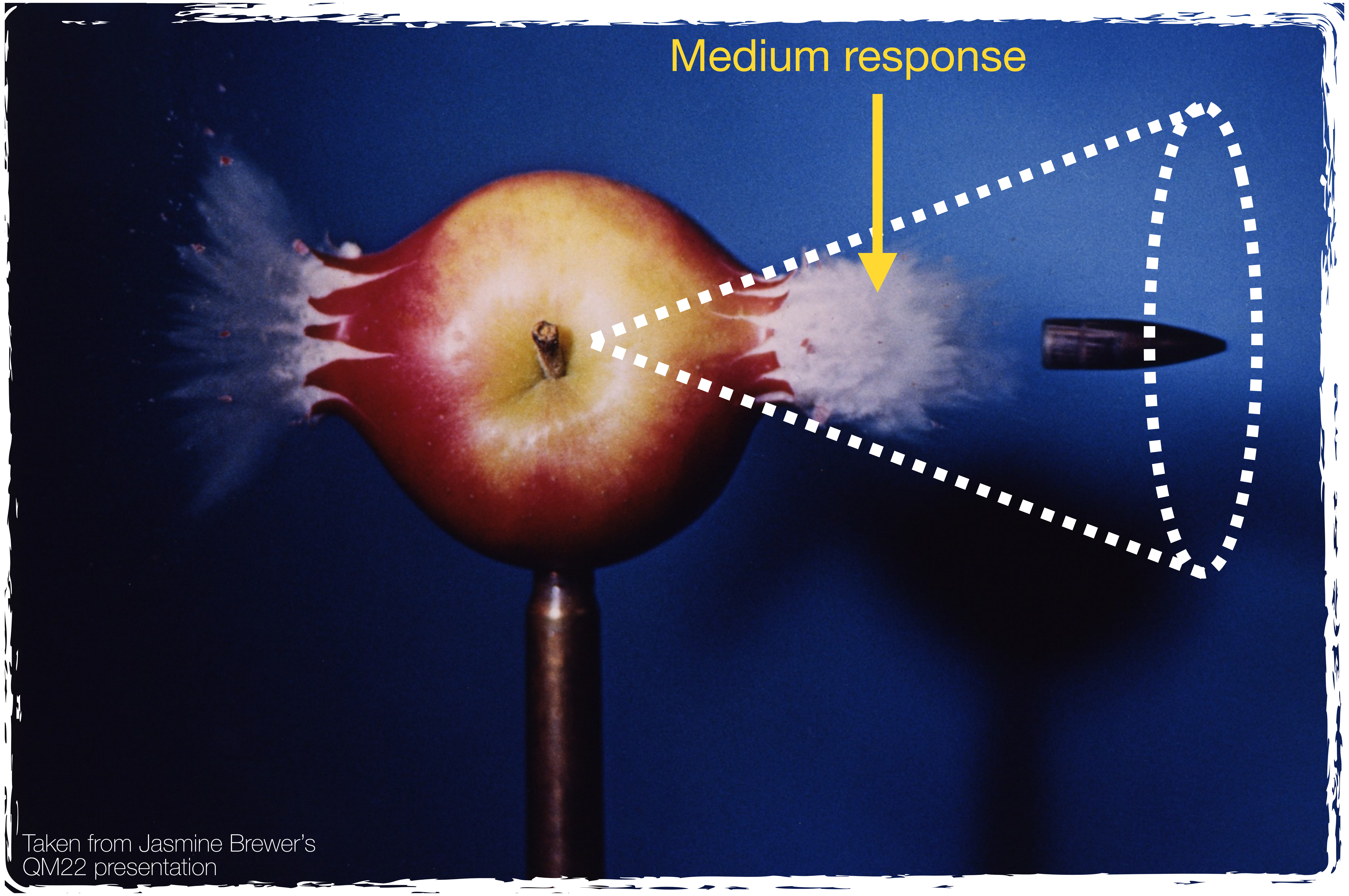
Experimental overview of medium-response-sensitive observables



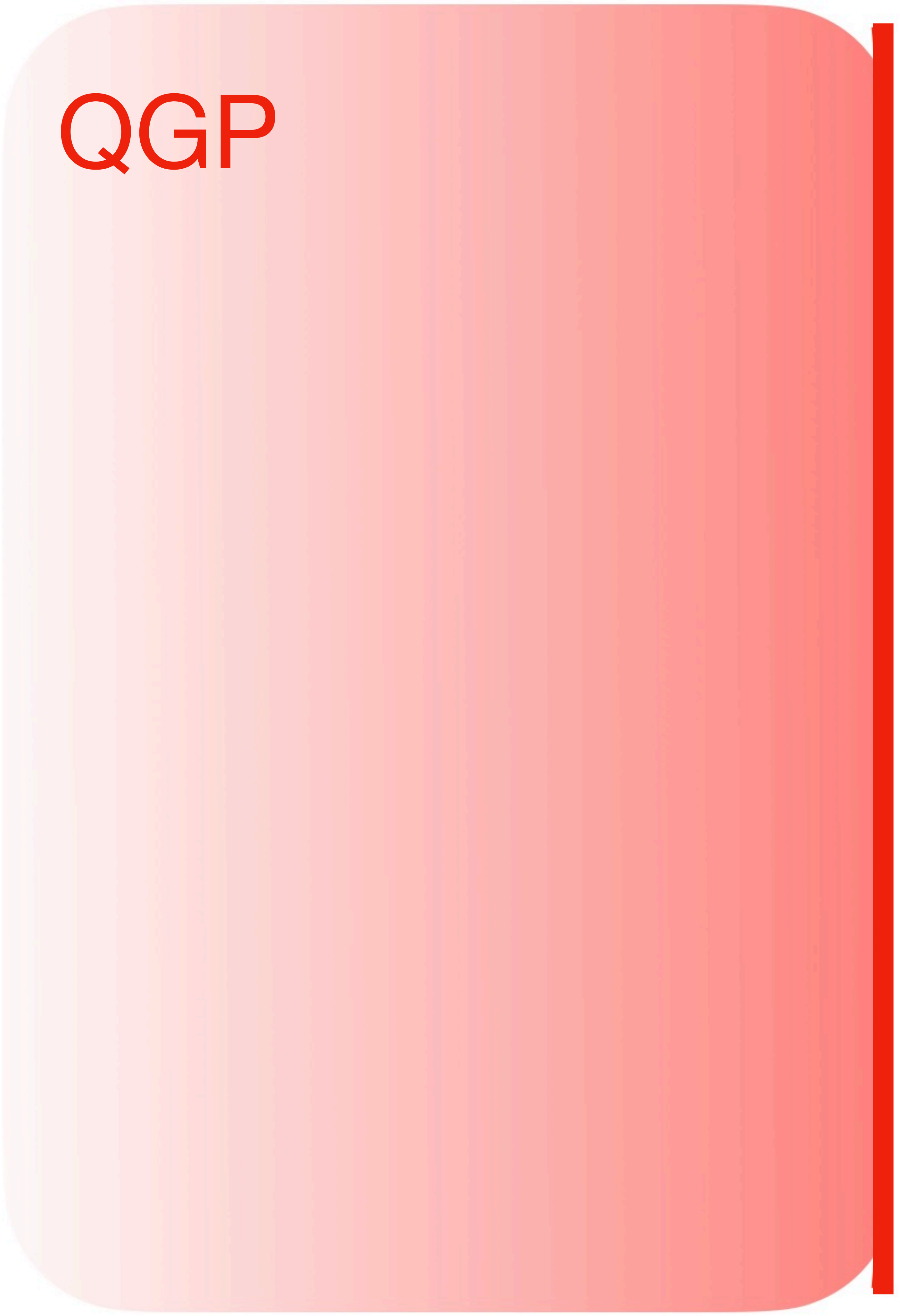
Rey Cruz-Torres
reynier@lbl.gov
June 15, 2022

BERKELEY LAB

FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

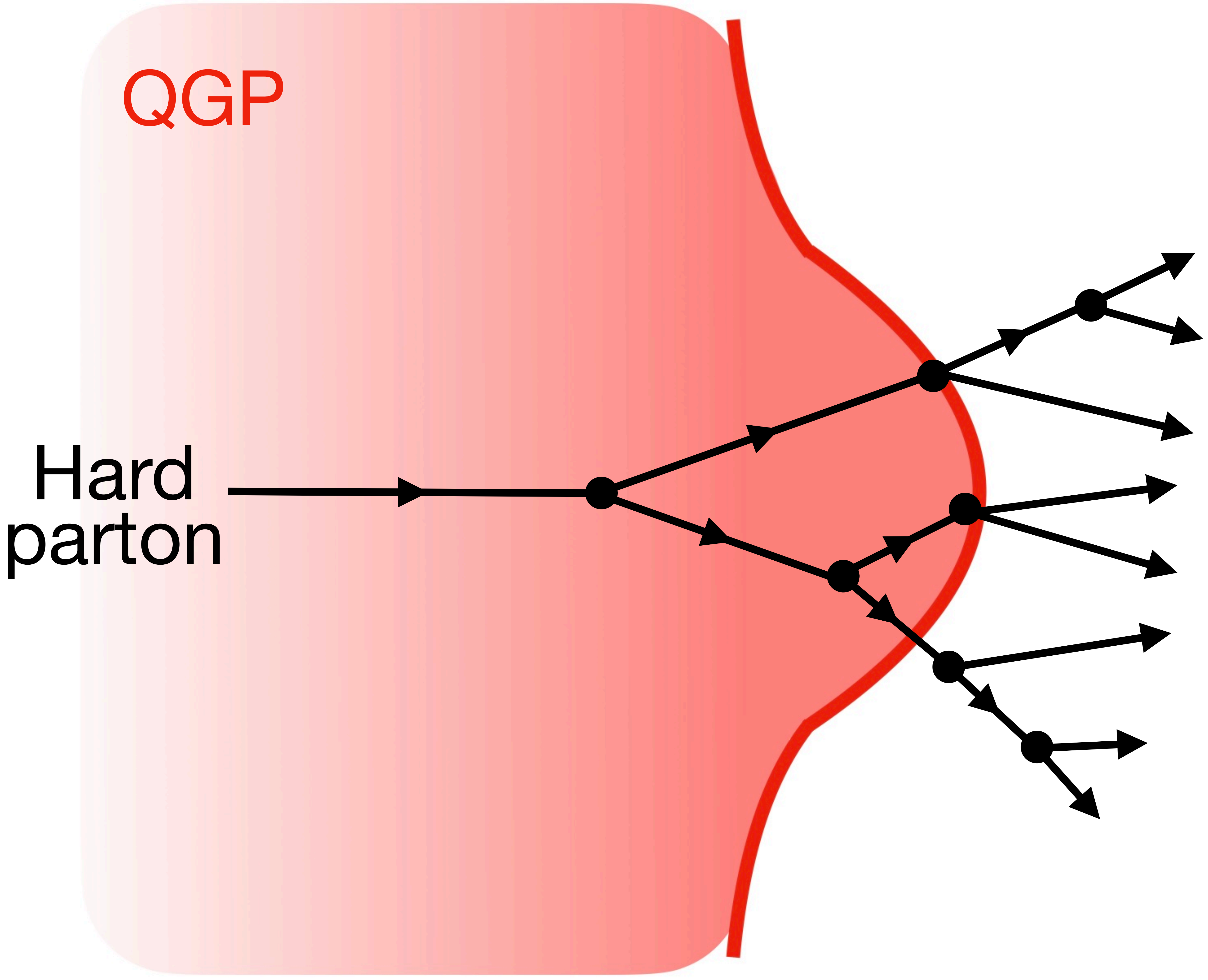
Medium response



correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Medium response

Jets traversing QGP transfer momentum to medium



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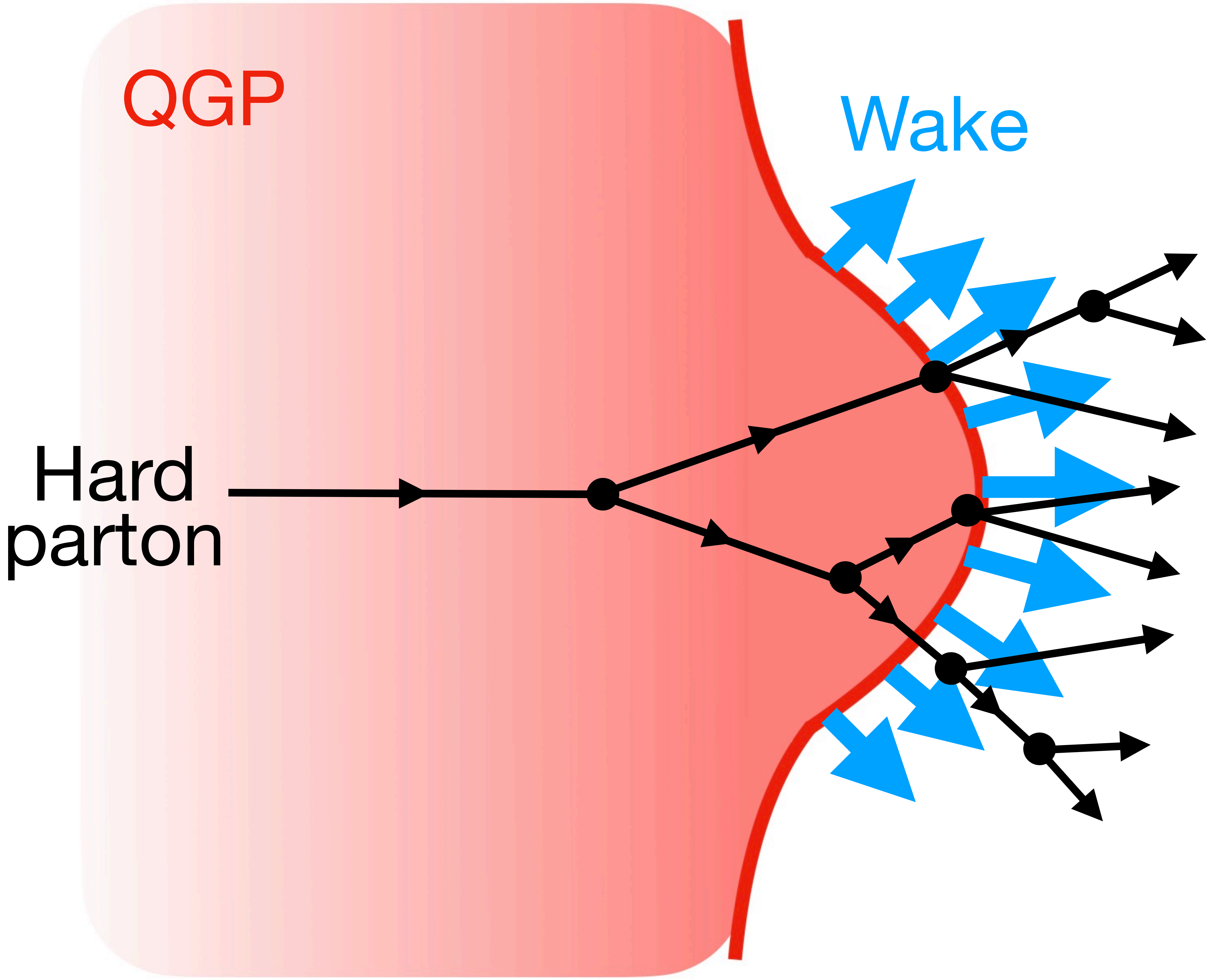
Medium response

Medium partons acquire additional momentum that correlates their direction with the jet



This creates a wake

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Medium response

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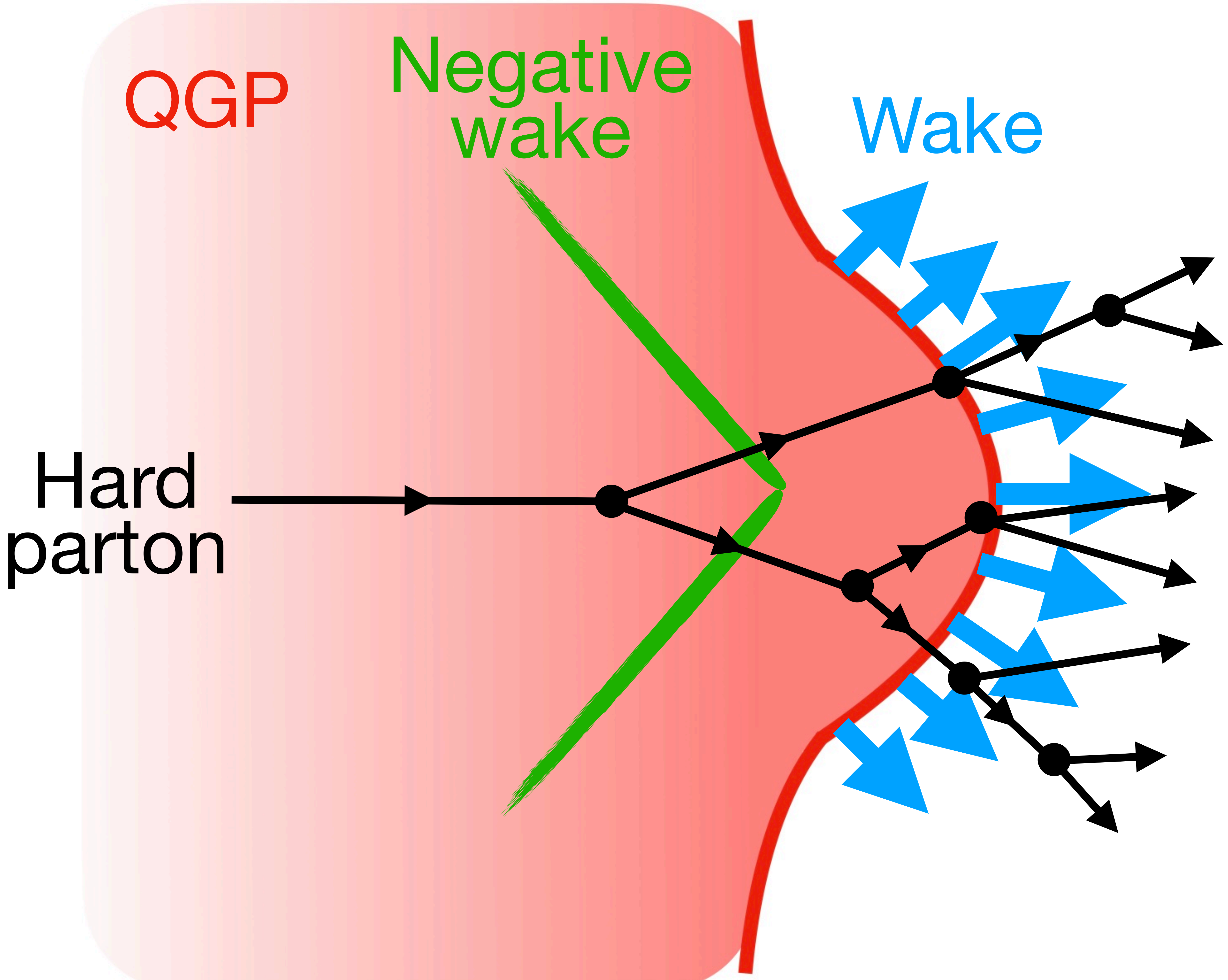
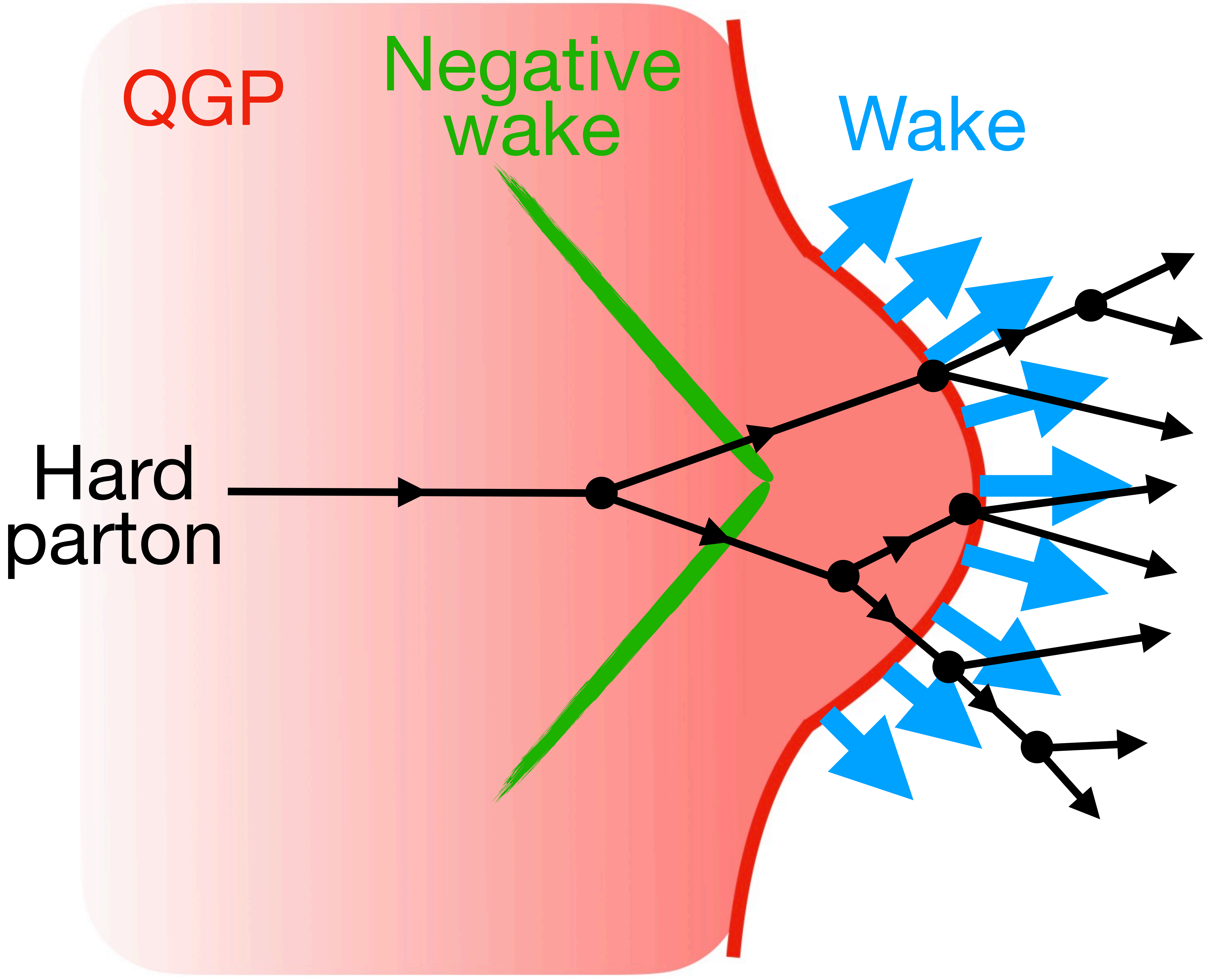


This creates a wake

correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Medium response

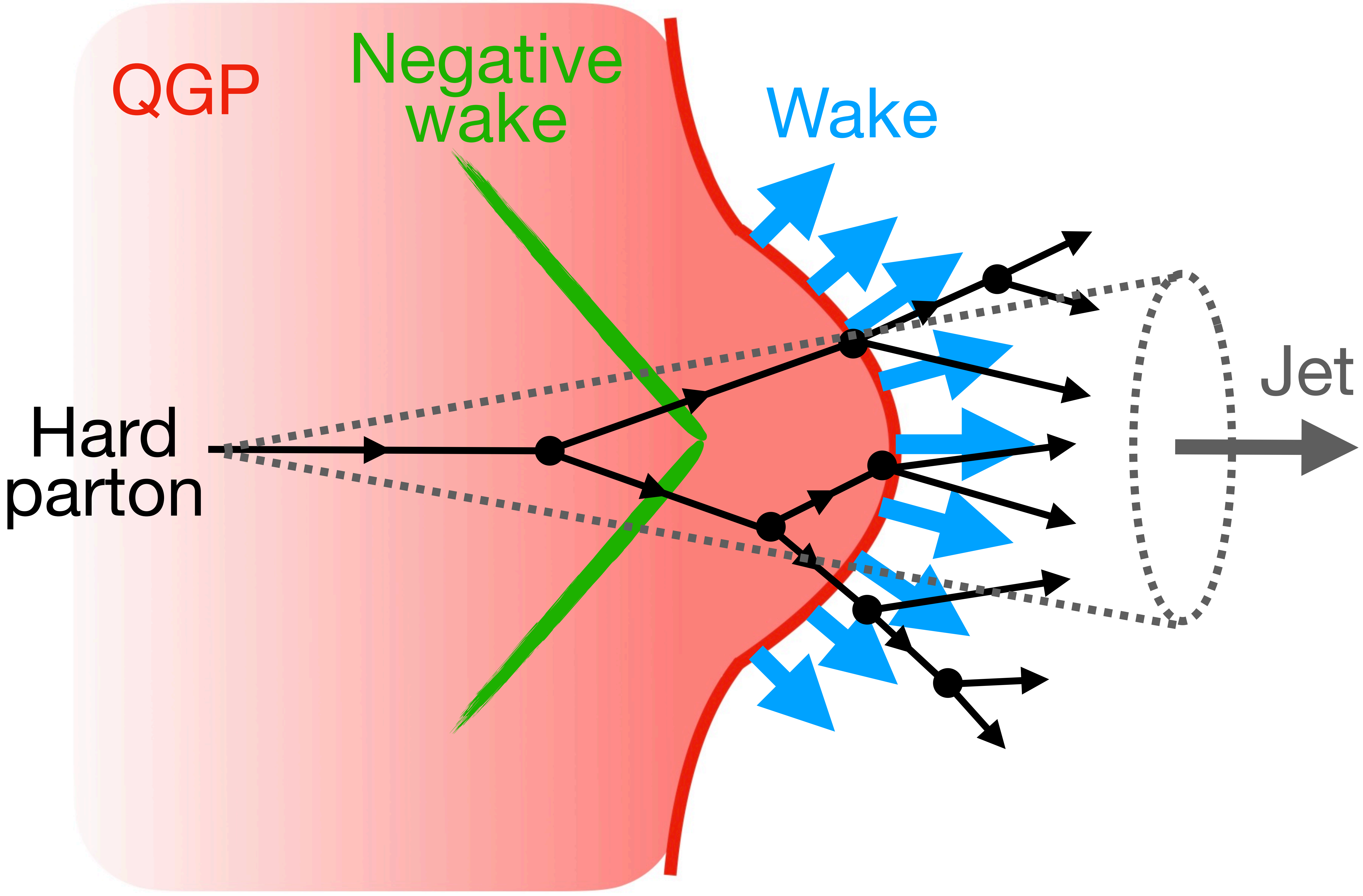
Background-subtraction techniques do not (should not) remove the momentum component acquired through the medium-jet interaction



correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Medium response

Finding jets (or knowing their direction) can be used to study medium response

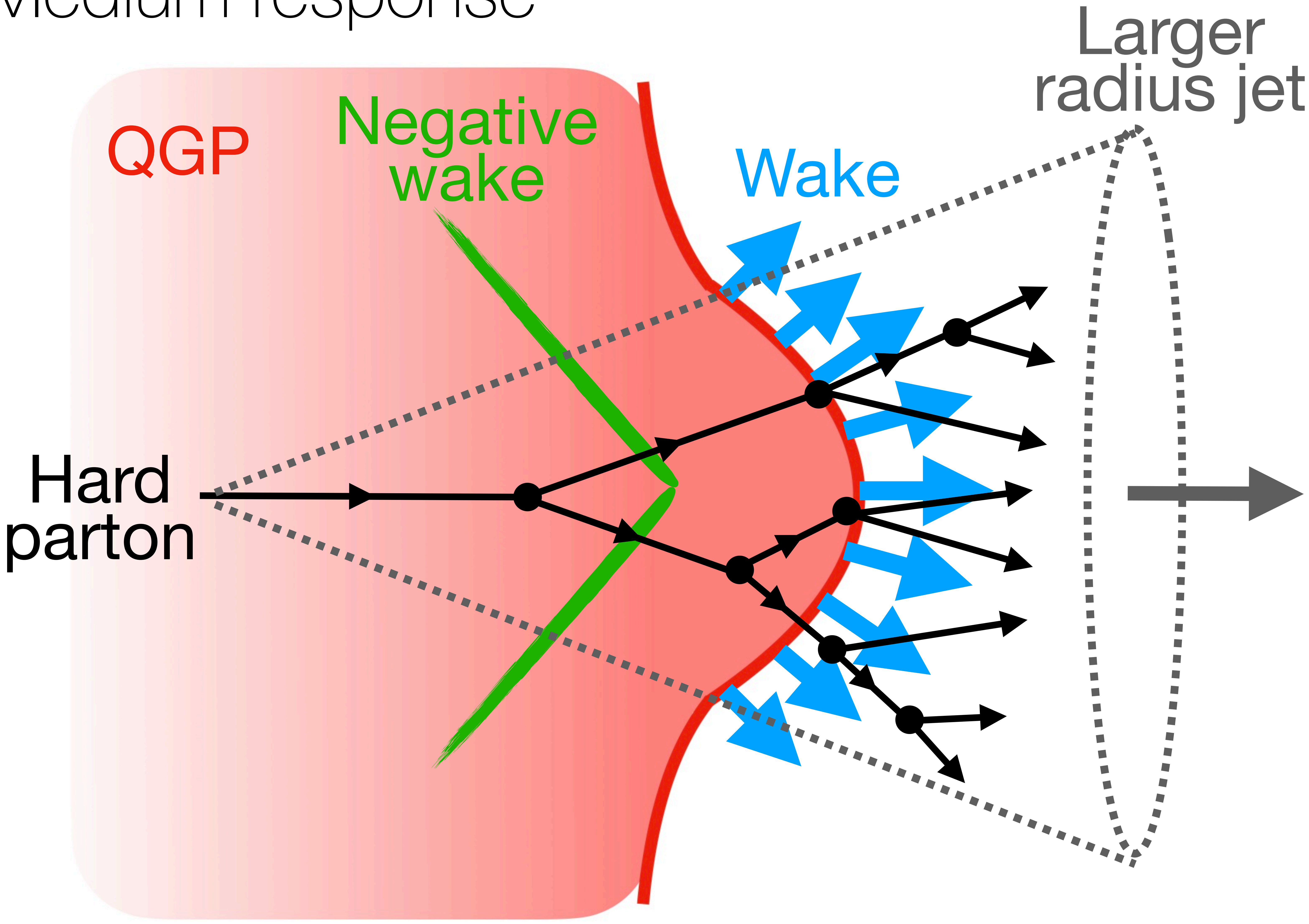


correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Medium response

Finding jets (or knowing their direction) can be used to study medium response

Large-radius jets capture more of this effect

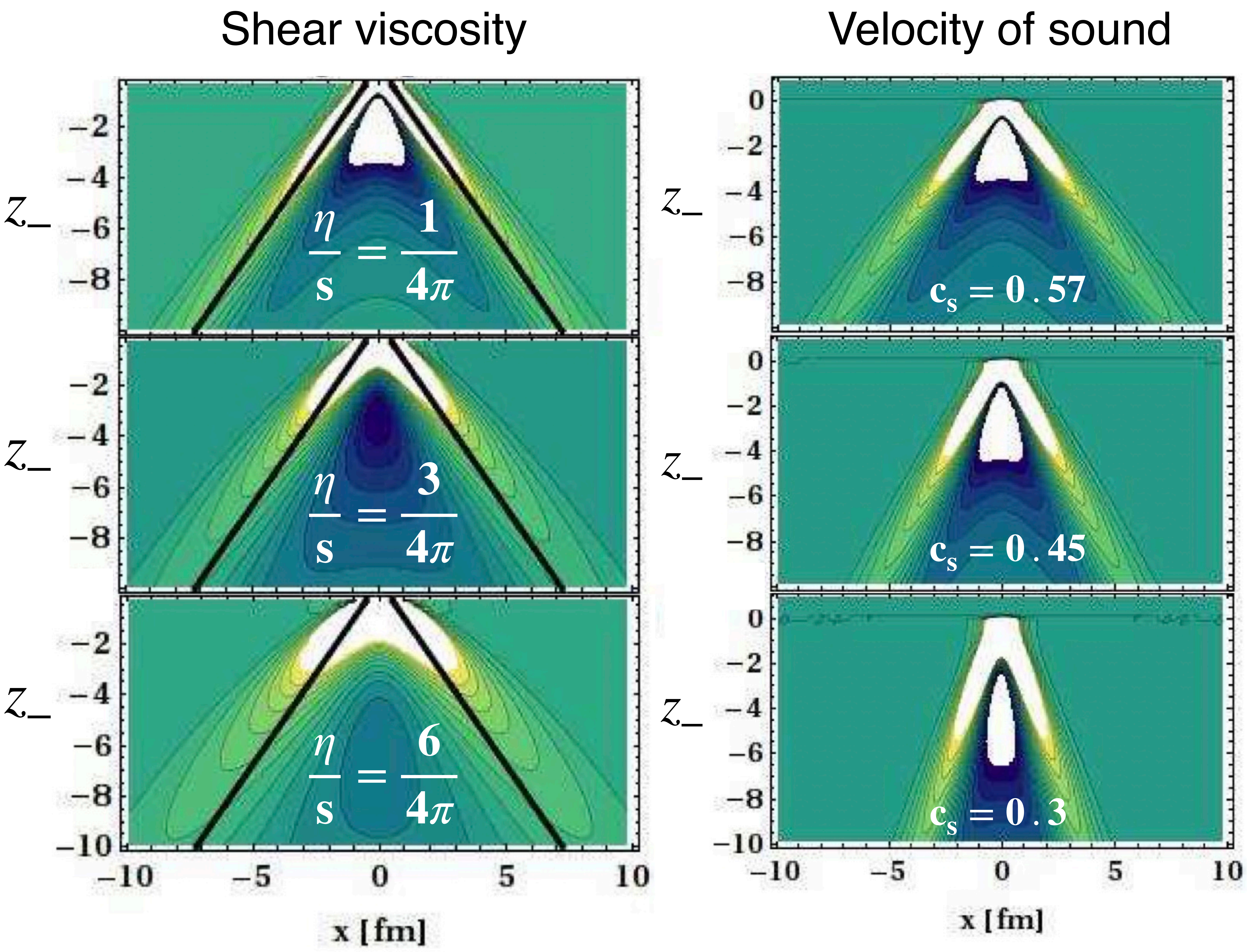


correlated background, medium response, wake, recoils, Mach-cone, jet-induced medium flow, backreaction

Why study medium response?

- Full characterization of QGP
- Better understanding of observables in medium
- QGP bulk properties of the (velocity of sound, viscosities)
- thermalization: how fast is the jet energy is propagated and thermalized with the rest of the QGP?

  See talk by S Schlichting



PRC 79 (2009) 054909

Handful of theoretical models

See talk by:		Recoils	Hydro response	Deposited E as perturbation	Boltzmann-equation based
	JEWEL	✓			
	MARTINI	✓			
Y Tachibana, A Majumder	**JETSCAPE**	✓	✓		
	MATTER	✓			
	LBT	✓			
X-N Wang	**Coupled LBT**	✓	✓		
	Coupled Jet-Fluid		✓		
D Pablos Alfonso	**Hybrid**	✓		✓	
G-Y Qin	**AMPT**				✓
	BAMPS				✓

See more details and references here.

Handful of theoretical models

See talk by:		Recoils	Hydro response	Deposited E as perturbation	Boltzmann-equation based
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	MA[illegible]	✓			
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X-N Wang	Coupled LBT	✓	✓		
	Coupled Jet-Fluid		✓		
D Pablos Alfonso	Hybrid	✓		✓	
G-Y Qin	AMPT				✓
	BAMPS				✓

What is the right model for medium response?

how (non)perturbative are the interactions?

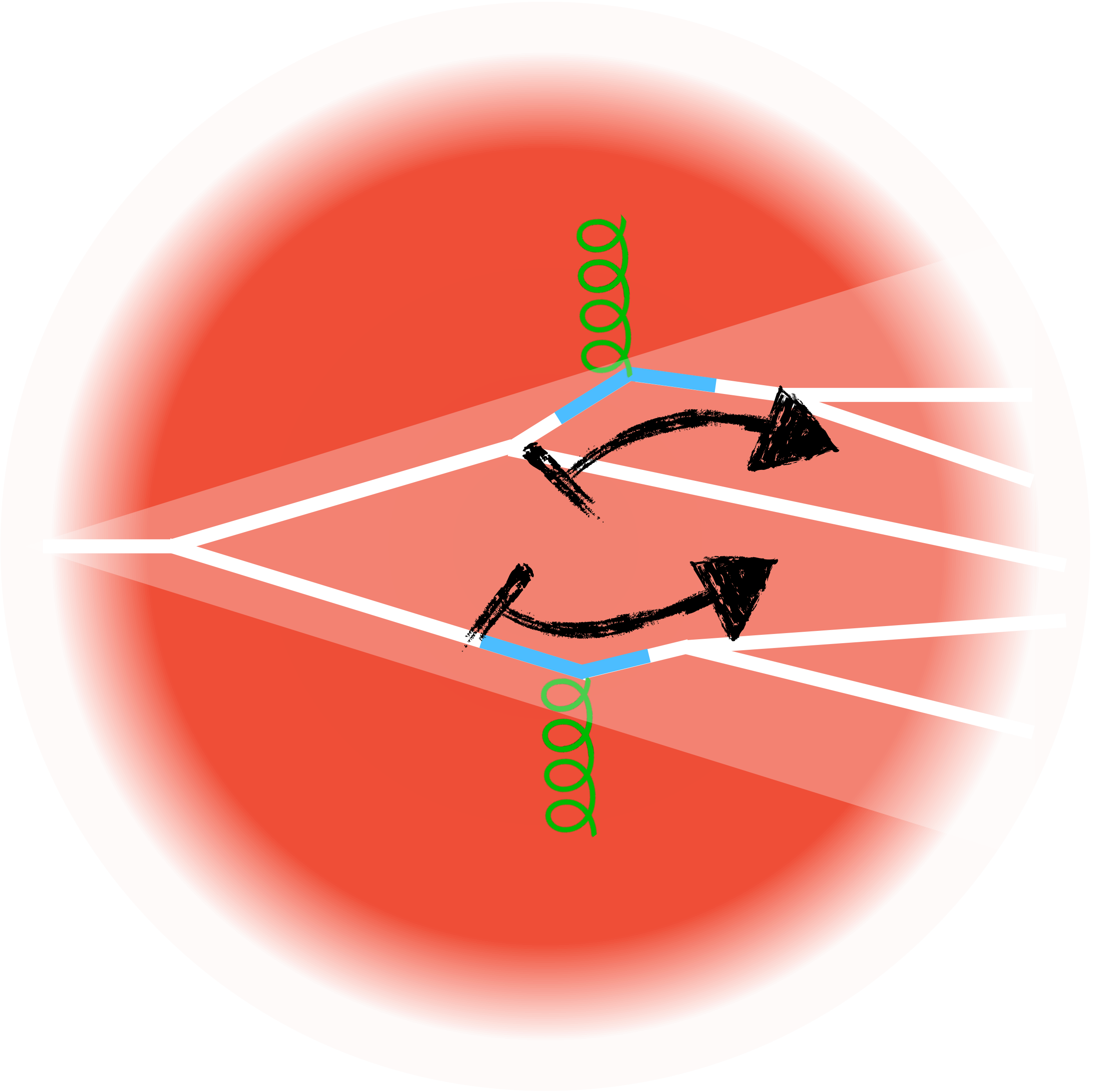
How much do recoils thermalize?

See more details and references here.

Where can we see the medium-response effect?

Where can we see the medium-response effect?

Substructure modification



Where can we see the medium-response effect?

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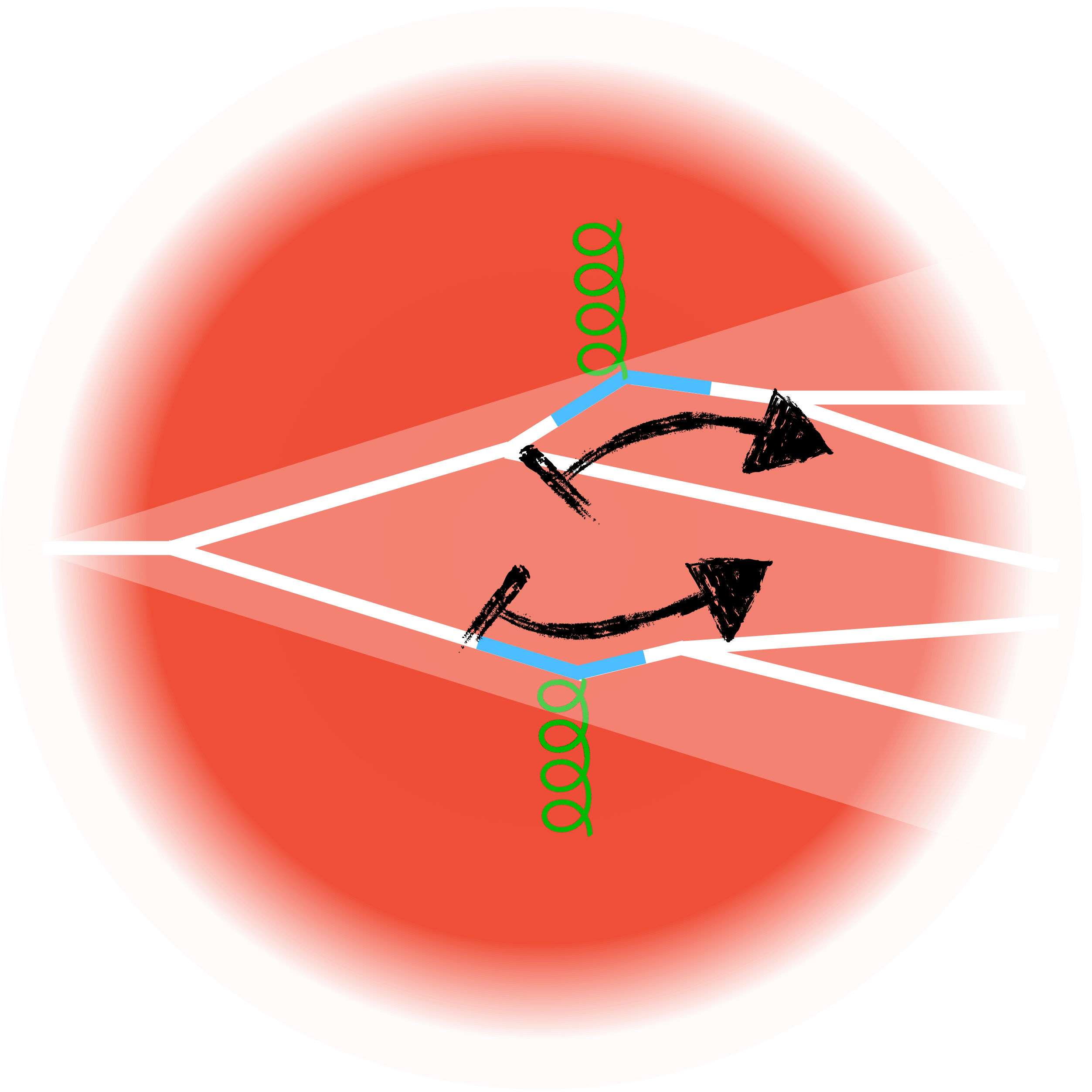
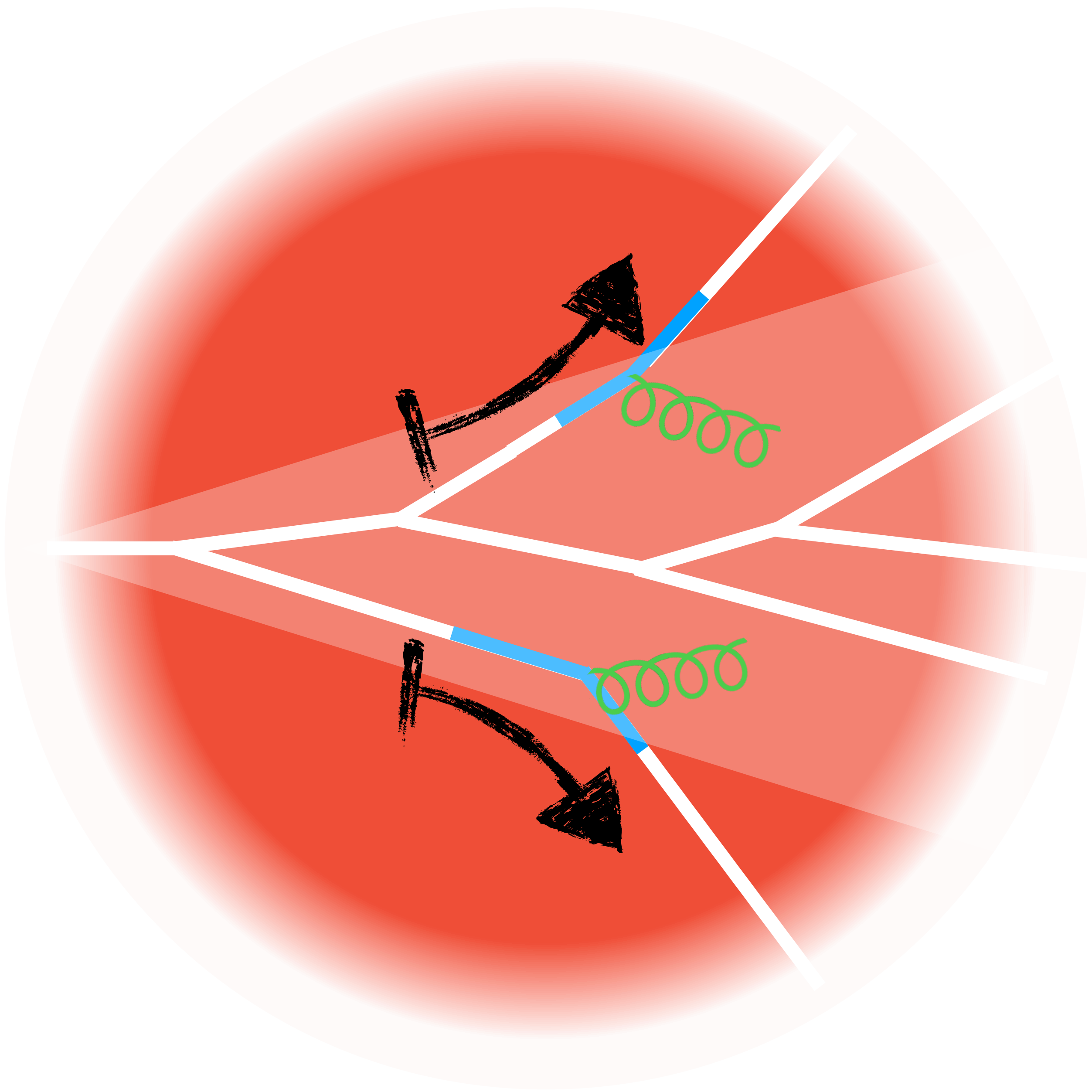


Jet energy “loss” (redistribution)



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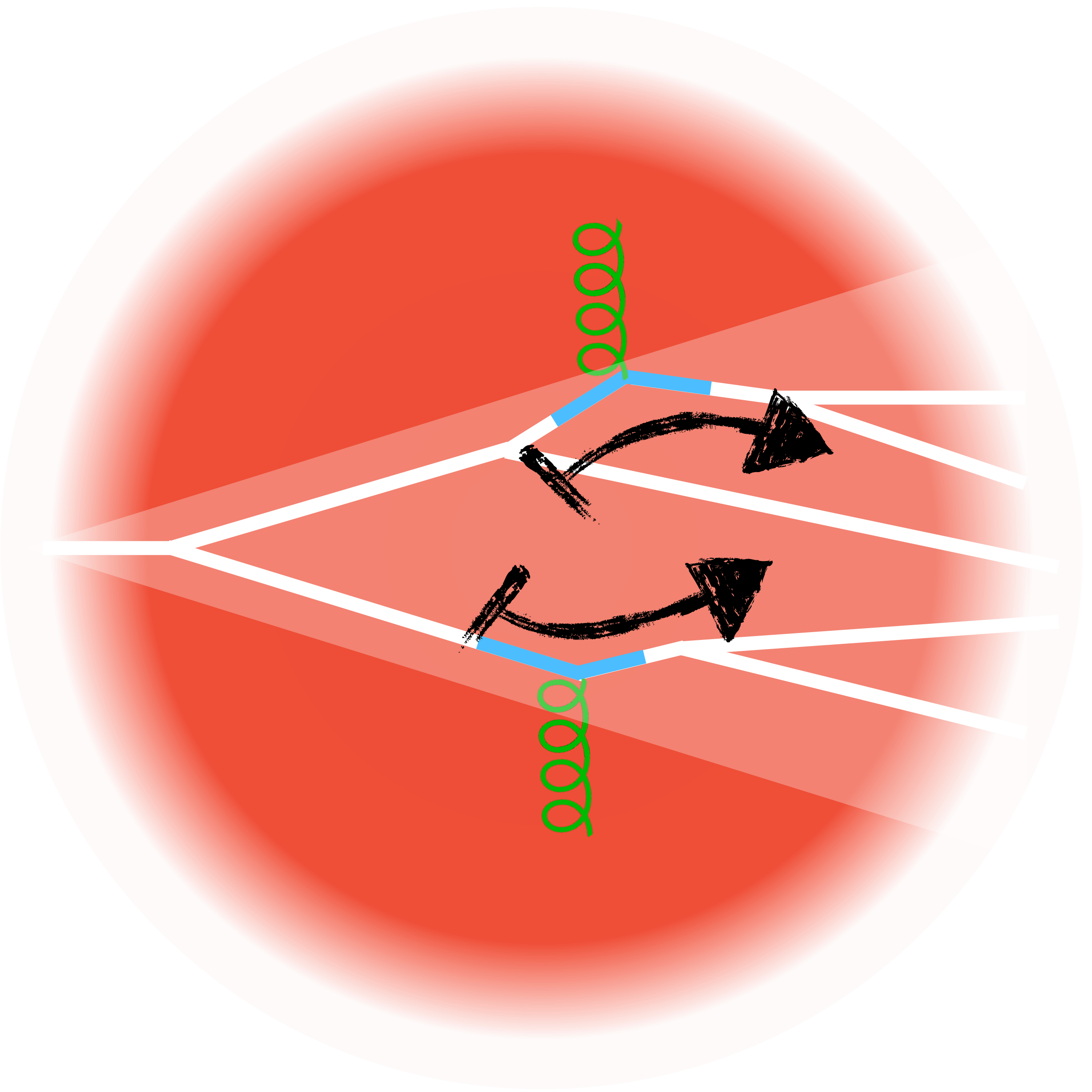

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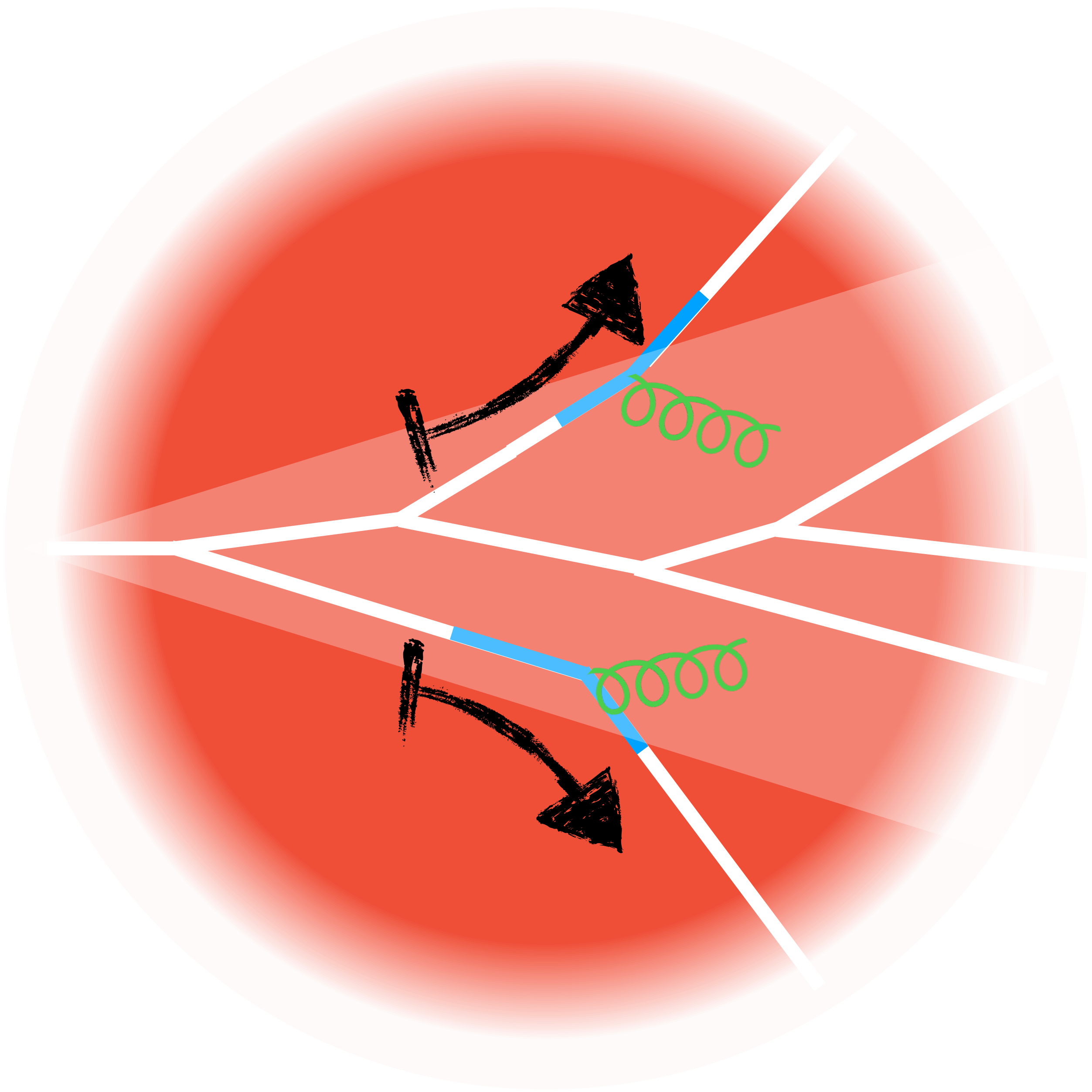
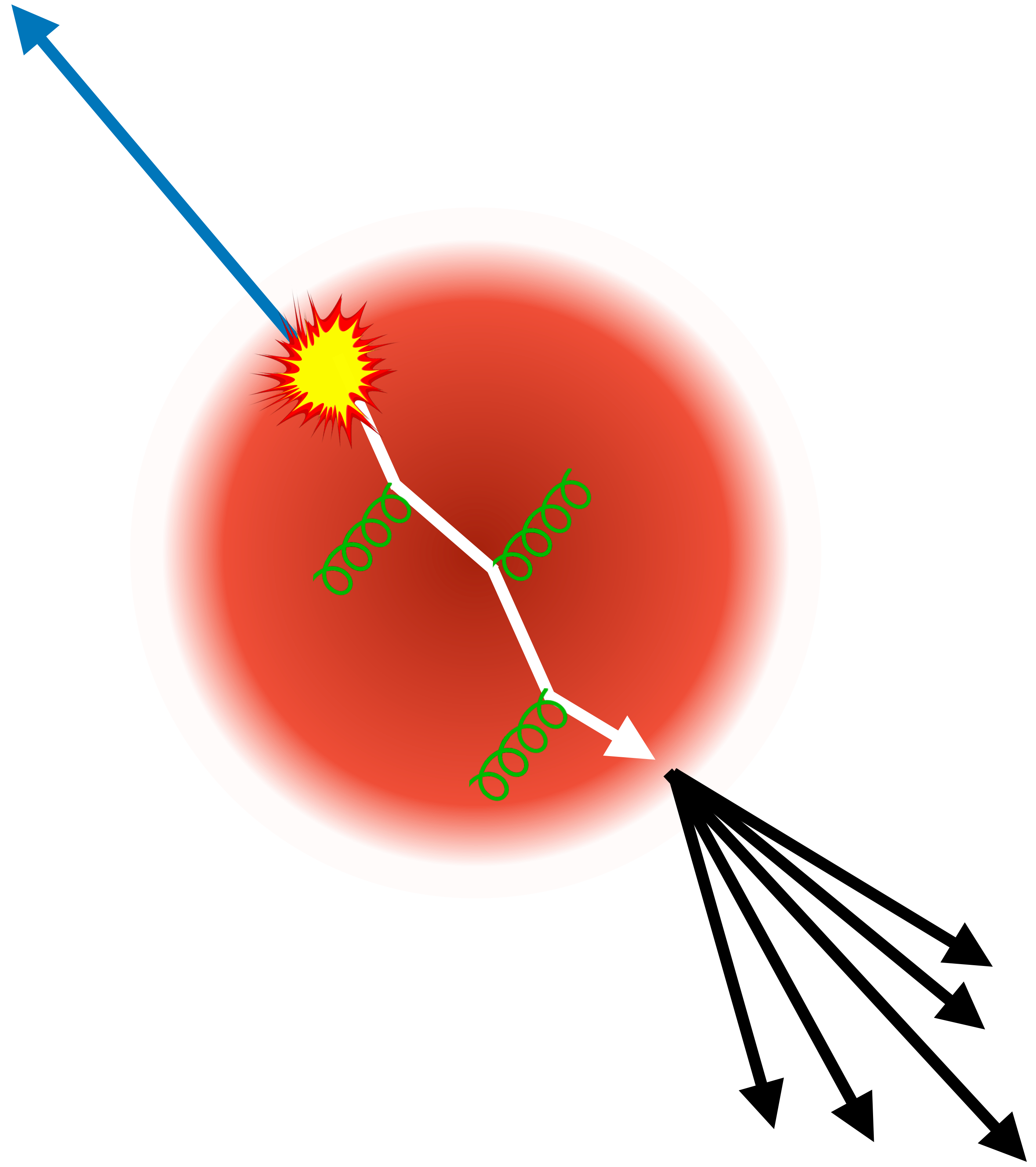
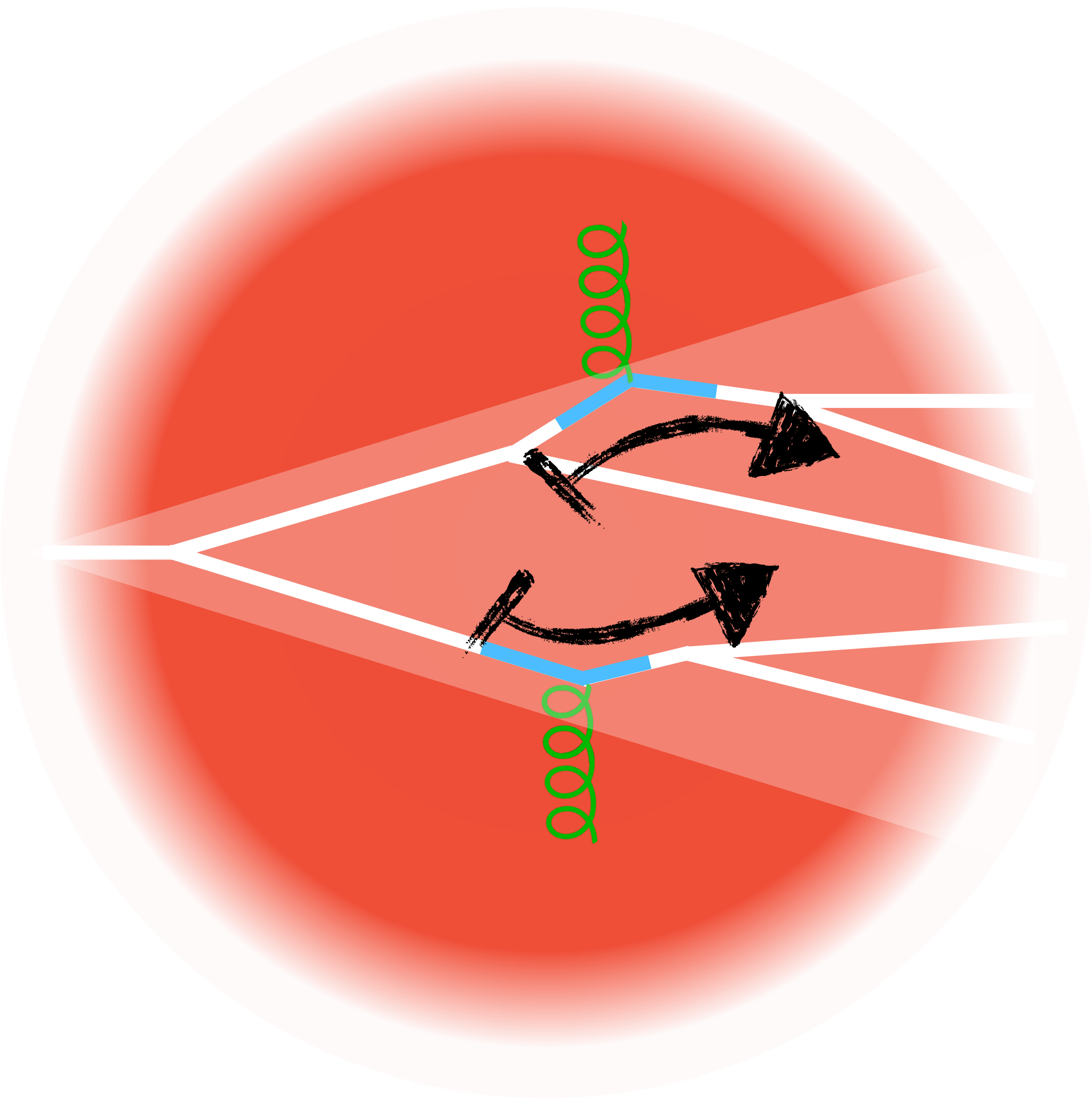


Hadrons recoiling from high-p_T trigger



Overview

Substructure modification



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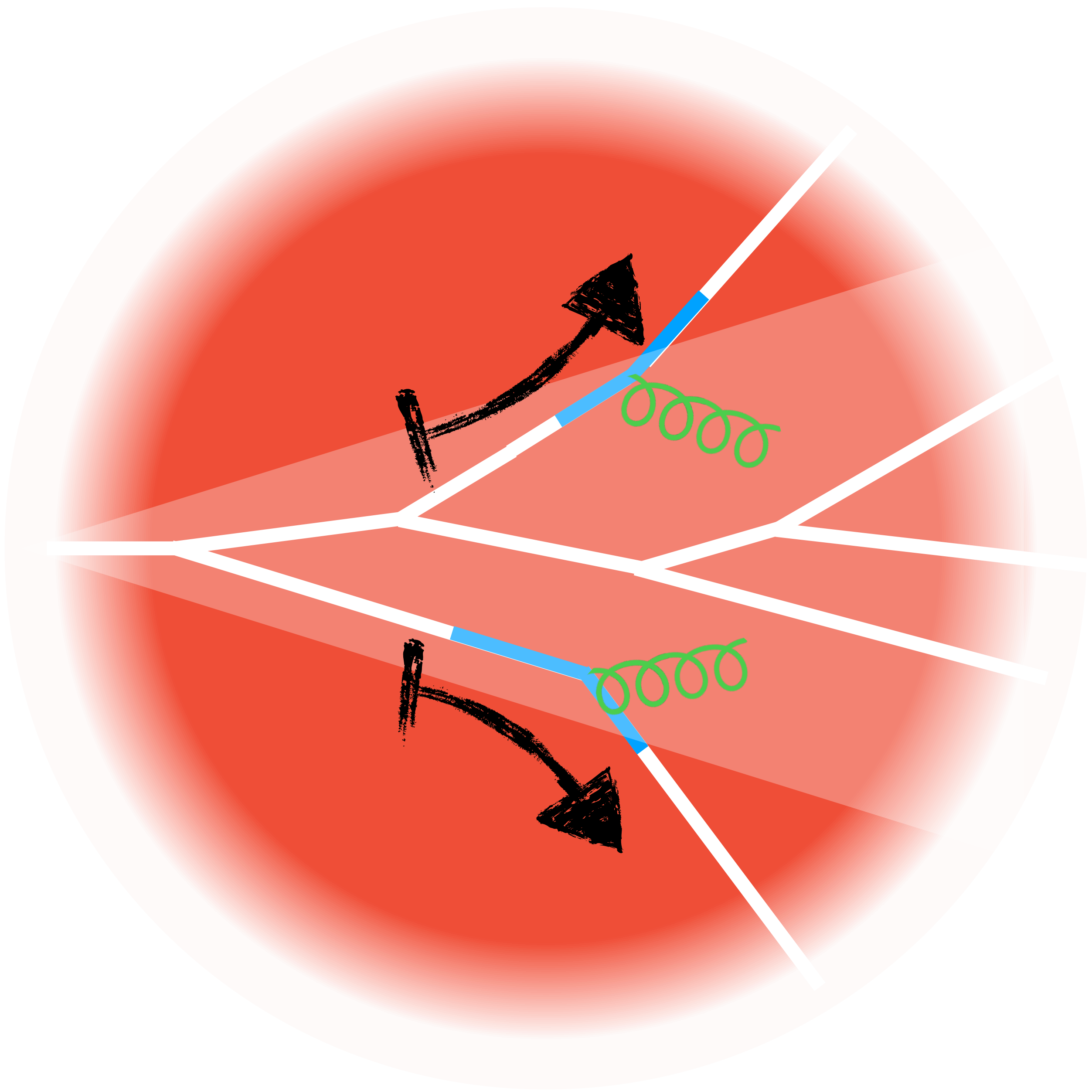

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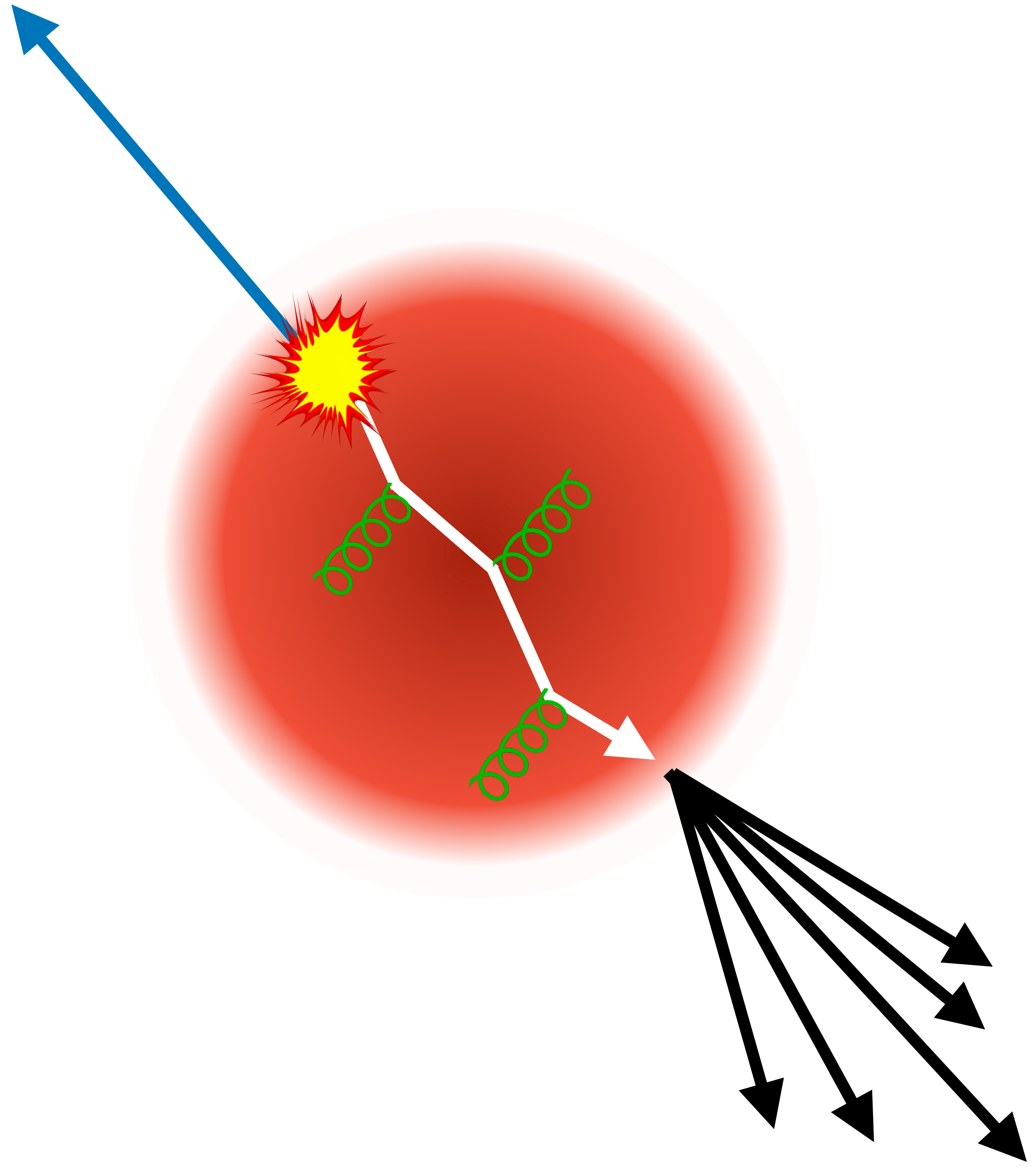


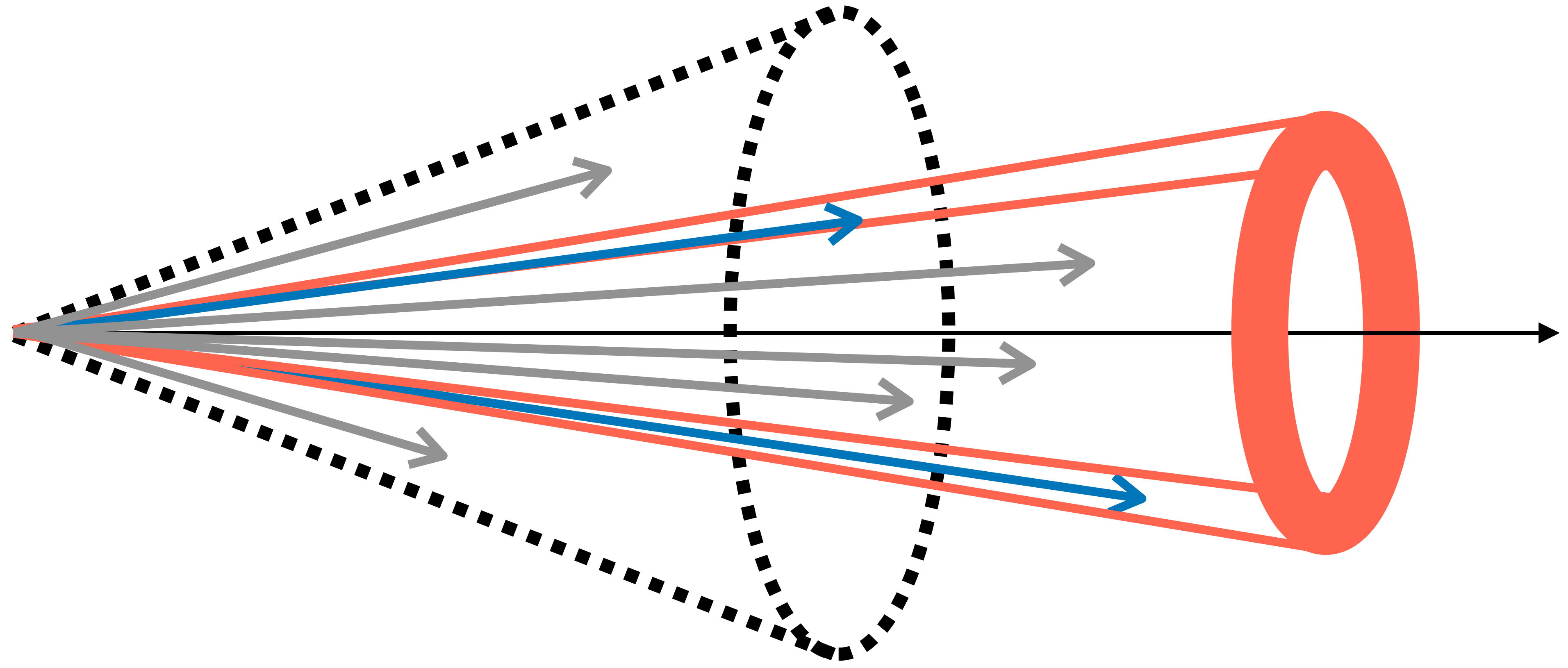
Jet shapes

CMS, PLB 730 (2014) 243

Describes how energy inside (and outside) jets is distributed in the radial direction

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\in[r_a,r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$

$$\delta r = 0.05$$



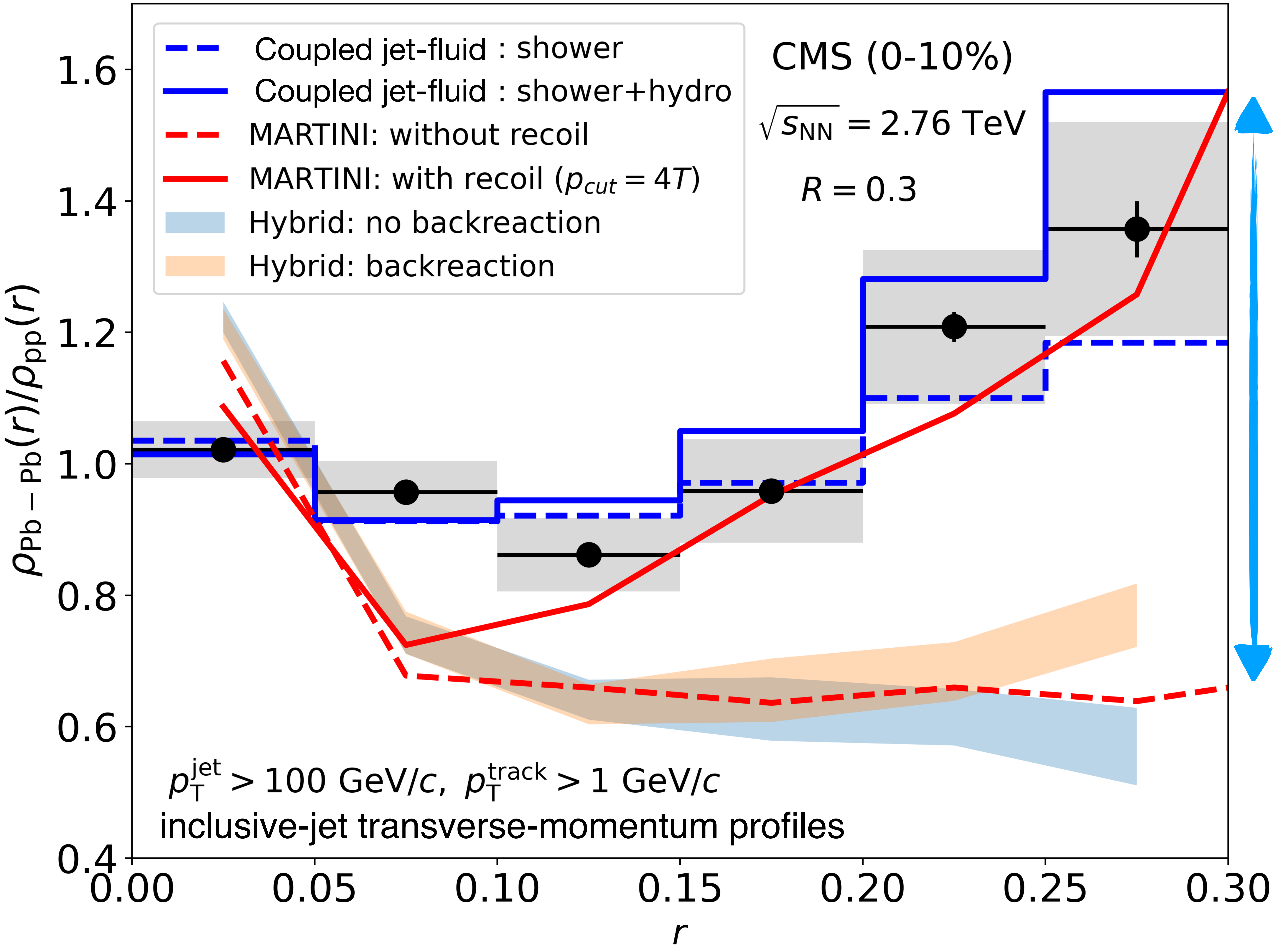


Fig adapted from PRC 95 (2017) 4, 044909, JHEP 03 (2017) 135, & NPA 982 (2019) 643

Jet shapes

Coupled jet-fluid model

PRC 95 (2017) 4, 044909

CMS-PAS-HIN-15-011

$\hat{q}_{q,0}$= 1.7 GeV^2/fm

ω_{cut} = 1.0 GeV/c

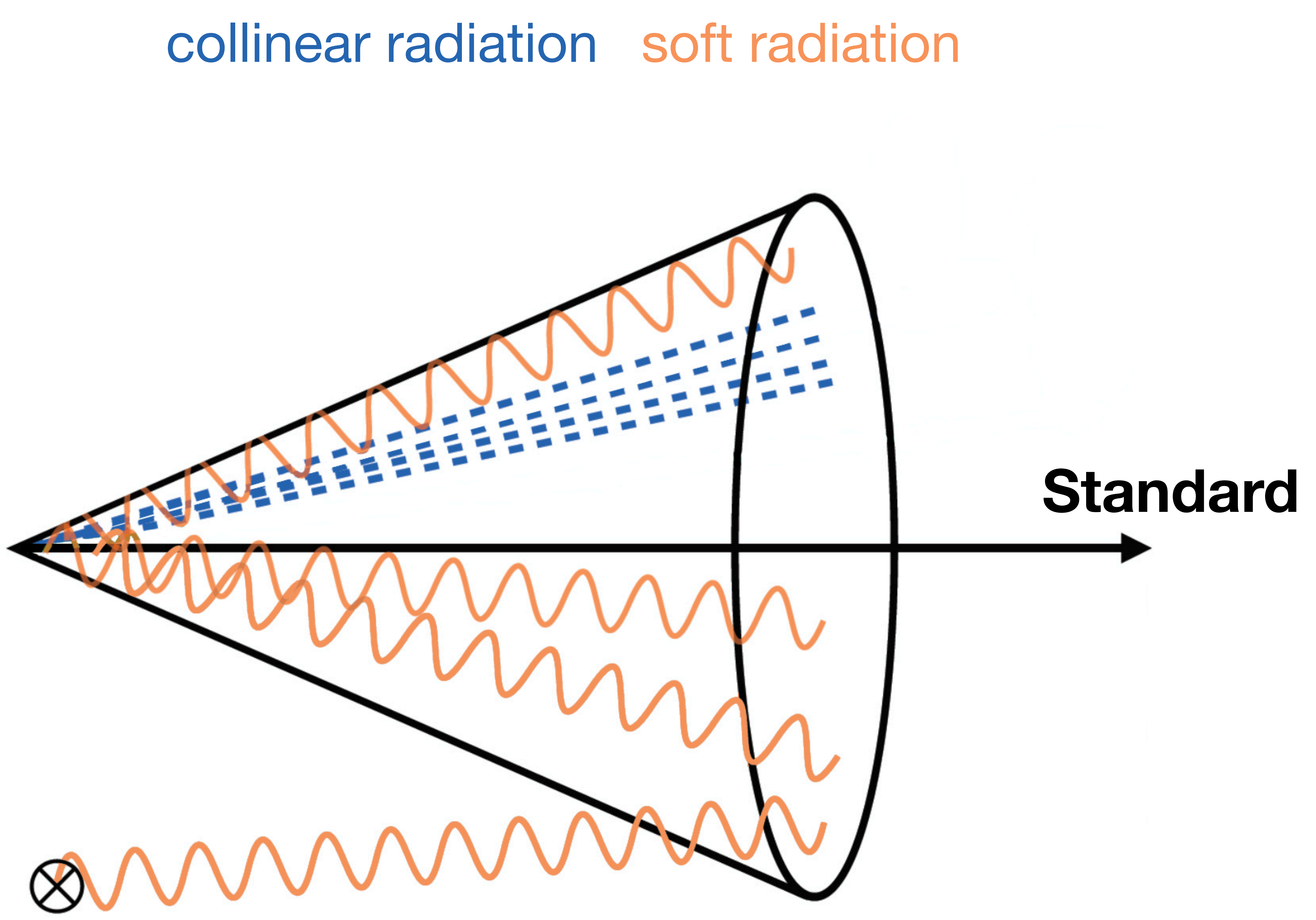
$p_T^{trk,\,hyd}$ > 0.5 GeV/c

Medium response dominates jet shape at very large angles from the jet direction.

Angle between jet axes

- Standard axis:

  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme



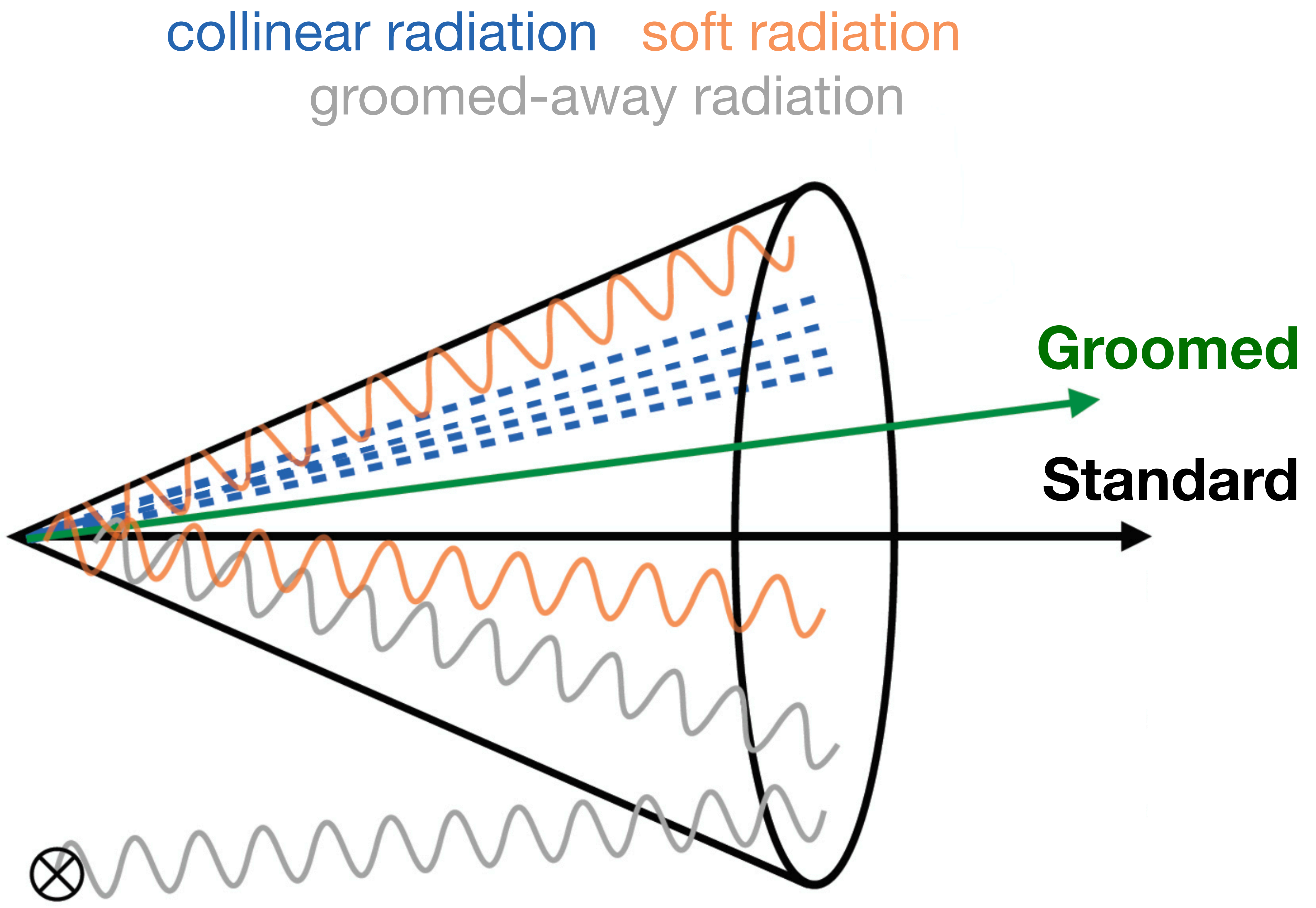
P. Cal et al., JHEP 04 (2020) 211

Substructure observable: $\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$ between two axes

Angle between jet axes

- **Standard axis:**
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- **Groomed axis:**
  standard axis of groomed (with Soft Drop) jet



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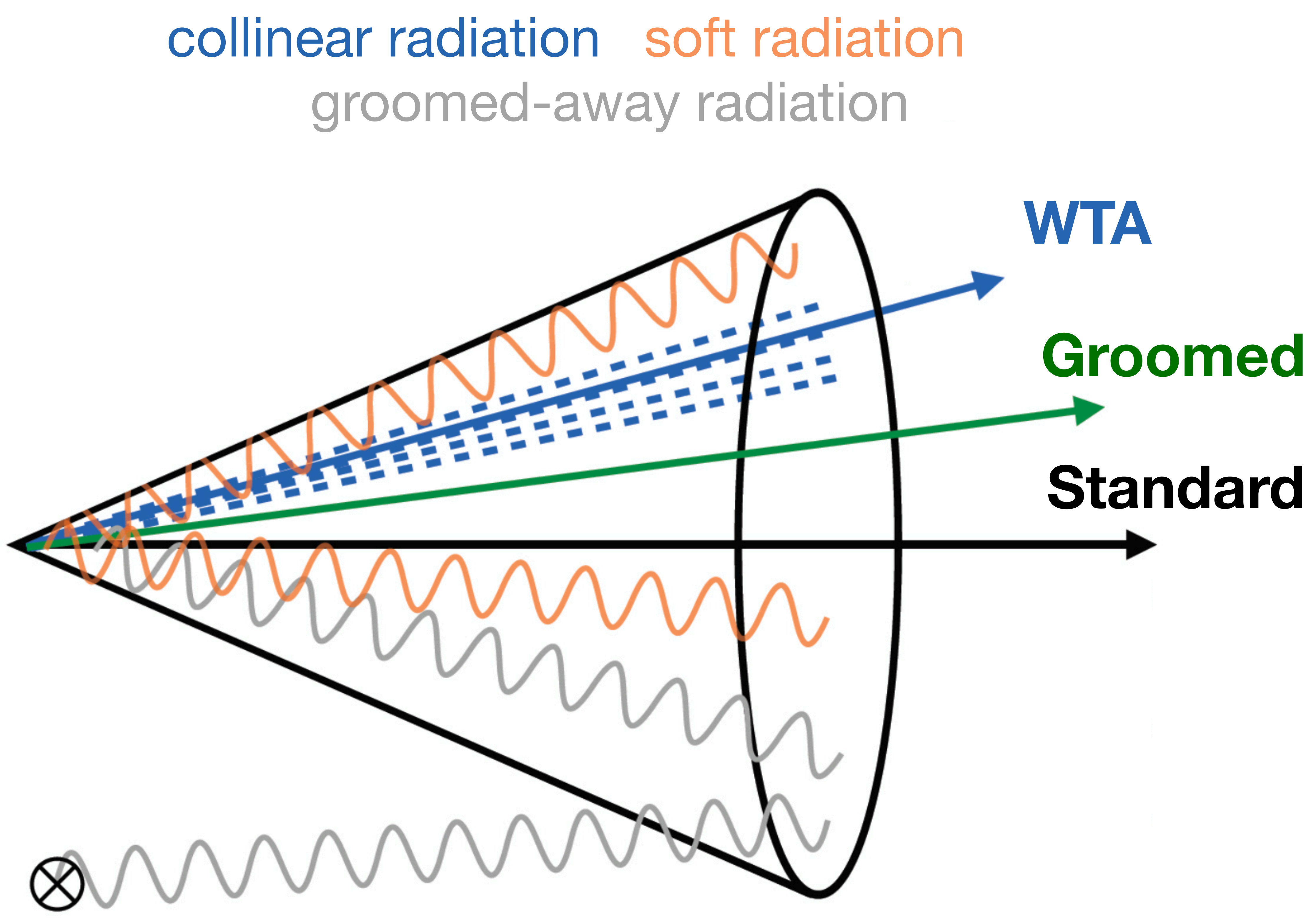
Angle between jet axes

- Standard axis:
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

- Groomed axis:
  standard axis of groomed (with Soft Drop) jet

- Winner-Takes-All (WTA) axis:
  - recluster jet with CA algorithm
  - $2 \to 1$ prong combination by taking direction of harder prong and $p_{\mathrm{T,\,tot}} = p_{\mathrm{T,\,1}} + p_{\mathrm{T,\,2}}$
  - Resulting axis insensitive to soft radiation at leading power



P. Cal et al., JHEP 04 (2020) 211

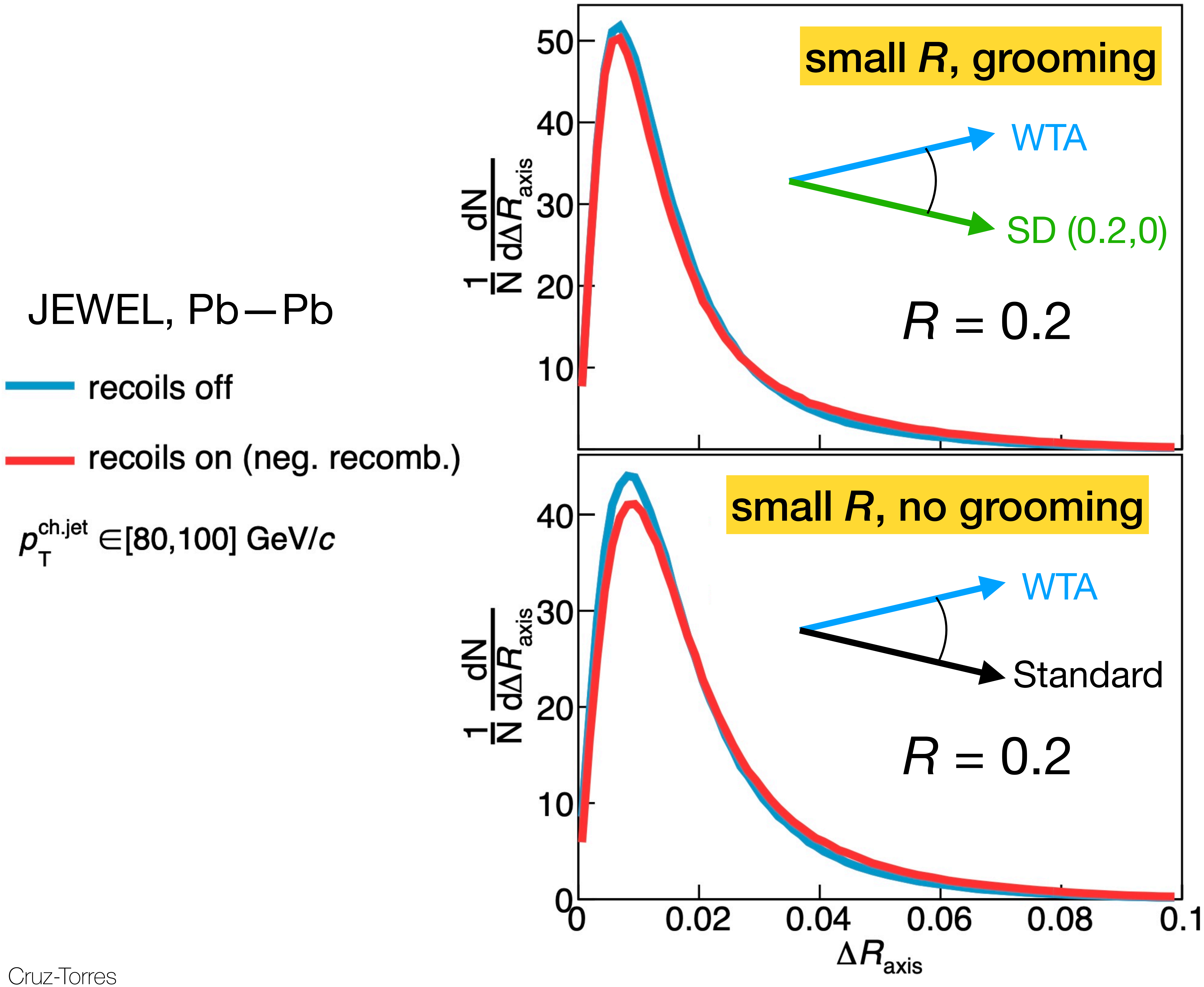
Substructure observable: $\Delta R_{\mathrm{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$ between two axes

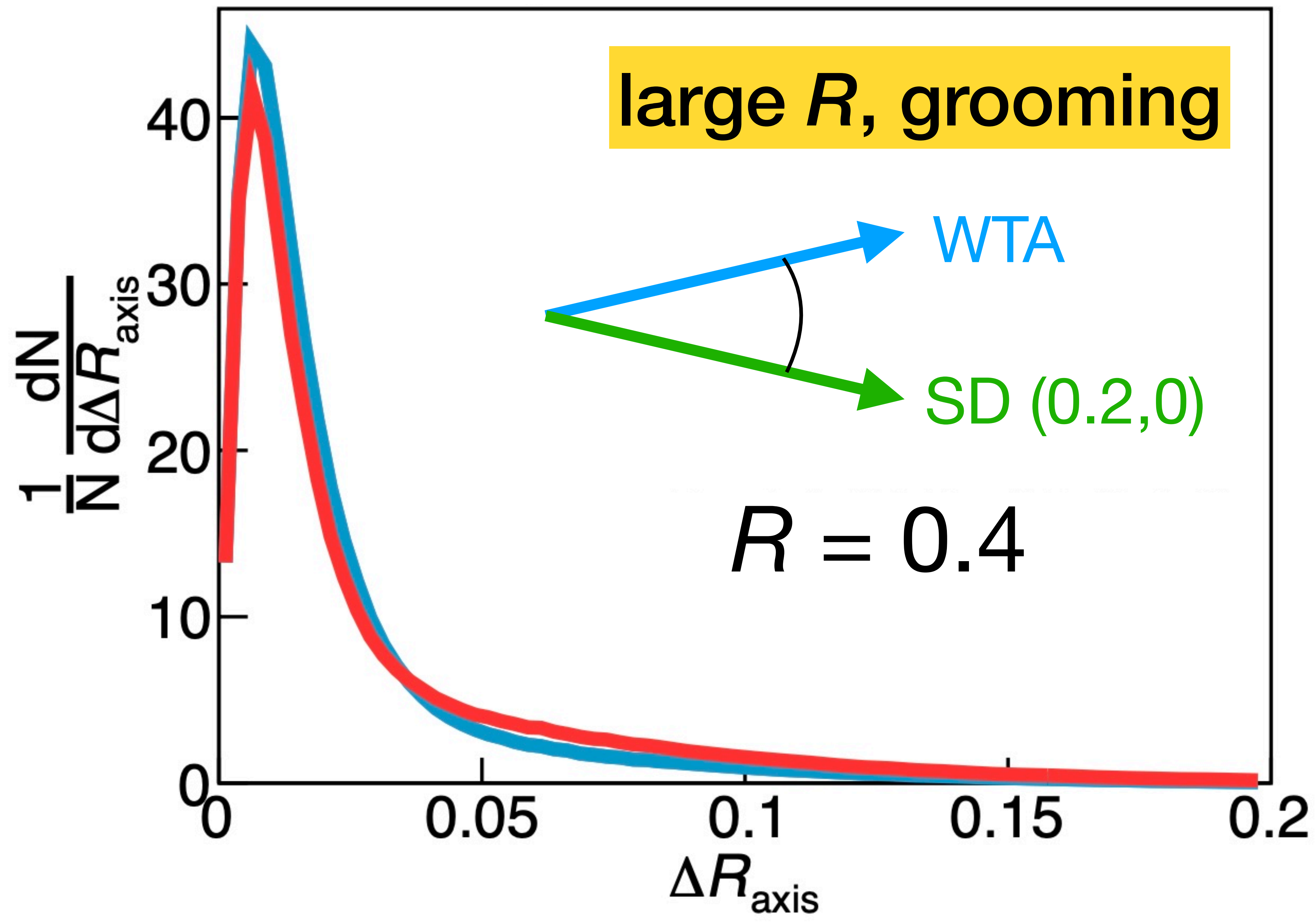
Medium response at large angles from jet

Very small differences between recoils on/off

Grooming systematically removes soft wide-angle radiation

Medium response at large angles from jet





Small-radius jet excludes wide-angle radiation (e.g. medium response)

Let's try with large R and no grooming

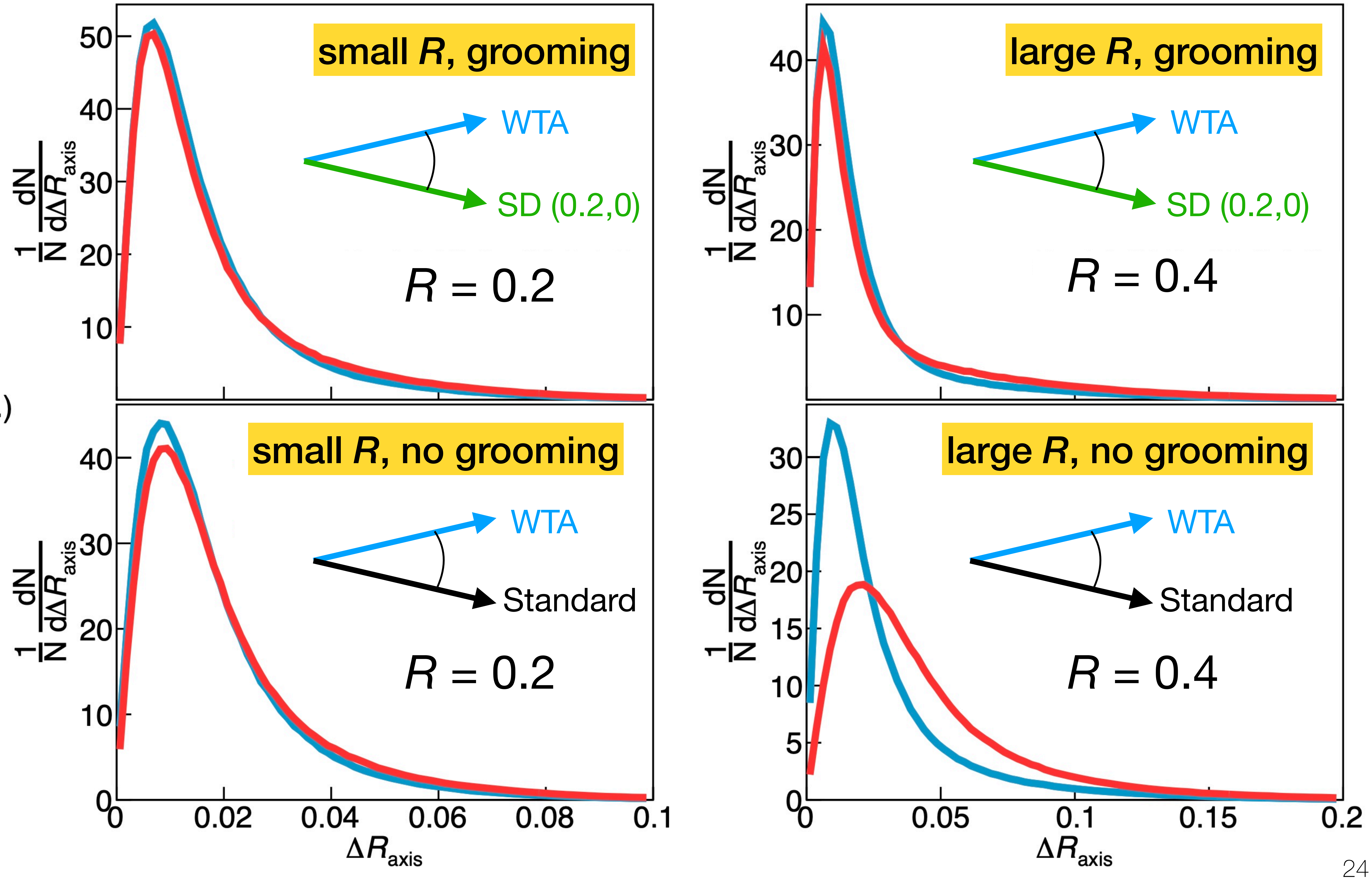
Medium response at large angles from jet

JEWEL, Pb—Pb

recoils off

recoils on (neg. recomb.)

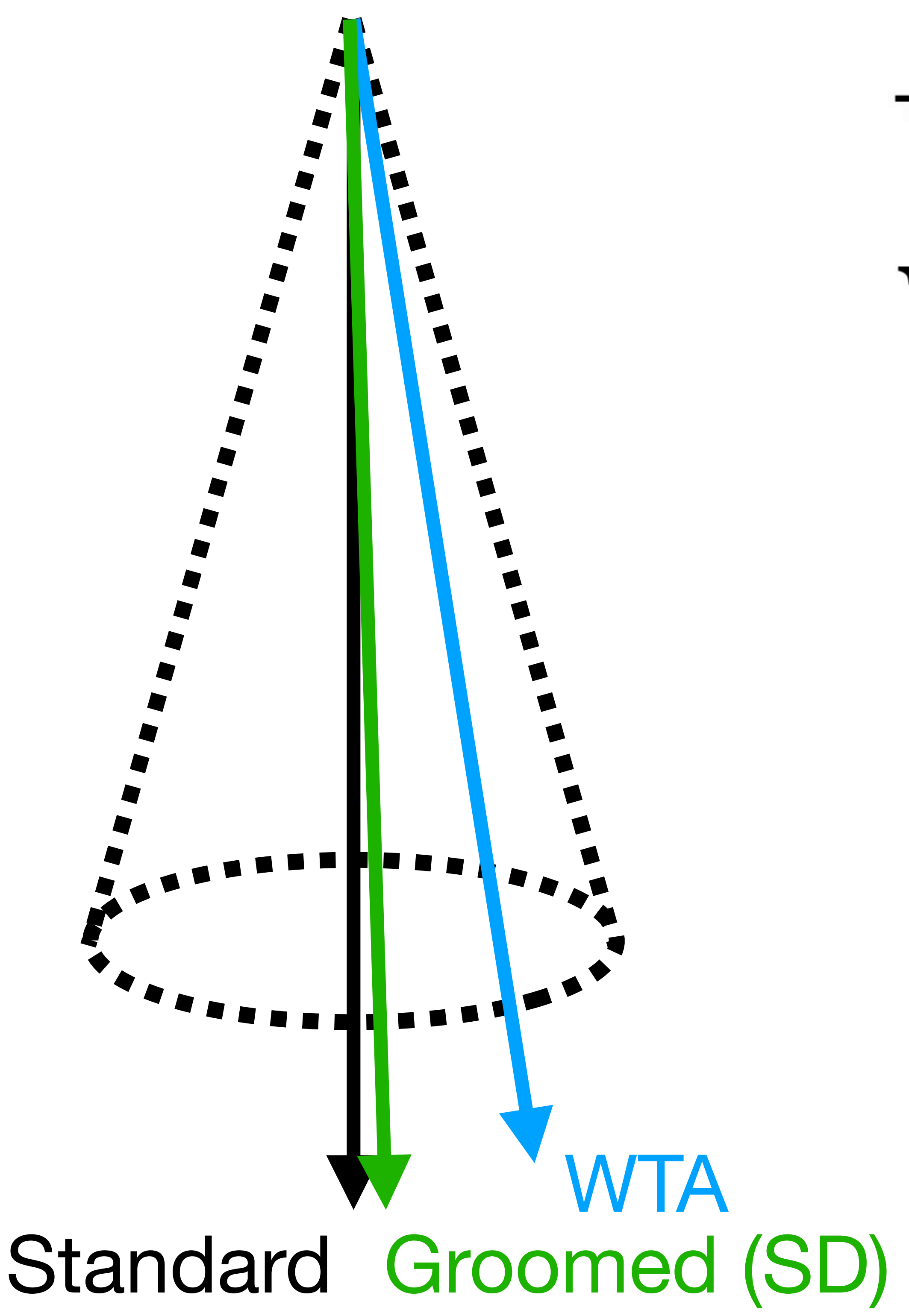
$p_{T}^{ch.jet} \in [80,100]$ GeV/c



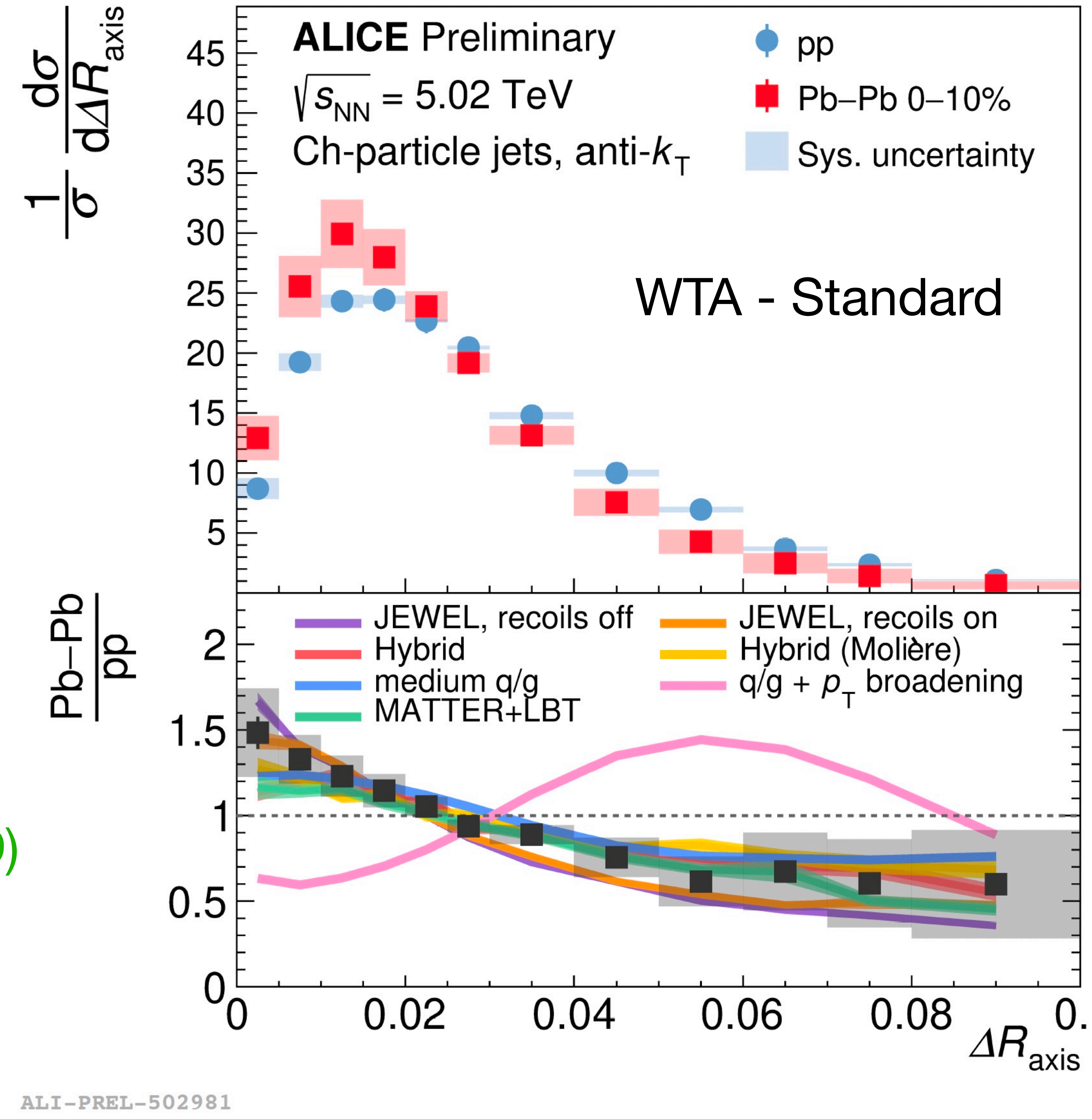
Angle between Standard and WTA axes

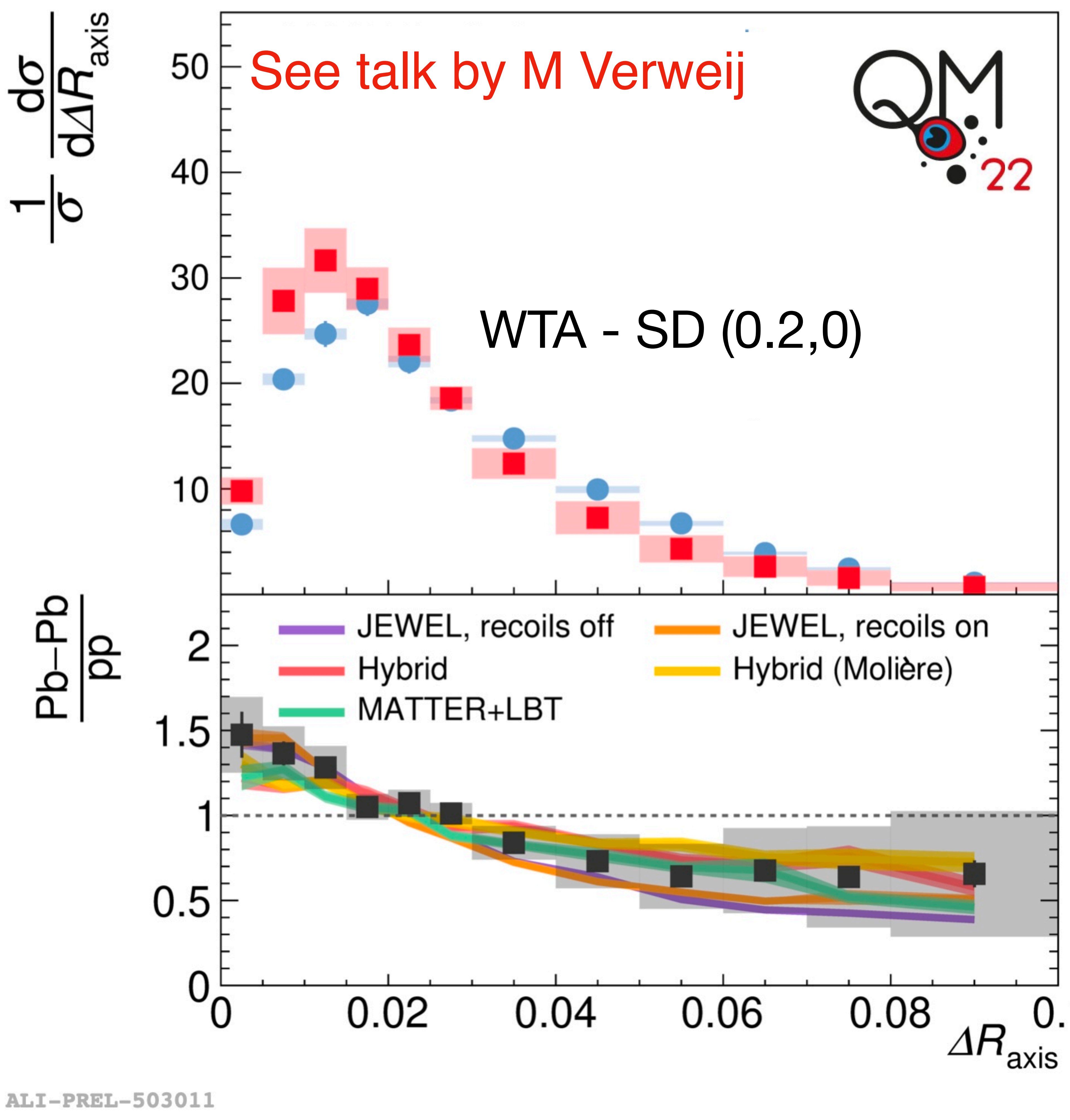
$R = 0.2$

$p_{\mathrm{T}}^{\mathrm{ch\ jet}} \in [40,60]\ \mathrm{GeV}/c$



More grooming





- narrowing trend observed
- Modification larger at lower $p_{\mathrm{T}}^{\mathrm{ch\ jet}}$

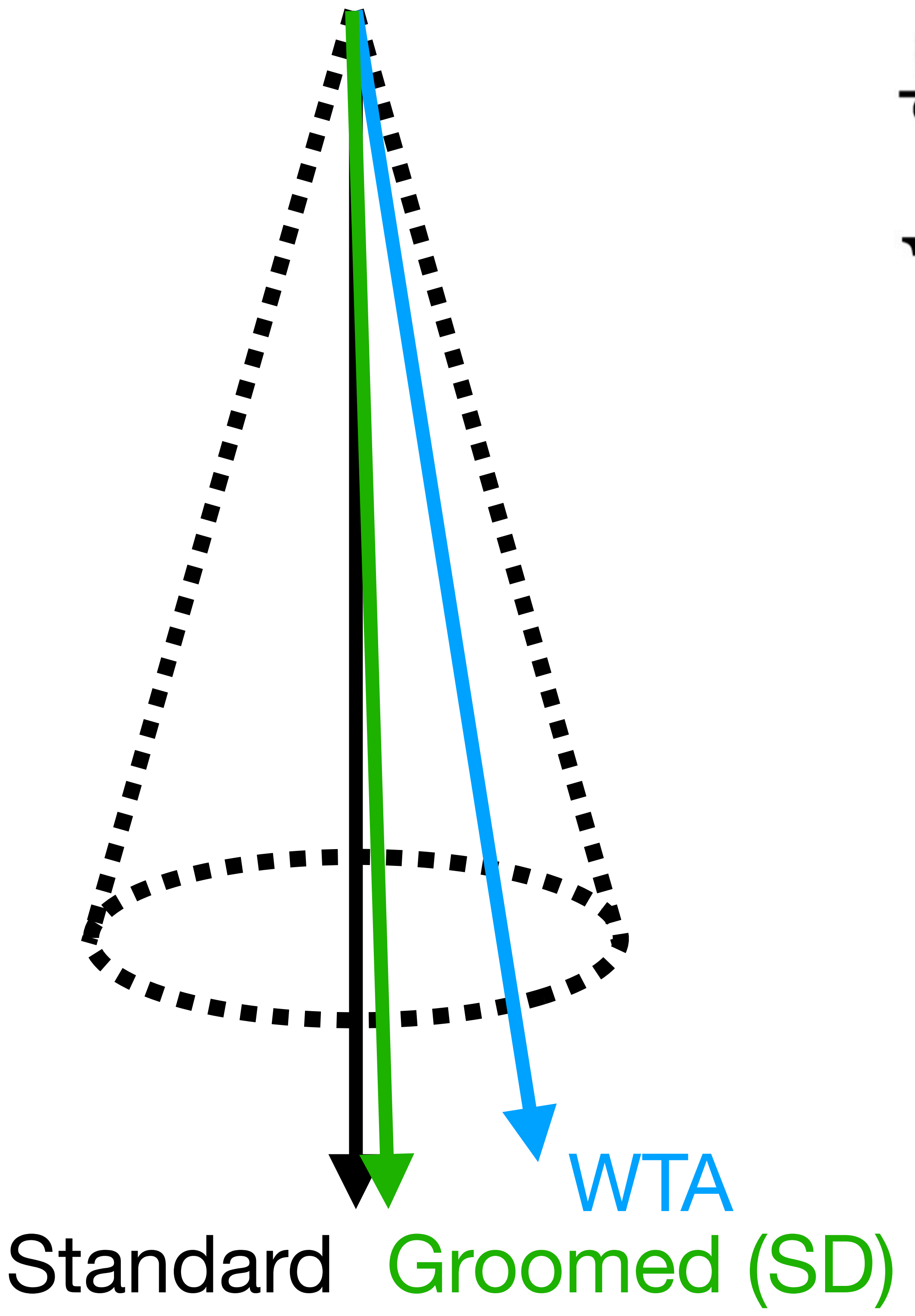
- Insensitivity to grooming
- Insensitivity to medium response for R=0.2

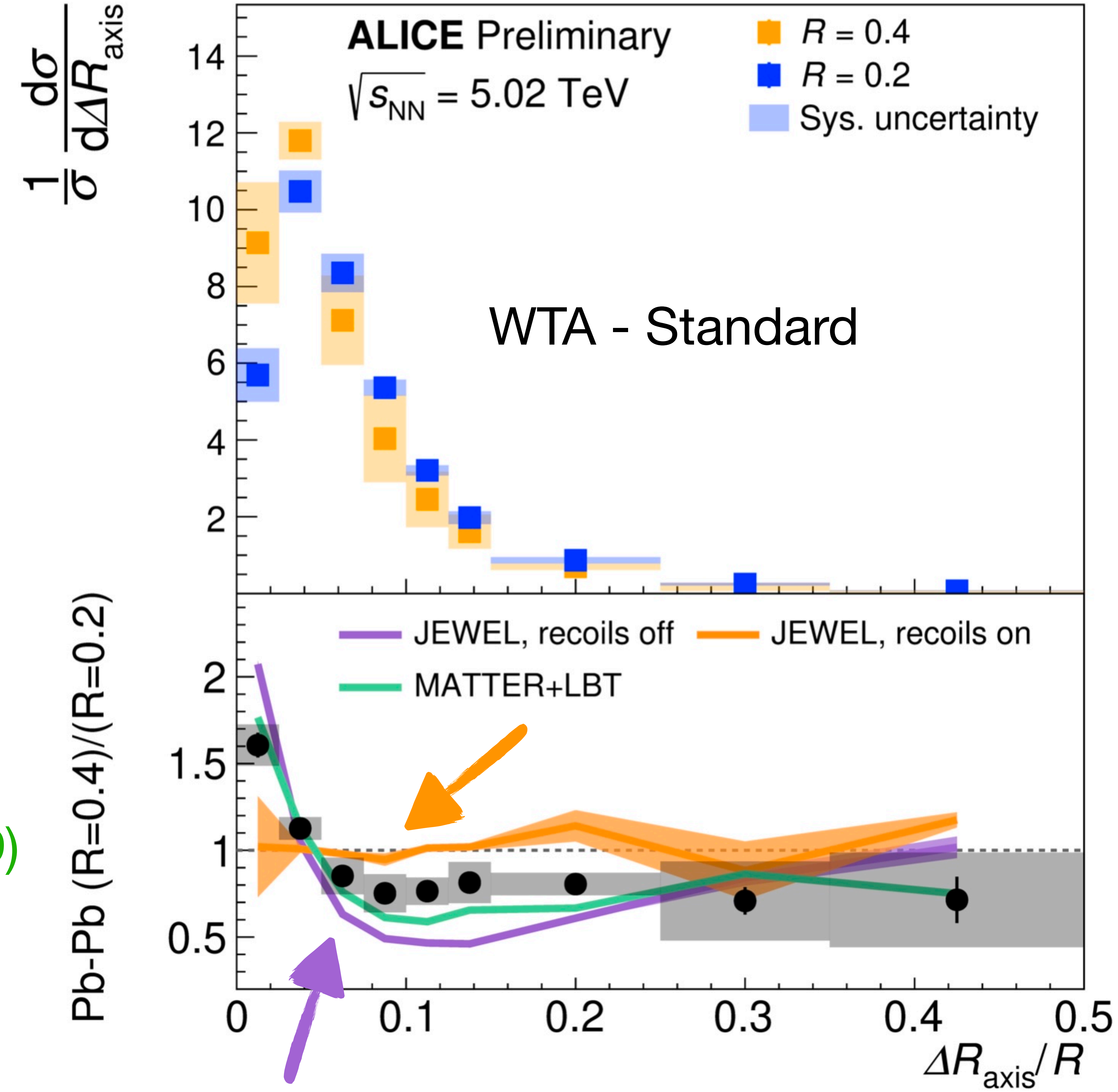
Pb—Pb results (no pp baseline)

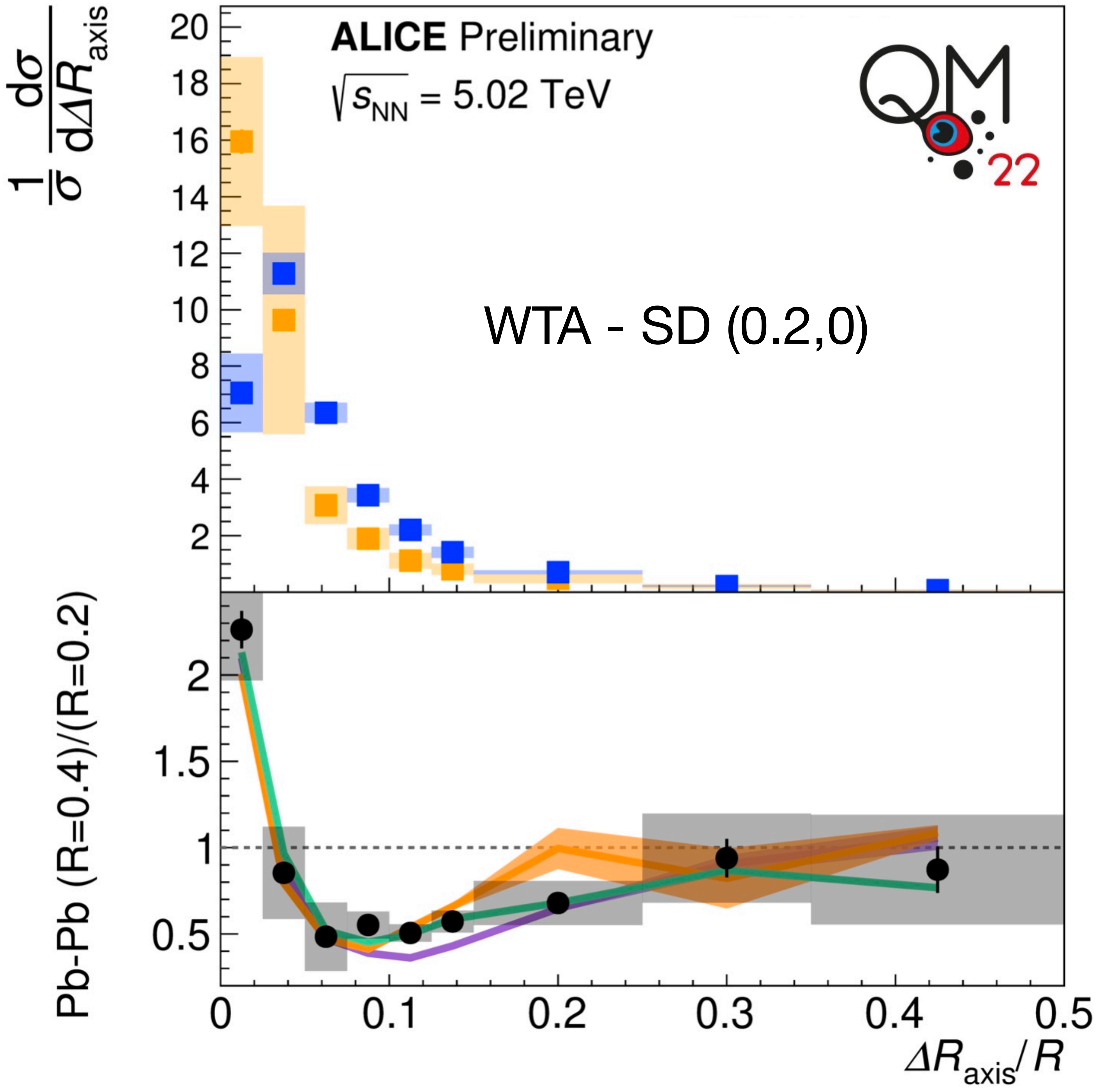
Pb—Pb (0-10%)

$p_{\mathrm{T}}^{\mathrm{ch\ jet}} \in [100, 140]$ GeV/c

More grooming





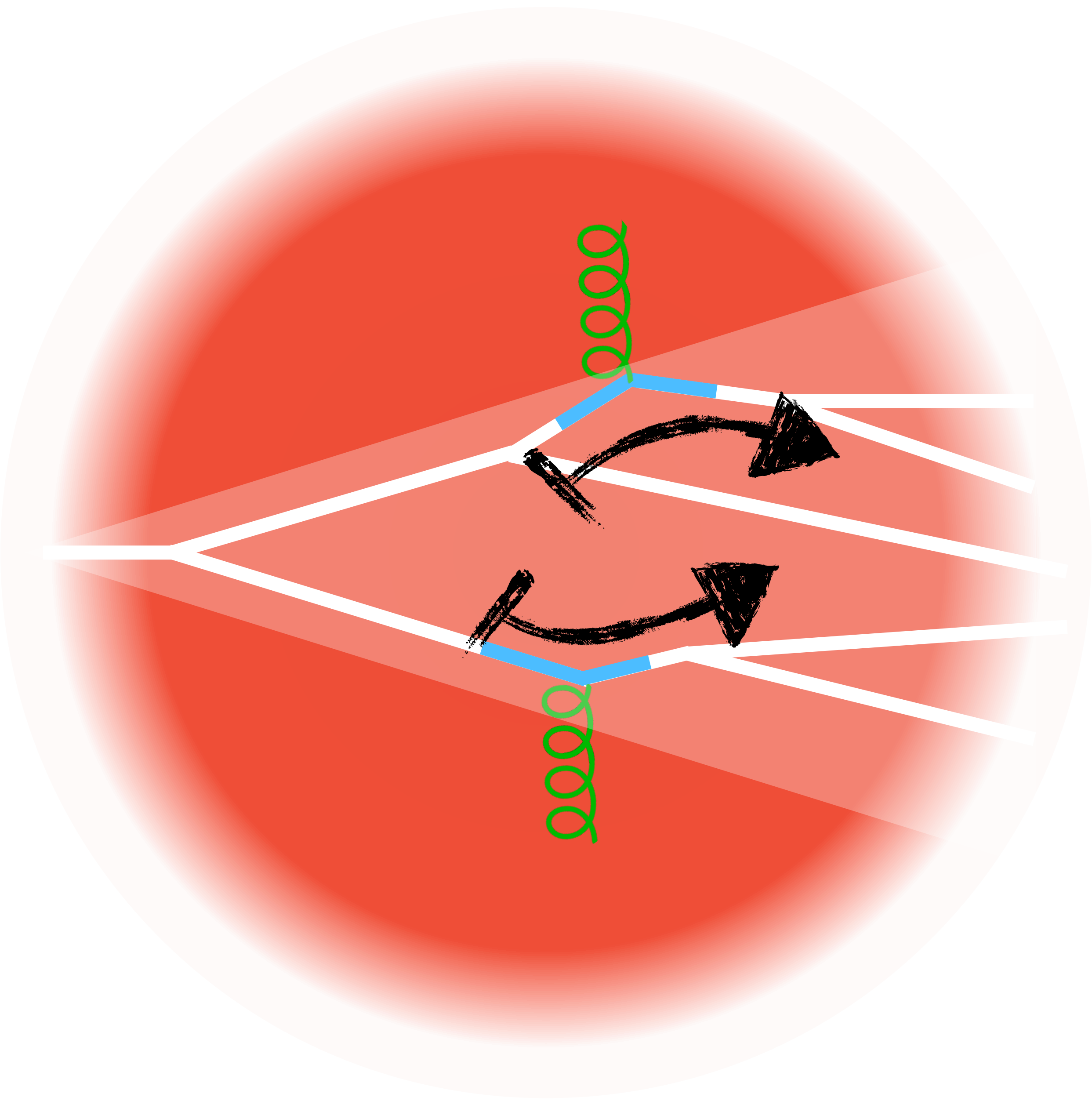


No pp baseline -> higher precision

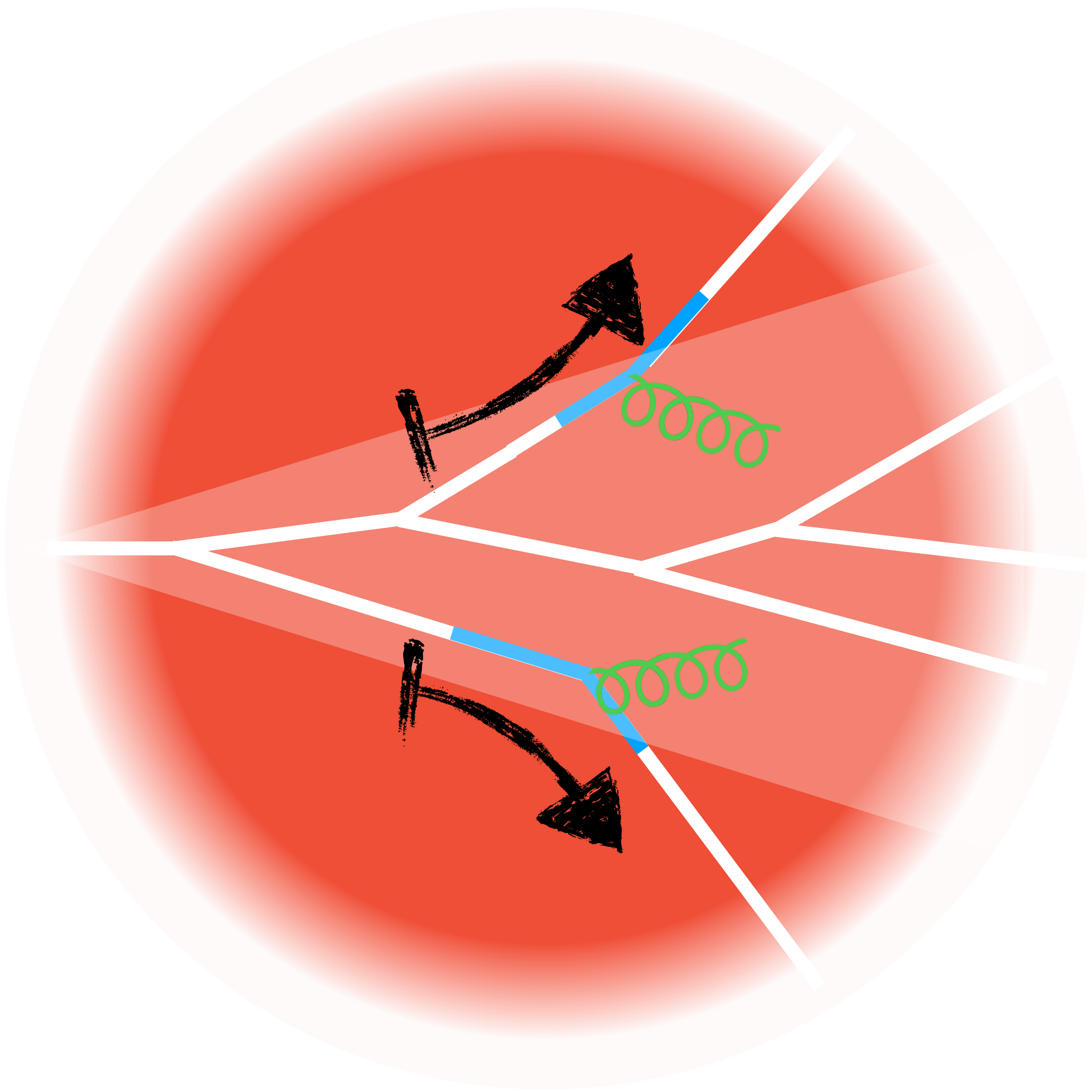
Sensitivity to medium response for large R and no grooming

Overview

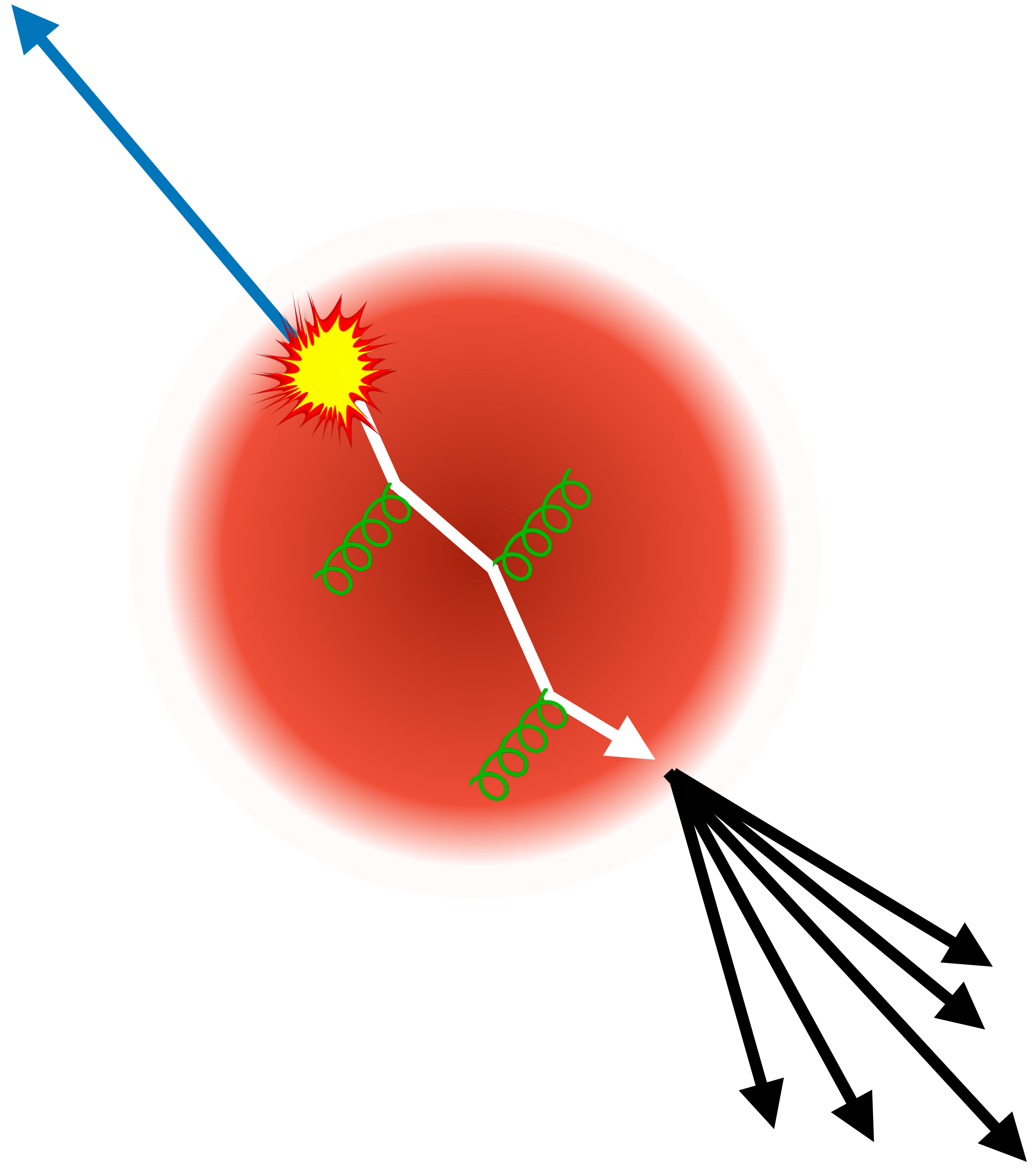
Substructure modification



Jet energy “loss” (redistribution)



Hadrons recoiling from high-p_T trigger



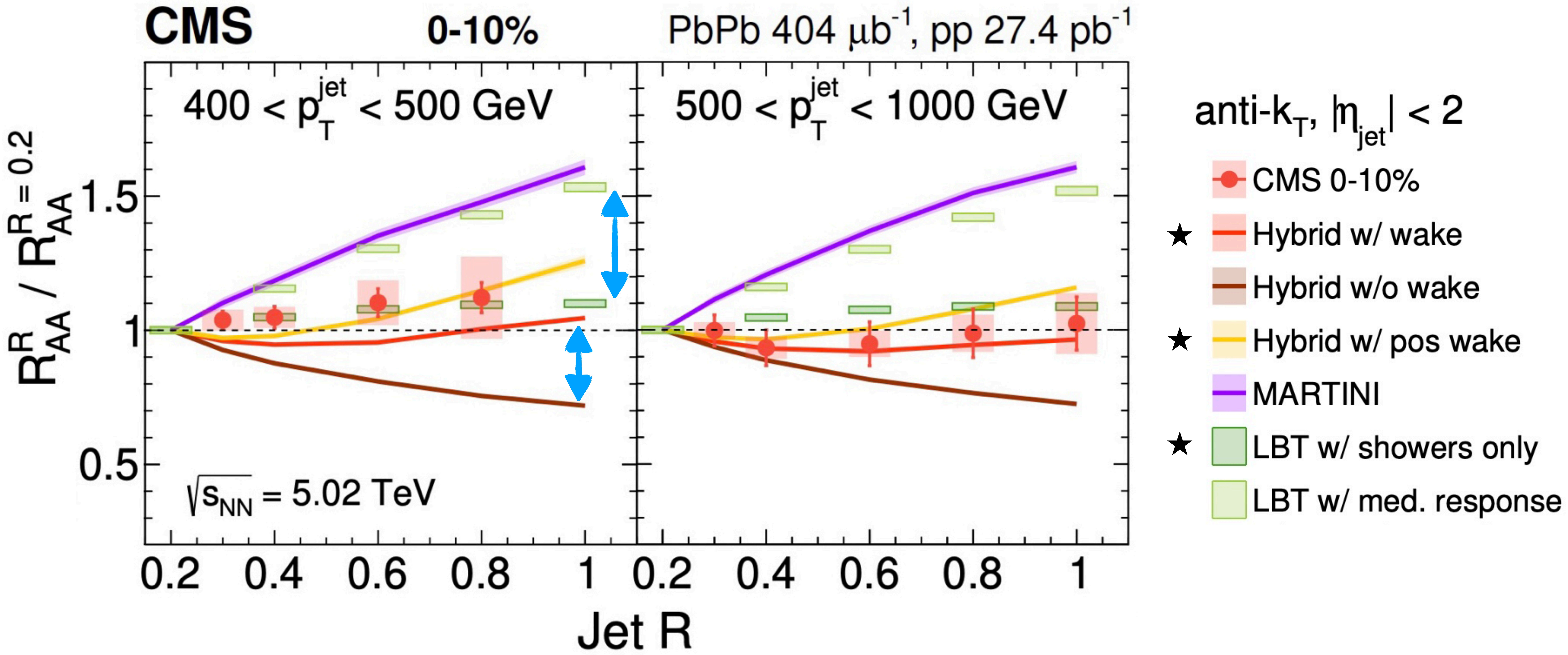
Jet R_{AA} ratios vs R

CMS JHEP 05 (2021) 284

- Data: R_{AA} little dependence on R
- Larger R → larger medium response effect

Jet R_{AA} ratios vs R

CMS JHEP 05 (2021) 284



- Data: R_{AA} little dependence on R
- Larger R → larger medium response effect

★ Some models describe the $R^{\mathrm{R}}_{\mathrm{AA}}/R^{\mathrm{R=0.2}}_{\mathrm{AA}}$ but…

Jet R_{AA}

CMS JHEP 05 (2021) 284

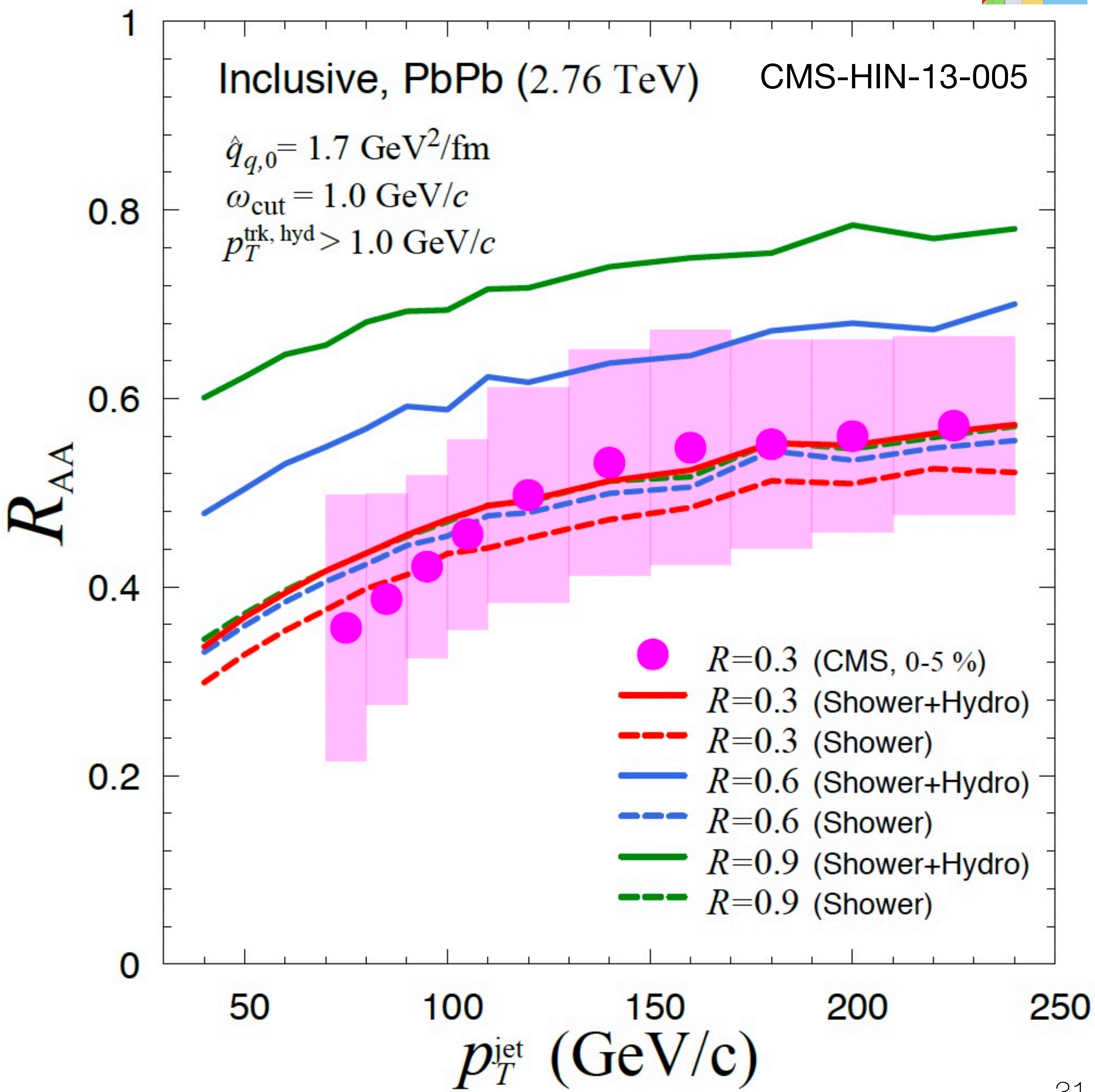
… they don't describe the individual R^{R}_{AA}

Jet R_{AA}

Coupled jet-fluid model

PRC 95 (2017) 4, 044909

- without medium response (- -): weak jet cone-size dependence
- with medium response (—):
  - jet partially recovers lost energy → increase of R_{AA}
  - increase of the jet cone-size dependence of R_{AA}



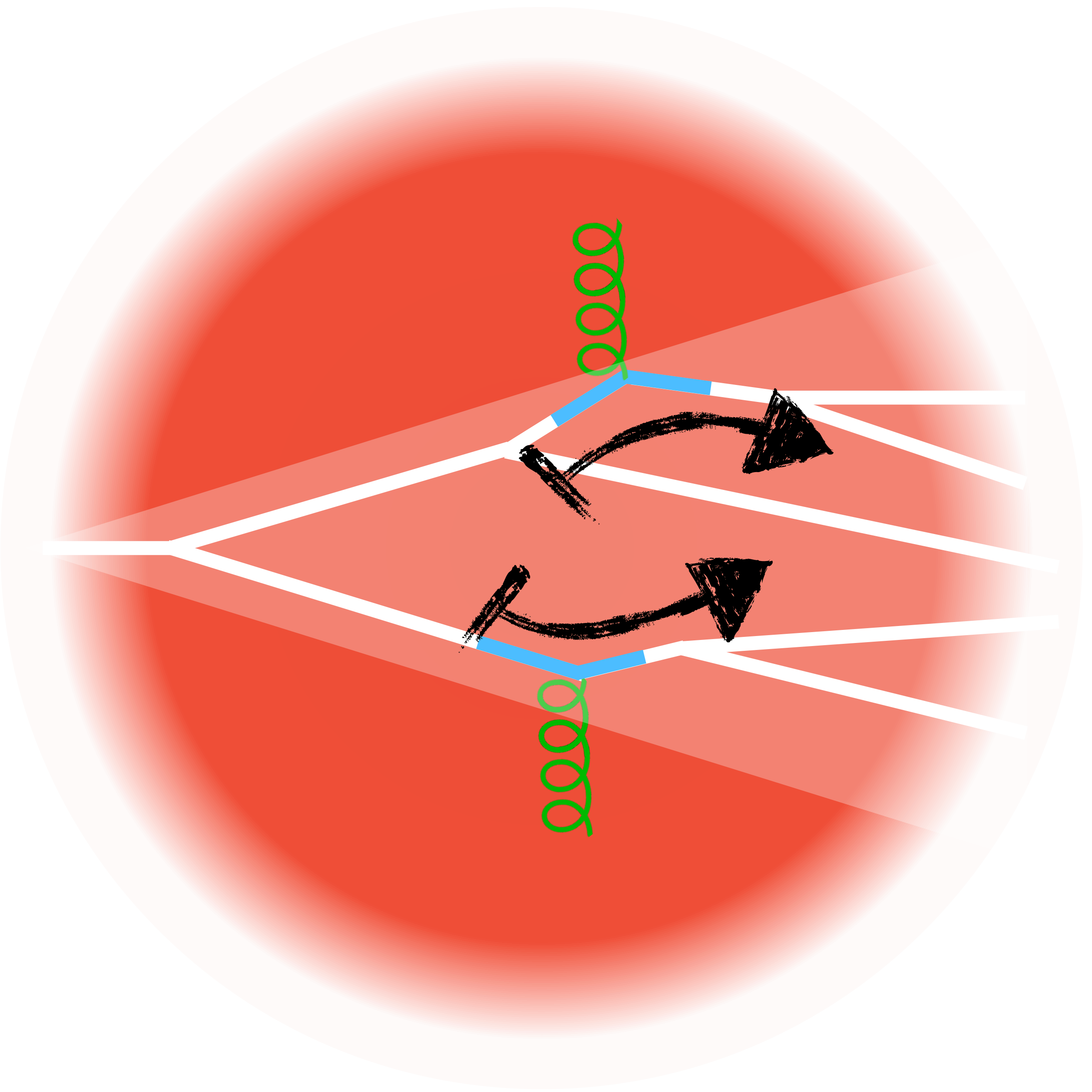
Jet R_{AA}

ML-based background estimator

Measuring down to lower p_T and larger R

Overview

Substructure modification



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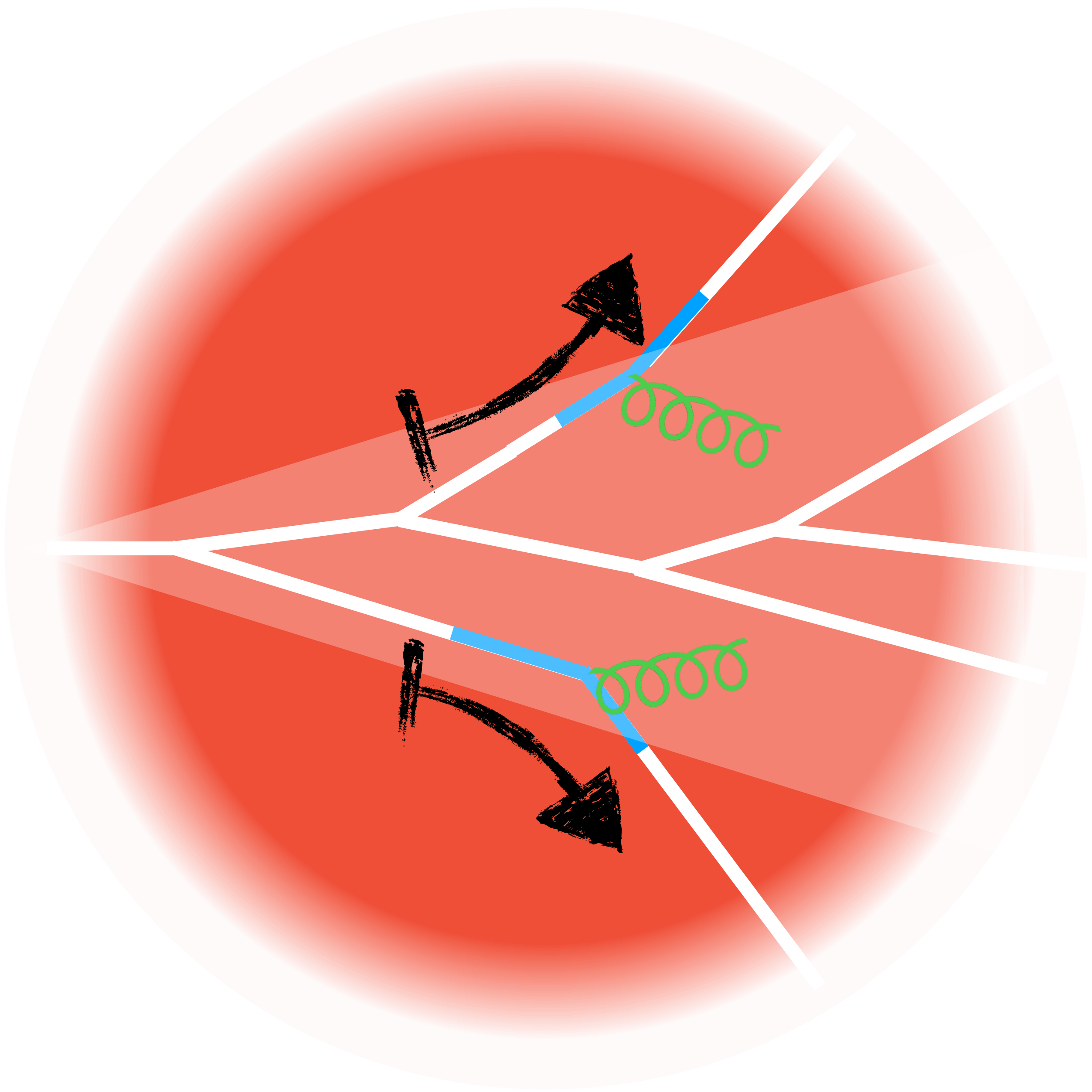

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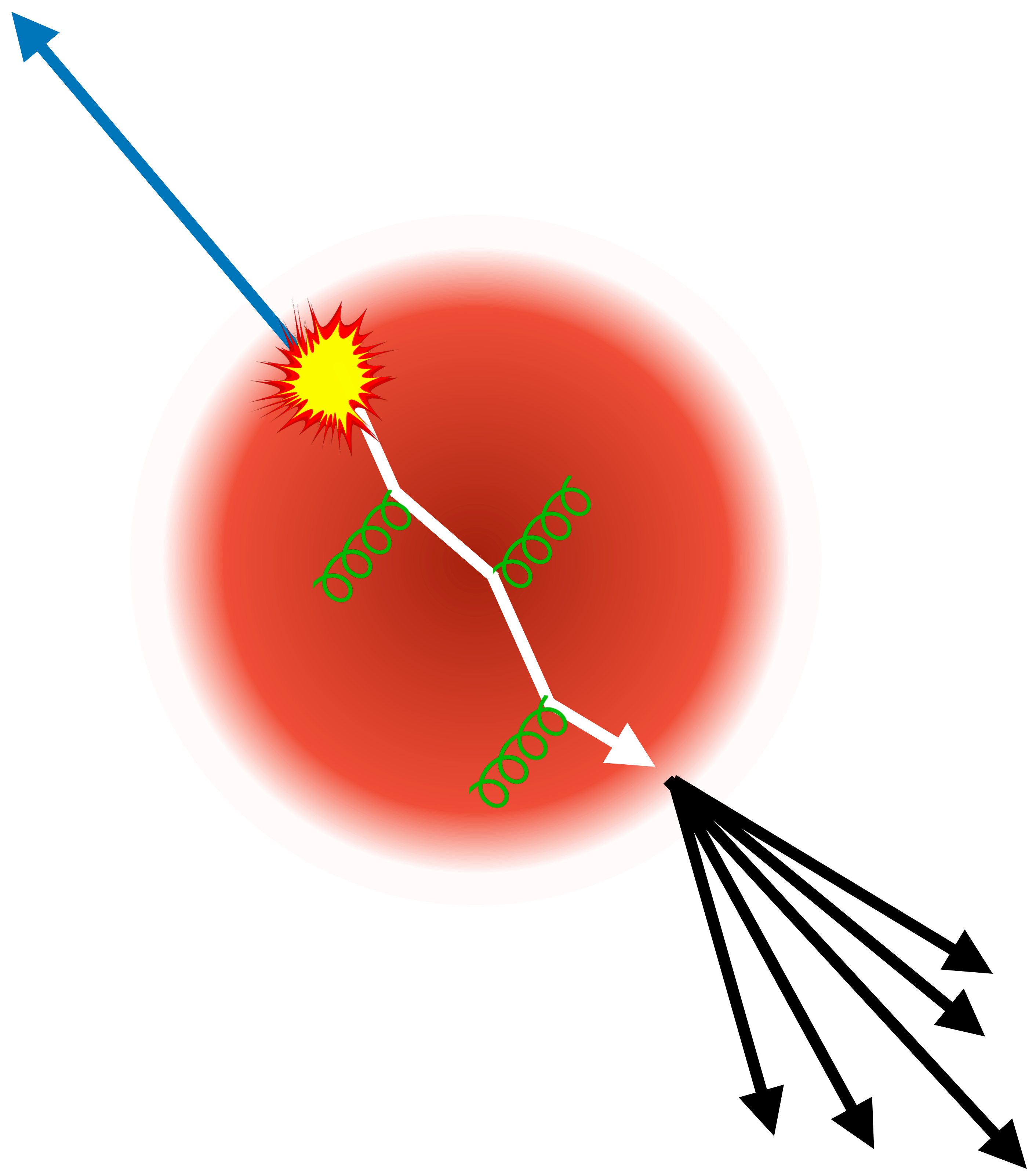
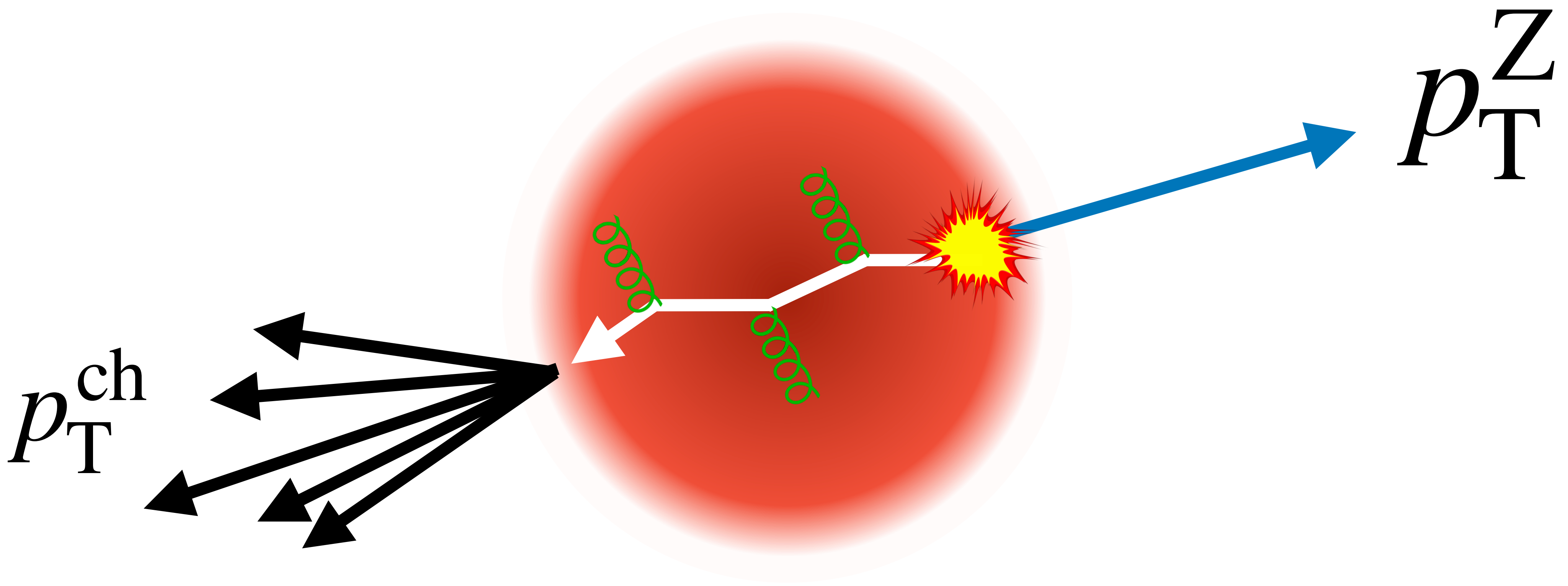


Charged particles recoiling against a Z

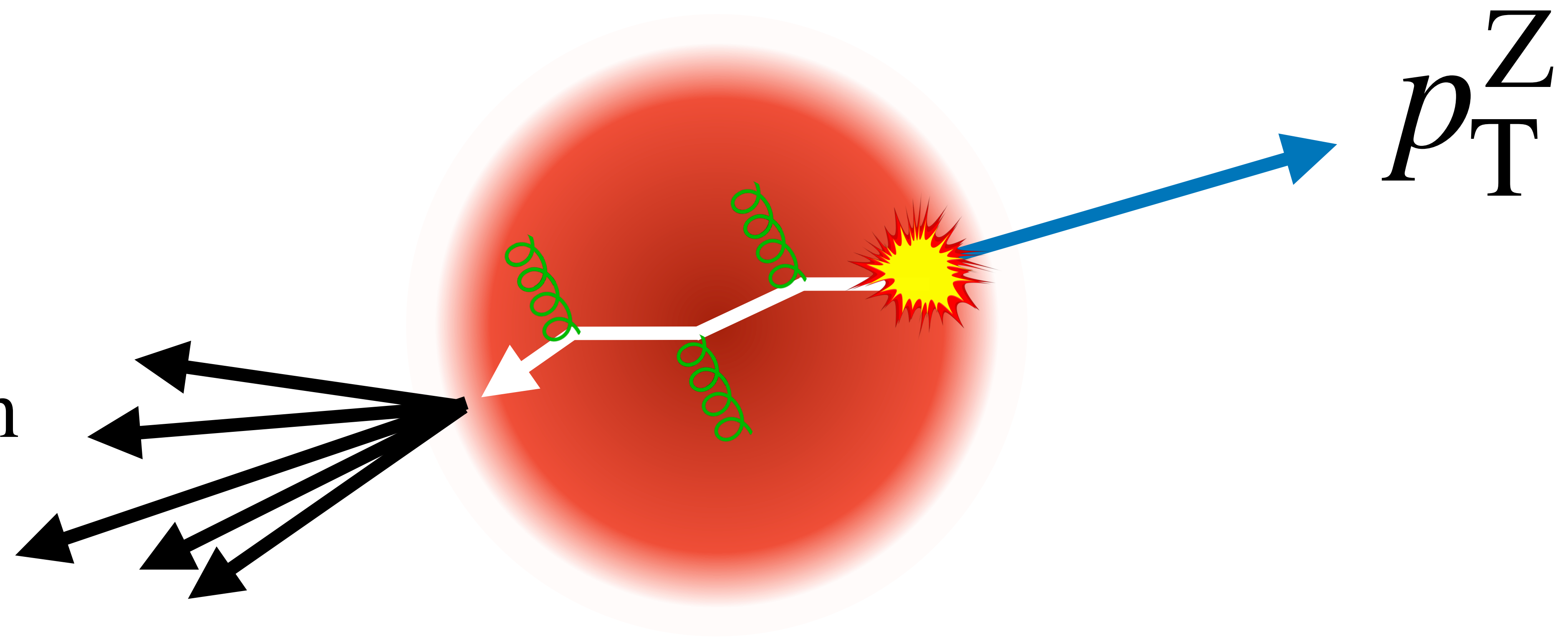
$$Y \equiv \frac{1}{N_{\mathrm{Z}}} \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{ch}}\, \mathrm{d}\Delta\phi} \qquad I_{\mathrm{AA}} = \frac{Y_{\mathrm{Pb-Pb}}}{Y_{\mathrm{pp}}}$$



Christopher McGinn's QM22 presentation

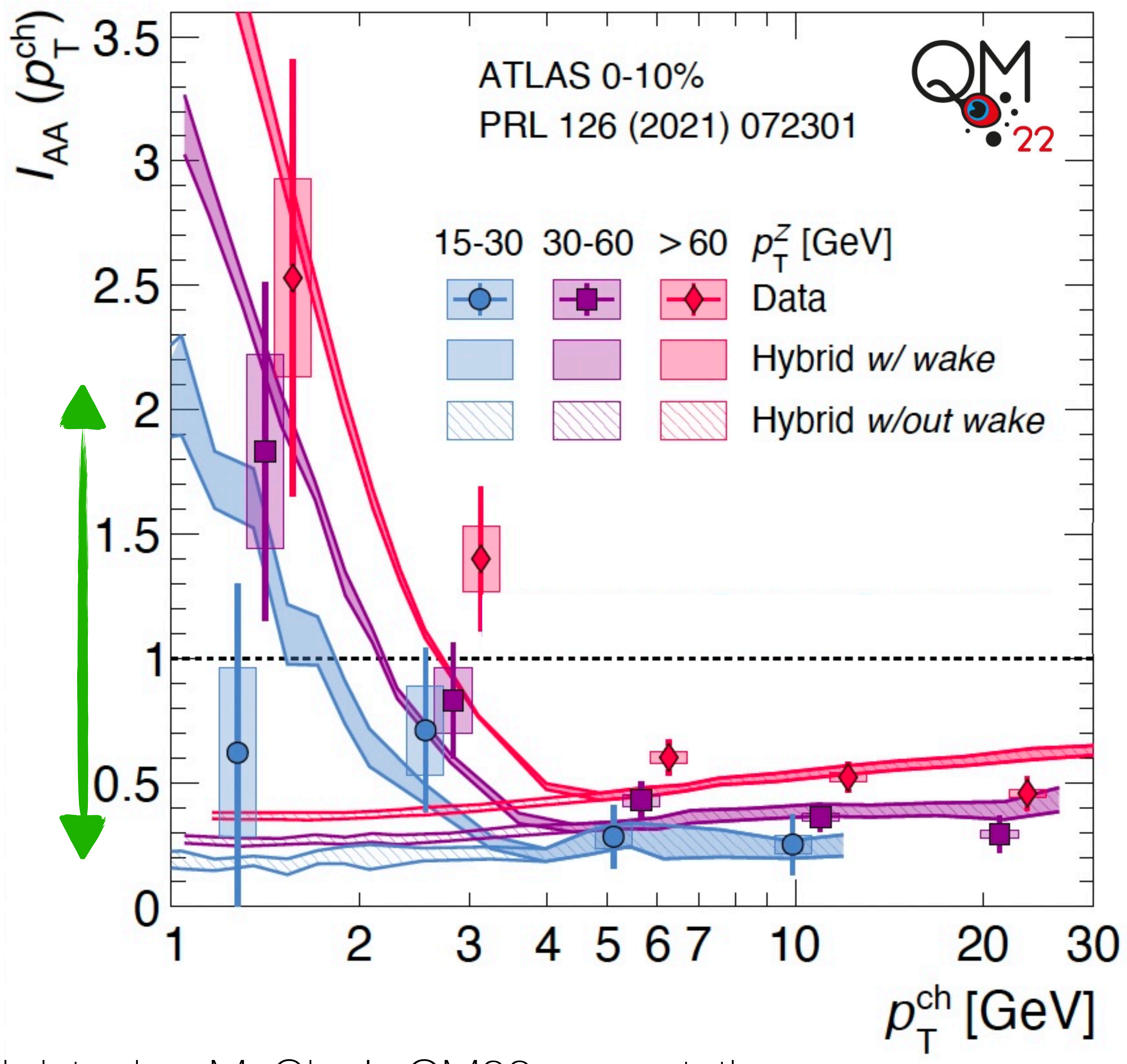
Charged particles recoiling against a Z

$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi} \qquad I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$



- Hybrid model with wake qualitatively describes rising trend at low p_T^{ch}

- Hybrid model without the wake does not describe the low-p_T^{ch} excess in data



Christopher McGinn's QM22 presentation

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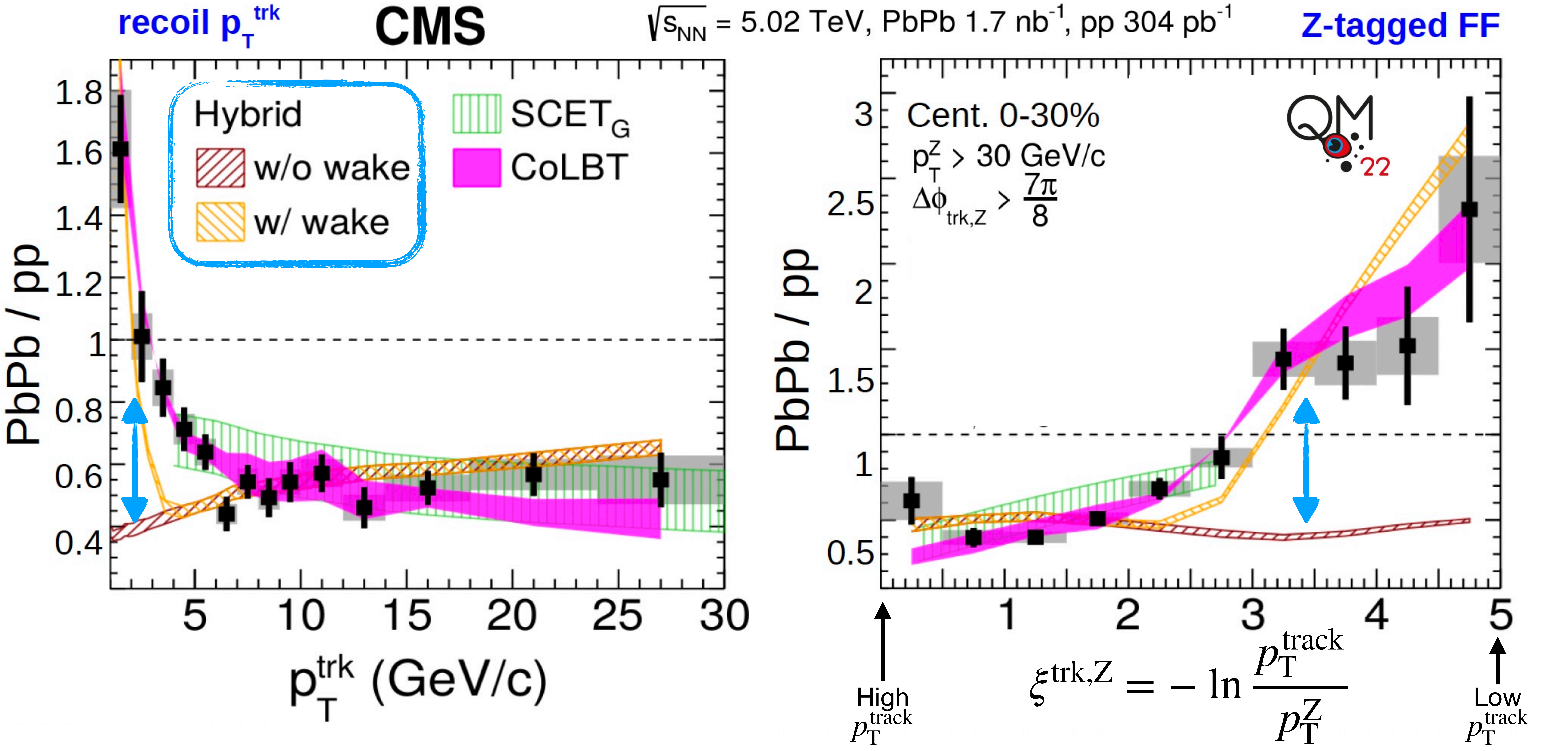
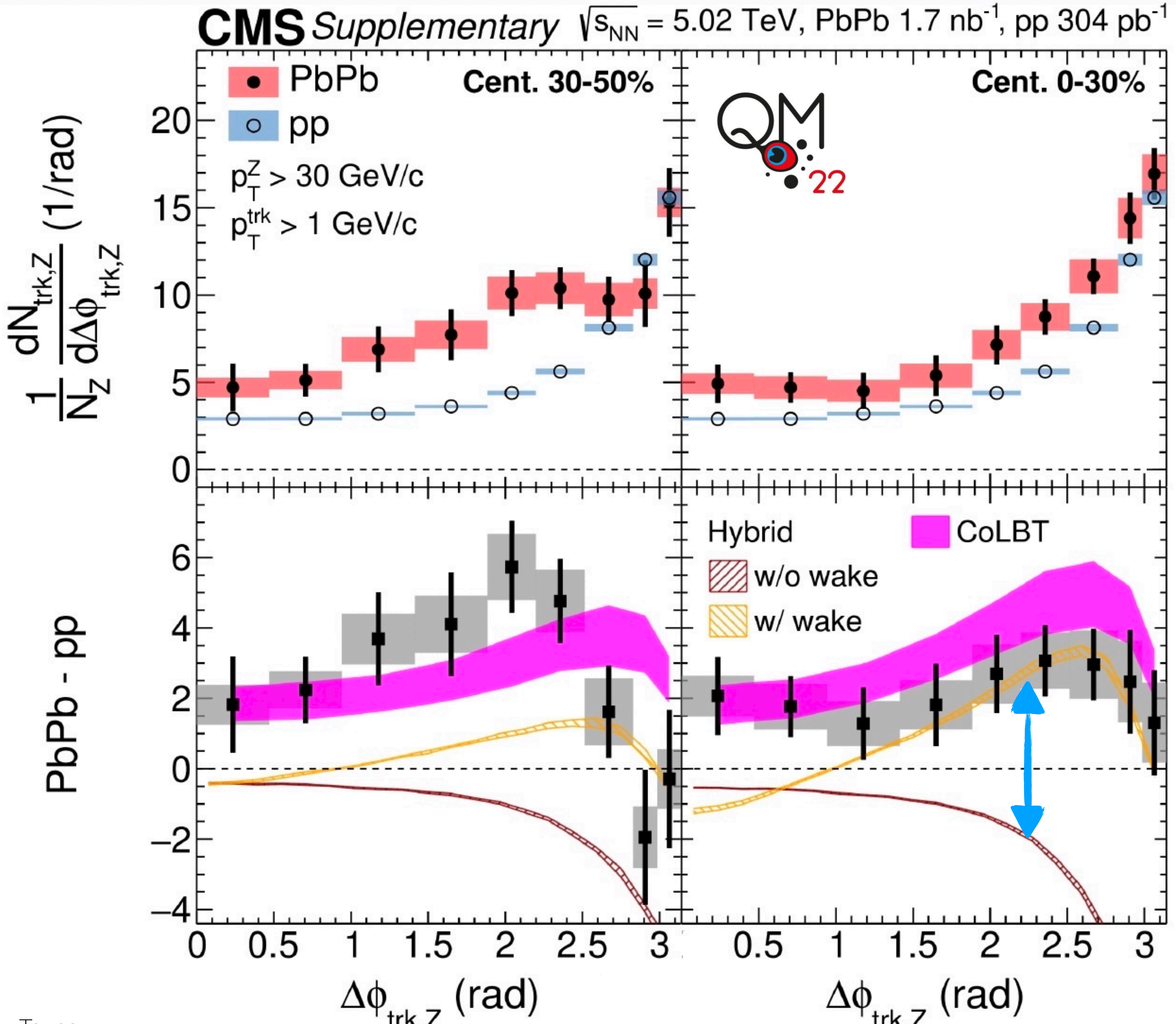
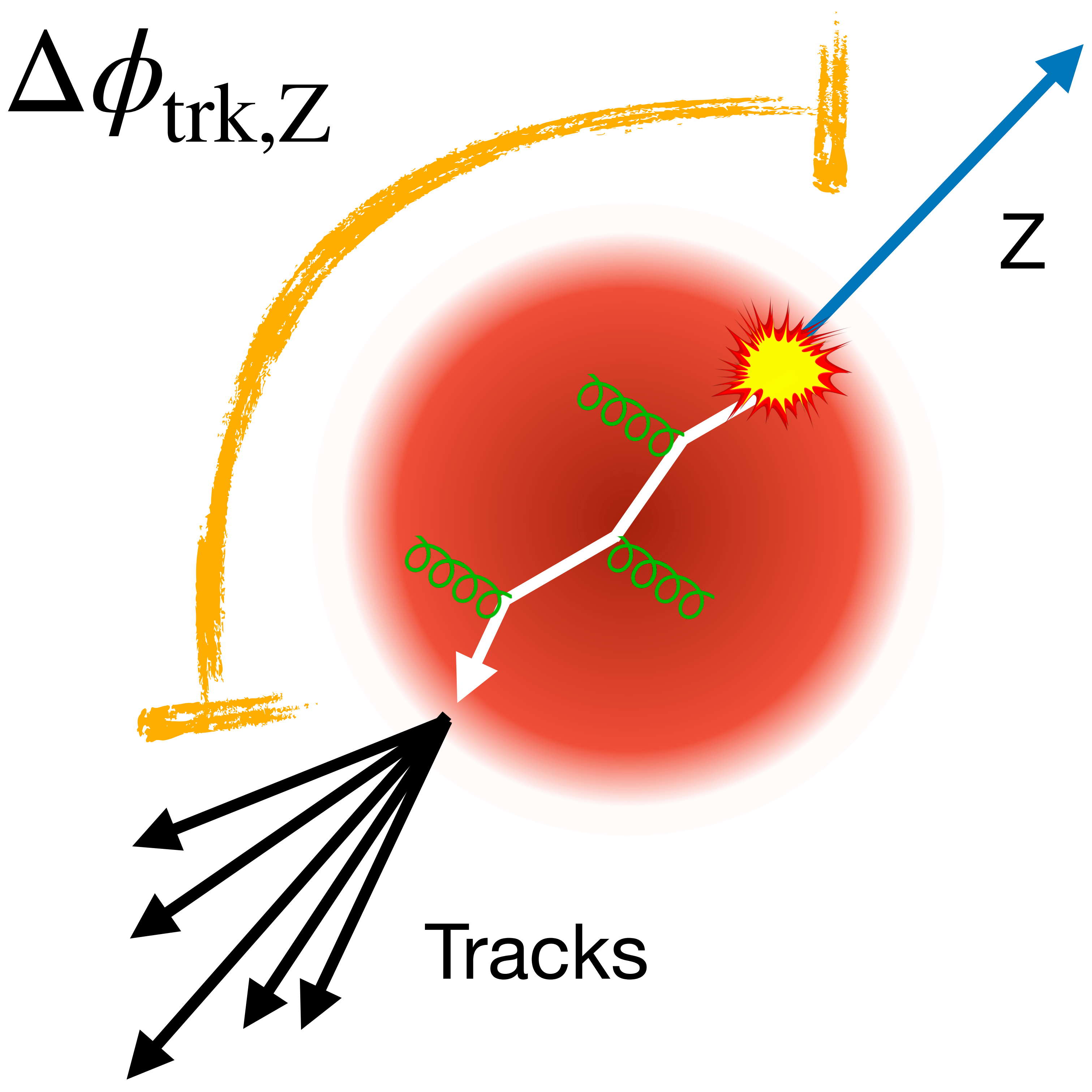


Kaya Tatar's QM22 presentation

Charged particles recoiling against a Z



Qualitative agreement between models with medium response and measured distribution



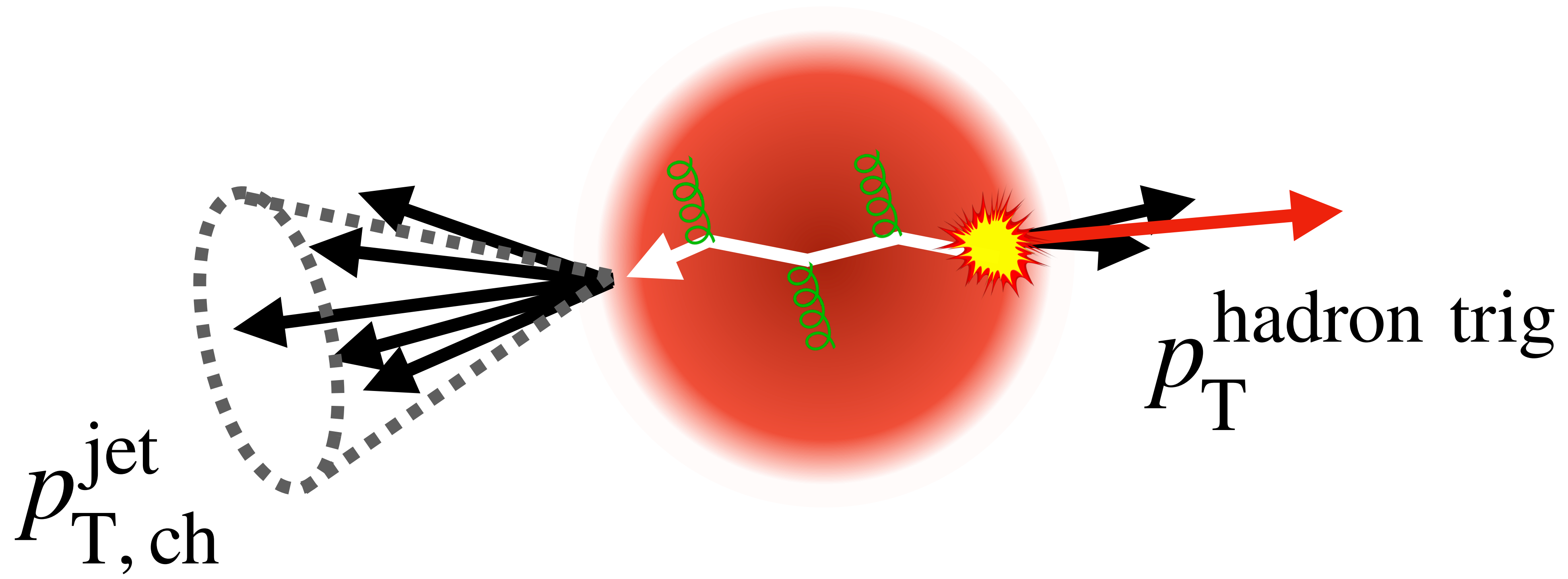
Kaya Tatar's QM22 presentation

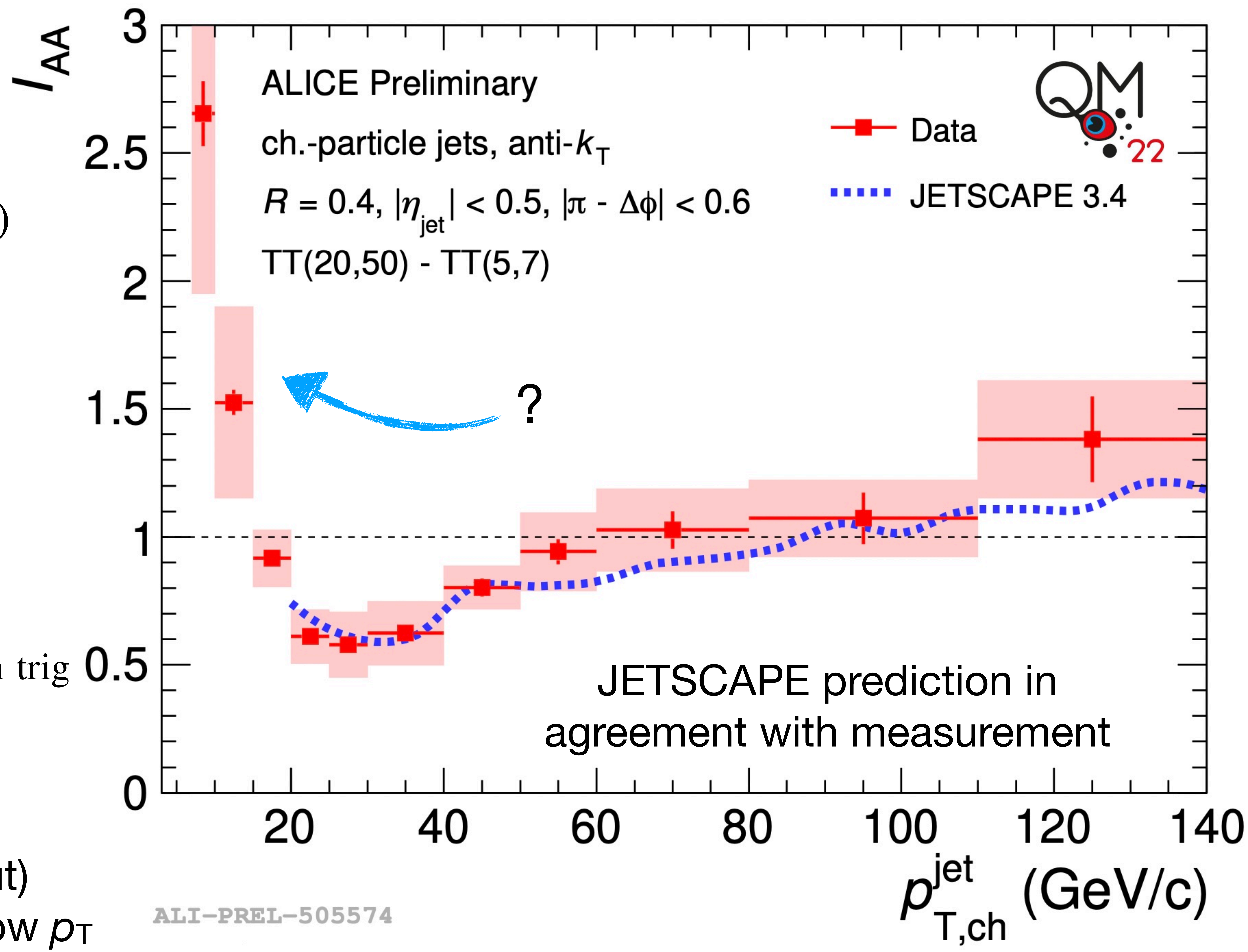
Semi-inclusive yield of jets recoiling from high-p_T hadron

$$n \equiv \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,ch}}^{\mathrm{jet}} \mathrm{d}\eta_{\mathrm{jet}}}$$

$$\Delta_{\mathrm{recoil}} = n(\mathrm{TT_{Sig}}) - c_{\mathrm{Ref}} \cdot n(\mathrm{TT_{Ref}})$$

$$I_{\mathrm{AA}} \equiv \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$



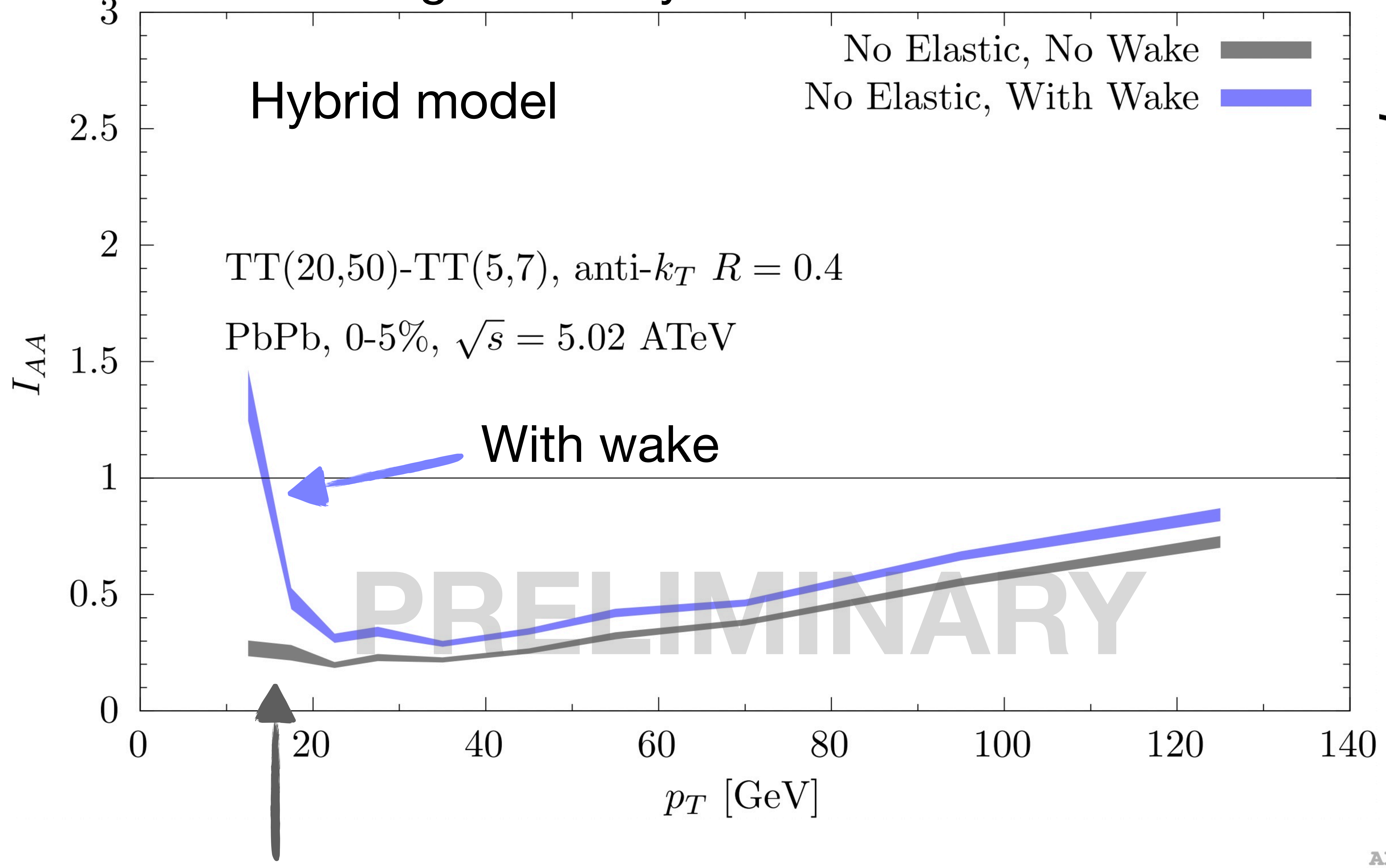


Need to compare models with(out) medium-response effects down to low p_T

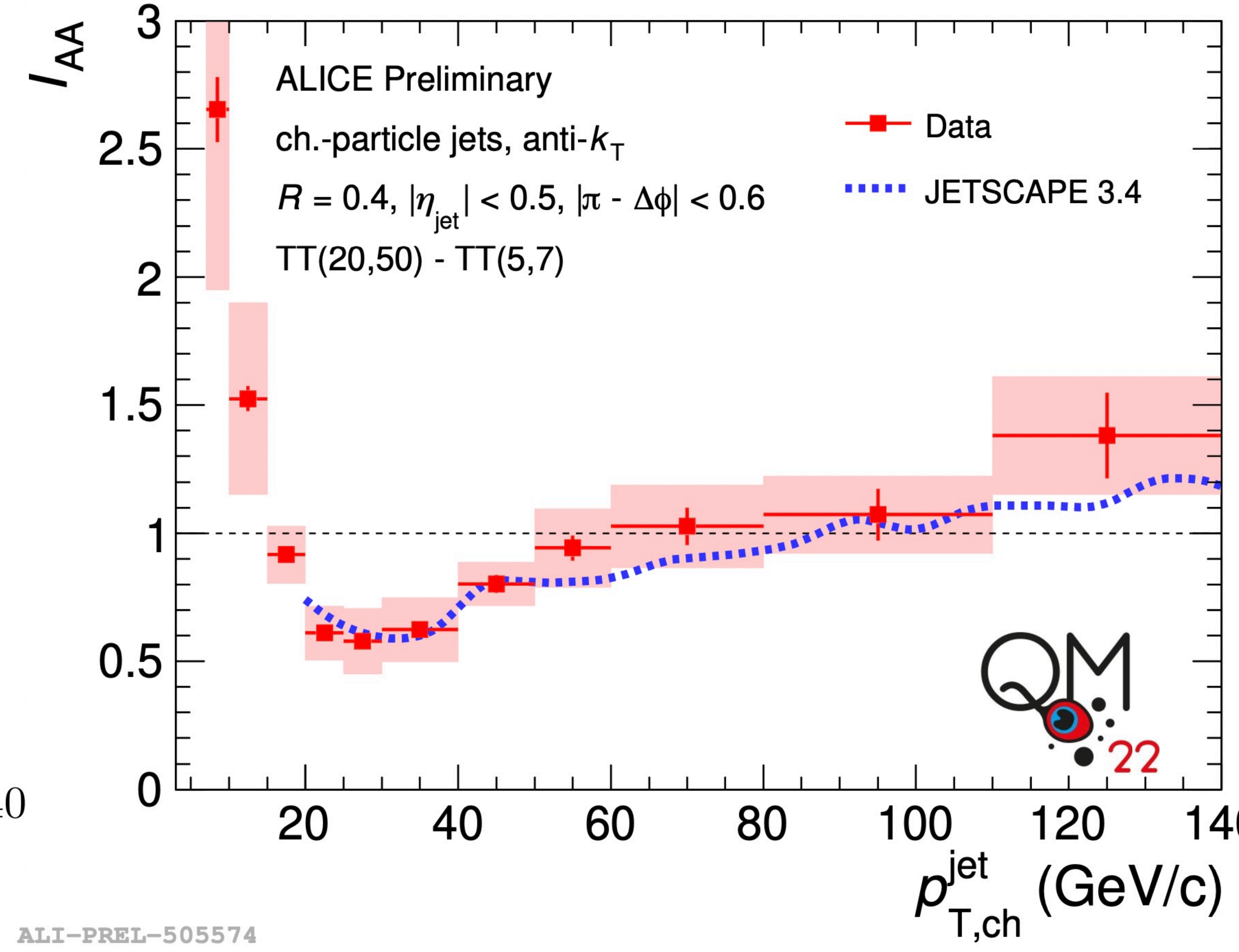
See talk by P Jacobs

Semi-inclusive yield of jets recoiling from high-p_T hadron

Fig. Courtesy of D Pablos Alfonso



Without wake



What should we do with this?

(my take as an experimentalist)

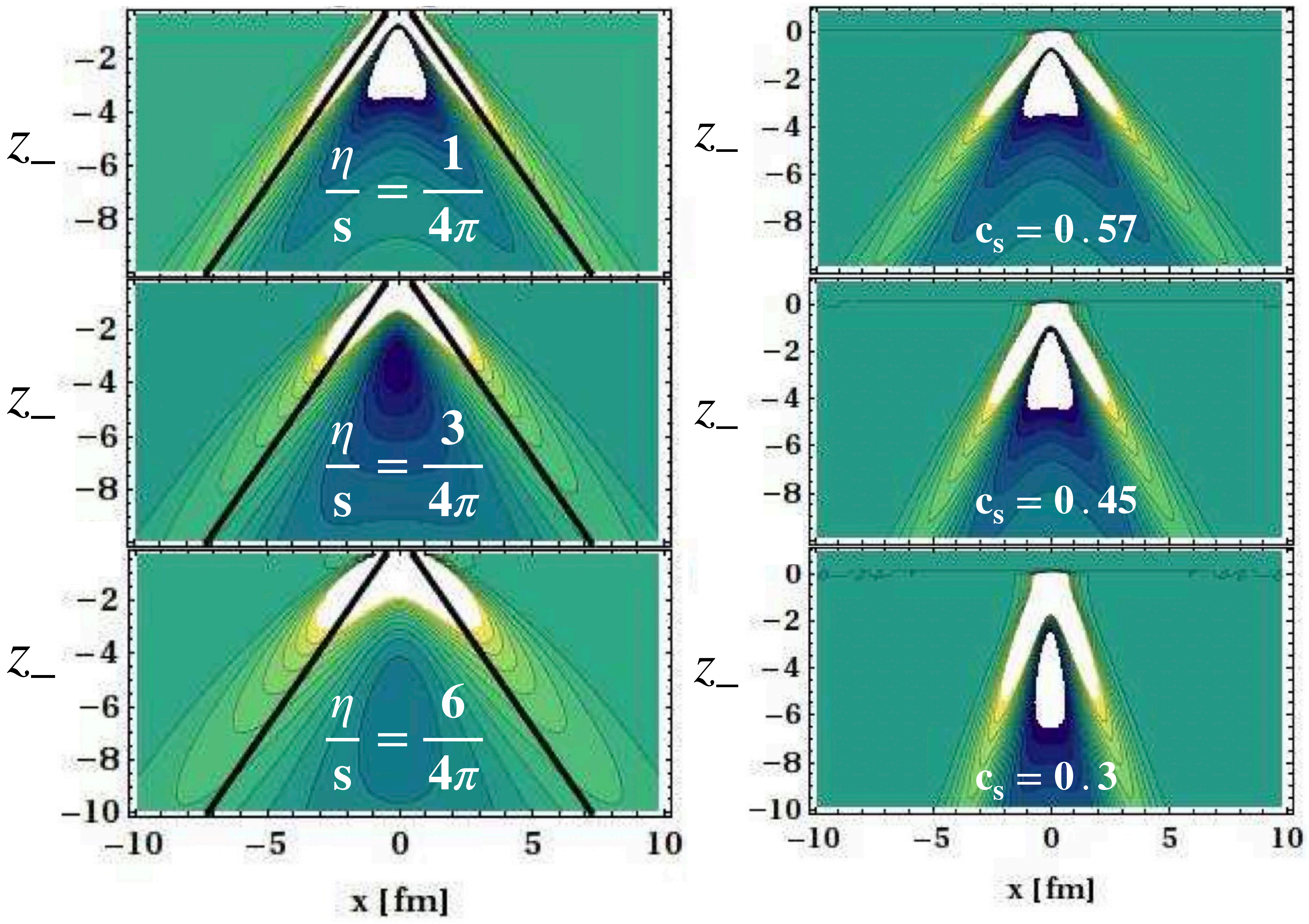
- Identification of new medium-response-sensitive observables

- Systematic study of medium-response models

- Bayesian inference to constrain parameterized medium response model

Summary

- Detailed description of jet-induced QGP medium response:
  - necessary for full characterization of QGP
  - can be sensitive to bulk properties of and thermalization mechanism in the QGP



Summary

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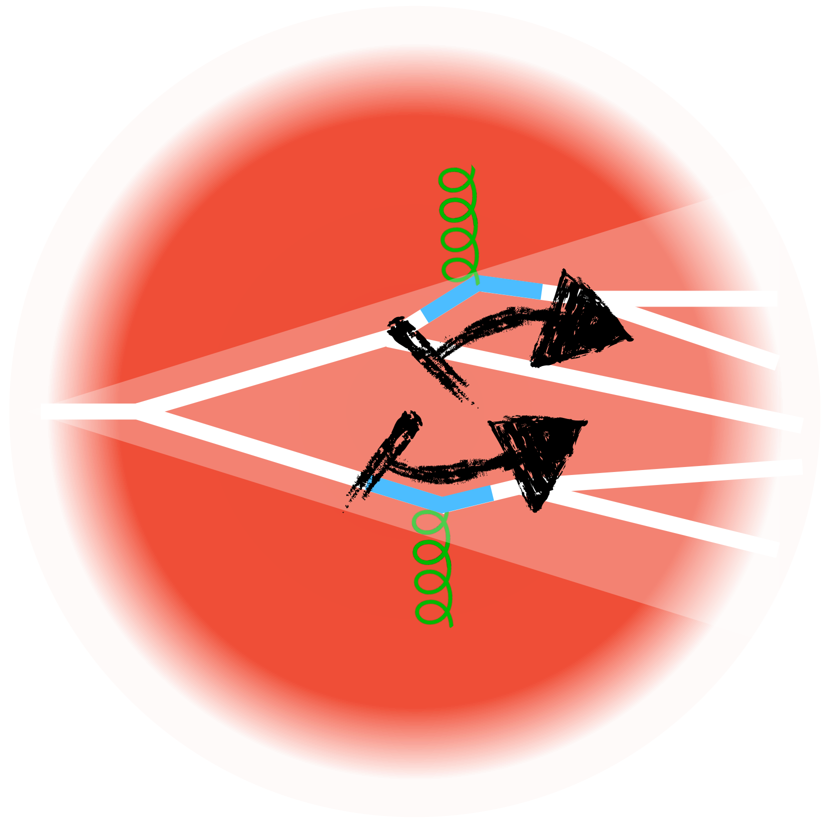
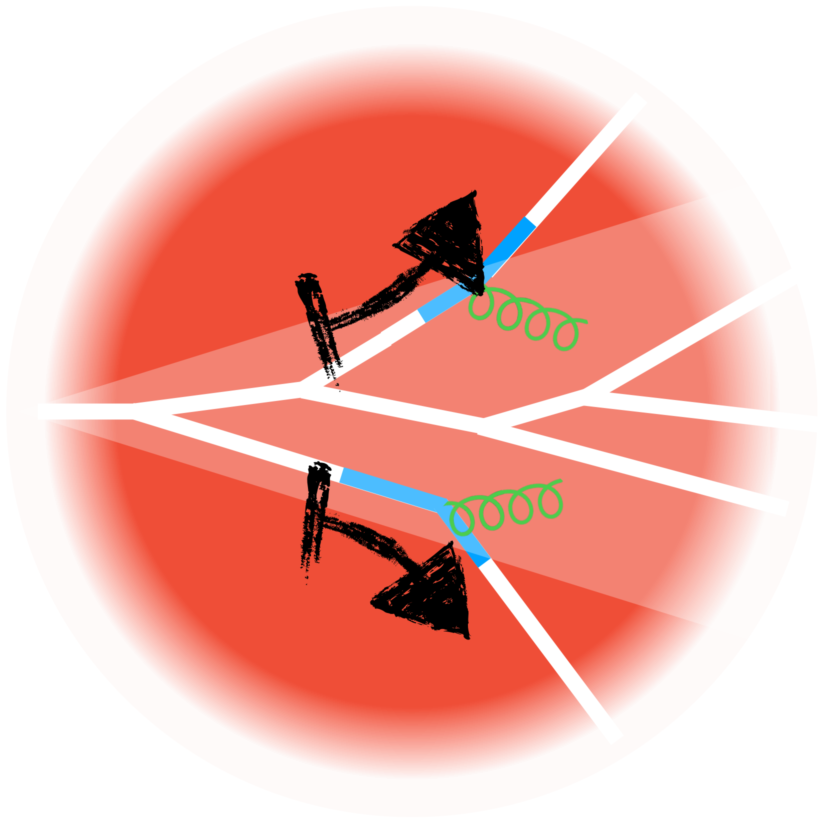
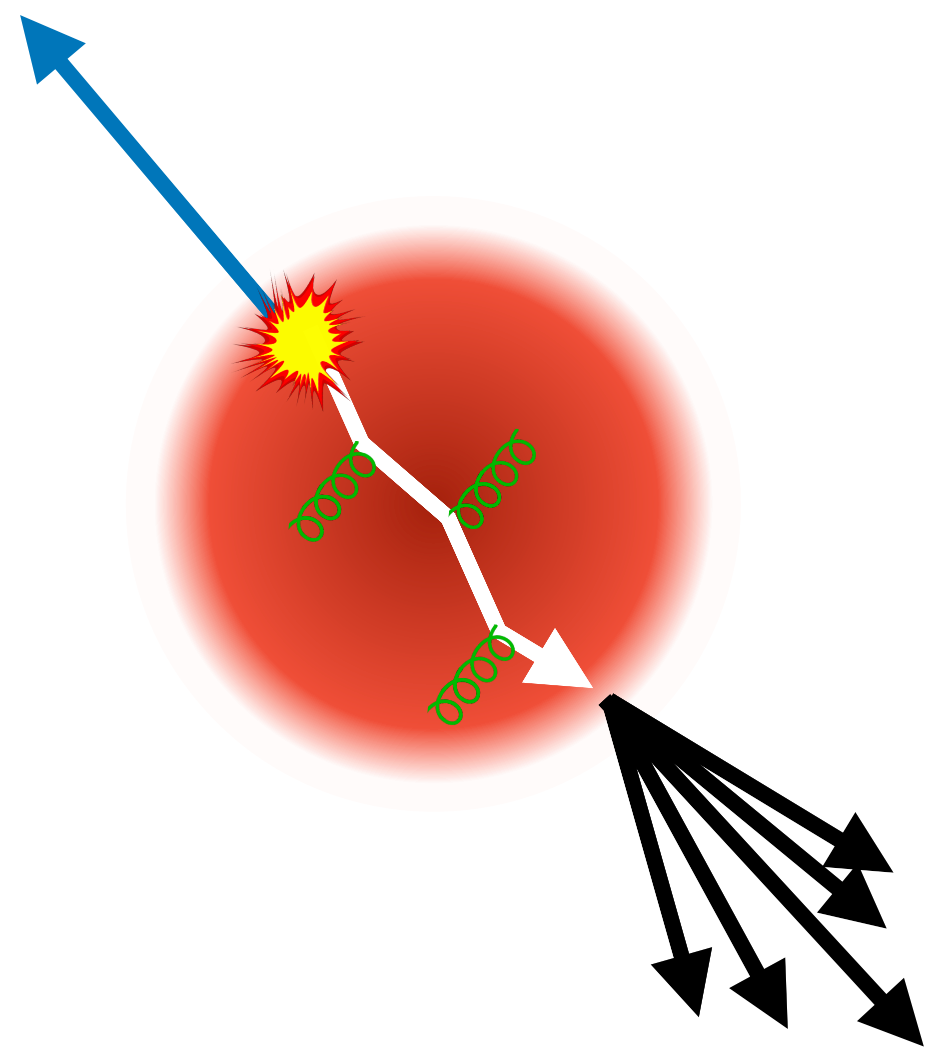


Substructure modification



Jet energy “loss” (redistribution)



Hadrons recoiling from high-p_T trigger

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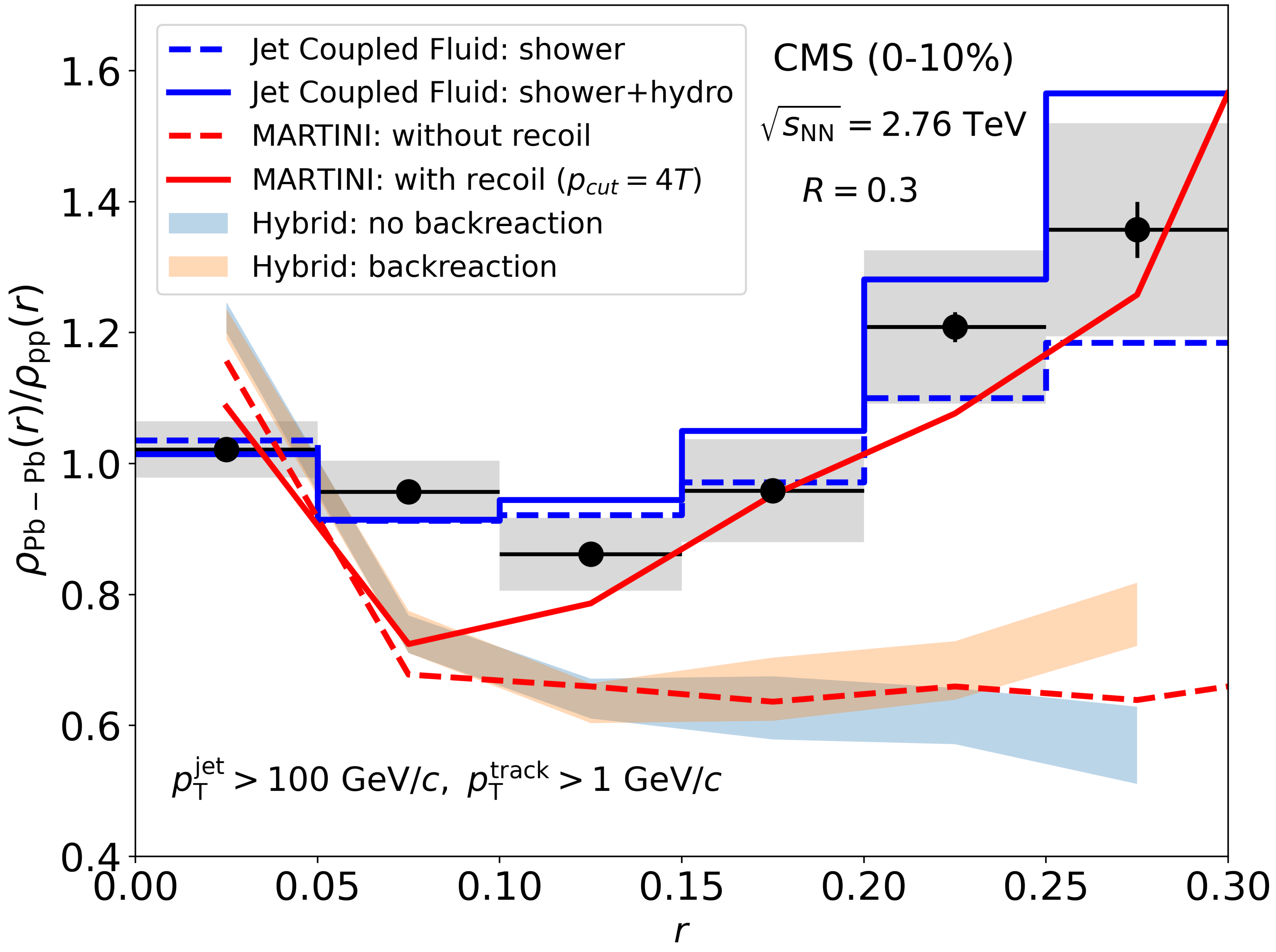

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- Caution: other effects can have similar signature to medium response (e.g. wide-angle radiation)

Thank you