Heavy Ions: theory overview

Konrad Tywoniuk

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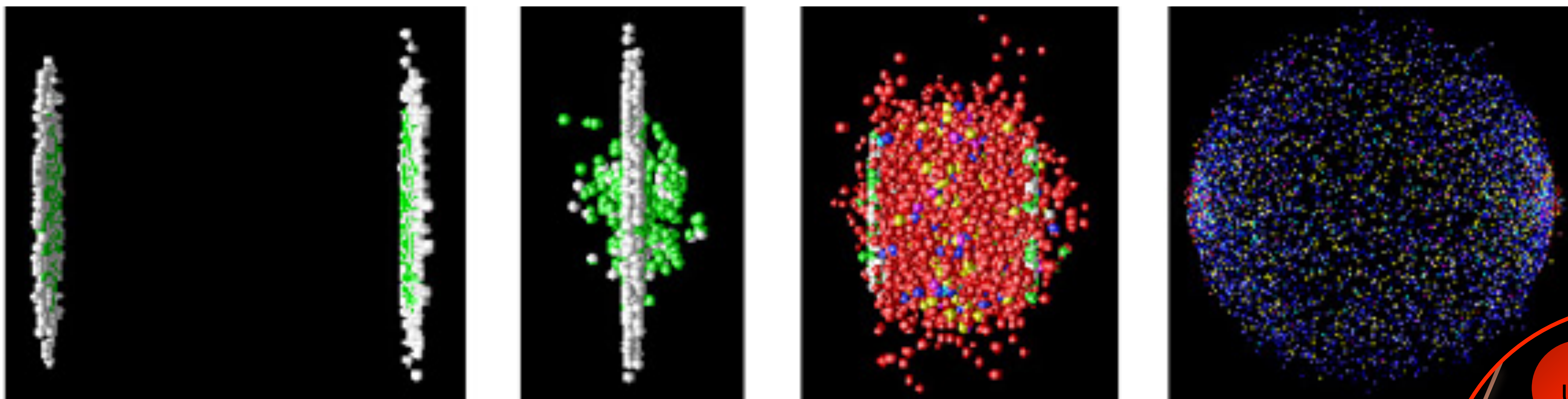
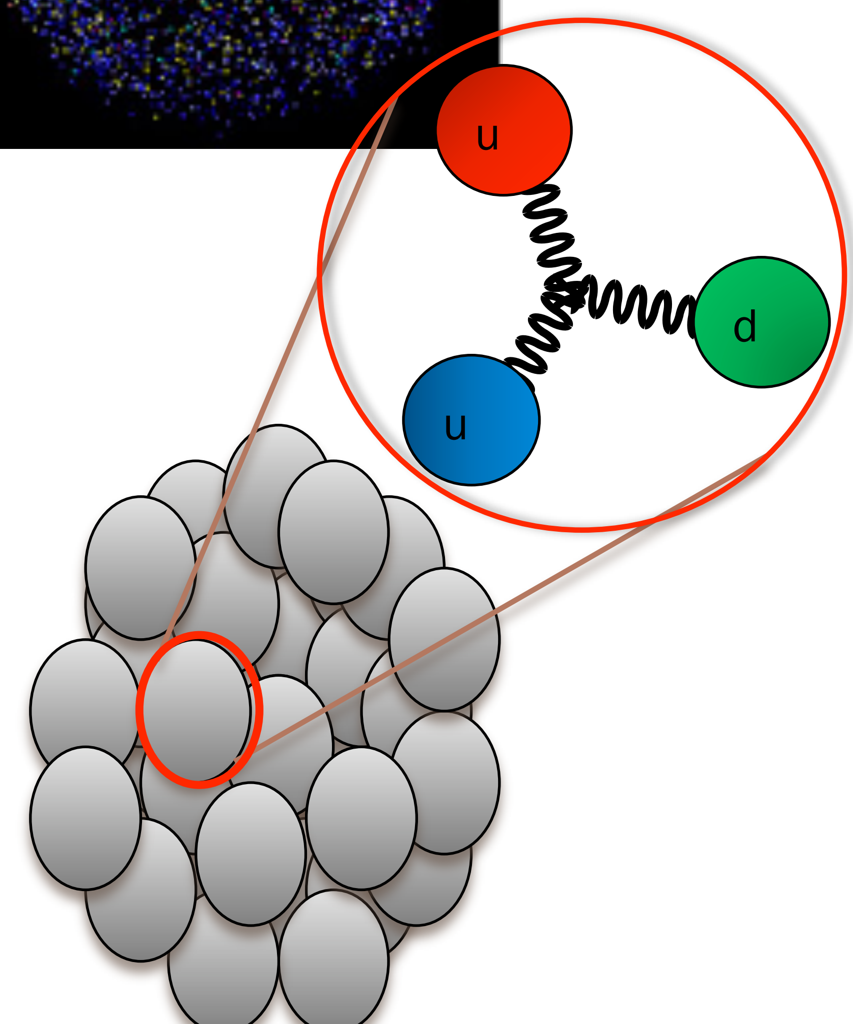
Nuclear physics at high energies

[Gross, Wilczek, Politzer, Cabbibo, T.D. Lee, Bjorken, Shuryak...]





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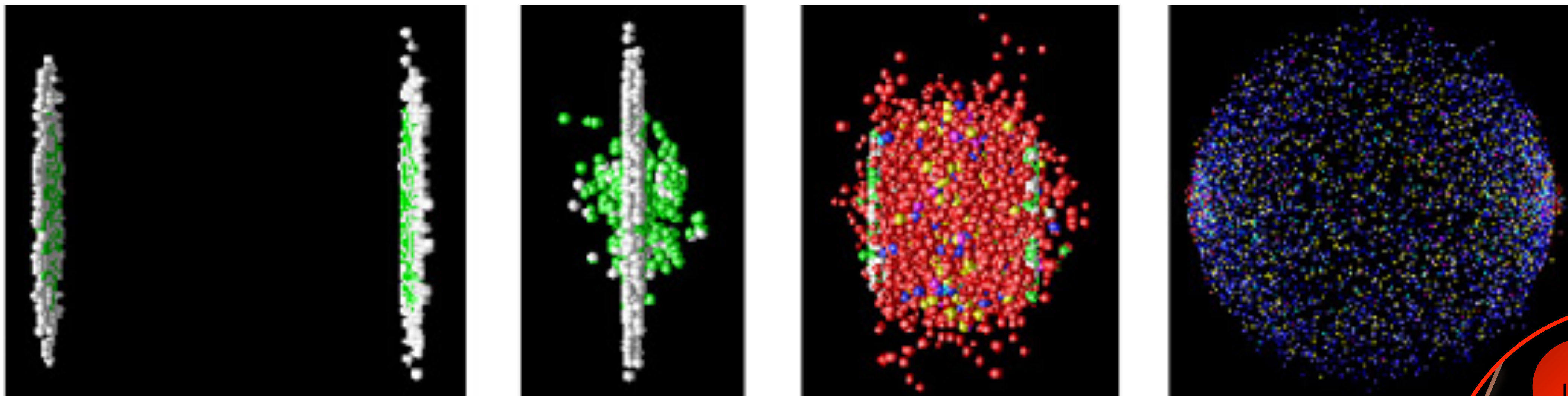
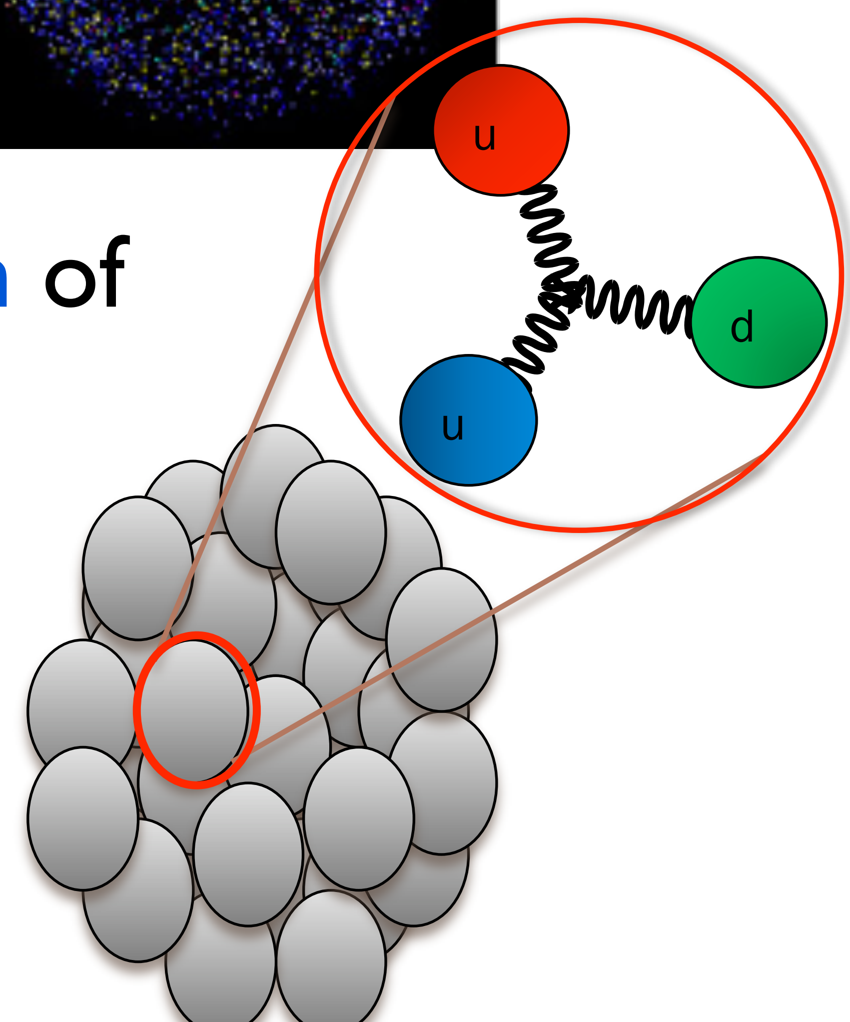


- the goal is to create large region of large energy density



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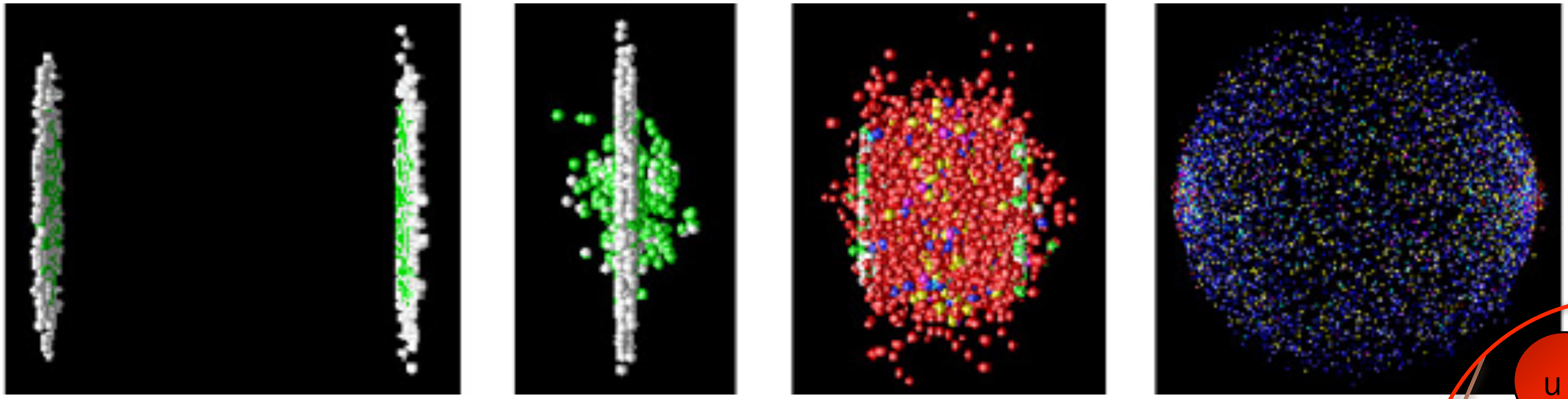

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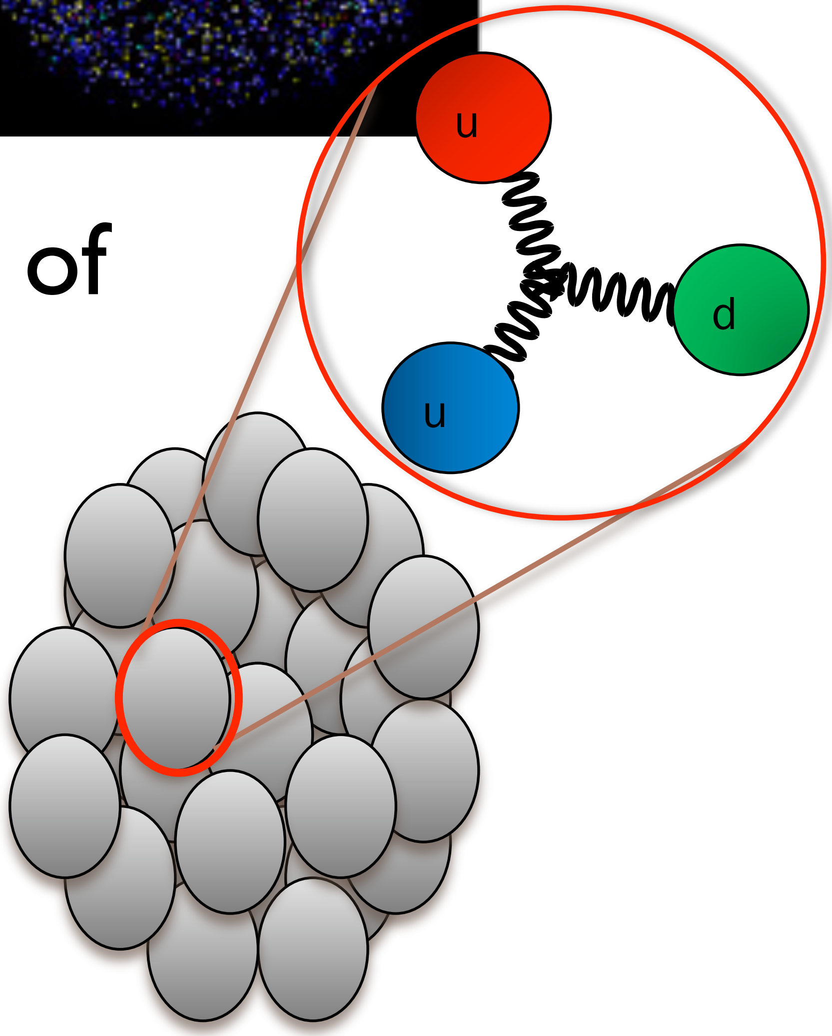

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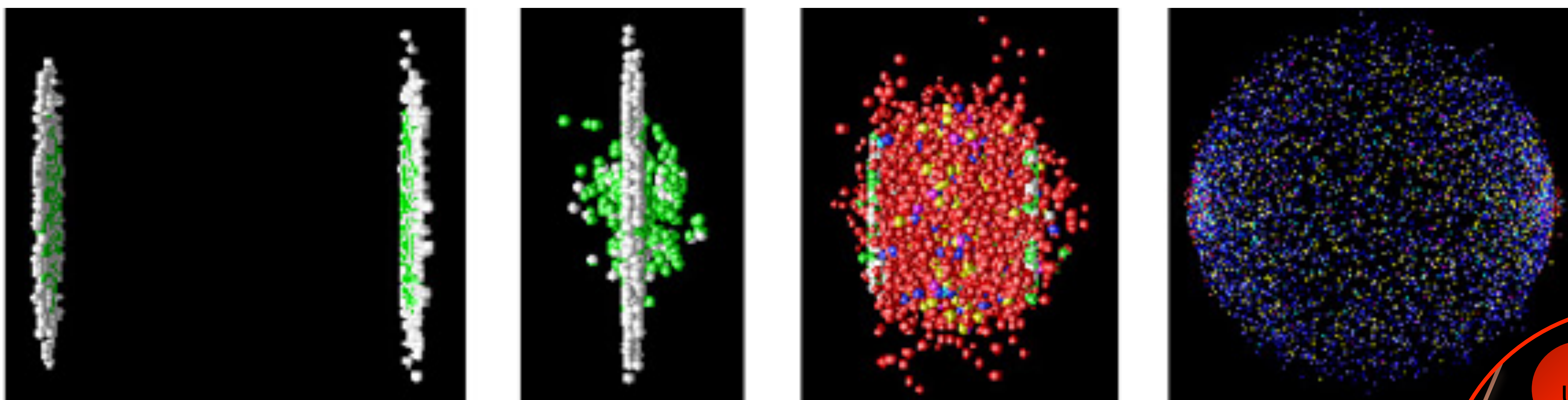
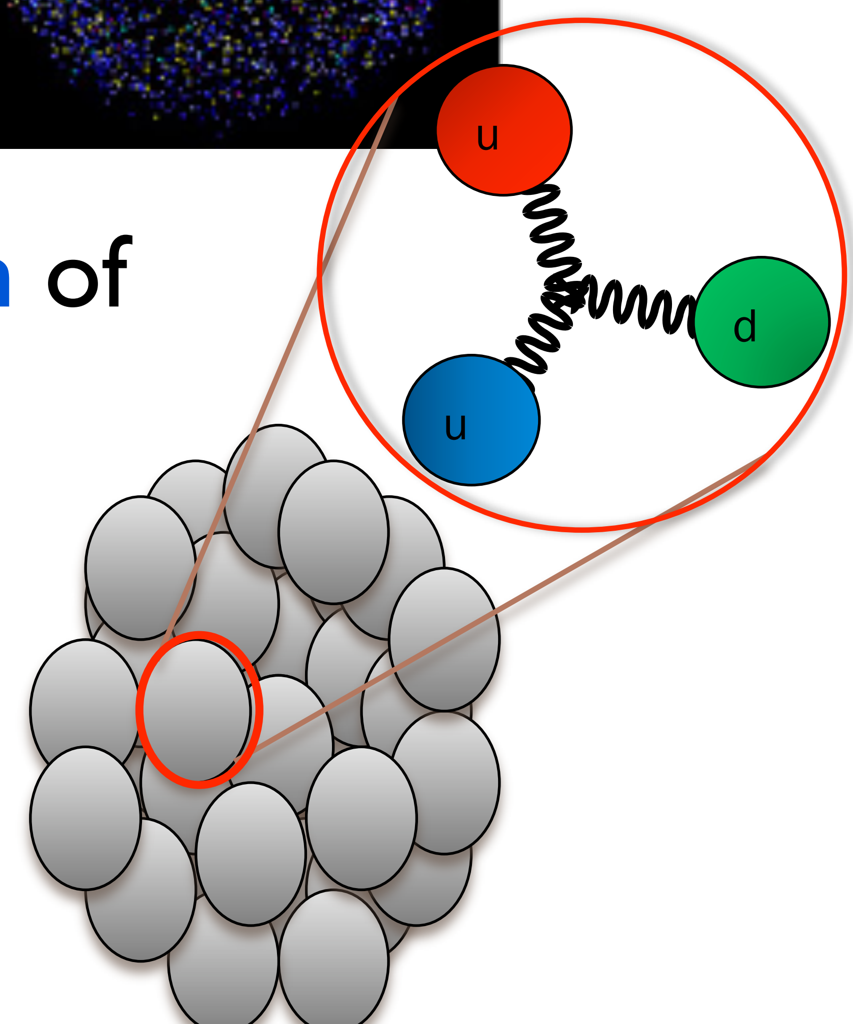


- the goal is to create large region of large energy density
- study of collective, dynamical properties of QCD
- early Universe on a short timescale!



How dense is the system?

- Experimental facilities
  - ✓ CERN SPS: 1986- $\sqrt{s}$ = 17.3 GeV; [In, Pb]
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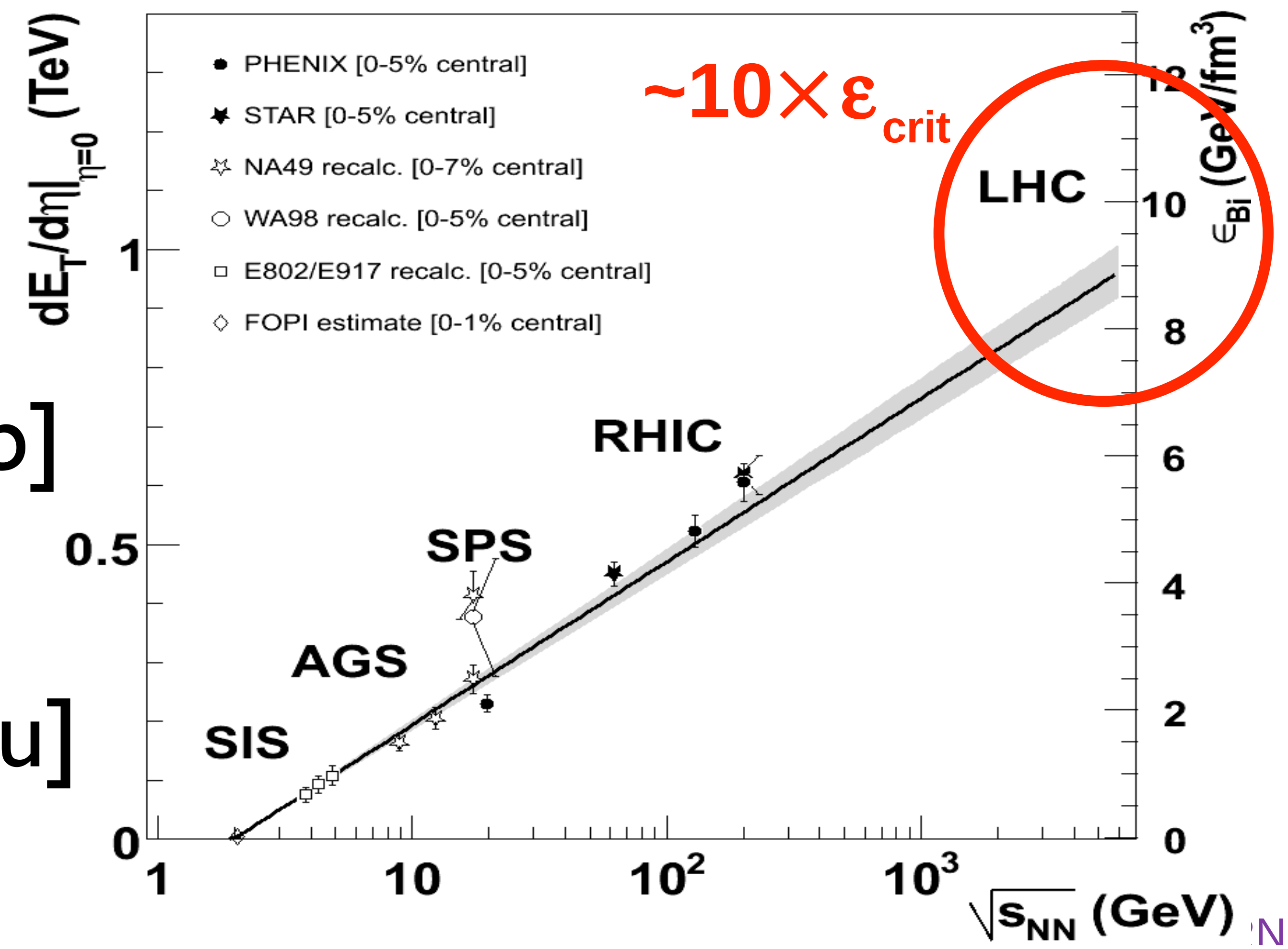
  - ✓ CERN LHC: 2010- $\sqrt{s}$ = 2.76, 5.5 TeV [Pb]



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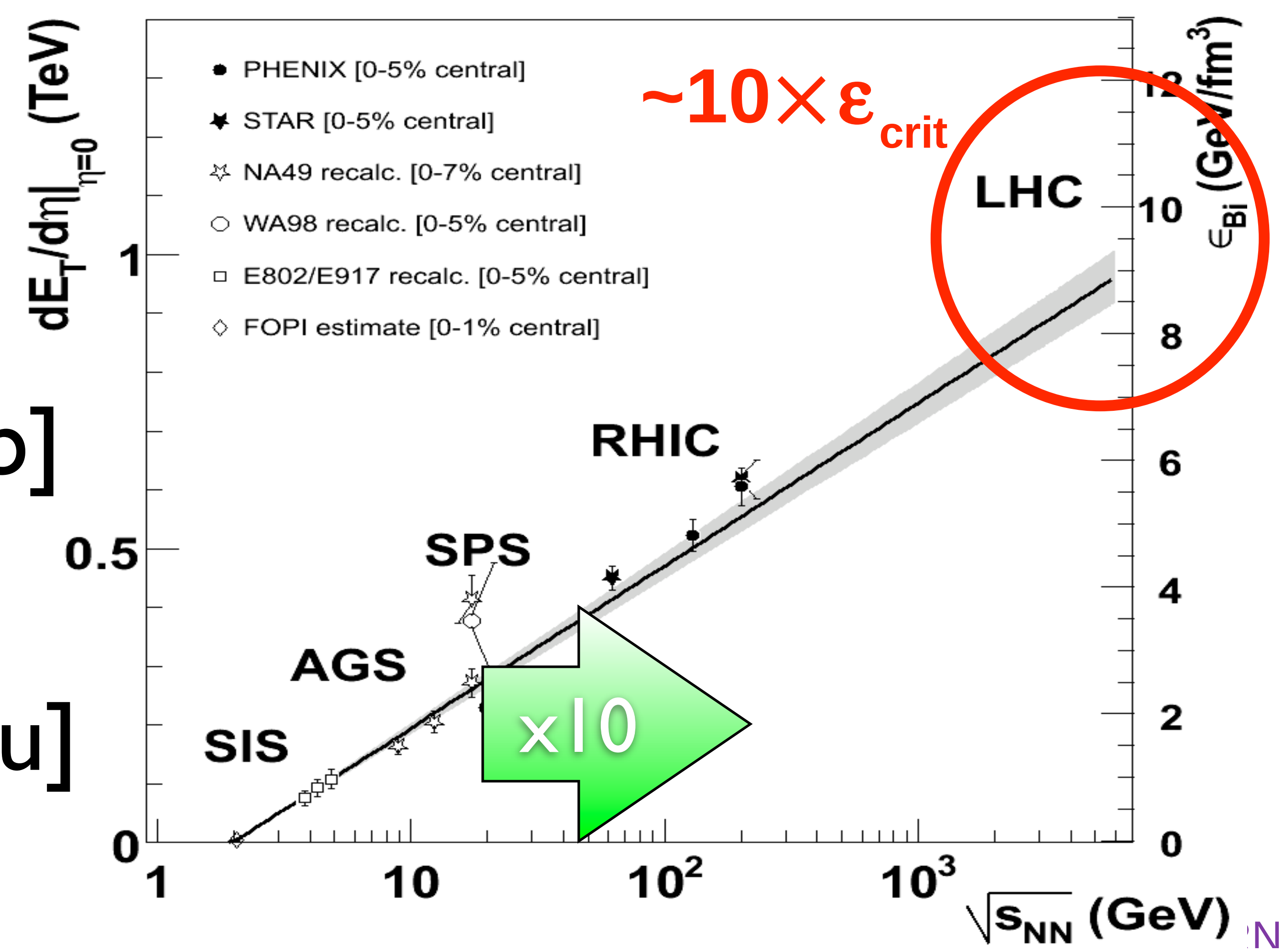

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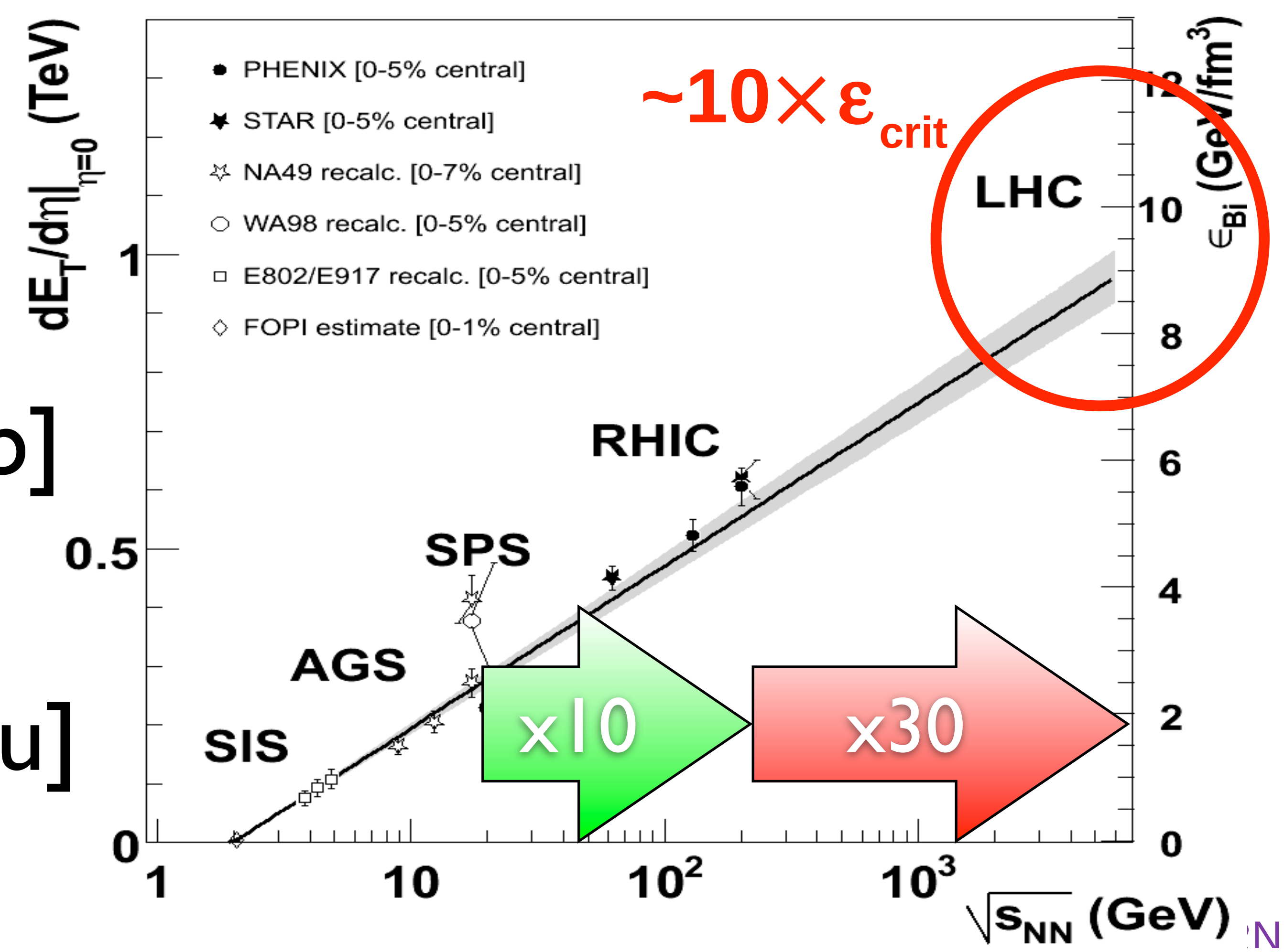

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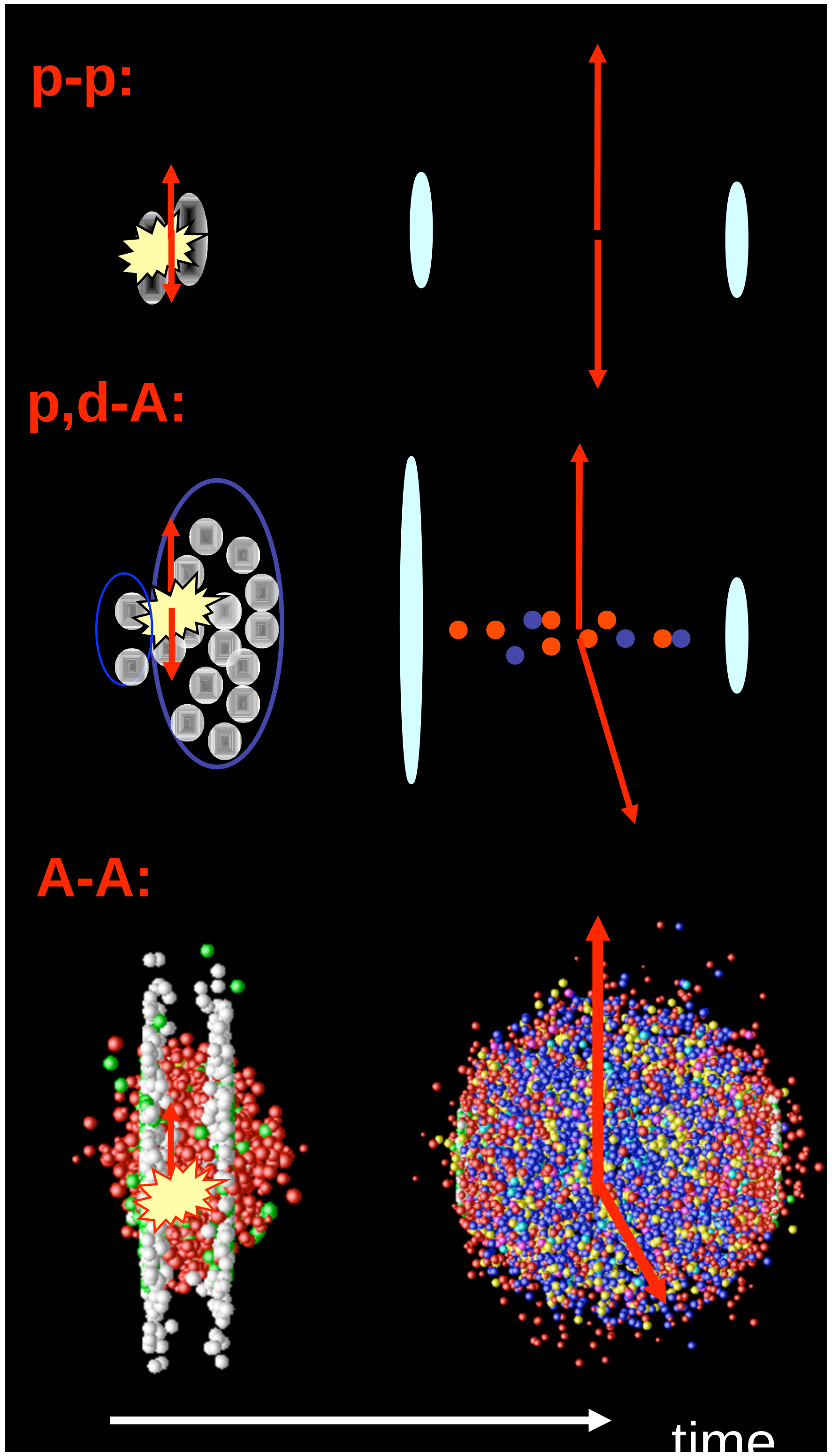
Baselines



- p-p: QCD vacuum
- p,d-A: cold nuclear matter
- A-A: hot & dense QCD matter

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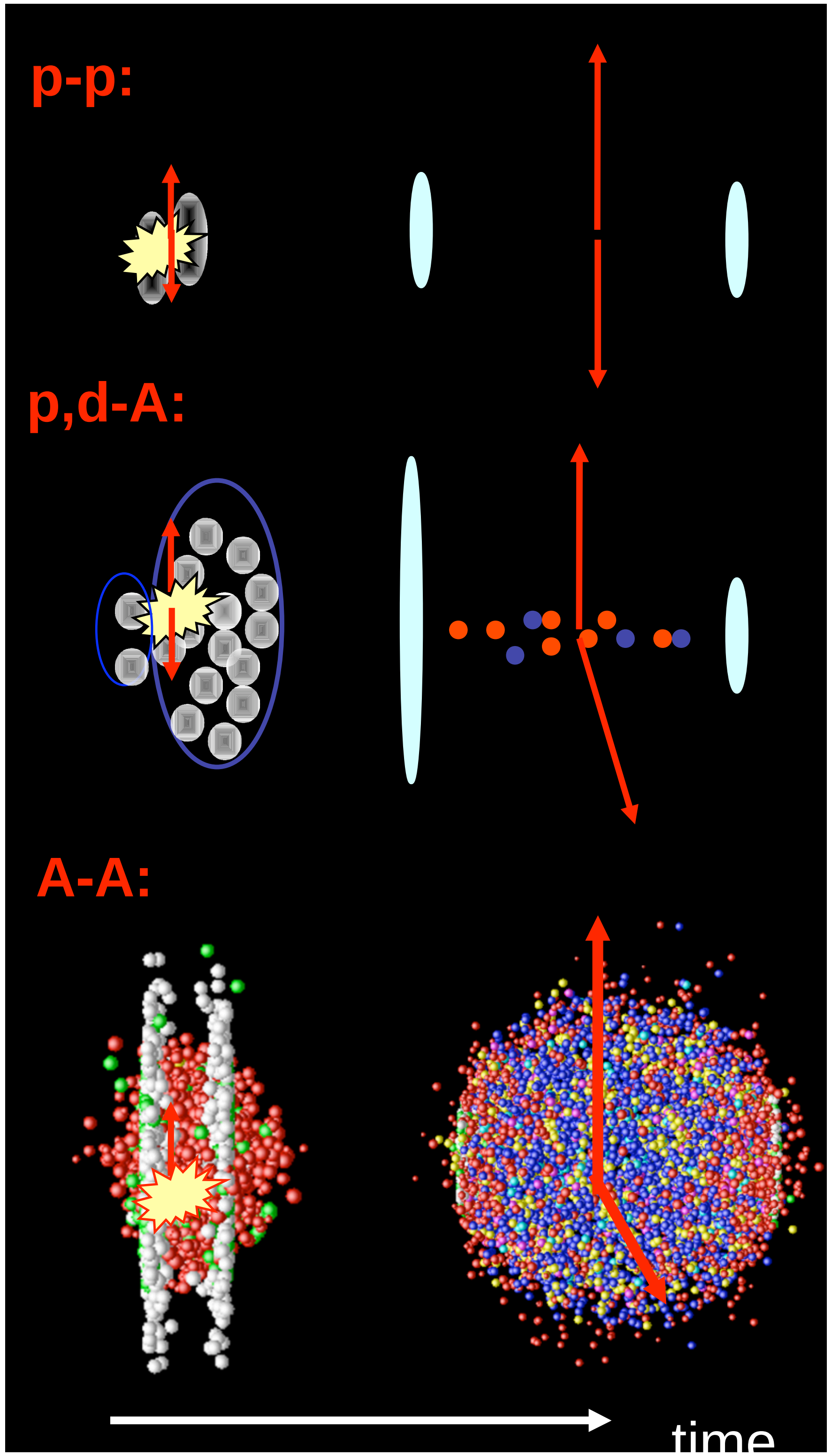

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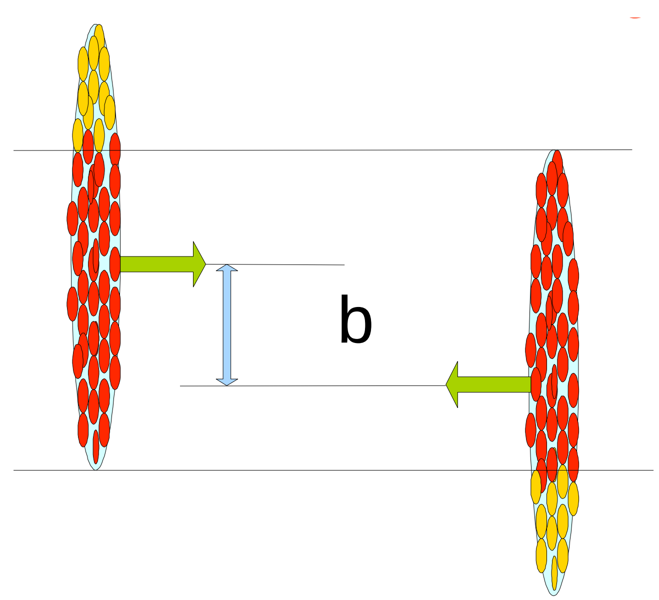
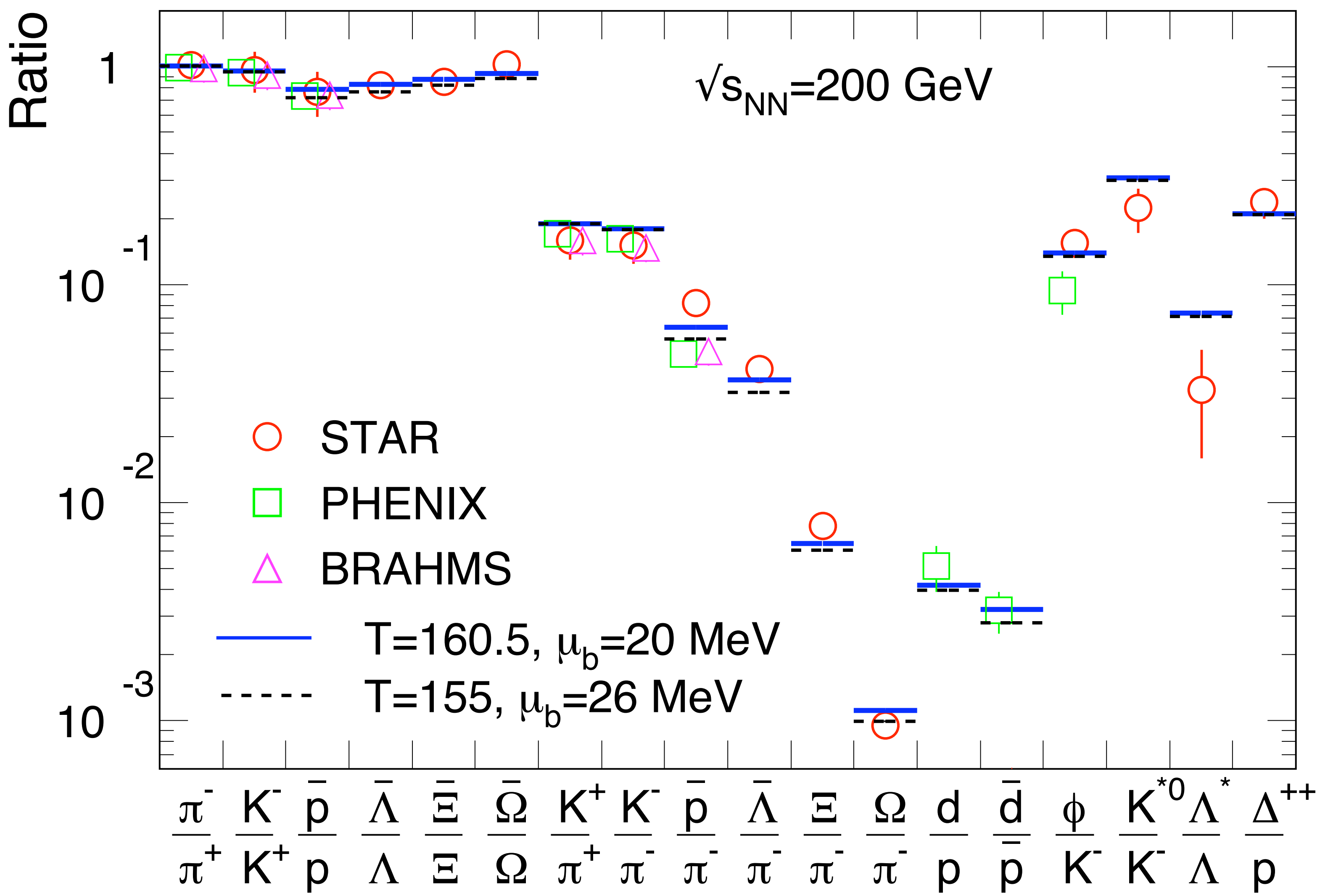


Plasma volume dialed varying impact parameter *b* ("centrality")

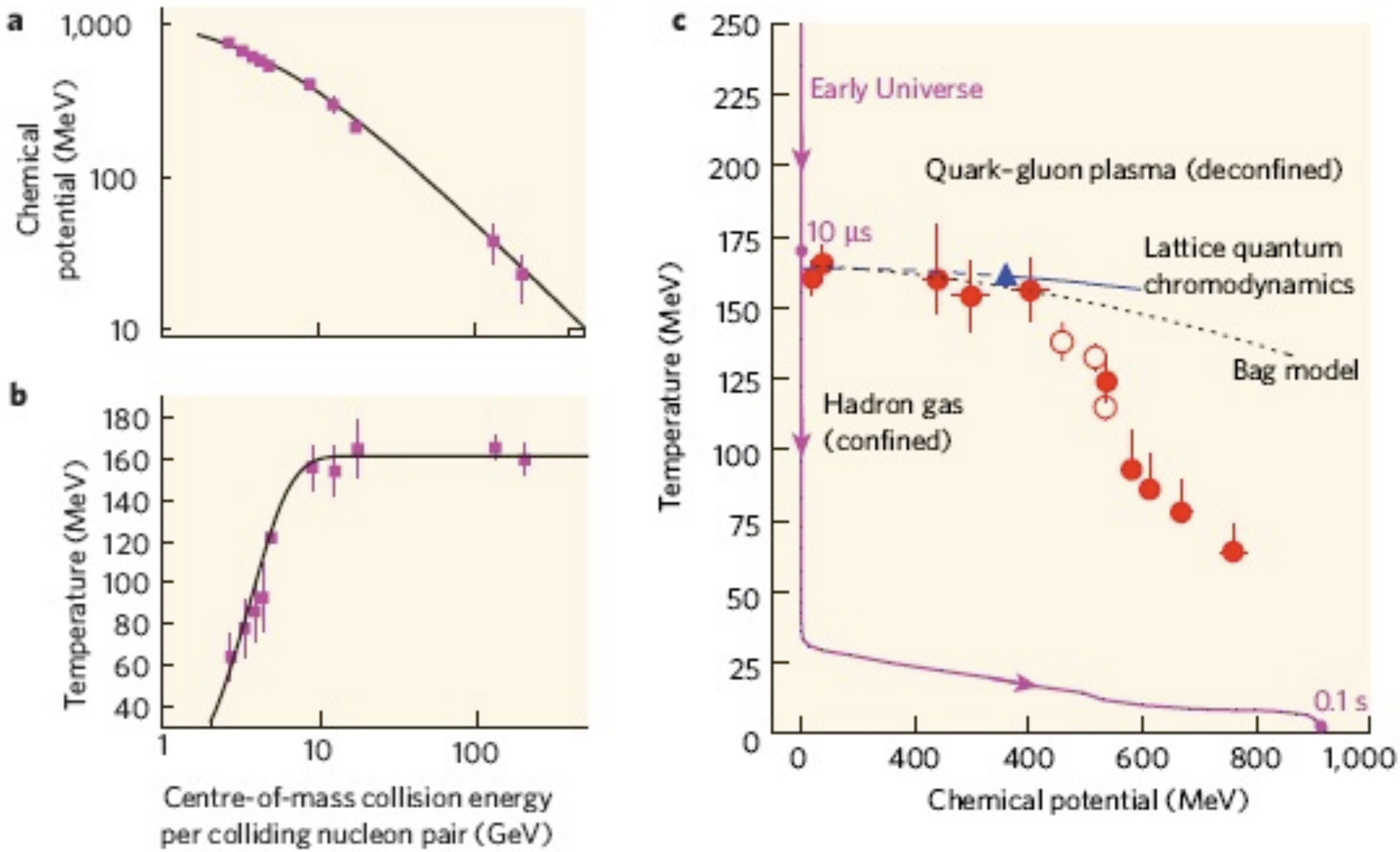
Hadron yields



- matter is hot
- almost transparent for baryons

The QCD phase diagram

[Braun-Munzinger, Stachel Nature (2007)]



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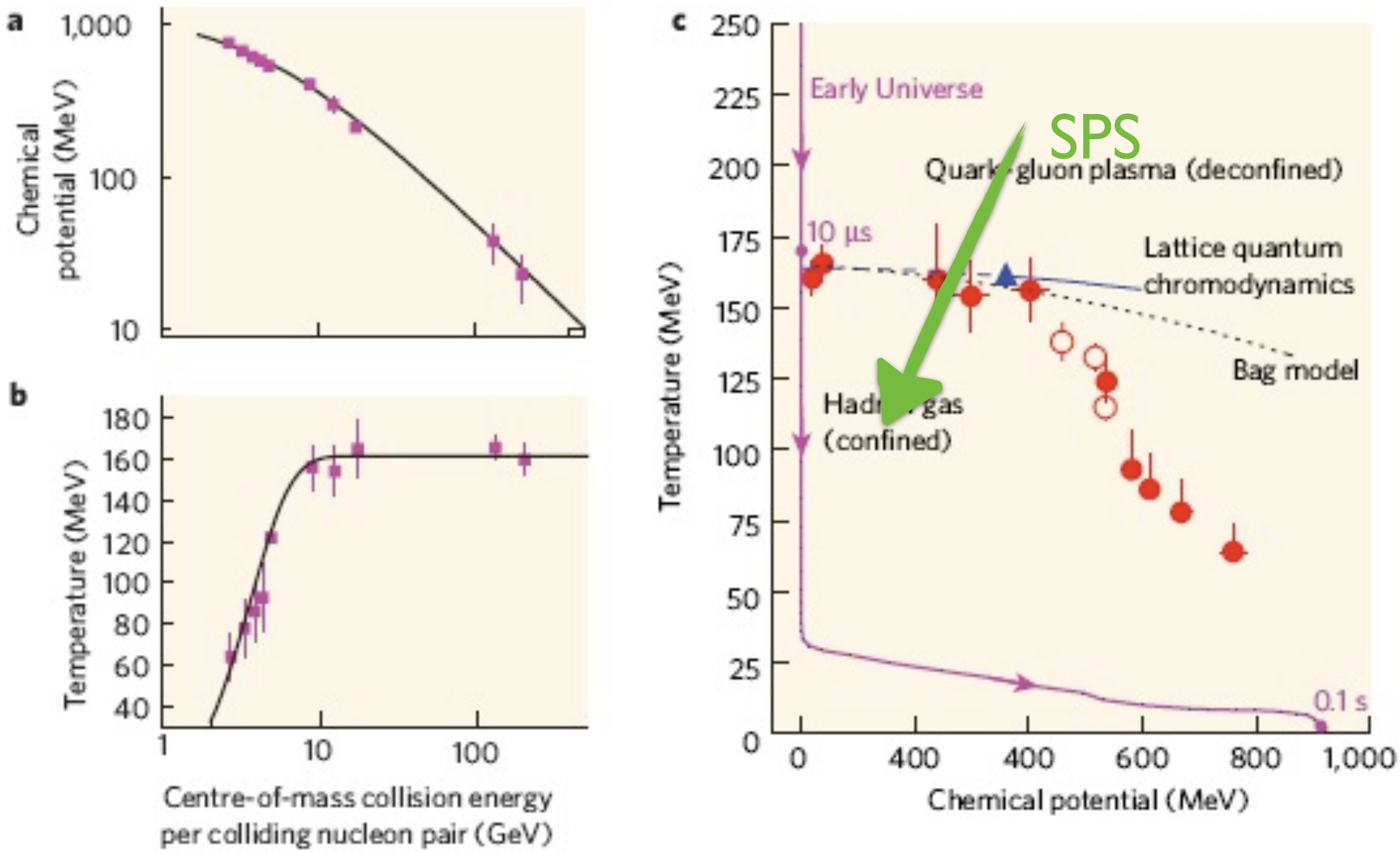

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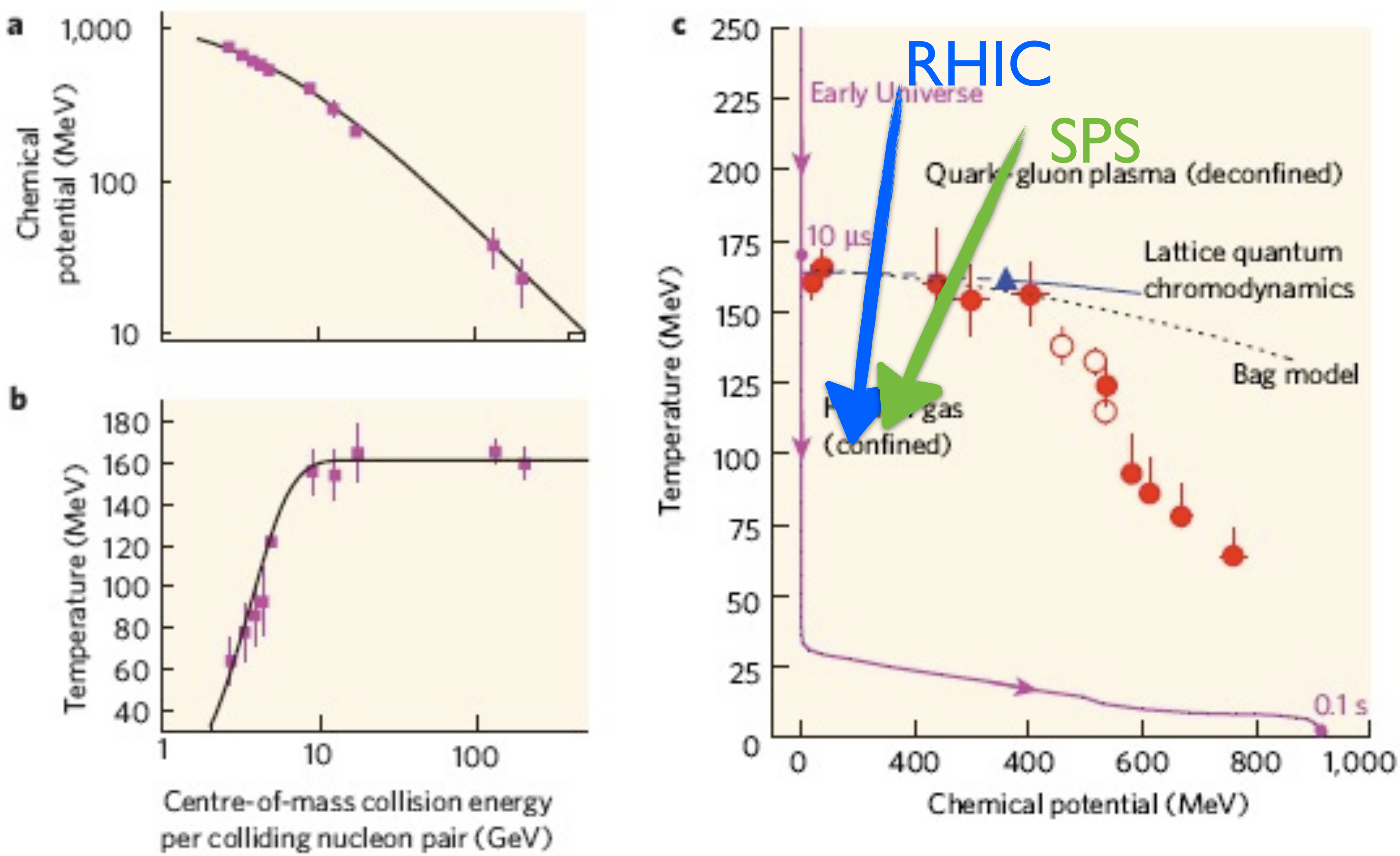

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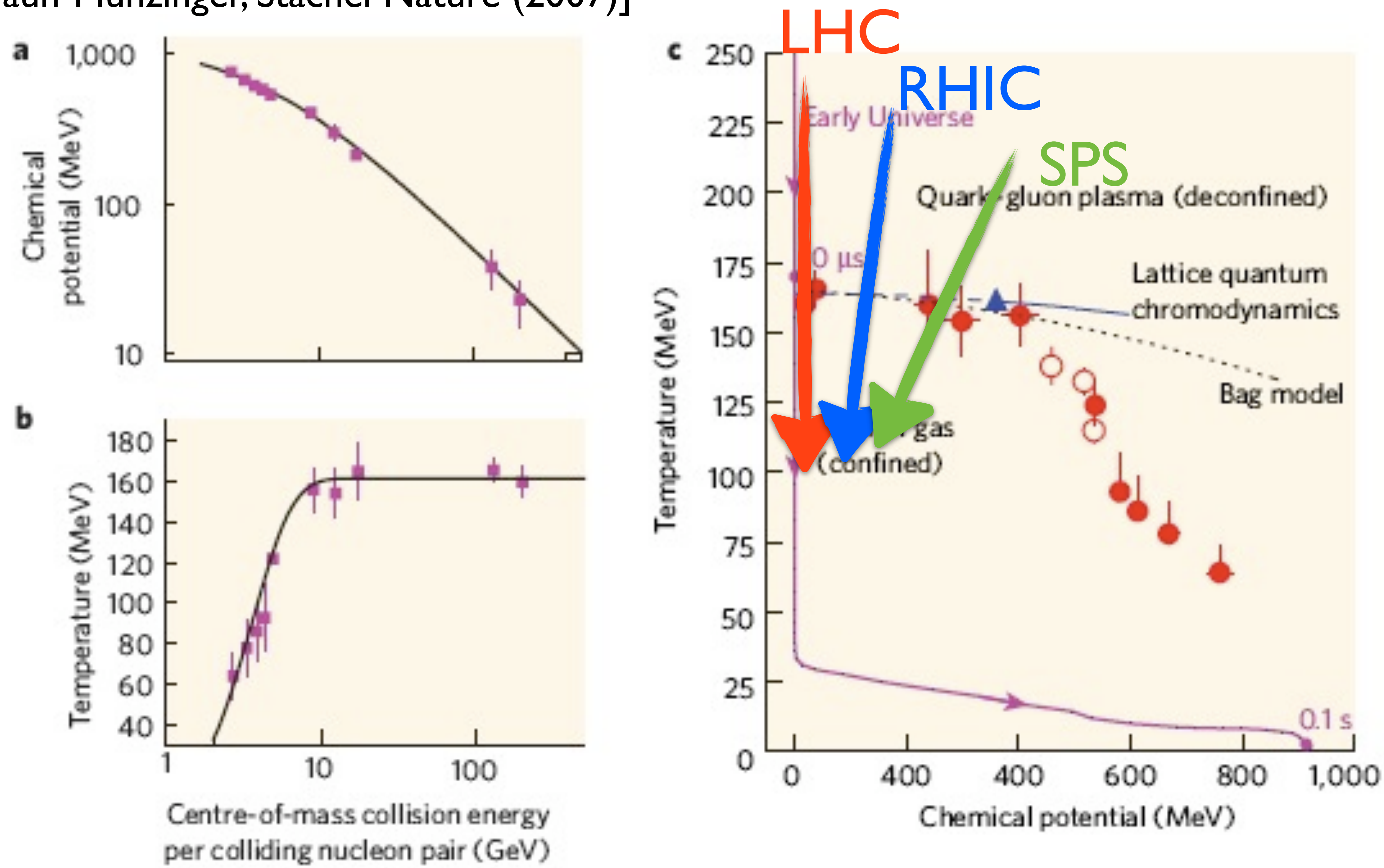
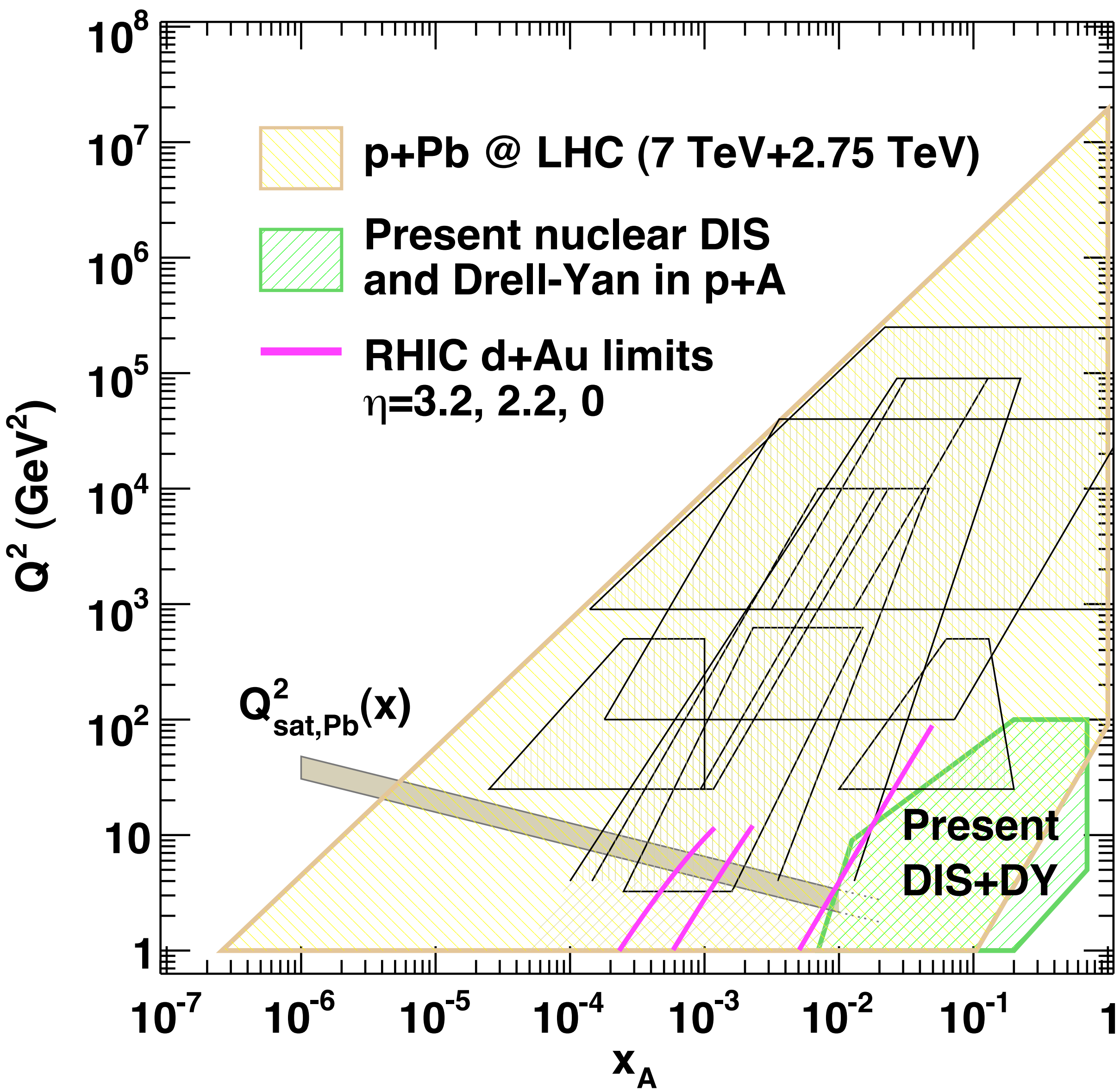


New territories @ LHC



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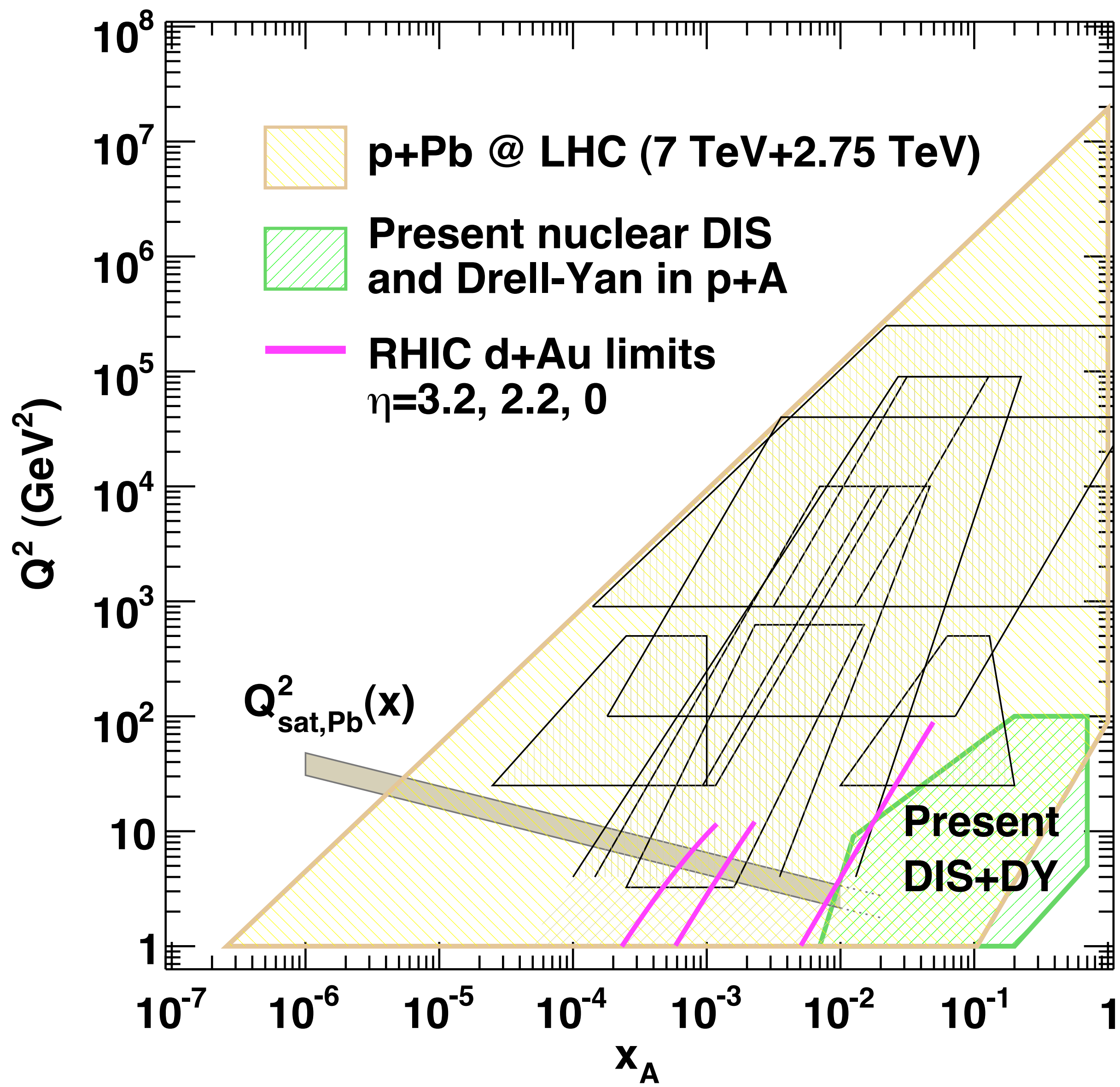

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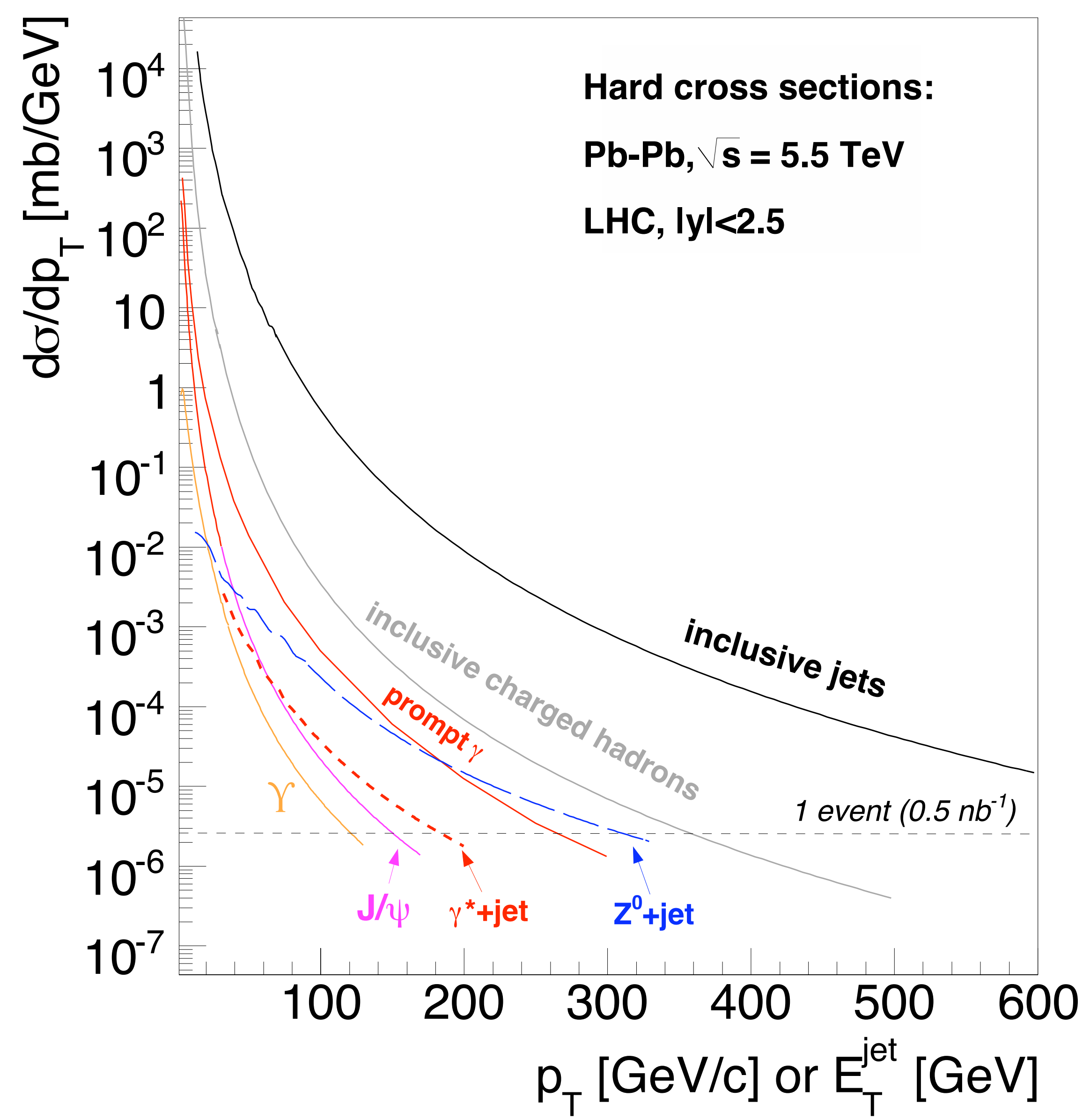

[D'Enterria 2008]

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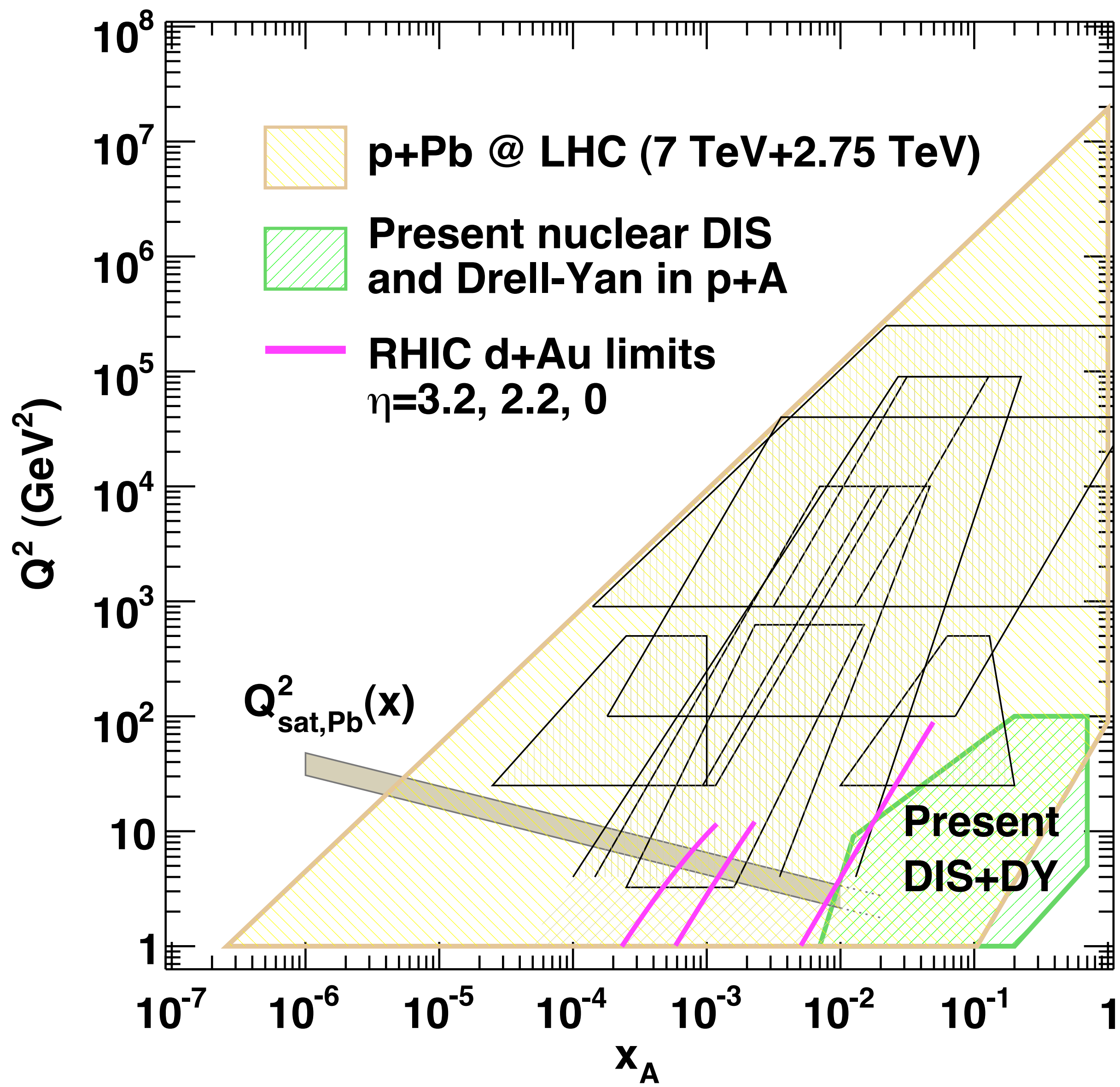

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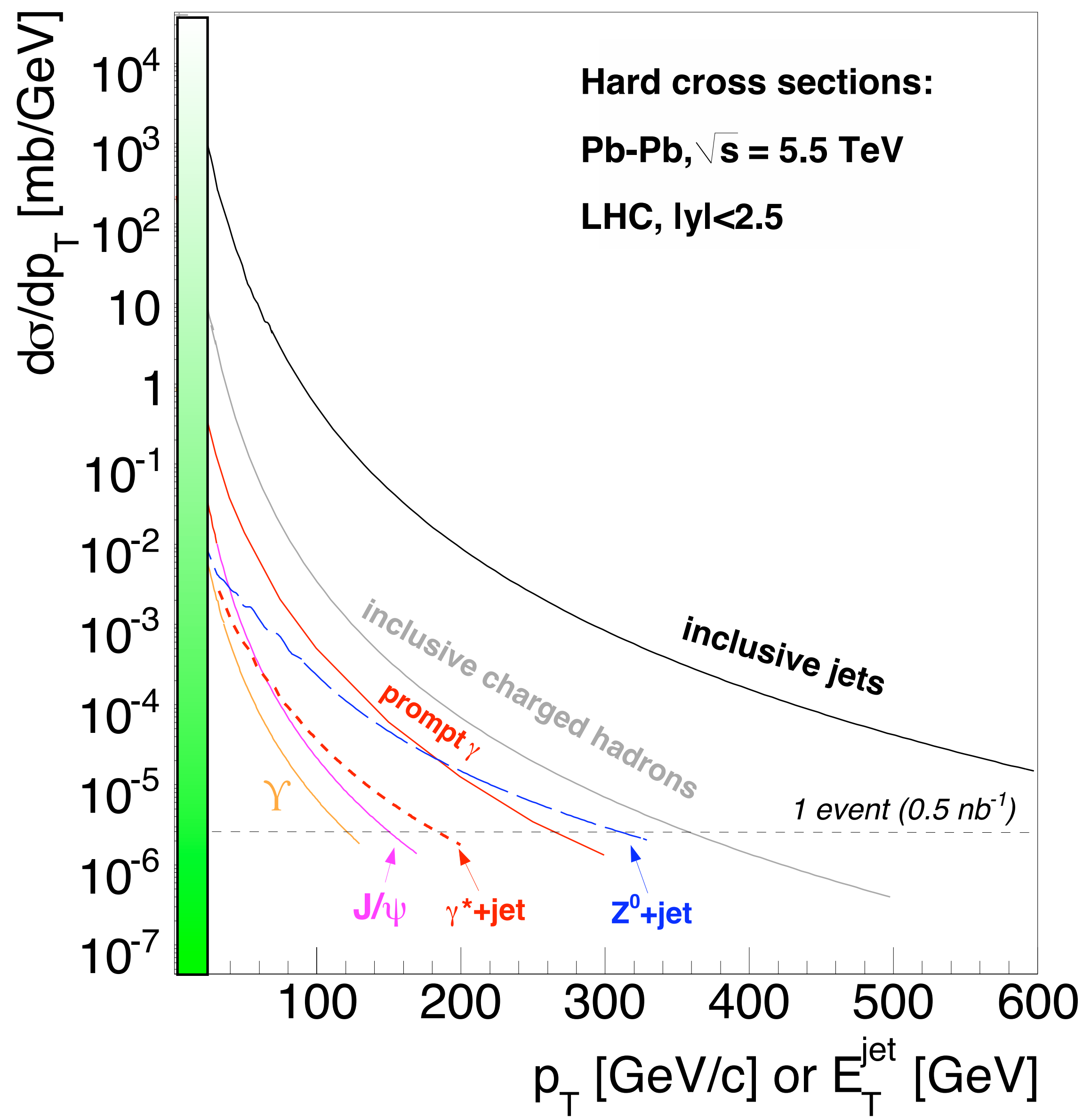

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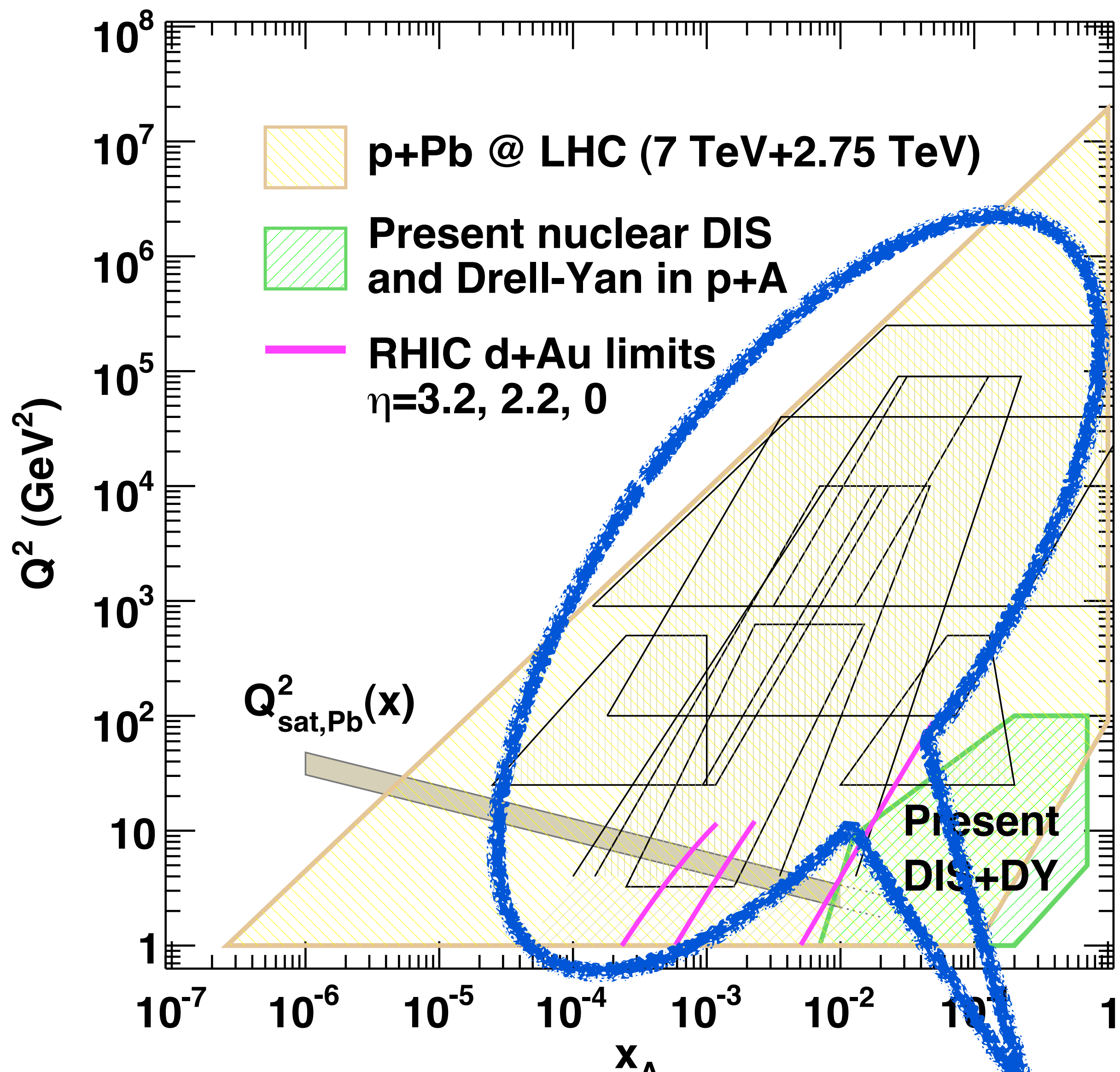

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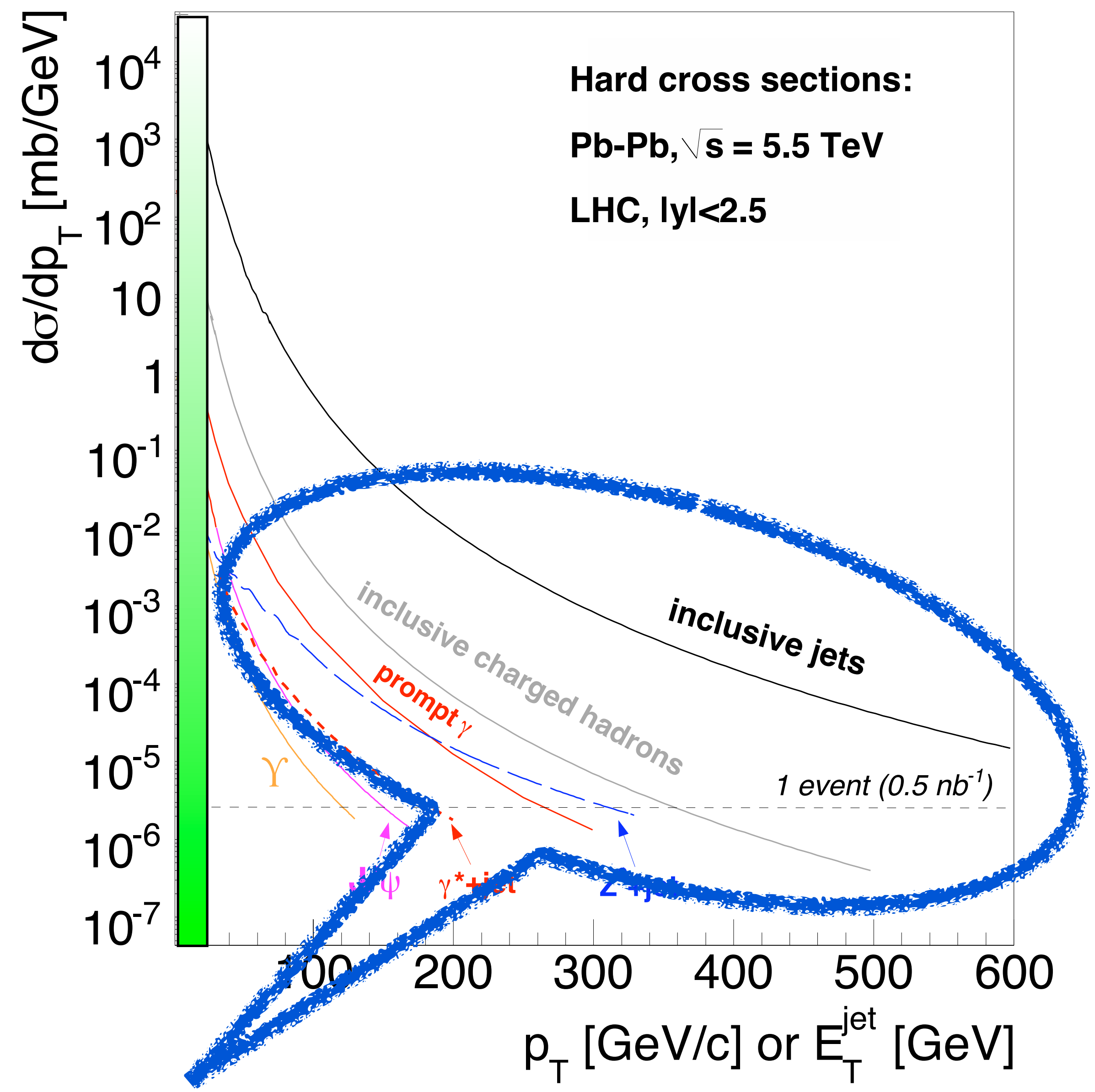

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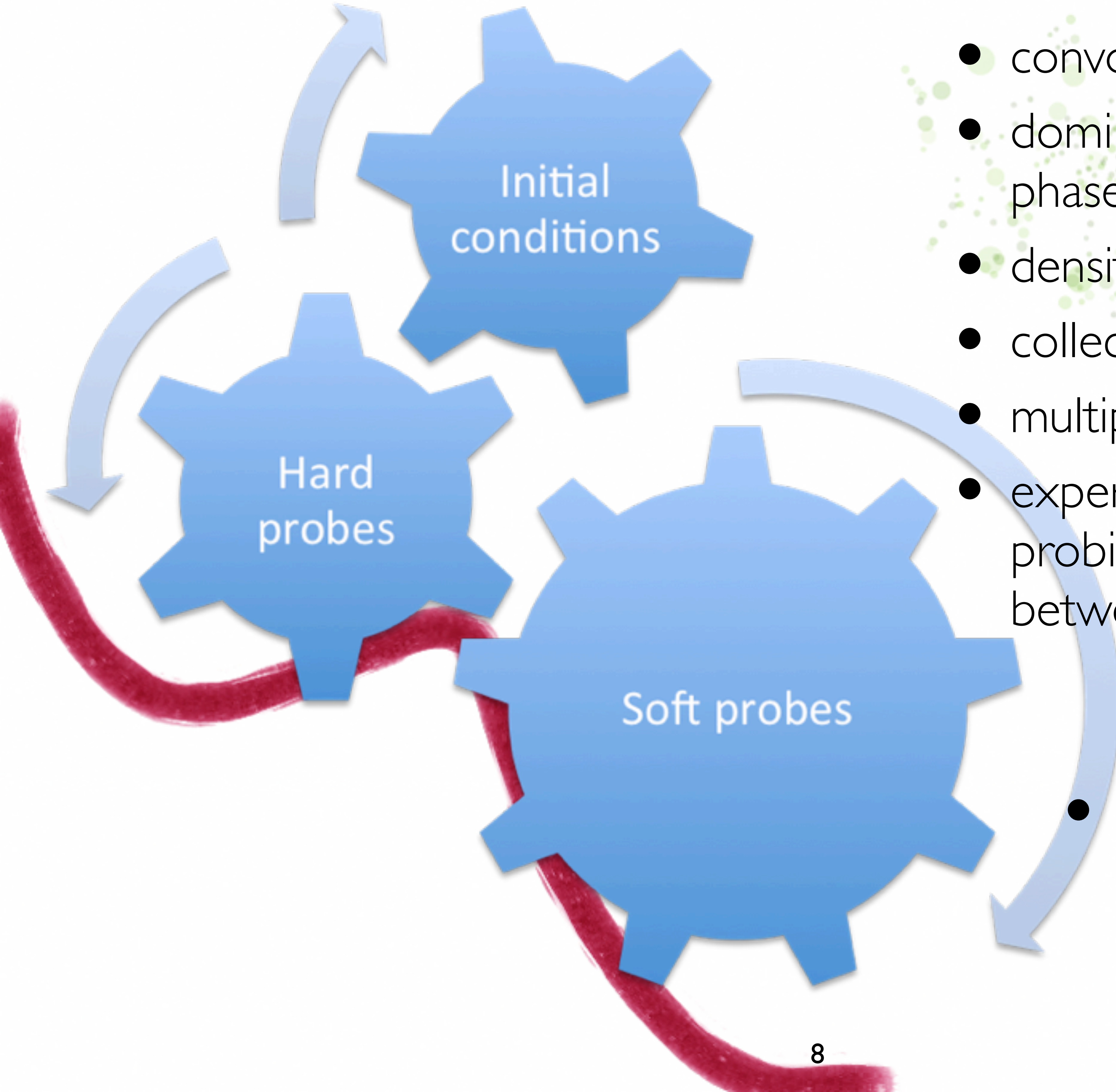
unexplored!



- convolution
- dominated by deconfined phase
- density effects
- collectivity
- multiple scattering
- experiments start (really) probing the relationship between them!

- Disclaimer: choice of topic/framework/ perspective is highly biased...

Initial state

Deep inelastic scattering

Target is probed with a highly energetic electron that emits a virtual photon ($-q_\gamma^2 = Q^2$).

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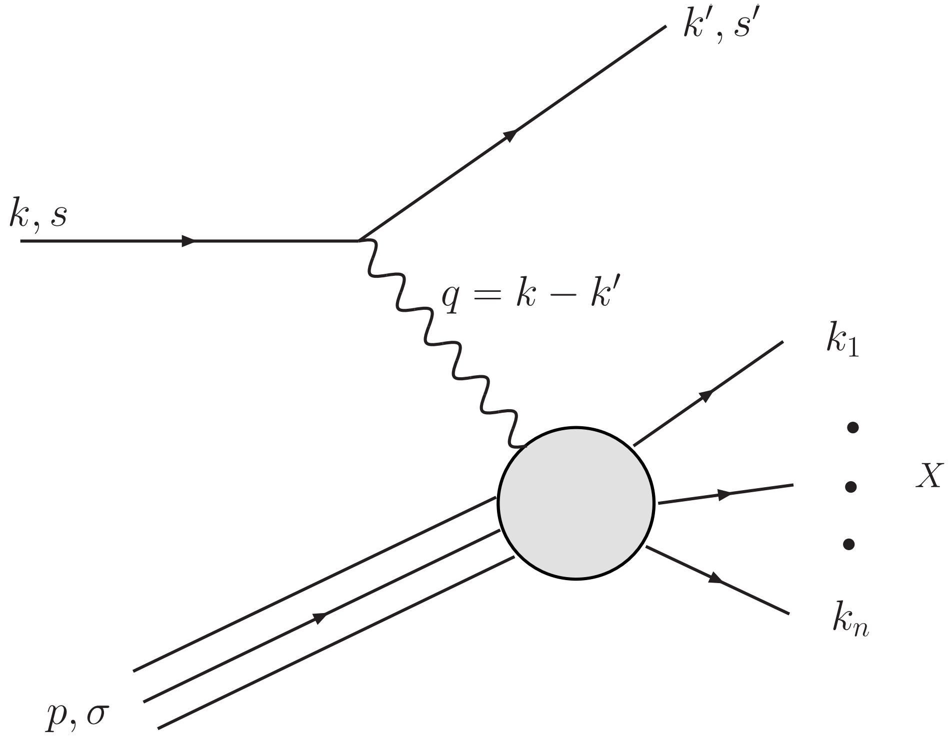

$$
\begin{aligned}
W^2 - m_p^2 &= (p+q)^2 - m_p^2 \\
&= 2\,p\cdot q\left(1 - \frac{-q^2}{2p\cdot q}\right) = 2\,p\cdot q(1-x)
\end{aligned}
$$

$$x = \frac{-q^2}{2p\cdot q}$$

momentum fraction carried by the parton probed by the virtual photon

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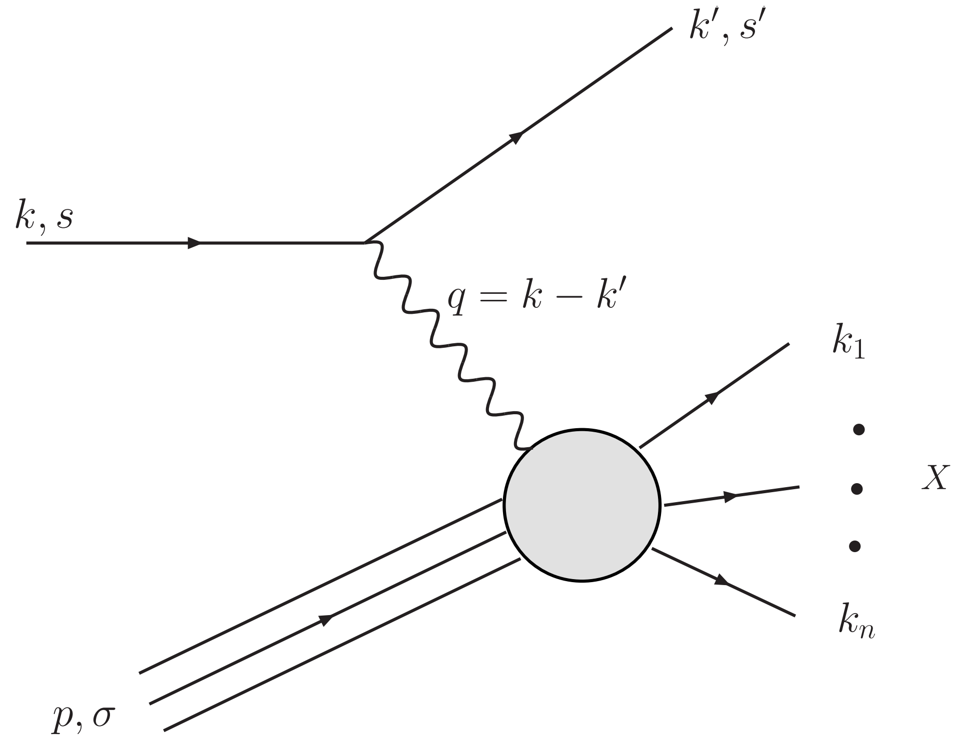

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i) DIS regime: $Q^2 >> M^2$

ii) HE regime: $s >> Q^2 \Rightarrow x \sim Q^2/s << 1$

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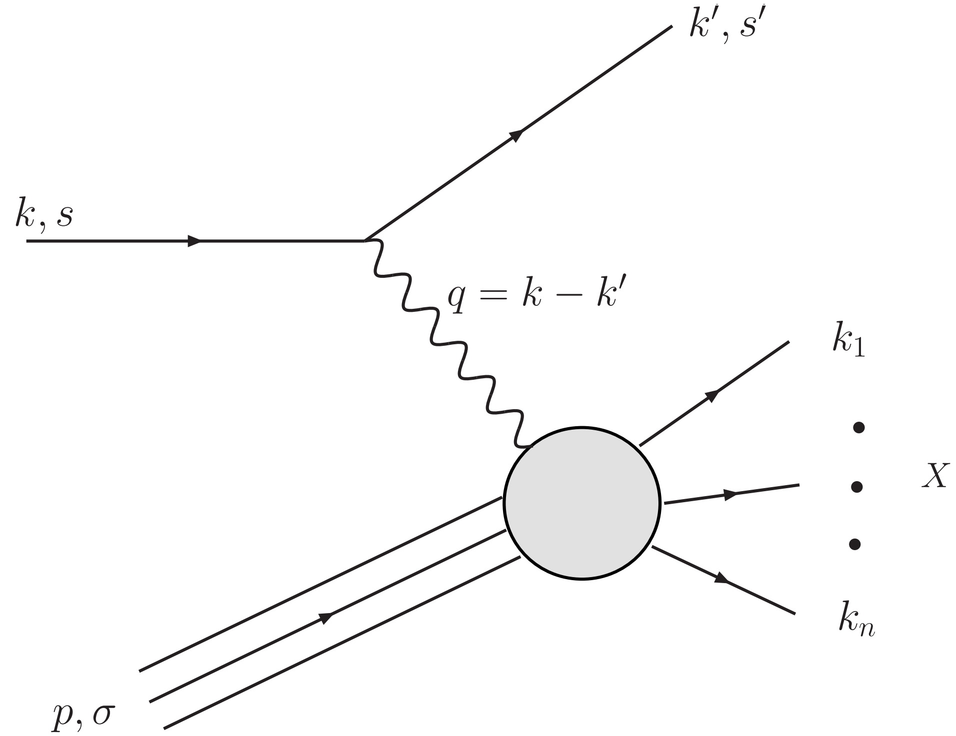

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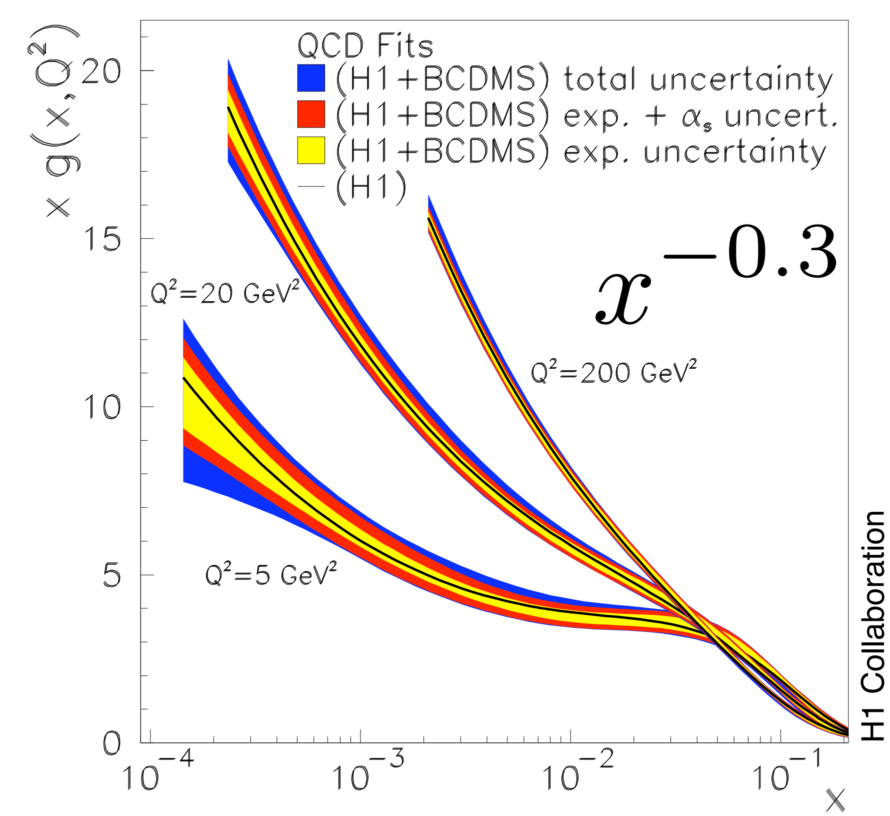

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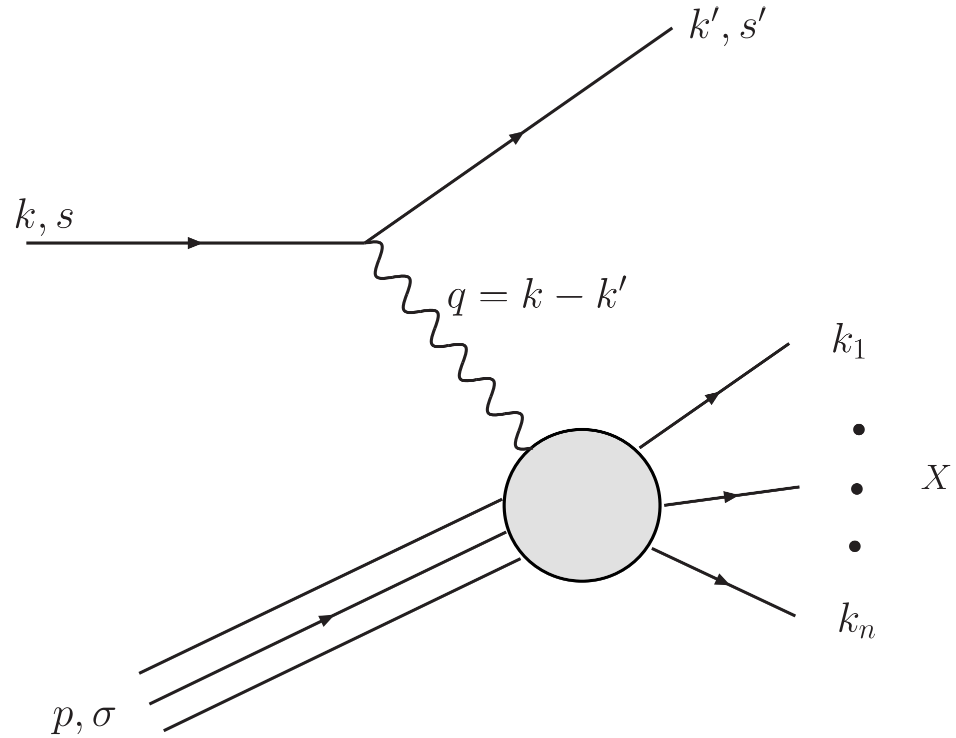

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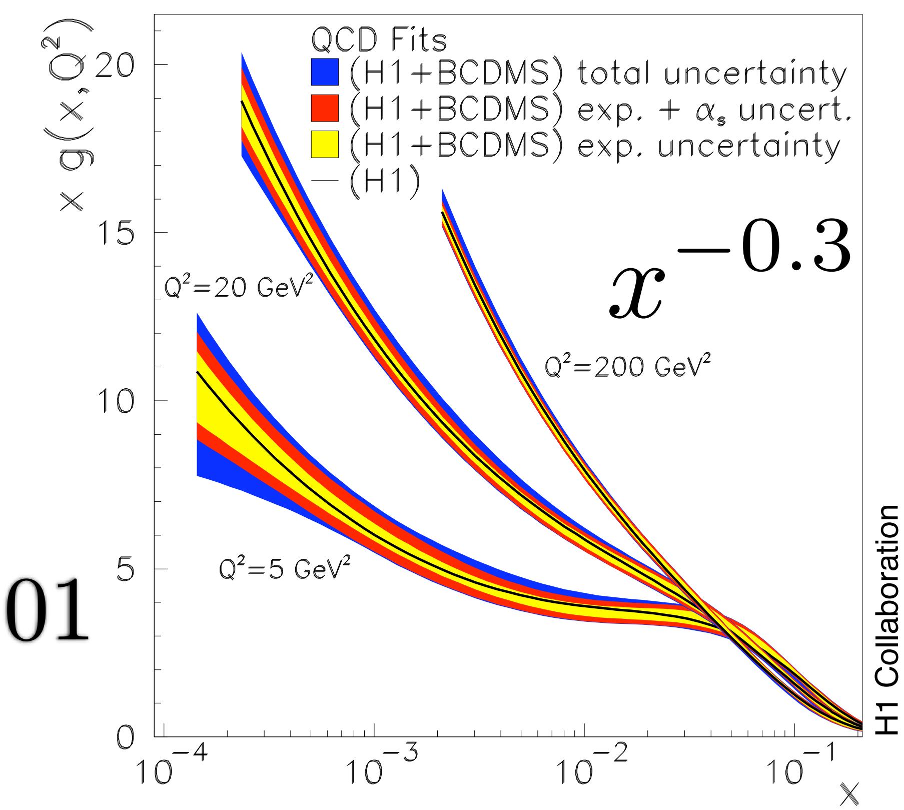
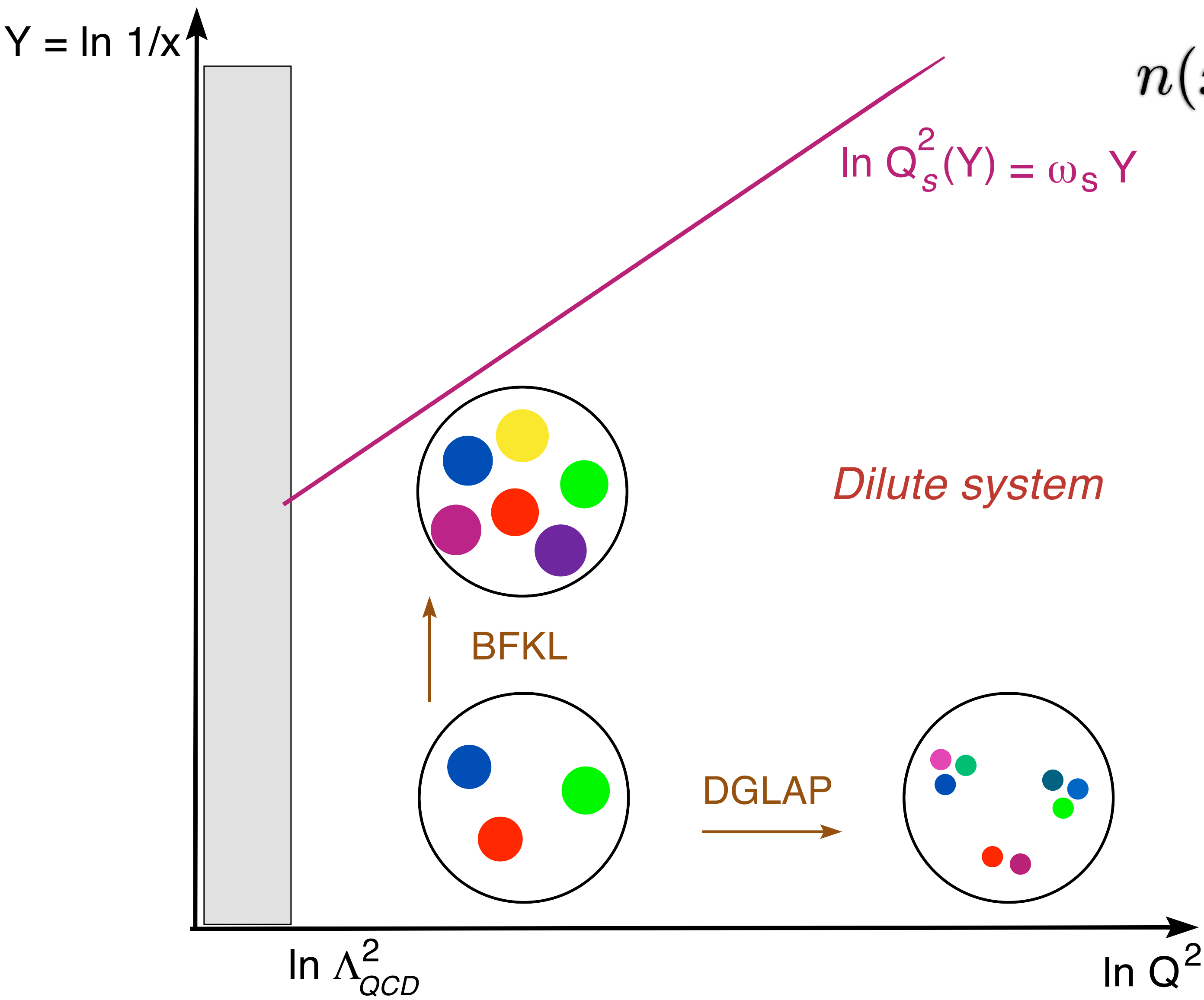
Most relvant for HIC! $x_A \simeq \frac{p_\perp}{\sqrt{s}} < 0.01$



Gluon saturation

Large gluon occupation number: $n(x, k_\perp) \sim 1/\alpha_s$

$$n(x, k_\perp) \equiv \frac{N(x, k_\perp)}{\pi R^2} \approx \frac{\pi}{Q^2} \times \frac{x\, g(x, Q^2)}{\pi R^2}$$



[Gribov, Levin, Ryskin, Mueller, McLerran...]

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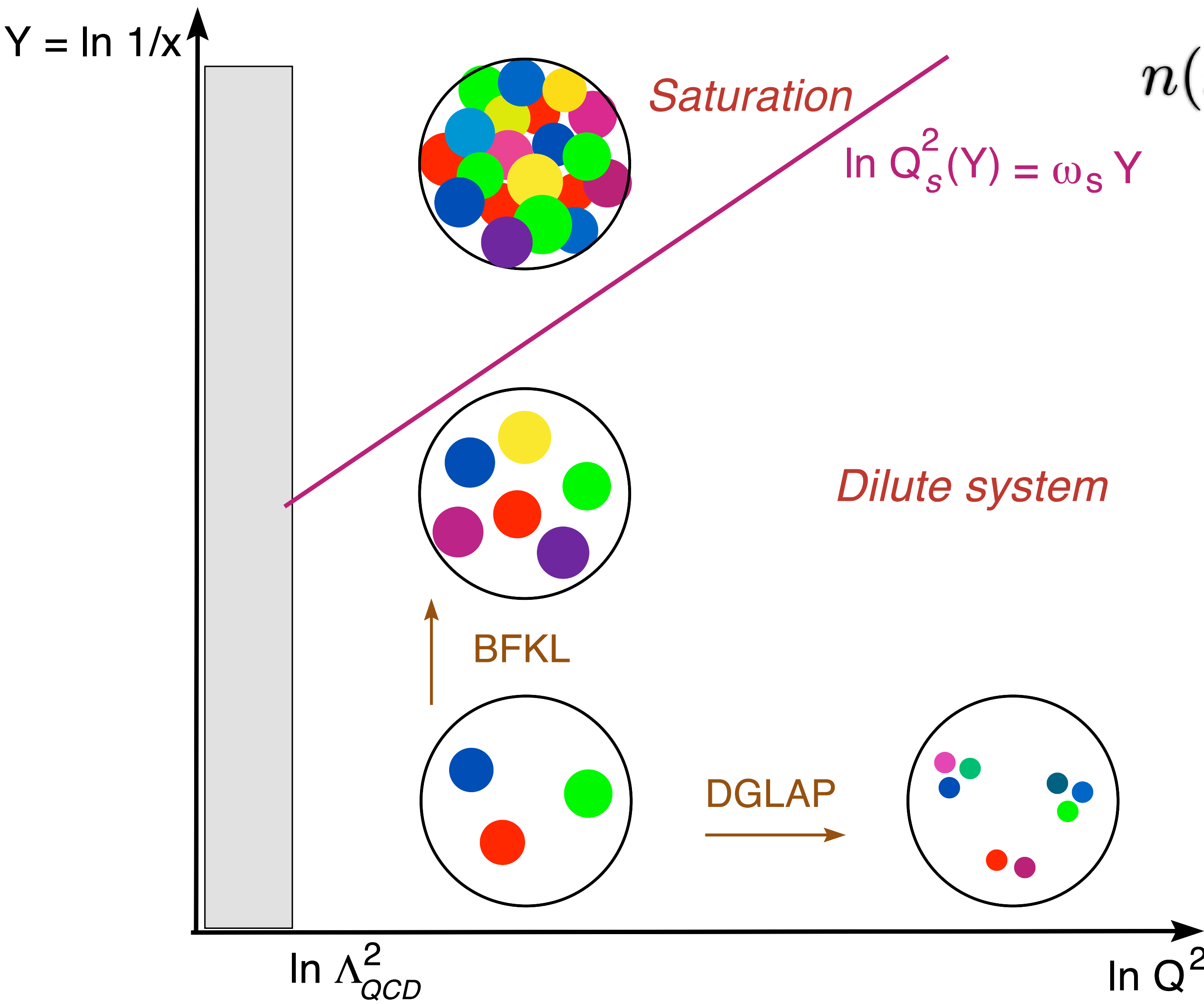

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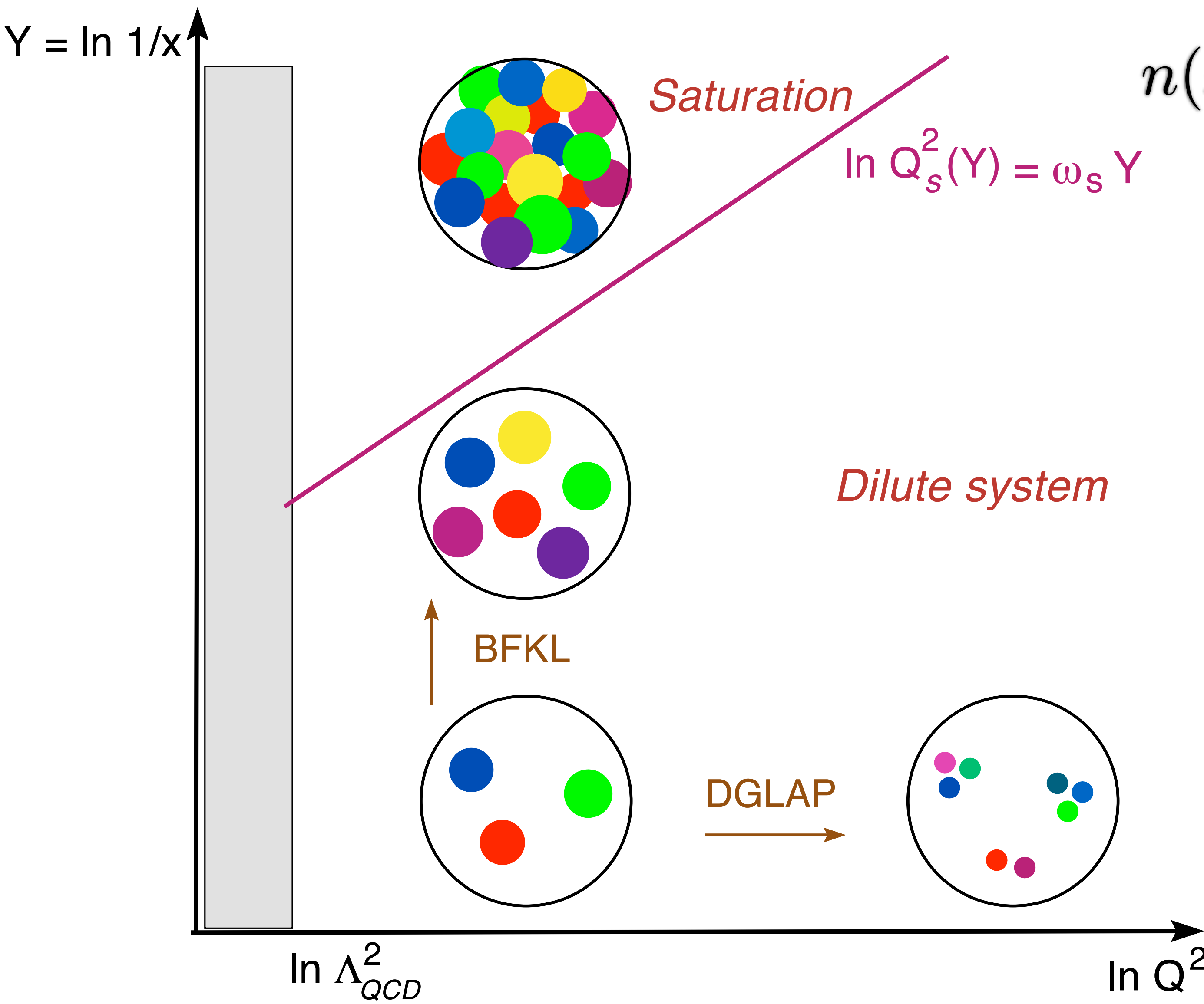

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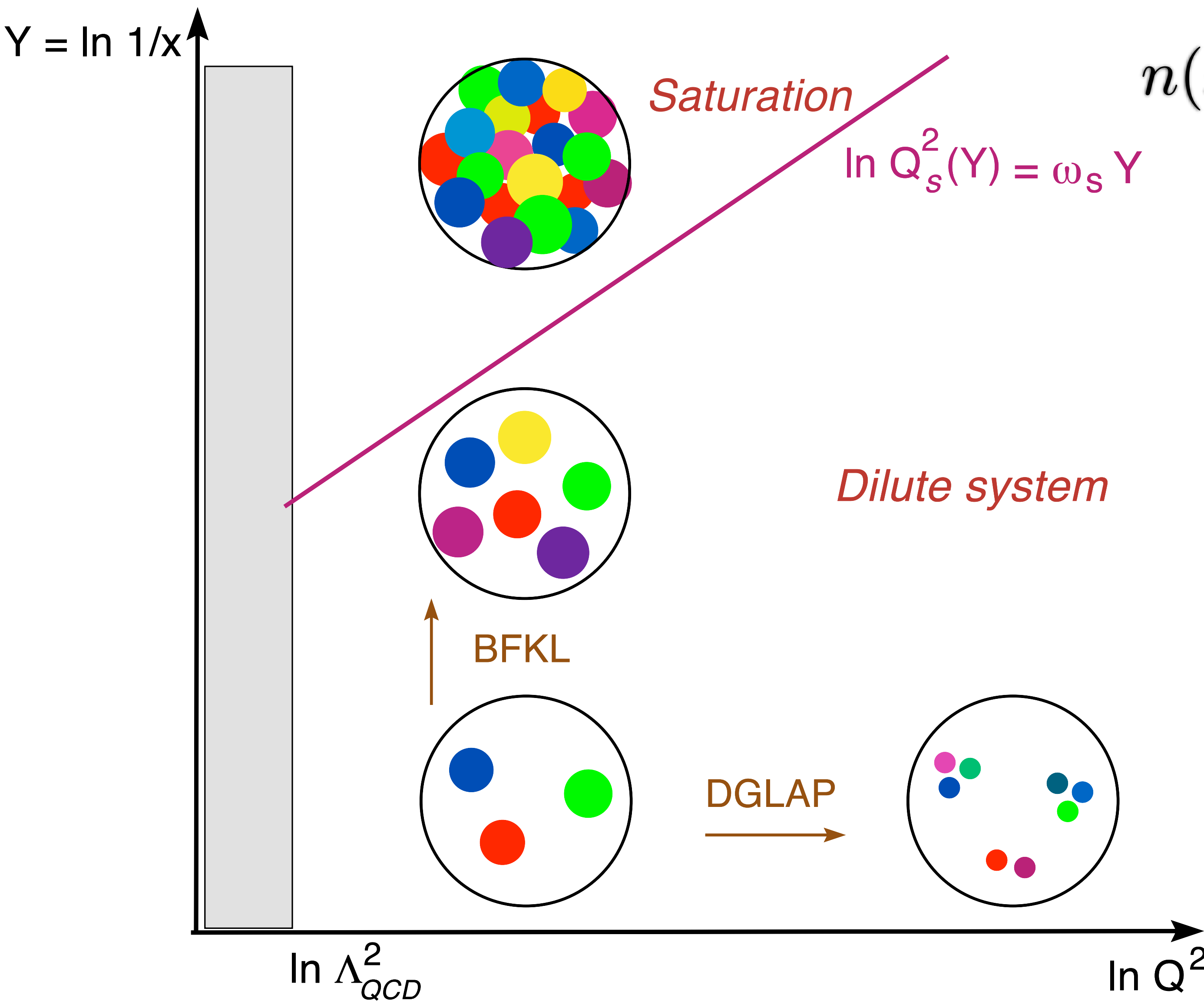

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There appears a new hard scale in the problem related to large densities → allows for perturbative treatment of soft processes!

$$Q_{A\,s}^2(x) \propto A^{1/3} Q_s^2(x)$$

High energy QCD

- collinear factorization
  - ✓ well-known framework
  - ✓ precision physics
  - ✓ so far, so good!
  - ✓ has its limitations

- “saturation”
  - ✓ unitarity
  - ✓ high-energy factorization
  - ✓ quantitative results are coming
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rcBK equation:

$$\frac{\mathcal{N}(r,Y)}{\partial \ln(1/x)} = \int d^2\mathbf{r_1}\ K^{\text{run}}(\mathbf{r},\mathbf{r_1},\mathbf{r_2})\,[\mathcal{N}(r_1,Y)+\mathcal{N}(r_2,Y) -\mathcal{N}(r,Y)-\mathcal{N}(r_1,Y)\,\mathcal{N}(r_2,Y)]$$

NLO: Balitksy, Kovchegov, Albacete, Weigert, Chirilli

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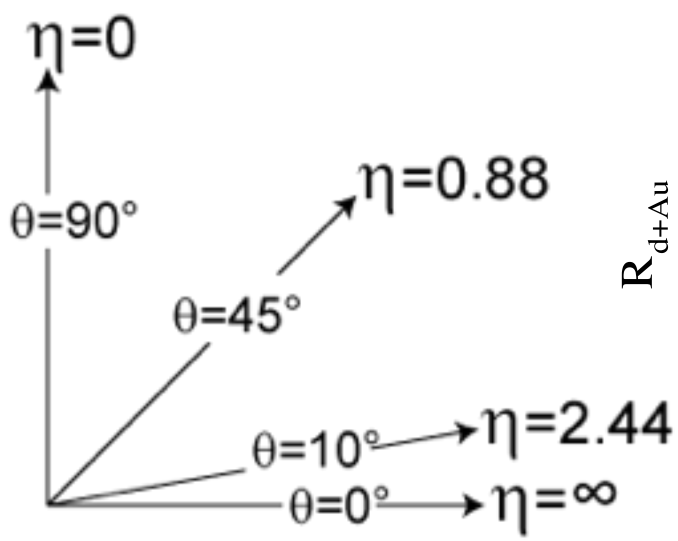
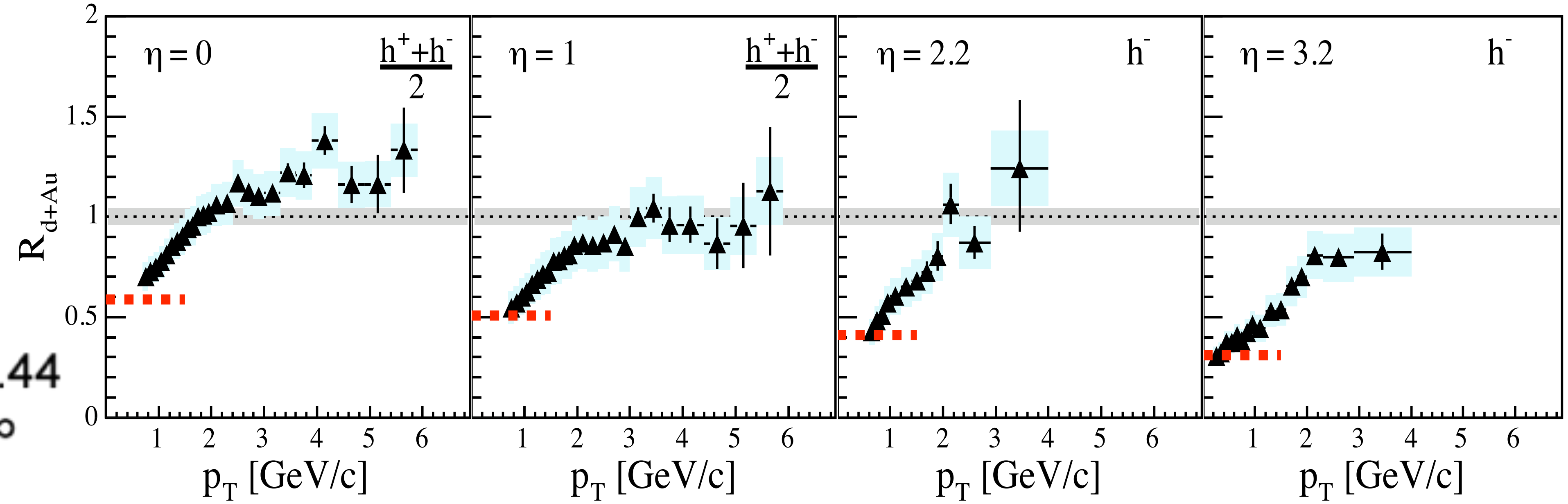
non-linear term

NLO: Balitksy, Kovchegov, Albacete, Weigert, Chirilli

Cold nuclear matter

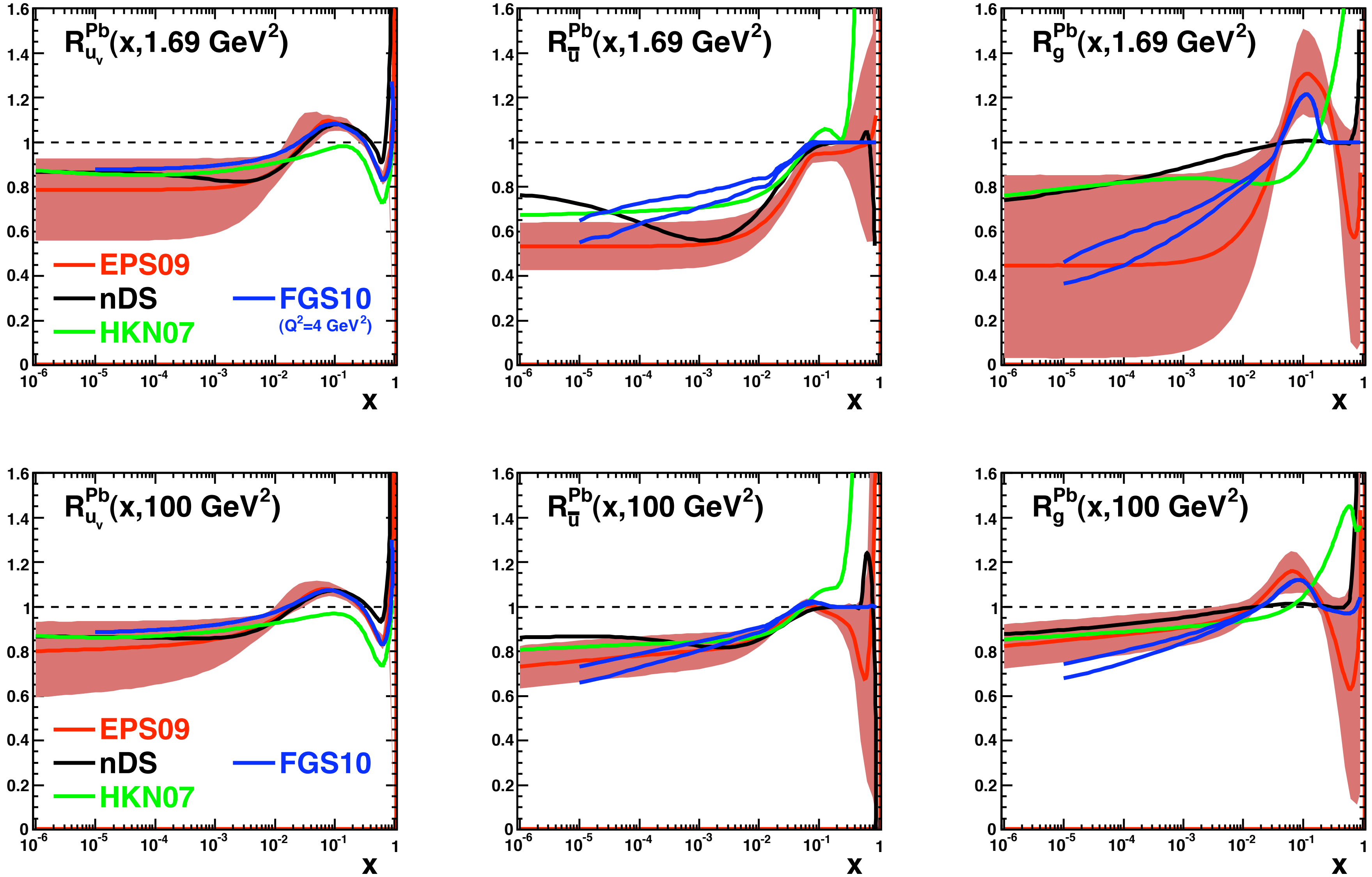




$$x_A \sim \frac{p_\perp}{\sqrt{s}} \exp\left(-\eta\right)$$

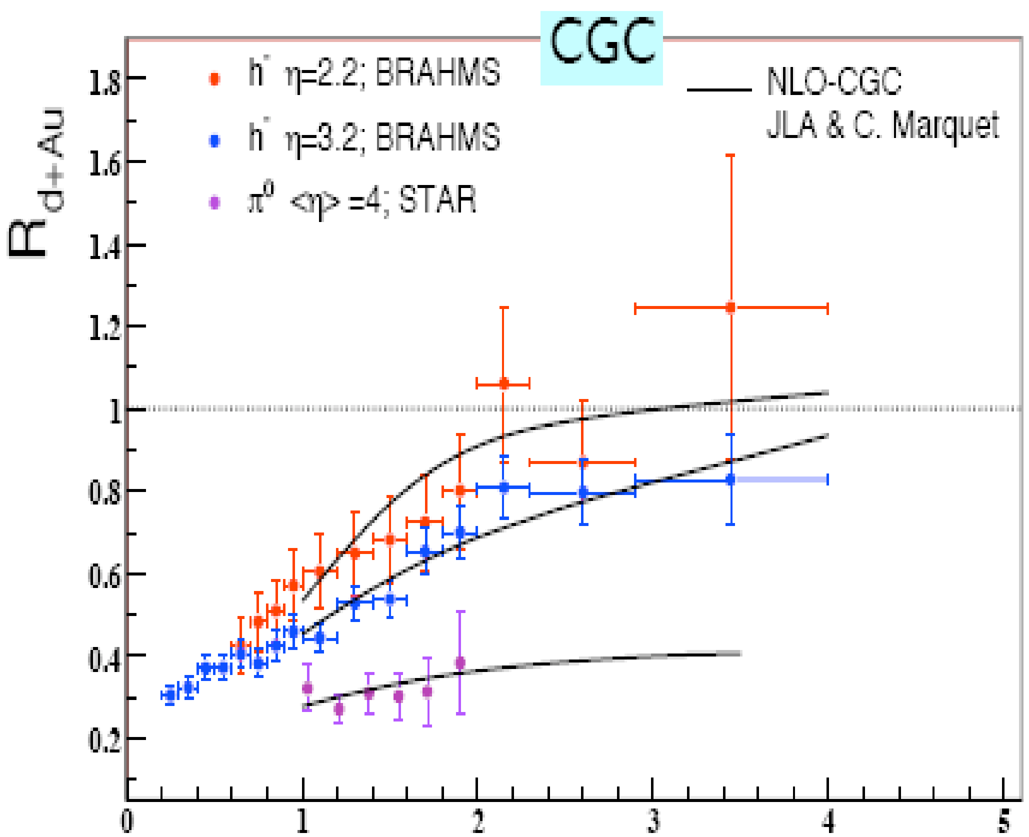
- forward rapidity means probing low-x gluons of the nucleus
- a systematic depletion is observed
- we're close to kinematical phase space - energy loss/ large-x effects (related to projectile) can be involved!

Models of nuclear PDFs

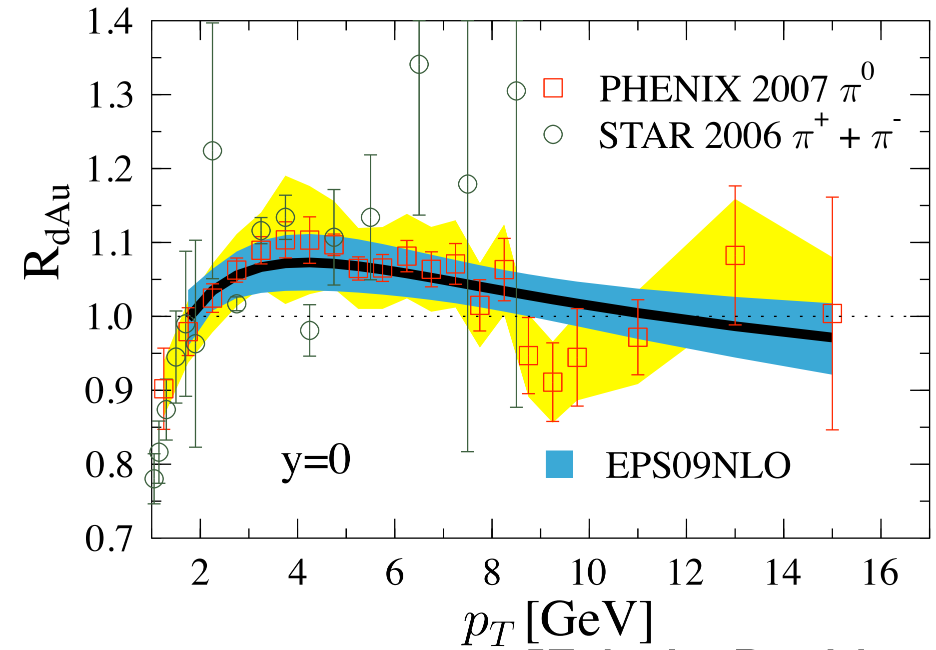


- IC from model (e.g. Regge theory) or fitted
- DGLAP evolution

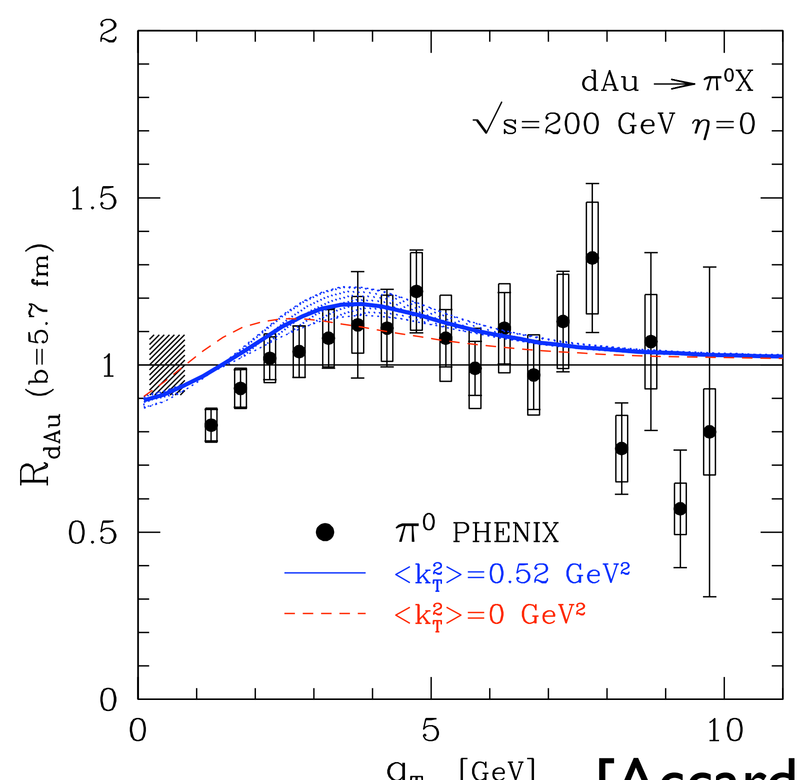
Different models



[Albacete, Marquet..]



[Eskola, Paukkunen, Salgado..]

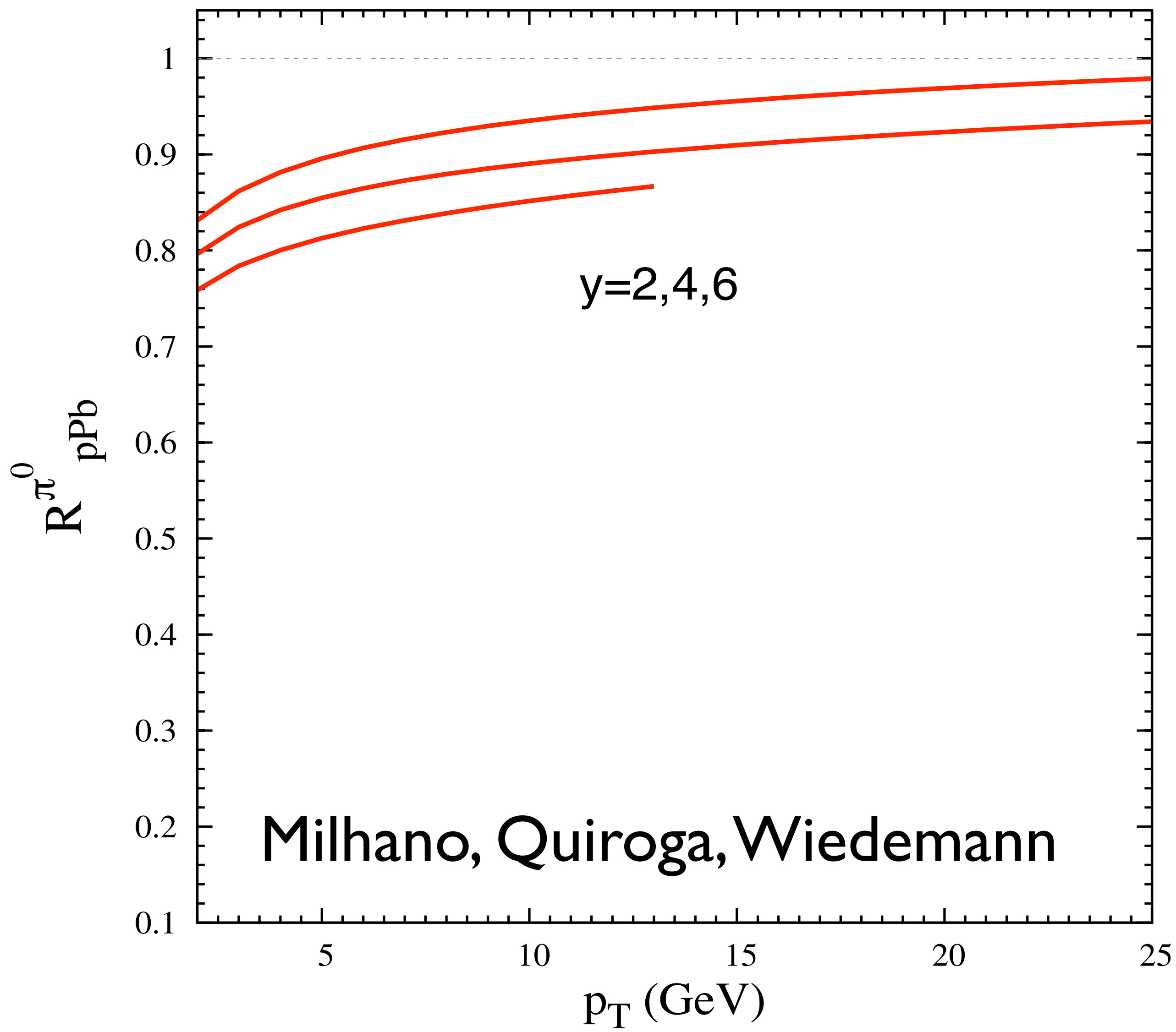


[Accardi, Treleani..]

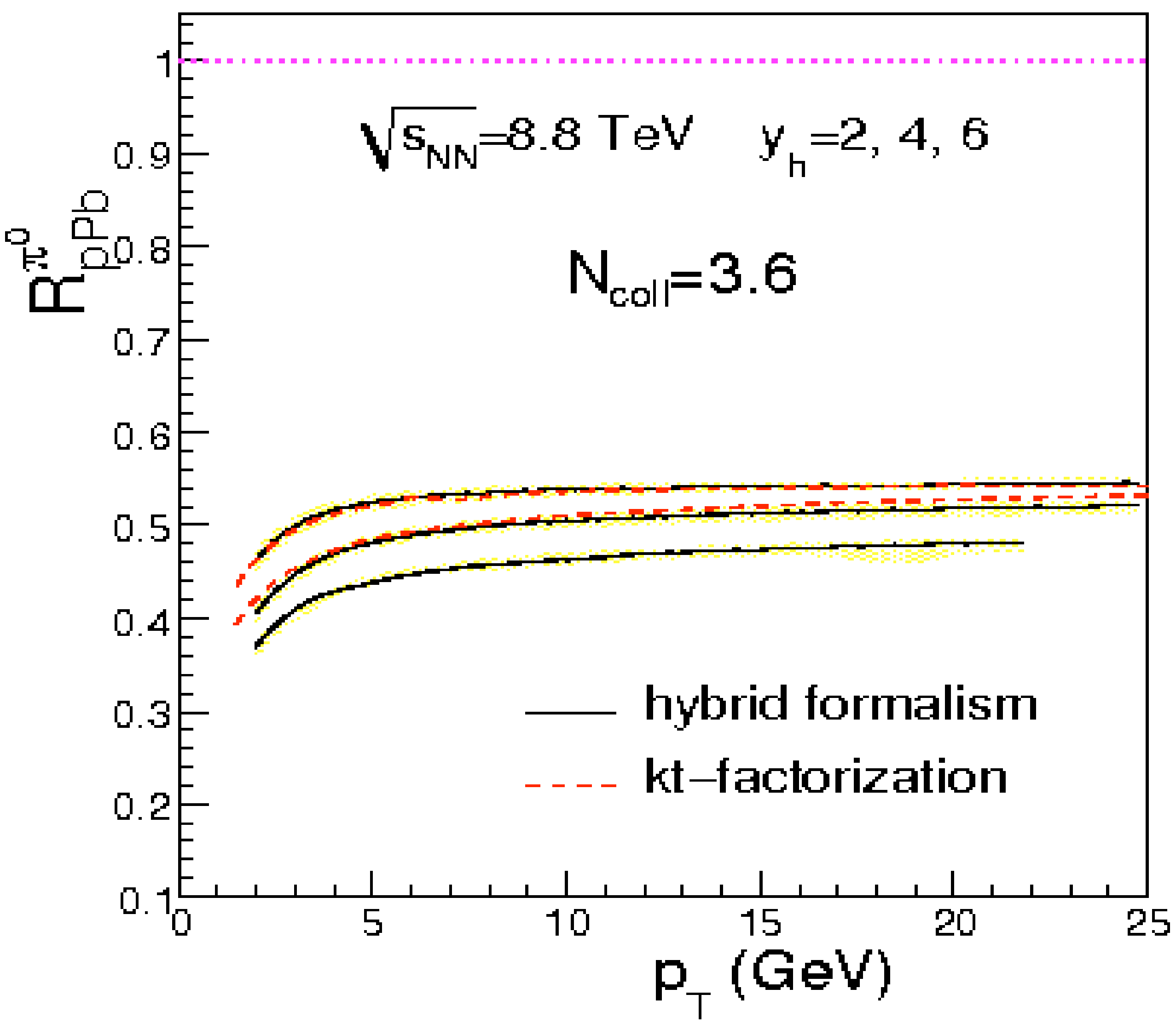
- ok at mid-rap
- forward strongly suppressed
- problem with pp?

Revealing saturation physics @ LHC

Collinear factorization nPDFs

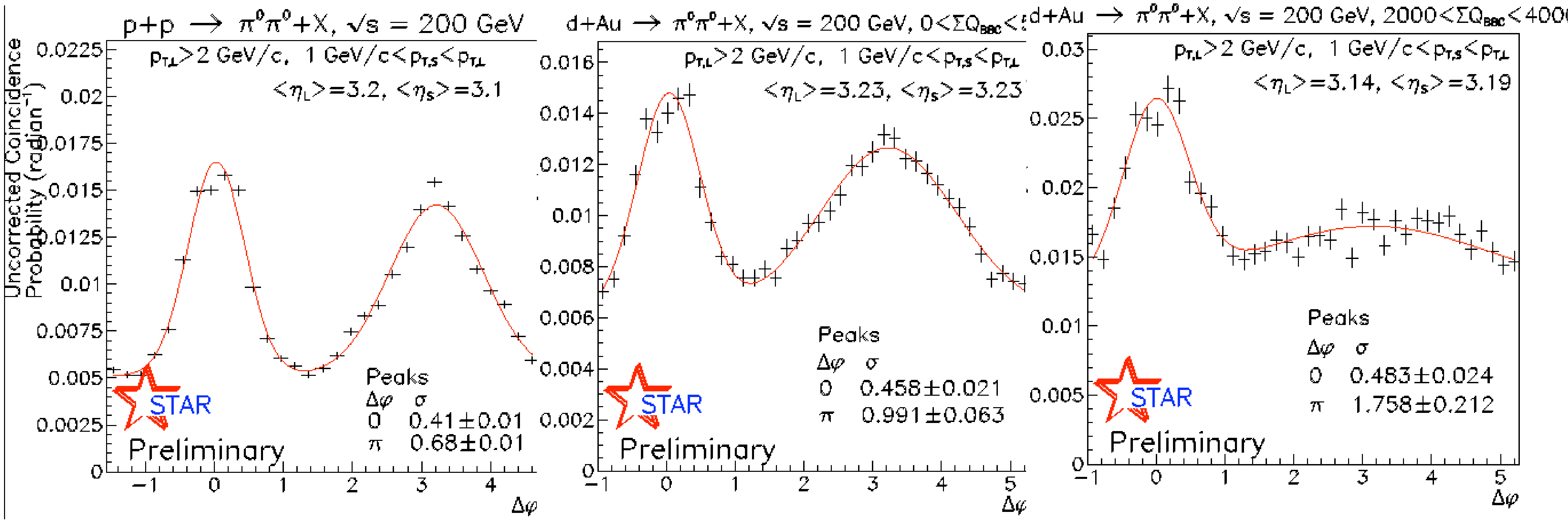


CGC Albacete and Marquet



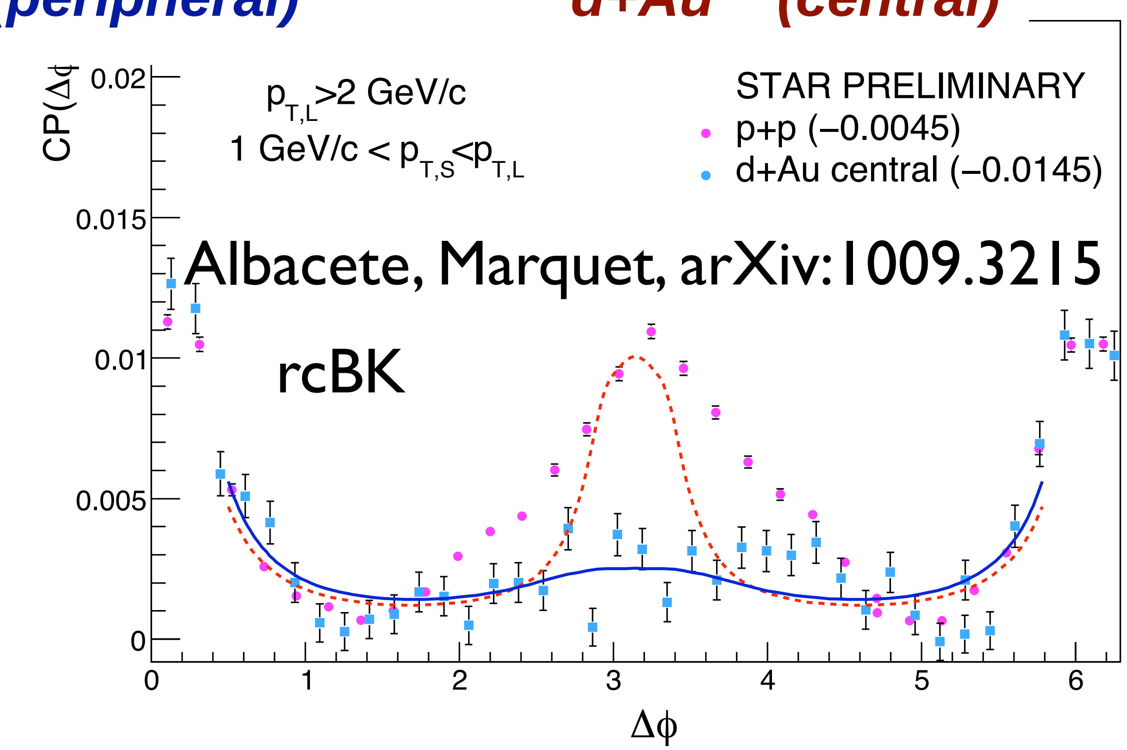
Huge differences in predictions for particle yields @ LHC!

Breakdown of factorization

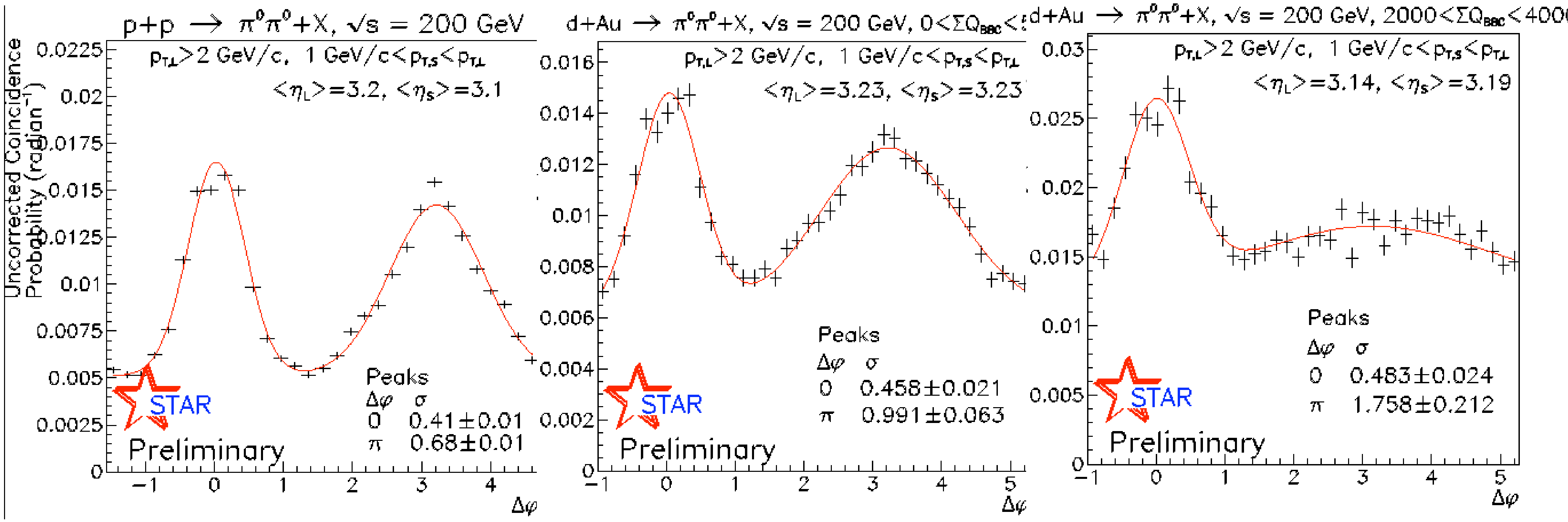


pp ***d+Au (peripheral)*** ***d+Au (central)***

2→1 rather than 2→2
process at forward rapidity!



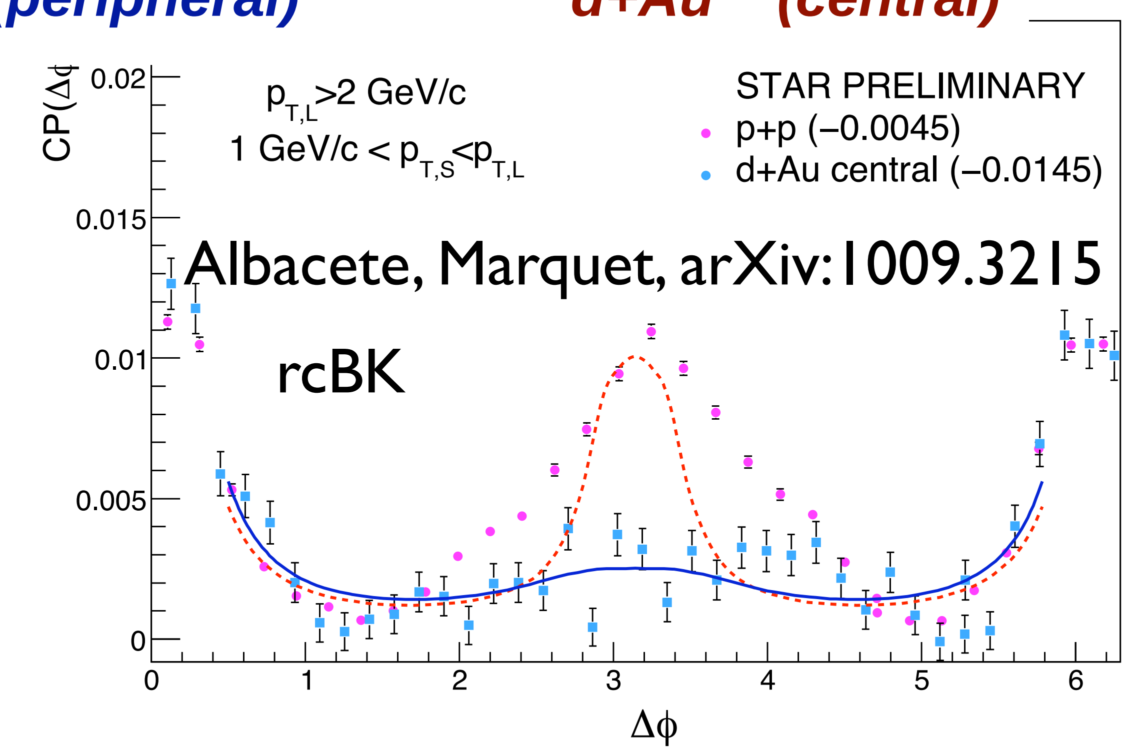
Breakdown of factorization



pp ***d+Au (peripheral)*** ***d+Au (central)***

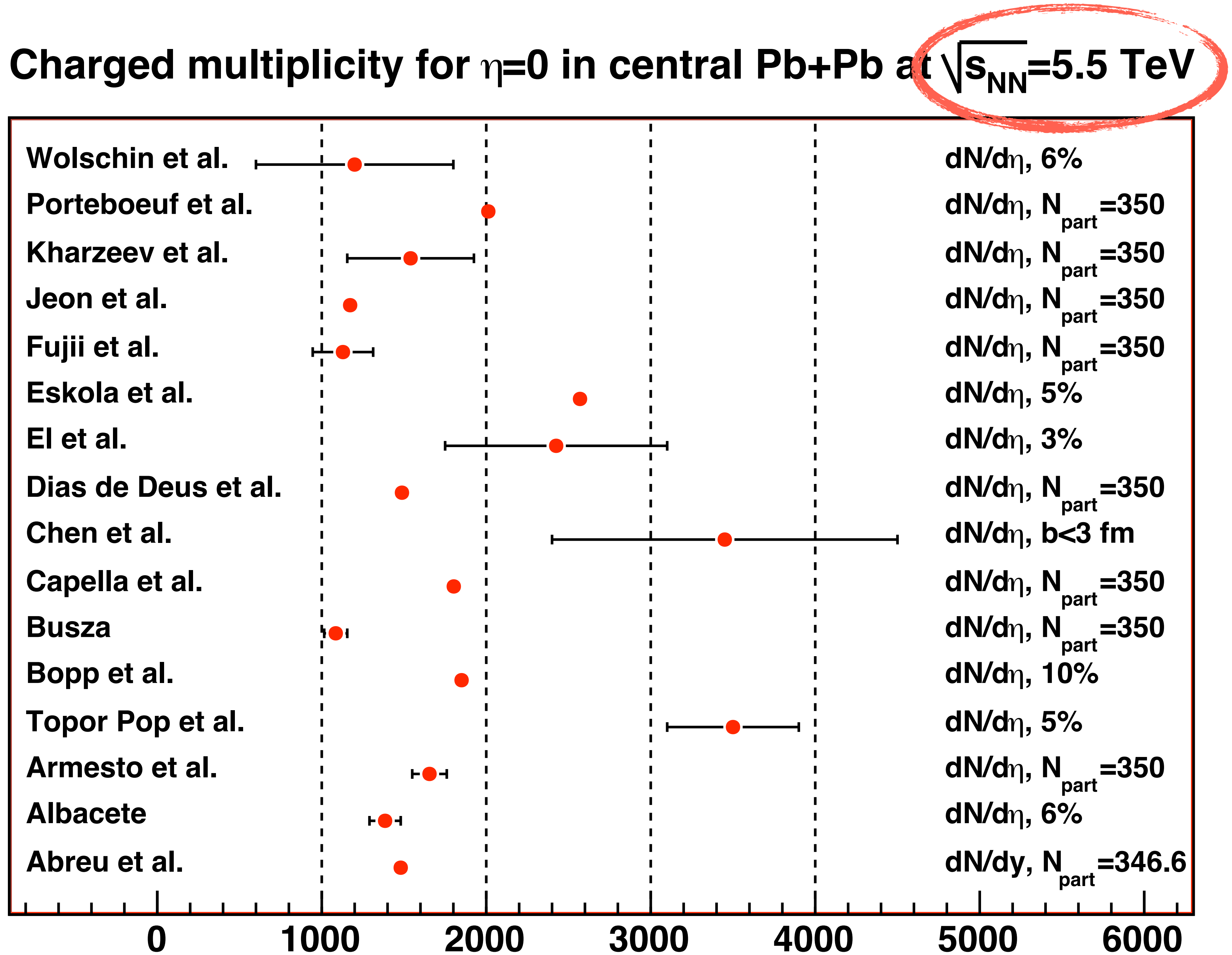
2→1 rather than 2→2 process at forward rapidity!

Strongest suggestion of breakdown of collinear factorization so far!



Soft probes

Multiplicity predictions



Proceedings from "Heavy Ion Collisions at the LHC - Last Call for LHC predictions" workshop, CERN 2007, arXiv:0711.0974

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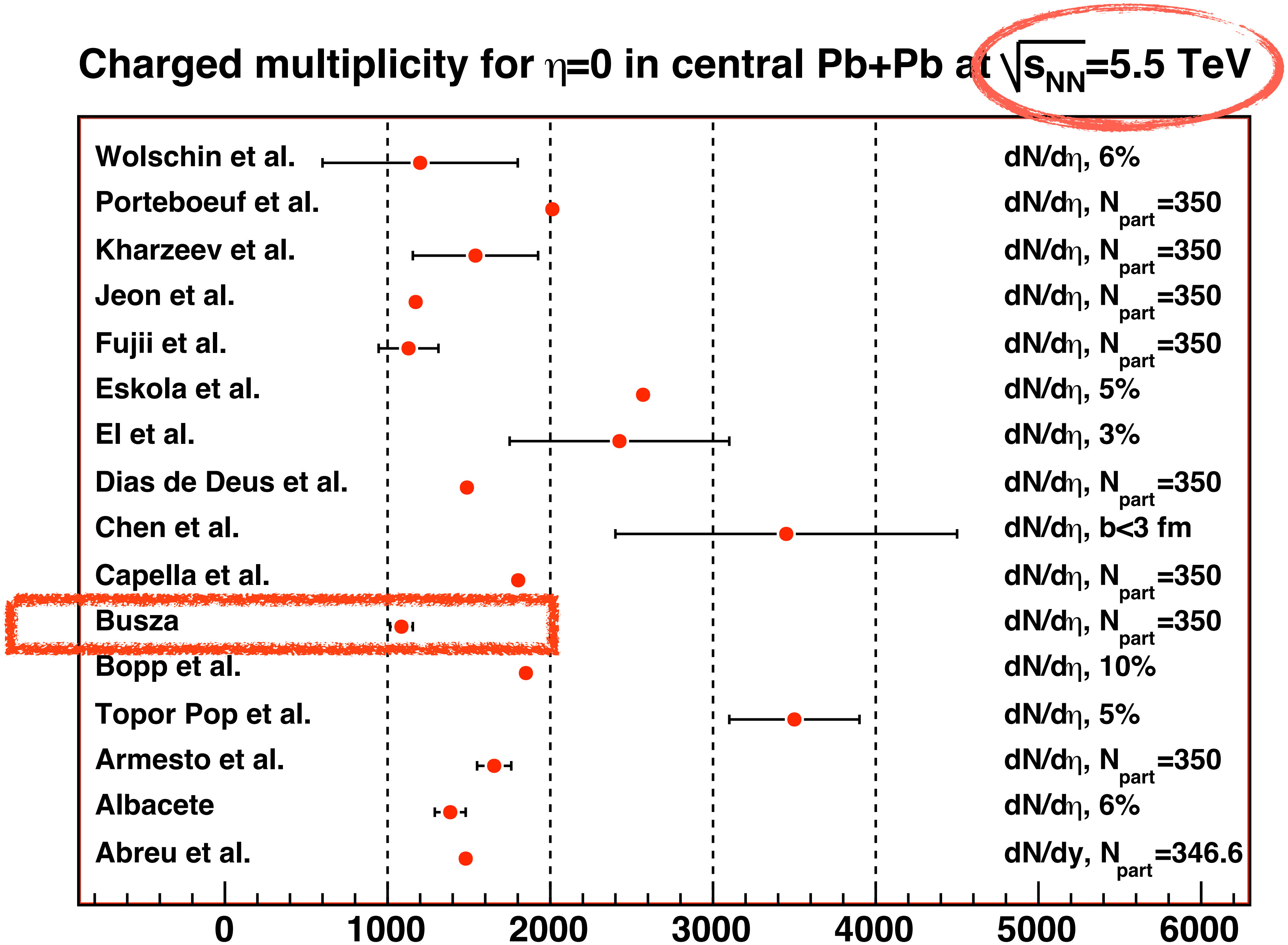

log-extrapolation from RHIC

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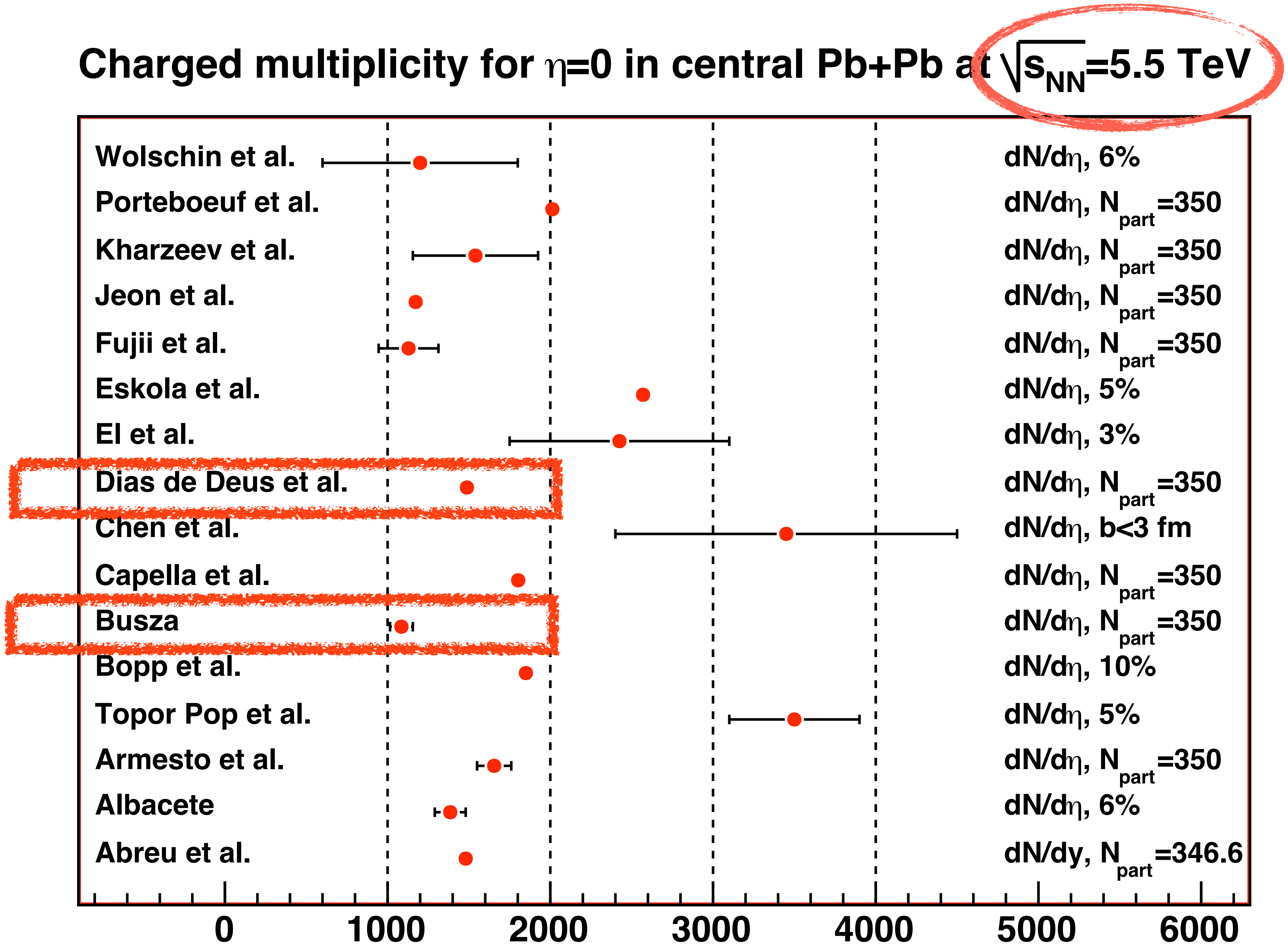
Multiplicity predictions

“percolation” of color strings

log-extrapolation from RHIC



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"naive" saturation

"percolation" of color strings

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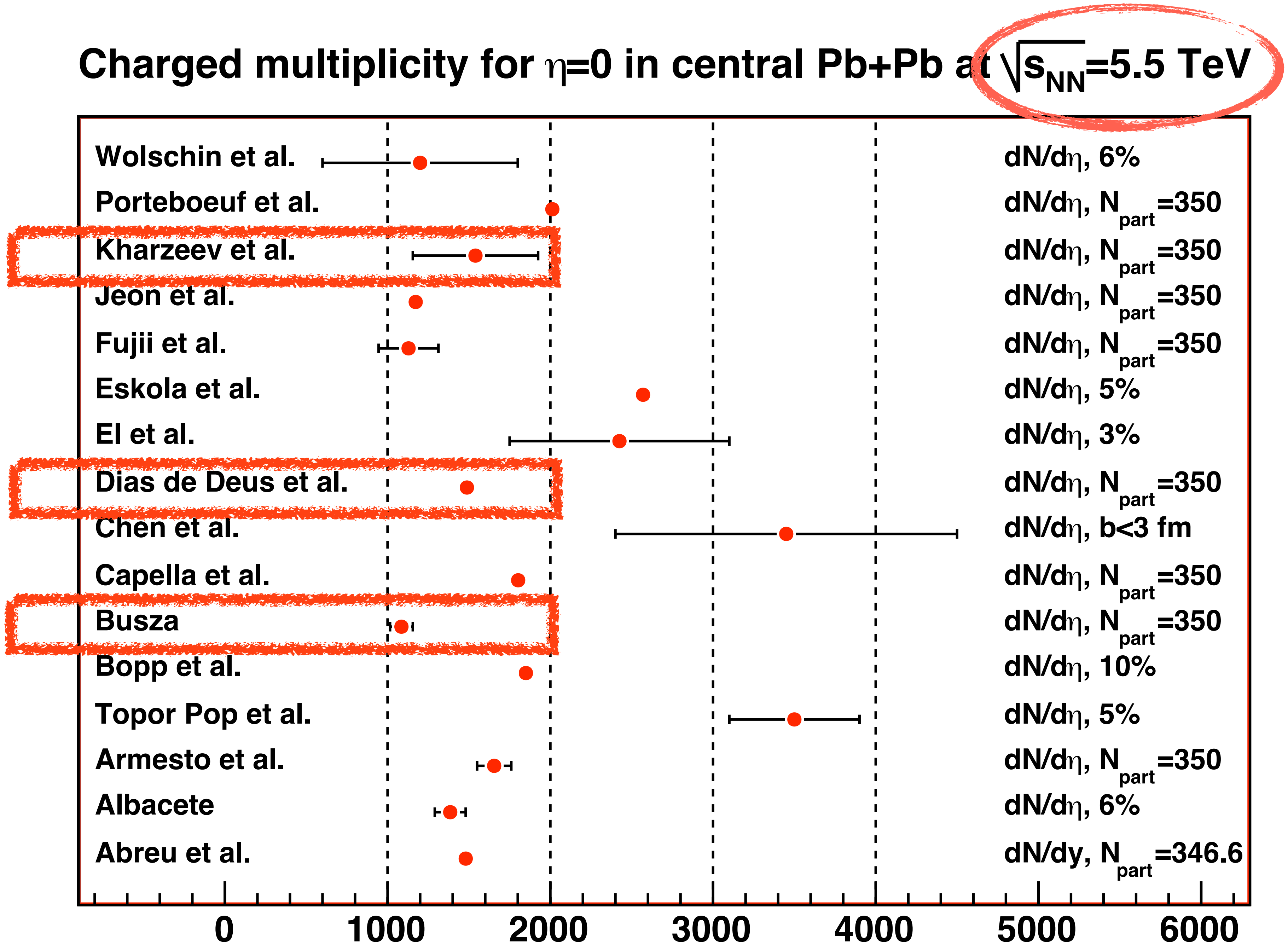

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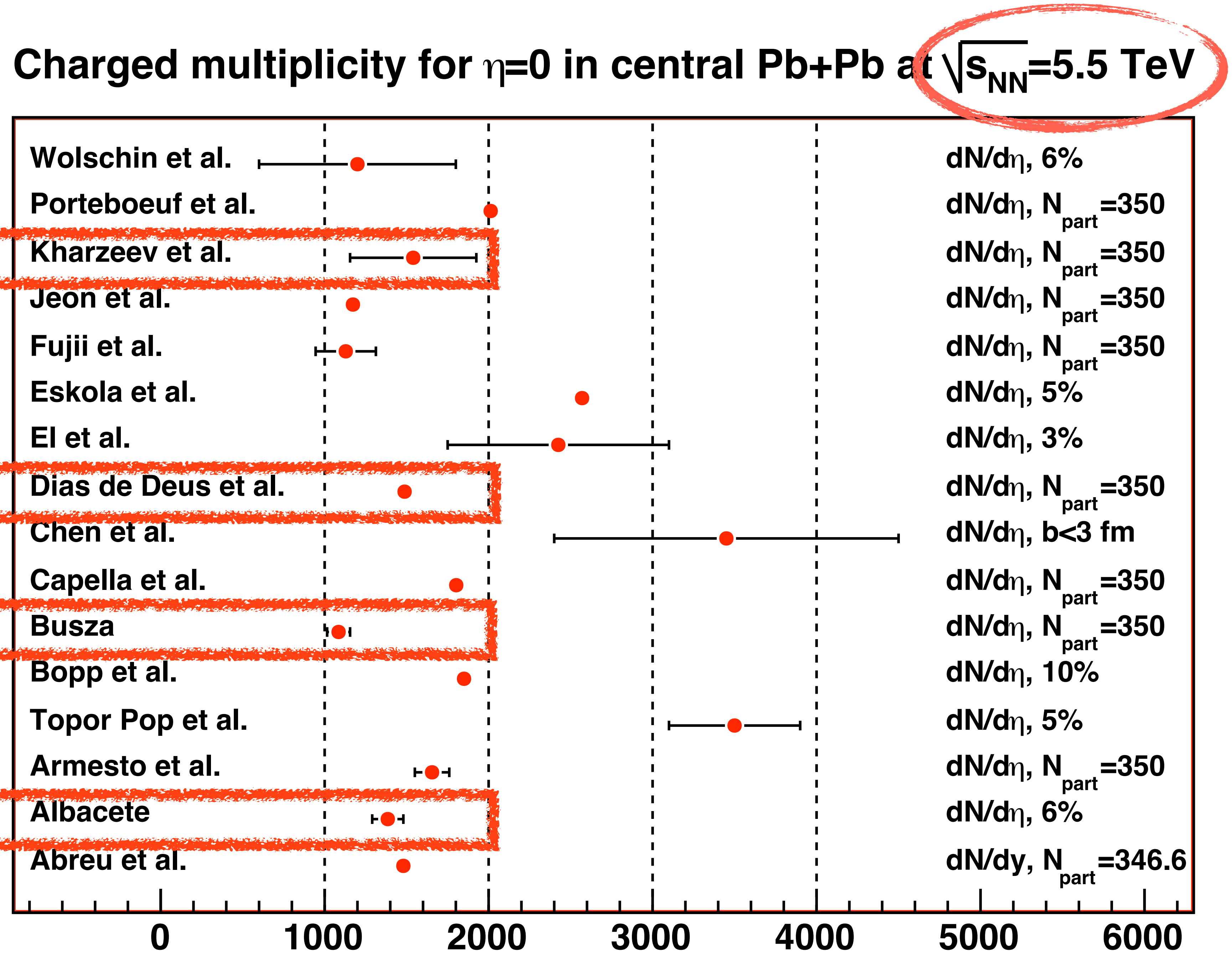
log-extrapolation from RHIC

running coupling saturation



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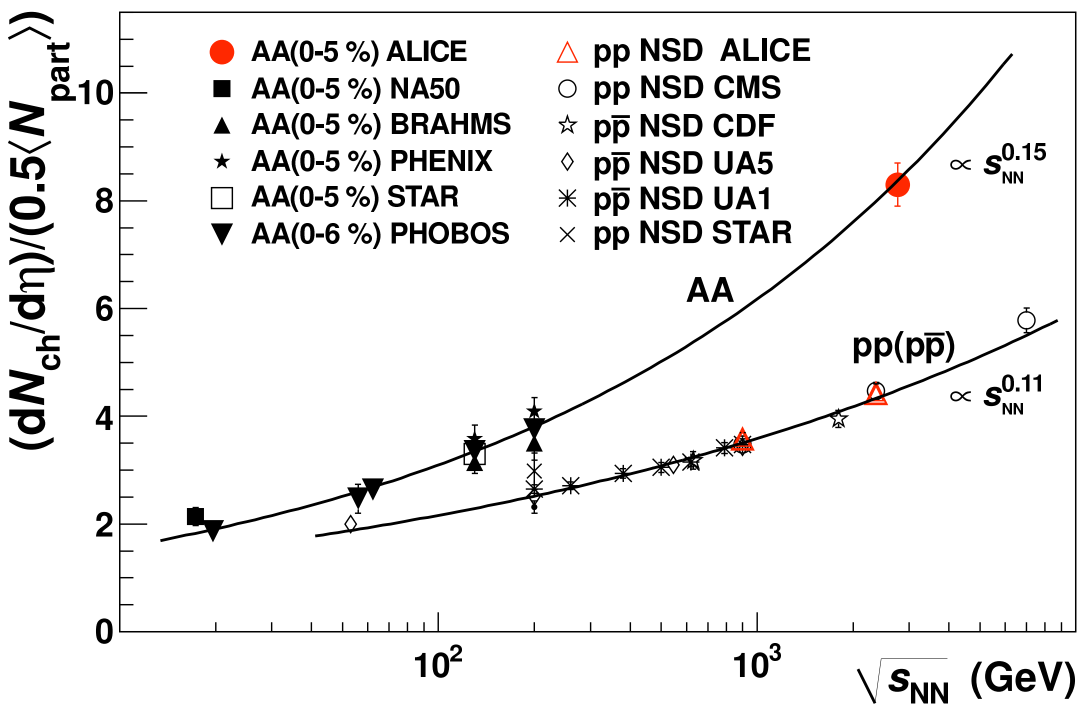
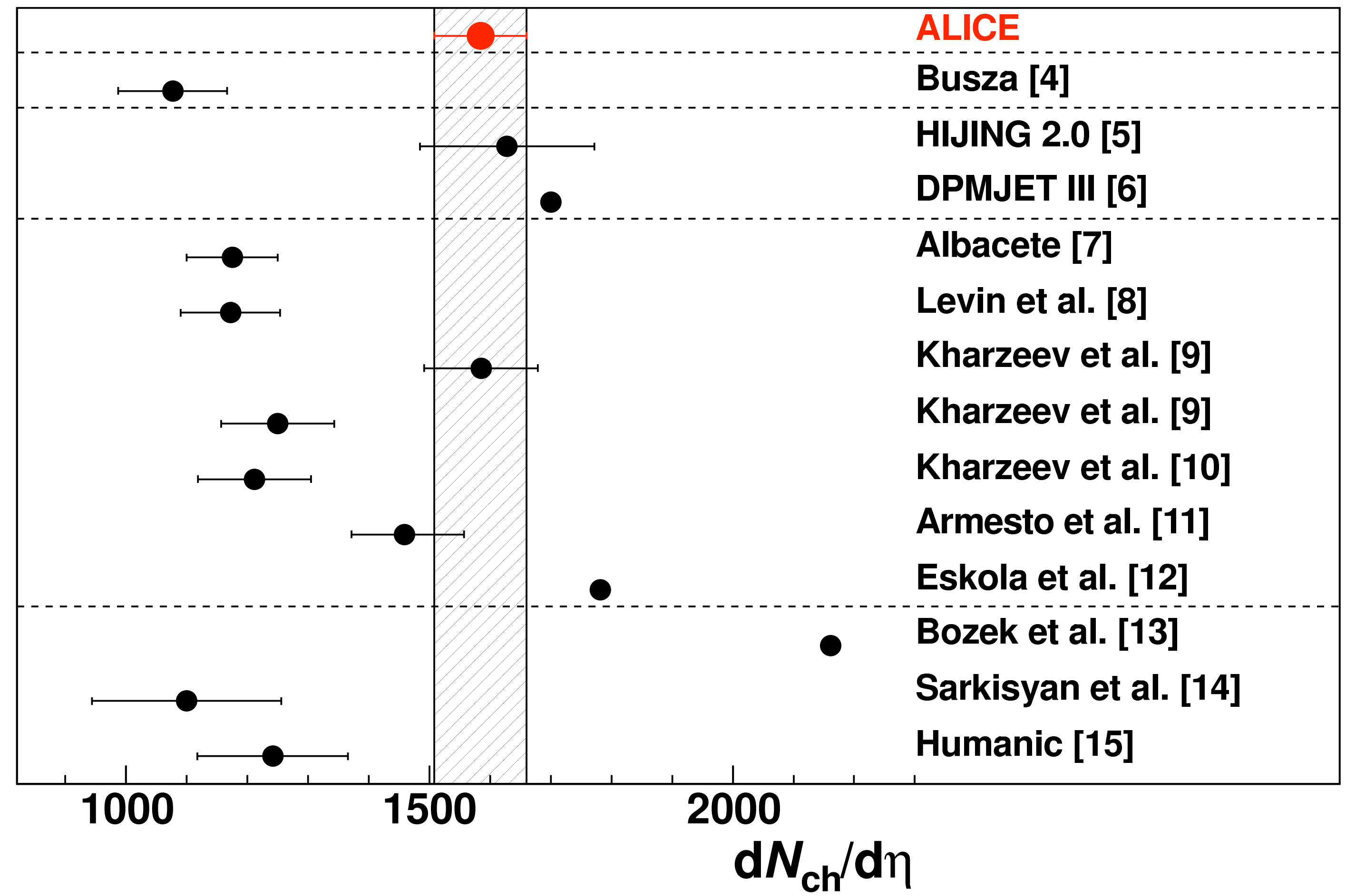
Multiplicity @ 2.76

ALICE Collaboration arxiv:1011.3916





- constrains initial conditions, such as the energy density, of the medium
- grows like DIS pomeron, $(\sqrt{s})^{0.3}$
- indicates strong screening in the hadronic wavefunction

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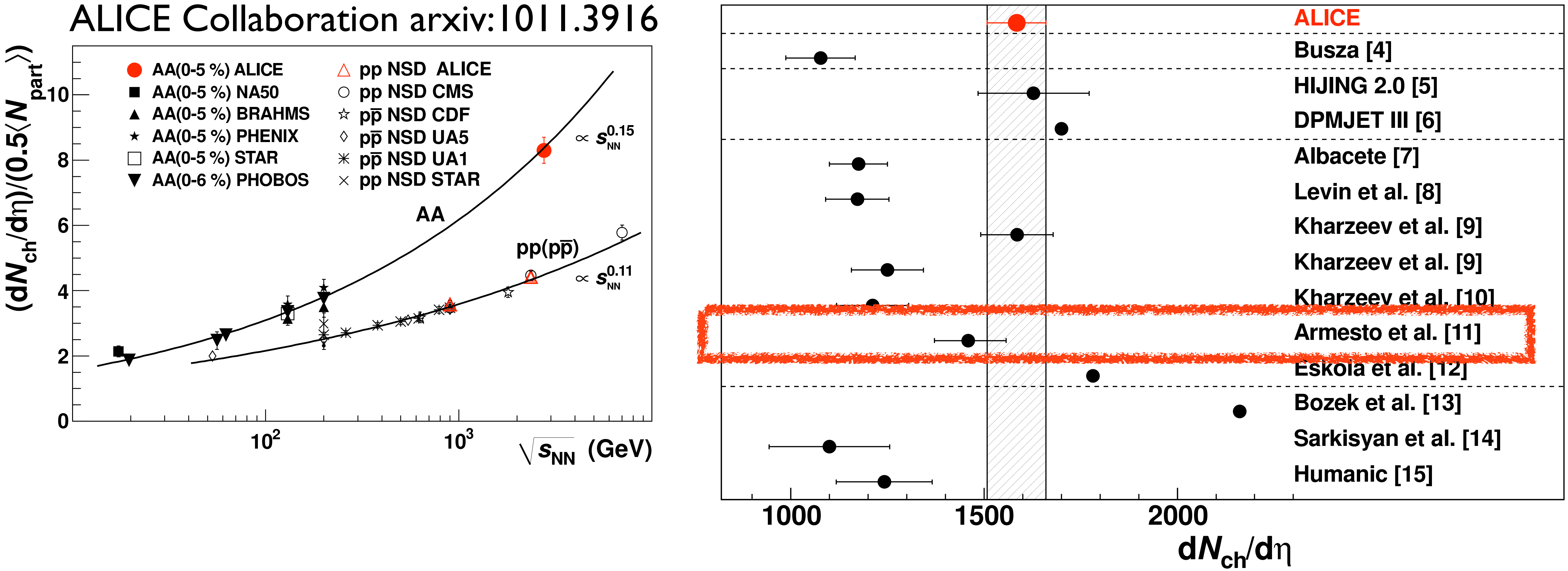

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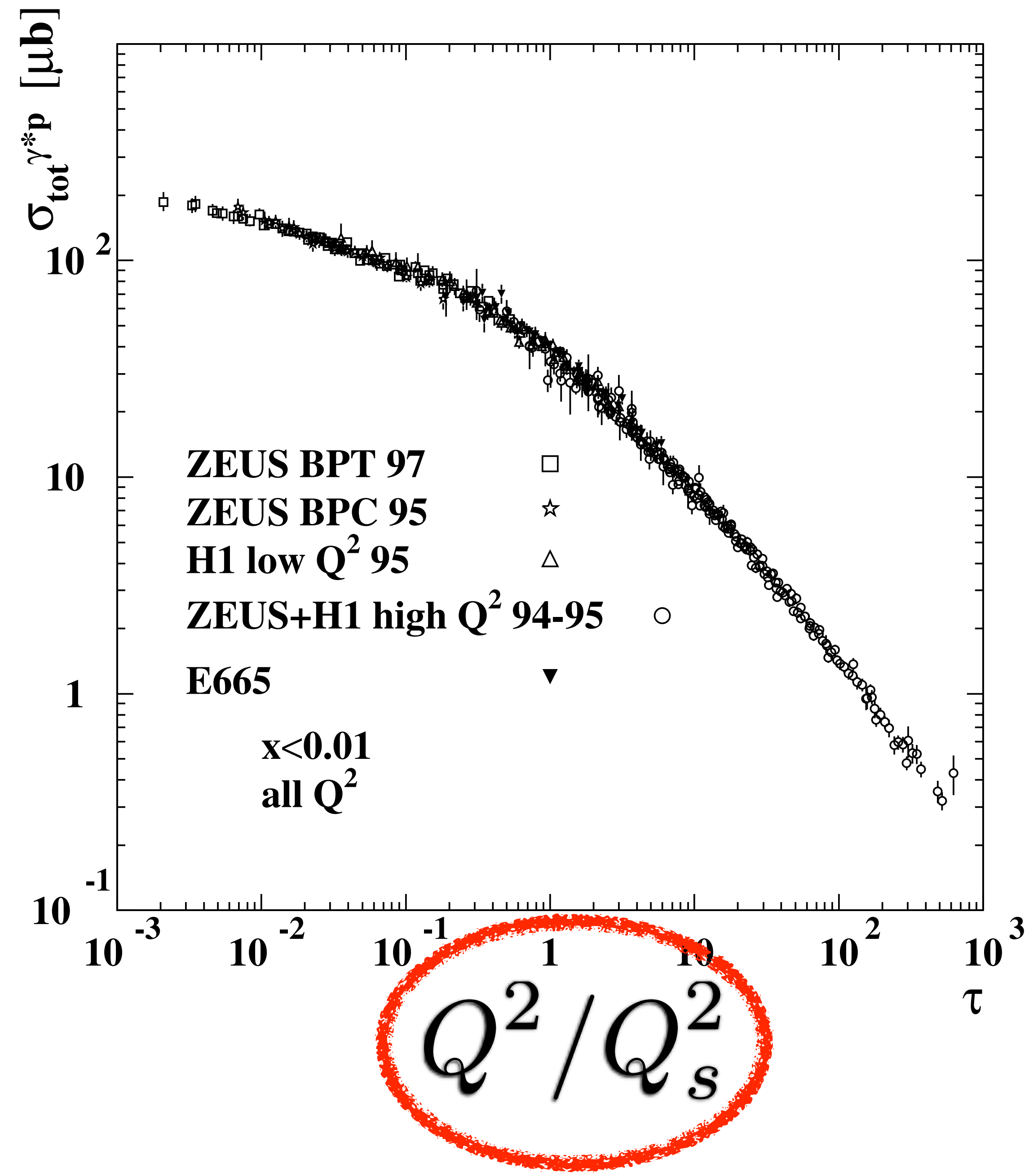
Geometrical scaling

- due to appearance of Q_s, there should be a scaling of data
- observed! (also for data beyond saturation application region..?)
- scaling exists in "standard" DGLAP too (although not so explicit)
- should tell the difference @ higher energies



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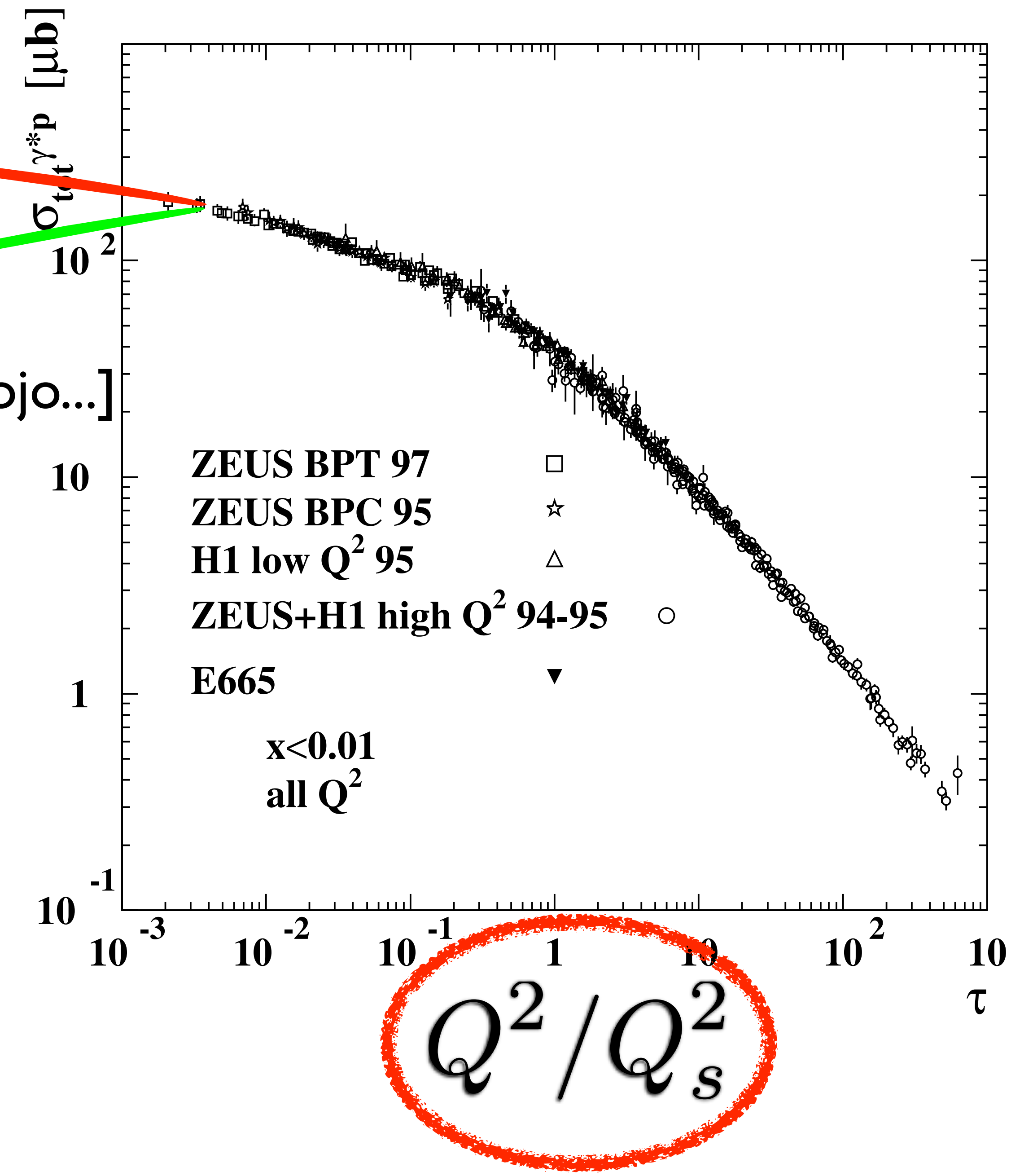
SAT

DGLAP

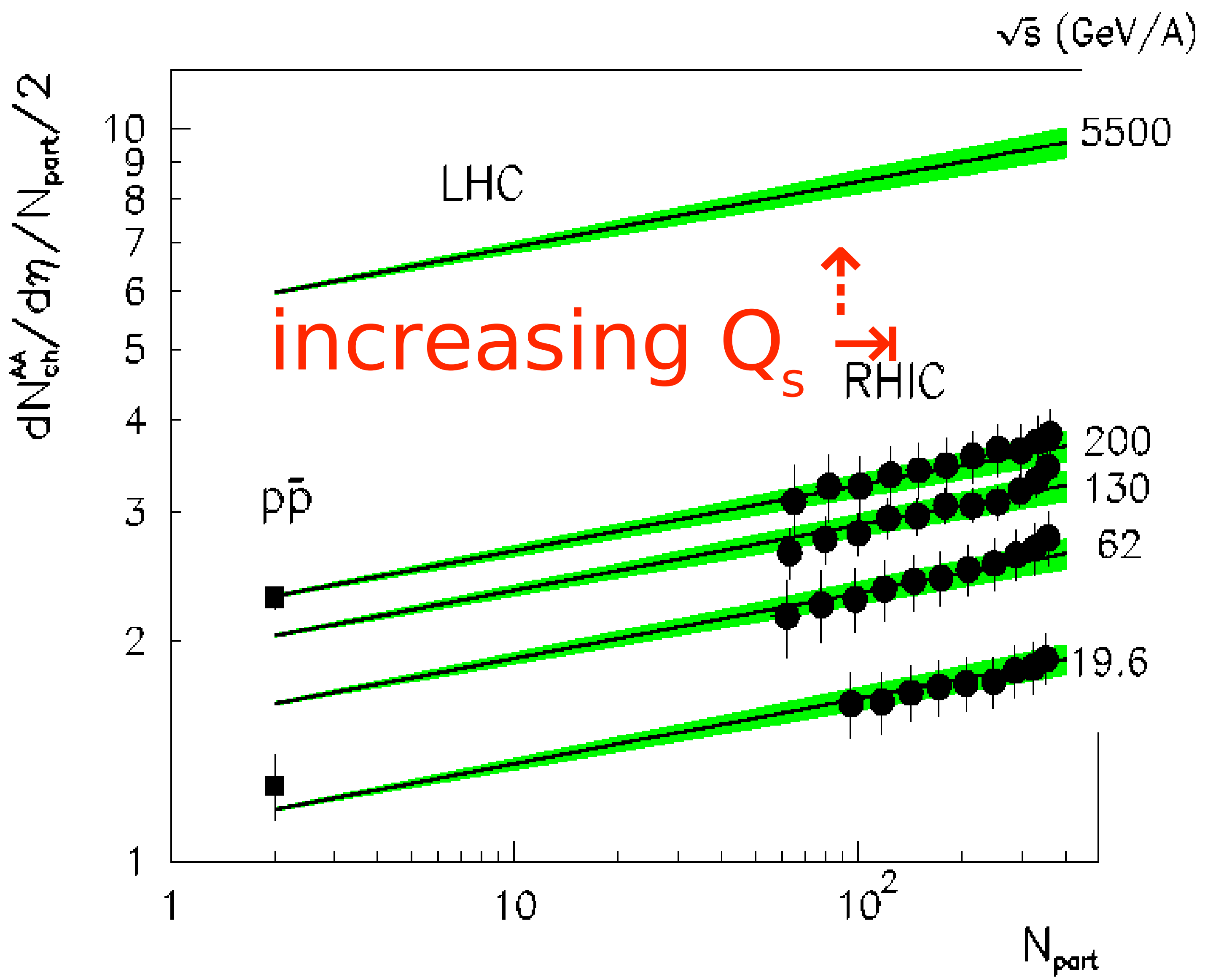
[Forte, Caola, Rojo...]



Multiplicity from geometrical scaling

[Armesto, Salgado, Wiedemann PRL (2005)]

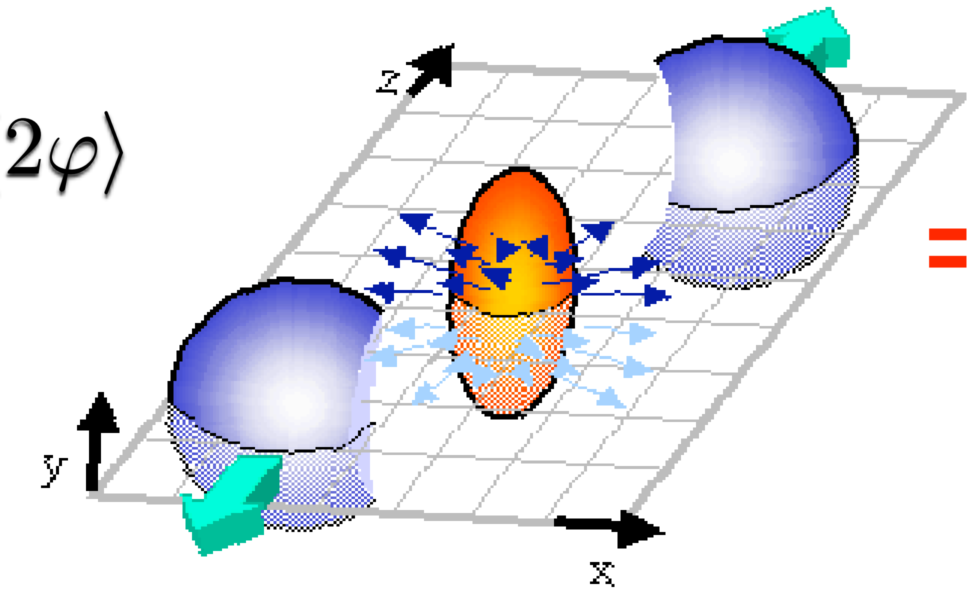
- DIS data consistent with $Q^2_{sat} \sim x^\lambda$, where $\lambda = 0.288$
- additional parameter fitted to go to the nuclear case
- multiplicities are given straightforwardly!
- factorization of geometry and saturation



$$Q^2_{\rm sat,A} = Q^2_{\rm sat,p}\left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\delta} \;\Rightarrow\; \left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Collective properties

$$\frac{dN}{d\varphi} \propto 1 + 2\, v_2\ \cos\langle 2\varphi \rangle$$



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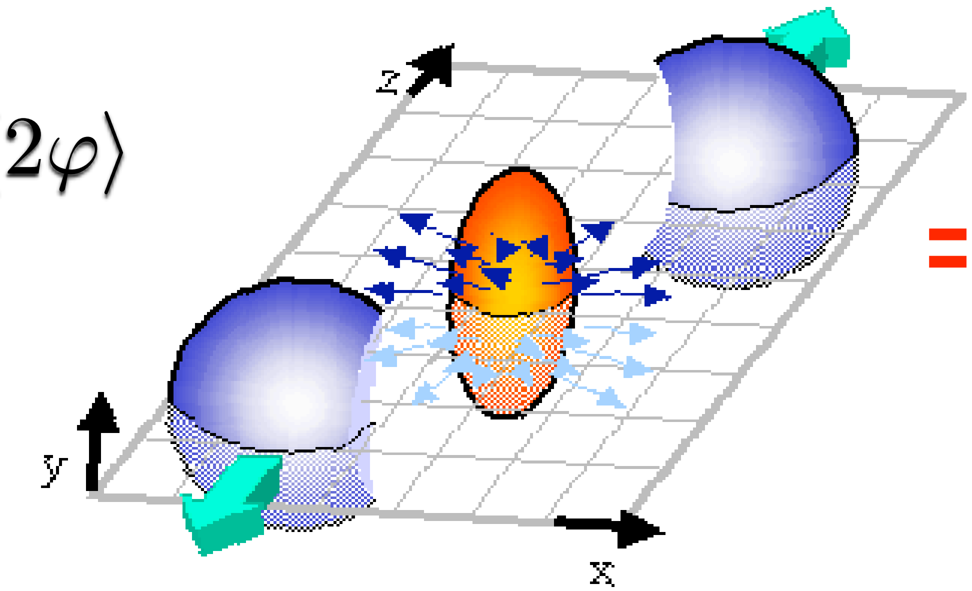

- input: initial condition, hadronization

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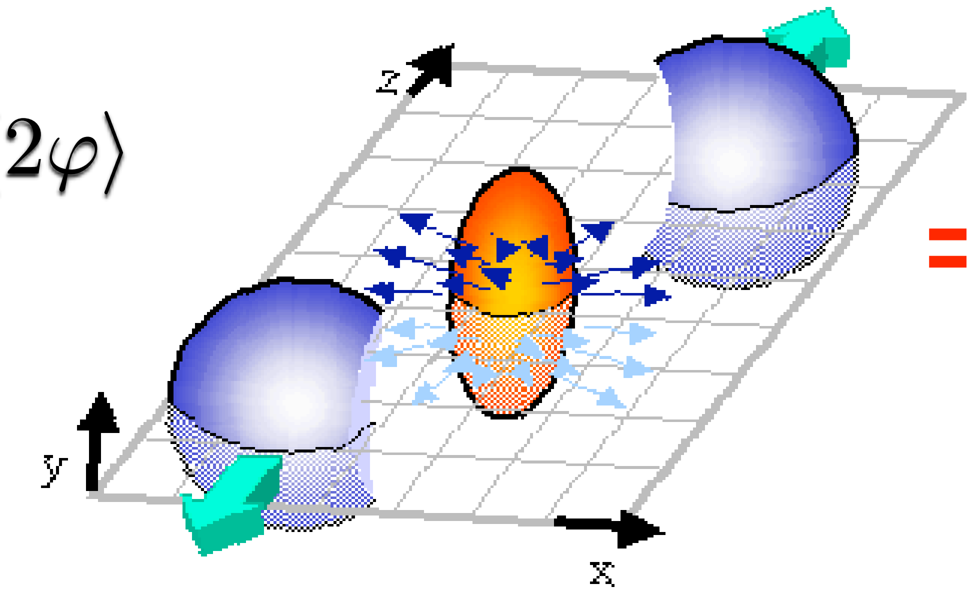

- input: initial condition, hadronization
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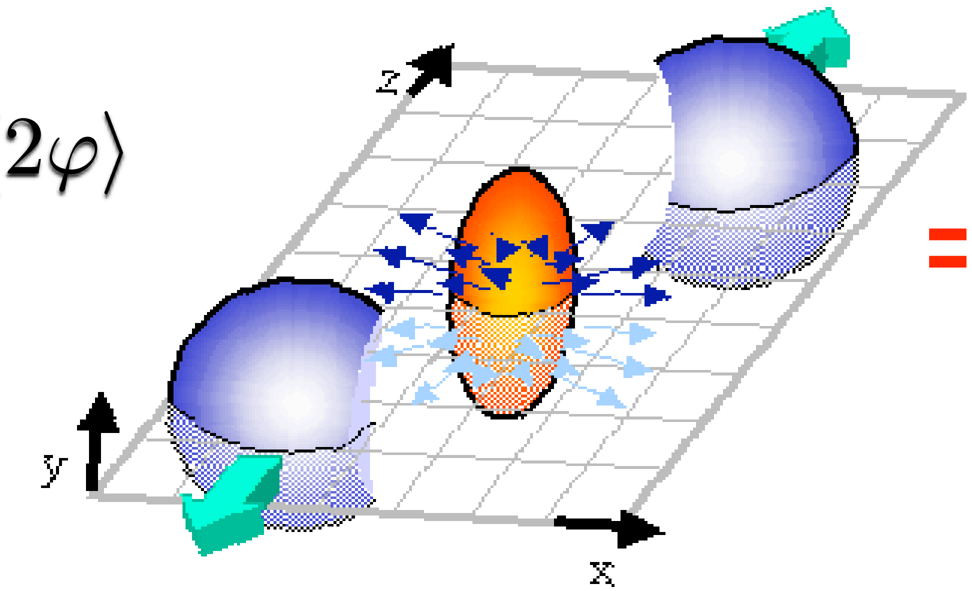
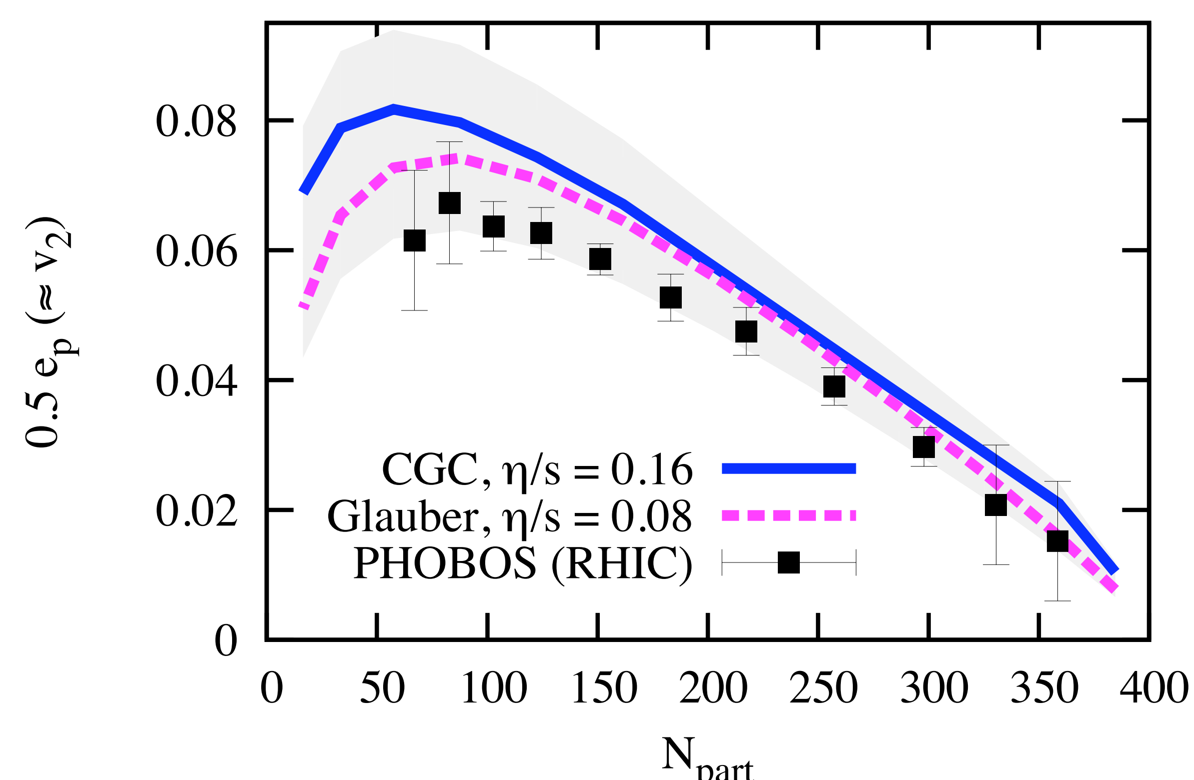
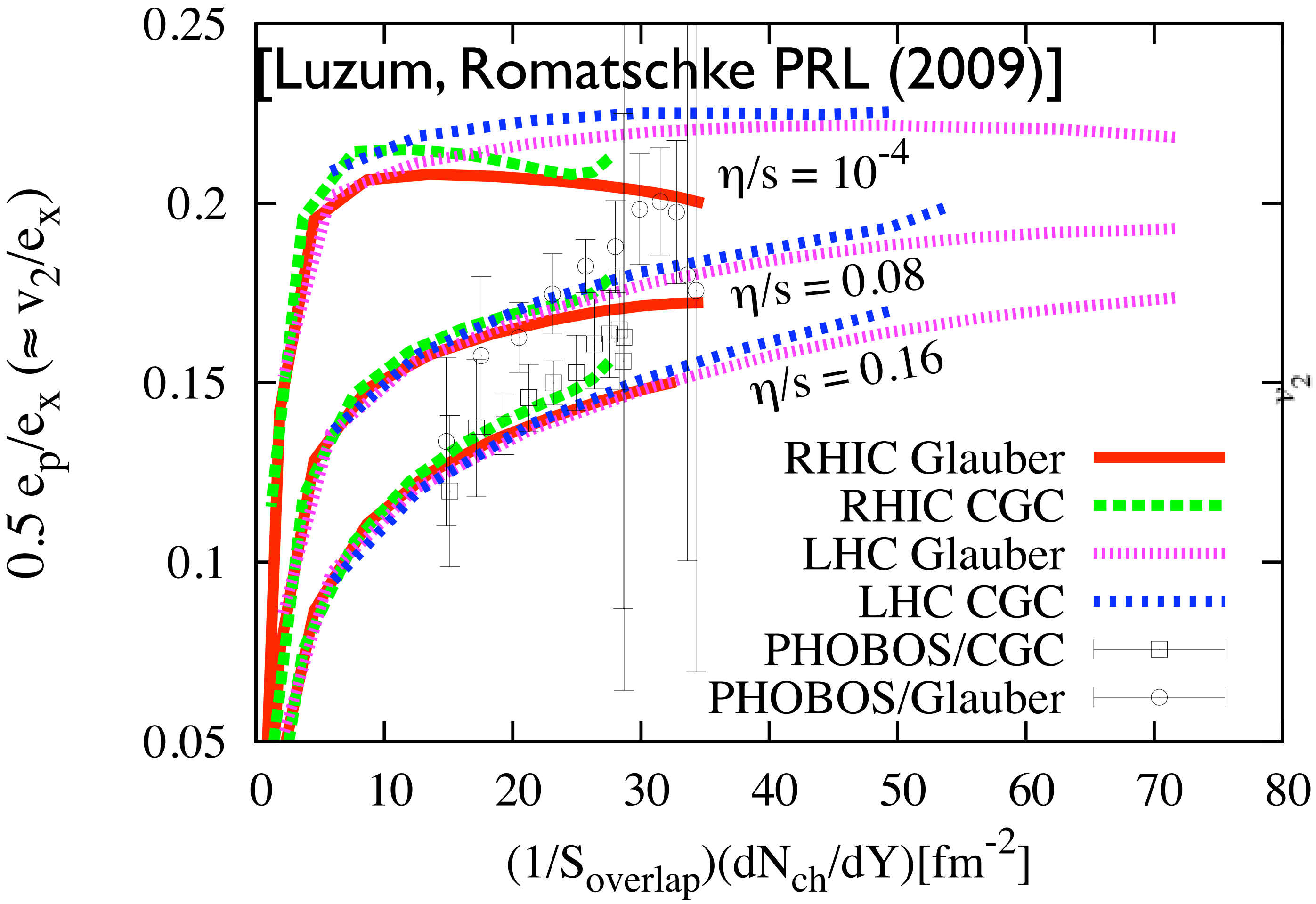


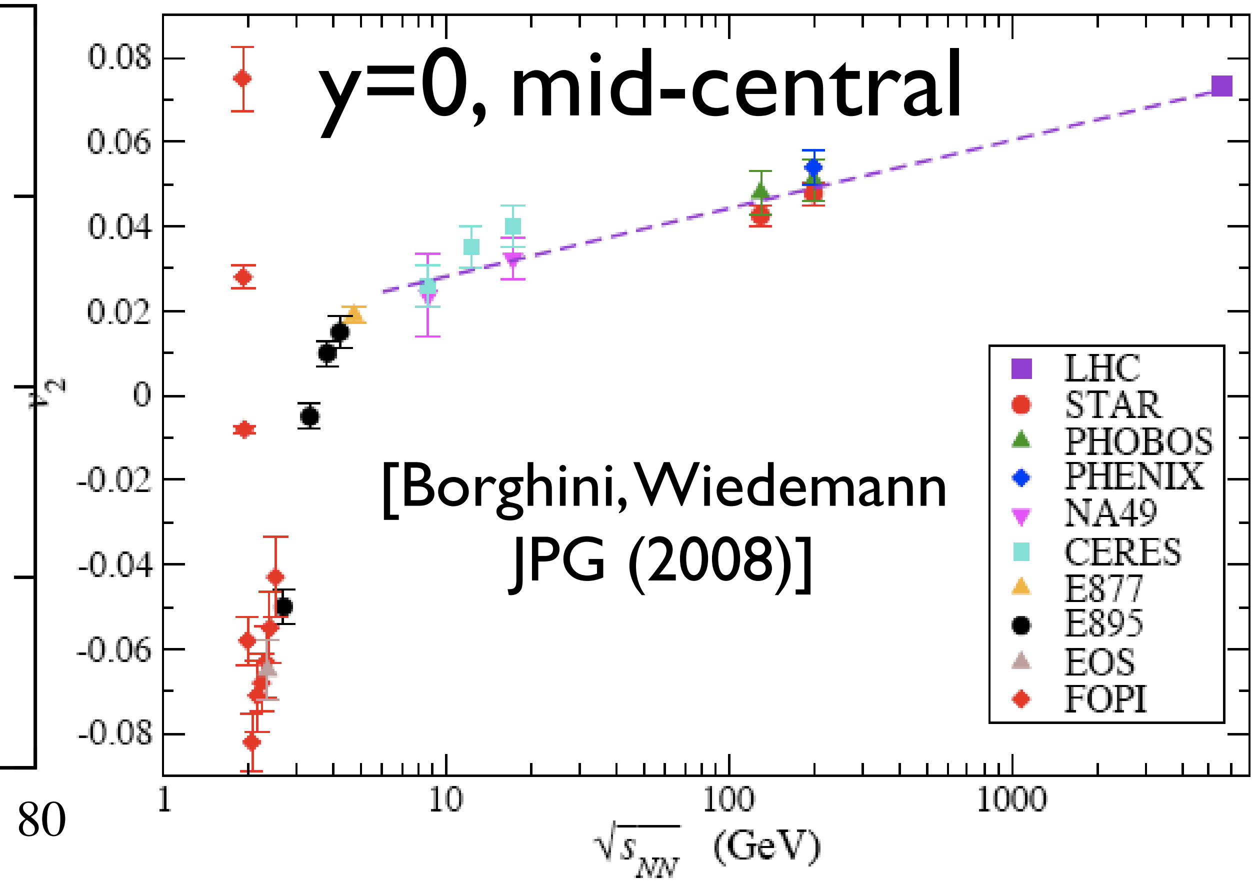
- input: initial condition, hadronization
- lattice-QCD EOS
- indications
  - ✓ early thermalization!
  - ✓ most perfect fluid
  - ✓ strongly interacting system

[Luzum, Romatschke PRL (2009)]



Predictions for v2

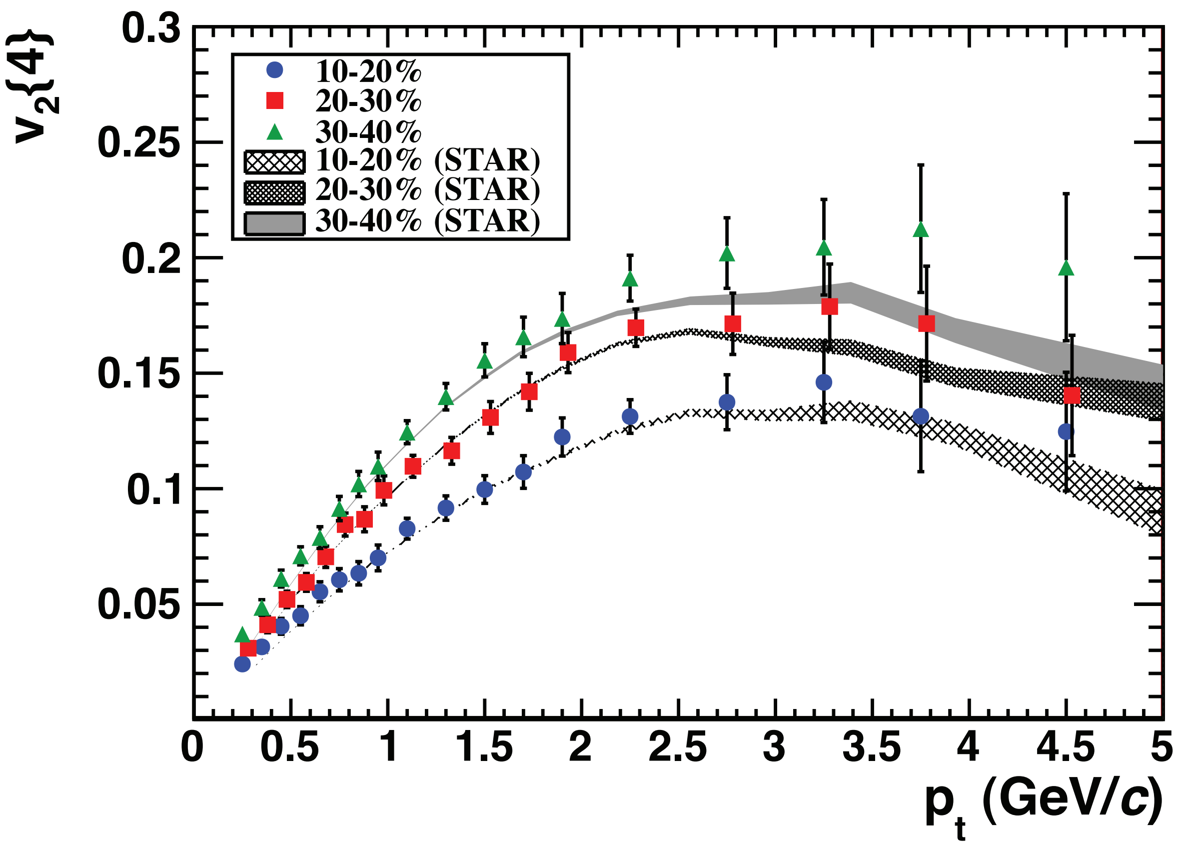


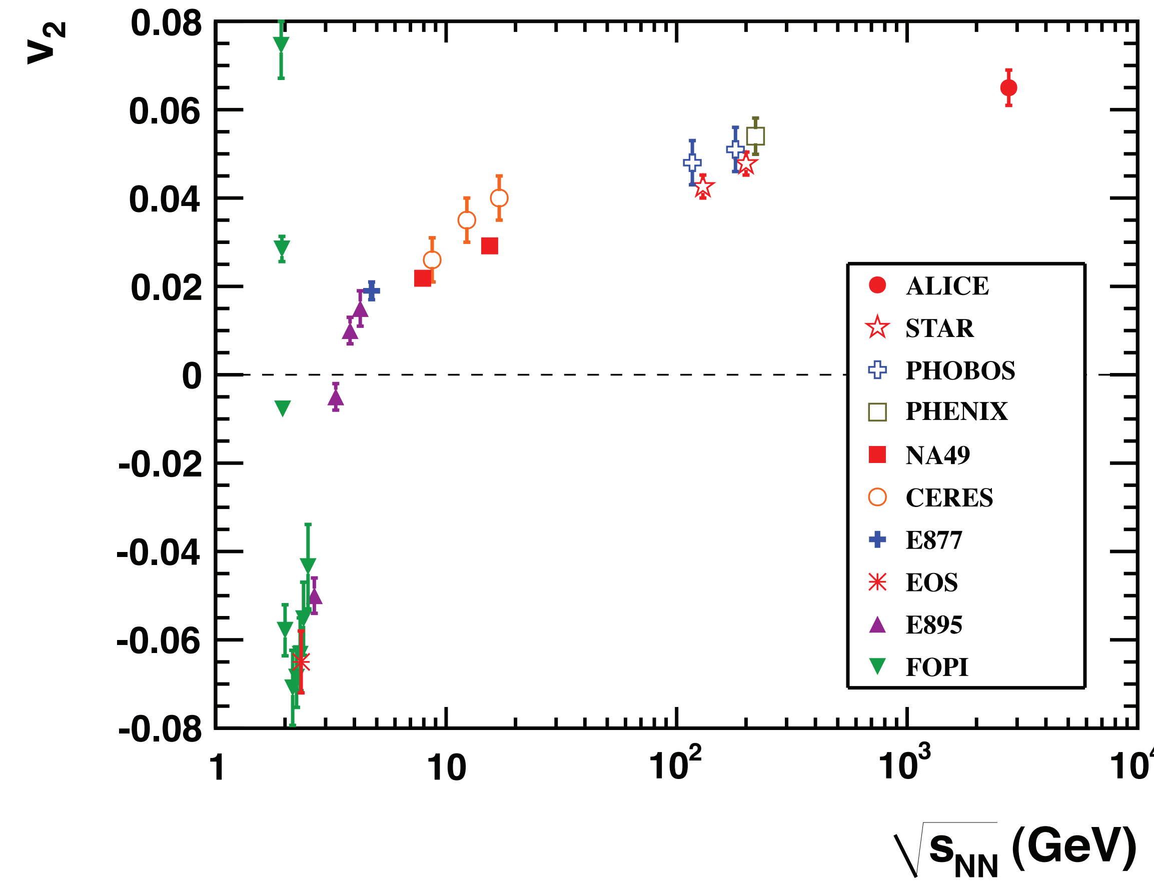


- Generic expectation: v_2 the smaller or the same at low p_T
- mean-p_T increases → increase in p_T-integrated v_2
- strong decrease at low p_T would signal an increase in the η/s ratio
- initial conditions have to be settled

Elliptic flow @ 2.76 GeV

ALICE Collaboration arXiv:1011.3914



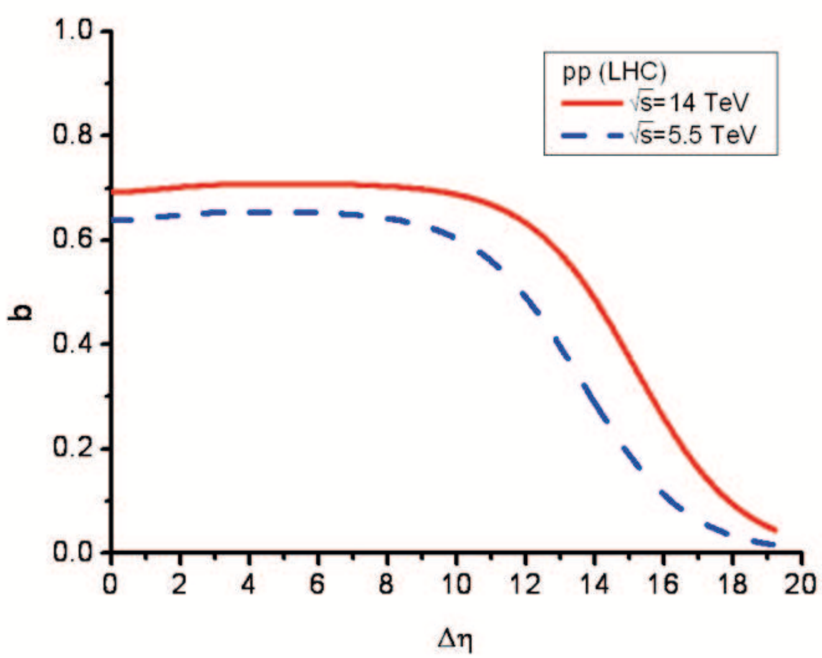


- v_2 at small p_T the same as at RHIC
  - ✓ similar (small) viscosity
- since mean p_T grows, total v_2 too
- probes qhat at large p_T

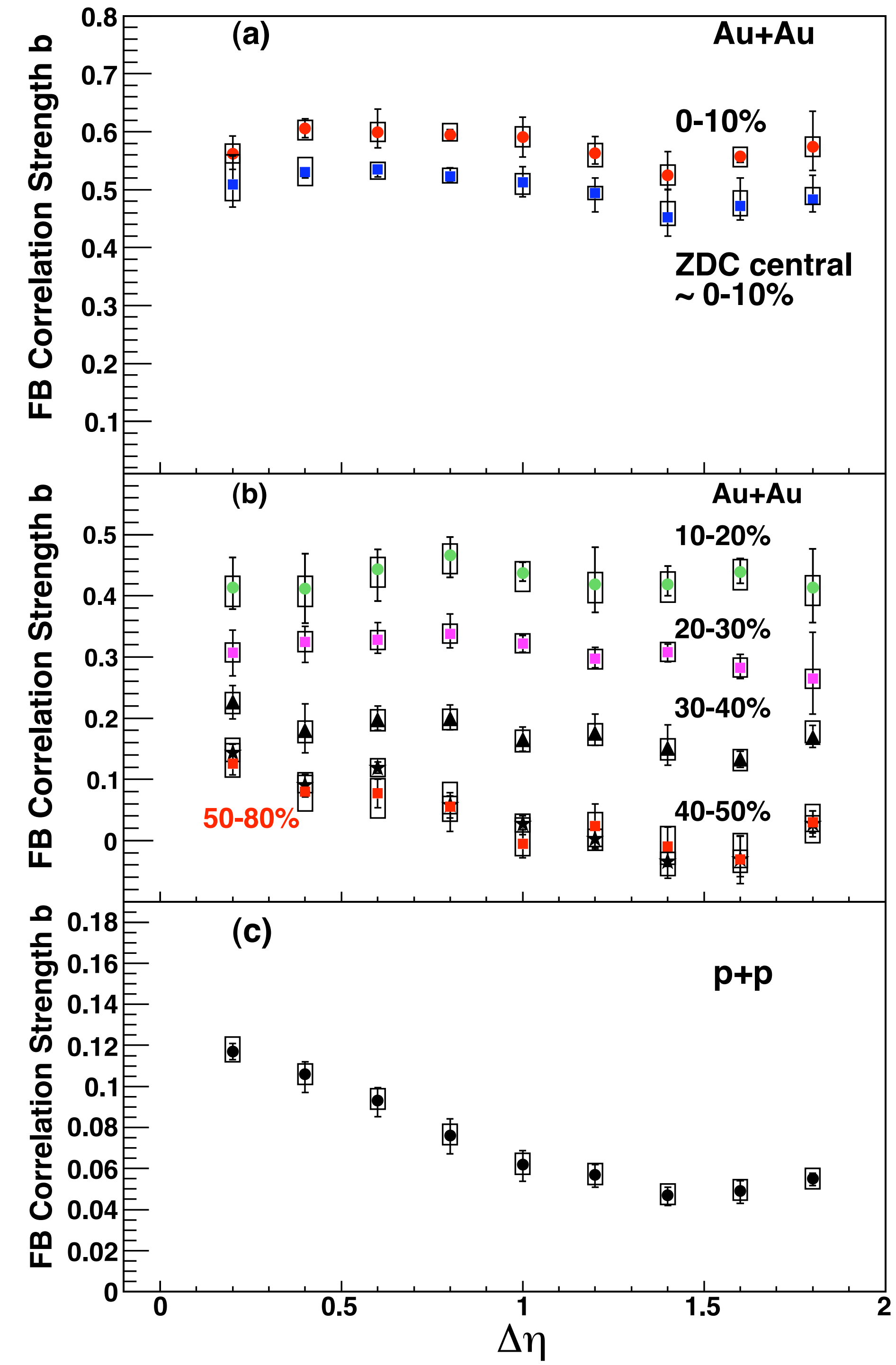
Long range correlations

$$b = \frac{\langle n_f n_b \rangle - \langle n_f \rangle \langle n_b \rangle}{\langle n_f^2 \rangle - \langle n_f \rangle^2}$$

- indicates strong correlations in the initial state
- can extend up to 15 units of rapidity!



Bautista, De Deus, Pajares, arXiv:1011.1870

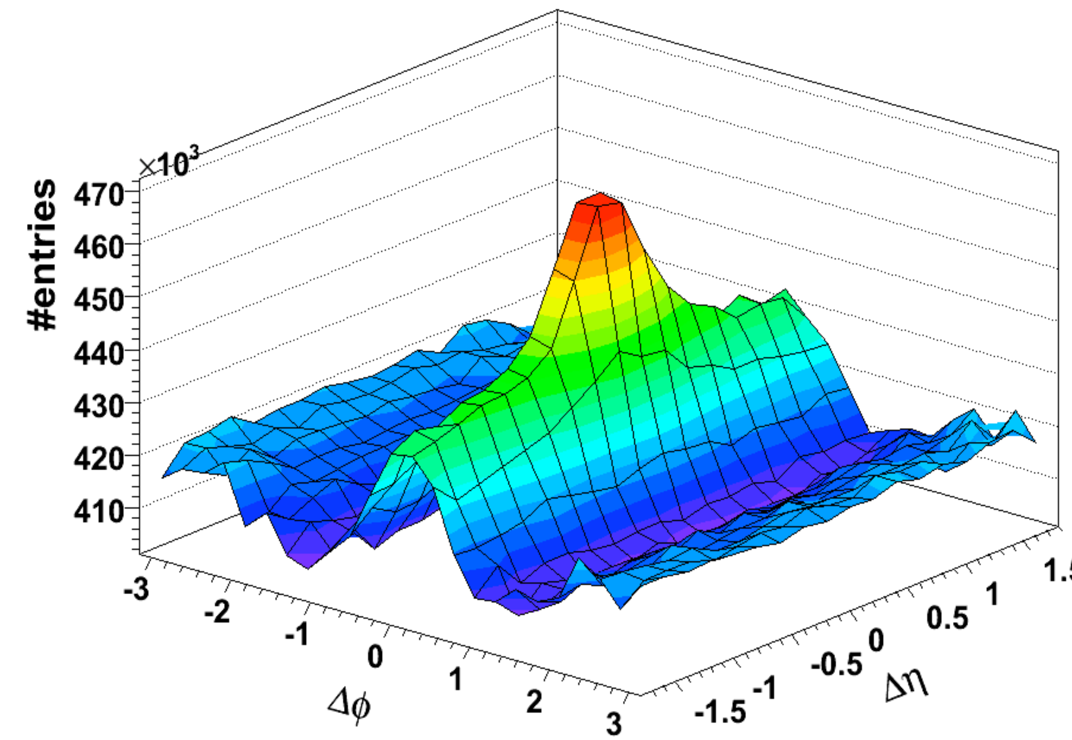


STAR Collaboration, PRL 103 (2009)

The "ridge"

p_T^{trig} : 3-4 , p_T^{assoc} : >2 GeV/c

STAR, J.Phys.G34:S679-684,2007



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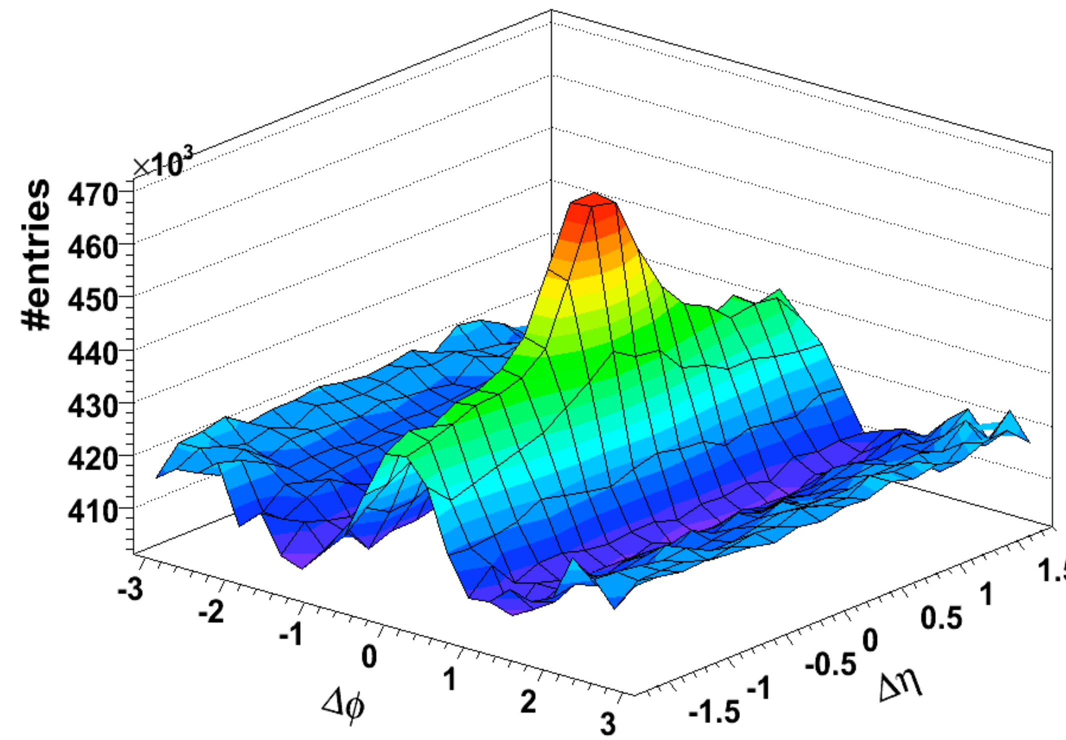

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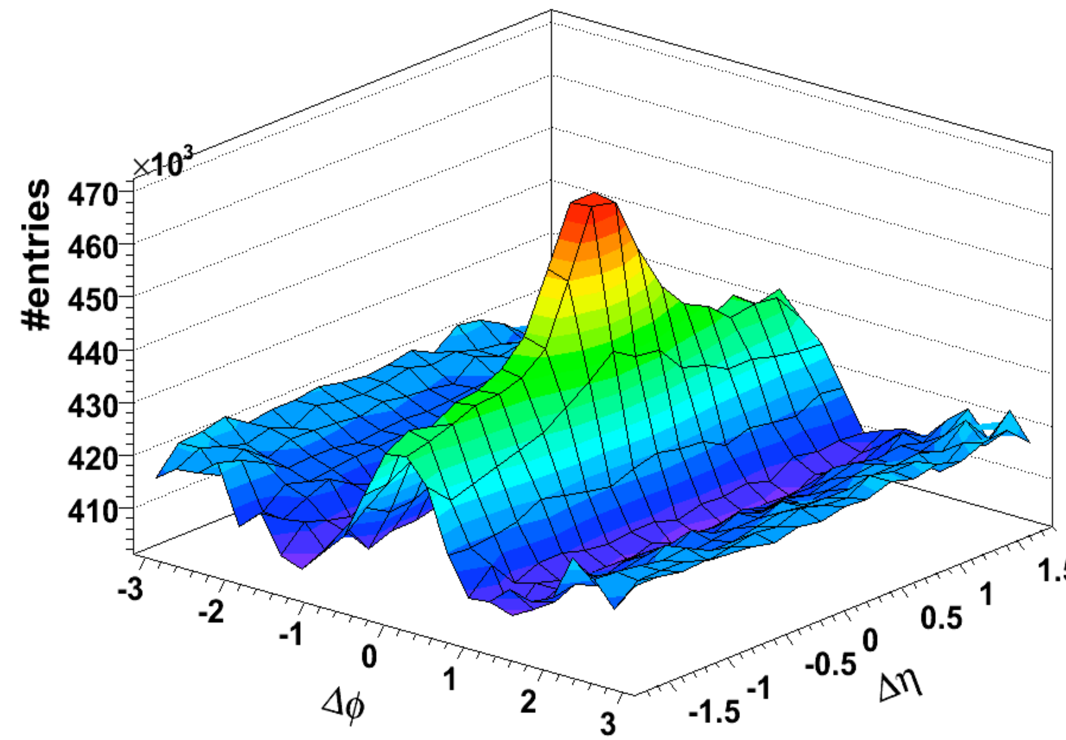

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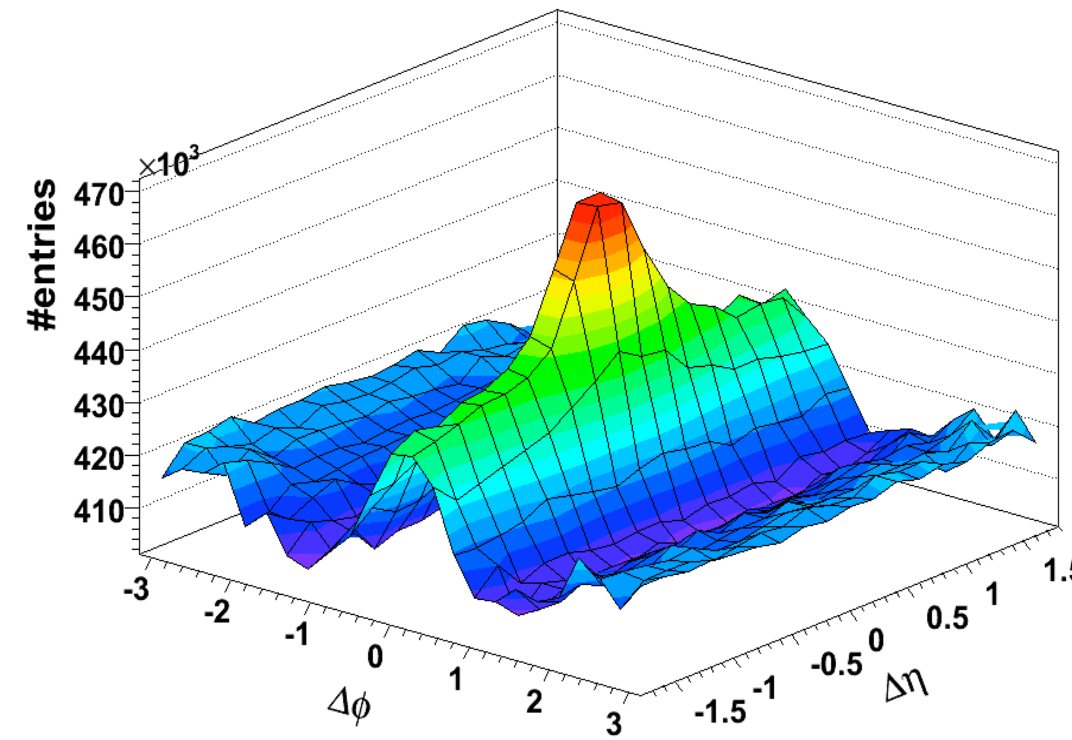

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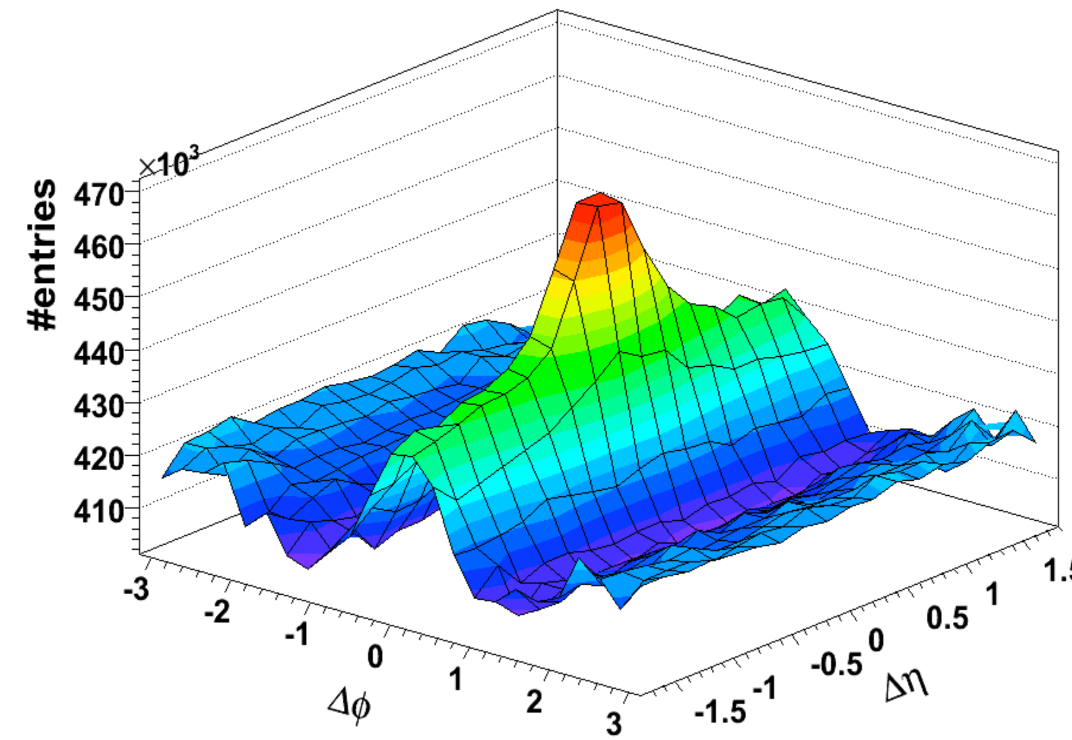

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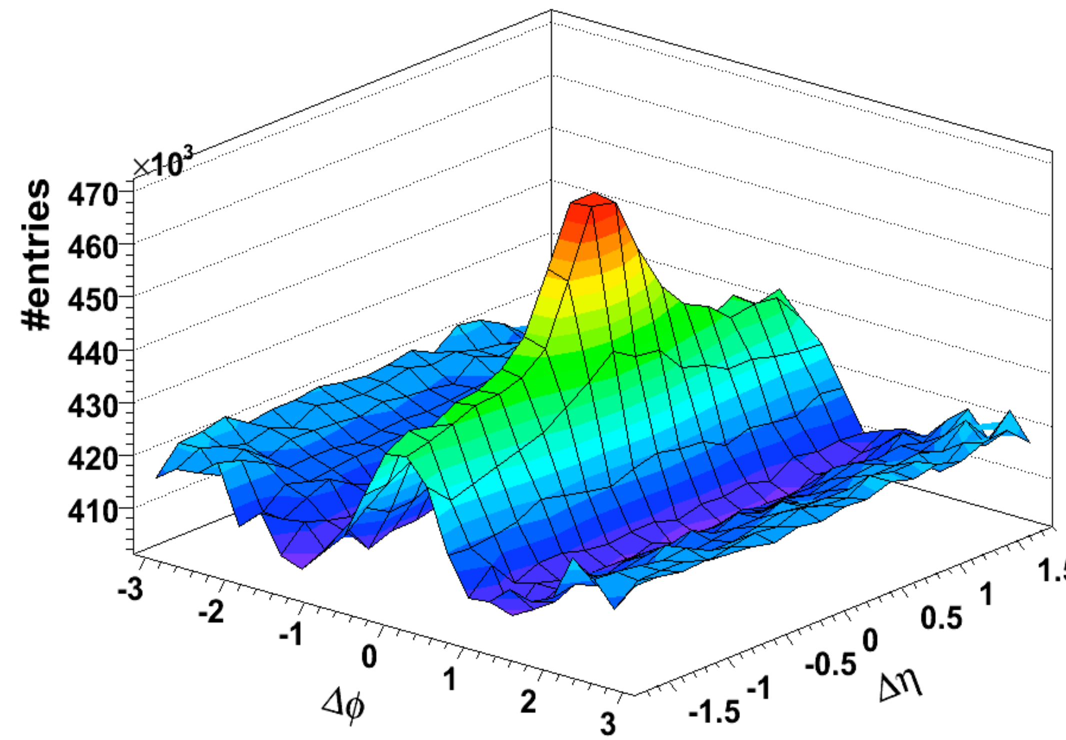

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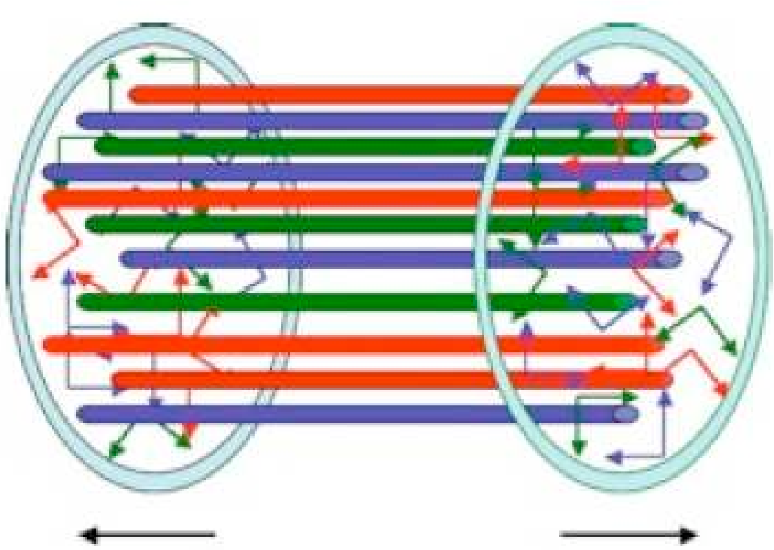

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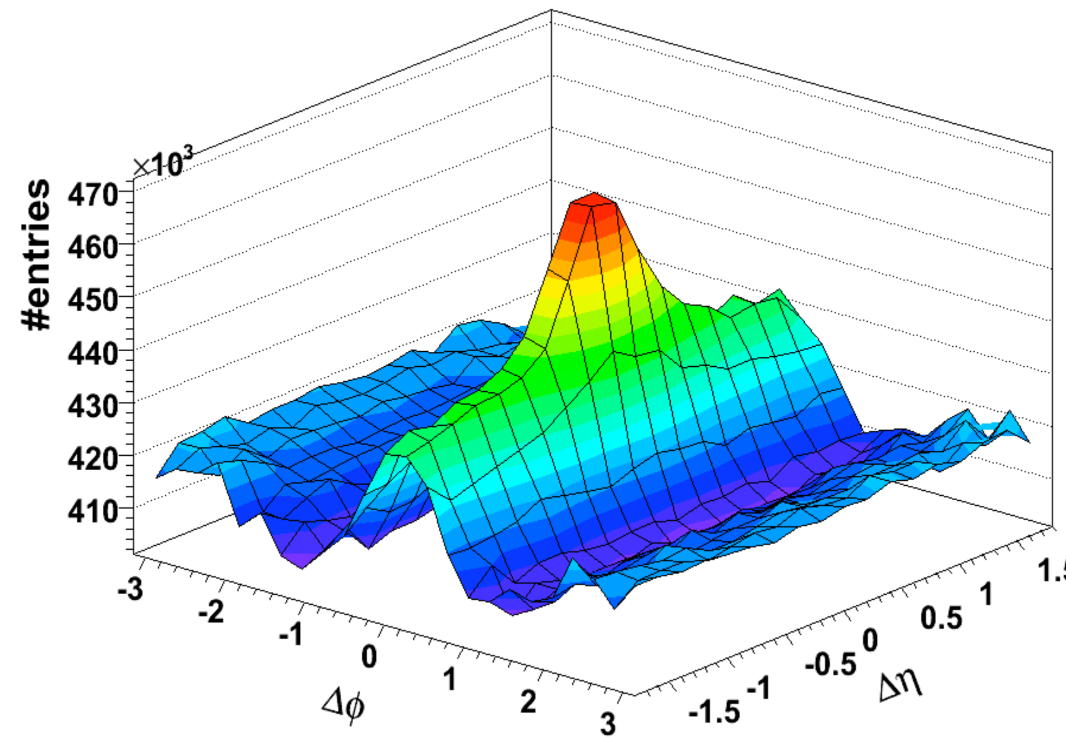

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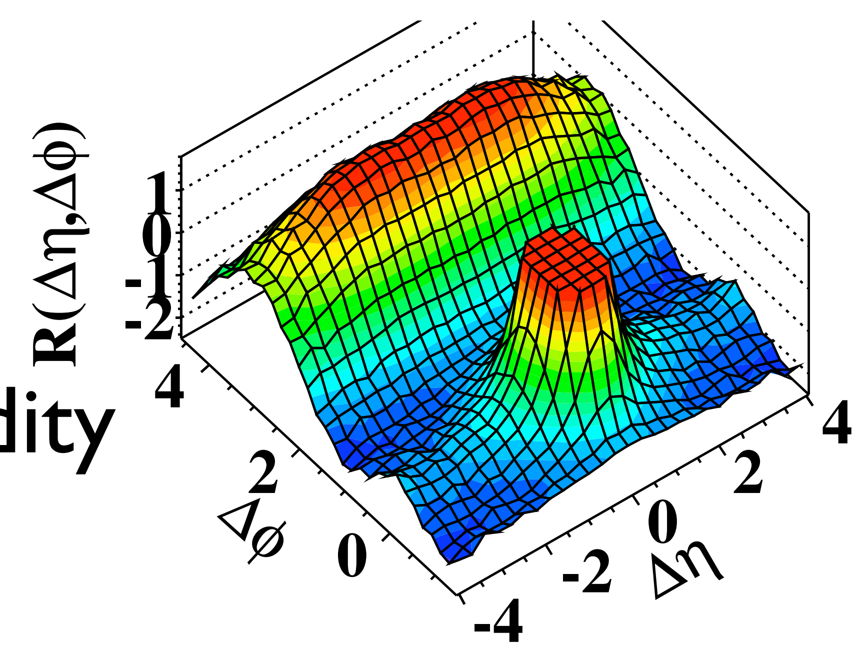
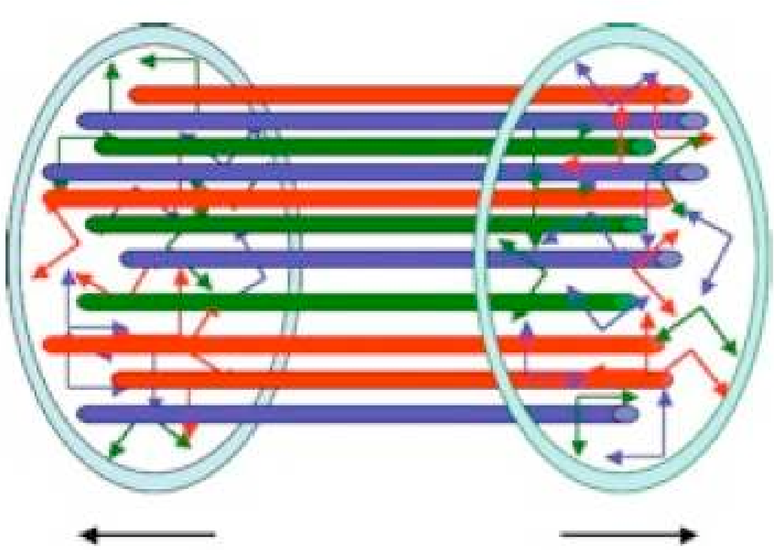
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

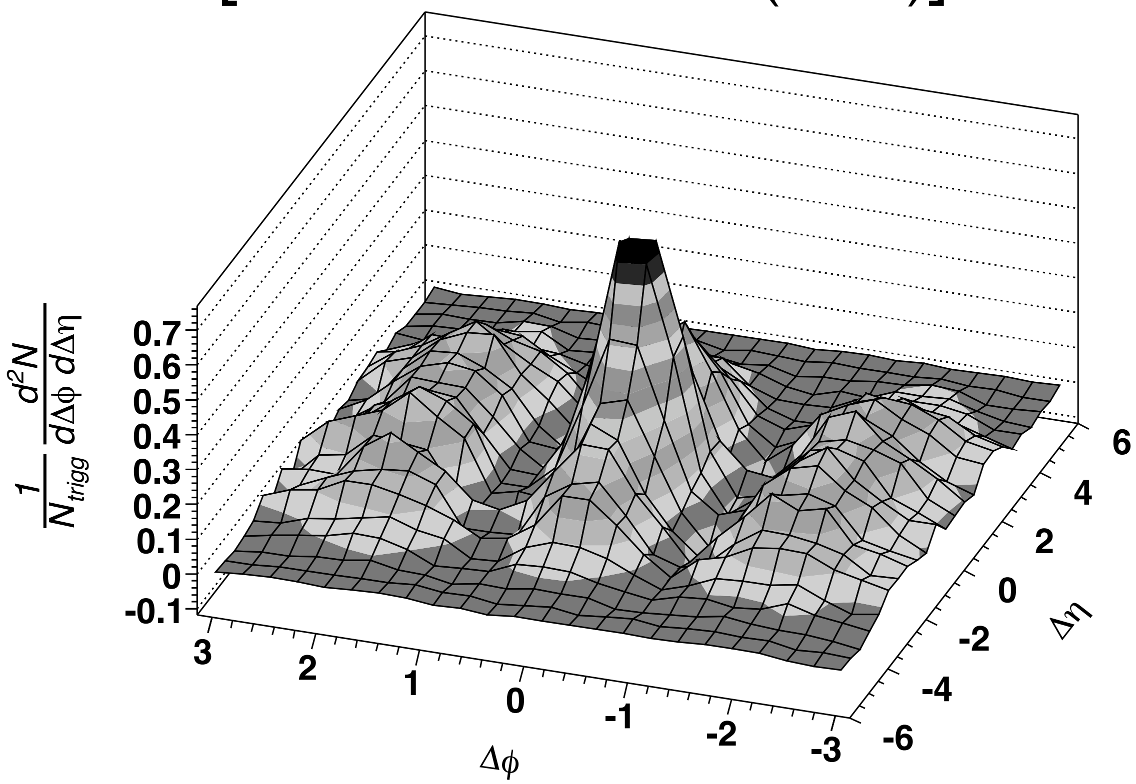


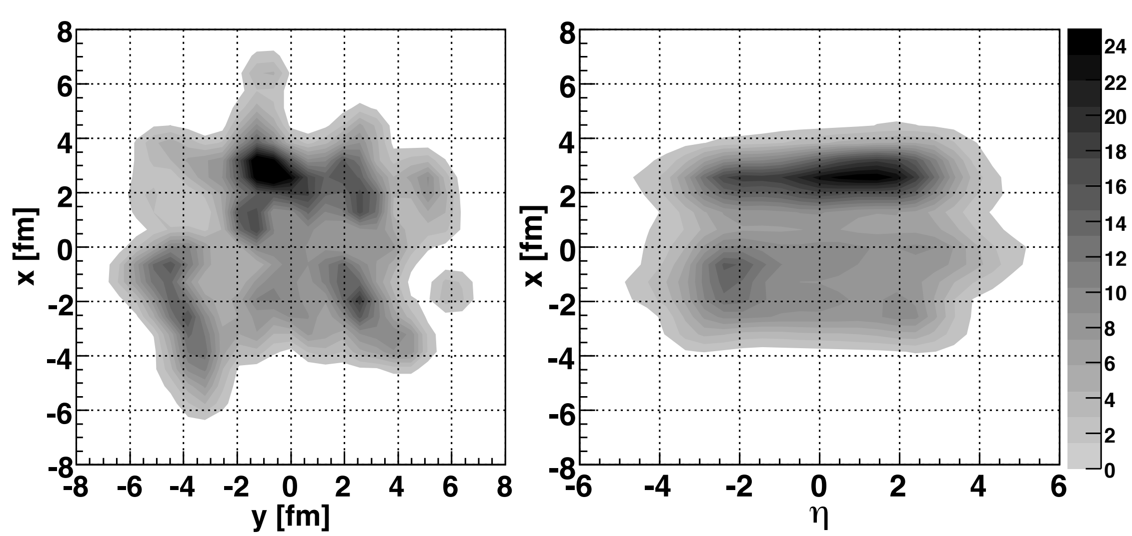


long-range rapidity corr in pp?

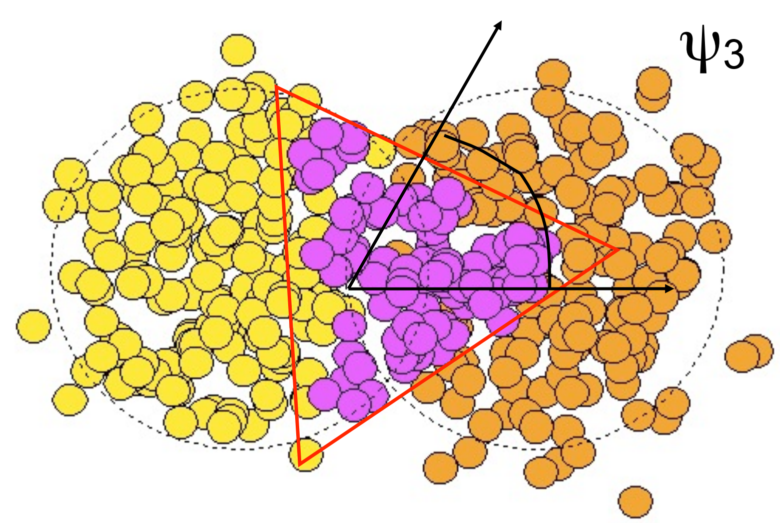
What about the IC?

[Takahashi et al. PRL (2009)]





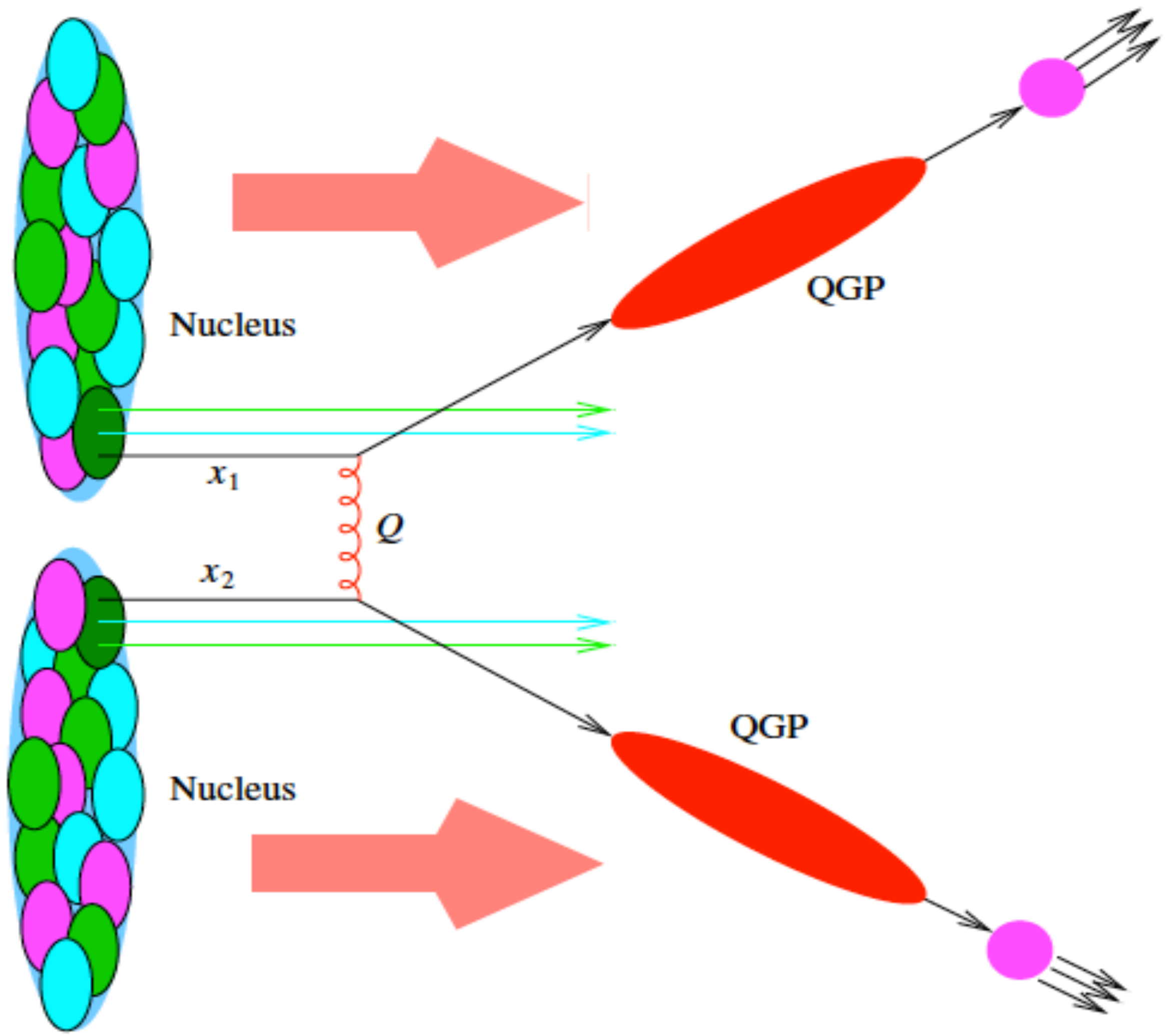
- NEXSPHERIO: uses IC from NEXUS Gribov-Regge model
- non-smooth IC
- generates ridge and apparent "Mach" cones
- could check IC??



$\sim v_3$

Hard probes

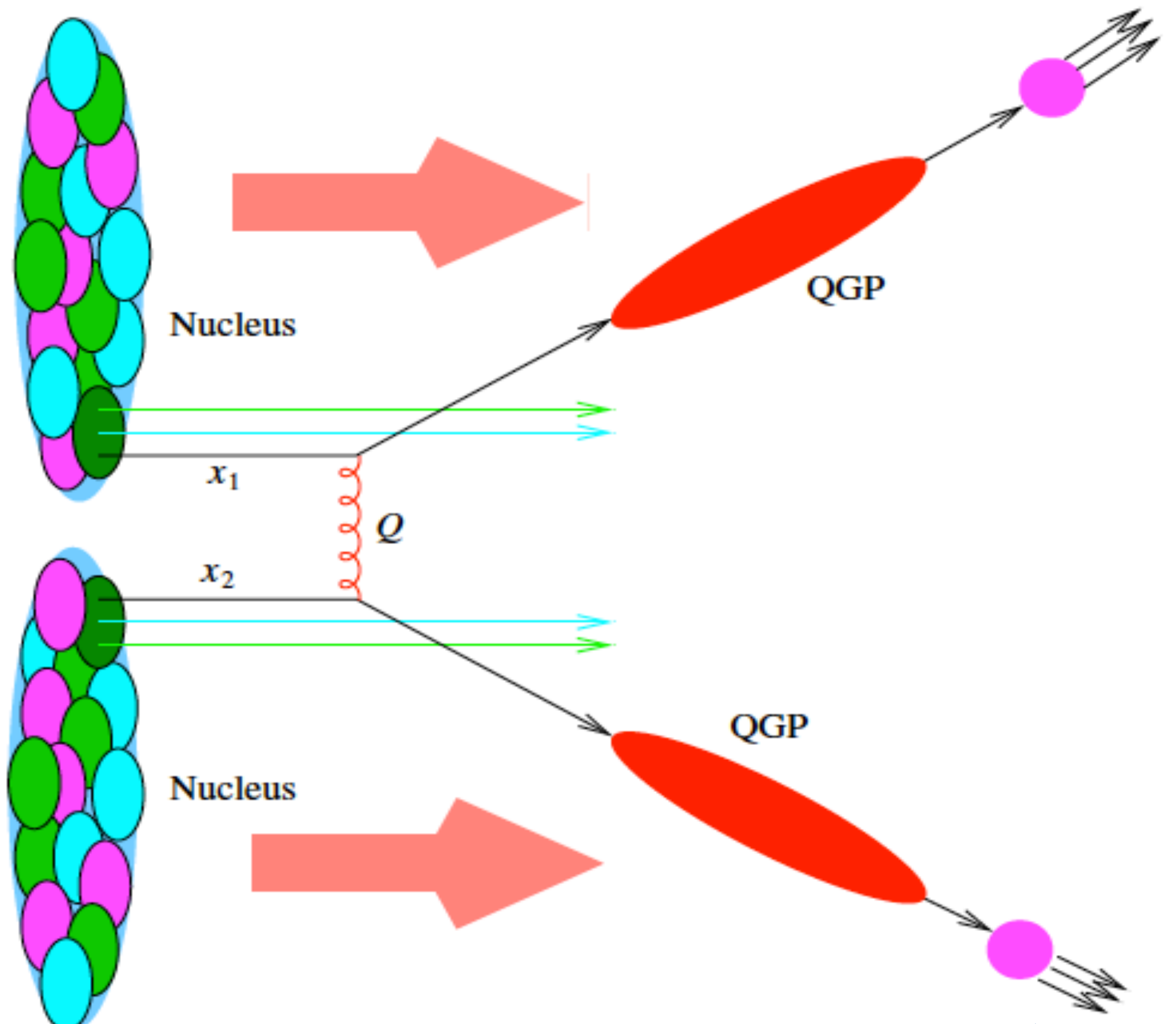
Hard probes



- processes associated with a large momentum transfer
- domain of perturbative QCD!
  - ✓ calculable
  - ✓ well-tested (e^+e^-, pp collisions)
- factorization

$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D(z, Q^2)$$

Hard probes



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nuclear parton distribution functions

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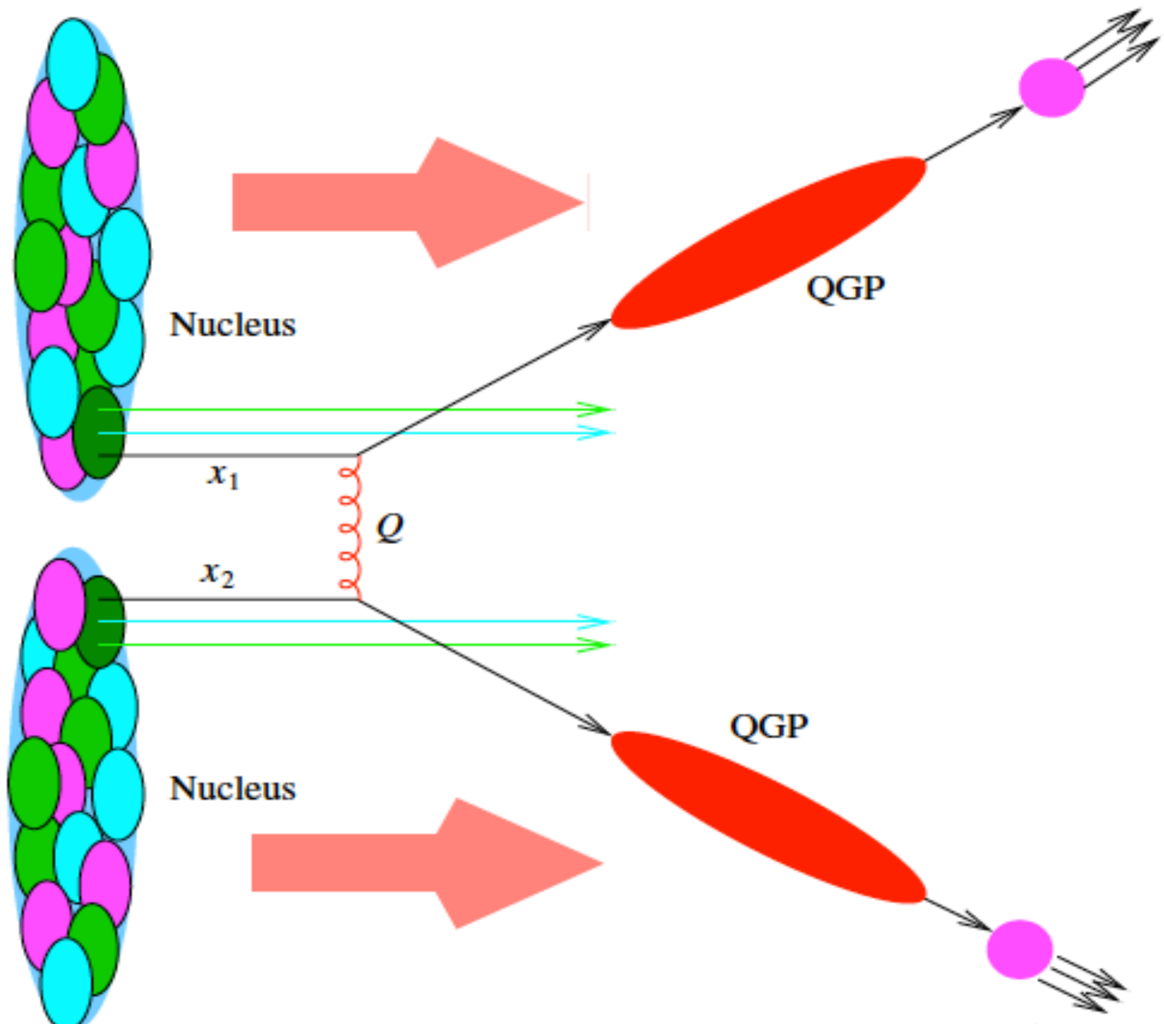

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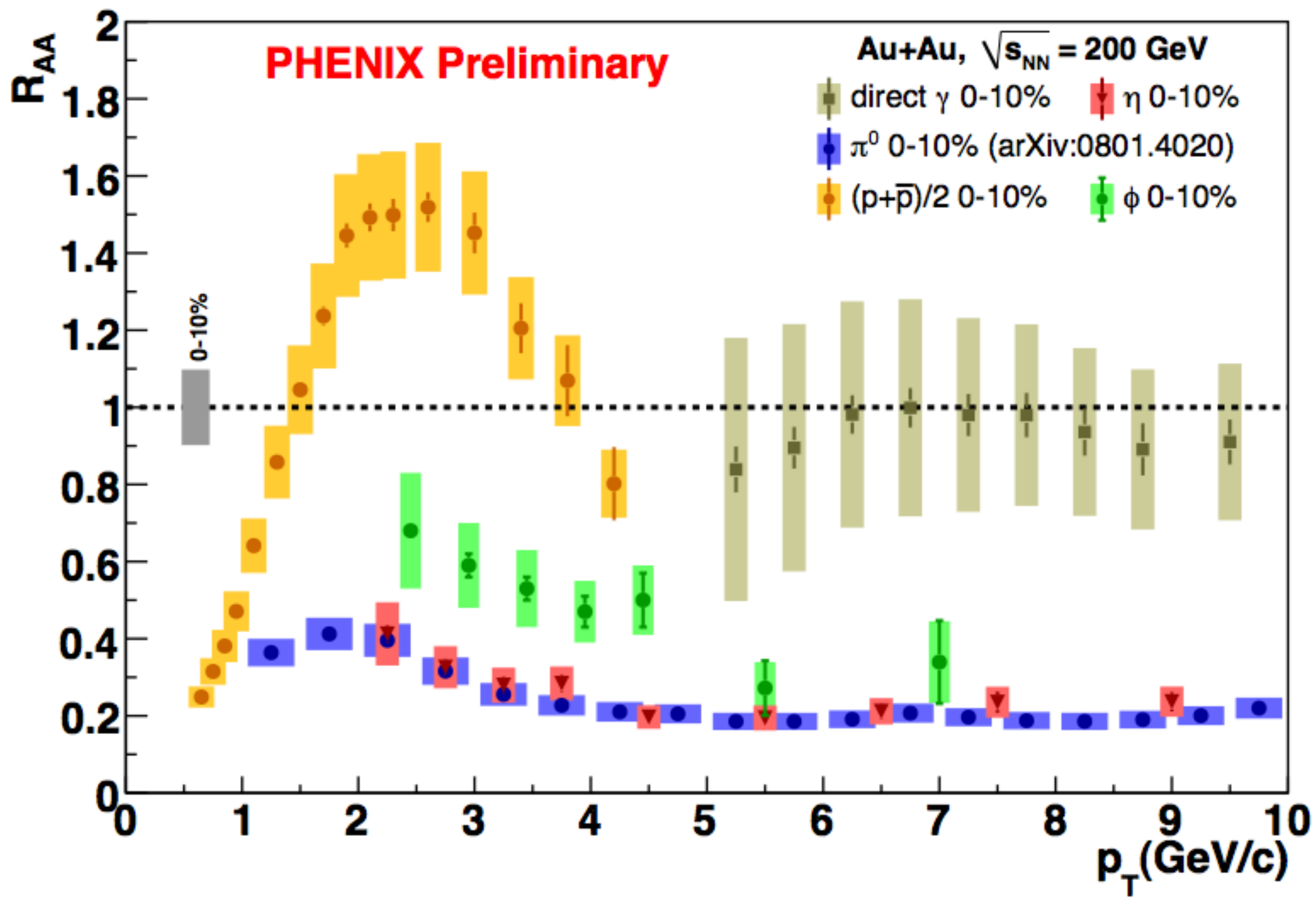
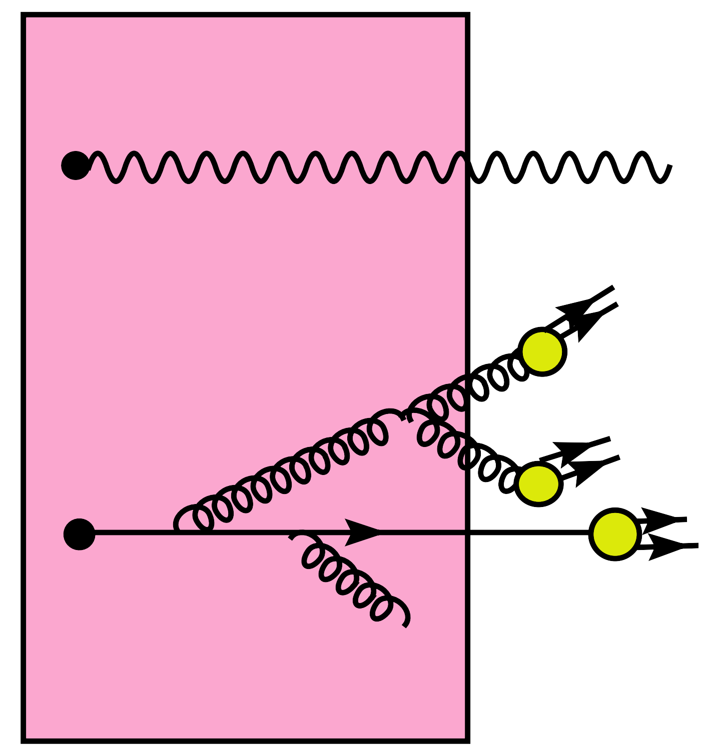
nuclear parton distribution functions

medium-modified fragmentation function

Leading particle suppression @ RHIC

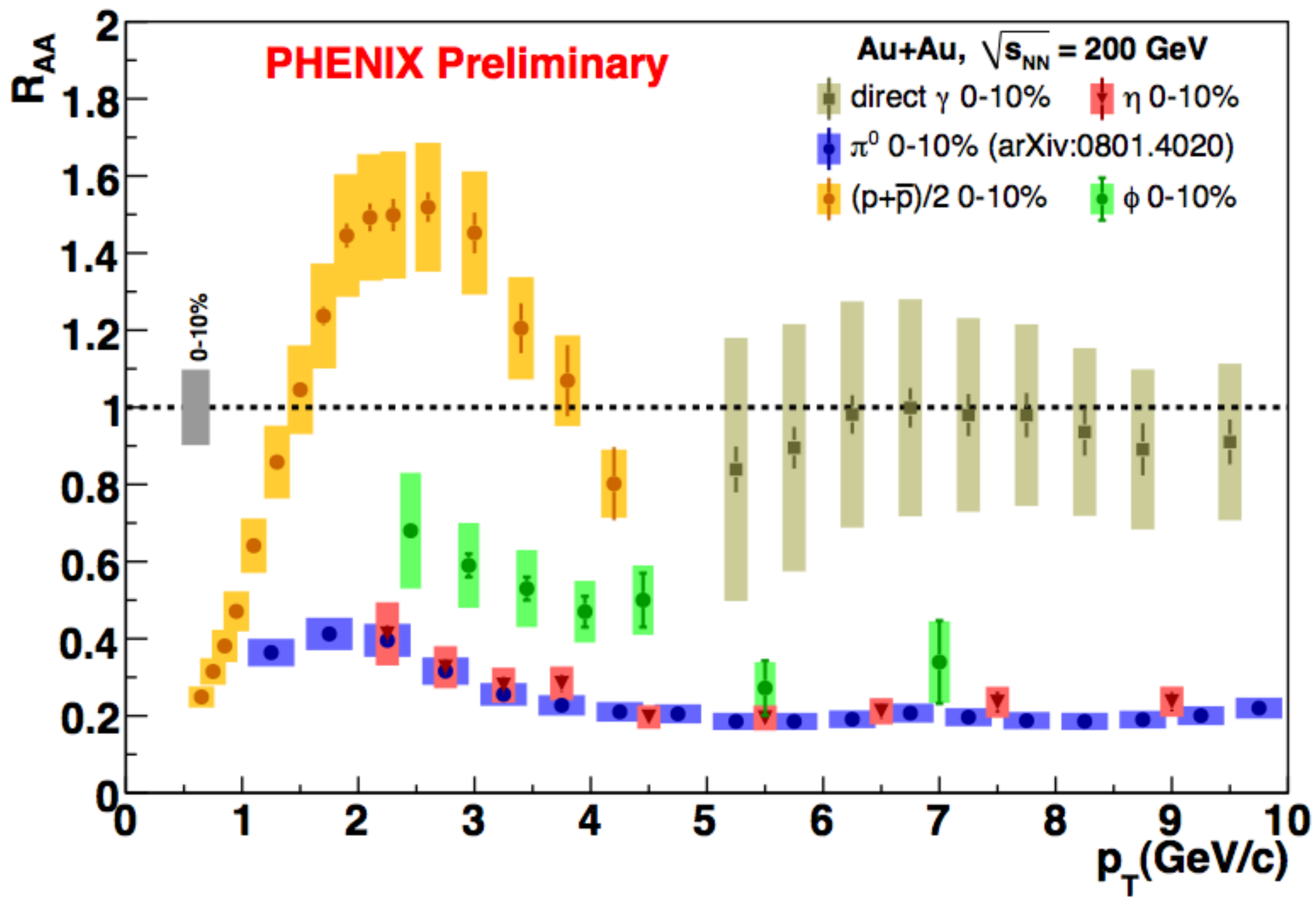


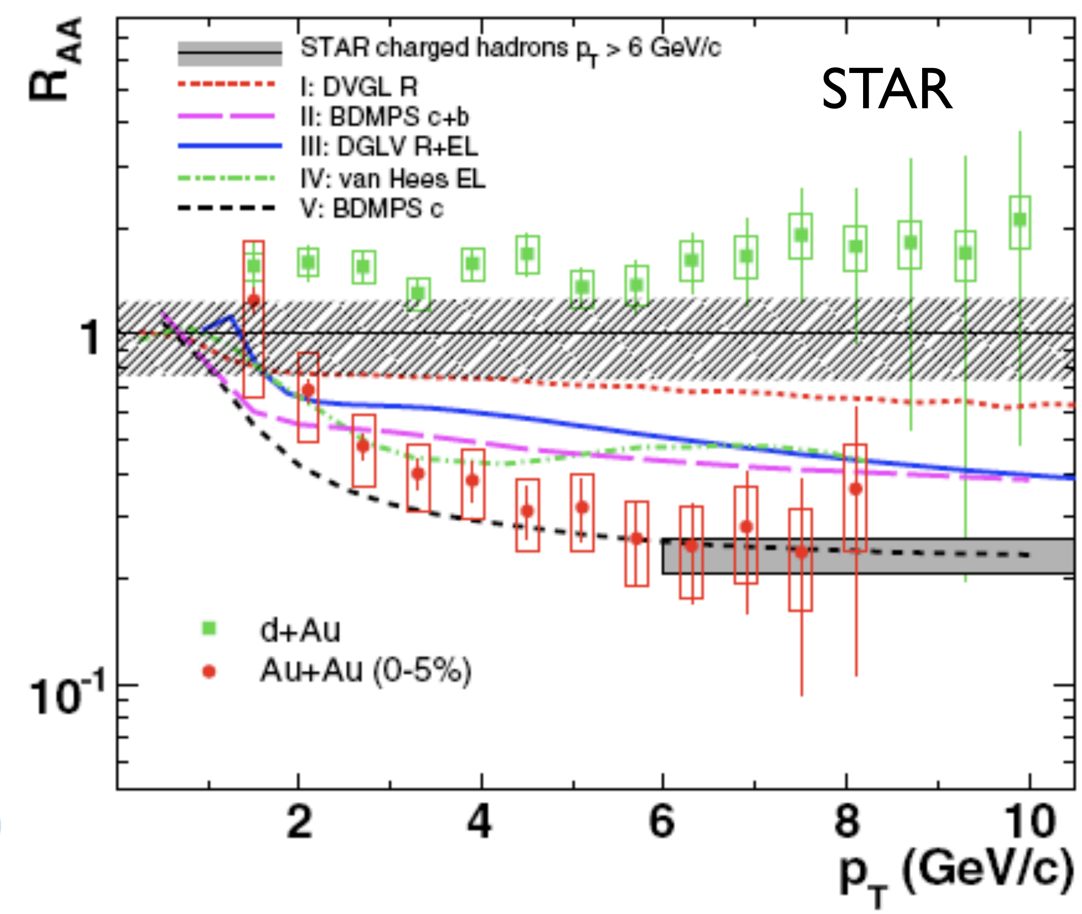


- matter is opaque for colored objects!
- suppression of heavy quarks!

$$R_{AA} = \frac{dN^{AA}/dp_\perp}{N_{coll} \times dN^{pp}/dp_\perp}$$

Leading particle suppression @ RHIC





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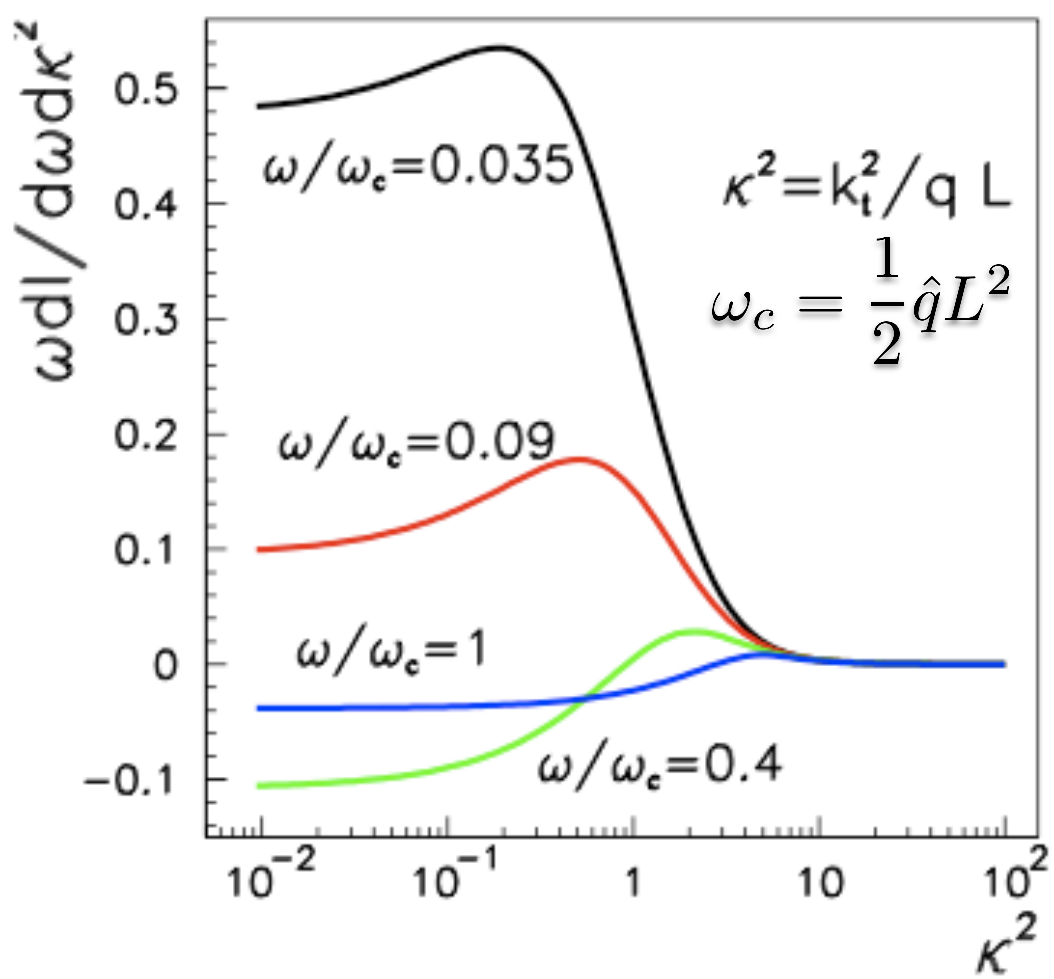
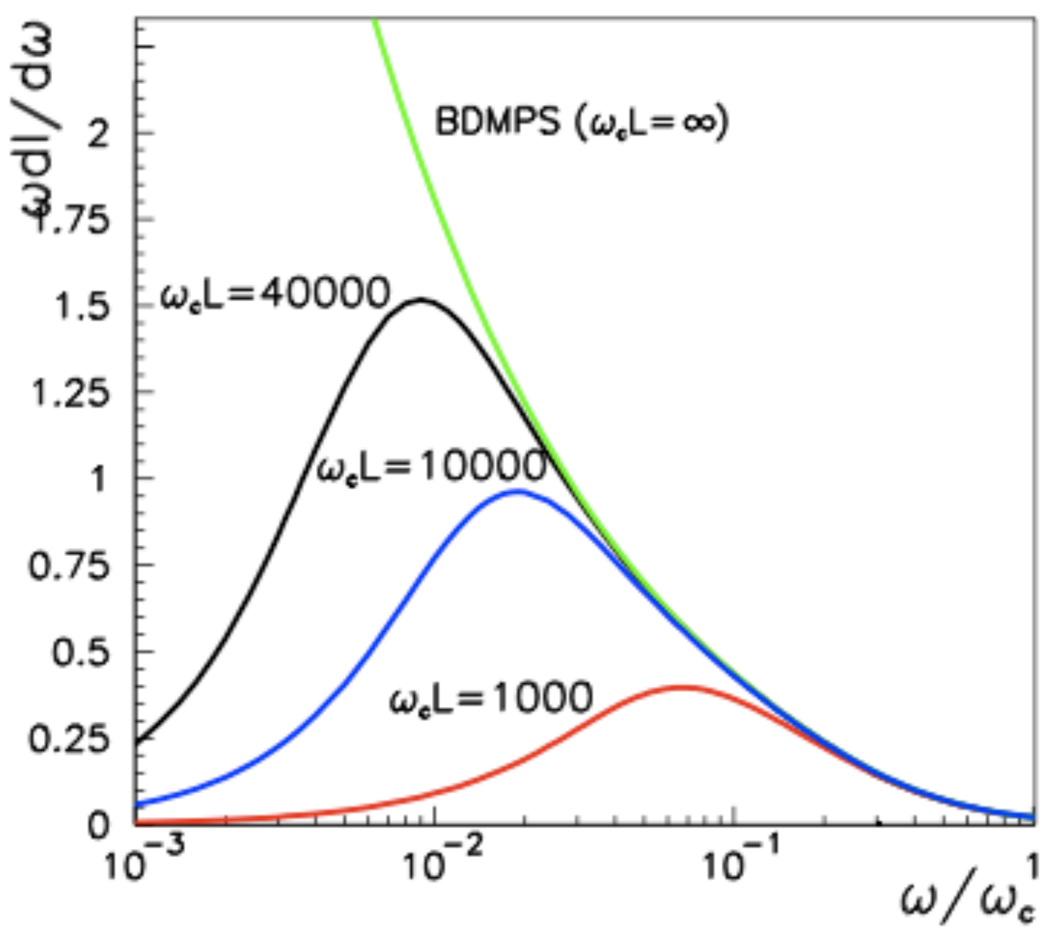
Radiative energy-loss in QGP

Energy loss: $\Delta E \simeq \frac{\alpha_s C_R}{2\pi} \hat{q} L^2$

Broadening: $k_\perp^2 \simeq \hat{q} L \propto \frac{\Delta E}{L}$

$$\lim_{R\to\infty} \omega \frac{dI}{d\omega} \simeq \frac{2\alpha_s C_R}{\pi} \begin{cases} \sqrt{\frac{\omega_c}{2\omega}} & \text{for } \omega < \omega_c\,, \\ \frac{1}{12}\left(\frac{\omega_c}{\omega}\right)^2 & \text{for } \omega > \omega_c \end{cases}$$





[Baier, Dokshitzer, Mueller, Peigné, Schiff, Gyulassy Wang, Levai, Vitev, Wiedemann, Salgado, Armesto...]

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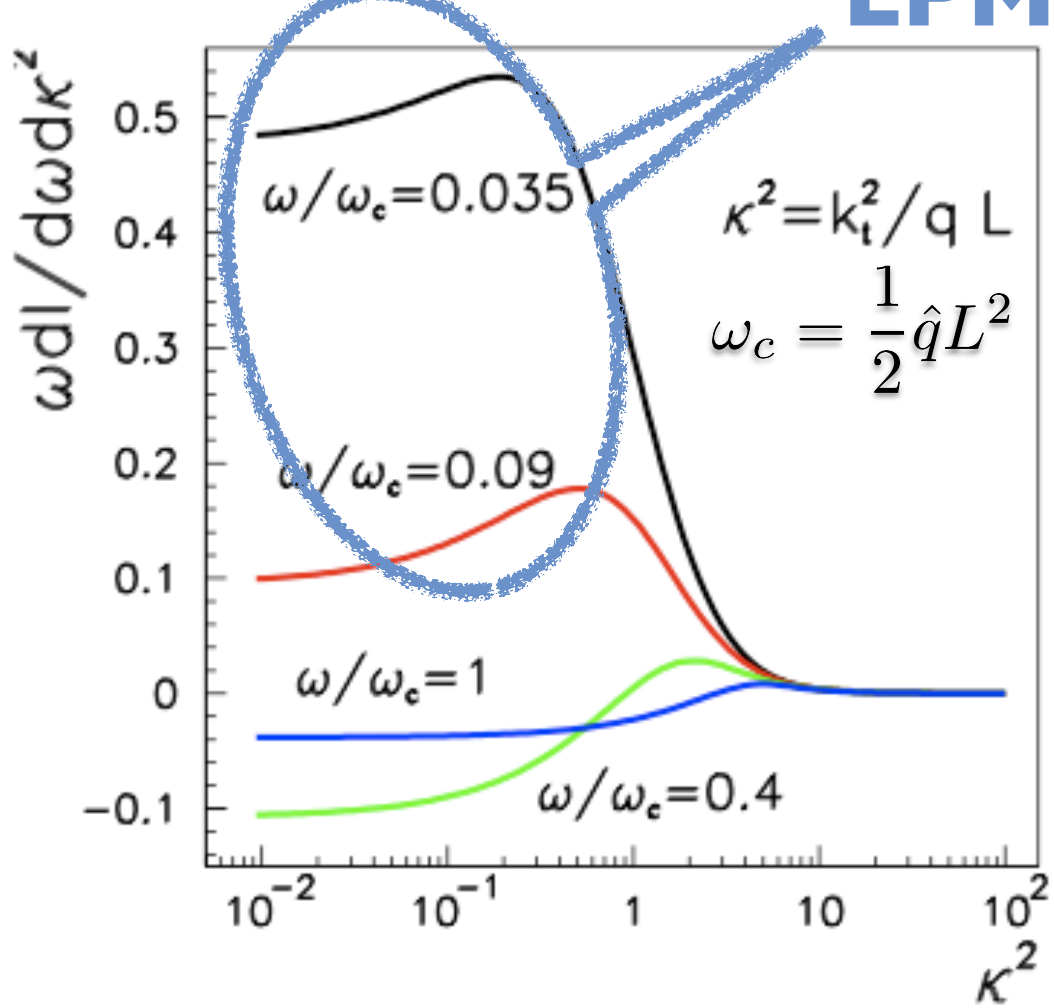
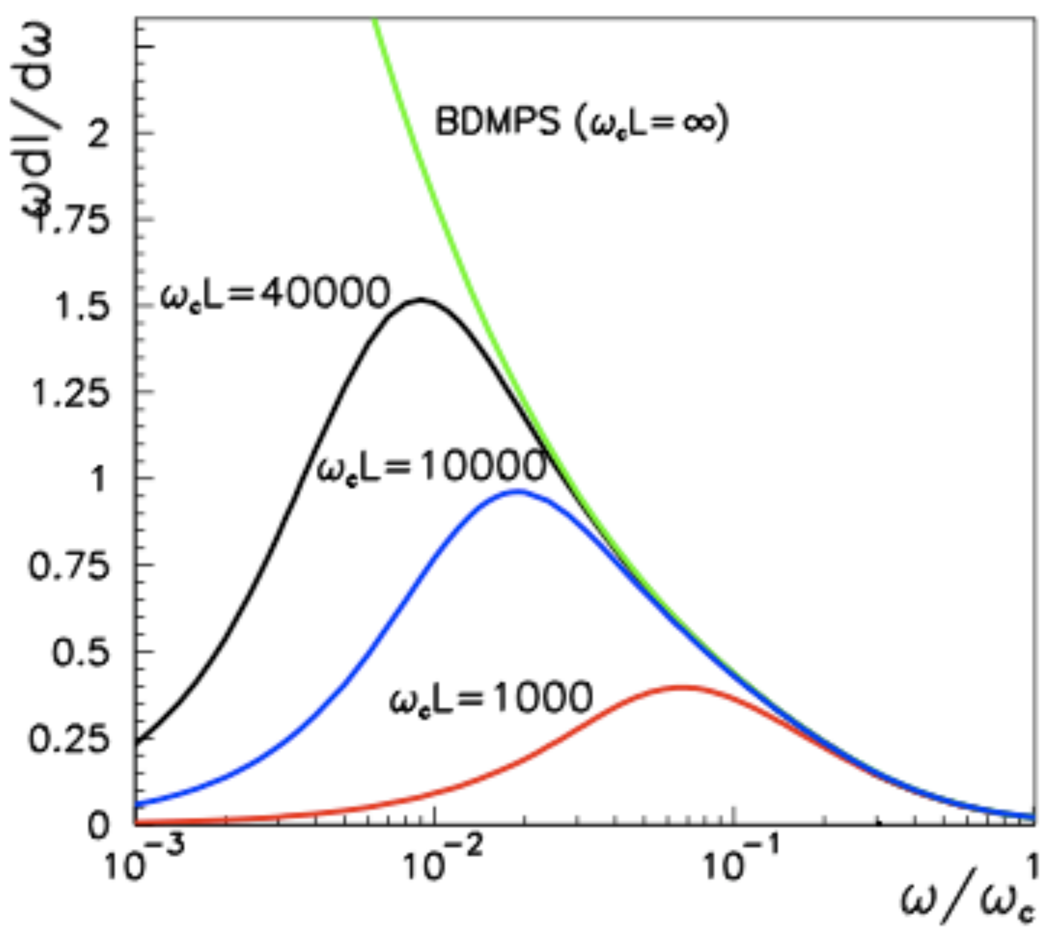
LPM suppression





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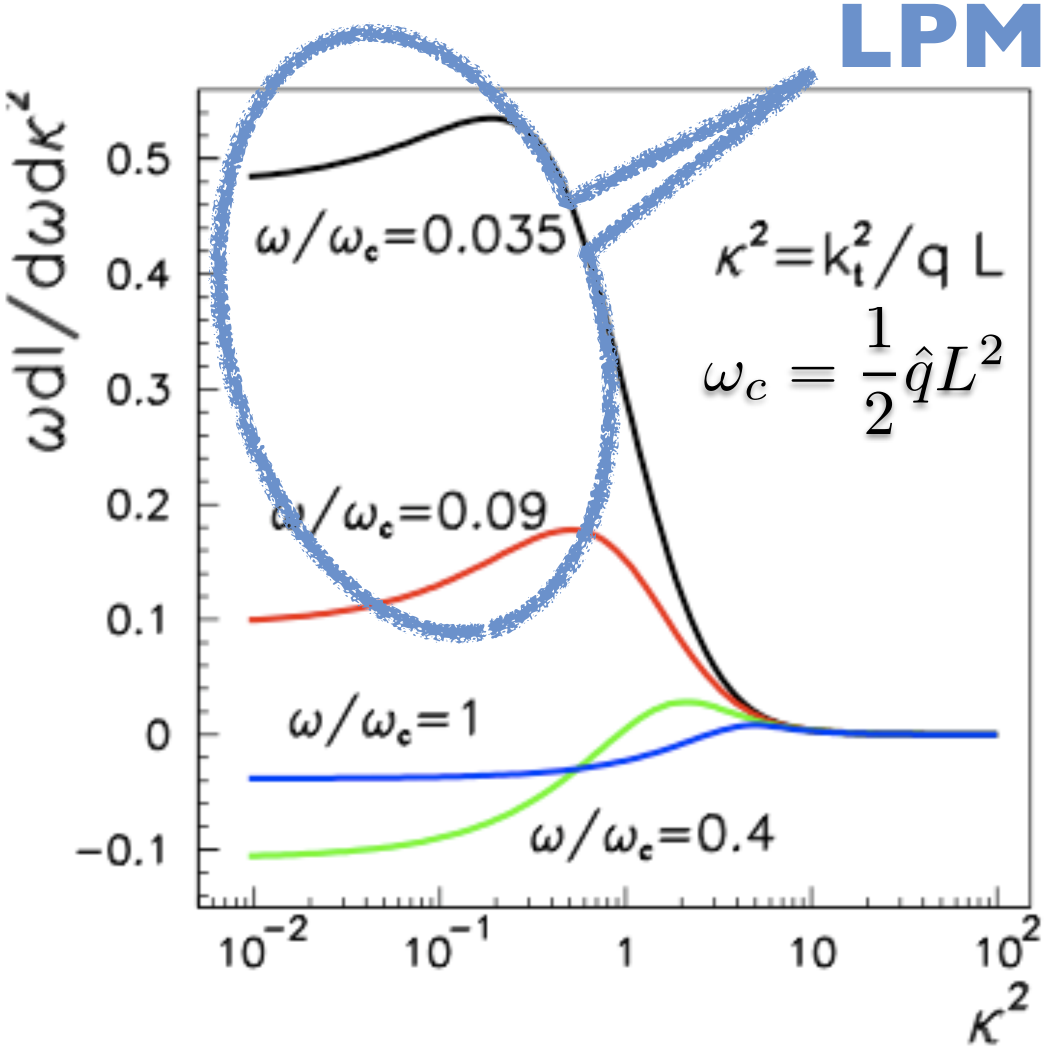
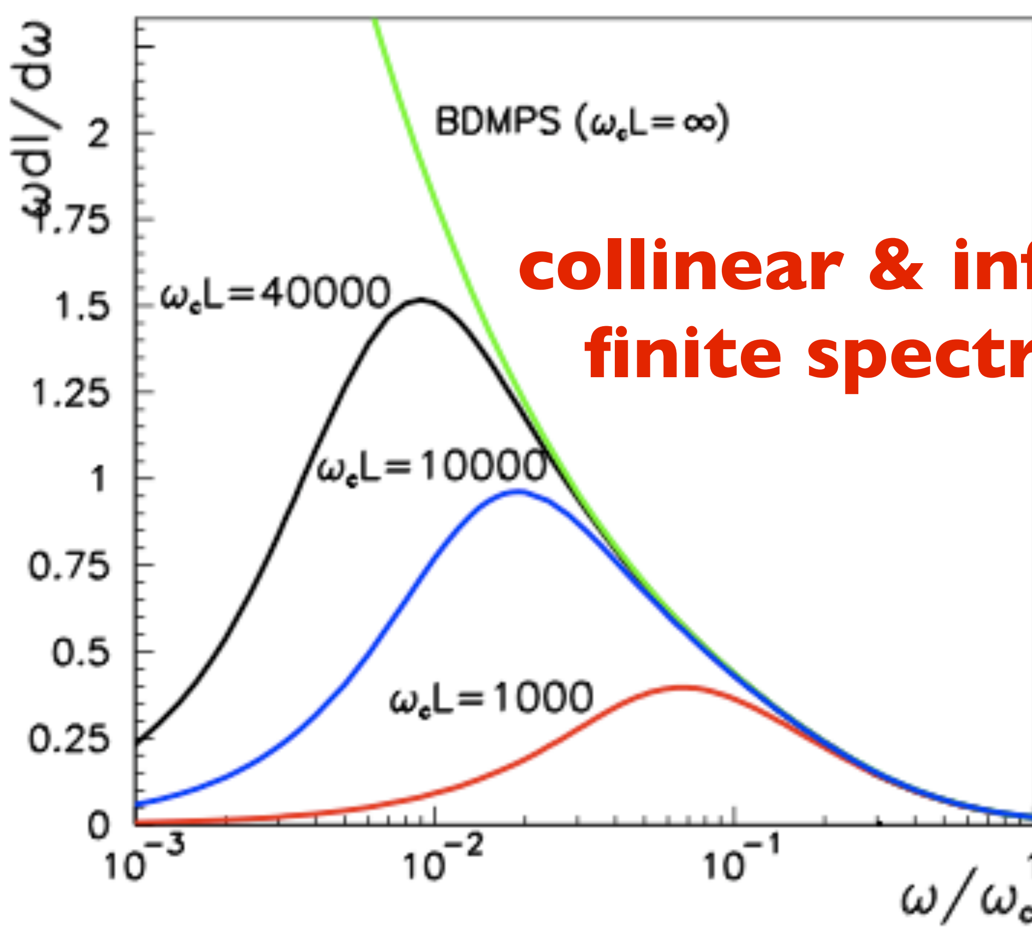
LPM suppression

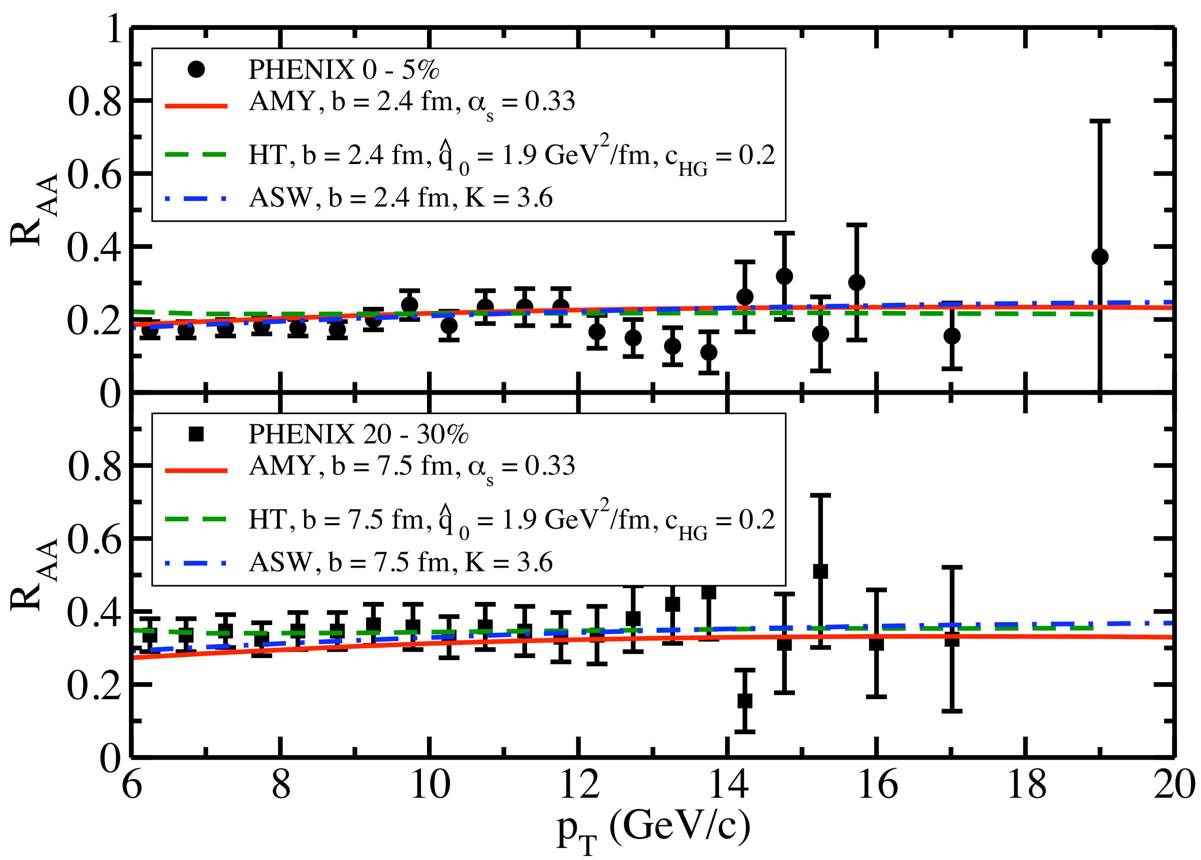




collinear & infrared finite spectrum!

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Gyulassy Wang, Levai, Vitev, Wiedemann, Salgado, Armesto...]

Extracted medium properties



"Brick" problem

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

Ideal gas: $\hat{q}_F \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq 2\epsilon^{3/4}$

In principle has also time dep: $\hat{q}(\tau) = \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha}$

Should be consistent with bulk observables!

Still a lot of uncertainties in the calculations...

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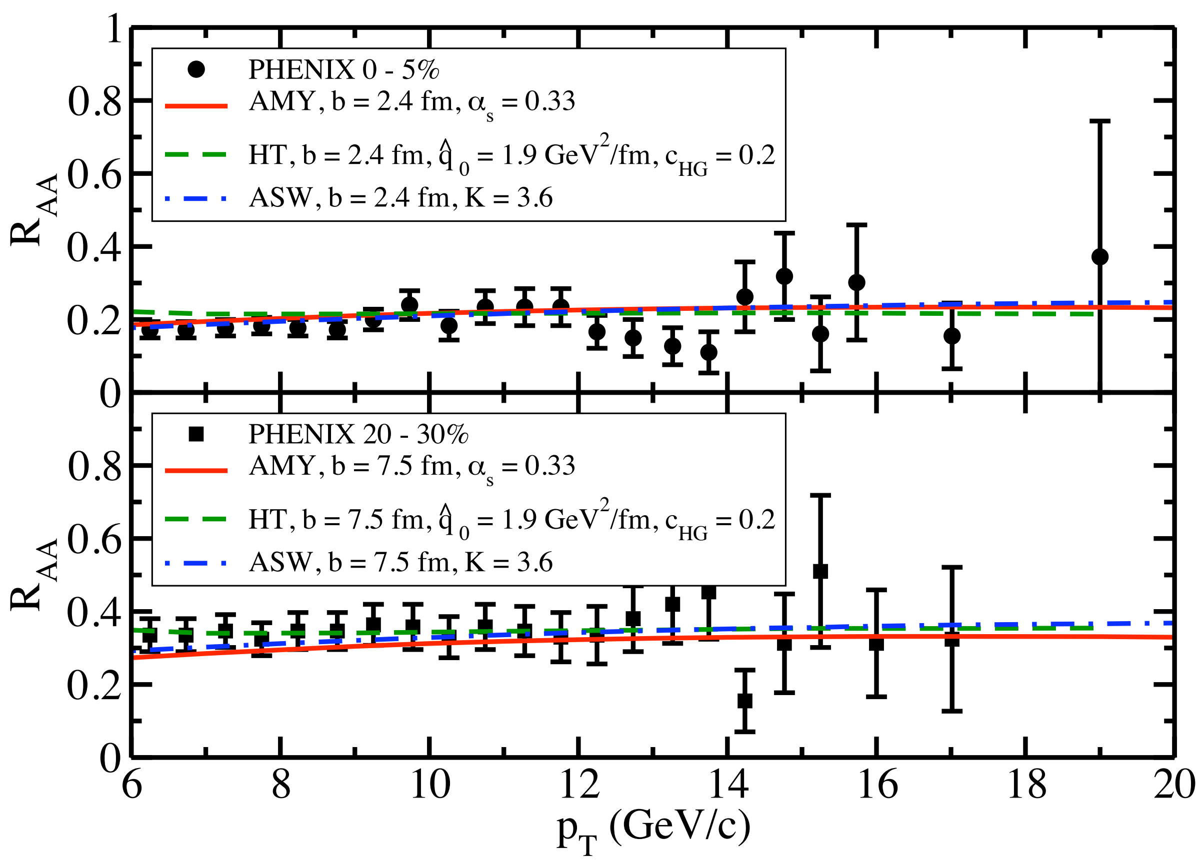

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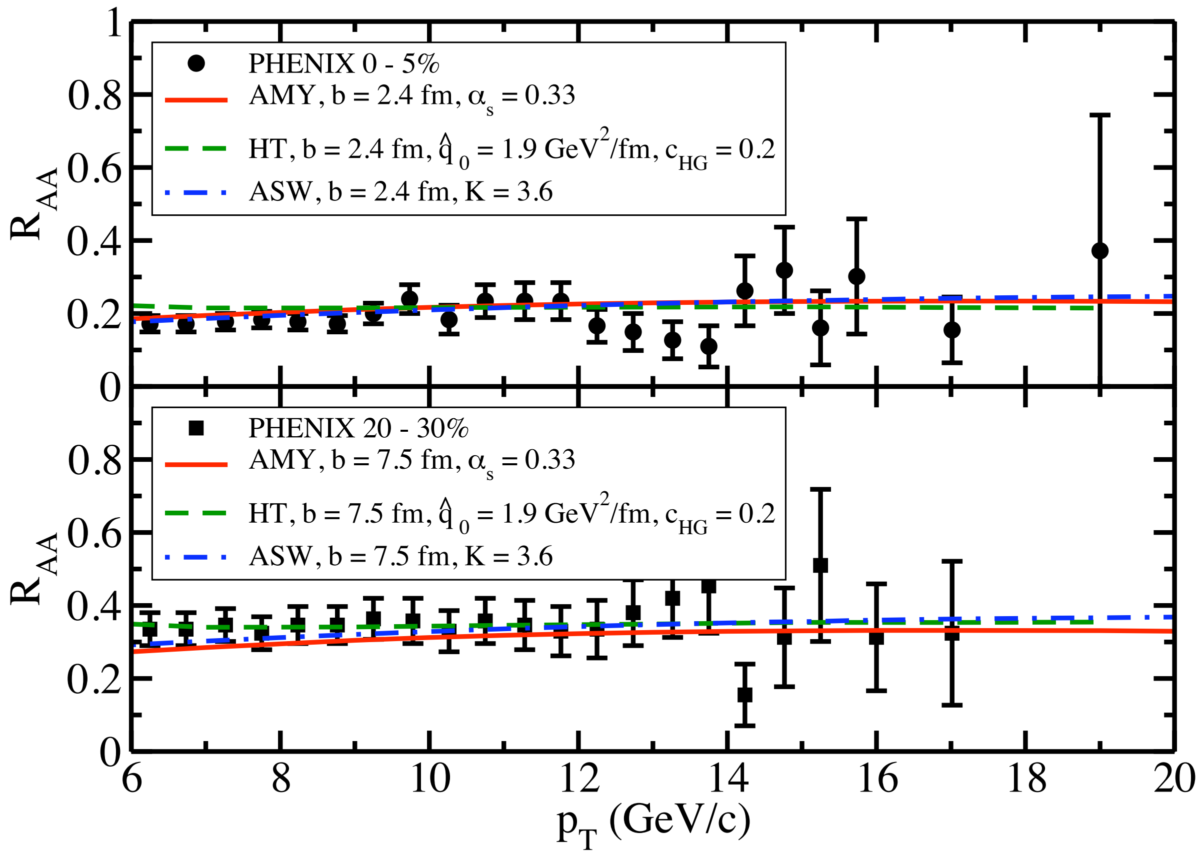

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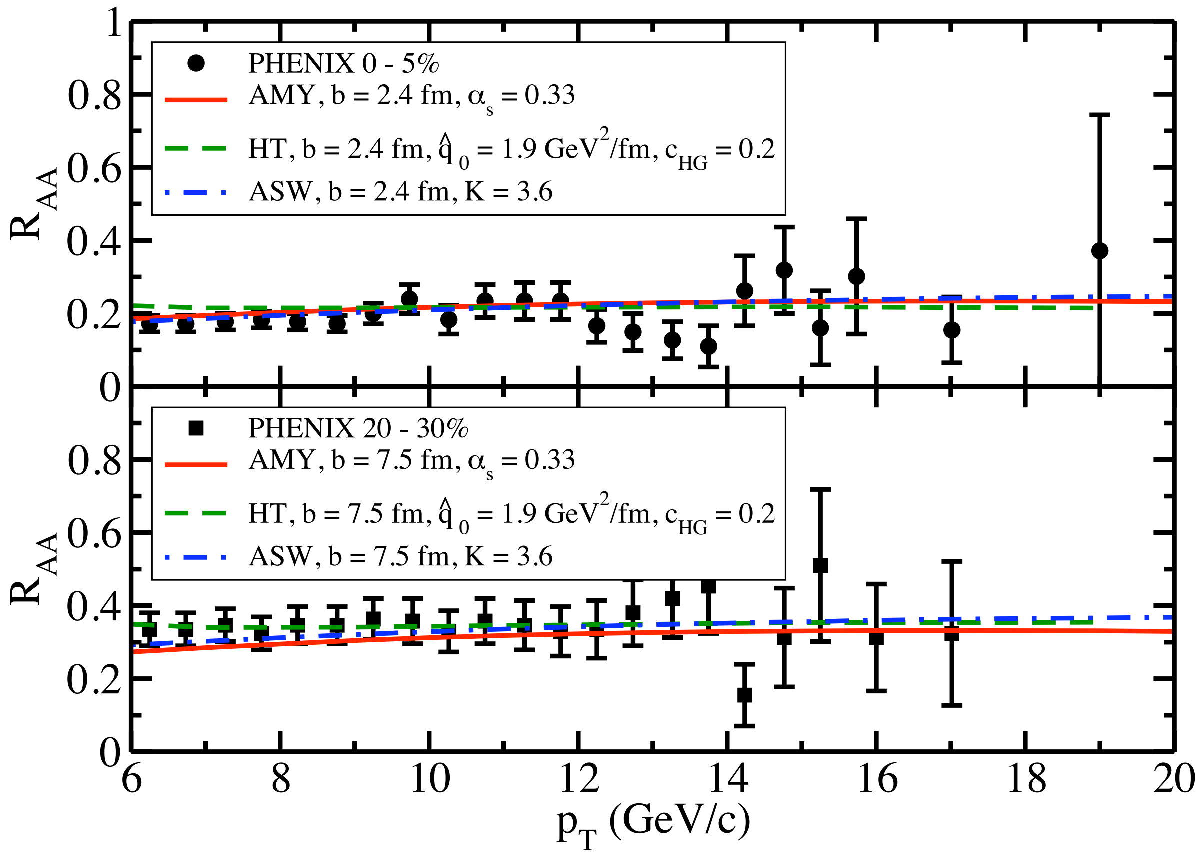

"Brick" problem

thermal approach

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	$10\ \mathrm{GeV}^2/\mathrm{fm}$	$2.3\ \mathrm{GeV}^2/\mathrm{fm}$	$4.1\ \mathrm{GeV}^2/\mathrm{fm}$
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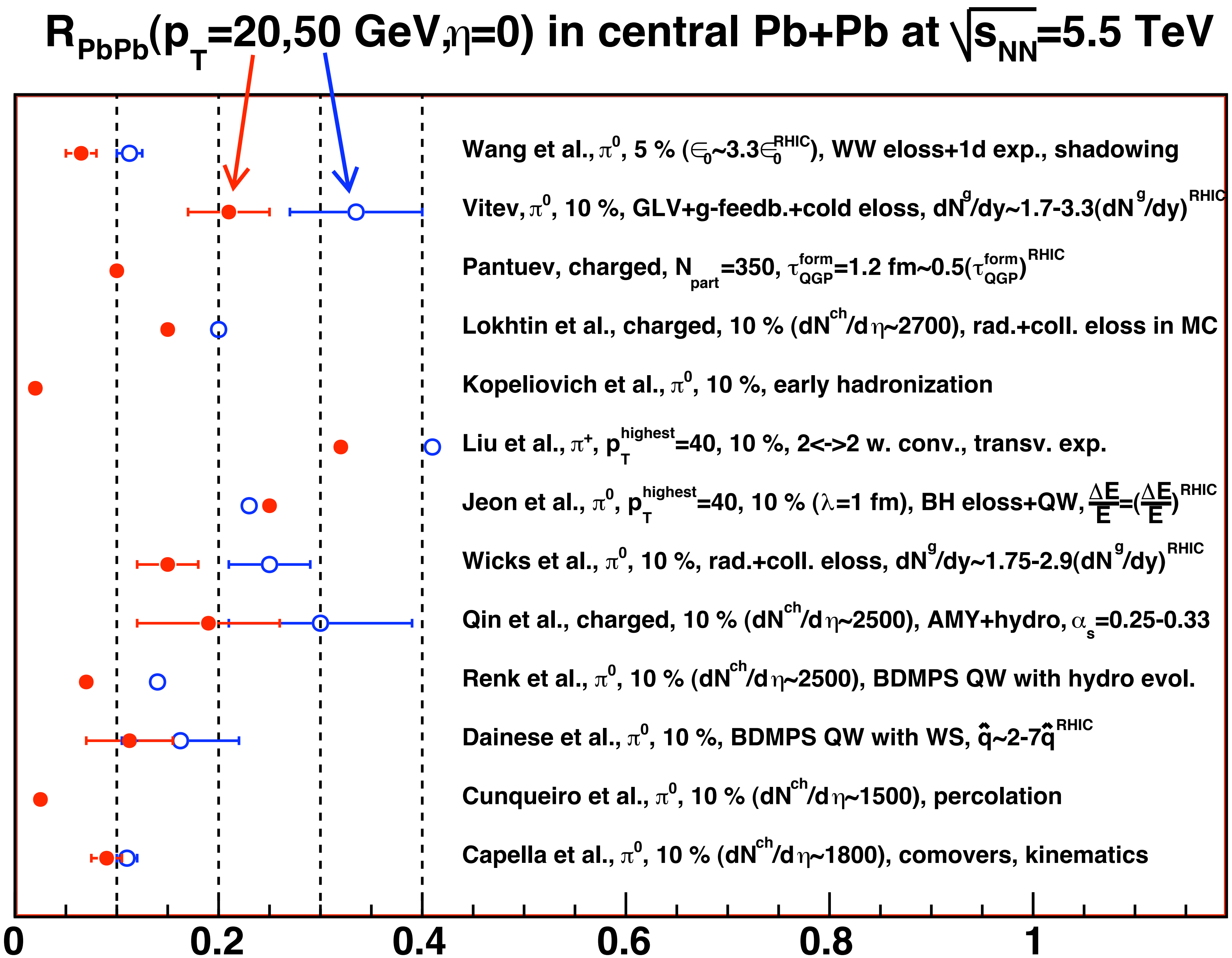
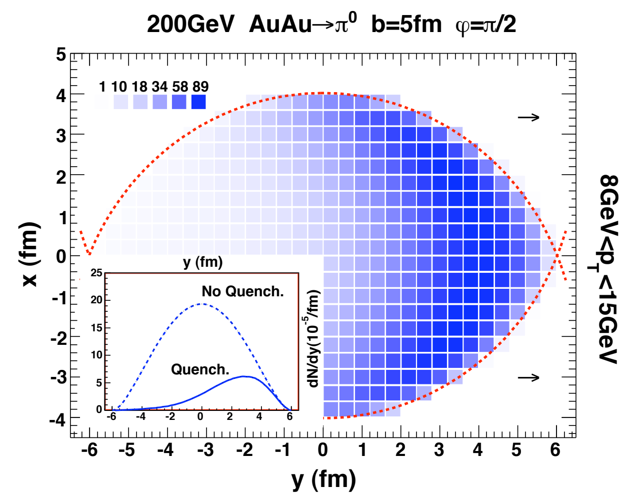
Jet quenching predictions

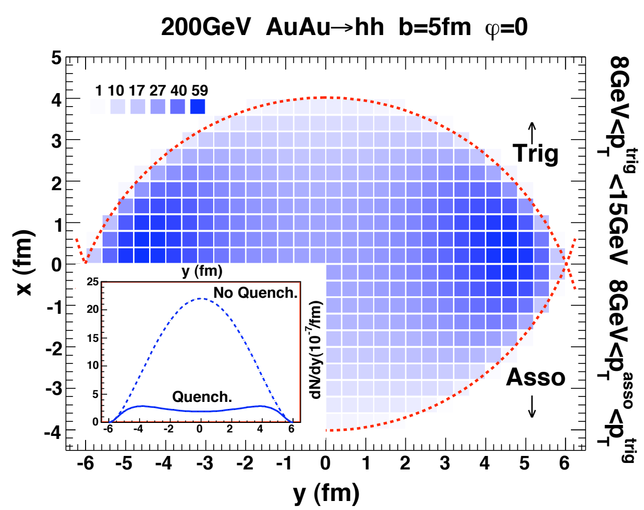


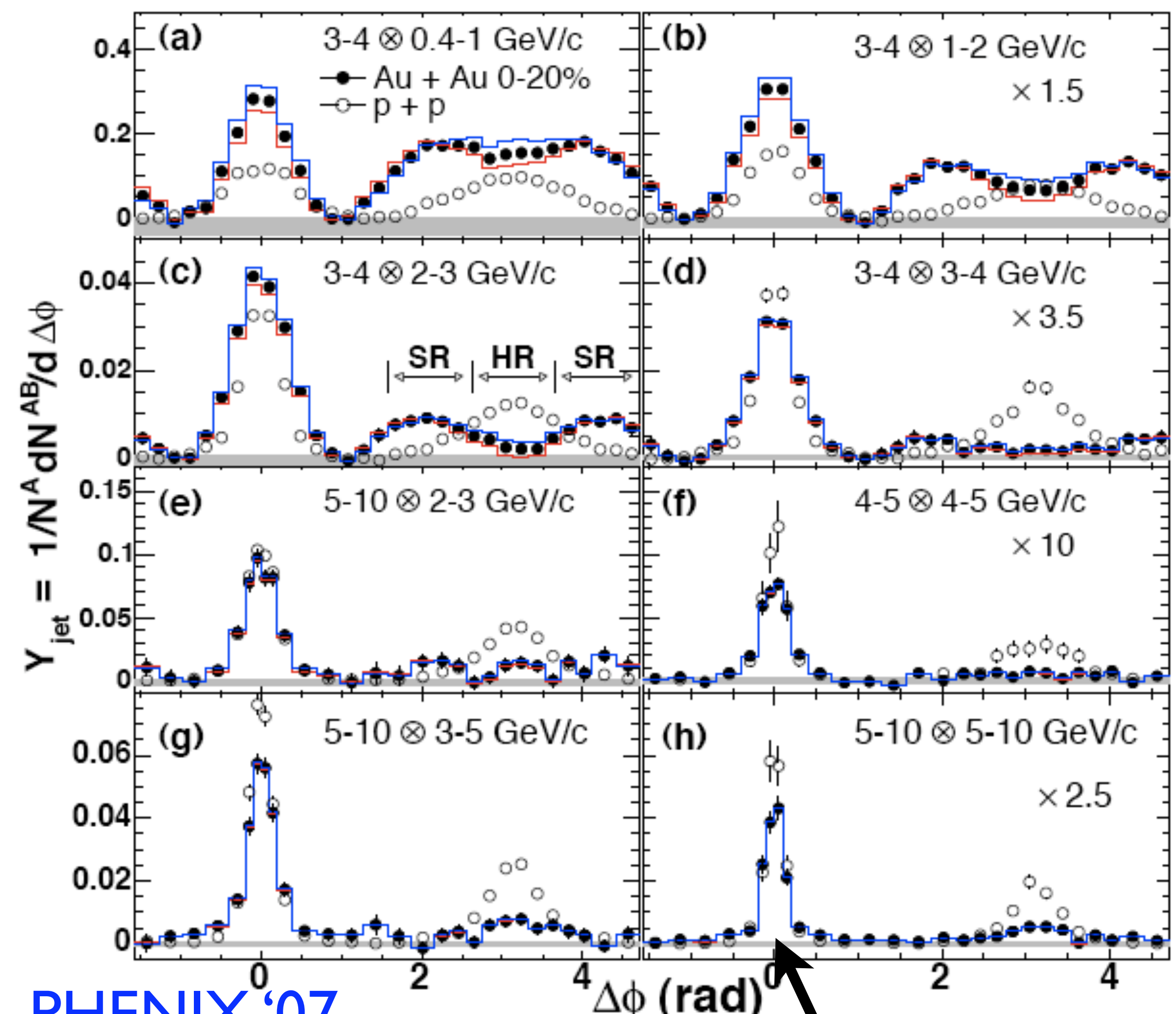
Proceedings from “Heavy Ion Collisions at the LHC - Last Call for LHC predictions” workshop, CERN 2007, arXiv:0711.0974

Back-to-back correlations

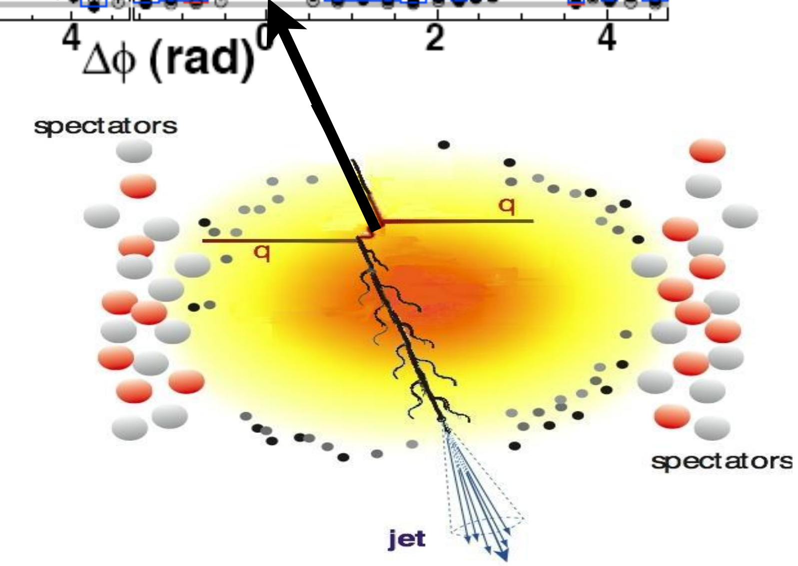
[Zhang et al.]





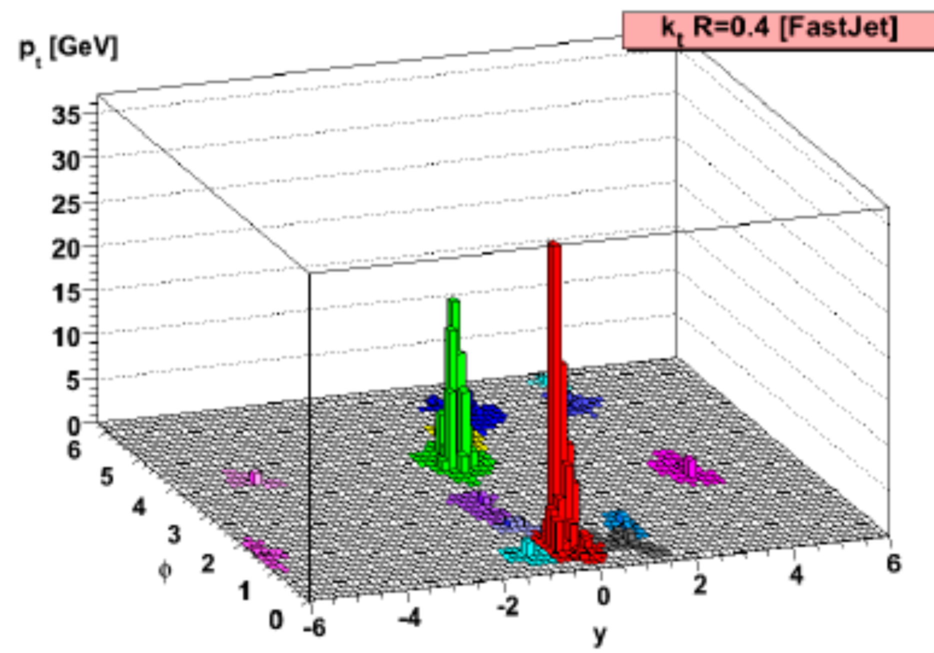


PHENIX '07



- jet in opposite direction is strongly suppressed
- complicated structures

Jets in HIC

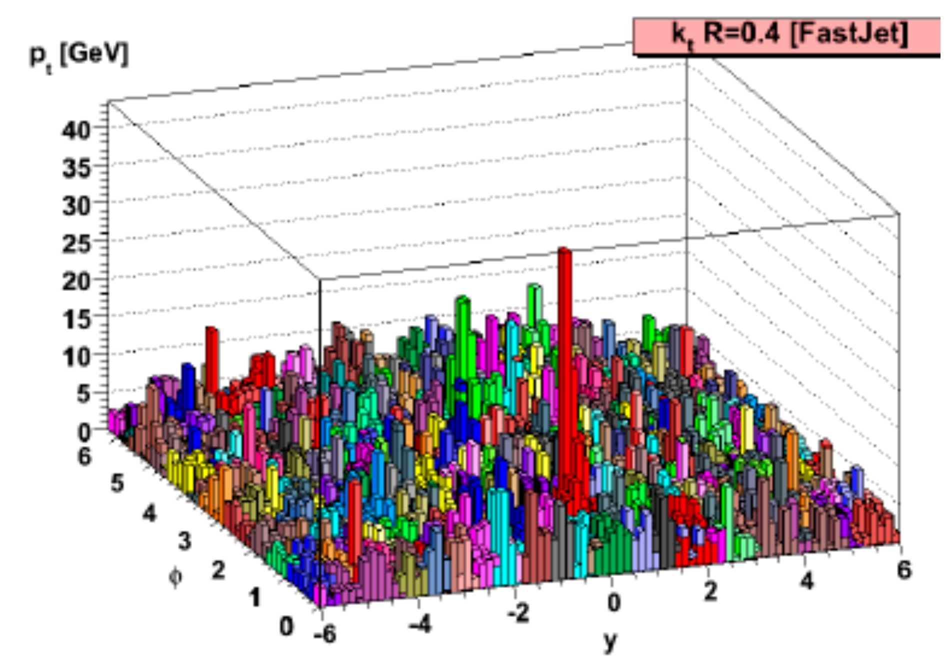


[Cacciari, Rojo, Salam, Soyez 2010]

An example hard event

$p_t \sim 100$ GeV

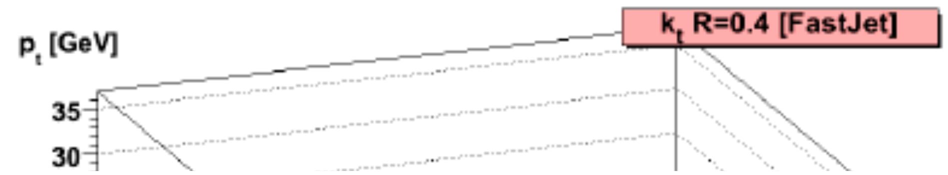
Generated with Pythia



Mixed into LHC HI environment

HydJet, $dN_{ch}/dy \simeq 1600$

Jets in HIC



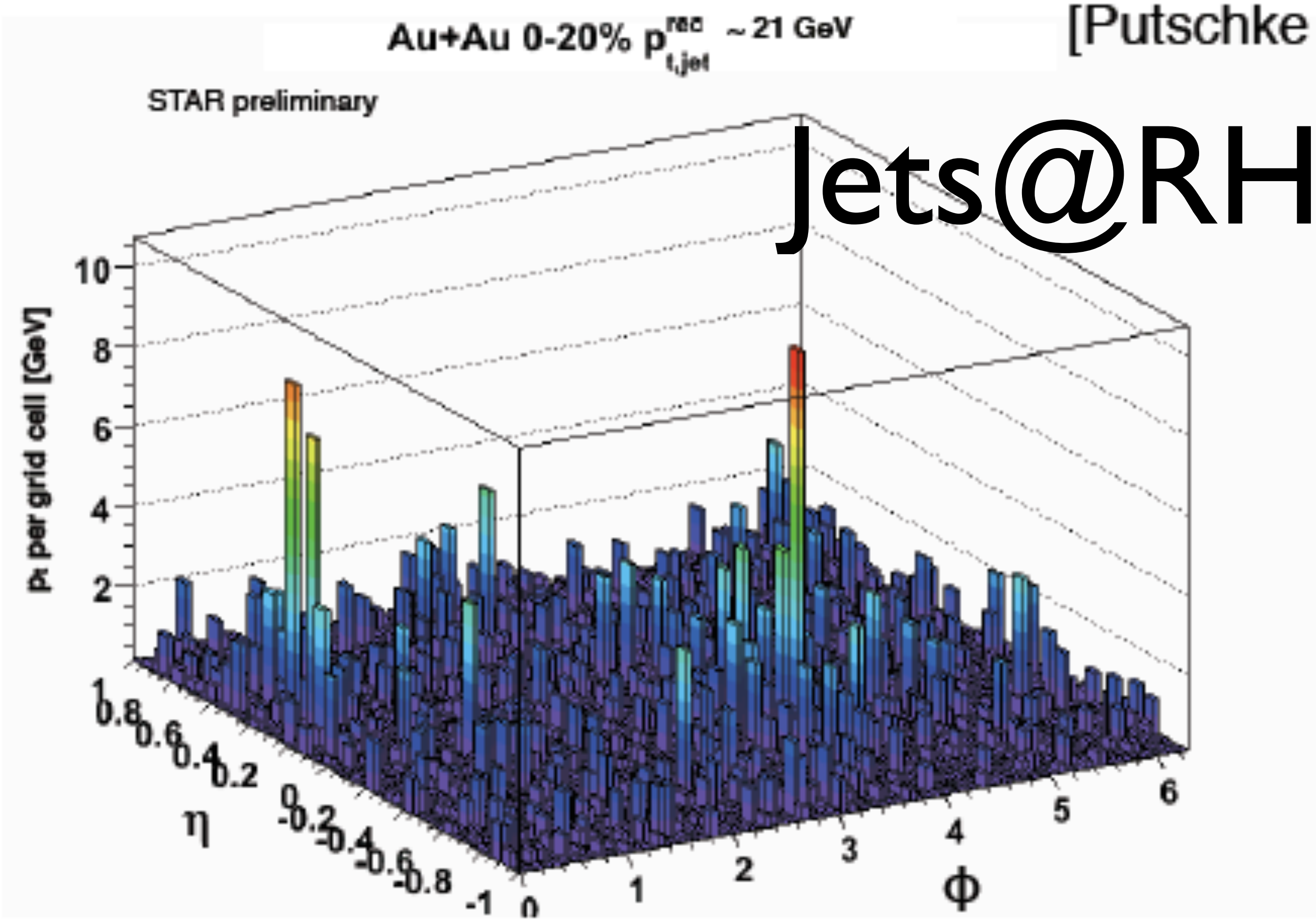
[Cacciari, Rojo, Salam, Soyez 2010]

First results appeared in HP2008!

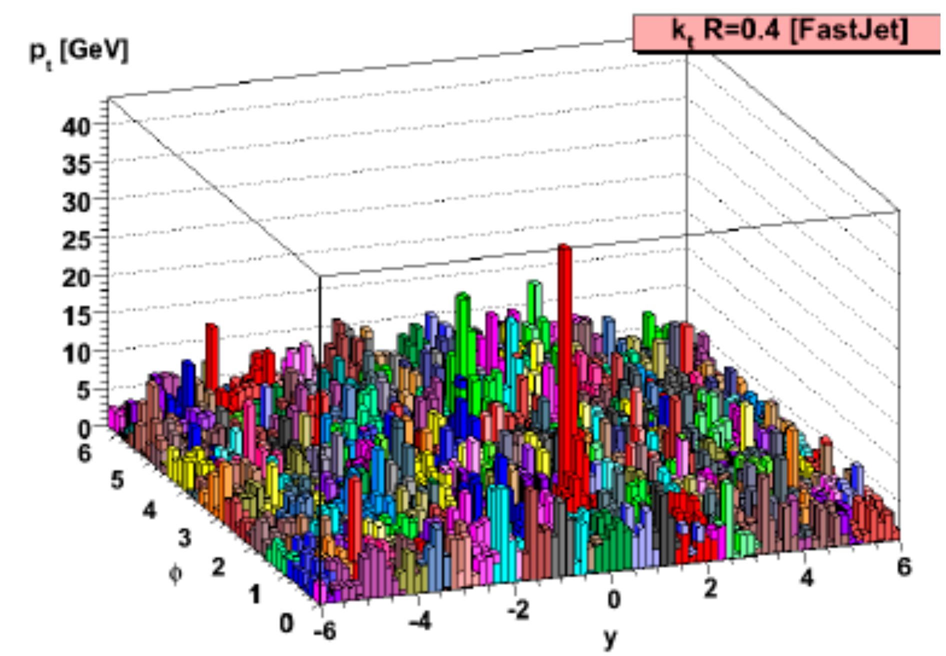
An example hard event

$p_t \sim 100$ GeV
Generated with Pythia

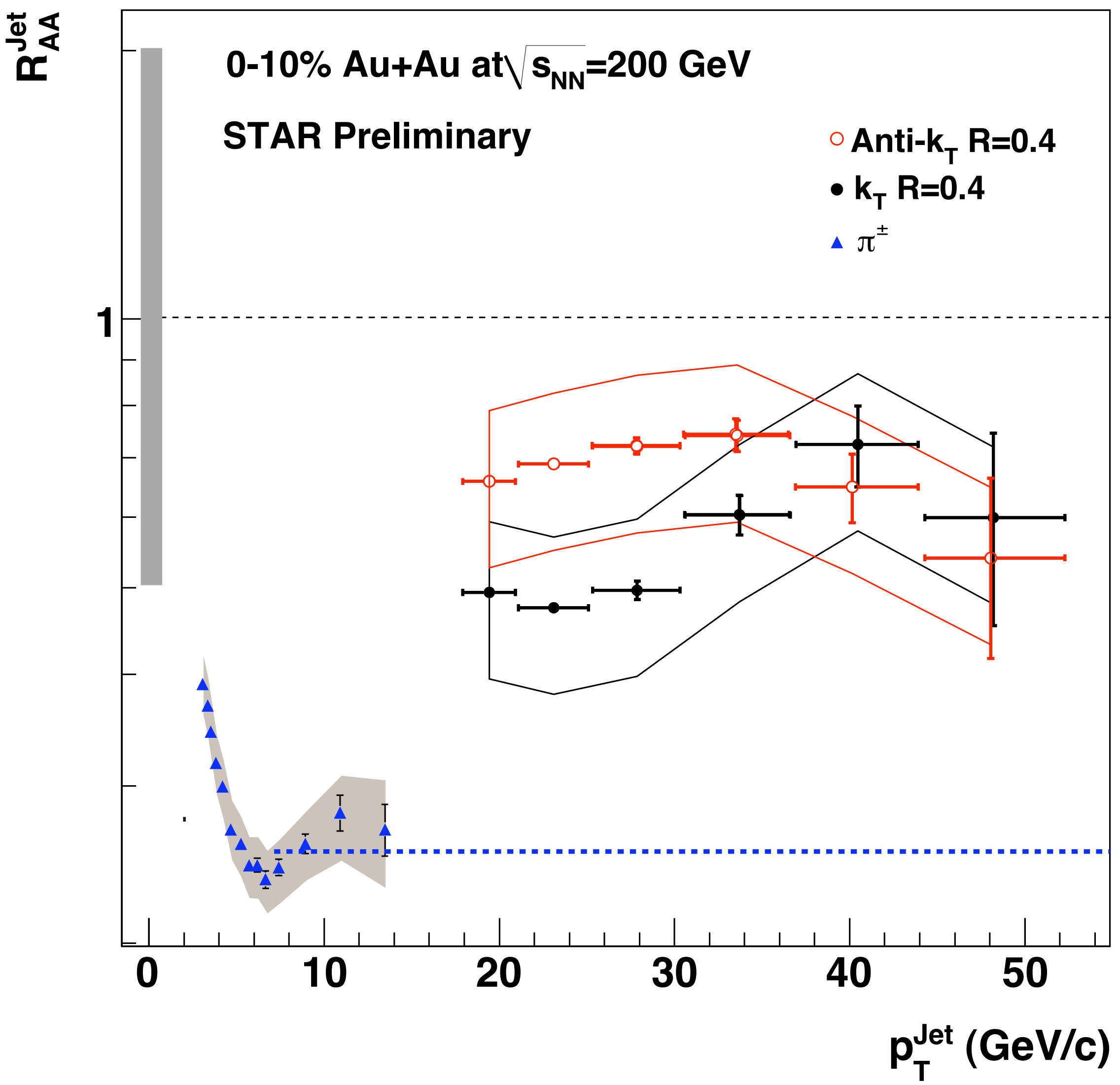
[Putschke HP08]



Jets@RHIC

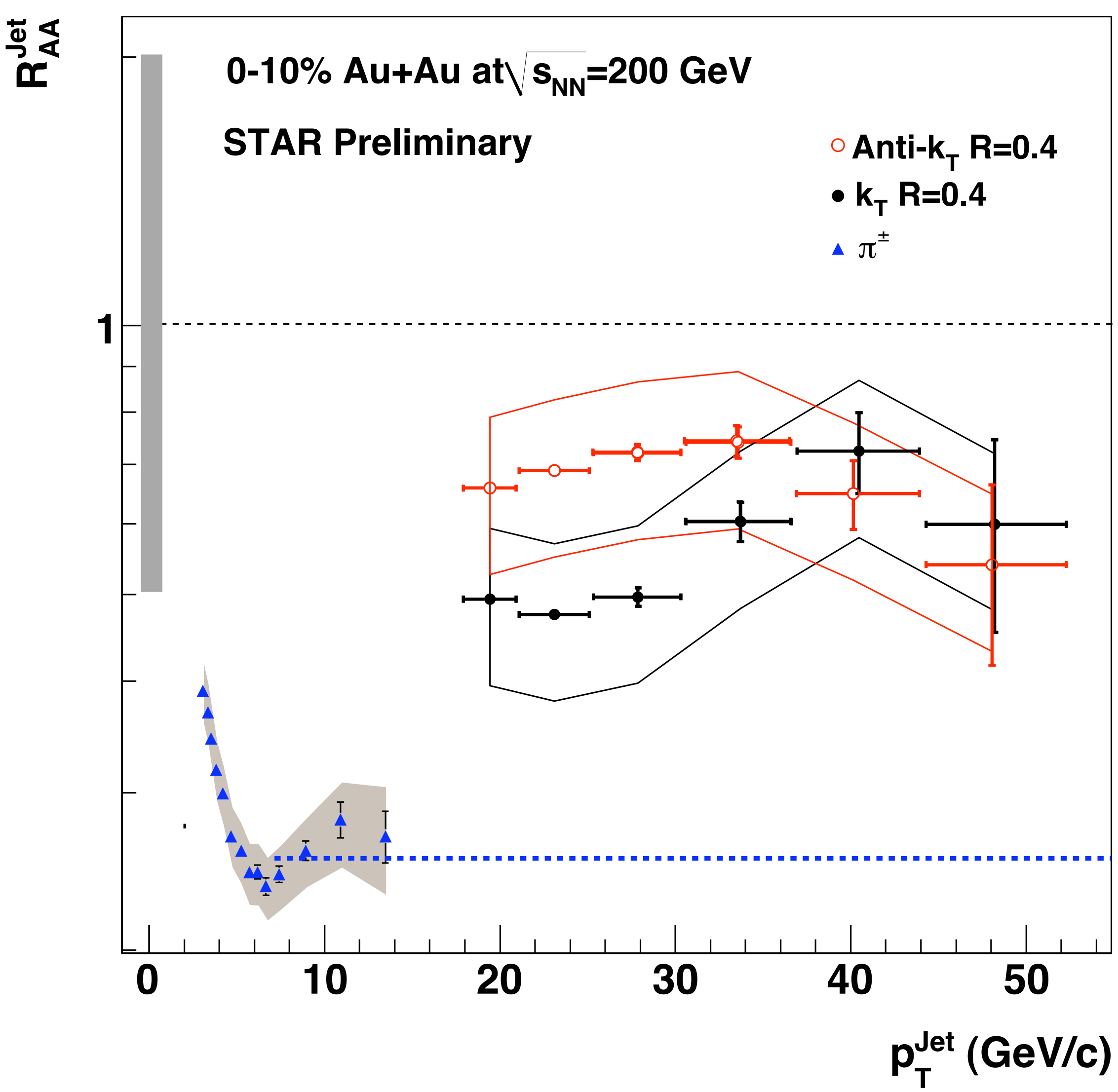


First jet measurements in HIC!



Out of cone emissions!

First jet measurements in HIC!



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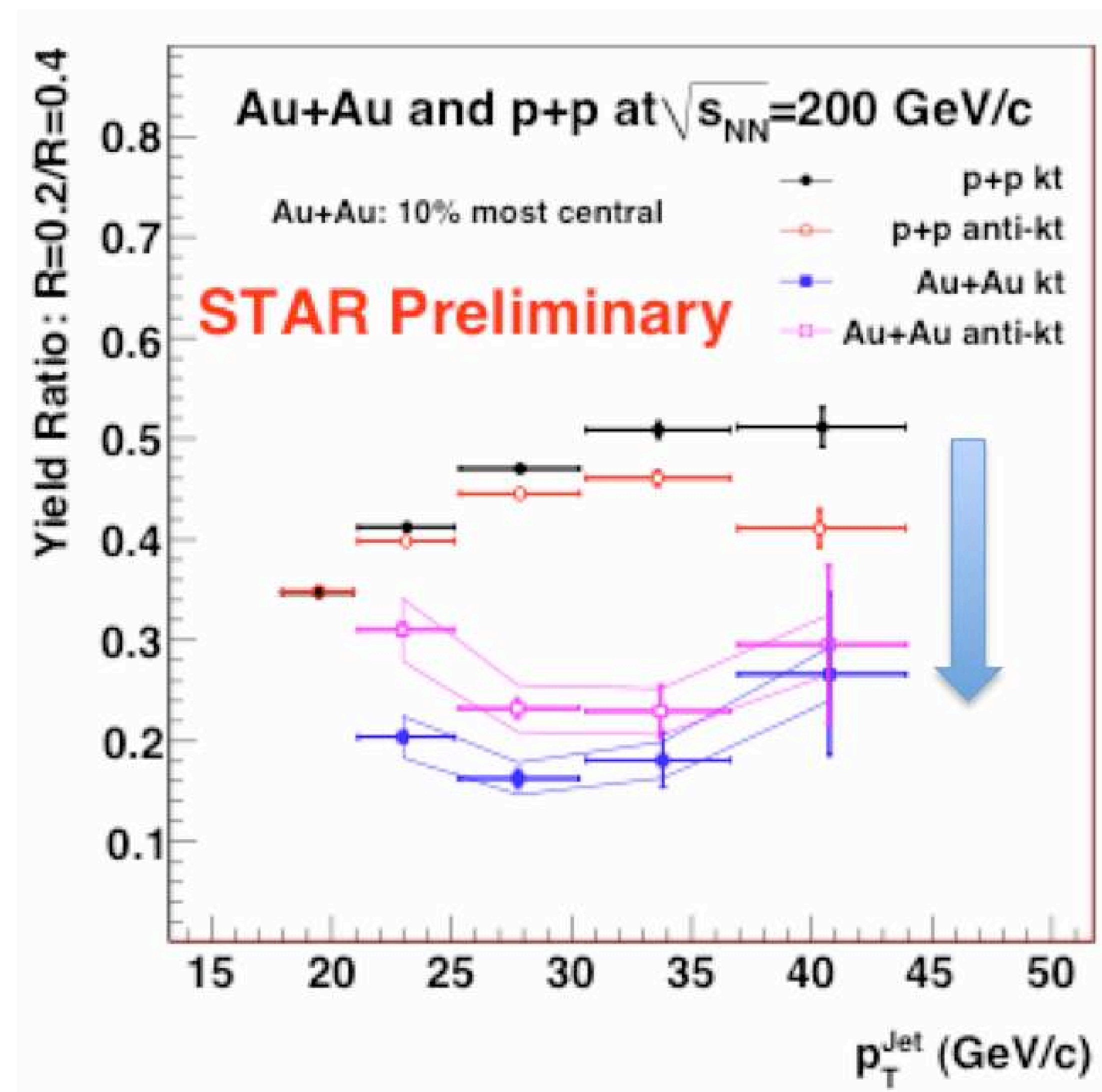
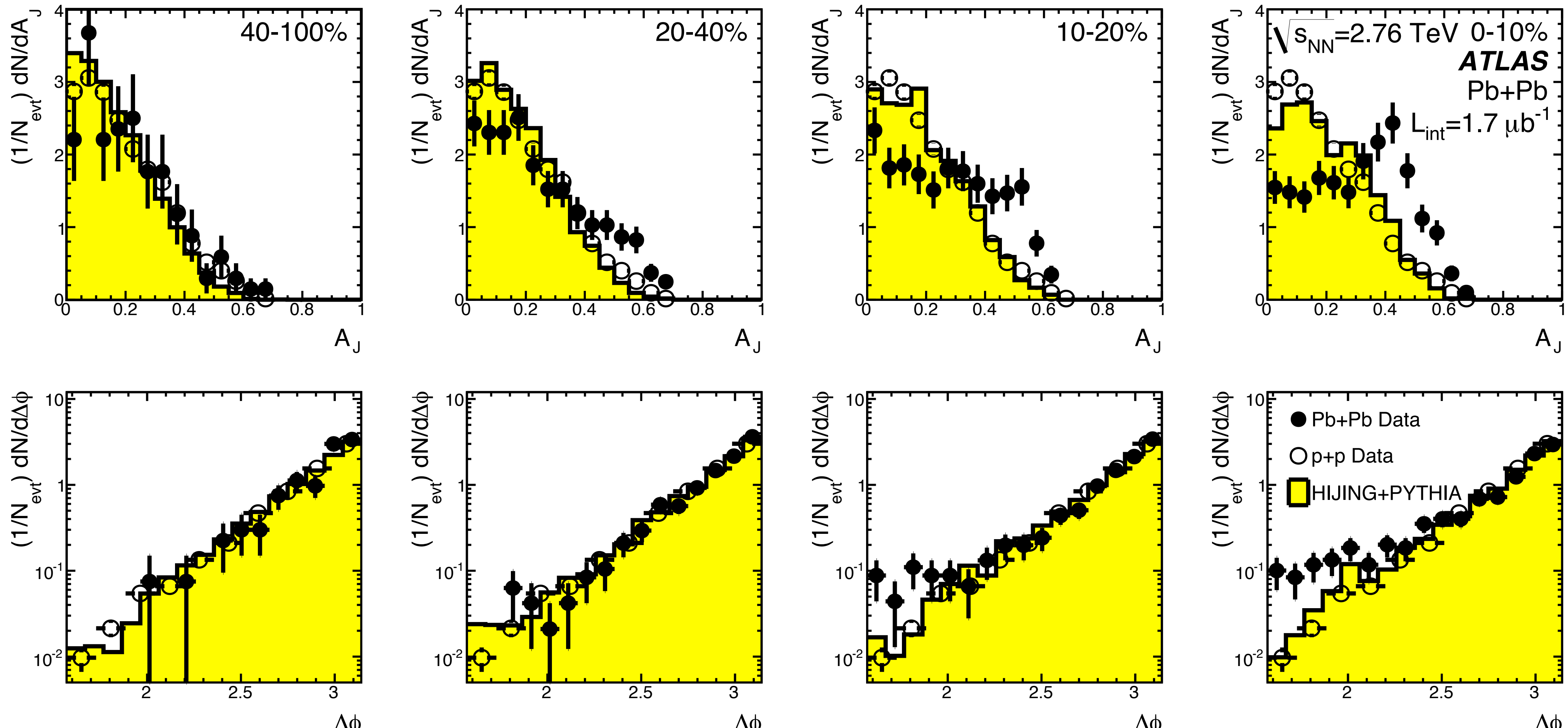


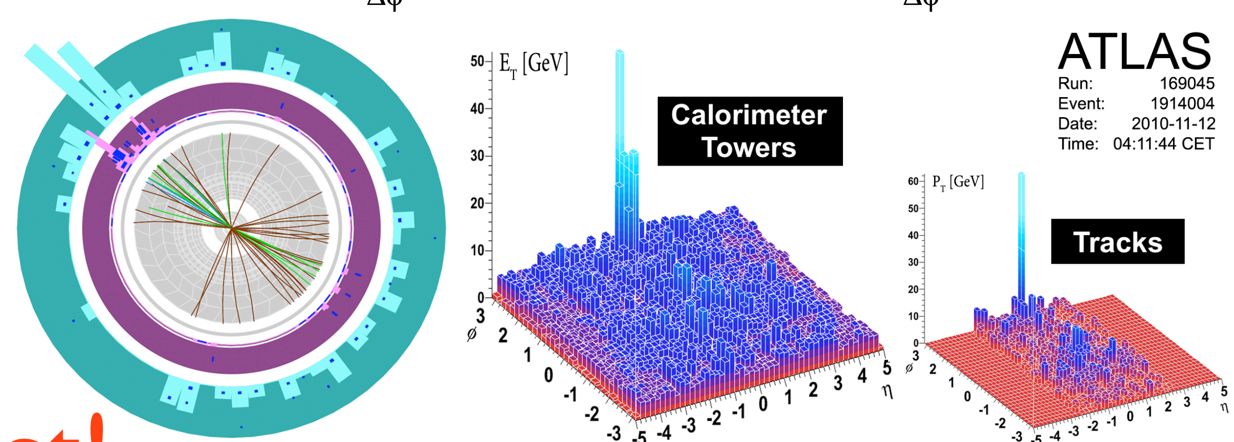
Jet doesn't get as collimated!

Dijet asymmetry @ 2.76 GeV



ATLAS Collaboration arXiv:1011.6182

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

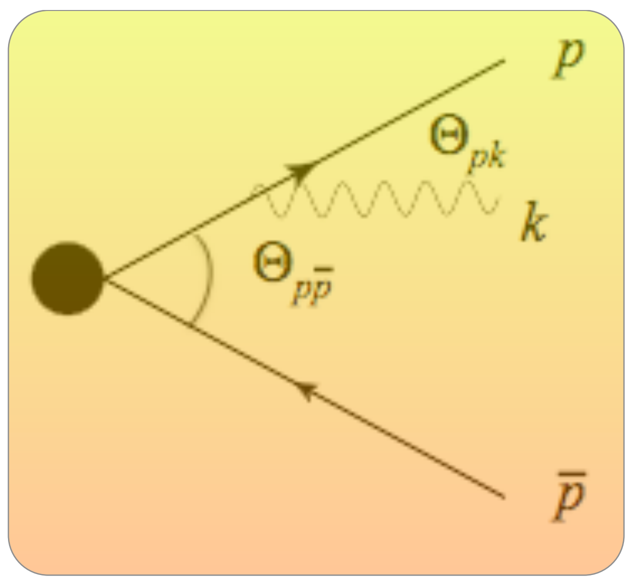


Signals strong medium effect!

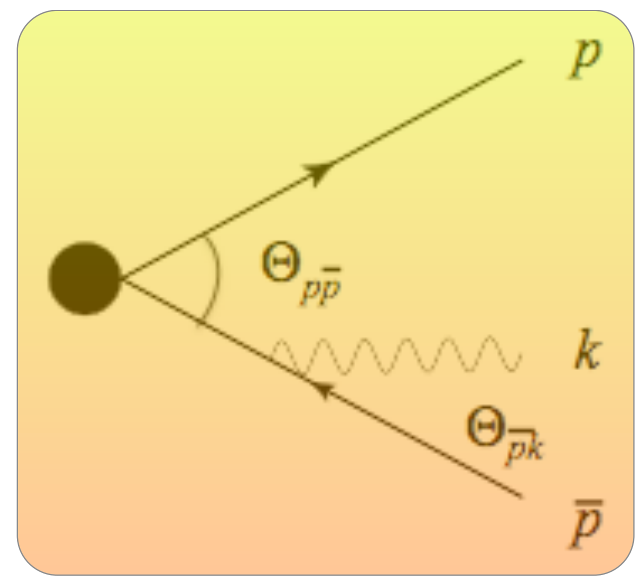
A missing ingredient

- ✓ Previous calculations treat 1-gluon emission.
- ✓ Know that we need at least 2 gluons to see QCD coherence!

$O(n_0^1)$



+



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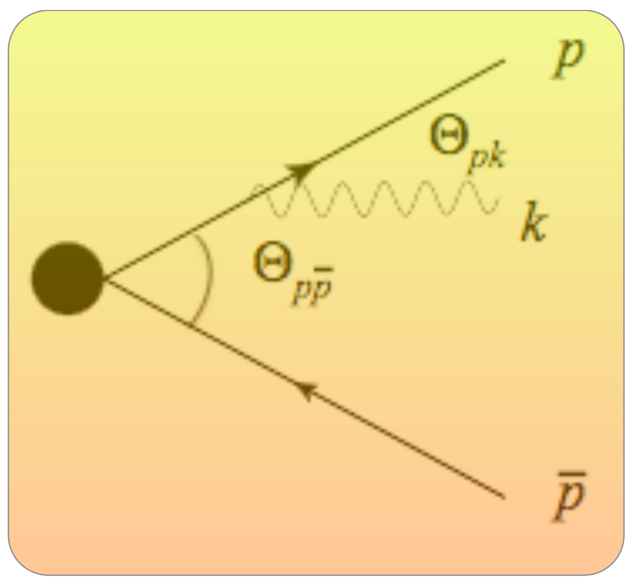
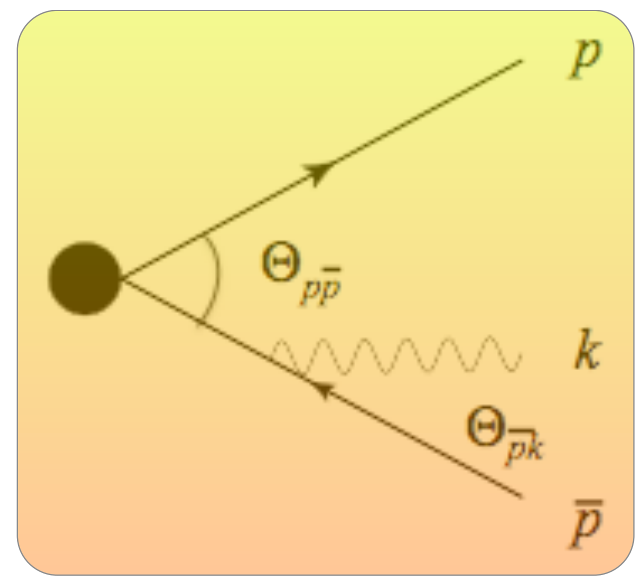
$O(n_0^1)$ 

+ 

Laboratory to study color coherence in medium...

- fixed opening angle → small angle approximation
- eikonal approximation → color rotation

Anti-angular ordering of medium-induced radiation

Mehtar-Tani, Salgado, KT, arXiv:1009.2965

$$dN_q = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta} \left(\Theta\left(\cos\theta - \cos\theta_{q\bar{q}}\right) + A(\theta_{q\bar{q}}, L)\Theta\left(\cos\theta_{q\bar{q}} - \cos\theta\right)\right)$$

$O(n_0^0 + n_0^1)$

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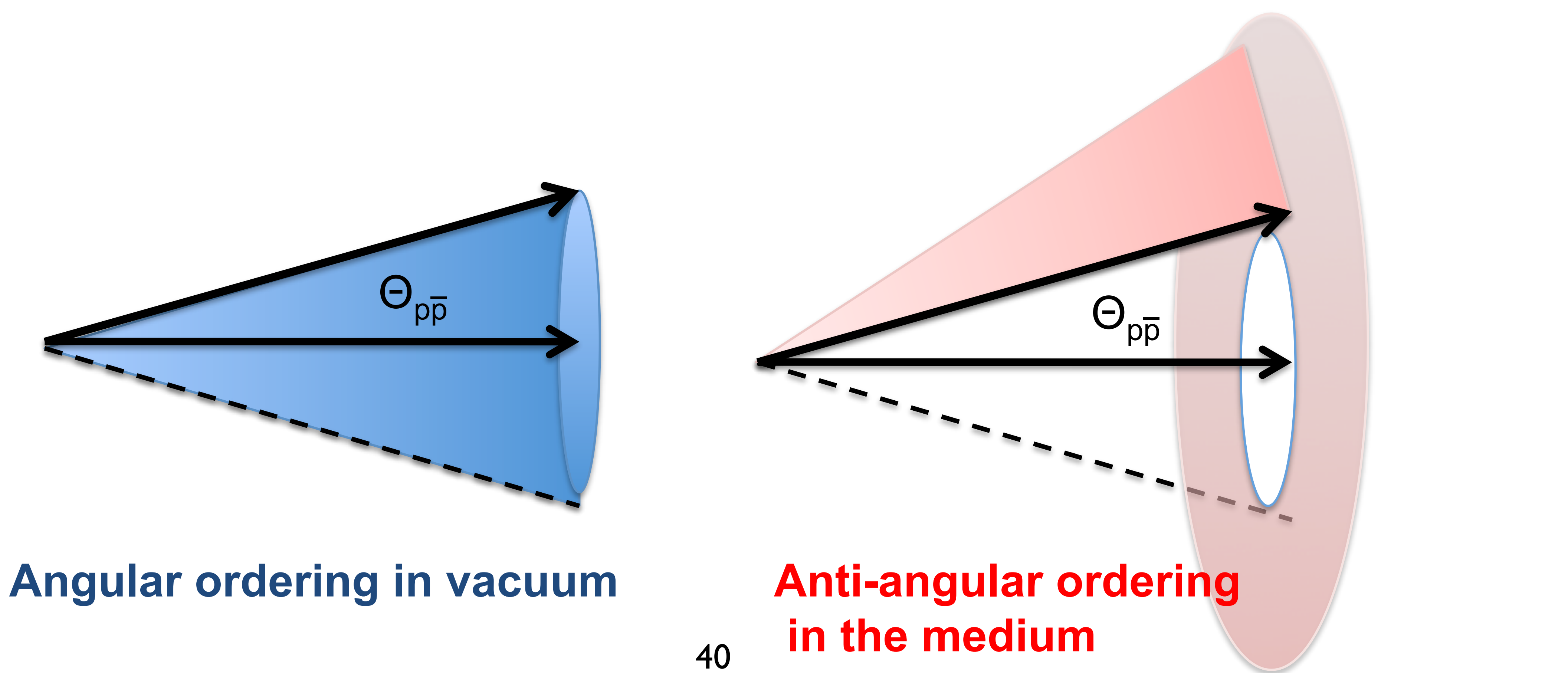

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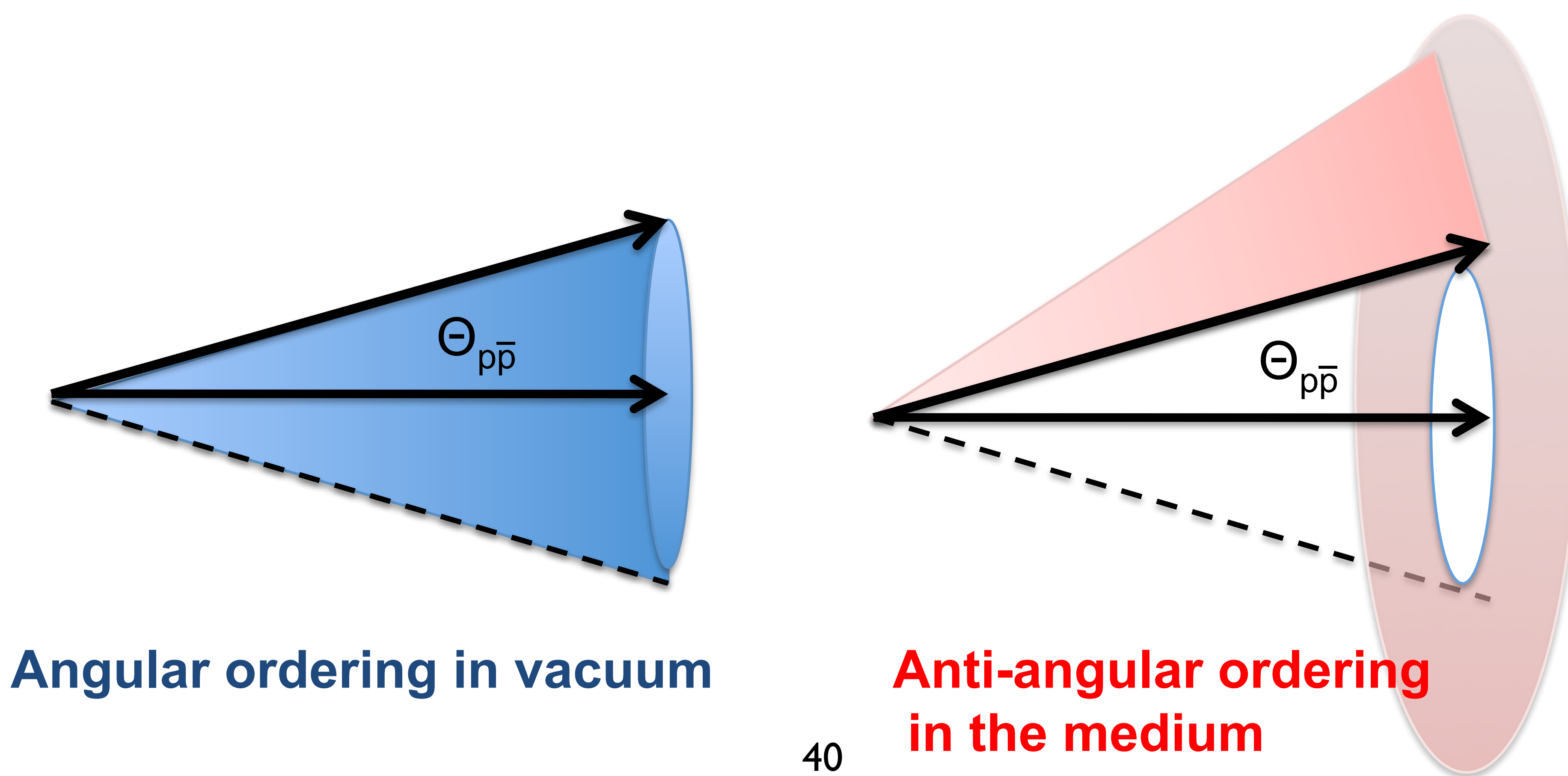

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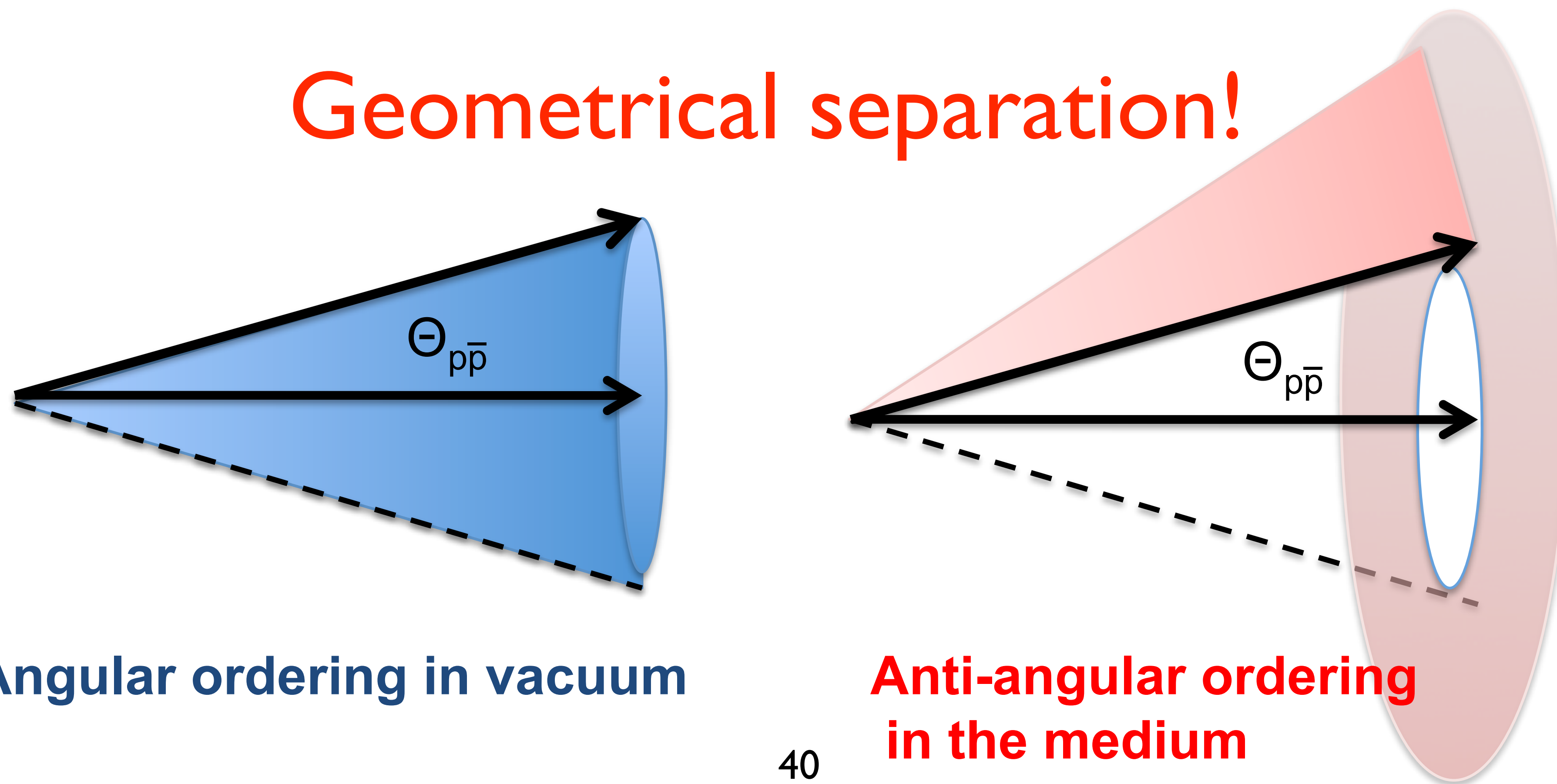
$O(n_0^0 + n_0^1)$

Geometrical separation!



Angular ordering in vacuum

Anti-angular ordering in the medium

Anti-angular ordering of medium-induced radiation

Mehtar-Tani, Salgado, KT, arXiv:1009.2965

$$dN_q = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\left(\Theta\left(\cos\theta - \cos\theta_{q\bar{q}}\right) + A(\theta_{q\bar{q}}, L)\Theta\left(\cos\theta_{q\bar{q}} - \cos\theta\right)\right)$$

$$A(\theta_{q\bar{q}}, L) \sim \frac{\hat{q}L^+}{6}(\theta_{q\bar{q}}L)^2 \ln\frac{1}{\theta_{q\bar{q}}L\ \mu_D} e^{-\omega\theta_{q\bar{q}}^2 L}$$

$O(n_0^0+n_0^1)$

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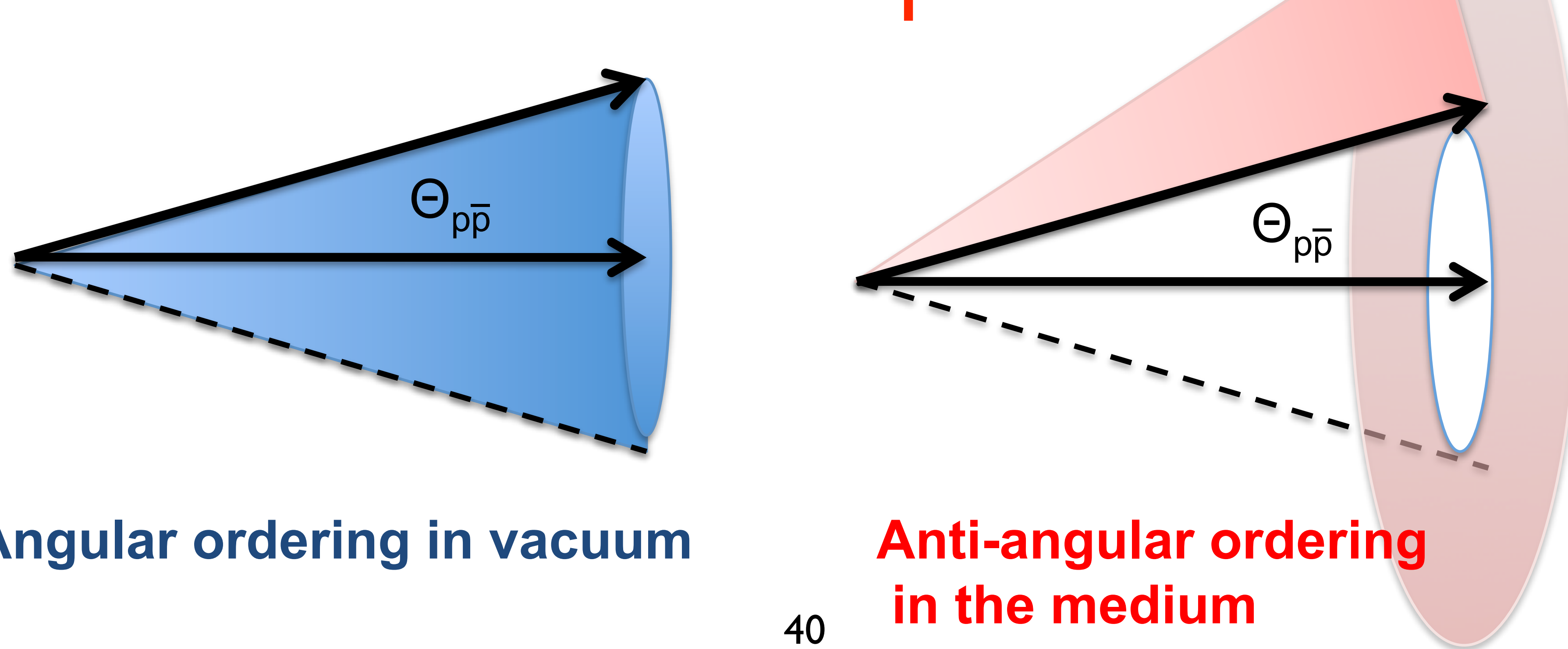
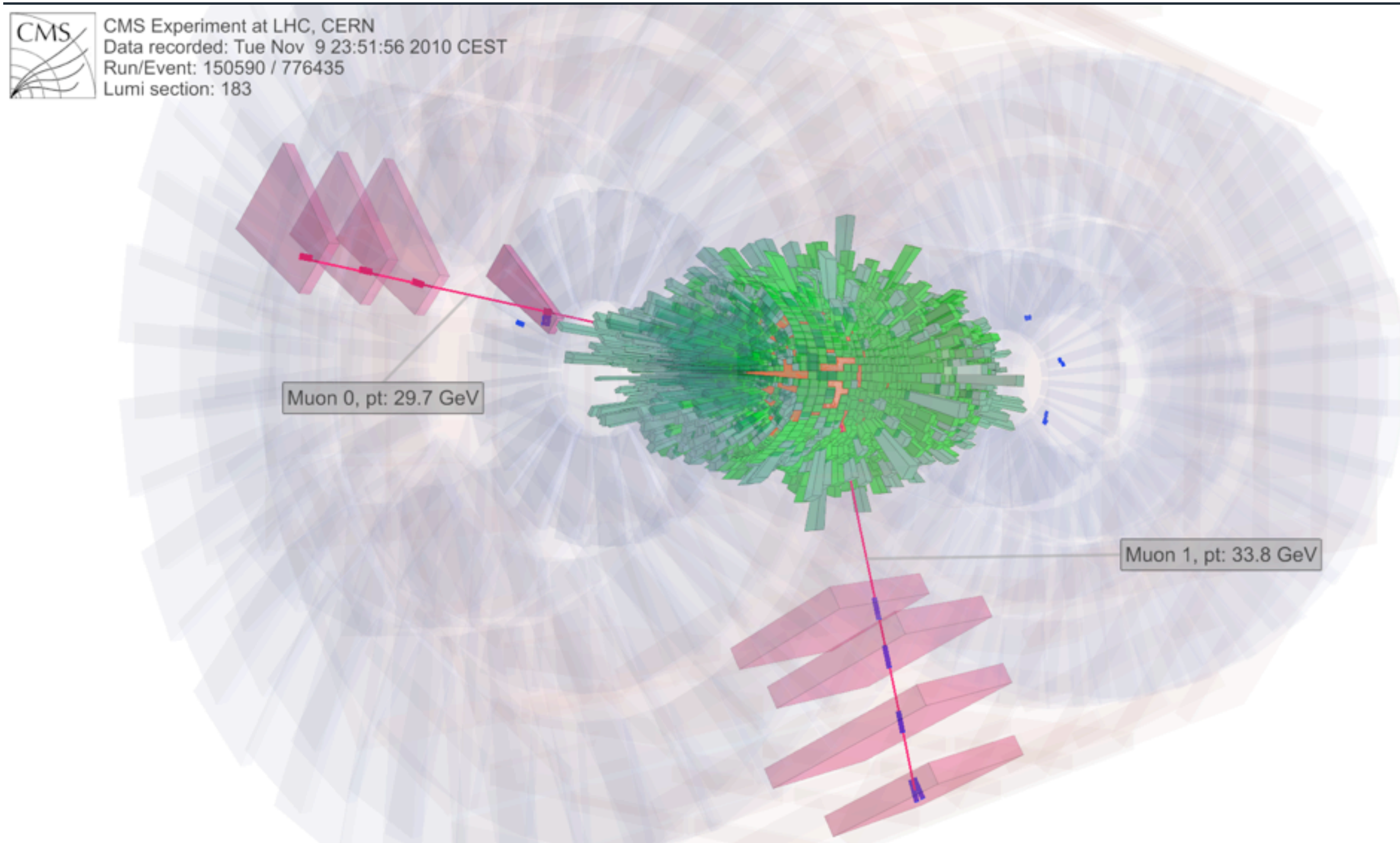




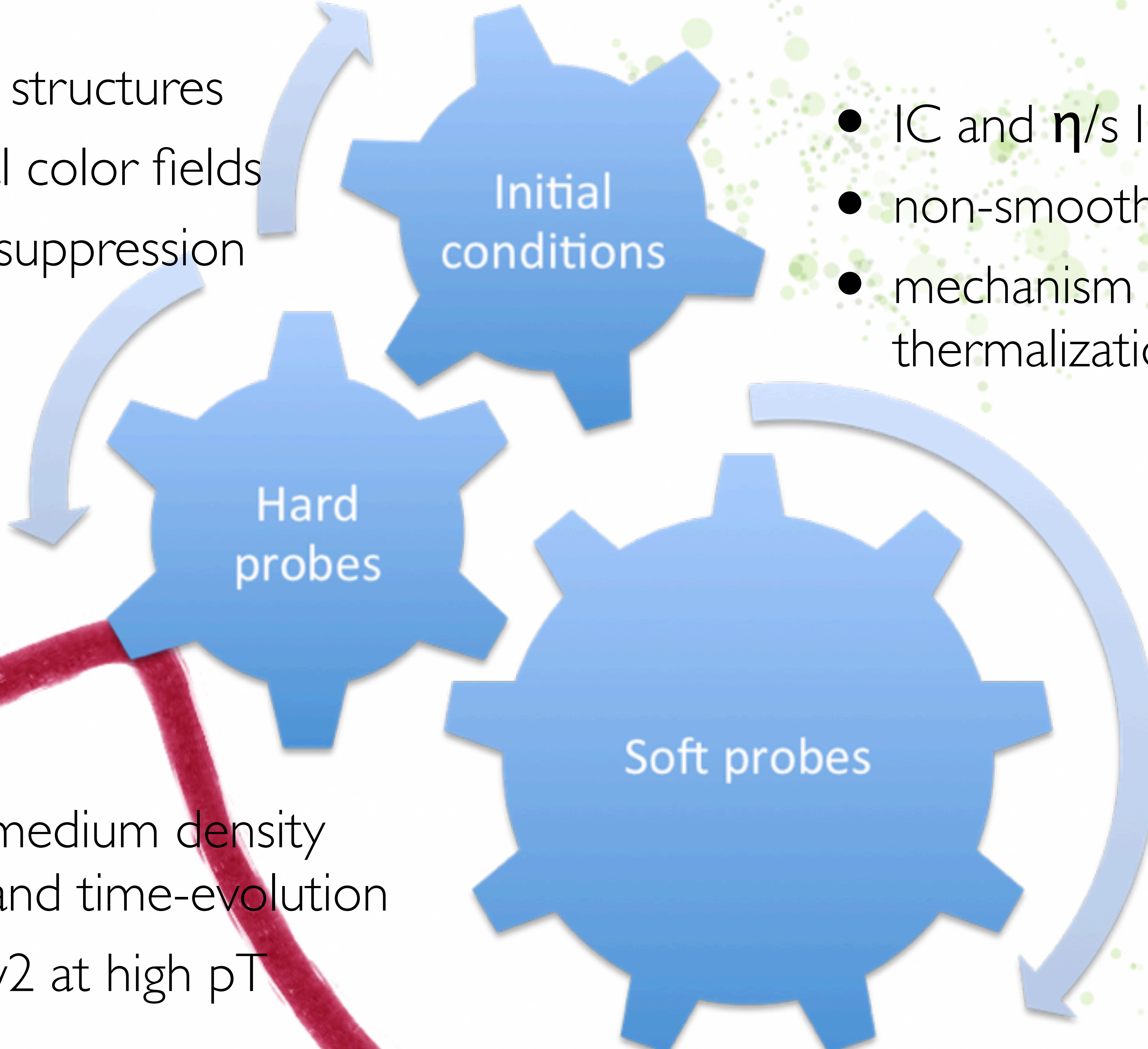
First ever Z observed in HIC!!

- ~~future~~ present is exciting!

Summary

- RHIC results suggest strong "collective" effects
  - ✓ screening of initial w.f. (cold)
  - ✓ early thermalization and low viscosity (hot)
  - ✓ strong effect on hard probes (dense)
- LHC gives access to a huge, hitherto unexplored kinematical regime:
  - ✓ small-x and large pT (jets!!)
- We will learn a lot....

- “ridge” structures
- classical color fields
- “cold” suppression



- IC and η/s linked
- non-smooth IC & v3
- mechanism for thermalization?

- medium density and time-evolution
- v2 at high pT