Jet (de)coherence in PbPb collisions at the LHC

Konrad Tywoniuk

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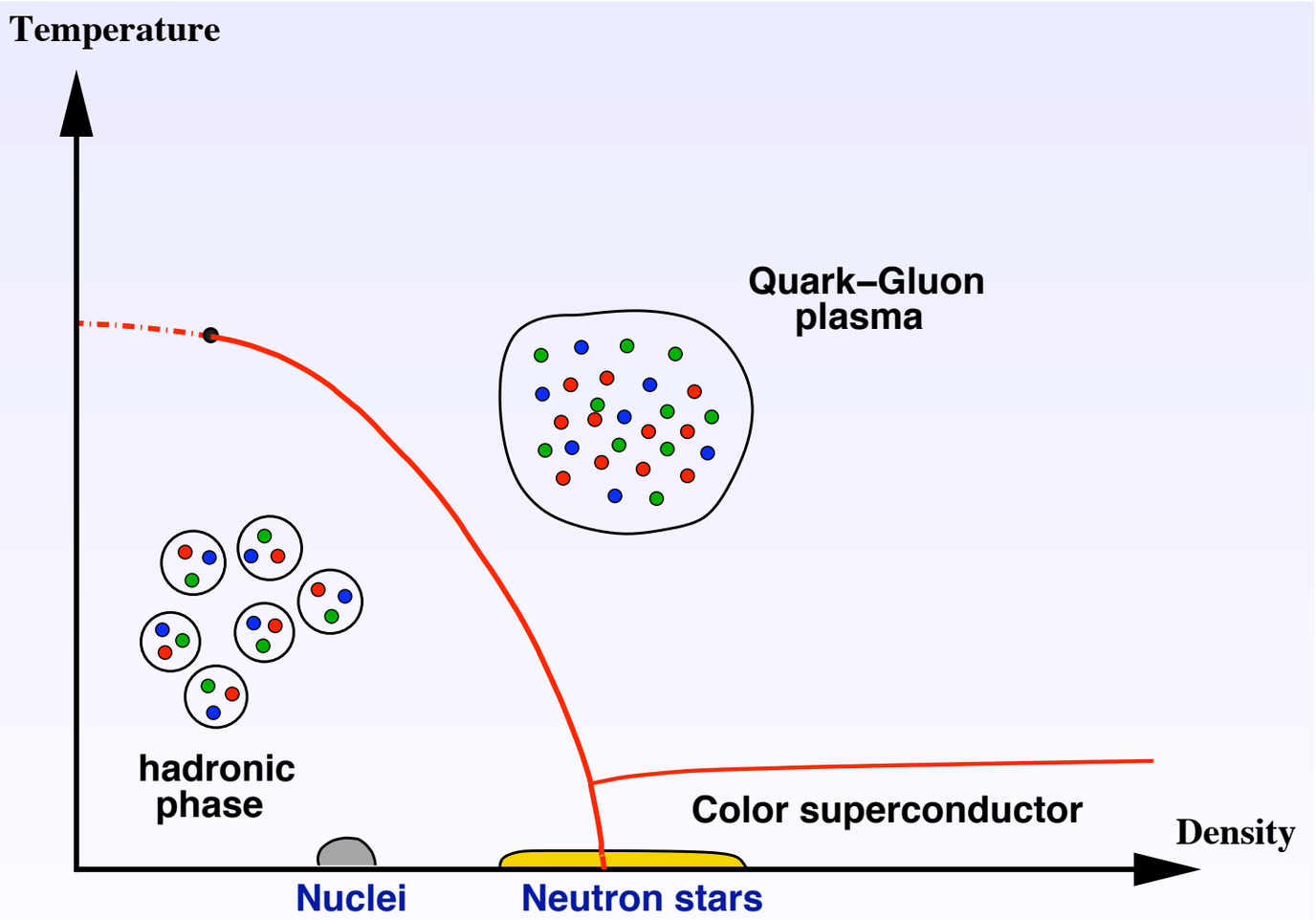
UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

It’s april, fool!

A taste of QGP

- deconfinement
- restoration of chiral symmetry
- asymptotic freedom
  - high T: gas of free quarks & gluons
  - intermediate T: strongly coupled system



What are the relevant degrees of freedom?

A taste of QGP

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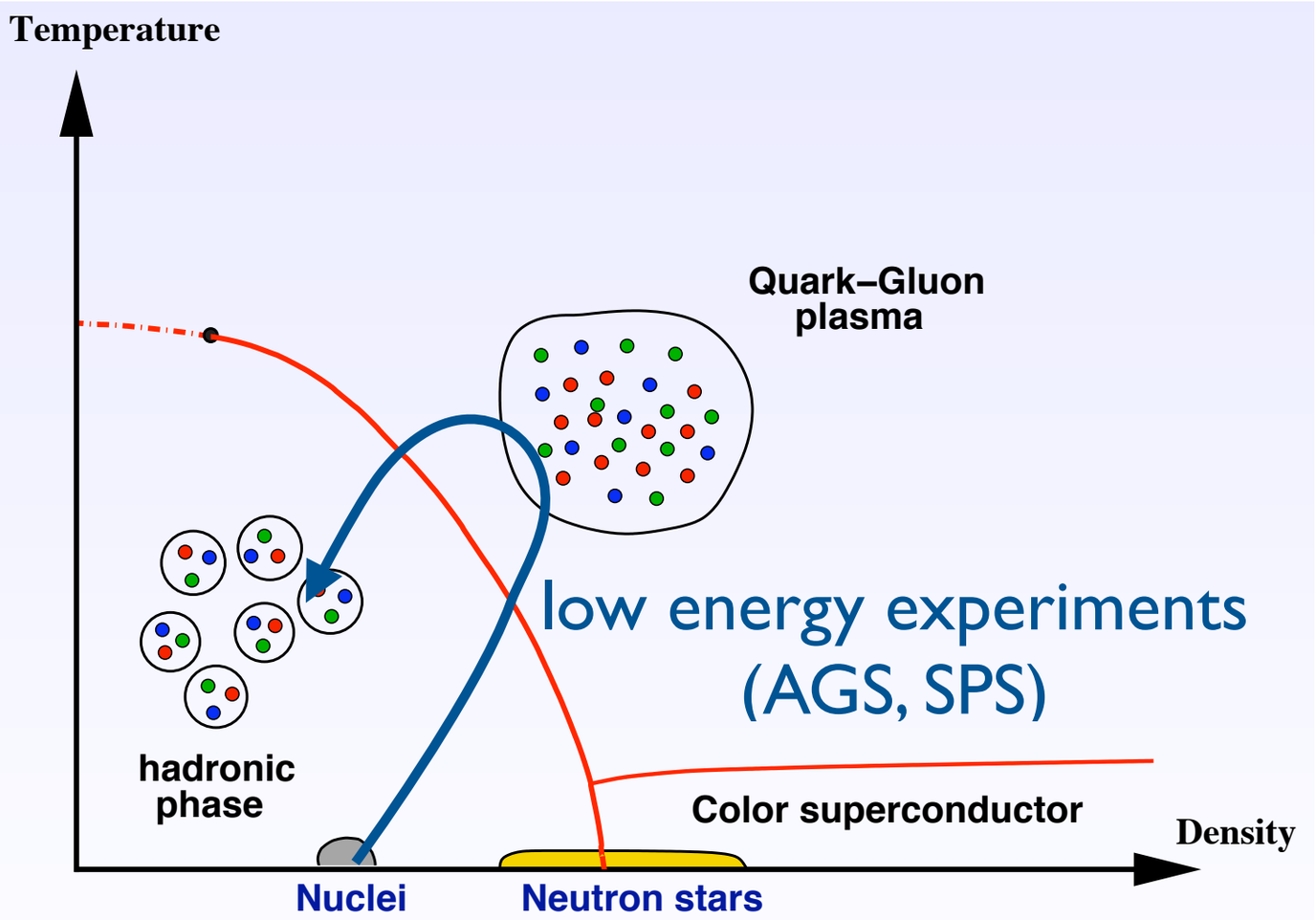

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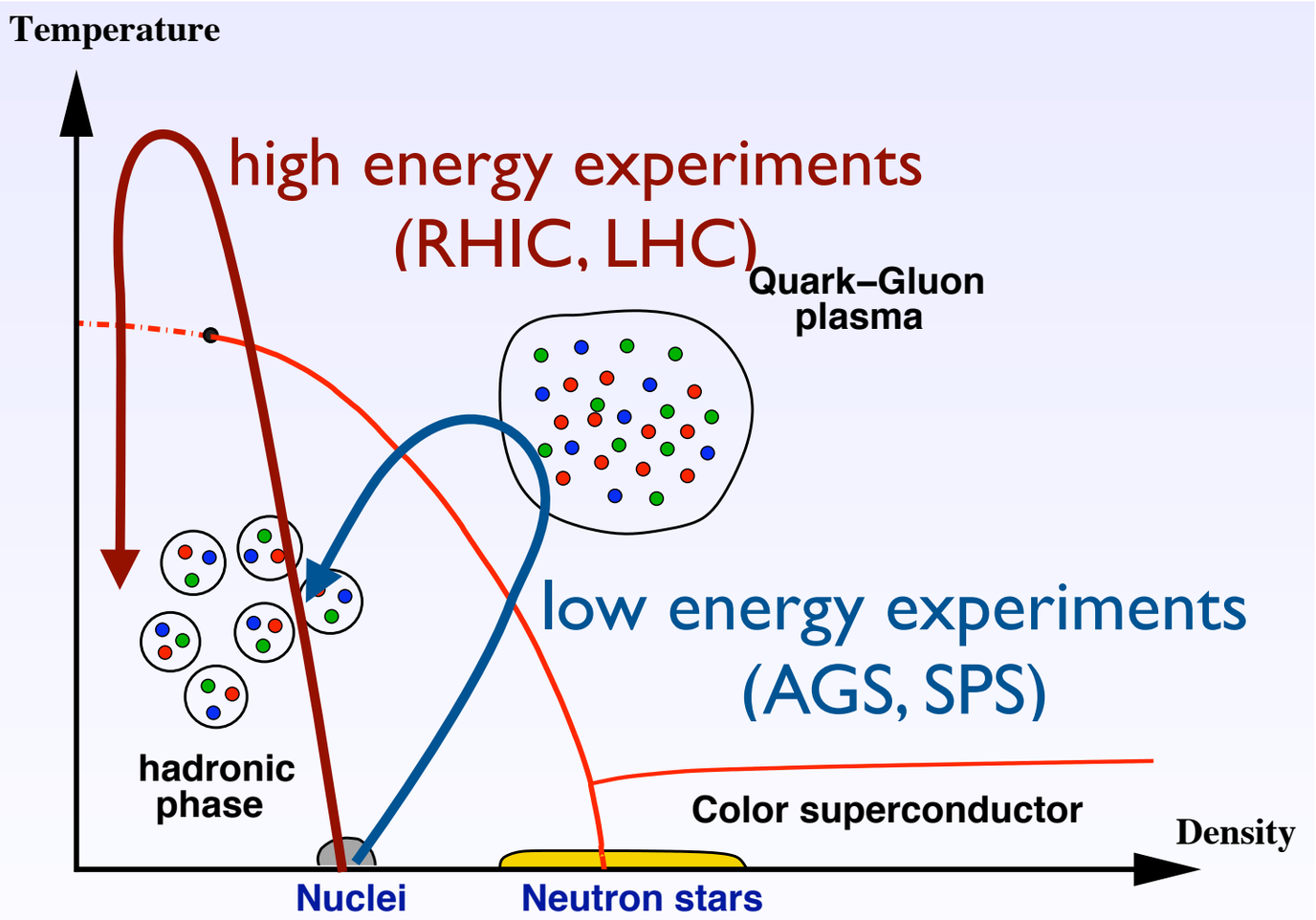
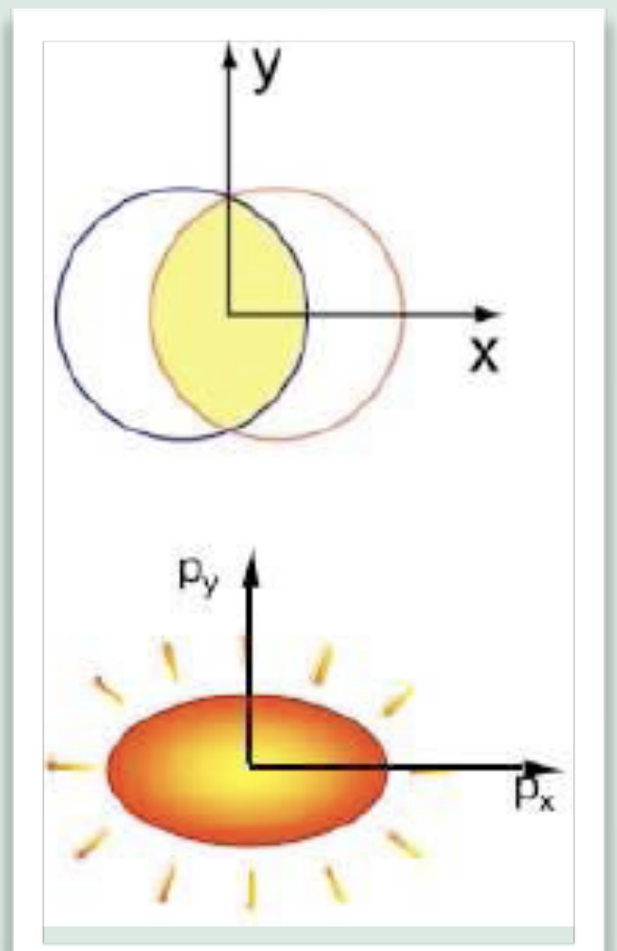


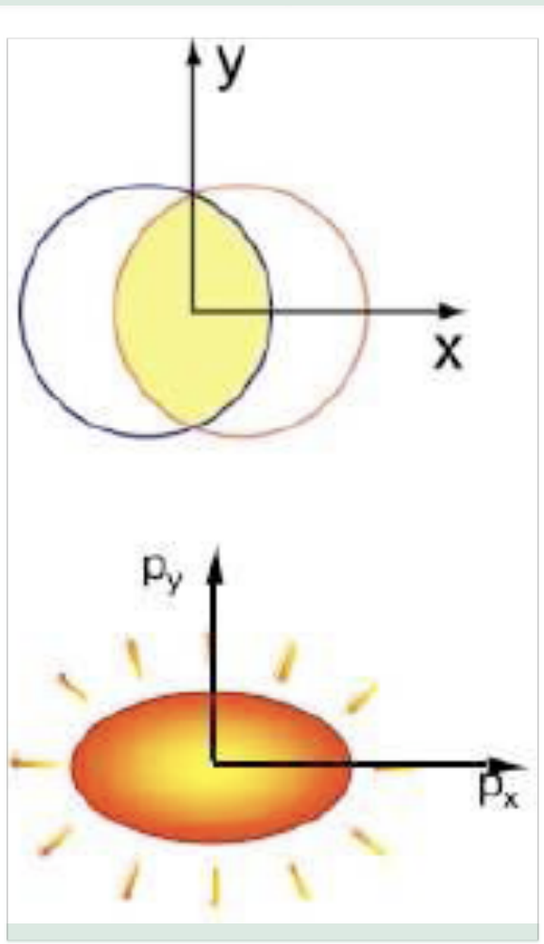
What are the relevant degrees of freedom?

Azimuthal asymmetry



naïve picture

Azimuthal asymmetry



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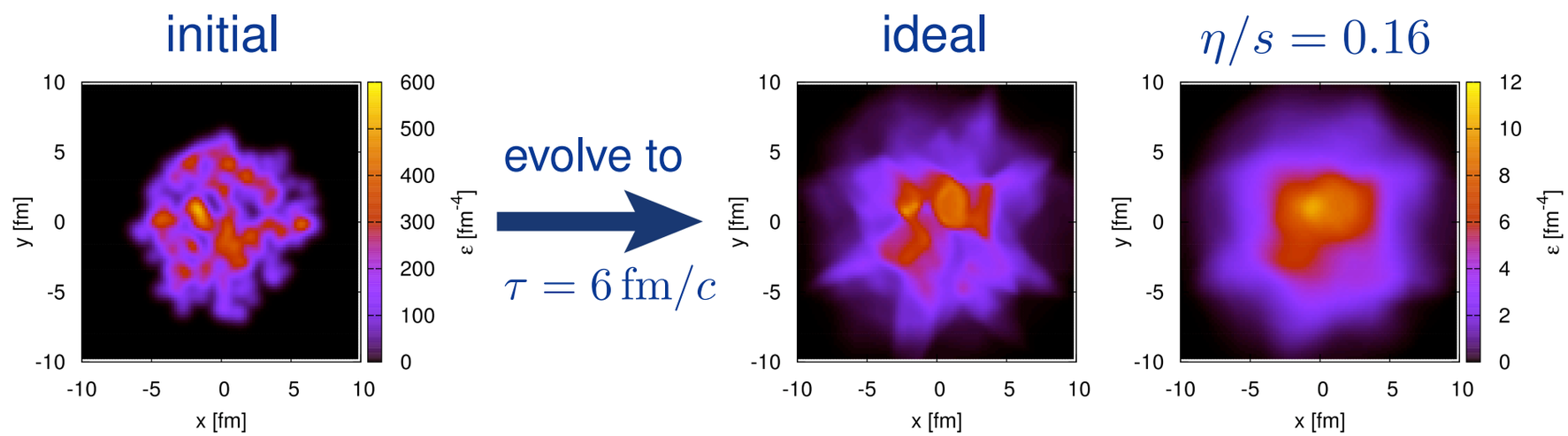


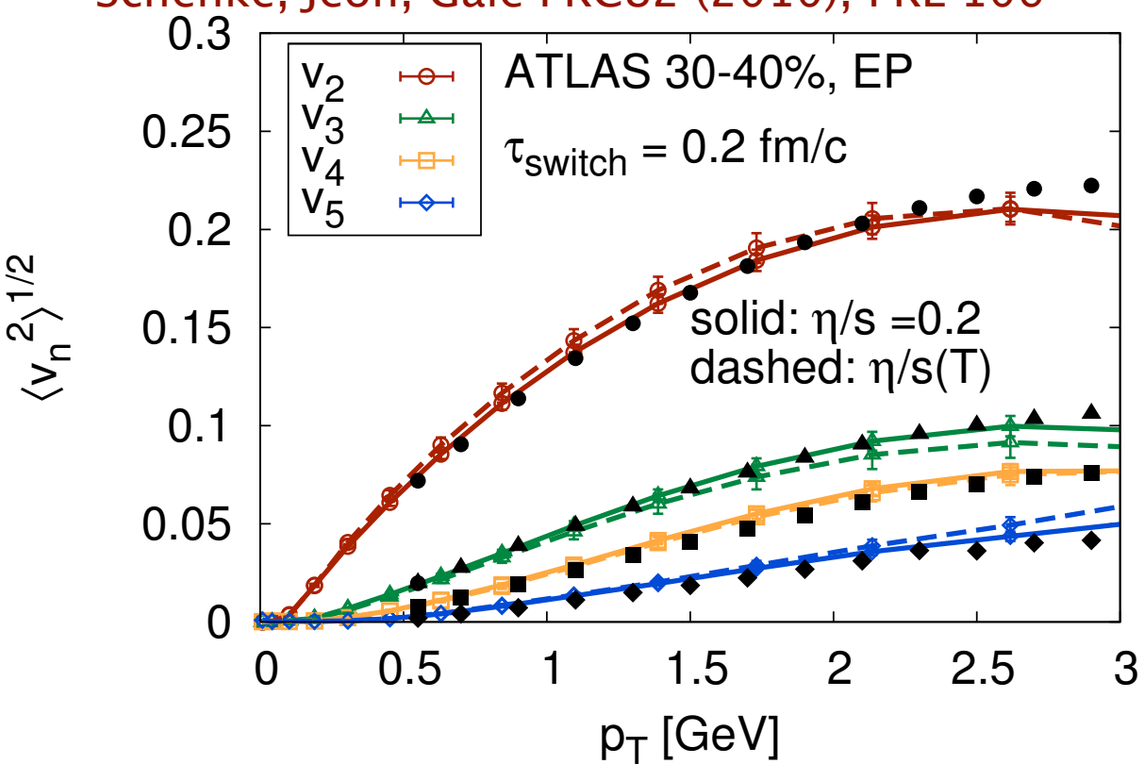
MUSIC B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)

- space anisotropy → momentum anisotropy
- imprint of quantum fluctuations!
- equilibration → hydrodynamical flow!

$$v_n = \langle \cos\left[n(\phi - \Psi_n)\right] \rangle$$

The QGP flows

Schenke, Jeon, Gale PRC82 (2010), PRL 106



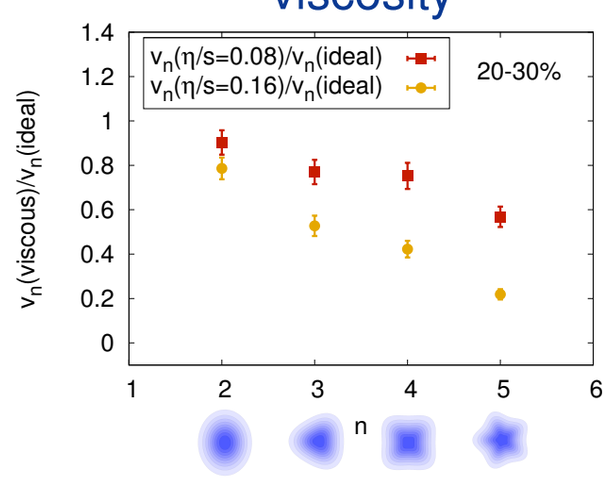
- transport coefficients can be found
- hierarchy of v_n coefficients consistent with almost perfect liquid

$$0.07 \leq \eta/s \leq 0.43$$

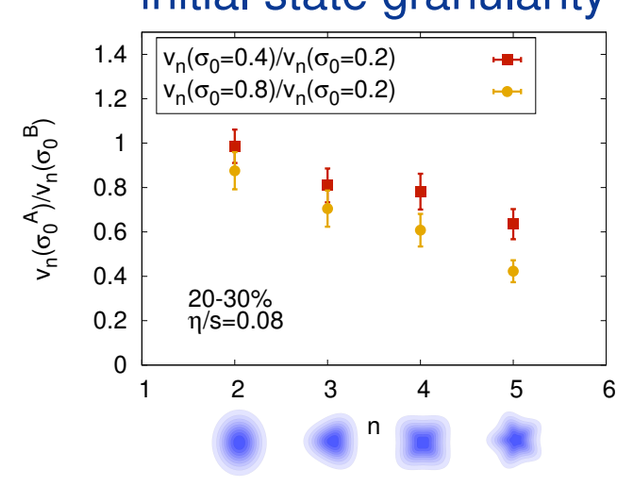
Luzum, Ollitrault et al.

- higher harmonics are more sensitive to viscosity and granularity

viscosity



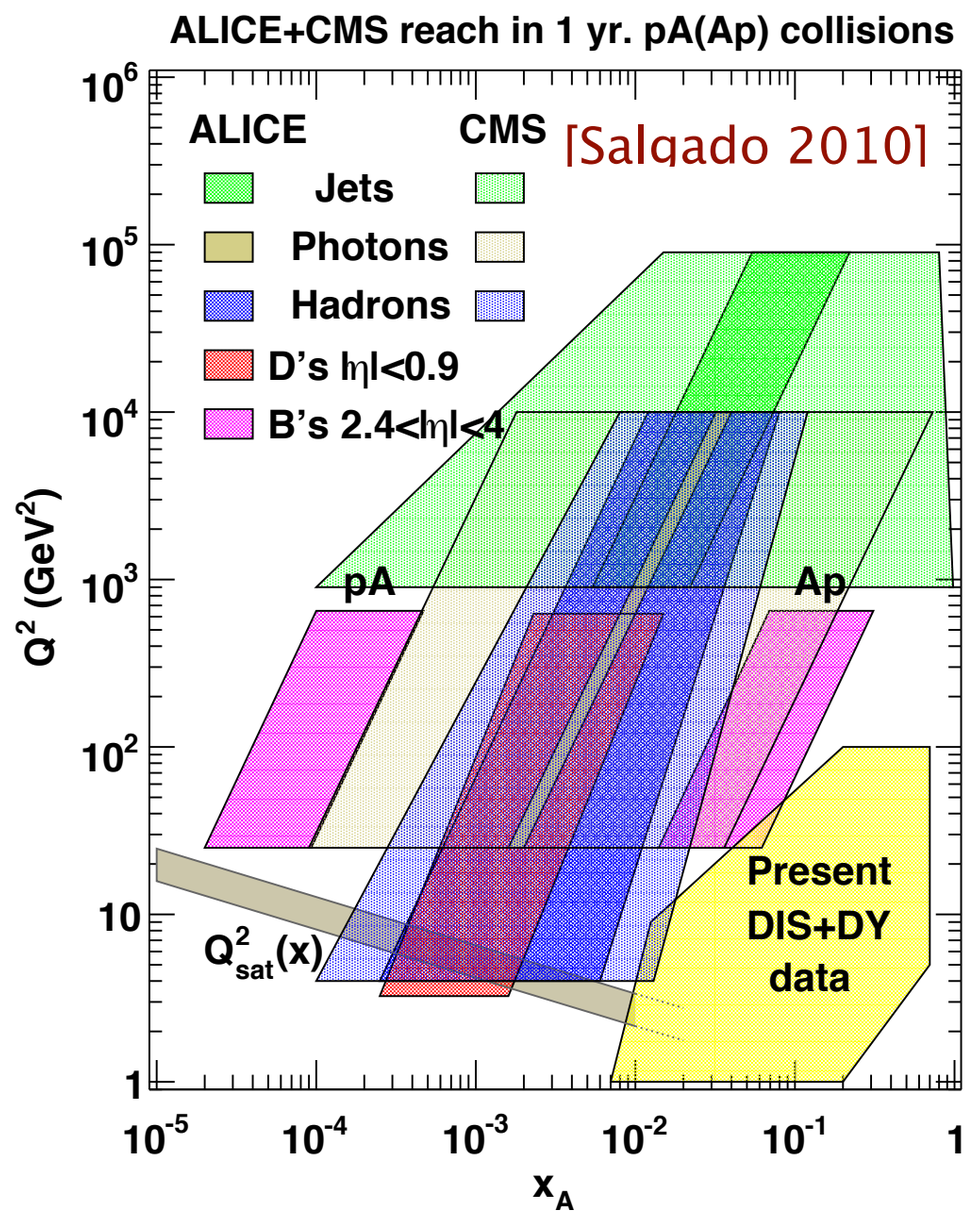
initial state granularity

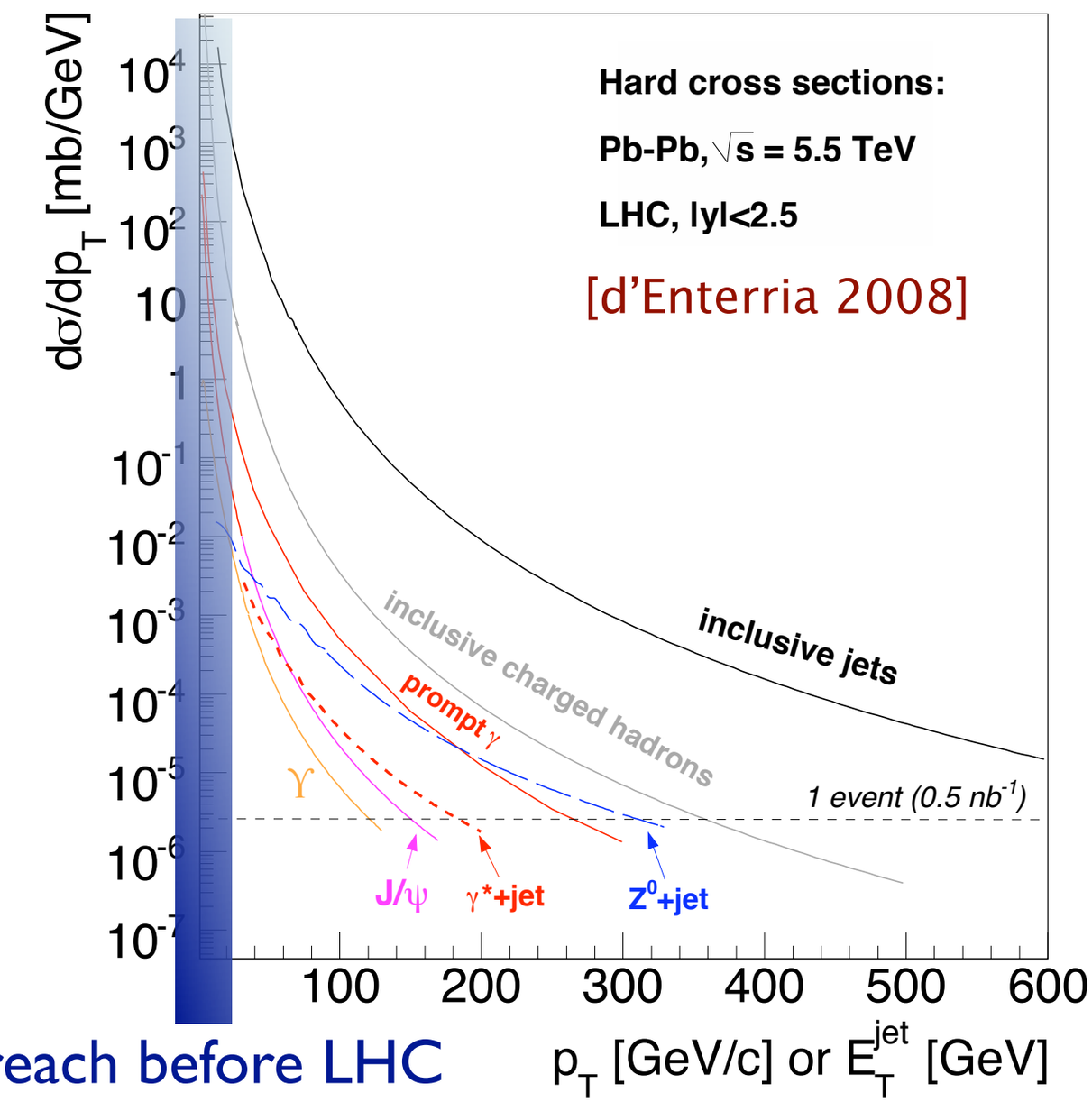


Bulk observables: An almost perfect liquid of quark-gluon matter is formed in the collision.

Can we explore this state with other observables?

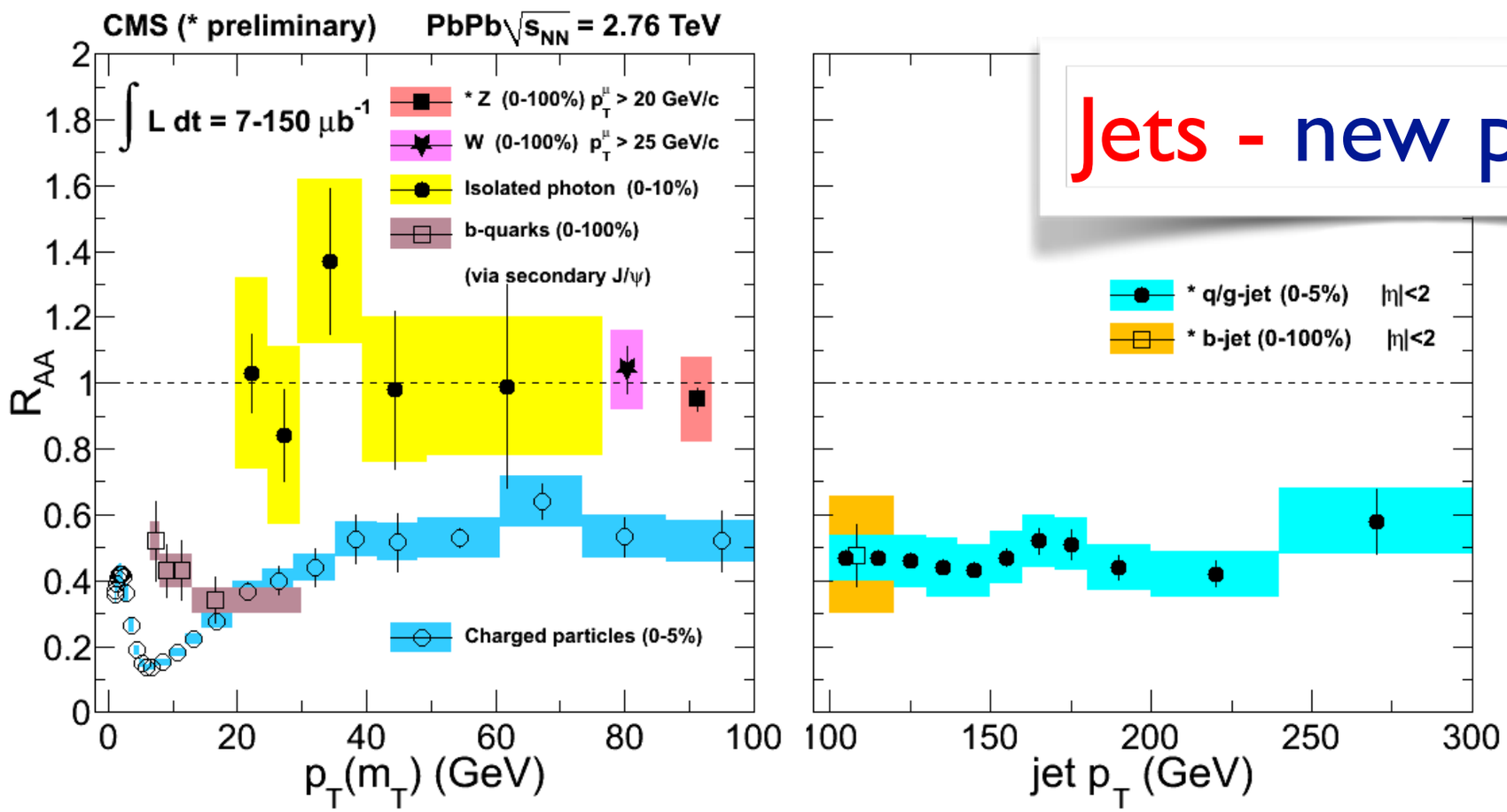
Hard probes





reach before LHC

The T-shirt plot

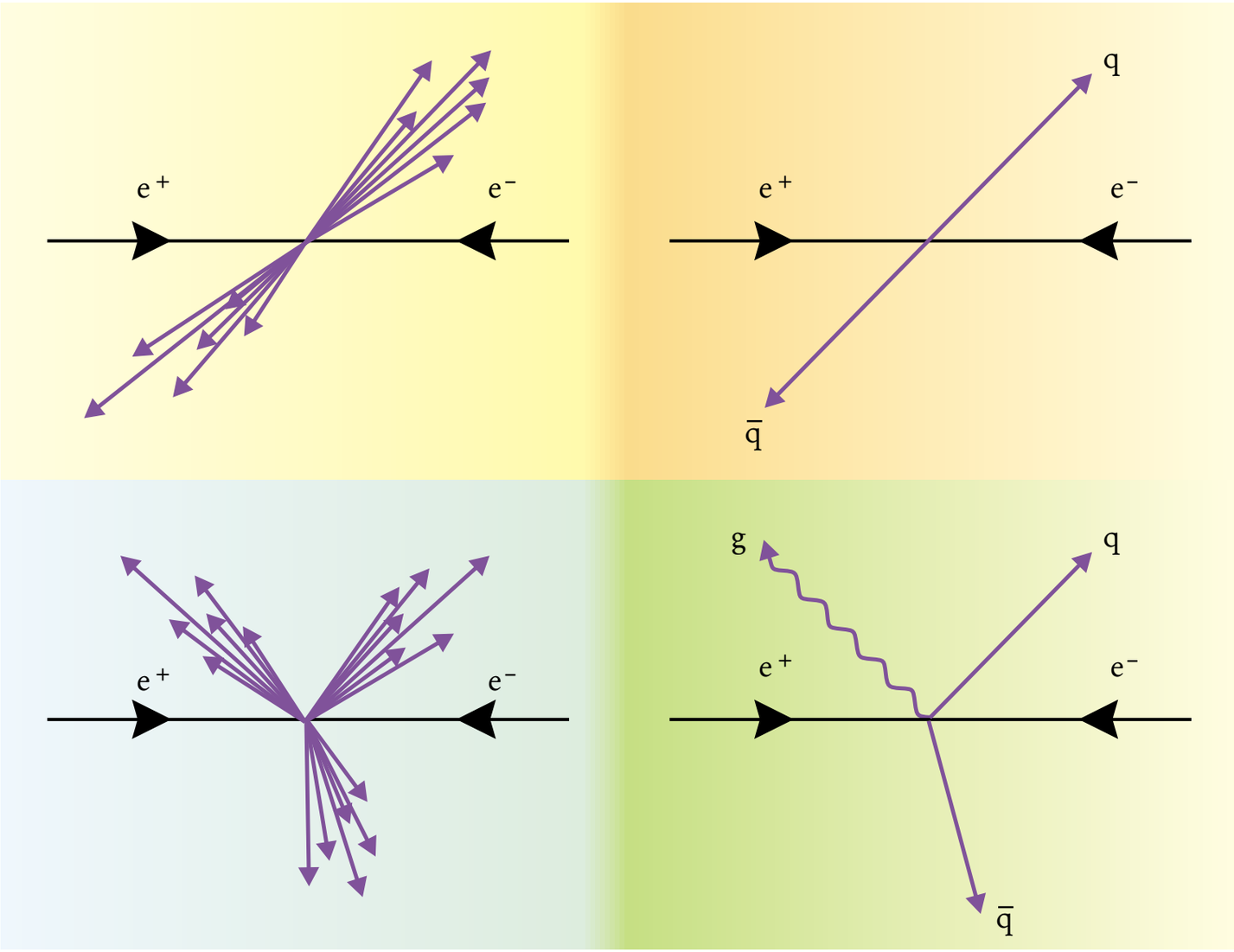


Jets - new probes!!

- jet quenching :: key discovery of RHIC
- color-less probes unmodified - baseline ok!
- universal suppression at high-p_T

Bjorken '82
Gyulassy, Plumer, Wang 1995
Baier, Dokshitzer, Mueller, Peigne, Schiff 1996
Gyulassy, Levai, Vitev 1997

Jets



- what we see as sprays of particles in the detector are originating from one parton
- a way to probe the quarks and gluons
- defining a jet is a contract between theory and experiment :: jet algorithms

Two main features

Resummation of double logarithms + single log corrections

$$\frac{1}{p\cdot k} = \frac{1}{E\omega(1-\cos\theta)} \;\Rightarrow\; \alpha_s \int_{Q_0}^{E} \frac{d\omega}{\omega} \int_{\omega/Q_0}^{1} \frac{d\theta}{\theta} \sim \alpha_s \log^2 \frac{E}{Q_0}$$

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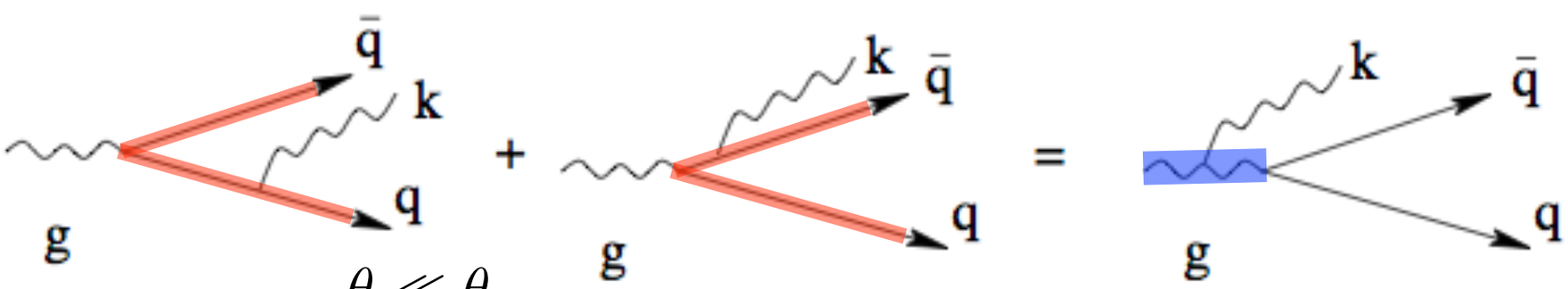
Color coherence = angular ordering



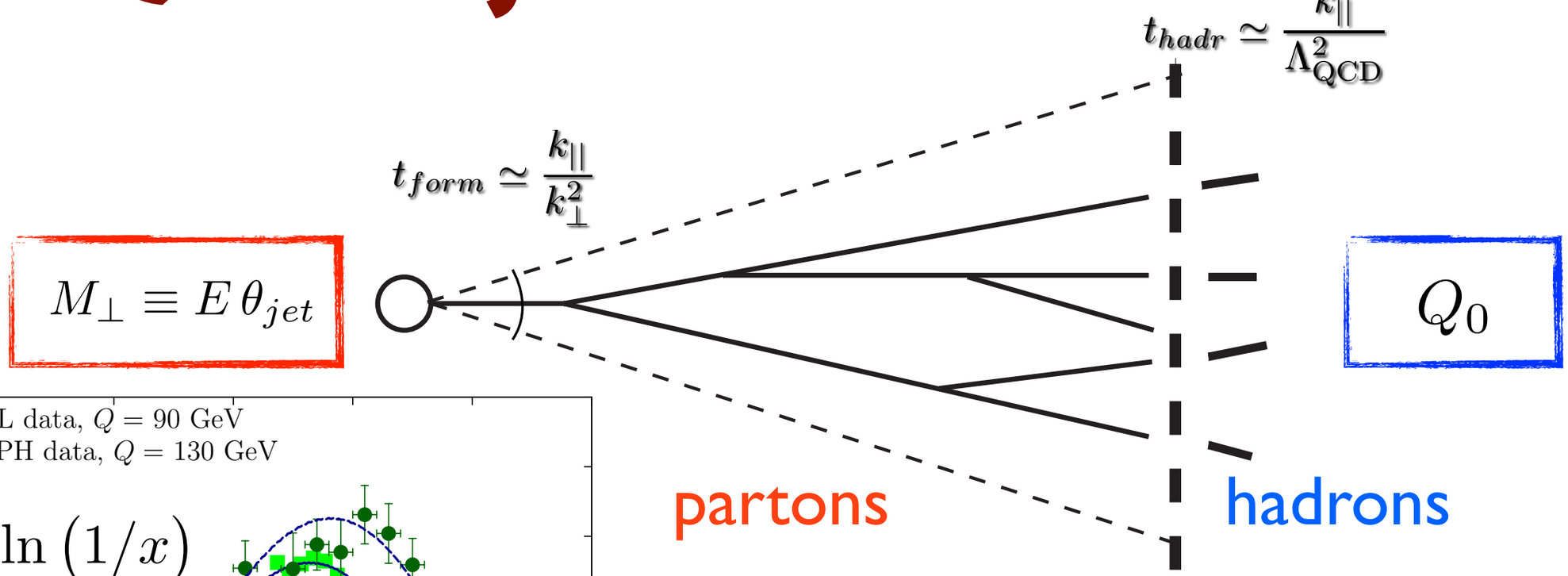
large-angle emissions are restored with the total charge!

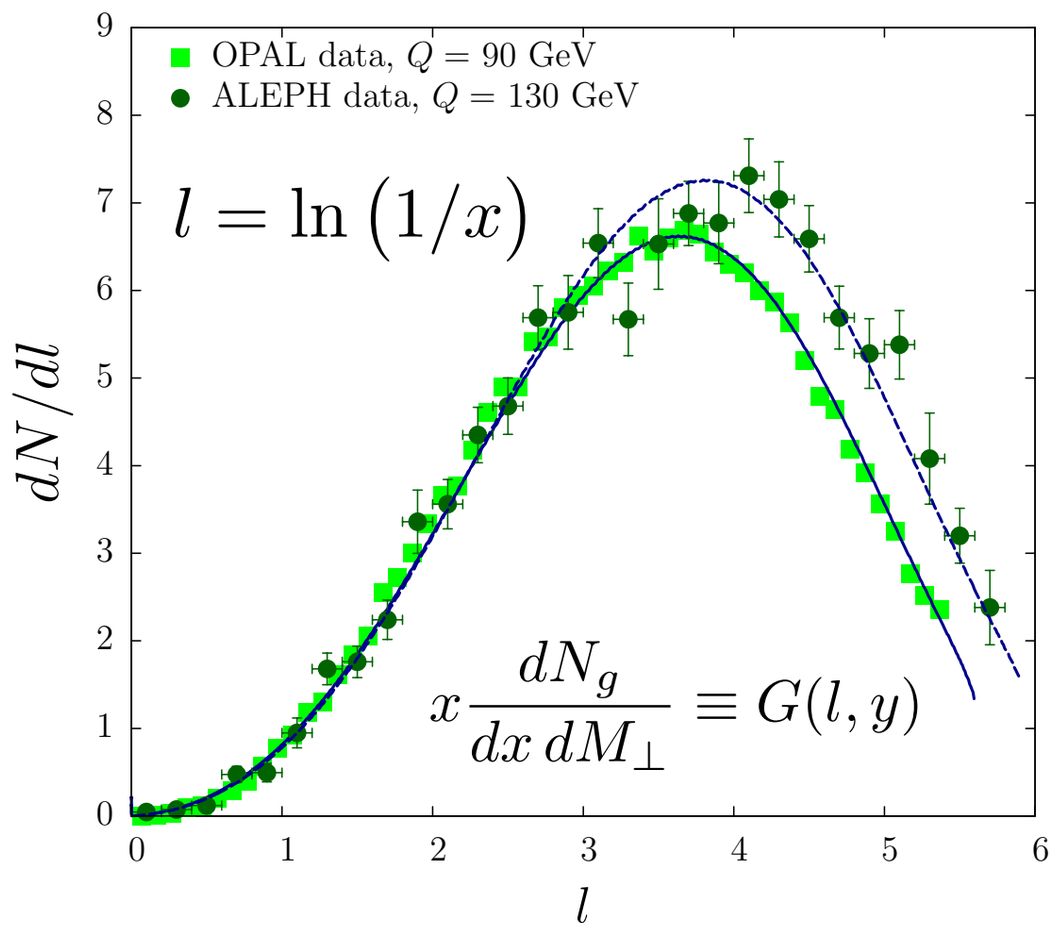
$$\theta \ll \theta_{q\bar{q}}$$

$$\omega \frac{dN_g}{d\omega d^2k_\perp} \propto \frac{\alpha_s C_F}{k_\perp^2} + (q \to \bar{q})$$

$$\omega \frac{dN_g}{d\omega d^2k_\perp} \propto \frac{\alpha_s C_A}{k_\perp^2} \qquad \theta \gg \theta_{q\bar{q}}$$

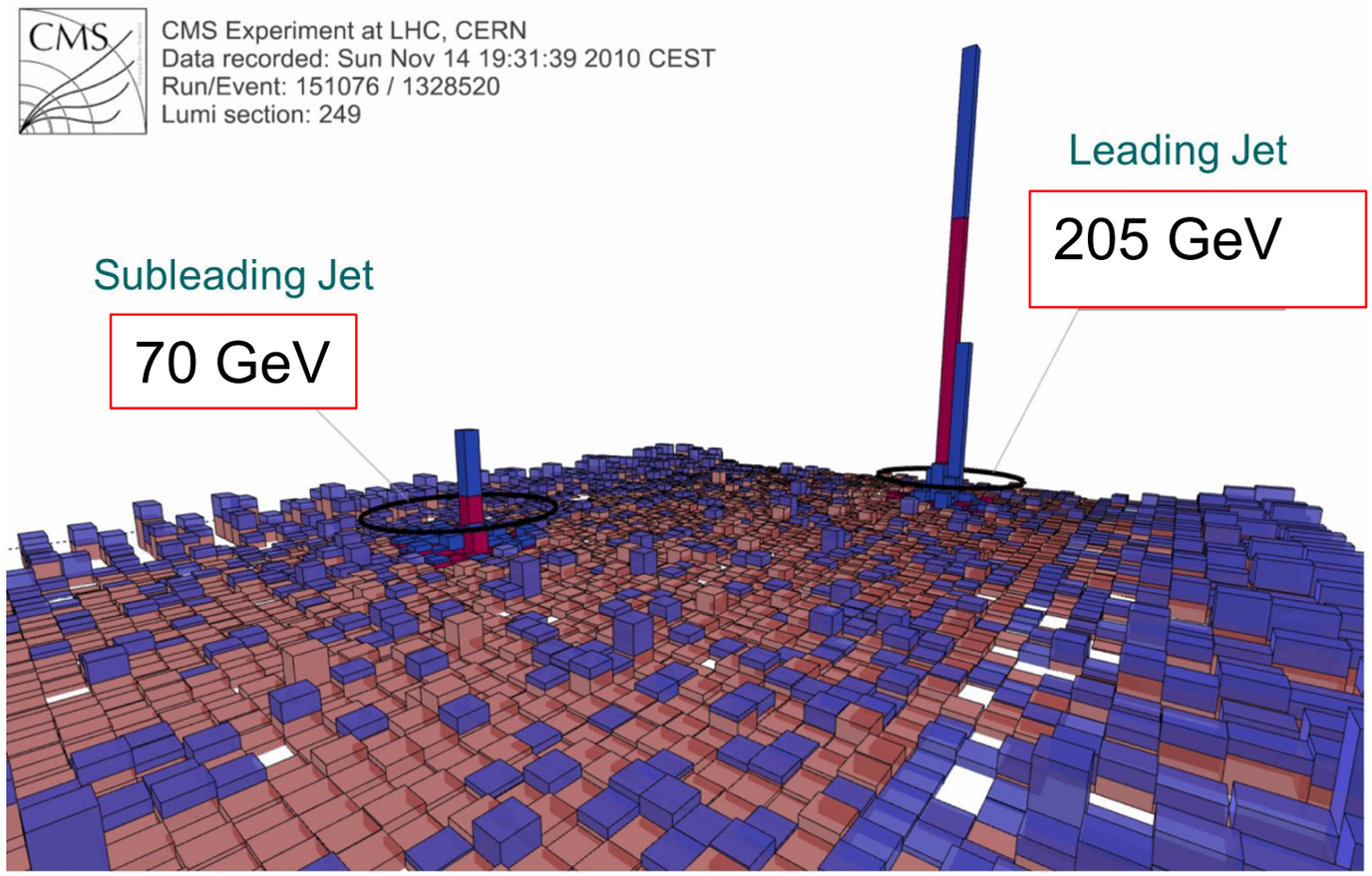
QCD jet in vacuum

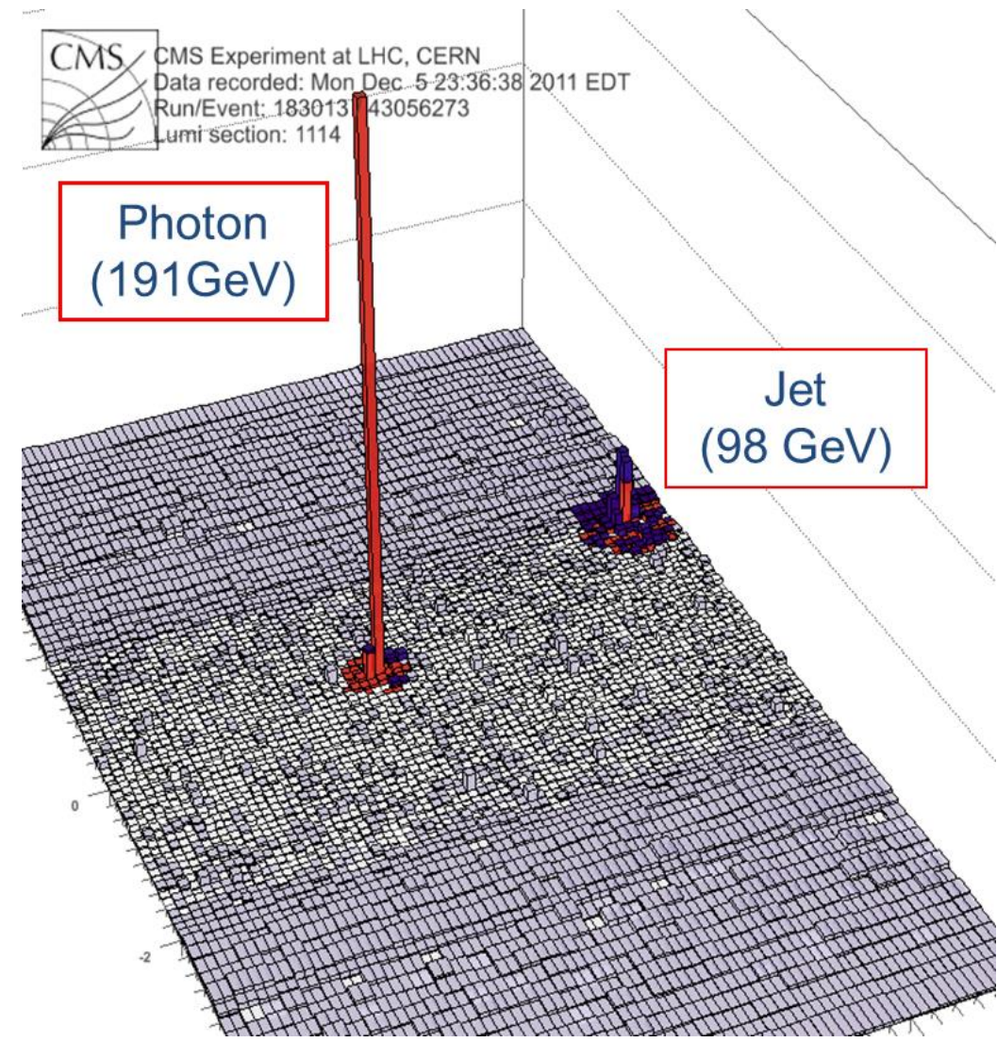




- probabilistic picture, factorization
- jet scales :: perturbative
- angular ordering :: essential for small x
- MLLA + LPHD (K factor)
- good description

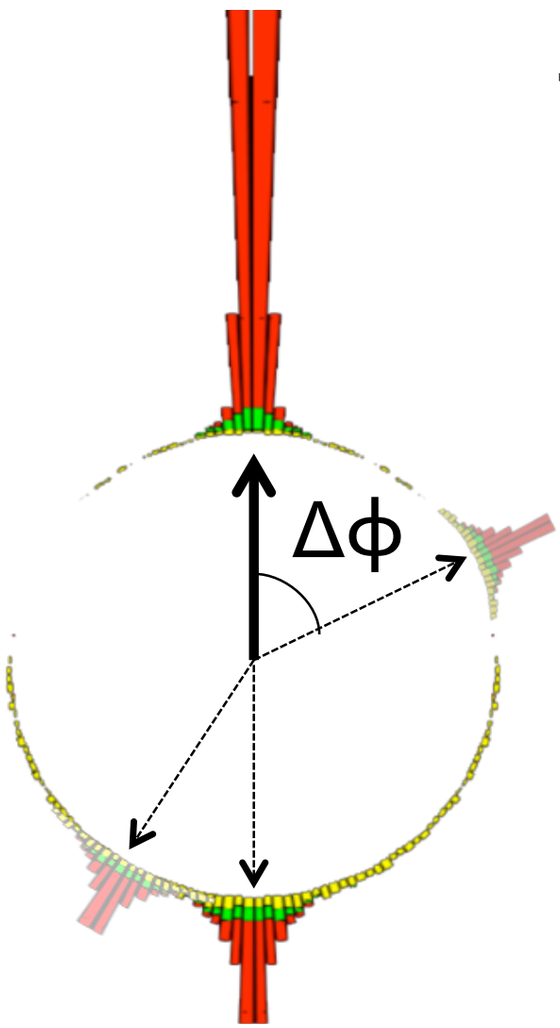
How do jets propagate in the background created in heavy-ion collisions?

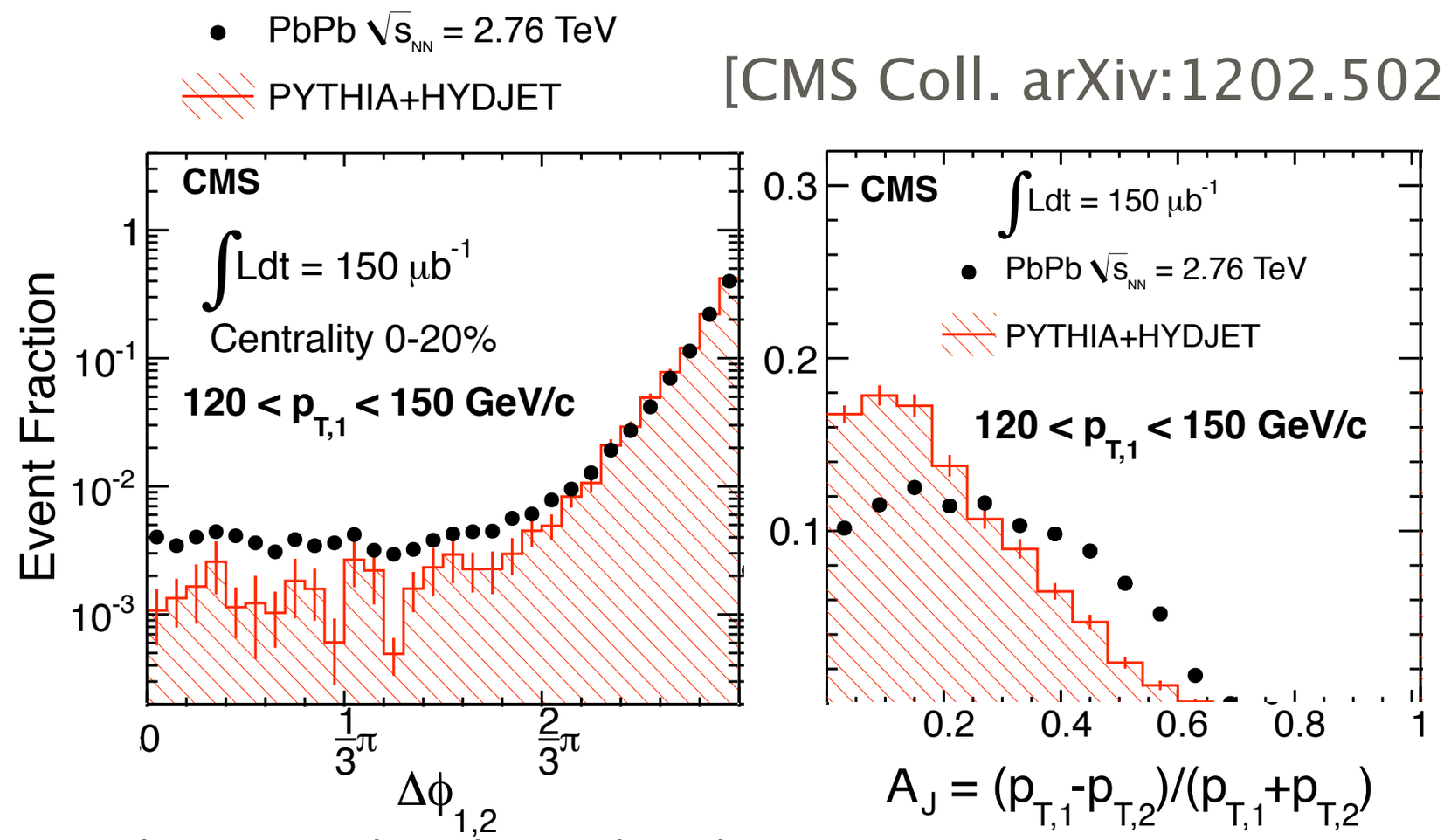

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Leading Jet
205 GeV
Subleading Jet
70 GeV


CMS Experiment at LHC, CERN
Data recorded: Mon Dec 5 23:36:38 2011 EDT
Run/Event: 183013 / 43056273
Lumi section: 1114
Photon
(191GeV)
Jet
(98 GeV)

Modified jets I

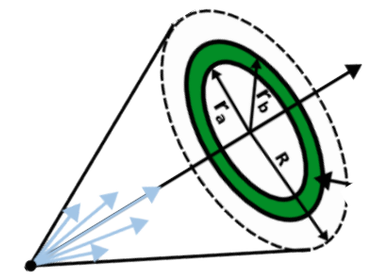
[CMS Coll. arXiv:1202.5022]



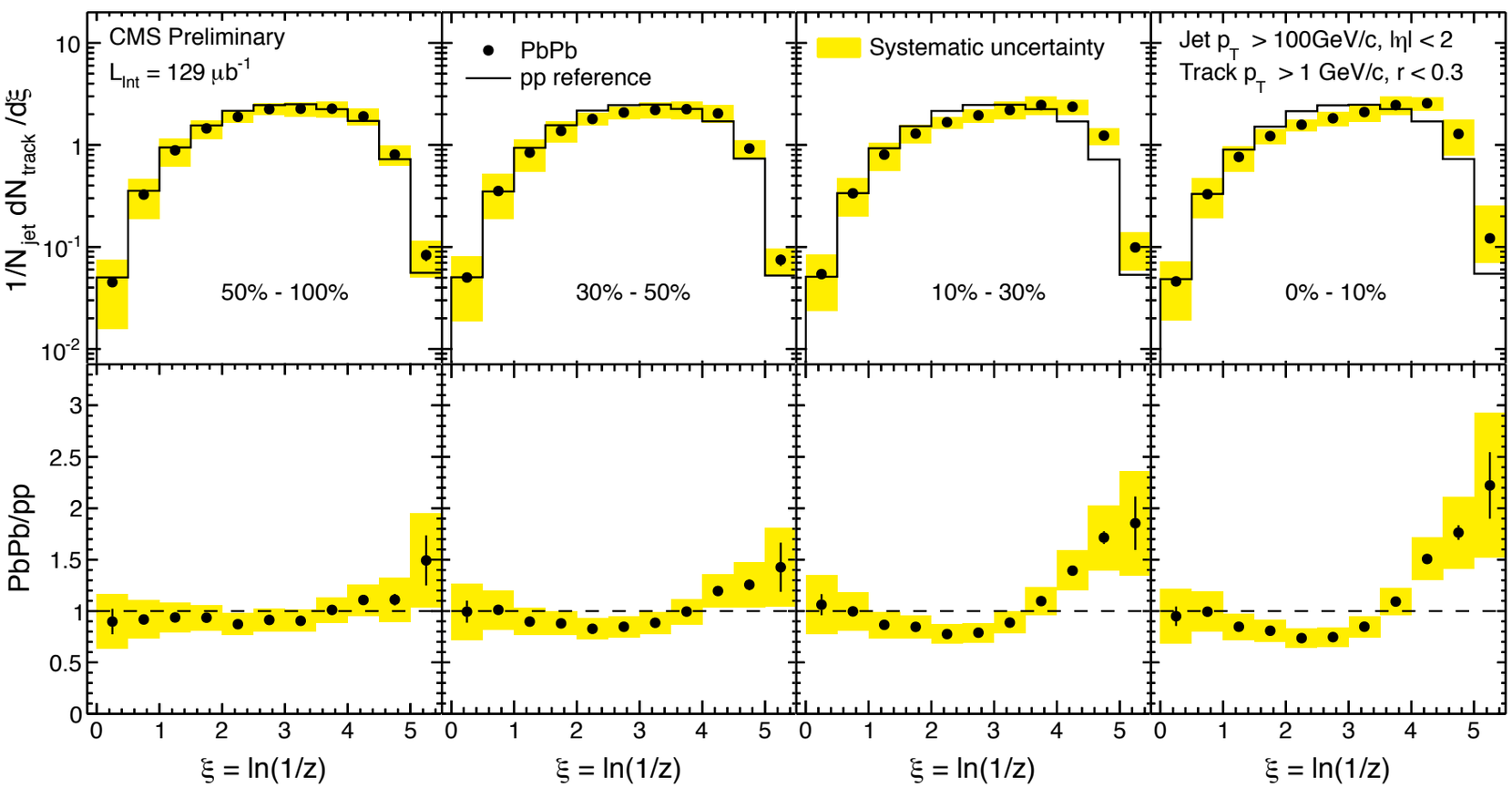


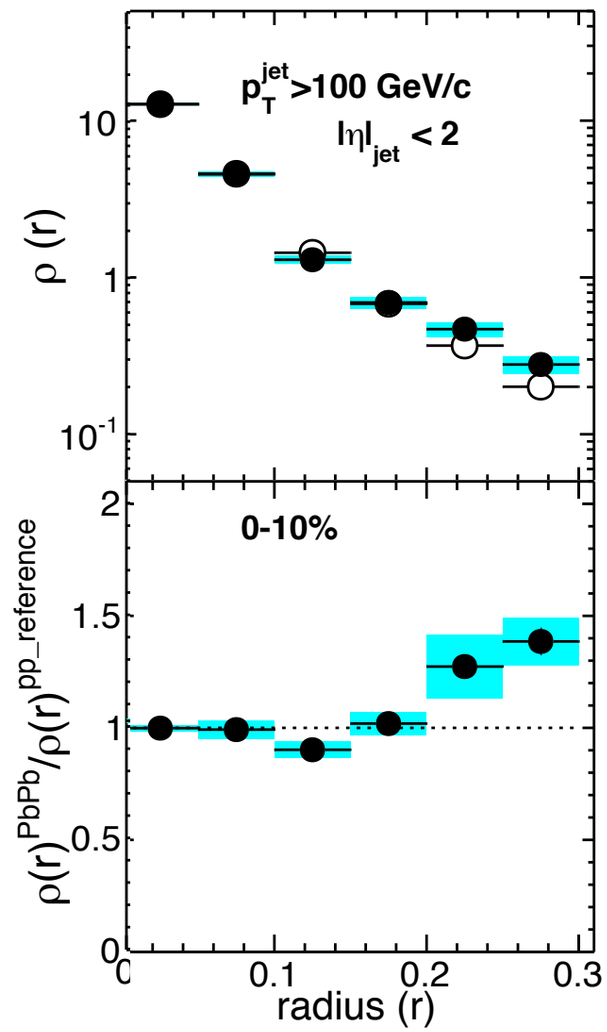
- jets are back-to-back
- large dijet energy asymmetry
  - recall: jets are suppressed (factor ~2)

Modified jets II



[CMS Coll. HIN-12-013]





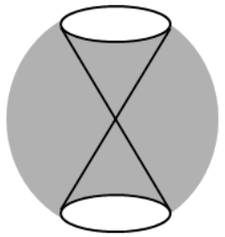
- modifications of intra-jet particle distribution on the edges of the jet

Modified jets III

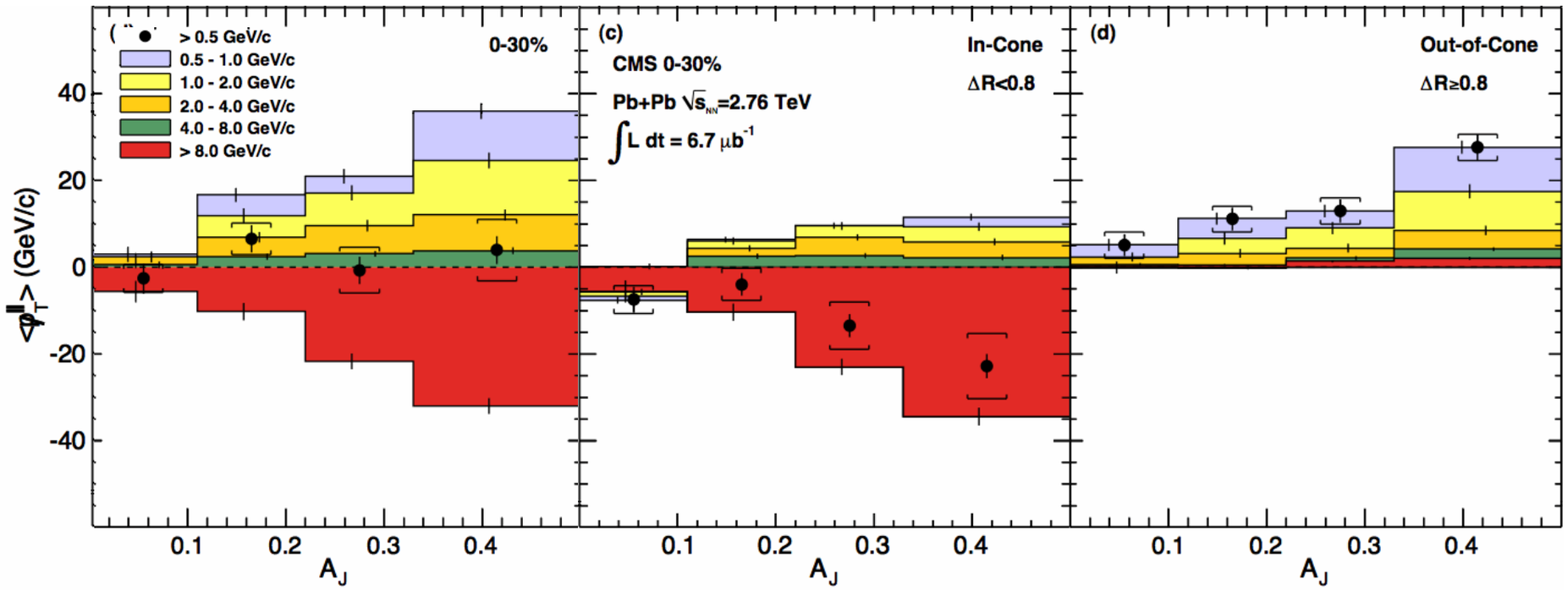
PRC 84 (2011) 024906

All tracks

Tracks in the jet cone ΔR<0.8



Tracks out of the jet cone ΔR>0.8



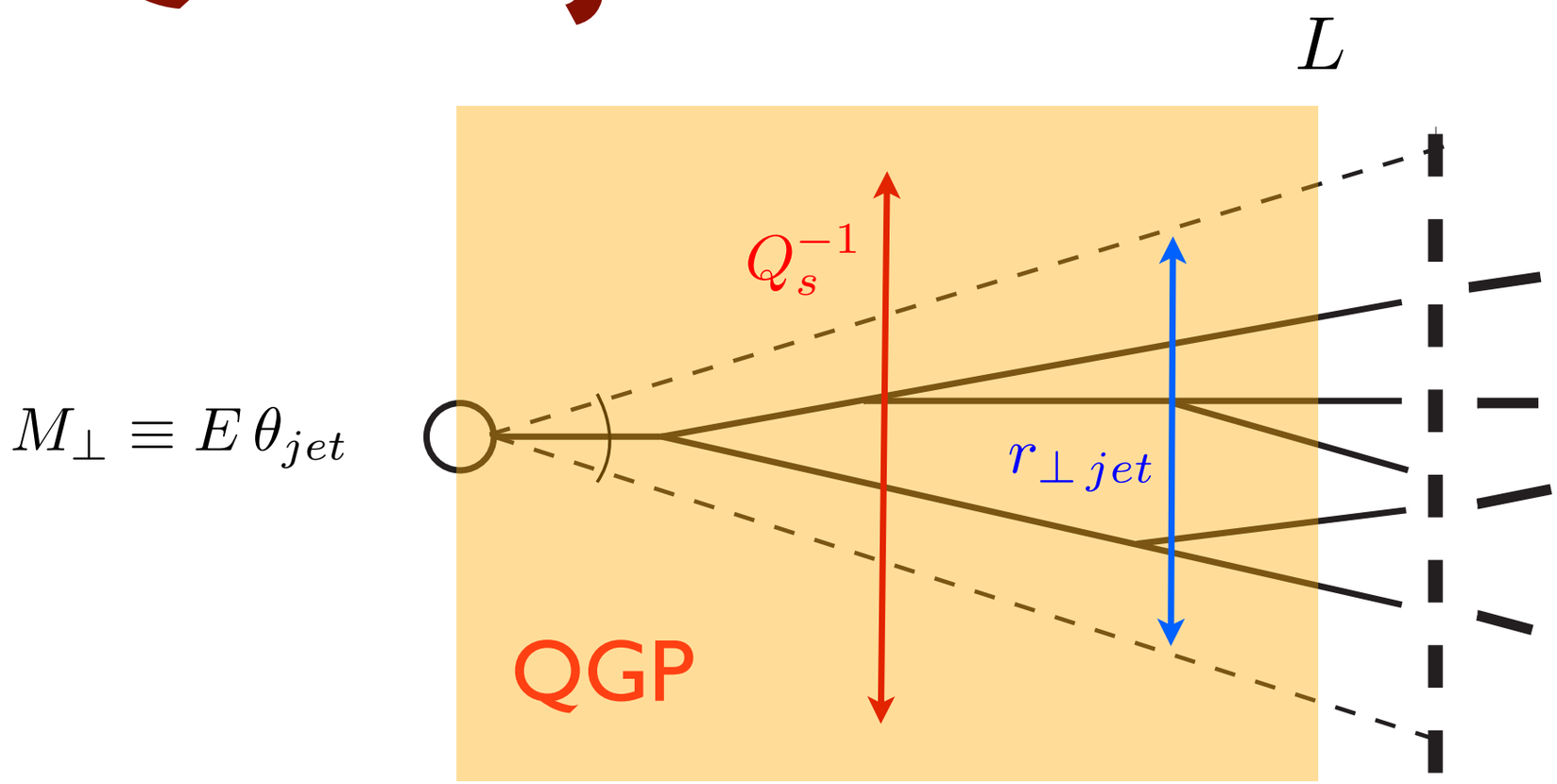
balanced

excess in leading jet direction

low p_T excess away from leading jet

10-15 % of the jet energy is found at ΔR>0.8

QCD jet in medium



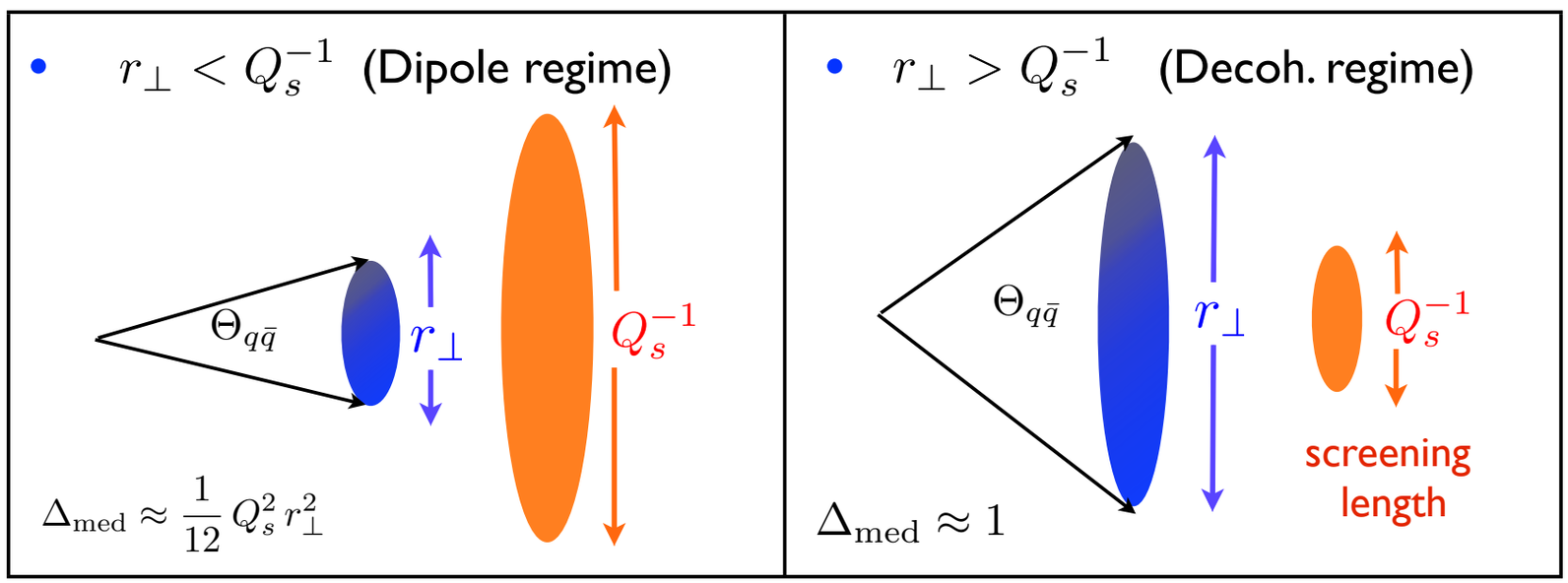
New scales:

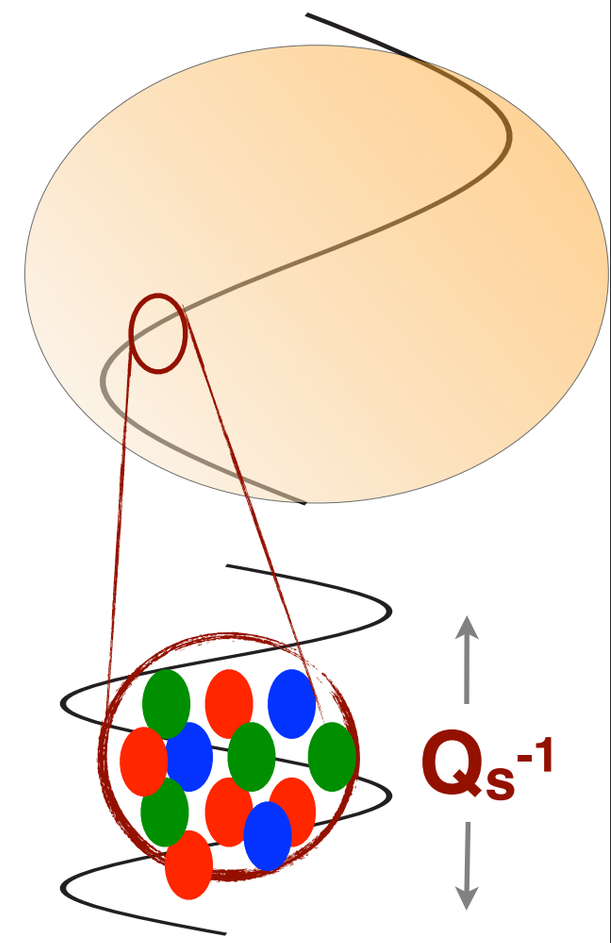
$$M_\perp \equiv E\,\theta_{jet}$$
$$Q_0 \sim \Lambda_{\rm QCD}$$

+

$$Q_s \equiv \sqrt{\hat{q}L} \equiv m_D\,\sqrt{N_{\rm scat}}$$
$$r_{\perp\,jet}^{-1} \equiv (\theta_{jet}L)^{-1}$$

Jet scales in the medium





$$\Delta_{\rm med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$$

the decoherence parameter

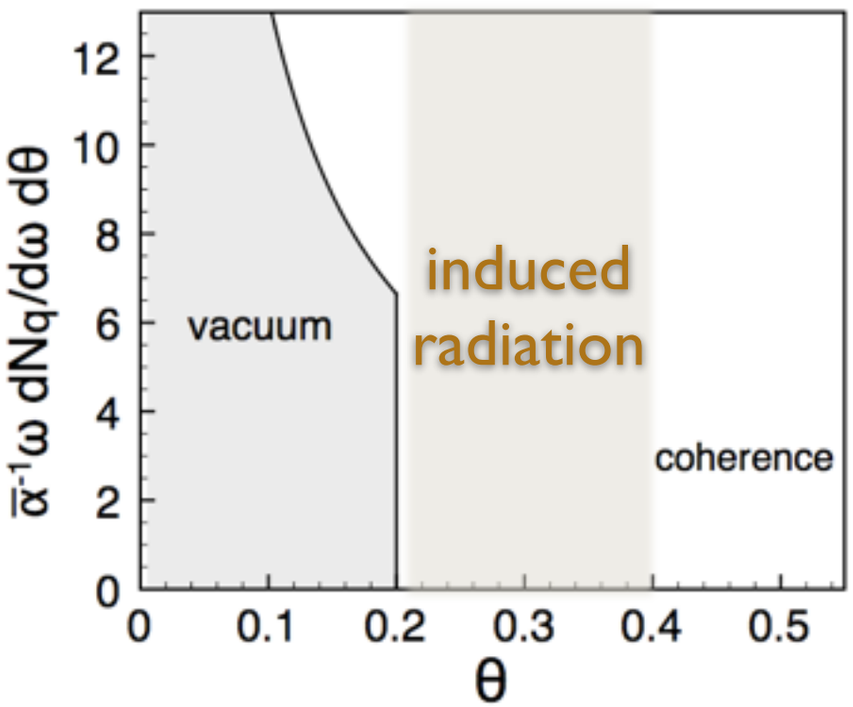
$$k_\perp < Q_{\rm hard}$$

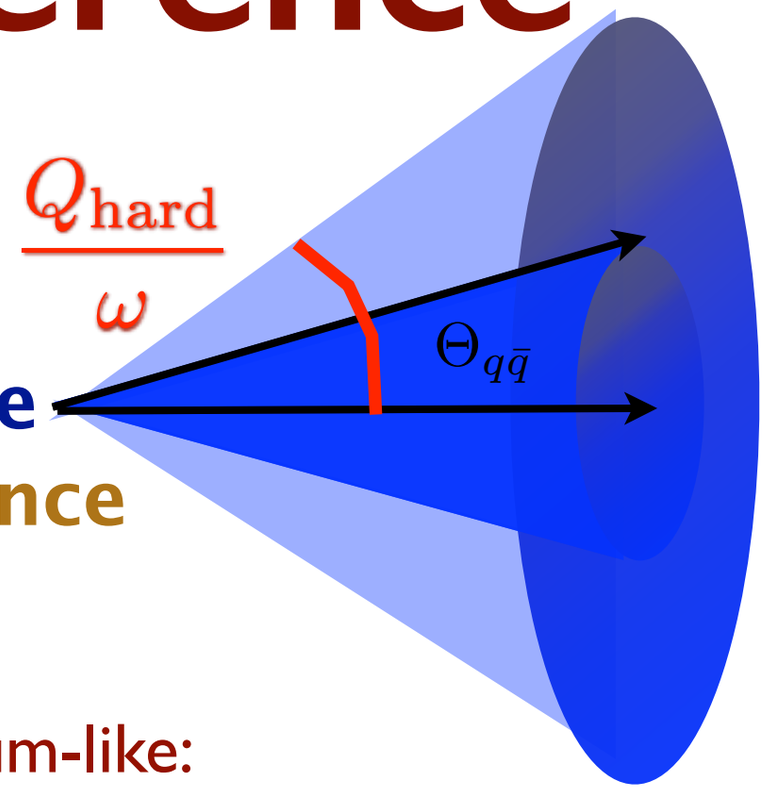
$r_\perp = \theta_{q\bar{q}} L$

$Q_s^2 = \hat{q}L$ characteristic momentum scale of the medium

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397
Casalderrrey-Solana, Iancu 1105.1760

Onset of decoherence





$\Delta_{\rm med} \to 0$ **Coherence**

$\Delta_{\rm med} \to 1$ **Decoherence**

In $\omega \to 0$ limit, only vacuum-like:

$$dN_q^{\rm tot} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\, d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right] .$$

$$Q_{\rm hard} = \max\left(r_\perp^{-1}, Q_s\right)$$

$$k_\perp < Q_{\rm hard}$$

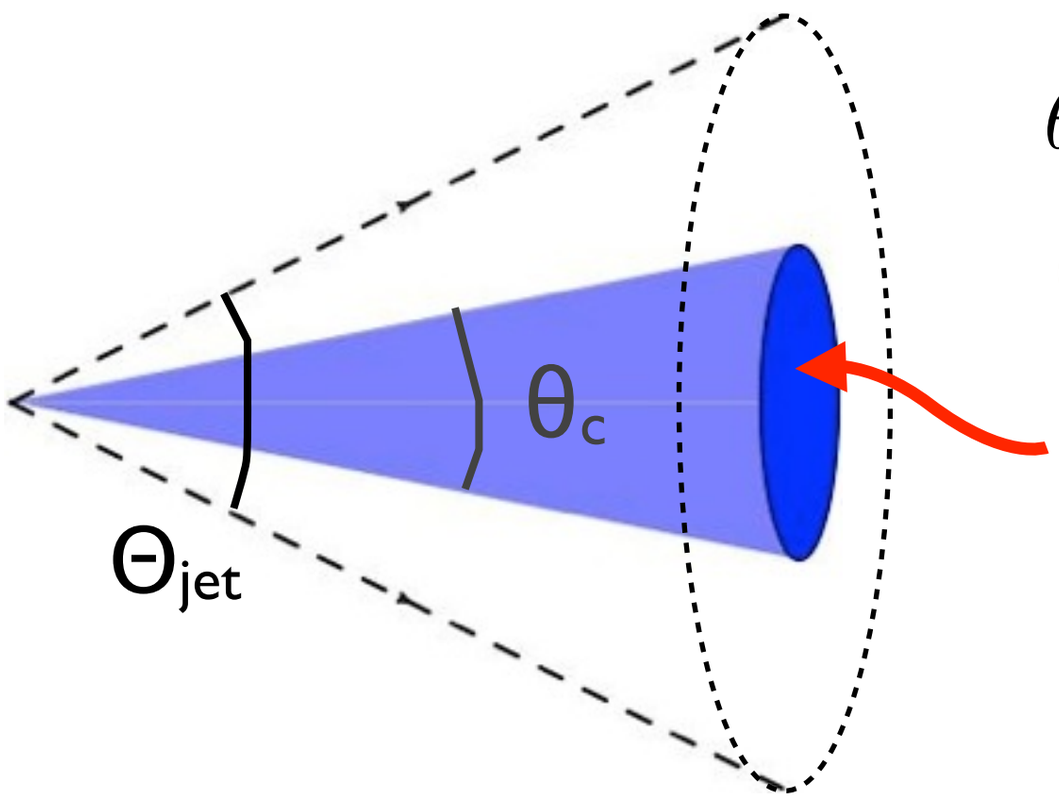
- decoherence opens phase space at large angles $\theta_{max}=Q_{hard}/\omega$
- modification of angular ordering

Resolving jet substructure

In terms of angles: $\Delta_{\rm med} = 1 - e^{-\Theta_{\rm jet}^2/\theta_c^2}$

$\theta_c = 1/\sqrt{\hat{q}L^3}$

jet definition (Θ_{jet}=R)!



Coherent inner 'core'

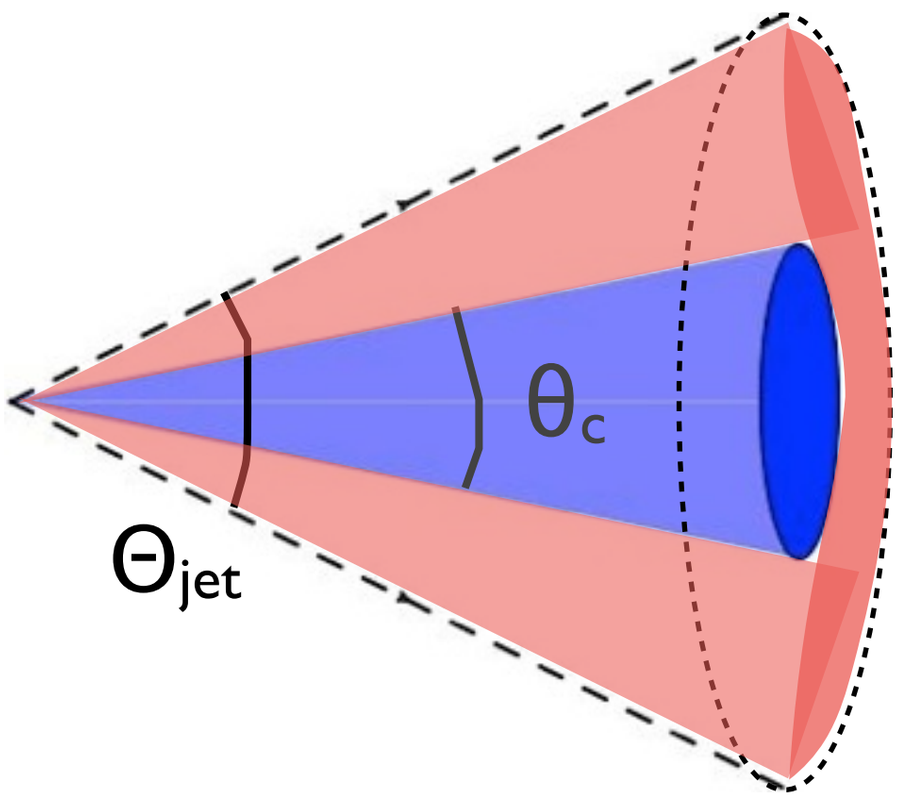
- branchings occurring inside the medium with $\theta < \theta_c$
- **hard modes** (with $k_\perp > Q_s$)
- the core interacts w/ medium coherently
- sensitive to energy loss

A large fraction of the jets contain 90% of their energy within a coherent core of **Θ**~0.1!

Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765
Perez-Ramos, Mathieu PLB 718 (2013) 1421 [arXiv:1207.2854]; Perez-Ramos, Renk arXiv:1401.5283

Resolving jet substructure

In terms of angles: $\Delta_{\rm med} = 1 - e^{-\Theta^2_{\rm jet}/\theta_c^2}$

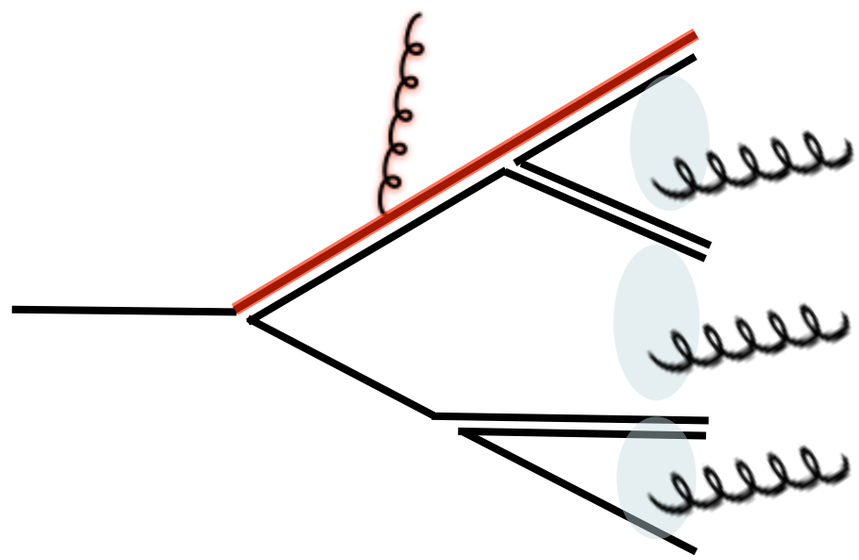


'Soft edge' of the jet

- softer components of the jet occupy the full angular range
  - do not carry a large energy fraction!
- will be sensitive to effects of decoherence
- modification of jet fragmentation function
  - sensitive to the angle Θc

Mehtar-Tani, KT 1401.8293

Factorization of radiation



- coherence :: leading contribution to inclusive spectra at high energies
- separation in angles :: only the total charge radiates
- allows to separate the treatment of the two different processes :: jet calculus

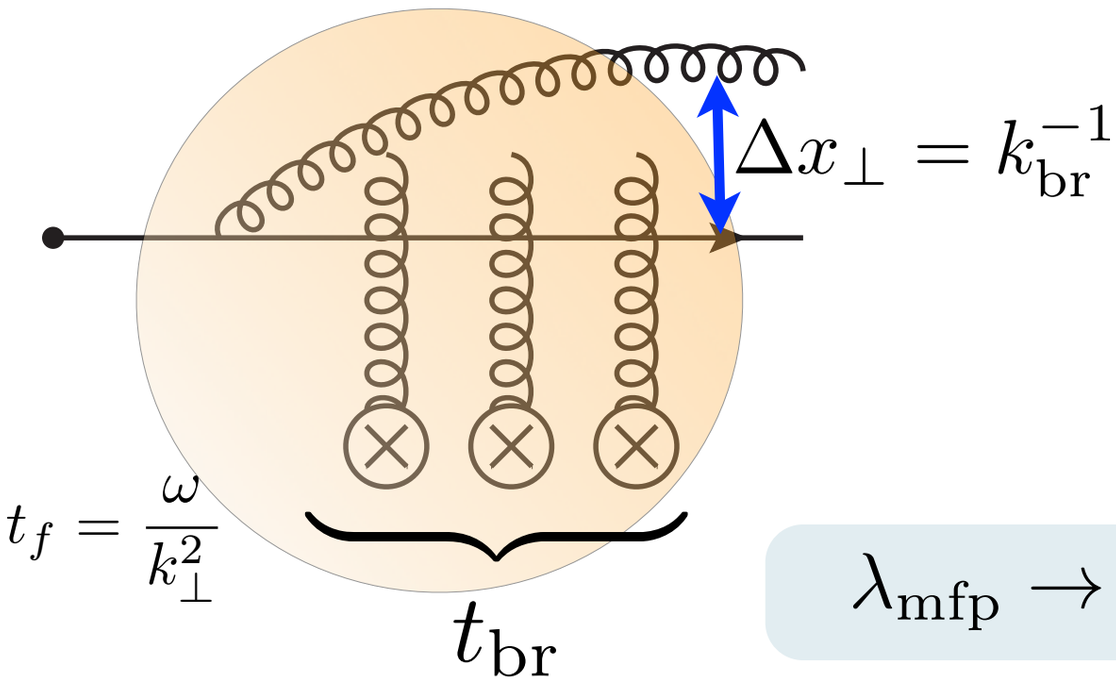
$$D^{\rm coh}_{\rm med}(x;Q,L) = \int_x^1 \frac{{\rm d}z}{z} D^{\rm vac}\left(\frac{x}{z};Q\right) D^{\rm med}_q(z,p_\perp,L)$$

small angle, vacuum-like evolution

medium induced, large angle radiation

Mehtar-Tani, KT 1401.8293

Induced radiation



Multiple scattering in the medium:

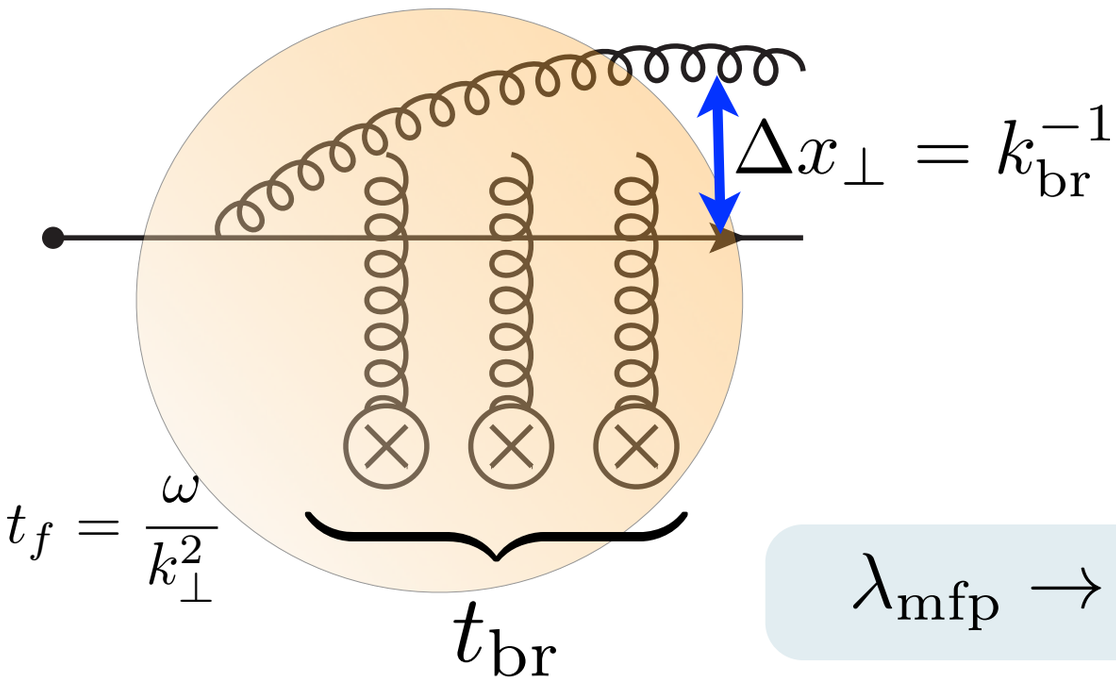
$$\left.\begin{aligned} t_{\rm br} &= \lambda_{\rm mfp} N_{\rm coh} \\ k_{\rm br}^2 &= \mu^2 N_{\rm coh} \end{aligned}\right\} \qquad \begin{aligned} t_{\rm br} &= \sqrt{\omega/\hat{q}} \\ k_{\rm br}^2 &= \sqrt{\hat{q}\omega} \end{aligned}$$

$\lambda_{\rm mfp} \to t_{\rm br}$ :: Landau-Pomeranchuk-Migdal effect

- any coherent color current in the medium experiences interactions :: stimulates radiation/new color currents
- cascade in the medium

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

Induced radiation



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Bethe-Heitler regime

$$t_{\rm br} \sim \lambda_{\rm mfp}$$

$$\omega_{\rm BH} = \lambda^2 \hat{q} \sim \lambda m_D^2$$

Factorization regime

$$t_{\rm br} \sim L$$

$$\omega_c = \hat{q} L^2$$

LPM regime

$$\omega_{\rm BH} \ll \omega \ll \omega_c$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

Medium cascade

Multiple emission regime

- independent emission
- possible in large media
- very soft radiation at large angles!

$$\omega_{\rm BH} \ll \omega \ll \bar{\alpha}^2 \omega_c$$

$$\theta \gg \theta_{\rm br} \equiv \left(\hat{q}/\omega^3\right)^{1/4}$$

Blaizot, Dominguez, Iancu, Mehtar-Tani 1209.4585

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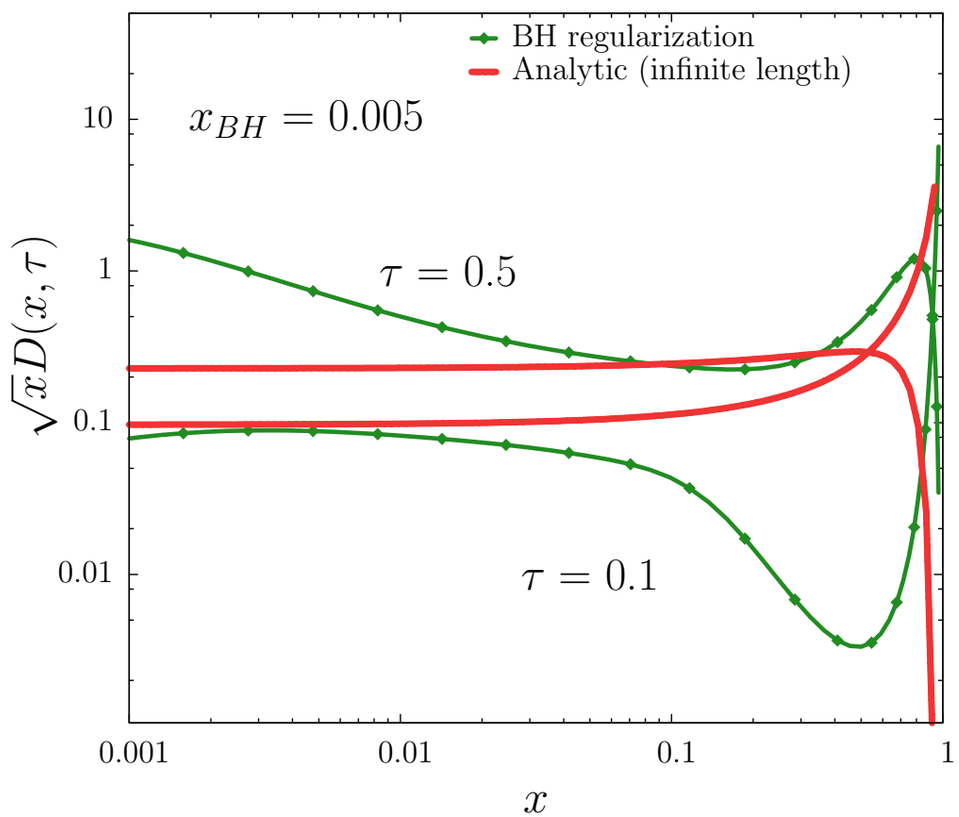
Blaizot, Dominguez, Iancu, Mehtar-Tani 1209.4585



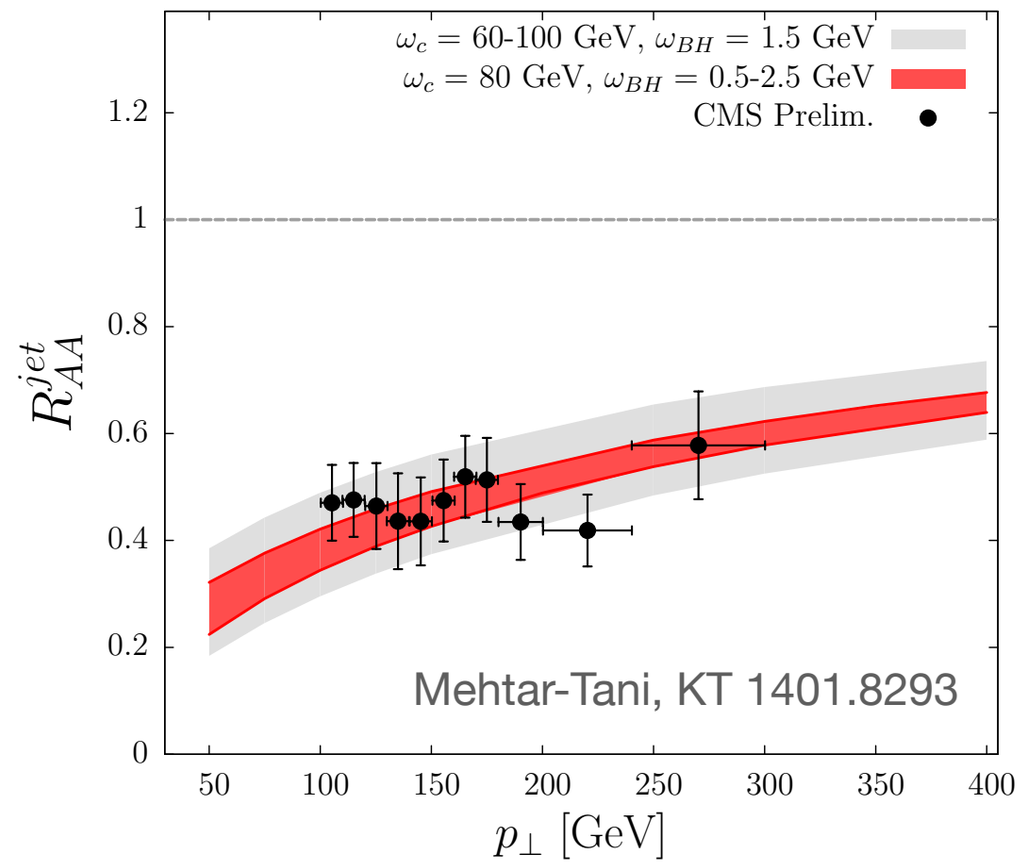
Evolution equation for $D^{\rm med}$:

- probabilistic interpretation
- turbulent flow: no intrinsic accumulation of energy
- effective in transporting sizeable energy to large angles

Jeon, Moore hep-ph/0309332; Baier, Mueller, Schiff, Son hep-ph/0009237
Blaizot, Iancu, Mehtar-Tani 1301.6102

Jet suppression

$$R_{AA}^{\rm jet} \equiv \frac{d^2 N^{\rm jet}_{\text{Pb-Pb}}(p_\perp)/d^2p_\perp}{T_{\rm AA}\, d^2\sigma^{\rm jet}_{\text{p-p}}(p_\perp)/d^2p_\perp}$$



Medium spectrum:

$$\frac{d^2 N^{\rm jet}_{\text{Pb-Pb}}(p_\perp)}{T_{\rm AA}\, d^2p_\perp} \simeq \int_0^1 \frac{dx}{x} D_q^{\rm med}\left(x, \frac{p_\perp}{x}, L\right) \frac{d^2\sigma^{\rm jet}_{\text{p-p}}\left(\frac{p_\perp}{x}\right)}{d^2p_\perp},$$

Vacuum spectrum: $\frac{d^2\sigma^{\rm jet}_{\text{p-p}}}{d^2p_\perp} \propto p_\perp^{-n}$

- governed by 'core' interactions!
- assuming quark jets
- allows to fix ω_c and ω_{BH} (fixing L = 2.5 fm)
- low-p_T sensitive to sub-leading resolved subjets

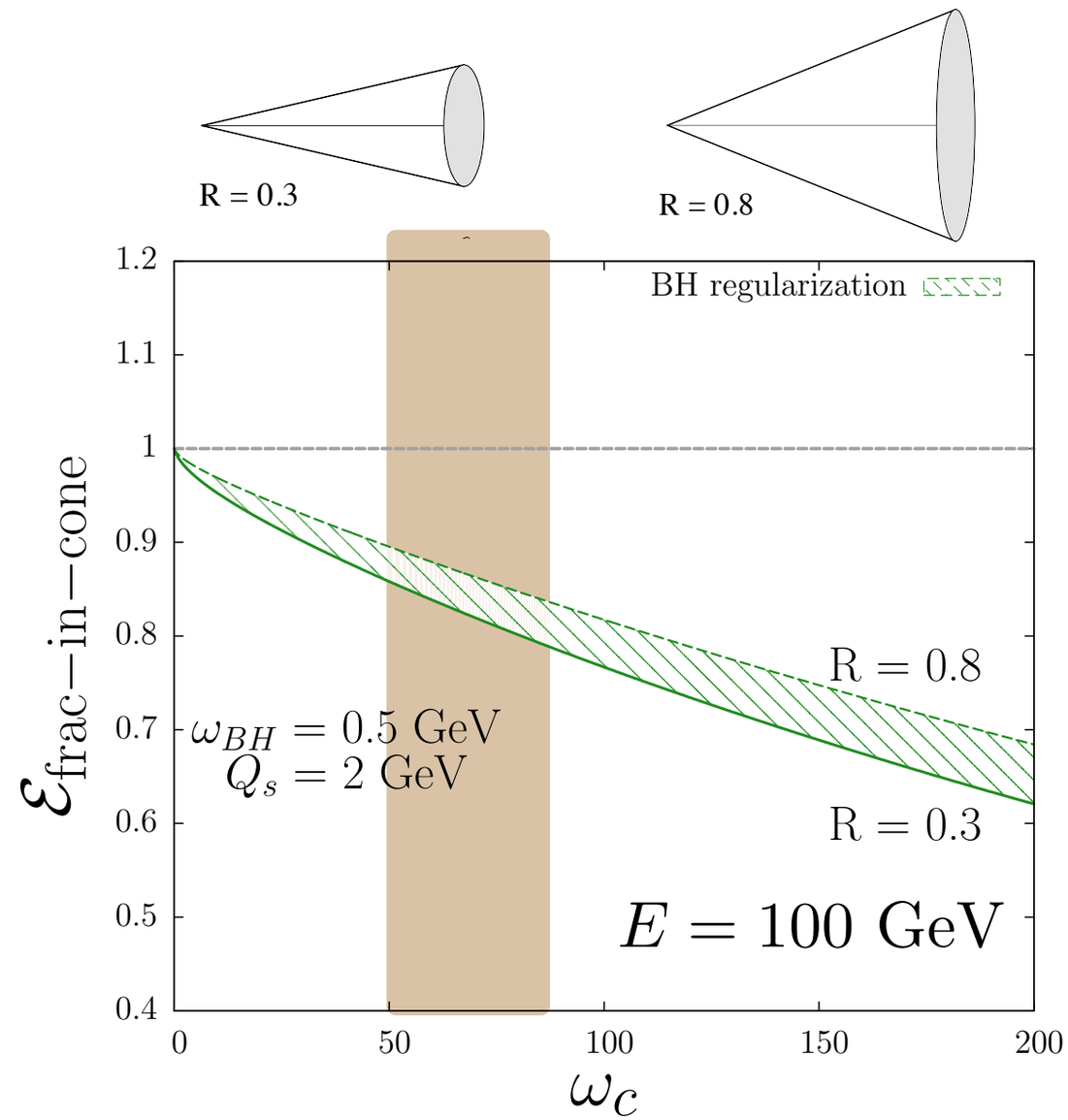
$Q_s = 3.6$ GeV

Momentum broadening

Average broadening (x~1, θ<θ$_c$):

$$D(x,\theta<\Theta_{jet}) = \int^{\Theta_{jet}} \frac{d^2\boldsymbol{k}}{(2\pi)^2}\mathcal{P}(\boldsymbol{k})\,D(x)\,,$$
$$= \left[1-\exp\left(-\frac{x^2 M_T^2}{Q_s^2}\right)\right] D(x)$$

- energy is transported via branching!
- little energy is recovered up to large cone angles, 10-15 % is missing
- jet axis :: **ΔΘ**jet ~ Q_s/E ~ 0.036
- sensitive to Bethe-Heitler regime!

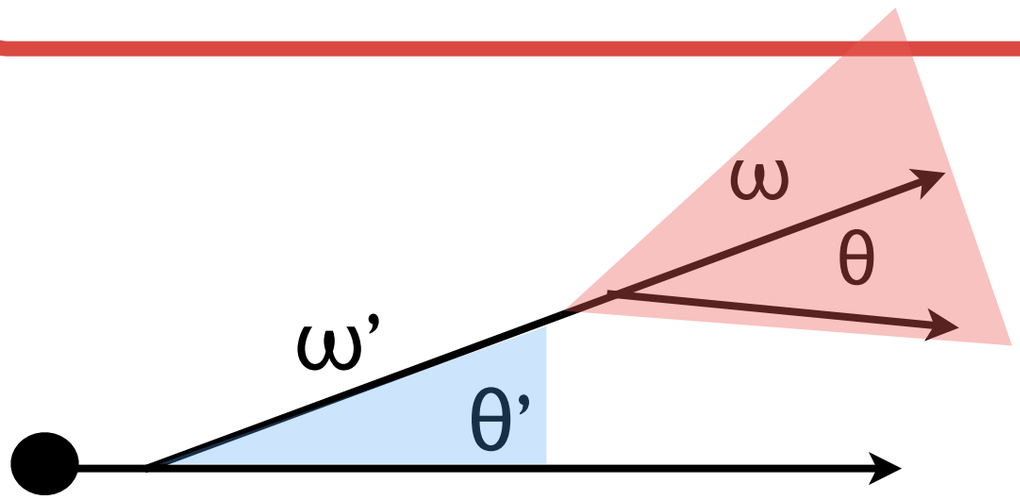


Mehtar-Tani, KT 1401.8293

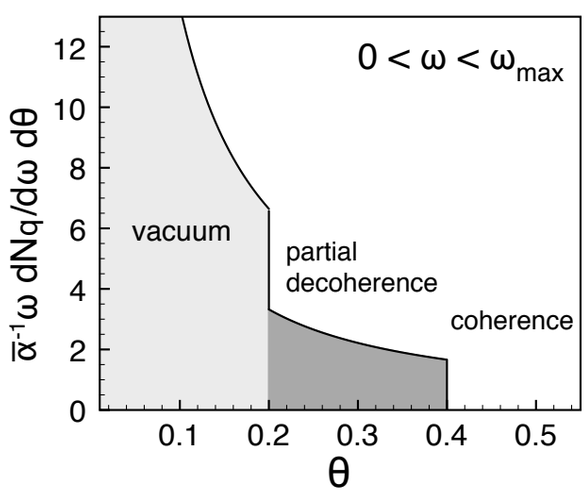
Decoherence

Going beyond the inclusive jet spectrum, the assumption of fully coherent jets fails miserably!

$$\Theta_{\rm jet} = 0.3$$
$$\Theta_c = 0.08$$



$$\Delta D^{\rm decoh}_{\rm med}(x;Q,\hat{q},L) = \int_{\omega}^{E} \frac{{\rm d}\omega'}{\omega'} \int_{Q_0/\omega}^{\Theta_{\rm jet}} \frac{{\rm d}\theta'}{\theta'} \times \Delta_{\rm med}(\theta')\alpha_s(\omega'\theta') \int_{\theta'}^{\theta_{\rm max}} \frac{{\rm d}\theta}{\theta}\,\alpha_s(\omega\theta)$$

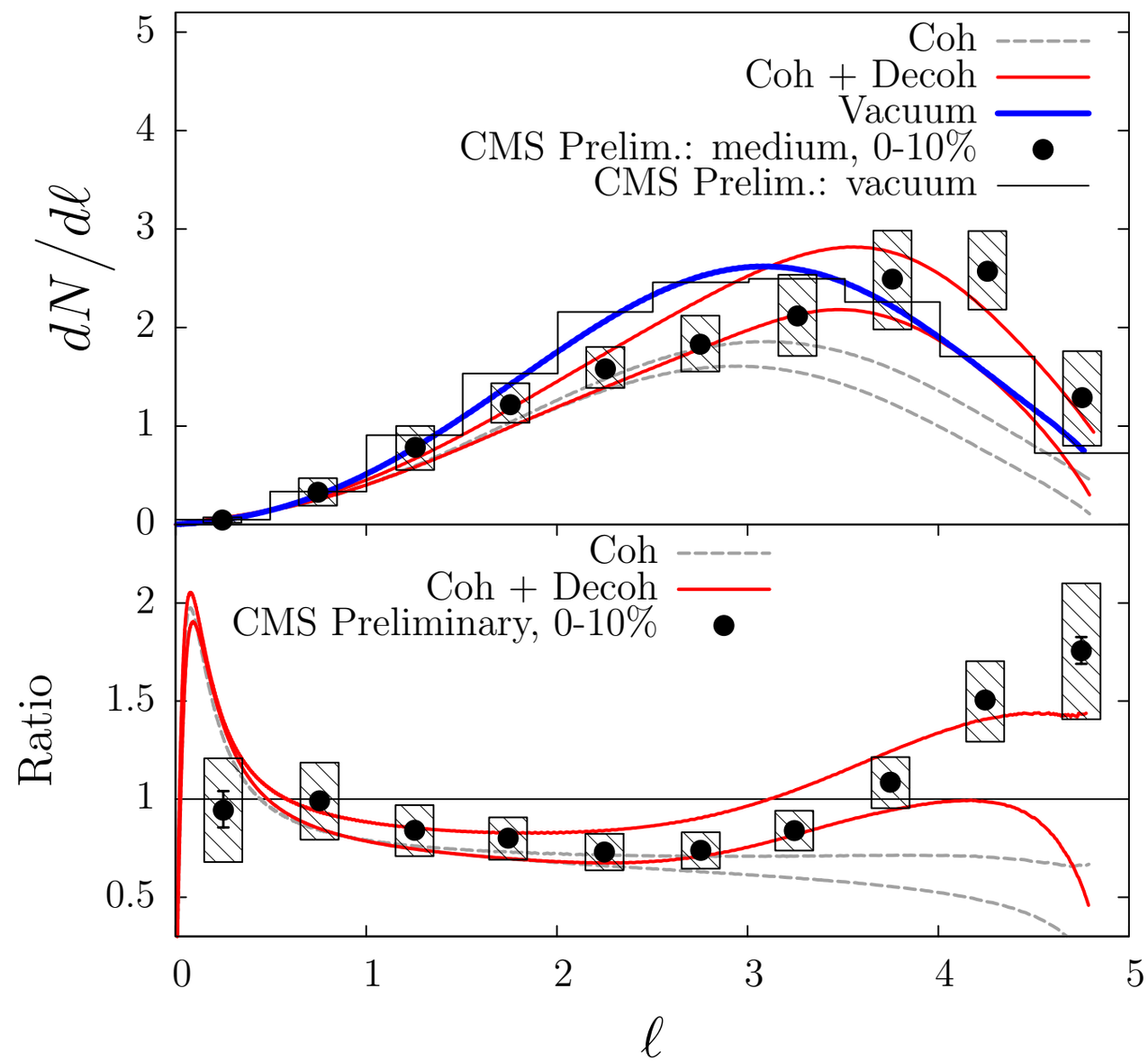


Calculate the decoherence (antiangular) contribution from 2nd emission in DLA w/ running coupling.

$$D^{\rm jet}_{\rm med}(x;Q,L) = D^{\rm coh}_{\rm med}(x;Q,L) + \Delta D^{\rm decoh}_{\rm med}(x;Q,L)$$

Fragmentation function

- vacuum baseline reproduced by MLLA :: valid close to the humpbacked plateau
- allow the jet energy to vary (due to energy loss)
- coherent jet quenching important for intermediate ℓ
- decoherence plays main role at large ℓ (small x)



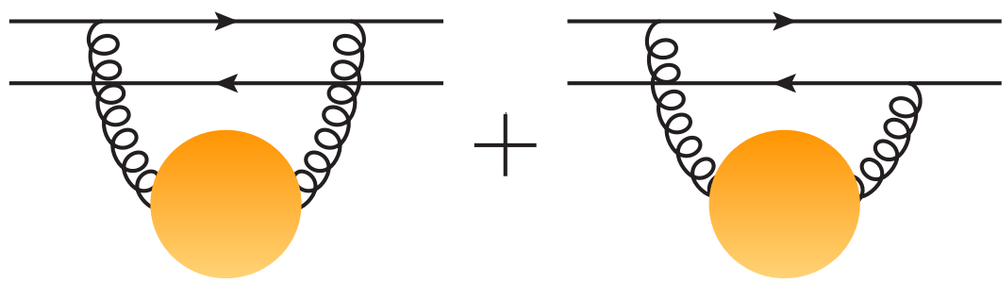
Mehtar-Tani, KT 1401.8293

Summary

- QGP created in heavy-ion collisions has many unforeseen and interesting properties
  - challenges our understanding of QCD
- jet quenching is a powerful tool to access properties (e.g. $\hat{q}$, $\hat{e}$ etc.) of the hot and dense QGP
  - resolved sub-jets are a consequence of color transparency (pQCD)
- separation of scales (angles)
  - jet 'core' :: energy loss
  - jet 'edge' :: modification of fragmentation function
  - large angle :: transport in the medium

backup

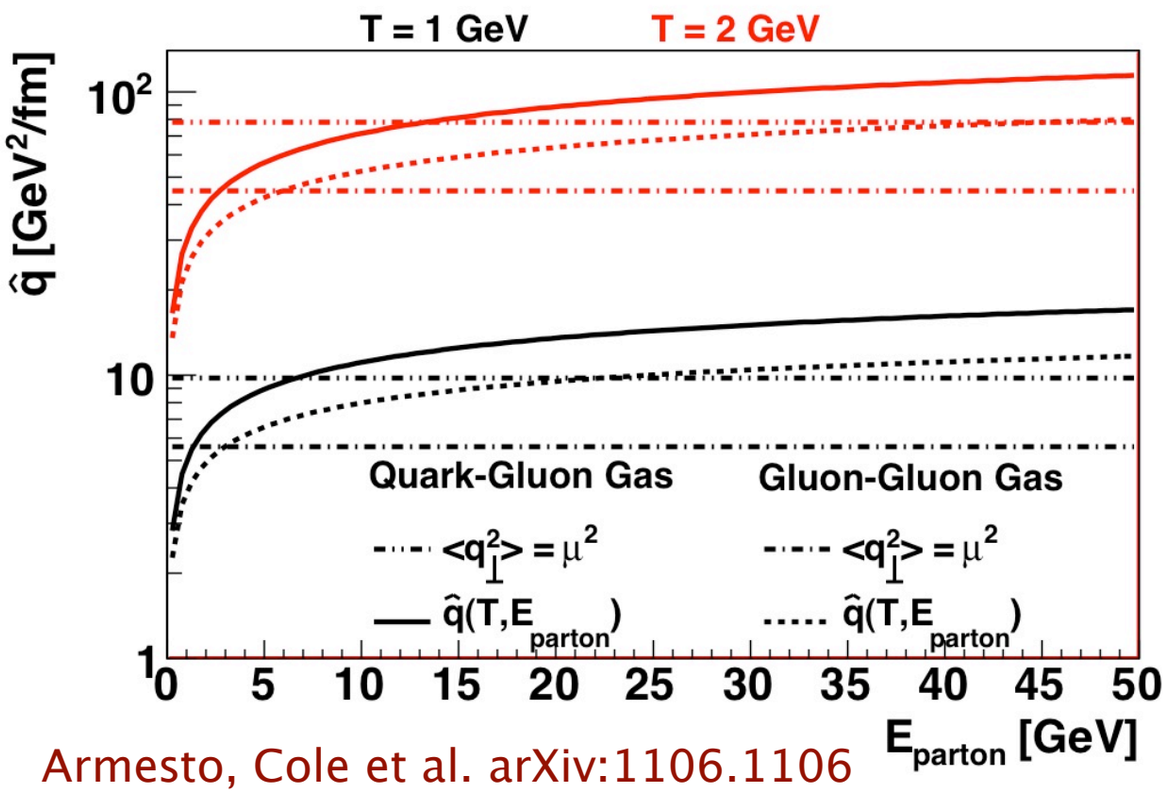
Transport coefficient



Elastic scattering kernel:

$$\mathcal{V}^2_{\rm HTL}(\boldsymbol{q}) = \frac{m_D^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$$

$$\hat{q}(t) \equiv \alpha_s n(t) \int_{|\boldsymbol{q}|<q^*} \frac{d\boldsymbol{q}^2}{2\pi}\, \boldsymbol{q}^2 \mathcal{V}^2(\boldsymbol{q})$$



Armesto, Cole et al. arXiv:1106.1106

- diffusion in k_T
- calculable in thermal pQCD
- radiative corrections

$$\hat{q} = 5.1\ \mathrm{GeV}^2/\mathrm{fm}$$

Liou, Mueller, Wu NPA916 (2013); Blaizot, Dominguez, Iancu, Mehtar-Tani arxiv: 1311.5823

Jet probabilistic evolution

$$d\langle \mathcal{P}_A^{BC} \rangle_\varphi = \frac{\alpha_s(k_\perp^2)}{2\pi} P_A^{BC}(z) dz \, \frac{d\theta}{\theta} \Theta\big(\theta_{fg} - \theta_{sf}\big)$$

- probability of A→BC splitting
- Altarelli-Parisi splitting function
- Markovian (branching) process

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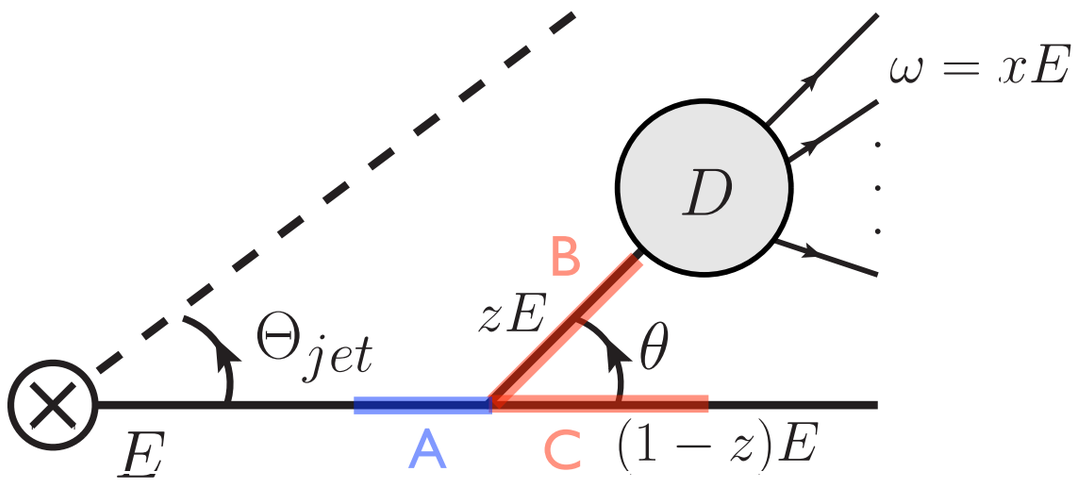

- resummation of multiple branchings
- angular ordering built in
- basis for MC models

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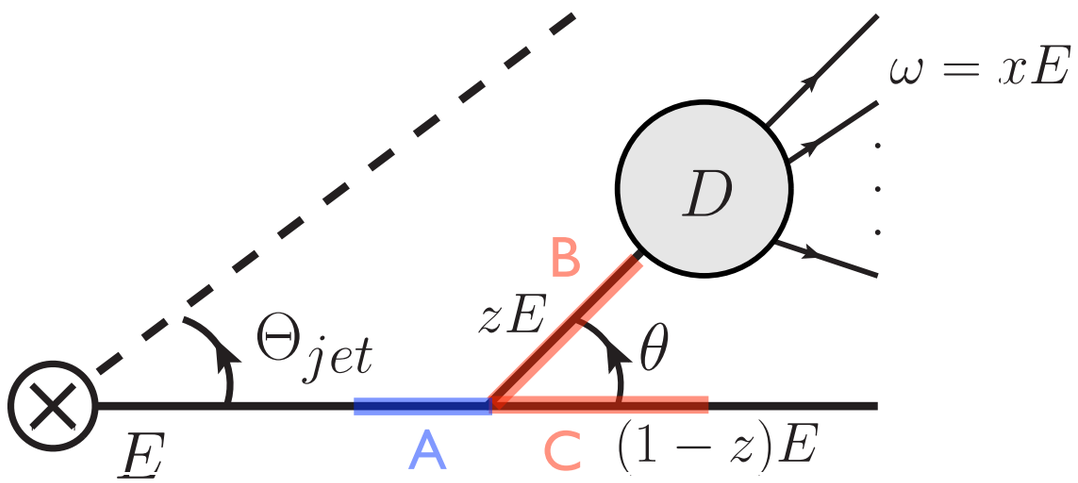

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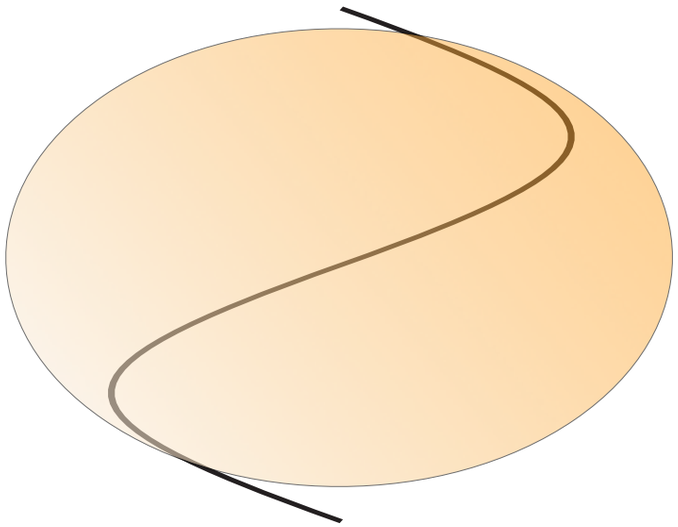
Sudakov form factor

probability of no splitting of particle A between two angles/momenta (scales)

$$\Delta_A(\theta_1, \theta_0) = \exp\left[- \int_{\theta_0}^{\theta_1} \int_0^1 \sum_{BC} d\langle \mathcal{P}_A^{BC} \rangle_\phi \right]$$

The medium scale

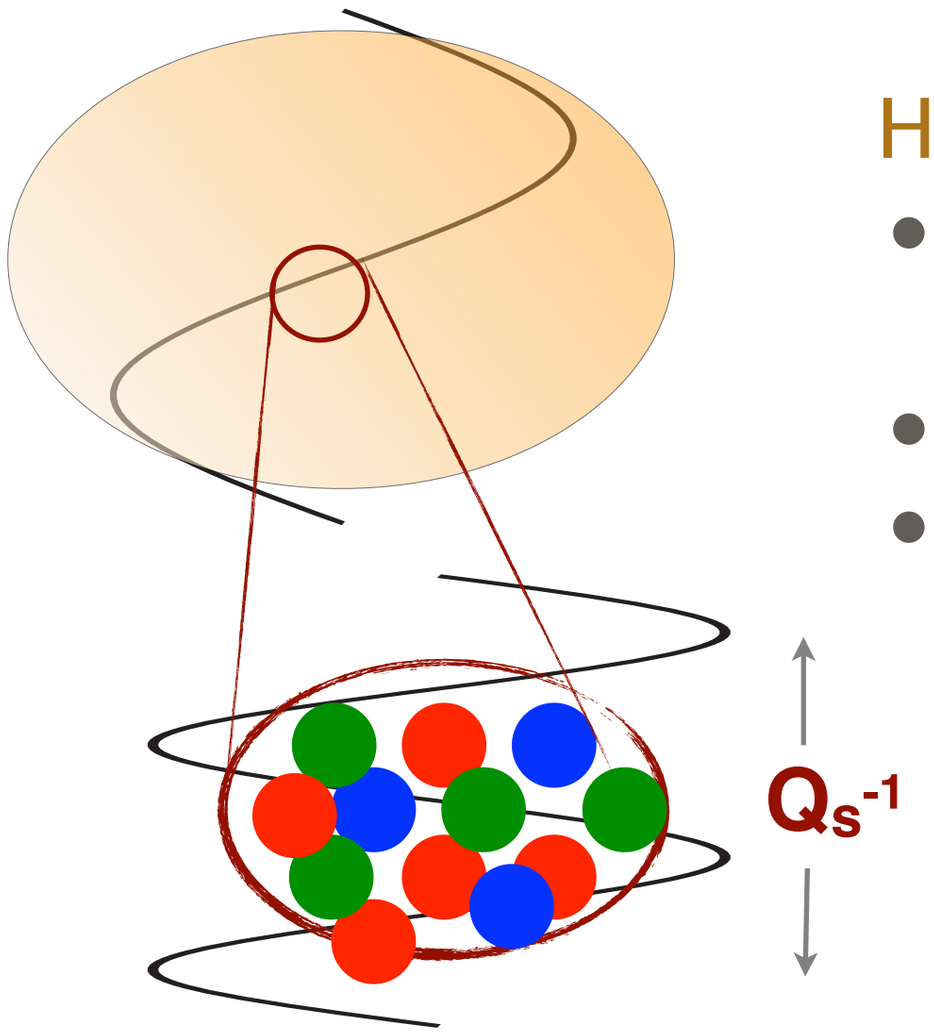


How is the medium resolved

- medium fluctuates with typical transverse wave length Q_s^{-1}
- zero color on average, $\boldsymbol{\lambda > Q_s^{-1}}$
- resolved by $\boldsymbol{\lambda < Q_s^{-1}}$

$$Q_s^2(t) = \hat{q}t$$

The medium scale



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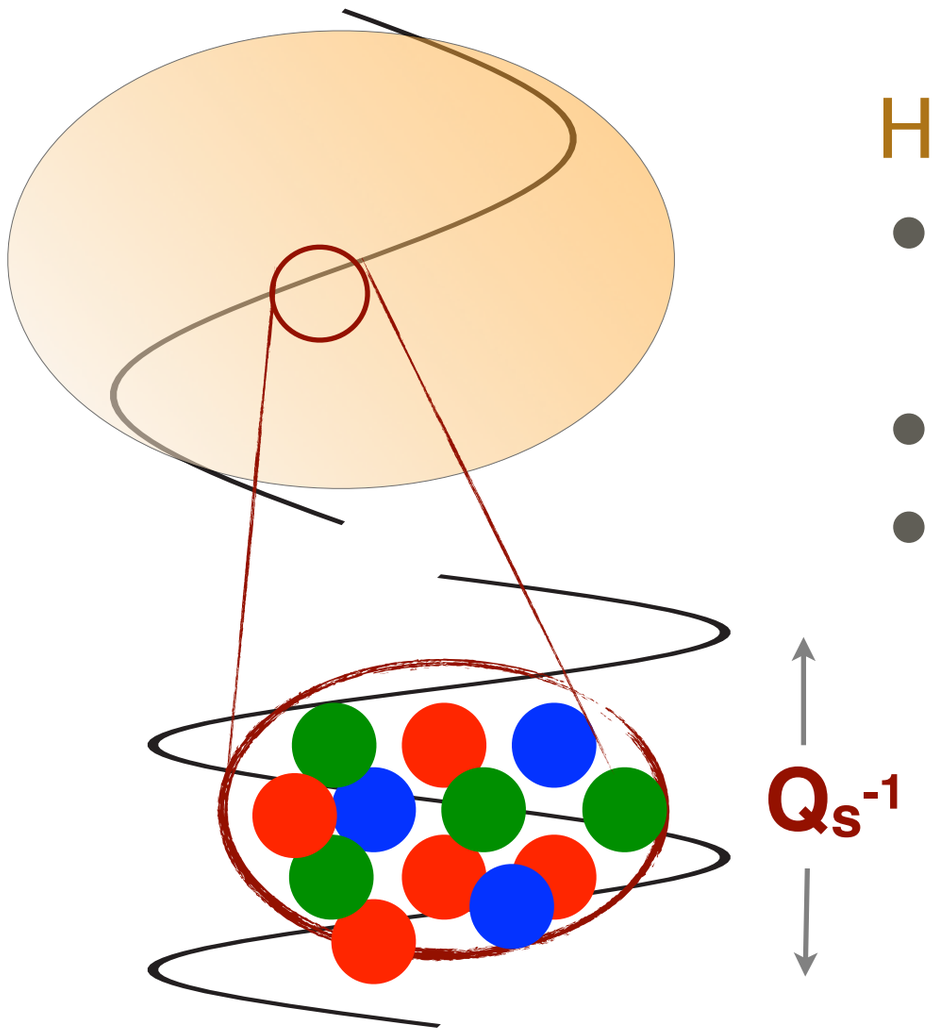

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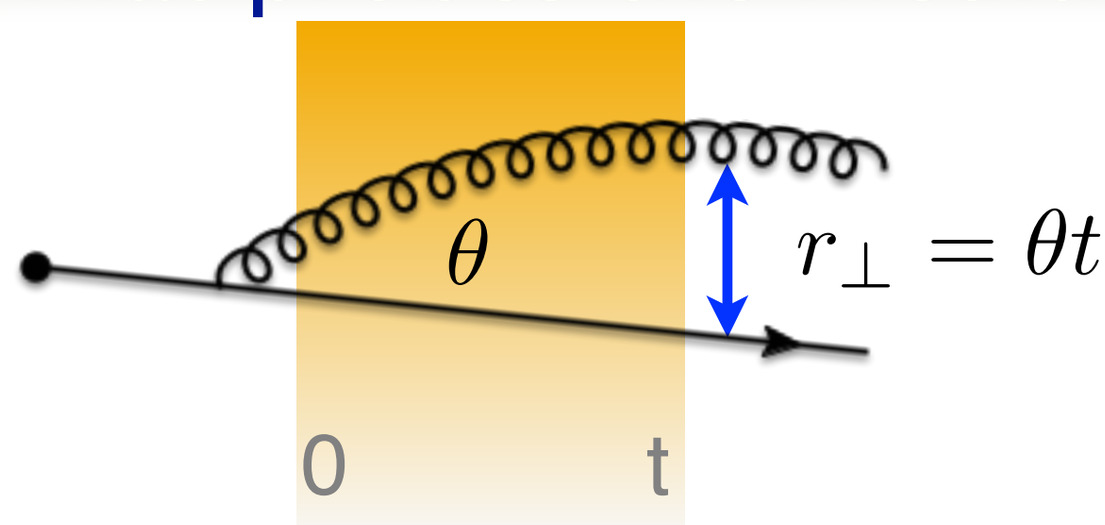
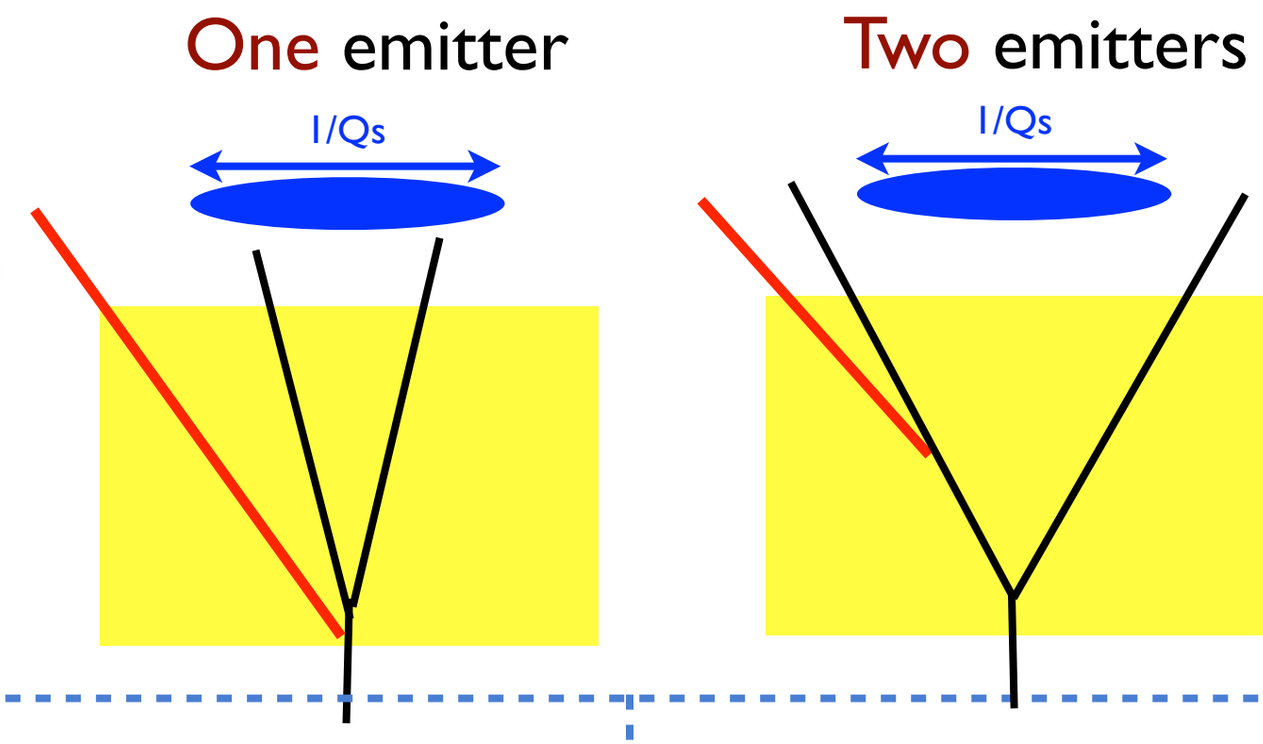
What probes the medium?



$$Q_{\rm hard} = \max\left(r_\perp^{-1}, Q_s\right)$$

$$k_\perp < Q_{\rm hard}$$



vacuum coherence (at large angles)	weak AAO,	AO completely broken, radiation up to k
"medium-induced"	radiation as total charge	radiation as independent charges

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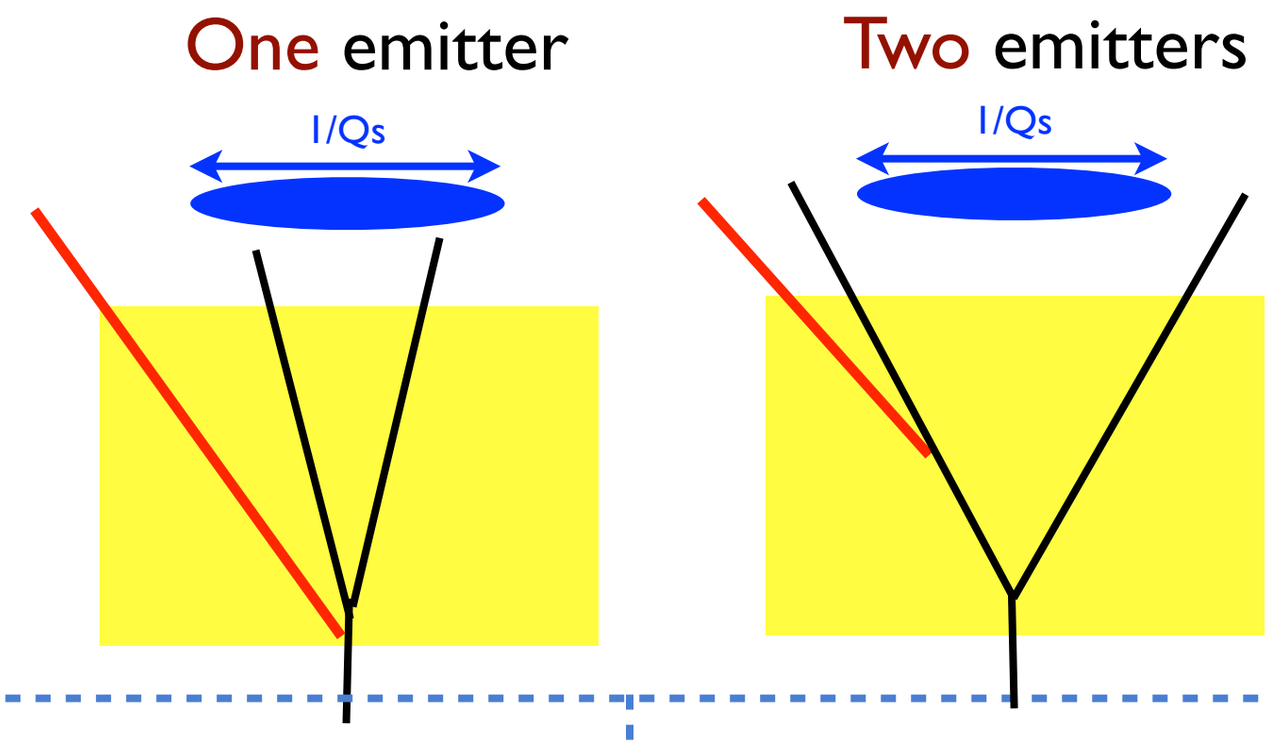

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→ importance of medium-resolved sub-jets!