Theory summary of Hard Probes 2012

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5th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions - Cagliari (Sardinia) May 27 - June 1 2012

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European Research Council
Established by the European Commission

The Manifesto revisited

"To resolve and study a medium of deconfined quarks and gluons at short spatial scales, hard probes are essential and have to be developed into as precise tools as possible." [Lourenço & Satz, HP2004]

As of 2012, **hard probes have yet to fulfill their promise**.

In the case of jets and quarkonia, the study is mainly theory limited. Given good data, we do not yet know how to reliably extract $\hat{q}$ and $\hat{e}$. We do not yet know which jet observables are most sensitive to the physics we want to learn.

A quantitative theory of quarkonium suppression is just emerging. In the case of photons and dileptons, better data are needed.

But progress is being made, as HP2012 promises to show in abundance, and the goal appears ultimately reachable.

Berndt Muller (opening)

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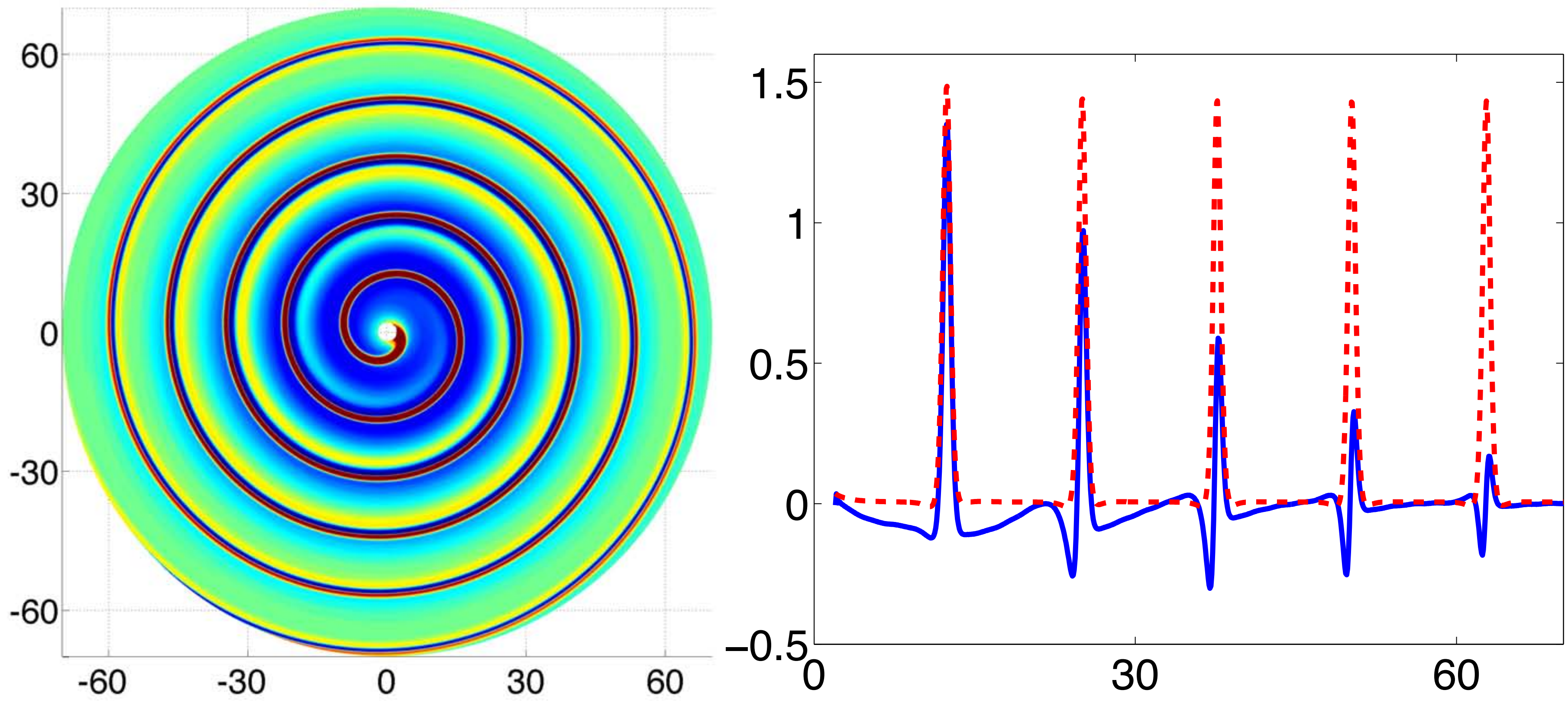
Monday, May 28, 12


Particle physics as I like it!
[quote from a Facebook friend]

The AdS/CFT connection...

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

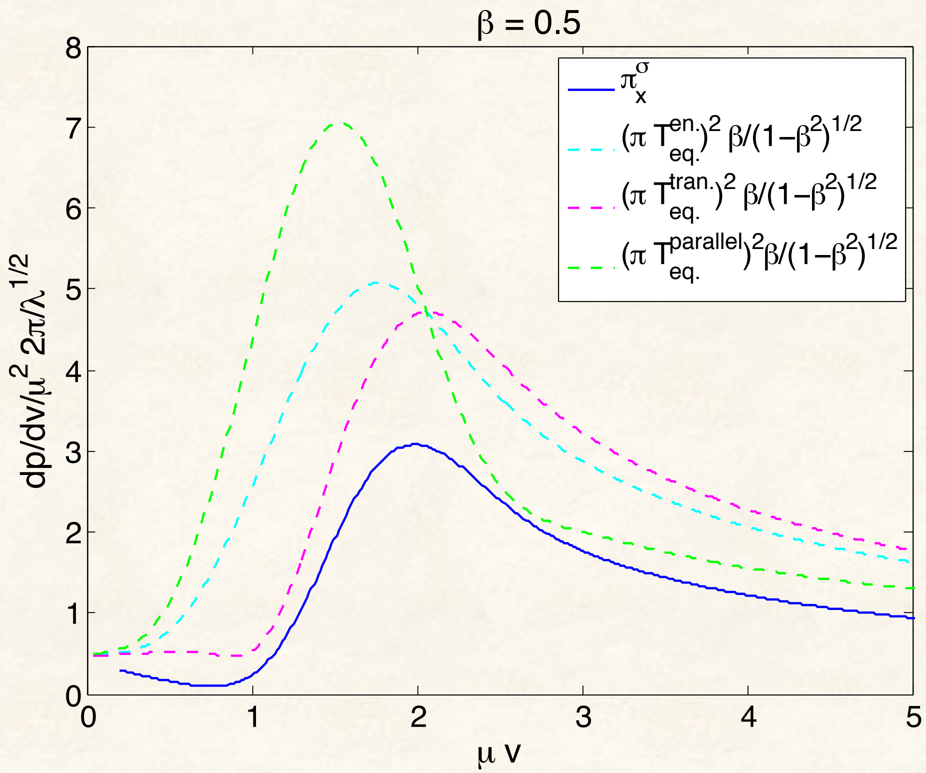


Quark in circular motion ($v = 0.5$; $R\pi T = 0.15$) makes a narrower beam of higher-q gluons that is attenuated more slowly as it shines through the strongly coupled plasma, leaving a sound wave farther behind.

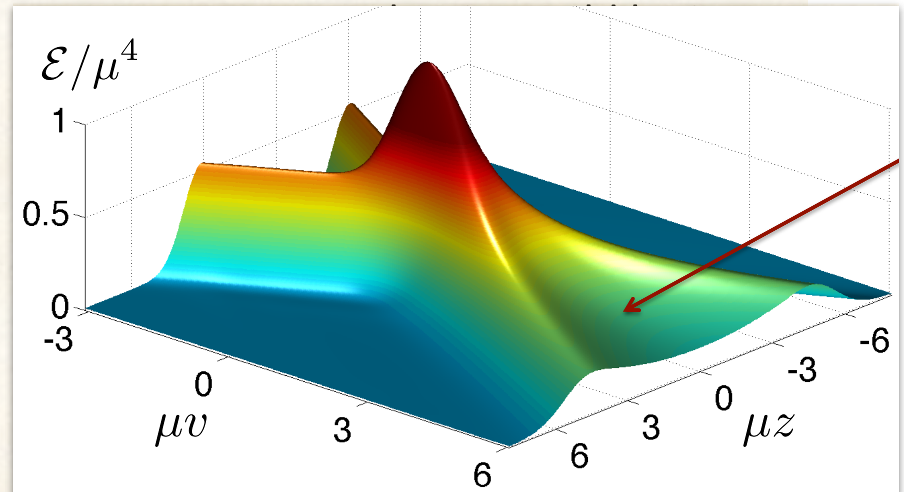
Krishna Rajagopal

Eloss in pre-equilibrium phase

Mindaugas Lekaveckas



- How does the drag force



drag force.

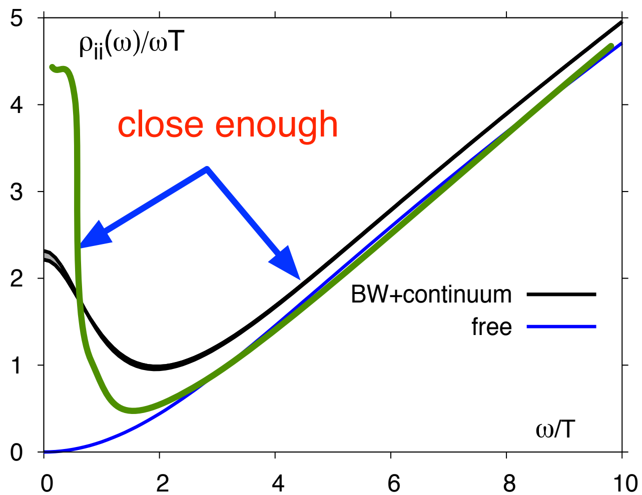
$$T^{\mu\nu}_{eq.} = \frac{\pi^2 N_c^2 T^4}{8}\mathrm{diag}(3,1,1,1)$$

- The actual drag force is somewhat smaller than any of the static expectations, and is certainly not larger!
- Pre-equilibrium energy loss is less than it would be in a static plasma with the same energy density or pressure! Counter-intuitive? It was to us…

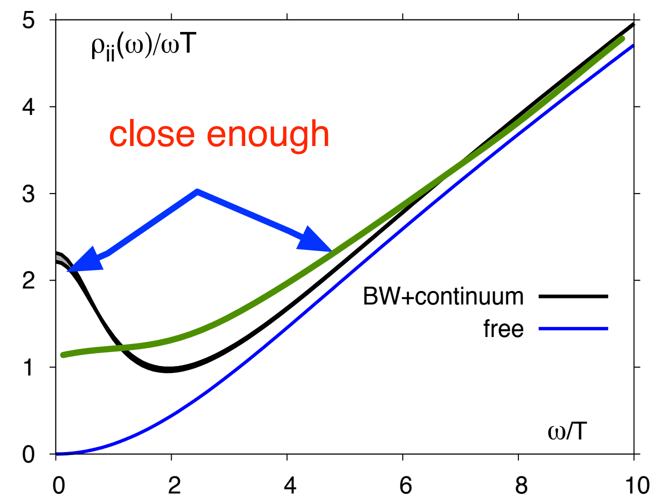
Spectral functions

Derek Teaney

Weak View



Strong View

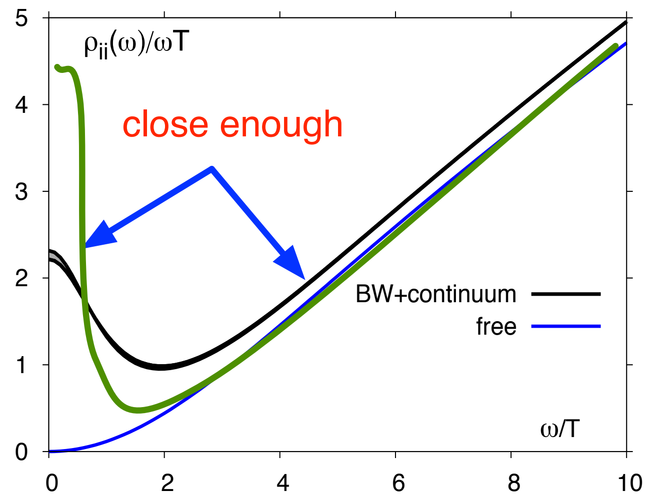


Lattice data are disastrously in between weak and strong

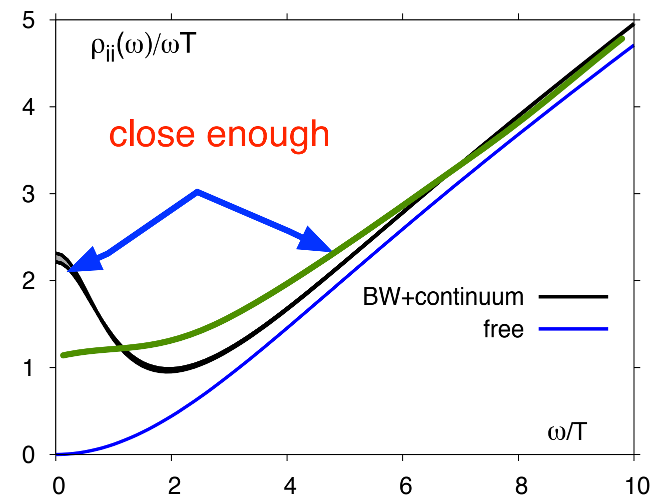
Spectral functions

Derek Teaney

Weak View



Strong View



– $P(k_\perp) \propto \exp(-\#k_\perp^2/(T^3L))$ **in strongly coupled plasma.** D'Eramo, Liu, Rajagopal, arXiv:1006.1367

– **For a weakly coupled plasma made of point scatterers, $P(k_\perp) \propto 1/k_\perp^4$ at large $k_\perp$. In the strongly coupled plasma of an asymptotically free gauge theory, this must win at large enough $k_\perp$.** D'Eramo, Lekaveckas, Liu, Rajagopal, in progress

Krishna Rajagopal

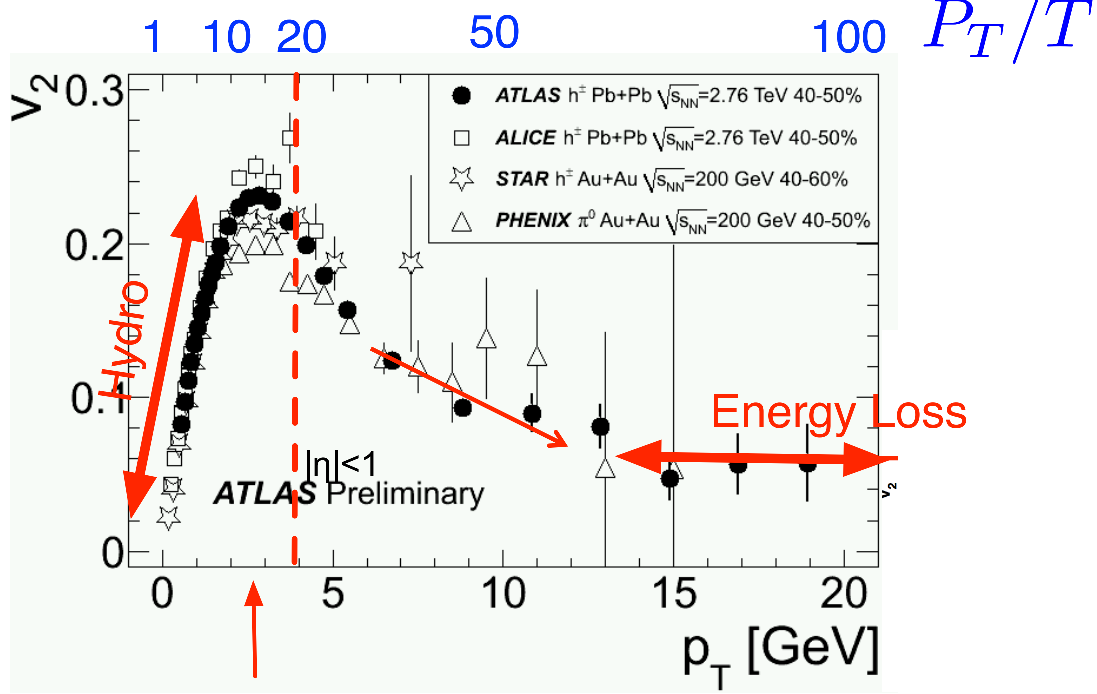
Light quarks

AdS Phenom for the timid

$P/(T\sqrt{\lambda}) < 1?$

Ads Phenom for the Brave!

$P/(TN_c^2) \gg 1!!!$



Derek Teaney

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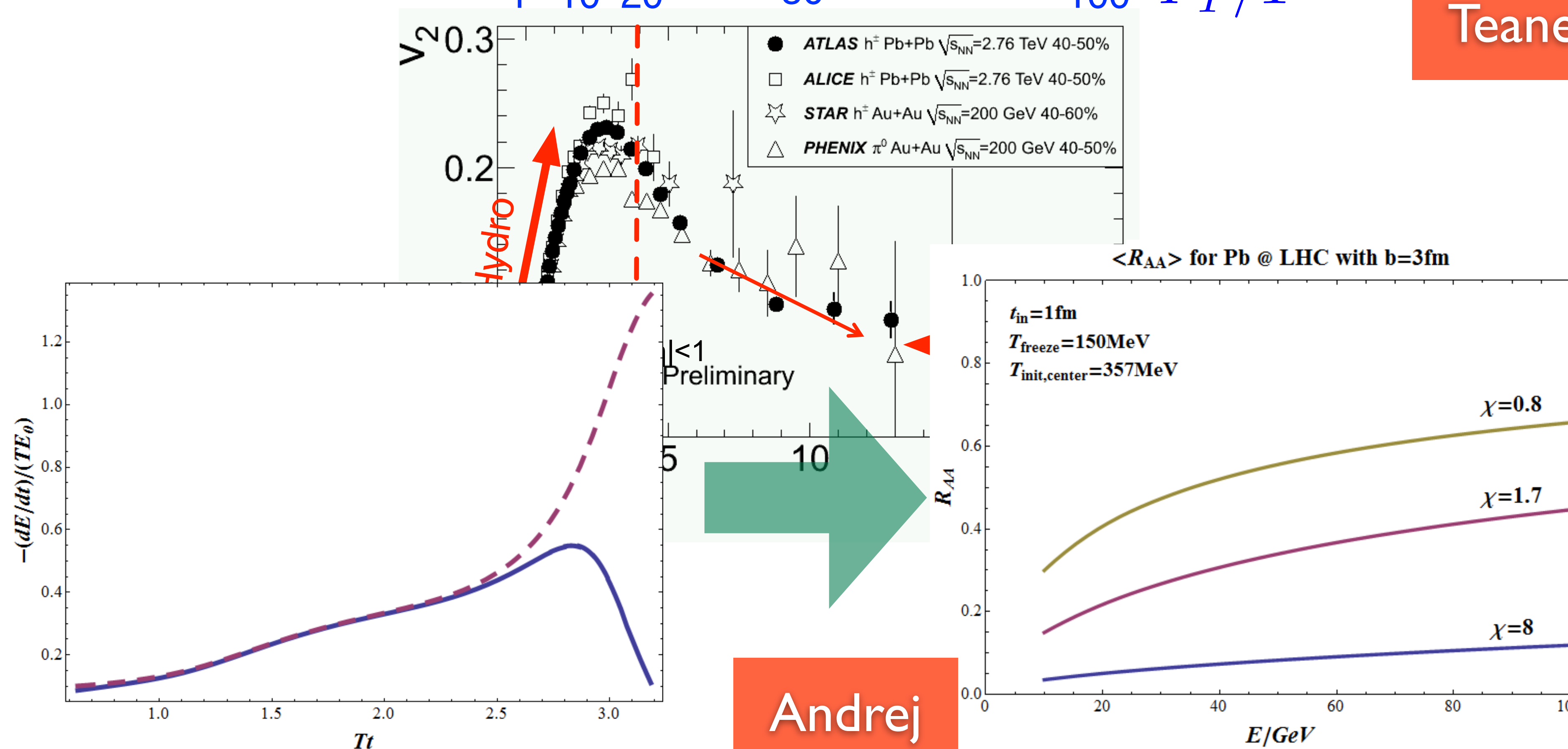
1 10 20 50 100 P_T/T



Andrej Ficnar

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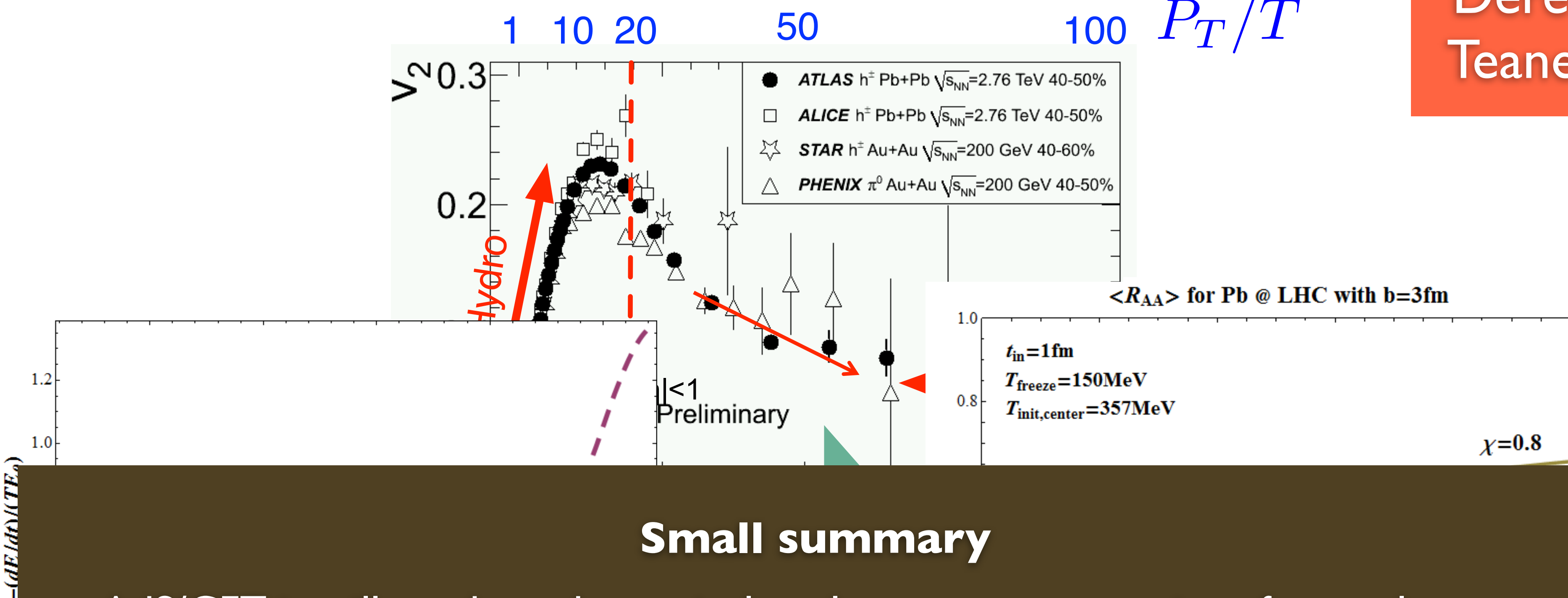


Small summary

—AdS/CFT is still our best theoretical tool to access properties of strongly interacting systems for dynamical quantities

— Relation with "reality" (lattice and experiment) reaching maturity in hot and dense media

CAS

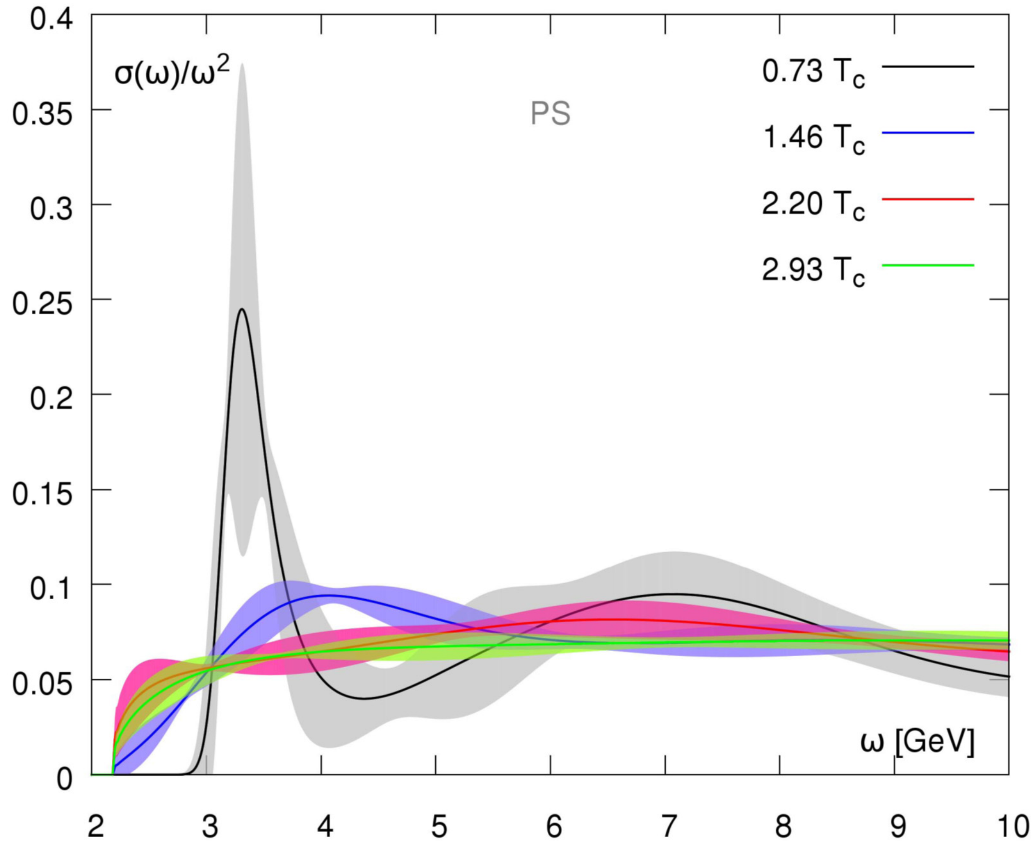
Quarkonia

Intriguing new data:
See next talk....

Charmonium Spectral function

[H.T.Ding, OK et al., arXiv:1204.4945]

from sophisticated Maximum Entropy Method analysis:



statistical error band from Jackknife analysis

no clear signal for bound states above 1.46 T_c

study of the interesting region closer to T_c on the way!

Olaf Kaczmarek

Charmonium Spectral function

[H.T.Ding, OK et al., arXiv:1204.4945]

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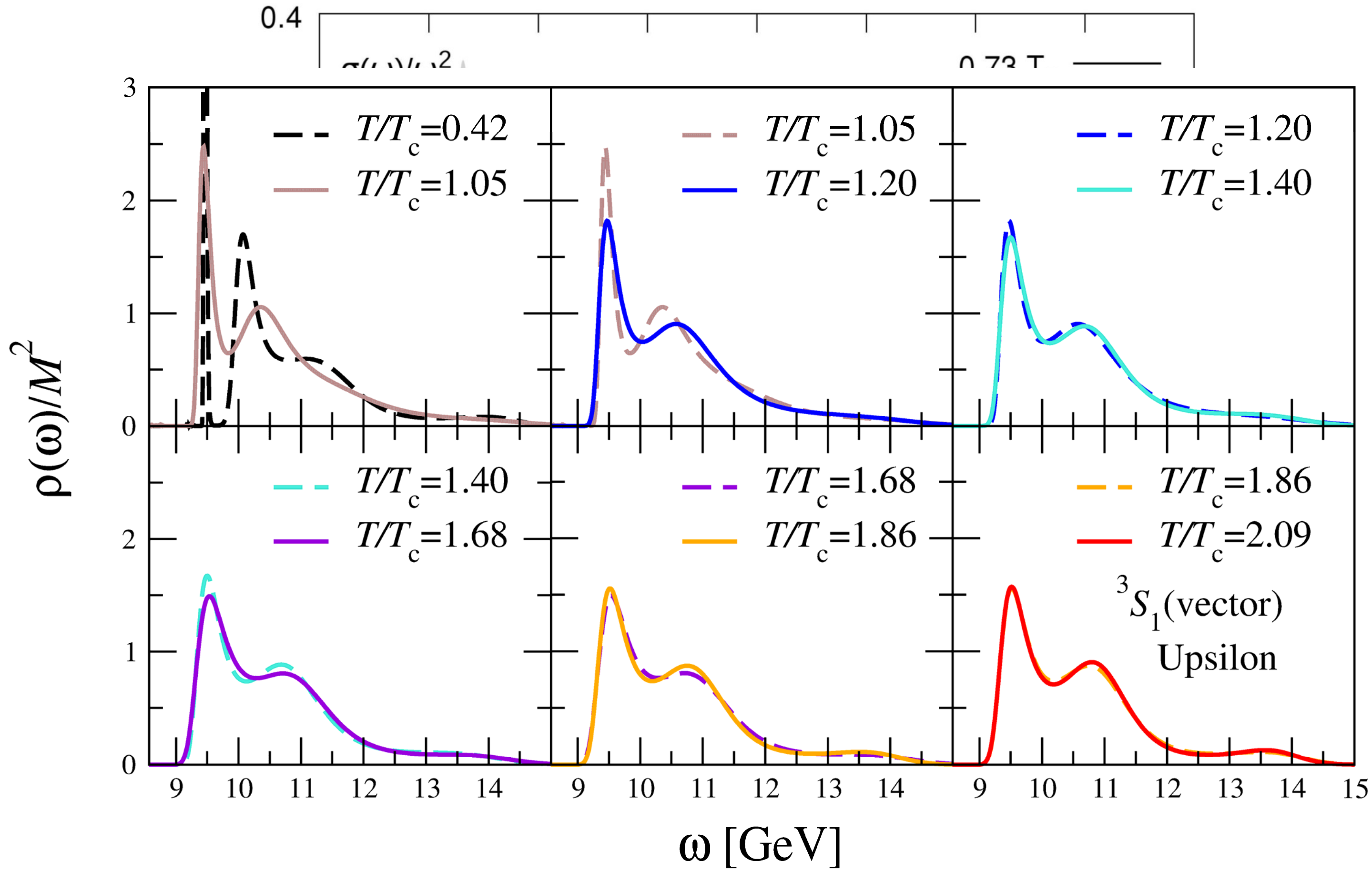

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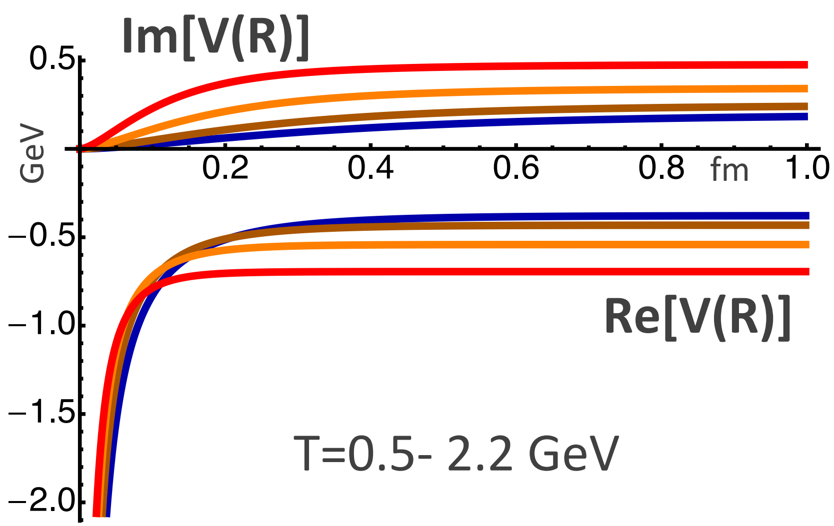
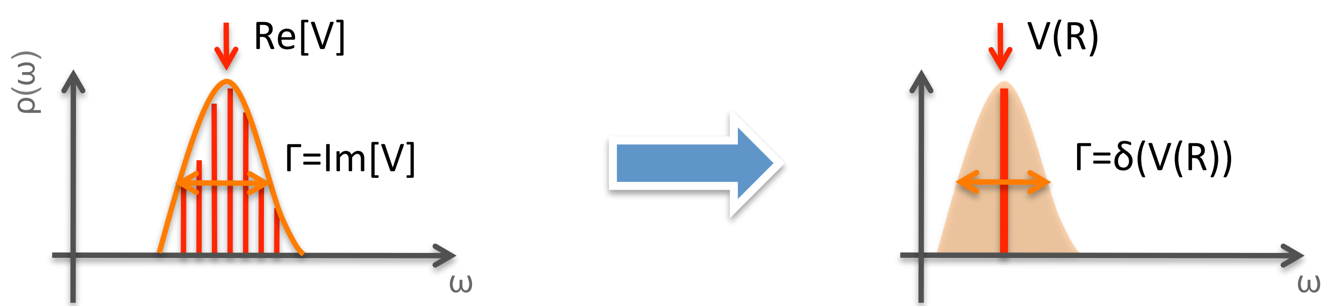
Olaf Kaczmarek

Effective theories and potentials

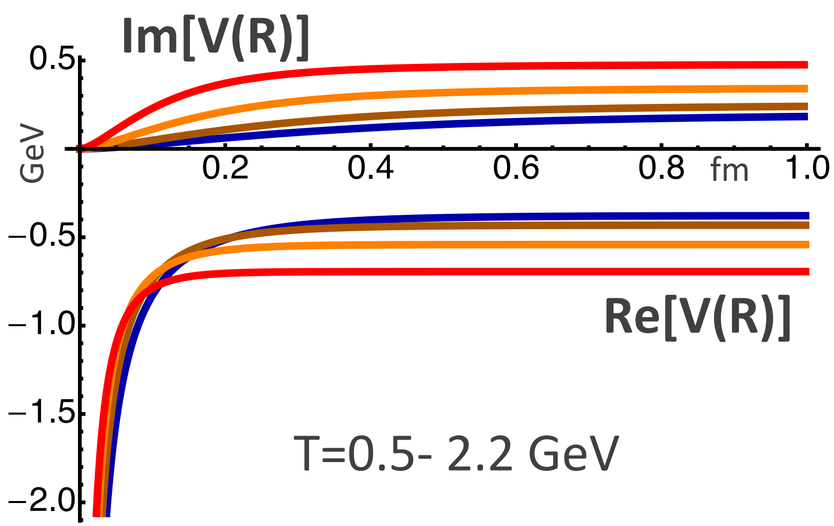


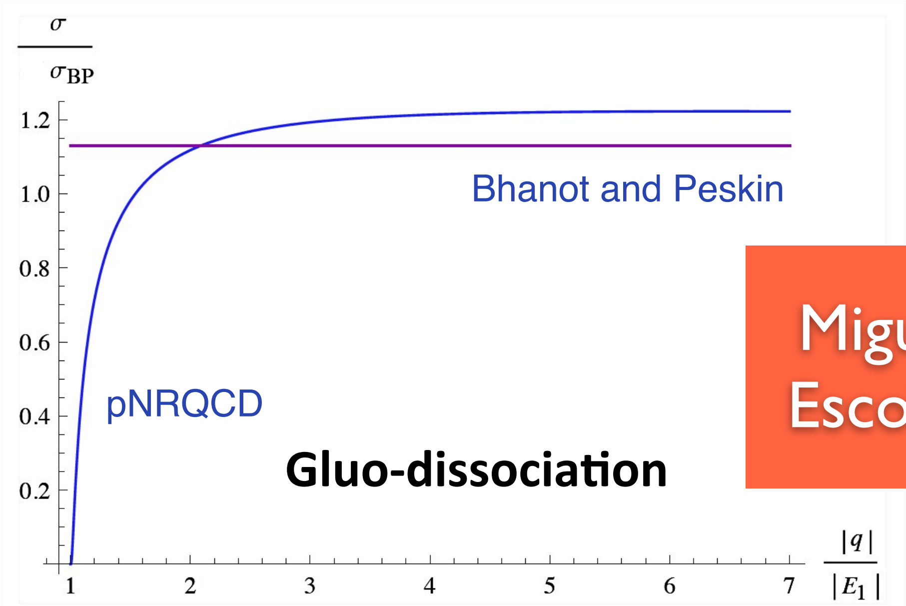
New proposal:
Stochastic Evolution of Heavy Quarkonia in the QGP : Open Quantum System



Alexander Rothkopf

Effective theories and potentials





Miguel A. Escobedo

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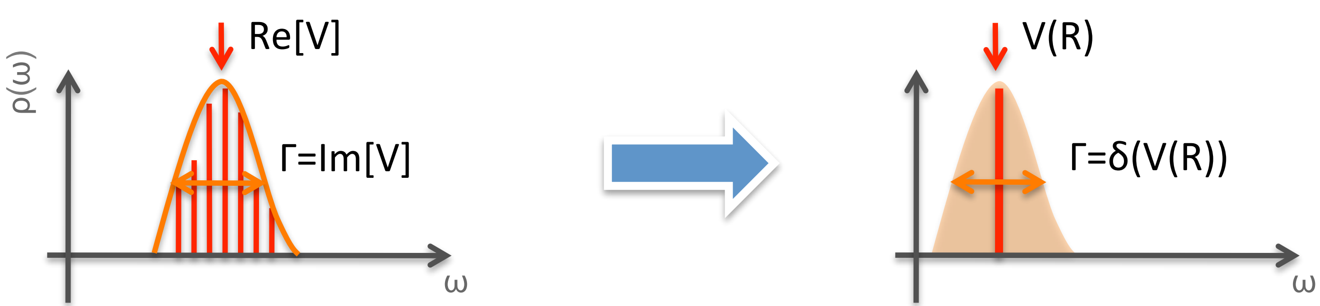
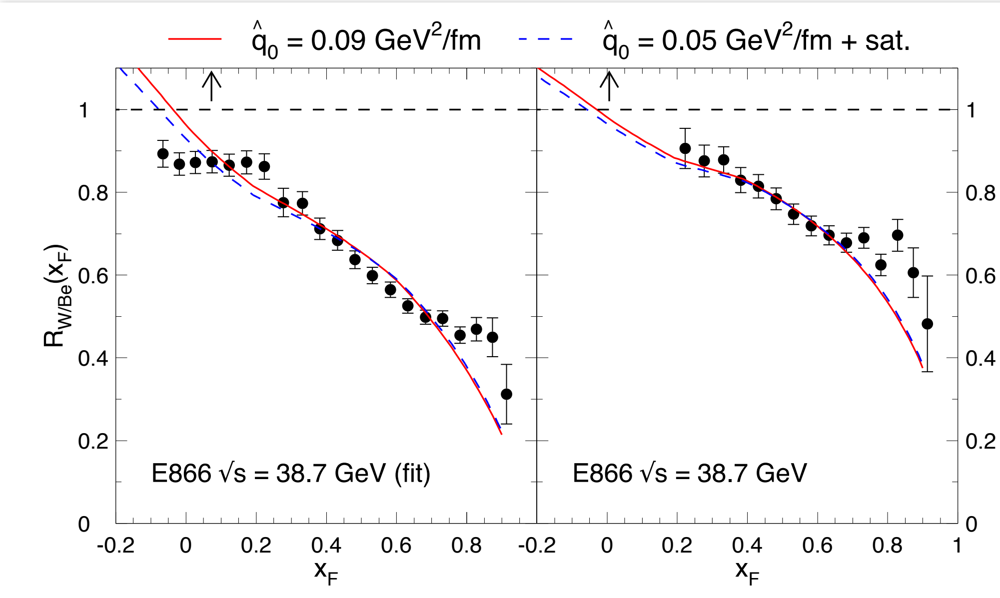
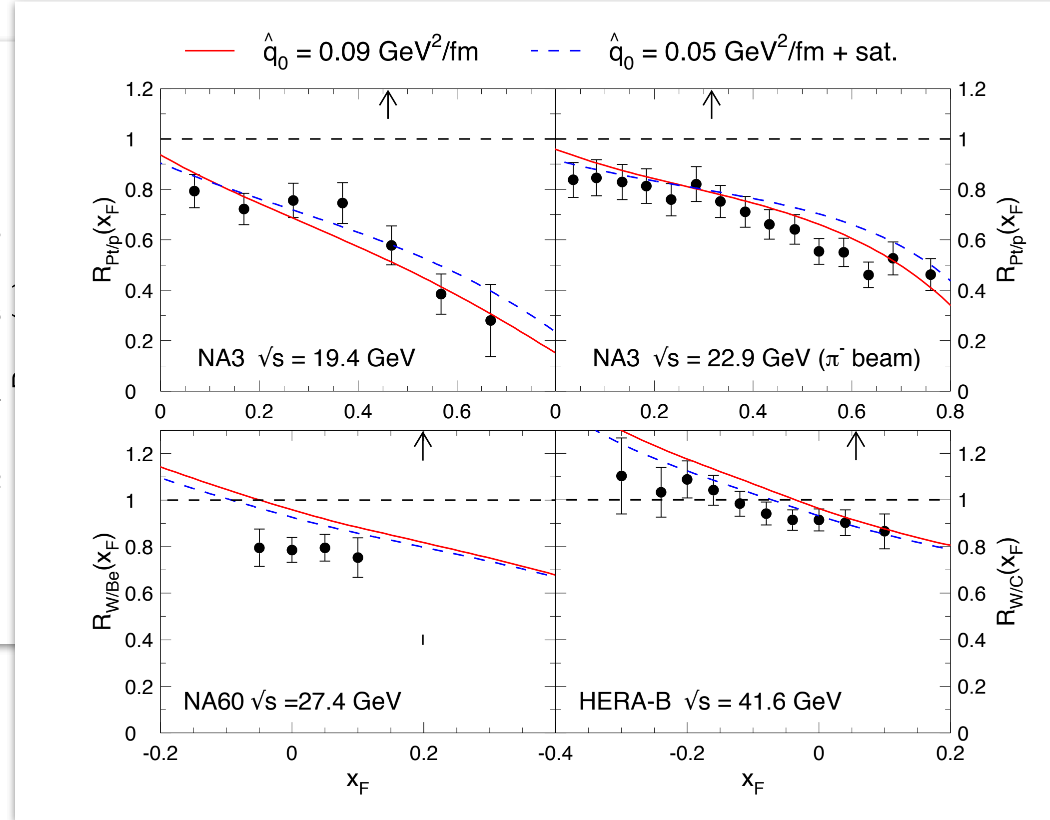
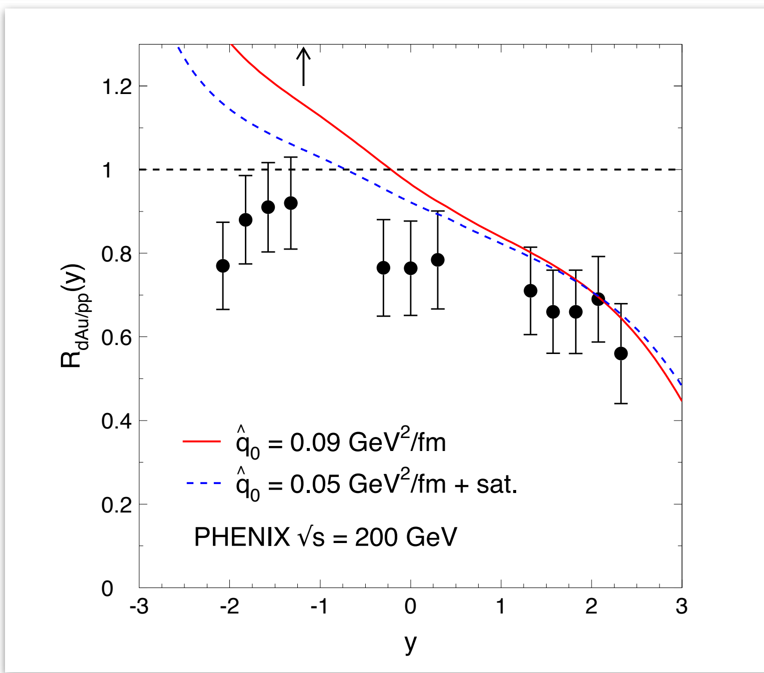


Alexander Rothkopf

CNM: Energy loss reloaded



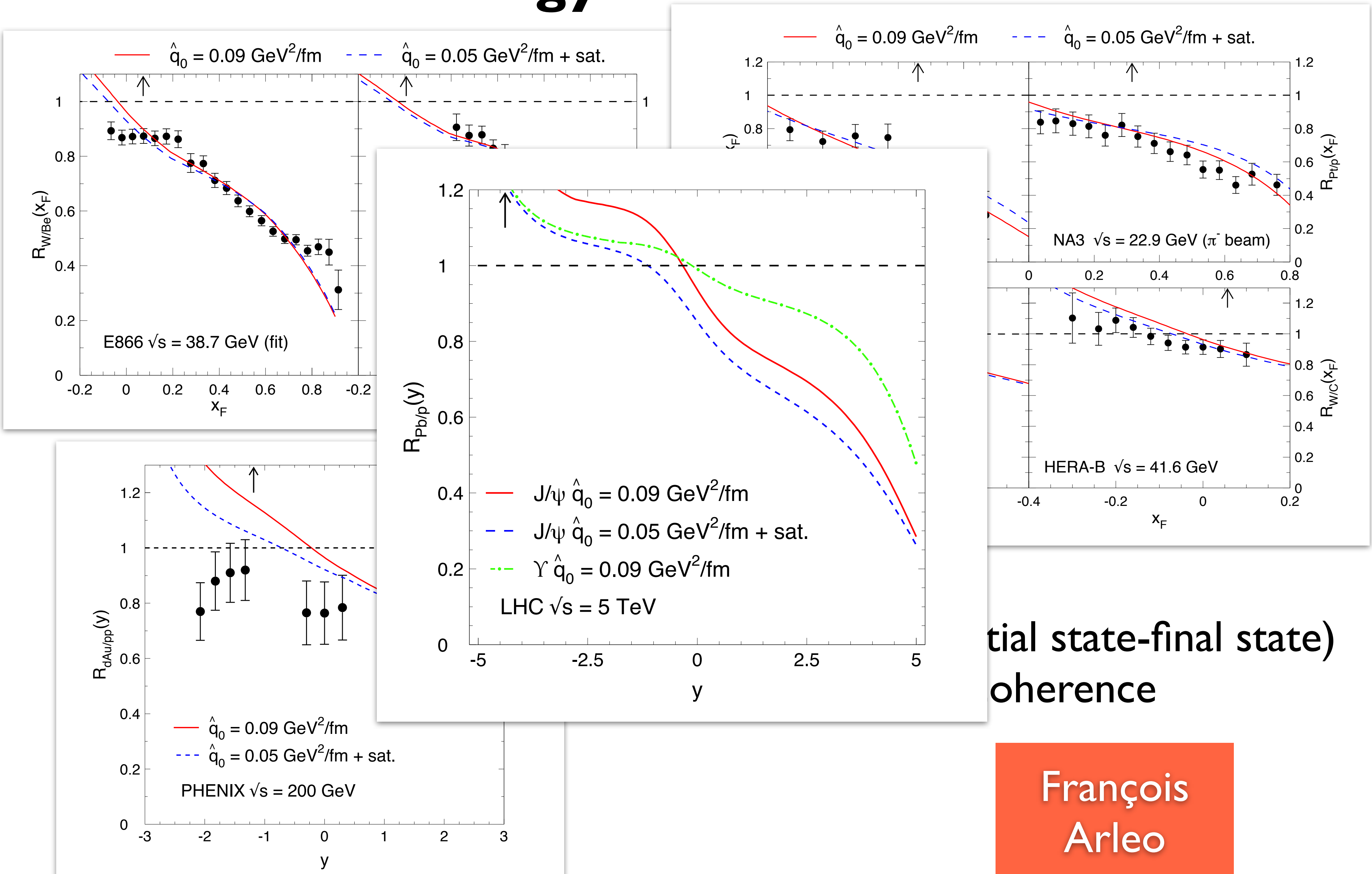




$\Delta E \sim E$ from (initial state-final state) color coherence

François Arleo

CNM: Energy loss reloaded

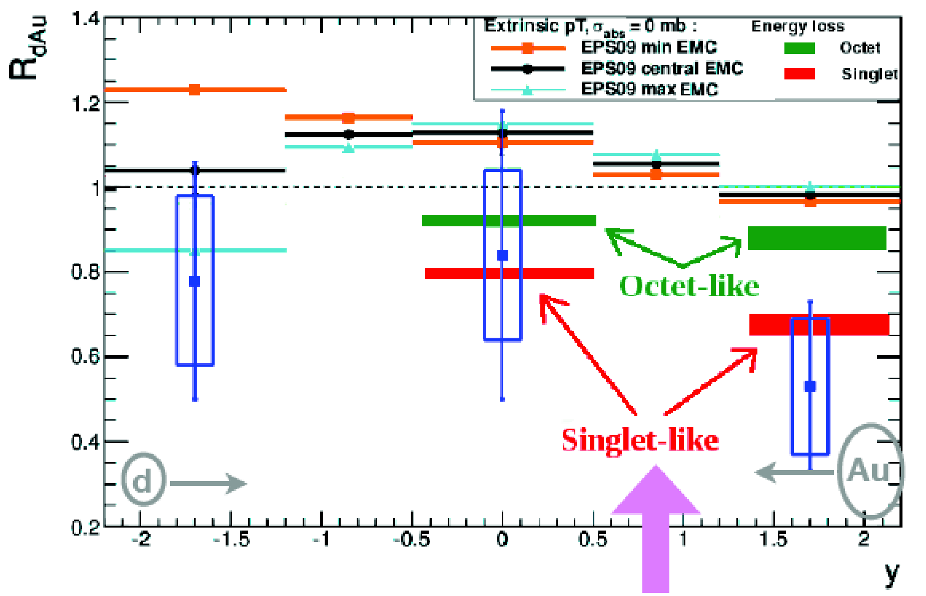


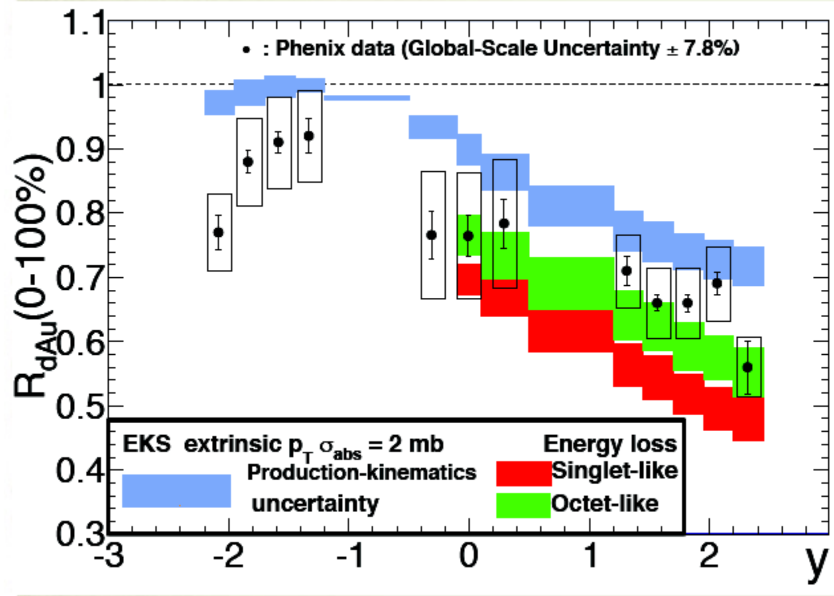
tial state-final state)

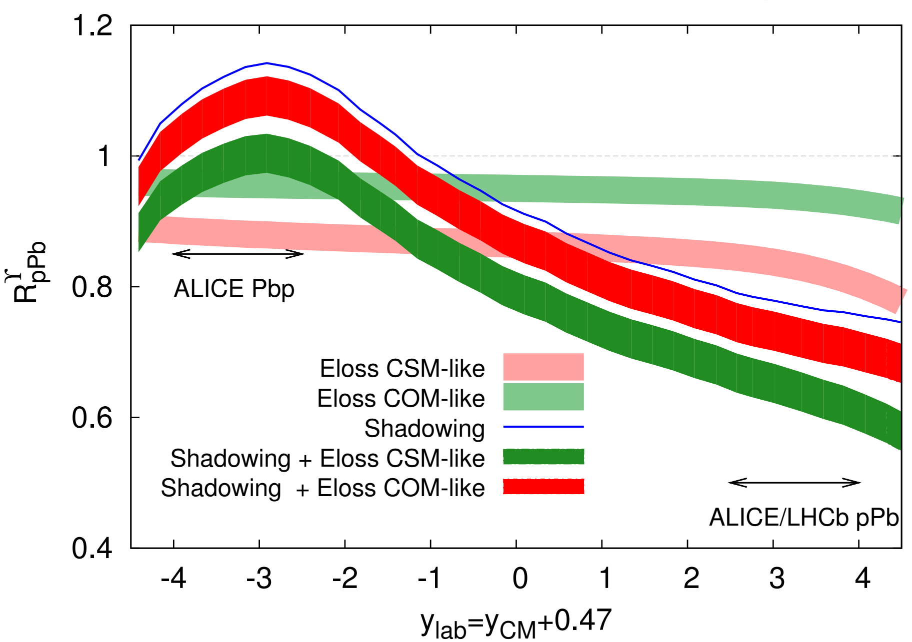
oherence

François Arleo

Cold nuclear matter in quarkonia

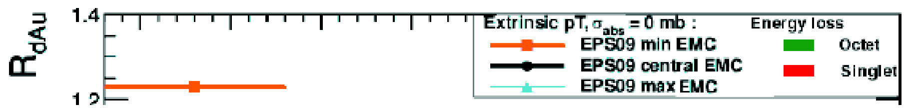


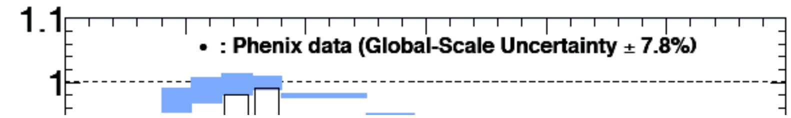




Jean-Philippe Lansberg

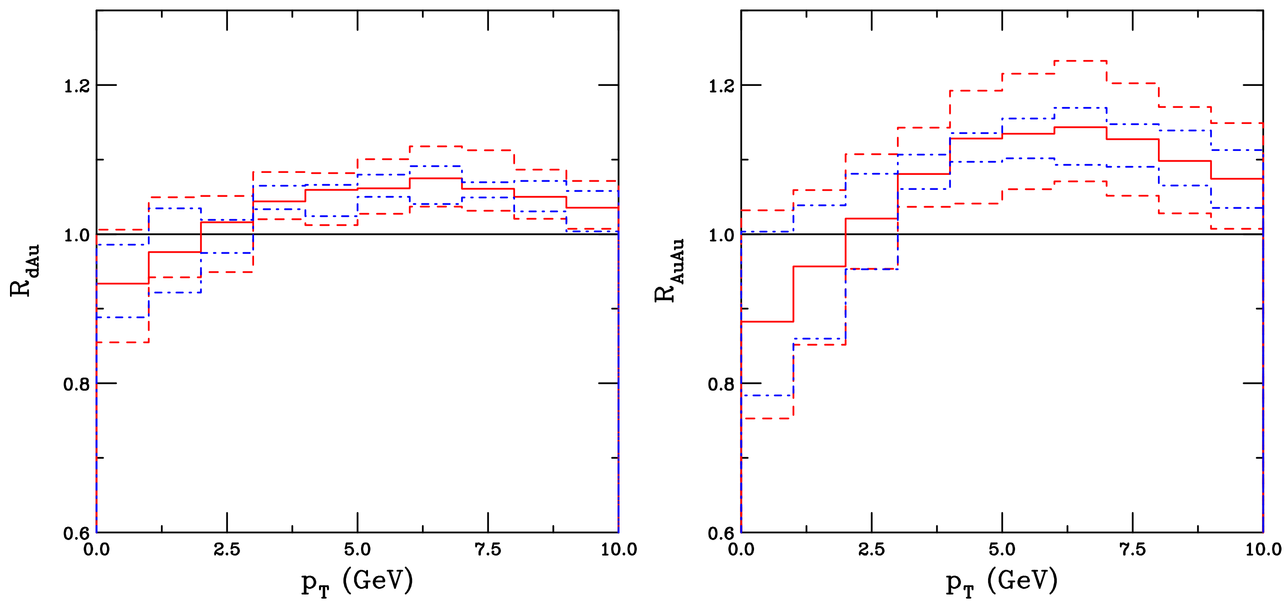
Cold nuclear matter in quarkonia



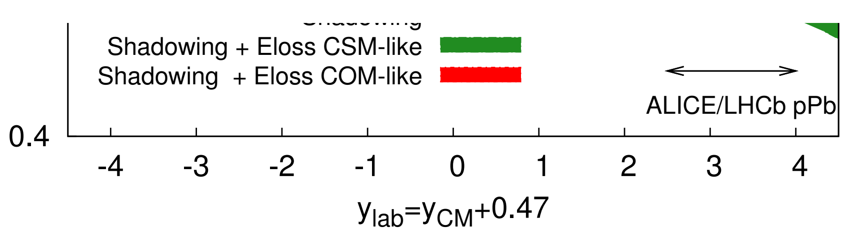


p_T Dependence of Shadowing Accessible at NLO

The pp, d+Au and Au+Au p_T distributions calculated with same intrinsic k_T kick
Scale dependence again reduced relative to nPDF uncertainties



Ramona Vogt

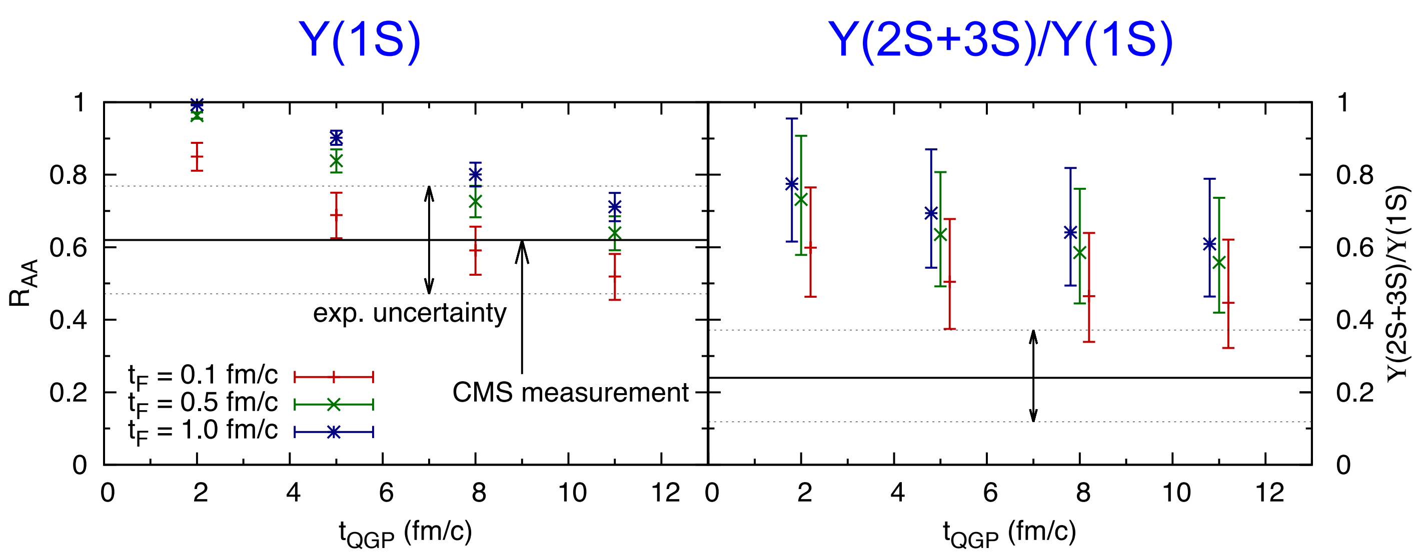


Theoretical vs. exp. Suppression factors

Consider

- Screening (potential model)
- Gluodissociation (OPE with string tension included)
- Collisional damping (imaginary part of potential)
- Feed-down from excited states

t_F: Y formation time
t_{QGP}: QGP lifetime
T_{max} @ t_F: 200-800 MeV



Georg Wolschin

Leaves room for additional suppression mechanisms in particular, for the excited states.

Hard_Probes_2012

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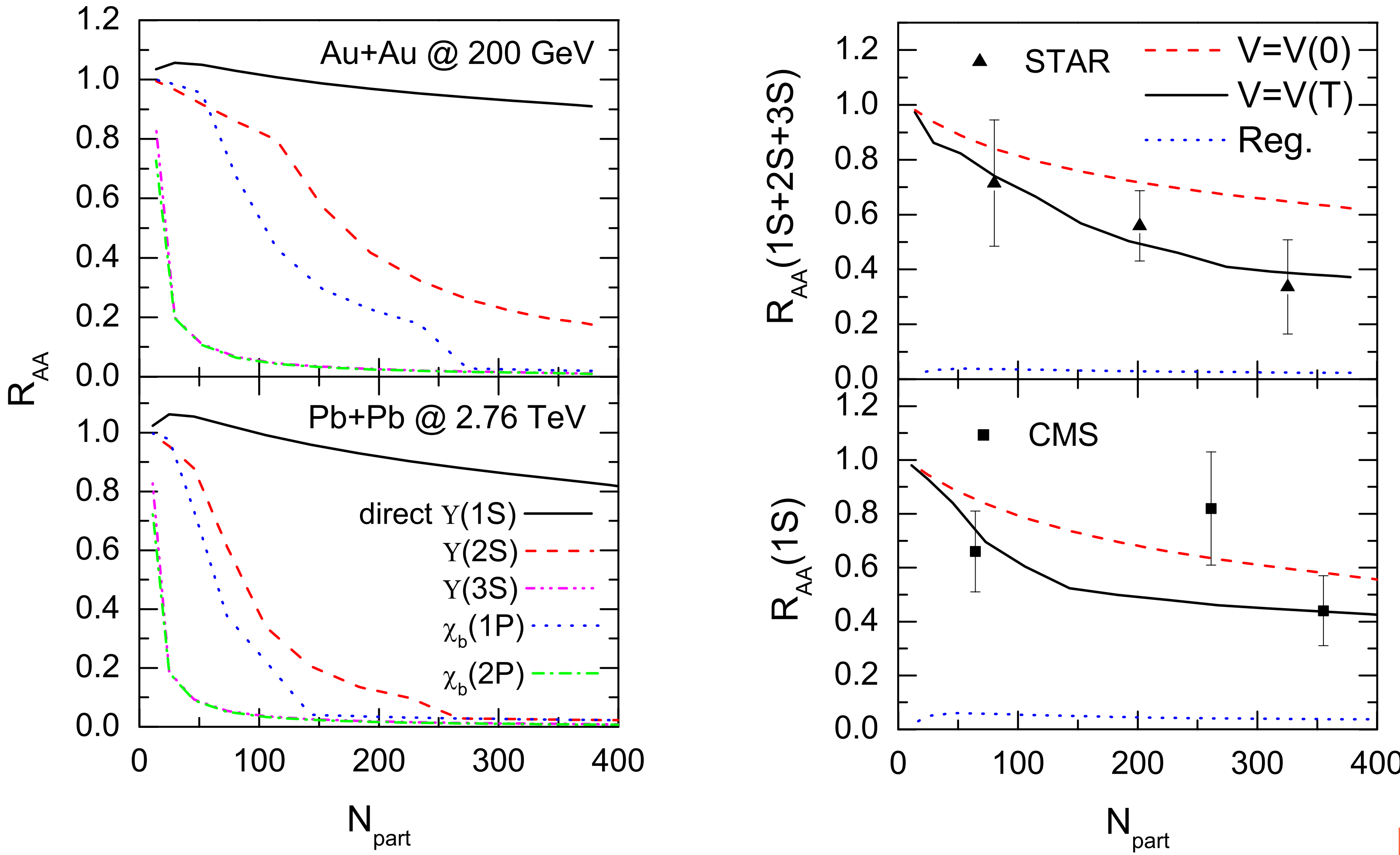
Nuclear modification factor for Υ(1S)



- Regeneration contribution is negligible
- Primordial excited bottomonia are largely dissociated
- Medium effects on bottomonia reduce R_{AA} of Υ(1S)

Che-Ming Ko

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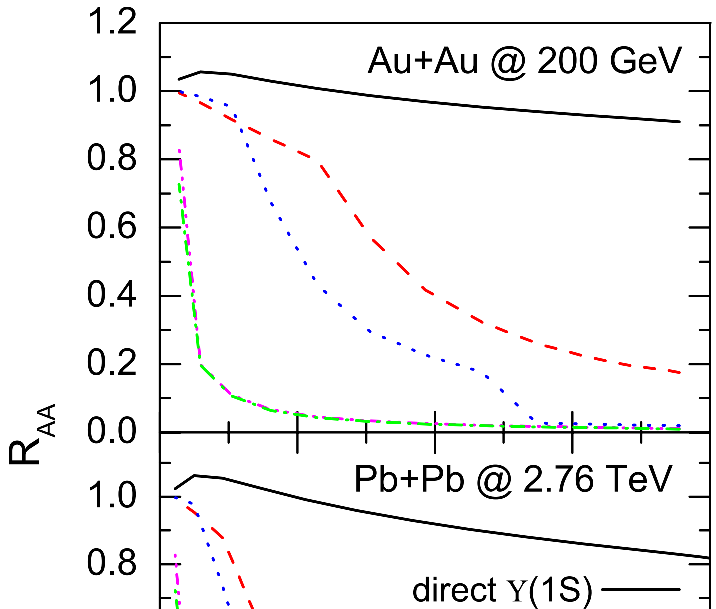
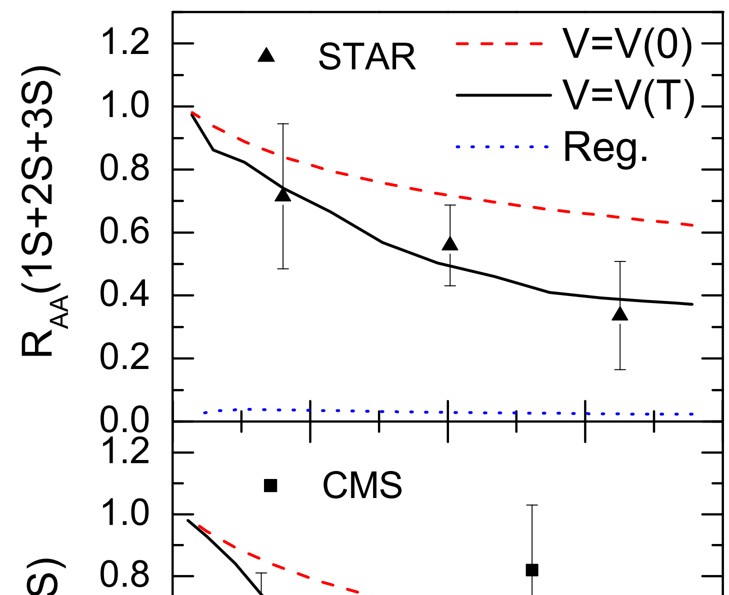
Nuclear modification factor for Υ(1S)





Small summary

— Experimental data present some quite simple tendencies, especially the centrality dependence of several quantities.

— Excited states: upsilons should provide strong constrains to models. Charmonia is a puzzle?

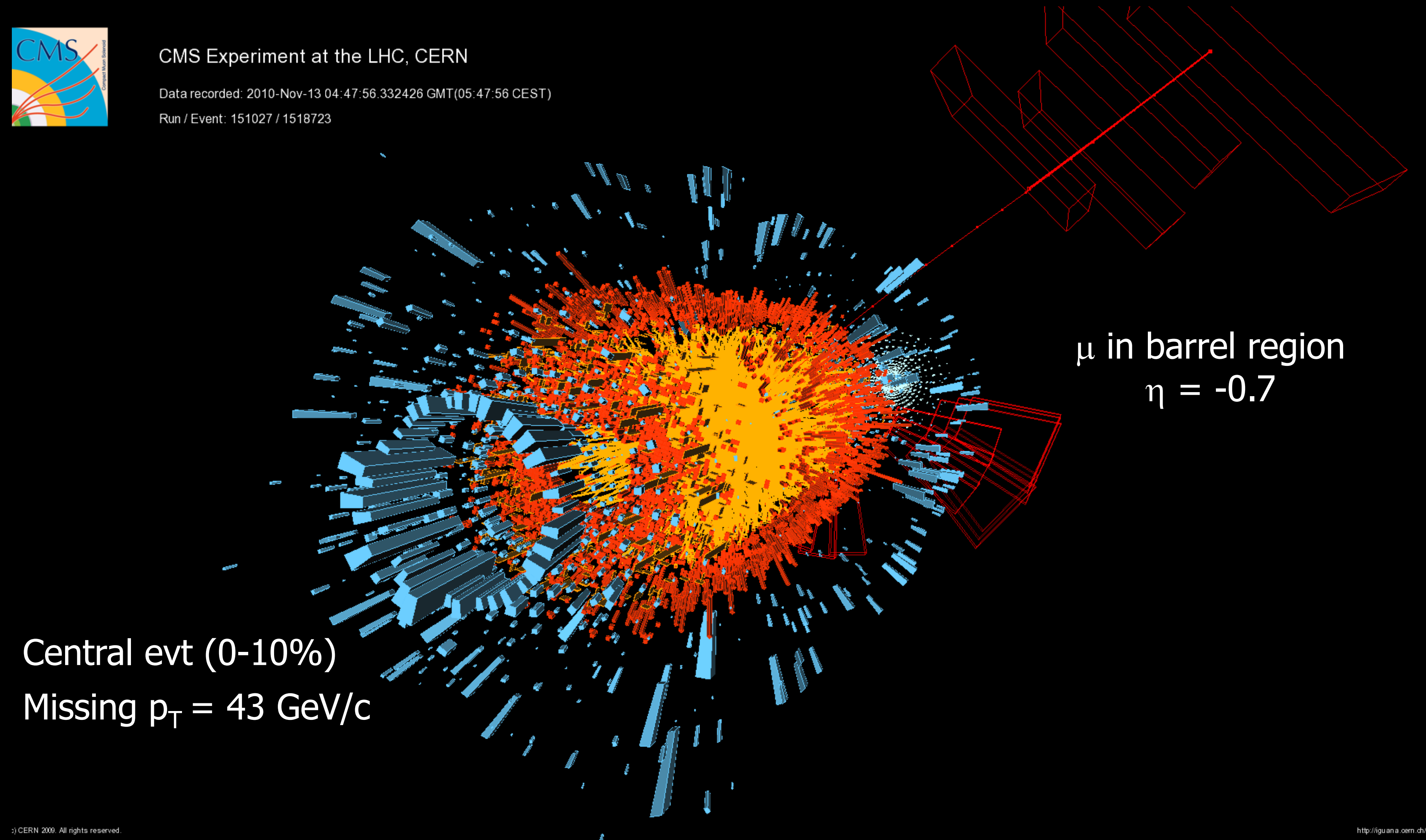
— Is a simple theoretical understanding compatible with data?

— A better TH control over the CNM effects under way - pPb will help...

ing

CAS

Electroweak probes

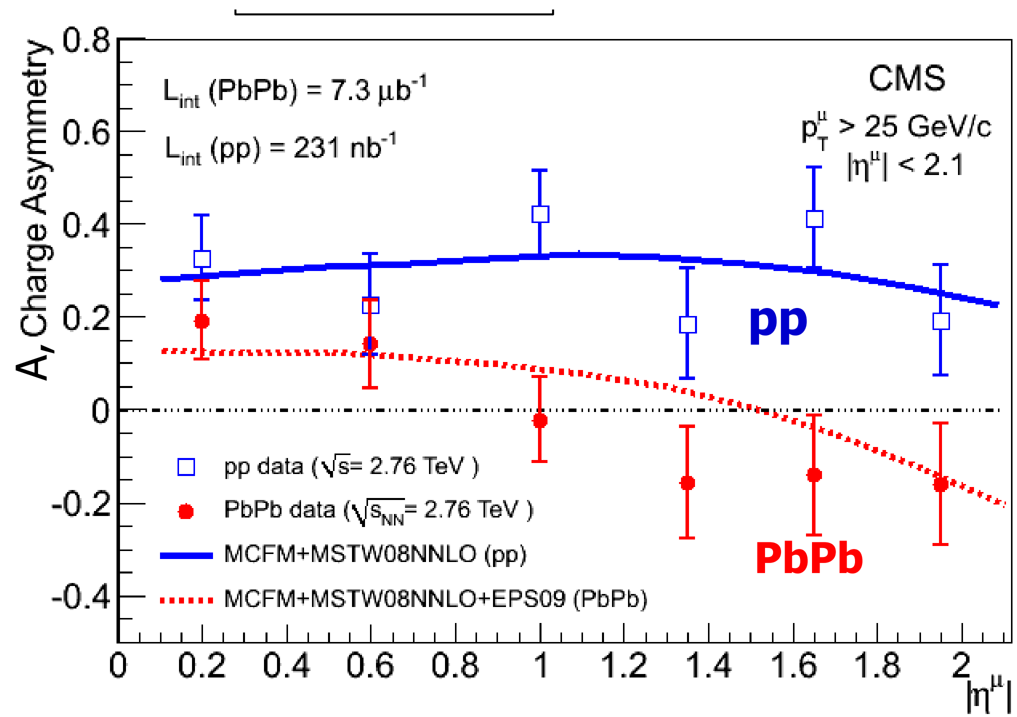


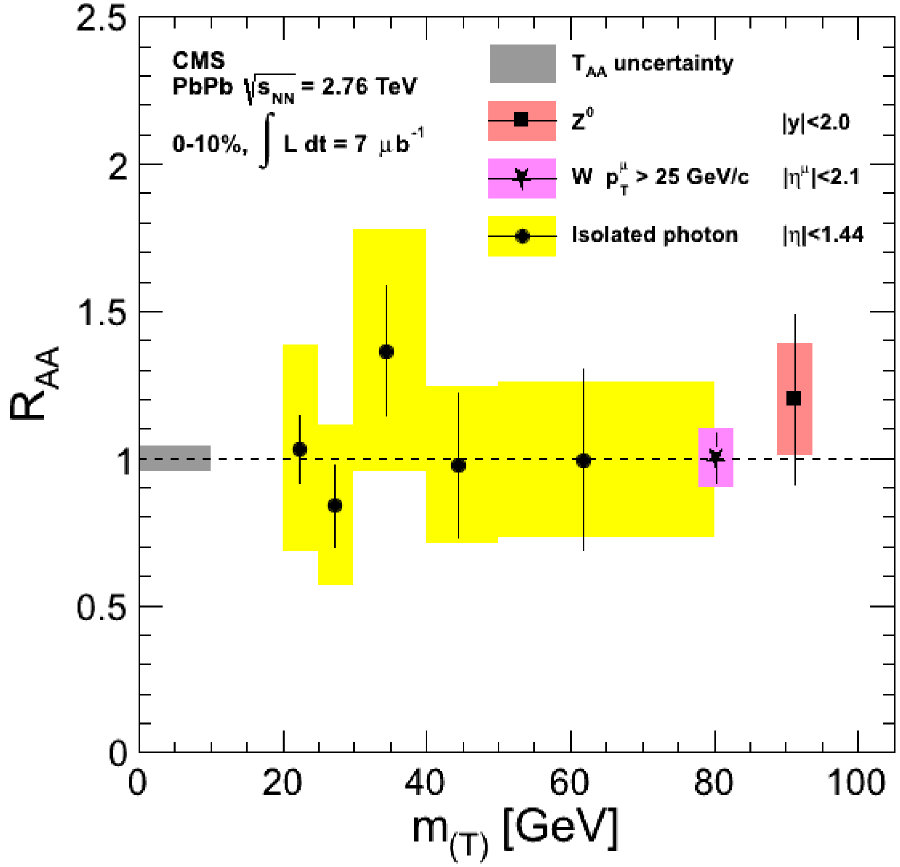
μ in barrel region
η = -0.7

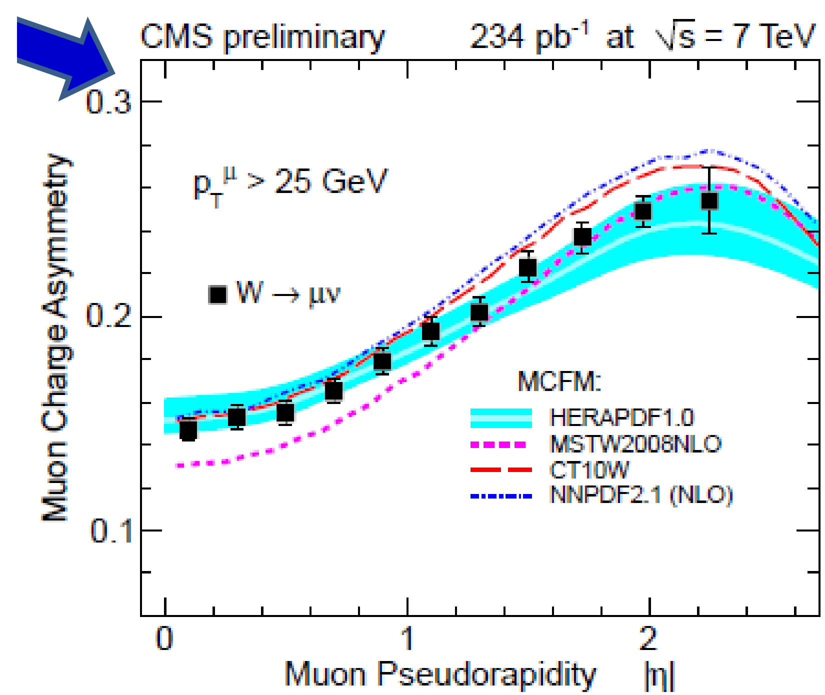
Central evt (0-10%)
Missing p_T = 43 GeV/c

Electroweak bosons (CMS)

Begoña de la Cruz

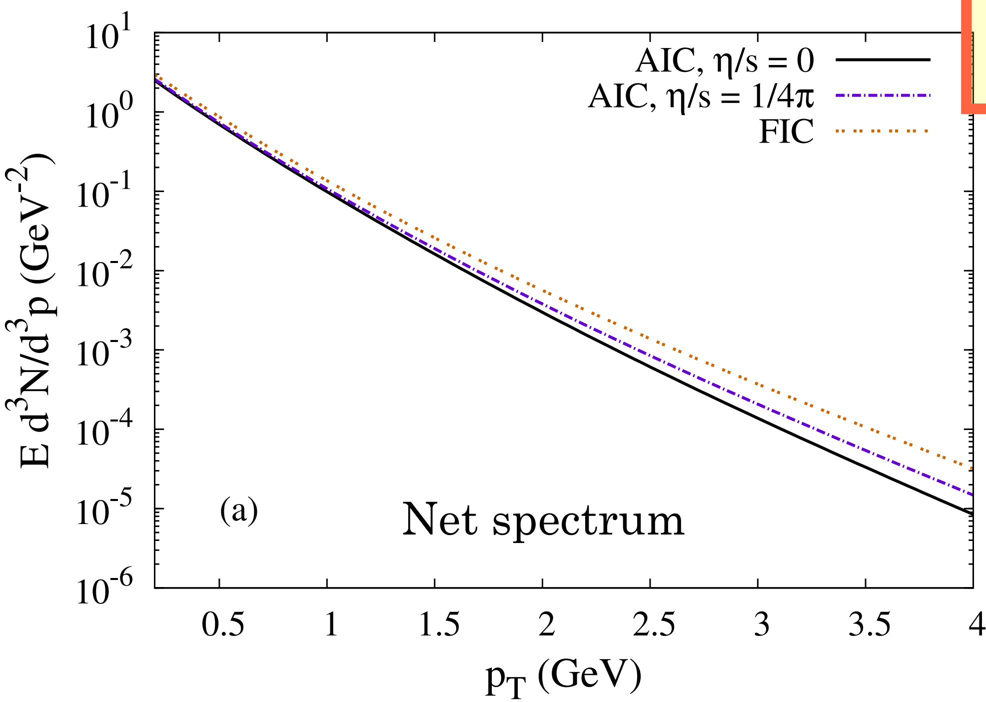






Charles Gale

More spectrum studies



- Combined with viscous corrections, FIC yield an enhancement by ≈5 @ 4 GeV, and ≈2 @ 2 GeV
- Temperature estimated by slopes can vary considerably
- HG enhancement is as big as that from the QGP, but net signal is down by an order of magnitude
- A combination of hot spots and blue shift hardens spectra

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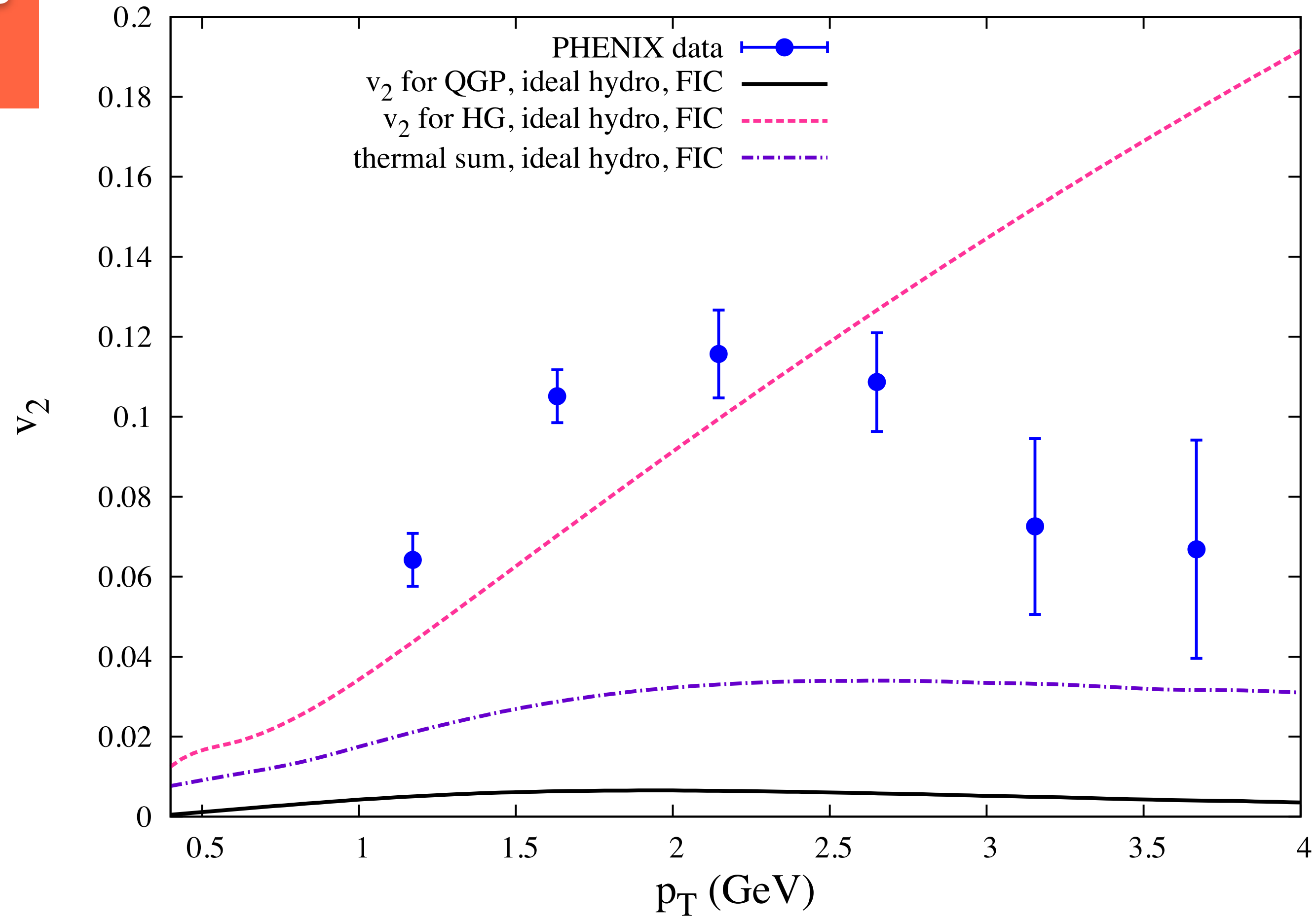
Hard Probes 2012

Charles Gale

Charles Gale

PHOTON v_2 DATA?



- New data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2

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Hard Probes 2012

Charles Gale

Initial state

Nuclear PDFs

Kari Eskola

DSZS vs. EPS09

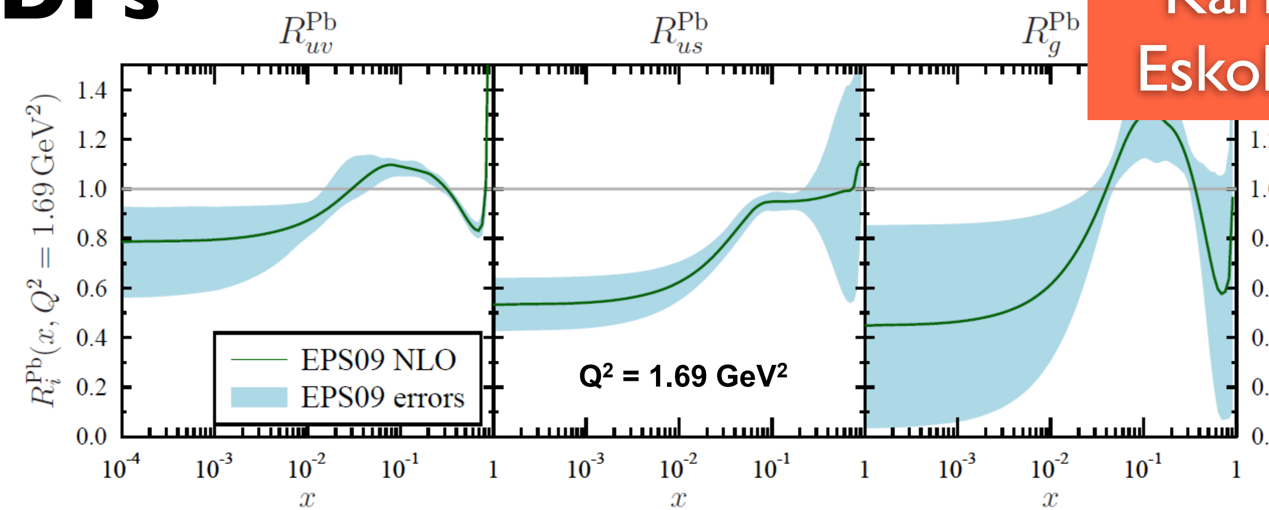
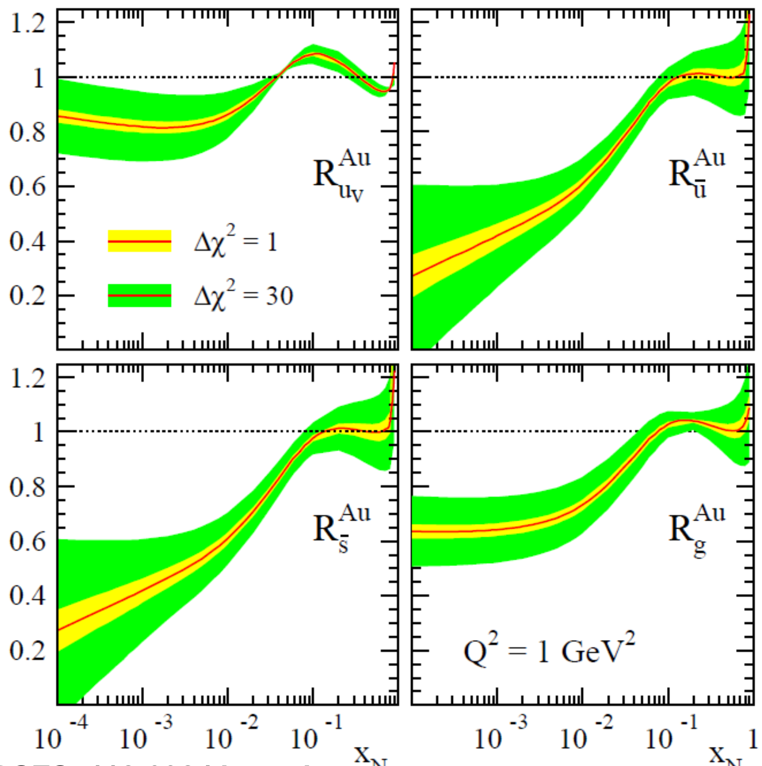


Fig. from 1205.5359 hep-ph



DSZS, 112.6324 hep-ph

The input modifications at Q_0

- **slightly <u>different</u> initial scales;**
  Q_0(EPS09) = 1.3 GeV
  Q_0(DSZS) = 1.0 GeV
- deltachi2 (DSZS) < deltachi2 (EPS09)
  → smaller error bands in DSZS?
- seem similar in gluon shadowings
  but after scale evolution they differ →
- **<u>no</u> gluon antishadowing in DSZS!** → →

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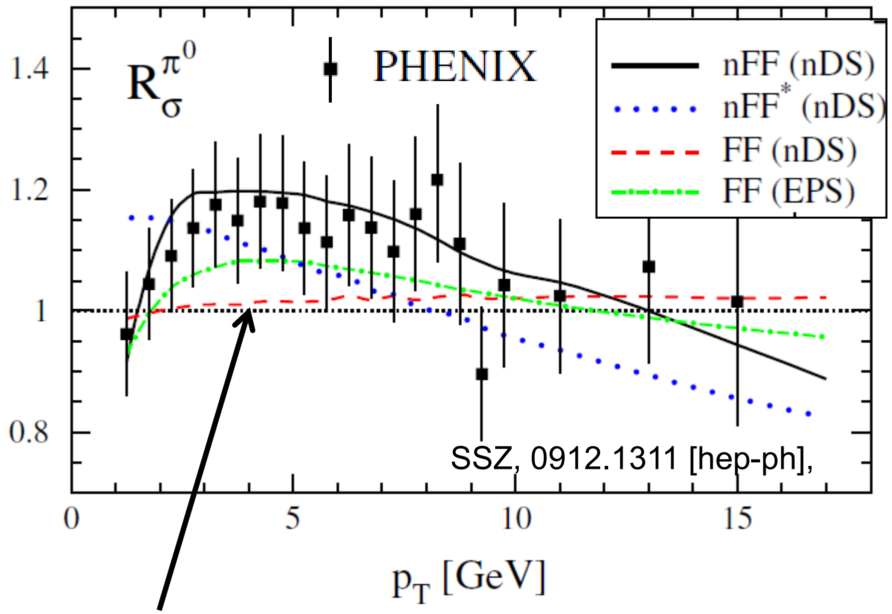
Nuclear FFs:

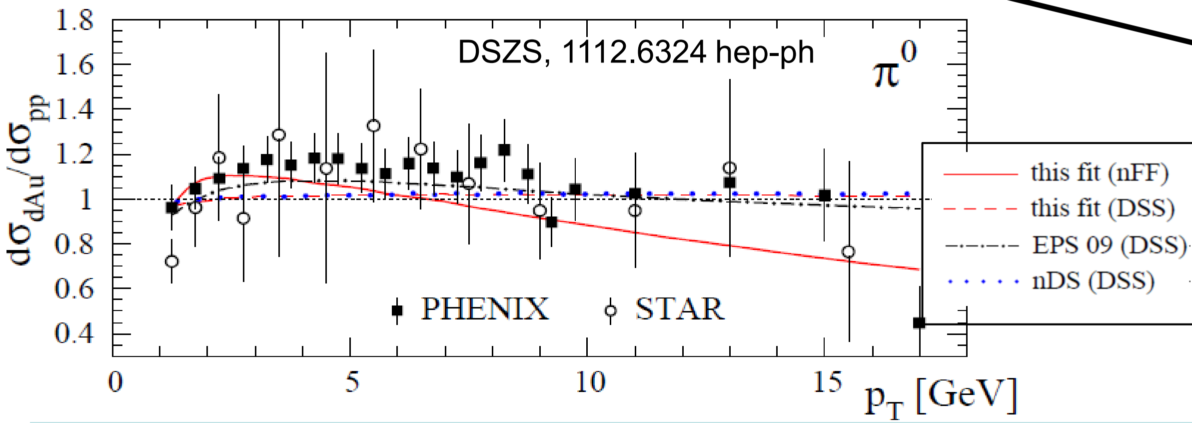
Sassot, Stratmann, Zurita
0912.1311 hep-ph, PRD81 (2010)

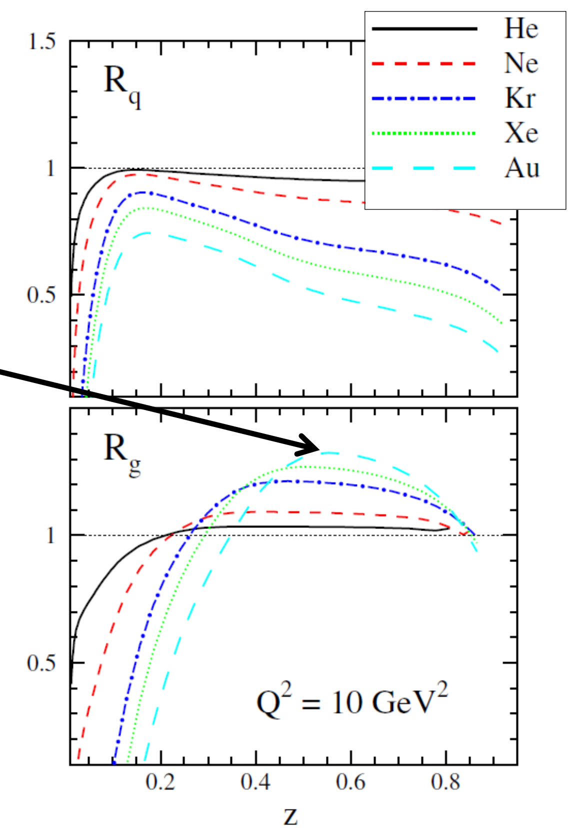
Kari Eskola

- HERMES SIDIS data
  → suppression for the nuclear quark D(z)
- PHENIX data on RdAu(pi0)
  STAR data on RdAu(pi)
  → **nuclear modifications for the gluon D(z)**



~No gluon antishadowing in the old nDS nPDFs used here
→The ~**entire** enhancement in R_{dAu} is translated
into an **enhancement of nuclear $D_g(z)$**





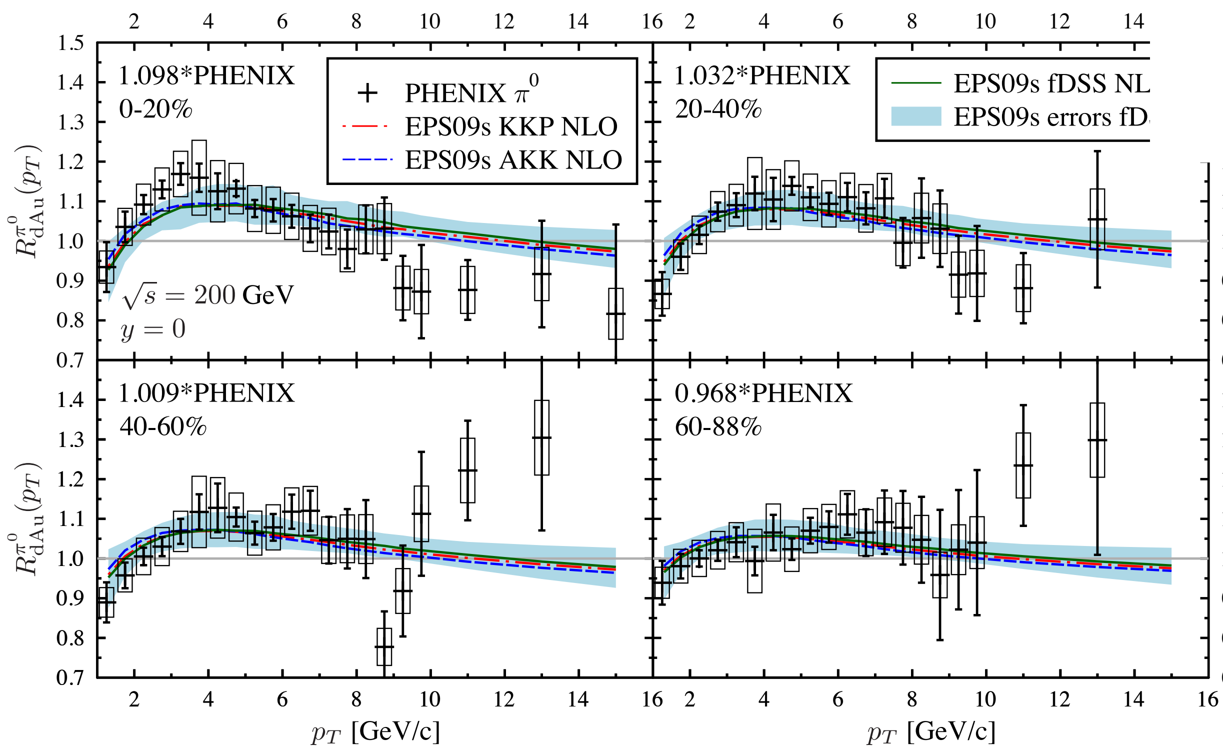
SSZ, 0912.1311 [hep-ph]

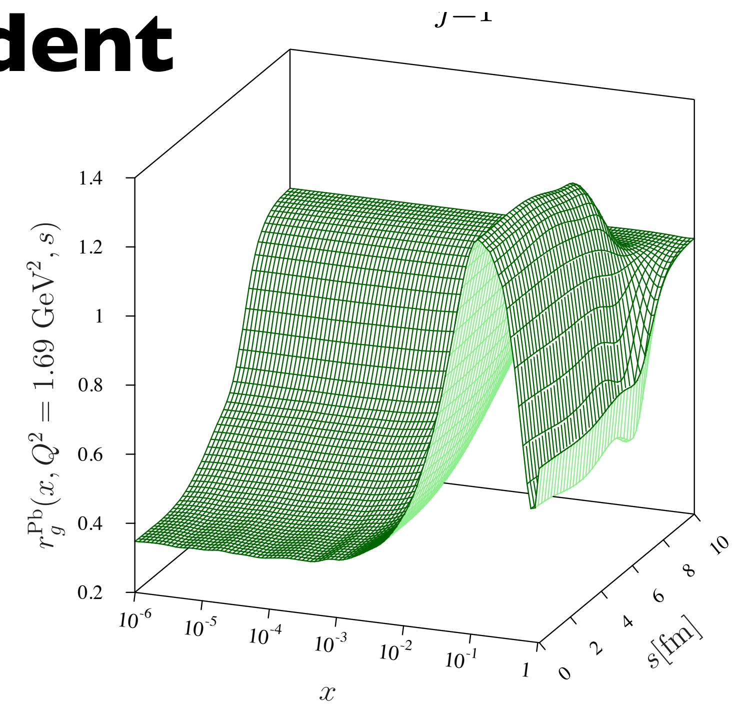
Same data are used in DSZS global nPDF fit
→**by construction, with nFF (or w. FF w/o data weights)**
no antishadowing for DSZS gluons

Impact parameter dependent nuclear PDFs

d+Au collisions at RHIC

R_{dAu} for π^0 production at $y = 0$ in different centrality class
in NLO (calculated with INCNLO)

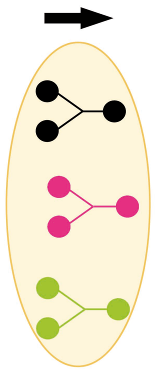




Ilkka Helenius

What the CGC is about : coherence effects

High gluon densities in the projectile/target



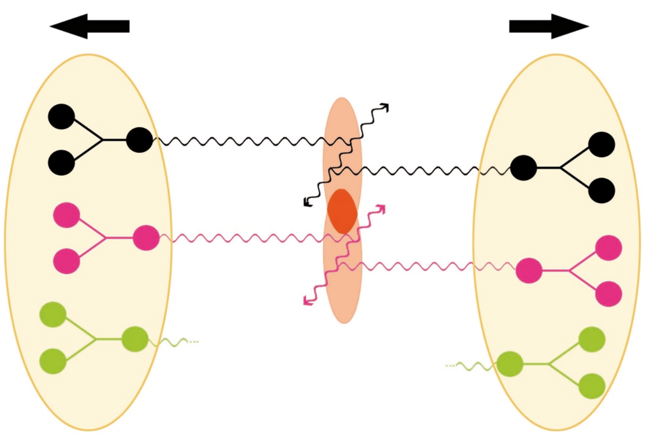
Saturation: gluon self-interactions tame the growth of gluon densities towards small-x

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^{\mathbf{2}}$$

radiation recombination

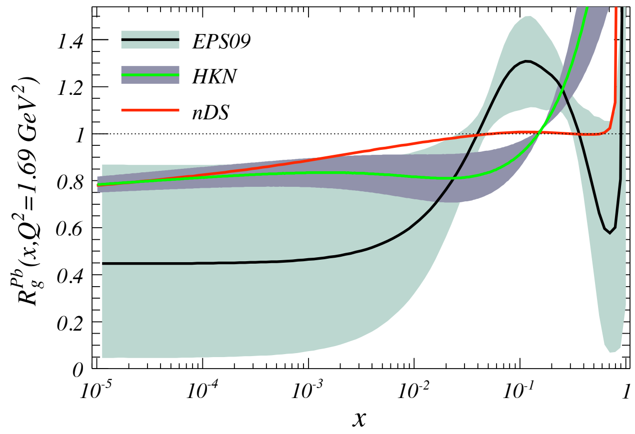
$$\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$$

Breakdown of independent particle production



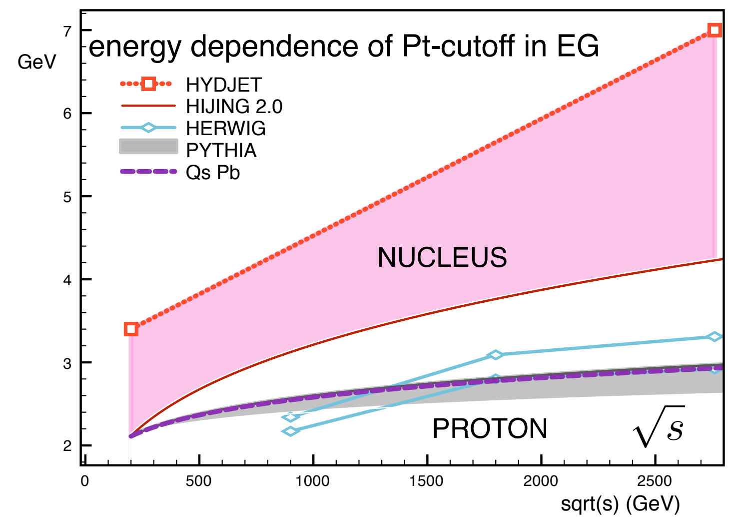
HIC phenomenology

- Nuclear shadowing, String fusion, percolation



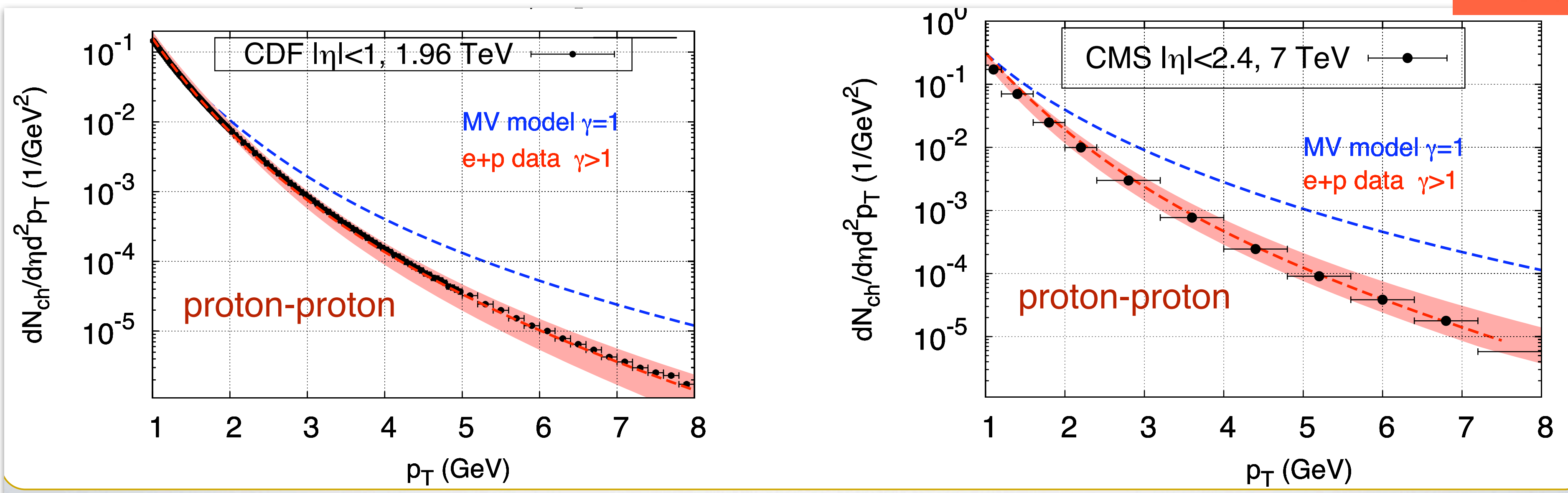
Javier Albacete

- Resummation of multiple scatterings
- kt-broadening
- Energy dependent cutoff in event generators



• **Is the CGC effective theory (at its present degree of accuracy) the best suited framework to quantify those coherence phenomena in LHC HI collisions?**

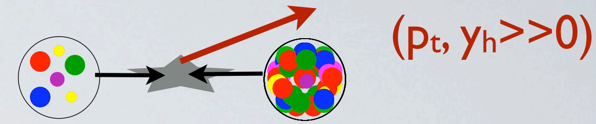
Javier Albacete

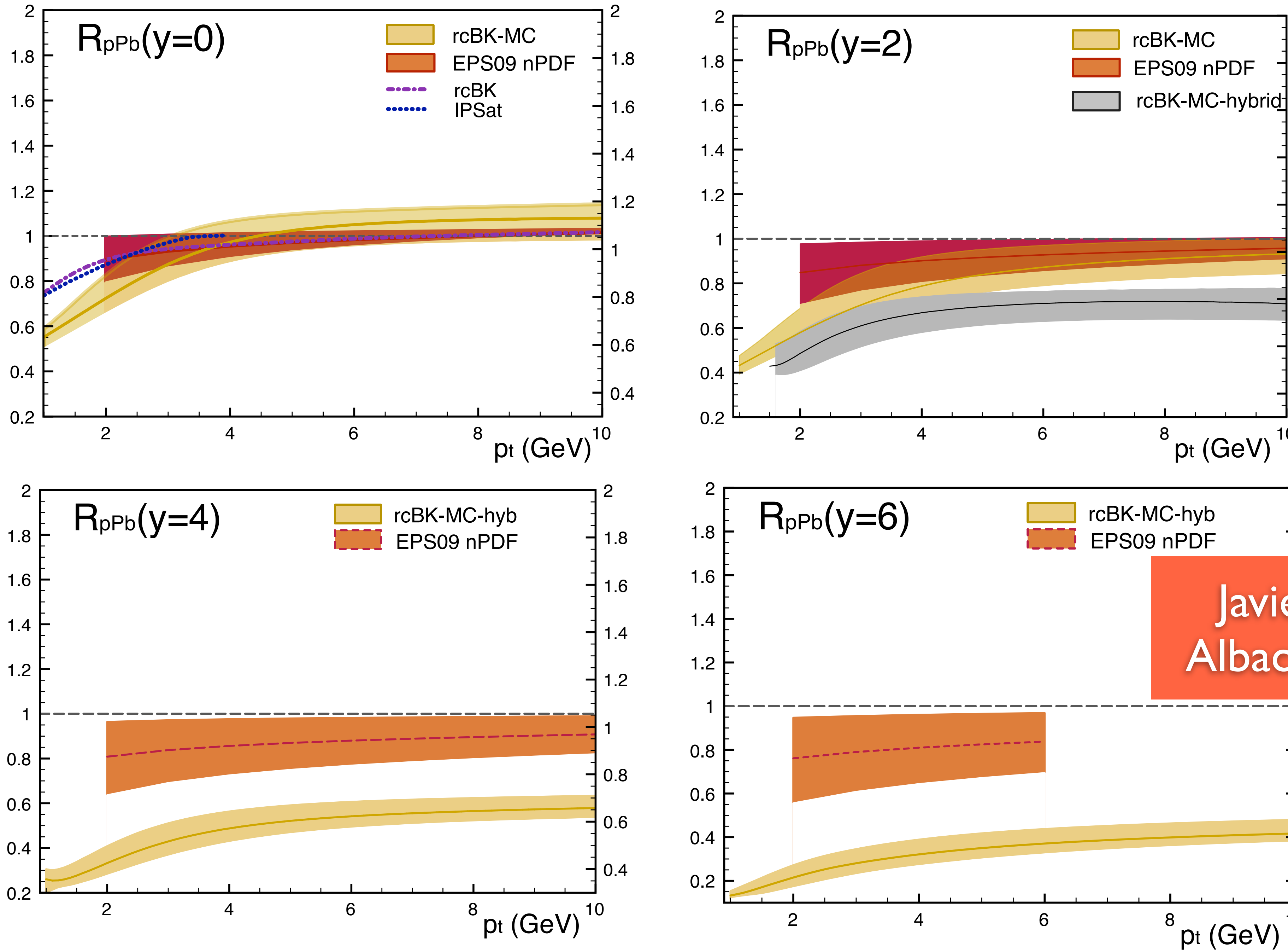


— The CGC is the best theoretical tool at our disposal to compute (from QCD) the initial conditions of a HIC.
— Uncertainties exist, especially for the nuclear case - need to be fixed by data (pPb) + theoretical developments

CAS

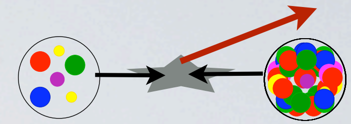
Moving forward: Testing the evolution

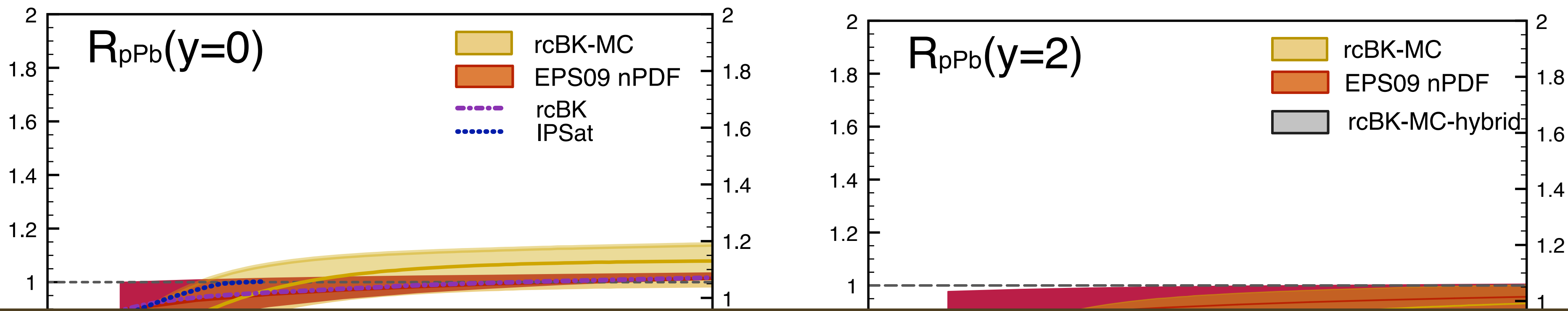




Javier Albacete

Moving forward: Testing the evolution



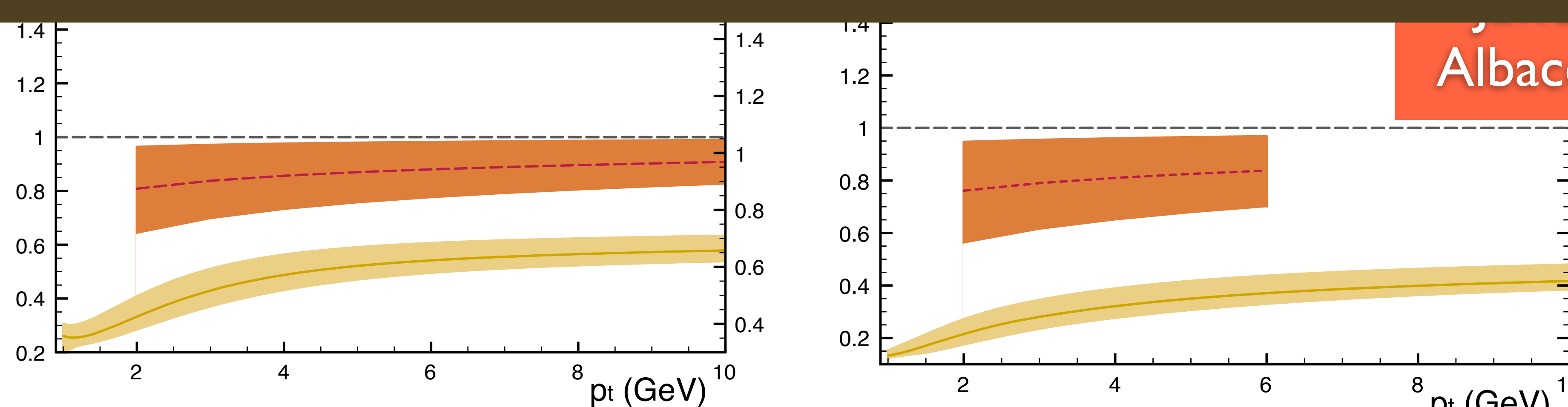


pPb@LHC discussion session

— The LHC capabilities for pPb measurements exceed by far this simple observable
— Fix a strategy for fully exploit the LHC new kinematical domains: reconstructed jets; EW boson; heavy flavor and quarkonia; forward rapidities
— Also: how a pPb run complements the future e+A machines
— Next week at CERN: http://indico.cern.ch/event/pAatLHC

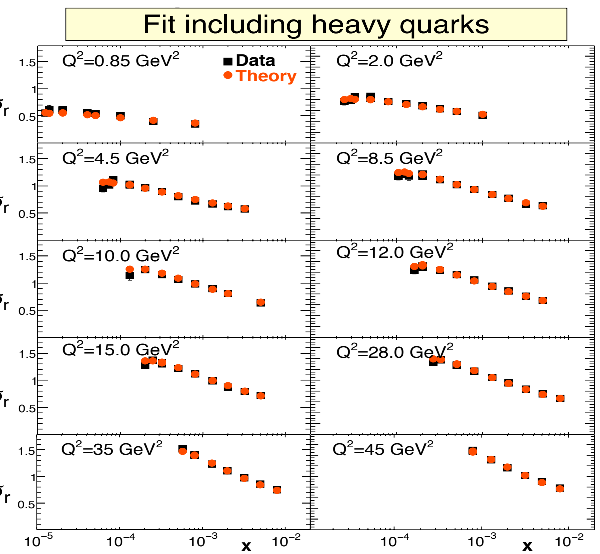
CAS

Albacete

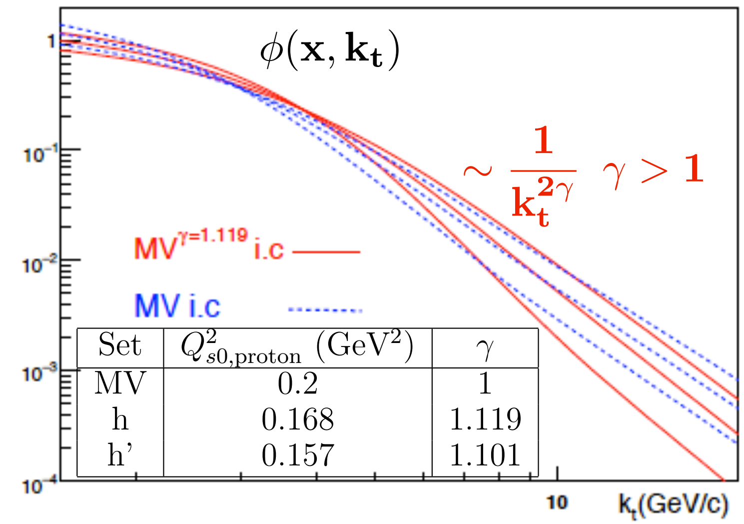


Precision analysis of DIS data

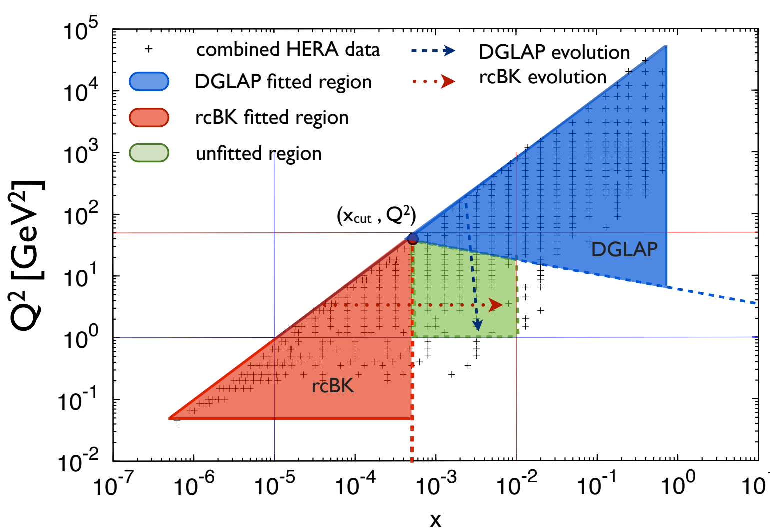
1. Global fits to e+p data at small-x

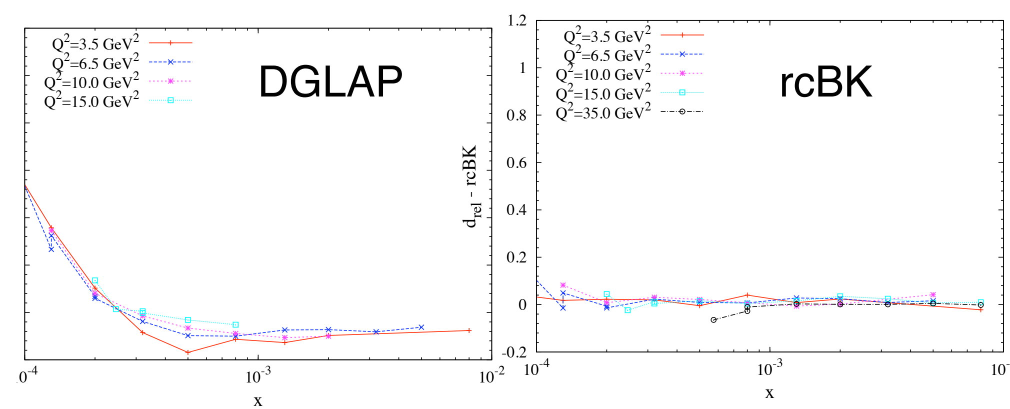


2. Extract NP fit parameters



3. Run consistency and stability checks



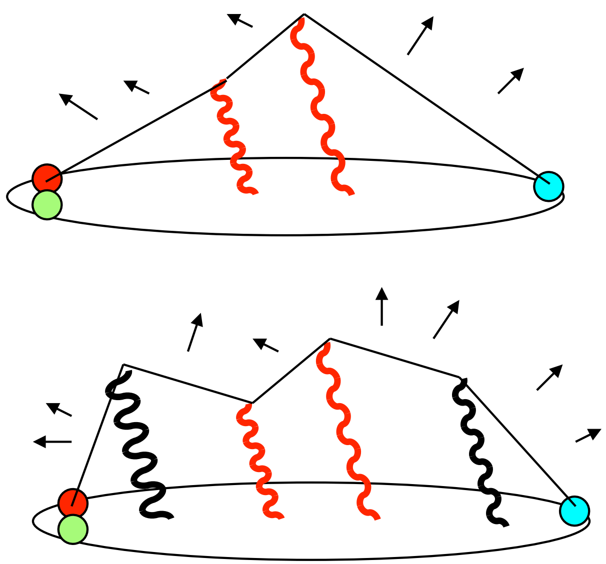


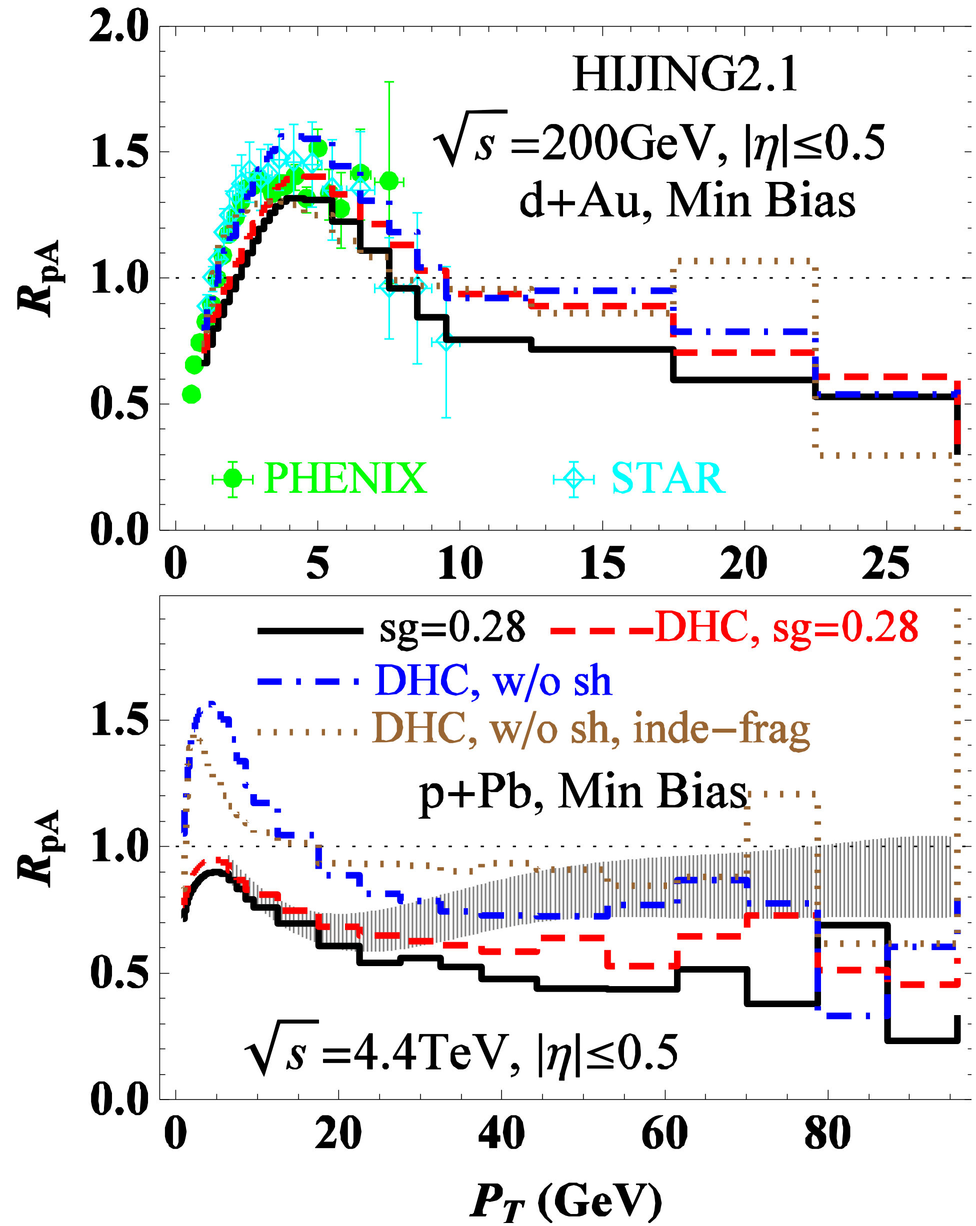
rcBK fits more stable than DGLAP fits at small-x

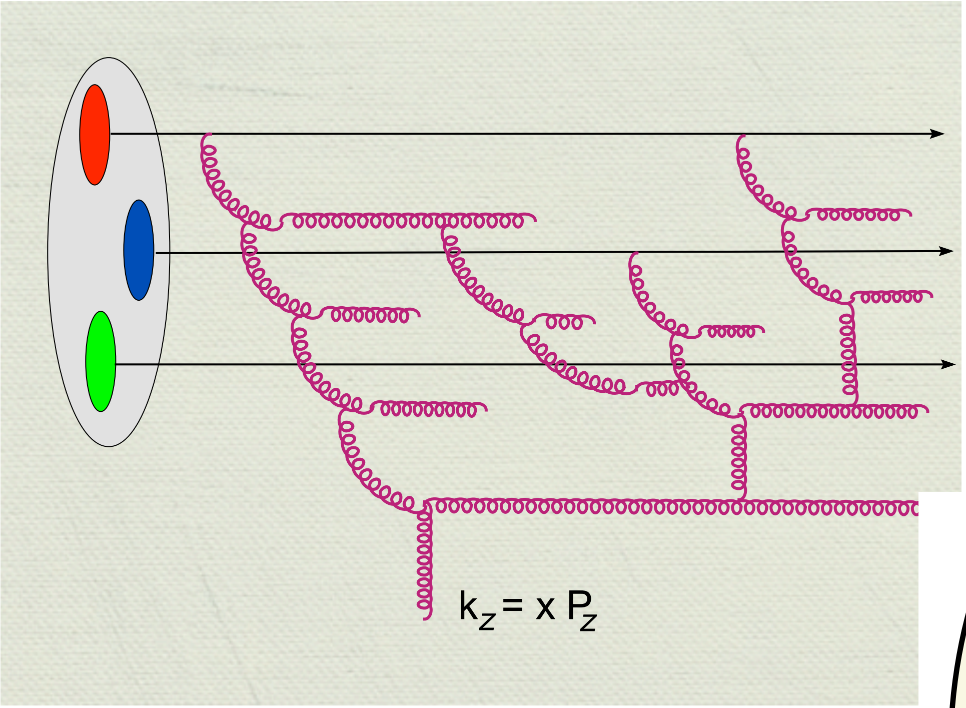
Paloma Quiroga

Predictions in Hijing for pA

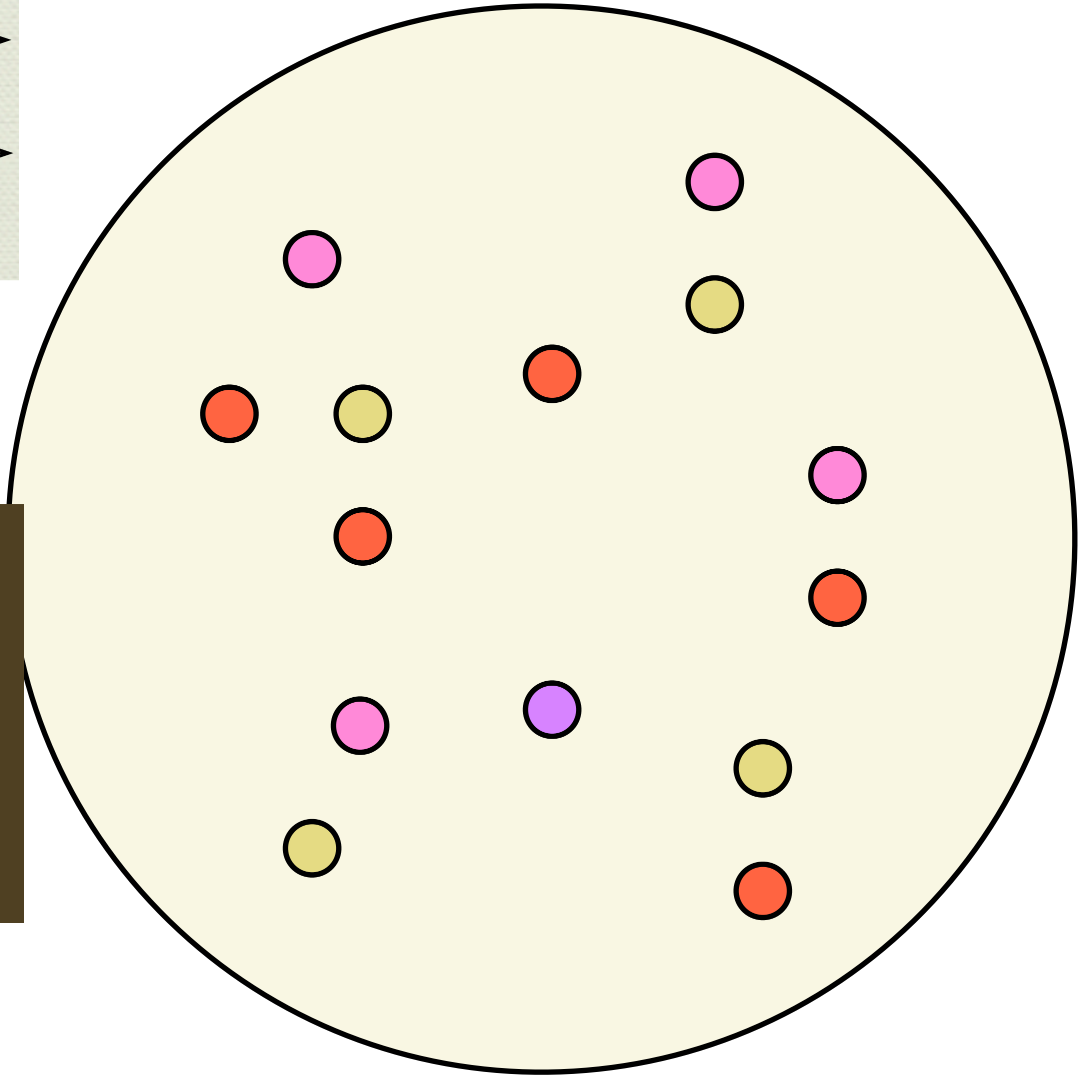
Wei-Tian Deng







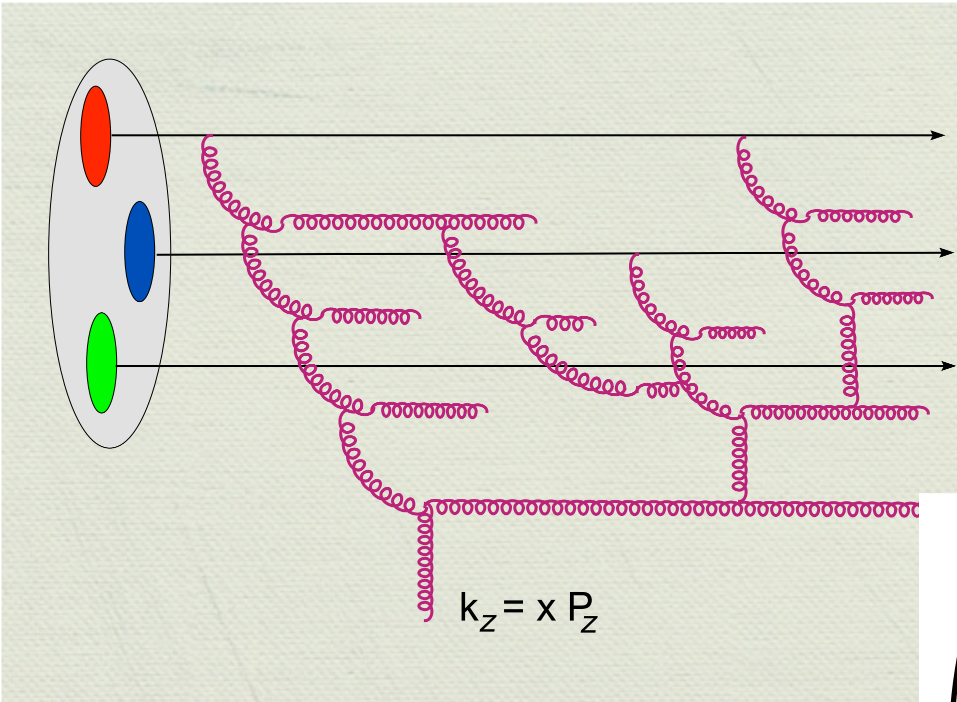
n-point correlators in the CGC

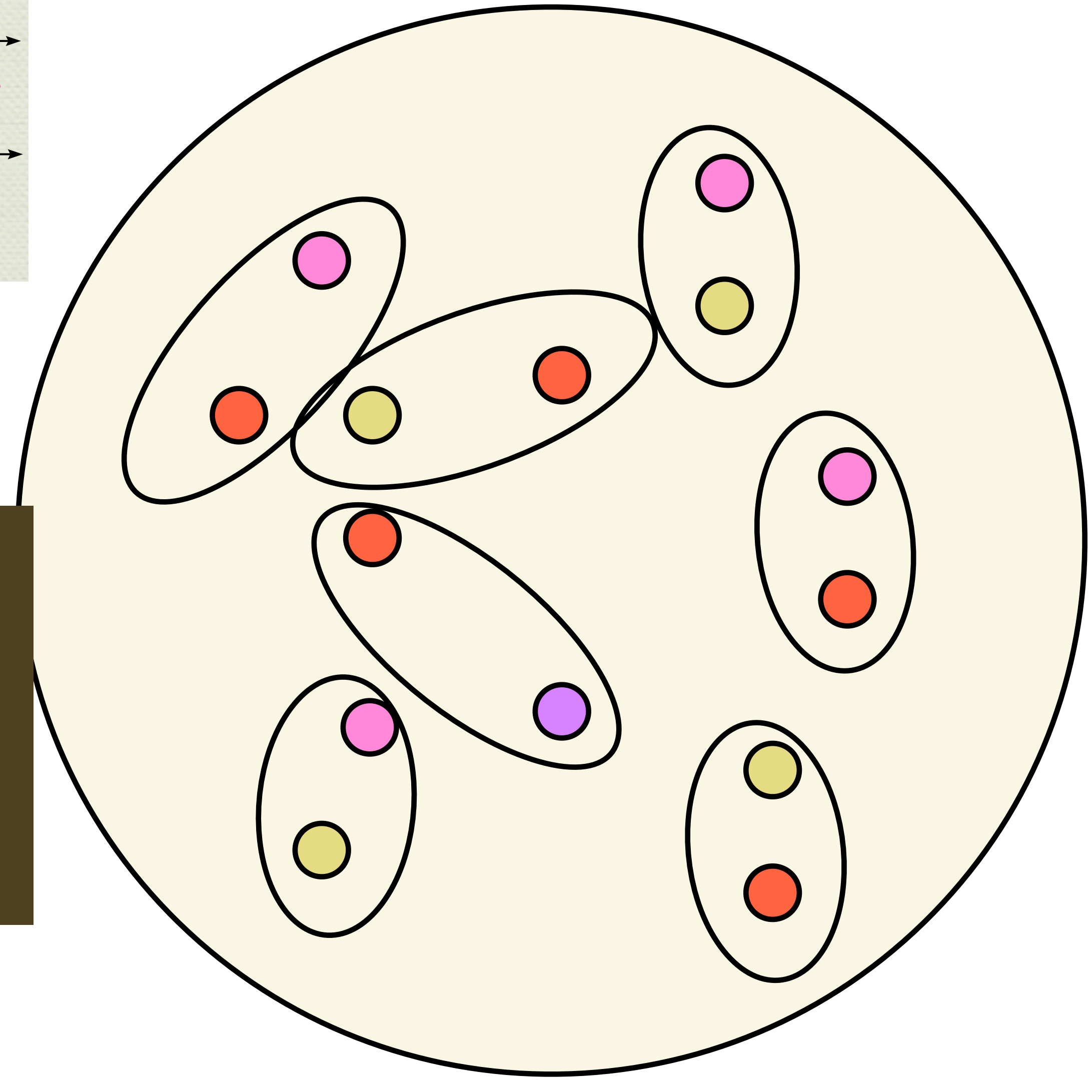


— The probes measure color correlation of the medium in the transverse plane
— n-point correlators appear for multiparticle correlations
[e.g. dihadron b2b at forward rapidities]

Dionisis Triantafyllopoulos
Tuomas Lappi

n-point correlators in the CGC





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Dionisis Triantafyllopoulos
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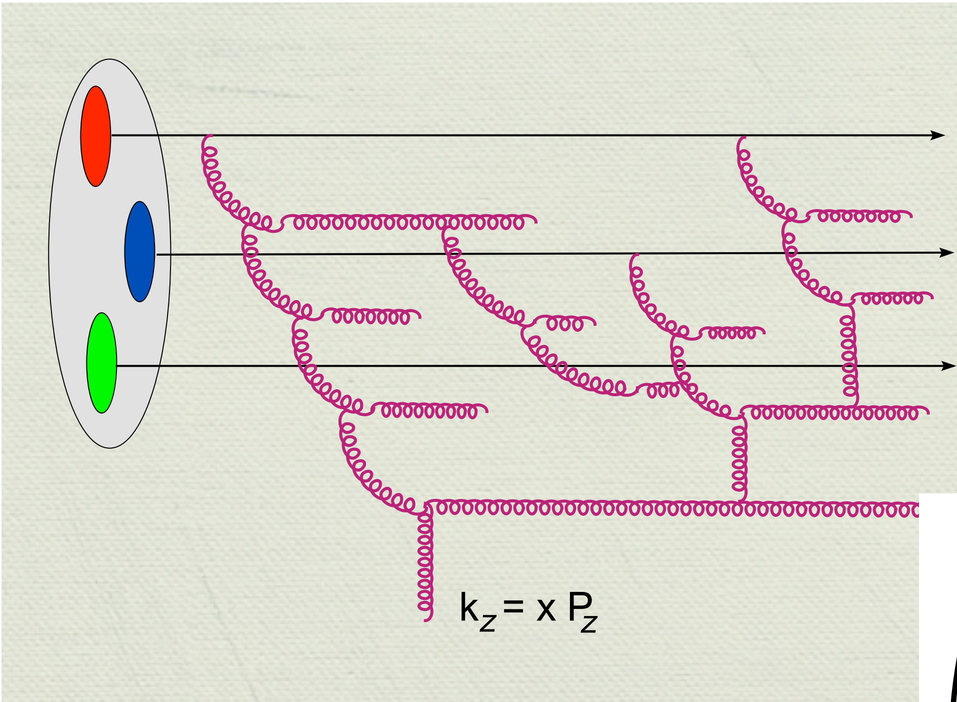
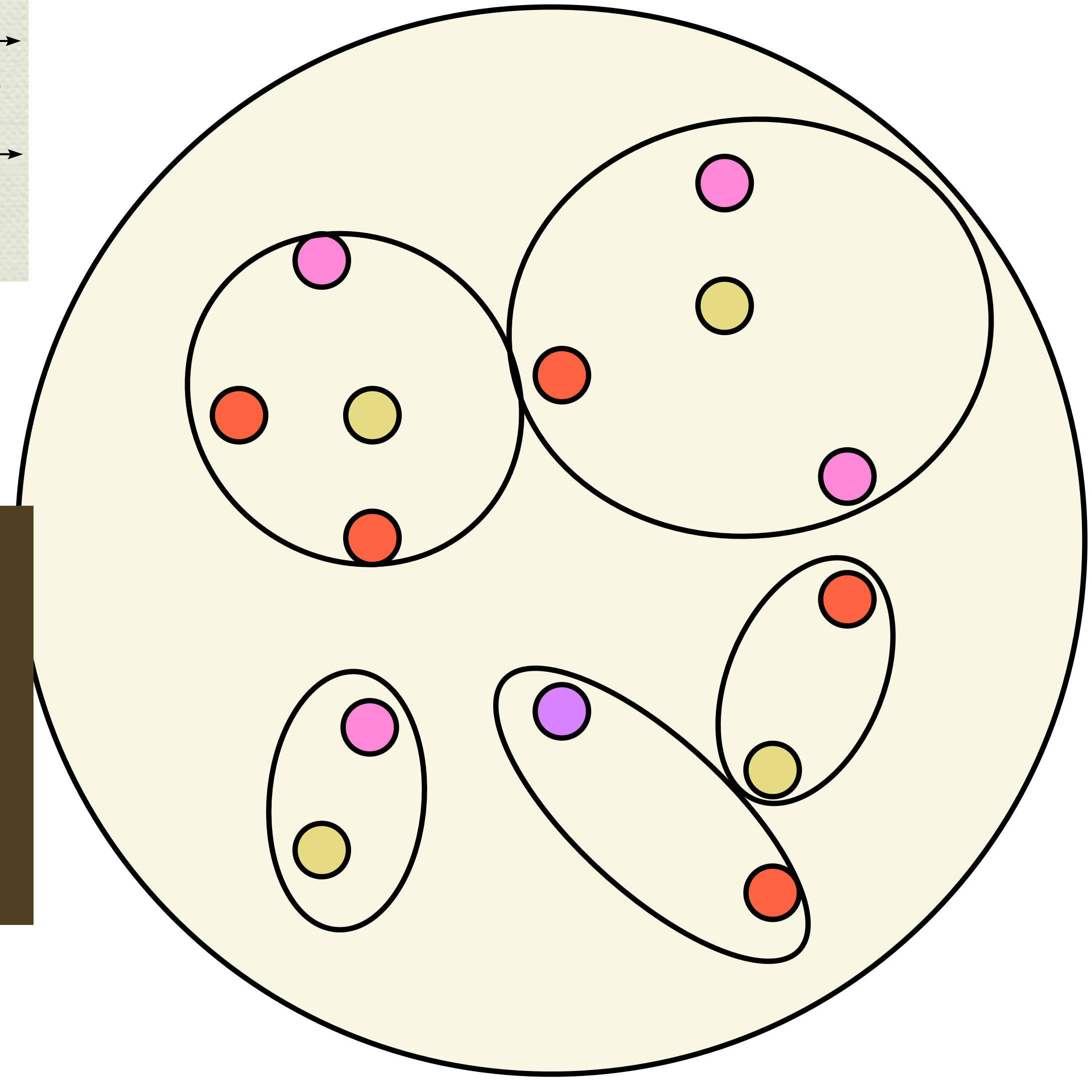
n-point correlators in the CGC





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[e.g. dihadron b2b at forward rapidities]

Dionisis Triantafyllopoulos
Tuomas Lappi

Evolution of quadrupole from JIMWLK

$$\frac{d}{dy}\langle Q(r,\bar r,\bar s,s)\rangle$$

$$= \frac{N_c\,\alpha_s}{(2\pi)^2}\int d^2z\Bigg\{\Bigg\langle\Bigg[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(r-s)^2}{(r-z)^2(s-z)^2}-\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}\Bigg]\,Q(z,\bar r,\bar s,s)\,S(r,z)$$

$$+\Bigg[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Bigg]\,Q(r,z,\bar s,s)\,S(z,\bar r)$$

$$+\Bigg[\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}-\frac{(\bar r-s)^2}{(s-z)^2(\bar r-z)^2}\Bigg]\,Q(r,\bar r,z,s)\,S(\bar s,z)$$

$$+\Bigg[\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Bigg]\,Q(r,\bar r,\bar s,z)\,S(z,s)$$

$$-\Bigg[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}+\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}\Bigg]\,Q(r,\bar r,\bar s,s)$$

$$-\Bigg[\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}-\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Bigg]\,S(r,s)\,S(\bar r,\bar s)$$

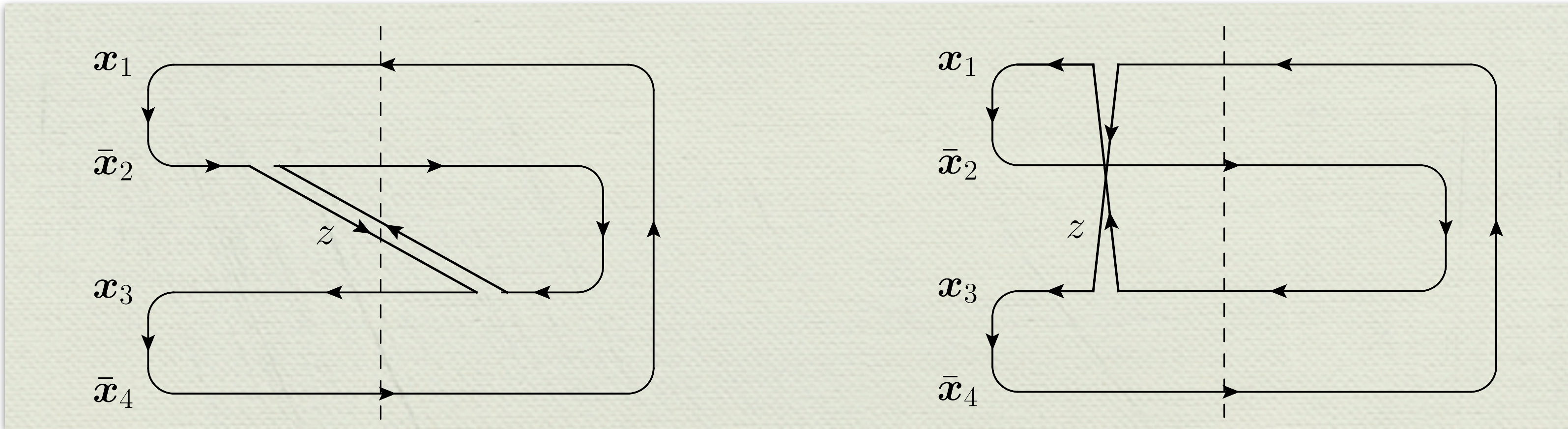
$$-\Bigg[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}-\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}\Bigg]\,S(r,\bar r)\,S(\bar s,s)\Bigg\rangle\Bigg\}$$

$$\frac{d}{d\,y}Q=\int P_1\,[Q\,S]-P_2\,[Q]+P_3[S\,S]$$ with $$P_1-P_2+P_3=0$$

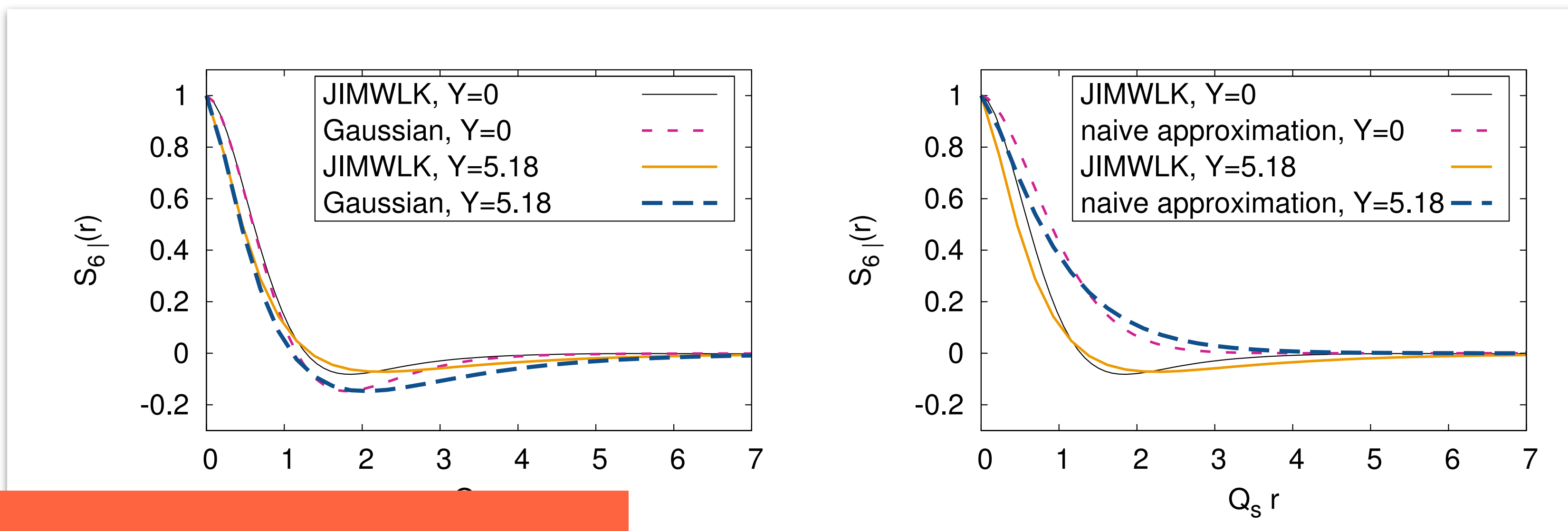
J. Jalilian-Marian, Y. Kovchegov: PRD70 (2004) 114017
Dominguez, Mueller, Munier, Xiao: PLB705 (2011) 106
J. Jalilian-Marian: Phys.Rev. D85 (2012) 014037

Jamal Jalilian-Marian

n-point correlators in the CGC



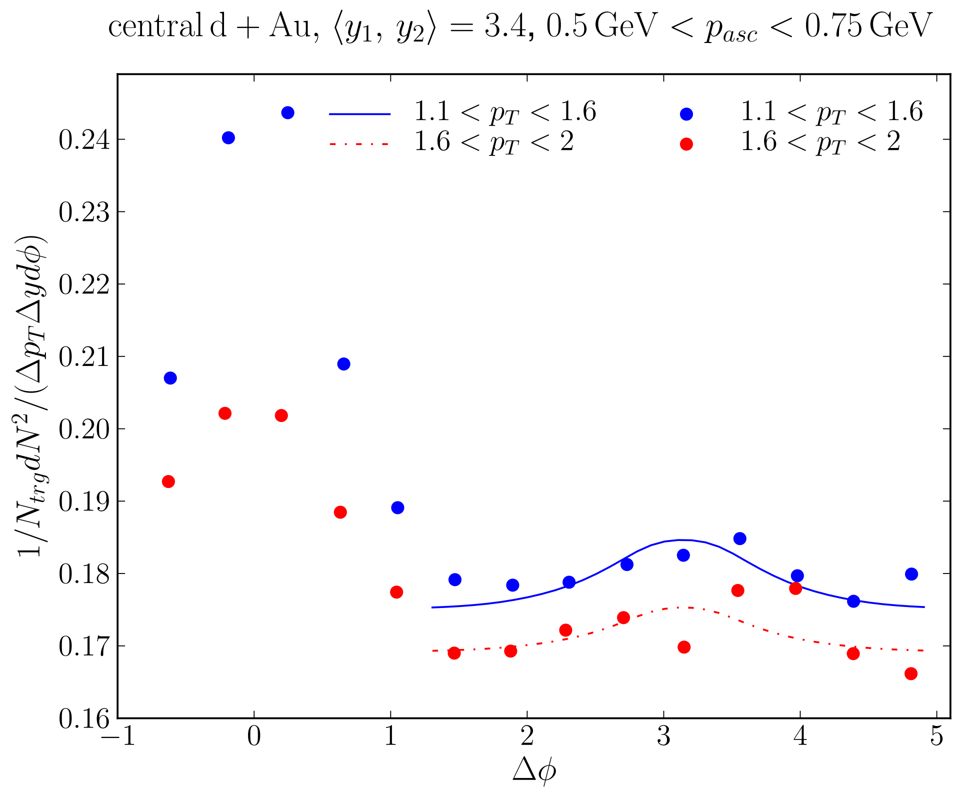
Factorization in terms of dipoles possible in the gaussian approximation (analytical and numerical solutions)



Dionisis Triantafyllopoulos
Tuomas Lappi, Heikki Mäntysaari

Results: Coincidence probability

Preliminary numerical results

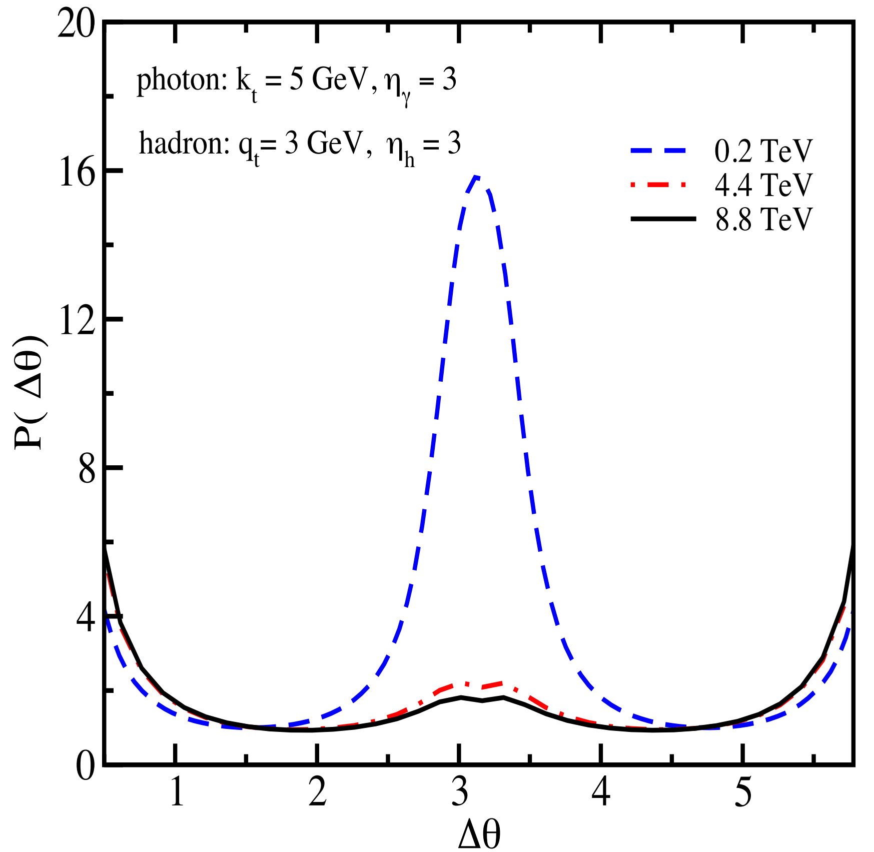


Heikki Mäntysaari

- Good description of central PHENIX data (pedestal from exp. data)
- Gaussian large-*Nc* approximation

IC: MV^γ, $Q_s^2 = 0.33\,\mathrm{GeV}^2$, data: PHENIX [1105.5112]

Photon-hadron azimuthal correlations; RHIC vs. the LHC



Amir Rezaeian

- Higher energy → more suppression of away-side correlations.

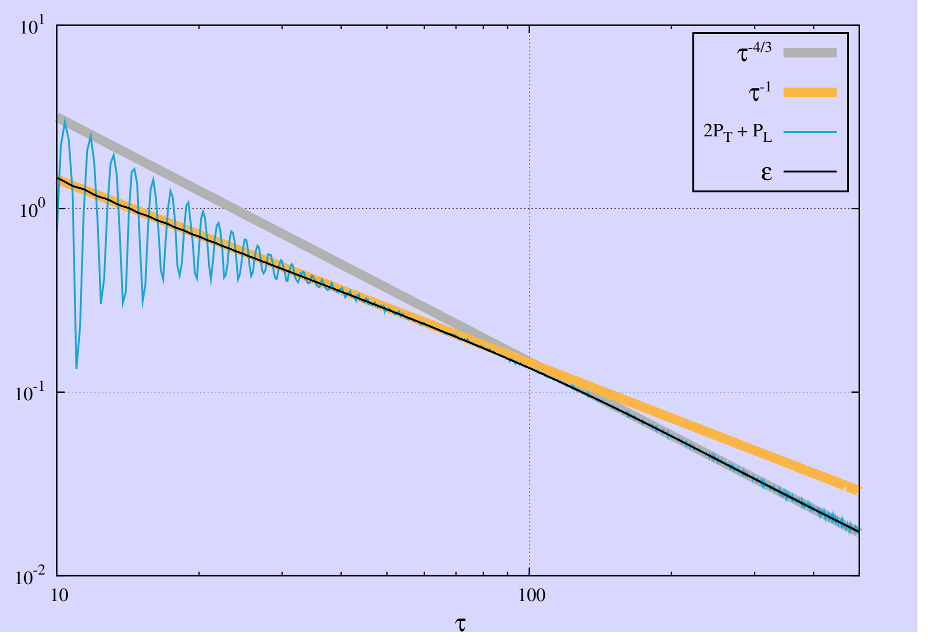
Towards equilibrium

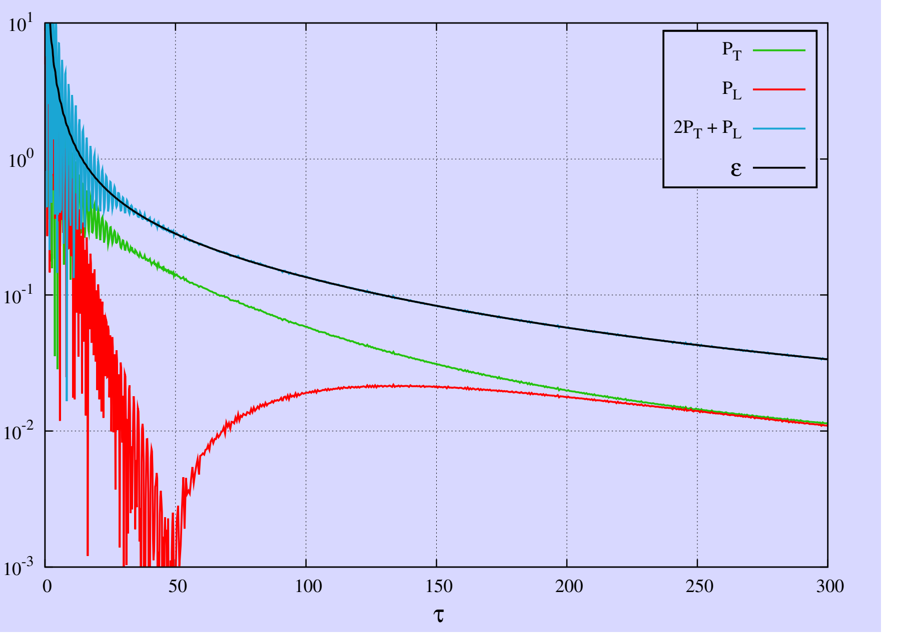
François Gelis

$T^{\mu\nu}$ for longitudinal $\vec{E}$ and $\vec{B}$

$$T^{\mu\nu}_{LO}(\tau = 0^+) = \mathrm{diag}\,(\epsilon, \epsilon, \epsilon, -\epsilon)$$

▷ far from ideal hydrodynamics



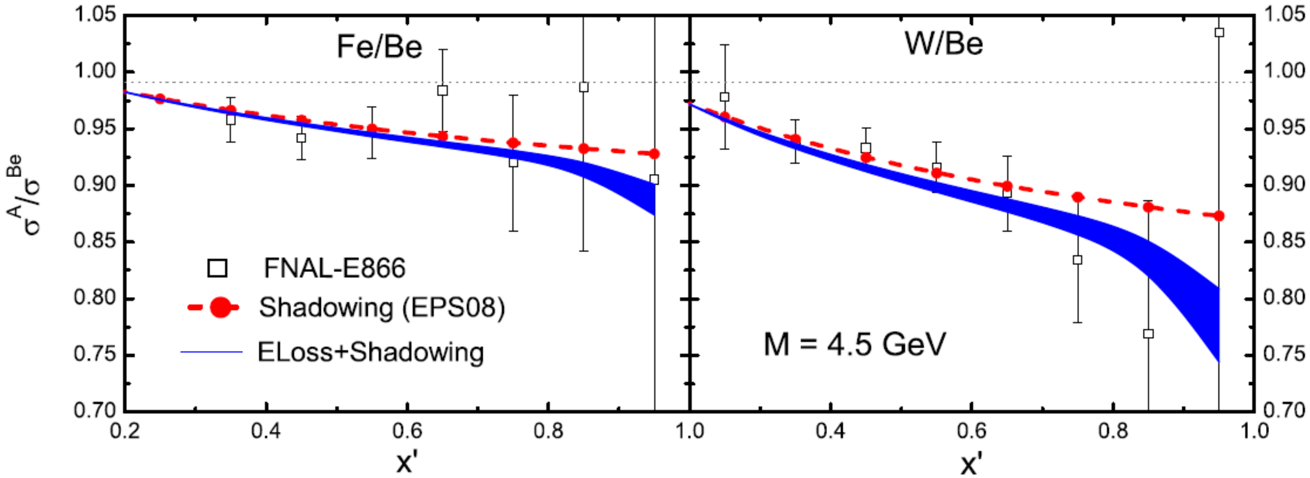


Resummation of secular terms stabilizes NLO
Approach to isotropization and thermalization, presence of BE condensates
[only scalar theory numerically studied for the moment]

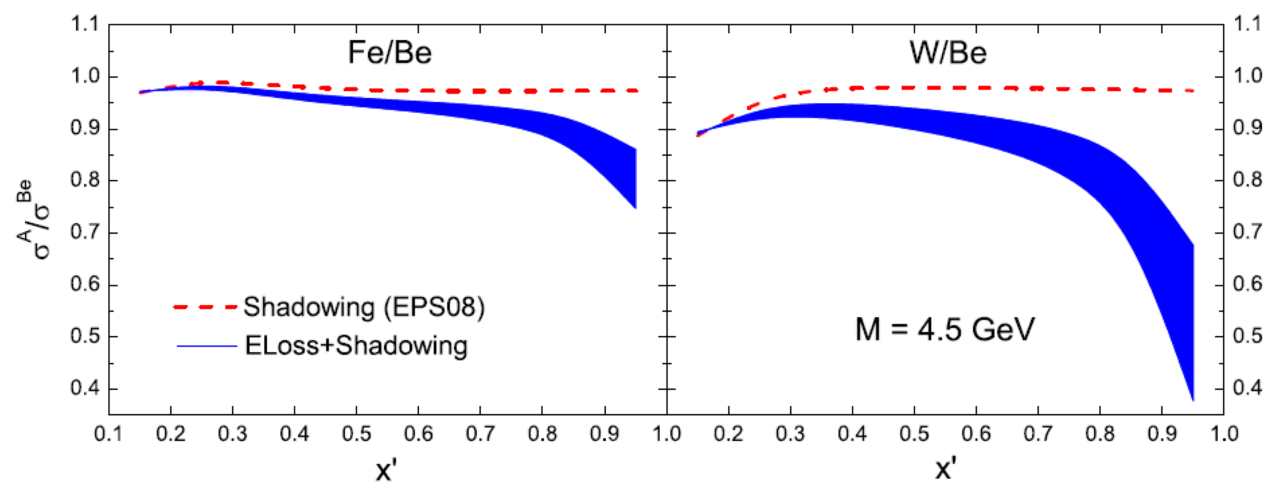
Cold nuclear matter energy loss

Xin-Nian Wang

Energy loss VS. Shadowing (FNAL-E866 ELab = 800 GeV)



Energy loss VS. Shadowing (FNAL-E906 ELab = 120 GeV)

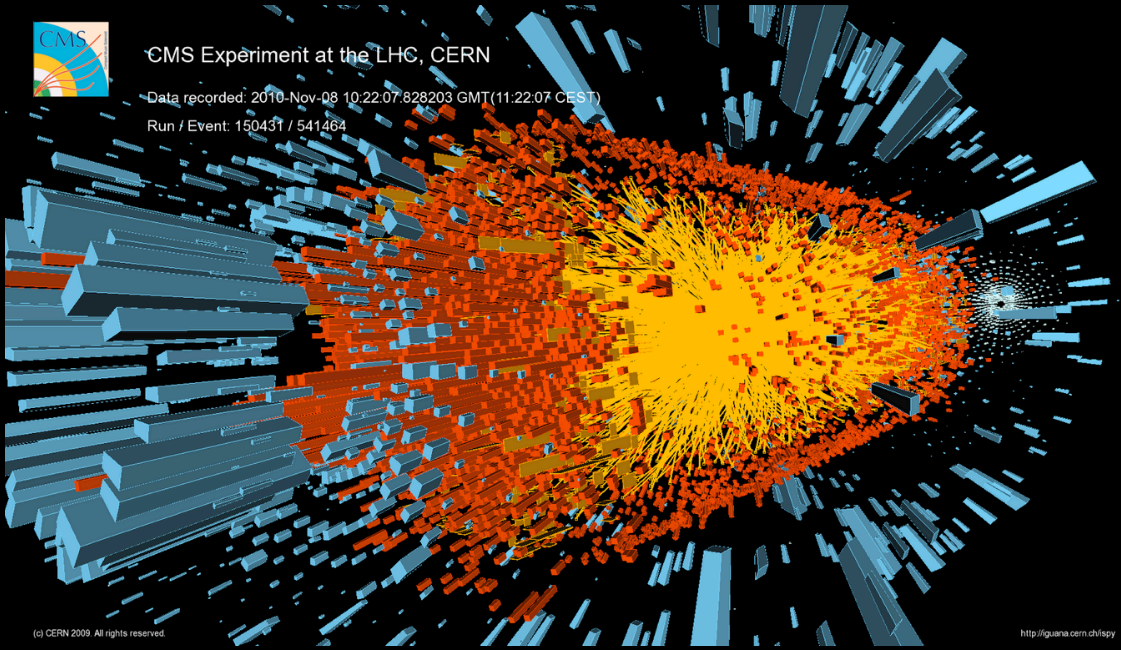


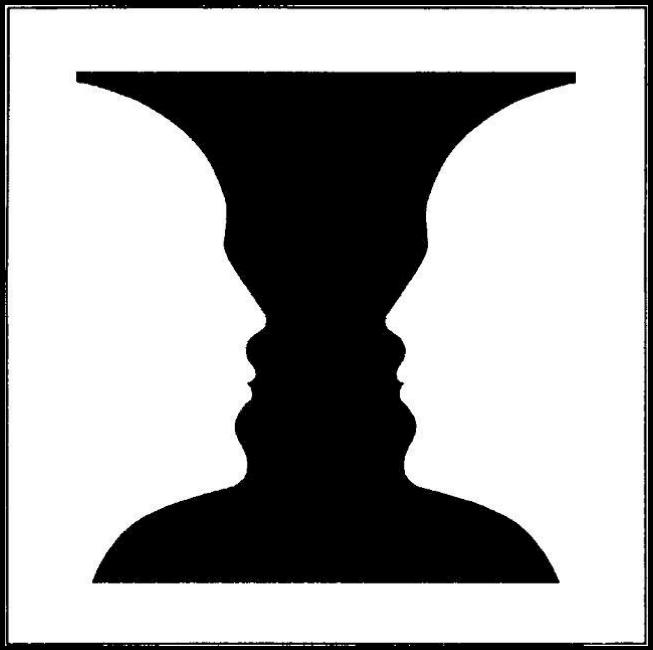
Relevance for the hadronic phase in nucleus-nucleus collisions
[XNW: 30% quenching from the hadronic phase]

JETS IN NUCLEAR COLLISIONS

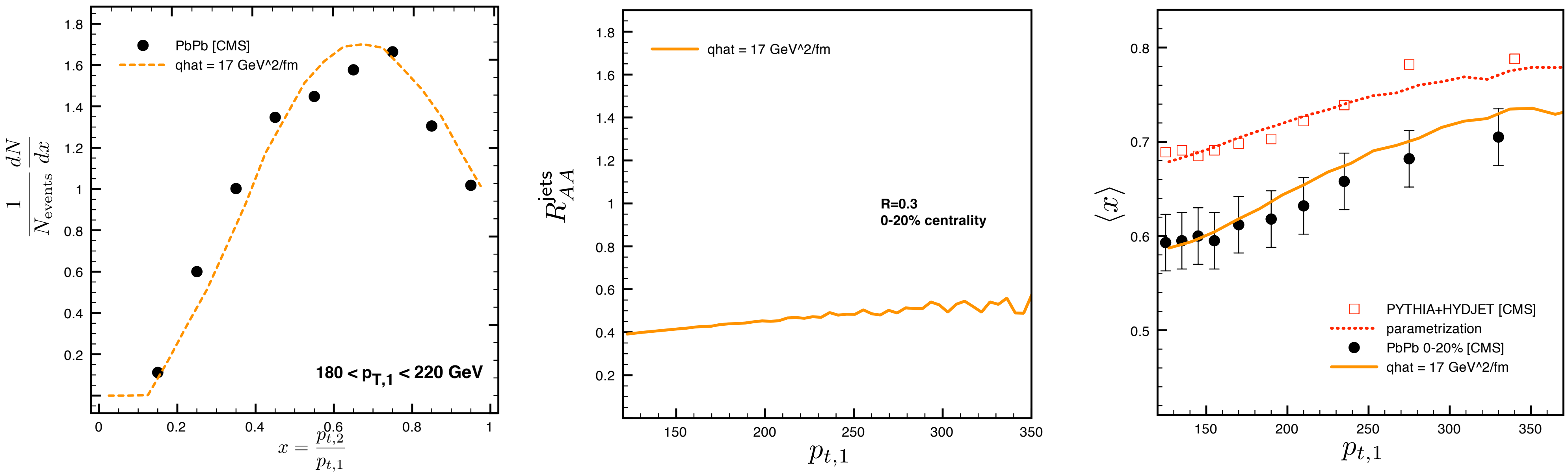
[including heavy quark at high-pT]

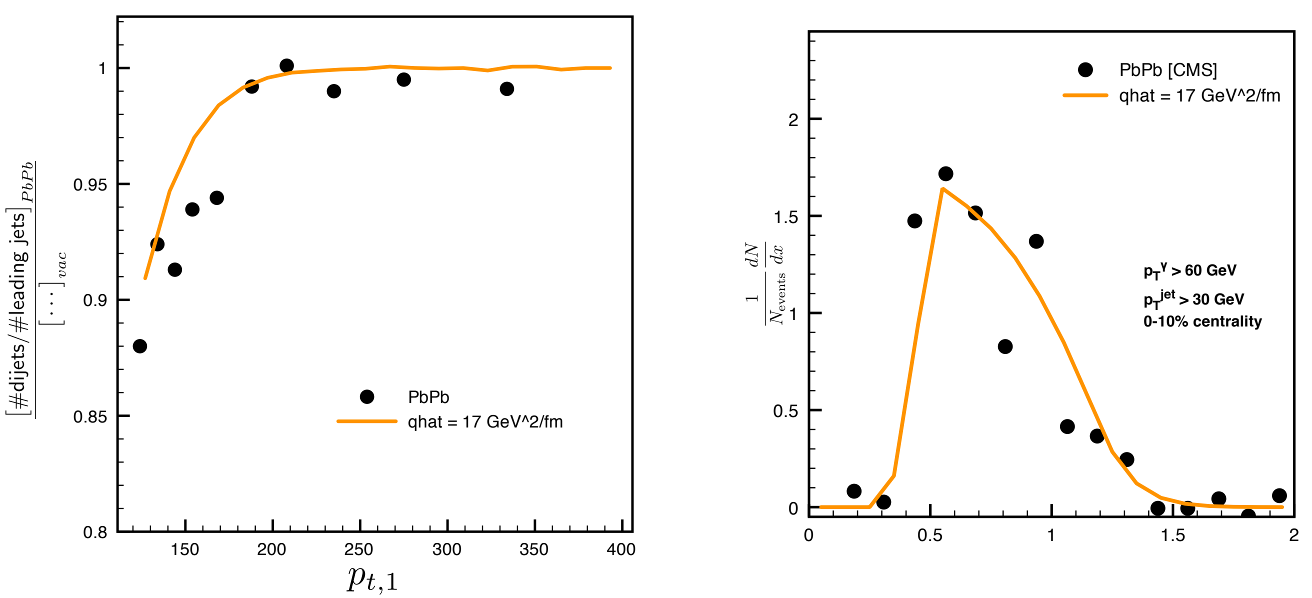
Phenomenology...





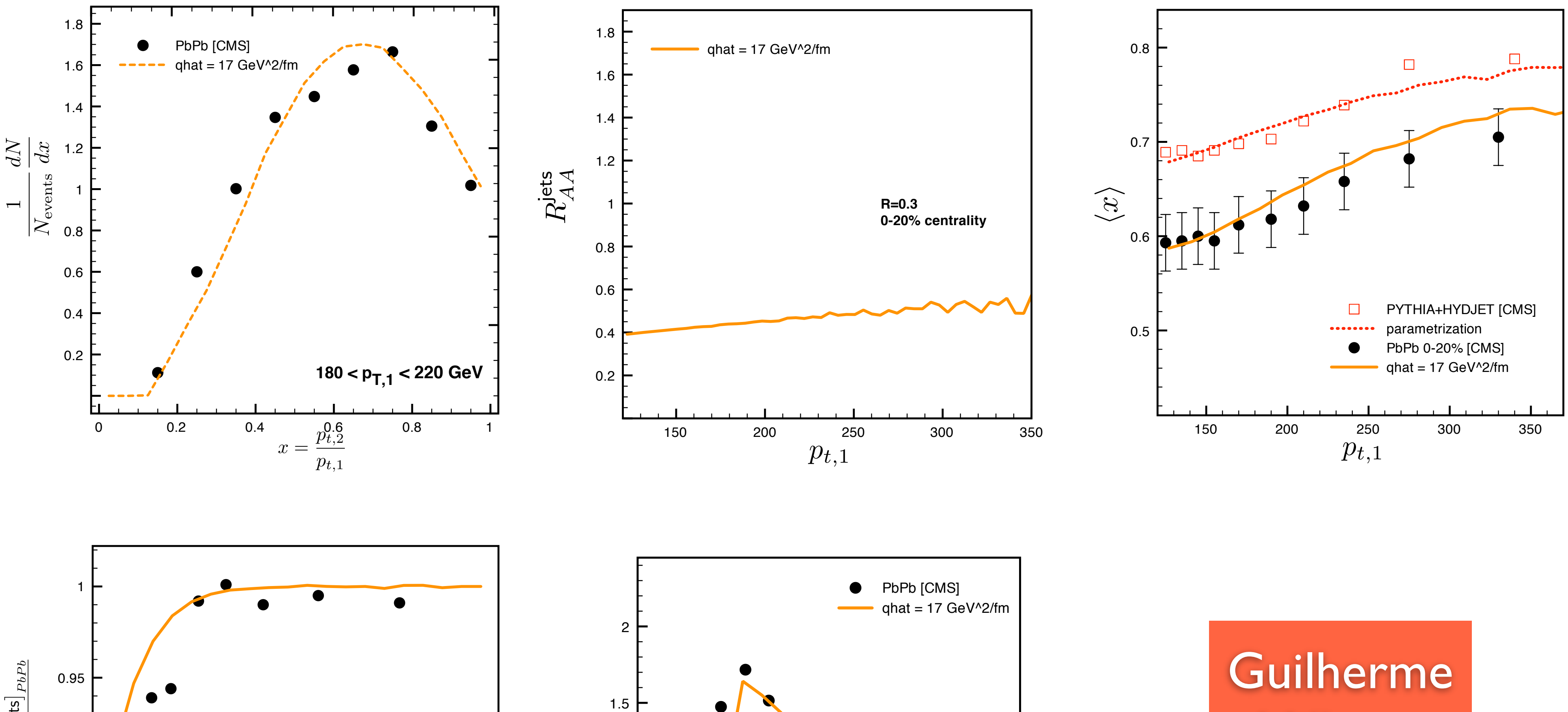
Jet collimation





Guilherme Milhano

Jet collimation



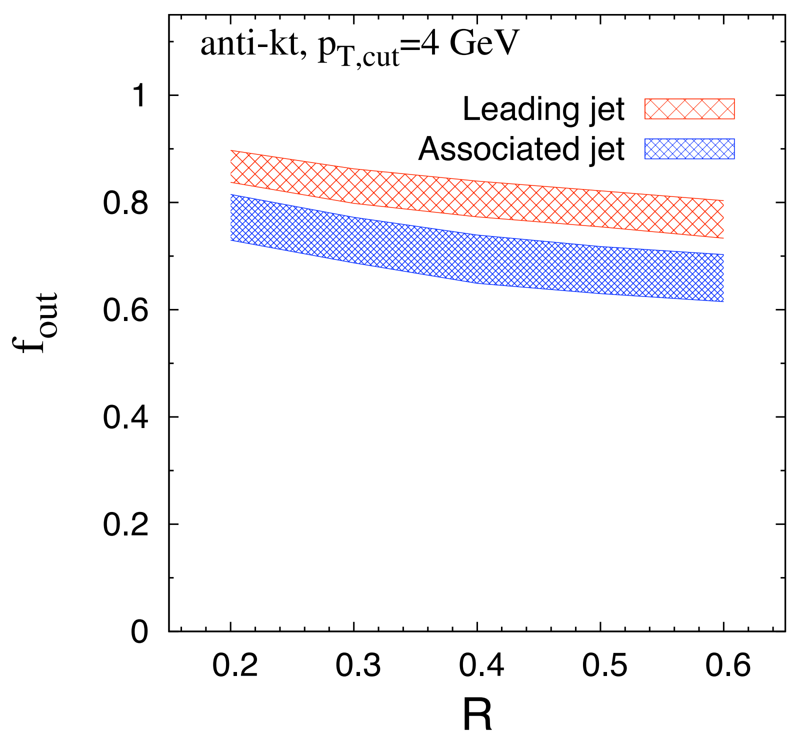
Guilherme

— Good description of the reconstructed jet data with a very simple model
— What does it mean? Has the model captured the main ingredients of the whole problem?

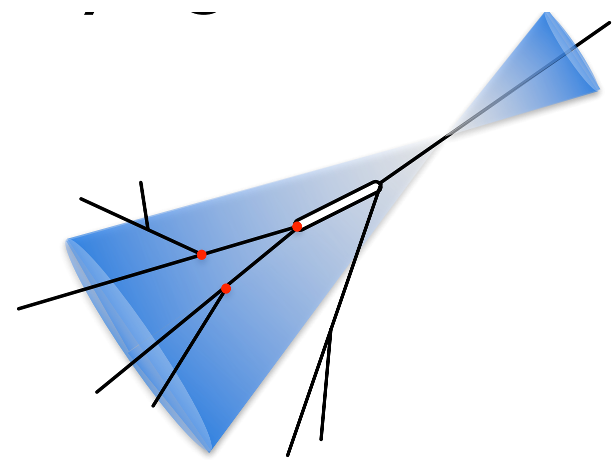
CAS

Parton formation times

Estimates of the formation times and vertexes using (vacuum) Pythia



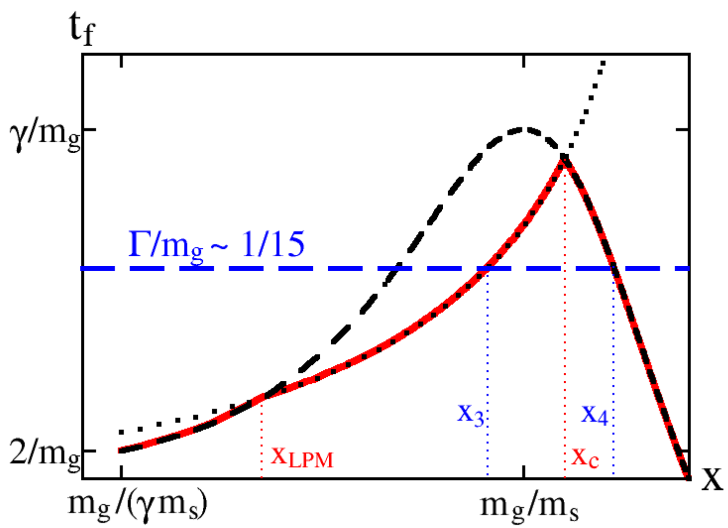
Jorge Casalderrei-Solana

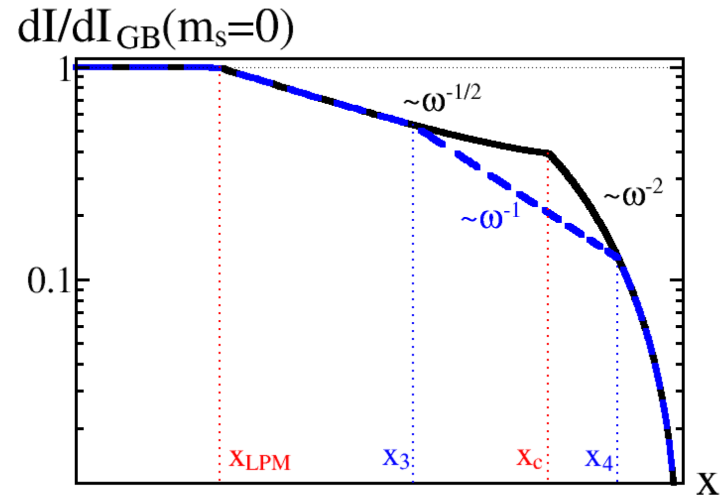


- A large fraction of fragments are emitted outside of the medium both for leading and associated jet

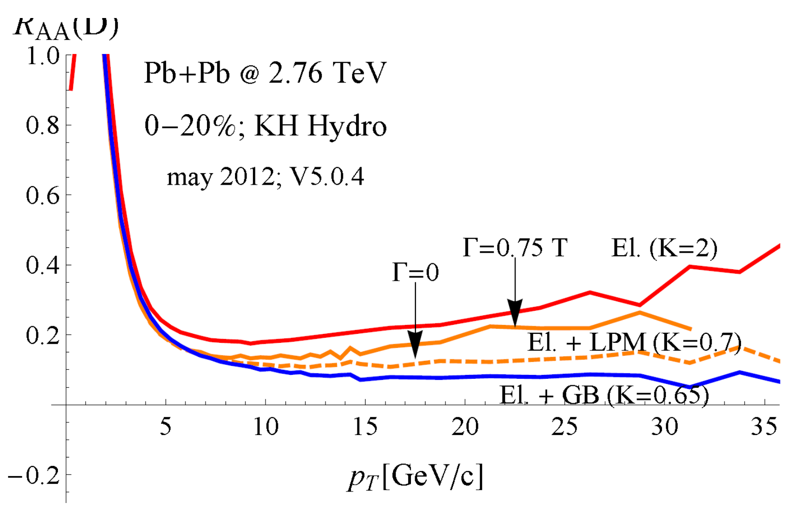
Gluon damping on radiative Eloss

- damping of already formed gluons *"trivial"*
- Is it possible that damping mechanisms influence the formation of radiation itself?





Marcus Bluhm

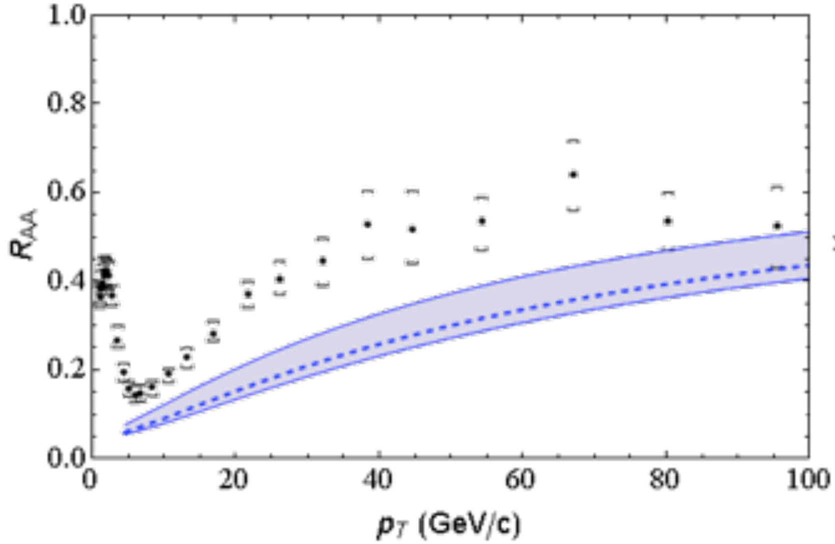


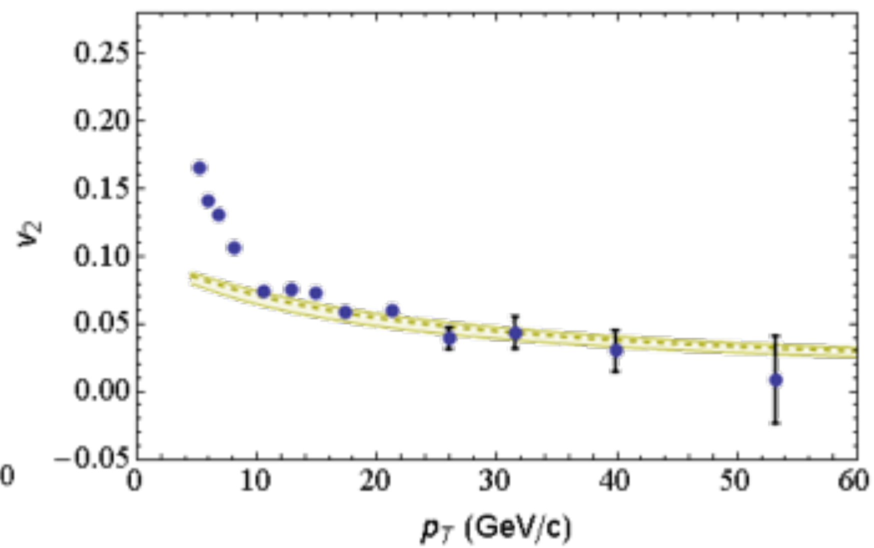
$$t_d \sim \frac{1}{\Gamma} \sim \frac{1}{g^4 T}$$

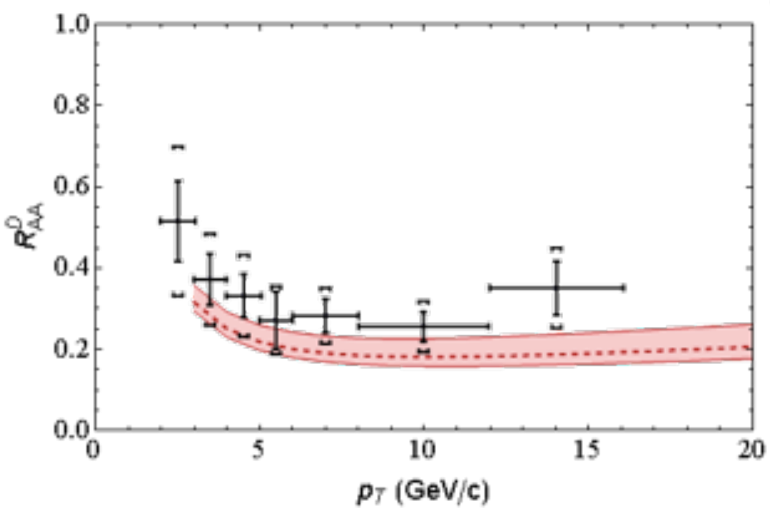
Effects when $t_d > t_f$

Pol B. Gossiaux

Models tested at RHIC





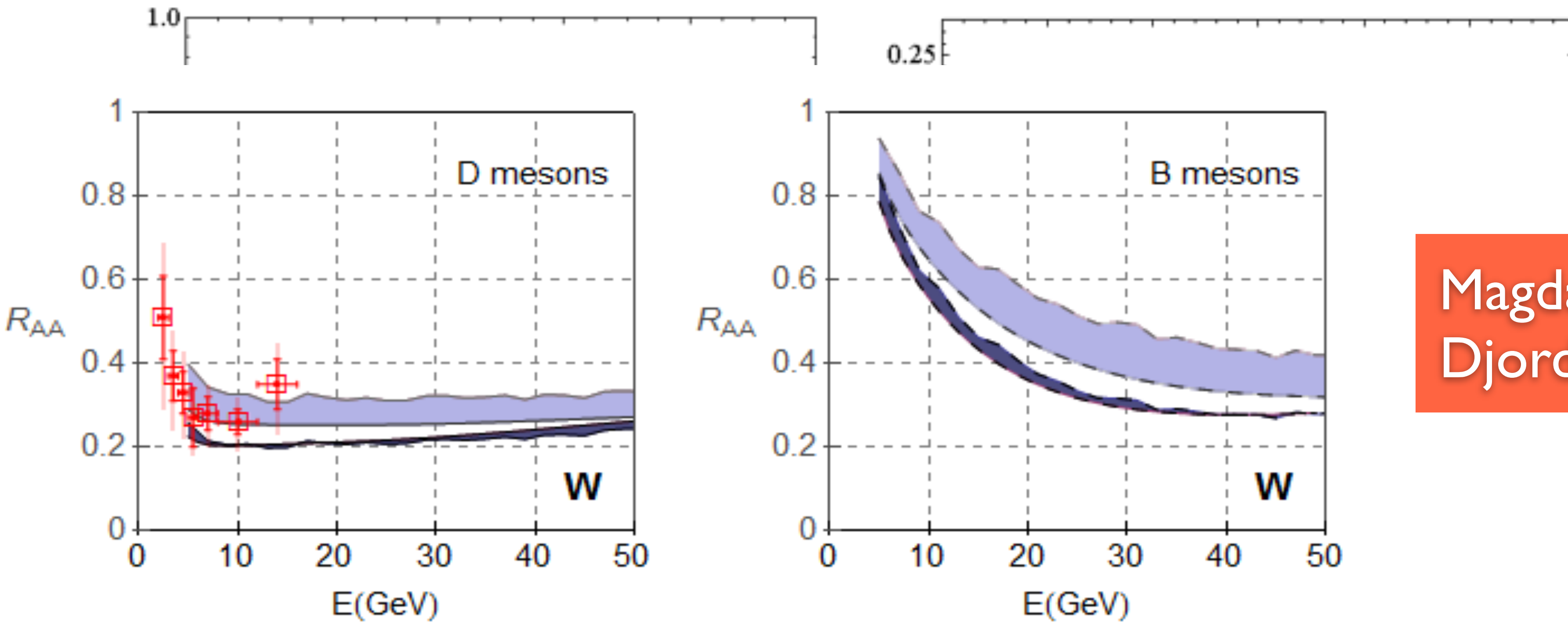


William Horowitz

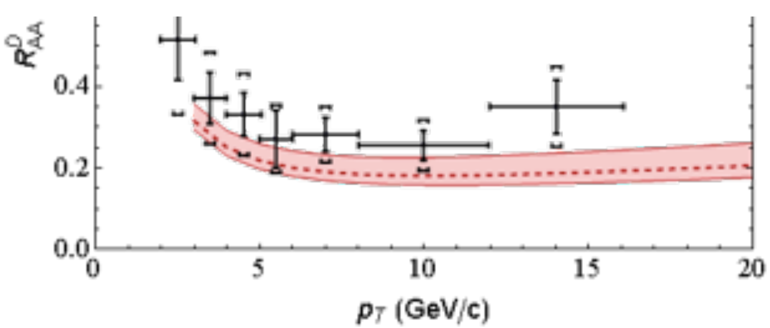
— In general the radiative energy loss models tested at RHIC provide reasonable results at the LHC without much fitting

CAS

Models tested at RHIC



Magdalena Djordjevic



William Horowitz

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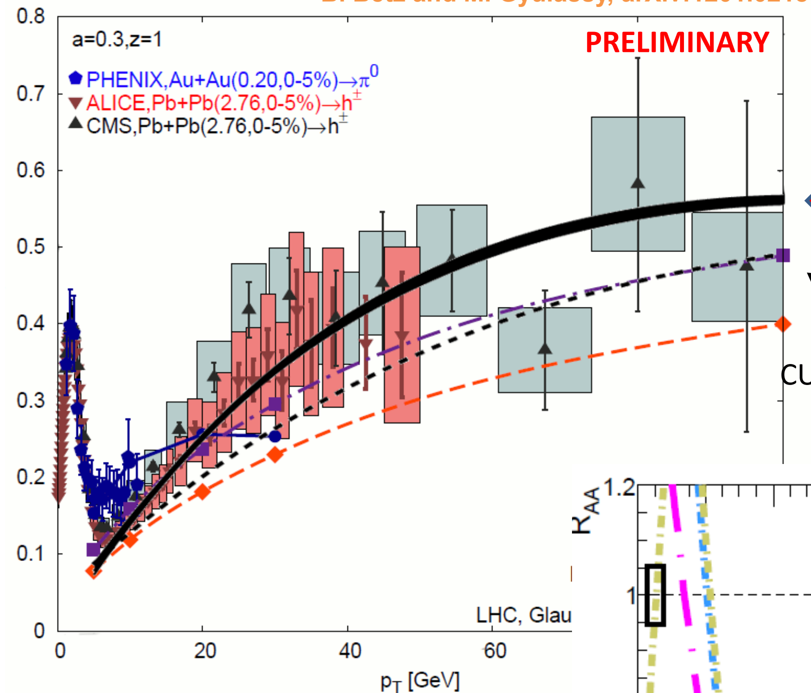
CAS

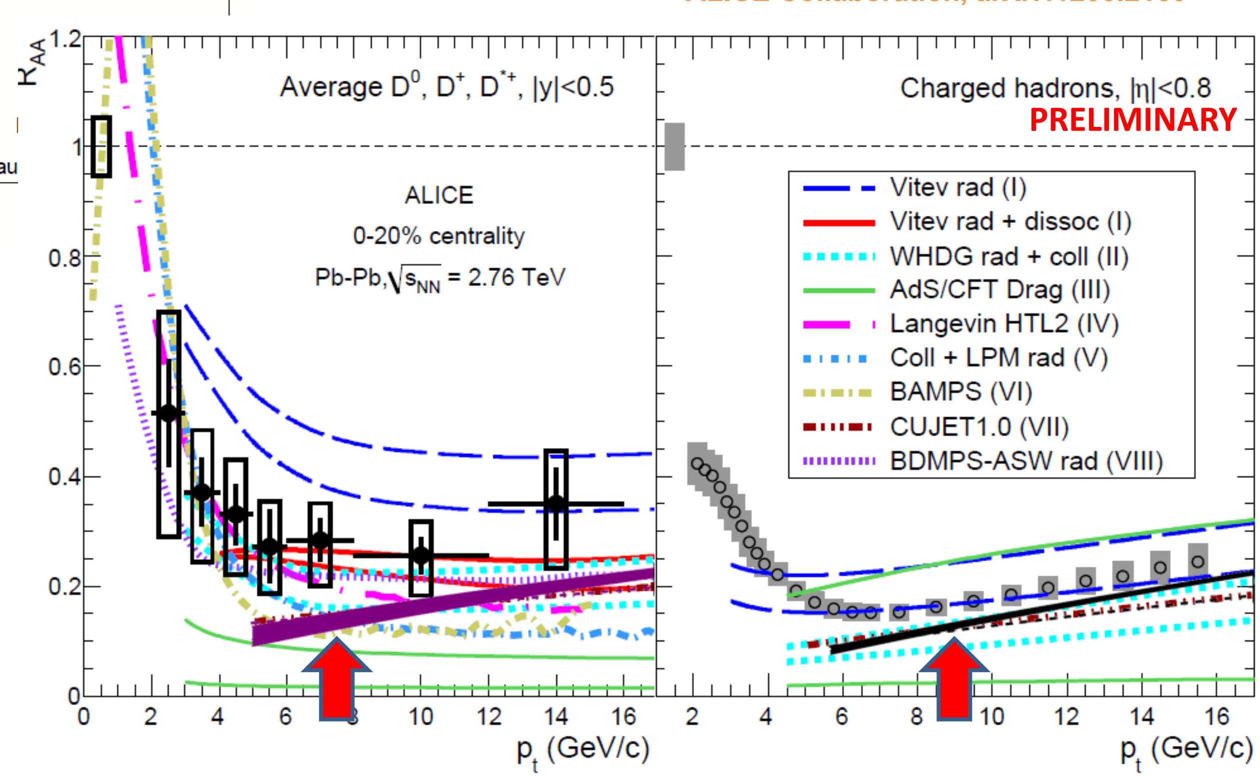
Models tested at RHIC

B. Betz and M. Gyulassy, arXiv:1201.0218



A new implementation of the DGLV energy loss, including the treatment of the initial partonic spectrum; geometry; running alpha-s...

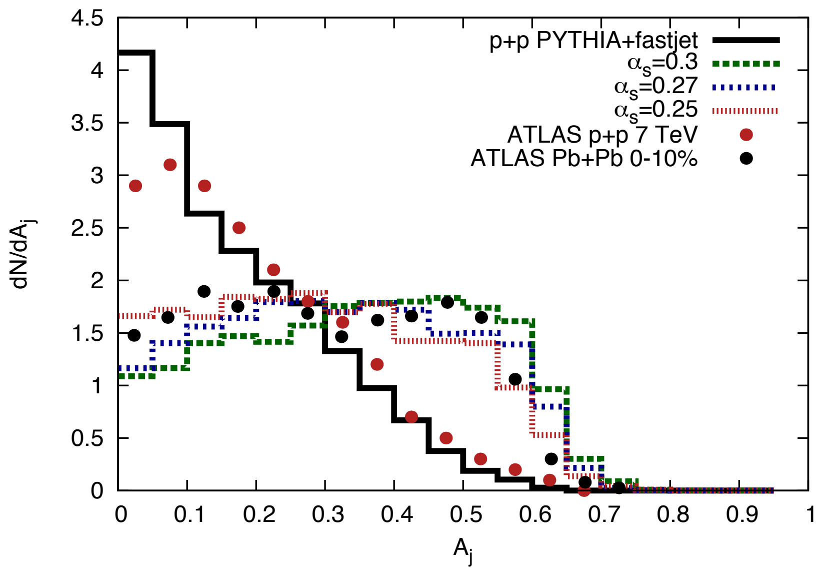
ALICE Collaboration, arXiv:1203.2160

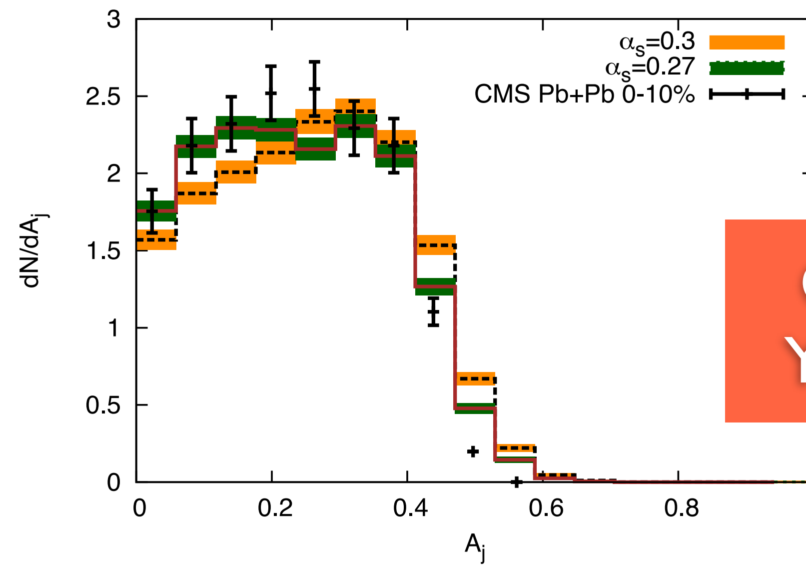


Alessandro Buzzatti

Dijets with MARTINI: applying all perturbative processes

Monte Carlo approaches



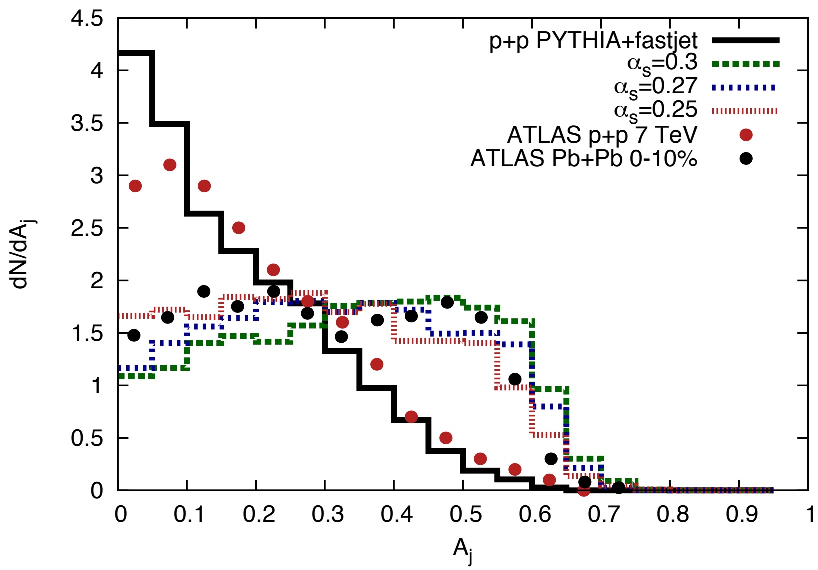


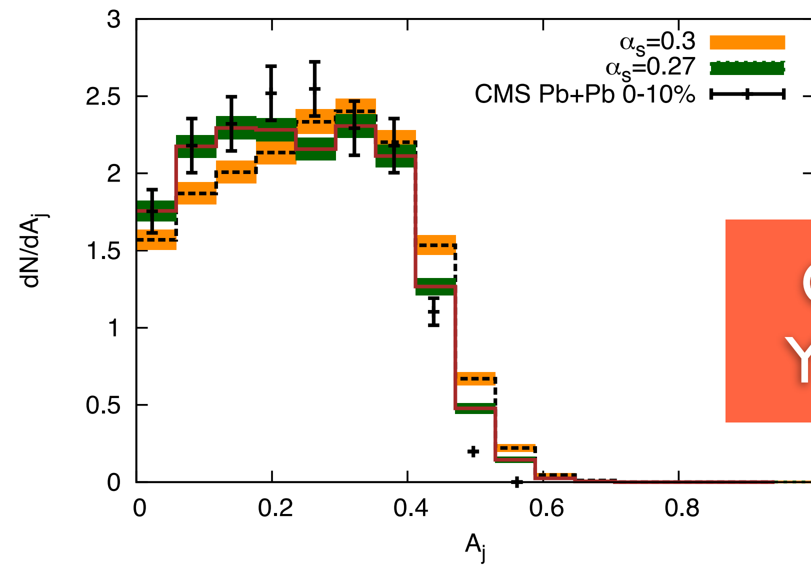
Clint Young

Physics conclusion: dN/dA_j can be explained with in-medium jet evolution to small z's, and collisions moving small-z partons out of the jet cone.

Dijets with MARTINI: applying all perturbative processes

Monte Carlo approaches





Clint Young

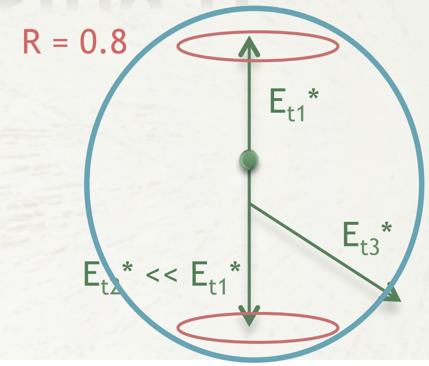
Physics conclusion: dN/dA_j can be explained with in-medium jet evolution to small z's, and collisions moving small-z partons out of the jet cone.

— Important to study all jet observables to reach a firm physics conclusion

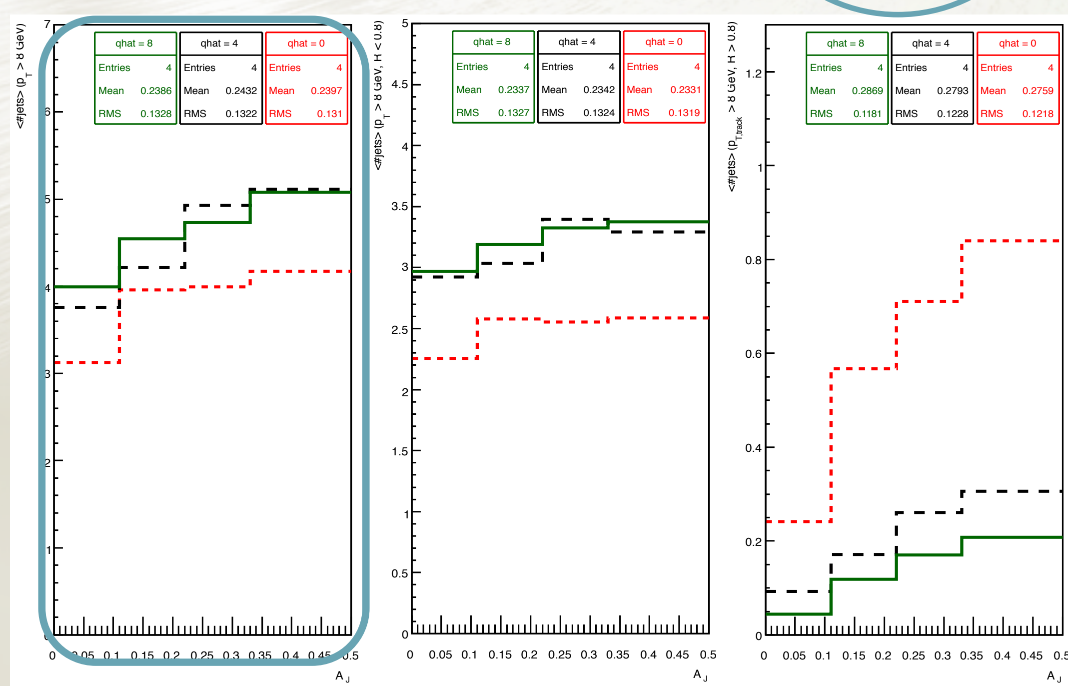
Monte Carlo approaches: QPhythia

Liliana Apolinario

Missing p_T



- Higher difference for larger values of A_J:
  - Already in pp there are events with $A_J > 0.3$:
    - Presence of tracks with p_T>8 GeV outside cone of R = 0.8 in simulation and PYTHIA
  - In data (PbPb), these tracks disappear, and also in Q-PYTHIA
    - Same events than before, but the third jet is now quenched ($E_t^* < E_t$)
      - No compelling need of large angle emission mechanisms?



Jet Reconstruction in HIC

Models tested at RHIC & MCs

- assuming the best choice of hydro model for each parton-medium interaction model: (all models tuned to describe R_{AA} in central 200 AGeV AuAu collisions)

	$R_{AA}^{RHIC}(\phi)$	$R_{AA}^{LHC}(P_T)$	I_{AA}^{RHIC}	I_{AA}^{LHC}	A_J^{LHC}	$A_J^{LHC}(E)$
elastic	**fails!**	works	**fails!**	fails	works	fails
ASW	works	fails	marginal	works	N/A	N/A
AdS	works	**fails!**	marginal	works	N/A	N/A
YaJEM	fails	fails	fails	fails	works	works
YaJEM-D	works	works	marginal	marginal	works	works
YaJEM-DE	works	works	works	works	works	works

- YaJEM-DE only viable candidate out of the tested models

$\rightarrow$ can other popular models be added to this matrix?

Thorsten Renk

— Need to be sure that the underlying physical mechanism is a sensitive one

MC discussion session

— Improvements in parton-shower evolution needed (TH)

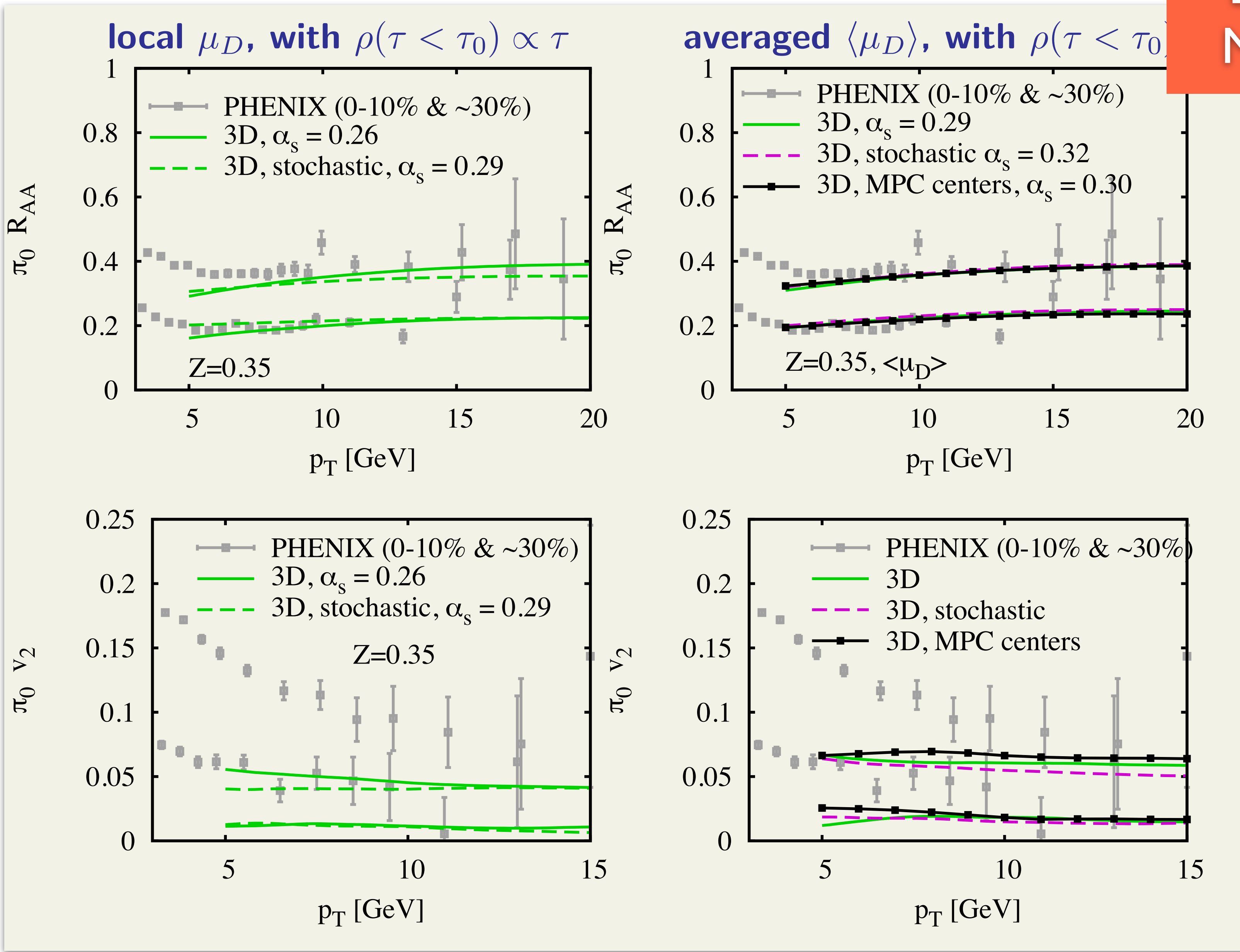
— Eventually MC generators should include realistic medium (hydro)

— At which stage are we in both experiment and theory?

CAS

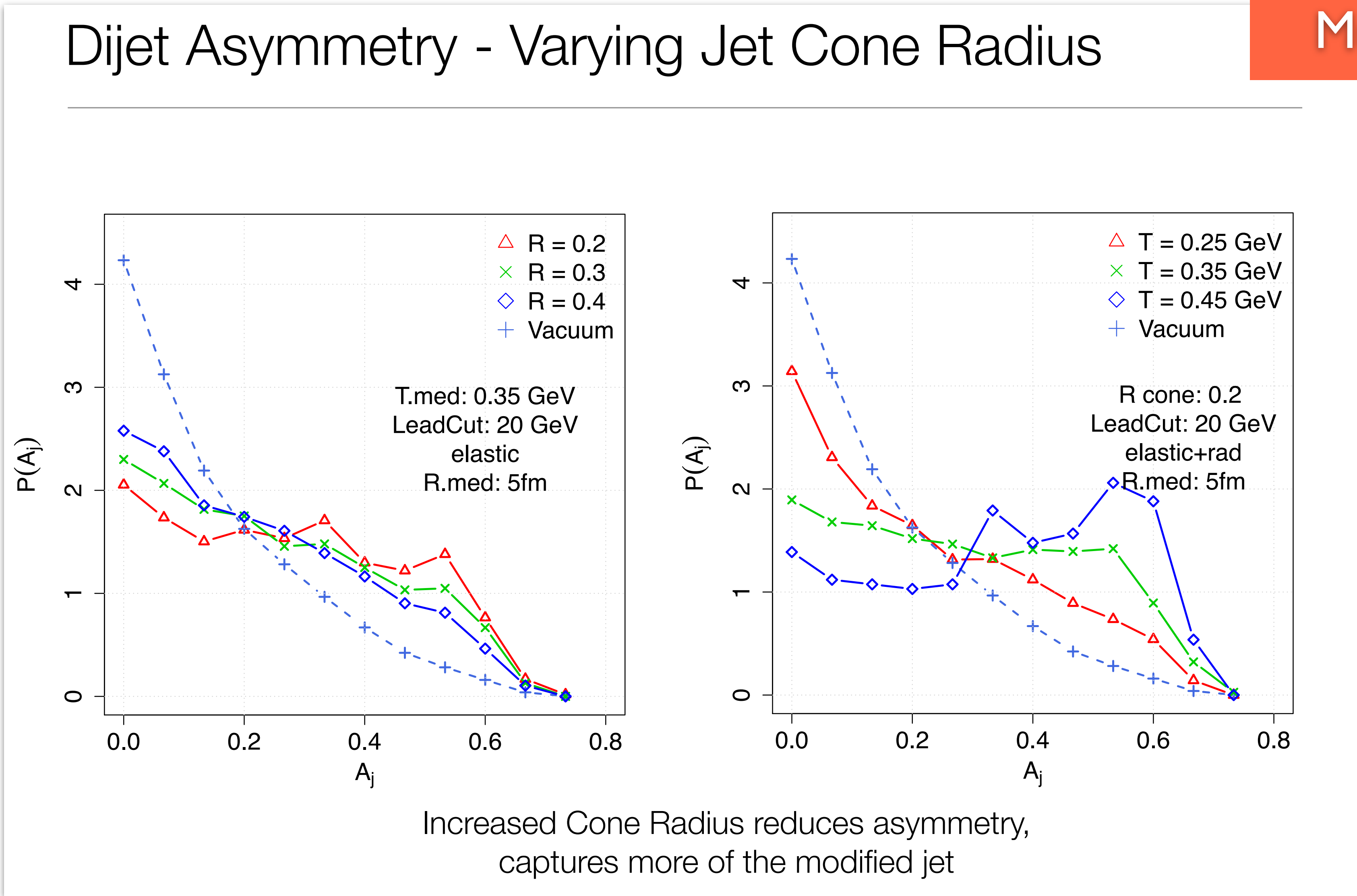
Transport models

Denes Molnar



Transport models

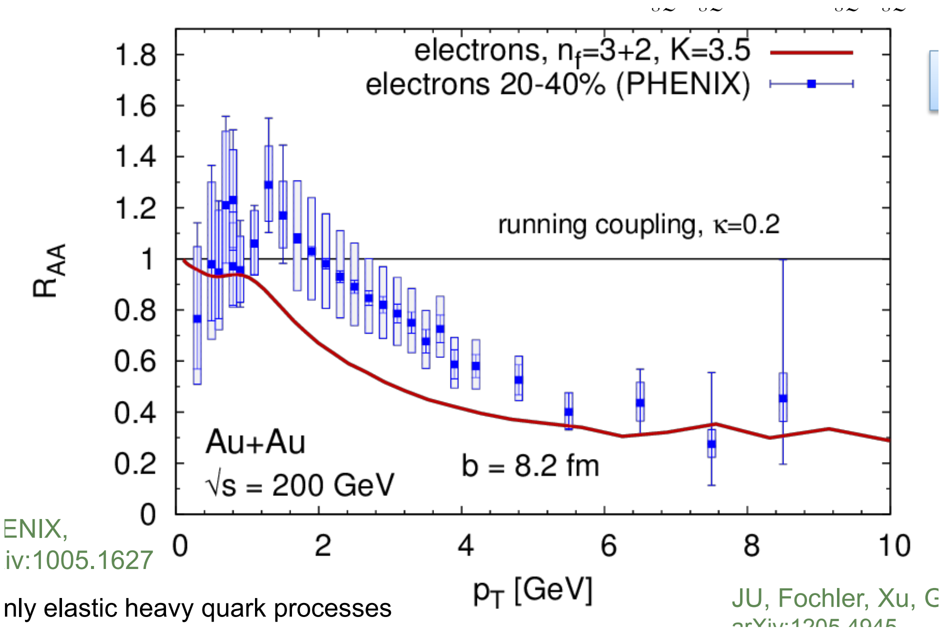
Berndt Muller

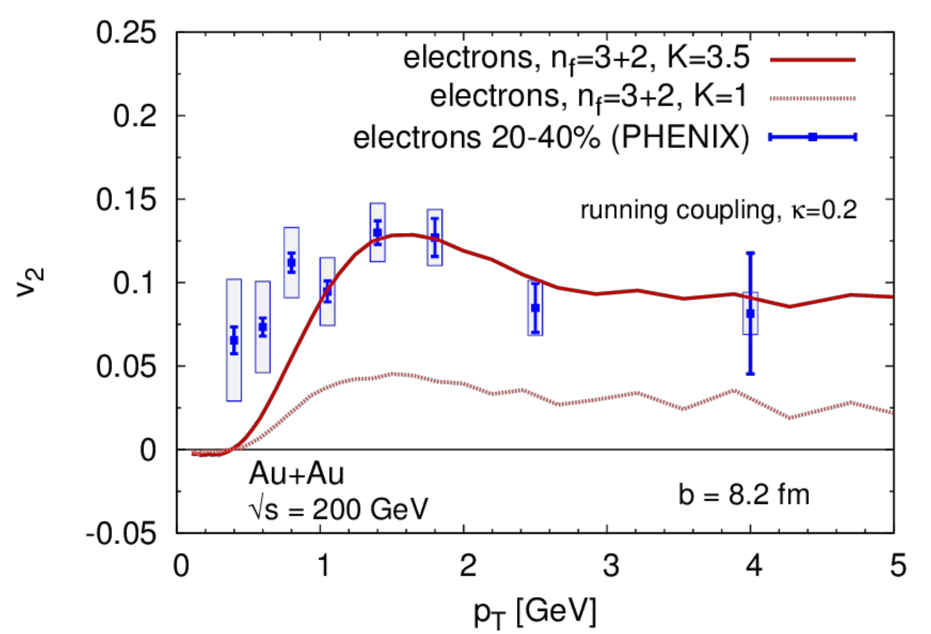


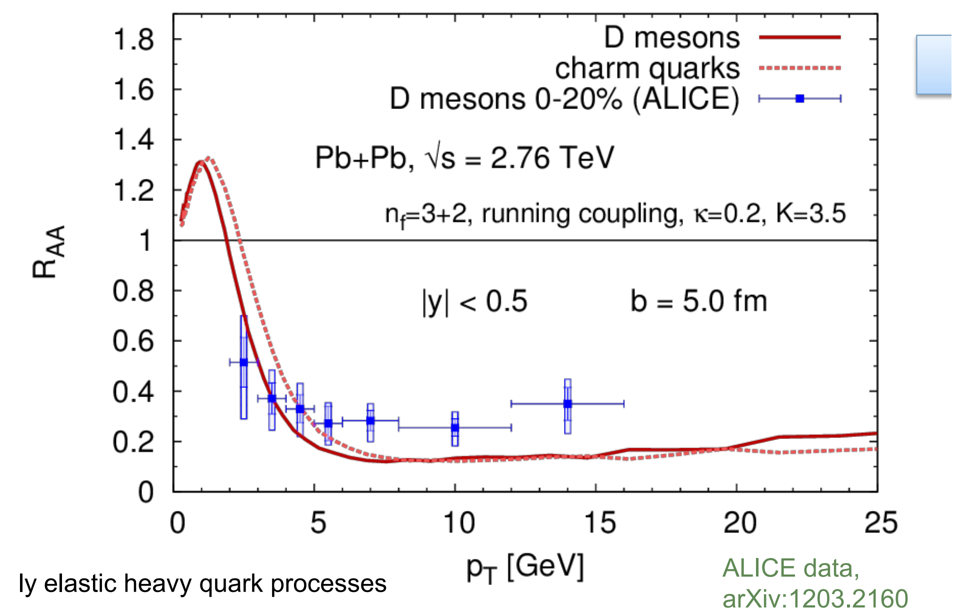
VNI/BMS models partonic transport via the Boltzmann equation.

Transport models: BAMPS

Jan Uphoff



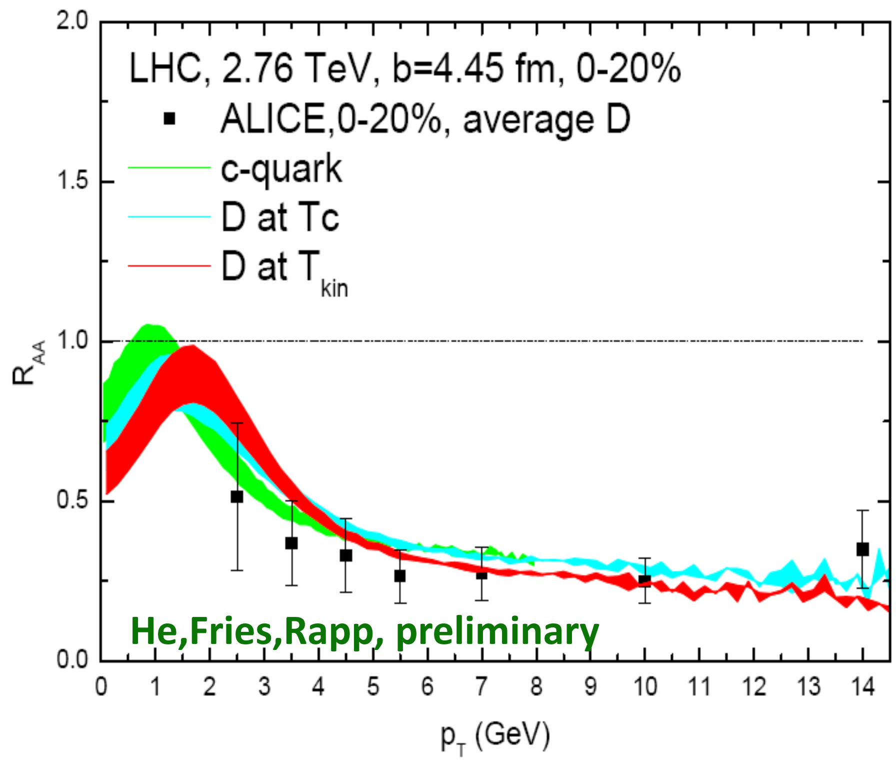


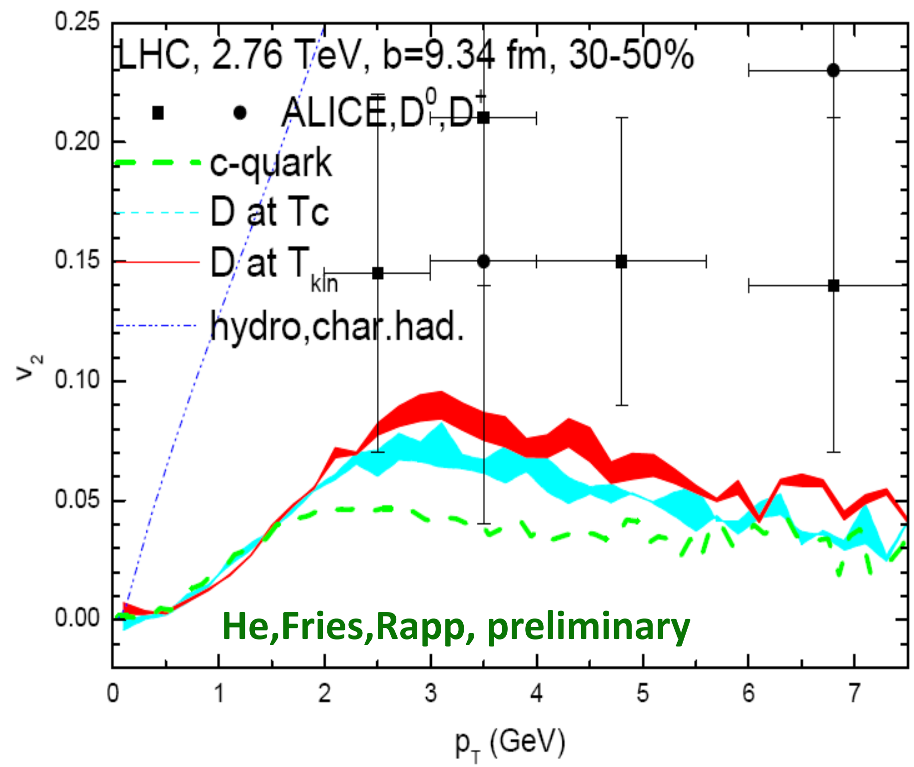


Transport models

Min He

3.3 Phenomenology: D-mesons LHC

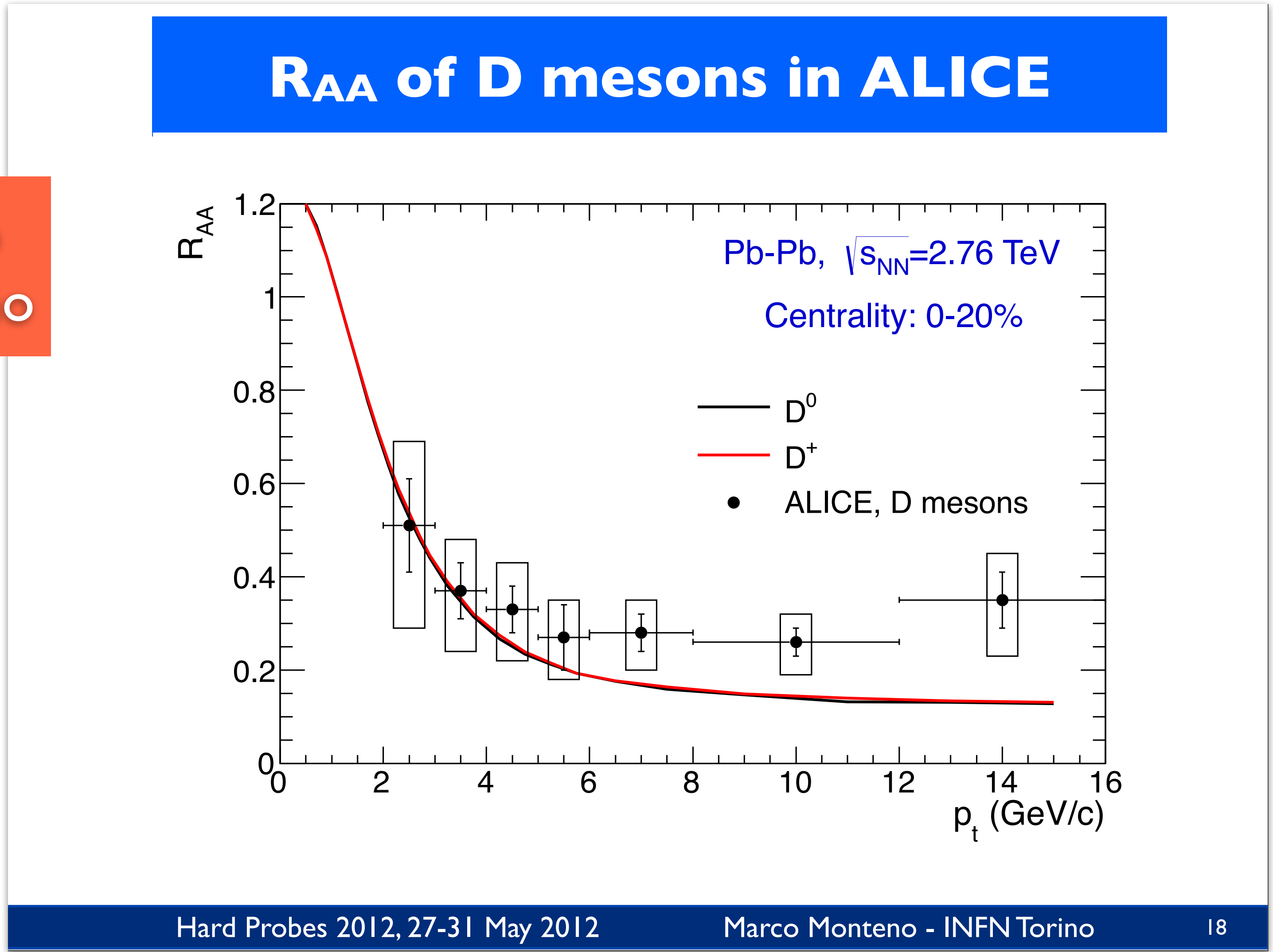




- **initial charm distribution: fit to D-meson spectrum in pp@LHC + delta frag.**
- **background medium: ideal hydro tuned to fit charged hadrons and Omega data**
- **R_{AA}: considerable shadowing, MNR-EPS09, 66%-78% + observable flow bump**
- **v_2 : QGP diffu. + coalescence + HRG diffu. (coal.prob. 52% - 90%)**

Langevin diffusion of HQ

Marco Monteno

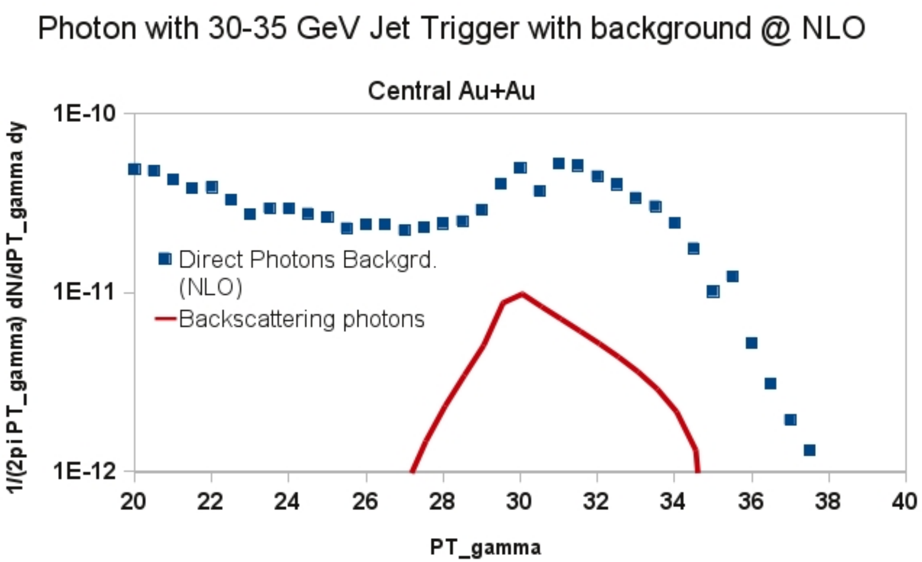


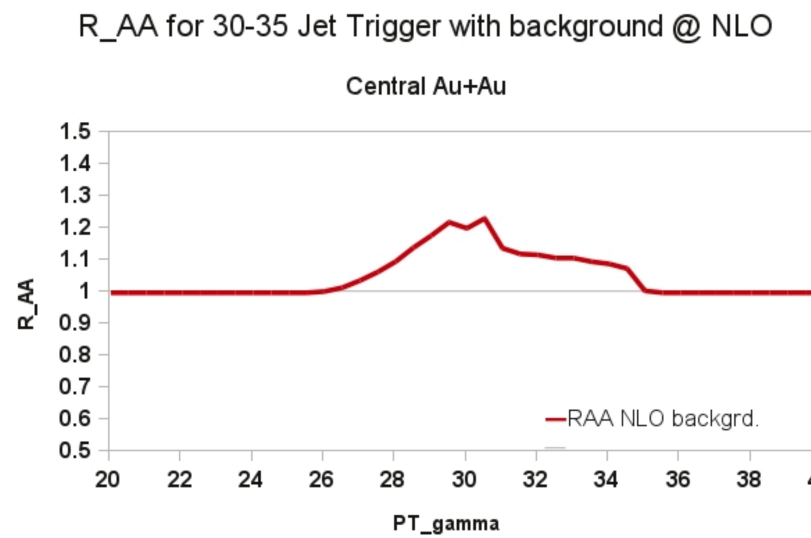
Elliptic flow underestimated

Jet-triggered photons

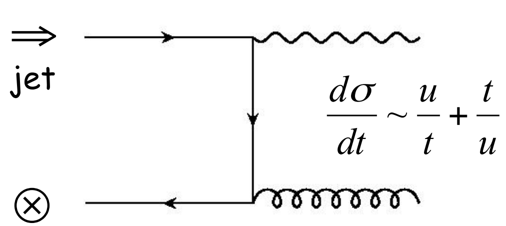
Rainer Fries

- Background calculated at NLO:





- Signal washed out but surviving.



$$\vec{p}_\gamma \approx \vec{p}_{jet}$$
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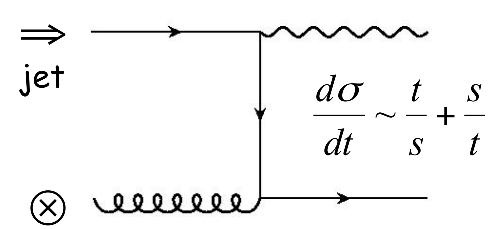
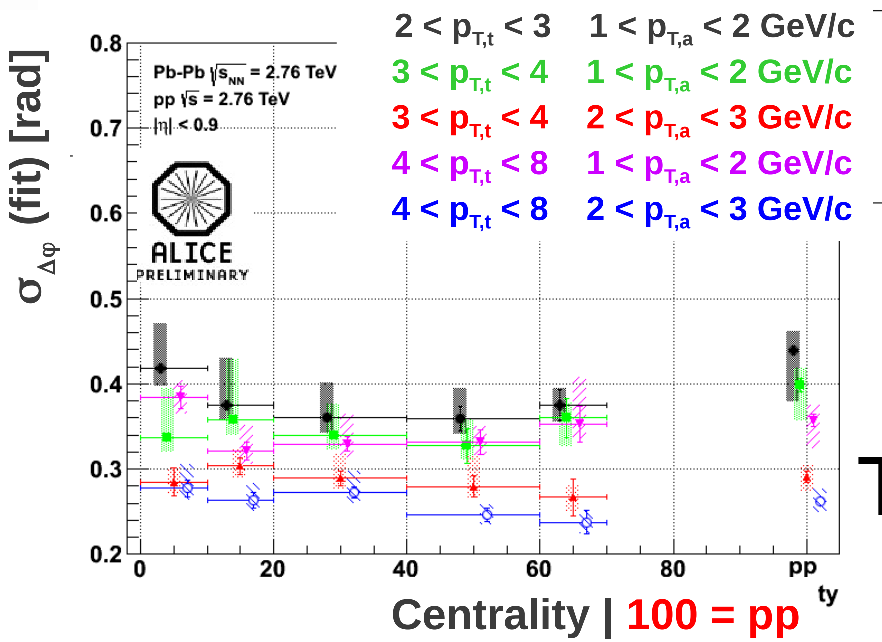
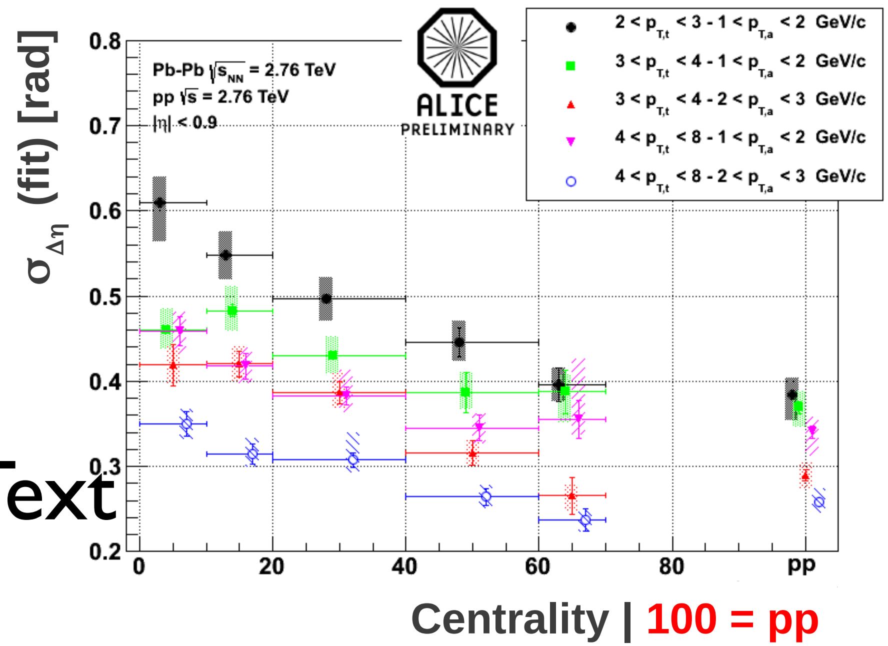


$\sigma_{\Delta\phi}, \sigma_{\Delta\eta}$ from Fit

Andreas Morsch



Text



- No centrality dependence of σ_ϕ
  - $p_{T,assoc}$ dependence governed by $j_T \sim p_{T,assoc}\, \sigma_\phi$ = const.
  - Same for σ_η in peripheral collisions
- Significant increase of σ_η towards central events
  - For the lowest p_T bin, eccentricity $(\sigma_\eta - \sigma_\phi) / (\sigma_\eta + \sigma_\phi)$ increases from 0 to 0.2
- Smooth continuation from peripheral to pp

$\sigma_{\Delta\phi}, \sigma_{\Delta\eta}$ from Fit

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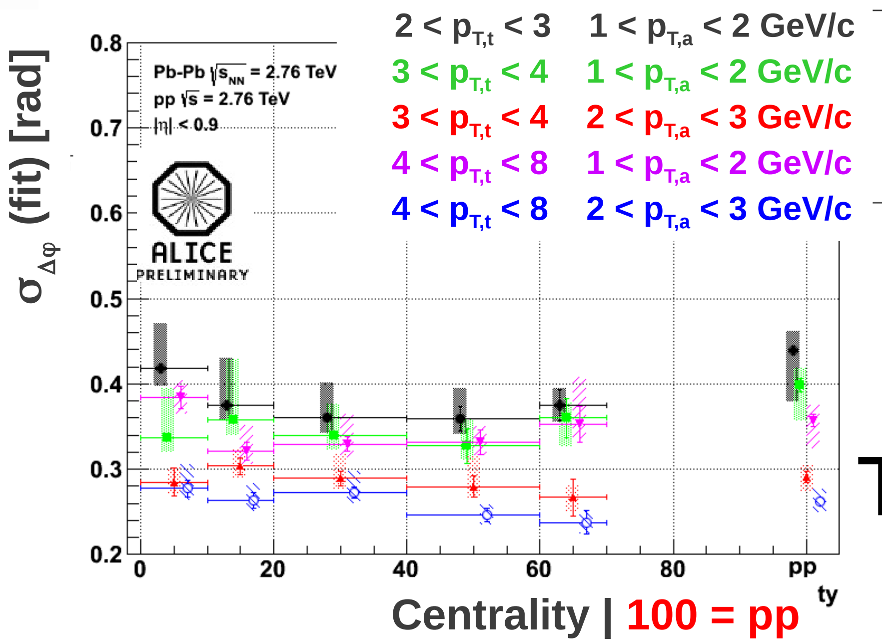

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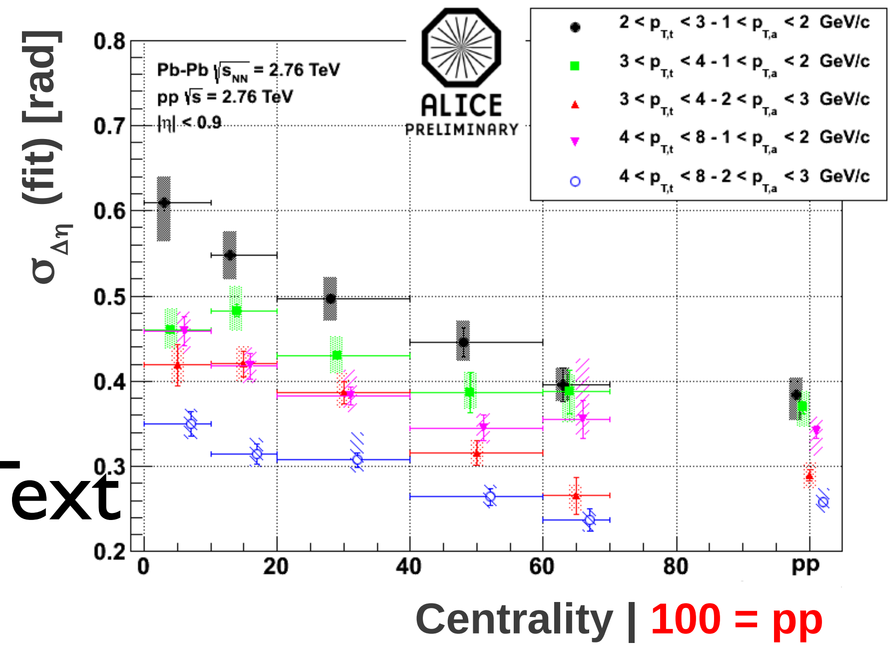

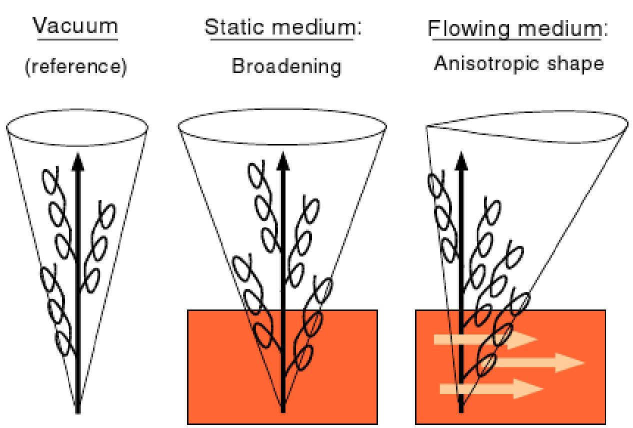

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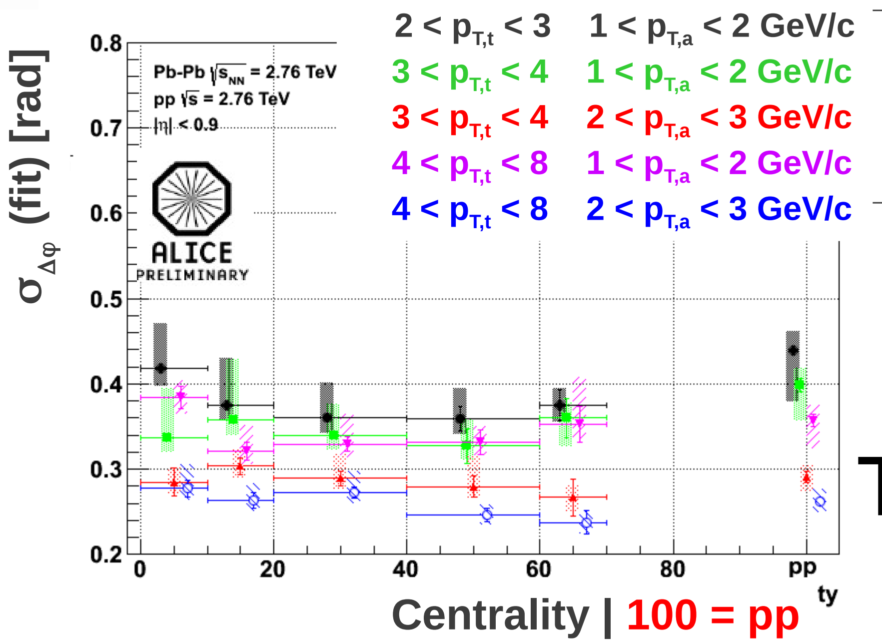

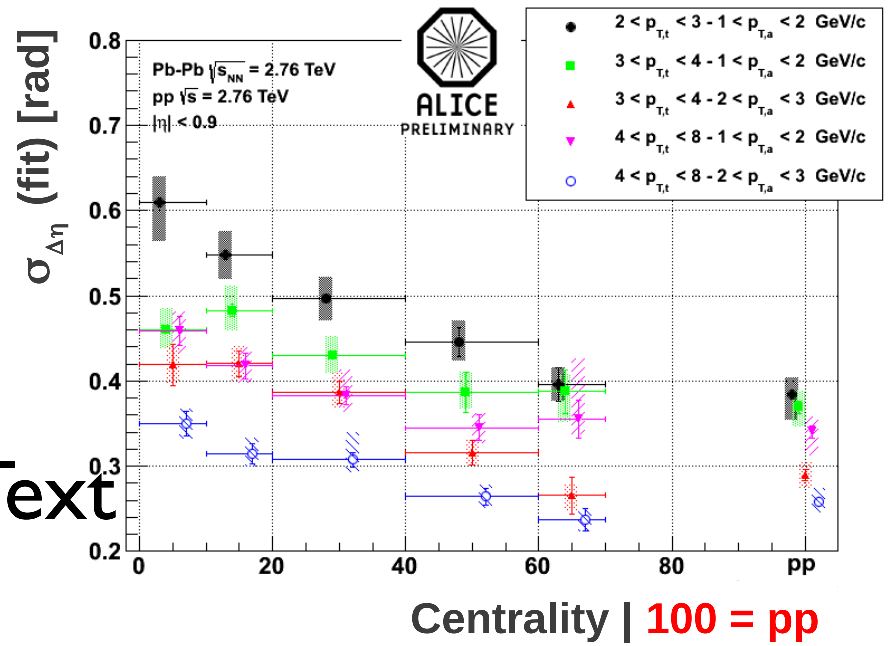

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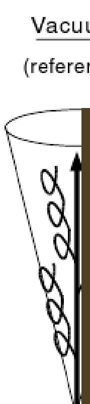


- No centrality dependence of σ_{ϕ}

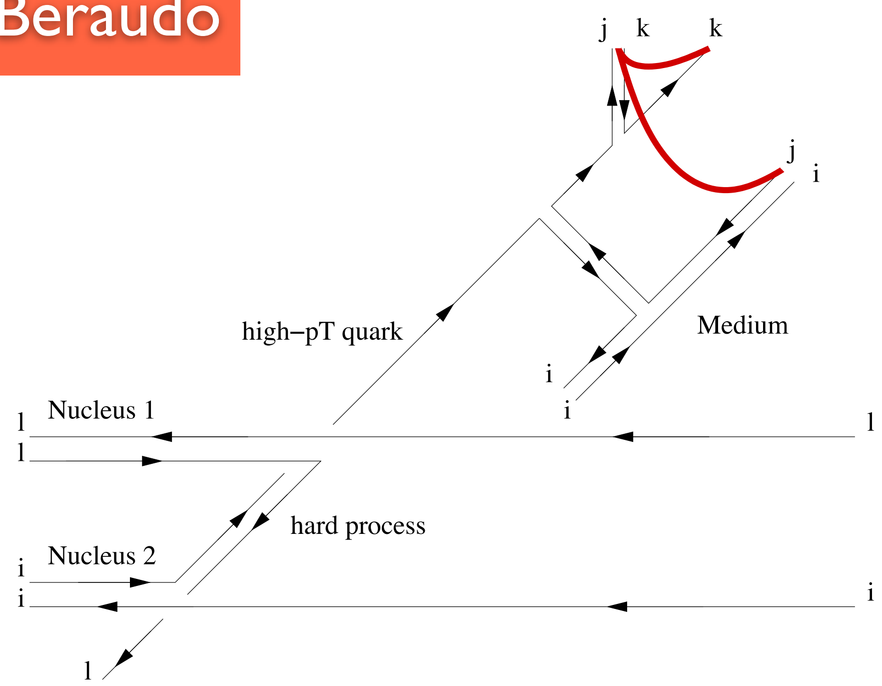
— Jet-medium interplay needs to be scrutinized theoretically
— When is the incoherent superposition of jet+medium breaking?
— Can this be seen in reconstructed jets? In fact: is this an issue for the reconstruction or theoretical implementations?

CAS

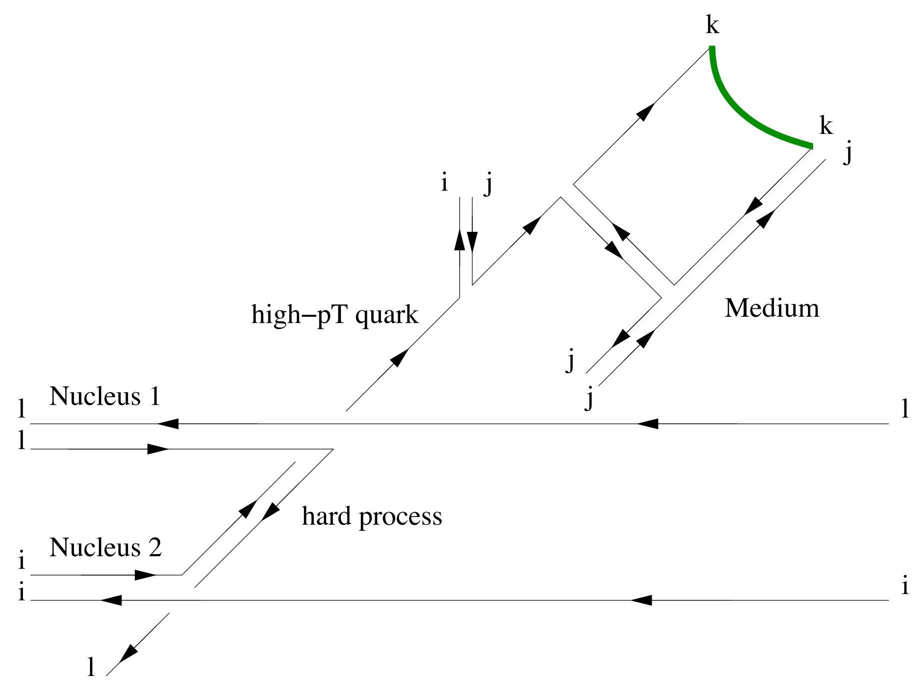
Theoretical improvements

Medium-induced radiation: color-flow (+ Lund string)

Andrea Beraudo



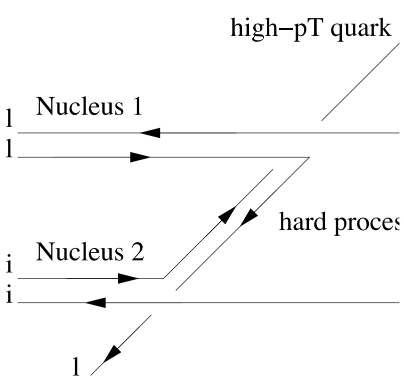
Radiated gluon is part of the string fragmenting into the leading hadron

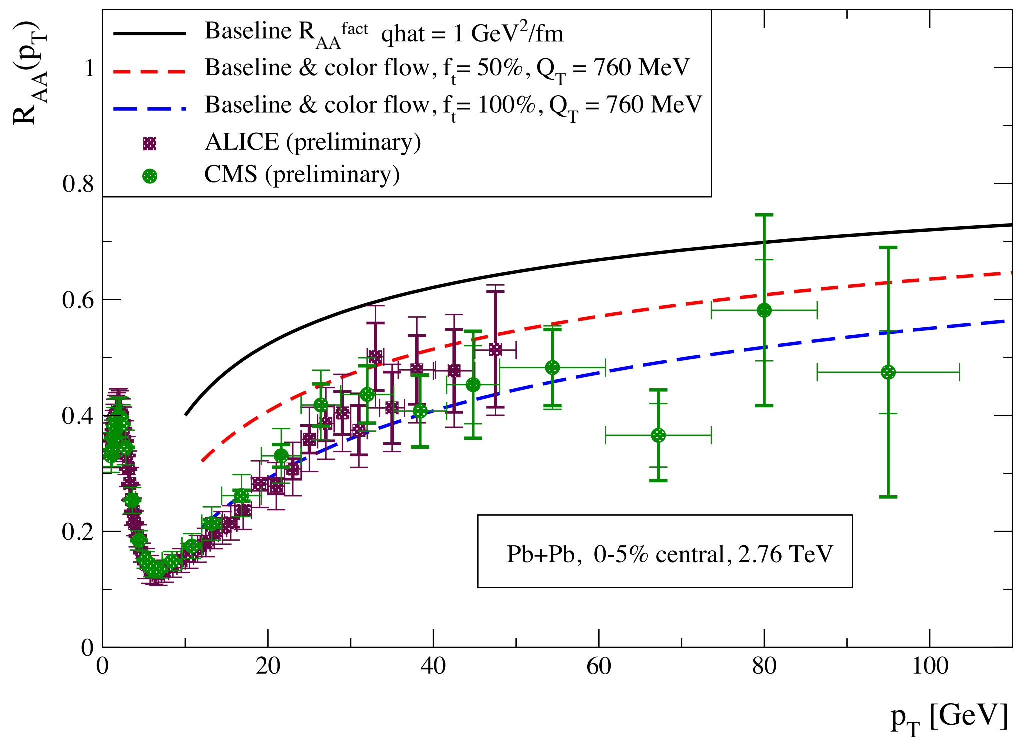


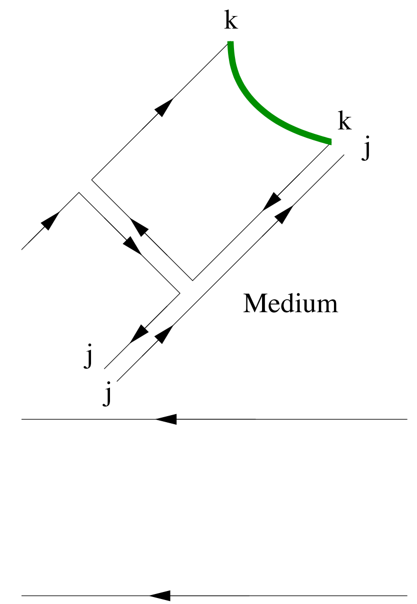
Gluon color decohered: its energy is lost and cannot contribute to the leading hadron

Medium-induced radiation: color-flow (+ Lund string)

Andrea Beraudo





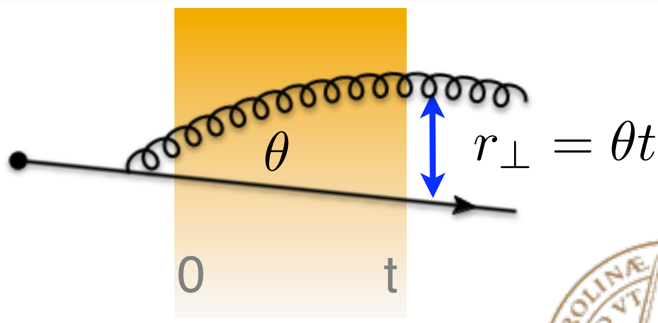


Radiated gluon is part of the string fragmenting into the leading hadron

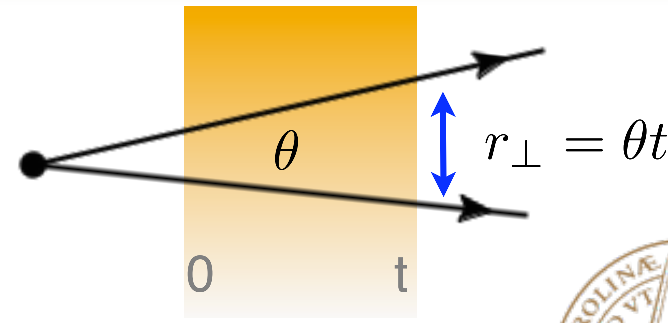
Gluon color decohered: its energy is lost and cannot contribute to the leading hadron

Role of color coherence $\tau_d \simeq (\hat{q}\theta_{q\bar{q}}^2)^{-1/3}$

What probes the medium?



What probes the medium?

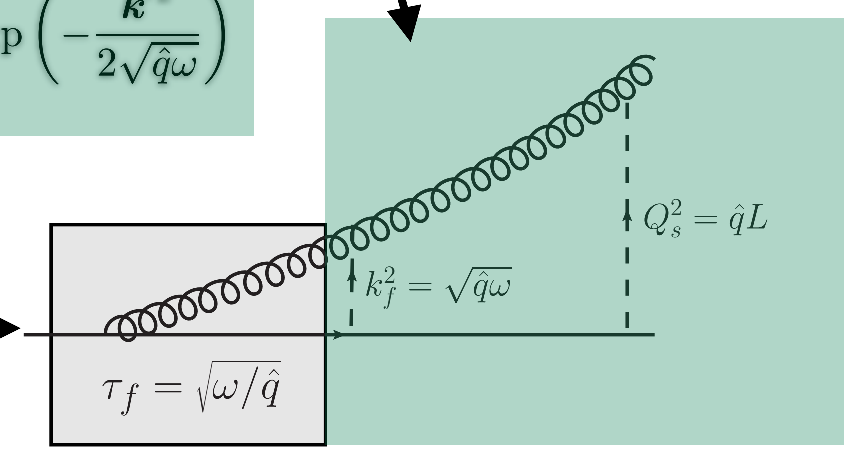


Konrad Tywoniuk

After decoherence time, the two out-coming partons radiate as independent

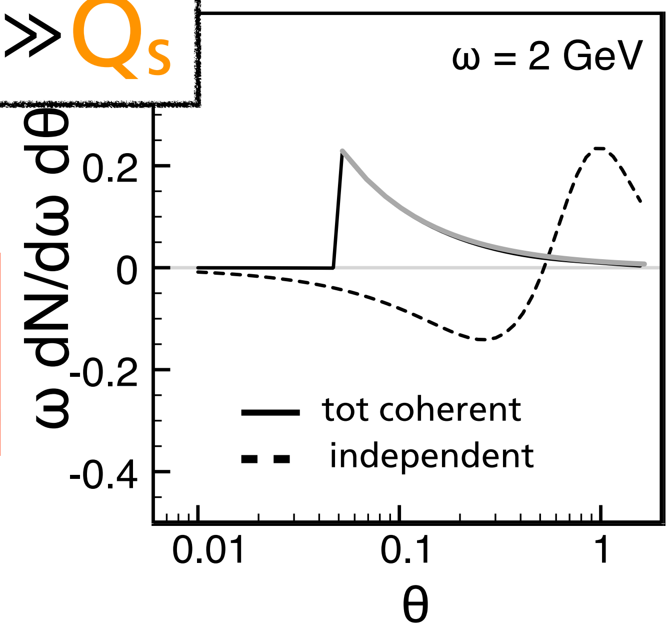
BDMPS and color decoherence

$$\mathcal{R}_q \simeq 4\omega \int_0^L dt \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t) \sin\left(\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right) \exp\left(-\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right)$$

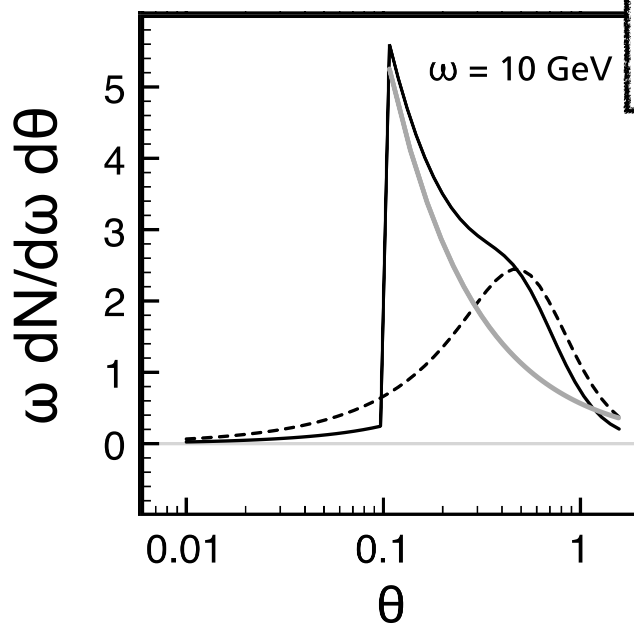


Antenna Angular spectrum

$r_\perp^{-1} \gg Q_s$



$r_\perp^{-1} \ll Q_s$



$\hat{q}$ = 10 GeV²/fm
L = 5 fm

Konrad Tywoniuk

"Dipole" regime

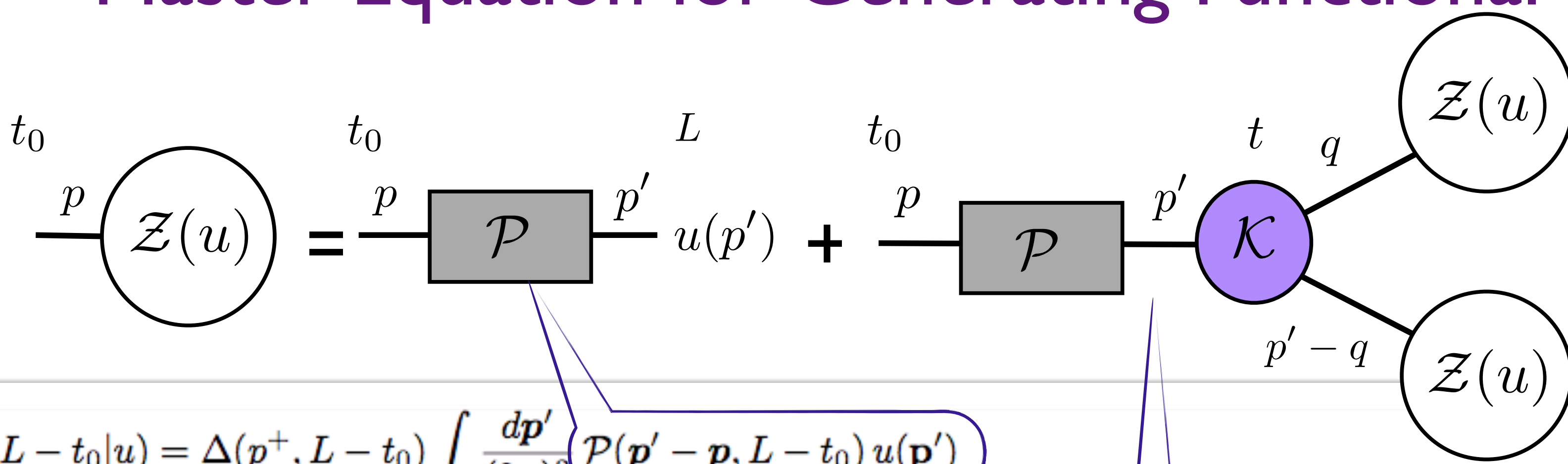
- antiangular spectrum
- independent component cancelled

"Decoherence" regime

- medium-induced rad. + antiangular spectrum
- soft sector universal

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**

Master Equation for Generating Functional $\frac{t_f}{L} \ll 1$



$$\mathcal{Z}(\mathbf{p}, L-t_0|u) = \Delta(p^+, L-t_0)\int \frac{d\mathbf{p}'}{(2\pi)^2}\mathcal{P}(\mathbf{p}'-\mathbf{p}, L-t_0)\,u(\mathbf{p}')$$
$$+\alpha_s\int_{t_0}^{L} dt\,\Delta(p^+, t-t_0)\int_0^1\frac{dz}{z}\int\frac{d\mathbf{p}'}{(2\pi)^2}\mathcal{P}(\mathbf{p}'-\mathbf{p}, L-t_0)\int\frac{d\mathbf{q}}{(2\pi)^2}\mathcal{K}(\mathbf{q}-z\mathbf{p}'|z)\,\mathcal{Z}(\mathbf{q}, L-t|u)\,\mathcal{Z}(\mathbf{p}'-\mathbf{q}, L-t|u)$$

- In-medium splitting function

$$\mathcal{K}_{BC}^{A}(\boldsymbol{q}-z\boldsymbol{p},\, z) = \frac{2}{p^+}P_{AB}(z)\ \sin\left[\frac{(\boldsymbol{q}-z\boldsymbol{p})^2}{2\boldsymbol{k}_{\rm br}^2}\right]\exp\left[-\frac{(\boldsymbol{q}-z\boldsymbol{p})^2}{2\boldsymbol{k}_{\rm br}^2}\right]$$

- Relative pT at branching time

$$\boldsymbol{k}_{\rm br}^2 = \sqrt{z(1-z)p^+\hat{q}_{\rm eff}}$$

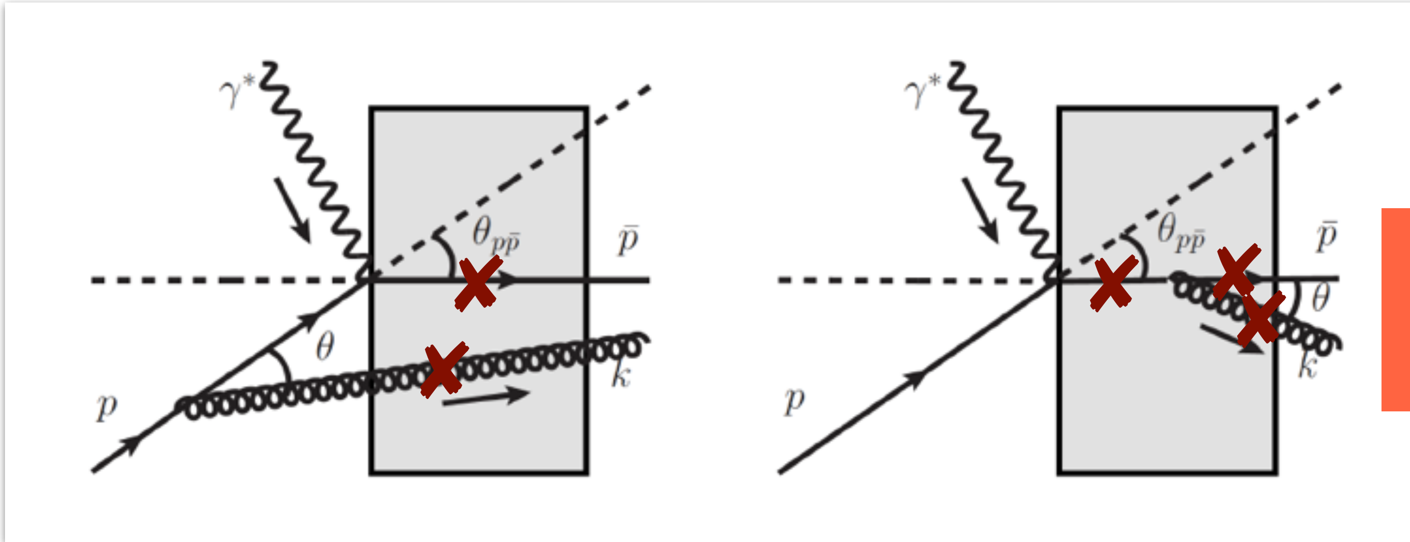
- Sudakov form factor:

Prob. not to emit
(Unitarity)

$$\Delta(p^+, L-t_0) = \exp\left[-\alpha_s(L-t_0)\int_0^1\frac{dz}{z}\mathcal{K}(z)\right]$$

Yacine Mehtar-Tani

Color coherence in t-channel



Mauricio Martínez

$$\mathcal{P}_{in} = (1 - \Delta_{med})(\mathcal{R}_{in} - \mathcal{J})$$ → Reduction of coherent gluon emission of the initial state

$$\mathcal{P}_{out} = \mathcal{R}_{out} - (1 - \Delta_{med})\mathcal{J}$$ → Partial decoherence of the final state

Valid as far as $\omega\theta_{qq}, k_\perp \ll m_D \Rightarrow$ Setting the scale !!

Relevant for DIS and proton-nucleus collision

Computations of qhat

Results

- Combining the results with the ones in covariant gauge we find

$$P(k_\perp) = \frac{1}{N_c}\int d^2x_\perp\, e^{ik_\perp\cdot x_\perp} \left\langle \mathrm{Tr}\left[T^\dagger(0,-\infty,x_\perp)\, W_F^\dagger[0,x_\perp]\, T(0,\infty,x_\perp) \, T^\dagger(0,\infty,0)\, W_F[0,0]\, T(0,-\infty,0)\right]\right\rangle$$

- The fields on the lower line are time ordered, the ones on the upper line anti-time ordered

  $\rightarrow$ Use Keldysh-Schwinger contour in path integral formalism

Michael Benzke

Computations of qhat

Results

- Combining the results with the ones in covariant gauge we find

$$
\begin{aligned}
P(k_\perp) \;=\; & \frac{1}{N_c}\int d^2x_\perp\, e^{ik_\perp\cdot x_\perp} \\
& \langle \mathrm{Tr}\big[\, T^\dagger(0,-\infty,x_\perp)\, W_F^\dagger[0,x_\perp]\, T(0,\infty,x_\perp) \\
& T^\dagger(0,\infty,0)\, W_F[0,0]\, T(0,-\infty,0)\big]\rangle
\end{aligned}
$$

Michael Benzke

at T=363, FF = 0.04 GeV^4

Lattice size ~ 2fm, E = 20 GeV, μ^2 = 1.3 GeV^2

Gluon $\hat{q}$ is C_A/C_F of quark $\hat{q}$

SU(2) has 3 gluons, SU(3) has 8,
and 6 quarks + antiquarks

$$\hat{q}(T = 363\mathrm{MeV}) = 3.7\mathrm{GeV}^2/\mathrm{fm} - 6.5\mathrm{GeV}^2/\mathrm{fm}$$

Abhijit Majumder

Computations of qhat

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Michael Benzke

at T=363, FF = 0.04 GeV^4

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r

Small summary

— Some impressive theoretical developments presented in HP'12 !

— A full in-medium parton shower could be around the corner (in some kinematic regimes), including color flow

— Role of color coherence essential - how to implement in (probabilistic) MC?

— Computations of qhat very promising and exciting

CAS

Summary

Hard probes is one of the pillars of HIC phenomenology

- *Impressive new data and theoretical developments in HP'12*

More progress ahead

- *Understanding the intriguing quarkonia data - a simple explanation?*
- *A complete picture of the parton shower in-medium evolution*
- *A consistent treatment of jet-medium interactions - role of flow?*
- *Improved Monte Carlo tools based on solid TH results*
- *Pin-down the nuclear PDFs / CGC -* ***pPb run***
- *Improve theoretical implementation of CGC - fix IC in nucleus-nucleus?*
- *Make full use of the newly available EW probes*