Jet substructure

An unexpected journey

Raghav Kunnawalkam Elayavalli (he/them)
Vanderbilt University
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Nov 17th, 2022
Seminar @ LIP, Lisbon

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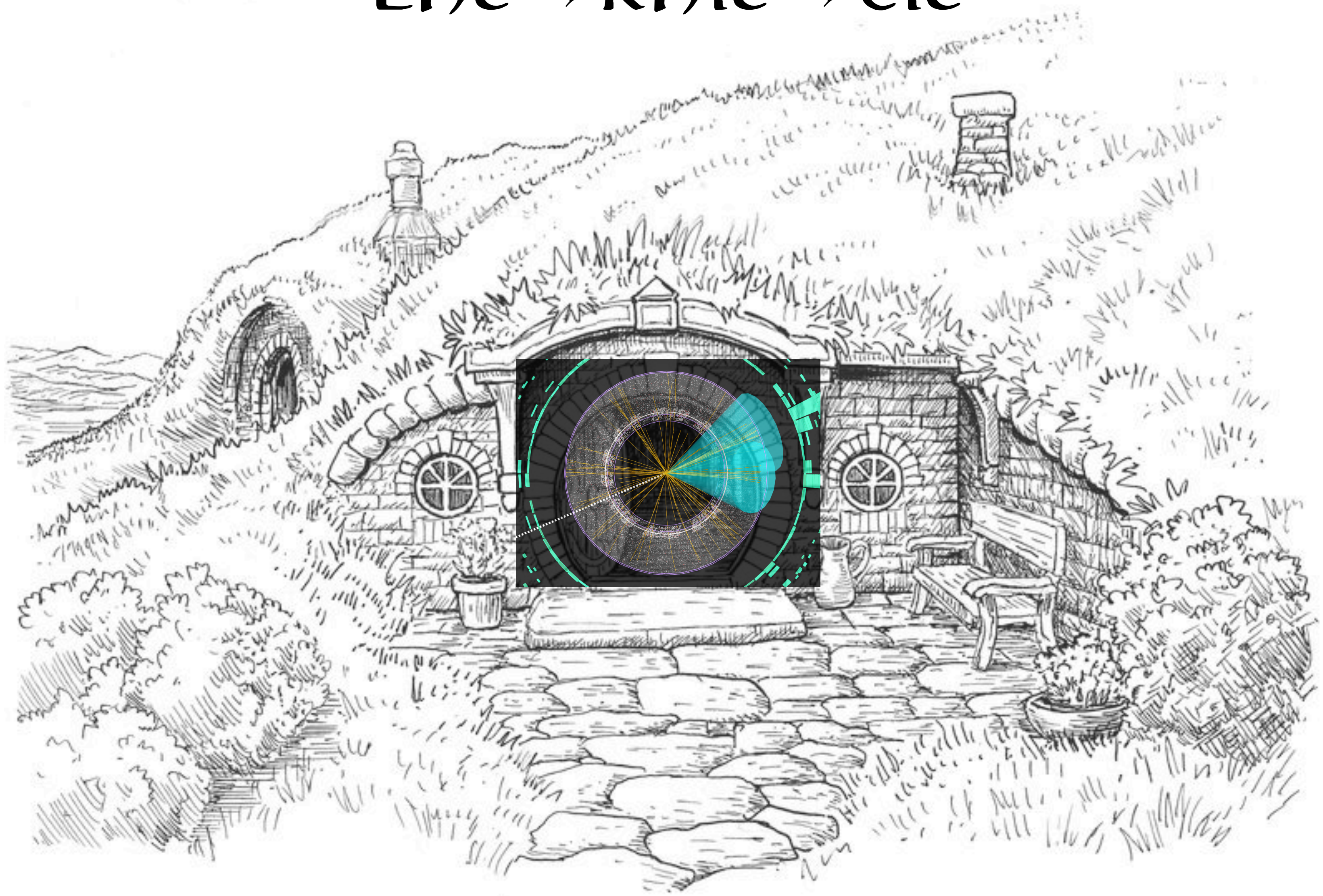
An unexpected journey from

LHC → RHIC → EIC



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pQCD and npQCD at the EIC

Completing the RHIC mission

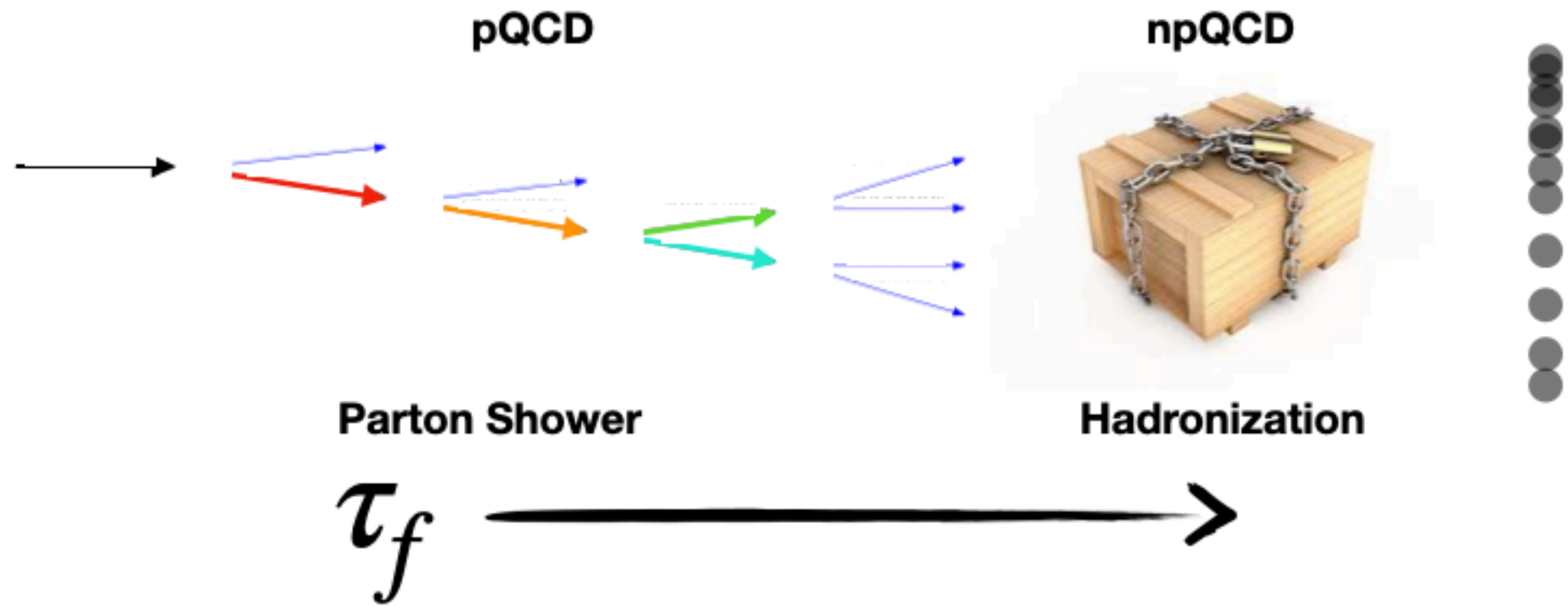
Introduction, motivation and current status

pQCD and npQCD at the EIC

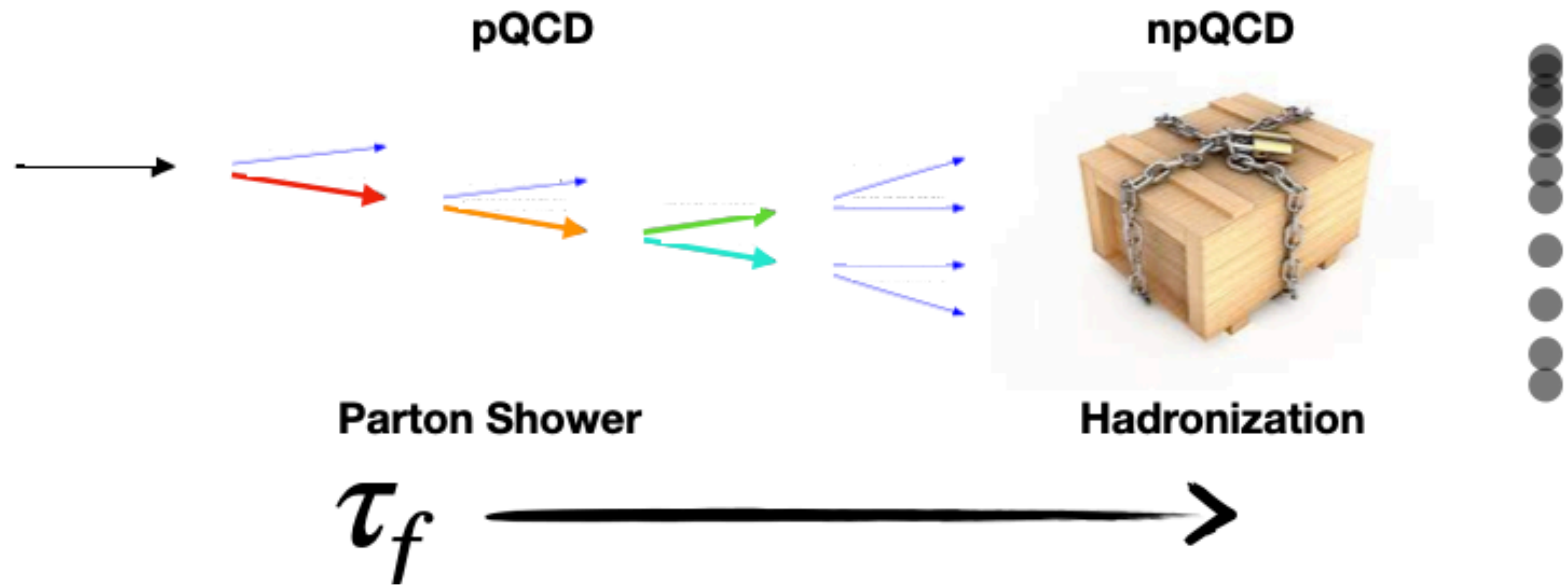
RHIC in 2023-2025

Introduction, motivation and current status

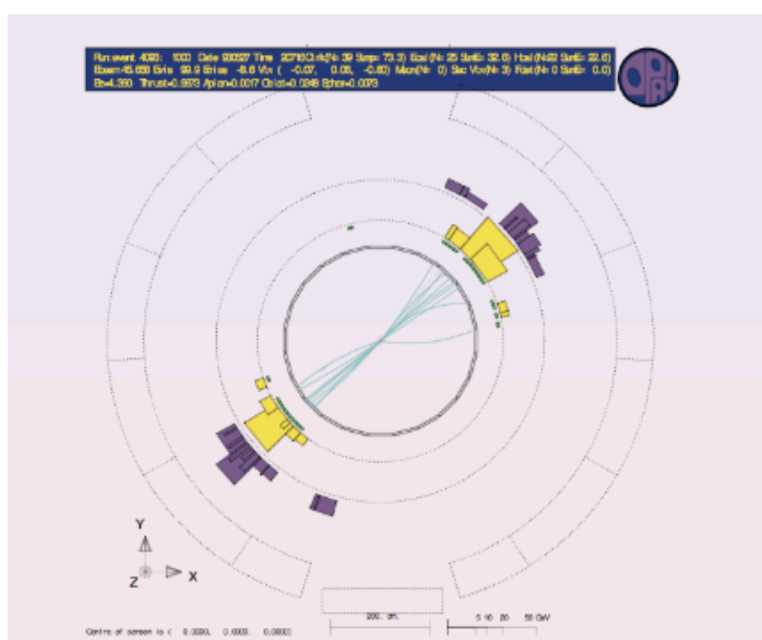
What are jets?



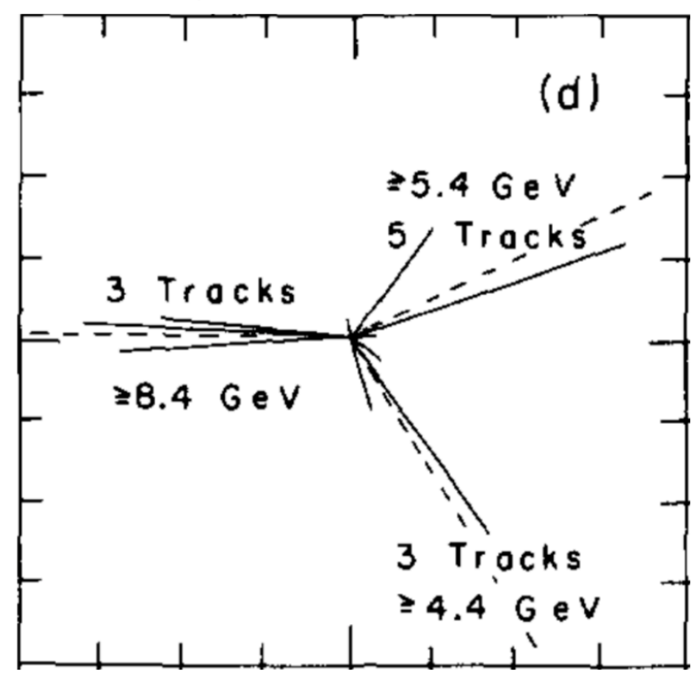
What are jets?



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



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



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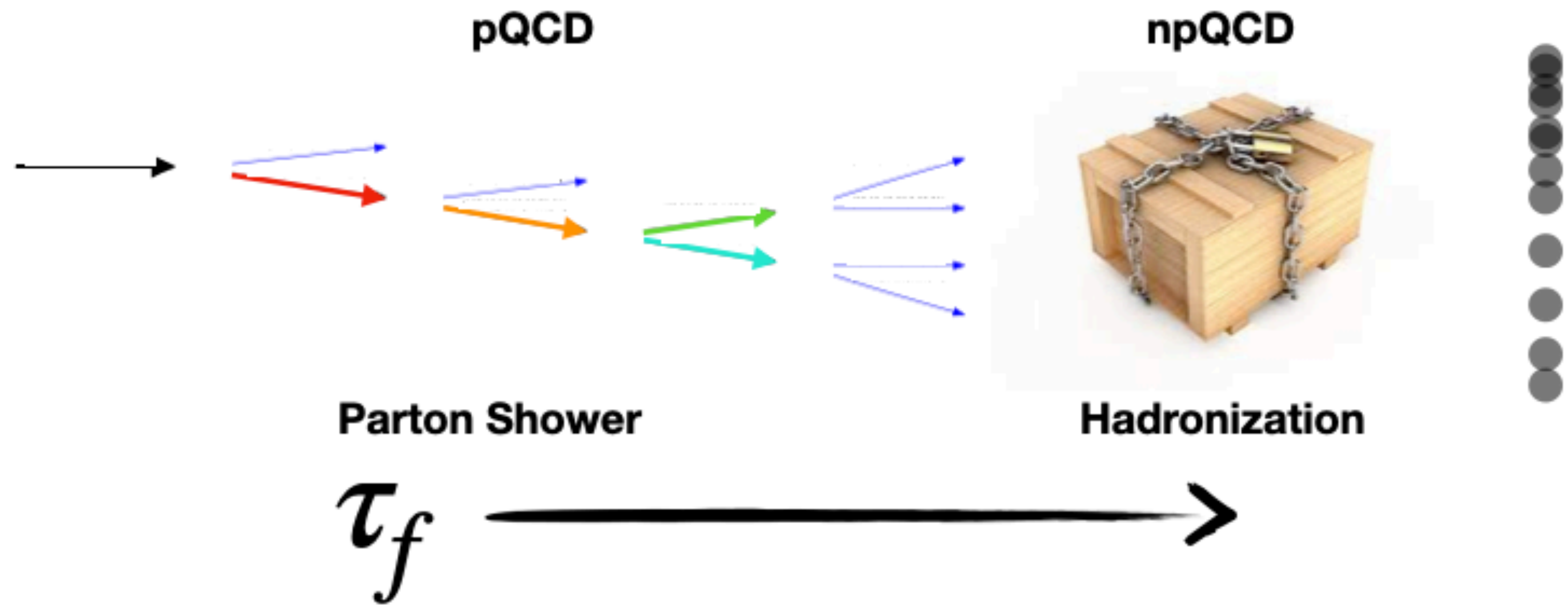
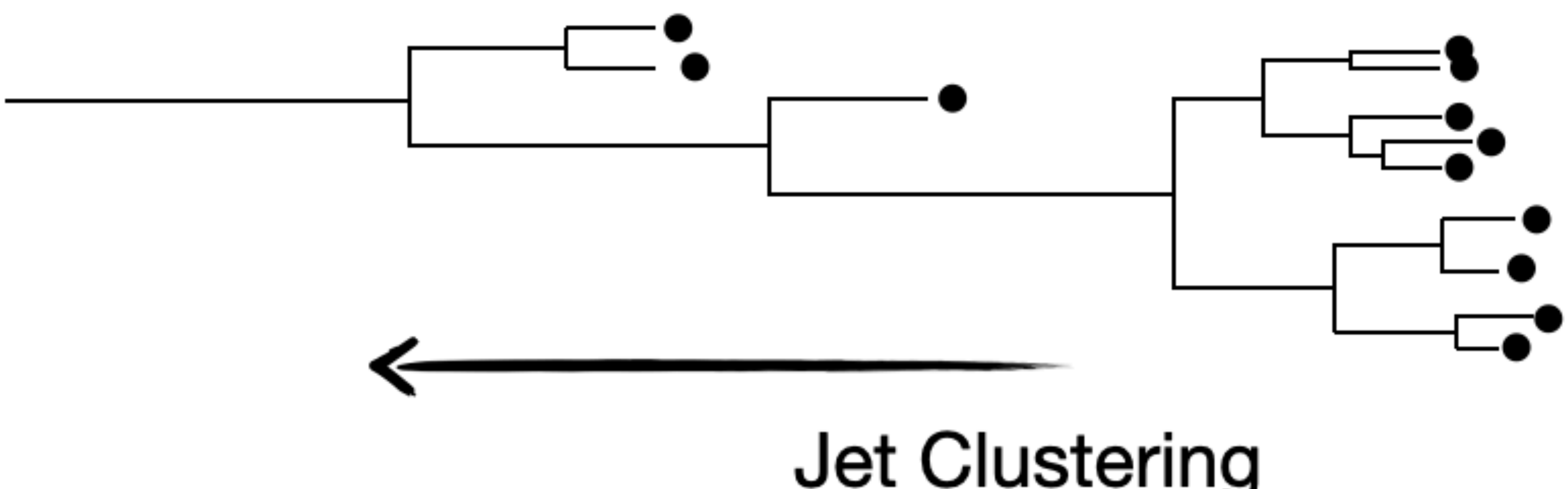
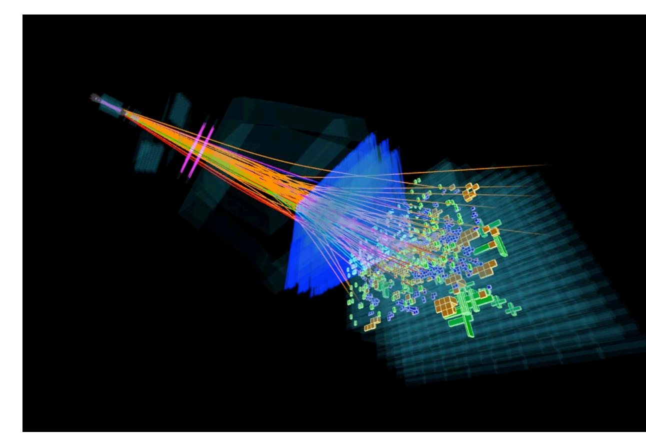
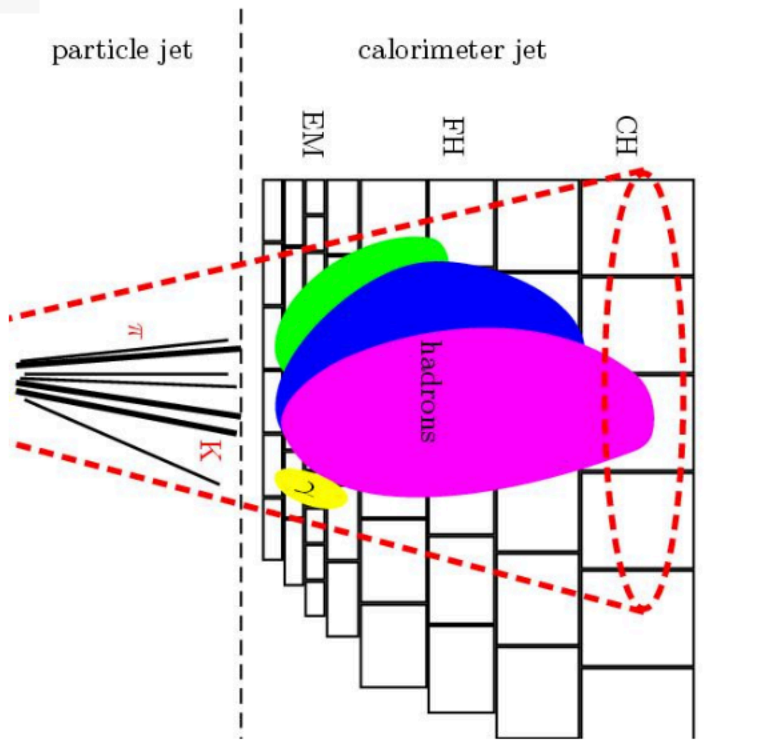
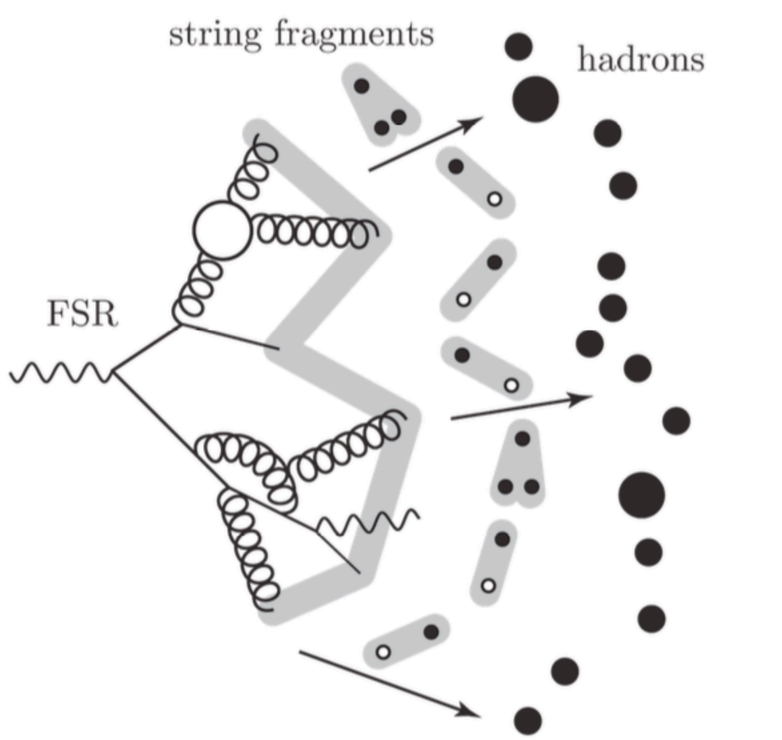
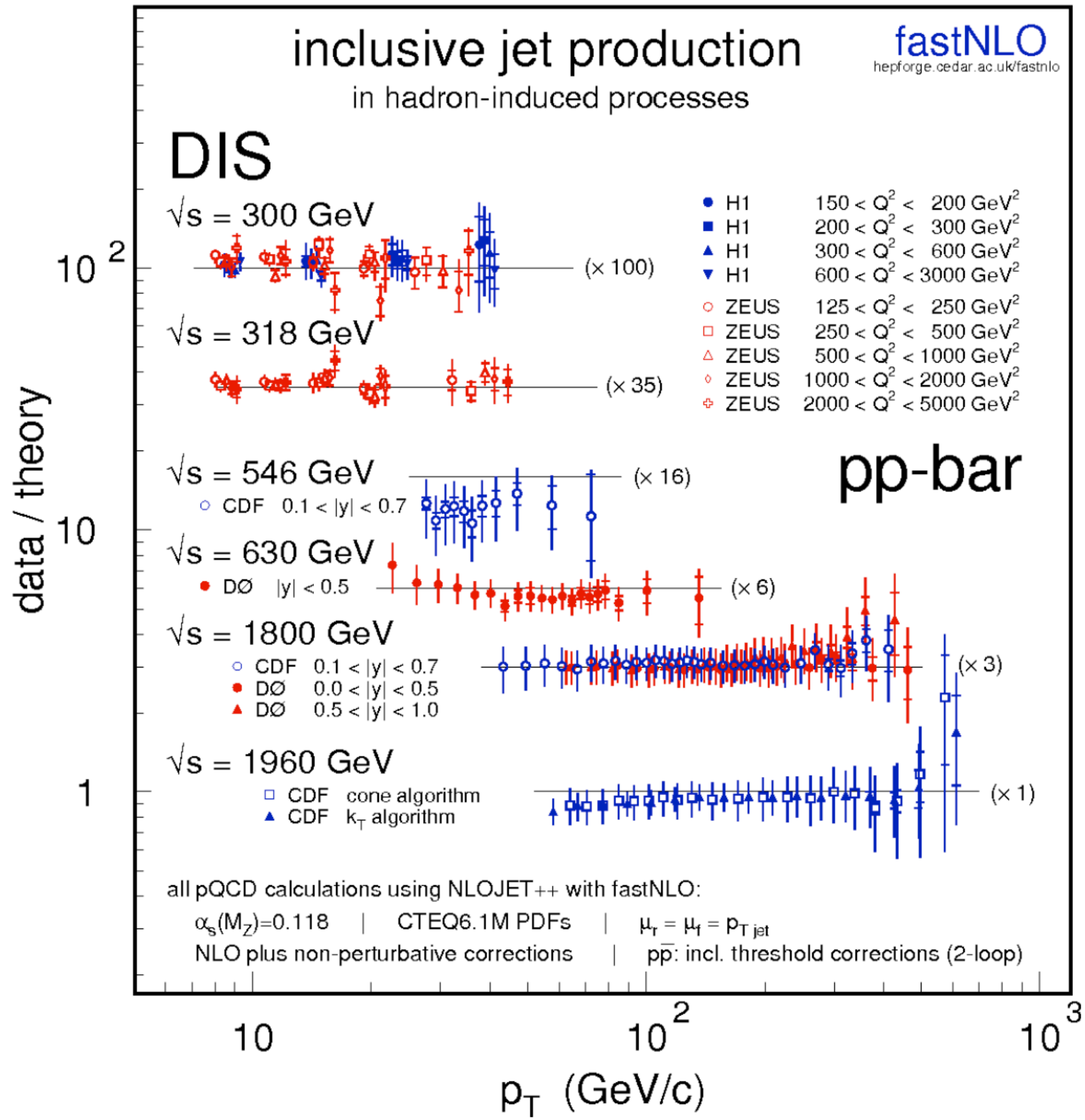




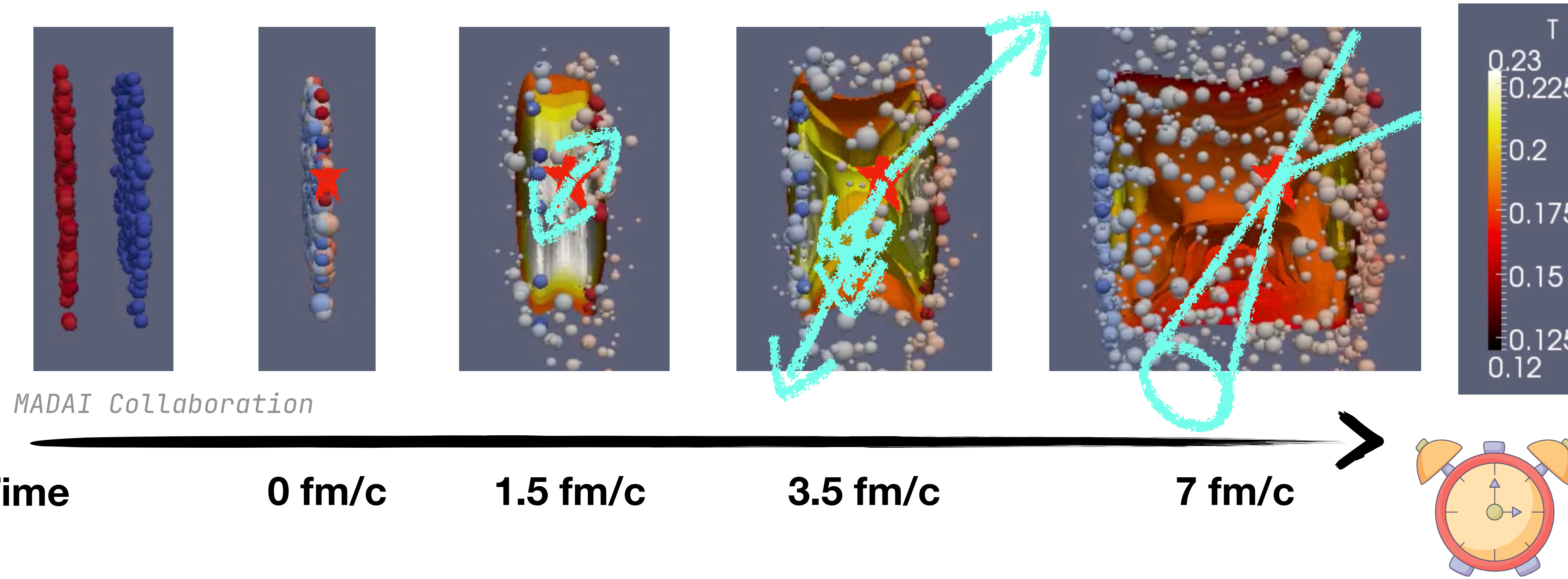



particle jet
calorimeter jet
EM
FH
CH
hadrons
π
K
γ


string fragments
hadrons
FSR


inclusive jet production
in hadron-induced processes
fastNLO
hepforge.cedar.ac.uk/fastnlo
DIS
√s = 300 GeV
(× 100)
√s = 318 GeV
(× 35)
H1 150 < Q² < 200 GeV²
H1 200 < Q² < 300 GeV²
H1 300 < Q² < 600 GeV²
H1 600 < Q² < 3000 GeV²
ZEUS 125 < Q² < 250 GeV²
ZEUS 250 < Q² < 500 GeV²
ZEUS 500 < Q² < 1000 GeV²
ZEUS 1000 < Q² < 2000 GeV²
ZEUS 2000 < Q² < 5000 GeV²
pp-bar
√s = 546 GeV
CDF 0.1 < |y| < 0.7
(× 16)
√s = 630 GeV
DØ |y| < 0.5
(× 6)
√s = 1800 GeV
CDF 0.1 < |y| < 0.7
DØ 0.0 < |y| < 0.5
DØ 0.5 < |y| < 1.0
(× 3)
√s = 1960 GeV
CDF cone algorithm
CDF kT algorithm
(× 1)
all pQCD calculations using NLOJET++ with fastNLO:
αs(MZ)=0.118 | CTEQ6.1M PDFs | μr = μf = pT jet
NLO plus non-perturbative corrections | pp̄: incl. threshold corrections (2-loop)
data / theory
pT (GeV/c)
10²
10
1
10
10²
10³

Jets and the QGP



Jets are produced early in the collision ($\tau_{\text{form}} \sim 1/Q^2$) and traverse the entire lifetime of the QGP

Makes for a great story!

The story of our field

According to Aristotle, a successful story needs three elements

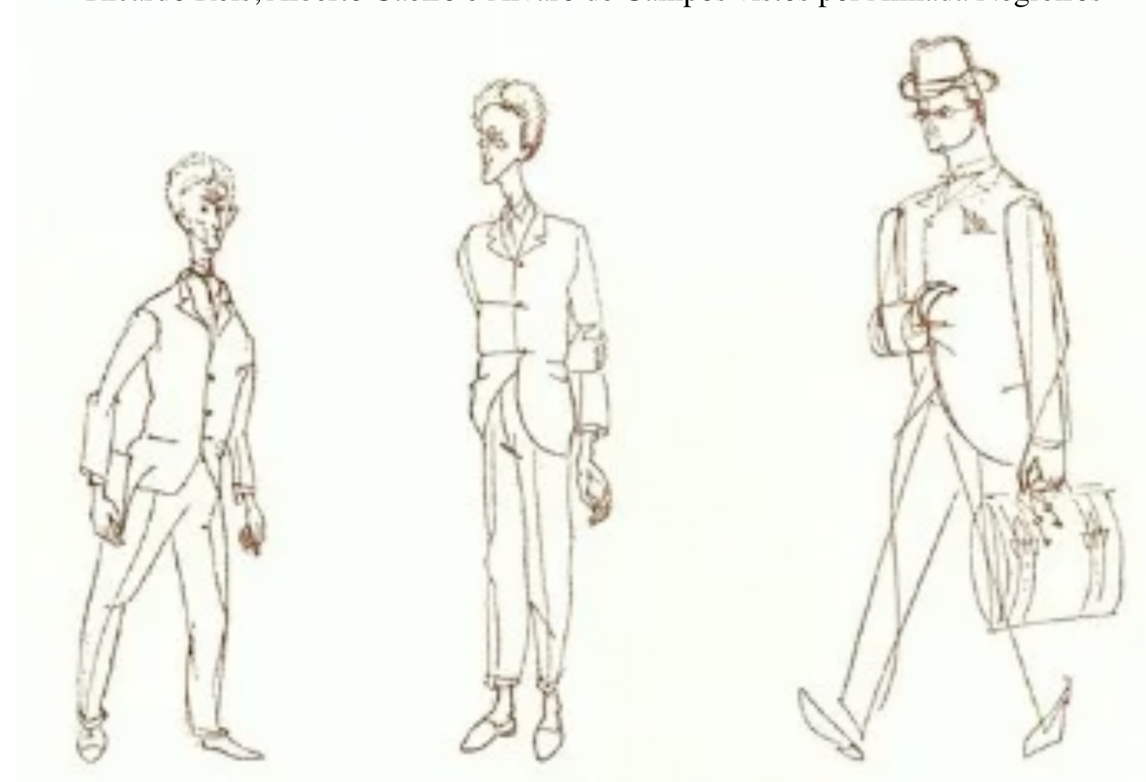
- *Harmartia* - a tragic flaw of the main character
  Jets originate from color charged quarks/gluons and interact with the QGP during their probabilistic parton showers - different jets are different

- *Anagnōrisis* - eureka moment
  Observe modification of jet properties, such as its momentum (R_{AA}), hadron distributions (jet shapes, FF) enables us to infer medium transport properties - medium modifies jets

- *Peripeteia* - reversal of fortune
  Realization that jet quenching is dependent on the character of jets and their topologies - different jets are quenched differently

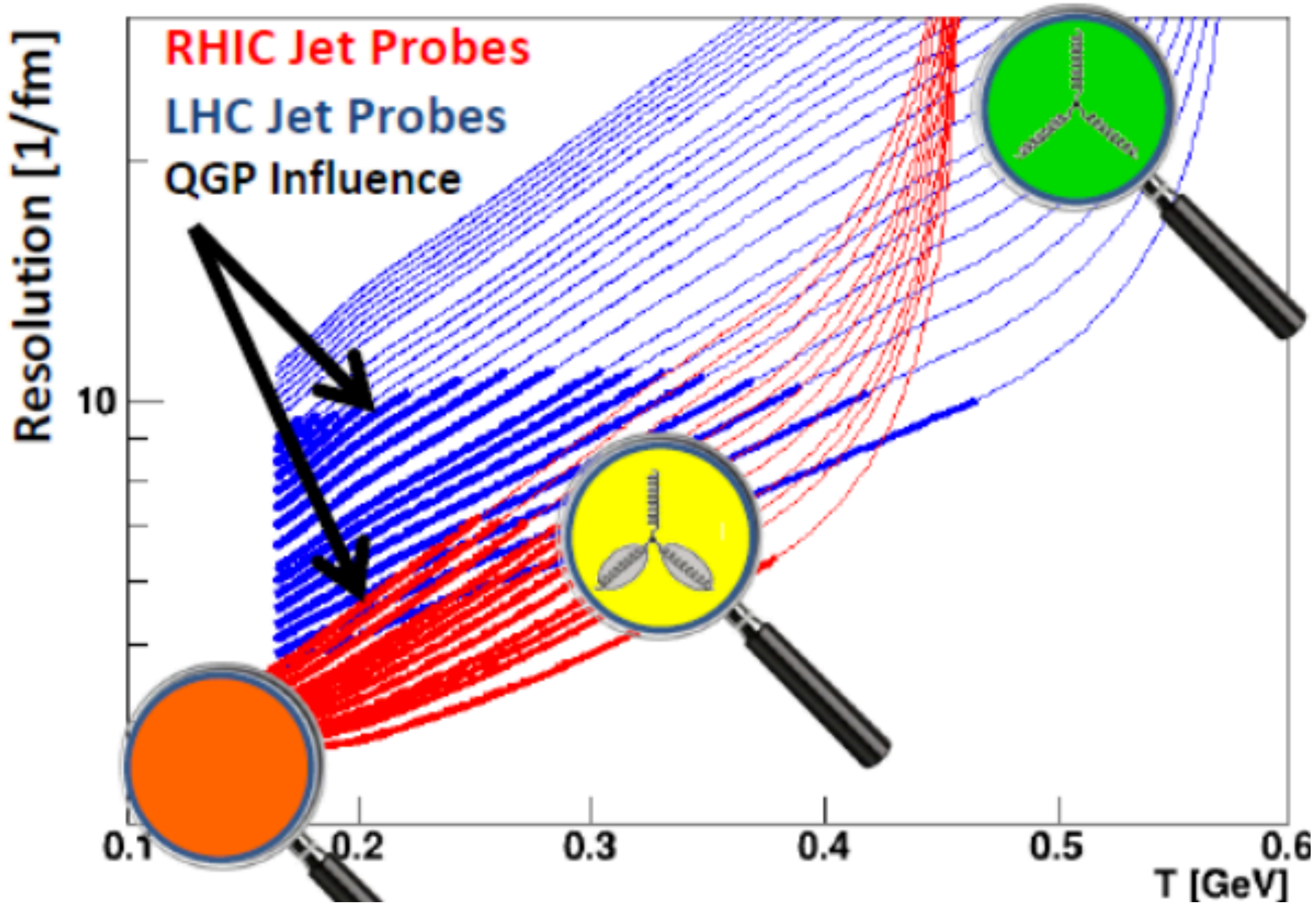
Jets for QGP transport properties

Ricardo Reis, Alberto Caeiro e Álvaro de Campos vistos por Almada Negreiros



Heterônimos de Fernando Pessoa

Jets for QGP transport properties



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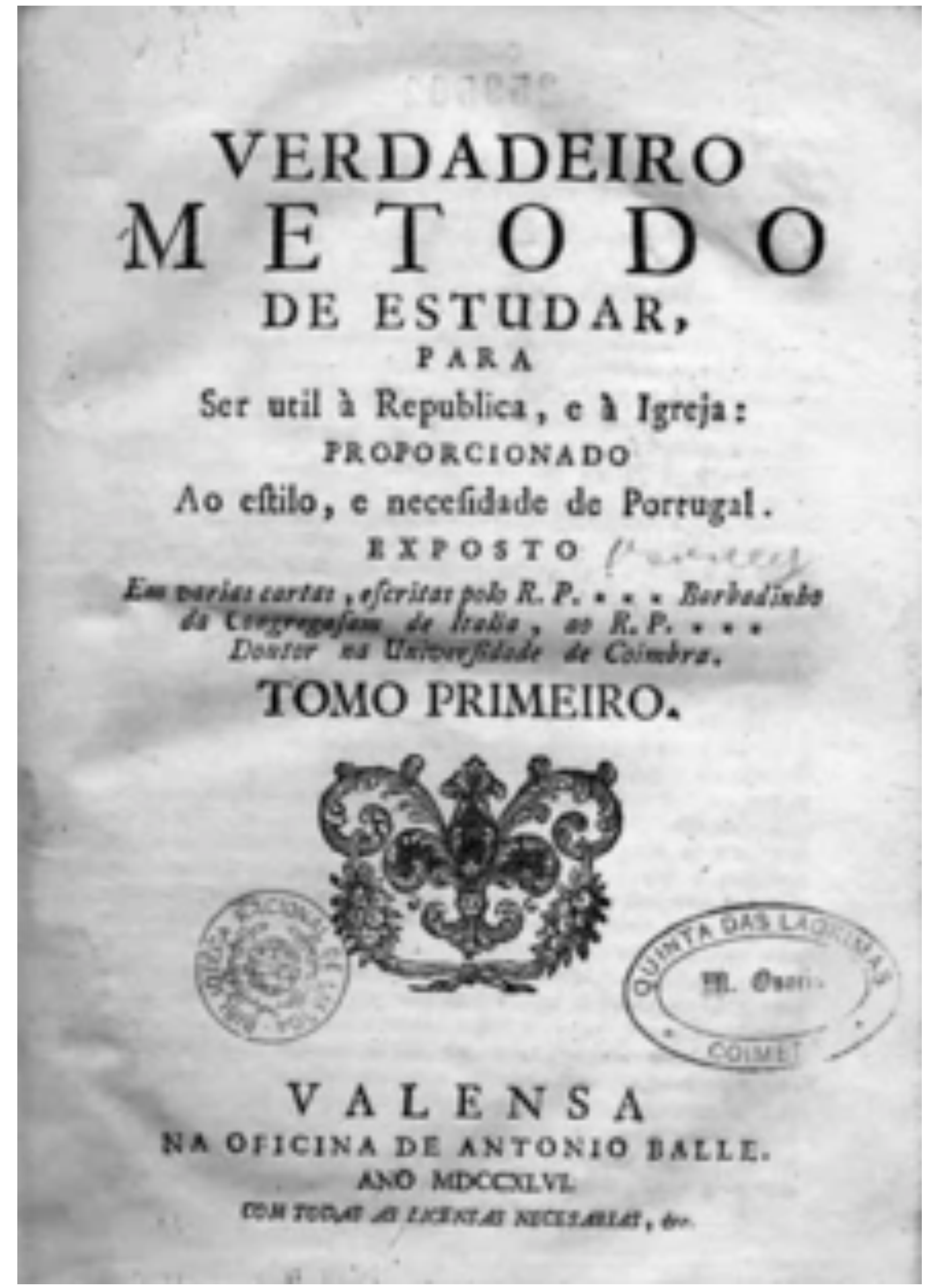
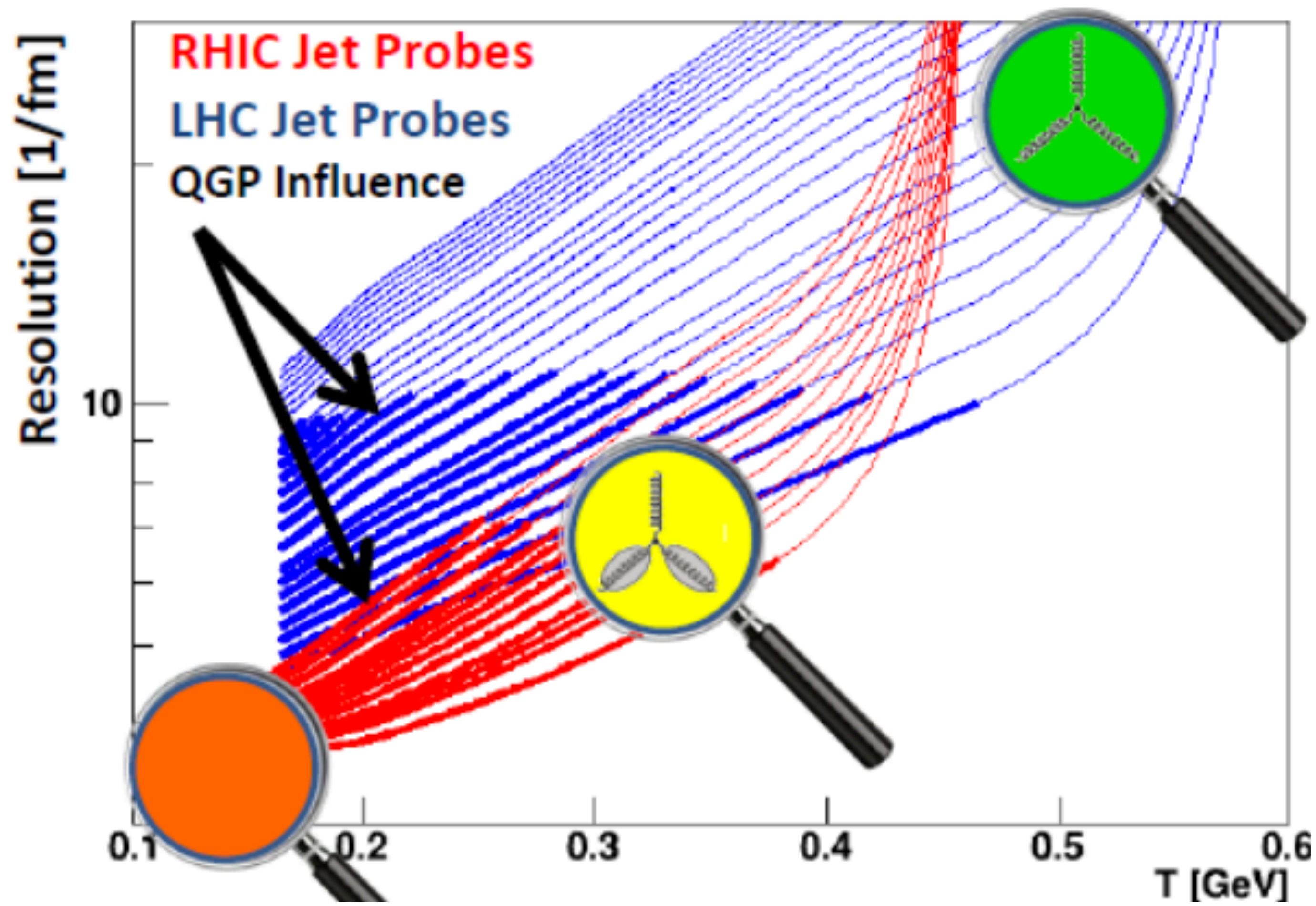
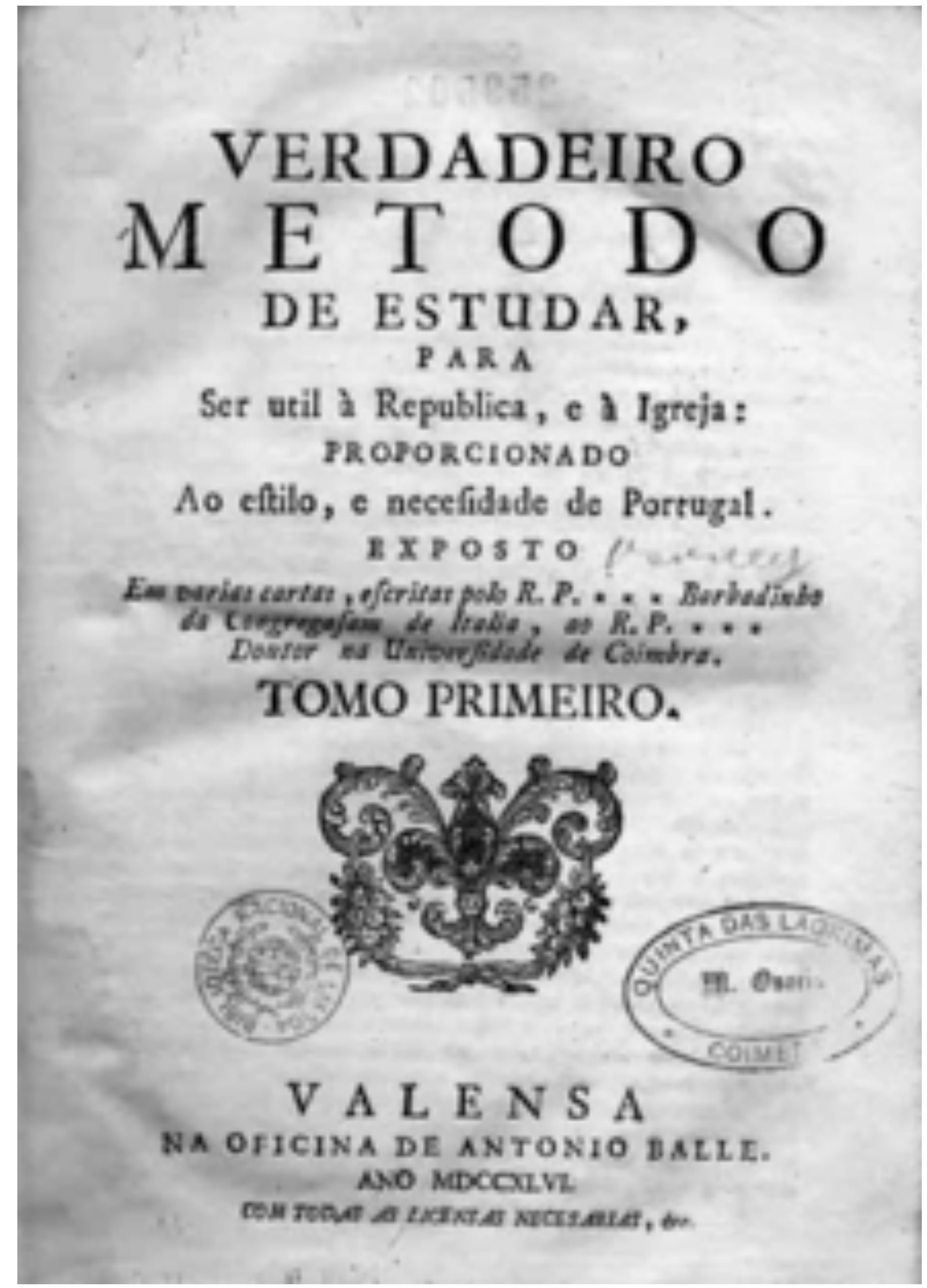

VERDADEIRO
METODO
DE ESTUDAR,
PARA
Ser util à Republica, e à Igreja:
PROPORCIONADO
Ao estilo, e necesidade de Portugal.
EXPOSTO
Em varias cartas, escritas polo R. P. . . . Barbadinho da Congregasam de Italia, ao R. P. . . . Doutor na Universidade de Coimbra.
TOMO PRIMEIRO.

VALENSA
NA OFICINA DE ANTONIO BALLE.
ANO MDCCXLVI.
COM TODAS AS LICENSAS NECESSARIAS, &c.

True Method of Studying by Luís António Verney

Jets for QGP transport properties





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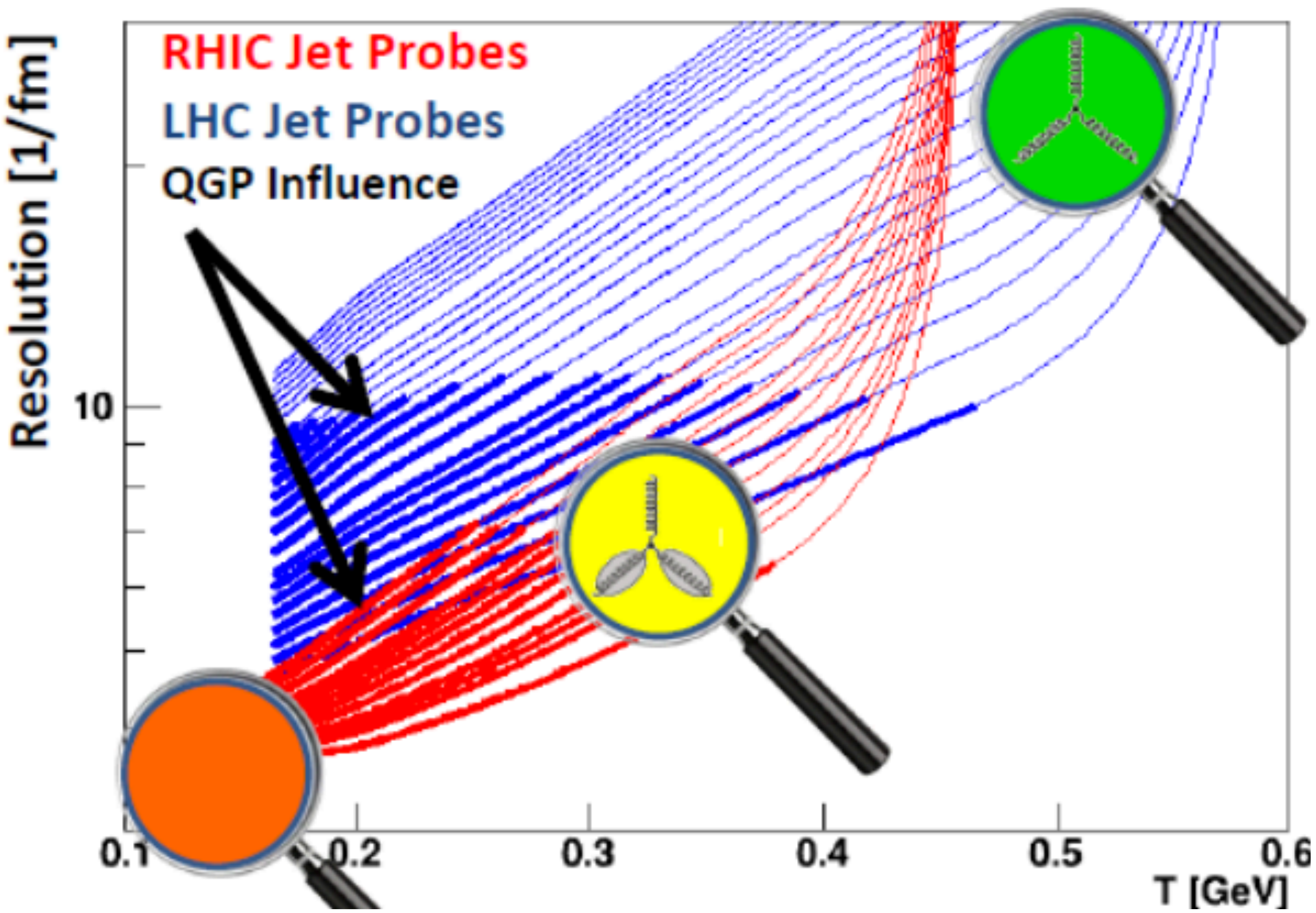
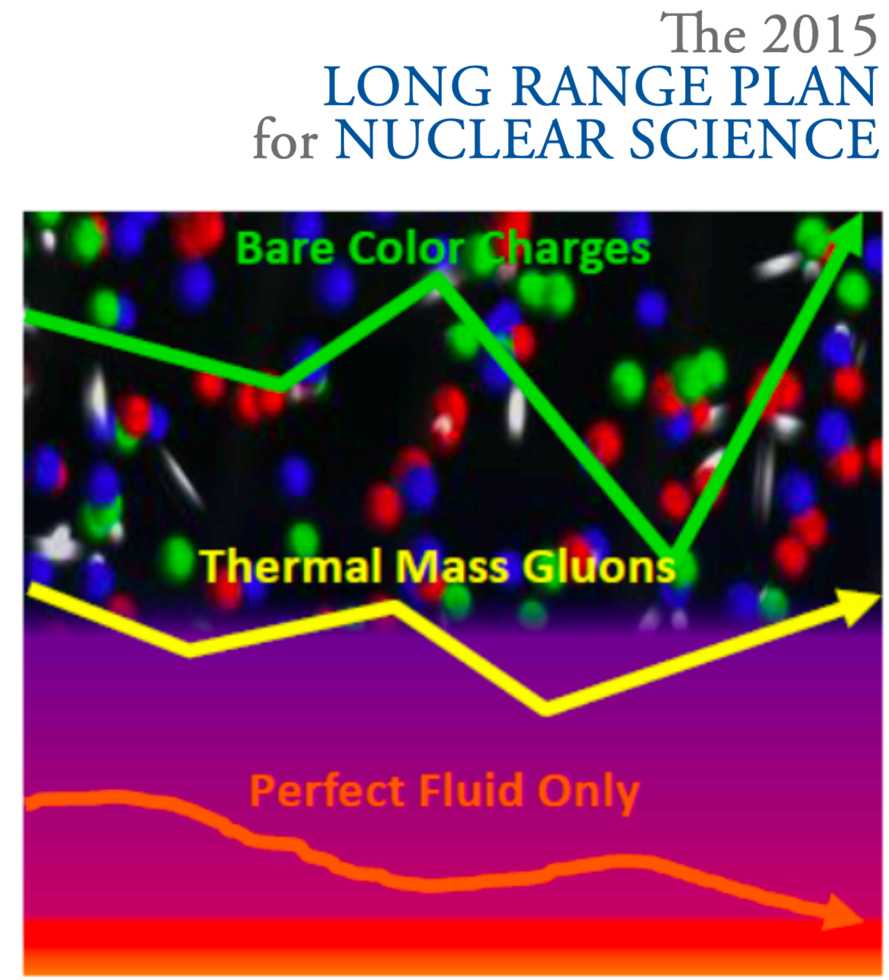




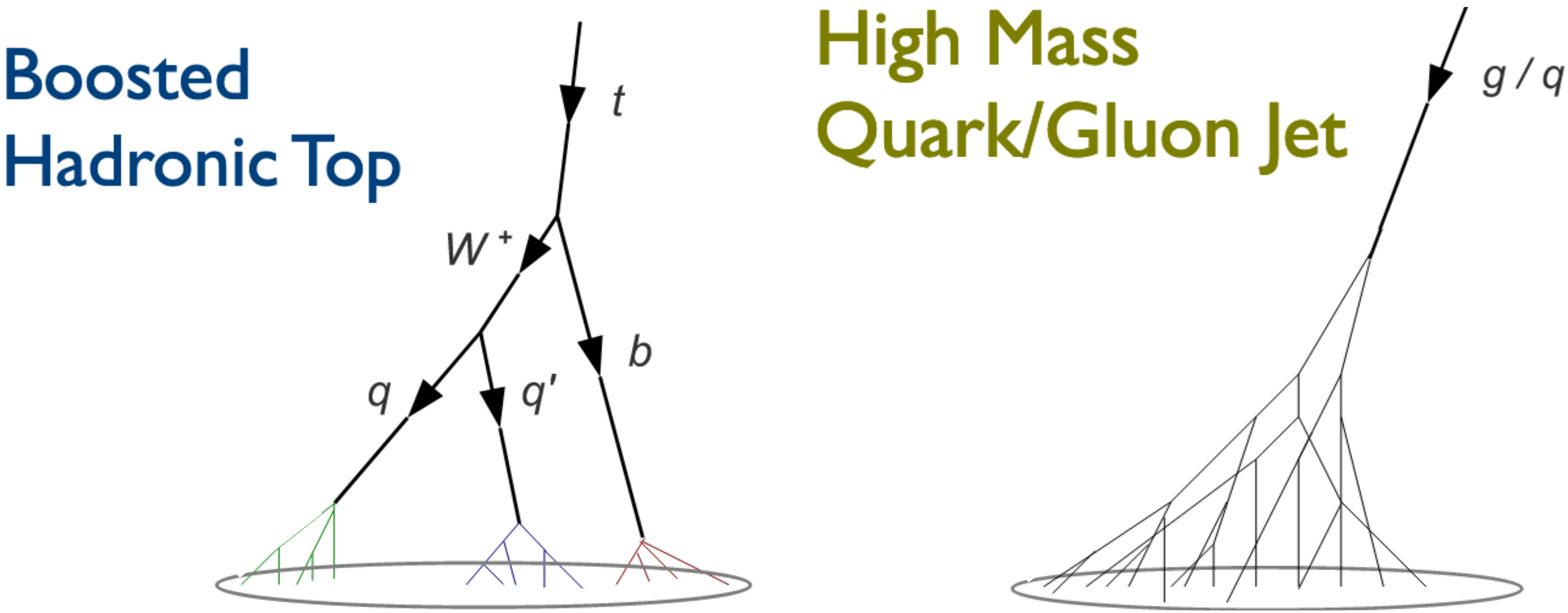
Microscopic properties of the QGP Medium
- structure at varying scales

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

Understand jet energy loss → Extract medium properties

Origin story of jet substructure

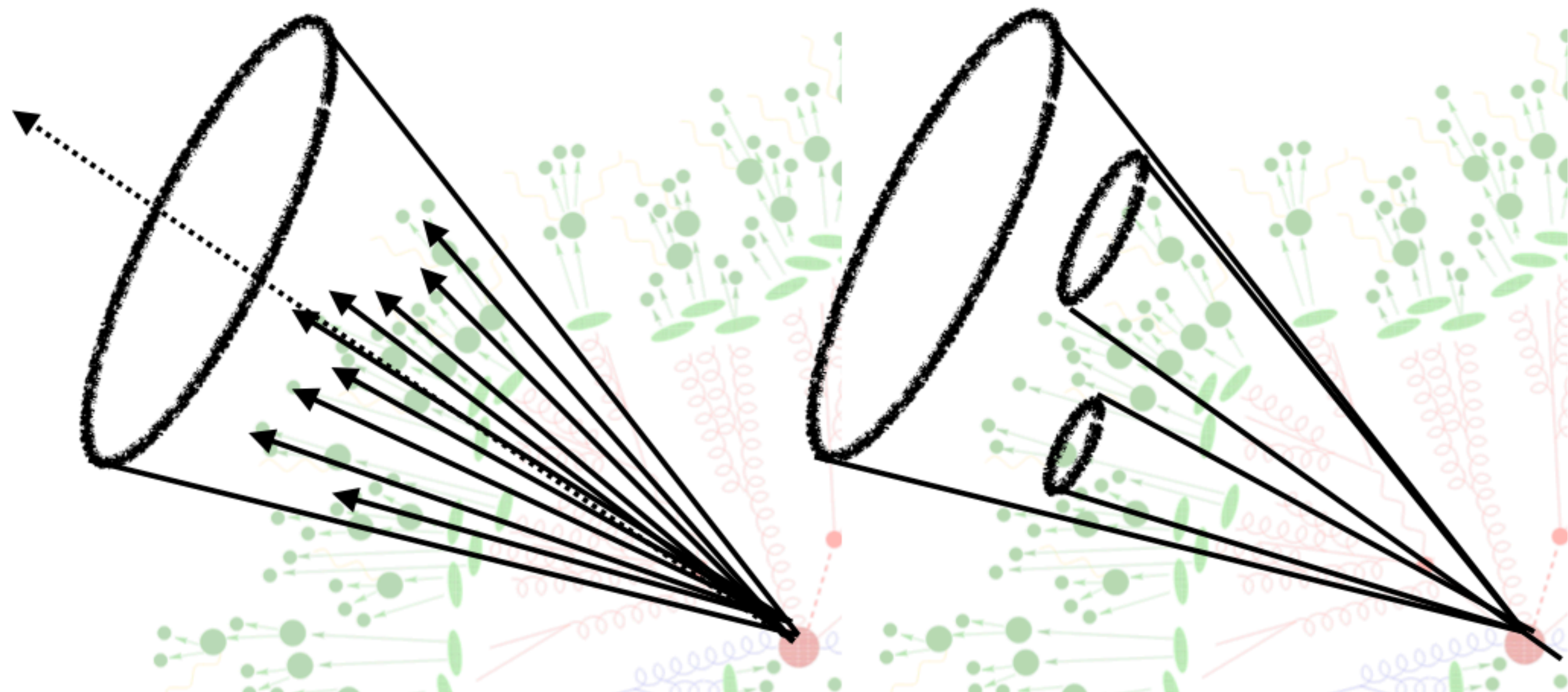
Jesse Thaler in 2011



Started with the goal of identifying boosted decay versus standard QCD

What is jet substructure?

A useful way to tag jet populations



Physics motivated combinations of particle distributions within the jet

Utilizes algorithmic structure of jet finding - (re) or (de) clustering

Jets for fundamental QCD

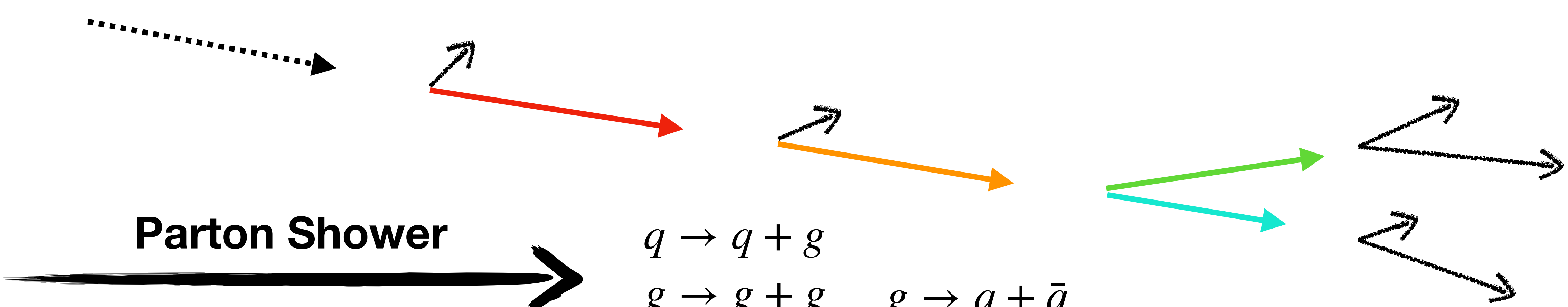
perturbative and non-perturbative

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

For example - this parton shower results in 6 partons before the hadronization stage in a MC model

How much of these splitting dynamics can we measure? And more importantly, connect to a physics picture?

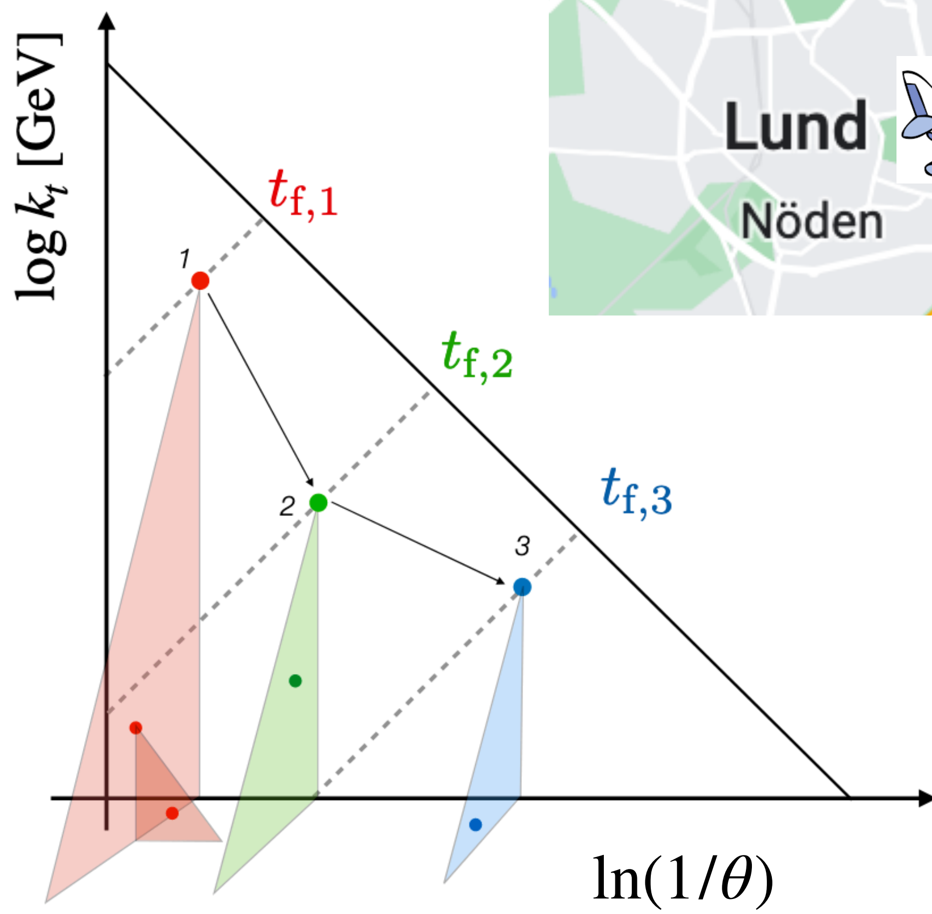
Sjöstrand, Skands, Eur. Phys. J. C39 (2005) 129-154



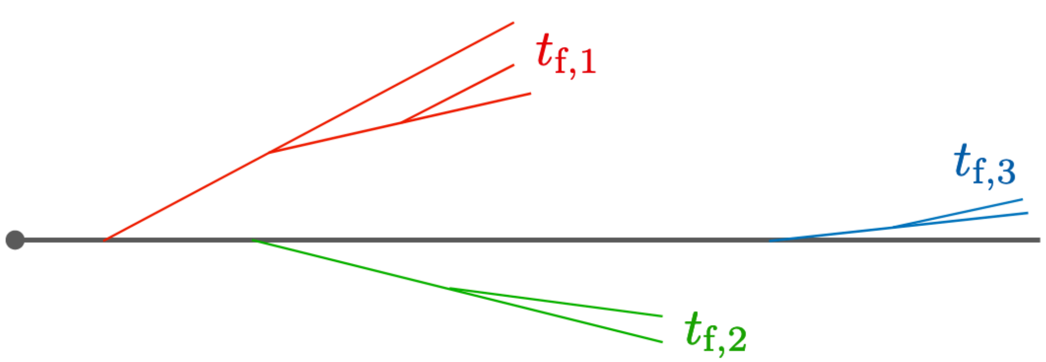
$q \to q + g$

$g \to g + g$ $\quad g \to q + \bar{q}$

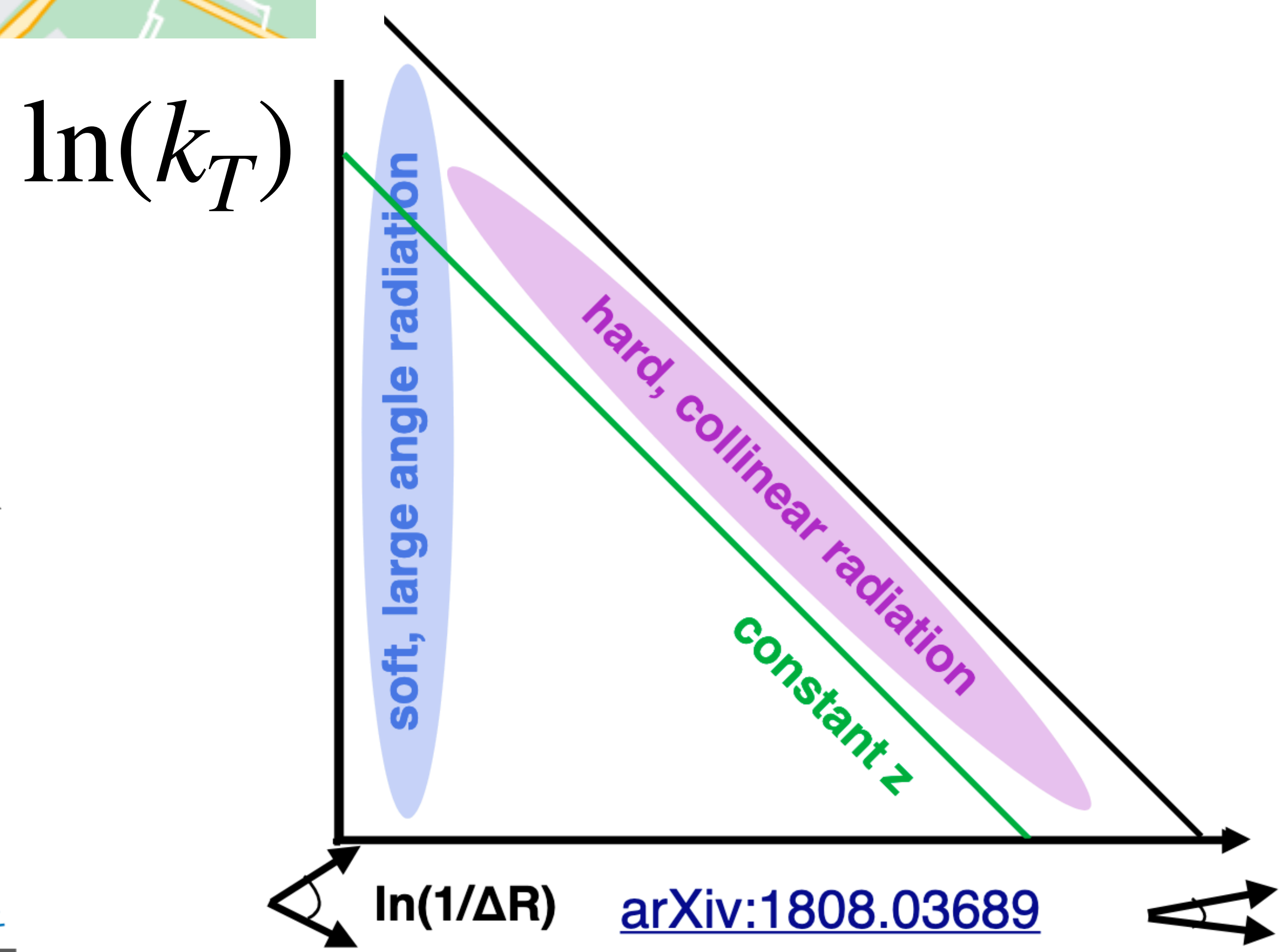
How to access the splitting kinematics?



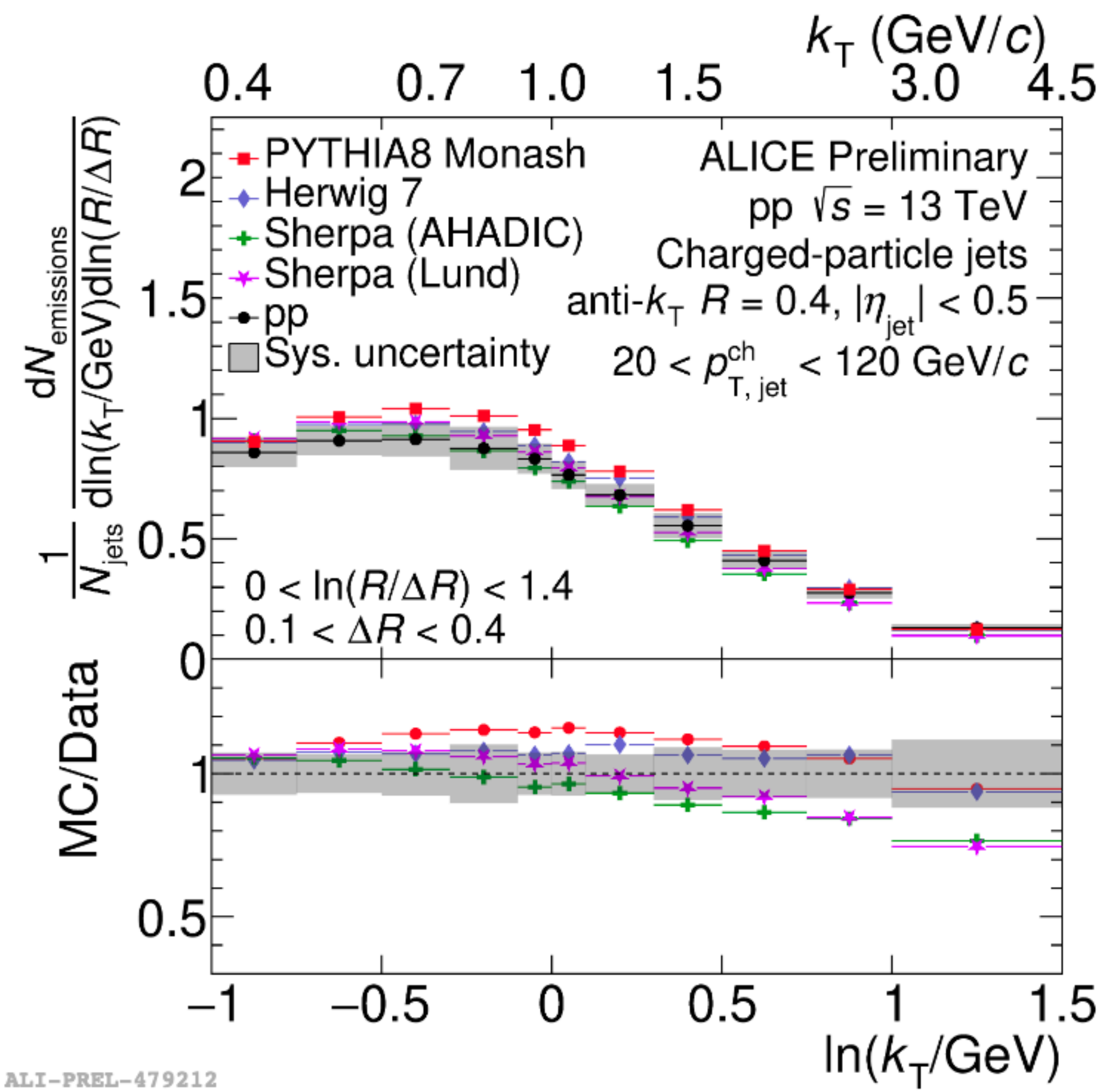
Konrad Tywoniuk (UB) @ QM 2019



$$k_T = z \cdot p_{\mathrm{T,parent}} \cdot \Delta R \ [GeV]$$



What are jets like in vacuum?

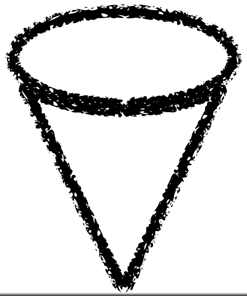


ALICE-PUBLIC-2021-002

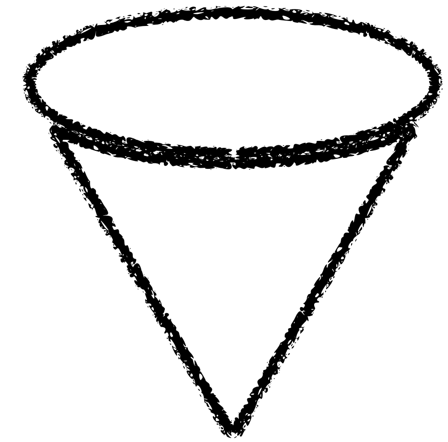
- Lower p_T jets at ALICE (20 - 120 GeV) also show interesting differences for large k_T splits
- Lund plane integrates over splits - can we measure the evolution of these observables along the jet shower?

$$k_T = z \cdot p_{\mathrm{T,parent}} \cdot \Delta R \; [GeV]$$

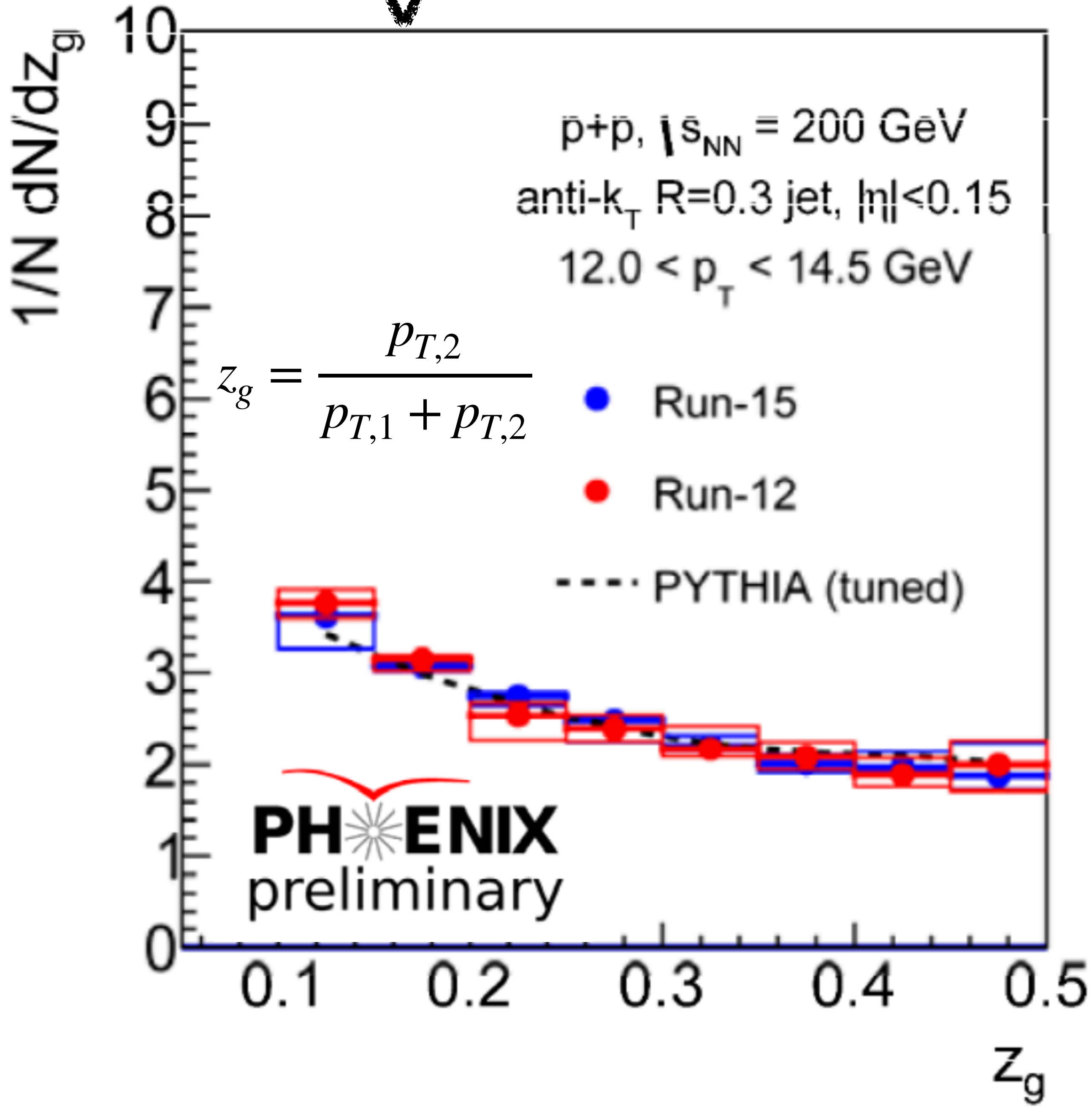
Jet substructure @ RHIC

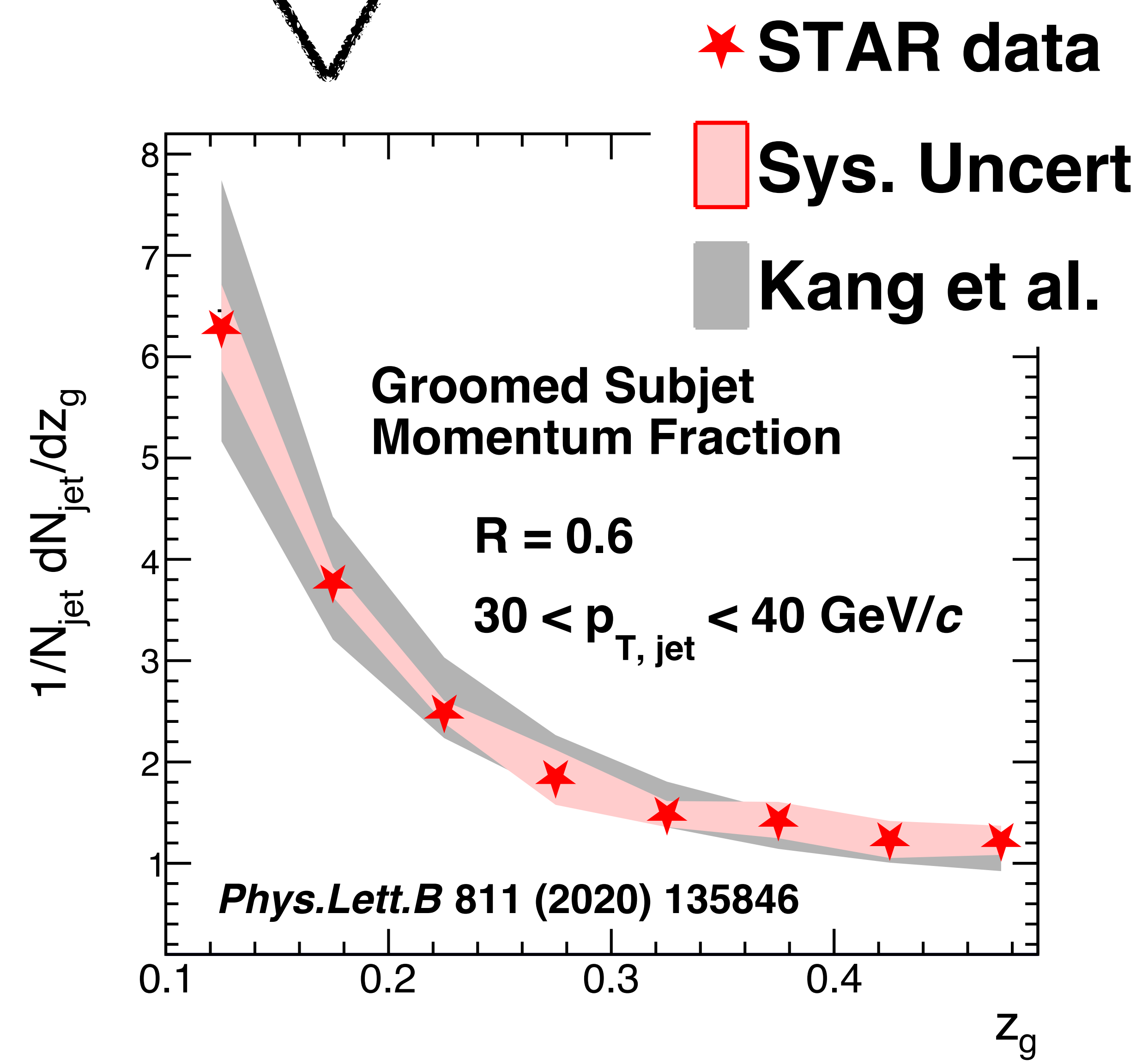


$12 < p_T^{jet} < 14.5$ GeV/c
$R = 0.3$ anti $-$ k_T



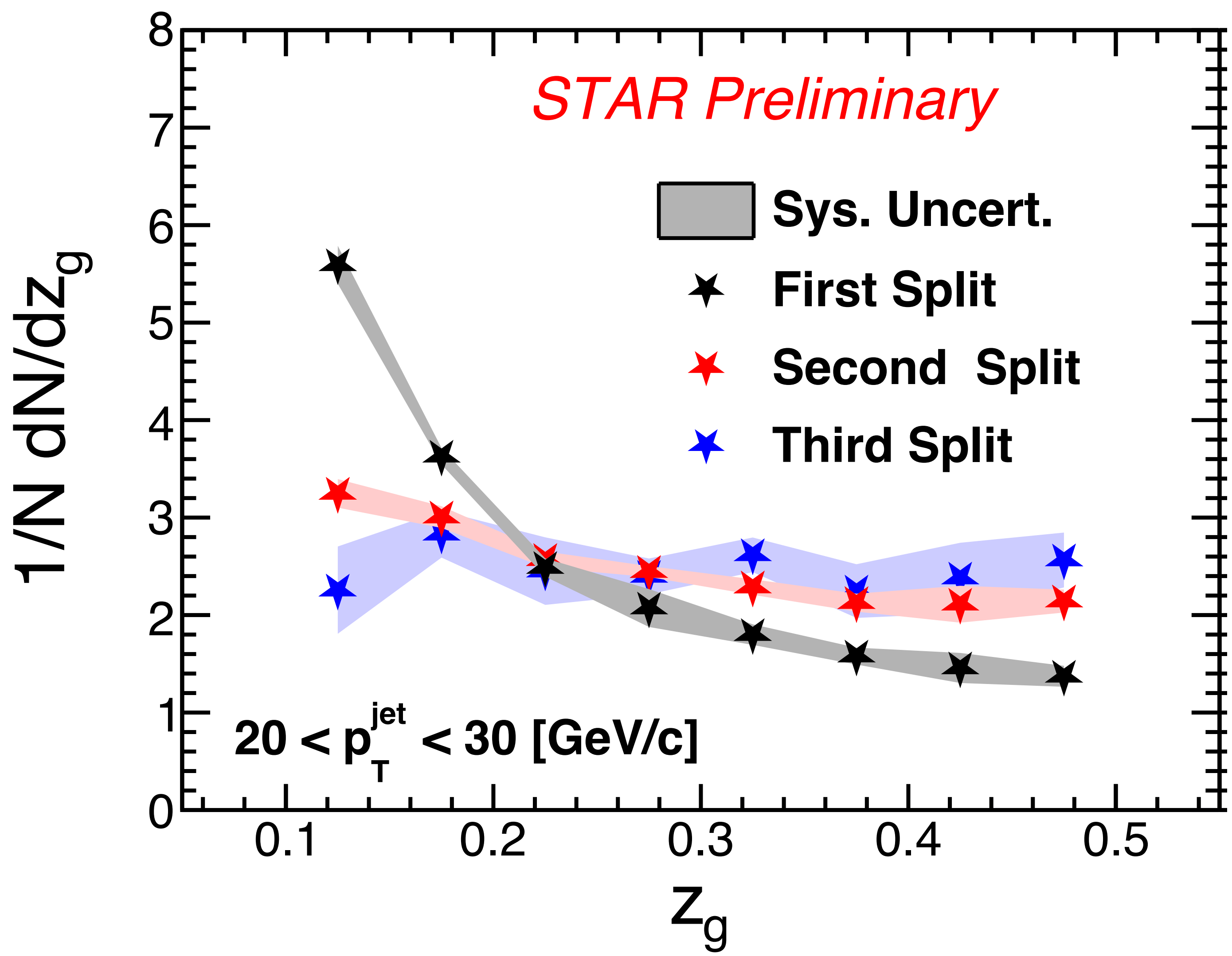
$30 < p_T^{jet} < 40$ GeV/c
$R = 0.6$ anti $-$ k_T





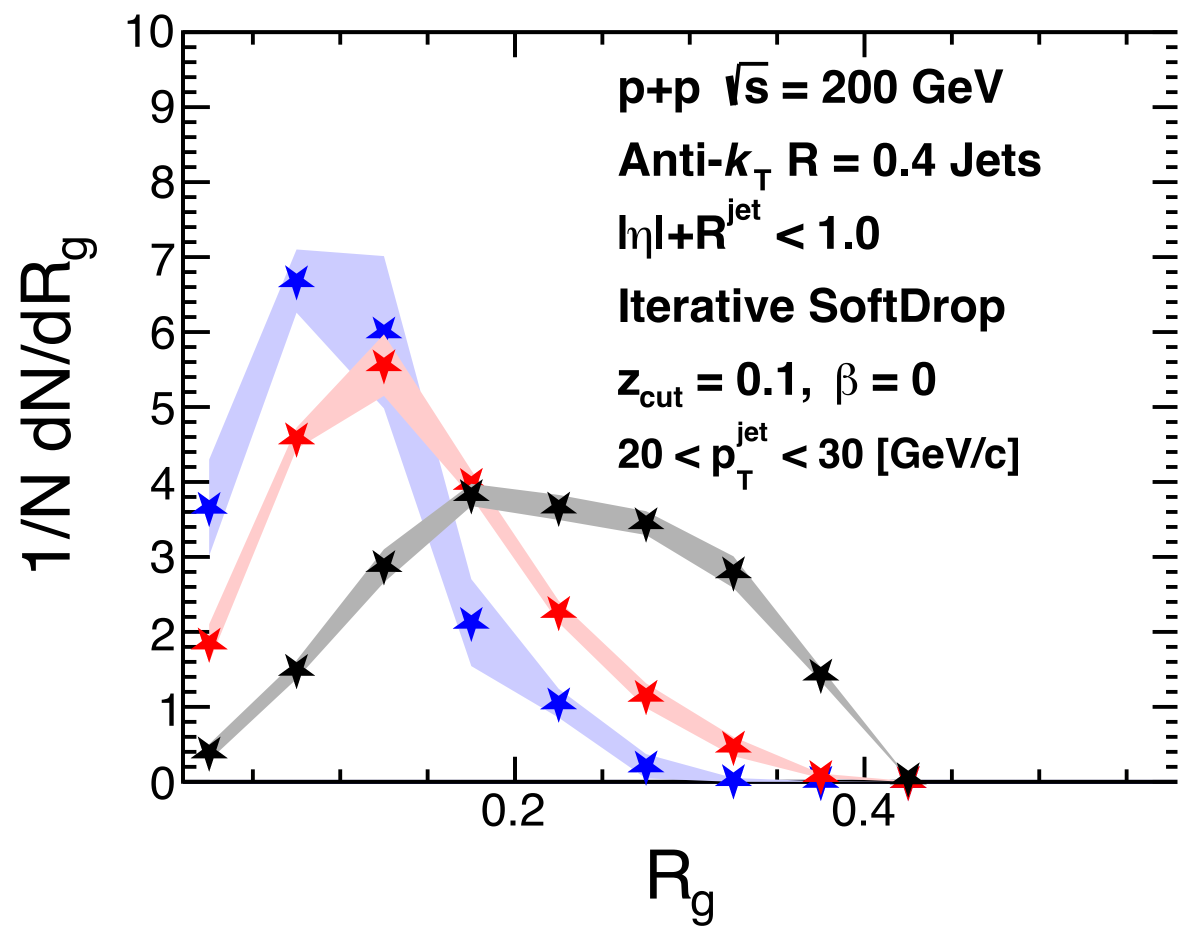
Scale dependence of jet substructure!

Delving further into the jet substructure



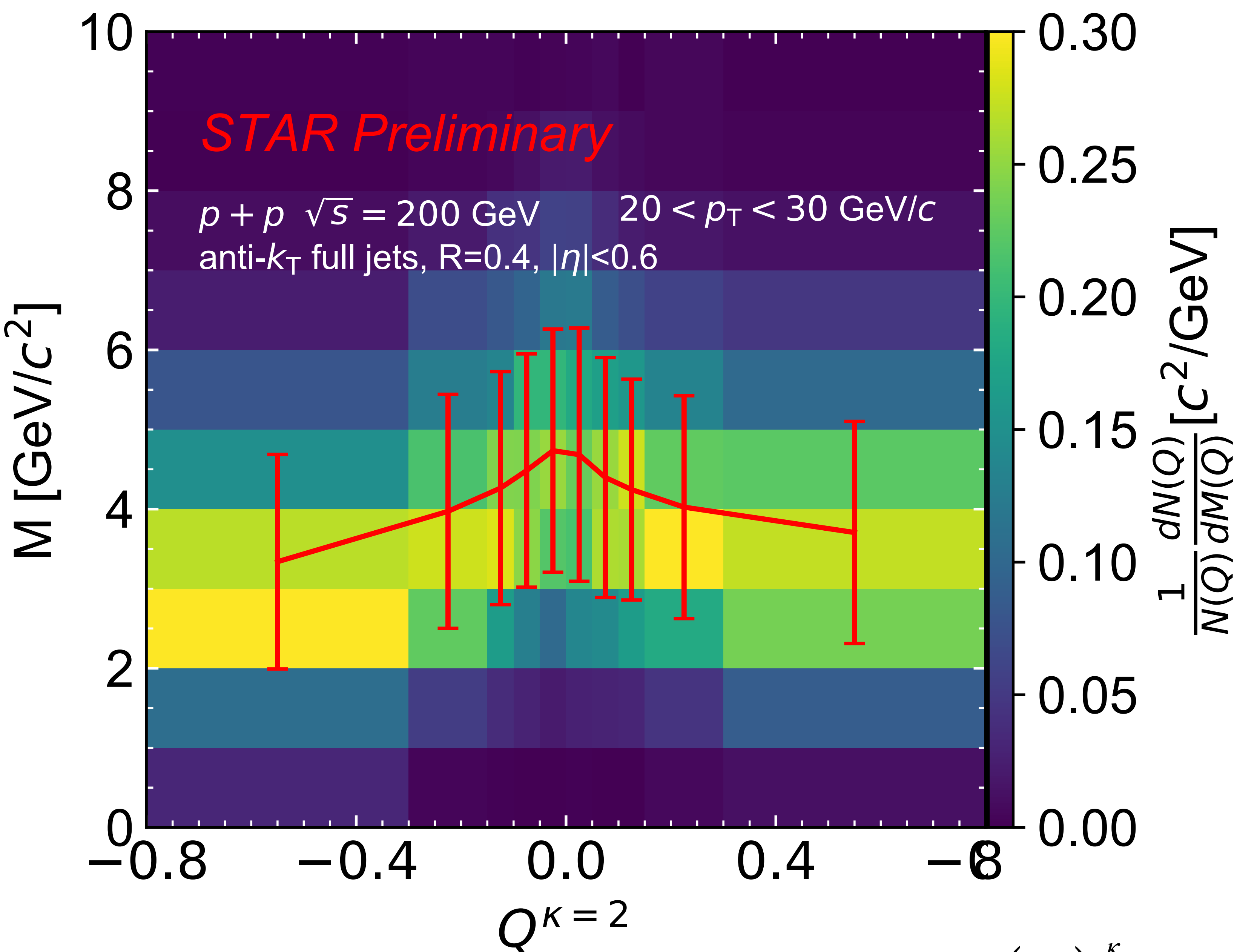
- **Flat z_g distribution and smaller $\langle R_g \rangle$** for the third split, where we observe collinear emissions

- Measured in 3 dimensions - p_T vs $z_g(R_g)$, split #
- Defines a time axis!



Monika Robotkova (NPI) @ QM 2022

Extending the dimensionality



Youqi Song (Yale) @ DNP 2022

$\kappa = 0$ Grant McNamara (Wayne) @ DNP 2022

$$Q = \sum_{i \in J} \left(\frac{p_T^i}{p_T^J} \right)^{\kappa} q_i$$

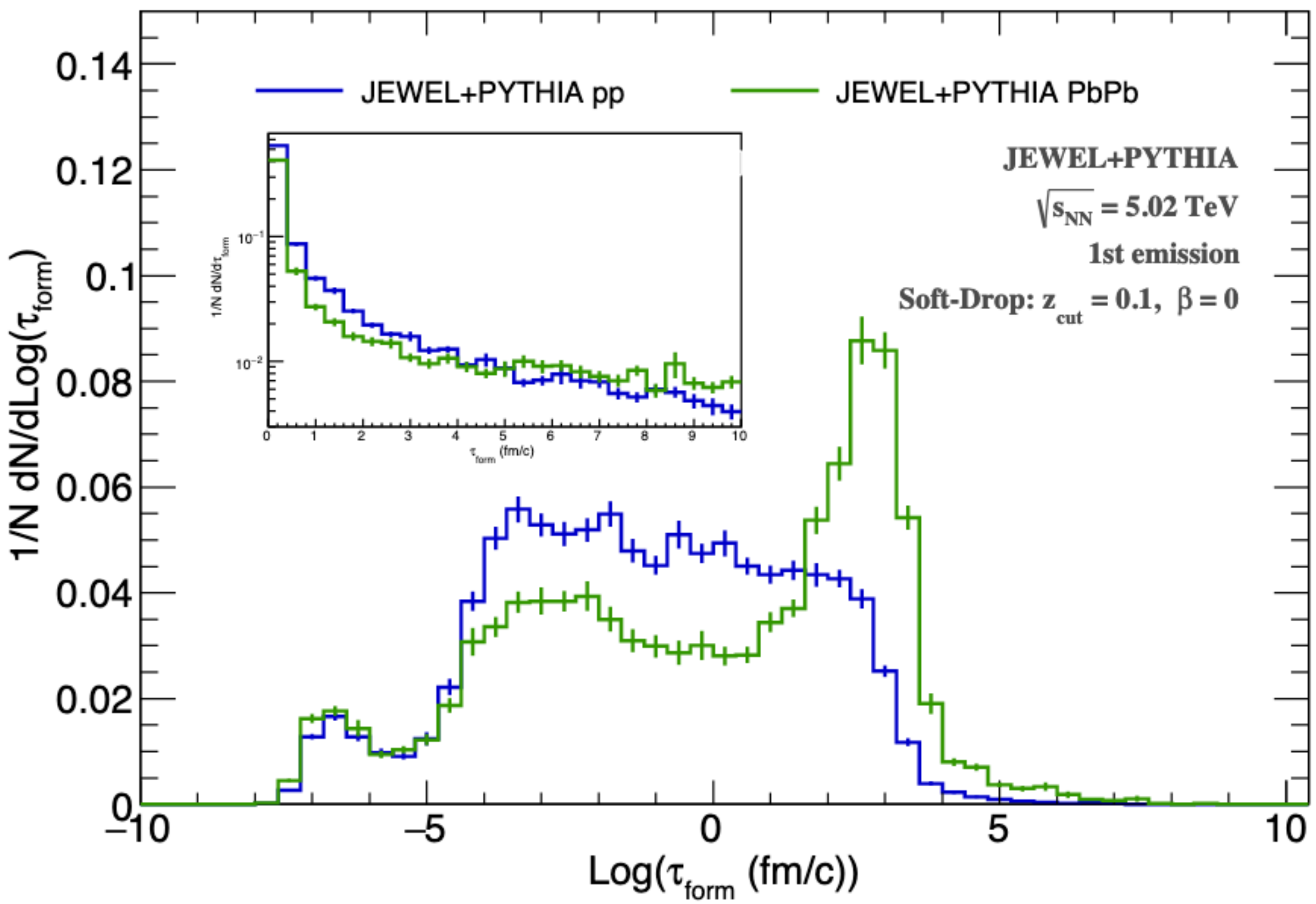
6D unfolded simultaneously via MultiFold machine learning technique

Andreassen et.al Phys. Rev. Lett. 124, 182001 (2020)

p_T vs Q vs M vs z_g vs R_g vs M_g

- Selecting on larger mass jets simultaneously sculpts your jet charge selection
- *Harmartia - different jets are different*

Extracting time dependence of quenching



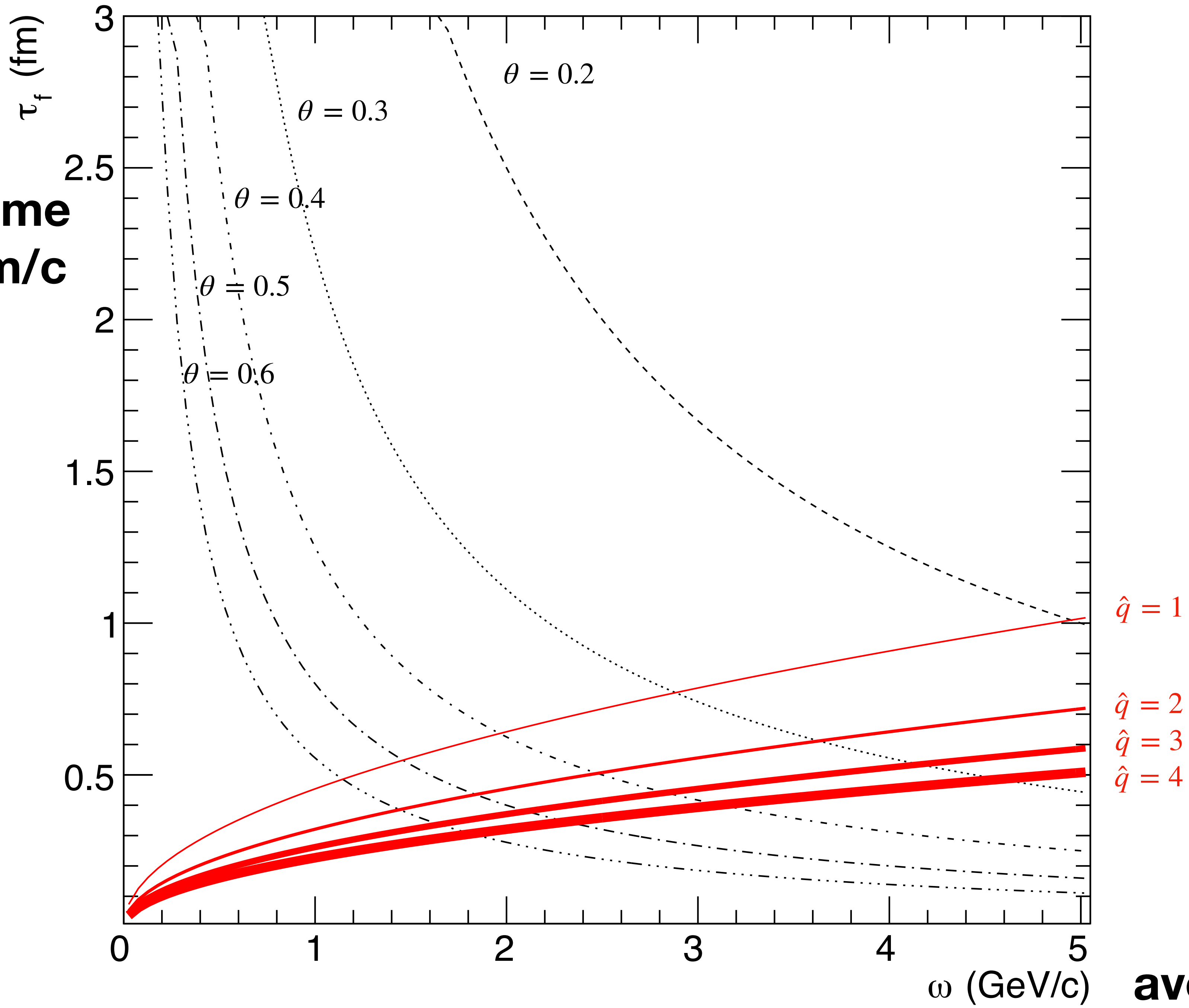
$$\tau_f = \frac{1}{z \cdot (1 - z) \cdot \theta^2 \cdot E} \quad [\text{fm}/c]$$

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

- τ_f is a combination of substructure observables that results in a 'time'
- Ensemble distributions of τ contain information related to the parton shower
- Useful handle in jet quenching studies

First steps in space-time differential energy loss

Time fm/c

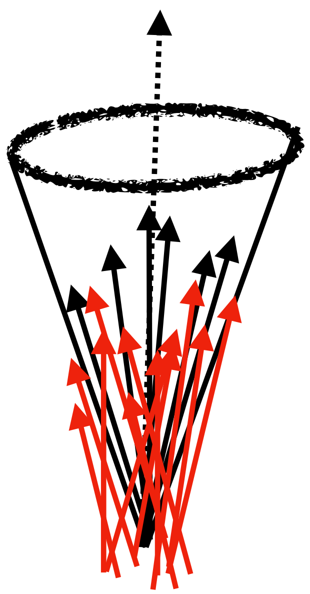


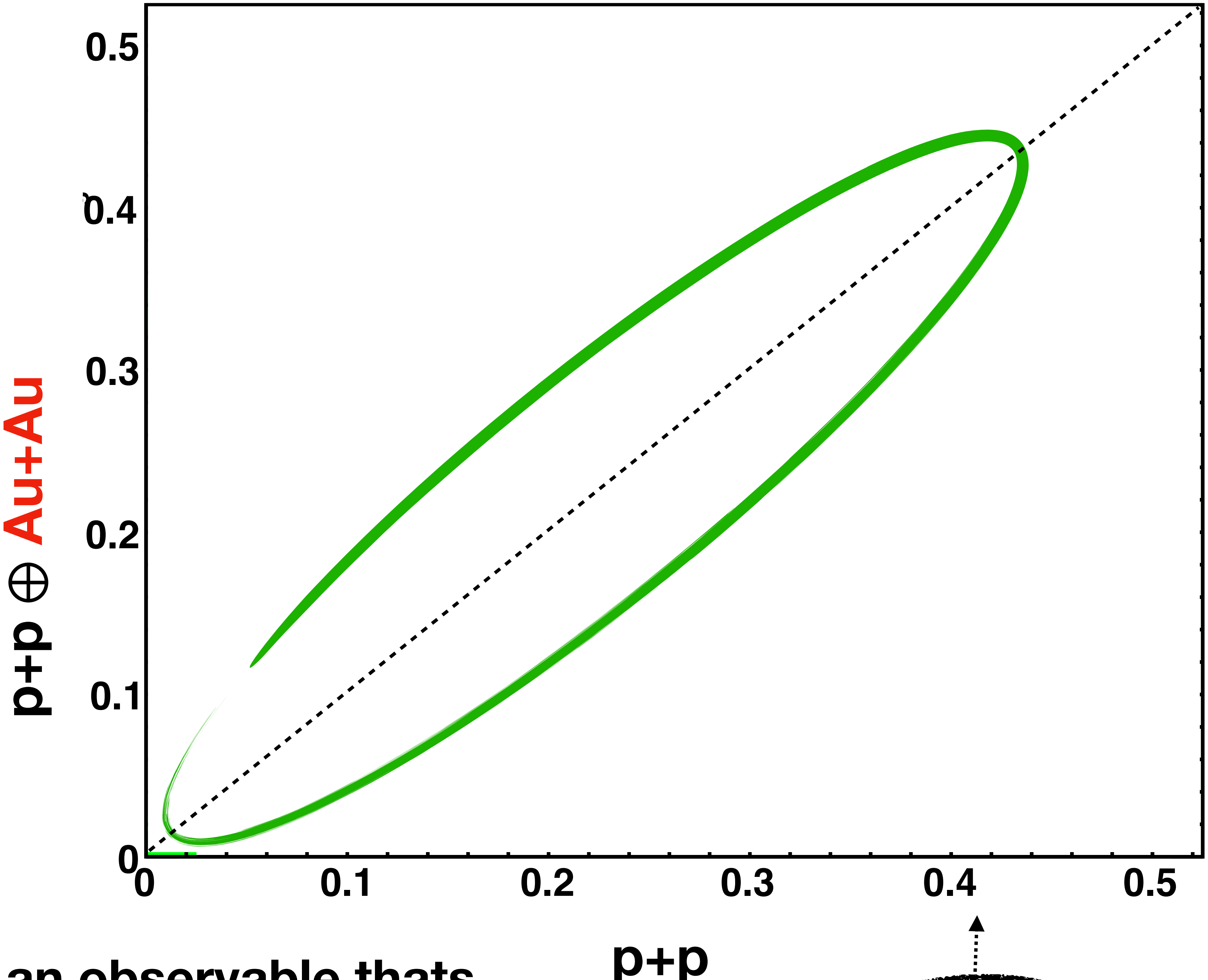
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

$$\hat{q} \equiv \frac{d\langle k_\perp^2 \rangle}{dL}$$

Transport parameter
average energy lost to the medium per distance traversed

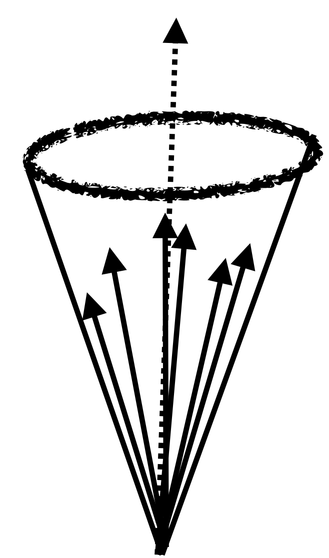


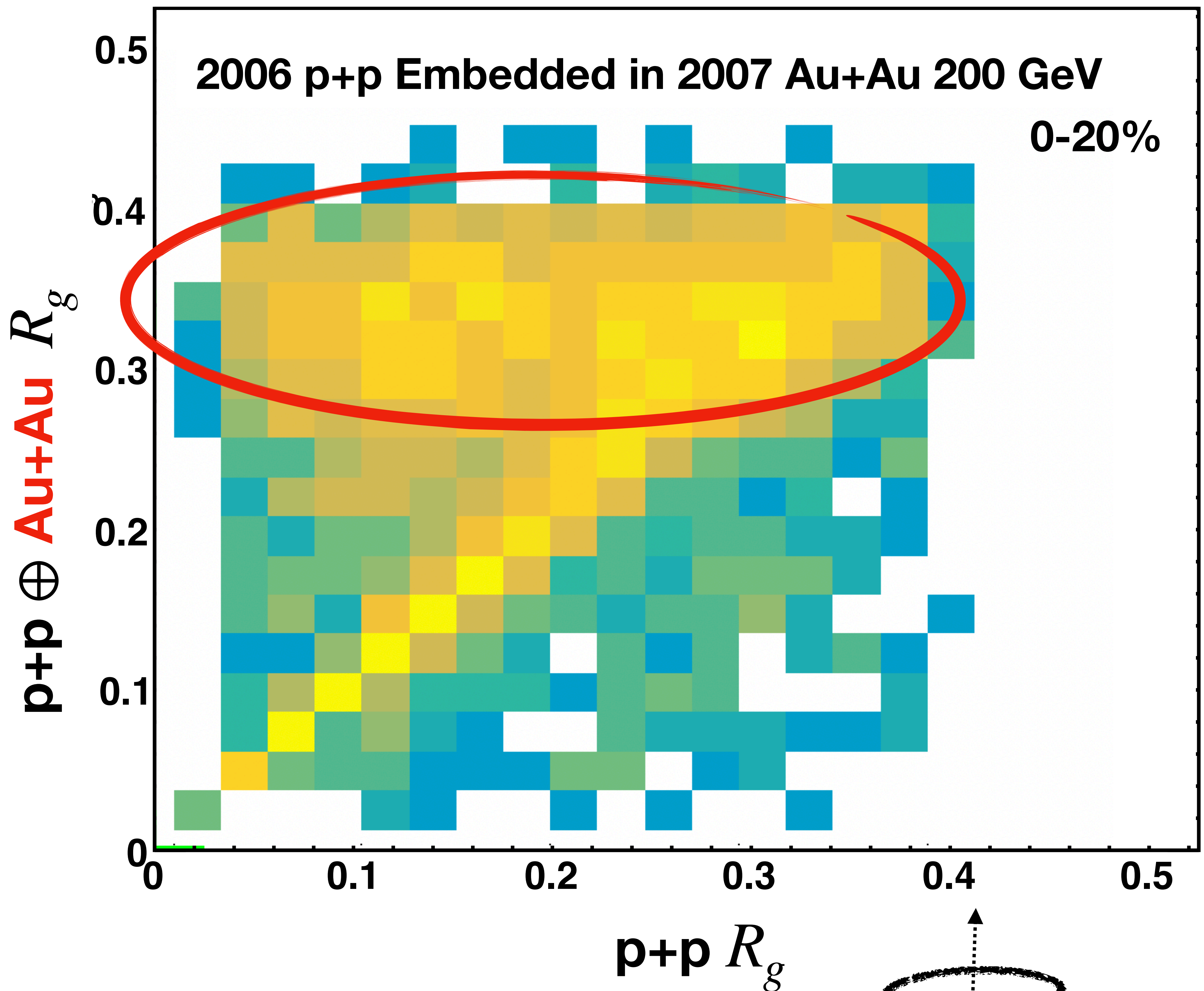


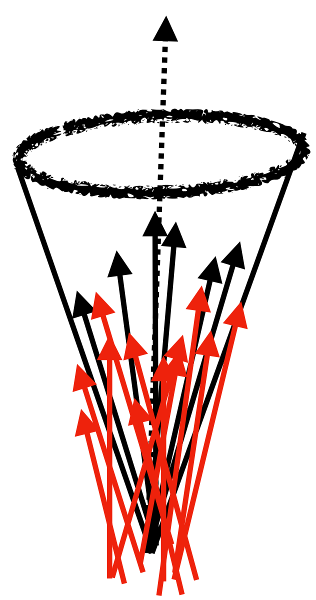
Ideally we want an observable thats

a) sensitive to jet physics

B) insensitive to UE



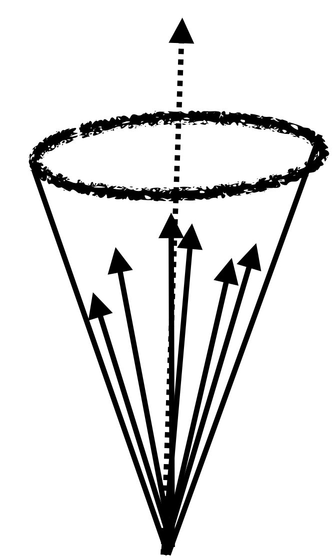




$\beta = 0$

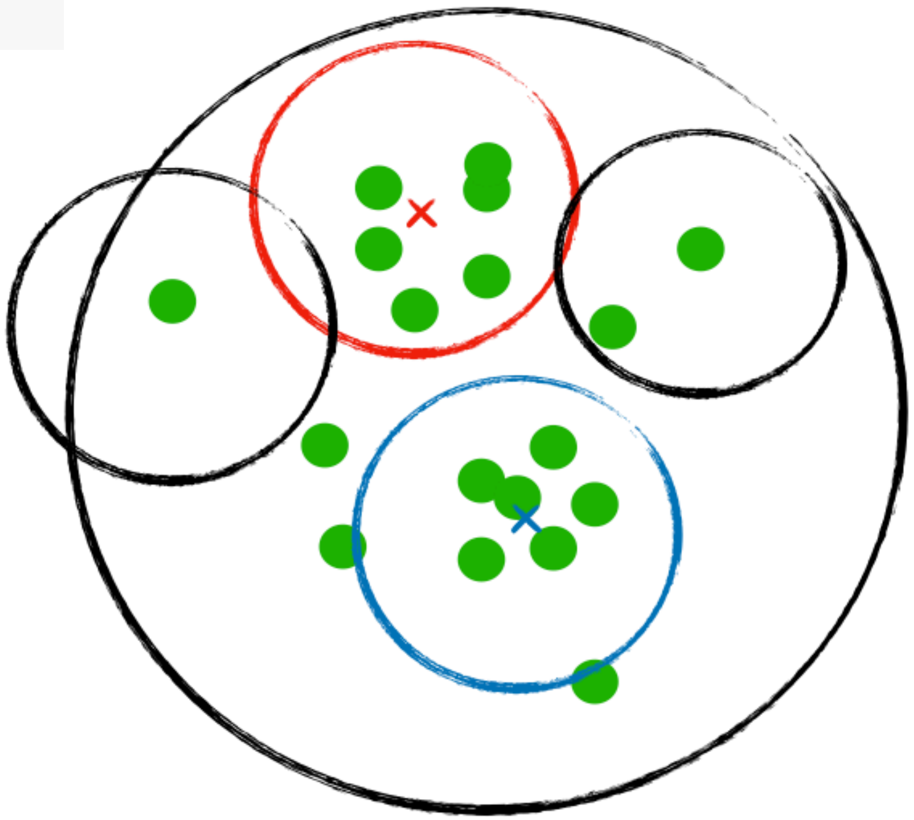
$z_{\text{cut}} = 0.1$

SoftDrop R_g sensitive to background fluctuations

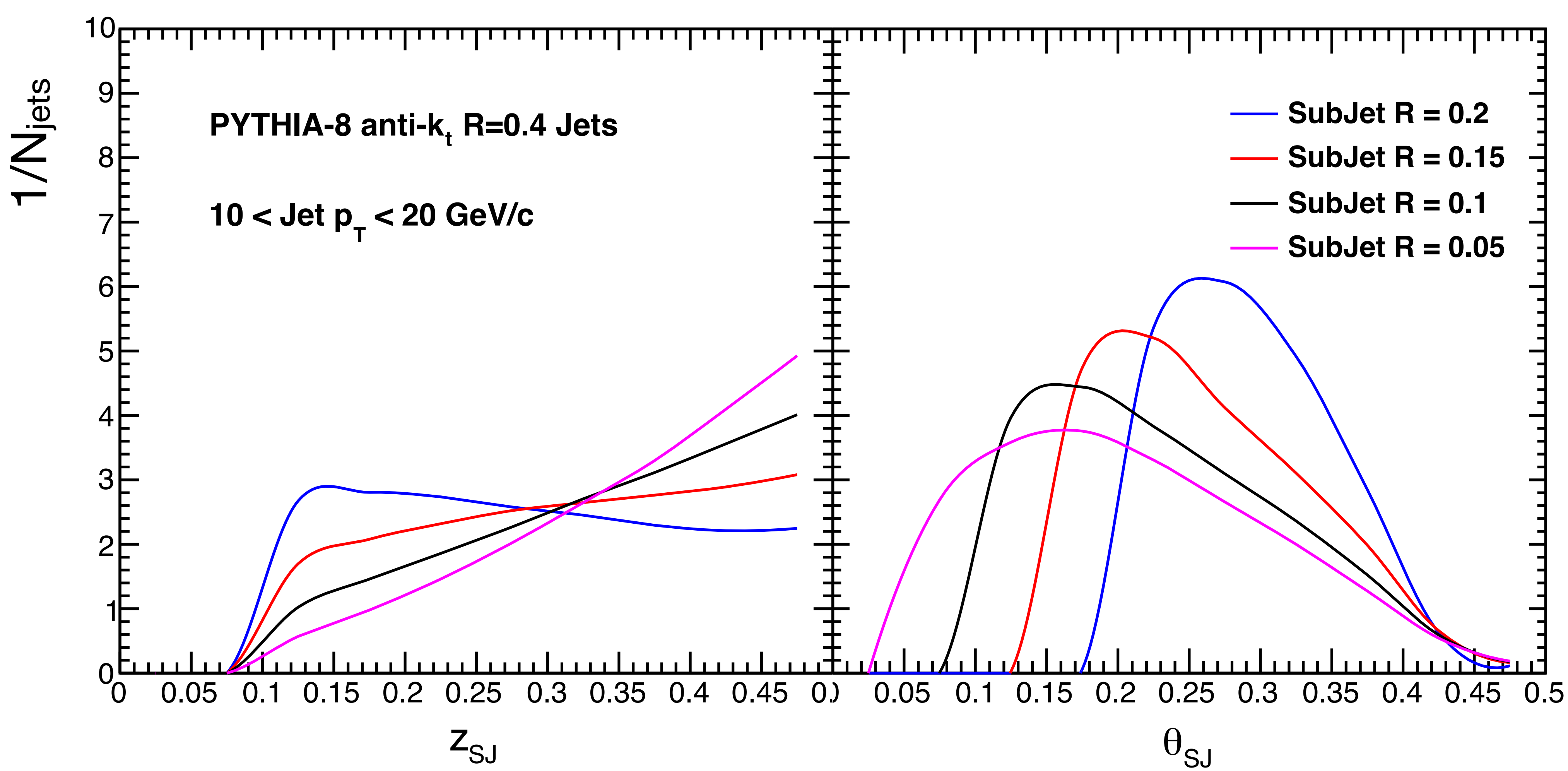


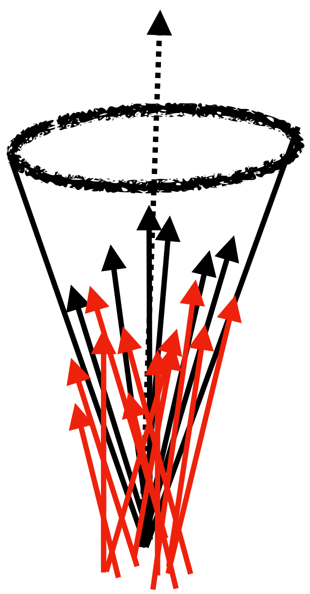
Apolinario et al. 1710.07607

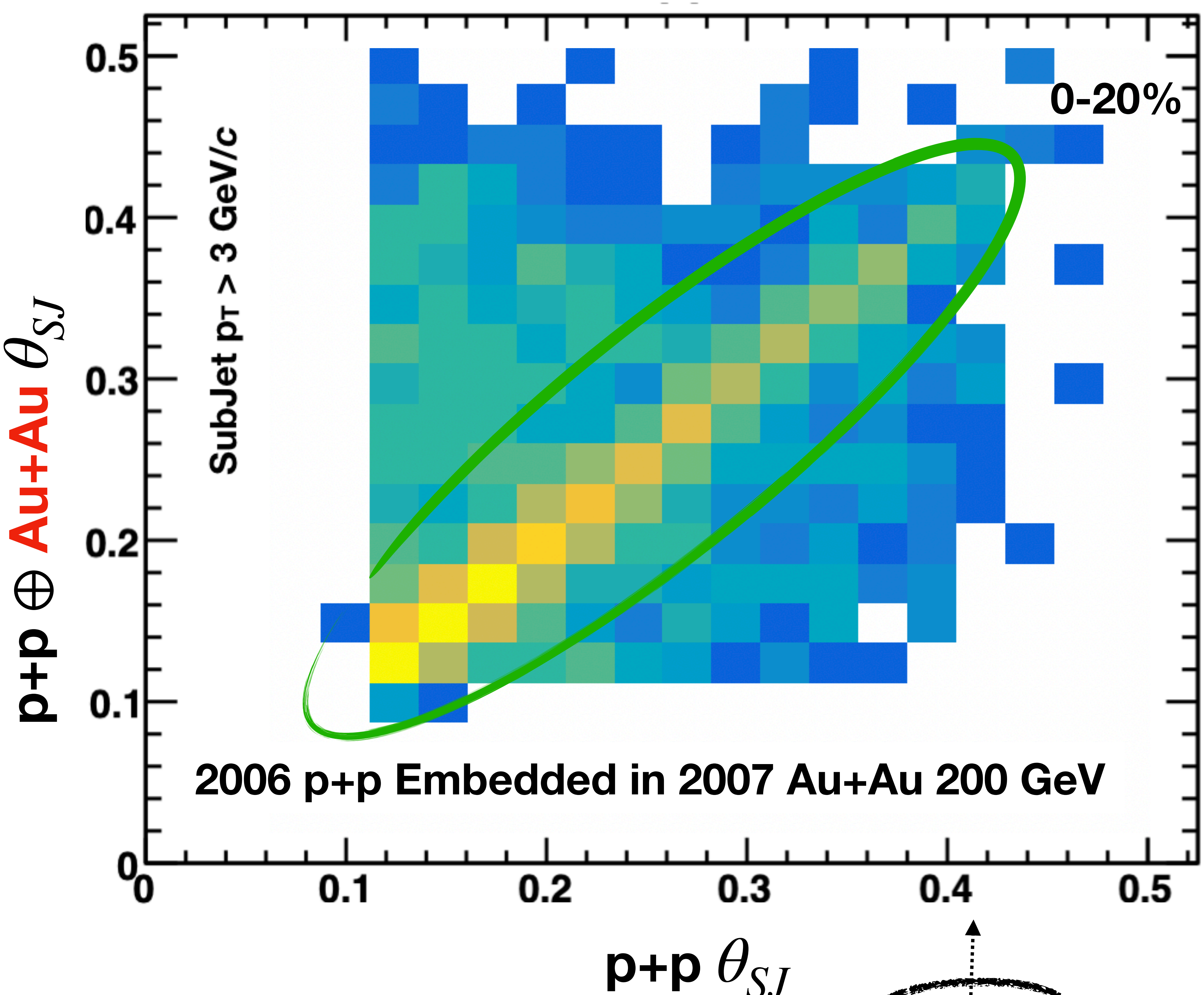
Sub-Jets to the rescue

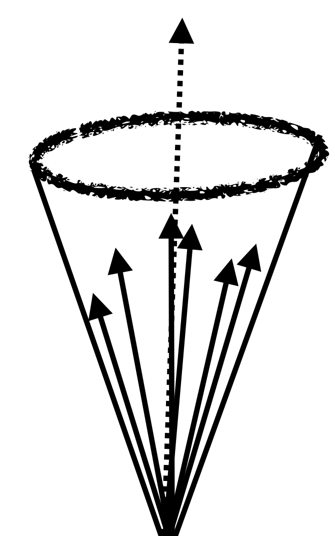


- Re-cluster jet constituents with a smaller radius - identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** SubJets
- z_{SJ} = **Blue p_T** / (**Blue p_T** + **Red p_T**)
- θ_{SJ} = **Δ R (Blue Axis, Red Axis)**







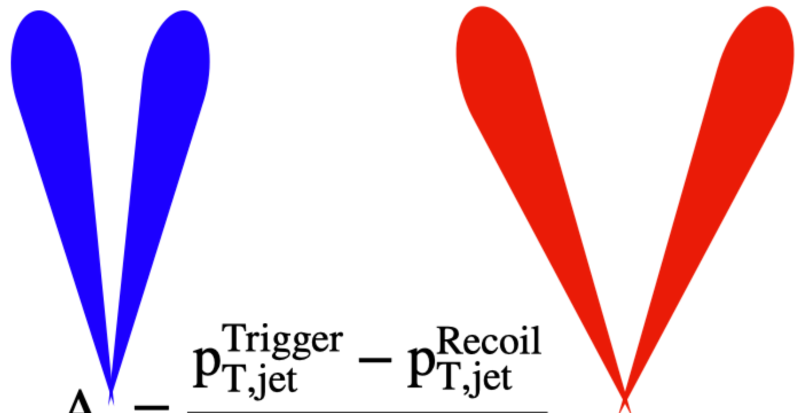


Two-SubJet observables robust to AuAu UE!

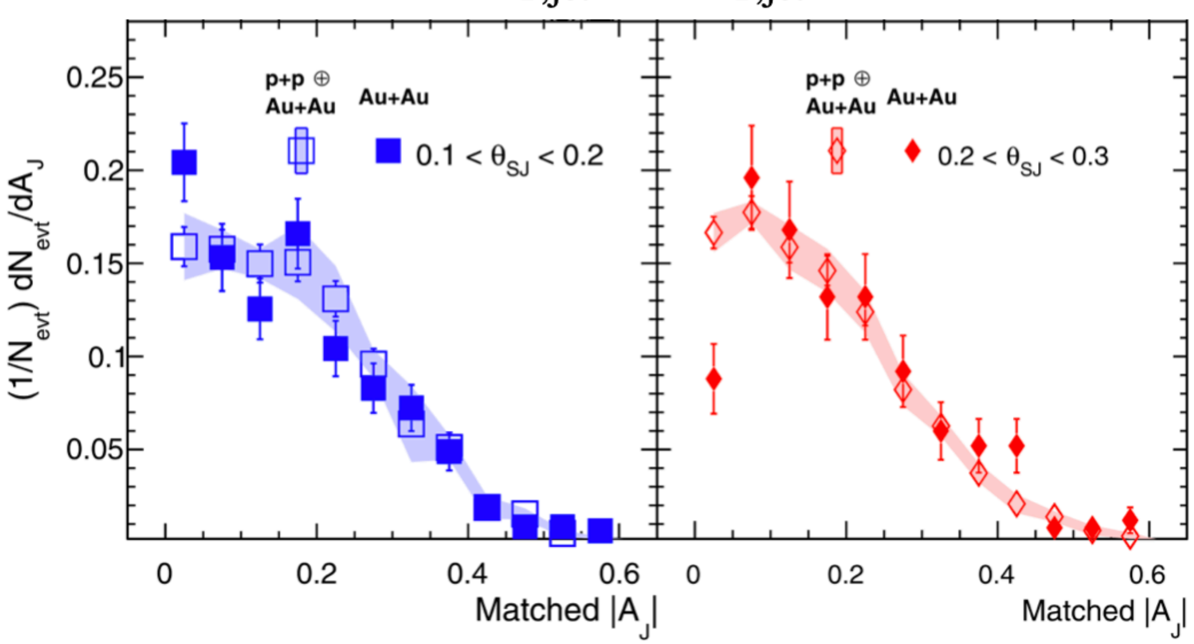
Subjet p_T selection based on medium scale!

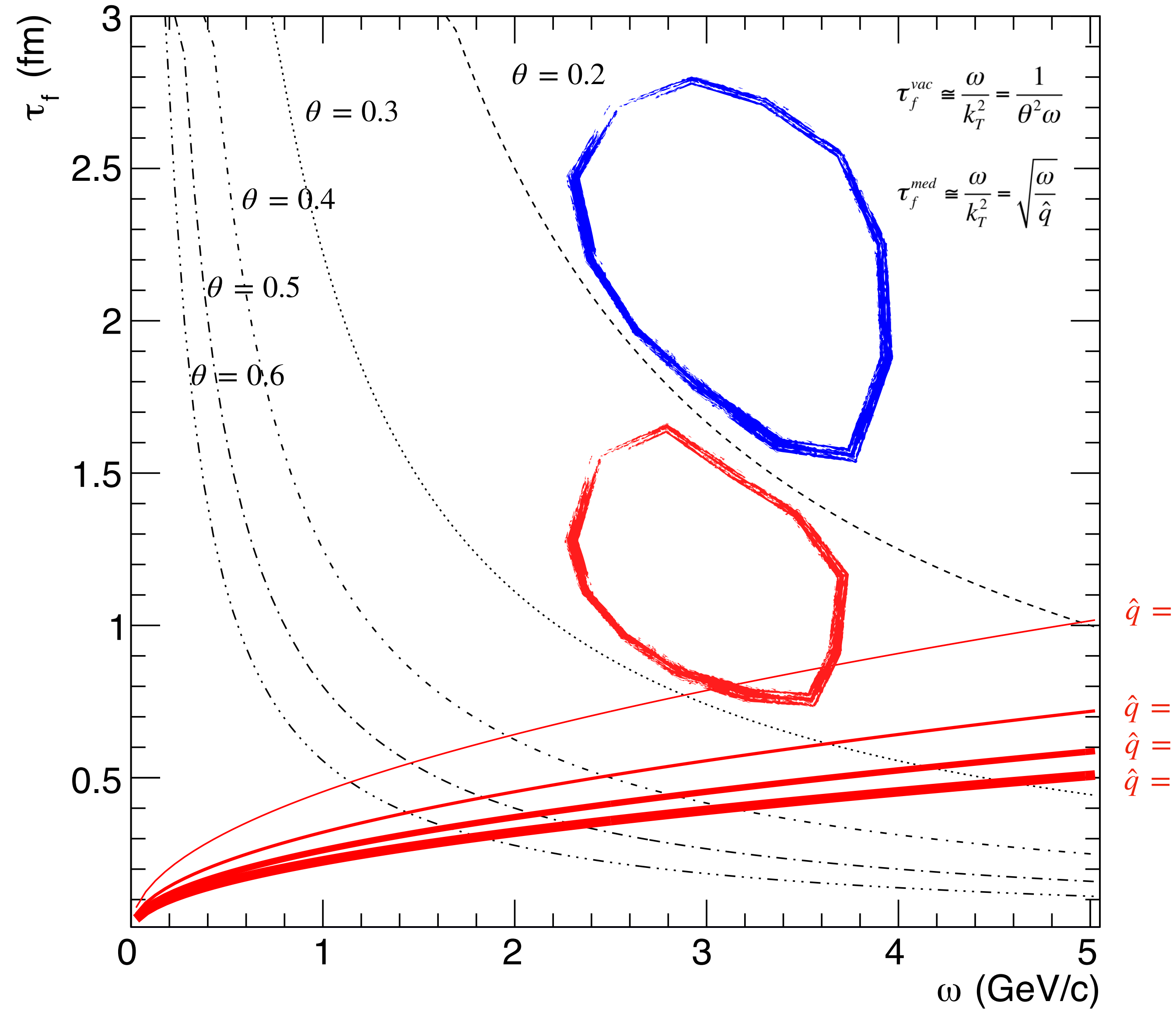
STAR Phys. Rev. C 105, 044906 (2022)

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



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





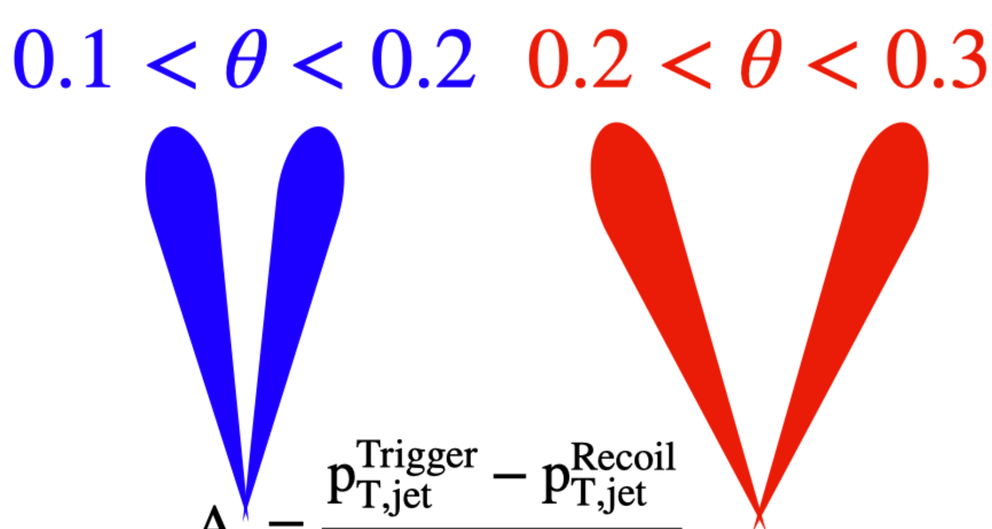
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

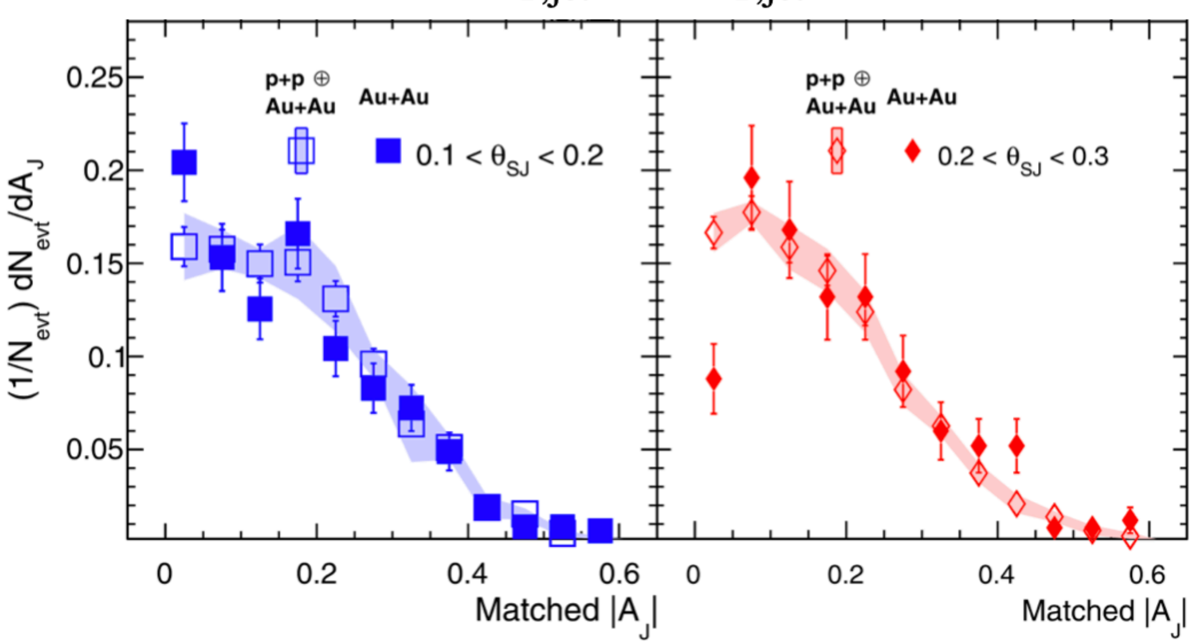
- No significant difference in energy loss signature between the two sets of biased jet populations at RHIC energies - $\theta_{SJ} > 0.1$

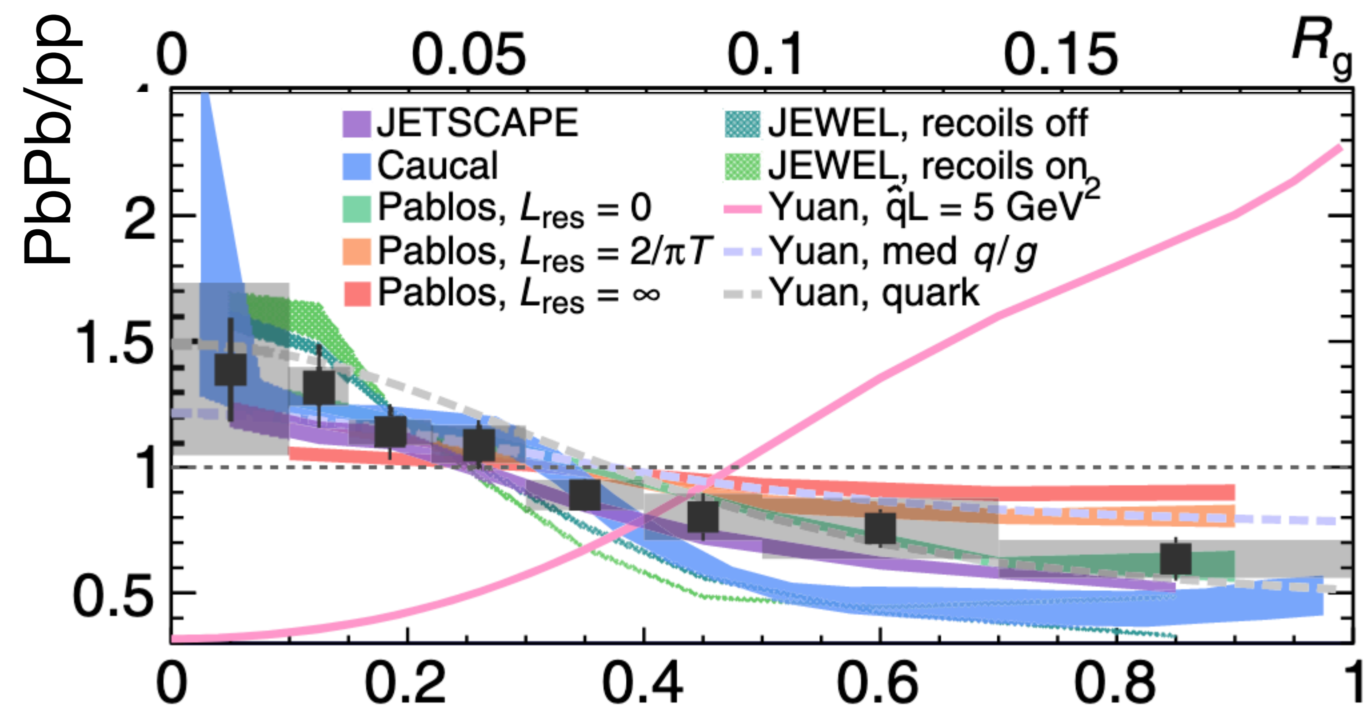
STAR Phys. Rev. C 105, 044906 (2022)

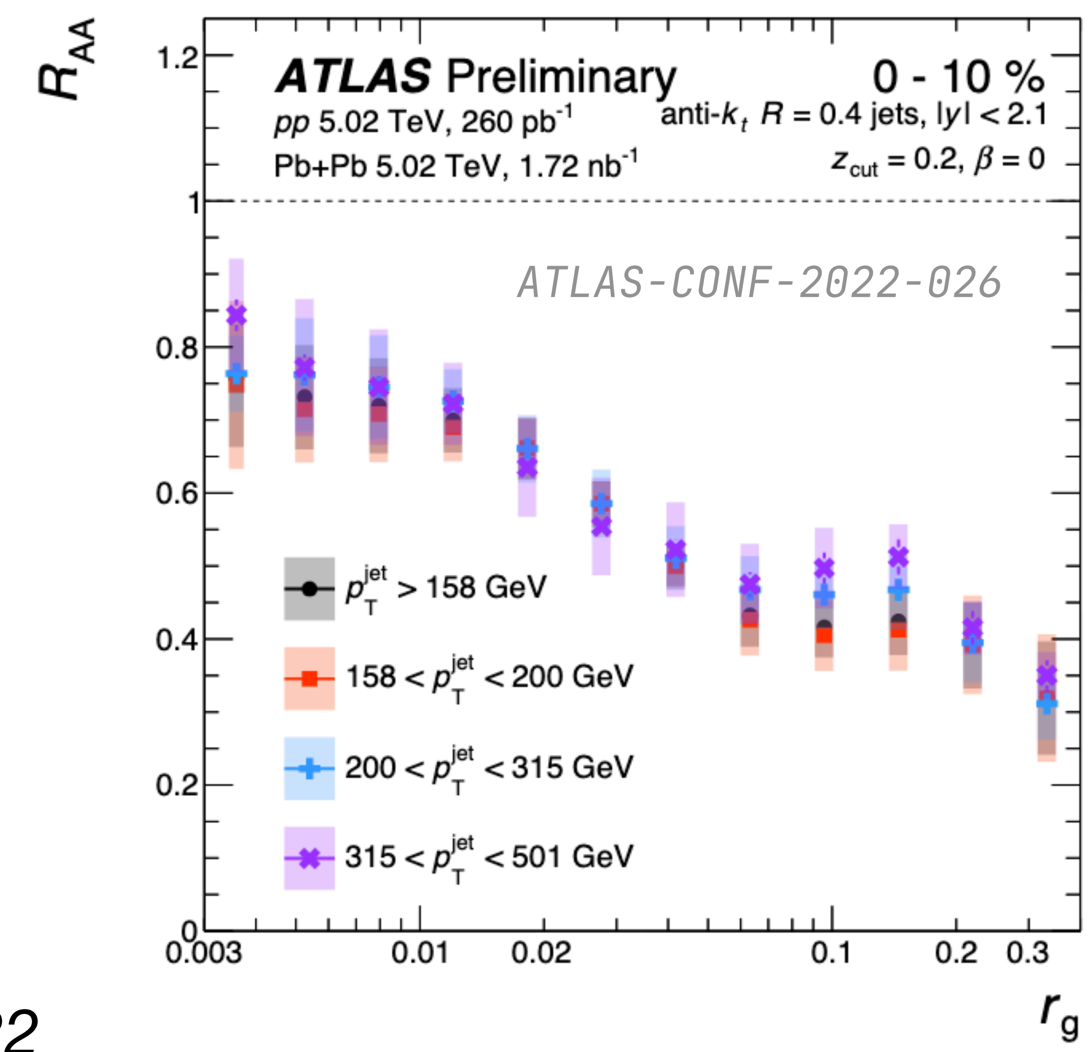
ALICE Phys. Rev. Lett. 128, 102001



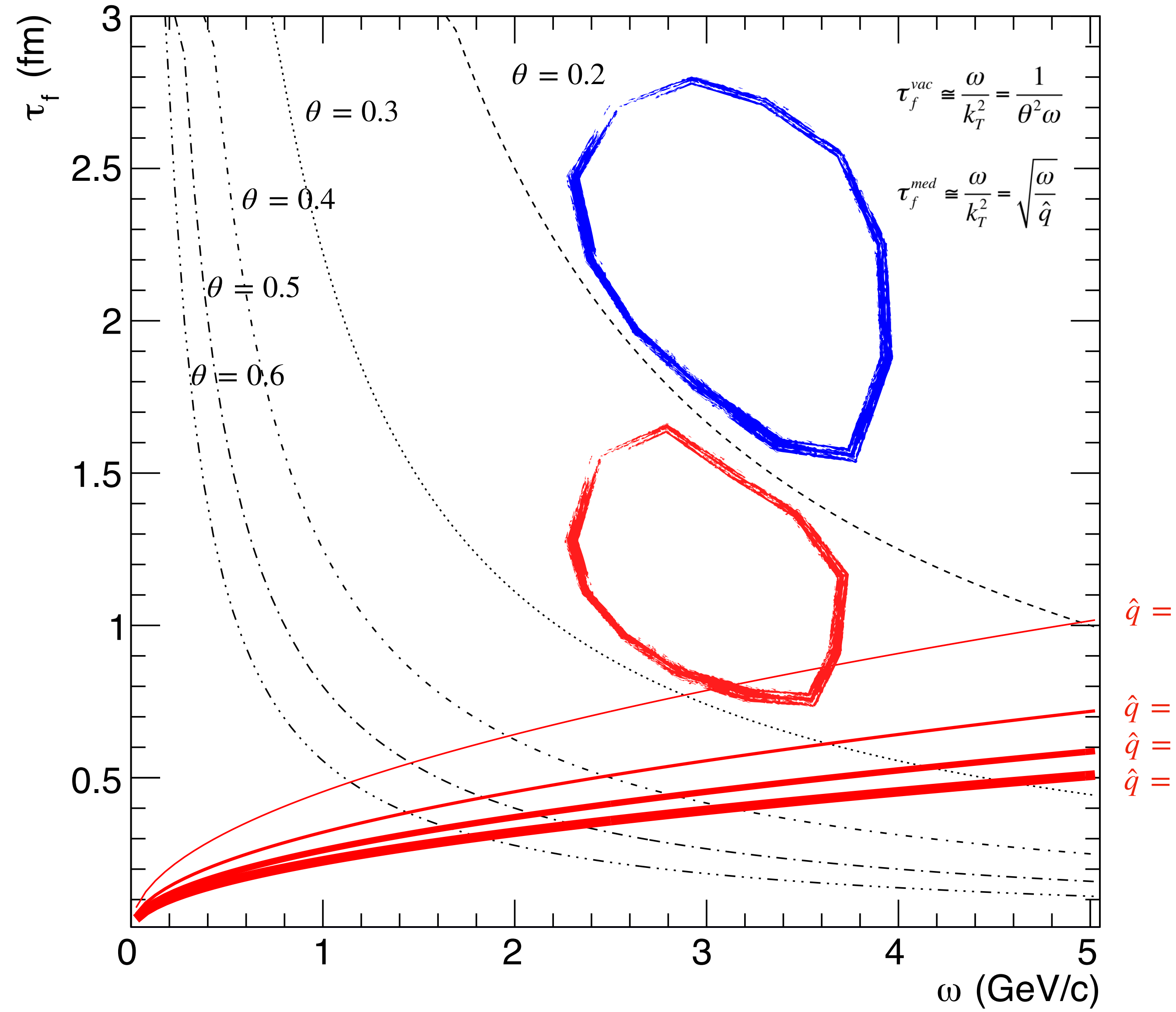
$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$







- Different methods of estimating angular dependence of quenching - subjets vs harder prongs!



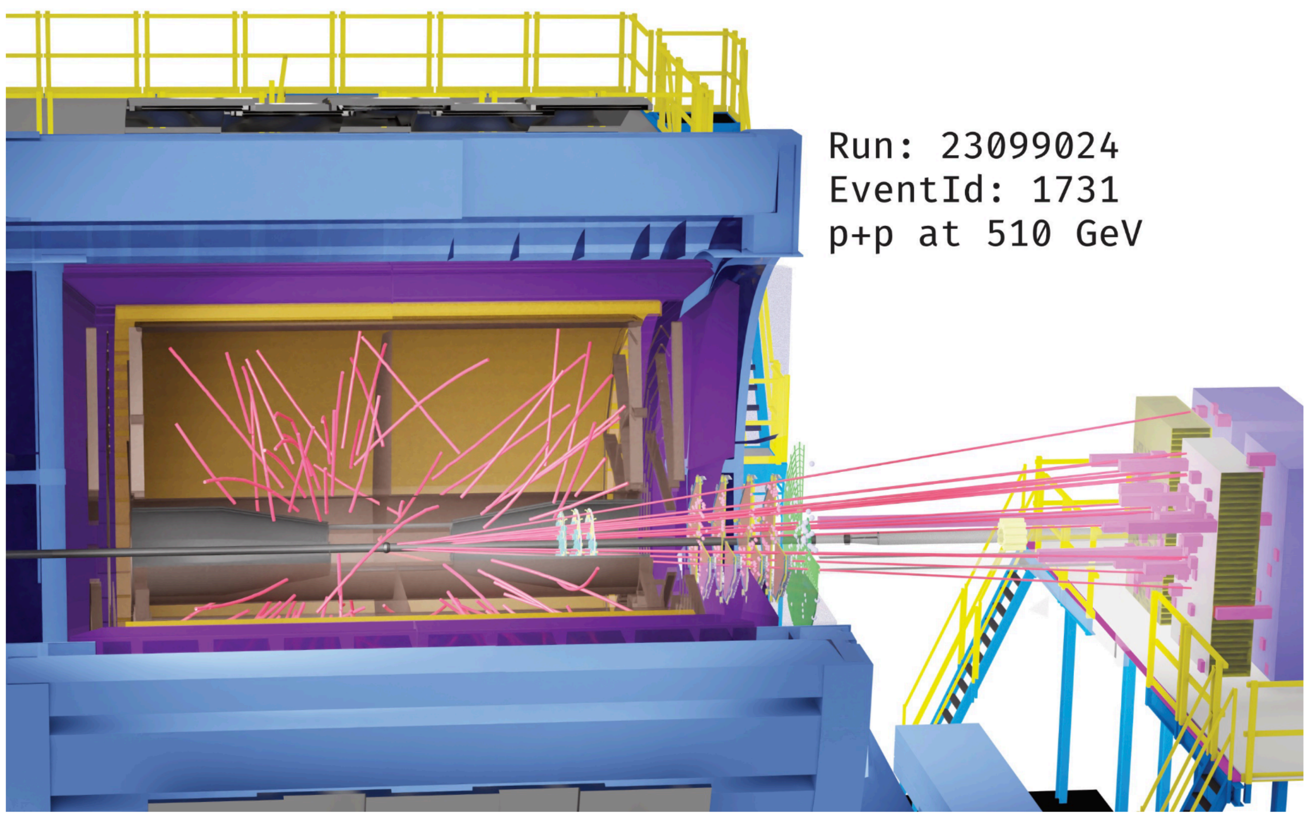
- Energy loss for these dijets is an experimental observation of soft radiation from a single color charge!
- Potential upper limit on the coherence length $\lambda_\perp \sim \frac{1}{\hat{q}t_f} \leq 0.1$

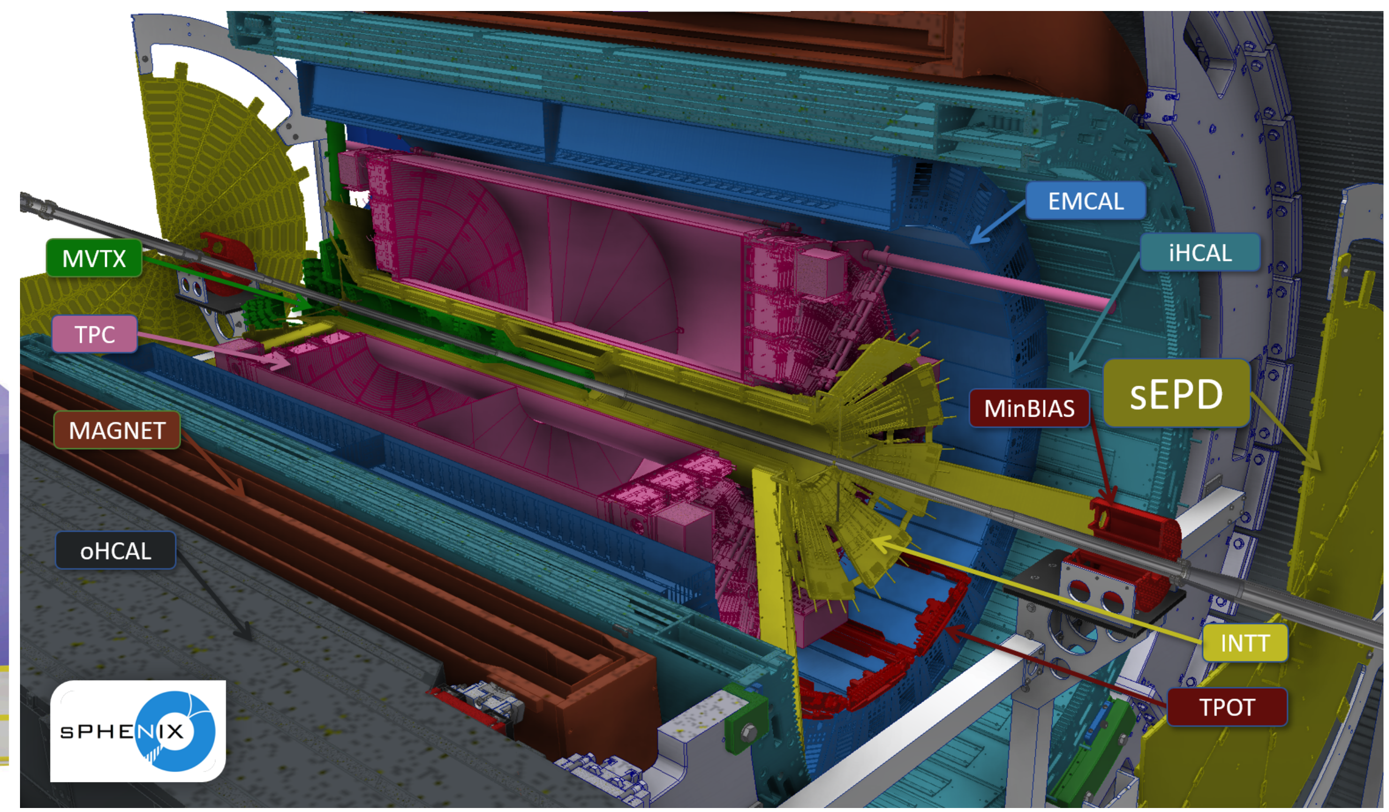
Completing the RHIC mission

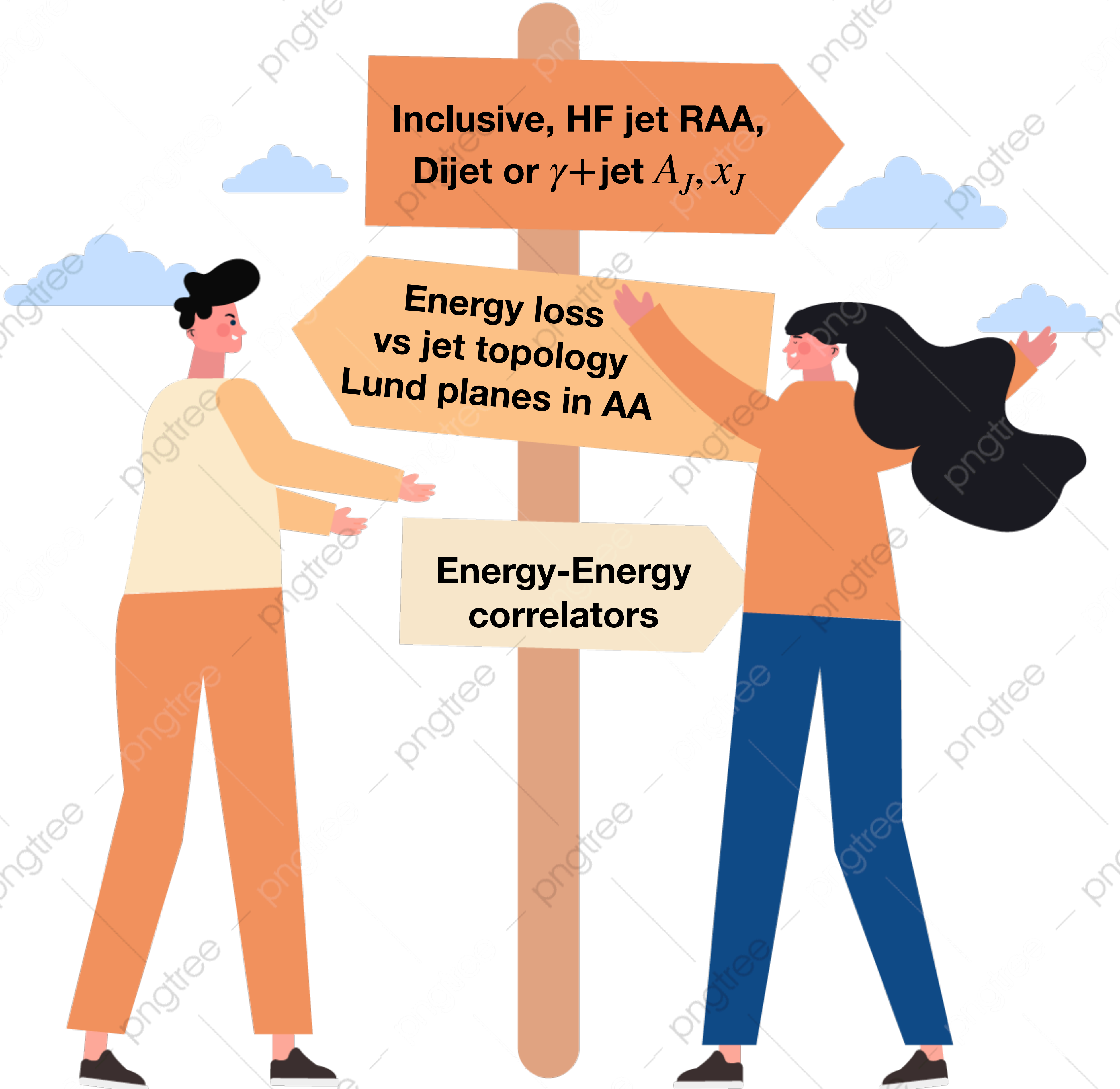
Introduction, motivation and current status

RHIC 2023-

STAR w/ iTPC and forward upgrade

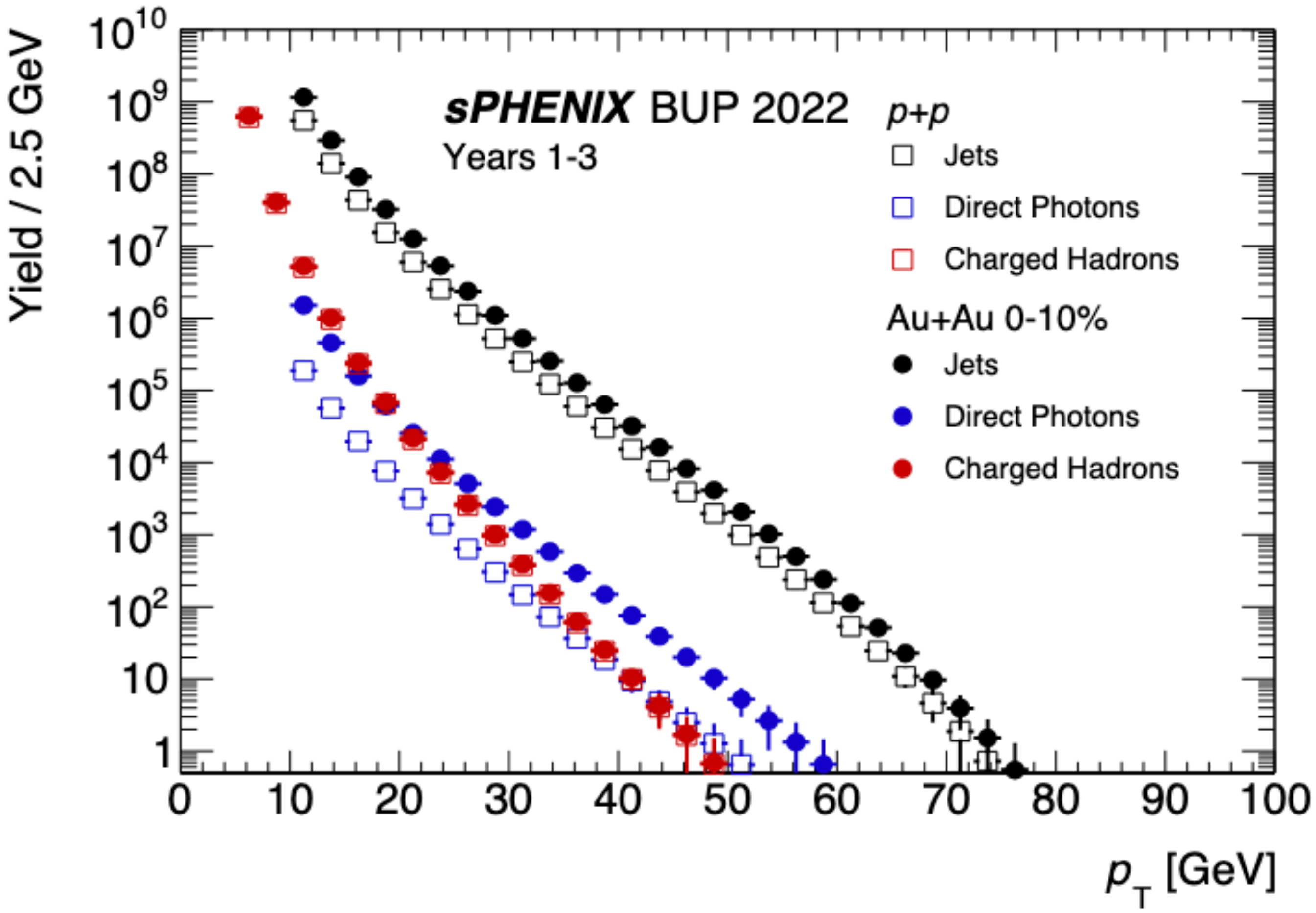




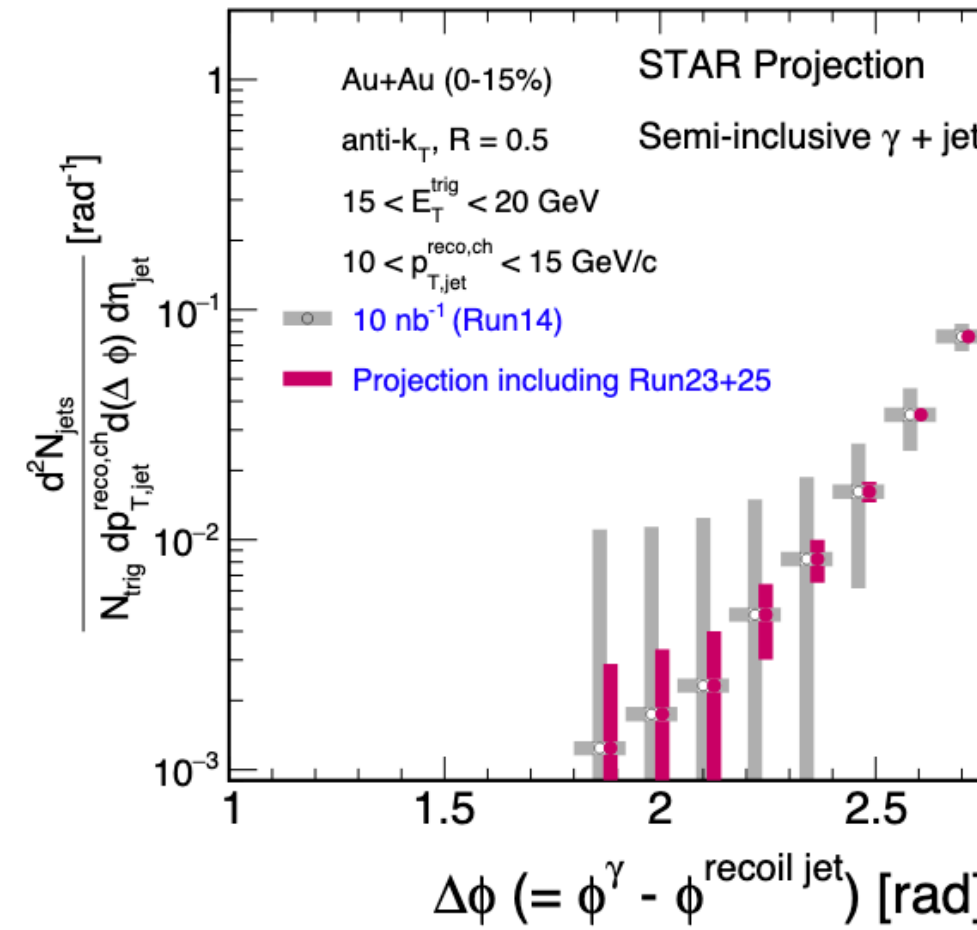

Inclusive, HF jet RAA,
Dijet or γ+jet A_J, x_J
Energy loss
vs jet topology
Lund planes in AA
Energy-Energy
correlators

Access to rare processes!

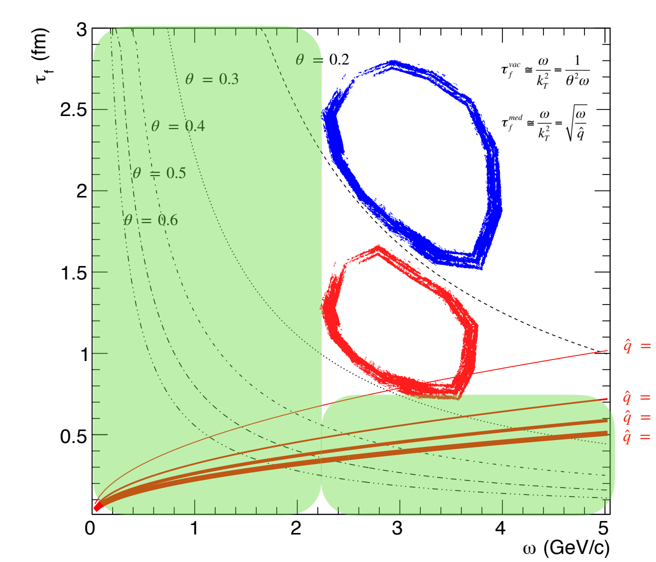
sPHENIX Beam Use Request Document 2022



STAR Beam Use Request Document 2022

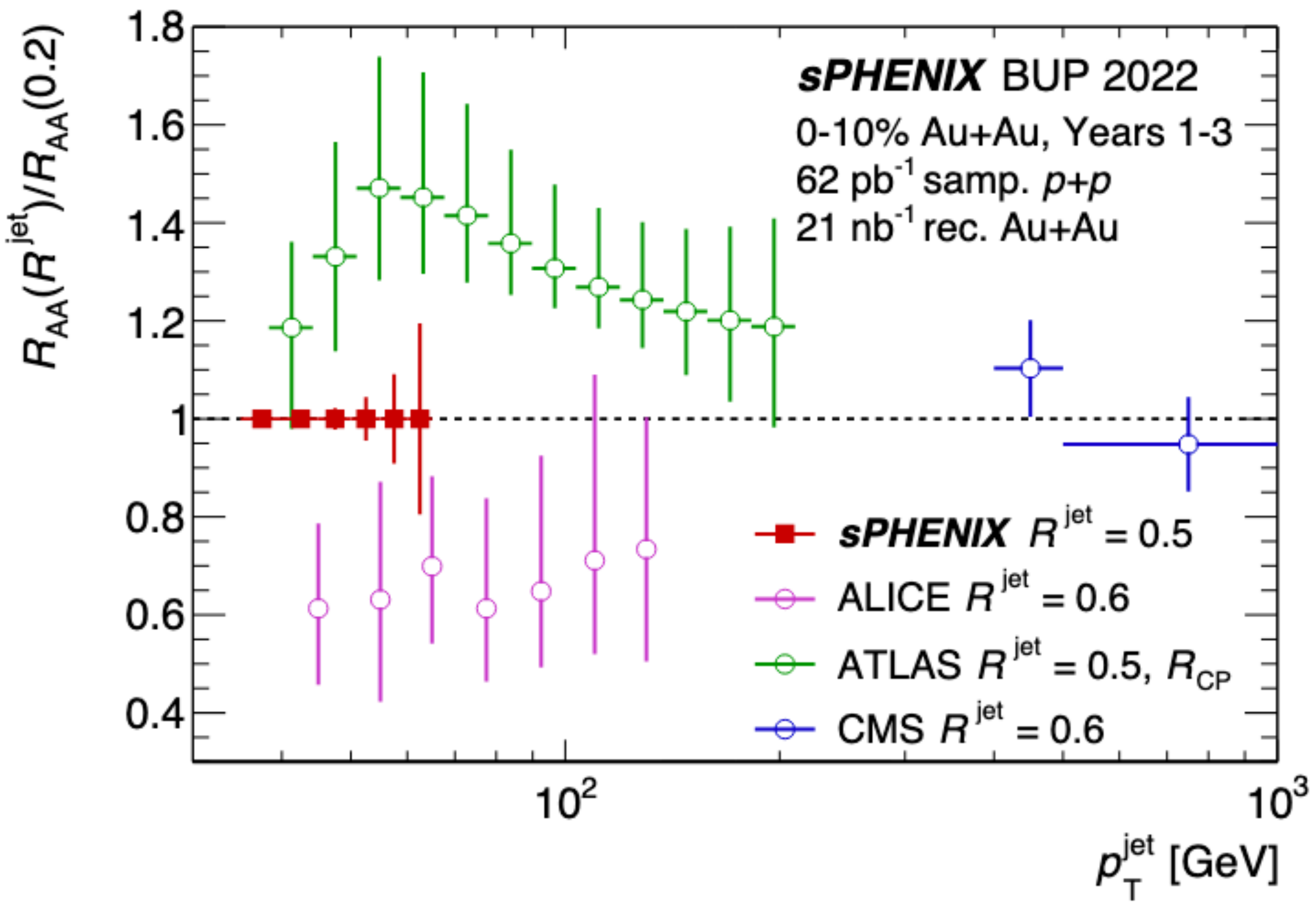


- Scan across emission phase-space with the large statistics dataset
- Differential Space-time tomography of the QGP

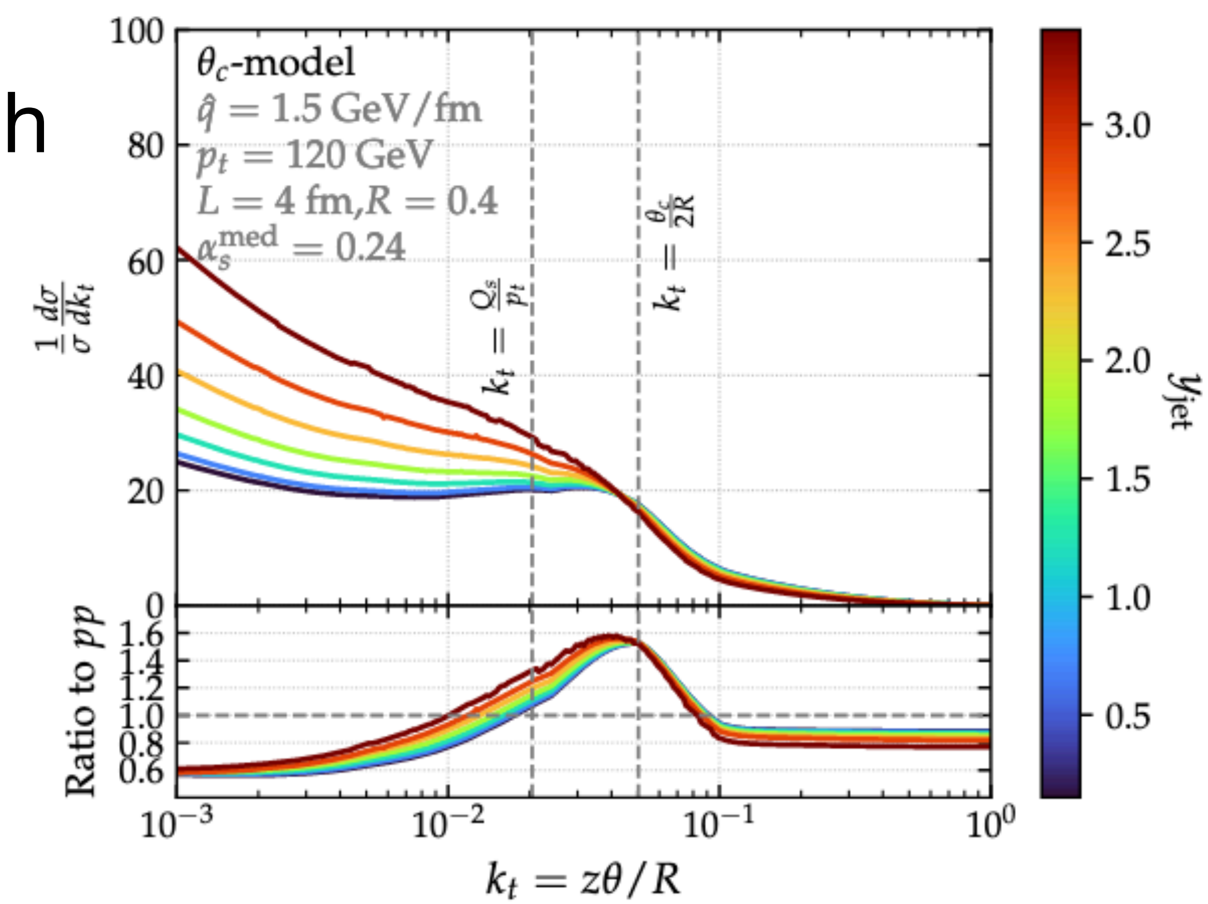


Extending the kinematic range of measurements

- Tagging events with forward jets or di-jets can offer clues into longitudinal transport properties with varying quark vs gluon fractions!



Dani Pablos and Alba Soto-Ontoso, 2210.07901

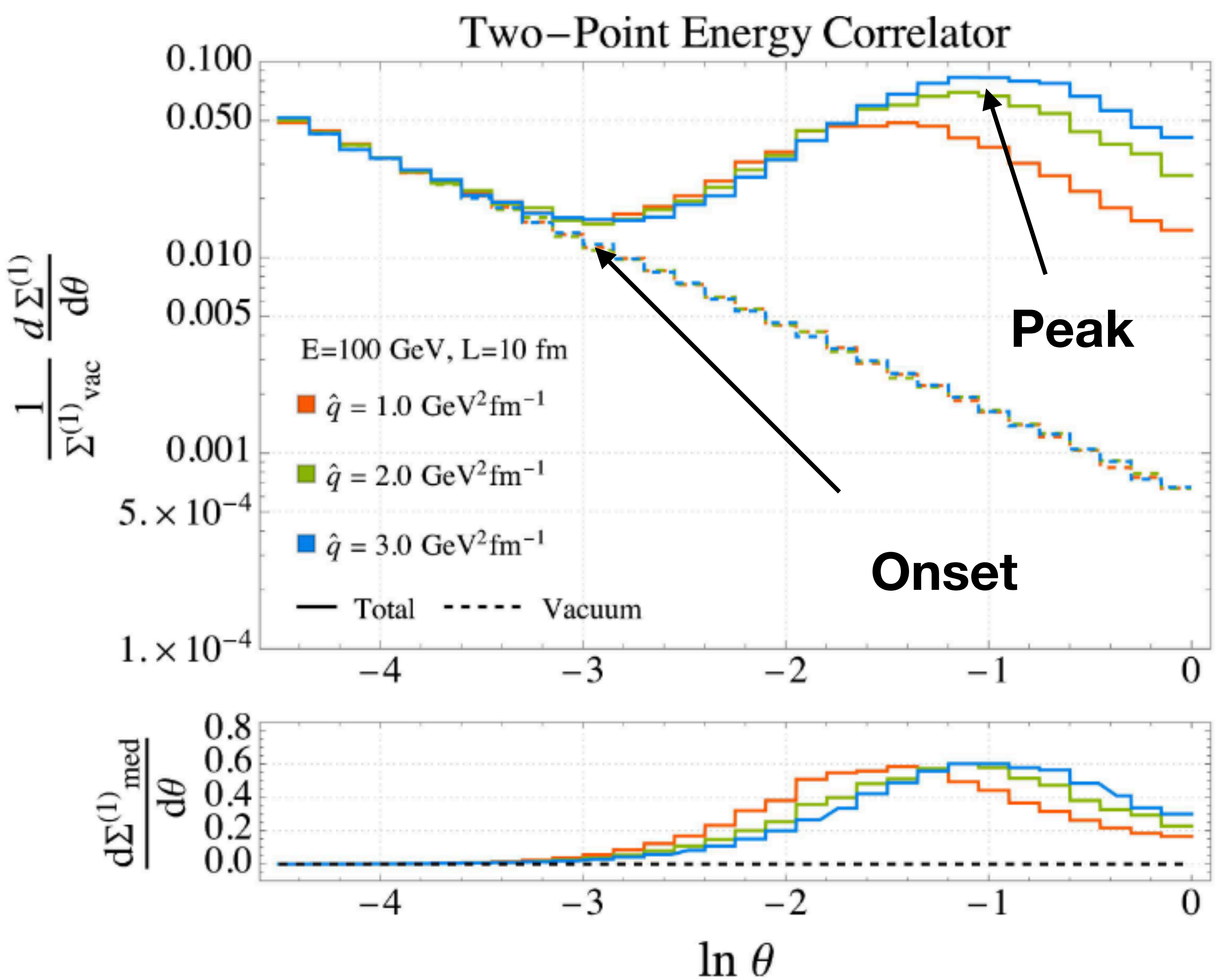


- Connect jets at RHIC to the LHC

Energy-Energy Correlators to resolve the scales

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \int \mathrm{d}\vec{n}_{1,2} \frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} \delta(\vec{n}_2 \cdot \vec{n}_1 - \cos\theta) \,.$$

Moult, et.al 2201.07800
Andres, RKE, et.al 2209.11236



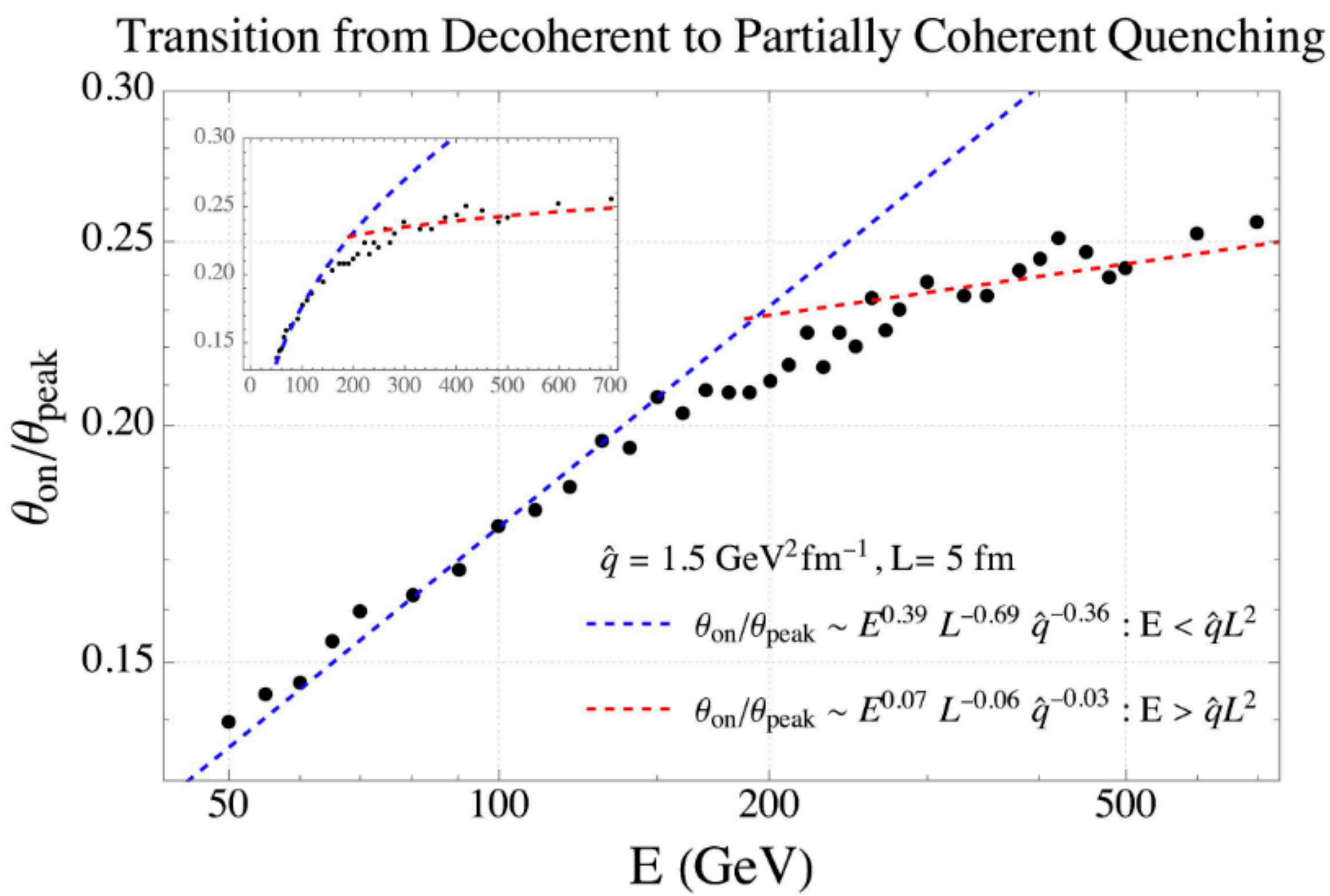
- Larger the $\hat{q}$ -> peak shifted to the right

Energy-Energy Correlators to resolve the scales

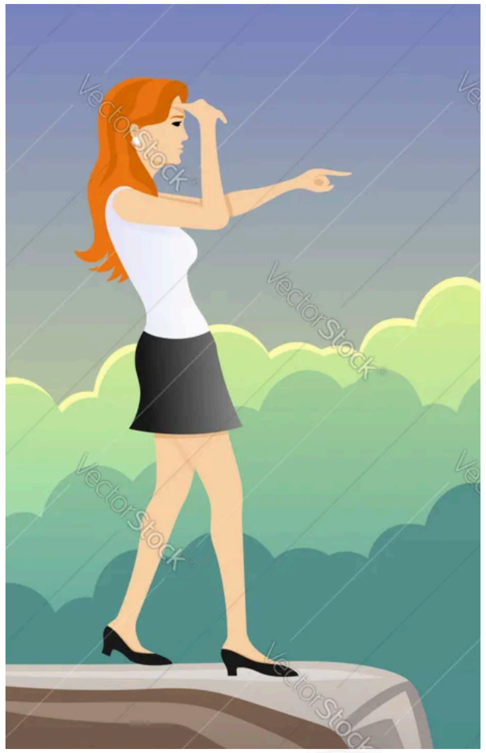
$$\frac{d\Sigma^{(n)}}{d\theta} = \int d\vec{n}_{1,2} \frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} \delta(\vec{n}_2 \cdot \vec{n}_1 - \cos\theta)\,.$$

Moult, et.al 2201.07800

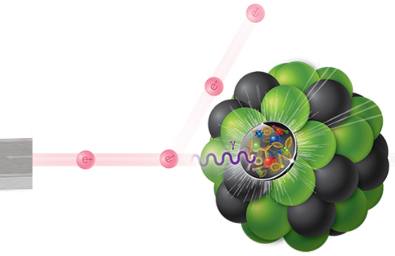
Andres, RKE, et.al 2209.11236



- Larger the $\hat{q}$ -> peak shifted to the right
- *Anagnōrisis* - medium modifies the jet and leaves its imprint



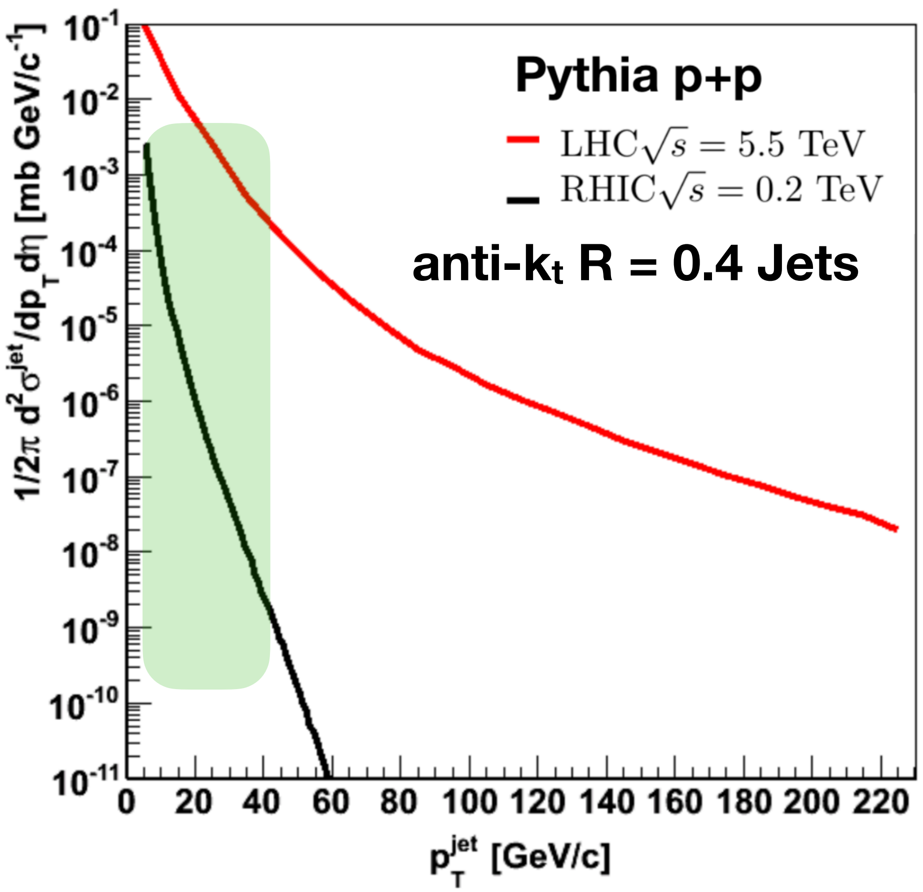
pQCD and npQCD at the EIC

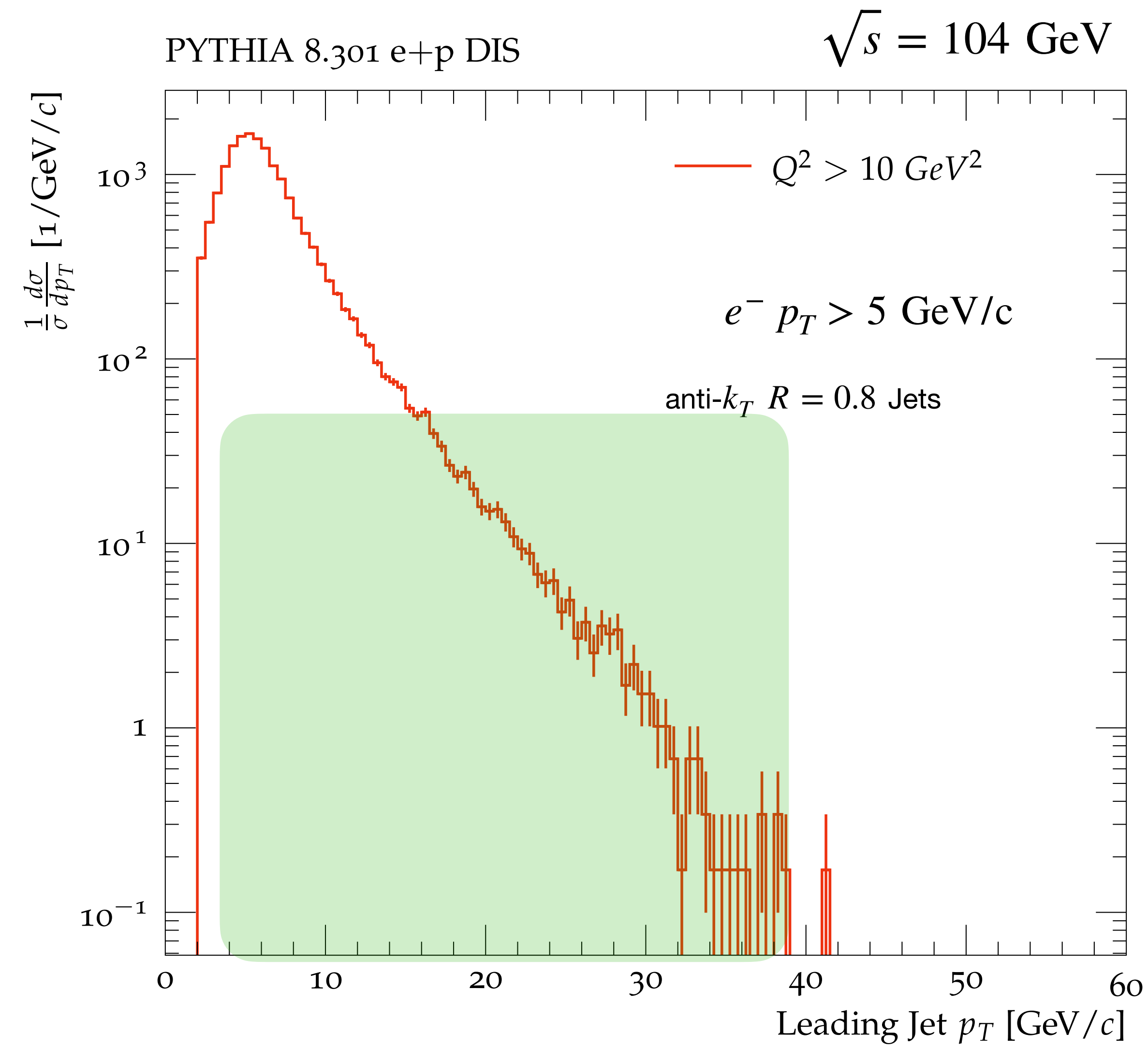


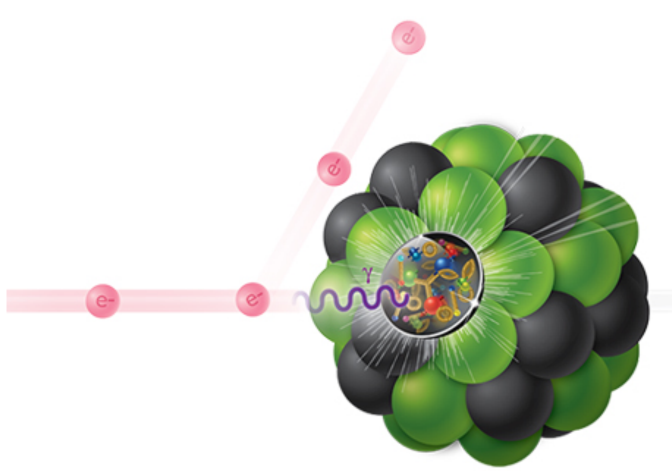
Completing the RHIC mission

Introduction, motivation and current status

Jets at the EIC





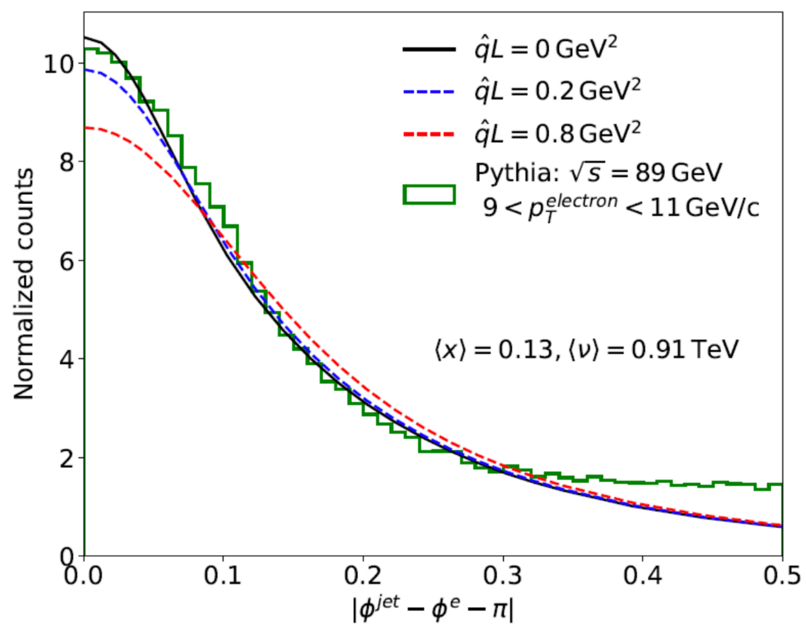


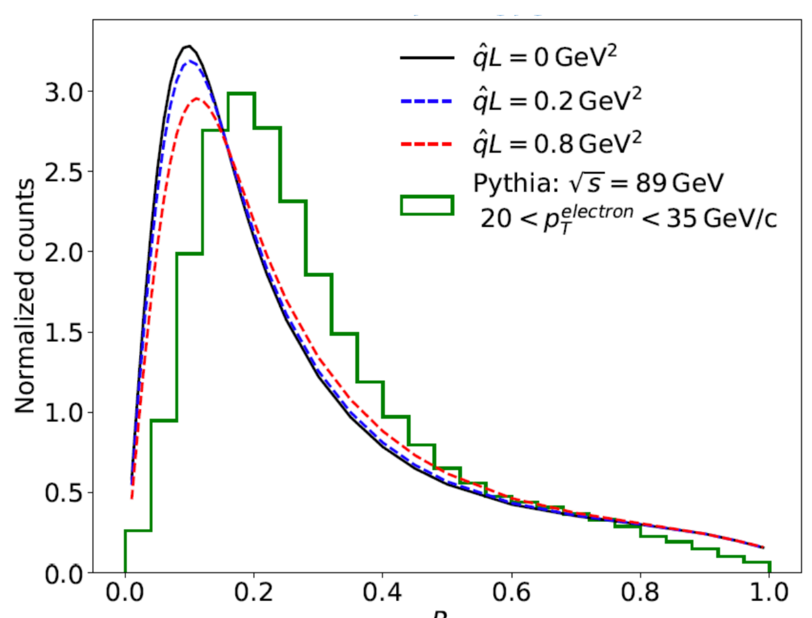
Similar jet kinematics with varied flavor composition and interaction scales

Jet in EIC **vs** Jet + 'soft-physics' in pp

Jet modifications at the EIC

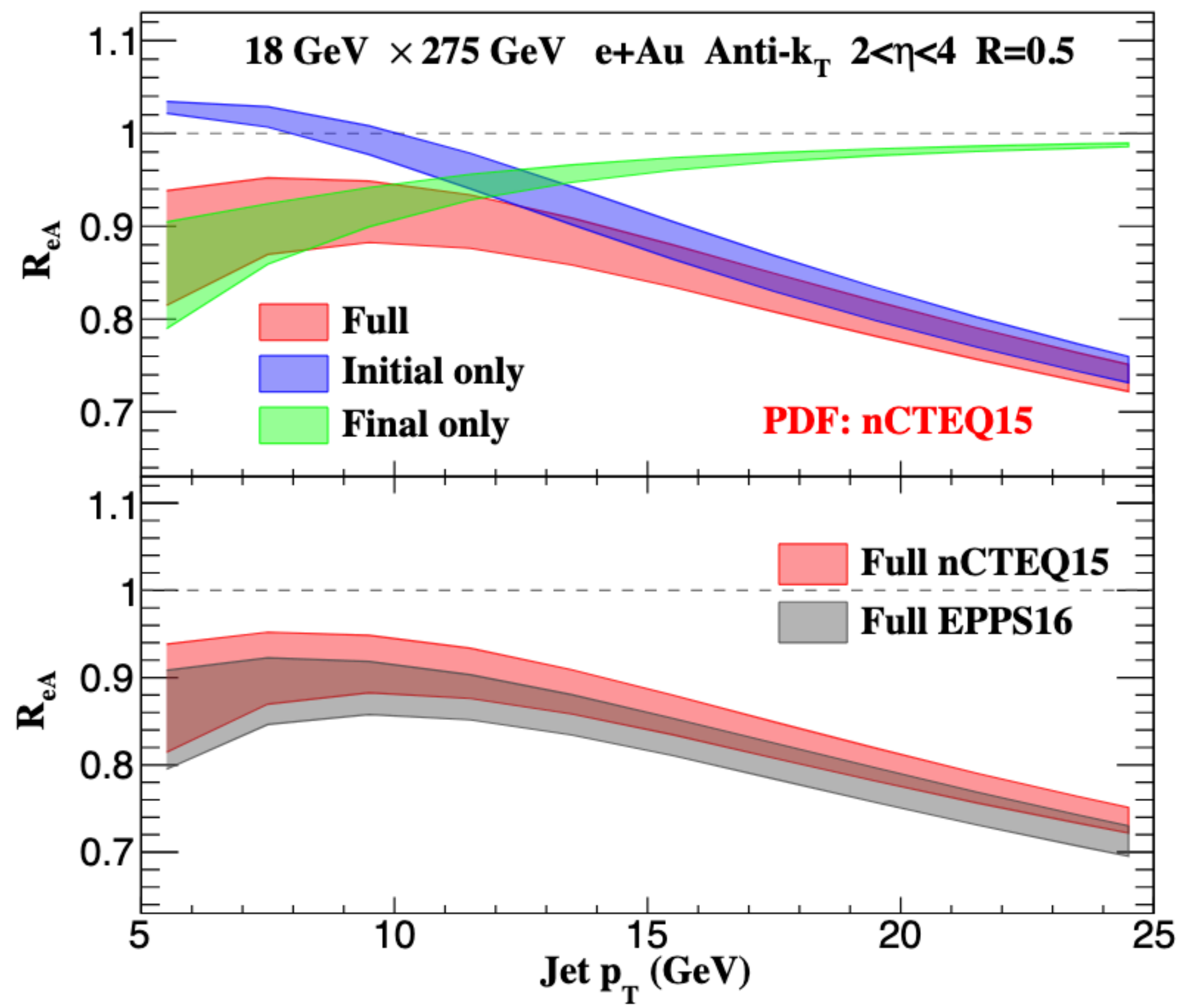
Lie et.al PRL 122 192003 (2019)





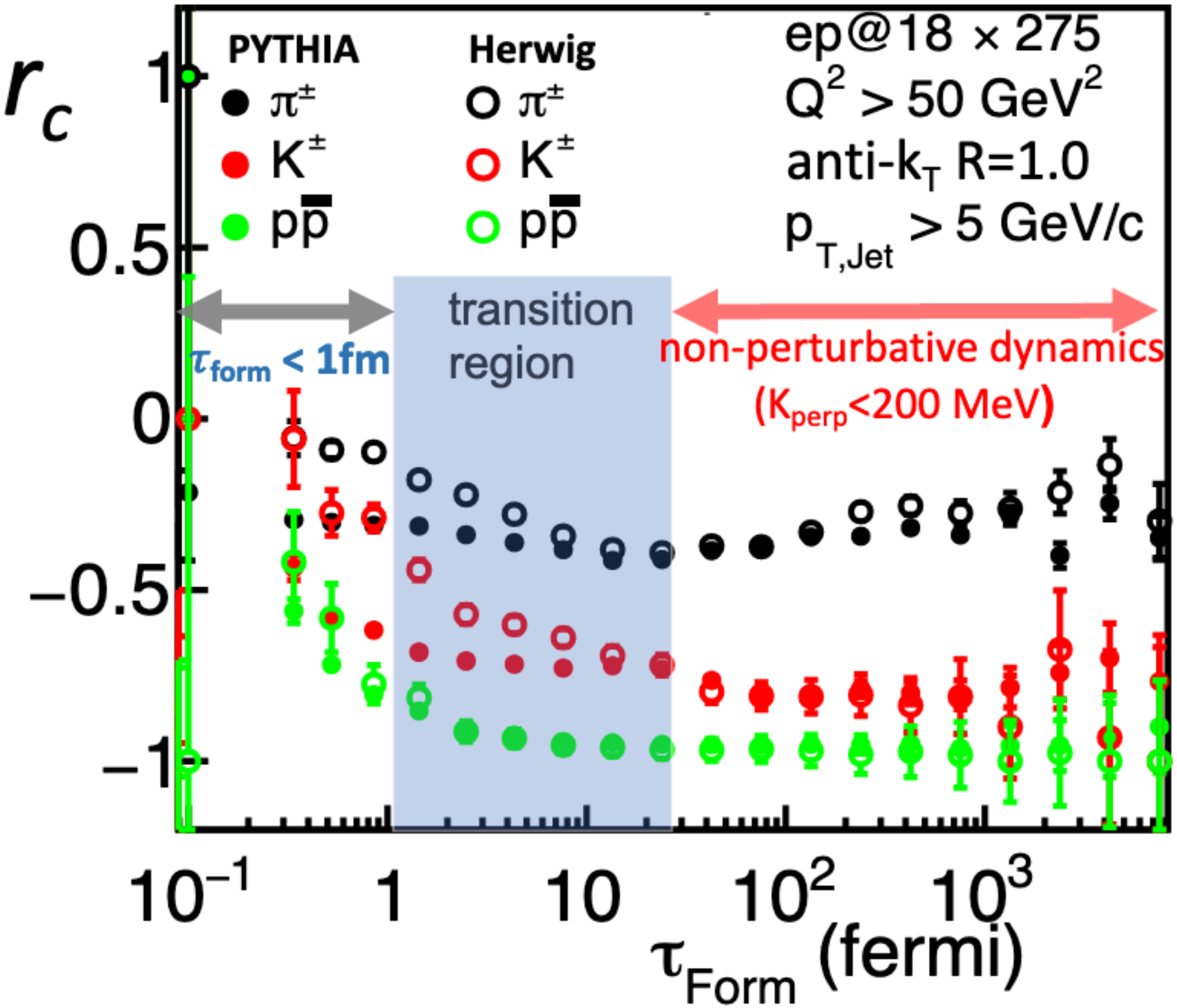
Arratia et.al
Phys. Rev. C 101, 065204 (2020)

Li, Hai Tao and Vitev, Ivan
Phys.Rev.Lett. 126 (2021) 25, 252001



- Jet kinematics and substructure observables show promising dependence on nuclear effects

Time dependence of hadronization - I

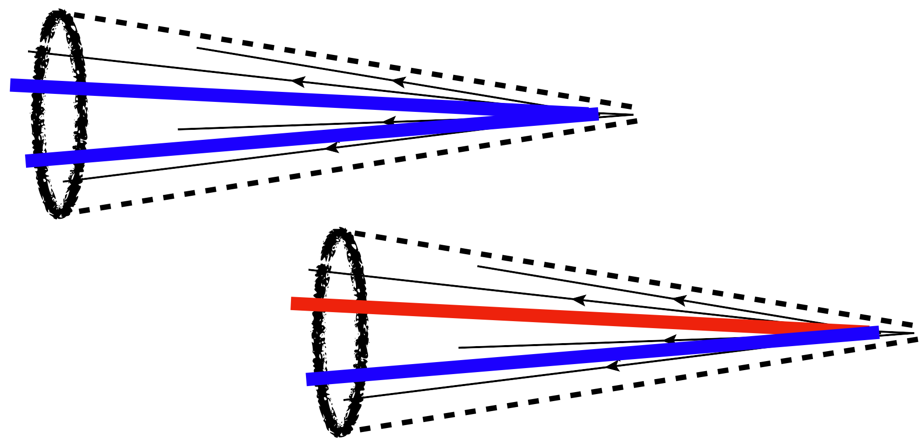


Chien et.al PhysRevD.105.L051502

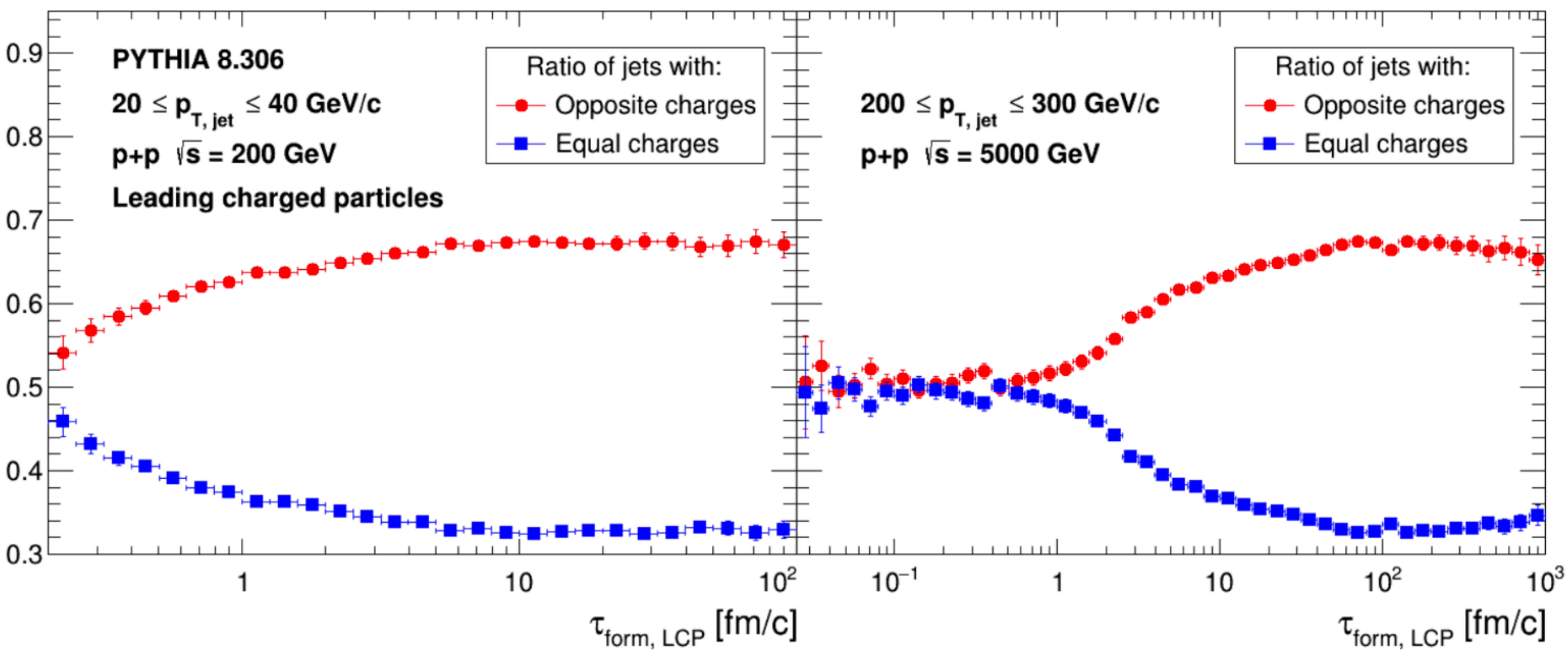
$$r_c = \frac{N_{LS} - N_{US}}{N_{LS} + N_{US}}$$

- With PID (up to 5 GeV) one can study particle production mechanisms across **'mostly' perturbative**, **fuzzy in-between** and **'mostly' non-perturbative**

Time dependence of hadronization - II



- Potential direct observation of string breaking and ‘electric’ charge production within a QCD shower



Nuno Madureira, Masters thesis (LIP)

Nuno Madureira, LA, RKE arXiv:2211.xxxx

Conclusions

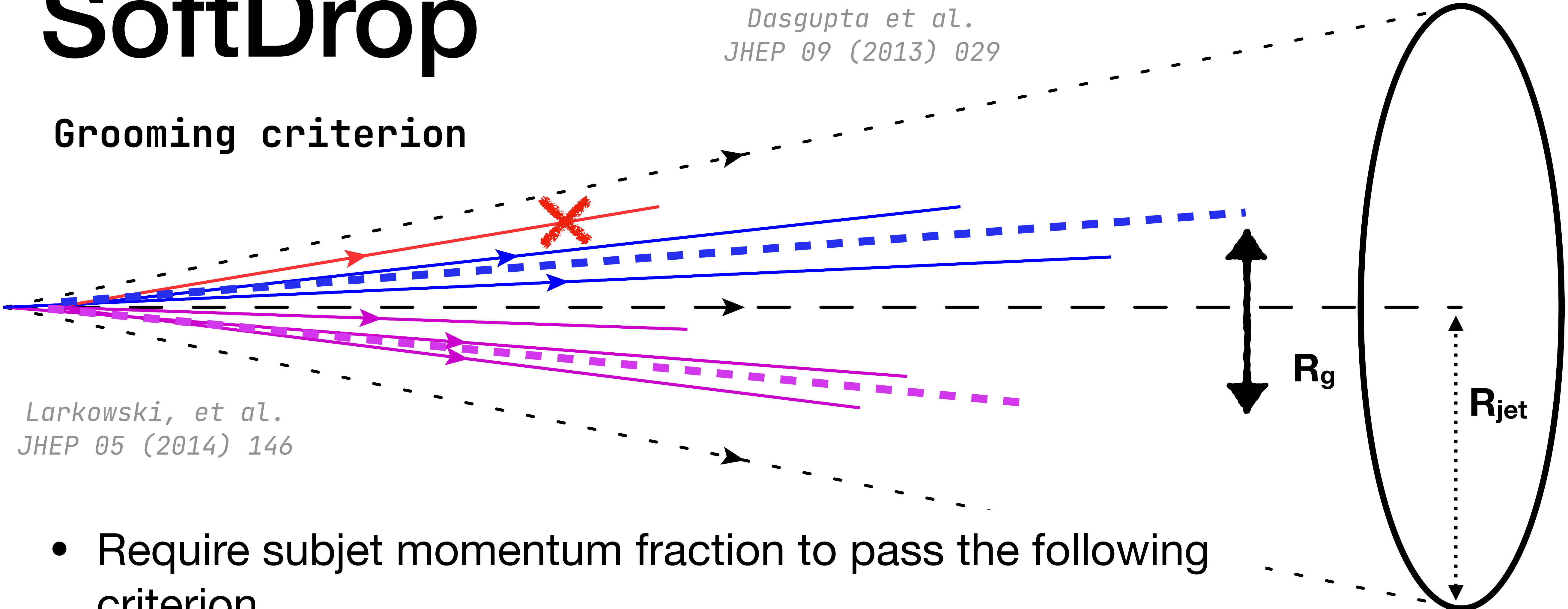
- *Harmartia, Anagnōrisis and Peripeteia*
- We are now heading to the era of QGP microstructure and precision QCD - *Peripeteia! Different jets are quenched differently*
- Goal is to exploit, tag and measure energy loss as a function of jet topology
- Explorations into the npQCD regime are well underway as groundwork for discovery physics @ the EIC

Bonus Slides

SoftDrop

Dasgupta et al.
JHEP 09 (2013) 029

Grooming criterion



Larkowski, et al.
JHEP 05 (2014) 146

- Require subjet momentum fraction to pass the following criterion

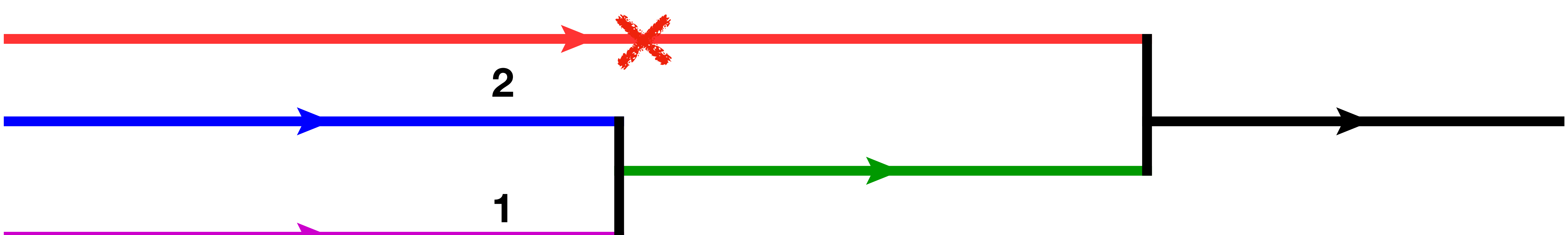
$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$

$$z_{cut} = 0.1$$

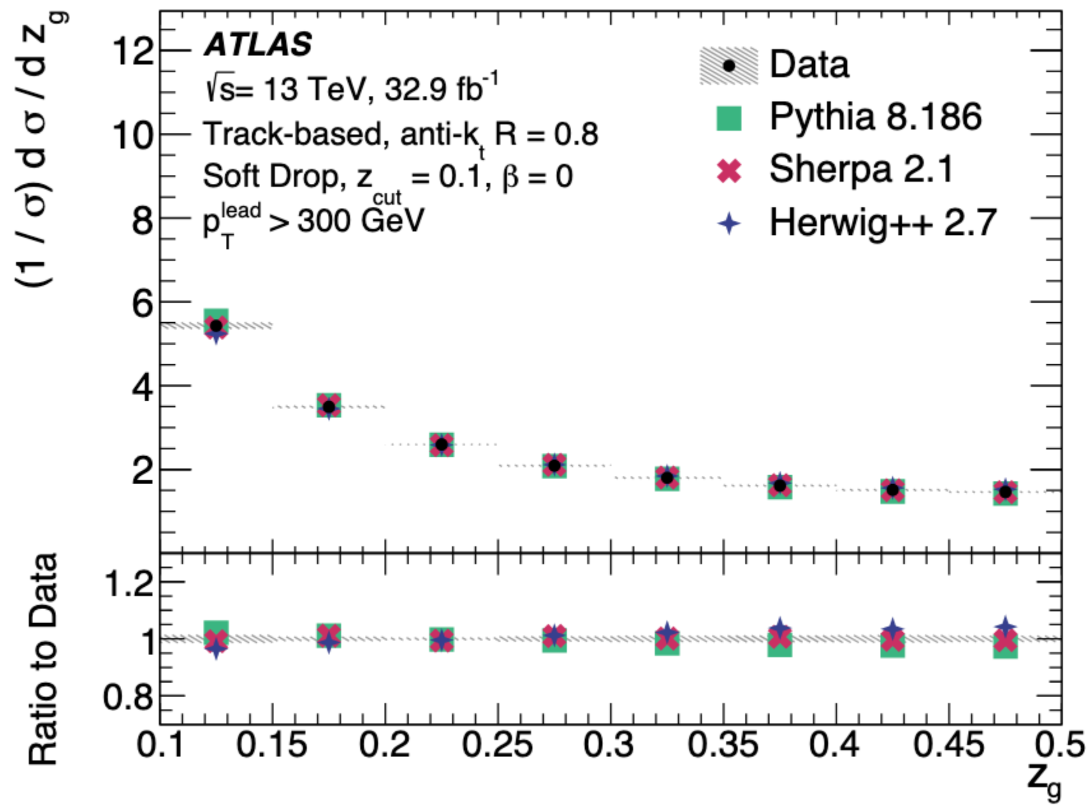
$$\beta = 0$$

- With the two surviving branches (first hard split) - we have two observables that characterize a jet's substructure

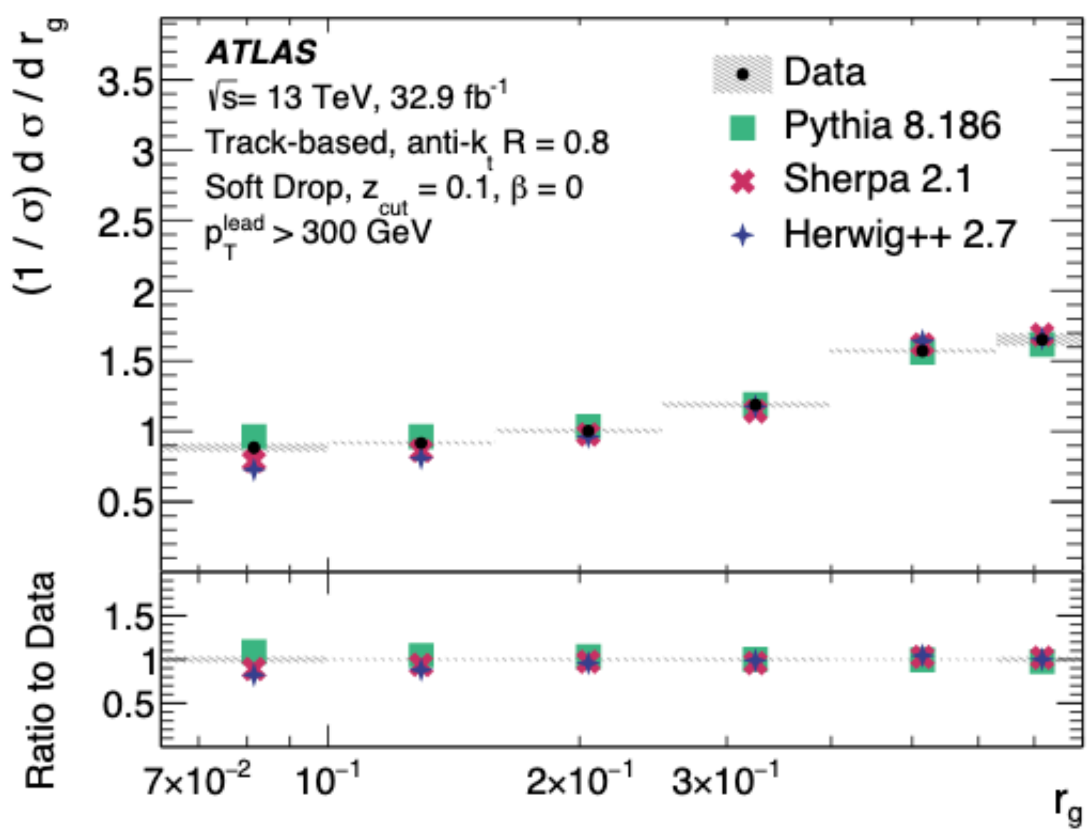
$$z_g, \ R_g$$

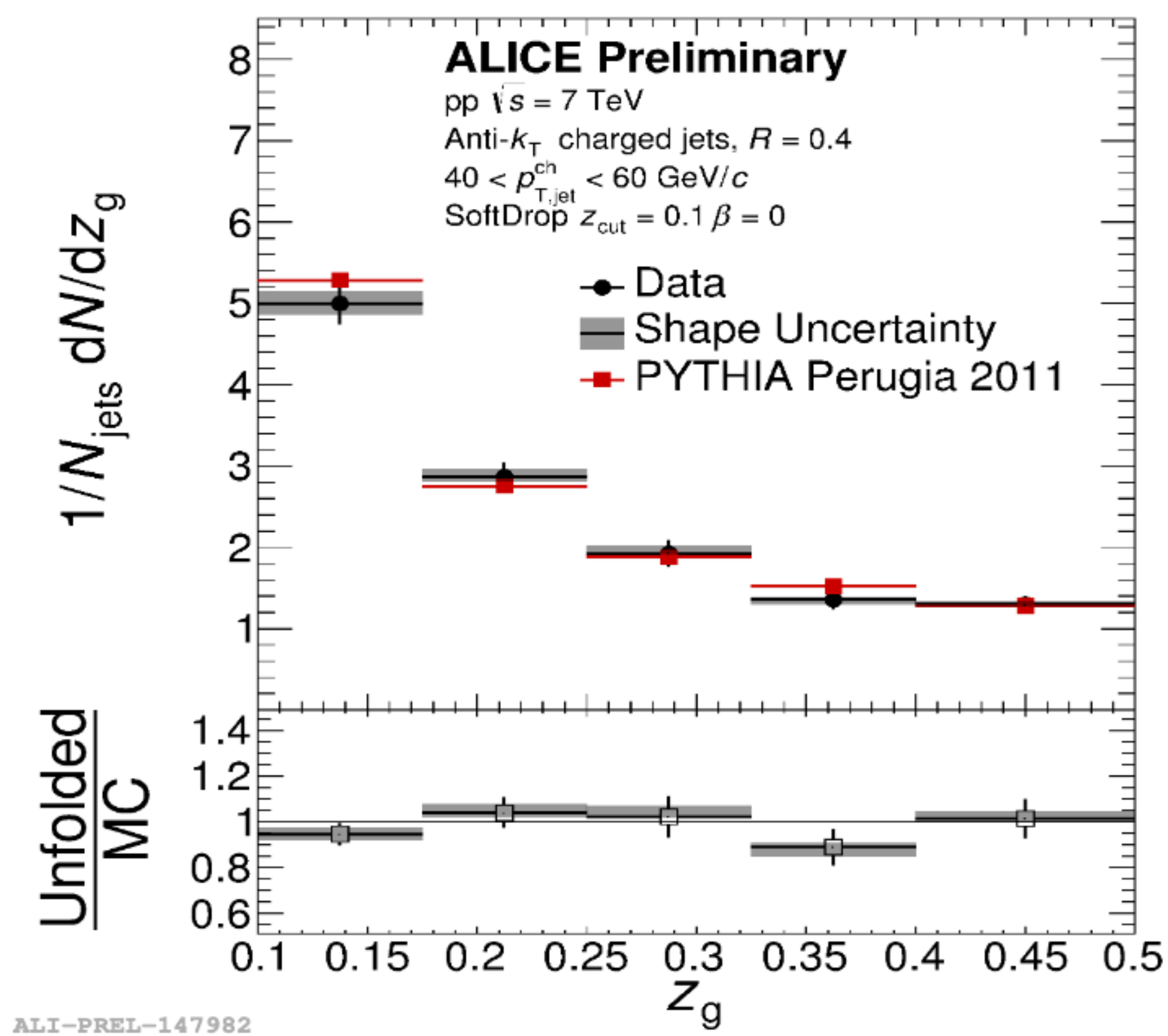


SoftDrop distributions in pp



ATLAS Phys. Rev. D 101, 052007 (2020)

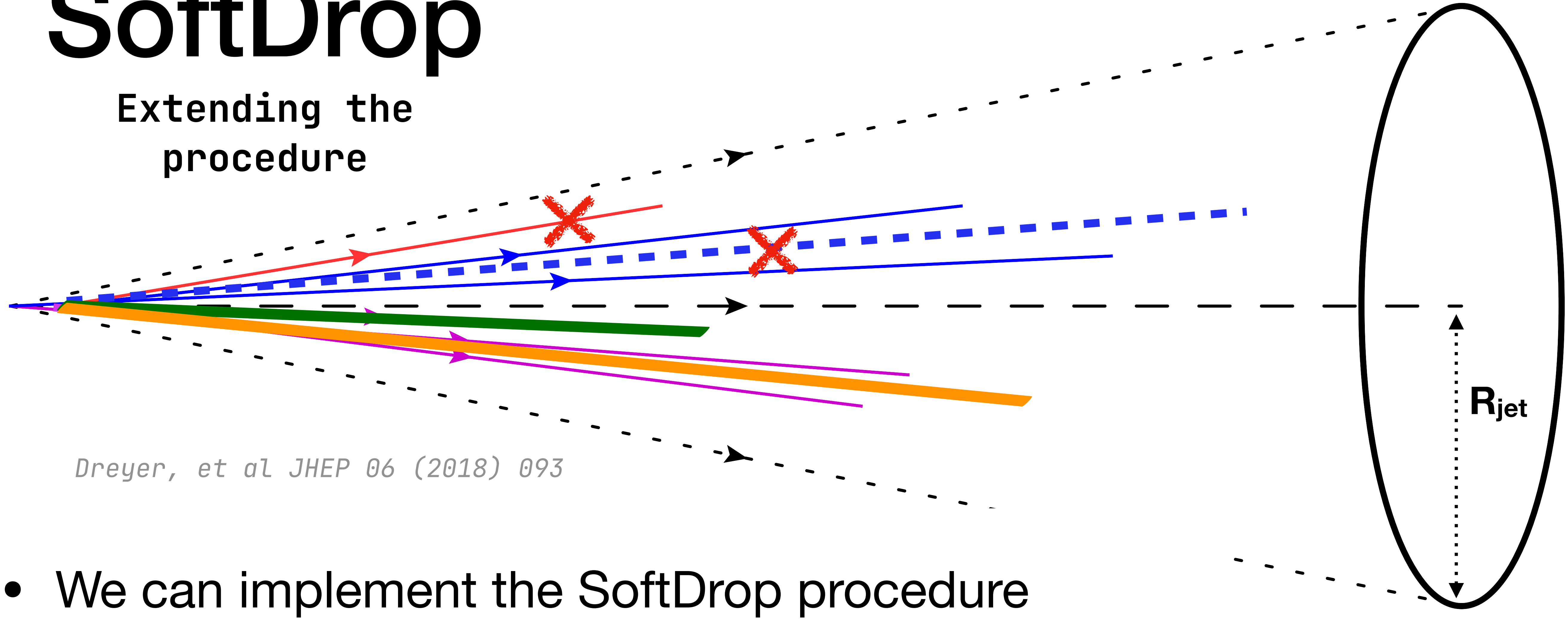




- Overall good agreement with MC
- Track based observables come with better precision

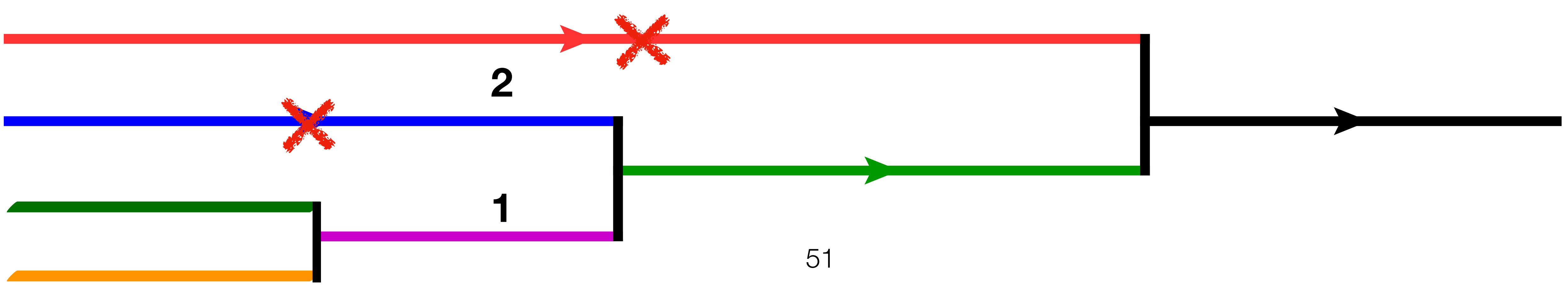
SoftDrop

Extending the procedure



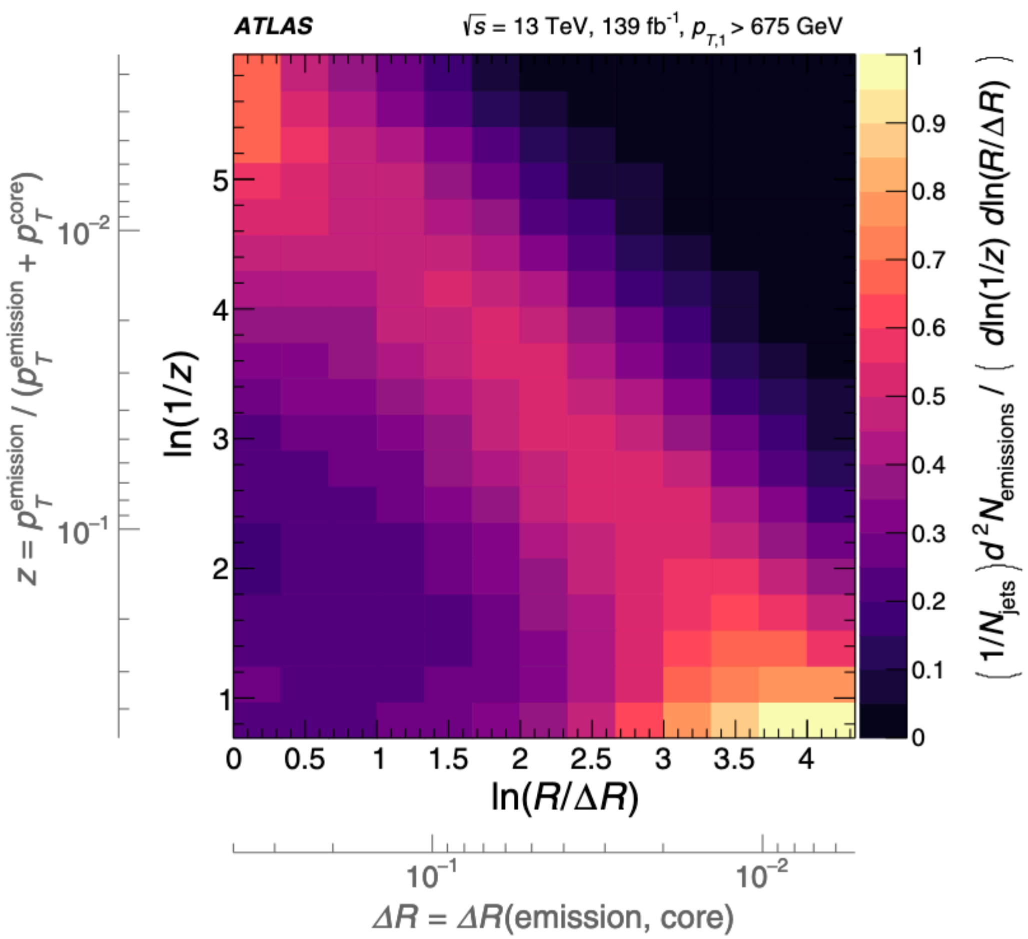
- We can implement the SoftDrop procedure throughout the CA tree -
  - Follow the hardest branch - Iterative SoftDrop
  - Following all branches - Recursive SoftDrop

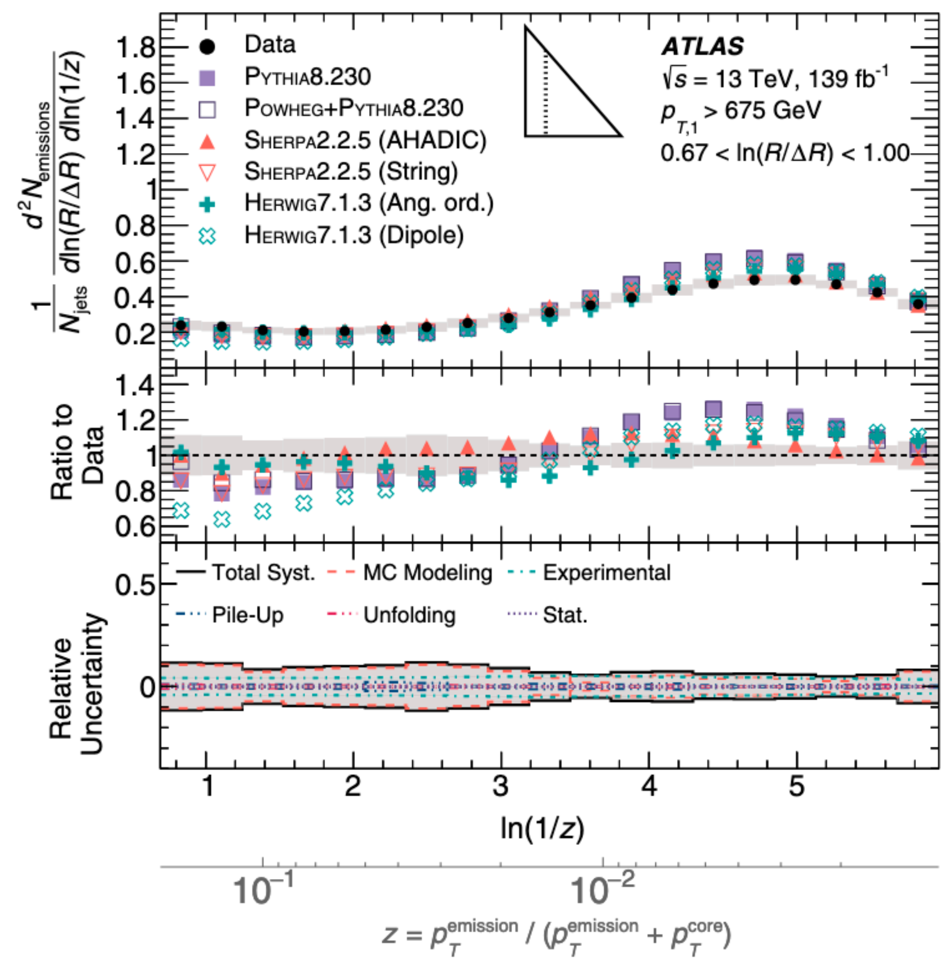
$$n_{\mathrm{SD}},\ z_g^n,\ R_g^n$$



Recent measurements of Lund Plane and their projections at the LHC

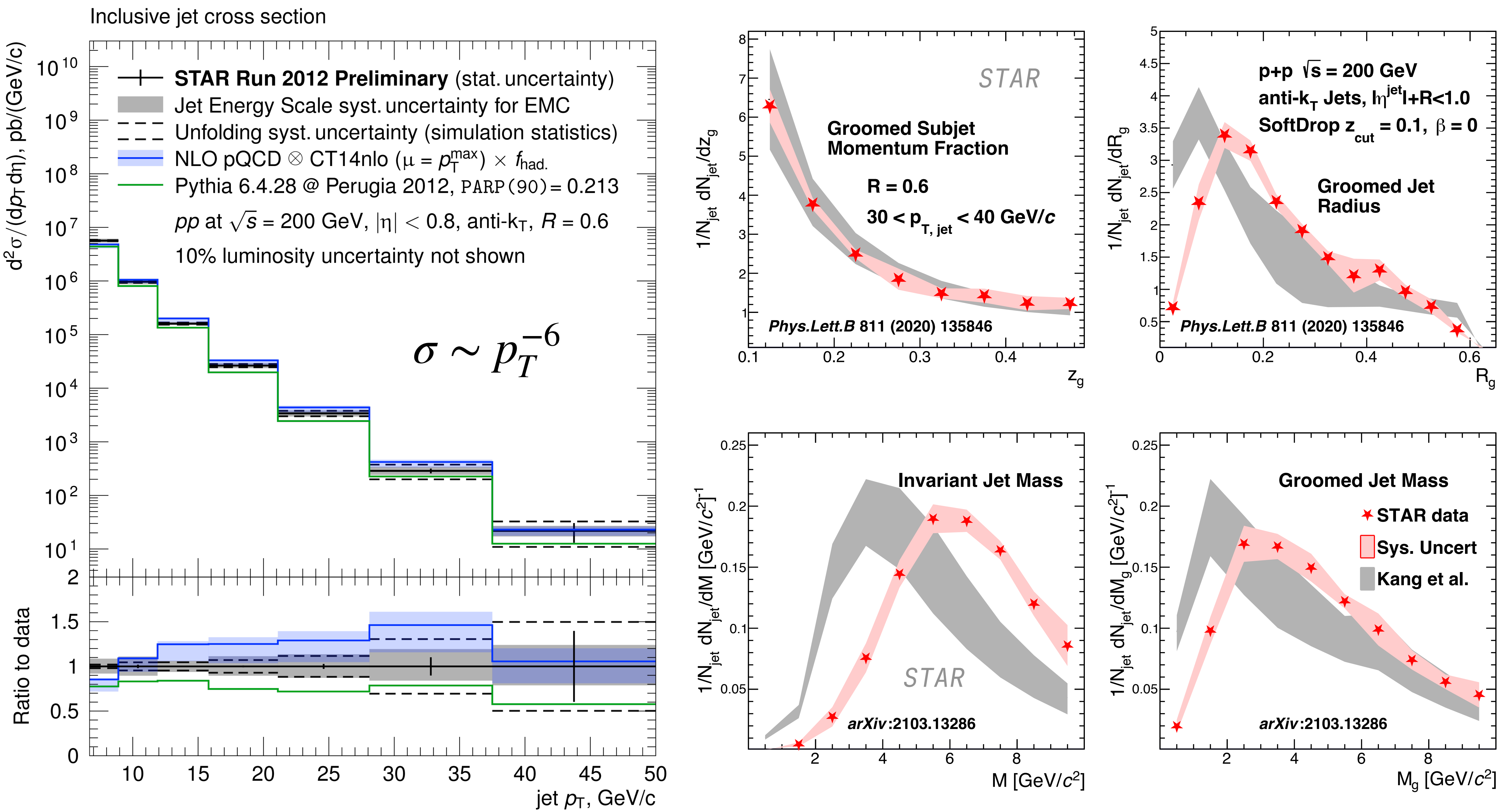
ATLAS, Phys. Rev. Lett. 124, 222002 (2020)





- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcase differences

Jets in pp $\sqrt{s} = 200$ GeV

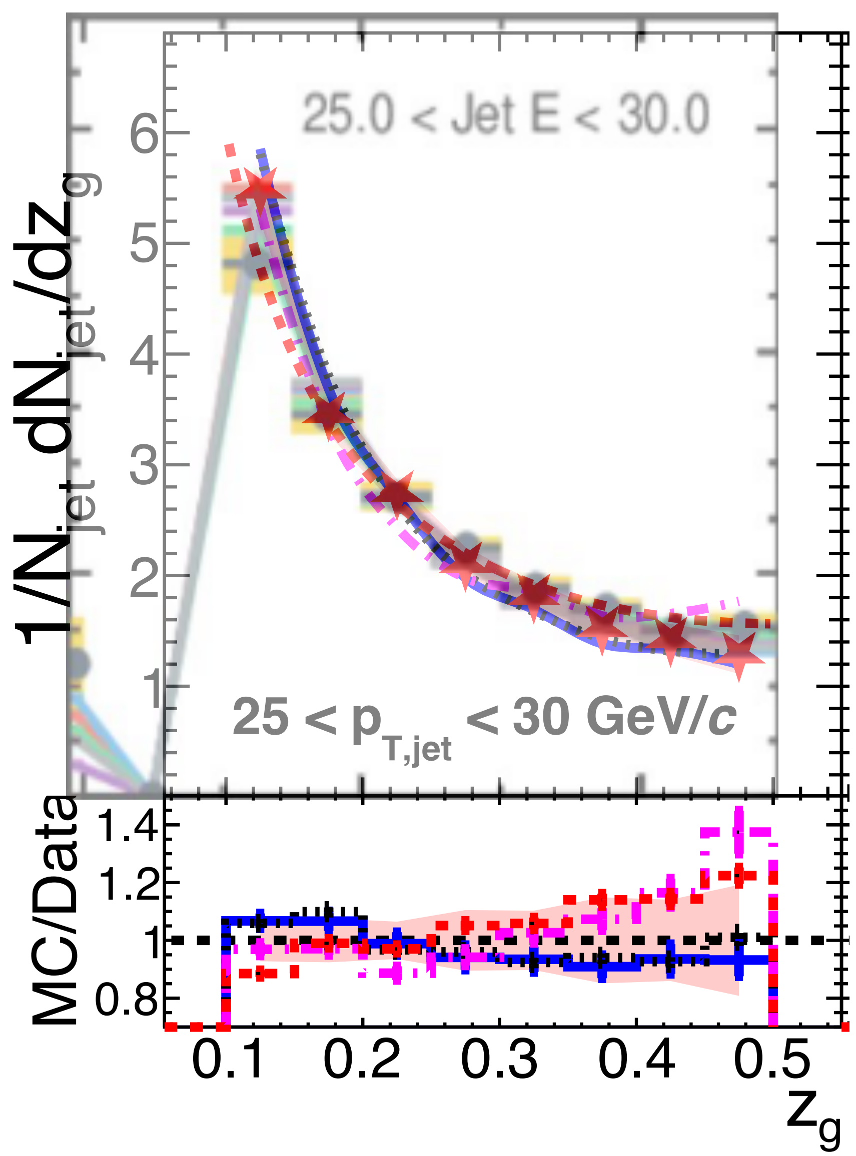


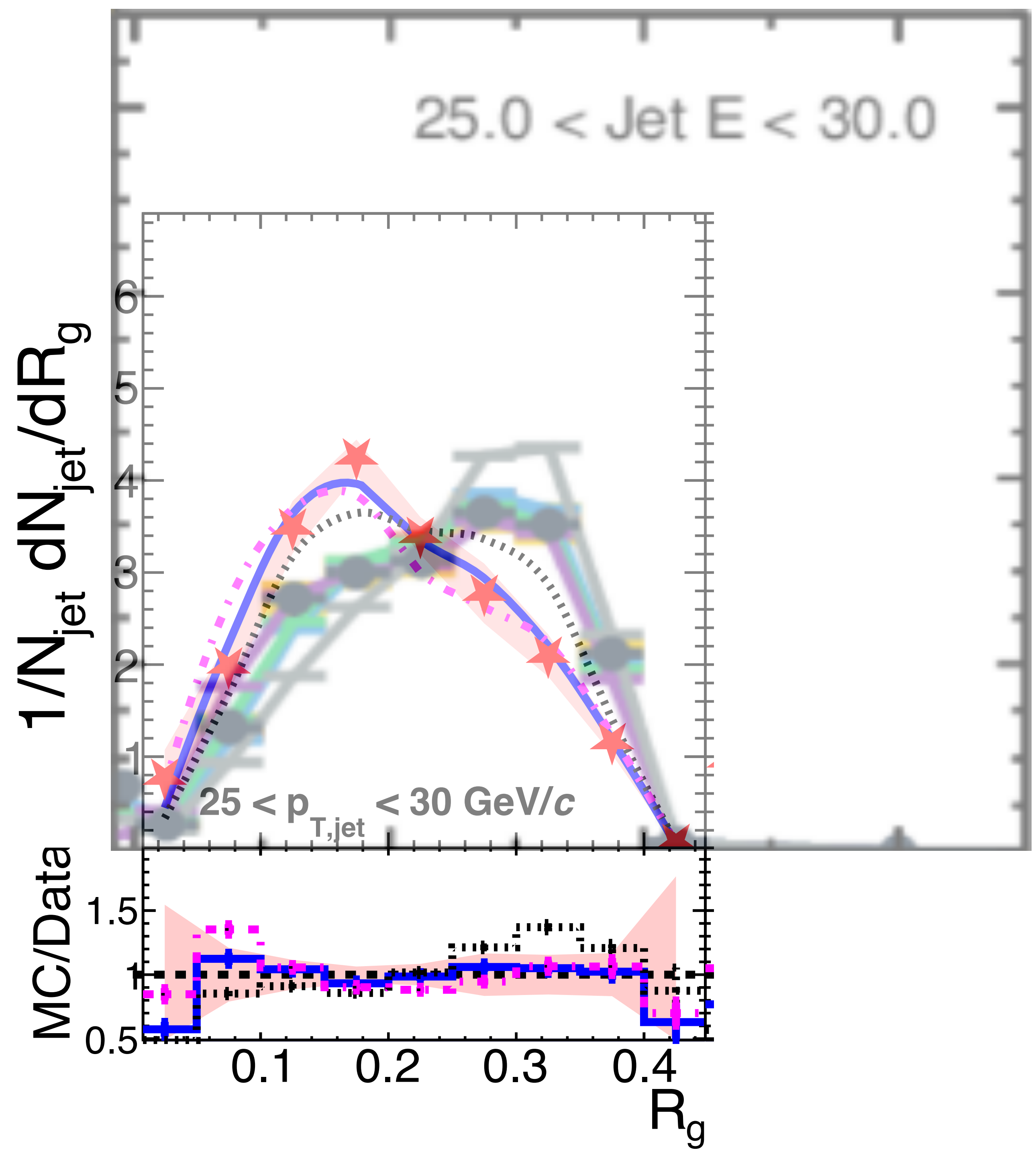
Unique population of jets with varied substructure!

Scales extend from jet $p_{\mathrm{T}} \rightarrow \Lambda_{\mathrm{QCD}}$

Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g

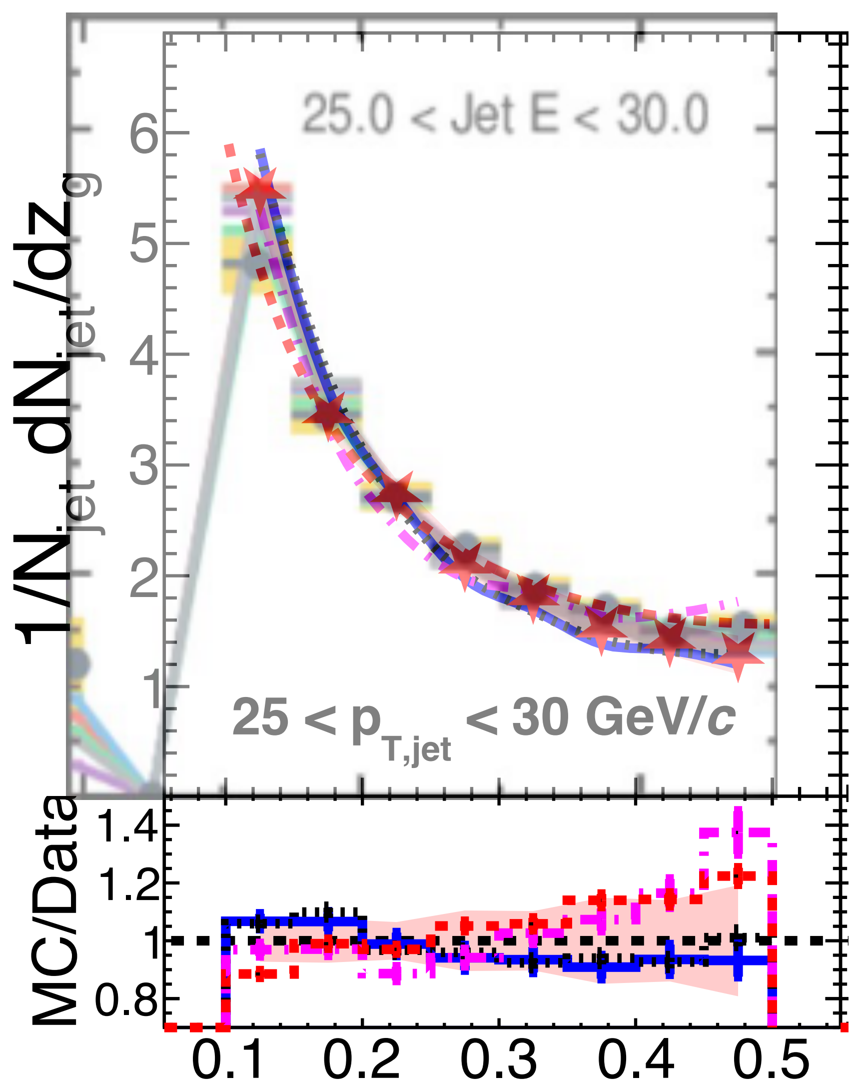


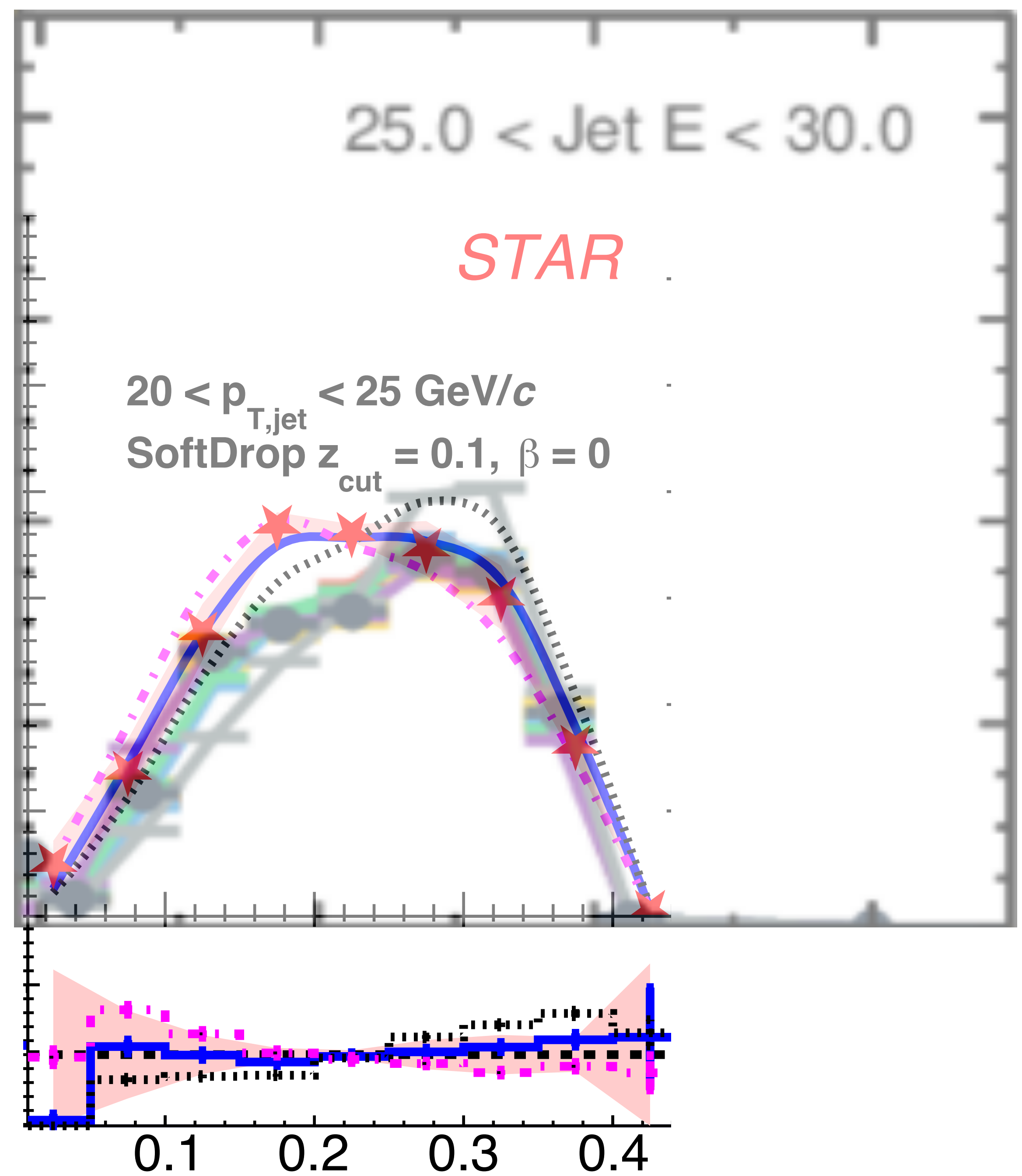


Is the comparison apples to apples?

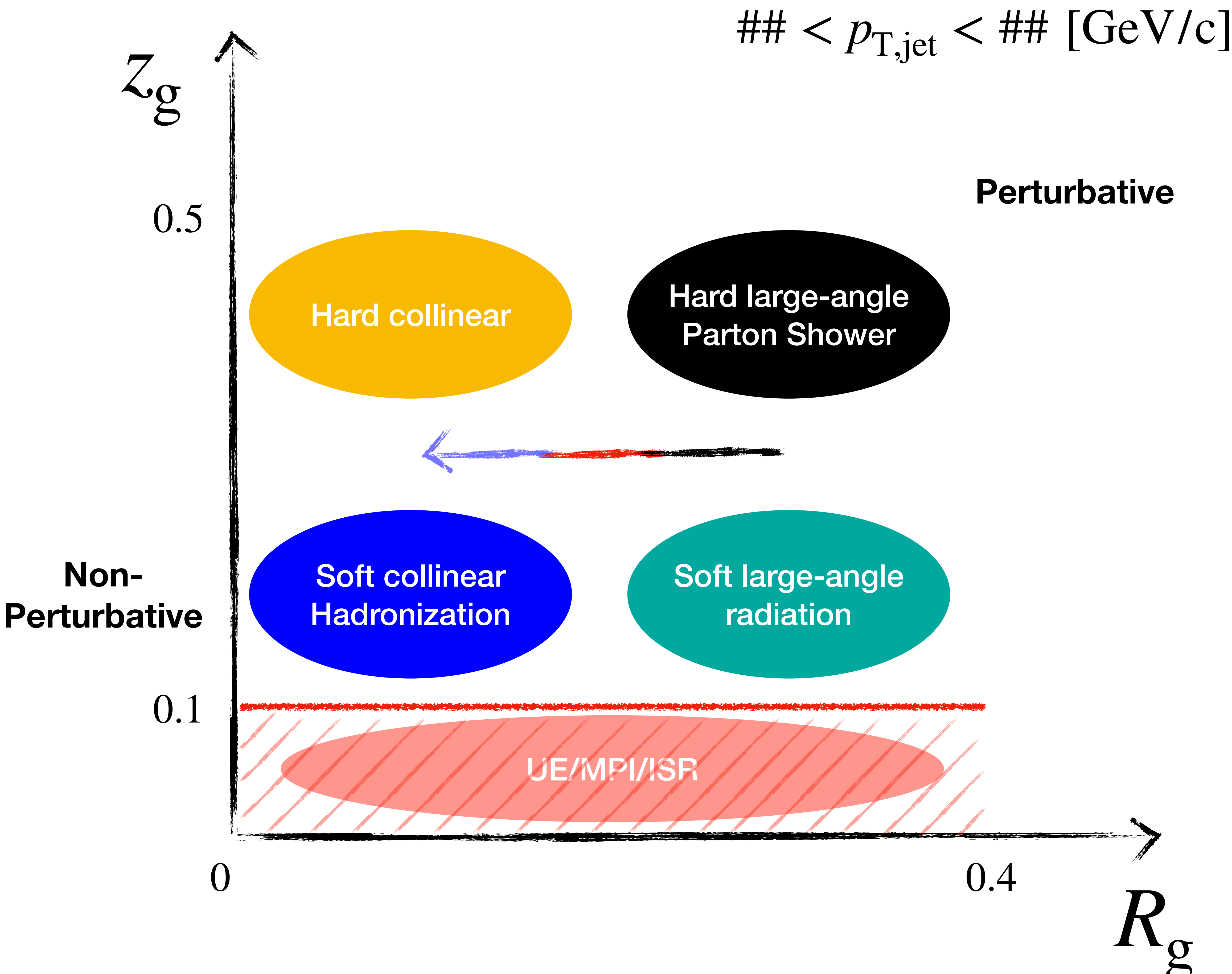
Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g



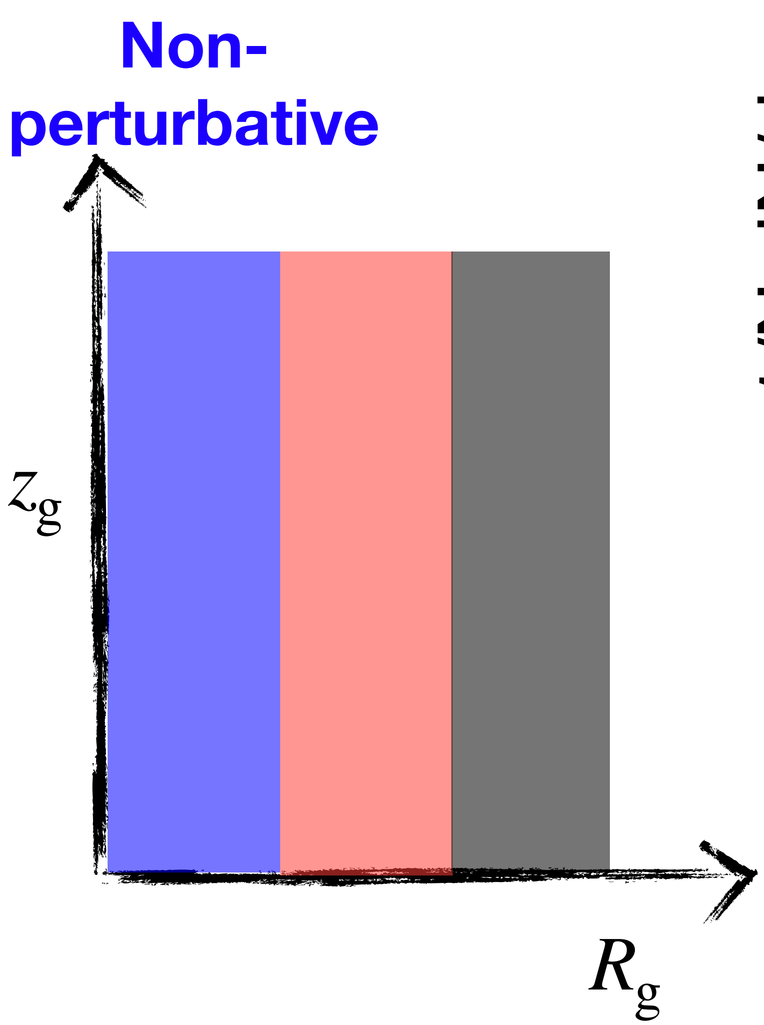


These jets in pp collisions have a $\langle M \rangle \approx 3$ GeV/c^2 plus there's hadronic component!

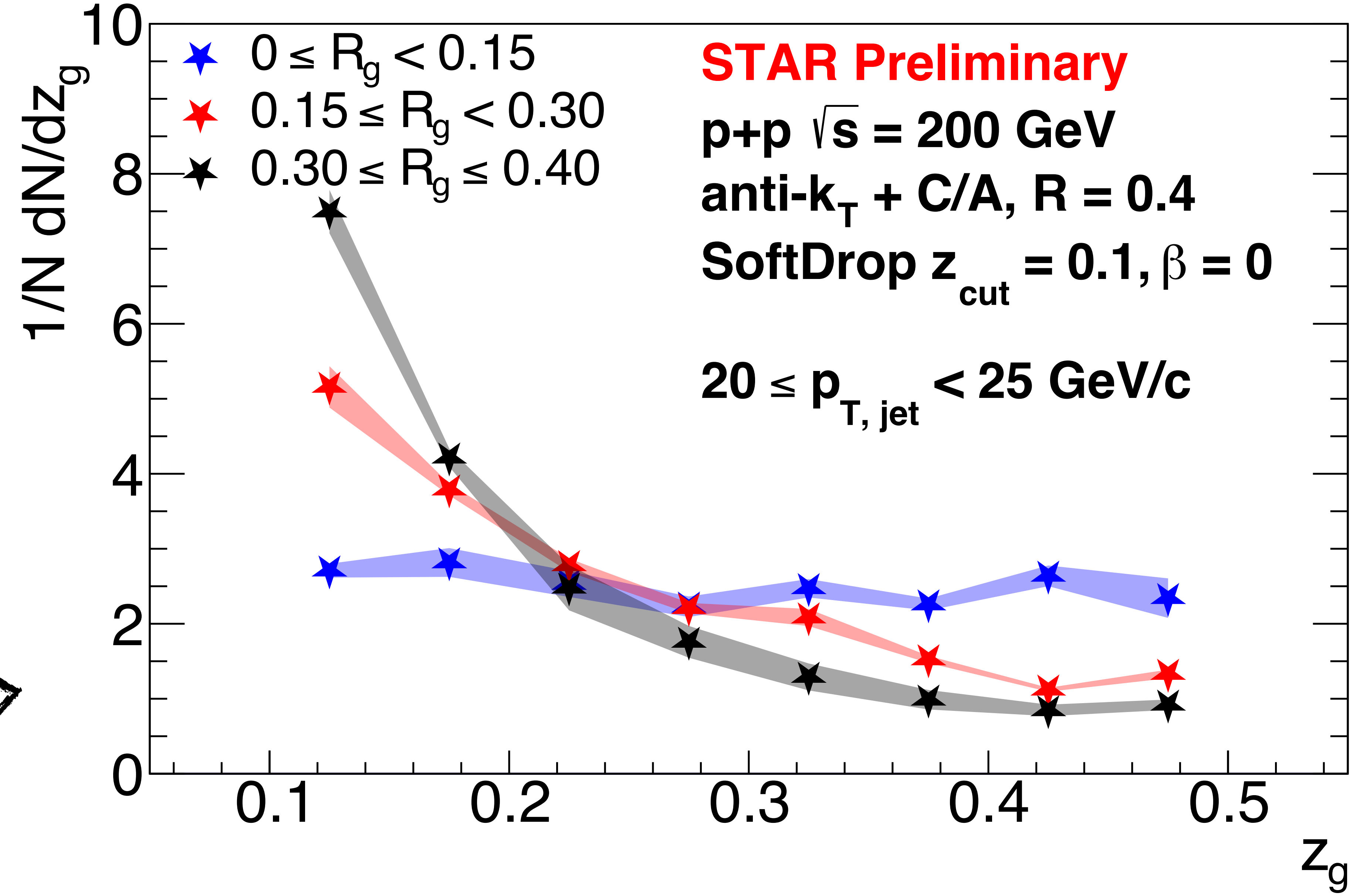


$\#\# < p_{T,jet} < \#\#$ [GeV/c]
z_g
Perturbative
0.5
Hard collinear
Hard large-angle Parton Shower
Non-Perturbative
Soft collinear Hadronization
Soft large-angle radiation
0.1
UE/MPI/ISR
0
0.4
R_g

Correlation between the splitting scales

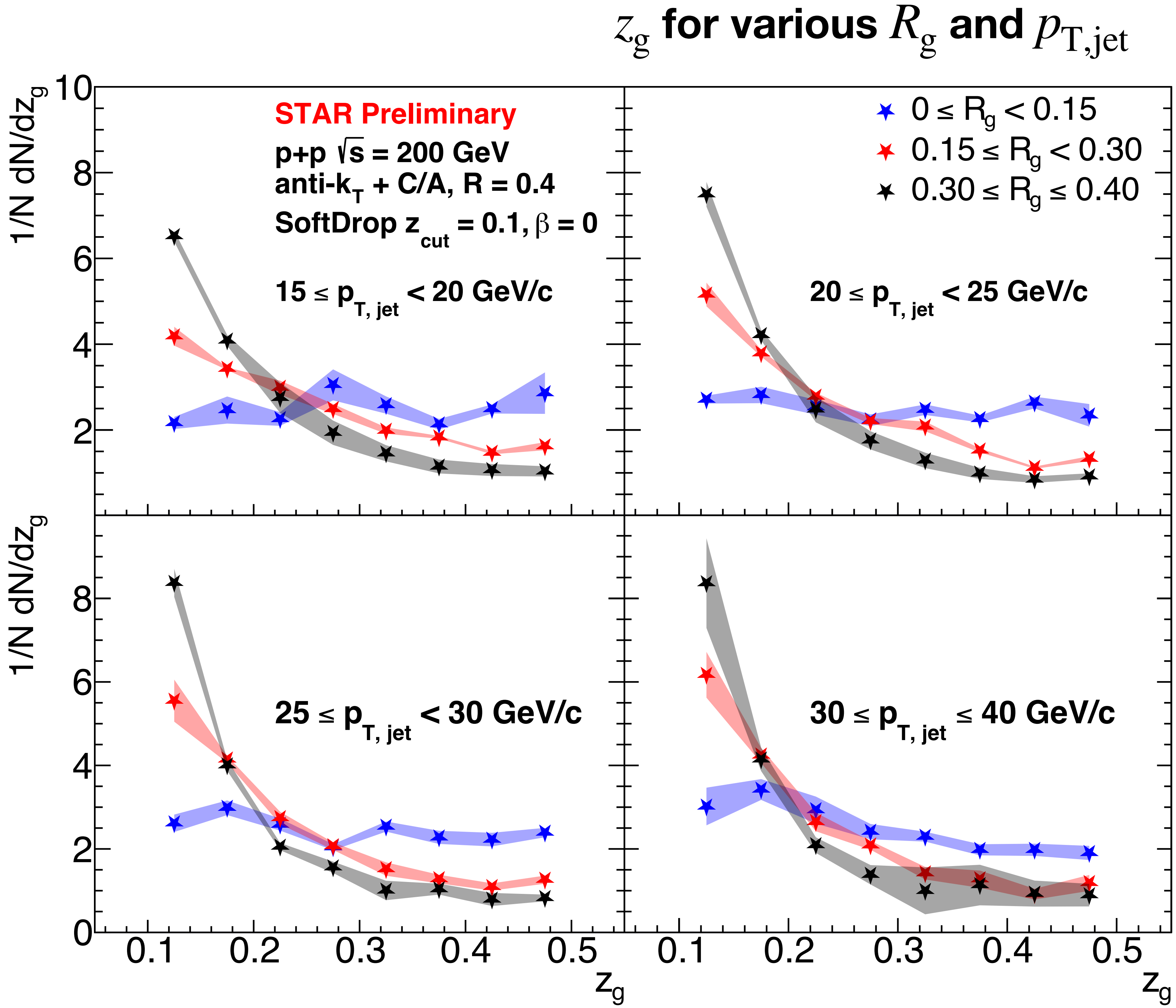


z_g **for various** R_g **at** $p_{T,jet}$ **range**



- Significant variation from selecting on R_g
- Evolution from **soft-wide angle splits** to **hard-collinear splits**

Evolution vs. $p_{\mathrm{T,jet}}$

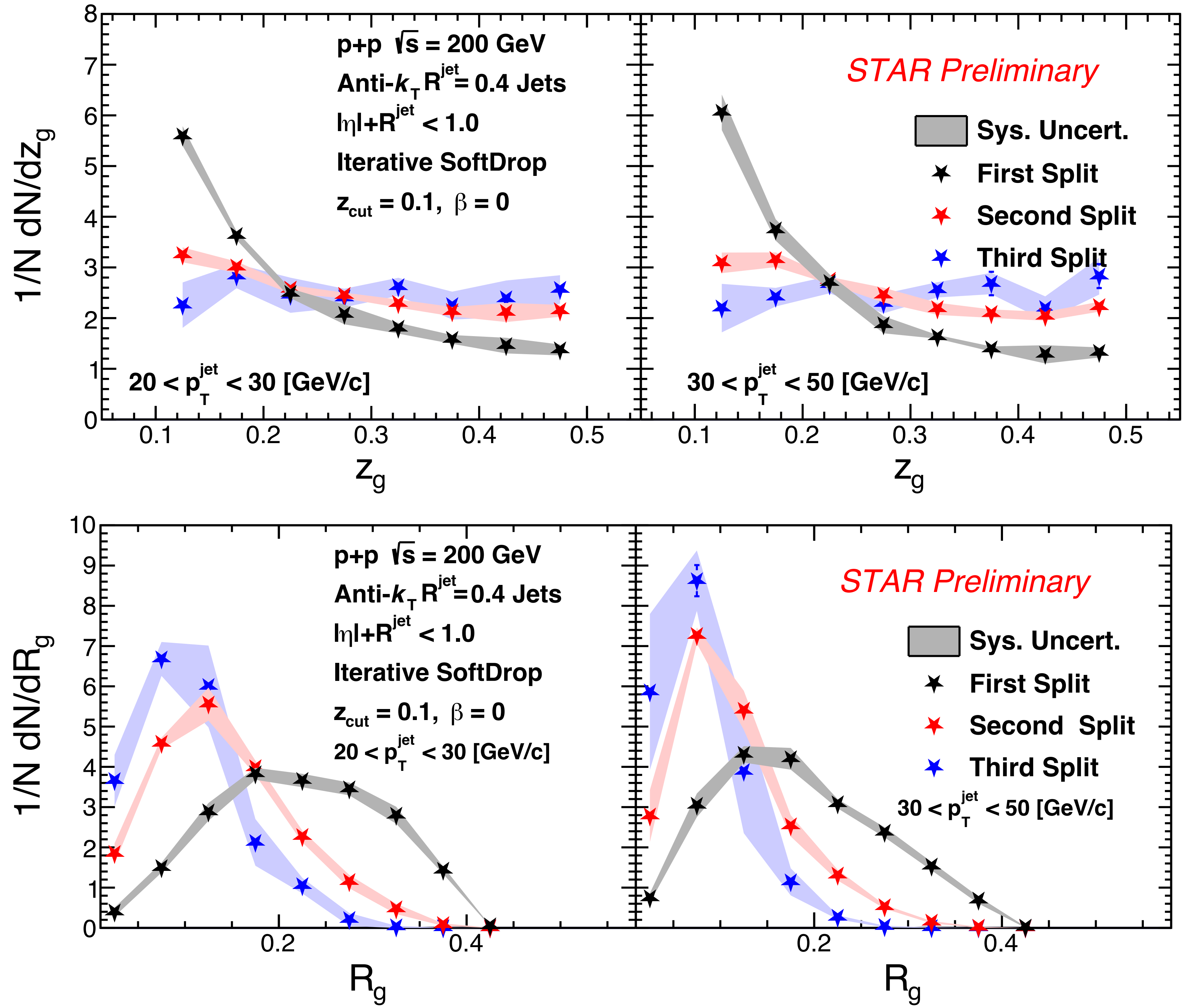


- Increasing jet p_{T} has a small to mild effect on substructure
- Selection on R_{g} determines **the z_{g} shape** - high degree of correlation
- **Phase space restrictions** matter!

Evolution of the splittings

1st, 2nd, 3rd splits for various $p_{\mathrm{T,jet}}$

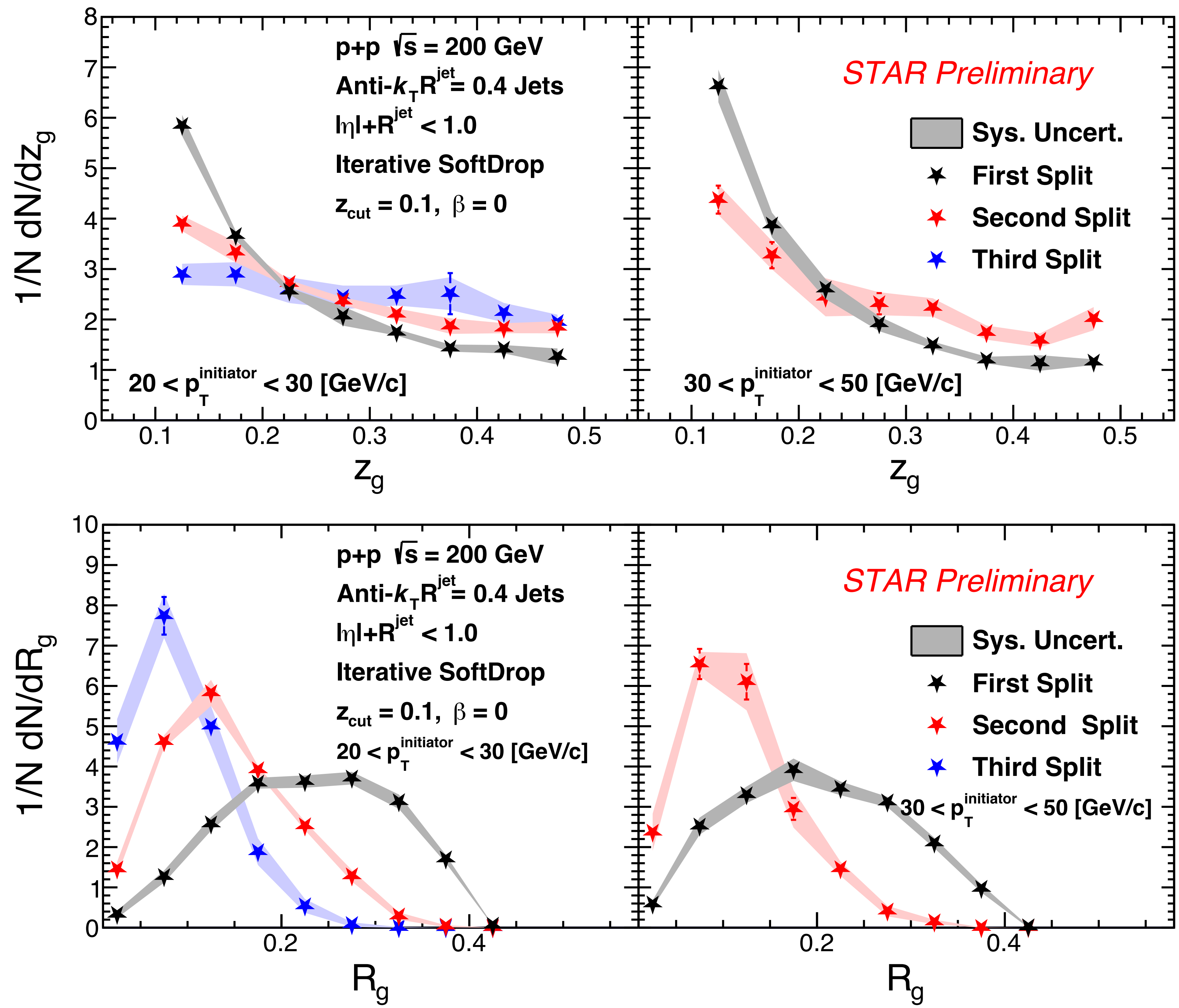
- **For a given jet $p_{\mathrm{T,jet}}$,** what are the z_g, R_g at 1st, 2nd and 3rd splits? Follow a jet…
- **Significant differences between first, second and third** splits
- Splitting **'z' becomes flat and the R_g quite narrow** for the third split where we observe collinear emissions



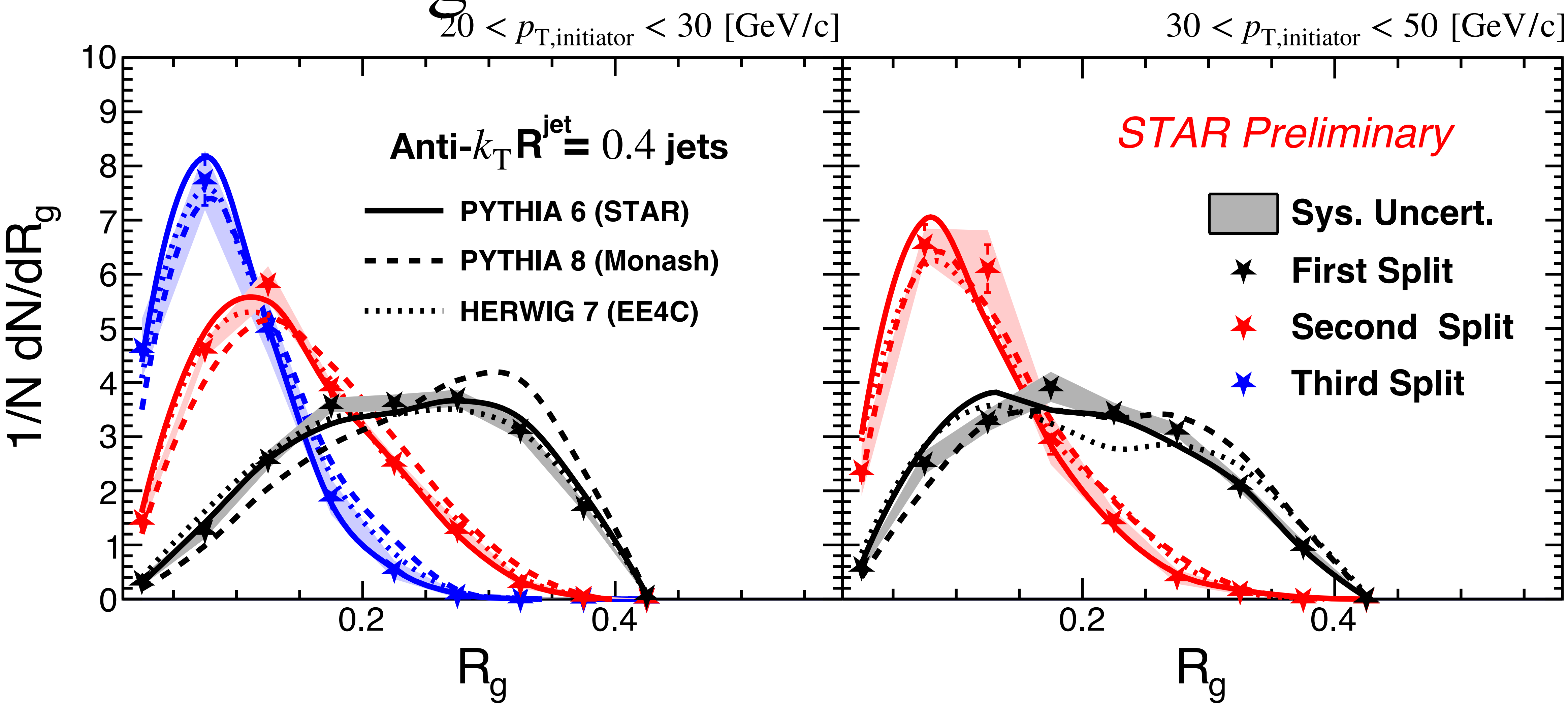
Evolution of the splittings

1st, 2nd, 3rd splits for various $p_{\mathrm{T,initiator}}$

- **For a given split with** $p_{\mathrm{T,initiator}}$, what are the z_g, R_g for 1st, 2nd and 3rd splits? Follow a split…
- **Splits are directly comparable** with each other - only difference is where they occur in the shower
- **Hint of differences between second split** z_g (similar R_g) for initiator vs. jet momenta selection



Comparisons with leading order MC - R_g for various initiator p_T



- Three MC (PYTHIA 6, PYTHIA 8, HERWIG 7) **models describe the overall trend of narrowing** of jet substructure for higher splits
- Availability of emission phase space depends on both jet momenta and split # - similar peaks of R_g for **third splits** on the left to **second splits** on the right

How to experimentally measure the formation time τ_f

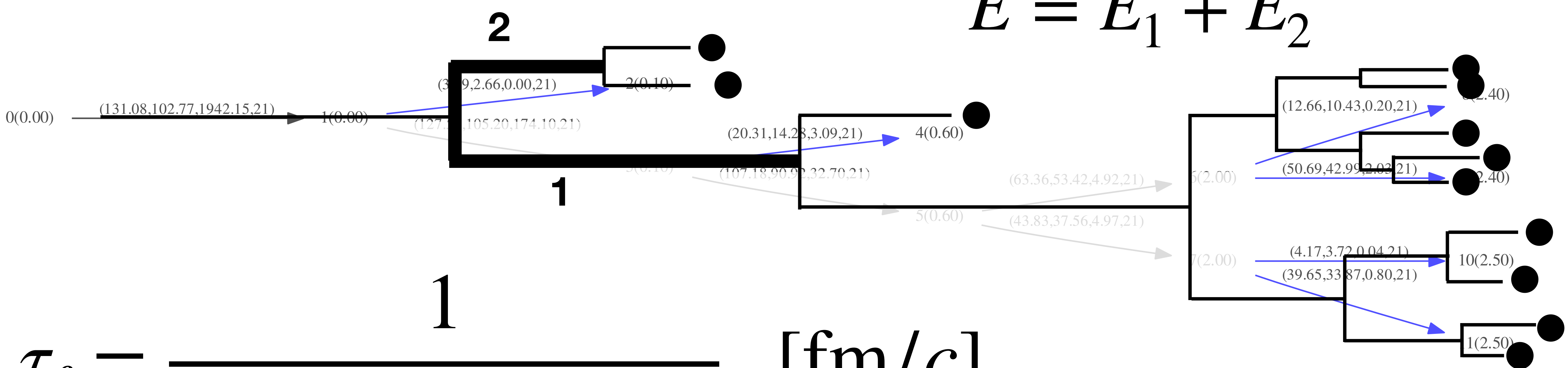
Take any two objects - in this case the first two surviving prongs after SoftDrop grooming

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

Dasgupta et al. JHEP 09 (2013) 029

Larkowski, et al. JHEP 05 (2014) 146

$$E = E_1 + E_2$$



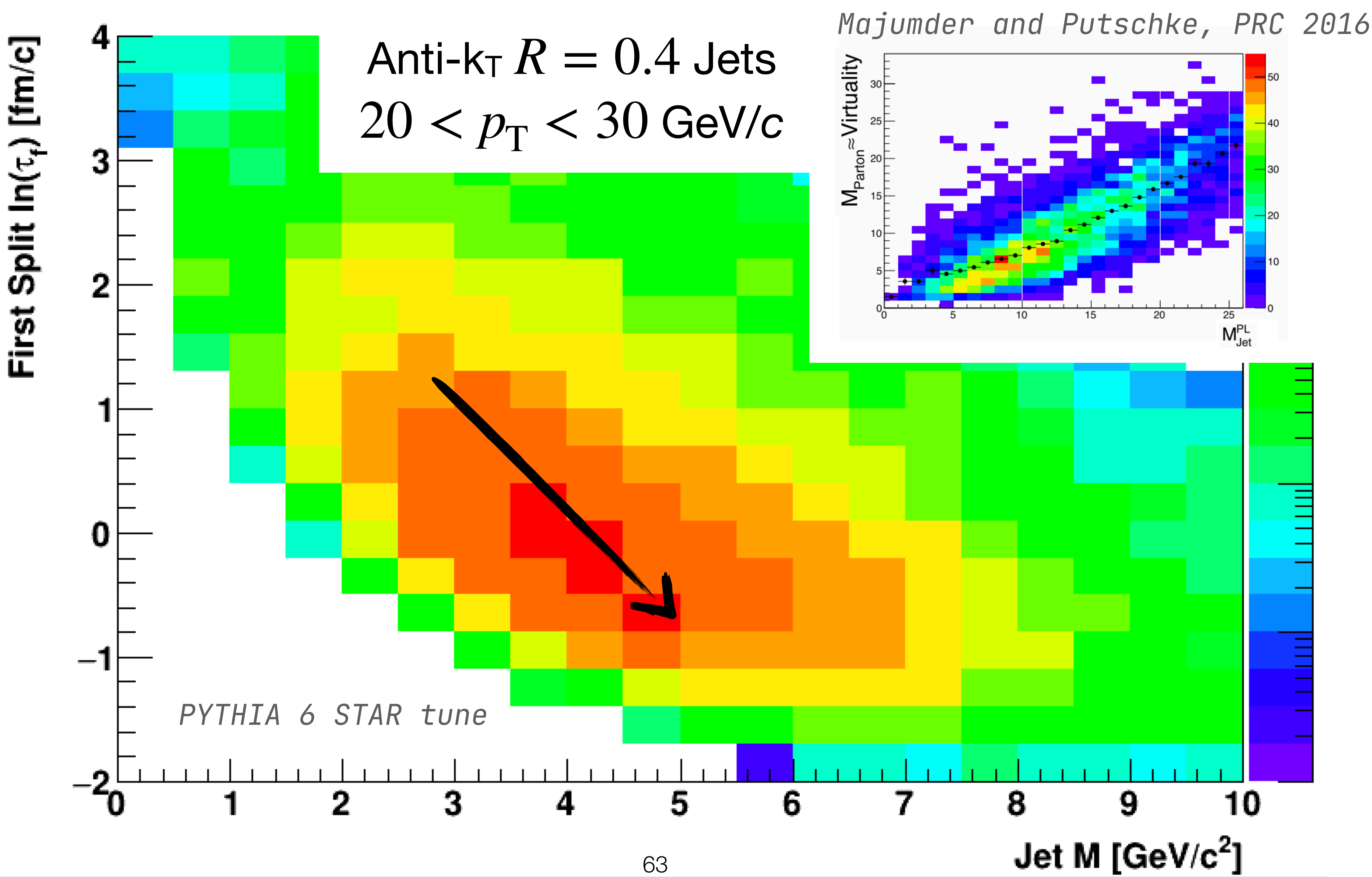
$$\tau_f = \frac{1}{z \cdot (1 - z) \cdot \theta^2 \cdot E} \ [\mathrm{fm}/c]$$

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

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

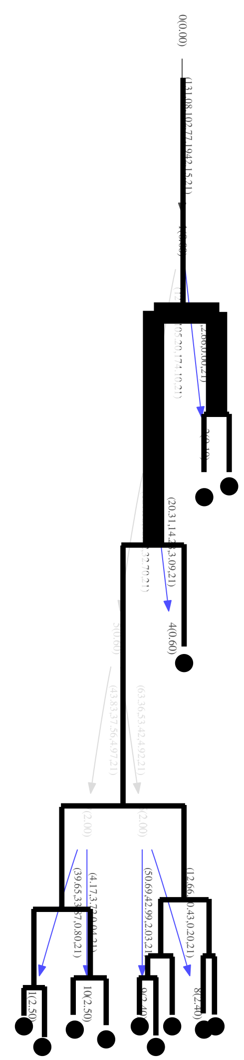
Chien et. al. 2109.15318

Formation time vs jet mass



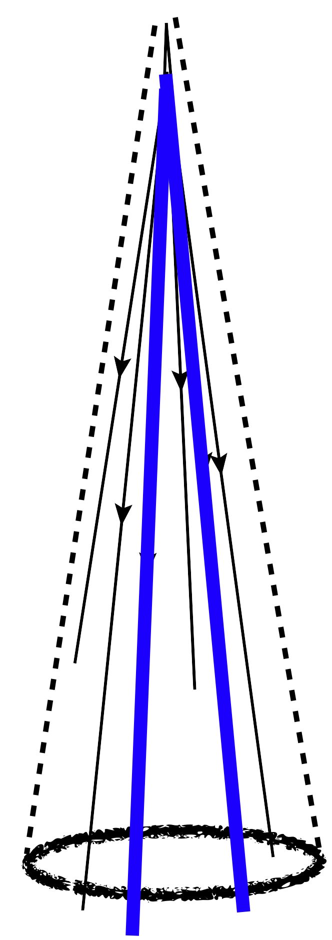
Identifying two regimes

- SoftDrop first split τ_f



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

- Leading and subleading ch-particle τ_f



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)

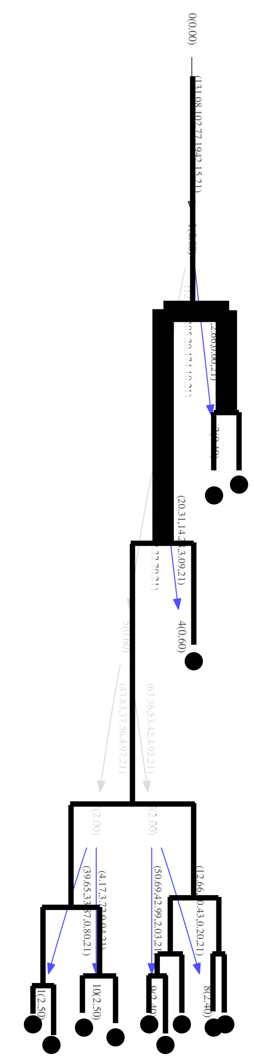
STAR Phys. Rev. D 104, 052007 (2021)

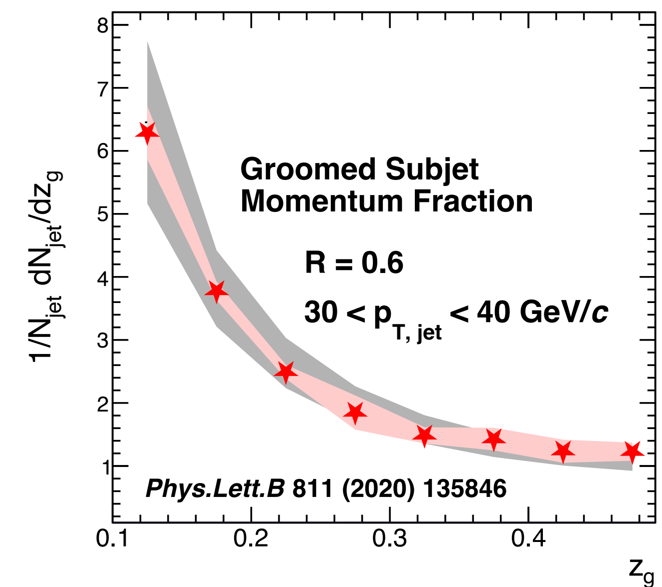
Kang, Lee, Liu, Neill and Ringer, JHEP (2020)

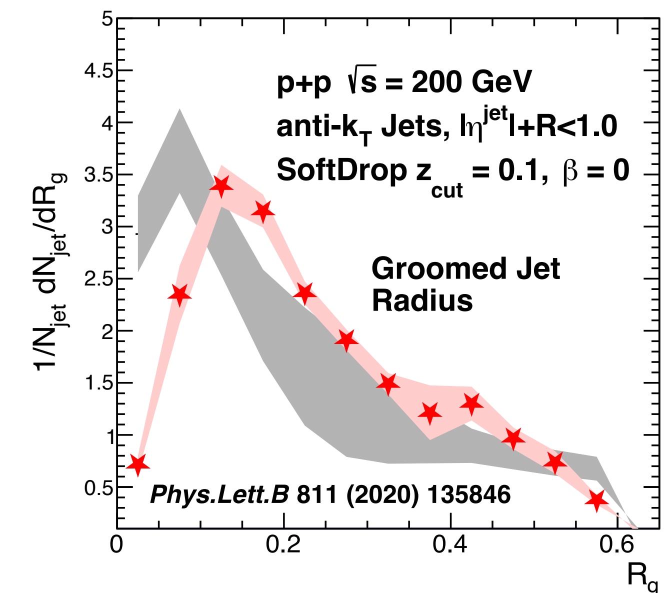
• SoftDrop first split τ_f

Expectations:

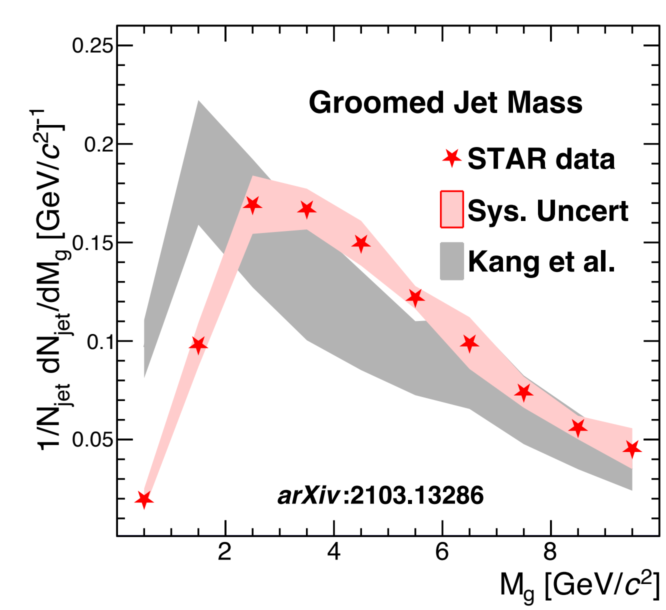
- **happen early in time with the expectation that first splits correspond to partonic splits**
- **Mostly perturbative in nature**



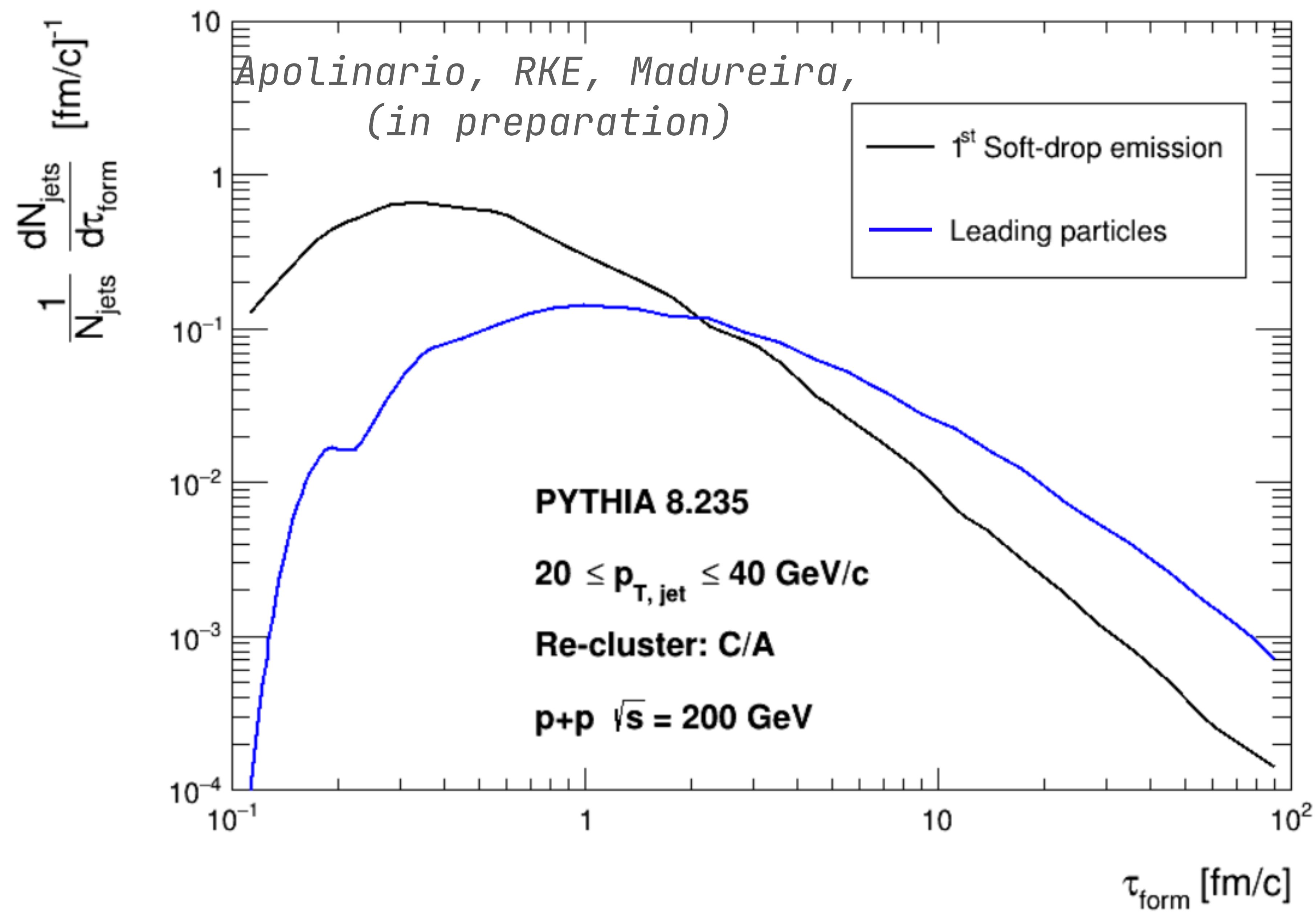




- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and high p_T



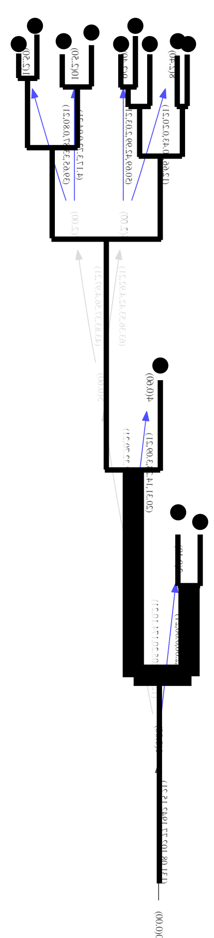
What do these distributions look like in PYTHIA?



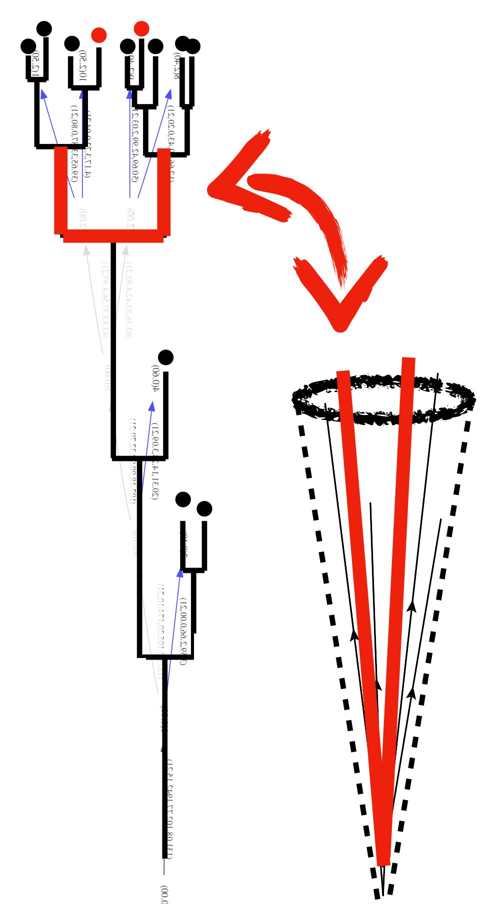
- As expected we see a significant shift between the two distributions
- Charged particles generally have a formation time much larger than the first splits

Connecting the two regimes

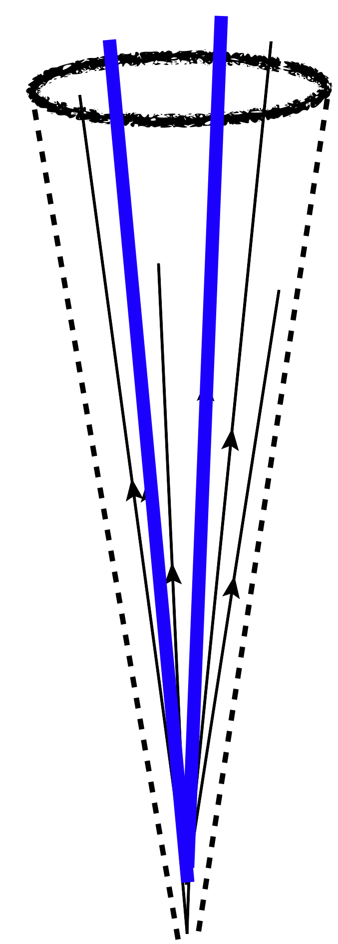
- SoftDrop first split τ_f



- SoftDrop split (varying z_{cut}) resolving the two leading charged particles

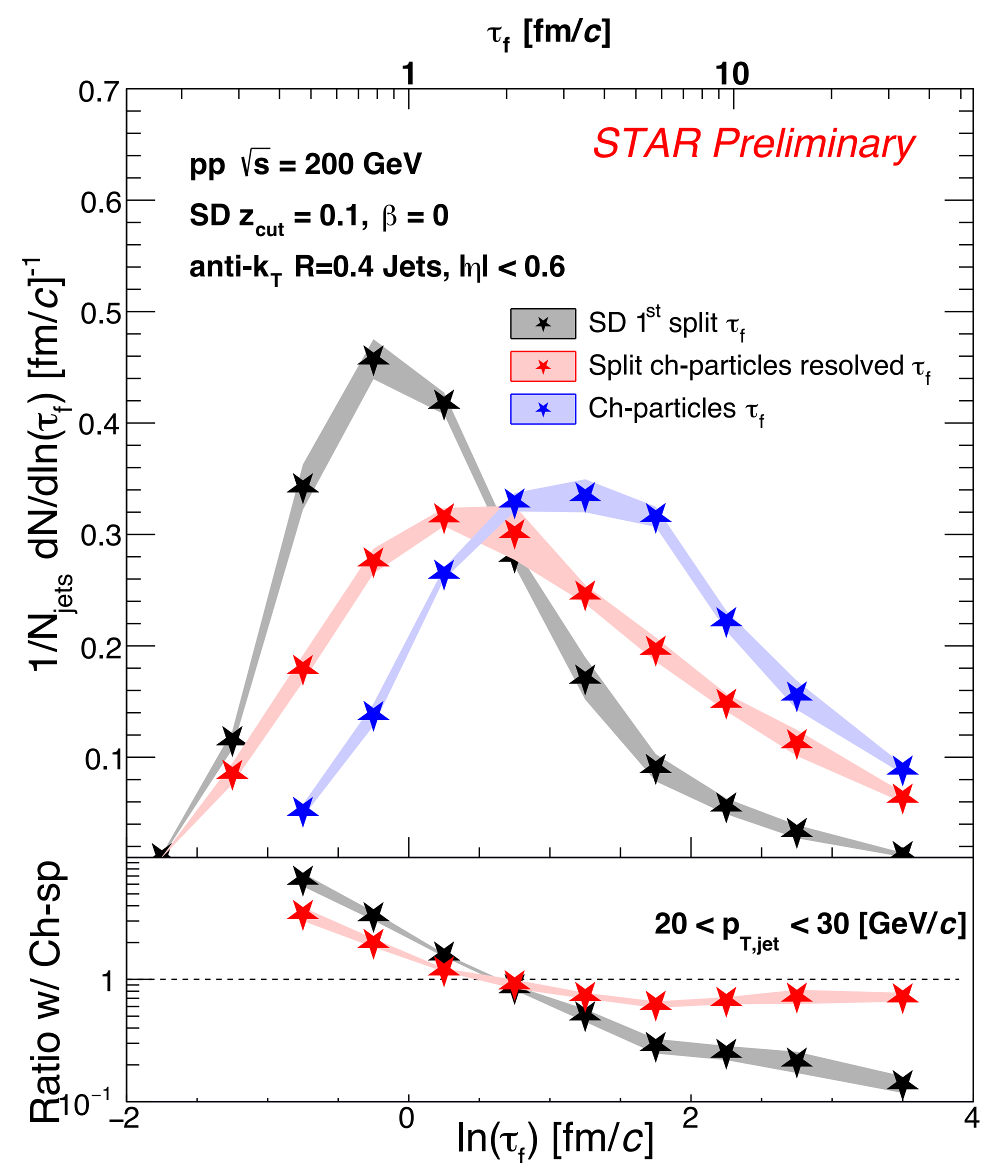


- Leading and subleading ch-particle τ_f



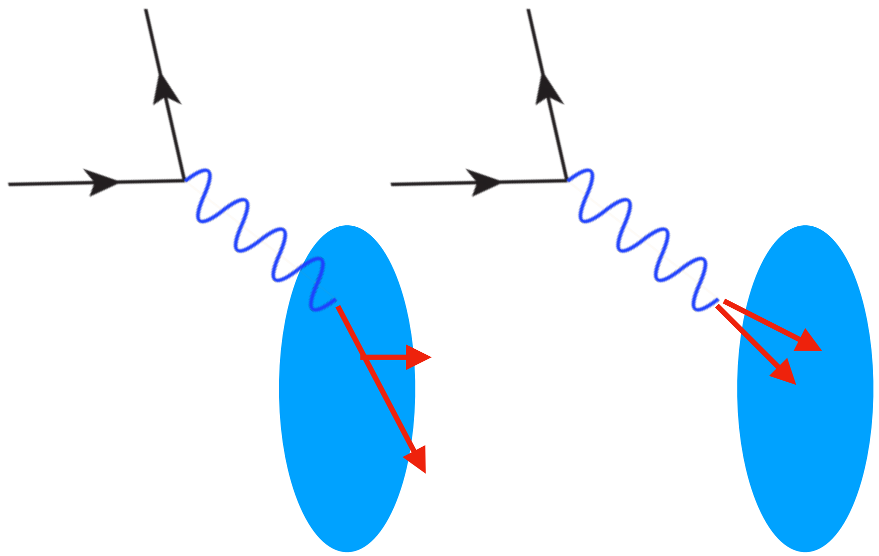
Formation times across various regimes within the jet shower

- **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**

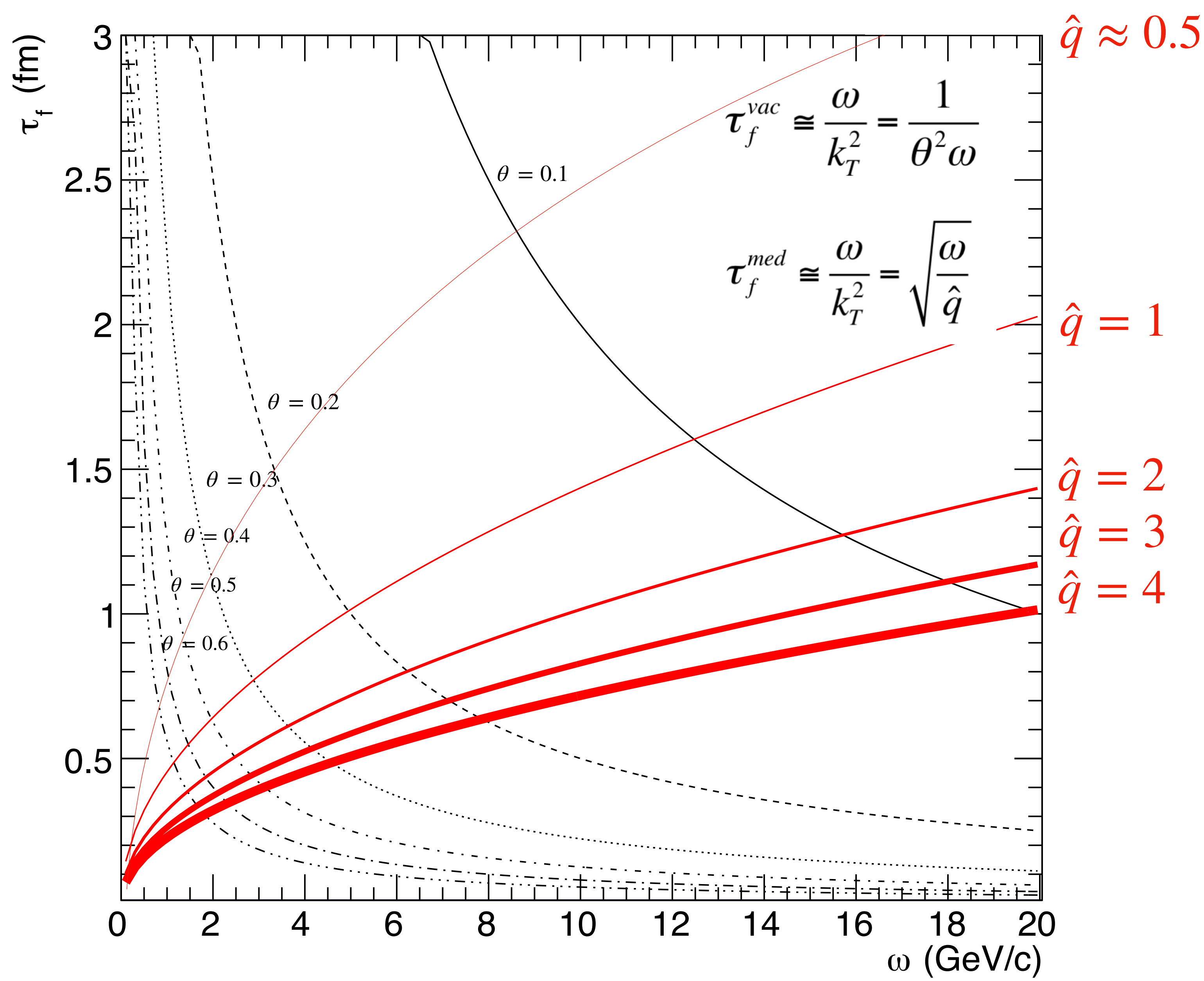


RKE (for STAR) pdf
Jets and 3D Imaging at the EIC Workshop

Exploiting substructure



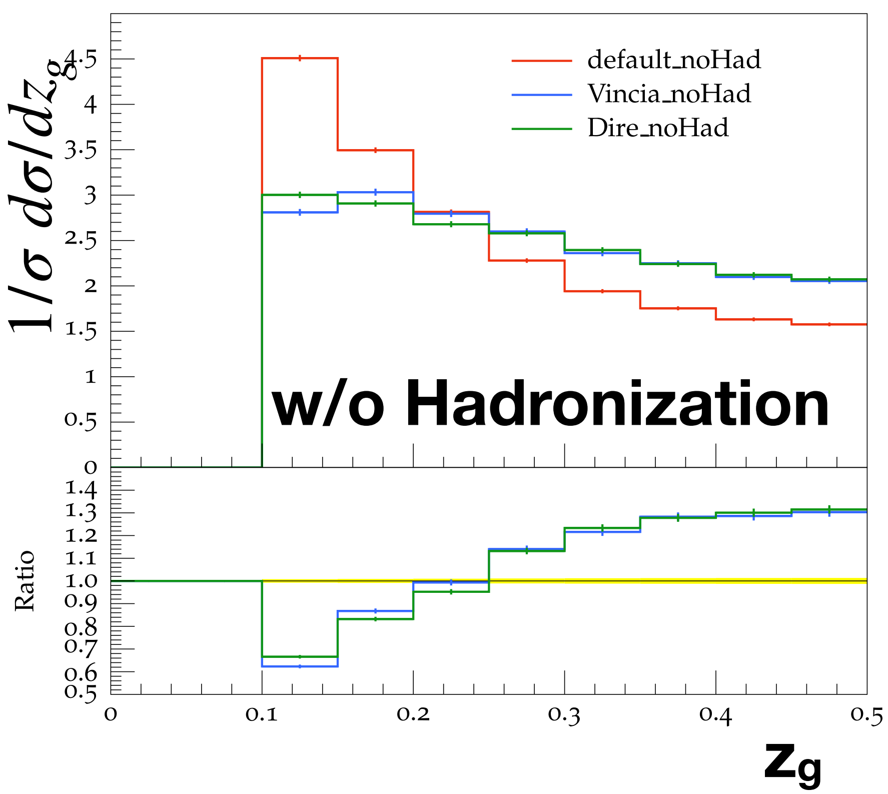
- With splitting/dijet energies roughly 5-30 GeV, we can study resolutions O(1-5) fm!
- Enabling differential measurements of similar kinematics but varying shower topology!



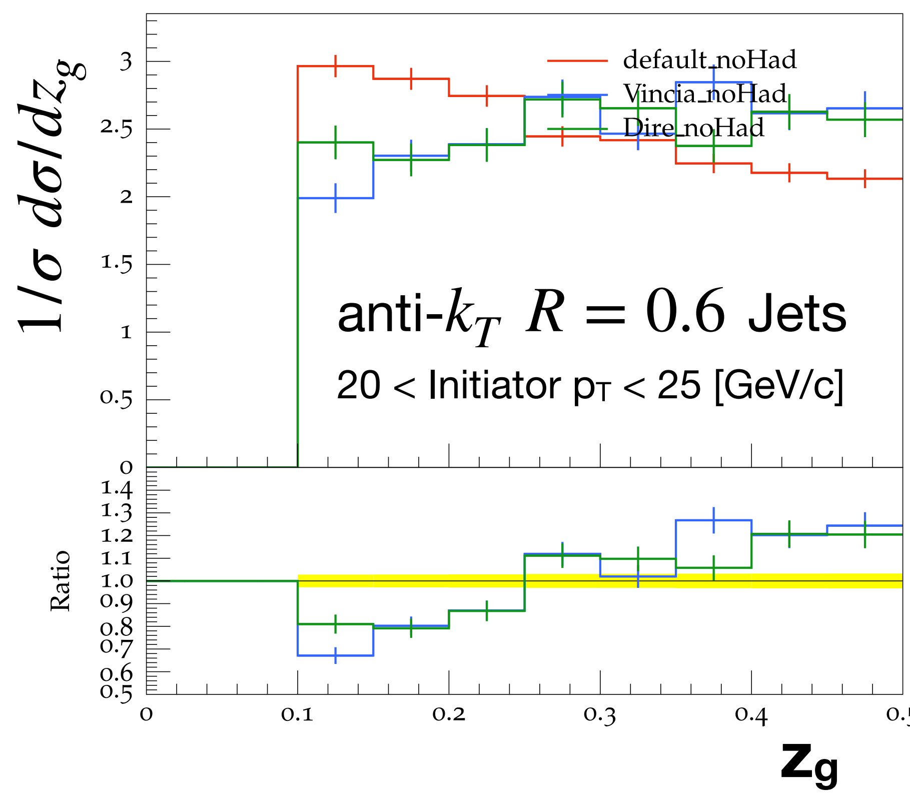
Effect of Parton Showers

PYTHIA 8.301

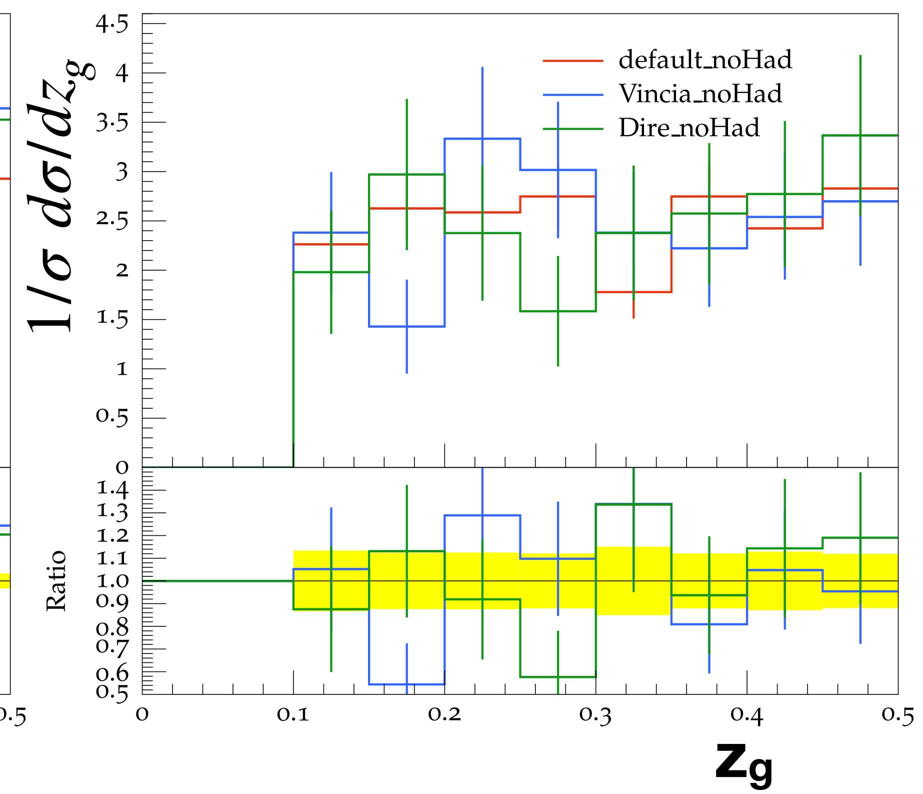
First Split



Second Split



Third Split



- At parton level, variations between shower models
- z_g shape becomes flatter as we move along the shower

2023-2025 @ RHIC

year	minimum bias [$\times 10^9$ events]	high-p_T int. luminosity [nb^{-1}]		
		all vz	$\|vz\|<70$cm	$\|vz\|<30$cm
2014 2016	2	27	19	16
2023 2025	20	40	36	24

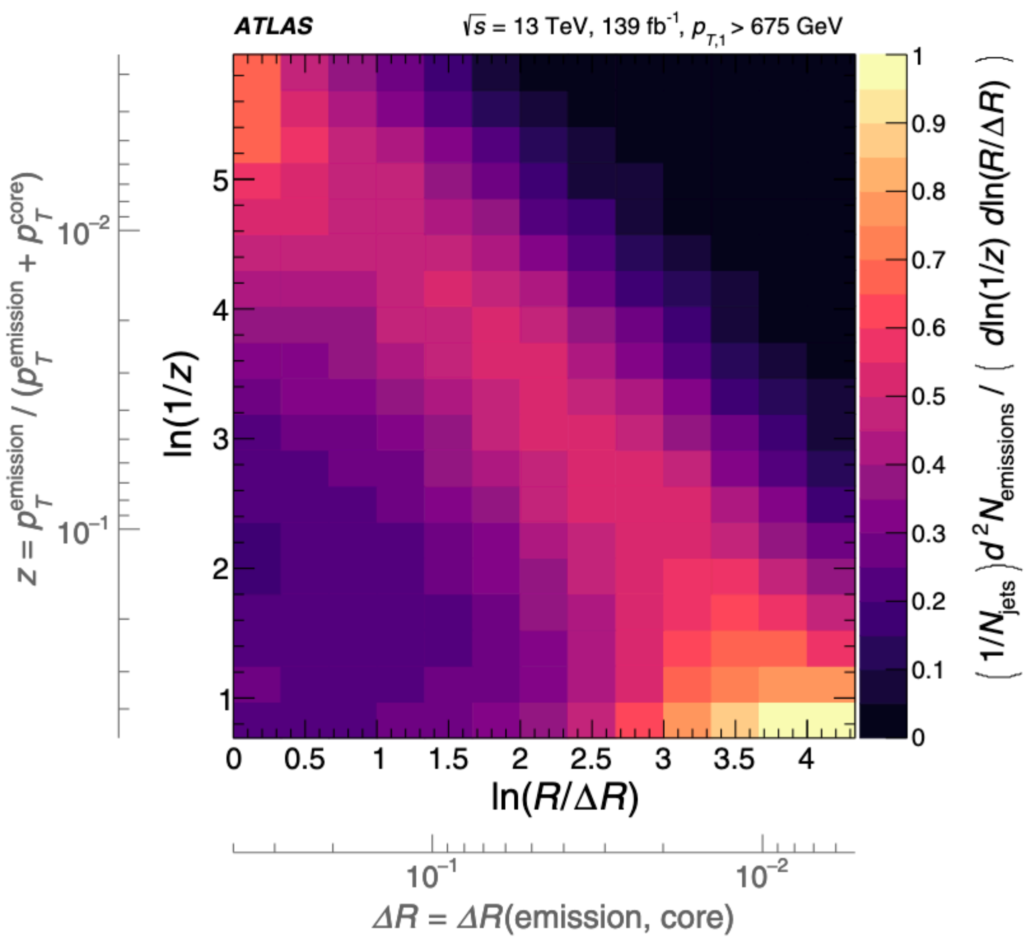
STAR w/ iTPC and forward upgrade

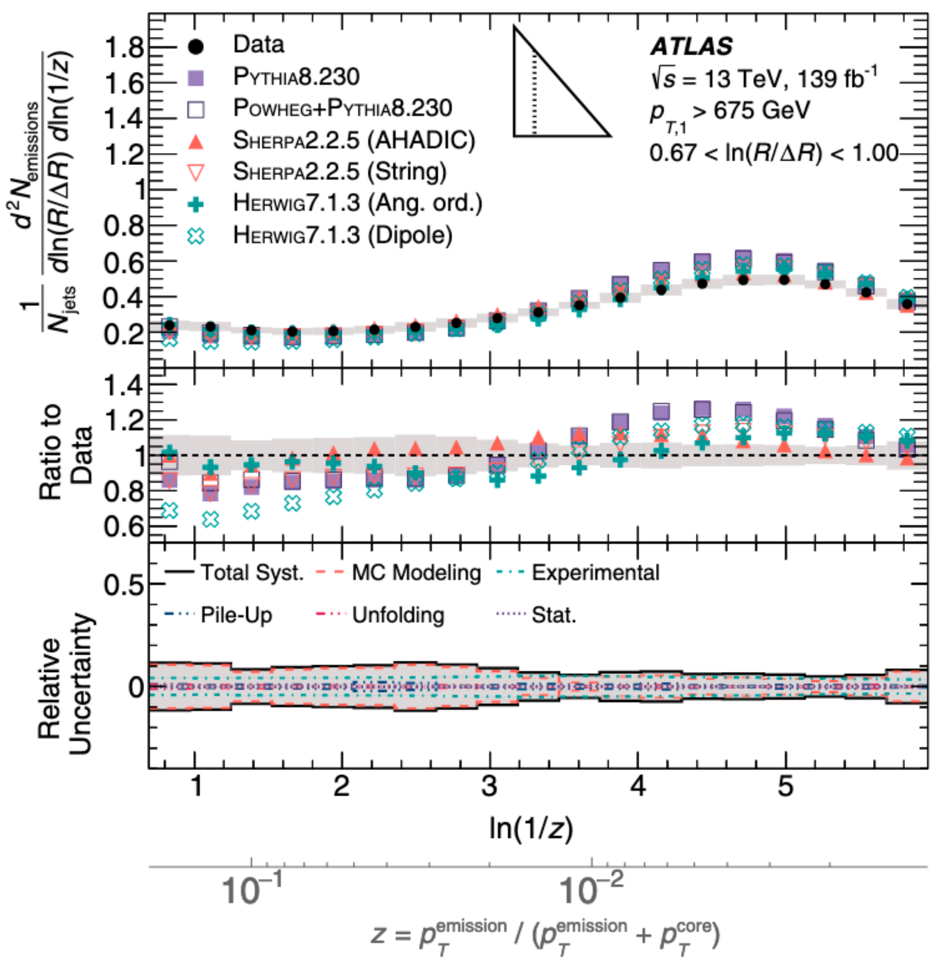
sPHENIX

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

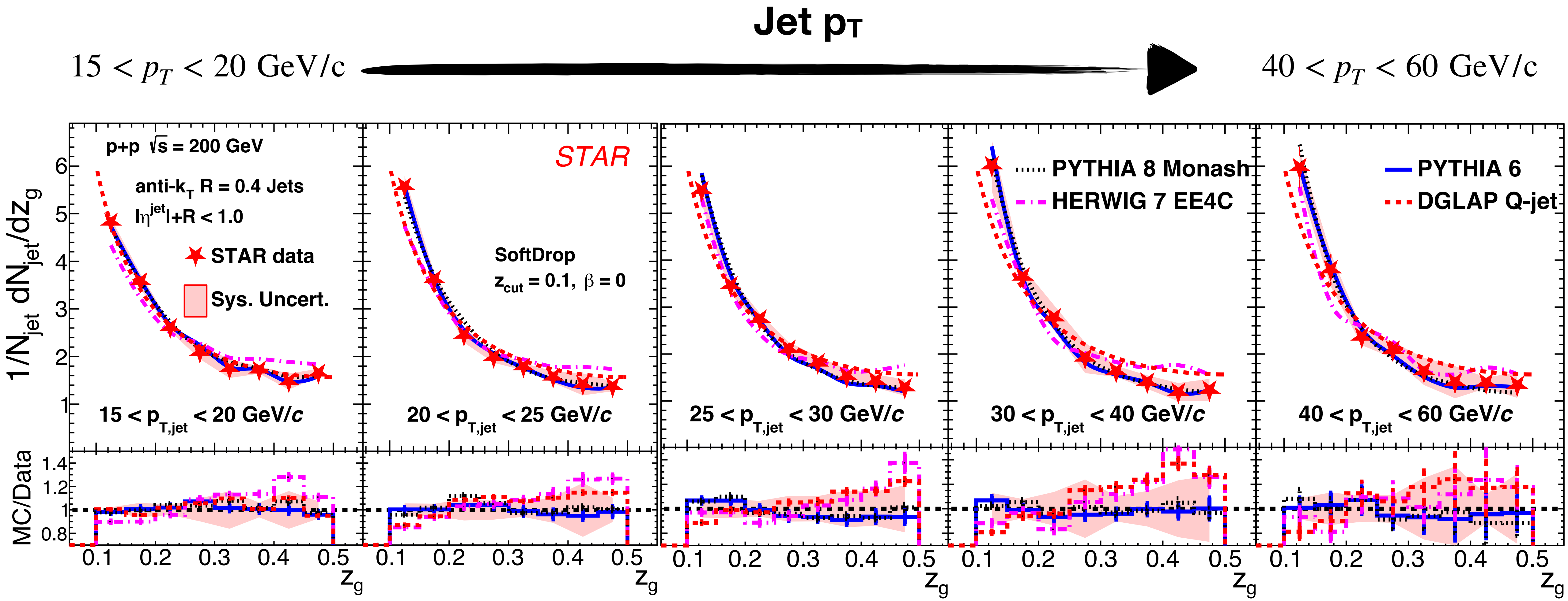
What are jets like in vacuum (pp) at the LHC?

ATLAS, Phys. Rev. Lett. 124, 222002 (2020)

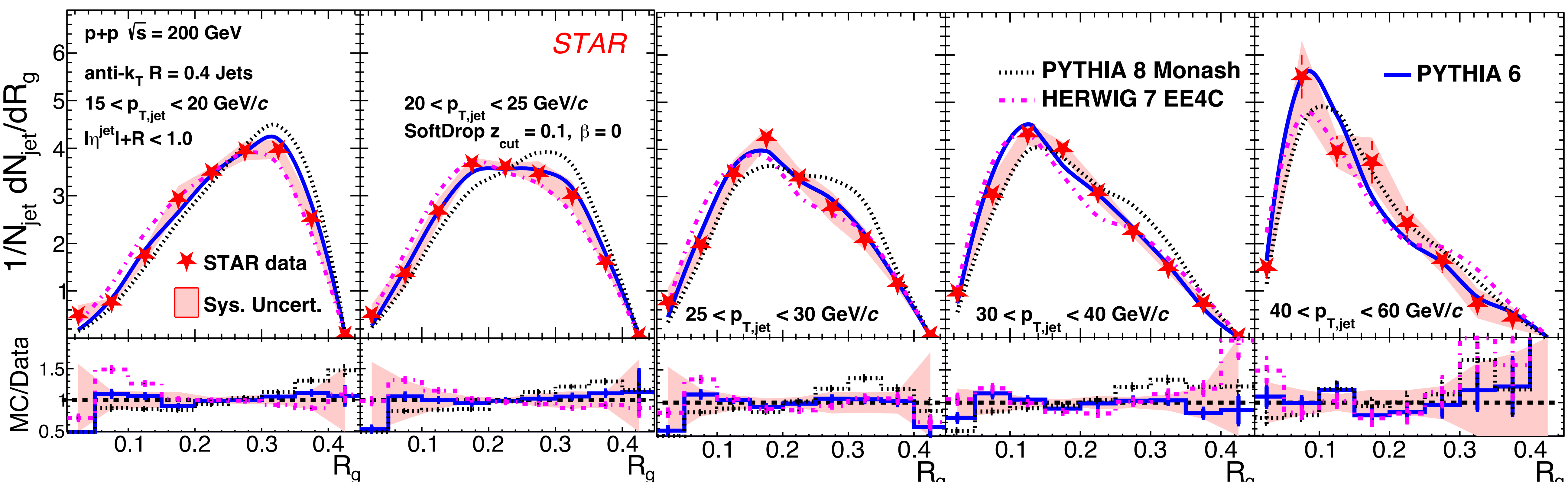


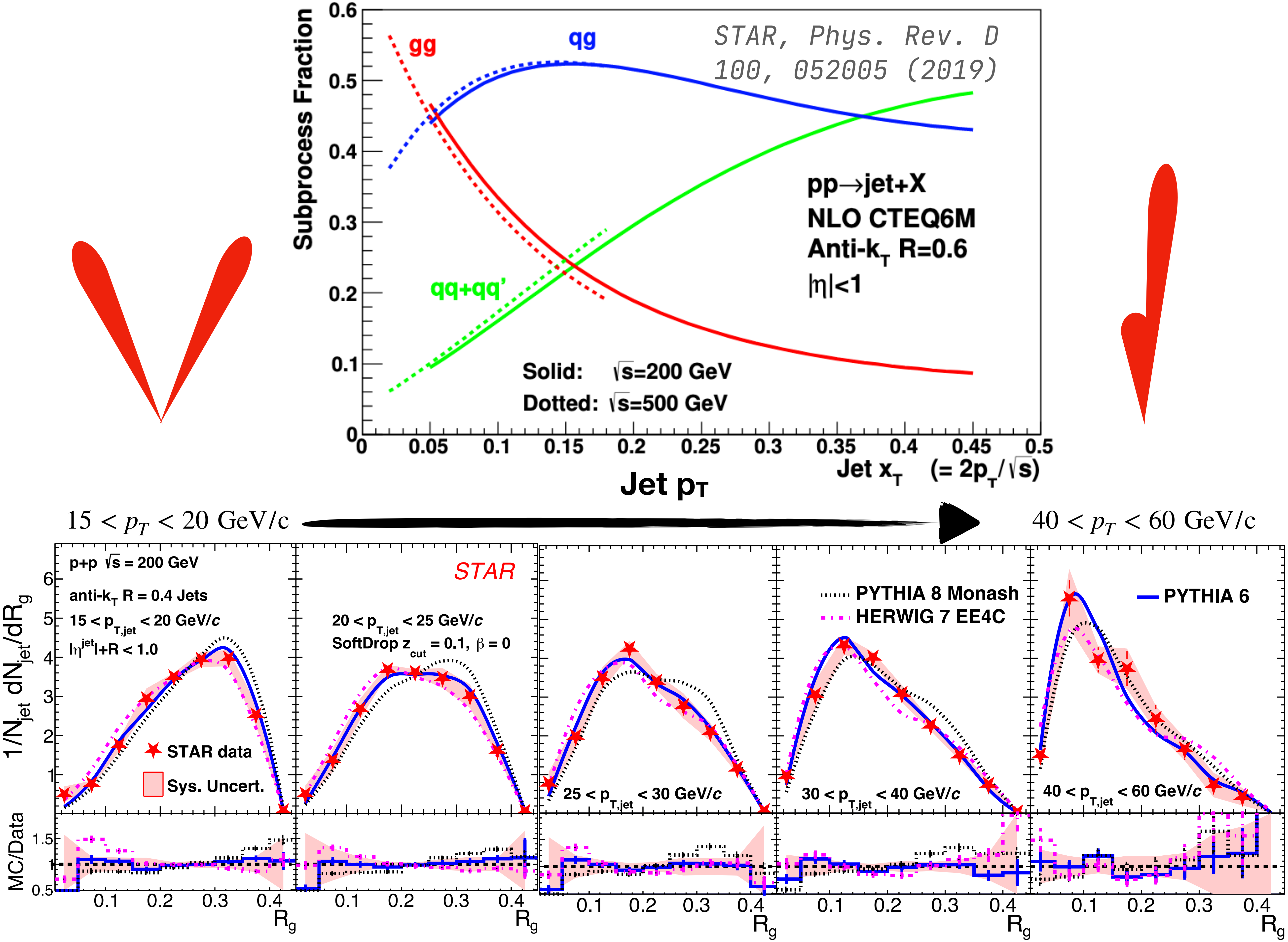


- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcases differences

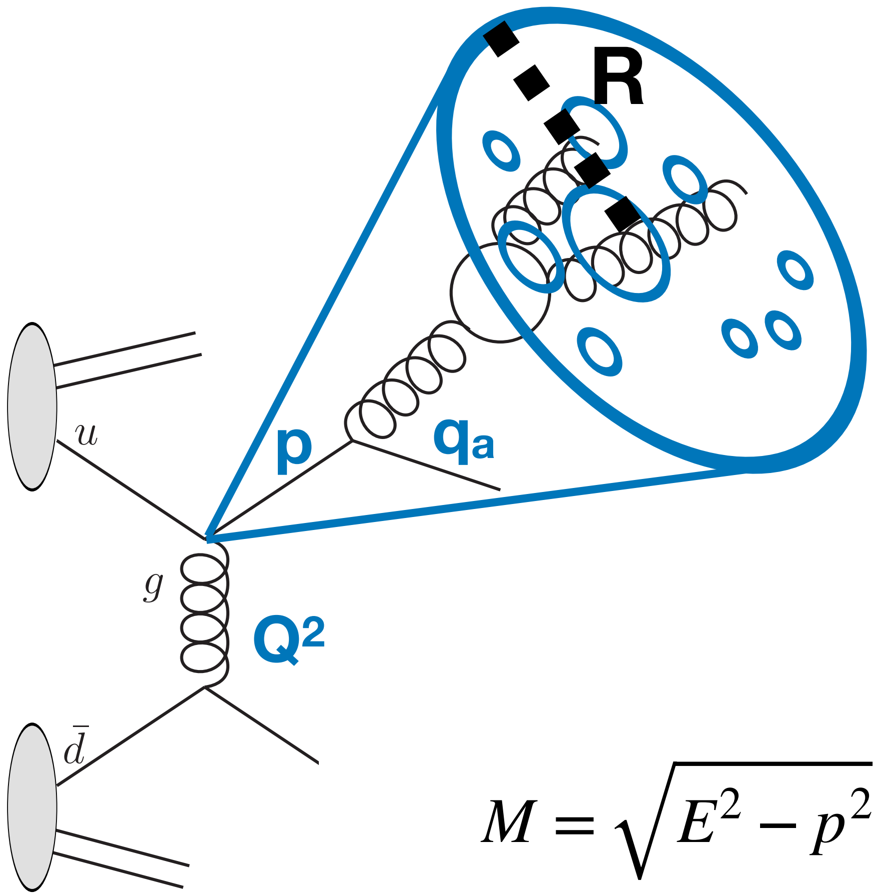


STAR, Phys. Lett. B 811 (2020)

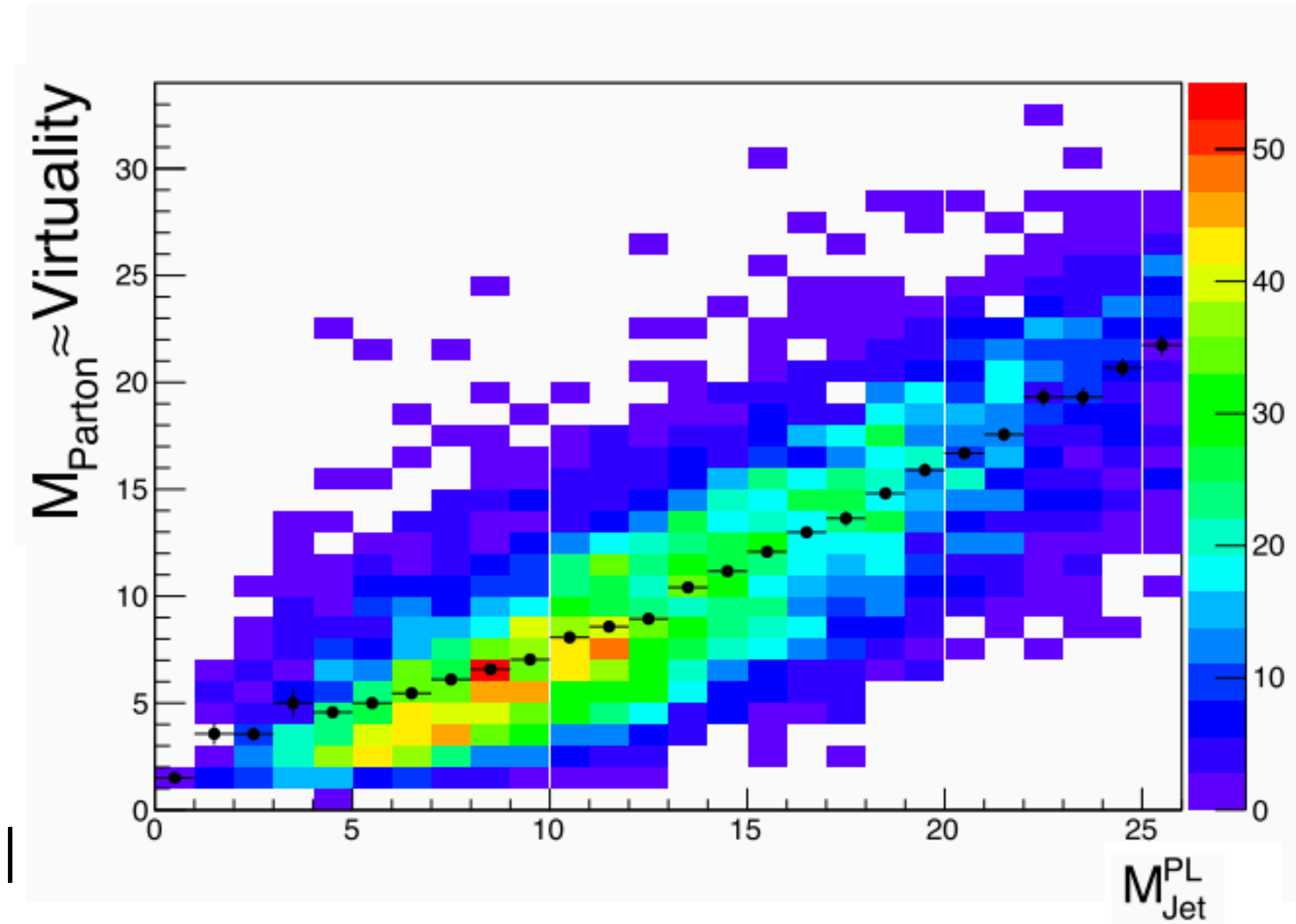



STAR, Phys. Rev. D 100, 052005 (2019)
Subprocess Fraction
gg
qg
qq+qq'
pp→jet+X
NLO CTEQ6M
Anti-k$_T$ R=0.6
|η|<1
Solid: √s=200 GeV
Dotted: √s=500 GeV
Jet x$_T$ (= 2p$_T$/√s)
Jet p$_T$
15 < p_T < 20 GeV/c
40 < p_T < 60 GeV/c
p+p √s = 200 GeV
anti-k$_T$ R = 0.4 Jets
15 < p$_{T,jet}$ < 20 GeV/c
|η^{jet}|+R < 1.0
STAR
20 < p$_{T,jet}$ < 25 GeV/c
SoftDrop z$_{cut}$ = 0.1, β = 0
25 < p$_{T,jet}$ < 30 GeV/c
30 < p$_{T,jet}$ < 40 GeV/c
40 < p$_{T,jet}$ < 60 GeV/c
PYTHIA 8 Monash
HERWIG 7 EE4C
PYTHIA 6
STAR data
Sys. Uncert.
1/N$_{jet}$ dN$_{jet}$/dR$_g$
MC/Data
R$_g$

Jet Mass



$$M = \sqrt{E^2 - p^2} = |\mathbf{p}|$$

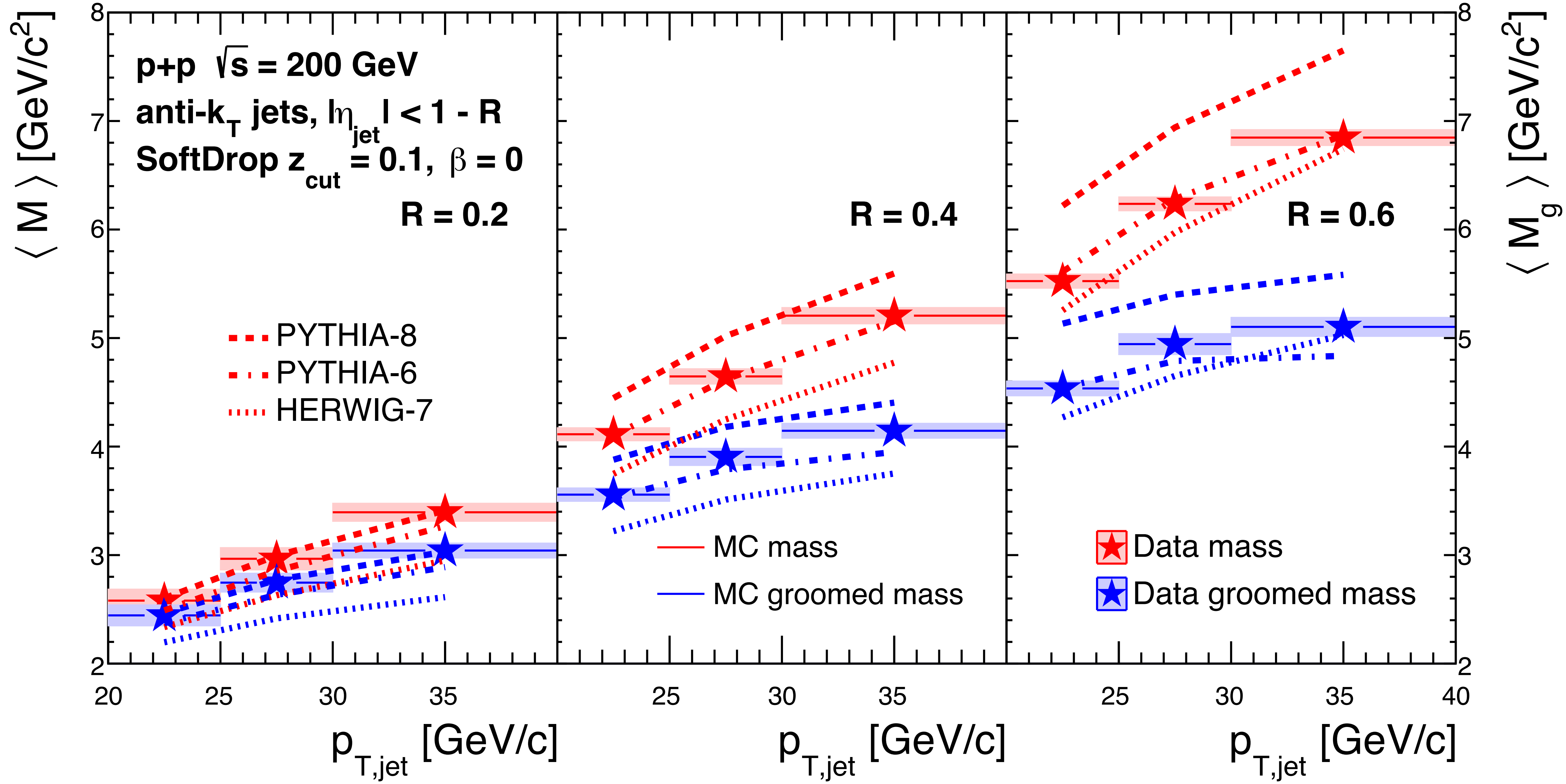


[no hadronization here - would smear correlation]

- Part of a broader class of angularity observables `Kang, Lee and Ringer, JHEP 2018`
- Sensitive to partonic dynamics i.e. virtuality `Majumder and Putschke, PRC 2016`
- Governs essentially the energy spread within a jet - ability to study differential properties of jets `ATLAS-CONF-2018-014` `ALICE, PLB 2018` `CMS, JHEP 2018`

Evolution of jet mass

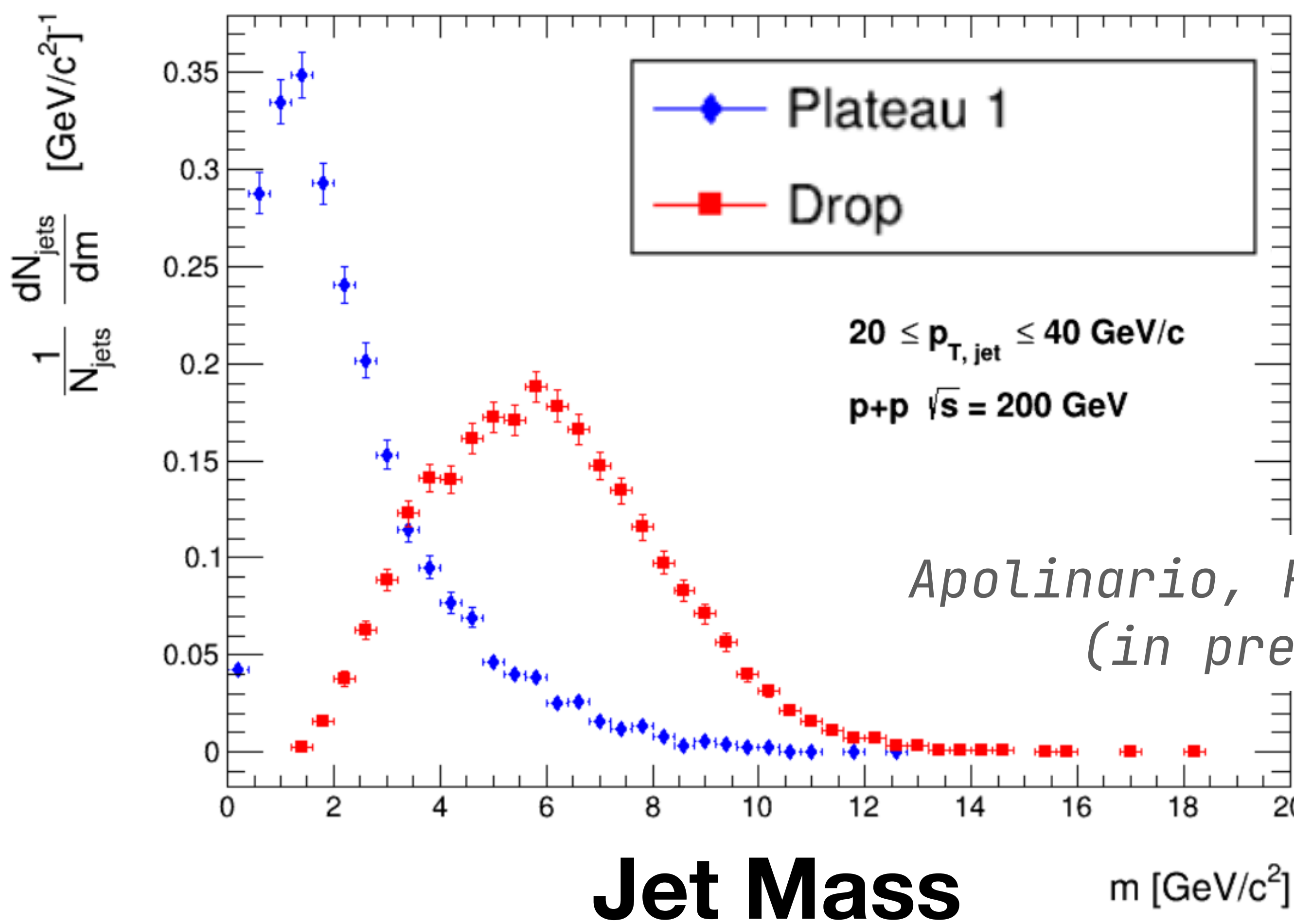
STAR Phys. Rev. D 104, 052007 (2021)



Significant reduction in the groomed jet mass due to removal of non-perturbative contributions around the jet periphery

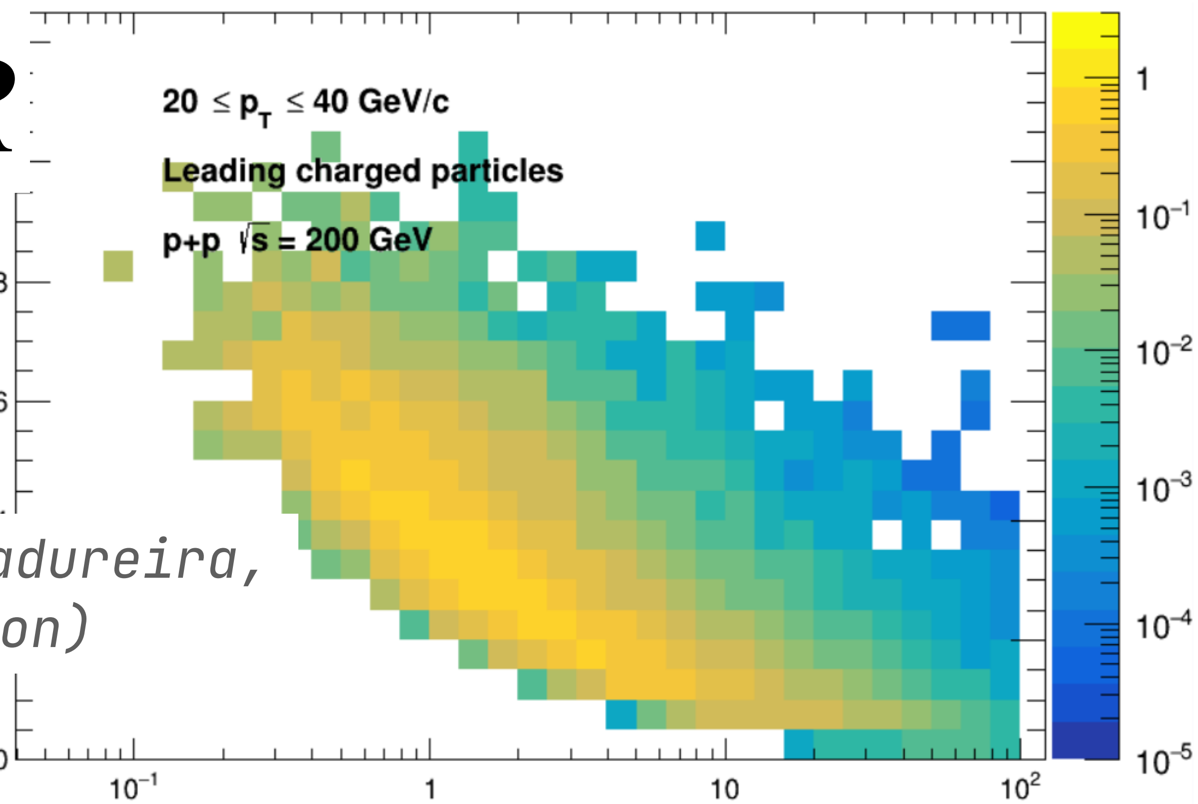
Where do we go from here?

Studying the plateau



Jet Mass

ΔR



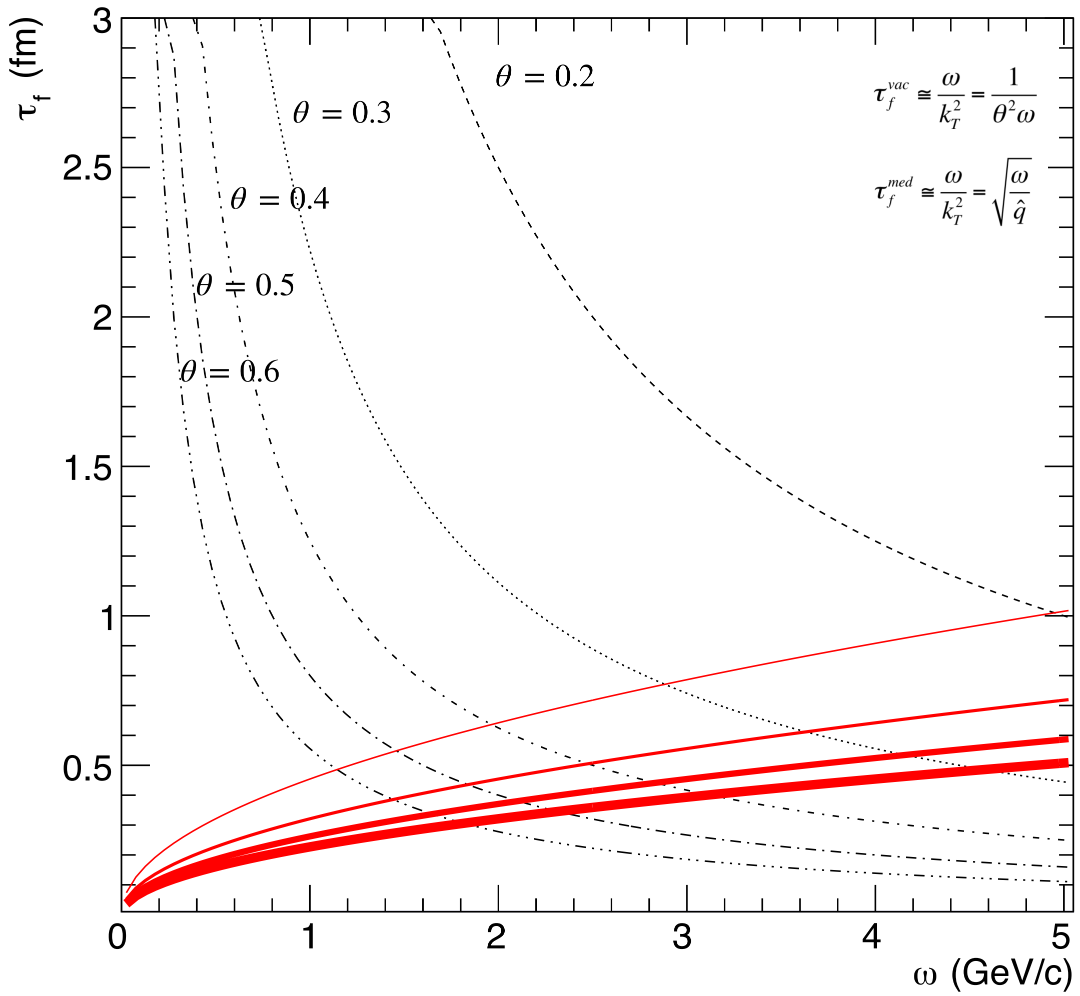
Charged Particle τ_f fm/c

Apolinario, RKE, Madureira, (in preparation)

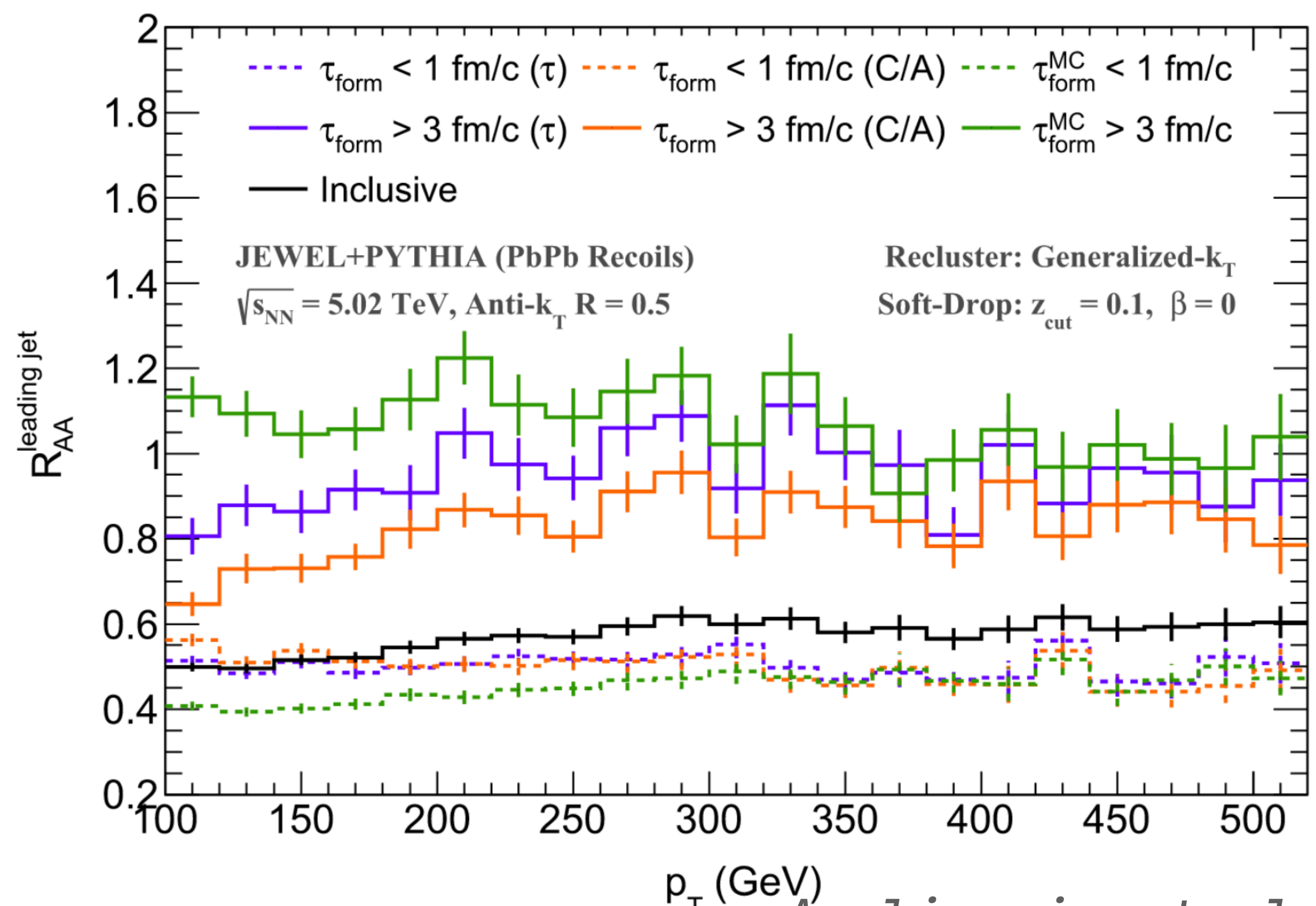
- Selection on the resolved formation time essentially sculpts the jet mass and opening angles
- Reproduce correlation between later times and smaller masses (virtuality) and narrower opening angles - Important handle on particle production and hadronization

Where do we go from here?

Time resolved QGP tomography



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

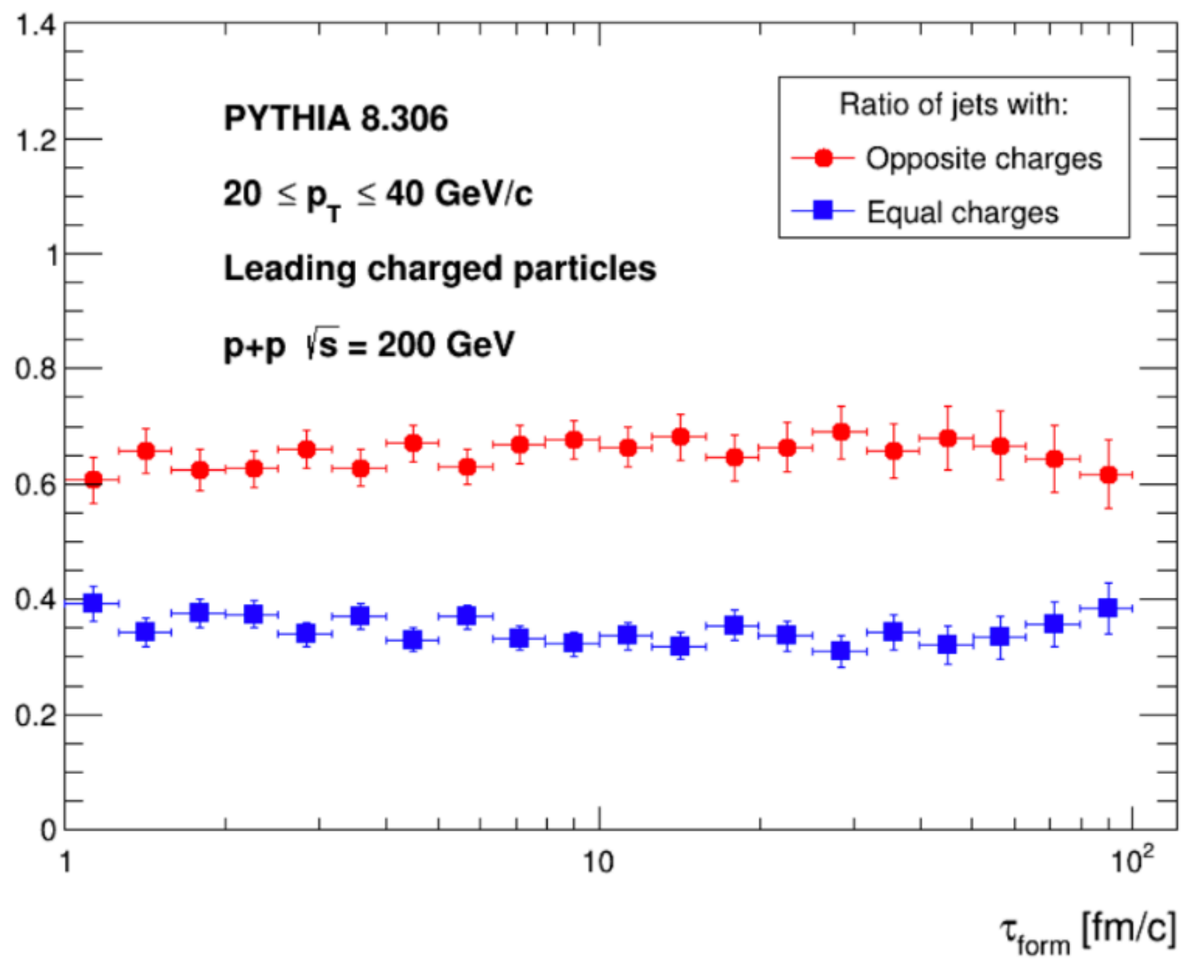


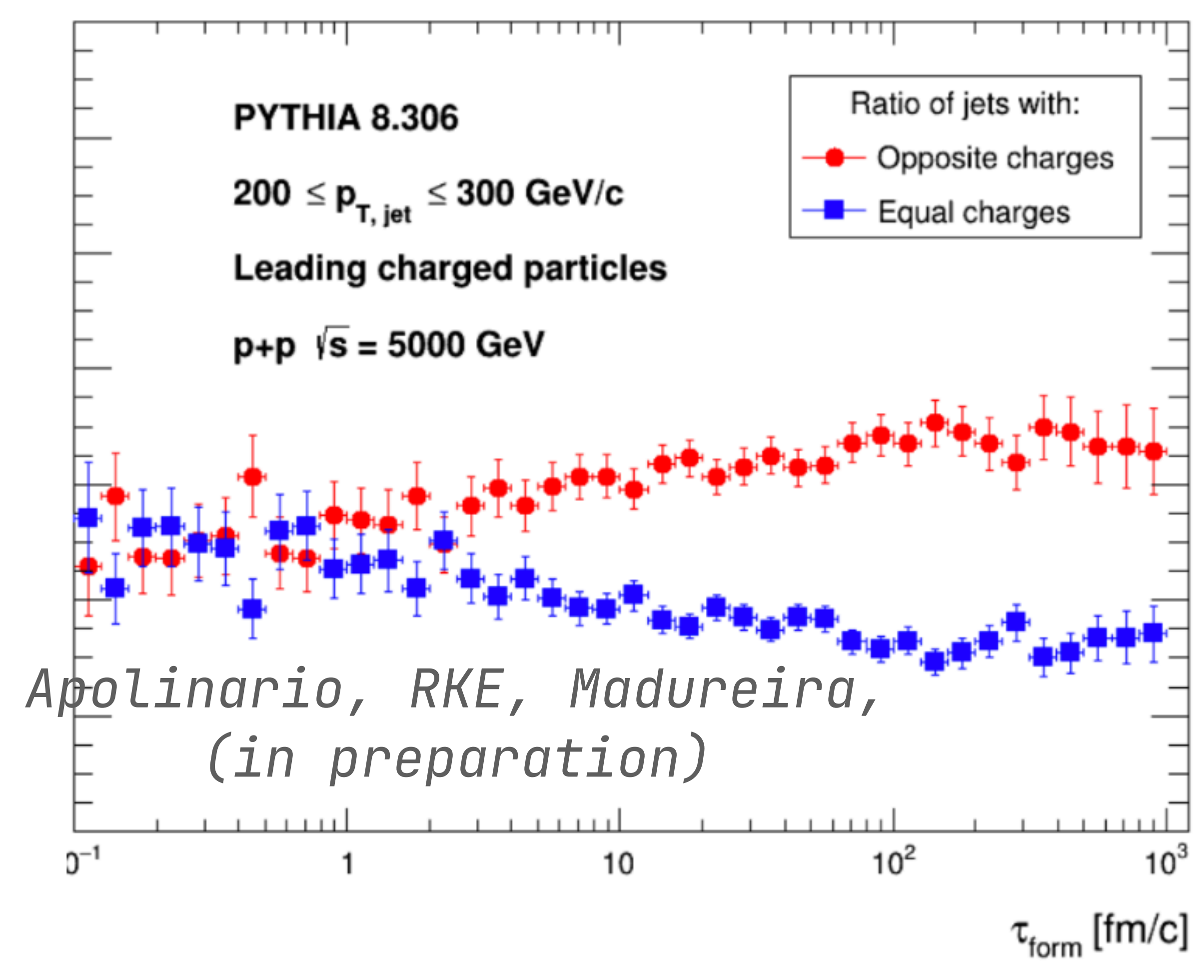
- Searching for hard medium induced gluon emissions, medium coherence length etc…

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

Where do we go from here?

Extending the charge-correlations in formation time

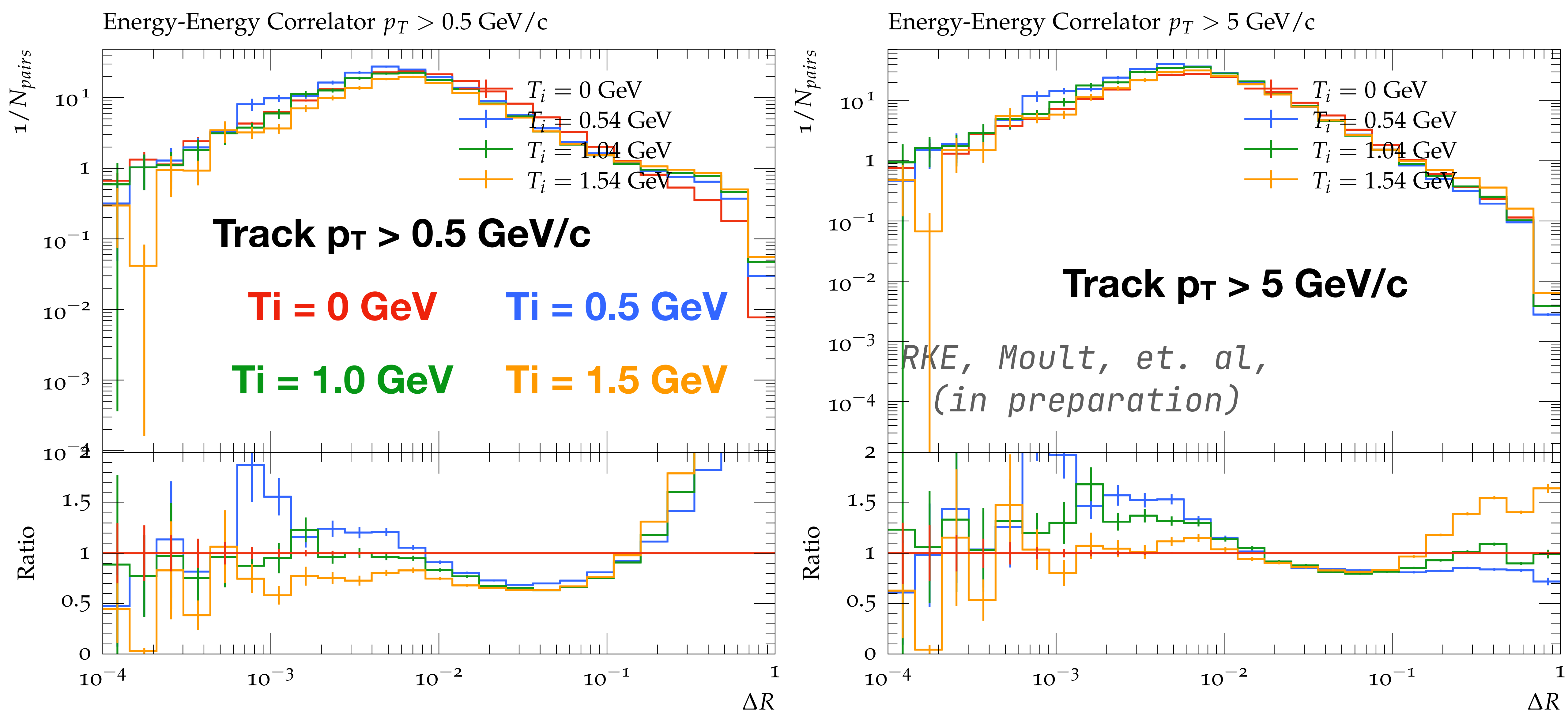




- Significant split in the formation times for 3rd particle to be opposite sign - quantitative categorizing of charge conservation in jets vs time
- Emerging as a new avenue thats complementary to jet substructure focused on understanding hadronization mechanisms

Where do we go from here?

Energy-Energy Correlators in Heavy Ions



- Energy correlators highlight impact of varying 'Temperature' on the jet shower

Measurements ongoing at STAR in pp and AuAu Collisions