The non-equilibrium dynamics of strongly correlated glue

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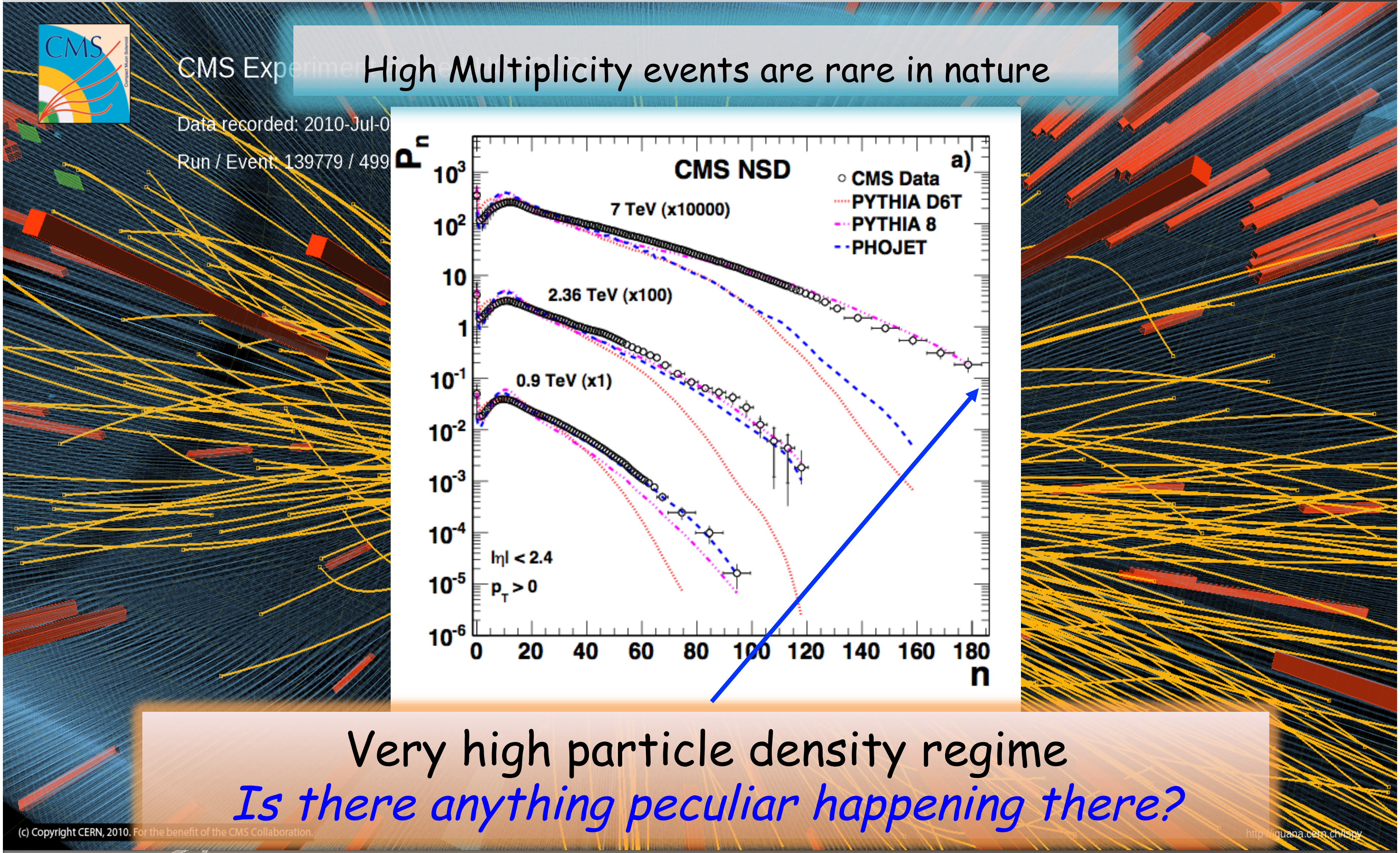
YITP symposium, Kyoto, December 2-6, 2013

High Multiplicity pp collisions

High Multiplicity events are rare in nature

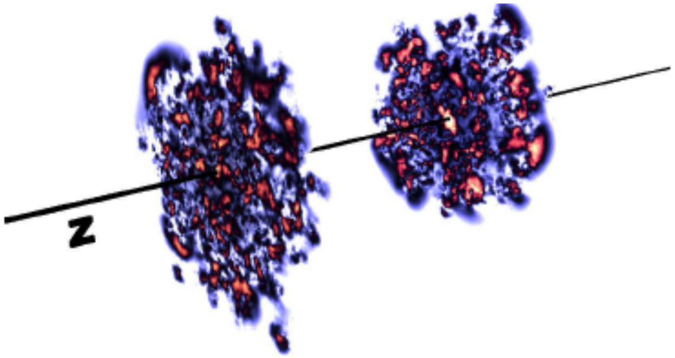


Very high particle density regime

Is there anything peculiar happening there?

Multiparticle production

How are ~ 150 hadrons per 5 units of rapidity produced in a single p+p event ?



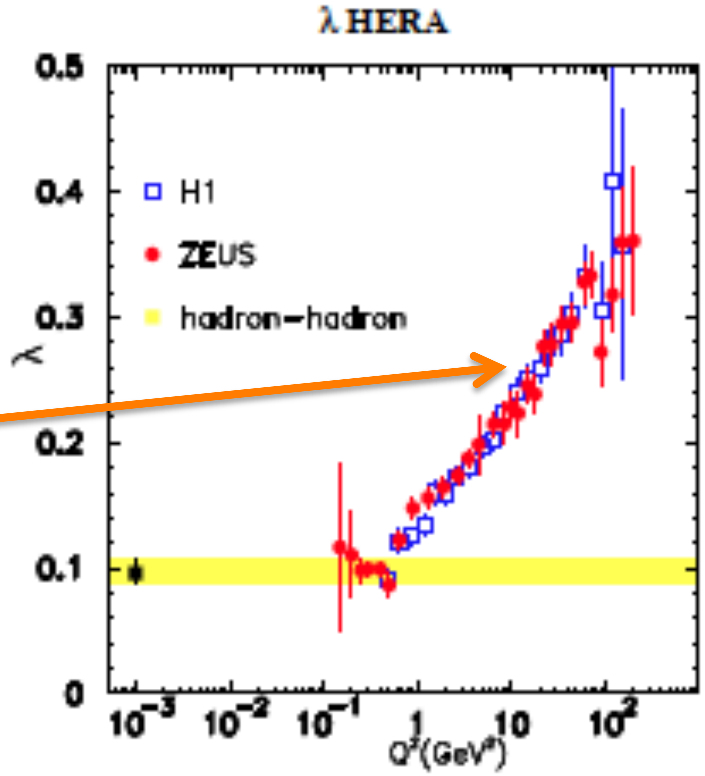
What's the guidance from HERA?

$$N_{\text{glue}}^{\text{proton}}(Q^2) = \int_{\text{xmin}}^{\text{xmax}} dx\, \frac{dN}{dx}(x, Q^2)$$

$$\sim \int_{\text{xmin}}^{\text{xmax}} dx\, \frac{1}{x^{1+\lambda(Q^2)}}$$

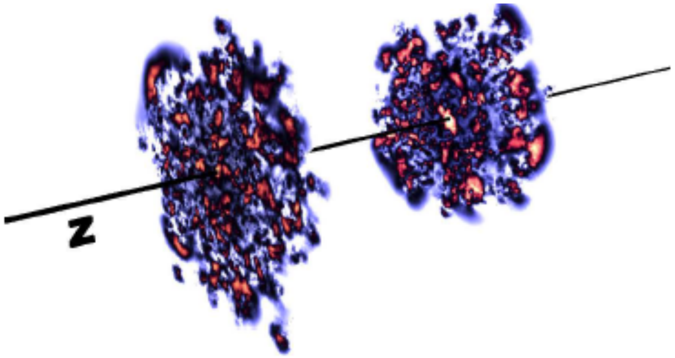
$$= \frac{1}{\lambda(Q^2)} \left(\frac{1}{x_{\text{min}}^{\lambda(Q^2)}} - \frac{1}{x_{\text{max}}^{\lambda(Q^2)}} \right)$$

$$\text{xmin}(Q^2 = 2, y = 0) = 2 \cdot 10^{-4}$$
$$\text{xmax}(Q^2 = 2, y = 2.4) = 2.2 \cdot 10^{-3}$$



Multiparticle production

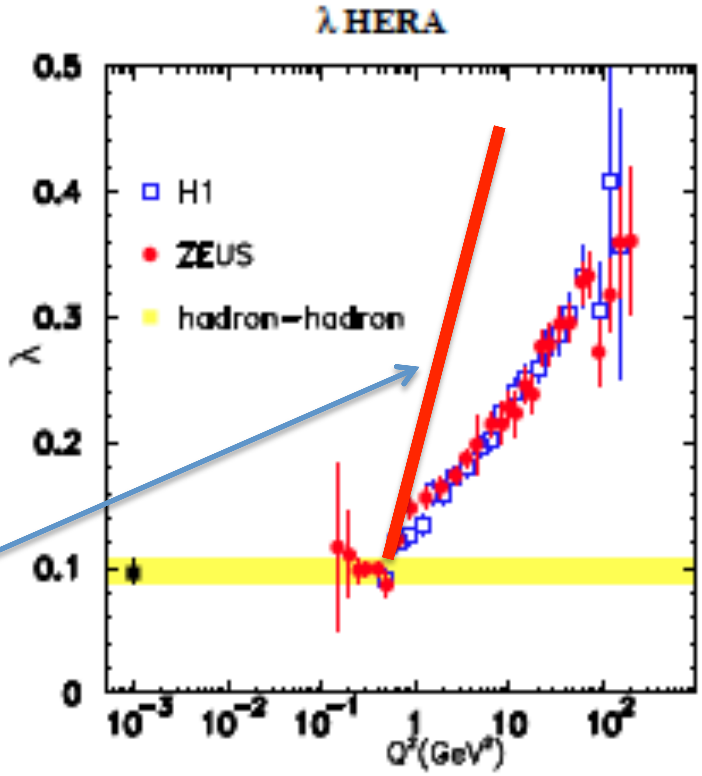
How are ~ 150 hadrons per 5 units of rapidity produced in a single p+p event ?



For λ=0.14, ~13 gluons produced in 5 units
~ min.bias hadron multiplicity

λ=0.3: ~45 gluons in 5 units,
λ=0.4: ~90 gluons in 5 units, in ball park…

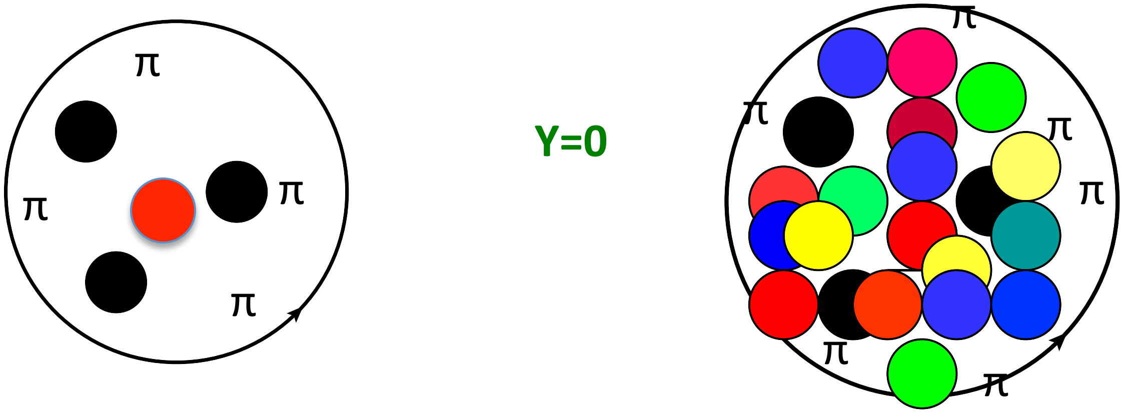
Very rapid effective growth of gluon dists. in such events…



The proton in a high multiplicity event

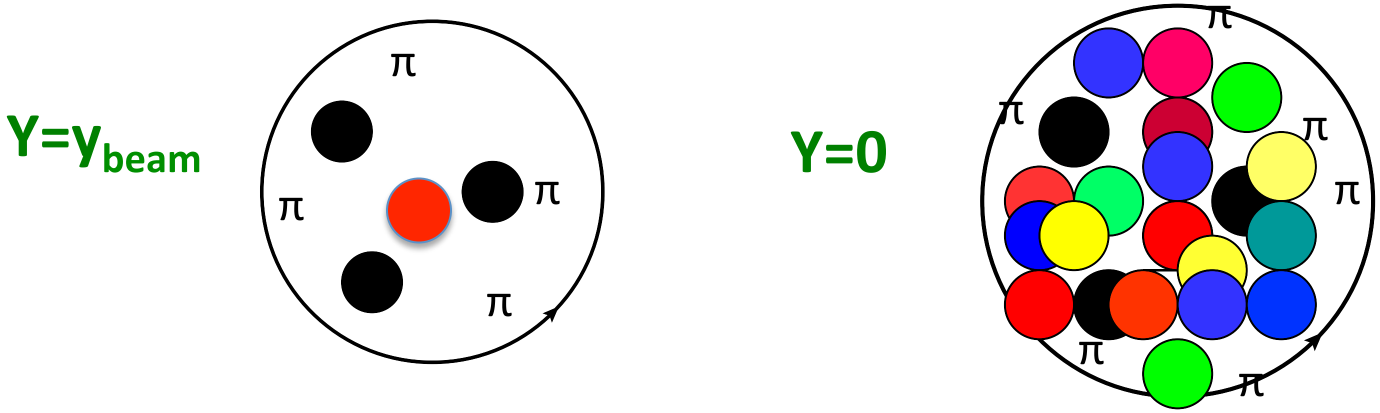
$Y=y_{beam}$

$Y=0$



For Q^2= 2 GeV^{2,}, what’s the proton’s gluon radius?

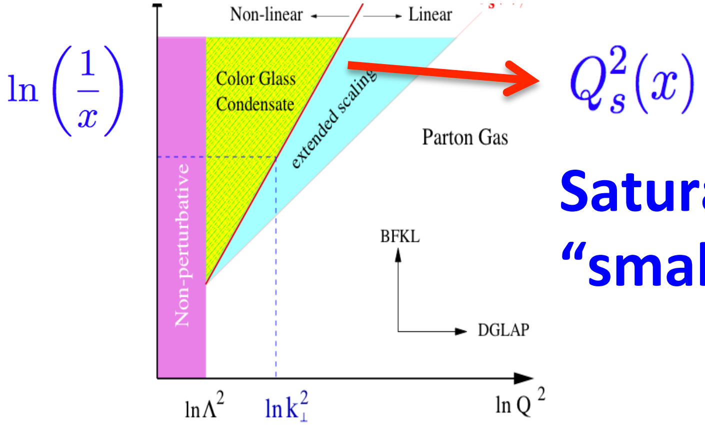
The proton in a high multiplicity event



For Q^2= 2 $GeV^{2,}$, what's the proton's gluon radius?

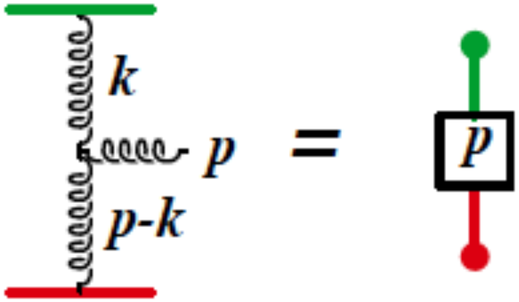
$$\frac{4\pi}{Q^2} * N_g(Q^2) = \pi R^2_{\rm glue}$$

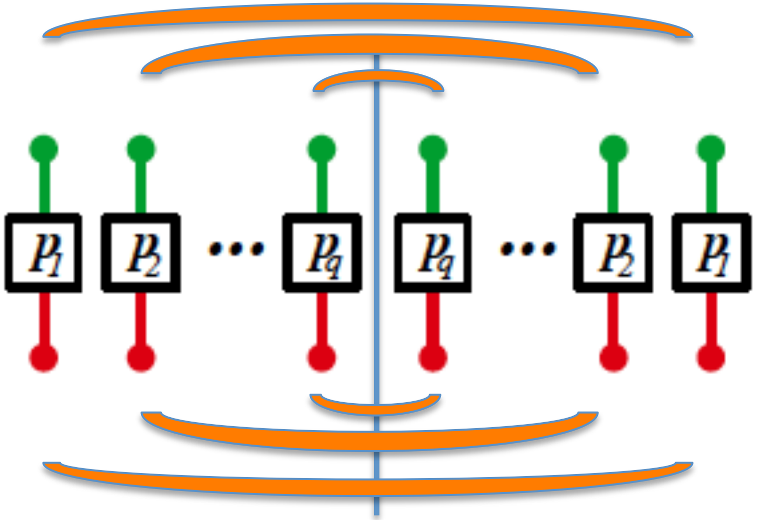
Gribov diffusion => R^2 ~ ln(s)
R_g grows much faster depending on N_g rate--will violate unitarity



Saturation regulates this by adding increasingly "smaller" gluons of size $1/Q_s(x)$ as x -> 0

Lasing gluons: Stimulated emission from Glasma flux tubes

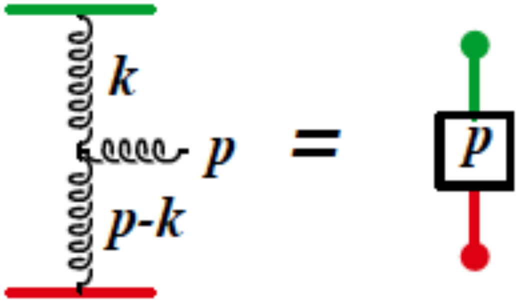




Dumitru,Gelis,McLerran,RV (2008)
Dusling,Fernandez-Fraile,RV (2009)
Gelis,Lappi,McLerran (2009)

Color combinatorics of cut graphs: a negative binomial distribution

Lasing gluons: Stimulated emission from Glasma flux tubes



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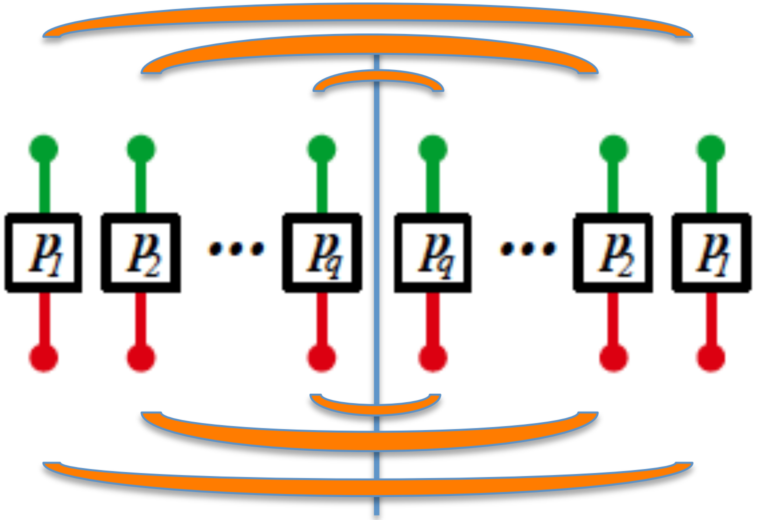
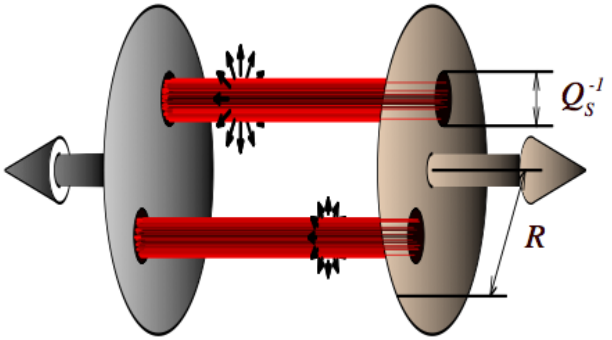


Color combinatorics of cut graphs: a negative binomial distribution

$$P_n^{\mathrm{NB}} = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

k=1: Bose-Einstein dist.
k=∞: Poisson distribution

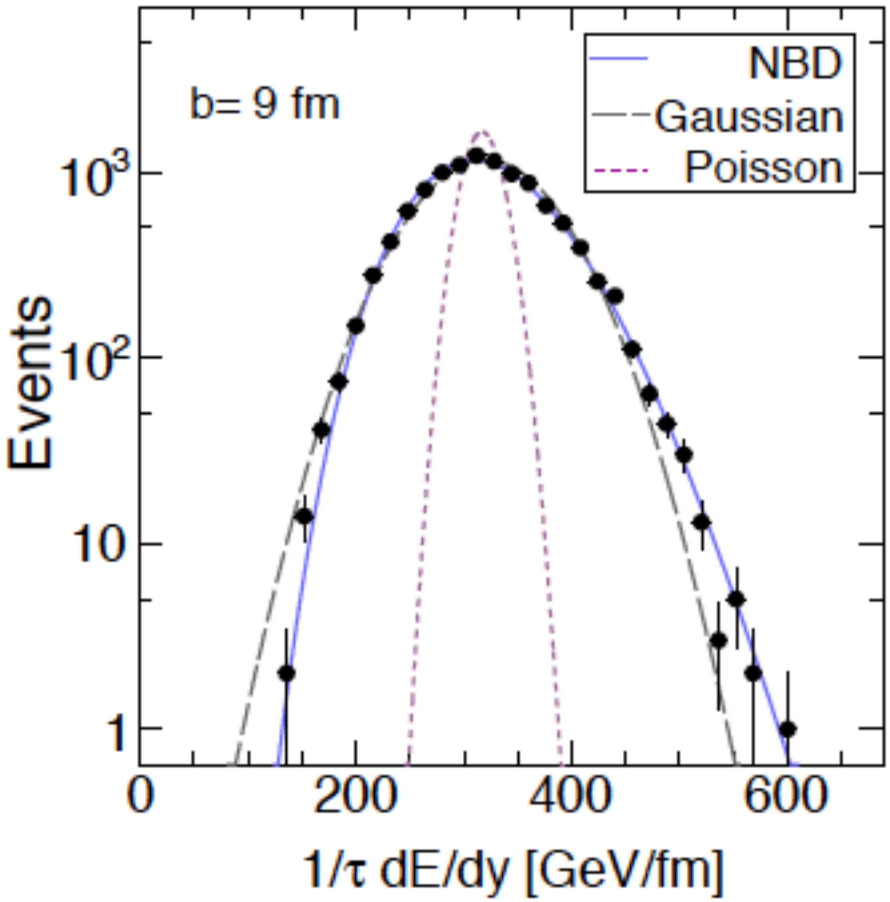
$$k = \kappa \frac{({N_c}^2-1) Q_s^2 S_\perp}{2\pi}$$



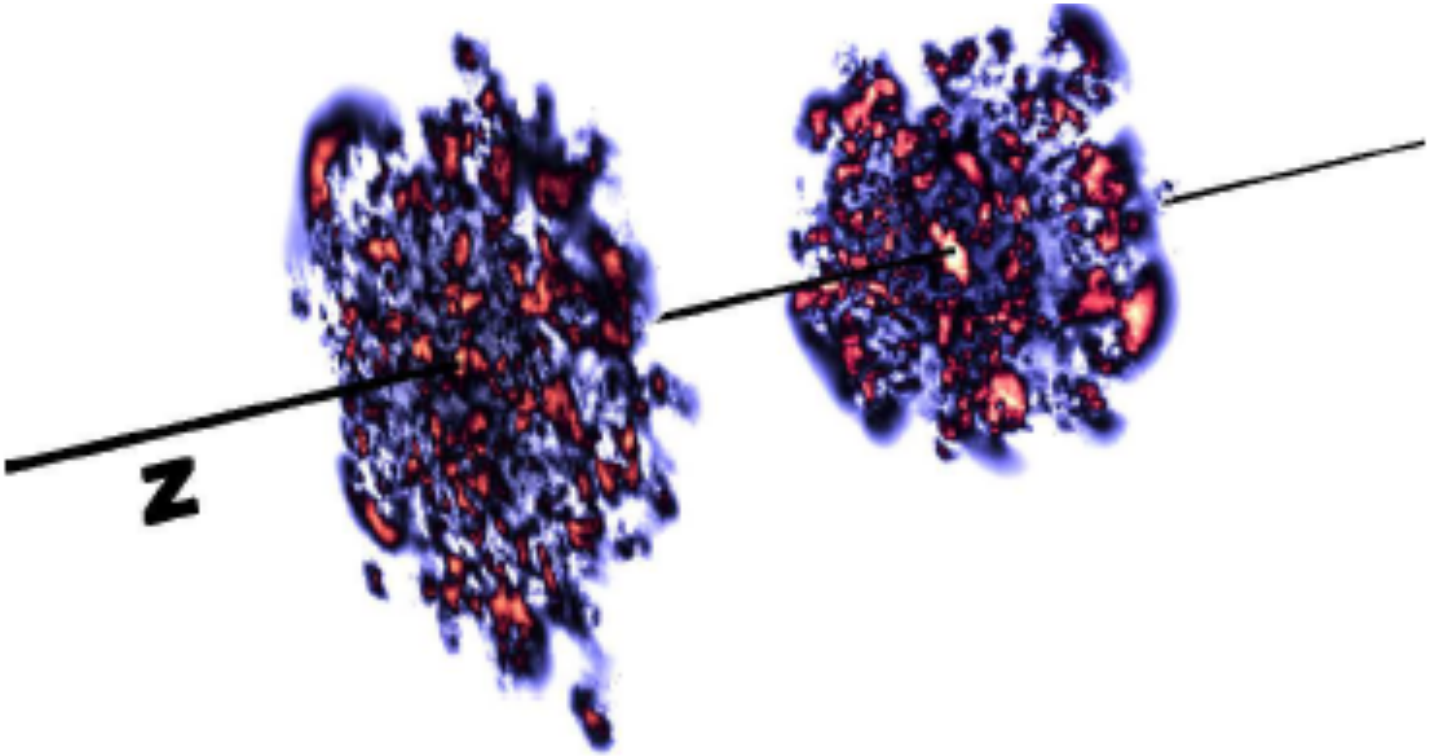
For $Q_S^2 \approx 1/S_T$
close to a Bose-dist!

Negative Binomial Distributions from non-perturbative Yang-Mills dynamics

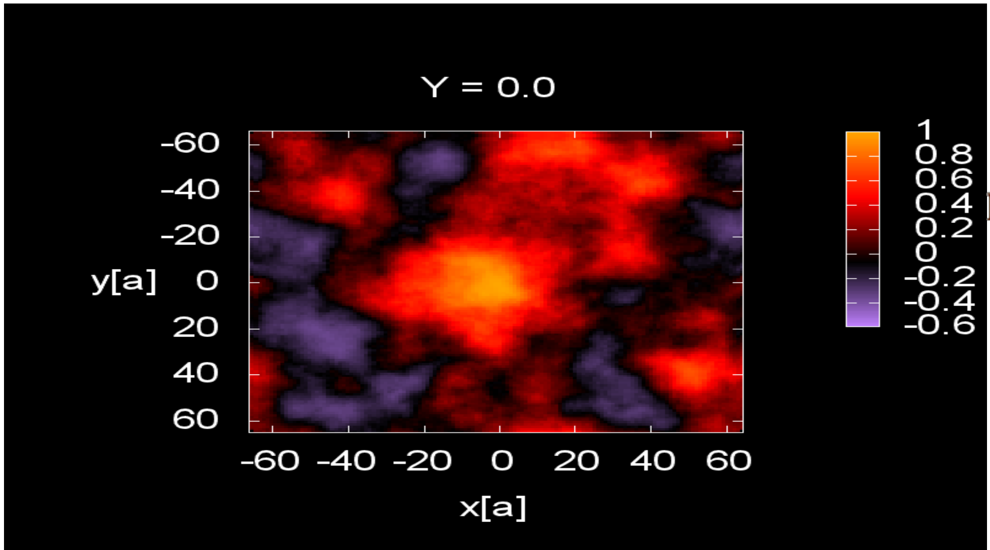
Schenke,Tribedy,RV:1202.6646



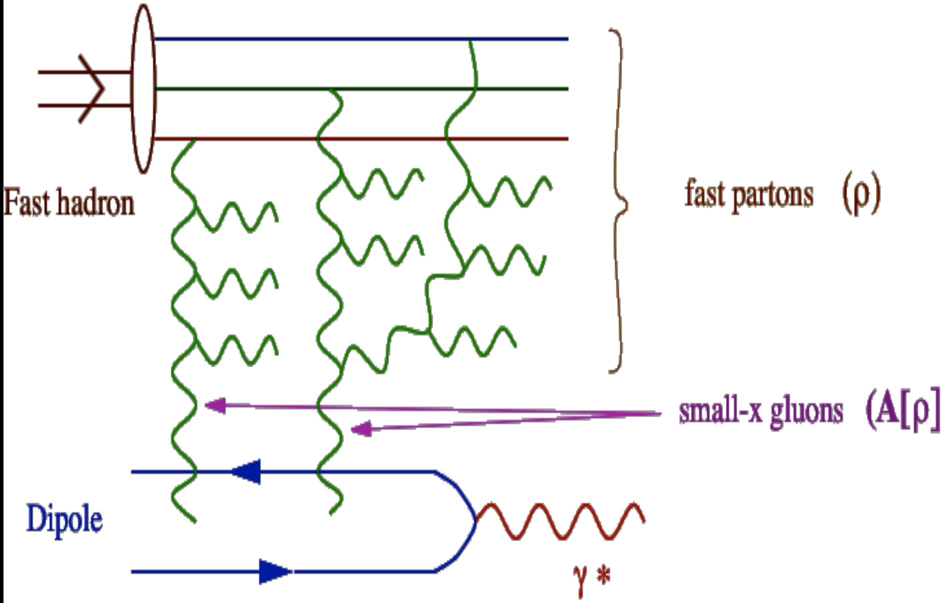
Colliding lumpy glue



Extracting lumpy glue in the proton



Dumitru,Jalilian-Marian,Lappi,Schenke,Venugopalan (2011)

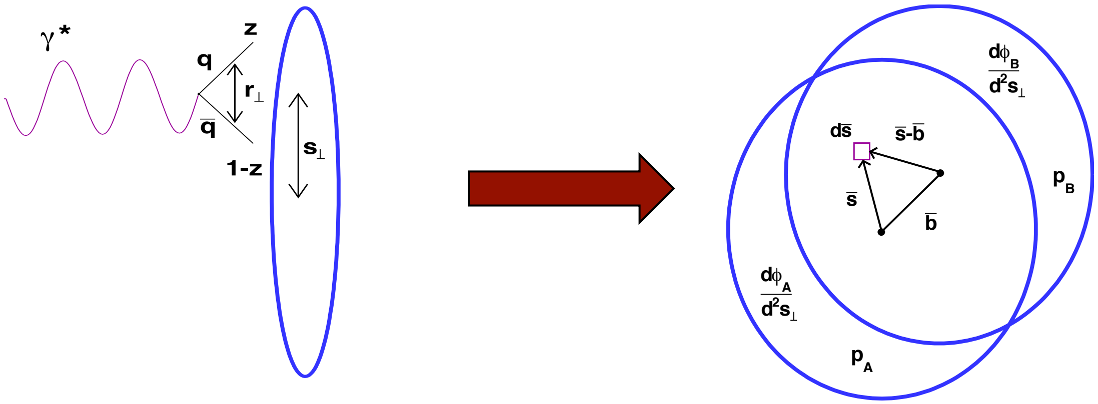


B-JIMWLK: the BBGKY hierarchy of gluodynamics

For recent status, see Tuomas Lappi's talk

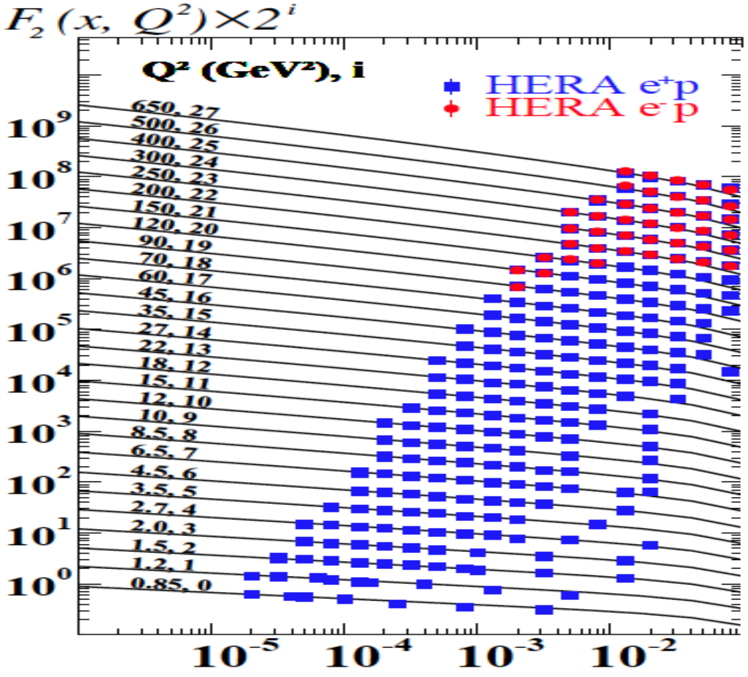
Extracting lumpy glue in the proton-IPSat model

Bartels,Golec-Biernat,Kowalski
Kowalski,Teaney
Kowalski,Motyka,Watt

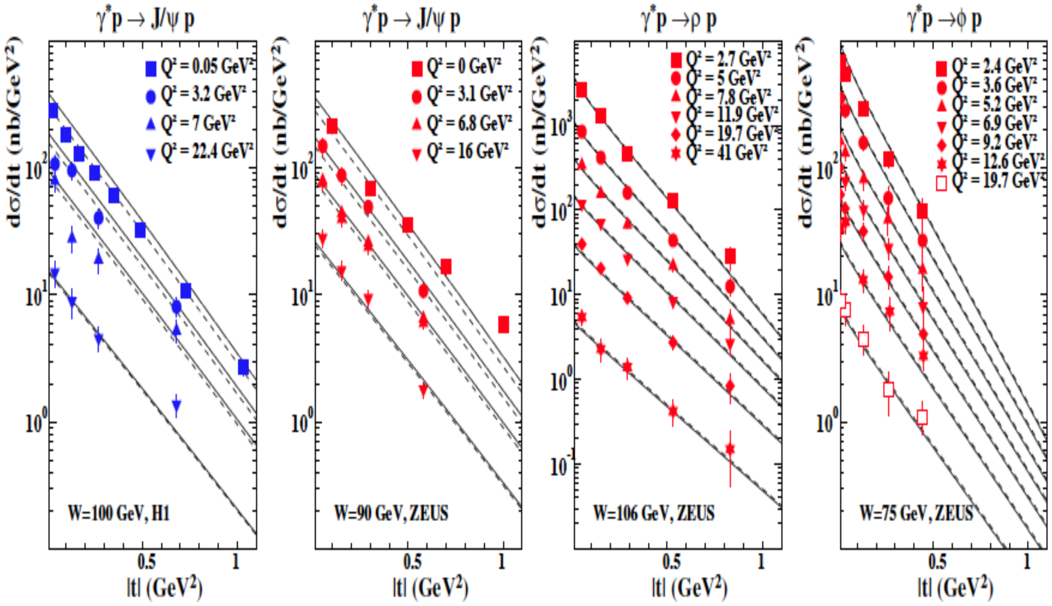


Very good agreement of IPSat model with combined HERA data

Rezaiean,Siddikov,Van der Klundert,RV:1212.2974

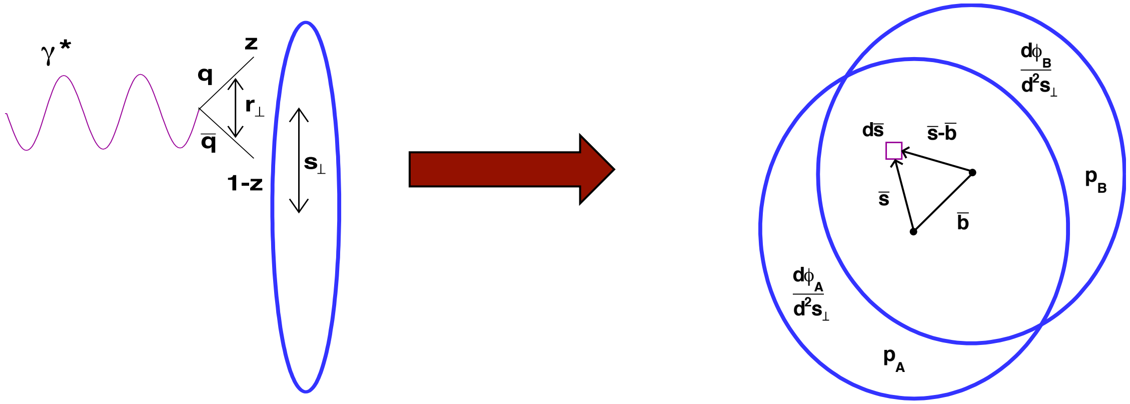


Inclusive DIS off proton



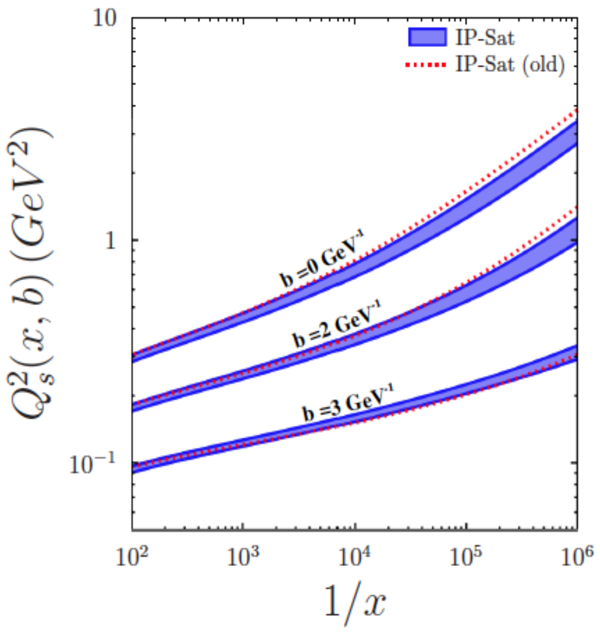
Exclusive DIS off proton

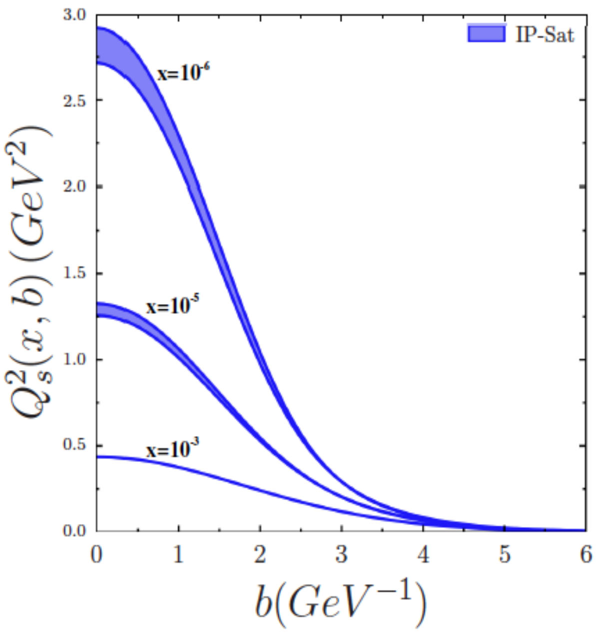
Colliding lumpy glue-IPSat model



Lumpy Q_S (b) profile from fits to combined HERA DIS data

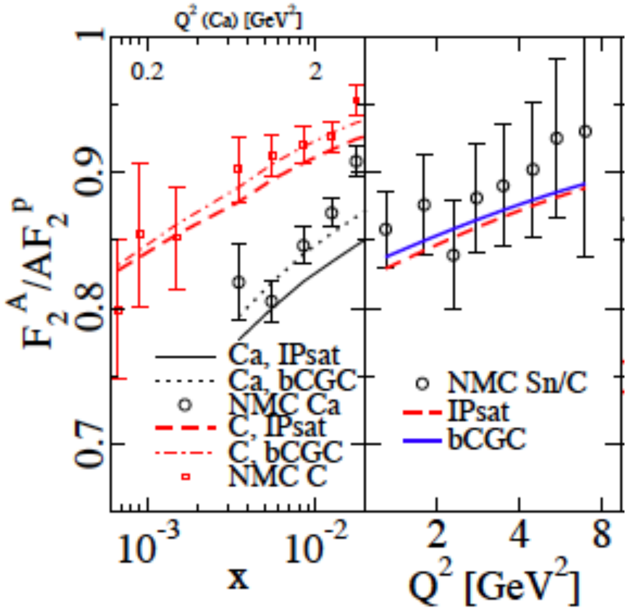
Rezaiean,Siddikov,Van der Klundert,RV:1212.2974

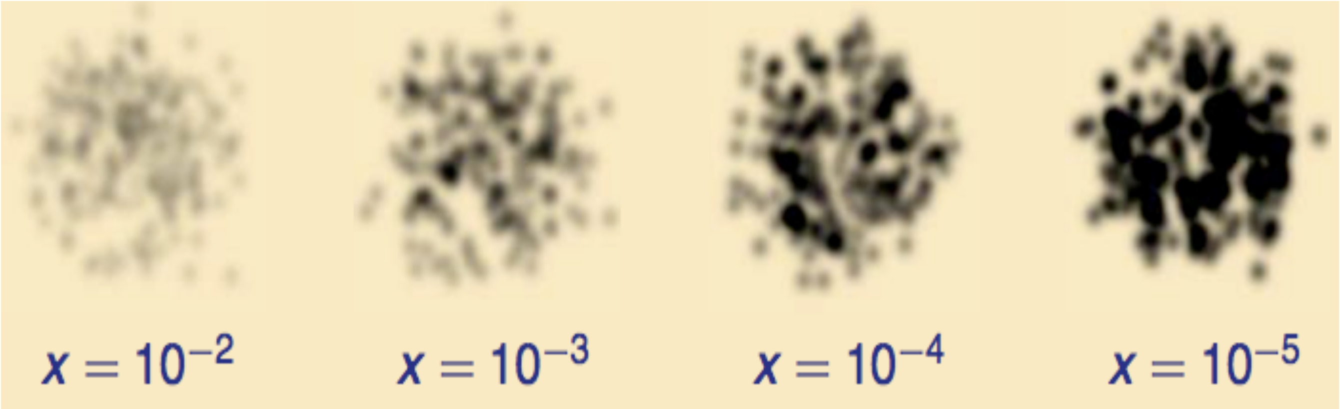




Lumpy nuclei: constrained by (limited) DIS data

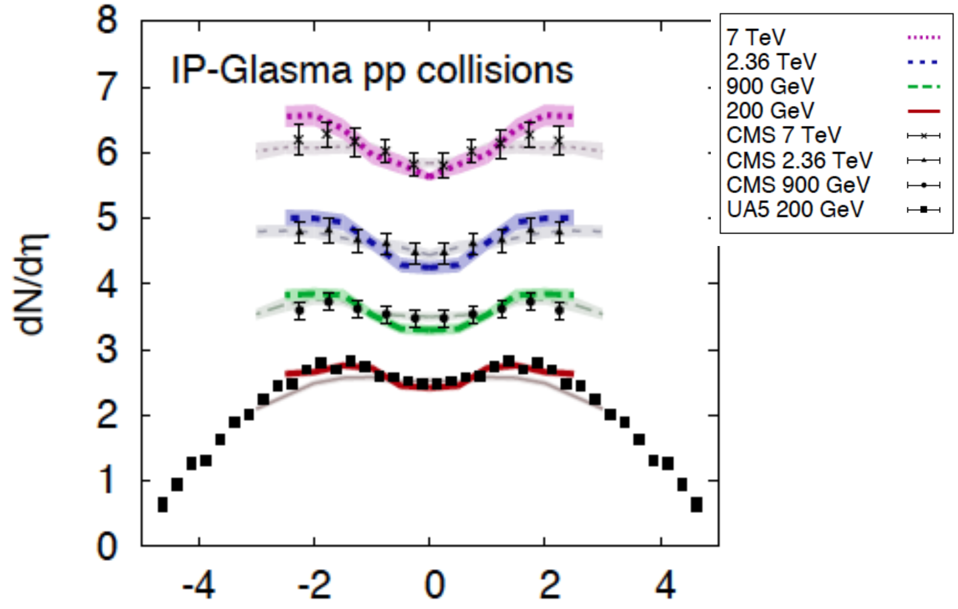
Kowalski, Lappi, RV, PRL (2008)

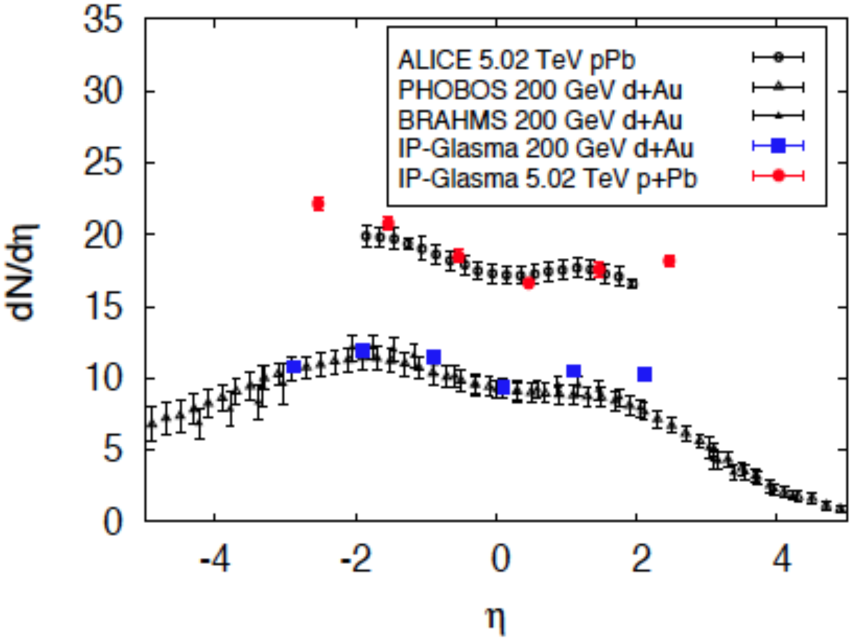


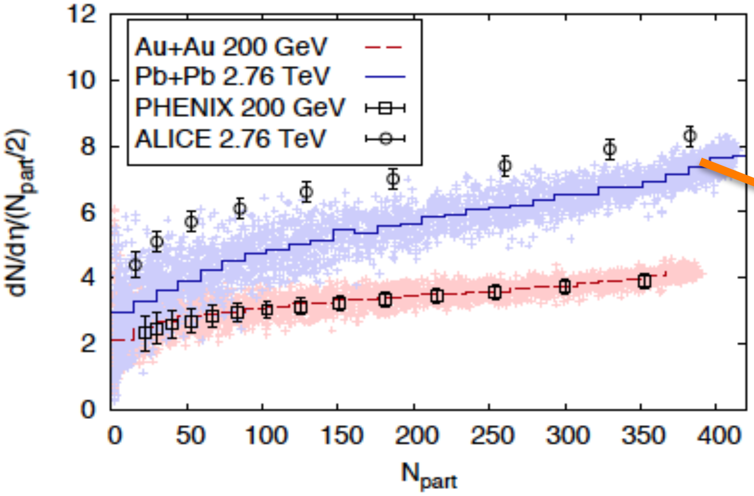


Multiplicities from Yang-Mills dynamics

Schenke,Tribedy,RV:1311.3636



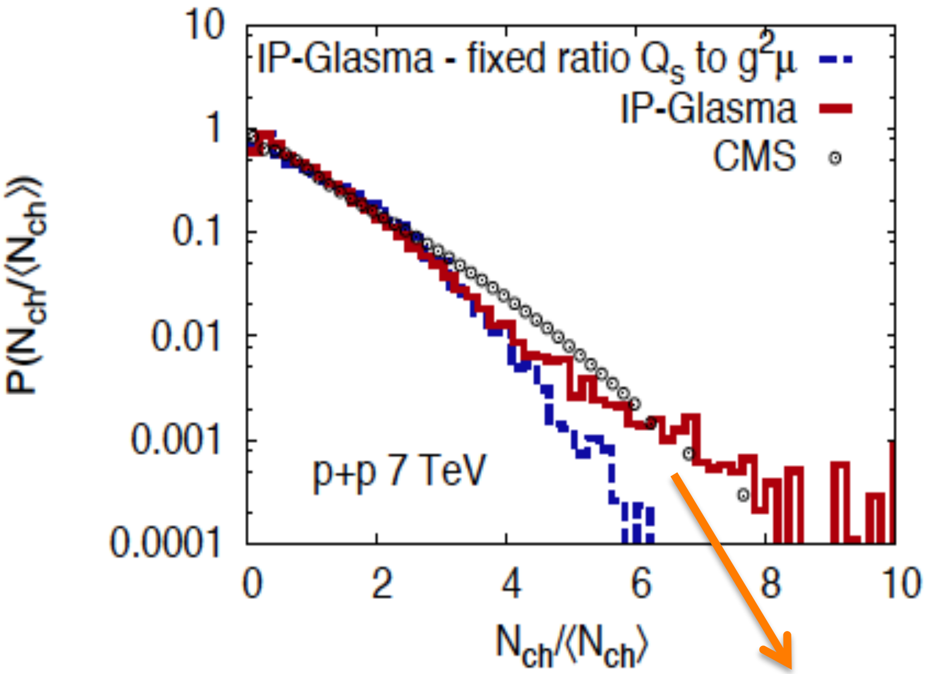


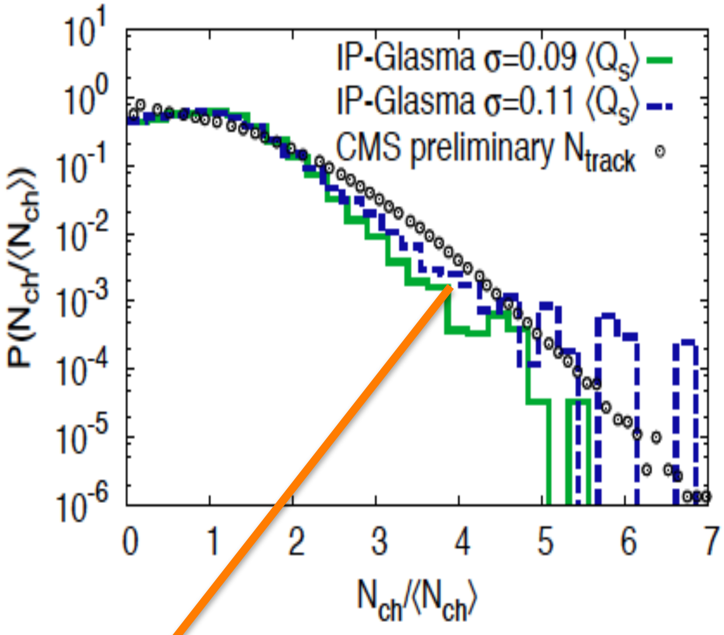


15% (30 %) shortfall for large N_{part} (low N_{part}) at LHC possibly due to the ~70% greater η/s

Multiplicity distributions from Yang-Mills dynamics

Schenke,Tribedy,RV:1311.3636



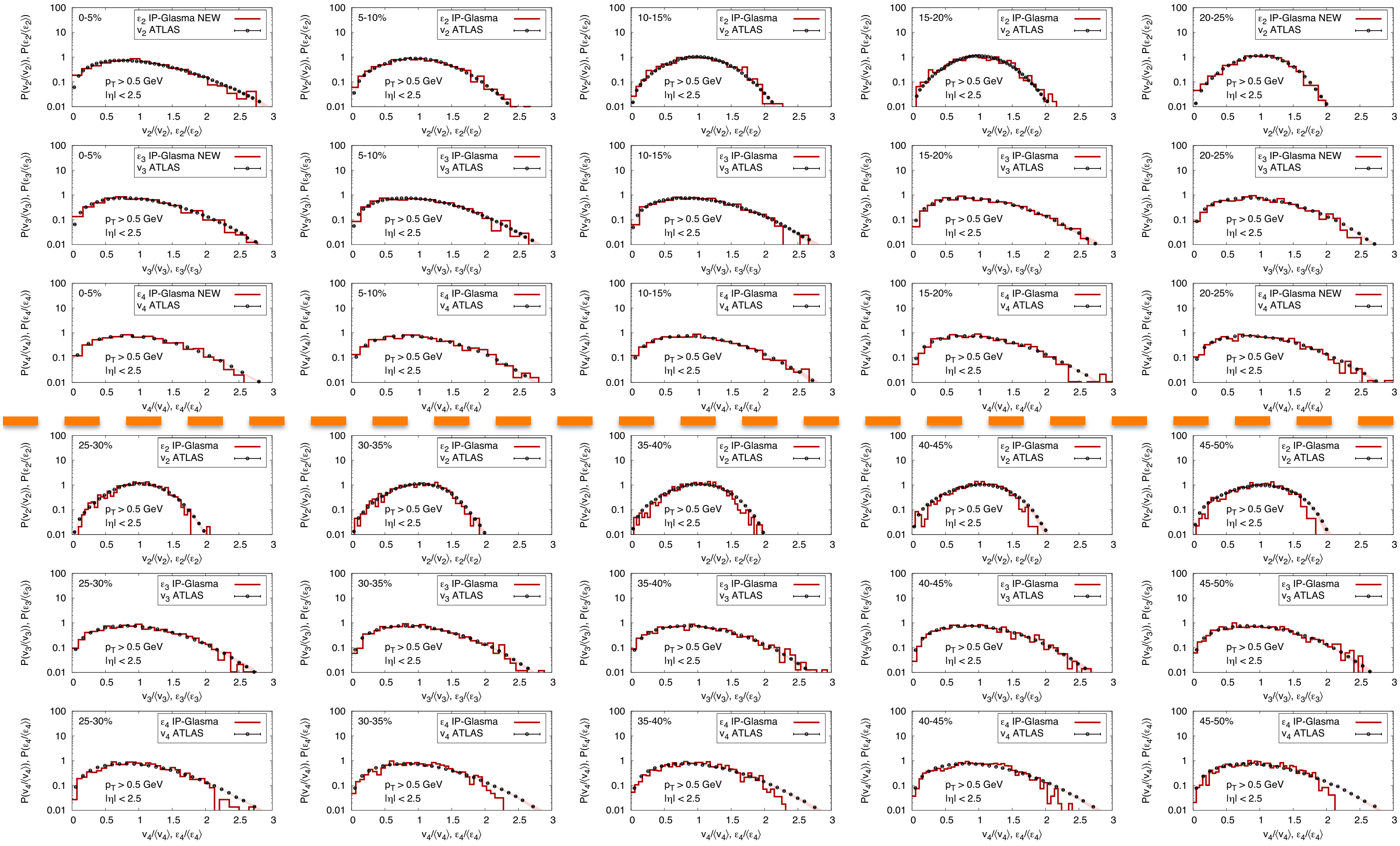


Additional gluon # fluctuations (beyond color charge fluctuations) appear to be necessary to describe multiplicity distributions in p+p and p+A
-much smaller role in A+A

See also, Dumitru and Petreska, 1209.4105

A+A eccentricity fluctuations from IP-Glasma

Beyond results presented in Gale et al 1209.6330



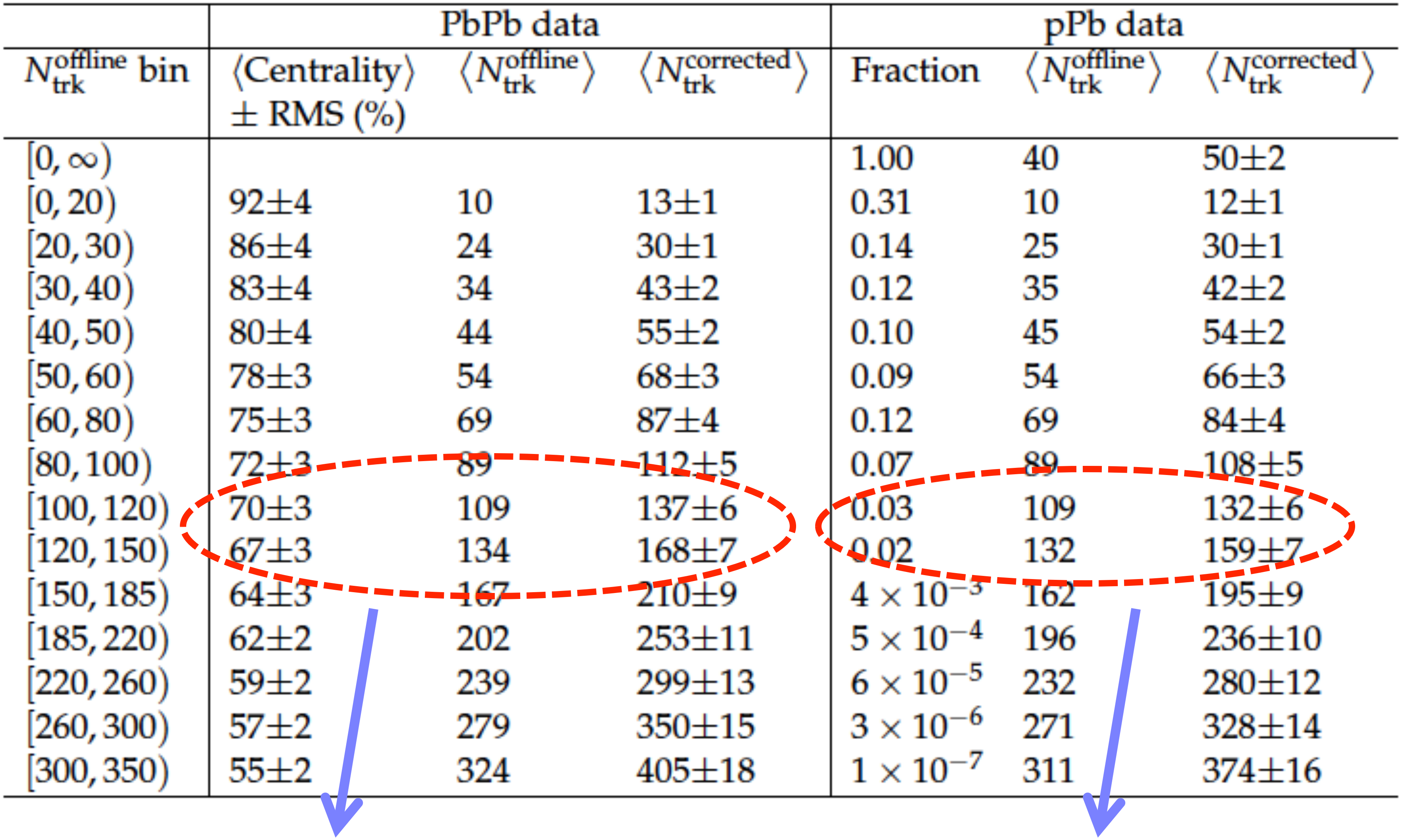
Mission accomplished ?

Far from it…many (possibly O(1)) systematic uncertainties

On the hydro side: bulk viscosity, hydrodynamic fluctuations

Non-equilibrium dynamics: big source of uncertainty
– especially important in peripheral events/small sized systems…

LHC p+A vs A+A collisions



	PbPb data			pPb data		
$N_{\text{trk}}^{\text{offline}}$ bin	$\langle\text{Centrality}\rangle$ $\pm$ RMS (%)	$\langle N_{\text{trk}}^{\text{offline}}\rangle$	$\langle N_{\text{trk}}^{\text{corrected}}\rangle$	Fraction	$\langle N_{\text{trk}}^{\text{offline}}\rangle$	$\langle N_{\text{trk}}^{\text{corrected}}\rangle$
$[0, \infty)$				1.00	40	50±2
$[0, 20)$	92±4	10	13±1	0.31	10	12±1
$[20, 30)$	86±4	24	30±1	0.14	25	30±1
$[30, 40)$	83±4	34	43±2	0.12	35	42±2
$[40, 50)$	80±4	44	55±2	0.10	45	54±2
$[50, 60)$	78±3	54	68±3	0.09	54	66±3
$[60, 80)$	75±3	69	87±4	0.12	69	84±4
$[80, 100)$	72±3	89	112±5	0.07	89	108±5
$[100, 120)$	70±3	109	137±6	0.03	109	132±6
$[120, 150)$	67±3	134	168±7	0.02	132	159±7
$[150, 185)$	64±3	167	210±9	4×10^{-3}	162	195±9
$[185, 220)$	62±2	202	253±11	5×10^{-4}	196	236±10
$[220, 260)$	59±2	239	299±13	6×10^{-5}	232	280±12
$[260, 300)$	57±2	279	350±15	3×10^{-6}	271	328±14
$[300, 350)$	55±2	324	405±18	1×10^{-7}	311	374±16

Peripheral A+A

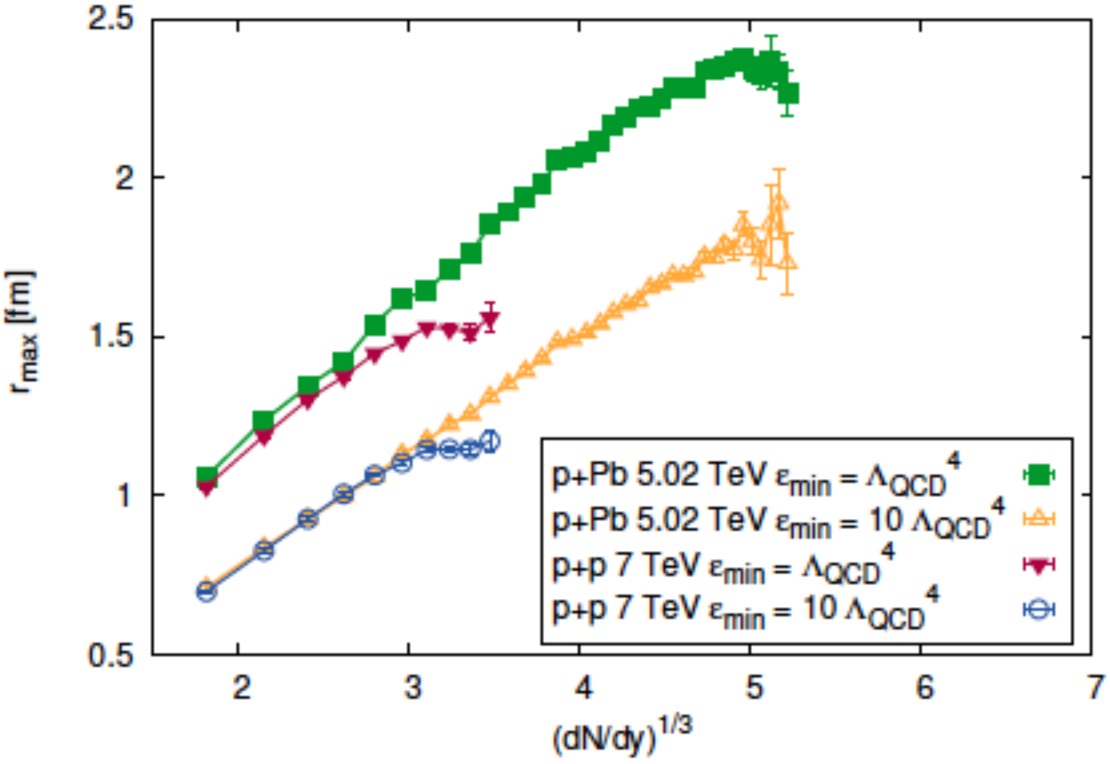
Central p+A

Flow in p+A? IP-Glasma+MUSIC model

CGC initial conditions: IP-Glasma model with Yang-Mills dynamics

Event-by-event viscous hydro with MUSIC

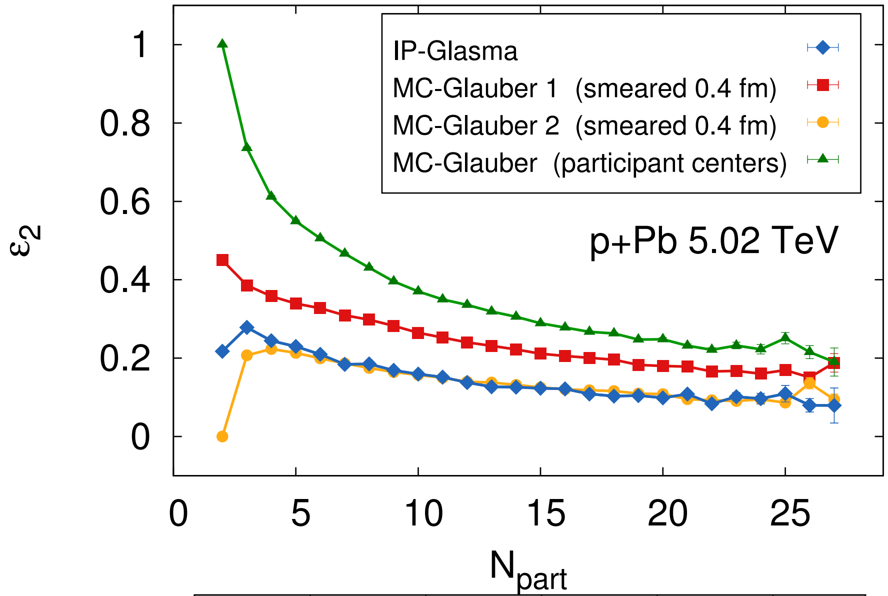
Bzdak,Schenke,Tribedy,RV:1304.3403

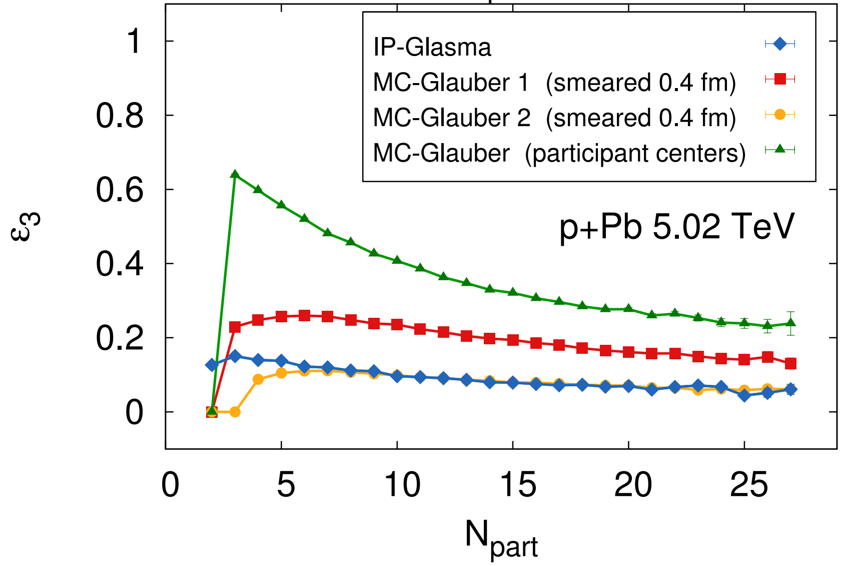


Initial radii are nearly identical in p+p and p+A until large multiplicity

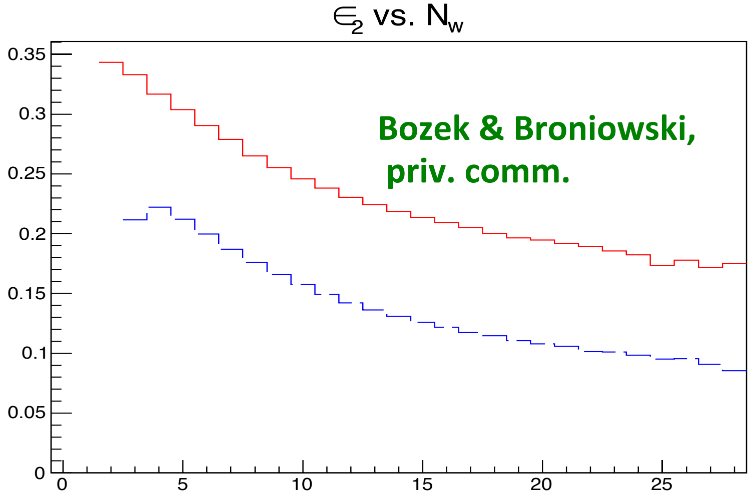
See McLerran,Praszalowicz,Schenke,1306.2350
& Rezaiean,Schmidt 1307.0825 for discussion of multiplicities

Flow in p+A? IP-Glasma vs “Glauber”





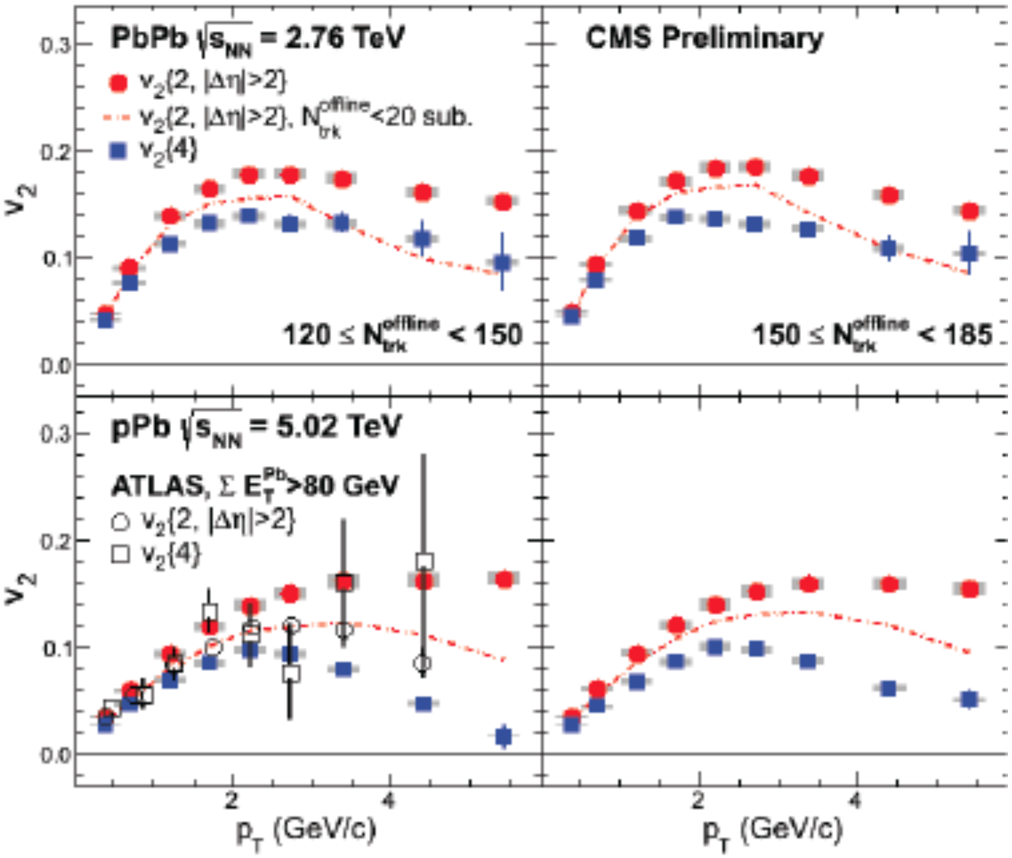
IP-Glasma, Bzdak,Schenke,Tribedy,RV:1304.3403
MC-Glauber: Bozek,Broniowski:1304.3044



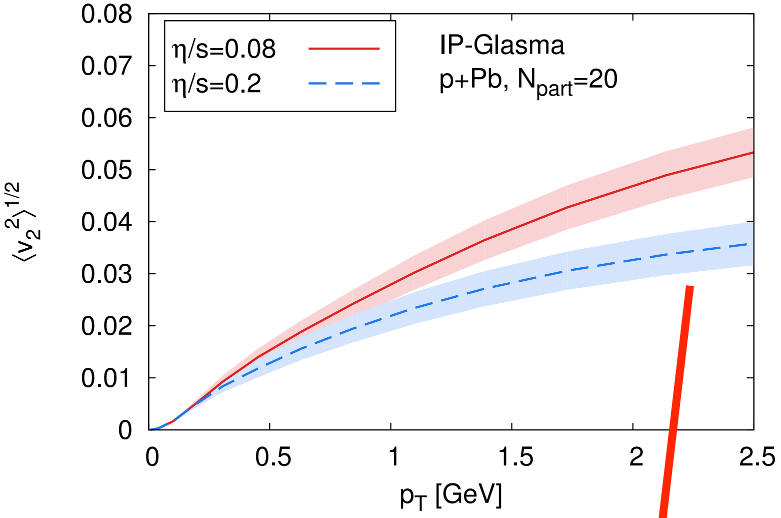
Bozek & Broniowski, priv. comm.

Hydro results VERY sensitive to initial conditions

Flow in p+A: IP-Glasma+MUSIC



IP-Glasma, Bzdak,Schenke,Tribedy,RV:1304.3403

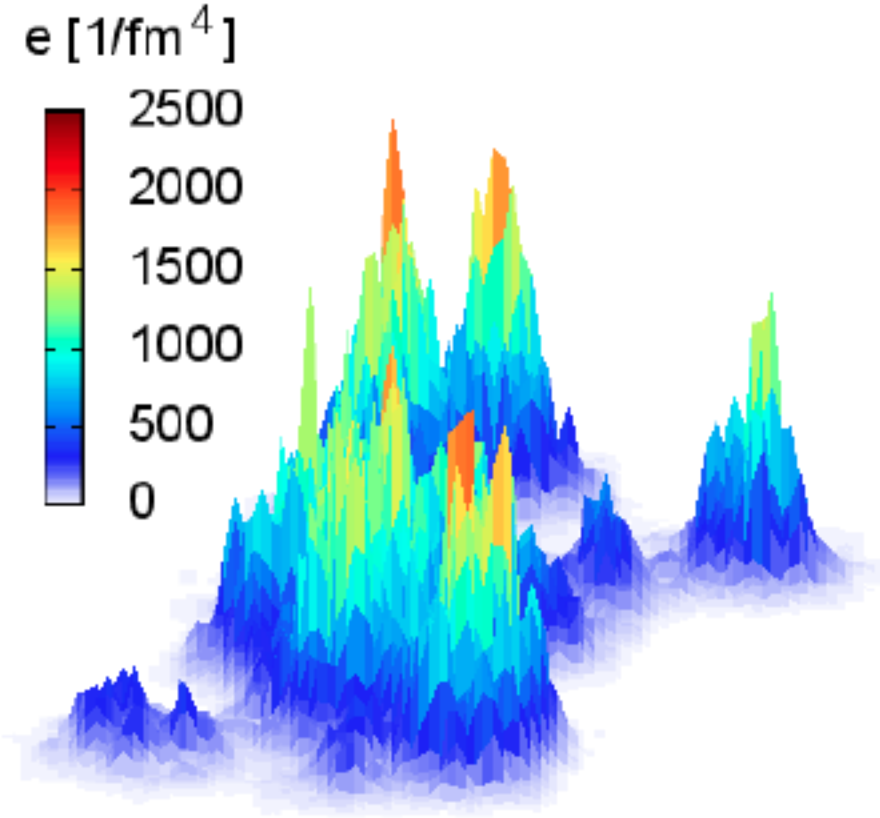


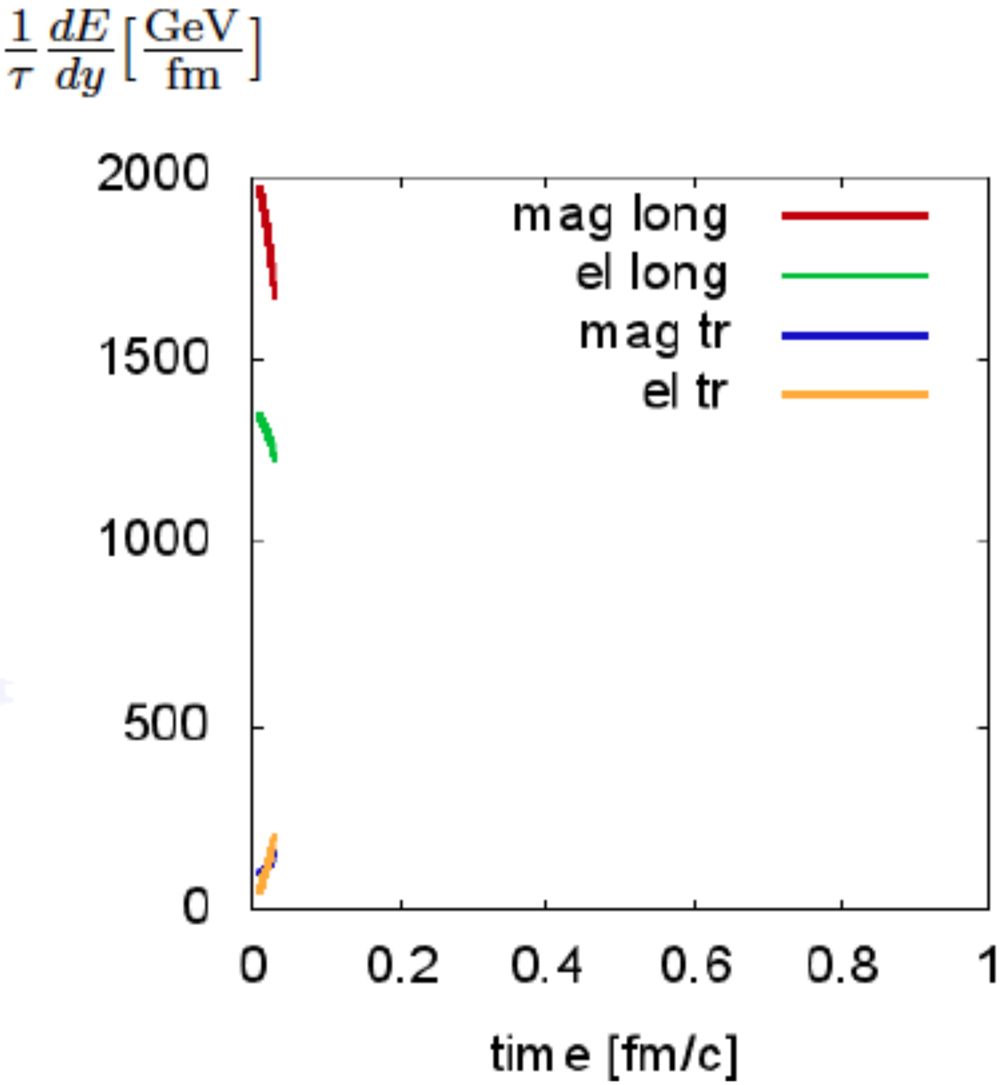
IP-Glasma result nearly 3 times smaller than data for $\eta/s=0.2$

◆ **Extend this framework to JIMWLK+Yang-Mills to include BOTH initial state AND final state event-by-event hydro with apples to apples centrality selection in p+p,p/d+A and A+A**

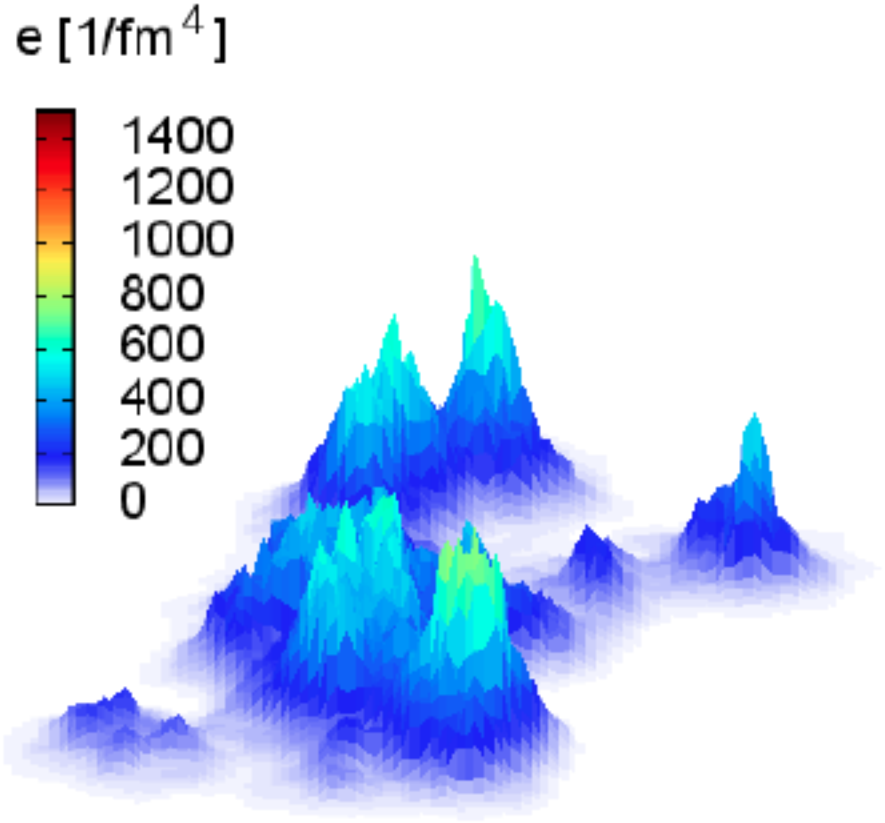
The ridge: my take, see 1312.0113

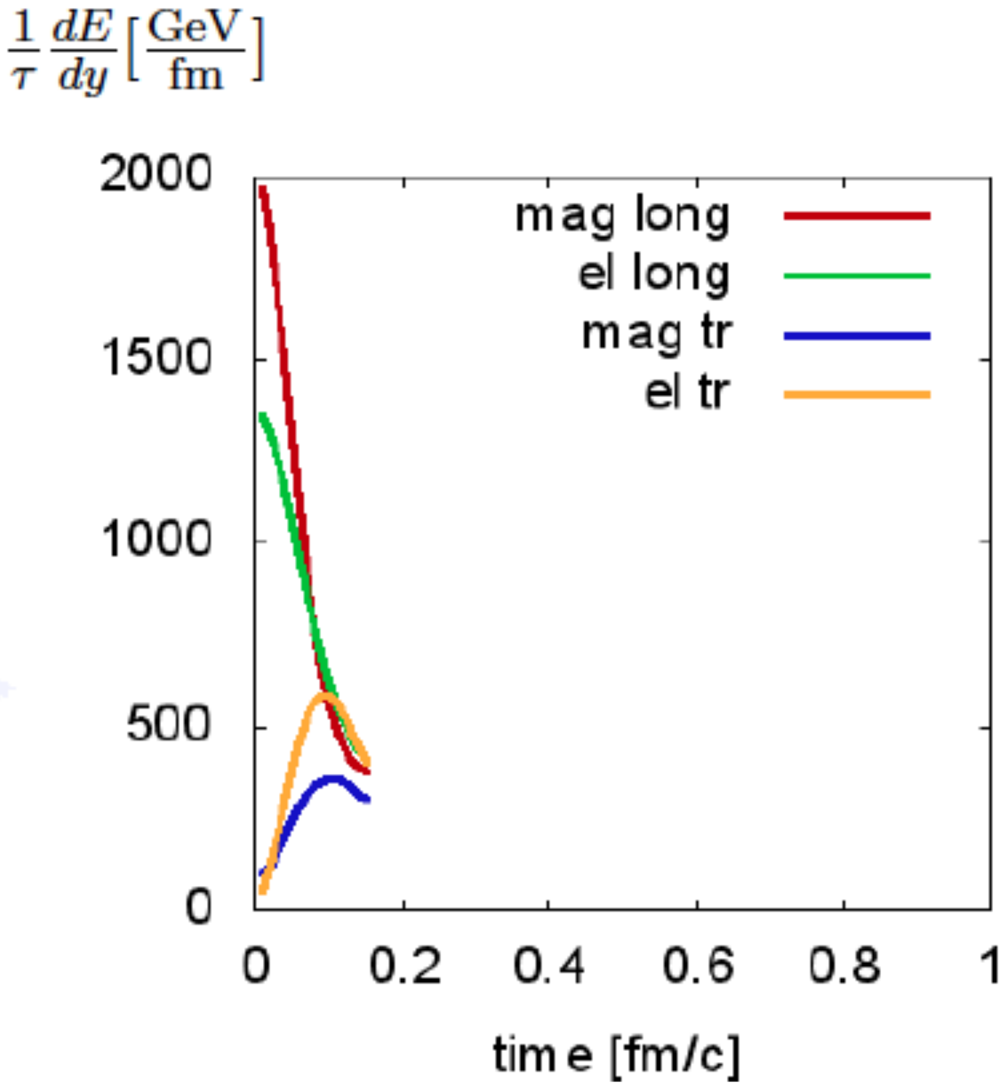
Classical Yang-Mills in IP-Glasma



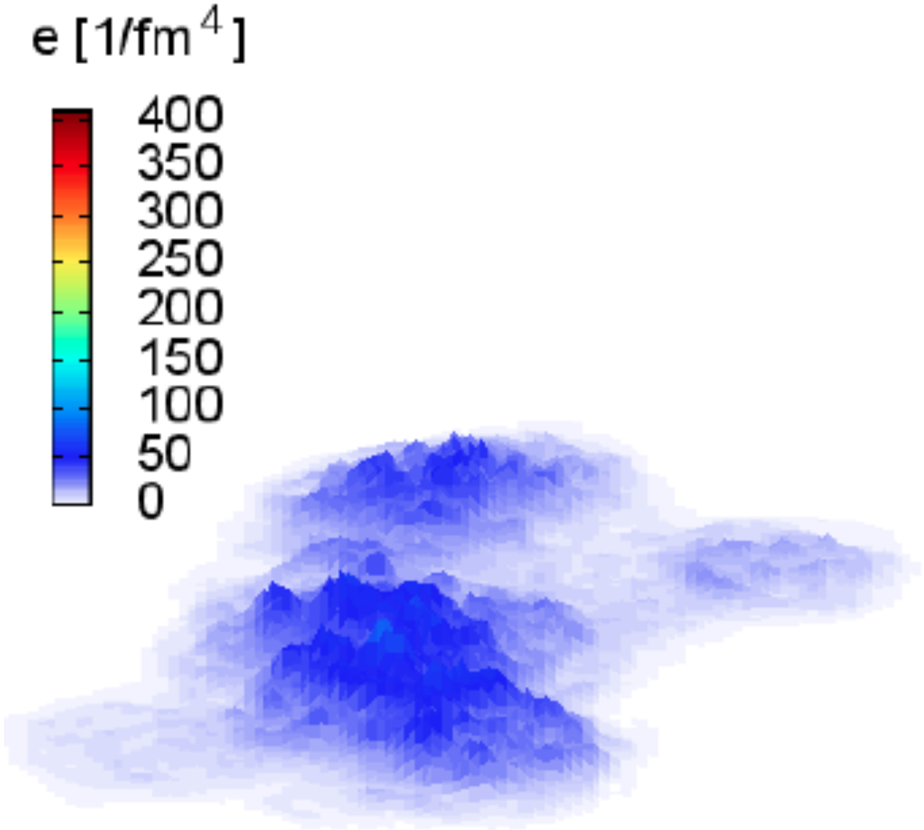


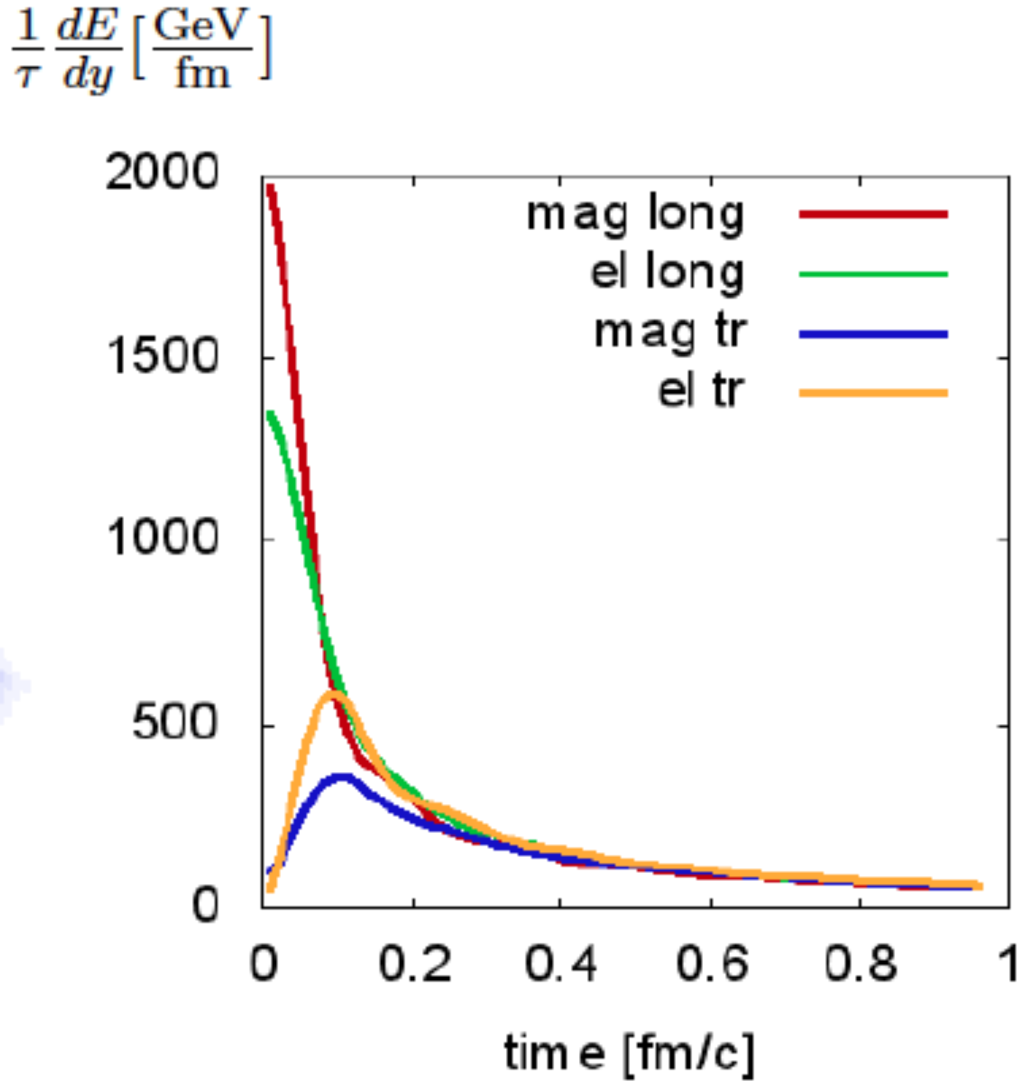
Classical Yang-Mills in IP-Glasma





Classical Yang-Mills in IP-Glasma





IP-Glasma: Boost invariant Classical Yang-Mills

Compute all components of $T_{\mu\nu}$

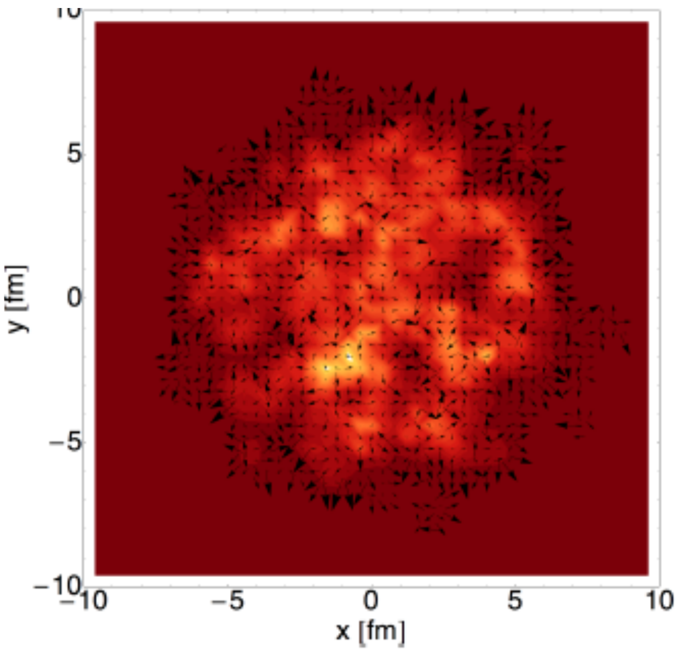
$$T_{\mu\nu}(\tau = 0) = \frac{1}{2}(B_z^2 + E_z^2) \times \mathrm{diag}(1, 1, 1, -1)$$

Initial longitudinal pressure is negative:

Goes to P_L =0 from below with time evolution

IP-Glasma: Boost invariant Classical Yang-Mills

Compute all components of $T_{\mu\nu}$

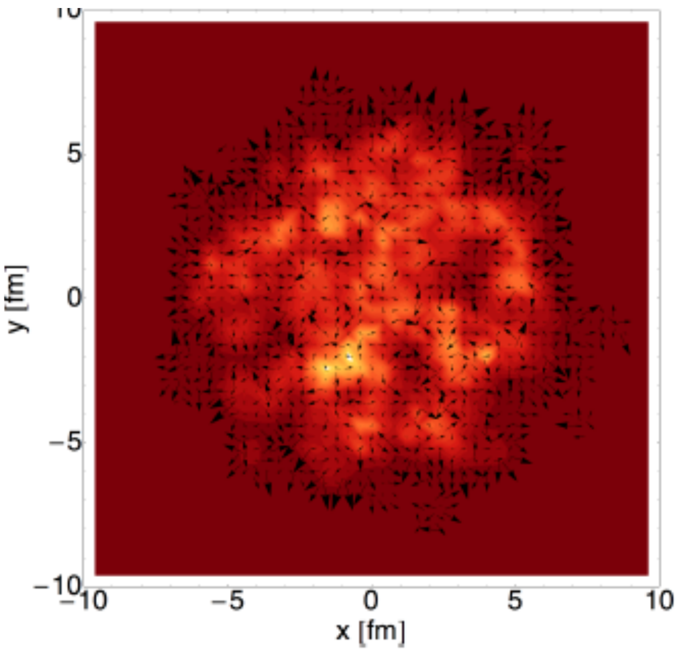


Energy density and (u_x, u_y) at $\tau = 0.4\,\mathrm{fm}/c$

Energy density and (u_x,u_y) from $u_\mu T^{\mu\nu} = \varepsilon u^\nu$

IP-Glasma: Boost invariant Classical Yang-Mills

Compute all components of $T_{\mu\nu}$



Energy density and (u_x, u_y) at $\tau = 0.4\,\mathrm{fm}/c$

Matching to viscous hydro is "brutal" : assume very rapid isotropization at initial hydro time

Sturm und drang

Initial state:
Far from equilibrium

Non-equilibrium dynamics

Final state:
Thermal equilibrium

How is thermal equilibrium achieved?

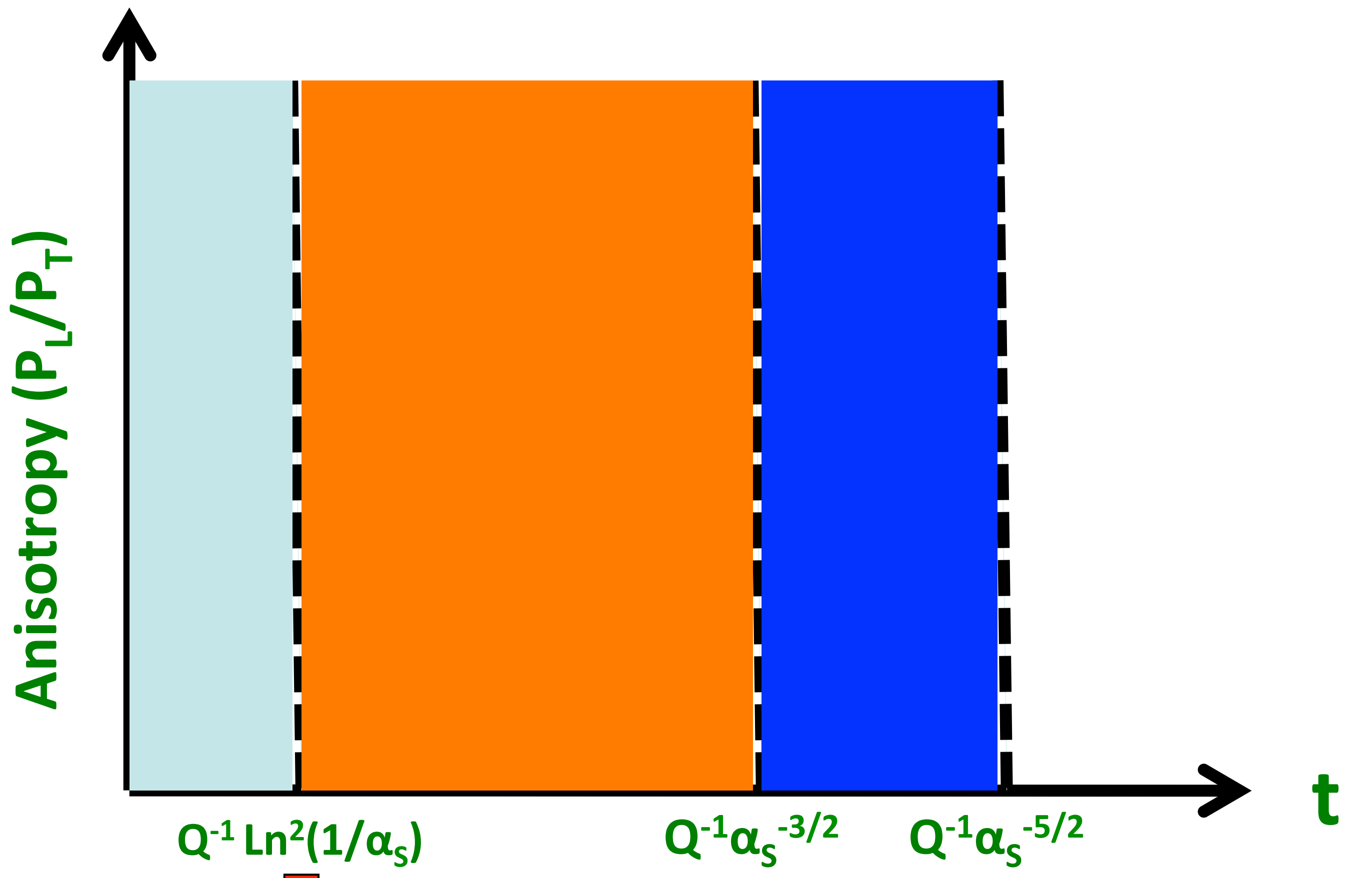
3+1-D classical expanding Yang-Mills simulations

- Epelbaum, Gelis; Fukushima
- Berges, Boguslavski, Schlichting, Venugopalan
- Attems, Rebhan, Strickland

❖ Very significant progress in large scale numerical YM simulations of strongly correlated dynamics that could generate significant flow —and in kinetic descriptions of such overoccupied systems

(Blaizot,Liao,McLerran)

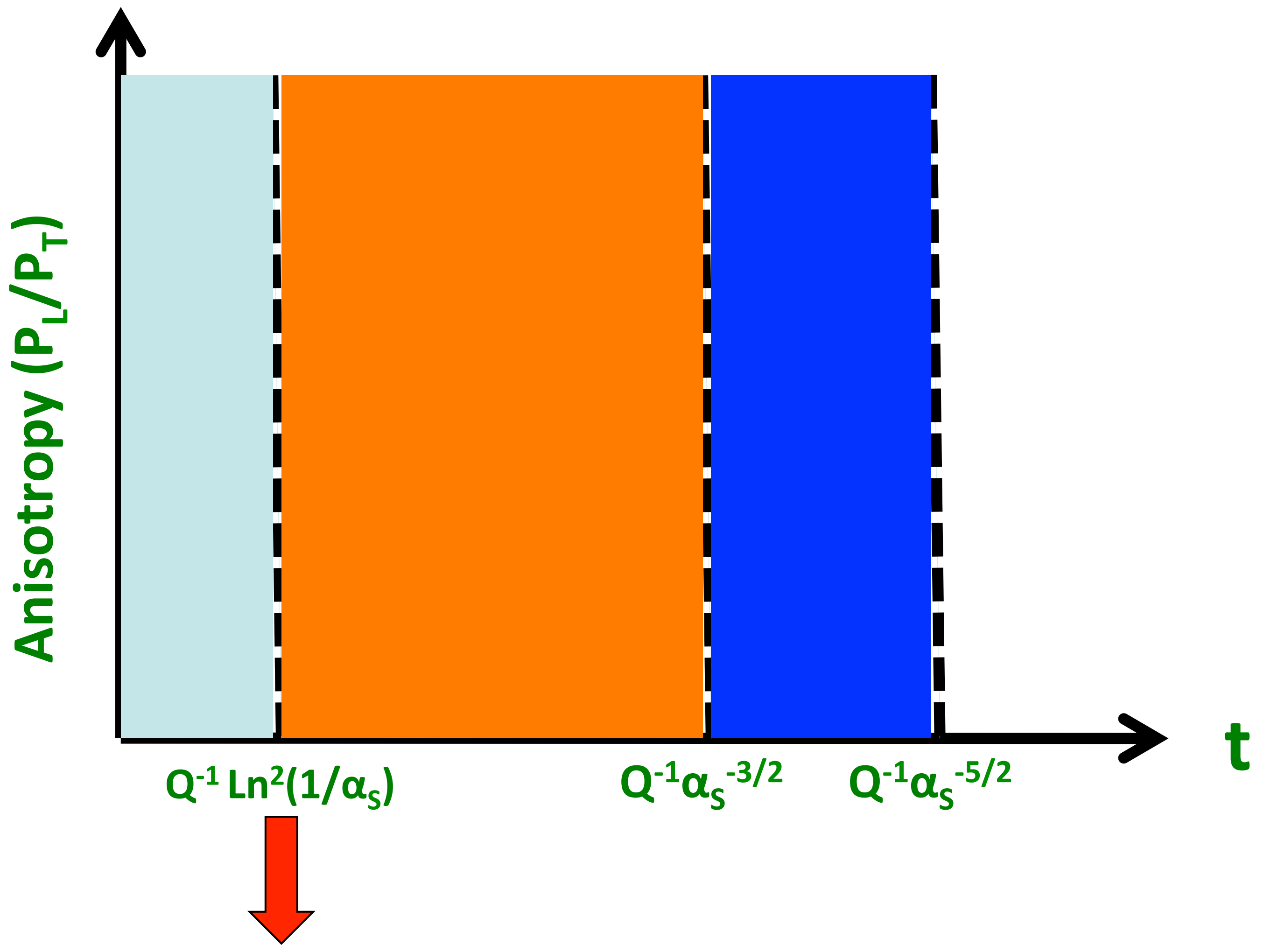
3+1-D classical Yang-Mills simulations



Instability dominated region

-quantum fluctuations become as large as the classical background – can lead to phase decoherence

3+1-D classical Yang-Mills simulations



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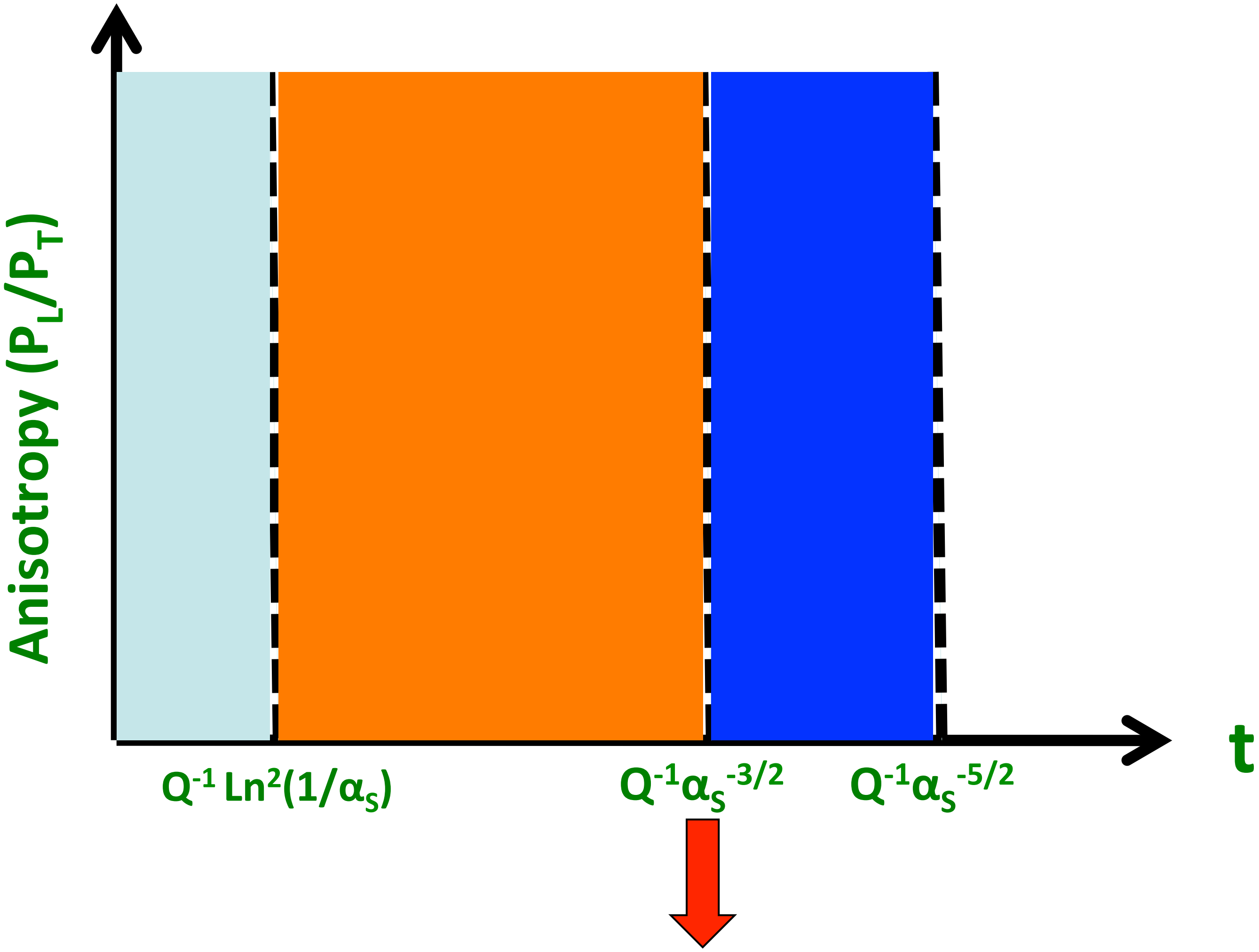
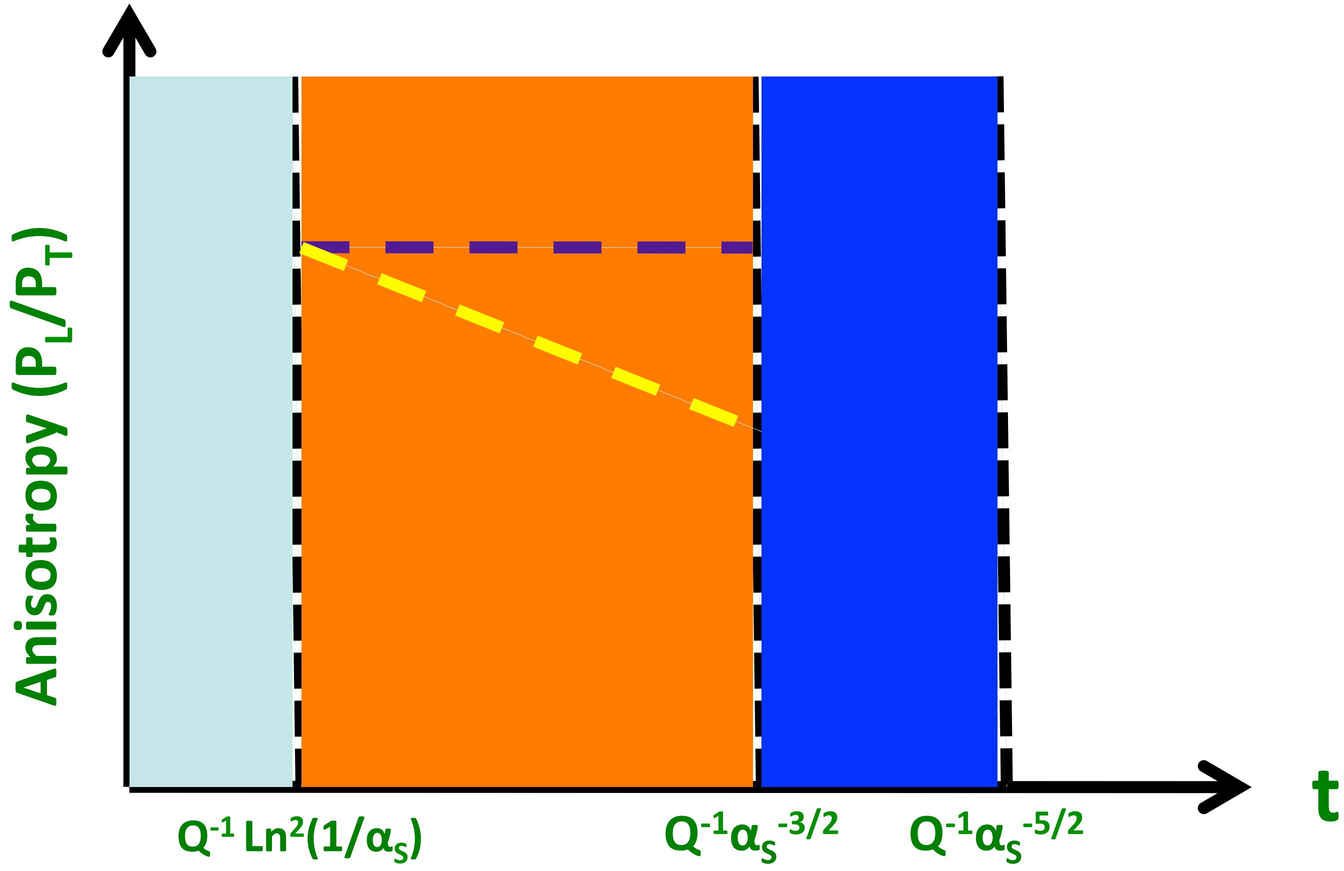


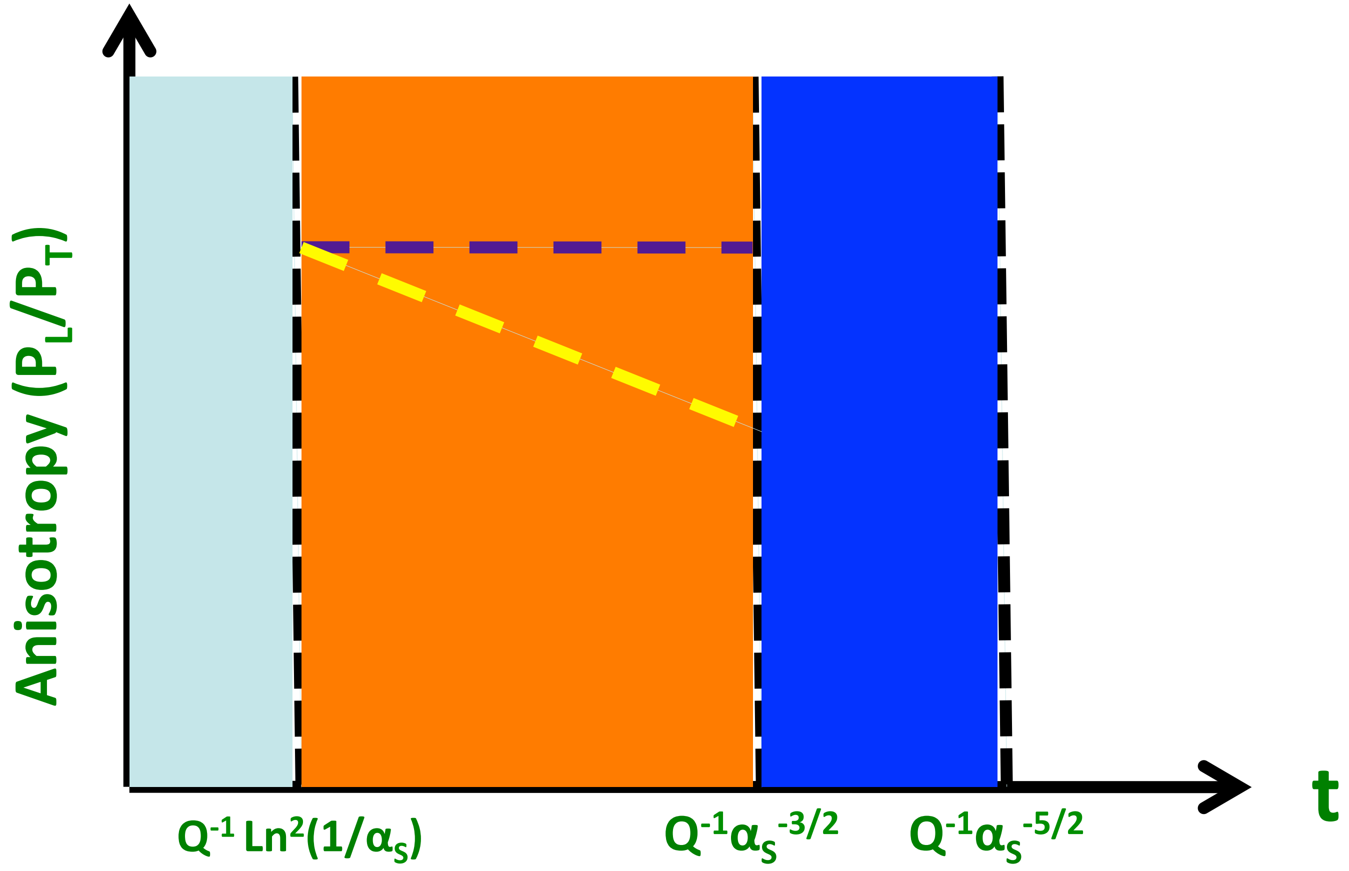
Strongly correlated dynamics up to here
-- strongest possible in QCD – for arbitrarily small α_S

3+1-D classical Yang-Mills simulations



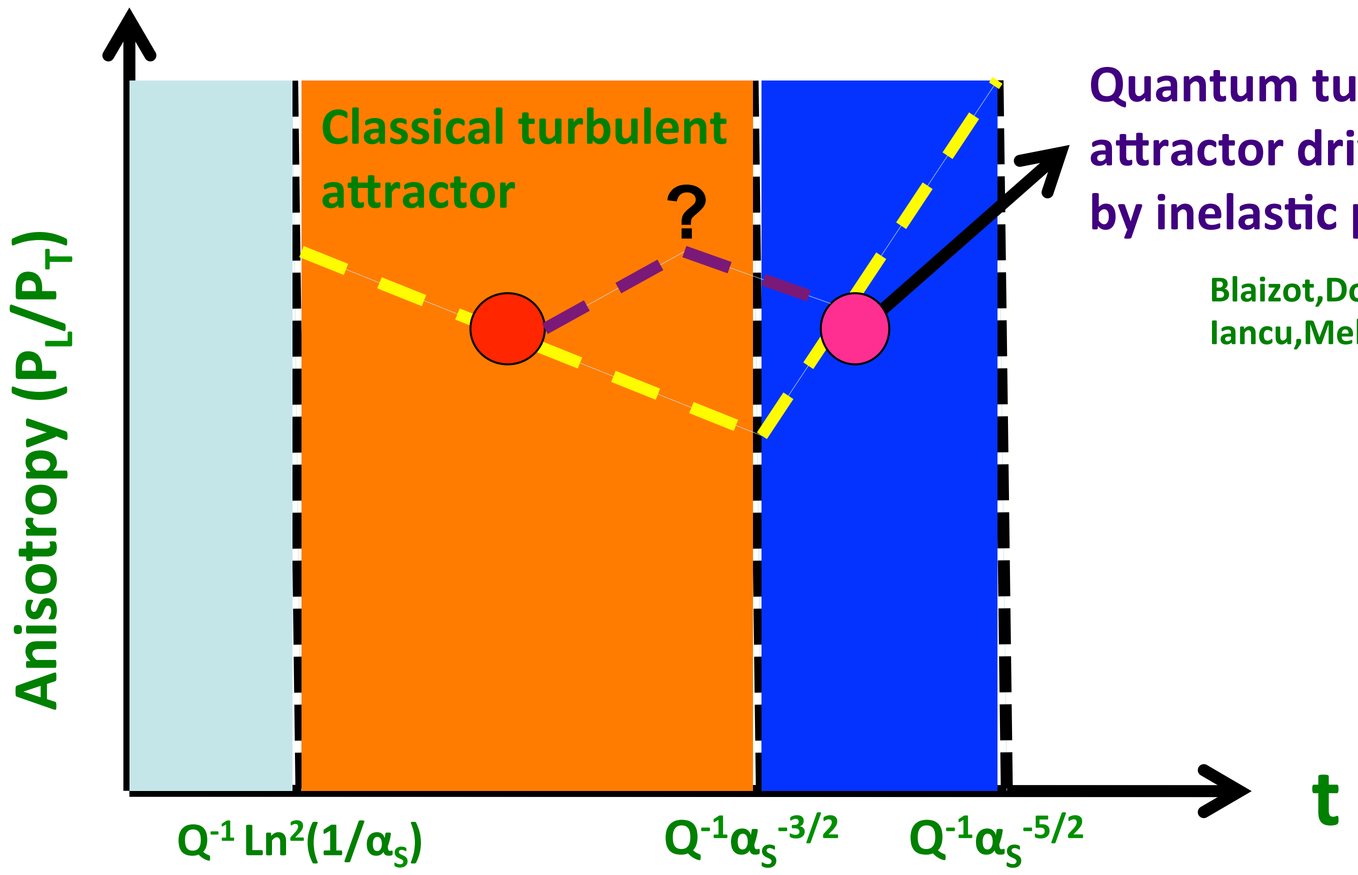
Open question: a) what happens when one cranks up the coupling ?
--all of these regions shrink
-- is there a reliable weak coupling regime where transient dynamics dominates through to isotropization?

3+1-D classical Yang-Mills simulations



This can be settled conclusively with existing “technology” + really smart young folks…

Quo vadis, thermalization ?

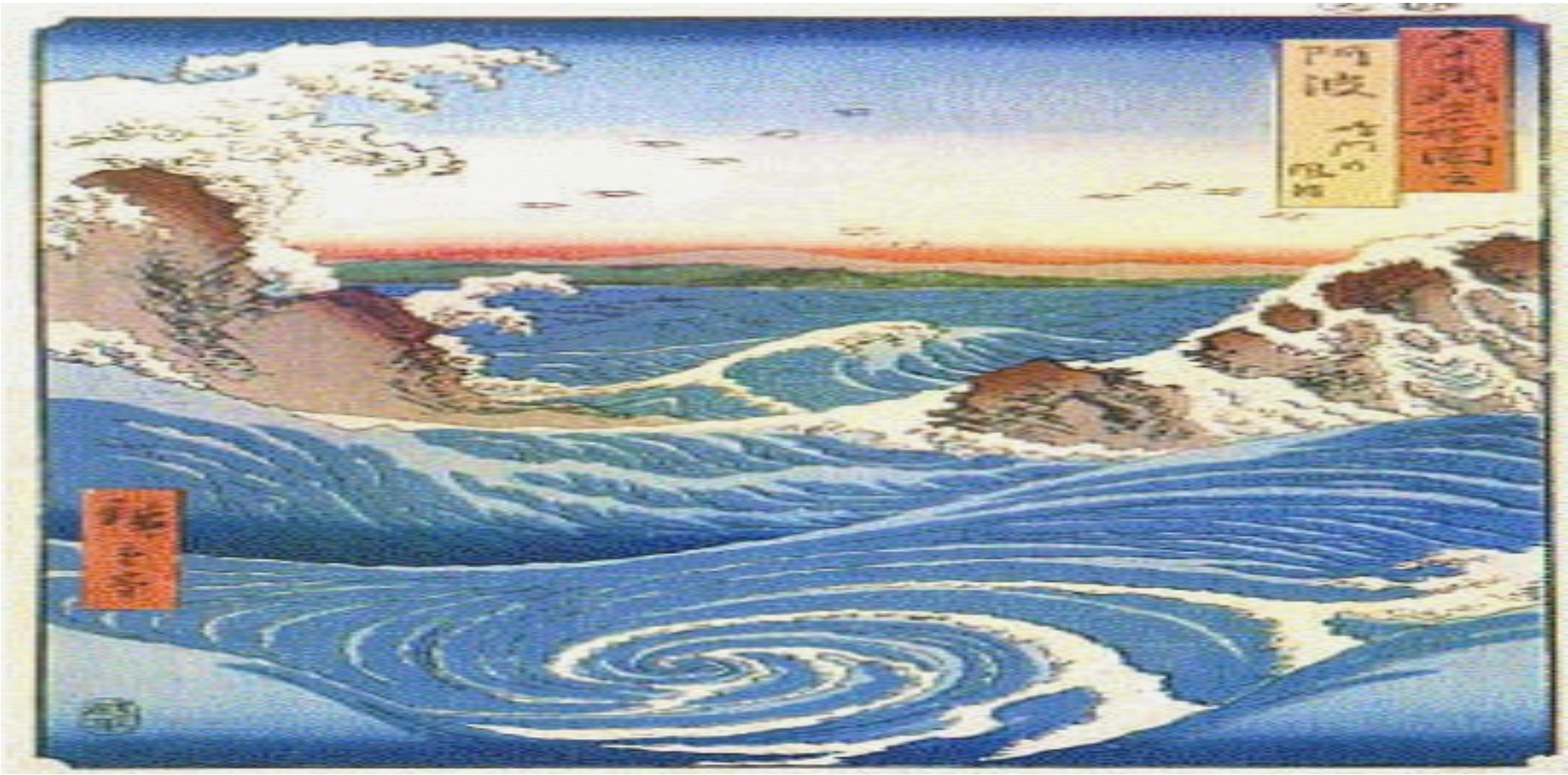


Quantum turbulent attractor driven by inelastic processes

Blaizot,Dominguez, Iancu,Mehtar-tani

Open question: can we compute the prefactors reliably ?

Universal non-thermal attractors in QCD



“Big whorls have little whorls, which feed on their velocity,
And little whorls have lesser whorls, and so on to viscosity.”

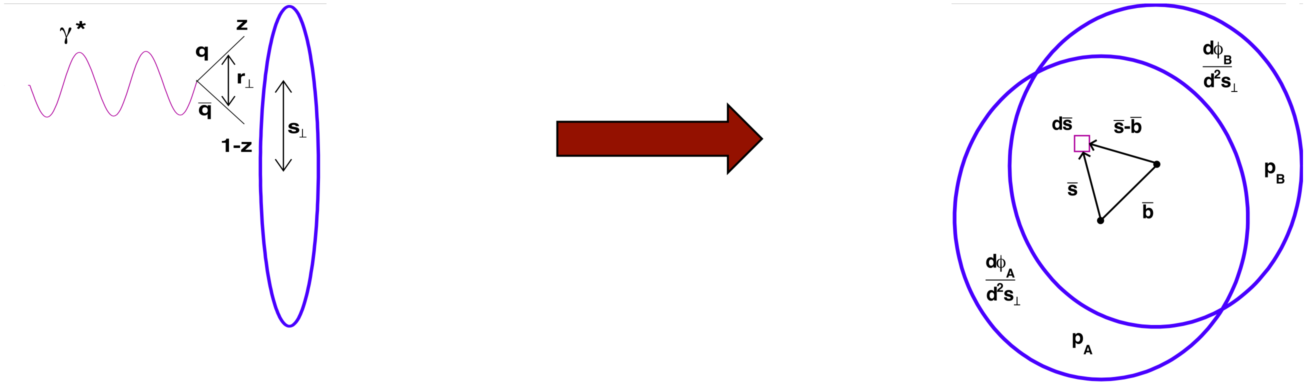
Many thanks to the organizers for this very enjoyable meeting!

Backup slides

From nuts to soup: I. constraining initial conditions

First understand e+p and p+p:

Global analysis of HERA data thus far performed only in the IP-Sat, b-CGC and rcBK saturation models - more detailed JIMWLK analysis is desirable and likely



Unintegrated proton gluon dist. from dipole cross-section:

$$\frac{d\phi(x,k_\perp|s_\perp)}{d^2 s_\perp} = \frac{k_\perp^2 N_c}{4\,\alpha_s}\int_0^\infty d^2 r_\perp\, e^{ik_\perp\cdot r_\perp}\left[1-\frac{1}{2}\,\frac{d\sigma^p_{\text{dip.}}}{d^2 s_\perp}(r_\perp,x,s_\perp)\right]^2$$

k_T factorization: compute inclusive dist. of produced gluons at given impact par. :

$$\frac{dN_g(b_\perp)}{dy\,d^2 p_\perp} = \frac{16\,\alpha_s}{\pi C_F}\,\frac{1}{p_\perp^2}\int\frac{d^2 k_\perp}{(2\pi)^5}\int d^2 s_\perp\,\frac{d\phi_A(x,k_\perp|s_\perp)}{d^2 s_\perp}\,\frac{d\phi_B(x,p_\perp-k_\perp|s_\perp-b_\perp)}{d^2 s_\perp}$$

The IP-Sat model

Bartels,Golec-Biernat,Kowalski
Kowalski,Teaney
Kowalski,Motyka,Watt

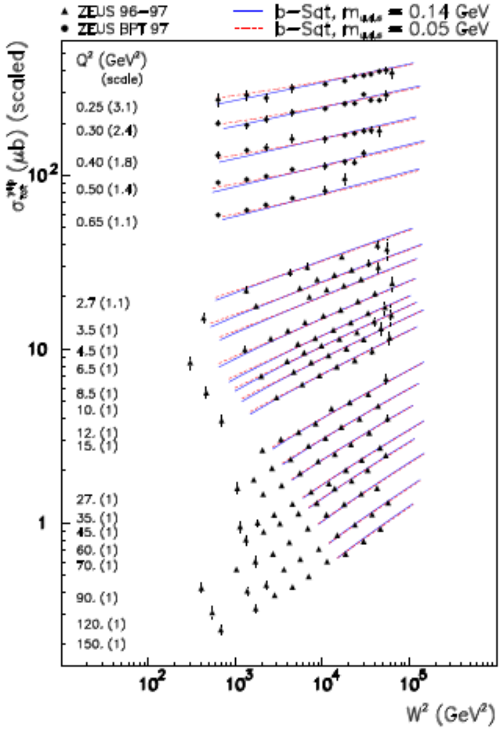
$$\frac{d\sigma^{p}_{dip}}{d^2 \mathbf{b}_\perp}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\mathcal{N}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_\perp{}^2 \alpha_s(\tilde{\mu}^2) x g(x, \tilde{\mu}^2) T_p(\mathbf{b}_\perp)\right)\right]$$

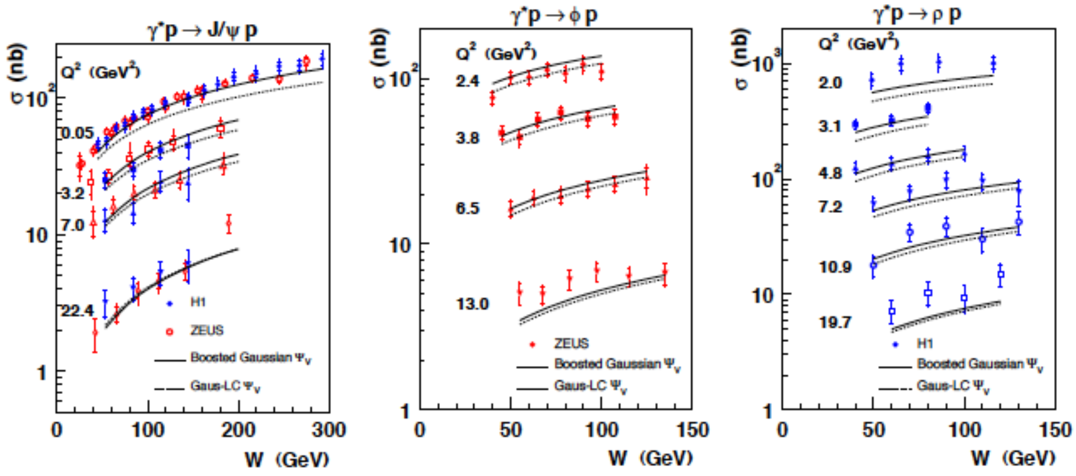
MV model extended to small x + impact parameter dependence

$$\tilde{\mu}^2 = \mu_0^2 + \frac{4}{r_\perp}^2$$

$$T_p(b_\perp) = e^{-\frac{b_\perp^2}{2B_G}}$$

Average gluon radius of the proton extracted from HERA diffractive data





X^2 ~ 1 fits to HERA inclusive,diffractive and exclusive small x data with few parameters

From nuts to soup: II. the IP-Glasma model

Schenke,Tribedy,RV:1202.6646

A. <u>Construct color charge distributions, event-by-event:</u>

- Positions of nucleons sampled from the Woods-Saxon distribution of each nucleus A and B

- IP-Sat provides $Q_S^2(x,b_T)$ for each nucleon – proportional to color charge squared per unit area $g^2\mu_p^2$ (details, see T. Lappi, arXiv:0711.3039)

- Add all $g^2\mu_p^2\,(x_T)$ to obtain $g^2\mu_A^2\,(x_T)$ and $g^2\mu_B^2\,(x_T)$

- Sample $\rho_{A,B}^a$ from local Gaussian distribution for each nucleus:

$$\langle \rho_k^a(x_\perp)\rho_l^b(y_\perp)\rangle = \delta_{kl}\delta^{ab}\delta^{(2)}(x_\perp - y_\perp)g^2\mu_{A,B}^2(x_\perp)$$

This gives the random static source distribution for event-by-event multi-particle production