Exploring and exploiting various regimes within the jet shower

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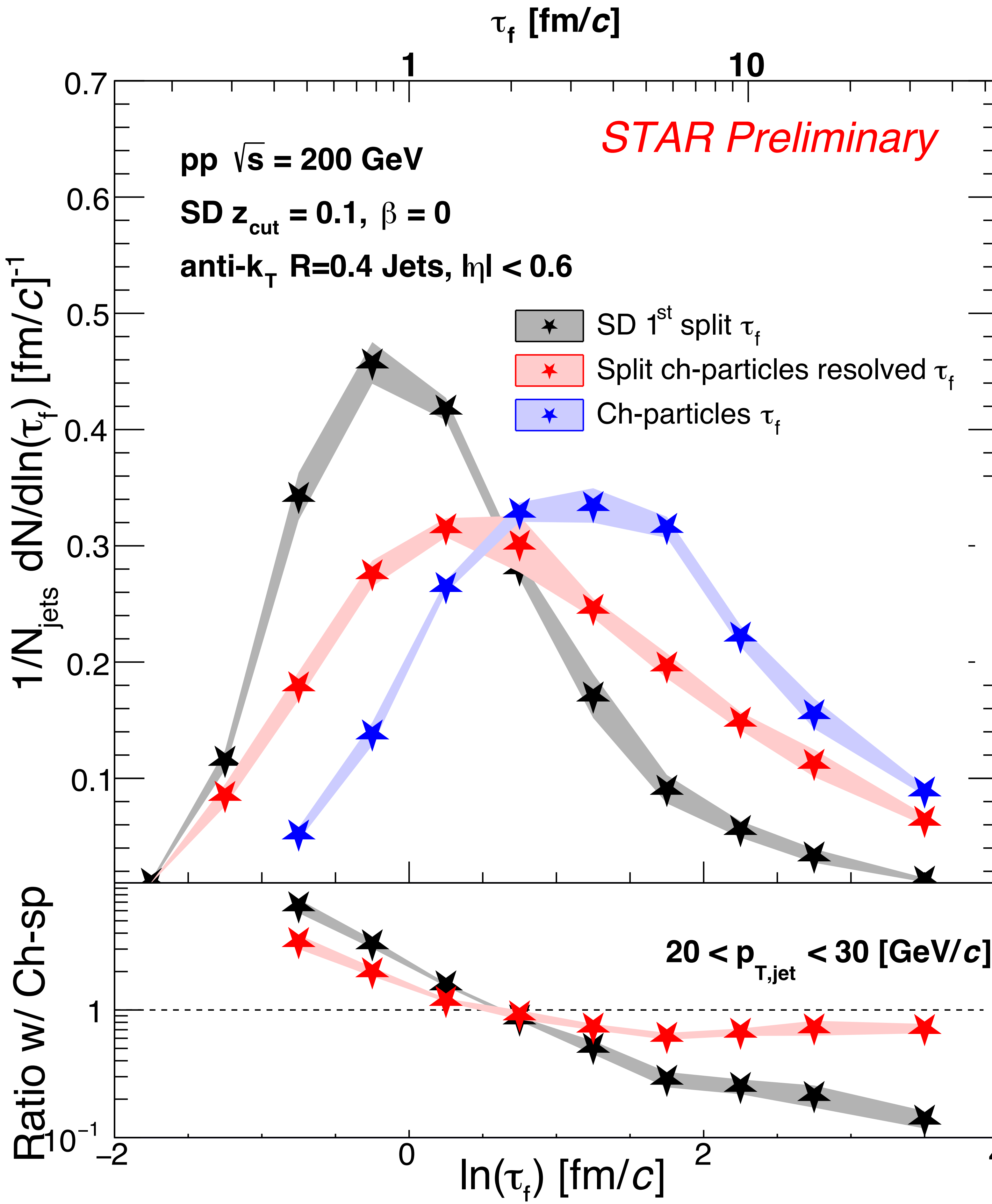
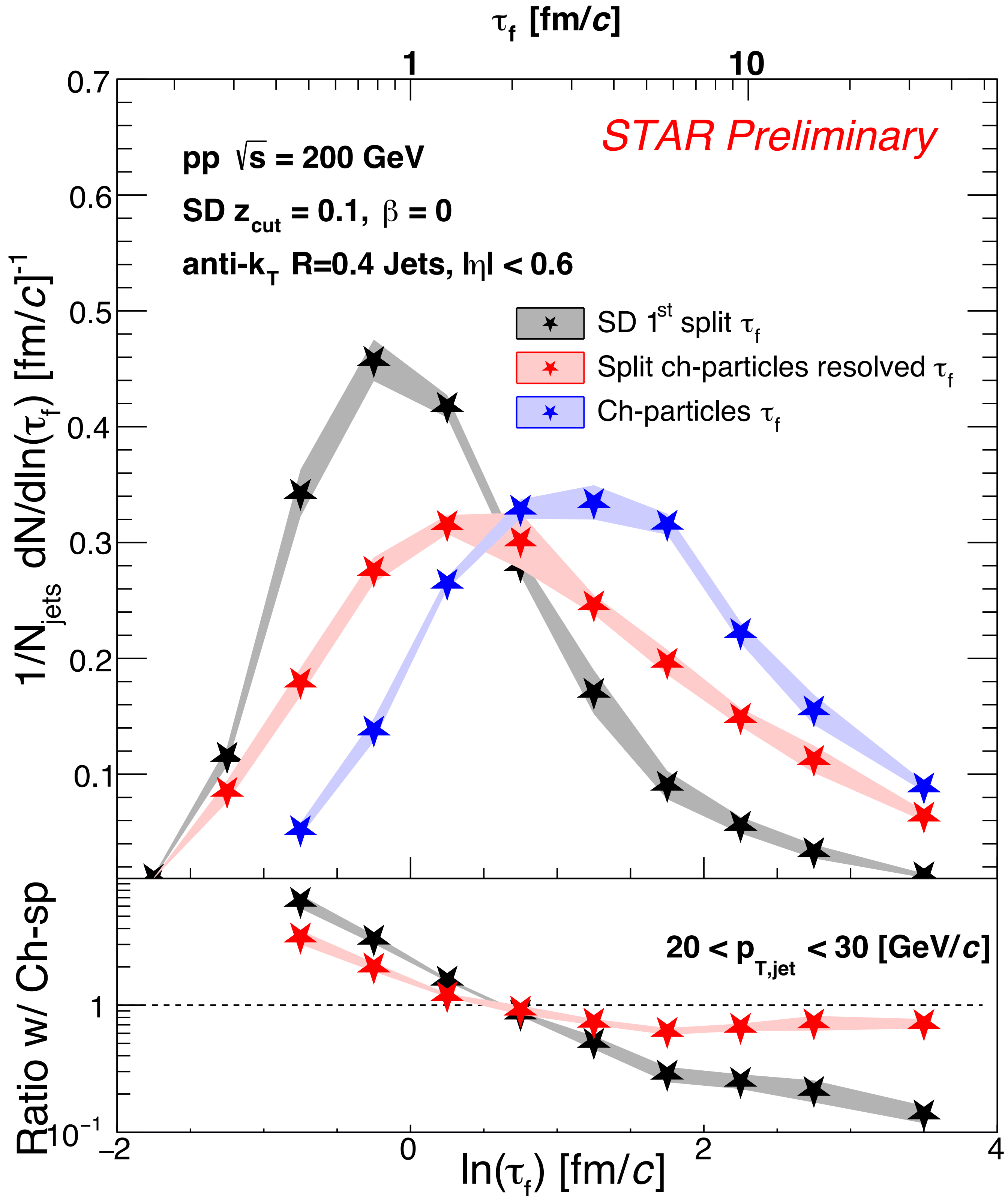
Winter Workshop on Nuclear Dynamics
Puerto Vallarta, Mexico

raghavke.me



Formation time (10^{-23} sec)

anti-k$_T$ R=0.4 jets



p+p $\sqrt{s} = 200$ GeV

Formation time

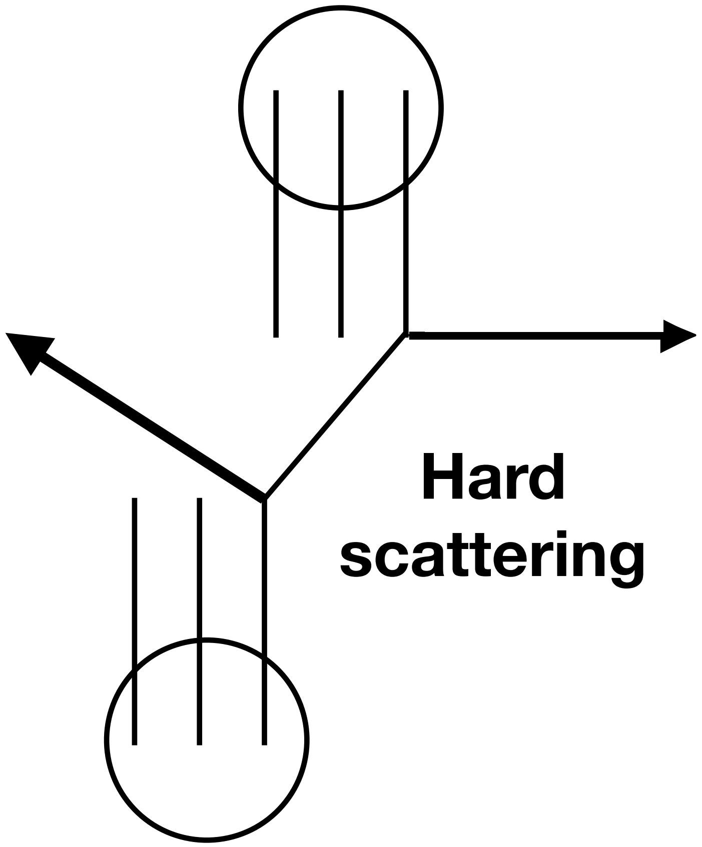
SoftDrop

Resolved split

Charged particles

Why look at this observable?

Simple picture of a hard scattering



- Large momentum transfer between constituent partons (quarks/gluons) of the two incoming nuclei
- What happens next to the scattered partons?
- Lets start with the basics

QCD evolution equations

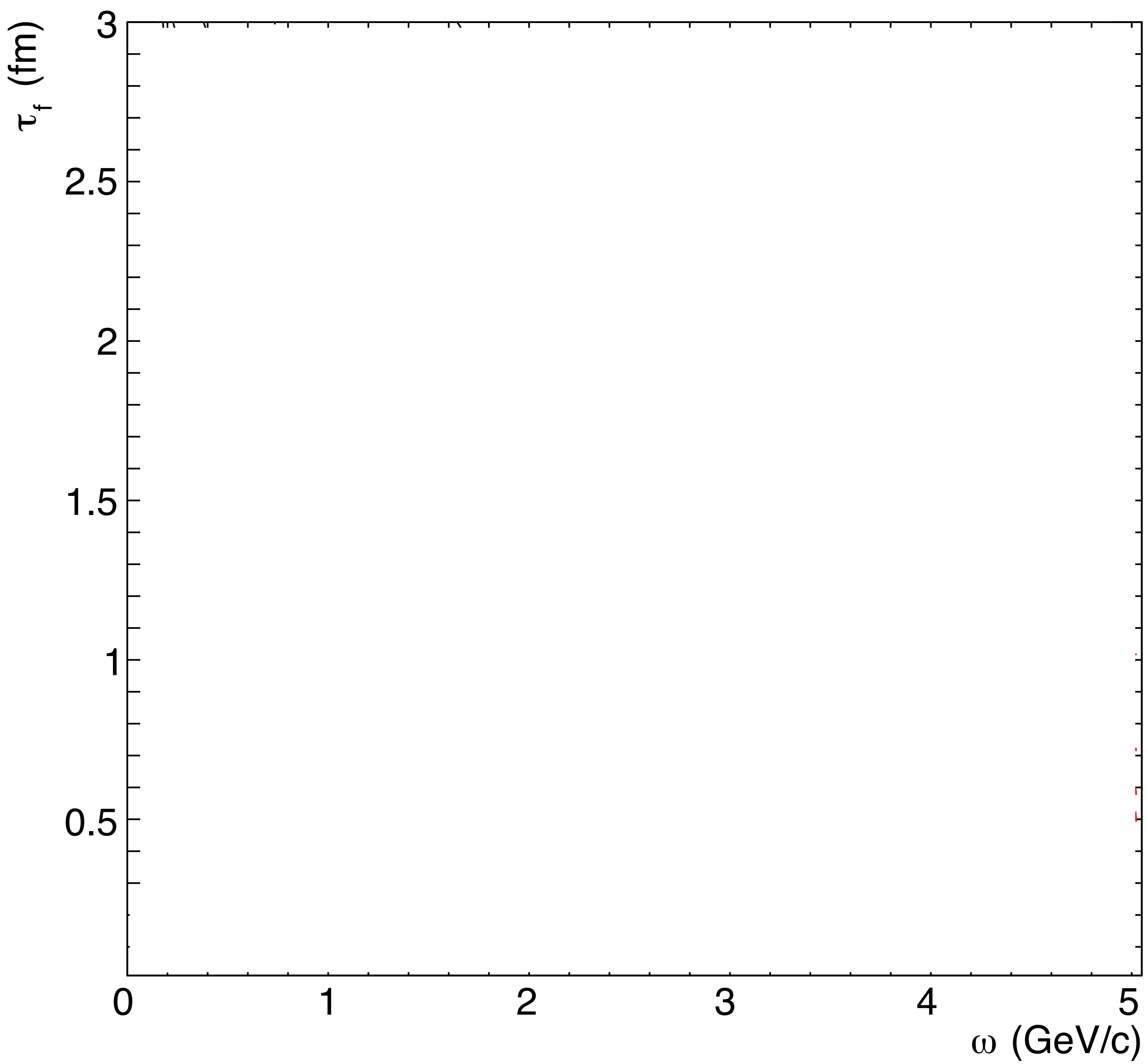
Dokshitzer, Sov. Phys. JETP 46 (1977) 641-653
Gribov, Lipitov Sov. J. Nucl. Phys. 15 (1972) 438-450
Altarelli, Parisi, Nucl. Phvs. B126 (1977) 298-318

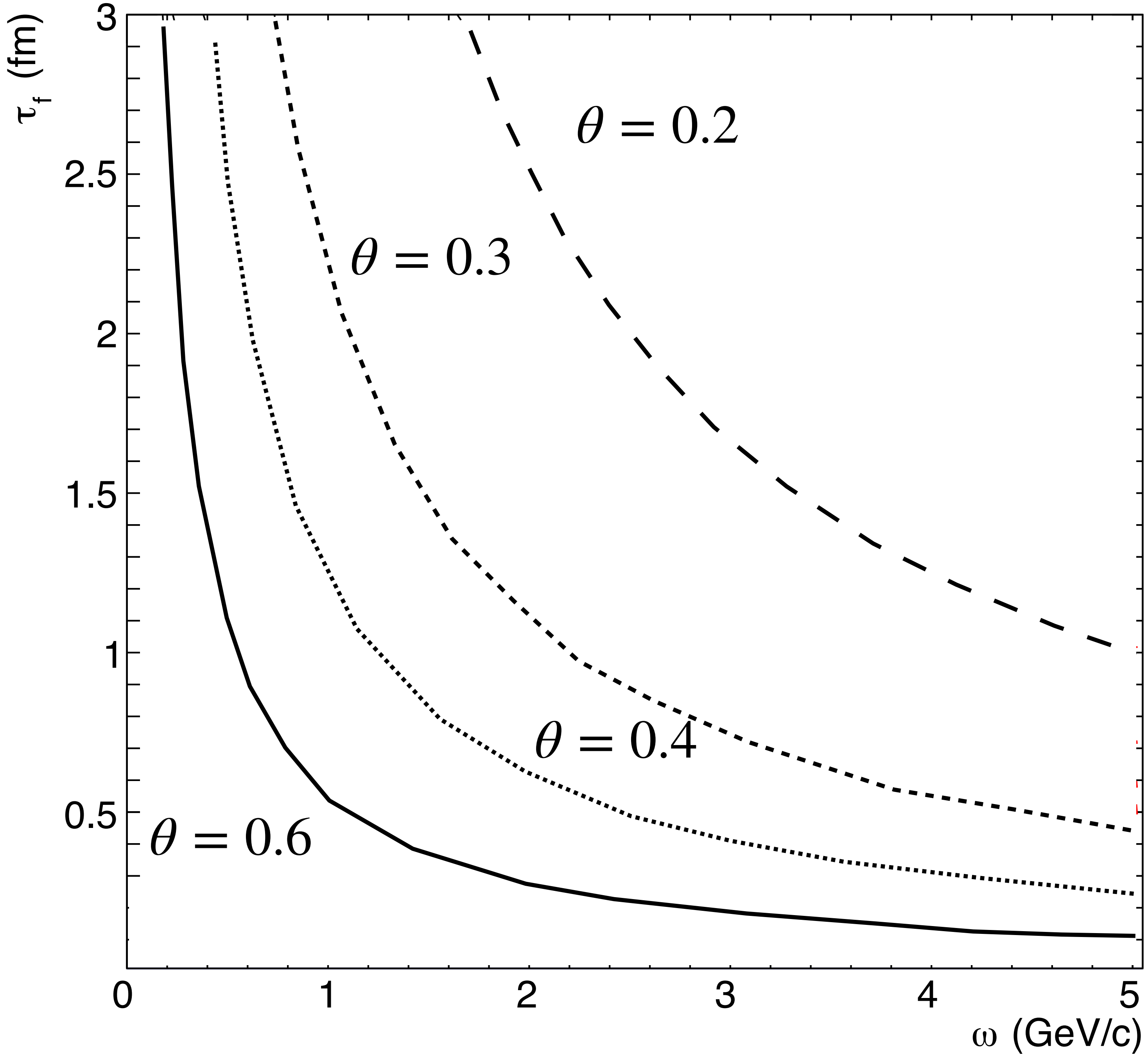
$$P_{qg}(z) = T_R\left[z^2 + (1-z)^2\right], \qquad P_{gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right],$$

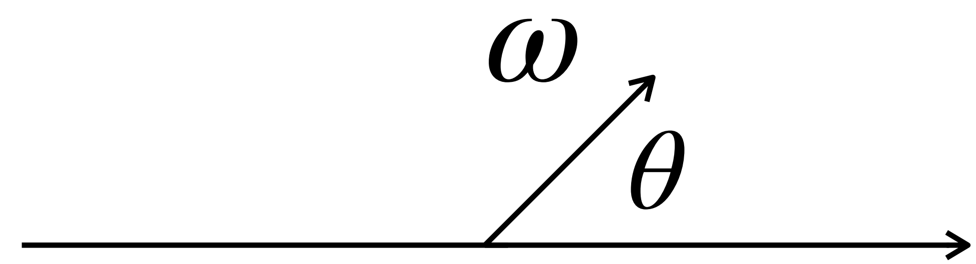
$$P_{gg}(z) = 2C_A\left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z)\right] + \delta(1-z)\frac{(11C_A - 4n_f T_R)}{6}.$$

Splitting probabilities

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

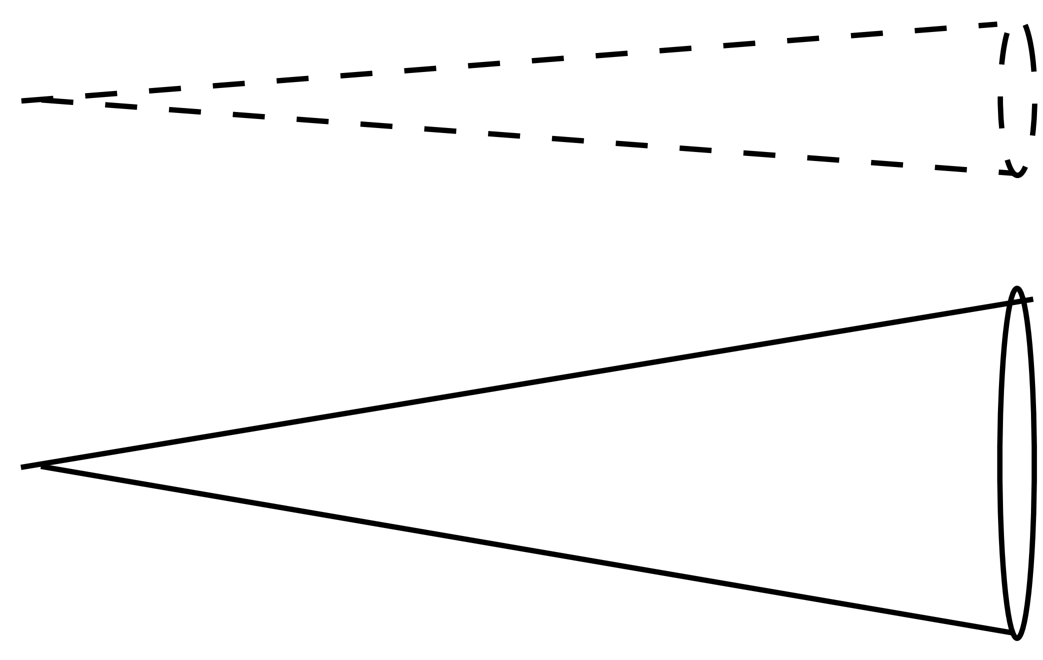






$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

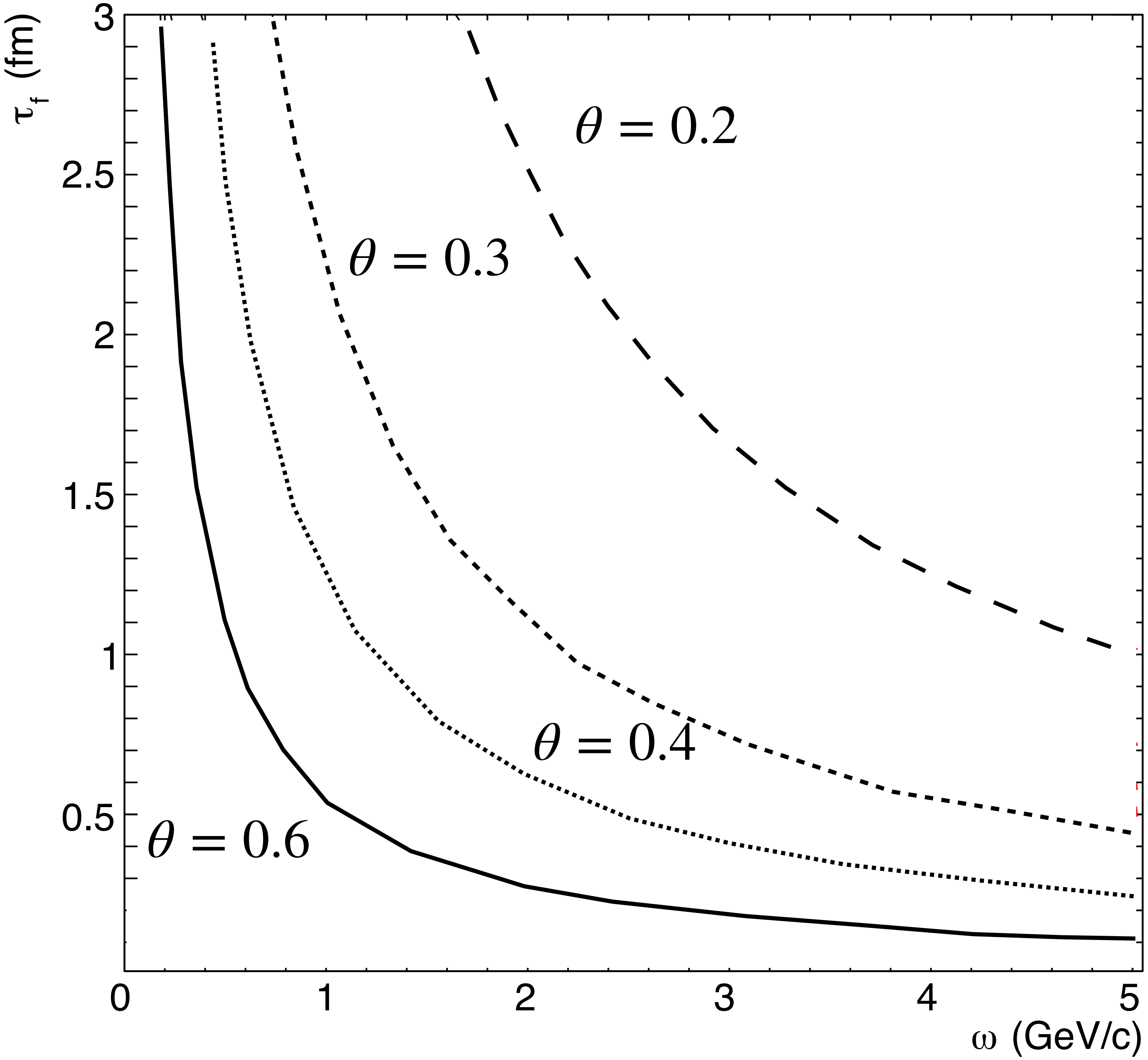
Narrow emission - late time



wide emission - early time

Splitting probability

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



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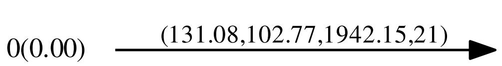
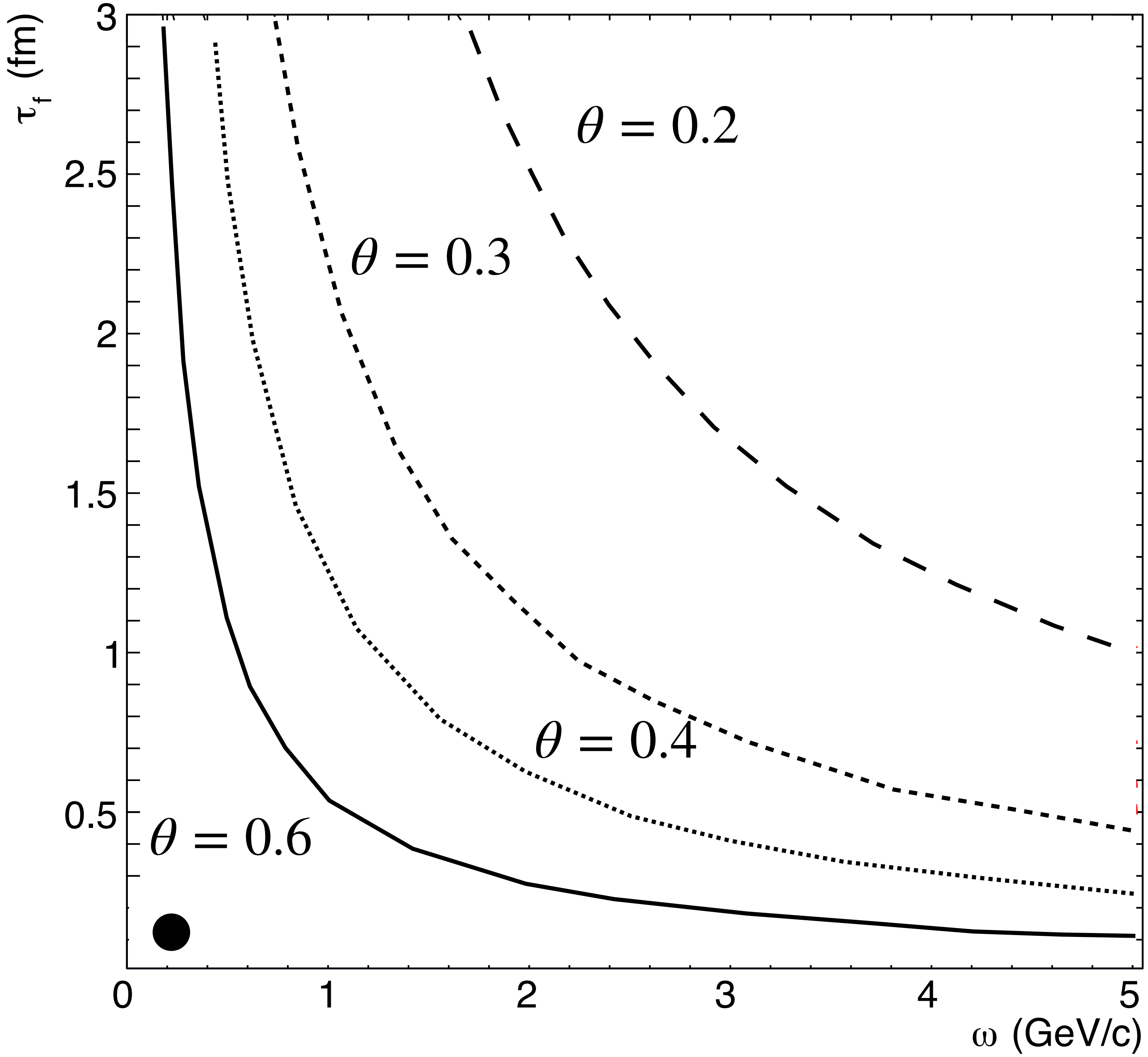


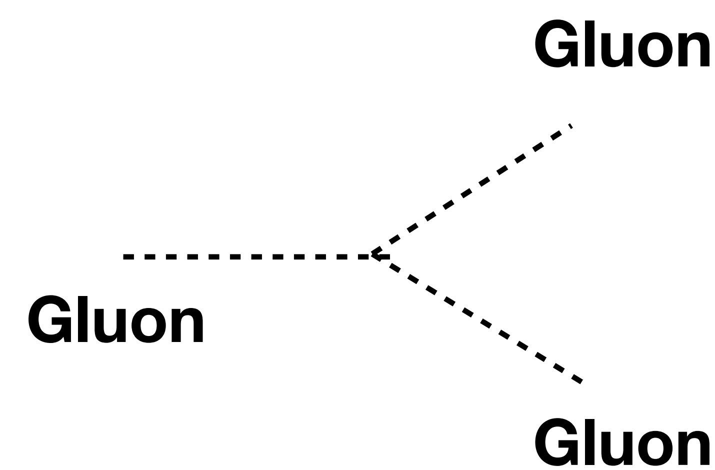
13.1 GeV

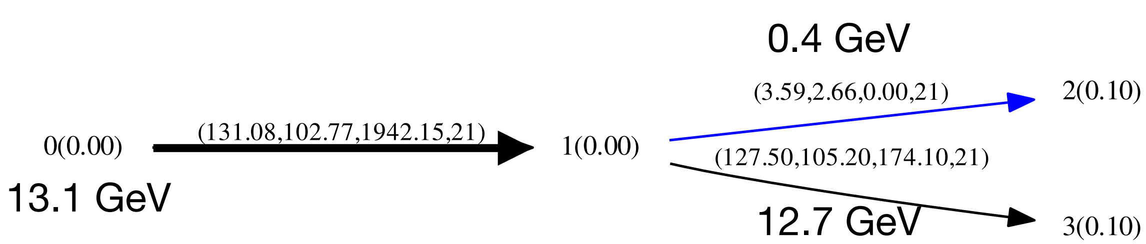
Gluon

Sjöstrand et. al.
Comput. Phys. Commun. 191 (2015) 159.



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





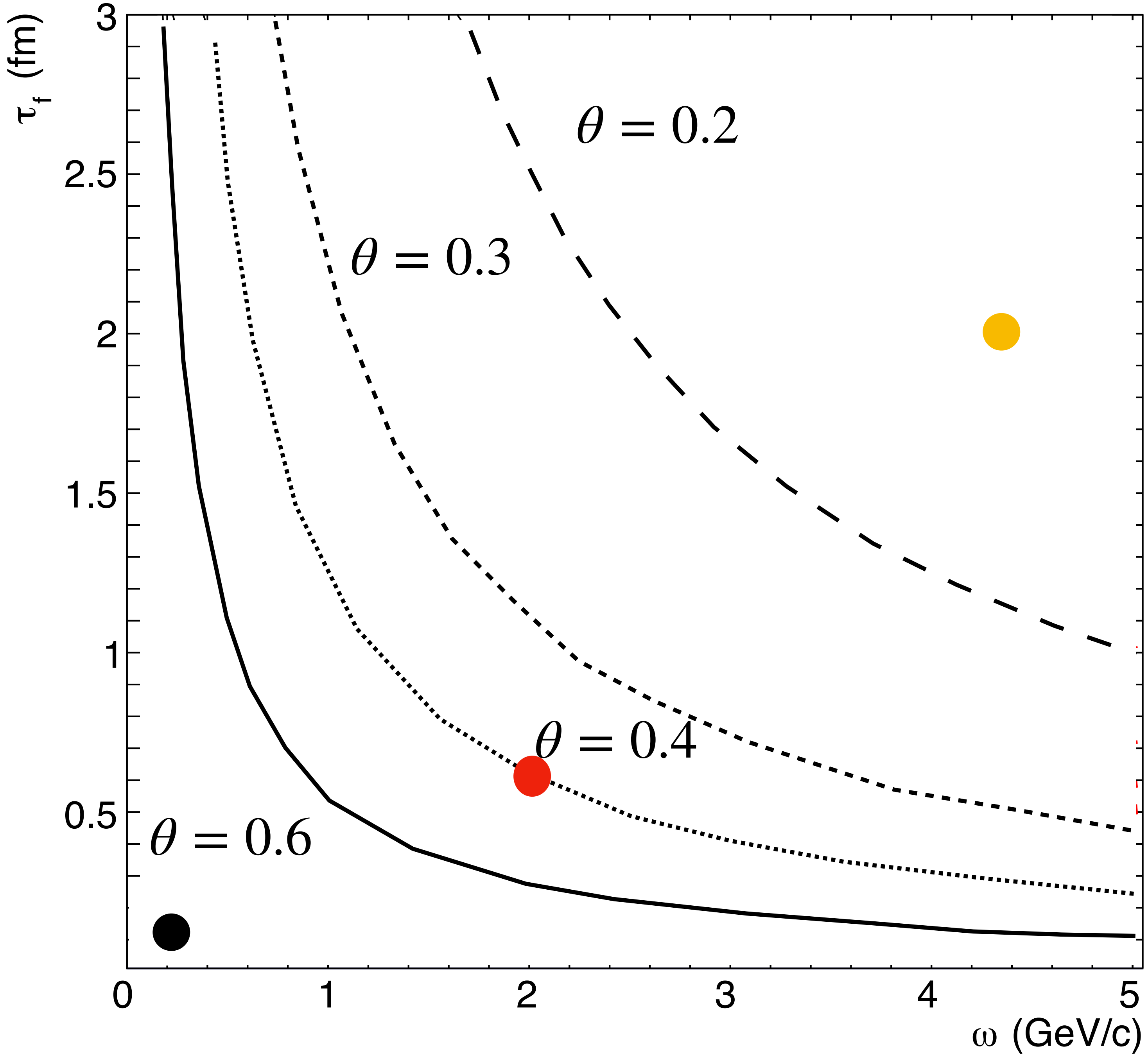
Sjöstrand, Skands,
Eur. Phys. J. C39 (2005) 129-154

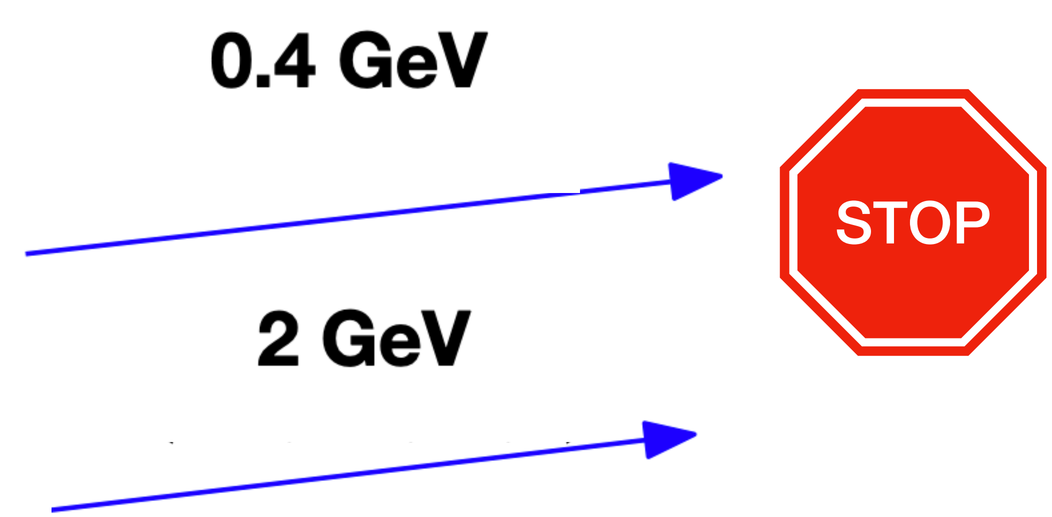
Gluon $g \to g + g$

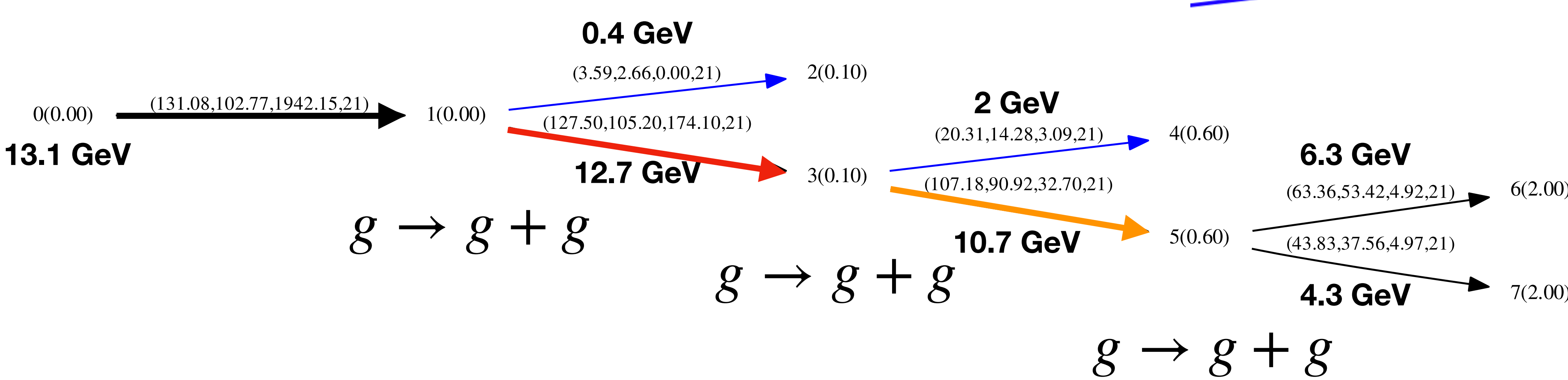
First emission in the parton shower

Graph - JETSCAPE collaboration
Nucl.Phys.A 982 (2019) 615-618

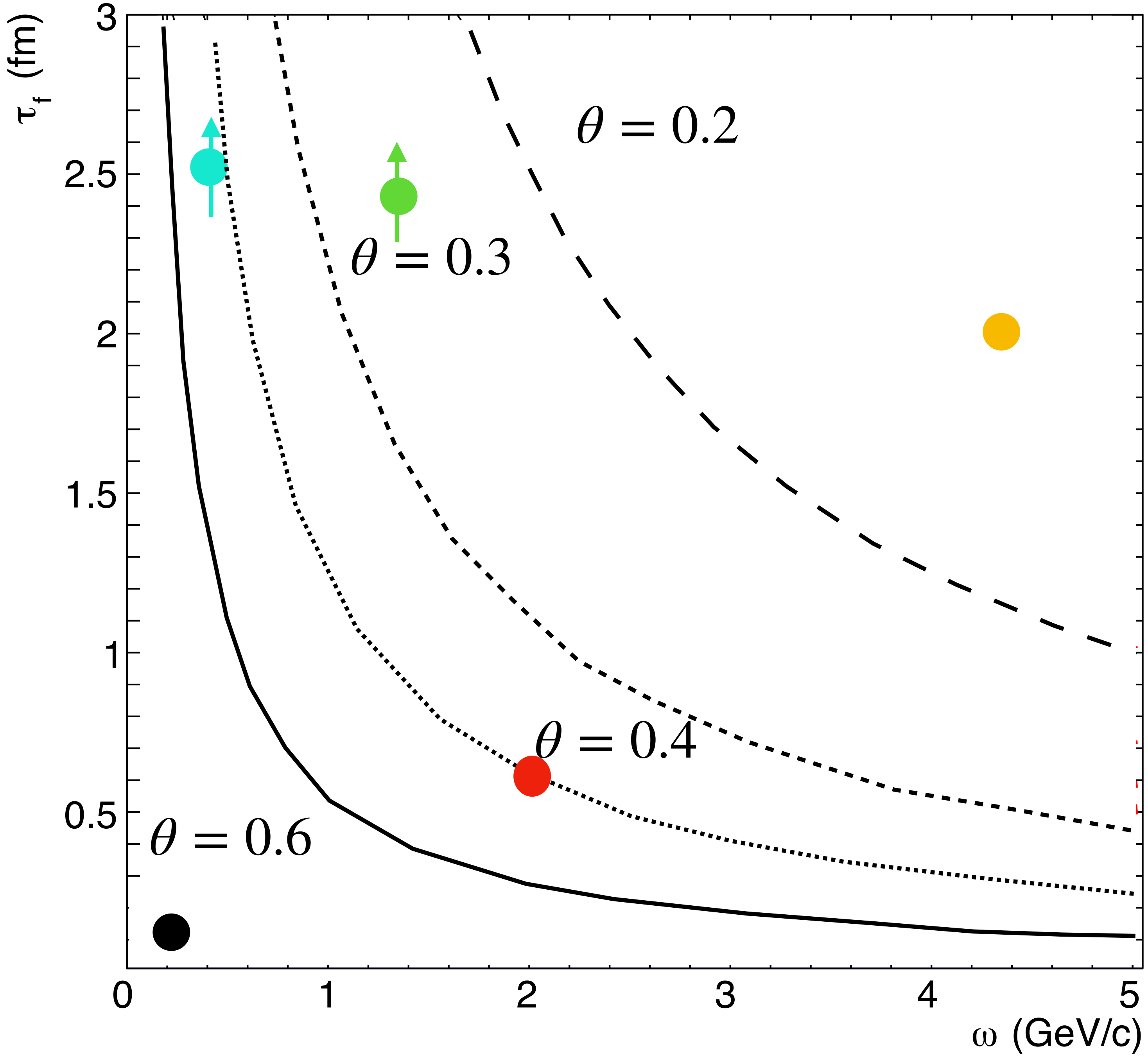
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

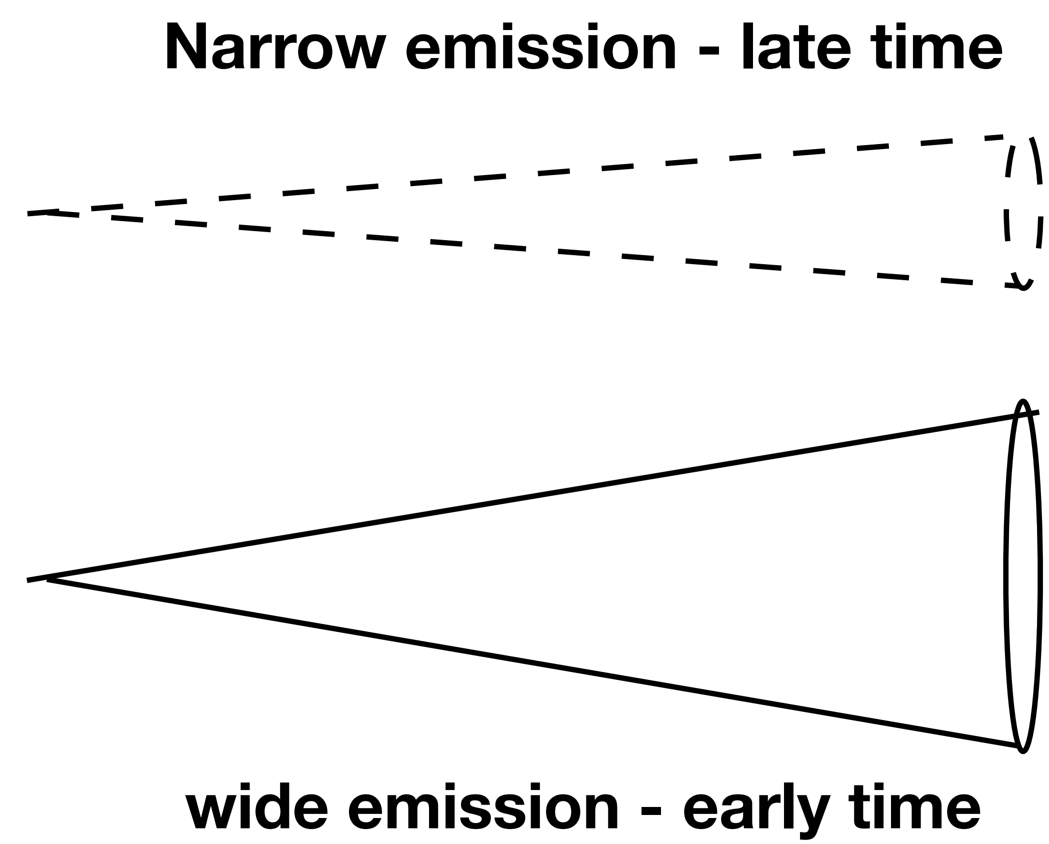


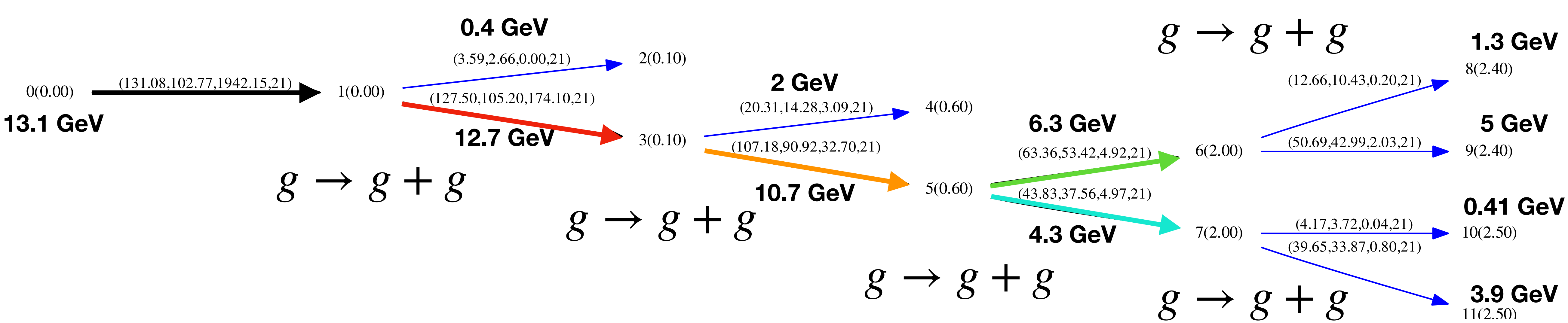




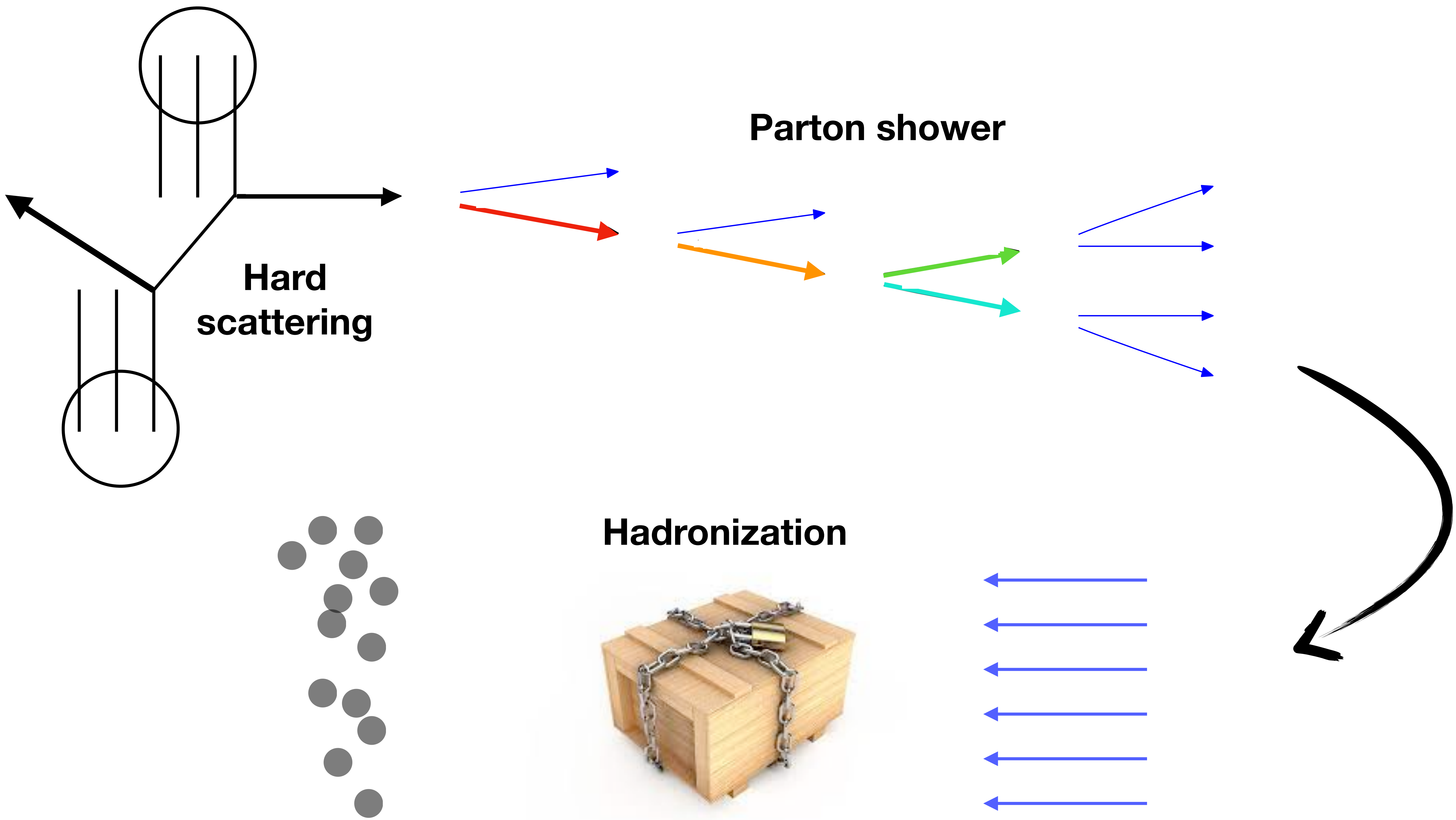
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$







Simple picture of jets in pp



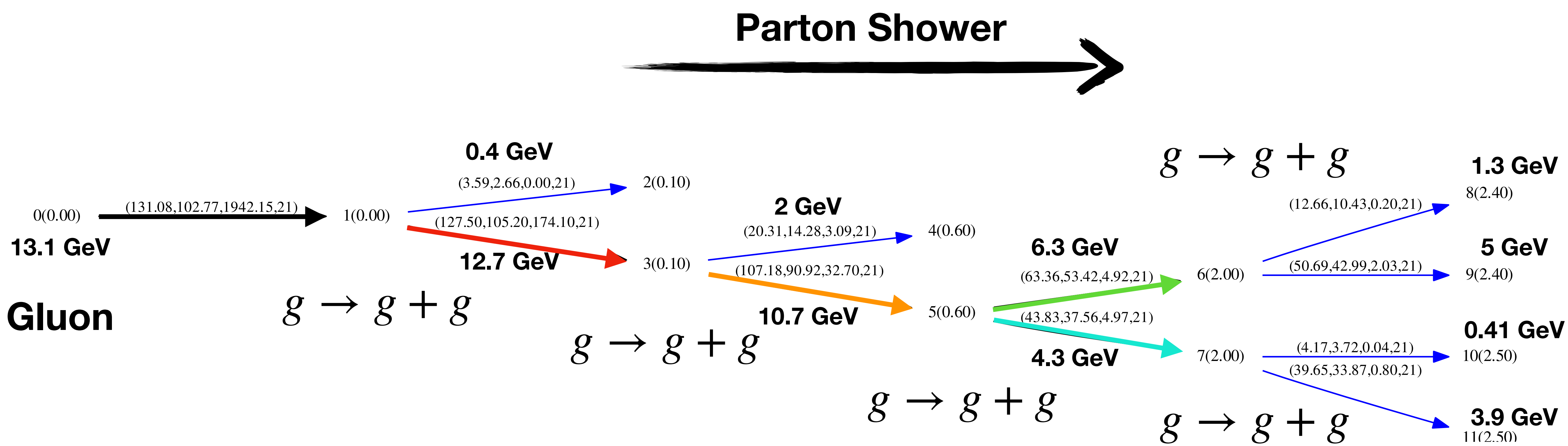
How can one connect the two regimes? parton shower to particles

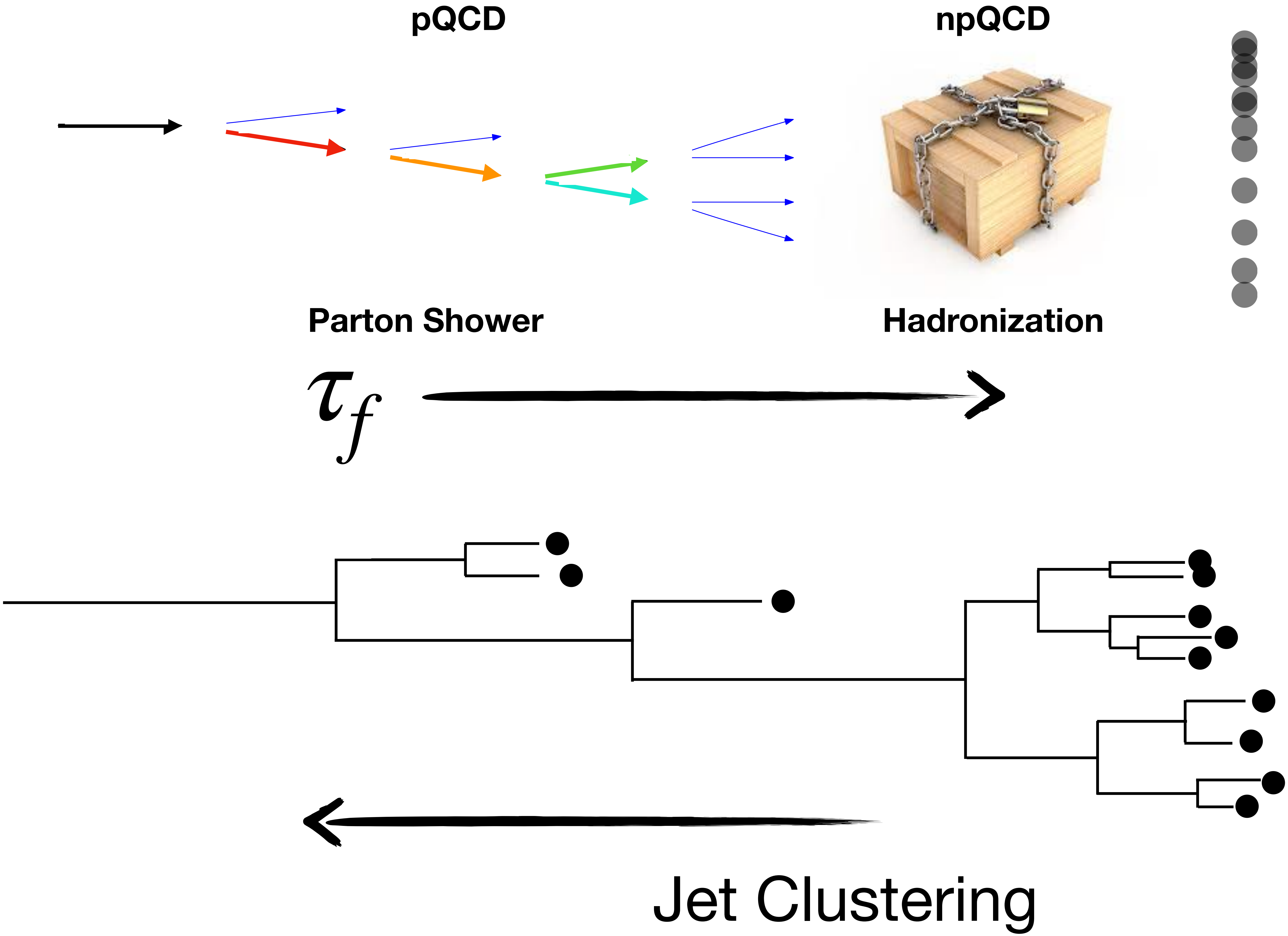
What do we want to measure?

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

This gluon resulted in 6 partons before the hadronization stage in the MC model

Sjöstrand, Skands, Eur. Phys. J. C39 (2005) 129-154




pQCD
npQCD
Parton Shower
Hadronization
τ_f
Jet Clustering

anti-kT R=0.4 jets

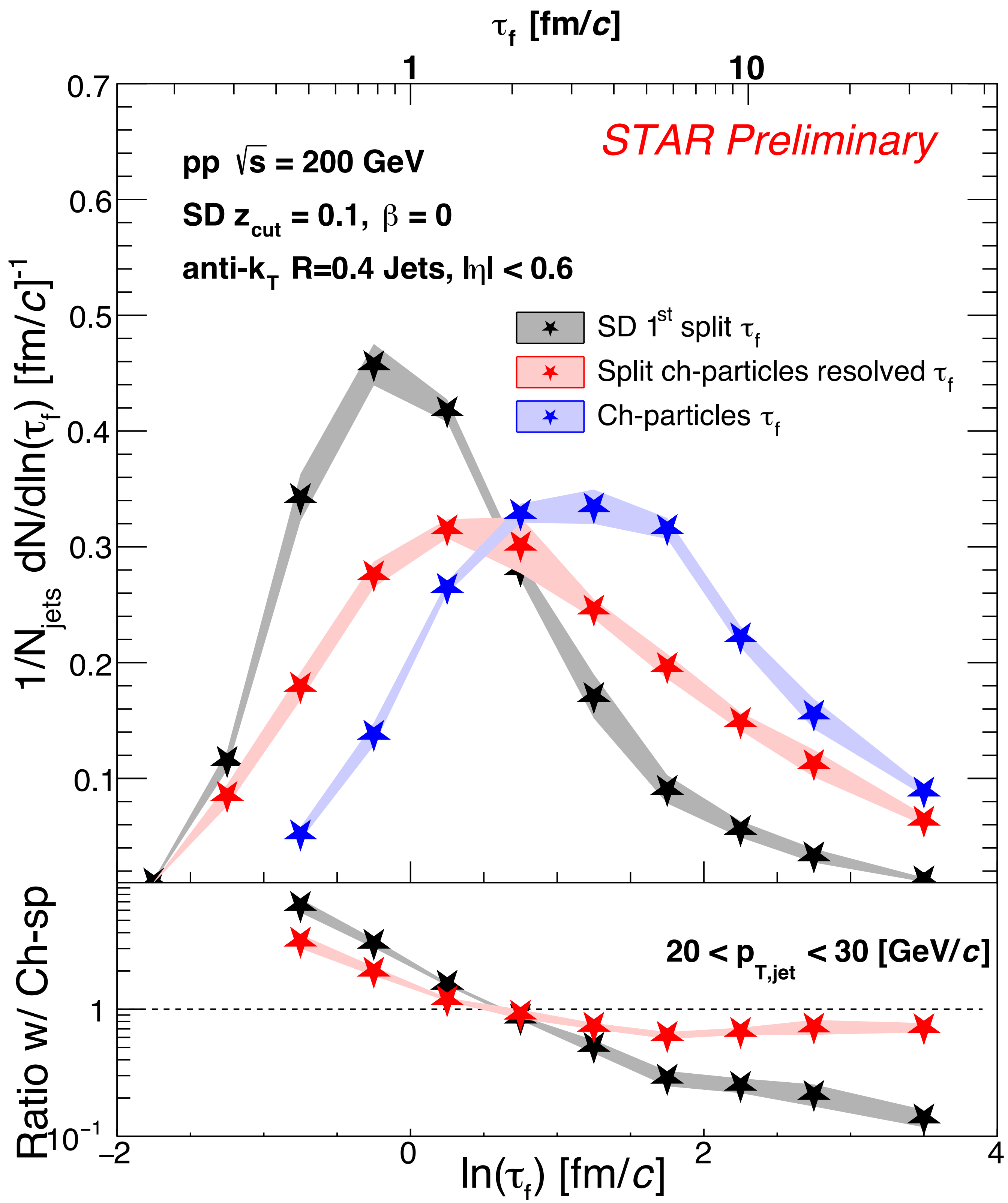
p+p $\sqrt{s} = 200$ GeV

Formation time

SoftDrop

Resolved split

Charged particles



How do we measure this?

How to experimentally measure the formation time τ_f

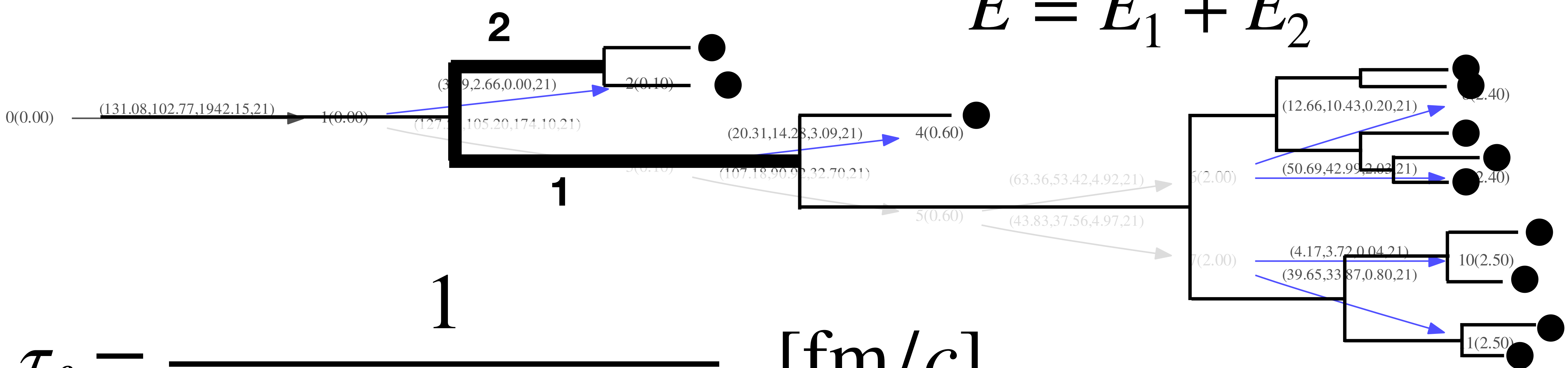
Take any two objects - in this case the first two surviving prongs after SoftDrop grooming

Dasgupta et al. JHEP 09 (2013) 029

Larkowski, et al. JHEP 05 (2014) 146

$$z = \frac{\min(\mathrm{p_{T,1}}, \mathrm{p_{T,2}})}{p_{T,1} + p_{T,2}}$$

$$E = E_1 + E_2$$



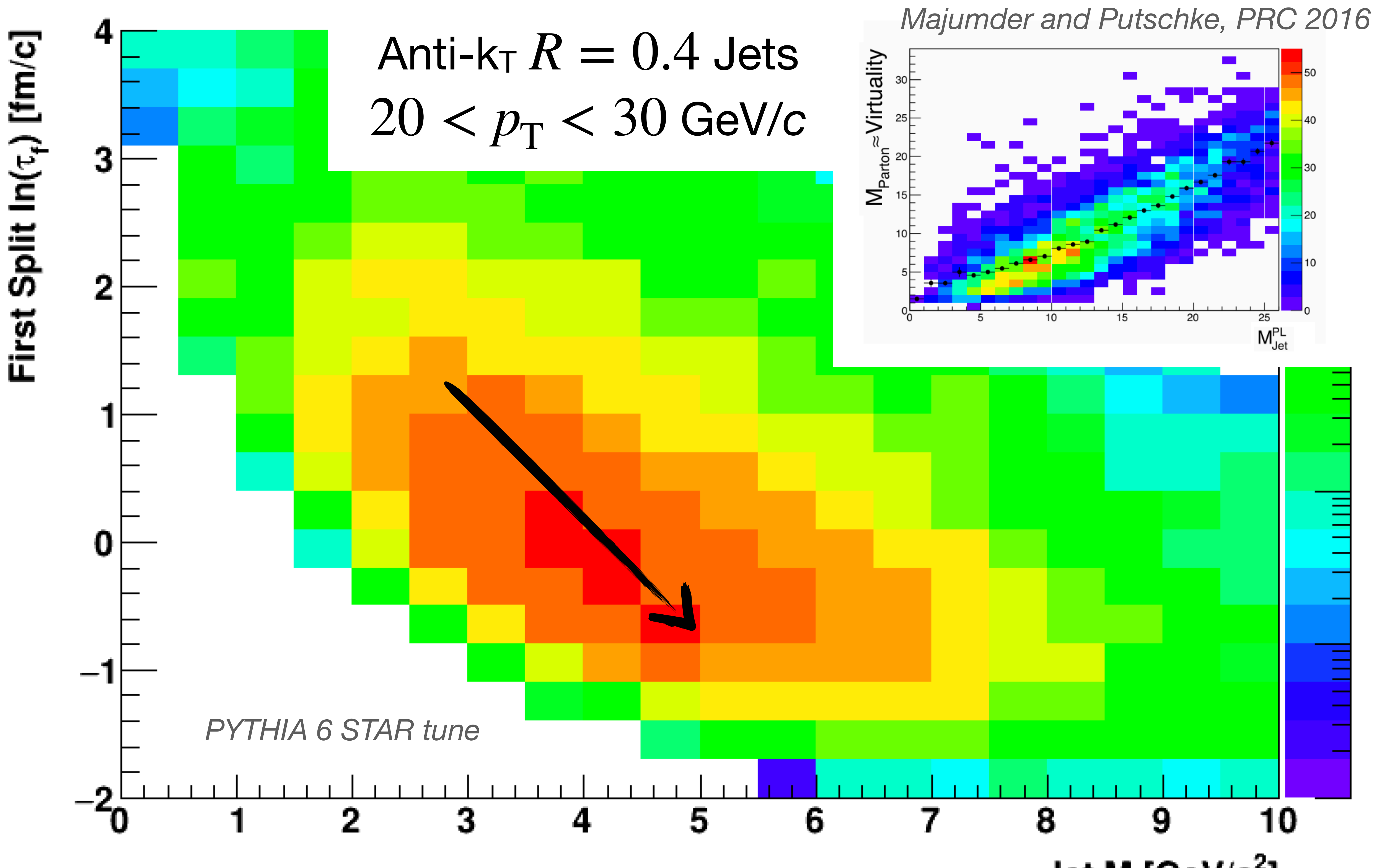
$$\tau_f = \frac{1}{z \cdot (1 - z) \cdot \theta^2 \cdot E} \quad [\mathrm{fm}/c]$$

$$\theta = \Delta R(1,2)$$

Apolinario et al. Eur. Phys. J. C 81 (2021) 6, 561

Chien et. al. 2109.15318

Formation time vs jet mass



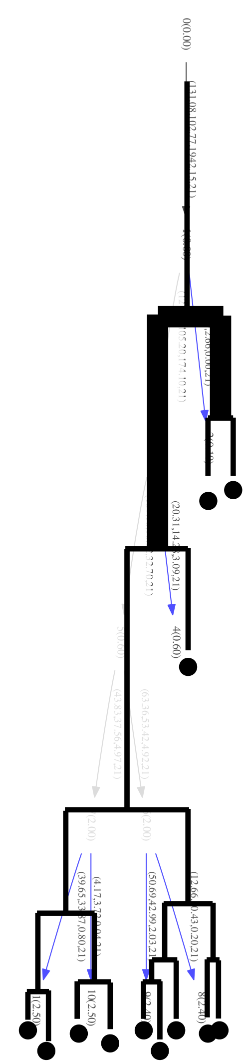
Identifying two regimes

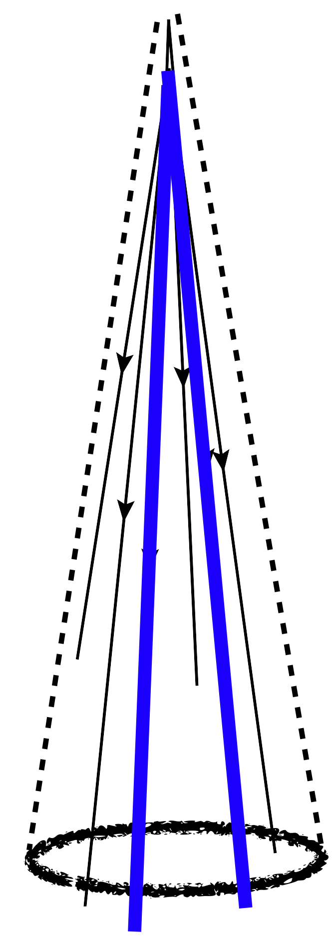
- SoftDrop first split τ_f

- Leading and subleading ch-particle τ_f

Expectations:

- **happen early in time with the expectation that first splits correspond to partonic splits**
- **Mostly perturbative in nature**





Expectations:

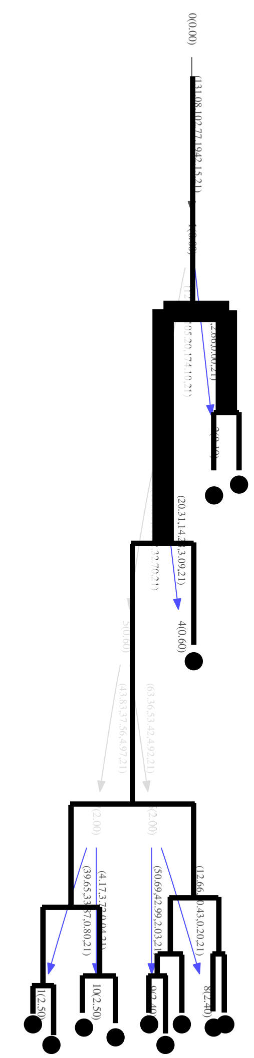
- **Occur later in time since its calculated using charged particles which occur at the end**
- **Mostly non-perturbative**

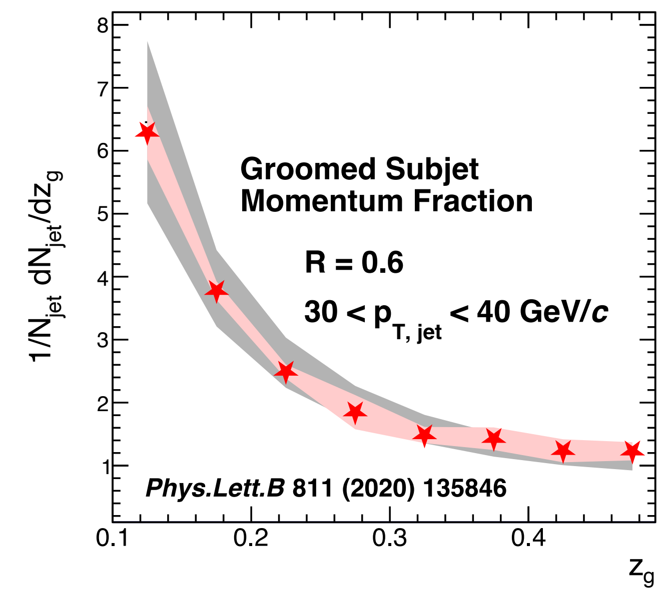
STAR Phys. Lett. B 811, 135846 (2020)
STAR Phys. Rev. D 104, 052007 (2021)
Kang, Lee, Liu, Neill and Ringer, JHEP (2020)

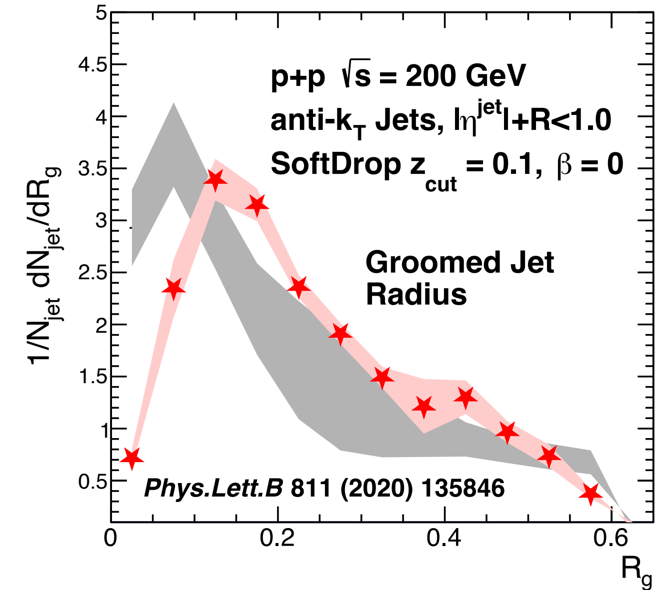
- SoftDrop first split τ_f

Expectations:

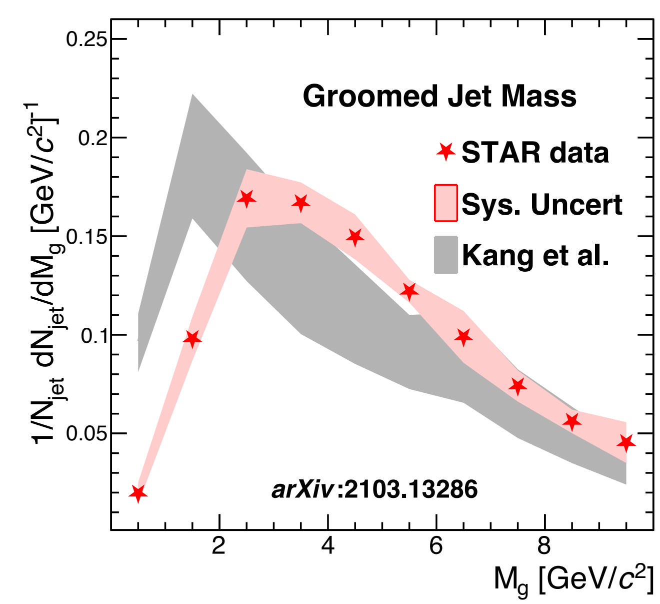
- **happen early in time with the expectation that first splits correspond to partonic splits**
- **Mostly perturbative in nature**



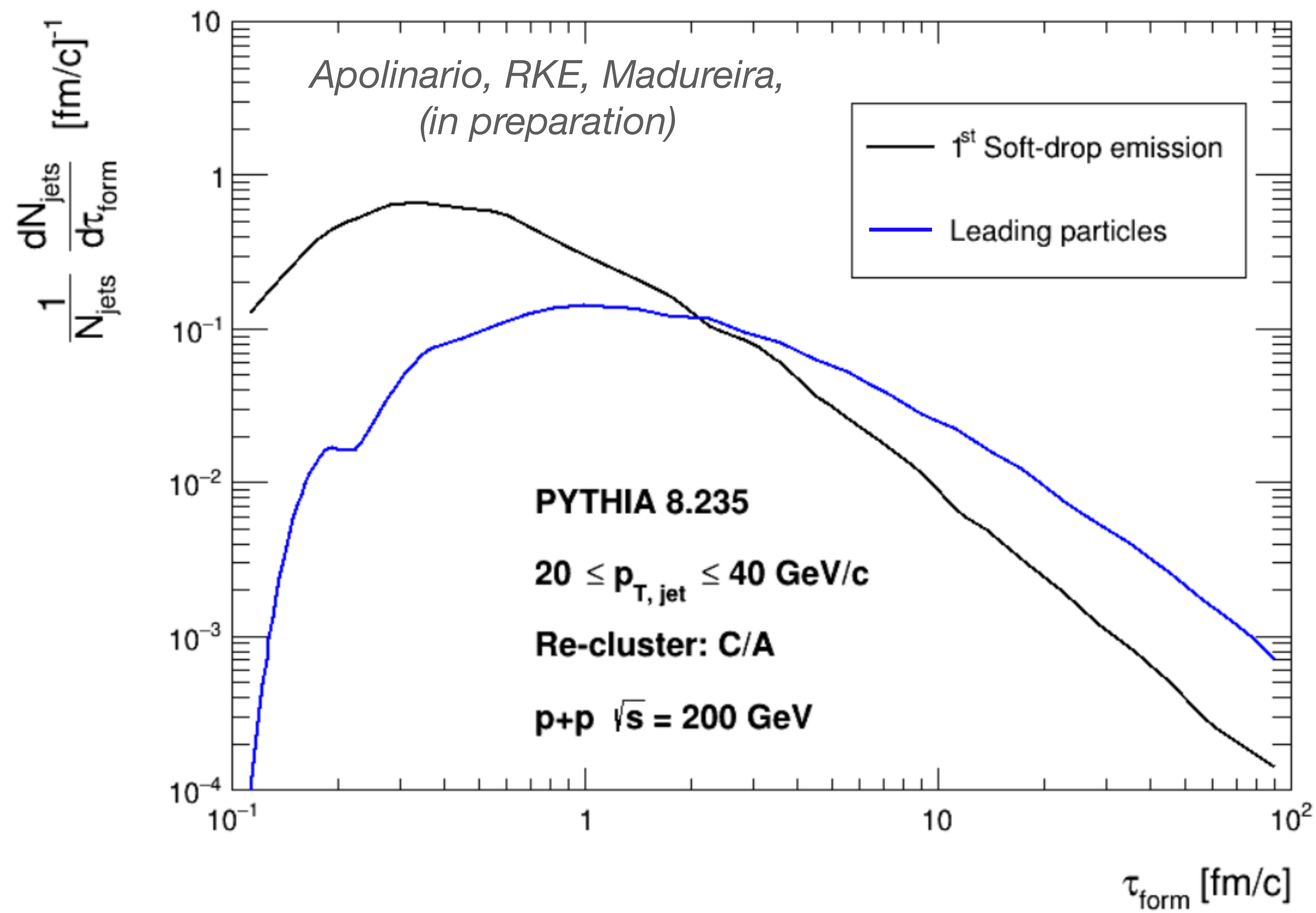




- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and high p_T



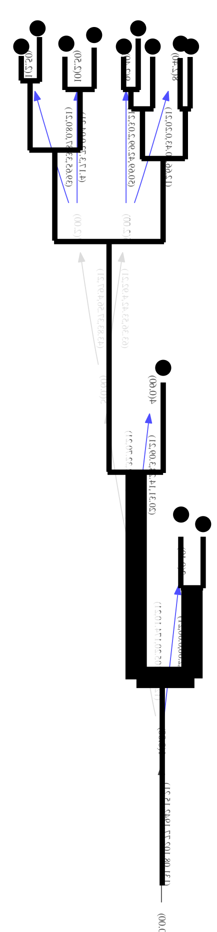
What do these distributions look like in PYTHIA?

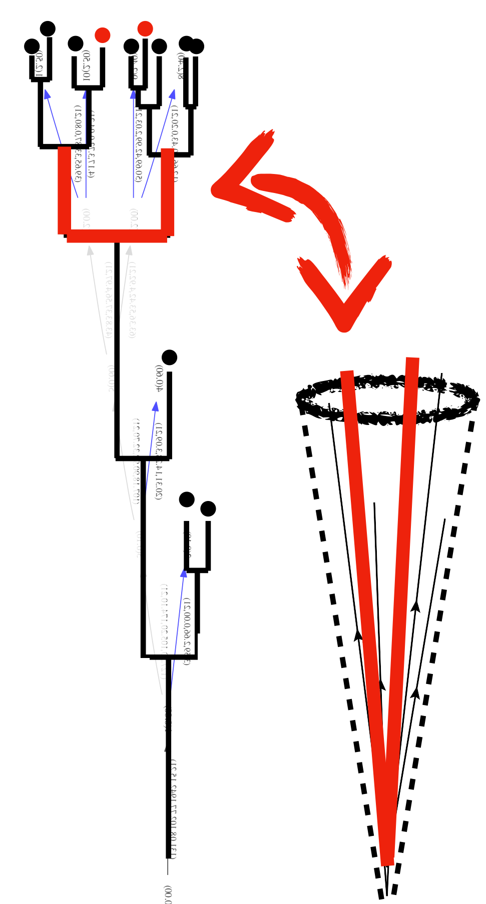


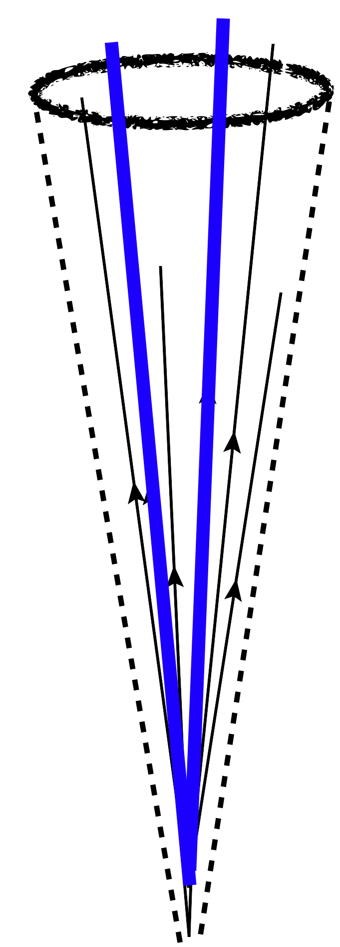
- As expected we see a significant shift between the two distributions
- Charged particles generally have a formation time much larger than the first splits

Connecting the two regimes

- SoftDrop first split τ_f
- SoftDrop split (varying z_{cut}) resolving the two leading charged particles
- Leading and subleading ch-particle τ_f



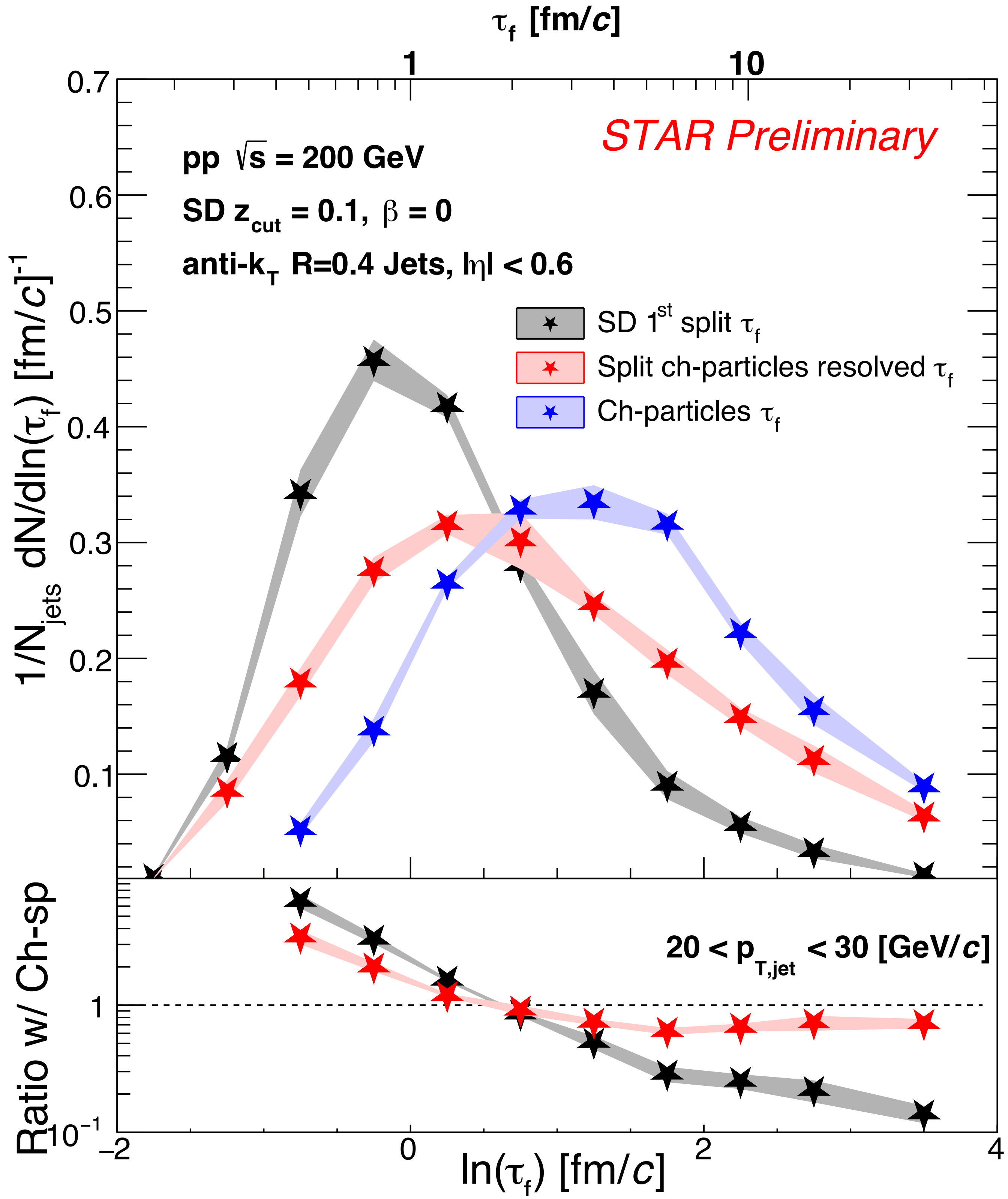




anti-kT R=0.4 jets

Formation time

Resolved split



p+p $\sqrt{s}$ = 200 GeV

SoftDrop

Charged particles

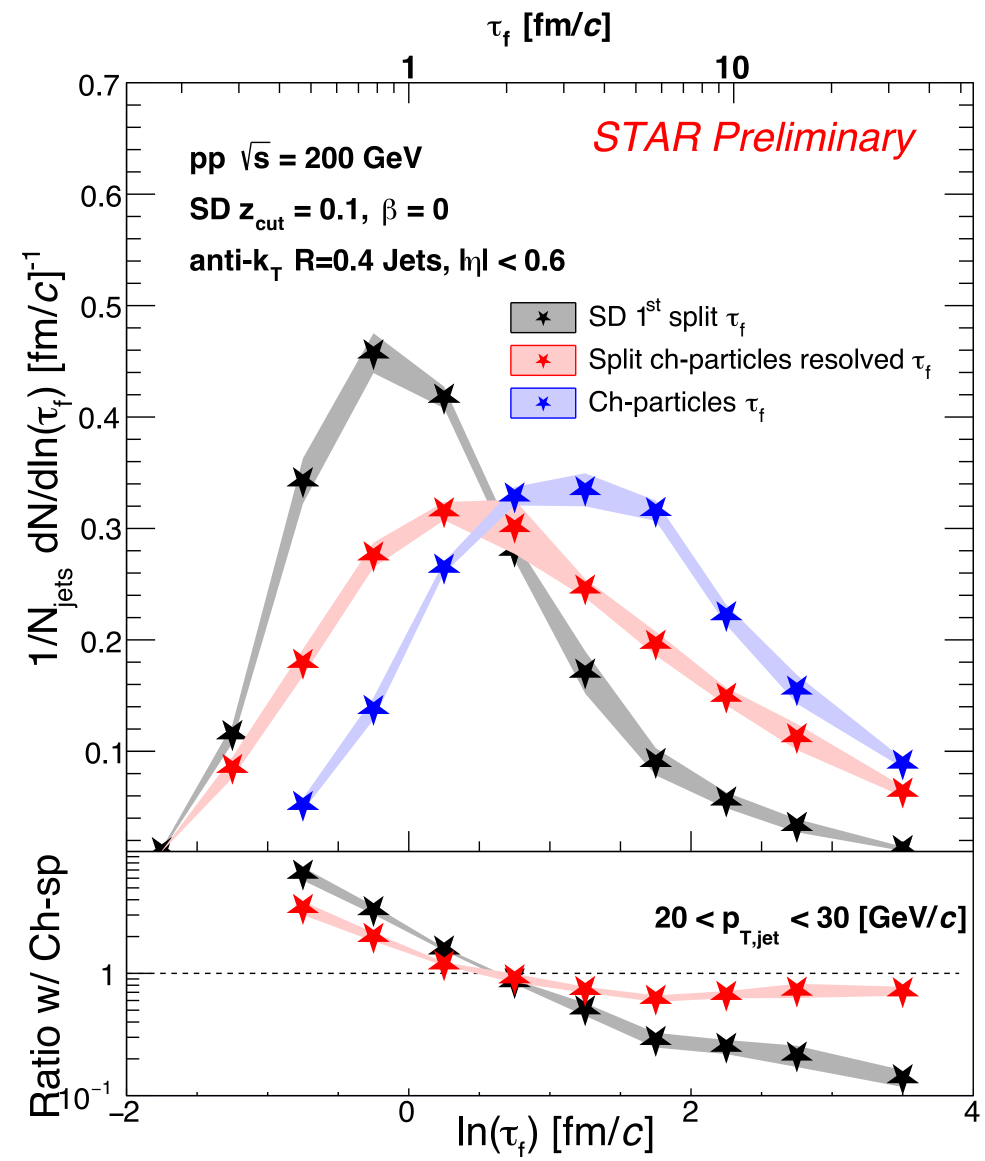
What is this telling us?

Formation times across various regimes within the jet shower

- **First measurements of formation time** from the jet splitting trees and from charged particles in the jet

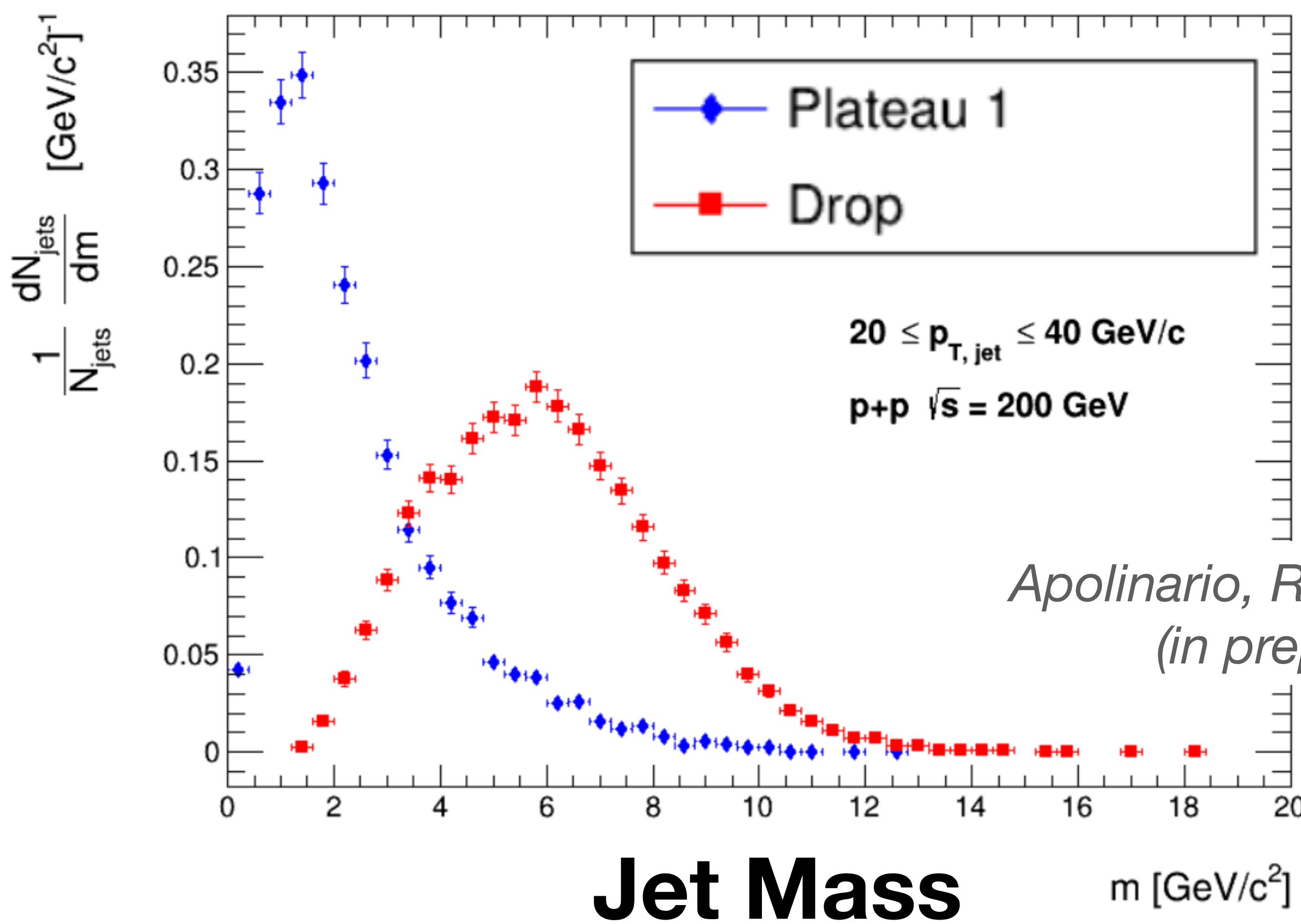
- **Resolved SD splits** show **similar shape** as the **charged particle split** at large τ_f values occurring in the predominantly **non-perturbative region**

- Comparison of the different splits highlights the transition from **pQCD to npQCD**

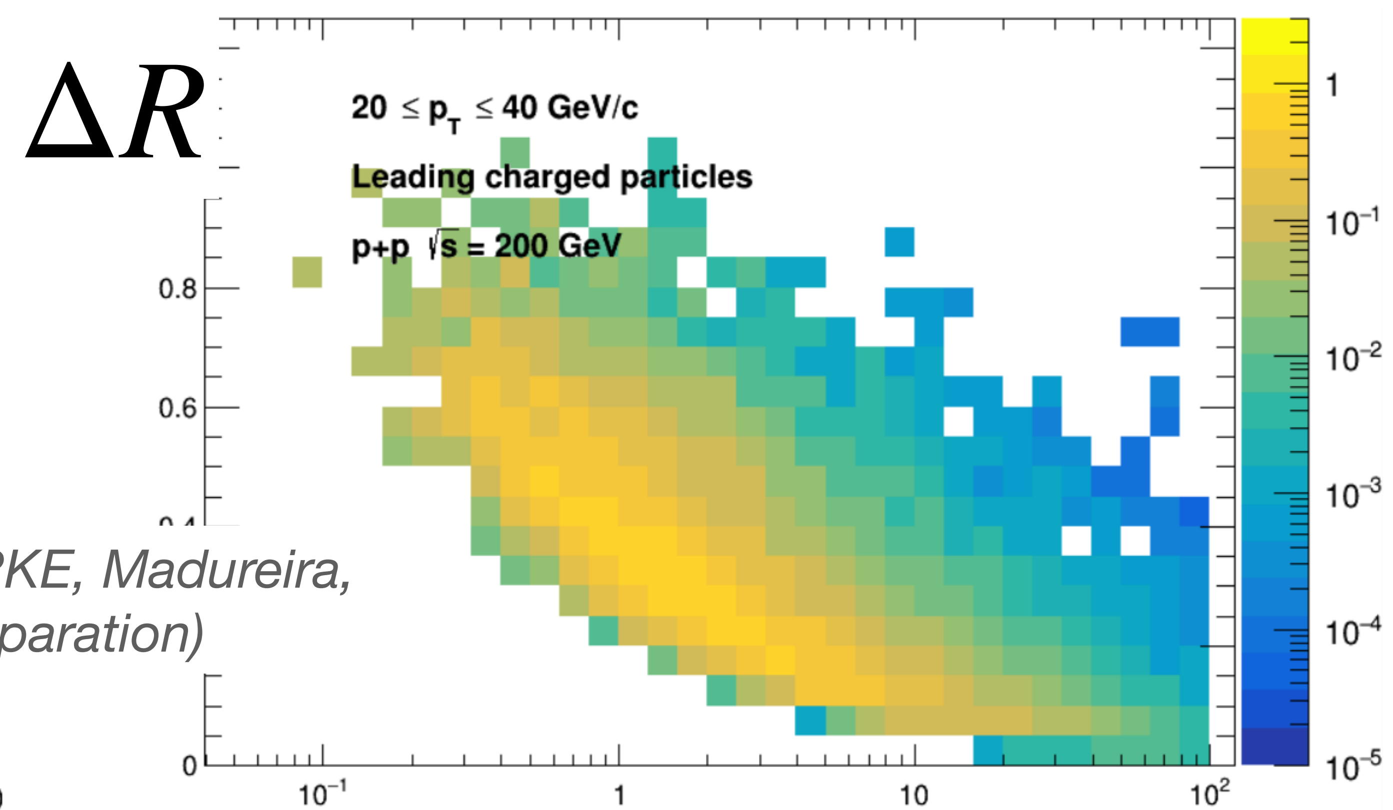


RKE (for STAR) pdf
Jets and 3D Imaging at the EIC Workshop

Studying the plateau



Jet Mass



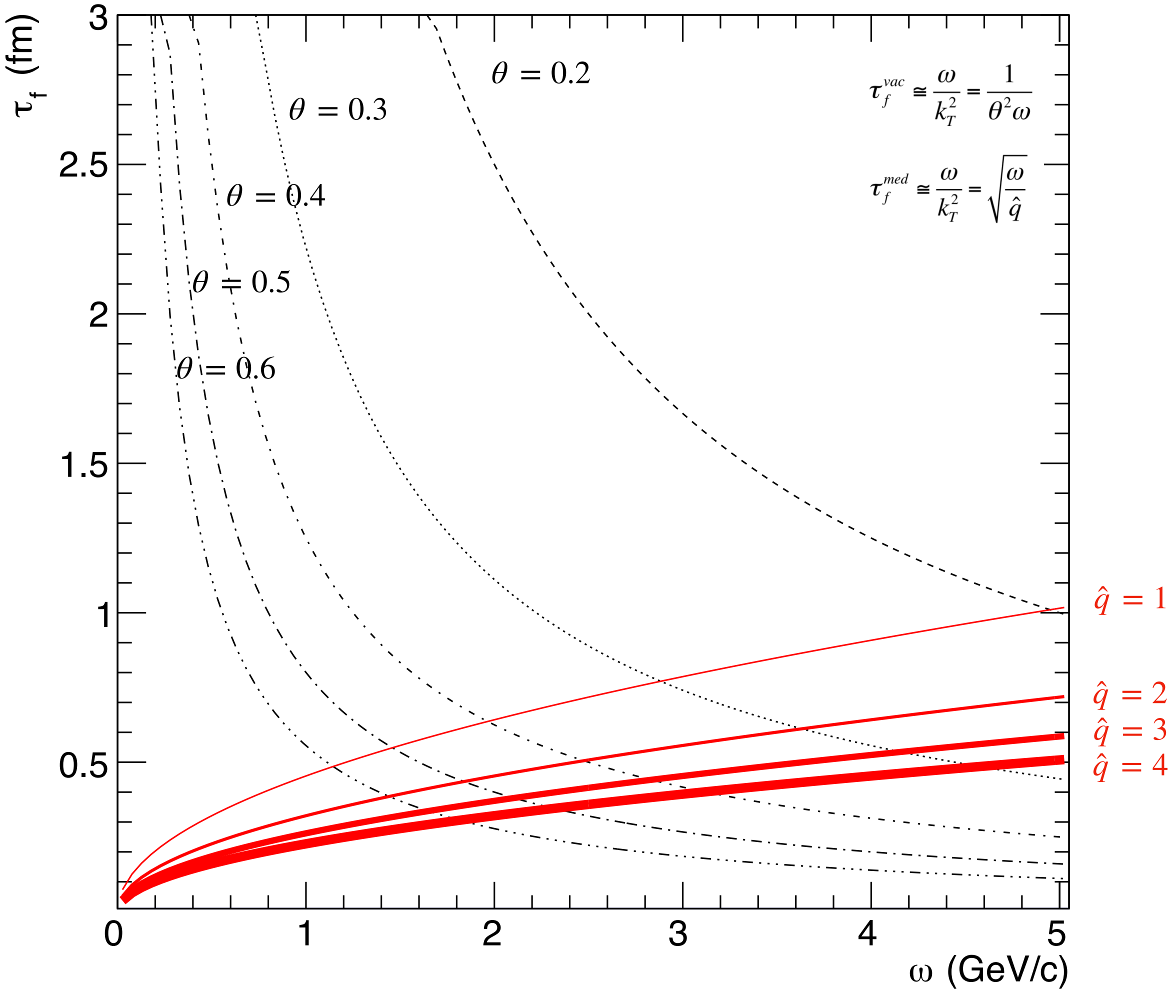
Charged Particle τ_f fm/c

Apolinario, RKE, Madureira,
(in preparation)

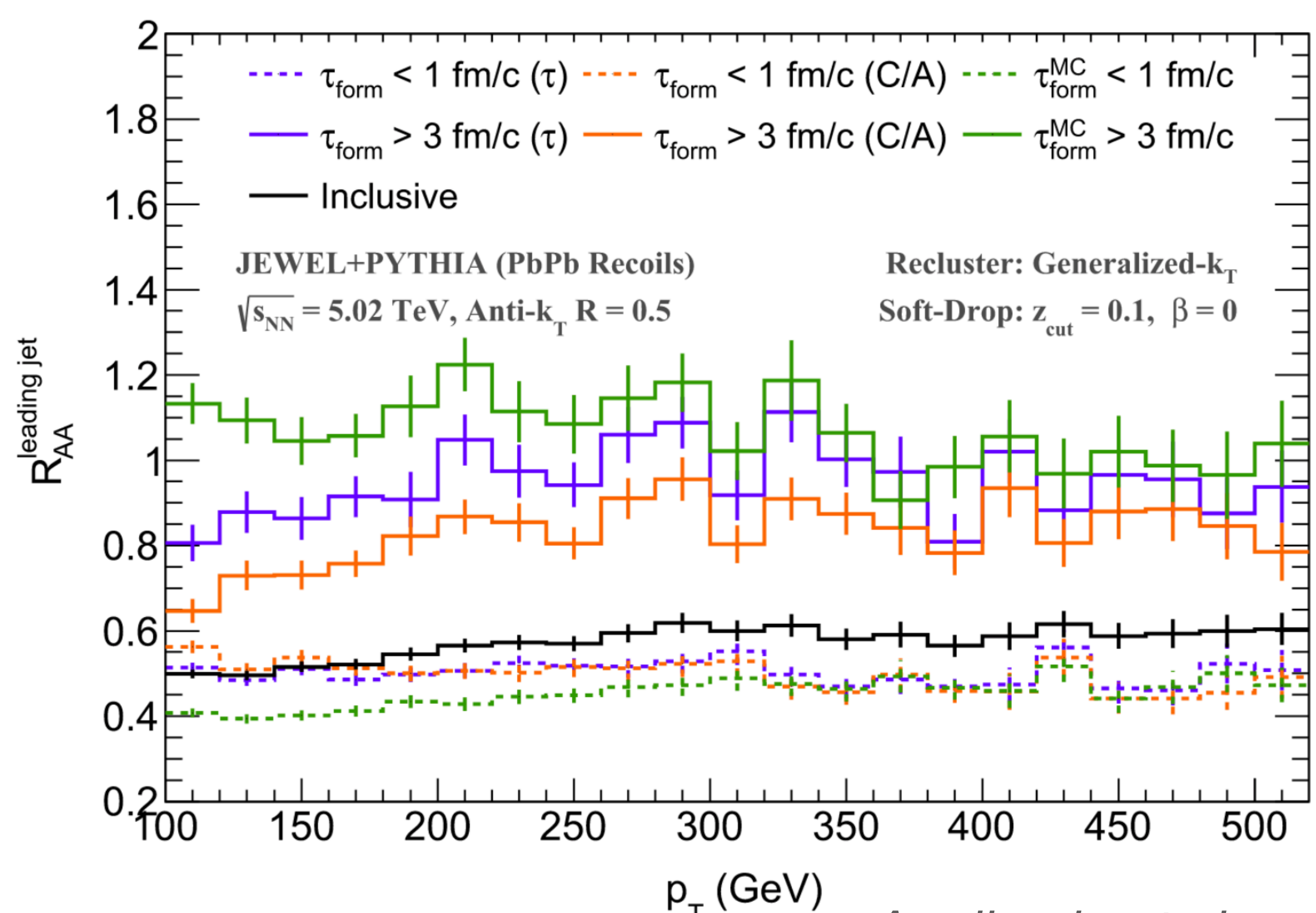
- Selection on the resolved formation time essentially sculpts the jet mass and opening angles
- Reproduce correlation between later times and smaller masses (virtuality) and narrower opening angles - Important handle on particle production and hadronization

Where do we go from here? - 1

Time resolved QGP tomography



- Scan across emission phase-space leads to first ever space-time tomography of the QGP

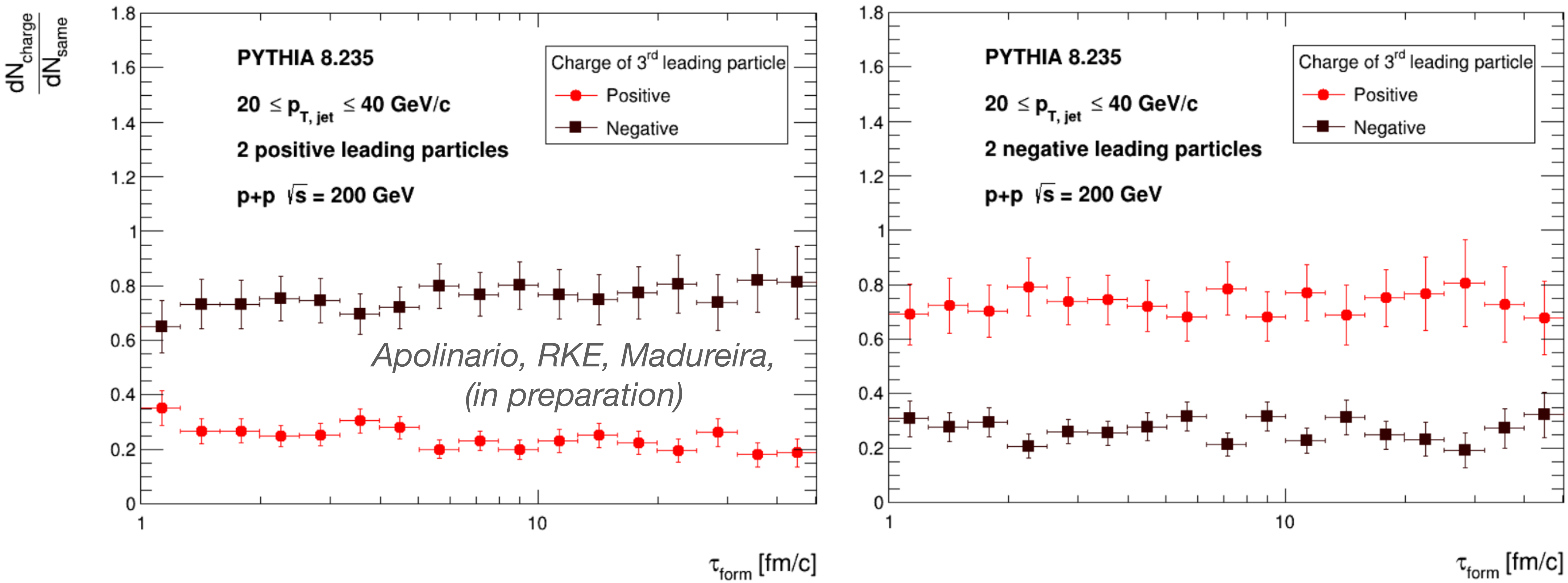


- Searching for hard medium induced gluon emissions, medium coherence length etc…

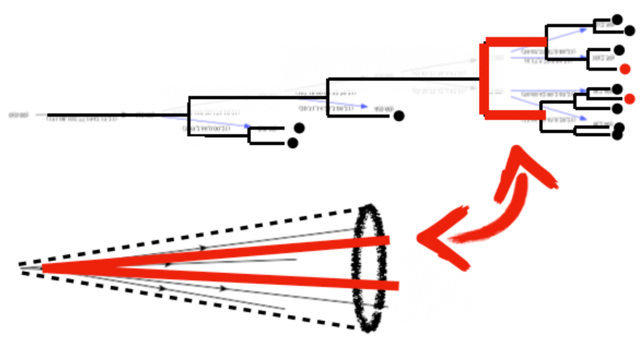
Apolinario et al.
Eur. Phys. J. C 81 (2021) 6, 561

Where do we go from here? - 2

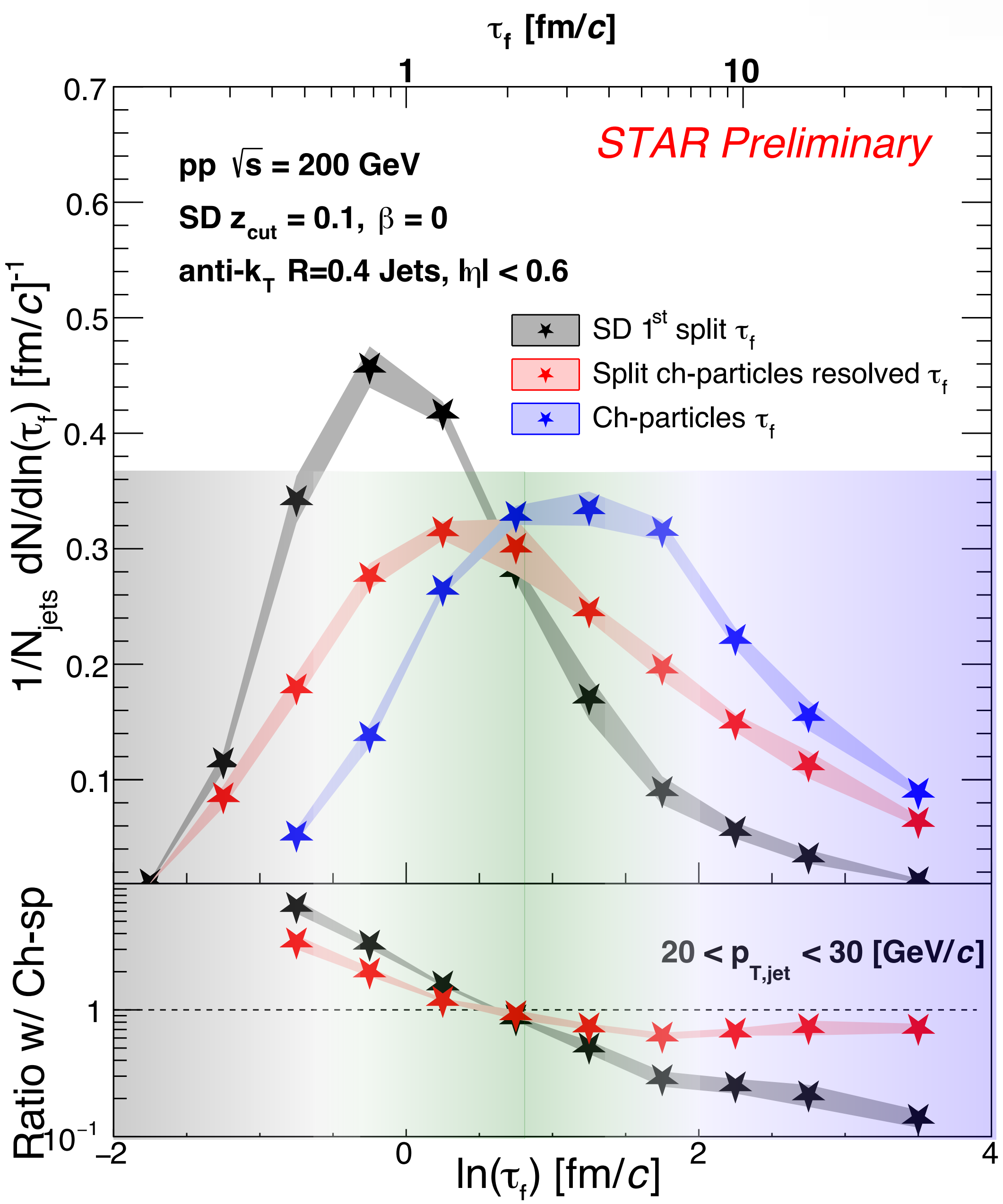
Extending the charge-correlations in formation time

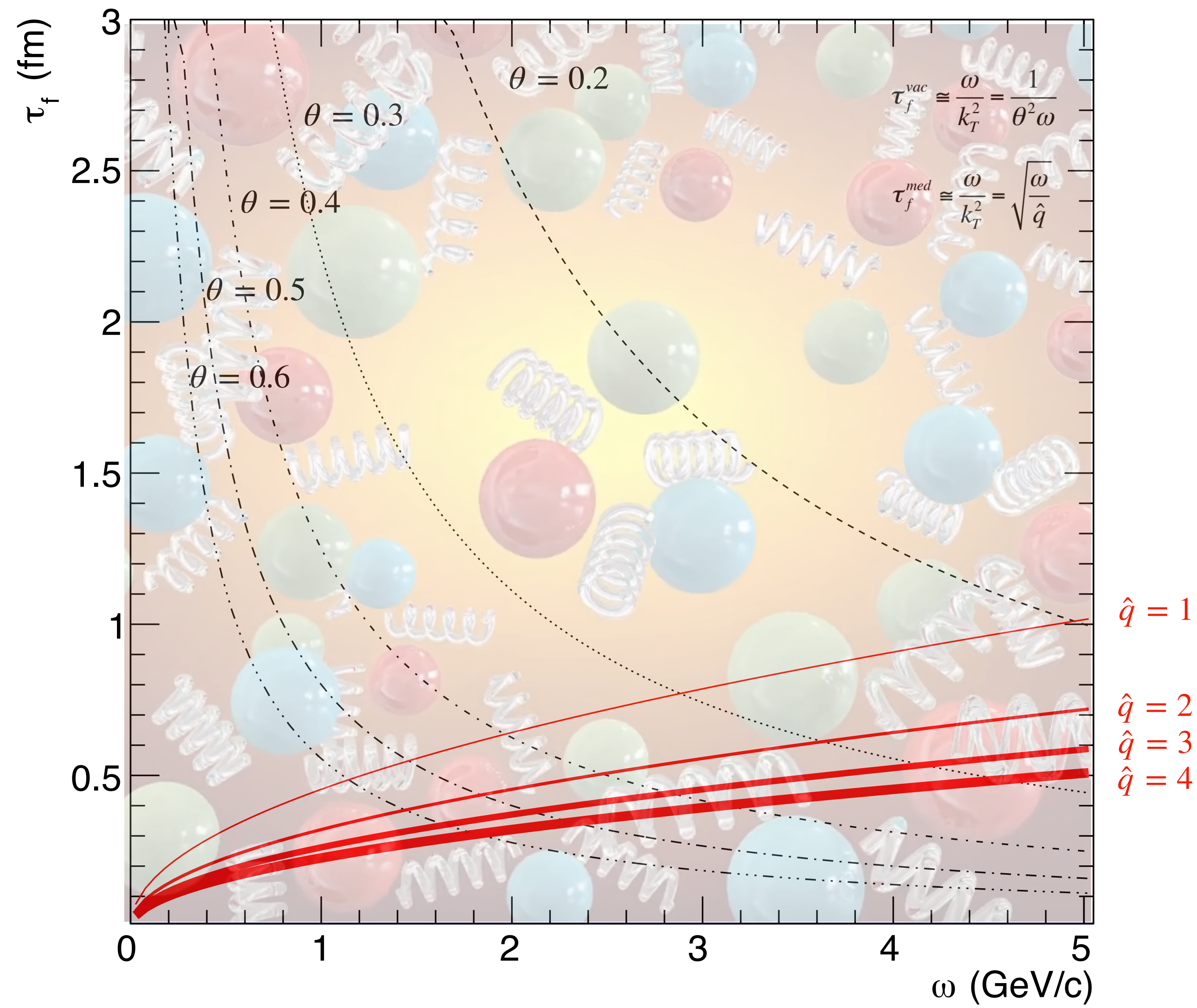


- Significant split in the formation times for 3rd particle to be opposite sign - quantitative categorizing of charge conservation in jets vs time
- Emerging as a new avenue thats complementary to jet substructure focused on understanding hadronization mechanisms

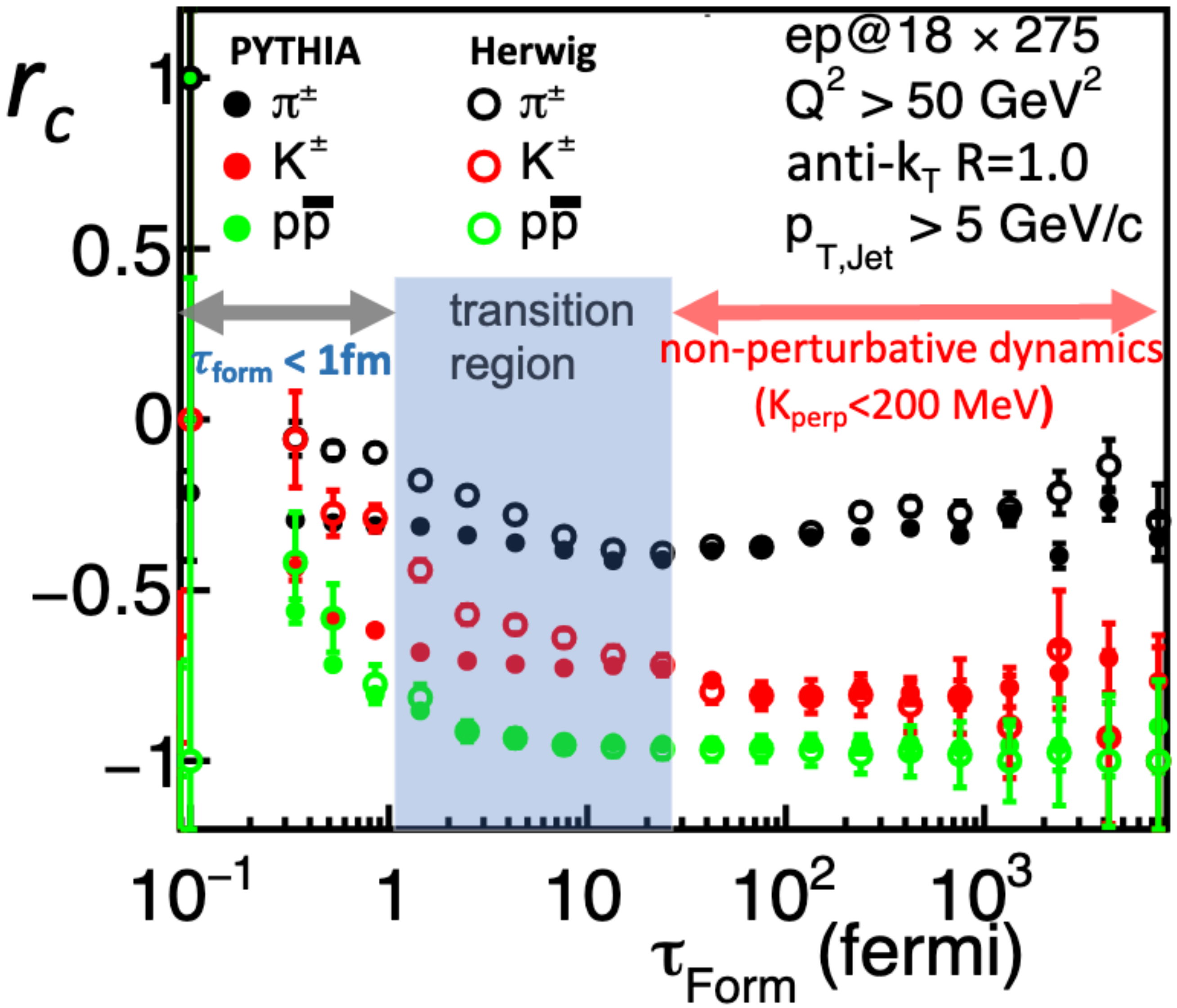



time


τf [fm/c]
1
10
STAR Preliminary
pp √s = 200 GeV
SD zcut = 0.1, β = 0
anti-kT R=0.4 Jets, |η| < 0.6
SD 1st split τf
Split ch-particles resolved τf
Ch-particles τf
1/Njets dN/dln(τf) [fm/c]-1
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20 < pT,jet < 30 [GeV/c]
Ratio w/ Ch-sp
1
10−1
−2
0
2
4
ln(τf) [fm/c]


τf (fm)
3
2.5
2
1.5
1
0.5
θ = 0.2
θ = 0.3
θ = 0.4
θ = 0.5
θ = 0.6
$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2\omega}$
$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$
$\hat{q} = 1$
$\hat{q} = 2$
$\hat{q} = 3$
$\hat{q} = 4$
0
1
2
3
4
5
ω (GeV/c)

Backup



$$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$$

Formation time : $[2z(1-z)\,P]/k_{perp}^2$

z : momentum fraction of NL particle

k_{perp}: Relative transverse momentum between L & NL

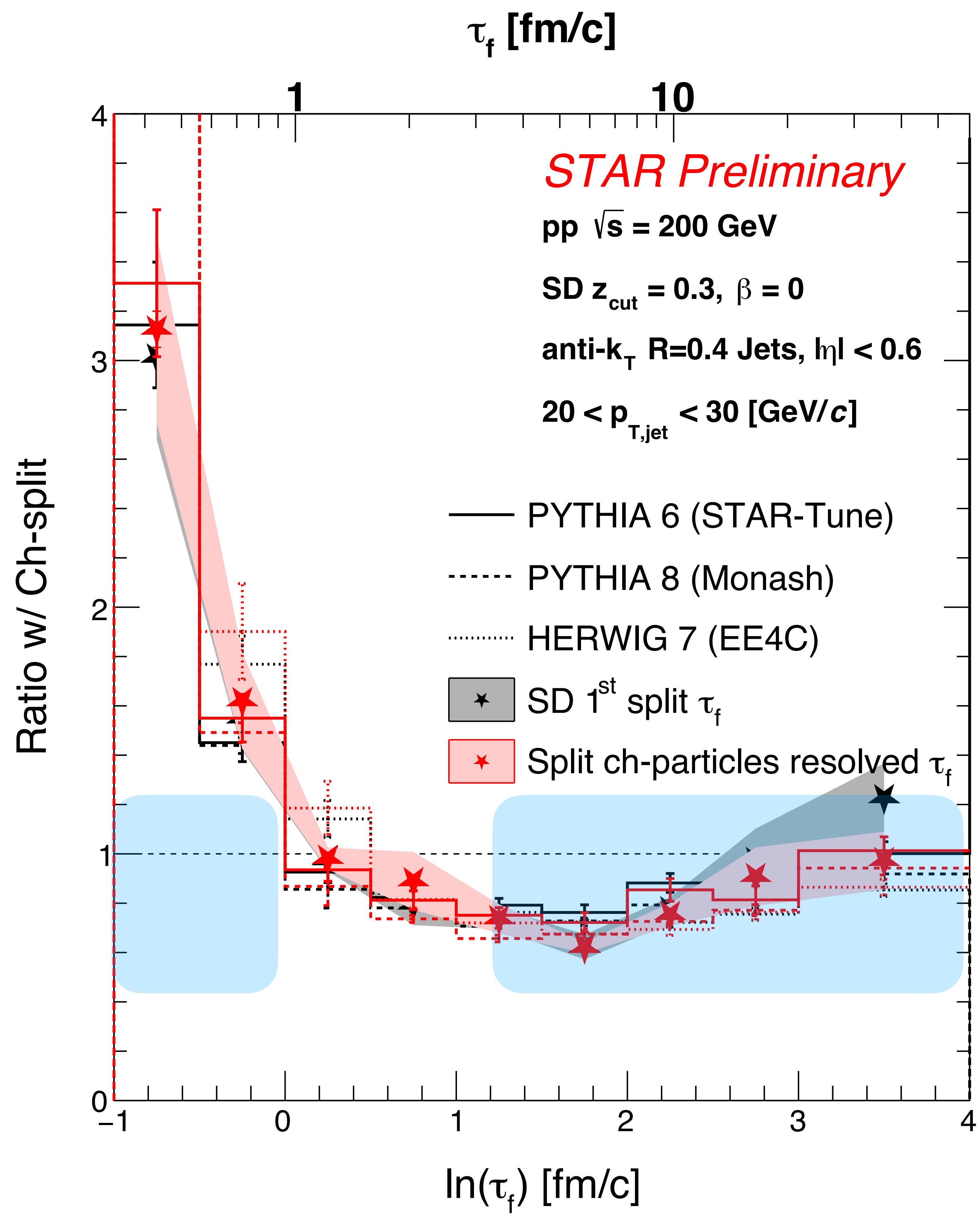
- There is strong flavor dependence in r_c
- In specific kinematic region PYTHIA and Herwig differ significantly

- Recent studies also show its usefulness from the theoretical POV on isolating regions where calculations are valid

- Fuzzy area, but overall one can separate out **'mostly' perturbative** and **'mostly' non-perturbative** regions based on τ

Comparison with MC

- PYTHIA 8, PYTHIA 6 and HERWIG 7 show similar behavior of crossover and flattening
- Hints of differences between PYTHIA 6/8 and HERWIG 7 in the crossover region (ratio goes from > 1 to < 1)
- Isolate two regions - Drop $\tau_f < 1\ \mathrm{fm/c}$ Plateau $\tau_f > 4\ \mathrm{fm/c}$



- Jet substructure program at STAR aims at **mapping jet evolution** at RHIC energies

- Data show a **gradual variation in the available phase space**
  - leading to modifications (e.g. virtuality evolution) in the observed splitting kinematics

- Observe increased probability of **significantly harder/symmetric splittings** at the **third/ narrow split** compared to the first and second splits

- Subjets at RHIC allow to **disentangle perturbative and non-perturbative dynamics of jet evolution** - these **third and narrow splits** for our low p_T jets end up bein quite close to the Λ_{QCD} scale