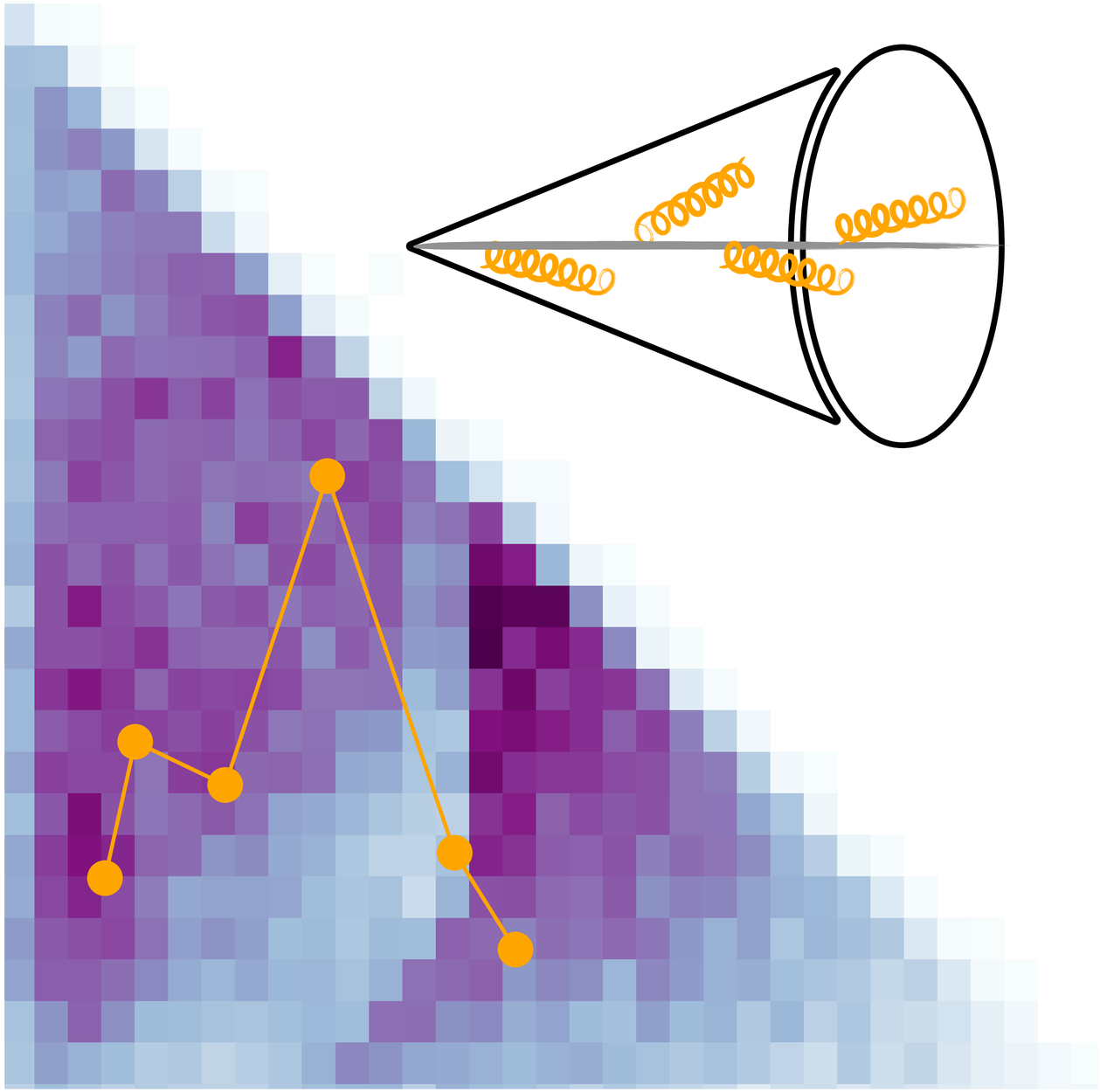
The power and limits of jet substructure in heavy-ion collisions

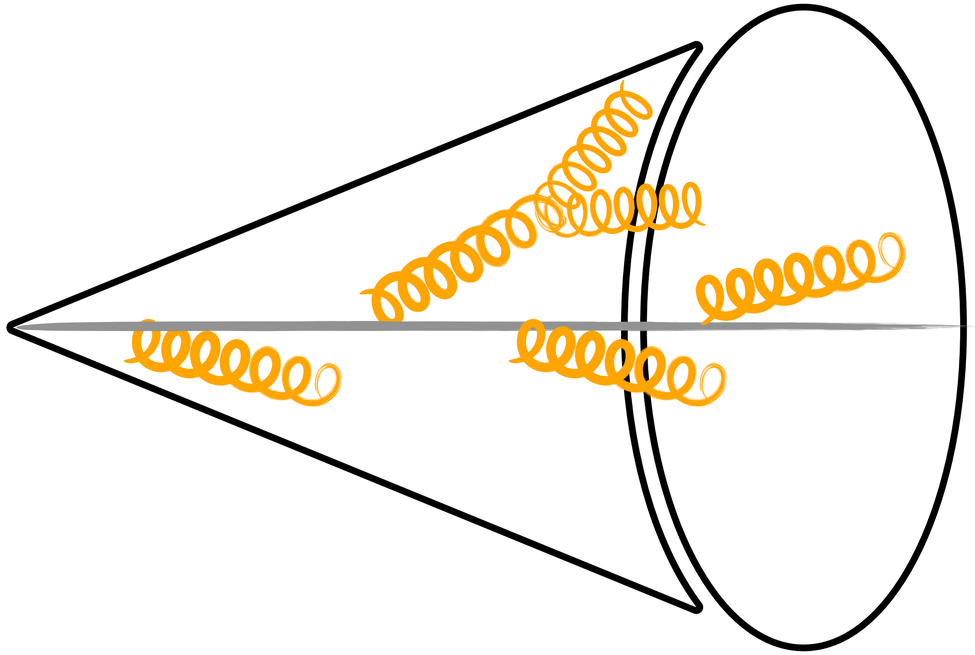


Alba Soto-Ontoso

11th Hard Probes

Aschaffenburg, 27th March, 2023

Jet substructure: going beyond the jet 4-momentum

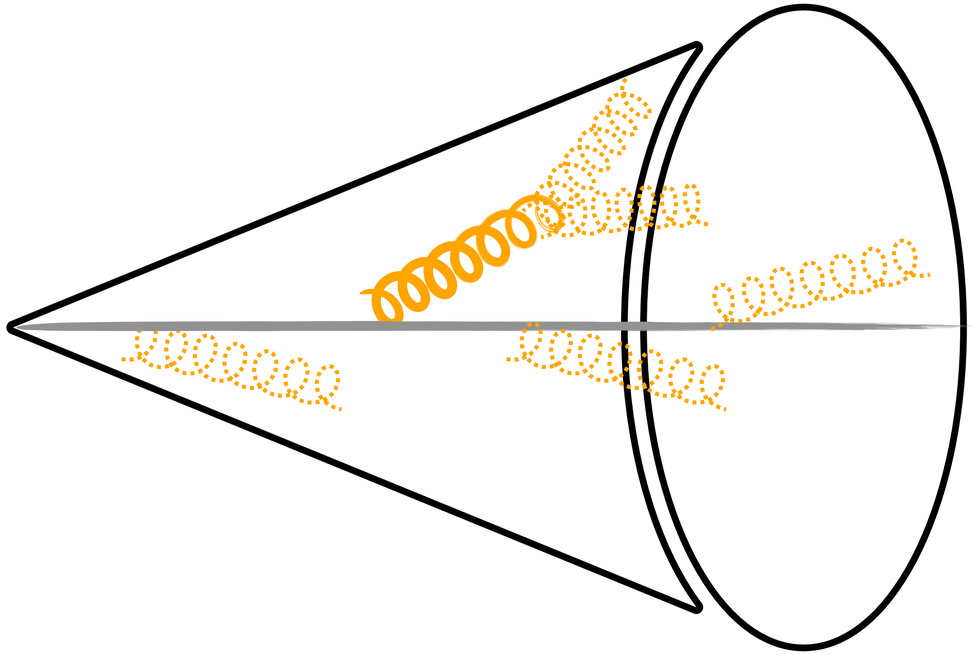


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_{i \in \mathrm{jet}} f(E_i, \theta_i)$$

energy angle

[Energy-energy correlators: Barata (Tue, 12:30h) , Dominguez (Wed, 15:40h), Holguin (Wed, 11:50h), Tamis (Wed, 11:30h)]

Groomed jet substructure: in this talk one splitting observables



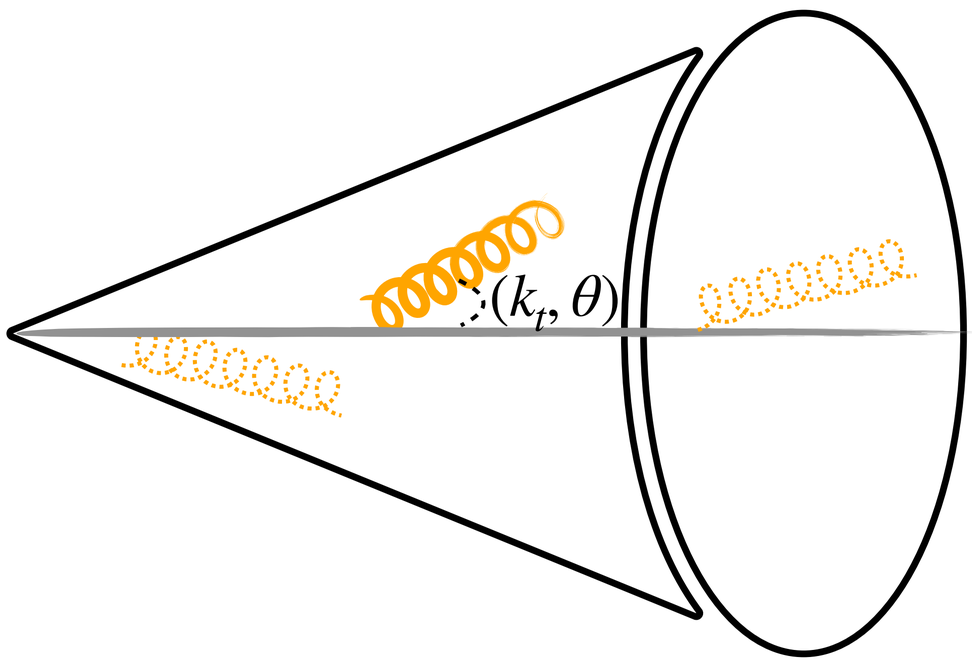
phase-space cut

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = f(E_i, \theta_i)\Theta(\Omega_i - \Omega)$$

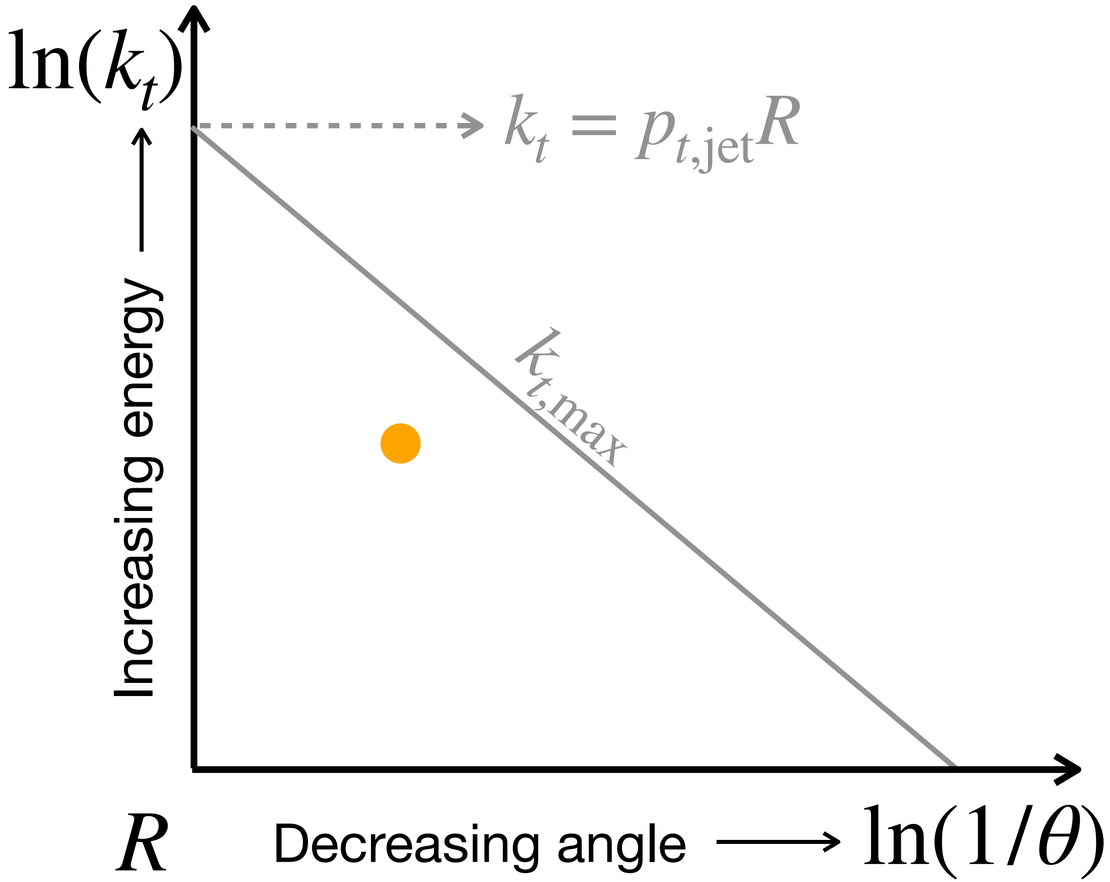
= groomed gluon

[Groomed substructure: Cunqueiro (Wed, 11:30h), Ehlers (Tue, 11:10h), Kunnawalkam Elayavalli (Tue 14:40 h), Pablos (Wed, 11:10h), Robotková (Thu, 09:00h), Rybar (Tue, 11:50h), Tachibana (Wed, 15:40h)]

Groomed jet substructure: 1-splitting observables (2D)



$k_t = z p_{t,\text{jet}} \theta$

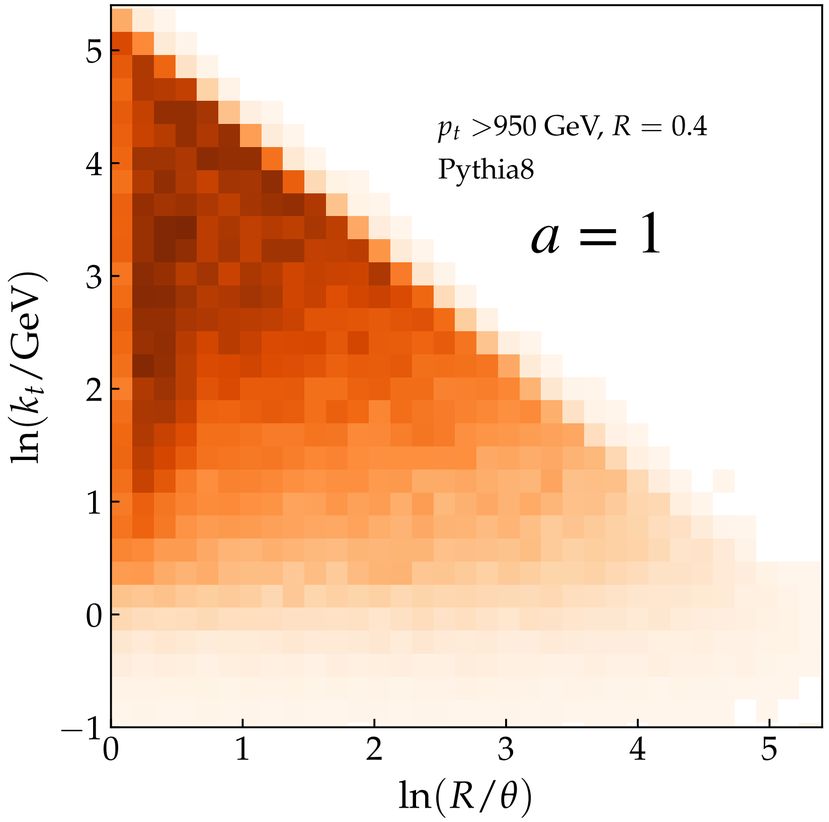


Groomed jet substructure: taggers in this talk

Dynamical grooming

[PRD 101 (2020) 3, 034004]

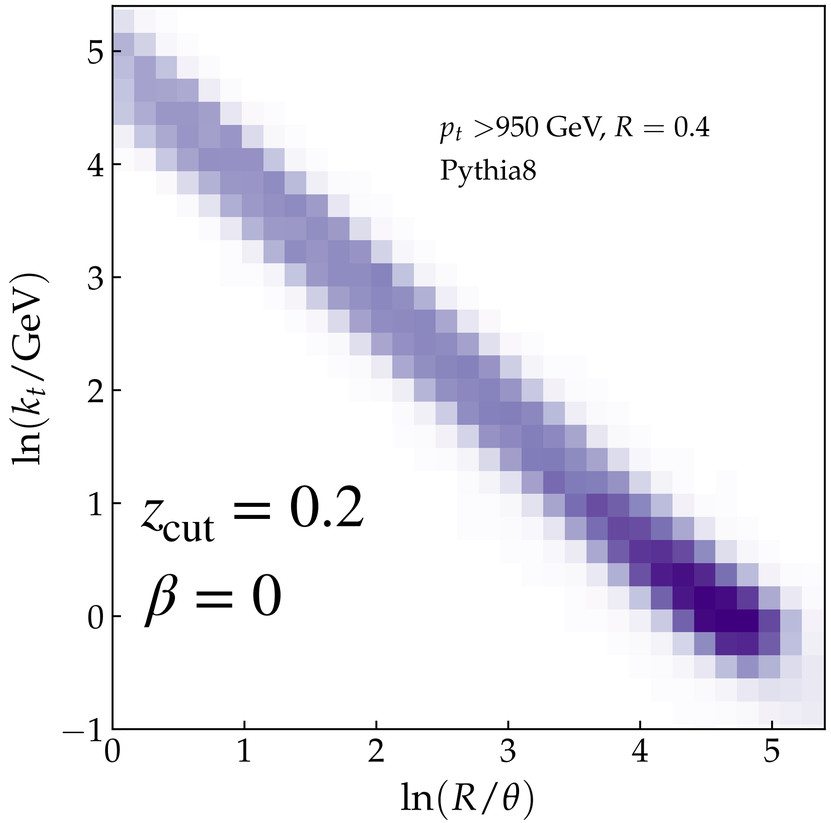
$$\max(z\theta^a)$$



SoftDrop

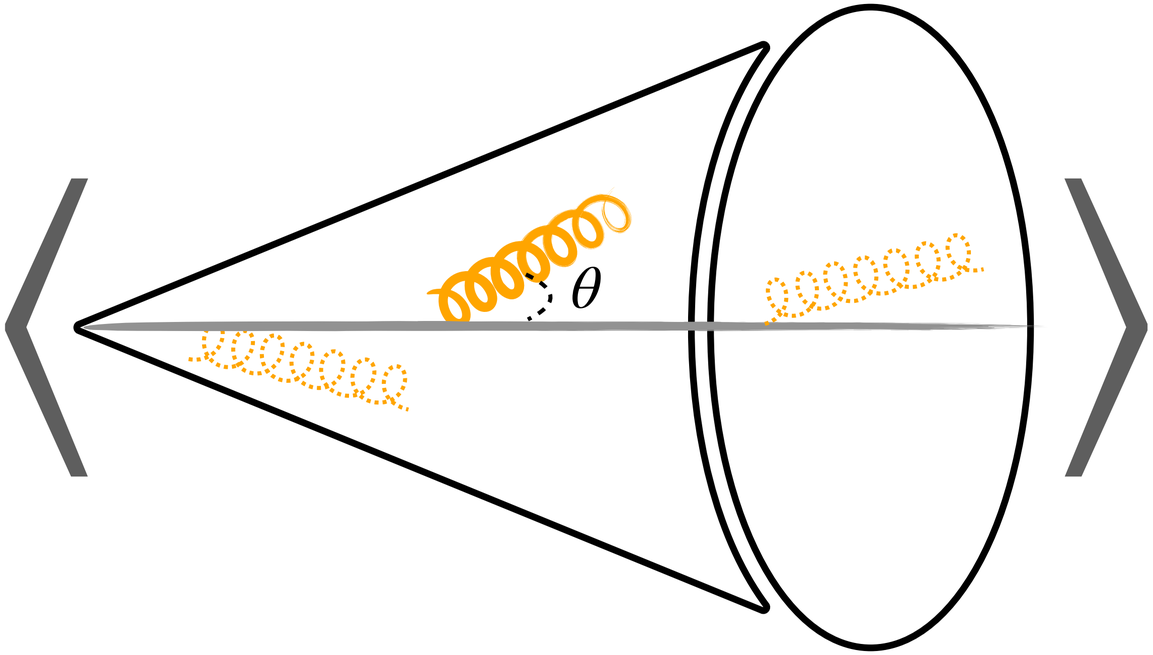
[JHEP 09 (2013) 029, JHEP 05 (2014) 146]

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

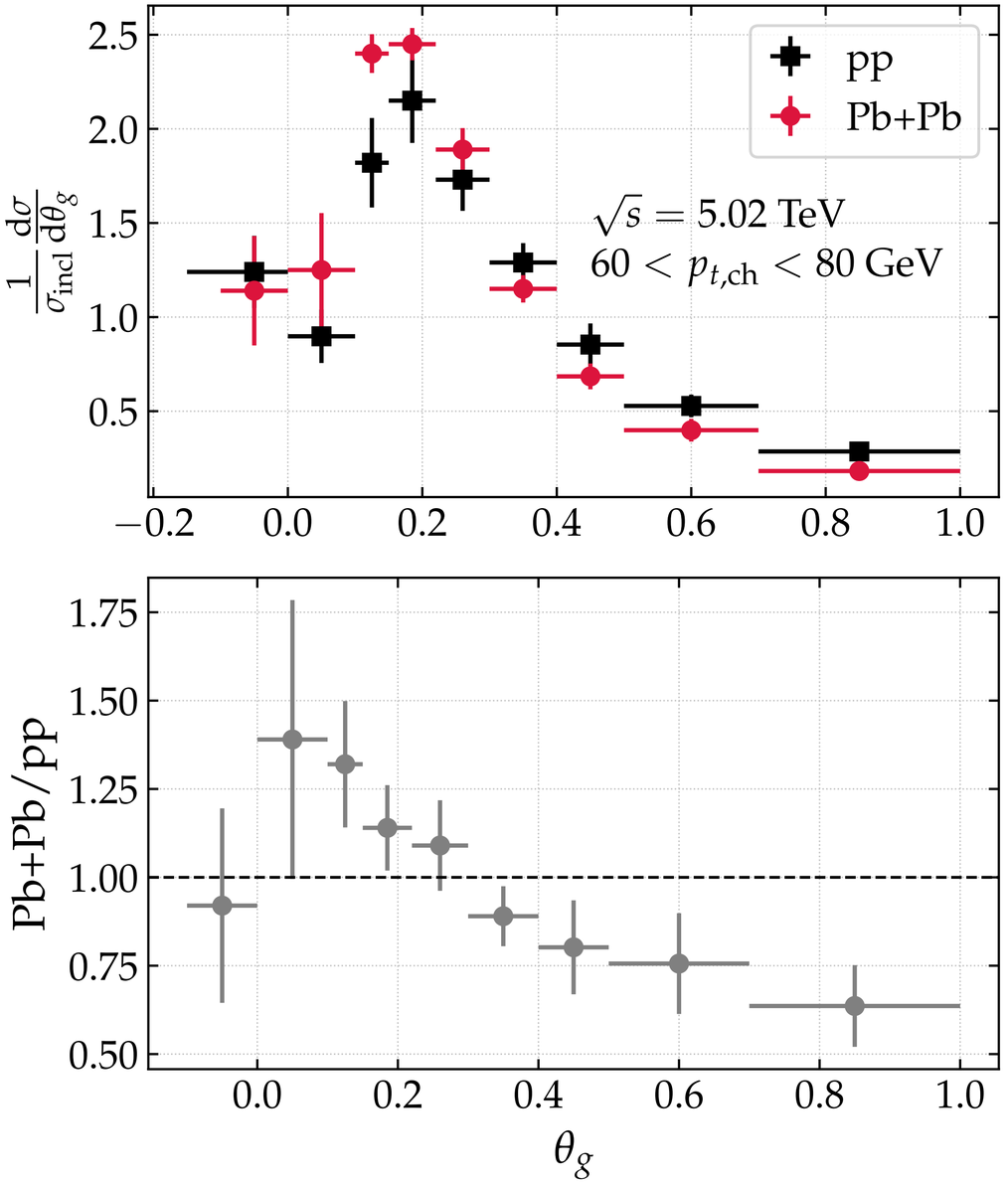


[Talks related to other taggers: Guerrero (Thu 09:20 h), Kunnawalkam Elayavalli (Tue 14:40 h)]

Groomed jet substructure: 1-splitting observables (1D)

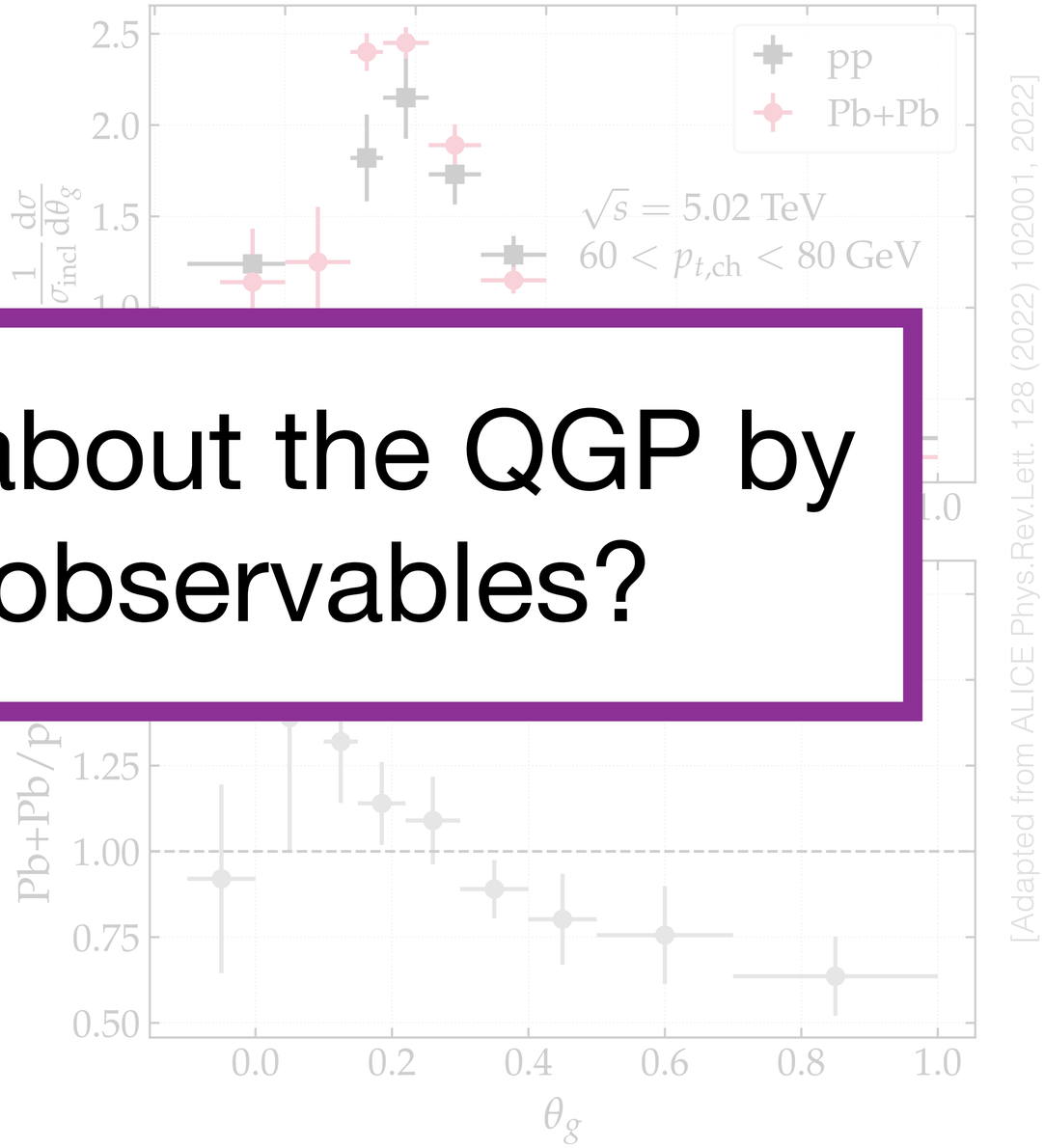


$\Theta(z > 0.2)$



[Adapted from PRL 128 (2022) 102001, 2022]

Groomed jet substructure: 1-splitting observables (1D)

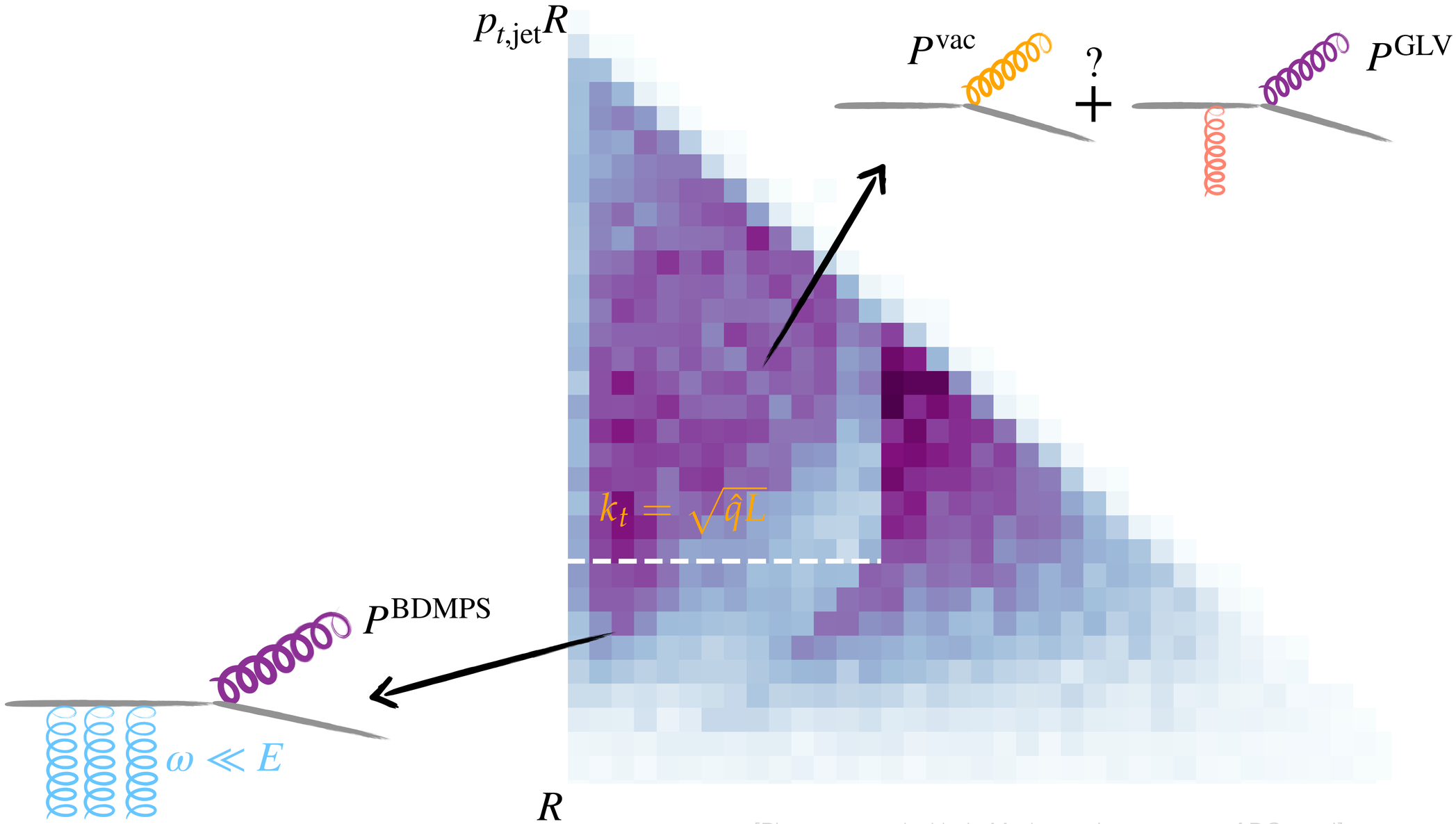


[Adapted from ALICE Phys.Rev.Lett. 128 (2022) 102001, 2022]

What can we learn about the QGP by studying 1-splitting observables?

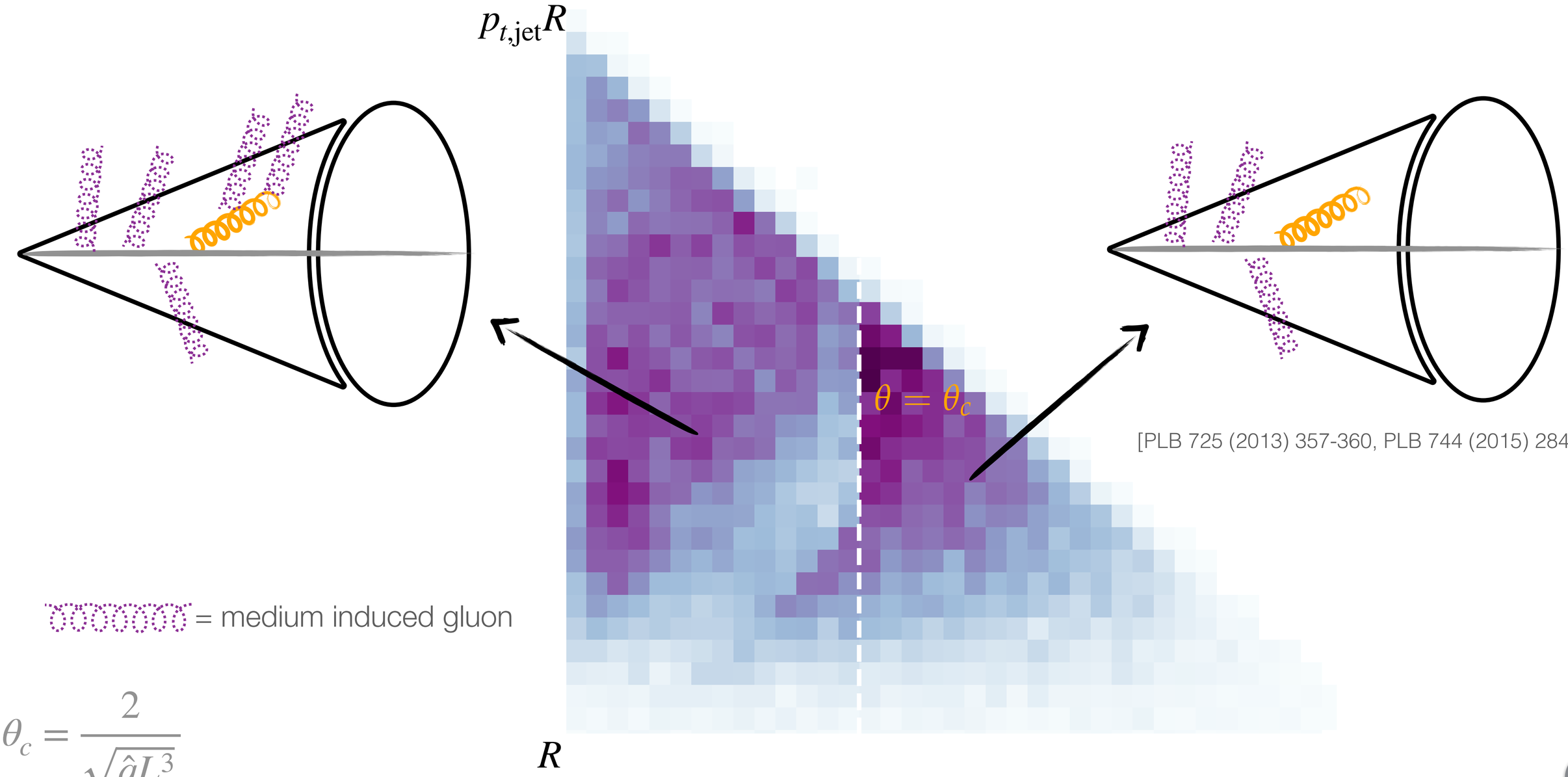
$\Theta(z > 0.2)$

Phase-space for in-medium jet evolution: branching kernel



[Plot generated with JetMed samples courtesy of P.Caucal]

Phase-space for in-medium jet evolution: energy loss



[PLB 725 (2013) 357-360, PLB 744 (2015) 284-287]

= medium induced gluon

$$\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

Status of analytic jet substructure calculations in heavy-ions

"SCET$_G$": $P^{\text{vac}} + \dfrac{\mathrm{dI}^{\text{med}}}{\mathrm{d}\omega \mathrm{d}k_t} \overset{\omega \ll 1}{\rightarrow} P^{\text{vac}} + \dfrac{\mathrm{dI}^{\text{GLV}}}{\mathrm{d}\omega \mathrm{d}k_t}$ (LO)

[PLB 706 (2012) 371-378, PRL 119 (2017) 11, 112301]

"q/g model": $P^{\text{vac}} \mathscr{B}^{\text{Gauss.}}(k_t)$ (DL)

[PLB 808 (2020) 135634]

$\Big\} \; \mathscr{E}(p_t, C_{F/A})$

"BDMPS-Z": $P^{\text{vac}} \Theta_{\text{veto}} + \dfrac{\mathrm{dI}}{\mathrm{d}\omega} \mathscr{B}^{\text{Gauss.}}(k_t)$, $\mathscr{E}(p_t, C_{F/A}, \theta)$ (DL)

[JHEP 04 (2017) 125, PRL 120 (2018) 232001,
PRD 105 (2022) 11, 114046]

LO=leading order, DL=double logarithm

Status of analytic jet substructure calculations in heavy-ions

"SCET$_G$": $P^{\text{vac}} + \frac{\mathrm{dI}^{\text{med}}}{\mathrm{d}\omega \mathrm{d}k_t} \overset{\omega \ll 1}{\rightarrow} P^{\text{vac}} + \frac{\mathrm{dI}^{\text{GLV}}}{\mathrm{d}\omega \mathrm{d}k_t}$ (LO) $\Big\} \mathscr{E}(p_t, C_{F/A})$

[PLB 706 (2012) 371-378, PRL 119 (2017) 11, 112301]

State-of-the-art is leading log accuracy

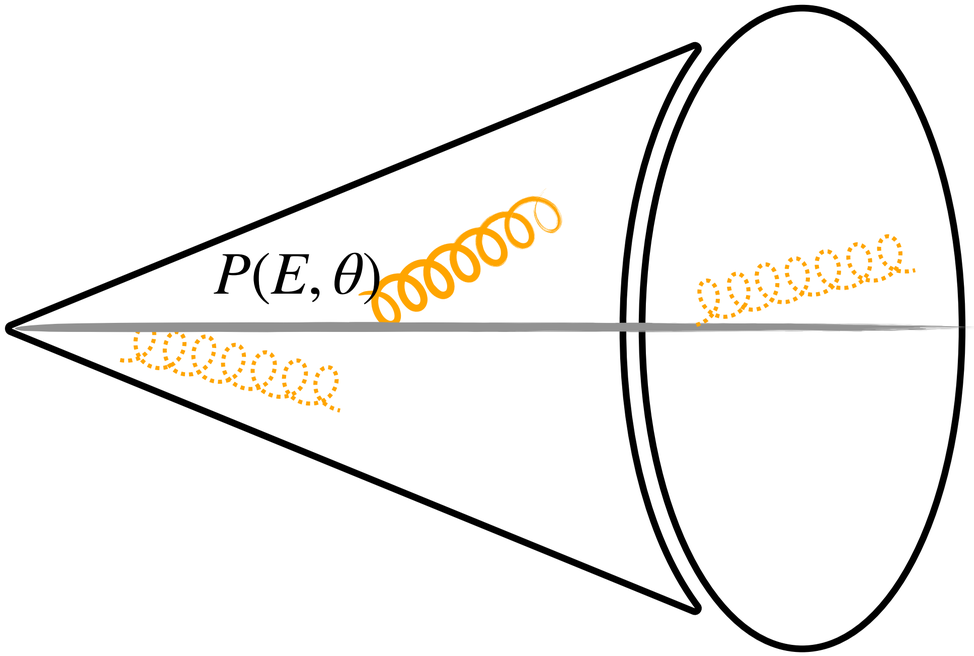
"BDMPS-Z": $P^{\text{vac}} \Theta_{\text{veto}} + \frac{\mathrm{dI}}{\mathrm{d}\omega} \mathscr{B}^{\text{Gauss.}}(k_t)$, $\mathscr{E}(p_t, C_{F/A}, \theta)$ (DL)

[JHEP 04 (2017) 125, PRL 120 (2018) 232001,
PRD 105 (2022) 11, 114046]

LO=leading order, DL=double logarithm

Theory developments relevant for jet substructure

Branching kernel



Better medium induced kernels

Andres (Mon, 16:40h)
[JHEP 07 (2020) 114, JHEP 03 (2021) 102]

Isaksen (Wed, 14:40h)
[JHEP 11 (2021) 125, 2303.12119]

Takacs (Thu, 09:00h)
[JHEP 02 (2023) 156]

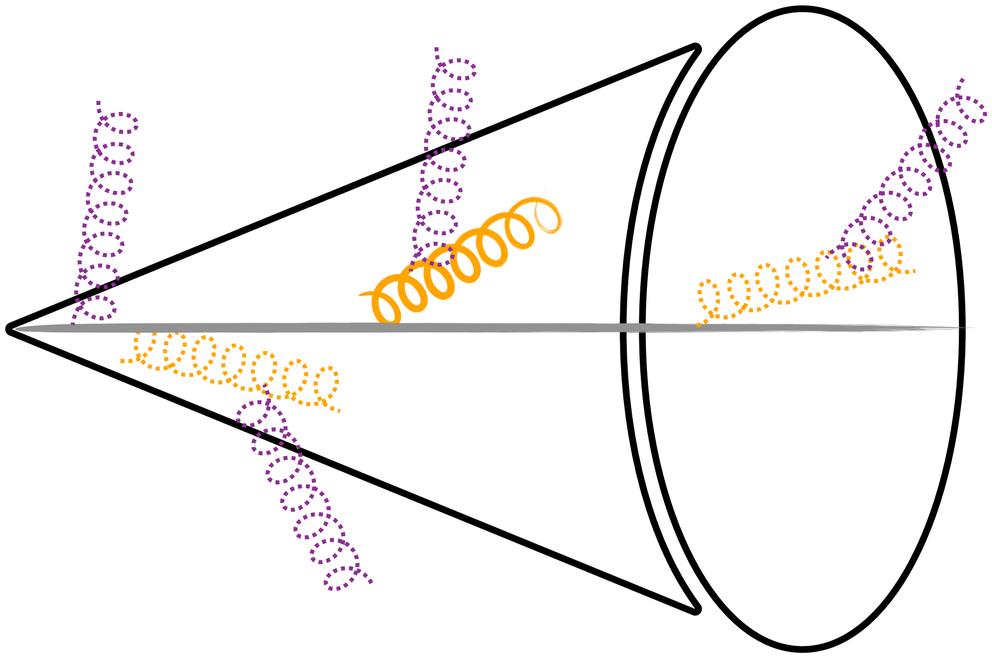
Phase-space beyond DL

$$P^{\text{vac}}\Theta_{\text{veto}} \overset{?}{+} \frac{\mathrm{d}I^{\text{med}}}{\mathrm{d}\omega \mathrm{d}k_t}$$

[JHEP 09 (2021) 153]

Theory developments relevant for jet substructure

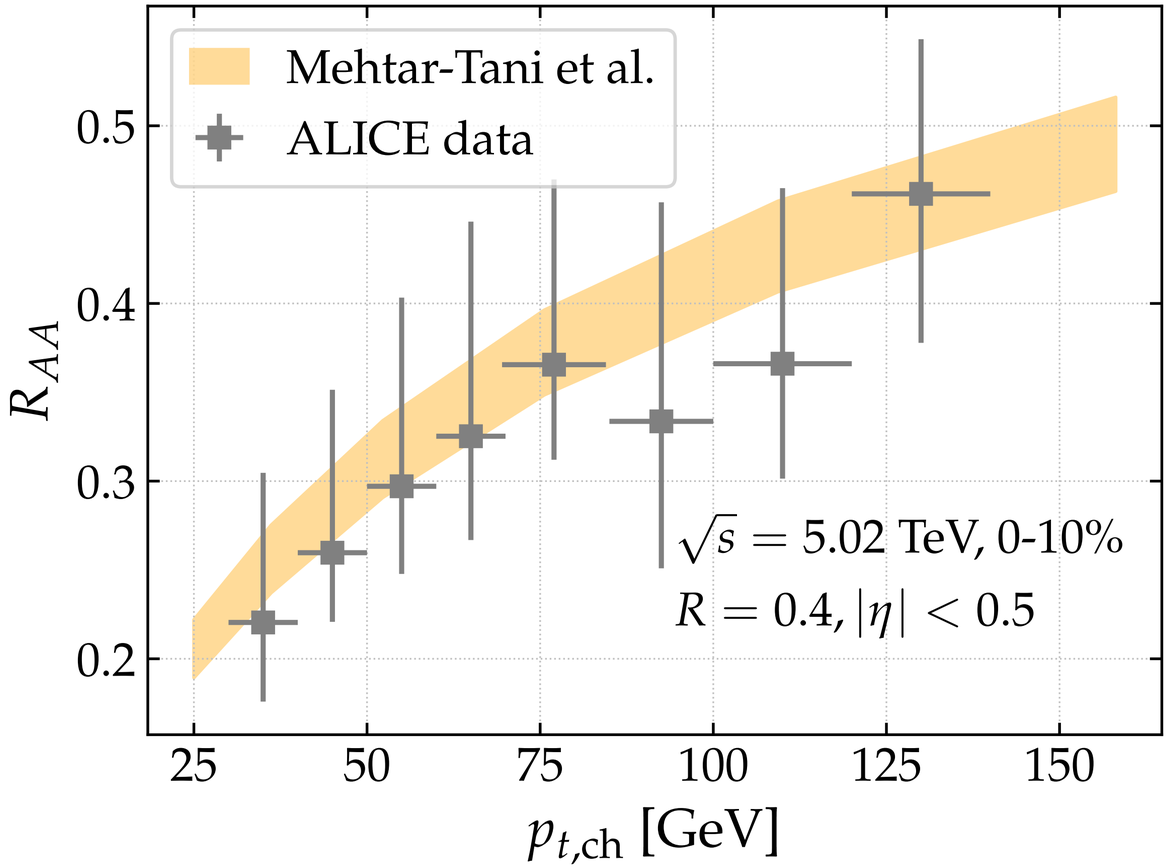
Energy loss



$$\mathscr{E}(p_t, C_{F/A}, \theta, n_{\mathrm{VLE}})$$

Tywoniuk (Wed, 12:30h)

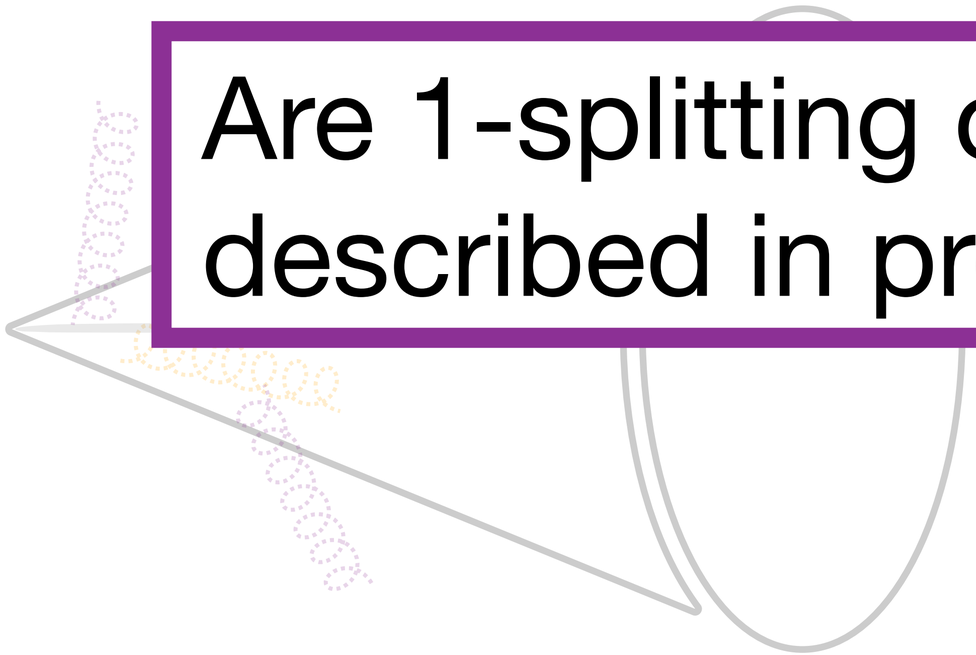
[PRL 127 (2021) 25, 252301, JHEP 10 (2021) 038]



[Adapted from arXiv: 2303.00592 thanks to H.Bossi]

Theory developments relevant for jet substructure

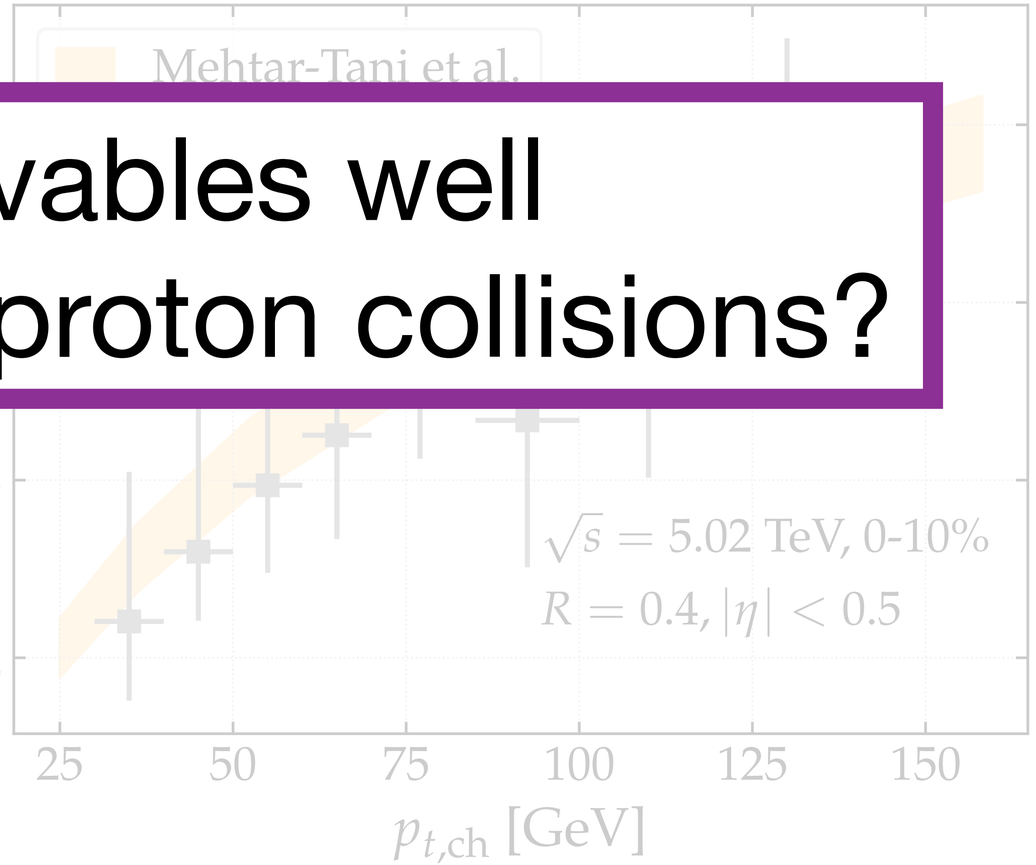
Energy loss



$\mathscr{E}(p_t, C_{F/A}, \theta, n_{\mathrm{VLE}})$

Tywoniuk (Wed, 12:30h)

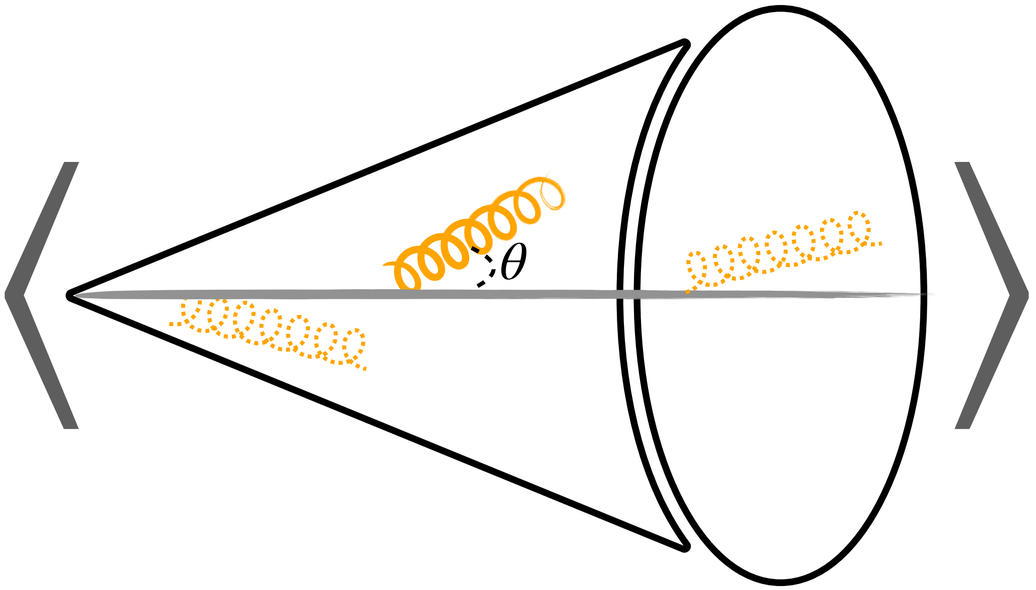
[PRL 127 (2021) 25, 252301, JHEP 10 (2021) 038]



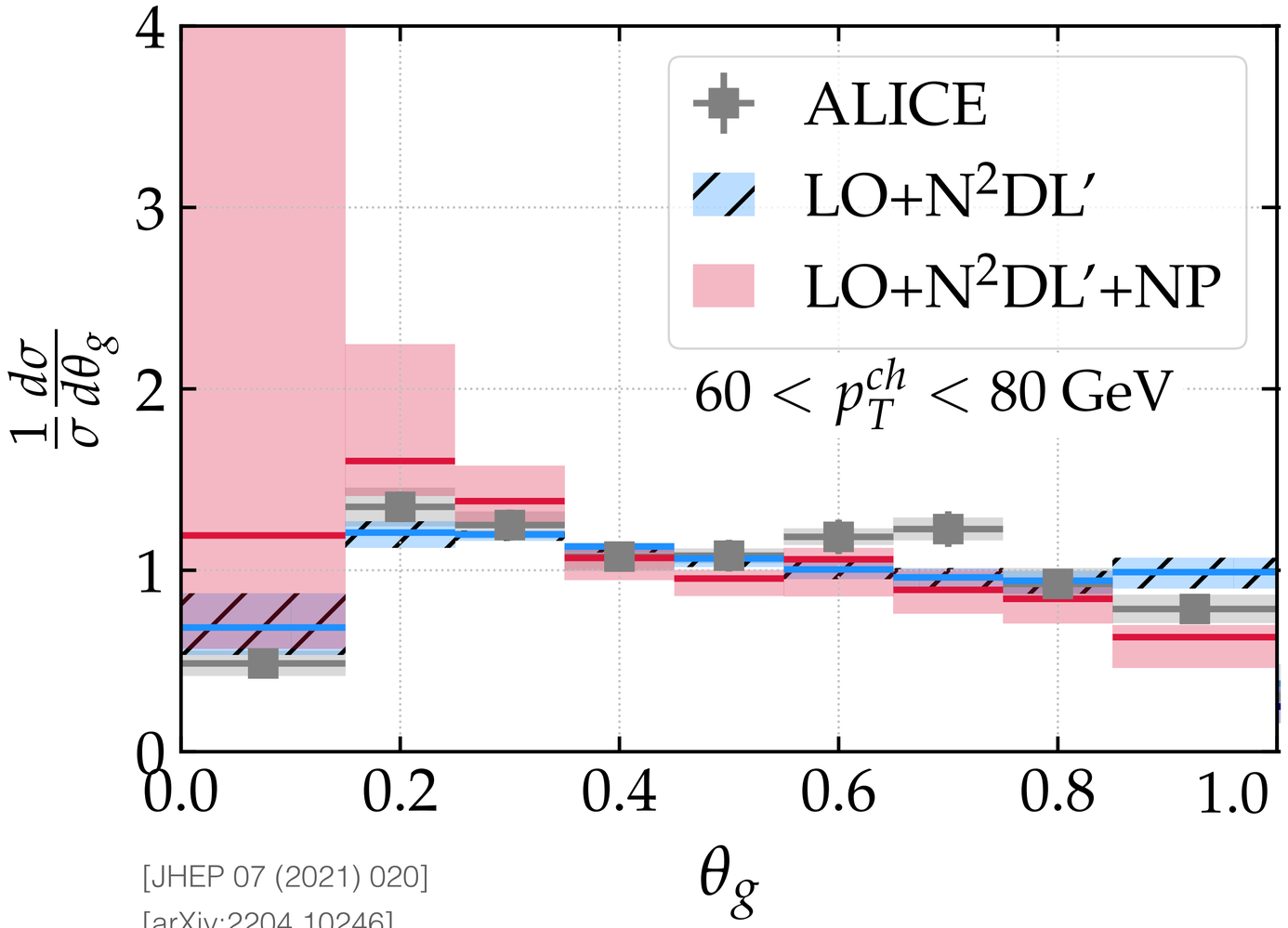
[Adapted from arXiv: 2303.00592]

Are 1-splitting observables well described in proton-proton collisions?

1-splitting observables in pp: semi-analytic calculations



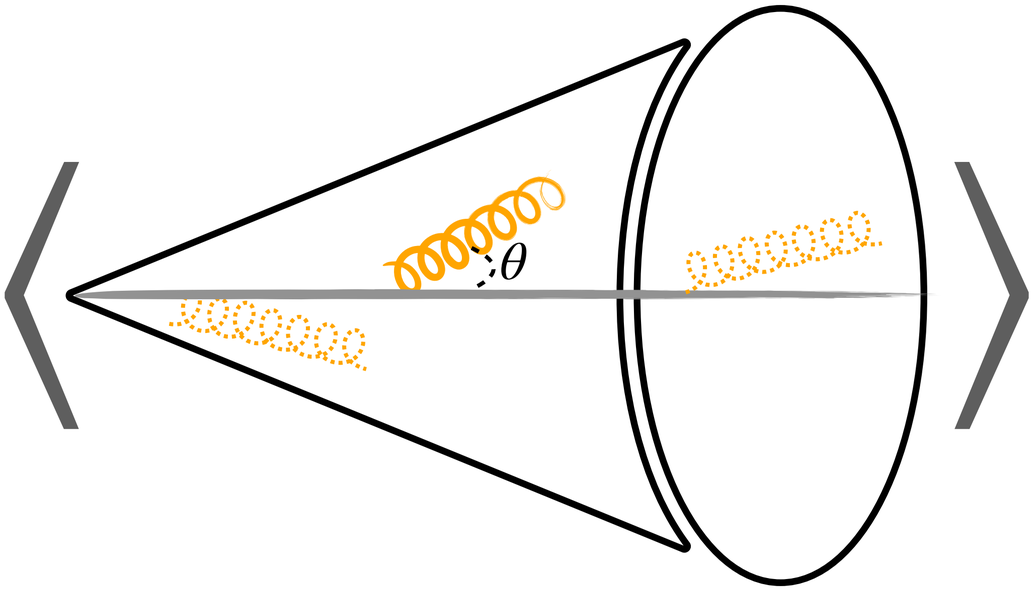
max k_t



[JHEP 07 (2021) 020]
[arXiv:2204.10246]

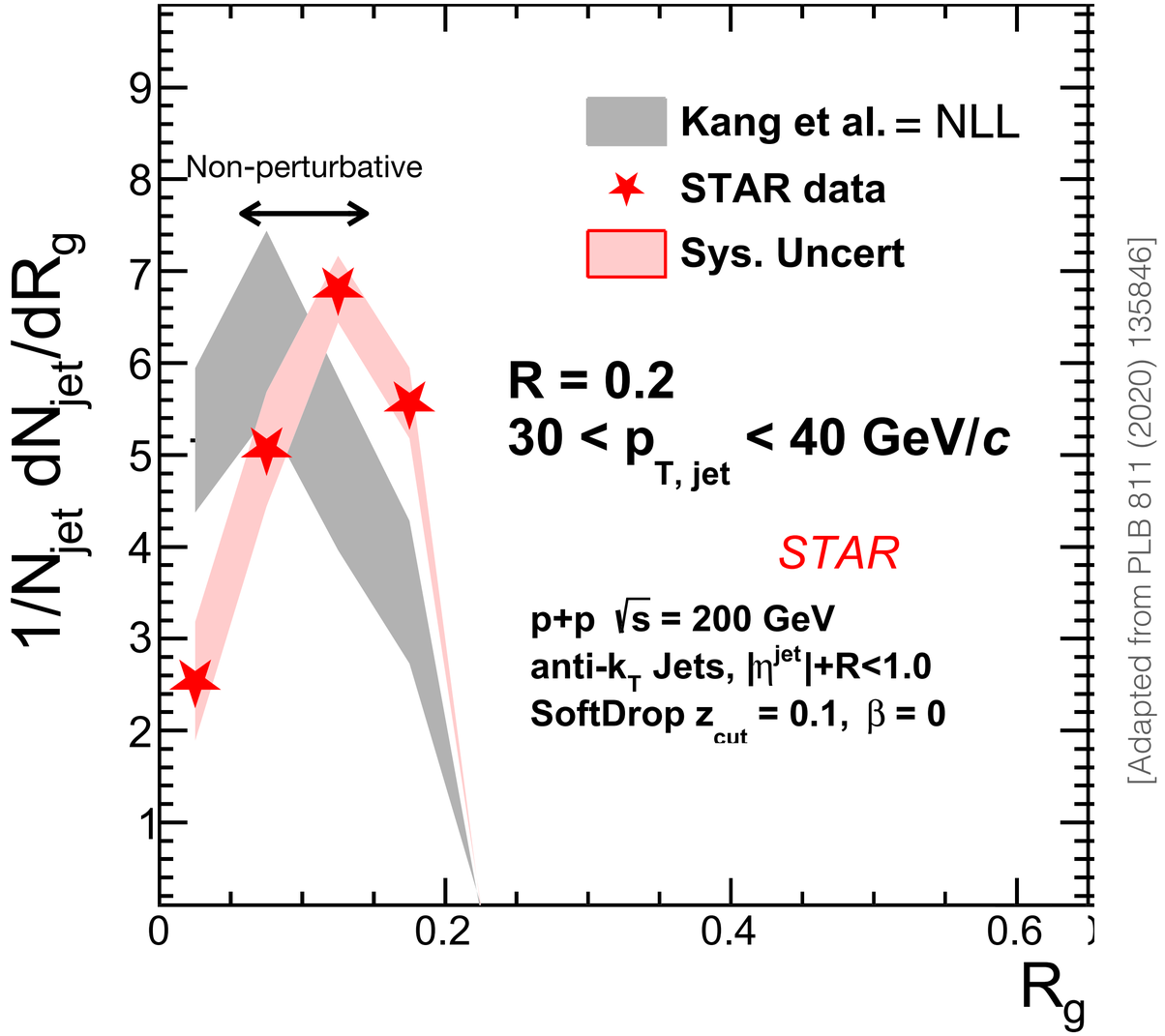
NP=hadron/parton (PYTHIA8)

1-splitting observables in pp: semi-analytic calculations



$$\Theta(z > 0.1)$$

[See 2204.10246 for theory (JHEP 2 (2020) 054)-to-data comparisons with SoftDrop]

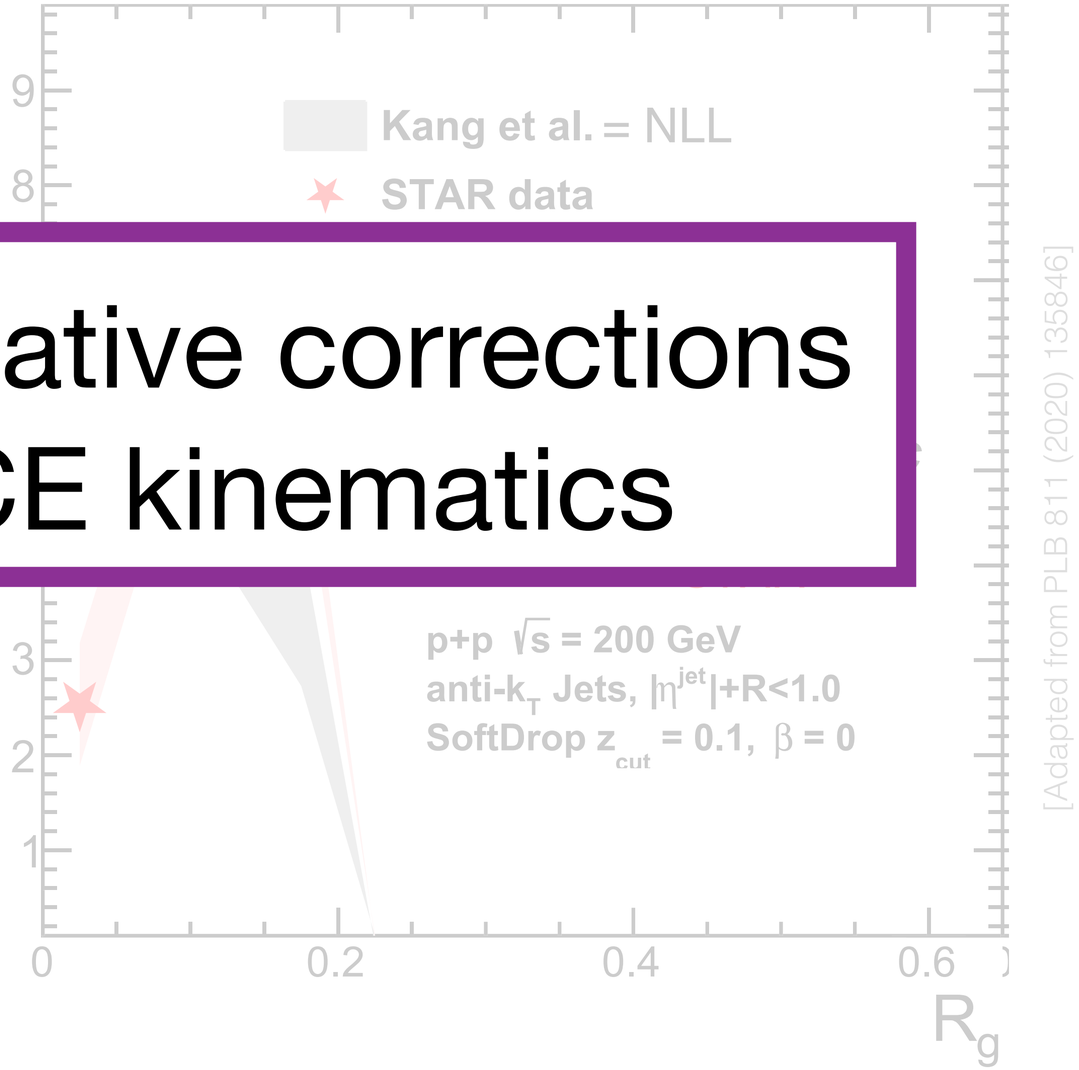


[Adapted from PLB 811 (2020) 135846]

1-splitting observables in pp: semi-analytic calculations

$\mathcal{O}(1)$ non-perturbative corrections for RHIC and ALICE kinematics

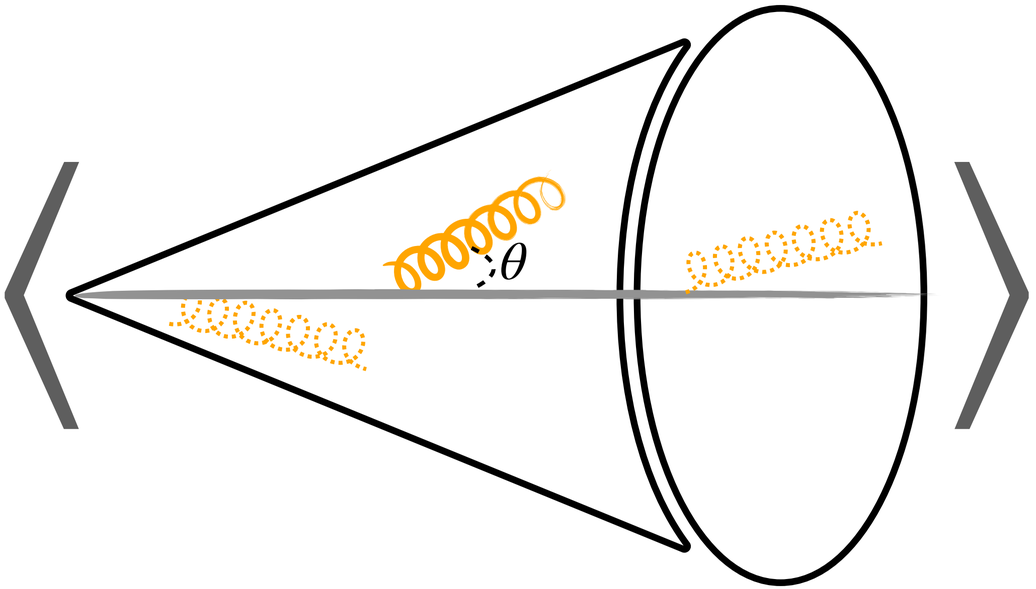
$\Theta(z > 0.1)$



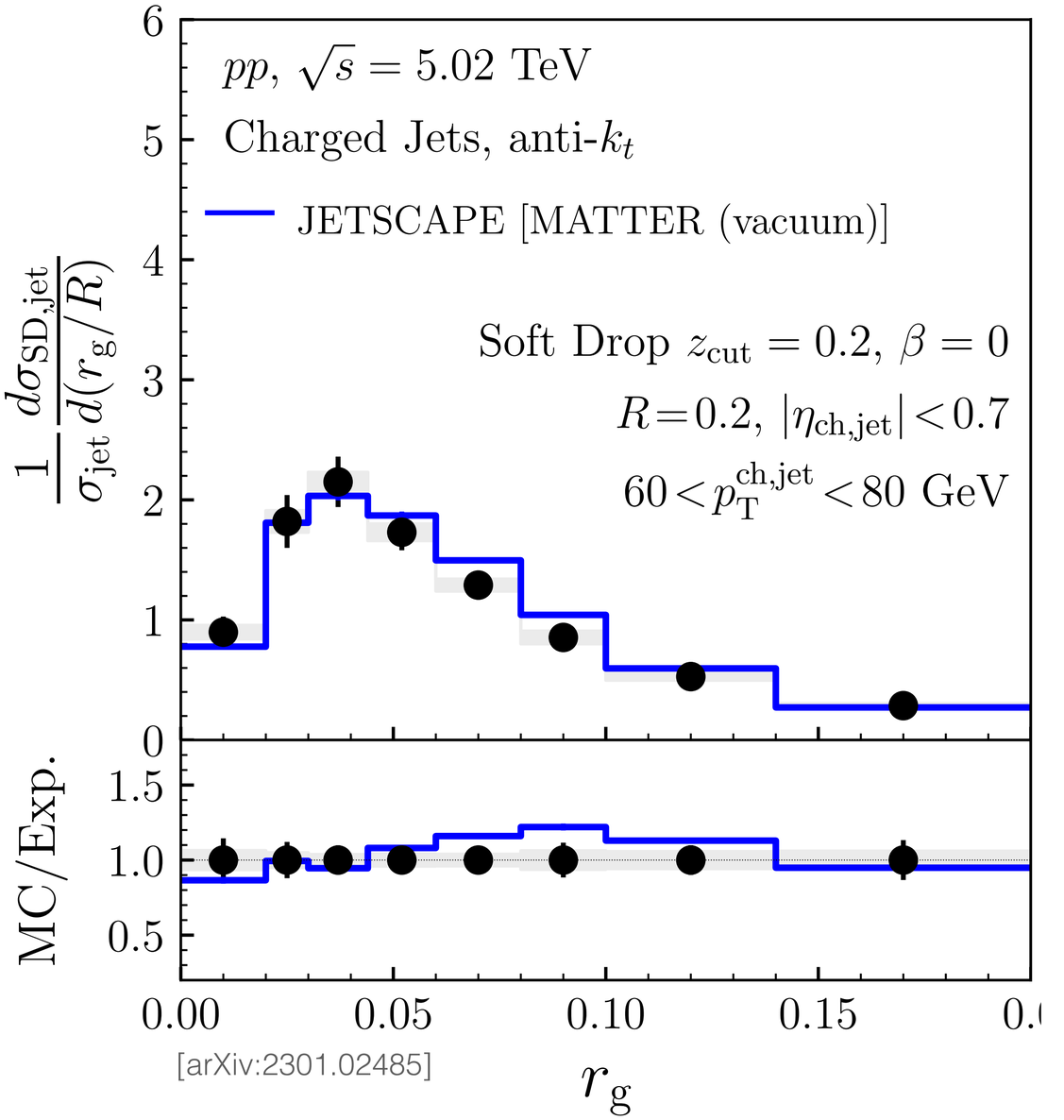
[Adapted from PLB 811 (2020) 135846]

[See 2204.10246 for theory (JHEP 2 (2020) 054)-to-data comparisons with SoftDrop]

1-splitting observables in pp: MC results

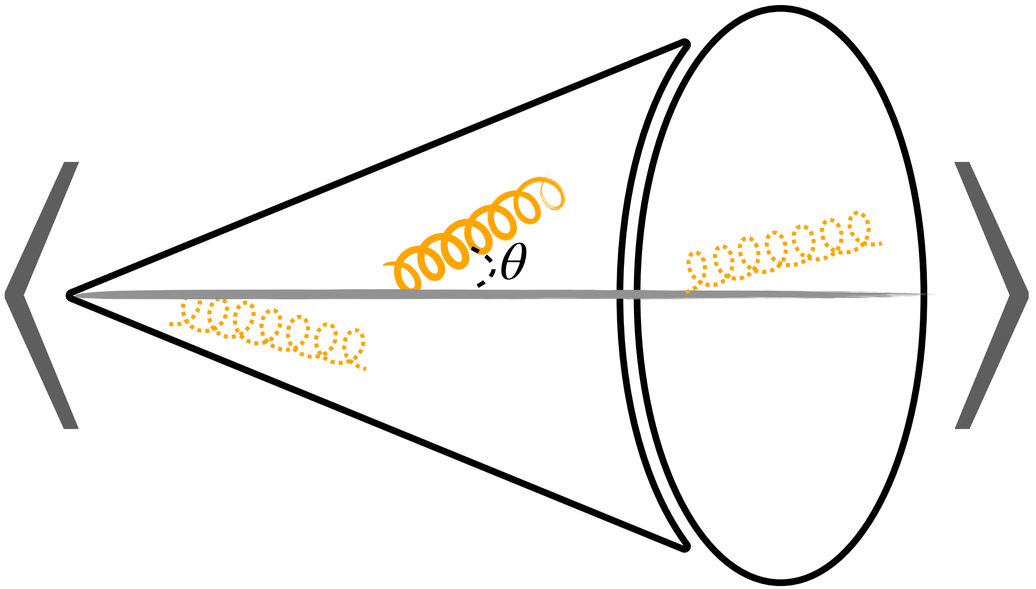


$\Theta(z > 0.2)$

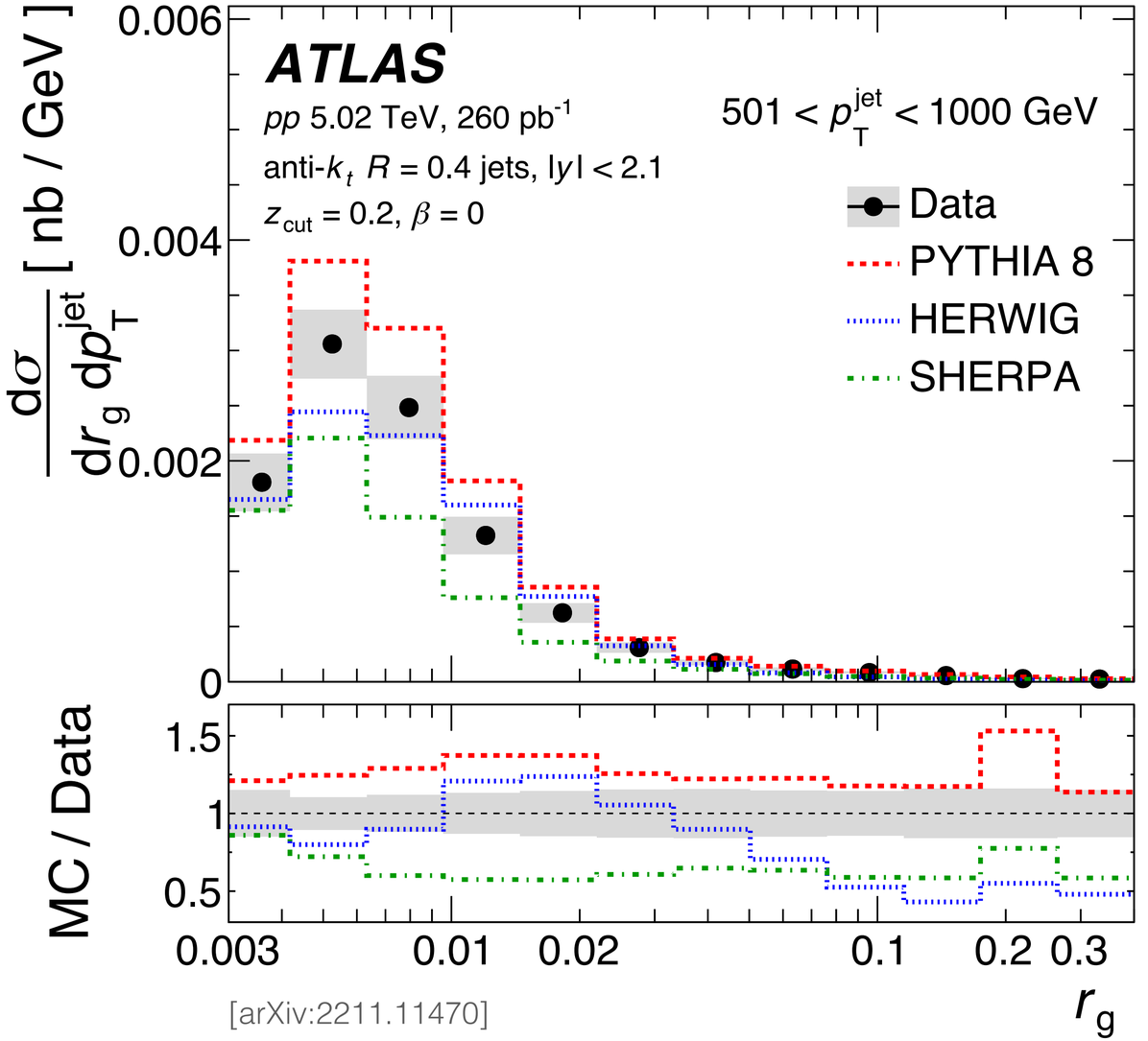


[arXiv:2301.02485]

1-splitting observables in pp: MC results



$\Theta(z > 0.2)$

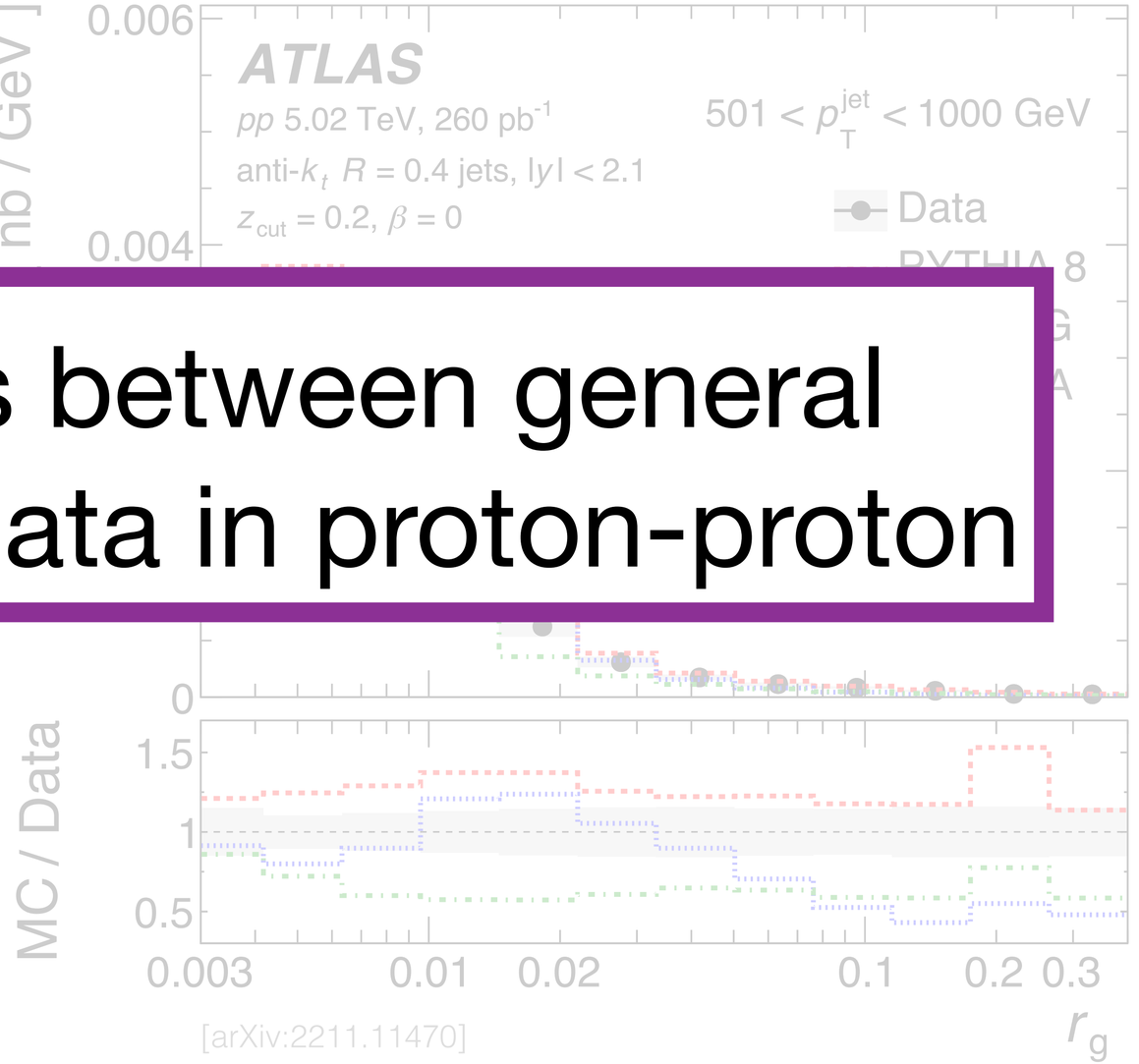


[arXiv:2211.11470]

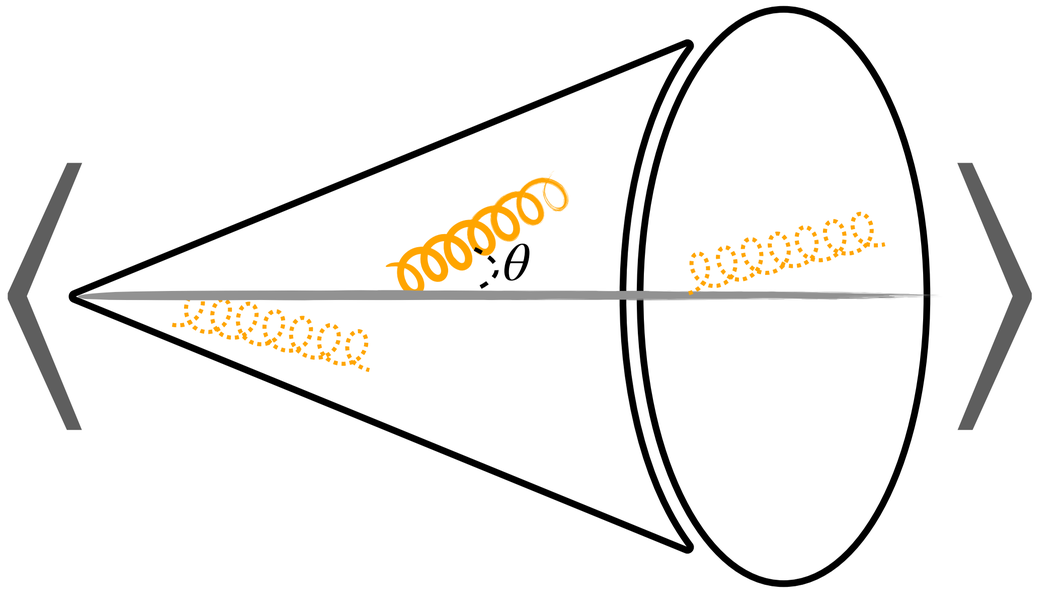
1-splitting observables in pp: MC results

$\mathcal{O}(1)$ discrepancies between general purpose MCs and data in proton-proton

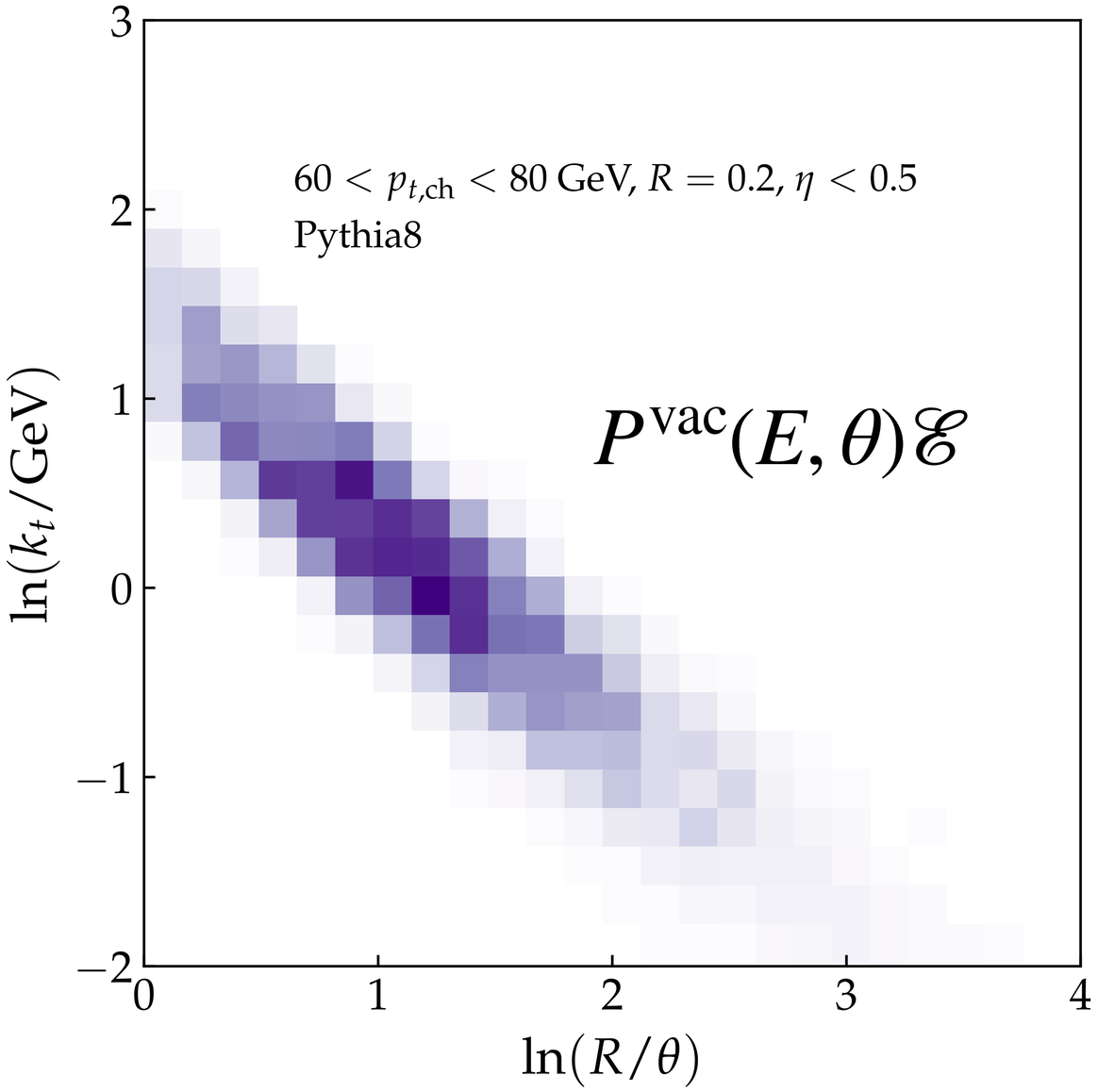
$\Theta(z > 0.2)$



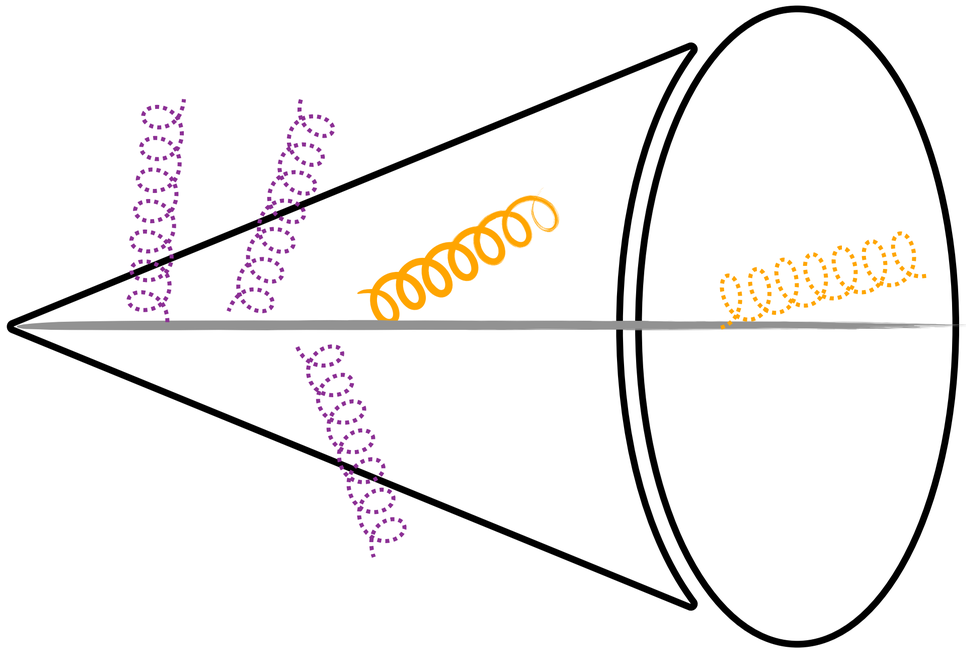
1-splitting observables in PbPb: phase-space analysis



$\Theta(z > 0.2)$

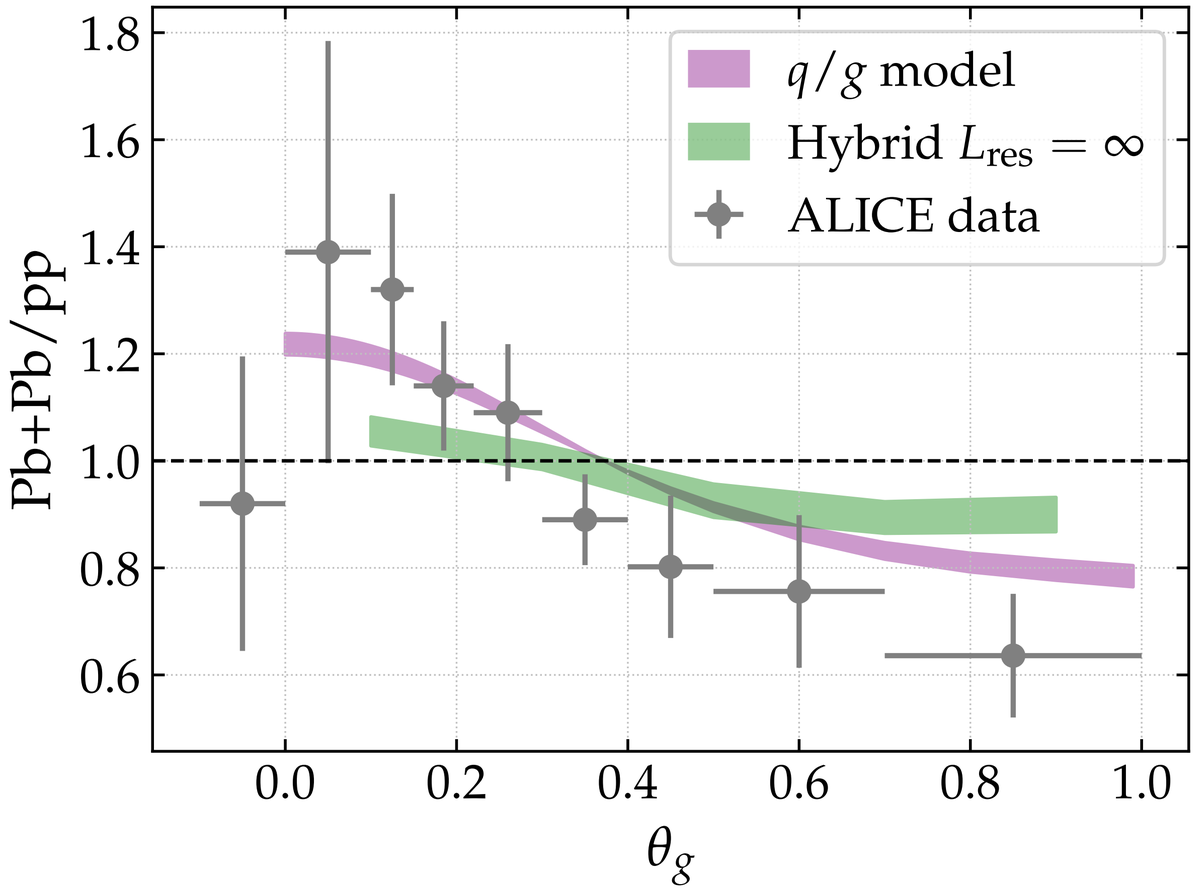


1-splitting observables in PbPb: role of critical angle



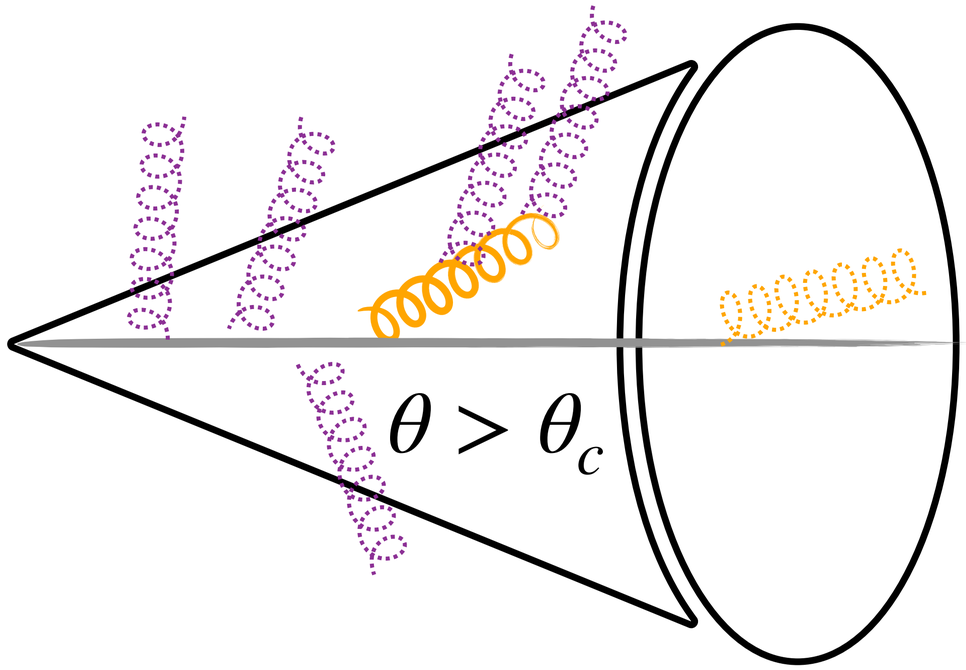
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A})$$

Pablos (Wed, 11:10h) [arXiv:2210.07901]

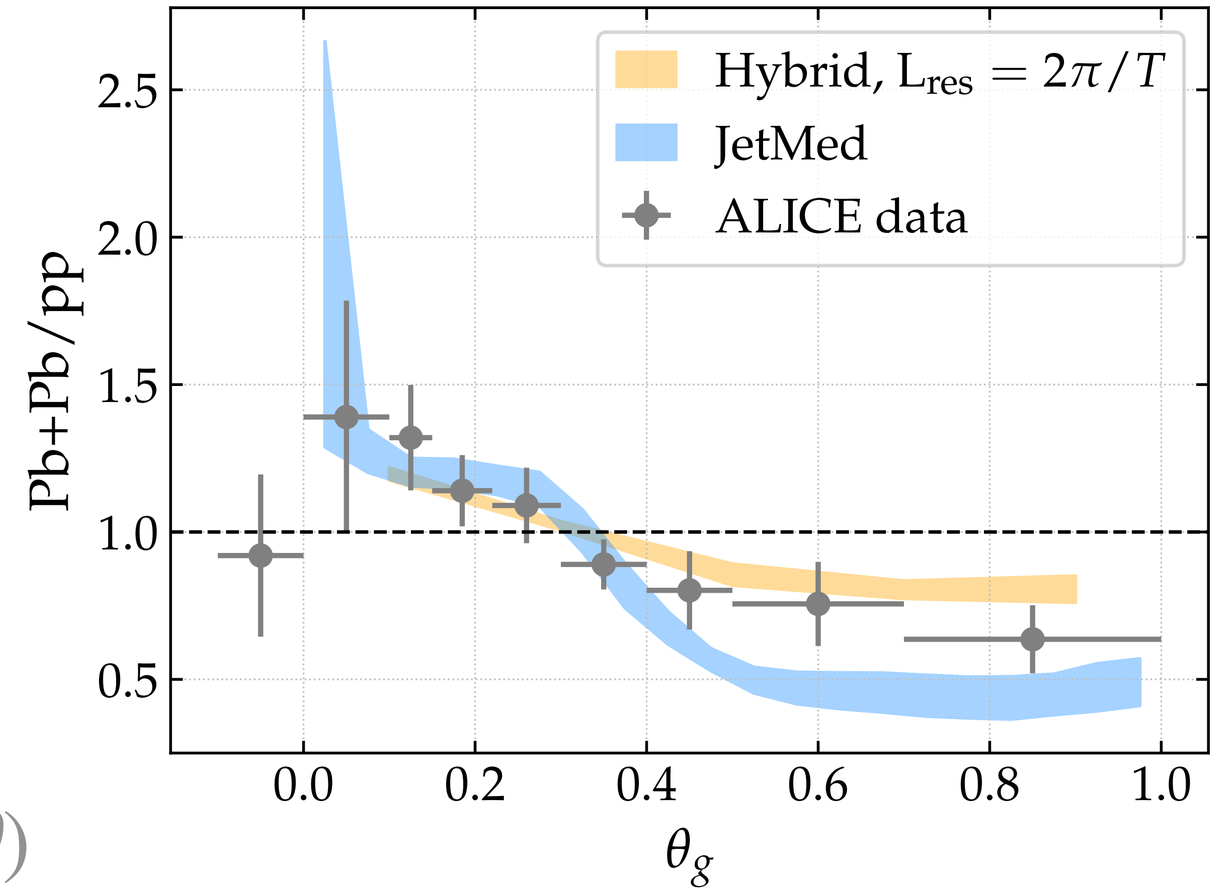


[Adapted from PRL 128 (2022) 102001, 2022 thanks to J.Mulligan]

1-splitting observables in PbPb: role of critical angle



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A}, \theta)$$

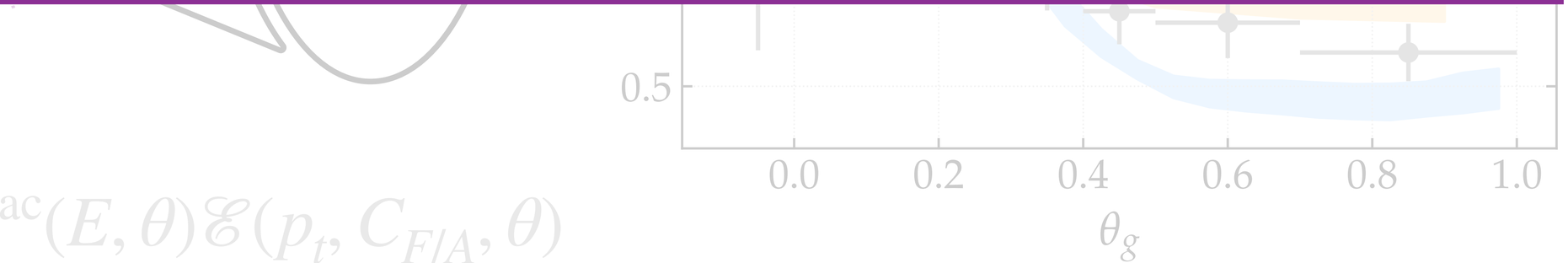


[Adapted from PRL 128 (2022) 102001, 2022 thanks to J.Mulligan]

[Qualitatively similar results found in 2211.11470]

1-splitting observables in PbPb: role of critical angle

Unambiguous experimental evidence of color decoherence (or medium modified splitting functions) has yet to be achieved



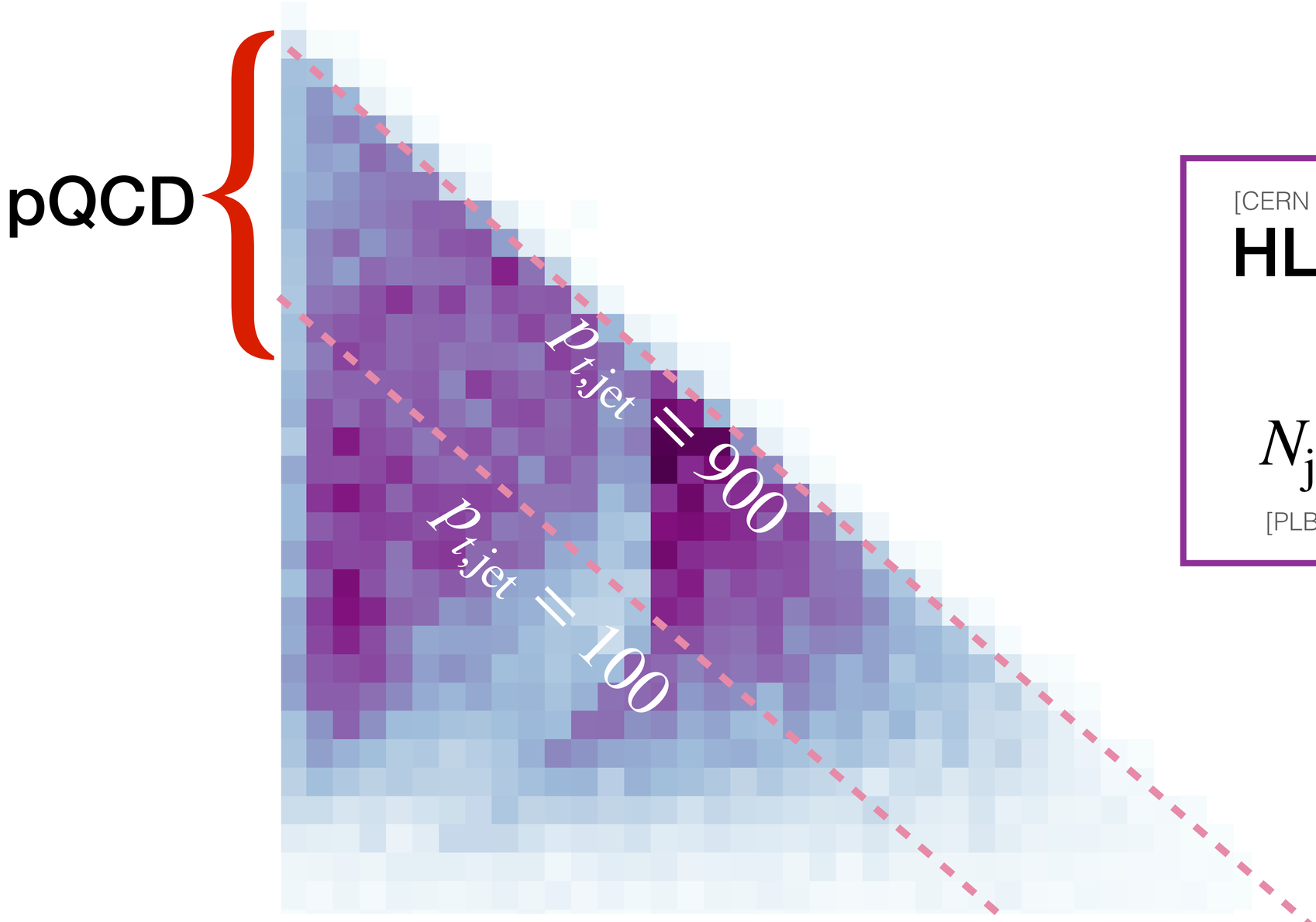
[Adapted from PRL 128 (2022) 102001, 2022]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A}, \theta)$$

[Qualitatively similar results found in 2211.11470]

A new take on jet substructure in heavy-ions at HL-LHC

[Work in progress with L.Cunqueiro, J.Holguin, D.Pablos, M.Spousta, A.Takacs and M.Verweij]



[CERN Yellow Rep.Monogr. 7 (2019) 1159-1410]

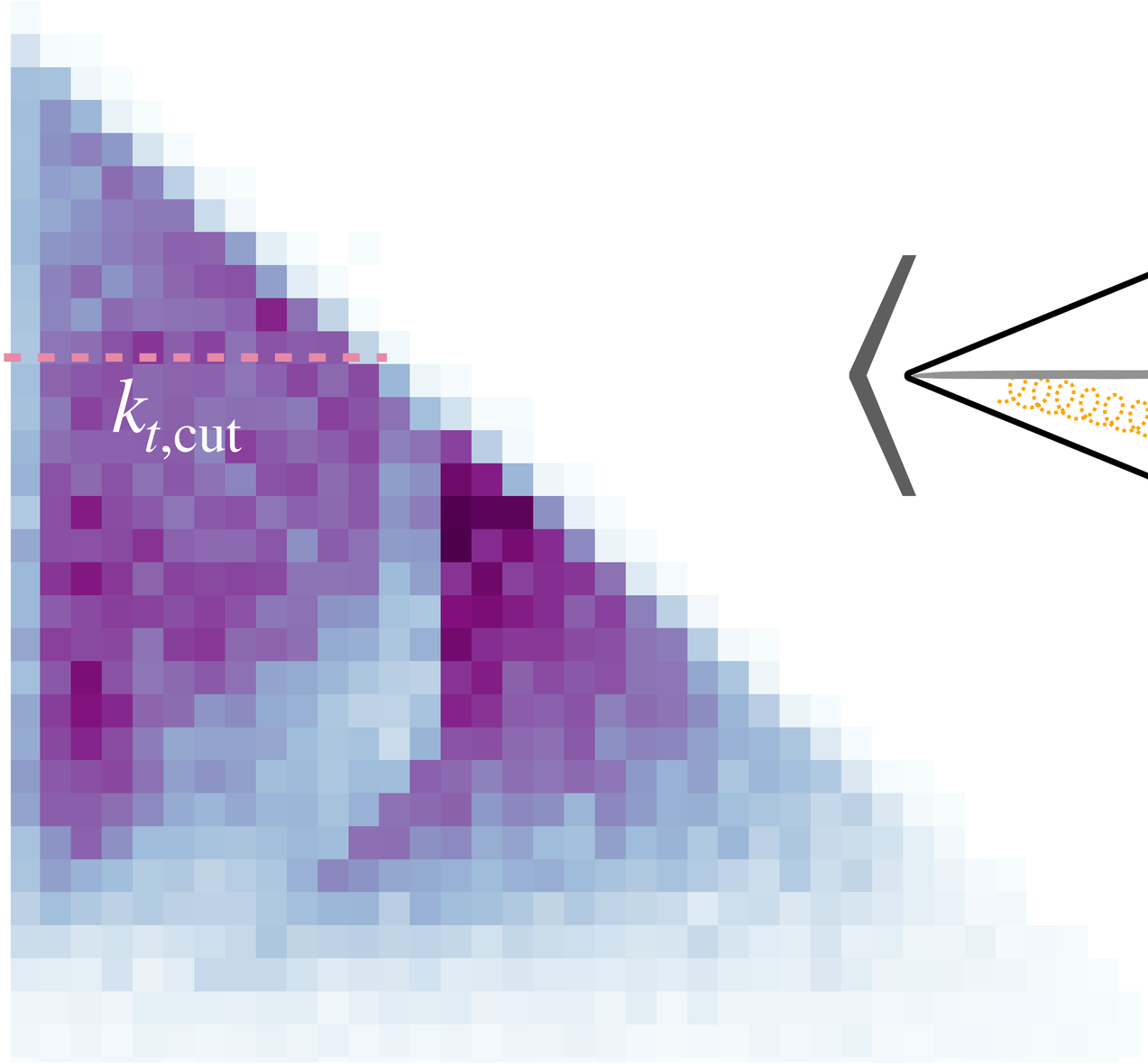
HL-LHC $= 10 \times \mathscr{L}$

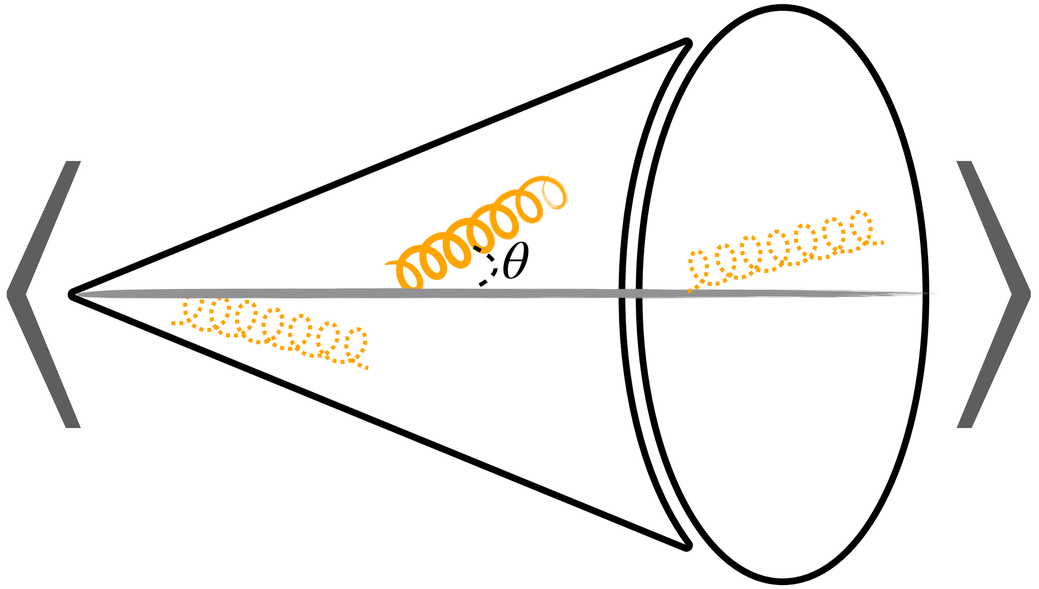
$$N_{\mathrm{jets},p_t>500} \sim \mathcal{O}(10^3)$$

[PLB 790 (2019) 108-128]

A new take on jet substructure in heavy-ions at HL-LHC

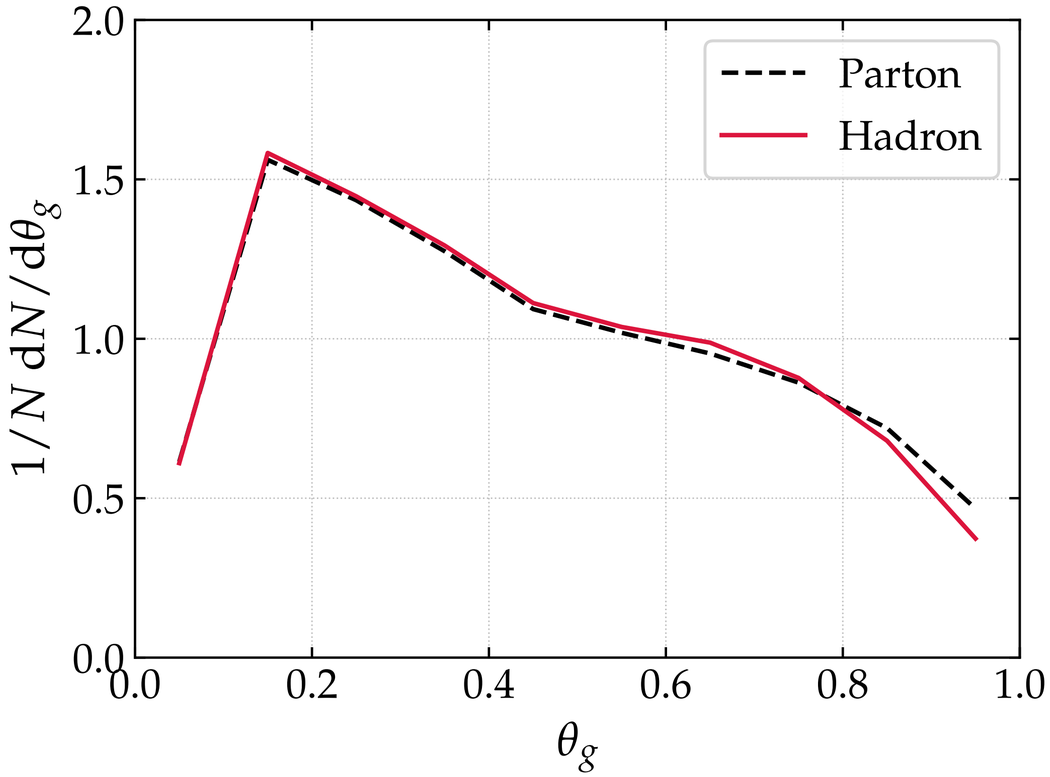
[Work in progress with L.Cunqueiro, J.Holguin, D.Pablos, M.Spousta, A.Takacs and M.Verweij]





$$\max k_t > k_{t,\mathrm{cut}}$$

Sensitivity to hadronisation in pp collisions



p_t >950 GeV, $R = 0.4$

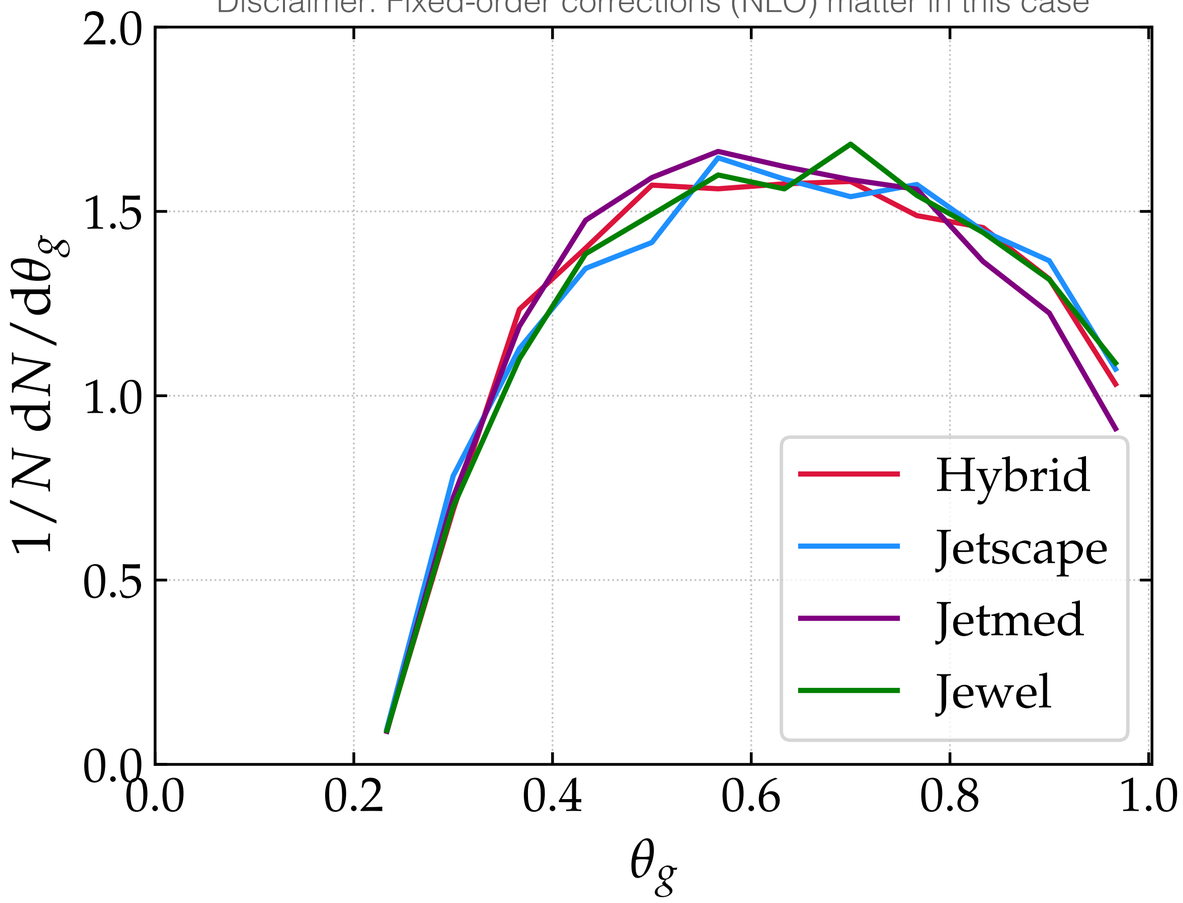
$k_{t,\mathrm{cut}}$ =8 GeV

Pythia8

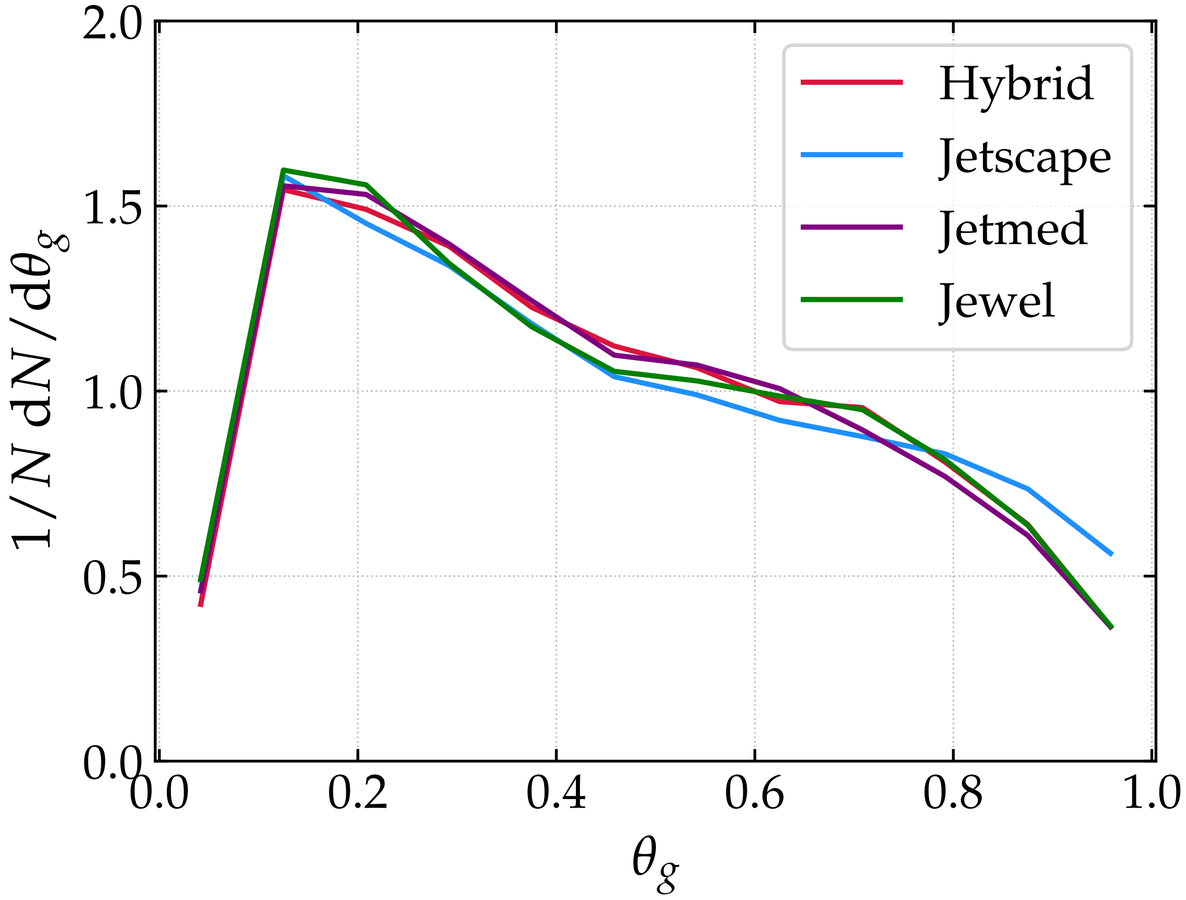
MC results in pp collisions

$k_{t,\mathrm{cut}} = 50$ GeV

Disclaimer: Fixed-order corrections (NLO) matter in this case

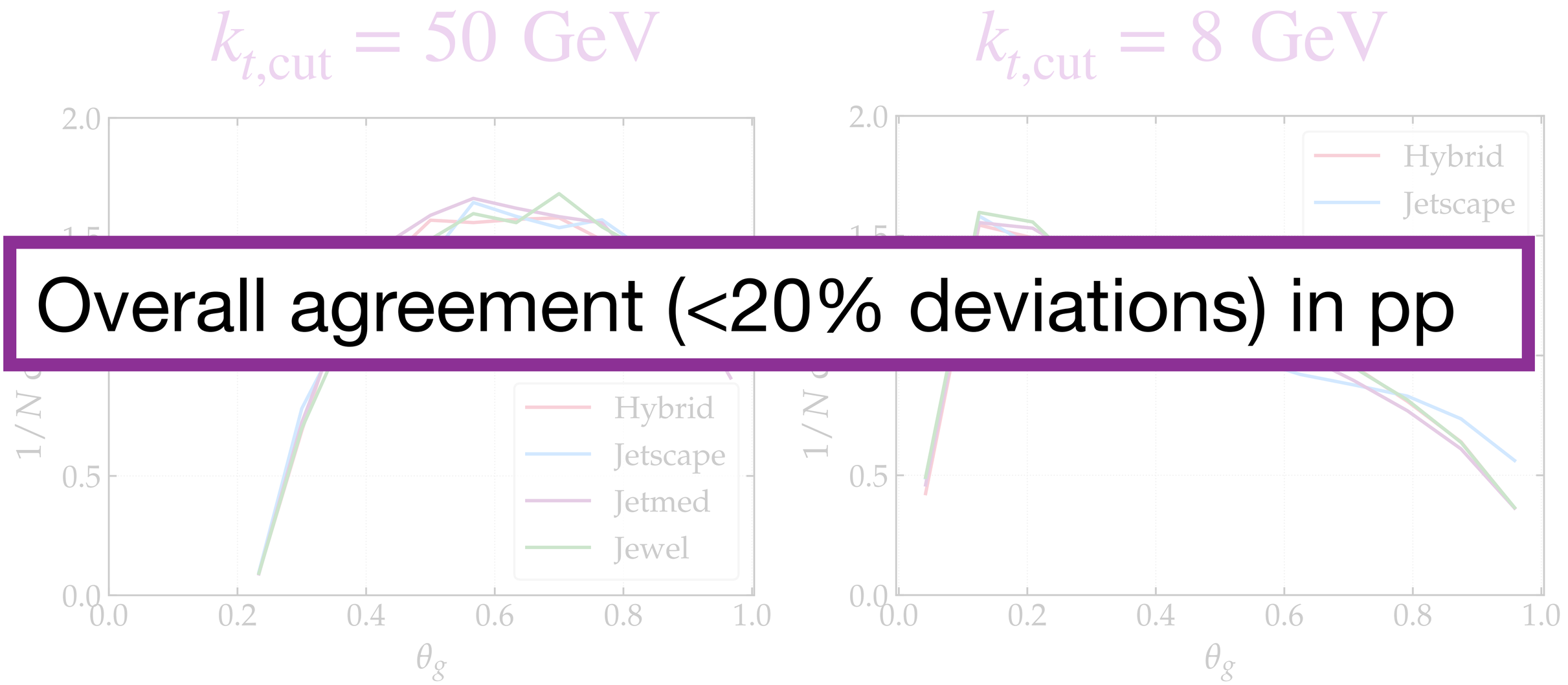


$k_{t,\mathrm{cut}} = 8$ GeV



[Hybrid: JHEP 10 (2014) 019, Jetscape: PRC 102 (2020) 5, 054906, Jetmed: PRL 120 (2018) 232001, Jewel: EPJC 60 (2009) 617-632]

MC results in pp collisions

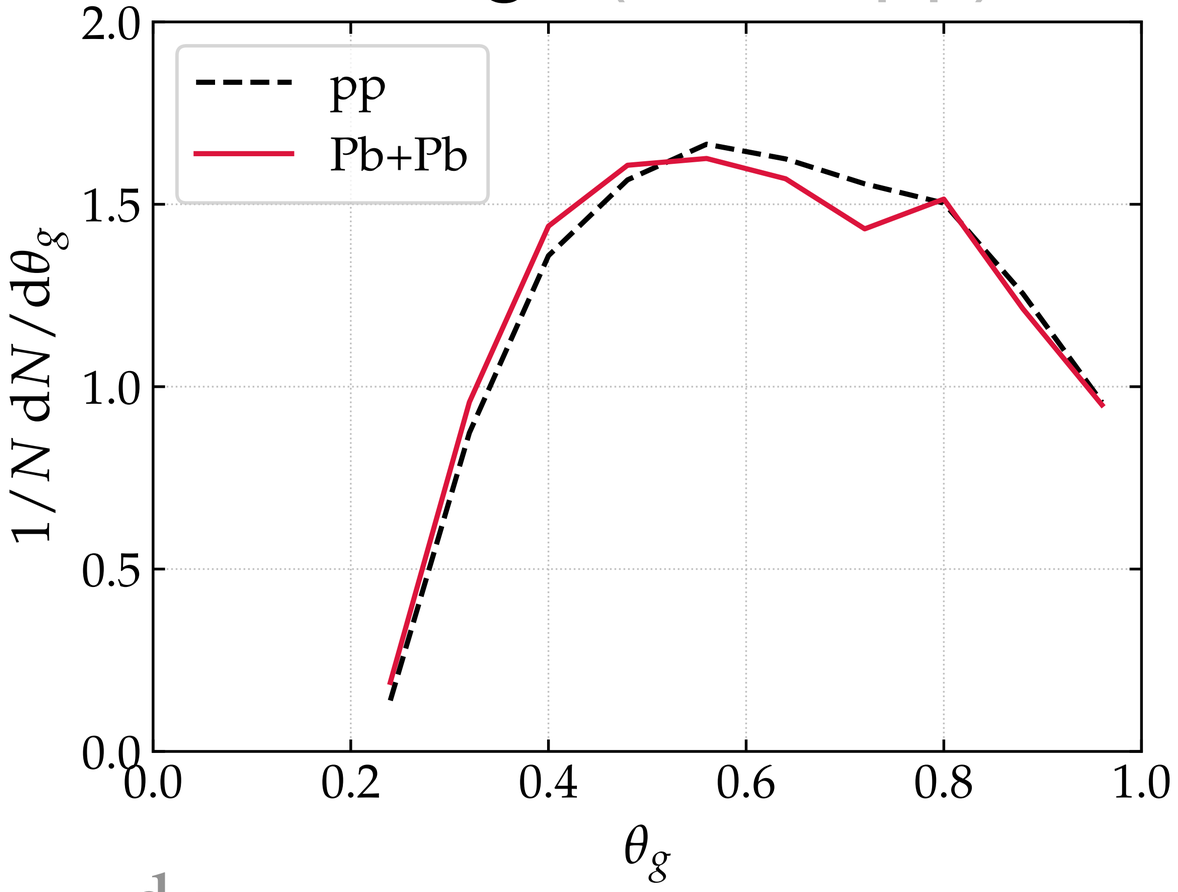


Overall agreement (<20% deviations) in pp

[Hybrid: JHEP 10 (2014) 019, Jetscape: PRC 102 (2020) 5, 054906, Jetmed: PRL 120 (2018) 232001, Jewel: EPJC 60 (2009) 617-632]

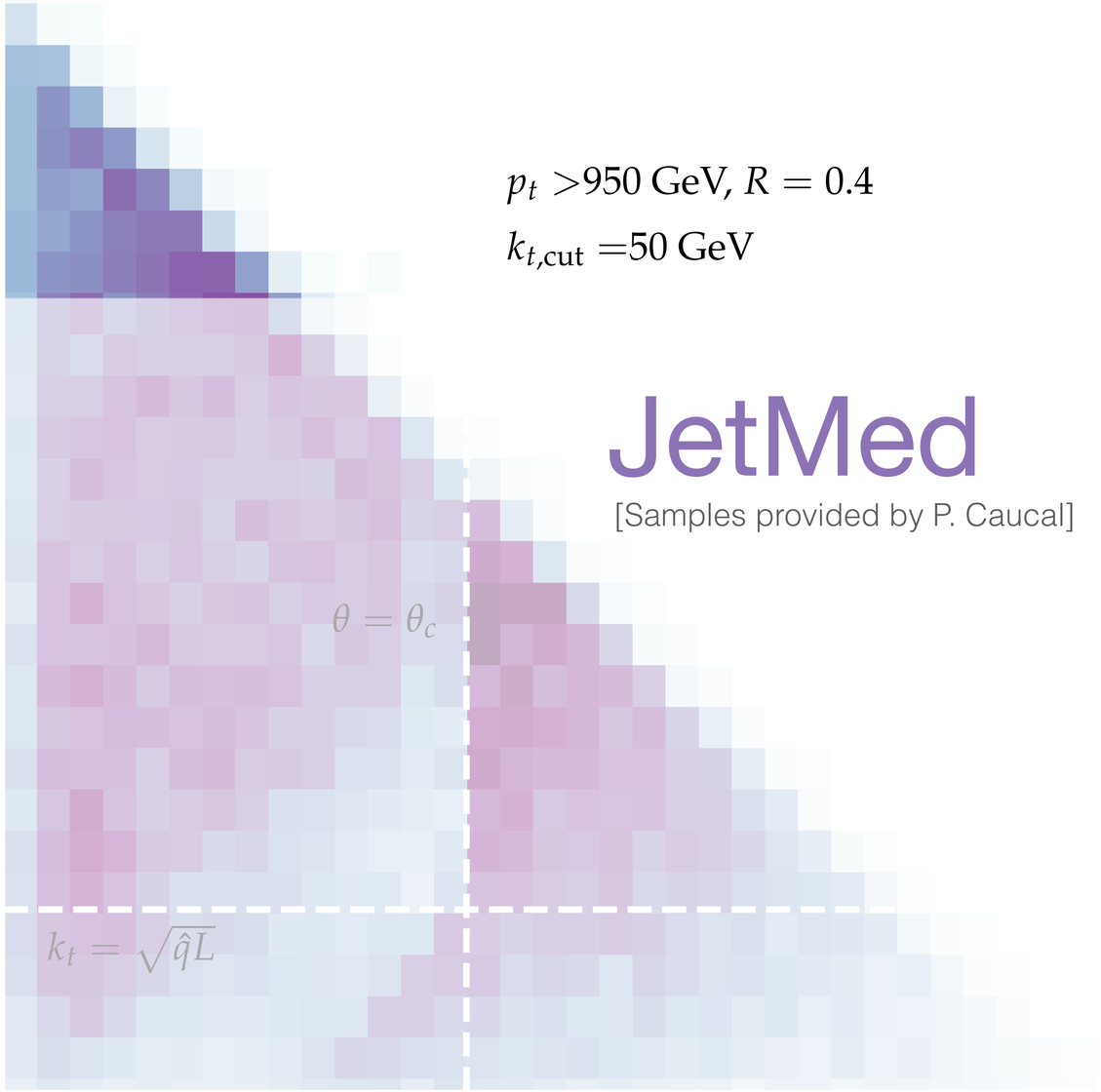
MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 50$ GeV

No change (wrt to pp)



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A})$$

[Same results in Hybrid, Jewel and Jetscape]



p_t >950 GeV, $R = 0.4$

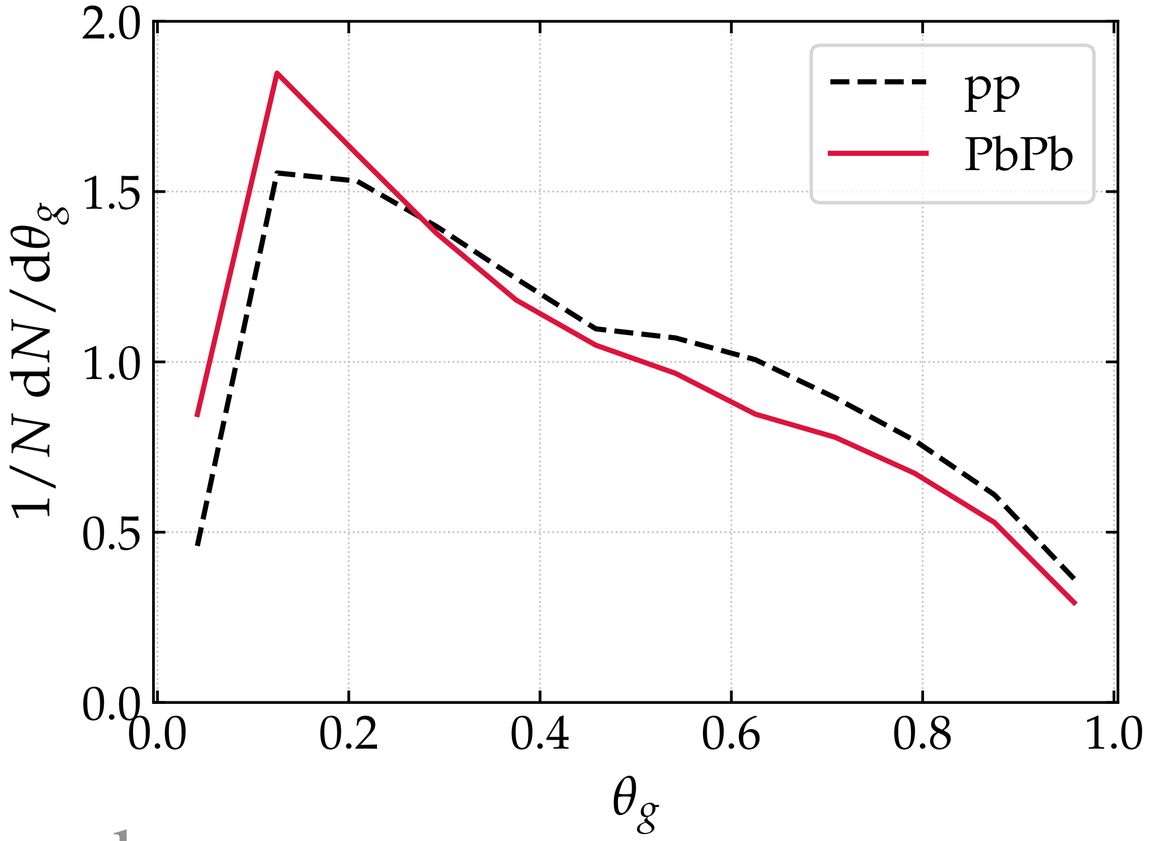
$k_{t,\mathrm{cut}}$ =50 GeV

JetMed

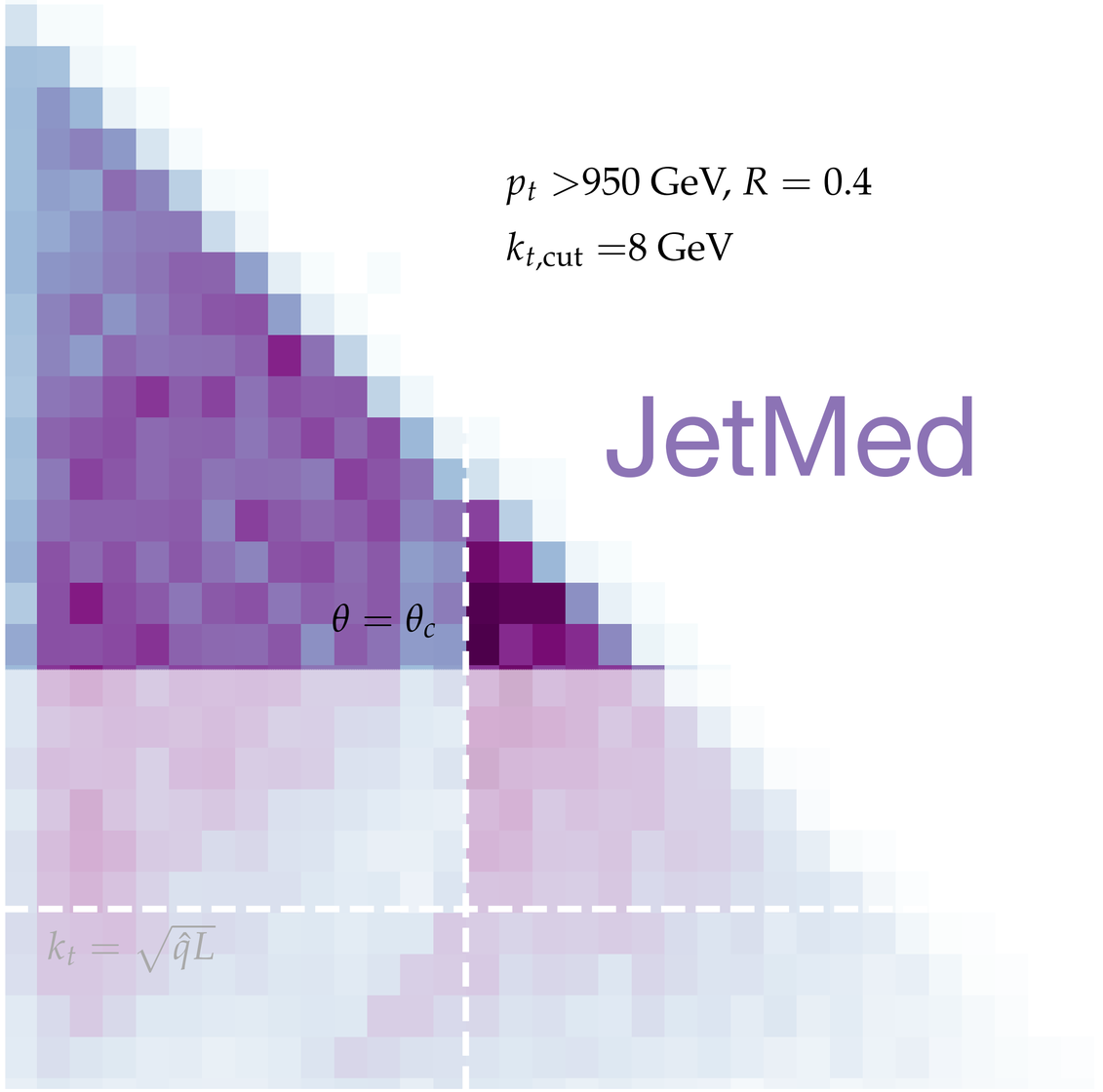
[Samples provided by P. Caucal]

MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 8$ GeV

Narrowing (wrt to pp)

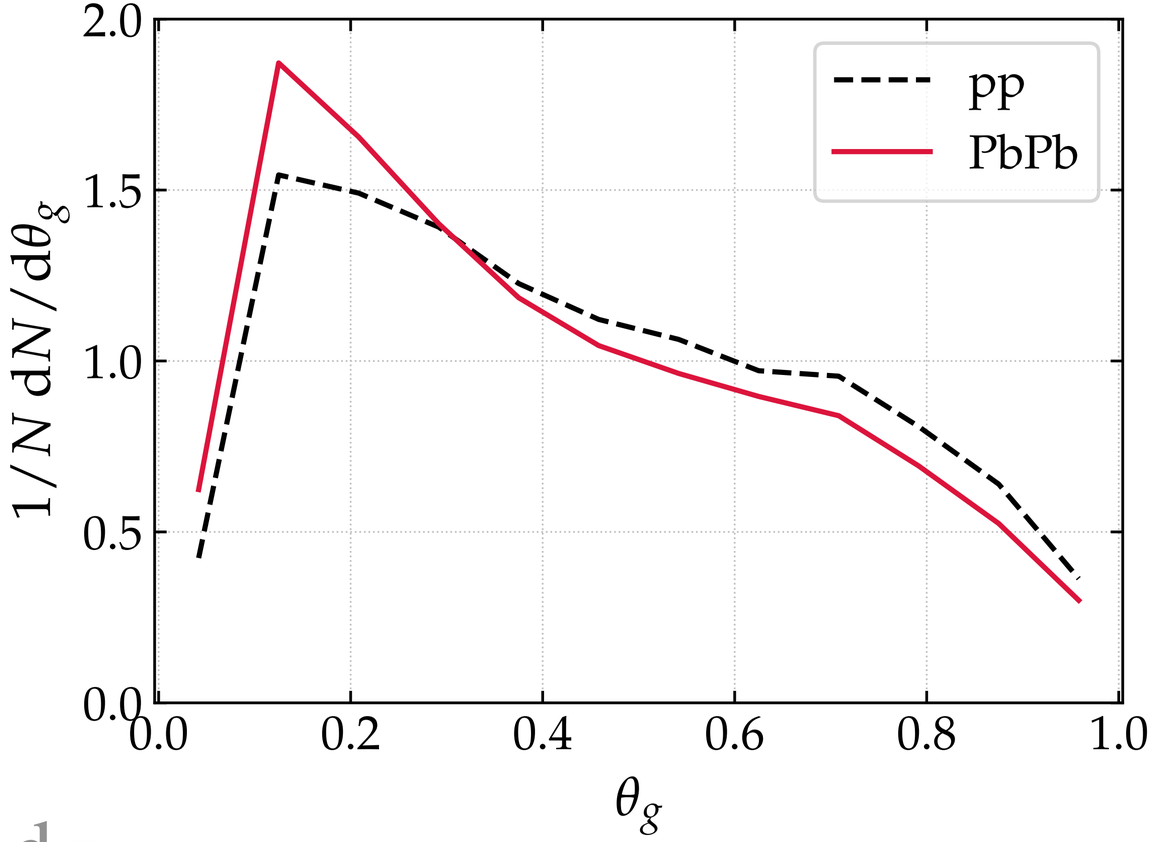


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A}, \theta)$$



MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 8$ GeV

Narrowing (wrt to pp)



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac}}(E,\theta)\mathscr{E}(p_t, C_{F/A}, n_{\mathrm{VLE}})$$

p_t >950 GeV, $R = 0.4$

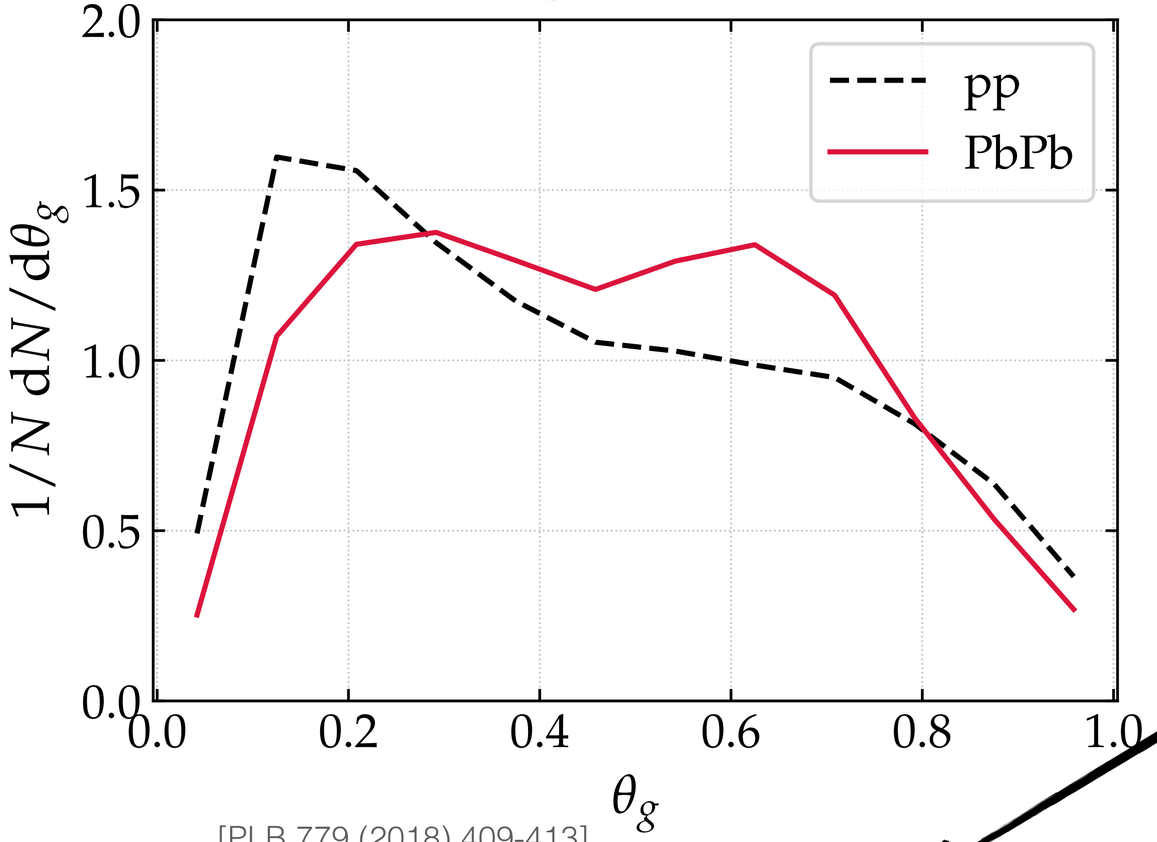
$k_{t,\mathrm{cut}}$ =8 GeV

Hybrid, L_{res}=0

[Samples provided by D. Pablos]

MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 8$ GeV

Broadening (wrt to pp)



[PLB 779 (2018) 409-413]

Medium response

[Not present in SoftDrop equivalent plot]

$p_t > 950$ GeV, $R = 0.4$

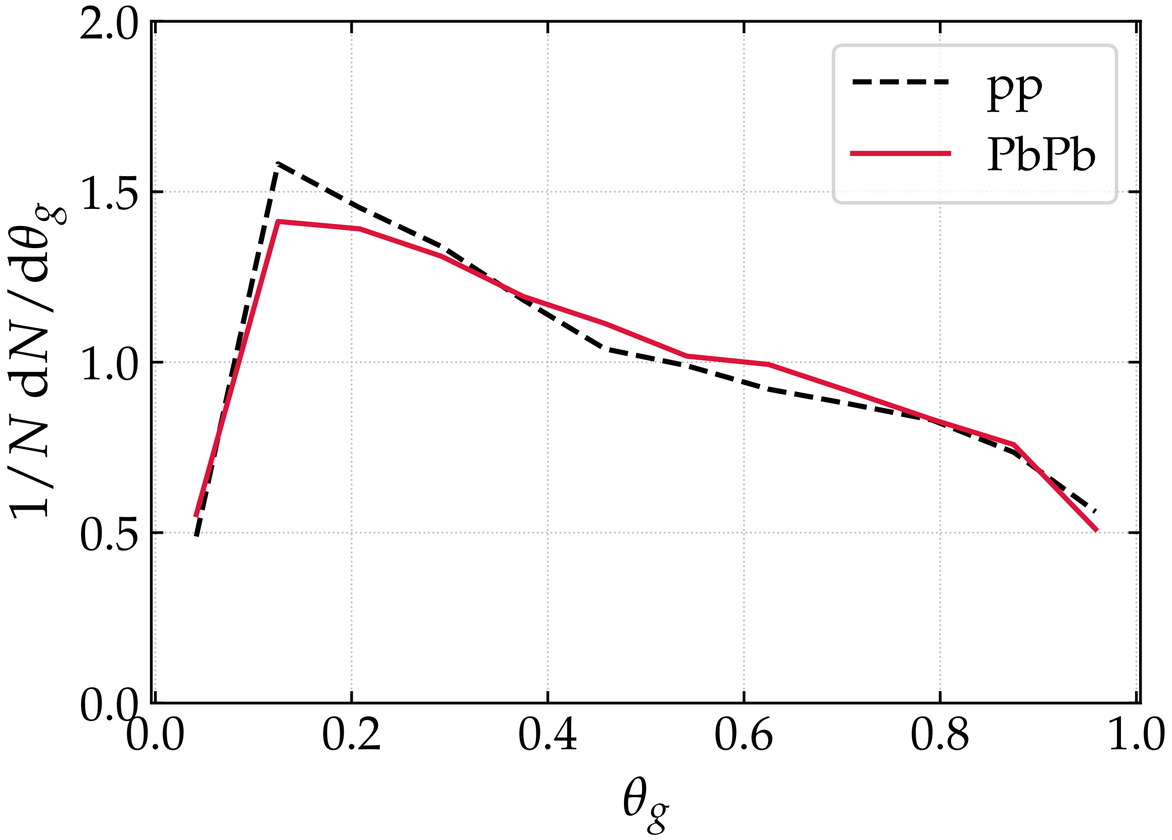
$k_{t,\mathrm{cut}} = 8$ GeV

Jewel

[Samples provided by M. Verweij
Subtraction as in EPJC 82 (2022) 11, 1010]

MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 8$ GeV

Broadening (wrt to pp)



$P^{\mathrm{vac}} + P^{\mathrm{med}}$

p_t >950 GeV, $R = 0.4$

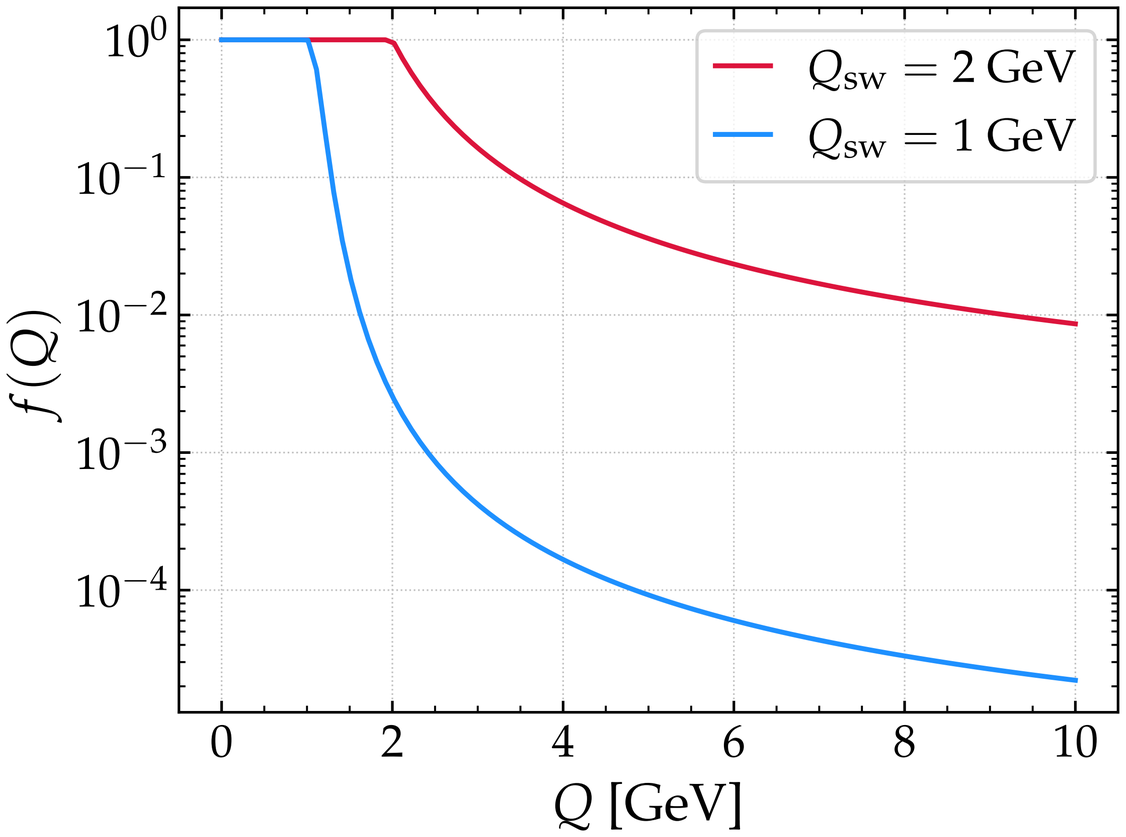
$k_{t,\mathrm{cut}}$ =8 GeV

Jetscape (MATTER only)

$f(Q) = 1$

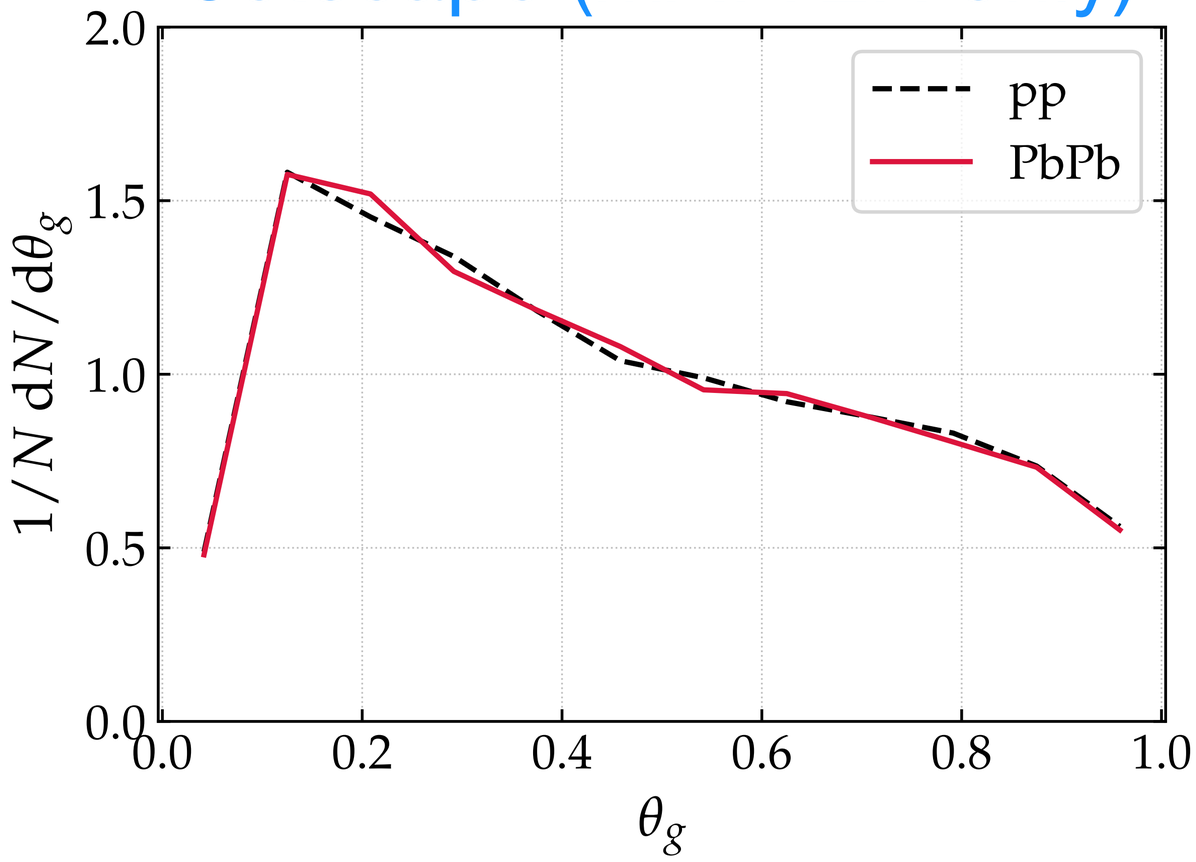
MC results in PbPb collisions: $k_{t,\mathrm{cut}} = 8$ GeV

$P^{\mathrm{vac}} + f(Q) P^{\mathrm{med}}$ [PRC 101 034908 (2020)]



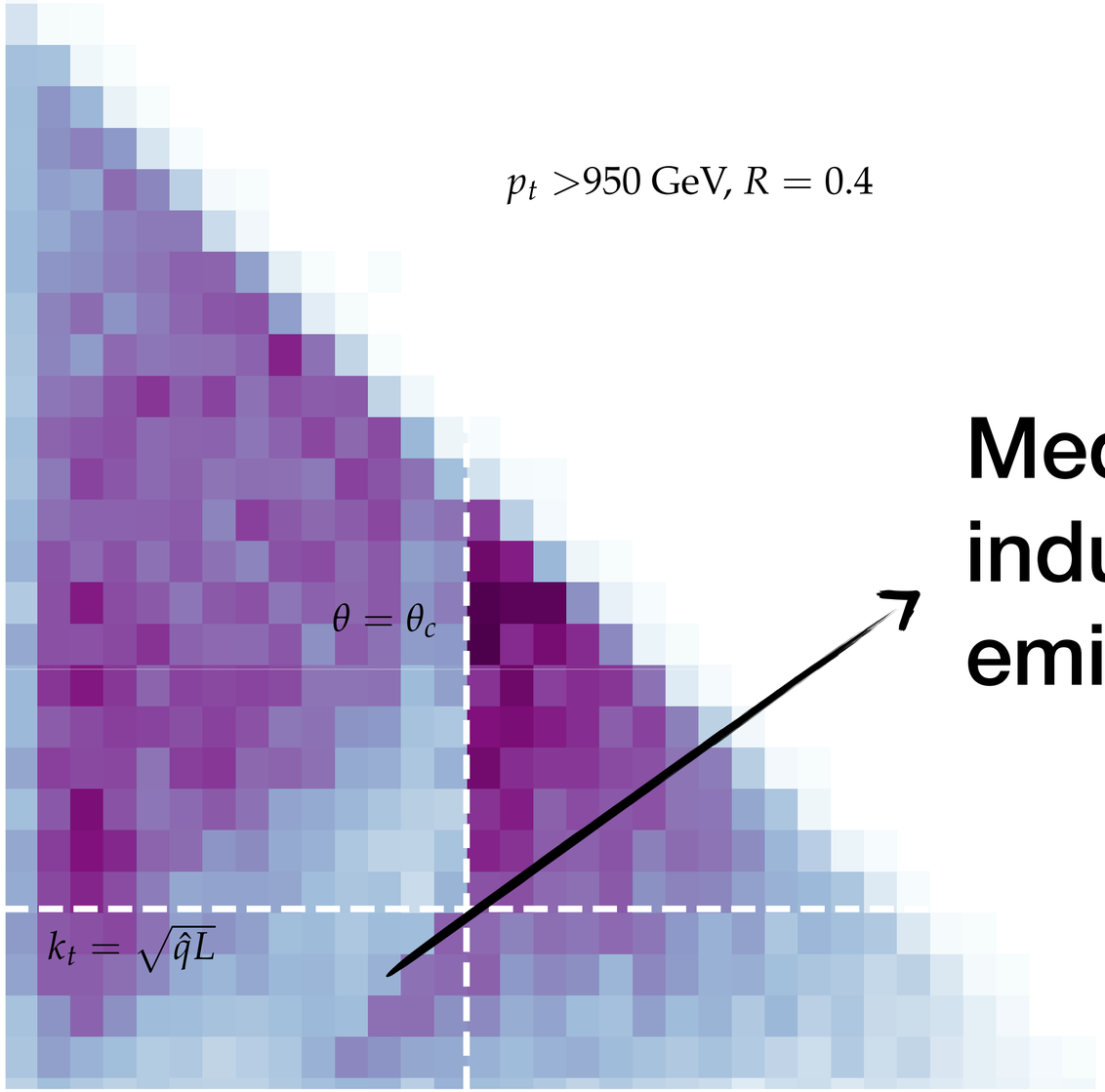
[PRC 88 (2013) 014909]

Jetscape (MATTER only)



Q=virtuality, Q_{sw}=scale to change from MATTER to LBT, results at parton level

Lower values of $k_{t,\mathrm{cut}}$ to tag medium induced emissions?



Medium induced emissions +

- Hadronisation
- Medium response
  [Yeonju Go talk Mon (17:30h)]
- Underlying event
  [PRC 102 (2020) 4, 044913]

Lower values of $k_{t,\mathrm{cut}}$ to tag medium induced emissions?

Exploit dead-cone suppression of vacuum radiation to access a clean, pQCD regime of medium induced emissions

Wed parallel session 11-12:30h

[arXiv:2211.11789, PRD 69 (2004) 114003]

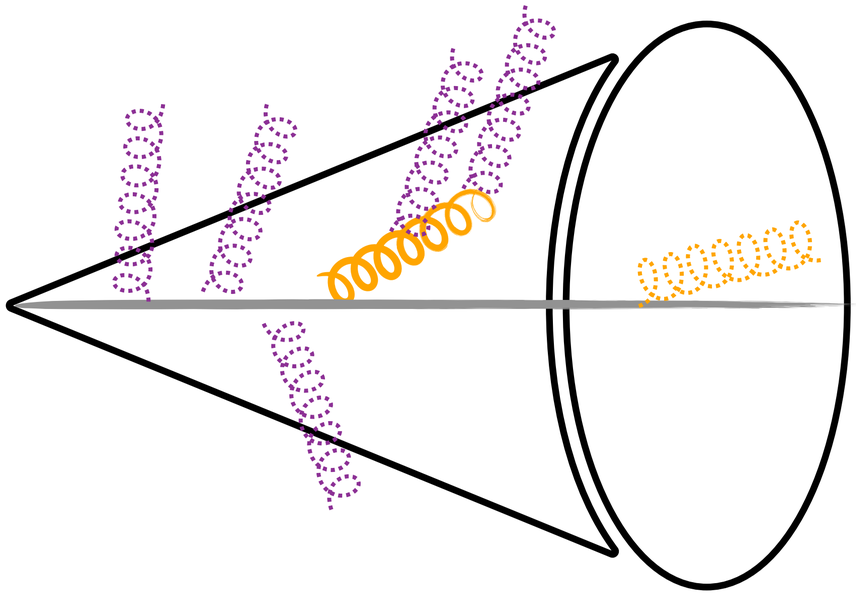
Underlying event

[PRC 102 (2020) 4, 044913]

$k_t = \sqrt{\hat{q}L}$

Conclusions

- One splitting observables in heavy-ion collisions are sensitive to



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \propto P^{\mathrm{vac,med}}(E,\theta)\mathscr{E}(p_t, C_{F/A}, \theta, n_{\mathrm{VLE}})$$

- Description of pp baseline is crucial for meaningful interpretation of data
- Evidence of jet substructure modification (i.e. not E-loss) remains elusive
- Exploit HL-LHC to maximise sensitivity to pQCD-like in-medium physics

Outlook

Better parton showers for proton-proton collisions [PanScales: JHEP 11 (2022) 019 , JHEP 11 (2022) 020]

Beyond leading-log understanding of in-medium jet physics [P. Arnold, S.Iqbal et al 2015-]

Jet substructure in Hard Probes 2024

pQCD as design guideline of in-medium jet observables

(Hopefully) exciting new results with Run3 data