Theory @ HP2013

stiαs, November 8th, 2013

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IPhT, Saclay

Meta-Summary

NUCLEAR PHYSICS

with sometimes a few bits of

UNCLEAR PHYSICS

But there were exciting moments that I will try to share with you

See also the talks by **X-N. Wang** and **R. Vogt**

Disclaimer

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The theory of Heavy Ion Collisions (I)

QCD

$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

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Old joke : A postdoc explains at length to a senior physicist the intricacies of a problem he is trying to solve. After listening for 30 minutes without saying a word, the senior physicist asks :
– *Do you have a Hamiltonian?*
– *Well.. Yes I do.*
– *So, what is your problem exactly?*

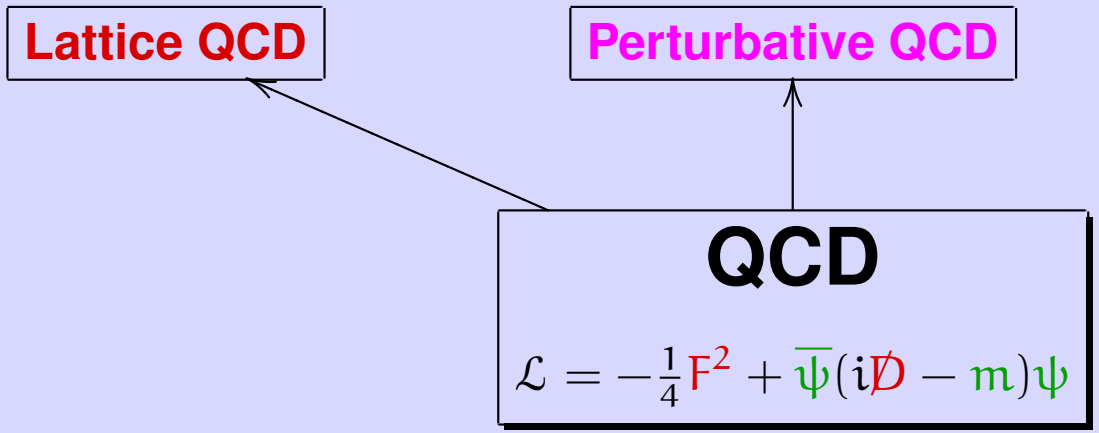
The theory of Heavy Ion Collisions (I)

Lattice QCD

QCD

$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

The theory of Heavy Ion Collisions (I)



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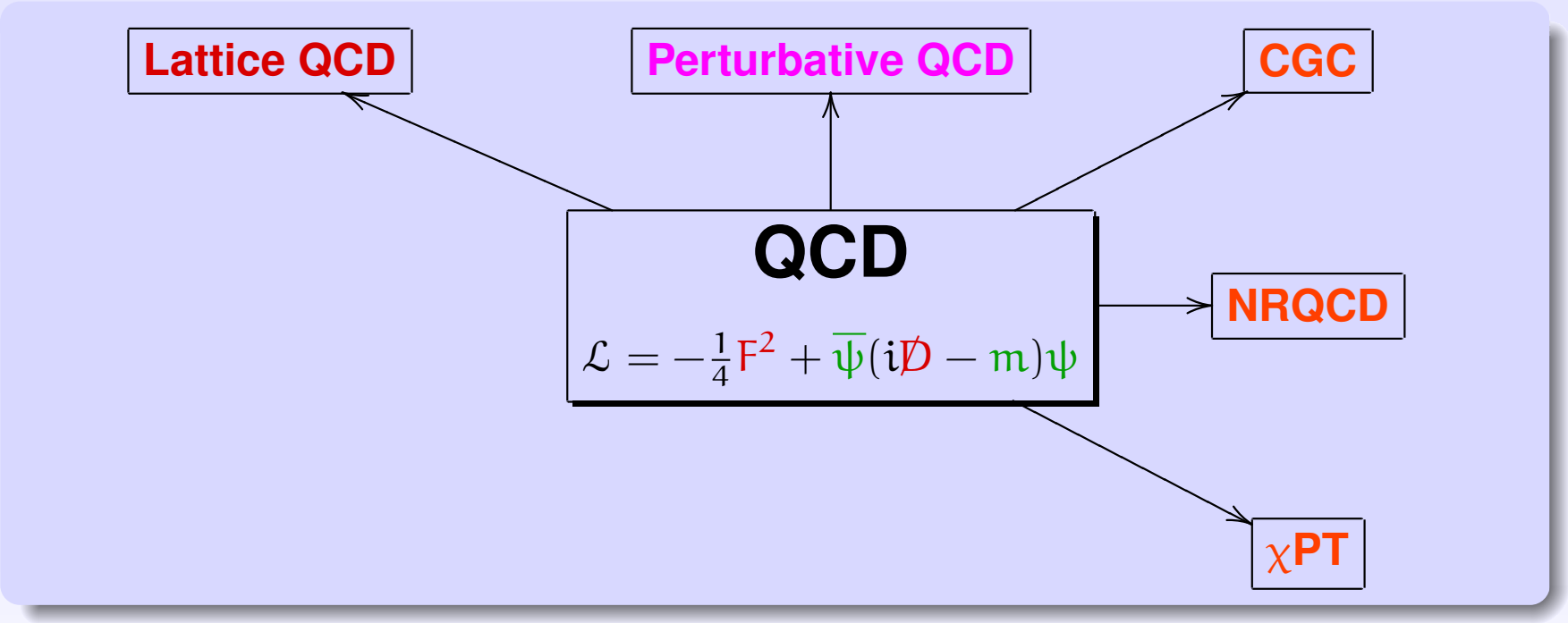

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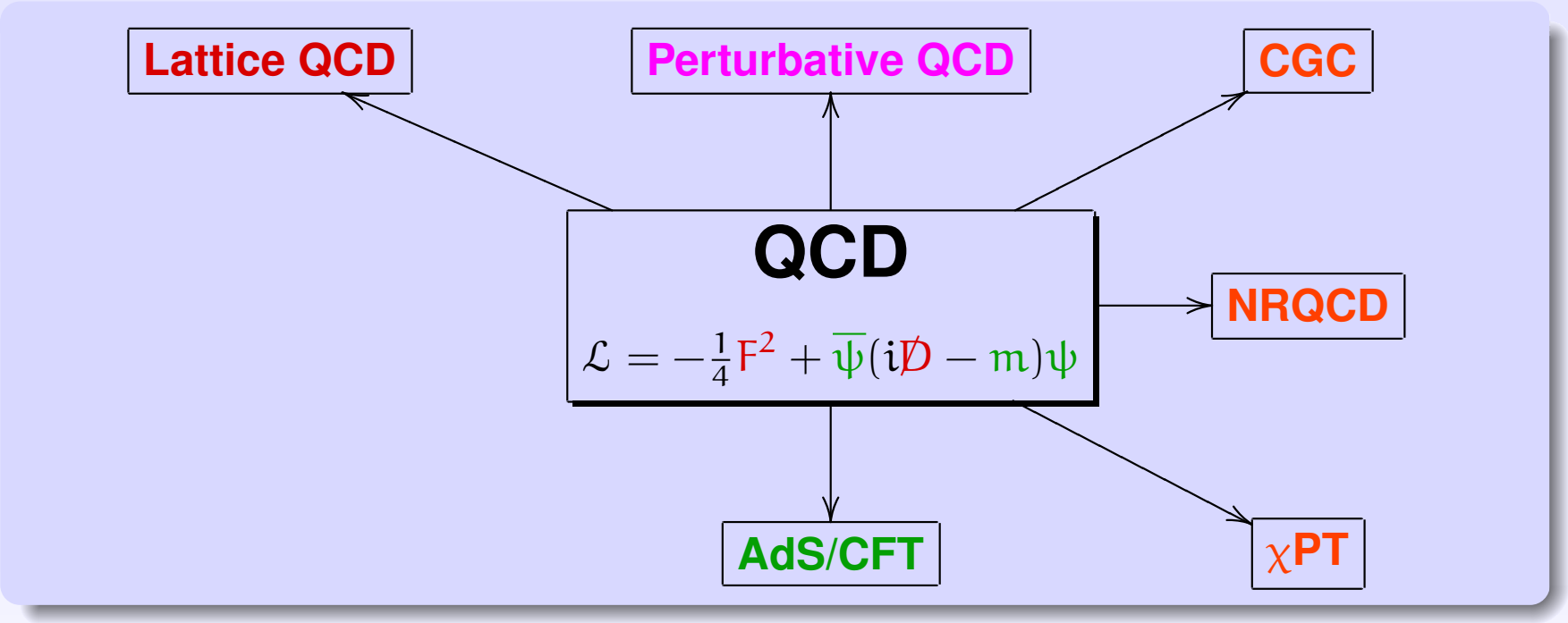

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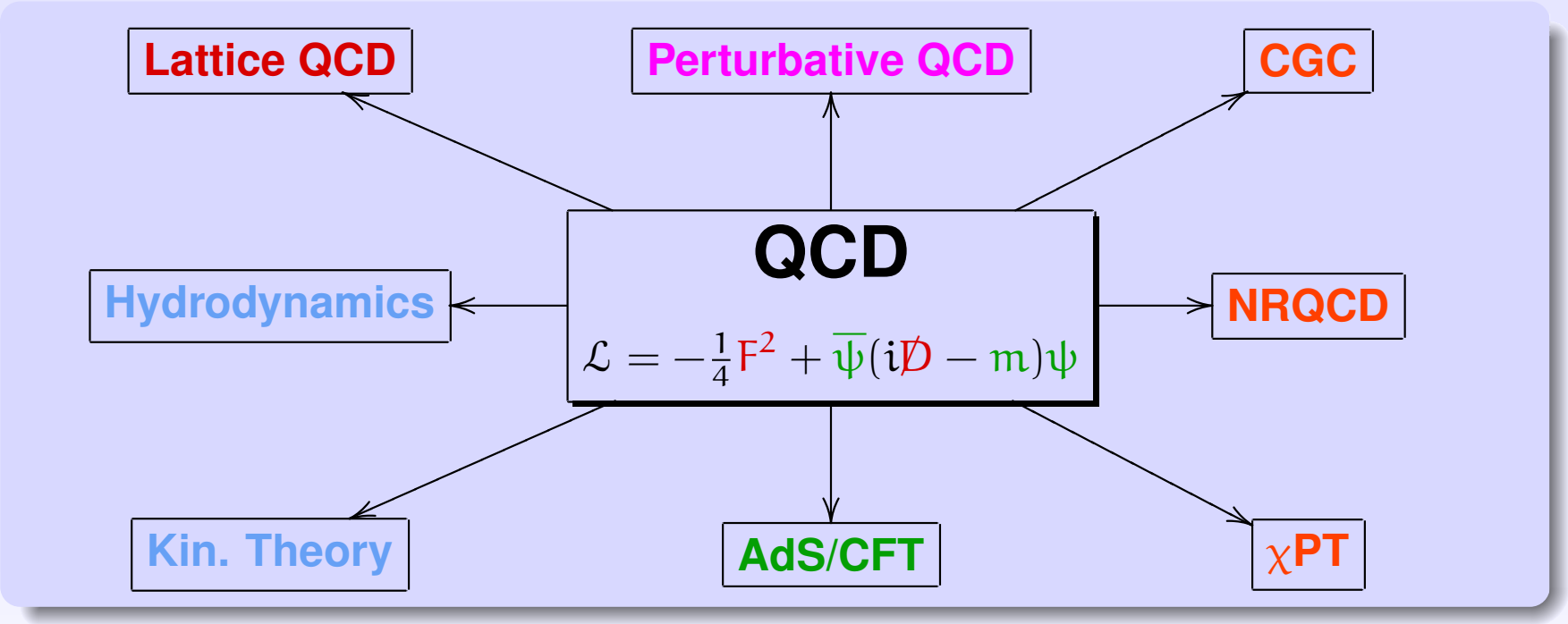

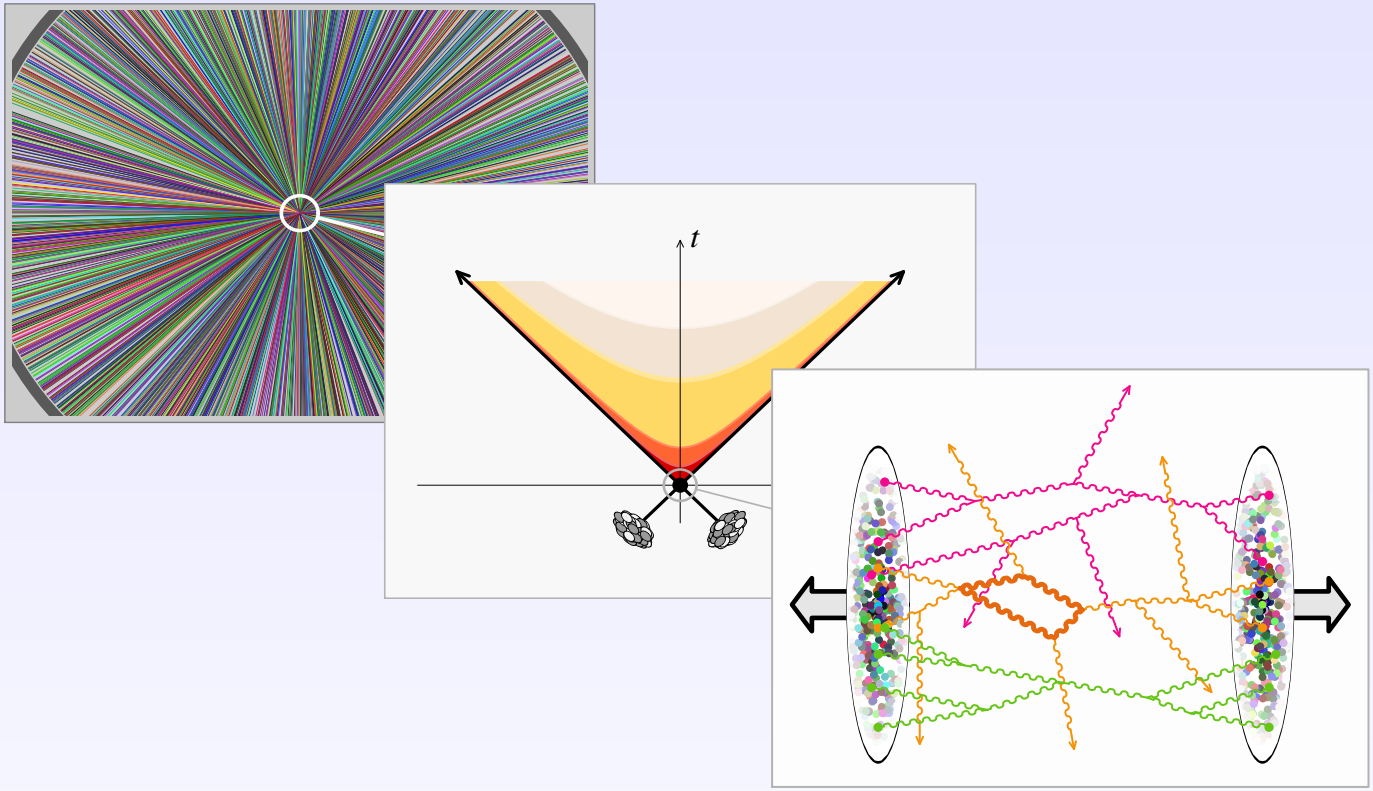

Goal : understand the microscopic dynamics of QCD from whatever we can measure in the final state of heavy ion collisions

The theory of Heavy Ion Collisions (II)

- Unfortunately, the outcome of a heavy ion collision also depends on a number of other rather mundane facts :

i. Nuclei are approximately spherical

ii. Their diameter is about 12 fermis

iii. They contain $A \approx 200$ nucleons

iv. The positions of these nucleons fluctuate event-by-event

- These properties have all an incidence on some observables
- None of them is interesting from the point of view of QCD
- We need observables that are independent of these trivial aspects of nuclear physics, or we need good models for them

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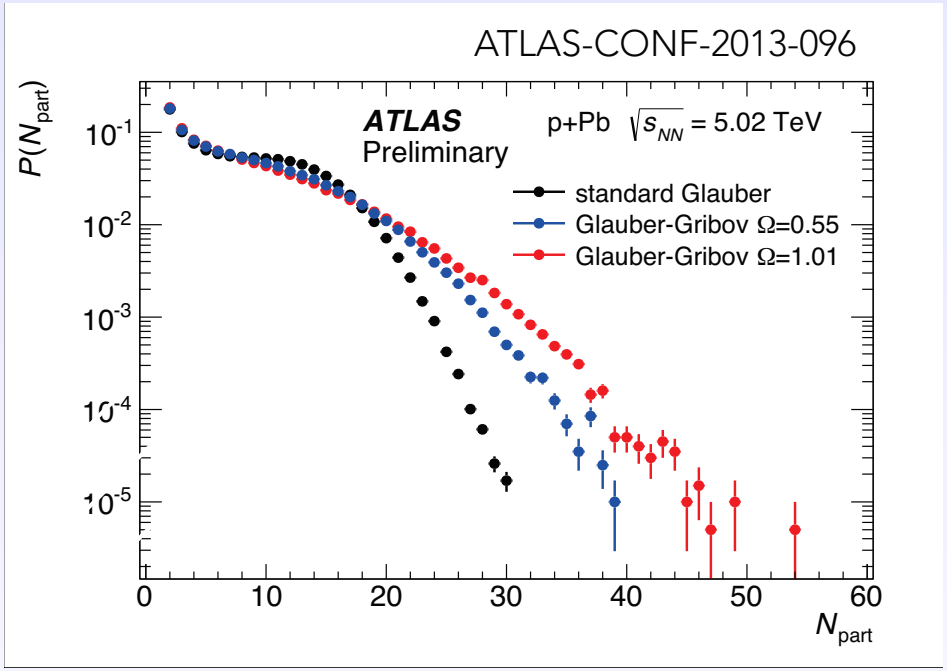
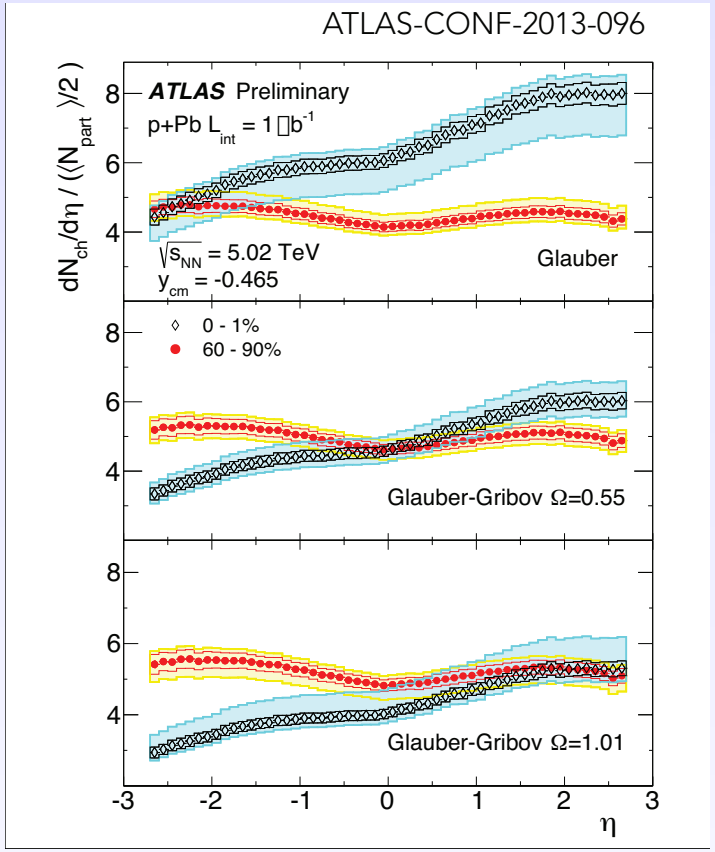
v. The nucleons may not be as simple as hard discs
(they may have “hotspots” that fluctuate themselves)

N_{part} is model dependent...



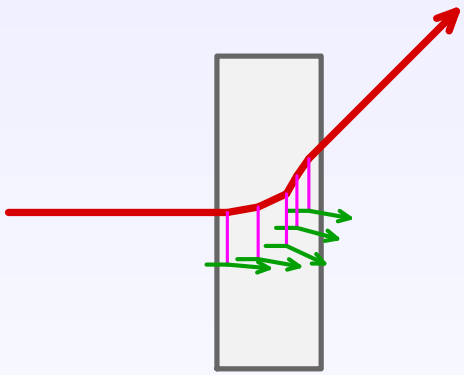


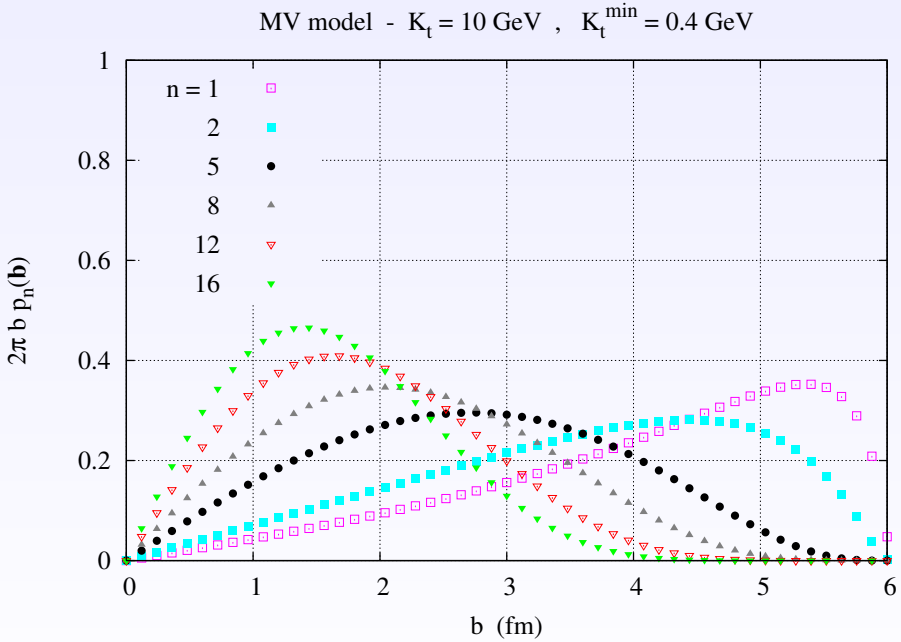
- May affect critically how we interpret “central” pA collisions...
- Simple remedy : show only “measured” quantities as much as possible (drawback : one looses a variable that gave us some intuition over the geometry of the collision in AA)

Defining centrality classes in pA collisions is a hard business

- Loose correlation between multiplicity and impact parameter
- Centrality classes much more “definition dependent” than in AA

Toy calculation in a CGC model **[Borghini et al., 2006]** :





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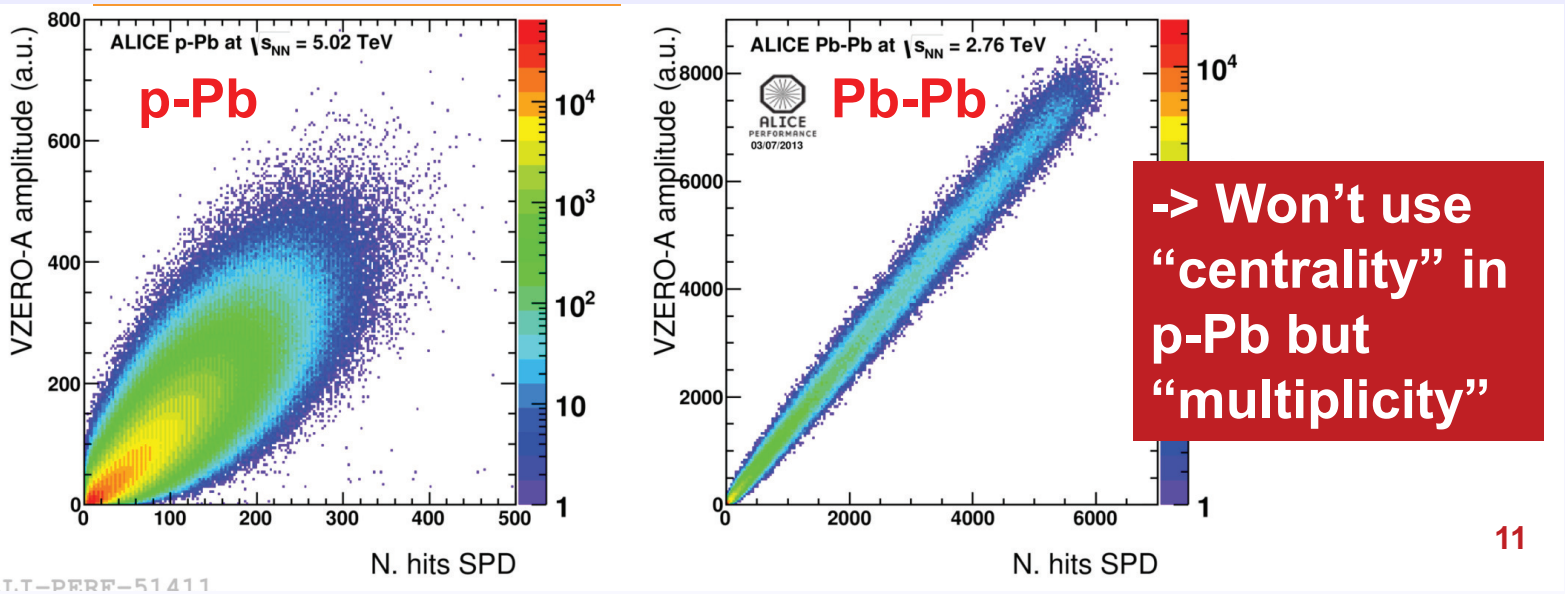
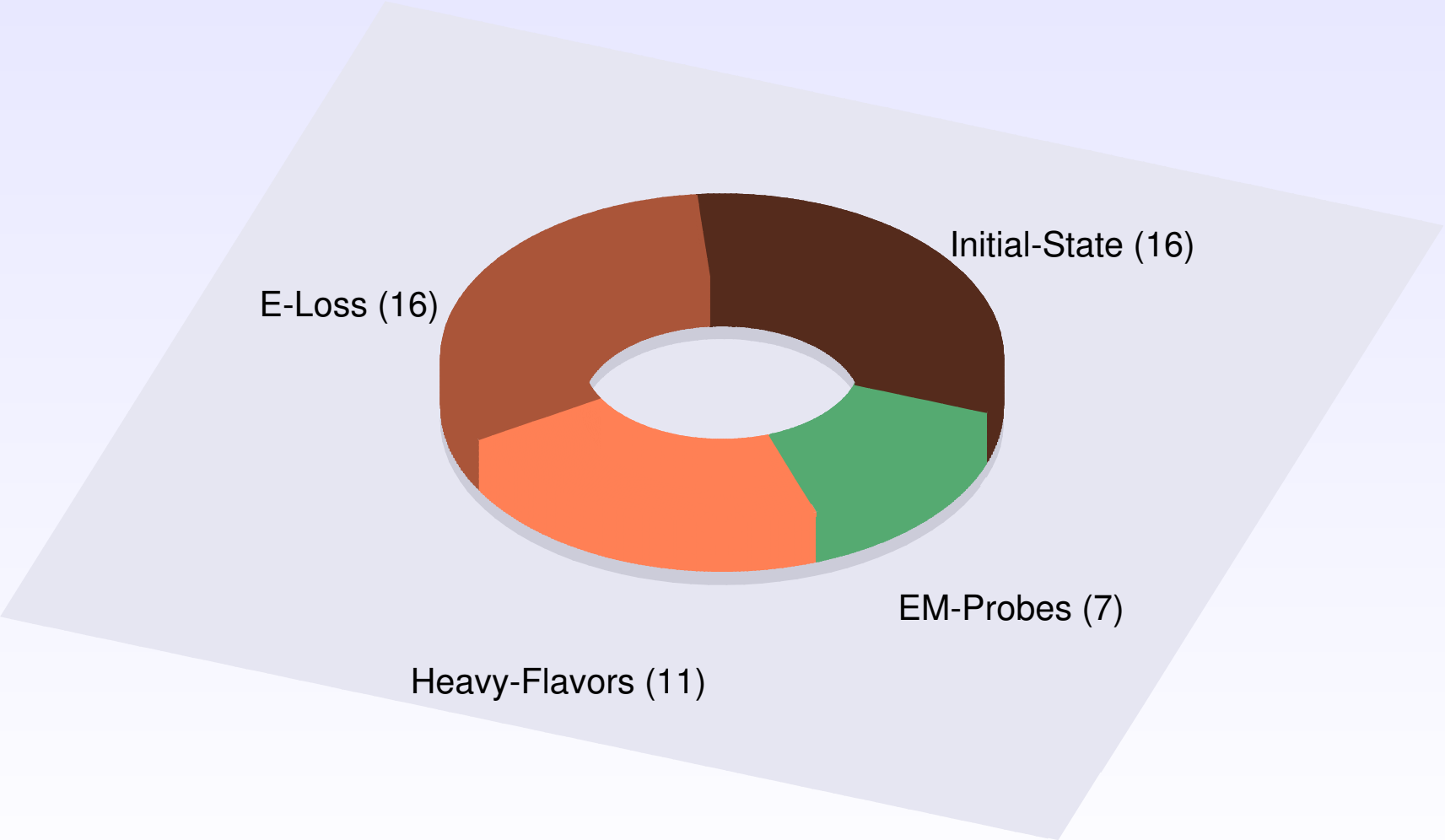


Theory talks by topic



Outline

1. Initial sate
2. Photons and dileptons
3. Jet Quenching
4. Heavy flavors and quarkonia

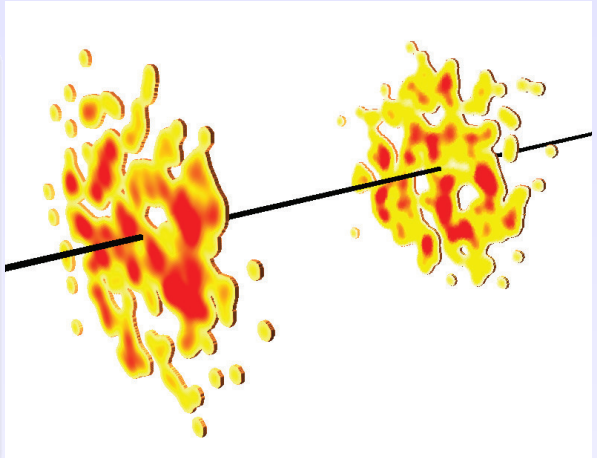
Initial State

Models of initial conditions for hydrodynamics [S. Jeon]

Many models...

Optical Glauber, MC Glauber, AMPT, NEXUS, MC-KLN, MC-rcBK, IP-GLasma

(ordered by the amount of QCD they contain...)



How to constrain them ?

- They differ in the spatial scales at which they have fluctuations
- Look at event-by-event flow fluctuations :

  initial shape harmonics : $\epsilon_n \quad \longrightarrow \quad$ flow harmonics : v_n

- Requires a reliable hydro evolution
- Depends on the viscosity

DGLAP

DGLAP based studies

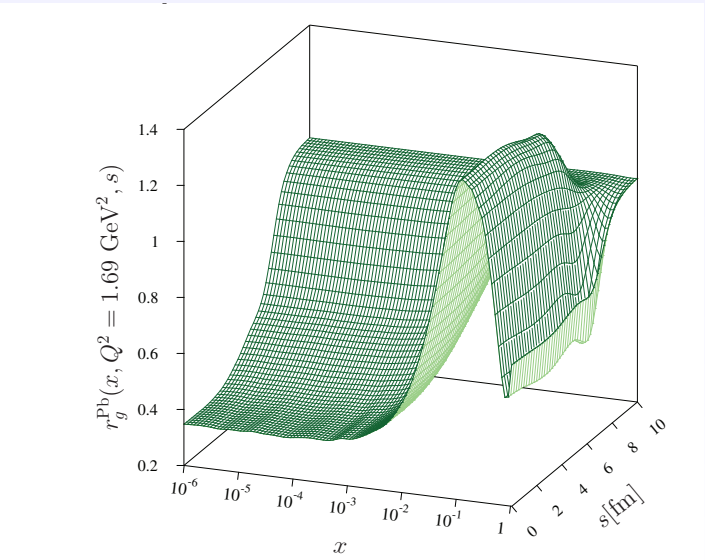
EKRT strikes back... [R. Paatelainen]

- Superposition of pp collisions + Minijet cross-section to NLO
- “Final state” saturation introduced via an infrared cutoff

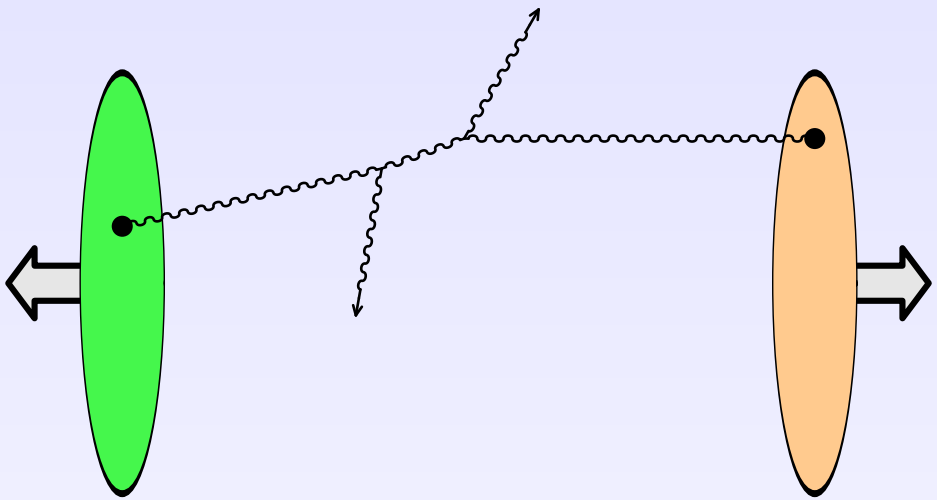
Impact parameter dependent nPDFs [I. Helenius]

- Include some nuclear modifications in standard PDFs
- Inconsistent if multiple scatterings are important

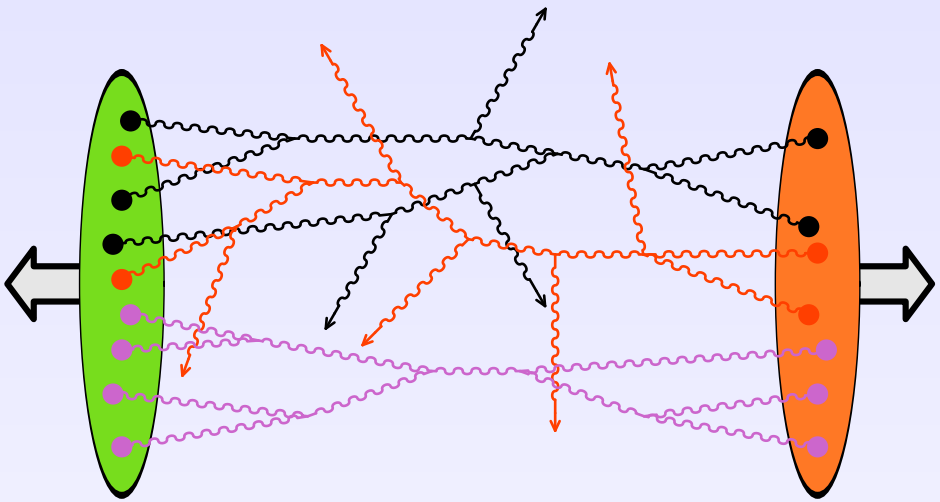
- Based on EPS09
- Study the $\mathbf{b}$-dependence of the nuclear modifications
- Compute π^0 and γ production in pA collisions



CGC



- For rare processes (electroweak interactions, high $P_\perp$, large mass,...), standard pQCD (with nuclear PDFs) is sufficient
  BUT: LO is generally very crude, and serious things start at NLO



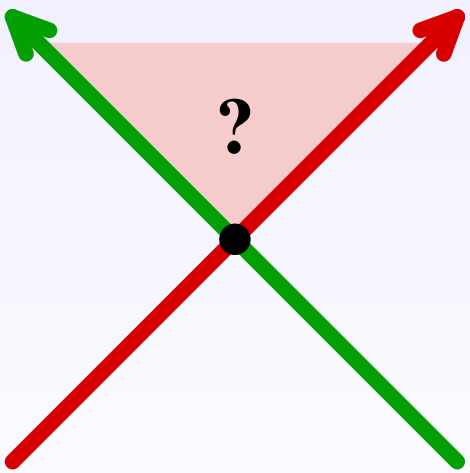
- For rare processes (electroweak interactions, high $P_\perp$, large mass,...), standard pQCD (with nuclear PDFs) is sufficient
  BUT: LO is generally very crude, and serious things start at NLO
- For the bulk of parton production, saturation effects become important $\Longrightarrow$ Color Glass Condensate

Color Glass Condensate

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + A_\mu \cdot (J_1^\mu + J_2^\mu)$$

$W_{1,2}[J]$ (distribution of the currents $J_{1,2}$)

$\frac{\partial W}{\partial Y} = \mathcal{H} W$ (JIMWLK equation : energy dependence)

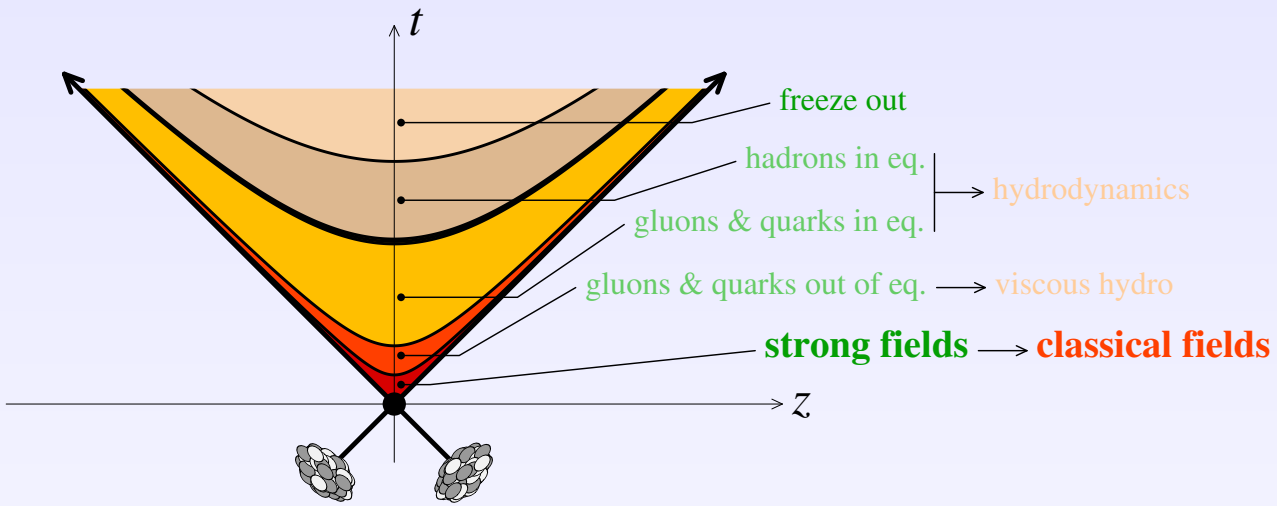


State of the art ~ 2012 :

- Evolution at Leading Log
  BK approximation used in practice
  BK approximation known up to NLO
- Calculations for AA :
  LO : classical field approximation
  Energy density, gluon spectrum
  Factorization for inclusive observables
- Calculations for pA :
  Particle spectra
  2-particle correlations

Limitations / Shortcomings ~ 2012

- In AA collisions, describes only the early stages



- Negligible longitudinal pressure at LO : $P_L/P_T \approx 0$
  But : large NLO corrections expected due to the Weibel instability

- The Leading Log evolution has no running coupling : too fast

Numerical solution of JIMWLK [T. Lappi]

JIMWLK $\Leftrightarrow$ diffusion equation

$$\frac{\partial W[U]}{\partial Y} = \int_{u,v} \frac{\delta}{\delta U_u} \eta_{uv} \frac{\delta}{\delta U_v} W[U]$$

Y = time , U_u = "spatial" coordinate

- Can be remapped into a random walk described by a Langevin equation ("straightforward" to solve numerically)
- Prescription to include running coupling effects : modify the noise correlation function

$$\langle \xi_u \xi_v \rangle \sim \alpha_s \delta(u-v) = \alpha_s \int \frac{d^2k}{(2\pi)^2} e^{ik\cdot(u-v)} \to \int \frac{d^2k}{(2\pi)^2} \alpha_s(k)\, e^{ik\cdot(u-v)}$$

- Note 1 : Next to Leading Log JIMWLK equation now derived [A. Kovner, M. Lublinsky], [S. Caron-Huot]
- Note 2 : Some kinematical improvements to the LO can account for a good part of NLO (shown in the case of BK by G. Beuf)

2-gluon correlations in pA collisions

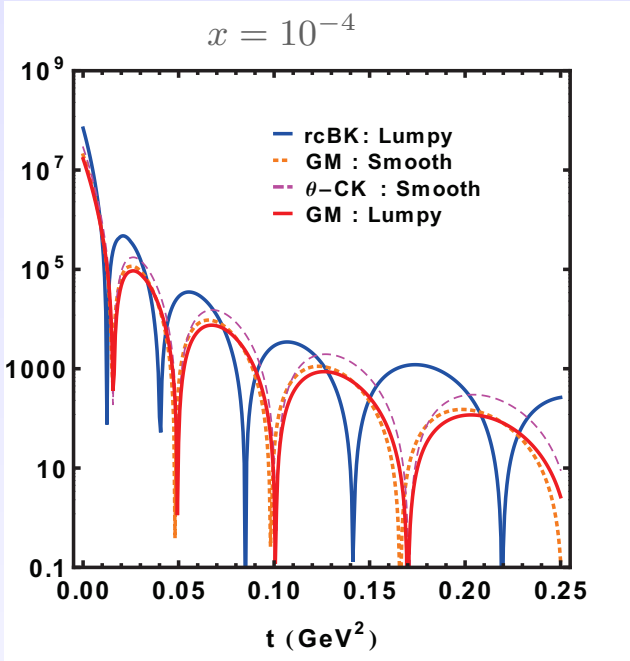
Rapidity evolution for the 2-gluon spectrum [E. Iancu]

- Ridge calculation : inclusive 2-gluon spectrum for a wide separation in rapidity
- The standard JIMWLK evolution is fully inclusive : it integrates over virtual and real contributions for all the gluons in the rapidity evolution
- Idea : "tag" some gluons in the course of the evolution, that should be produced in the final state
- Expressible as a Langevin process
  But : computational cost scales as $\sim S_\perp \times S_\perp$

Initial state mechanisms for near-side correlations [A. Kovner]

- Without invoking any flow, there are several mechanisms by which one gets ridge correlations in pp and pA collisions
- The large N_c limit is tricky in a dense medium **[M. Lublinsky]**

J/Ψ production in eA collisions [A. Ramnath] [G. Jackson]



- Probe of the nuclear gluon distribution and its spatial distribution
- Controlled by a 4-point correlator, but mixes with a 6-point function in the rapidity evolution

Gaussian truncation

$$\left\langle \cdots \right\rangle_Y = \exp\left\{ -\frac{1}{2}\int^Y dy \int_{u,v} G_{y,uv}\nabla_u\nabla_v \right\} \cdots$$

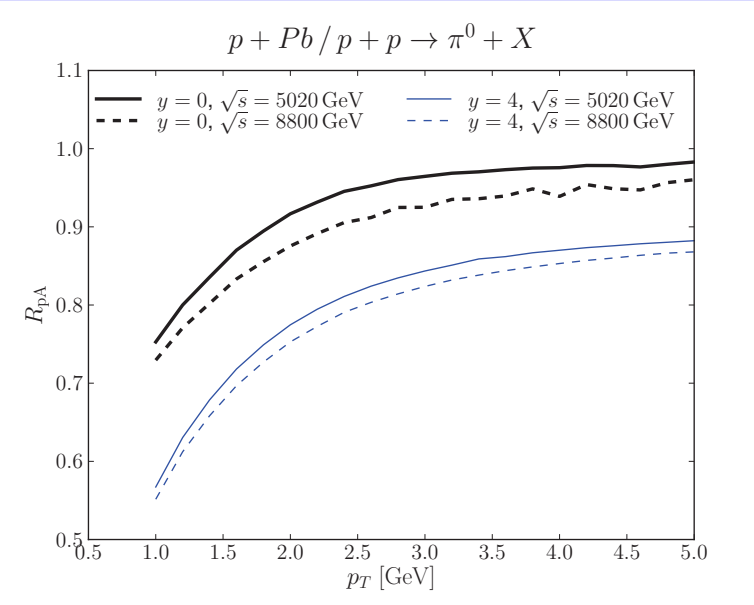
- Gives closed expressions for the $n+2$-point function in the evolution equation for a n-point function

CGC application to pA collisions

Hybrid formalism : DGLAP + k_T-factorization [B. Xiao]

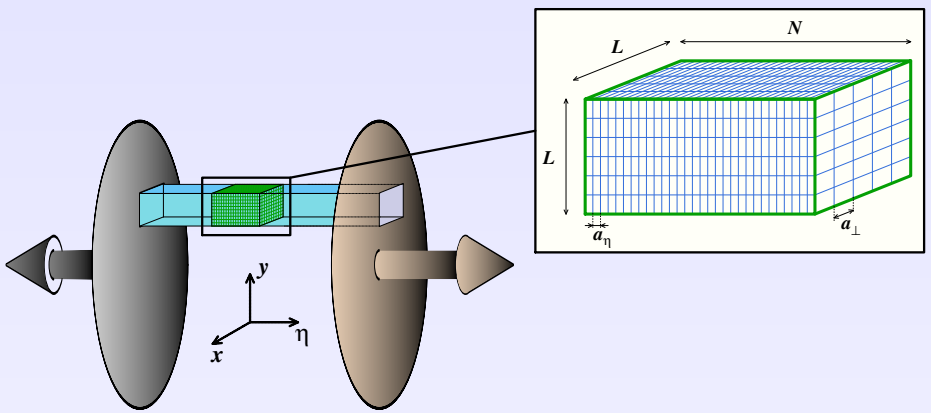
- Use standard collinear factorization for the proton
- k_T-factorization + BK for the nucleus
- Factorization established up to Leading Log

k_T-factorization + BK evolution [H. Mantysaari]



- Constrain the source model on ep collisions in DIS
- Compute π^0 spectrum for pp and pA collisions
- Evolution done with the running coupling BK equation
- Assume k_T-factorization (OK for pp and pA collisions)

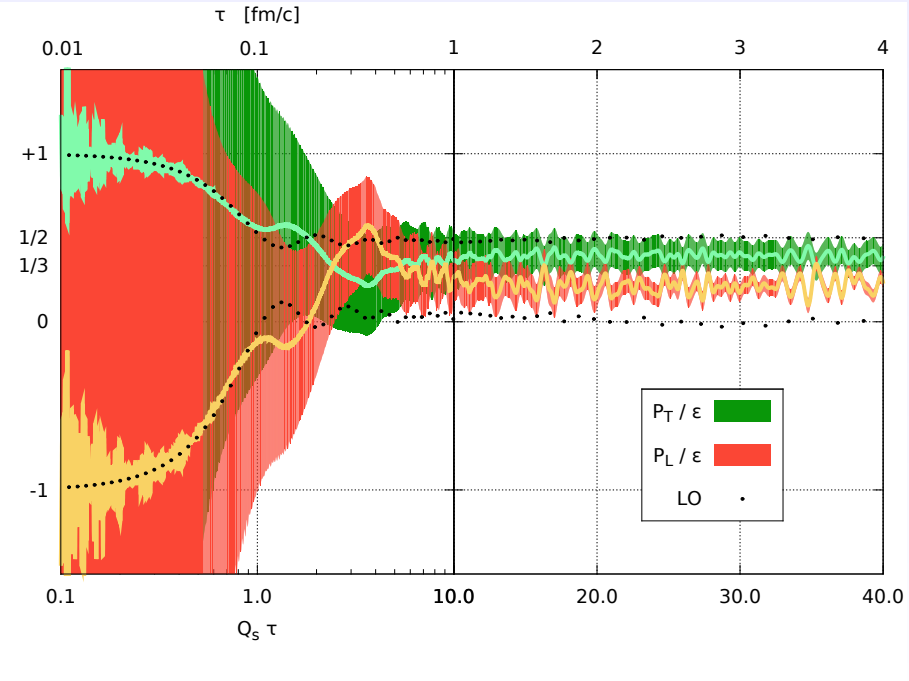
Pressure isotropization in AA collisions [T. Epelbaum]



- NLO included via fluctuations of the initial classical fields
- Spectrum of fluctuations calculated analytically at $Q_s\tau_0 \ll 1$
- 3+1 dim classical Yang-Mills simulation at $\tau > \tau_0$

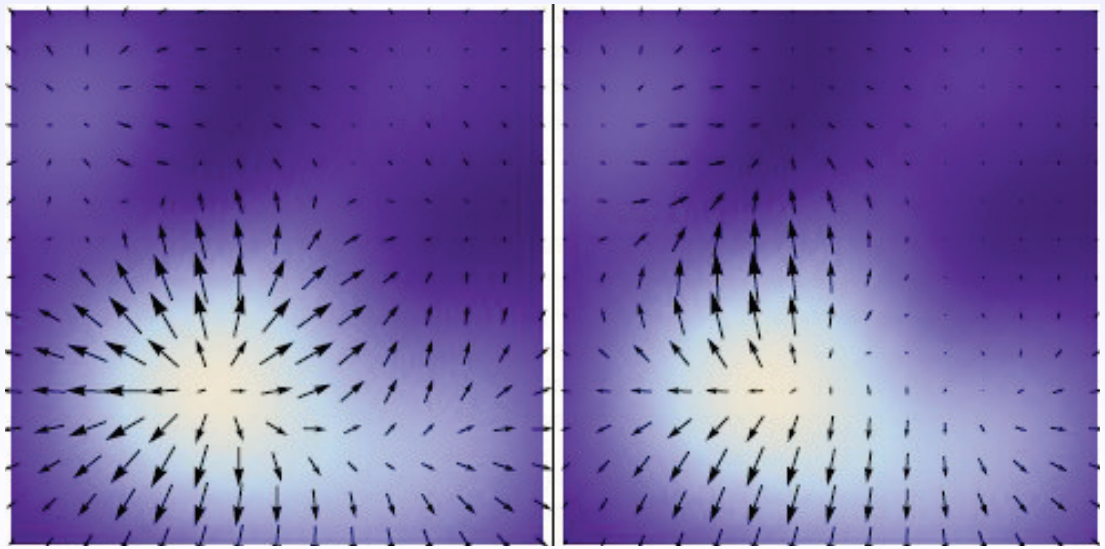
Results

- Rapid increase of P_L/P_T
- Works at rather small couplings
- Small effective $\eta/s \lesssim 1$



Early flow from classical fields [R. Fries]

- When $\tau \to 0$, the Poynting vector is exactly zero ($\mathbf{E}, \mathbf{B}$ are longitudinal)
- At small but non-zero τ, $T^{0i} \neq 0$:
  - rapidity even component $\sim \tau\, \partial^i \epsilon$
  - rapidity odd component $\sim \tau\, \epsilon^{ij} \Big([D^j, B_z] E_z - [D^j, E_z] B_z \Big)$

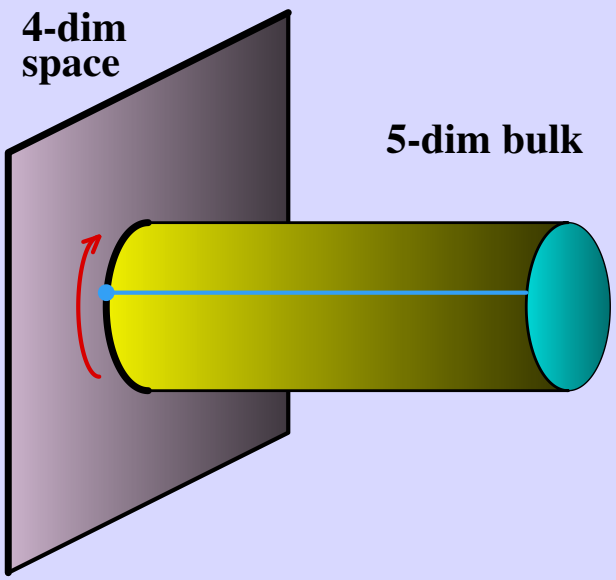


AdS/CFT

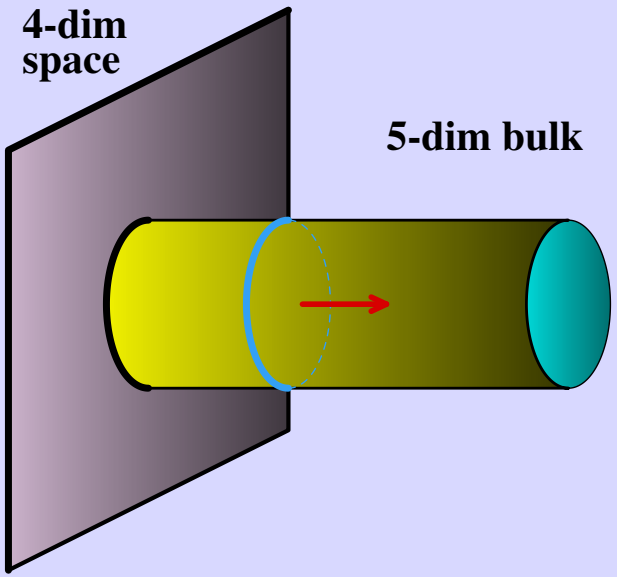
Gauge-gravity duality

- Most QCD tools (except lattice) do not work at strong coupling
- Quantum Field Theory – Gravity duality :

Vacuum fluctuation in $\mathbb{R}^4$

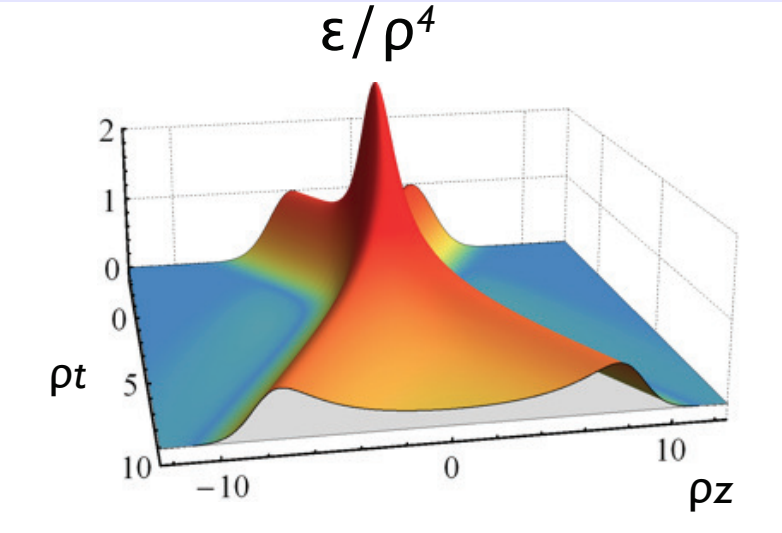


Closed loop : graviton



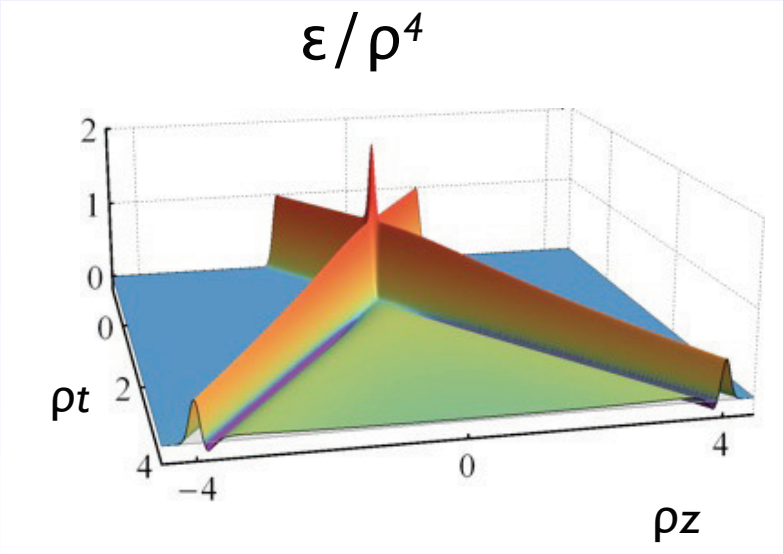
- On firm grounds for $\mathcal{N} = 4$ SUSY Yang-Mills theory
- Bulk calculation "simple" only in the limit $g^2 N_c \to \infty$

Shockwave collision in AdS/CFT [J. Casalderey-Solana]



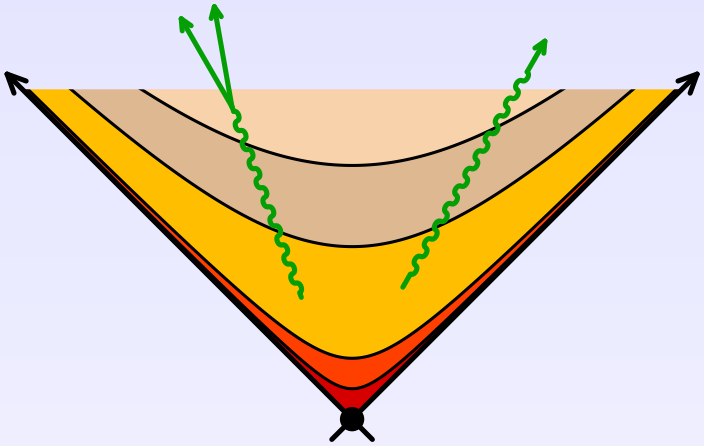
- Two shockwaves with a Gaussian profile of width ω (mimics Lorentz contraction in a collision at $\sqrt{s} \sim \omega^{-1}$)

- Low energy, large width : strong stopping and Landau-like behavior
- High energy, narrow width : weak stopping, Bjorken-like



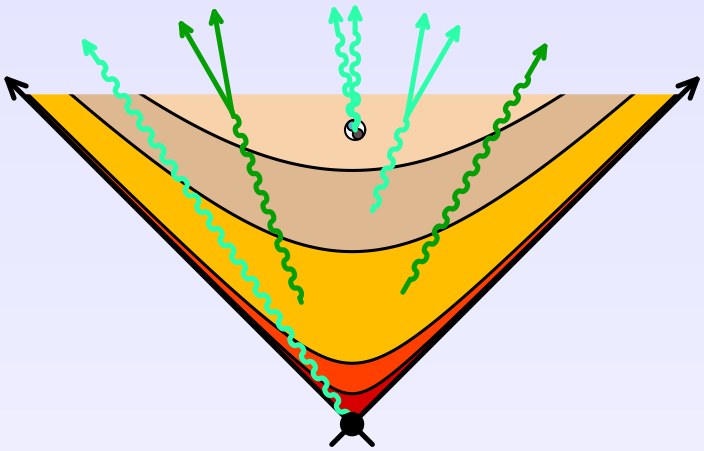
Photons and Dileptons

Photons and dileptons



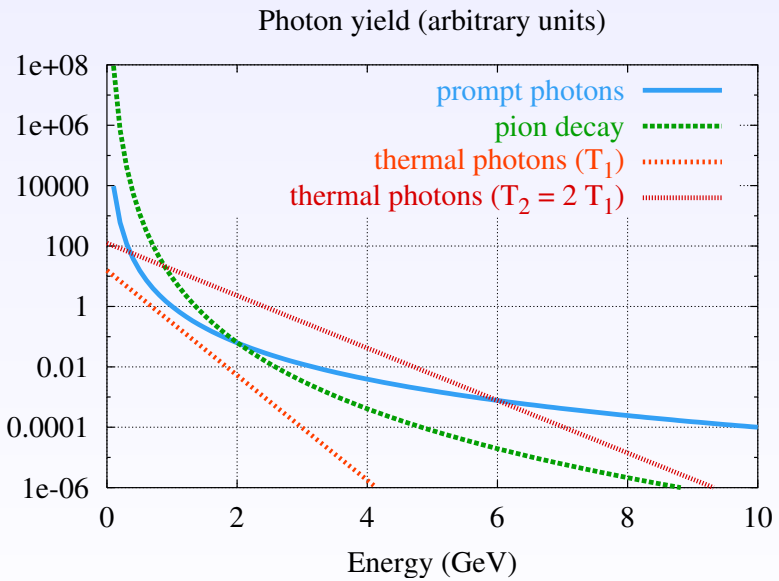
- Thermal rates $\sim T^4$
- Sensitive to the early temperature

Photons and dileptons



- Thermal rates $\sim T^4$
- Sensitive to the early temperature
- But many other sources make the signal extraction difficult

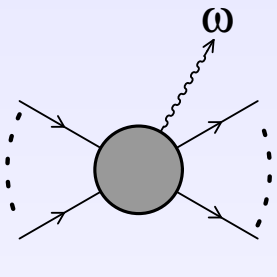
Thermal photons potentially visible at low p_T
They escape the medium without further interaction



Photon spectrum calculations

- Rate from kinetic approach :

$$\omega \frac{dN_\gamma}{dt dV d^3\vec{q}} \propto \int_{\left(\substack{\text{unobserved}\\ \text{particles}}\right)} \left| \right.$$



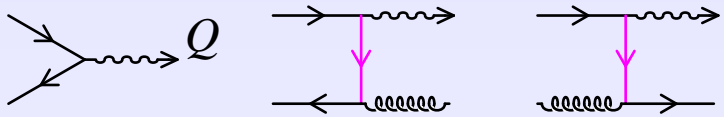
$$\left.\right|^2 \quad \begin{array}{c} f(\omega_1)\cdots f(\omega_n)\times \\ (1\pm f(\omega'_1))\cdots(1\pm f(\omega'_p)) \end{array}$$

- Rate from QCD at finite temperature :

$$\omega \frac{dN_\gamma}{dt dV d^3\vec{q}} \propto \frac{1}{e^{\omega/T}-1} \, \mathrm{Im} \, \underbrace{\Pi^\mu{}_\mu(\omega,\vec{q})}_{\text{photon self-energy}}$$

Physics of photon/dilepton production

1985 – 1992 : Problem solved?



(the possibly singular t-exchange gives only a gentle log)

Physics of photon/dilepton production

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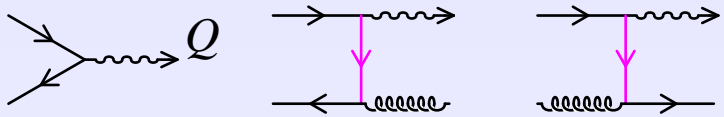

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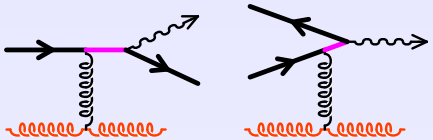
1996 – 1998 : new contributions of the same order



$$\alpha_s \frac{T^2}{m_D^2} \sim 1$$

Physics of photon/dilepton production

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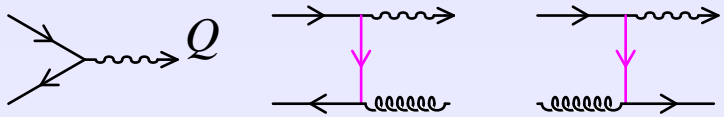

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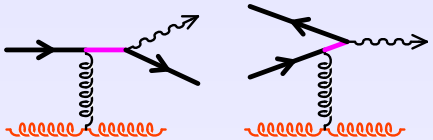
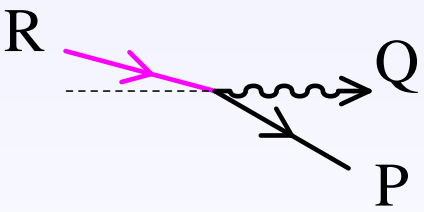
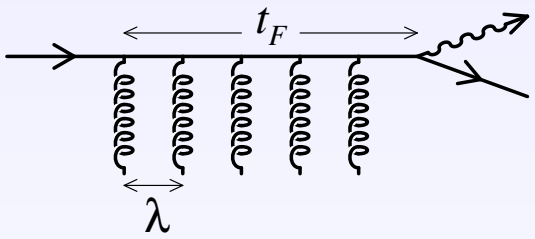


$$\alpha_s \frac{T^2}{m_D^2} \sim 1$$

2000 : LPM effect is important

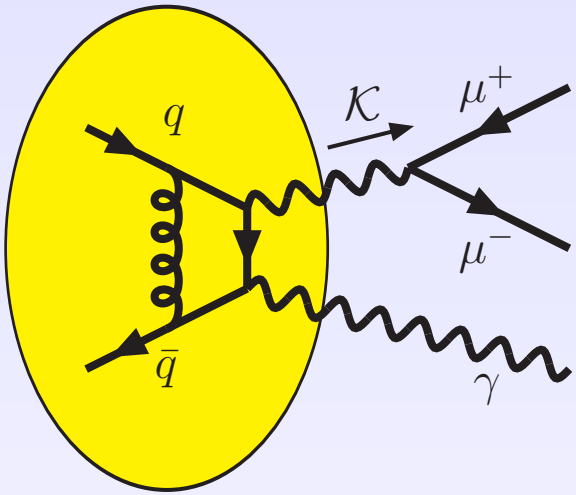


$$t_F^{-1} = \frac{\omega}{2p_0 r_0}\left[\vec{p}_\perp^{\,2} + m_q^2\right]$$

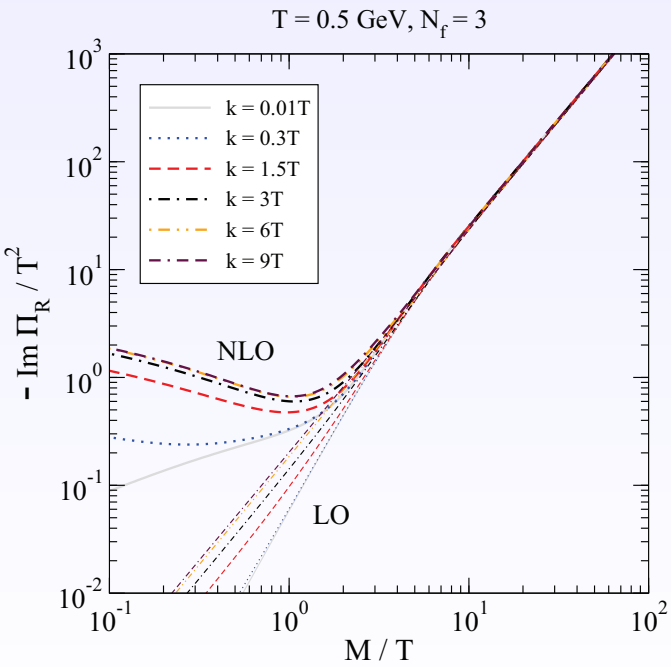


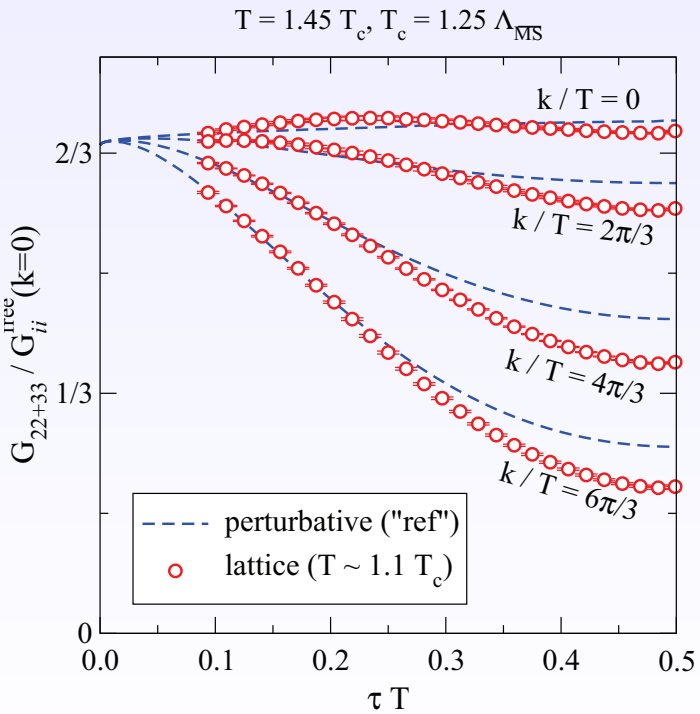
- **2001 :** full LO photon rate
- **2002 :** LPM resummation for low mass dileptons

Dilepton rate at NLO [M. Laine]

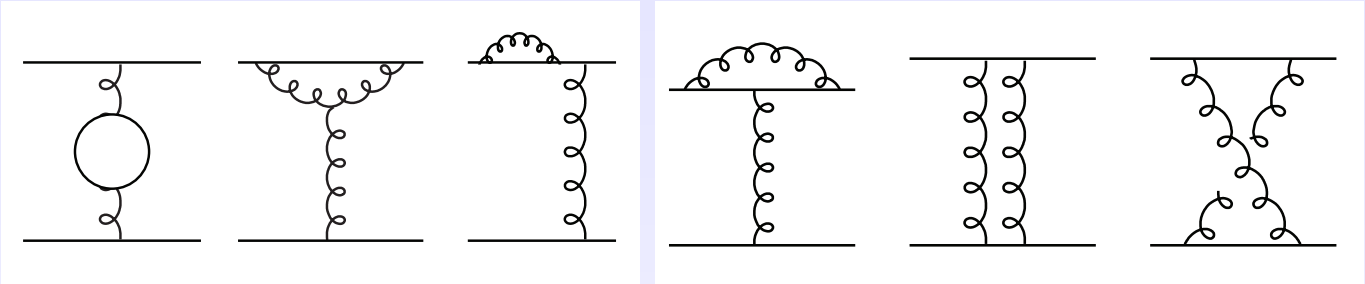


- Dilepton rate at NLO (i.e. $\mathrm{Im}\Pi$ at two loops), for invariant masses that are not too small
- NLO/LO becomes large for $M/T \lesssim 1$ (new channels that open up at NLO?)
- Reasonable agreement of the imaginary time correlator with lattice calculations

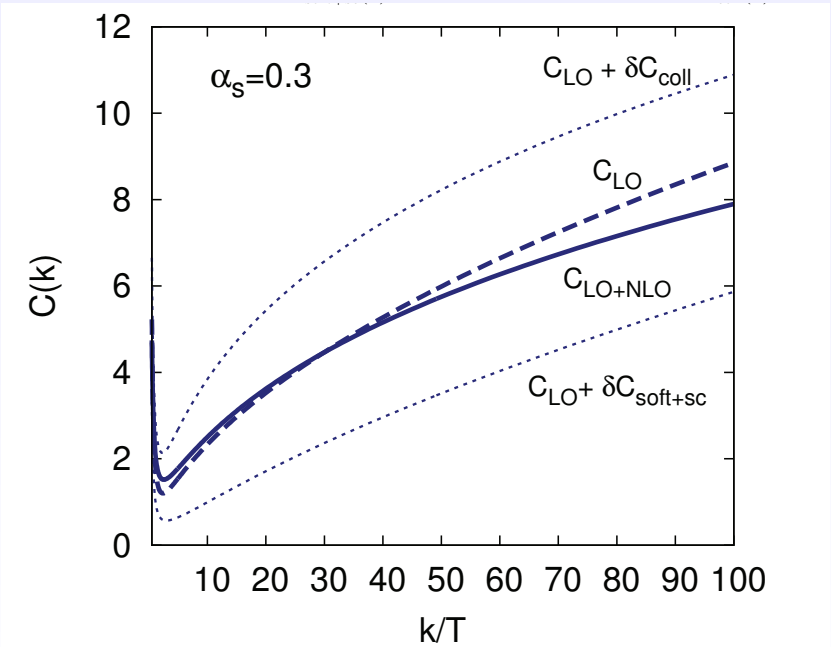




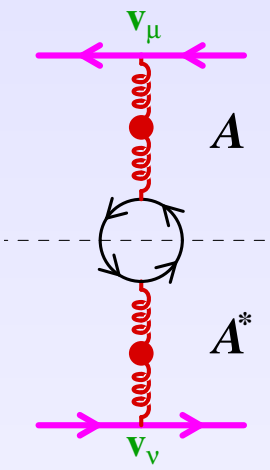
Real photon rate at NLO [J. Ghiglieri]



- $\mathcal{O}(g)$ correction relative to the LO result
- LO+NLO remarkably close to LO (mostly accidental)
- Lots of goodies in terms of new tricks to perform these calculations
- Work in progress : extend to NLO the AMY model of energy loss



Digression on the collision kernel $\mathcal{C}(q_\perp)$ (I)



Plays a role in :

- Photon/dilepton rates (LPM resummation)
- In-medium broadening :

$$\Delta k_\perp^2 \text{ per collision} = \int \frac{d^2 \mathbf{q}_\perp}{(2\pi)^2}\, q_\perp^2\, \mathcal{C}(\mathbf{q}_\perp)$$

- Expression in terms of in-medium gluon spectral functions :

$$\mathcal{C}(\mathbf{q}_\perp) = \int \frac{dq_0\, dq_z}{(2\pi)^2}\, 2\pi\delta(q_0 - q_z)\, \widehat{v}_\mu \widehat{v}_\nu \left(\rho_L^{\mu\nu}(Q) + \rho_T^{\mu\nu}(Q)\right)$$

- Fourier transform given by a correlator of light-like Wilson lines :

$$e^{-\ell \mathcal{C}(r_\perp)} = \frac{1}{N_c}\, \mathrm{Tr}\left(U(0_\perp) U^\dagger(\mathbf{r}_\perp)\right)$$

Digression on the collision kernel $\mathcal{C}(q_\perp)$ (II)

2002 : Leading Order

$$\mathcal{C}(q_\perp) = \frac{1}{q_\perp^2} - \frac{1}{q_\perp^2 + m_D^2}$$

2009 : NLO [S. Caron-Huot]

Digression on the collision kernel $\mathcal{C}(q_\perp)$ (II)

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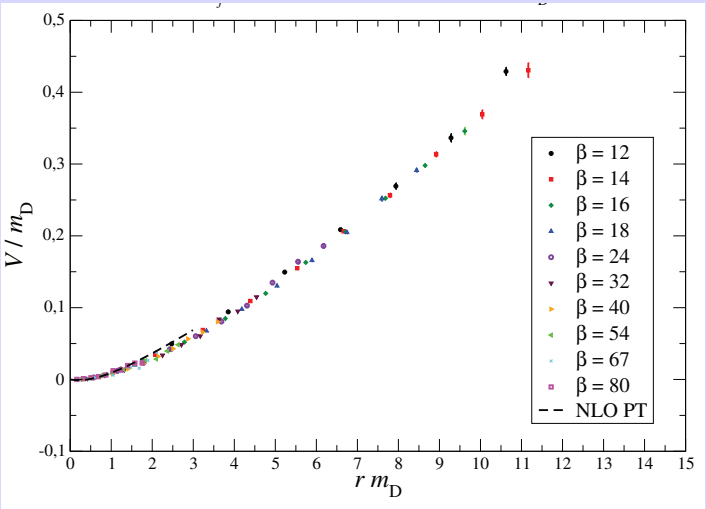
2009 : NLO [S. Caron-Huot]

Lattice evaluation [M. Panero]



- Dimensional reduction : 3-dim Yang-Mills theory + adjoint A_0
- Parameter matching to reproduce the QCD soft sector
- $\widehat{q} \sim 6$ GeV^2/fm at RHIC temperatures

Digression on the collision kernel $\mathcal{C}(q_\perp)$ (III)

Modification to include magnetic screening [M. Djordjevic]

$$\frac{1}{q_\perp^2} - \frac{1}{q_\perp^2 + m_D^2} \quad \rightarrow \quad \frac{1}{q_\perp^2 + m_M^2} - \frac{1}{q_\perp^2 + m_D^2}$$

- m_M = magnetic screening mass $\sim g^2 T$ (non perturbative)
- Seems to help with the energy loss of heavy quarks

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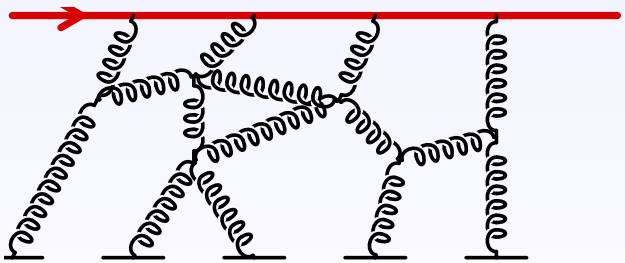
- Warning : when one starts playing with the $g^2 T$ scale, things may become really horrible...



because one is considering interactions whose range is as large as the soft mean free path

Folding into hydrodynamics [U. Heinz] [C. Shen] [G. Vujanovic]

- Main steps :
  - compute the rate with the T of the fluid cell
  - boost the local rate by the fluid velocity
  - integrate the rate over space and time
- T extracted by a fit $\sim \exp(-p_\perp/T)$ IS NOT the QGP temperature
- Interplay with viscous hydrodynamics : non zero $\pi^{\mu\nu} \Leftrightarrow f \neq f_{equi}$

  The rates must be calculated with non-equilibrium distributions consistent with the shear tensor. Done for $2 \to 2$ processes, in progress for the LPM resummation (to have the full LO rate)

  Some sensitivity of the photon v_2 to the viscous relaxation time

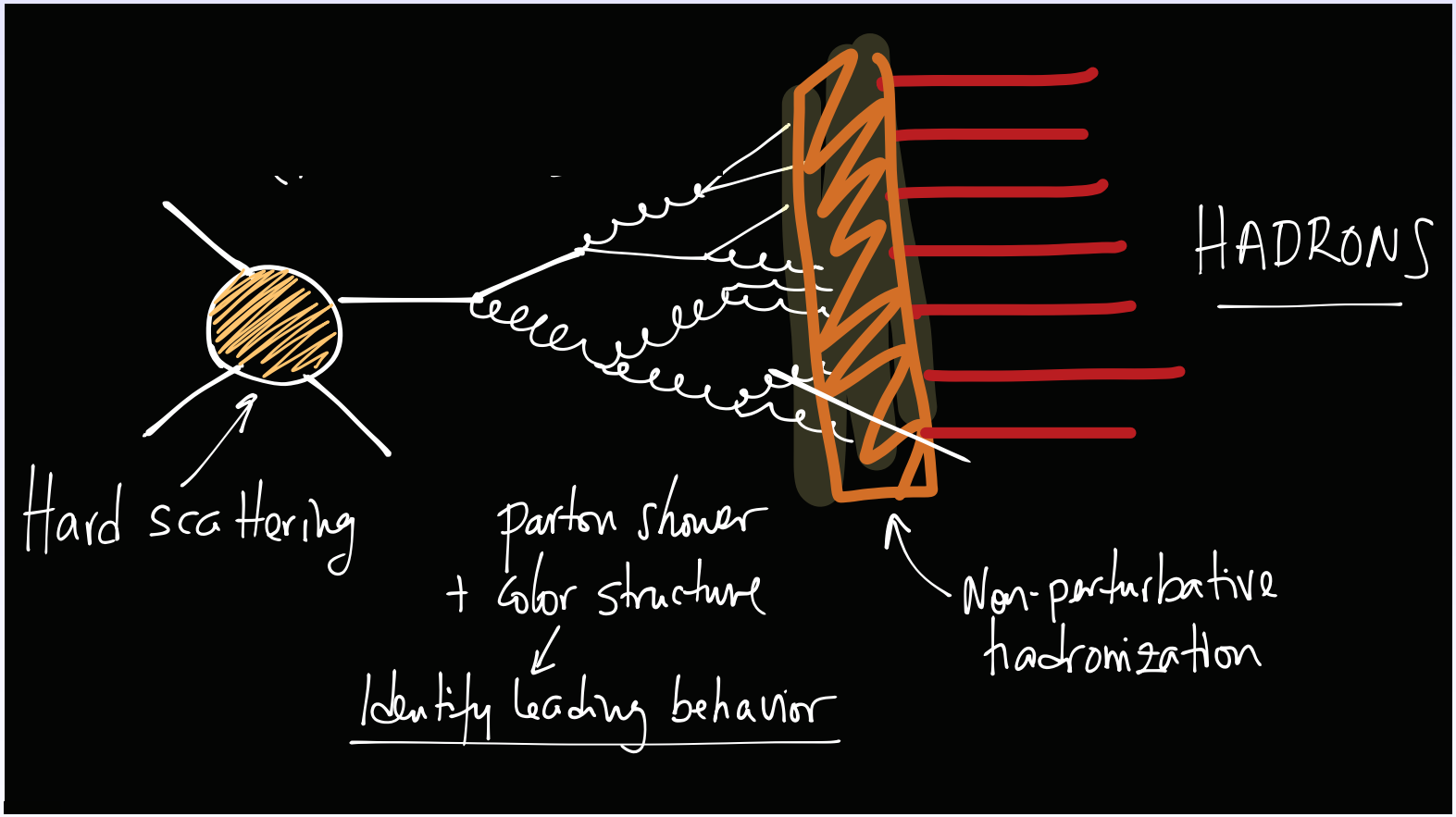
Persistent disagreements with data :

- **Yield too small, v_2 too small (by a large factor ~ 4)**

Seems to suggest that photon production may be underestimated in the later stages of the fireball evolution (where flow is most developed) [W. Cassing] : hadron gas model that improves on this

Jet Quenching

The big picture [C. Salgado]



Beyond BDMPS

Basic facts for a single emission

Soft and collinear divergences

$$dP \sim \alpha_s \, C_R \, \frac{dx}{x} \frac{d^2 \mathbf{k}_\perp}{k_\perp^2}$$

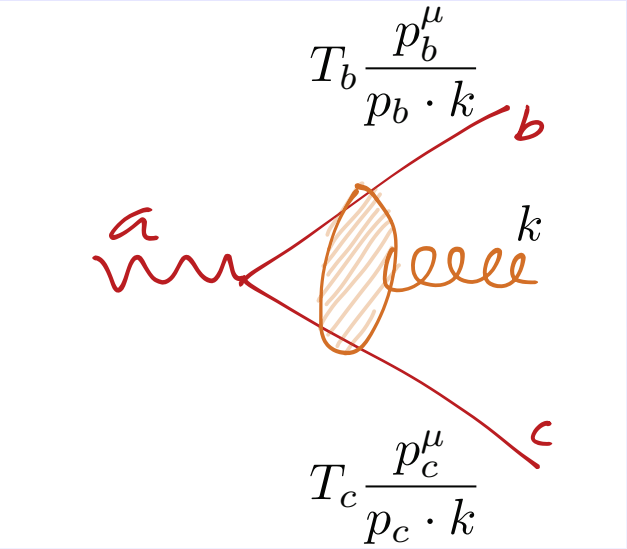
BDMPS-Z theory

- Momentum broadening : $k_\perp^2 \sim \hat{q}\, t_f$
- Formation time : $t_f \sim \frac{\omega}{k_\perp^2} \quad \Rightarrow \quad t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$
- t_f must be less than L. No emission if : $\omega > \omega_c = \hat{q}\, L^2$
- Emission angle : $\theta \sim \frac{k_\perp}{\omega} \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$
- Mean energy lost in a single emission : $\langle \omega \rangle \sim \alpha_s \omega_c \sim \alpha_s \hat{q}\, L^2$
  Dominated by ω close to the upper limit ω_c. The energy stays in a small cone : does not explain dijet asymmetries
  Soft gluons are emitted at large angle, but many emissions are needed to lose a lot of energy

Coherence effects in multiple emissions [C. Salgado]

Vacuum antenna effects

- Gluons emitted at large angle have a large transverse wavelength $\lambda_\perp \sim \frac{1}{\theta\omega}$
- The emitting system has a size $r_\perp \sim \Theta t_f \sim \frac{\Theta}{\theta^2\omega}$
- In-cone $(\theta < \Theta)$: $\lambda_\perp < r_\perp$: independent emission by each quark
- Out-of-cone $(\theta > \Theta)$: $\lambda_\perp > r_\perp$: coherent emission by $q + \bar{q}$ system



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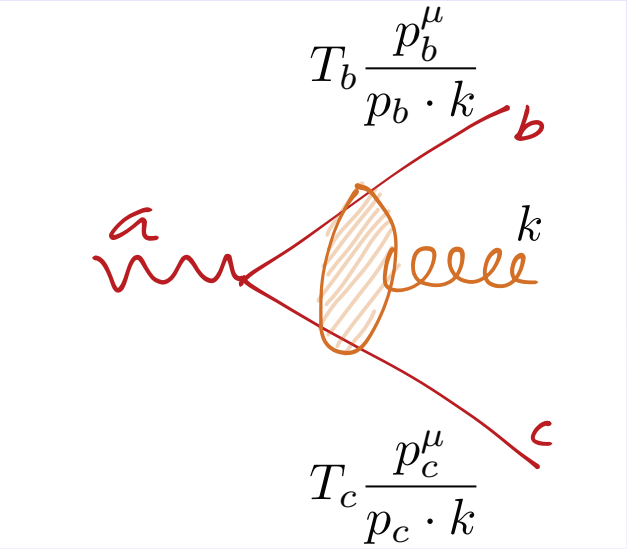
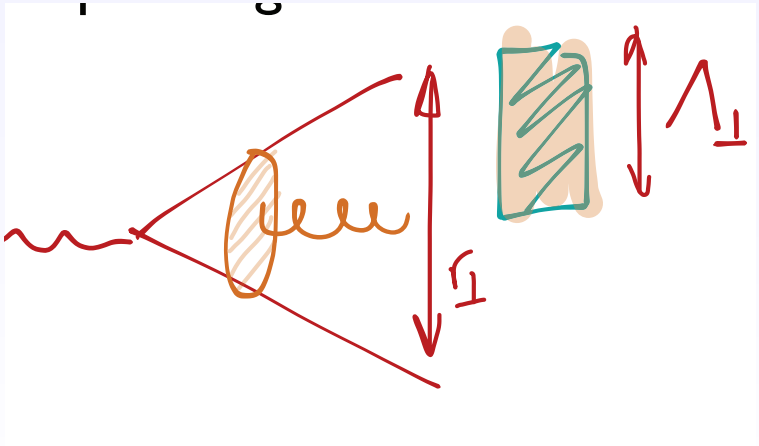


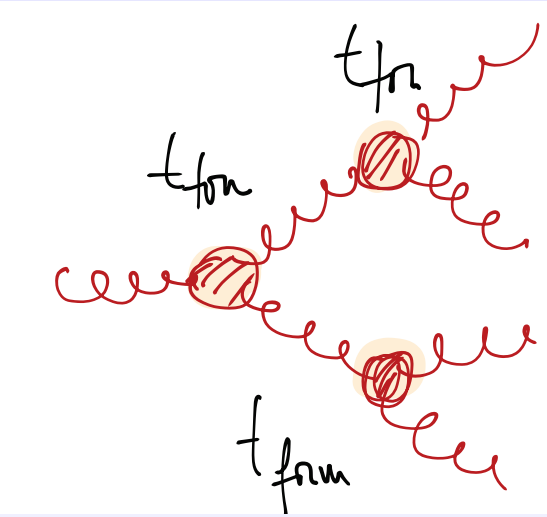


What happens in medium?

- The above geometric argument remains valid
- If the color field of the medium varies over $r_\perp$, then the q and the $\bar{q}$ lose their color coherence

Probabilistic description [E. Iancu] [Y. Mehtar-Tani]

- Decoherence time : $t_{\rm decoh} \sim \frac{1}{(\widehat{q}\,\theta^2)^{1/3}}$
  Comparable to the formation time
- Soft emissions out-of-cone are not suppressed
- Emissions separated by $\Delta t \gg t_f$ are incoherent $\Rightarrow$ probabilistic



Democratic branchings

- Vacuum : $dP \sim \alpha_s \frac{dx}{x}$ In medium : $dP \sim \alpha_s \frac{dx}{x} \sqrt{\frac{\omega_c}{x\,\omega_{\rm parent}}}$
- Probability ~ 1 regardless of x if $\omega_{\rm parent} \sim \alpha_s^2 \omega_c$
- Out of cone, the energy is rapidly degraded into many soft gluons that carry $\omega \sim T$

Anomalous L-dependence of the energy loss [Y. Mehtar-Tani]

- Gluon emissions contribute to the accumulated $\mathbf{k}_\perp$ of the emitter
- Effectively, as if $\widehat{q}$ was larger
- Effect suppressed by α_s but enhanced by double logs
- If resummed, modifies the power of L in $\langle\omega\rangle$

$$\langle\omega\rangle \sim \alpha_s \widehat{q}_0 \, L^2 \left(\frac{\widehat{q}_0 L}{m_D^2}\right)^{\sqrt{4\alpha_s N_c/\pi}}$$

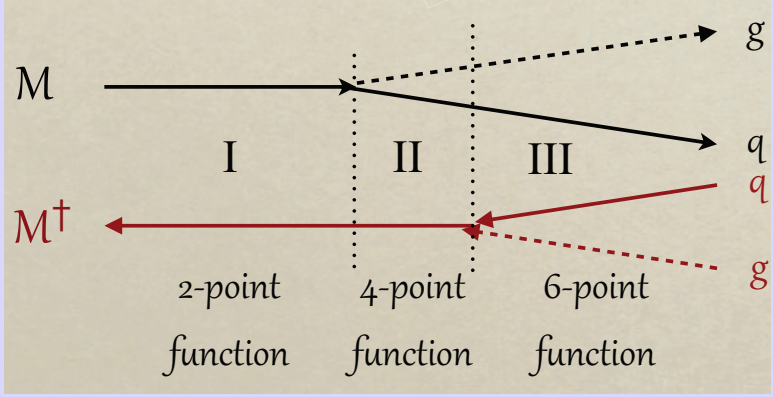
Between the plain BDMPS result and strong coupling results

- BDMPS : L^2 AdS/CFT : L^3

Various technical improvements

Complete single gluon emission off a quark [L. Apolinario]

- Calculation of correlators of 2,4 and 6 Wilson lines
- In- and out-of-medium emission and their interference



Mass effect on the decohence of a Qg dipole [M. Calvo]

- The mass of the heavy quark enhances the decoherence
- Effect more pronounced for Qg than $Q\overline{Q}$
- Implies a larger energy loss (still needs to be quantified)

AdS/CFT

Energy loss and AdS/CFT

Test of generic E-loss models with jet tomography [B. Betz]

- Assume : $\frac{dE}{dz} = -\kappa\, E^a\, z^b\, T^{2-a+b}$
  - $b = 1$: radiative
  - $b = 0$: elastic
  - $b = 2$: AdS/CFT
- Embedded in viscous hydro (VISH2+1 or Romatschke-Luzum)
- $b = 1$ seems to fit best the data both at RHIC and LHC (standard AdS/CFT has too strong quenching)

AdS/CFT still alive... [A. Ficnar]

- Use finite endpoint momentum strings ("more realistic description of an energetic quark")
- Result that interpolates from collisional ($b = 0$) to "old AdS" ($b = 2$) behavior

Hybrid weak/strong coupling approach [D. Pablos]

The devil is in the details...

Other things that matter in practice

Influence of the details of the bulk evolution [D. Molnar]

- R_{AA} not very sensitive to the details, v_2 much more sensitive
- Using a Lorentz covariant formulation is probably a good idea...

Trigger biases [T. Renk]

- By triggering on certain conditions, one may bias the event sample in several ways :
  - Kinematics
  - Geometry (location of the hard scattering)
  - Chemistry (flavor of the original parton)
  - Details of the shower mechanism
- **Good news :** use this to one's advantage to select specially interesting situations
- **Bad news :** much more work when comparing with data

Real-world implementations

CUJET (rcDGLV + 2+1-dim hydrp) [J. Xu]

Jets embedded in hydro expansion [Y. Tachibana] [R. Andrade]

Collisional energy loss via Boltzmann transport [J. Tan] [Y. Zhu]

- Leading parton = small perturbation $\delta f(\mathbf{p})$ of the distribution
- Linearized Boltzmann equation for $\delta f(\mathbf{p})$

Medium cascade with partial decoherence [K. Tyvoniuk]

- Based on ideas in **[C. Salgado]**, **[E. Iancu]**, **[Y. Mehtar-Tani]**

JEWEL [K. Zapp]

- Medium seen by the jet is a collection of quasi-free partons
- Matrix elements (non-eikonal kinematics) + parton shower
- LPM effect

Heavy flavors and and Quarkonia

Energy Loss

Heavy quark energy loss

Recent history :

- Dead cone effect : no emission in a cone that grows with the quark mass $\theta_{\text{excluded}} = M/E$

  Naively, one thus expected less energy loss for heavy quarks

- Data showed that they are almost as suppressed as light partons
- Triggered a lot of interest for strong coupling approaches
- Revived interest in collisional energy loss, that turned out to be important

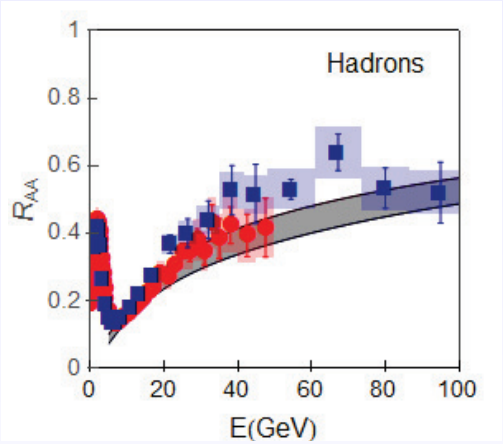
pQCD approach [M. Djordjevic]

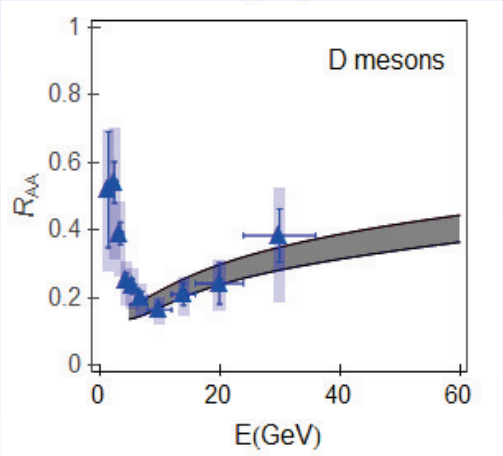
Ingredient list

- Initial momentum distribution for the heavy quarks
- Parton energy loss (collisional and radiative)
- Fragmentation functions (assumed to take place in vacuum)
- Decay of D and B mesons

Collisions

- Non-static scattering centers
- Finite size medium
- Magnetic screening
- Running coupling





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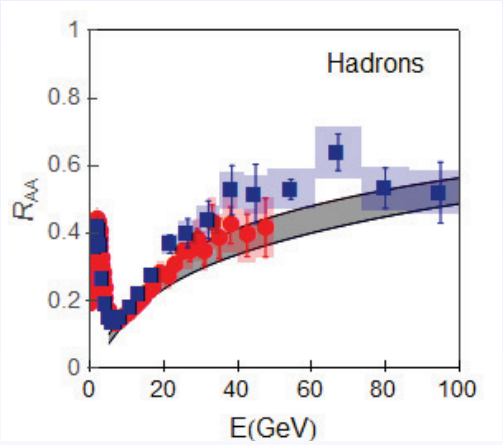
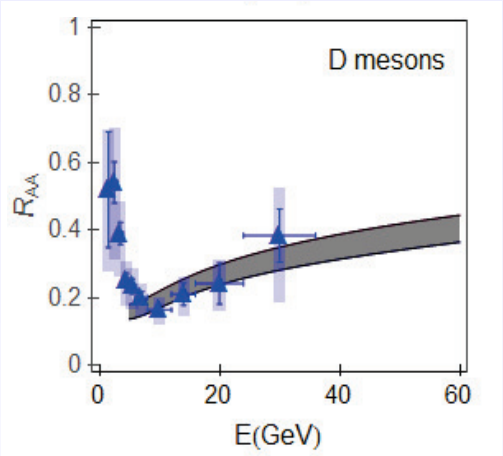


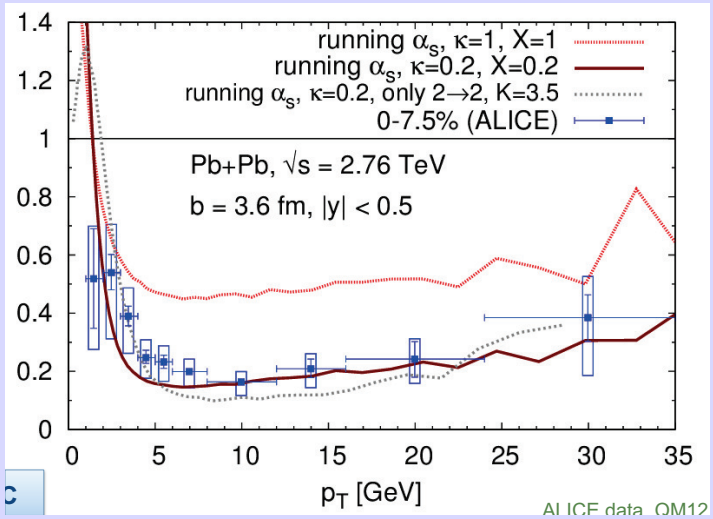


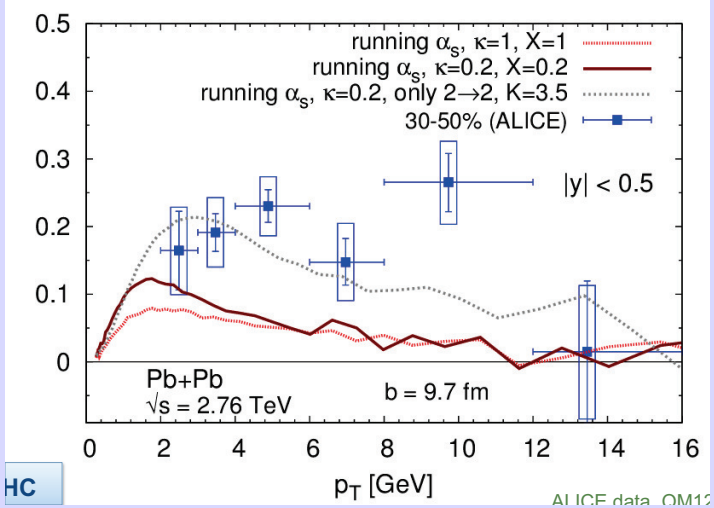
A bit frustrating

- Not easy to pinpoint what caused the improvement
- Seems like an addition of several little changes

Parton transport – BAMPS [C. Greiner] [J. Uphoff]

- Parton cascade with $2 \to 2$, $2 \to 3$ and $3 \to 2$ processes
- LPM effect : interference effect $\Rightarrow$ not included in transport models. Can be modeled by vetoing rescatterings during formation time of the emitted gluon
- Improvement over the Gunion-Bertsch approximations for the inelastic cross-sections (used in previous versions)
- Faster thermalization
- Reasonable R_{AA}
- Tension between R_{AA} and v_2 for heavy quarks

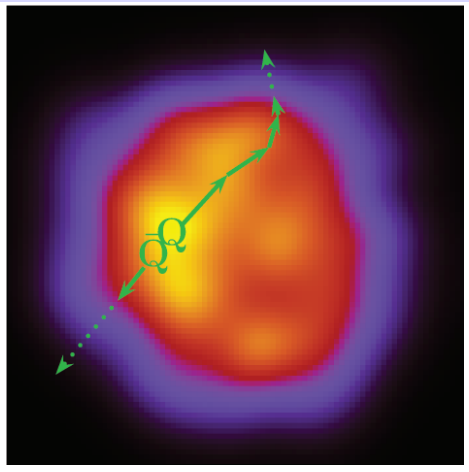




More transport or transport-like ideas

MC@sHQ + EPOS [M. Nahrgang] [P.B. Gossiaux]

- Born cross-sections, with HTL effects + K-factor
- Running α_s
- Boltzmann transport
- EPOS background



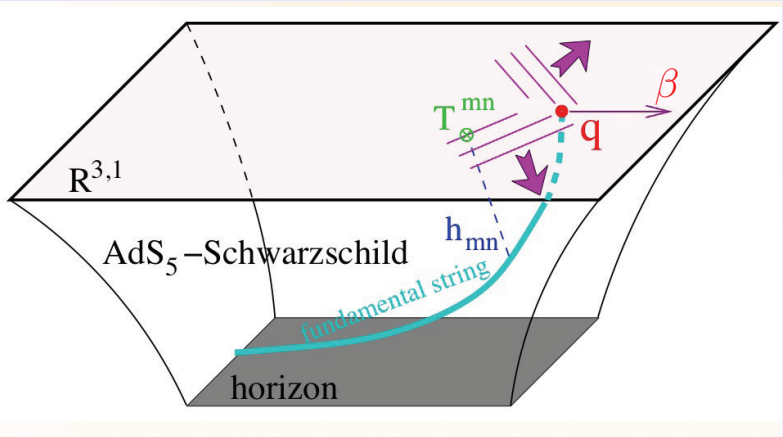
Langevin + radiative energy loss [S. Cao]

- Modified Langevin equation to include radiative energy loss :

$$\frac{d\mathbf{p}}{dt} = -\eta_D\,\mathbf{p} + \xi + \mathbf{f}_g$$

Langevin + viscous hydro [M. Nardi]

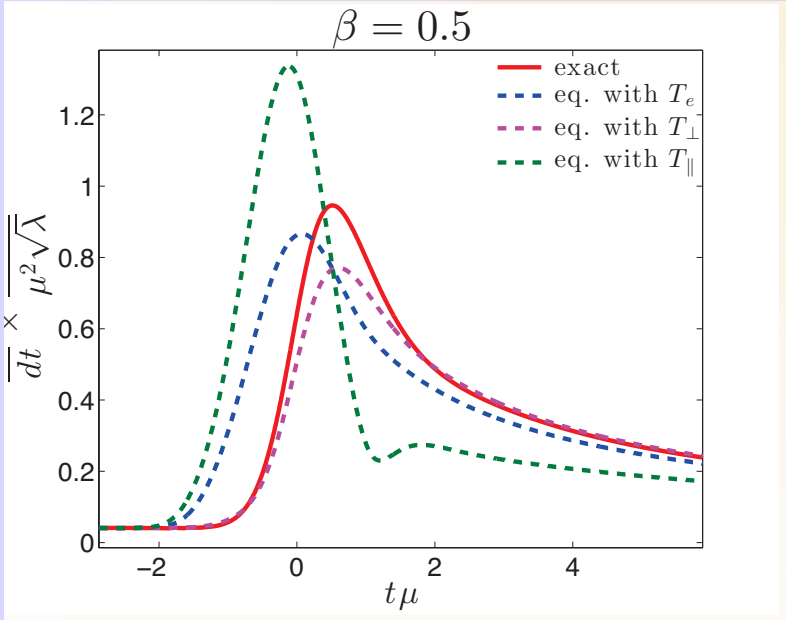
AdS/CFT [M. Lekaveckas]



- Heavy quark = endpoint on the boundary of a string that dives into the bulk
- Drag force in a static plasma :

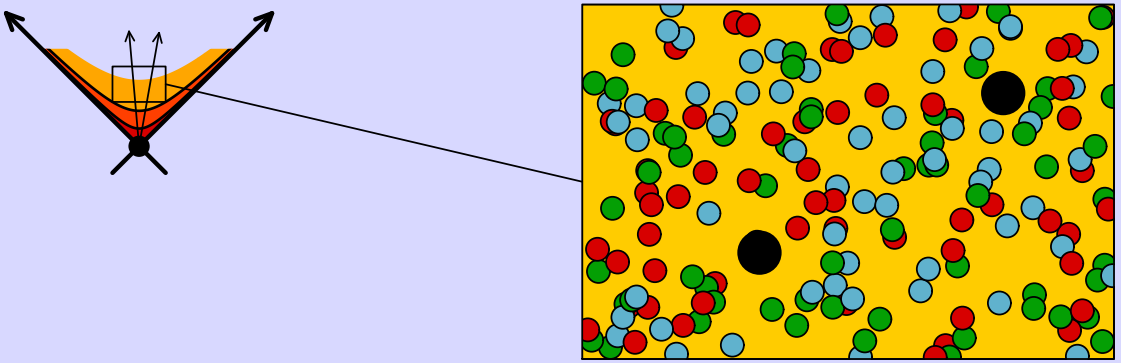
$$\frac{d\vec{p}}{dt} = \frac{\sqrt{\lambda}}{2\pi}(\pi T)^2 \frac{\beta}{\sqrt{1-\beta^2}}$$

This work : drag force in a plasma with anisotropic $T^{\mu\nu}$

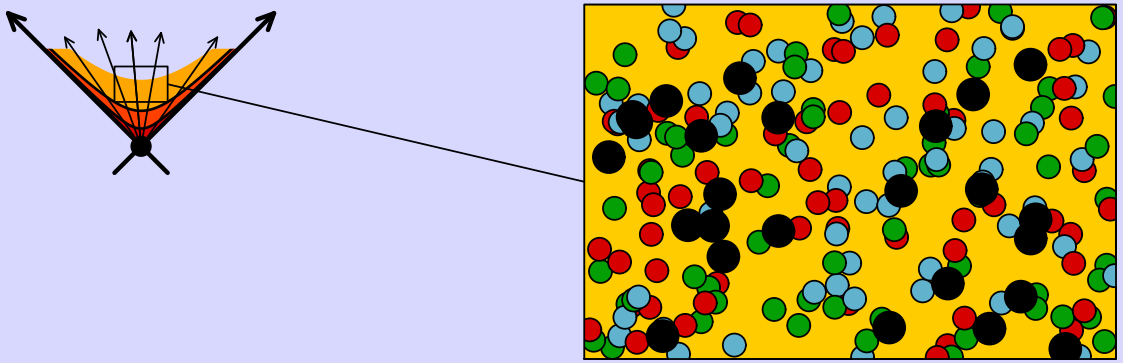


- Drag force slightly different from what one would get from the transverse or longitudinal components alone
- But comparable in magnitude
- Delay time for the drag to establish, proportional to the boost factor of the quark

Quarkonia Suppression



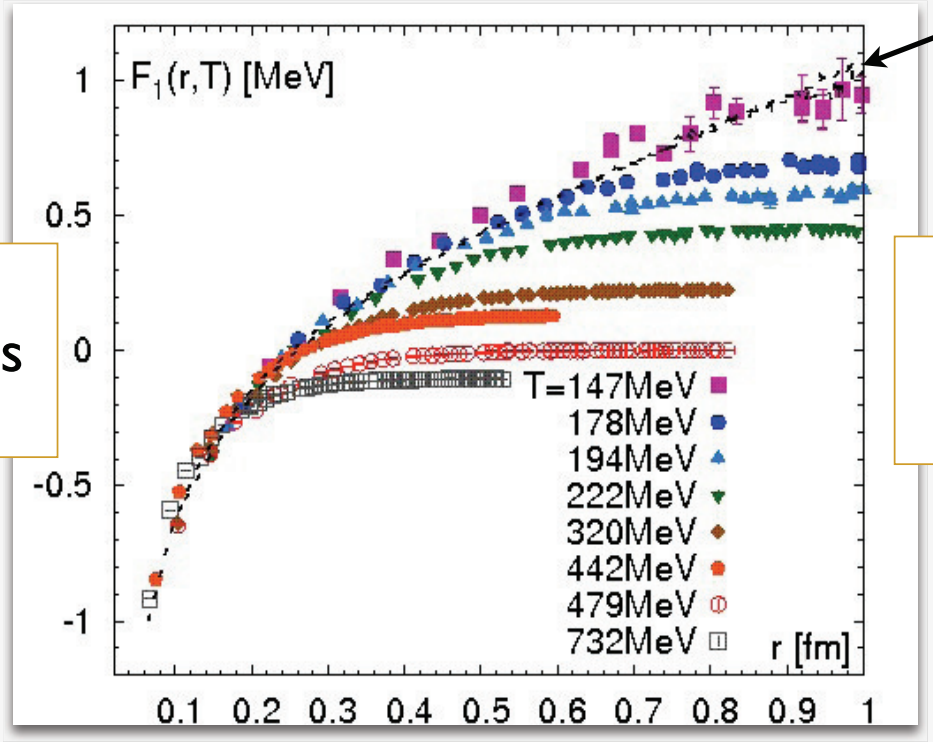
- When the Debye screening radius becomes smaller than the bound state radius, expect suppression



- When the Debye screening radius becomes smaller than the bound state radius, expect suppression
- However, if many $Q\overline{Q}$ pairs are produced, they may recombine (at LHC $\sim$ 100 $c\overline{c}$ pairs in central collisions)
- For J/ψ, feed down by decay of higher lying states

Singlet free energy of a static $Q\overline{Q}$ pair

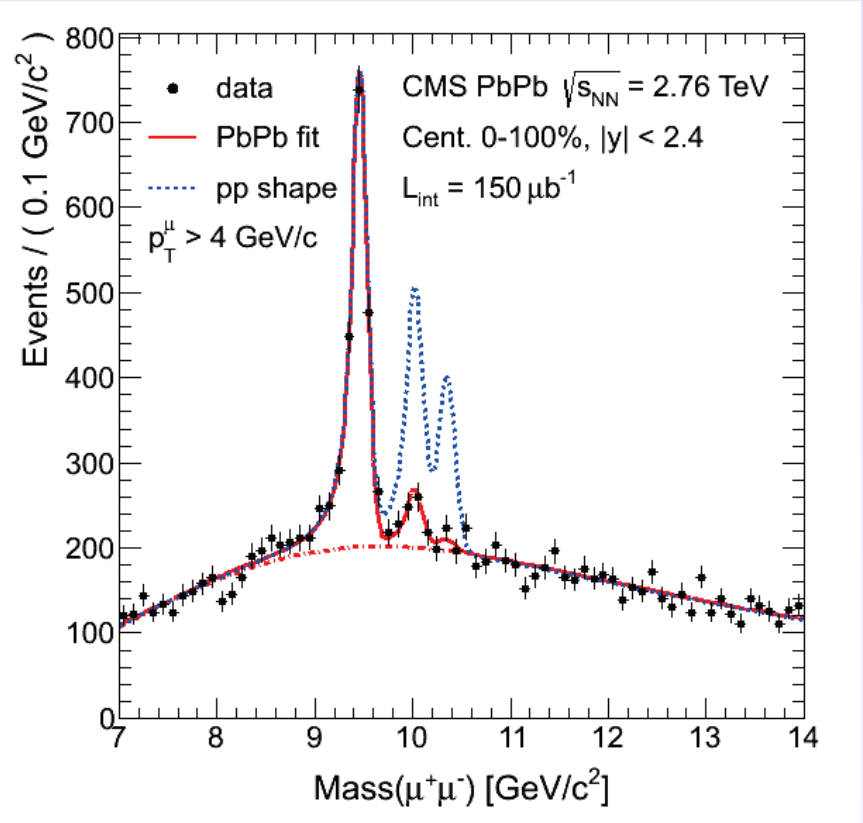
$r < r_{med}(T)$
vacuum physics
$F_1(r,T) = V(r)$



T=0

$r > r_{scr}(T)$
screening
$F_1(r,T) = F_1(T)$

Bazavov, Petreczky, arXiv:1211.5638

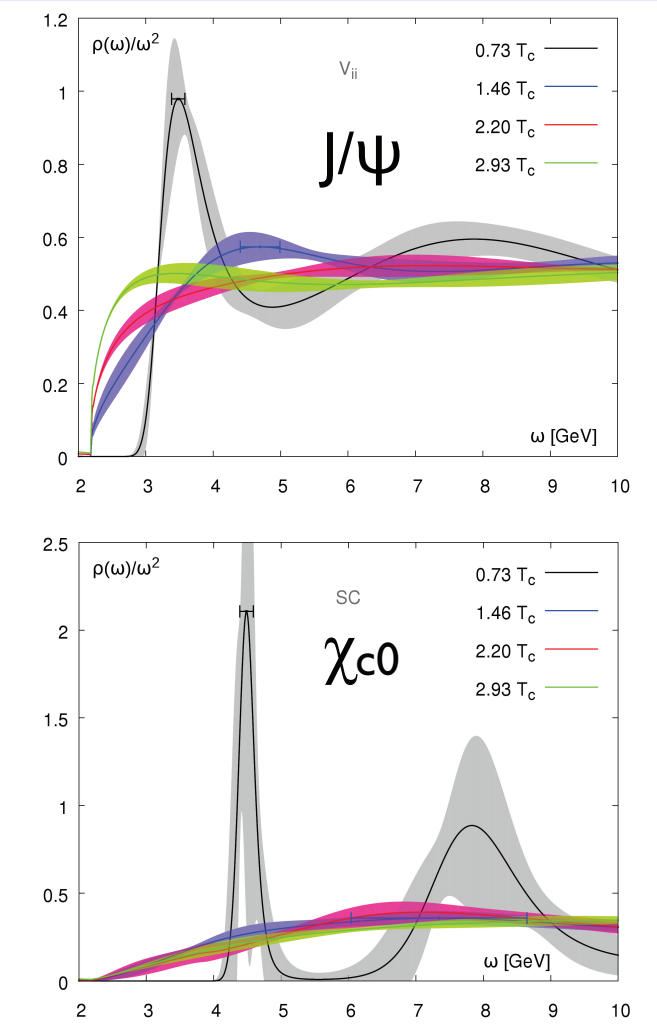


- Very clean successive suppression pattern for Υ's
- No recombination effects
- No feed down from anywhere

Spectral function on the lattice [H.T. Ding]

$$G_E(\tau, \mathbf{p}) = \int_0^\infty d\omega\, \sigma(\omega, \mathbf{p})\, \frac{\cosh(\omega(\tau - \beta/2))}{\sinh(\omega\beta/2)}$$

- On the lattice, calculate G_E at a discrete set of points $\tau = n a_t$
- Invert the spectral integral (ill posed problem without extra constraints...)
- Maximum Entropy Method : input prior knowledge about $\sigma(\omega, \mathbf{p})$ to make the inversion possible
- Additional difficulty : G_E is not very sensitive to changes of σ

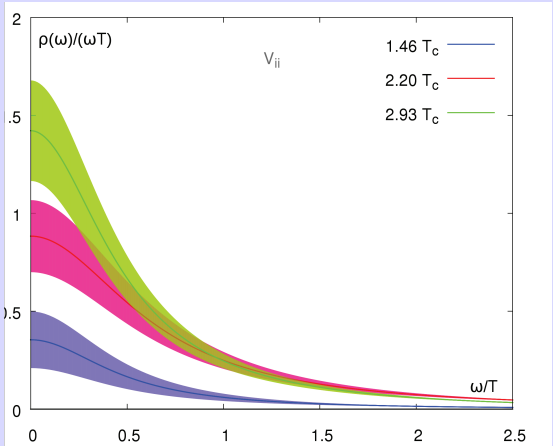


Other applications

Heavy quark diffusion constant

$$D \sim \lim_{\omega \to 0} \frac{\sigma(\omega, 0)}{\omega}$$

- So far, only quenched QCD
- Same method for electrical conductivity and dilepton rates



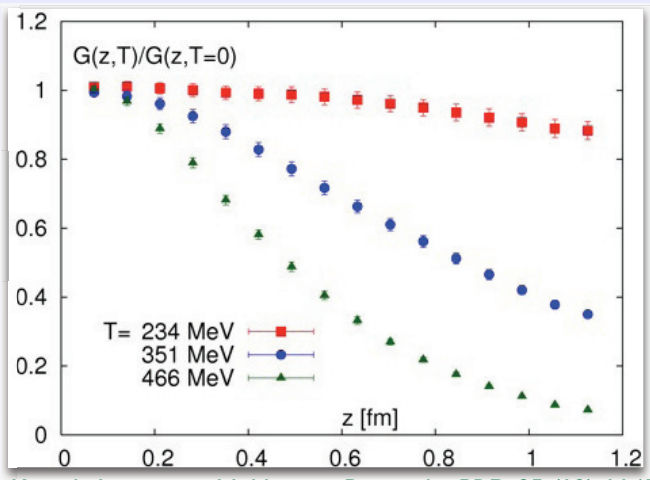
HTD et al., Phys. Rev. D 86 (2012) 014509

Spatial correlators [A. Mocsy]

$$G(z) \equiv \int_0^\beta d\tau \int dx dy \ \langle J(\tau, \mathbf{x}) J(0, \mathbf{0}) \rangle$$

- z not limited by $1/T$
- Related to the spectral function :

$$G(z) = \int dz \, e^{ip_z z} \int_0^\infty d\omega \, \frac{\sigma(\omega, (0, 0, p_z))}{\omega}$$



Karsch, Laermann, Mukherjee, Petreczky, PRD 85 (12) 114501

Clear evidence of a change with the temperature

pNRQCD and potential models

- pNRQCD = effective theory for heavy quarks :

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\overline{q}\not{D}\,q}_{\text{light quarks and gluons}} + S^\dagger\left[i\partial_t - \frac{(i\boldsymbol{\nabla})^2}{M} - V_s(r)\right]S + \cdots$$

- S = singlet $Q\overline{Q}$ field
- $V_s(r)$ = potential. Generally complex
  The real and imaginary parts of V_s are related to peak shift and broadening of the spectral function
- Tree level dynamics for S: Schroedinger equation

$$\left[i\partial_t - \frac{(i\boldsymbol{\nabla})^2}{M} - V_s(r)\right]S = 0$$

Where do we get the potential from ? [P. Petreczky]

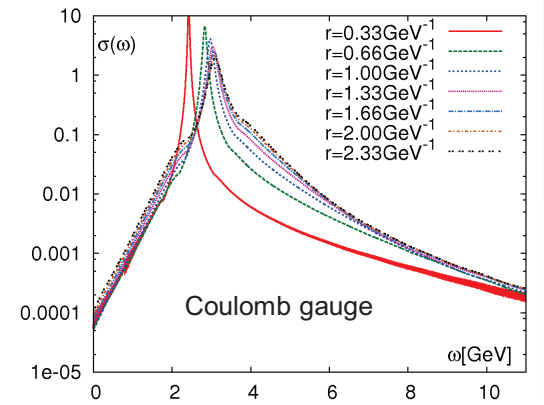
- In the past, the singlet free energy F_1 was used as V_s
- No imaginary part

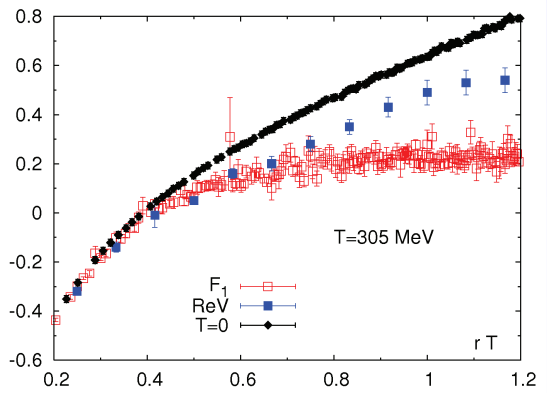
Potential from lattice (based on [Rothkopf, 2009])

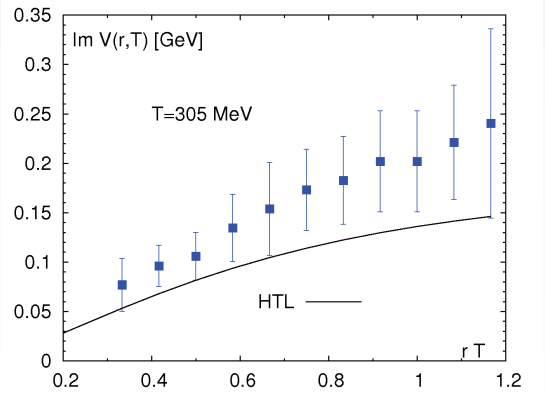
- Spectral representation of Wilson loops

$$W(\tau, r) = \int d\omega \; \sigma(\omega) \; e^{-\omega\tau}$$

- $\mathrm{Re}\, V_s$ and $\mathrm{Im}\, V_s$ obtained as peak position and width of $\sigma(\omega)$

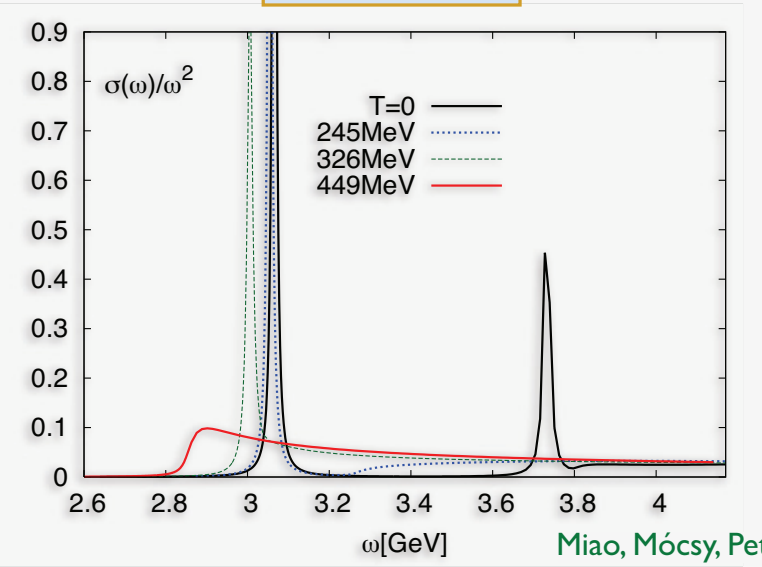




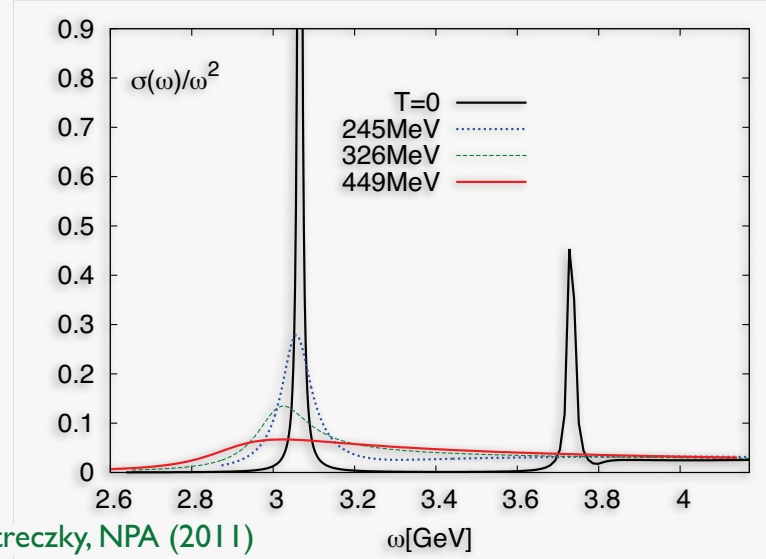


Role of the imaginary part [A. Mocsy]

Im $V_s(r) = 0$



Im $V_s(r) \neq 0$



Miao, Mócsy, Petreczky, NPA (2011)

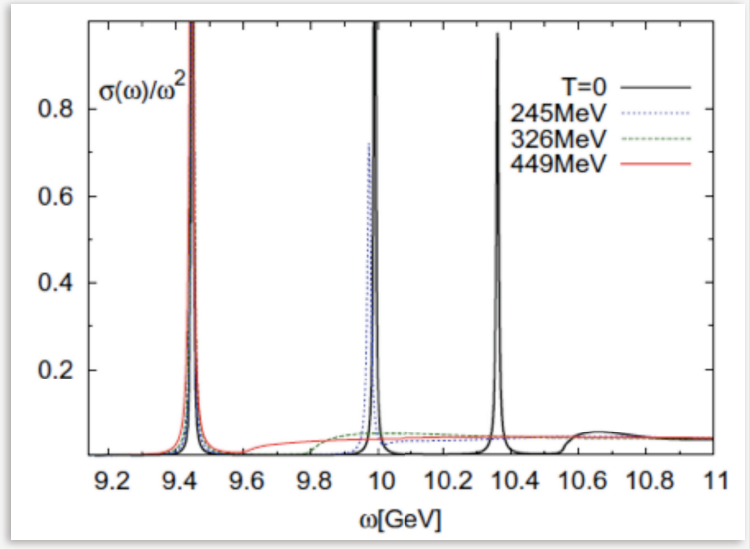
1S survives for $T = 330$ MeV
reduced binding energy

dramatic broadening
all states dissolves for $T > 240$ MeV

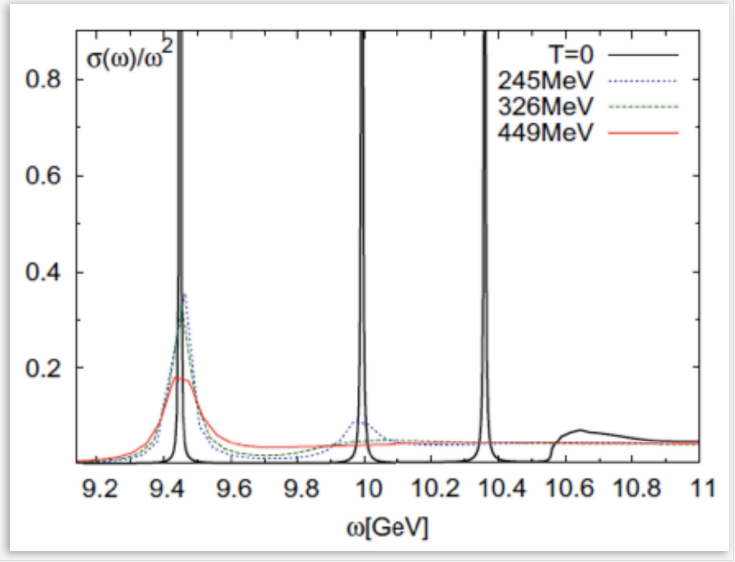
No charmonium state could survive above T= 240 MeV

Role of the imaginary part [A. Mocsy]

Im $V_s(r) = 0$



Im $V_s(r) \neq 0$



Miao, Mócsy, Petreczky, NPA (2011)

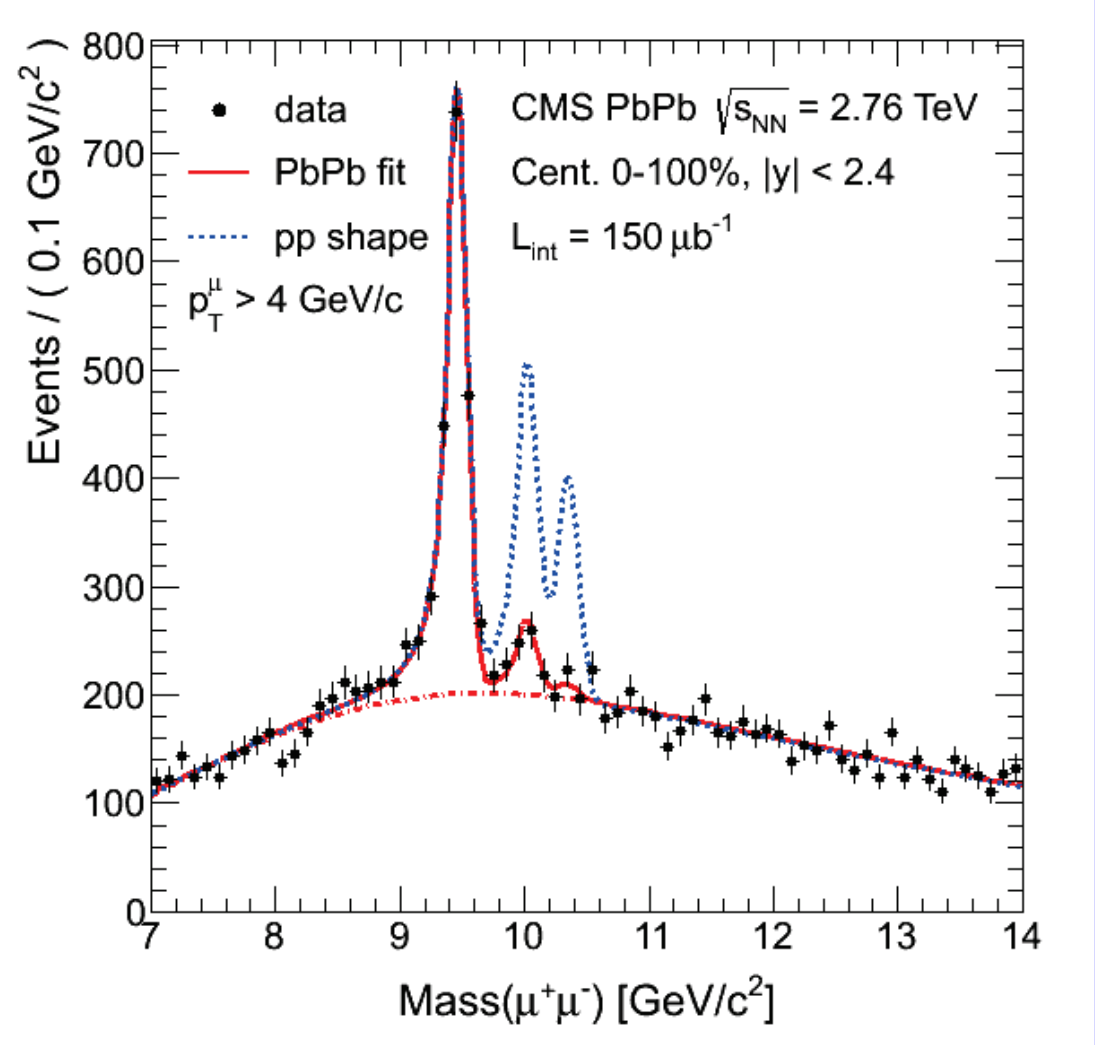
1S and 2S there at high T
reduced binding energies

Dramatic broadening
Re part has little effect

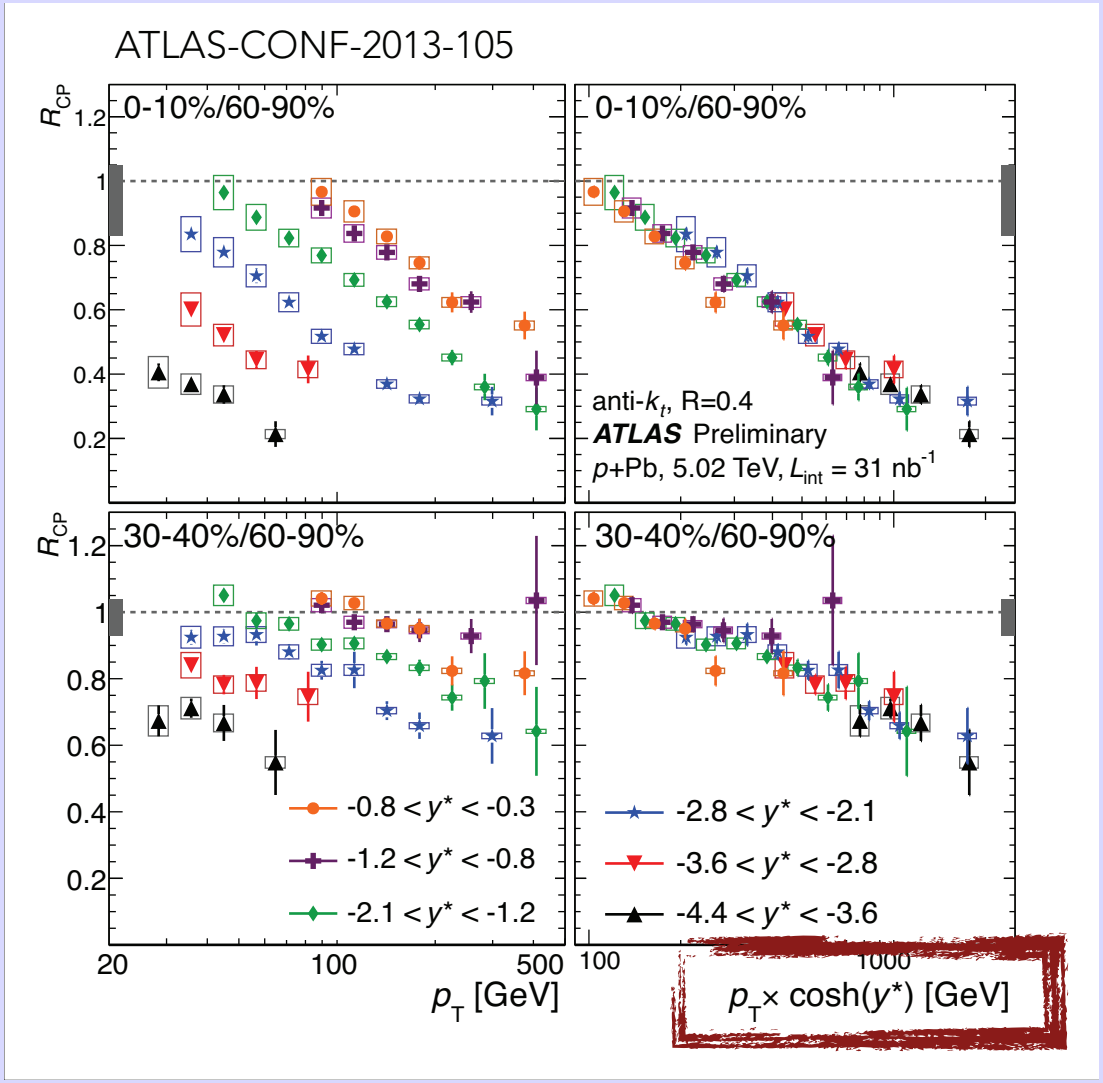
Υ(2S) and Υ (3S) melts by $T \sim 250$ MeV and Υ(1S) melts by 450 MeV

Most discussed plots

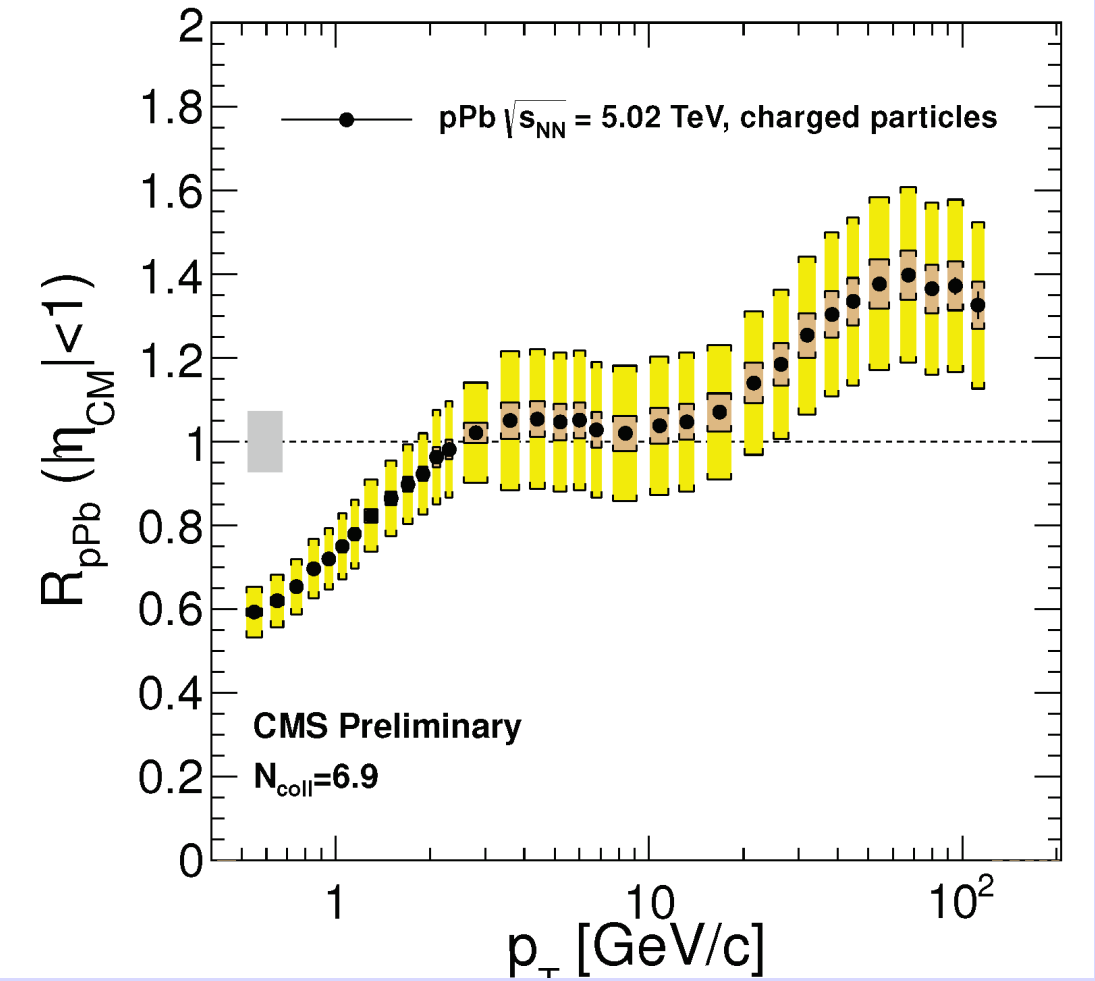
The most "Textbook-Like" plot



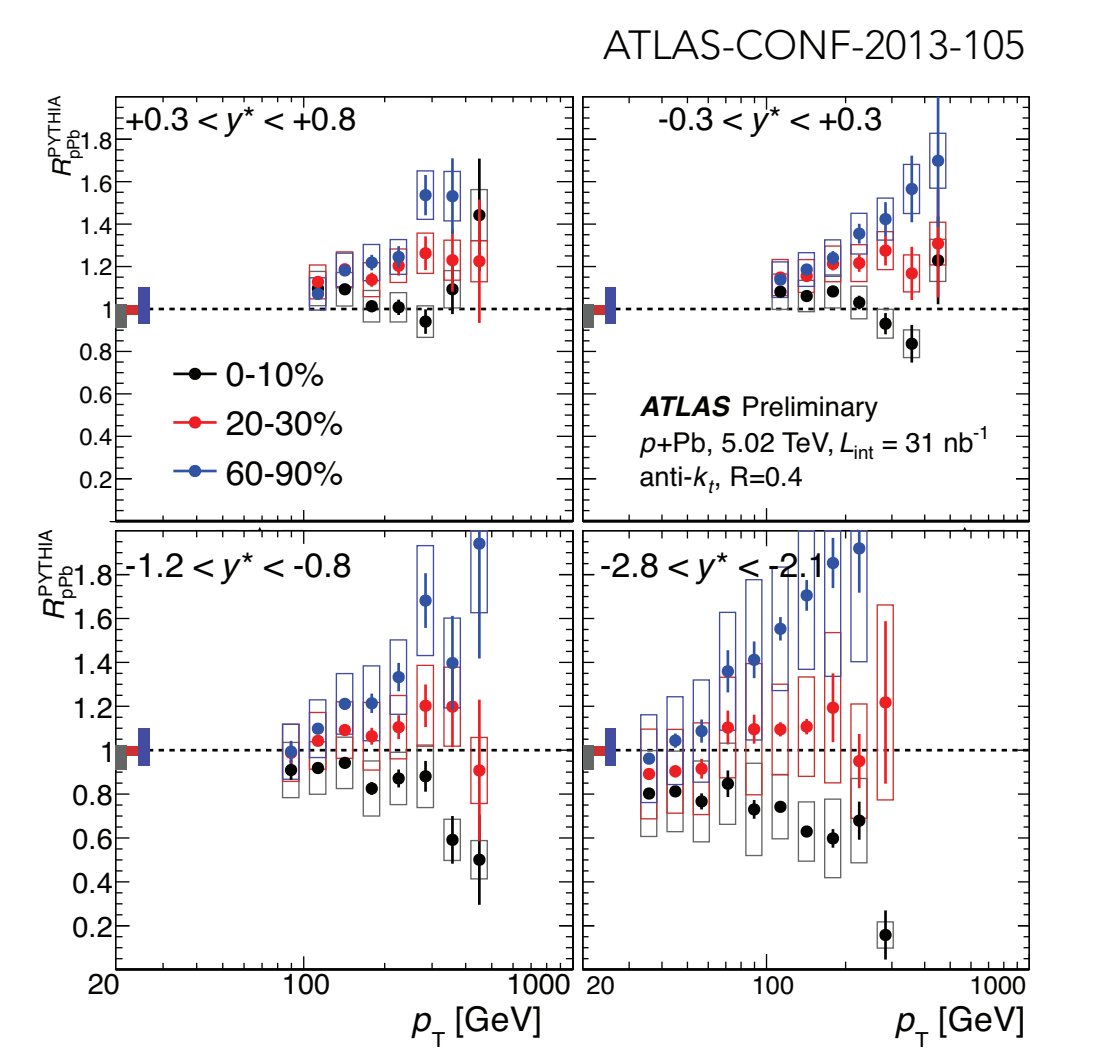
The most "Intriguing" plot



The most "Mind-Boggling" plot



Runner up for the most "Mind-Boggling" plot award



Summary of the Summary

- Progress in many areas since the previous Hard Probes

  Both in the “hardcore” theory, and in the modeling of the collisions

- Some things are even starting to be fully understandable from a QCD perspective

- Lots of new data that will take a while to digest

  A lot of confusion related to pA results

  Not the controlled situation we had imagined...

Thanks !