Hard probes：理論から

EM (photon, leptons, EW...)

Jets (E loss, tomography, ...)

HF (dead cone, diffusion const... flow...)

H. Fujii

HIC & QGP

何かq, qbar, gの集団が出来ている!

ダイナミックな系を如何に特徴つけるか？

一方、測定精度･記述は順調に向上!

Hard probes：理論から

EM (photon, leptons, EW...)

Jets (E loss, tomography, ...)

HF (dead cone, diffusion const... flow...)

Plenary +

	BALL ROOM 1 3rd Floor	BALL ROOM 2 3rd Floor	BALL ROOM 3 3rd Floor	HONGKONG ROOM 2nd Floor
TUESDAY AM1	COL I	JET I	SMA I	EM I
TUESDAY AM2	CP I	SMA II	HF I	QCD I
TUESDAY PM1	COL II	CHI I	HF II	NTH I
TUESDAY PM2	COL III	INI I	HF III	FAC
WEDNESDAY AM1	CP II	JET II	COL IV	NTH II
WEDNESDAY AM2	SMA III	JET III	CHI II	QCD II
WEDNESDAY PM1	CHI III	JET IV	SMA IV	INI II
WEDNESDAY PM2	QCD III	HF IV	EM II	QMA

Hard probes：理論から

EM (photon, leptons, EW...)

Jets (E loss, tomography, ...)

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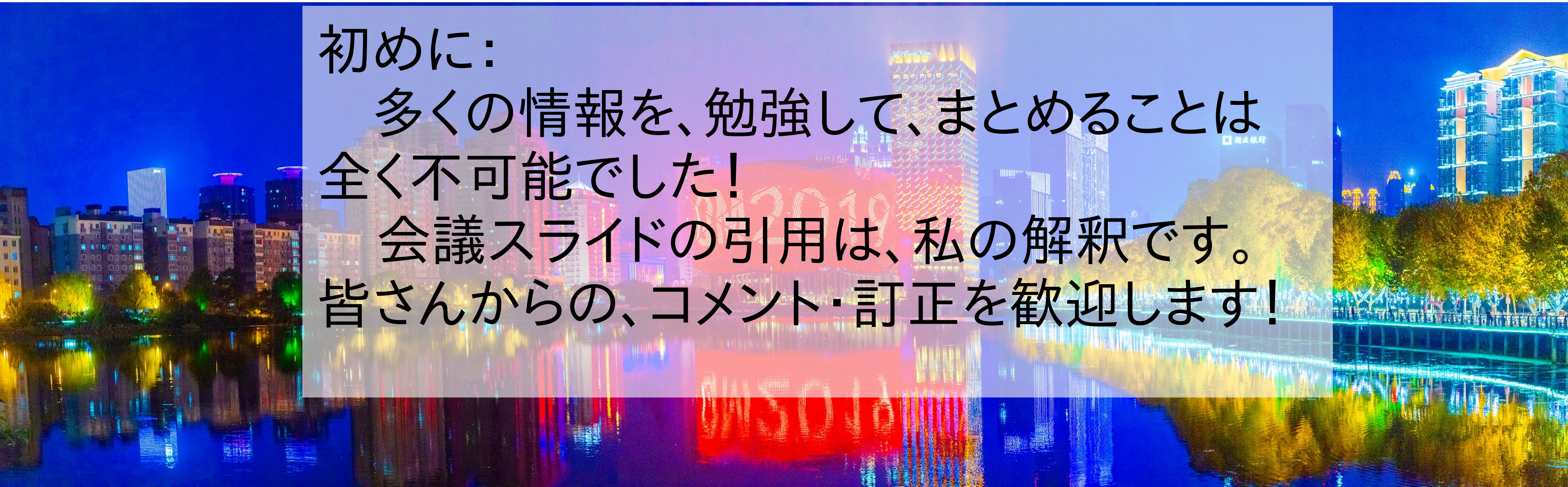


初めに:
　多くの情報を、勉強して、まとめることは
全く不可能でした!
　会議スライドの引用は、私の解釈です。
皆さんからの、コメント・訂正を歓迎します!

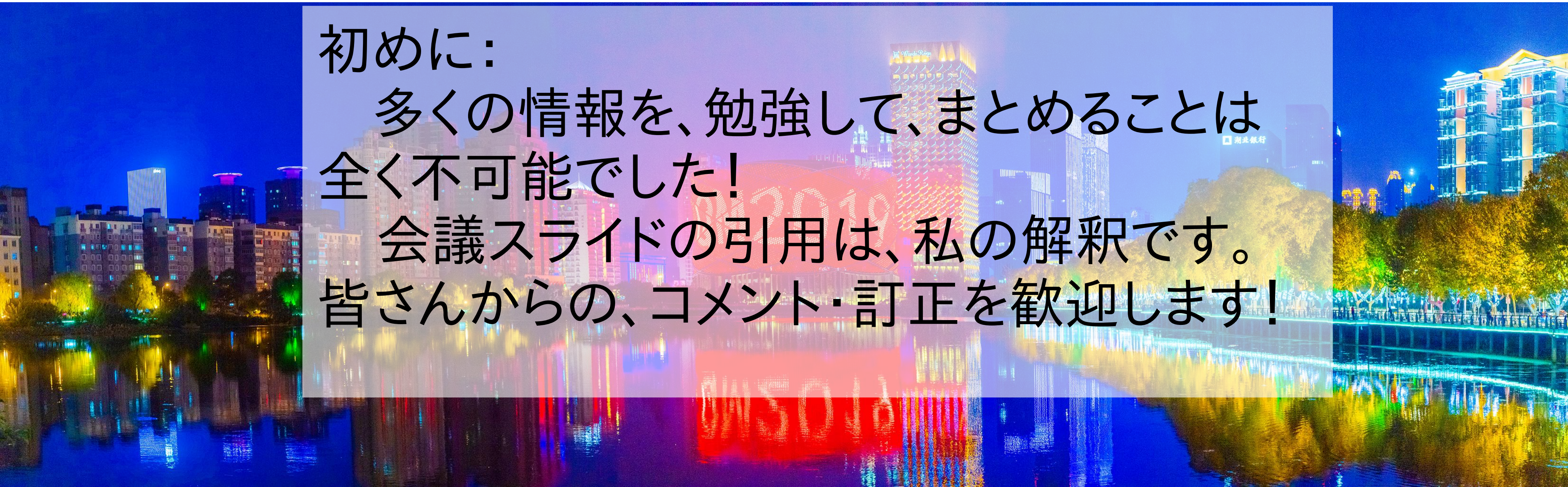
Hard probes：理論から

EM (photon, leptons, EW...)

Jets (E loss, tomography, ...)

HF (dead cone, diffusion const... flow...)

しかも、ほんの少し



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皆さんからの、コメント･訂正を歓迎します!

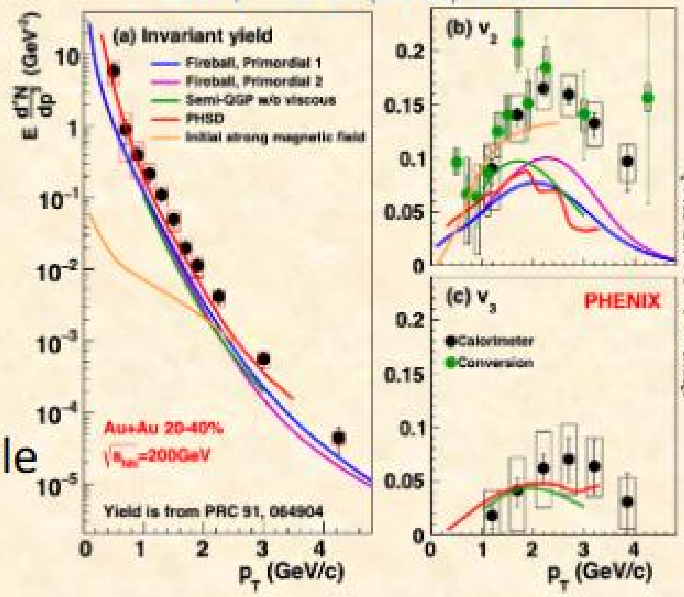
直接光子

Frank Geurts' slide

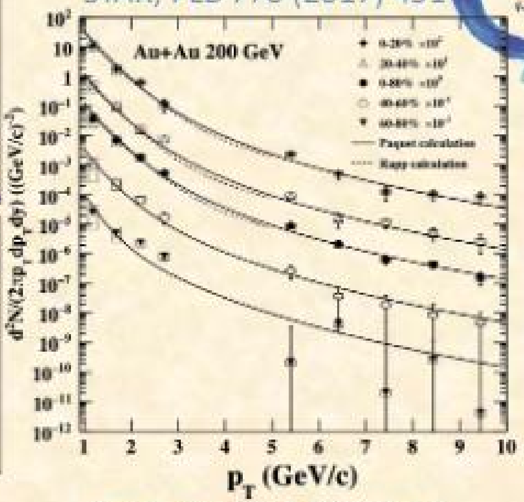
Direct Photon Puzzle

- Large yields
  - suggestive of large T
  - early stage
- Large flow
  - collective flow needs to build up
  - late stage
- Challenge to theoretically reconcile

PHENIX, PRC 94 (2016) 064901



STAR, PLB 770 (2017) 451



- STAR: no large yields
- ALICE: large uncertainties in Pb+Pb
  - ∴ puzzle is not significant at $\sqrt{s_{NN}}$=2.76TeV

➢Improved quality by ALICE on η/π^0

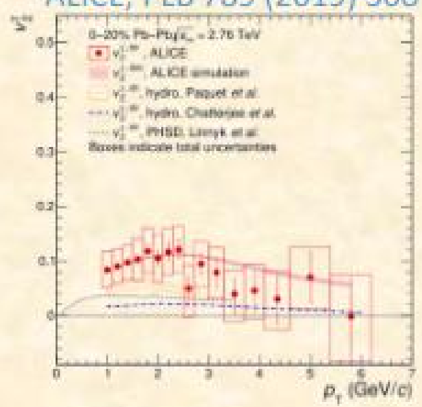
Mike Sas, talk #247

➢ π^0 down to p_T=0.4GeV/c

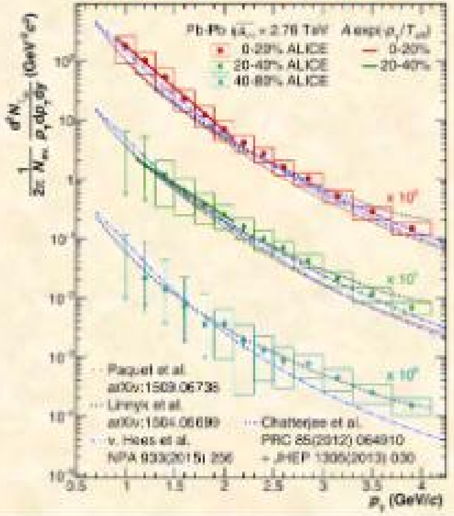
➢ η down to p_T=0.8GeV/c

❖New data from PHENIX ...

ALICE, PLB 789 (2019) 308



ALICE, PLB 754 (2016) 23



QM2019 - Wuhan 9

QMでの光子の講演要点

C. Gale: pre-equilibrium stage by KoMPoST

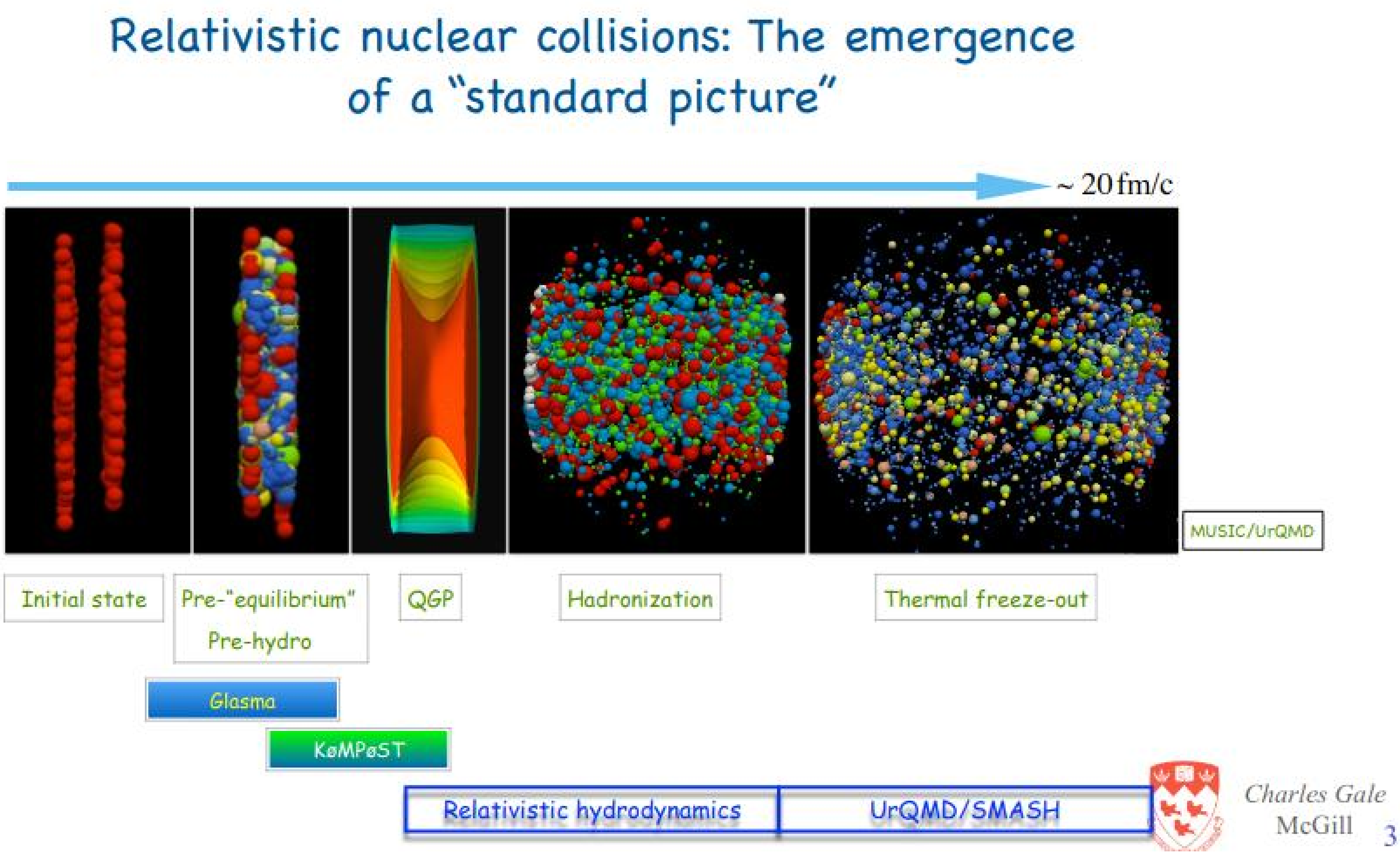
Anna Schafer: non-eq. hadronic stage by MUSIC+SMASH

Jessica Churchill: pre-equlib. + hydro: Boltzmann eq.

from over-populated pure glues --> v2 unchanged

直接光子

C. Gale: pre-equilibrium stage: KoMPoST



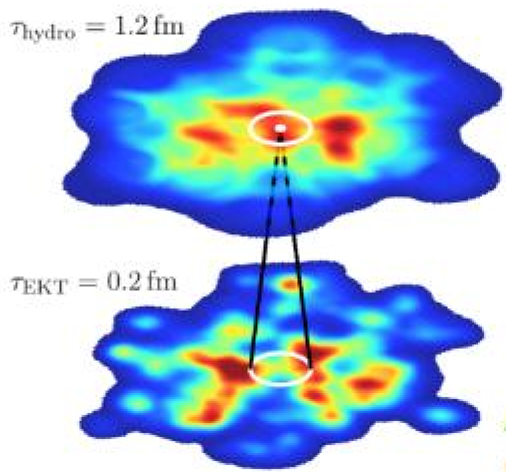
直接光子

C. Gale: pre-equilibrium stage: KoMPoST

KøMPøST

An EKT approach to the pre-hydro phase

$$\partial_\tau f_{x_\perp,\mathrm{p}} + \frac{\mathrm{p}}{|p|}\cdot\nabla_{x_\perp}\partial_\tau f_{x_\perp,\mathrm{p}} - \frac{p_z}{\tau} = -C\left[f_{x_\perp,\mathrm{p}}\right]$$



$$T^{\mu\nu}(t_{EKT},\mathbf{x}) = \overline{T}^{\mu\nu}_{\mathrm{x}} + \delta T^{\mu\nu}_{\mathrm{x}}(t_{EKT},\mathbf{x})$$

$$\delta T^{\mu\nu}(t_{\mathrm{hydro}},\mathbf{x}) = \frac{\overline{T}^{\tau\tau}_{\mathrm{x}}(\tau_{\mathrm{hydro}})}{\overline{T}^{\tau\tau}_{\mathrm{x}}(\tau_{\mathrm{EKT}})} \times \int d^2\mathrm{x}' G^{\mu\nu}_{\alpha\beta}(\mathbf{x},\mathbf{x}',\tau_{\mathrm{hydro}},\tau_{\mathrm{EKT}})\delta T^{\alpha\beta}_{\mathrm{x}}(\tau_{\mathrm{EKT}},\mathbf{x}')$$

Linear response

Advantages:

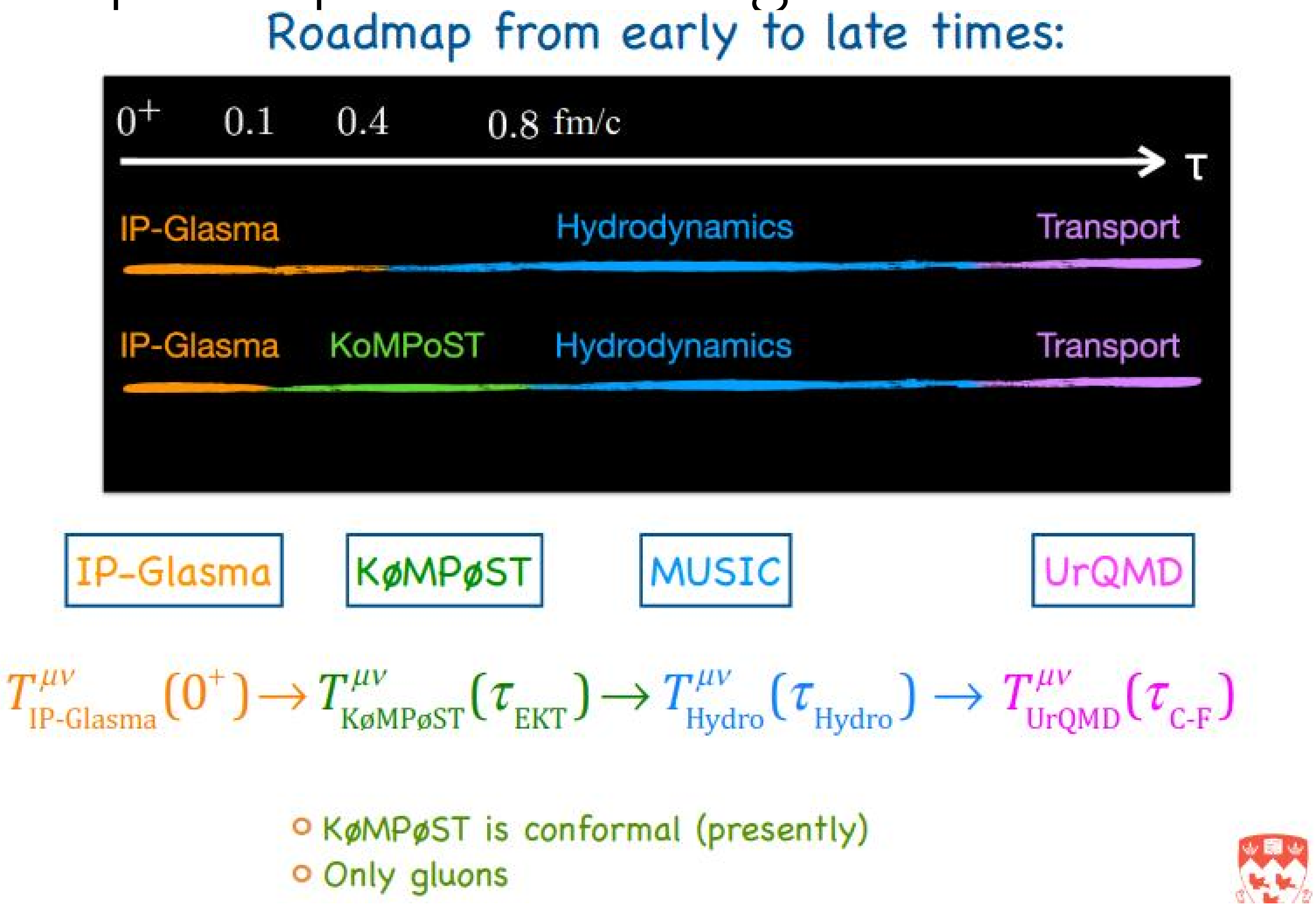
- BE is 6+1 dimensions in general
- Owing to scaling property, Green's functions can be evaluated and stored

Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019)

Charles Gale
McGill 6

直接光子

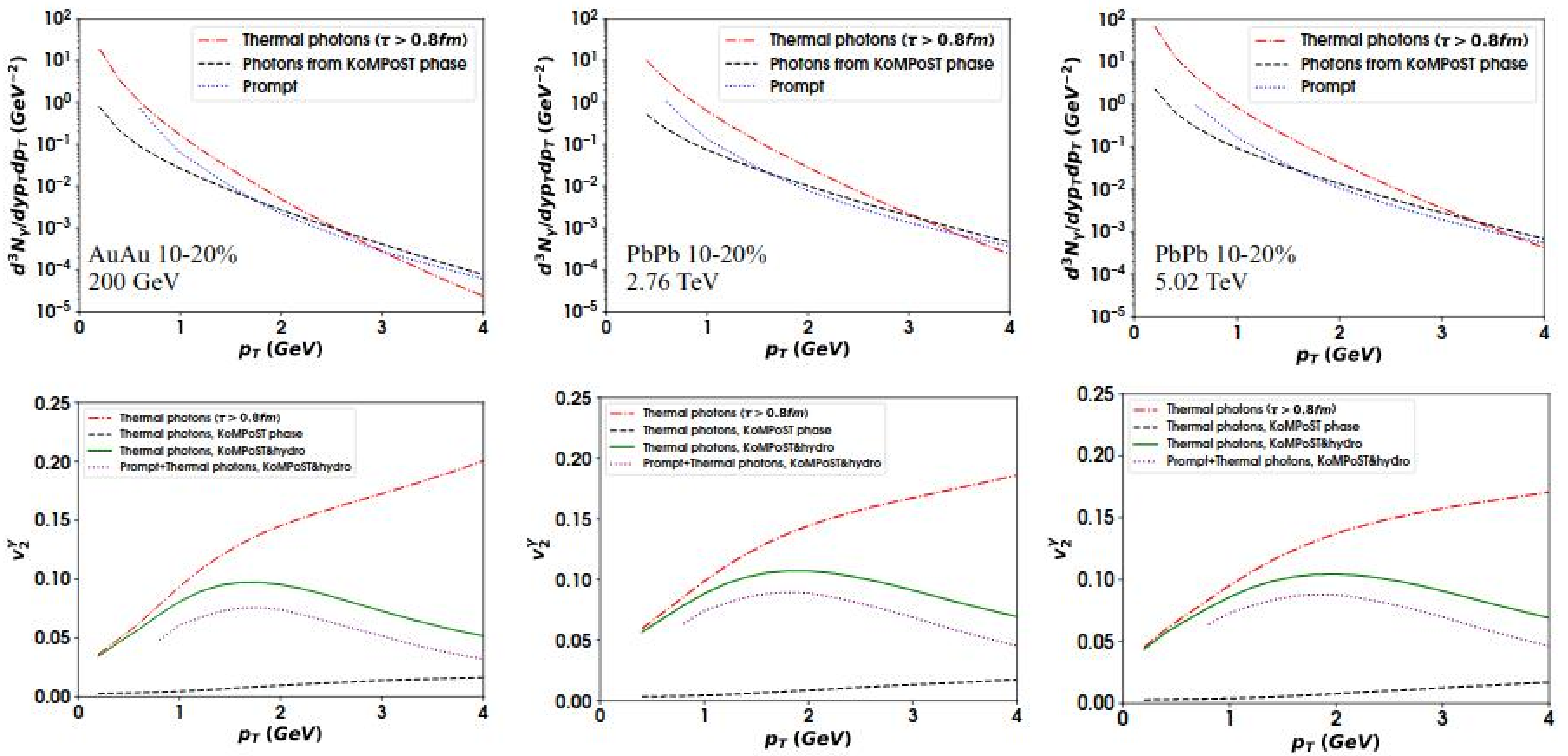
C. Gale: pre-equilibrium stage: KoMPoST



直接光子

C. Gale: pre-equilibrium stage: KoMPoST

What about photons?

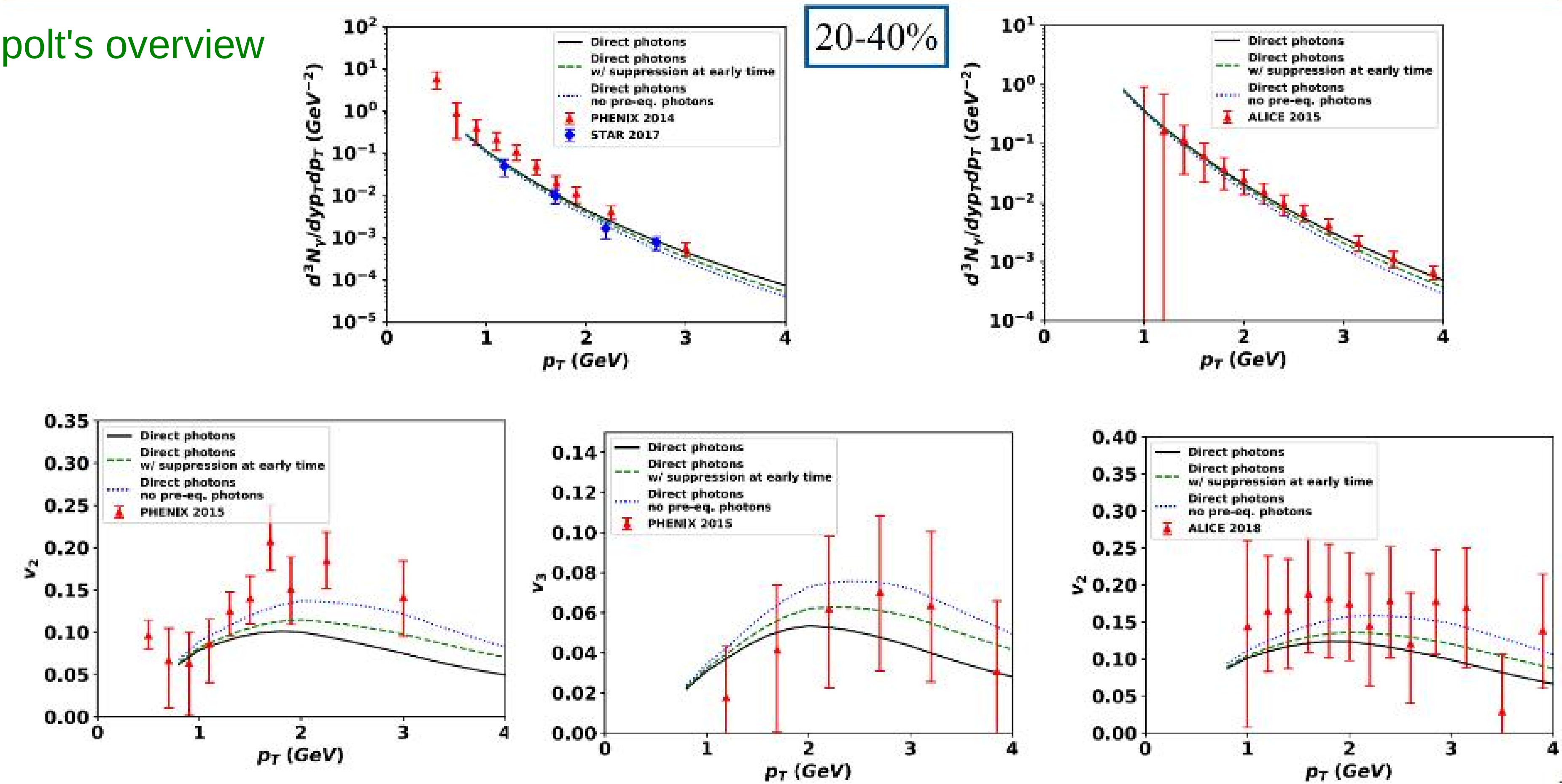


直接光子

C. Gale: pre-equilibrium stage: KoMPoST

Update presented at Quark Matter 2019 (Charles Gale)

Tripolt's overview



Measurement of the $\gamma\gamma \rightarrow e^{+}e^{-}$ Process and its Angular Correlations

in UPC and Peripheral Au+Au Collisions with the STAR Detector

Daniel Brandenburg
For the STAR Collaboration
(Shandong University, BNL/CFNS)
Quark Matter 2019 Wuhan, China

武汉 2019

STAR

BROOKHAVEN NATIONAL LABORATORY

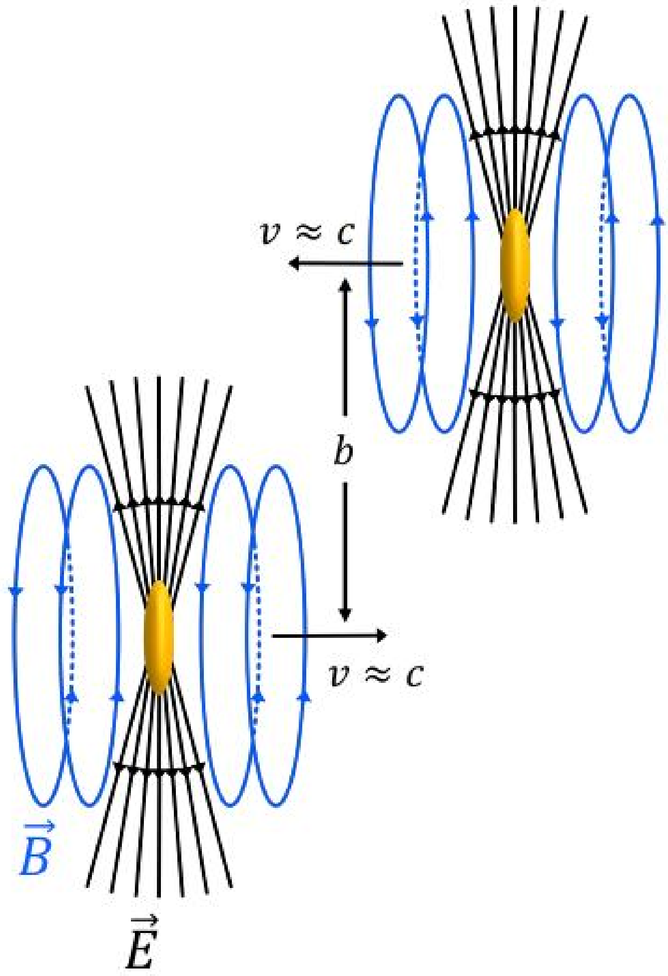
In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

Center for Frontiers in Nuclear Science

SHANDONG UNIVERSITY 1901

11/05/19 Daniel Brandenburg

Ultra-Peripheral Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

Weizäcker-Williams Equivalent Photon Approximation (EPA):
→ In a specific phase space, EM fields can be quantized as a flux of **real photons**
Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

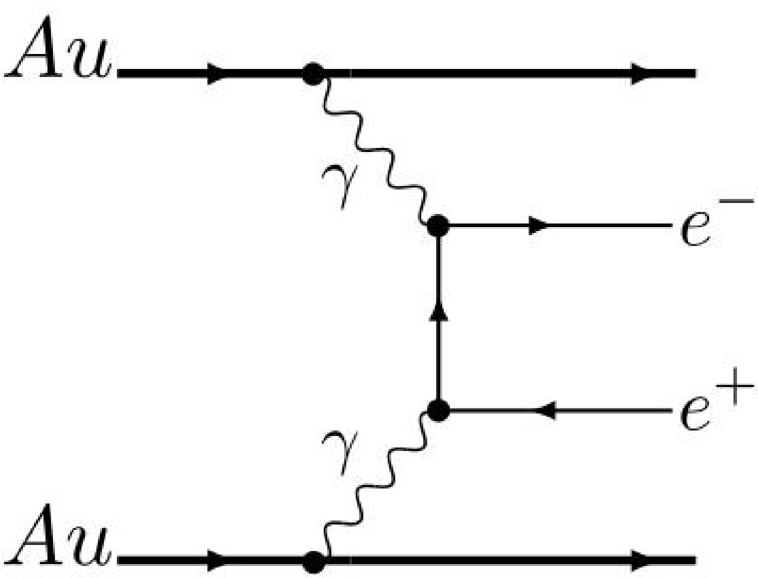
$Z\alpha \approx 1$ → High photon density
Magnetic field strength $\vec{\mathrm{B}} \approx 10^{14} - 10^{16}$ T
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Test QED under extreme conditions

$\gamma\gamma \rightarrow e^+e^-$ Process

1934 Breit & Wheeler : "Collision of two Light Quanta"

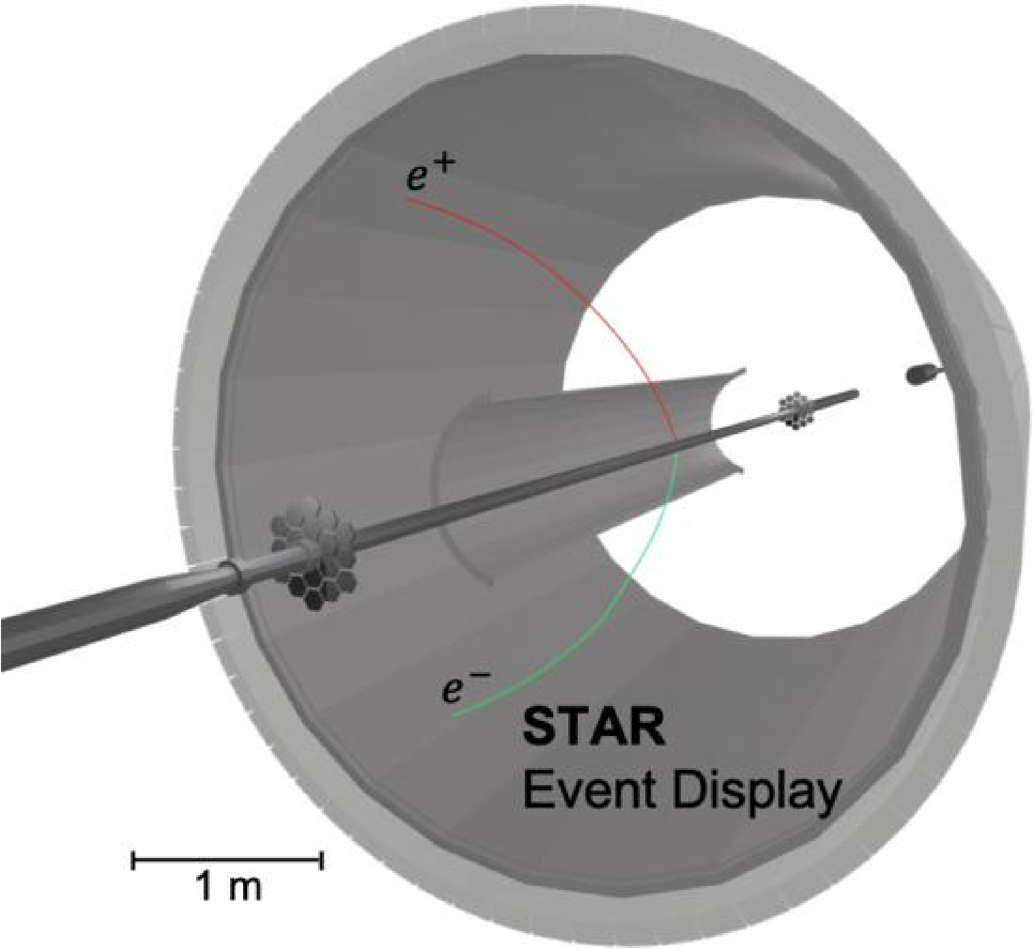
G. Breit and J. A. Wheeler. *Physical Review* 46 (1934): 1087



1. Identifying $\gamma\gamma \rightarrow e^+e^-$ process in ultra-peripheral heavy-ion collisions
2. Ultra-peripheral vs. peripheral
3. First Earth-based observation of vacuum birefringence
4. Applications

11/05/19 Daniel Brandenburg 3

Signatures of the $\gamma\gamma \to e^+e^-$ Process

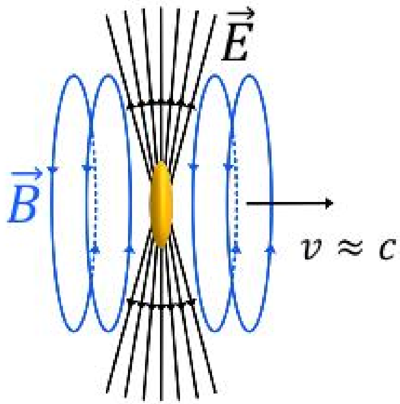


1. Exclusive production of e^+e^- pair
2. Smooth invariant mass spectra (No vector mesons)
3. Individual e^+/e^- preferentially aligned in beam direction
4. Production peaked at very low $P_\perp$ (pair transverse momentum)

Birefringence of the QED Vacuum

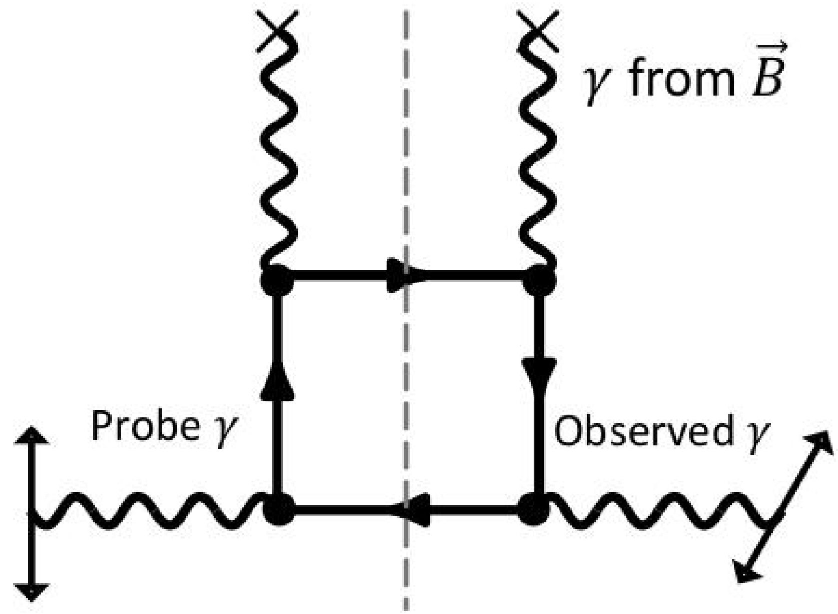
Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$

Lorentz contraction of EM fields →
Quasi-real photons should be linearly polarized ($\vec{E} \perp \vec{B} \perp \vec{k}$)



Can we observe vacuum birefringence in ultra-peripheral collisions?

Feynman Diagram for Vacuum Birefringence



$Real(n)$ = transmission process $\gamma\gamma \to \gamma\gamma$
$Imag(n)$ = absorption process $\gamma\gamma \to e^{+}e^{-}$ (diagram cut)

S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Birefringence of the QED Vacuum

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
QED calculation: arxiv : 1911.00237

Recently realized, $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$ leads to **$\cos(n\Delta\phi)$ modulations** in polarized $\gamma\gamma \to e^+e^-$ [1]

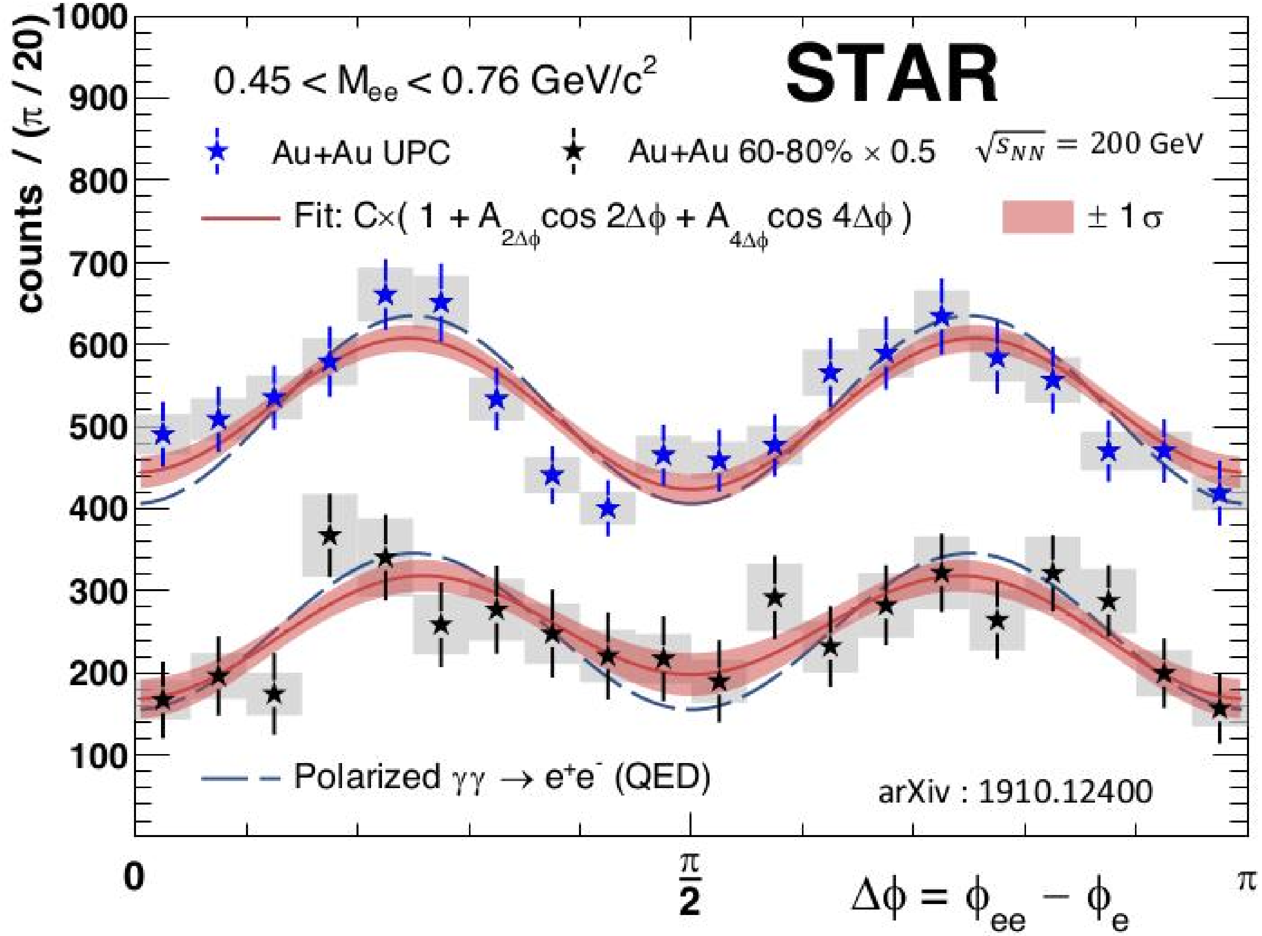
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}$(%)	16.8 ± 2.5	22	18.8 / 16

Peripheral (60−80%)

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}$(%)	27±6	39	10.2 / 17



→ **<u>First Earth-based observation</u> (6.7σ level) of vacuum birefringence**

Jets

Jets

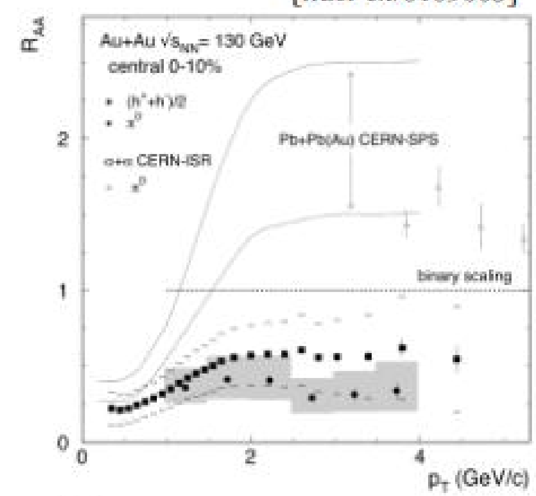
[ATLAS: Phys. Rev. Lett. 105 (2010) 252303]
[CMS: Phys. Rev. C 84 (2011) 024906]

[STAR: Phys. Rev. Lett. 89 (2002) 202301]
[PHENIX: Phys.Rev.Lett. 88 (2002) 022301]
[ALICE: Phys. Lett. B 696 (2011) 30-39]

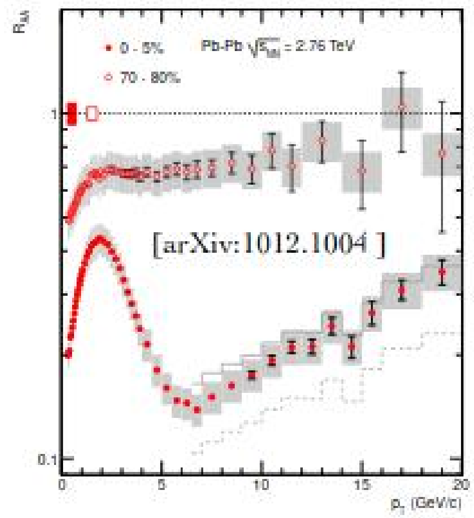
First Measurements

- Hard probes @ RHIC and @ LHC:
  - Charged particle suppression
  - Di-jet asymmetry

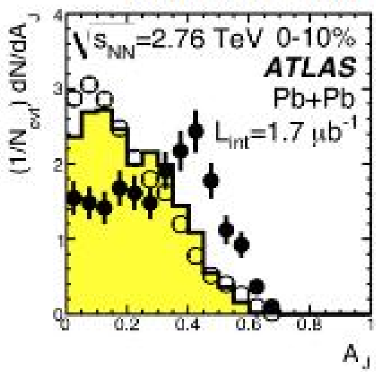
[nucl-ex/0109003]



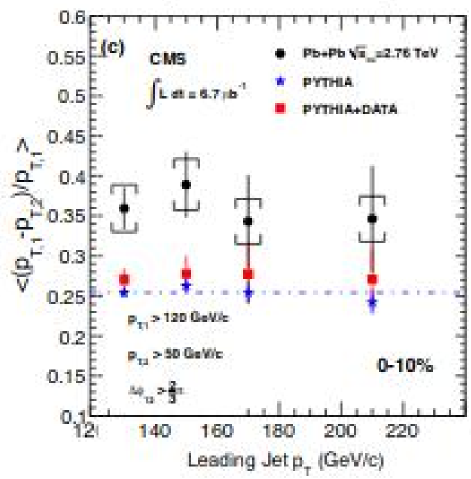
[arXiv:1012.1004]

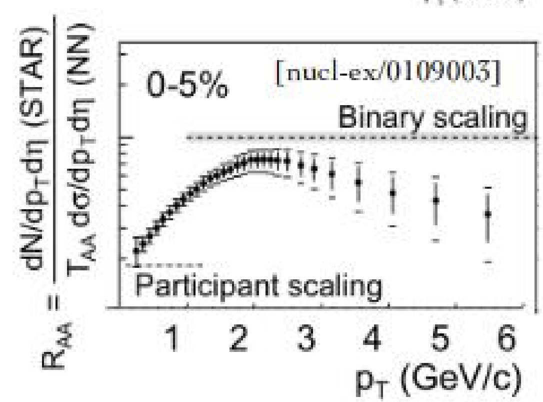


[arXiv:1011.6182]



[arXiv:1102.1957]



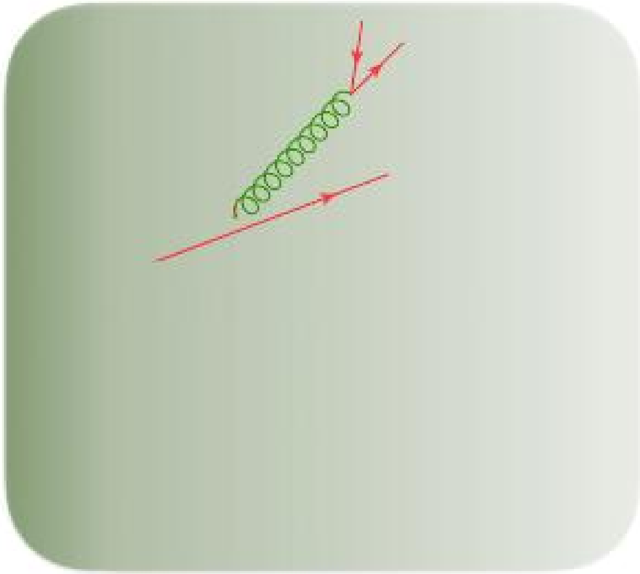


Measurement of 1st QGP property with HP:
Jet Transport Coefficient

Jets

Road so far

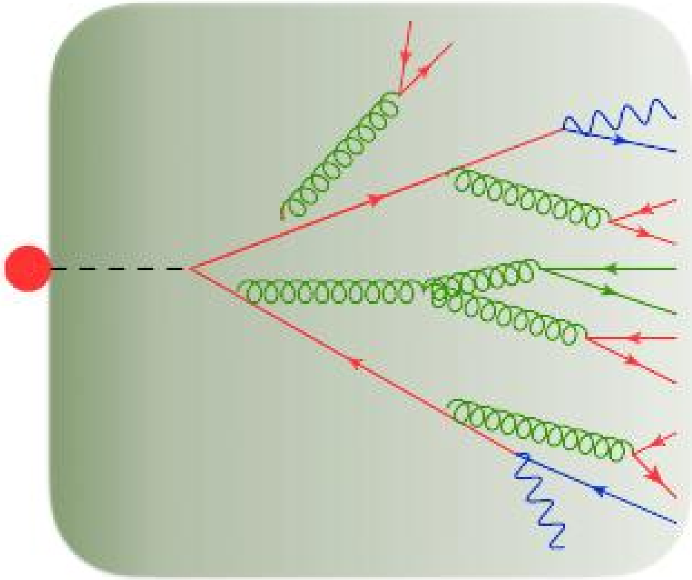
- Theory and Phenomenology: long evolution from:



Jets

Road so far

- Theory and Phenomenology: long evolution from:
  - Single particle energy loss description to in-medium parton shower

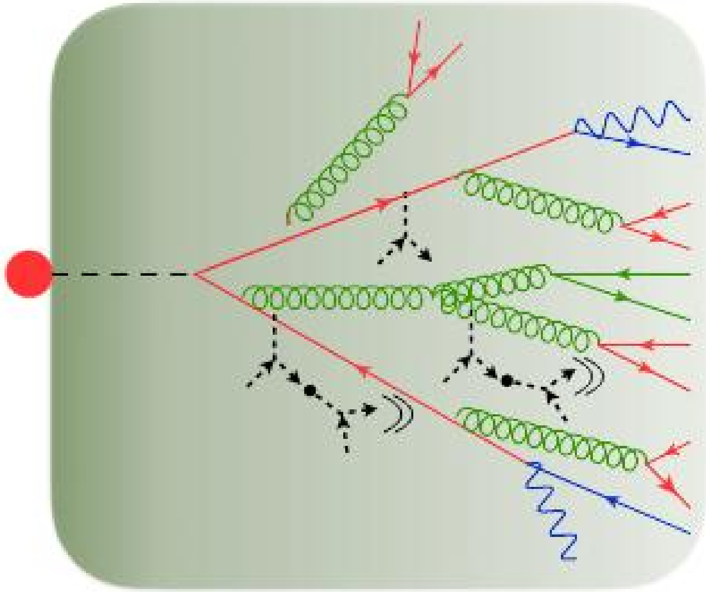


L. Apolinário 8 Quark Matter 2019

Jets

Road so far

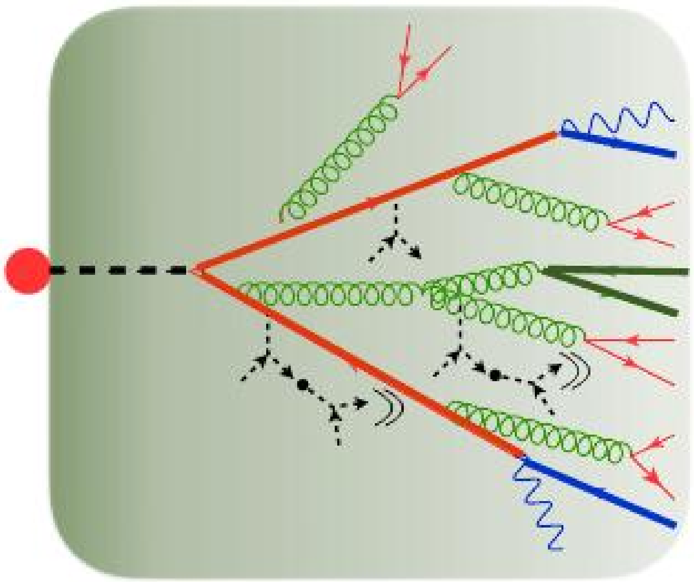
- Theory and Phenomenology: long evolution from:
  - Single particle energy loss description to in-medium parton shower
  - Medium-induced gluon radiation to include medium response



Jets

Road so far

- Theory and Phenomenology: long evolution from:
  - Single particle energy loss description to in-medium parton shower
  - Medium-induced gluon radiation to include medium response
  - Light and Heavy-quark description



K. Tywoniuk Fr.9h30

T. Luo Fr.10h00

S. Cao Fr.14h30

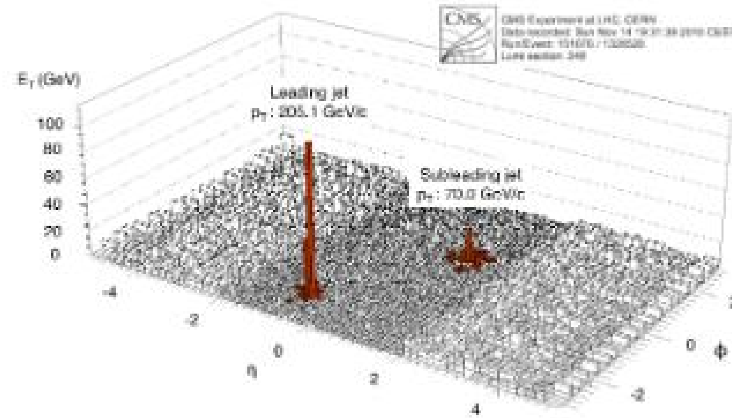
A. Rothkopf Fr.15h00

L. Apolinário 8 Quark Matter 2019

Jets

Road so far

- Experiment: increase of novel observables:
  - Single particle measurements to full jet
  - Calibrated probes (not needing pp as a reference)
  - More differential jet observables (subjet structures: zg, Lund planes,…)

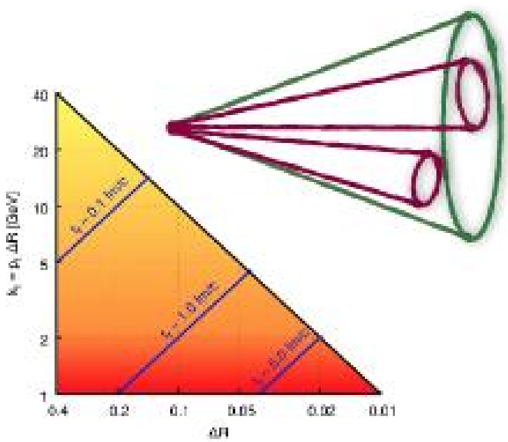


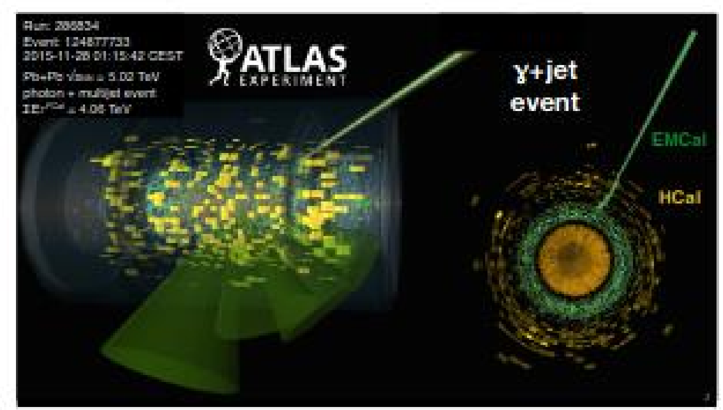
B. Trzeciak Fr.9h00

Y. Chen Fr.10h50

J. Wang Fr.14h00

Z. Tang Fr.14h00



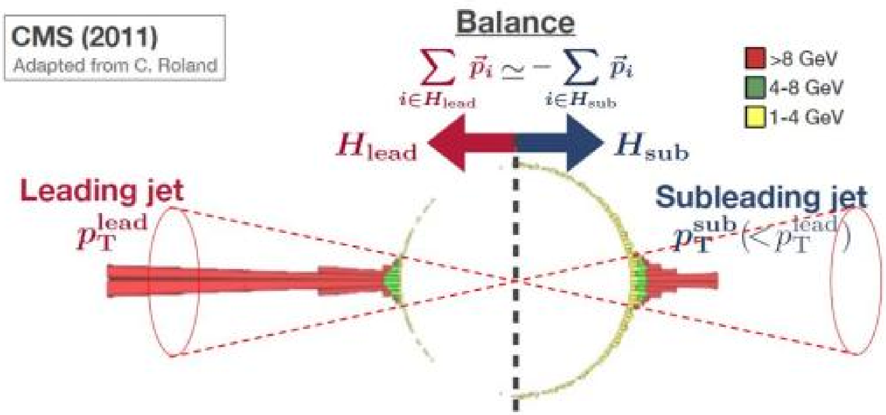


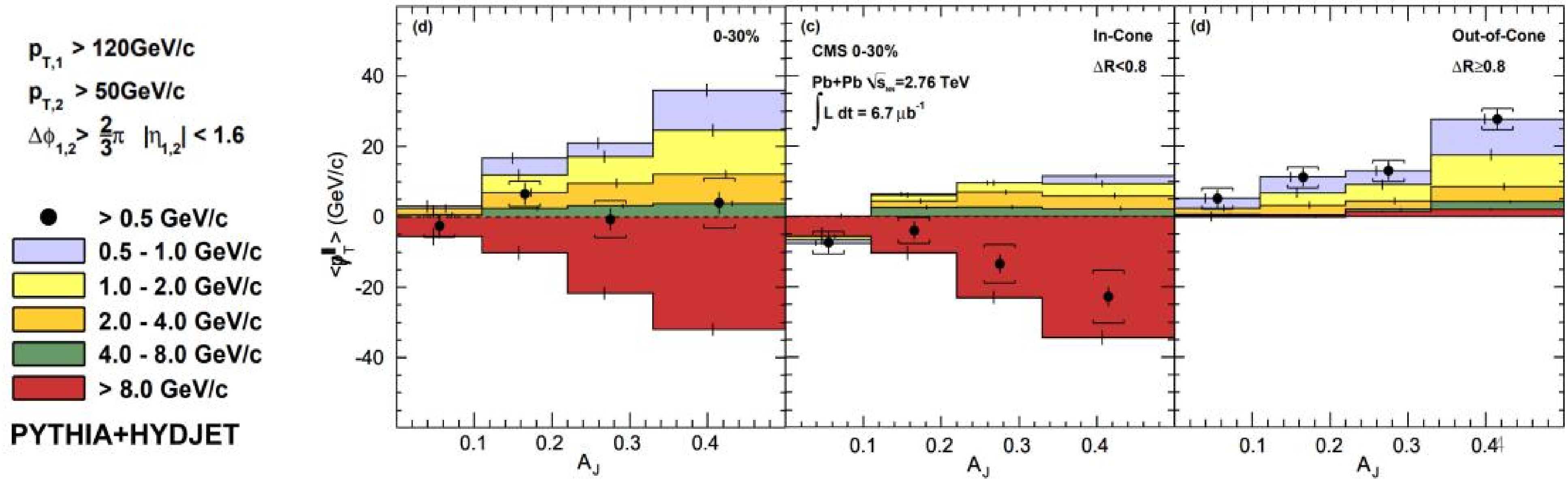
Jets

Luo's slide

Where does the lost energy go ?

- The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.



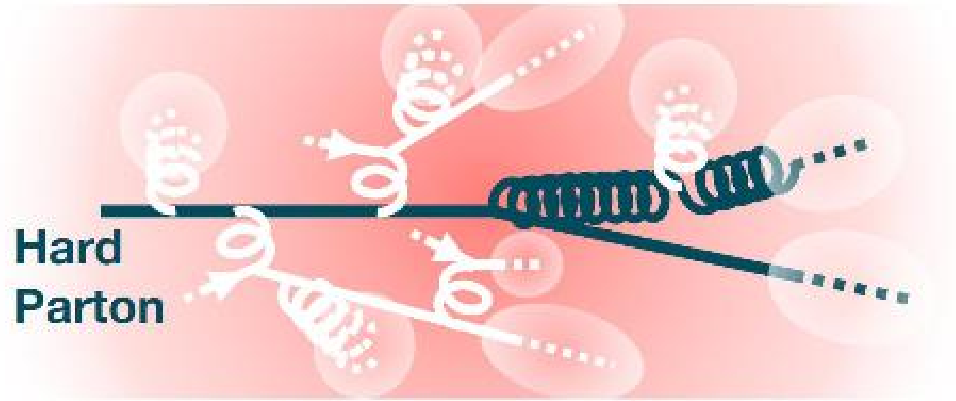


Jets

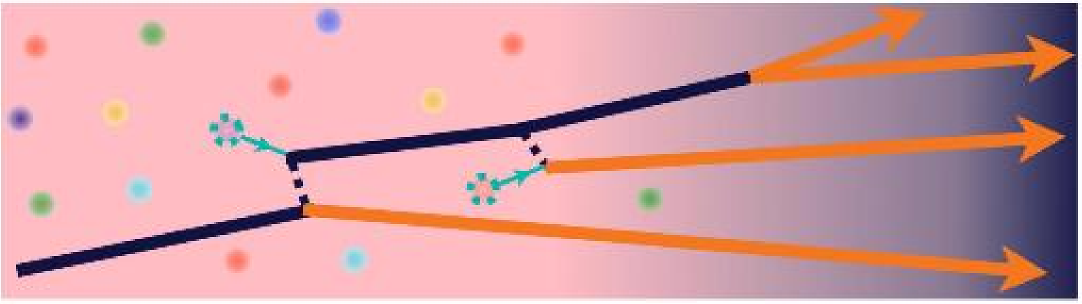
Thermalization & Propagation

Luo's slide

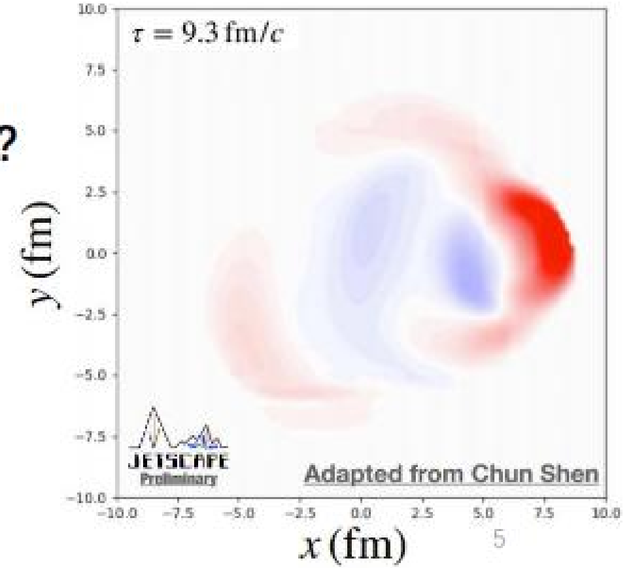
- **Thermalization : How does the deposited energy thermalize?**

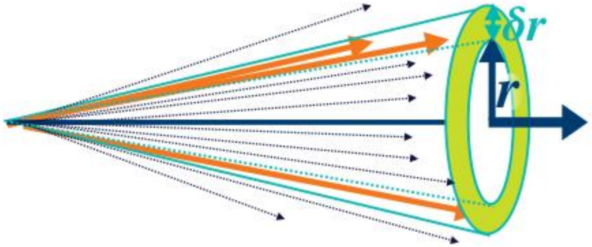


- **Propagation: How does the deposited energy propagate?**



Yasuki Tachibana: Tuesday





Jets

$$r = \sqrt{(\eta_{\mathrm{trk}} - \eta_{\mathrm{jet}})^2 + (\phi_{\mathrm{trk}} - \phi_{\mathrm{jet}})^2}$$

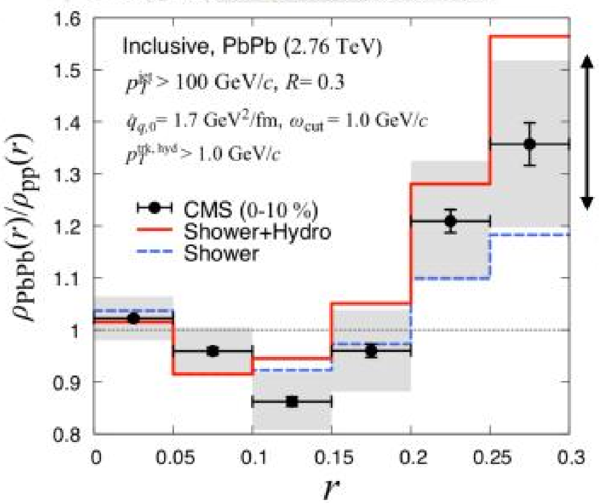
[Tachibana, Chang, Qin (17)]
[Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17)]
[Park, Jeon, Gale (18)]

Thermalisation

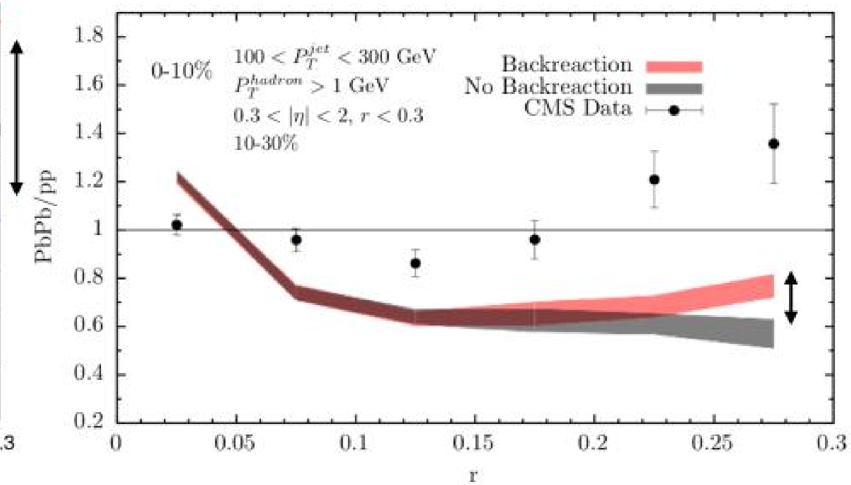
Also in jet hadro-chemistry:
W. Chen Jet I

- Mostly seen in jet radial profile but signatures of each approach is very different:

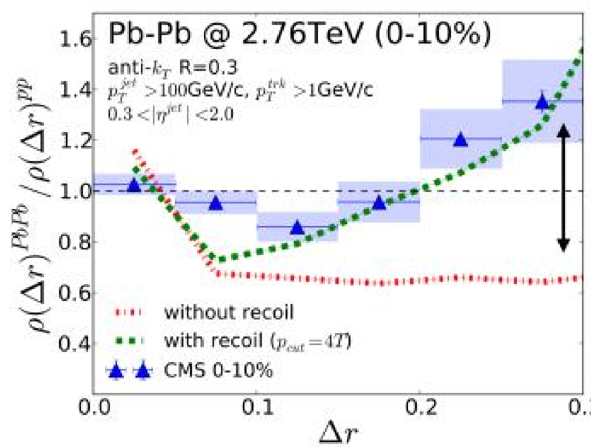
[Coupled Jet-Fluid: 1701.07951]



[Hybrid: 1609.05842]



[MARTINI:1807.06550]



Several uncertainties… But seems to be necessary to describe excess of particles at large angles…

A Comprehensive MC Framework for Jet-Quenching

large in scope or content
(MULTI-OBSERVABLE)

structure for supporting, defining, or enclosing
(**MODULAR**)

JETSCAPE JEWEL JET Collaboration

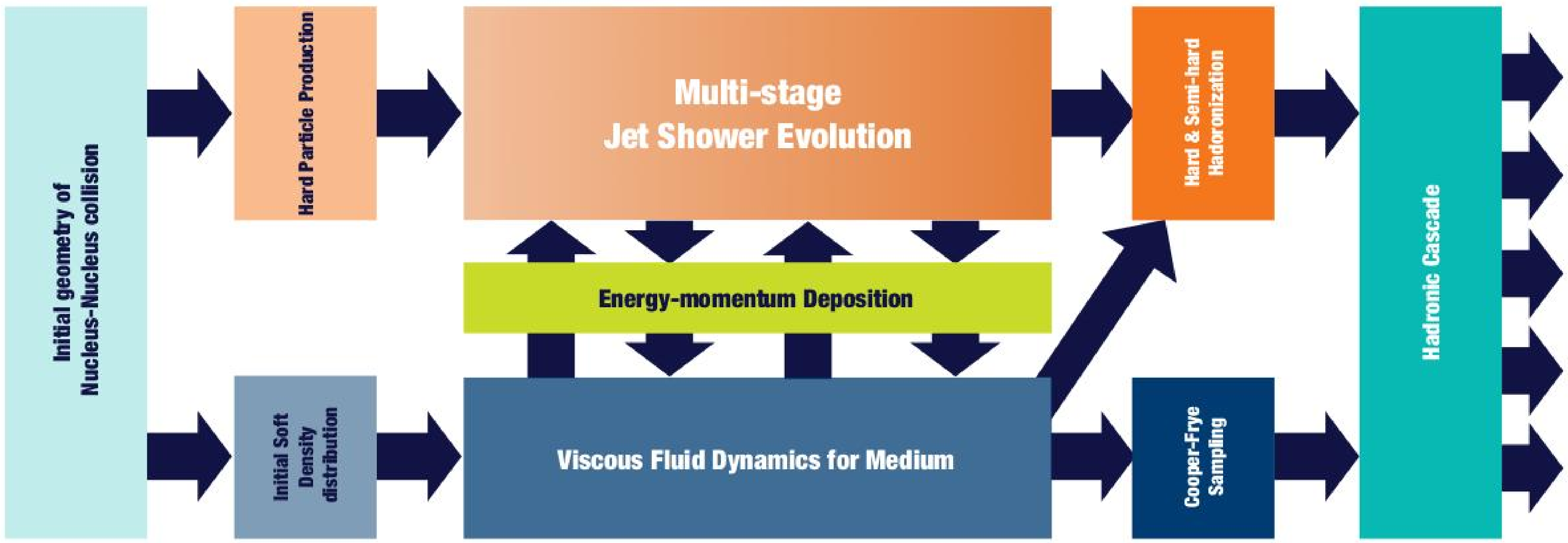
(Wayne State University) Ron Soltz (LLNL)

JETSCAPE

- **MC event generator package for heavy ion collisions**
  - JETSCAPE 2.0 available on GitHub github.com/JETSCAPE
  - General, modular and highly extensible Talk by R. Soltz (Fri)

Y. Tachibana

Event Generator Ingredients



Jet quenching models with medium response

Luo's slide

- JEWEL [BDMPS-Z] : recoiled partons transported. (modified parton shower)
- LBT [HT] : recoiled partons transported. (shower + transport)
- MARTINI [AMY] : recoiled partons transported. (shower + transport)

} Recoil-medium rescattering

HT: higher twists

- CoLBT-hydro [HT] : Transport + Hydro parallel simulation. (shower + transport)
- Hybrid [AdS/CFT] : fully thermalized wake. (modified parton shower)
- Coupled Jet-Fluid [HT] : solve Boltzmann equation + Hydro simulation
- EPOS3-HQ : YaJEM + Hydro parallel simulation. (modified parton shower)

} Energy momentum deposition into Hydro

Jet quenching models with medium response

Luo's slide

modified parton shower + transport

JETSCAPE
- Matter [HT] + LBT [HT] : recoiled partons transported.
- Matter [HT] + MARTINI [AMY] : recoiled partons transported.
- Matter [HT] + ADS/CFT: Hydro simulation.

Recoil-medium rescattering

Energy momentum deposition into Hydro

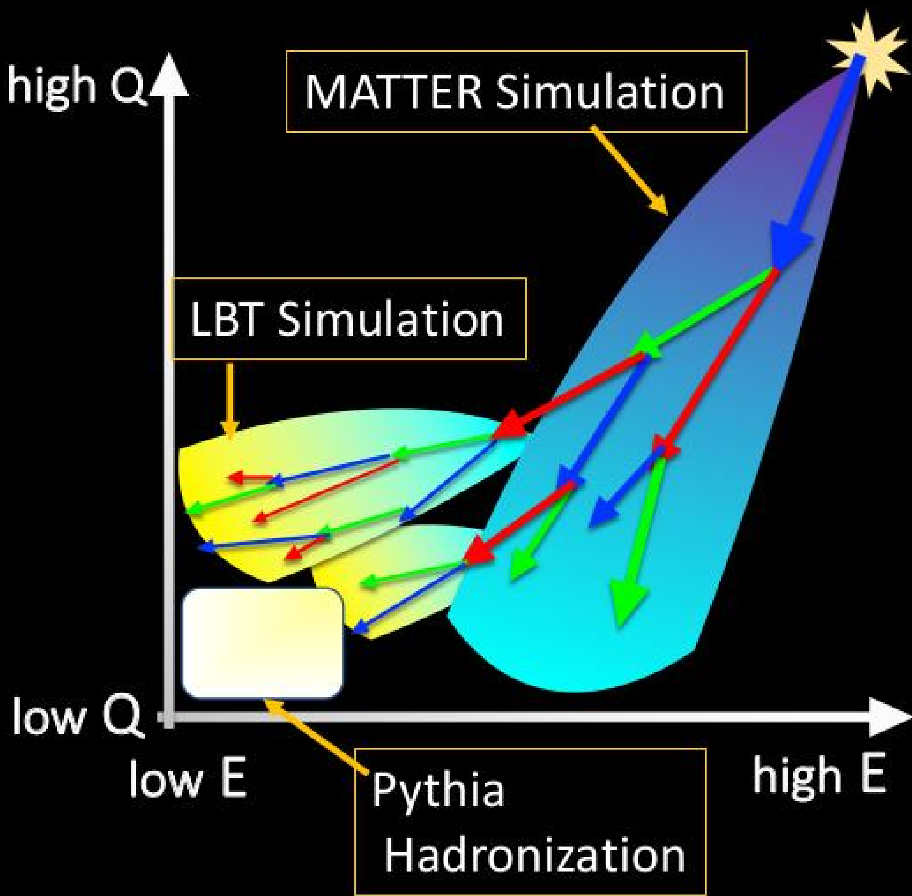
- AMPT
- BAMPS

Particle scattering for both medium and jet

- Linearized viscous hydrodynamics with source

JETSCAPE

Multi-stage parton evolution in JETSCAPE



- High→Lower Q, High E: Rapid virtuality loss through radiation (MATTER using Higher Twist)
- Low Q, High→Lower E: Scattering is important (Linear Boltzmann Transport)
- Low Q, Low E: Hadronization physics important (partons→Pythia for hadronization)

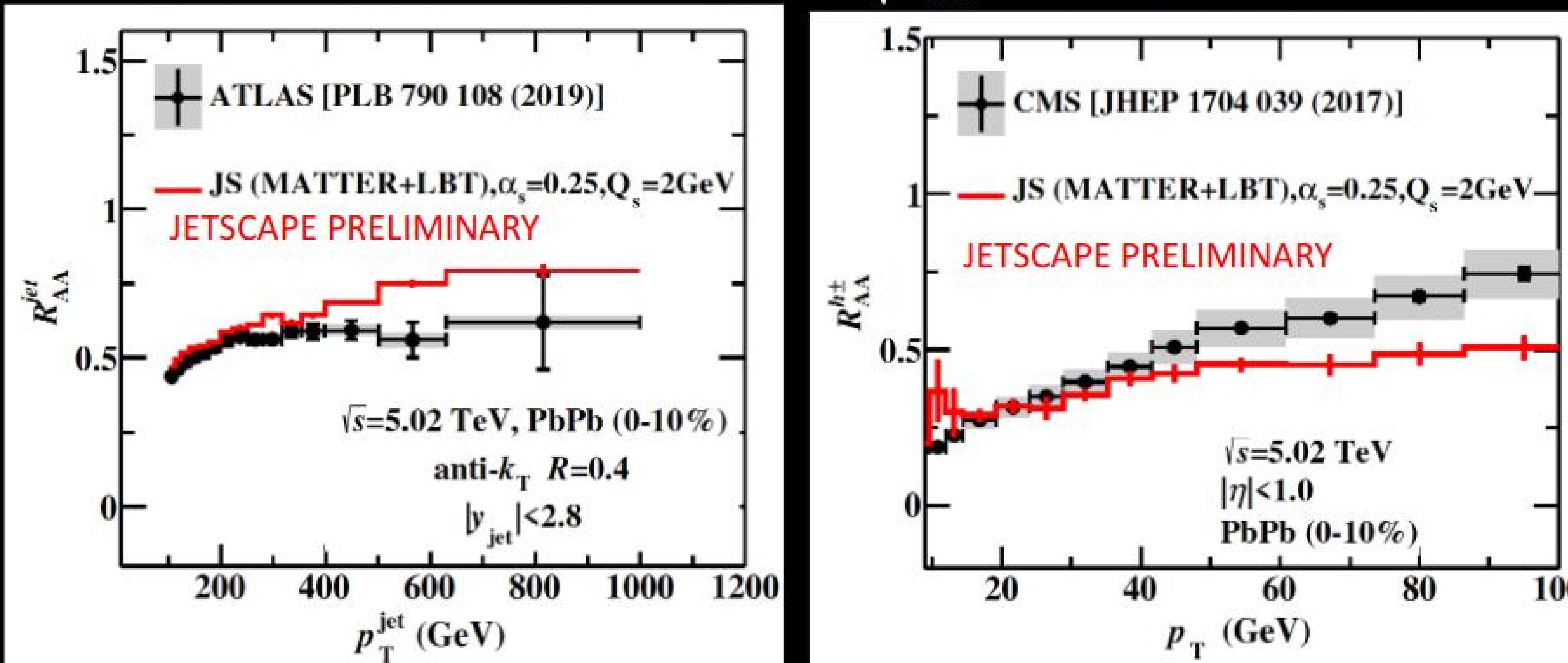
Different physics mechanisms for in-medium energy loss in different kinematic regimes ⇒ a multi-stage approach is needed for accurate description

Slide G. Vujanovic

6

JETSCAPE

JETSCAPE tune to 0-10% PbPb at $\sqrt{s_{NN}} = 5.02\ TeV$ to data



- Jet and charged hadron R_{AA} used to tune parameters, i.e. $\alpha_s = 0.25$ and $Q_s = 2GeV$ (for more details see talk by **Amit Kumar**)
- No additional tuning was done for D^0 meson R_{AA}

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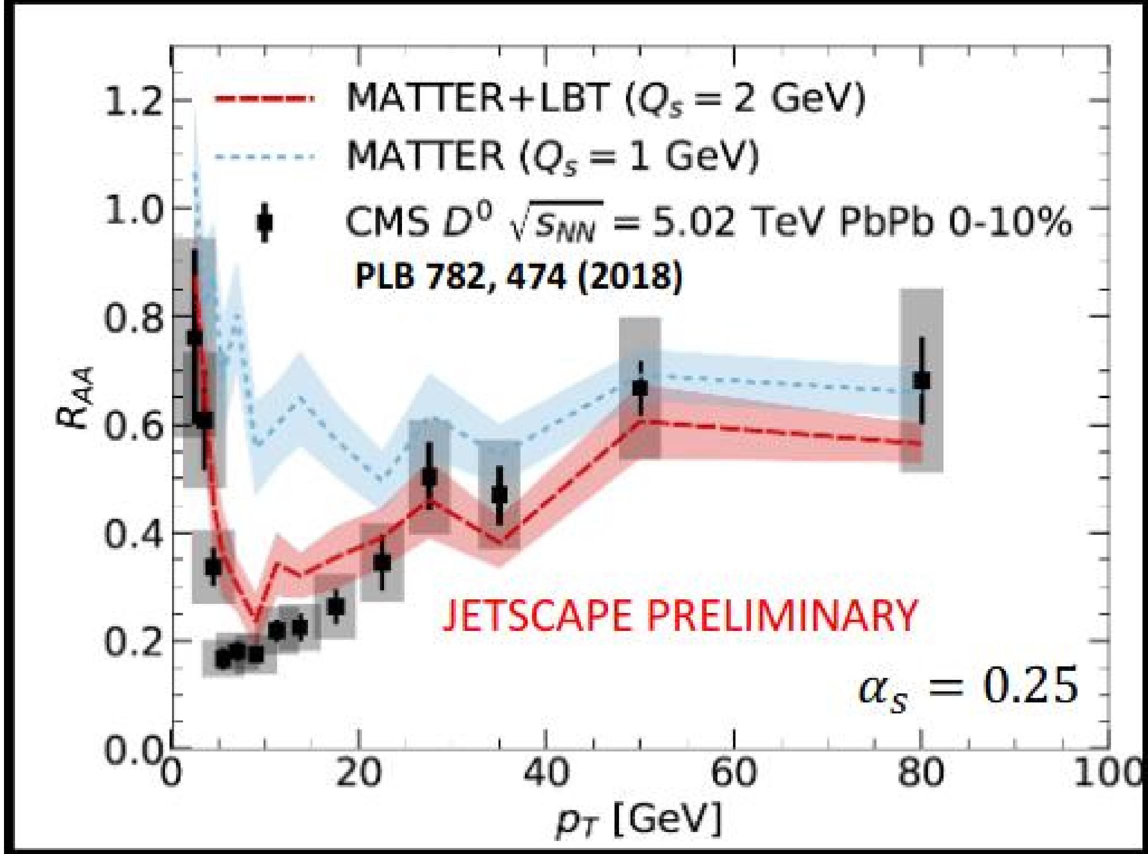
 on a given QGP evolution profile?

JETSCAPE

D^0 mesons R_{AA} vs CMS data from PbPb at $\sqrt{s_{NN}} = 5.02\ TeV$



- MATTER alone has few scatterings with the QGP before Pythia hadronization
  $\Rightarrow R_{AA}$ close to 0.5
- MATTER +LBT has many scatterings with the QGP, owing to LBT, before Pythia hadronization
  $\Rightarrow R_{AA}$ can go much closer to 0.1
- Using a multi-scale approach allows to balance the contributions from few vs multiple scattering, and ultimately gives an improved description of R_{AA}

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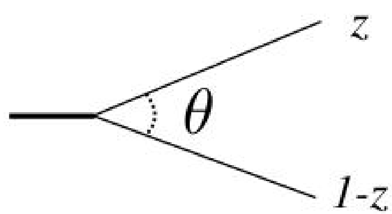
on a given QGP evolution profile?

Jet structure

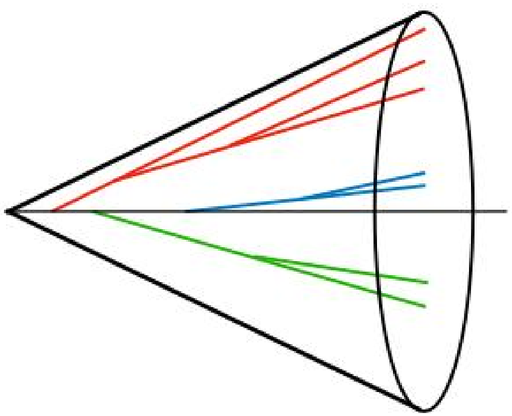
VACUUM SPLITTING



Generic 1→2 (on-shell) splitting in QCD:

$$d\Pi_{a\to bc} = \frac{\alpha_s}{\pi}\frac{d\theta}{\theta}P_{ba}^{(c)}(z)dz \approx \frac{2\alpha_s C_R}{\pi}\frac{d\theta}{\theta}\frac{dz}{z}$$

Diverges for soft & collinear radiation!



Large phase space for radiation compensates α_s!

$$\text{Prob} = \frac{\alpha_s C_R}{\pi}\log^2\frac{p_T R}{\Lambda_{\text{QCD}}} \gg 1$$

Need for resummation of collinear logarithms for final-state radiation.

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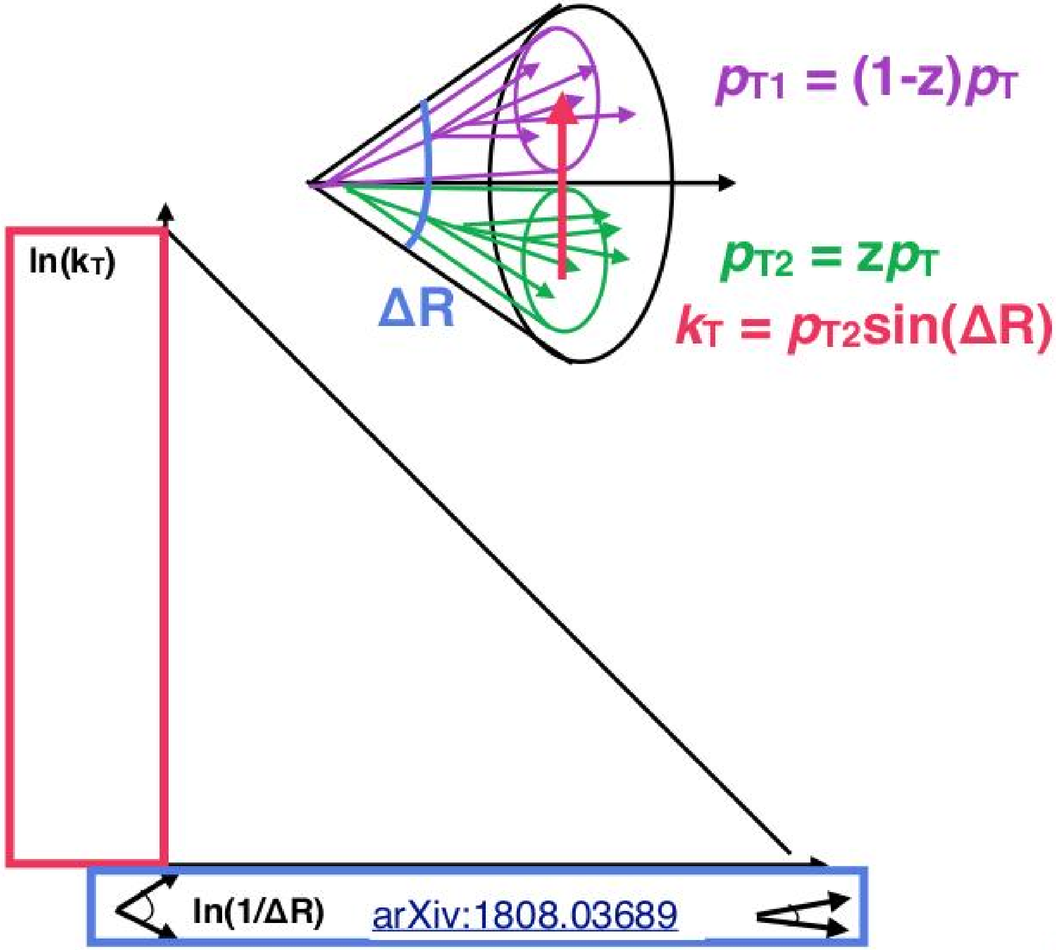
Jet structure

Exploring the Lund Plane: in vacuum

- Lund Diagram*: phase space of jet splitting
  *Z. Phys. C43 (1989)
  JHEP 12 (2018)

- k_T: relative transverse momentum of subjets

- ΔR: opening angle between subjets



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Jet structure

Exploring the Lund Plane: in vacuum

- Lund Diagram*: phase space of jet splitting

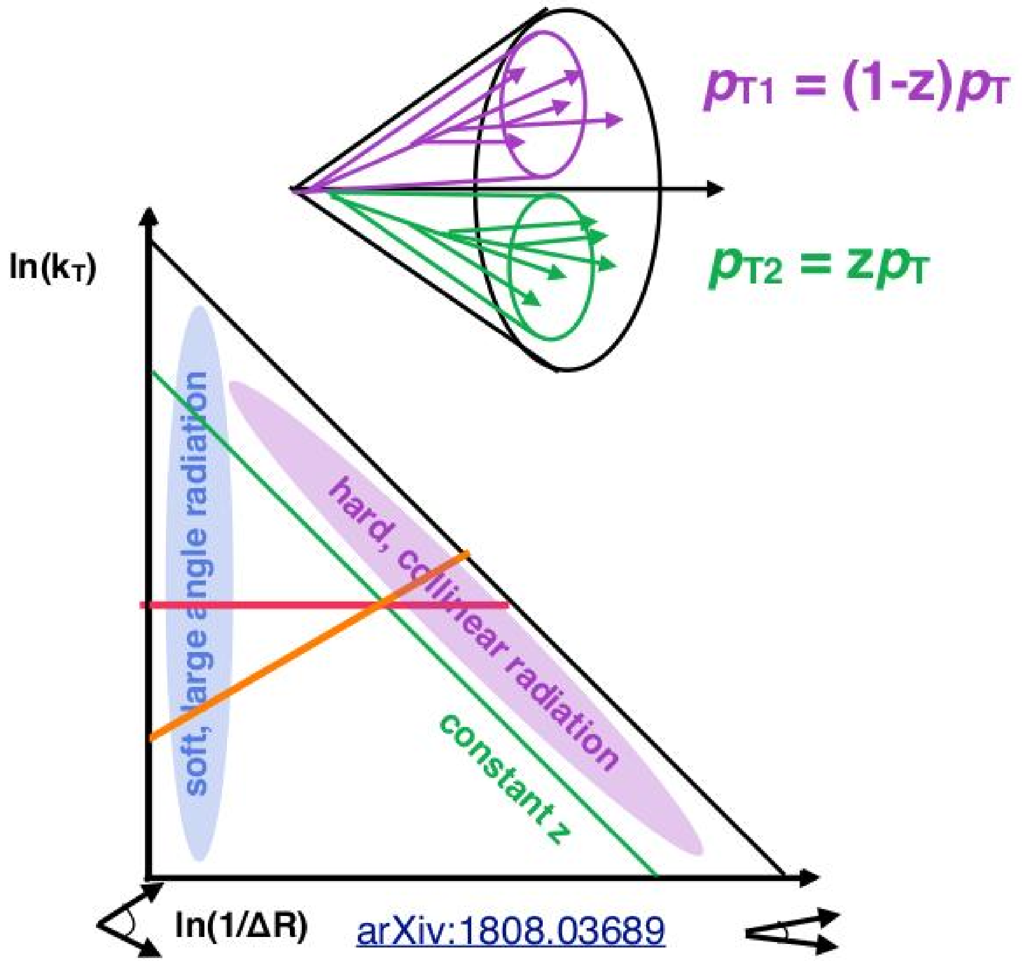
*Z. Phys. C43 (1989)
JHEP 12 (2018)

- $\log(k_{\mathrm{T}}) > 0$ separates perturbative from non-perturbative regime

- Formation time: how long until the splitting occurred

$$t_{\mathrm{f}} = \frac{1}{(1-z)k_{\mathrm{T}}\Delta R}$$

Y. L. Dokshitzer, et.al.



arXiv:1808.03689

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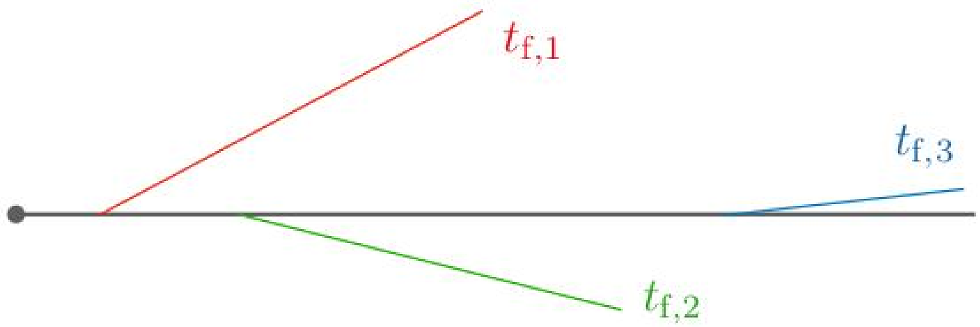
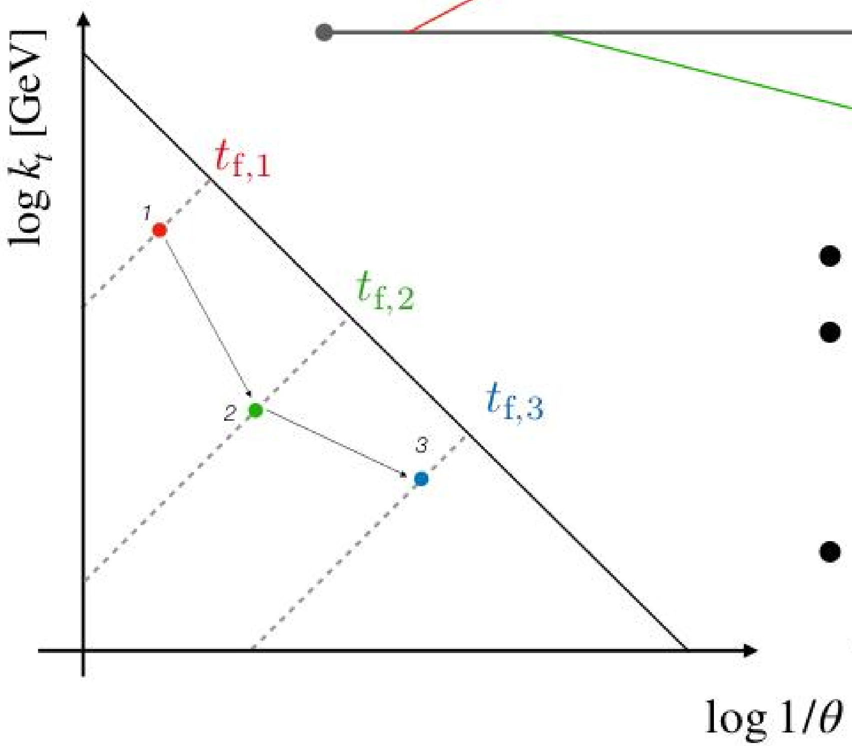
Jet structure

SPACE-TIME PICTURE OF A JET

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)





- semi-classical picture, angular ordering
- **Lund diagram** (primary emission plane)
  - secondary branchings located on independent "leaves"
- accessed in experimental data using jet reconstruction (C/A algorithm)

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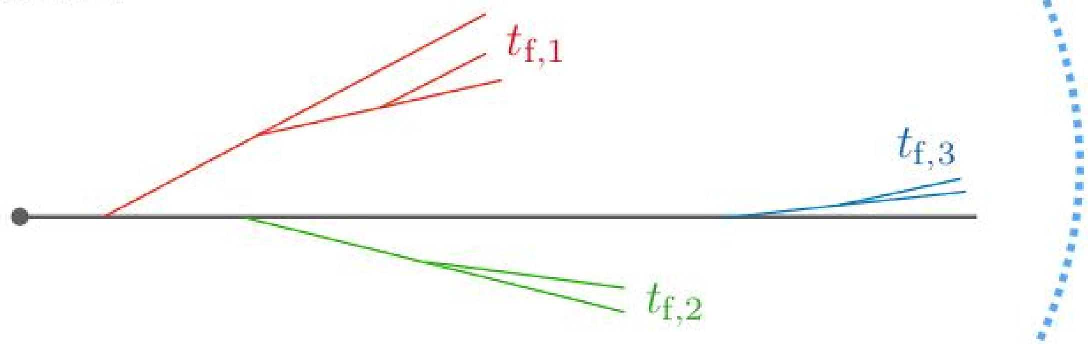
Jet structure

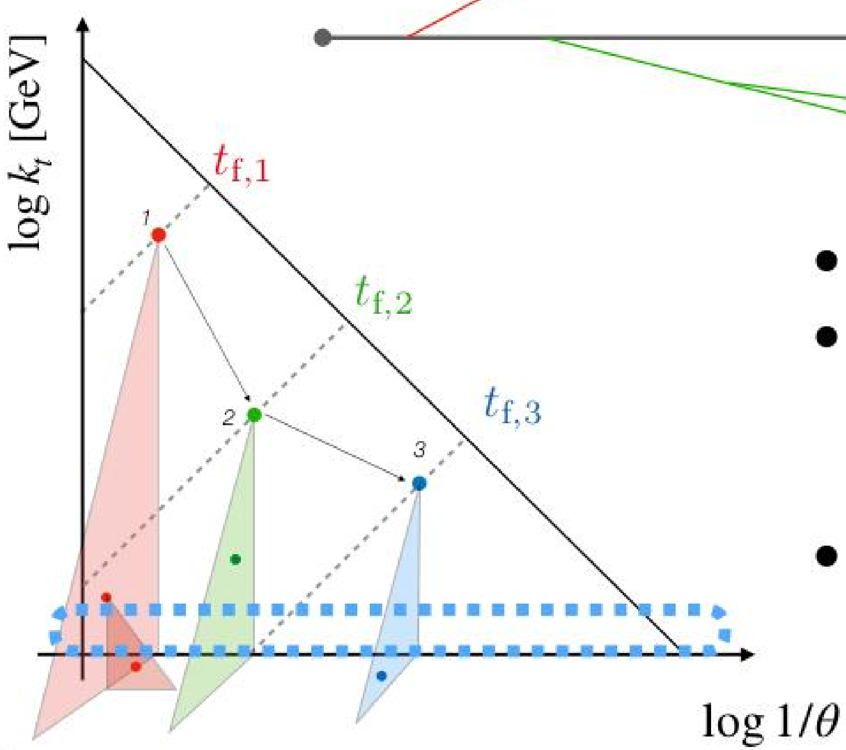
SPACE-TIME PICTURE OF A JET

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



hadronization

from $t_f \sim (Q_0 R)^{-1} \sim 2\,\mathrm{fm}$
to $t_f \sim E/Q_0^2 \sim 300\,\mathrm{fm}$



- semi-classical picture, angular ordering
- **Lund diagram** (primary emission plane)
  - secondary branchings located on independent "leaves"
- accessed in experimental data using jet reconstruction (C/A algorithm)

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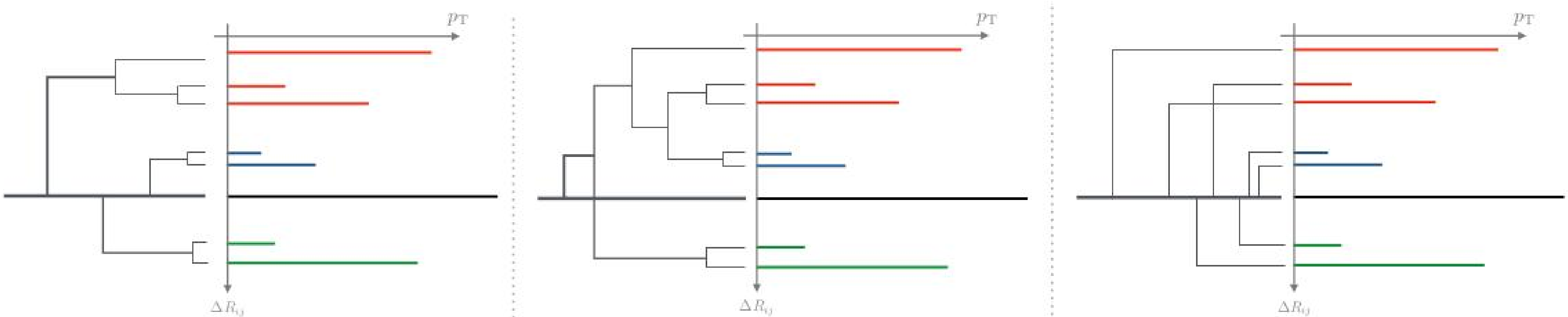
Jet structure

RECOMBINATION ALGORITHMS

Pairwise clustering of particles that minimize $d_{ij} = \min(p_{\mathrm{T},i}^{2\alpha}, p_{\mathrm{T},j}^{2\alpha})\Delta R_{ij}^2/R^2$



1) Cambridge/Aachen (CA)

[Dokshitzer, Leder, Moretti, Webber (1997)]

- only angular measure (α=0)
- ideal for substructure measurements

2) k_t algorithm

[Catani, Dokshitzer, Seymour, Webber (1993); Ellis, Soper (1993)]

- k_t weighted metric ($\alpha = 1$)
- sensitive to soft activity

3) anti-k_t algorithm

[Cacciari, Salam, Soyez (2008)]

- anti-k_t weighted metric ($\alpha = -1$)
- resilient to soft activity, ideal for identifying candidate jets

Jets are separated whenever beam distance is shortest $d_{iB} = p_{\mathrm{T},i}^{2\alpha}$

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Jet structure

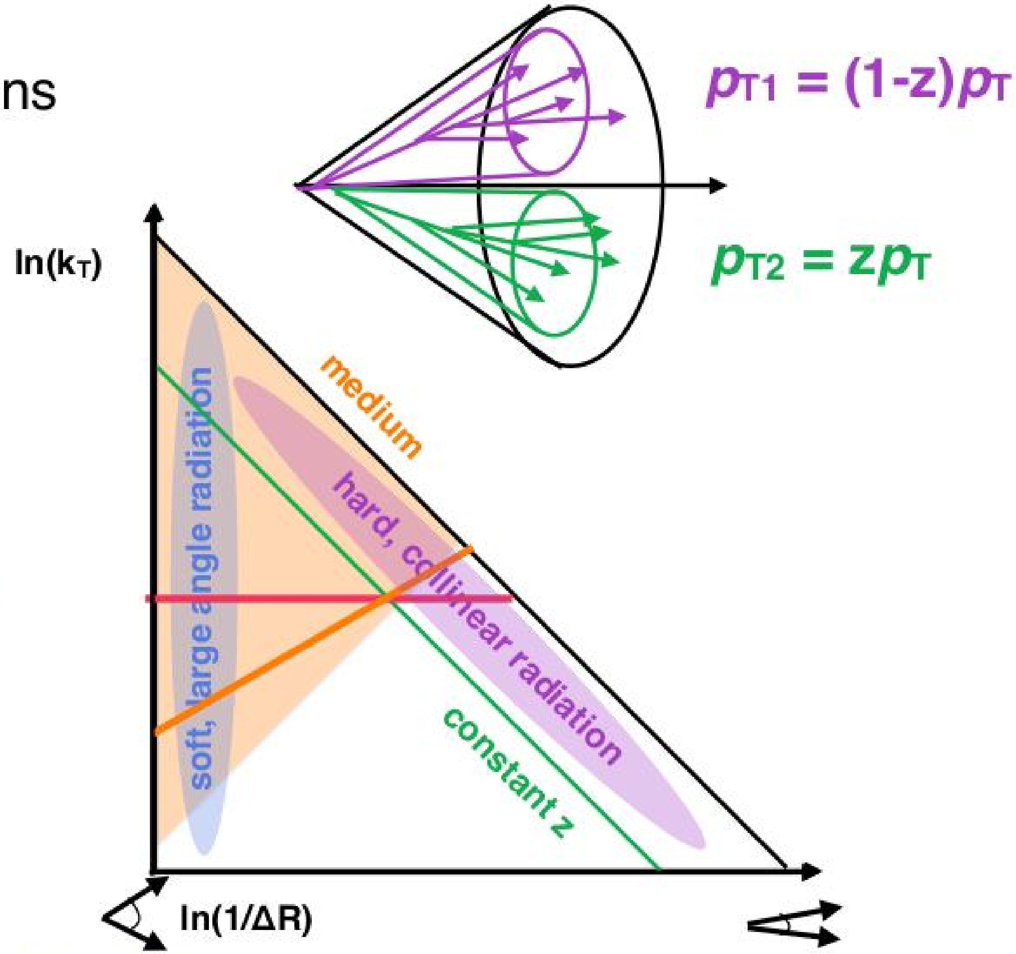
Exploring the Lund Plane: in medium

- Jet splittings in heavy-ion (HI) collisions

➡ in/out of medium splittings
- Earlier/wider splittings experience more medium

➡ Vacuum splittings vs. non-perturbative in-medium splittings

➡ Coherence vs. decoherence
- Split jets should be more quenched



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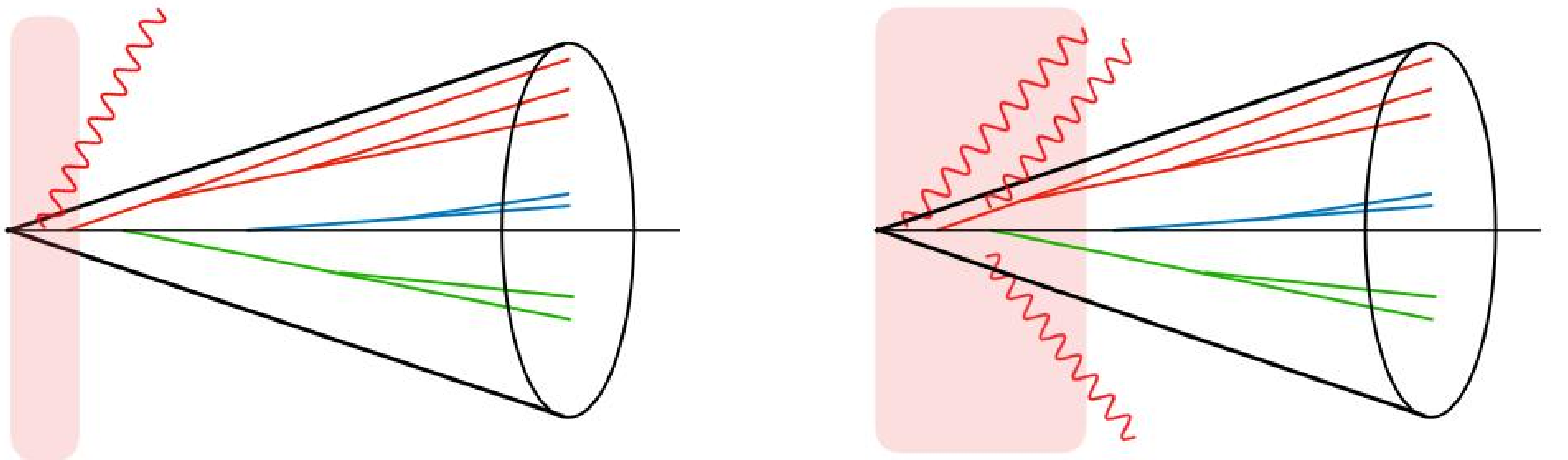
Jet structure



new element: importance of jet substructure fluctuations!

also seen in MC studies: Milhano, Zapp 1512.08107; Casalderrey-Solana, Milhano, Pablos, Rajagopal 1808.07386

Ringer (Wed 09:40)

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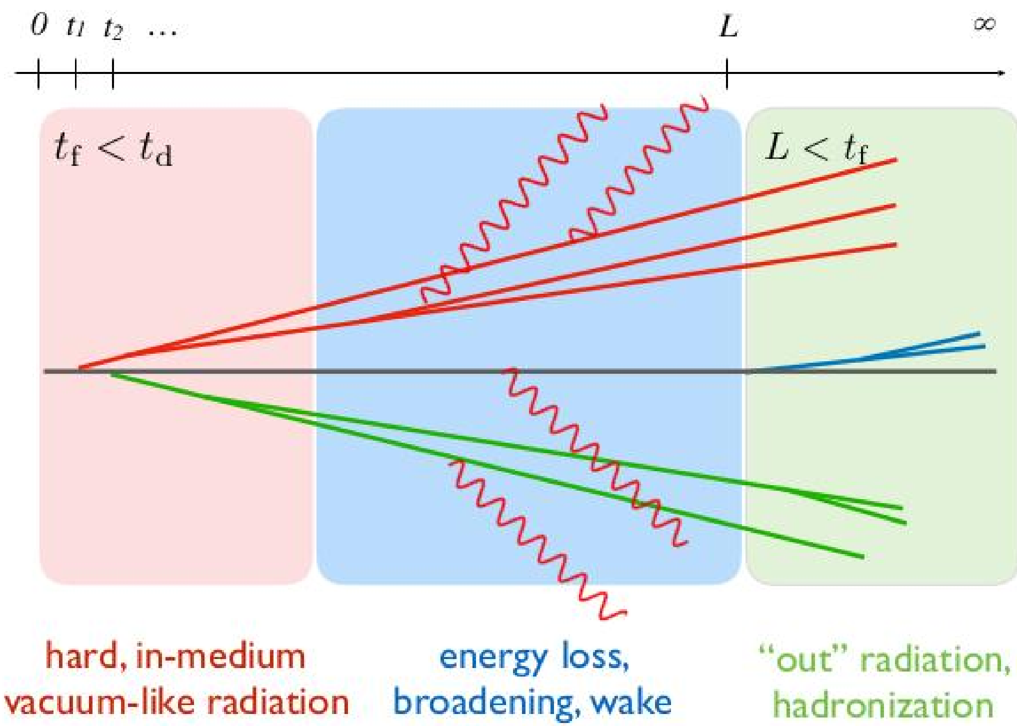
Jet structure

EMERGING PROBABILISTIC PICTURE



[See also Caucal, Iancu, Soyez, Mueller 1801.09703]

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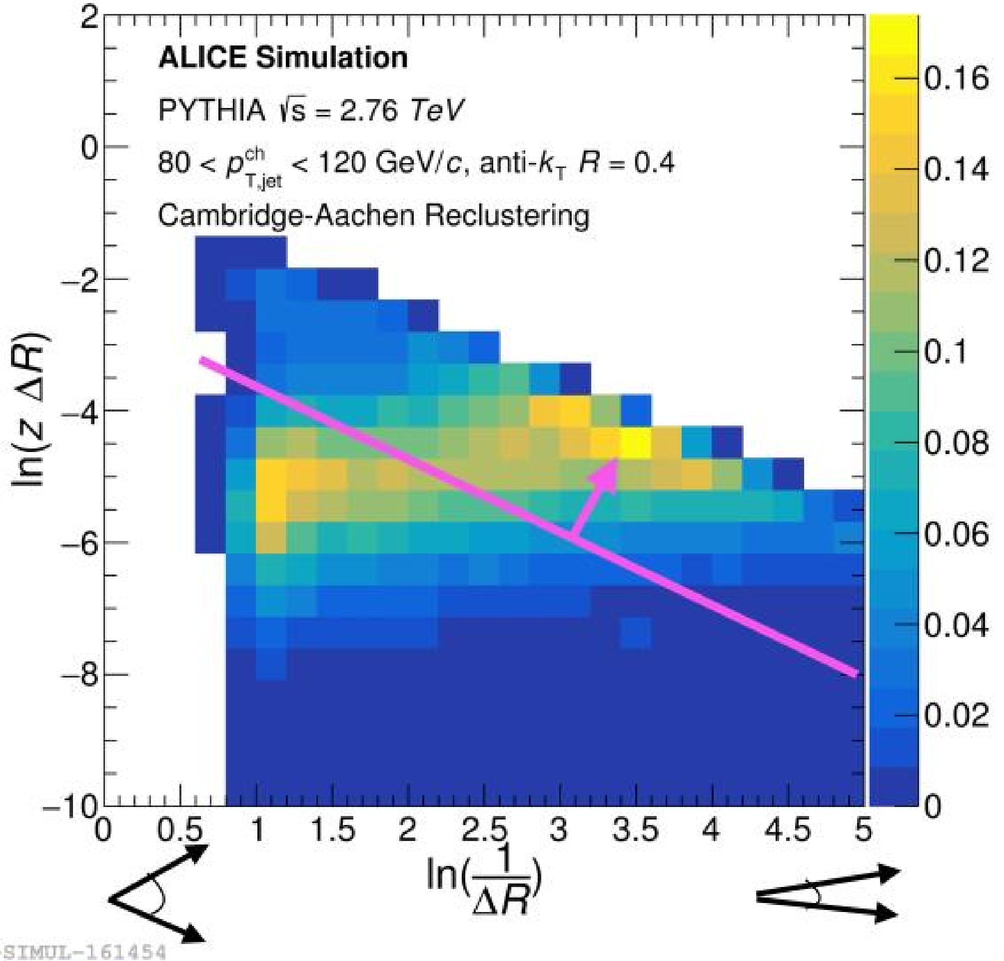
Jet structure

Soft drop grooming

- Reconstruct anti-k_T R=0.4 charged jets between 80-120 GeV/c with jet-by-jet constituent background subtraction* (in HI collisions) *JHEP 06 (2014) 092
- Recluster jets with Cambridge/Aachen (C/A)* to enforce angular ordering and fill *primary* Lund diagram with splitting information *JHEP 9708:001,1997



- Soft drop grooming to access hard splitting

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

$$z_g > z_{cut}\,\theta^{\beta} \qquad \theta = \frac{\Delta R}{R}$$

- Default condition: $z_{cut} = 0.1$, $\beta = 0$

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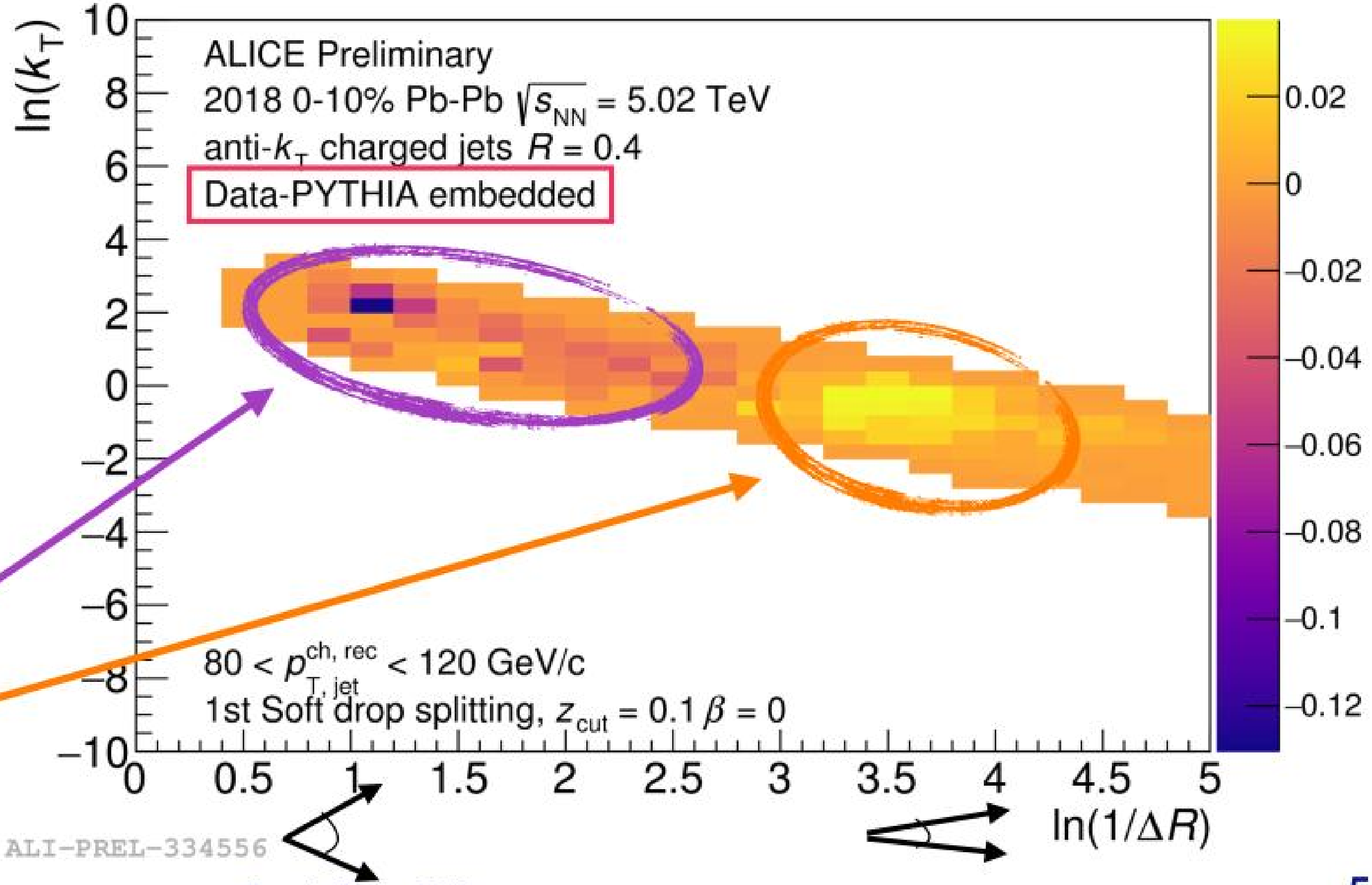
Jet structure

Exploring the Lund Plane in Data

New 2018 0-10% Pb-Pb collision data at 5.02 TeV

- Compare to PYTHIA8 embedded into real 0-10% Pb-Pb collisions
- Subtract the embedded MC from the data in order to remove the effects from the large HI background
- Suppression at large ΔR and enhancement at small ΔR



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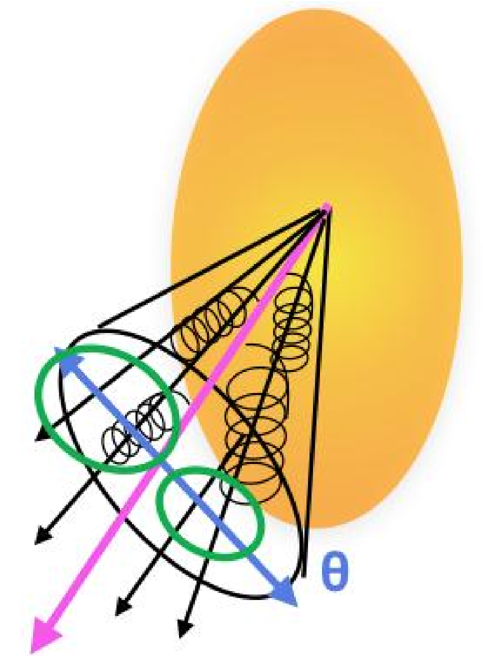
Jet structure

Groomed variables

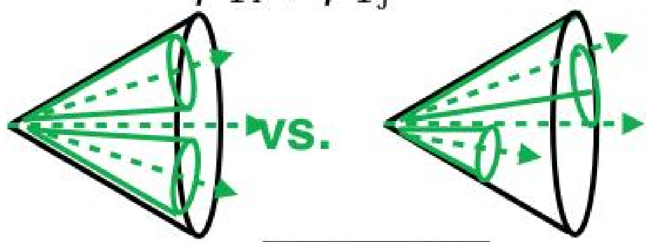
- Soft drop grooming variables probe jet splitting

➡ z_g: shared momentum fraction between two hardest subjets in parton shower

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$



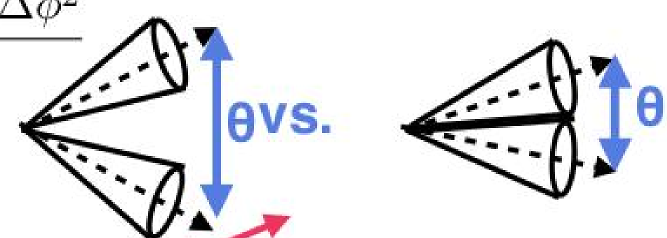
How symmetric is the jet splitting?



➡ θ_g: distance between subjets

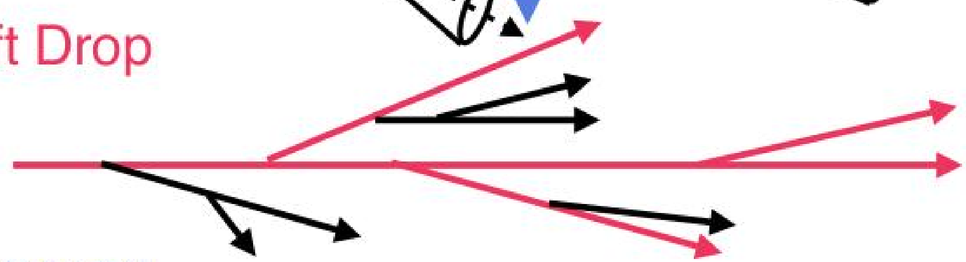
$$\theta_g = \frac{R_g}{R} = \frac{\sqrt{\Delta\eta^2 + \Delta\phi^2}}{R}$$

How far apart are the subjets?



➡ n_{SD}: number of splittings passing Soft Drop

Number of subjets within a jet?



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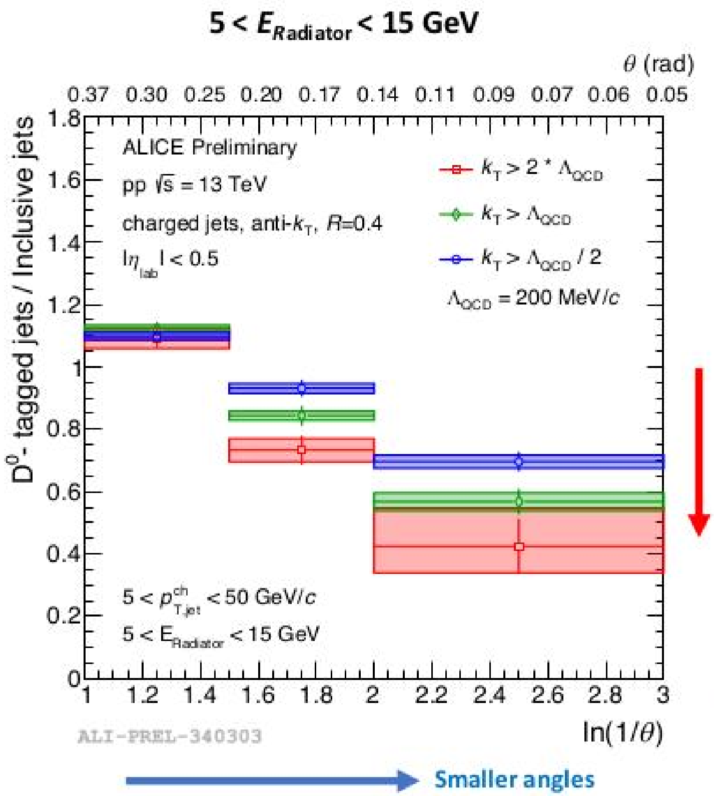
Dead cone

The Dead-Cone Uncovered



Suppression of splittings in D^0-tagged jets compared to inclusive jets

First direct observation of the dead-cone effect!

- Ratio of angular projections of D^0 and inclusive jet splittings are made
- **Suppression** of splittings at **small angles** in heavy flavour jets due to the dead-cone effect
- The magnitude of suppression increases at smaller angles
- The suppression also increases with stricter cuts on k_T
  - Contamination of hadronisation effects reduced

Nima Zardoshti - Quark Matter 2019 Wuhan 15

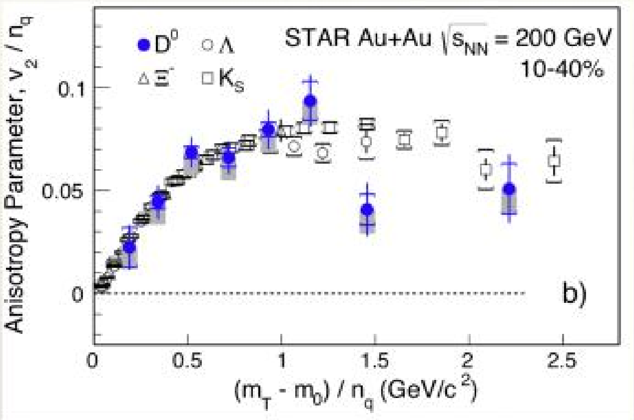
Heavy Flavor

Heavy Flavor

Heavy quark physics at different scales

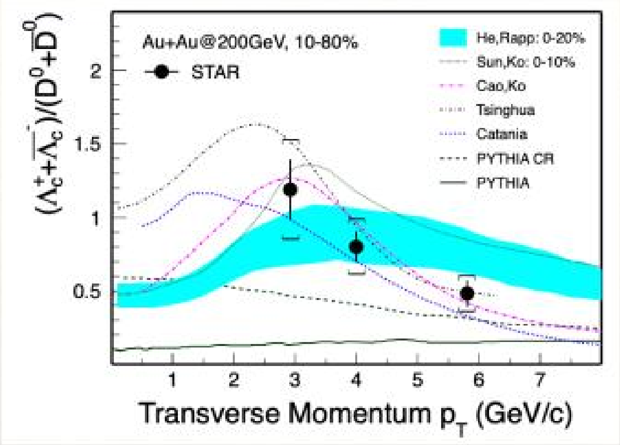
Cao's slide

low p_T



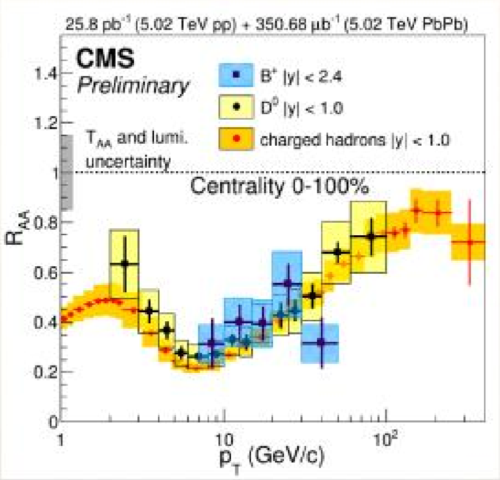
- Study the thermalization process of heavy quarks
- Constrain the color potential of HQ-medium interaction

medium p_T



- Study the hadronization process of heavy quarks
- Constrain the in-medium hadron wave-function

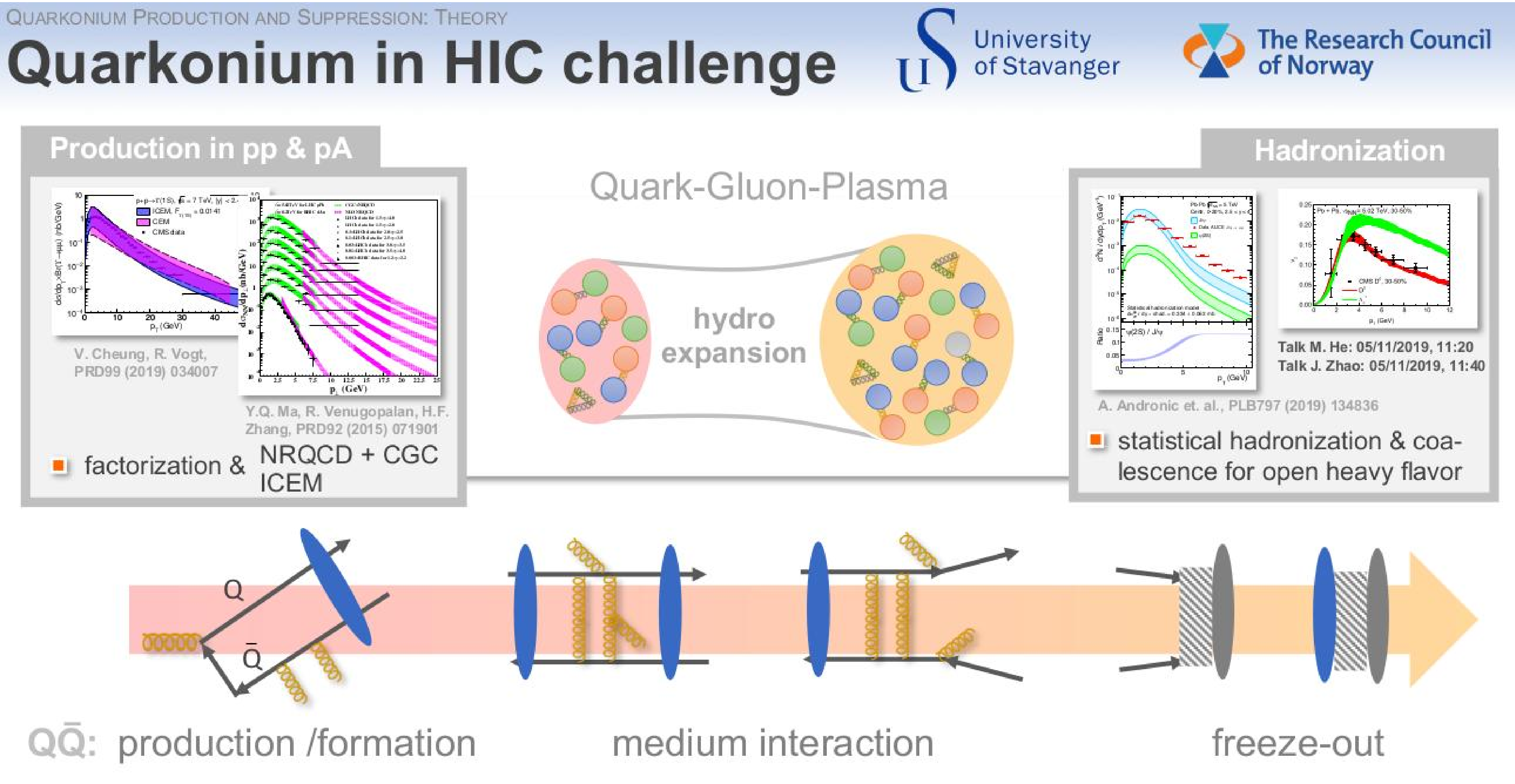
high p_T



- Study the energy loss process of heavy quarks
- Constrain the flavor hierarchy of parton energy loss

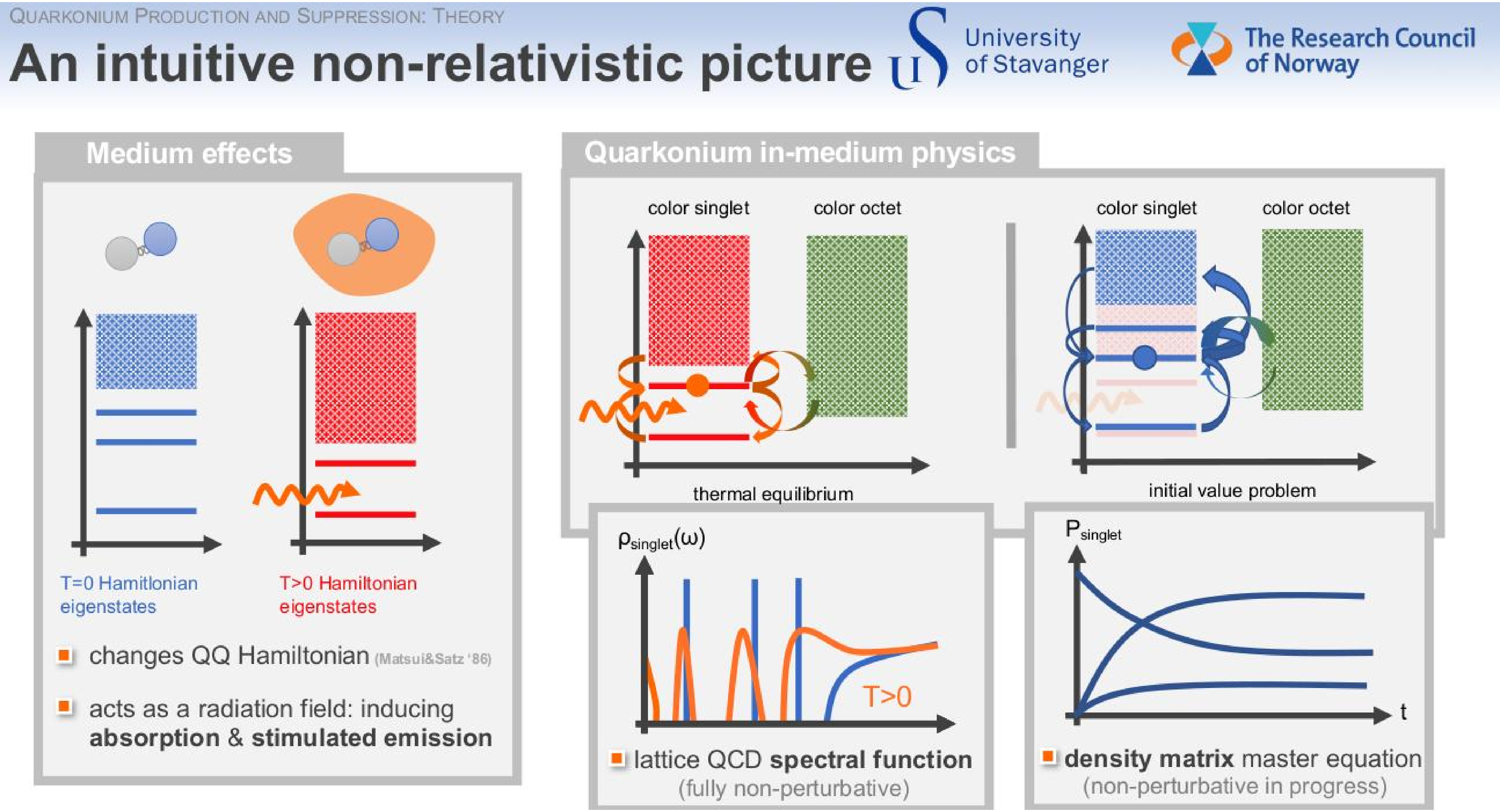
3

Quarkonium



QUARKONIUM PRODUCTION AND SUPPRESSION: THEORY
Quarkonium in HIC challenge
University of Stavanger
The Research Council of Norway
Production in pp & pA
V. Cheung, R. Vogt, PRD99 (2019) 034007
Y.Q. Ma, R. Venugopalan, H.F. Zhang, PRD92 (2015) 071901
factorization & NRQCD + CGC
ICEM
Quark-Gluon-Plasma
hydro
expansion
Hadronization
Talk M. He: 05/11/2019, 11:20
Talk J. Zhao: 05/11/2019, 11:40
A. Andronic et. al., PLB797 (2019) 134836
statistical hadronization & coalescence for open heavy flavor
Q
Q̄
QQ̄: production /formation
medium interaction
freeze-out

Quarkonium


QUARKONIUM PRODUCTION AND SUPPRESSION: THEORY
An intuitive non-relativistic picture
University of Stavanger
The Research Council of Norway
Medium effects
T=0 Hamiltonian eigenstates
T>0 Hamiltonian eigenstates
changes QQ Hamiltonian (Matsui&Satz '86)
acts as a radiation field: inducing absorption & stimulated emission
Quarkonium in-medium physics
color singlet
color octet
thermal equilibrium
color singlet
color octet
initial value problem
ρsinglet(ω)
T>0
lattice QCD spectral function
(fully non-perturbative)
Psinglet
t
density matrix master equation
(non-perturbative in progress)

Quarkonium

Open-quantum-systems

University of Stavanger — The Research Council of Norway

- Require **general real-time approach** for quarkonium coupled to a thermal medium

$$H = H_{Q\bar{Q}} \otimes I_{med} + I_{Q\bar{Q}} \otimes H_{med} + H_{int}$$

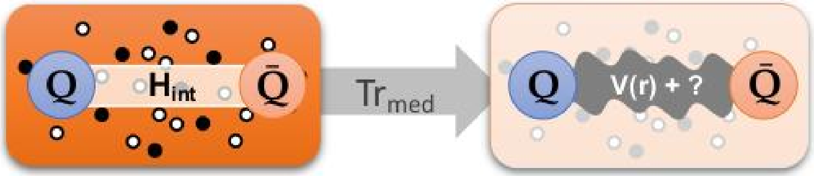
overall system is closed, hermitean Hamiltonian

$$H_{\rm int} = \sum_m \Sigma_m \otimes \Xi_m$$

Σ (in QQ̄ space) Ξ (in medium)

$$\frac{d\rho}{dt} = -i[H, \rho]$$

von Neumann equation



$$\rho_{Q\bar{Q}} = {\rm Tr}_{med}\left[\rho\right] \qquad \frac{d}{dt}\rho_{Q\bar{Q}} = ?$$

Goal: Dynamics of reduced density matrix

coarse graining leads to **non-reversible dynamics** from QCD

- **Separation of time-scales** determines the nature of the e.o.m. :

Environment relaxation scale τ_E : $\langle \Xi_m(t)\Xi_m(0)\rangle \sim e^{-t/\tau_E}$

QQ̄ system scale τ_S: $\tau_S \sim 1/|\omega - \omega'|$

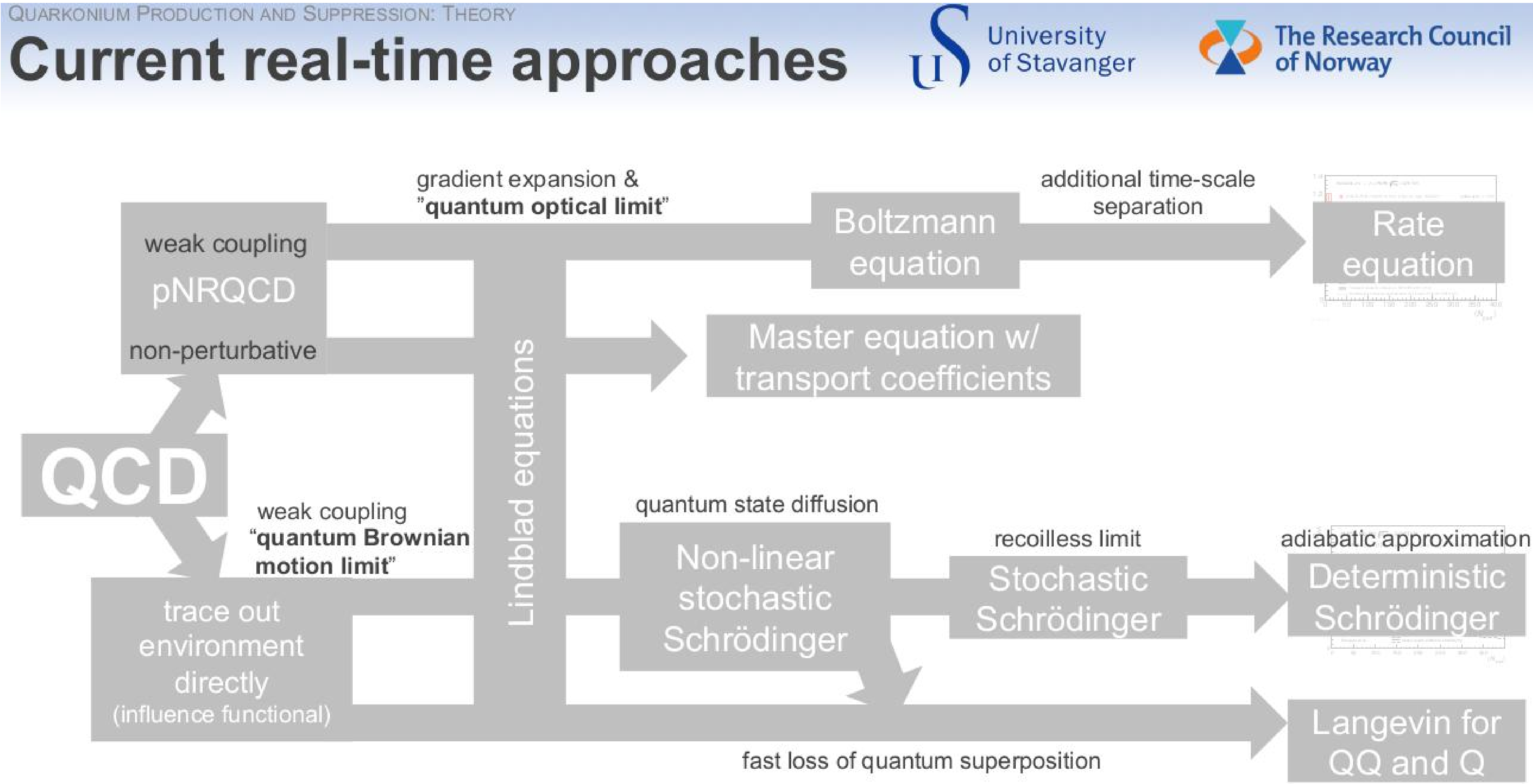
QQ̄ relaxation scale $\tau_{\rm rel}$: $\langle p(t)\rangle \propto e^{-t/\tau_{\rm rel}}$

- In case of Markovian time evolution ($\tau_E \ll \tau_{\rm rel}$) leads to a **Lindblad equation:**

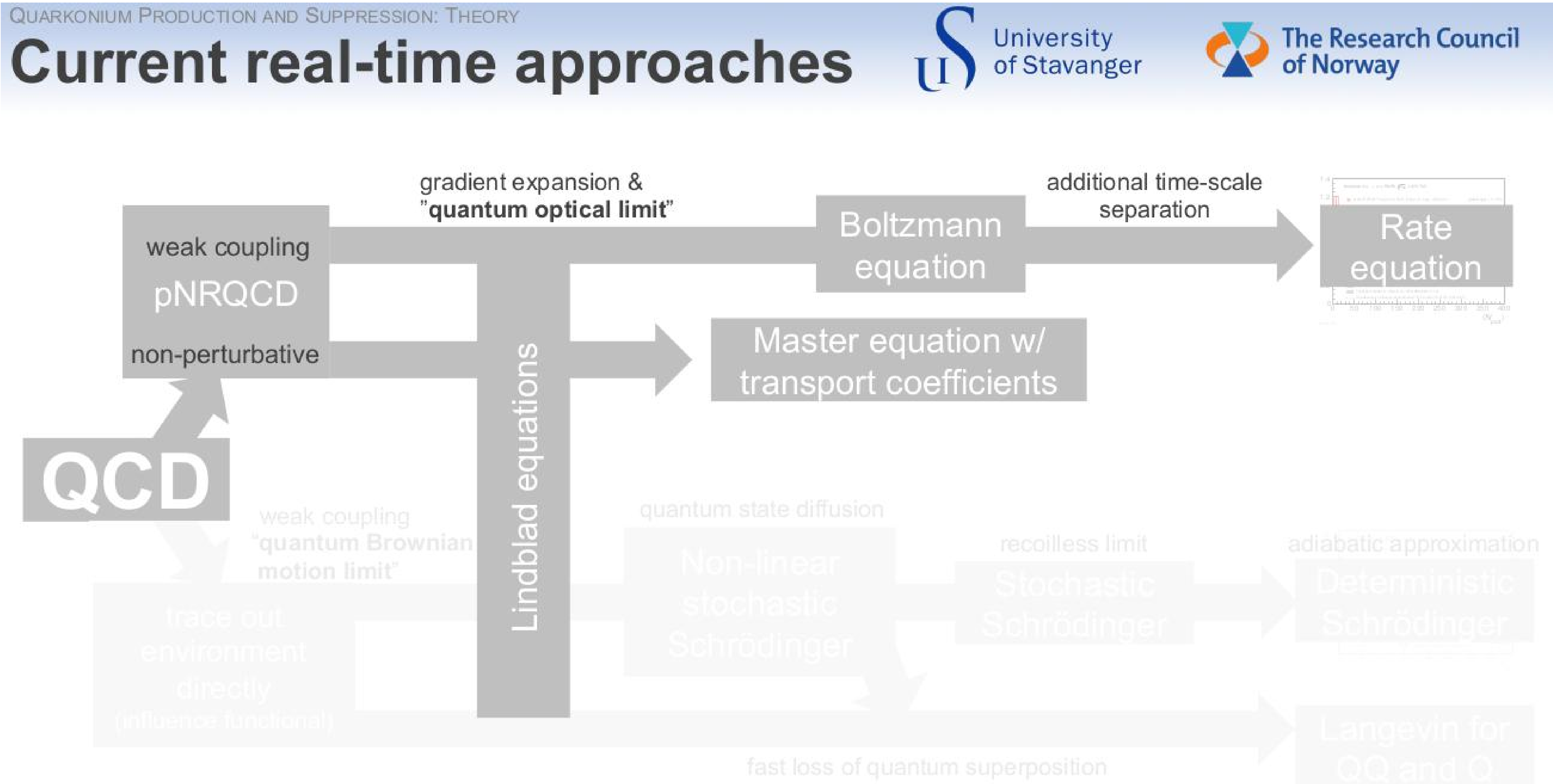
$$\frac{d}{dt}\rho_{Q\bar{Q}} = -i[\tilde{H}_{Q\bar{Q}}, \rho_{Q\bar{Q}}] + \sum_k \gamma_k \left(L_k \rho_{Q\bar{Q}} L_k^\dagger - \frac{1}{2} L_k^\dagger L_k \rho_{Q\bar{Q}} - \frac{1}{2}\rho_{Q\bar{Q}} L_k^\dagger L_k \right)$$

$$\langle n|\rho_{Q\bar{Q}}|n\rangle > 0, \forall n$$
$$\rho_{Q\bar{Q}}^\dagger = \rho_{Q\bar{Q}}, \quad {\rm Tr}[\rho_{Q\bar{Q}}] = 1$$

Quarkonium


QUARKONIUM PRODUCTION AND SUPPRESSION: THEORY
Current real-time approaches
University of Stavanger
The Research Council of Norway
QCD
weak coupling
pNRQCD
non-perturbative
gradient expansion & "quantum optical limit"
Boltzmann equation
additional time-scale separation
Rate equation
Master equation w/ transport coefficients
Lindblad equations
weak coupling "quantum Brownian motion limit"
trace out environment directly (influence functional)
quantum state diffusion
Non-linear stochastic Schrödinger
recoilless limit
Stochastic Schrödinger
adiabatic approximation
Deterministic Schrödinger
Langevin for QQ and Q
fast loss of quantum superposition

Quarkonium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gradient expansion &
"quantum optical limit"
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QCD
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quantum state diffusion
Non-linear stochastic Schrödinger
recoilless limit
Stochastic Schrödinger
adiabatic approximation
Deterministic Schrödinger
trace out environment directly
(influence functional)
fast loss of quantum superposition

Quarkonium

Quarkonium Production in Heavy Ion Collisions: from Open Quantum System to Transport Equation

Xiaojun Yao

Collaborators: Berndt Müller, Steffen Bass, Thomas Mehen, Weiyao Ke, Yingru Xu

Quark Matter 2019
Nov. 05, 2019, Wuhan, China

Quarkonium

Open Quantum System

- Total system = system + environment: $H = H_S + H_E + H_I$

$$\rho(t=0) = \rho_S \otimes \rho_E$$

System & environment

(Heavy quark pairs & QGP)

→ **Unitary evolution** / **Time reversible** →

$$U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)$$

System & environment

↓ **Trace out (integrate out) environment** ↓

$$\rho_S(t=0)$$

System (heavy quark pairs)

→ **Non-unitary** / **Time irreversible** →

$$\mathrm{Tr}_E\left[U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)\right]$$

4

Xiaojun Yao (MIT)

Quarkonium

From Open Quantum System to Transport Equation

Weak coupling to 2nd order: Lindblad equation

$$\rho_S(t) = \rho_S(0) - i\left[tH_S + \sum_{a,b} \sigma_{ab}(t) L_{ab}, \rho_S(0)\right] + \sum_{a,b,c,d} \gamma_{ab,cd}\left(L_{ab}\rho_S(0)L_{cd}^{\dagger} - \frac{1}{2}\{L_{cd}^{\dagger}L_{ab}, \rho_S\}\right)$$

Static screening

Markovian approximation

Wigner transform

Recombination

Dissociation

Boltzmann transport equation

$$\frac{\partial}{\partial t} f_{nls}(\boldsymbol{x}, \boldsymbol{k}, t) + \boldsymbol{v} \cdot \nabla_{\boldsymbol{x}} f_{nls}(\boldsymbol{x}, \boldsymbol{k}, t) = \mathcal{C}_{nls}^{(+)}(\boldsymbol{x}, \boldsymbol{k}, t) - \mathcal{C}_{nls}^{(-)}(\boldsymbol{x}, \boldsymbol{k}, t)$$

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XY T.Mehen, arXiv:1811.07027

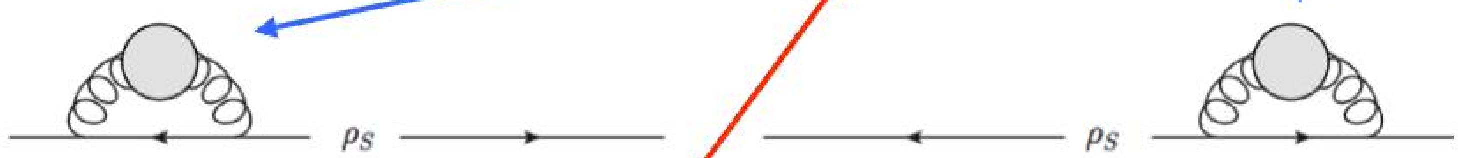
Quarkonium

Screening and Recombination in Same Framework

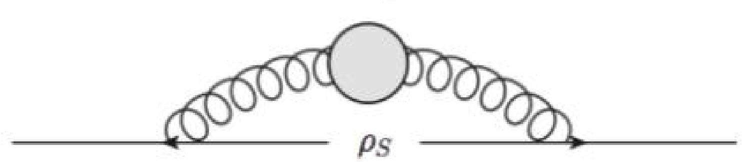
Weak coupling to 2nd order: Lindblad equation

$$\rho_S(t)=\rho_S(0)-i\left[tH_S+\sum_{a,b}\sigma_{ab}(t)L_{ab},\rho_S(0)\right]+\sum_{a,b,c,d}\gamma_{ab,cd}\left(L_{ab}\rho_S(0)L^{\dagger}_{cd}-\frac{1}{2}\{L^{\dagger}_{cd}L_{ab},\rho_S\}\right)$$

Same diagram as for screening



New diagram in this approach gives recombination



7

XY T.Mehen, arXiv:1811.07027

Quarkonium

Two Key Assumptions Justified from Scale Hierarchy

- Two key assumptions:

  1. **System interacts weekly with environment?**
  2. **Markovian approximation (no memory effect)?**

- Justified from separation of scales and effective field theory (potential NRQCD)

$$M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D$$

$v^2 \sim 0.3$ charmonium

$v^2 \sim 0.1$ bottomonium

1. **Dipole interaction between quarkonium and QGP** $rT \sim \frac{T}{Mv} \lesssim v$
2. **System relaxation time >> environment correlation time (coarse graining)**

$$(rT)^2 T \ll T$$

8

Xiaojun Yao (MIT)

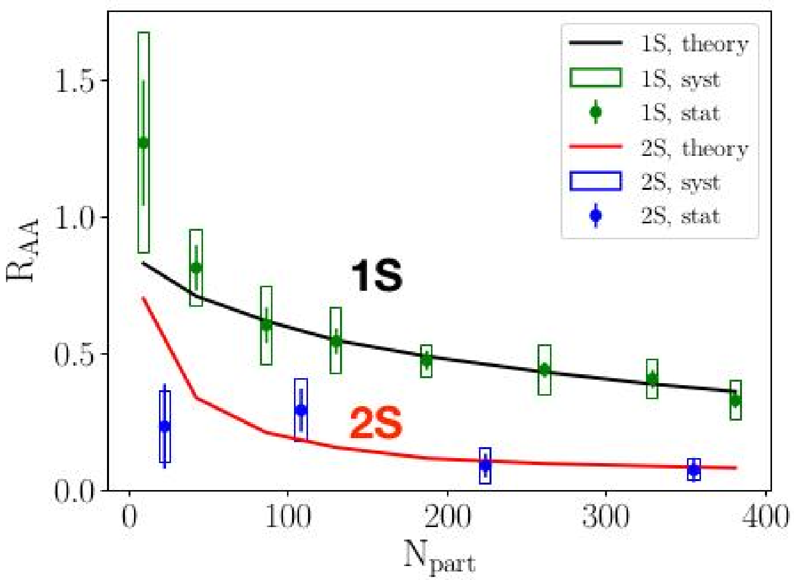
Quarkonium

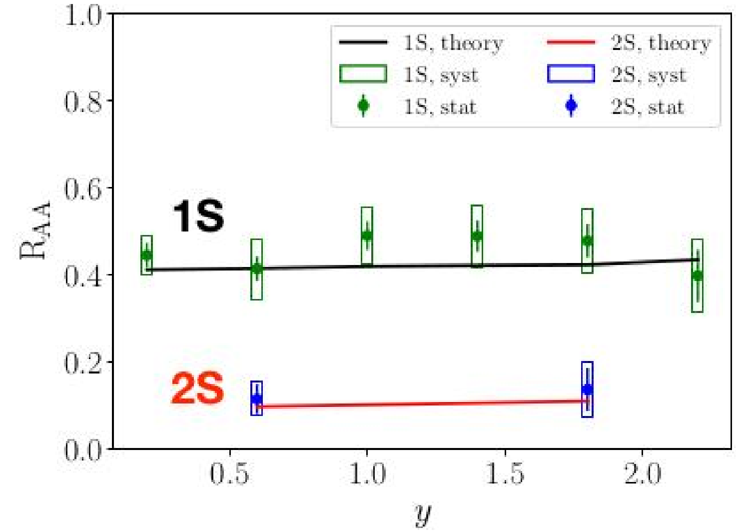
Upsilon in 2760 GeV PbPb Collision

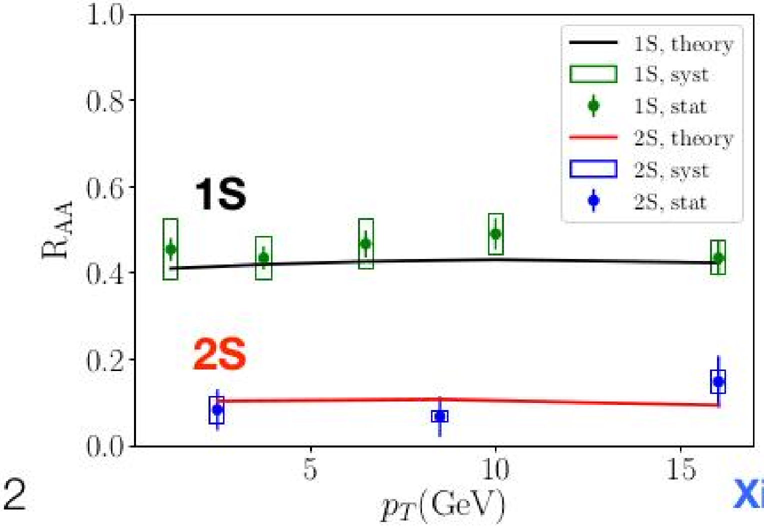
Fix $\alpha_s = 0.3$

Tune $T_{\mathrm{melt}}(2S) = 210\ \mathrm{MeV}$

Tune $V_s = -C_F \dfrac{0.42}{r}$







XY, W.Ke, Y,Xu, S,Bass, B.Müller arXiv:1807.06199

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Xiaojun Yao (MIT)

Hard probes：理論から

まだ、色々話題がありましたが、、、

量子系発展から流体発展までのスケールの記述はムズい

Hard probes：理論から

まだ、色々話題がありましたが、、、

量子系発展から流体発展までのスケールの記述は**面白い**