Initial conditions from jets: pA & AA

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Initial Stages 2019
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Why jets?

- Jet is a well defined observable (jet algorithm)

- Jet algorithms are infrared and collinear safe
    - No need of fragmentation functions

- Under control and widely employed in p-p collisions

Higgs searches, BSM physics, PDF fits…

- Versatile: access to different time and energy scales

Jets in heavy-ions?

- Production of high-energy parton unlikely to interfere with the medium formation
  Good probe!

- Jet quenching → Extracting the properties of the QGP
  Initial stages??

Small systems

Jet quenching is the only QGP signature **not observed** in small systems

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T ("recombination")	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[318, 638, 669]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed†	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

† J/ψ ↑, Υ(↓) w.r.t. RHIC energies.

No signal of jet quenching!

arXiv:1812.06772

Jets in pPb

- Much easier than in PbPb

- No jet quenching → Probe of **initial stages**
  (up to now)

- Currently data on:
  - Full jets
  - HF jets — See F. Colamaria talk (Wed afternoon)
  - Charged jets

  } $R_{pPb} \approx 1$ → No insight on nPDFs
  (within the uncertainties)

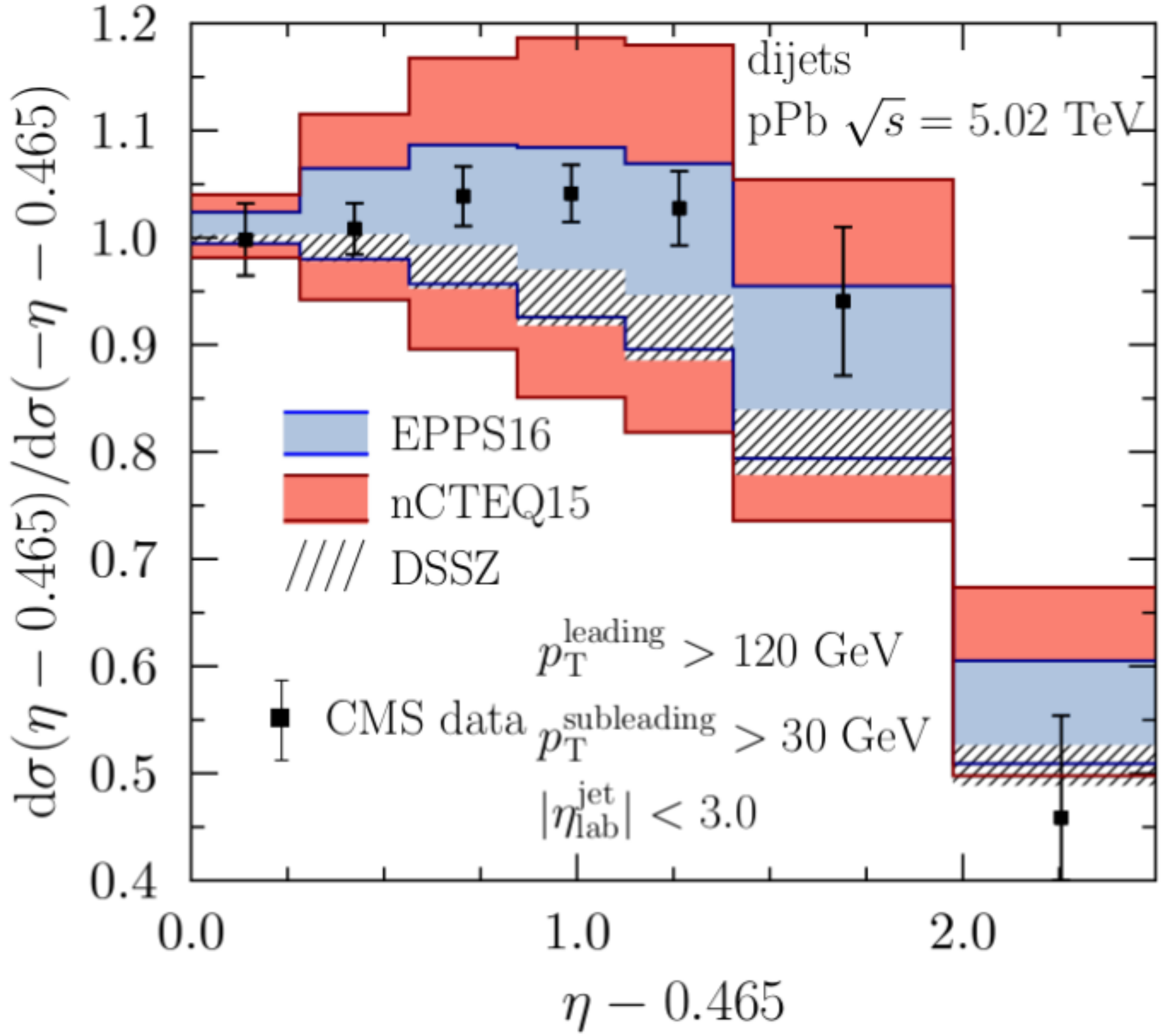
  - Dijets → Different nPDFs differ up to 20% → Useful to **constrain nPDFs**

Constraining nPDFs with (di)jets

See talks from: P. Zurita (Monday)
N. Valle (Tuesday)
E. Chapon (Tuesday)

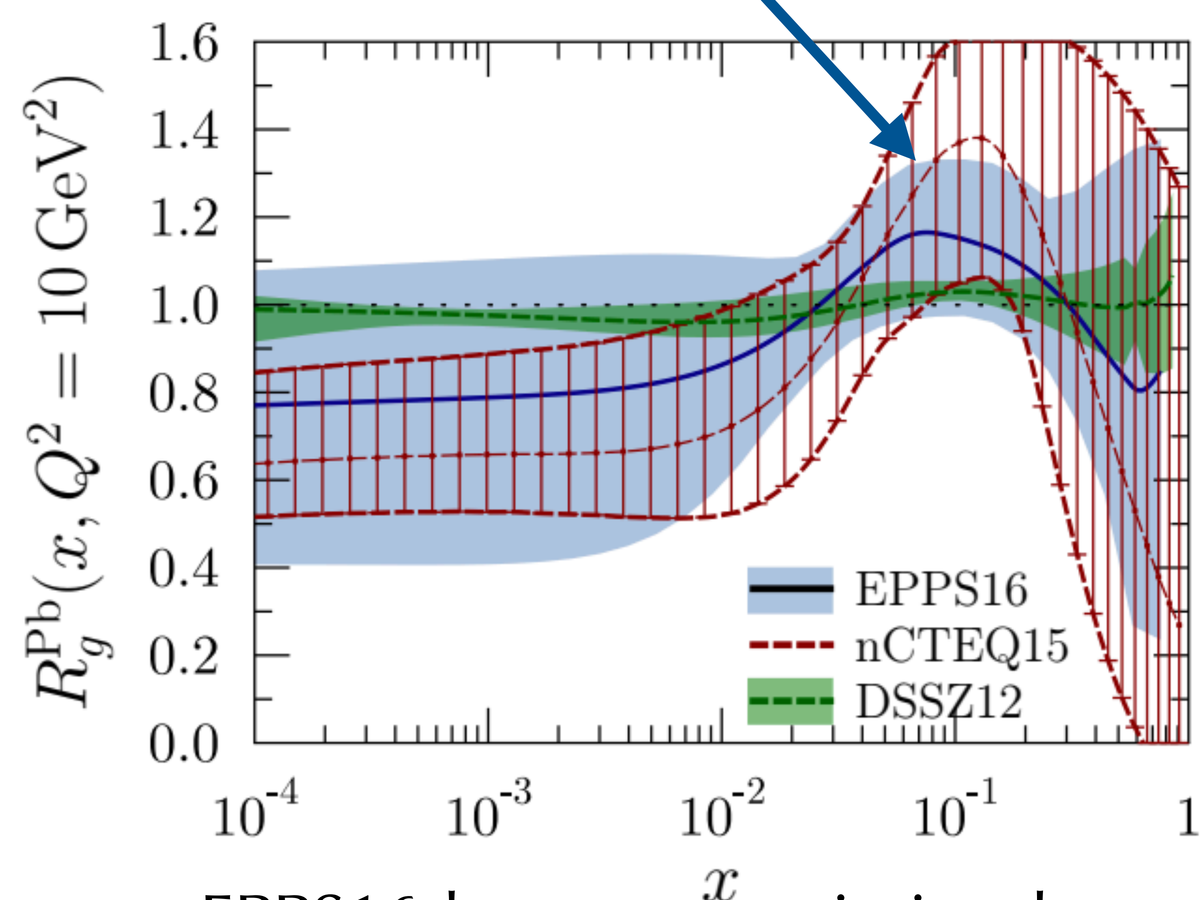
Run I Dijet data in EPPS16

- EPPS16 includes Run I **dijet forward-to-backward** data in p-Pb: constraints on the **gluon at large *x*** $(x \gtrsim 0.1)$



$\eta > 0:$ antishadowing, $\eta < 0:$ EMC effect

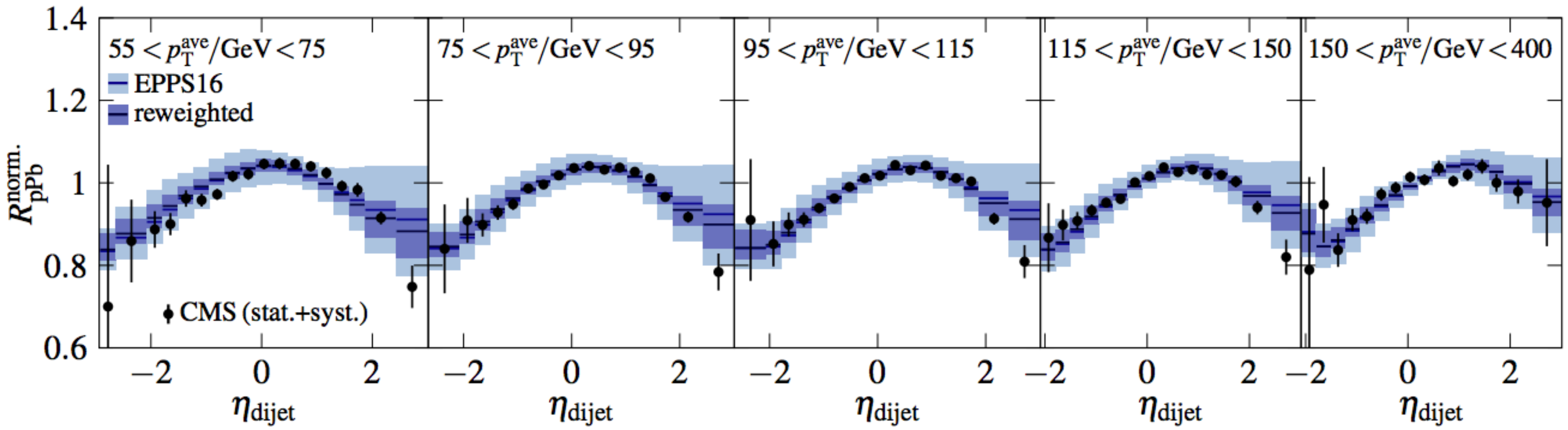
Enhancement



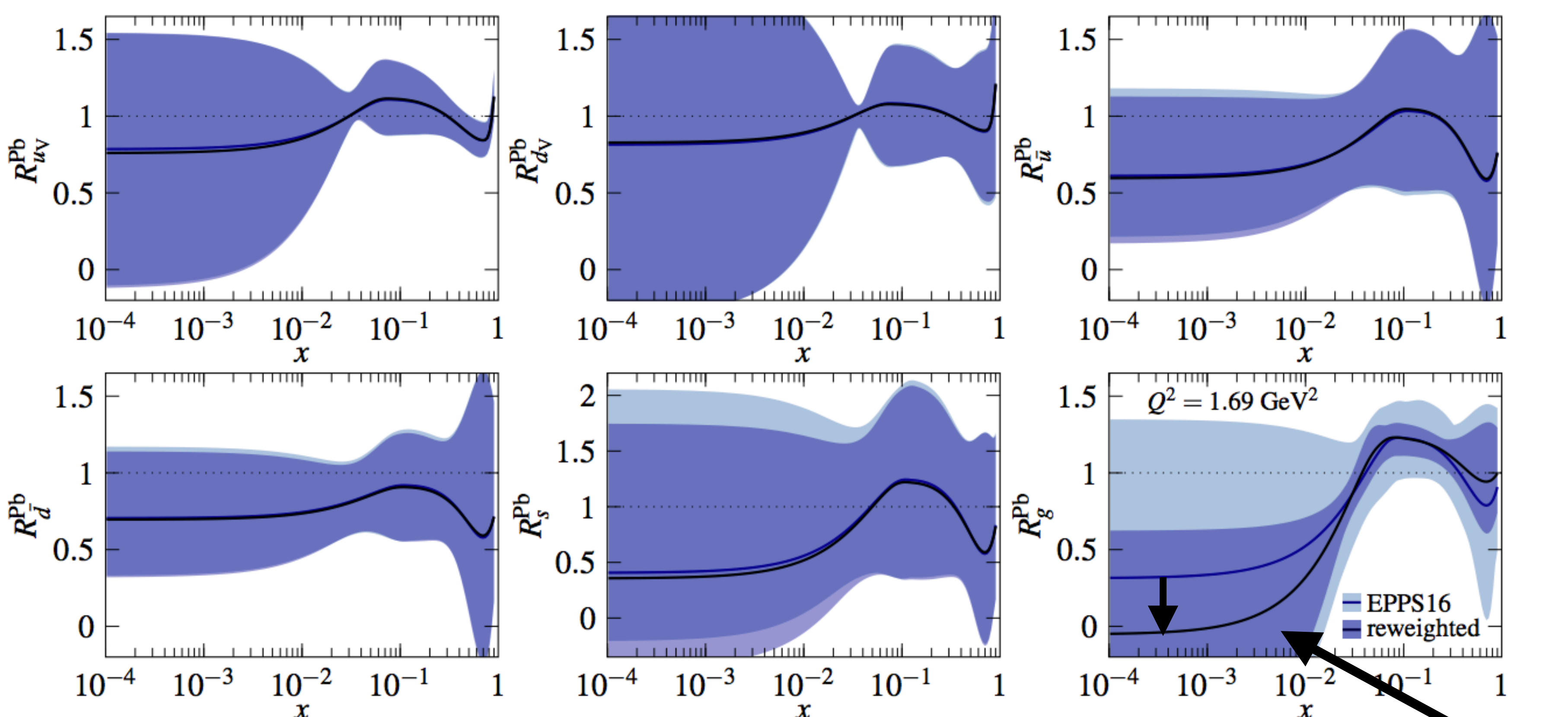
EPPS16 large uncertainties due to more free-parameters and more flexible parametrization

EPPS16: Eur. Phys. J. C 77 163 (2017)

Impact of dijet Run 2 CMS data



Non quadratic reweighting of EPPS16 NLO nPDFs



CMS dijet **p-Pb/p-p ratio** at 5.02 TeV $\left(x \gtrsim 3 \cdot 10^{-2}\right)$

Reduction of uncertainties of the nuclear gluon

More shadowing

Eur. Phys. J. C **79**, no. 6, 511 (2019)
Eskola, Paakkinen and Paukkunen

Nuclear gluons at RHIC

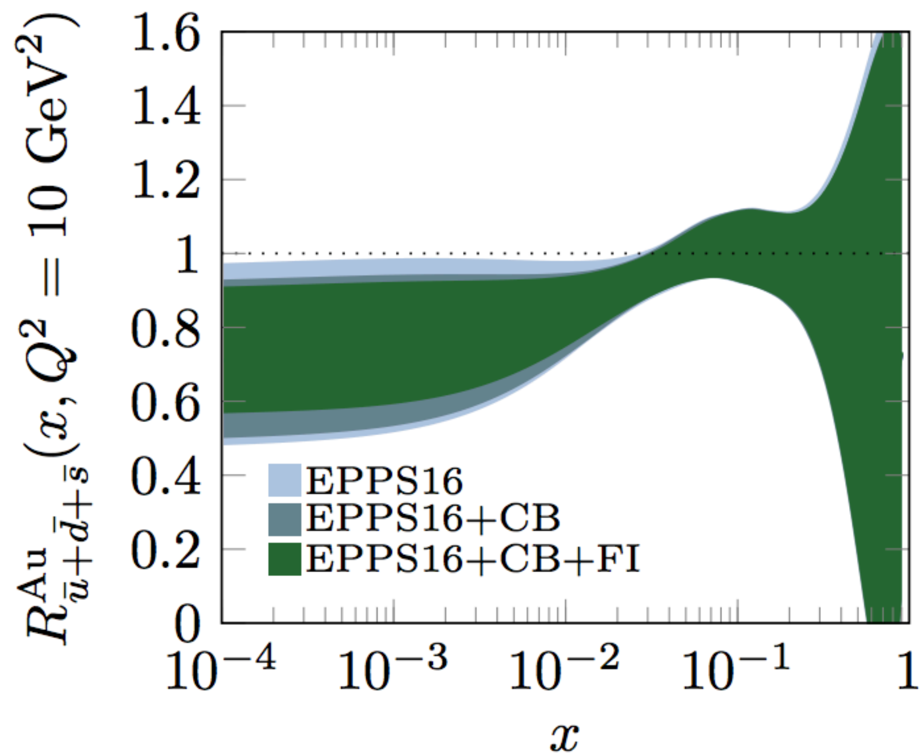
- Reweighting of **pseudodata** of future sPHENIX and STAR upgrades

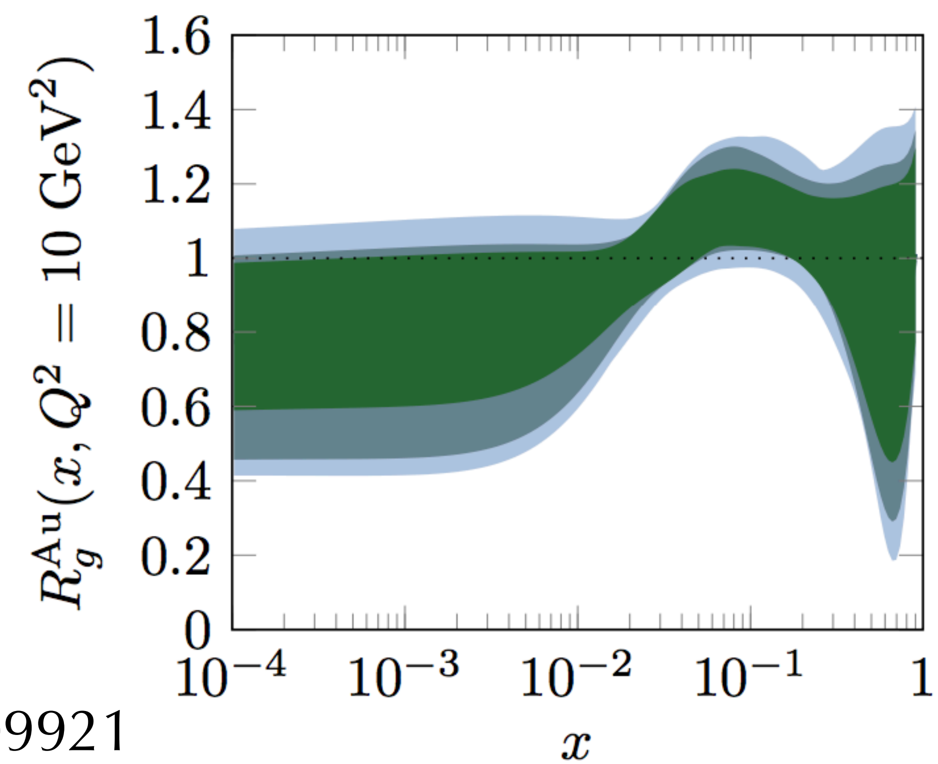
- Forward and central rapidity pseudodata considered

Central-central	Forward-central	Forward-forward
Drell-Yan		Drell-Yan
Dijets	Dijets	
Photon-jet		

- **Several observables** considered to overcome the normalization of the R_{pA}

- DY is only able to constrain the gluon at low-*x* when employed with other observables (dijets, photon-jet)





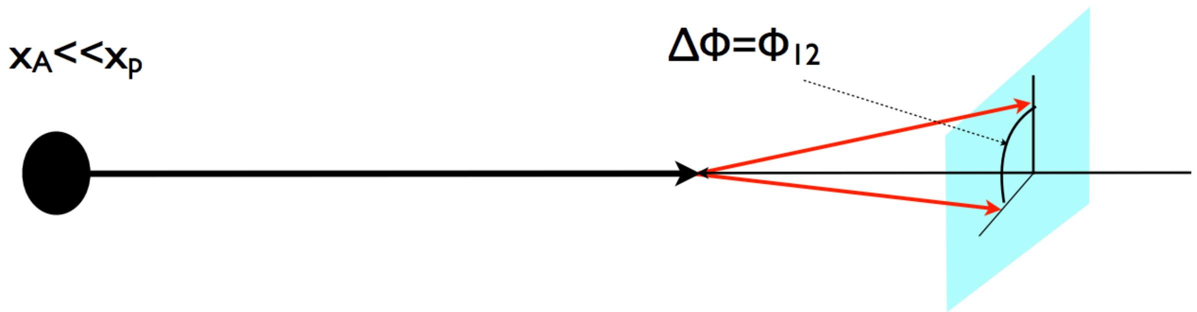
arXiv:1904.09921
Helenius, Lajoie, Osborn, Paakkinen, Paukkunen

Correlations in pA/eA

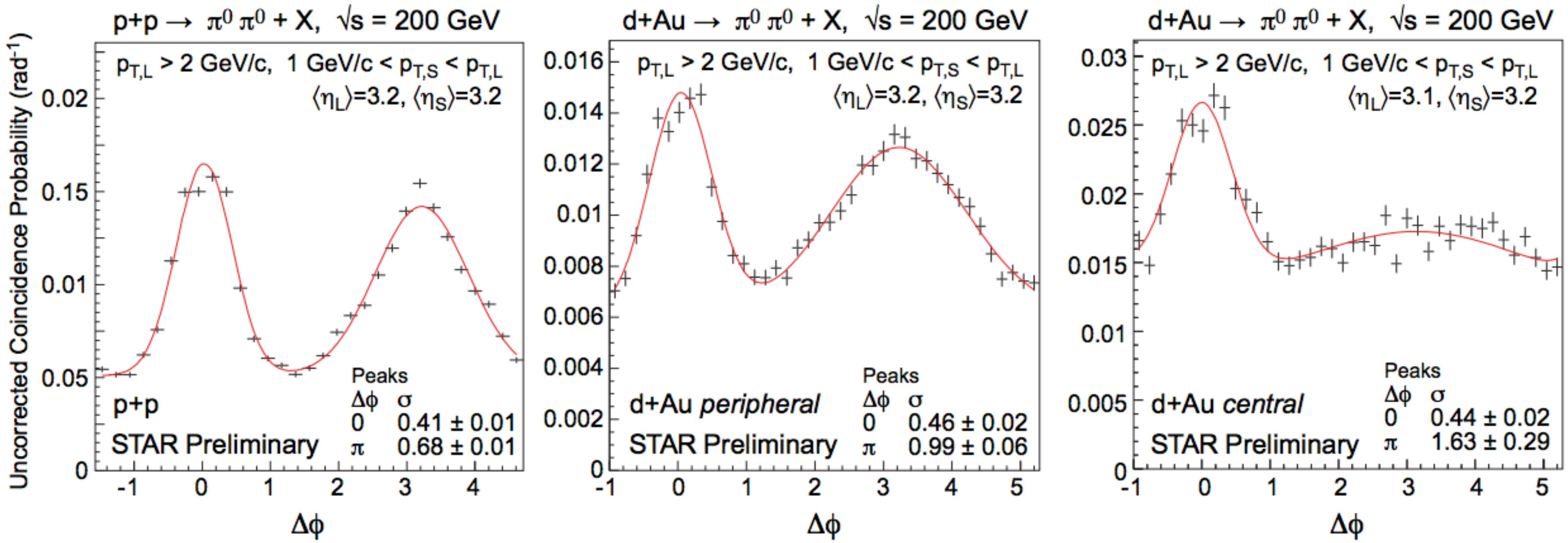
Di-hadron (de)correlations

- In the saturation regime: the away-side peak is expected to broaden

Kharzeev, Eugene Levin, McLerran
Nucl. Phys. A748 627 (2005)



E. Braidot, Nucl. Phys. A 854, 168 (2011)

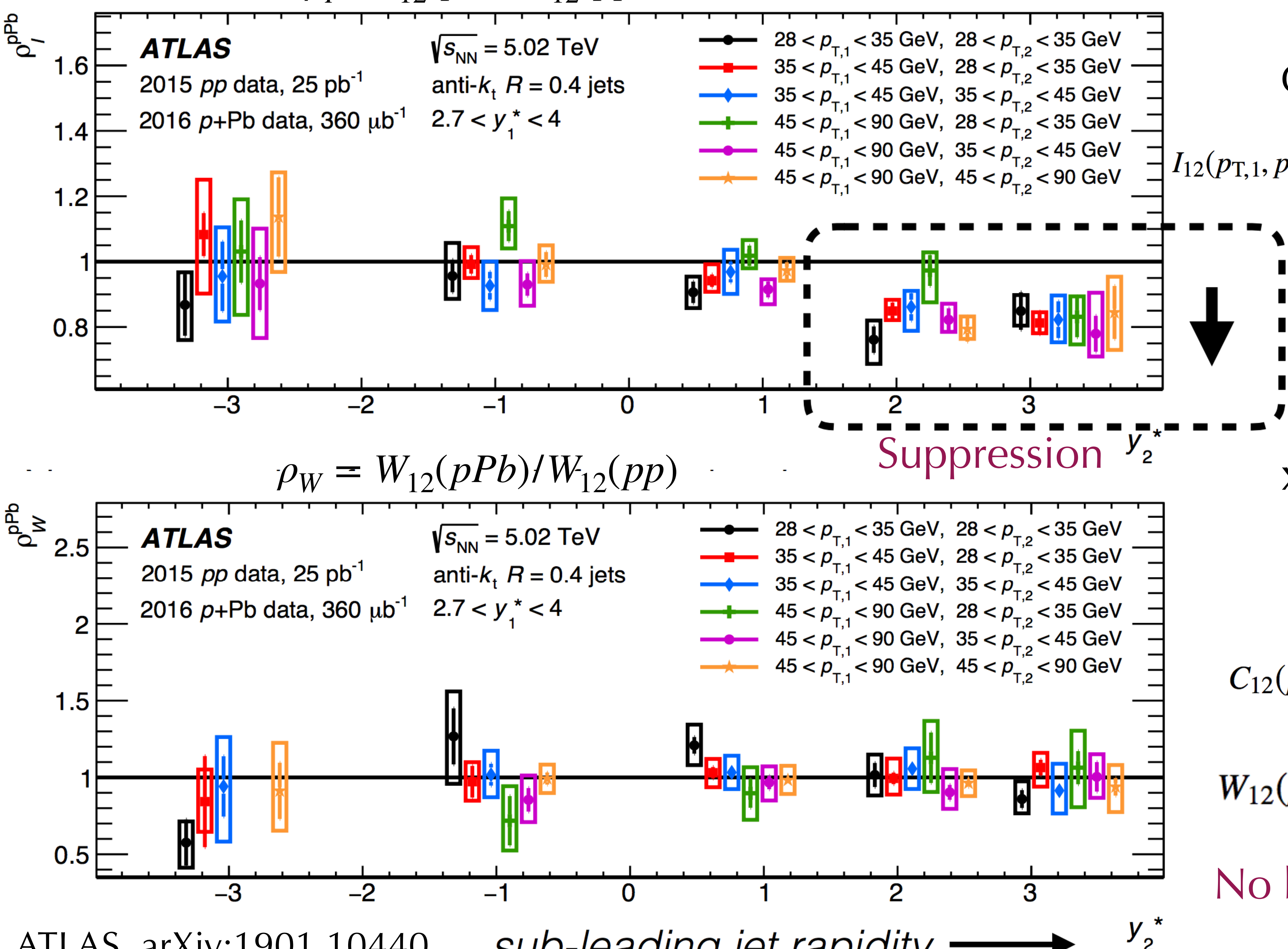


- Hints of saturation at RHIC (other mechanisms proposed to explain this suppression)
- We still need the ultimate experimental proof of saturation

Dijet (de)correlations

See D. Perepelitsa talk (Wed afternoon)

$\rho_I = I_{12}(pPb)/I_{12}(pp)$



Conditional jet yield:

$$I_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{d^4N_{12}}{dy_1^* dy_2^* dp_{T,1} dp_{T,2}}$$

$x_A \sim 10^{-4}$ to 10^{-3}

$$C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{dN_{12}}{d\Delta\phi}$$

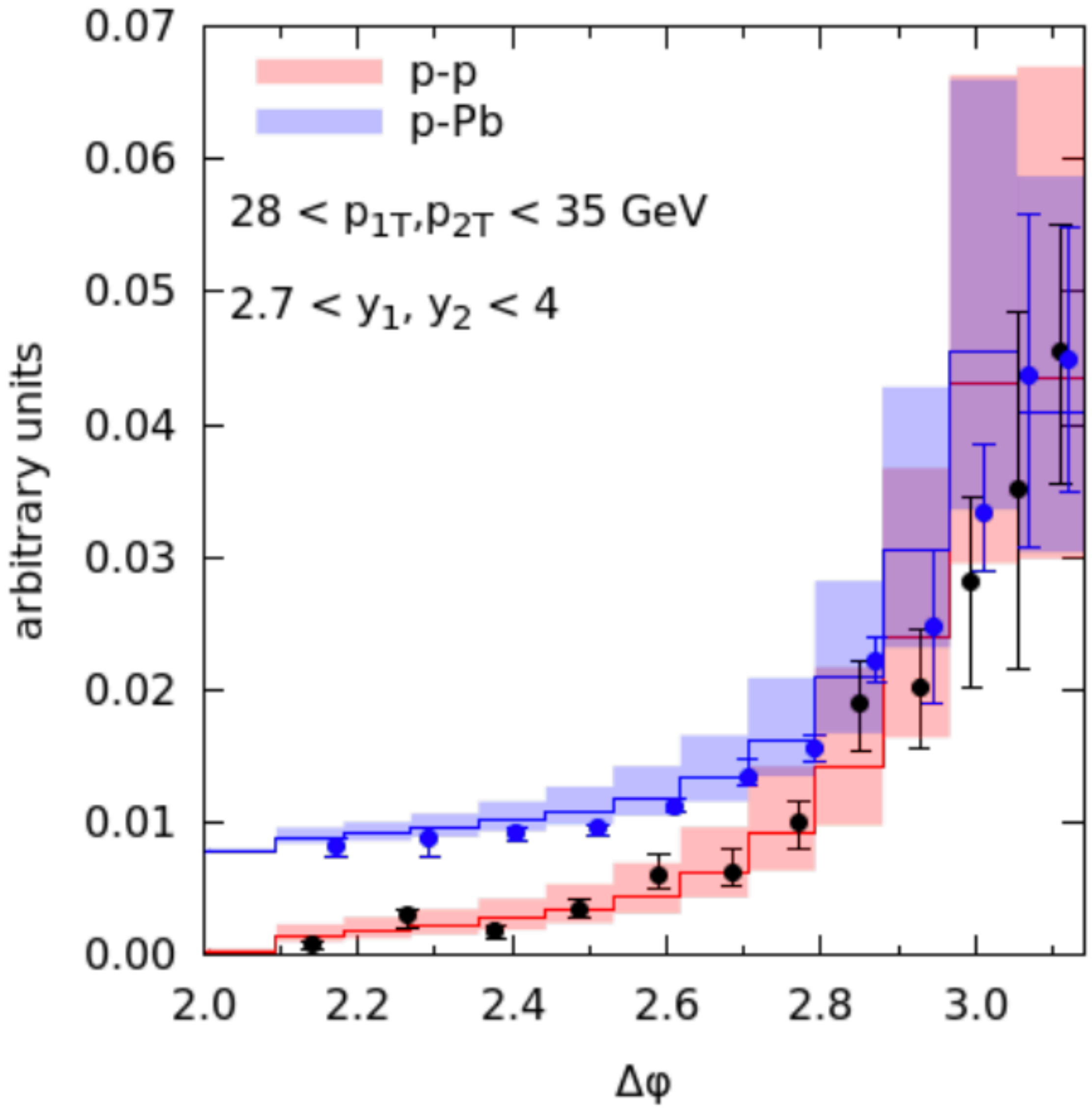
$$W_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \mathrm{RMS}(C_{12})$$

No broadening!

ATLAS, arXiv:1901.10440

Dijet (de)correlations

See D. Perepelitsa talk
(Wed afternoon)

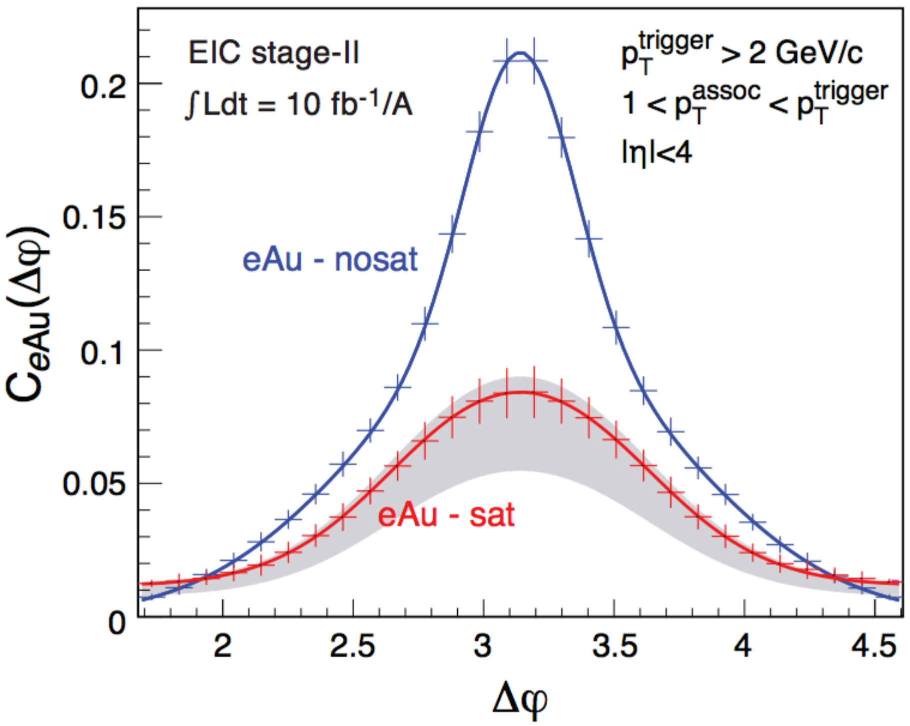


arXiv:1903.01361
van Hameren, Kotko, Kutak, Sapeta

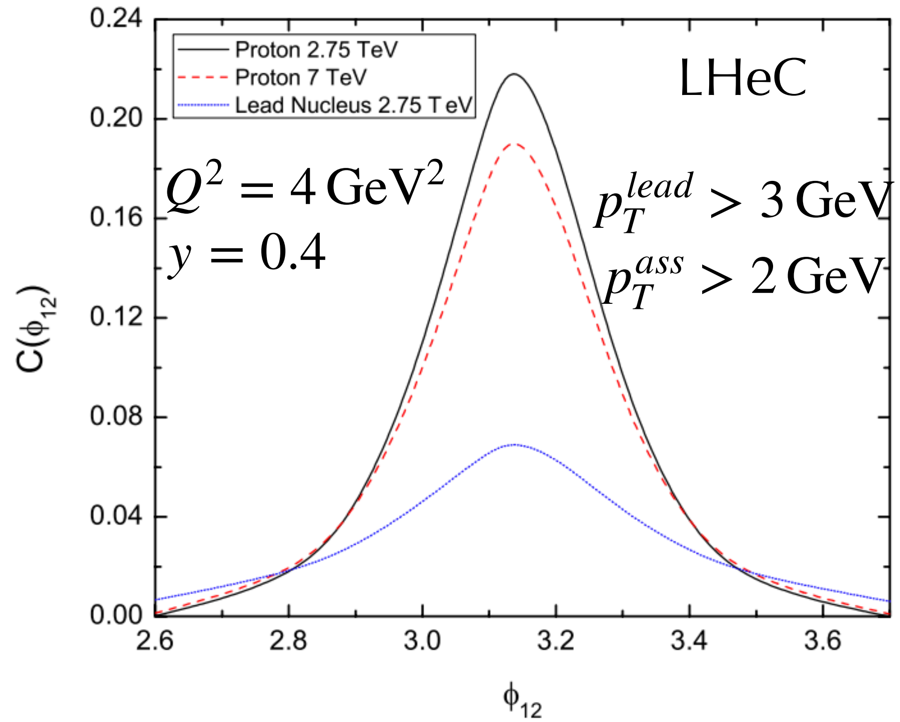
Good description
ITMD factorization+ Sudakov resummation

Correlations at the EIC/LHeC/FCC

- Di-hadron correlations at the EIC and LHeC (eA)
- Di-jet correlations at the FCC (pPb)

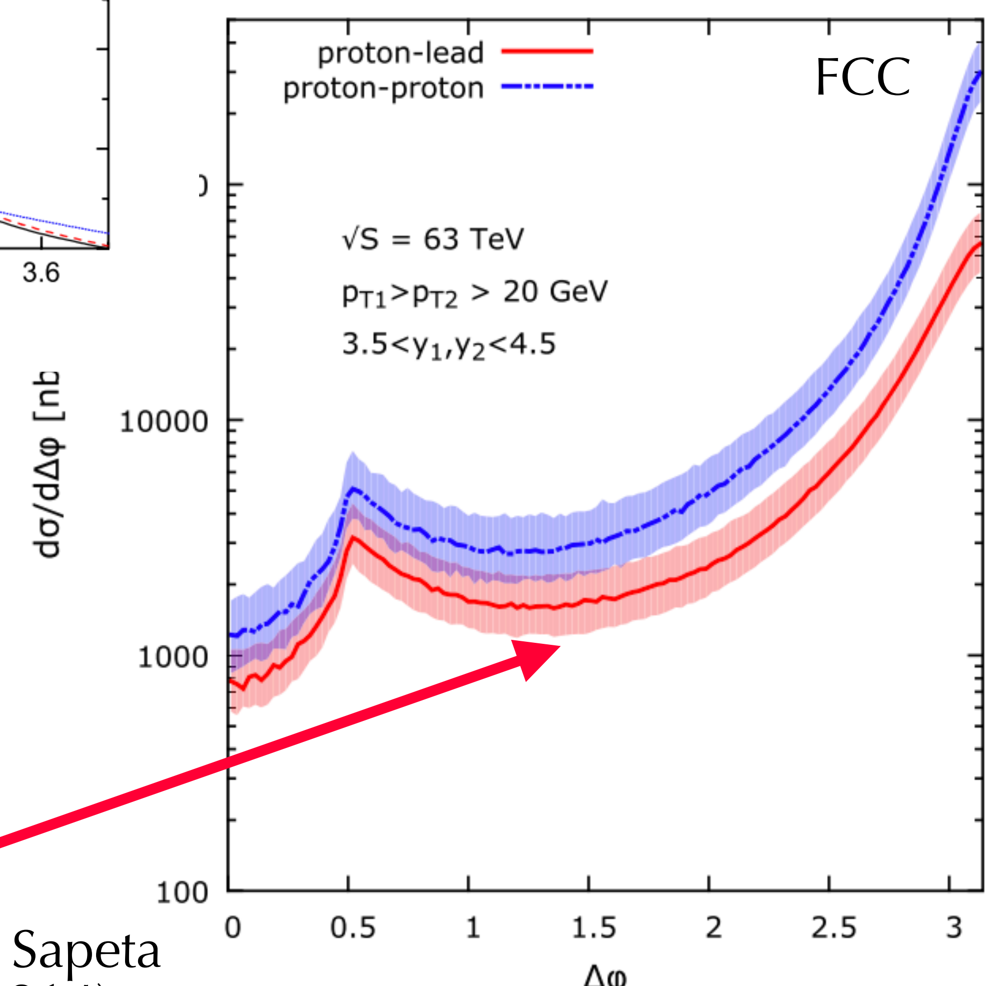


EIC white paper
arXiv:1212.1701



LHec white paper,
arXiv: 1206.2913

FCC Physics Opportunities
Eur. Phys. J. C 79 474 (2019)



Dominguez, Marquet, Xiao, Yuan
Phys. Rev. D83, 105005 (2011)

Dominguez, Xiao,Yuan
Phys.Rev.Lett.106 022301 (2011)

Zheng, Aschenauer, Lee, Xiao,
Phys. Rev. D89 074037 (2014)

Hameren, Kotko, Kutak, Marquet, Sapeta
Phys. Rev. D 89(9), 094014 (2014)

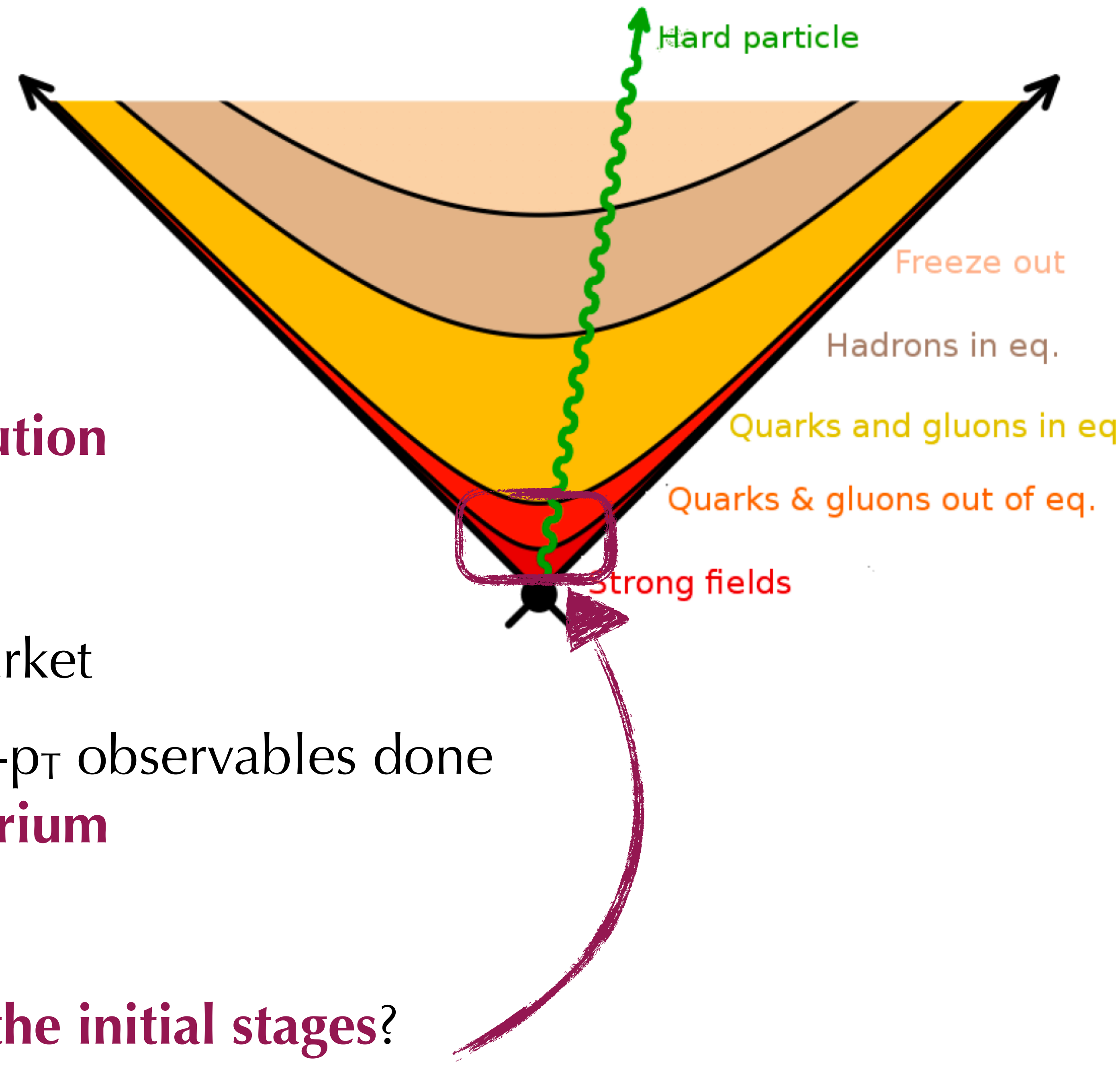
Jets & initial stages in AA

Jets in A-A

- Mainly used to study **jet quenching**

- Most of hard probes/jets are produced with the collision

Jets **witness the space-time system evolution**



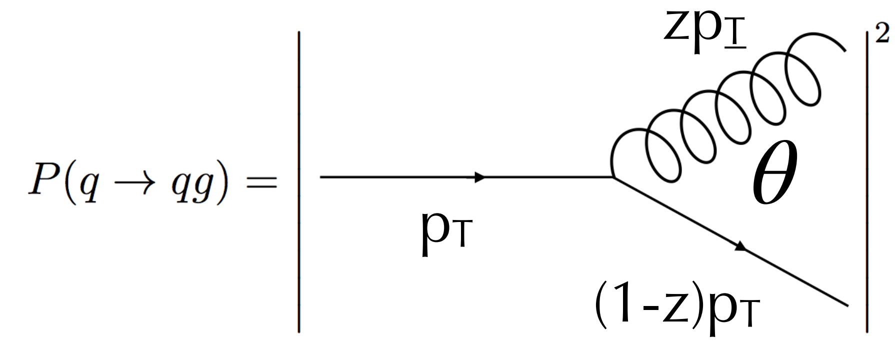
- Many jet quenching models in the market

Phenomenological comparisons to high-p_T observables done **assuming a thermalized QGP in equilibrium**

- How **sensitive are jet observables to the initial stages**?

Mapping the branching

- Lund plane uniformly populated with emissions (in vacuum) $dP \propto \frac{dz}{z}\frac{d\theta}{\theta}$



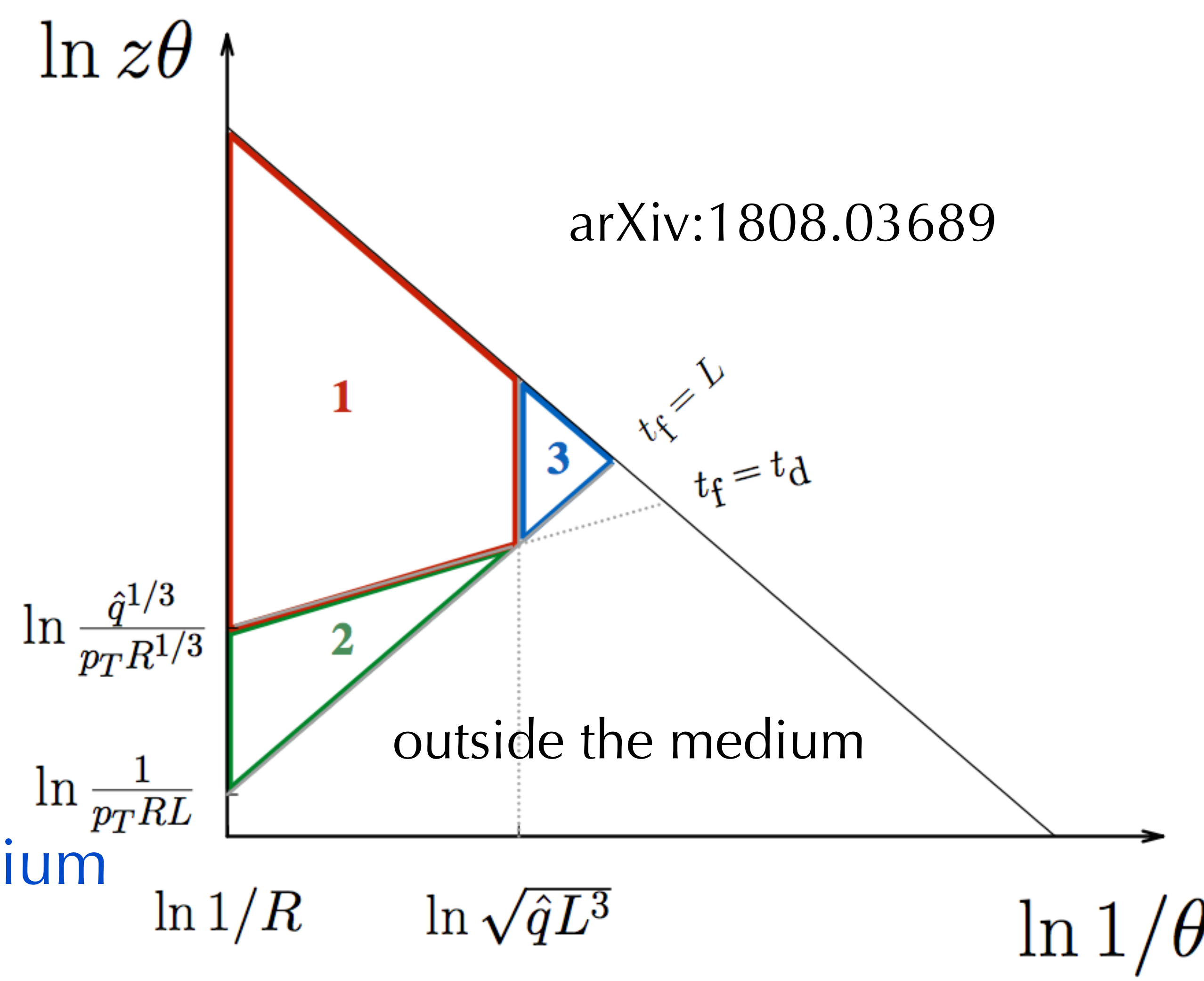
- How do medium scales impact on jet observables?

- Different types of emissions:

1) $t_f < t_d < L$: in-medium vacuum splittings

2) $t_d \lesssim t_f$: medium dominates

3) $t_d > L$: antenna never resolved by the medium

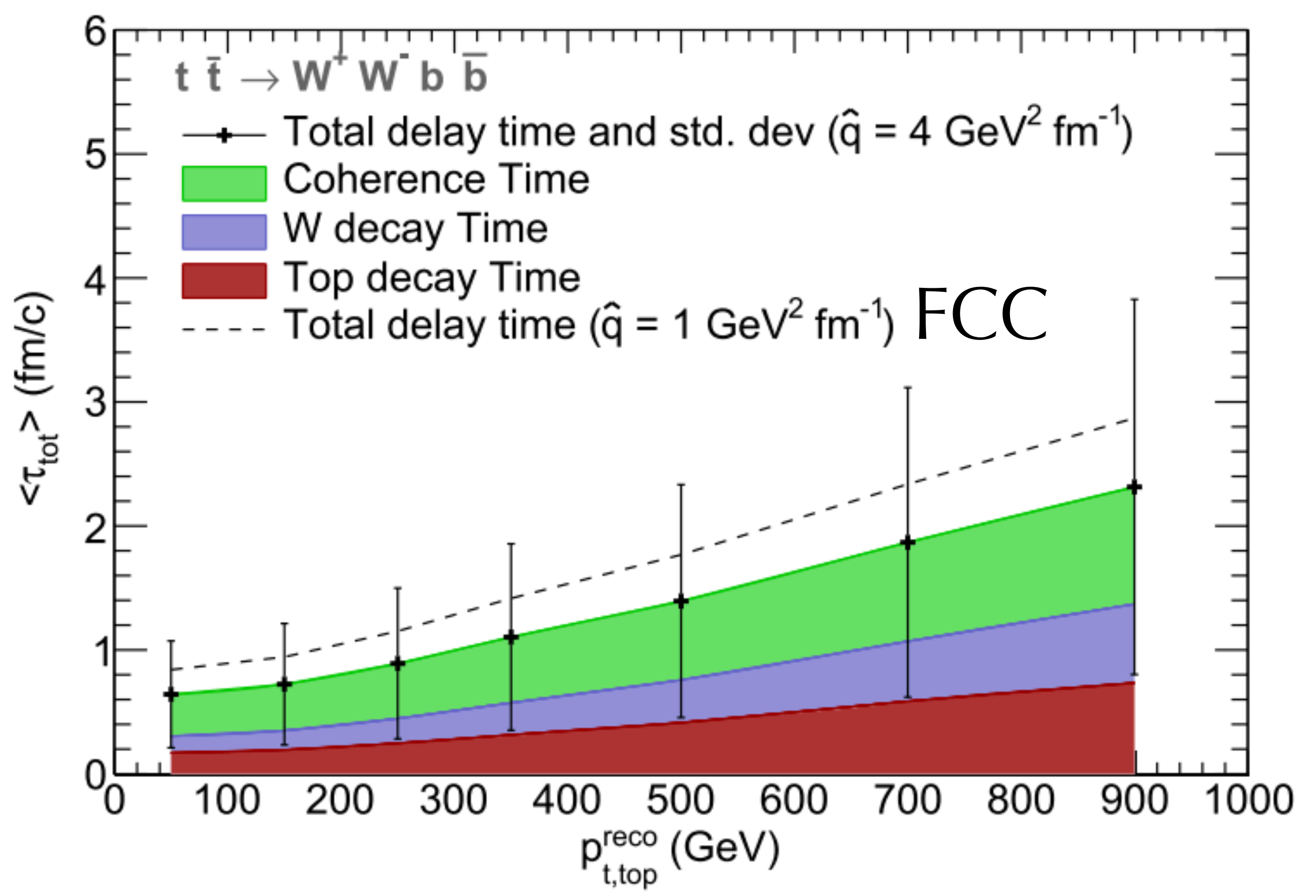


Boosted tops

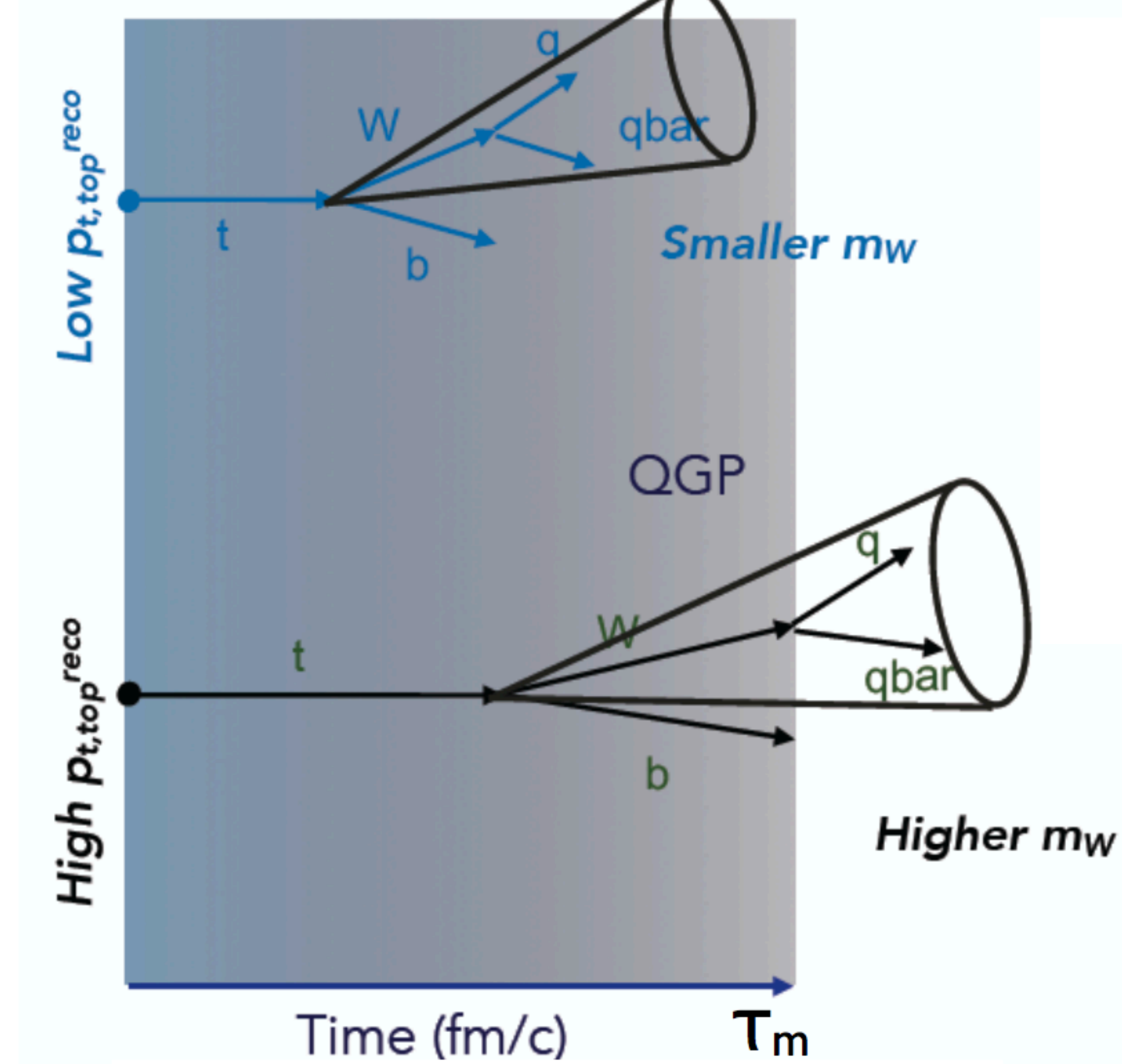
Apolinário, Milhano, Salam, Salgado
PRL 120, 232301 (2018)

- Large energies (FCC) make boosted tops available

- Controlling the boost of the top ⟶ **Controlling when jets start to interact** with medium



$0.5 < t < 3$ fm

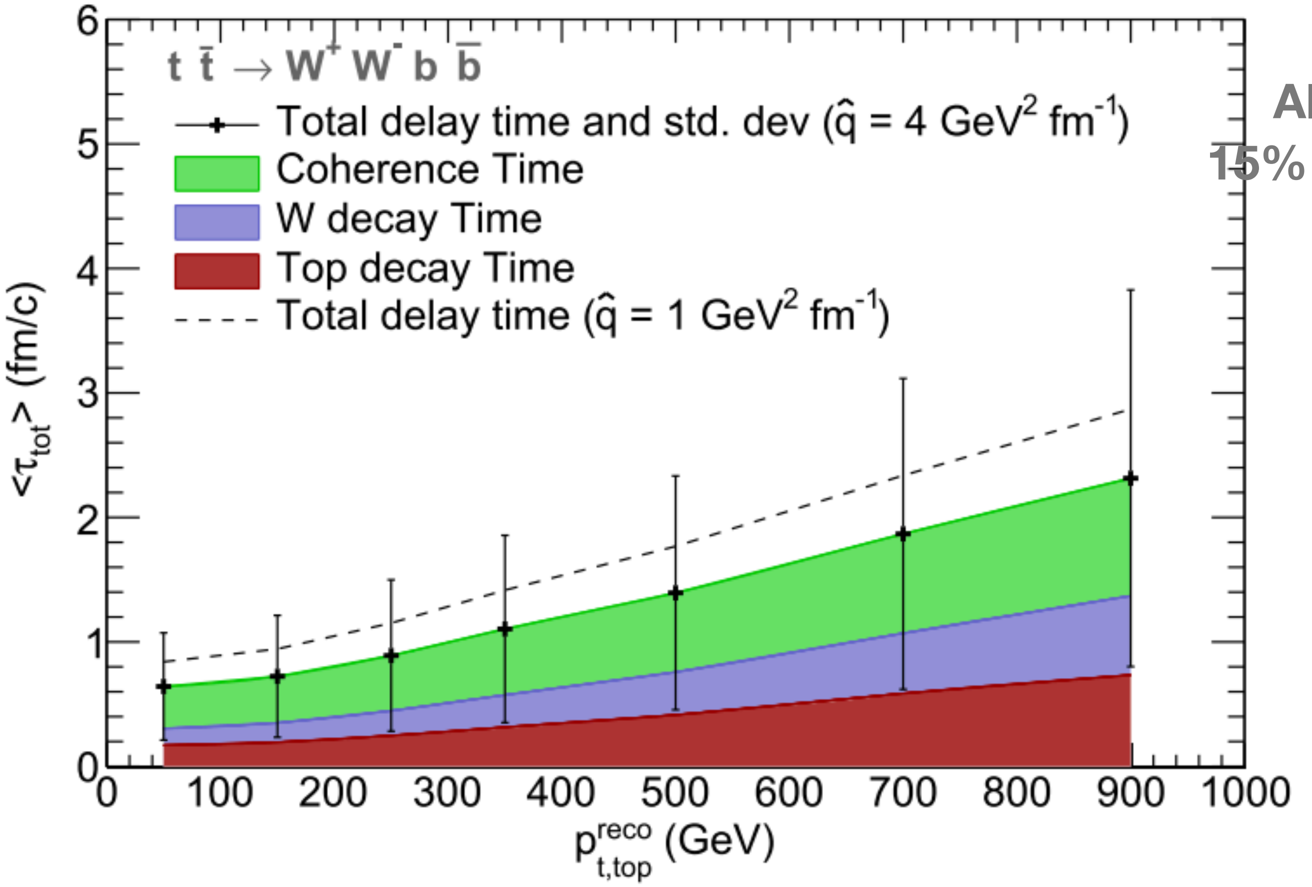


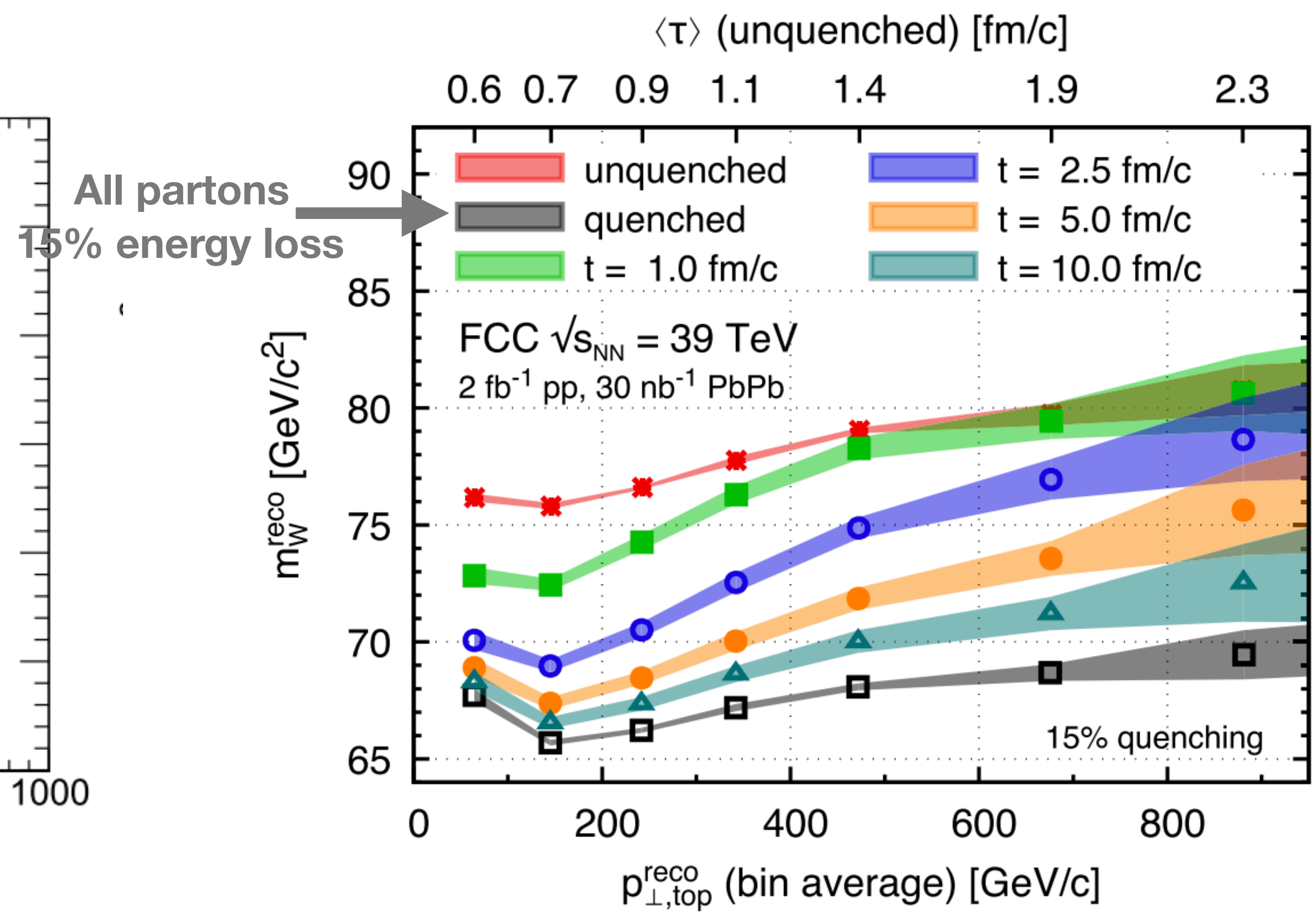
$$\langle \tau_{\rm tot} \rangle = \gamma_{t,{\rm top}} \tau_{\rm top} + \gamma_{t,W} \tau_W + \tau_d$$

Boosted tops

Apolinário, Milhano, Salam, Salgado
PRL 120, 232301 (2018)

- **Reconstructed W mass** as a function of the top p_T: useful to probe **QGP evolution**

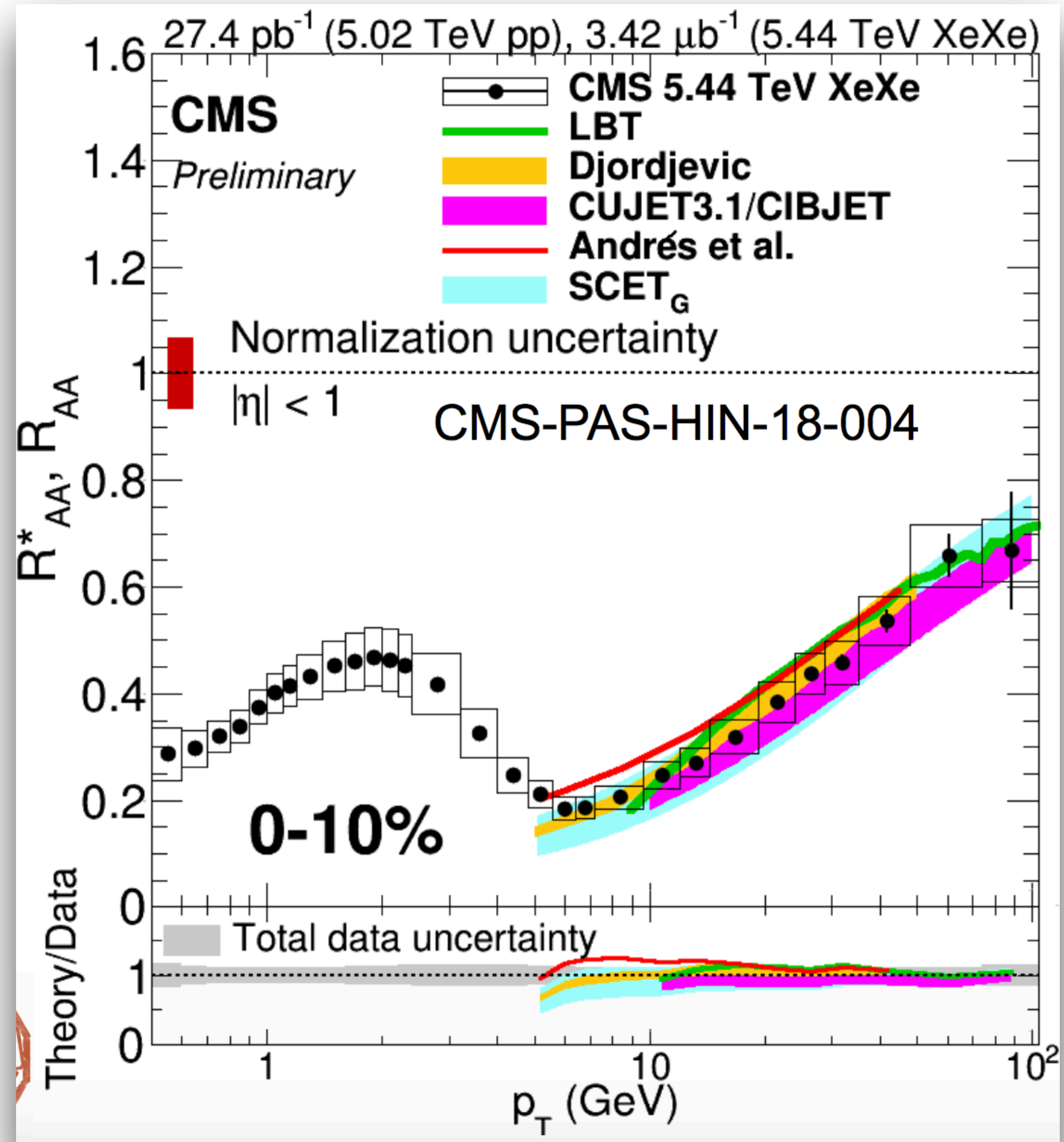




- **Access** to both **small and large times** of the medium evolution with jet quenching

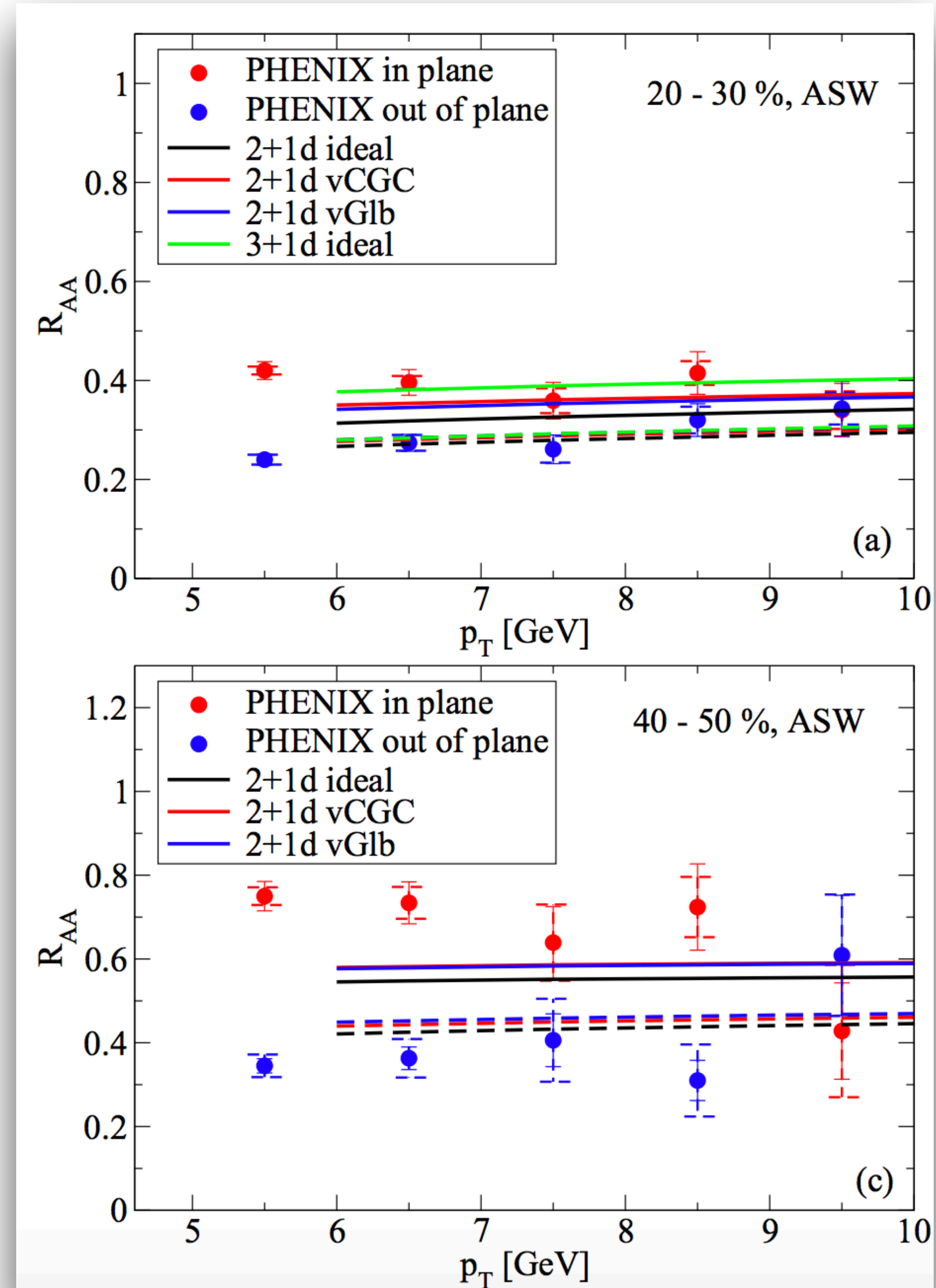
Jet quenching as a chronometer of the yoctosecond structure of the evolution process

R_{AA} and high-p_T v_2



Austin Baty, QM2018

Smooth averaged hydros



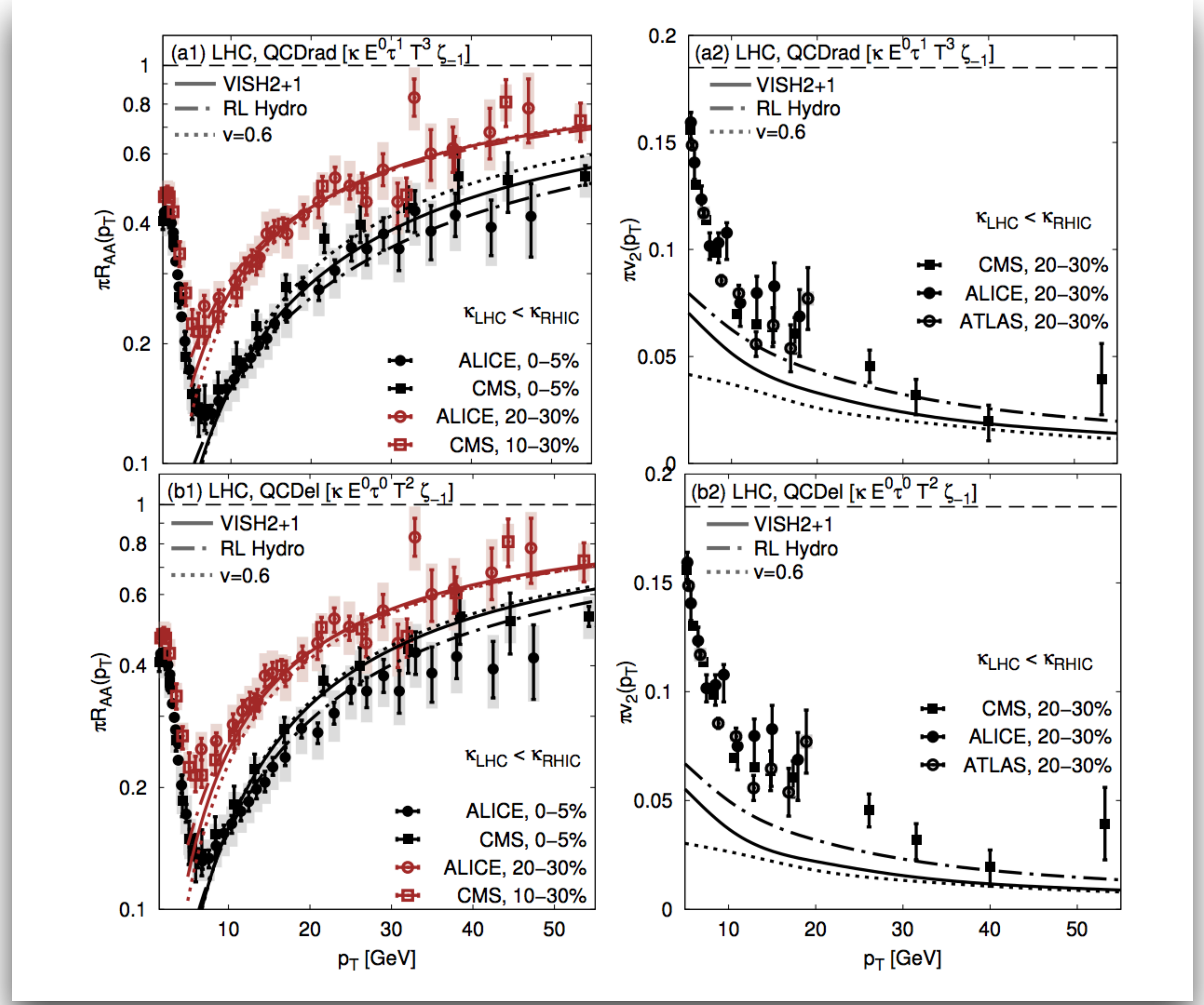
Renk, Holopainen, Heinz, Shen
Phys. Rev. C 83 (2011) 014910

High-p_T v_2

Betz and Gyulassy
JHEP 08, 090 (2014)

$$\frac{dE}{dL} \sim LT^3$$

$$\frac{dE}{dL} \sim T^2$$



The scalar product

Average over all the events

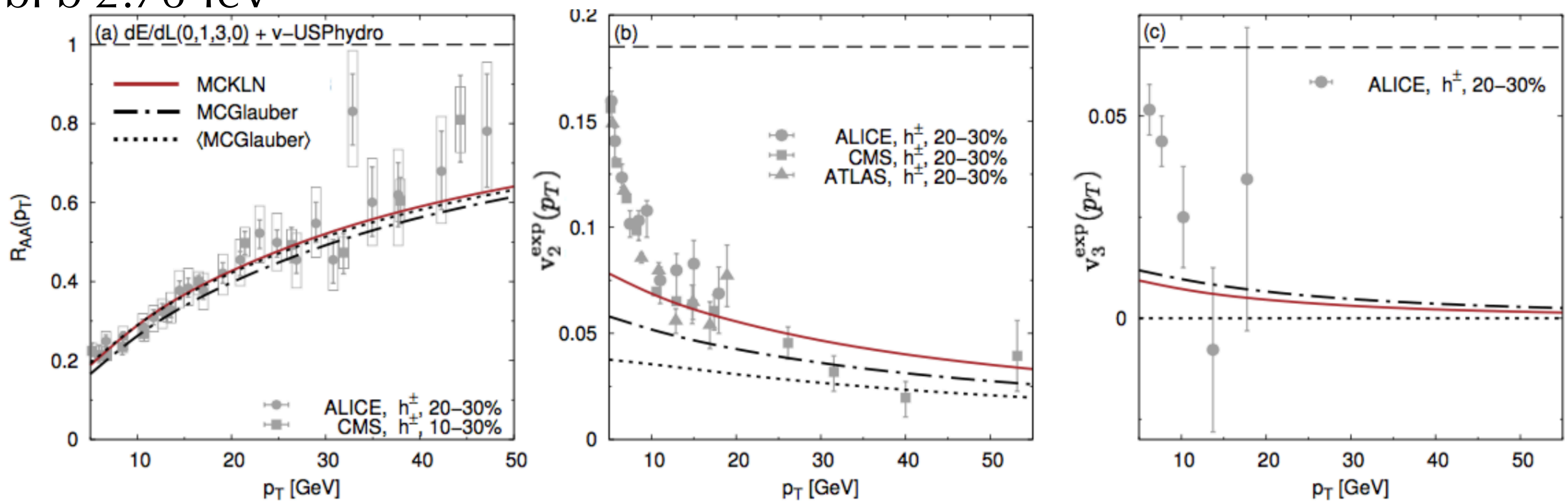
$$\frac{R_{AA}(p_T,\phi)}{R_{AA}(p_T)} = 1 + 2\sum_{n=1}^{\infty} v_n^{hard}(p_T)\cos\left[n\phi - n\psi_n^{hard}(p_T)\right]$$

$$v_n^{exp}(p_T) = \frac{\left\langle v_n^{soft}\, v_n^{hard}(p_T)\cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right)\right]\right\rangle}{\sqrt{\left\langle\left(v_n^{soft}\right)^2\right\rangle}}$$

Luzum, Ollitrault, Phys. Rev. C87 (2013) 044907

Noronha-Hostler et al. Phys. Rev. Lett. 116, 252301 (2016)

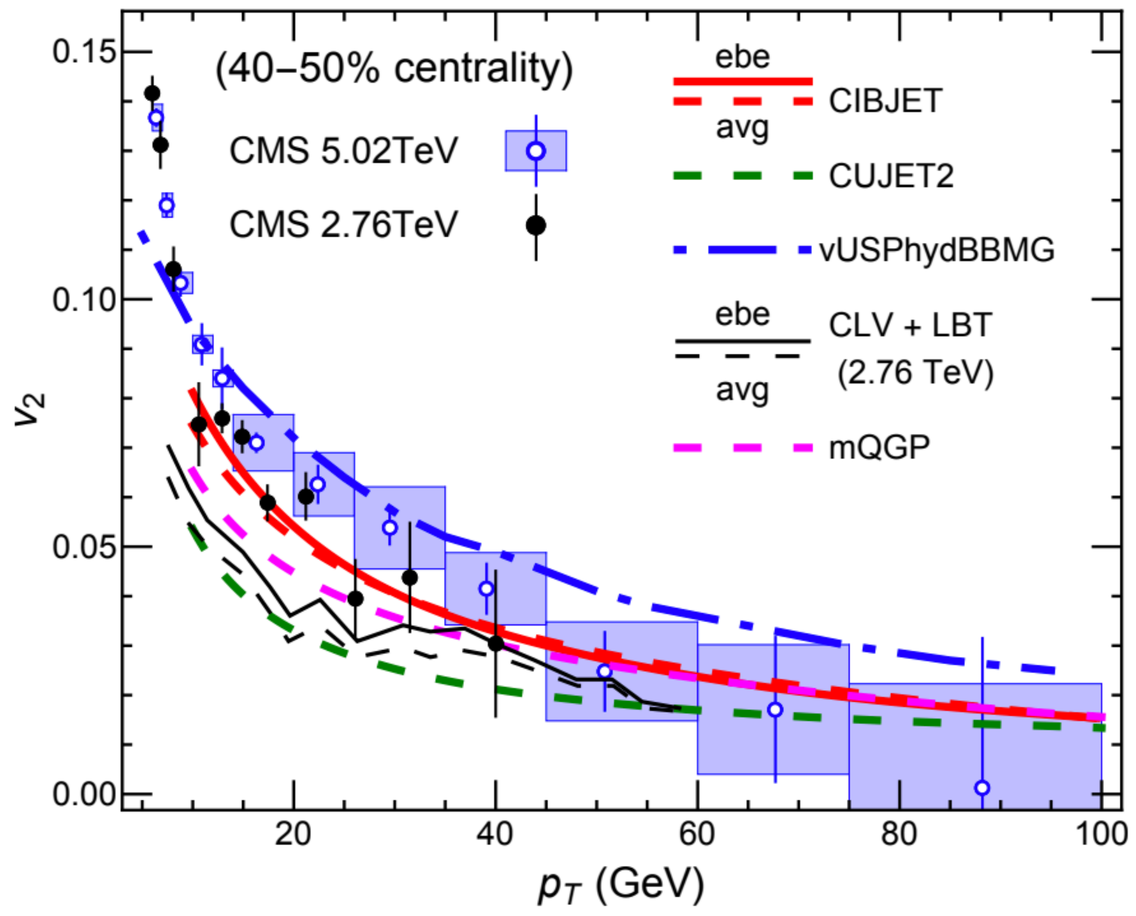
PbPb 2.76 TeV



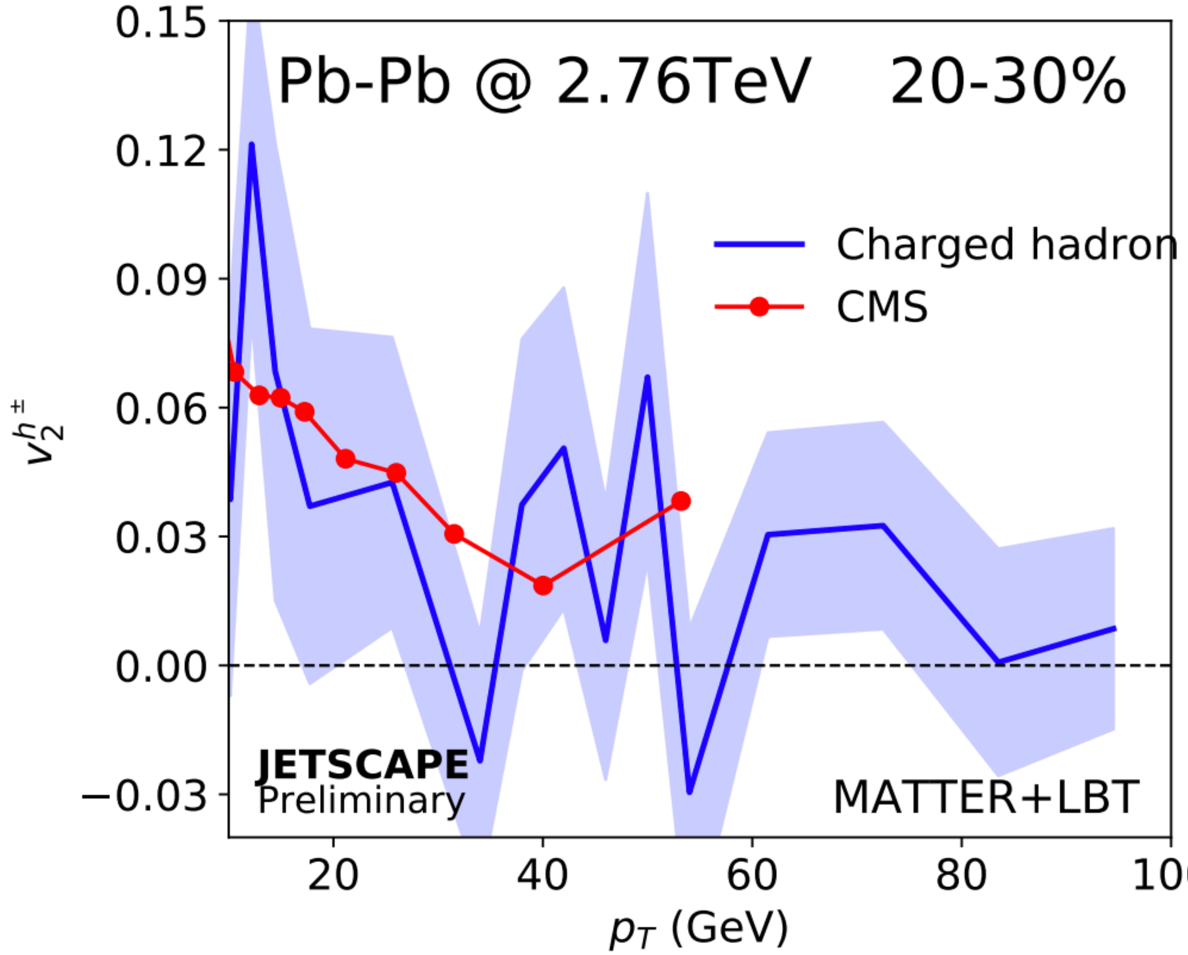
Energy loss $\frac{dE}{dL} \sim LT^3$

Hydro: v-USPhydro $\tau_0 = 0.6\,\text{fm}$

High-p_T v_2



Shi, Liao, Gyulassy
Chin. Phys. C42 (2018) 10 104104



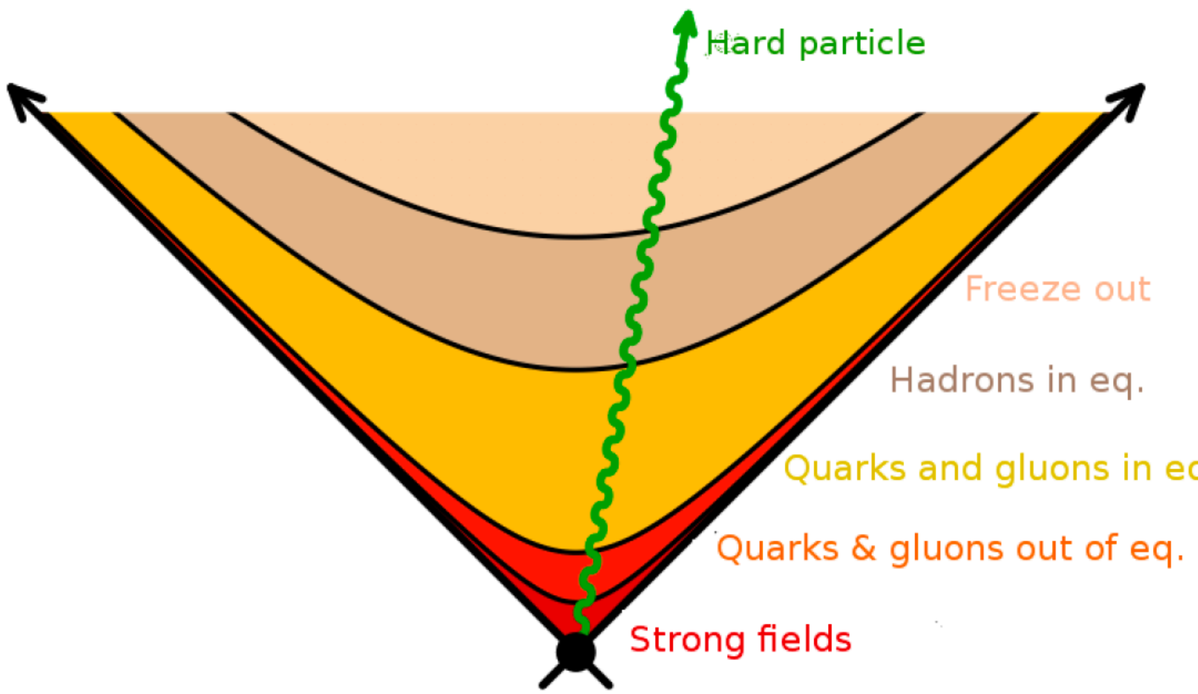
JETSCAPE
arXiv: 1902.05934

What are the ingredients?

- Many different energy models/hydros describing the high-p_T v_2 in the last years

- Let's go back to the (common) assumptions:

What are we doing with the pre-equilibrium phase of the system?



- The **quenching set to start at the initialization time** of the hydro (usually ~0.6 fm)

No energy loss before thermalization?

Proof of concept

CA, Armesto, Niemi, Paatelainen, Salgado
arXiv: 1902.03231

- Take a hydro with pre-equilibrium evolution:
  - EKRT EbyE hydrodynamics

    Niemi, Eskola, Paatelainen
    Phys. Rev. C 93, 024907 (2016)

    Initial conditions: minijets + saturation model

    $\tau_f = 0.197\,\text{fm}$ (**smaller** than usual)

- Take an energy loss model
  - Quenching Weights (QWs)

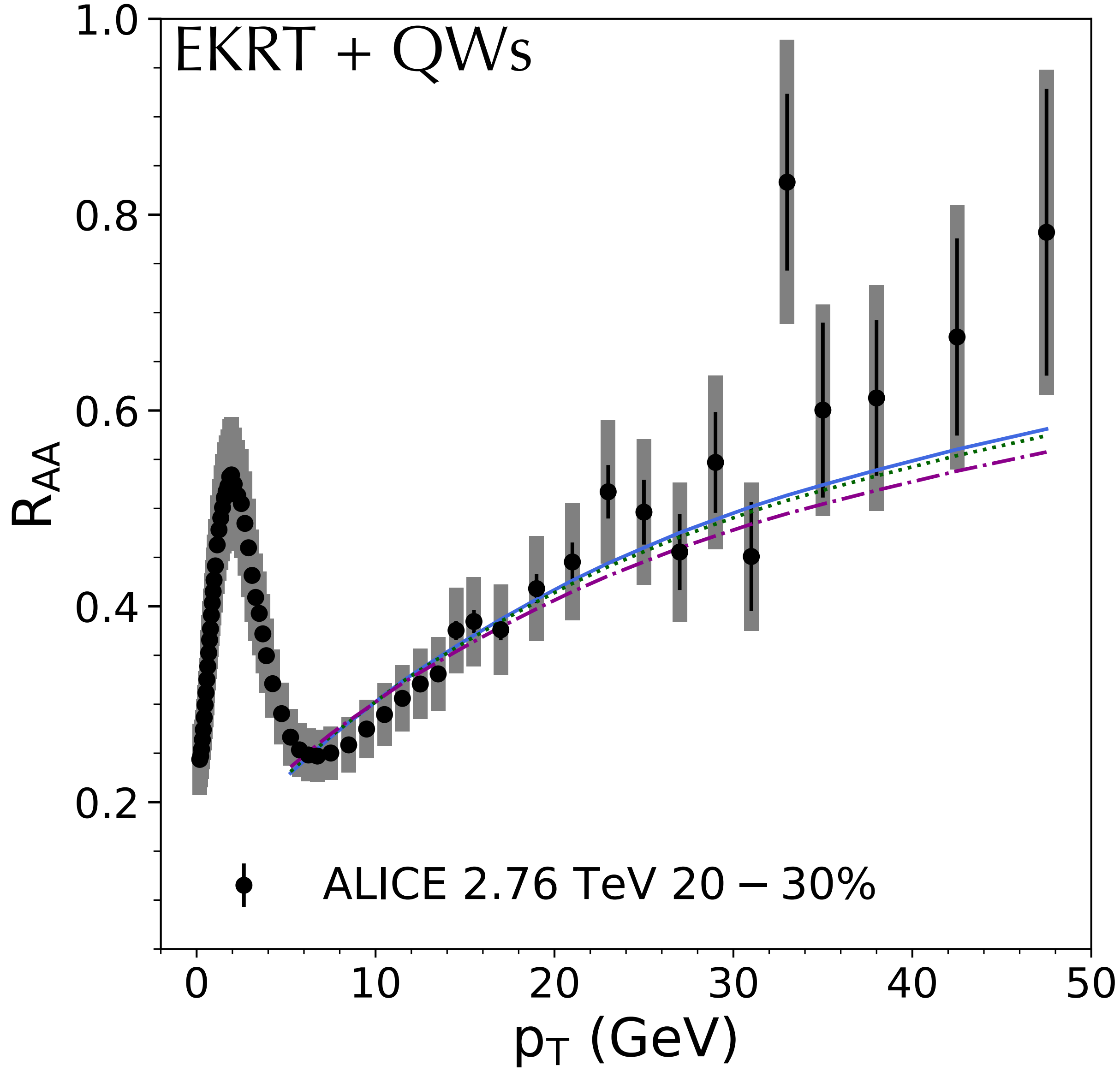
    $$\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$$

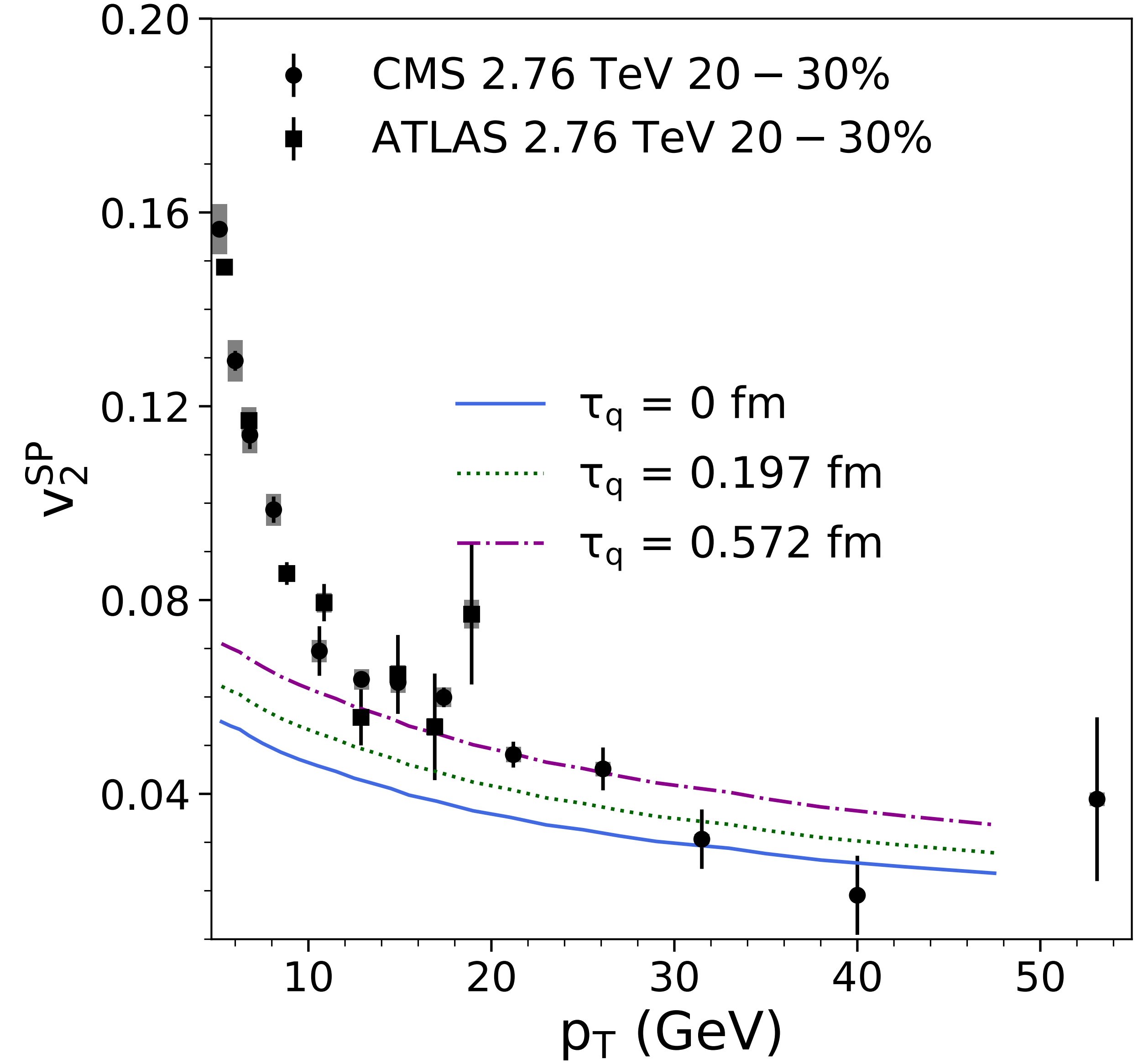
    Salgado and Wiedemann
    Phys. Rev. D 68, 01400 (2003)

- Compute the v_2 in the hard sector using the scalar product

High-p_T v_2 as a probe of IS

CA, Armesto, Niemi, Paatelainen, Salgado
arXiv: 1902.03231

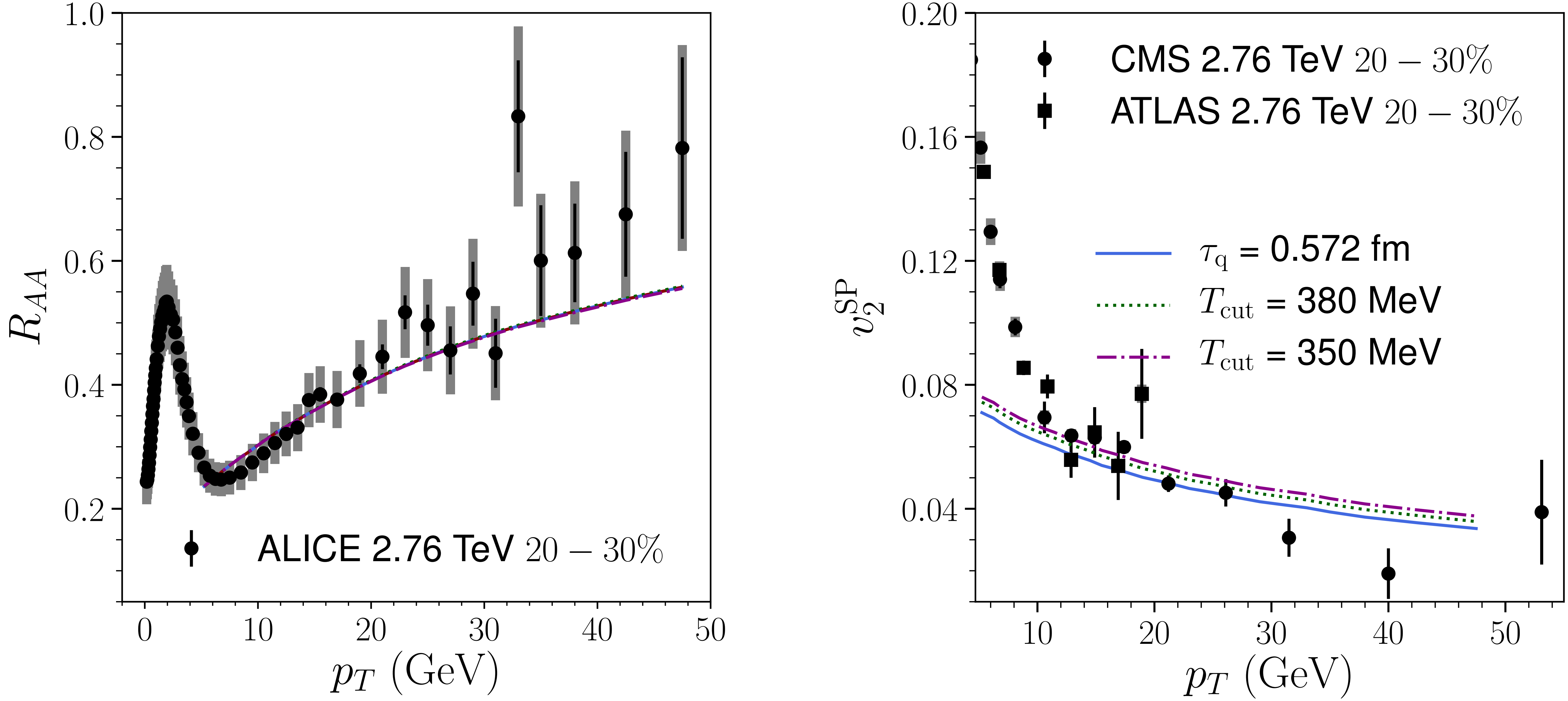




High-p_T harmonics are very sensitive to initial stages!

High-p_T v_2 as a probe of IS

CA, Armesto, Niemi, Paatelainen, Salgado
arXiv: 1902.03231



High-p_T harmonics are very sensitive to initial stages!

Eccentricity from hard probes

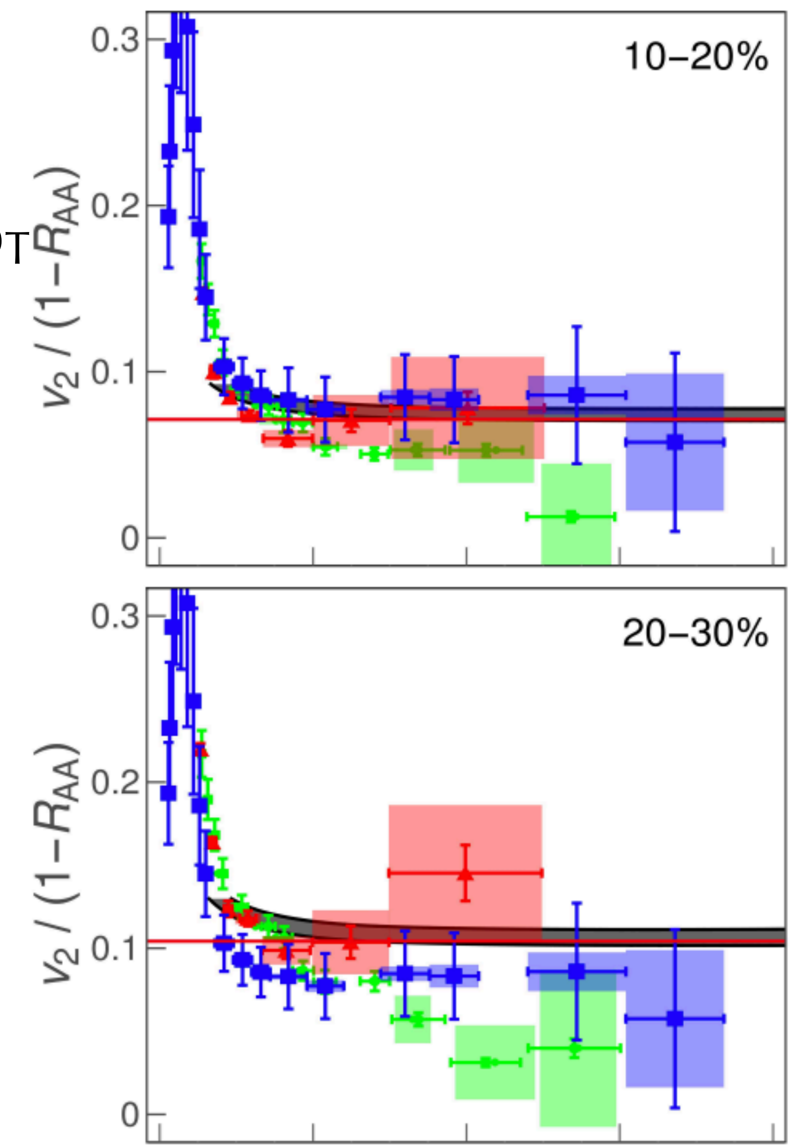
- Using scaling arguments: $v_2/(1-R_{AA})$ is proportional to the initial anisotropy at high-p_T

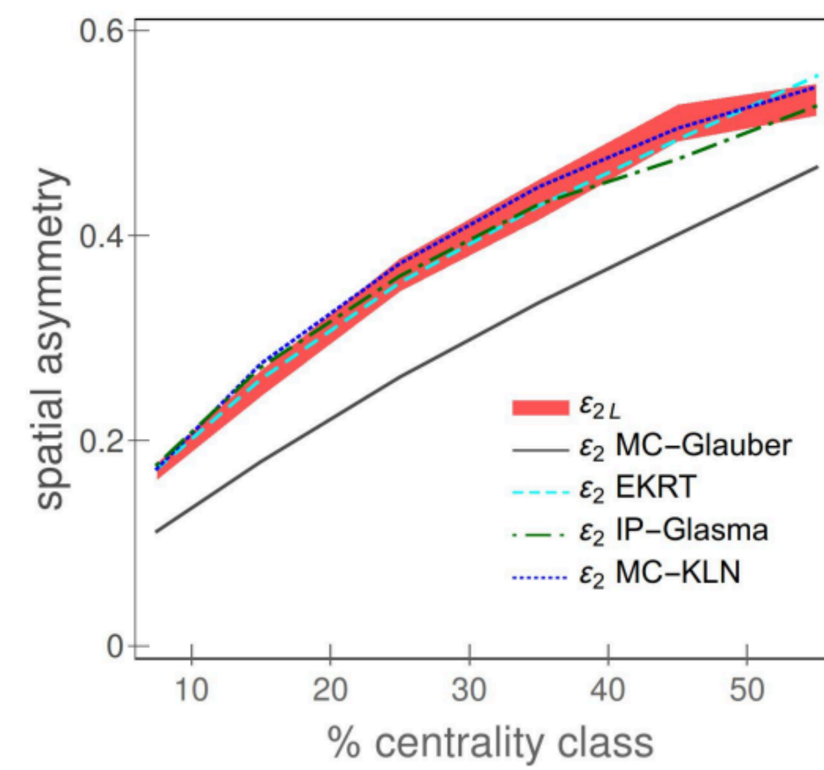
See M. Djordjevic talk
(Wed afternoon)

- $v_2/(1-R_{AA})$ is only determined by the initial geometry at high-p_T

- *Extraction* of the eccentricity from high-p_T data

- Not a fit (yet). Need of more precise data





Dreena-B framework

arXiv:1903.06829
Djordjevic, Stojku, Djordjevic, Huovinen

Conclusions

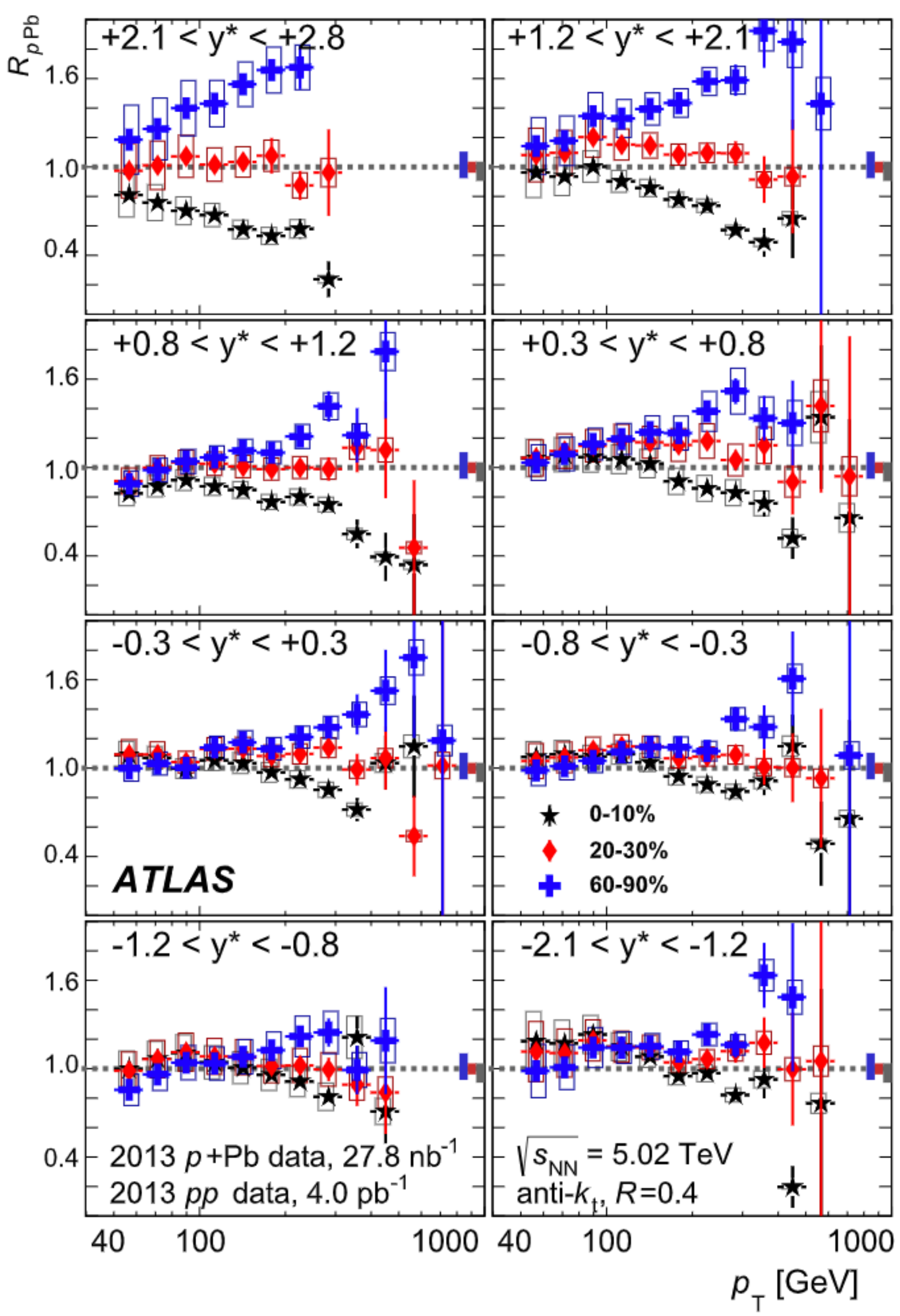
- Jets in p-A and A-A are a good probe of initial stages
- Jet quenching not seen in p-A
- (di)jets in p-A show an important constraining power of nPDFs
- Using jets in A-A to study the early stages is a subject on its early stages
- First proposals to use jets to access early times come from 2018-2019 (Boosted tops, switching off the energy loss to describe high-p_T harmonics…)
- Is a new era of jet quenching for initial stages coming?

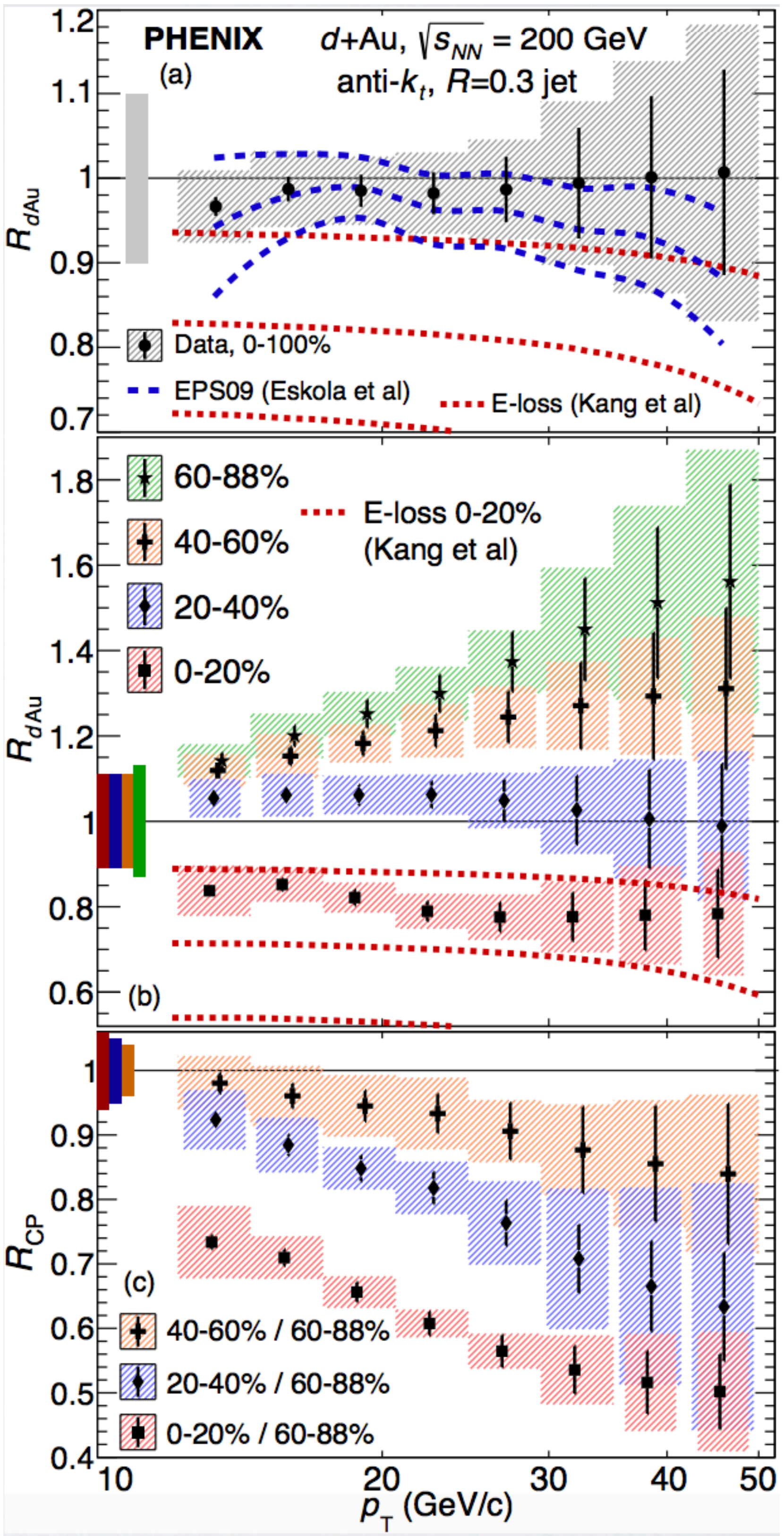
Thanks!

Backup

Constraining nPDFs

Centrality splitting

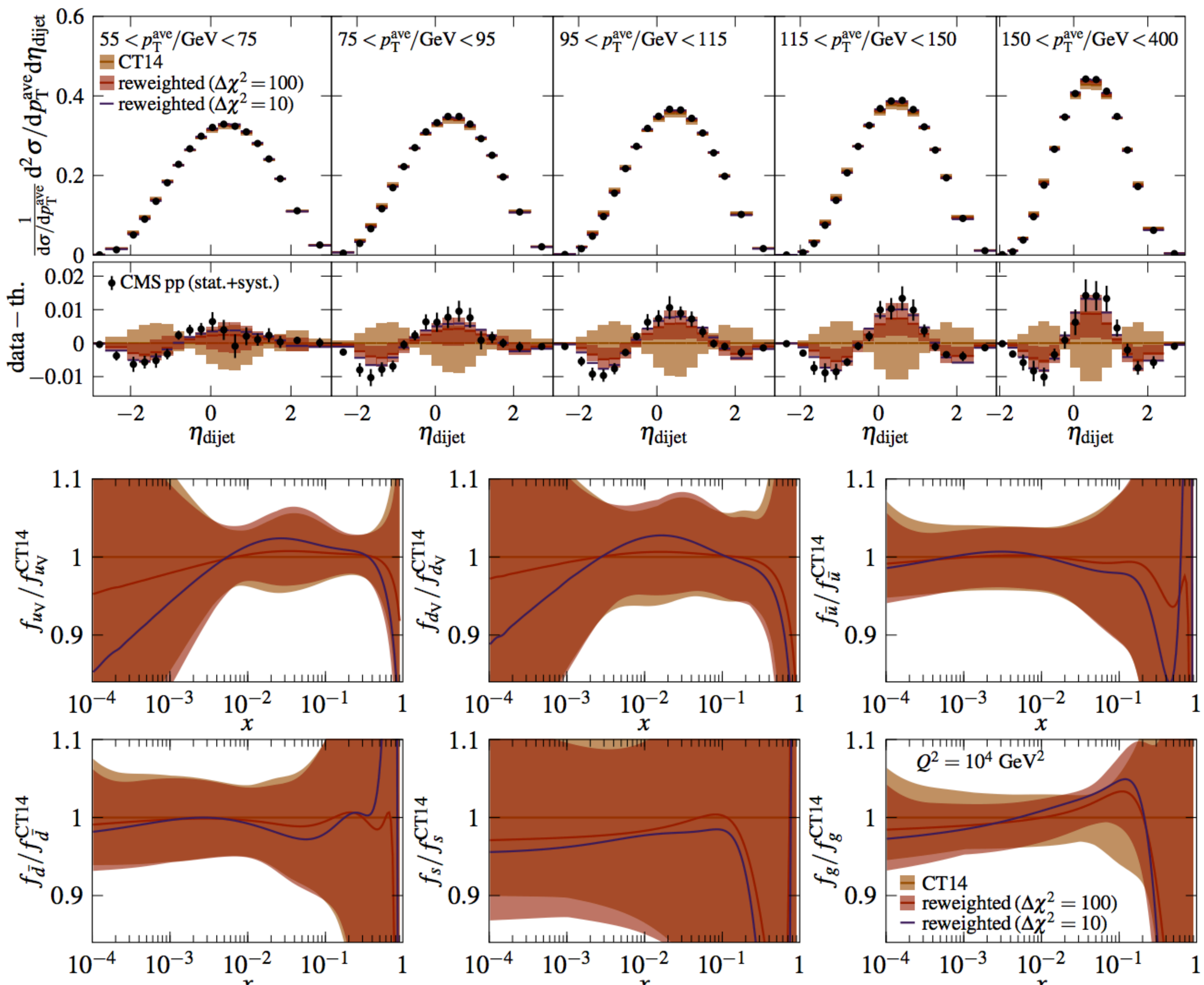




nPDFs: status

	EPPS16	DSSZ12	KA15	NCTEQ15
Order in α_s	NLO	NLO	NNLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓
Neutrino-nucleus DIS	✓	✓		
Drell-Yan dilepton π+A[1]	✓			
LHC p+Pb jet data	✓			
LHC p+Pb W, Z data	✓			
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	1811	1579	1479	708
free parameters	20	25	16	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	52	30	N.N	35
Free proton baseline PDFs	CT14NLO	MSTW2008	JR09	CTEQ6M-like
Heavy-quark effects	✓	✓		✓
Flavour separation	full	none	none	some
Reference	[ARXIV:1612.05741	[PR D85 074028]	[PRD 93, 014026]	[PR D93 085037]

Non-quadratic reweighting



Eur. Phys. J. C **79**, no. 6, 511 (2019)
Eskola, Paakkinen and Paukkunen

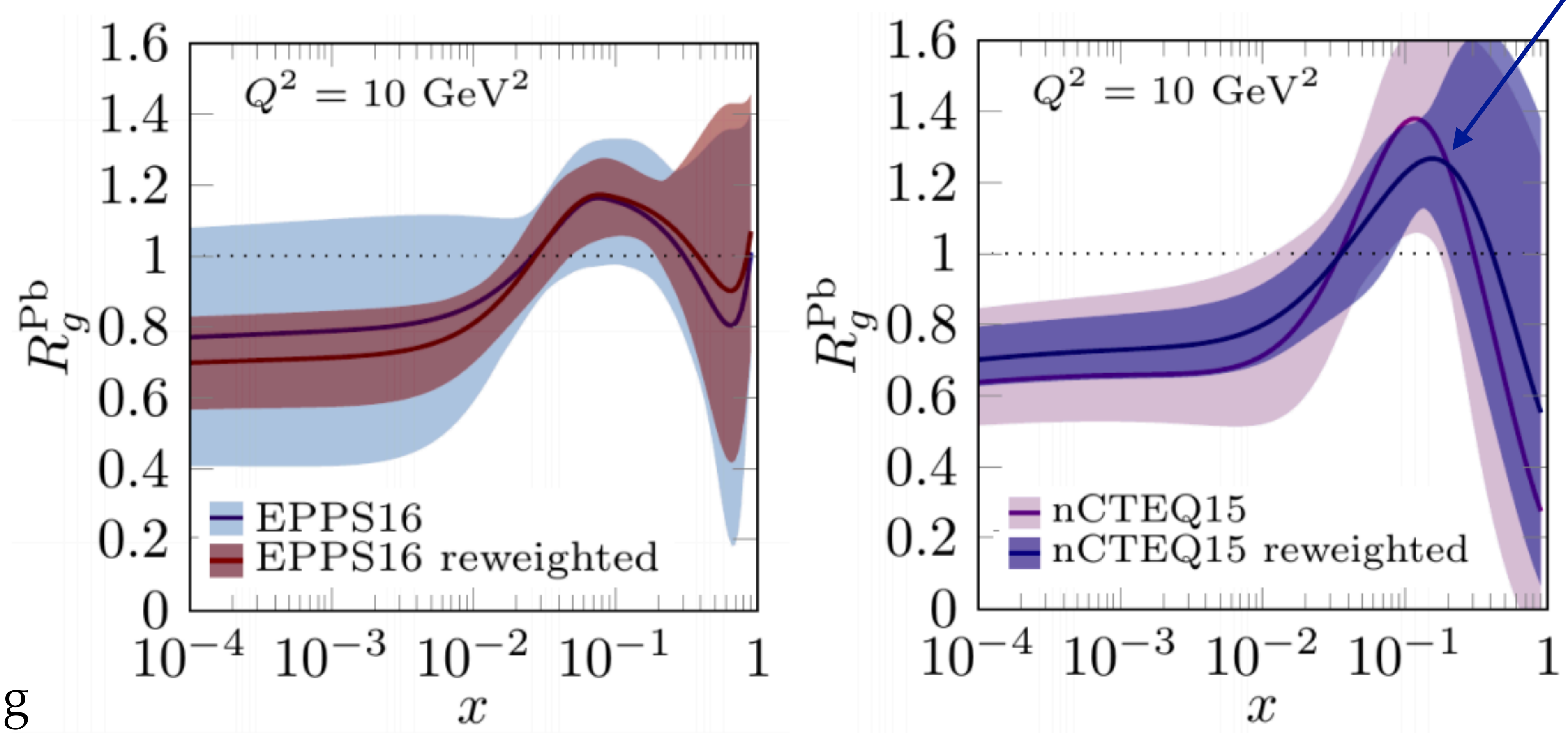
Non quadratic reweighing of CT14 NLO proton PDFs

CMS dijet pseudorapidity distributions in p-p at 5.02 TeV

Large modifications in the gluon

D meson production in pPb

Less antishadowing preferred



Reweighting

D^0-meson LHCb data at forward and backward rapidities in pPb

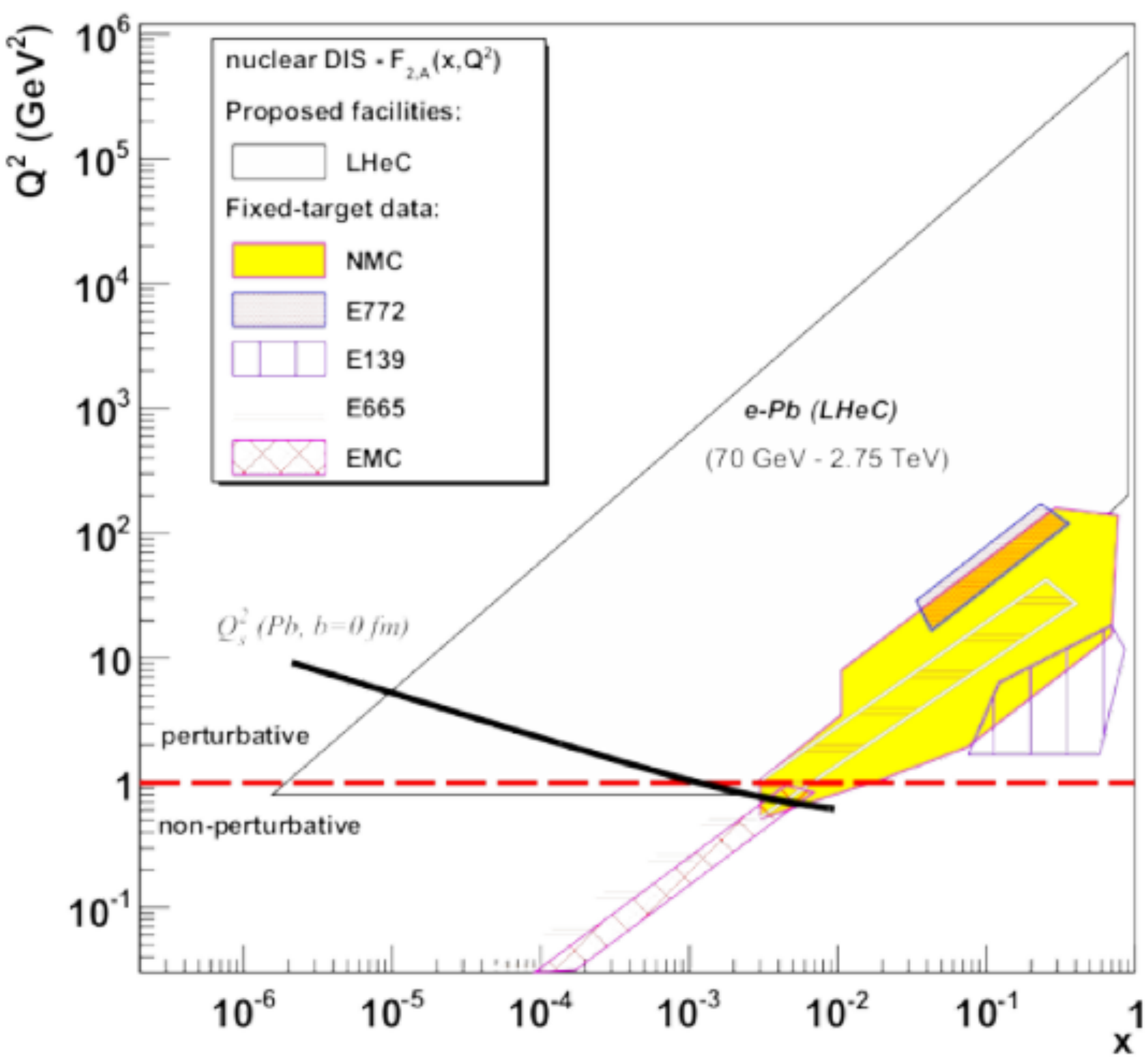
Eskola, Helenius, Paakkinen and Paukkunen
arXiv:1906.02512

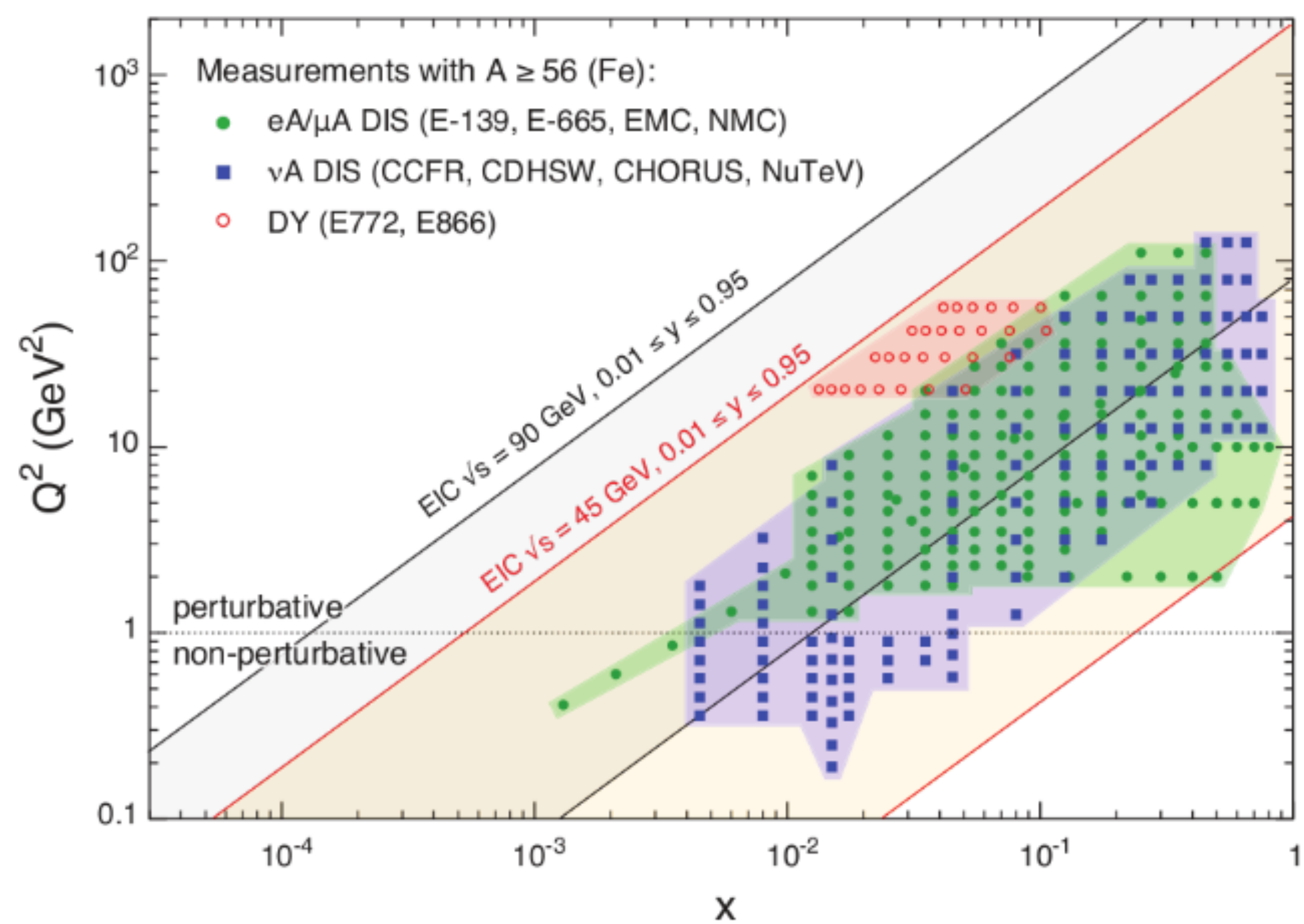
NLO in pQCD + S-ACOT-m_T

Reduction of the uncertainties on the nuclear gluon modification

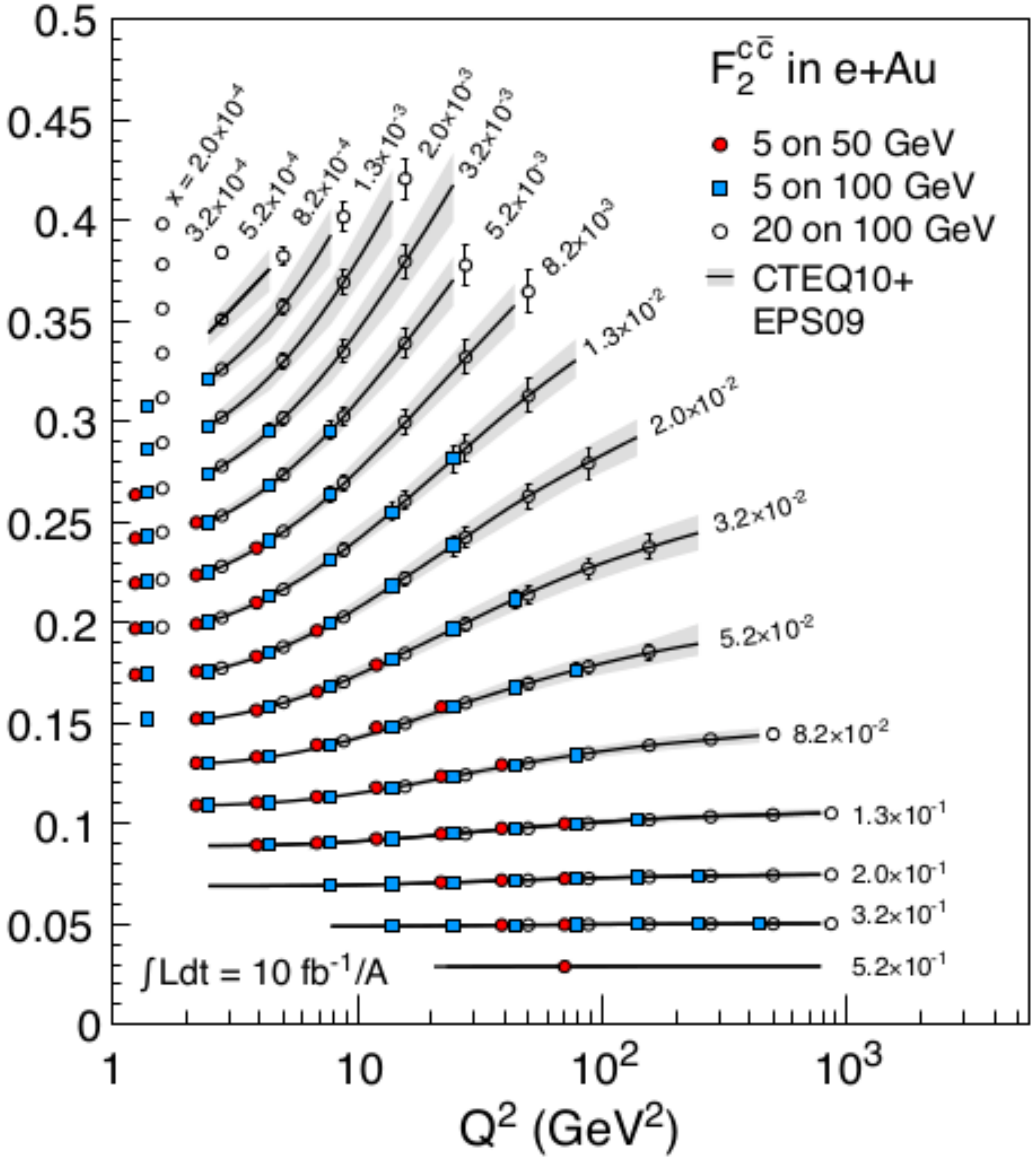
This data could be include with no tension in future global fits

Kinematics: LHeC & EIC

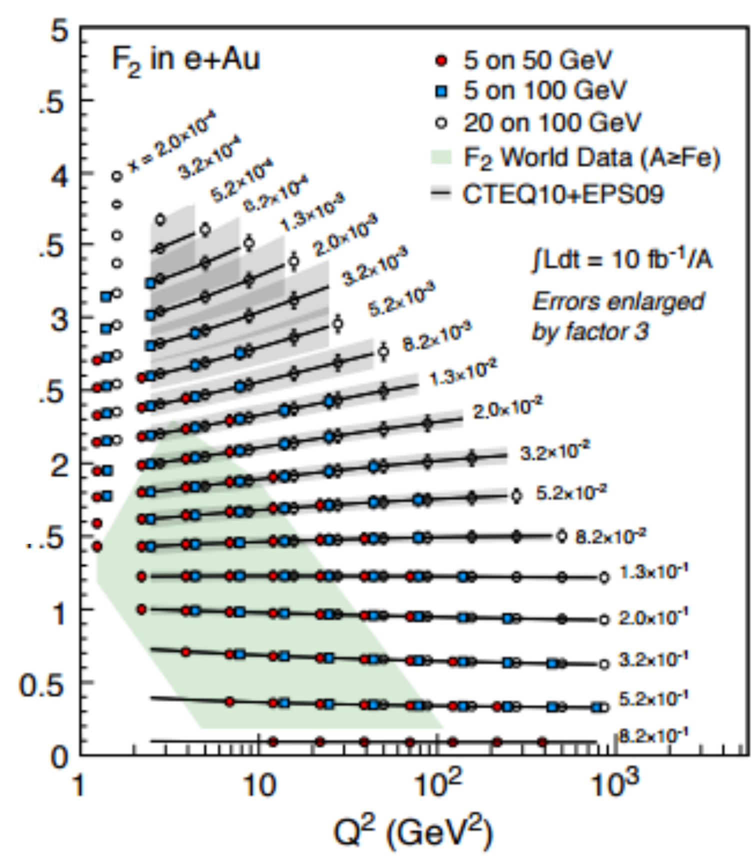


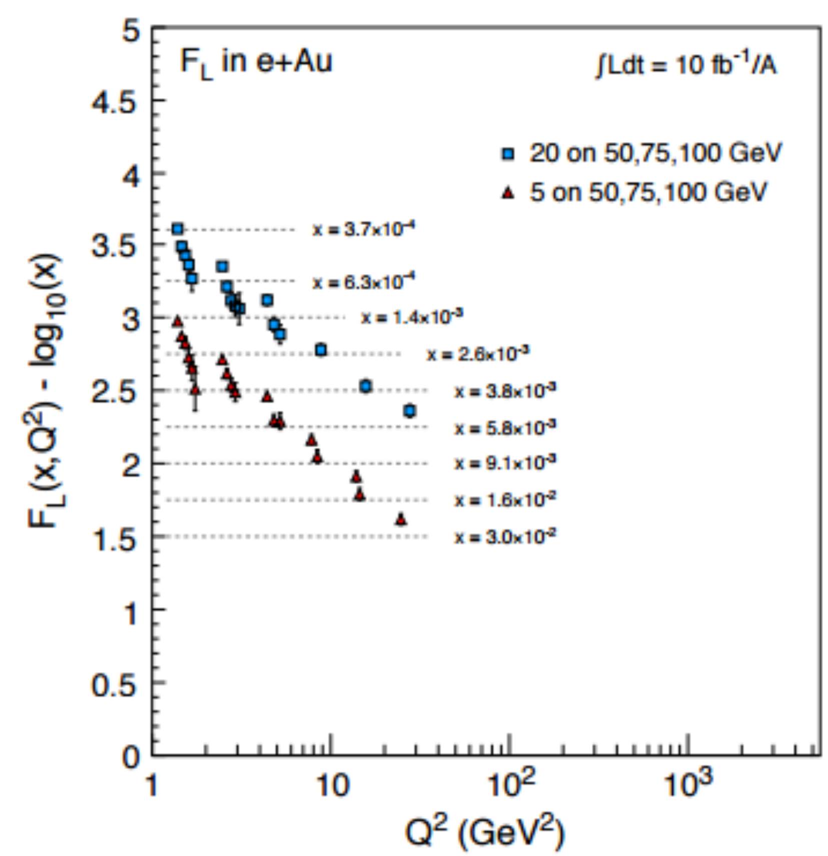


EIC



Never measured in eA!





EKRT hydrodynamics

- EKRT <u>event by event </u>hydrodynamics

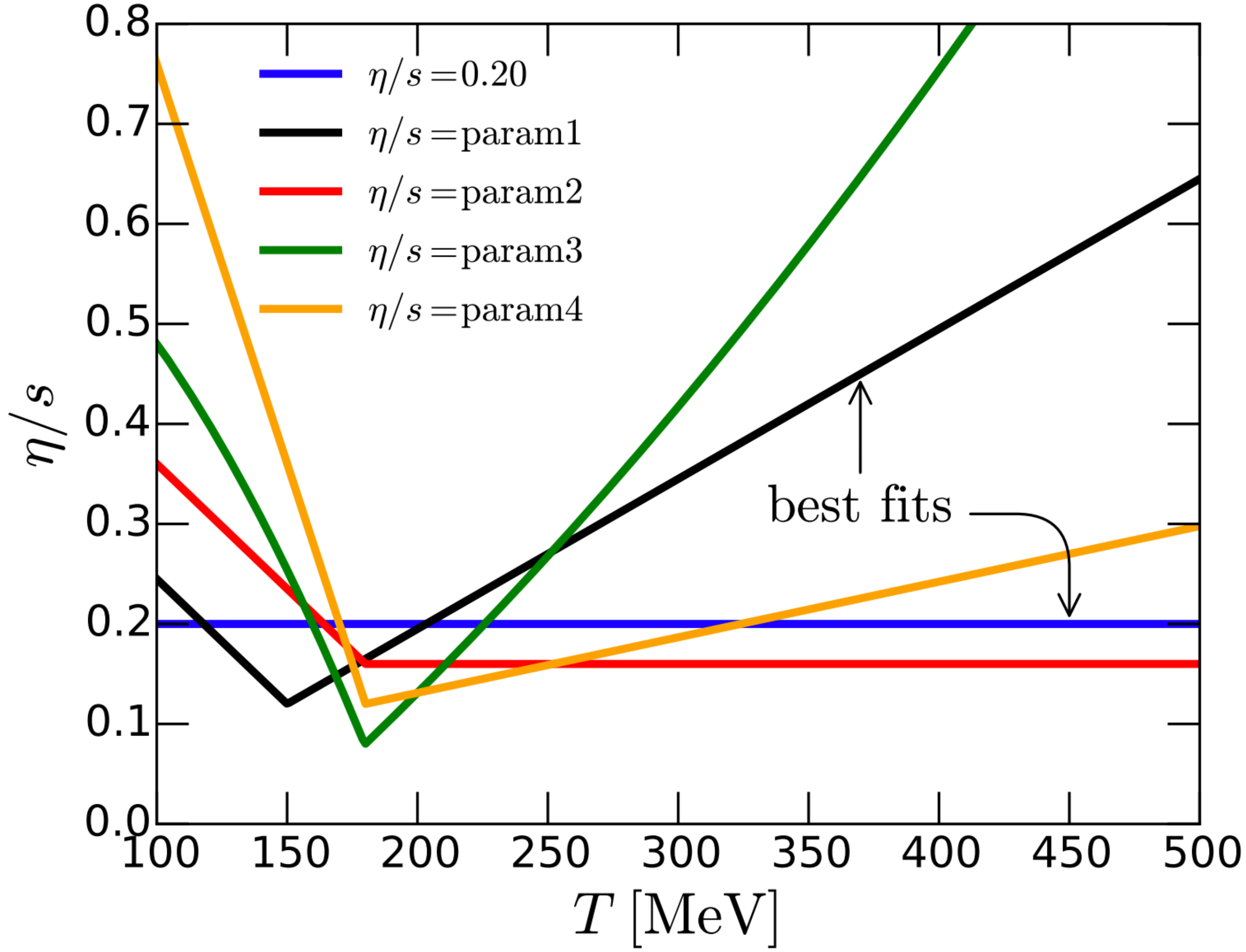
Initial conditions: minijets + saturation model

$$\tau_f = 0.197\,\mathrm{fm}$$

$$\eta/s = param1$$

$$T_{\mathrm{ch}} = 175\,\mathrm{MeV}$$

$$T_{\mathrm{dec}} = 100\,\mathrm{MeV}$$



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Quenching Weights

- Computed in the Multiple Soft Scattering approximation

$$\sigma(\mathbf{r})n(\xi) \simeq \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$$

Perturbative tails neglected

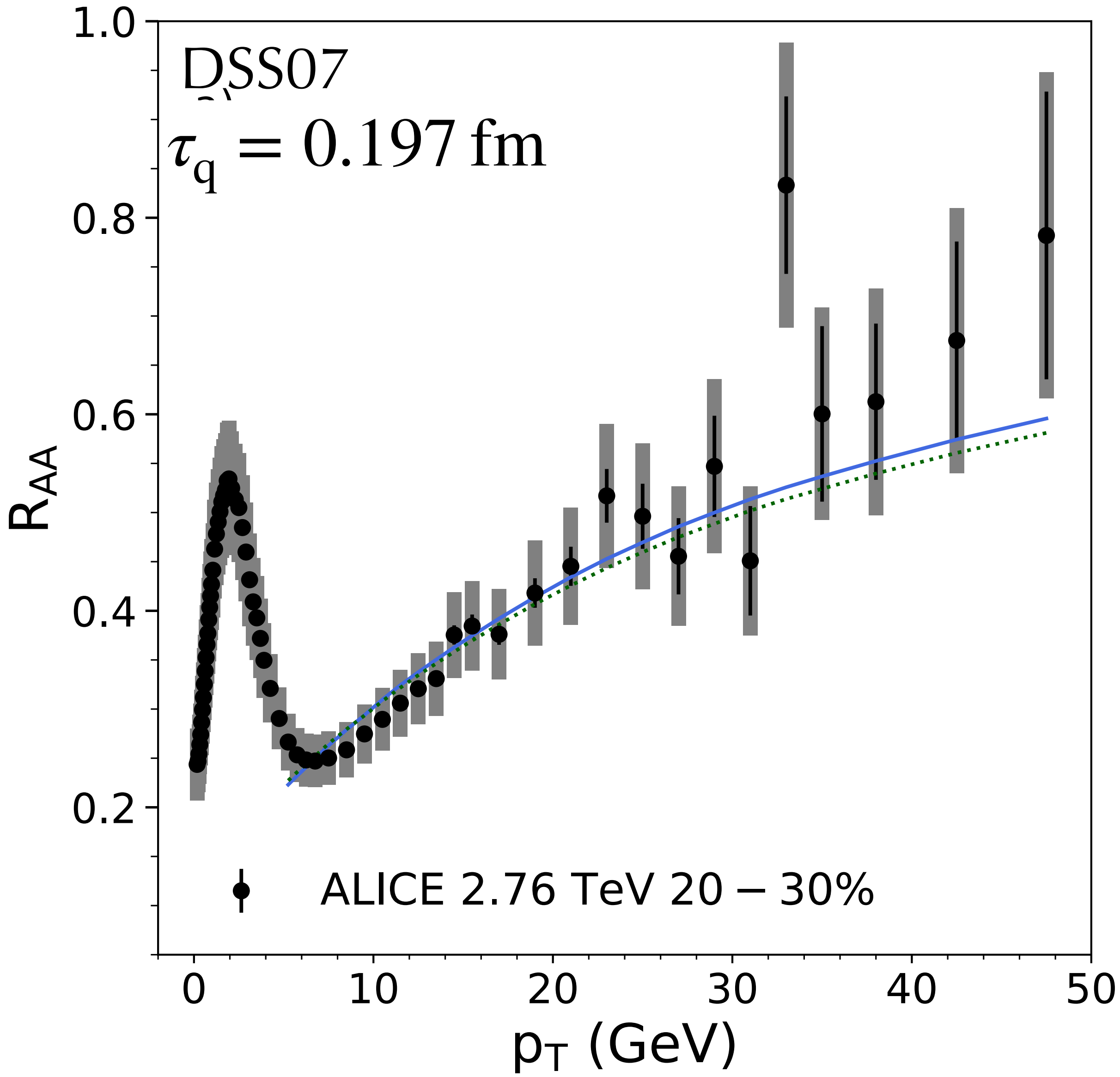
- Relation between $\hat{q}$ and the hydrodynamic properties of the medium

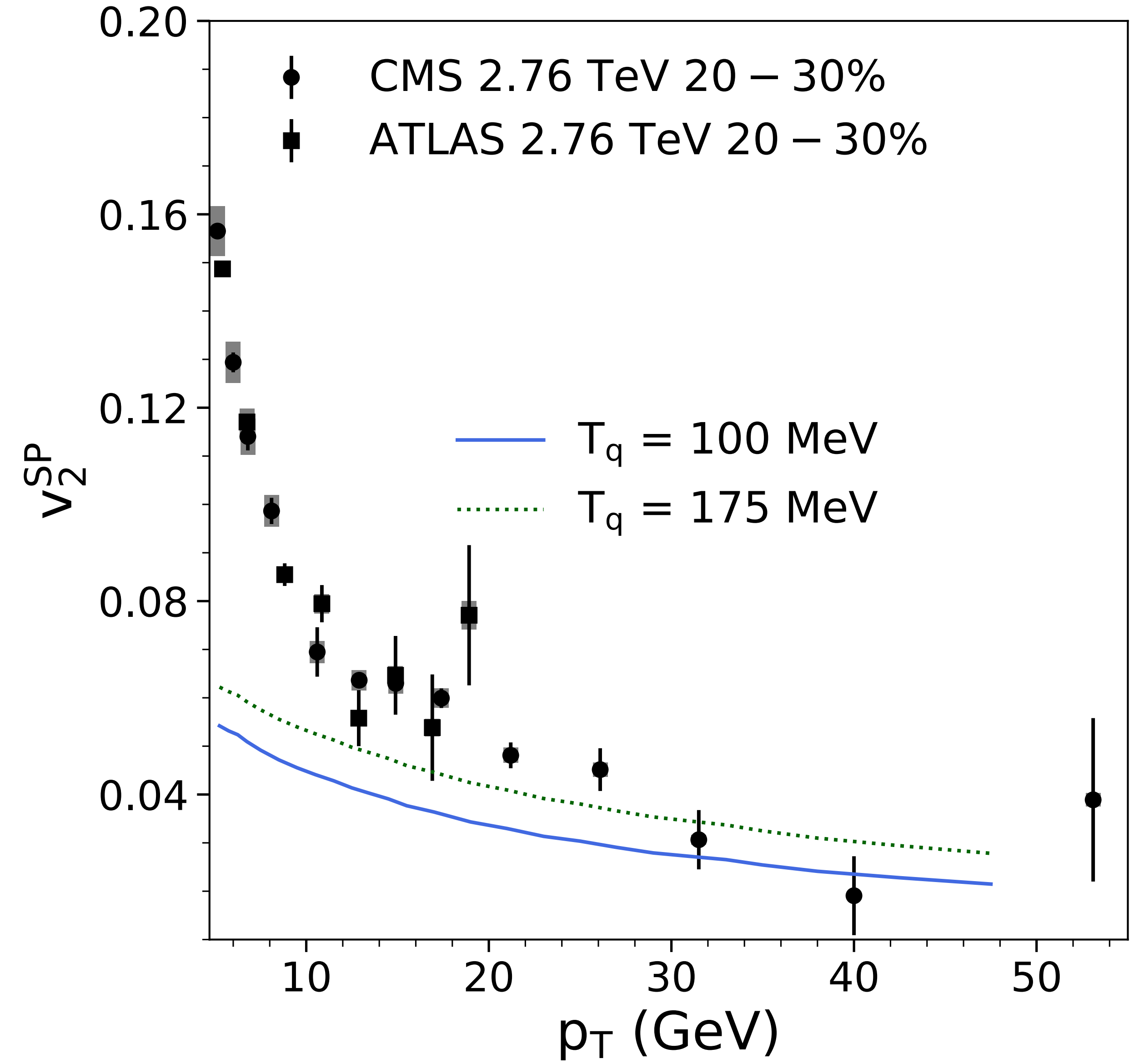
$$\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$$

Fitting parameter

EKRT hydro

Dependence on T_q





High-p_T v_2 still not well described. Better with NO energy loss in the hadronic phase

N=1 opacity

DSS07

$T_{dec} \approx 175$ MeV

$\eta/s = param1$