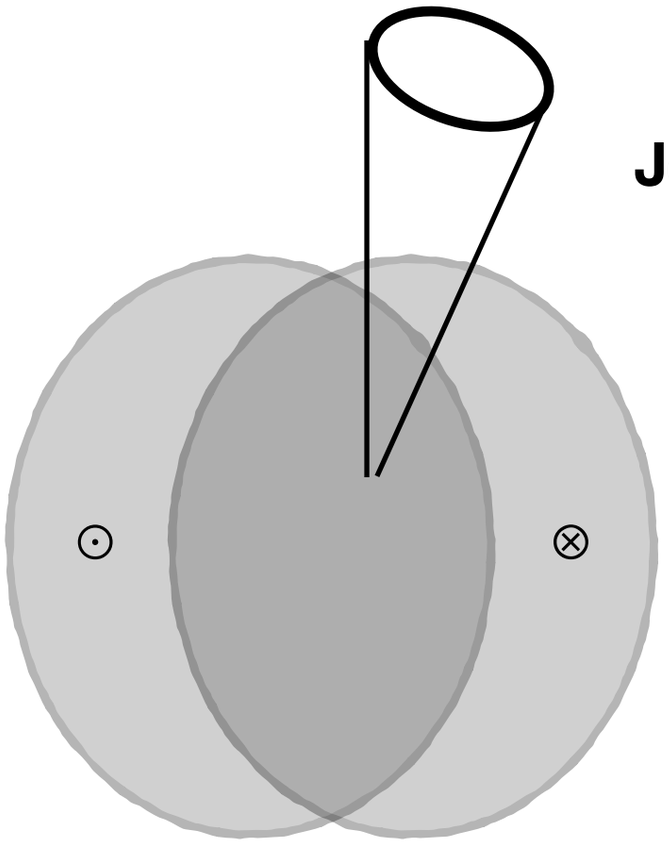
Lets hold on another second, why do we trust RAA?

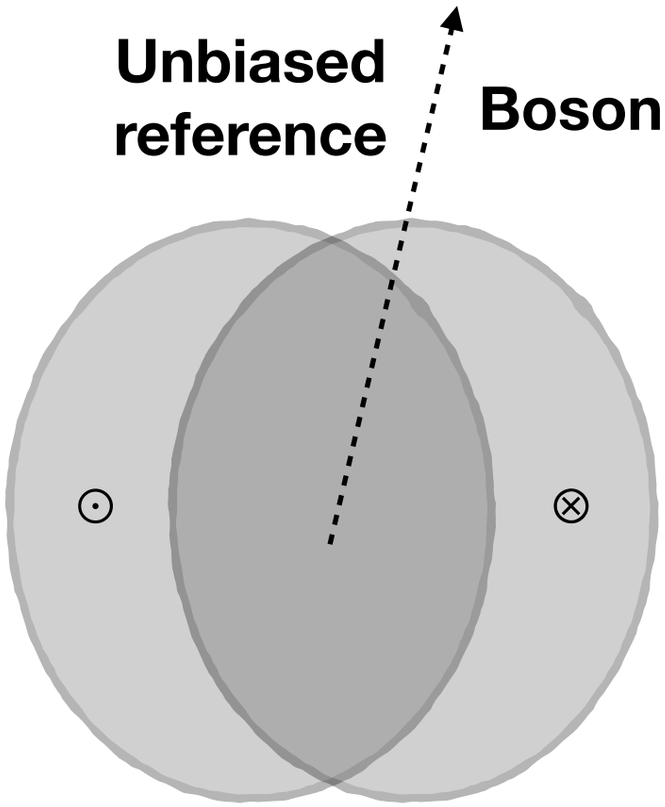


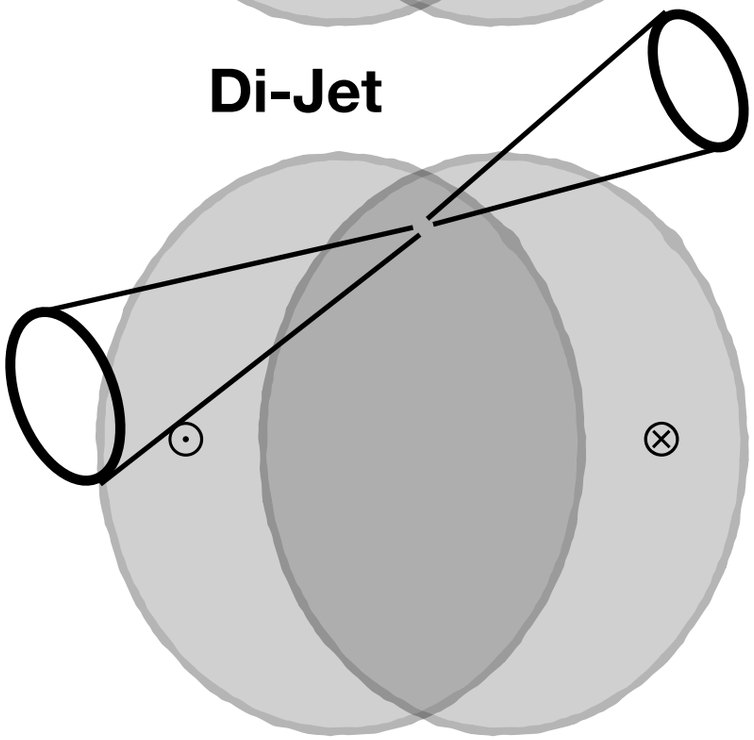
- Scaling by the number of binary collisions reproduces the yield of electro-weak bosons $\gamma, W^{\pm}, Z^0$

Not all events are created equal

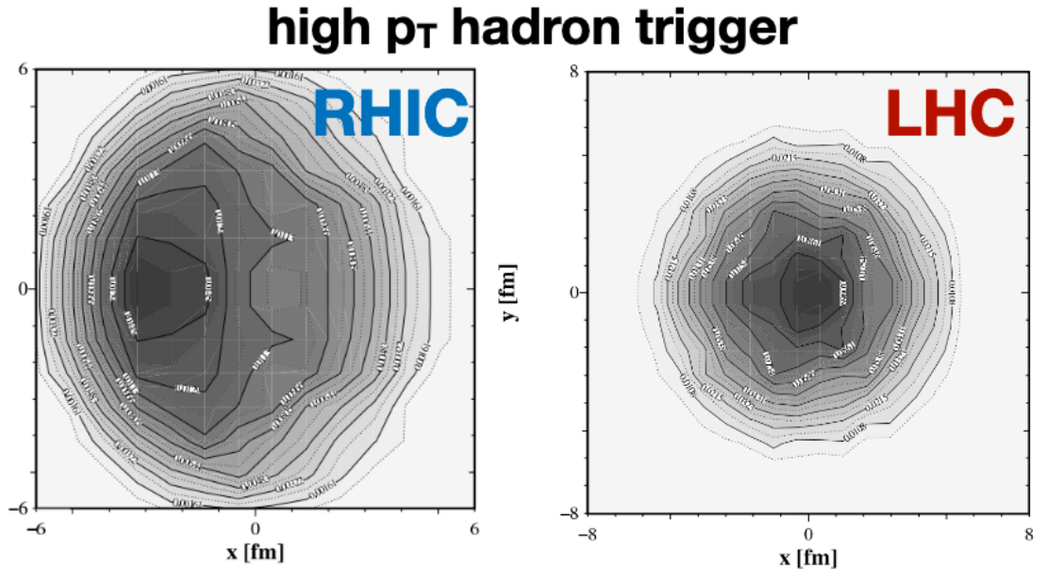








- Each of these event selections come with their own biases
- Important to understand their effect on an observable



Renk, PRC 85 064908 (2012), 87 024905 (2013)

1st gen - what did we learn?

- Colored probes are opaque whereas QGP appearing transparent to EW probes (γ, Z, W)

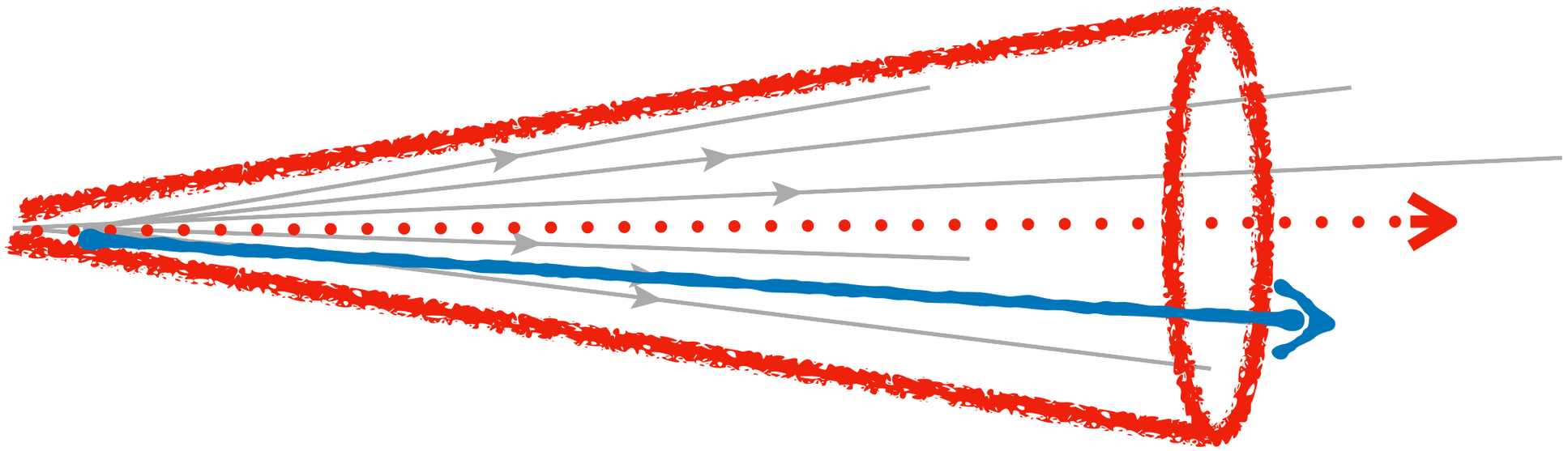
  - R_{AA} Nuclear modification factor (comparing yield in AA w.r.t binary collisions scaled pp) for γ/Z ~ 1, hadrons ~ 0.2 and **Jet R_{AA} ~ 0.5** (even at high p_T! With mild momentum dependence)

- **Large momentum asymmetry** in Di-jet, γ/Z+Jet pairs

- Large spread of quenched energy - **Broadening effect**

ATLAS Heavy Ion Publications
ALICE Heavy Ion Publications
CMS Heavy Ion Publications
STAR Publications
PHENIX Publications

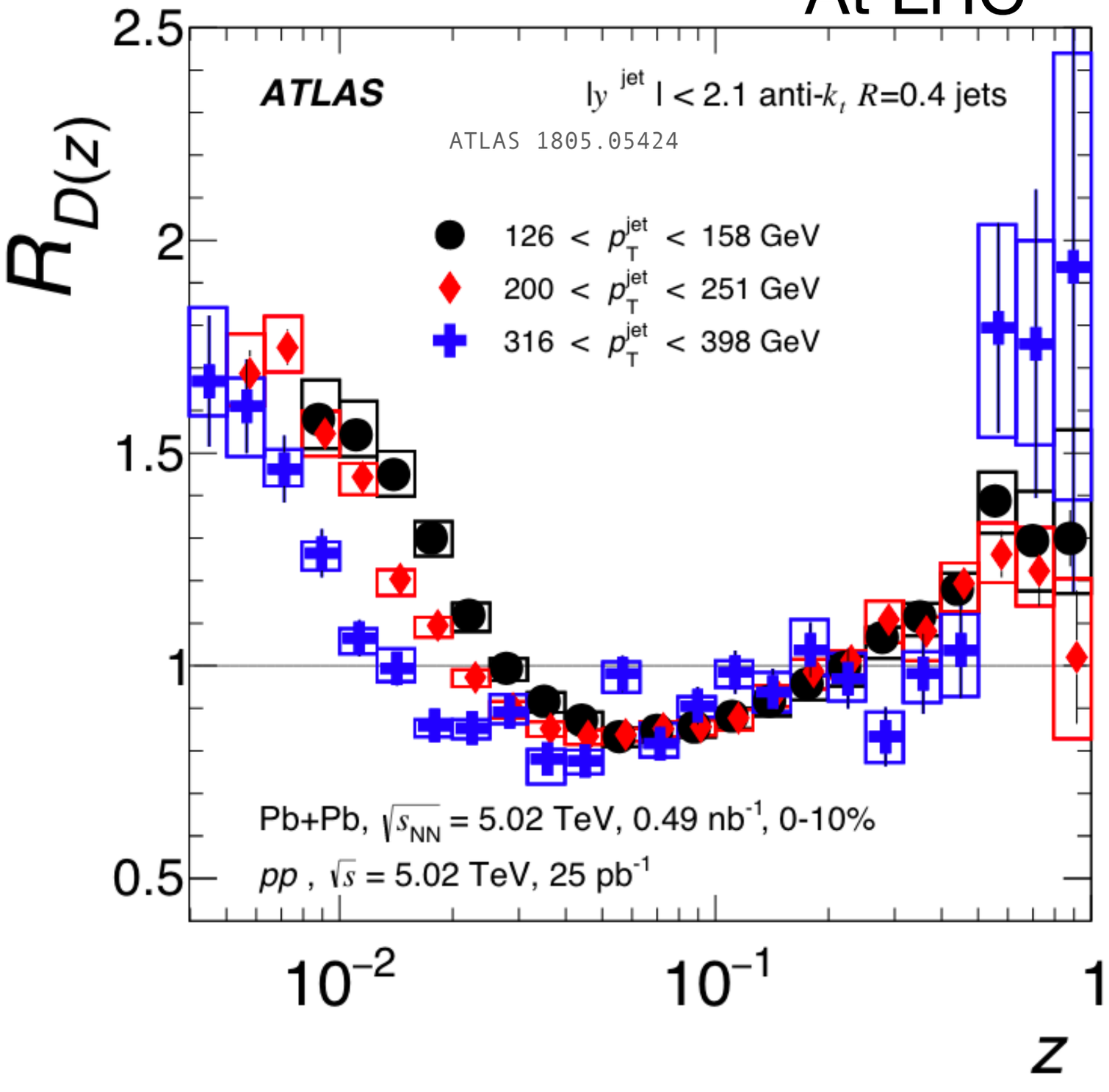
2nd generation Jet Measurements



Jet structure looks at particle production within the jet

Intra-jet particle production

At LHC

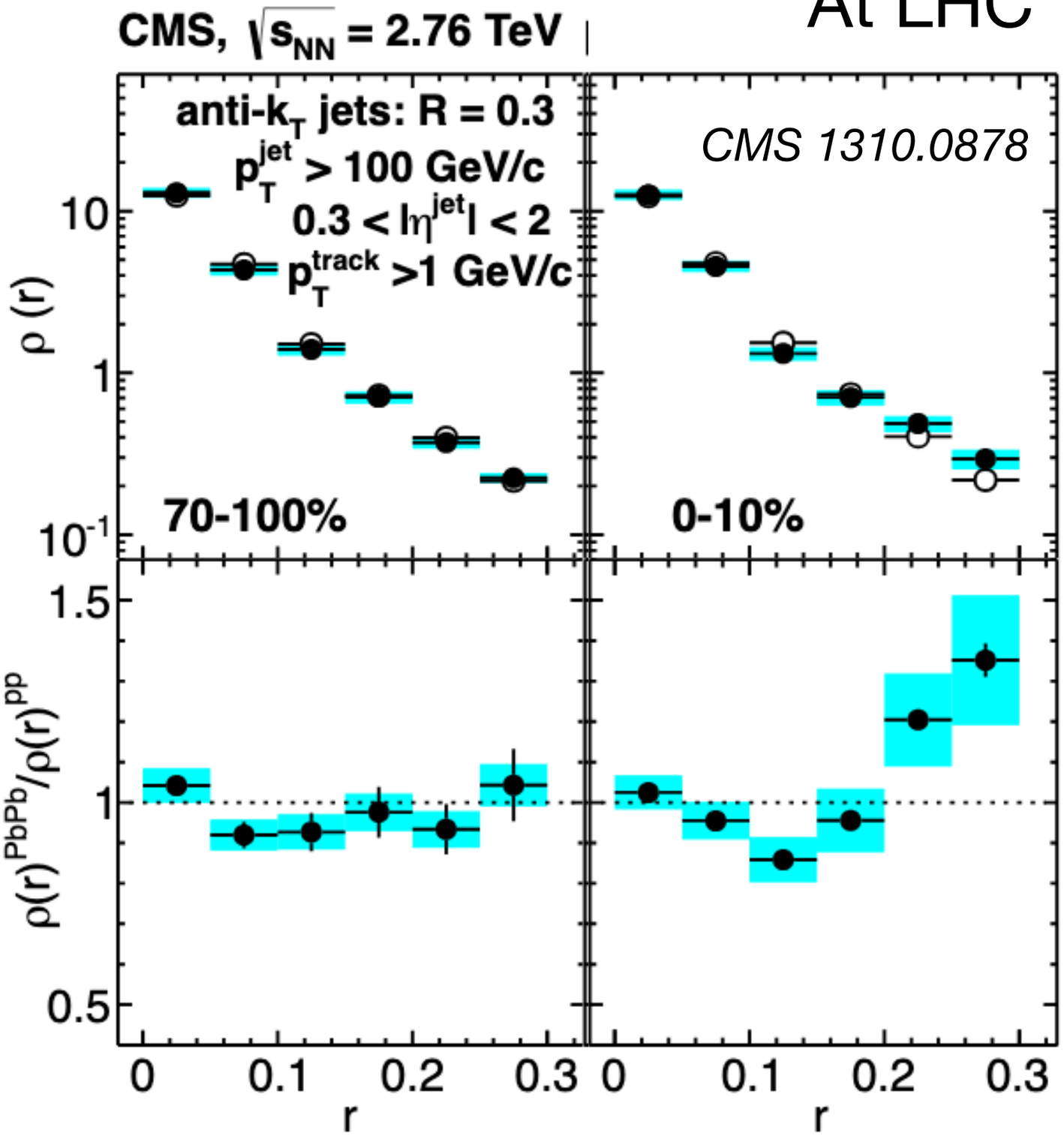


- Enhancement of low z hadrons at similar p_T (3.5 GeV) - points to a medium scale!
- Interesting observation of possible enhancement at high z

$$z = \frac{p_{T,trk}}{p_{T,jet}}$$

Intra-jet particle production

At LHC

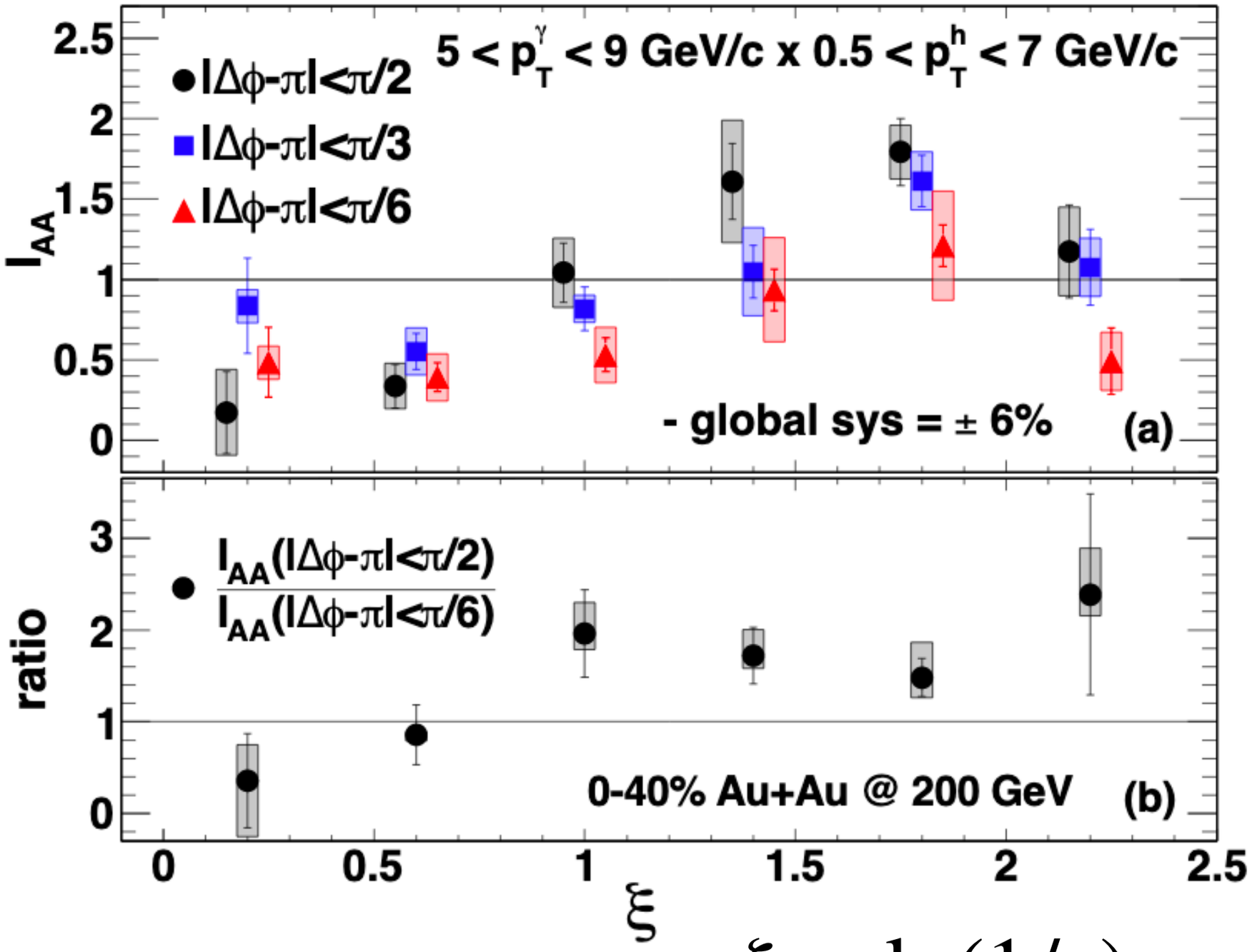


- Enhancement of hadrons around the edges of the jet cone (and extending beyond)
- Interesting observation of possible narrowing at the jet core!
- Convolution of effects including varying parton flavor and kinematic selection

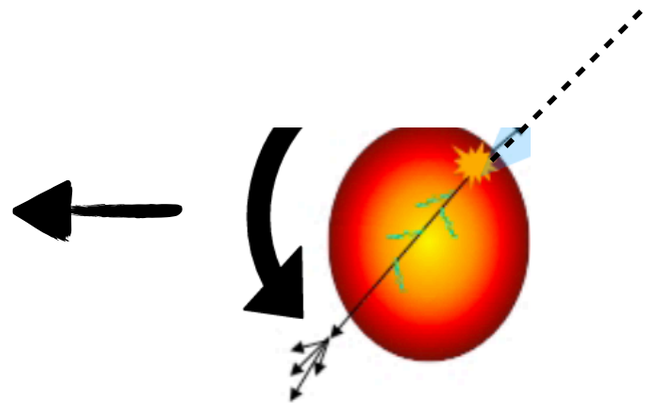
Jet/γ-Hadron correlations

At RHIC

PHENIX 1212.3323



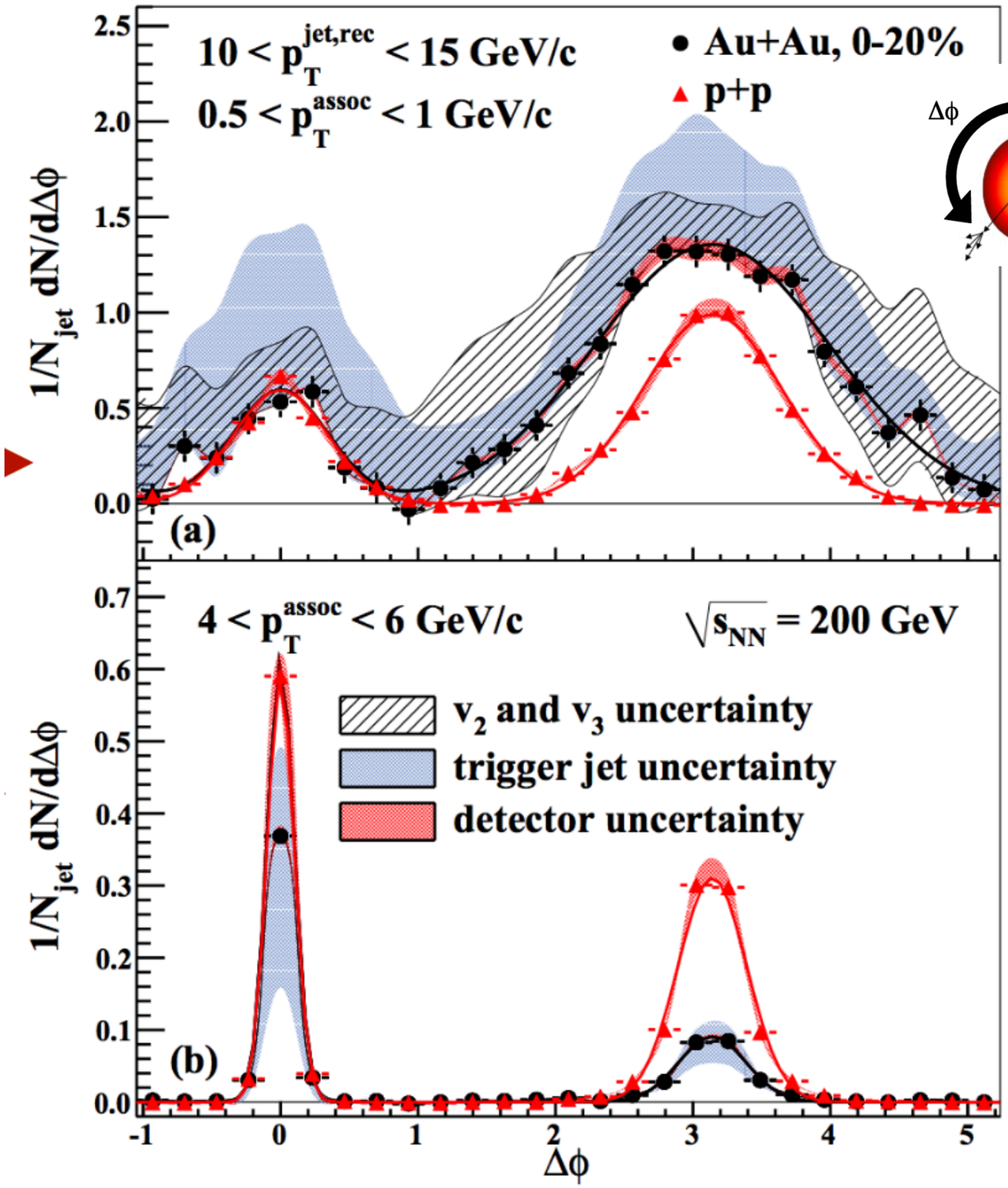
$$\xi = \ln(1/z)$$

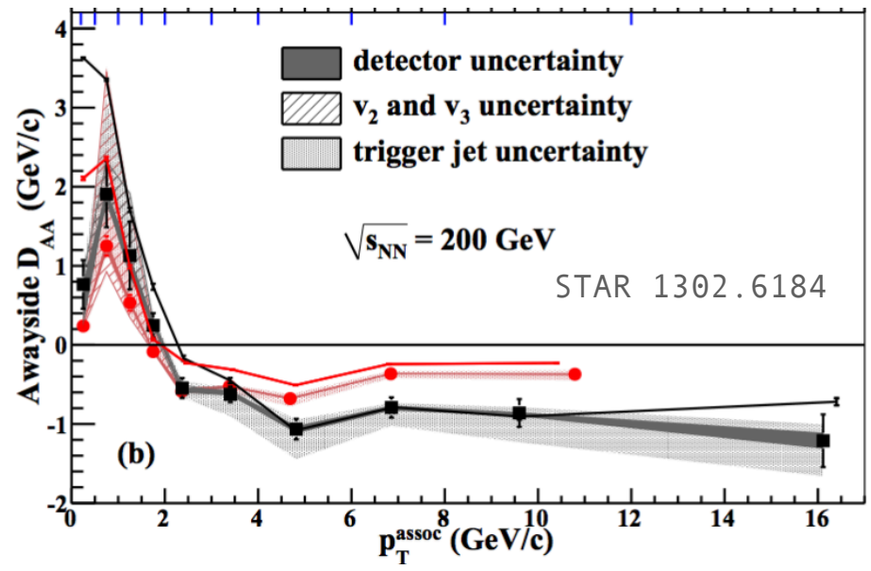


- Suppression of low ξ (high p_T tracks) recoiling off photons
- Clear and consistent signal of enhancement and broadening of recoil jet's low p_T constituents.

Jet/γ-Hadron correlations

At RHIC





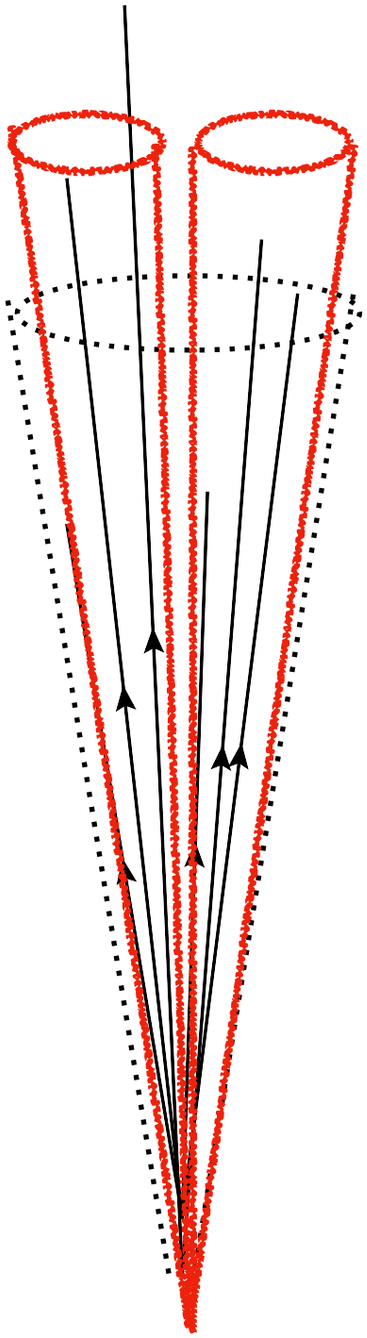
- Energy lost by high p_T (> 2GeV) constituents recovered by low p_T (0.2-2 GeV) excess
- Medium scale (2GeV vs 3.5GeV at LHC) smaller at RHIC as expected

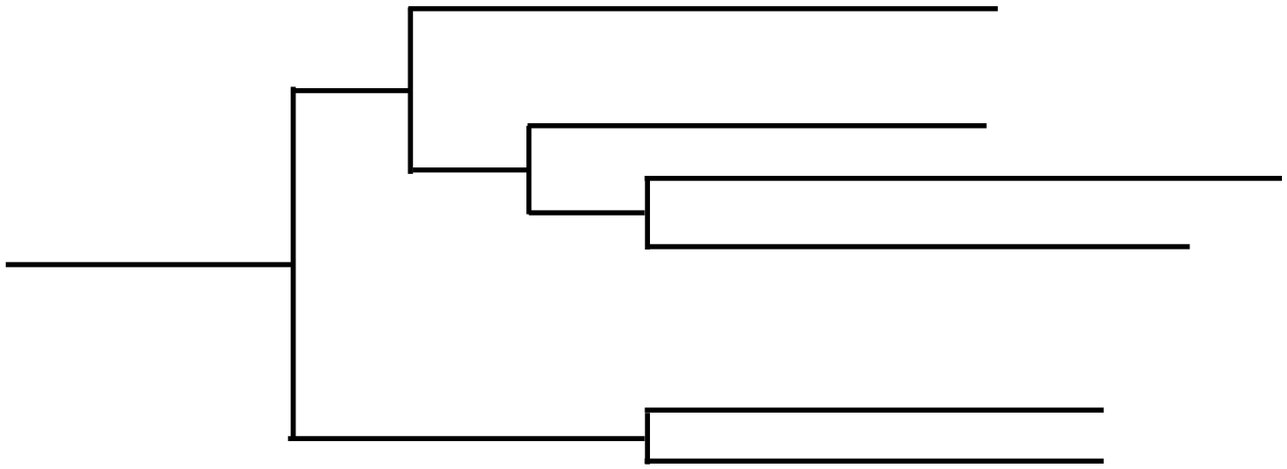
2nd gen - what did we learn?

- Observation of **fragmentation modification at low z and around the jet** - Highlights need for and use of calibrated probes with good reference
- Modification appears to occur at a fixed energy scale
- Large spread of quenched energy - **Broadening effect**
- But we still don't know the ‘How’ of energy loss

ATLAS Heavy Ion Publications
ALICE Heavy Ion Publications
CMS Heavy Ion Publications
STAR Publications
PHENIX Publications

3rd generation Jet Measurements





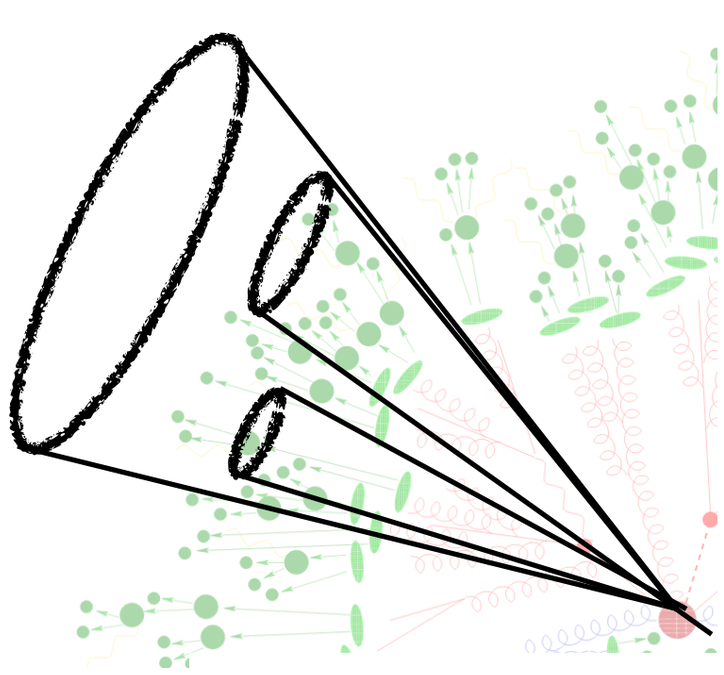
Exploit clustering information to look inside jets and study the evolution

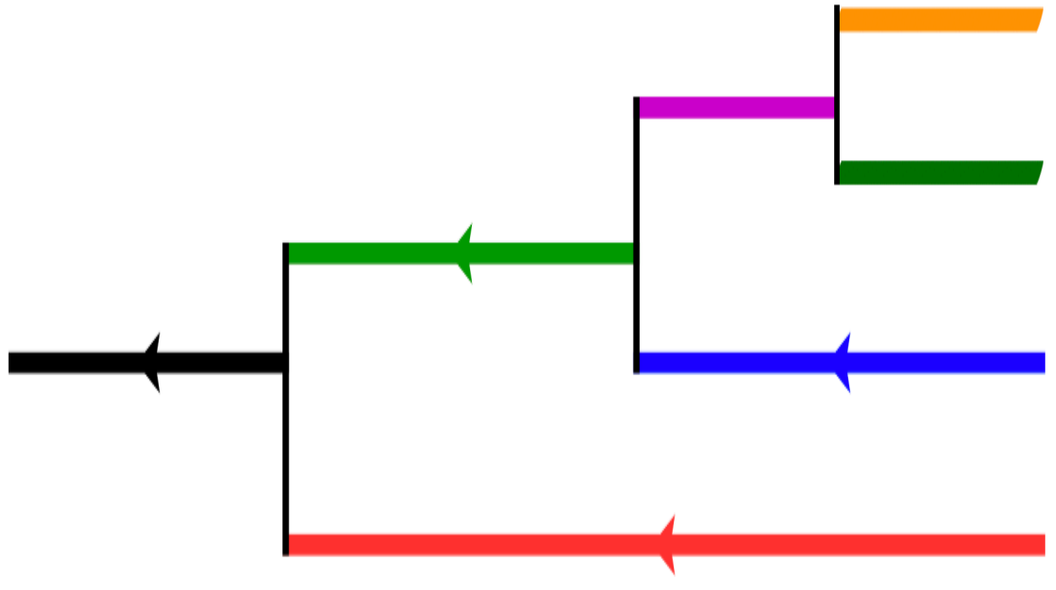
What is Jet SubStructure

- Structures within jets - built via correlations or algorithms

- SoftDrop - Utilizing the clustering information to build a tree

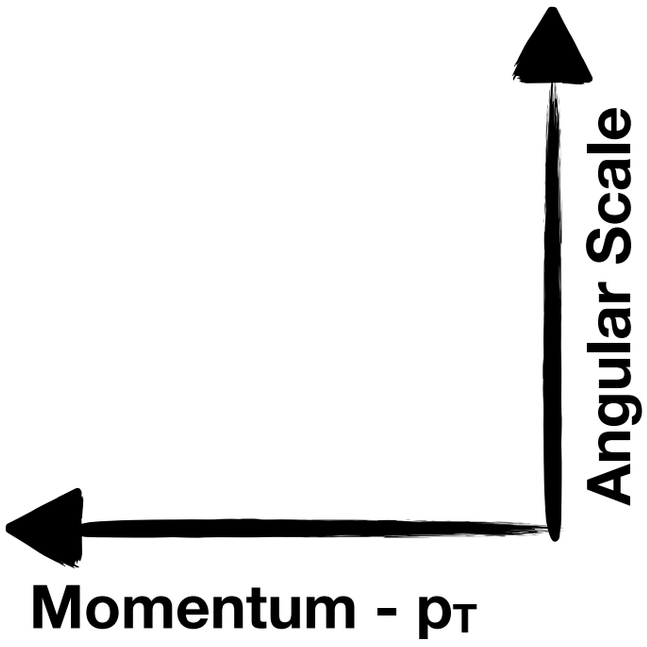
- JSS observables such as z, θ are of course dependent on the algorithm and jet definitions etc…

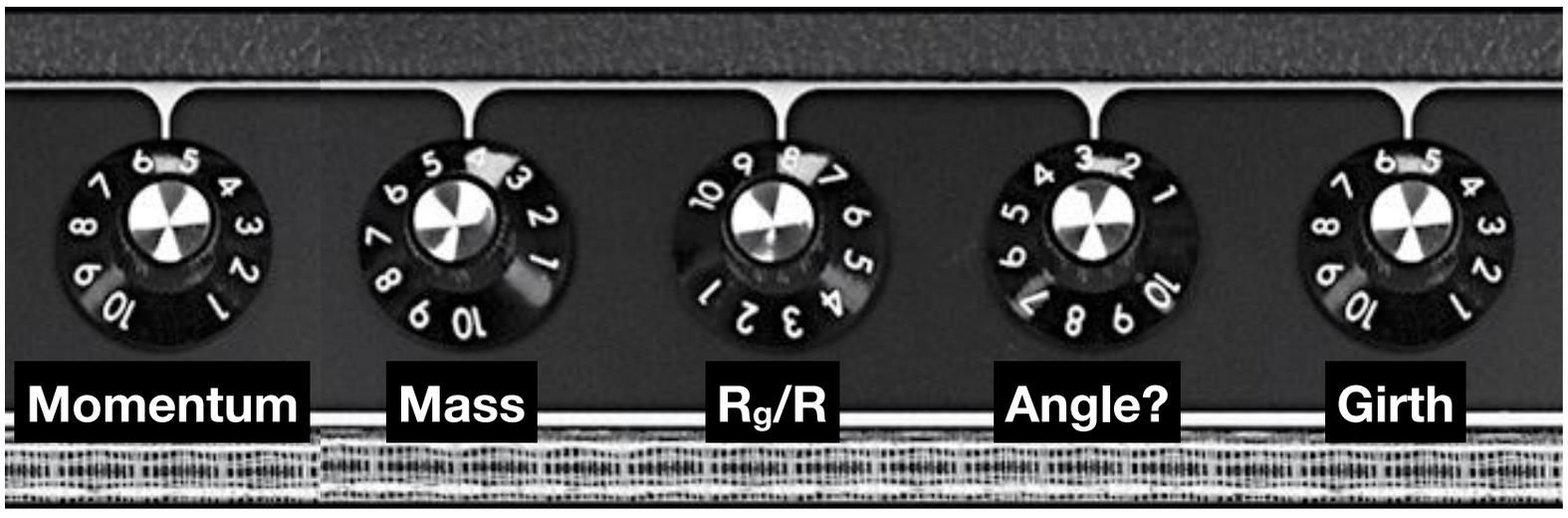




Key Idea
Use jet-substructure as a selection tool

Identify jet observable(s) sensitive to the parton shower kinematics



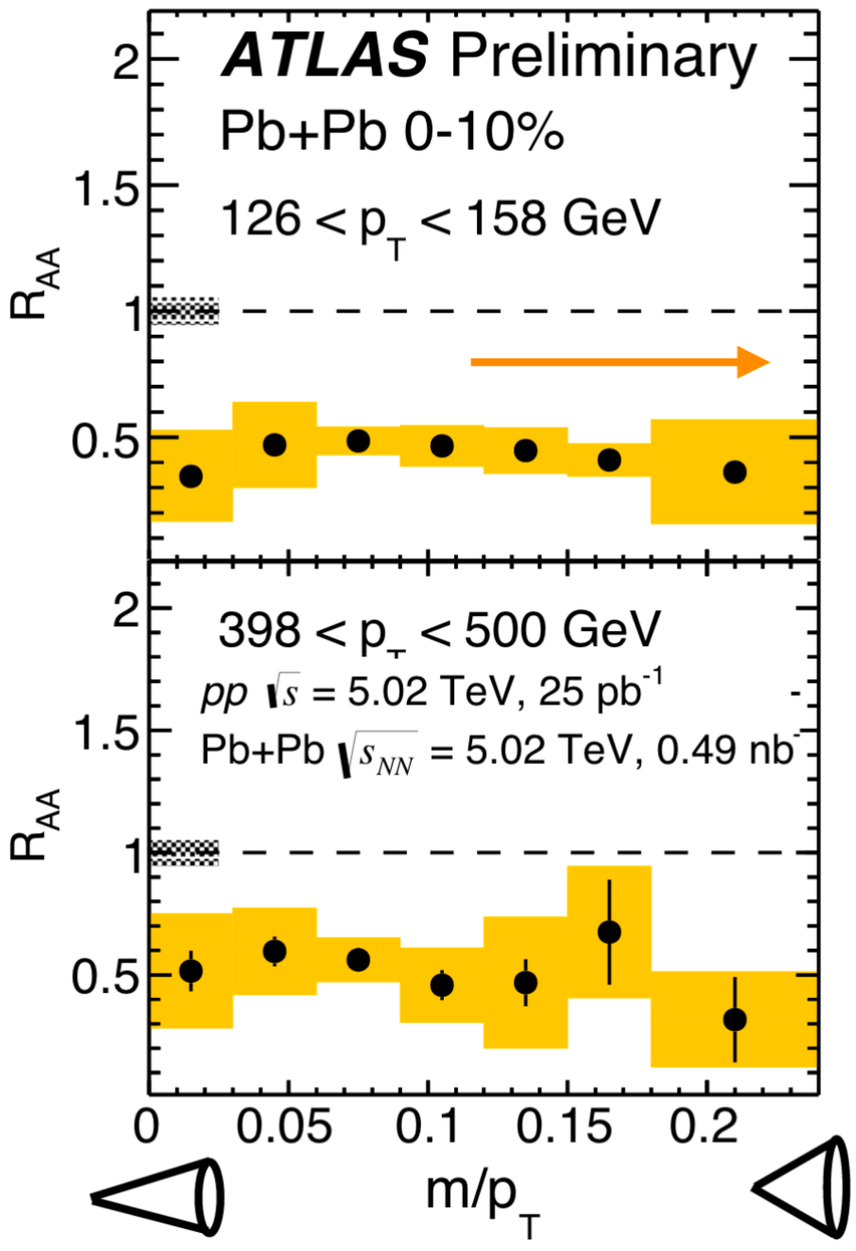


...

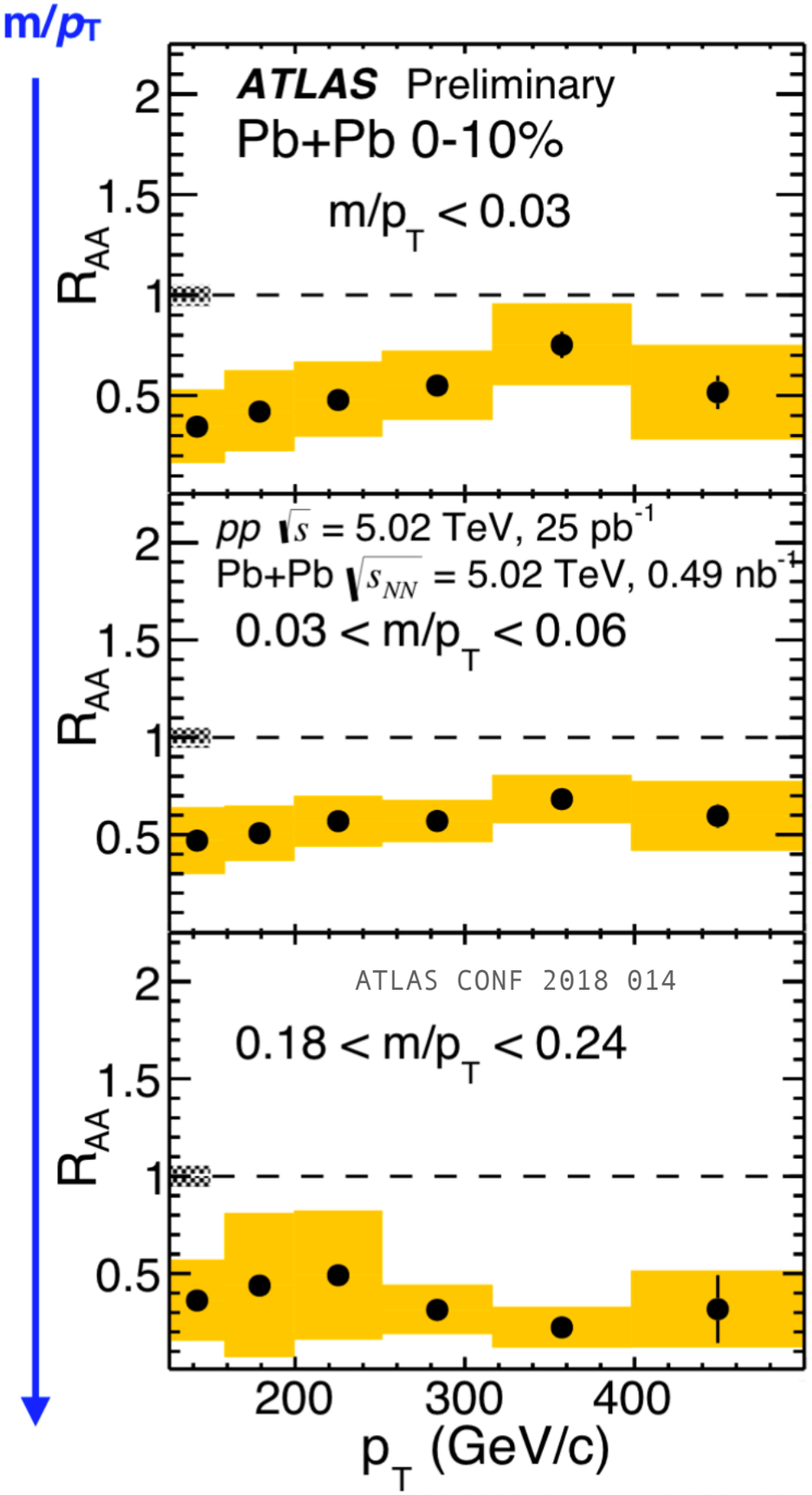
Partonic energy loss via a differential study in momentum scale and angular scale

R_{AA} for various Mass selections

Figures taken from Laura Haver's talk at WWND 2019



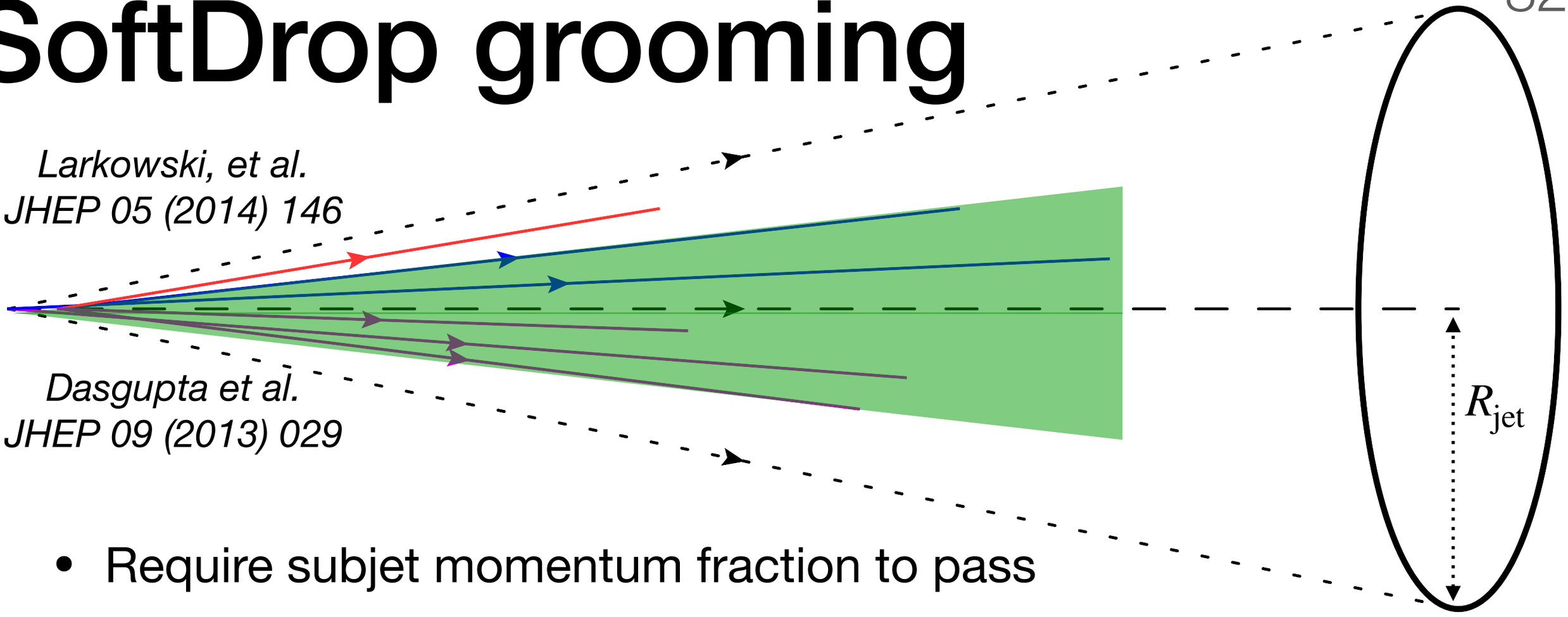
- Observe no significant effect of varying m/p_T
- Jet p_T possibly too high?
- m/p_T bins include jets of varying mass/ smeared resolution scales?
- Mass cancellation effects from quenching vs medium response possible?



SoftDrop grooming

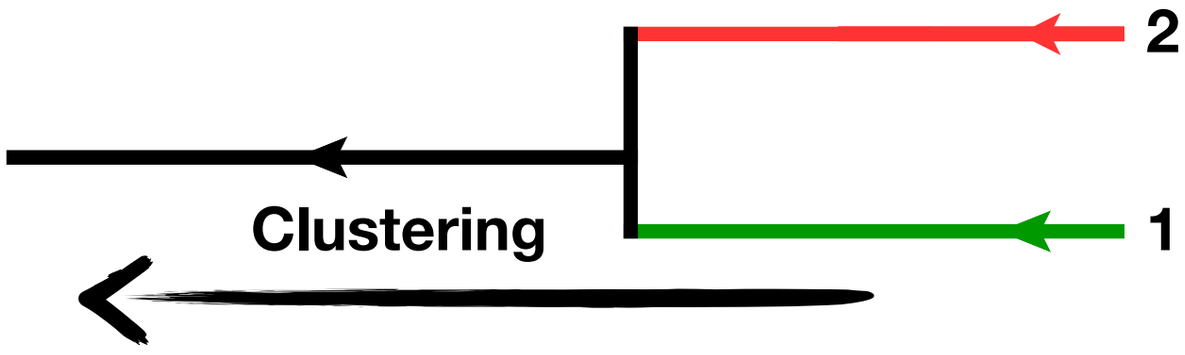
Larkowski, et al.
JHEP 05 (2014) 146

Dasgupta et al.
JHEP 09 (2013) 029



- Require subjet momentum fraction to pass

$$z_{\text{g}} = \frac{\min(\text{p}_{\text{T},1}, \text{p}_{\text{T},2})}{p_{\text{T},1} + p_{\text{T},2}} > z_{\text{cut}}(R_{\text{g}}/R_{\text{jet}})^{\beta} \qquad \begin{aligned} z_{\text{cut}} &= 0.1 \\ \beta &= 0 \end{aligned}$$



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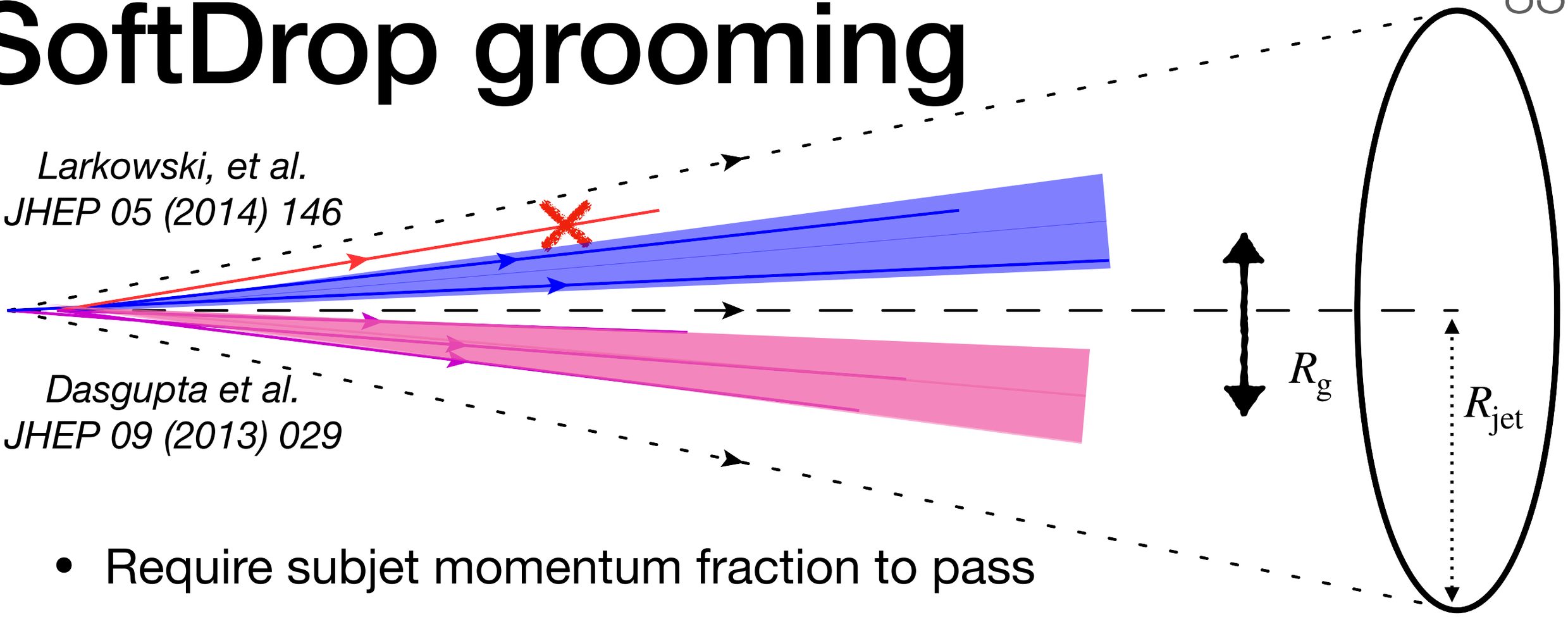
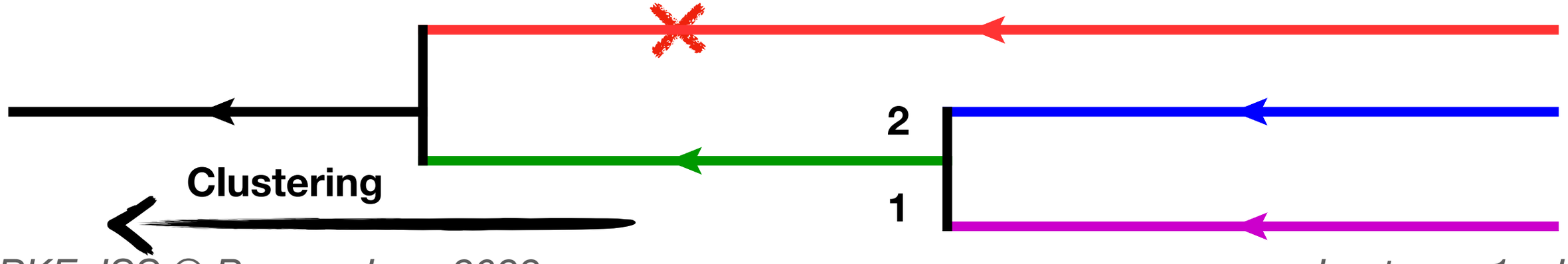


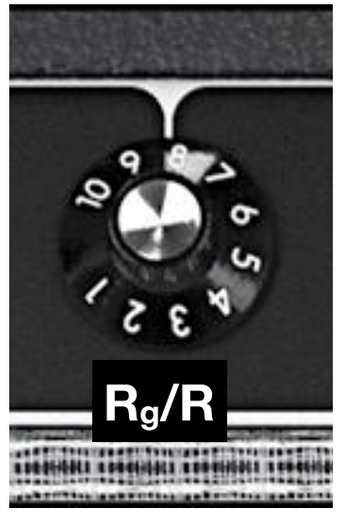
- Require subjet momentum fraction to pass

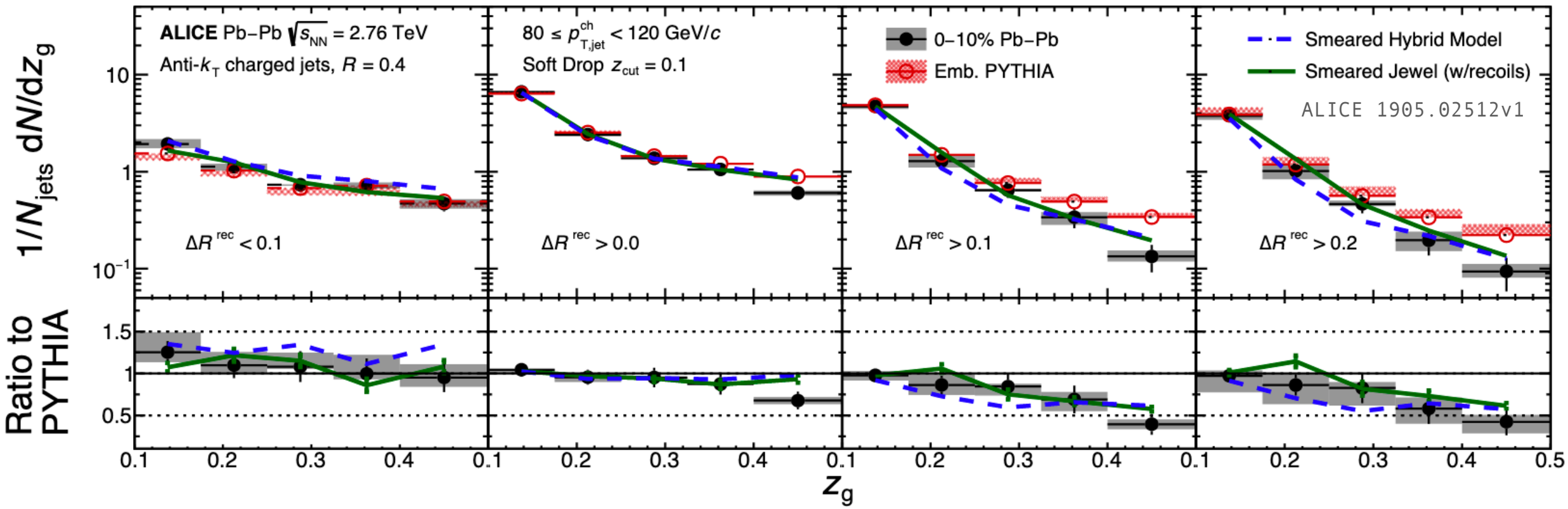
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta} \qquad \begin{array}{l} z_{cut} = 0.1 \\ \beta = 0 \end{array}$$

- With the two surviving branches (first hard split) - we define observables that characterize jet substructure z_g, R_g



Softdrop splitting at varying opening angles

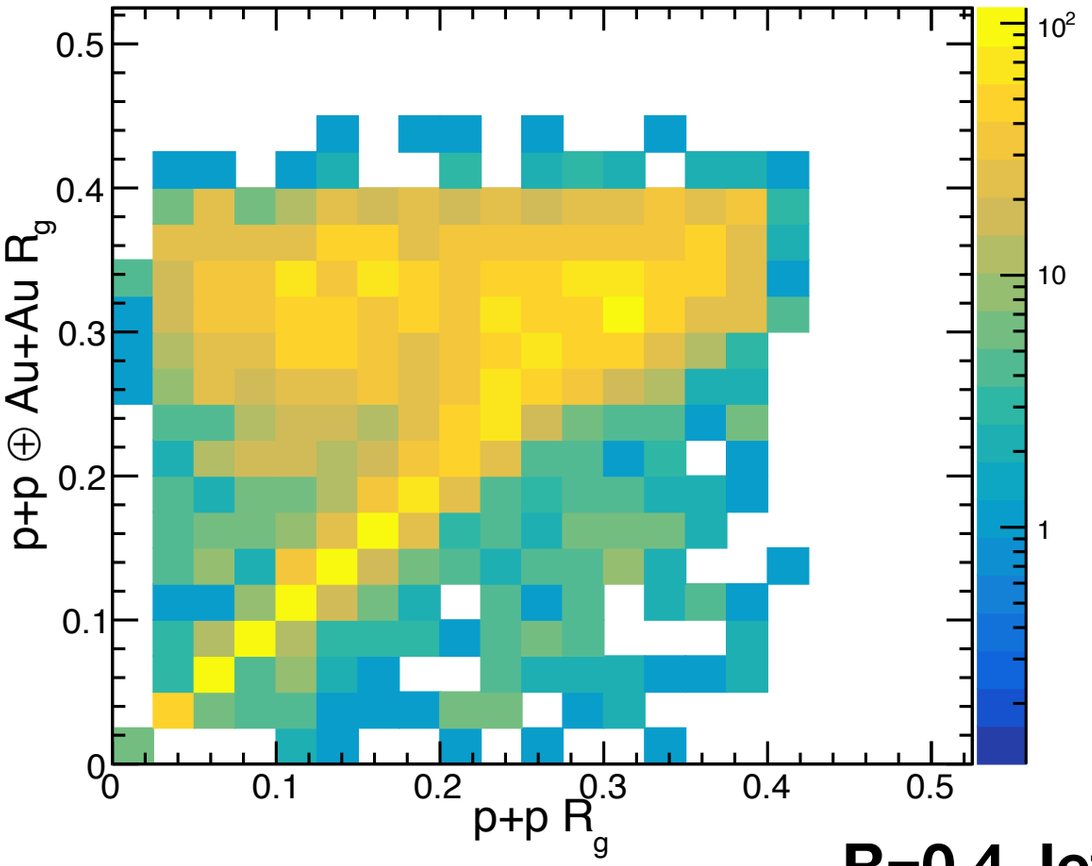




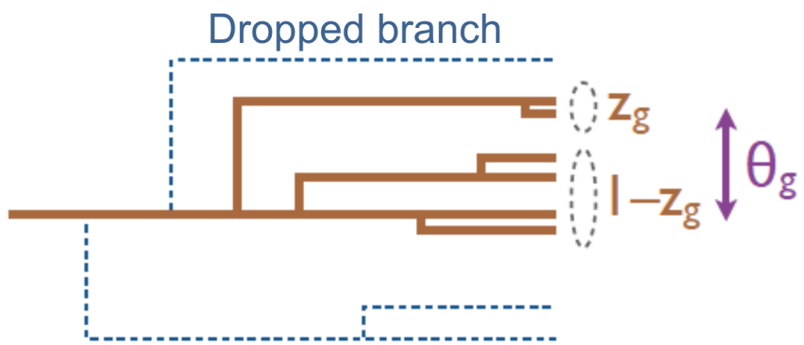
- Suppression of wide angle z_g splits and enhancement of narrow angle z_g
- MC models are generally able to reproduce the trend but further systematic studies are needed to discriminate these models

Choosing a robust observable

STAR Phys. Rev. C 105, 044906 (2022)



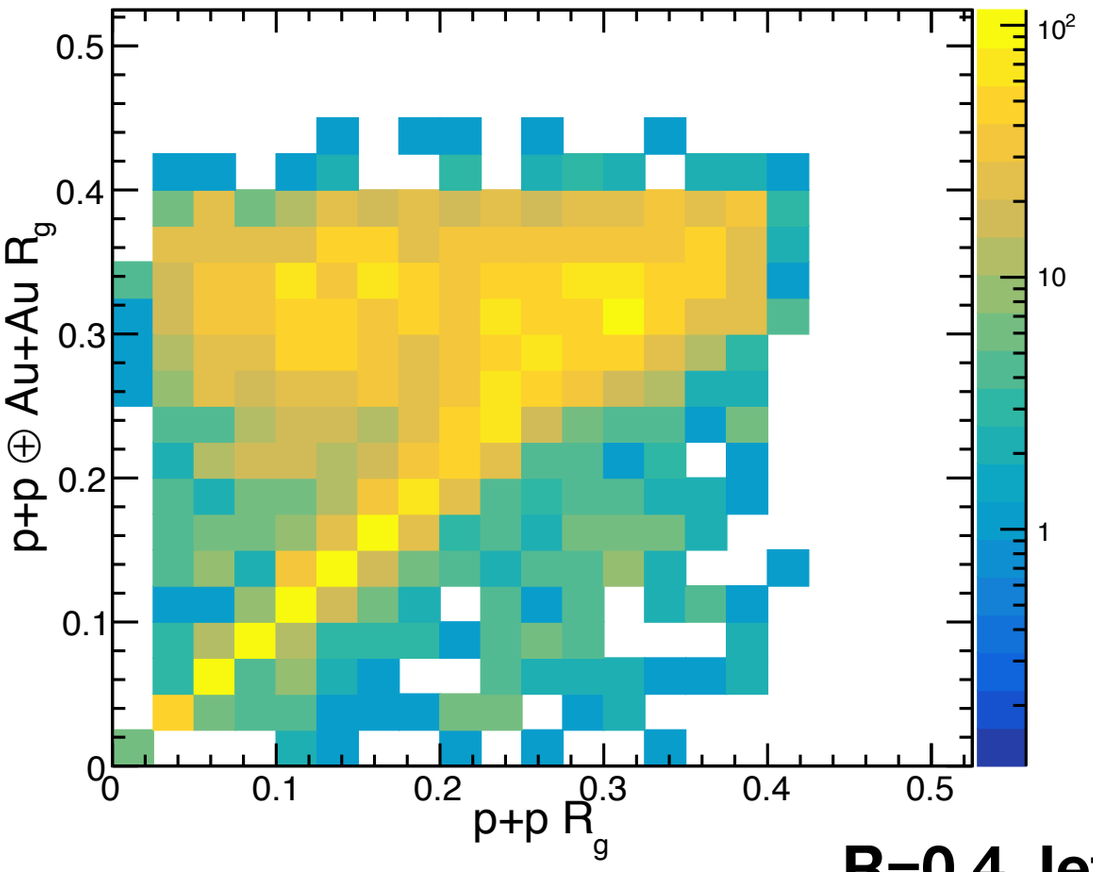
R=0.4 Jets

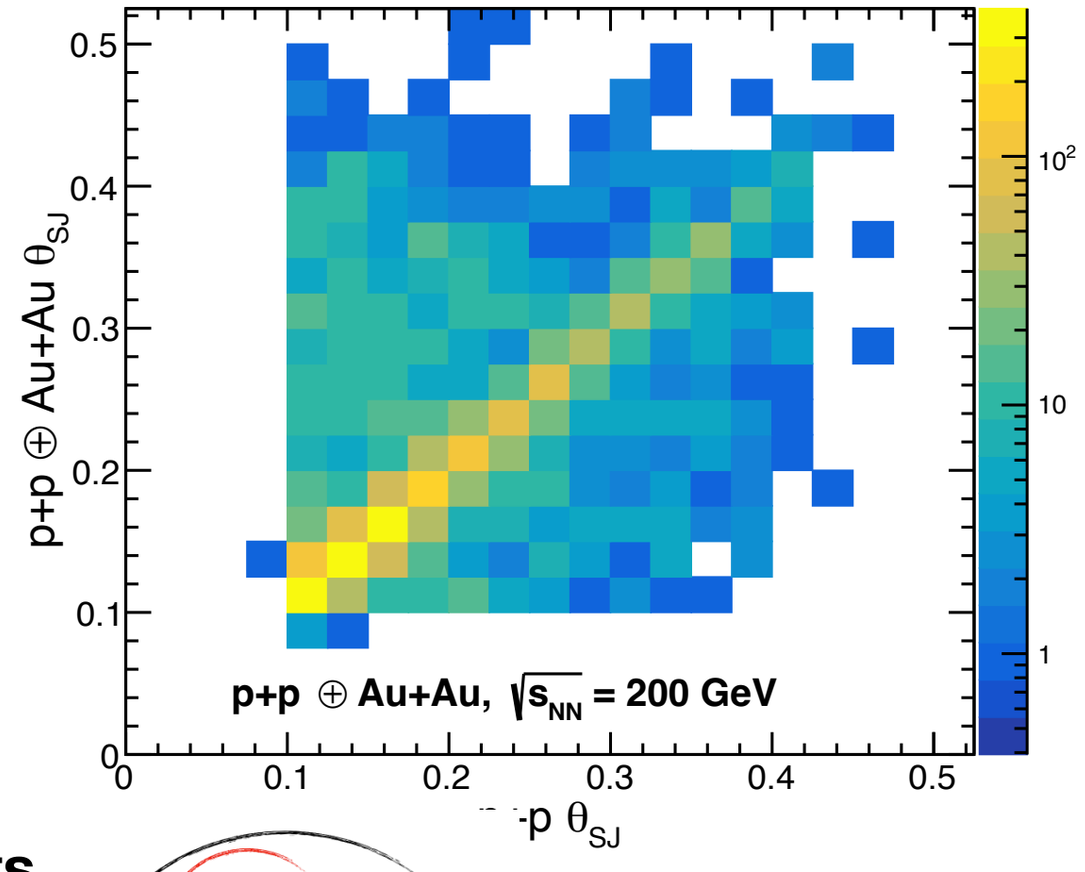


Momentum fraction threshold

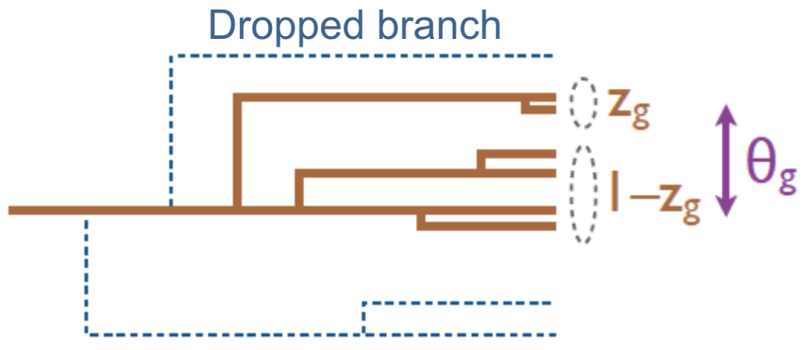
Choosing a robust observable

STAR Phys. Rev. C 105, 044906 (2022)

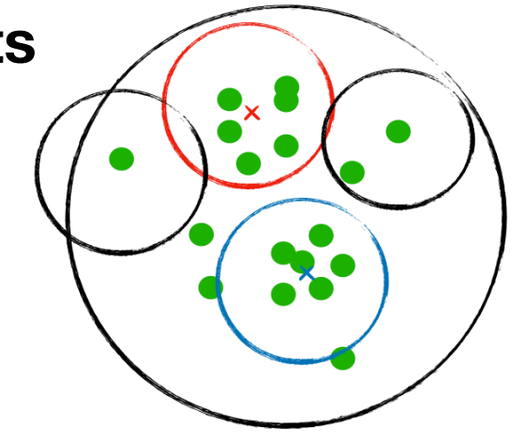




R=0.4 Jets



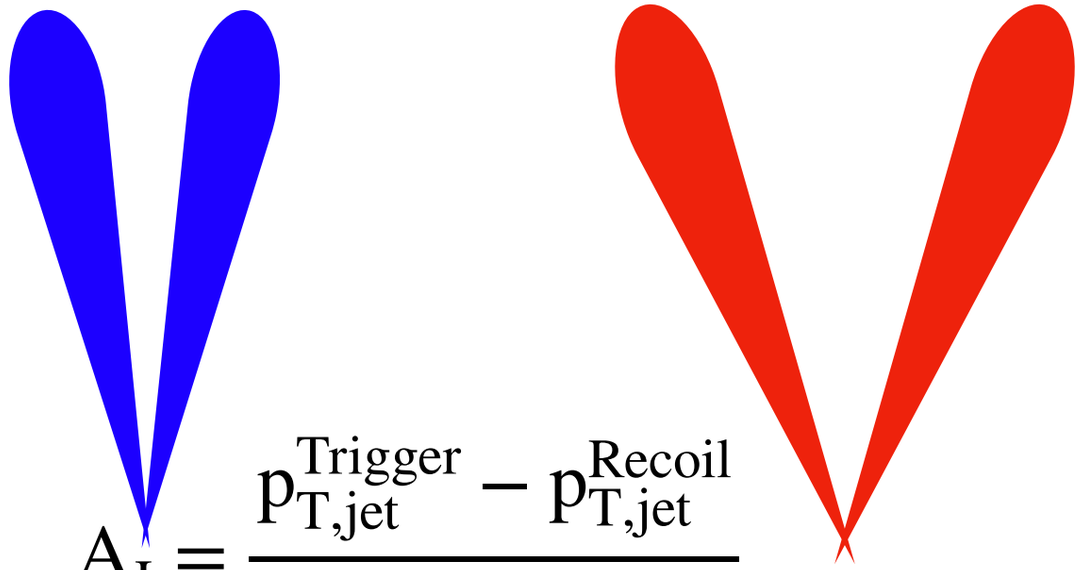
Momentum fraction threshold



anti-k_T R=0.1
Leading subjet
Sub-leading subjet
θ_{SJ} = Δ R (Blue Axis, Red Axis)

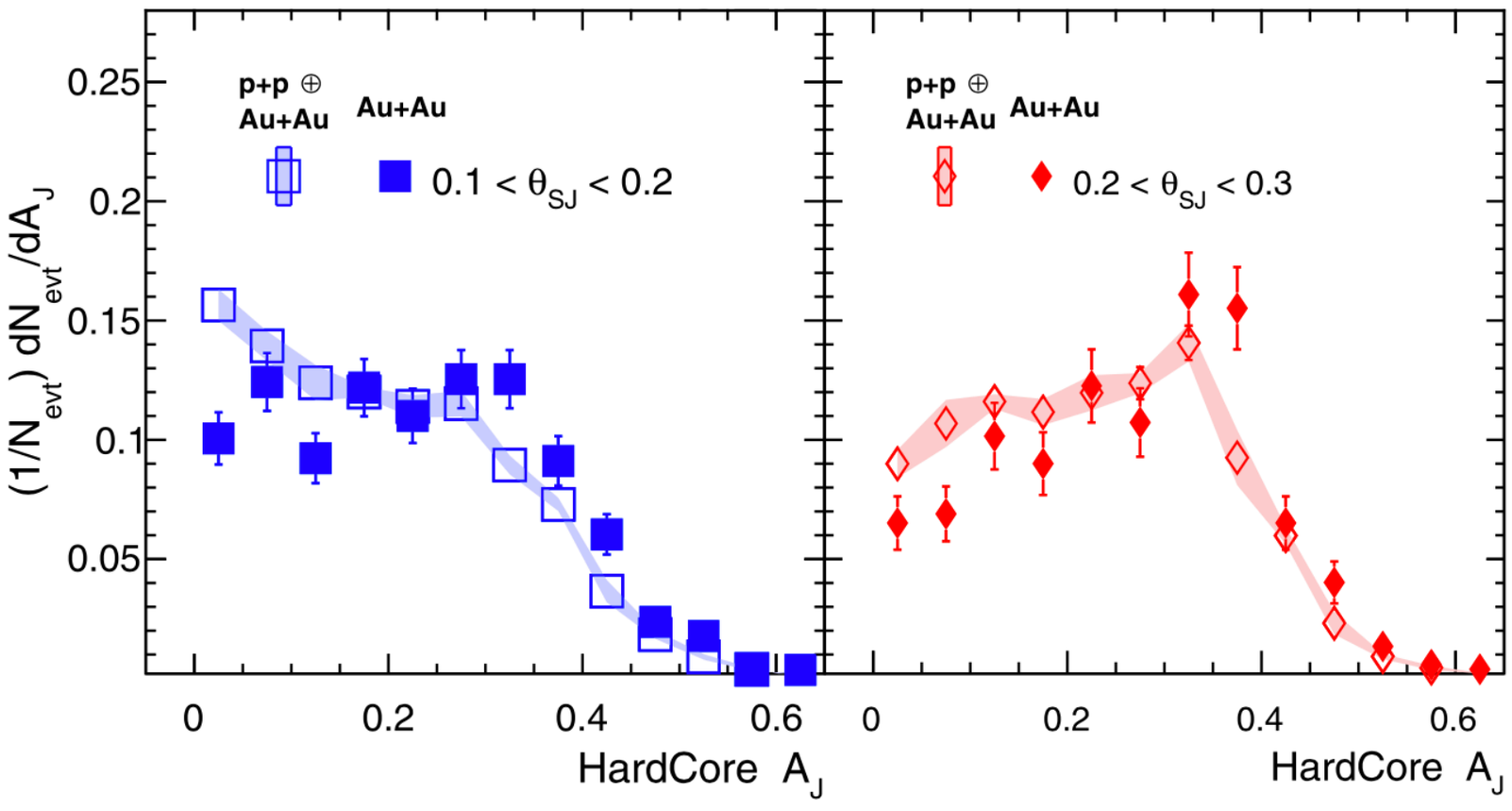
Momentum threshold

$0.1 < \theta < 0.2$ $0.2 < \theta < 0.3$

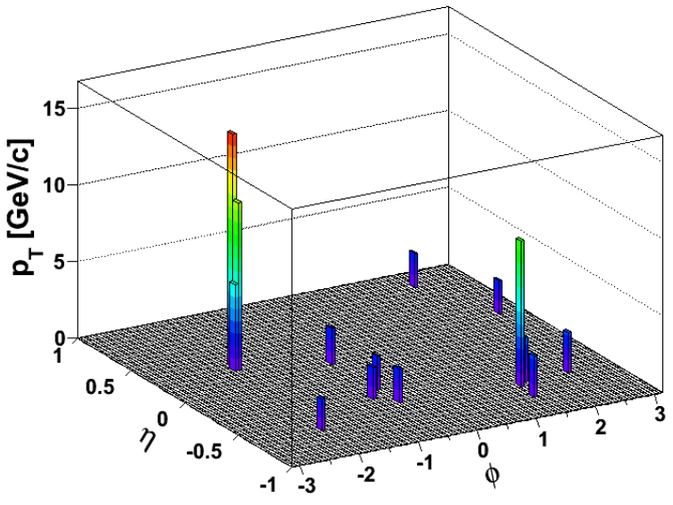


$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

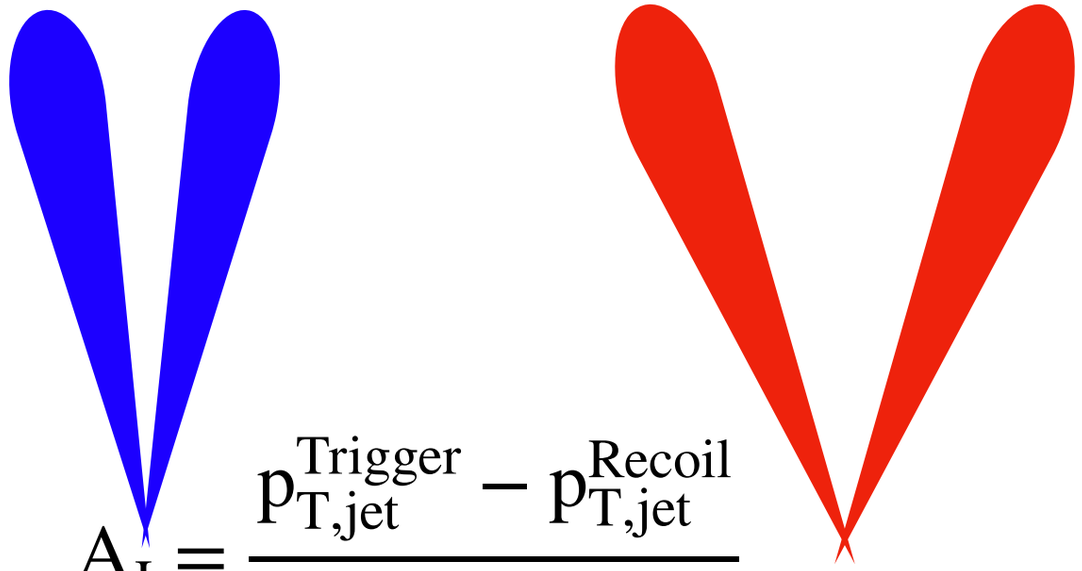
STAR 2109.09793



- Imbalance is independent on opening angle

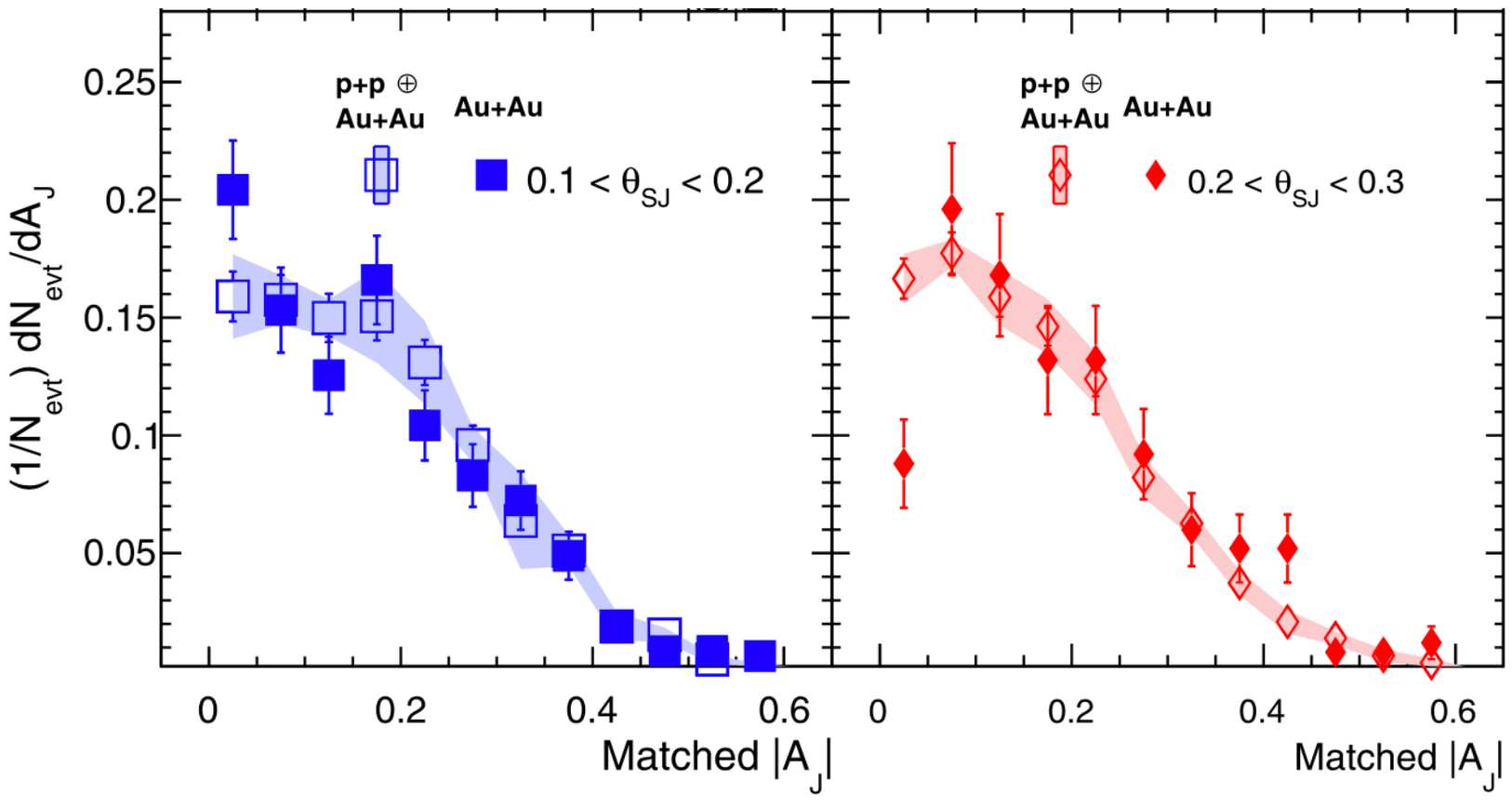


$0.1 < \theta < 0.2$ $0.2 < \theta < 0.3$

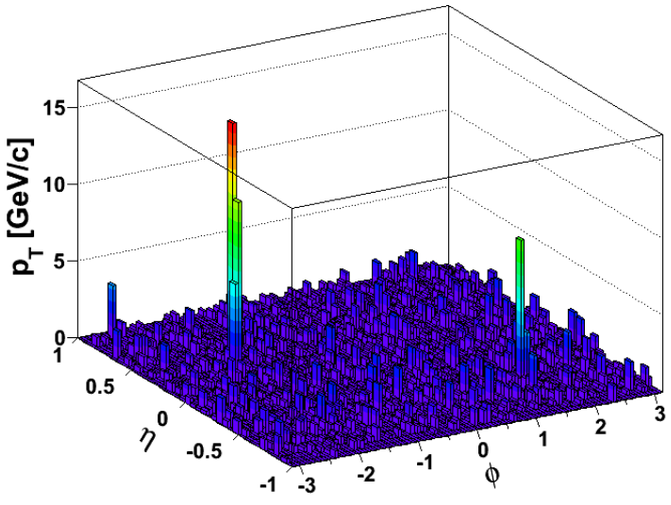


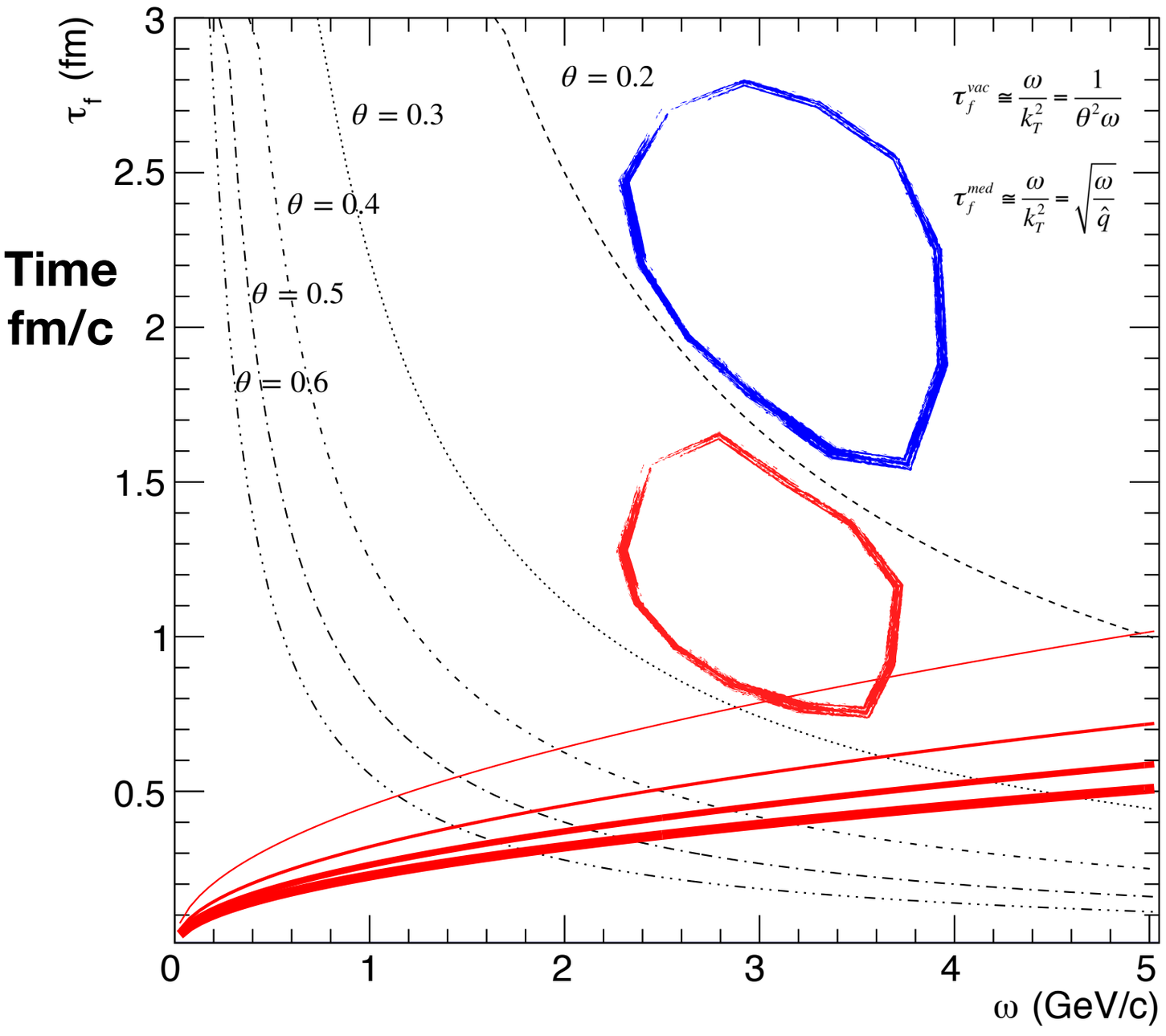
$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

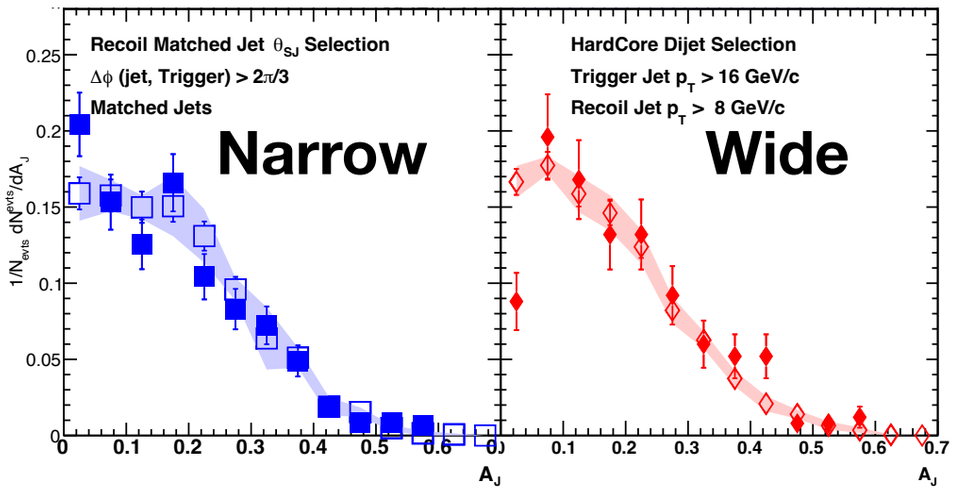
STAR 2109.09793

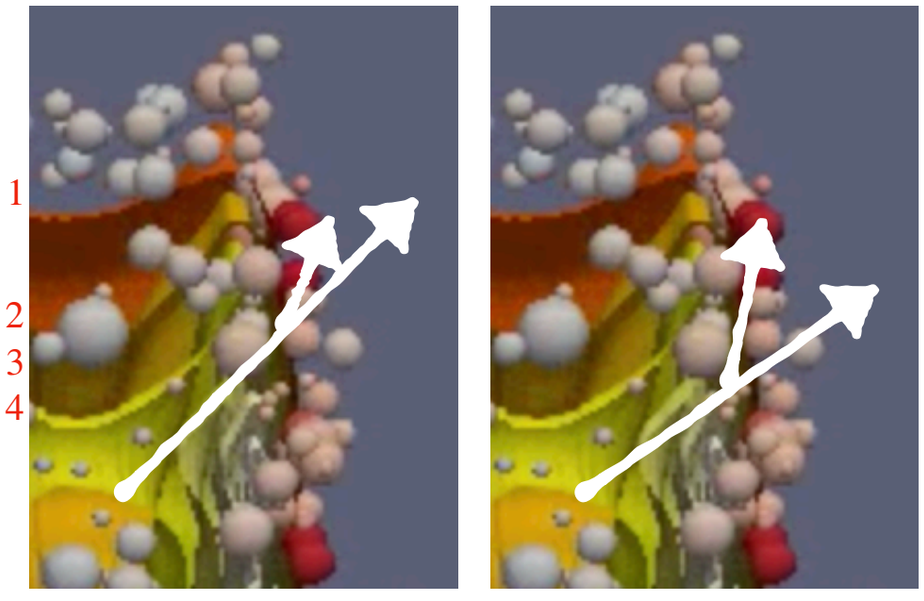


- Balancing is also independent on opening angle









- Energy loss for these dijets is an experimental observation of soft radiation from a single color charge!
- Potential upper limit on the coherence length $\lambda_\perp \sim \frac{1}{\hat{q} t_f} \leq 0.1$

3rd gen jet measurements ongoing!

- Jet substructure enables a **systematic exploration of parton-QGP interactions**

- **Tagging jets** of particular angular scales and studying their **calibrated energy loss** can point us towards quantitative measurements of the QGP's microscopic properties

- Differential measurements further constrain theoretical scenarios and **probe medium at varying resolution scales**

- Consistent picture of energy loss at RHIC for specially selected dijets via **soft gluon emission from a single color charge**

Backup