Heavy ion collisions at the LHC: New perspectives

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Strong interaction

- "Dilute" systems (linear dynamics) DIS, pp...

  $\longrightarrow$Great success of QCD phenomenology

  $\longrightarrow$ need (important) refinements

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  ⟶ need (important) refinements

- New frontier ⟶ Study QCD under extreme conditions

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  ⟶ High Densities
  ⟶ High Temperatures

Strong interaction

- "Dilute" systems (linear dynamics) DIS, pp...

⟶Great success of QCD phenomenology

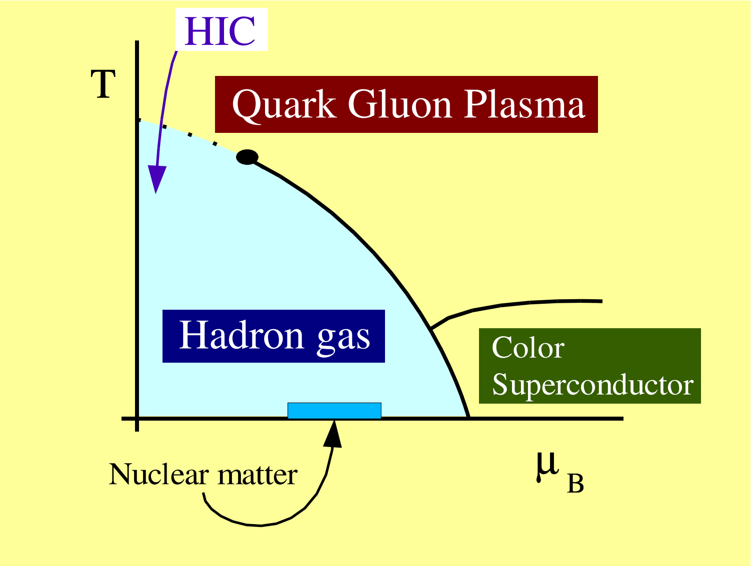
⟶ need (important) refinements

- New frontier ⟶ Study QCD under extreme conditions

⟶ High Densities	(mainly in)
⟶ High Temperatures	Nuclear collisions

High-energy heavy ion collisions

- Main goal: Produce and study a Quark Gluon Plasma (QGP)
  - Deconfined state of quarks and gluons
  - Predicted by QCD



- Large densities needed
  - How are these densities produced? (initial state)
  - How does it thermalize?
  - How to study this medium? (final state)

Experiments

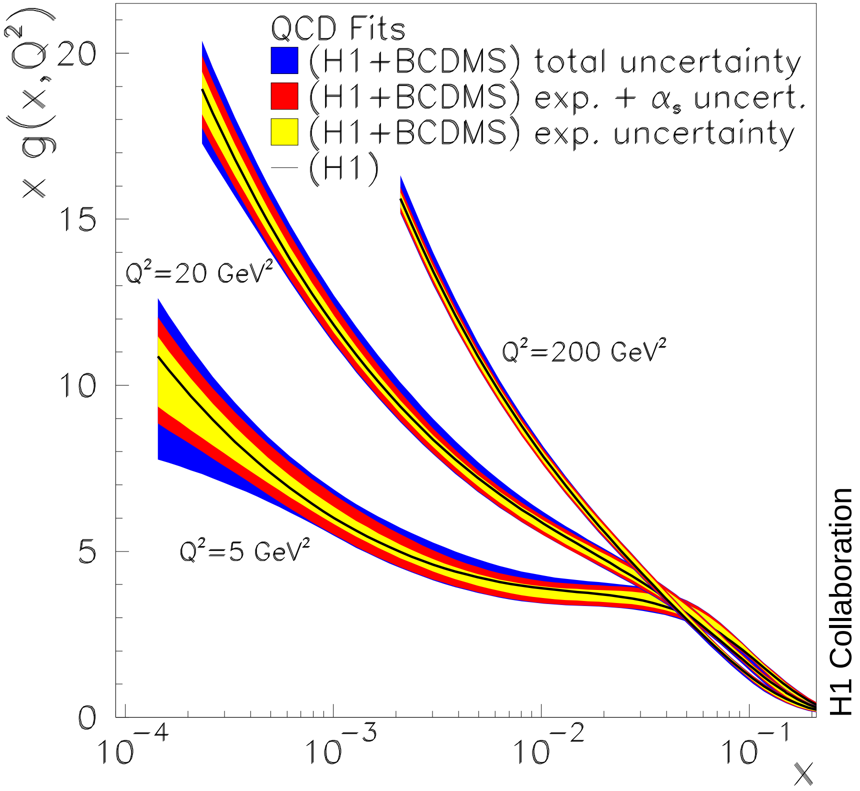
- SPS at CERN.
  - Have collided pA at $p_{\mathrm{lab}} = 450$ GeV/c, SU at $p_{\mathrm{lab}} = 200$ AGeV/c and PbPb at $p_{\mathrm{lab}} = 158$ AGeV/c.
  - The program is almost finished now
- RHIC at BNL
  - pp, dAu, AuAu and CuCu at $\sqrt{s} = 20 \ldots 200$ AGeV
  - RHIC II will improve detectors for rare processes and enhance statistics
- LHC at CERN
  - Will collide PbPb at $\sqrt{s} = 5500$ AGeV also pPb or dPb (under discussion) at $\sqrt{s} = 8200$

(Linear) evolution equations in QCD.

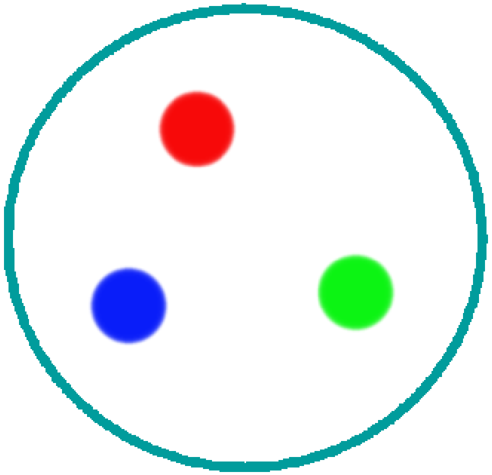
$\longrightarrow$ proton structure (DIS)

$\longrightarrow$ jets

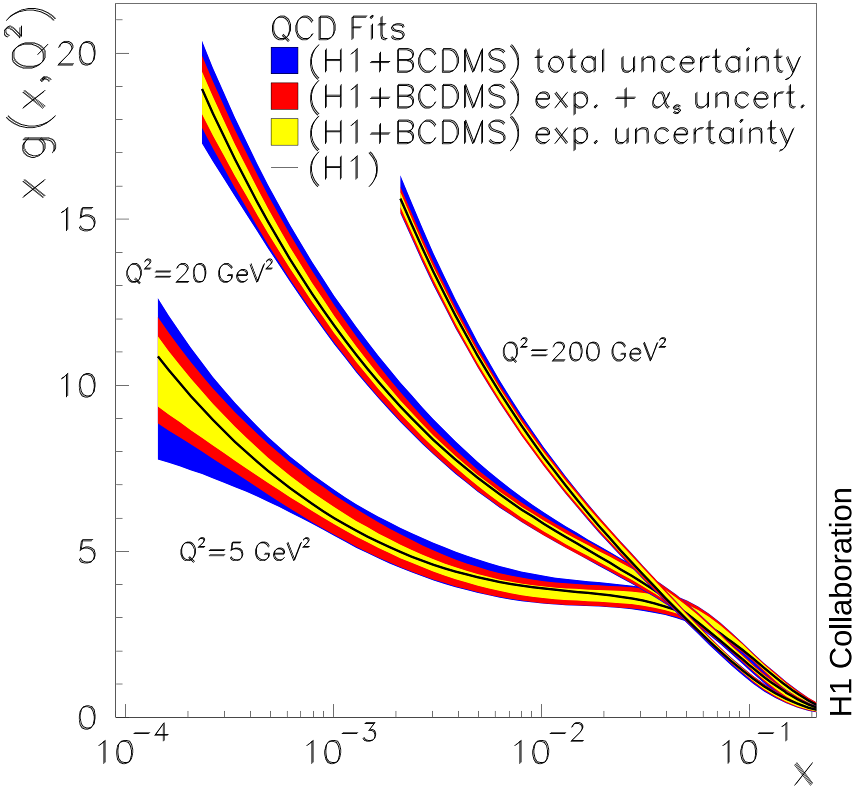
Proton gluon distributions



Gluon distributions inside the proton (H1 collaboration).



Proton gluon distributions



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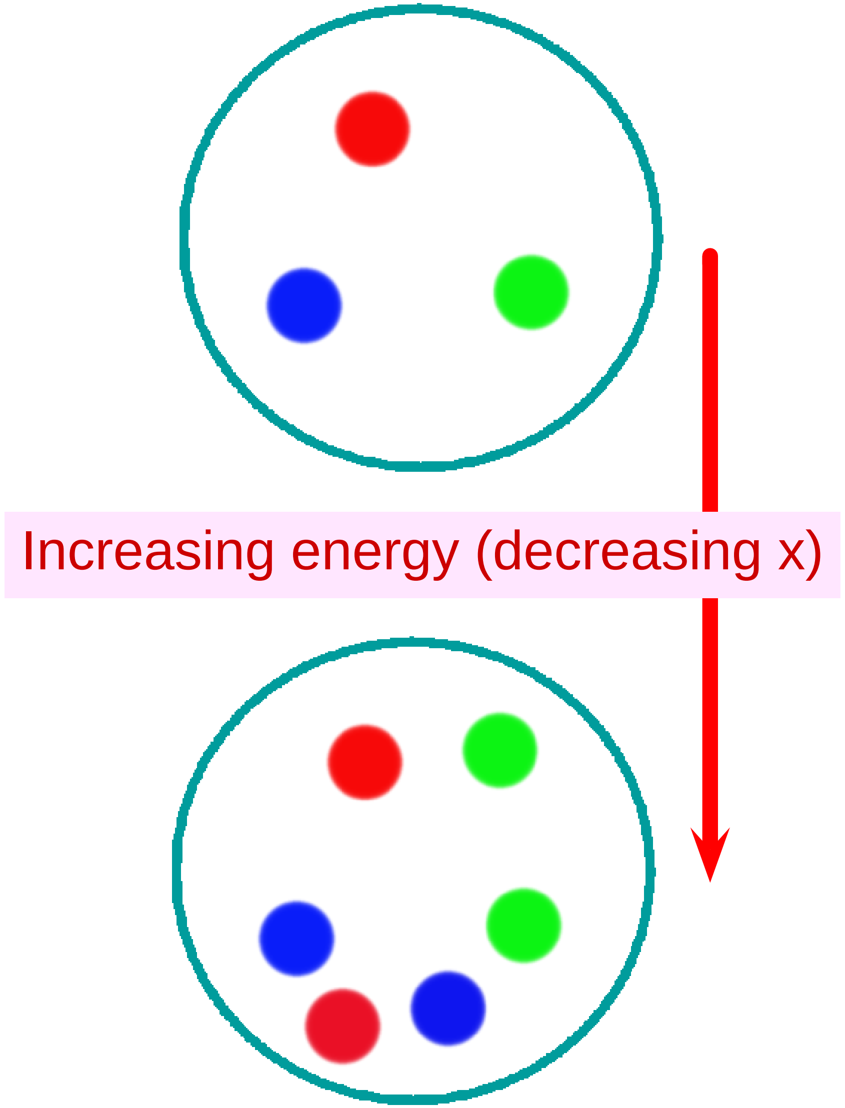
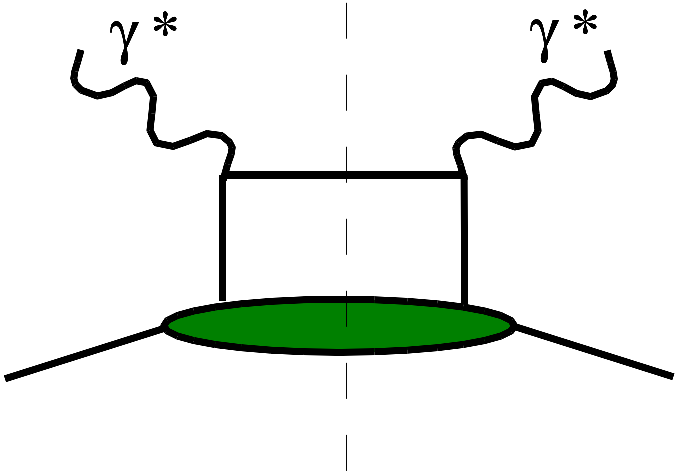


Increasing energy (decreasing x)

Deep inelastic scattering (DIS)

- DIS measures the quark content of the proton



Deep inelastic scattering (DIS)

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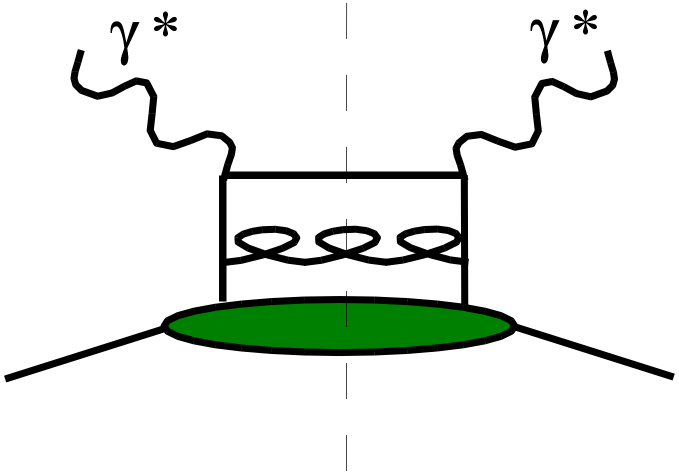
- Quantum corrections ex.

$\rightarrow 1/k_t^2$ singularities



Deep inelastic scattering (DIS)

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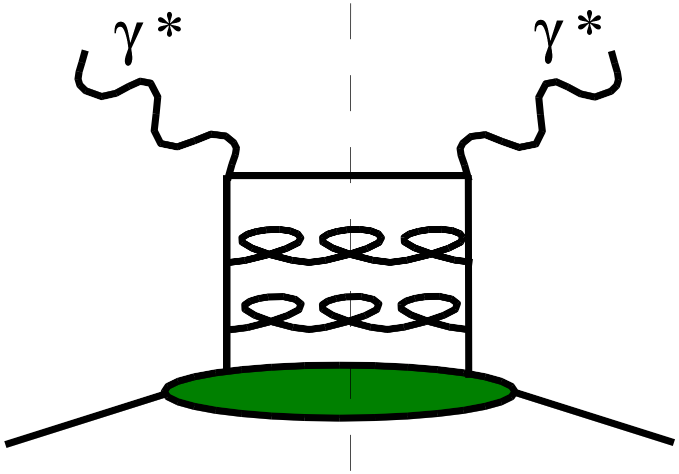
- Resum singularities $\rightarrow$ DGLAP equations



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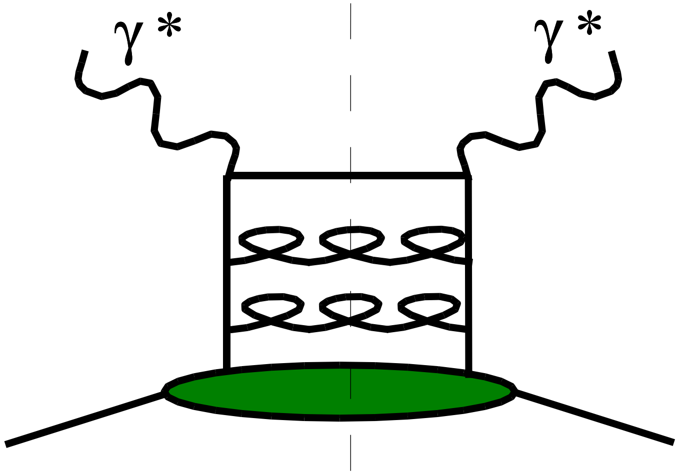


- ⇒ DIS measures the quark content of the proton
- ⇒ Quantum corrections ex.  $\rightarrow 1/k_t^2$ singularities
- ⇒ Resum singularities → DGLAP equations

[Dokshitzer, Gribov, Lipatov, Altarelli, Parisi]

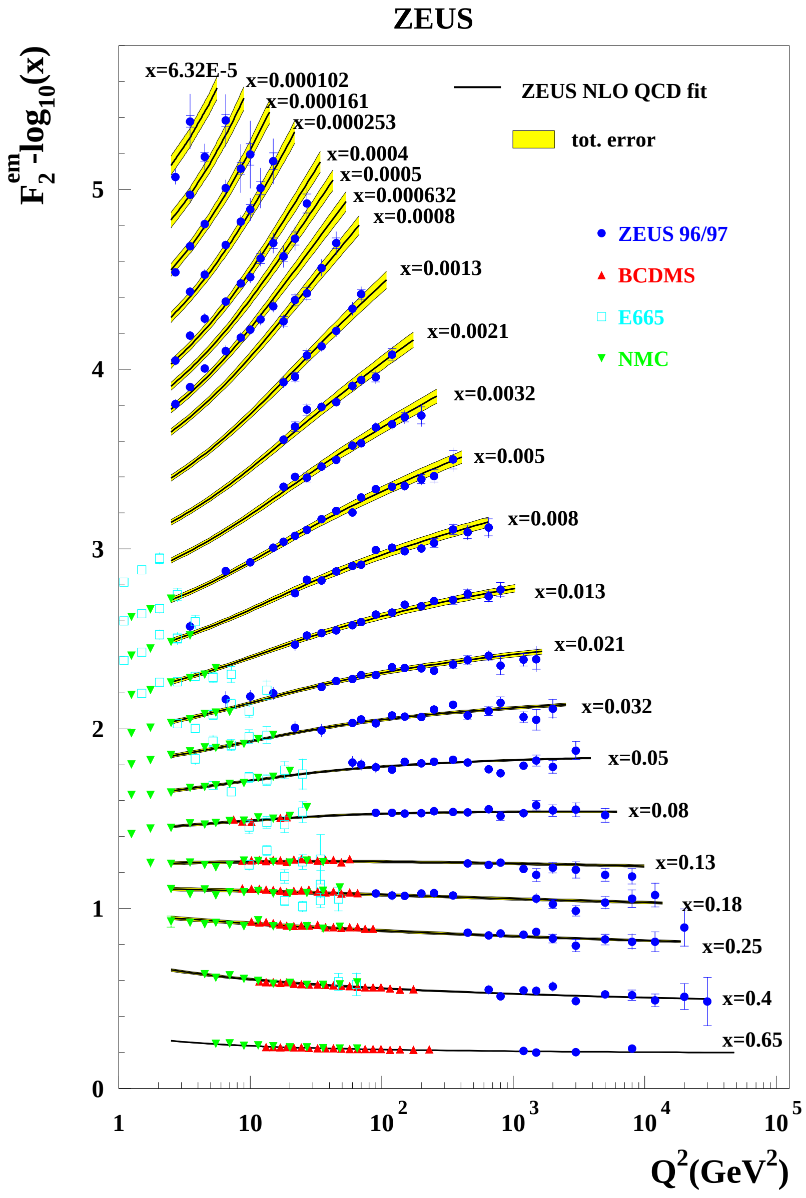
$$\frac{\partial q(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \left(P_{qq} \otimes q + P_{qg} \otimes g\right)$$

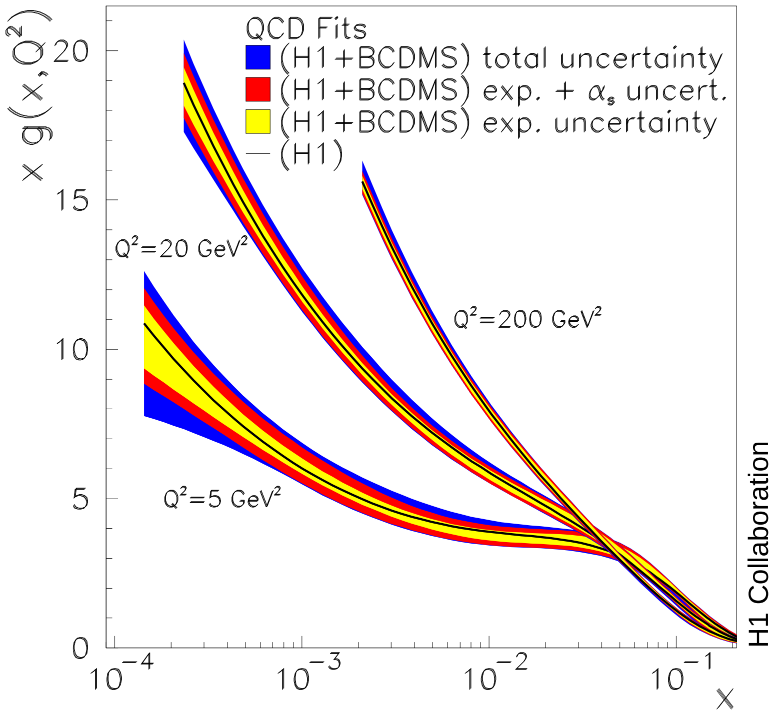
$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \left(P_{gq} \otimes q + P_{gg} \otimes g\right)$$

The structure function F_2 at LO is

$$F_2(x,Q^2) = \frac{4}{9}\left[u(x,Q^2) + \bar{u}(x,Q^2)\right] + \frac{1}{9}\left[d(x,Q^2) + \bar{d}(x,Q^2)\right] + \frac{1}{9} s(x,Q^2) + \ldots$$

Structure functions





Gluons extracted from fit to data using DGLAP equations.

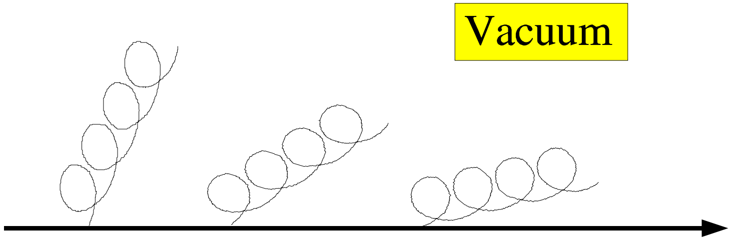
⇒ Strong increase of gluon density at small-x

$x \equiv$ fraction of momentum.

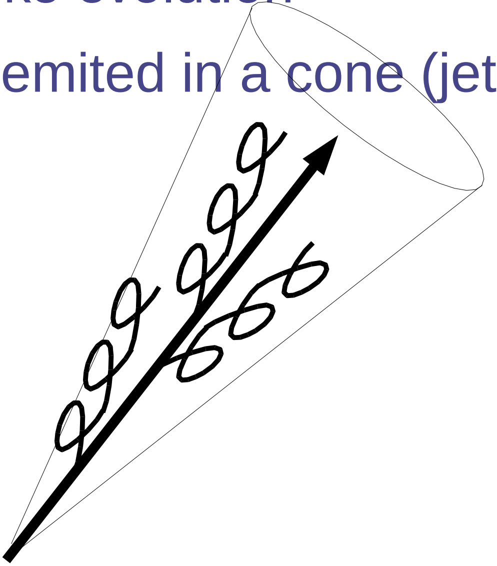
Jets: fragmentation in the vacuum

A Delphi 2-jet event from CERN

- ⇛ A high-p_t quark/gluon produced in a e^+e^-, pp... collision radiates gluons to become on-shell.

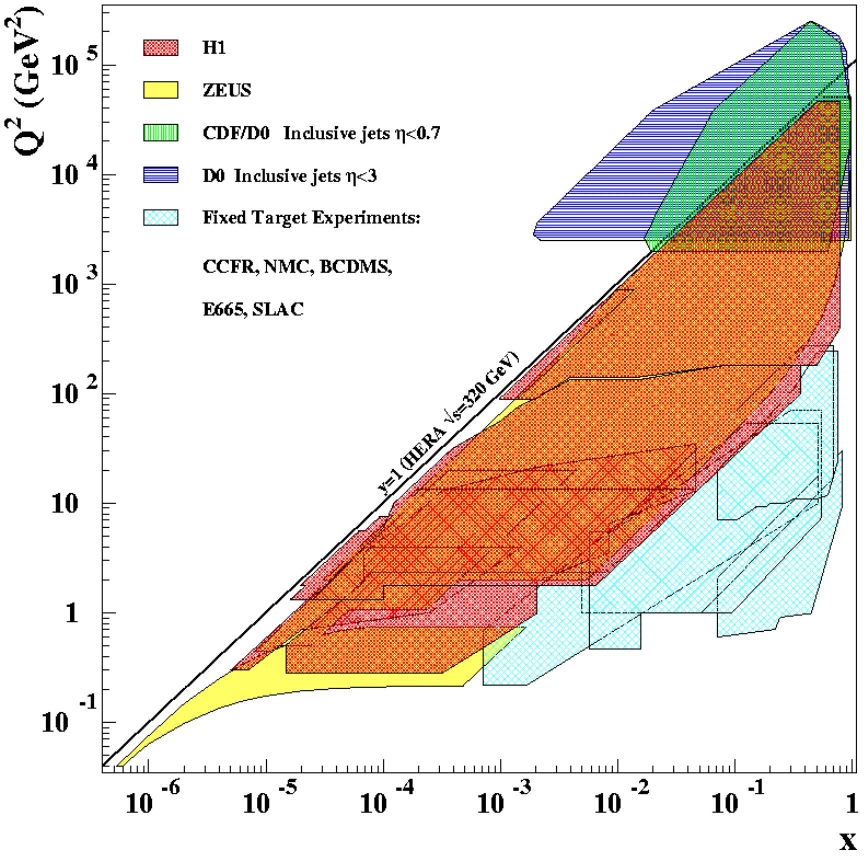


- ⇛ DGLAP-like evolution
- ⇛ Particles emited in a cone (jet)

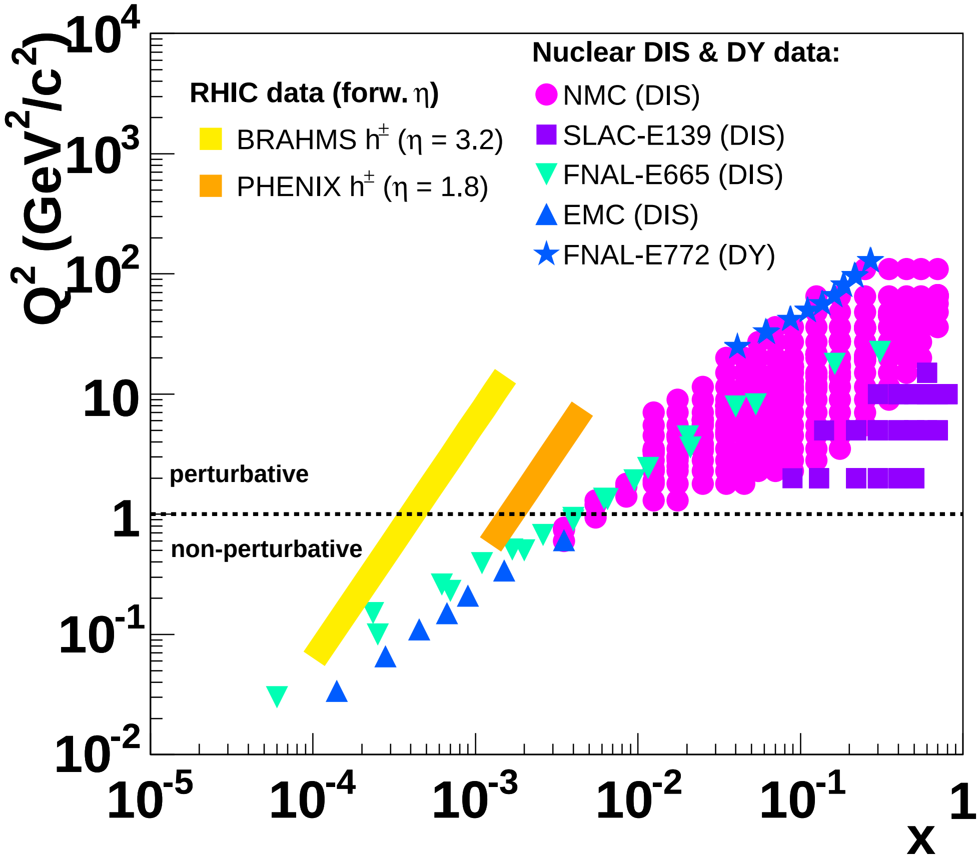


Kinematical regions studied

proton

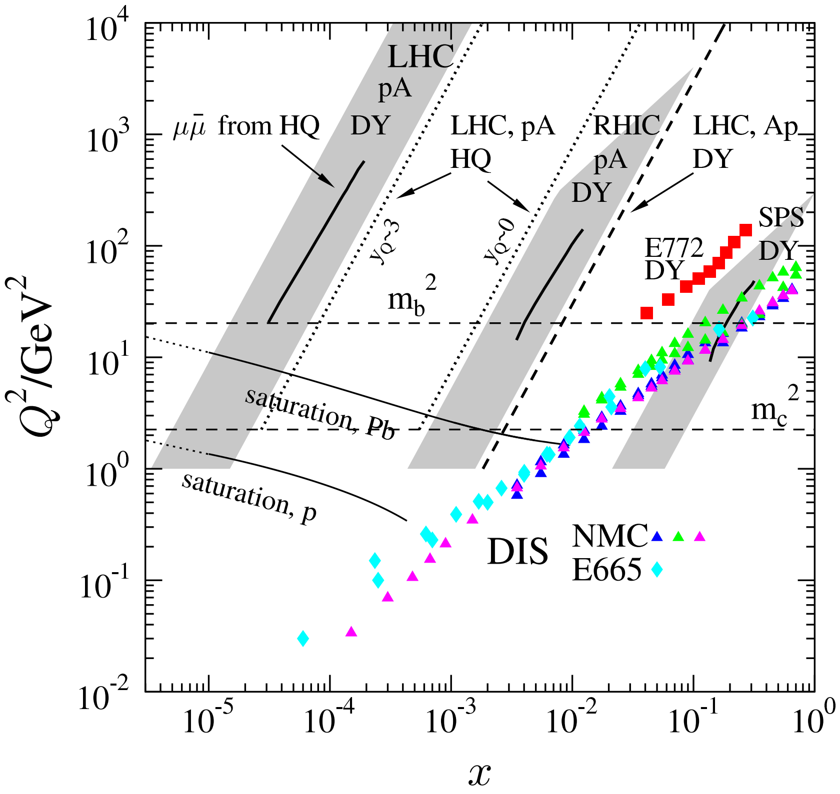


nuclei



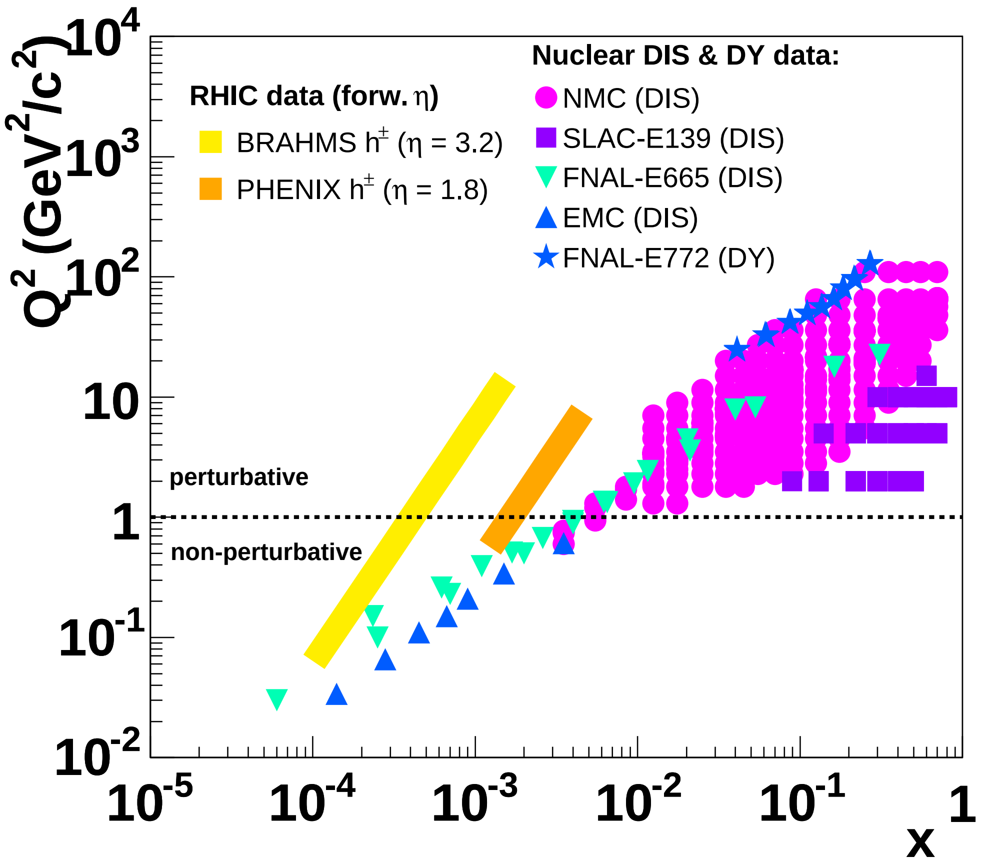
D’Enterria nucl-ex/0406012

Kinematical regions studied



Eskola *et al.* hep-ph/0302170

nuclei



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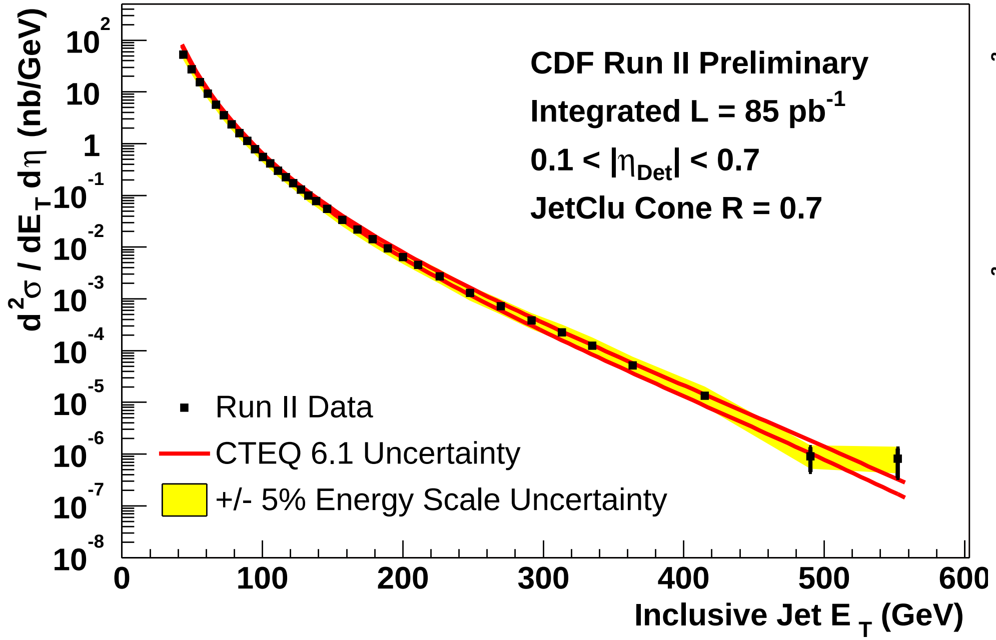
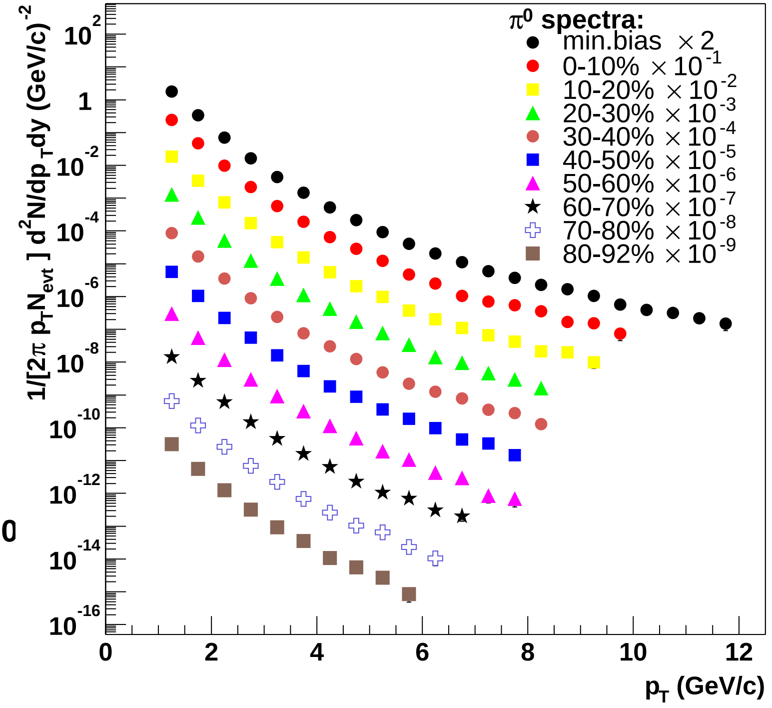
High-p_t tails

proton



Latino hep-ex/0401020

nuclei



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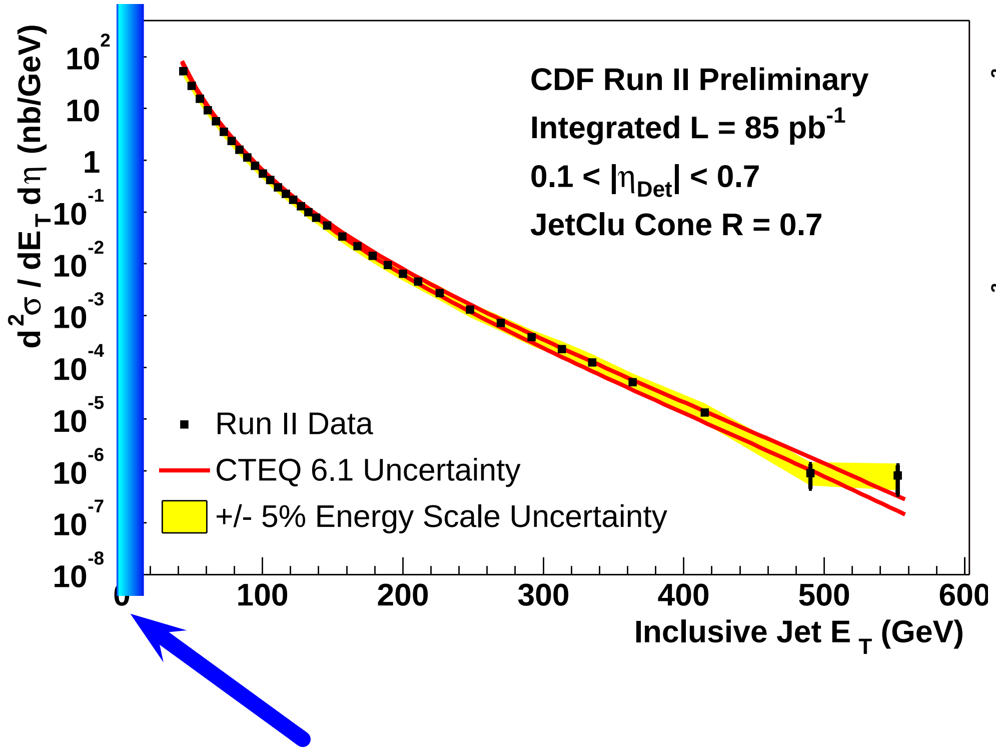
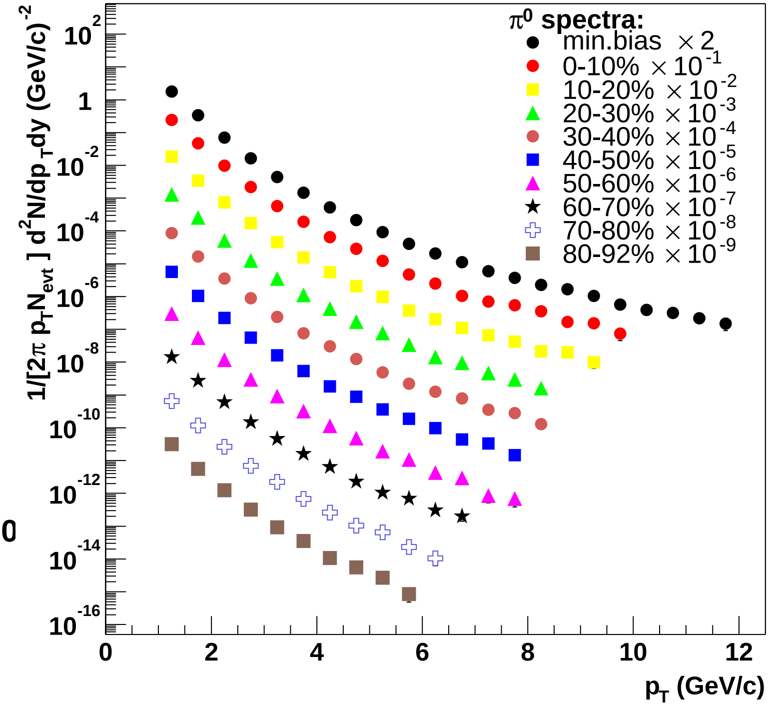
High-p_t tails

proton



nuclei studied here

nuclei



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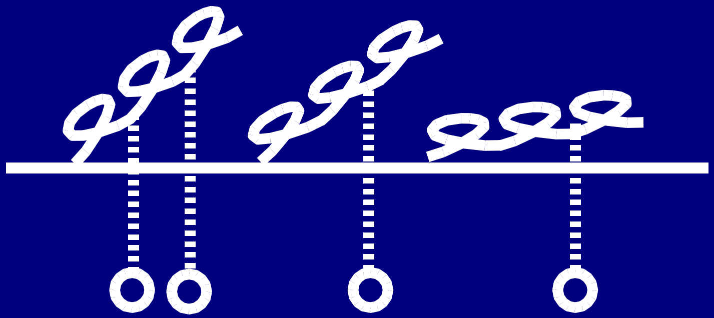
QCD at high densities

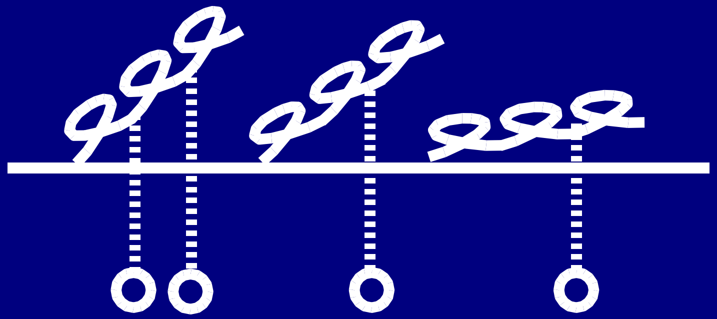


⟶ New (non-linear) ev. equations

parton distributions: saturation

⟶ Jet shapes modified

QCD at high densities

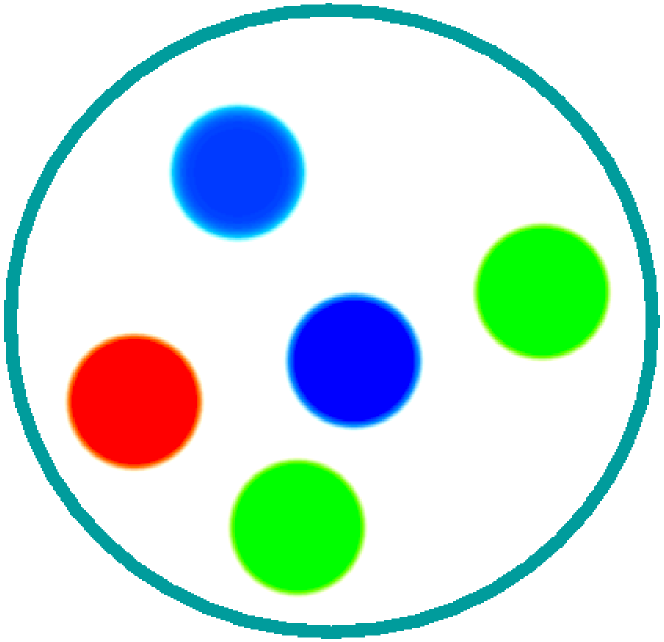


$\longrightarrow$ New (non-linear) ev. equations parton distributions: saturation

$\longrightarrow$ Jet shapes modified

Saturation of partonic densities: picture

(transverse plane of the collision)

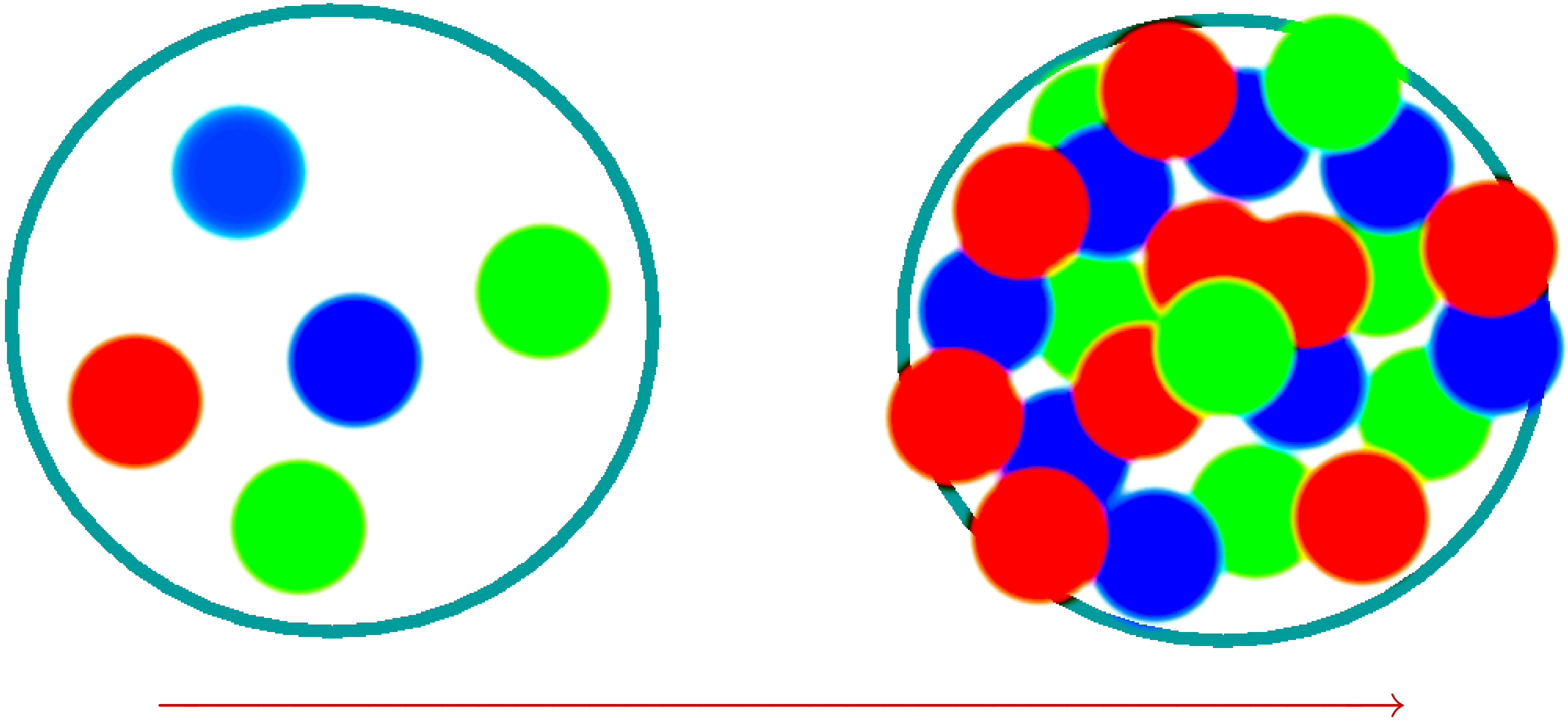


Saturation of partonic densities: picture

(transverse plane of the collision)

Saturation scale $Q_{\rm sat}$ when interaction probab. $\mathcal{O}(1)$

$$\alpha_S(Q^2_{\rm sat})xg(x,Q^2_{\rm sat})/Q^2_{\rm sat} \sim 1$$



increasing energy (decreasing x)

Saturated gluon distributions

Numerical solutions of the Balitsky-Kovchegov equation

⇛ Non-linear terms tame the growth
$\longrightarrow$ saturation scale.

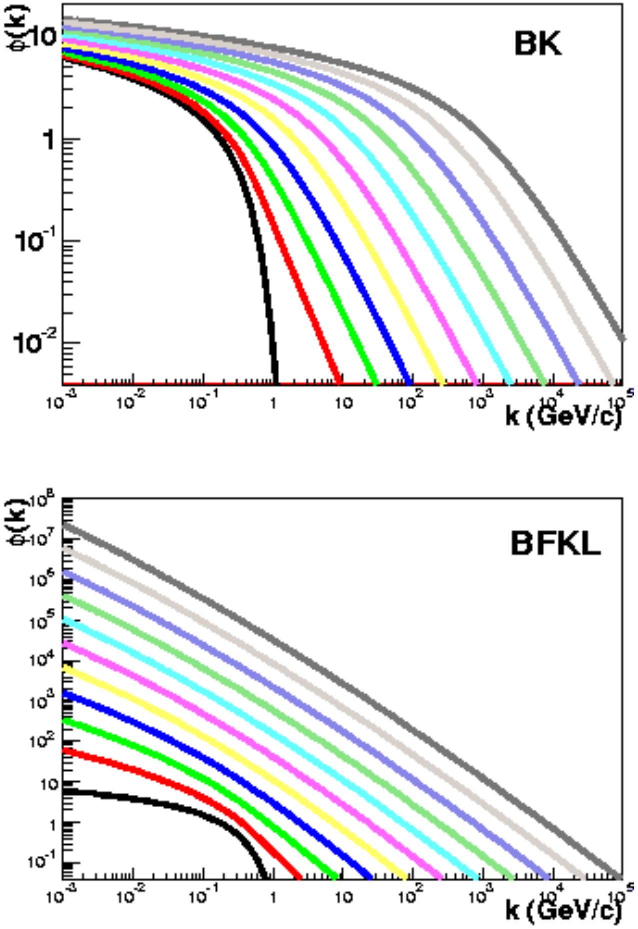
$$\phi(k,y) \sim \begin{cases} \log \frac{Q^2_{\rm sat}}{k^2} & \text{for } k \ll Q_{\rm sat}(y) \\ \left(\frac{Q^2_{\rm sat}}{k^2}\right)^{\gamma} & \text{for } k \gg Q_{\rm sat}(y) \end{cases}$$

➘ Main scale of the problem; cut-off.

$$Q^2_{\rm sat}(y) \propto \exp\{-\lambda\, y\}$$

⇛ Universal curve for large y:
$\longrightarrow$ geometric scaling.

$$\phi(k,y) \longrightarrow \phi\left(\frac{k}{Q_{\rm sat}(y)}\right)$$



Albacete *et al* 2003

Confronting saturation ideas with data

Geometric scaling in lepton-hadron data

- All lepton-proton data with $x \leq$0.01 only function of

$$\tau_p = \frac{Q^2}{Q^2_{\rm sat}}; \quad Q^2_{\rm sat} \sim x^{-\lambda}$$

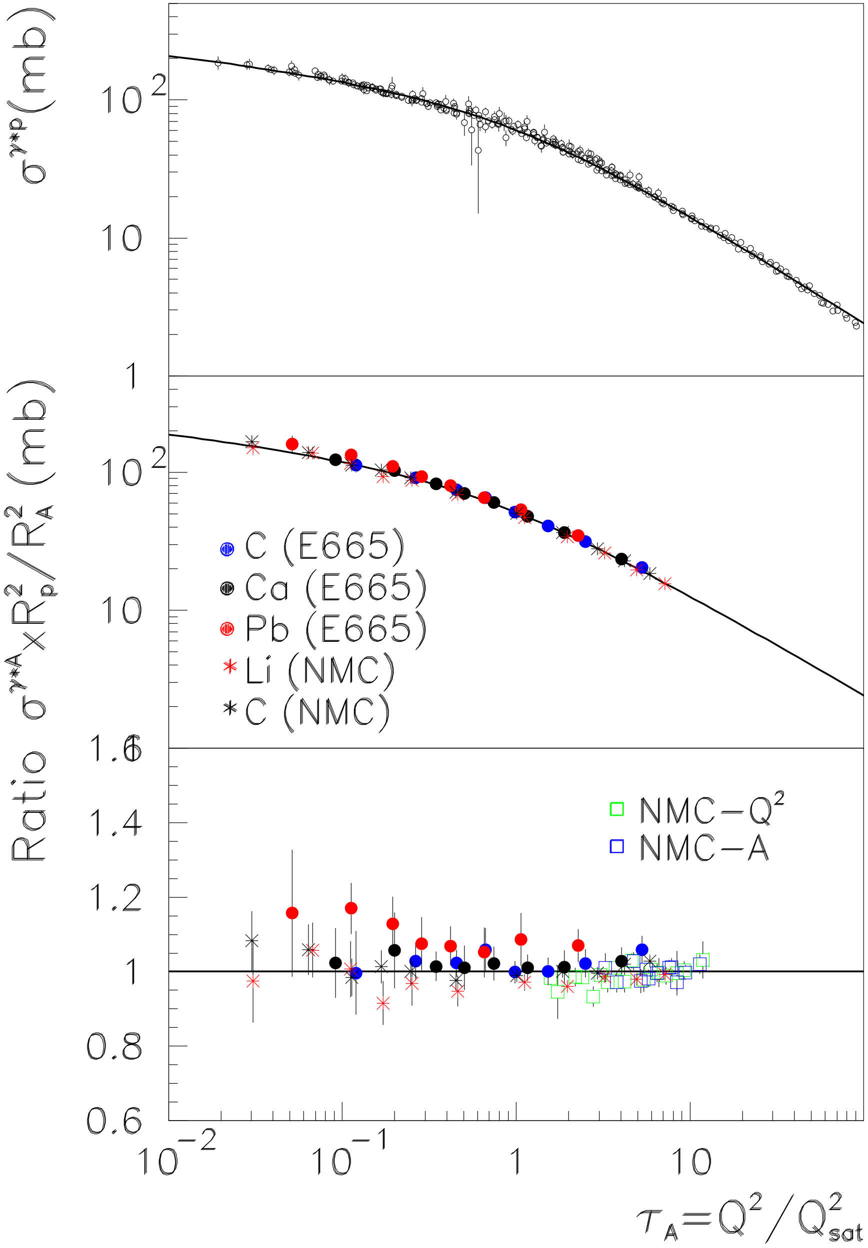
Stasto, Golec-Biernat, Kwiecinski 2001

- Also lepton-nucleus data show scaling when A included

$$\tau_A = \tau_p \left(\frac{AR_p^2}{R_A^2}\right)^{1/\delta} \sim x^{\lambda} A^{1/3\delta}$$

Armesto, Salgado, Wiedemann (2004)

$$\lambda \sim 0.3; \quad \delta \sim 0.8$$



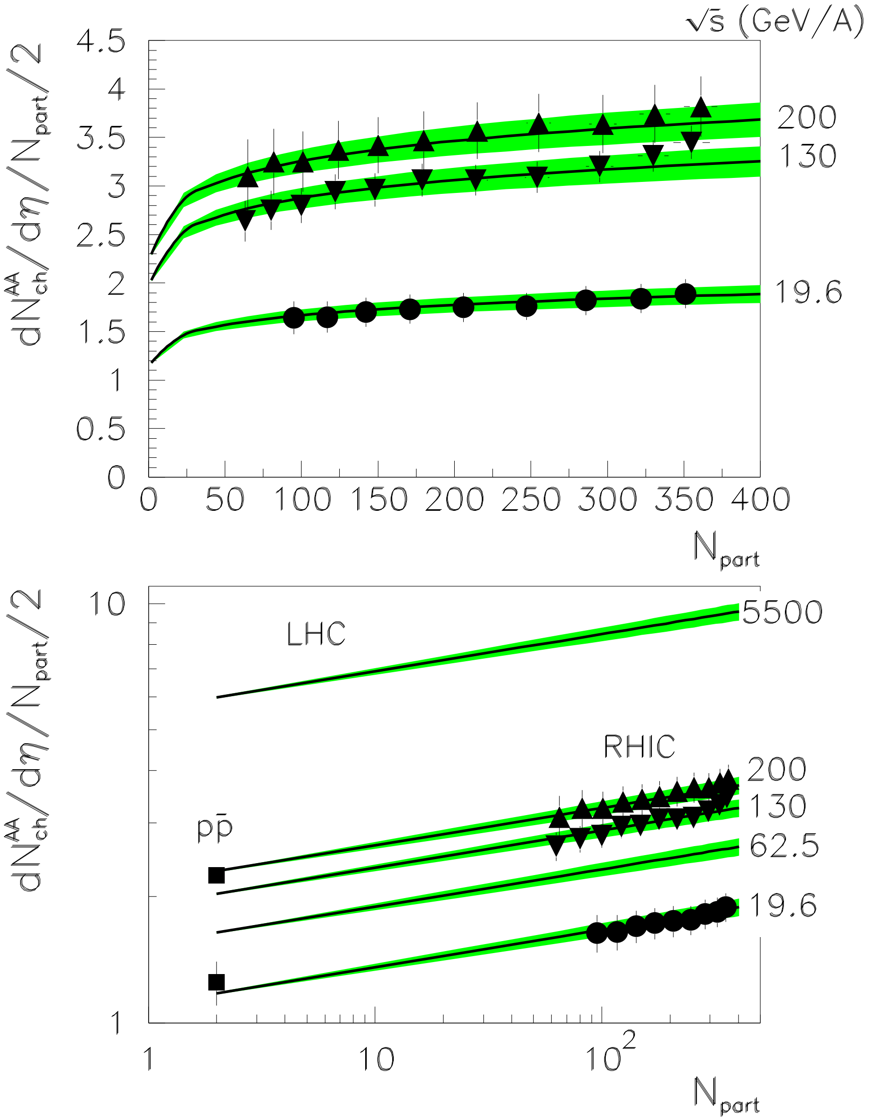
Multiplicities and geometric scaling

- Assuming the same scaling for particle production in nucleus-nucleus collisions

$$N^{AA} \sim S_A Q^2_{\rm sat} \Longrightarrow$$

$$\left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}} .$$

Armesto, Salgado, Wiedemann (2004)

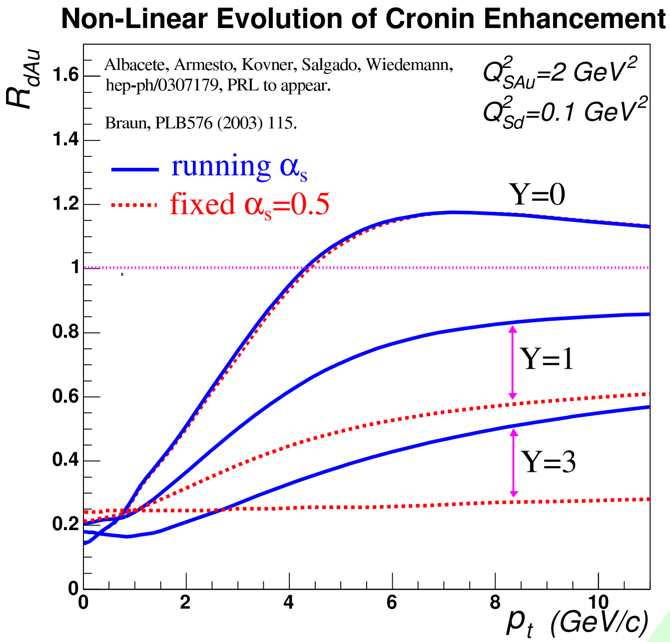


- λ → Energy dependence (lepton-proton data)
- δ → $N_{\rm part}$ dependence (lepton-nucleus data)

Fixes initial conditions for the created medium

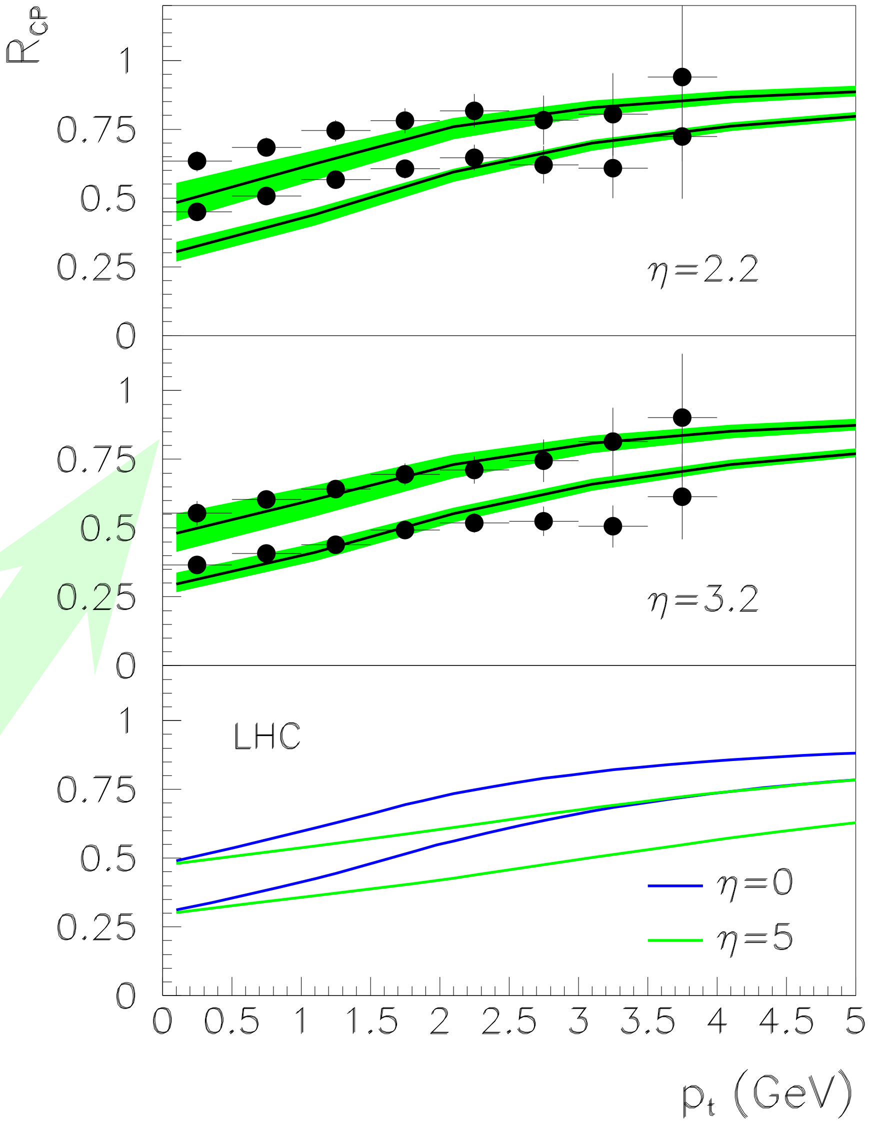
Geometric scaling and dAu data

BK evolution $\Longrightarrow$ suppression



Albacete et al. (2003)

Data from BRAHMS at RHIC



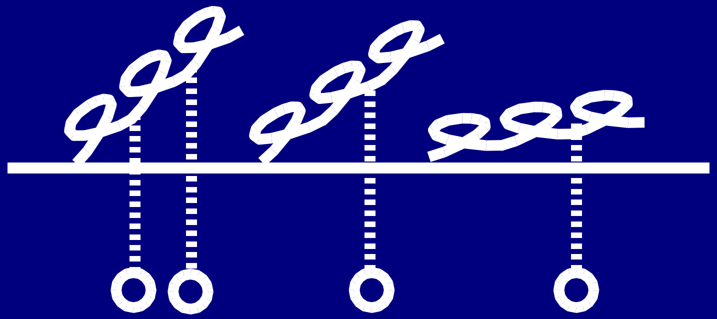
Saturation and data

- Main properties of BK equation compatible with experimental data
  - saturation scale
  - scaling solution
- Accident?? A global description of data using evolution equations is still missing – linear equations also describe the data

Provides the general framework

- Initial conditions for the dense medium (far from thermal equilibrium)
  - $n \sim \frac{1}{\alpha_S}$
- Fast thermalization?
  - $\tau_0 \sim \frac{1}{Q_{\rm sat}} \sim$ 0.2 fm at RHIC
- Very active field in last years

QCD at high densities



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parton distributions: saturation

⟶ Jet shapes modified

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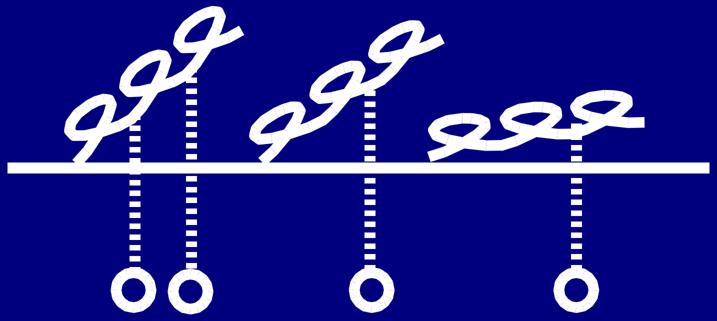

⟶ New (non-linear) ev. equations parton distributions: saturation

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Why high-p_t?

Different scales studied

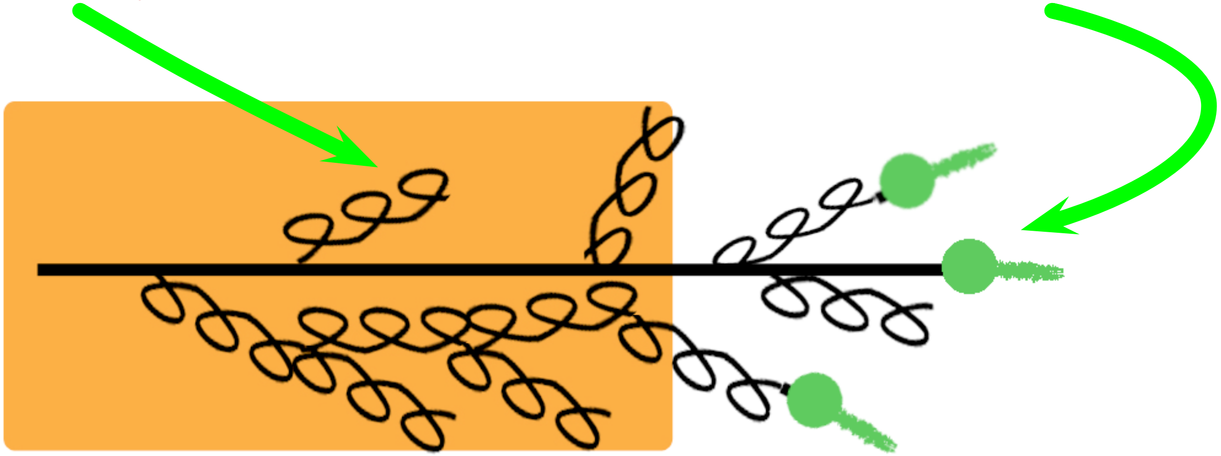
Unique property of jet quenching as a probe of the medium

Radiation formation time

$$t_{\text{form}} \sim \frac{\omega}{k_t^2} \sim \frac{1}{p_t^{\text{assoc}} \sin\theta}$$

Hadronization time

$$t_{\text{had}} \sim \frac{E}{m} R_{\text{had}} \sim \frac{p_t^{\text{lead}}}{m} R_{\text{had}}$$



⇒ $t_{\text{form}} \leq L \Longrightarrow$ shower in a medium

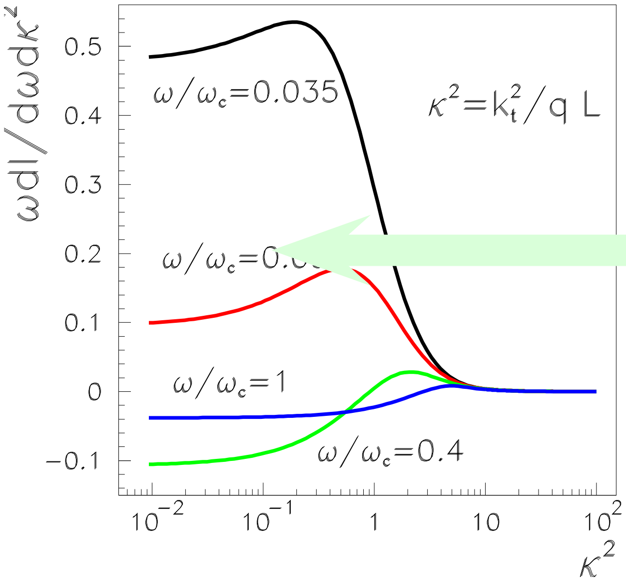
⇒ R_{had} not known for a medium

- Conservative estimate [meson/baryon in AuAu] $\Longrightarrow p_t \gtrsim$ 6 GeV

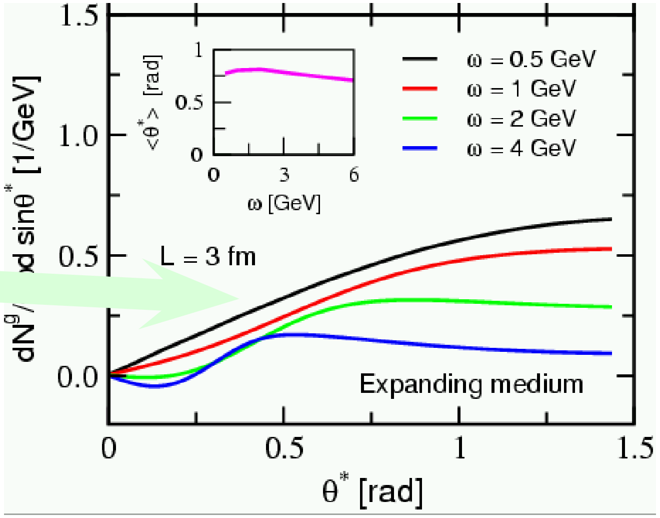
⇒ Intermediate $p_t \longrightarrow$ interplay radiation–thermalization–hadronization

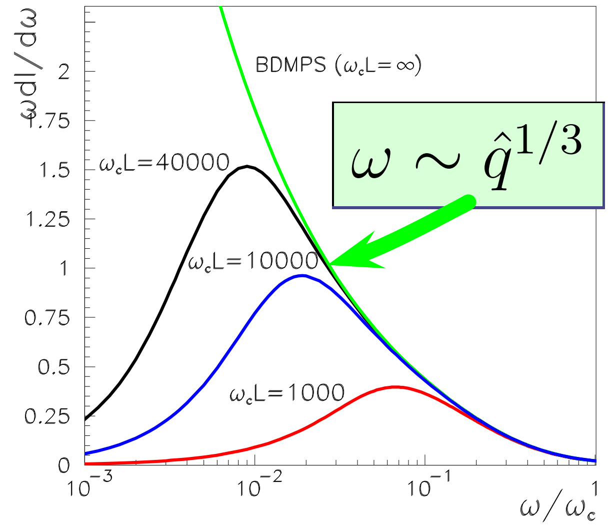
The Medium-induced gluon radiation spectrum

[BDMPS (1996); Zakharov (1997); Wiedemann (2000); GLV (2000)]



Coherence/
Formation time





$$\omega \sim \hat{q}^{1/3}$$

⇛ Spectrum IR and collinear finite

[Salgado,Wiedemann 2003; Vitev 2005]

⇛ Spectrum softer than in the vacuum

⇛ Medium: transport coefficient

$$\hat{q} \simeq \frac{\langle k_t^2 \rangle}{\lambda} \propto n(\xi)$$

➘ High-p_t suppression: $\Delta E \sim \alpha_S \hat{q}\, L^2$

➘ Jet-broadening: $k_t^2 \sim \Delta E/\alpha_S L$ BDMPS 97

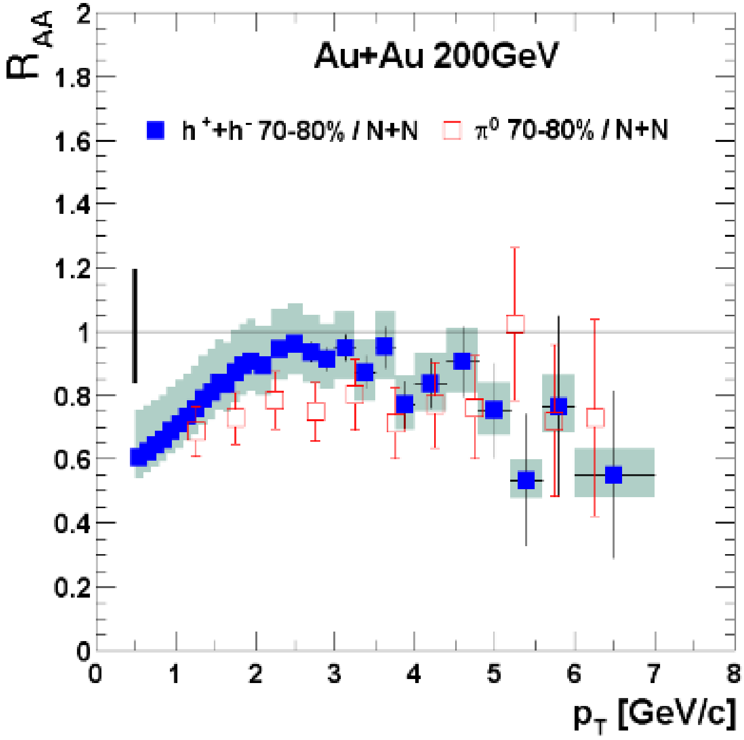
Inclusive particle suppression

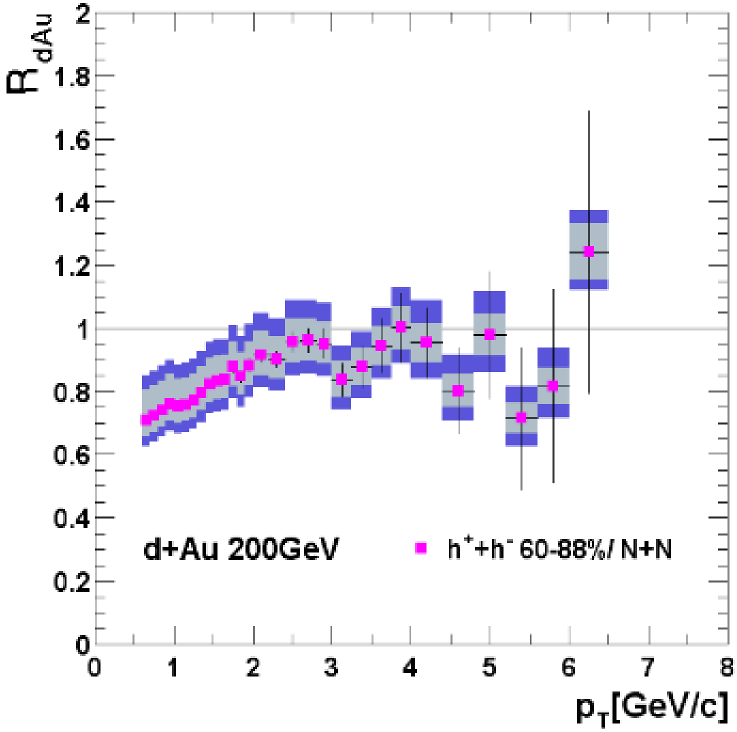
$\longrightarrow$ light mesons

$\longrightarrow$ heavy quarks

High-p_t I: Inclusive particle spectra

$$R_{AA(dA)} = \frac{1}{N_{\rm coll}} \frac{dN^h_{AA(dA)}/dp_t}{dN^h_{pp}/dp_t}$$





Centrality dependence

Peripheral collisions scale with $N_{\rm coll}$ for $p_t \gtrsim 2$ GeV/c.

High-p_t I: Inclusive particle spectra

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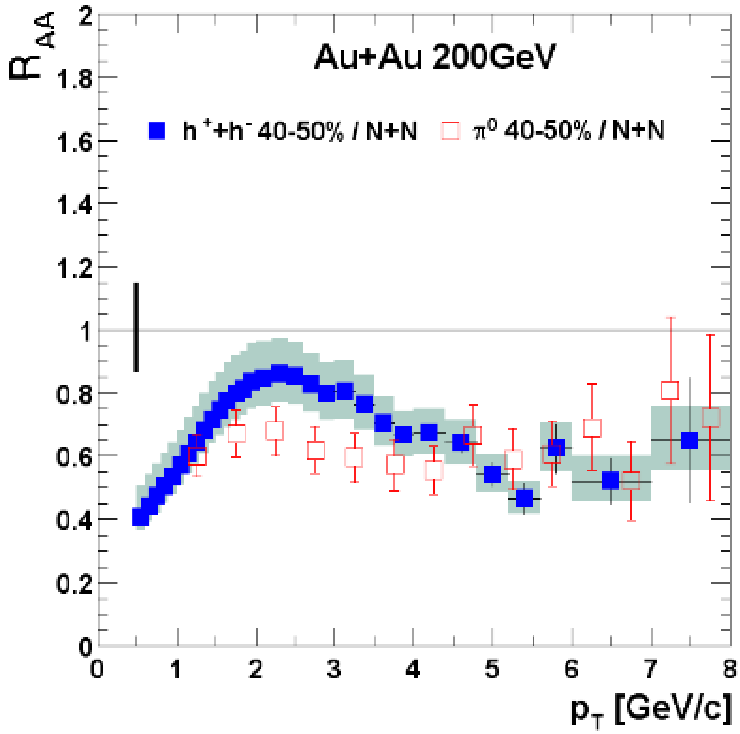

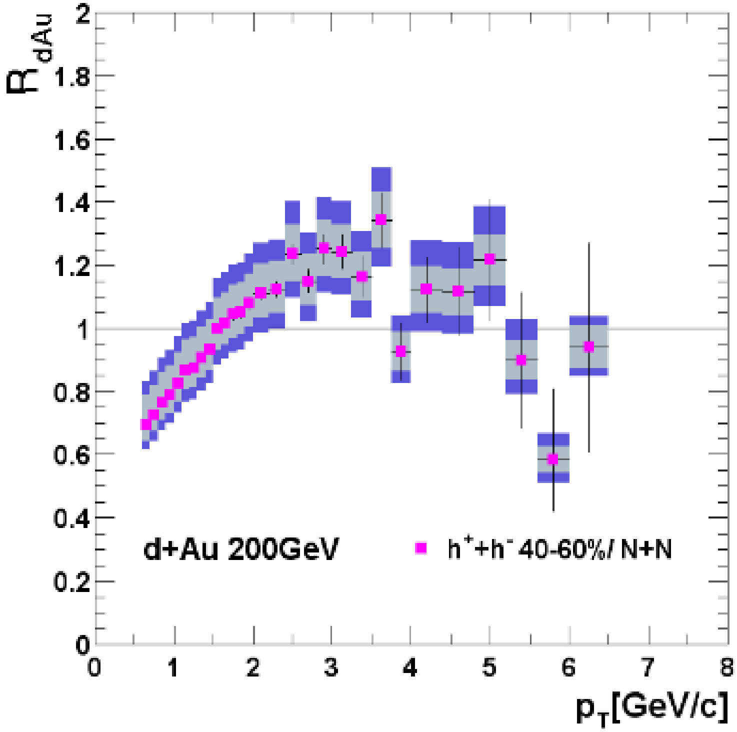

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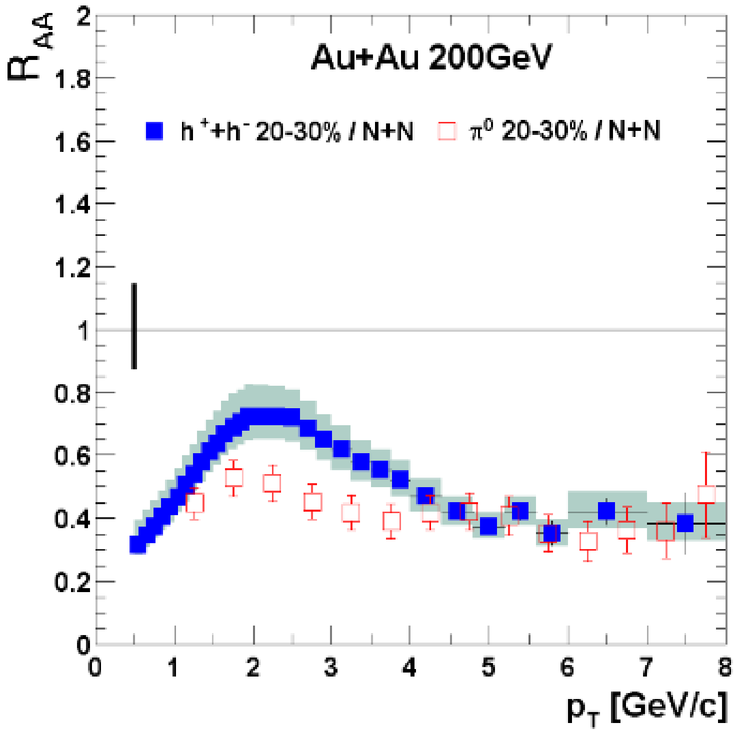

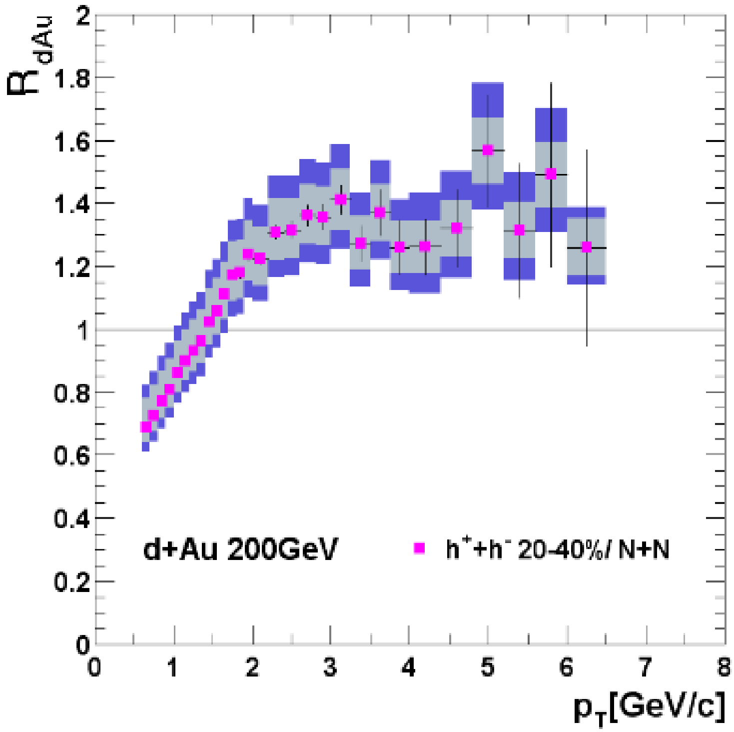

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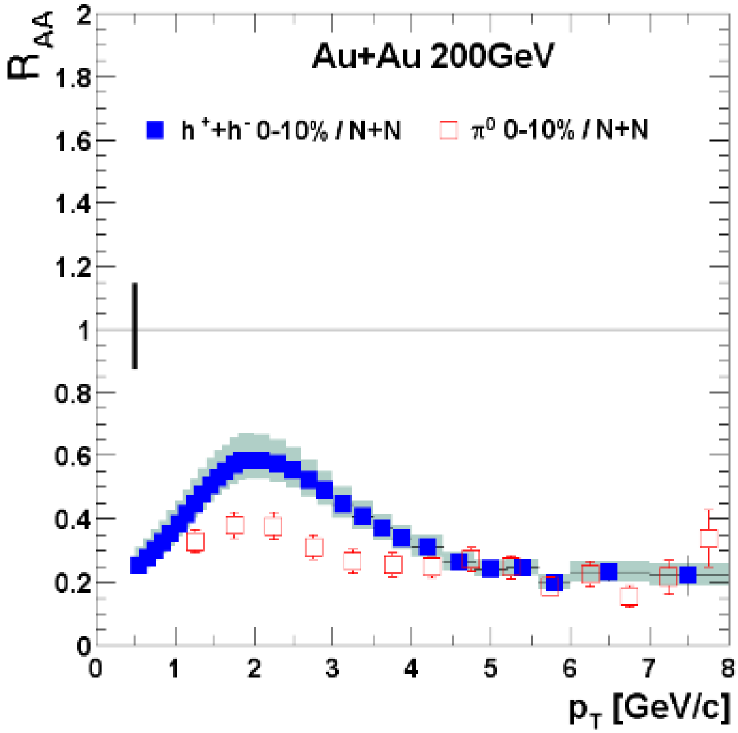
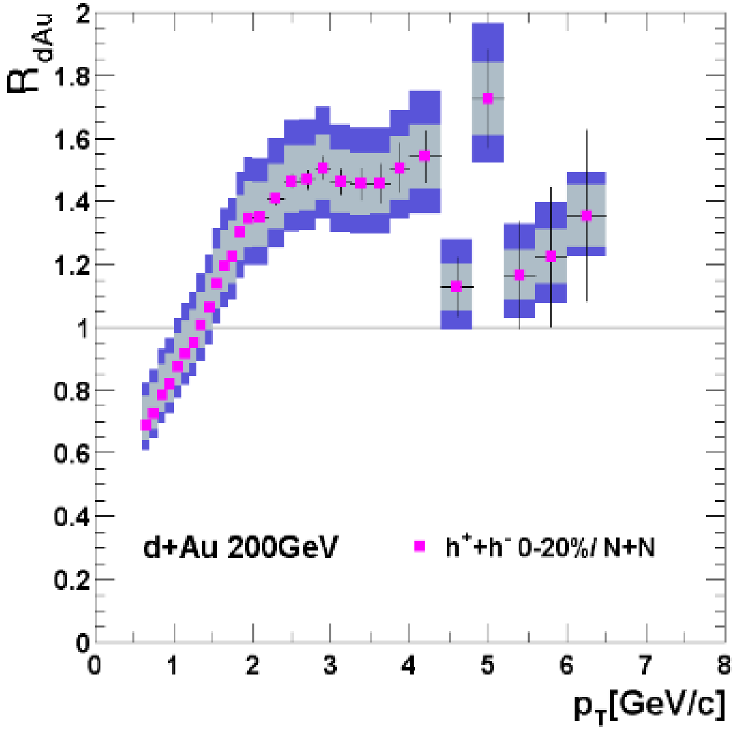




Centrality dependence

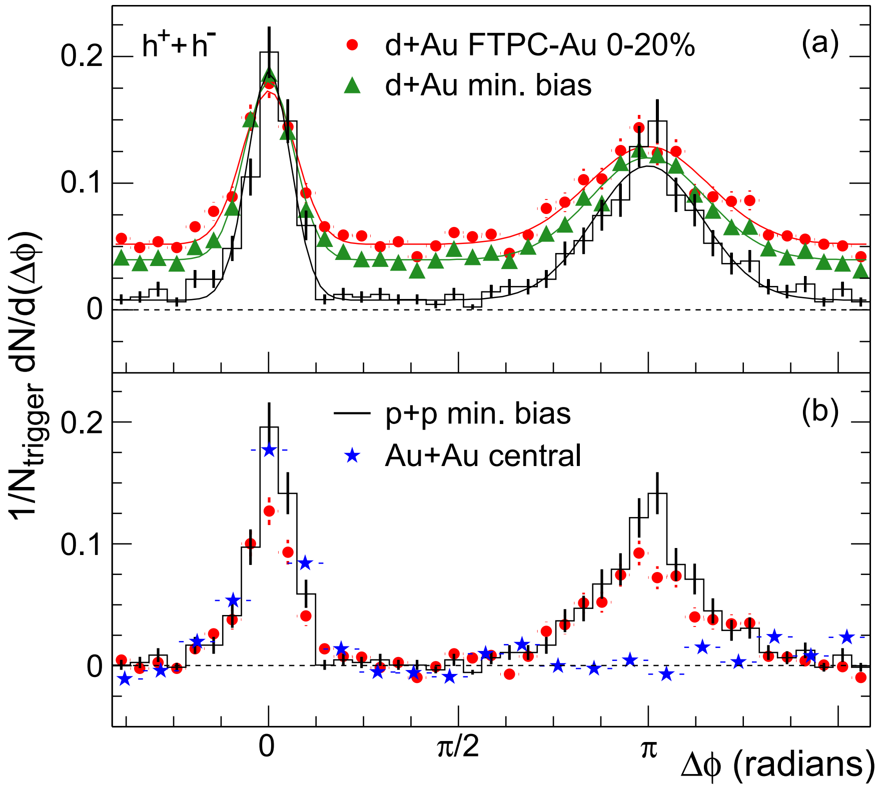
Suppression in AuAu due to final state.

High-p_t II: back-to-back correlations.

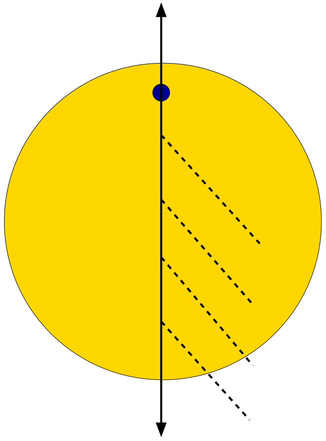
⇒ Azimuthal distributions ($0< |\Delta\eta| <1.4$, $4< p_T^{trig} <6$ GeV/c).

⇒ Typical of jet production.

STAR data (PRL 91 (2003) 072304)



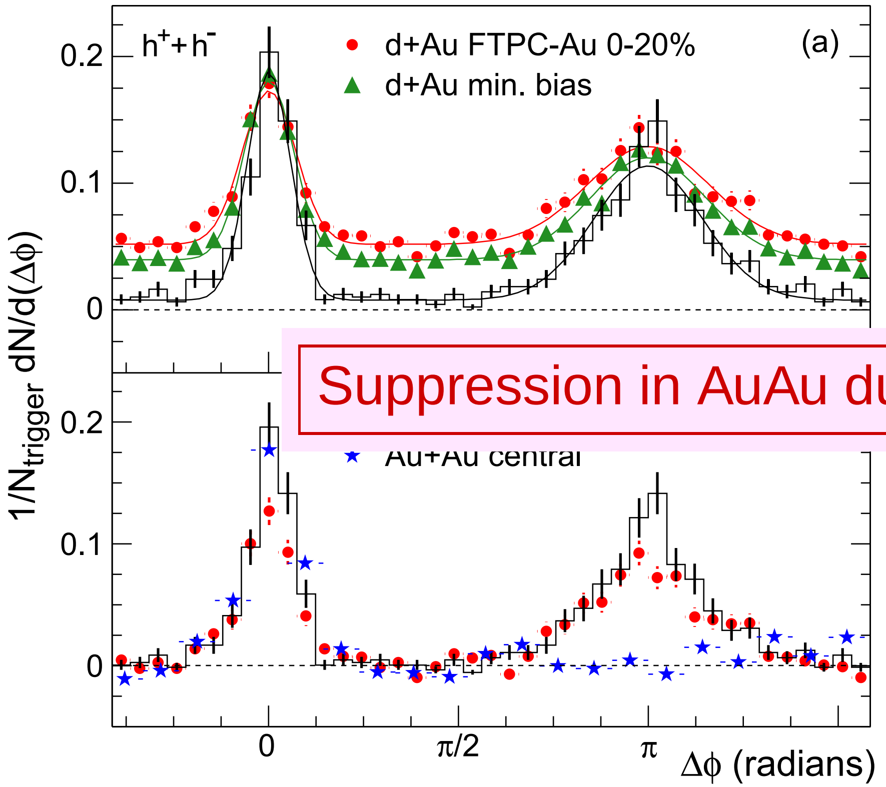
Particles produced close to the surface are less suppressed. (Notice that $\Delta E \sim \alpha_S L^2$)



High-p_t II: back-to-back correlations.

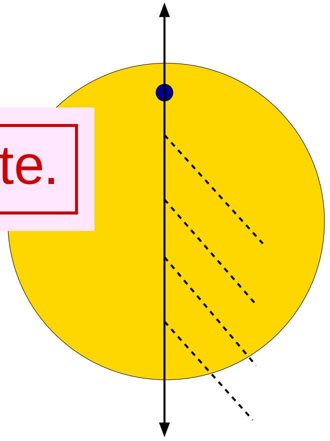
- ⇛ Azimuthal distributions (0$< |\Delta\eta| <$1.4, 4$< p_T^{trig} <$6 GeV/c).
- ⇛ Typical of jet production.

STAR data (PRL 91 (2003) 072304)



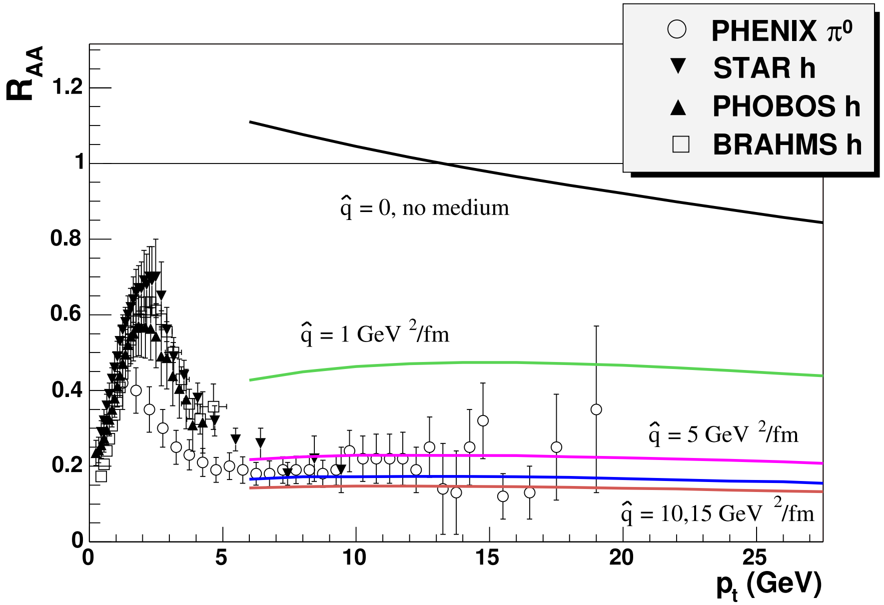
Suppression in AuAu due to final state.

Particles produced close to the surface are less suppressed. (Notice that $\Delta E \sim \alpha_S L^2$)

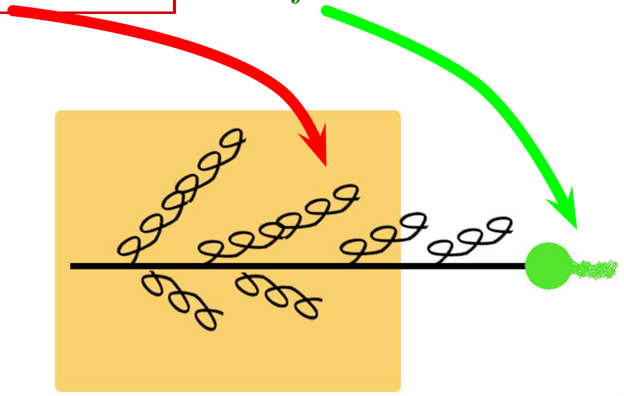


R_{AA} for light mesons at RHIC

$$d\sigma^{AA\to h+X}_{\text{(med)}} = \sum_f d\sigma^{AA\to f+X}_{\text{(vac)}} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{\text{(vac)}}_{f\to h}(z,\mu_F^2)\,.$$



[Eskola, Honkanen, Salgado, Wiedemann (2004)]



⇛ Multiple emission: Poisson distribution

⇛ Hadronization in vacuum at high-p_t

⇛ Data favors a large time-averaged transport coefficient

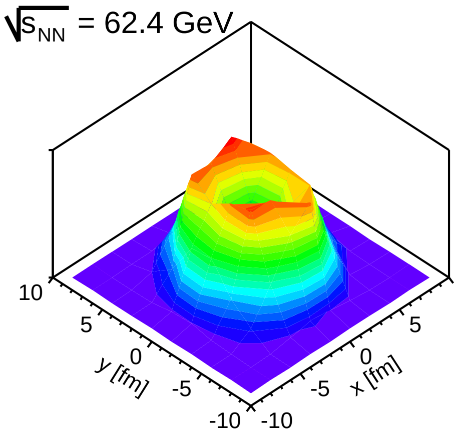
$$\boxed{\hat{q} \sim 5 \ldots 15 \frac{GeV^2}{fm}}$$

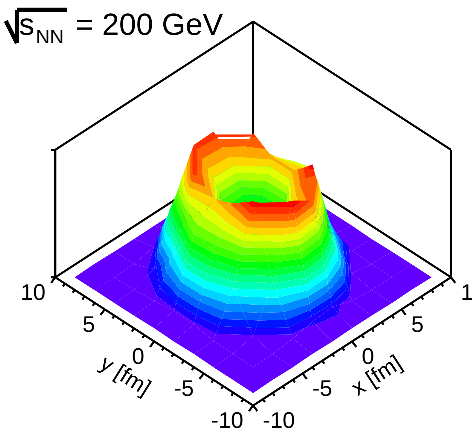
[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

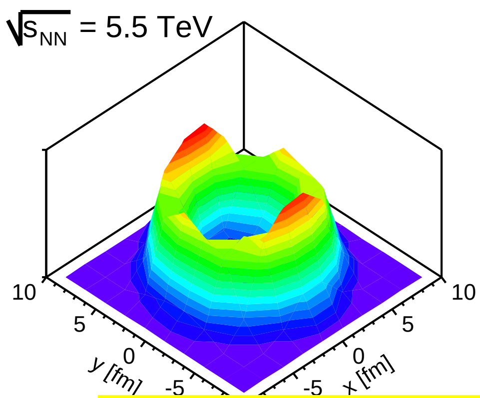
Surface emission

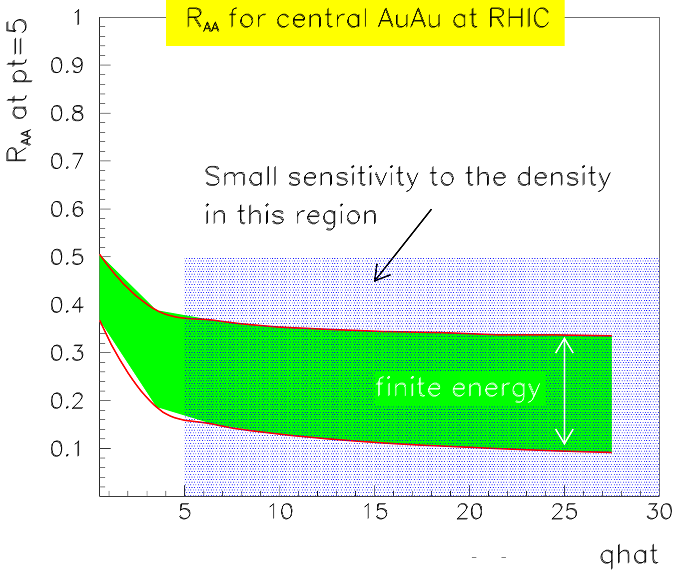
The medium produced at RHIC is so dense that only particles produced close to the surface can escape [Muller (2003)]

[Dainese, Loizides, Paic (2004); Eskola, Honkanen, Salgado, Wiedemann (2004)]







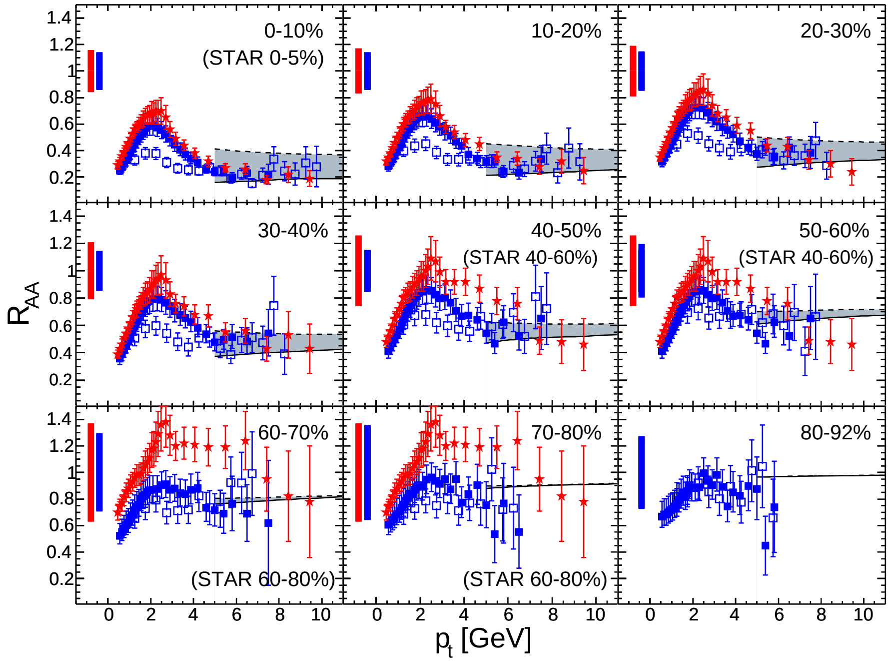


⇒ Perturbative spectrum $\sim 1/p_t^n,\ n \sim 7$

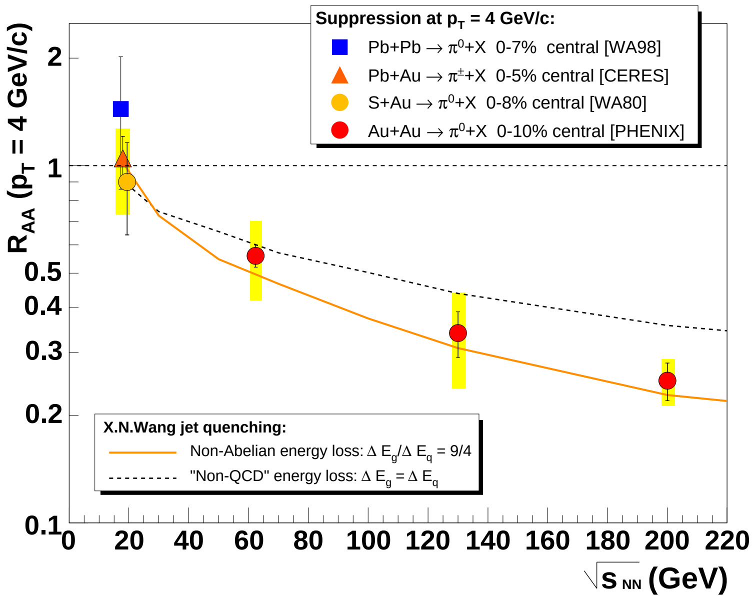
- Trigger bias to small energy loss
- Trigger bias to surface emission
- Sensitivity to $\hat{q}$ small (affect determination of medium density)

Energy and centrality dependence

$$\hat{q} \propto \text{density}$$



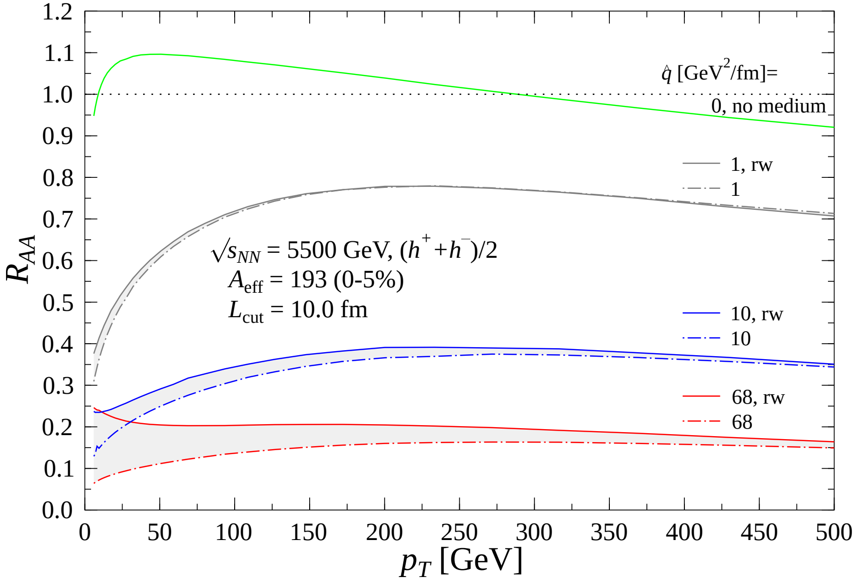
[Dainese, Loizides, Paic (2005)]



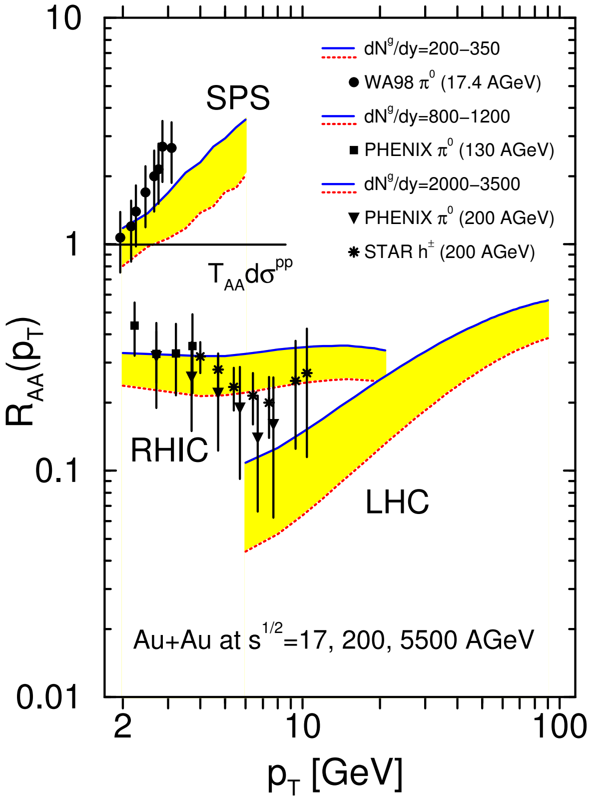
[Fig. from D'Enterria (2005)]

Extrapolation to the LHC

Scale $\hat{q}$ by the expected density at the LHC



[Eskola, Honkanen, Salgado, Wiedemann 2004]



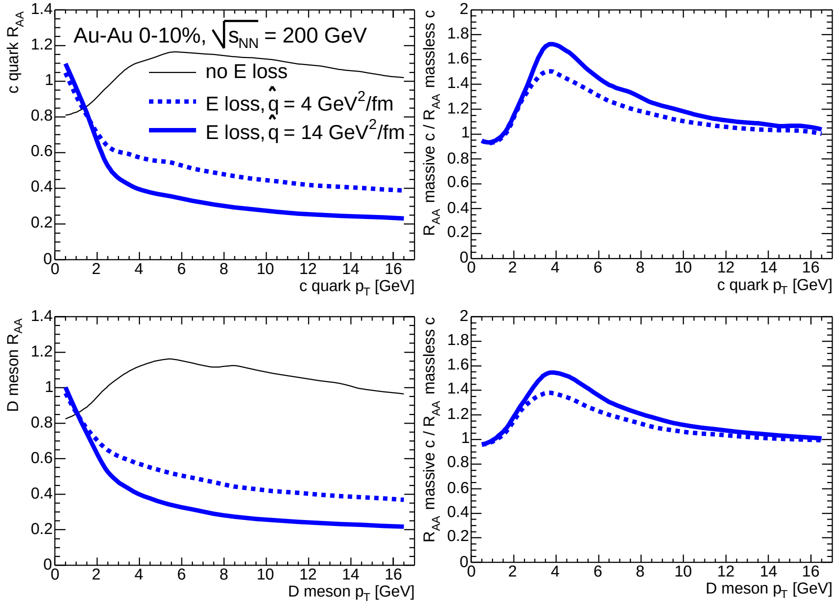
[Gyulassy, Vitev 2002]

High-p_t hadrons are fragile objects even at the LHC

Heavy flavor at RHIC

[Dokshitzer, Kharzeev 2001; Djordjevic, Gyulassy 2003; Zhang, Wang, Wang 2003; Armesto, Salgado, Wiedemann 2004]

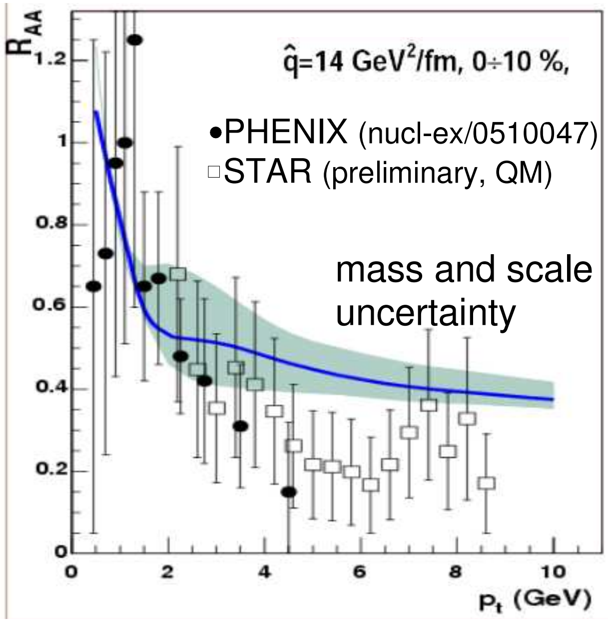
Flavor + mass hierarchy: $\Delta E_g > \Delta E_q^{\mathrm{m}=0} > \Delta E_Q^{\mathrm{m}\neq 0}$



[Armesto, Dainese, Salgado, Wiedemann 2005]

- ⇛ Charm quark suppression similar to light mesons
- ⇛ Possibility to further constrain $\hat{q}$

Only non-photonic e measured
Contribution from b-decays

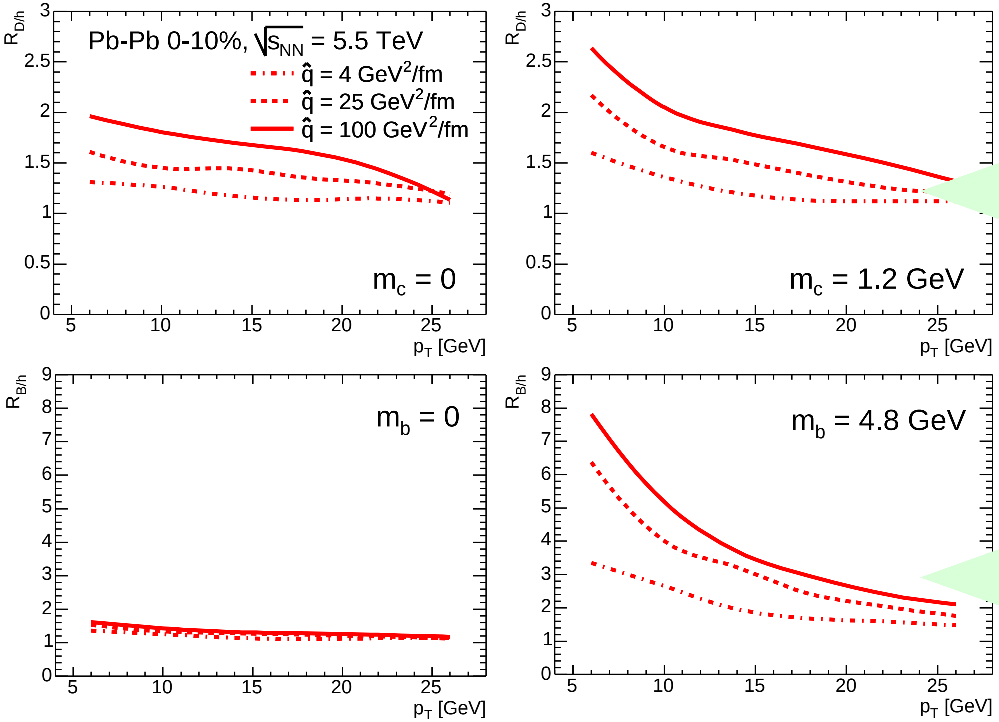


[Armesto, Cacciari, Dainese, Salgado, Wiedemann, in preparation]

Constrain $b/c \rightarrow e^-$ with pp!

Heavy-to-light ratios at the LHC

D/h and B/h ratios for the LHC

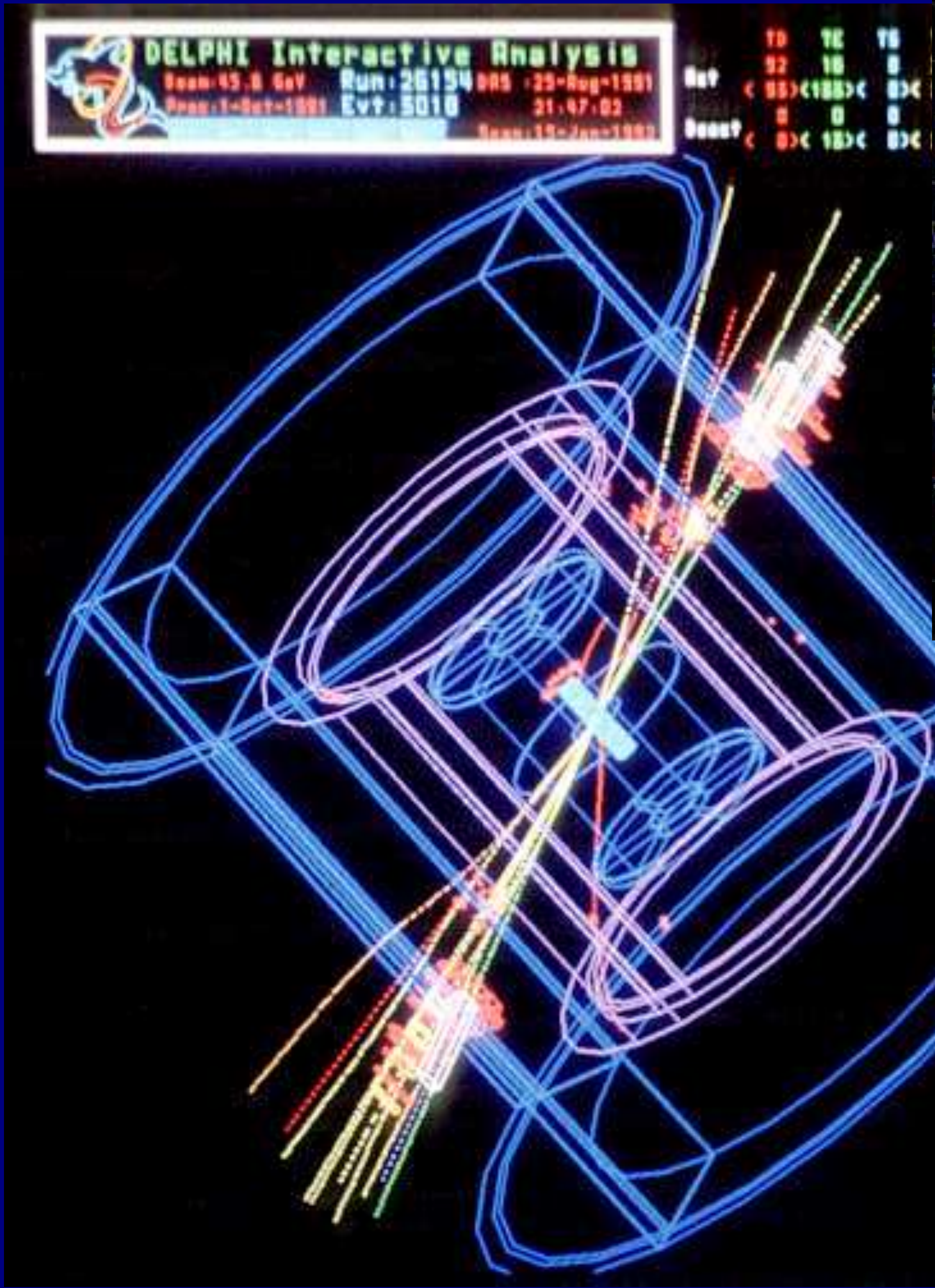


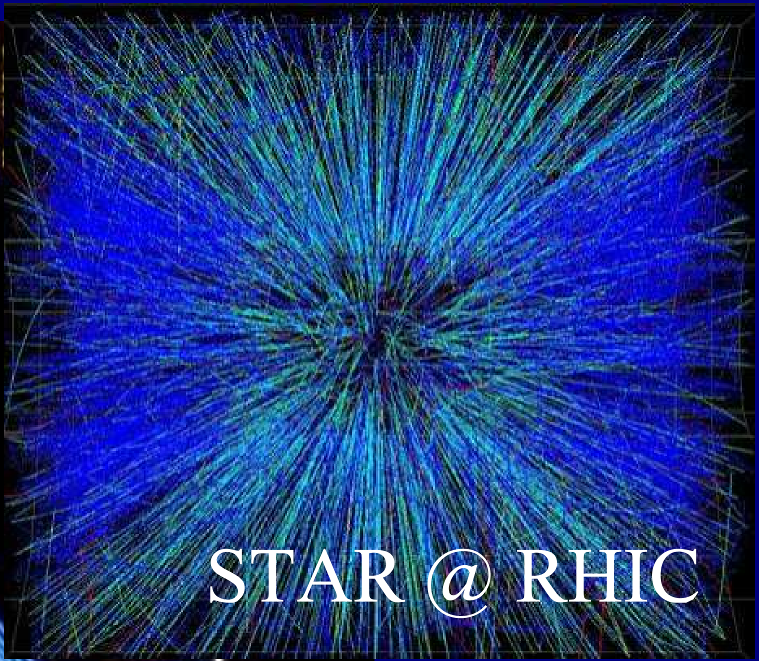
charm
gluon/quark dominates

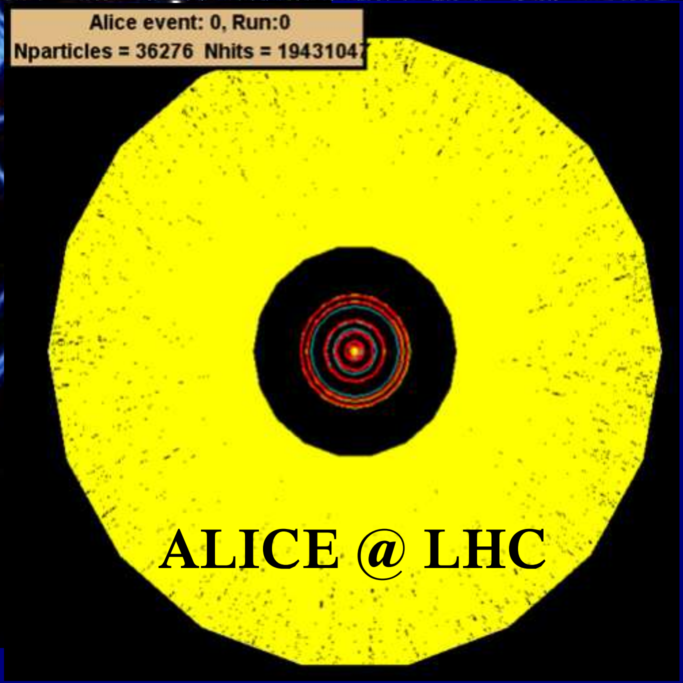
beauty
Mass effect dominates

[Armesto, Dainese, Salgado, Wiedemann (2005)]

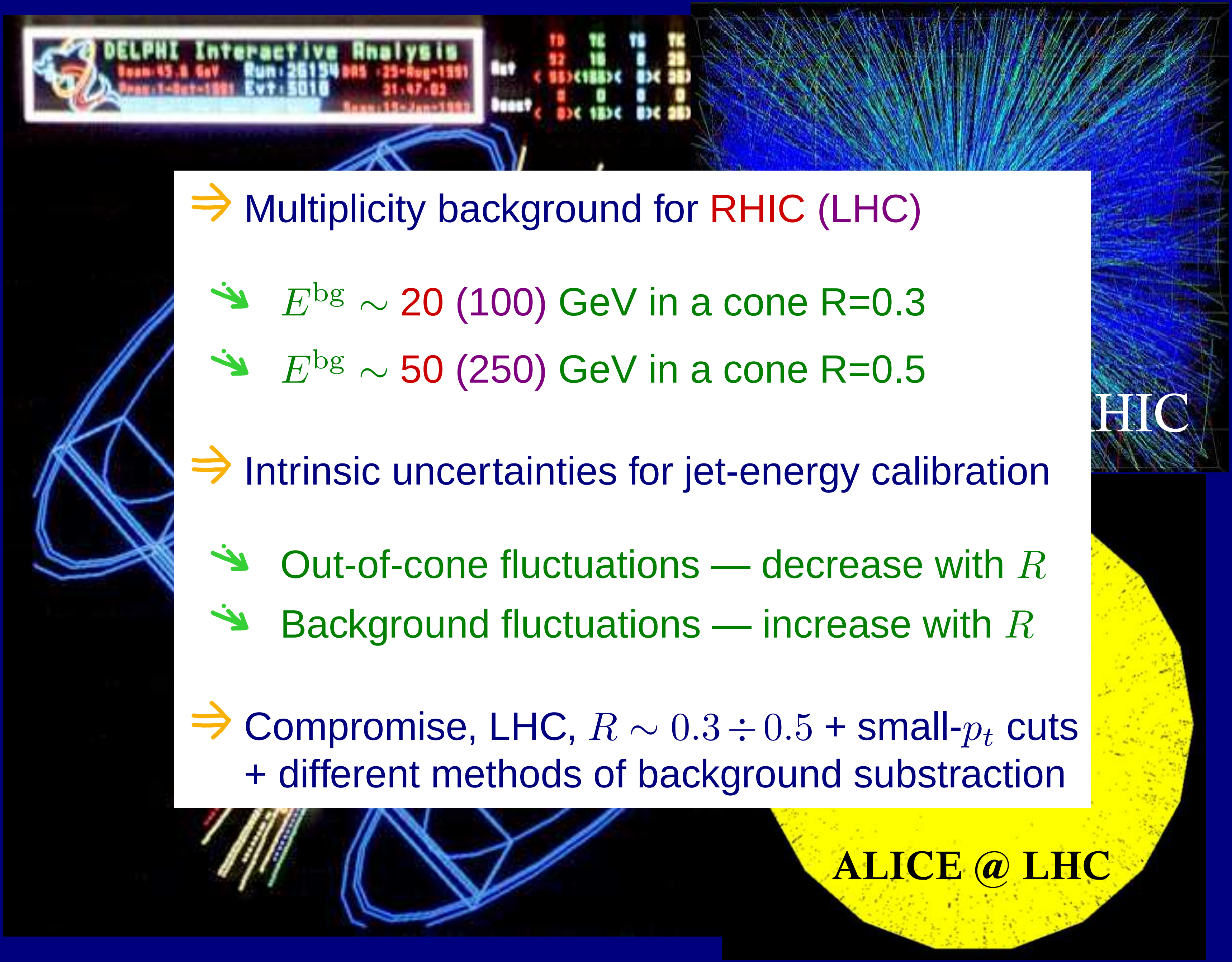
Jets in HIC???


DELPHI Interactive Analysis
Run:26154
Evt:5010


STAR @ RHIC


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 19431047
ALICE @ LHC

Jets in HIC???



⇒ Multiplicity background for RHIC (LHC)

- $E^{\rm bg} \sim$ 20 (100) GeV in a cone R=0.3
- $E^{\rm bg} \sim$ 50 (250) GeV in a cone R=0.5

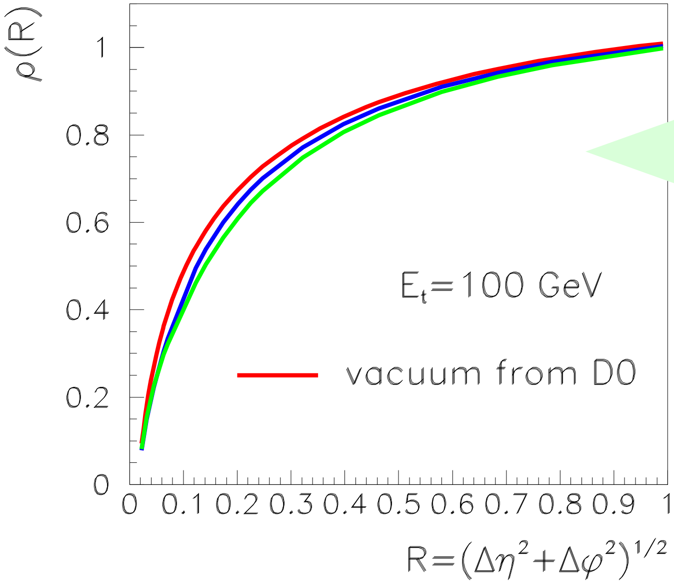
⇒ Intrinsic uncertainties for jet-energy calibration

- Out-of-cone fluctuations — decrease with R
- Background fluctuations — increase with R

⇒ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-p_t cuts + different methods of background substraction

Jet heating at the LHC

Medium-modification of jet shapes, E_t=100 GeV [Salgado, Wiedemann 2004]



⇛ Fraction of the energy inside a cone

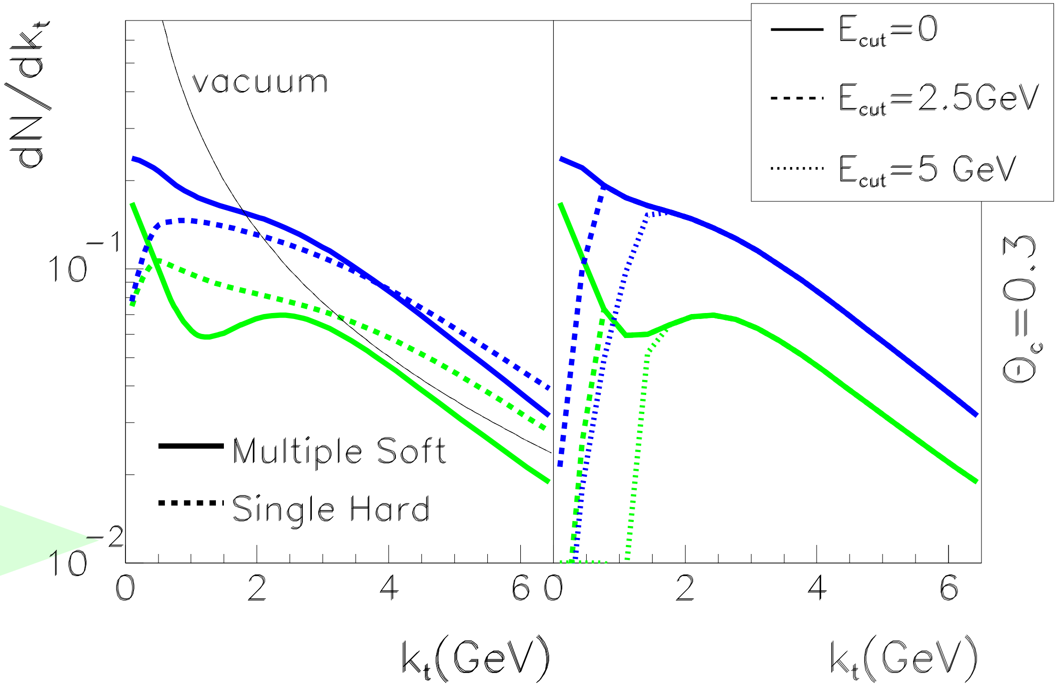
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

$$\rho(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

⇛ Jet energy calibration for $R \sim$ 0.3

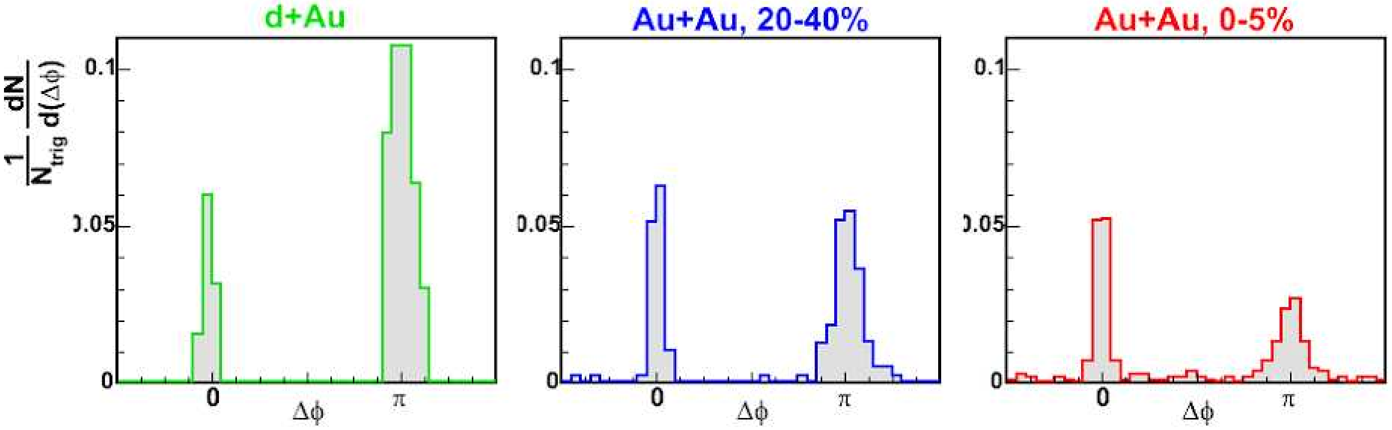
⇛ k_t-dependence of the multiplicity inside a cone

⇛ Large broadening



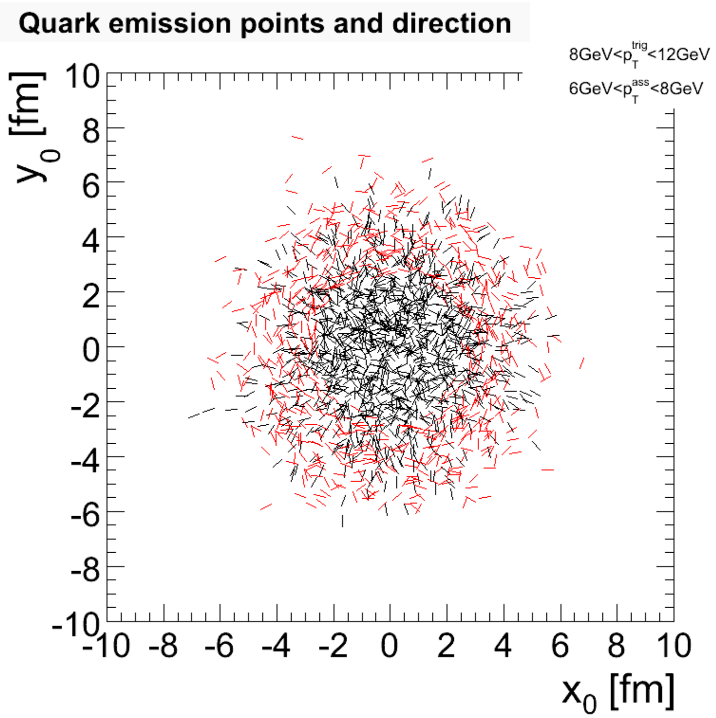
Two-particle correlations ⟶ jets at RHIC

$8 < p_t^{\mathrm{trig}} < 15 GeV; p_t^{\mathrm{assoc}} > 6$ [D. Magestro QM05]



- ⇛ Suppression of the away-side peak
- ⇛ But, no significant broadening seen
- ⇛ Trigger bias effects $\Longrightarrow$ Surface+tangential emission

  [Dainese, Loizides, Paic 2005]



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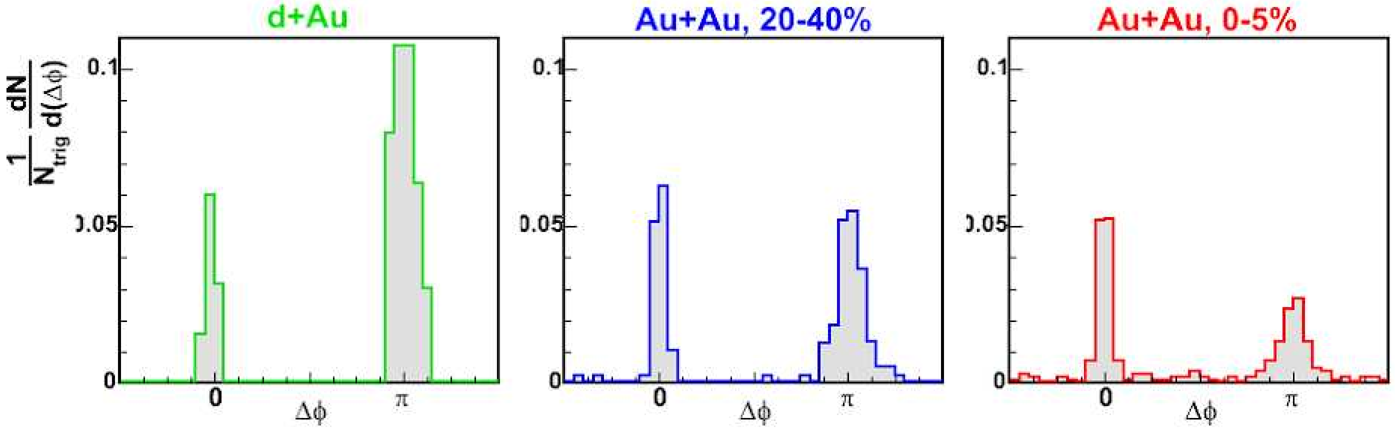
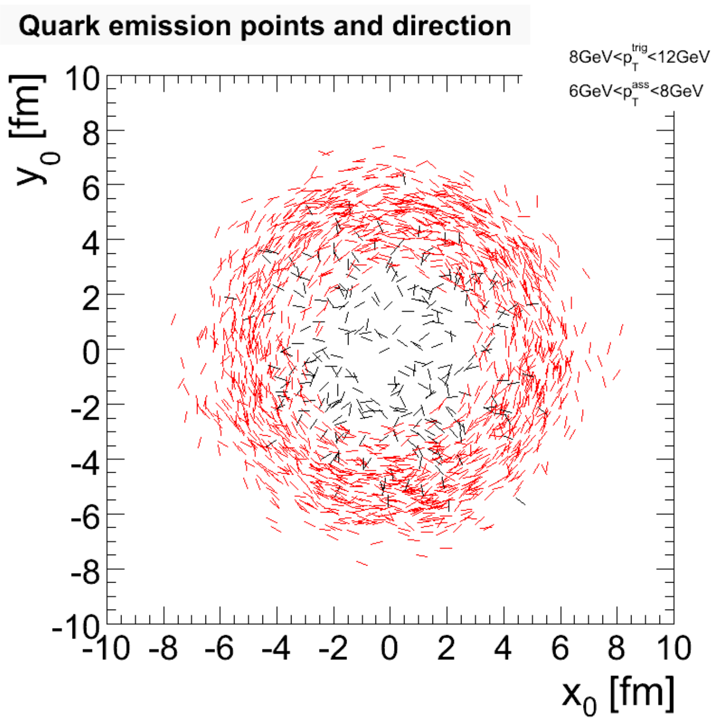




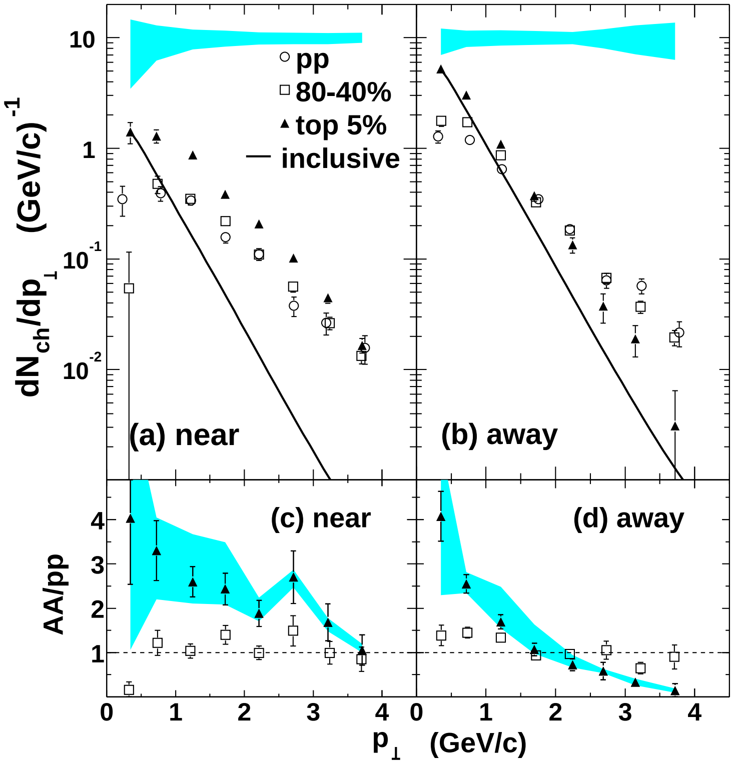
⇛ Suppression of the away-side peak

⇛ But, no significant broadening seen

⇛ Trigger bias effects ⟹
Surface+tangential emission
[Dainese, Loizides, Paic 2005]

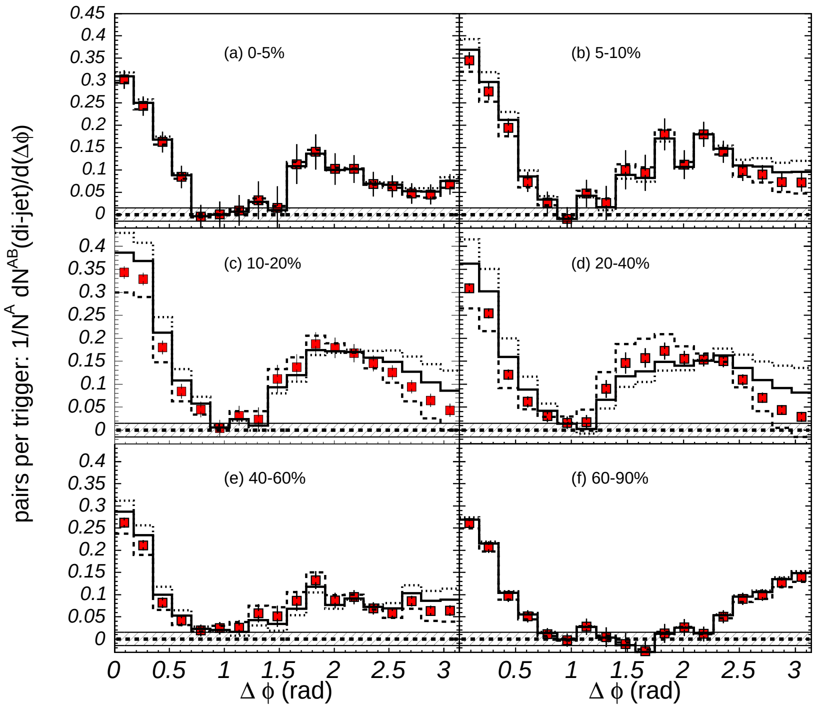
Removing the cut-off at RHIC

Interplay between the soft bulk and high-p_t



[STAR Collaboration 2005]

$4 \leq p_t^{\mathrm{trig}} \leq 6$ GeV



[PHENIX Collaboration 2005]

$2.5 \leq p_t^{\mathrm{trig}} \leq 4$ GeV; $1 \leq p_t^{\mathrm{assoc}} \leq 2.5$ GeV

- ⇒ Associated particles are softer
- ⇒ Large broadening (two-peaks?) in the away side

Removing the cut-off at RHIC: Interpretations

- ⇛ Shock waves: measure sound velocity in the medium

  [Satarov,Stoeker,Mishustin 2005; Casalderrey-Solana,Shuryak,Teaney 2004; Ruppert,Muller 2005]
- ⇛ Cherenkov radiation [Dremin 2005; Koch, Majumder, Wang 2005]
- ⇛ Initial state effect [Baier, Kovner, Nardi, Wiedemann 2005]
- ⇛ Jet quenching + flow [Armesto, Salgado, Wiedemann 2004]

Medium–induced gluon radiation

- ⇛ Softer than vacuum $\longrightarrow$ maximum at $\omega \sim \hat{q}^{1/3} \sim 1...3$ GeV
- ⇛ Small-energy radiation $\Longrightarrow$ Large angle
  - ➘ Possibility of secondary radiation for large angle
- ⇛ Effect disappears for increasing $p_t^{\rm assoc} \gtrsim \hat{q}^{1/3}$

Limitations/future developments

$\longrightarrow$ Medium

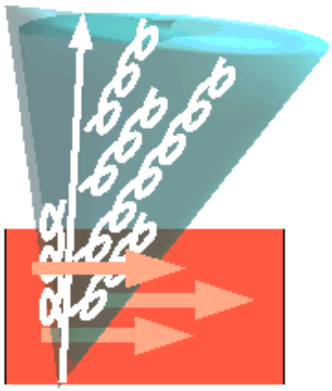
$\longrightarrow$ Shower evolution

Improving the model of the medium

Beyond the medium as a collection of static scattering centers

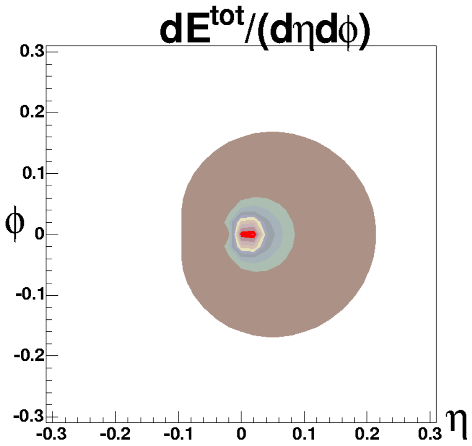
- Hydro: consistent picture of low-p_t RHIC data given by $T^{\mu\nu}$ + E.o.S.
  - $T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$ is the fundamental object describing the medium $\Longrightarrow$ $\hat{q}(T^{\mu\nu})$
  - Example, longitudinal flow $\hat{q} = c\, \epsilon^{3/4} \rightarrow c\, (T^{zz})^{3/4} = c\,(p + \Delta p)^{3/4}$

$$\Delta p = (\epsilon + p) u^z u^z = 4p \frac{\beta^2}{1 - \beta^2}$$



- Flow: additional source of induced radiation
- Asymmetric jet shapes in the $\eta \times \phi$ plane

Armesto, Salgado, Wiedemann 2004



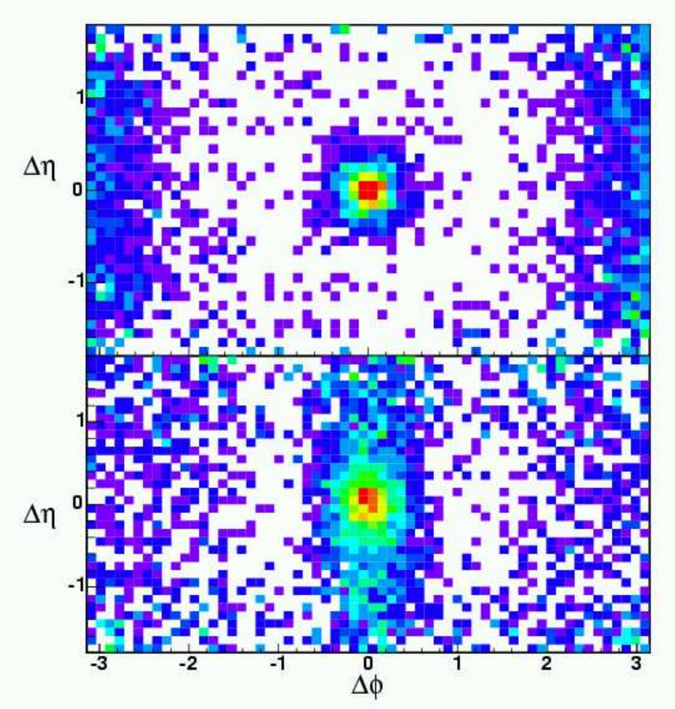
- Full 3-D hydrodynamical simulation coupled to jet-quenching needed

Measuring collective flow with jets

Longitudinal flow

Space-time picture of collision

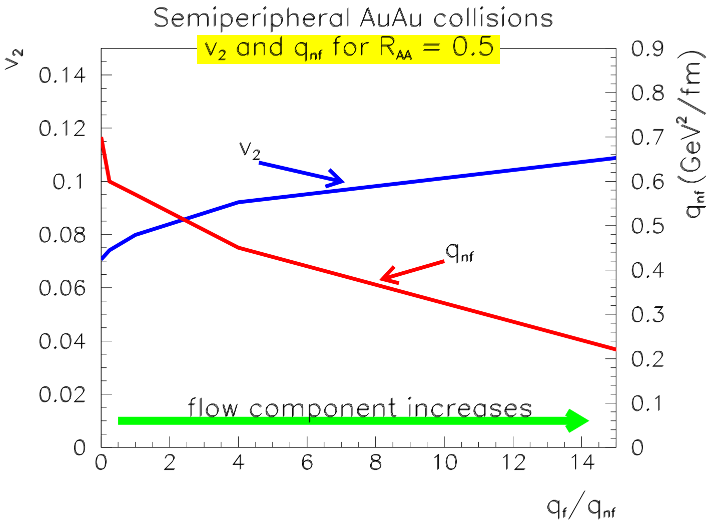
[STAR preliminary, D. Magestro HP04]



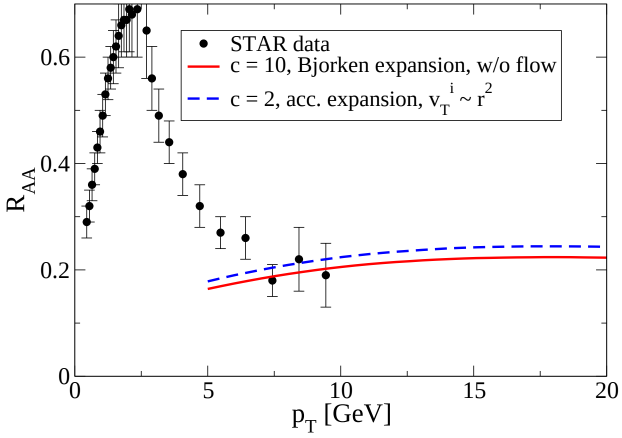
$$3\,\mathrm{GeV} < p_t^{\mathrm{trigg}} < 6\,\mathrm{GeV};$$
$$2\,\mathrm{GeV} < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trigg}}$$

Transverse flow

[Armesto, Salgado, Wiedemann 2004]



[Renk, Ruppert 2005]



Improving the shower evolution

- Beyond the independent (Poisson) gluon emission
  - Include energy constraints
  - Include possibility of secondary branching...
- In the vacuum DGLAP evolution equations, or implemented in MC by Sudakov form factors

$$\Delta(t_0,t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P_{j,i}(z)\right] ,$$

  giving the probability of no-branching
- Can this be generalized to the medium?

$$\omega \frac{dI^{\rm vac}}{d\omega dk_t^2} \sim \frac{1}{k_t^2} \qquad\qquad \omega \frac{dI^{\rm med}}{d\omega dk_t^2} \sim \frac{1}{k_t^4}\left(\frac{\omega_c}{\omega}\right)^n ; n = \frac{1}{2}....2$$

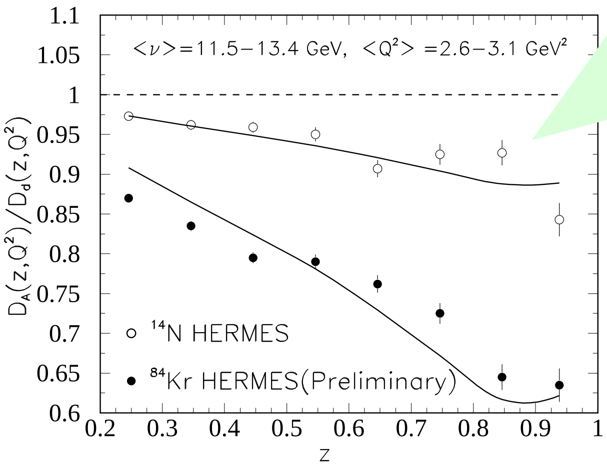
  - With formation time effects regularizing the divergences

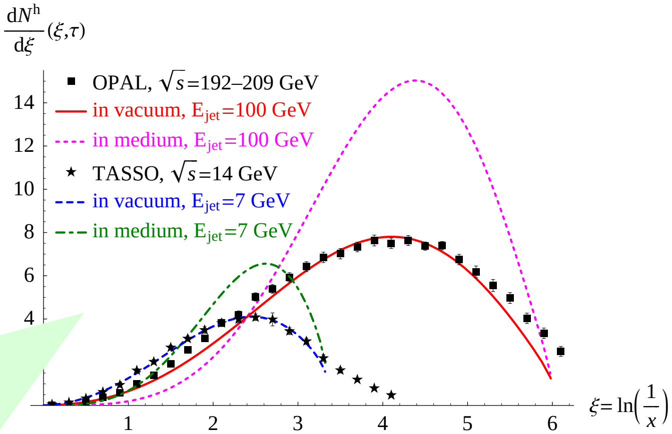
Toward an evolution equation

Is there a Q^2-dependence on the energy loss?

- Medium–modified fragmentation functions computed as higher-twist corrections in nuclear-DIS [Guo, Wang 2000–2003]

$$\tilde{P}_{ji}(z,x,x_L,l_T^2) = P_{ji}(z) + \Delta P_{ji}(z,x,x_L,l_T^2)\,; \quad \Delta P_{ji}(z,x,x_L,l_T^2) \propto \frac{1}{l_T^2}$$





- Enhance the singular parts of the vacuum splitting functions in the Modified-Leading-Log-Approximation [Borghini, Wiedemann 2005]

$$P_{qq}(z) = C_F\left(\frac{2(1+f_{\rm med})}{(1-z)_+} - (1-z)\right)$$

Jet quenching and the QGP

- Very large value of $\hat{q} \sim$ 5...15 GeV^2/fm obtained from fit to the data
  - Taking $\hat{q} = c\,\epsilon^{3/4} \Rightarrow c \gtrsim$ 5 $c_{\rm ideal}^{QGP}$ [estimation for ideal QGP: Baier 2002]
  - Expectations from relation to CGC: $Q^2_{\rm sat} \sim \hat{q}\,L \gtrsim \mathcal{O}(10$ GeV$^2)$

$\hat{q} \gtrsim$ 5 times larger than expected

- Why? Several possibilities
  - Formalism not quantitatively reliable? (incomplete)
  - Scattering cross sections $\gtrsim$ 5 times larger than perturbative estimates $\Longrightarrow$ relation with sQGP hypothesis
  - Flow effects very significant: $\hat{q}$ measures ϵ AND flow
- Jet quenching has the potential to give answer to these questions and study the medium properties with a quantified effect.

Summary

- Very dense medium created in central AuAu collisions at RHIC
- Jet quenching is the dominant medium mechanism at high-p_t
  - Energy loss due to medium-induced gluon radiation is the best candidate to explain this effect. Reasonable description of data.
- Intricate interplay between parton branching and medium dynamics
  - Flow fields affect jet evolution

Main (still) open questions

- What is the nature of the medium created in HIC?
- What is the mechanism of equilibration?
  - Which part of the spectrum is equilibrated? Jet heating.
- And... what is the relation with lattice QCD results?

LHC at CERN – 2007/2008