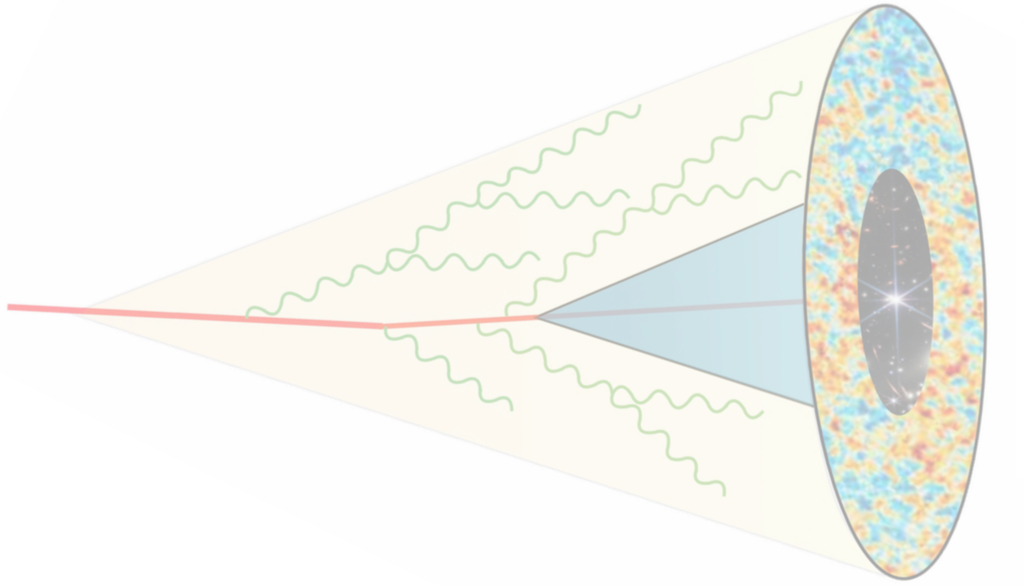
A Journey in Jet Sub-Structure from RHIC to EIC



Raghav Kunnawalkam Elayavalli (they/them)

1st Lund Jet Plane Institute @ CERN July 2023

VANDERBILT UNIVERSITY

pQCD and npQCD at the EIC

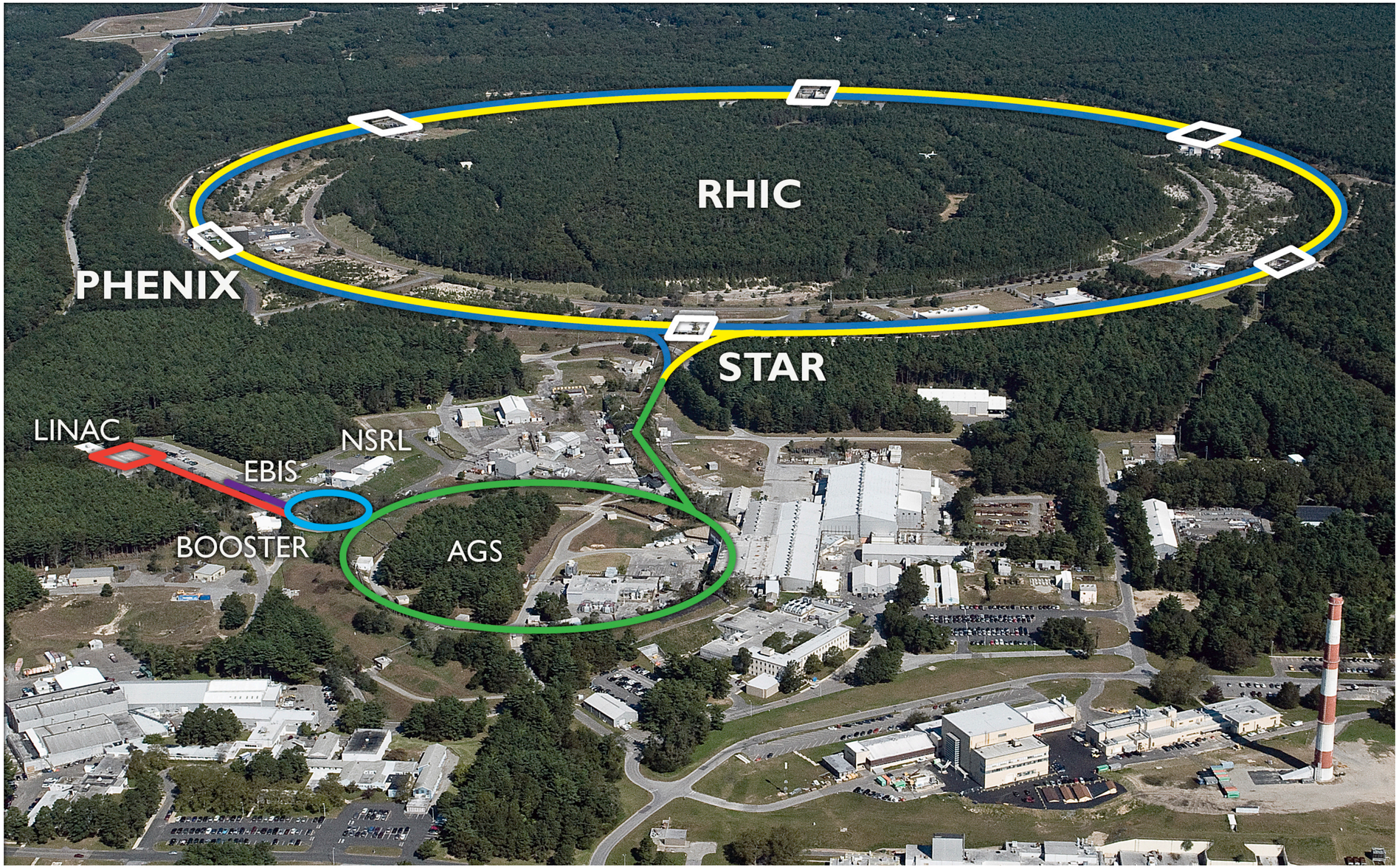
Completing the RHIC mission

STAR

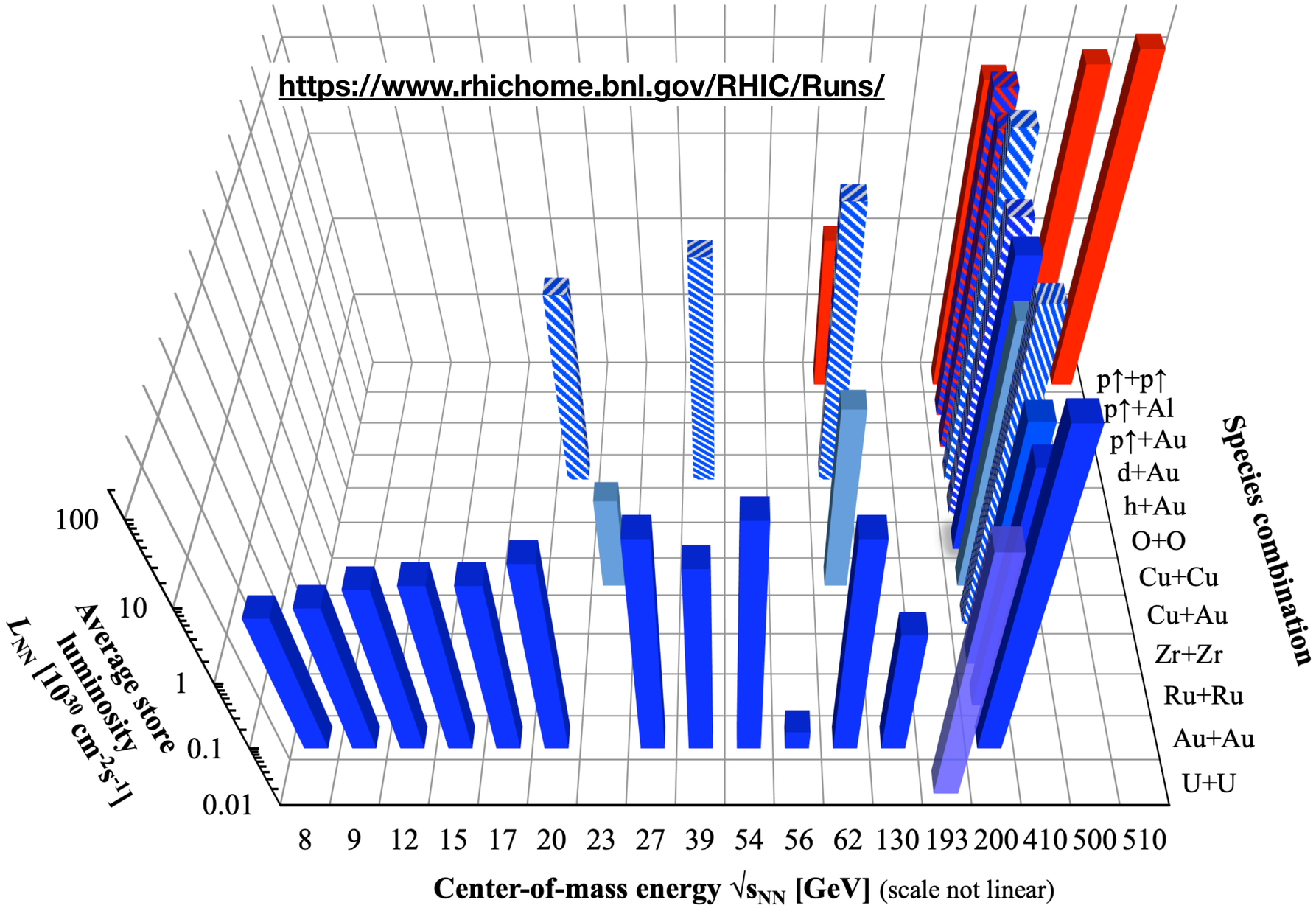
sPHENIX

Introduction, motivation and current status

Relativistic Heavy Ion Collider @ BNL



RHIC energies, species combinations and luminosities (Run-1 to 22)

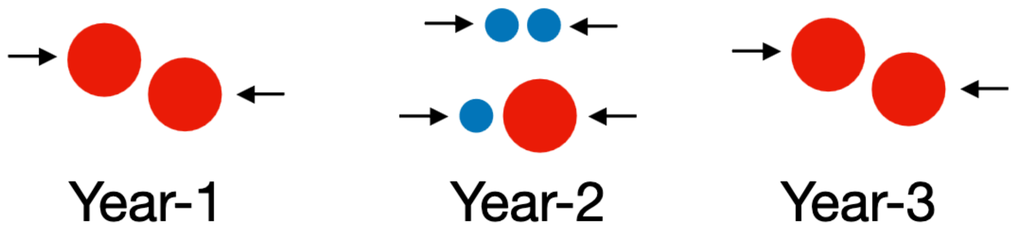


Next steps at RHIC!

"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.** (2) **Map the phase diagram of QCD with experiments planned at RHIC." (completed data taking in 2021)**

US NSAC Nuclear Physics Long Range Plan 2015

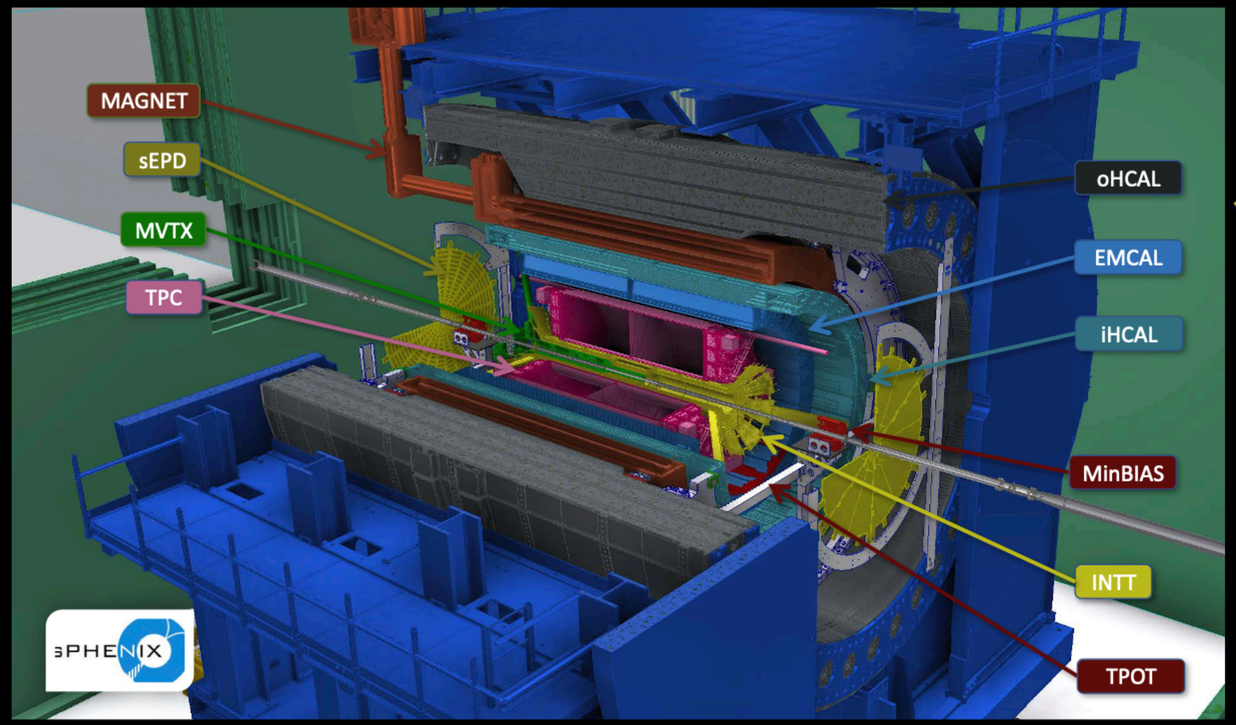
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	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}



sPHENIX Beam User Proposal 2022

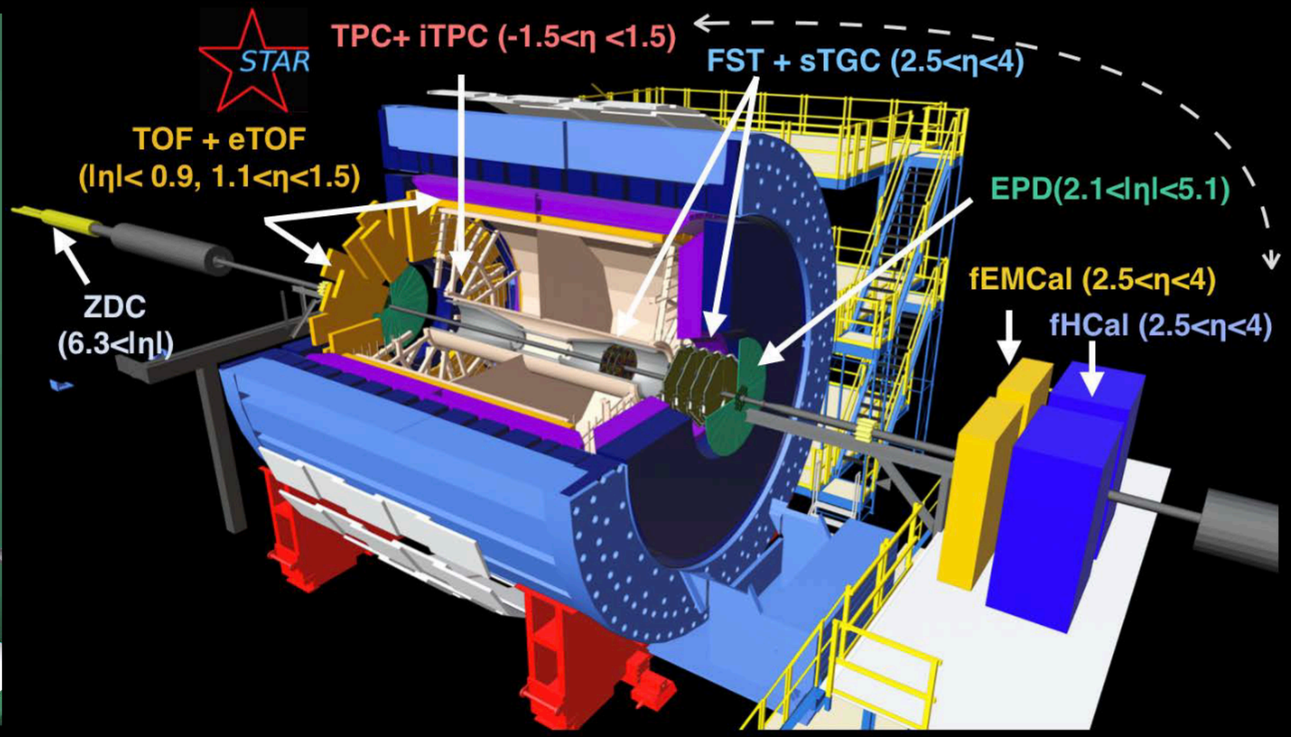
sPHENIX

Unique, purpose-built sPHENIX detector for precision on hard probes

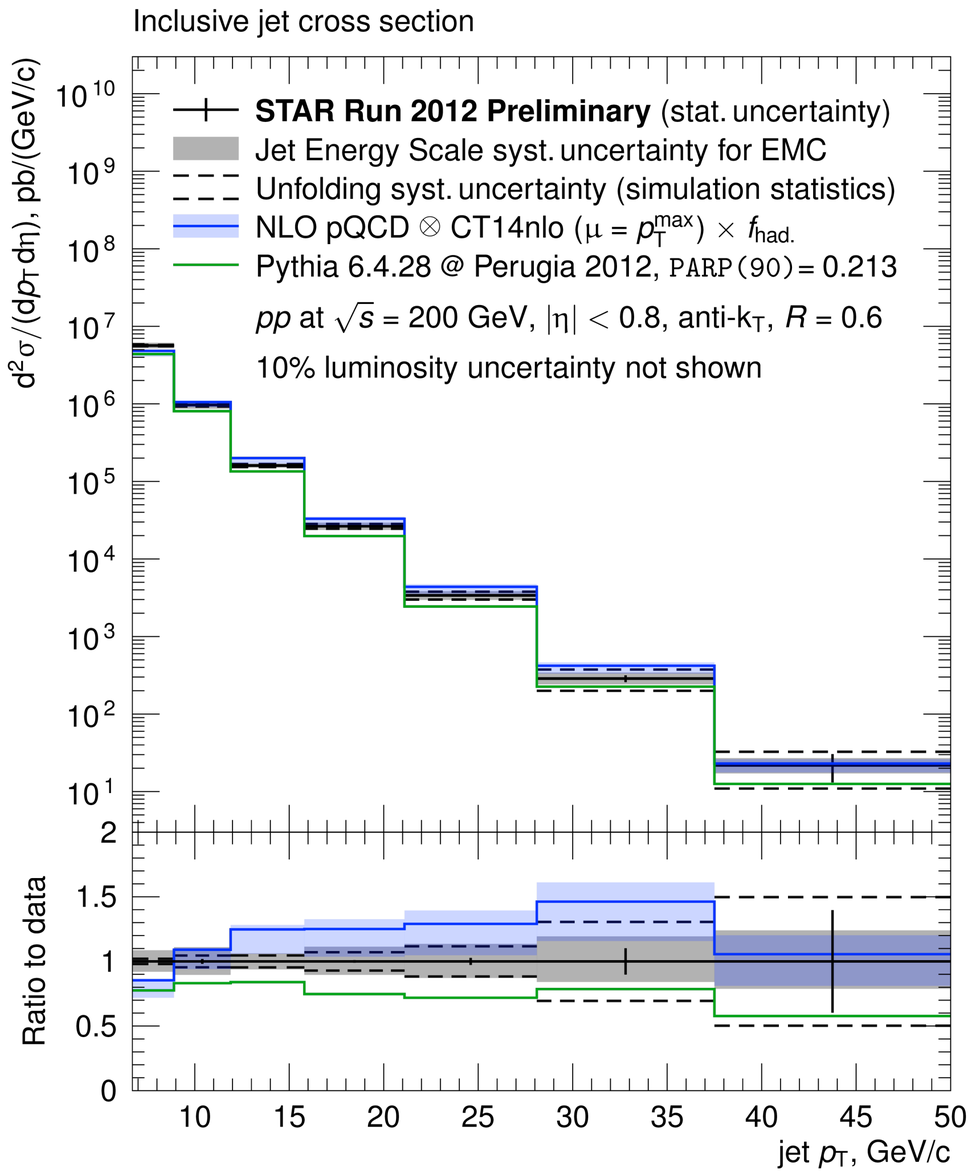


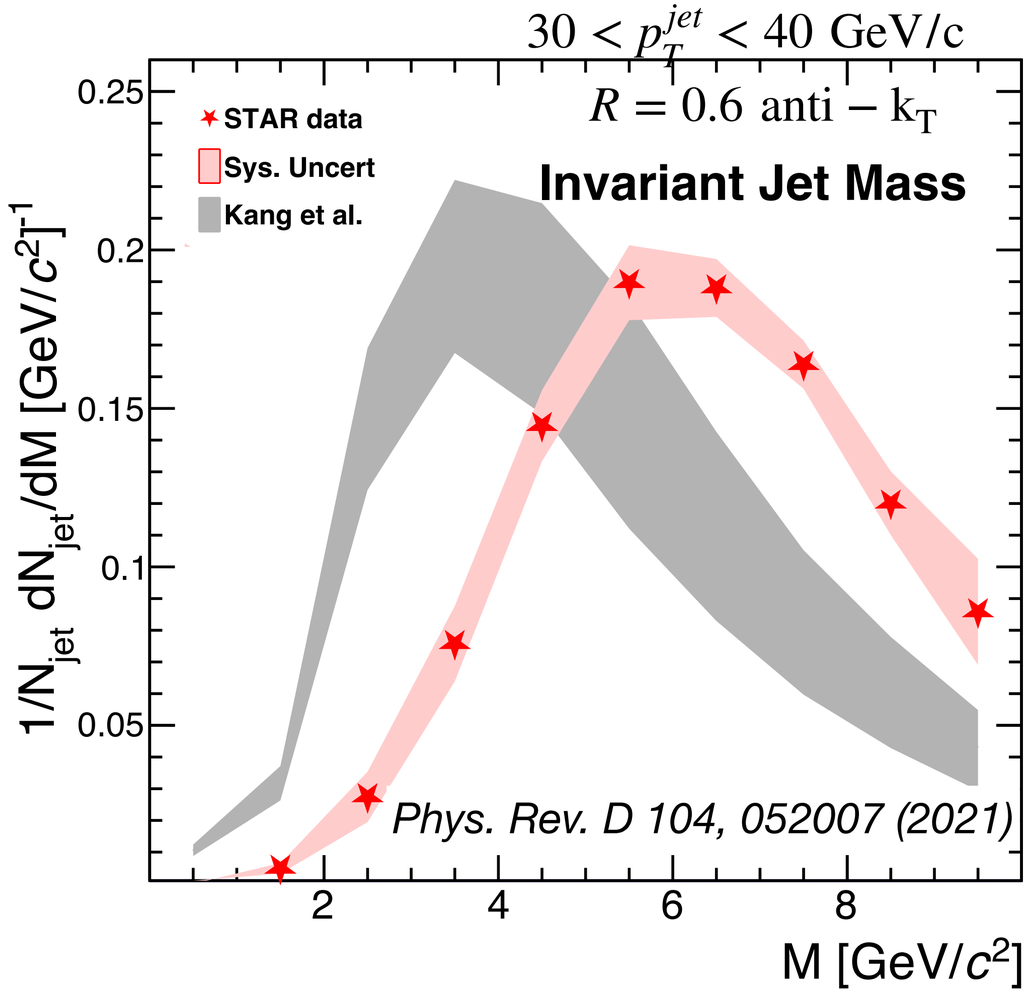
STAR

Significant new forward and mid-rapidity capabilities of the upgraded STAR detector



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

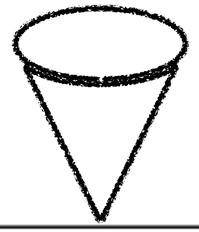




Unique population of jets with varied substructure!

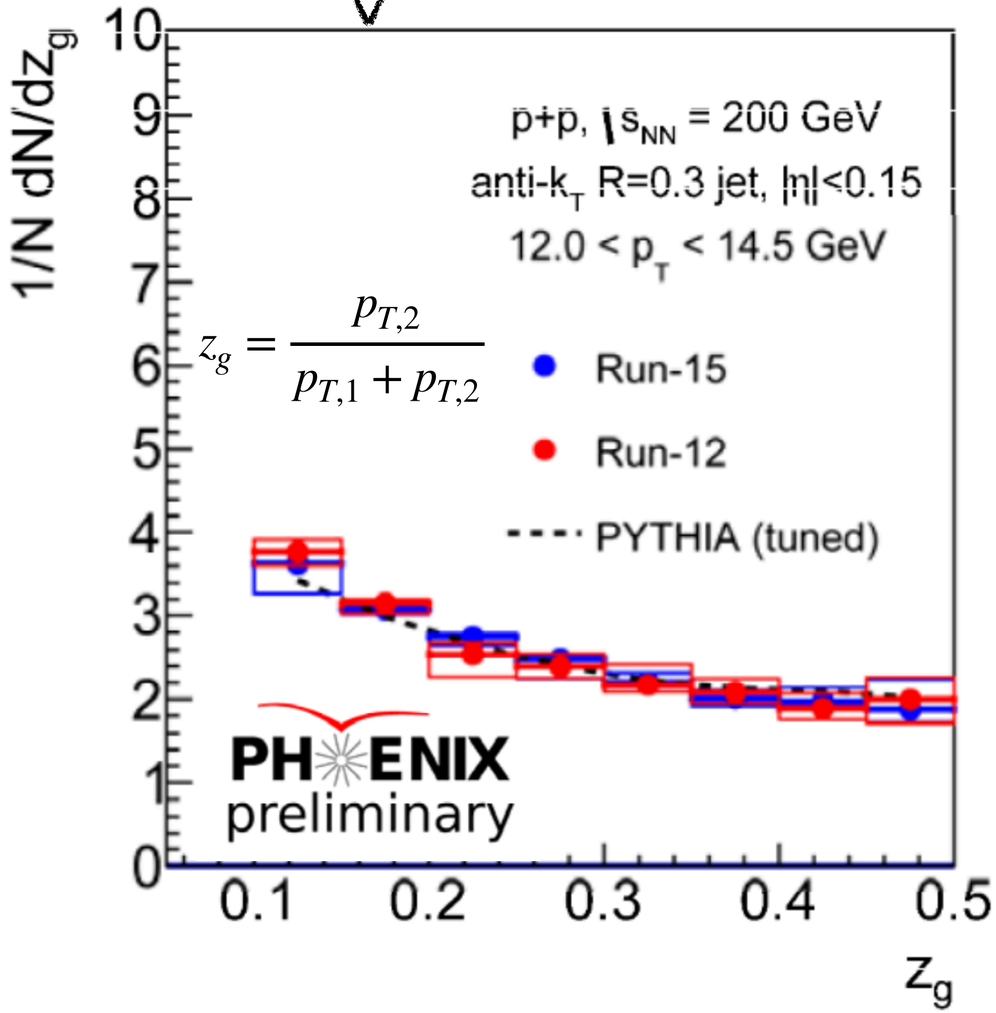
Scales extend from jet $p_T \rightarrow \Lambda_{QCD}$

Jet substructure @ RHIC



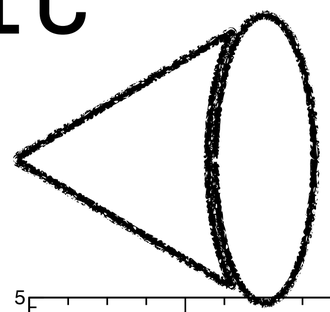
$12 < p_T^{jet} < 14.5$ GeV/c

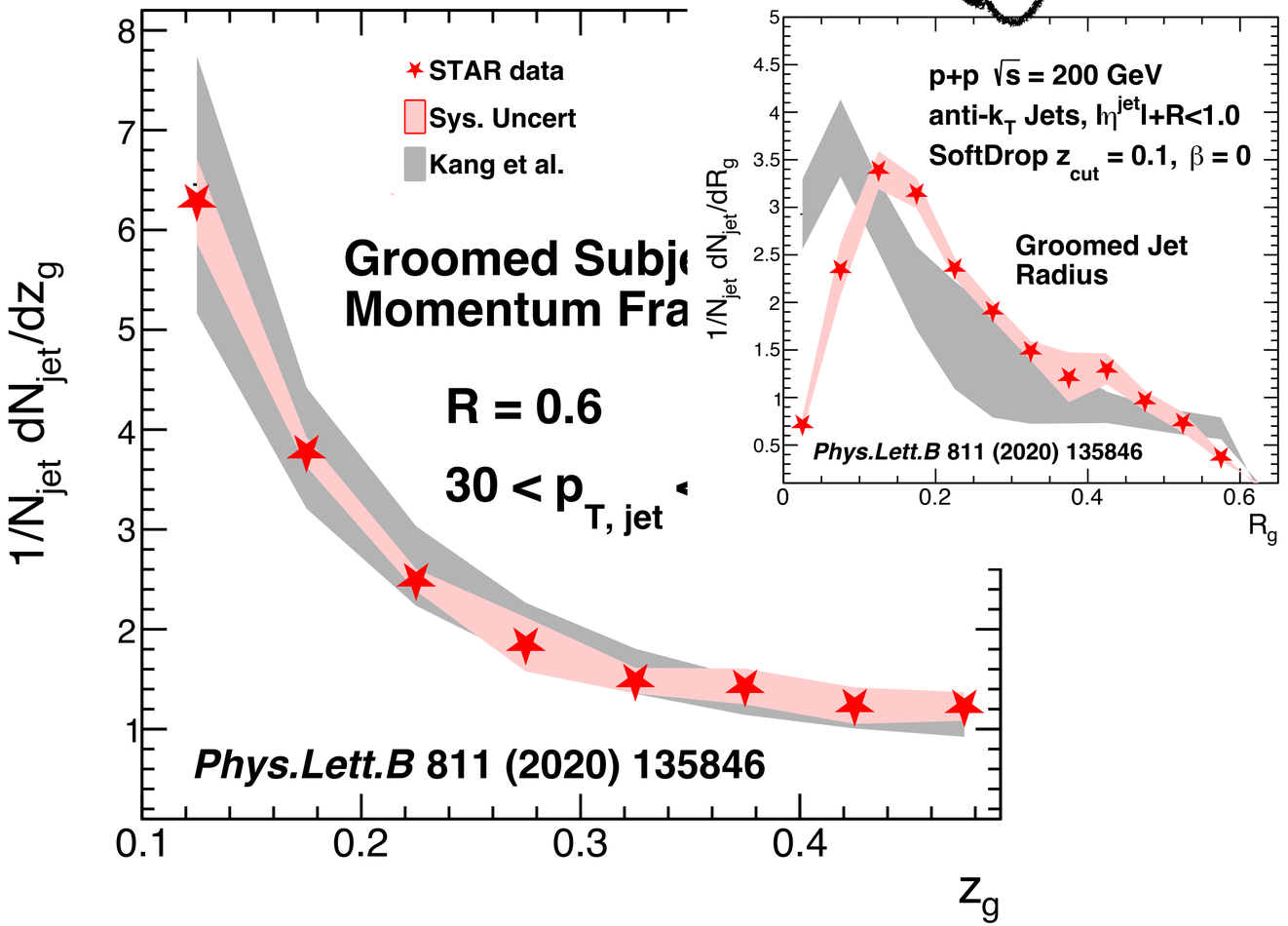
$R = 0.3$ anti $- k_T$



$30 < p_T^{jet} < 40$ GeV/c

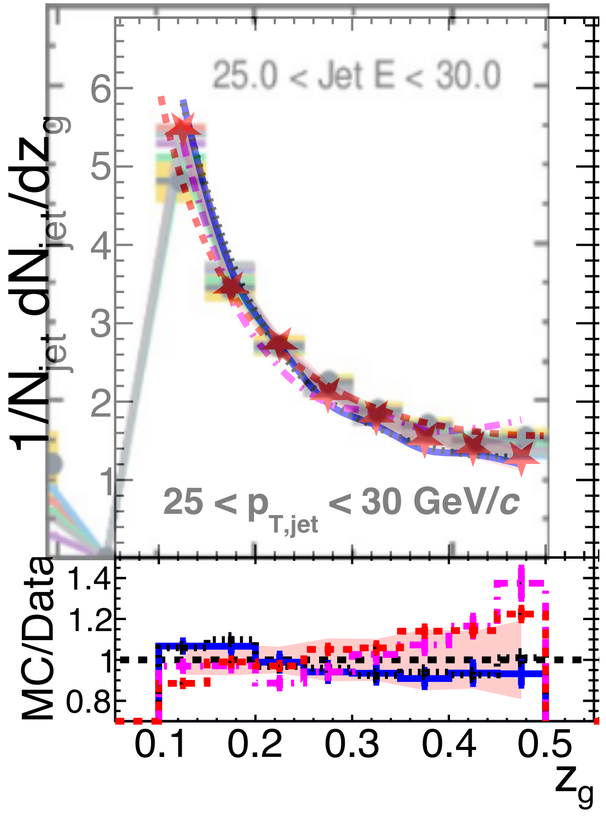
$R = 0.6$ anti $- k_T$

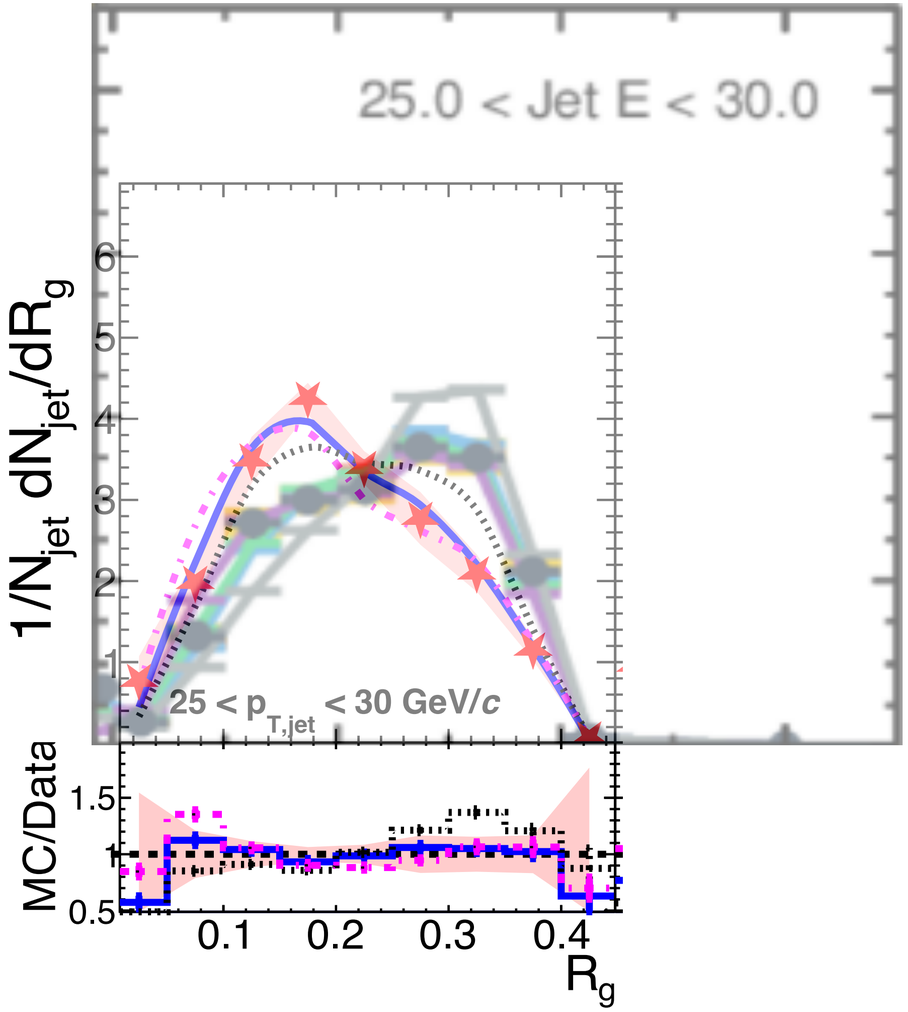




Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g



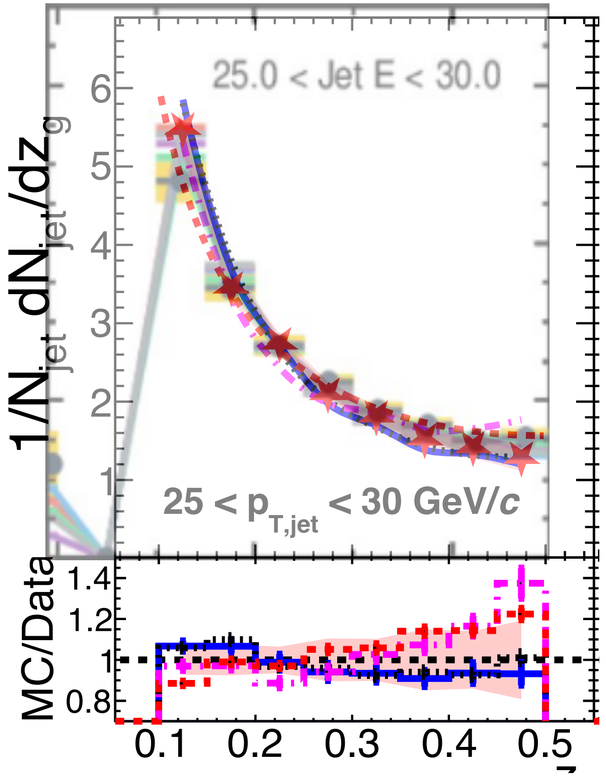


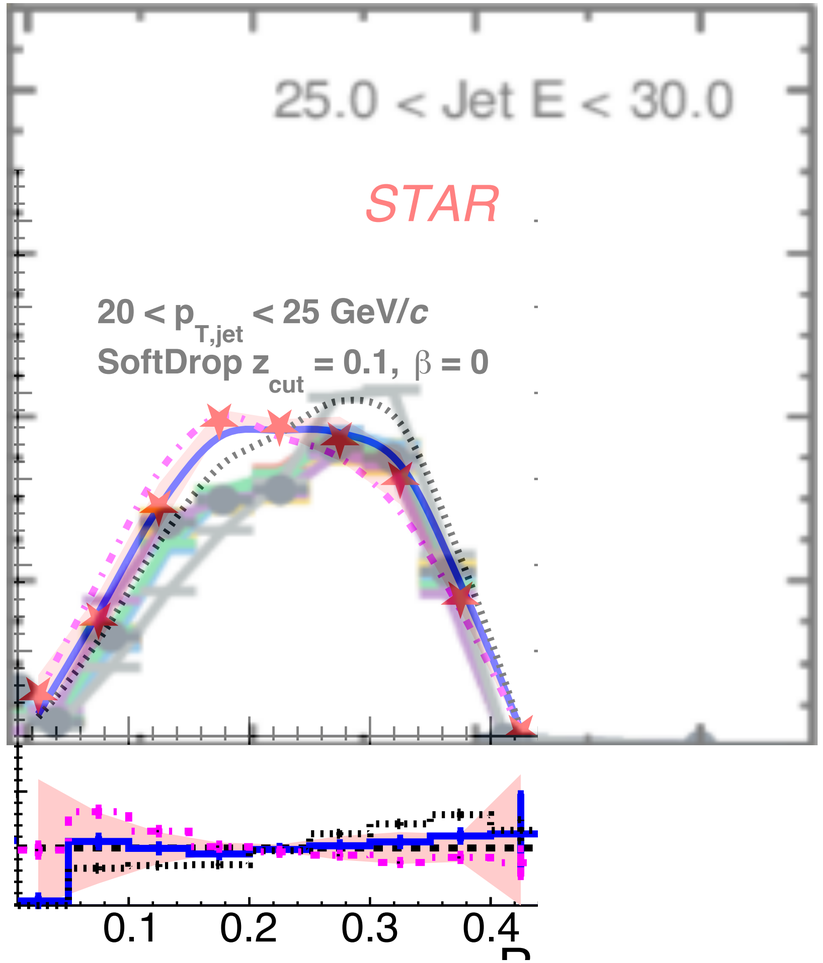
Yi Chen, et. al
JHEP 06 (2022) 008

Is the comparison apples to apples?

Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g

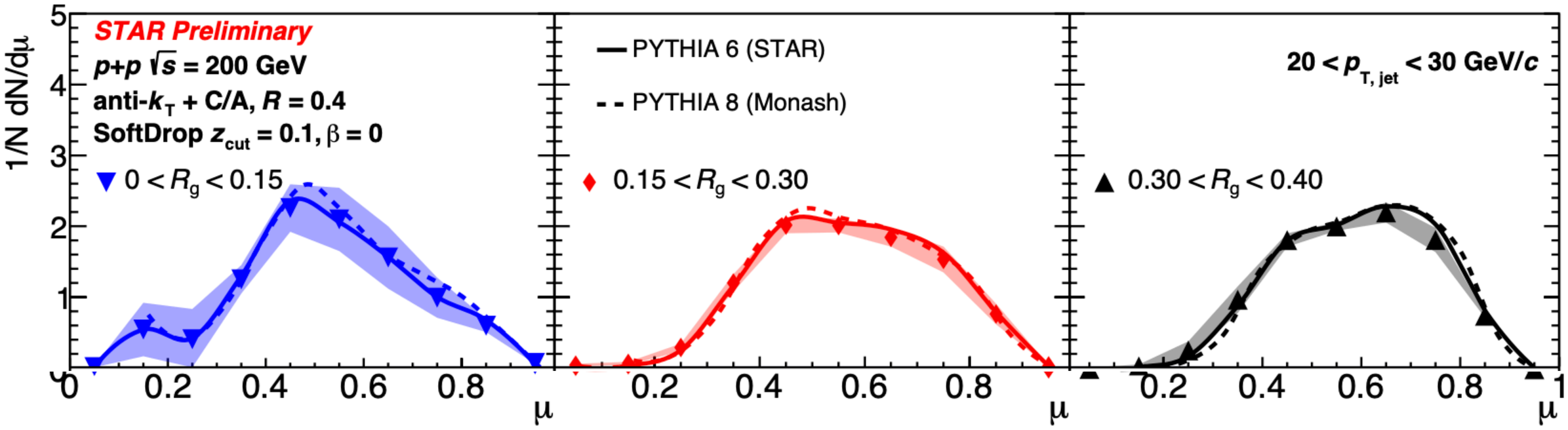




Yi Chen, et. al
JHEP 06 (2022) 008

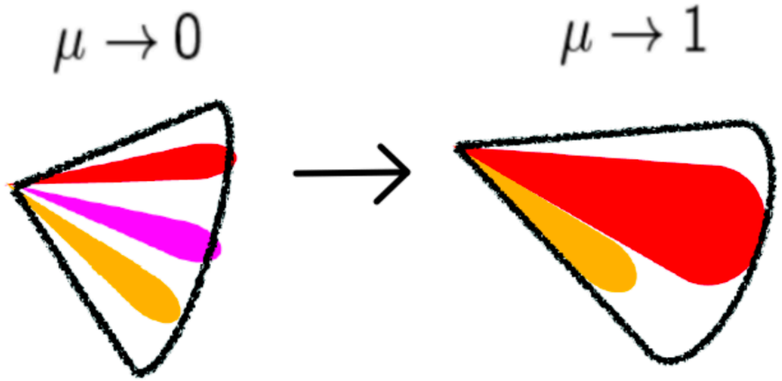
These jets in pp collisions have a $\langle M \rangle \approx 3 - 5$ GeV/c^2 plus there's hadronic component!

Virtuality evolution within jets



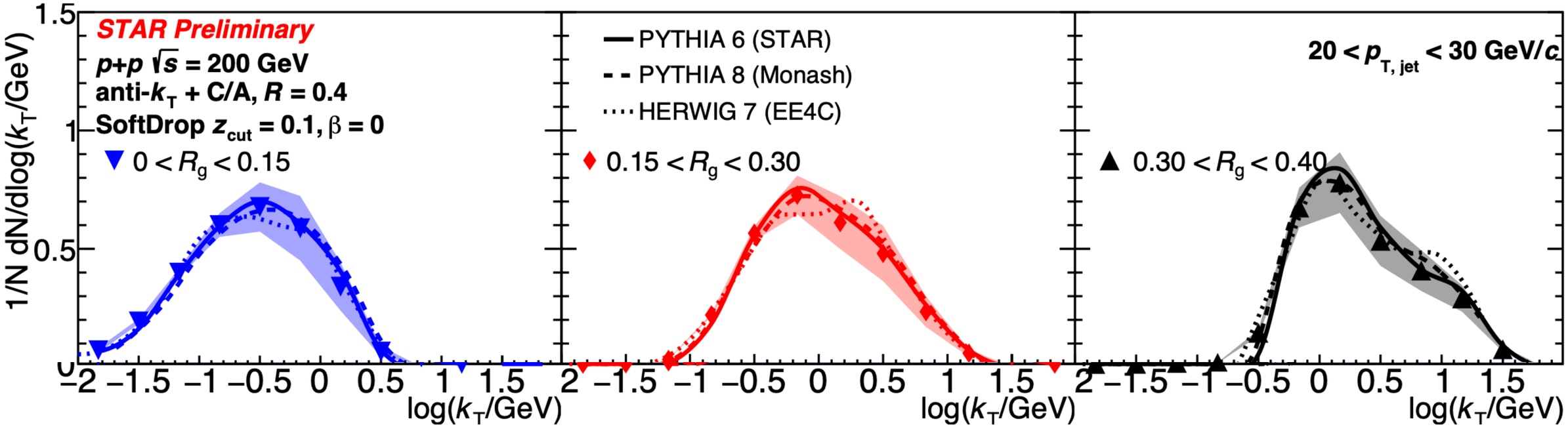
Monika Robotkova (CTU) @ HP 2023

Dasgupta et. al.
JHEP09 (2013) 029



- Narrower splittings result in a faster reduction of virtuality!

Evolution in k_T

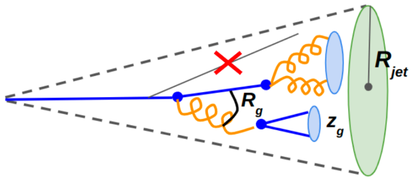


Dreyer, Salam, Soyez, JHEP 12 (2018) 064

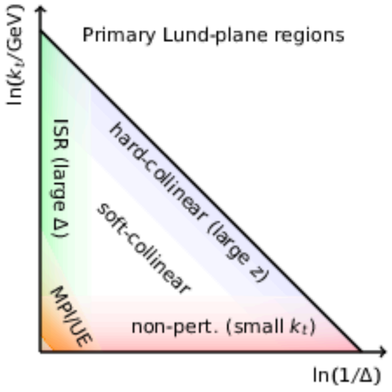
- Shift in the scale of the splitting kinematics with opening angle!

Monika Robotkova (CTU) @ HP 2023

Dasgupta et. al. JHEP09 (2013) 029

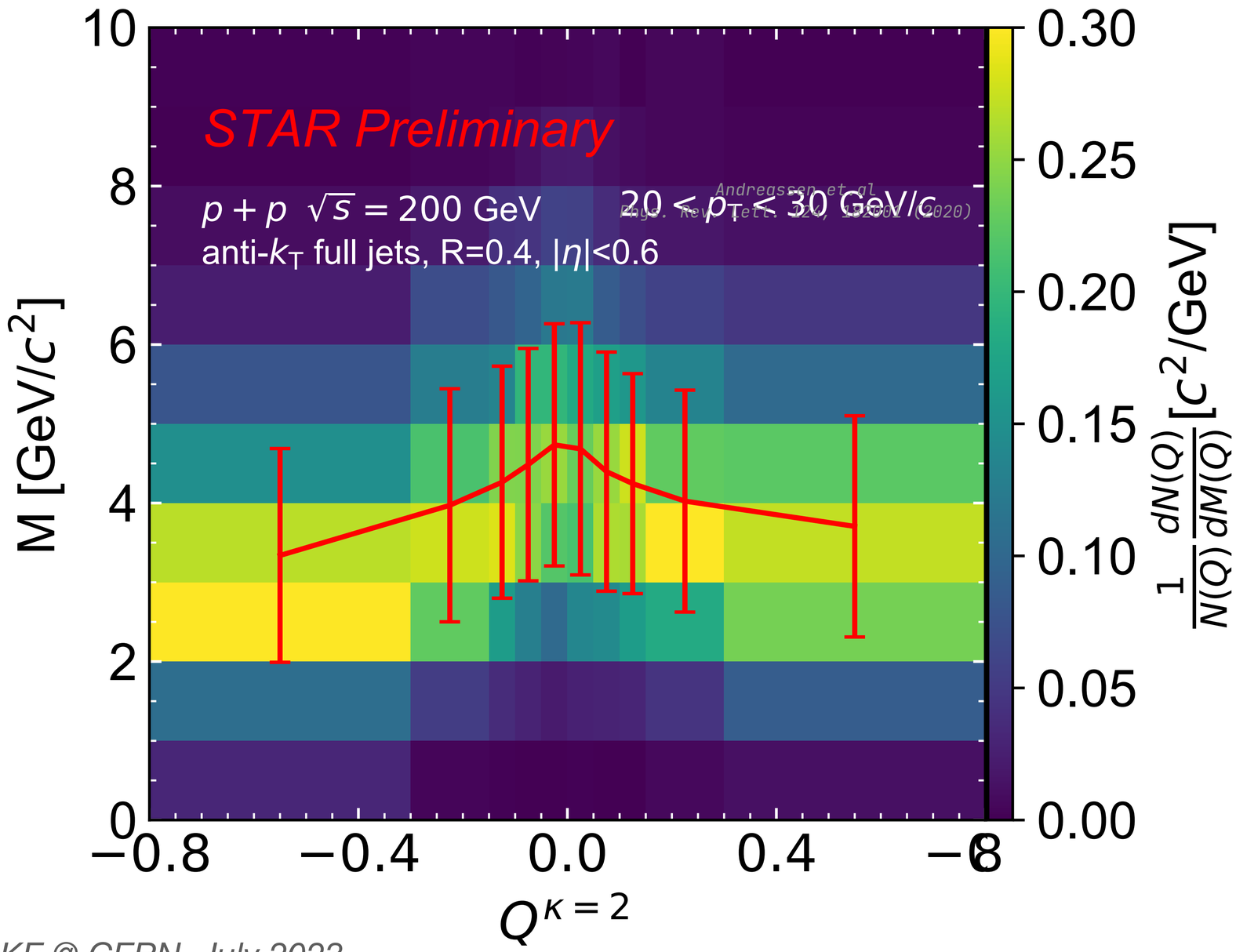


$$k_T = z_g p_{T,\mathrm{jet}} \sin R_g$$



Extending the dimensionality

Andreasson et al.
Phys.Rev.Lett. 124 (2020) 18, 182001



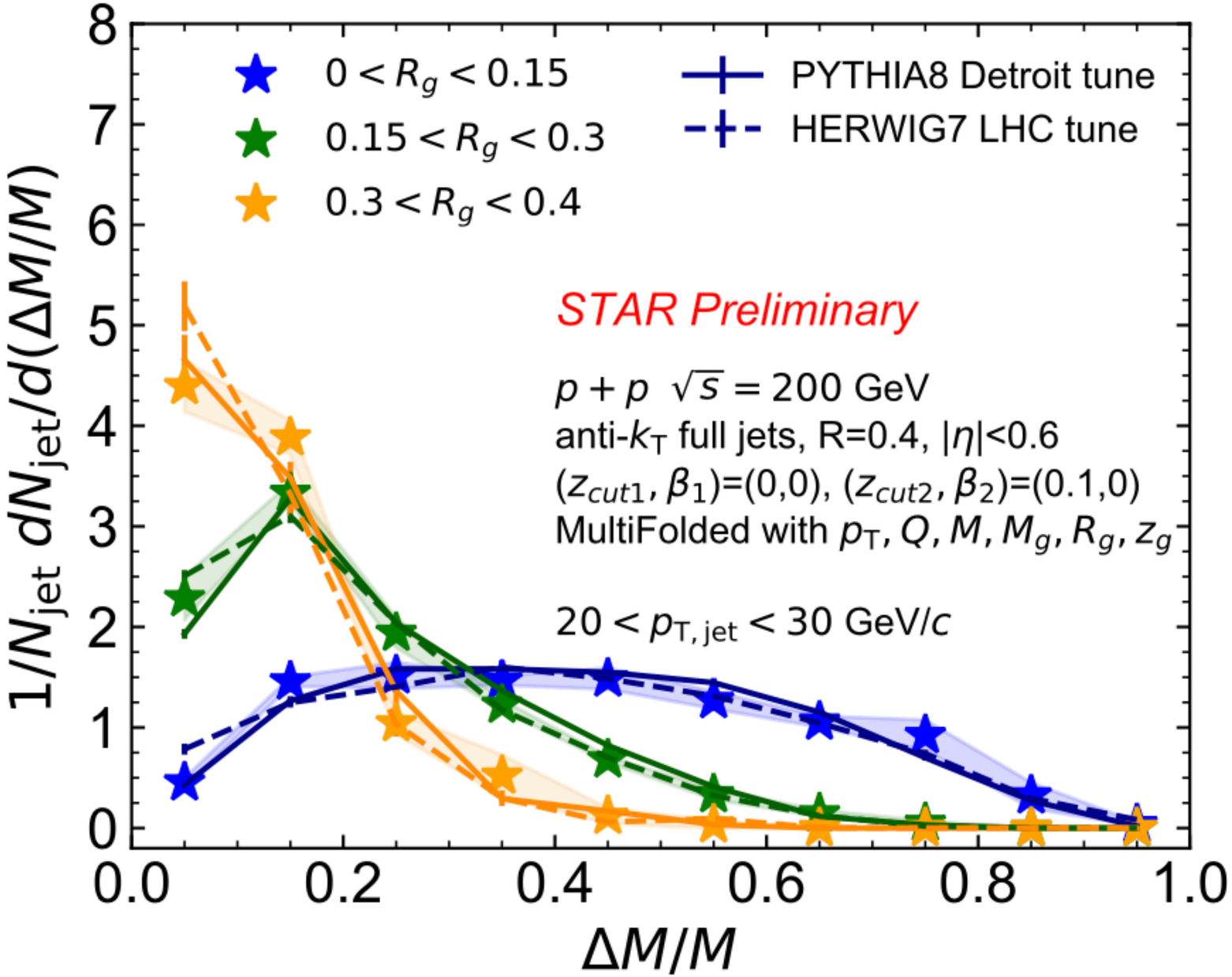
6D unfolded simultaneously via MultiFold machine learning technique

$$Q = \sum_{i \in J} \left(\frac{p_T^i}{p_T^J} \right)^{\kappa} q_i \qquad p_T \text{ vs } Q \text{ vs } M \text{ vs } z_g \text{ vs } R_g \text{ vs } M_g$$

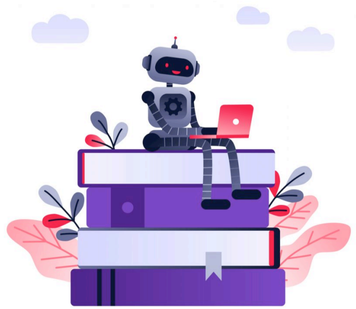
Youqi Song (Yale) @ DNP 2022

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

- Selecting on larger mass jets simultaneously sculpts your jet charge selection



Multifold allowed us to measure this!



Youqi Song (Yale) @ DIS 2023

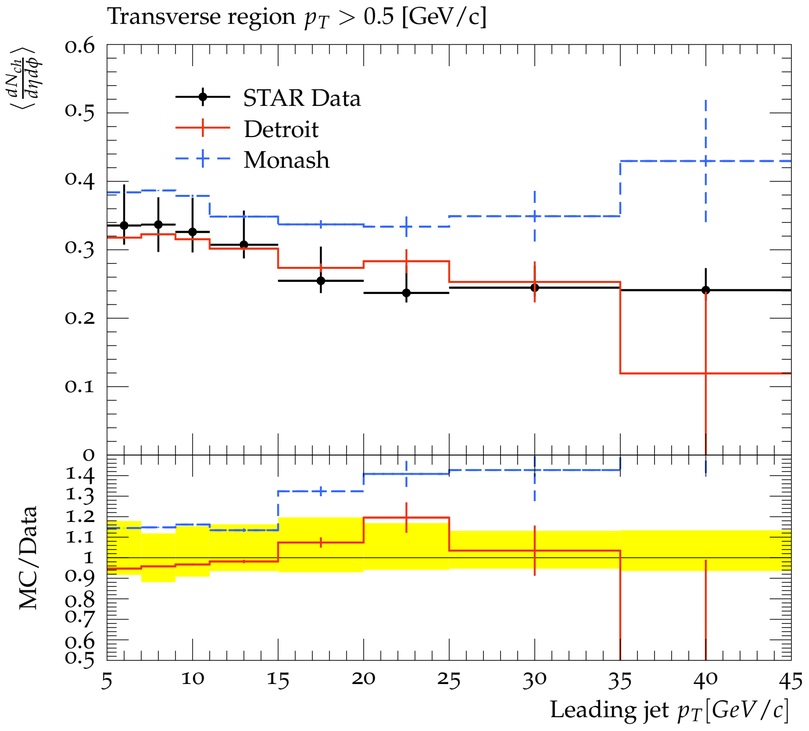
Andreassen et.al
Phys. Rev. Lett. 124, 182001 (2020)

The more you groom, the further along the shower you go!

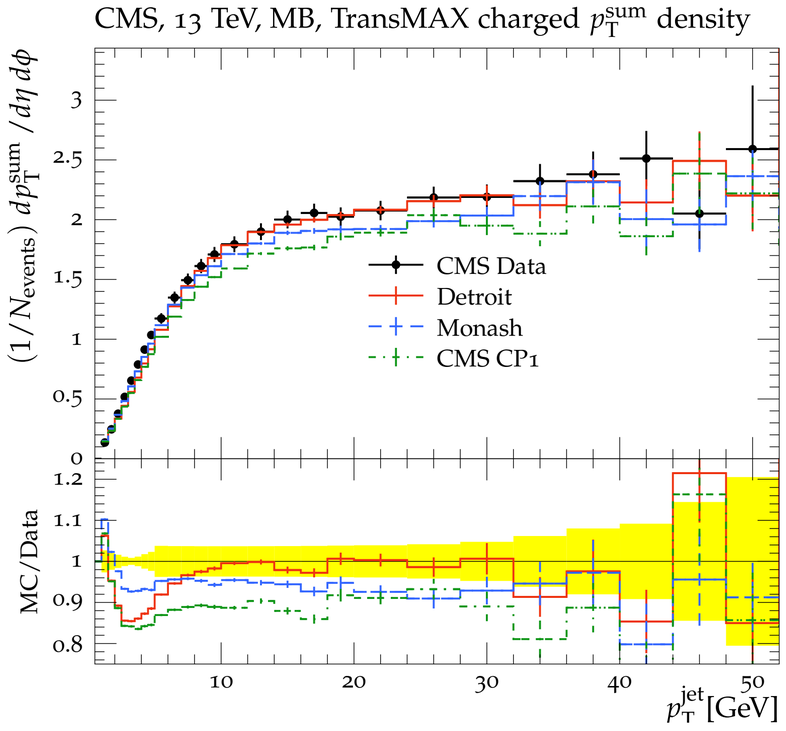
Detour… PYTHIA 8 Detroit Tune

New Monte Carlo tune that accurately describes mid-rapidity data from **RHIC to LHC**

M Aguillar et. al, Phys. Rev. D 105 (2022) 1, 016011

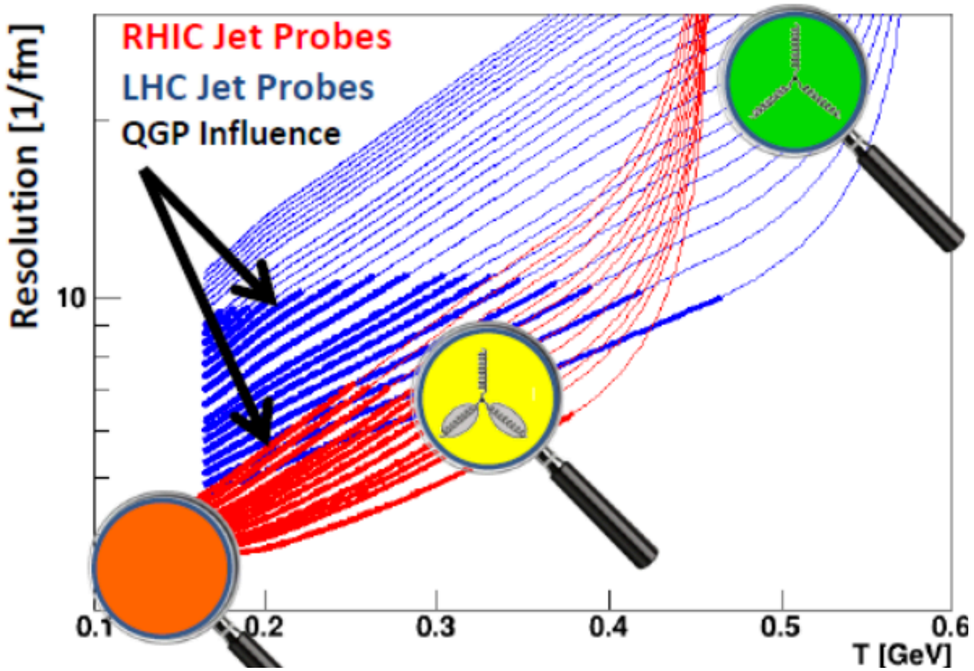


$\sqrt{s} = 200$ GeV

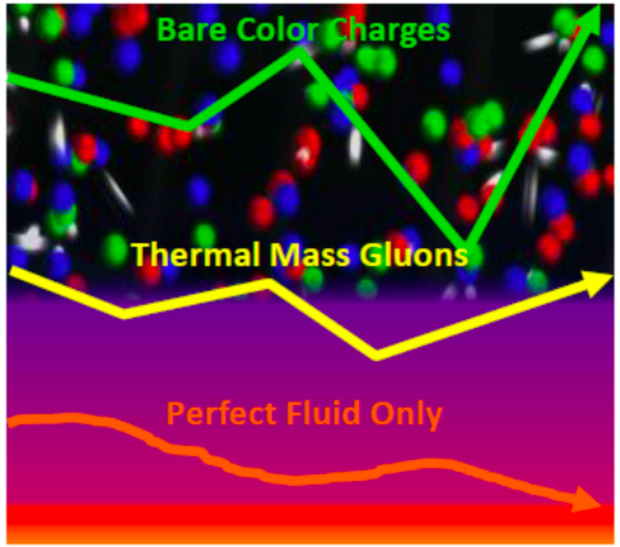


$\sqrt{s} = 13000$ GeV

Jets for QGP transport properties



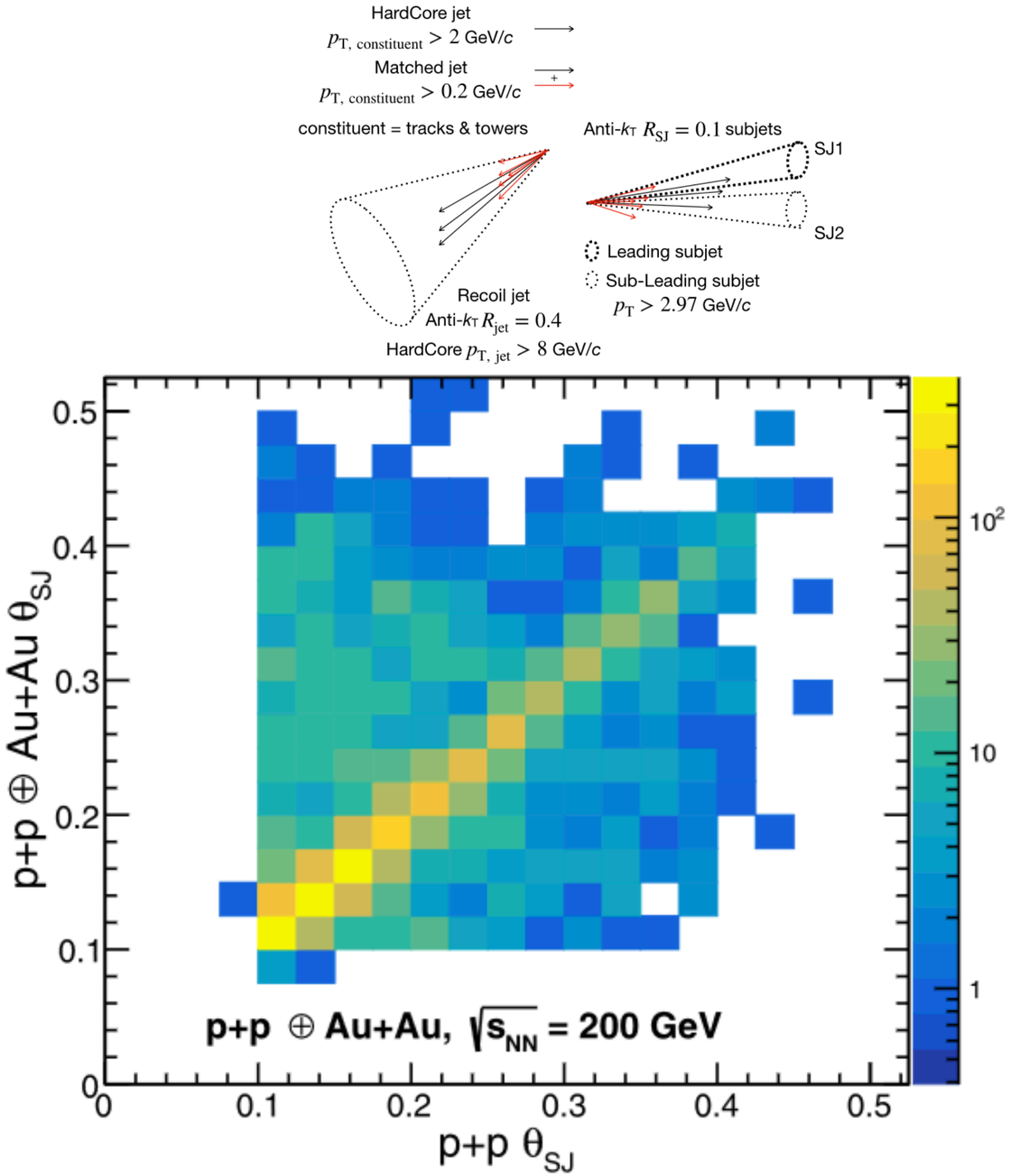
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

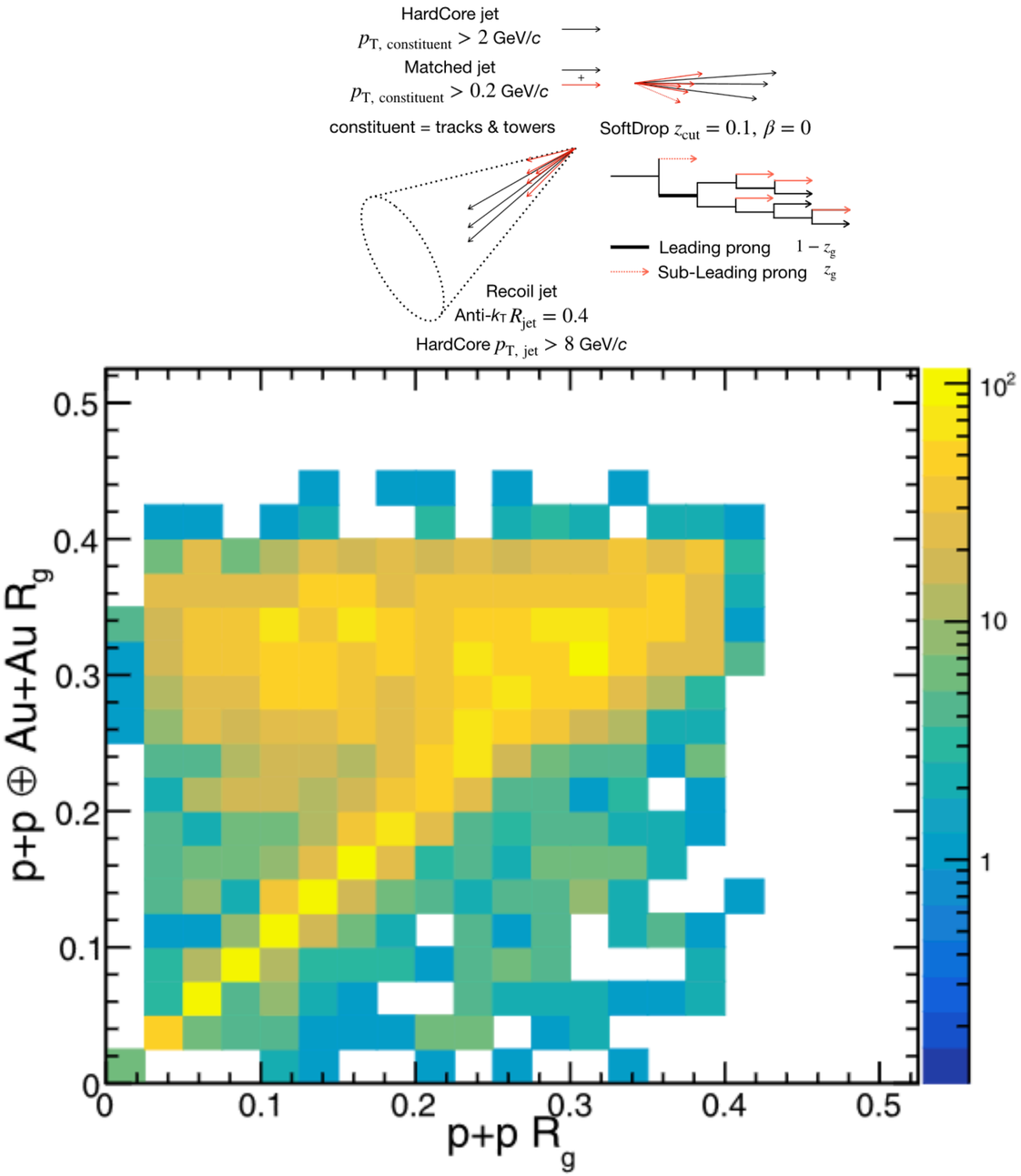


Microscopic properties of the QGP Medium - structure at varying scales

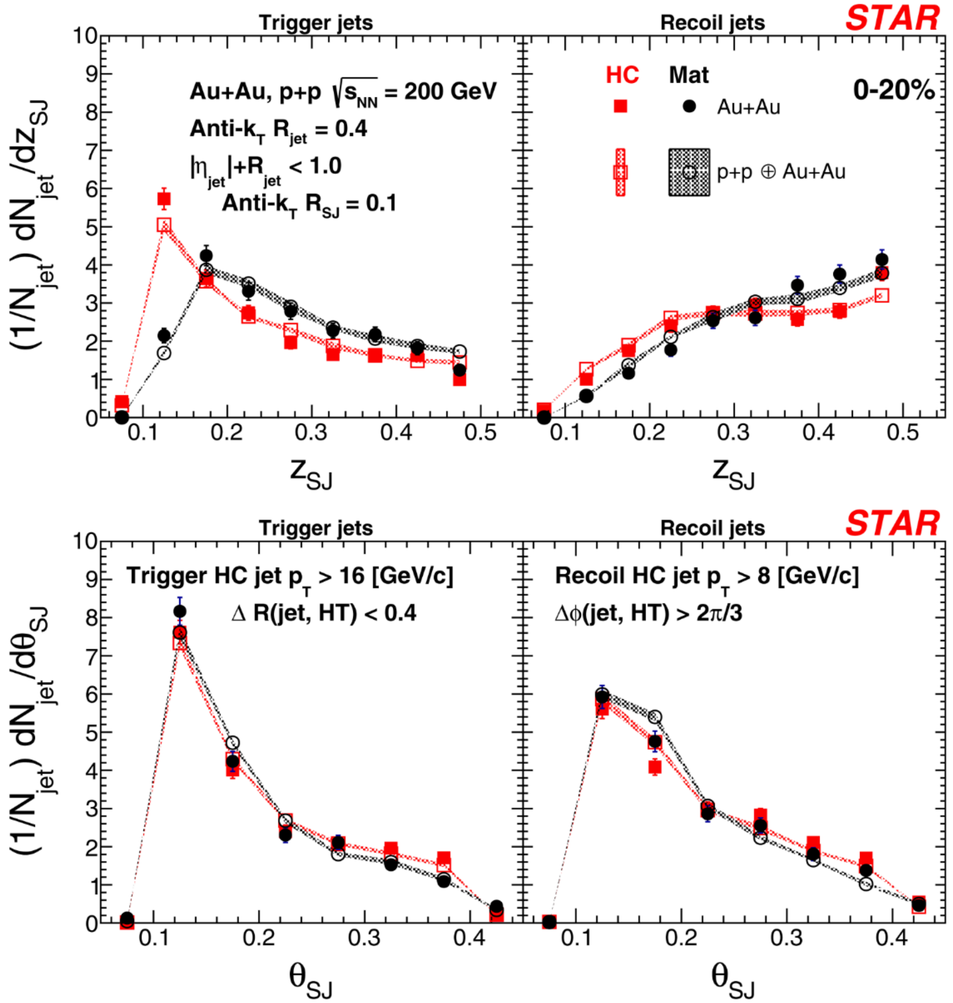
This is inherently a two step process that is not mutually exclusive

Understand jet energy loss → Extract medium properties

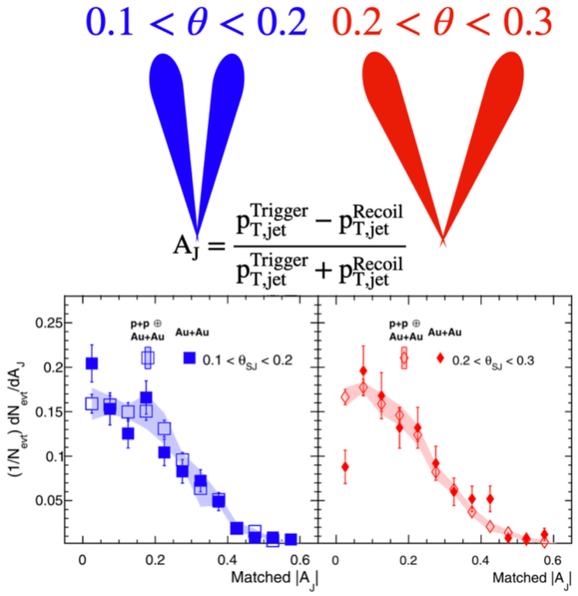

HardCore jet
$p_{T,\,constituent} > 2$ GeV/c
Matched jet
$p_{T,\,constituent} > 0.2$ GeV/c
constituent = tracks & towers
Anti-k_T $R_{SJ} = 0.1$ subjets
SJ1
SJ2
Leading subjet
Sub-Leading subjet
$p_T > 2.97$ GeV/c
Recoil jet
Anti-k_T $R_{jet} = 0.4$
HardCore $p_{T,\,jet} > 8$ GeV/c
p+p ⊕ Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
p+p ⊕ Au+Au θ_{SJ}
p+p θ_{SJ}


HardCore jet
$p_{T,\,constituent} > 2$ GeV/c
Matched jet
$p_{T,\,constituent} > 0.2$ GeV/c
constituent = tracks & towers
SoftDrop $z_{cut} = 0.1$, $\beta = 0$
Leading prong $1 - z_g$
Sub-Leading prong z_g
Recoil jet
Anti-k_T $R_{jet} = 0.4$
HardCore $p_{T,\,jet} > 8$ GeV/c
p+p ⊕ Au+Au R_g
p+p R_g

Usefulness of differential measurements in heavy ions!

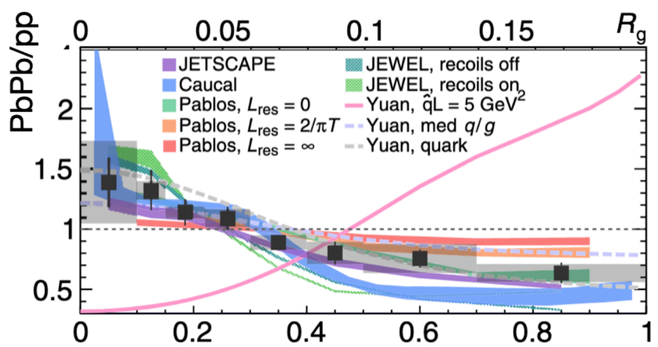


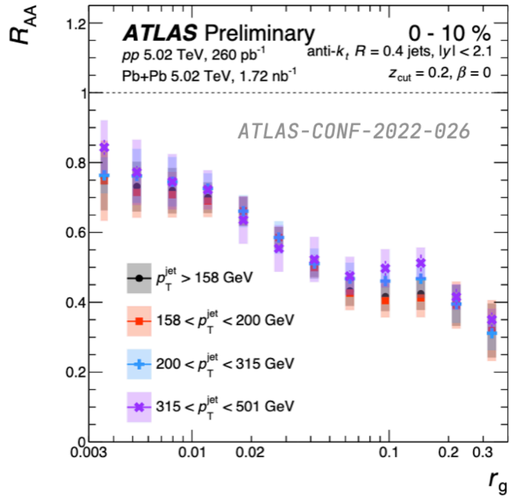
STAR Phys. Rev. C 105, 044906 (2022)



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

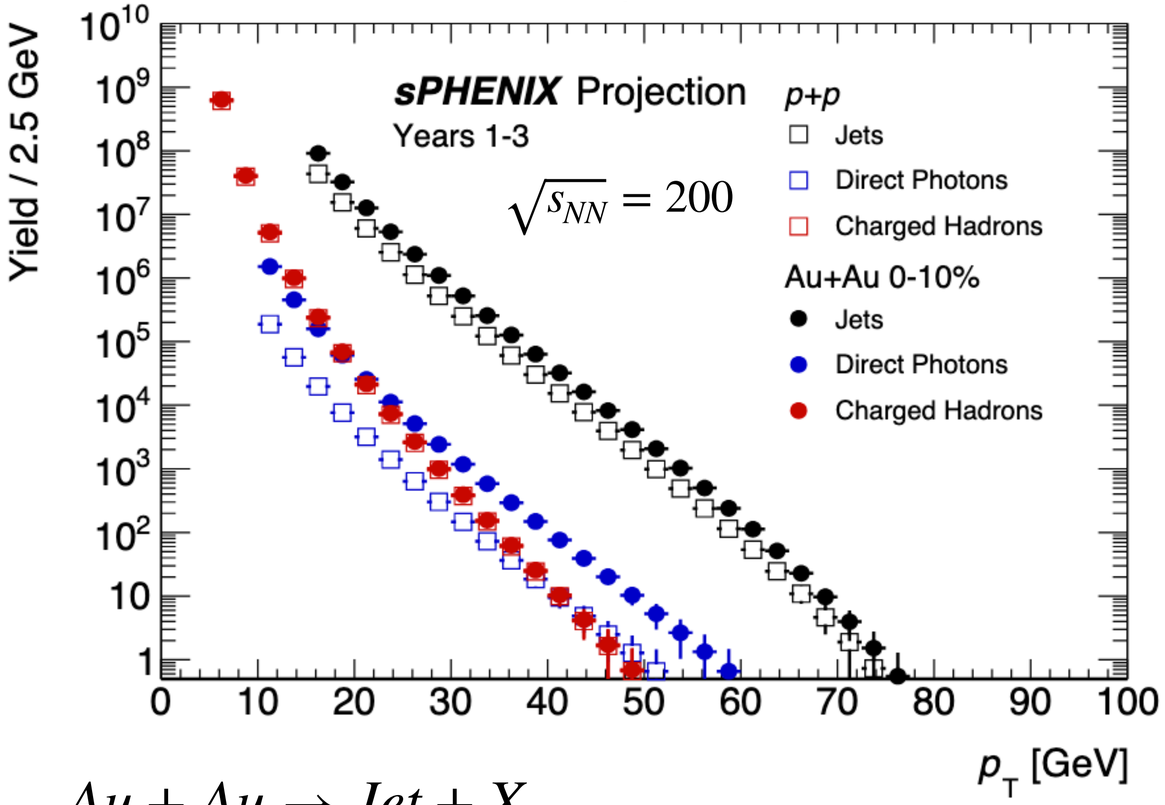
ALICE Phys. Rev. Lett. 128, 102001





Vary the jet selection bias - Substructure does not seem to be modified even though jets lose energy!

sPHENIX Beam Use Request Document 2021



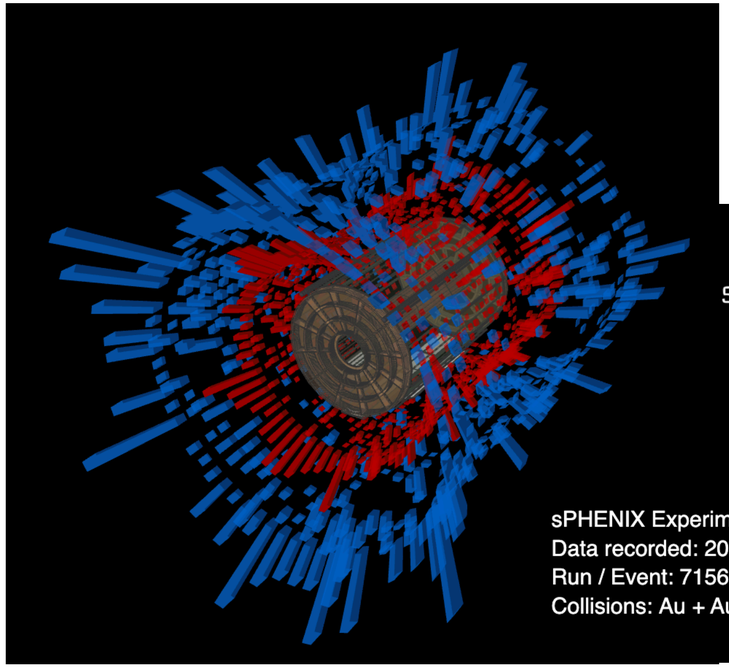
$$Au + Au \rightarrow Jet + X$$

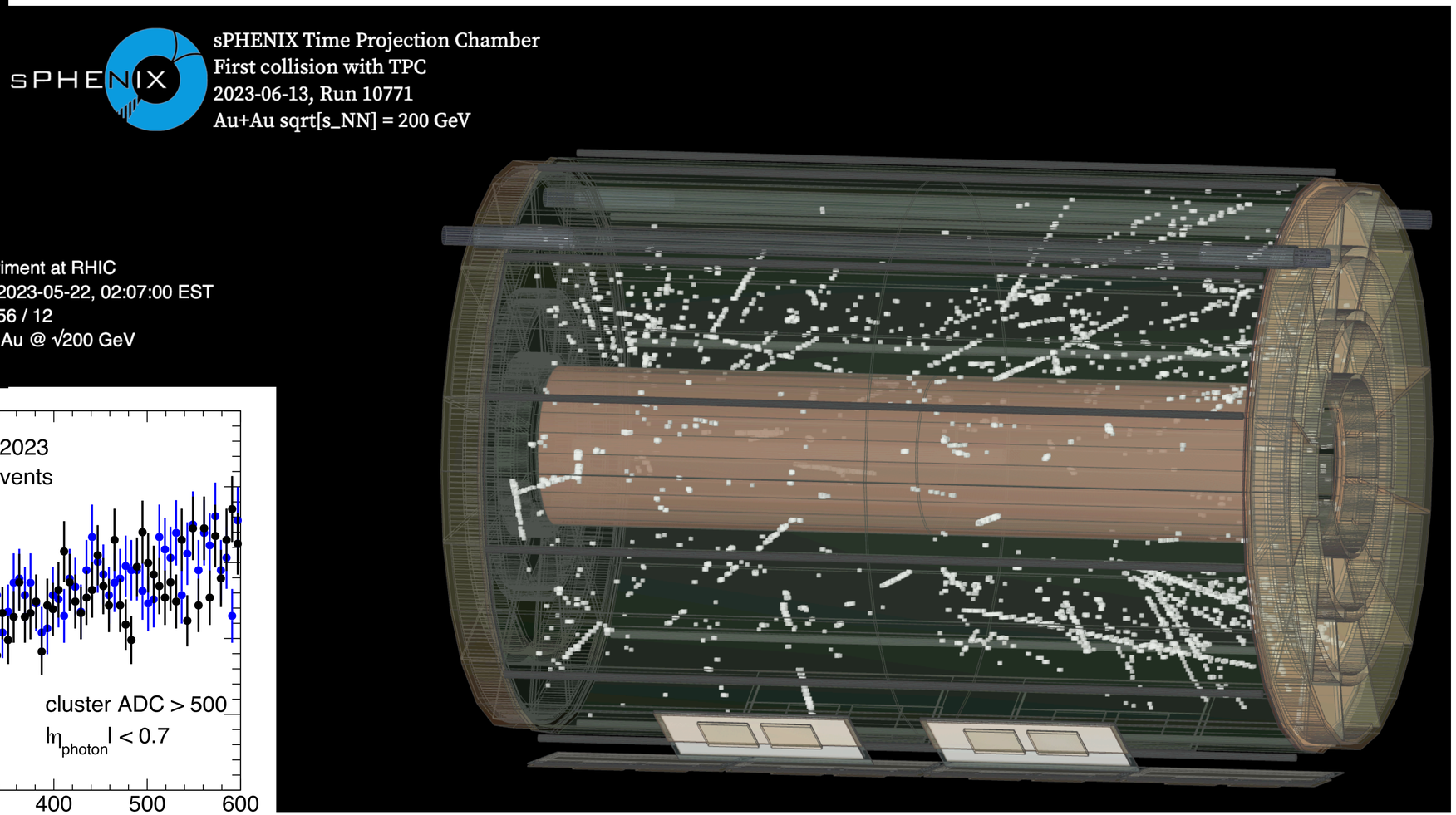
$$Au + Au \rightarrow \gamma + Jet + X$$

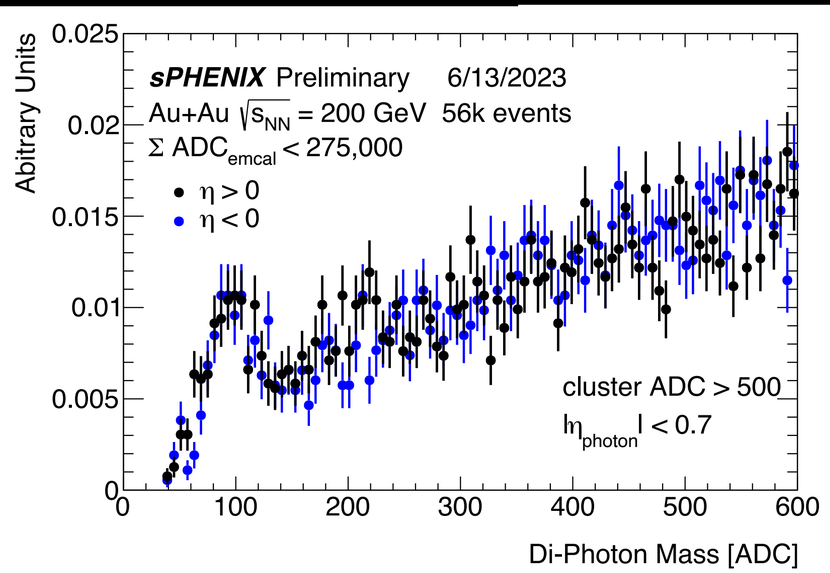
$$Au + Au \rightarrow h^{\pm,0} + X$$

- Streaming readout allows high data-taking rate enabling slicing and dicing across phase-space
- Factor of 30 increase in data comparison to previous measurement on opening angle

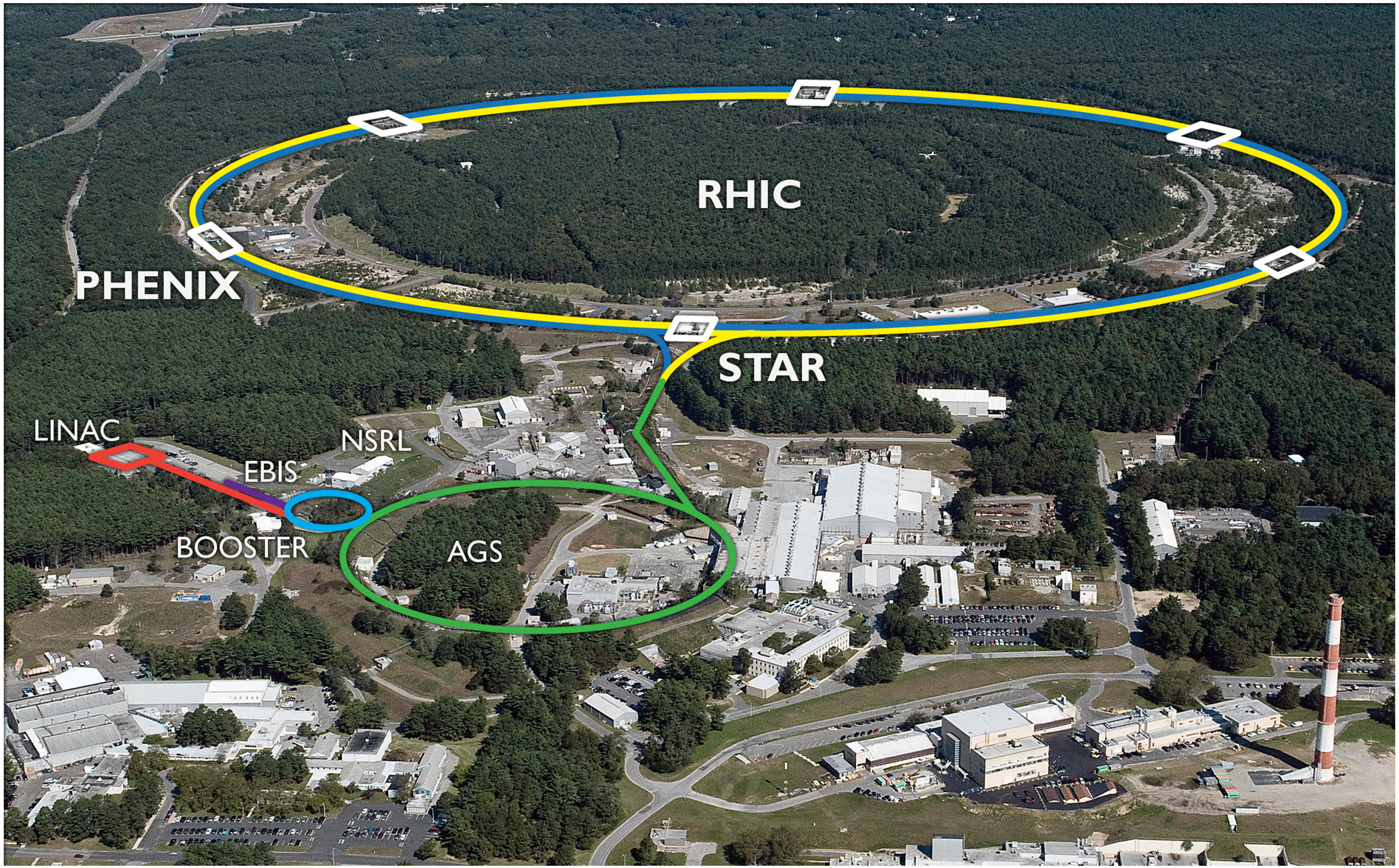
New from sPHENIX!



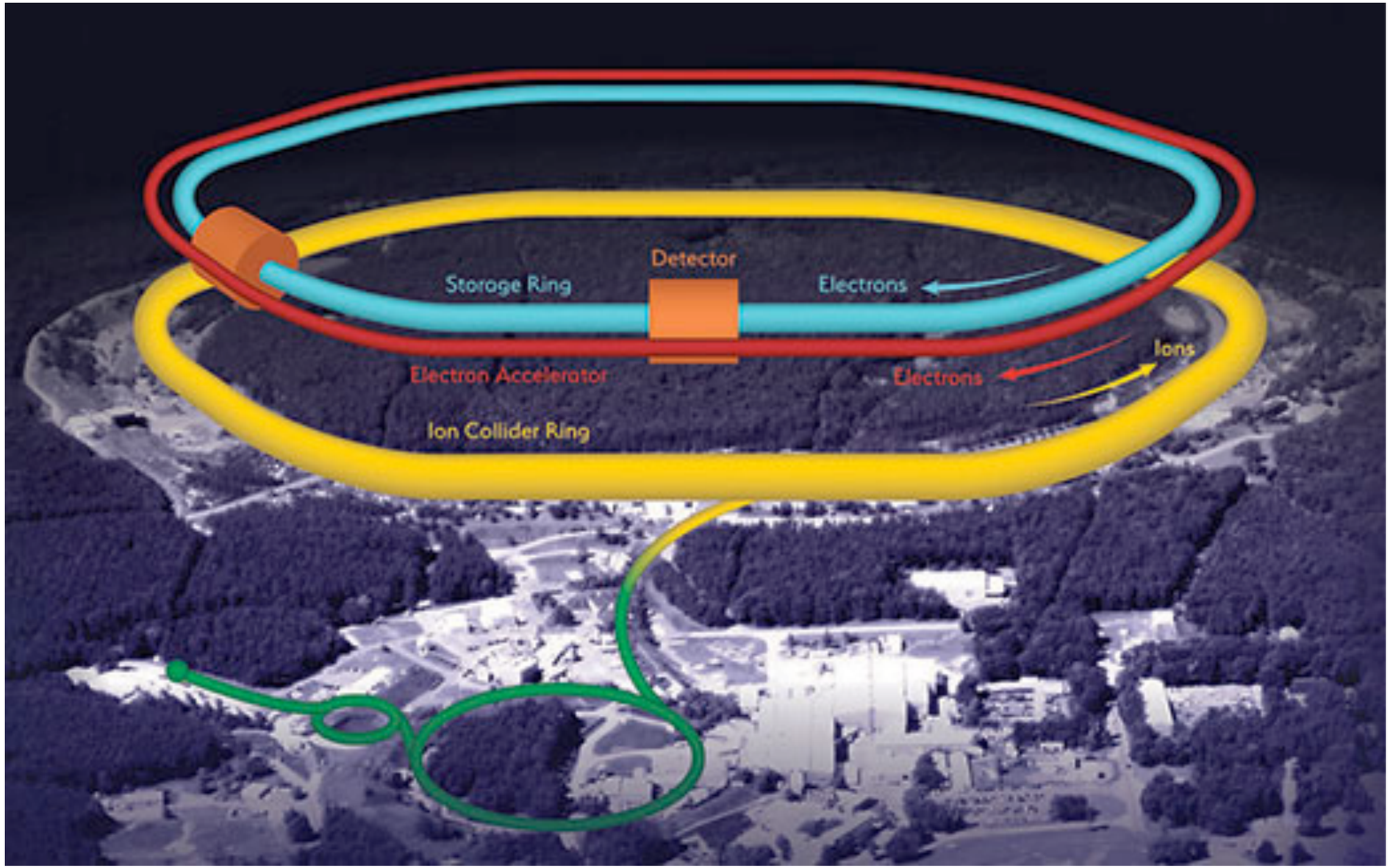


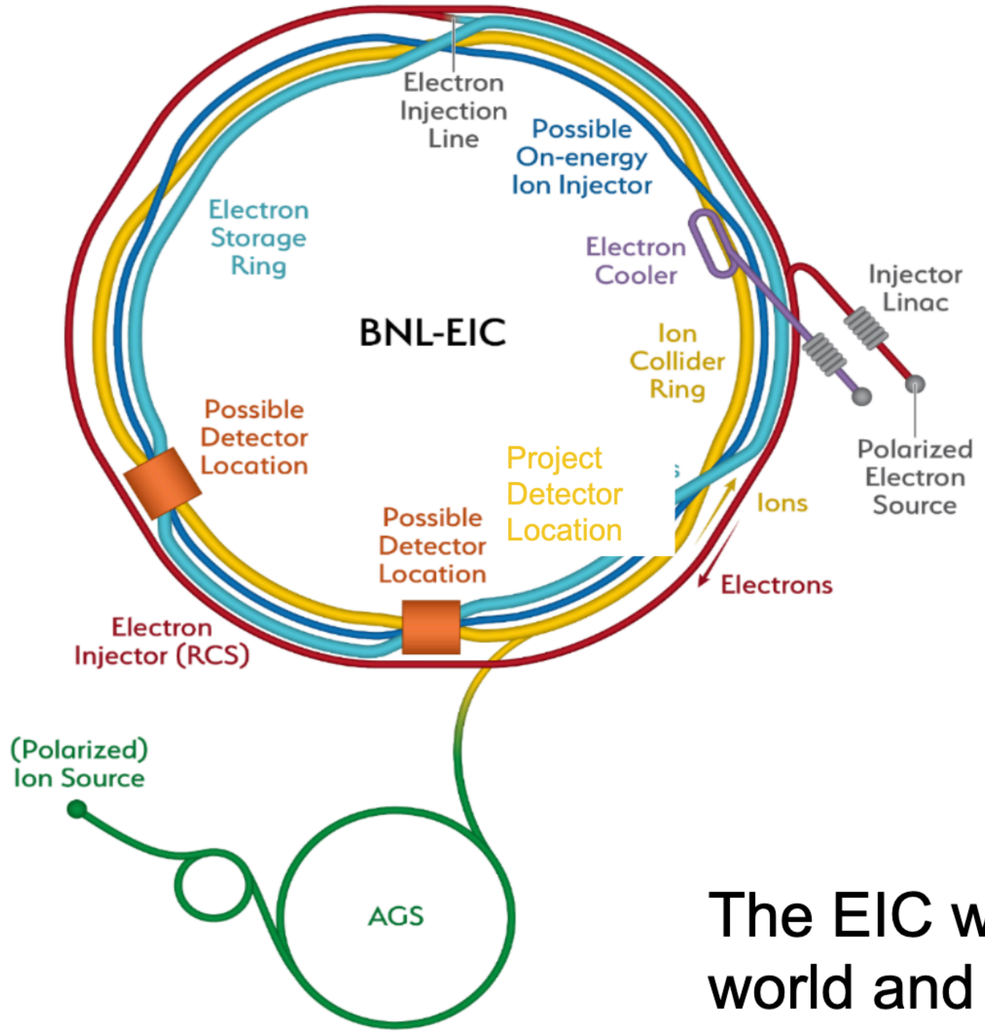


Relativistic Heavy Ion Collider @ BNL



Electron Ion Collider @ BNL





Recent Progress

Successful OPA Progress Review 1/ 2023

Significant Project staffing increases via IRA

Pursuing Long Lead (CD3a) followed by CD-2

- Hadron Storage Ring
- Hadron Injector Complex
- Electron Storage Ring
- Electron Injector Synchrotron
- Electron Cooler
- Possible On-energy Hadron Injector Ring

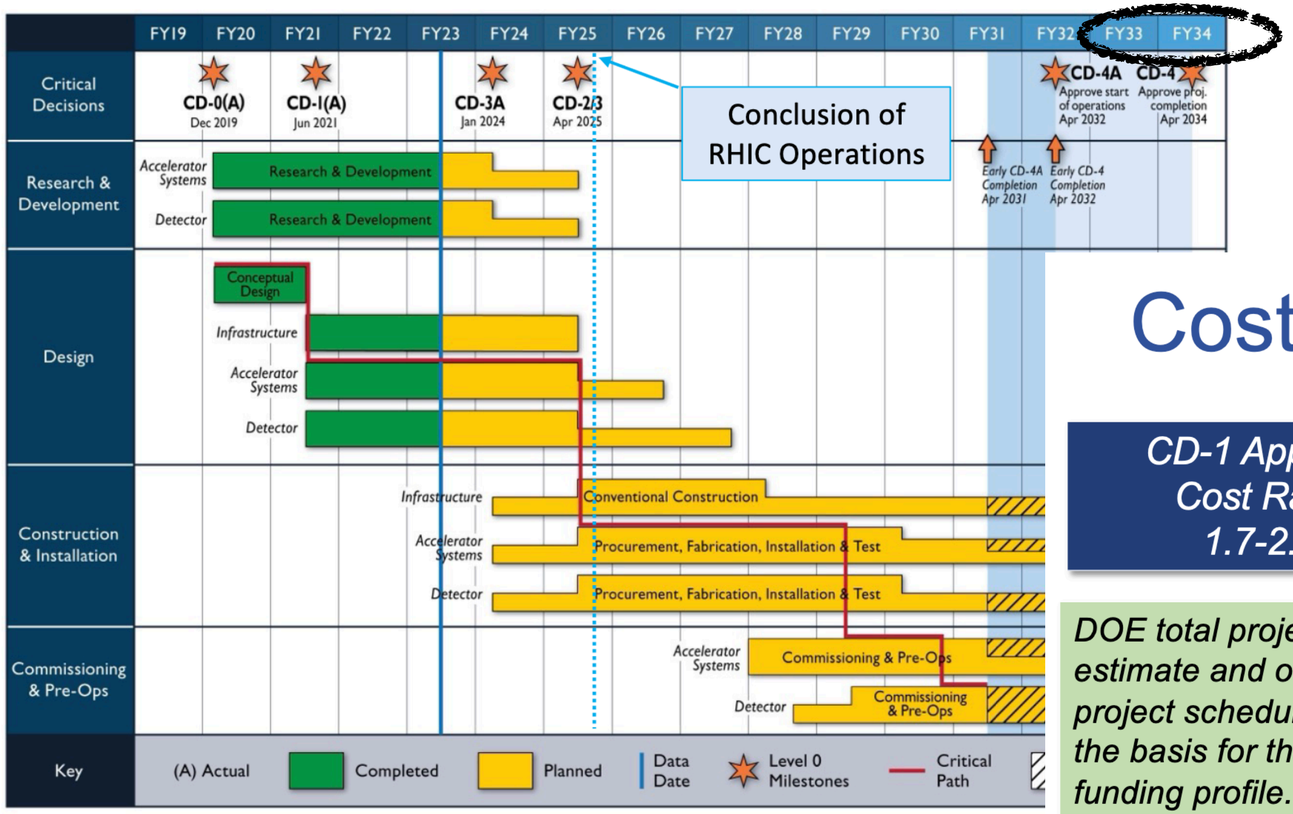
The EIC will be the most advanced accelerator in the world and the only new collider built for decades. It will keep US capability in accelerators physics number one

U.S. DEPARTMENT OF ENERGY | Office of Science

19

Slide by Tim Hallman (DoE) at the GHP meeting 2023

EIC Schedule



When?

How much?

Cost Estimate Status (DOE)

CD-1 Approved Cost Range 1.7-2.8B

DOE total project cost estimate and overall project schedule provide the basis for the DOE funding profile.

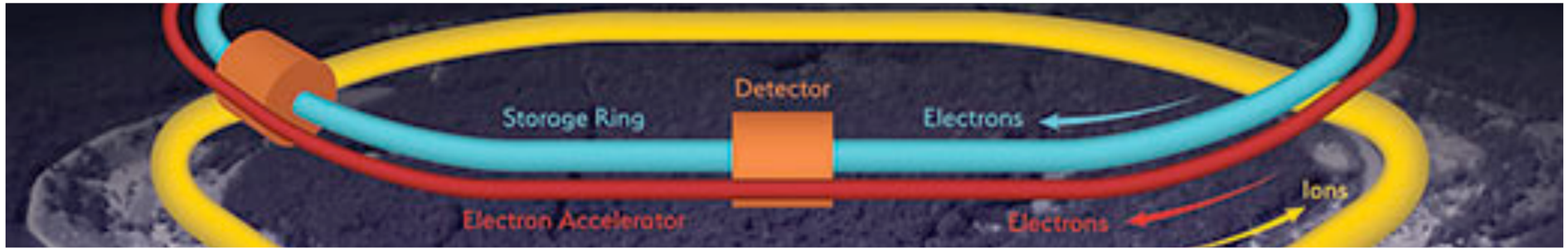
$150M IKC assumptions: $50M accelerator $100M detector (1/3)

10% on LOE activities 35% on balance

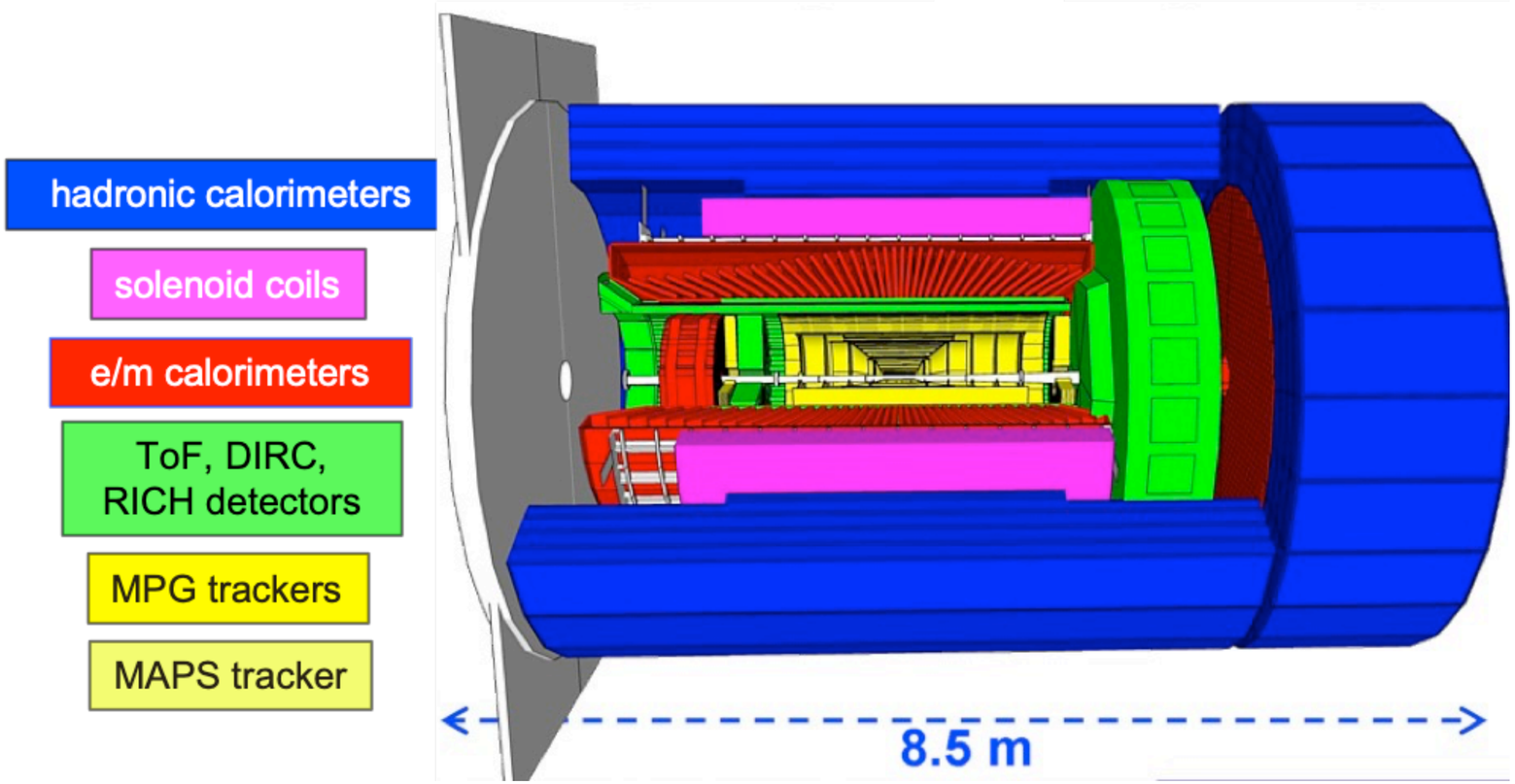
WBS	DOE+IRA schedule working Jan-2023	
6.01 - Project Management	$	184,214,124
6.02 - Accelerator Dev. & R&D	$	74,971,335
6.03 - Injector System	$	187,982,740
6.04 - Electron Storage Ring	$	180,590,034
6.05 - Hadron Ring	$	108,733,042
6.06 - Interaction Region & Detector Interface	$	167,463,407
6.07 - Accelerator Systems Support	$	218,809,284
6.08 - RF Systems	$	366,647,360
6.09 - Cryogenics	$	144,964,733
6.10 - Detector	$	225,873,364
6.11 - Infrastructure	$	[illegible]
6.12 - Pre-Operations	$	51,119,308
P6 Total (incl. escalation & overhead)	**$**	**2,162,911,663**
Approved Scope_Cost Changes to be Implemented in P6	$	82,748,000
Less Excess Escalation for activies beyond CD-4 dates (estimated)	$	(58,003,992)
Less In Kind Contributions balance (not coded in P6)	$	(86,977,421)
Less Actual Costs (AC) thru Nov. 22	$	(69,781,005)
Total work to go	**$**	**2,030,897,245**
Contingency	$	627,598,742
Total w Contingency	**$**	**2,658,495,987**
Actual Costs (AC) thru Nov-2022	$	69,781,005
Estimated Total Project Cost	**$**	**2,728,276,992**

Electron-Ion Collider 12

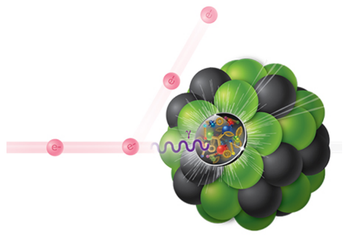
Slides by Haiyan Gao (BNL ALD for NPP)
James Yeck (BNL ALD for EIC)
GHP 2023 @ Minneapolis


Detector
Storage Ring
Electrons
Ions
Electron Accelerator
Electrons

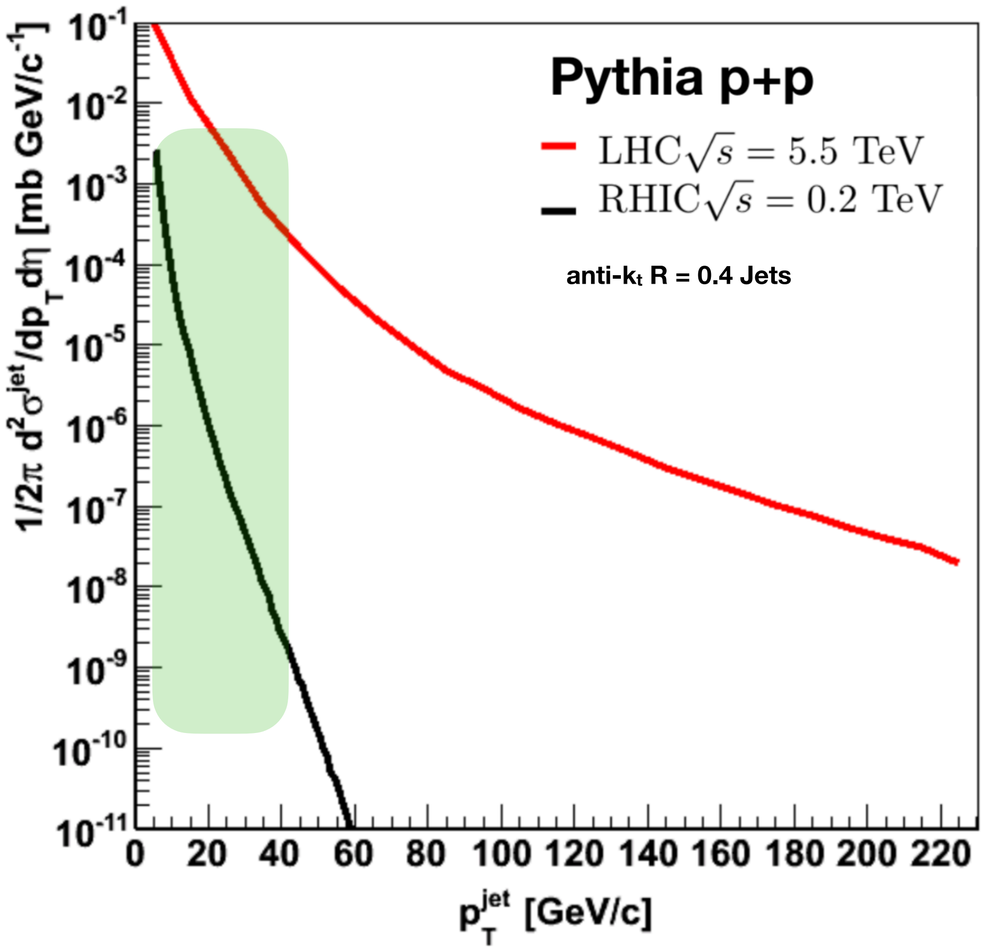
ePIC

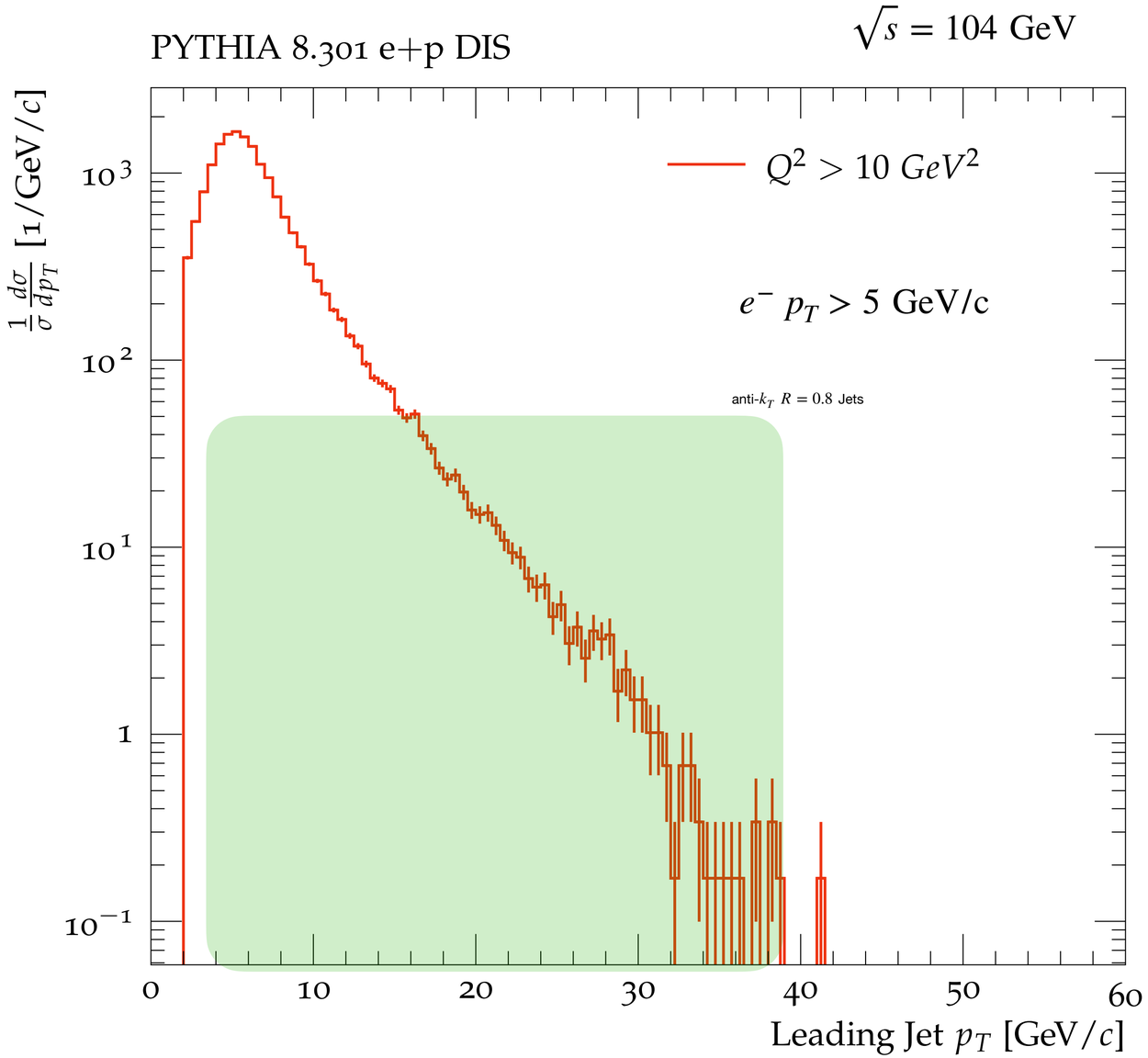

hadronic calorimeters
solenoid coils
e/m calorimeters
ToF, DIRC,
RICH detectors
MPG trackers
MAPS tracker
8.5 m

Jets at the EIC

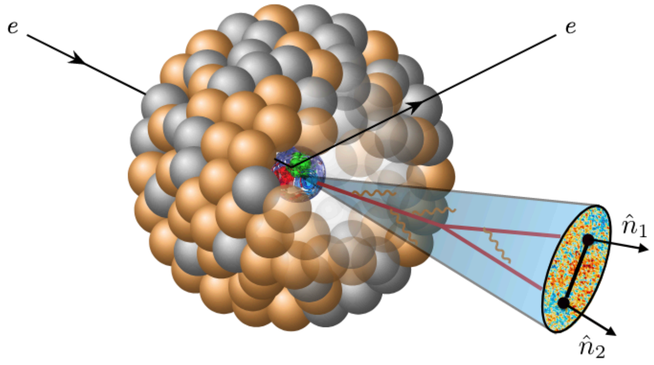


Similar jet kinematics with varied flavor composition and interaction scales



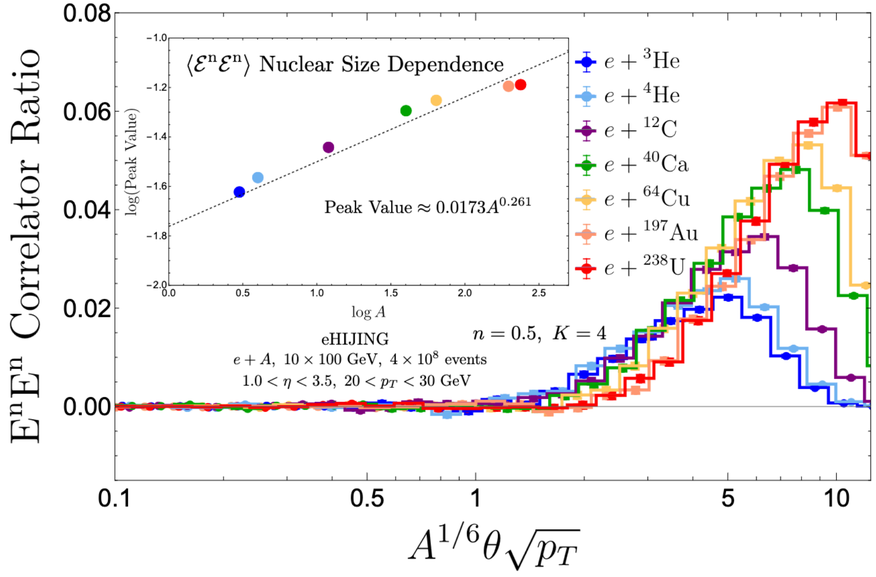


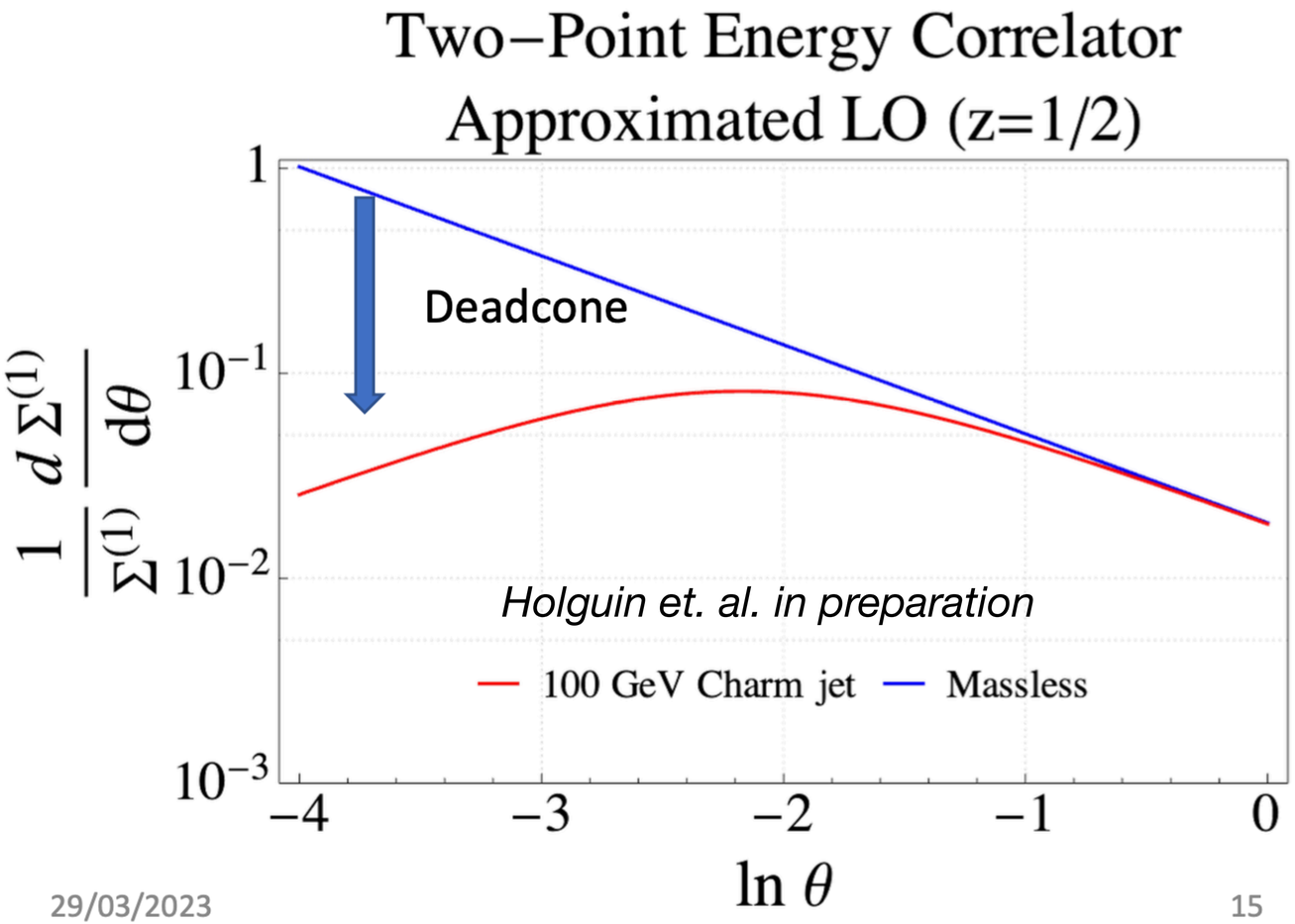
Extracting physics via the angular structure of particle distribution within jets



See talk by Jack Holguin (Ecole) @ HP 2023

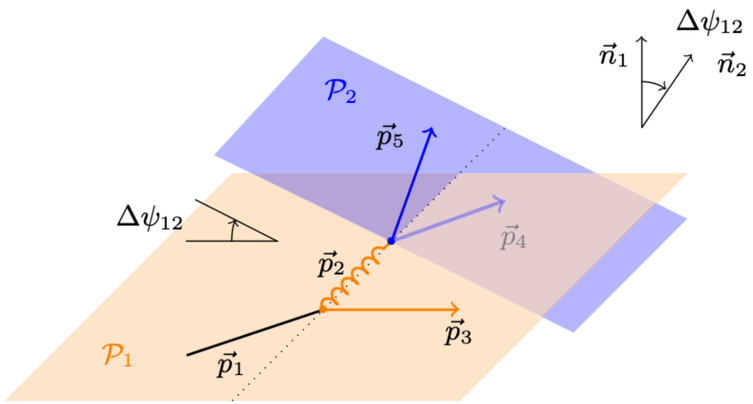
Devereaux et. al arXiv:.2303.08143



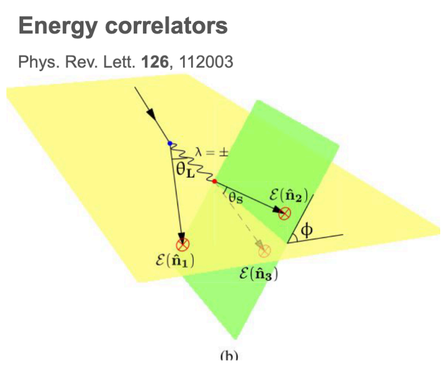


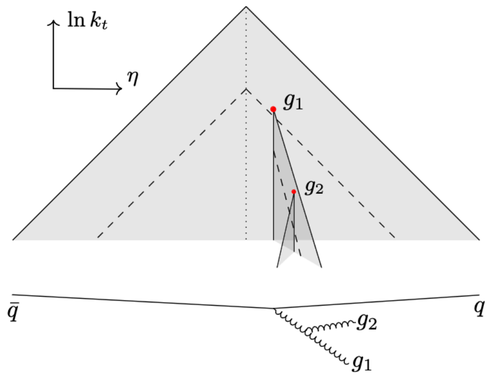
Lund planes and projections at the EIC

Baseline at RHIC!



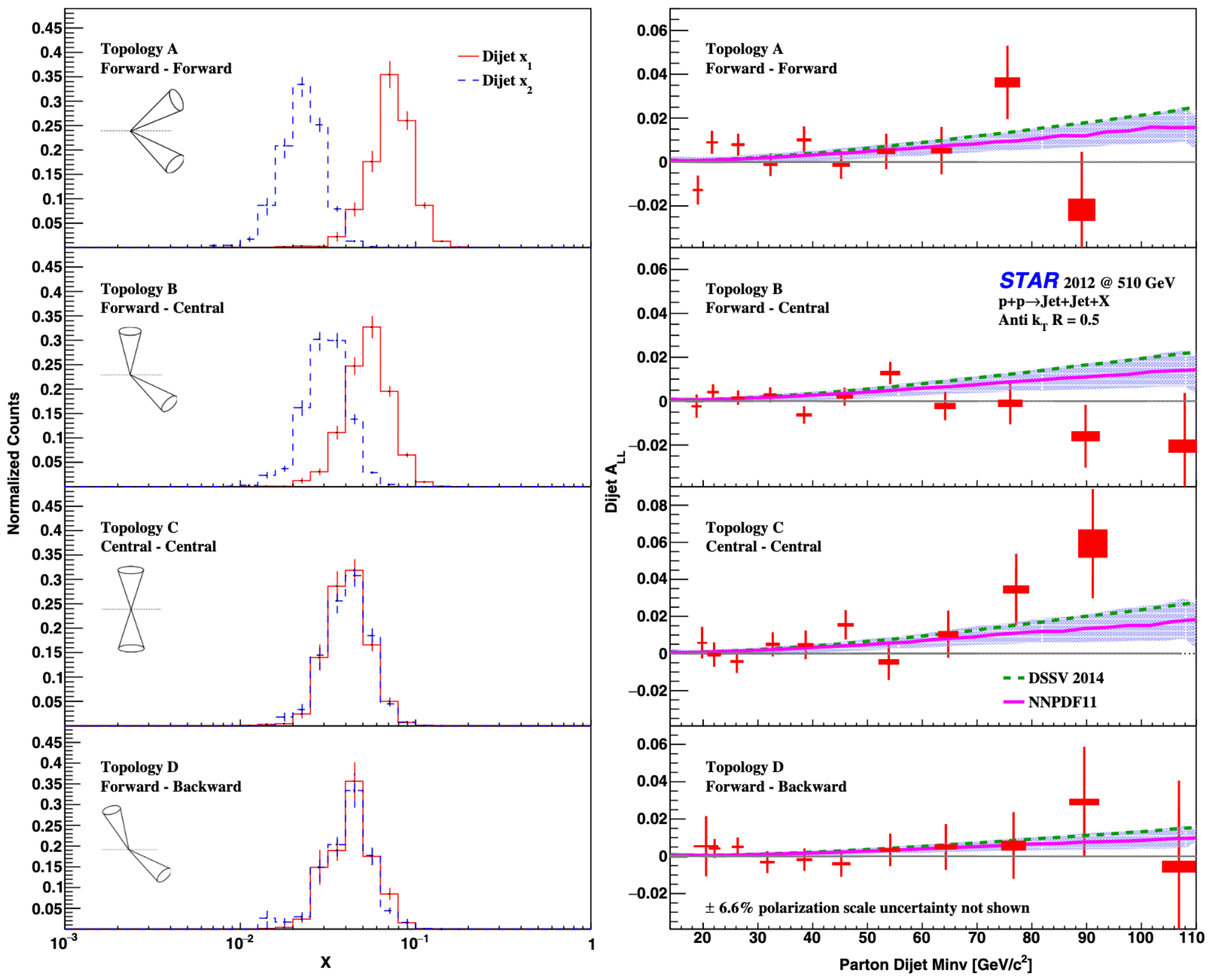
Karlberg et.al Eur. Phys. J. C (2021) 81:681



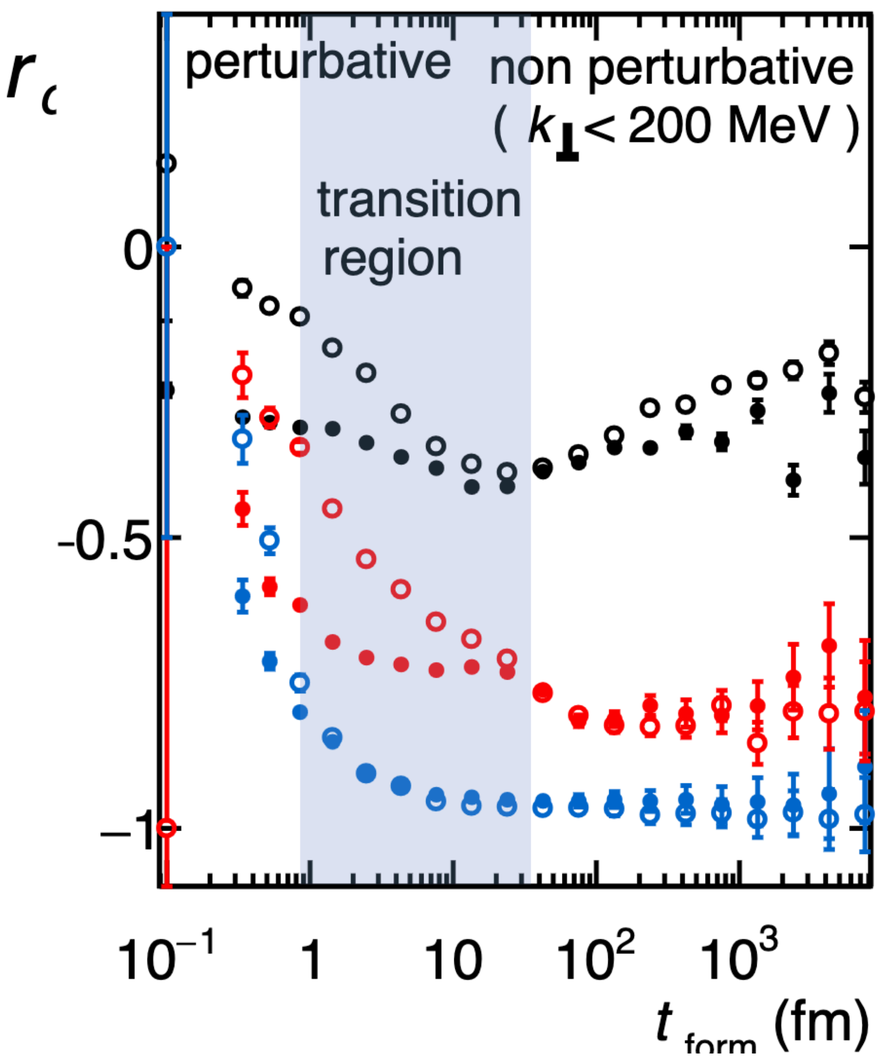


Provide ways to explore smoothly transition to non-perturbative regime
Potentially new ways to address EIC science ??

STAR Phys. Rev. D 100, 052005 (2019) 135846



Why look at the formation time and charged particles



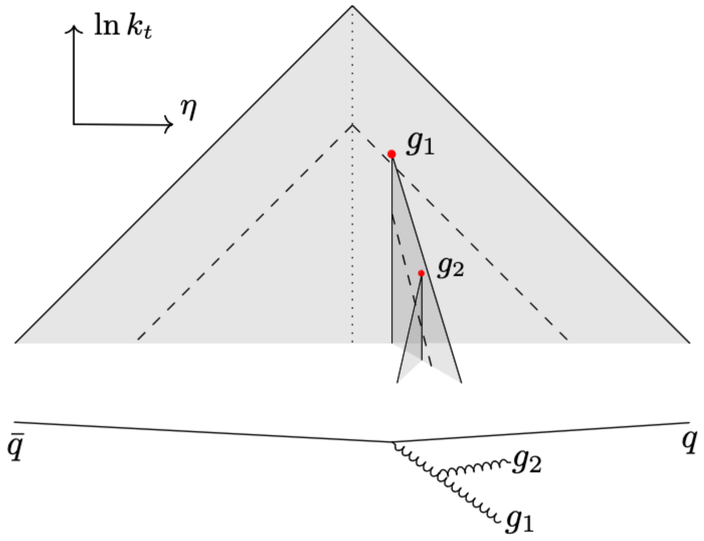
- Recent studies also show its usefulness from the theoretical POV on isolating regions where calculations are valid
- Fuzzy area, but overall one can separate out **'mostly' perturbative** and **'mostly' non-perturbative** regions based on formation time

PYTHIA	Herwig
● $\pi^\pm$	○ $\pi^\pm$
● $K^\pm$	○ $K^\pm$
● $p\bar{p}$	○ $p\bar{p}$

$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \overline{h_2}}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \overline{h_2}}/dX} .$$

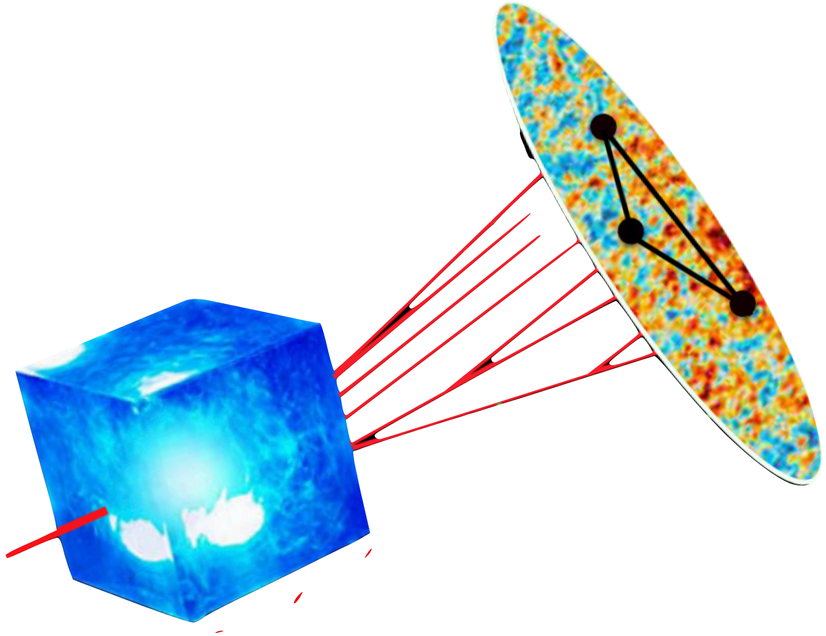
Y-T Chien, A Deshpande, M Mondal, G Sterman
arXiv: 2109.15318

The road ahead!



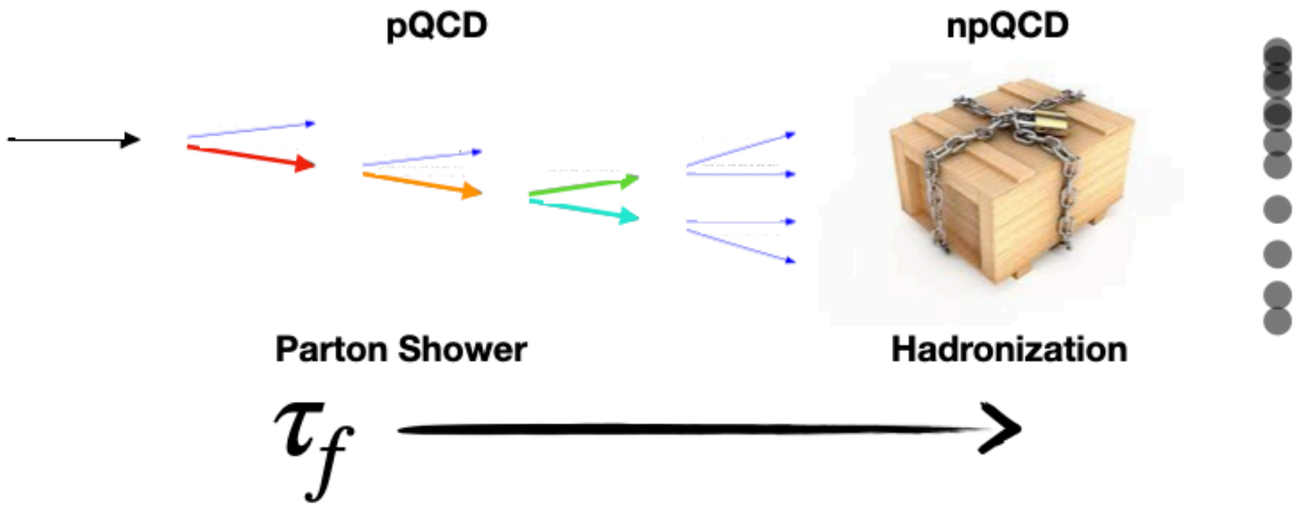
- The era of precision jet substructure is upon us!
- Tools available that allow us to separate scape dependent physics for example - pQCD vs npQCD

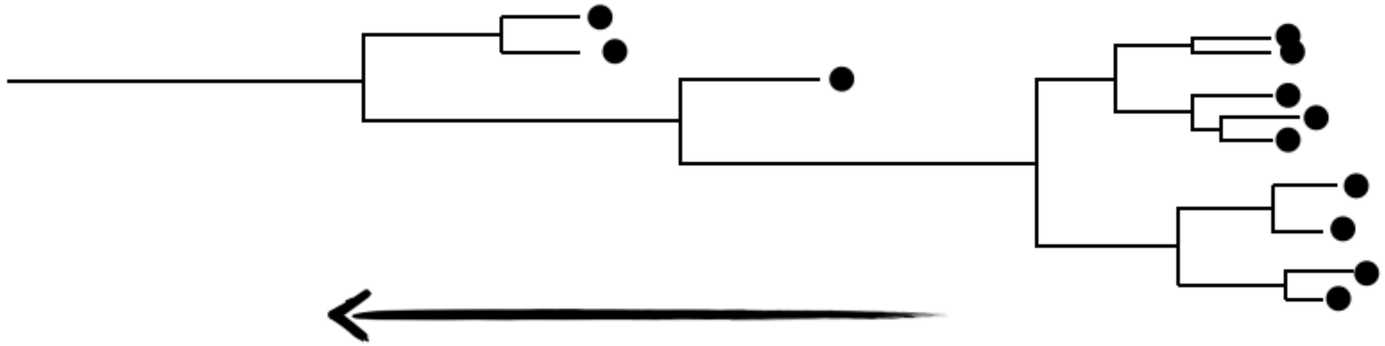
- Track the space-time evolution of fundamental particles
- Interactions with a ‘medium’ are potentially imprinted on the

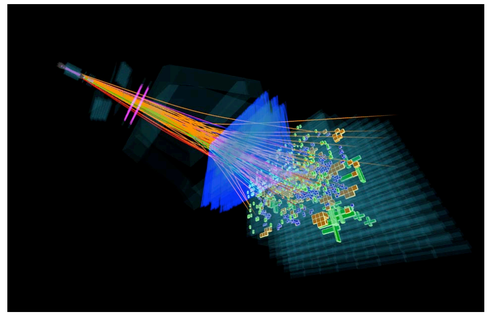


Backup

Conceptual picture of jets



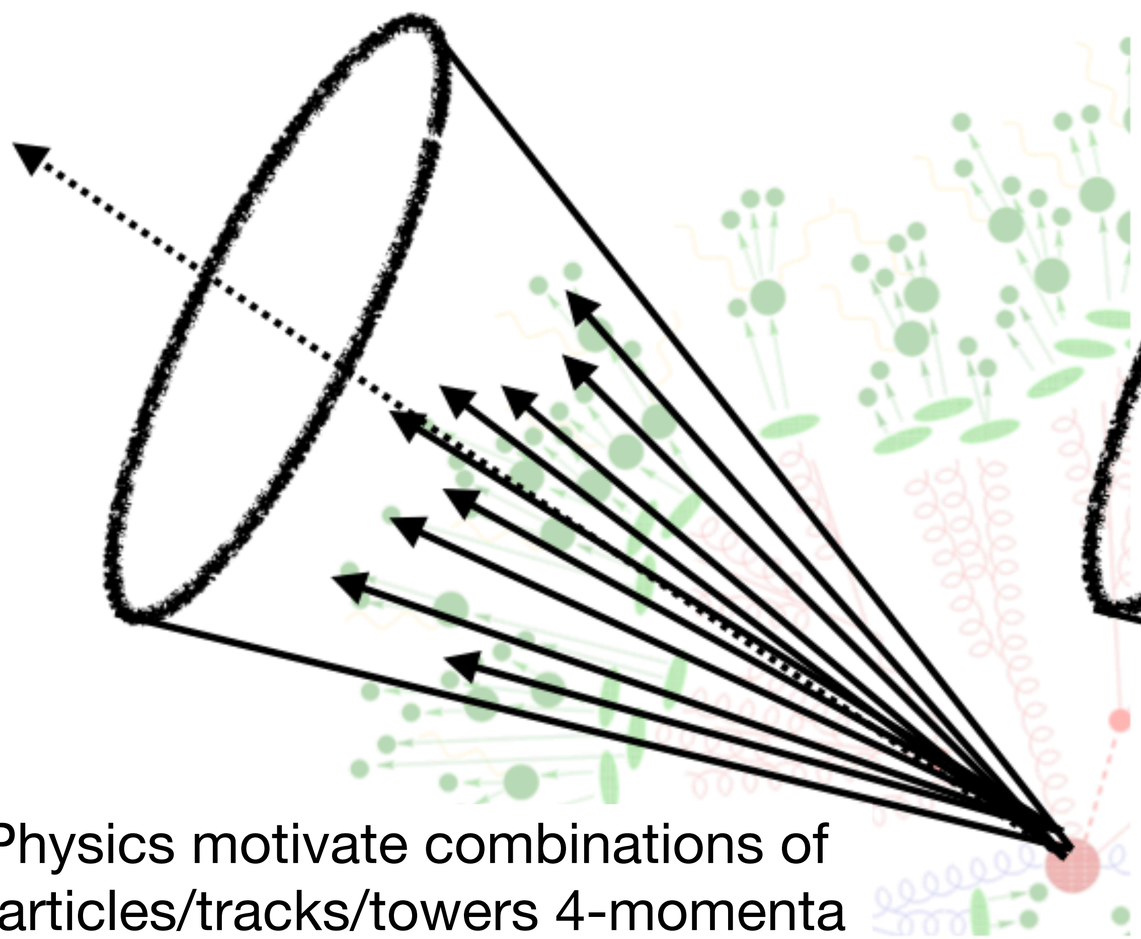




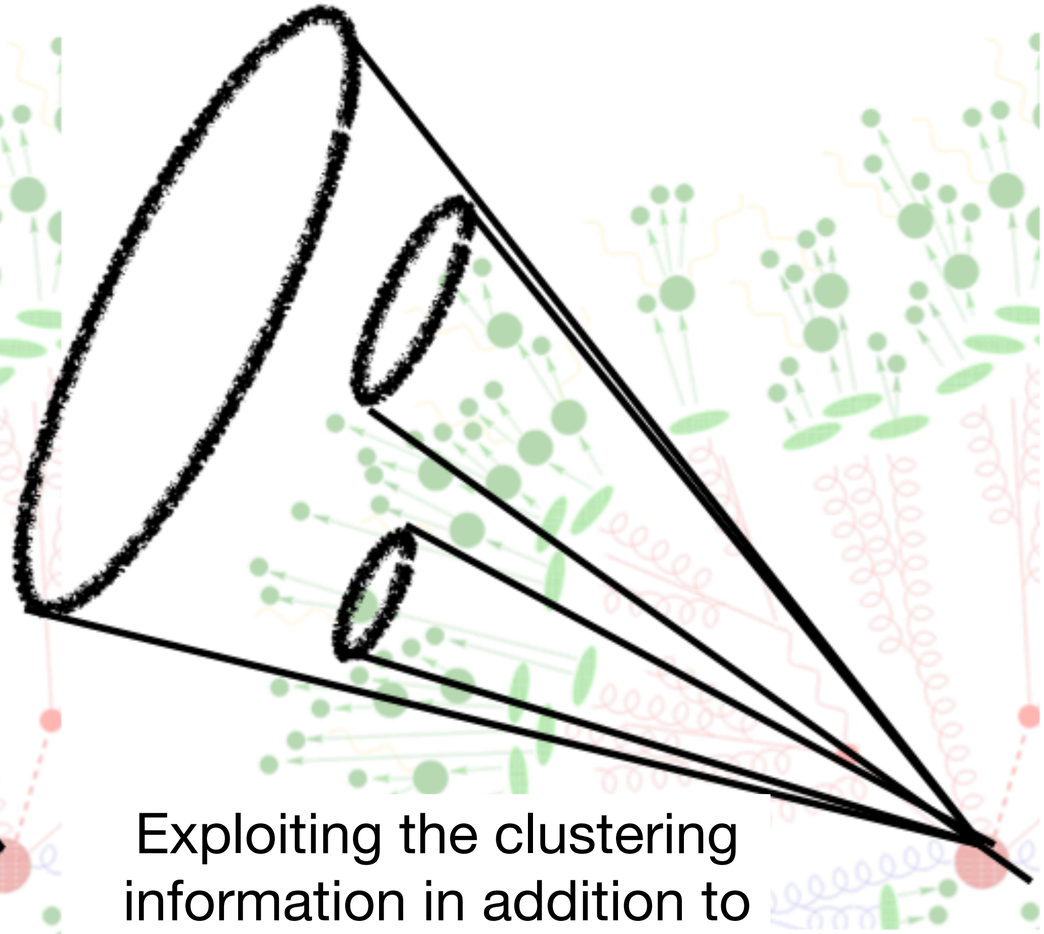
Jet Clustering

What is jet substructure?

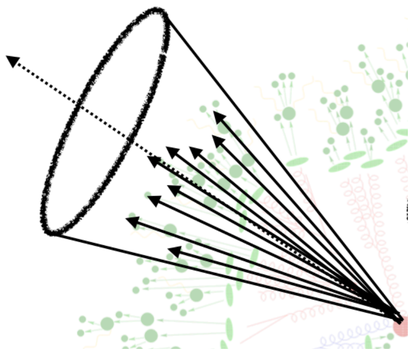
A useful way to tag jet populations



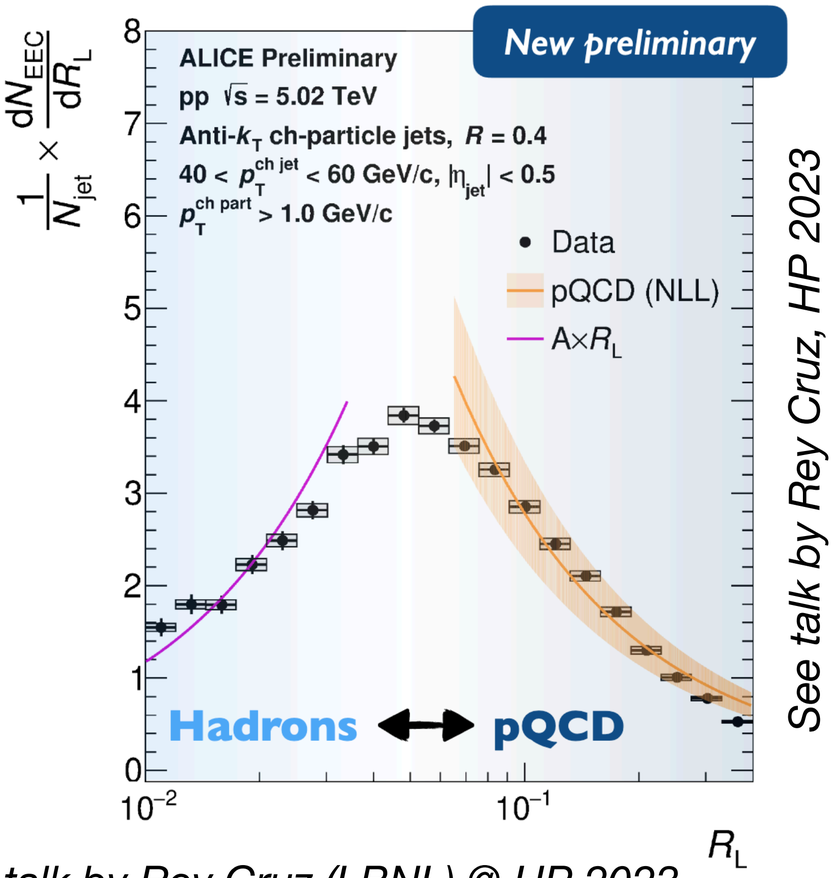
Physics motivate combinations of particles/tracks/towers 4-momenta



Exploiting the clustering information in addition to measured 4-momenta



Evidence for transition

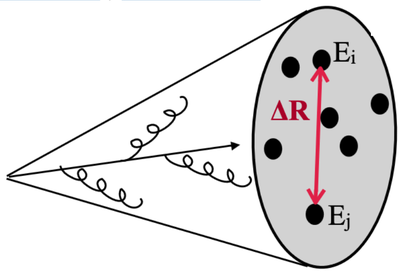


See talk by Rey Cruz, HP 2023

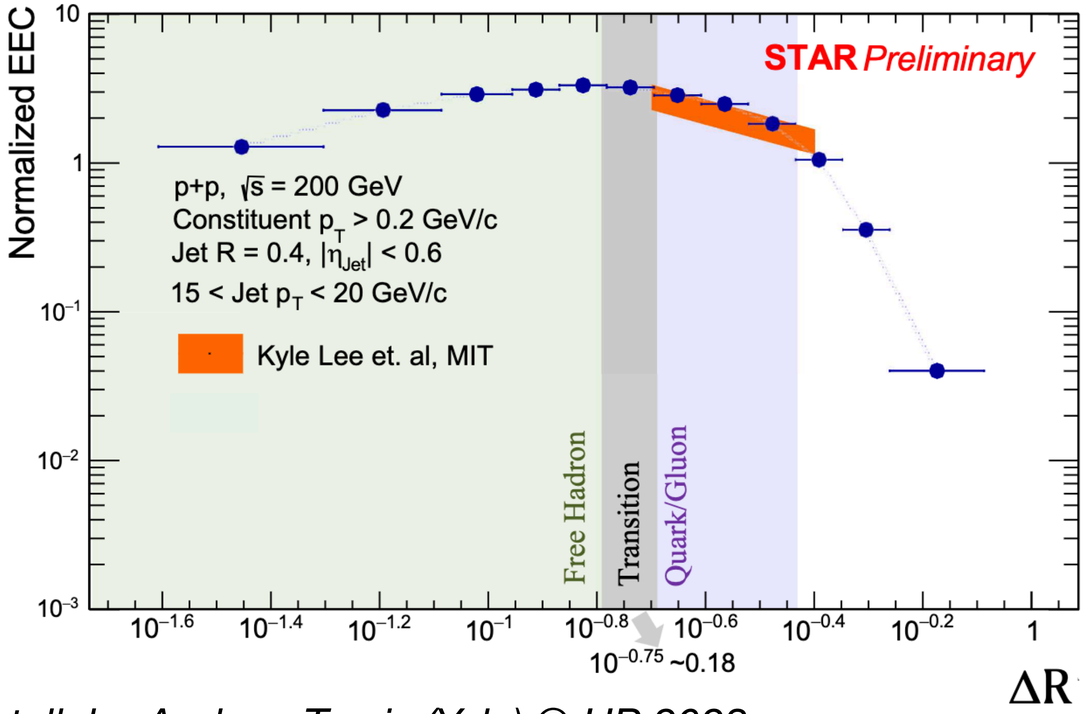
See talk by Rey Cruz (LBNL) @ HP 2023

"field theory faces reality"

arXiv:2205.03414 , 2209.11236

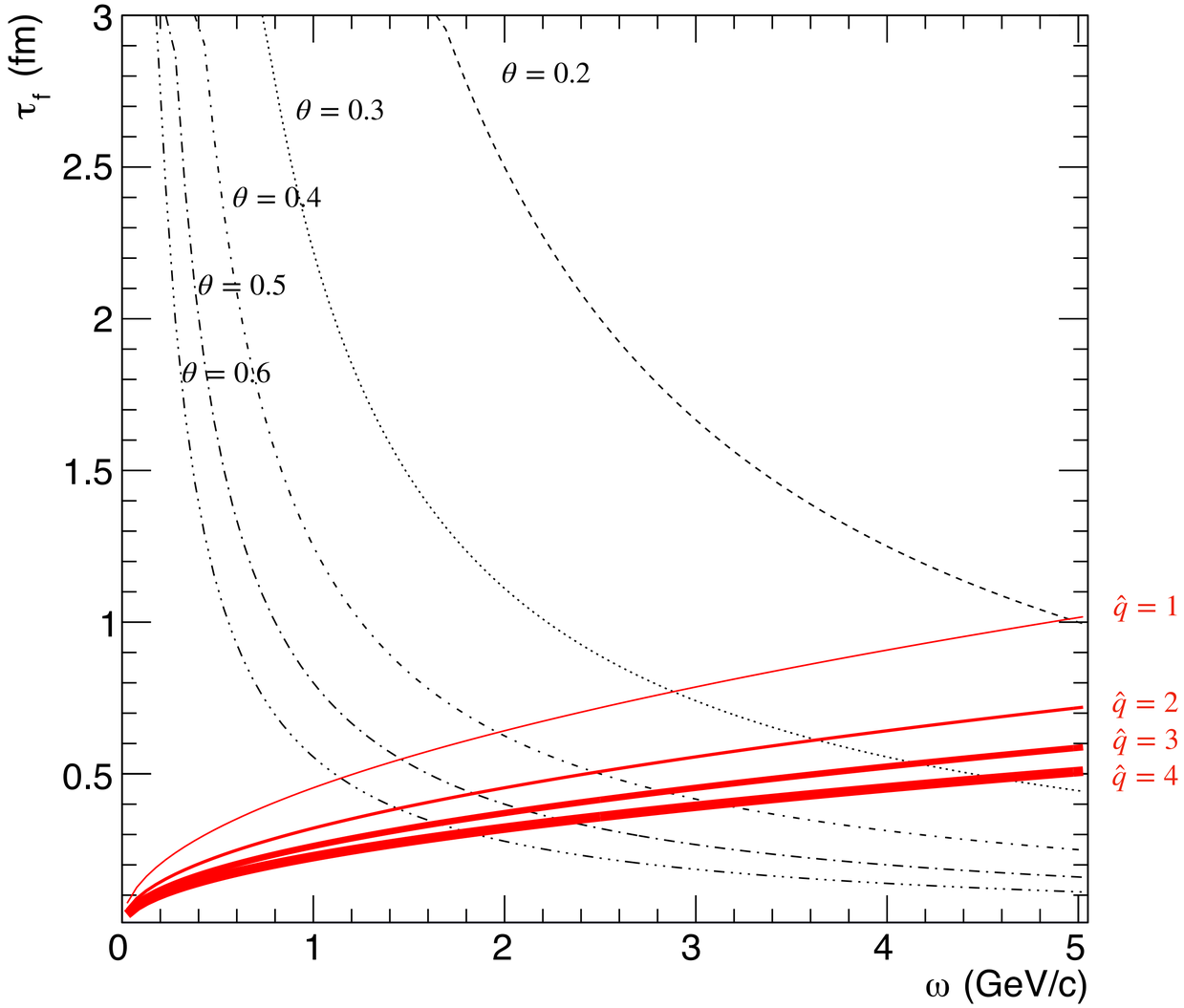


- Transition indicated as a function of the opening angle - which we know is related to the time scale!



See talk by Andrew Tamis (Yale) @ HP 2023

First steps in space-time differential energy loss

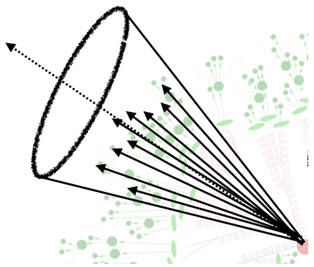


$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

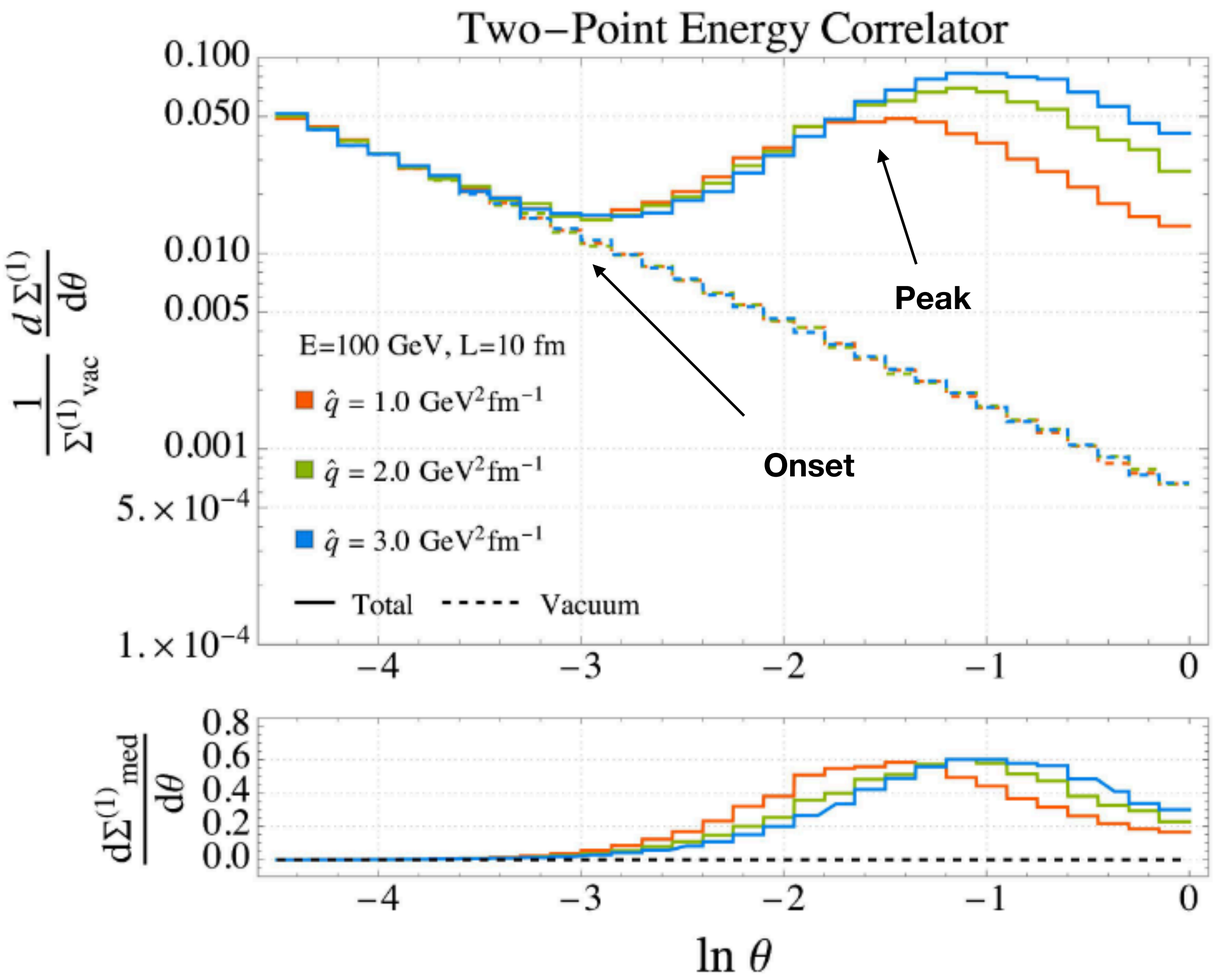
$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

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

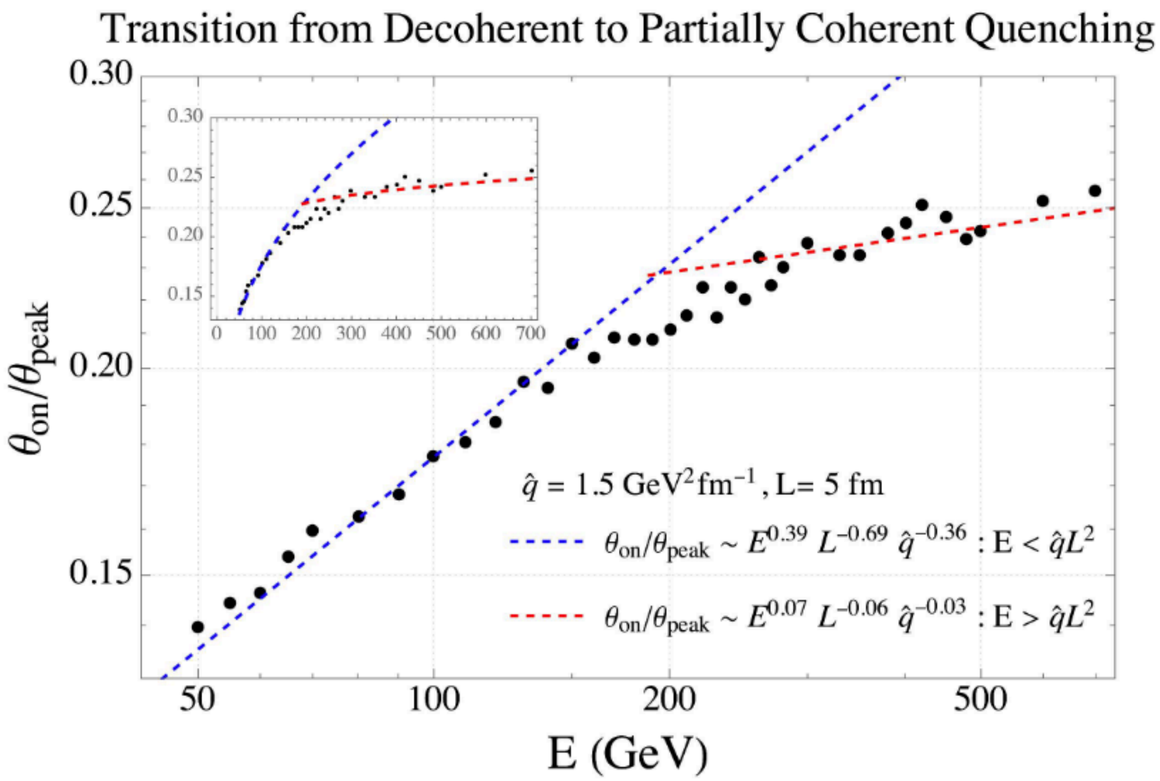
Transport parameter
average energy lost to the medium
per distance traversed



EECs in Heavy Ions

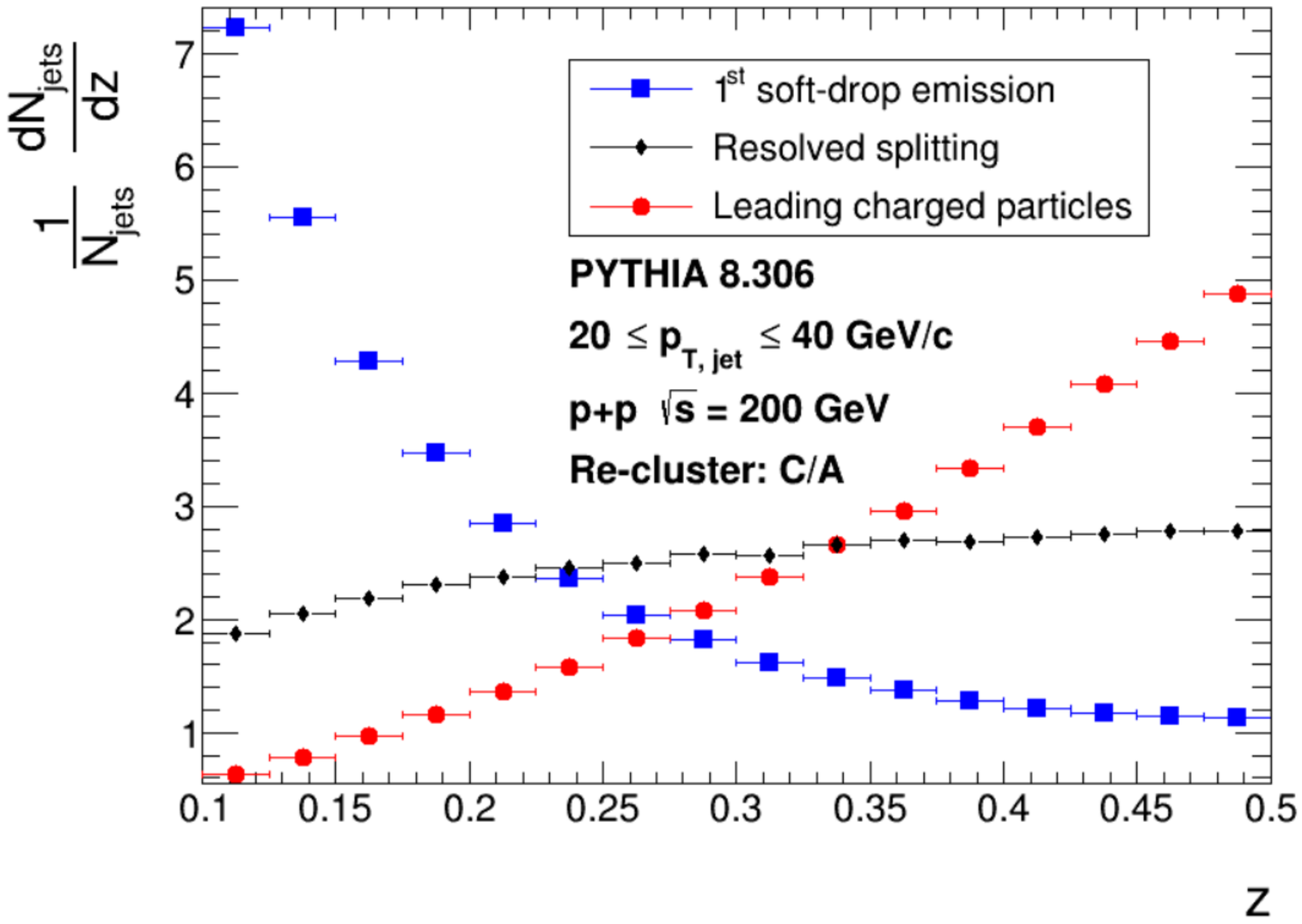


- Larger the $\hat{q}$ -> peak shifted to the right



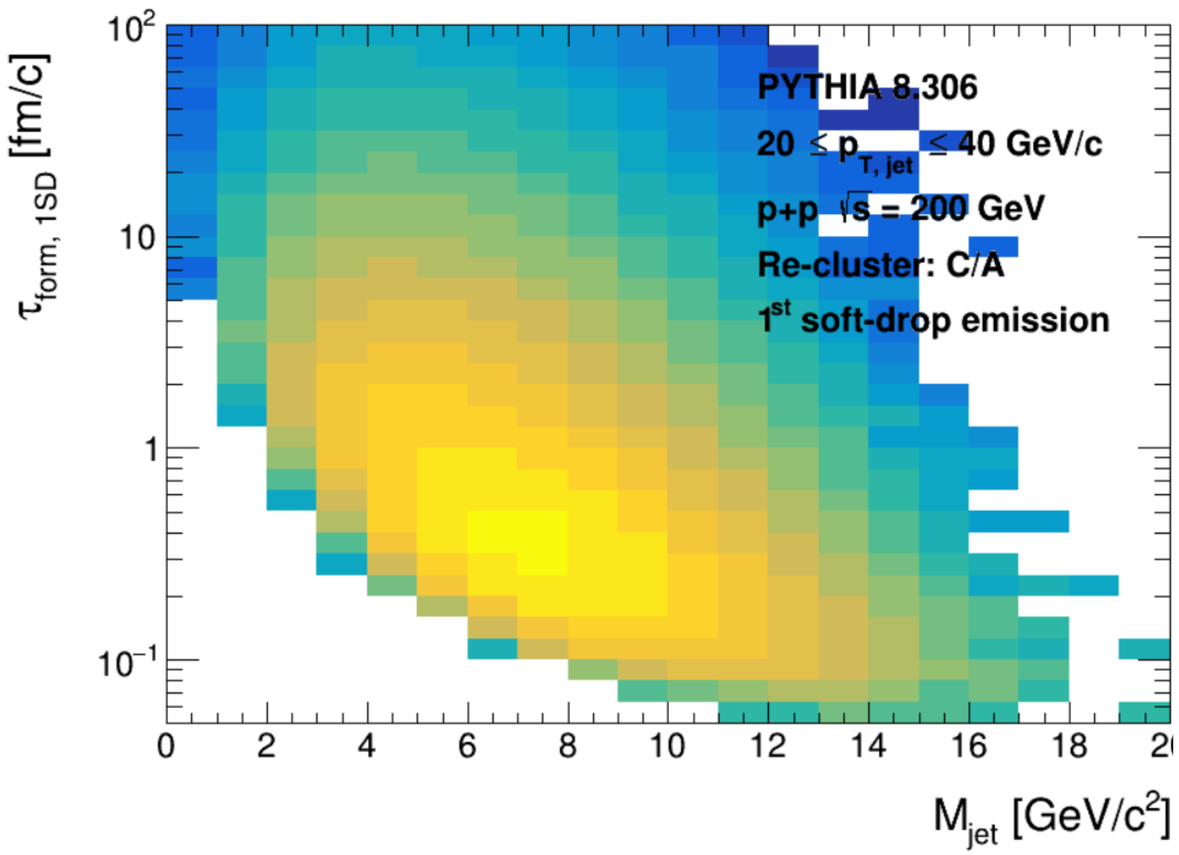
Moult, et.al 2201.07800 *Andres, RKE, et.al 2209.11236*

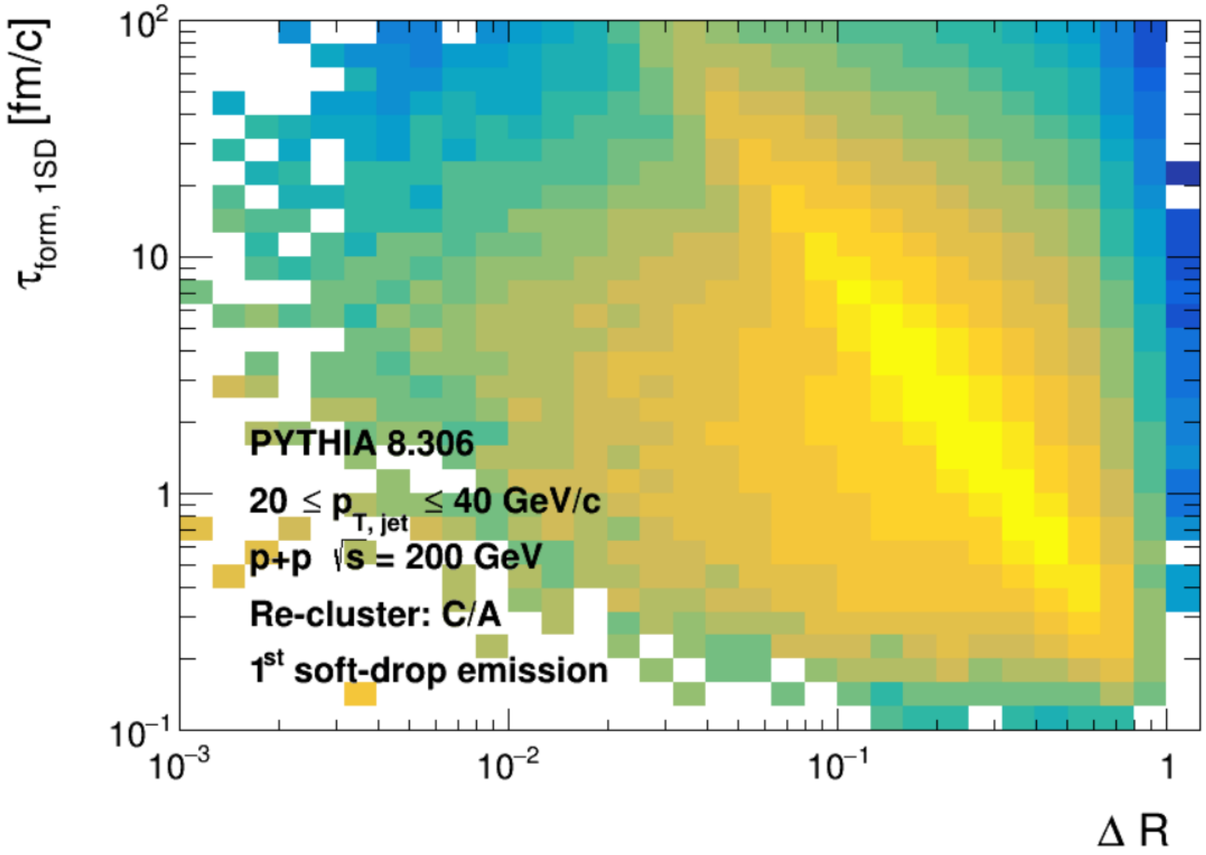
Lets quantify the splitting shapes



- We would nominally expect the following ordering 1SD -> RSD -> LCP
- 1SD is a steeply falling distribution reminiscent of DGLAP leading order
- LCP is significantly peaked at larger values
- RSD is somewhere in the middle

How to think about the time observable

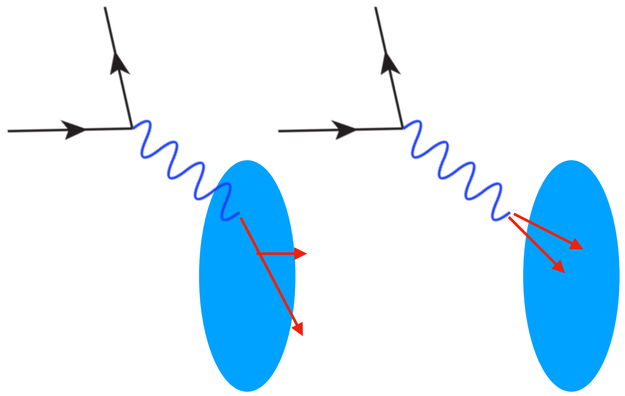


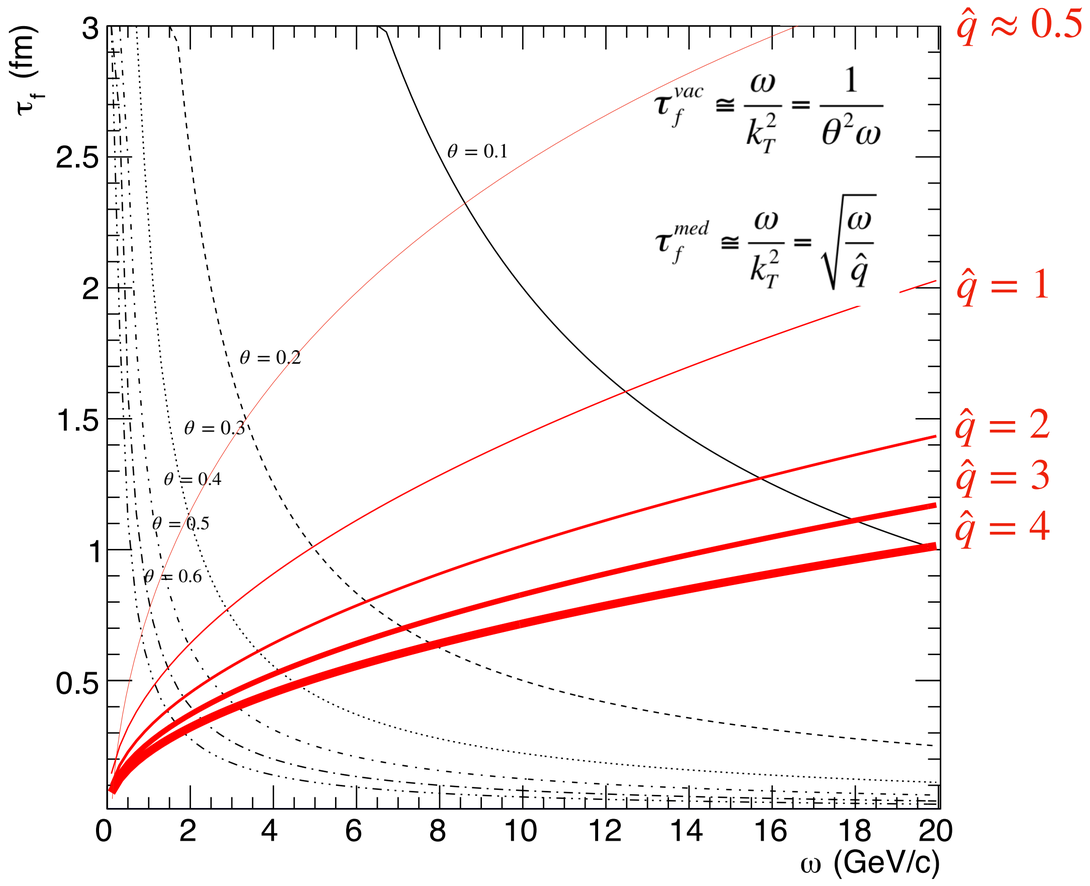


Large mass - early time - larger opening angle - large virtuality
Allows a selection of jets based on space-time structure

Measuring the parton shower

Studies of CNM and initial state vs resolution scale and τ_f

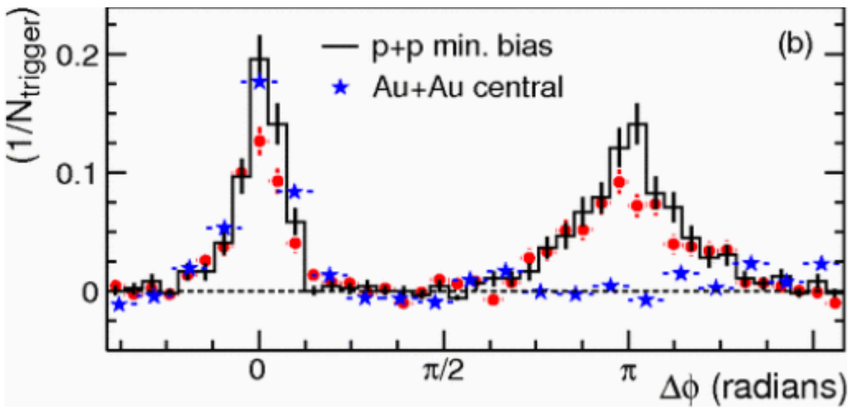


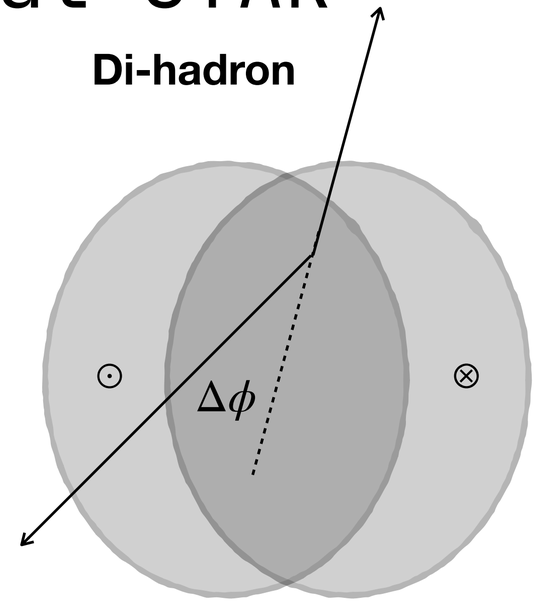


- With splitting/dijet energies roughly 5-30 GeV, we can study resolutions O(1-5) fm!
- Enabling differential measurements of similar kinematics but varying shower topology!

Evolution of jet quenching measurements at STAR

STAR Phys. Rev. Lett. 91, 072304 (2003)

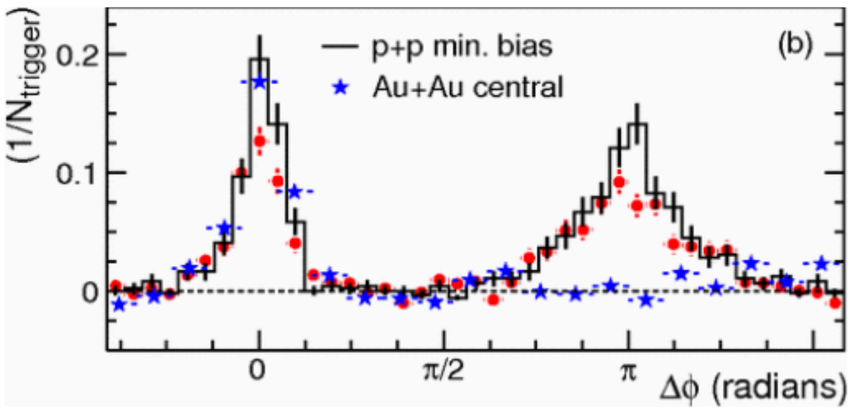




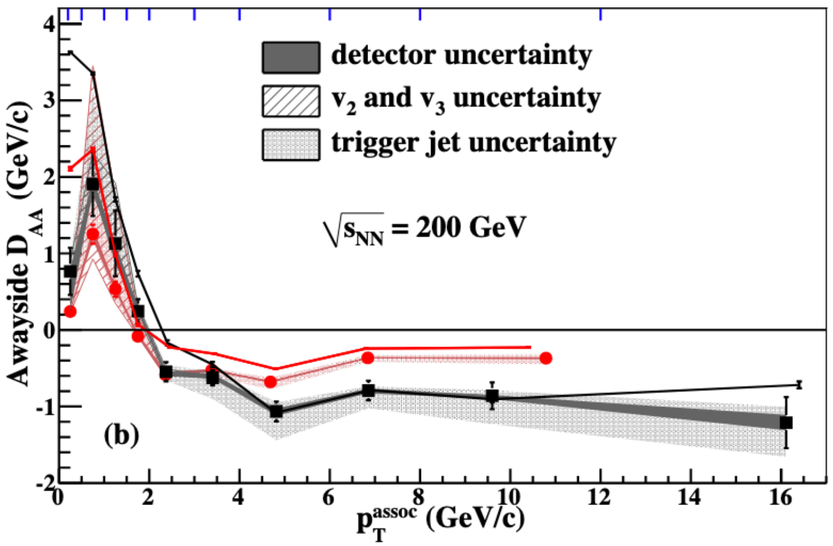
- Di-hadron correlation based on the trigger particle (top left)
- Marked suppression of 'Away side' or back-to-back yield

Evolution of jet quenching measurements at STAR

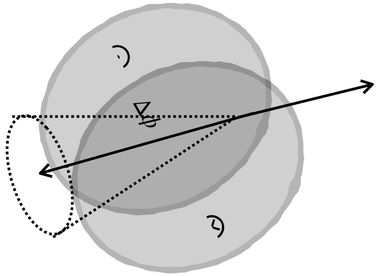
STAR Phys. Rev. Lett. 91, 072304 (2003)



STAR Phys. Rev. Lett. 112, 122301 (2014)

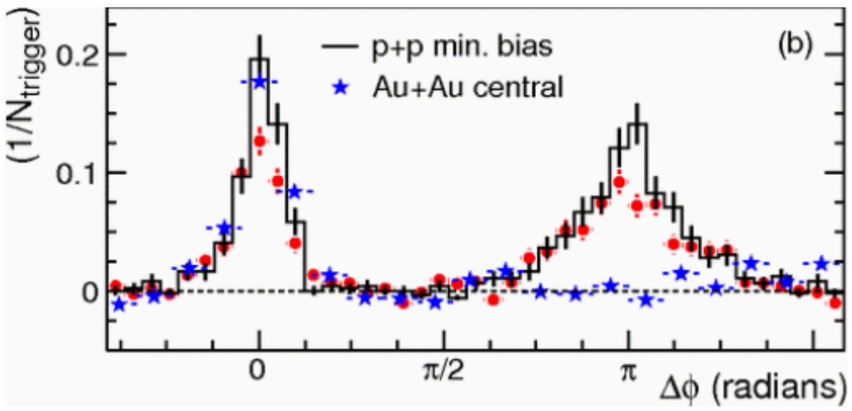


- Jet-hadron correlations show a marked suppression of associated tracks with $p_T > 2$ GeV
- Consequently, an enhancement of soft particles $0.2 < p_T < 2.0$ GeV is observed within the jet cone

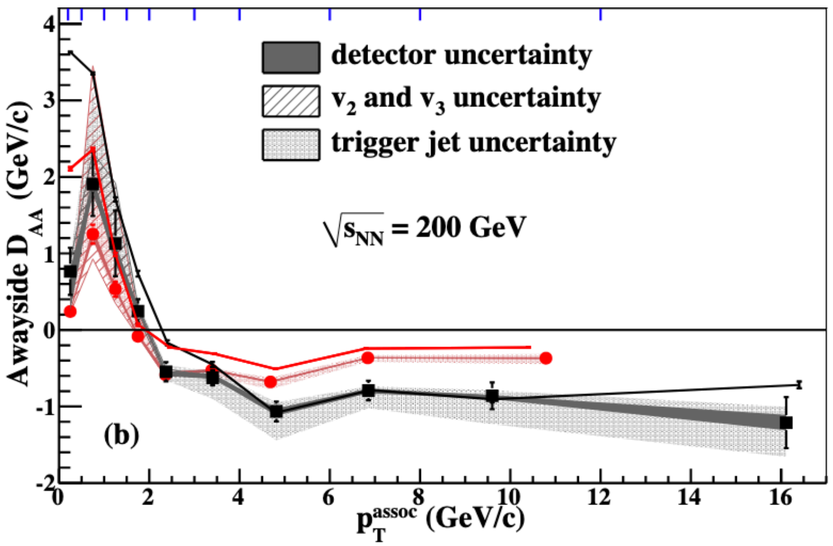


Evolution of jet quenching measurements at STAR

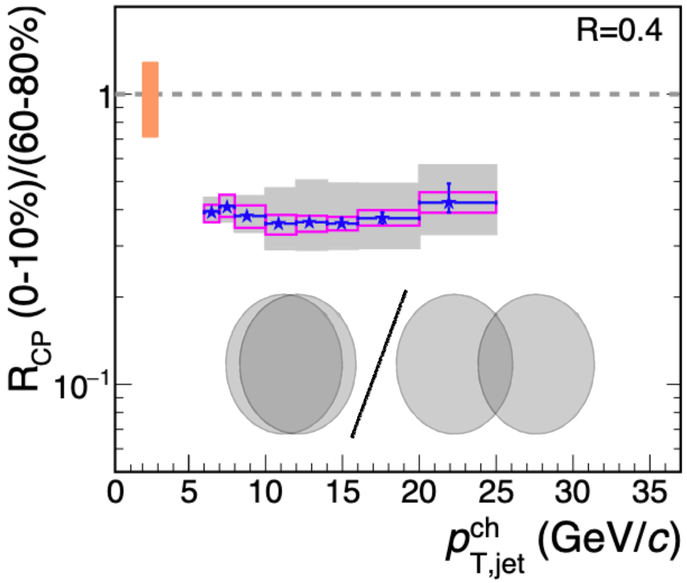
STAR Phys. Rev. Lett. 91, 072304 (2003)



STAR Phys. Rev. Lett. 112, 122301 (2014)



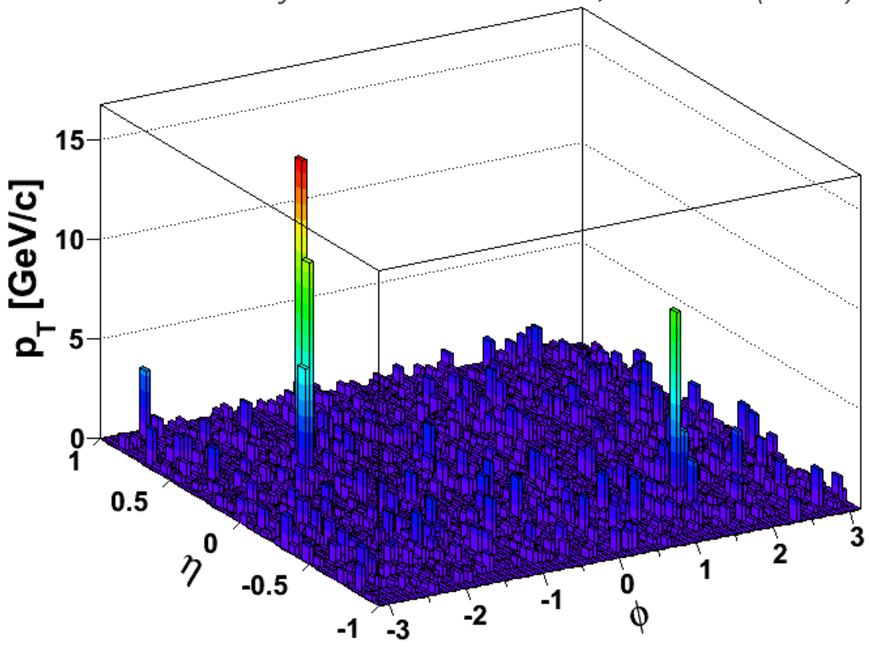
STAR Phys. Rev. C 102 5, 054913 (2020)



- Central to peripheral ratios for reconstructed inclusive charged jets indicate $\approx 60\,\%$ suppression

Selecting a di-jet sample at STAR

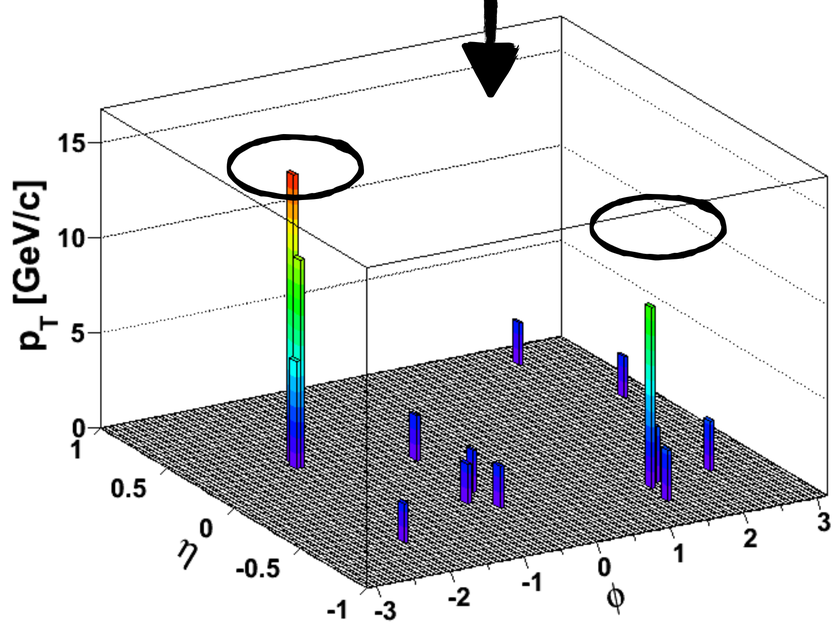
STAR Phys. Rev. Lett. 119 6, 062301 (2017)



- Resulting di-jets free of combinatorial jets and background

HardCore Selection

$p_T > 2$ GeV/c

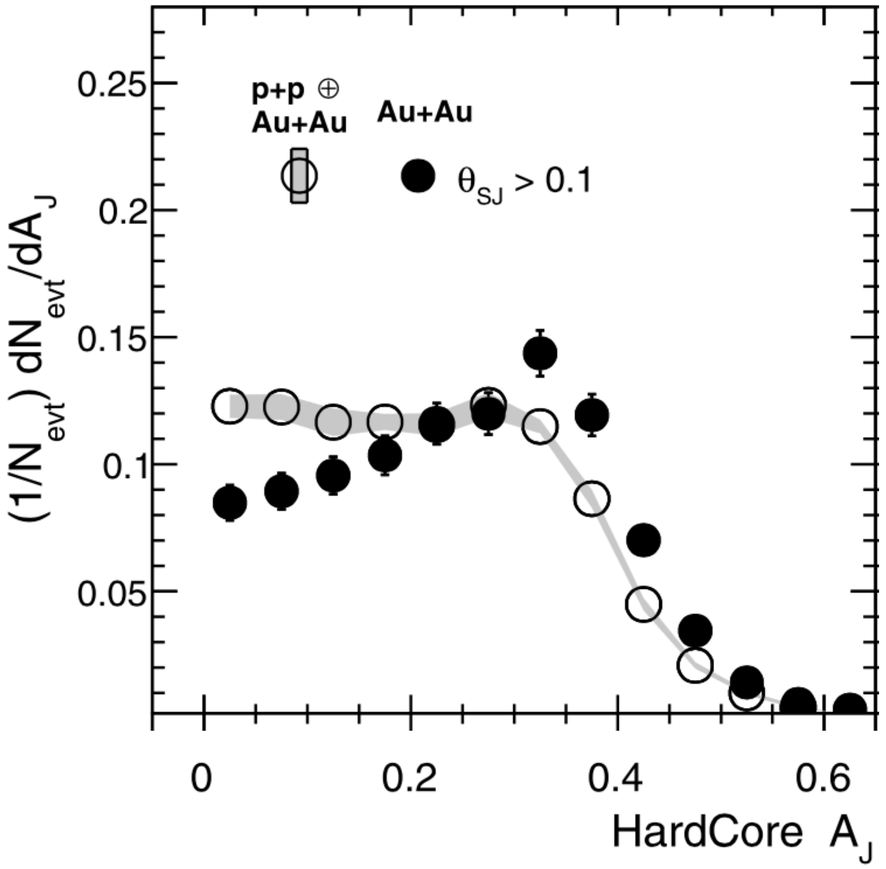


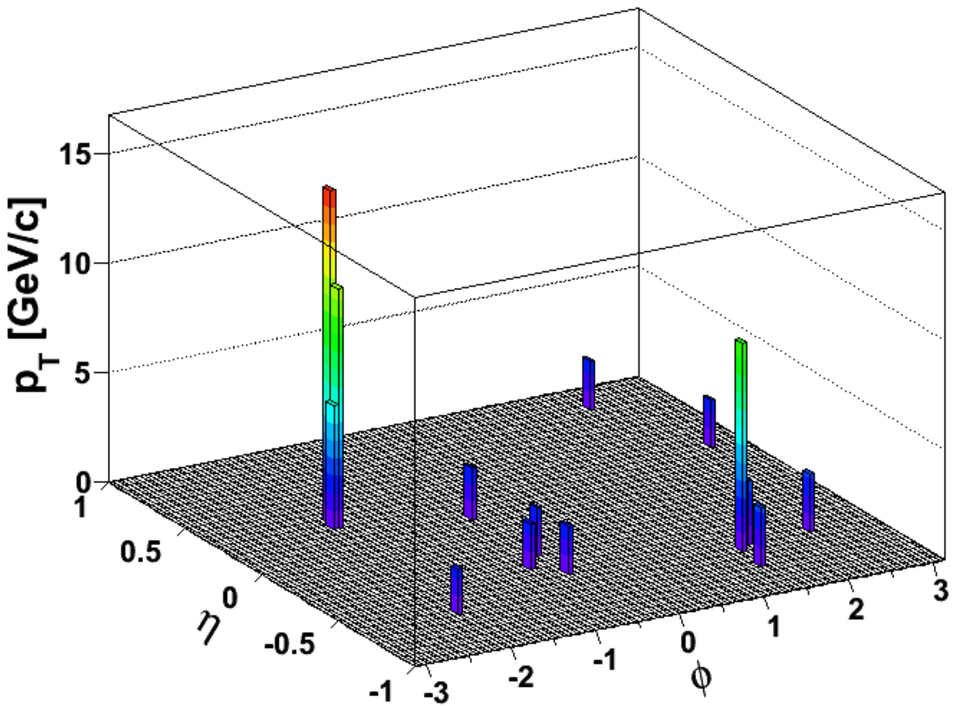
- Significant bias in jet fragmentation but lets utilize the bias to our advantage!

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

- 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

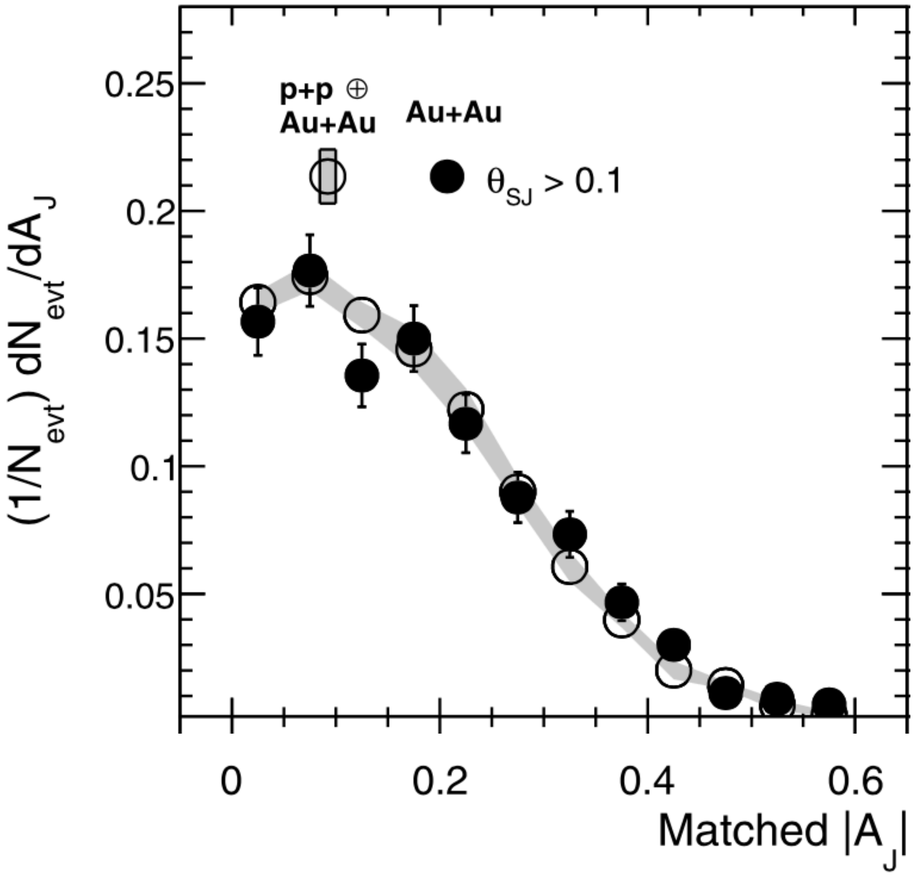


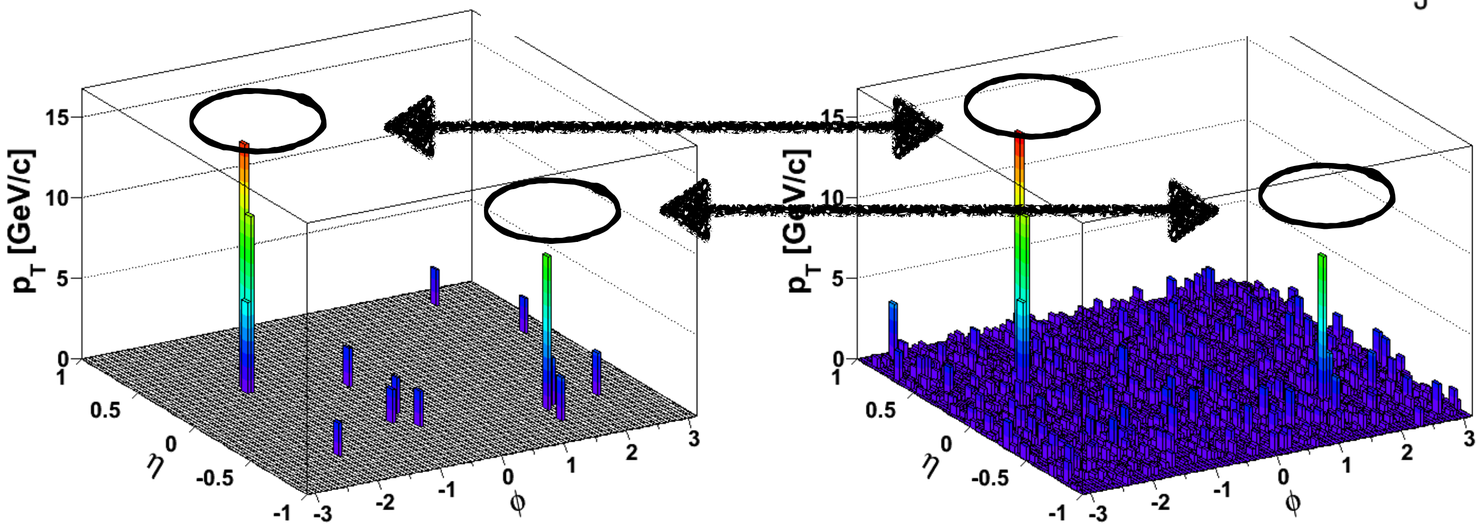


- Where is the quenched energy?

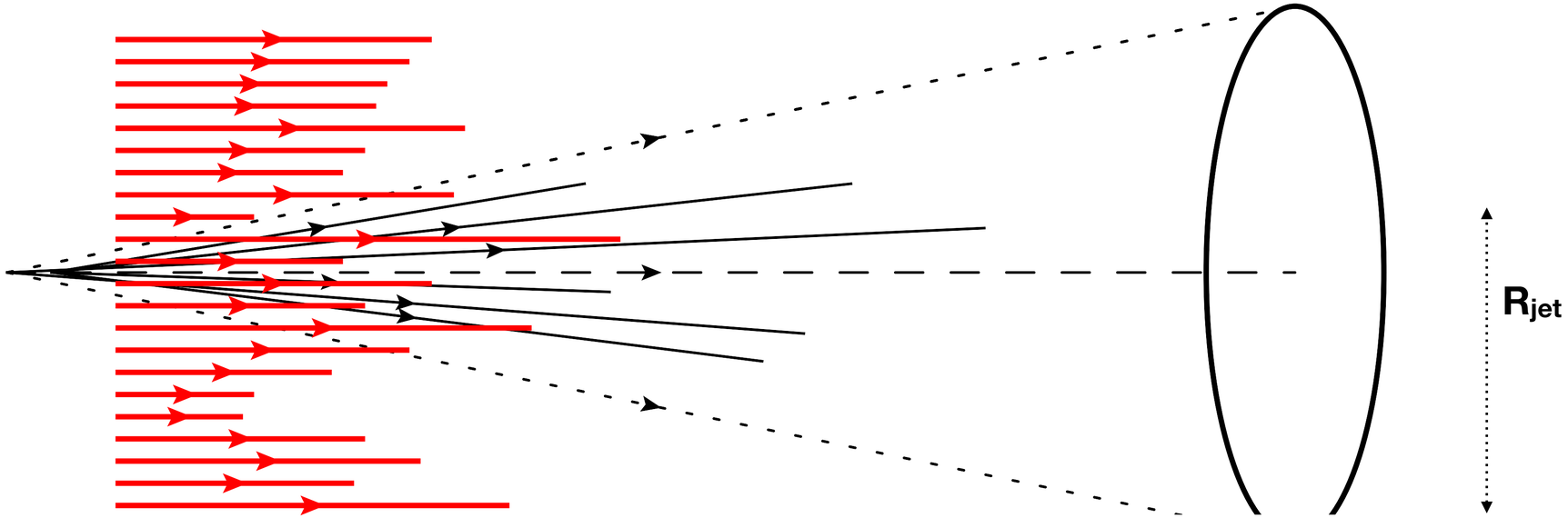
$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

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



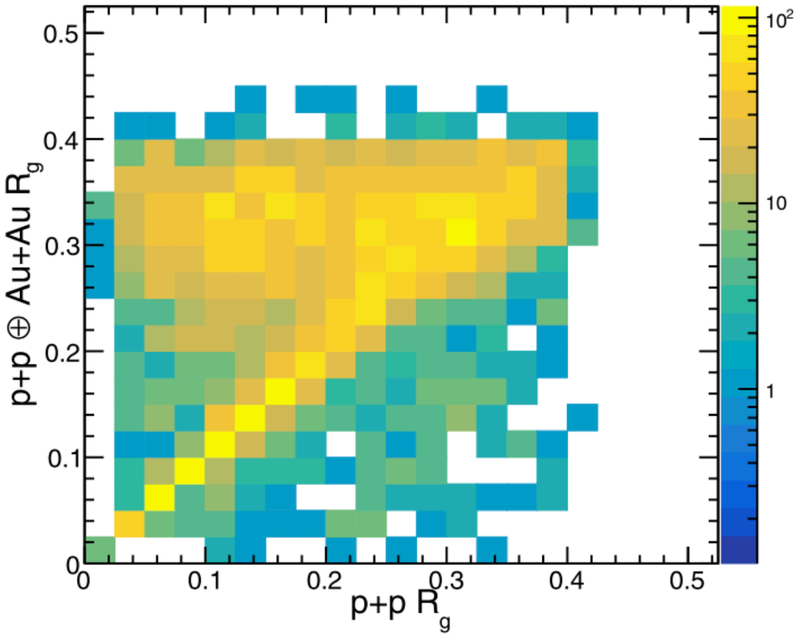


R_g in a heavy ion environment



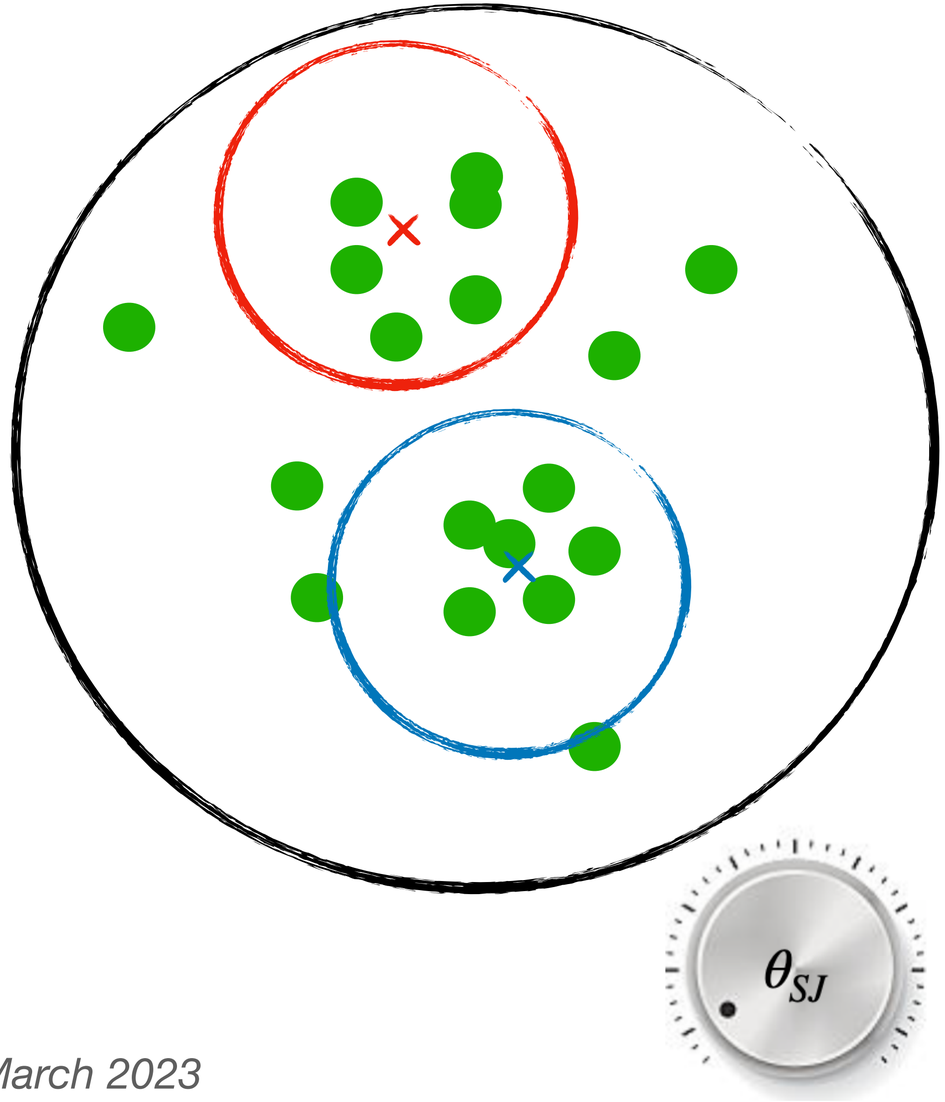
- SoftDrop R_g sensitive to background fluctuations

We need an observable that is more **robust** to the Au+Au fluctuating underlying event but still **sensitive** to jet kinematics

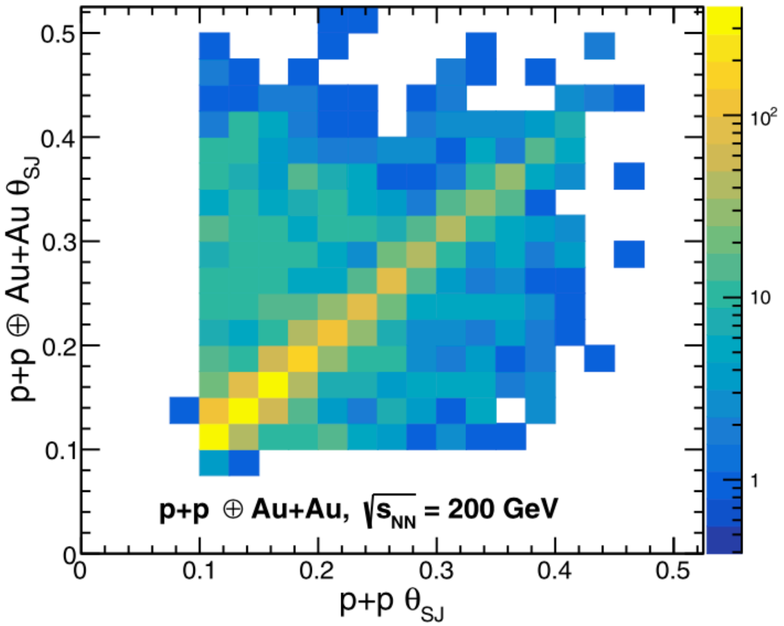


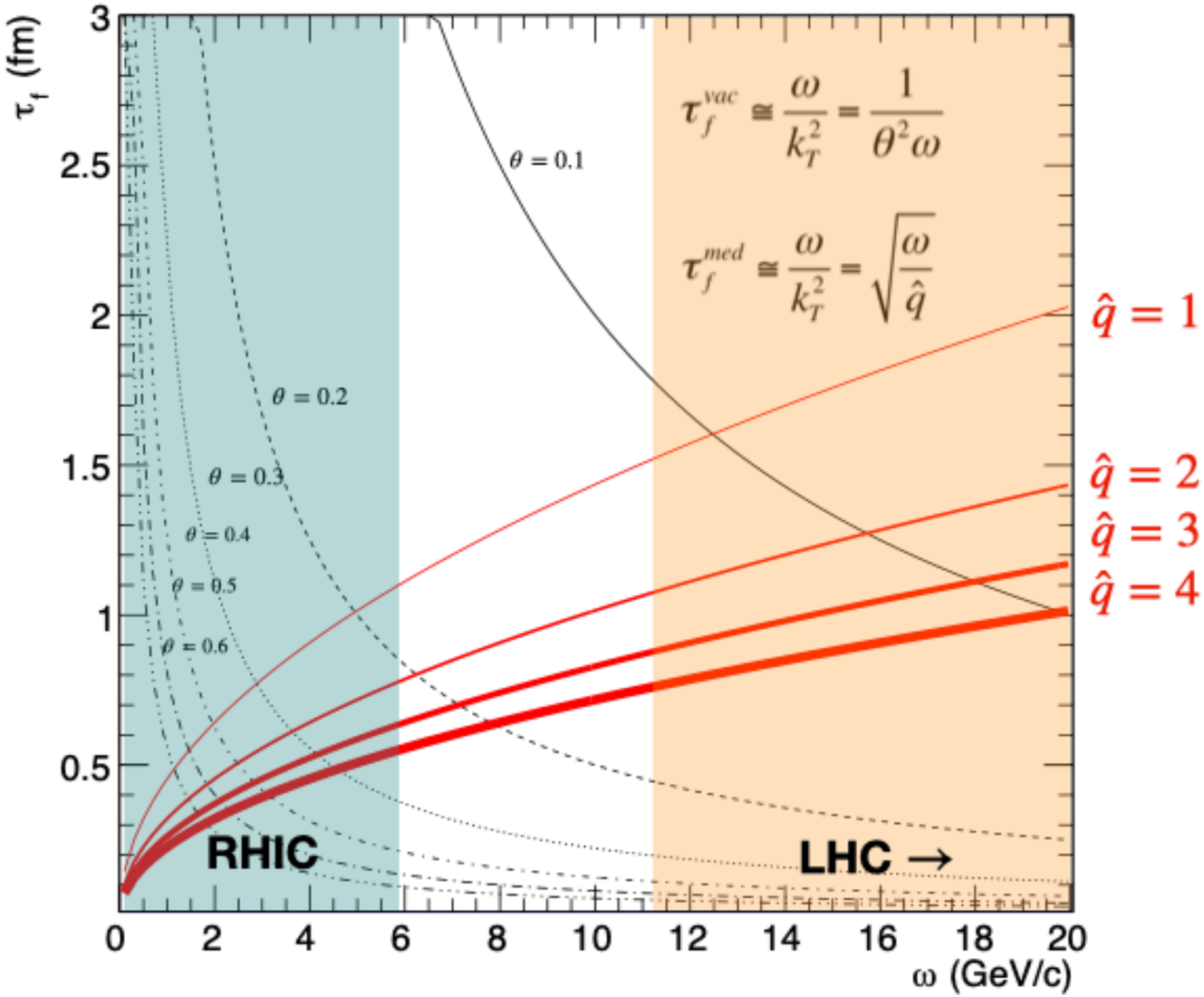
Introducing - subjets

Apolinario, et al. Eur. Phys. J. C (2018) 78:529



- Cluster all jet constituents into anti-k_t jets of smaller radius (0.1)
- 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)**

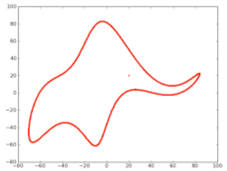




Vacuum Splittings

Medium Induced Splittings

Parameters within PYTHIA that we tune



Setting	Default	New
PDF:pSet	13	17
MultipartonInteractions:ecmRef	7 TeV	200 GeV
MultipartonInteractions:bprofile	3	2
Tuning Parameter	**Default**	**Range**
MultipartonInteractions:pT0Ref	2.28 GeV	0.5-2.5 GeV
MultipartonInteractions:ecmPow	0.215	0.0-0.25
MultipartonInteractions:coreRadius	0.4	0.1-1.0
MultipartonInteractions:coreFraction	0.5	0.0-1.0
ColourReconnection:range	1.8	1.0-9.0

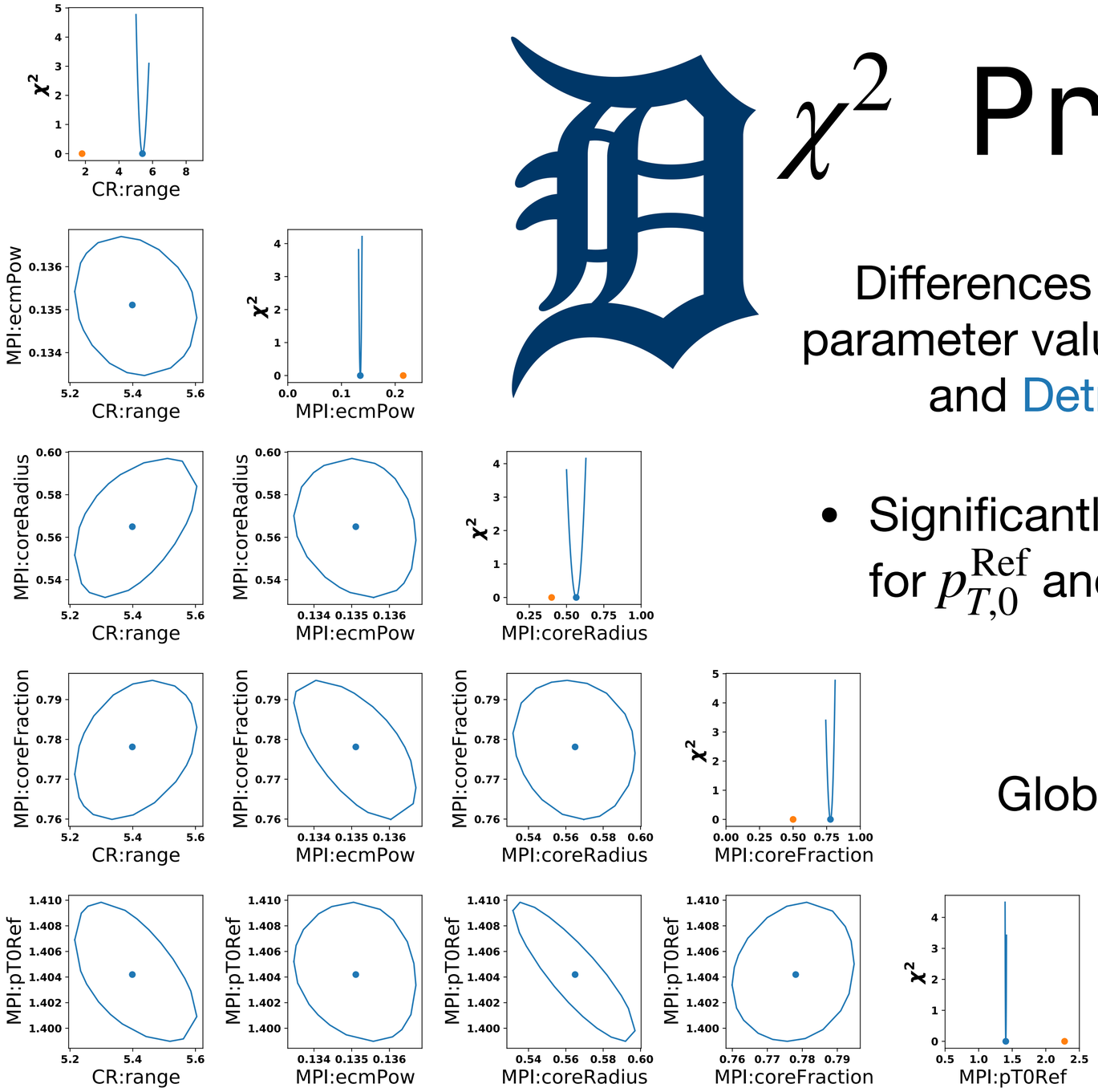
`mode` **MultipartonInteractions:bProfile** (`default = 3`; `minimum = 0`; `maximum = 4`)
Choice of impact parameter profile for the incoming hadron beams.
`option` **0** : no impact parameter dependence at all.
`option` **1** : a simple Gaussian matter distribution; no free parameters.
`option` **2** : a double Gaussian matter distribution, with the two free parameters *coreRadius* and *coreFraction*.
`option` **3** : an overlap function (i.e. the convolution of the matter distributions of the two incoming hadrons) of the form *exp(- b^expPow)*, where *expPow* is a free parameter.

`parm` **ColourReconnection:range** (`default = 1.8`; `minimum = 0.`; `maximum = 10.`)
The `range` parameter defined above. The higher this number is the more reconnections can occur. For values above unity the reconnection rate tends to saturate, since then most systems are already connected with each other. This is why 10 is set as an effective upper limit, beyond which it is not meaningful to let the parameter go.

- Start from PYTHIA 8.303 w/ Monash tune with updated PDF to NNPDF 3.1 w/ LO $\alpha_s(M_z) = 0.13$
- Reference Energy set to 200 GeV

- String parameters are left to the default Monash values
- Note: whatever Monash can't do w.r.t strangeness or baryons etc… Detroit also cannot do.

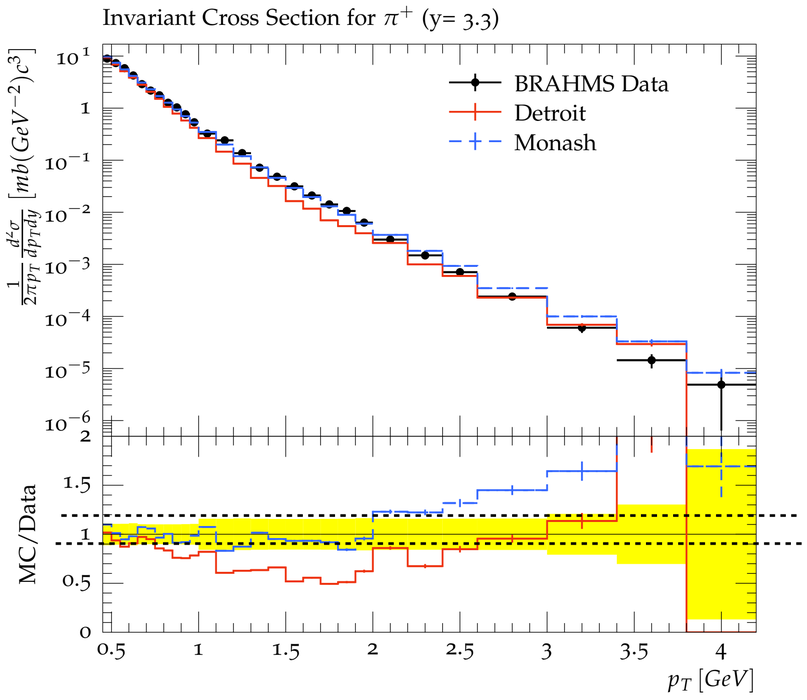
χ^2 Profiles

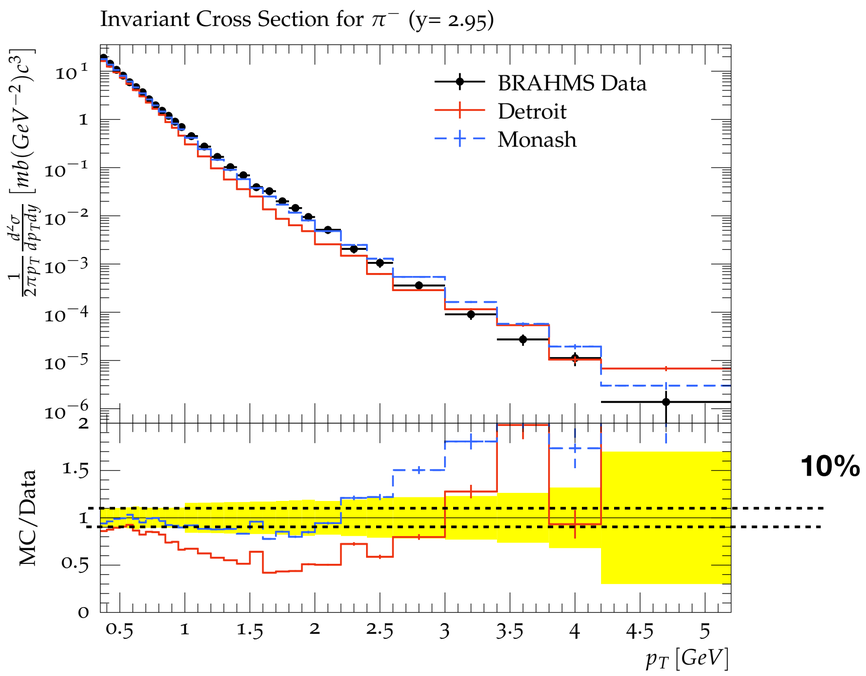


Differences between the parameter values for Monash and Detroit tunes

- Significantly smaller values for $p_{T,0}^{\mathrm{Ref}}$ and ecm exponent

Global χ^2/n.d.f. = 1.2





- Both Monash and Detroit tunes can't describe forward pion spectra from BRAHMS or STAR
- New tune does worse than Monash
- Simultaneous tune with mid-rapidity and larger tune-able phase space (ISR) unable to recover MC/data agreement