

# INTERACTIONS W/ ULI

(HOW SMALL IS TOO SMALL?)

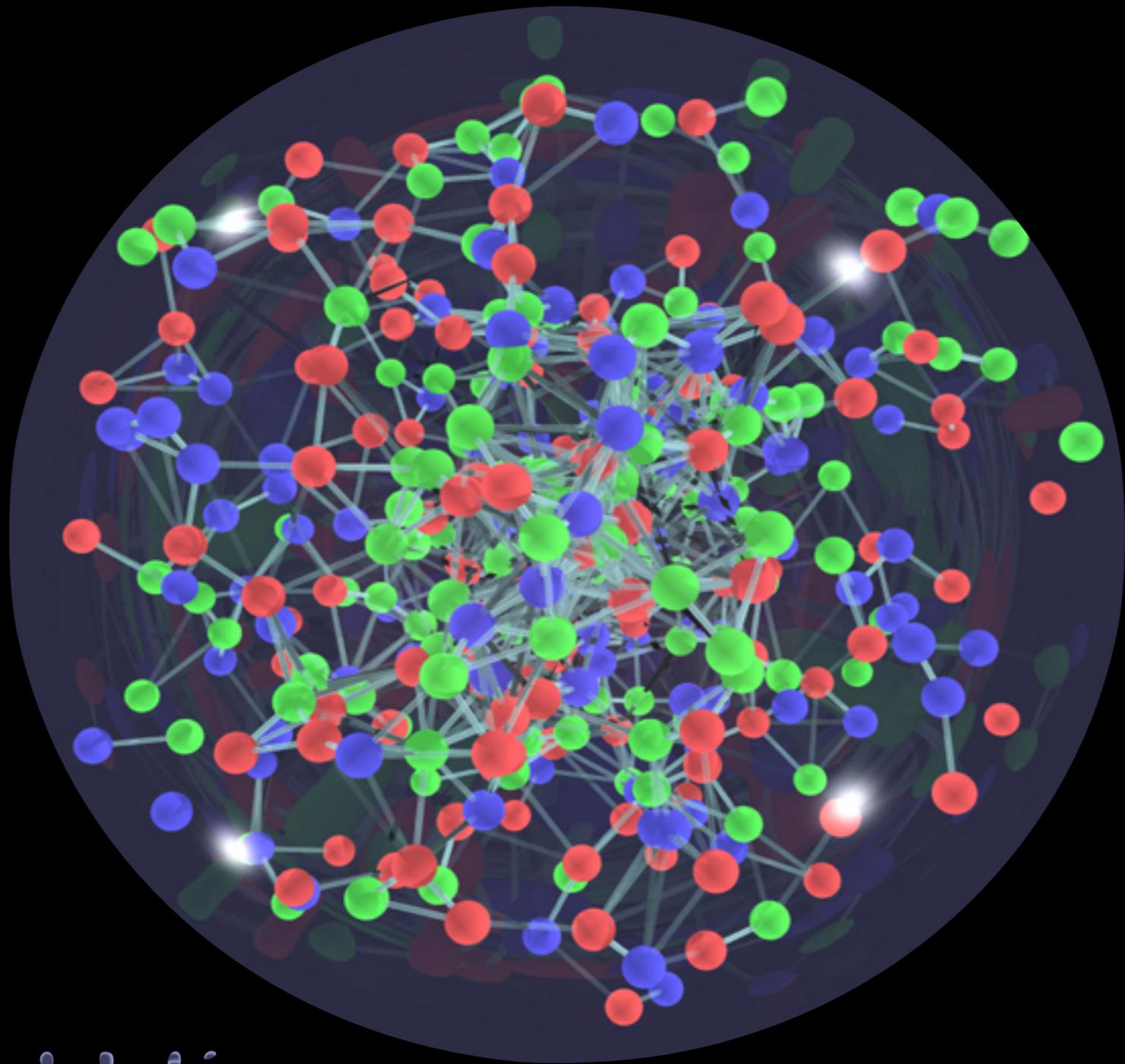
PETER STEINBERG

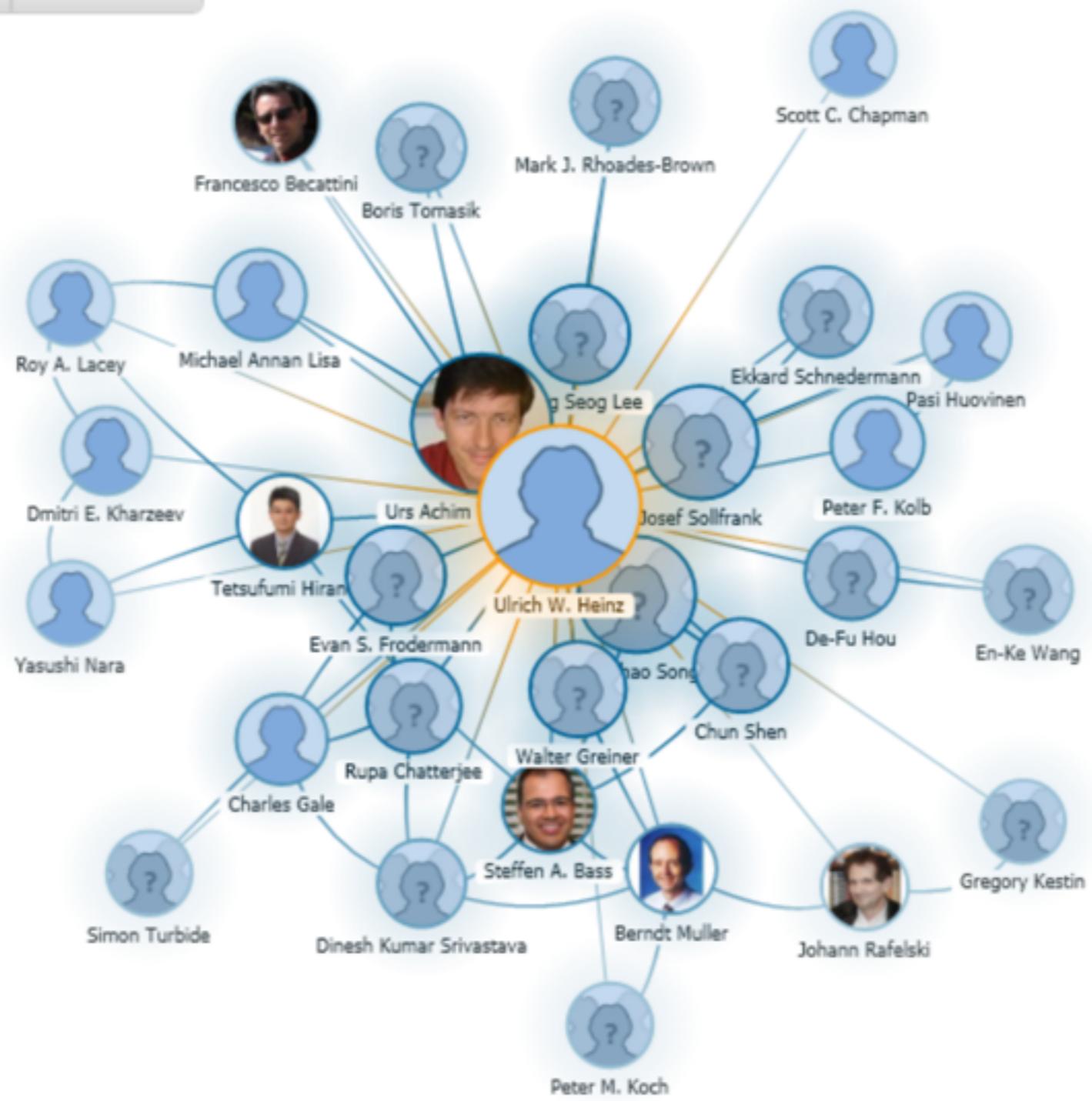
BROOKHAVEN NATIONAL LABORATORY, USA

**ULTRA-RELATIVISTICH HEAVY IONZ**

JULY 20, 2016







# INITIAL STAGES 2016, LISBON

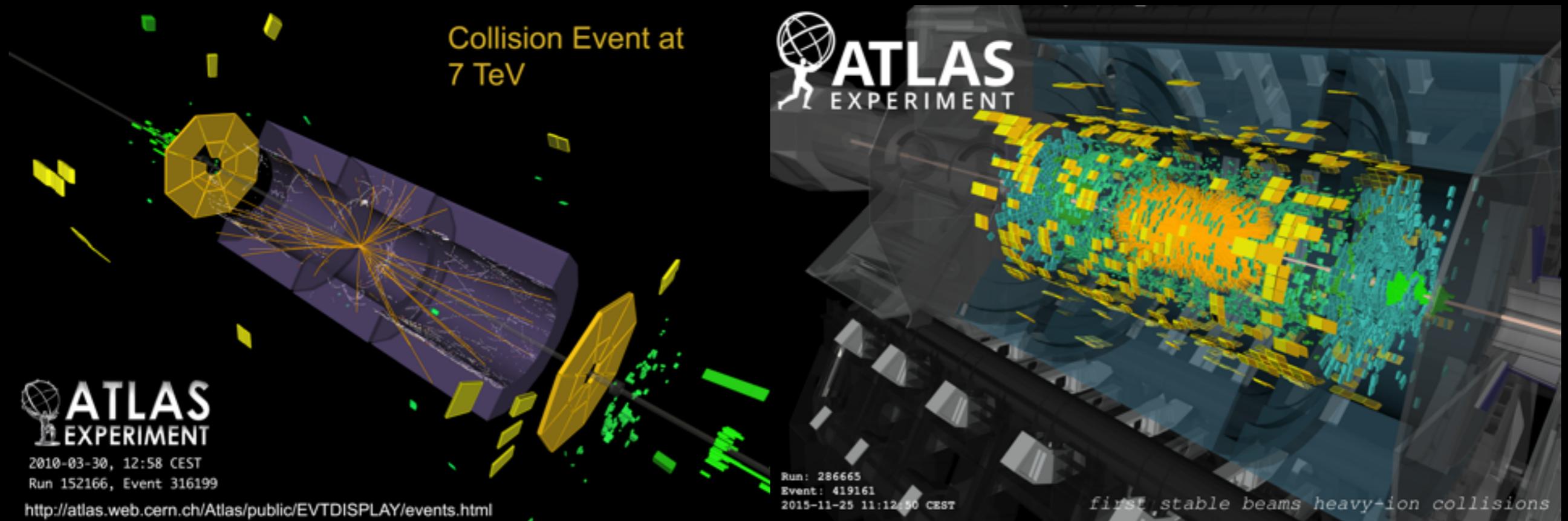


# HEINZ V MUELLER



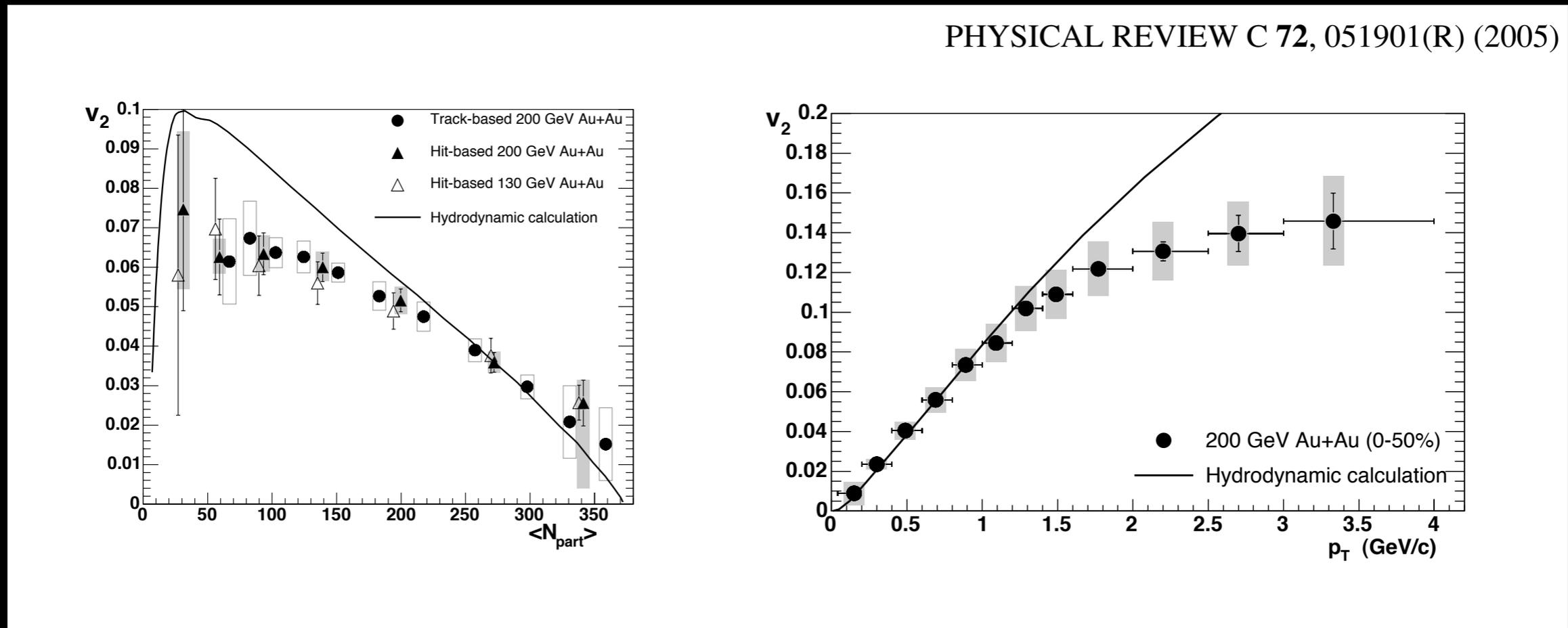
Mueller: 20 particles in  $\Delta\eta=5$  was far too small to support hydro  
Heinz: many considerations point to the possibility of flow in pp

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Mueller: 20 particles in  $\Delta\eta=5$  was far too small to support hydro  
Heinz: many considerations point to the possibility of flow in pp

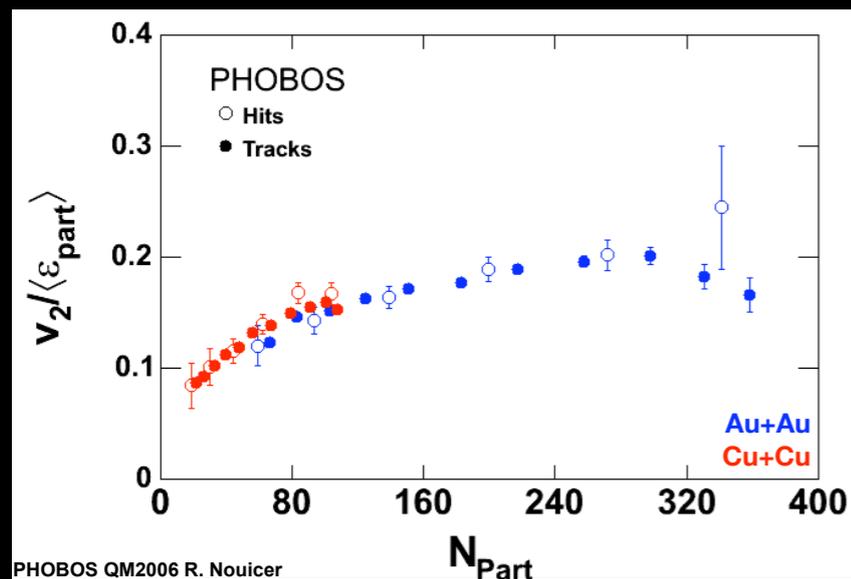
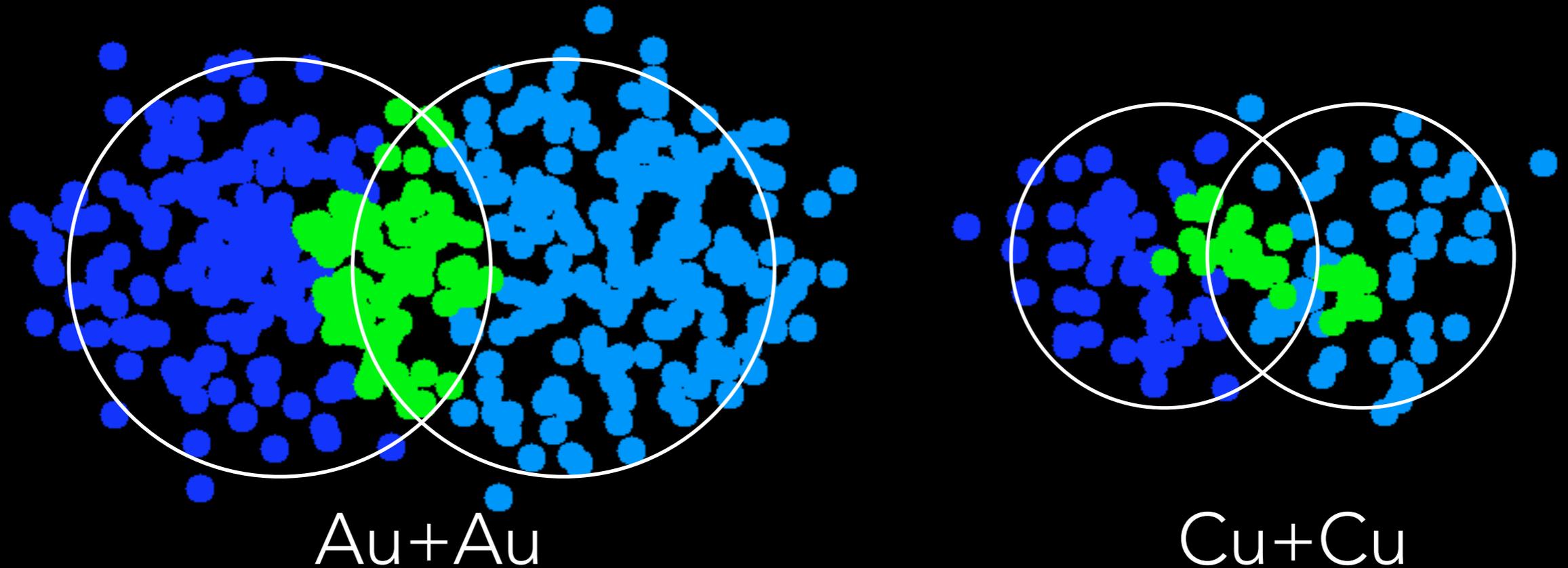
# EARLY RHIC DATA: ELLIPTIC FLOW



Many others have discussed the importance of Uli's work in understanding the data, esp. the work w/ Kolb, Huovinen et al.

However, amidst the broad agreement in centrality &  $p_T$ , we weren't picky about the possible disagreements in peripheral (no thermalization?) or central (large errors) collisions.

# PARTICIPANT ECCENTRICITY



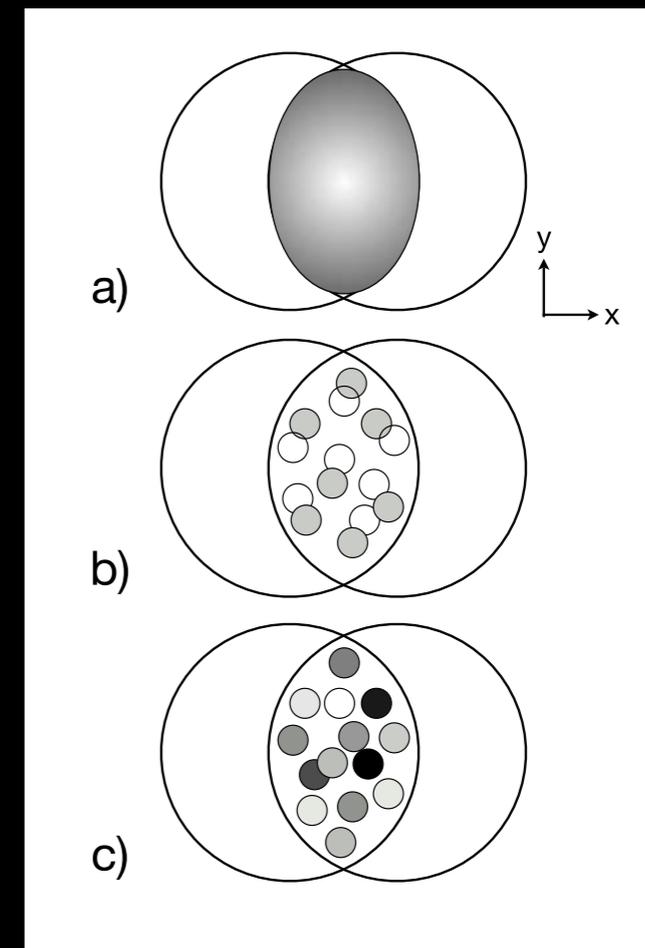
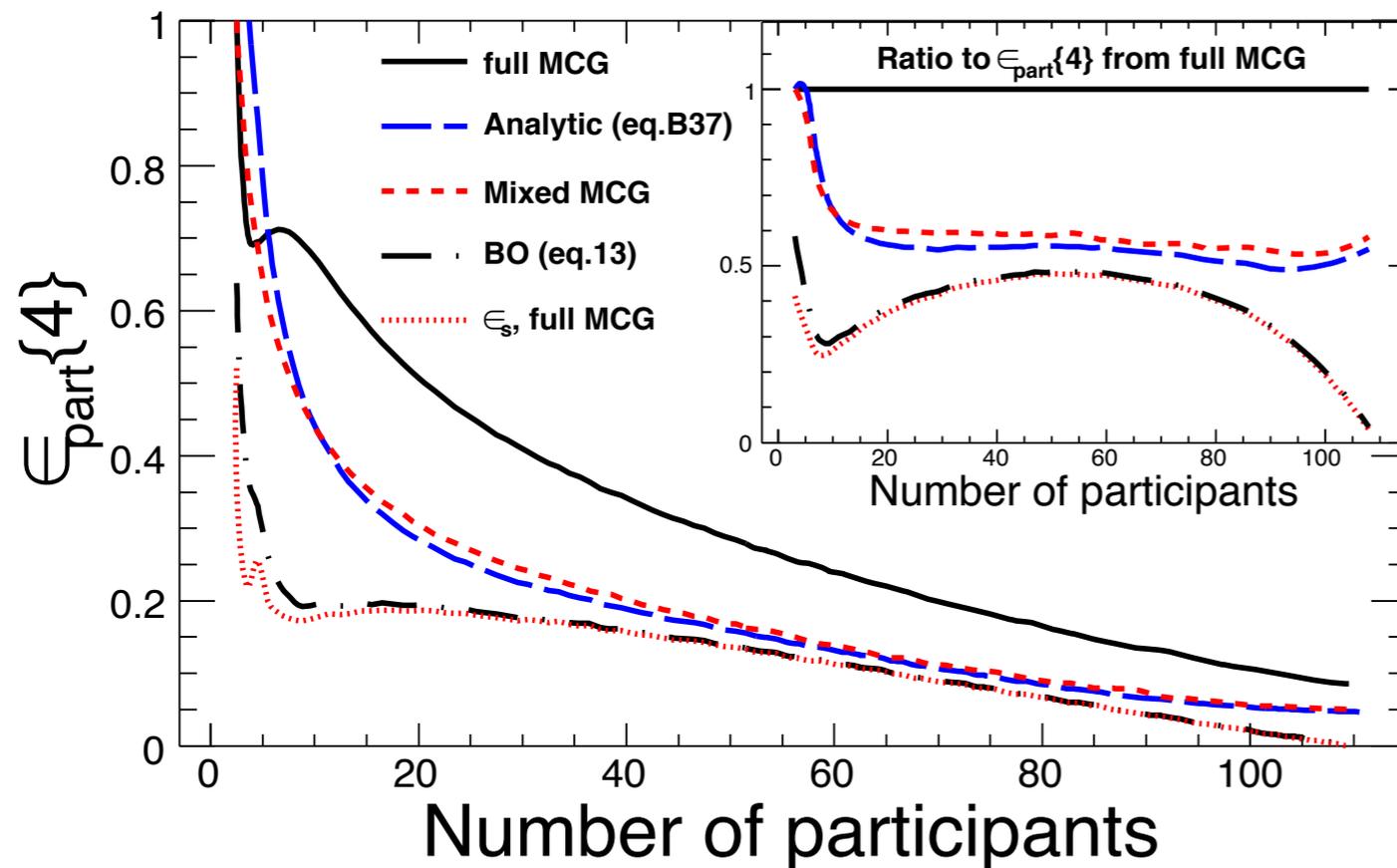
Only by taking the (nucleon sized?)  
**local fluctuations** seriously  
could we understand both  
Cu+Cu and Au+Au

# ULI + PHOBOS

PHYSICAL REVIEW C 77, 014906 (2008)

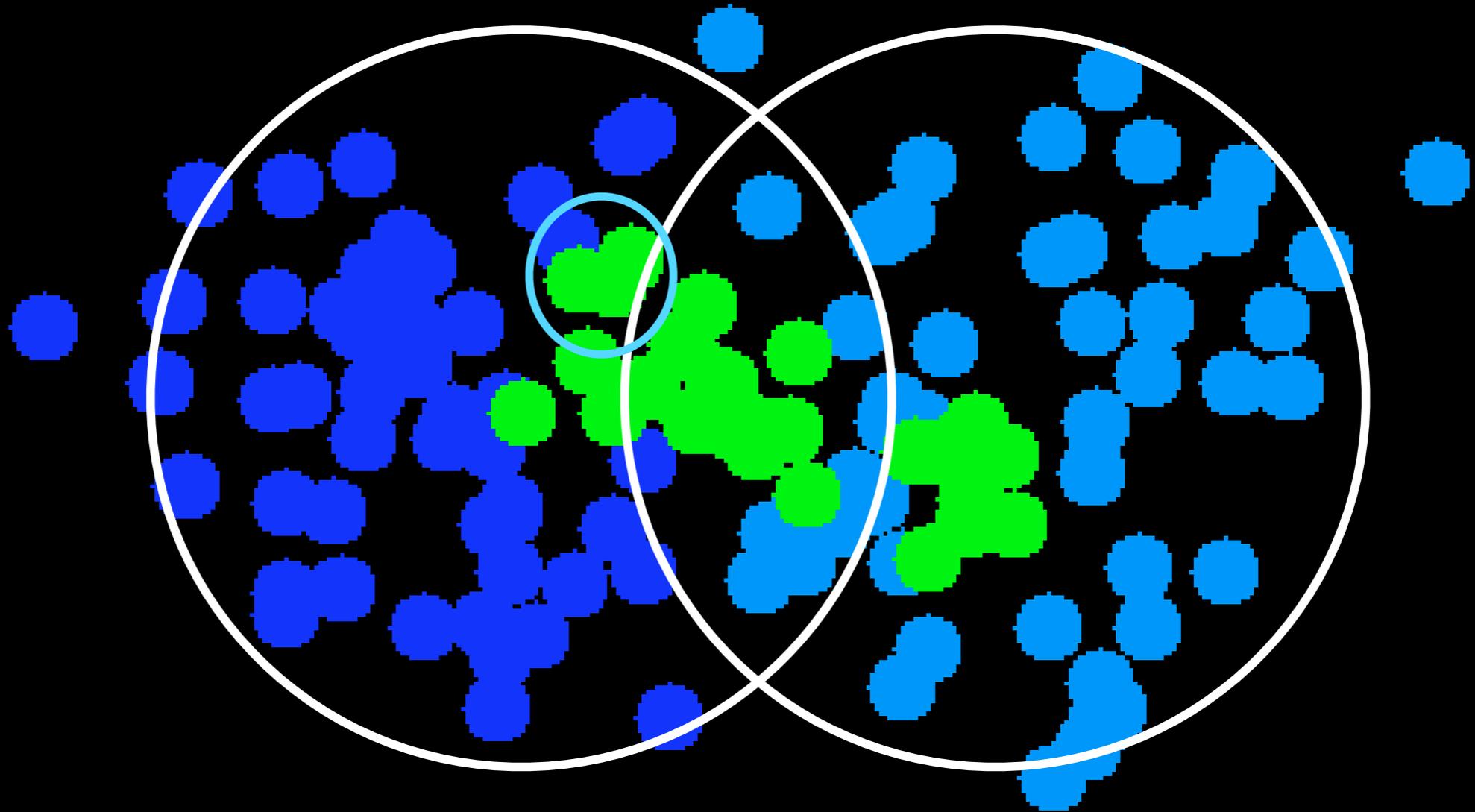
## Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus-nucleus collisions

B. Alver,<sup>4</sup> B. B. Back,<sup>1</sup> M. D. Baker,<sup>2</sup> M. Ballintijn,<sup>4</sup> D. S. Barton,<sup>2</sup> R. R. Betts,<sup>7</sup> R. Bindel,<sup>8</sup> W. Busza,<sup>4</sup> V. Chetluru,<sup>7</sup> E. García,<sup>7</sup> T. Gburek,<sup>3</sup> J. Hamblen,<sup>9</sup> U. Heinz,<sup>6</sup> D. J. Hofman,<sup>7</sup> R. S. Hollis,<sup>7</sup> A. Jordanova,<sup>7</sup> W. Li,<sup>4</sup> C. Loizides,<sup>4</sup> S. Manly,<sup>9</sup> A. C. Mignerey,<sup>8</sup> R. Nouicer,<sup>2</sup> A. Olszewski,<sup>3</sup> C. Reed,<sup>4</sup> C. Roland,<sup>4</sup> G. Roland,<sup>4</sup> J. Sagerer,<sup>7</sup> P. Steinberg,<sup>2</sup> G. S. F. Stephans,<sup>4</sup> M. B. Tonjes,<sup>8</sup> A. Trzupek,<sup>3</sup> G. J. van Nieuwenhuizen,<sup>4</sup> S. S. Vaurynovich,<sup>4</sup> R. Verrier,<sup>4</sup> G. I. Veres,<sup>4</sup> P. Walters,<sup>9</sup> E. Wenger,<sup>4</sup> B. Wosiek,<sup>3</sup> K. Woźniak,<sup>3</sup> and B. Wyslouch<sup>4</sup>



Fundamental result, only truly visible in Cu+Cu was that MC Glauber is fundamentally different than optical: participants come in N+N pairs!

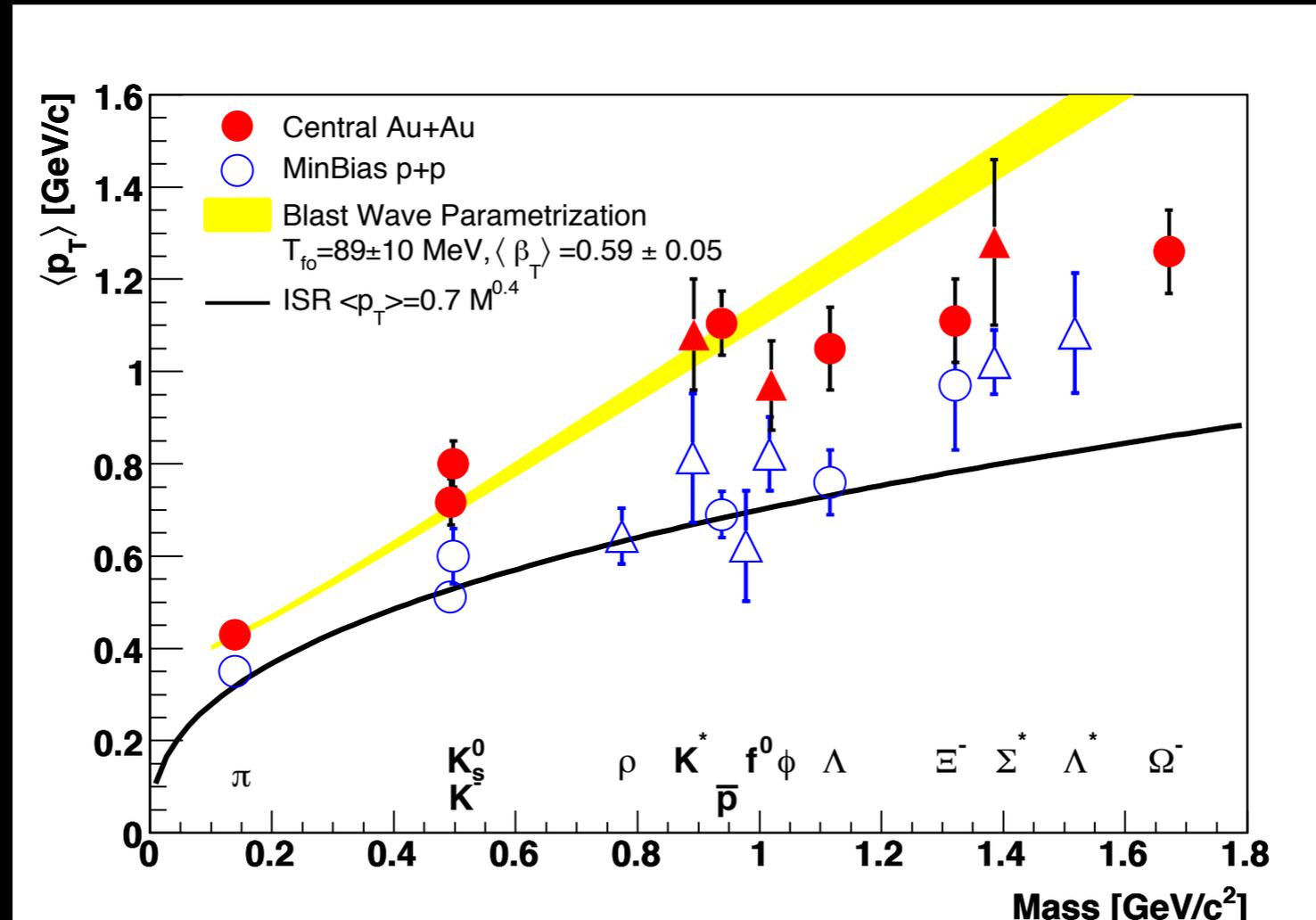
# HOW SMALL IS SMALL?



If we accept the reality of thermalization in hot spots,  
what about even smaller systems?

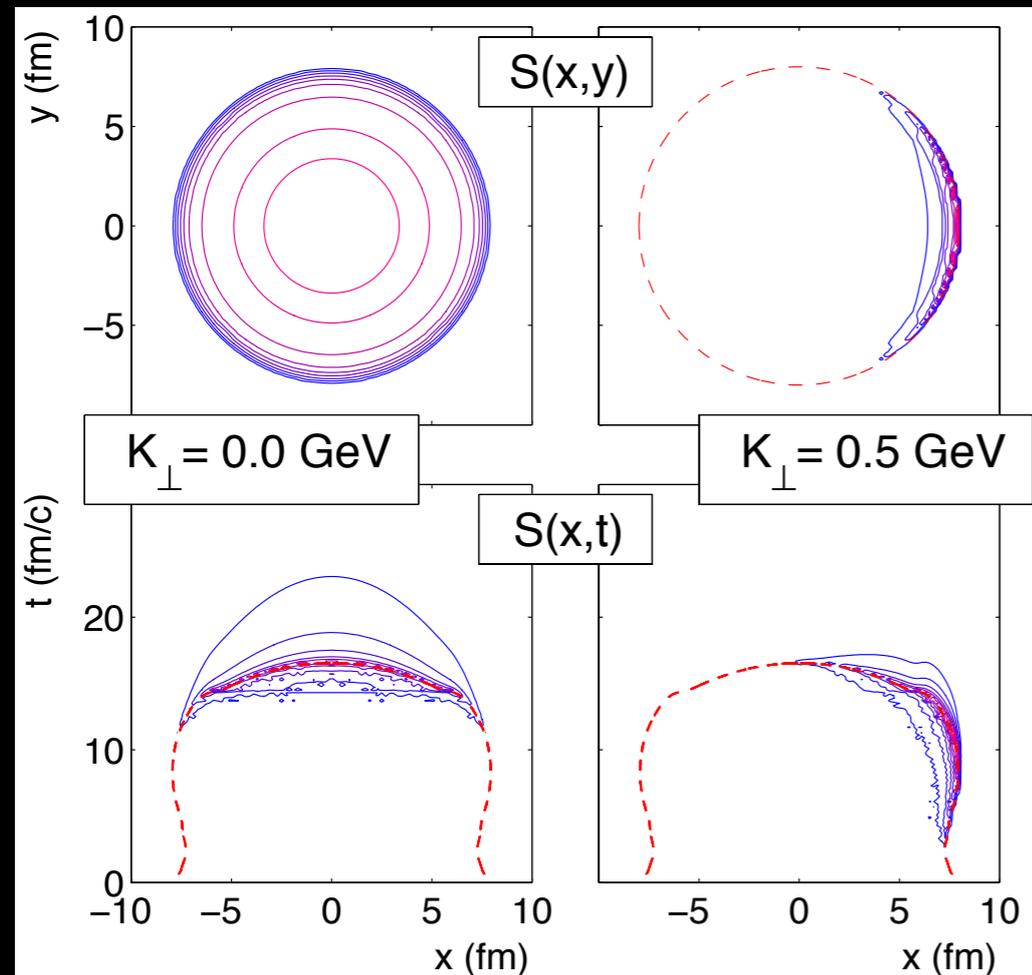
# EARLY RHIC DATA: RADIAL FLOW

S. Salur, PhD thesis

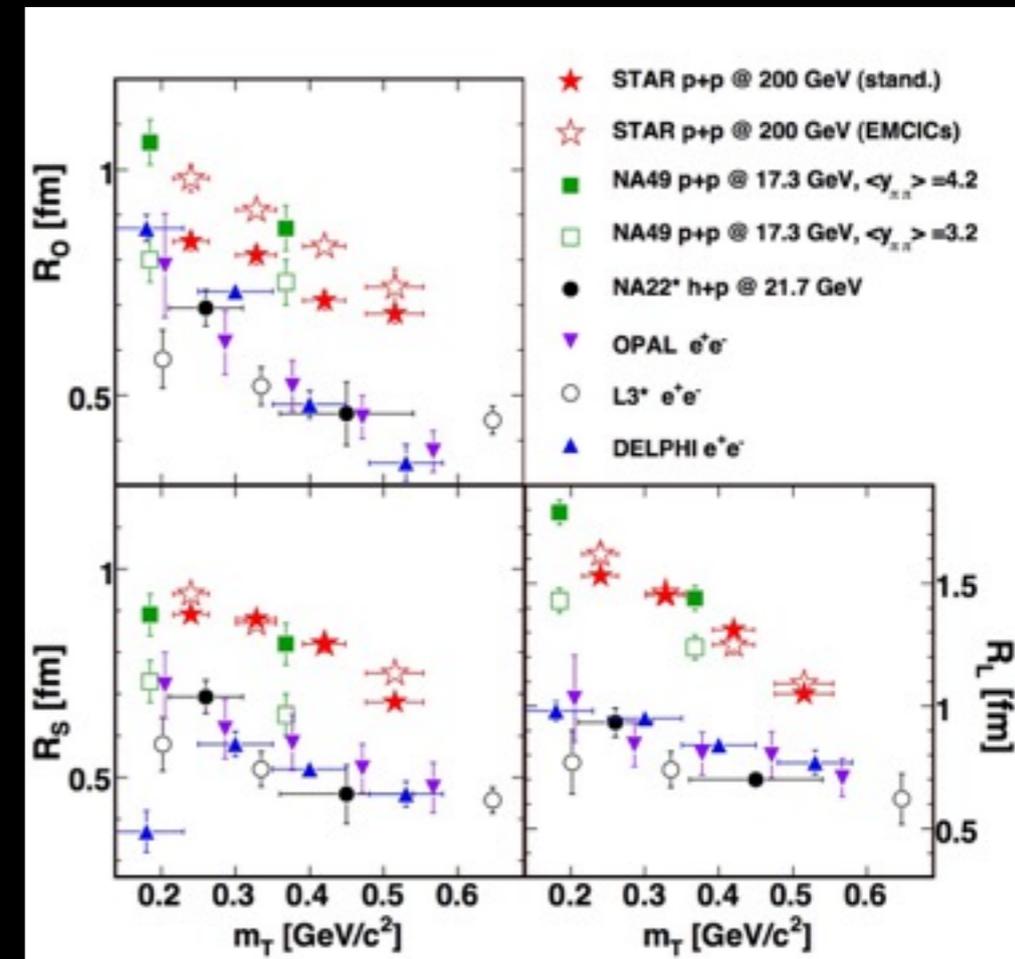


Old data (2003) but illustrative:  
is pp qualitatively or quantitatively different?  
Generally, we used different explanations  
(e.g. string breaking) to describe similar phenomena

# EARLY RHIC DATA: RADIAL FLOW

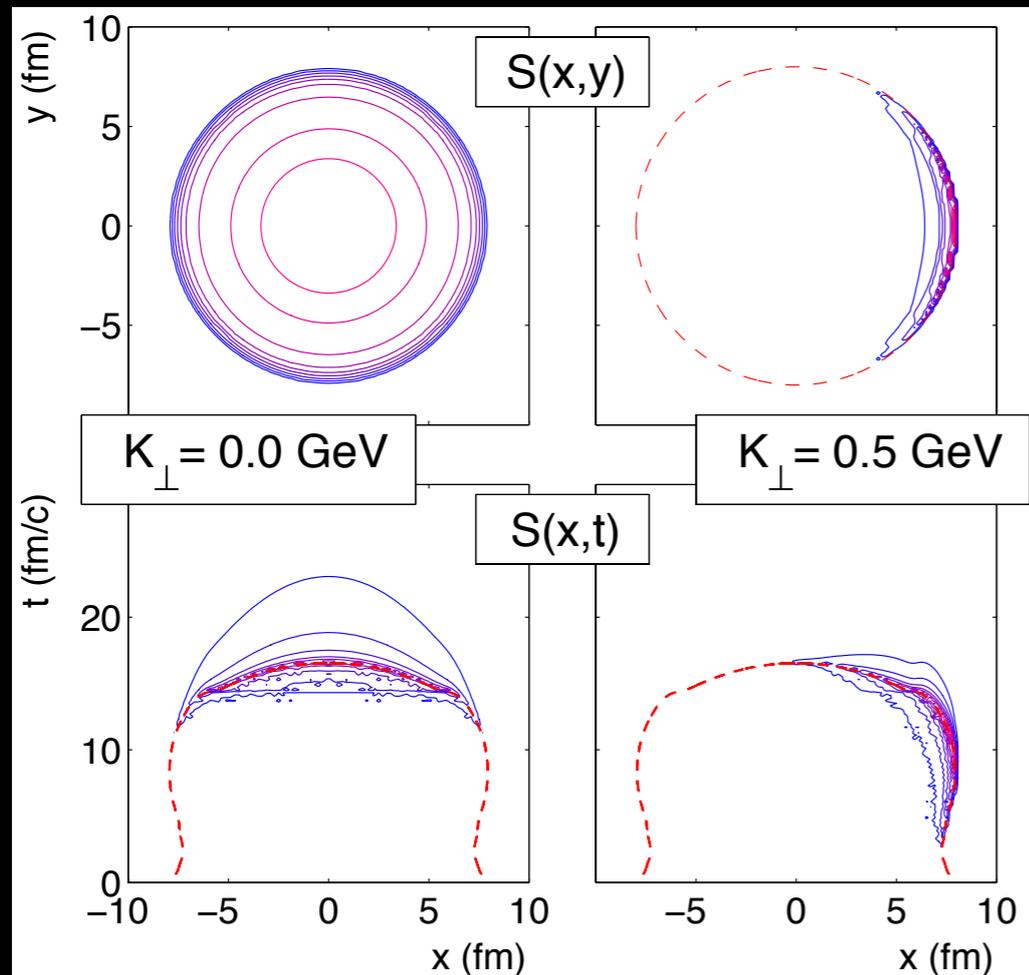


P. Kolb's thesis  
(which remains a textbook  
for the basic physics & results!)

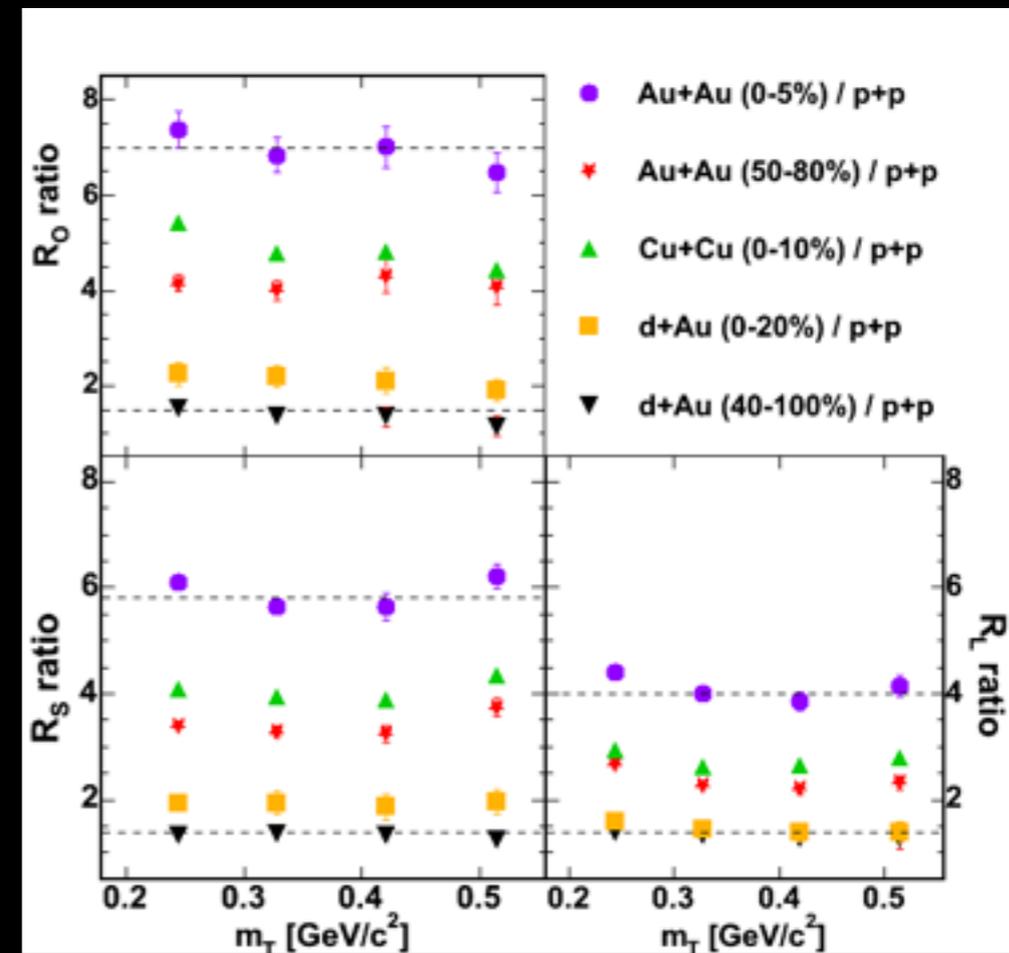


Small system data (compiled by  
Chajacki) for pp and e+e-

# EARLY RHIC DATA: RADIAL FLOW



P. Kolb's thesis  
(which remains a textbook  
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STAR data on the  $m_T$   
dependence of radii in  
A+A, d+Au & p+p:  
same dependence = radial flow?

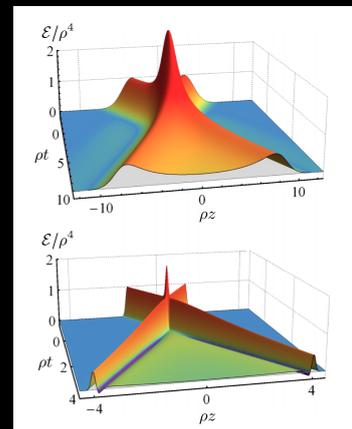
Again, similar data, different explanations

DELETED MATERIAL

# DELETED MATERIAL

~~Comparisons of multiplicities ( $A+A$  to  $e^+e^-$ ):  
does rapid thermalization explain total multiplicities?~~

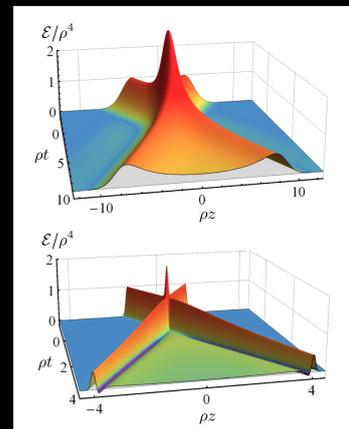
~~The question of Bjorken scaling  
(& the "birth" and "death" and "rebirth"  
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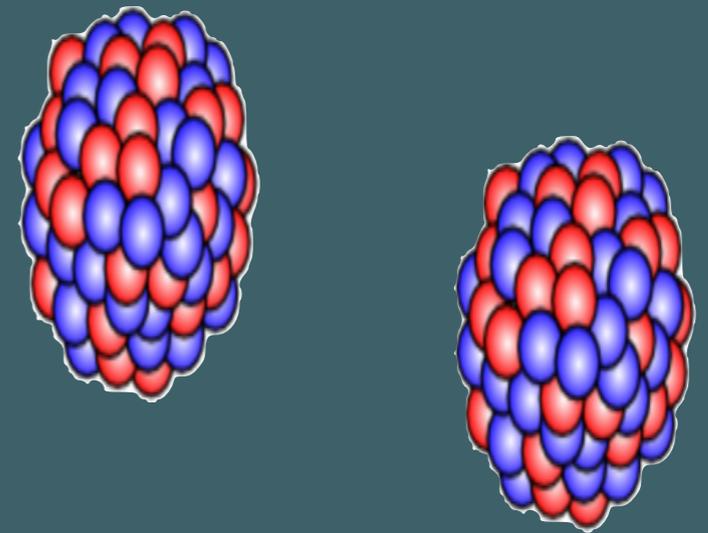
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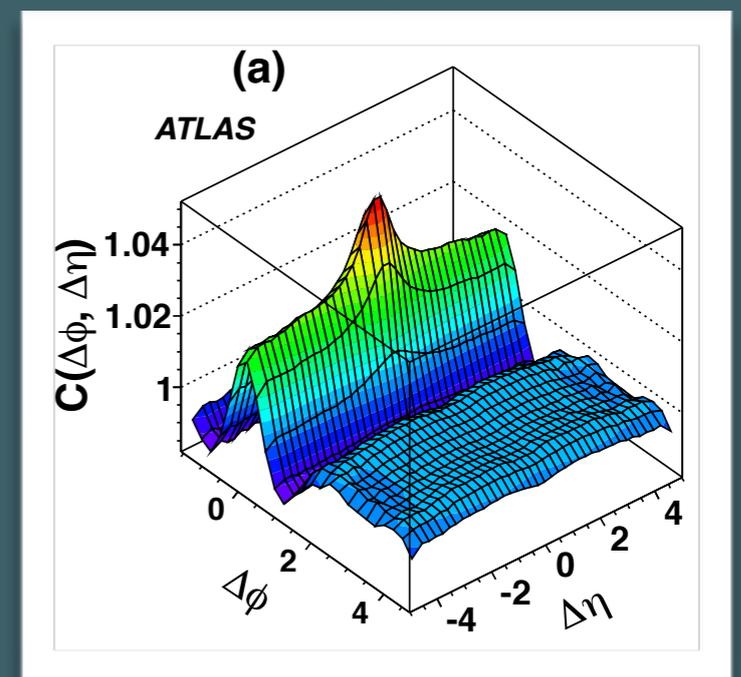
Happy birthday, Uli! :)

# A TALE OF THREE SYSTEMS

As a community, we have established collective behavior in Pb+Pb,  
what about smaller systems?



*Pb+Pb*

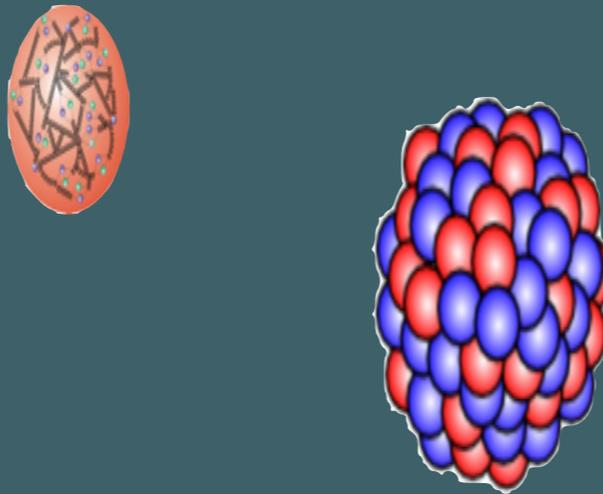
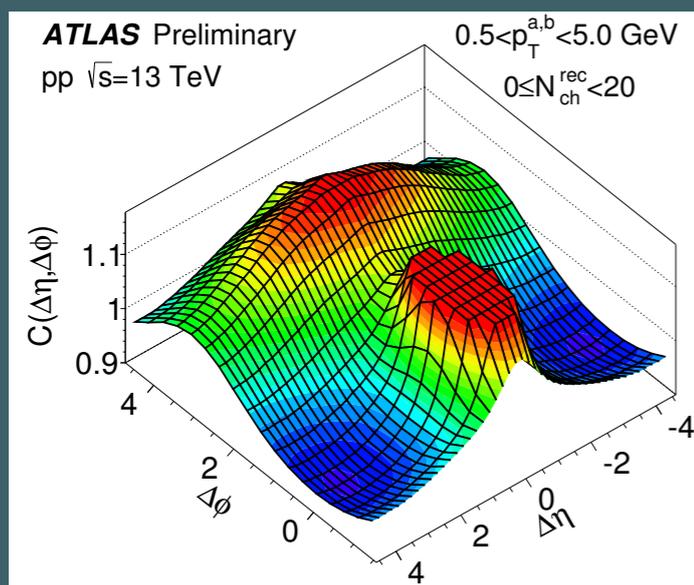


# A TALE OF THREE SYSTEMS

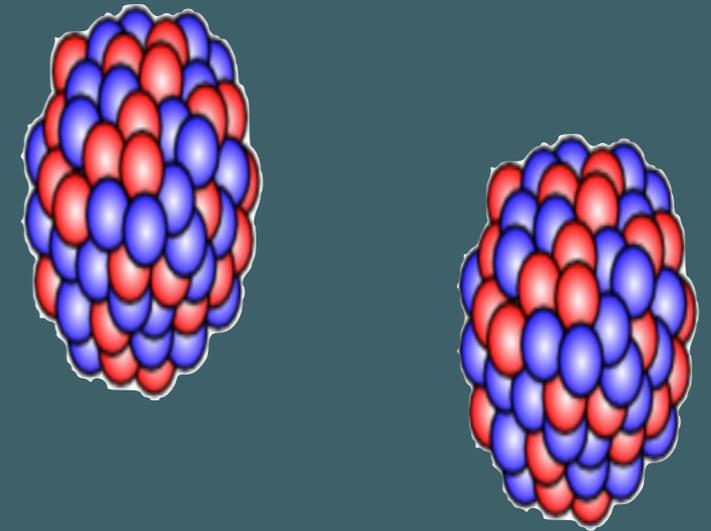
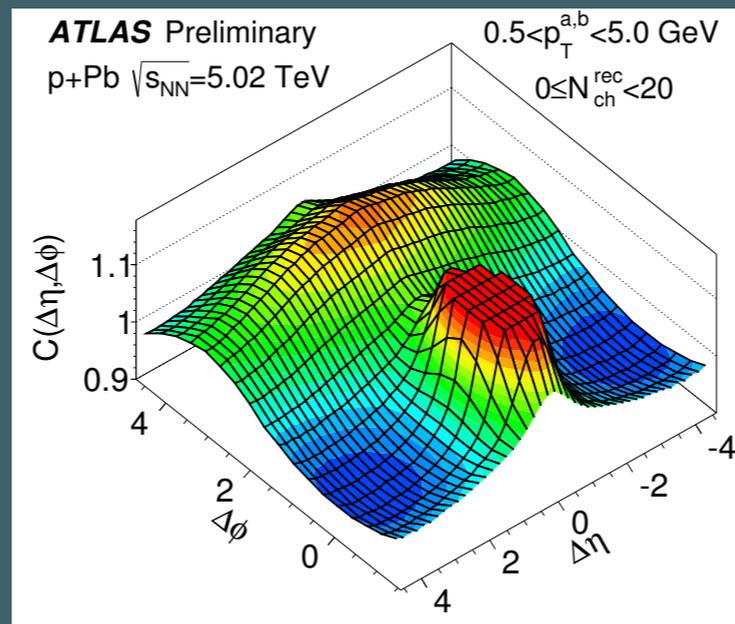
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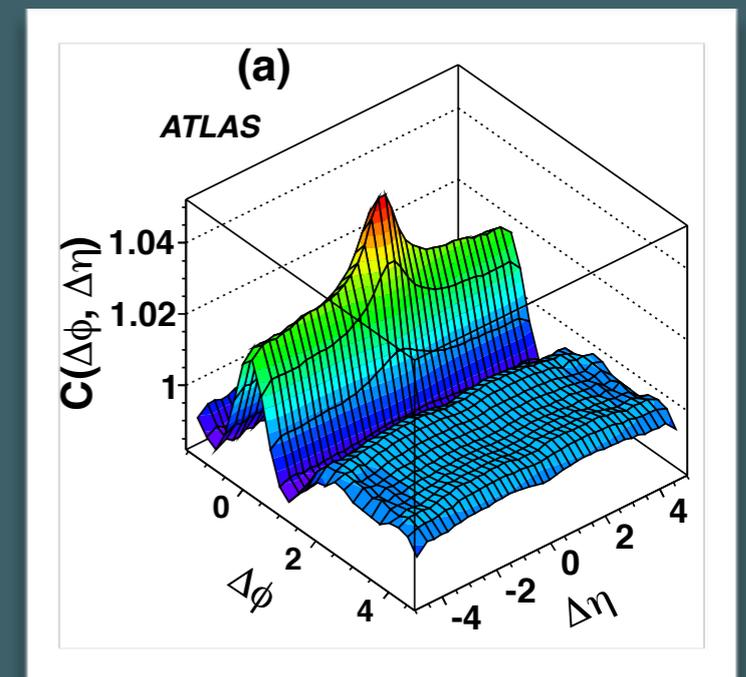
$p+p$



$p+Pb$



$Pb+Pb$



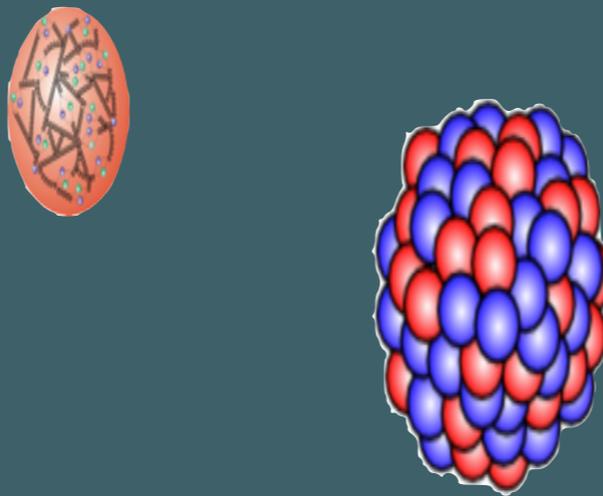
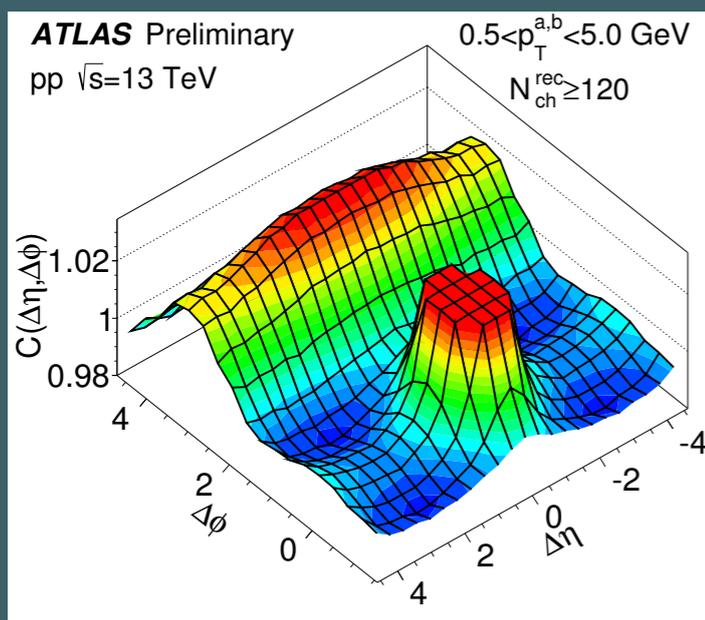
For "peripheral" p+p & p+Pb, no long range behavior at  $\Delta\phi=0$

# A TALE OF THREE SYSTEMS

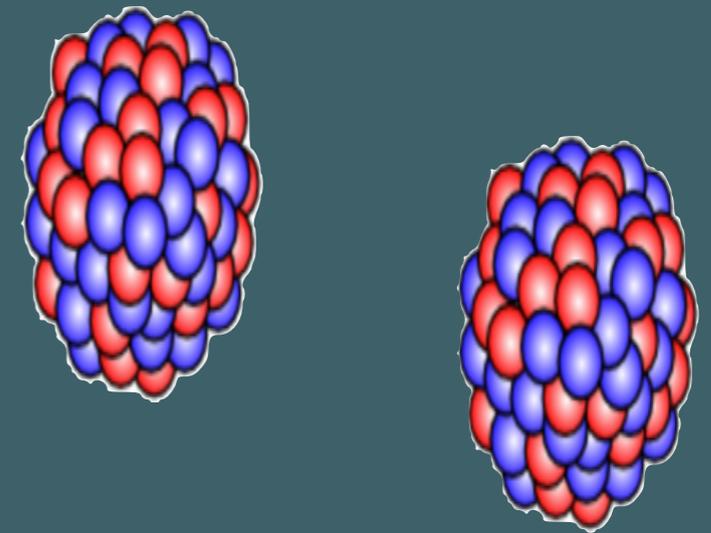
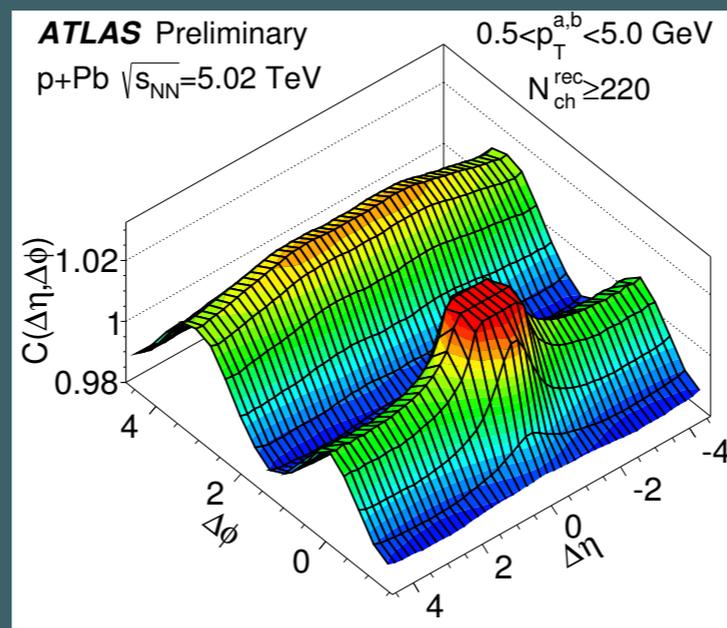
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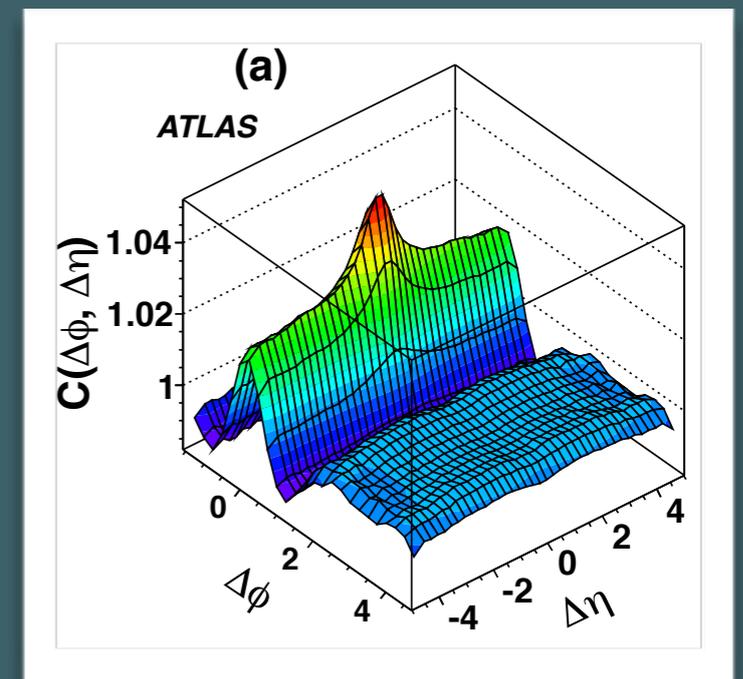
$p+p$



$p+Pb$



$Pb+Pb$



Increase the multiplicity, and a "ridge" clearly appears!

# "EXCAVATING" THE RIDGE

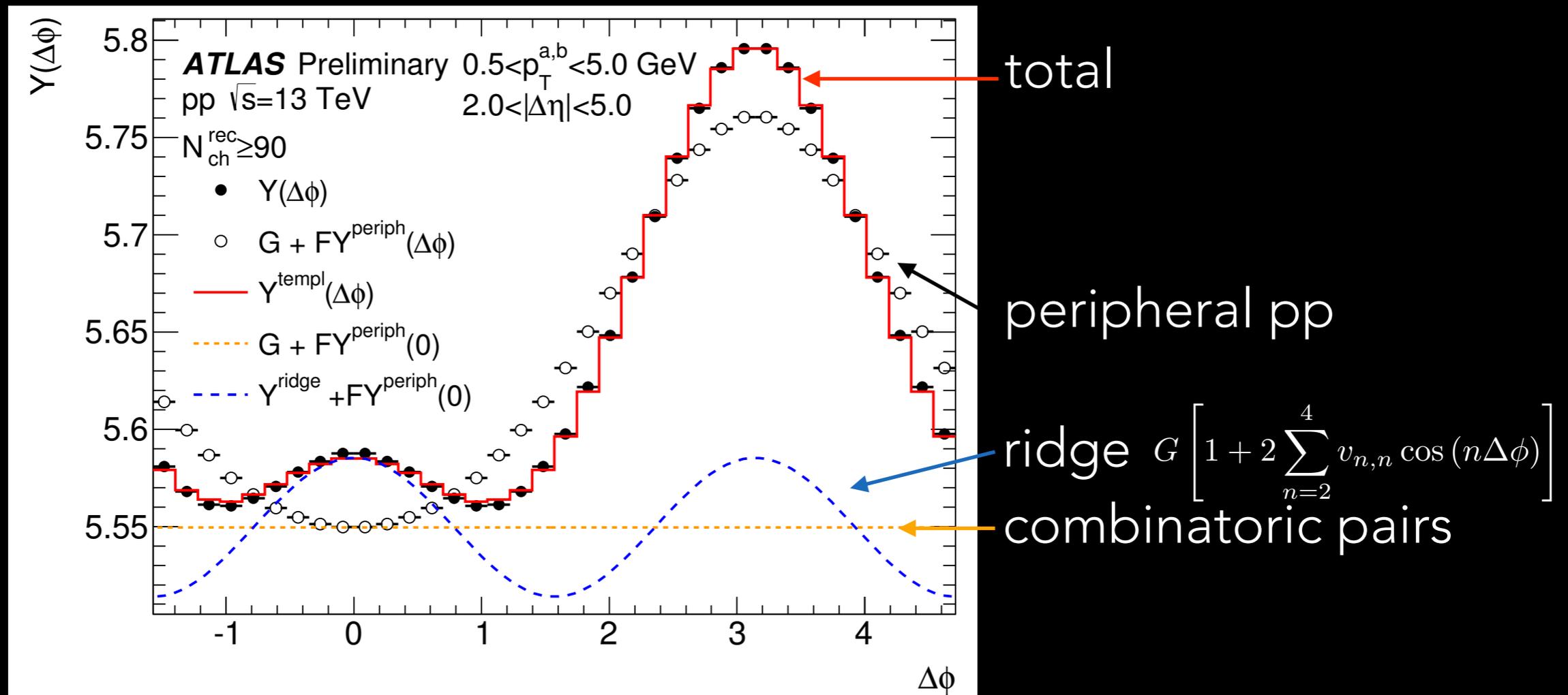
PRL 116, 172301 (2016)  
ATLAS-CONF-2016-025



Does the ridge really disappear at low multiplicities?  
(as CMS reported in 2010)

# RIDGE "EXCAVATION"

PRL 116, 172301 (2016)  
ATLAS-CONF-2016-025



ATLAS fit procedure, decomposes per-trigger yield ( $\sim B \times C$ )

YIELD IN  
"PERIPHERAL" PP

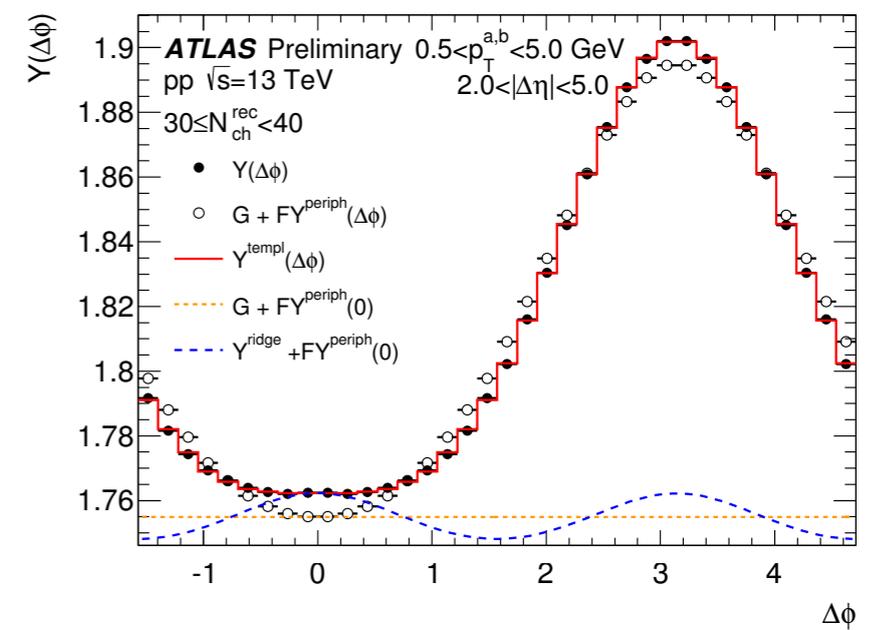
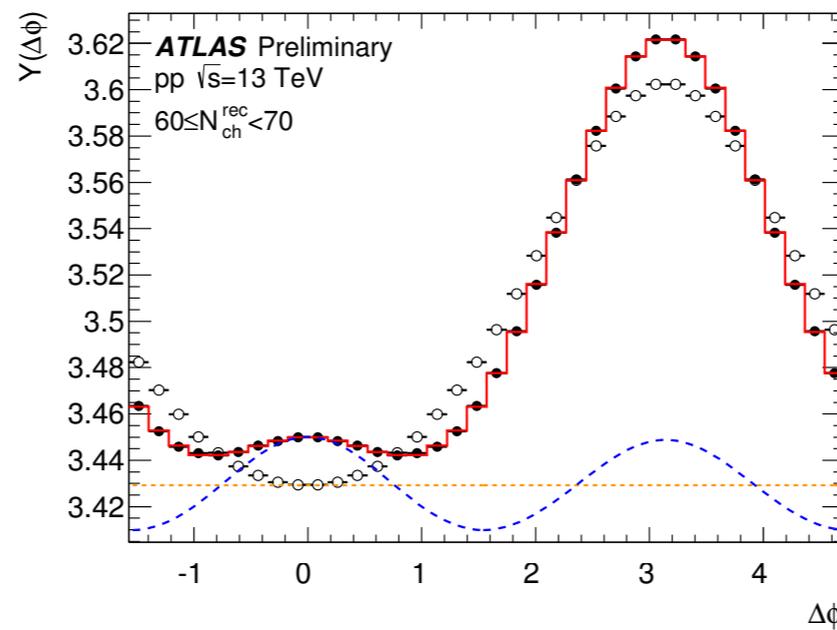
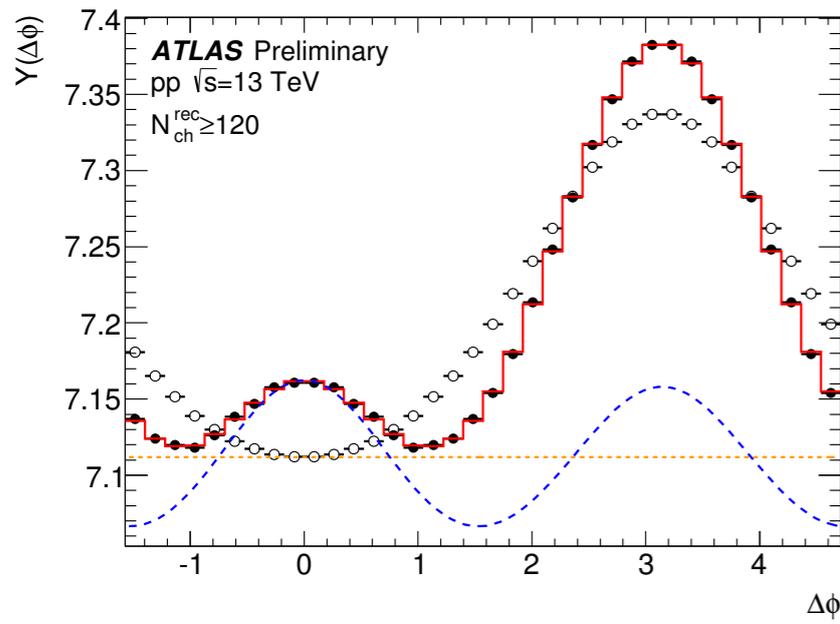
RIDGE  
(SINUSOIDAL)

COMBINATORIC

Unexpectedly provides explanation for narrowing around  $\Delta\phi \sim \pi$

# RIDGE "EXCAVATION"

PRL 116, 172301 (2016)  
ATLAS-CONF-2016-025



High multiplicity

Medium multiplicity

Low multiplicity

Ridge term needed for **all** multiplicities,  
even when ridge **seems** to disappear for low  $N_{ch}$

YIELD IN  
"PERIPHERAL" PP

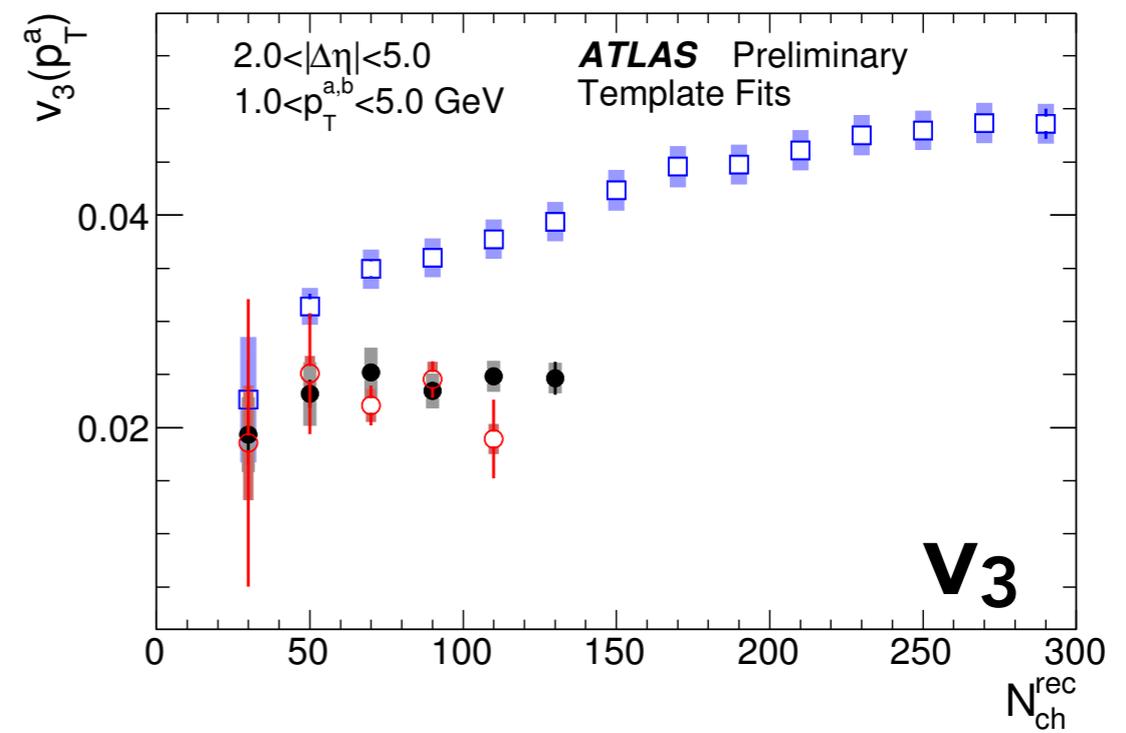
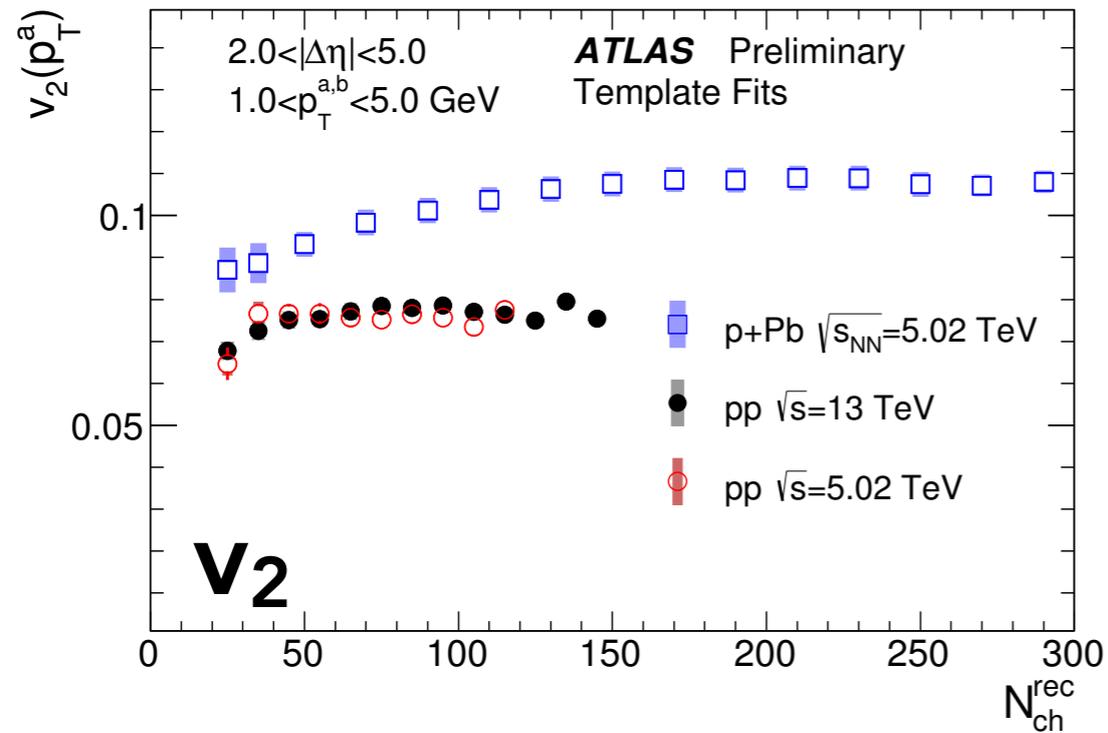
RIDGE  
(SINUSOIDAL)

COMBINATORIC

$$G \left[ 1 + 2 \sum_{n=2}^4 v_{n,n} \cos(n\Delta\phi) \right]$$

# HARMONIC FLOW IN PP?

PRL 116, 172301 (2016)  
ATLAS-CONF-2016-025

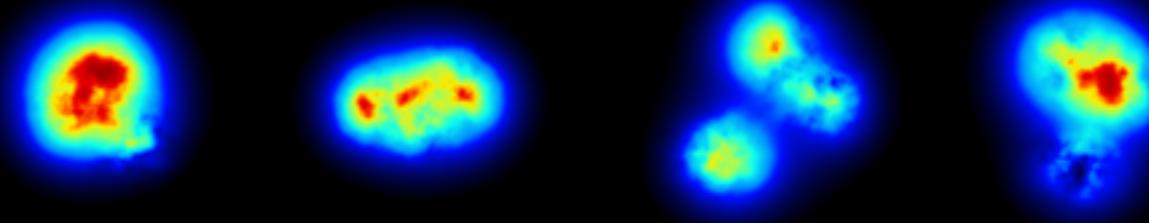


Sinusoidal term in pp underlying event persists to lower multiplicities!

Are all pp collisions "collective" at some level?

New questions: what is the "shape" of a proton?

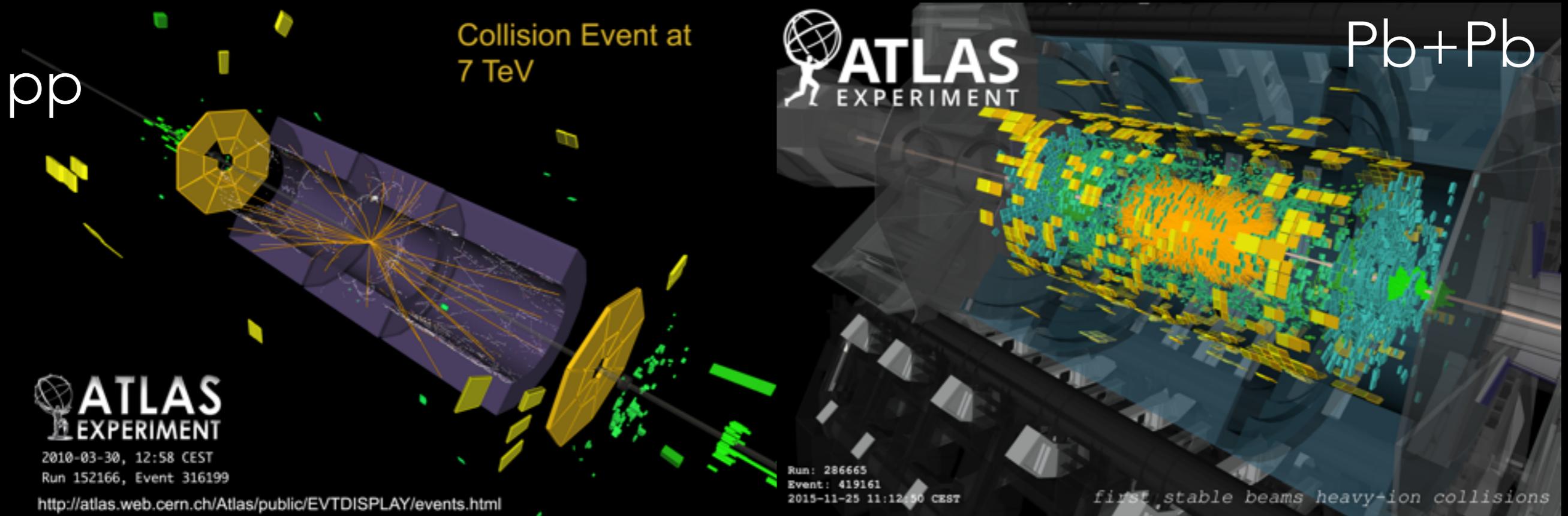
Does it fluctuate event to event?



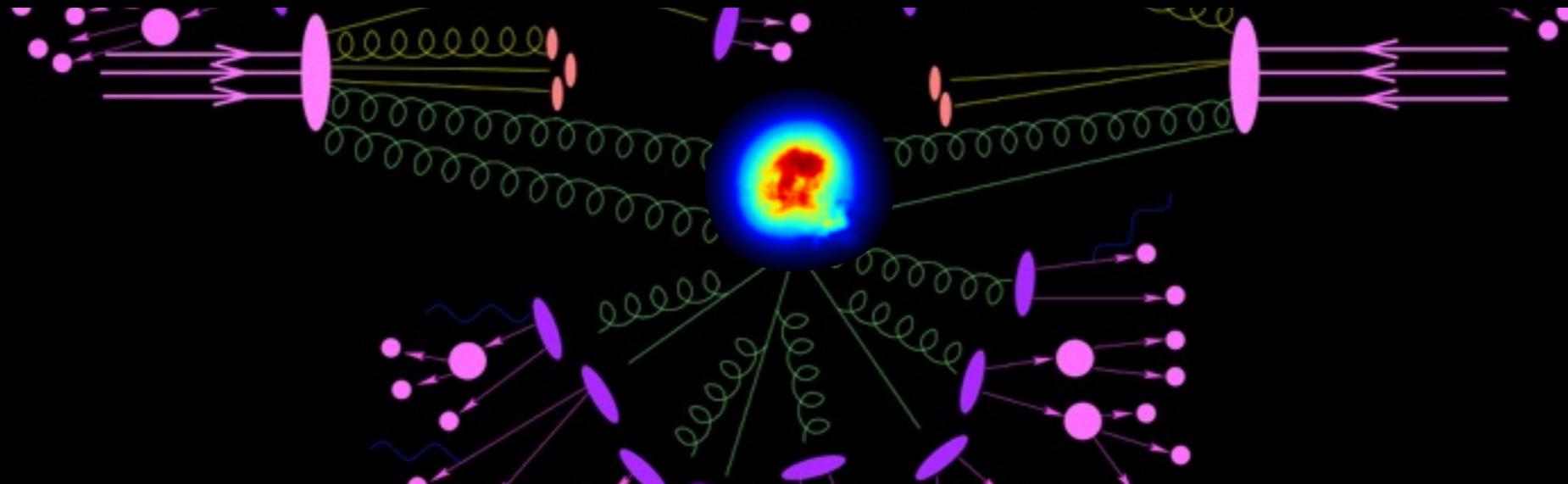
examples from Schenke,  
arXiv:1603.04349



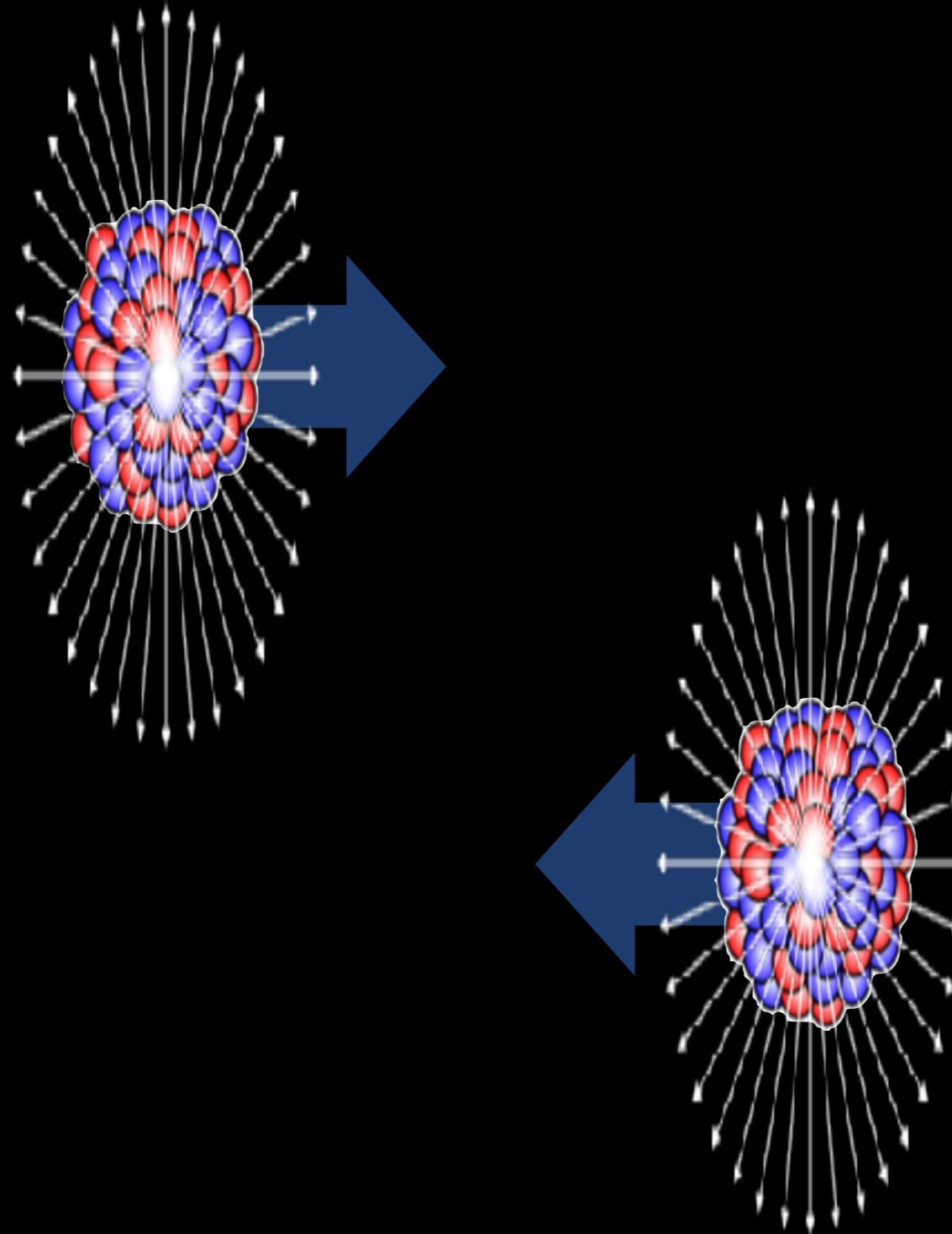
# COLLECTIVITY EVERYWHERE?



Intriguing prospect: Pb+Pb may provide a new perspective on the pp underlying event.

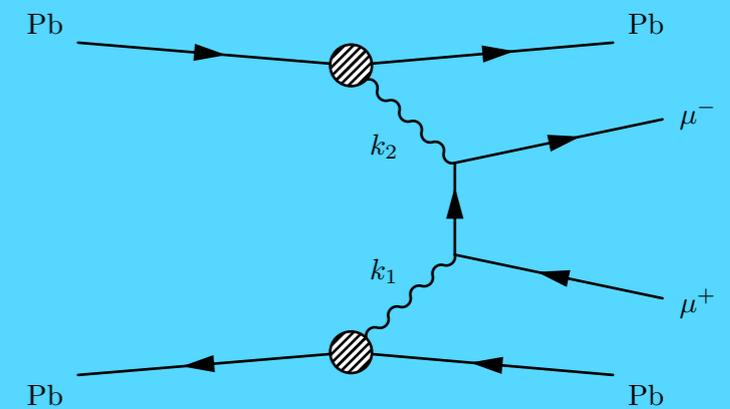
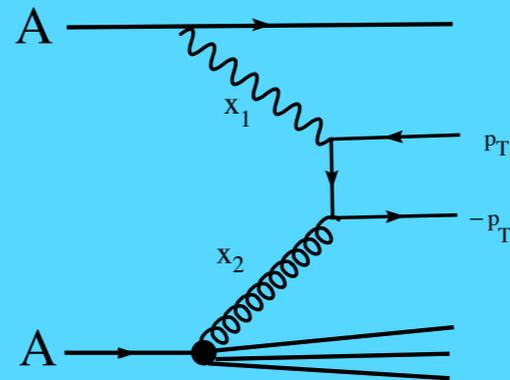
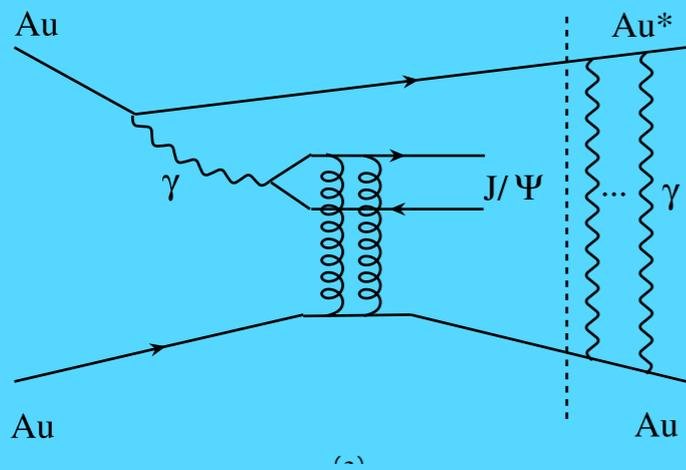


# ENCORE: ULTRA-PERIPHERAL COLLISIONS



Strong EM fields, highly contracted: quasi-real photons

# ULTRA-PERIPHERAL PHYSICS @ LHC



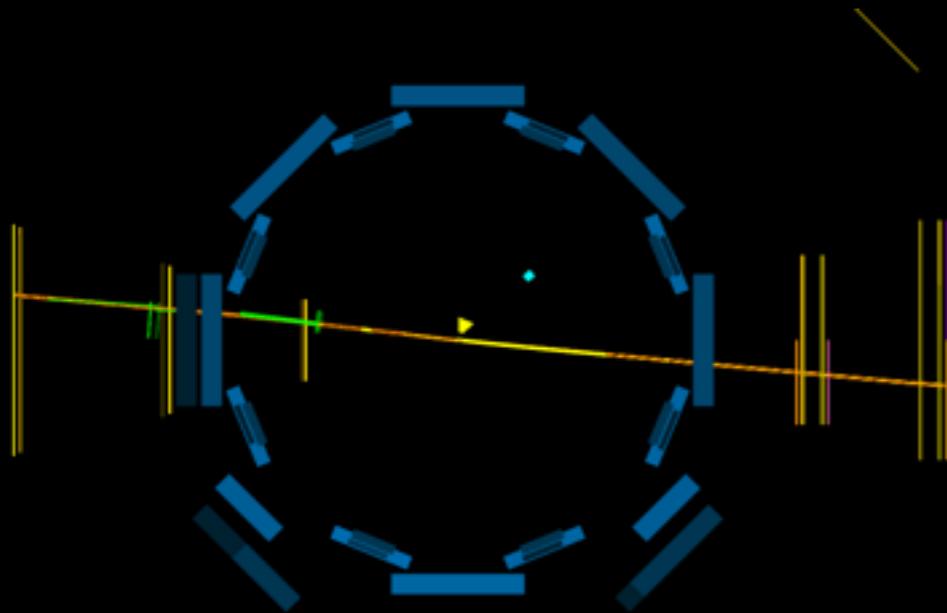
**Photon-pomeron:**  
production of vector mesons  
(sensitivity to  $nPDF$ )

**Photo-nuclear:**  
jet photoproduction  
(probe  $nPDF$  directly)

**Photon-photon:**  
dilepton production  
(& other exclusive states)

First Run 2 result  
from ATLAS

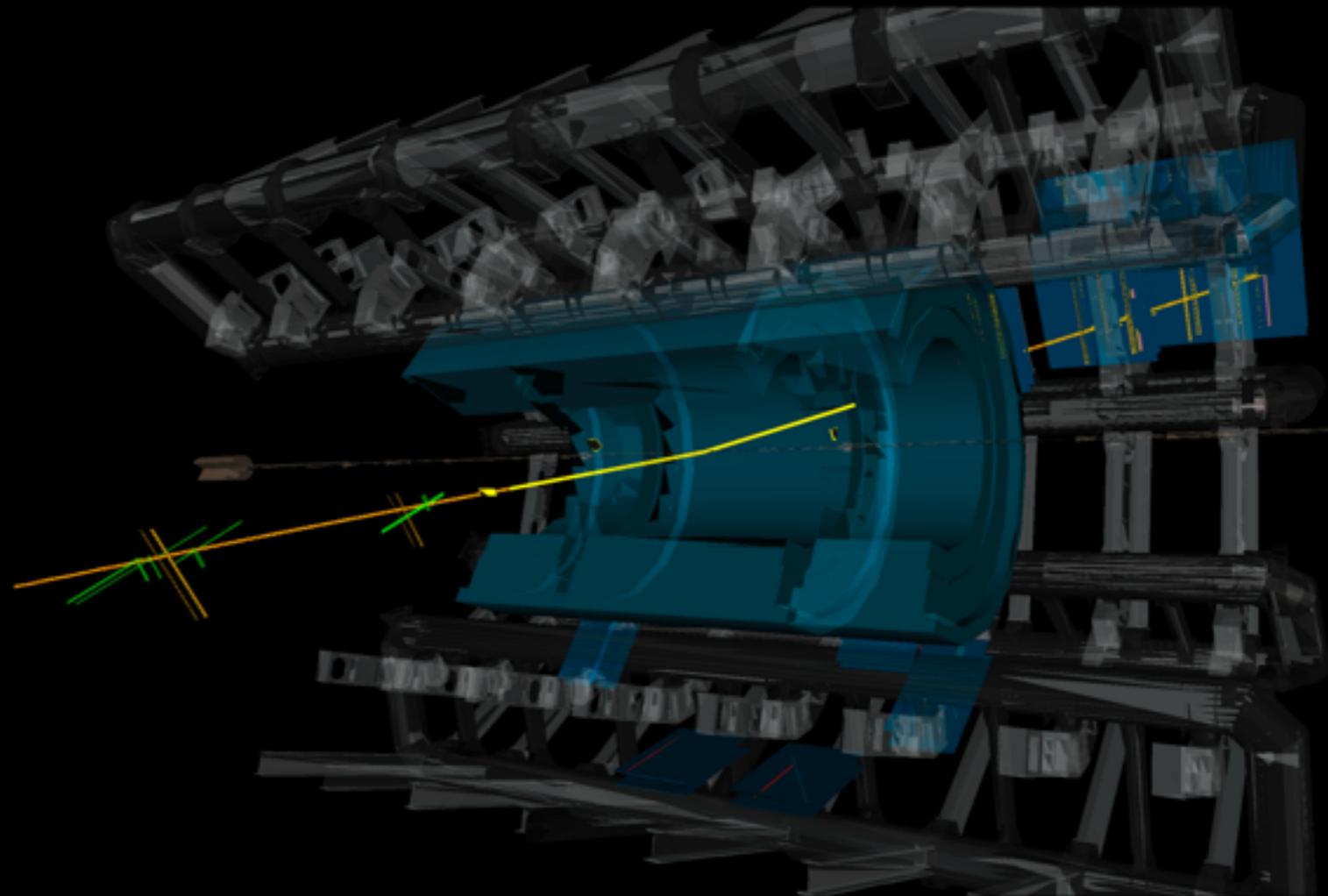
# EXCLUSIVE DIMUON EVENT



Run: 287038  
Event: 71765109  
2015-11-30 23:20:10 CEST

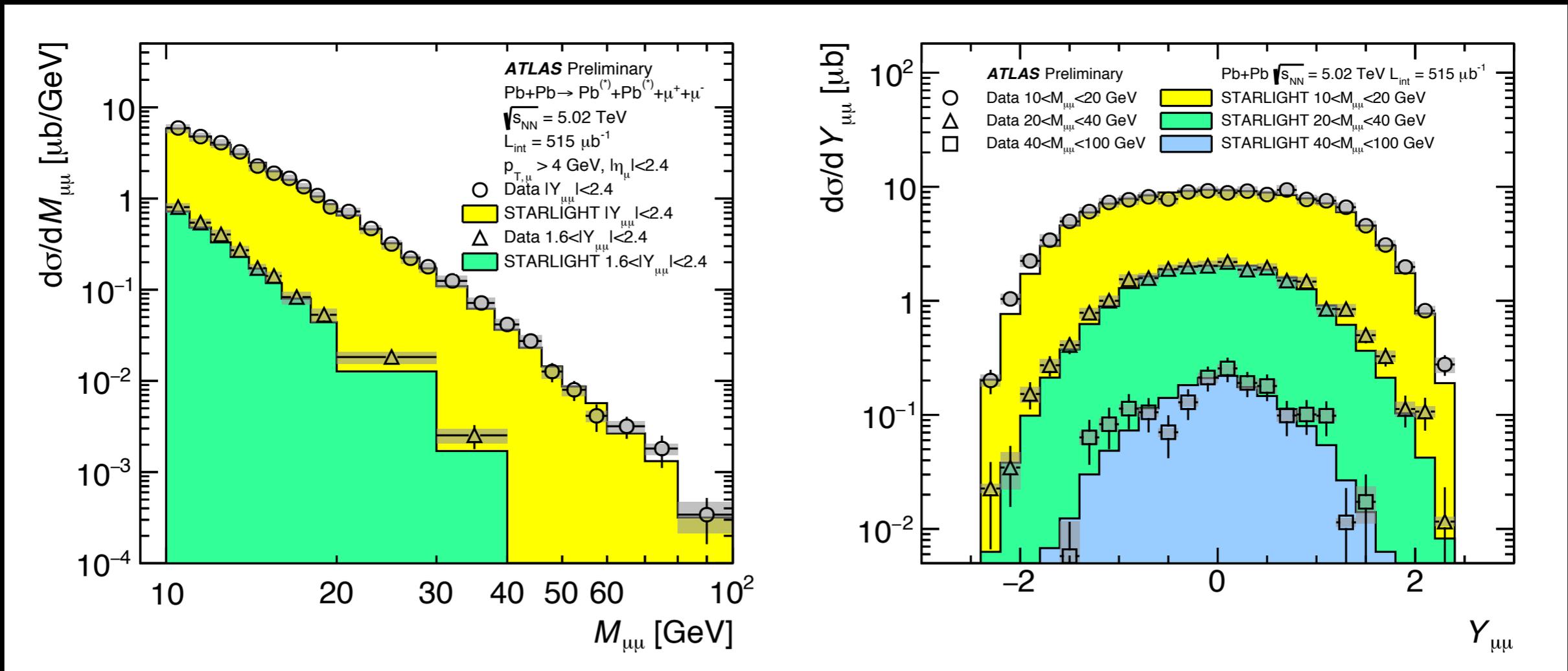
$M_{\mu\mu} = 173 \text{ GeV}$

Dimuons UPC Pb+Pb 5.02 TeV



# SPECTRAL SHAPES IN DATA AND MC

ATLAS-CONF-2016-025

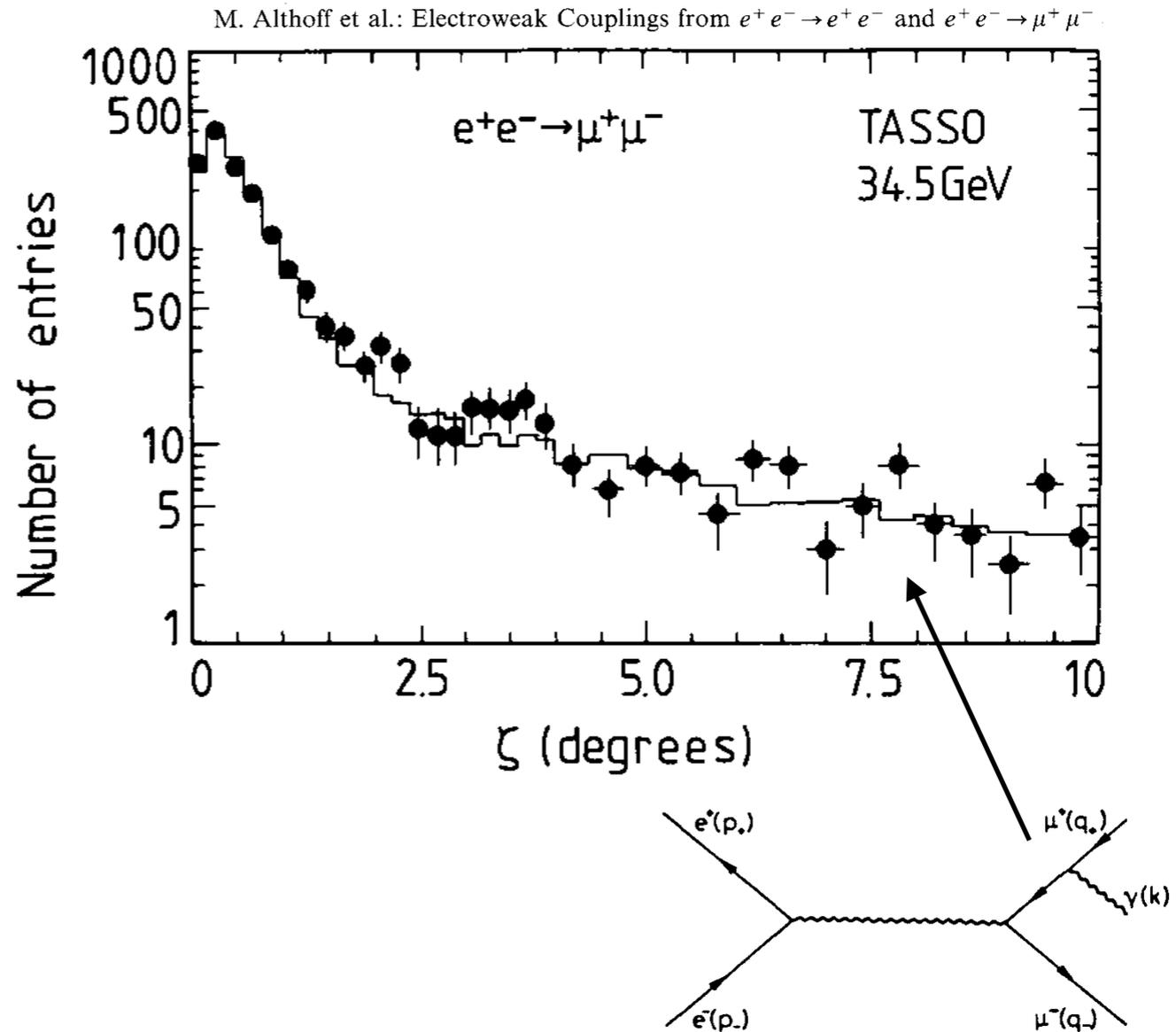
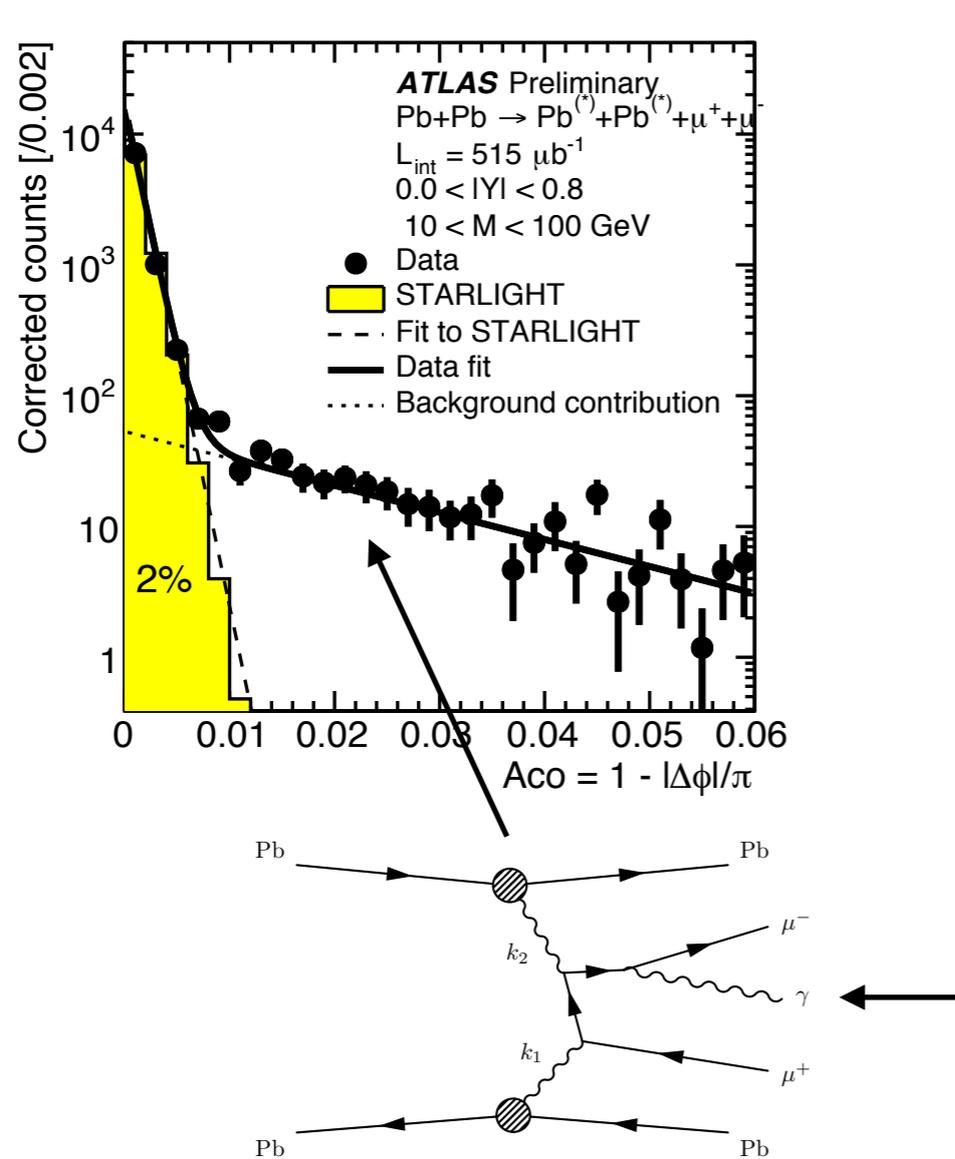


STARLIGHT MC implements collisions of Weisacker-Williams quasi-real photons + QED  $\mu^\pm$  production: good agreement with new ATLAS data.

Will help calibrate incoming photon flux (e.g.  $\gamma+A$ ,  $\gamma+p$ )

# QED ATTACKS

ATLAS-CONF-2016-025

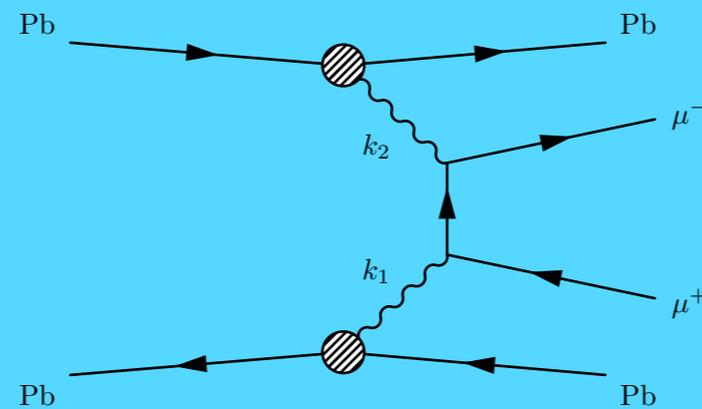
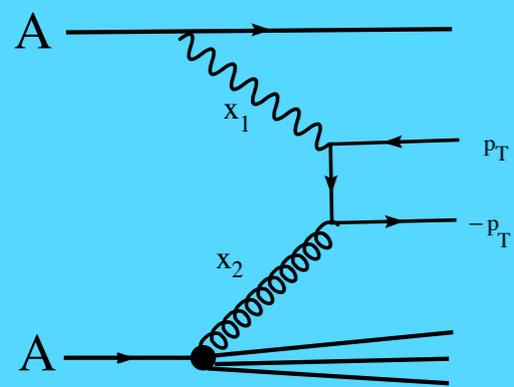


STARLIGHT calculations only include pure  $\mu^+\mu^-$ , w/ no final state QED.

Clearly required in  $e^+e^- \rightarrow \mu^+\mu^-$ , e.g. from DESY.

Not easily available in existing MC codes: exploring several avenues

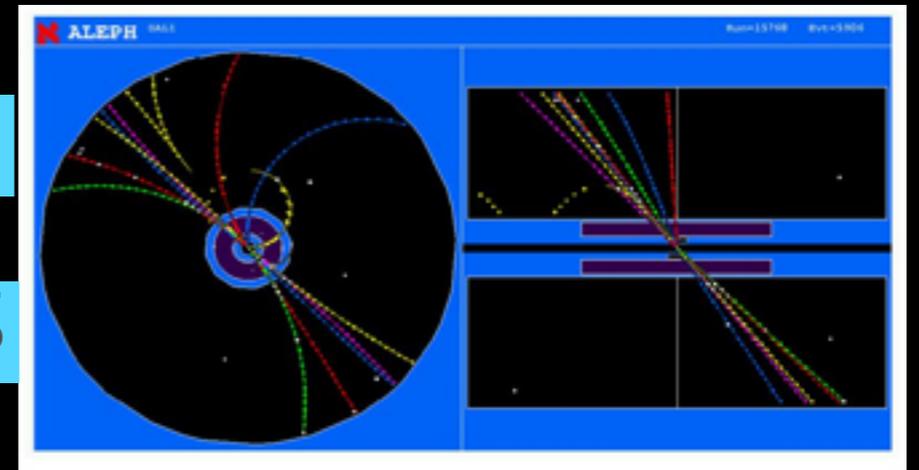
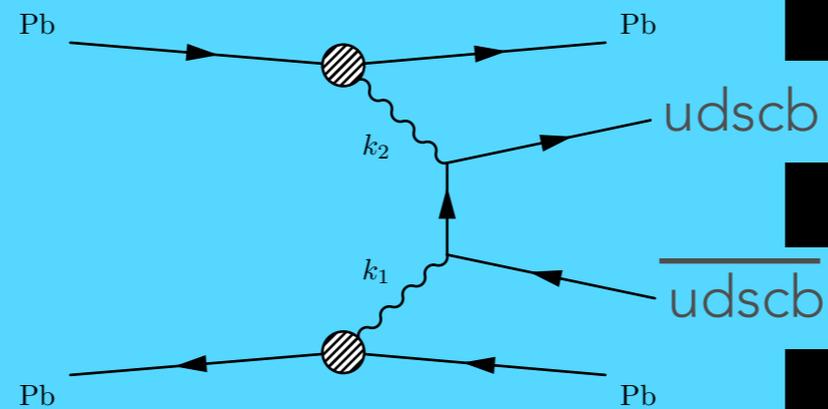
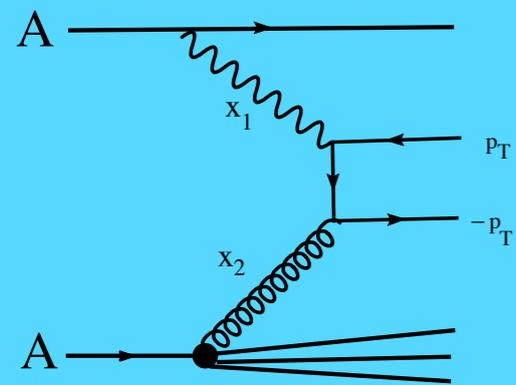
# ULTRA-PERIPHERAL PHYSICS @ LHC



*Photo-nuclear:  
jet photoproduction  
(probe nPDF directly)*

*Photon-photon:  
dilepton production  
(& other exclusive states)*

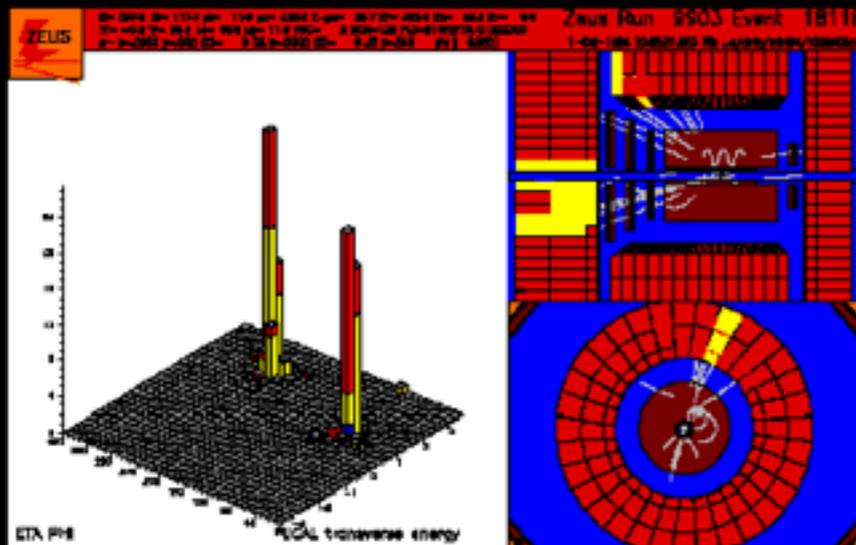
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*Photo-nuclear:  
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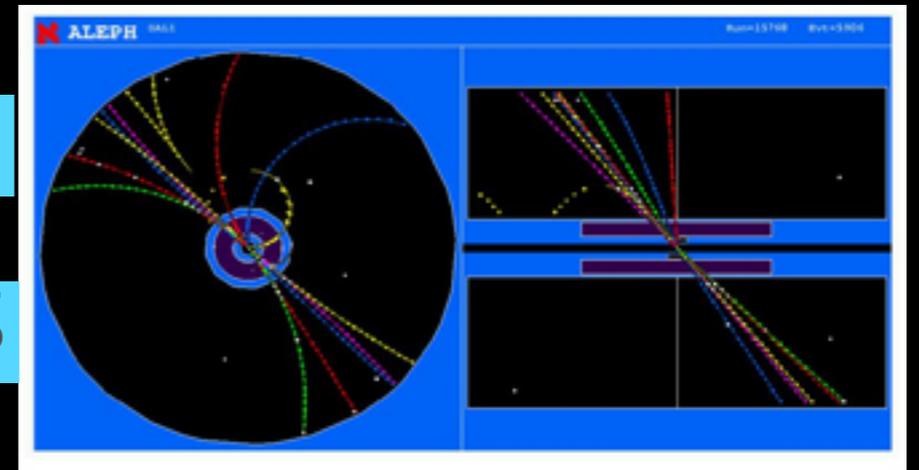
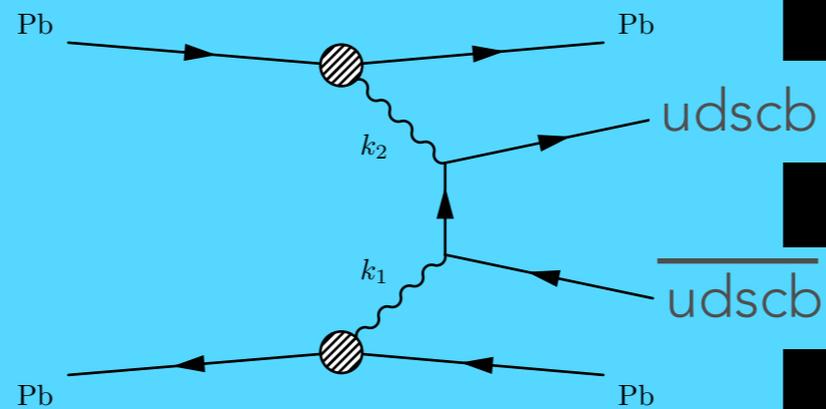
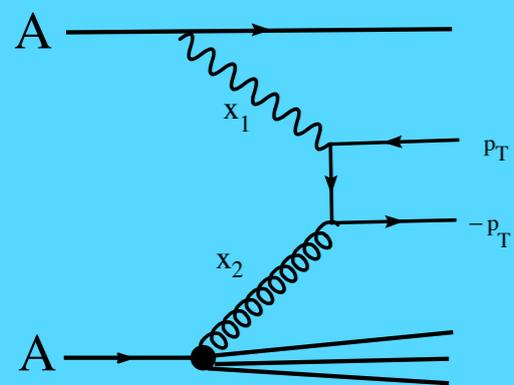
*Photon-photon:  
dilepton production  
(& other exclusive states)*

*exclusive hadrons  
or jets*



*inclusive and dijet  
photoproduction*

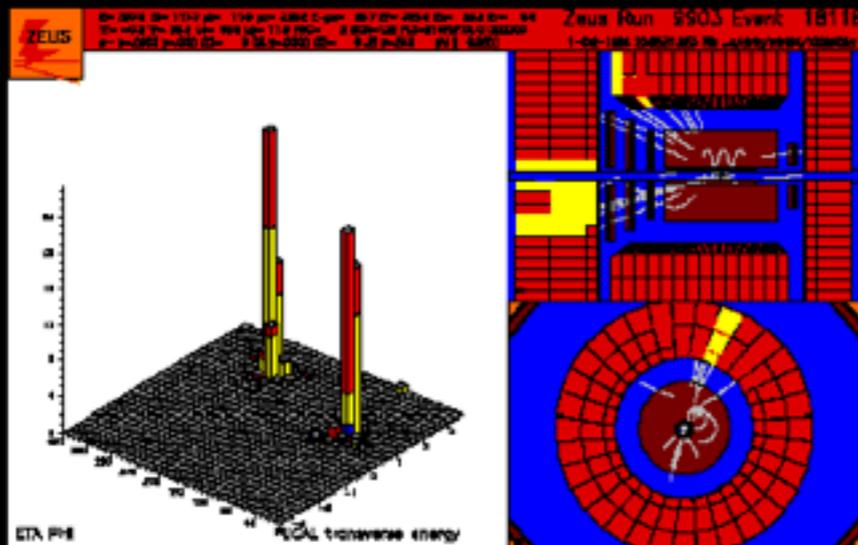
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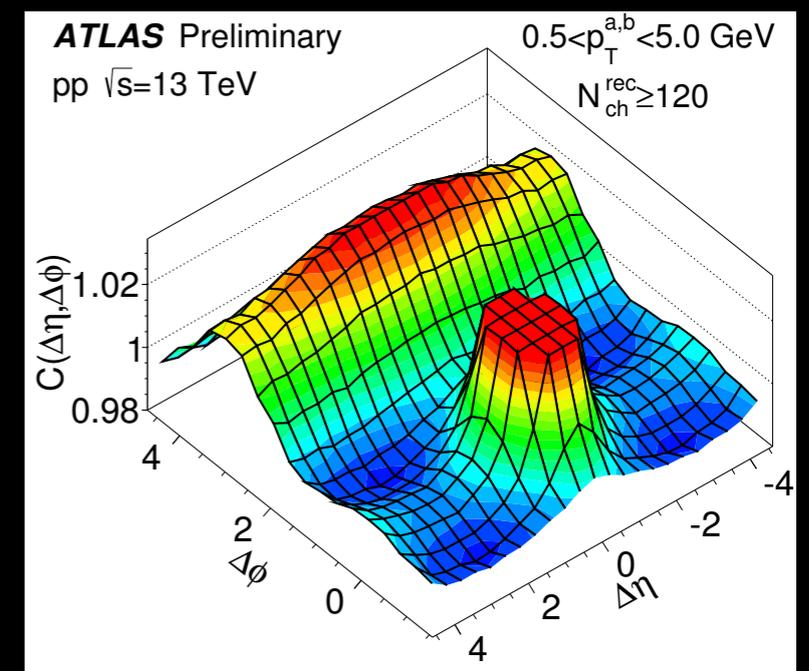
*Photo-nuclear:  
jet photoproduction  
(probe nPDF directly)*

*Photon-photon:  
dilepton production  
(& other exclusive states)*

*exclusive hadrons  
or jets*



*inclusive and dijet  
photoproduction*

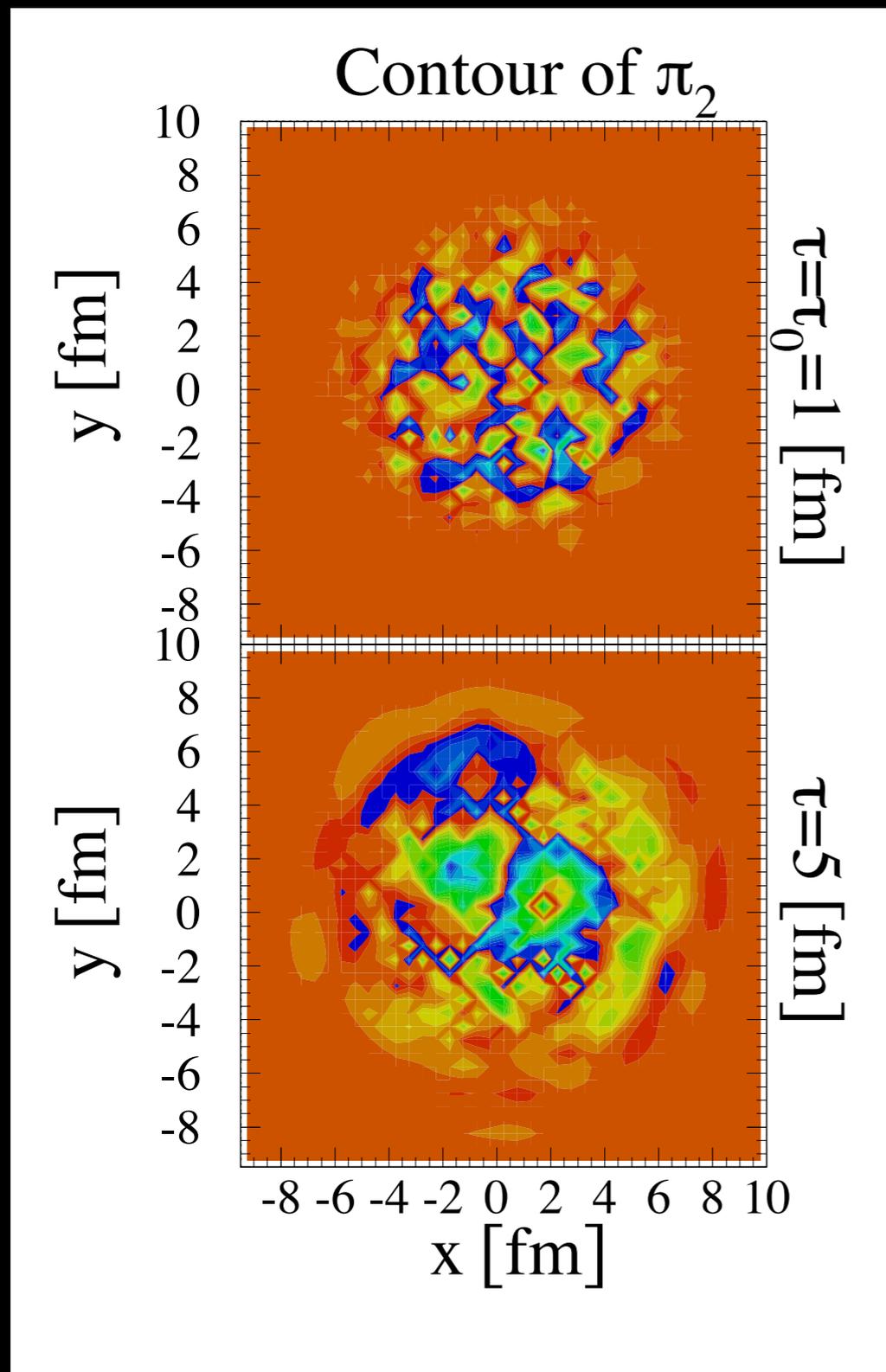


?



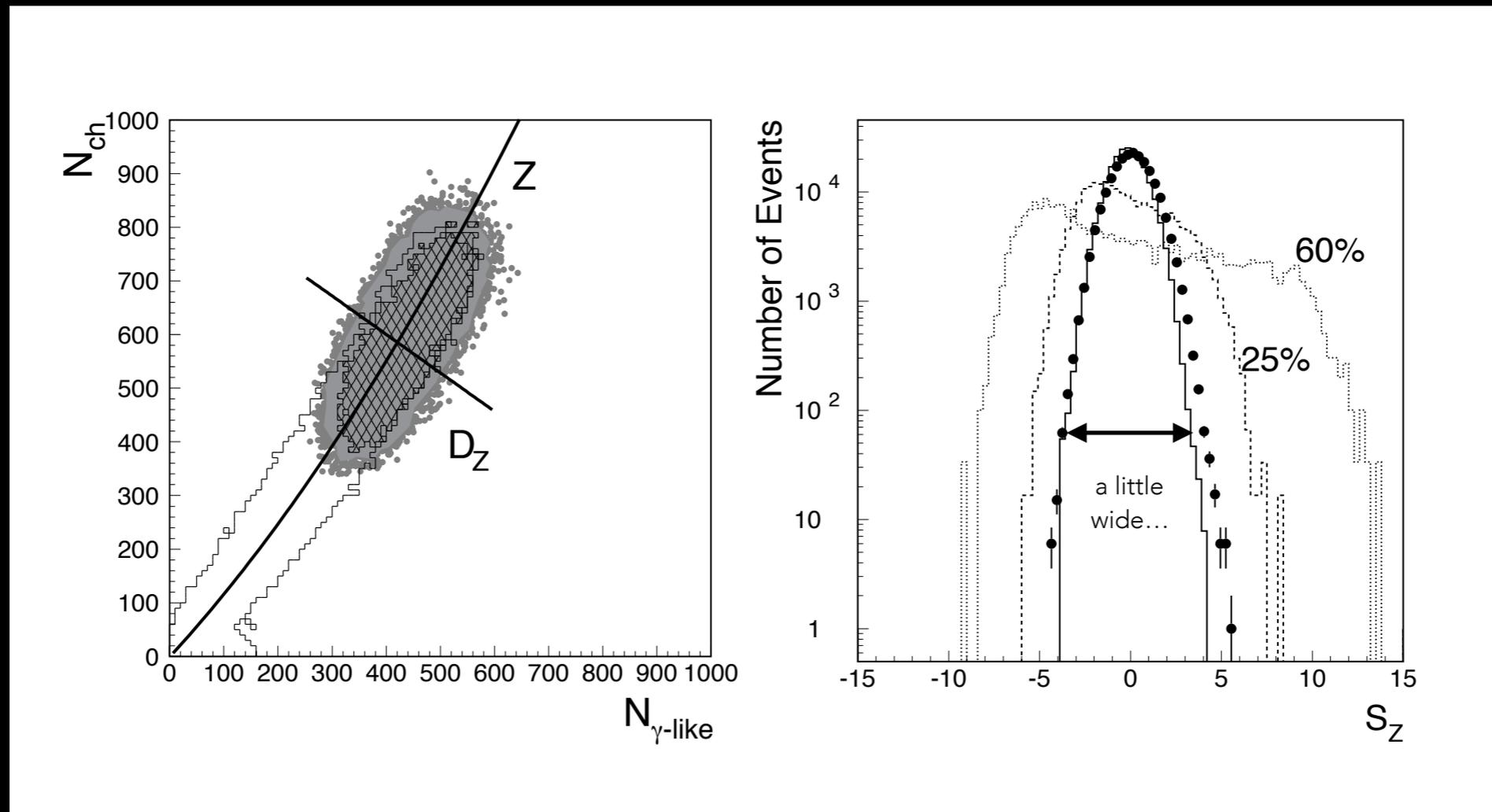
Thanks, Uli (from me, and ATLAS)

# PREHISTORY: DCCs (mid-1990's)



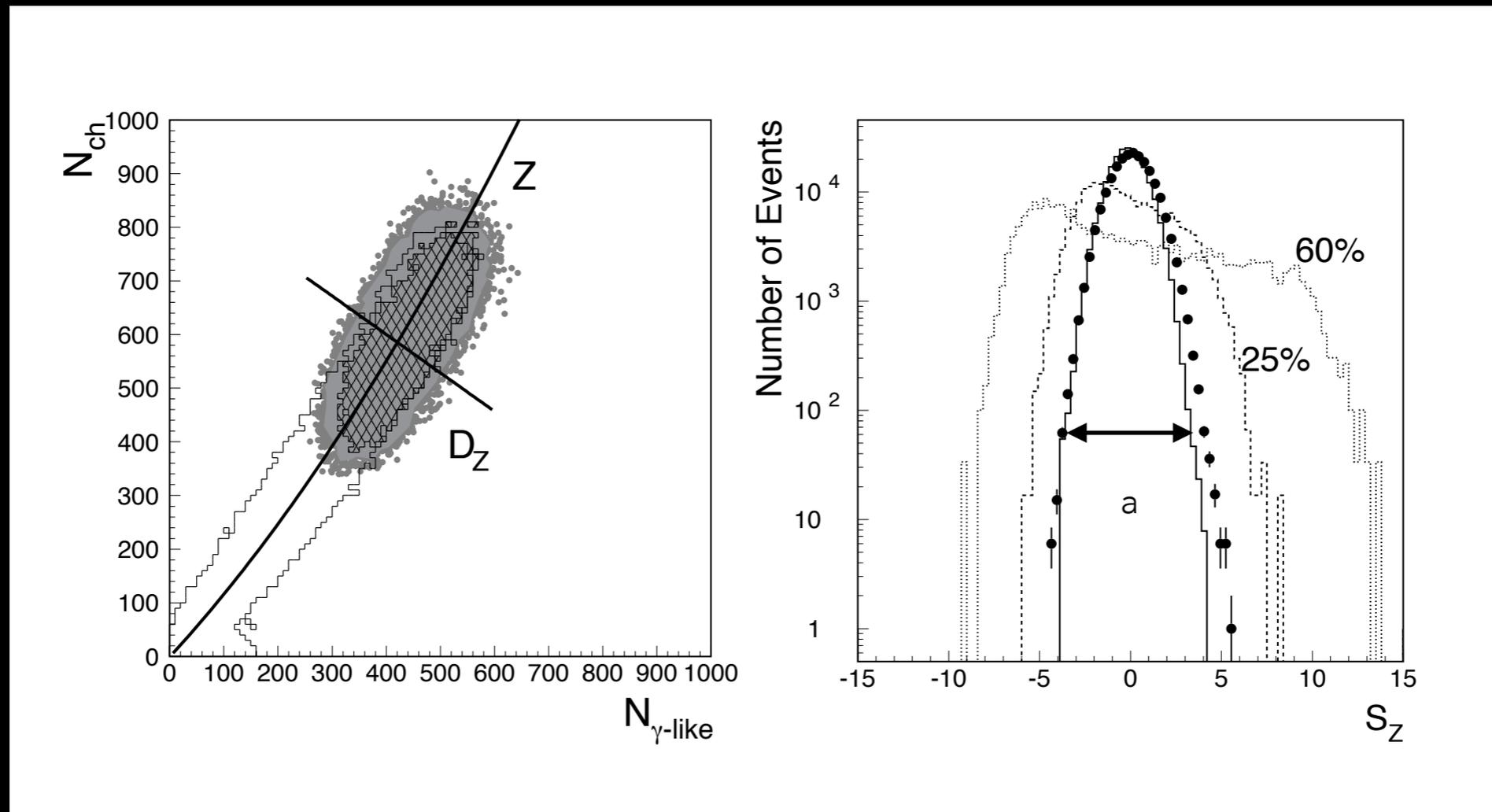
Chiral fields (linear  $\sigma$  model)  
disordered in initial state:  
in "quench" conditions  
(out of equilibrium)  
→ coherent pion domains  
causing large charge/neutral  
pion fluctuations

# SEARCH FOR DCCs (1997)



Clearly no large DCCs running in the streets.  
But the fluctuations were wider than MC

# SEARCH FOR DCCs (1997)

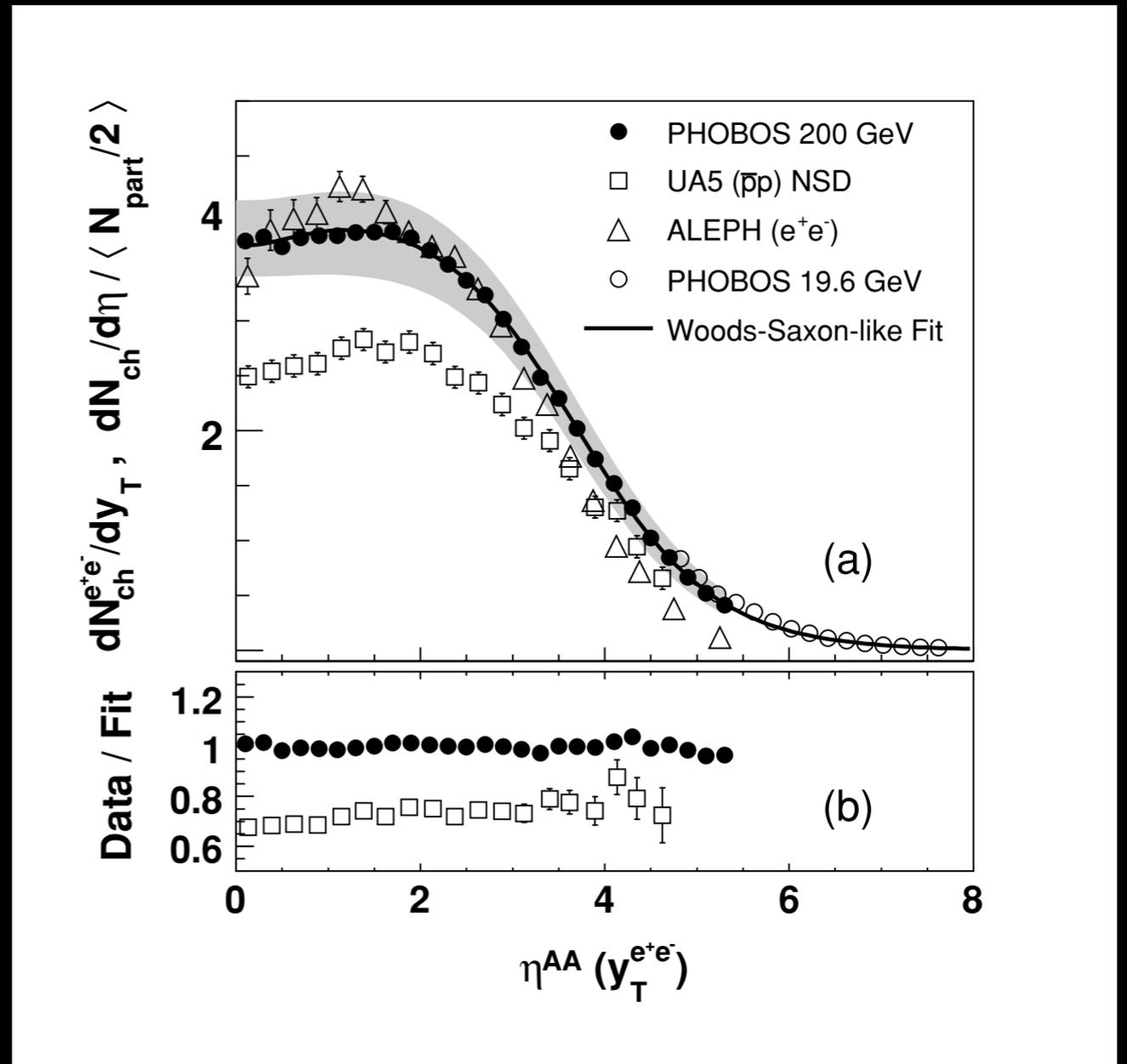
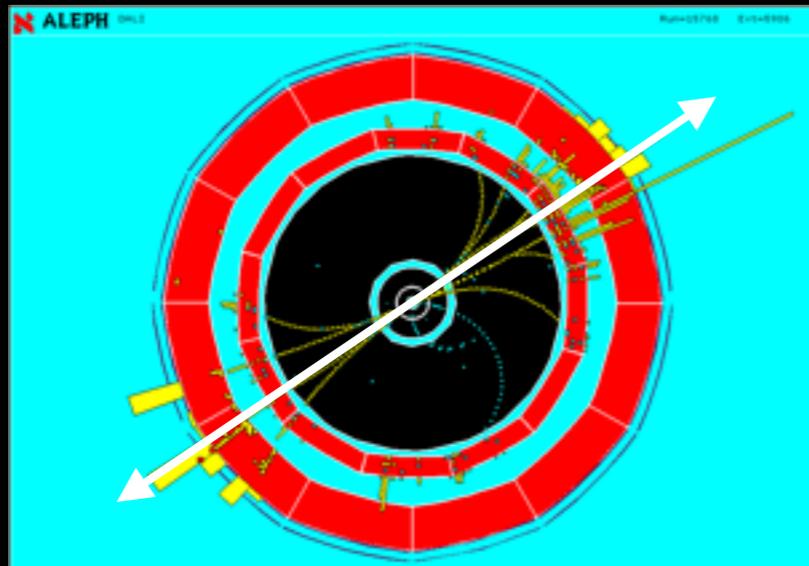
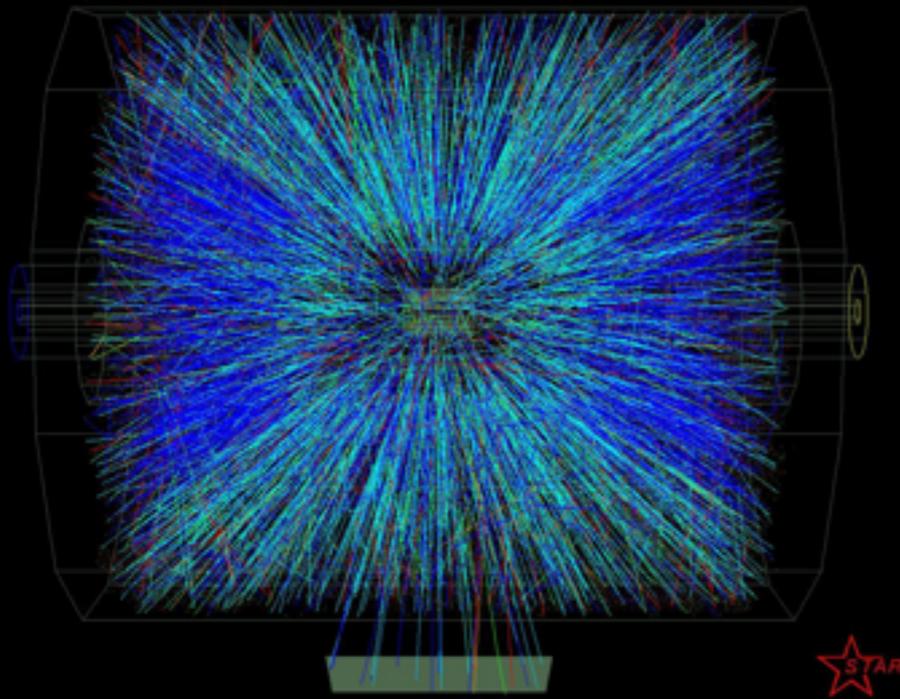


In 1999, I worked up a formalism based on Urs' multi particle BEC weights to quantify non-binomial fluctuations as a function of phase space density. It was very exciting for me (I was 29) to "explain" DCCs using BEC...

until Uli discovered a bug, and Urs retracted his paper :(

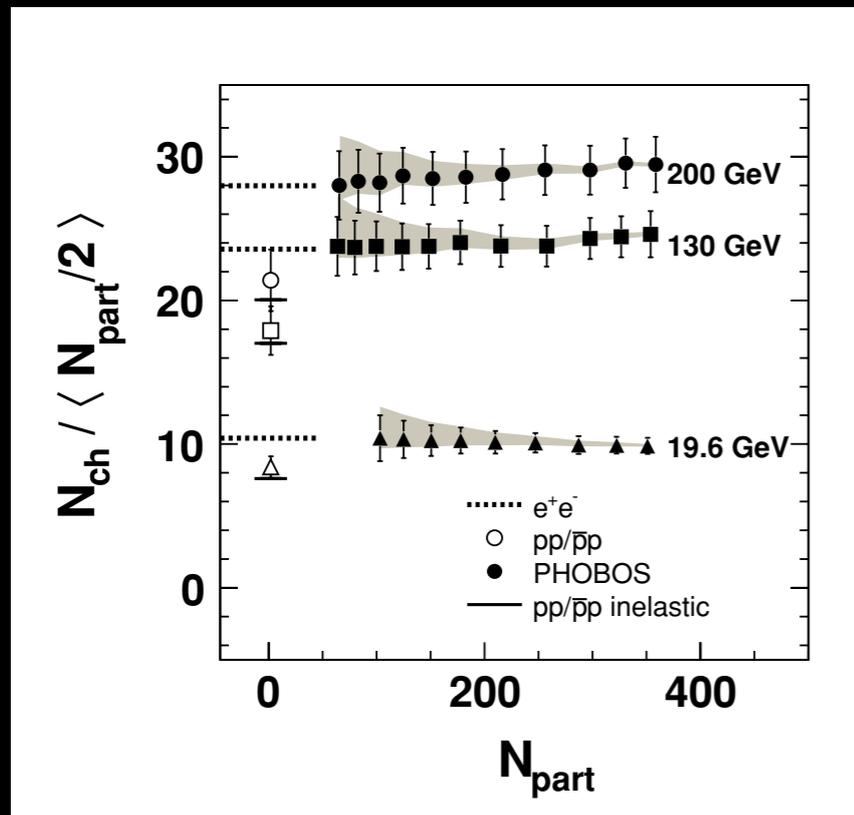


# 1. (PSEUDO)RAPIDITY DISTRIBUTIONS

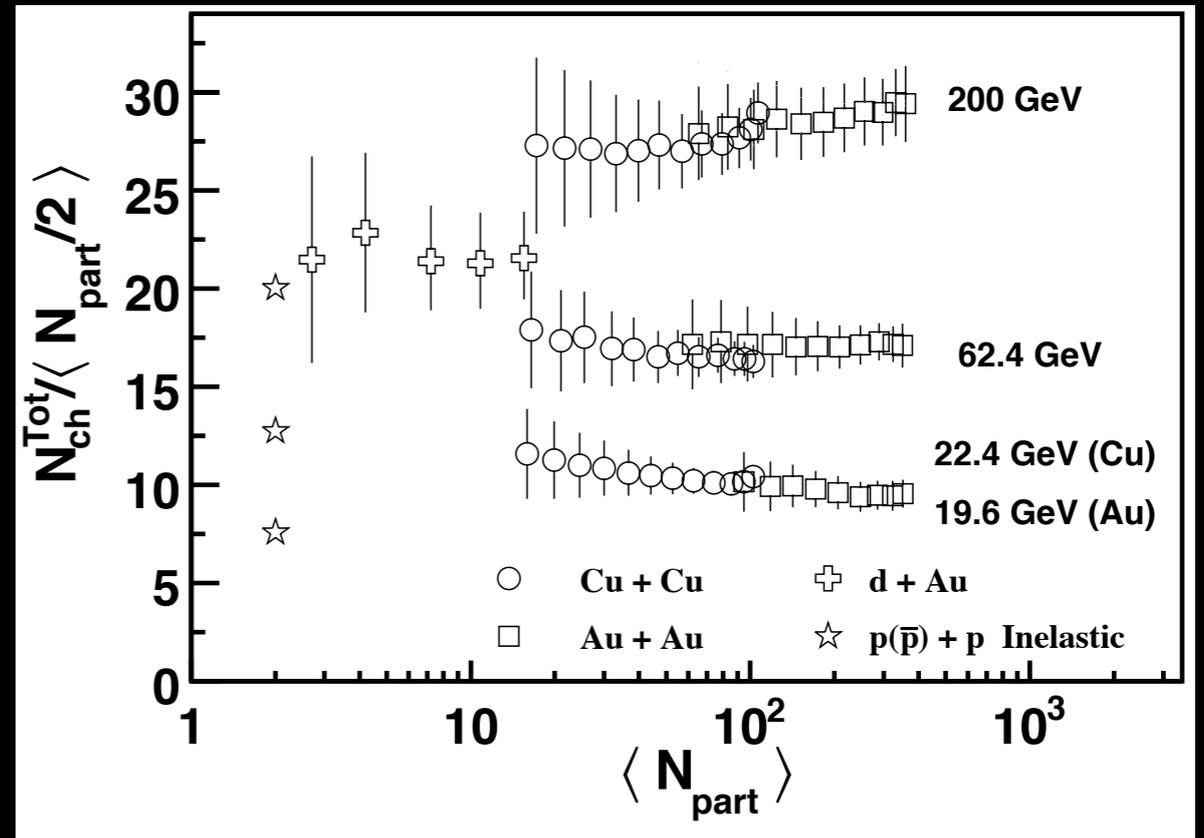


~similar shape in p+p, Au+Au &  $e^+e^-$   
 Merely "phase space"?

# 2. PARTICIPANT SCALING



2001: Au+Au

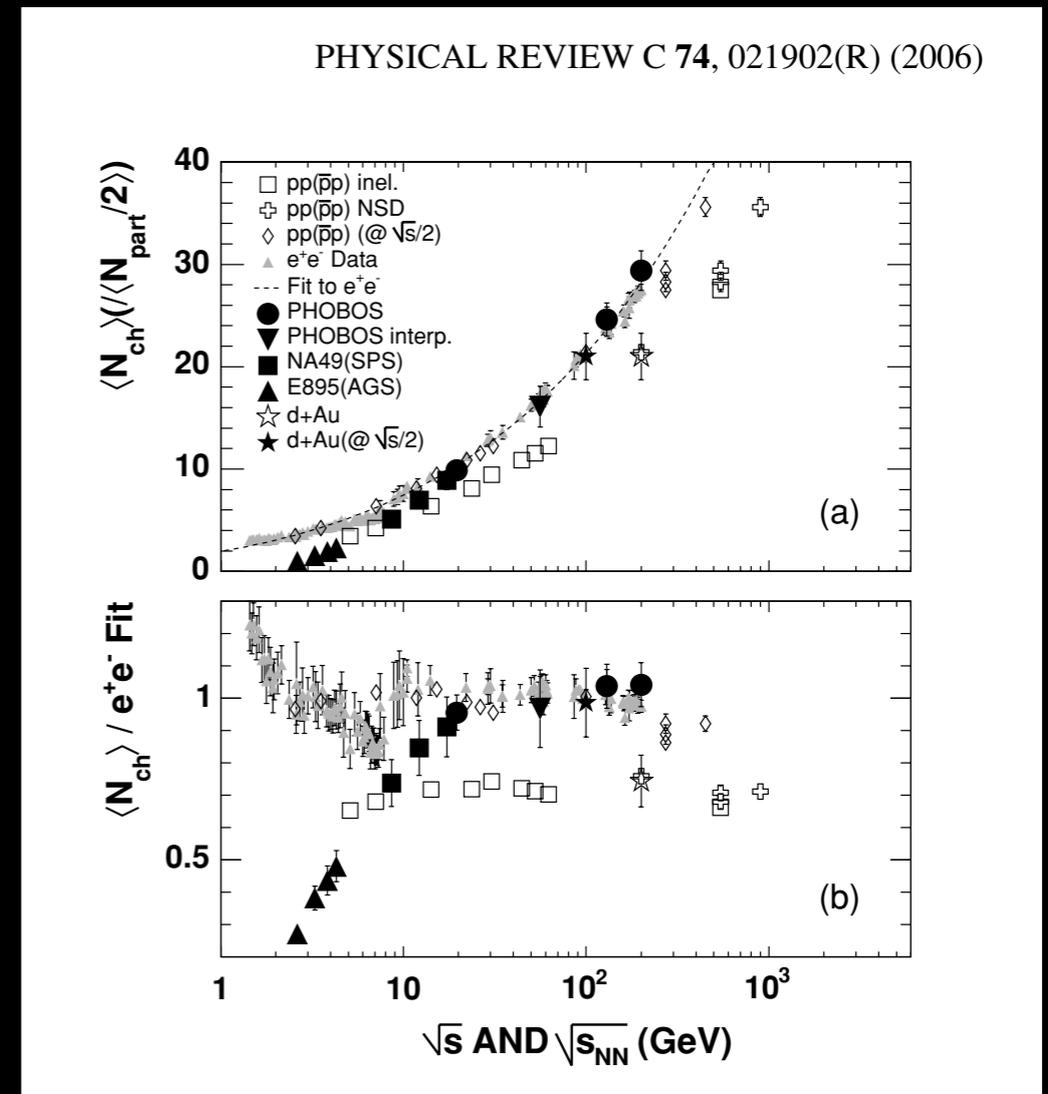
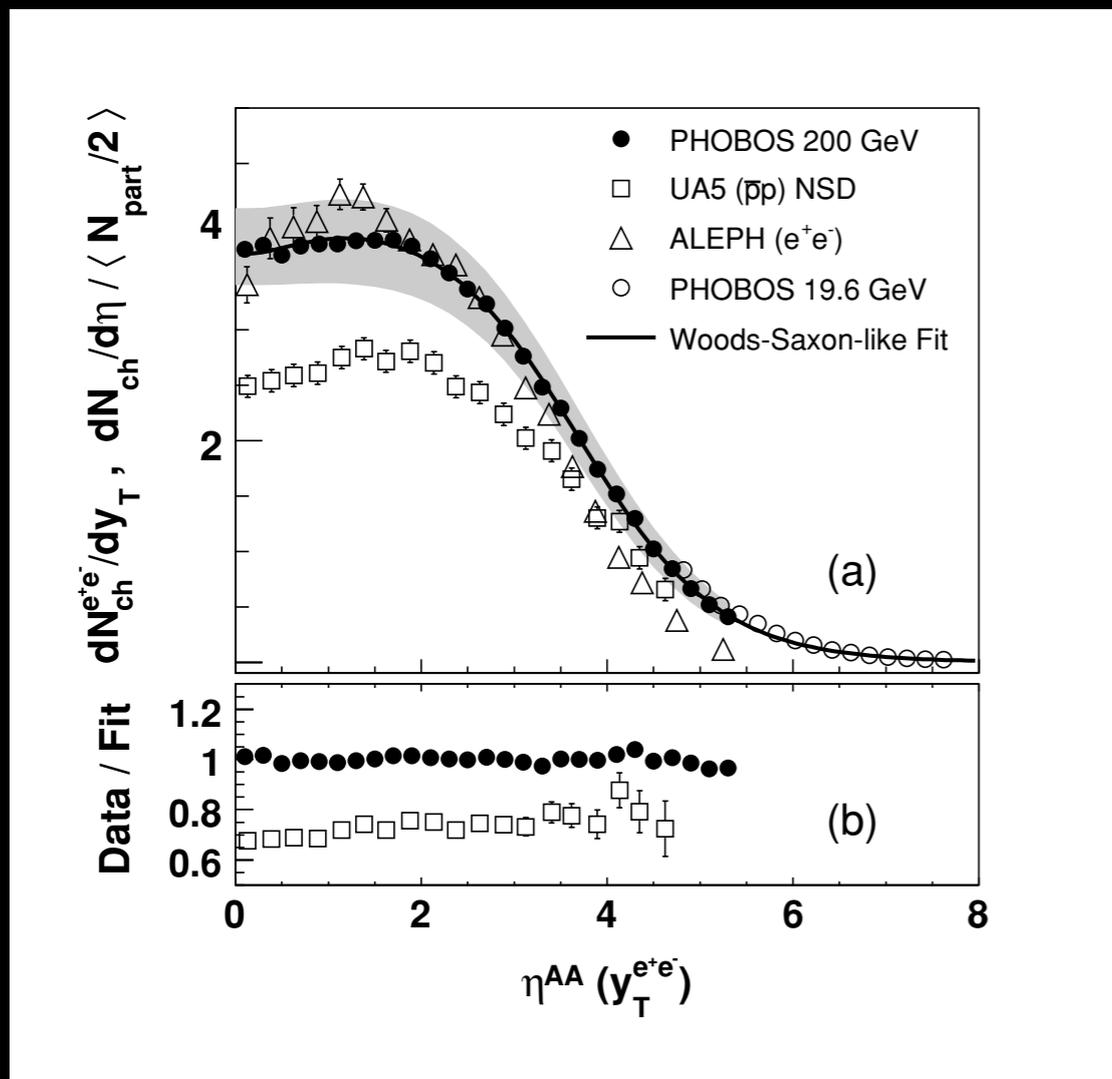


2005: Au+Au, Cu+Cu, d+Au

Integrate over  $4\pi \rightarrow N_{ch} \sim N_{part}$  (all systems!)

cf. "quark scaling" only at  $\eta \sim 0$

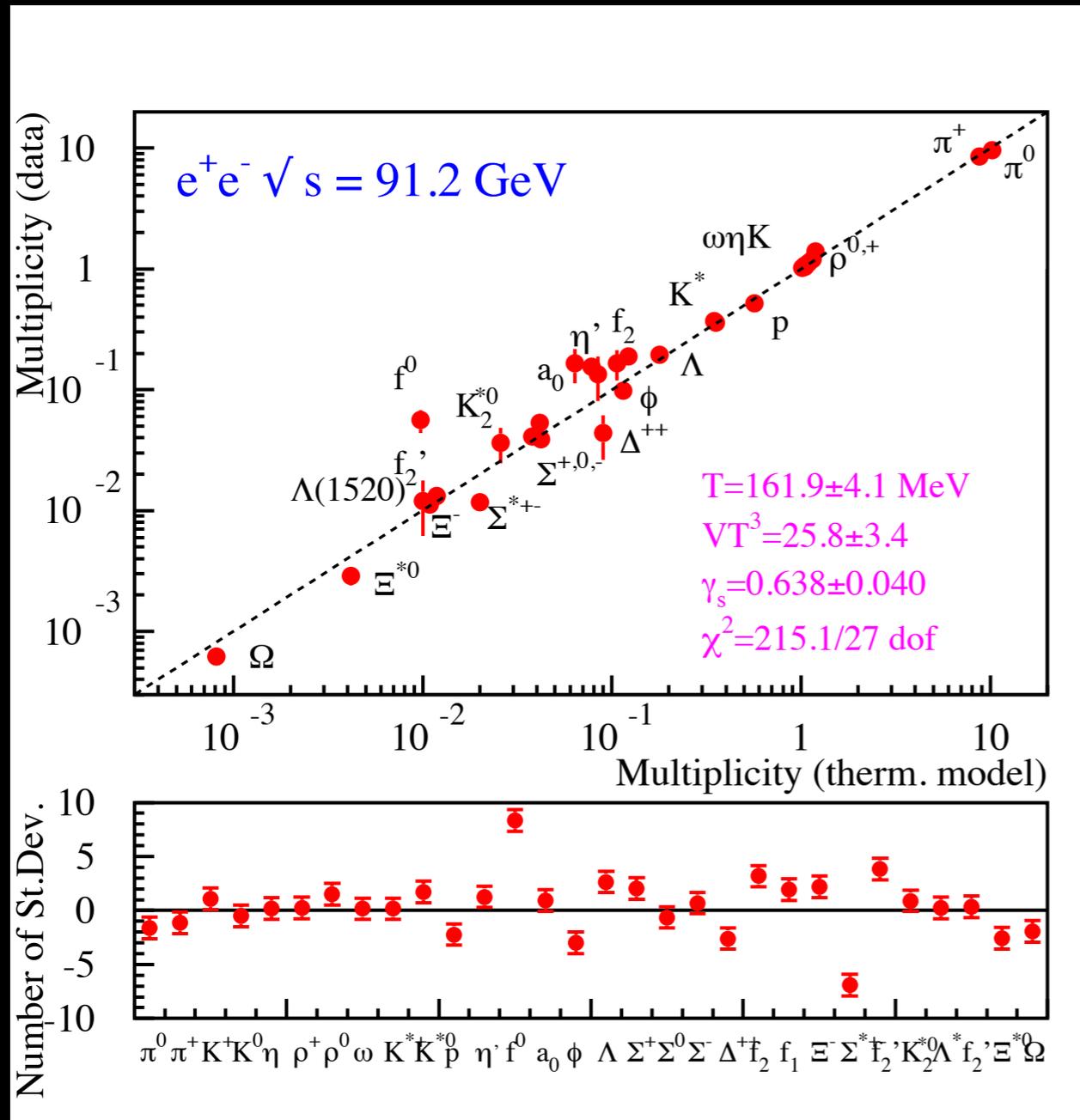
# IS PARTICLE PRODUCTION "UNIVERSAL" ?



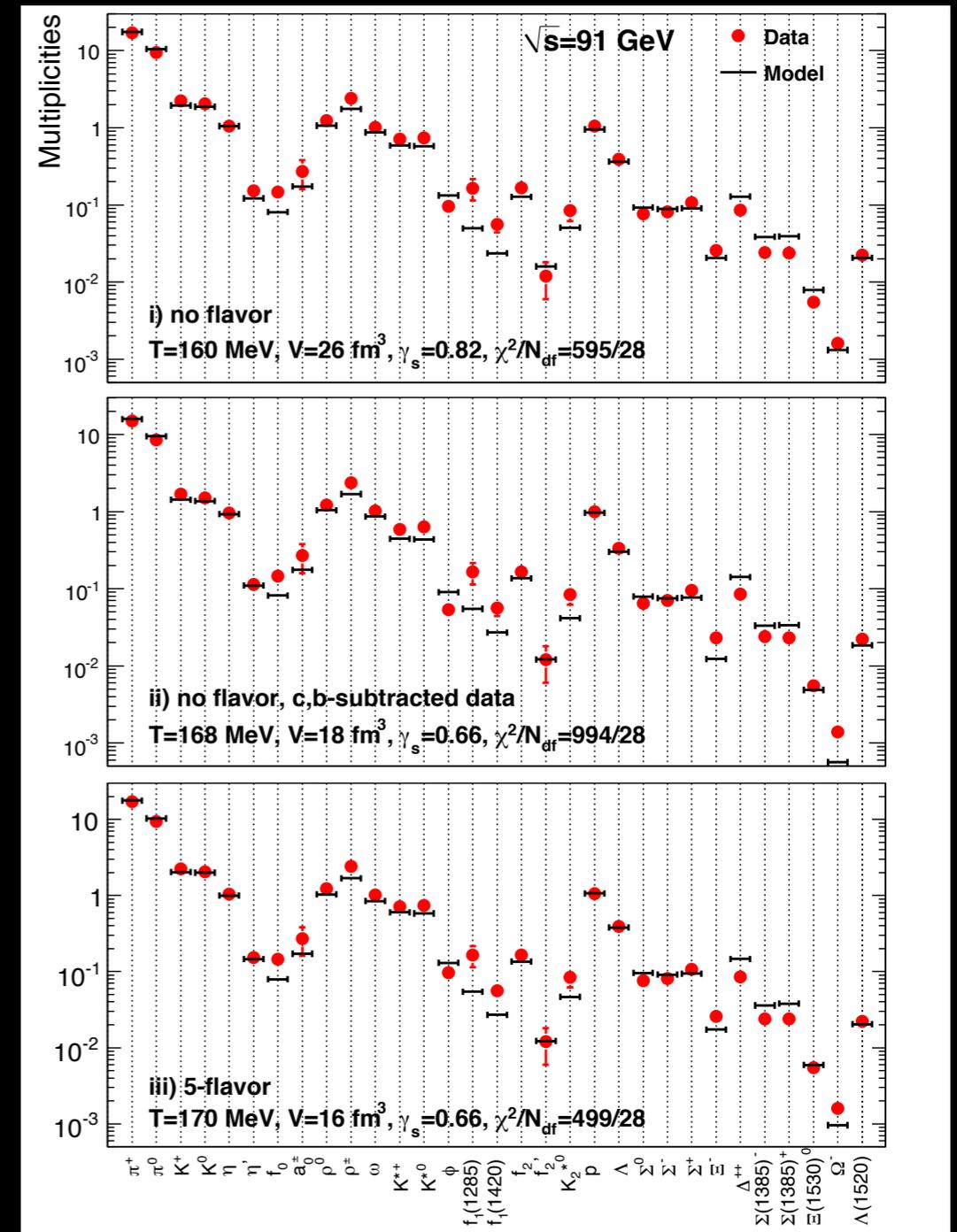
$$A+A \sim p+p (@ \sqrt{s}/2) \sim e^+e^-$$

$$A+A \quad \frac{dN_{ch}}{d\eta} / (N_{part}/2) \sim \frac{dN_{ch}}{dy_T} \quad e^+e^-$$

# THERMAL FITS TO LEP DATA



Becattini, 0901.3643



Andronic et al, 0804.432

# EXPLAINING "UNIVERSALITY"

These observations were very puzzling.  
How could the  $dN/dy$  and  $N_{ch}$  in all systems coincide?

Al Mueller's answer: an accident.  
pQCD does not need statistical physics.

# EXPLAINING "UNIVERSALITY"

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Al Mueller's answer: an accident.  
pQCD does not need statistical physics.

Sometime in 2003, I discovered that Peter Carruthers had been pondering the same issues more than 30 years before

## HERETICAL MODELS OF PARTICLE PRODUCTION\*

P. Carruthers†

*Laboratory of Nuclear Studies  
Cornell University  
Ithaca, New York 14850*

### I. INTRODUCTION

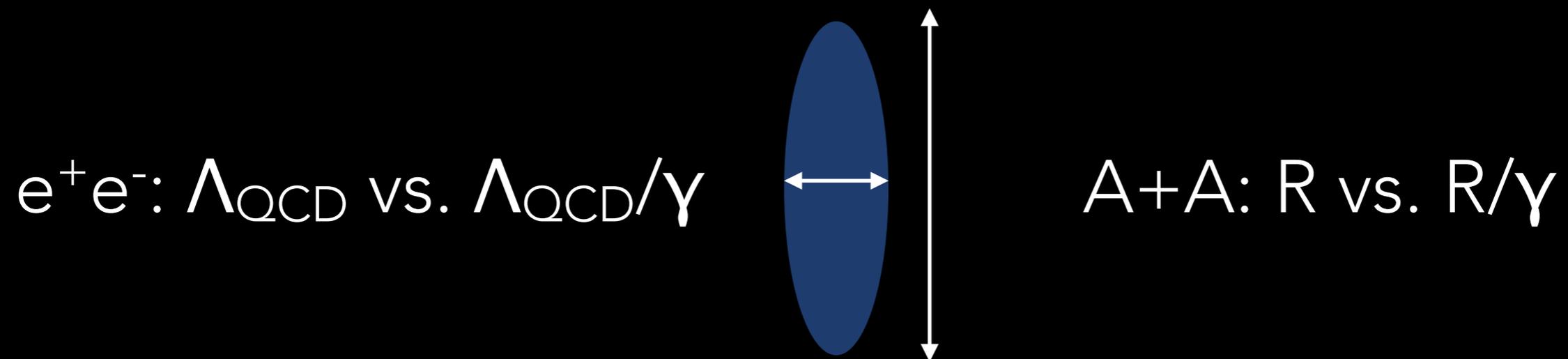
A true heresy should arise in the context of an established faith. Presently little is established about the mechanism of particle production in collisions of extremely high energy, but nevertheless there exists a peculiar orthodoxy of belief in the descriptions of such processes by multiperipheral and parton models. Moreover, recent data have been analyzed in such a manner as to give these speculations a perhaps undeserved patina of truth. The heresies presented here are of two sorts.

# EXPLAINING "UNIVERSALITY"

These observations were very puzzling.

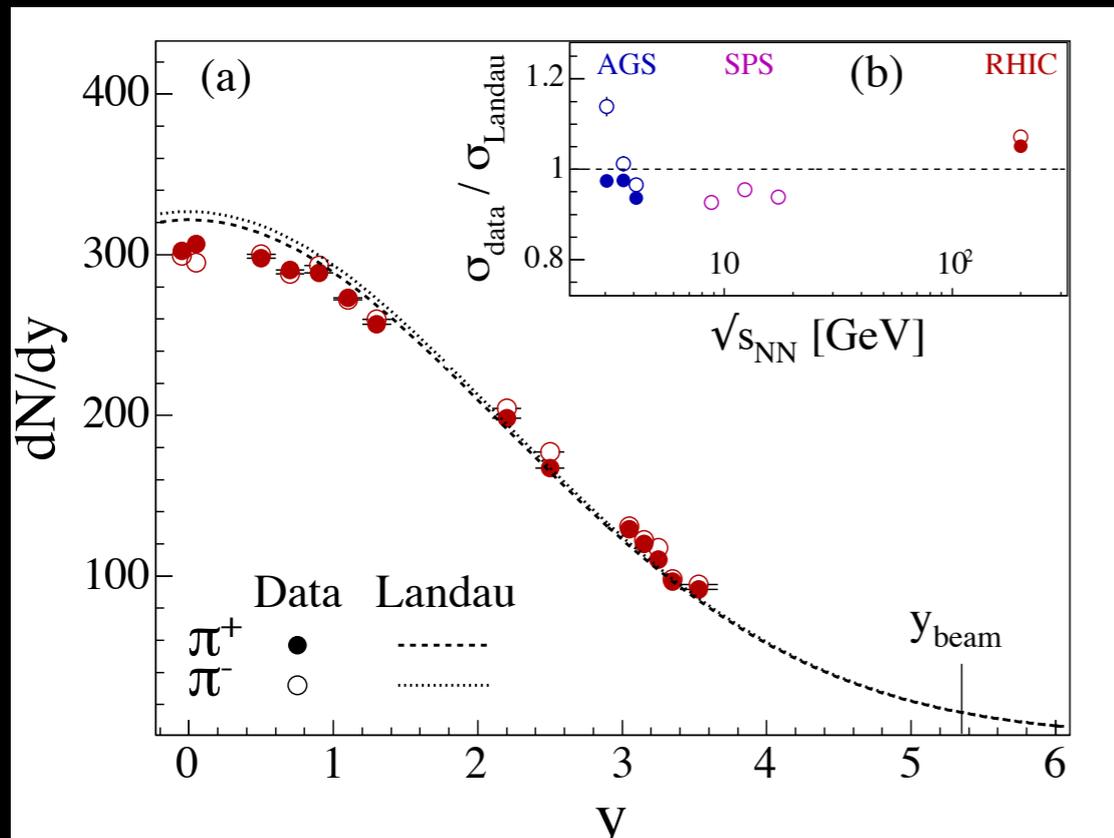
How could the  $dN/dy$  and  $N_{ch}$  in all systems coincide?

1. Very early thermalization,  $t_0 = R/\gamma$
2. Multiplicities scaling as  $s^{1/4}$  (Lorentz contraction + EOS)
3.  $dN/dy$  gaussian with  $\sigma \sim \sqrt{(\ln s)}$  (expansion)

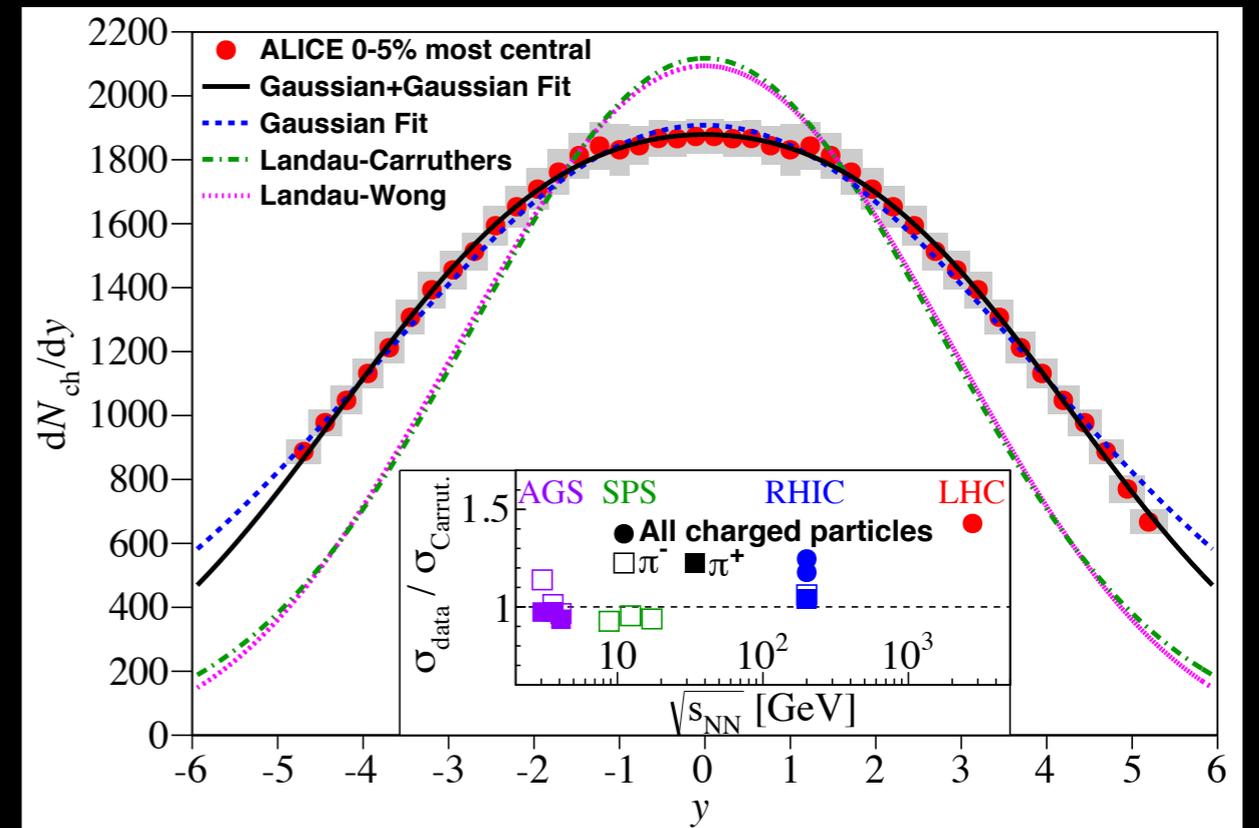


Fun to consider strongest assumption:  
all strongly-interacting systems behave this way

# LANDAU: "BORN" AT RHIC, "DEAD" AT THE LHC!



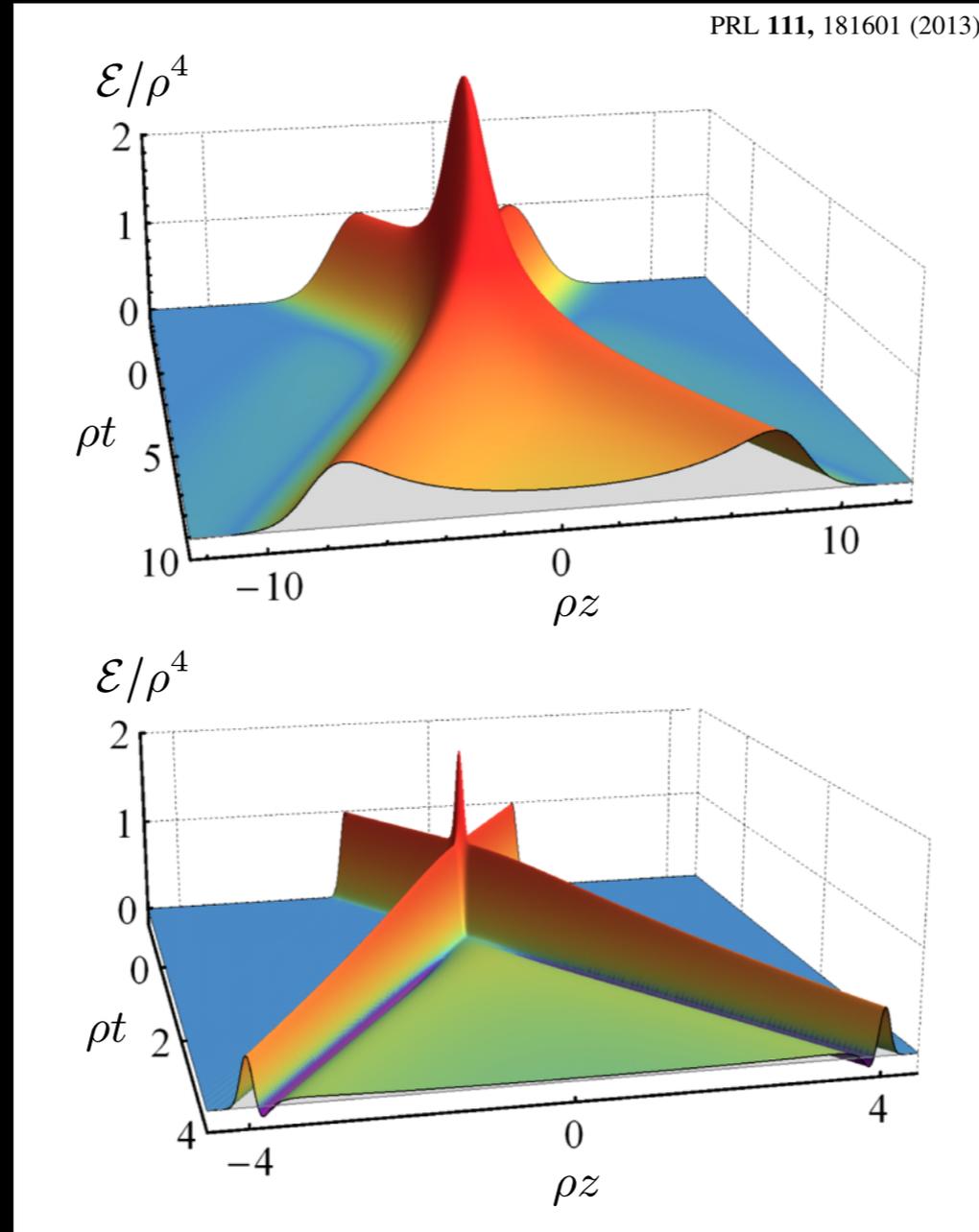
BRAHMS PID  $dN/dy$   
(still found to be inconsistent  
w/ PHOBOS  $dN_{ch}/d\eta$ )



ALICE extrapolated  $dN/d\eta$  to  $dN/dy$

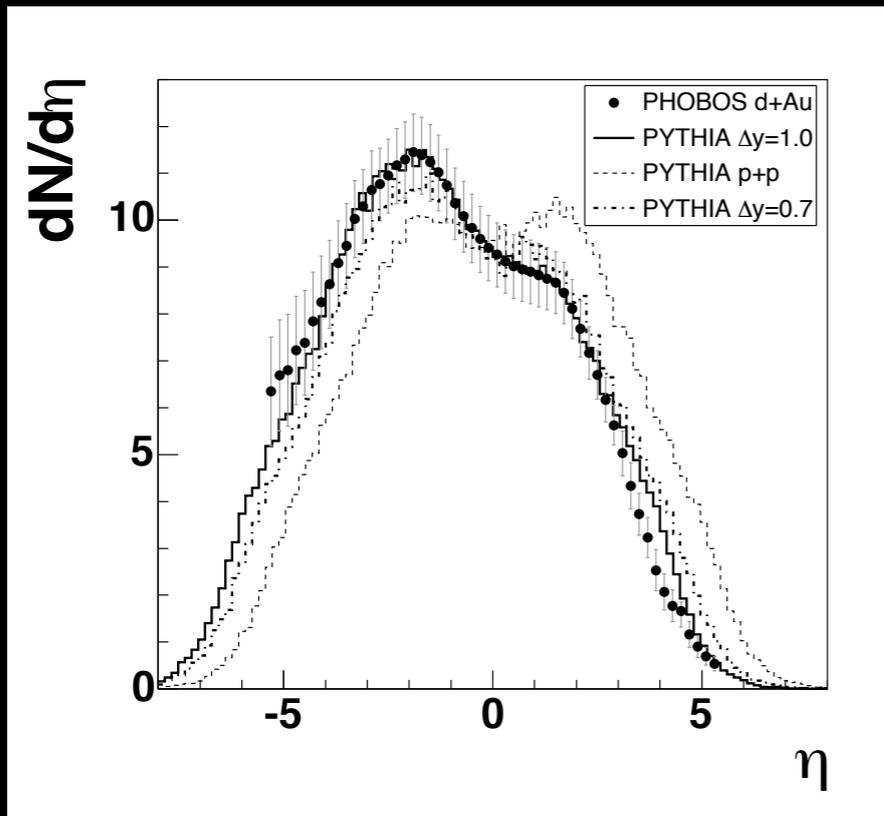
Boost invariance apparently violated in general,  
but Gaussians are too narrow.

# CAN LANDAU & BJORKEN BE FRIENDS?



Casalderrey-Solana, et al: colliding shock waves in AdS/CFT  
 $\sqrt{s}$  controls the thickness: transition from stopping to transparency.  
Not a full model, and  $dN/dy$  still narrow even for full stopping.

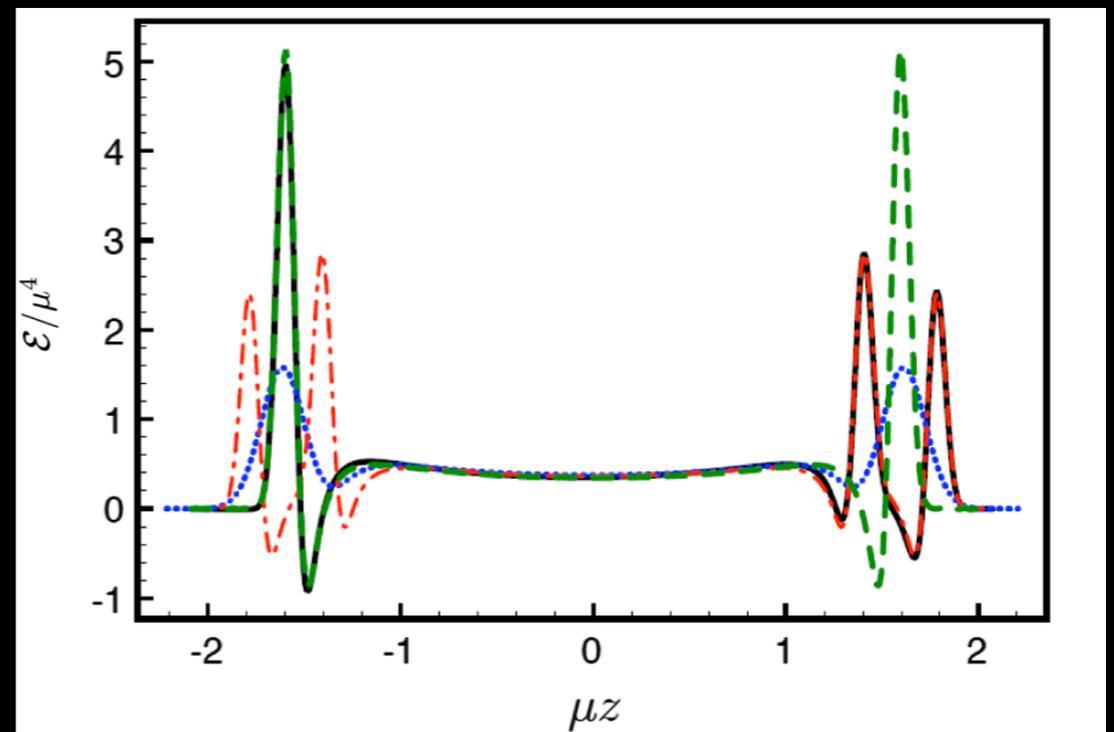
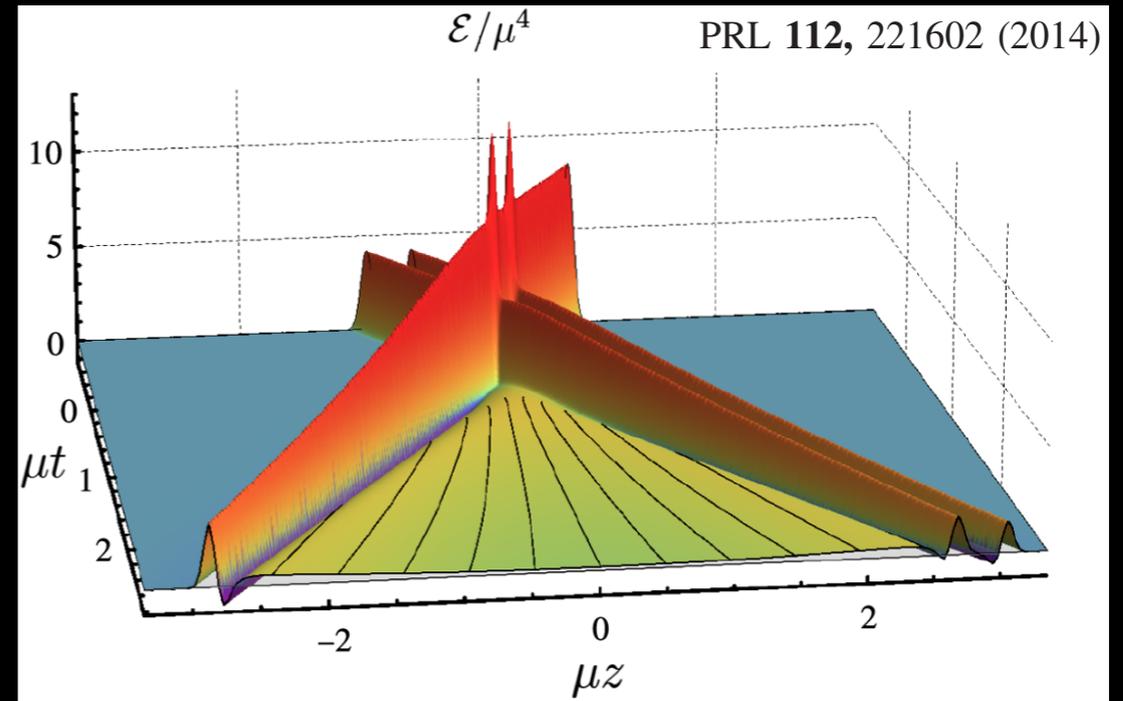
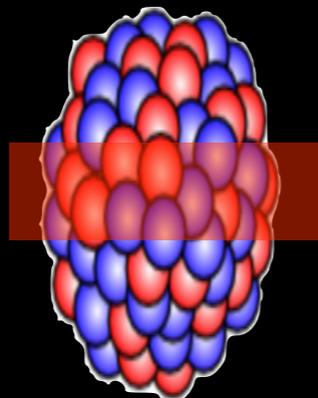
# LONGITUDINAL INITIAL CONDITIONS?



PAS, nucl-ex/0703002

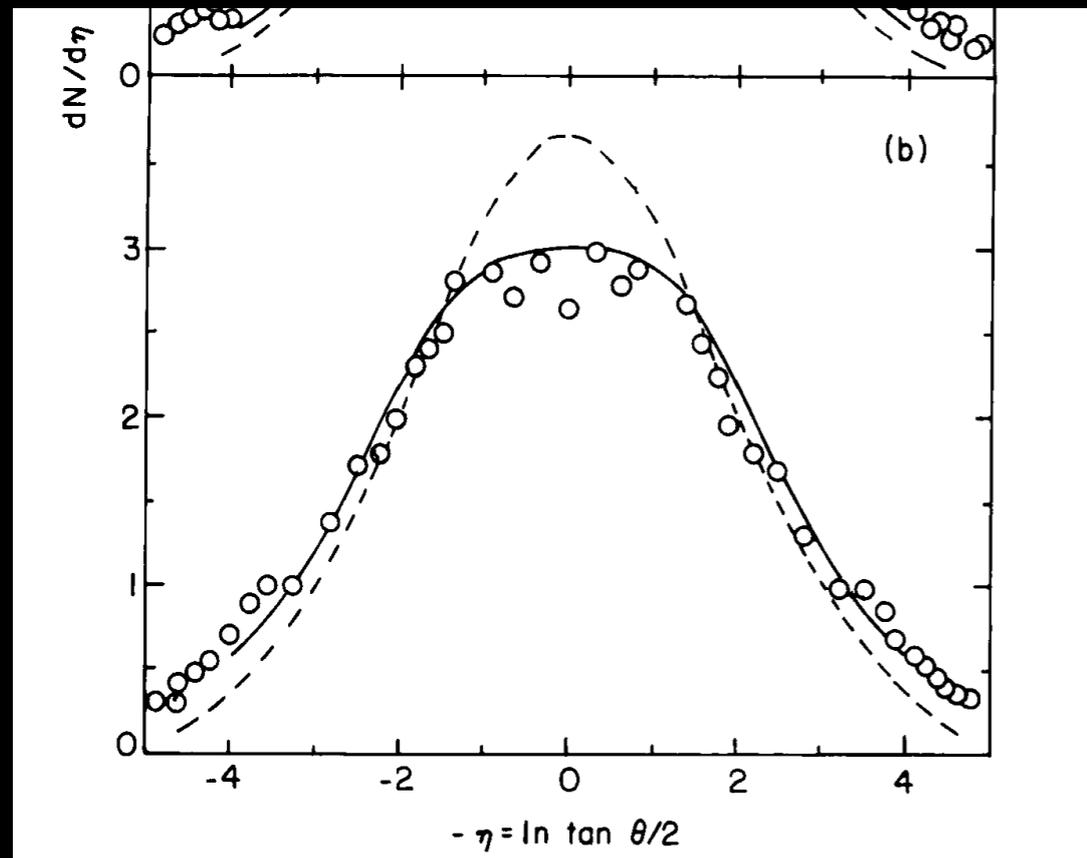
Should we be thinking in terms of independent fragmentation, or does the initial state "feel" the initial longitudinal momentum imbalance?

$$\Delta y = \frac{1}{2} \ln \left( \frac{N_{part,A}}{N_{part,B}} \right)$$

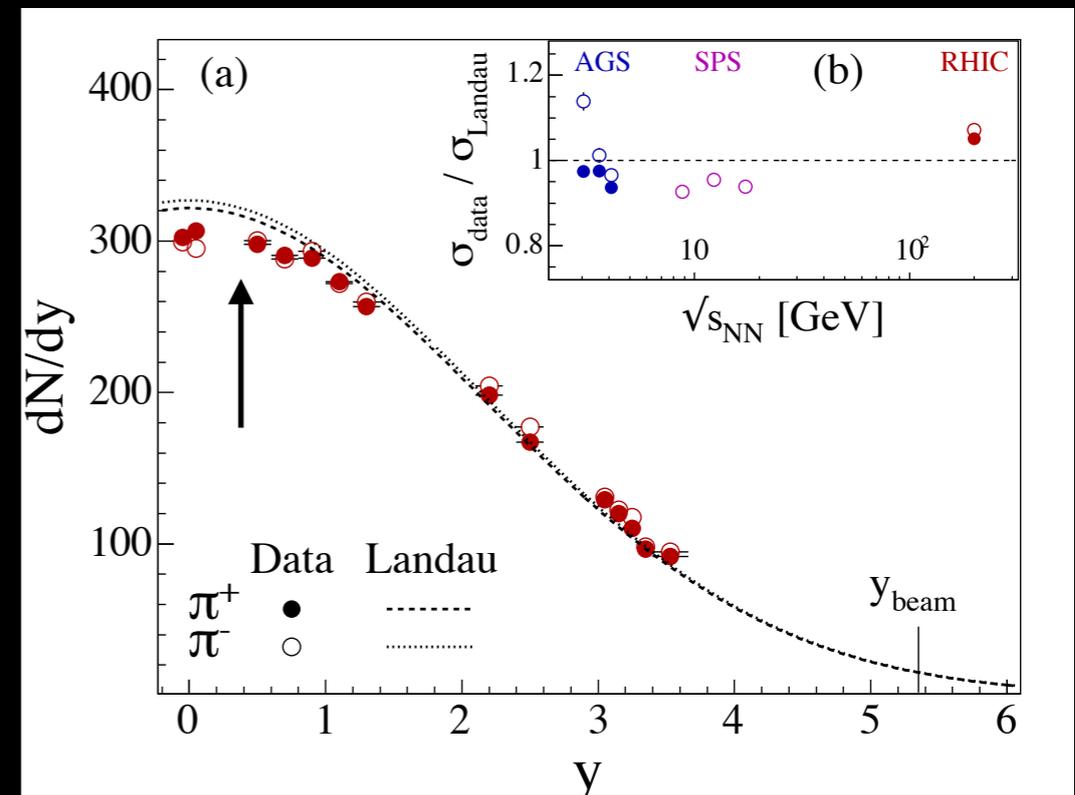


Casalderrey-Solana, et al: colliding "trains" of shock waves

# BOOST INVARIANCE?



ISR data



BRAHMS data

ISR data interpreted as emergence of plateau, as was the early  $4\pi$  RHIC data. An ongoing argument. Doesn't help that PHOBOS & BRAHMS data are inconsistent.

# THE END OF LANDAU @ LHC

