Perturbative and non-perturbative effects in jets at RHIC

CFNS Workshop:
Advancing the Understanding of Non-Perturbative QCD Using Energy Flows
September 19, 2022

Isaac Mooney (Wayne State University → Yale University)

Introduction

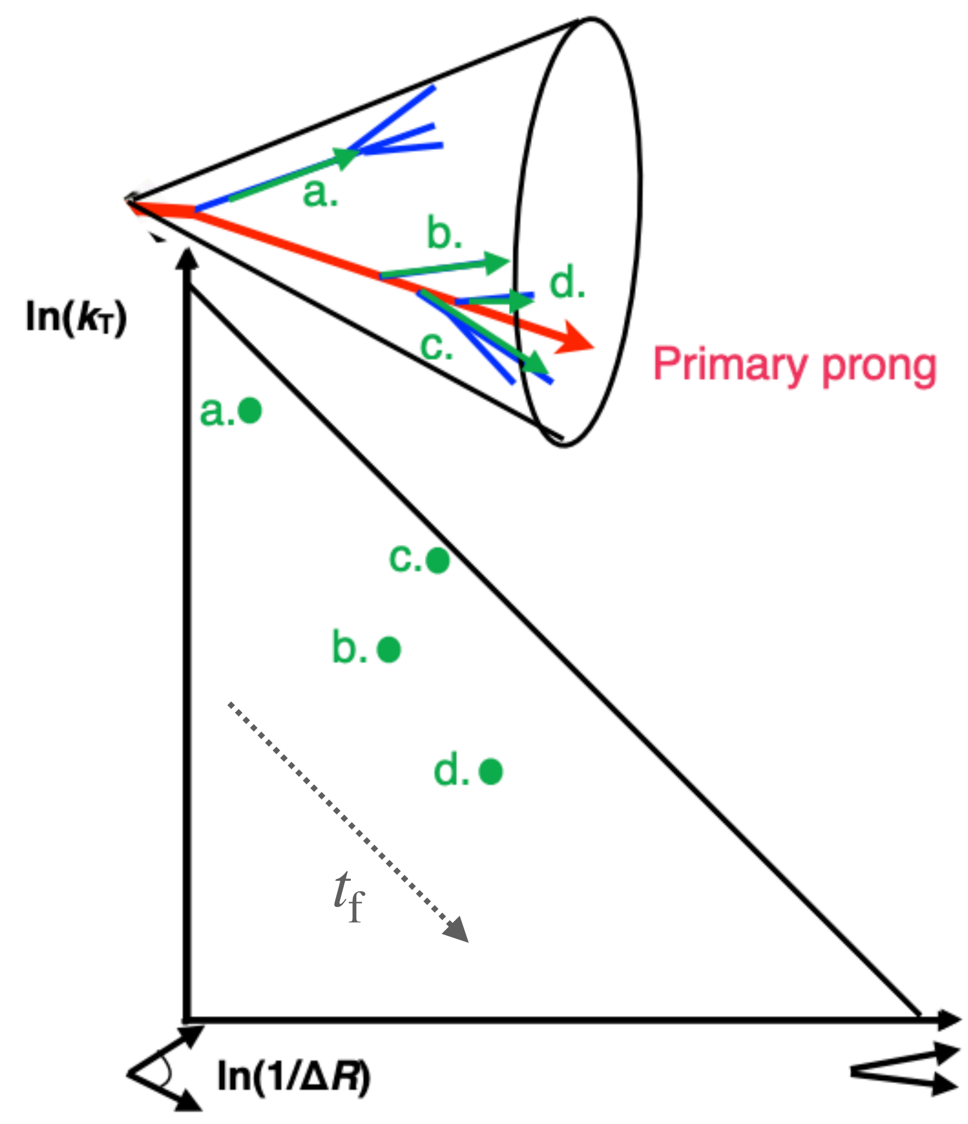
Jets

Multi-scale: perturbative ("early"-stage) + non-perturbative QCD ("late", e.g. hadronization)

Data ~ theory for e.g. jet X-sec, using only pQCD production (and PDFs)

But understanding substructure requires calculations/MC for later/softer/narrower splits
+ measurements which highlight them!

Image: Laura Havener



$$t_f \sim \theta^{-2} E^{-1}$$

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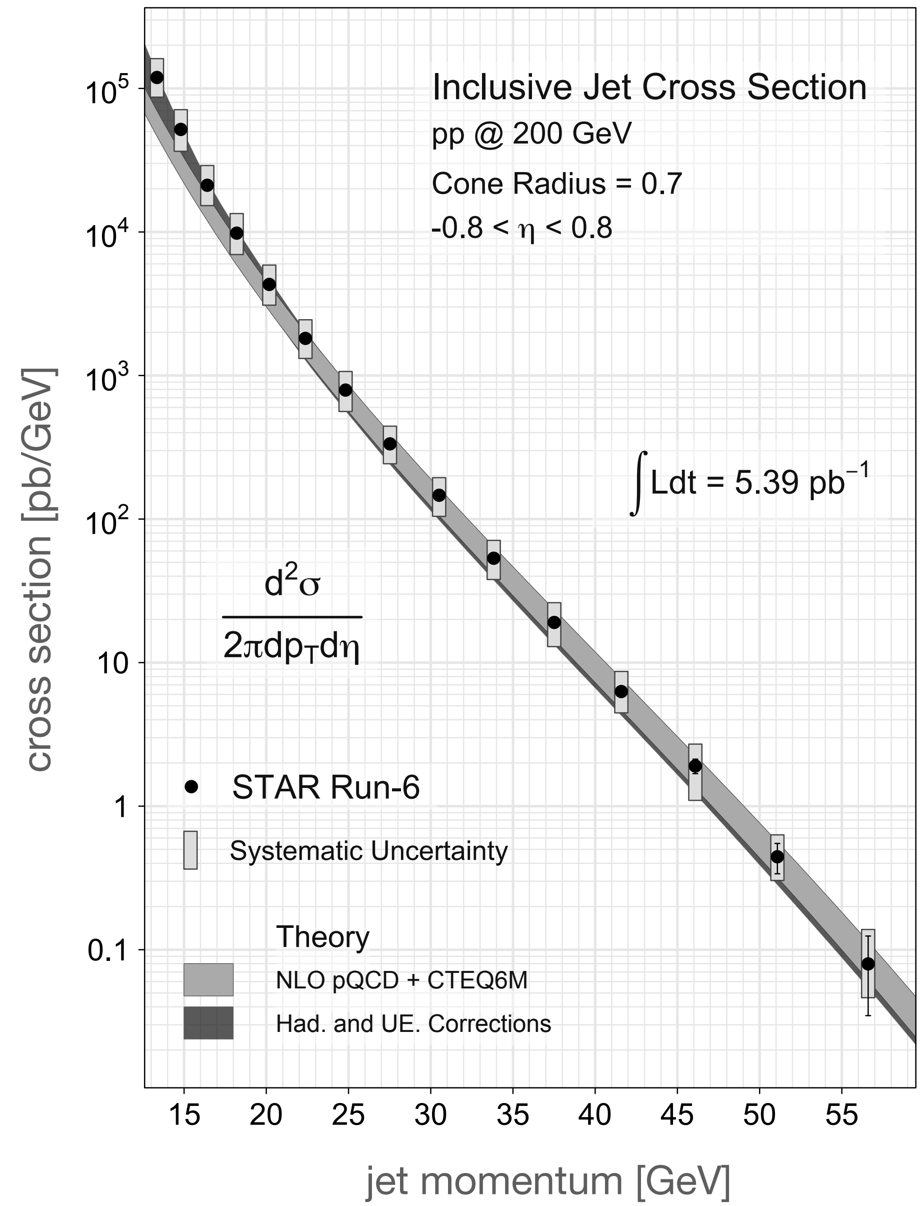
Tai Sakuma, thesis



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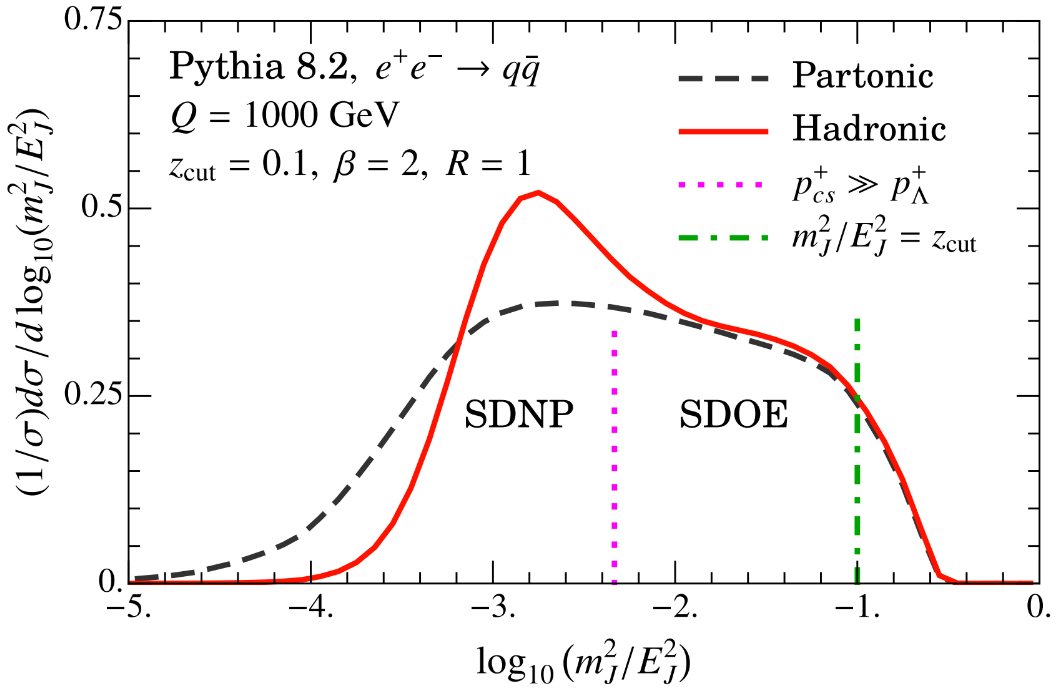
Hoang, Mantry, Pathak, Stewart, [JHEP 12 (2019) 002]

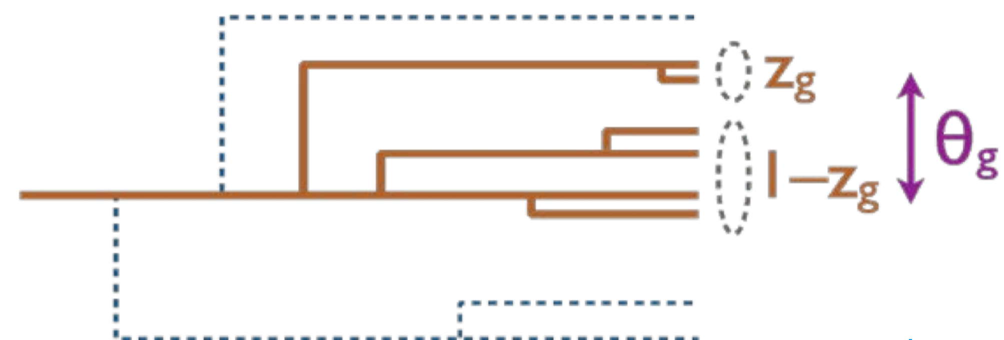


Avoiding NP

SoftDrop grooming

Suppress wide-angle non-perturbative radiation for more direct theory comparison; closer to parton-level

Image



Image

momentum fraction, z_g

angle, R_g

$$z > z_{\mathrm{cut}}\ \theta^{\beta}$$

energy threshold

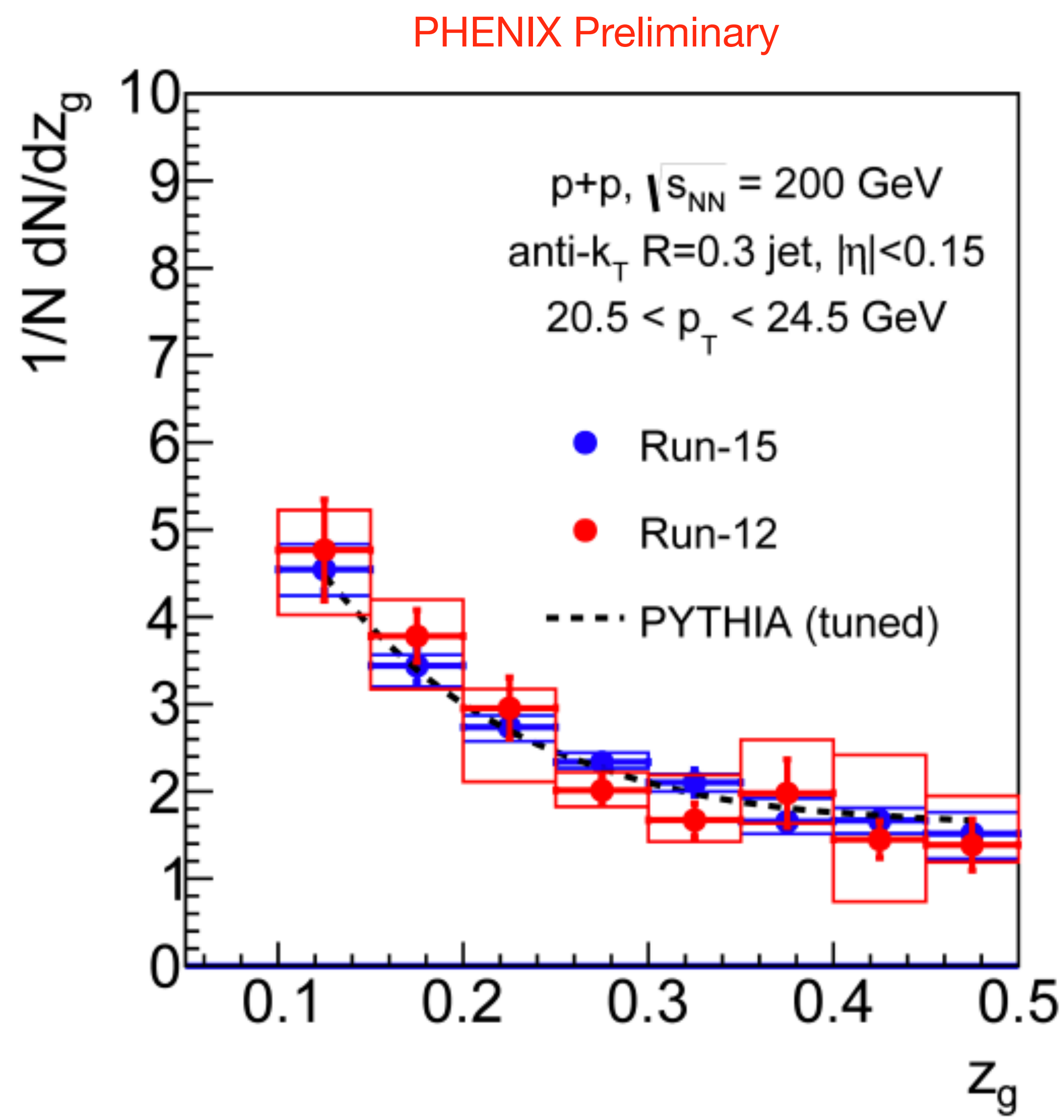
angular exponent

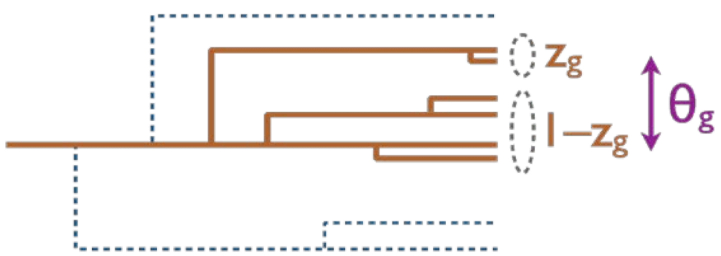
Approach: decluster angular-ordered splitting tree by removing prongs which fail the criterion

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

Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014), 146

SD measurements

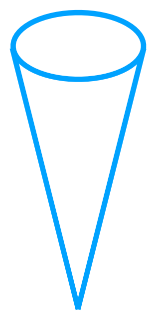


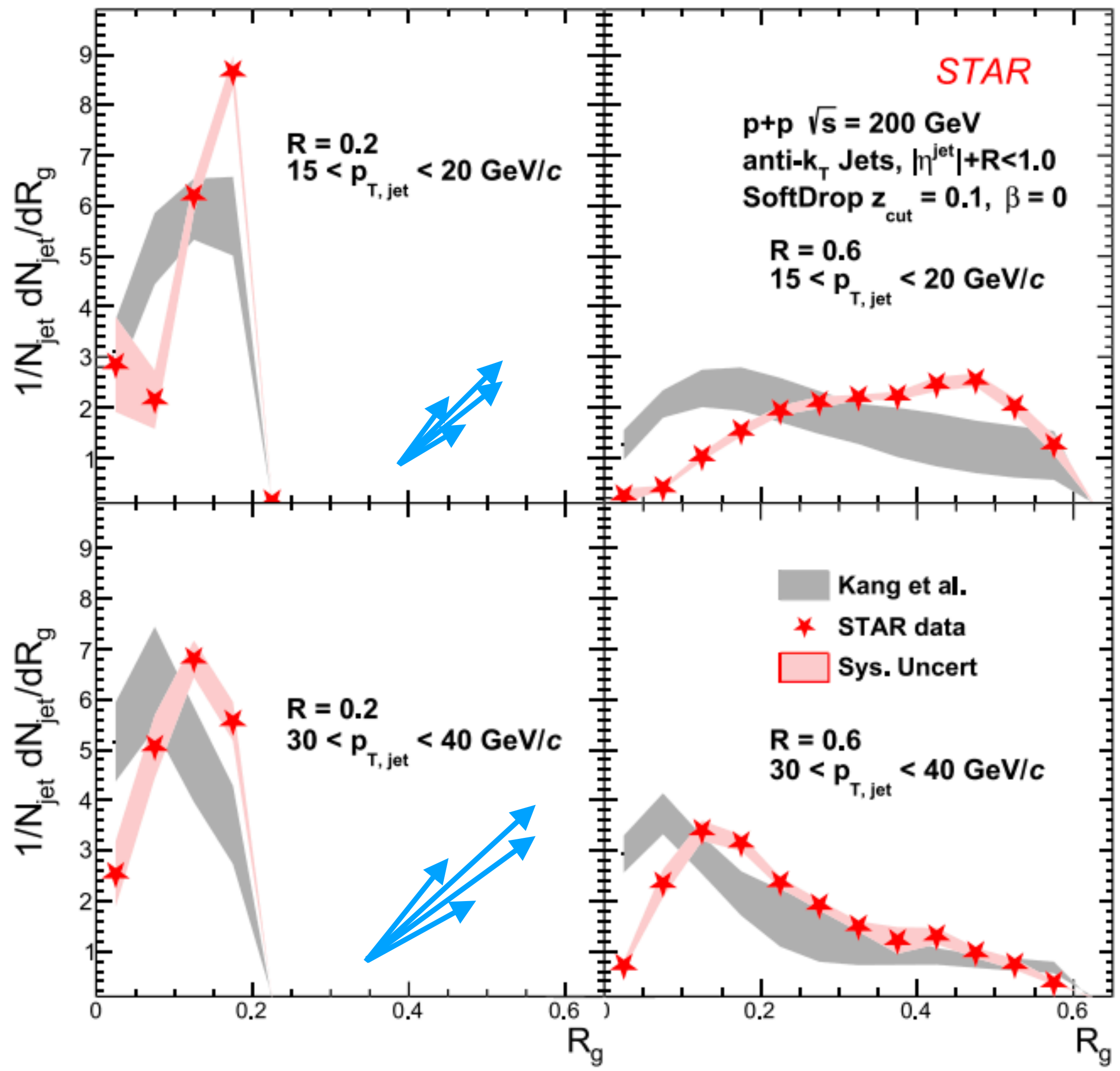


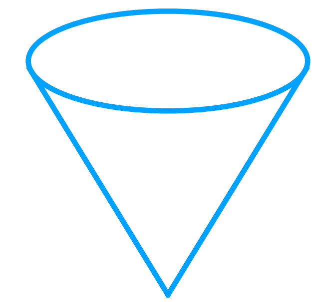
Overall rough agreement with MCs (although MPI have to be tuned)

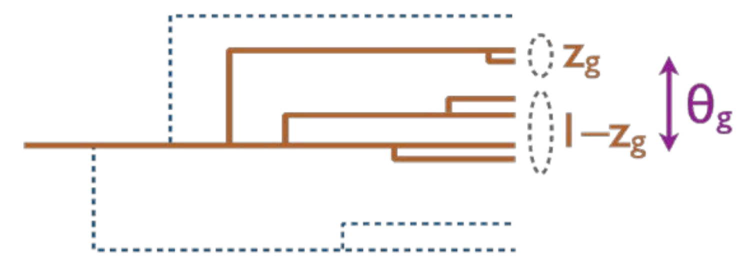
SD measurements

PLB 811 (2020) 135846







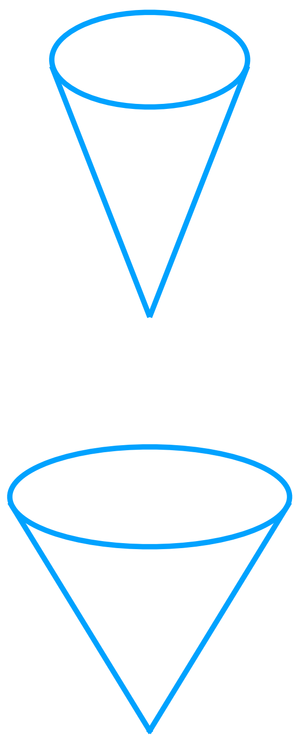


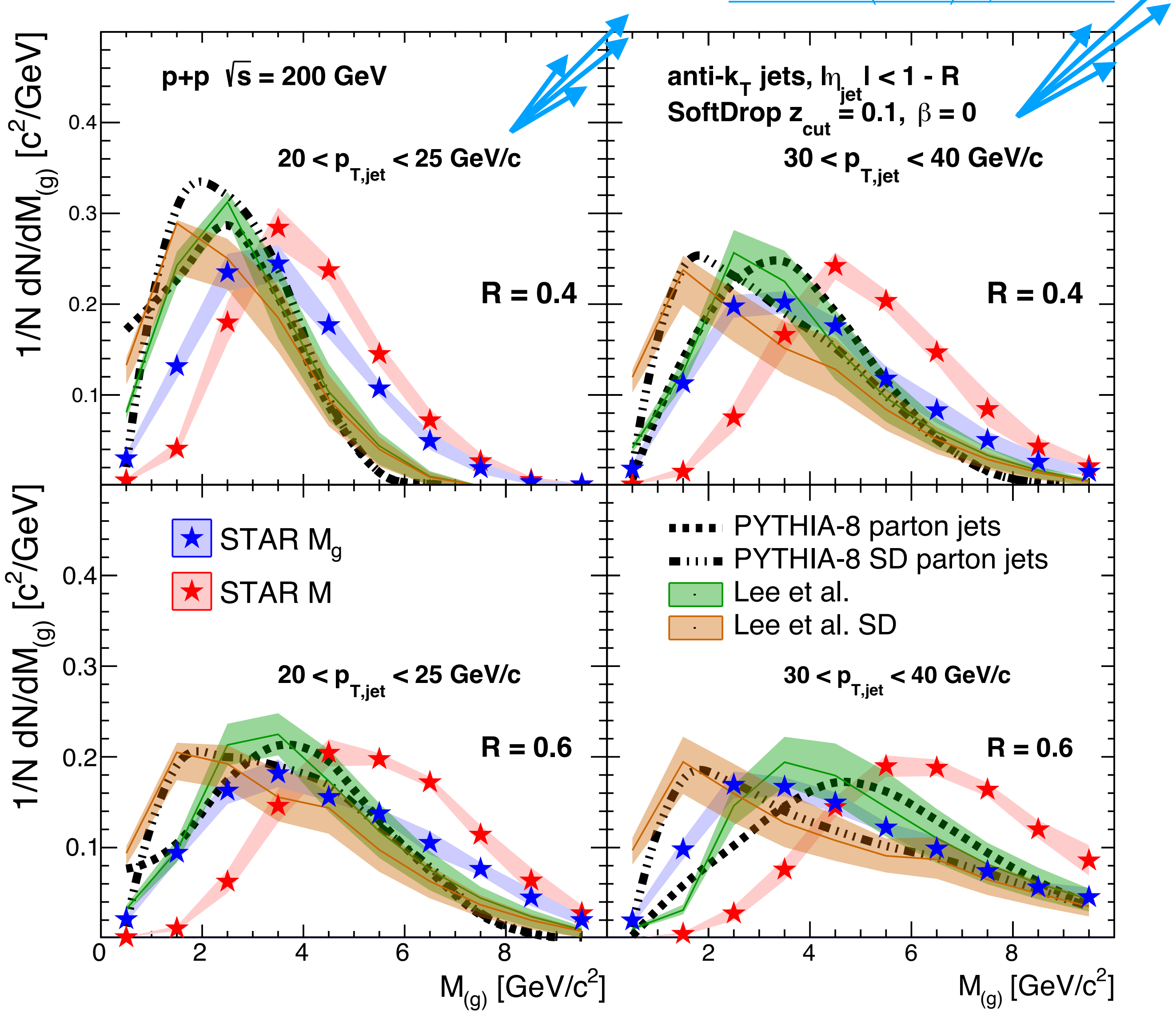
Overall rough agreement with MCs (although MPI have to be tuned) but perturbative calculations not enough especially for small p_{T}, R at RHIC:

hard scale $\sim p_{\mathrm{T}}R$; jet grooming scale $\sim z_{\mathrm{cut}}p_{\mathrm{T}}R$

SD measurements

PRD 104 (2021) 5, 052007





$$M^2 \sim p_{\mathrm{T,jet}} \sum_{i \in J} p_{\mathrm{T},i} \Delta R_{iJ}^2$$

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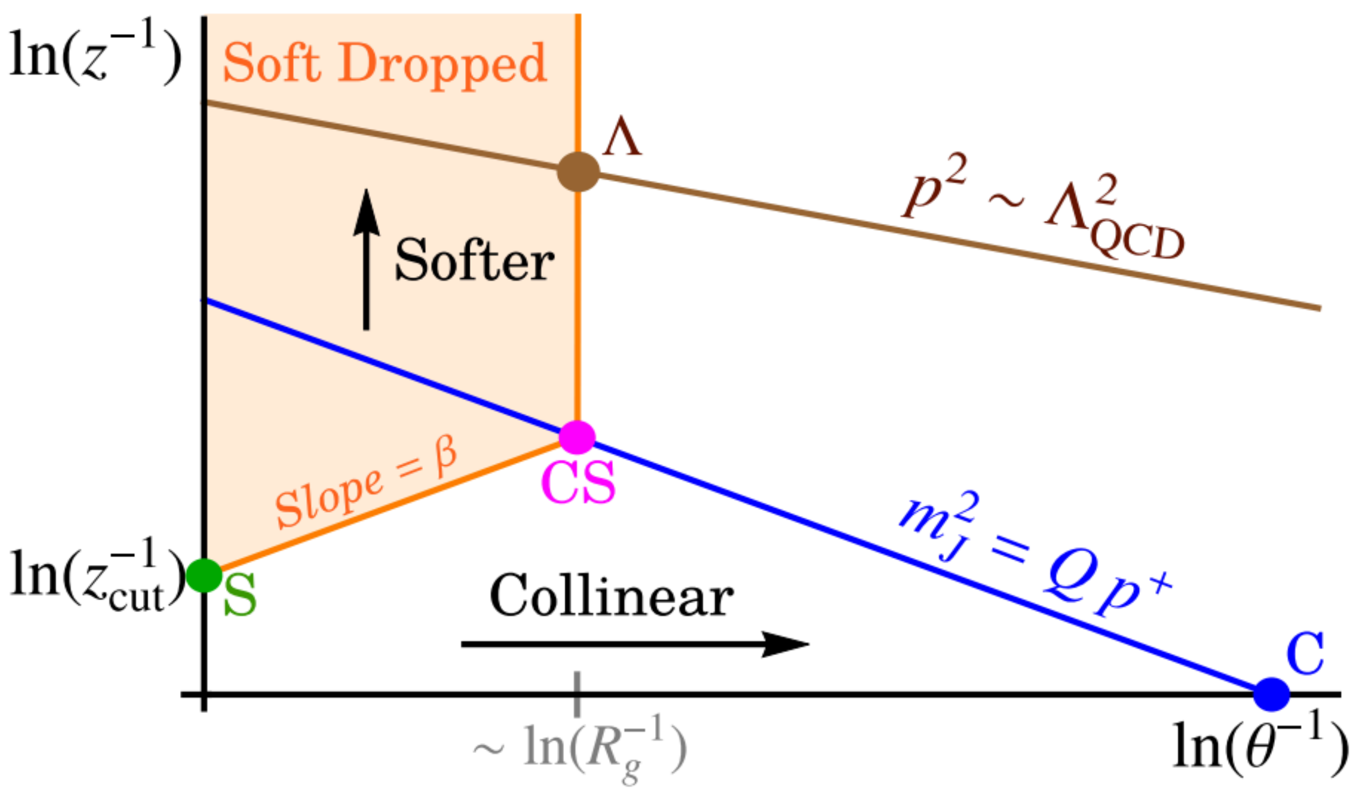
Caveat: SD contains NP!



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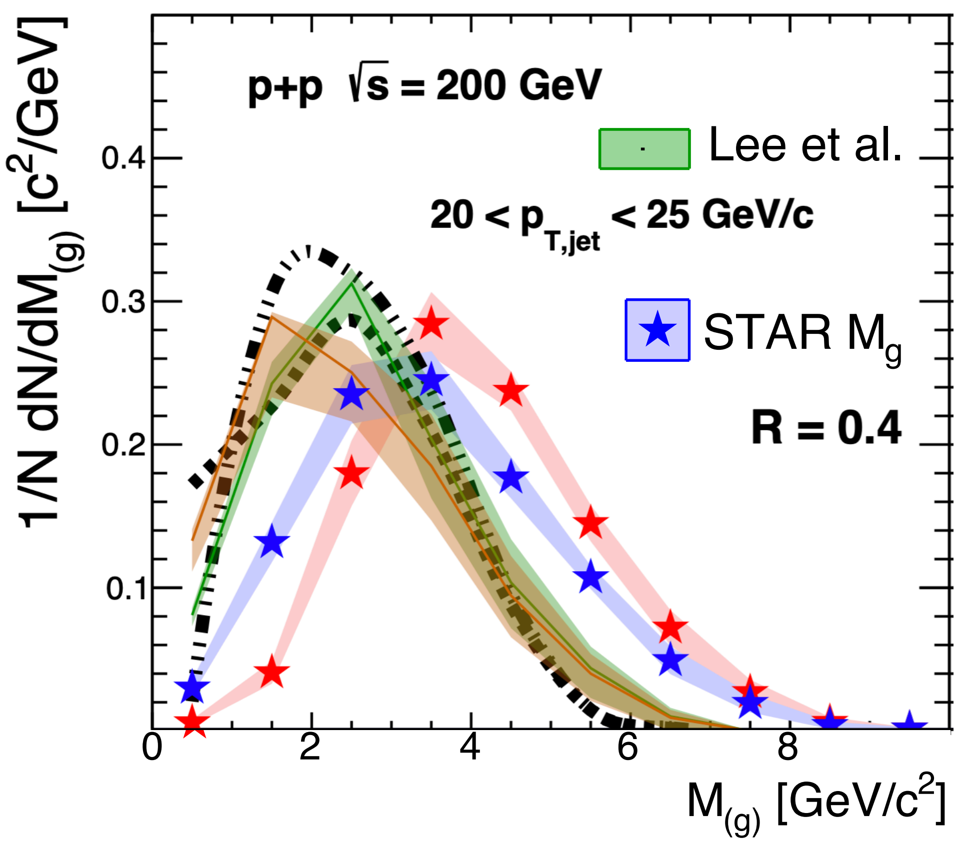
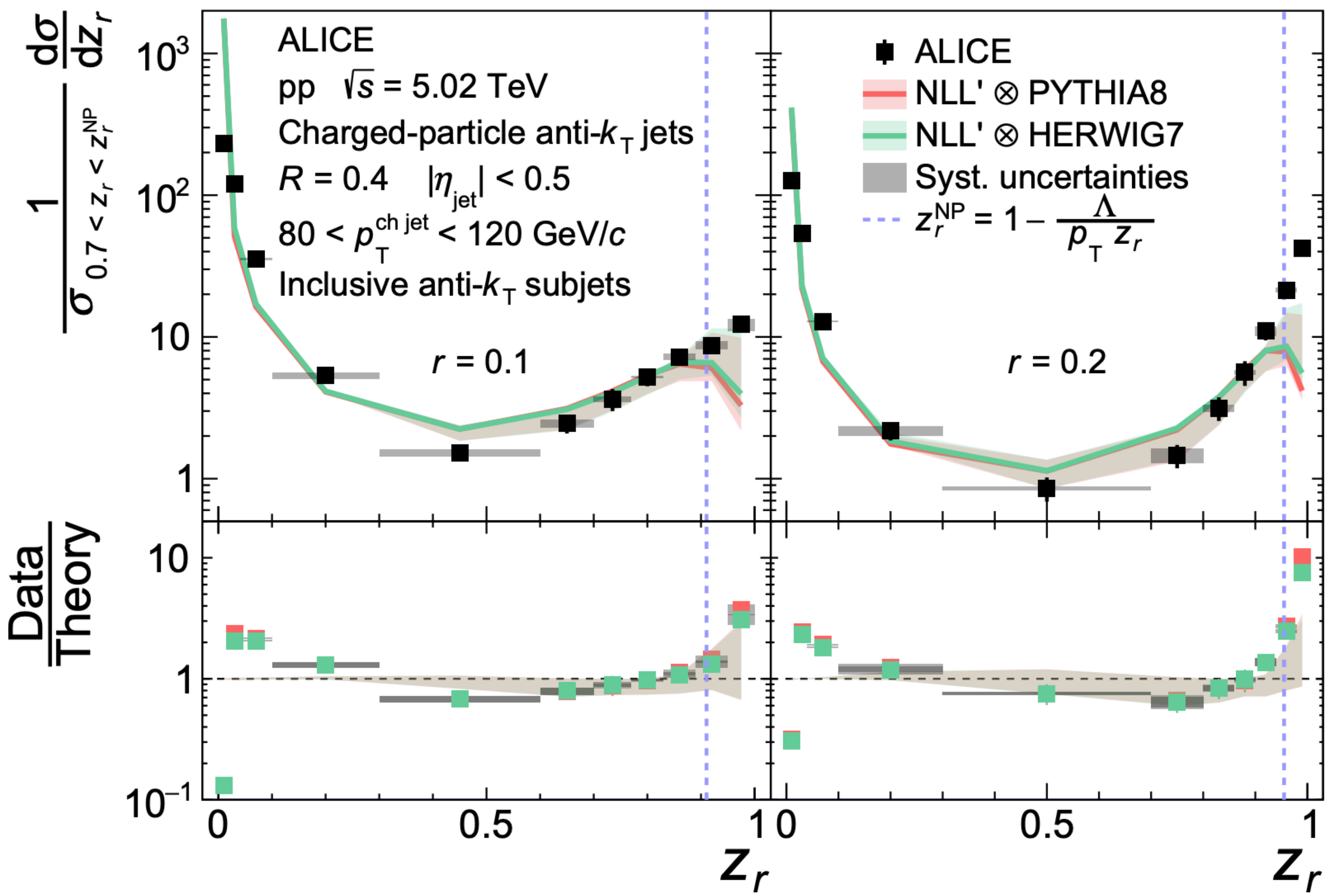


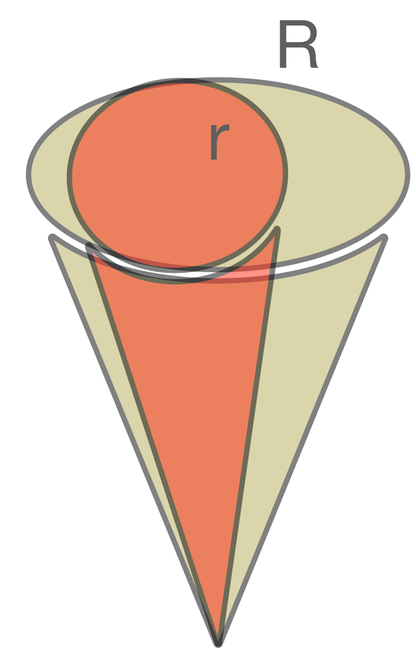
Small contribution (power corrections) for larger mass region, but larger effect at smaller mass!

Subjets

ALICE, arXiv:2204.10270



Kang, Ringer, Waalewijn, JHEP 07 (2017) 064



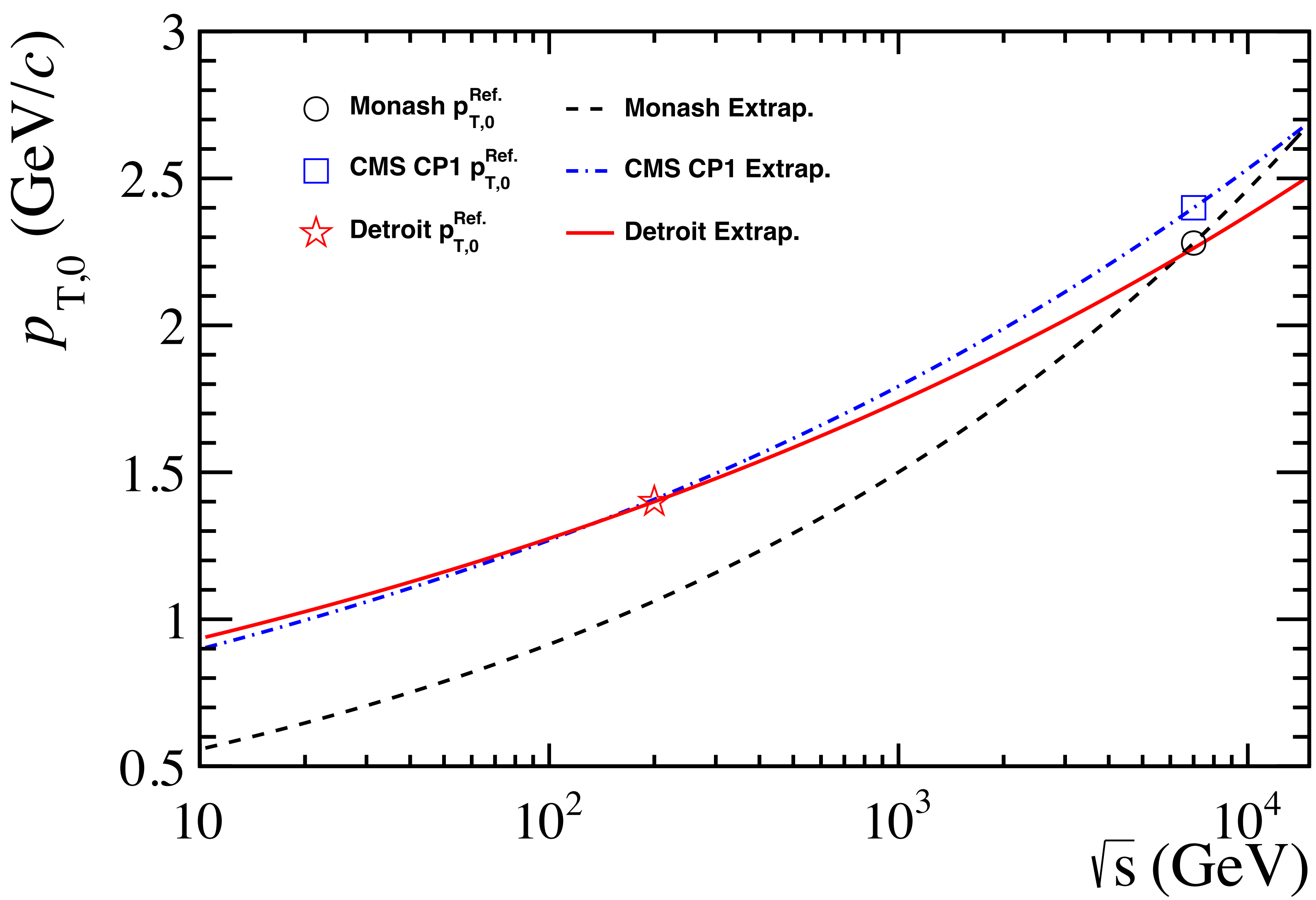
Subjets reduce AA background contamination[1]
NP parton→hadron FFs not involved
ALICE result comparable to perturbative calculation in mid-z region

[1]STAR, PRC 105 (2022) 4, 044906

Embracing NP

MPI regularization

Aguilar, Chang, Kunnawalkam Elayavalli, Fatemi, He, Ji, Kalinkin, Kelsey, IAM, Verkest, [PRD 105 (2022) 016011]



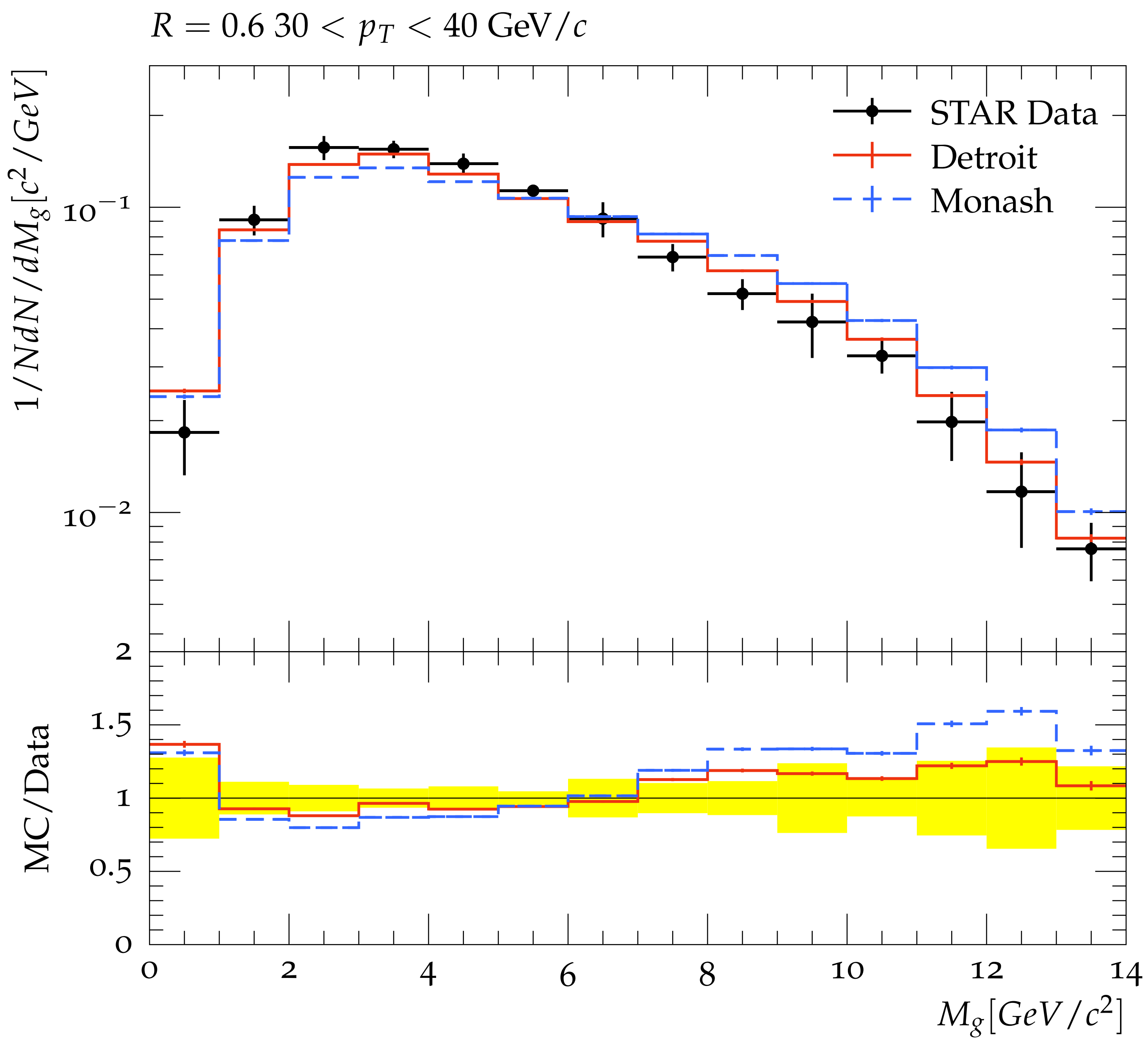
Increasing $p_{\mathrm{T},0}$ regularizes NP MPI starting at higher p_{T}

→ reduced impact on e.g. X-sec: $\hat{\sigma} = (p_{\mathrm{T}}^2 + p_{\mathrm{T},0}^2)^{-1}$

Getting MPI right at RHIC

Detroit Tune

Aguilar, Chang, Kunnawalkam Elayavalli, Fatemi, He, Ji, Kalinkin, Kelsey, IAM, Verkest, [PRD 105 (2022) 016011]



Even tuning exclusively MC MPI parameters improves jet description!

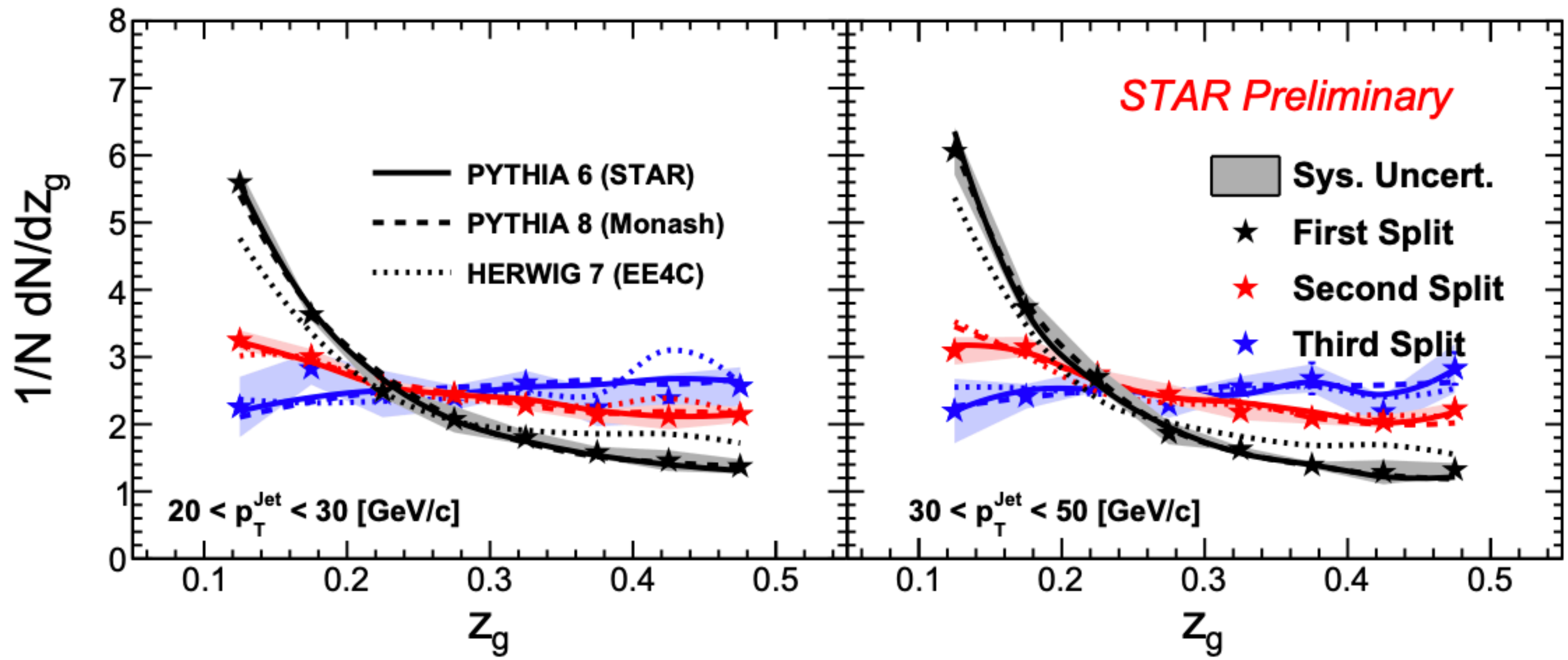
Iterative SD

Following evolution of the hardest branch

LO AP splitting kernel (q→g) $\sim 0.3\frac{1+z^2}{1-z} + \frac{1+(1-z)^2}{z}$

Gradual shift away from perturbative at **first split** to more **symmetric splittings** as jet evolves down to Λ_{QCD}

hadronization $\sim z^0$



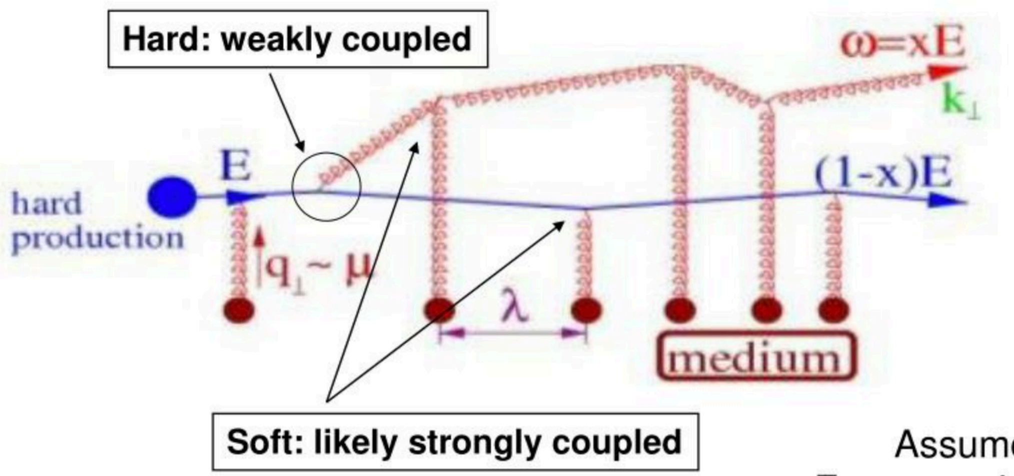
In-medium

$$C(q_\perp) \equiv \frac{(2\pi)^2 \mathrm{d}^3\Gamma}{\mathrm{d}^2 q_\perp \mathrm{d}L} \rightarrow \text{NP!}$$

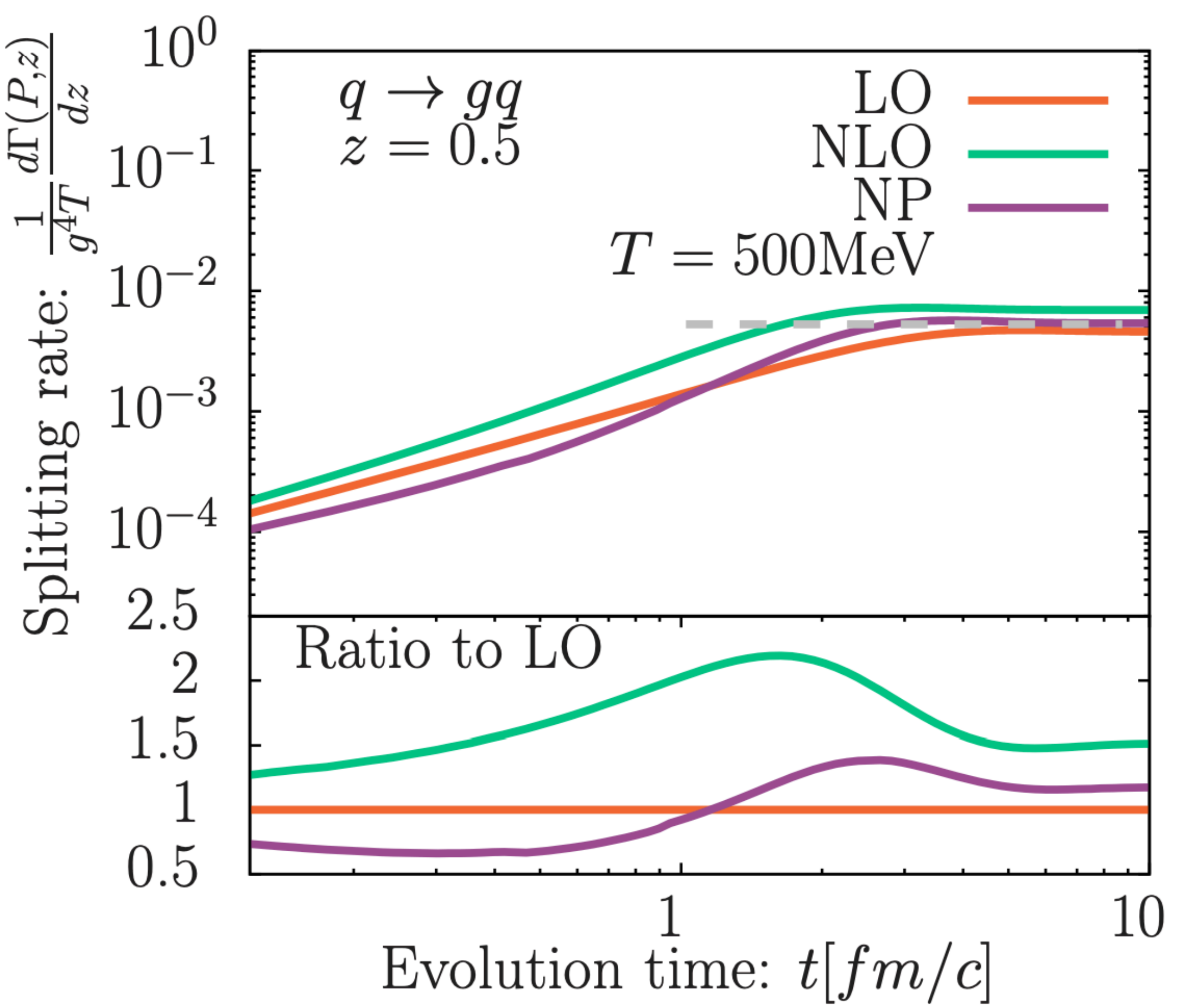
Analytic calculations of medium-modification should include NP effects as well!

Moore, Schlichting, Schlusser, Soudi, EPJ Web Conf. 258 (2022) 05001

Image: Hong Liu

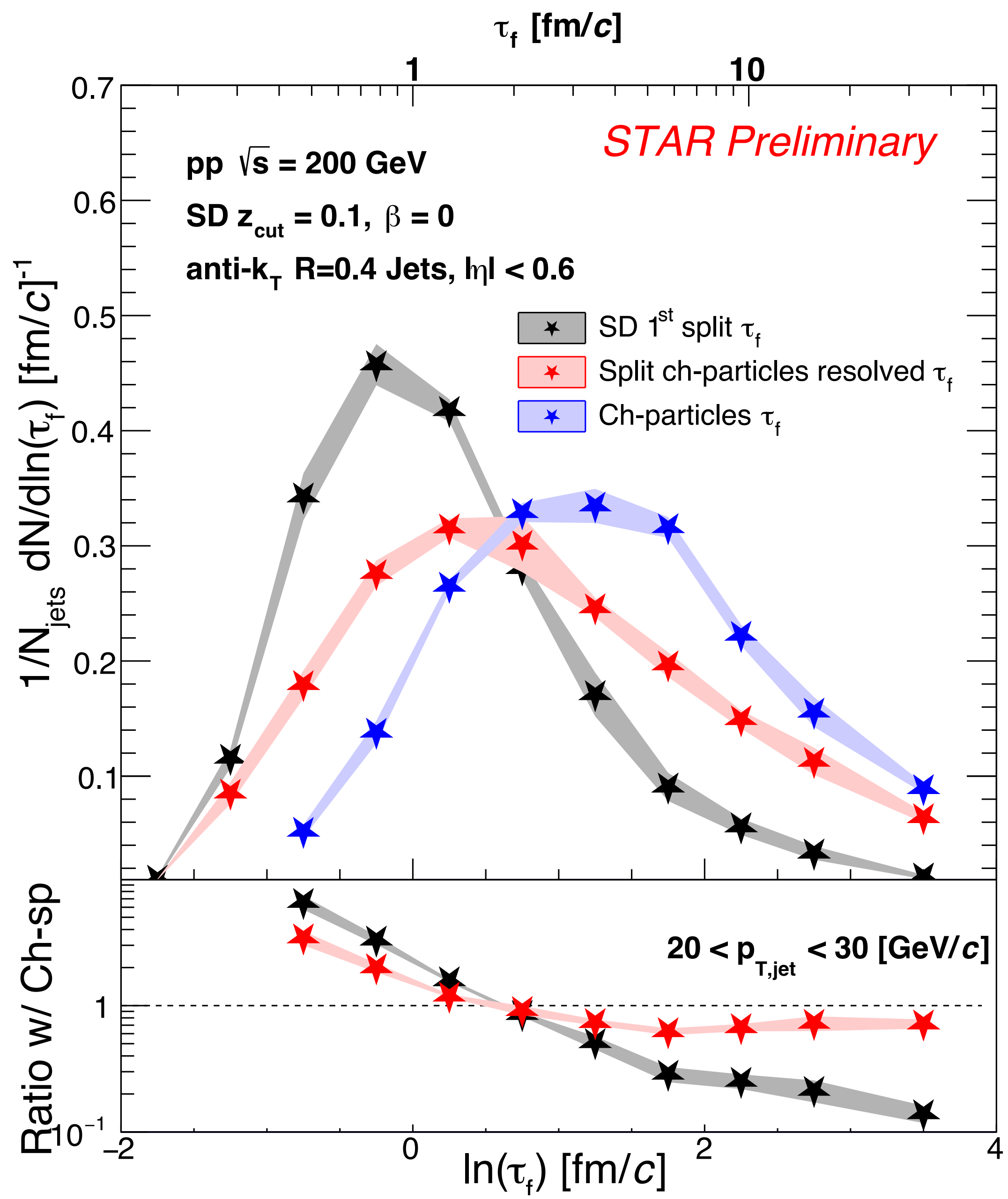


Assume:
E >> ω >> k⊥ >>T



Time

pp



$$t_{\rm f} = \frac{1}{z(1-z)\theta^2 E}$$

Now we have a handle on formation time in vacuum, but can we determine an “evolution time” in QGP?

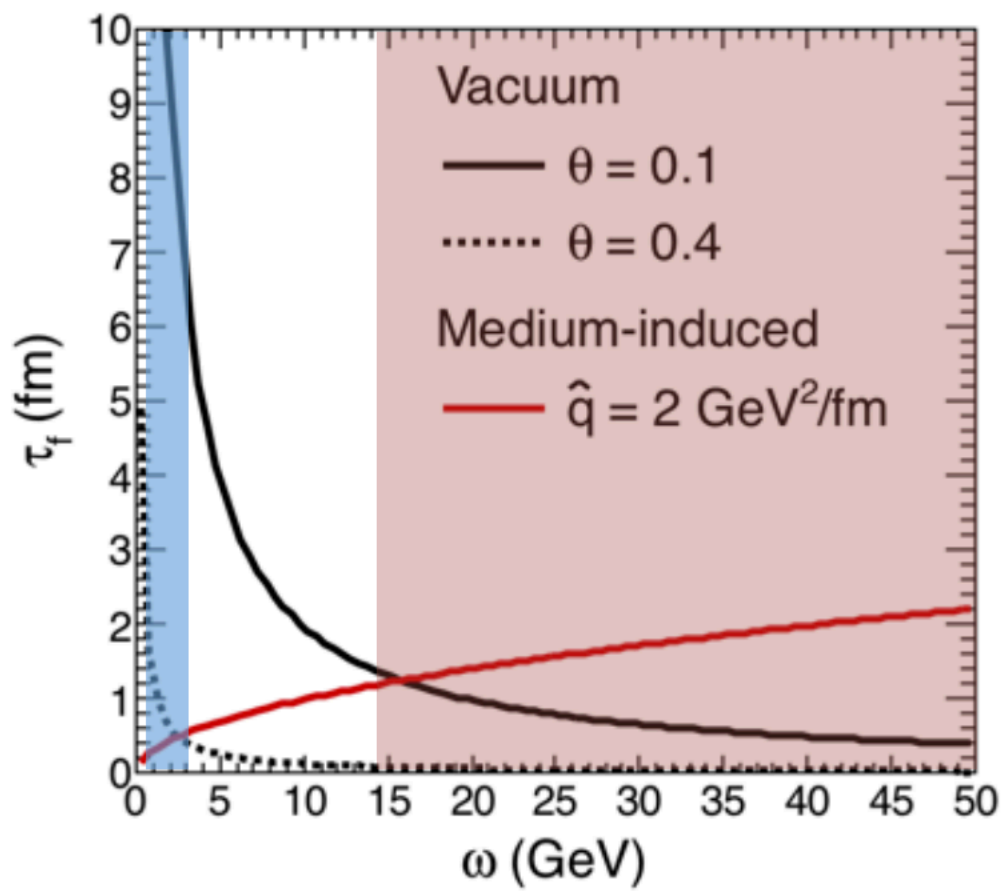
Time

AA?

How long does a parton/jet spend in the QGP?
Can get *formation time of a given split* even in medium, without angular-ordered QCD shower[1]

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

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



Phase space covered for z_g=0.1

STAR

CMS

Verweij, QM 2017

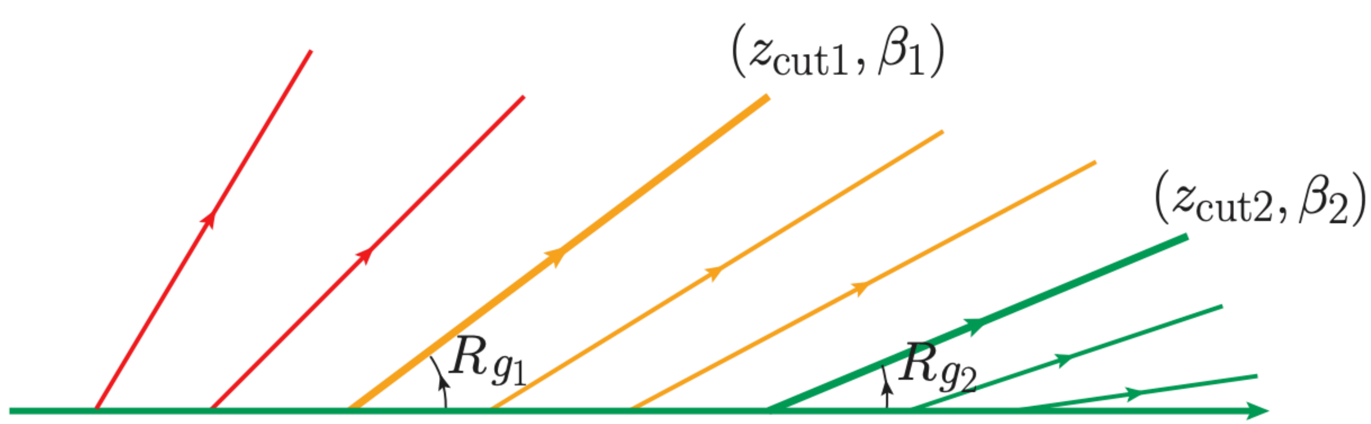
But many soft/NP radiations in-medium can produce different final state

[1]Apolinário, Cordeiro, Zapp, EPJC 81 (2021) 6, 561

Future

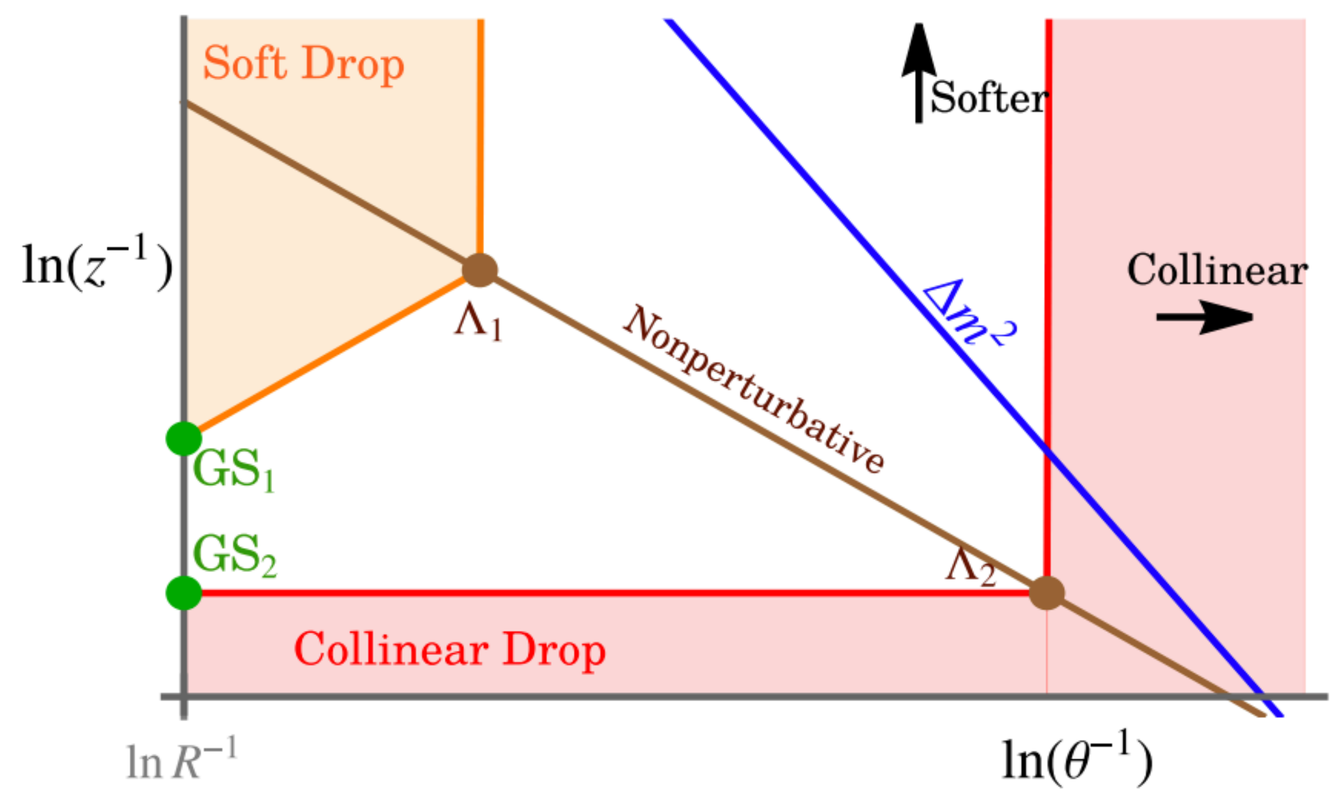
Collinear drop

Chien, Stewart, JHEP 06 (2020) 064



Remove widest-angle radiation to reduce UE effects, focus on NP hadronization in intermediate region

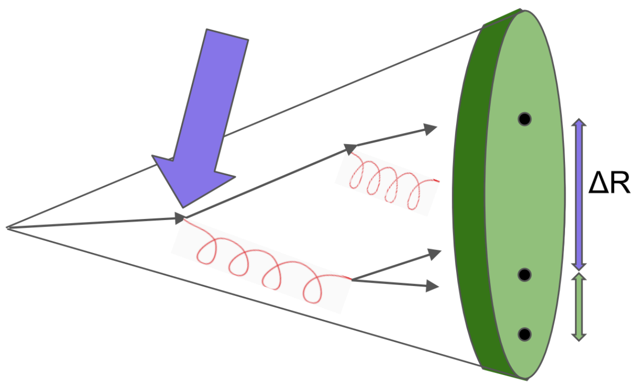
In principle, simple to measure if SD jet mass has already been done!



Stewart, Yao, arXiv:2203.14980

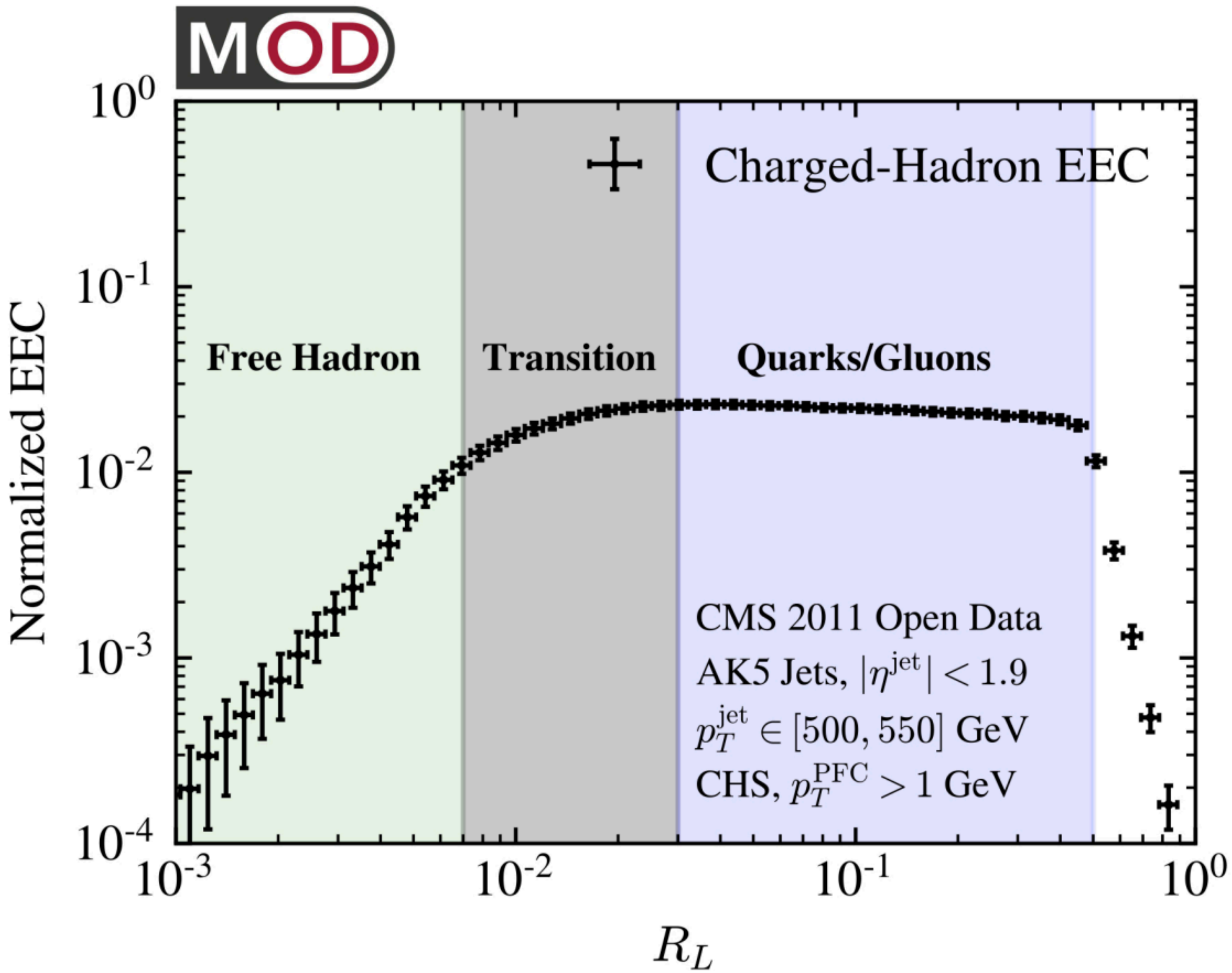
Future
EECs

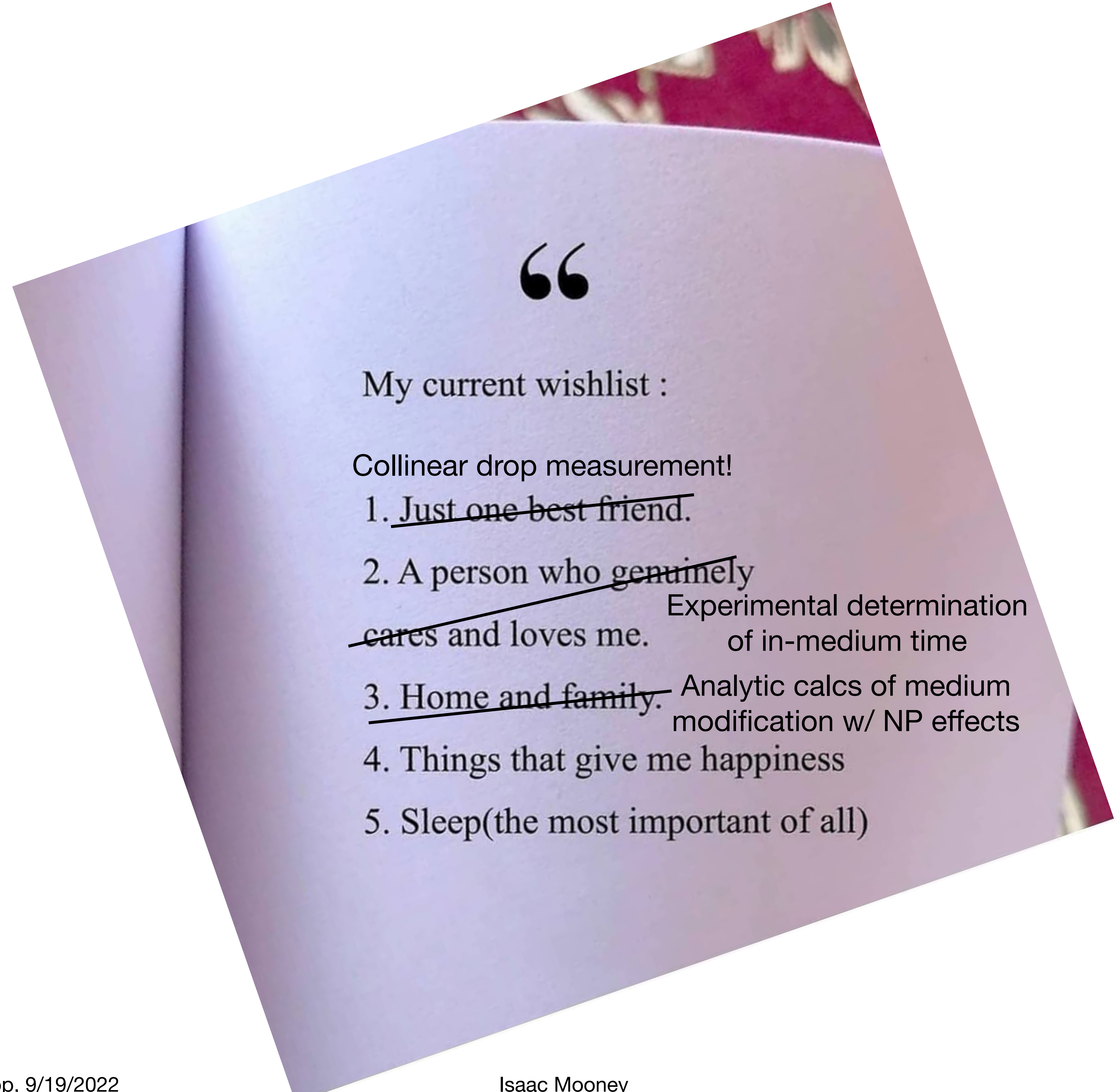
Image: Andrew Tamis



Ongoing work at STAR! (refer to Andrew's flash talk)

“Free hadron” corresponds to randomly distributed particles




"
My current wishlist :
Collinear drop measurement!
1. ~~Just one best friend.~~
2. A person who ~~genuinely~~
~~cares~~ and loves me.
Experimental determination
of in-medium time
3. ~~Home and family.~~
Analytic calcs of medium
modification w/ NP effects
4. Things that give me happiness
5. Sleep(the most important of all)

Backup