International Symposium on Multiparticle Dynamics

40th (XL) edition, Antwerp (Belgium), 21 - 25 September 2010

THEORY SUMMARY

Edmond Iancu
IPhT Saclay and CERN

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Thanks Keynote and Adobe for obvious reasons.

I hope after my talk some of you will be still my friends !

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ISMD at the time of LHC

- LHC : an immense opportunity for the ensemble of the high-energy physics community...
  and especially for the one involved in the ISMD series.

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- ... and a change in paradigms (already shaken by HERA, RHIC, and the Tevatron)

ISMD at the time of LHC

- ``The bulk of particle production is controlled by non-perturbative, soft, phenomena"

ISMD at the time of LHC

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- A plethora of new techniques and strategies, either borrowed from pQCD (NNLO, partons showers ...), or developed on purpose (multiparticle interactions, color glass condensate ...)

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- ISMD at a turn-over

High p_T Interactions

Alexandre Glazov & Massimiliano Grazzini

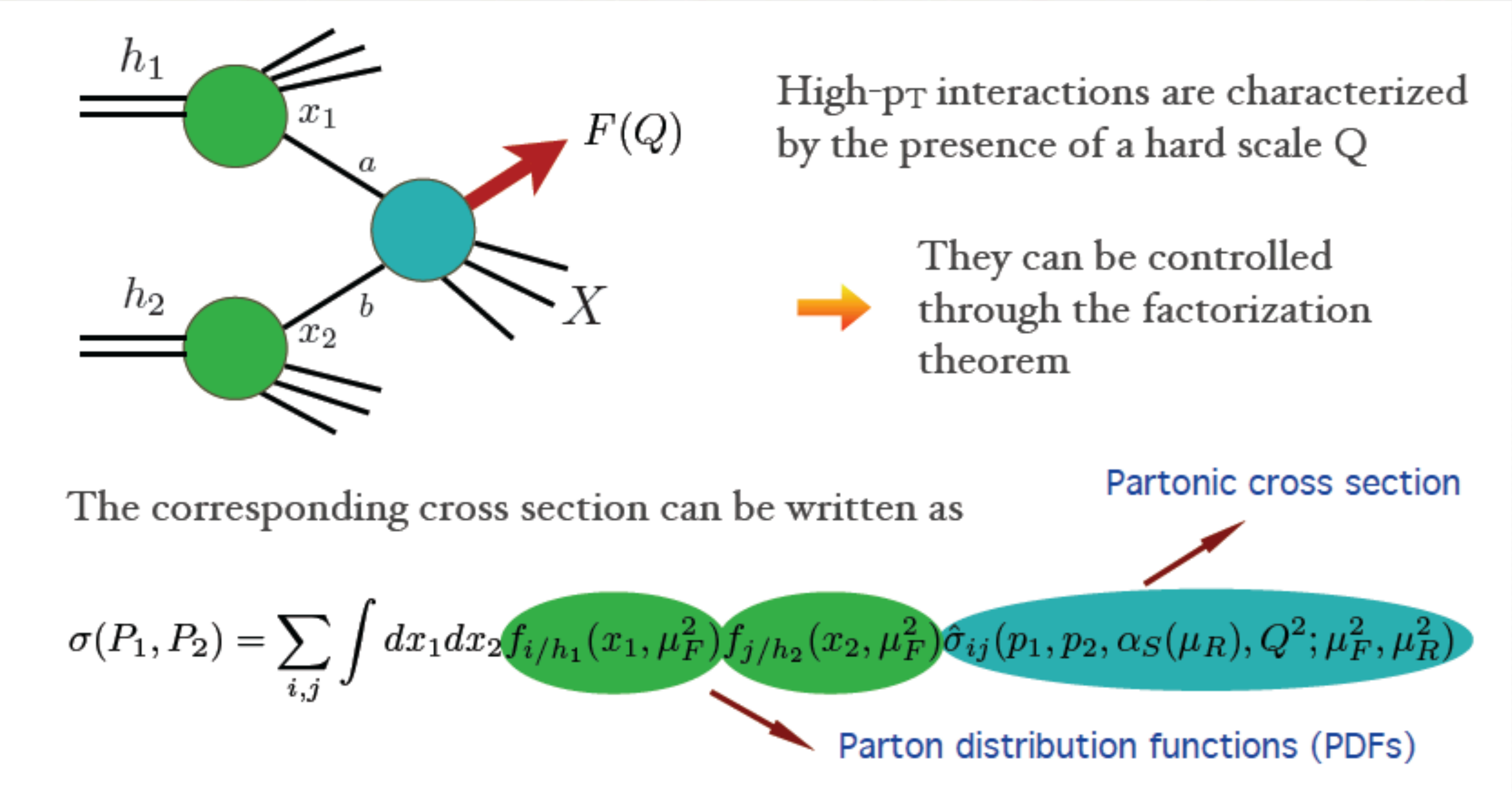
Introduction: *Massimiliano Grazzini* *(INFN)*

- What role for high-pT interactions at the LHC ?
- High-pT events are the most interesting as far as new physics searches are concerned
- New physics signals could lie in the tail of kinematic distributions

→ need good control of signal vs. background

- pQCD calculations are in principle under control

Introduction: *Massimiliano Grazzini* (INFN)



High-p_T interactions are characterized by the presence of a hard scale Q

→ They can be controlled through the factorization theorem

The corresponding cross section can be written as

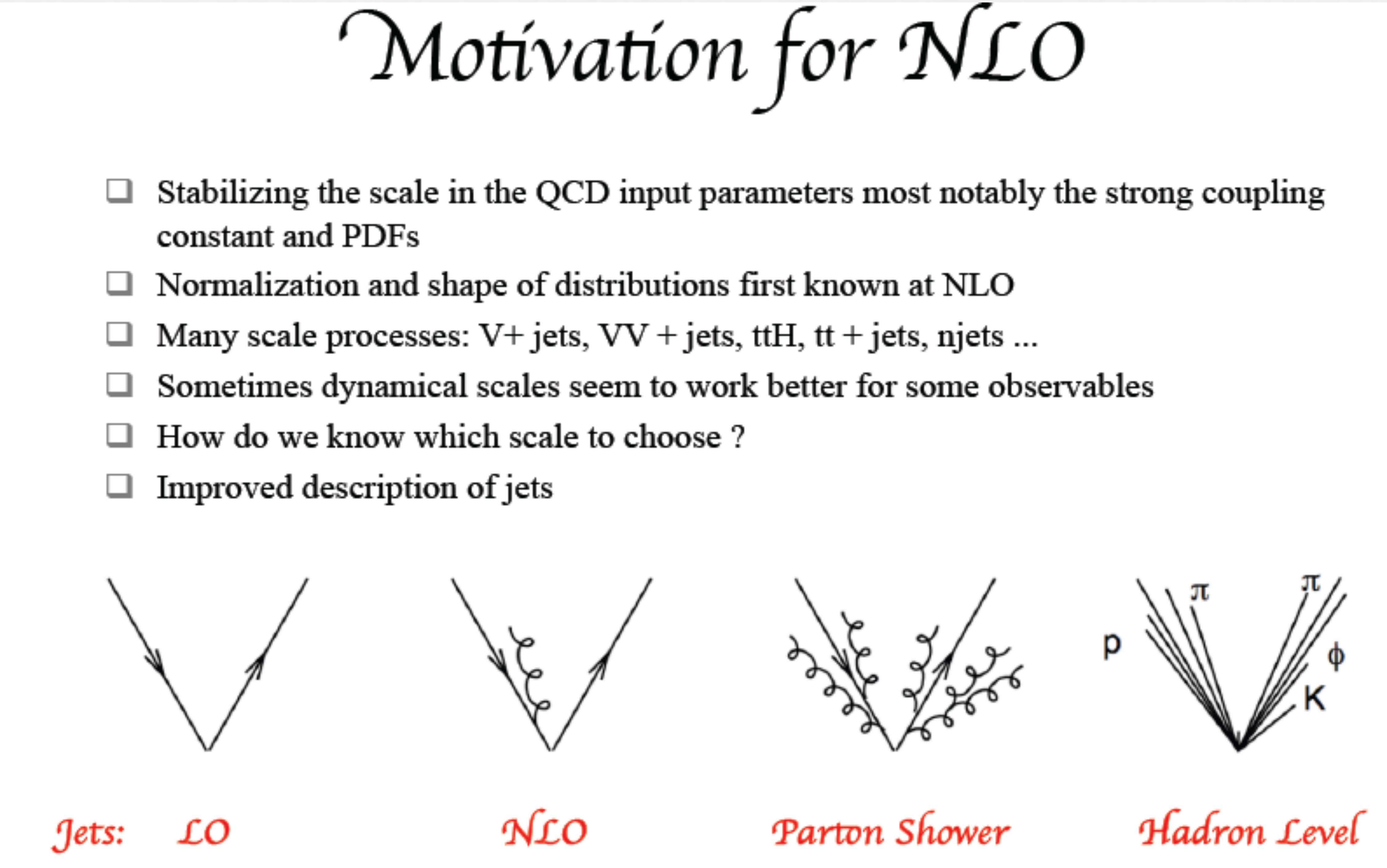
Partonic cross section

$$\sigma(P_1,P_2) = \sum_{i,j}\int dx_1 dx_2 f_{i/h_1}(x_1,\mu_F^2)f_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2;\mu_F^2,\mu_R^2)$$

Parton distribution functions (PDFs)

NLO calculations are mandatory. NNLO are even better.

Malgorzata Worek (Bergische Univ, Wuppertal)



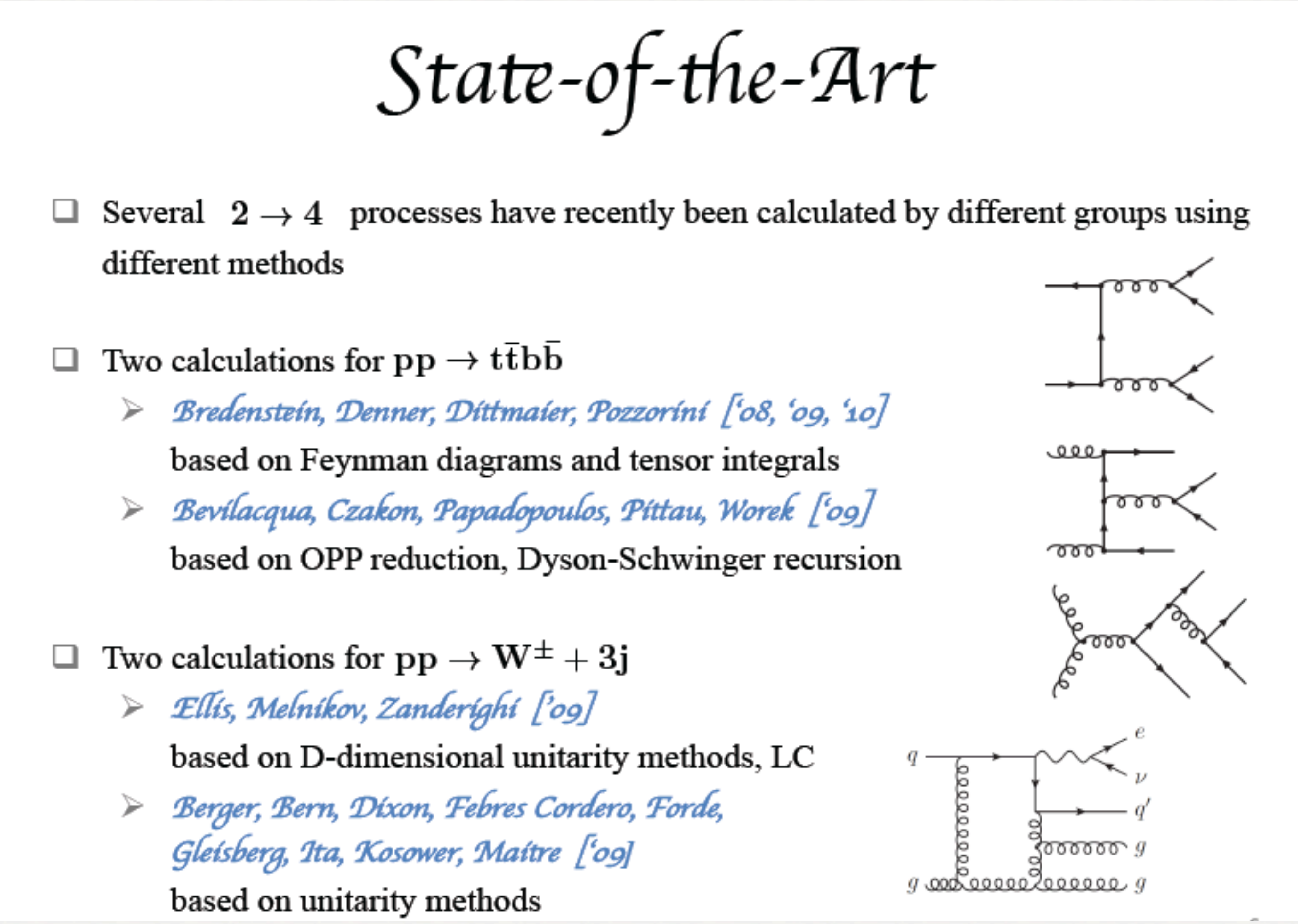
Motivation for NLO

- ☐ Stabilizing the scale in the QCD input parameters most notably the strong coupling constant and PDFs
- ☐ Normalization and shape of distributions first known at NLO
- ☐ Many scale processes: V+ jets, VV + jets, ttH, tt + jets, njets ...
- ☐ Sometimes dynamical scales seem to work better for some observables
- ☐ How do we know which scale to choose ?
- ☐ Improved description of jets

Jets: LO NLO Parton Shower Hadron Level

Malgorzata Worek (Bergische Univ, Wuppertal)

Recent developments in NLO QCD calculations



State-of-the-Art

- Several $2 \to 4$ processes have recently been calculated by different groups using different methods
- Two calculations for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$
    - *Bredenstein, Denner, Dittmaier, Pozzorini ['08, '09, '10]* based on Feynman diagrams and tensor integrals
    - *Bevilacqua, Czakon, Papadopoulos, Pittau, Worek ['09]* based on OPP reduction, Dyson-Schwinger recursion
- Two calculations for $\mathrm{pp} \to \mathrm{W^{\pm}} + 3\mathrm{j}$
    - *Ellis, Melnikov, Zanderighi ['09]* based on D-dimensional unitarity methods, LC
    - *Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre ['09]* based on unitarity methods

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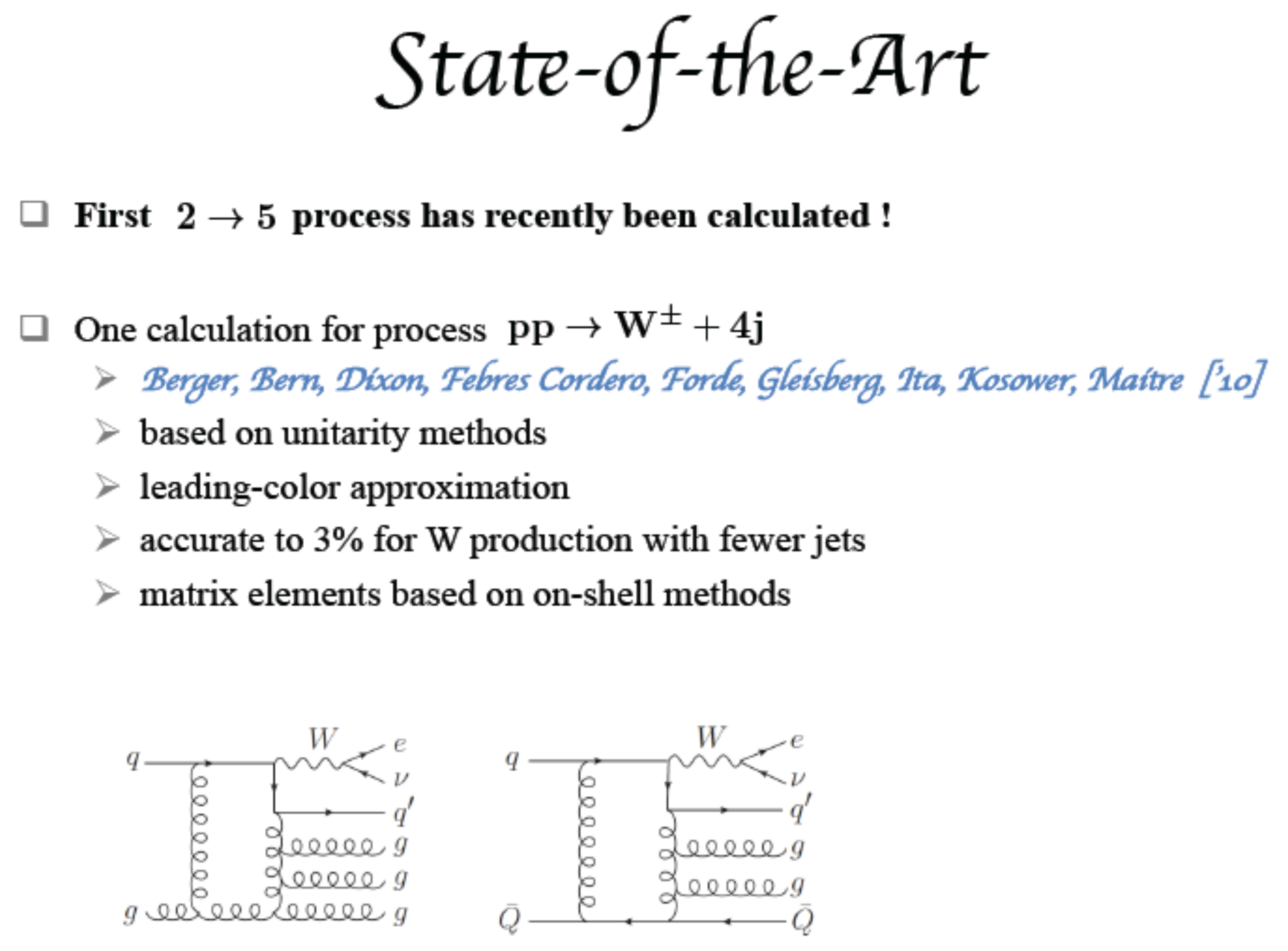
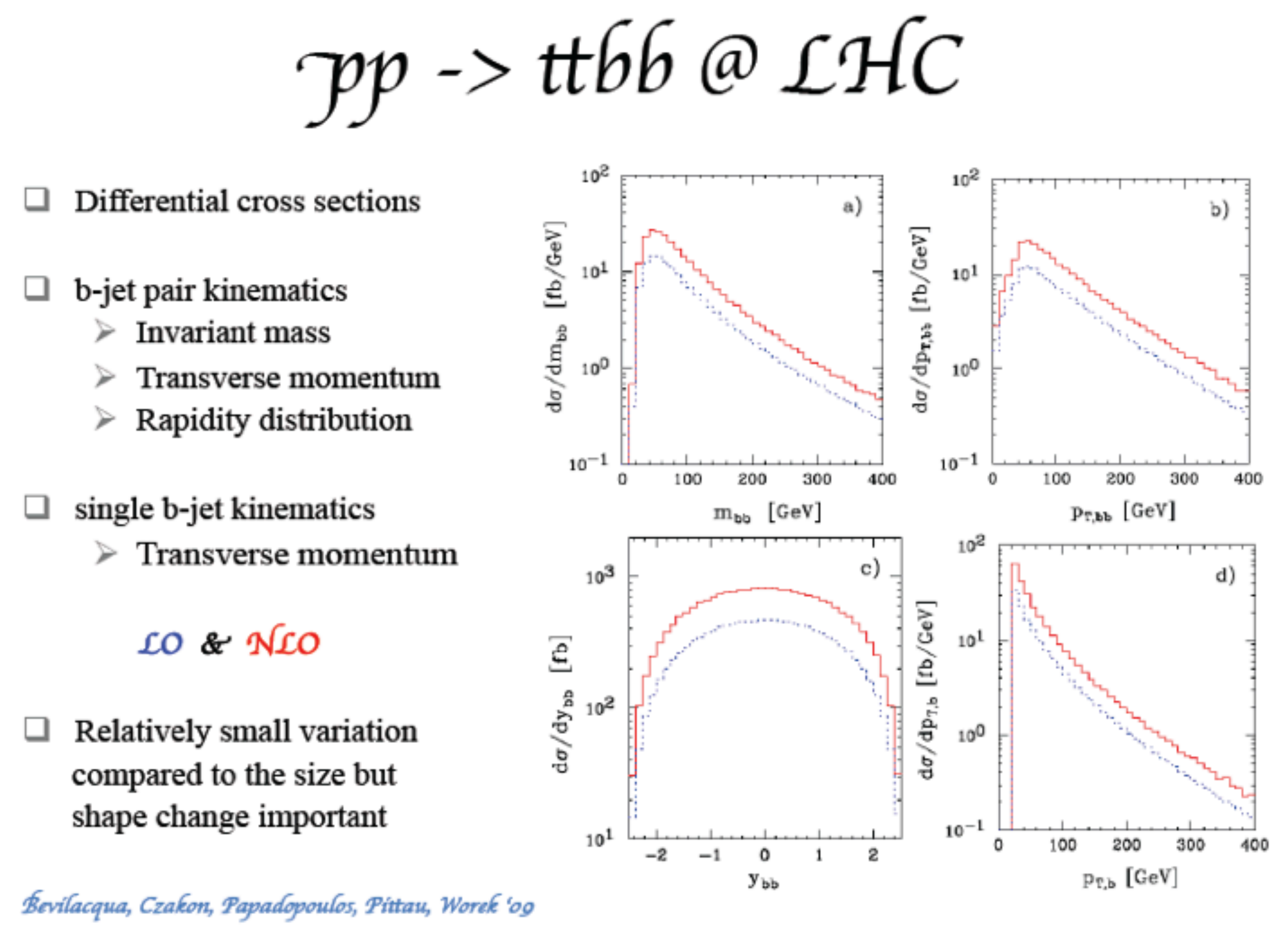


State-of-the-Art

- **First $2 \to 5$ process has recently been calculated !**
- One calculation for process $\mathrm{pp} \to \mathrm{W}^{\pm} + 4\mathrm{j}$
  - *Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maître ['10]*
  - based on unitarity methods
  - leading-color approximation
  - accurate to 3% for W production with fewer jets
  - matrix elements based on on-shell methods

Malgorzata Worek (Bergische Univ, Wuppertal)

Recent developments in NLO QCD calculations



pp -> ttbb @ LHC

- ☐ Differential cross sections
- ☐ b-jet pair kinematics
  - ➢ Invariant mass
  - ➢ Transverse momentum
  - ➢ Rapidity distribution
- ☐ single b-jet kinematics
  - ➢ Transverse momentum

LO & NLO

- ☐ Relatively small variation compared to the size but shape change important

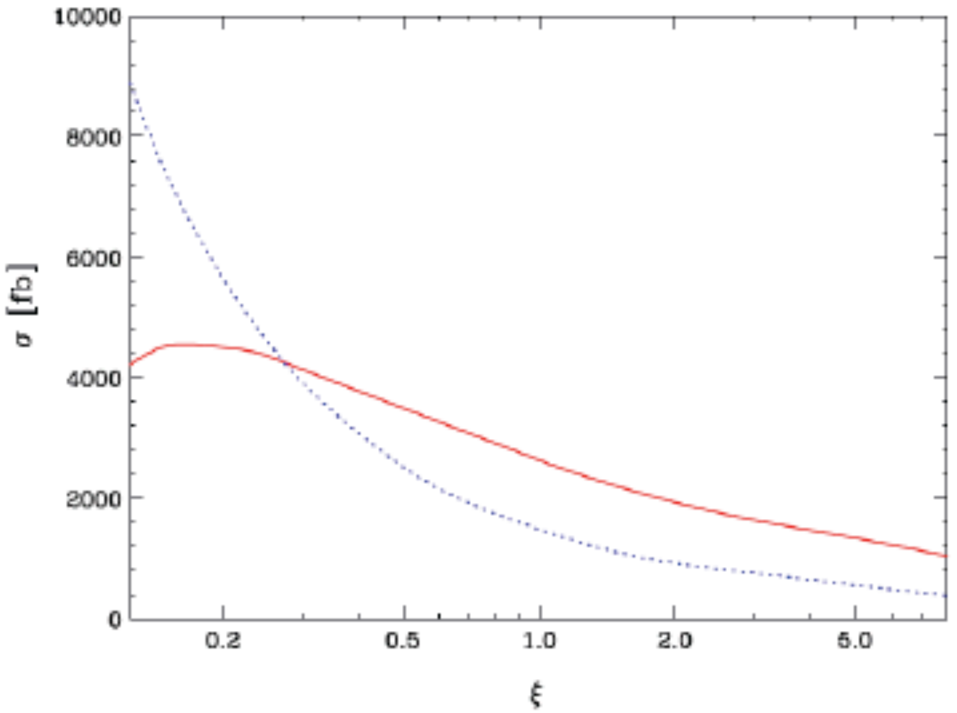
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

Malgorzata Worek (Bergische Univ, Wuppertal)

Recent developments in NLO QCD calculations

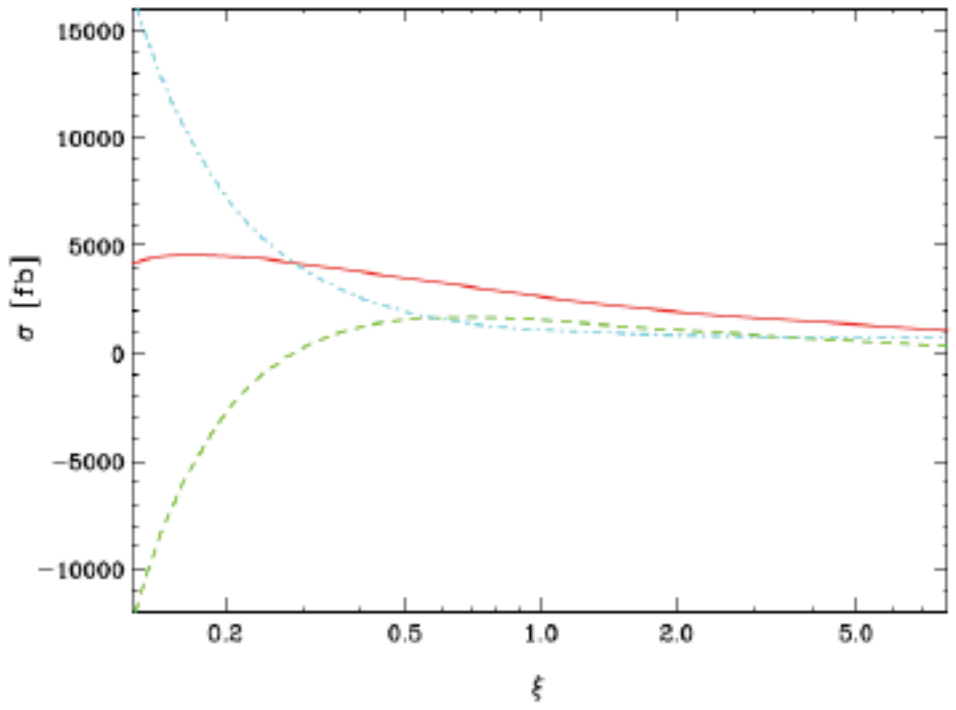
pp -> ttbb @ LHC

- ☐ Scale dependence graphically



Varying scale up or down by a factor two changes cross section by **70% @ LO** and by **33% @ NLO**

Scale dependence at NLO decomposed into contribution of *Virtual Corrections* & *Real Radiation*



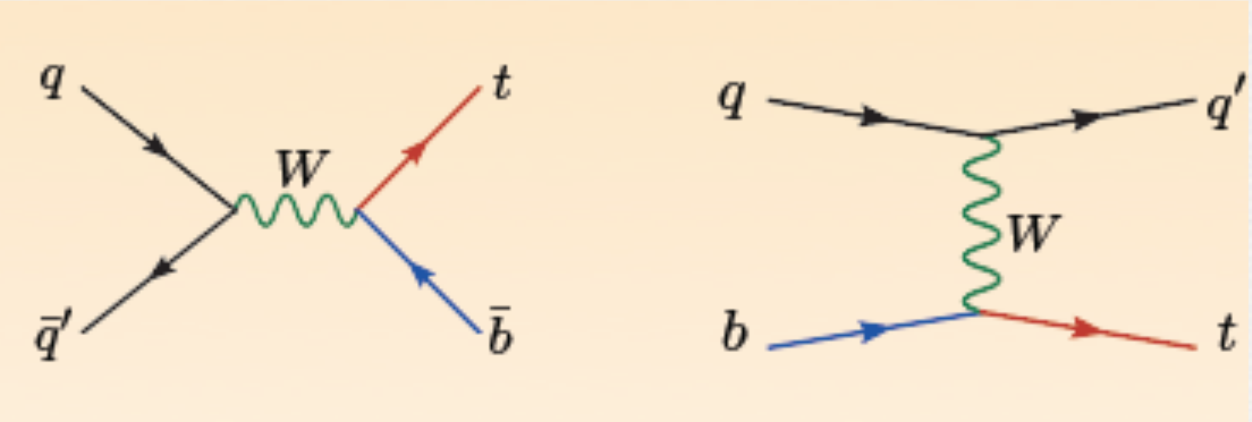
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

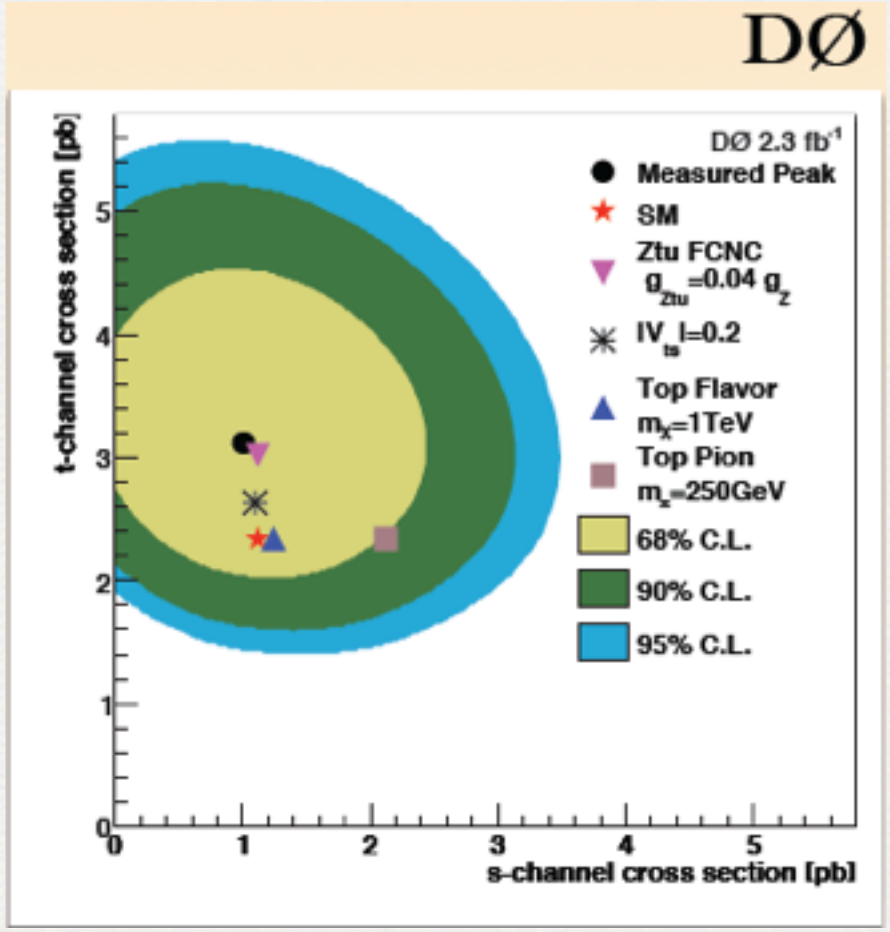
Rikkert Frederix (University of Zürich)

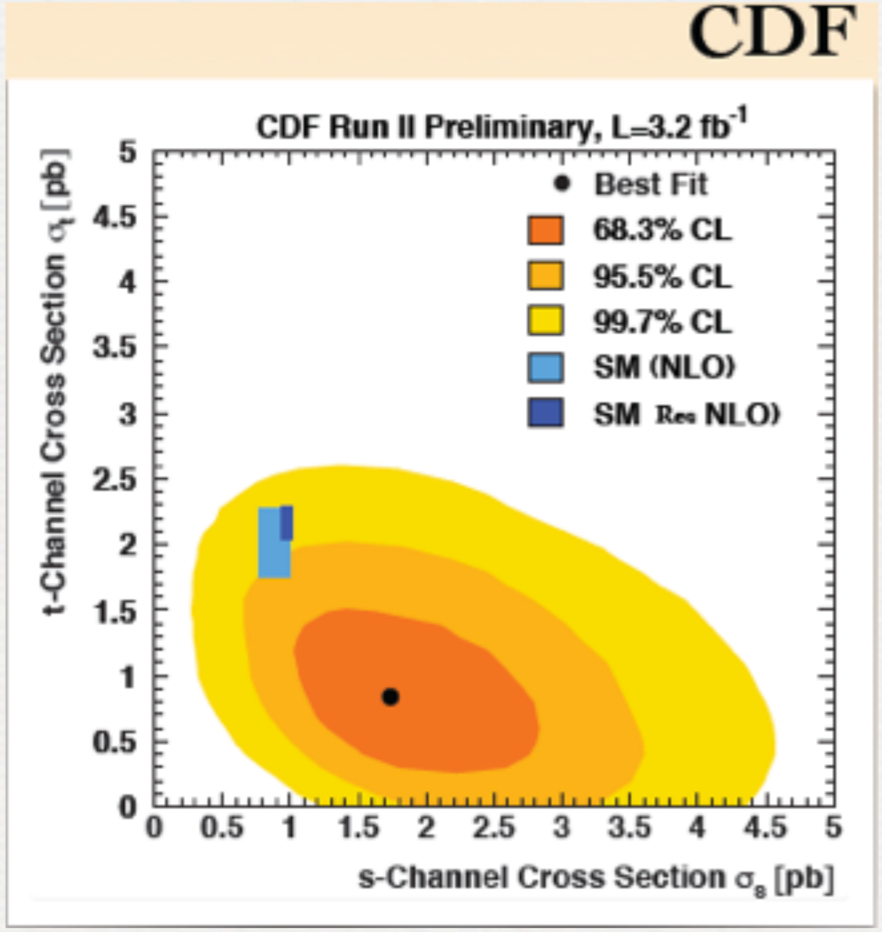
Top quark phenomenology

- Any hint for BSM physics in the top quark production at the Tevatron ?
- No clear hints, but a couple of 2 sigma deviations from SM
- Need for NNLO computations *(e.g., top quark charge asymmetry)* and/or matching to parton showers
- s-channel versus t-channel cross-sections: deviation seen by CDF but not by DØ

Rikkert Frederix (cont.)







s- versus t-channel deviation by CDF:
not explained by new NLO calculation !

Forward Physics & Cosmic Rays

Monika Grothe, Francesco Hautmann & Sergey Ostapchenko

Introduction: *Francesco Hautmann* (Oxford Univ.)

♦ With the advent of the LHC, forward physics becomes largely a new field both from theory and experiment standpoints.

♦ At the LHC:

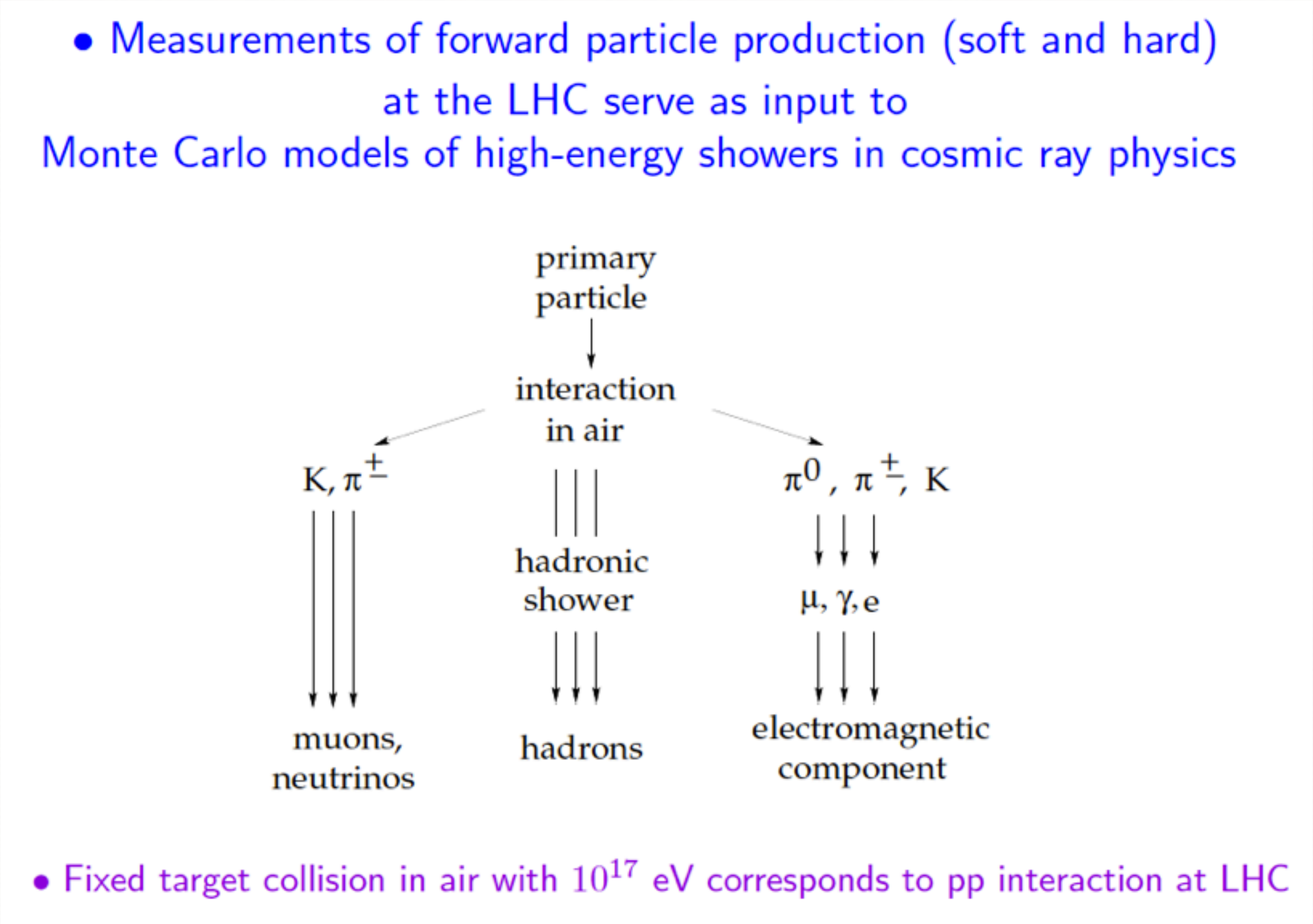
- ✦ forward processes involve both soft and hard production
- ✦ phase space opening up for large √s ⇒ multiple-scale processes
- ✦ unprecedented coverage of large rapidities (calorimeters + proton taggers)
- ✦ forward particle production at high p_T
- ✦ dijet production (one forward + one central) at high p_T
- ✦ from soft or semi-hard, the `small-*x*' physics becomes essentially hard !

Theoretical issues in forward physics (in particular at LHC)

- ⁎ Forward physics at LHC will be \`small-x physics' even for hard $p_T \sim M_Z$
- ⁎ High energy evolution : resummation of $\left(\alpha_s \ln(1/x)\right)^n$
- ⁎ Evolution equations are non-local in p_T (BFKL, CCFM ...)
- ⁎ Need to work with \`unintegrated parton distributions' (aka TMD's)
- ⁎ Breakdown of the collinear factorization
- ⁎ New factorization scheme : k_T factorization
- ⁎ Unitarity corrections: multiparticle interactions, parton saturation
  (I shall return to this topic later: \`High density systems')

From LHC to Cosmic Rays

[talk by G. Rodriguez]



- Measurements of forward particle production (soft and hard) at the LHC serve as input to Monte Carlo models of high-energy showers in cosmic ray physics

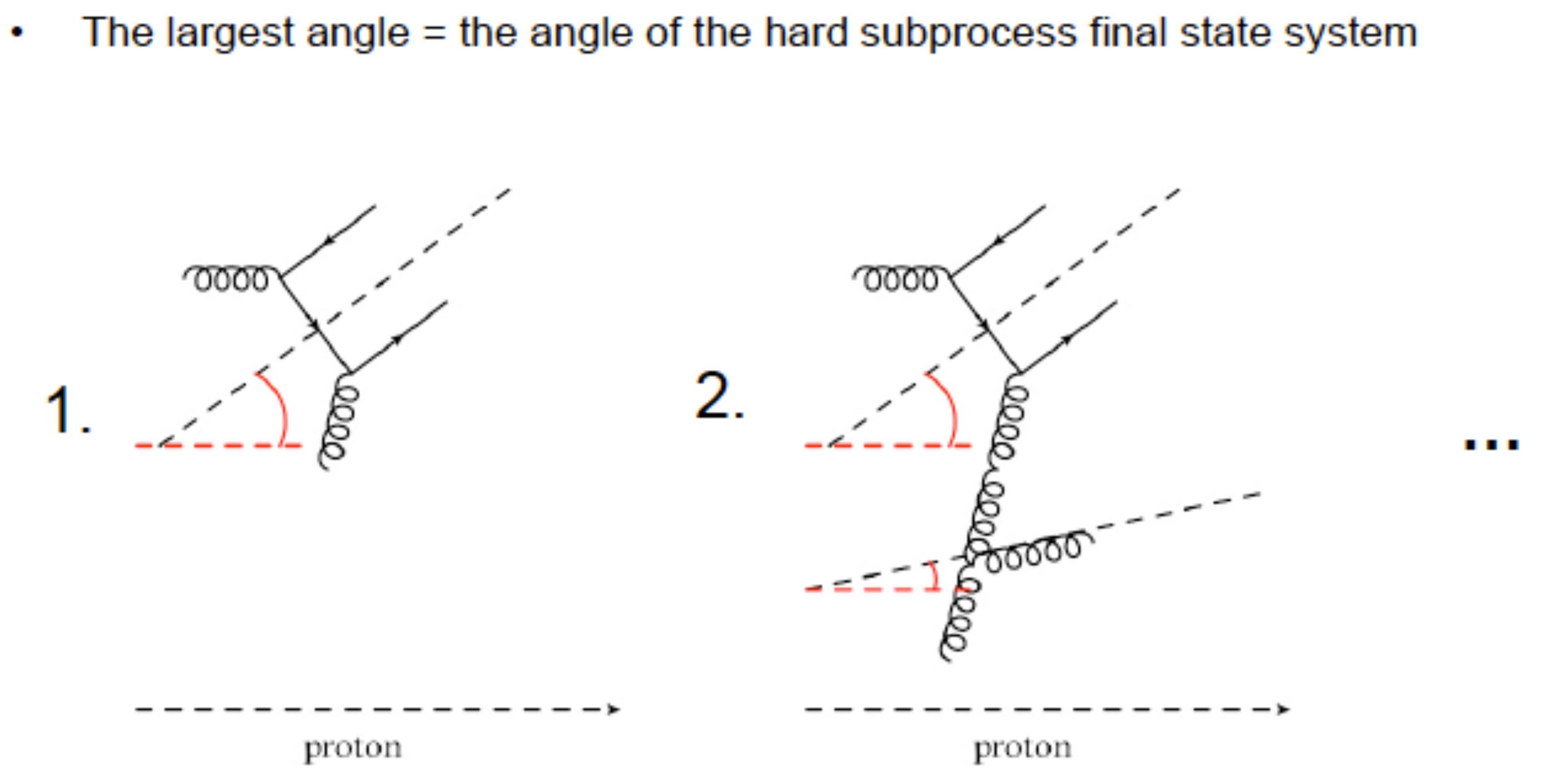
- Fixed target collision in air with 10^{17} eV corresponds to pp interaction at LHC

Michal Deak (*UAM, Madrid*)

Phenomenology with unintegrated parton showers

CASCADE: Monte Carlo generator based on CCFM *(H. Jung, 01)*

✦ Coherence in gluon radiation implies angular ordering

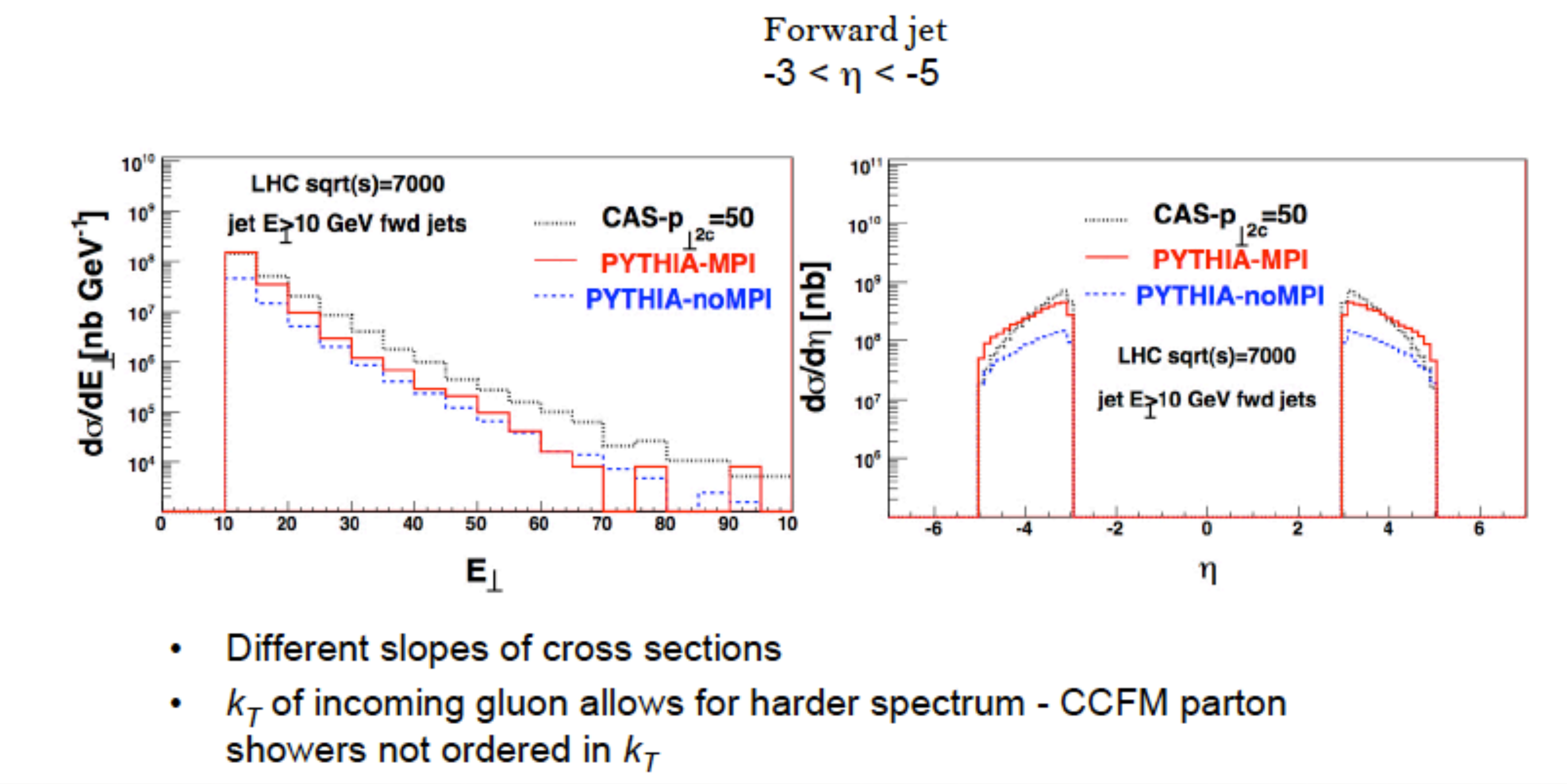


- The largest angle = the angle of the hard subprocess final state system

✦ Irrelevant for inclusive distributions, important for particle prod.

Michal Deak (cont.)

- Consistent with small-x phenomenology at HERA
- Significant deviations from PYTHIA at LHC



Forward jet

$-3 < \eta < -5$

- Different slopes of cross sections
- k_T of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in k_T

Michal Deak (cont.)

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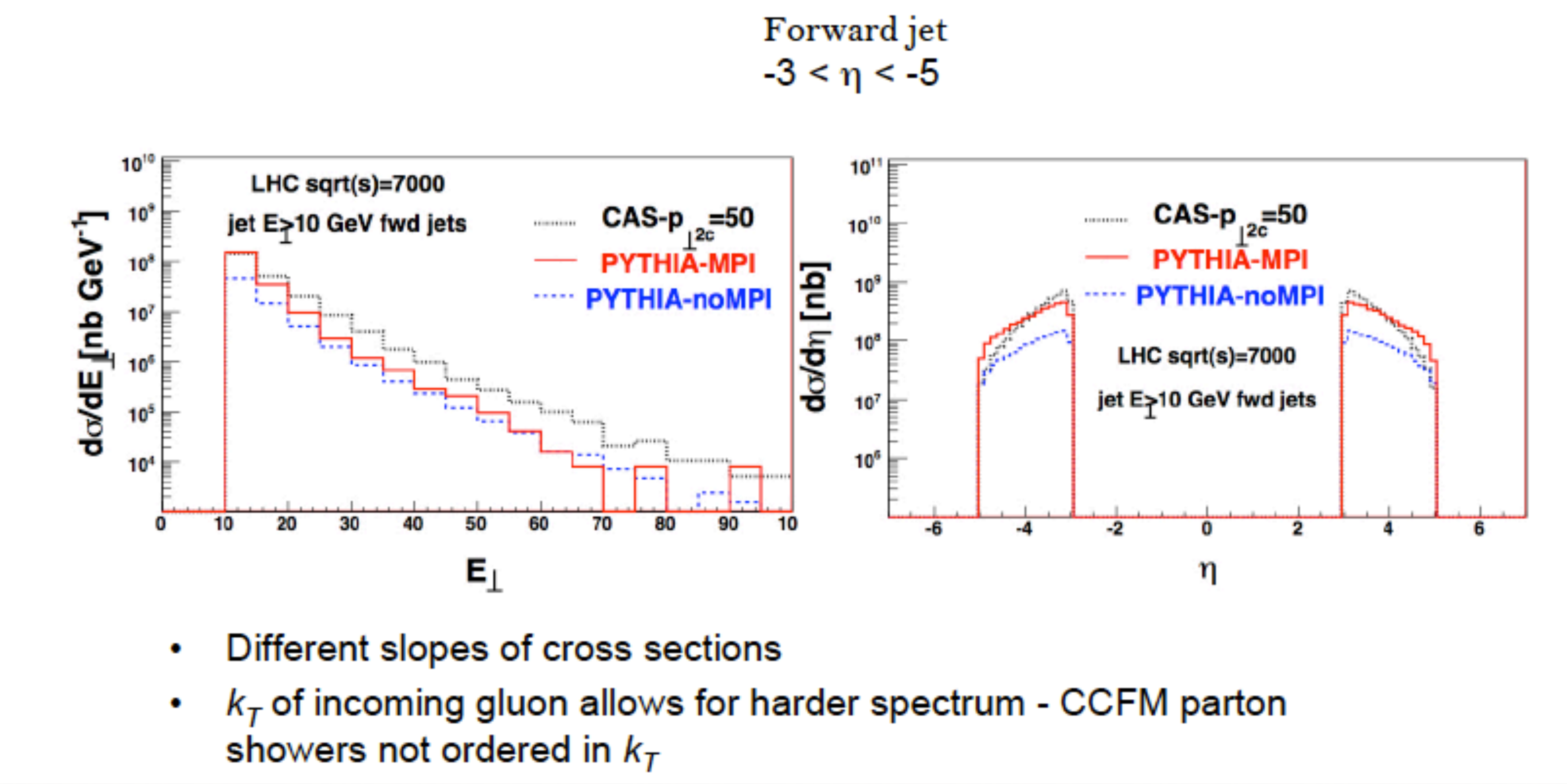


Forward jet
-3 < η < -5

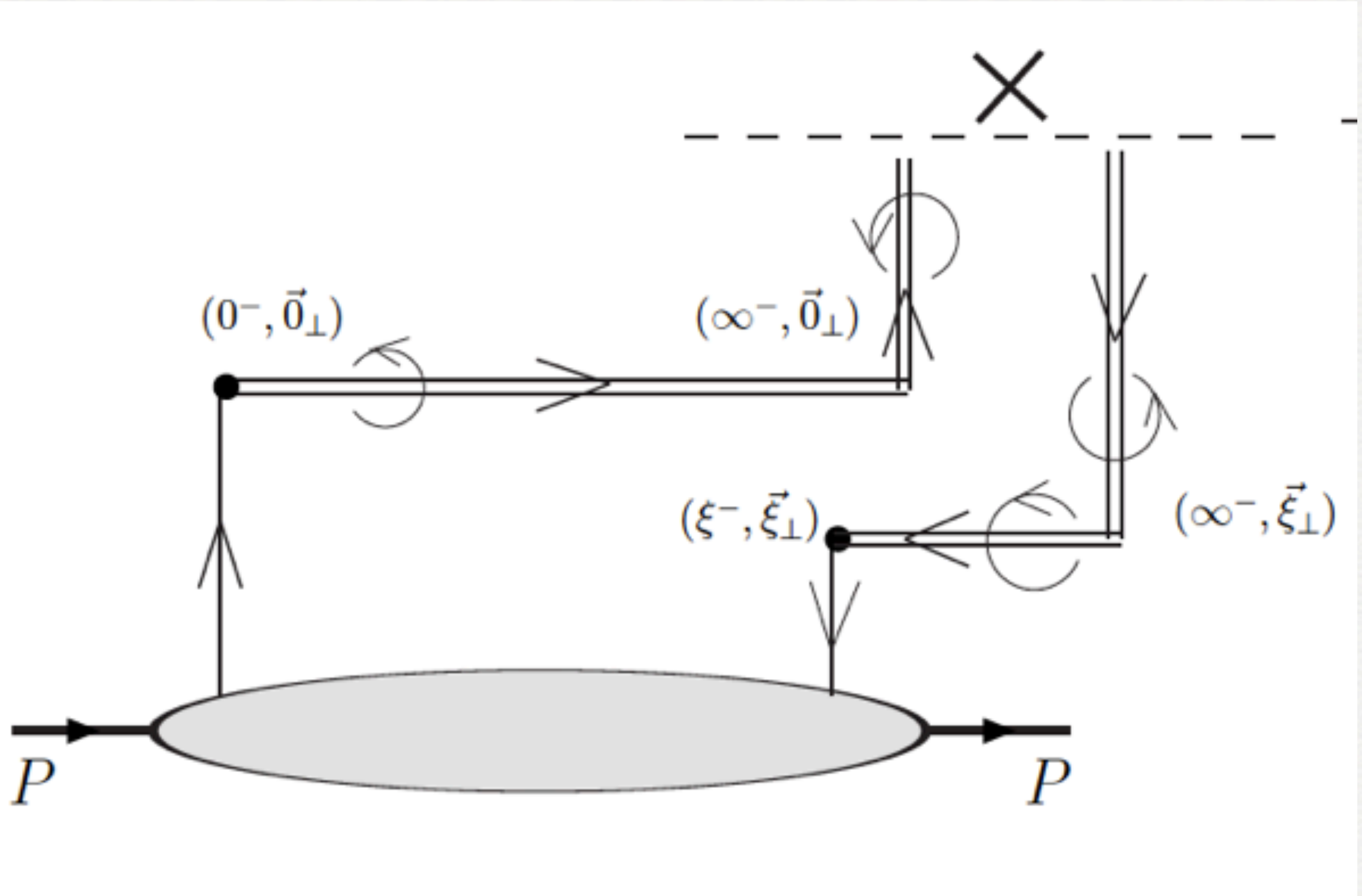
- Different slopes of cross sections
- k_T of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in k_T

N.B. One also knows how to efficiently implement unitarity corrections (saturation) *[E. Avsar, E.I., arXiv:0906.2683 [hep-ph]]*

Igor Cherednikov *(Dubna & INFN)*

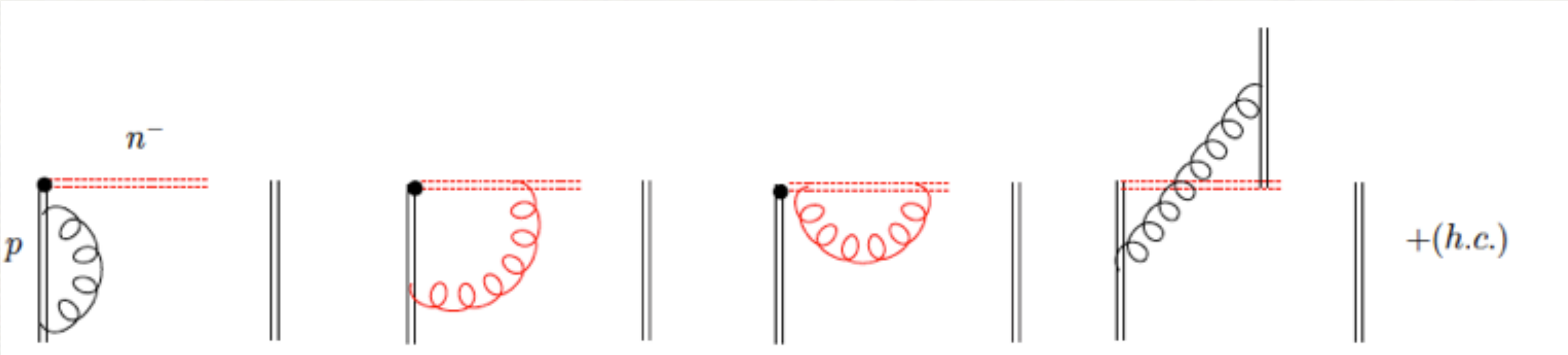
Developments on unintegrated PDFs

- ✦ Phase-space parton densities $(\eta, k_\perp, x_\perp)$
- ✦ Fourier transform of non-local 2-point operators
- ✦ Gauge links (Wilson lines) to ensure gauge invariance



Igor Cherednikov (cont.)

- ✦ Problems with UV divergences associated with quantum evolution :
- ✦ Transverse divergences which reflect the DGLAP evolution.
- ✦ Rapidity divergences which reflect BFKL.
- ✦ Overlapping divergences (how to evolve in both directions simultaneously ?)

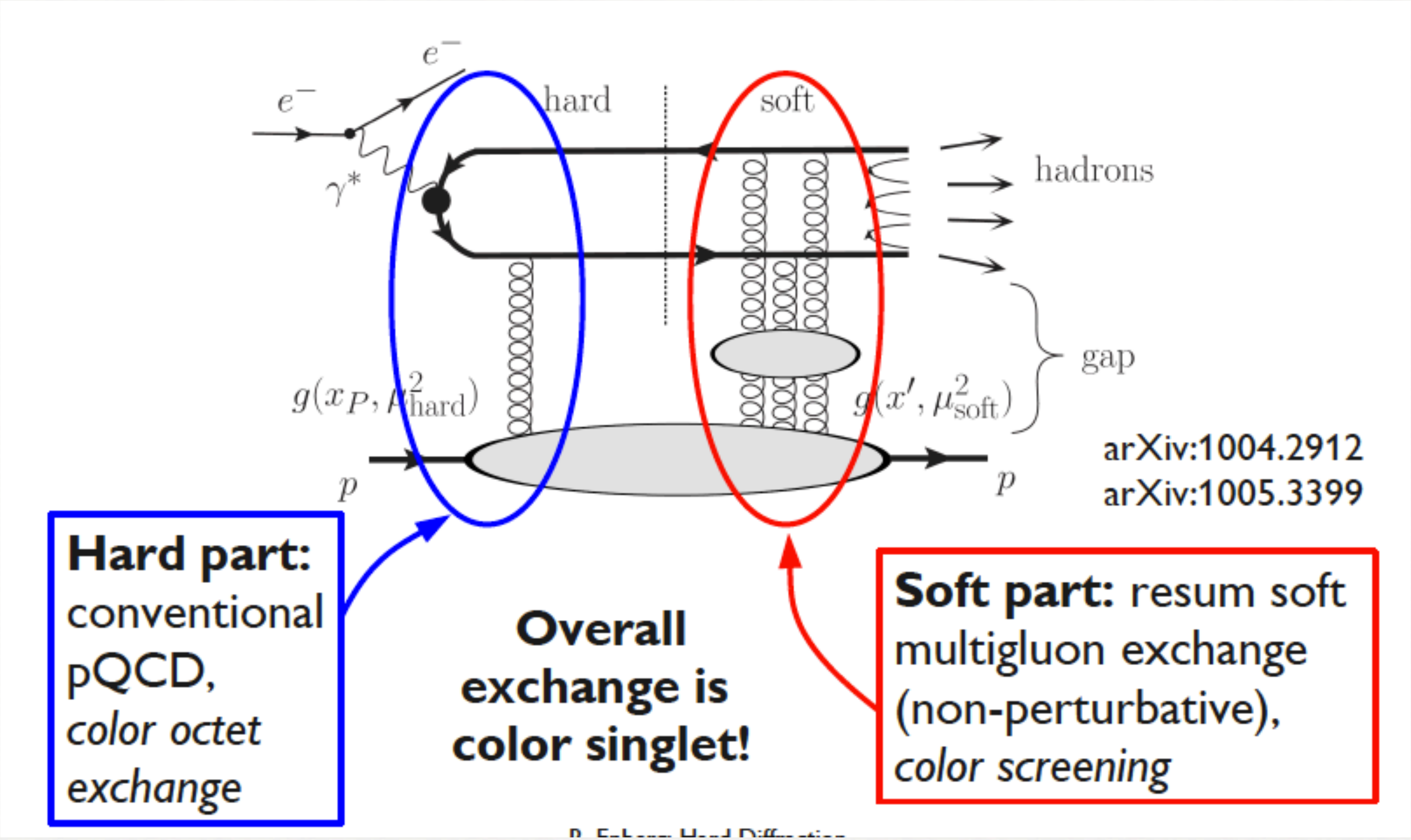


- ✦ Other conceptual and technical problems
- ✦ Lack of rigorous proof of factorization, non-universality (Wilson lines) ...


...A LOT OF WORK IN FRONT OF US!

Rikard Enberg (Uppsala University)

Hard diffraction



arXiv:1004.2912
arXiv:1005.3399

Hard part: conventional pQCD, *color octet exchange*

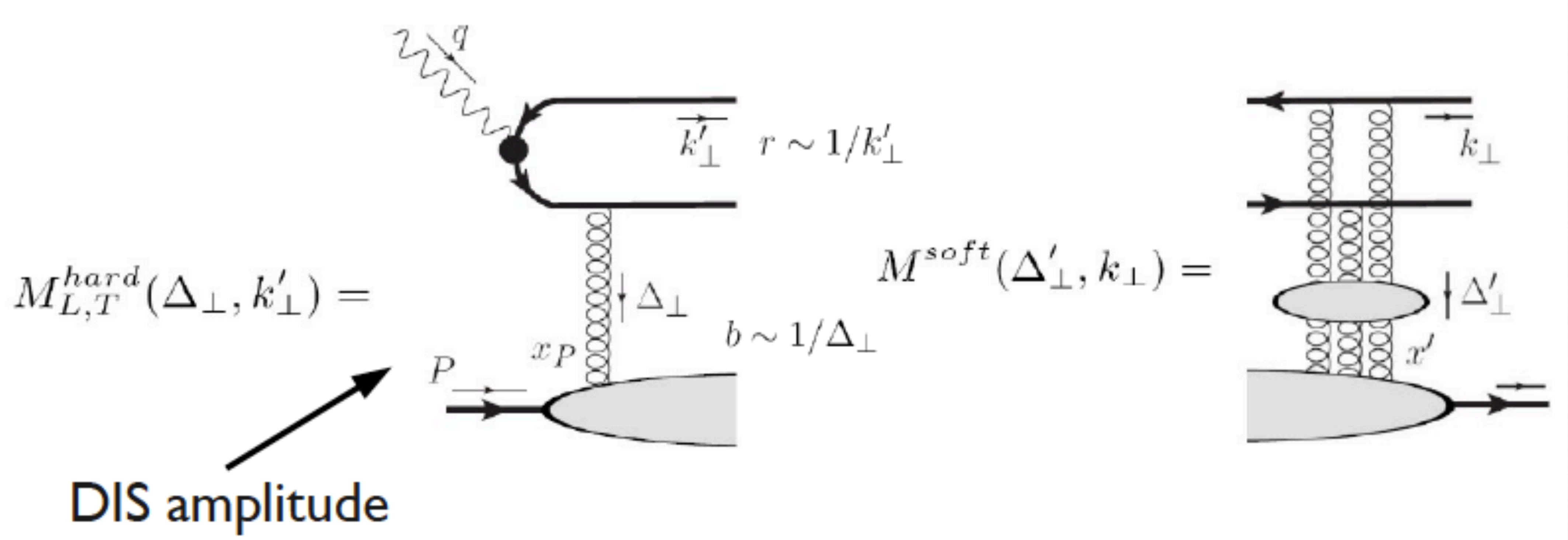
Overall exchange is color singlet!

Soft part: resum soft multigluon exchange (non-perturbative), *color screening*

Soft color exchanges in final state “after” hard process

Rikard Enberg (cont.)

- ✦ Assume hard - soft factorization:



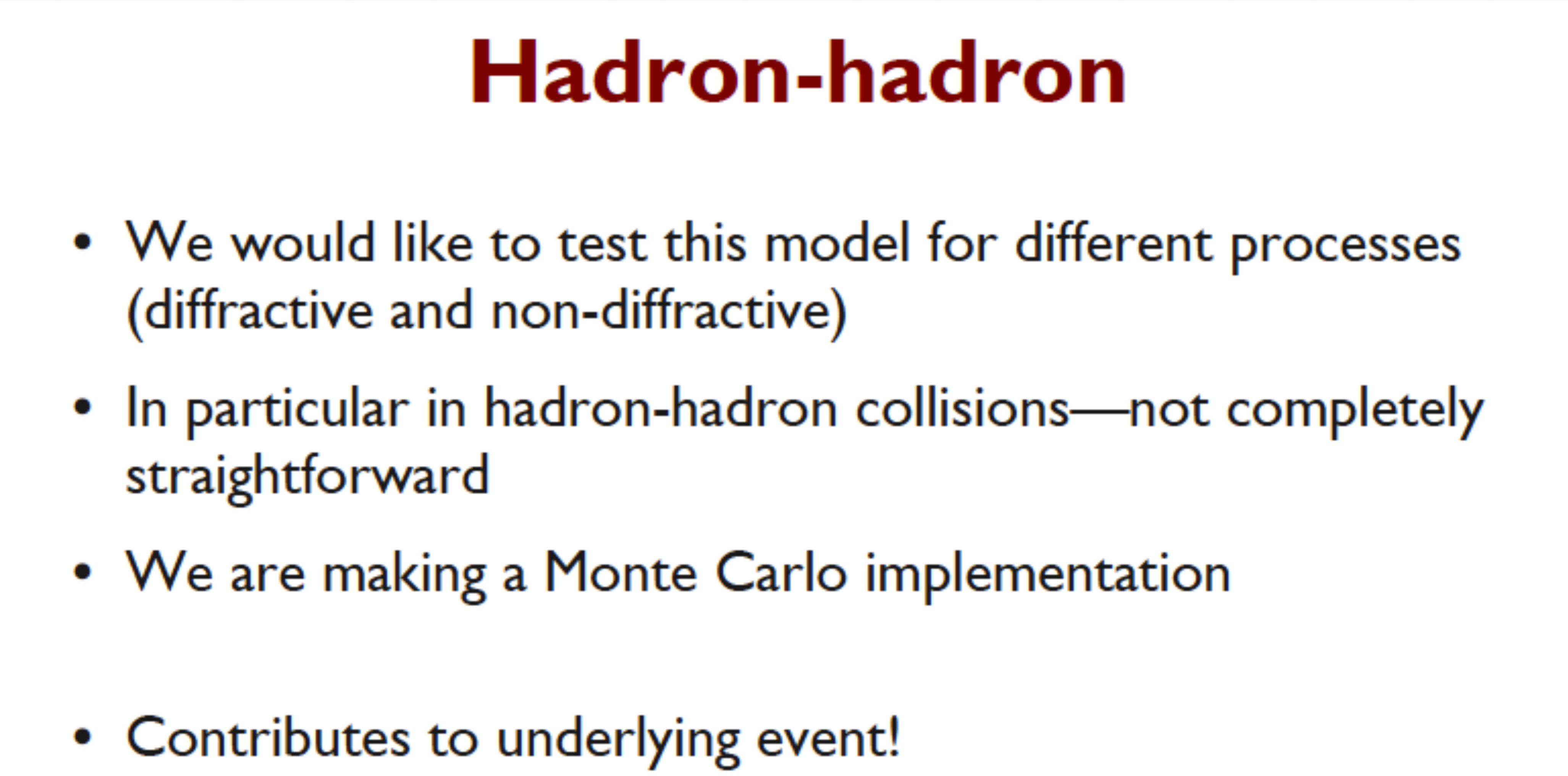
- ✦ Resum soft gluon exchanges in the eikonal + planar (large Nc) approximations

- ✦ Good fit to DIS diffraction at HERA for $Q^2 > 12$ GeV^2

- ✦ At lower Q^2, larger uncertainties from the gluon PDF.

Rikard Enberg (cont.)

And, of course, the next step is ...



Hadron-hadron

- We would like to test this model for different processes (diffractive and non-diffractive)
- In particular in hadron-hadron collisions—not completely straightforward
- We are making a Monte Carlo implementation

- Contributes to underlying event!

Rikard Enberg (cont.)

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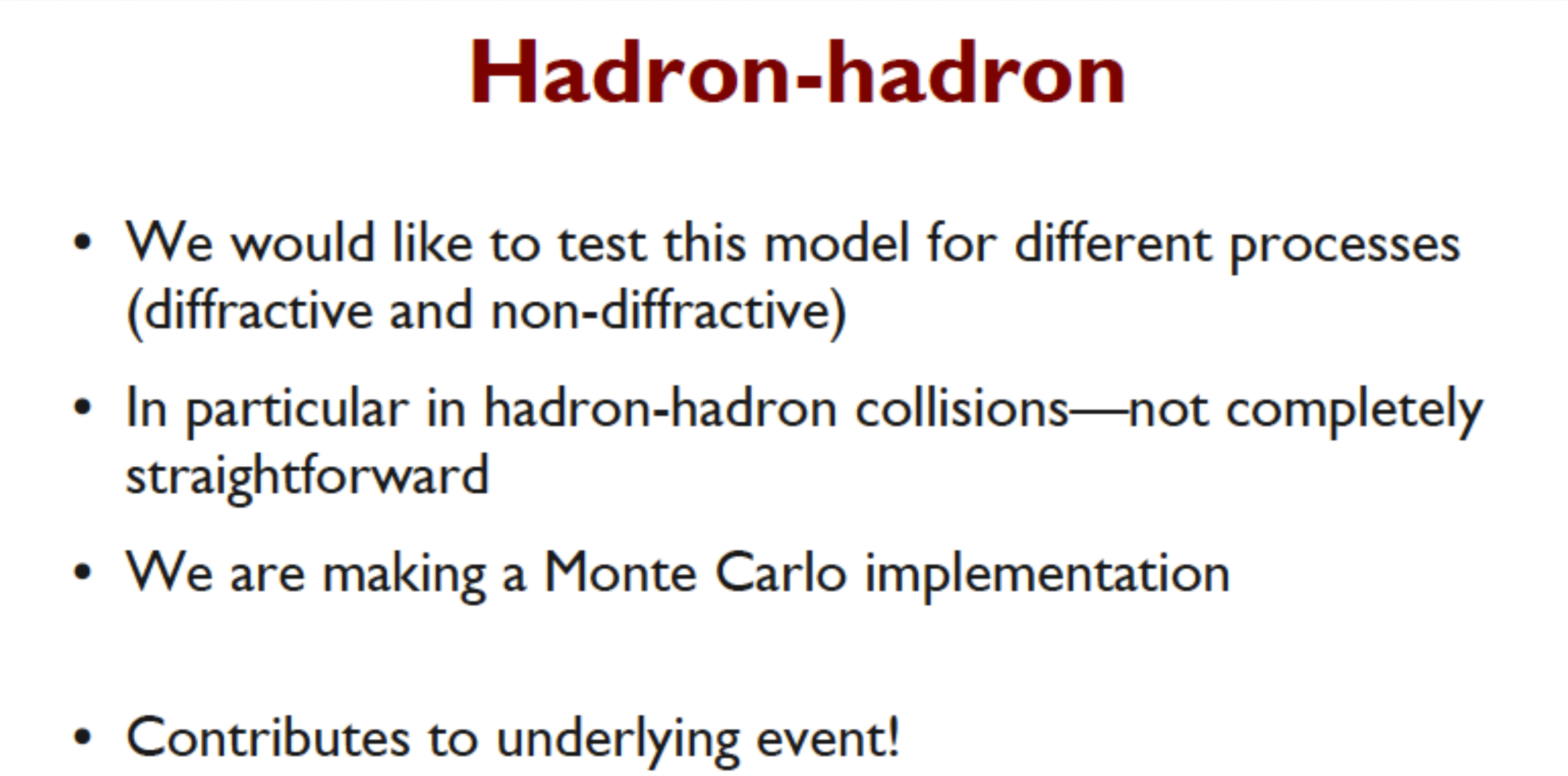

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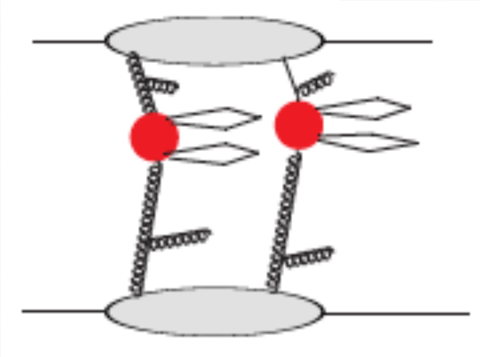
✦ Perhaps the approach needs a better treatment of the hard sector at low Q^2 (MPI in the hard exchange)



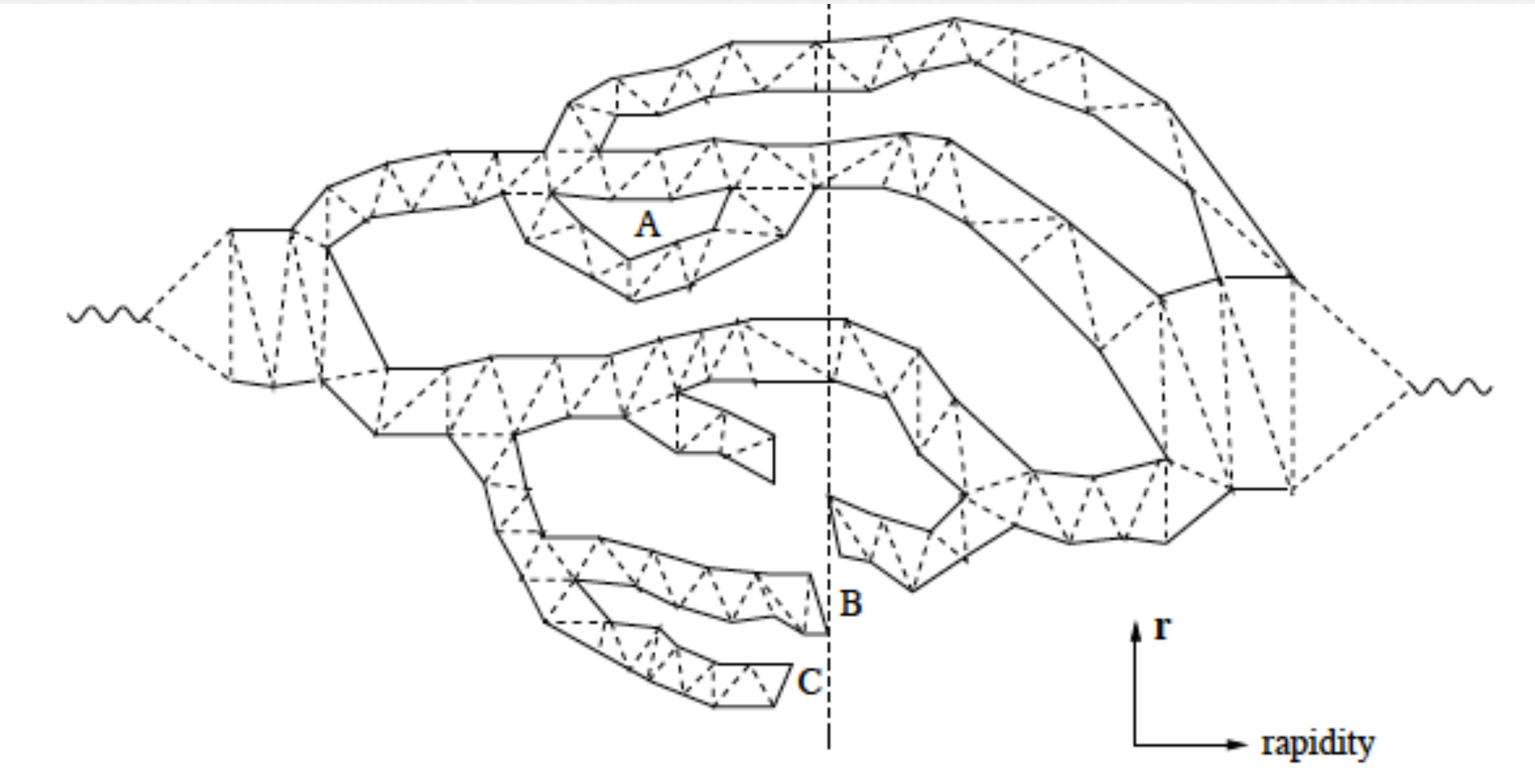
Gosta Gustafson *(Lund University)*

Multiple interactions, diffraction, and the BFKL pomeron

- A quasi-perfect model (*`Lund Dipole Cascade'*)

a model for the complete high-energy evolution in pQCD, including BFKL w. non-leading effects, saturation and stochasticity in gluon emissions.

→ the mythique Pomeron loops



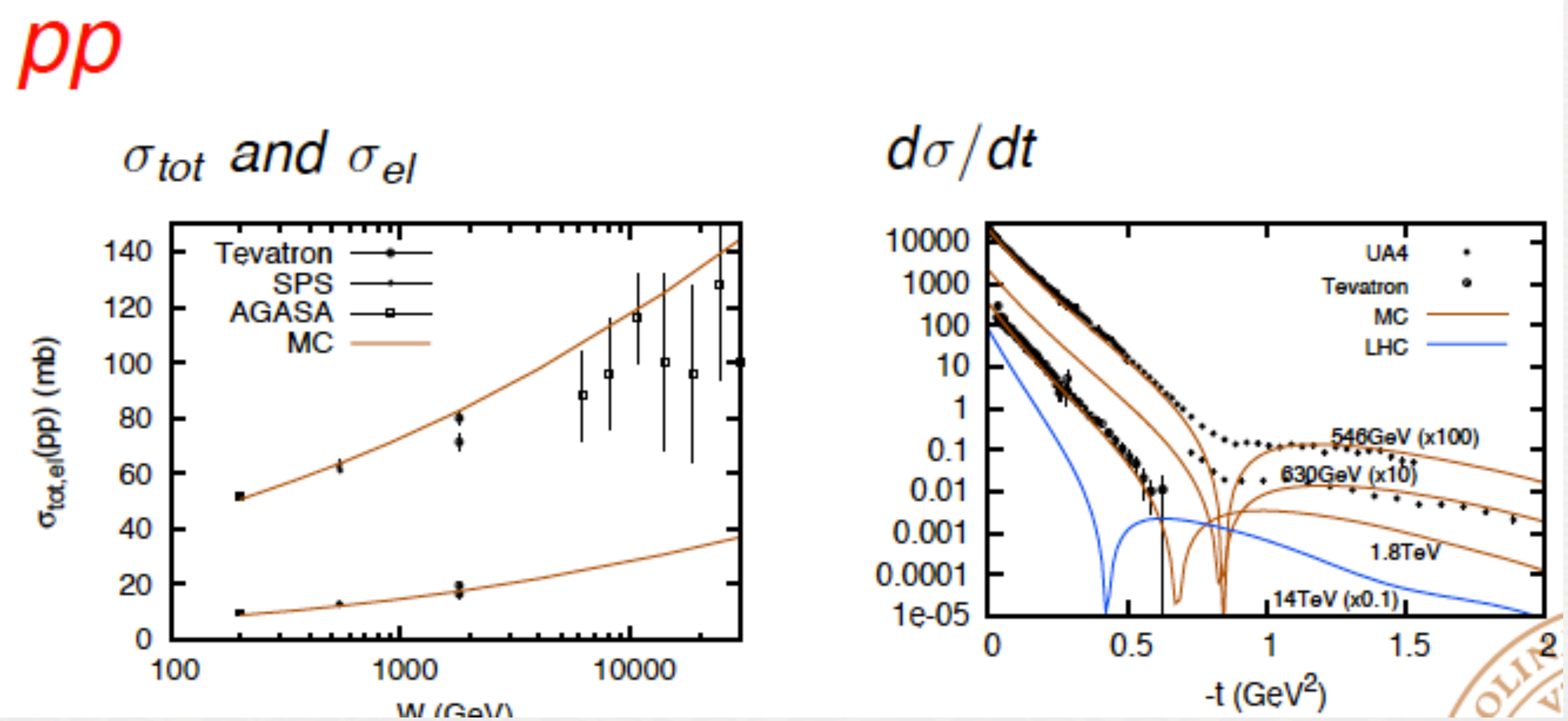
Gosta Gustafson (cont.)

✦ Why is this still just a `model' ?

- NLO effects in BFKL not fully included (not even at large Nc)
- saturation effects treated in a heuristic way: `dipole swing' (color recombin.)
- string picture for hadronization (PYTHIA)

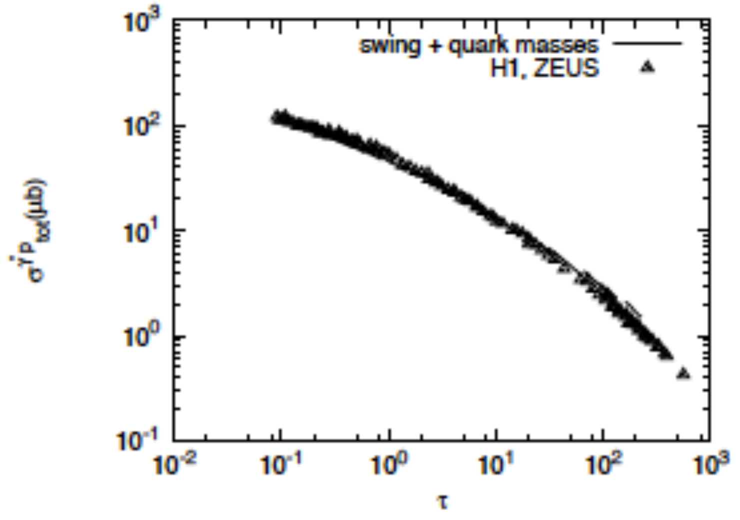
... but it would be very hard to do any better !

✦ Good fits to DIS and pp (including diffraction) with 2 params



Gosta Gustafson (cont.)

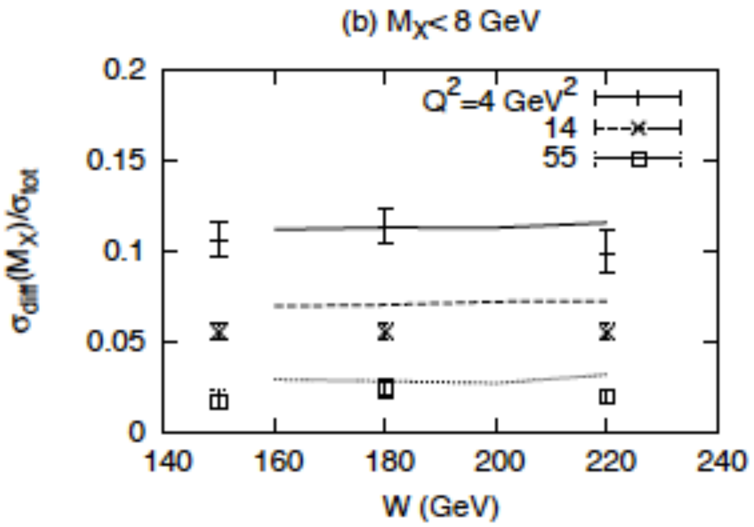
$\gamma^* p$



Satisfies geometric scaling

Diffractive excitation: $\gamma^* p$

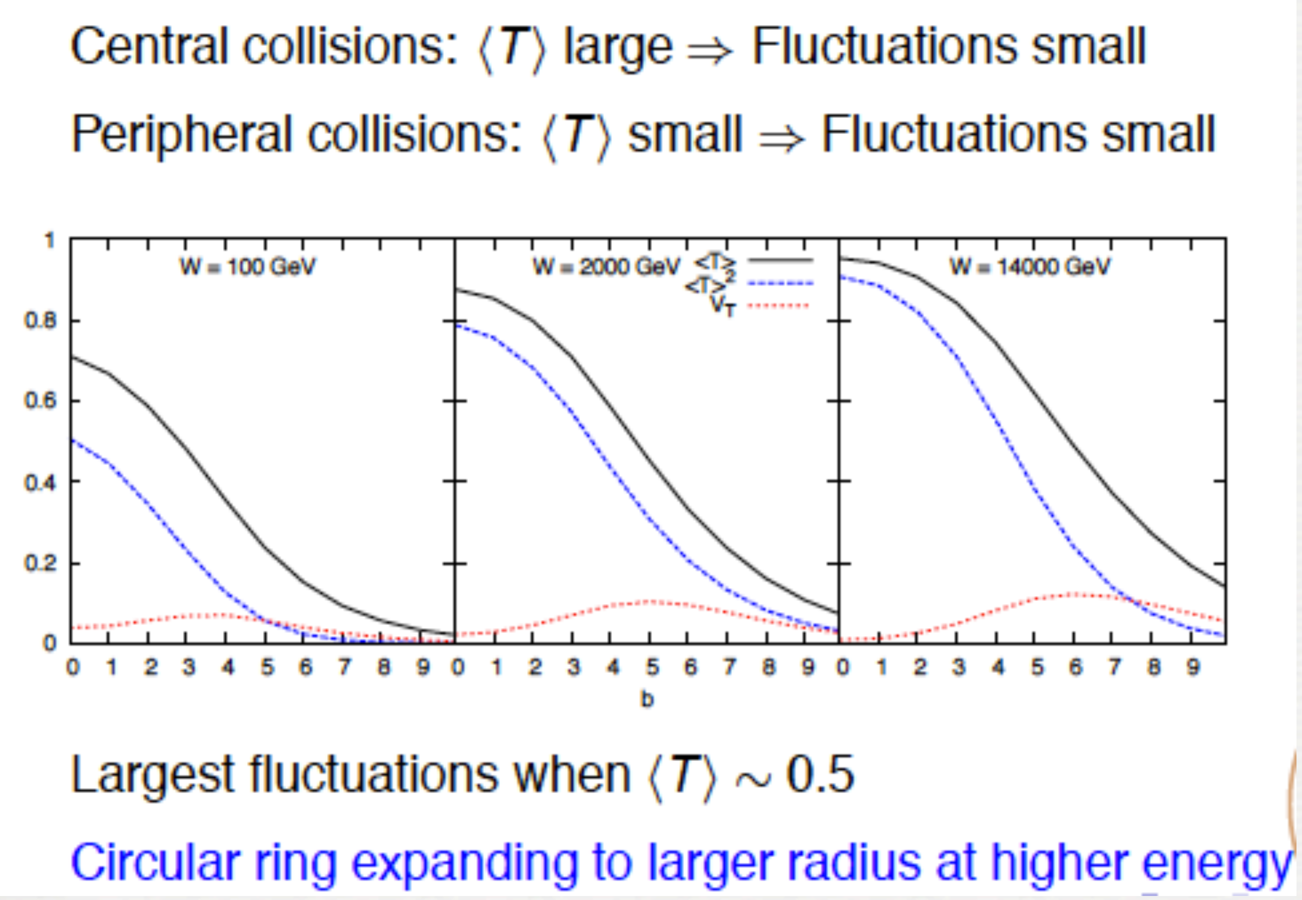
Example $M_X < 8$ GeV, $Q^2 = 4, 14, 55\,\mathrm{GeV}^2$.



- ✦ Diffraction comes from partonic flucts, so like in Good-Walker

- ✦ Unitarity corrections are truly essential:
- ✦ they suppress fluctuations in the high density region
- ✦ in pp, the central scattering amplitude is close to one
- ✦ without saturation: `hard Pomeron' with $\alpha(0) = 1.21 \quad \alpha' = 0.2$

Gosta Gustafson (cont.)

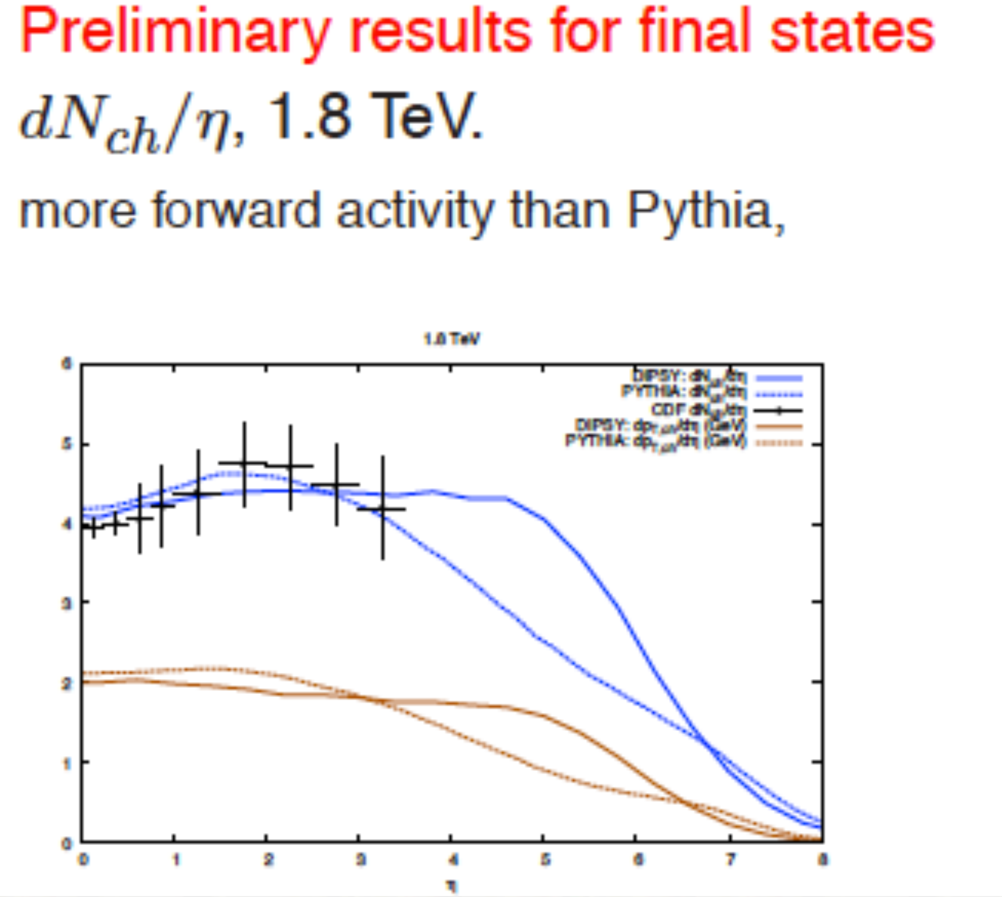


Central collisions: $\langle T \rangle$ large $\Rightarrow$ Fluctuations small

Peripheral collisions: $\langle T \rangle$ small $\Rightarrow$ Fluctuations small

Largest fluctuations when $\langle T \rangle \sim 0.5$

Circular ring expanding to larger radius at higher energy



Preliminary results for final states

dN_{ch}/η, 1.8 TeV.

more forward activity than Pythia,

- ✦ Fluctuations in the dilute regime are suppressed by running coupling.
- ✦ Final states in pp : More forward activity than Pythia

High Density Systems

conveners: Cyrille Marquet & Raimond Snellings

The Color Glass Condensate

an approximation of QCD to describe the nuclear wave function at small-x, using classical fields

The Glasma

the pre-equilibrium phase, resulting of the collisions of two CGCs, during which classical fields decay into a particles

Finite temperature lattice QCD

a laboratory to study the transition from the deconfined phase into the hadronic phase, and to explore the QCD phase diagram

Bulk observables

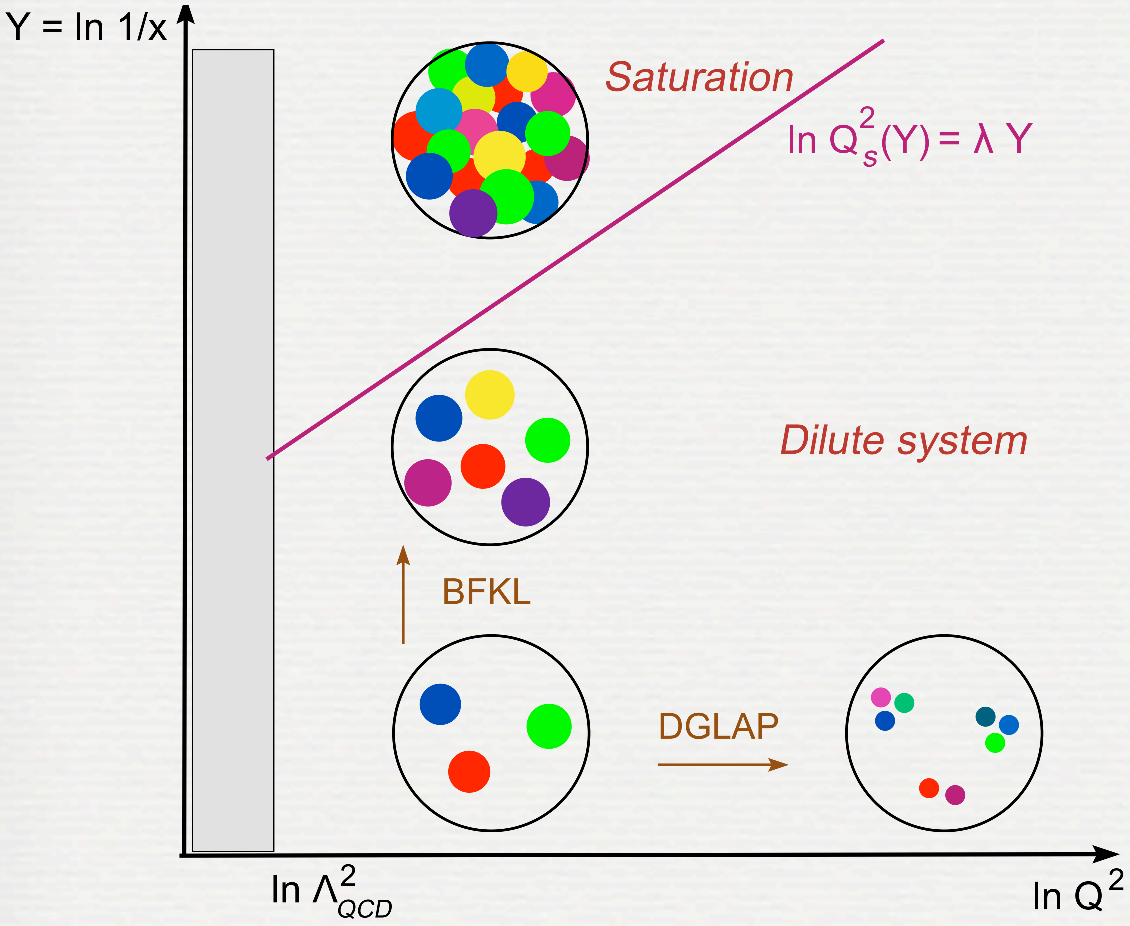
properties of the collective behavior of the (thermalized ?) low-p_T particles (quarks/gluons then hadrons) composing the plasma

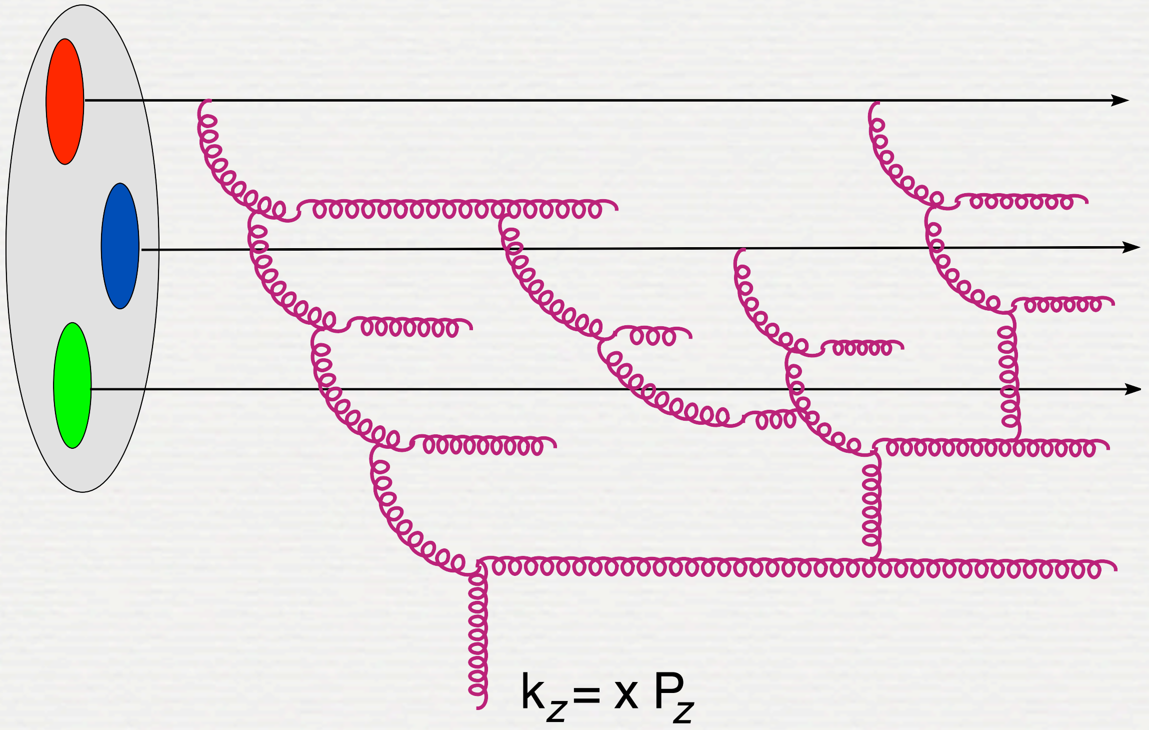
Hard Probes

rare high-p_T particles created at early times that have propagated through the evolving plasma

Gluon saturation at small x

- At high density, gluons overlap and interact with each other
- Gluons size and occupation # : $\Delta x_\perp \sim 1/k_\perp,\ n(x,k_\perp) \sim 1/x^\lambda$
- Non-linear effects for sufficiently small x and $k_\perp$





Color Glass Condensate

(Mclerran & Venugopalan, 94; E.I. McLerran, Leonidov, 2001)

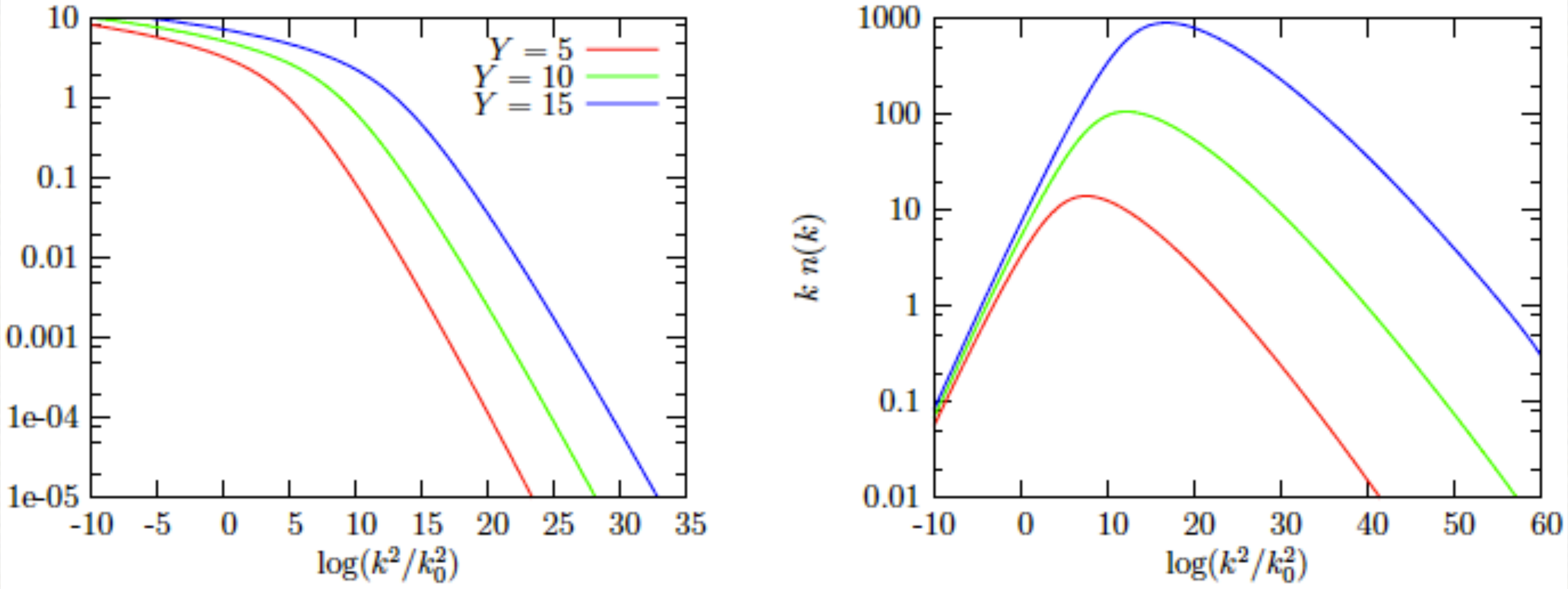
- The form of gluonic matter made by the gluons at saturation
- The result of an equilibrium between gluon radiation and gluon recombination, for occupation numbers $n \sim 1/\alpha_s \gg 1$
- With increasing energy, this equilibrium shows up at increasingly large values of the transverse momentum :

$$Q_s^2(x) \simeq Q_0^2\, x^{-\lambda_s} \quad \text{with} \quad \lambda_s \simeq 0.2 - 0.3$$

- The bulk of a hadron wavefunction becomes perturbative
- Typical transverse momentum inside the hadron $k_\perp \sim Q_s(x)$

Color Glass Condensate

$$xG(x,Q^2) = \int \mathrm{d}^2b \int^Q \mathrm{d}k\, k\, n(x,k)$$



The typical transverse momentum of the gluons is $\sim Q_s(Y)$

- Essentially, $n(x,k_T)$ = the unintegrated gluon distribution.
  (proper definition in terms of a dipole S-matrix)
- Generalized versions of k_T - factorization ... case by case.
  (inclusive particle production, di-jets, ..)
- Observables that have been tested in d+Au collisions at RHIC.

Javier Albacete (IPhT Saclay)

NLO-CGC phenomenology in e+A, p+A and A+A collisions

✦The CGC formalism enters the precision era !
(inclusion of NLO effects, notably the running coupling,
in the BK-JIMWLK equations)

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2r_1\, K(r,r_1,r_2)\,[\mathcal{N}(r_1,x)+\mathcal{N}(r_2,x)-\mathcal{N}(r,x)-\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

$$K^{\rm run}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\, r_2^2}+\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)}-1\right)+\frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)}-1\right)\right]$$

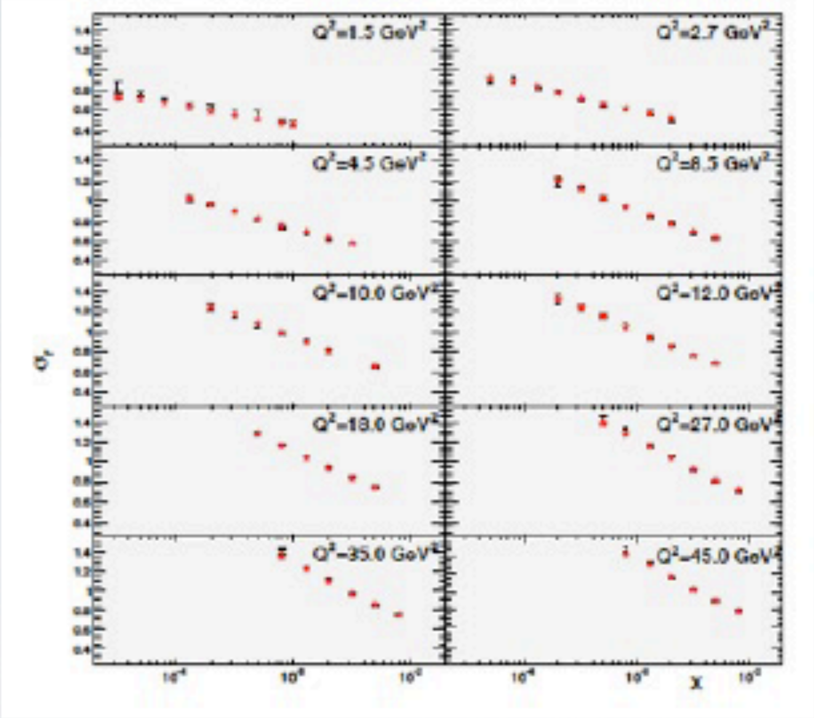
✦... and thus it becomes consistent with the experimental data
(simultaneous description of small-x data in DIS at d+Au)

✦ The non-linear effects are essential, at least for d+Au

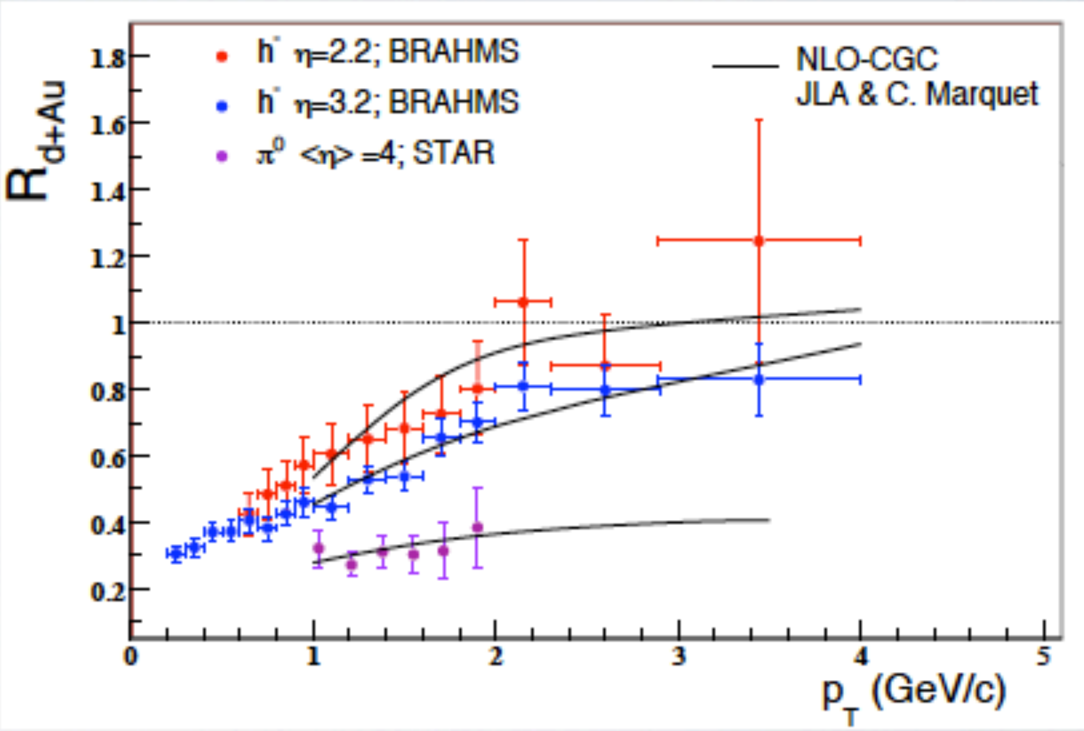
Javier Albacete *(IPhT Saclay)*

NLO-CGC phenomenology in e+A, p+A and A+A collisions

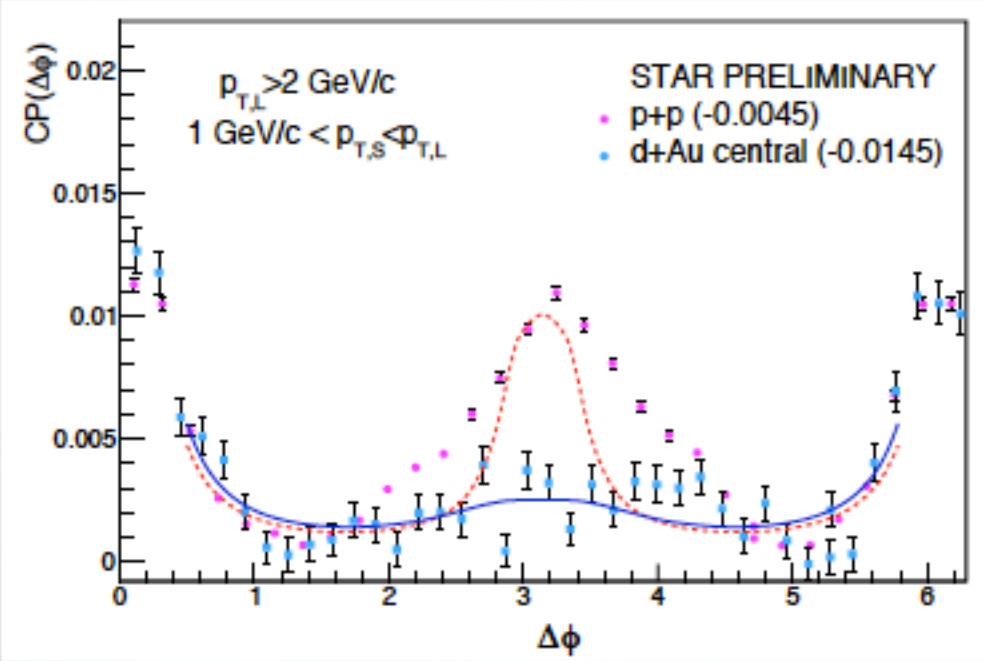
DIS structure functions



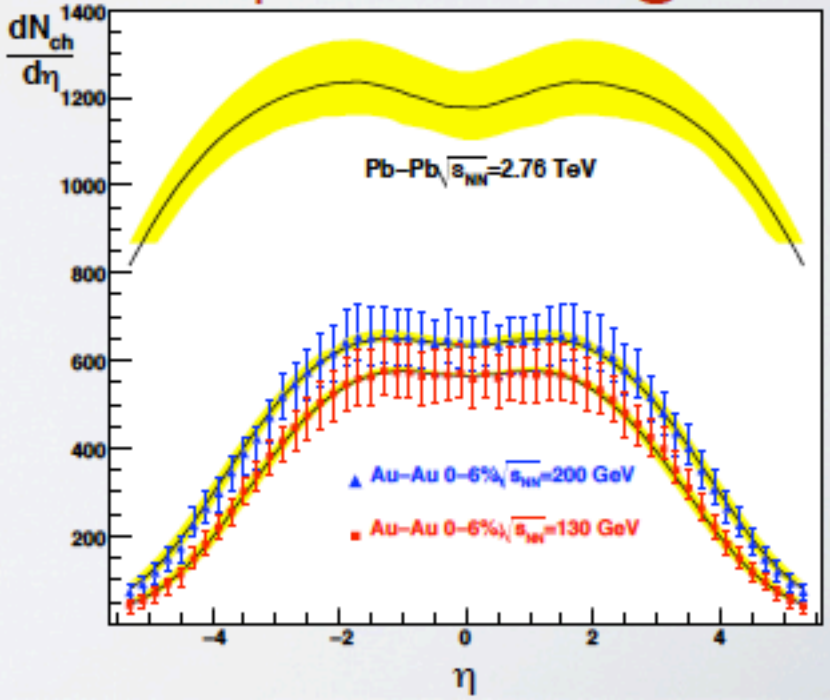
Single inclusive production in d+Au and p+p coll



forward di-hadrons correlations in d+Au @ RHIC



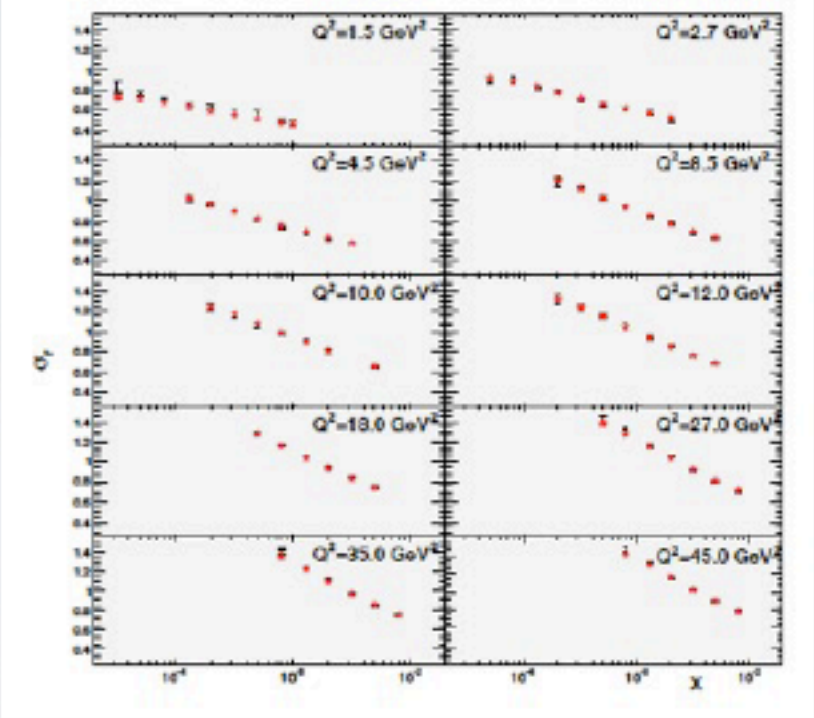
Multiplicities in Au+Au @ RHIC



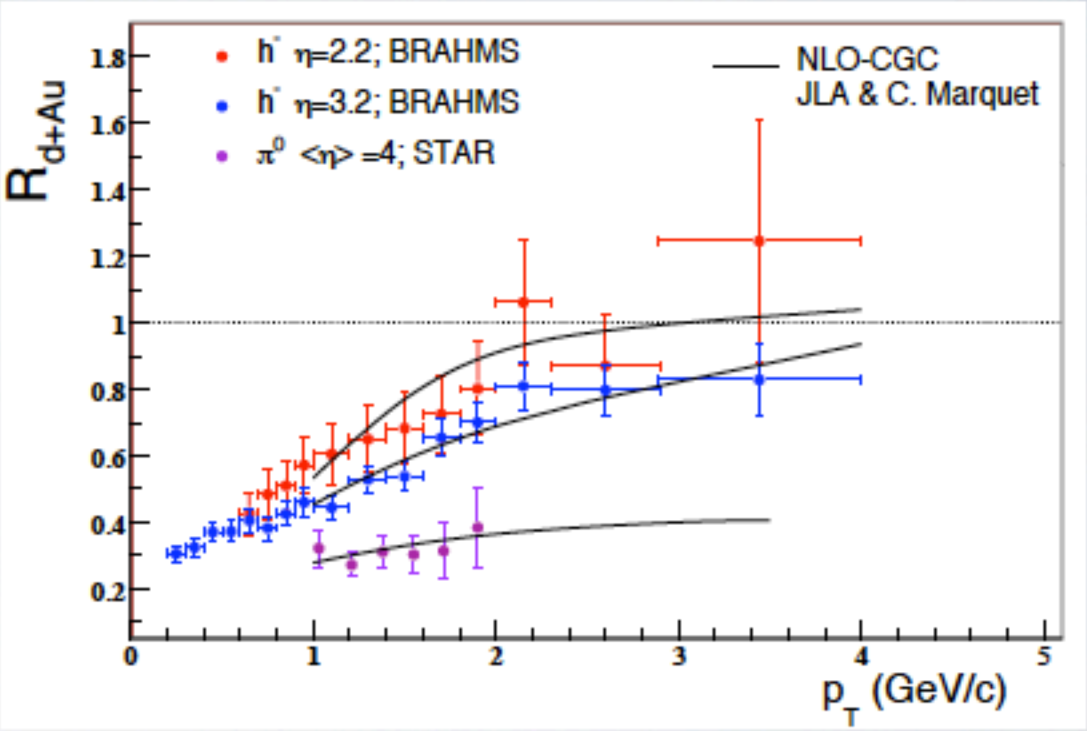
Javier Albacete (*IPhT Saclay*)

NLO-CGC phenomenology in e+A, p+A and A+A collisions

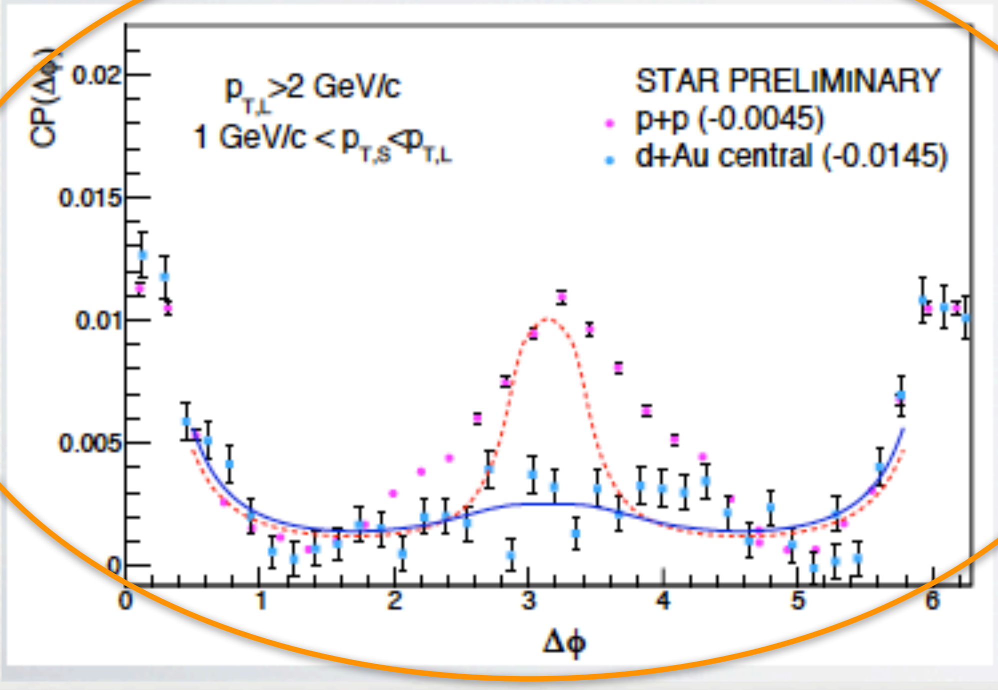
DIS structure functions



Single inclusive production in d+Au and p+p coll



forward di-hadrons correlations in d+Au @ RHIC



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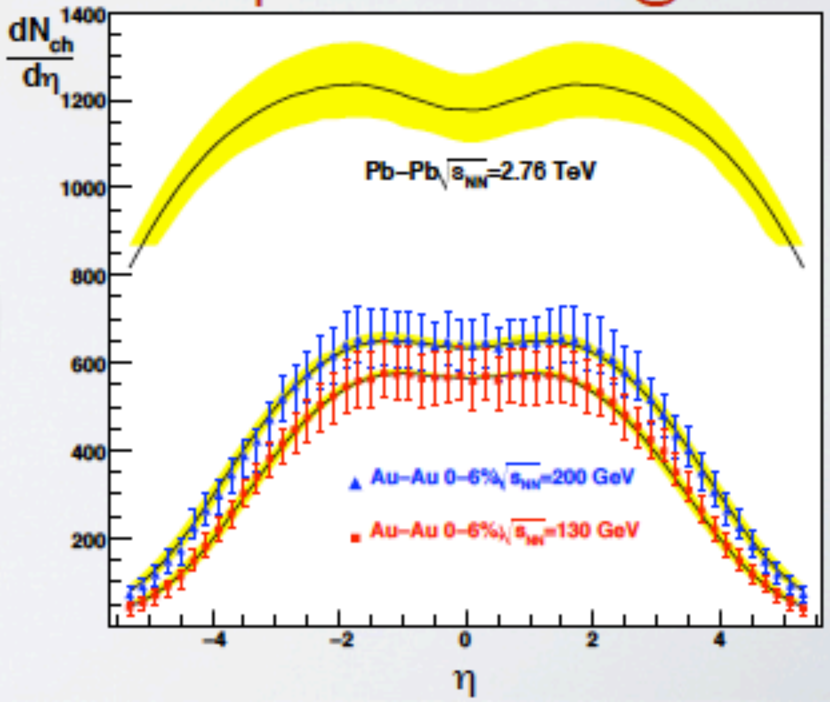
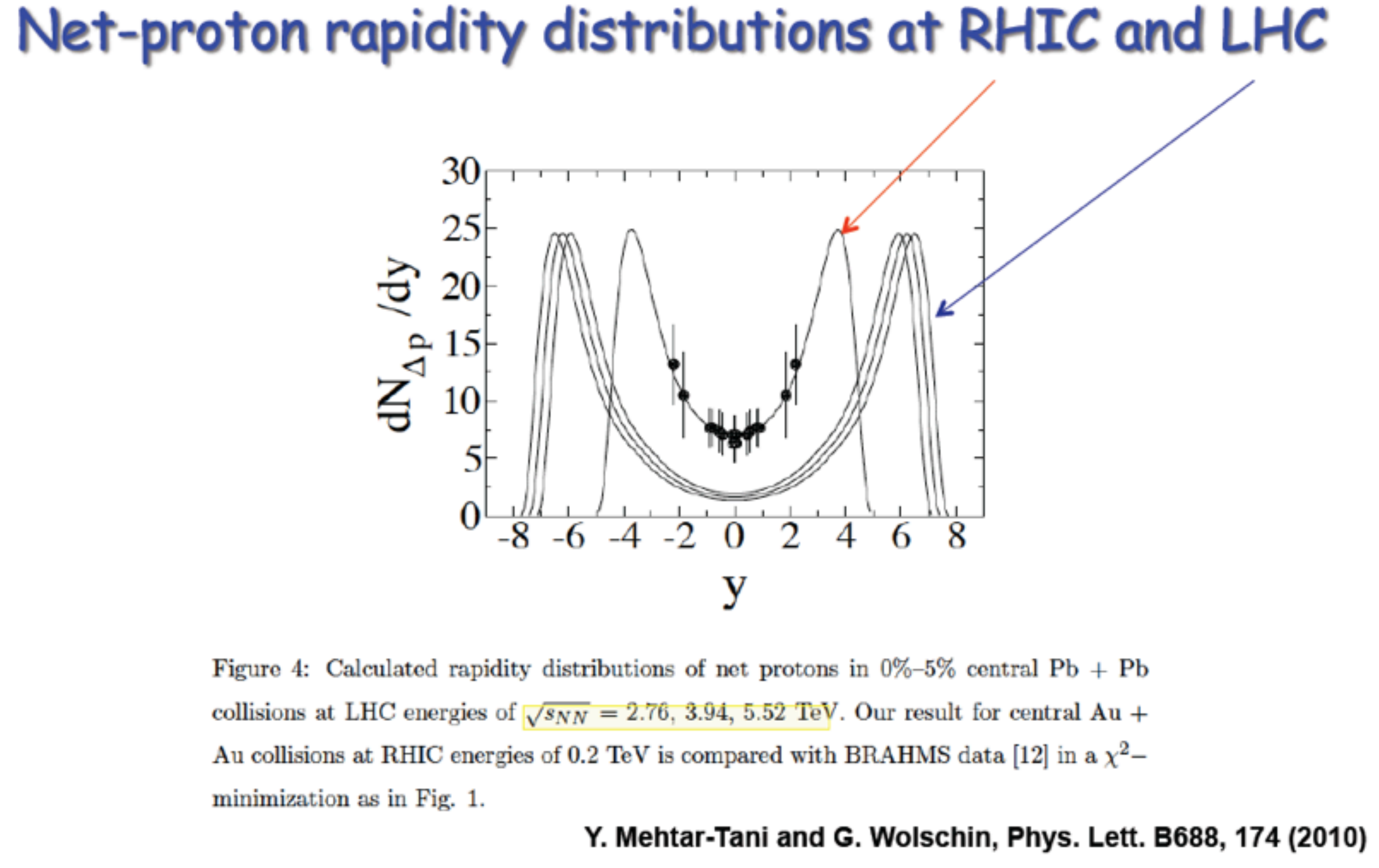


Georg Wolschin (*Heidelberg University*)

Heavy ions at LHC energies: predictions for net baryon distributions

Via interactions, valence quarks (or leading baryons) can be deviated towards central rapidities



Net-proton rapidity distributions at RHIC and LHC

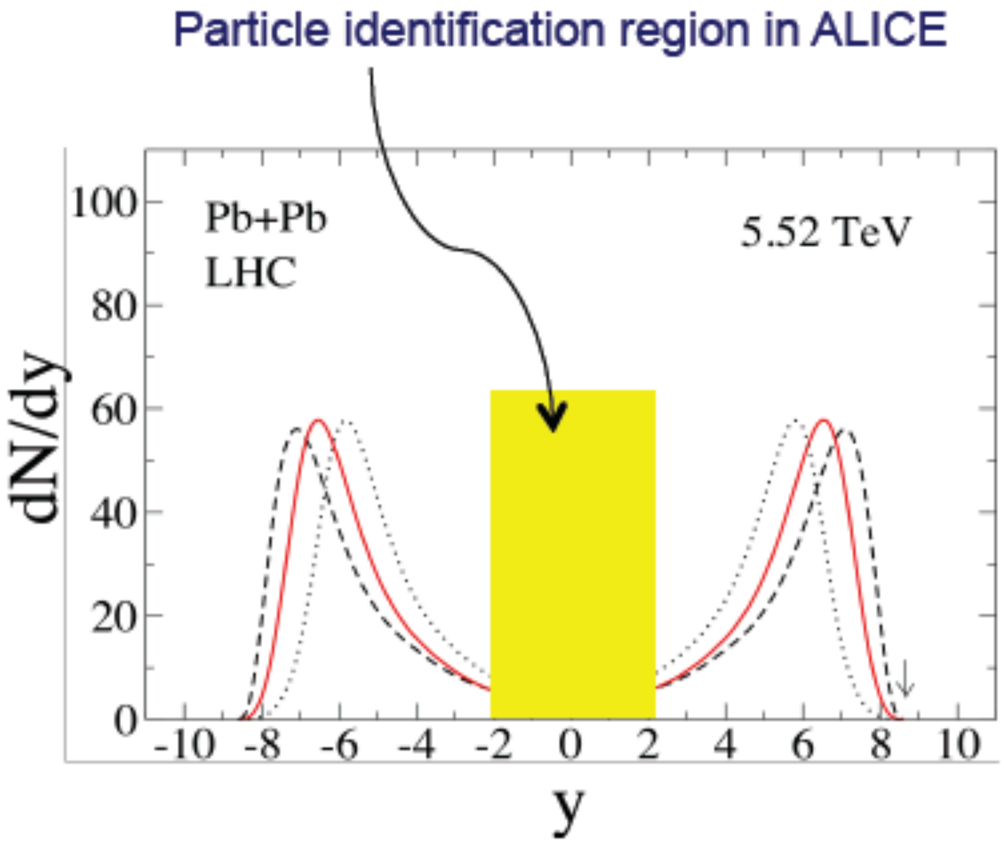
Figure 4: Calculated rapidity distributions of net protons in 0%–5% central Pb + Pb collisions at LHC energies of $\sqrt{s_{NN}} = 2.76, 3.94, 5.52$ TeV. Our result for central Au + Au collisions at RHIC energies of 0.2 TeV is compared with BRAHMS data [12] in a χ^2–minimization as in Fig. 1.

Y. Mehtar-Tani and G. Wolschin, Phys. Lett. B688, 174 (2010)

Georg Wolschin (Heidelberg University)

Heavy ions at LHC energies: predictions for net baryon distributions

The positions of the fragmentation peaks are quite sensitive to saturation effects in the nuclear target.



Y. Mehtar-Tani and GW
Phys. Rev. Lett. 102,182301 (2009)

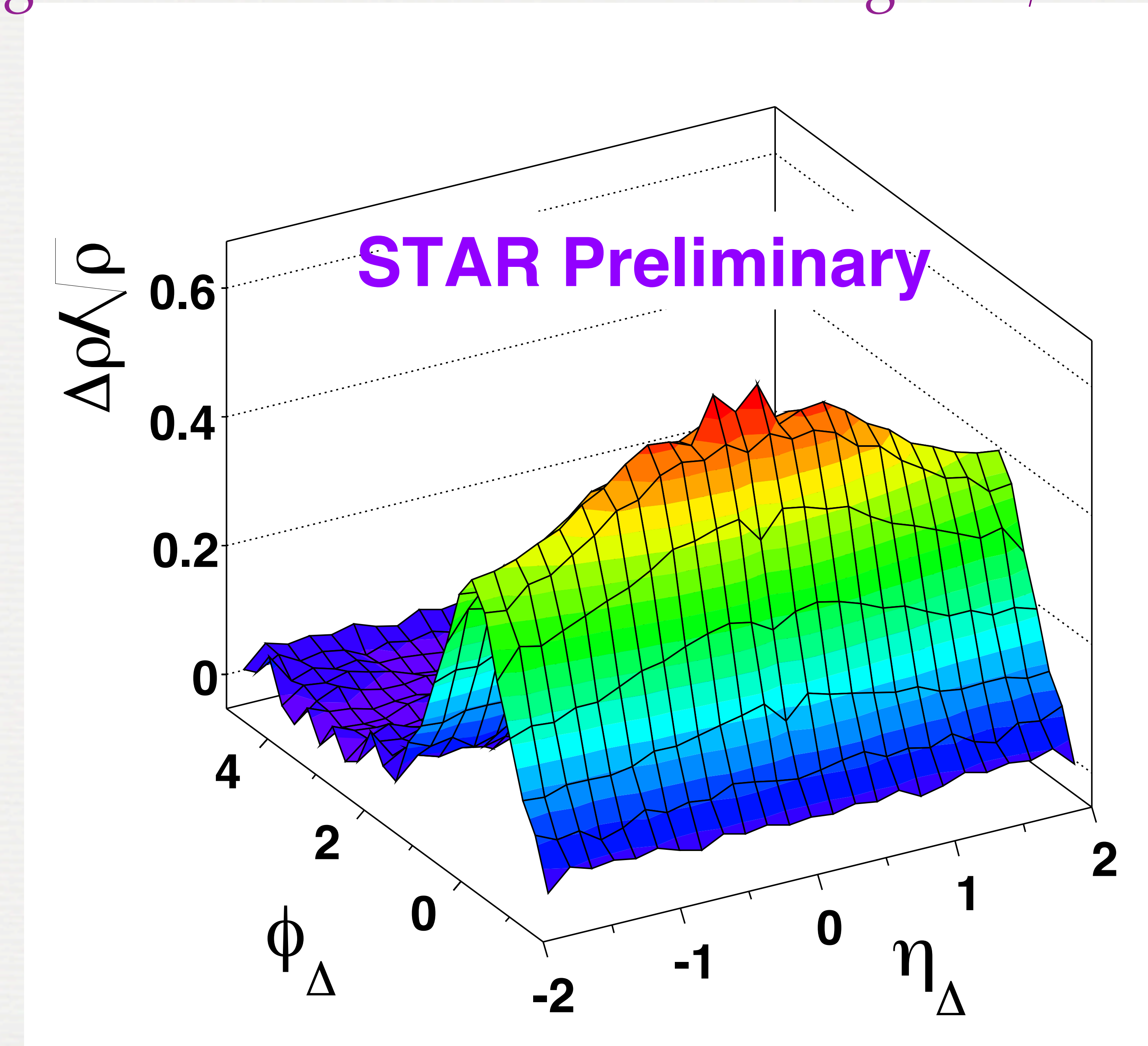
- Central (0-5%) Pb+Pb collisions, $y_{beam} = 8.68$
- Dashed black curve: λ= 0
  Solid red curve: λ = 0.15
  Dotted black curve: λ= 0.3
- A larger gluon saturation scale produces more baryon stopping at LHC as well.
- The midrapidity value of the net-baryon distribution is small, but finite: dN/dy (y = 0) ≈ 4. The **total yield** is normalized to the number of baryon participants, $N_B \approx 357$.

$$Q_s^2(x) \; = \; A^{1/3}\, Q_0^2\, x^{-\lambda}$$

Ridge Effect @ RHIC

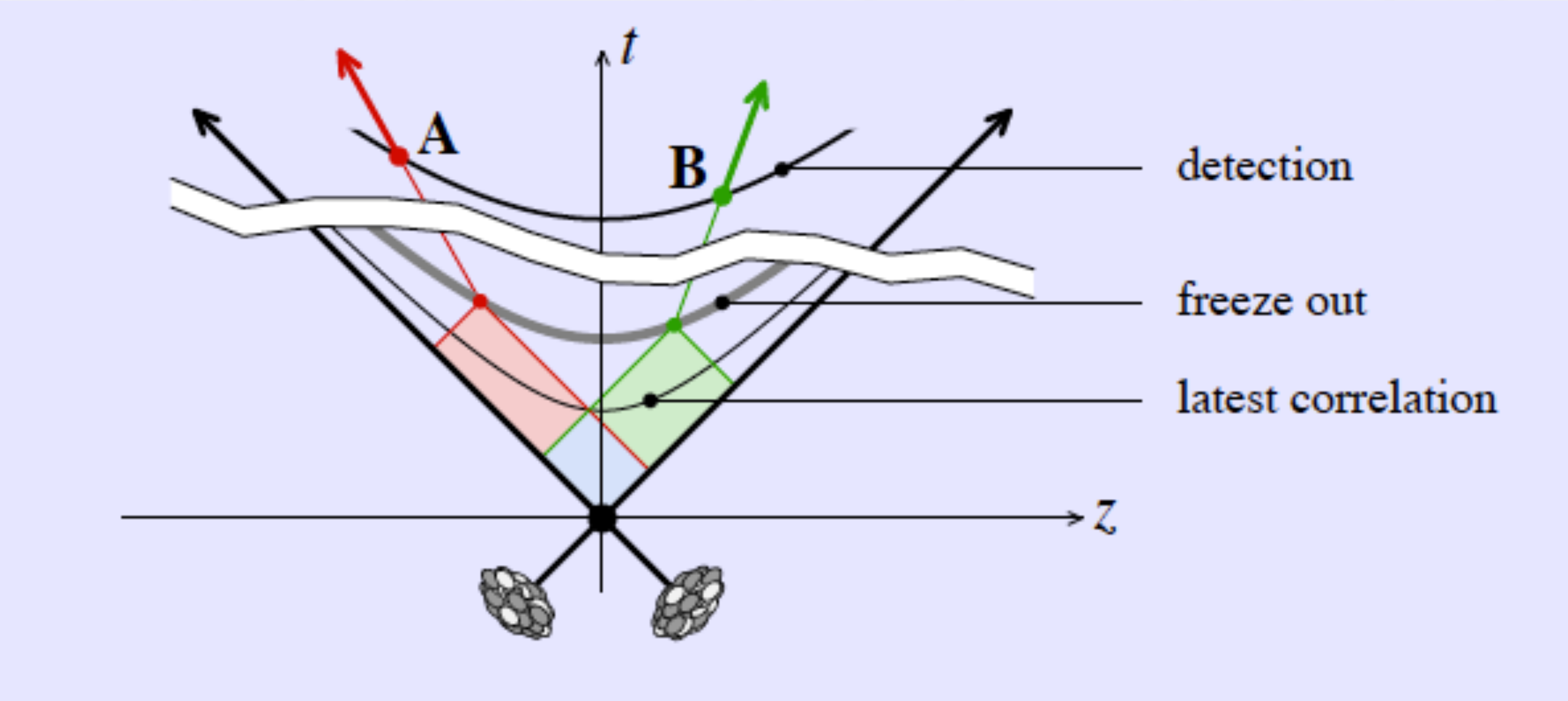
2-hadron correlations in the events triggered by a jet

- ✦ long range correlations in rapidity $\Delta\eta$
- ✦ strong collimation in the azimuthal angle $\Delta\phi$



Importance of initial rapidity correlations

Long range rapidity correlations must be created early !

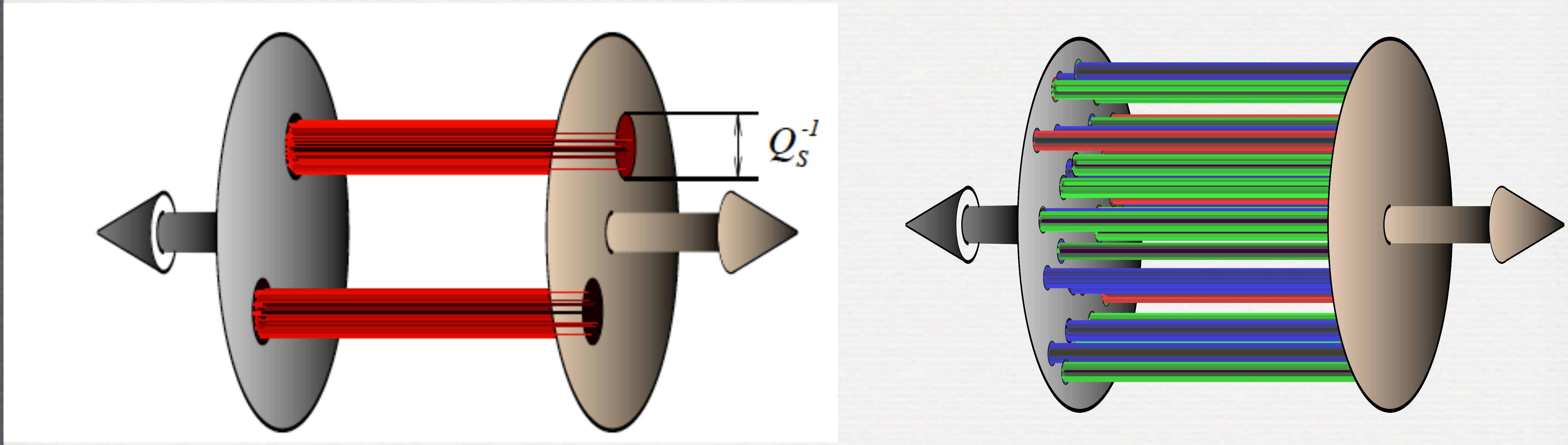


$$t_{\mathrm{correlation}} \;\leq\; t_{\mathrm{freeze\ out}}\ \mathrm{e}^{-\frac{1}{2}\Delta\eta}$$

What are the initial conditions for heavy ion collisions ?

Flux tubes in the Glasma

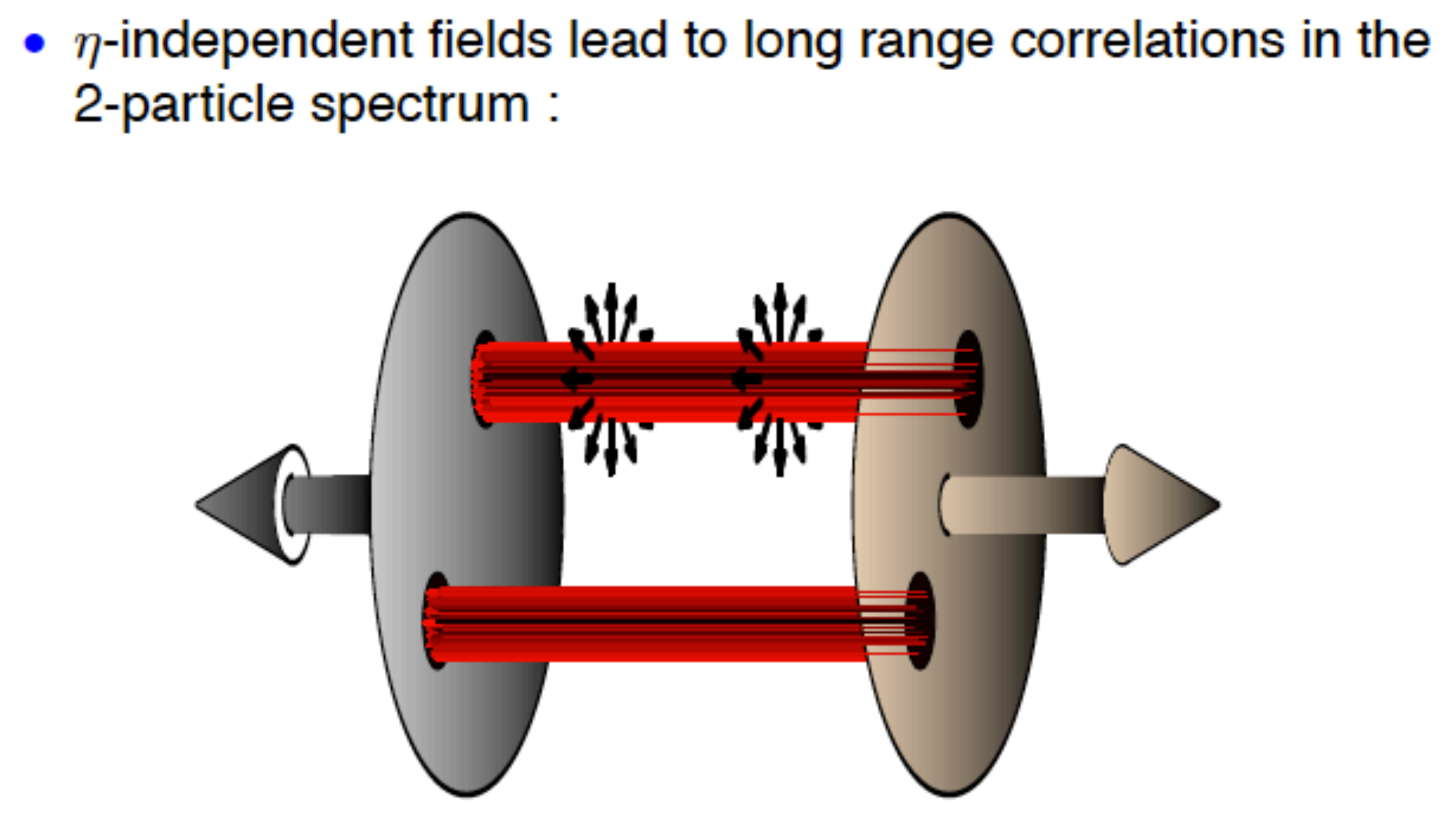
CGC predicts longitudinal `flux tubes' (chromo–$\vec{\mathbf{E}}$ and $\vec{\mathbf{B}}$)
extending between the projectiles



- The color correlation length in the transverse plane is Q_s^{-1}

  ▷ flux tubes of diameter Q_s^{-1}, filling up the transverse area
- The correlation length in the η direction is $\Delta\eta \sim \alpha_s^{-1}$

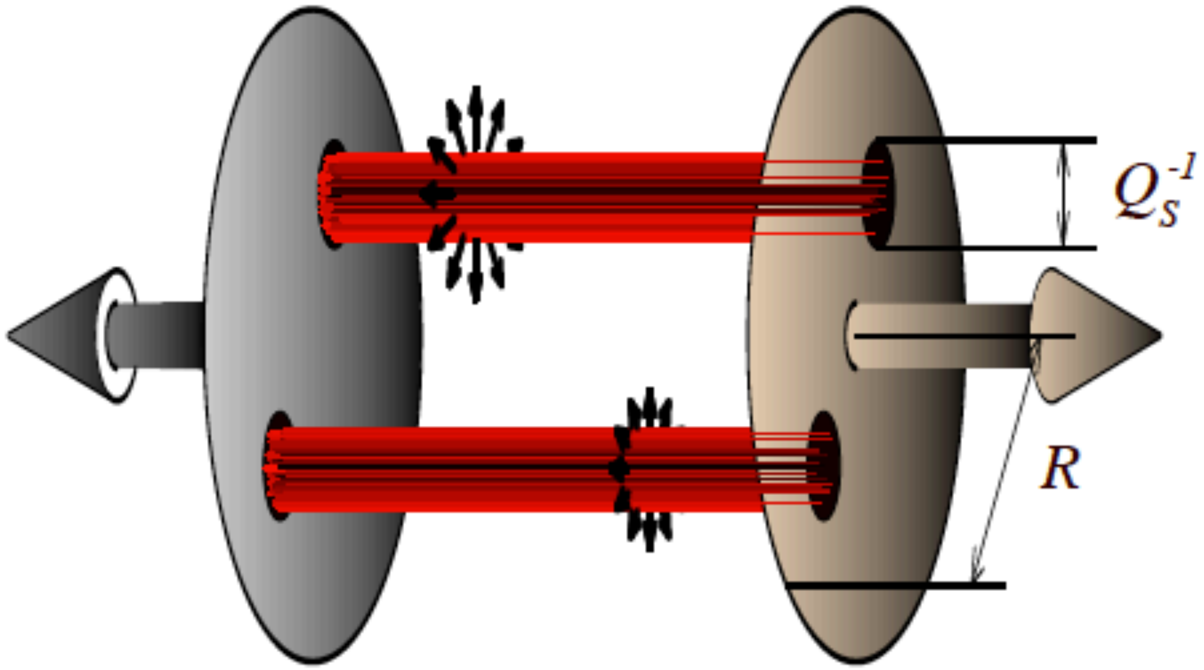
2-hadron correlations from the CGC



- η-independent fields lead to long range correlations in the 2-particle spectrum :

2-hadron correlations from the CGC

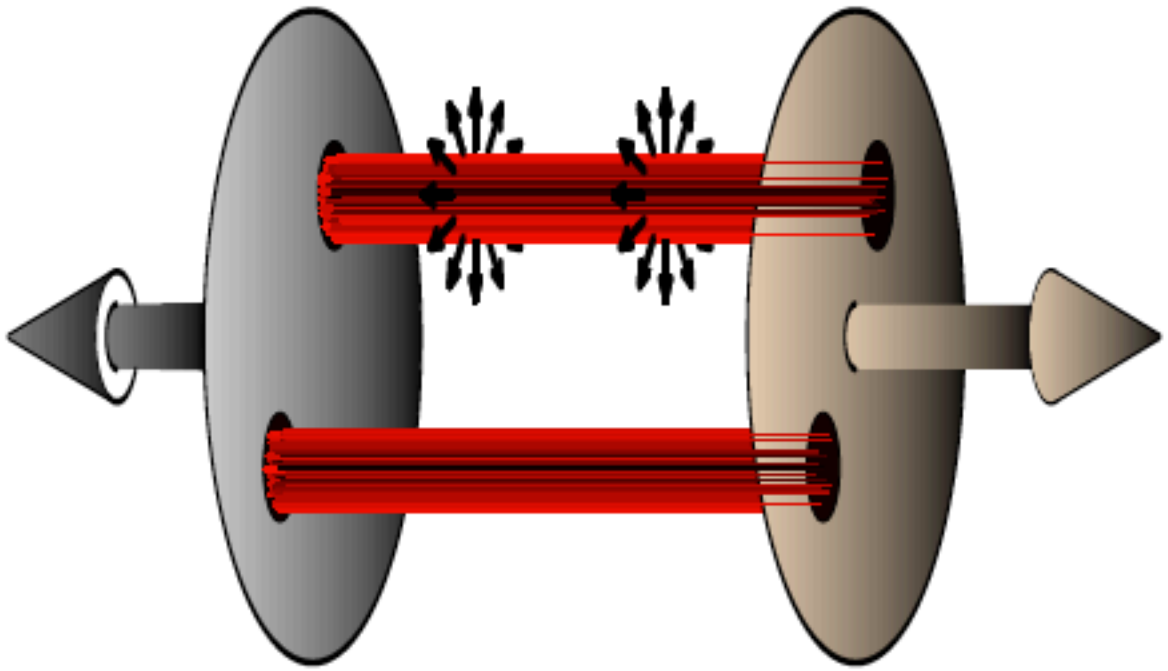
- η-independent fields lead to long range correlations in the 2-particle spectrum :



- Particles emitted by different flux tubes are not correlated
  - ▷ $(RQ_s)^{-2}$ sets the strength of the correlation

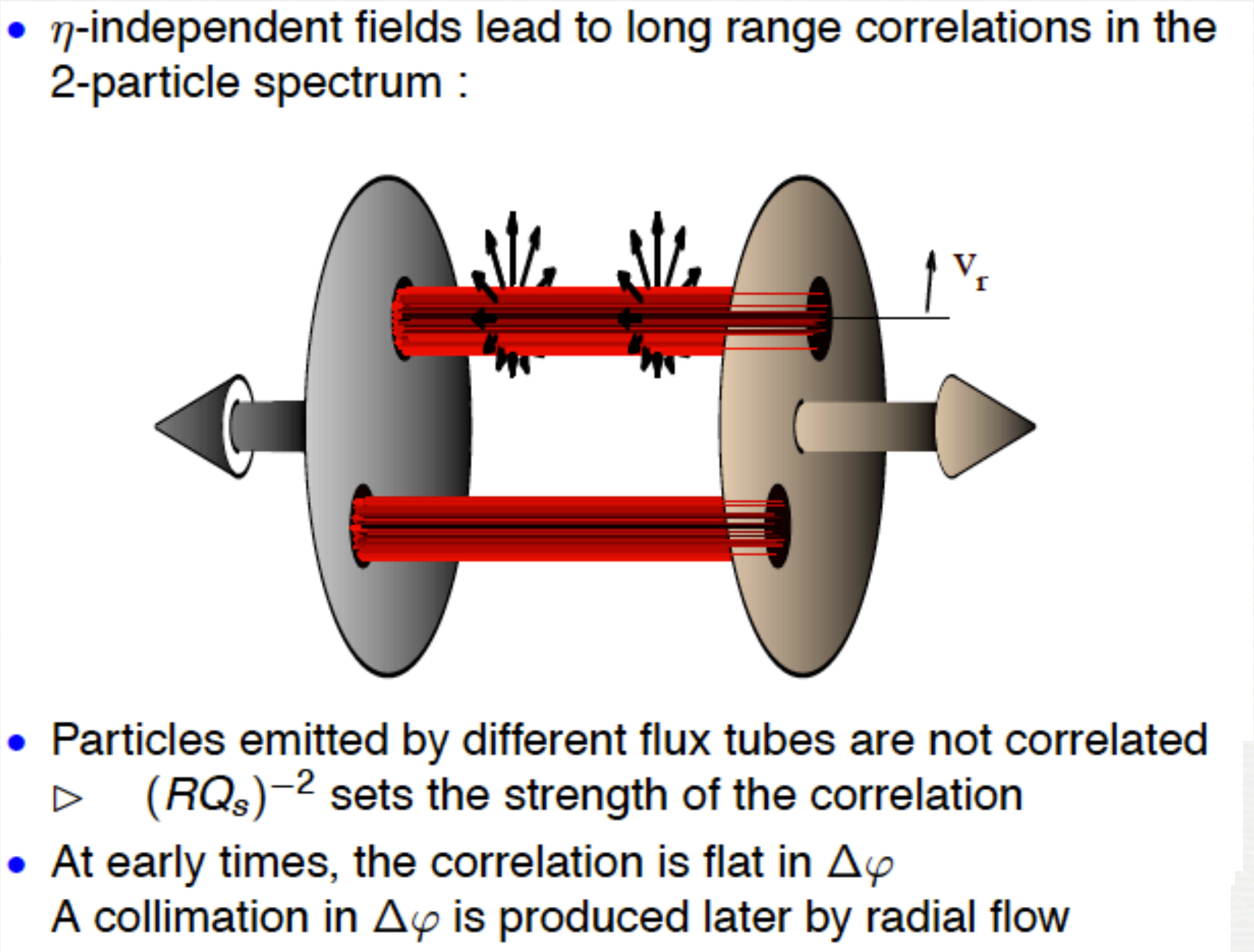
2-hadron correlations from the CGC

- η-independent fields lead to long range correlations in the 2-particle spectrum :



- Particles emitted by different flux tubes are not correlated
  - ▷ $(RQ_s)^{-2}$ sets the strength of the correlation
- At early times, the correlation is flat in $\Delta\varphi$

2-hadron correlations from the CGC



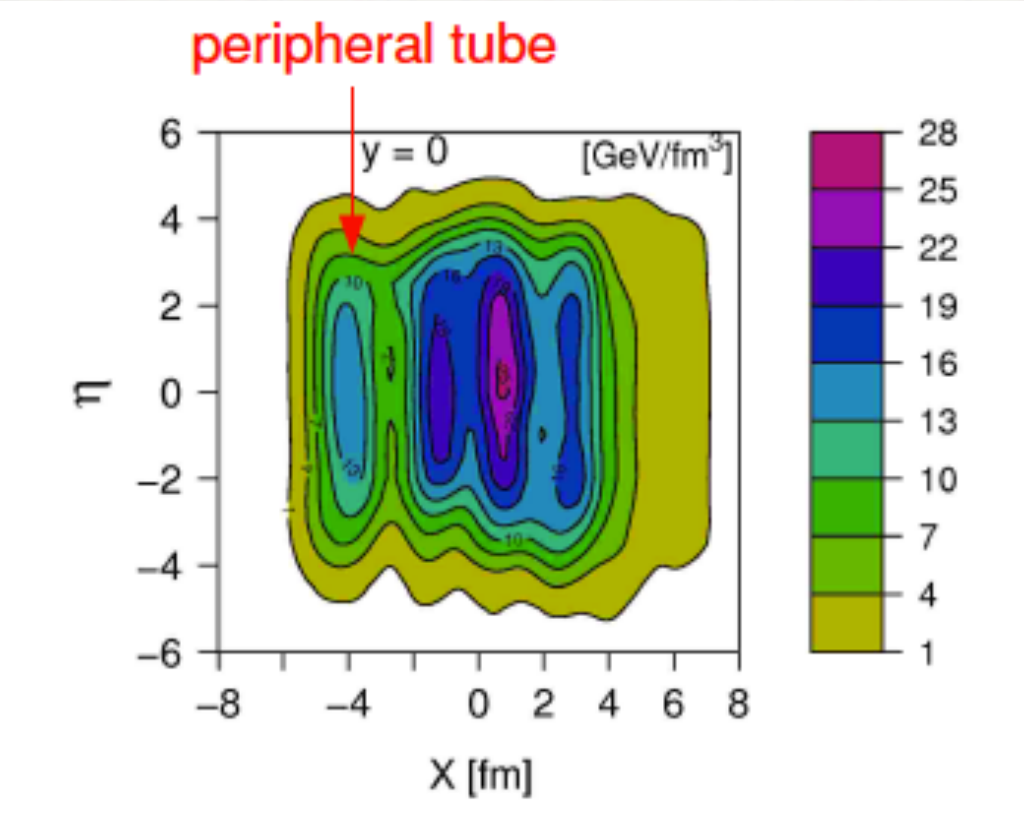
- η-independent fields lead to long range correlations in the 2-particle spectrum :
- Particles emitted by different flux tubes are not correlated
  - ▷ $(RQ_s)^{-2}$ sets the strength of the correlation
- At early times, the correlation is flat in $\Delta\varphi$
  A collimation in $\Delta\varphi$ is produced later by radial flow

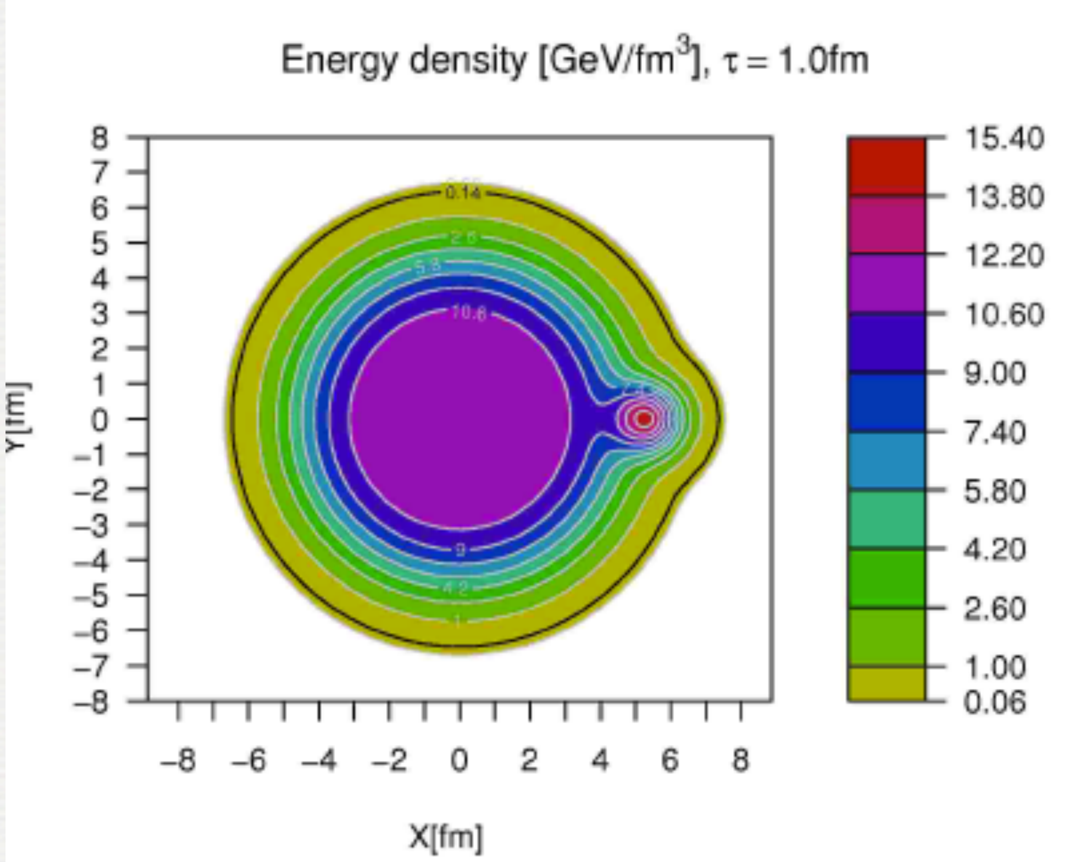
Rone Andrade & Yogiro Hama

(Universidade de São Paulo)

Two-particle correlations from fluctuations via HYDRO

How do the correlations propagate from the initial conditions to the final hadrons ? One or more ridges ?




Energy density [GeV/fm³], τ = 1.0fm

Use hydro to evolve initial conds with the appropriate flucts

Rone Andrade & Yogiro Hama

(Universidade de São Paulo)

Two-particle correlations from fluctuations via HYDRO

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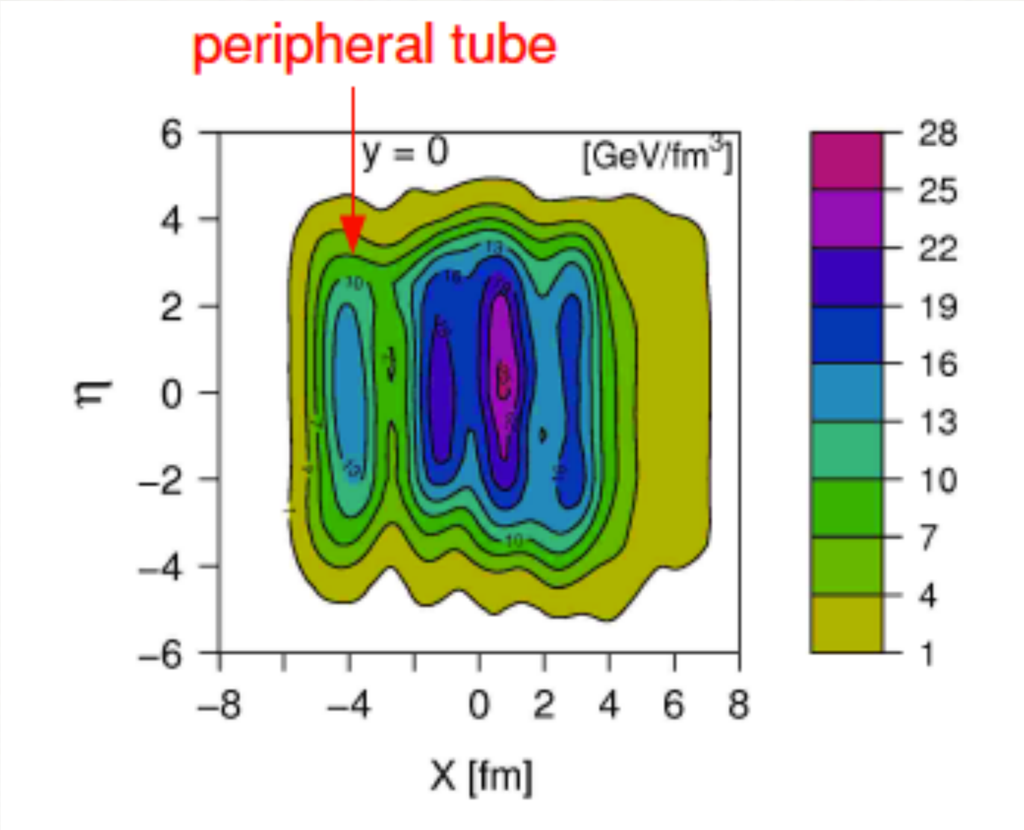

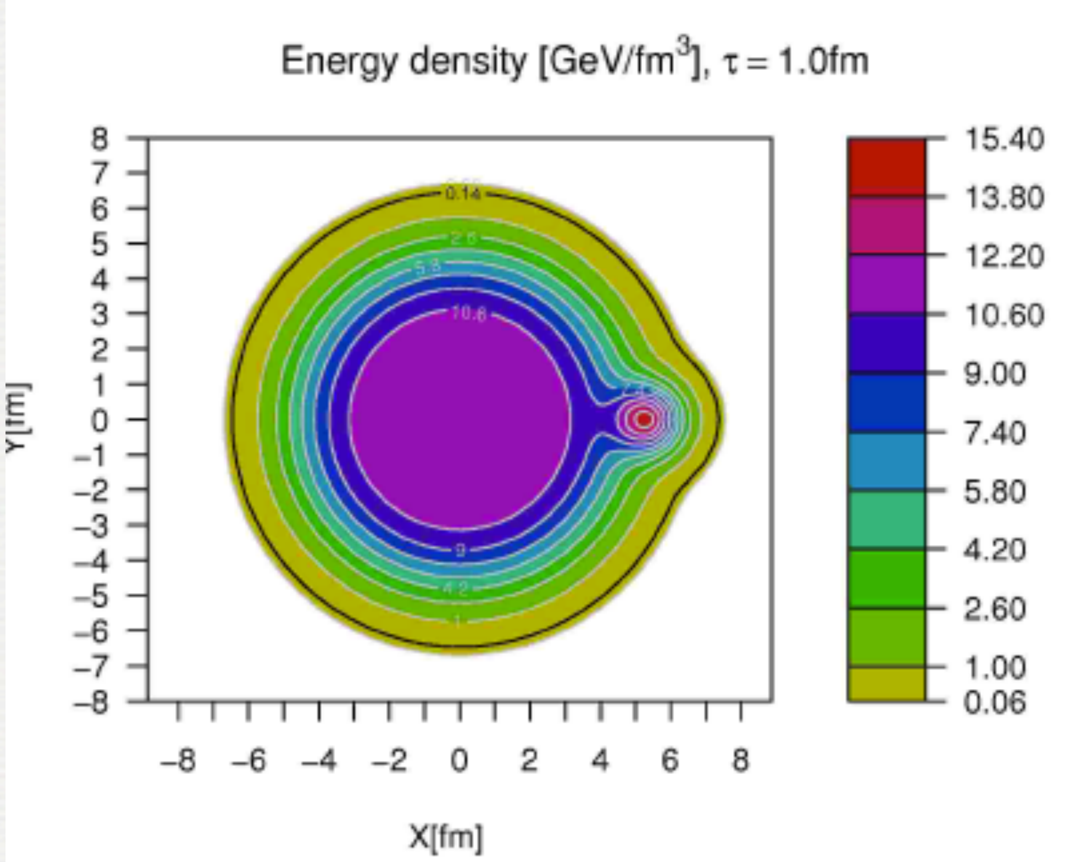

Rone Andrade & Yogiro Hama

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Two-particle correlations from fluctuations via HYDRO

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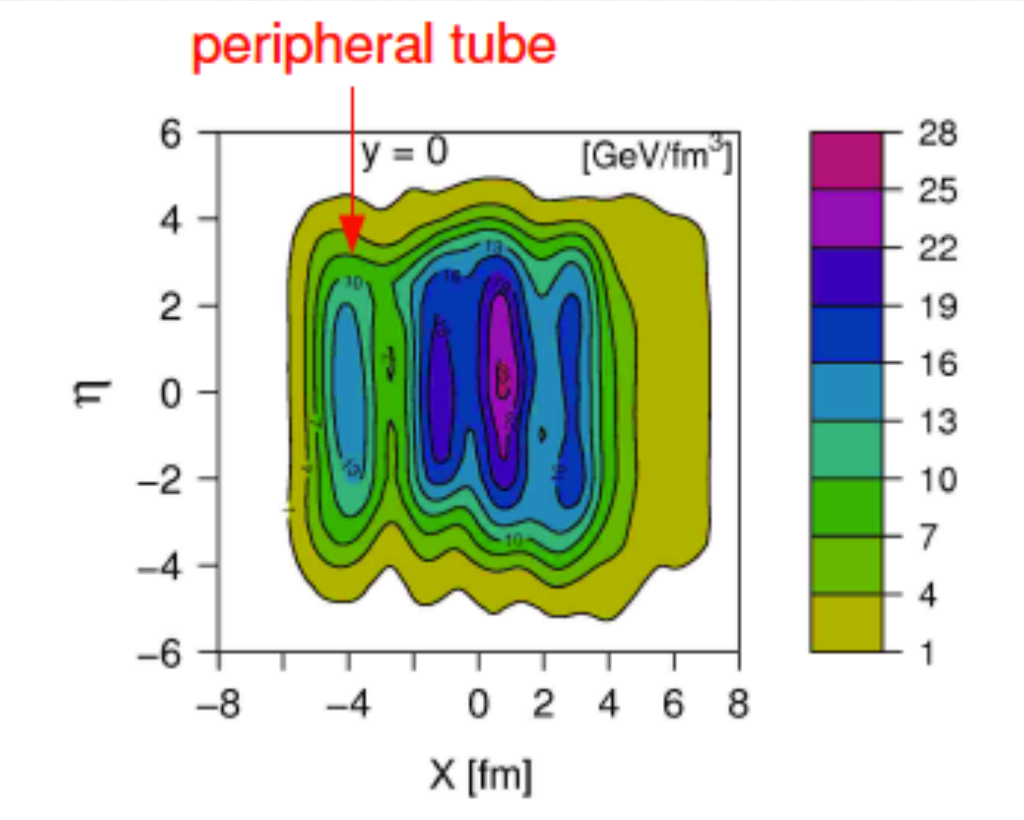
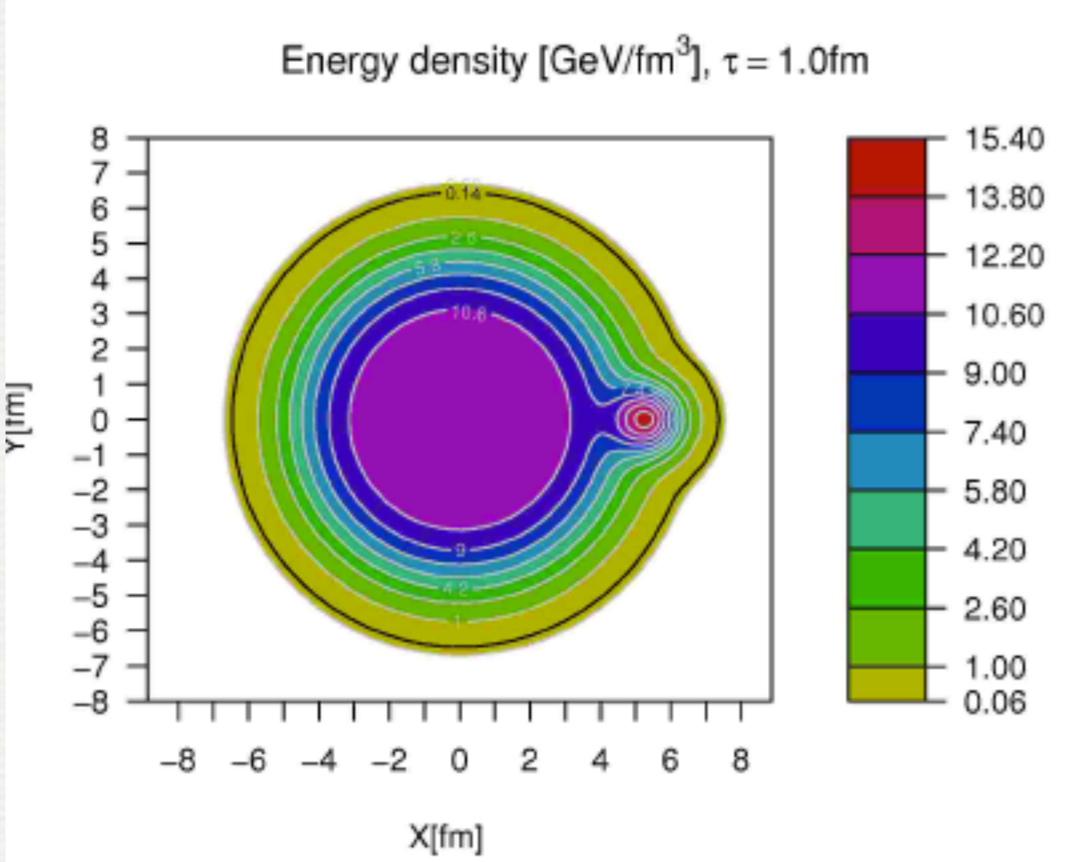
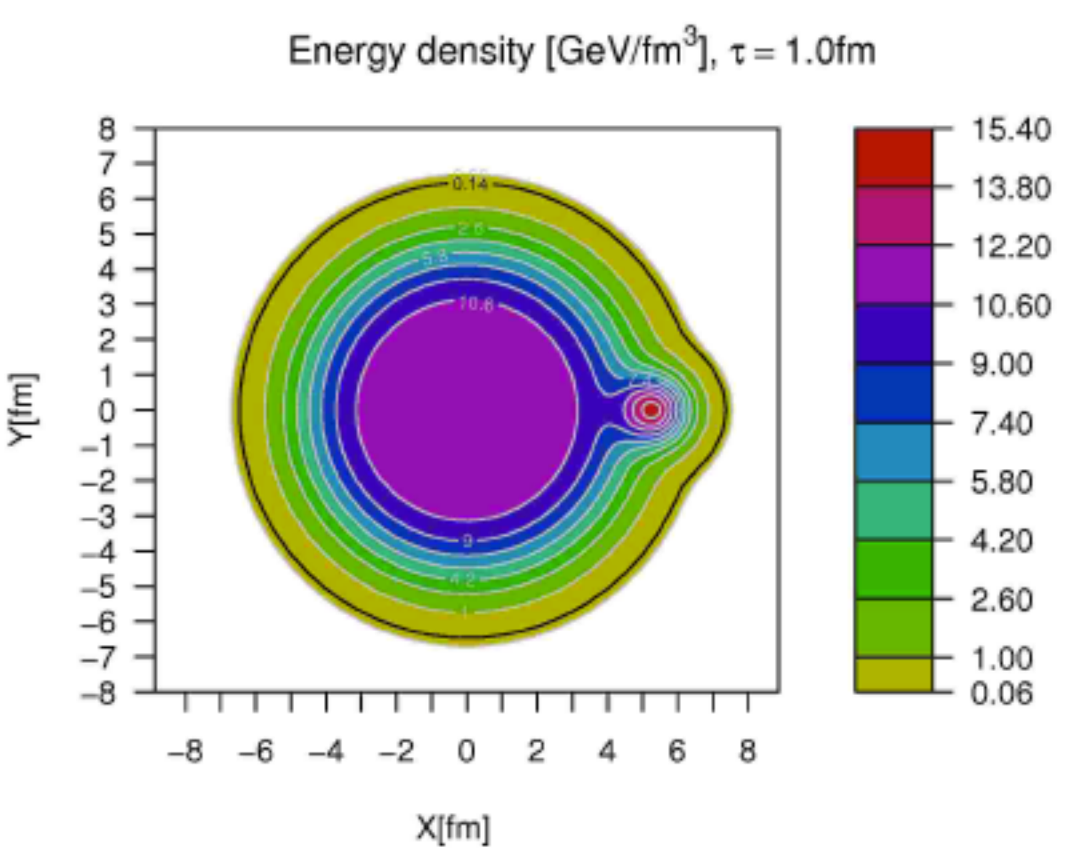




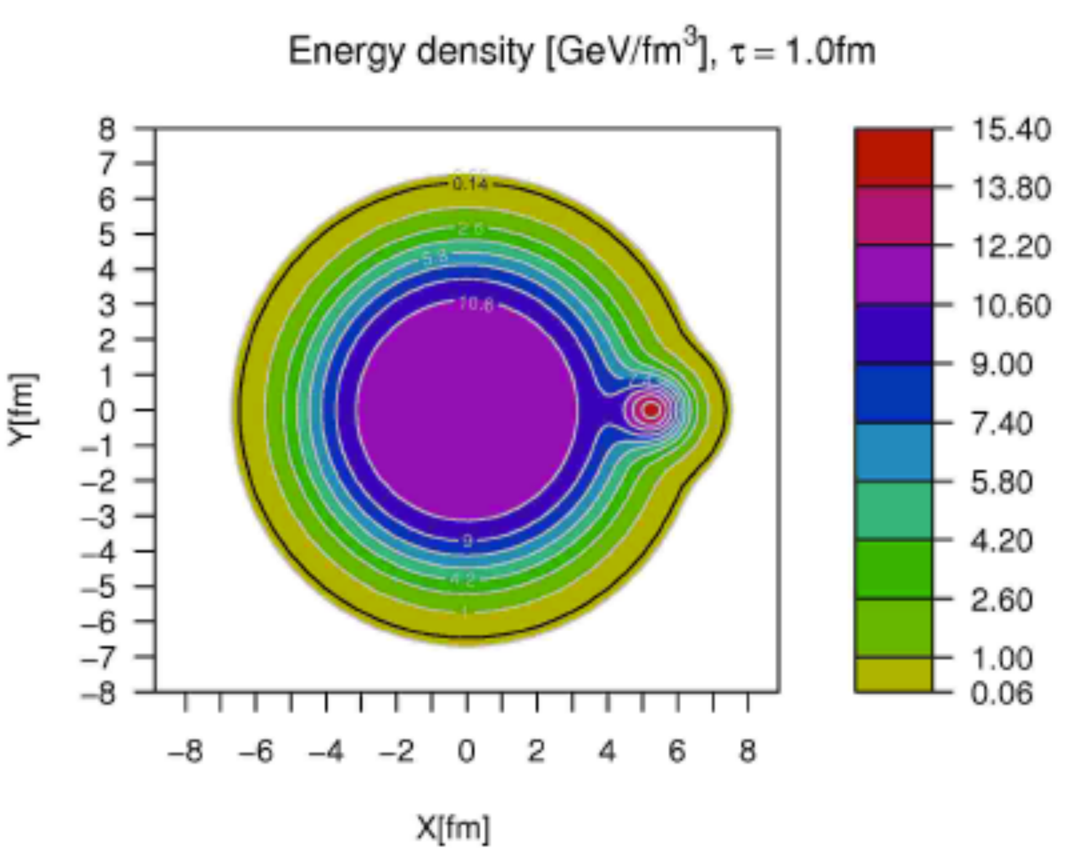
Simplify the problem, to better understand the mechanism at work:

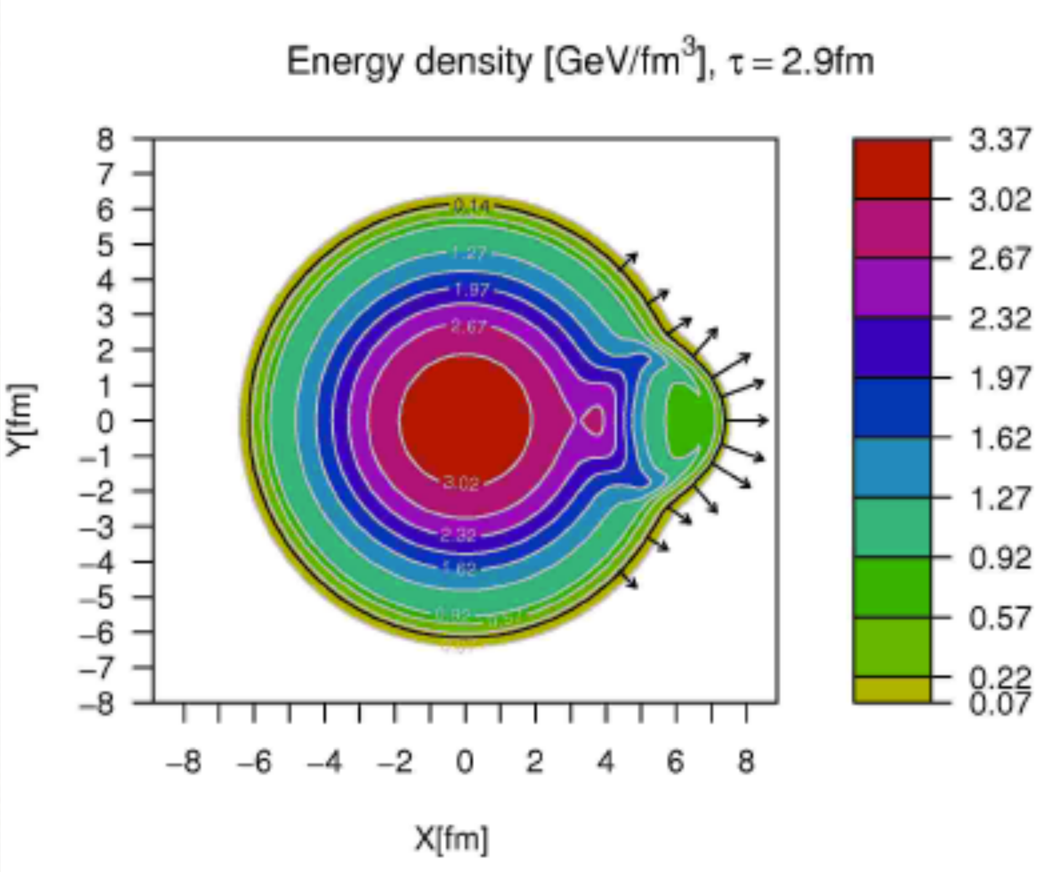
take a single flux tube in a uniform background !

Rone Andrade & Yogiro Hama

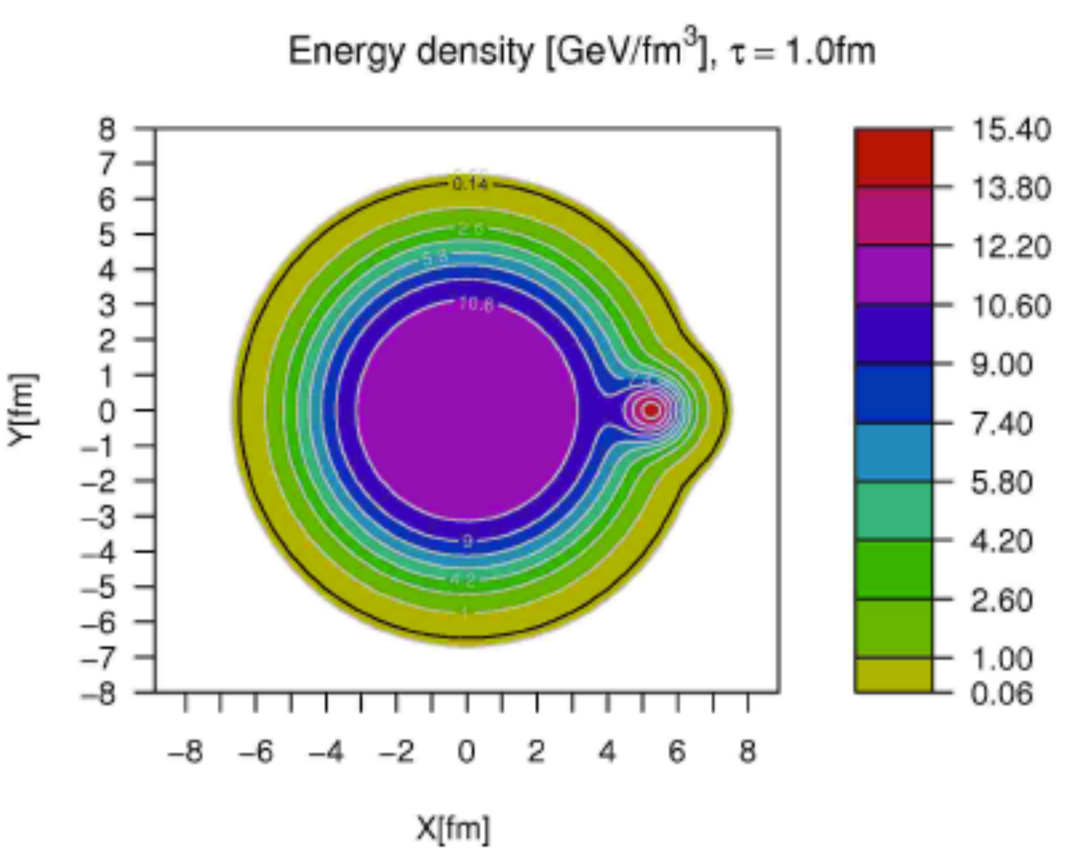


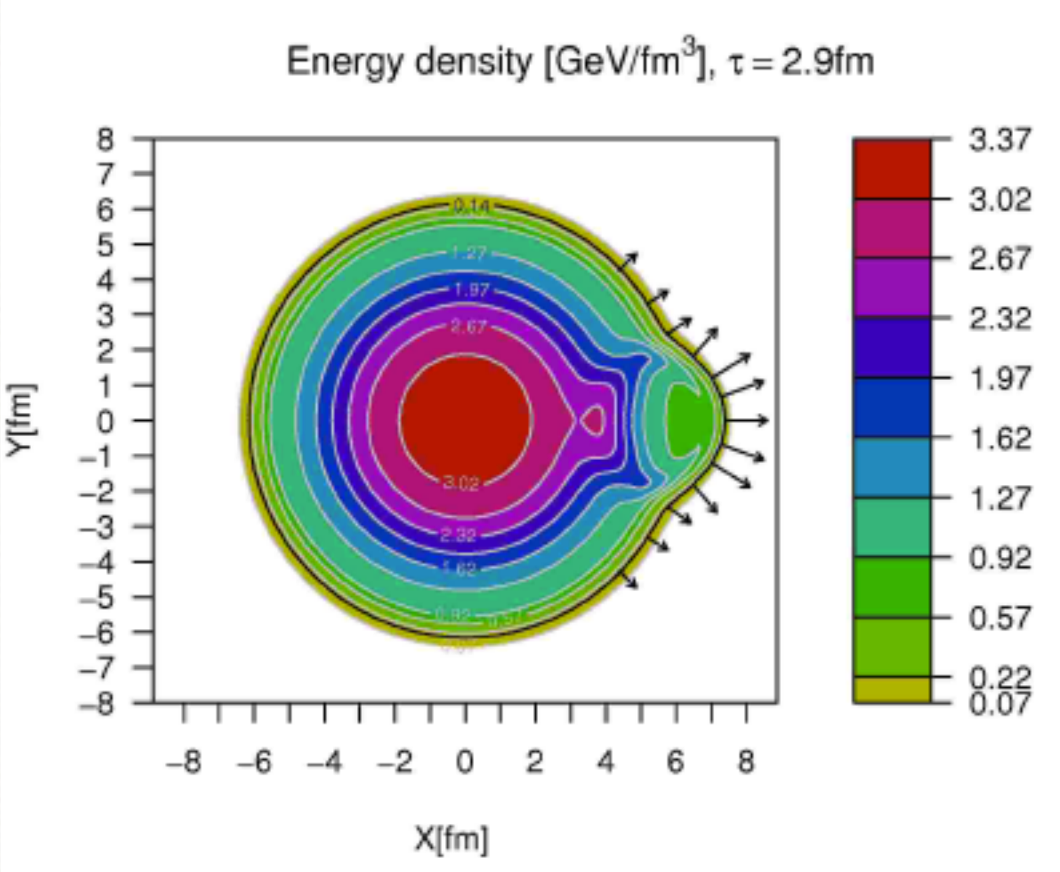
Rone Andrade & Yogiro Hama

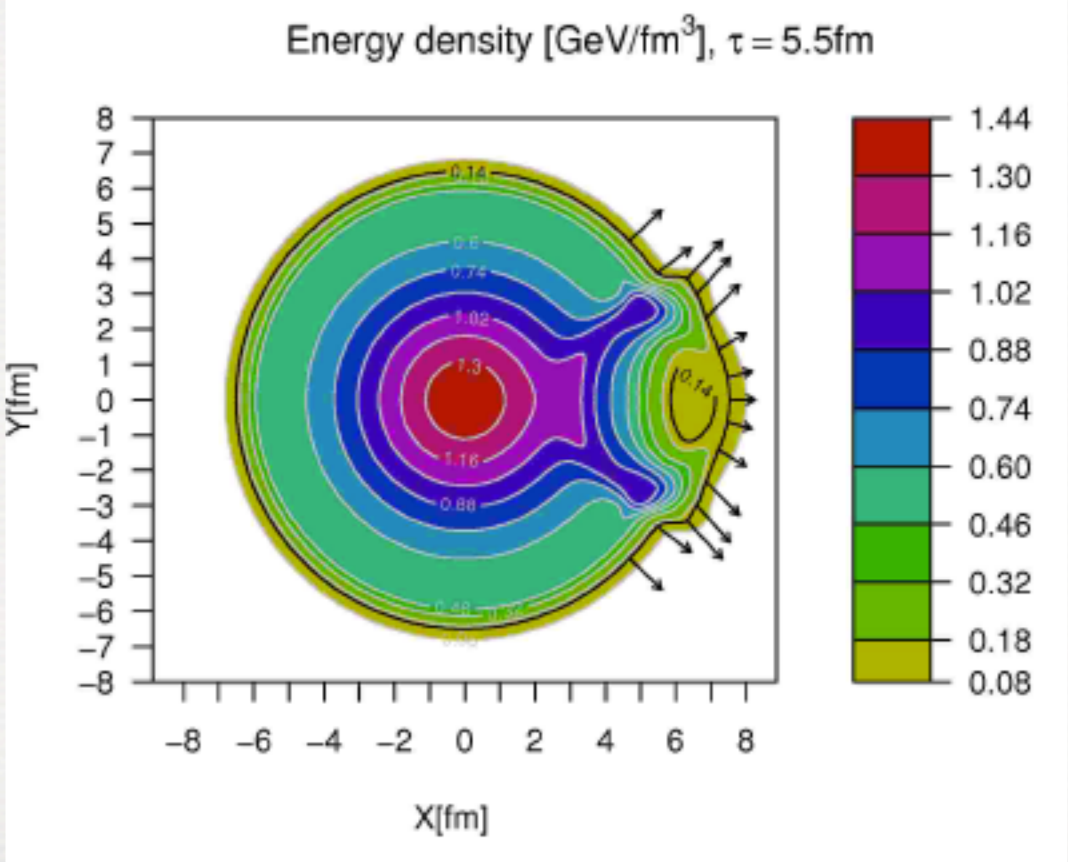




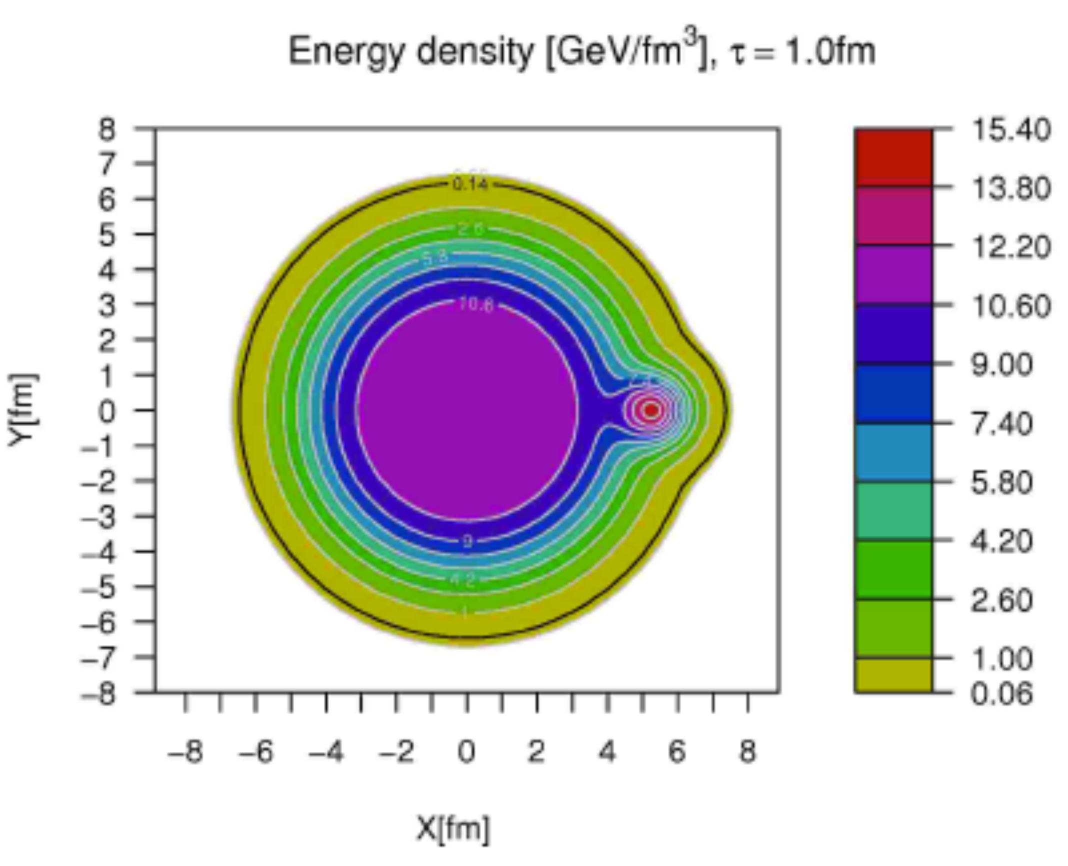
Rone Andrade & Yogiro Hama

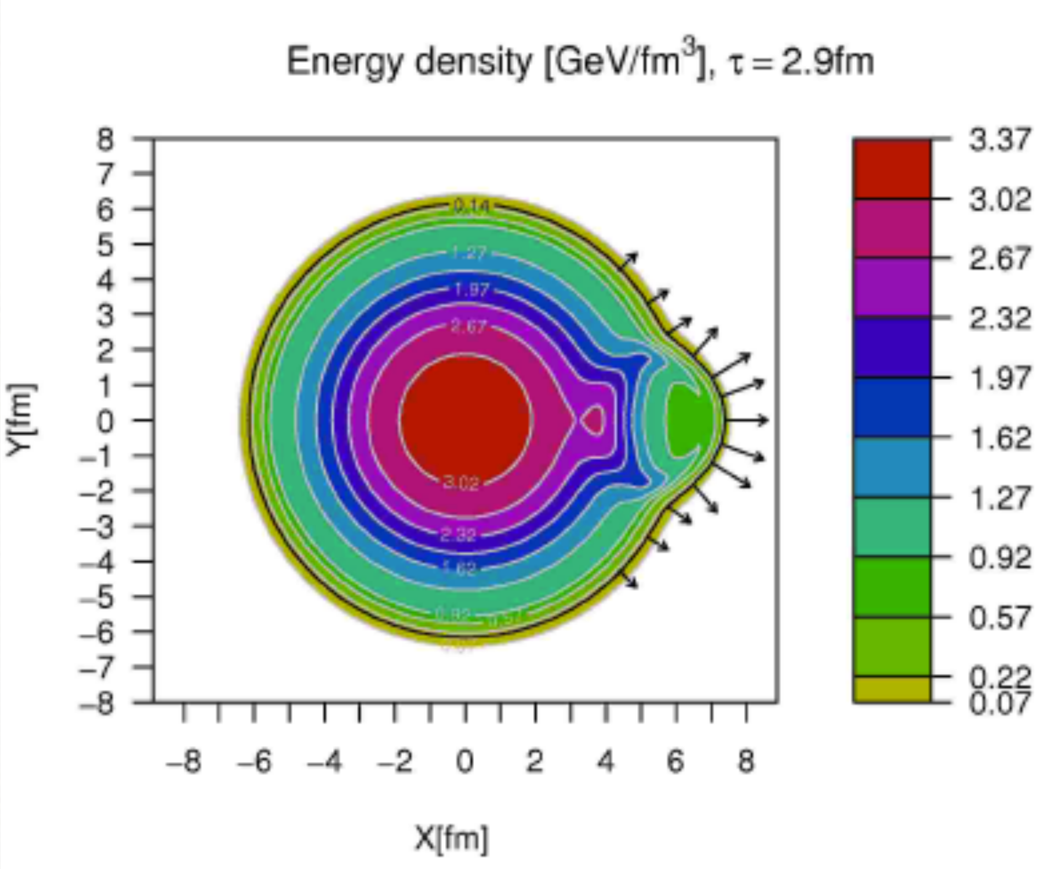


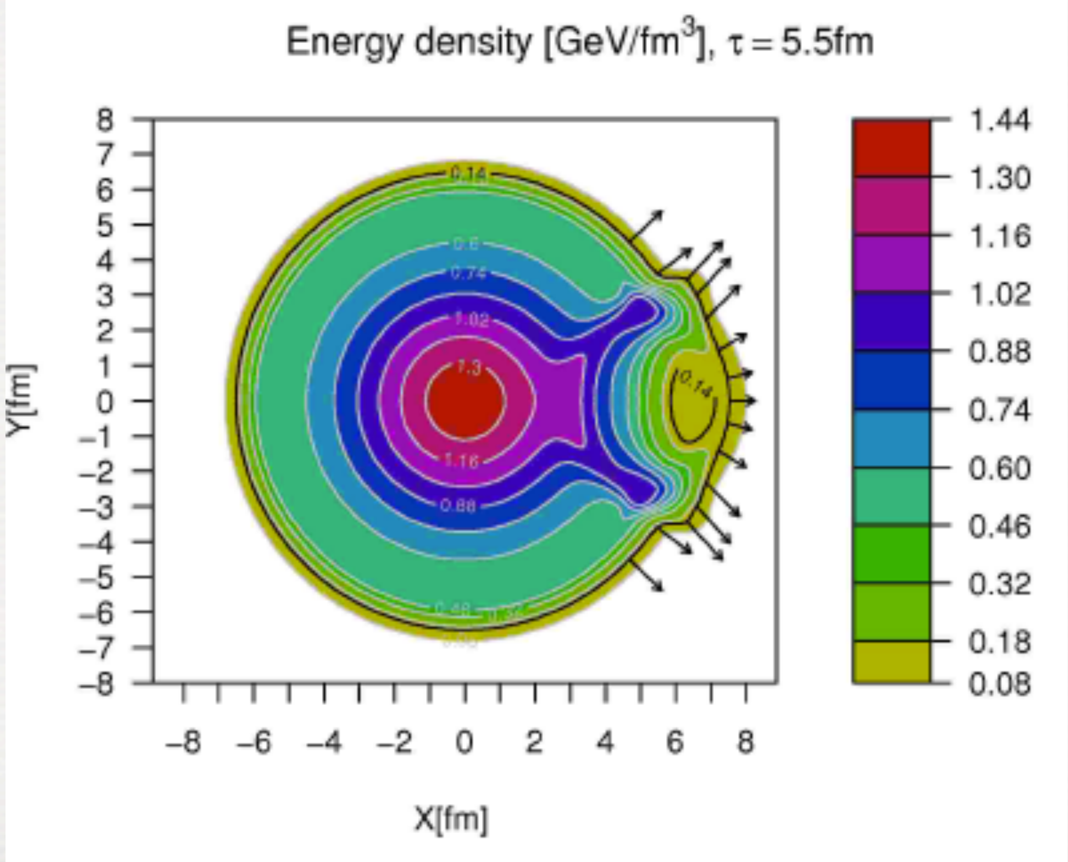


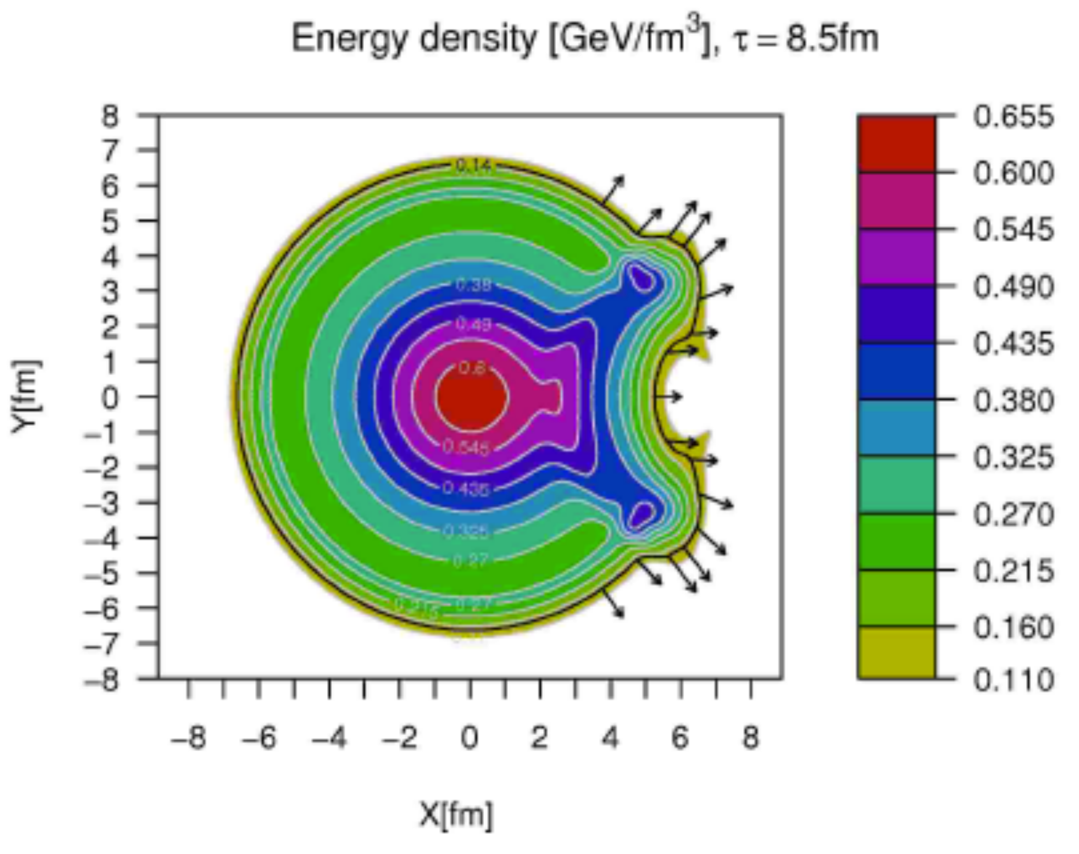


Rone Andrade & Yogiro Hama

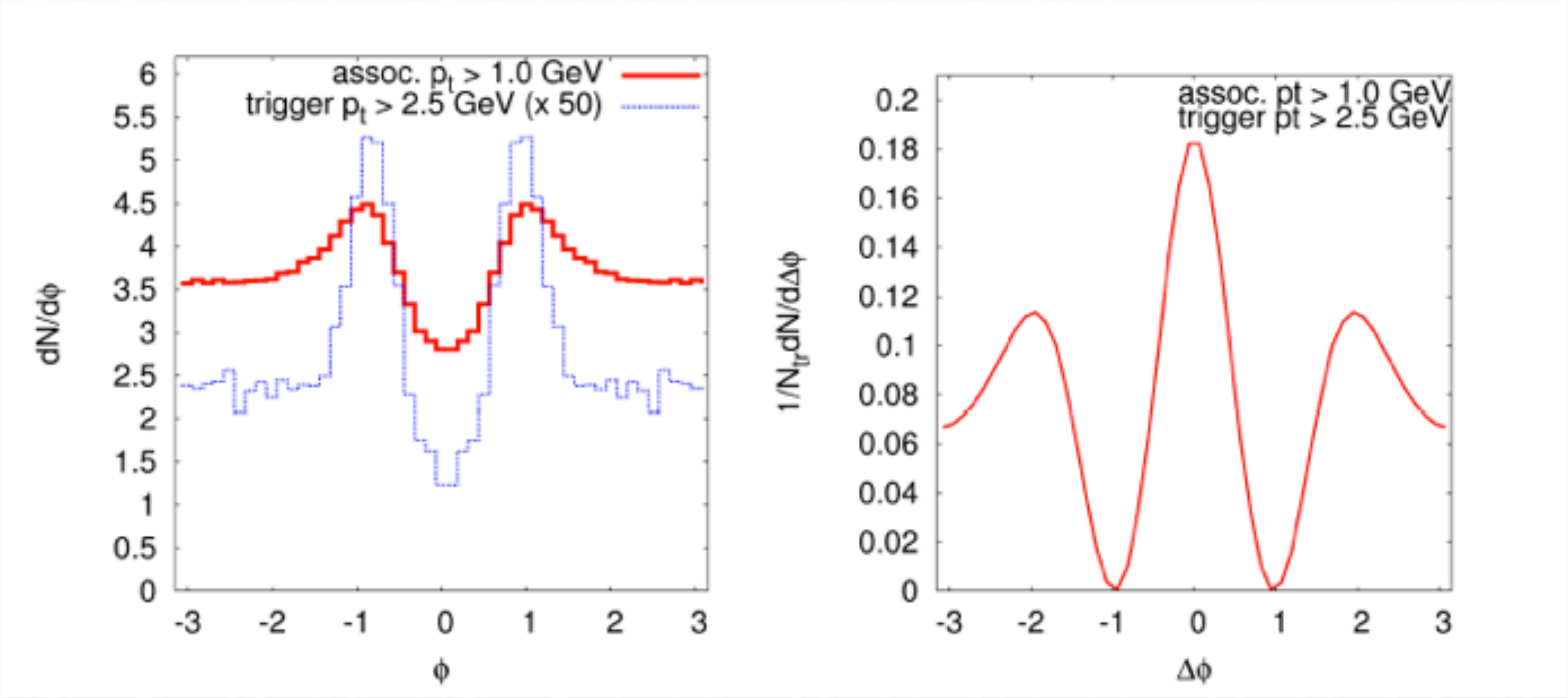

Energy density [GeV/fm^3], $\tau = 1.0$fm


Energy density [GeV/fm^3], $\tau = 2.9$fm

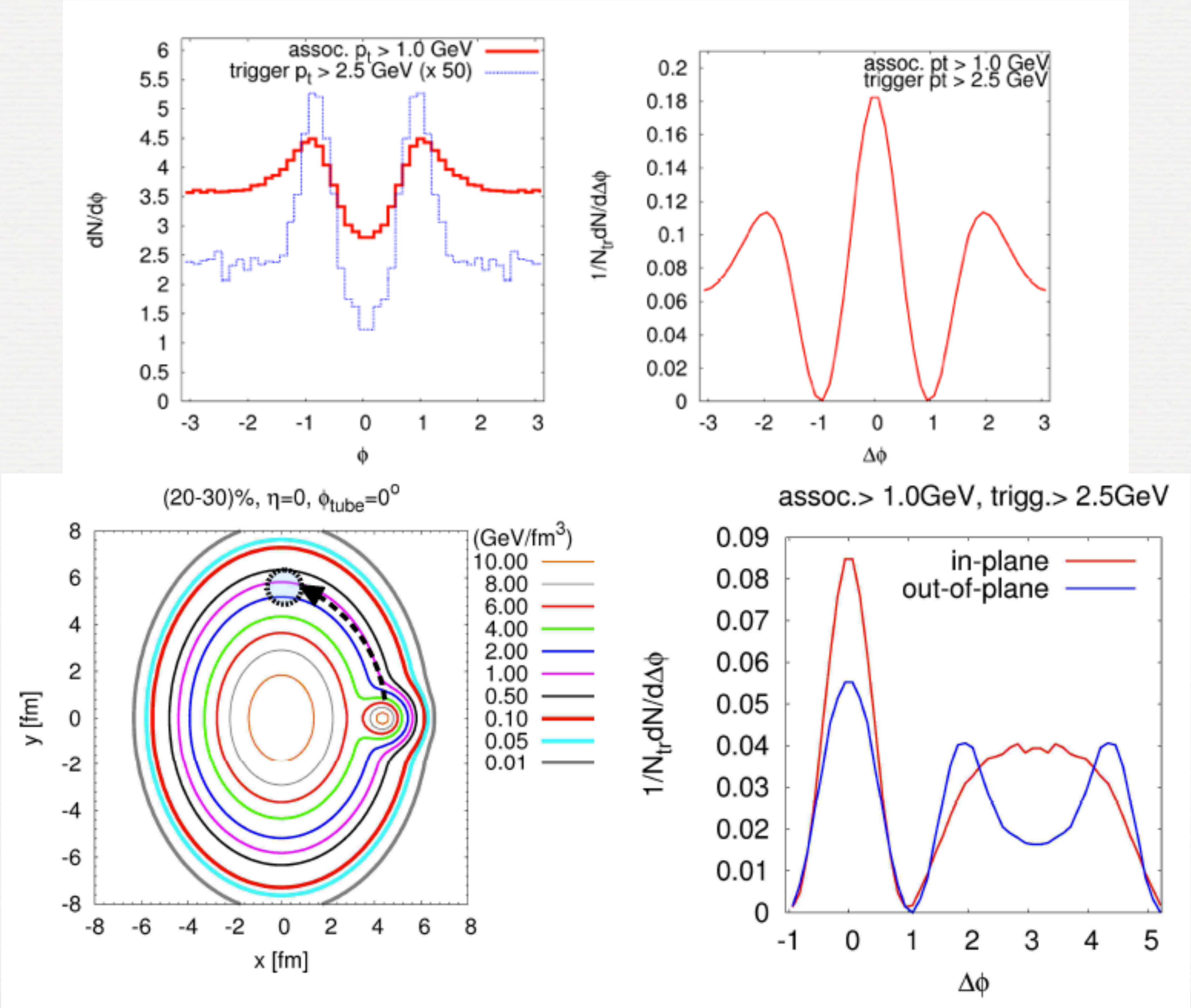

Energy density [GeV/fm^3], $\tau = 5.5$fm


Energy density [GeV/fm^3], $\tau = 8.5$fm

Rone Andrade & Yogiro Hama



Rone Andrade & Yogiro Hama



Wojciech Florkowski & Piotr Bozek

(Institute Of Nuclear Physics, Krakow)

Thermalization from highly anisotropic Hydrodynamics

✦ Why does the QGP matter produced at RHIC thermalize that fast ?

✦What are the best observables to probe the approach towards equil. ?

ADHYDRO: highly-anisotropic and strongly dissipative hydrodynamics:

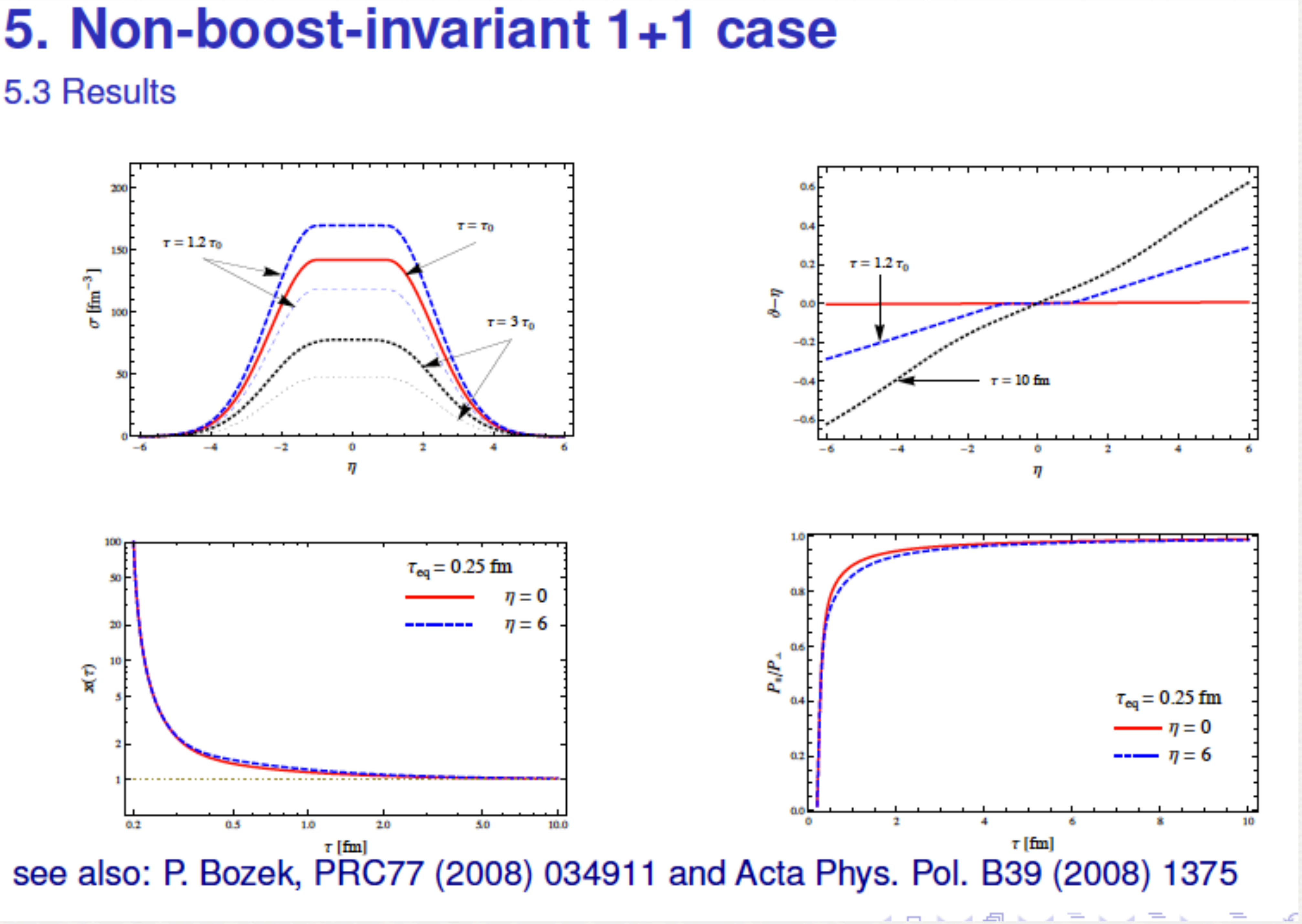
- hydrodynamics-like model for early stages of heavy-ion collisions
- dissipation is introduced via an entropy source which vanishes for the isotropic fluid
- the energy-momentum tensor has a diagonal form but the longitudinal and transverse pressures are different

$$T^{\mu\nu}\Big|_{\tau\ll 1/Q_s} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & \varepsilon & 0 & 0 \\ 0 & 0 & \varepsilon & 0 \\ 0 & 0 & 0 & -\varepsilon \end{pmatrix}$$

$$T^{\mu\nu}_{\text{perfect hydro}} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

$$T^{\mu\nu} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P_\perp & 0 & 0 \\ 0 & 0 & P_\perp & 0 \\ 0 & 0 & 0 & P_\parallel \end{pmatrix}$$

Wojciech Florkowski (cont)



5. Non-boost-invariant 1+1 case

5.3 Results

see also: P. Bozek, PRC77 (2008) 034911 and Acta Phys. Pol. B39 (2008) 1375

$x(\tau)$ = ratio of transverse and longitudinal temperatures

Piotr Bozek (cont)

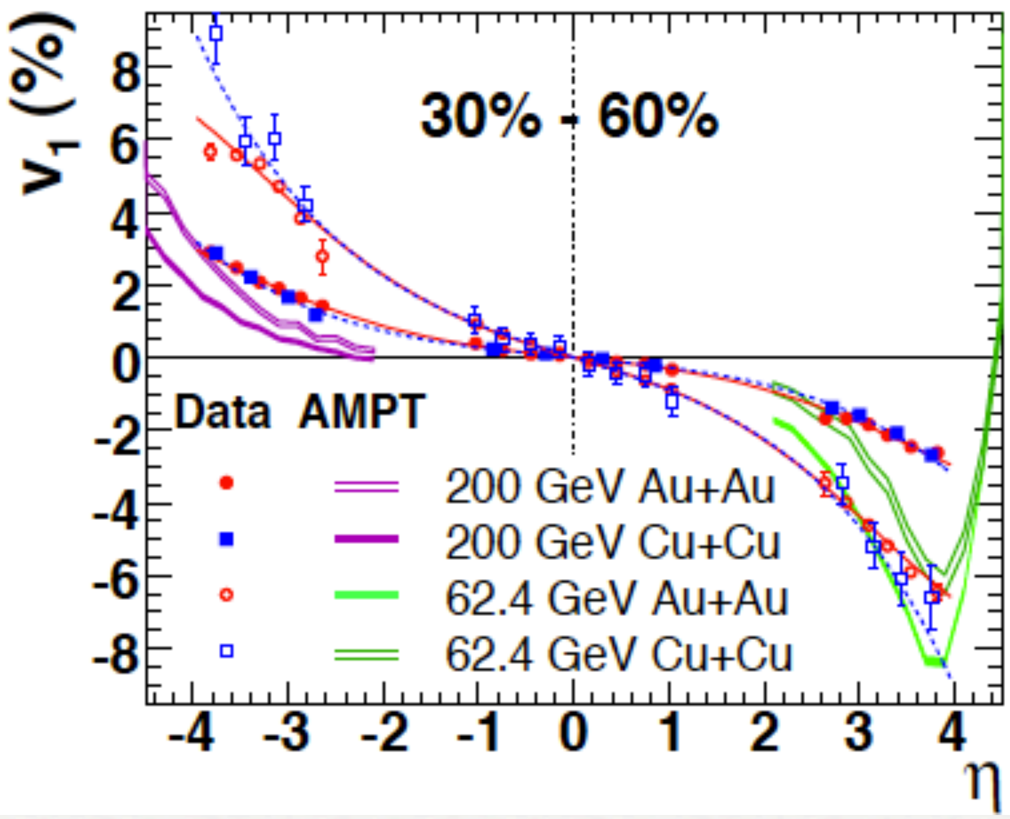
Standard observables are not sensitive to early dissipation

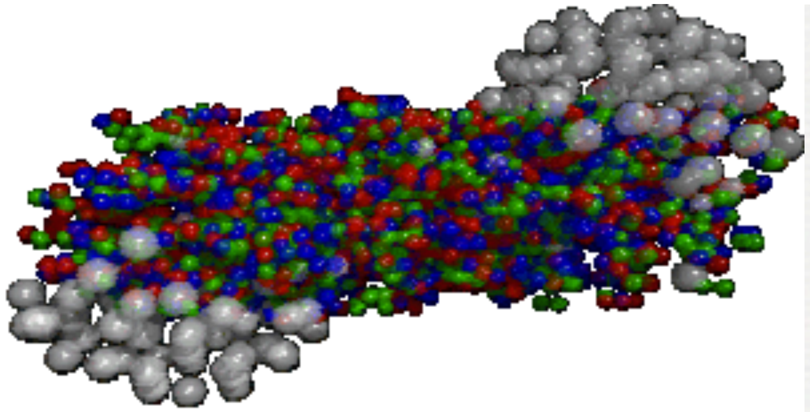
transverse or longitudinal expansion alone is insufficient

transverse + longitudinal expansion = directed flow

and

it happens very early

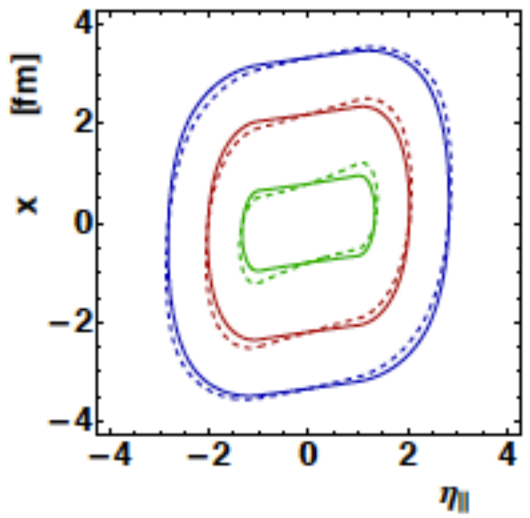




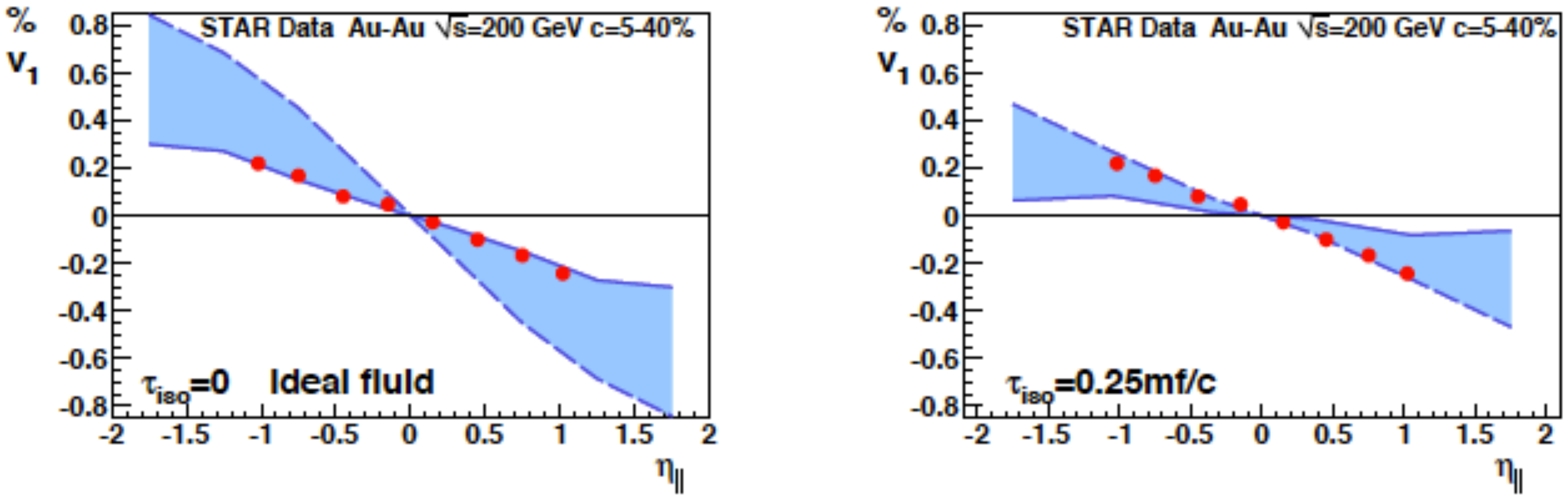
- large flow at 200GeV
- anti-flow

$$\frac{dN}{d^2p\,dy} = \frac{dN}{2\pi p\,dp}dy\,(1+2v_1\cos\phi+2v_2\cos 2\phi+\dots)$$

Piotr Bozek (cont)



tilt →**HYDRO**→ v_1

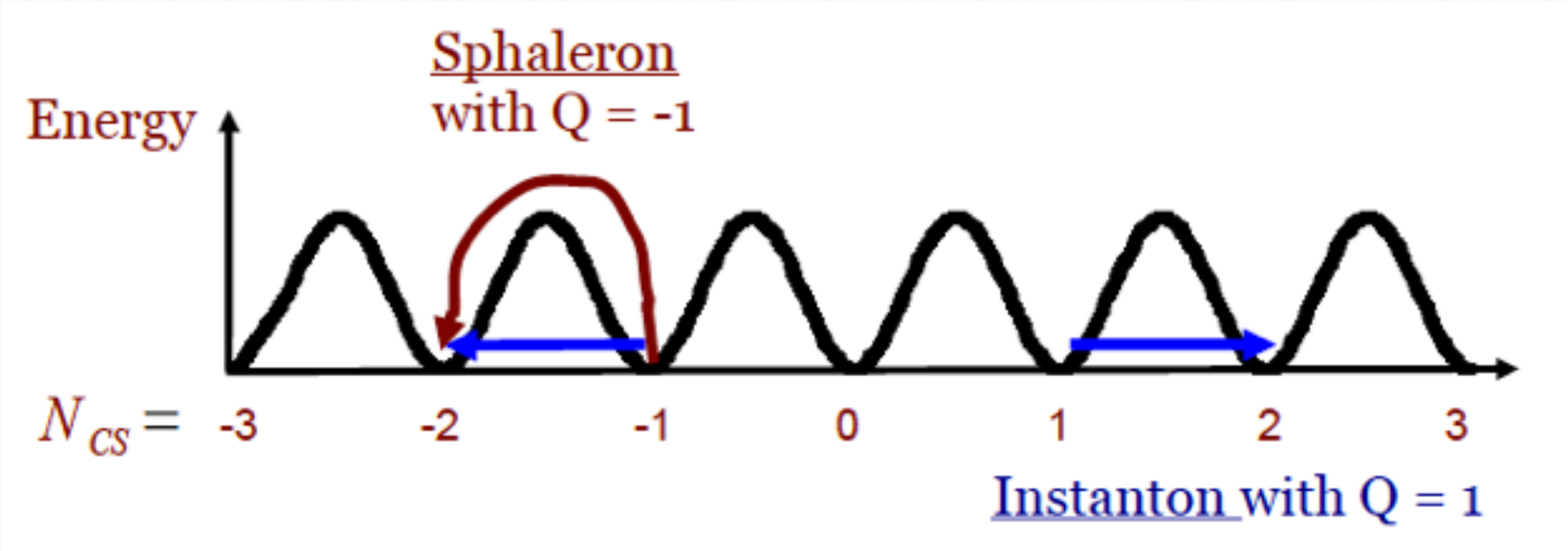


$$\boxed{0 \leq \tau_{iso} \leq 0.25\mathrm{fm/c}}$$

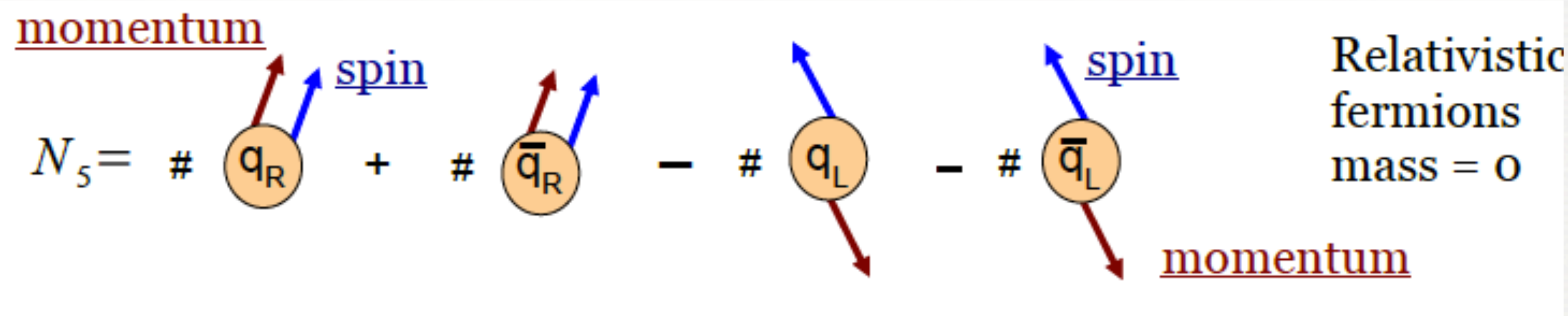
Harmen Warringa (J. W. Goethe University)

P- and CP-odd effects in hot and dense matter

Topological charge fluctuations in a medium: $< Q >= 0\,, \quad < Q^2 > \neq 0$

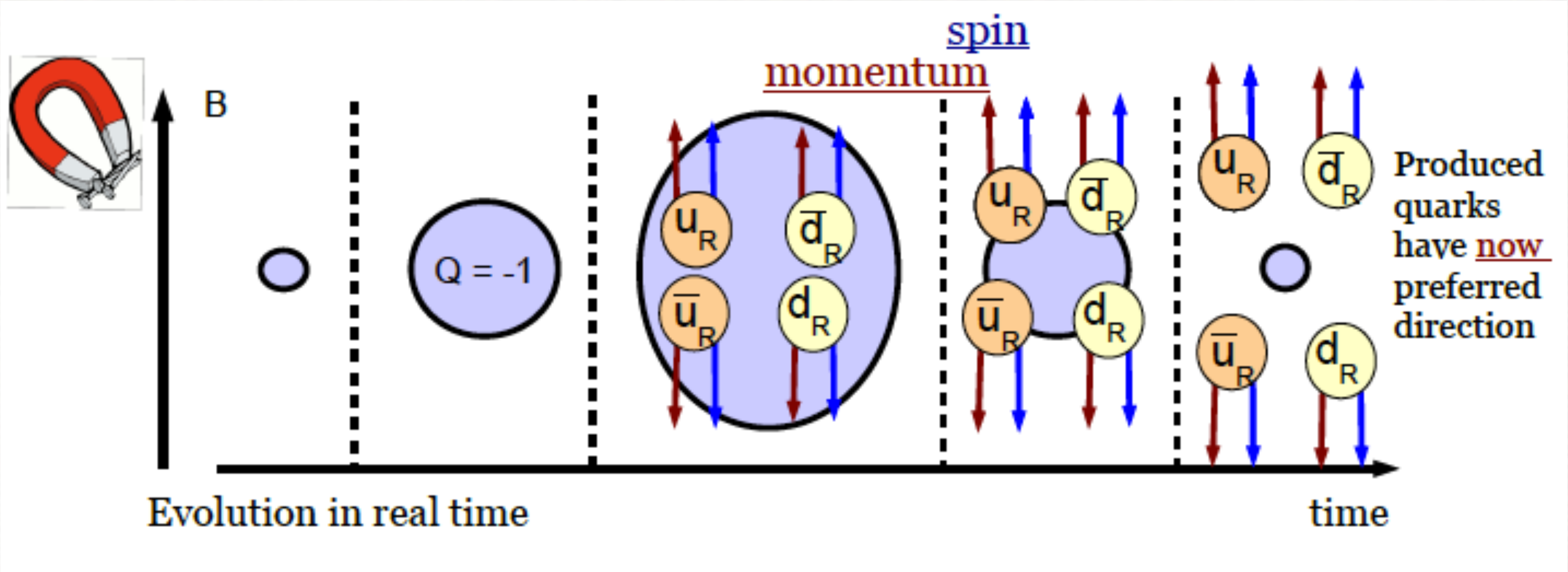


... induce (via the axial anomaly) flucts. in the quark chirality: $< N_5^2 > \neq 0$



Harmen Warringa (cont.)

... which lead to charge separation in the presence of a magnetic field :



All these conditions are satisfied in peripheral heavy ion collisions ...

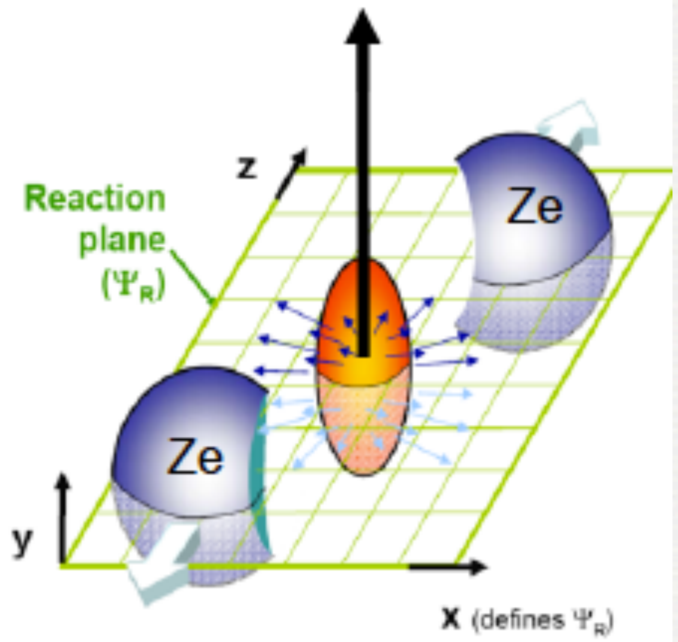
... and could lead to event-by-event flucts in the electric charge density !

``Chiral Magnetic Effect”

Harmen Warringa (cont.)

Charge correlations at RHIC

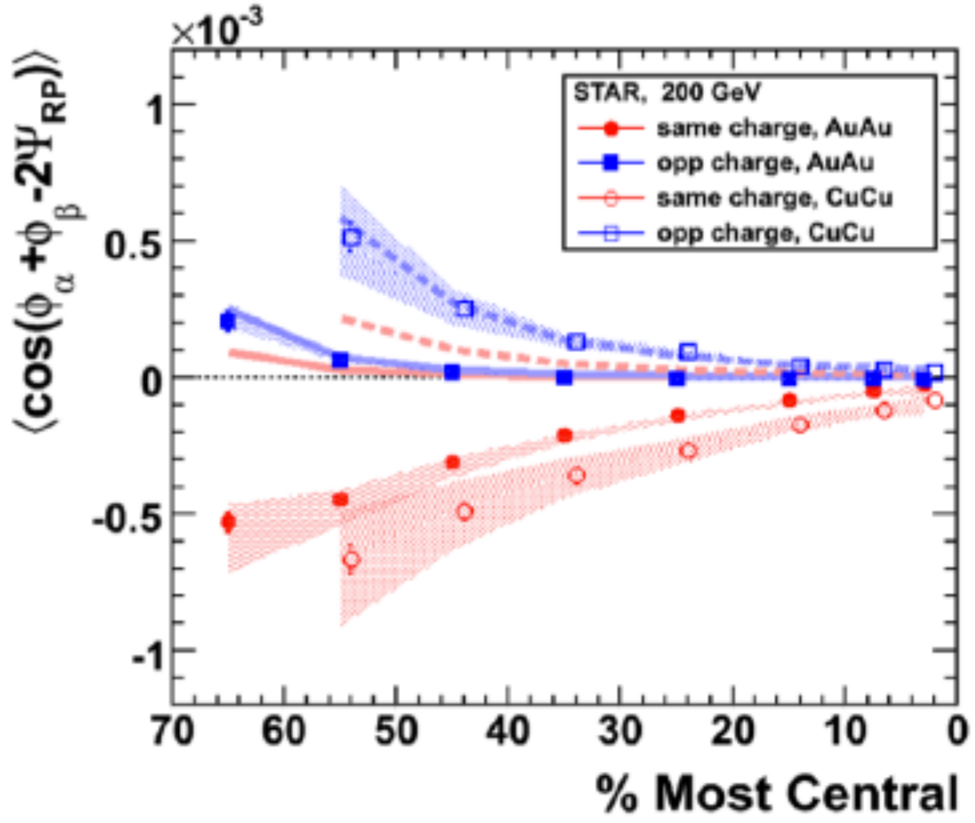
Magnetic field B



$$eB(\tau = 0.2\ \mathrm{fm/c}) \approx$$
$$10^3 \sim 10^4\,\mathrm{MeV}^2 \approx 10^{18}\,\mathrm{G}$$

Au-Au and Cu-Cu @ 200 GeV

min. bias, $|\eta| < 1.0$, $0.15 < p_t < 2\,\mathrm{GeV/c}$



Data cannot be explained by

HIJING
HIJING+v2,
MeVSIM,
UrQMD

STAR, Phys.Rev.Lett. **103**, 251601 (2009) and arXiv:0909.1717

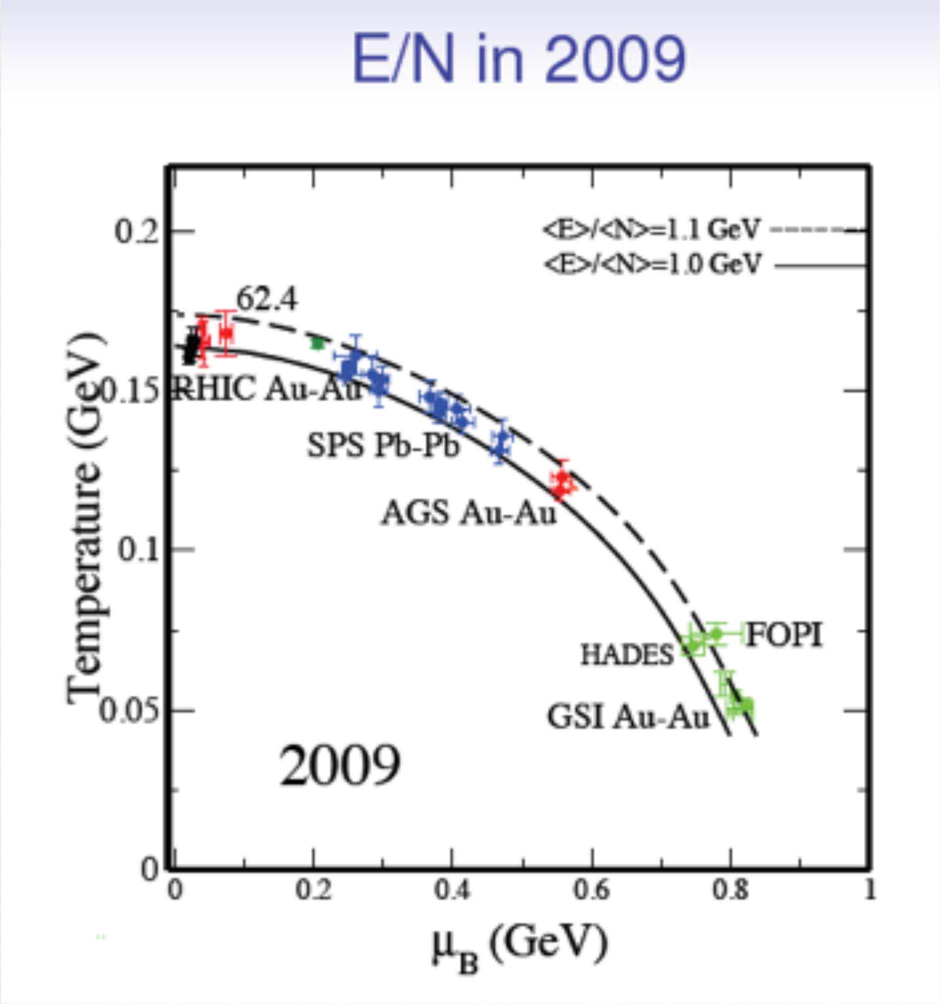
Puzzles:

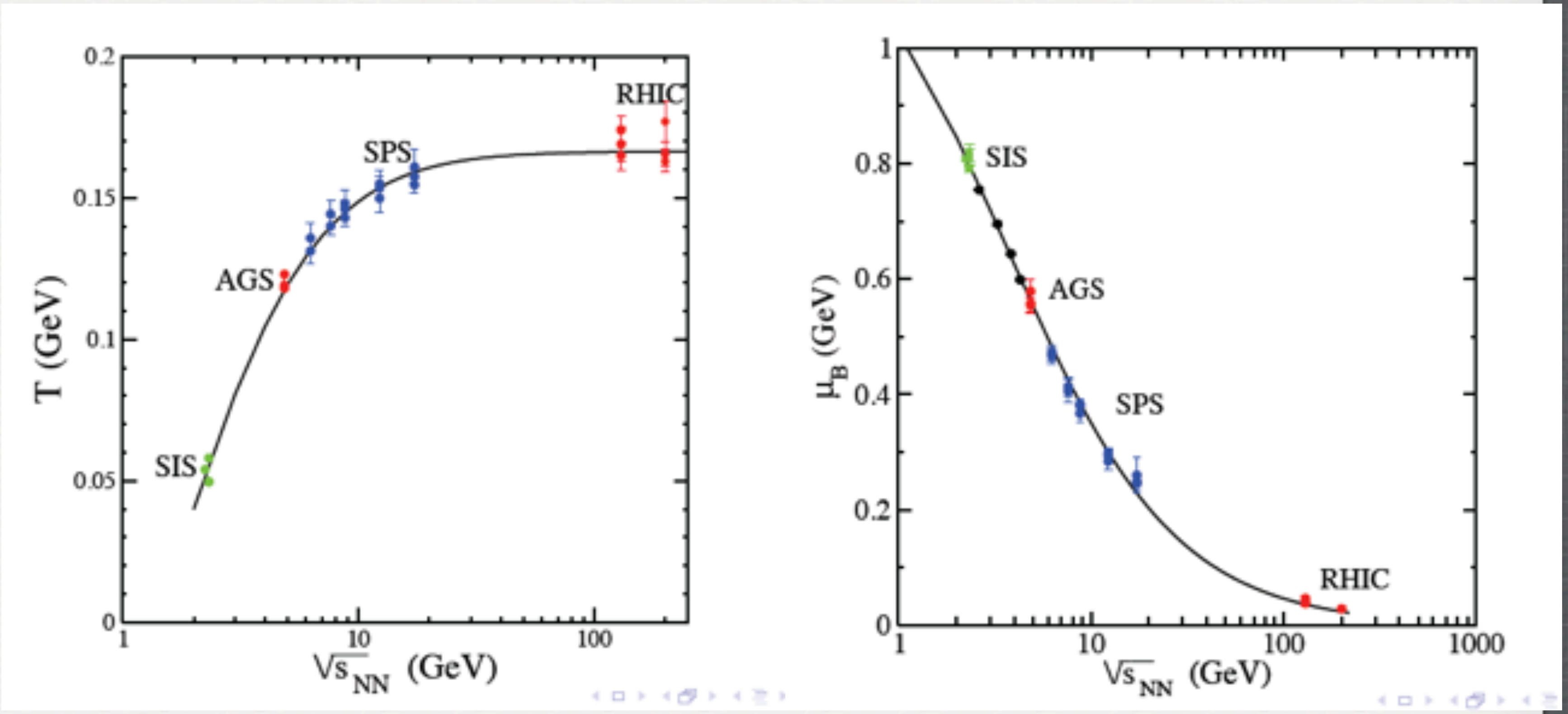
- Backgrounds, Voloshin ('04), Asakawa, Majumdar & Mueller ('10)
- Interpretation of data, F. Wang ('09), Bzdak, Koch & Liao ('10)

Jean Cleymans *(Univ. Of Cape Town)*

Status of chemical equilibrium in HIC

The evidence for chemical equilibrium is very strong.


E/N in 2009



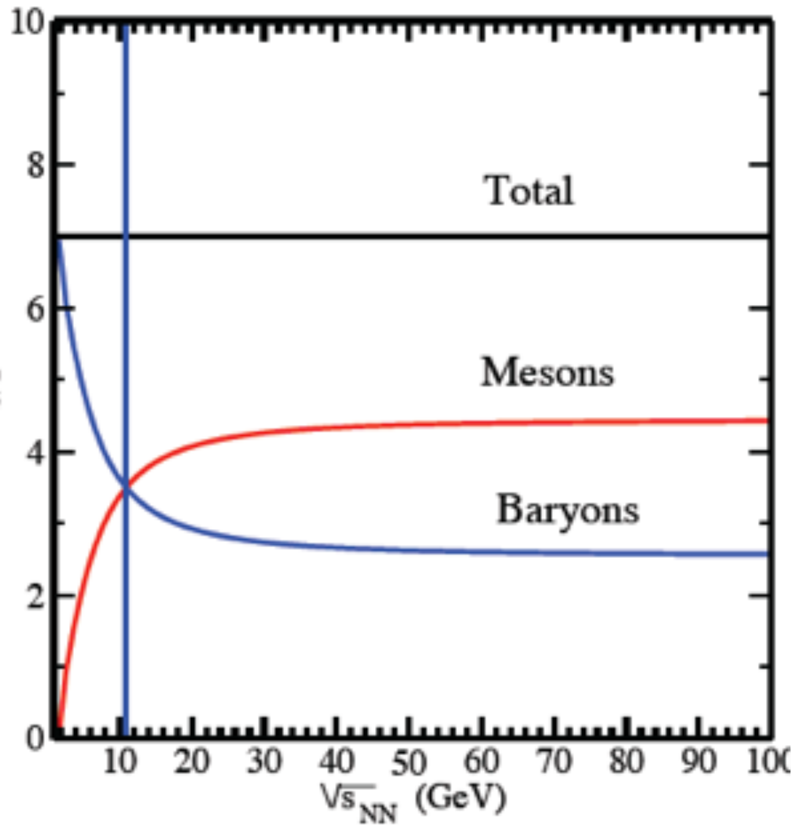
Chemical Freeze-Out

This is moreover in agreement with the first results at LHC.

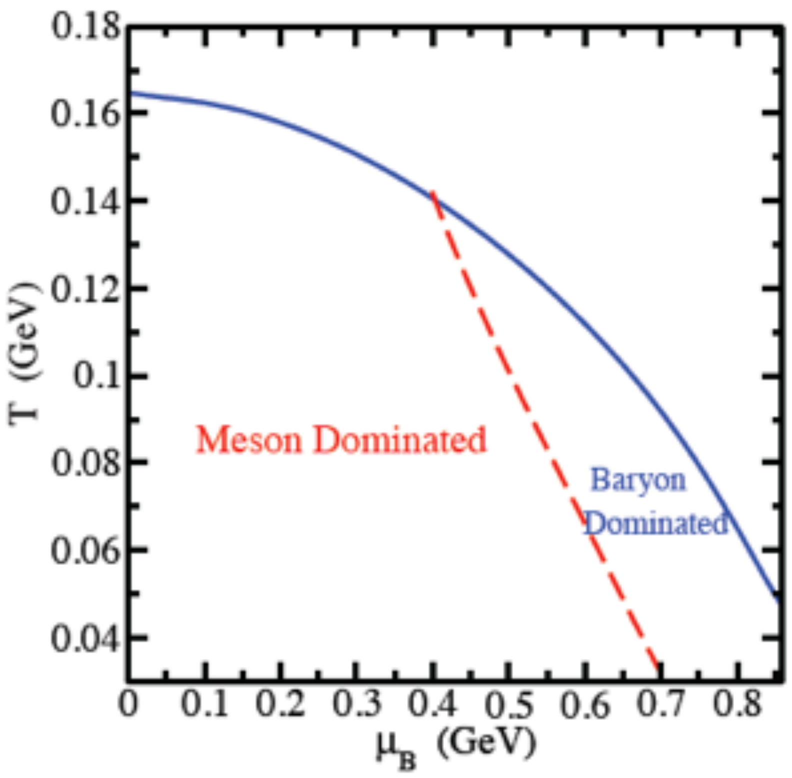
Jean Cleymans (Univ. Of Cape Town)

- The roller-coaster seen in the particle ratios corresponds to a transition from a baryon-dominated to a meson-dominated hadronic gas. This transition occurs at a
  - temperature $T = 151$ MeV,
  - baryon chemical potential $\mu_B = 327$ MeV,
  - energy $\sqrt{s_{NN}} = 11$ GeV.

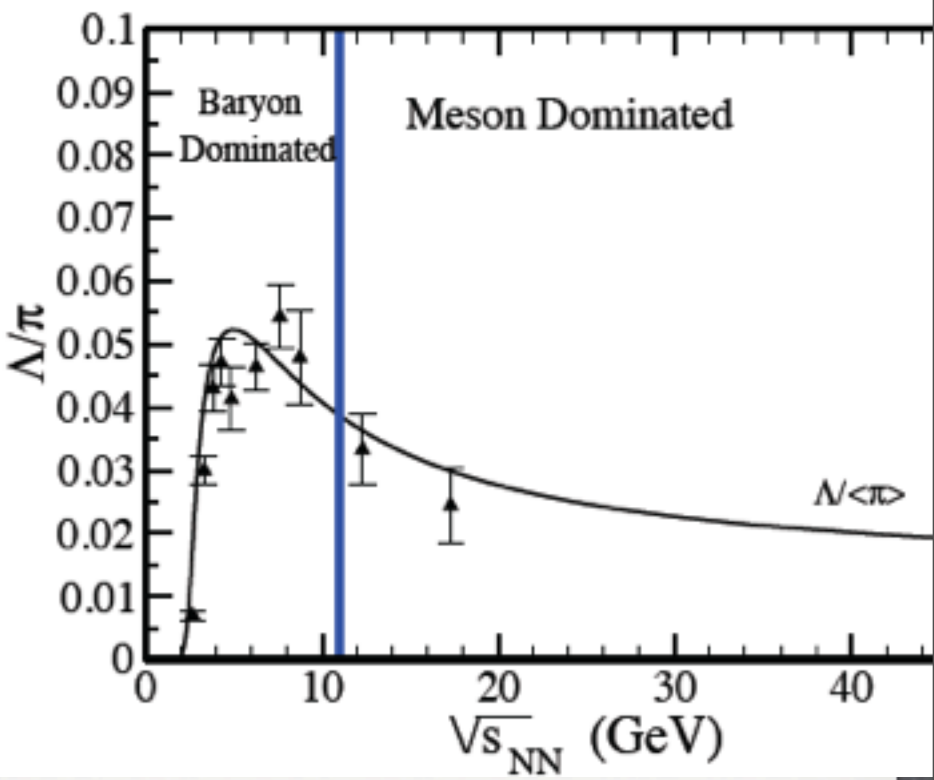
s/T^3



Transition

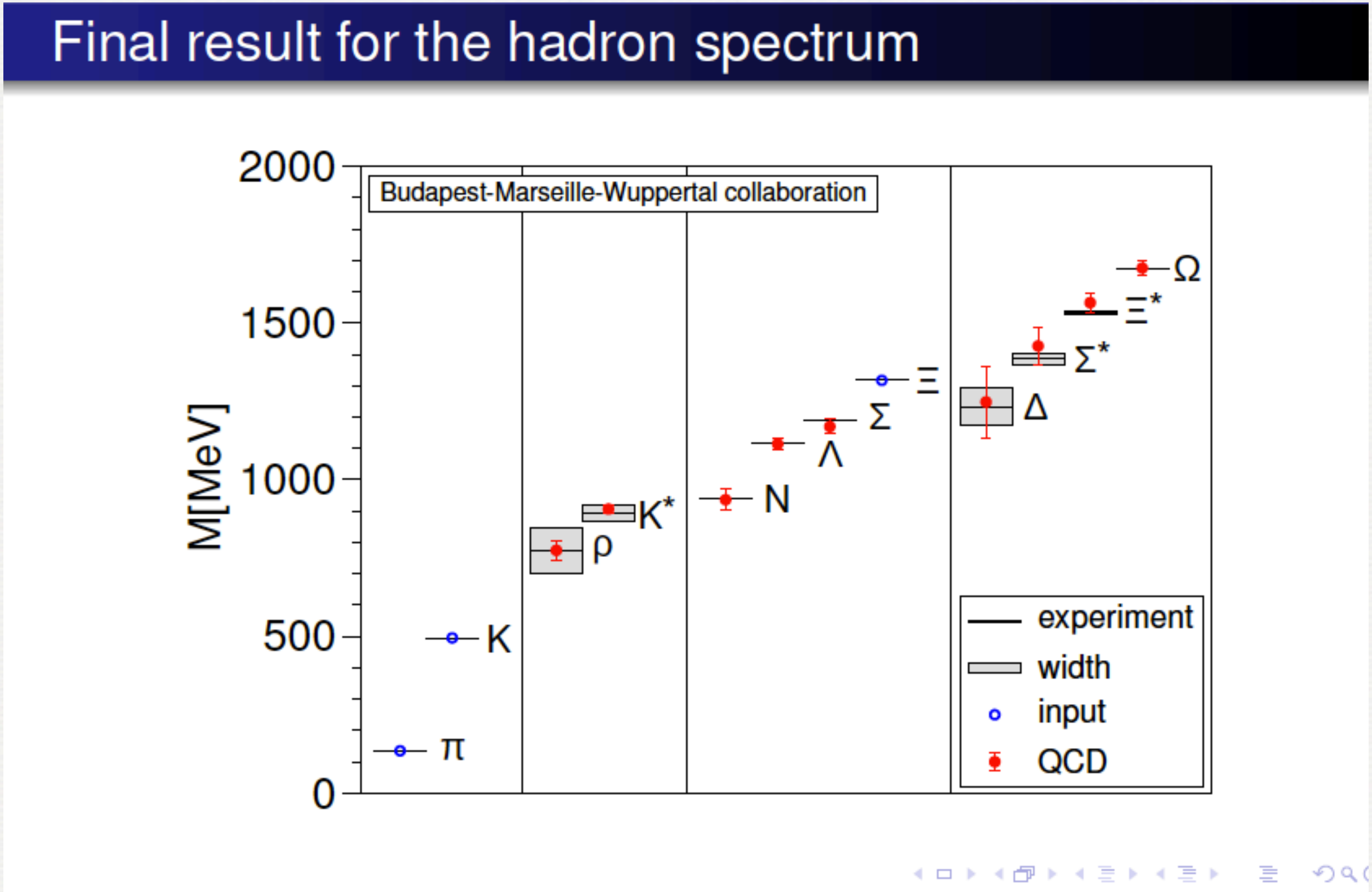


Λ/π Ratio



Zoltan Fodor (*Uni Wuppertal & Eotvos*)

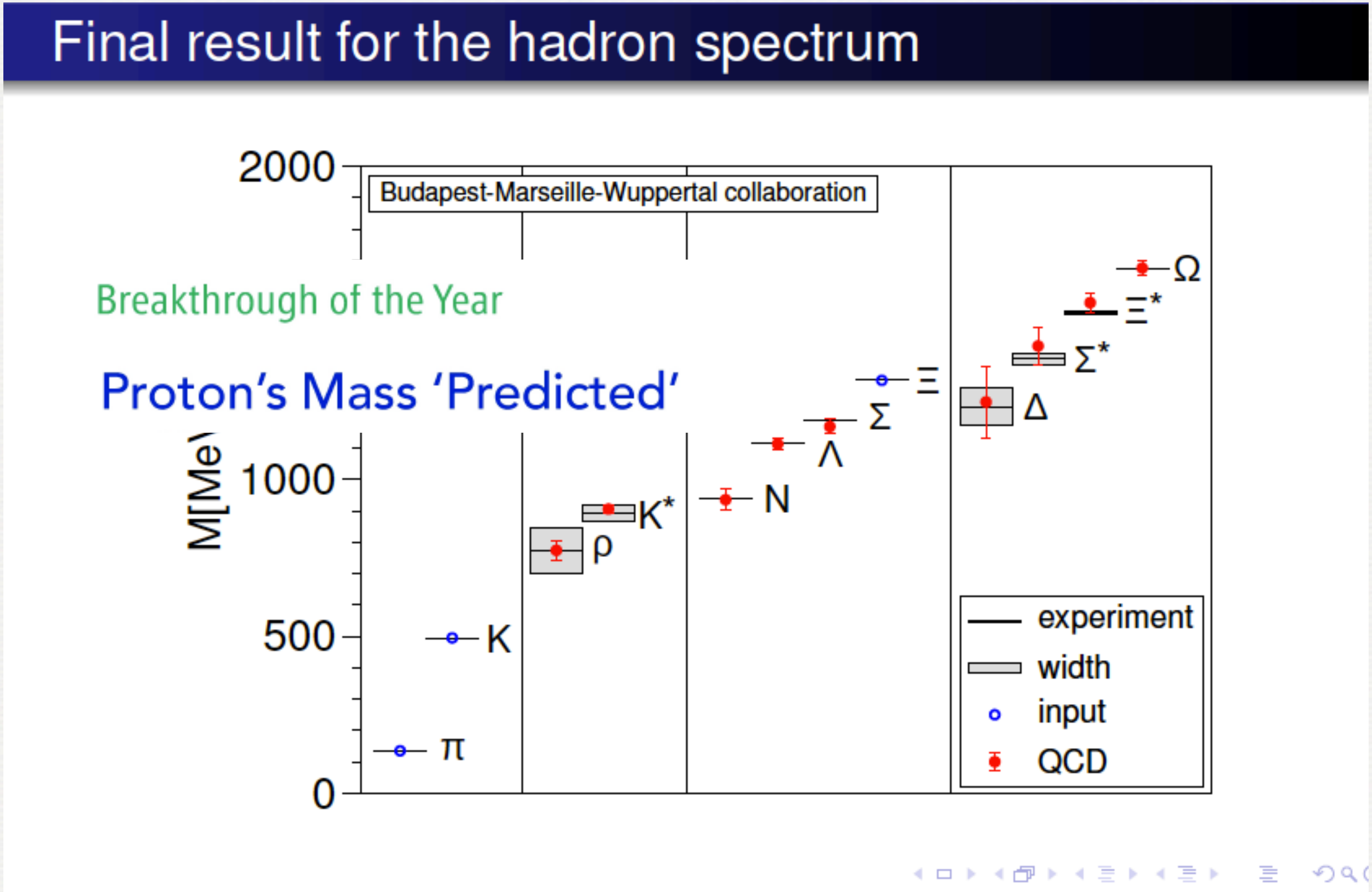
Recent results in lattice QCD



Final result for the hadron spectrum

Zoltan Fodor (Uni Wuppertal & Eotvos)

Recent results in lattice QCD



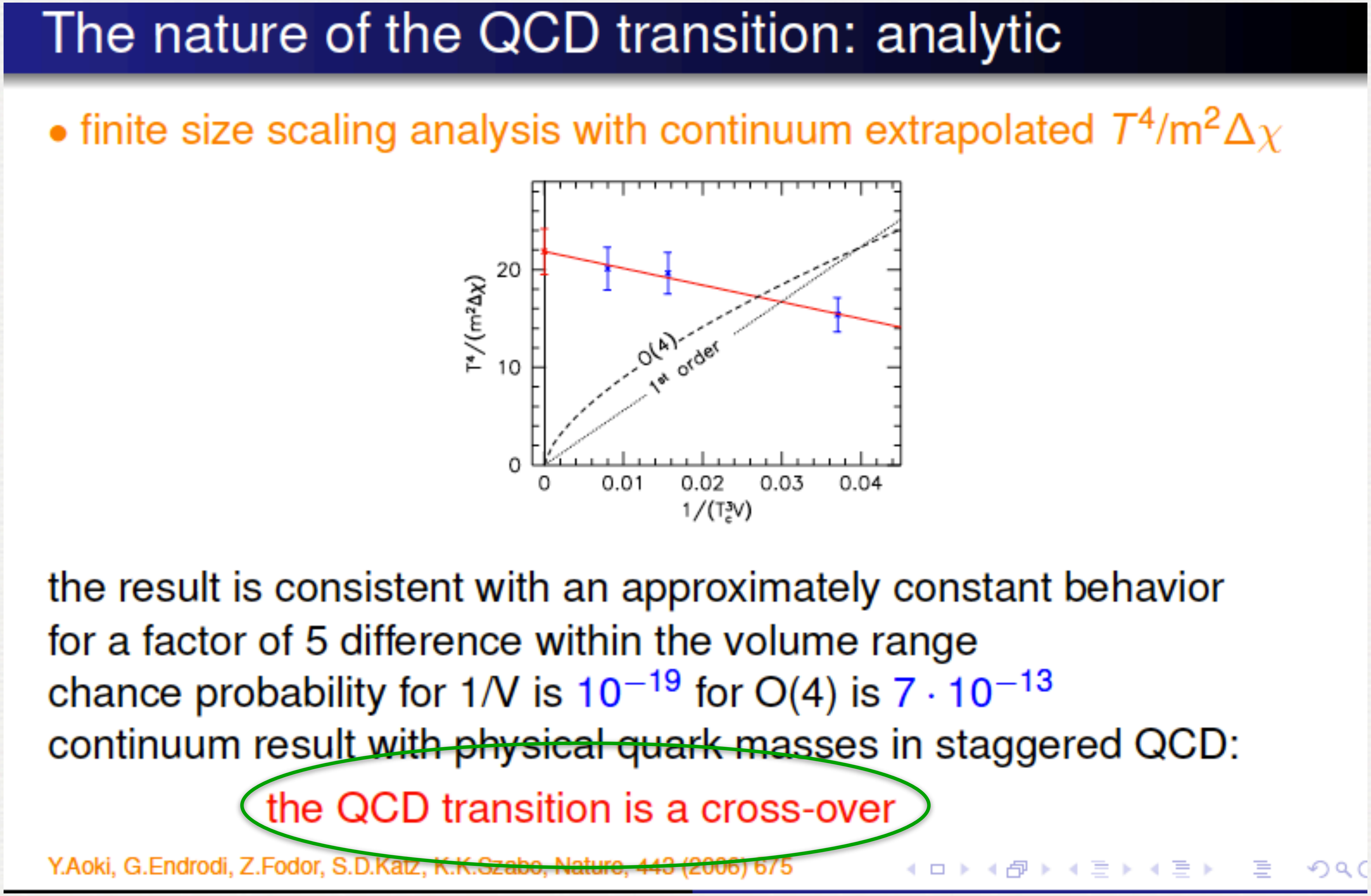
Final result for the hadron spectrum

Breakthrough of the Year

Proton's Mass 'Predicted'

Zoltan Fodor (Uni Wuppertal & Eotvos)

Finite-T & deconfinement



The nature of the QCD transition: analytic

- finite size scaling analysis with continuum extrapolated $T^4/m^2\Delta\chi$

the result is consistent with an approximately constant behavior for a factor of 5 difference within the volume range

chance probability for 1/V is 10^{-19} for O(4) is $7 \cdot 10^{-13}$

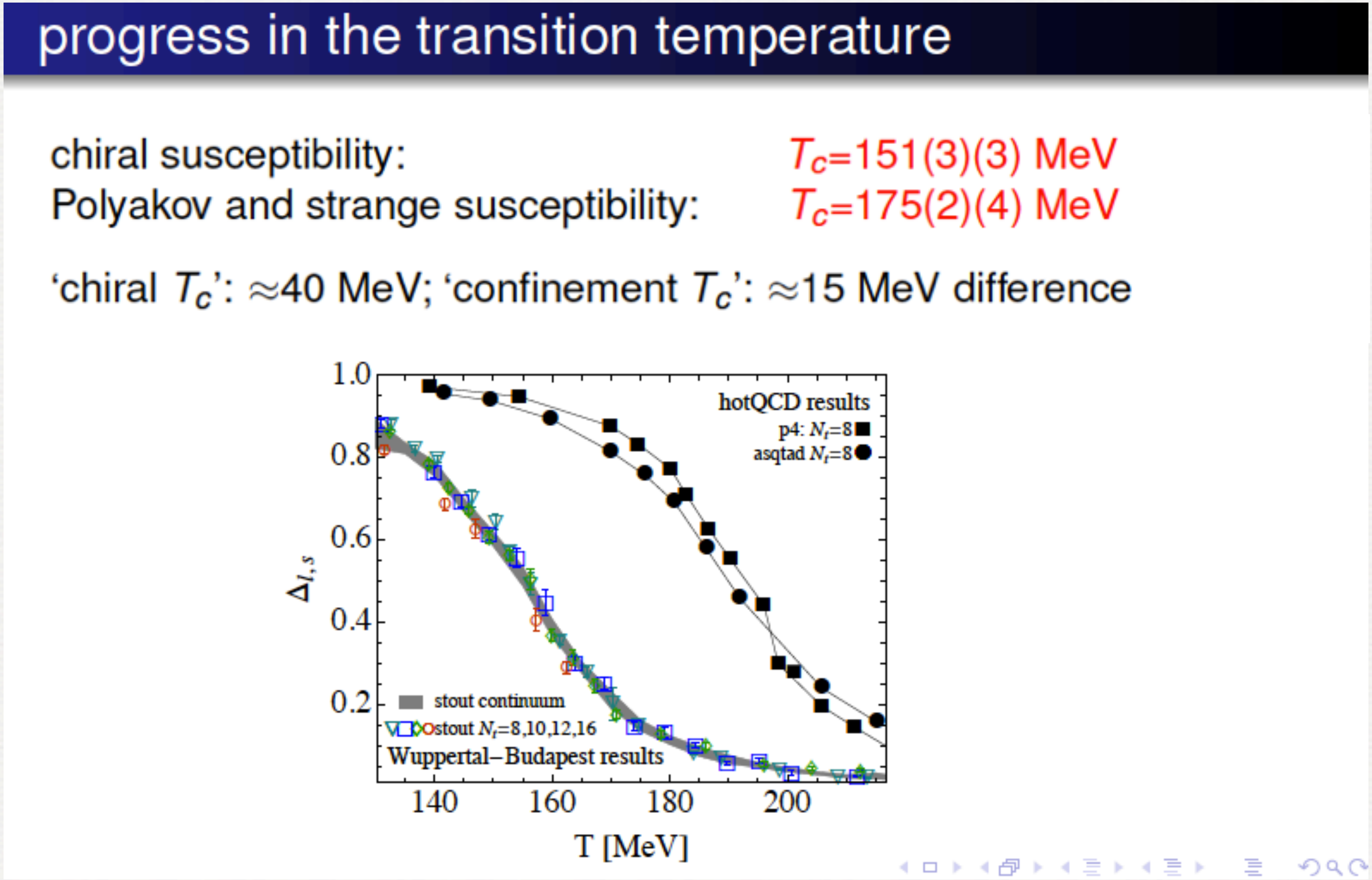
continuum result with physical quark masses in staggered QCD:

the QCD transition is a cross-over

Y.Aoki, G.Endrodi, Z.Fodor, S.D.Katz, K.K.Szabo, Nature, 443 (2006) 675

Zoltan Fodor *(Uni Wuppertal & Eotvos)*

Finite-T & deconfinement



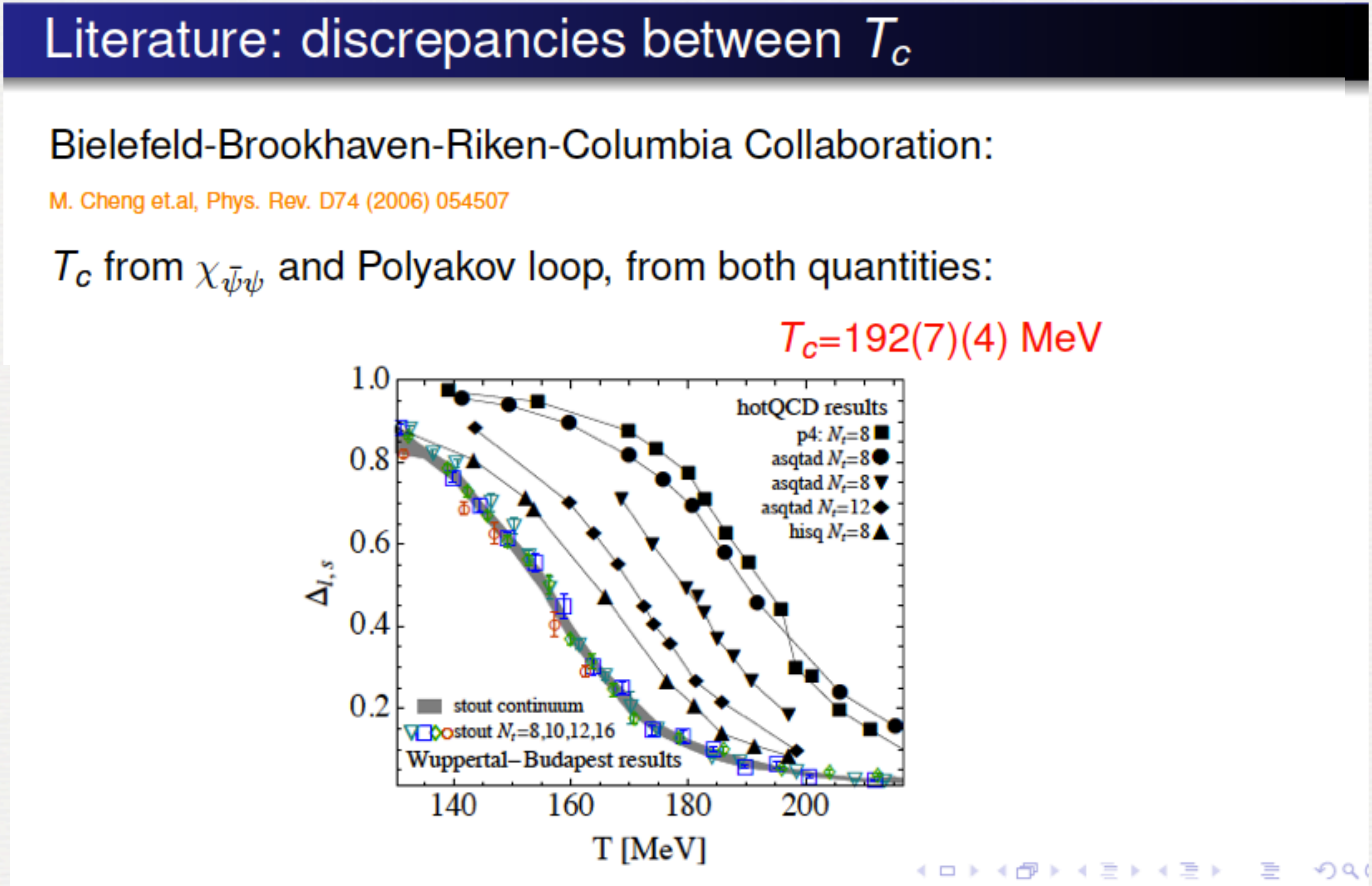
progress in the transition temperature

chiral susceptibility: T_c=151(3)(3) MeV
Polyakov and strange susceptibility: T_c=175(2)(4) MeV

'chiral T_c': ≈40 MeV; 'confinement T_c': ≈15 MeV difference

Zoltan Fodor (Uni Wuppertal & Eotvos)

Resolving a long term debate



Literature: discrepancies between T_c

Bielefeld-Brookhaven-Riken-Columbia Collaboration:

M. Cheng et.al, Phys. Rev. D74 (2006) 054507

T_c from $\chi_{\bar\psi\psi}$ and Polyakov loop, from both quantities:

T_c=192(7)(4) MeV

Zoltan Fodor (Uni Wuppertal & Eotvos)

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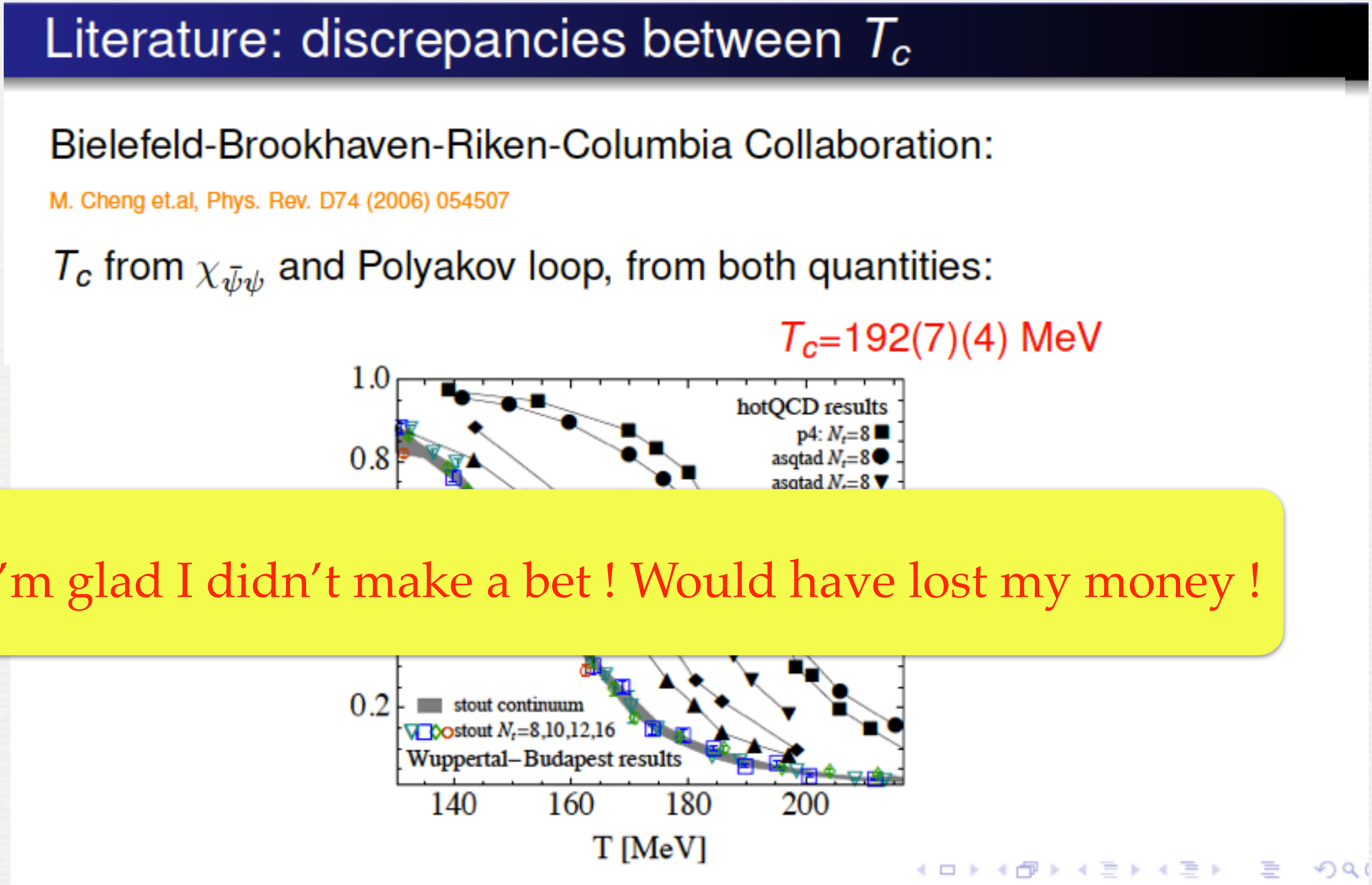

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T_c from $\chi_{\bar{\psi}\psi}$ and Polyakov loop, from both quantities:

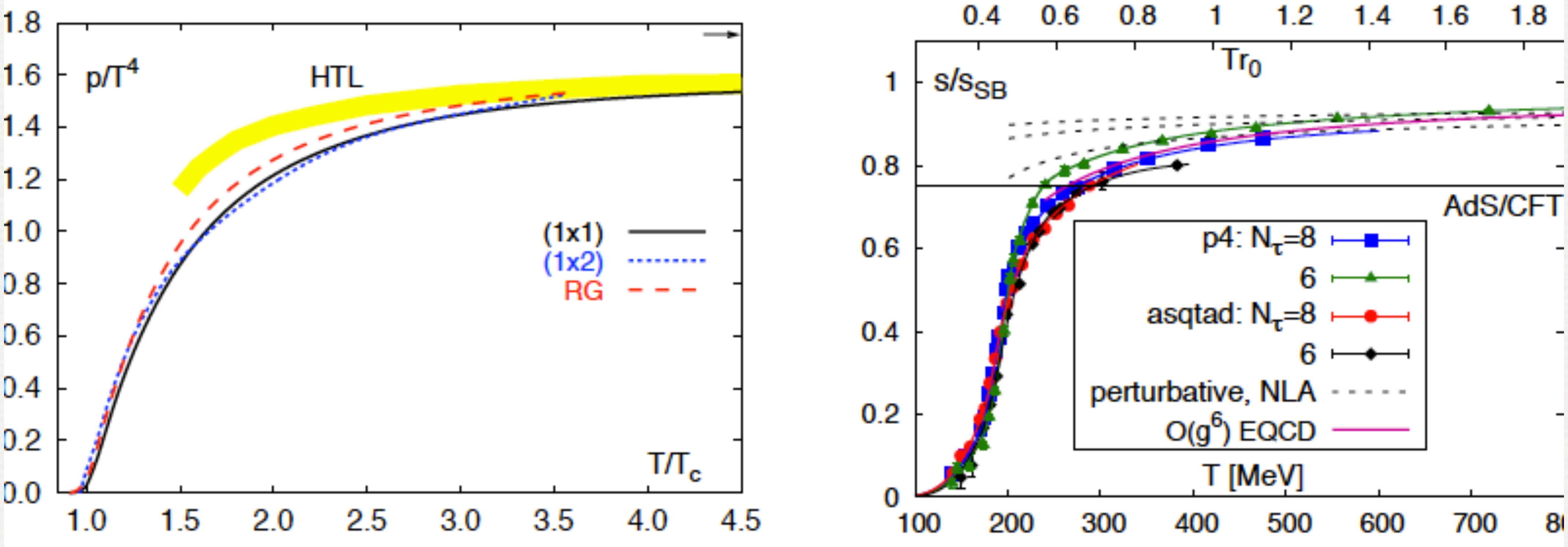
T_c=192(7)(4) MeV

I'm glad I didn't make a bet ! Would have lost my money !

Smooth cross-over to the QGP

Lattice QCD

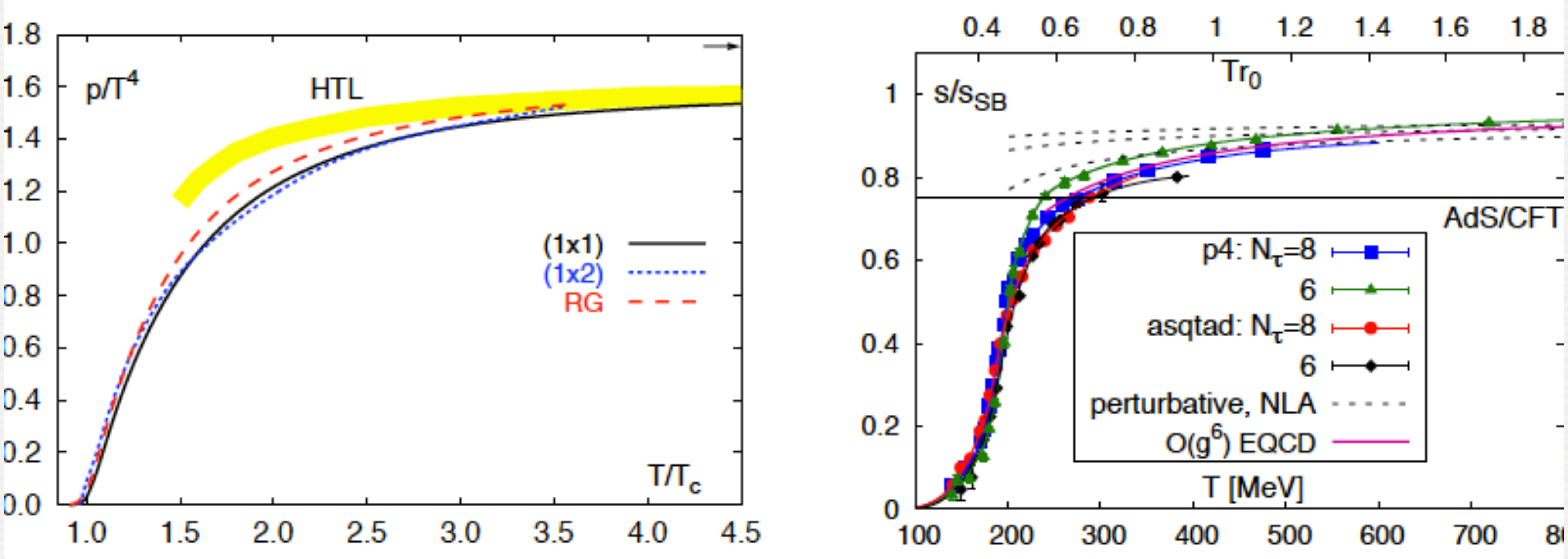
QGP: Weak Or Strong Coupling ?



- For $T \gtrsim 2.5T_c$, the lattice results are well reproduced by resummed perturbation theory! *(Blaizot, Rebhan, E. I., 2000)*
- Weakly coupled 'quasiparticles' (quarks and gluons)

N=4 SYM in the strong coupling limit $\lambda \equiv g^2 N_c \to \infty$ $\quad S/S_{\rm SB} = \frac{3}{4}$

QGP: Weak Or Strong Coupling ?



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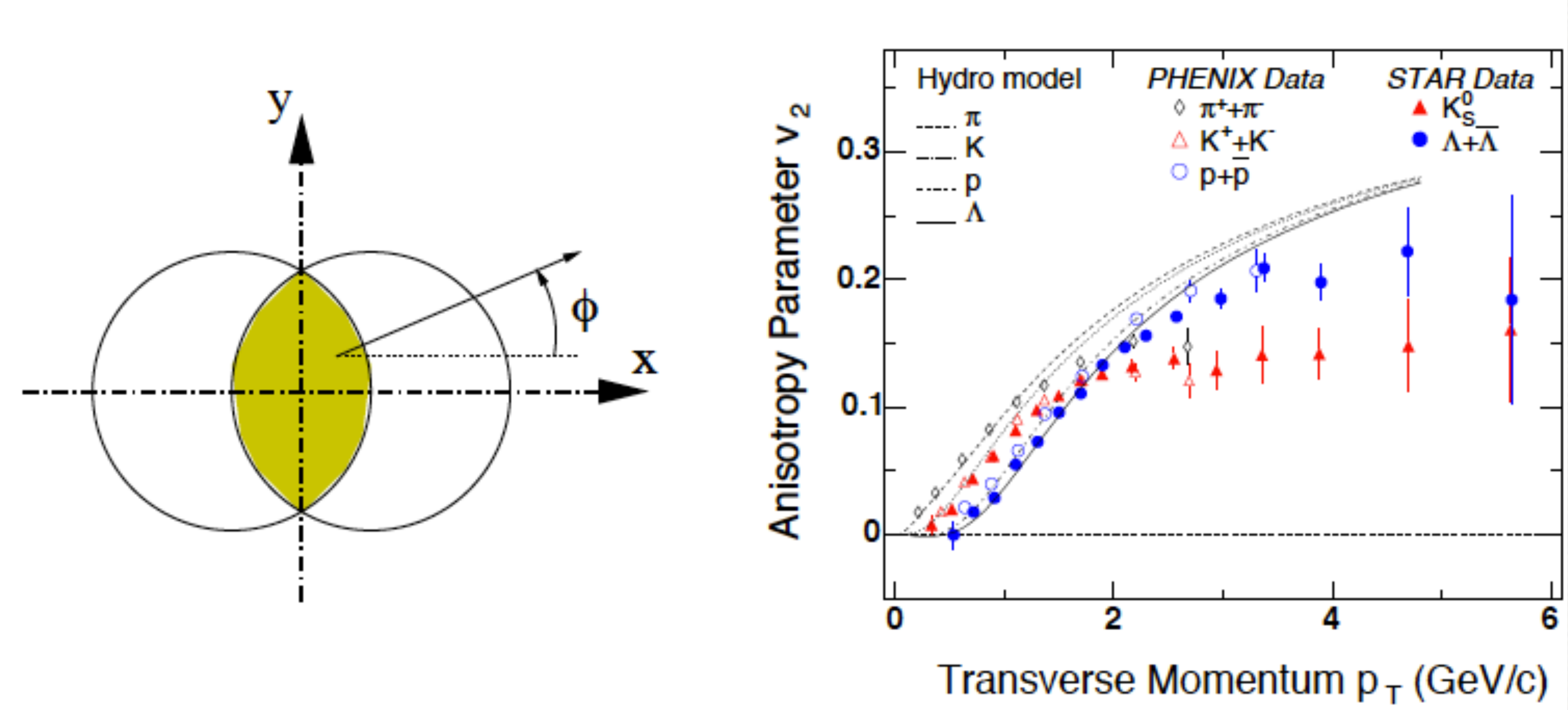
- Weakly coupled 'quasiparticles' (quarks and gluons)

N=4 SYM in the strong coupling limit $\lambda \equiv g^2 N_c \to \infty$ $\quad S/S_{\rm SB} = \dfrac{3}{4}$

And so what ??

QGP: The case for a strong coupling

RHIC is serving us the perfect fluid !

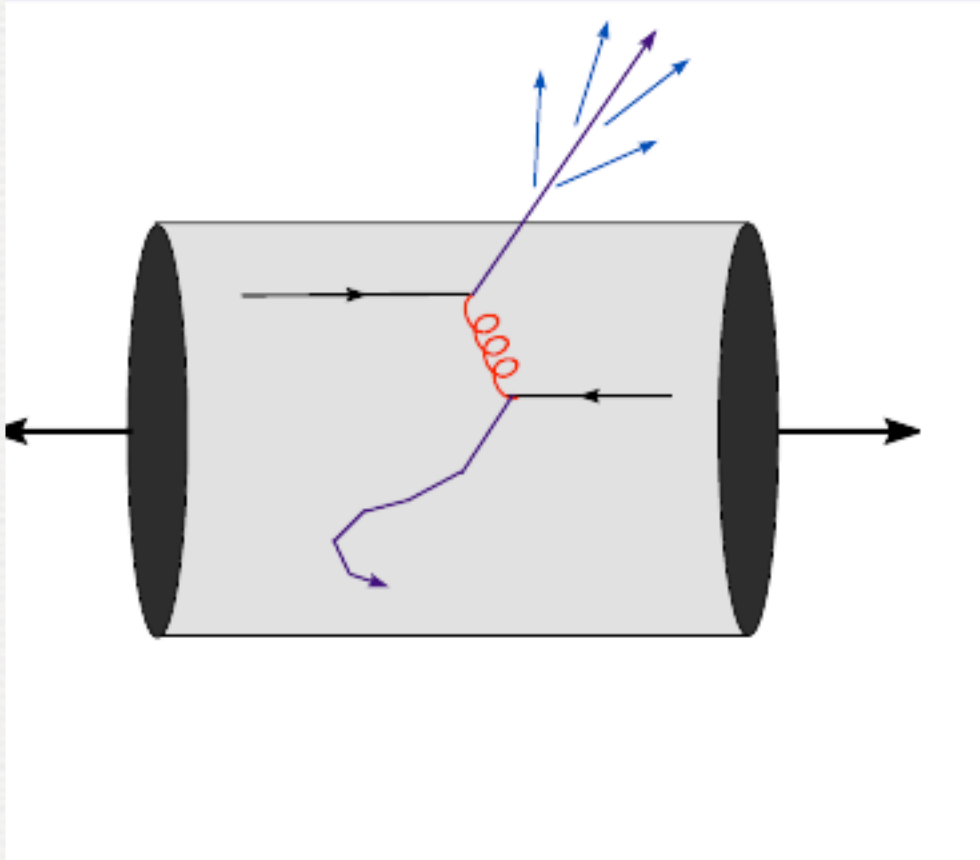


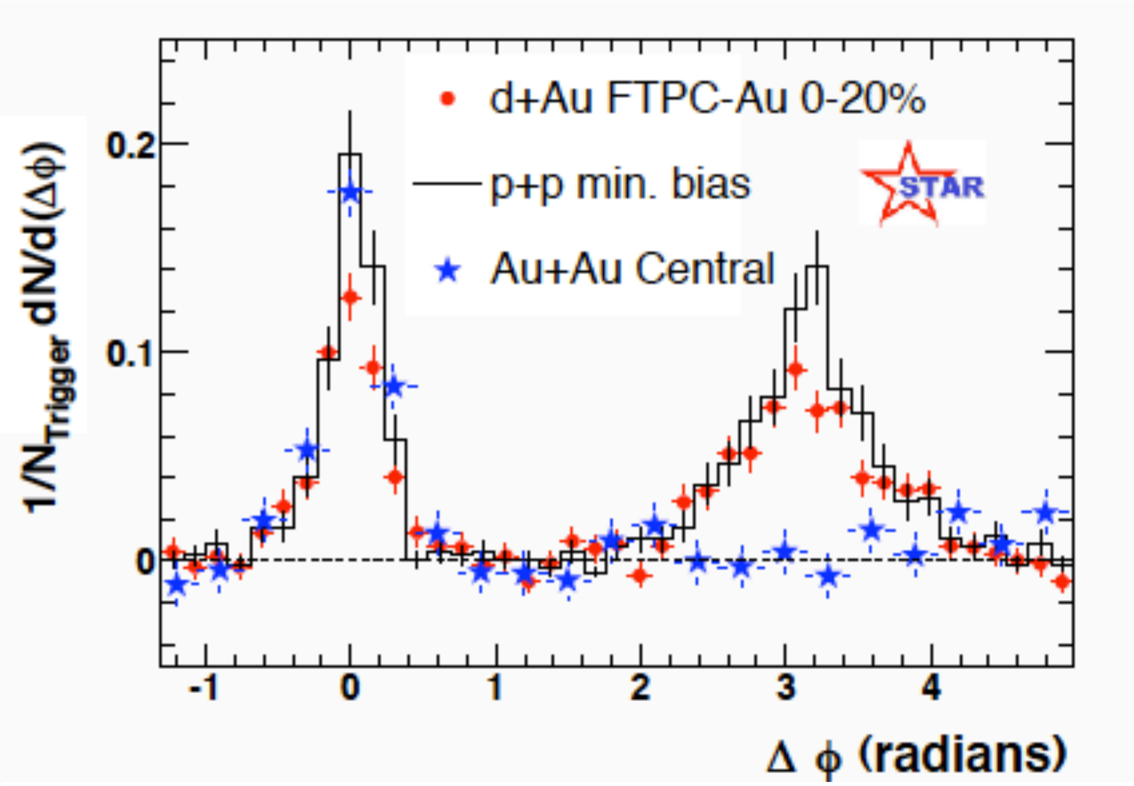
Elliptic flow (even heavy quarks show flow !)

- Well described by hydrodynamical calculations with very small viscosity/entropy ratio: “perfect fluid”

QGP: The case for a strong coupling

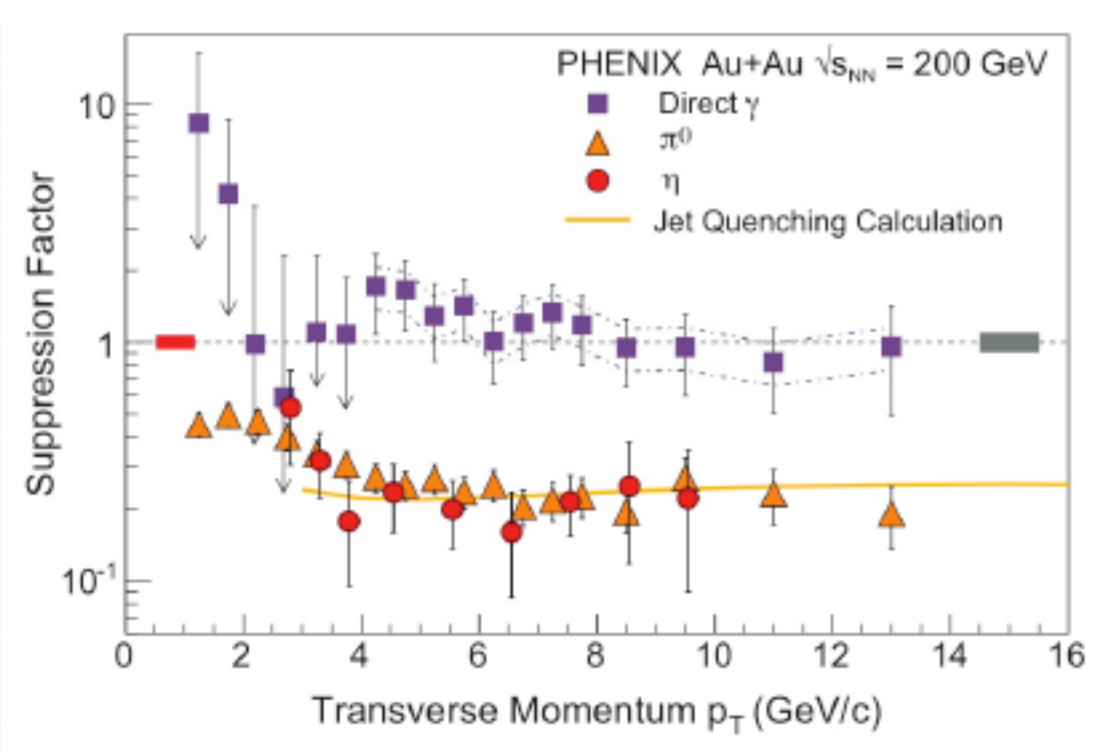
RHIC is serving us the perfect fluid !





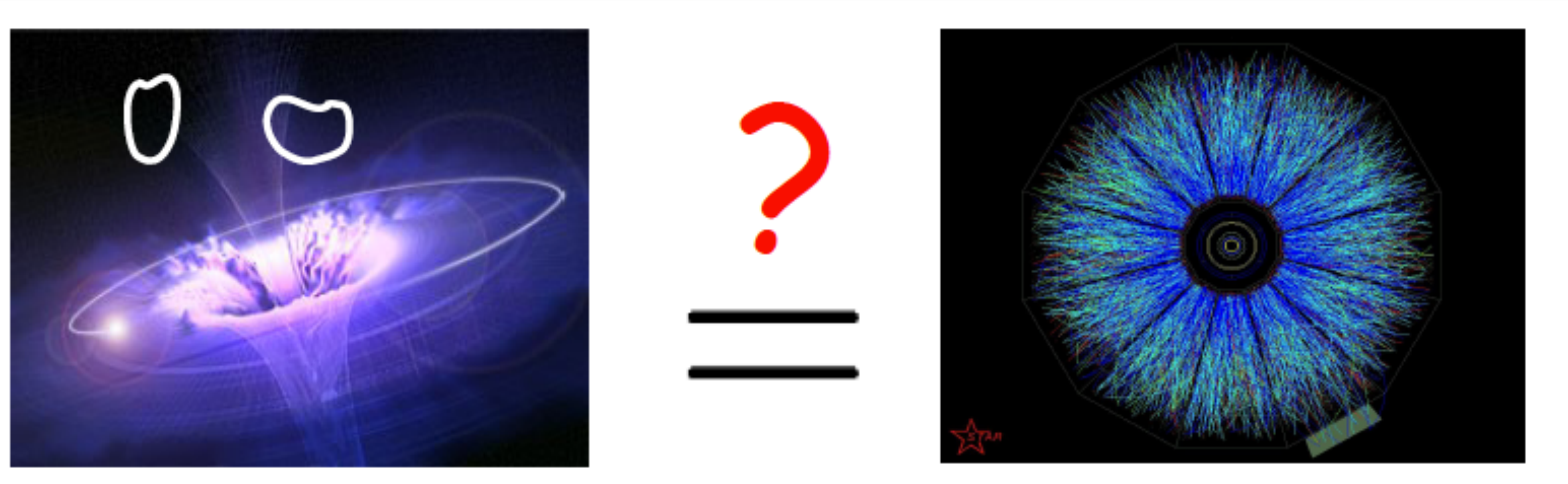
Jet quenching

(seems too large to beperturbative)



Jorge Noronha (Columbia University)

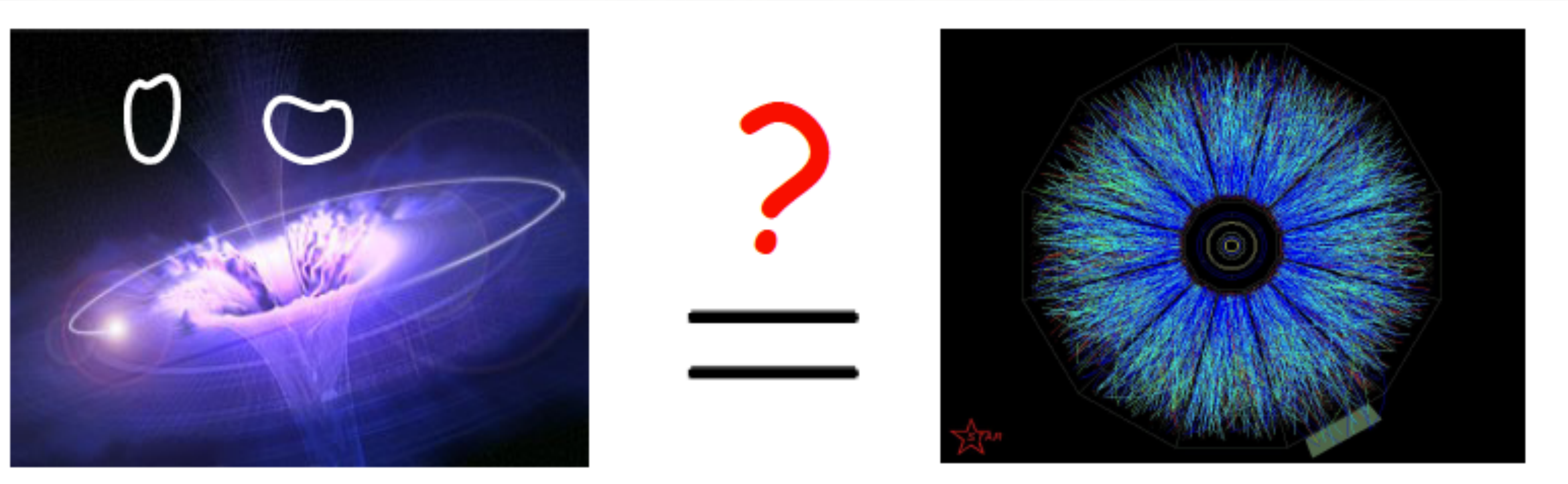
AdS/CFT approaches to problems in relativistic heavy-ion collisions



Do you speak AdS/CFT ?

Jorge Noronha (Columbia University)

AdS/CFT approaches to problems in relativistic heavy-ion collisions



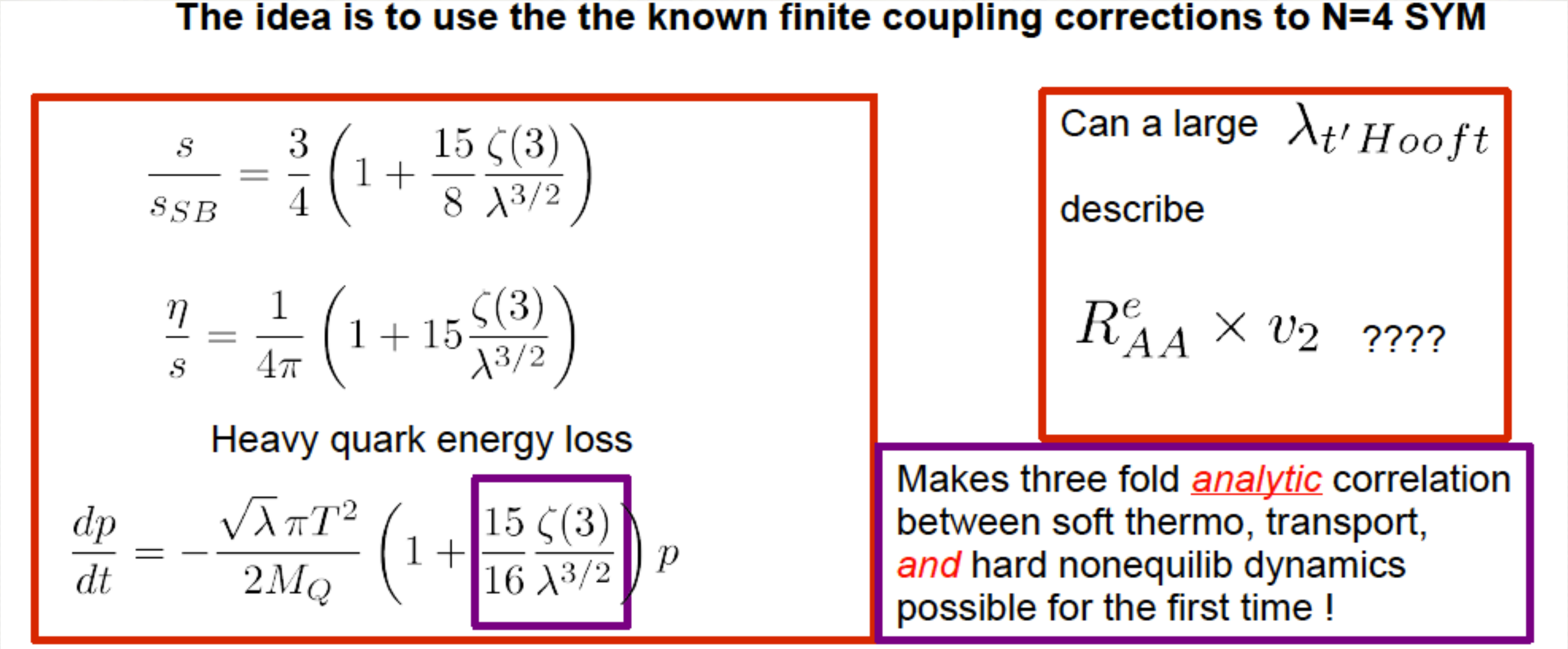
Do you speak AdS/CFT ?

- ✦ It strictly applies to a cousin of QCD (N=4 SYM).
- ✦ The two theories are quite similar in the deconfined phase

Jorge Noronha (Columbia University)

AdS/CFT approaches to problems in relativistic heavy-ion collisions

Can one have a consistent phenomenology within AdS/CFT ?



The idea is to use the the known finite coupling corrections to N=4 SYM

$$\frac{s}{s_{SB}} = \frac{3}{4}\left(1 + \frac{15}{8}\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + 15\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

Heavy quark energy loss

$$\frac{dp}{dt} = -\frac{\sqrt{\lambda}\,\pi T^2}{2M_Q}\left(1 + \boxed{\frac{15}{16}\frac{\zeta(3)}{\lambda^{3/2}}}\right) p$$

Can a large $\lambda_{t'Hooft}$

describe

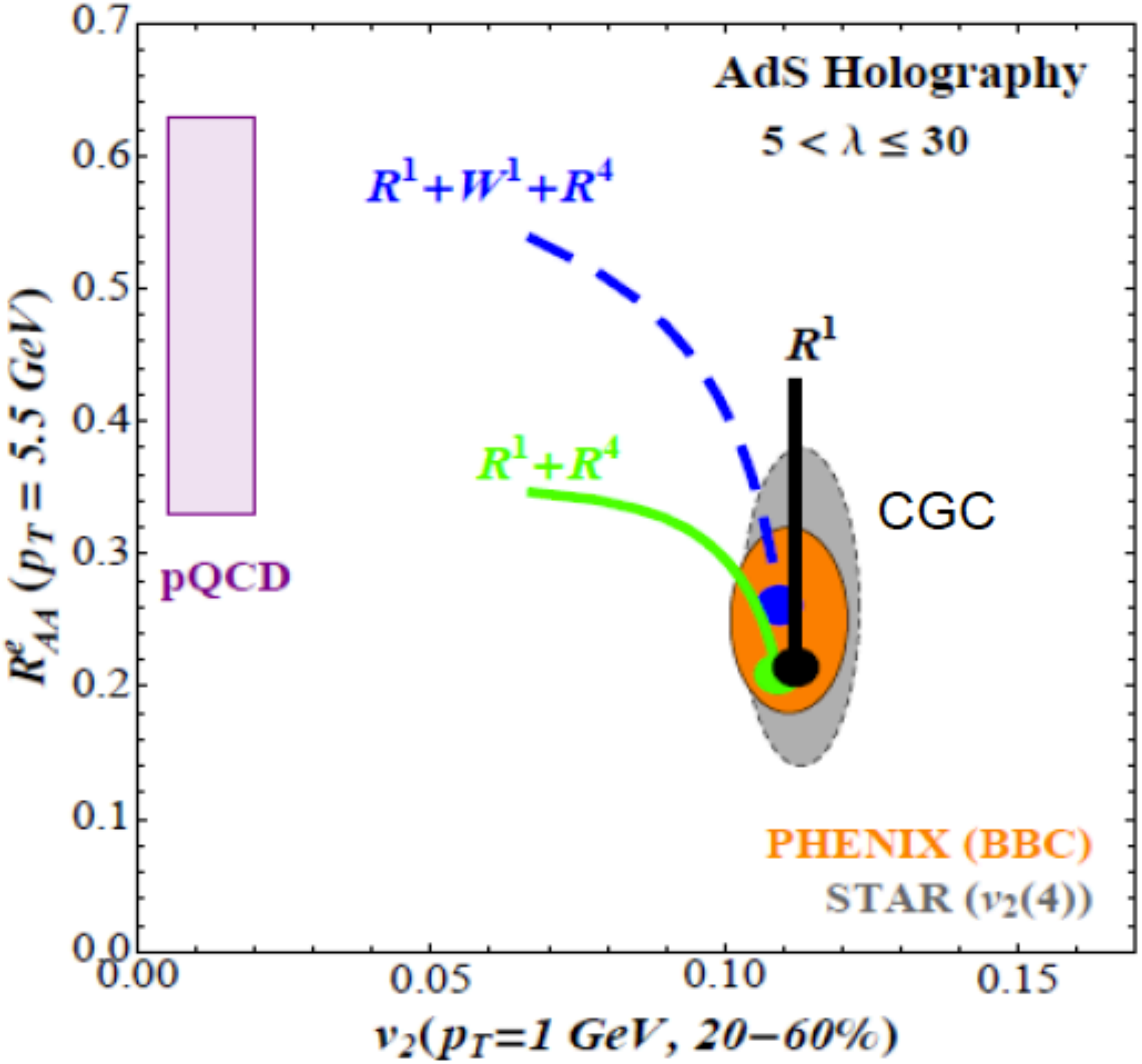
$R^{e}_{AA} \times v_2$????

Makes three fold *analytic* correlation between soft thermo, transport, *and* hard nonequilib dynamics possible for the first time !

Jorge Noronha (Columbia University)

AdS/CFT approaches to problems in relativistic heavy-ion collisions

Wordsheet fluctuations do not matter much!



EVIDENCE FOR

STRONGLY

COUPLED

BEHAVIOR ???

Glauber initial conditions cannot describe correlations!!!

Jorge Noronha (Columbia University)

AdS/CFT approaches to problems in relativistic heavy-ion collisions

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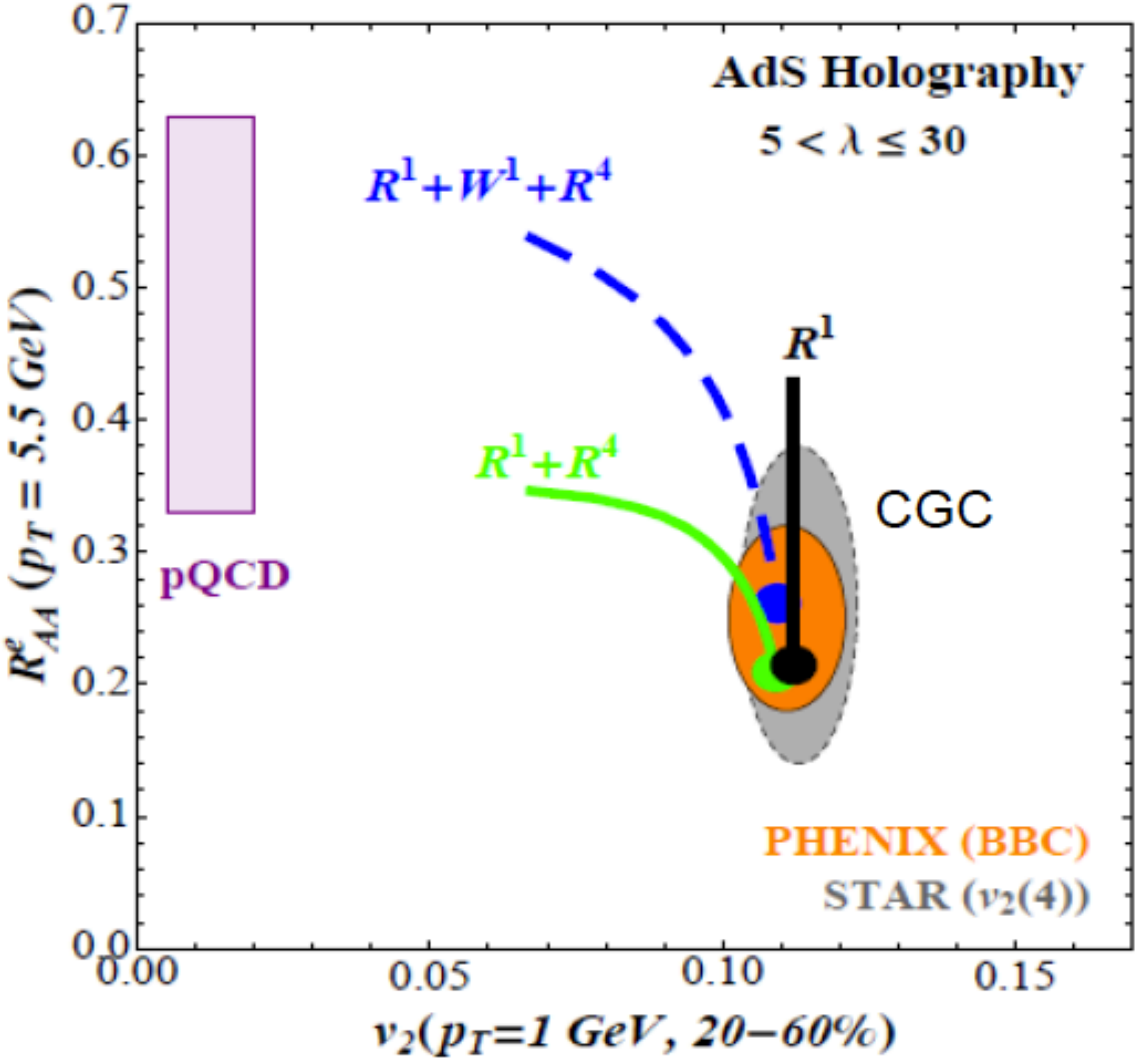


EVIDENCE FOR STRONGLY COUPLED BEHAVIOR ???

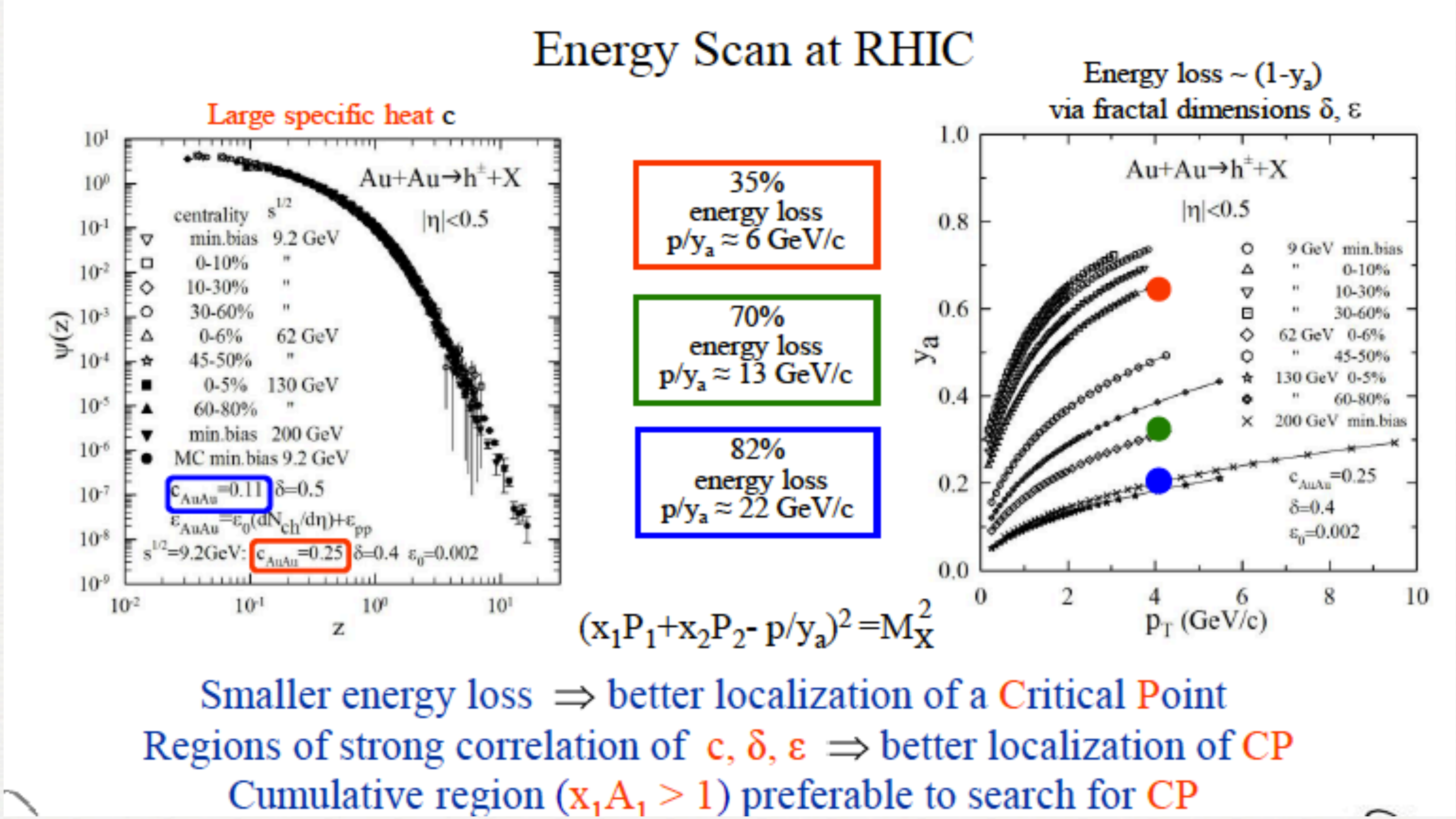
Glauber initial conditions cannot describe correlations!!!

Mikhail Tokarev *(JINR, Dubna)*

Energy loss in heavy ion collisions

Scaling law for particle production due to self-similarity of partonic interactions.

Going from p+p to Au+Au ➡ phase transition in the fractal dimension



Energy Scan at RHIC

Large specific heat c

35% energy loss $p/y_a \approx 6$ GeV/c

70% energy loss $p/y_a \approx 13$ GeV/c

82% energy loss $p/y_a \approx 22$ GeV/c

Energy loss ~ $(1-y_a)$ via fractal dimensions δ, ε

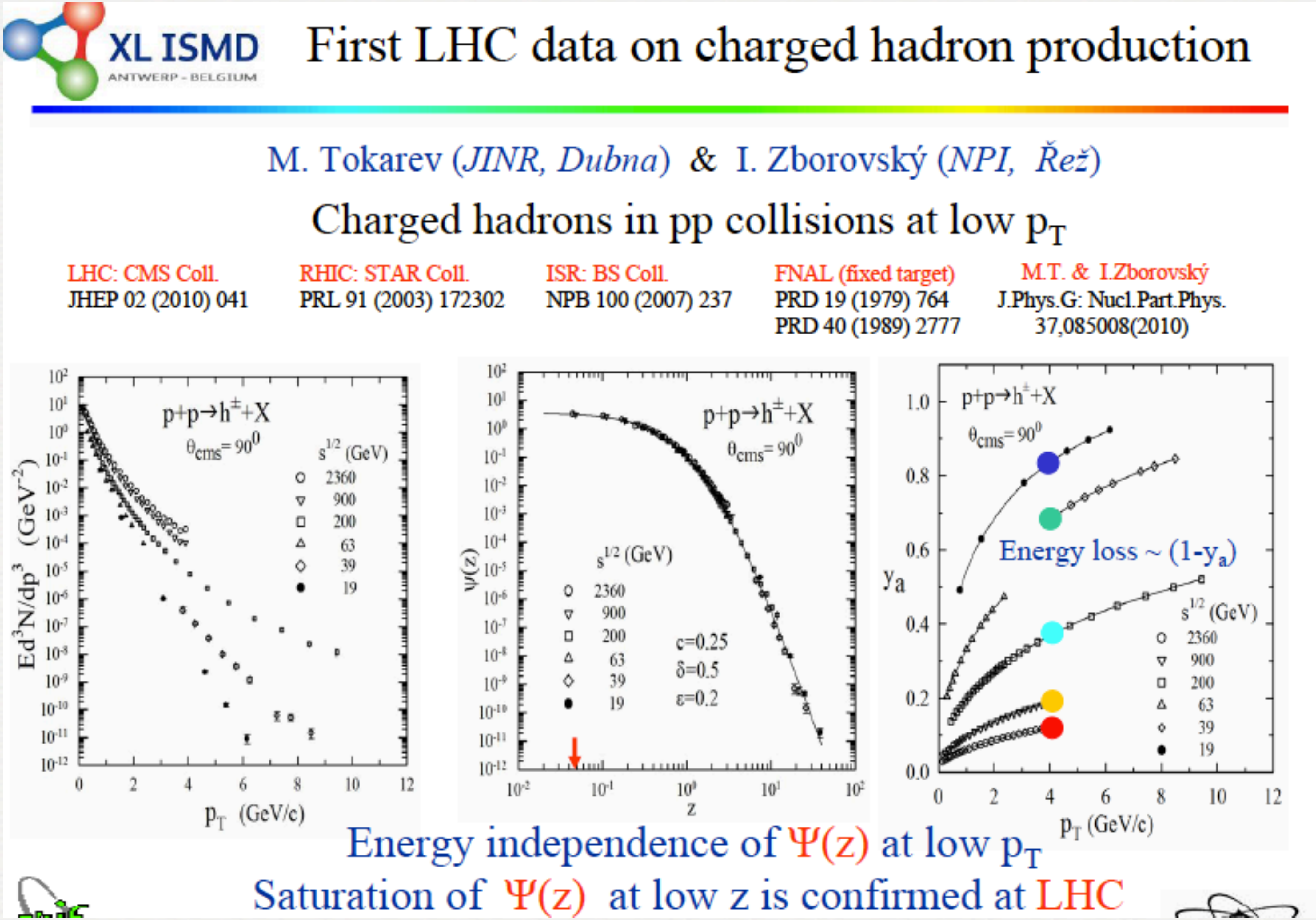
$$(x_1P_1+x_2P_2-p/y_a)^2=M_X^2$$

Smaller energy loss ⇒ better localization of a Critical Point

Regions of strong correlation of c, δ, ε ⇒ better localization of CP

Cumulative region $(x_1 A_1 > 1)$ preferable to search for CP

Mikhail Tokarev (JINR, Dubna)



XL ISMD
ANTWERP - BELGIUM

First LHC data on charged hadron production

M. Tokarev (*JINR, Dubna*) & I. Zborovský (*NPI, Řež*)

Charged hadrons in pp collisions at low p_T

LHC: CMS Coll.	RHIC: STAR Coll.	ISR: BS Coll.	FNAL (fixed target)	M.T. & I.Zborovský
JHEP 02 (2010) 041	PRL 91 (2003) 172302	NPB 100 (2007) 237	PRD 19 (1979) 764 PRD 40 (1989) 2777	J.Phys.G: Nucl.Part.Phys. 37,085008(2010)

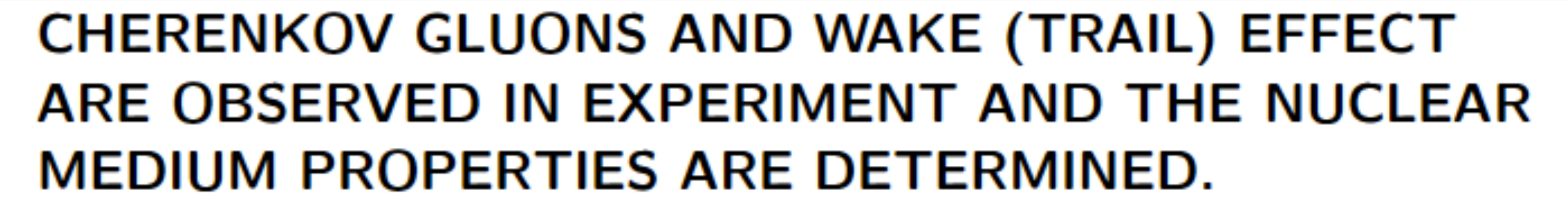
Energy loss ~ $(1-y_a)$

Energy independence of $\Psi(z)$ at low p_T

Saturation of $\Psi(z)$ at low z is confirmed at LHC

Igor Dremin *(P.N. Lebedev Inst., Moscow)*

Effects of macroscopic QCD observed in A+A collisions


CHERENKOV GLUONS AND WAKE (TRAIL) EFFECT ARE OBSERVED IN EXPERIMENT AND THE NUCLEAR MEDIUM PROPERTIES ARE DETERMINED.

Igor Dremin *(P.N. Lebedev Inst., Moscow)*

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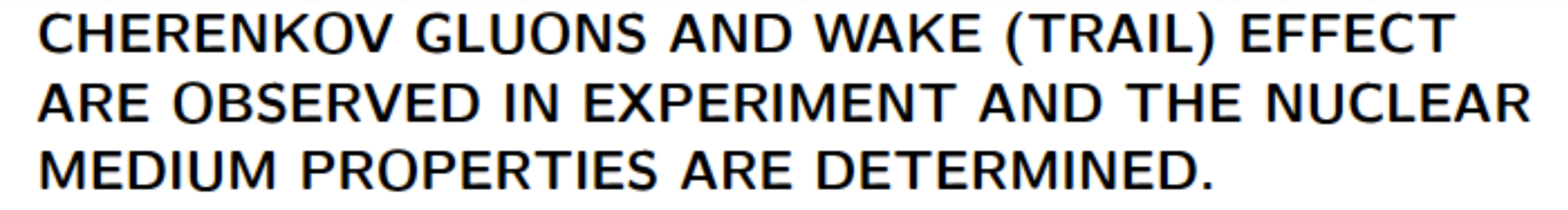

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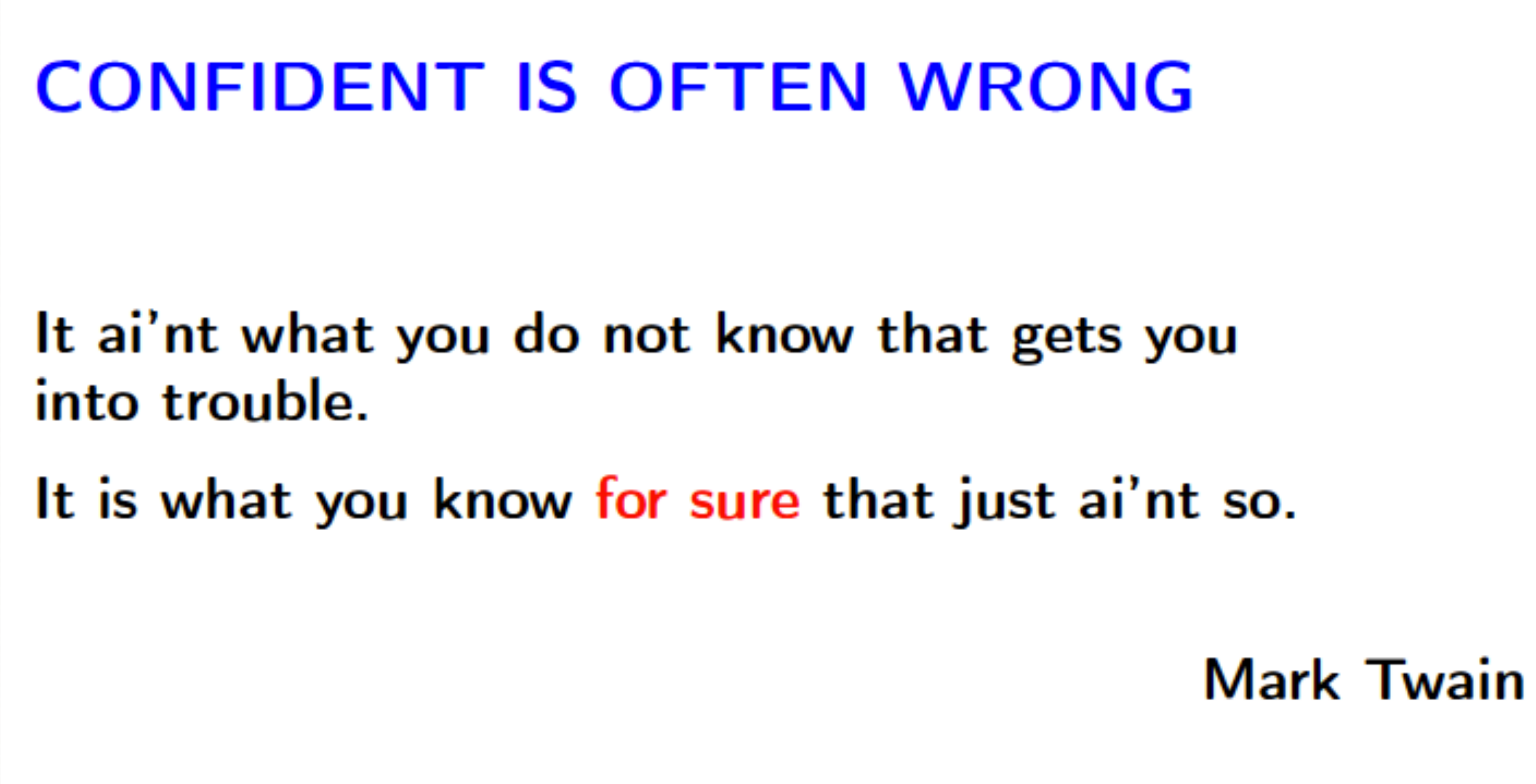


CONFIDENT IS OFTEN WRONG

It ai'nt what you do not know that gets you into trouble.

It is what you know for sure that just ai'nt so.

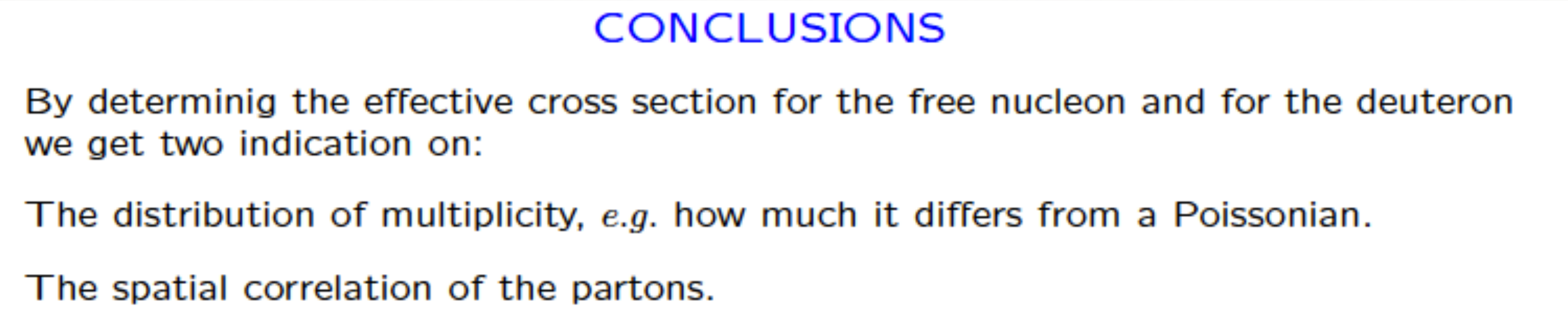
Mark Twain

Giorgio Calucci (I.N.F.N.)

Nucleon-deuteron collision as a probe of the partonic distributions

How to study 2-body distributions in a hadron wavefunction ?

Study events with hard QCD double scattering of partons of a same hadron.
Such events become more and more abundant when the energy of the colliding hadrons grows.



CONCLUSIONS

By determinig the effective cross section for the free nucleon and for the deuteron we get two indication on:

The distribution of multiplicity, *e.g.* how much it differs from a Poissonian.

The spatial correlation of the partons.

Soft Interactions

conveners: Rick Field & Risot Orava

- Minimum bias, single particle spectra, model tuning
- Total & (in)elastic cross sections
- Low energy experiments
- Underlying events, background structure
- Hadron spectroscopy

Introduction: *Rick Field* *(University Of Florida)*

Minimum Bias Summary

- How well did we* do at predicting the LHC underlying event at 900 GeV and 7 TeV ?

** `We' = PYTHIA Tune DW*

Introduction: *Rick Field* *(University Of Florida)*

Minimum Bias Summary

- How well did we* do at predicting the LHC underlying event at 900 GeV and 7 TeV ?

Introduction: *Rick Field* *(University Of Florida)*

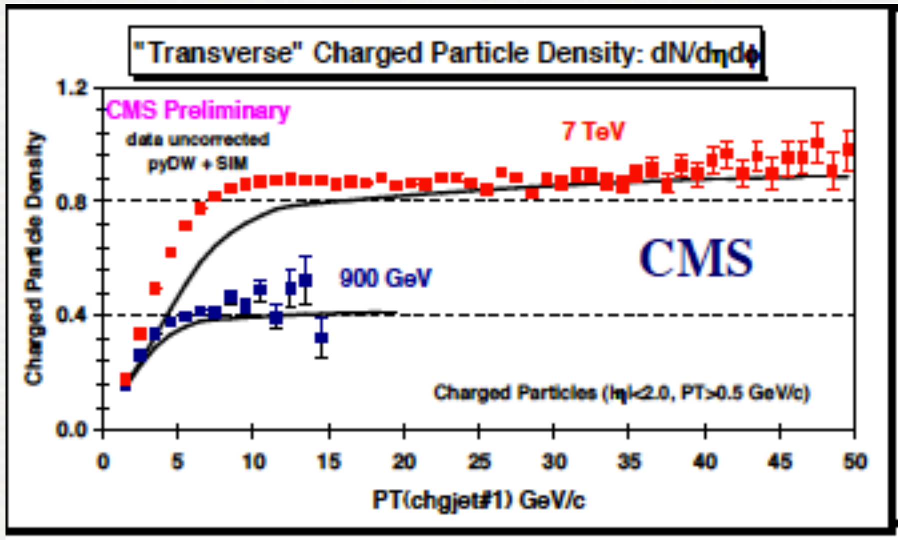
Minimum Bias Summary

- How well did we* do at predicting the LHC underlying event at 900 GeV and 7 TeV ?

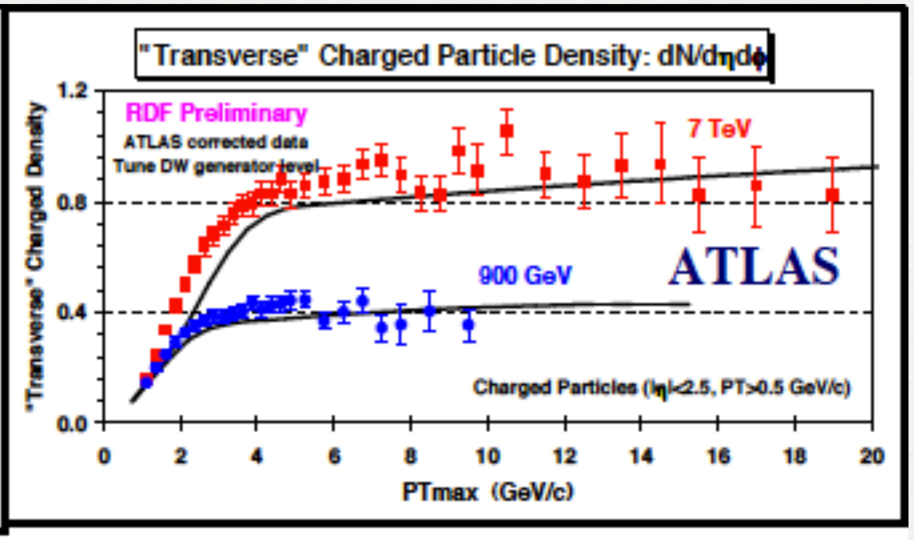
- The answer in short:

We did relatively well ... but not perfect !

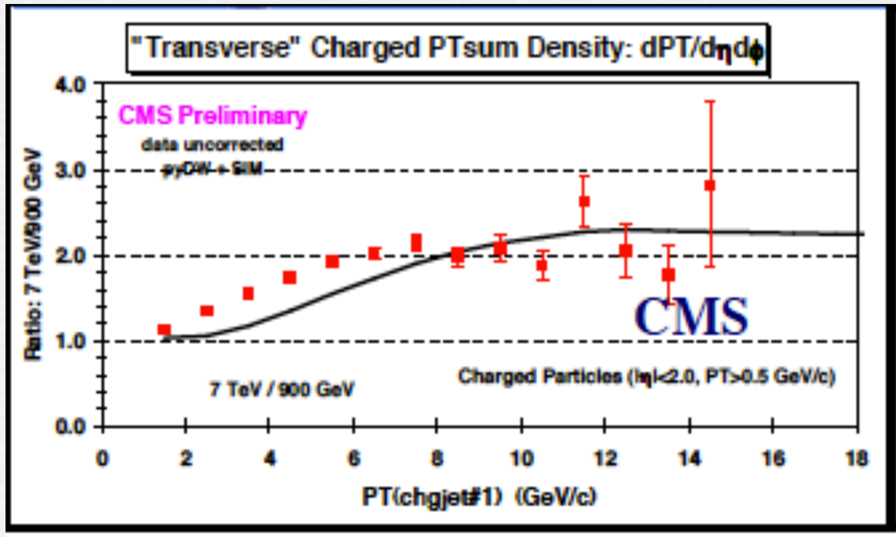
Rick Field : Minimum Bias Summary



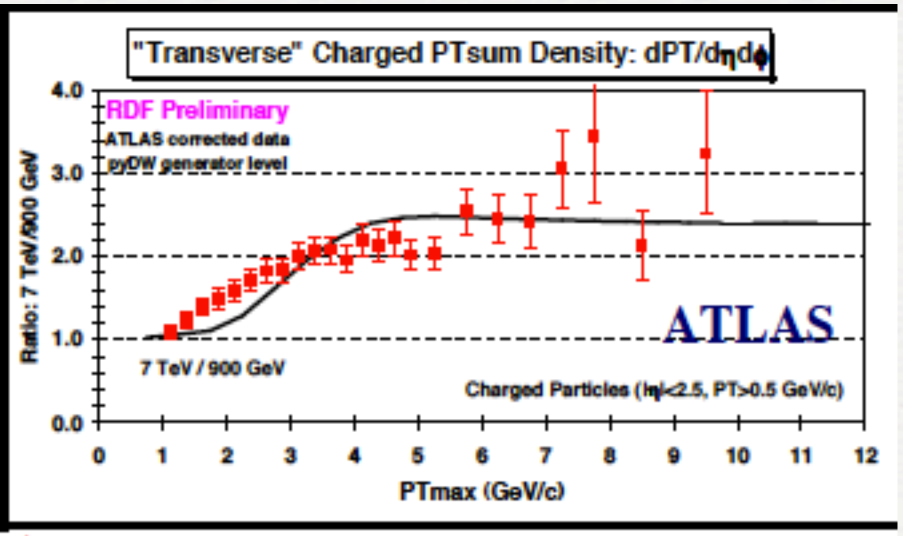
➧ CMS preliminary data at 900 GeV and 7 TeV



➧ ATLAS preliminary data at 900 GeV and 7 TeV



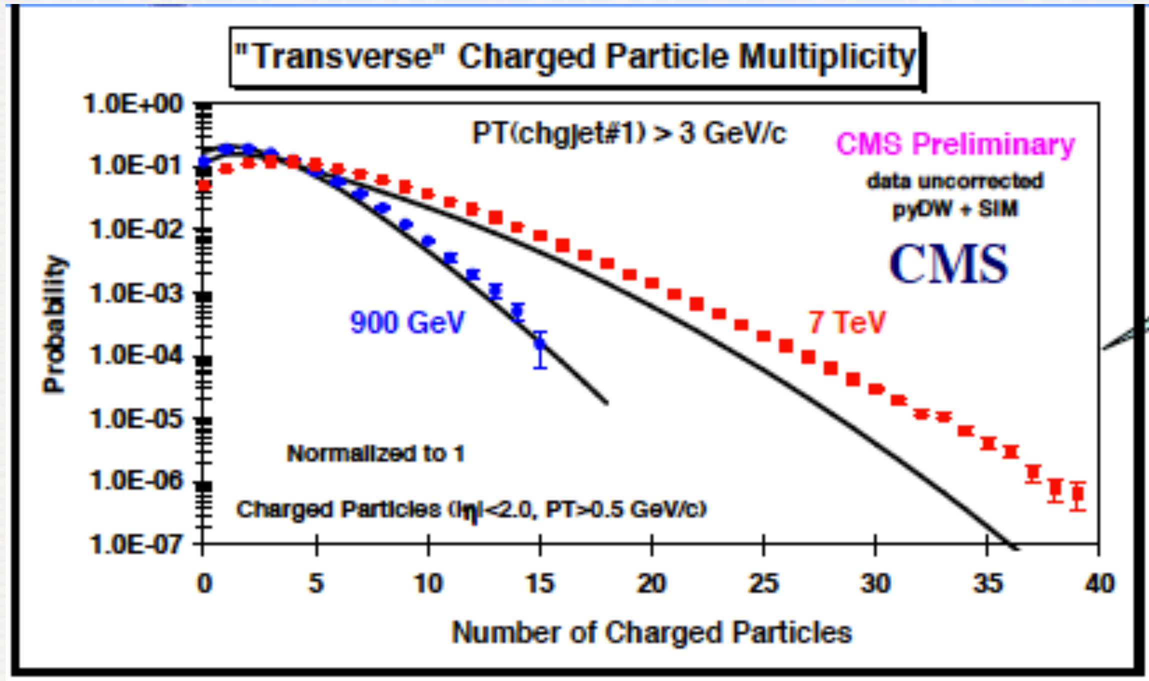
➧ Ratio of the CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged



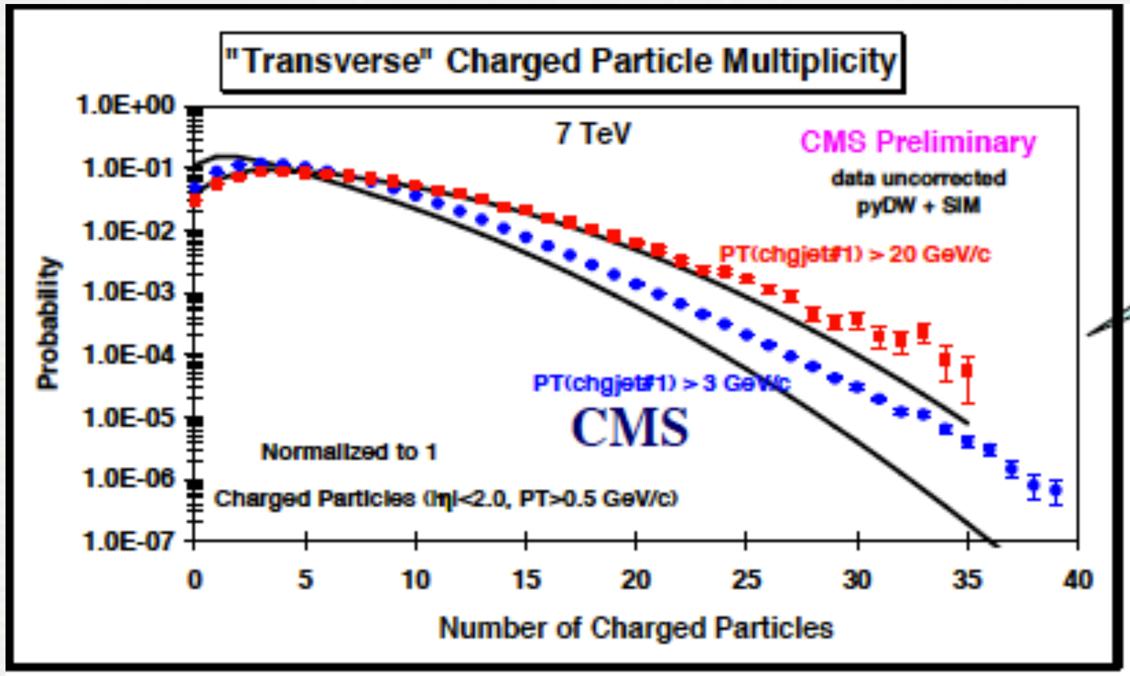
➧ Ratio of the ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged

More soft particles than expected !

Rick Field : Minimum Bias Summary



Same hard scale at two different center-of-mass energies!

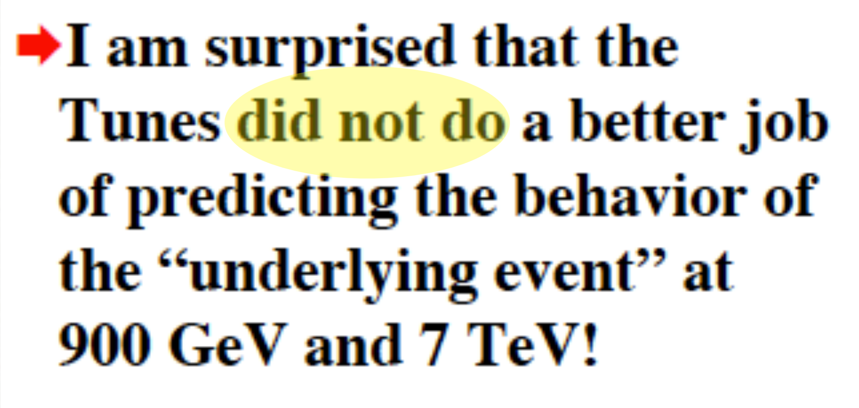


Same center-of-mass energy at two different hard scales!

More high-multiplicity events !

Rick Field : Minimum Bias Summary

Rick seems to be
unpleasantly surprised ...



➡ I am surprised that the Tunes did not do a better job of predicting the behavior of the “underlying event” at 900 GeV and 7 TeV!

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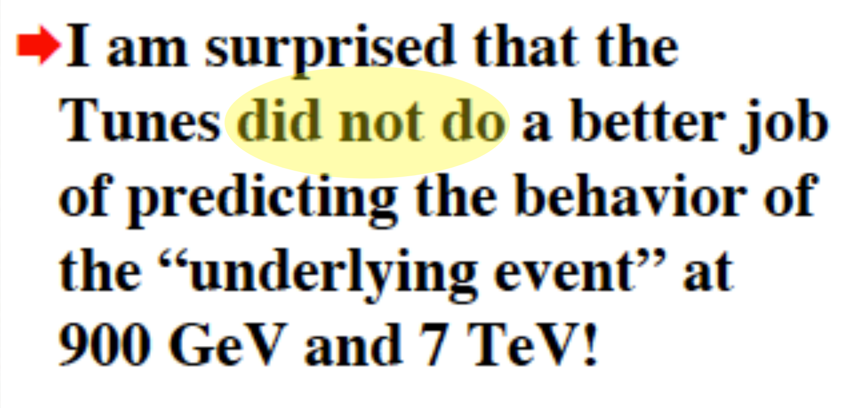

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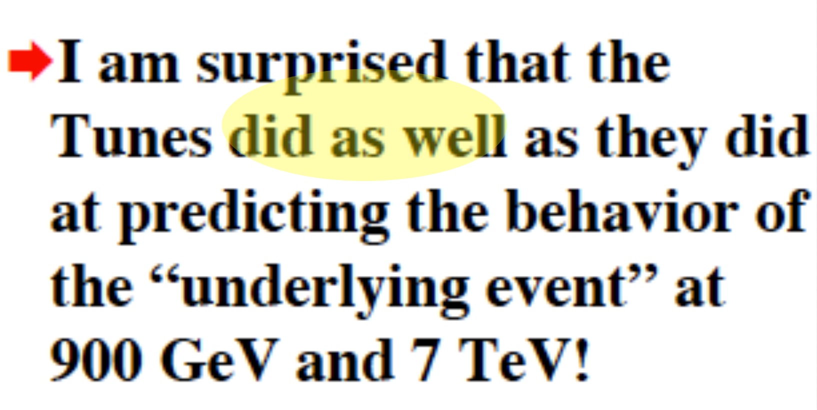

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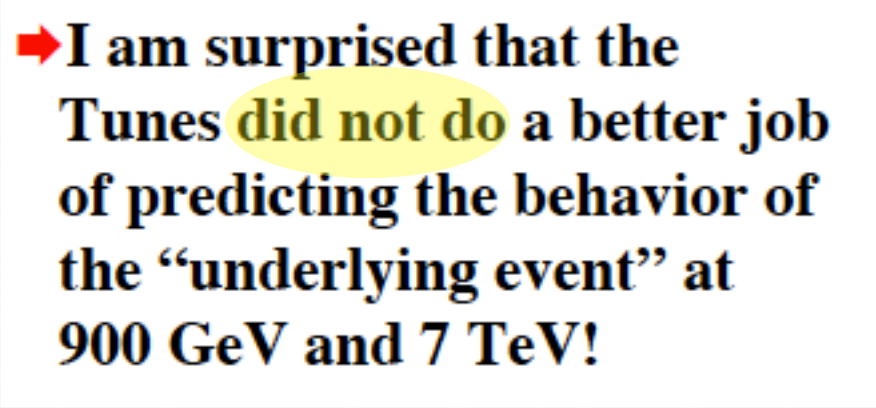

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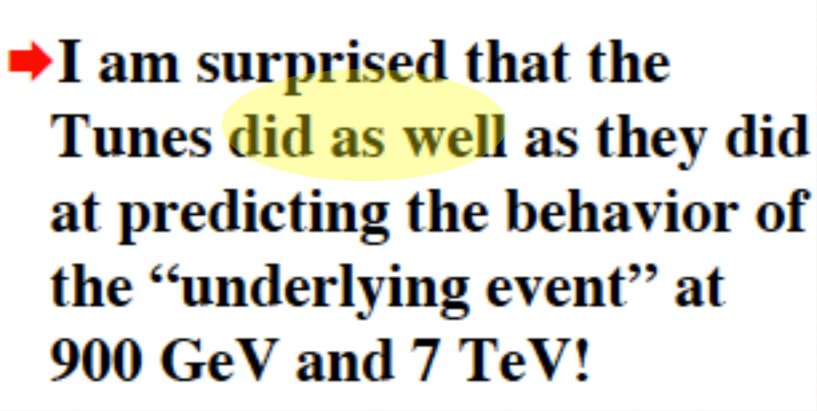

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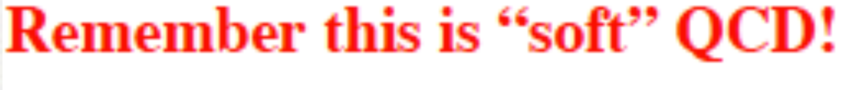
... but in fact he is not surprised at all !



Remember this is “soft” QCD!

Rick Field : Minimum Bias Summary

Rick seems to be
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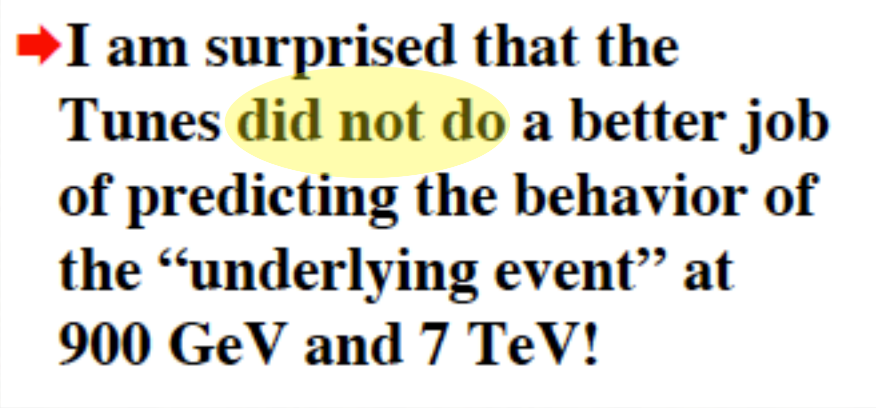

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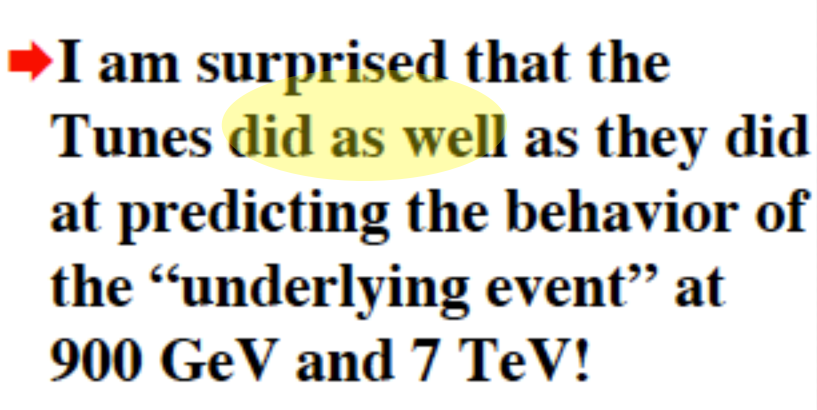

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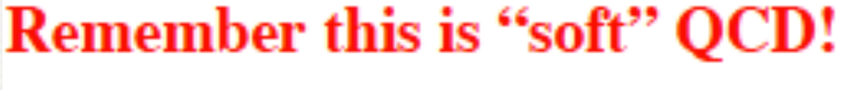


Remember this is “soft” QCD!

... and so am I !

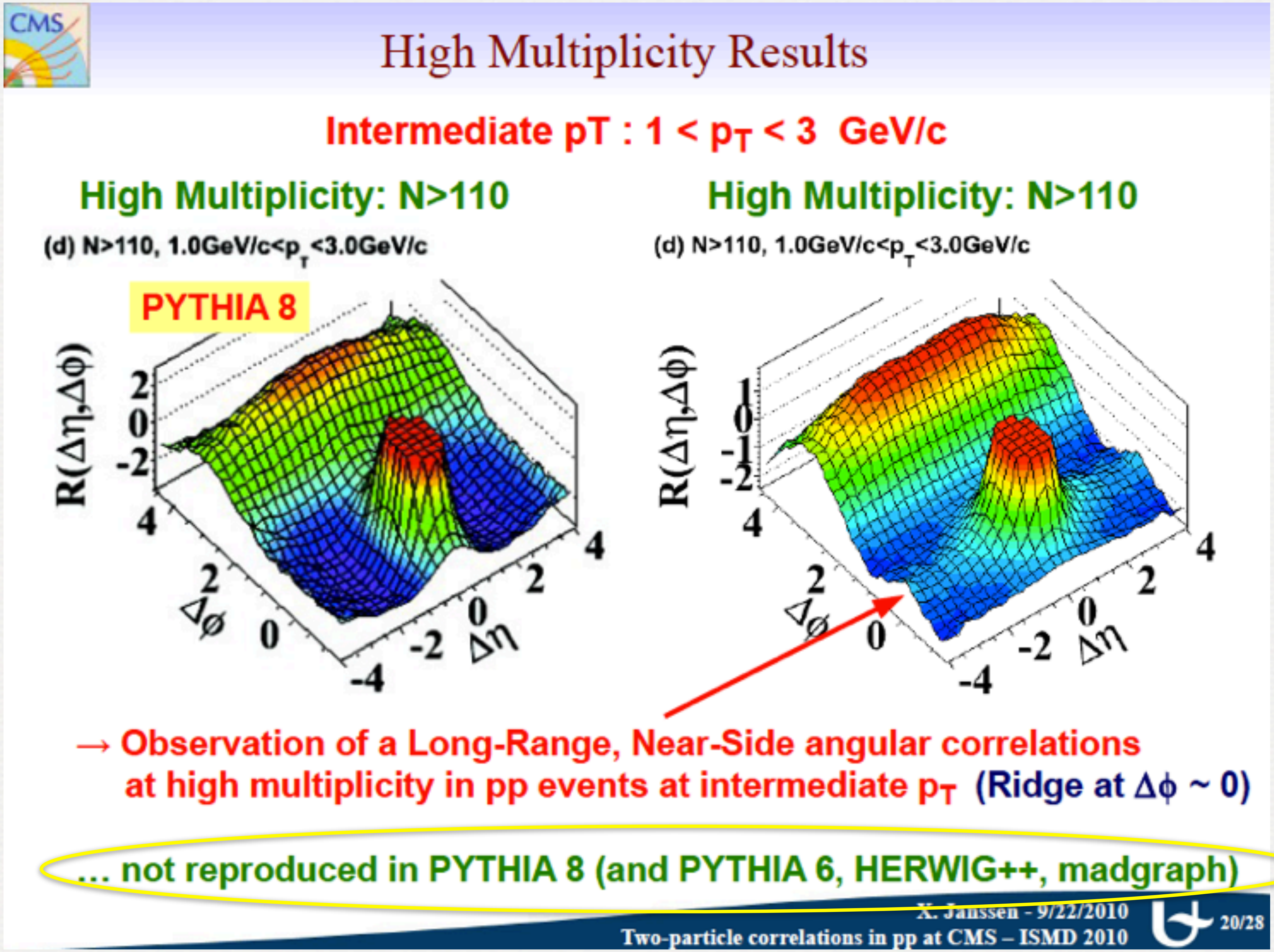
To Pythia Or Not To Be

- Although not being fluent in PYTHIA myself ...
- ... I appreciate that it is an essential tool for the phenomenology
- ... but I am also aware about its physics limitations ...
- ... that one cannot circumvent for ever by retuning ...
- ... but this is likely not going to be a disaster for LHC ...
- ... provided we know what we can predict and what we cannot

Pythia: What Is Missing ...

- N(N)LO corrections to hard processes plus matching with parton showers: this can / will be done !
- first-principle (or at least more precise) description of hadronization (soft processes): little (no) hope !
- semi-hard ($p_T \sim 1$ to 5 GeV) processes responsible for unitarity (gluon saturation, multiparticle interactions) ...
- ... this could be done (pQCD) but it is very hard (since difficult to reconcile with a MC generator)
- need a new type of event generator (field-theoretical language)

There Is Interesting Live (and Physics) Beyond PYTHIA



High Multiplicity Results

Intermediate pT : 1 < p_T < 3 GeV/c

High Multiplicity: N>110

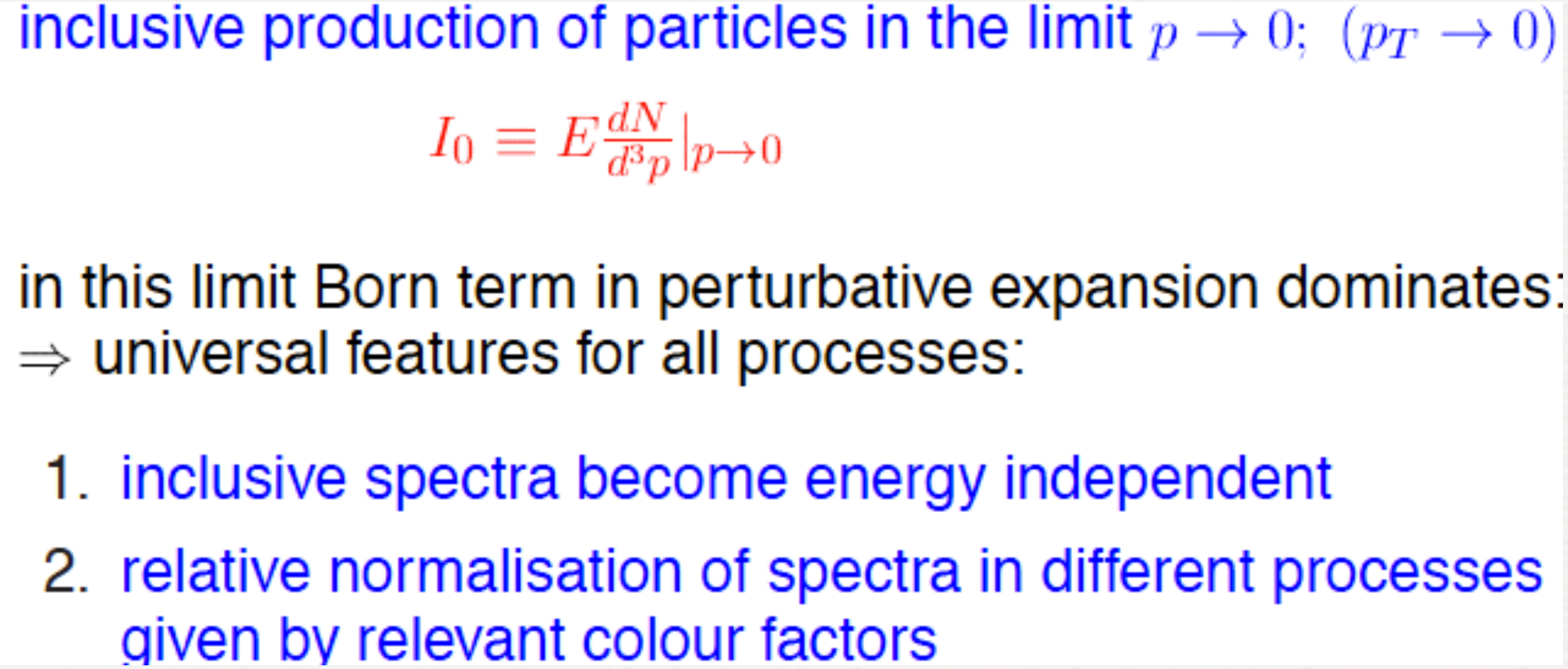
High Multiplicity: N>110

→ Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)

… not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)

Wolfgang Ochs (Max Planck, Münich)

Limiting soft particle emission in e+e-, hadronic and nuclear collisions



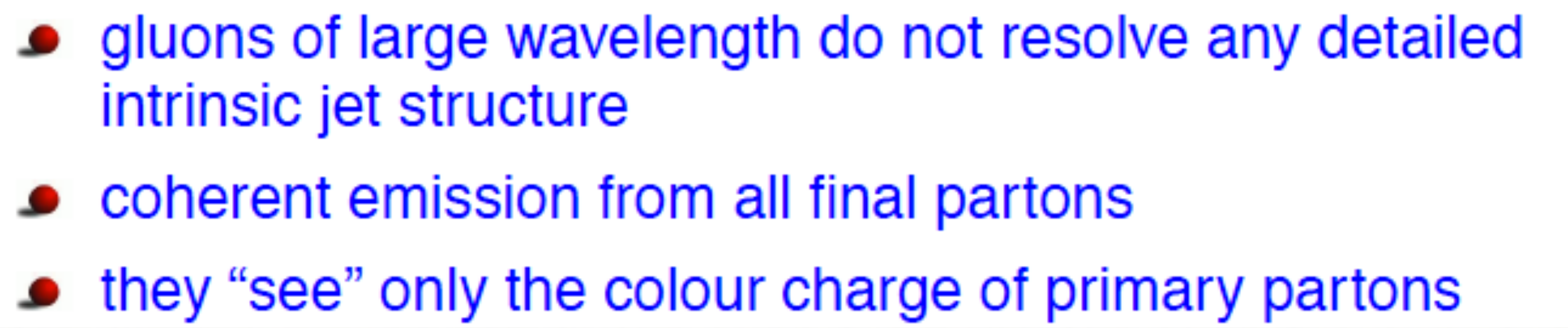
inclusive production of particles in the limit $p \to 0$; $(p_T \to 0)$

$$I_0 \equiv E\frac{dN}{d^3p}|_{p\to 0}$$

in this limit Born term in perturbative expansion dominates:
$\Rightarrow$ universal features for all processes:

1. inclusive spectra become energy independent
2. relative normalisation of spectra in different processes given by relevant colour factors

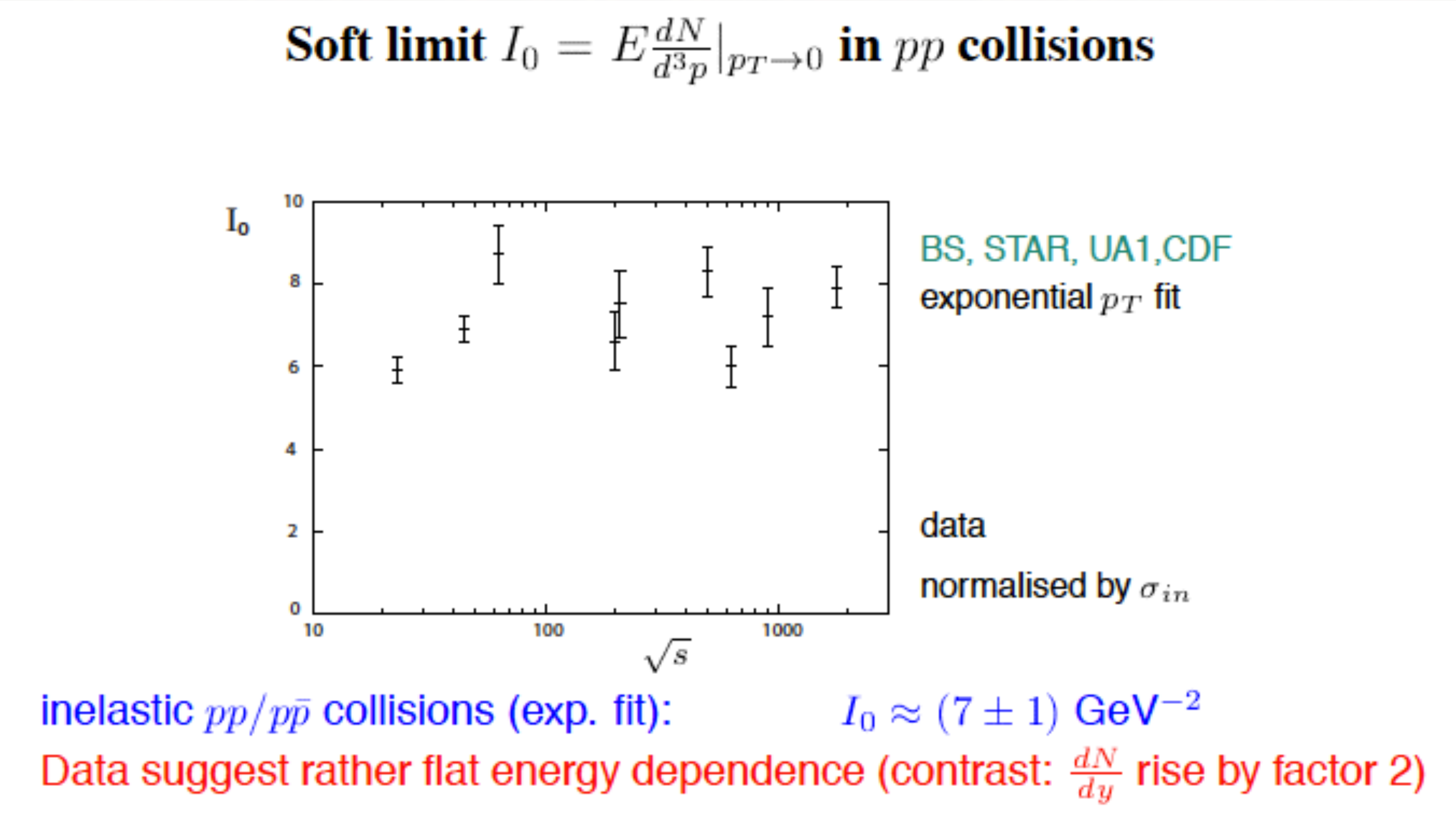
Why ?



- gluons of large wavelength do not resolve any detailed intrinsic jet structure
- coherent emission from all final partons
- they “see” only the colour charge of primary partons

Wolfgang Ochs *(Max Planck, Münich)*

Limiting soft particle emission in e+e-, hadronic and nuclear collisions



Soft limit $I_0 = E\frac{dN}{d^3p}|_{p_T\to 0}$ in pp collisions

BS, STAR, UA1,CDF

exponential p_T fit

data

normalised by σ_{in}

inelastic $pp/p\bar{p}$ collisions (exp. fit): $I_0 \approx (7 \pm 1)$ GeV^{-2}

Data suggest rather flat energy dependence (contrast: $\frac{dN}{dy}$ rise by factor 2)

However, the situation may change at LHC ...

- LHC:
  New incoherent sources: $I_0(pp)$ rising with energy?

Hanna Gröngvist (Univ. Of Helsinki, 3rd Year)

Before finishing her Bachelor, Hanna gave us a talk on :

Matrix Model Duality

(work in collaboration with Volker Schomerus, DESY)

Hanna Grönqvist (Univ. Of Helsinki, 3rd Year)

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~~*Matrix M*[illegible]*l Duality*~~

~~*(work in coll*[illegible]*ora*[illegible]*on with Volker Sch*[illegible]*nerus, DESY)*~~

Hanna Grönqvist (Univ. Of Helsinki, 3rd Year)

Before finishing her Bachelor, Hanna gave us a talk on :

~~*Matrix Model Duality*~~

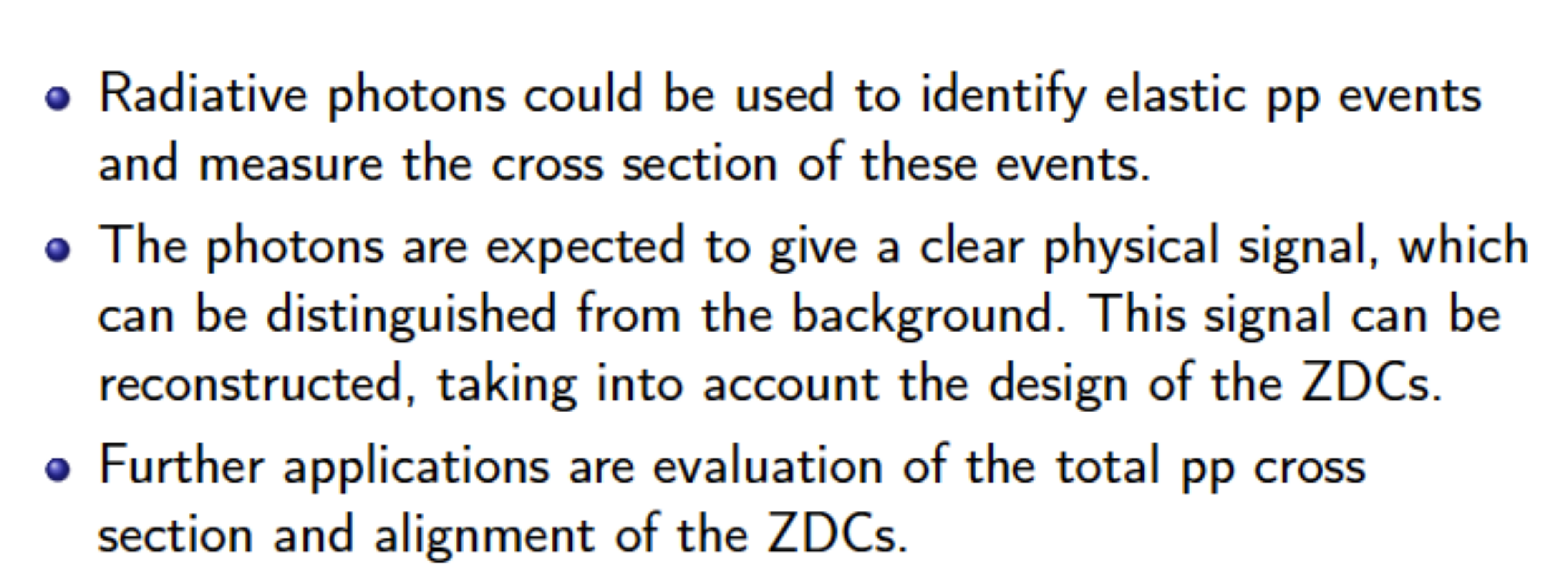
~~*(work in collaboration with Volker Schomerus, DESY)*~~

Sorry, Hanna is working on string theory only during vacations !

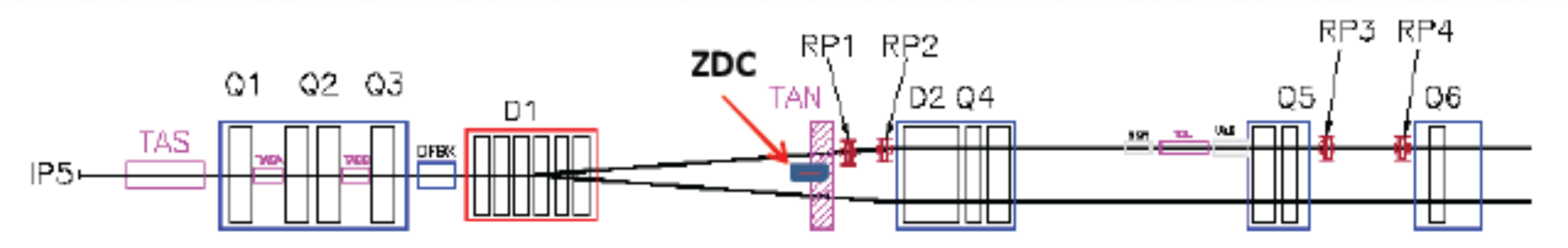
Hanna Grönqvist (Univ. Of Helsinki, **3rd Year**)

Detecting Elastic pp Scattering by Radiative Photons at the LHC

Bremsstrahlung photons at LHC would be interesting since



- Radiative photons could be used to identify elastic pp events and measure the cross section of these events.
- The photons are expected to give a clear physical signal, which can be distinguished from the background. This signal can be reconstructed, taking into account the design of the ZDCs.
- Further applications are evaluation of the total pp cross section and alignment of the ZDCs.

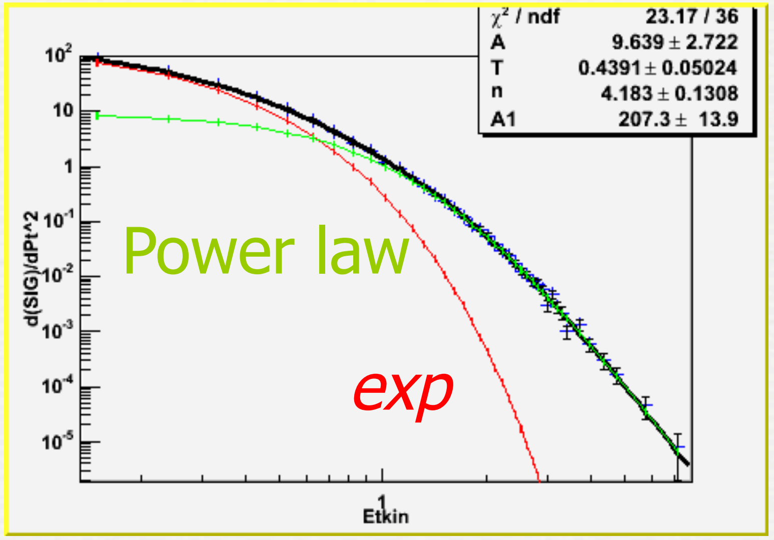


Andrei Rostovtsev (ITEP)

Inclusive hadron production spectra in collider experiments

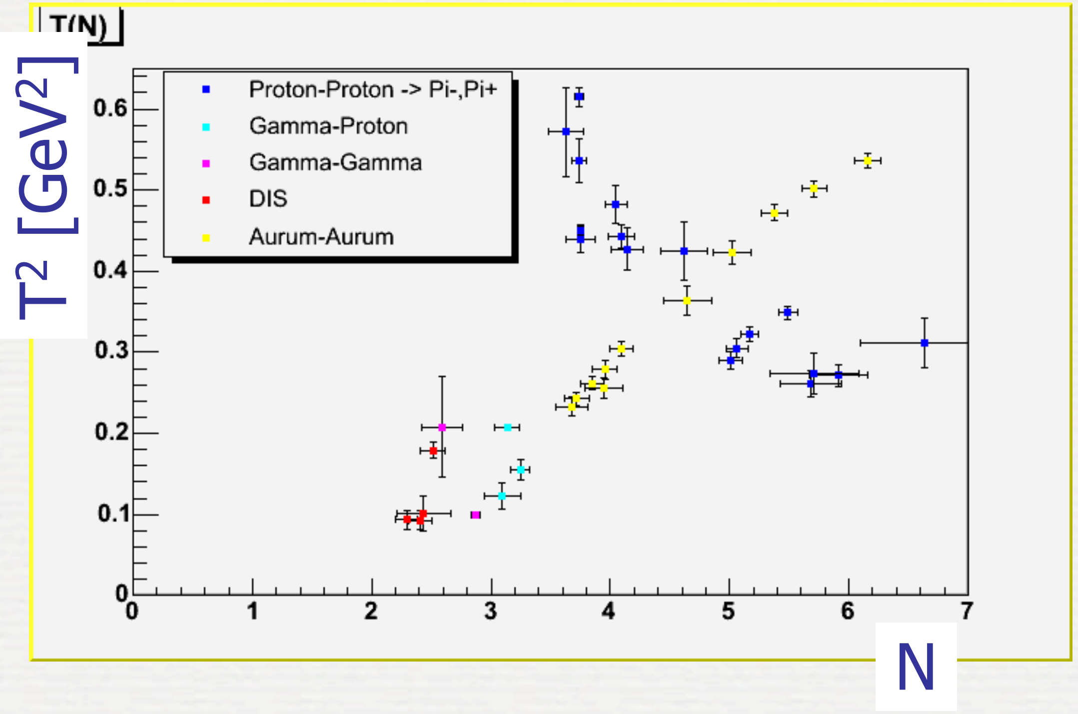
Describe spectra with a sum of exponential and power law

$$\frac{d\sigma}{dP_T^2} = A_e \cdot \exp(-E_T^{kin}/T_e) + A/(1+P_T^2/T^2N)^N$$



The data fit requires both "thermal" and "non-thermal" contributions

Parameter map

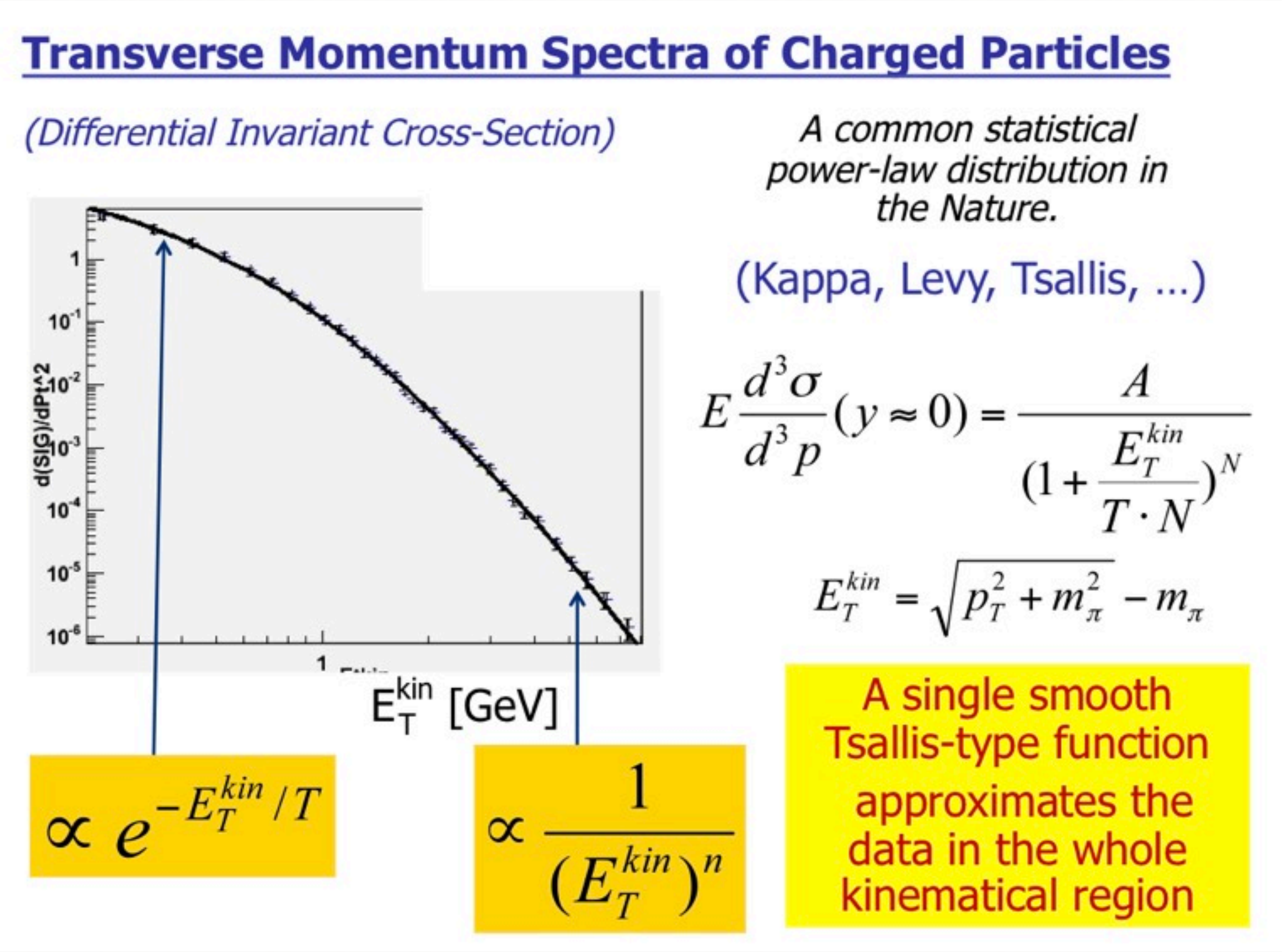


Heavy Ion mid centrality (minimum bias) interactions look similar to single pp minimum bias interactions at the same collision energy

What makes *AuAu* and *pp* spectra different in shape? – Boltzman contrn.

Andrei Rostovtsev (ITEP)

Inclusive hadron production spectra in collider experiments



Transverse Momentum Spectra of Charged Particles

(Differential Invariant Cross-Section)

A common statistical power-law distribution in the Nature.

(Kappa, Levy, Tsallis, …)

$$E\frac{d^3\sigma}{d^3p}(y\approx 0)=\frac{A}{\left(1+\frac{E_T^{kin}}{T\cdot N}\right)^N}$$

$$E_T^{kin}=\sqrt{p_T^2+m_\pi^2}-m_\pi$$

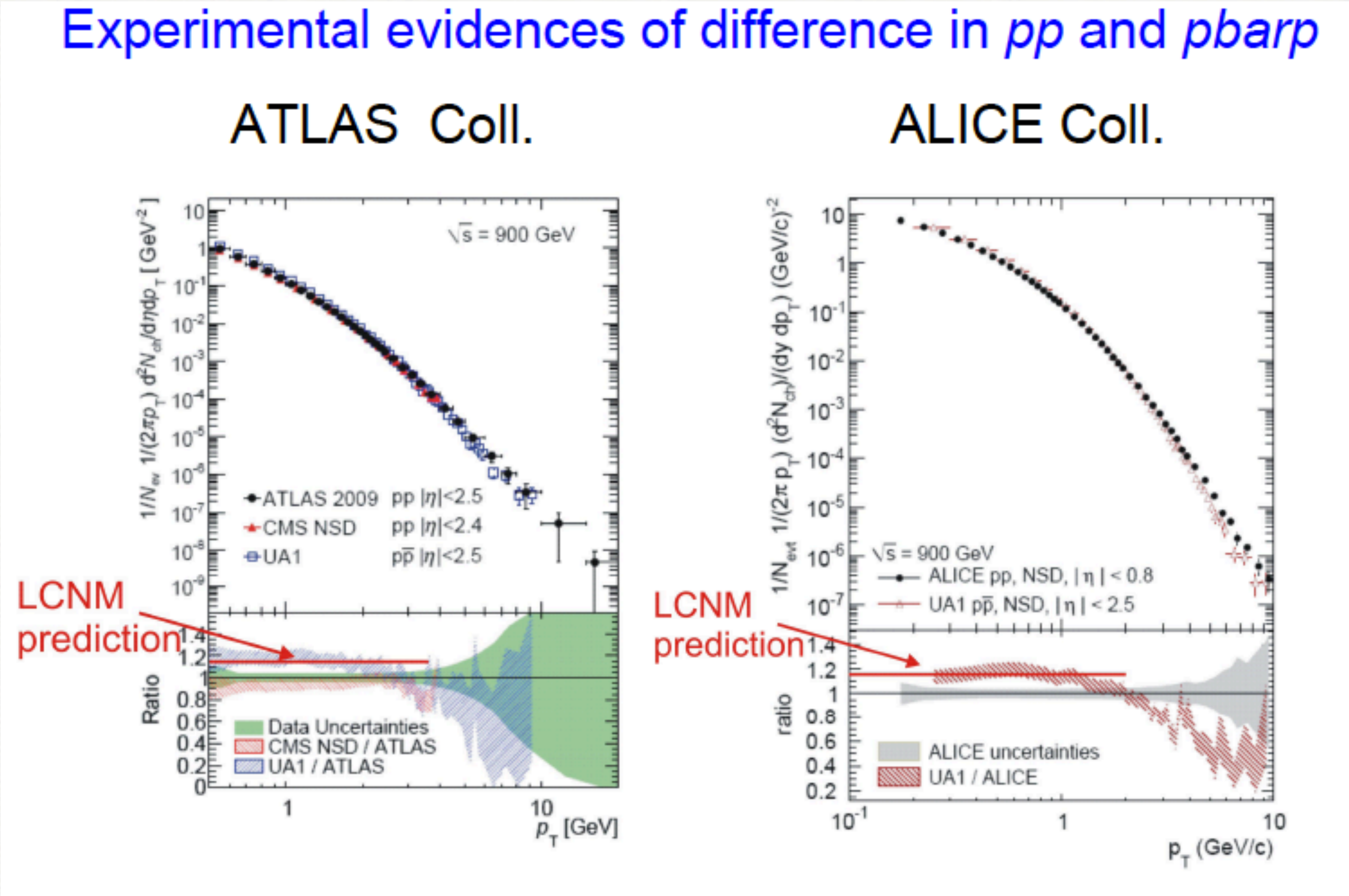
$$\propto e^{-E_T^{kin}/T}$$

$$\propto \frac{1}{(E_T^{kin})^n}$$

A single smooth Tsallis-type function approximates the data in the whole kinematical region

Victor Abramovsky (Novgorod Univ.)

Inclusive cross sections of p+p and p+pbar scattering



Experimental evidences of difference in *pp* and *pbarp*

ATLAS Coll.

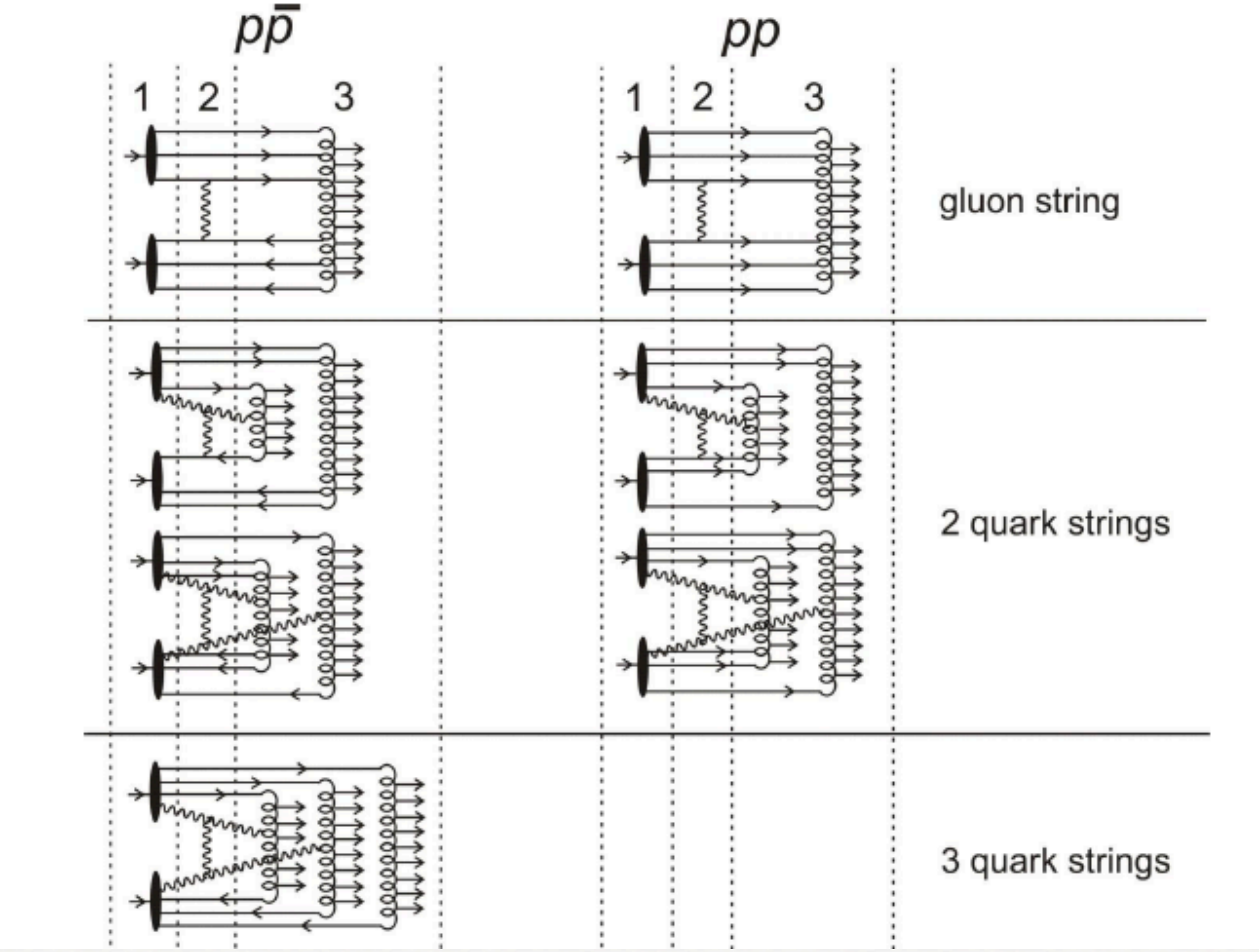
ALICE Coll.

LCNM prediction

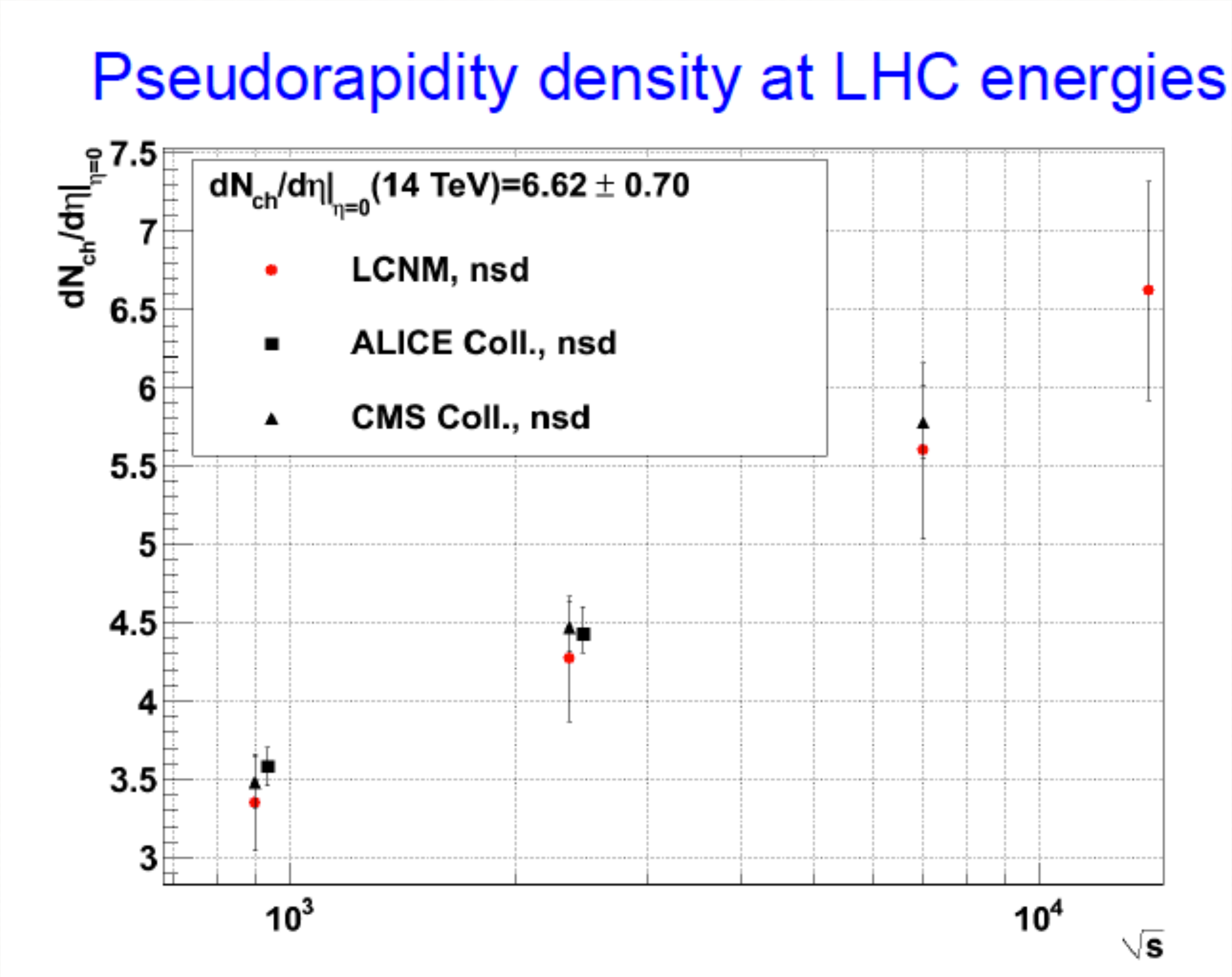
LCNM prediction

Victor Abramovsky (Novgorod Univ.)

Low Constituents Number Model (LCNM)



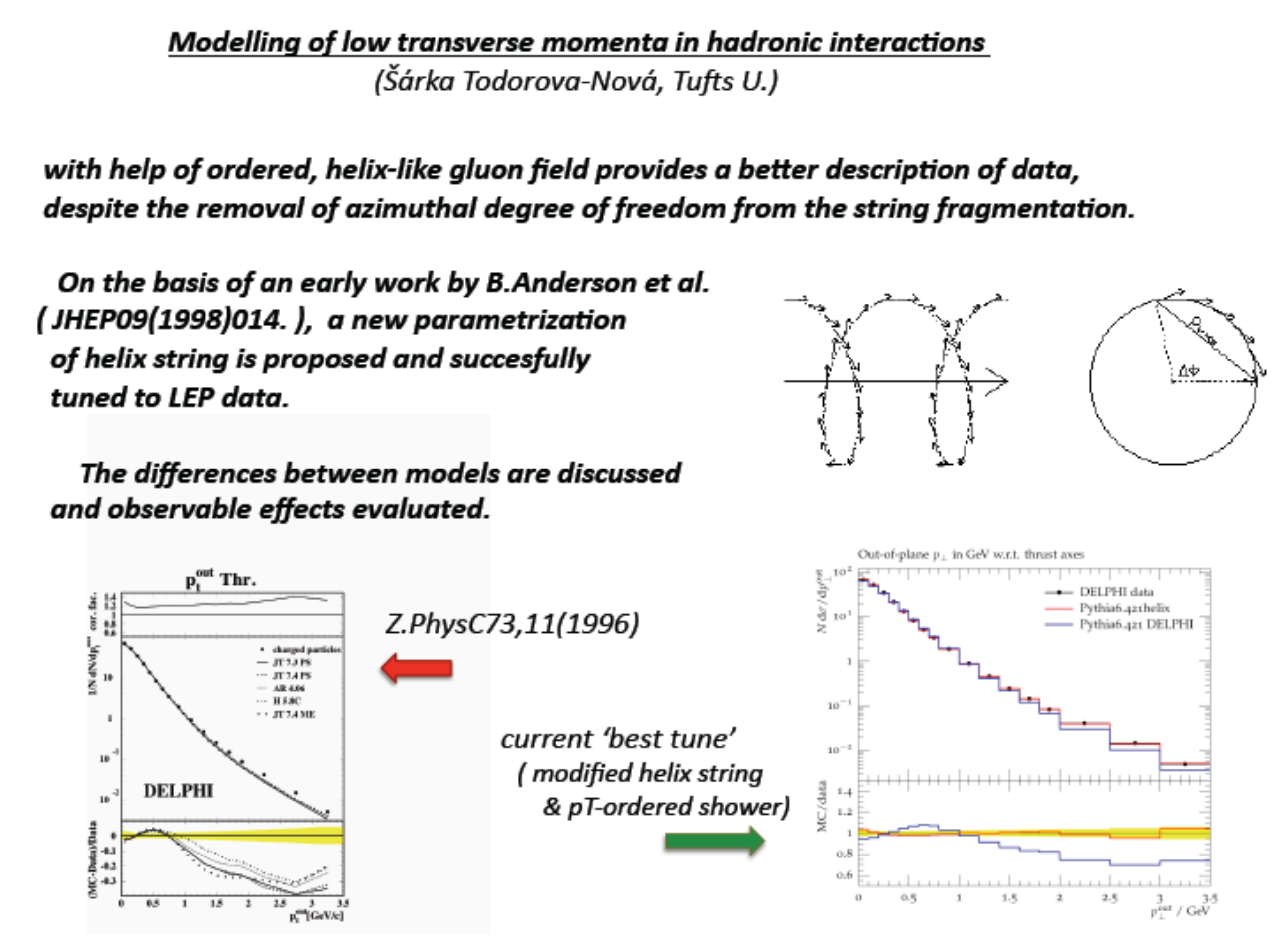
Victor Abramovsky (Novgorod Univ.)



Pseudorapidity density at LHC energies

Sarka Todorova (Tufts University)

Modelling of low transverse momentum in hadronic interactions



Modelling of low transverse momenta in hadronic interactions

(Šárka Todorova-Nová, Tufts U.)

with help of ordered, helix-like gluon field provides a better description of data, despite the removal of azimuthal degree of freedom from the string fragmentation.

On the basis of an early work by B.Anderson et al. (JHEP09(1998)014.), a new parametrization of helix string is proposed and succesfully tuned to LEP data.

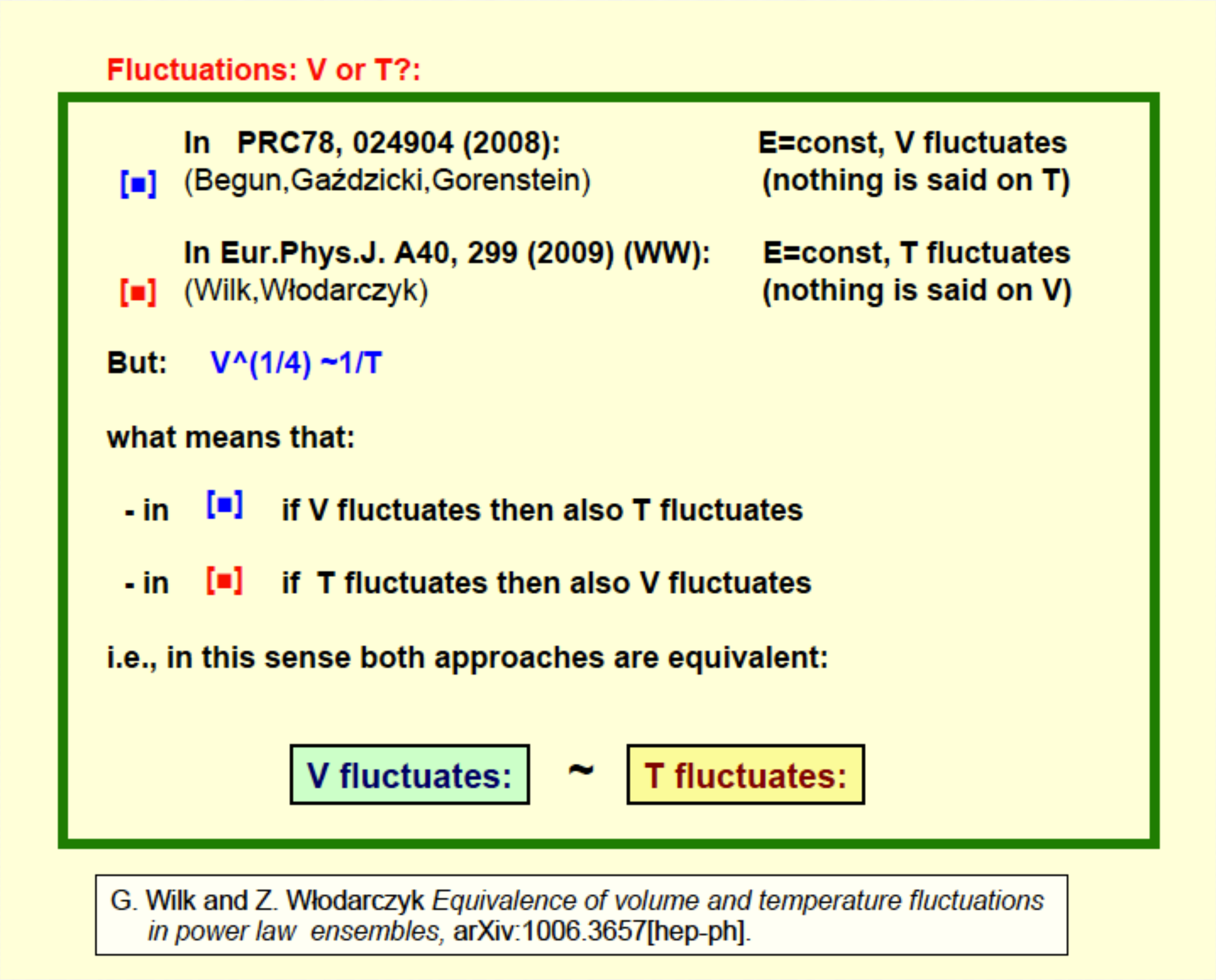
The differences between models are discussed and observable effects evaluated.

Z.PhysC73,11(1996)

current 'best tune' (modified helix string & pT-ordered shower)

Grzegorz Wilk *(Andrzej Soltan Inst., Warsaw)*

Power-law ensembles: fluctuations of volume or



Fluctuations: V or T?:

[🟦]	**In PRC78, 024904 (2008):** (Begun,Gaździcki,Gorenstein)	**E=const, V fluctuates** **(nothing is said on T)**
[🟥]	**In Eur.Phys.J. A40, 299 (2009) (WW):** (Wilk,Włodarczyk)	**E=const, T fluctuates** **(nothing is said on V)**

But: **V^(1/4) ~1/T**

what means that:

- **in** [🟦] **if V fluctuates then also T fluctuates**
- **in** [🟥] **if T fluctuates then also V fluctuates**

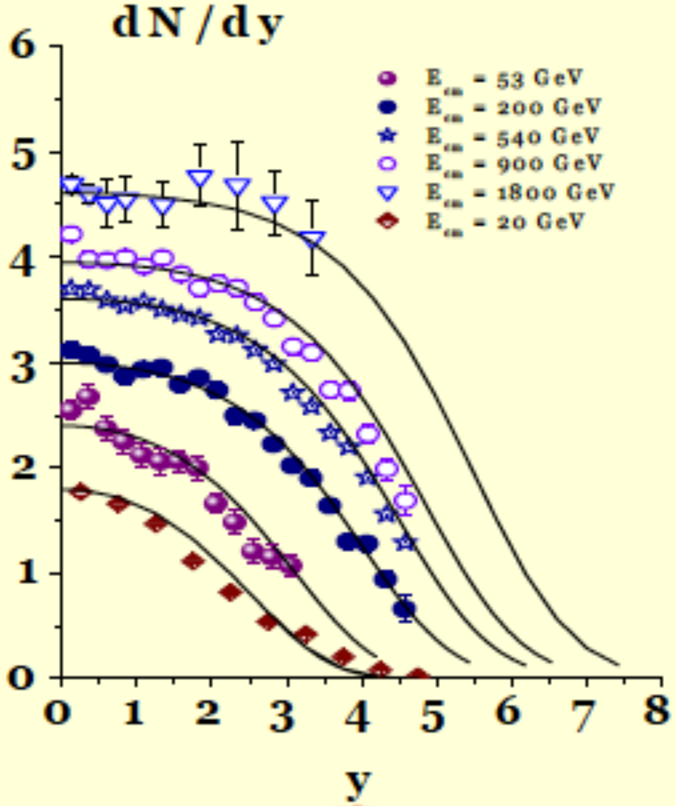
i.e., in this sense both approaches are equivalent:

V fluctuates: ~ **T fluctuates:**

G. Wilk and Z. Włodarczyk *Equivalence of volume and temperature fluctuations in power law ensembles,* arXiv:1006.3657[hep-ph].

Grzegorz Wilk (cont)

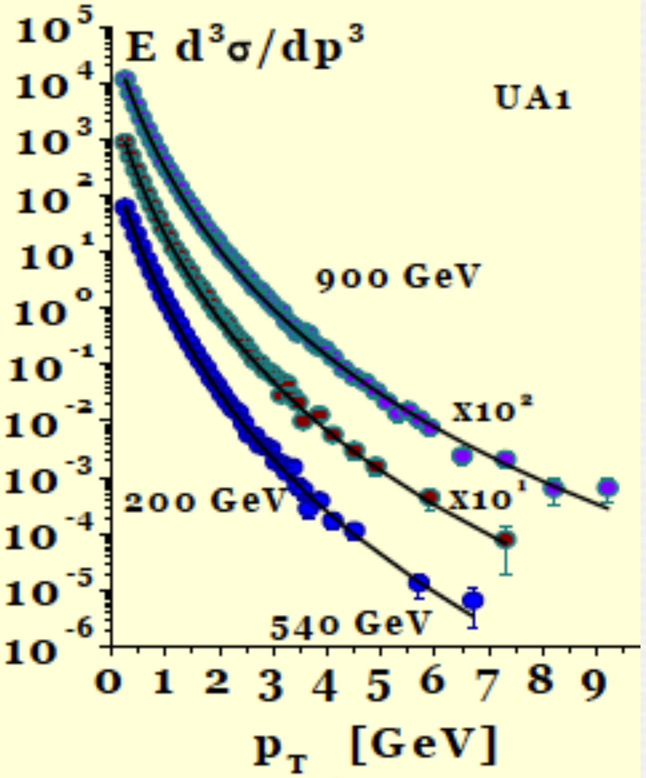
Different observables -> different fluctuations -> different parametrs q



q from pp collisions
(or from peripheral
AA collisions):

$q_L > q_T$

$q_L \approx q$ obtained
from multiplicity
distribution P(N)
(which has NBD form)



$S^{1/2}$	q_L	$T_L=1/\beta_L$
200	1.203	12.12
546	1.262	22.38
900	1.291	29.47

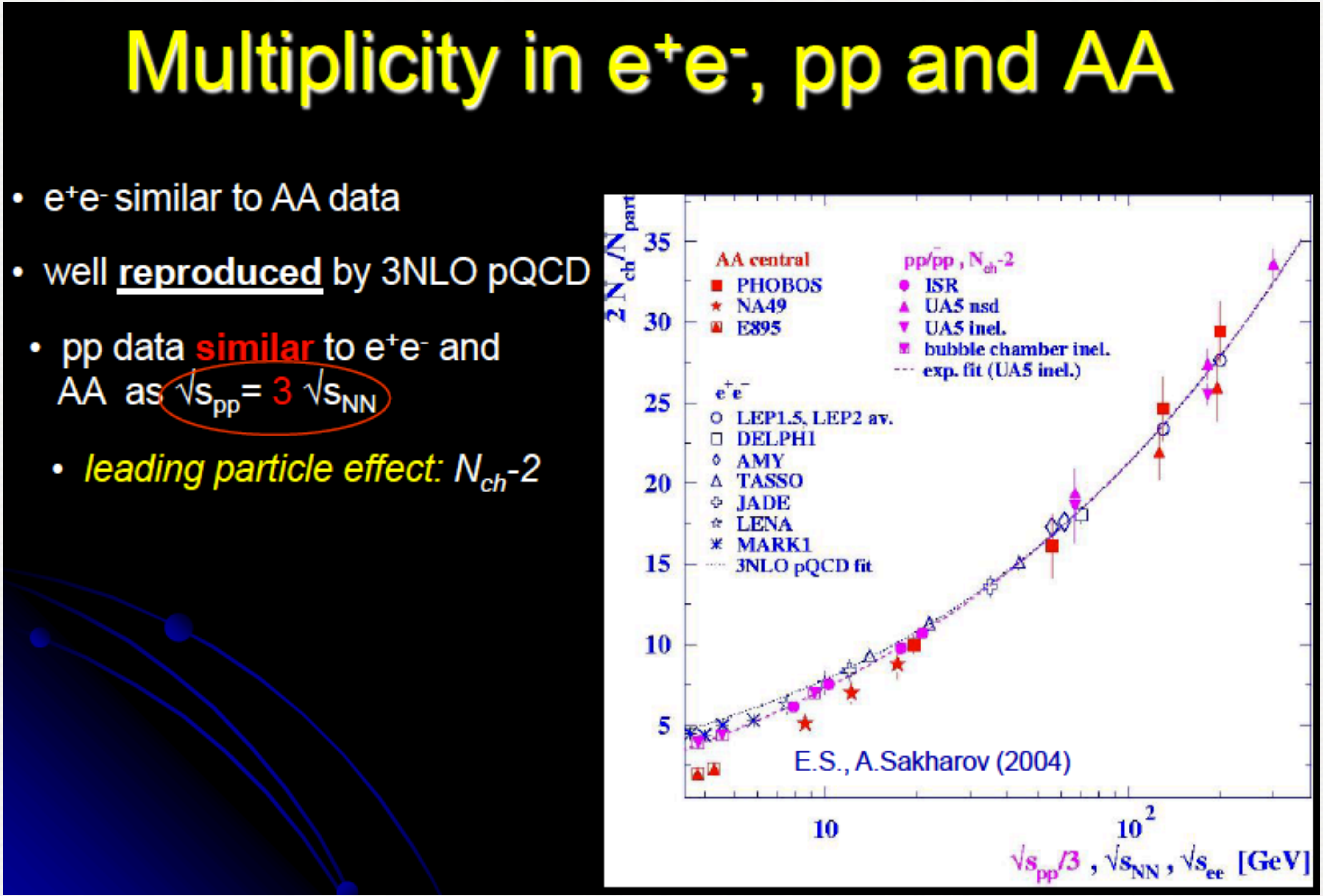
In general:
bigger (q-1) means
bigger fluctuations,
q=1 means
no fluctuations.

$S^{1/2}$	q_T	$T_T=1/\beta_T$
200	1.095	0.134
546	1.105	0.135
900	1.110	0.140

Navarra,Utyuzh,Wilk,Włodarczyk, Physica **A340** (2004) 467

Edward Sarkisyan-Grinbaum (Univ. Texas/CERN)

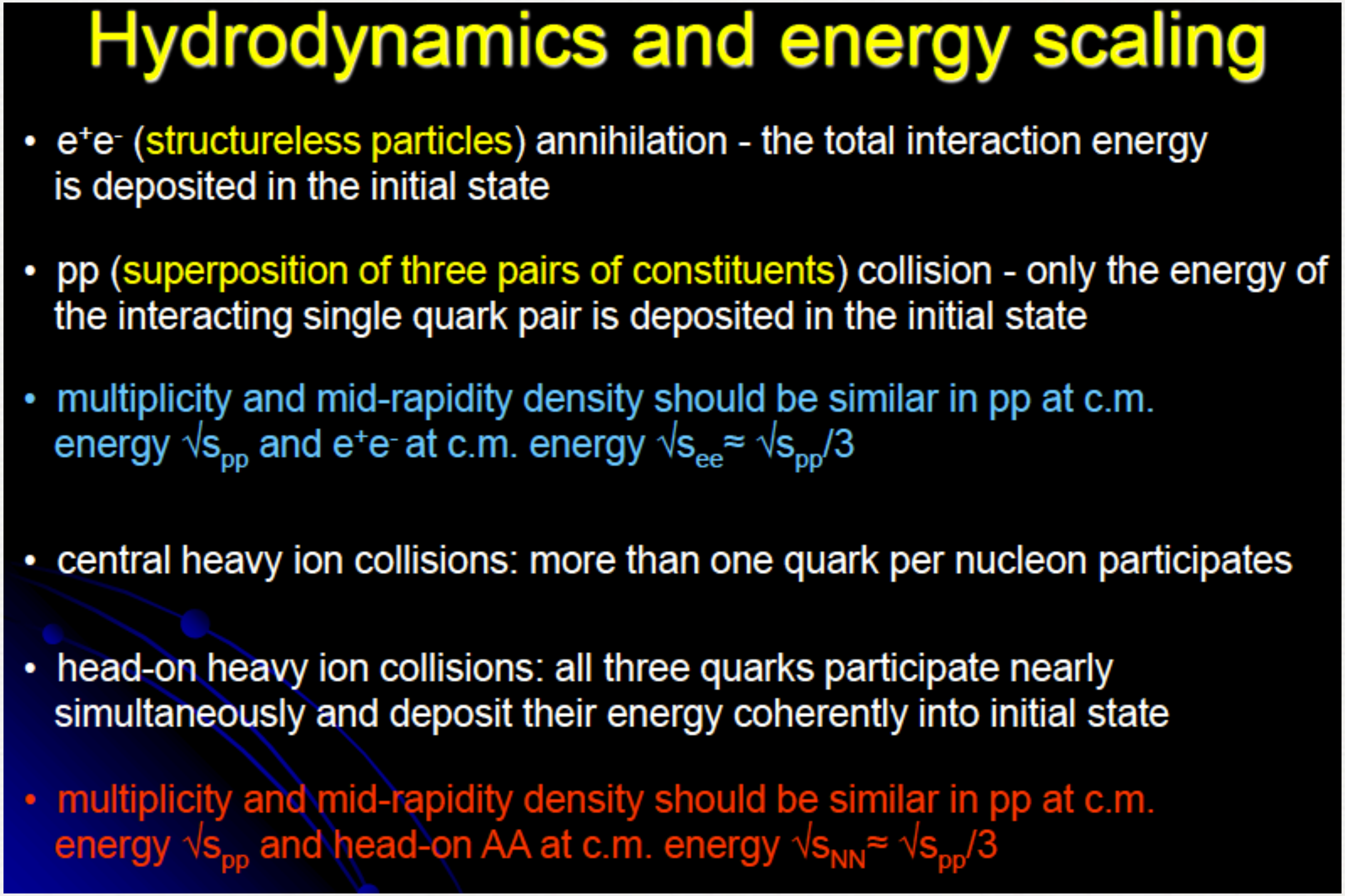
Multihadron production in nuclear and particle interactions



Multiplicity in e^+e^-, pp and AA

- e^+e^- similar to AA data
- well **reproduced** by 3NLO pQCD
  - pp data similar to e^+e^- and AA as $\sqrt{s_{pp}} = 3\sqrt{s_{NN}}$
    - *leading particle effect:* N_{ch}-2

Edward Sarkisyan-Grinbaum (cont.)

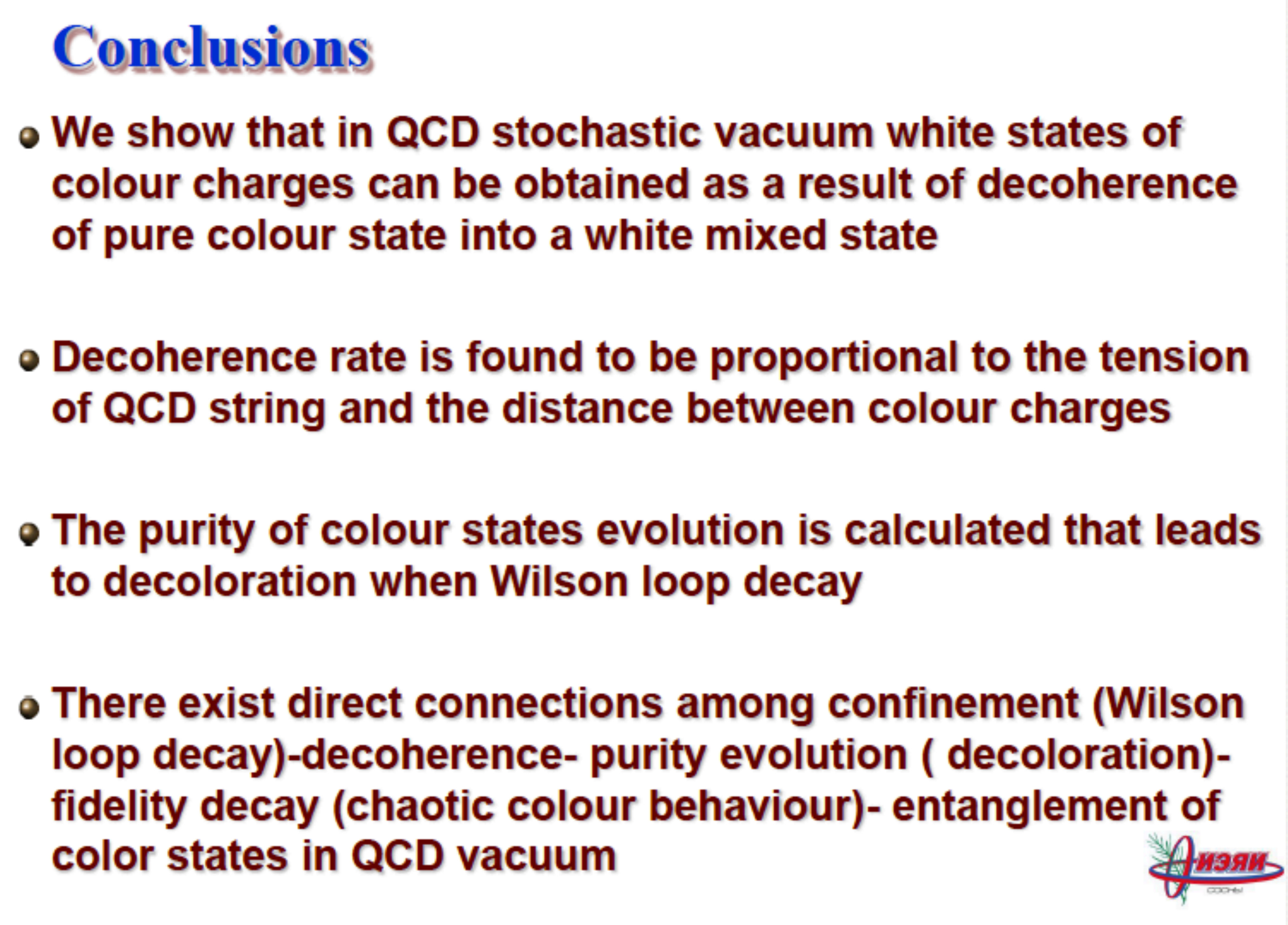


Hydrodynamics and energy scaling

- e^+e^- (structureless particles) annihilation - the total interaction energy is deposited in the initial state
- pp (superposition of three pairs of constituents) collision - only the energy of the interacting single quark pair is deposited in the initial state
- multiplicity and mid-rapidity density should be similar in pp at c.m. energy $\sqrt{s_{pp}}$ and e^+e^- at c.m. energy $\sqrt{s_{ee}} \approx \sqrt{s_{pp}}/3$
- central heavy ion collisions: more than one quark per nucleon participates
- head-on heavy ion collisions: all three quarks participate nearly simultaneously and deposit their energy coherently into initial state
- multiplicity and mid-rapidity density should be similar in pp at c.m. energy $\sqrt{s_{pp}}$ and head-on AA at c.m. energy $\sqrt{s_{NN}} \approx \sqrt{s_{pp}}/3$

Viacheslav Kuvshinov *(JIPNR, Minsk)*

Wilson loop decay and quark decoloration in QCD vacuum



Conclusions

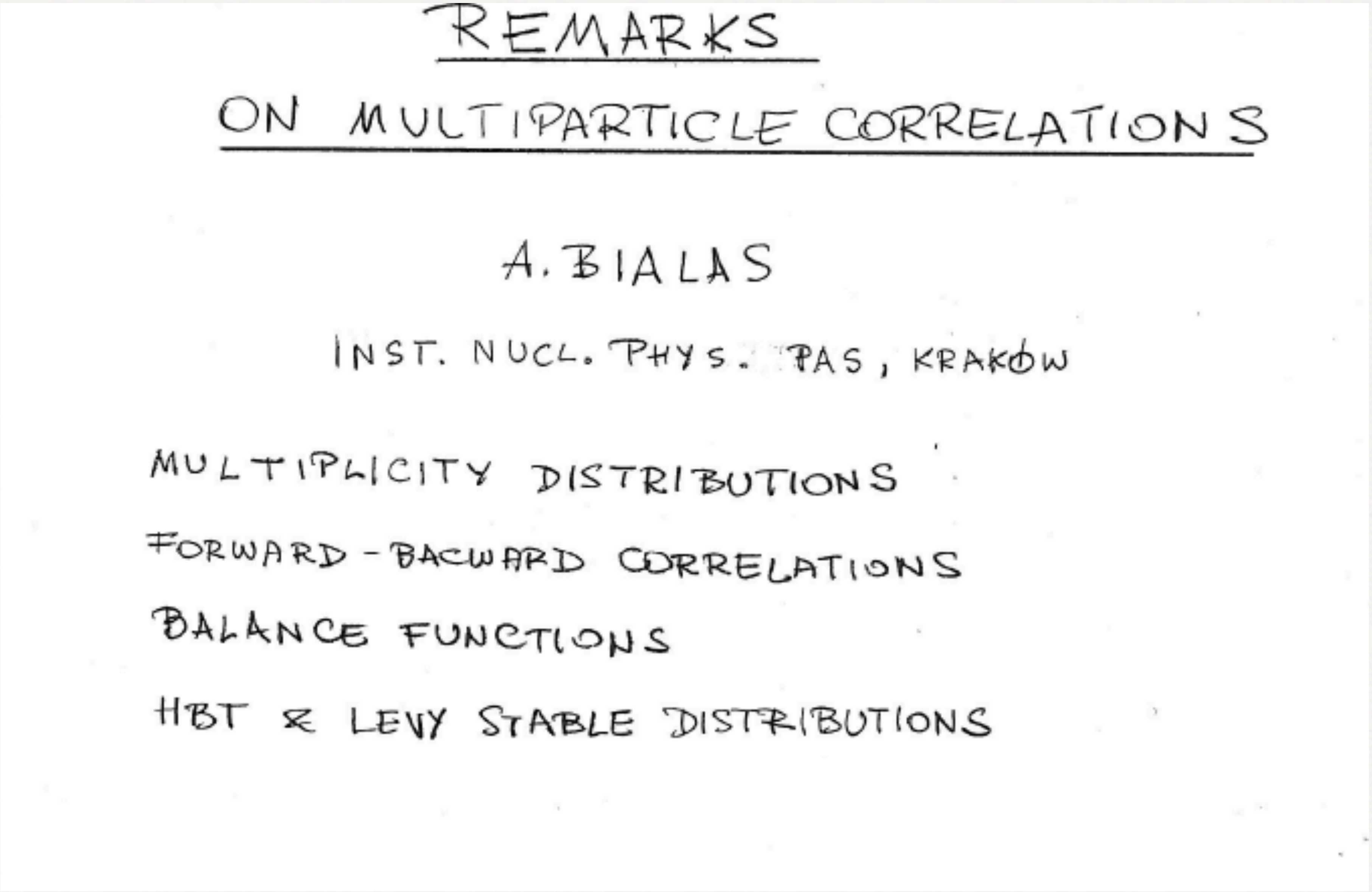
- We show that in QCD stochastic vacuum white states of colour charges can be obtained as a result of decoherence of pure colour state into a white mixed state
- Decoherence rate is found to be proportional to the tension of QCD string and the distance between colour charges
- The purity of colour states evolution is calculated that leads to decoloration when Wilson loop decay
- There exist direct connections among confinement (Wilson loop decay)-decoherence- purity evolution (decoloration)-fidelity decay (chaotic colour behaviour)- entanglement of color states in QCD vacuum

Multiplarticle Correlations

Krzysztof Fialkowski & Edward Sarkisyan-Grinbaum

- Event and jet shapes
- Medium properties from jet probes
- Fragmentation, recombination and correlations

Andrzej Bialas (Inst. Nucl. Phys. PAS, Krakow)



REMARKS ON MULTIPARTICLE CORRELATIONS

A. BIALAS

INST. NUCL. PHYS. PAS, KRAKÓW

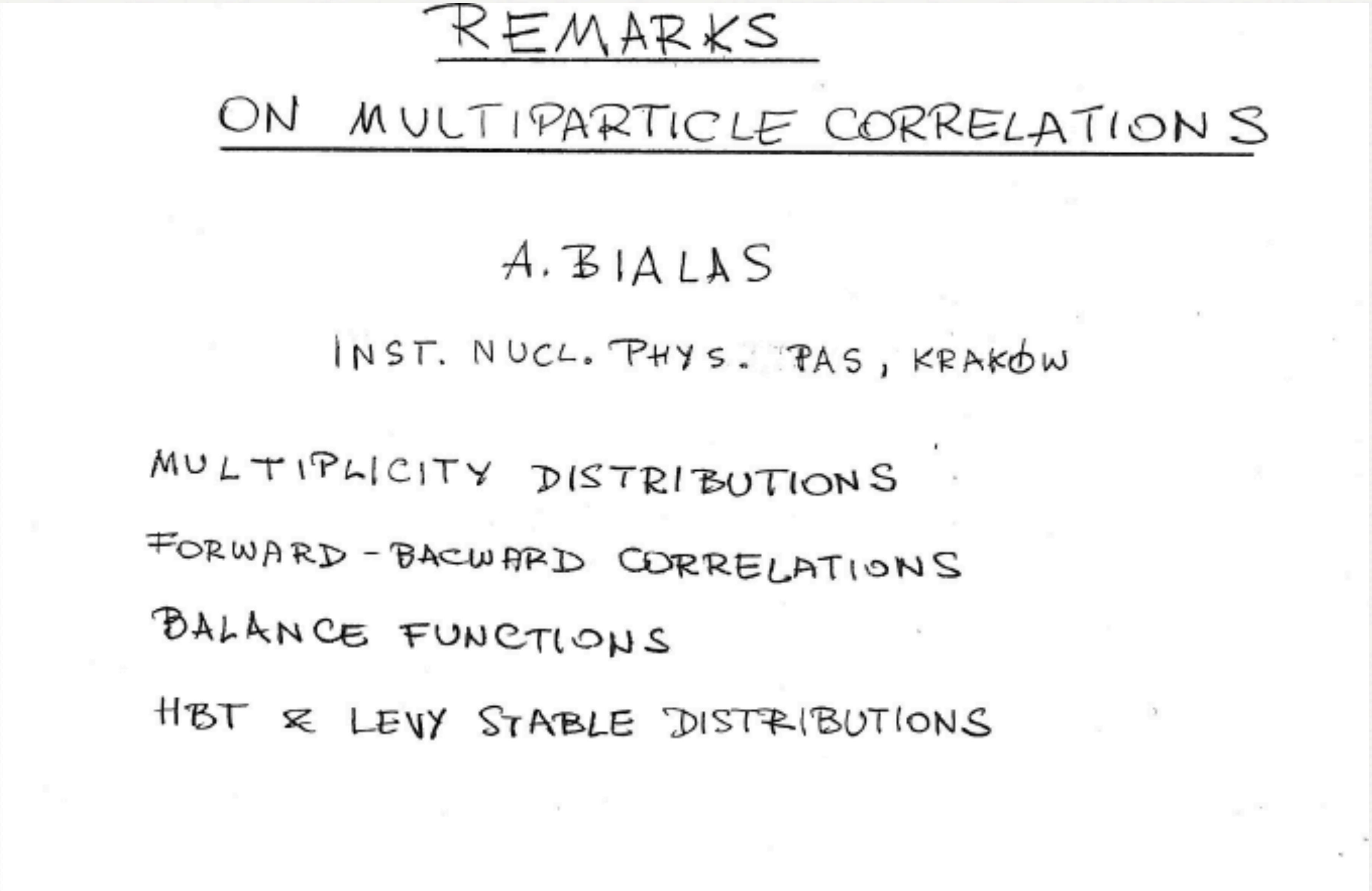
MULTIPLICITY DISTRIBUTIONS

FORWARD - BACWARD CORRELATIONS

BALANCE FUNCTIONS

HBT & LEVY STABLE DISTRIBUTIONS

Andrzej Bialas (Inst. Nucl. Phys. PAS, Krakow)



REMARKS ON MULTIPARTICLE CORRELATIONS

A. BIALAS

INST. NUCL. PHYS. PAS, KRAKÓW

MULTIPLICITY DISTRIBUTIONS

FORWARD - BACWARD CORRELATIONS

BALANCE FUNCTIONS

HBT & LEVY STABLE DISTRIBUTIONS

I cannot explain that better than Andrej !

Tamas Csorgo (Harvard University)

In-medium η′ mass reduction from Bose-Einstein correlation in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions at RHIC

What is the fate of a meson in the medium preduced in AA ?

What about the heaviest would-be Goldstone boson η' ?

From SSB, One expects massless mesons.
However, the flavour symmetry is inexact.

RHIC data (BE correls + dileptons) suggest this mass is reduced.
How to verify that and compute the reduction ?

Look at particle abundancy (Hagedorn model) !

$$\sigma_i \sim (m/2\pi)^{3/2} e^{-m/T_H}$$

T_H~160 MeV Hagedorn-temperature

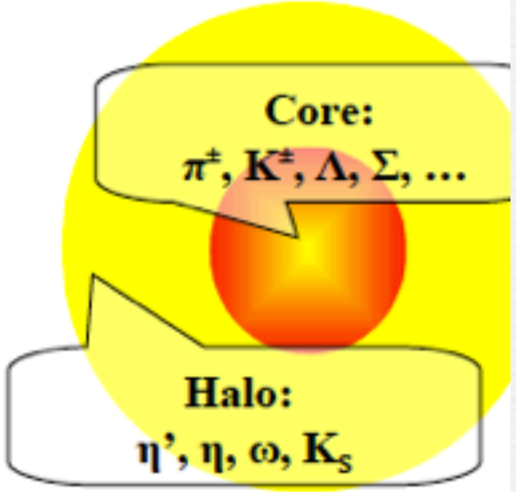
Consequence of the reduced mass:
An increased abundancy of η' mesons

This can be inferred from HBT correlations !

- Pions from QM freezeout
  - Primordial (from phase transition)
  - Fast decaying resonances
  - Long-life resonances (ω,η,η',K_S^0) → Halo

Primordial and fast decaying resonances: Core

T. Cs, B. Lörstad, hep-ph/9411307



- Correlation

$$C(\Delta k, K) \simeq 1 + \lambda_* R_c(\Delta k, K) \qquad R_c(\Delta k, K) = \frac{|\tilde{S}_c(\Delta k, K)|^2}{|\tilde{S}_c(\Delta k = 0, K = p)|^2}$$

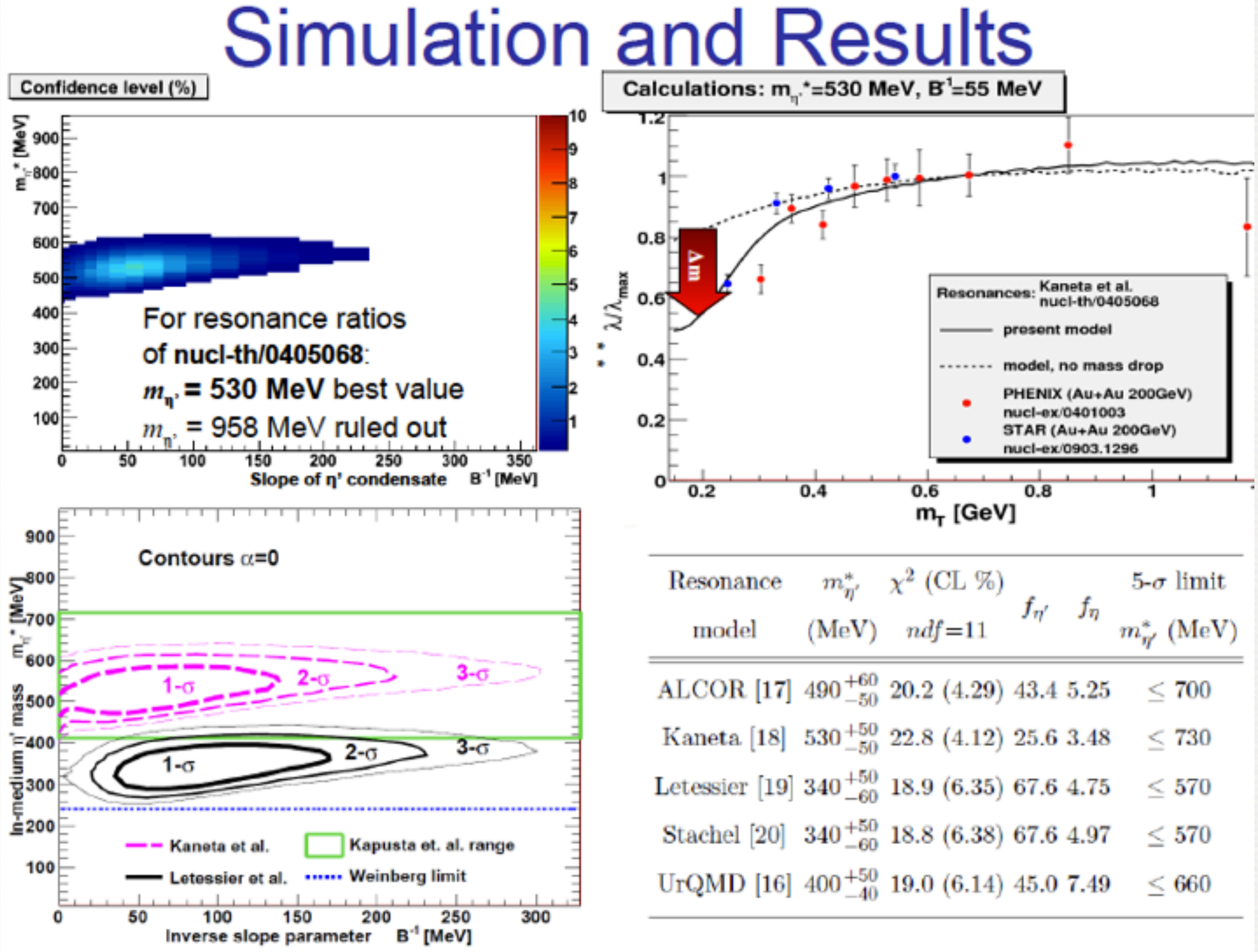
- Intercept $\lambda_*(m_t) = \left[\frac{N^{\pi^+}_{core}(m_t)}{N^{\pi^+}_{core}(m_t) + N^{\pi^+}_{halo}(m_t)}\right]^2$

$$N^{\pi^+}_{halo} = N_{\omega\to\pi^+} + N_{\eta\to\pi^+} + N_{\eta'\to\pi^+} + N_{K^0_S\to\pi^+}$$

$$N = C m_t^{\alpha} e^{-m_T/T_{eff}}, T_{eff} = T_{fo} + m\langle u_T\rangle^2$$

- Correlation measurent ↔ $\lambda^*(m_T)$ ↔ core−halo ratio

Tamas Csorgo (Harvard University)

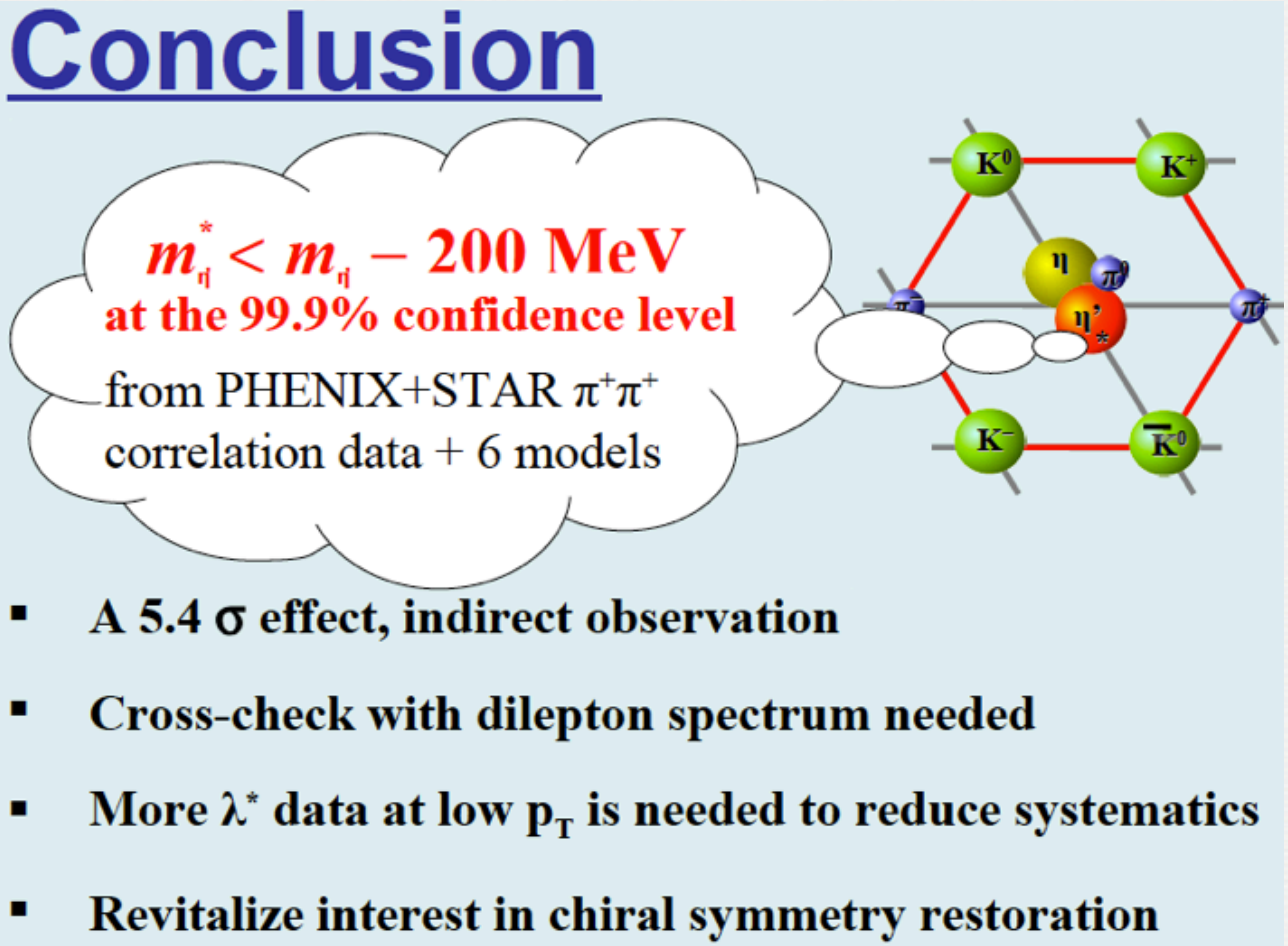


Simulation and Results

For resonance ratios
of **nucl-th/0405068**:
$m_{\eta'}$ = 530 MeV best value
$m_{\eta'}$ = 958 MeV ruled out

Resonance model	$m_{\eta'}^*$ (MeV)	χ^2 (CL %) ndf=11	$f_{\eta'}$	f_η	5-σ limit $m_{\eta'}^*$ (MeV)
ALCOR [17]	490^{+60}_{-50}	20.2 (4.29)	43.4	5.25	$\leq$ 700
Kaneta [18]	530^{+50}_{-50}	22.8 (4.12)	25.6	3.48	$\leq$ 730
Letessier [19]	340^{+50}_{-60}	18.9 (6.35)	67.6	4.75	$\leq$ 570
Stachel [20]	340^{+50}_{-60}	18.8 (6.38)	67.6	4.97	$\leq$ 570
UrQMD [16]	400^{+50}_{-40}	19.0 (6.14)	45.0	7.49	$\leq$ 660

Tamas Csorgo (Harvard University)



Conclusion

$m_{\eta'}^{*} < m_{\eta'} - 200$ MeV

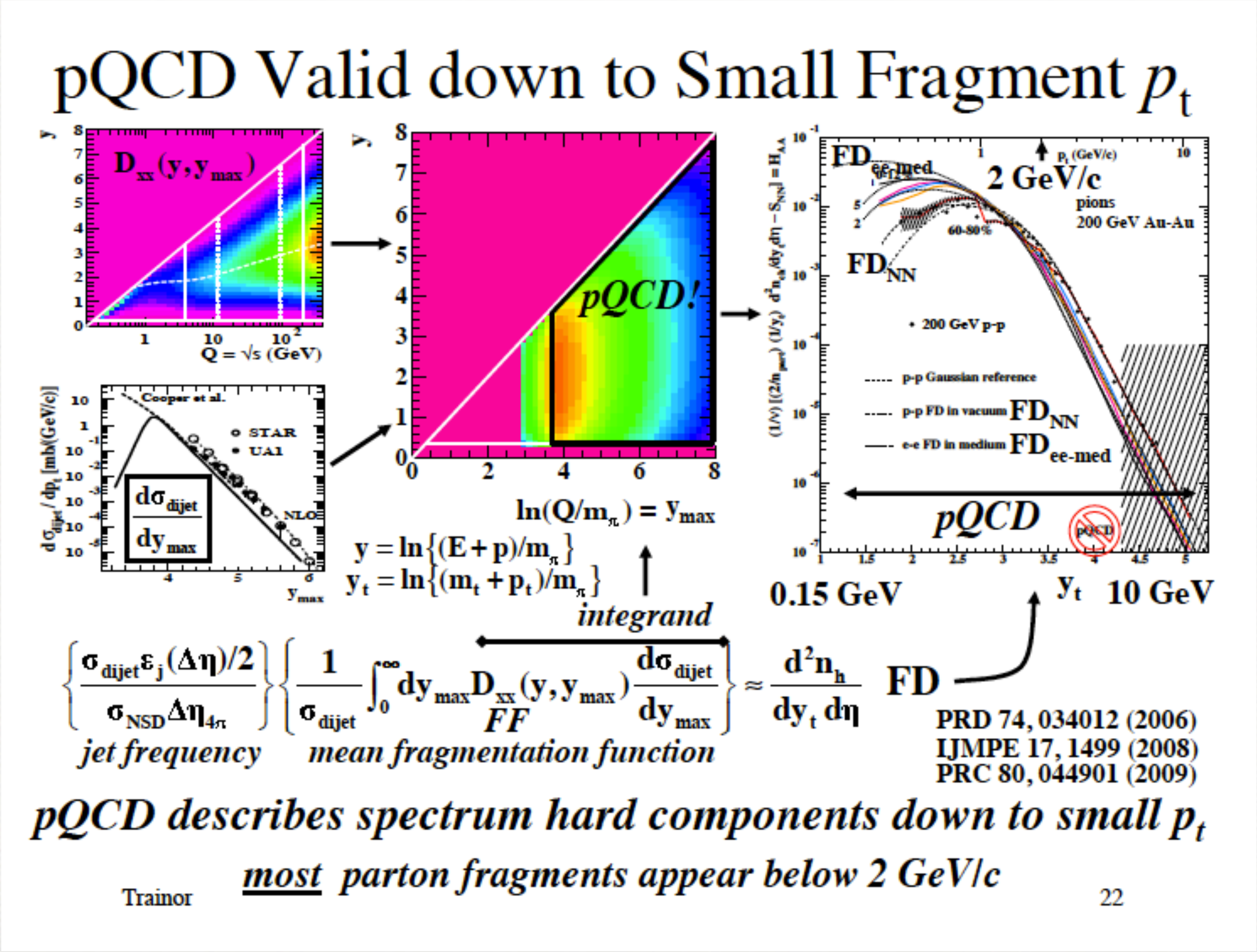
at the 99.9% confidence level

from PHENIX+STAR $\pi^+\pi^+$ correlation data + 6 models

- **A 5.4 σ effect, indirect observation**
- **Cross-check with dilepton spectrum needed**
- **More λ^* data at low p_T is needed to reduce systematics**
- **Revitalize interest in chiral symmetry restoration**

Thomas A. Trainor (University Of Washington)

Understanding RHIC collisions: Modified QCD fragmentation vs. quark coalescence from a thermalized flowing medium



pQCD Valid down to Small Fragment p_t

$$\ln(Q/m_\pi) = y_{max}$$

$$y = \ln\{(E+p)/m_\pi\}$$
$$y_t = \ln\{(m_t+p_t)/m_\pi\}$$

integrand

$$\left\{\frac{\sigma_{dijet}\,\varepsilon_j(\Delta\eta)/2}{\sigma_{NSD}\,\Delta\eta_{4\pi}}\right\}\left\{\frac{1}{\sigma_{dijet}}\int_0^\infty dy_{max}\,\underbrace{D_{xx}(y,y_{max})}_{FF}\,\frac{d\sigma_{dijet}}{dy_{max}}\right\} \approx \frac{d^2n_h}{dy_t\,d\eta} \quad \text{FD}$$

jet frequency *mean fragmentation function*

PRD 74, 034012 (2006)
IJMPE 17, 1499 (2008)
PRC 80, 044901 (2009)

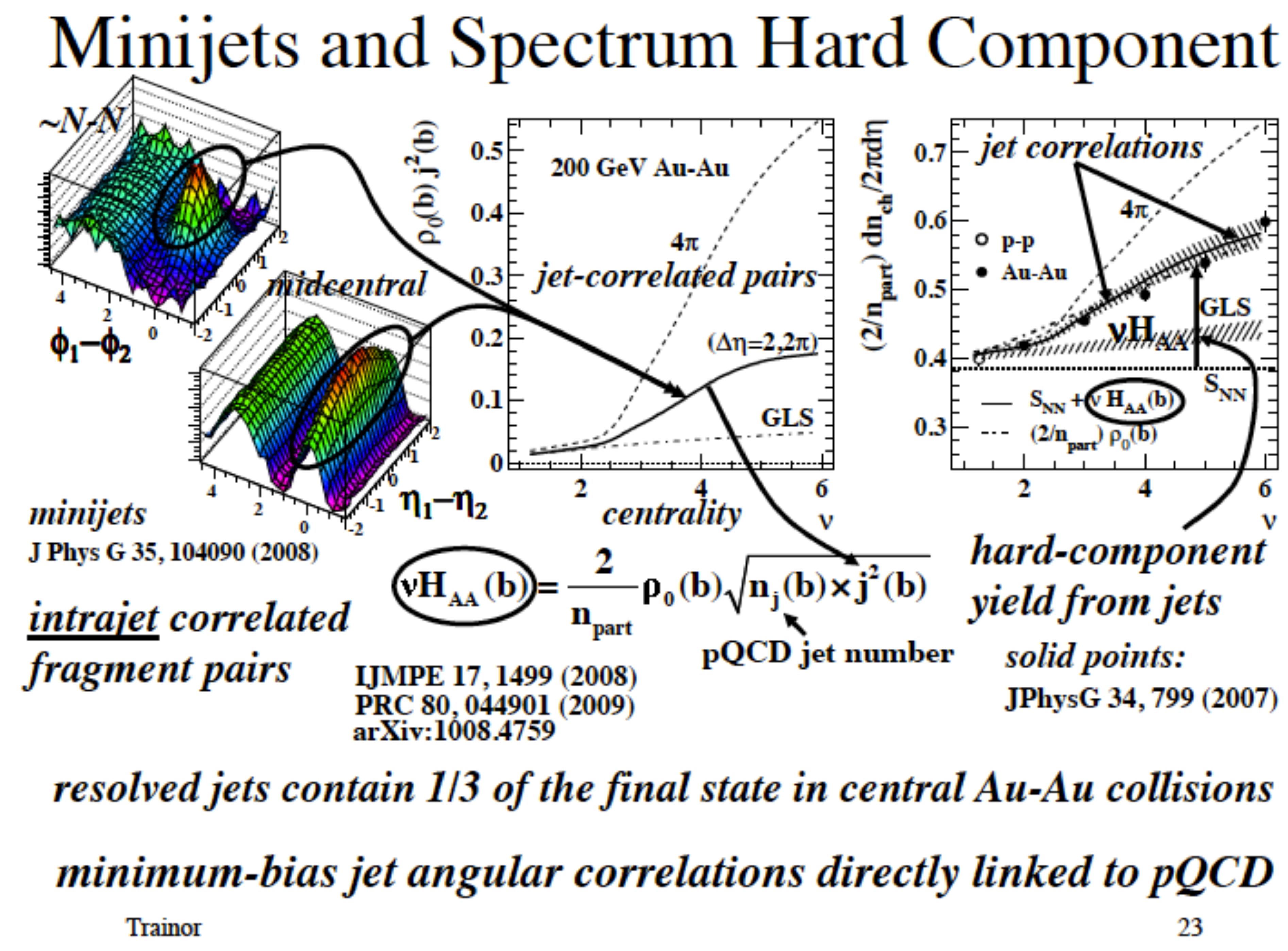
pQCD describes spectrum hard components down to small p_t

***most** parton fragments appear below 2 GeV/c*

Trainor

22

Thomas A. Trainor (University Of Washington)



Minijets and Spectrum Hard Component

minijets
J Phys G 35, 104090 (2008)

$$\boxed{\nu H_{AA}(b)} = \frac{2}{n_{part}} \rho_0(b) \sqrt{n_j(b) \times j^2(b)}$$

pQCD jet number

intrajet correlated fragment pairs

IJMPE 17, 1499 (2008)
PRC 80, 044901 (2009)
arXiv:1008.4759

hard-component yield from jets

solid points:
JPhysG 34, 799 (2007)

resolved jets contain 1/3 of the final state in central Au-Au collisions

minimum-bias jet angular correlations directly linked to pQCD

Trainor 23

Multiparticle Dynamics ... 40 years later

- *Happy Birthday ISMD !!!!*

Multiparticle Dynamics ... 40 years later

- *Happy Birthday ISMD !!!!*

- *Thank you for your attention !*