Q-PYTHIA

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N. Armesto, L. Cunqueiro, CAS, arXiv:0907.1014

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What do we know

- *Jet quenching has been established at RHIC as a fundamental tool in the study of hot matter in heavy-ion collisions*
  - *Inclusive particle measurements*
- *"Radiative energy-loss" quite successful*
- *Vacuum (pQCD) needs of resummation of gluon radiation - DGLAP eqs. are "one piece" of the hard cross-section*

(Some) problems

- **Inclusive measurements have trigger bias effects**
  - *Average energy-loss not accurate. Solution: resum medium gluons independently (Baier et al, 2001)*
  - *Ok, for inclusive quantities (spectrum is finite)*
- **Difficult to deal with for more exclusive measurements**
- **Energy-momentum conservation**
- **Other effects could play a role**
  - *e.g. HQ still a problem*

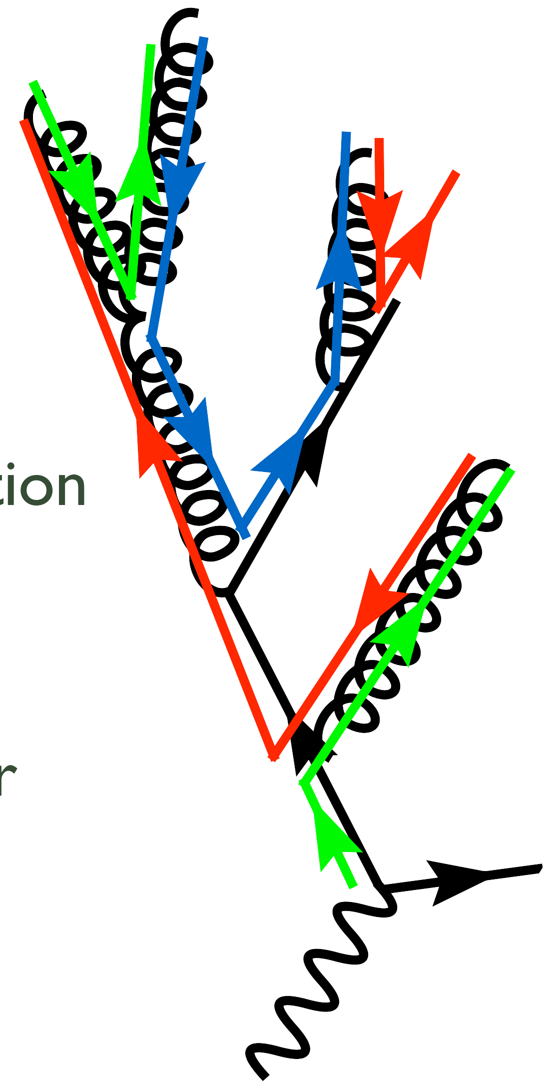
Jets and new developments

- **Exploratory studies up to now**
- **One main goal: to have a Monte Carlo implementation**
  - *Armesto, Corcella, Cunqueiro, Salgado (Q-PYTHIA, Q-HERWIG) **
  - *Zapp, Ingelman, Rathsman, Stachel, Wiedemann (JEWEL)*
  - *Lokhtin, Petrushanko, Snigirev, Teplov ... (PYQUEN)*
  - *Renk (YaJEM)*

* *Discussed here.*

Modifications of jet evolution I

- ⇛ Gluon multiplication is a building block of the hard cross sections
- ⇛ Medium-induced gluon radiation
  - Modifies the partonic structure
  - Larger multiplicities
  - Modified jet shapes (broadening...)
- ⇛ Non-eikonal corrections to the partons propagation in medium (a.k.a. collisional E loss)
- ⇛ Role of ordering variables
- ⇛ Modification of the color structure of the shower
- ⇛ Role of the non-perturbative hadronization
- ⇛ Energy flow from/to the medium



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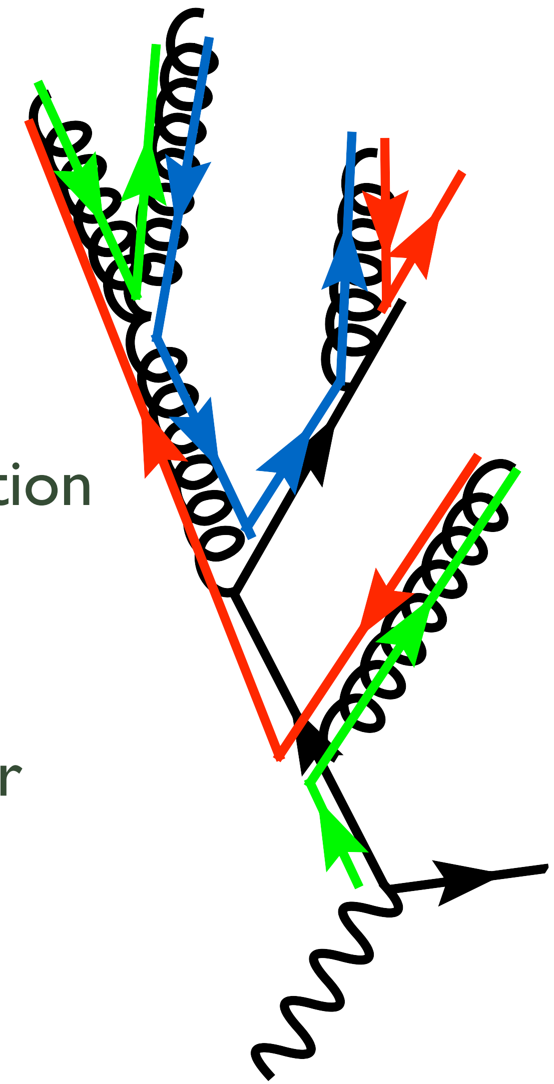


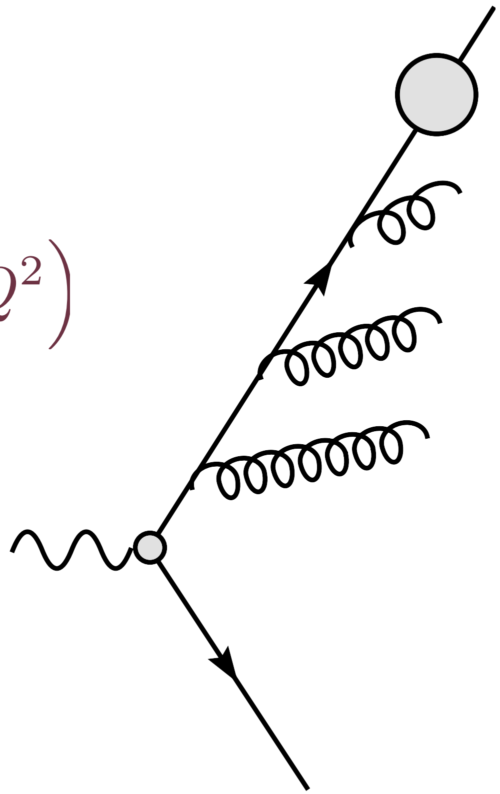
Ordering

- In the vacuum: an ordering variable exists, virtuality, angle...
  - Independent gluon emision except for the ordering
- The extension of the medium indicates that "time" should play a role as an ordering variable
  - Gluon formation time interferes with extension of the medium
  - **Space-time picture** of the showering becomes essential
  - What is the ordering variable for multiple gluon emision
- Here, we will assume that virtuality dictates ordering
- Formation-time effects will also be included
  - Mixed approach: ordering in virtuality (or angle) but some radiation is forbidden

Splitting probabilities

⇛ DGLAP evolution for FF in vacuum

$$\frac{\partial D_i^h(x,Q^2)}{\partial \log Q^2} = \sum_j \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{ji}(z) D_j\left(\frac{x}{z}, Q^2\right)$$



⇛ The splitting function controls the evolution

$$P(z) = C_F\left[\frac{1+z^2}{1-z}\right]$$

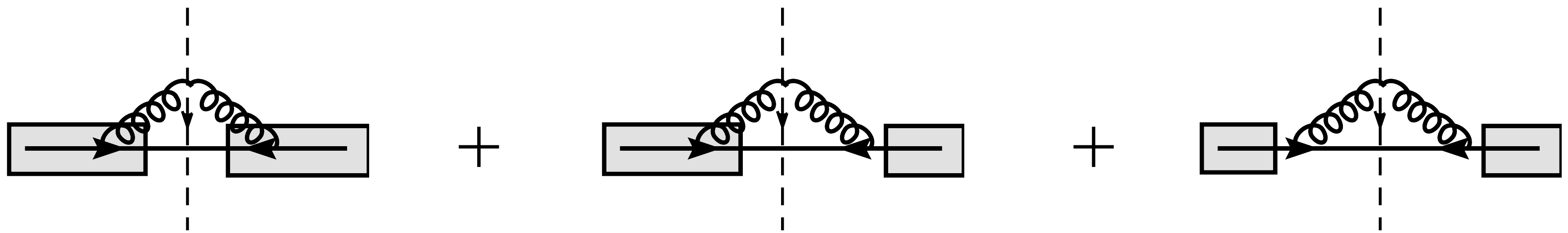
⇛ Proposal: define a medium-modified splitting probability

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z)$$

[Wang, Guo 2001; Borghini, Wiedemann 2005; Polosa, Salgado 2006; Armesto, Cunqueiro, Salgado, Xiang 2007; Majumder 2009...]

Medium-modified splittings

⇛ Remember that the total gluon radiation has vacuum+medium



$$\frac{dI}{dzdk_\perp^2} = \frac{dI^{\rm med}}{dzdk_\perp^2} + \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)$$

⇛ So, define the medium-modified part of the splitting probability as

$$\frac{dI}{dzdk_\perp^2} = \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}\Delta P^{\rm med}(z) + \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z) \quad \Longrightarrow \quad \Delta P(z) \equiv \frac{2\pi k_\perp^2}{\alpha_s}\frac{dI^{\rm med}}{dzdk_\perp^2}$$

[Polosa, Salgado 2006; Armesto, Cunqueiro, Salgado, Xiang 2007; Armesto, Cunqueiro, Salgado 2009; also Wang, Guo, Majumder; Borghini, Sapeta, Wiedemann]

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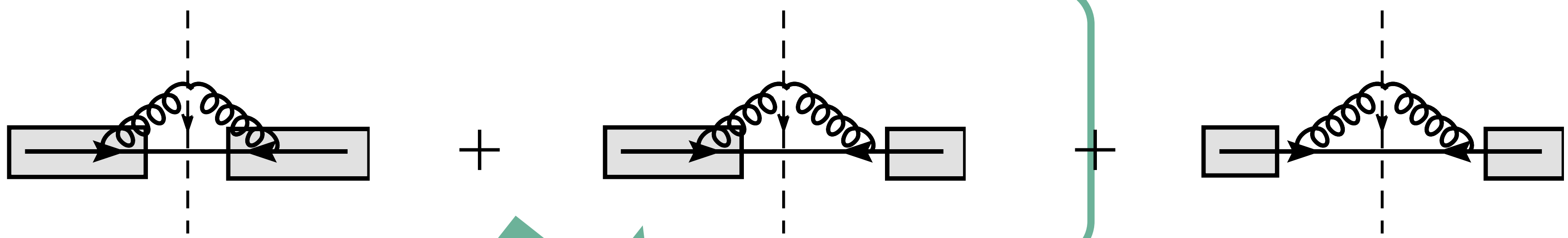

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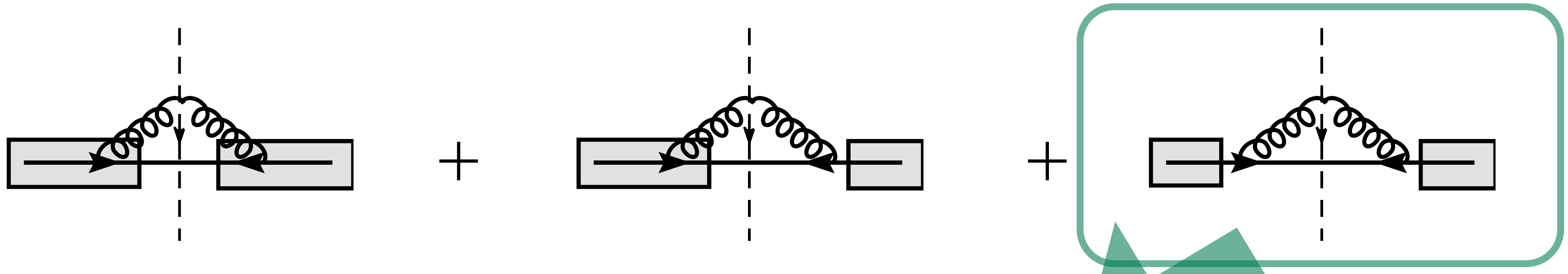

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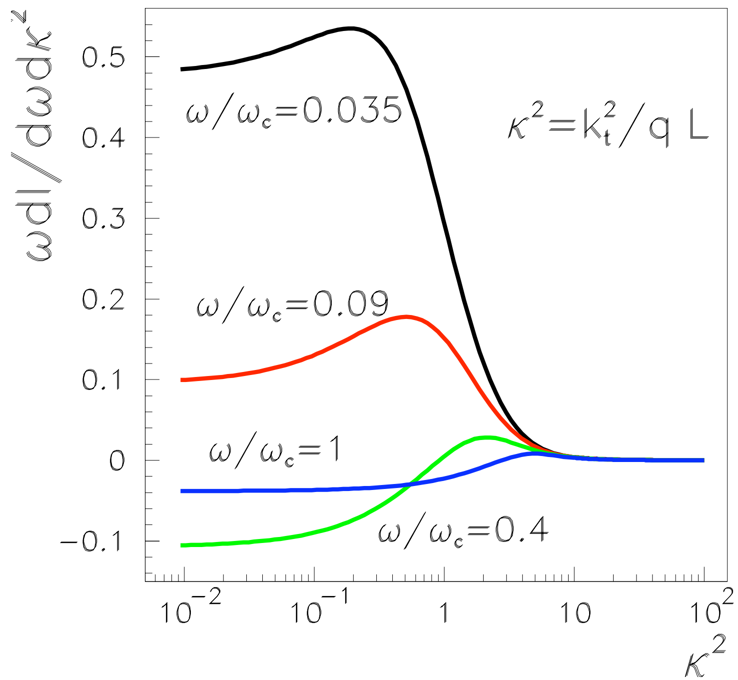
The medium-induced gluon radiation

⇛ **Numerical results** $\kappa^2 = \frac{k_\perp^2}{\hat{q} L} \quad \omega_c = \frac{1}{2}\,\hat{q}\,L^2$

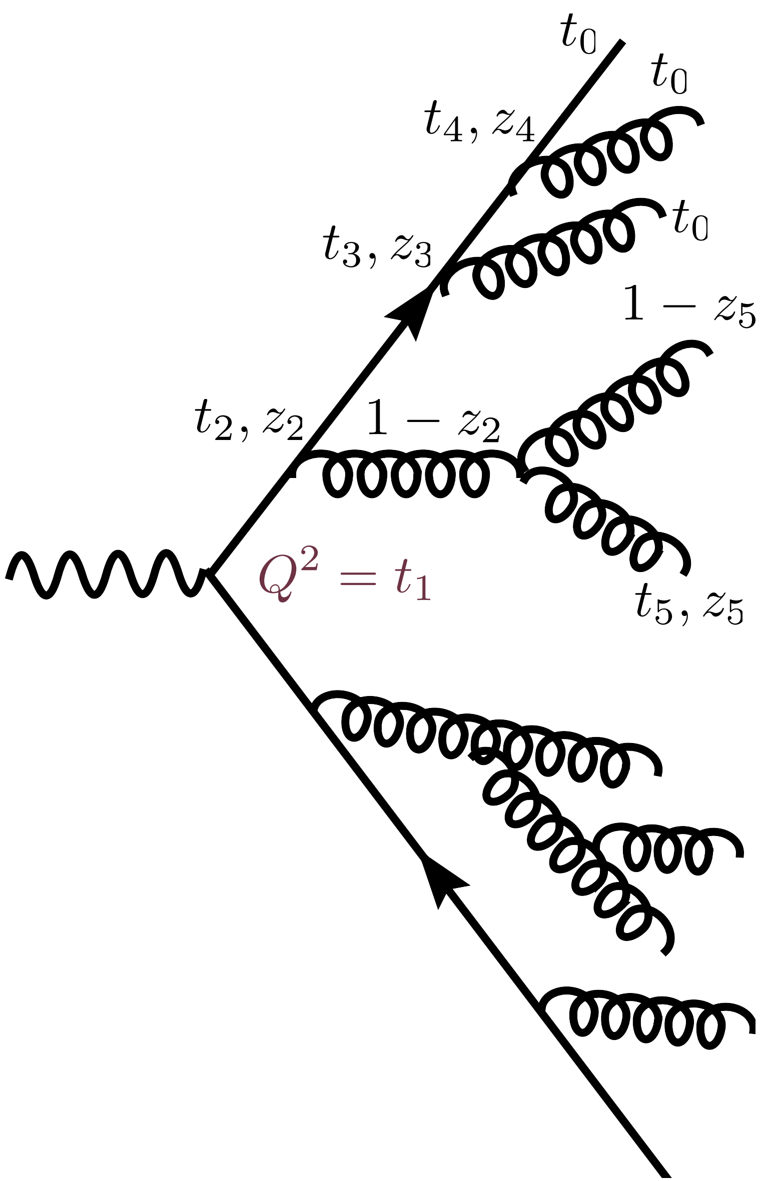


⇛ **Transport coefficient (a.k.a. jet quenching parameter)**

$$\hat{q} \simeq \frac{\langle k_\perp^2 \rangle}{\lambda}$$

Monte Carlo implementation

Branching process in MC parton showers



$t_1 > t_2 > t_3 > \cdots > t_0 = \mathcal{O}(1\,\mathrm{GeV}^2)$

1) The hard process is generated
   - i) Virtuality $Q^2 = t_1$

2) Resolvable branching at (t_2, z_2)
   - i) Gives qg with fract. of momentum z_2
   - ii) q branches again at (t_3, z_3)
   - iii) q branches again at (t_4, z_4)
   - iv) No branching is found with $t < t_0$
     - → Branching stops

3) Gluon branches at (t_5, z_5)
   - i) No branching is found with $t < t_0$
     - → Branching stops

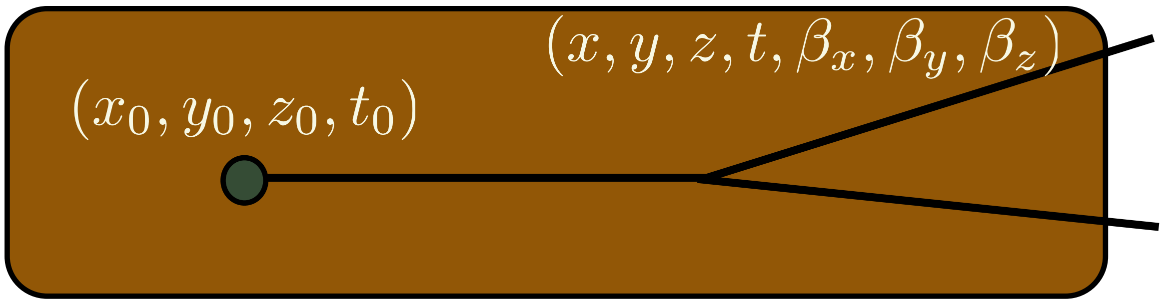
4) Distribution of gluons in the final state has to be hadronized

Q-PYTHIA

- Fortran program, uses PYTHIA-6.4.18 defaults.
  - We modify *only* PYSHOW, providing additional auxiliary routines: black box for the user.
  - So, Q-PYTHIA is usual PYTHIA with a modified parton shower

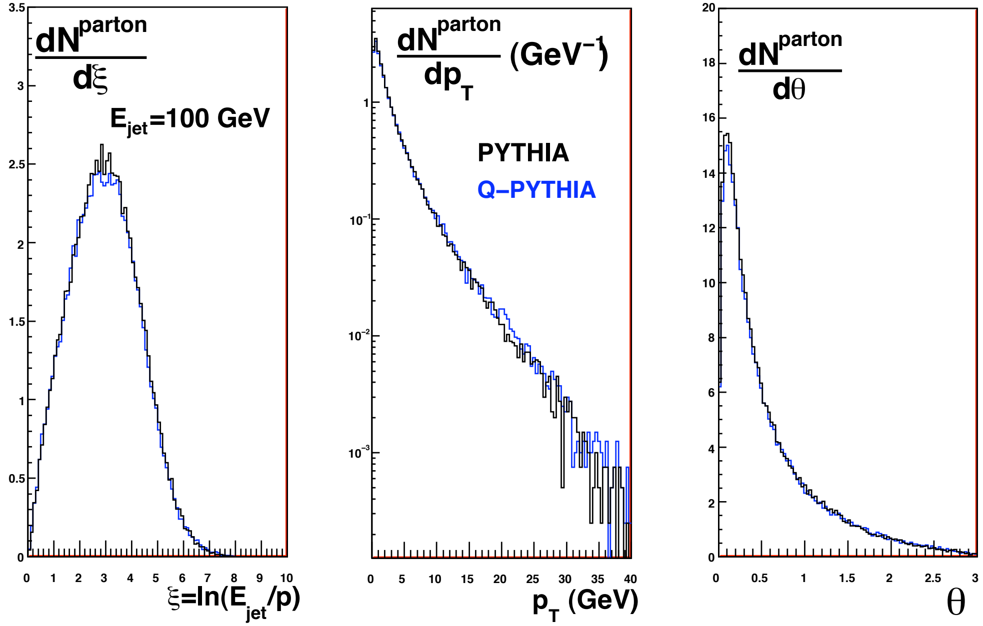
[Notice, however, that this is not an official PYTHIA release]

- User-defined:
  - **QPYGIN**: Position of hard scattering - jet origin - (x_0, y_0, z_0, t_0)
  - **QPYGEO**, which contains medium modelling: Values of $\hat{q}L$ and $\omega_c = \hat{q}L^2/2$ at point of branching $(x, y, z, t, \beta_x, \beta_y, \beta_z)$



The modifications in PYTHIA I

- We include a new contribution to the splitting probability
- However, PYSHOW uses the small-x approximation
  - First: include exact splitting functions and numerical integrate



- First check: we recover usual PYTHIA results

The modifications in PYTHIA II

- Next: change the splitting functions (as explained before)

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z)$$

- Ordering:
  - Dice the radiation with usual PYTHIA (virtuality)
  - Correct for formation time

$$t_{\rm form} \simeq \frac{2\omega}{k_t^2}$$

  - We need to evaluate $\Delta P(z, t, E, \hat{q}, L)$
  - First splitting: L
  - Second splitting: $L - t_{\rm form,1}, \;\; L - t_{\rm form,1} - t_{\rm form,2}$,....
  - (Energy evolution is also included)

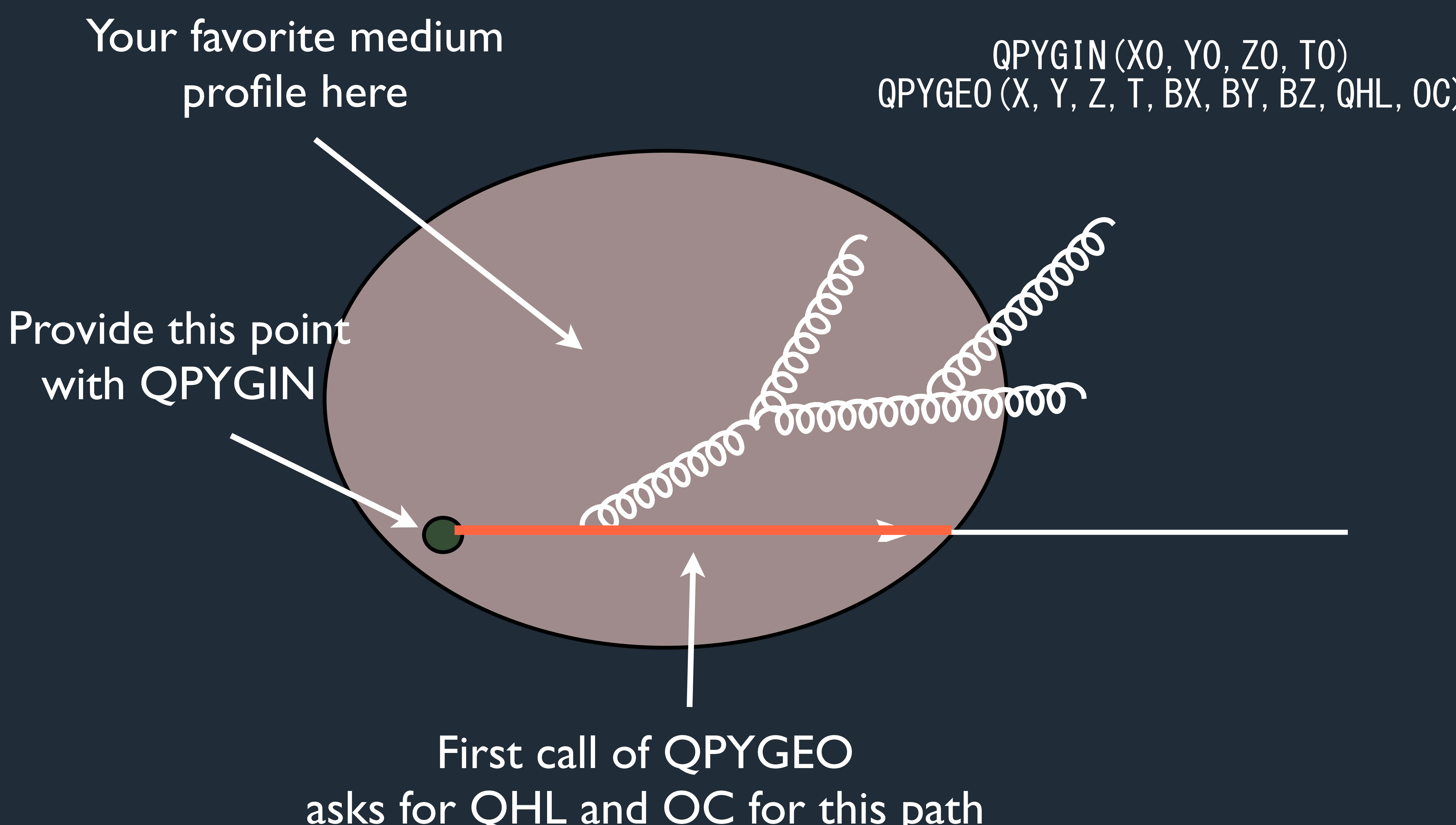
Routines QPYGIN and QPYGEO

⇛ Transparent for the user through geometry routines

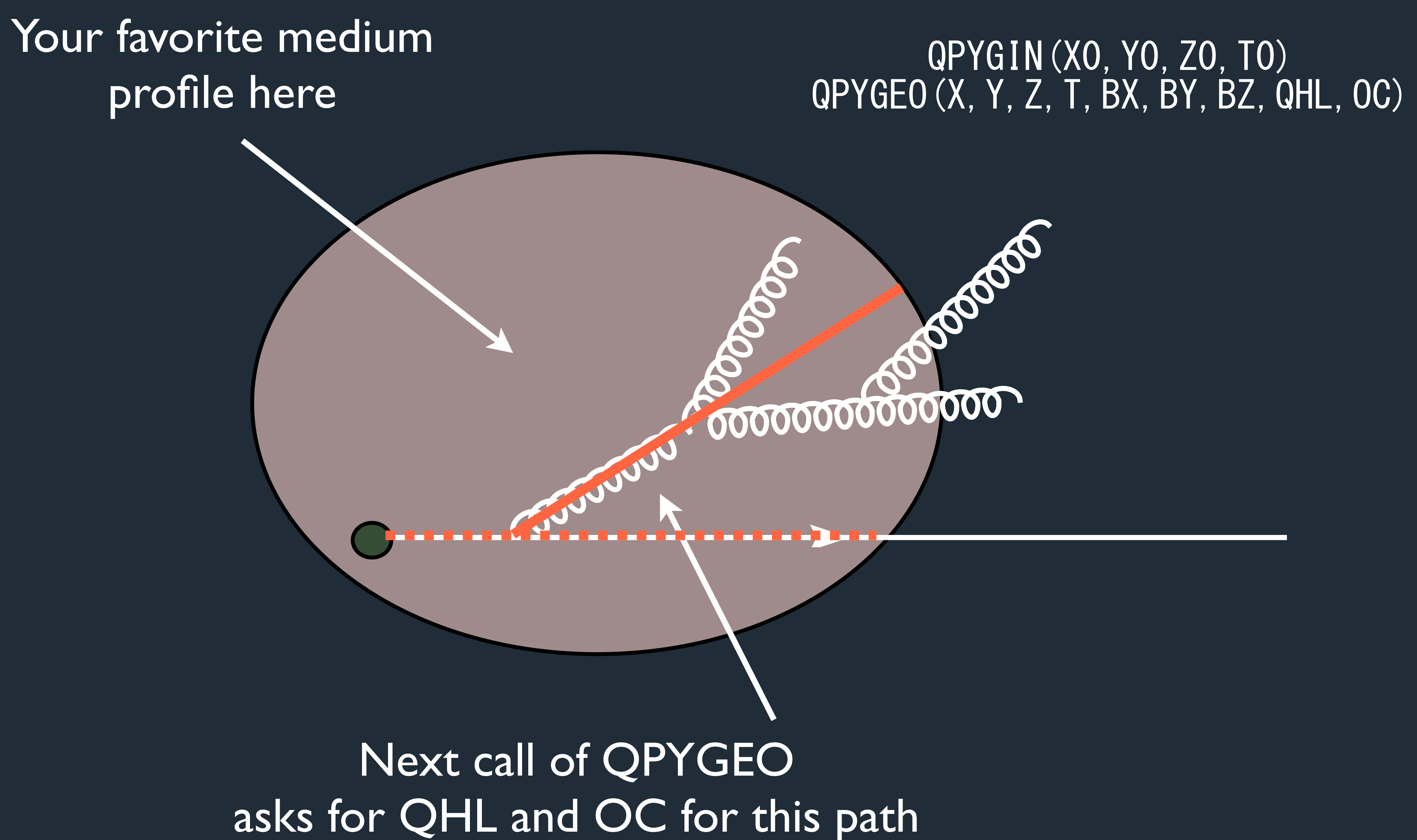
```
      SUBROUTINE QPYGIN(X0,Y0,Z0,T0)
C     USER-DEFINED ROUTINE: IT SETS THE INITIAL POSITION AND TIME OF THE
C     PARENT BRANCHING PARTON (X, Y, Z, T, IN FM) IN THE CENTER-OF-MASS
C     FRAME OF THE HARD COLLISION (IF APPLICABLE FOR THE TYPE OF EVENTS
C     YOU ARE SIMULATING). INFORMATION ABOUT THE BOOST AND ROTATION IS
C     CONTAINED IN THE IN COMMON QPLT BELOW.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C     NOW THE COMMON CONTAINING THE VALUES OF THE TWO ANGLES AND THREE BOSST
C     PARAMETERS USED, IN PYSHOW, TO CHANGE THROUGH PYROBO FROM THE
C     CENTER-OF-MASS OF THE COLLISION TO THE CENTER-OF-MASS OF THE HARD
C     SCATTERING. THEY ARE THE ENTRIES THREE TO SEVEN IN ROUTINE PYROBO.
      COMMON/QPLT/AA1,
C     Example valid fo
      x0=0.d0 ! fm
      y0=0.d0 ! fm
      z0=0.d0 ! fm
      t0=0.d0 ! fm
```

```
      SUBROUTINE QPYGEO(X,Y,Z,T,BX,BY,BZ,QHL,OC)
C     USER-DEFINED ROUTINE:
C     The values of qhatL and omegac have to be computed
C     by the user, using his preferred medium model, in
C     this routine, which takes as input the position
C     x,y,z,t of the parton to branch, the trajectory
C     defined by the three-vector bx,by,bz,
C     (all values in the center-of-mass frame of the
C     hard collision), and returns the value of qhatL
C     (in GeV**2) and omegac (in GeV).
```

How to use the geometry routines



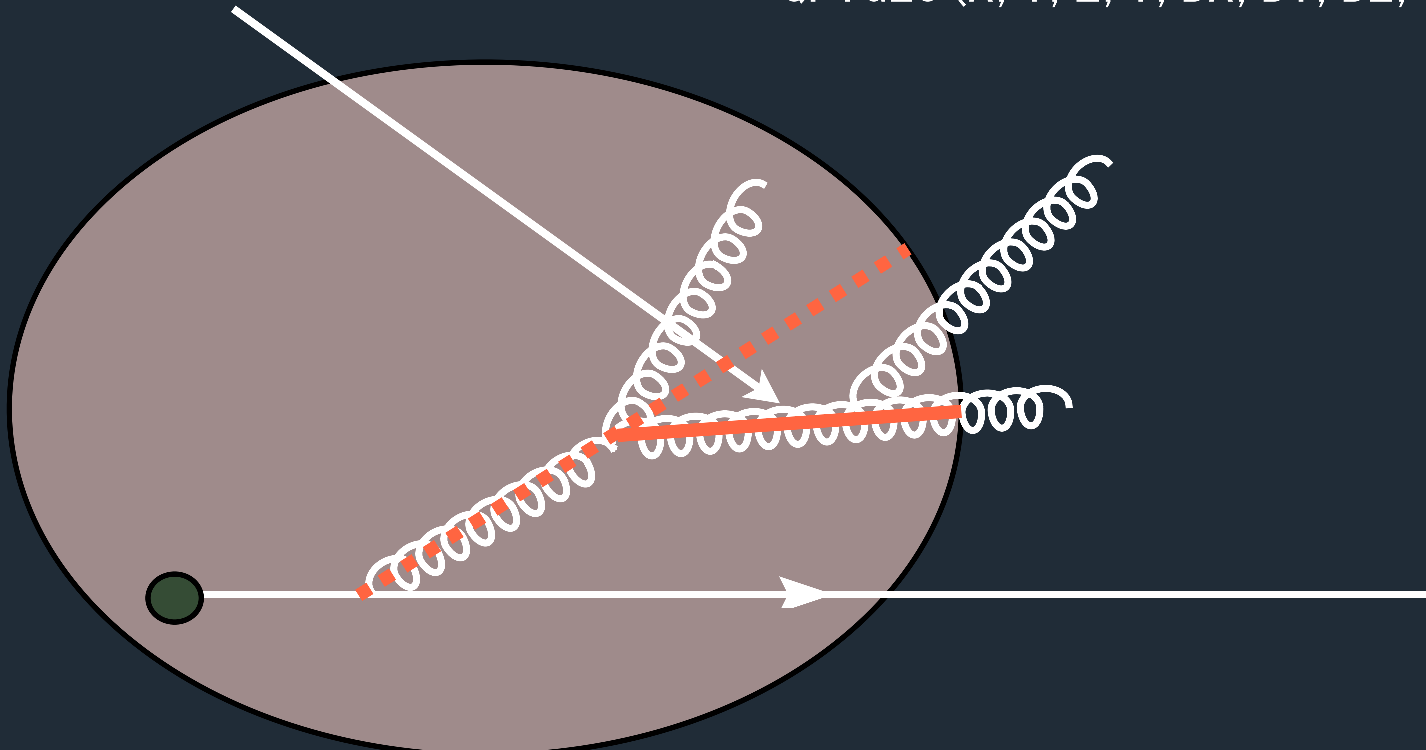
How to use the geometry routines



How to use the geometry routines

Next call of QPYGEO
asks for QHL and OC for this path

QPYGIN(X0, Y0, Z0, T0)
QPYGEO(X, Y, Z, T, BX, BY, BZ, QHL, OC)

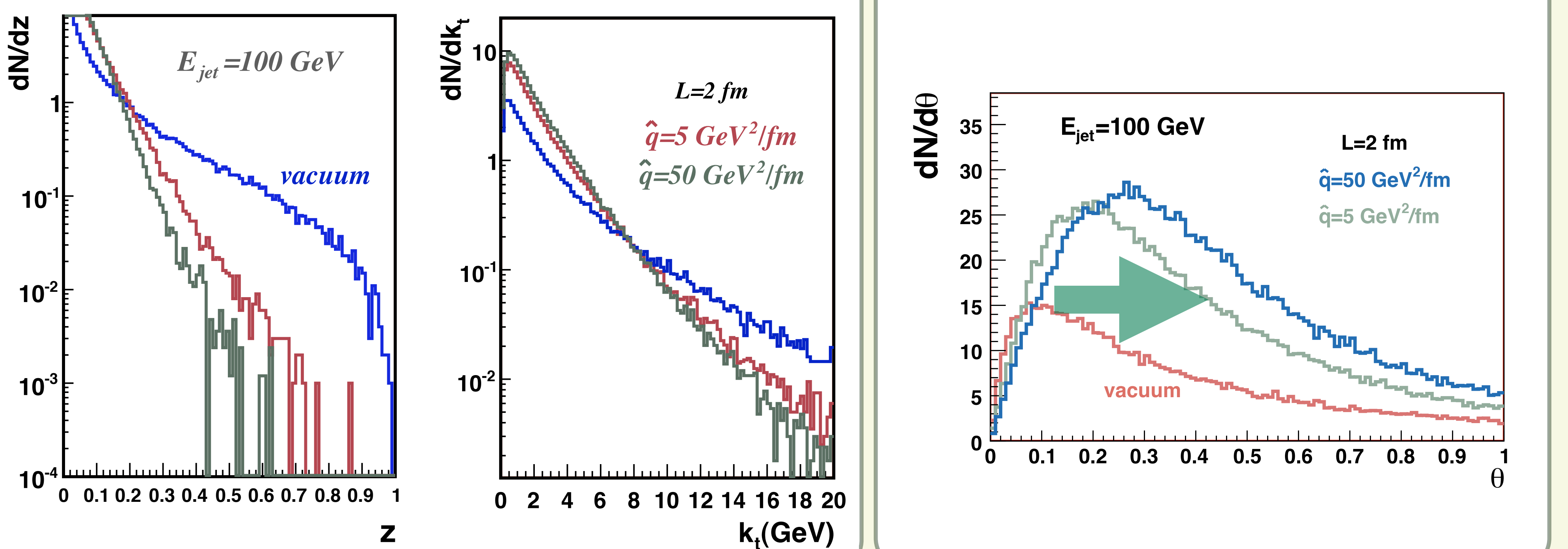


etc...

Results from Q-PYTHIA

Fragmentation function

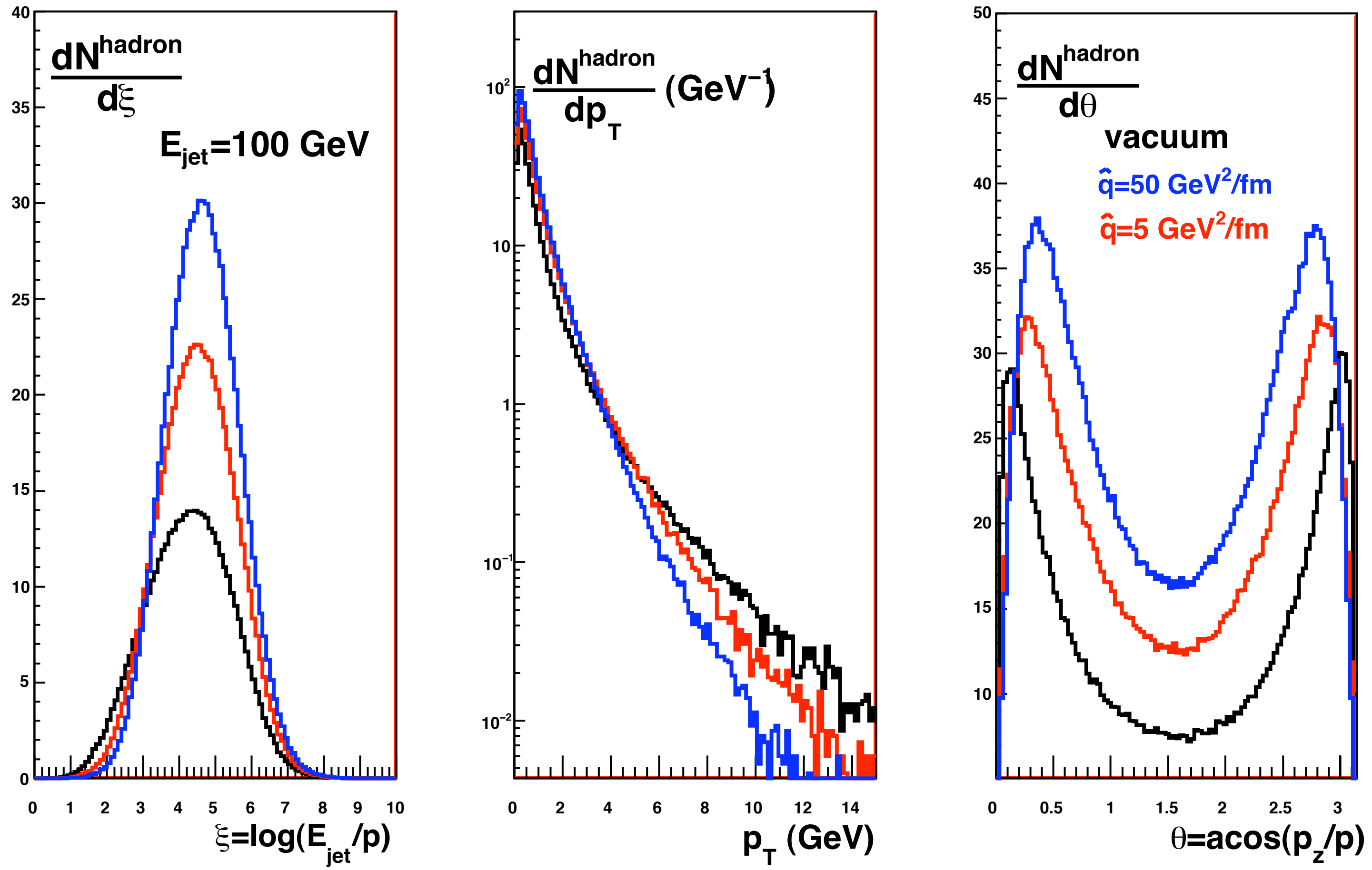
Angular distribution



⇒ Main medium-modifications in agreement with expectations

- Particle spectrum softens (energy loss)
- Larger emission angles (jet broadening)
- Larger multiplicity

Results including hadronization



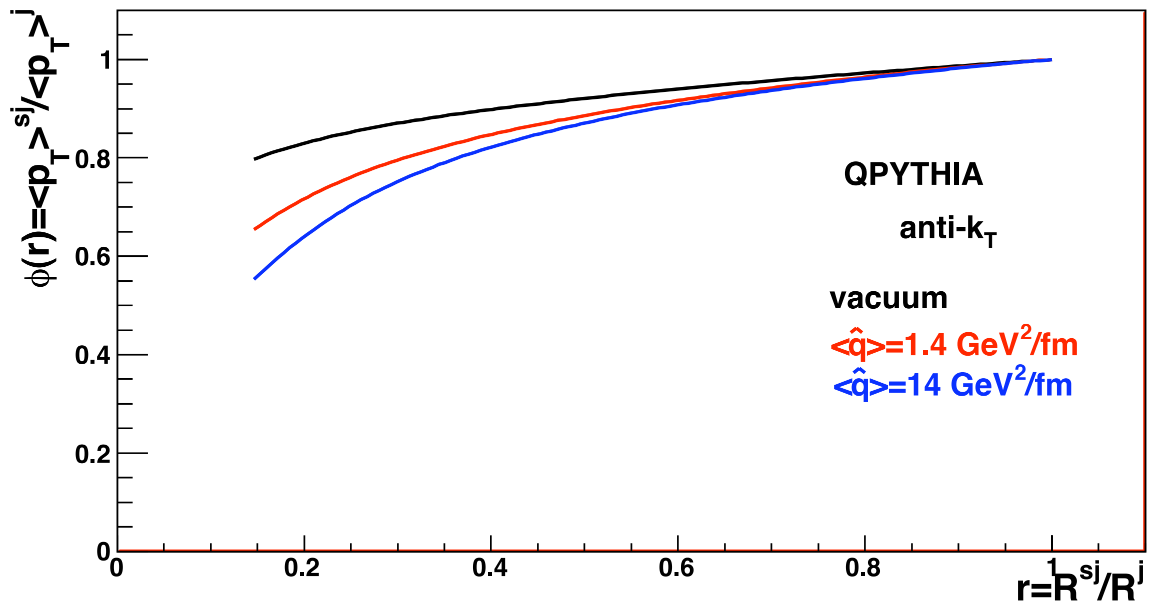
⇛ Effects are reduced by hadronization

⇛ Comparison of different hadronization models is important:

PYTHIA (string fragmentation) vs HERWIG (cluster hadronization)

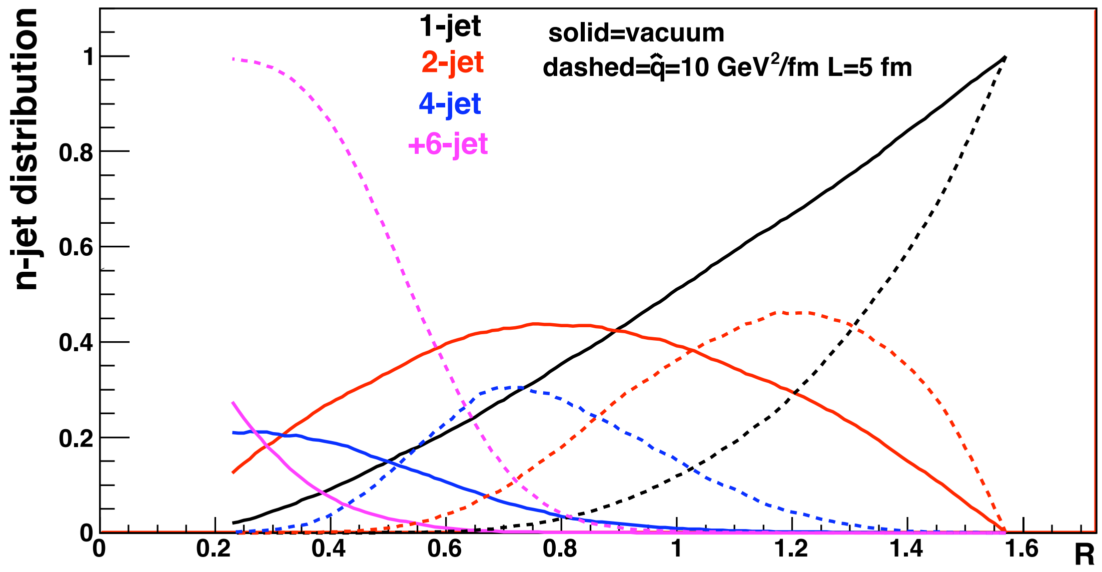
Jet shapes

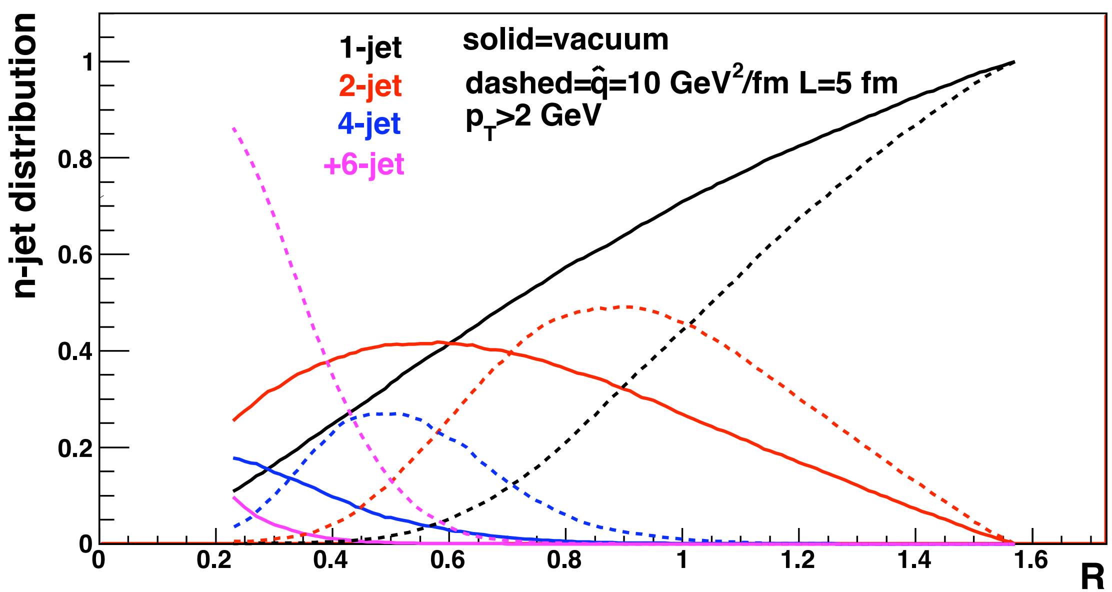
PQM geometry [Dainese, Loizides, Paic, 2004]



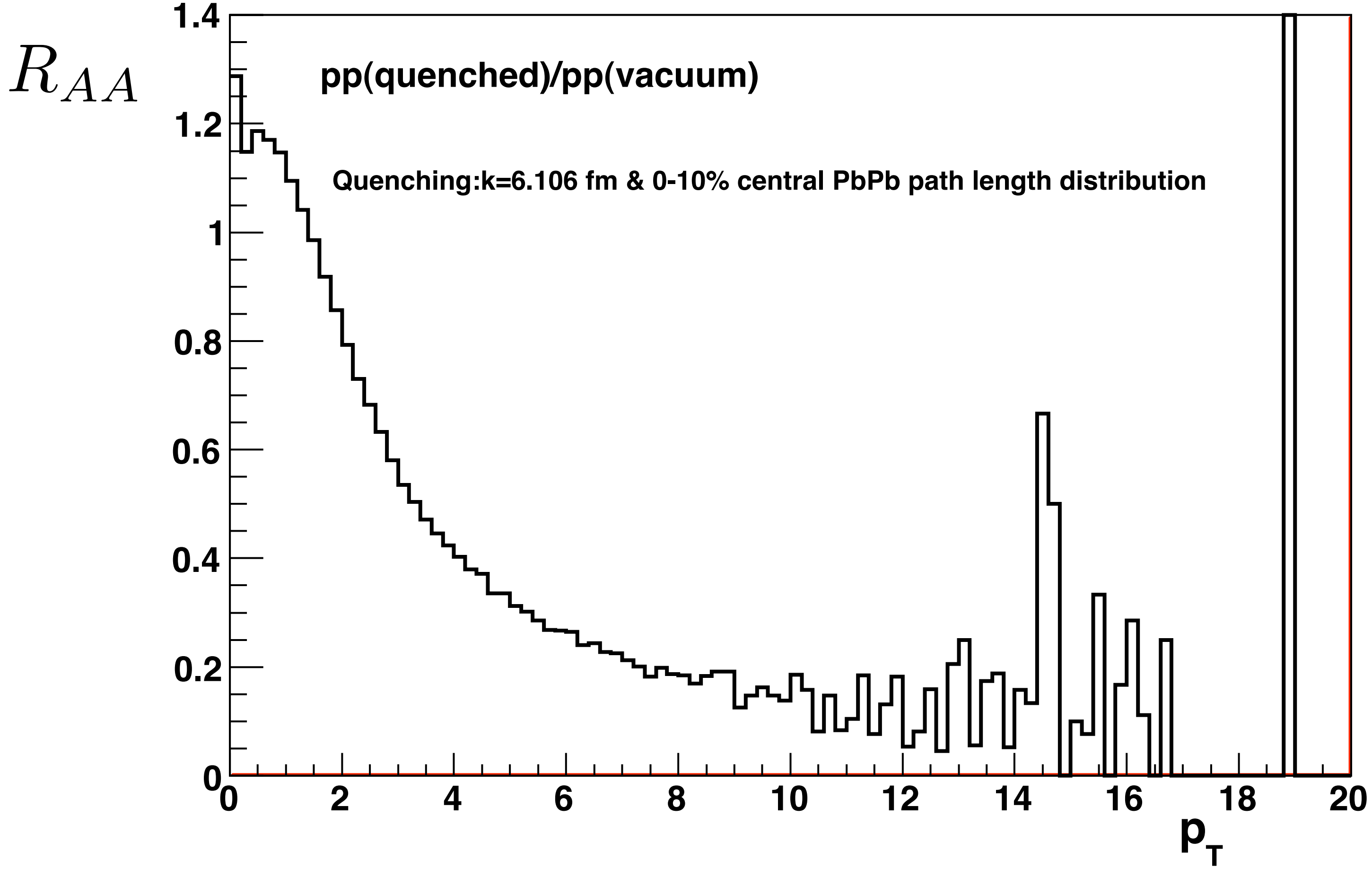
[Very idealized analysis - no background, etc...
more realistic calculation needed]

n-jet distributions





A check of consistency



PQM geometry [Dainese, Loizides, Paic, 2004]

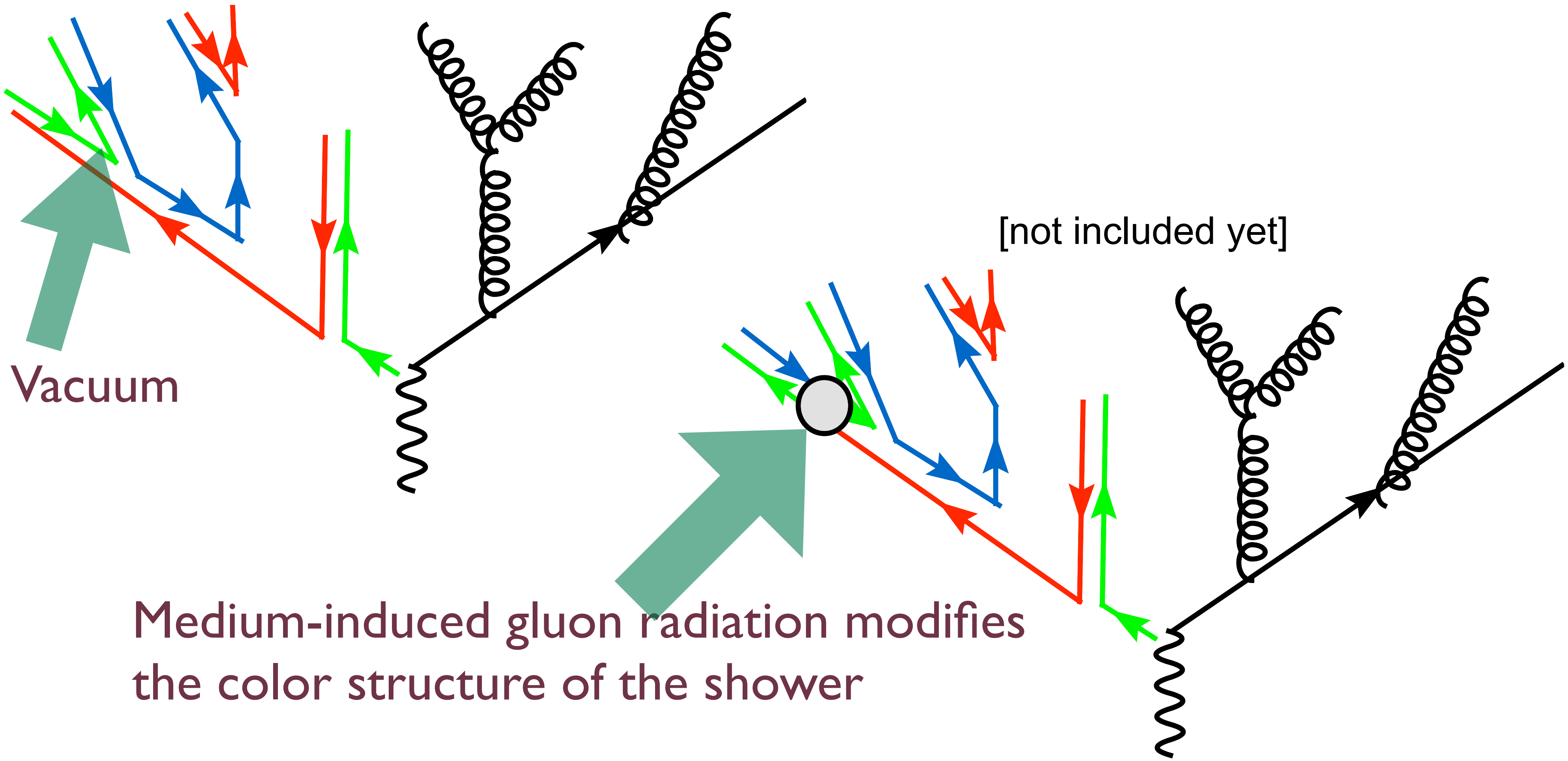
Future work

- Color structure of the shower
- Finite energy corrections to splitting functions
  - Elastic energy loss
- Interplay between virtuality and length
  - Space-time picture of the parton shower
  - Ordering variable in the medium case
- Role of hadronization: different models
- Energy flow from/to the medium
- Jet reconstruction in realistic environment

Color connections in the medium

⇛ The interaction of the radiated gluon with the medium is given by color exchange

- The color structure of the jet shower is modified



The brick...

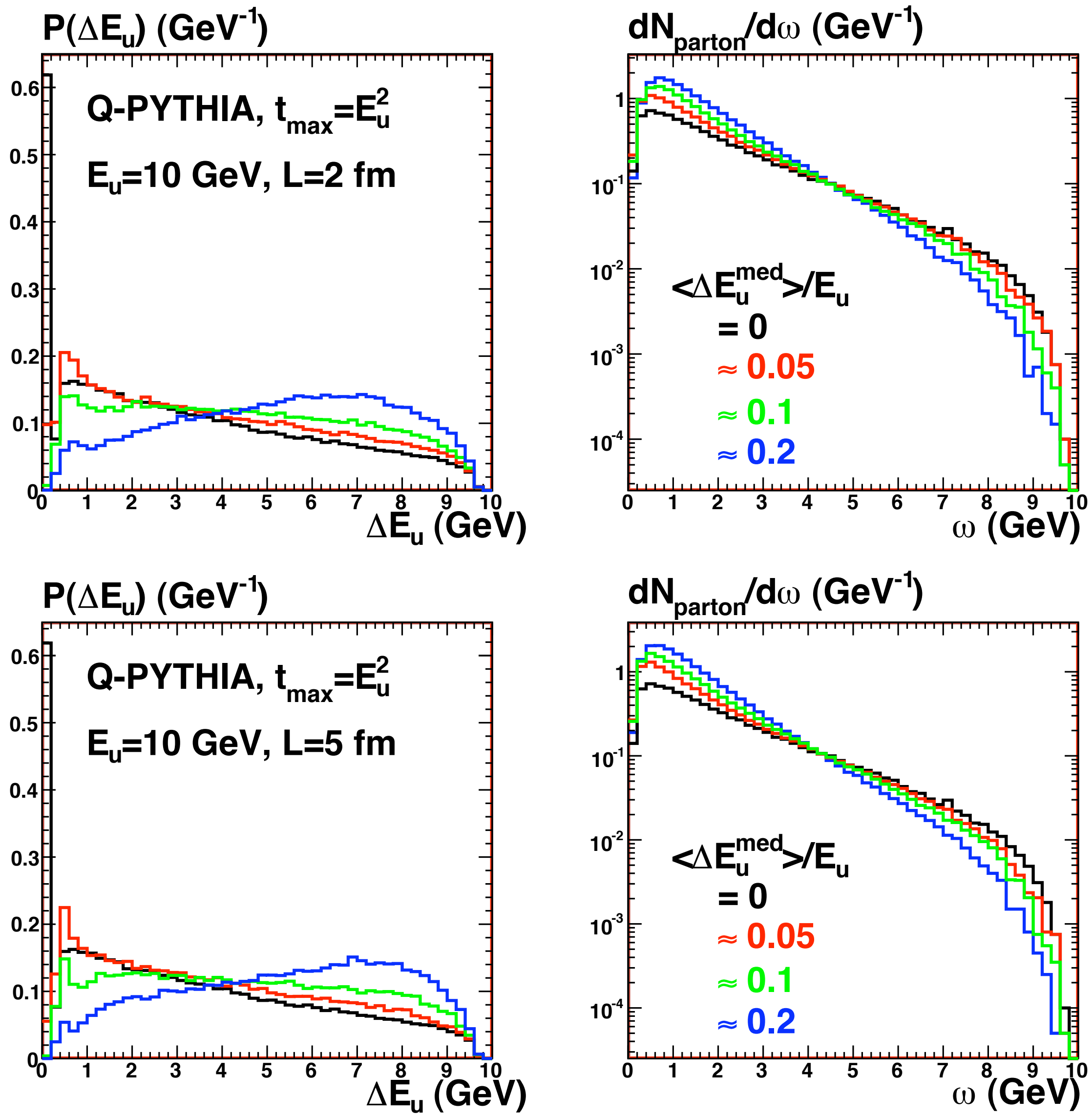
Not trivial in a MC. Our setup:

- *We start from a u quark at a given energy and look for the most energetic u quark in the final state*
- *The amount of energy loss in the vacuum is already rather large. This makes it difficult in the medium to reach the requested losses*

Results for the brick I

	E=10 GeV			E=100 GeV		
	$\hat{q}$	$\langle \Delta E \rangle$	$\langle n_p \rangle$	$\hat{q}$	$\langle \Delta E \rangle$	$\langle n_p \rangle$
Vacuum		3.411	1.67		49.098	5.28
L=2 fm	0.35	3.932	2.16	0.50	53.373	6.72
	1.50	4.437	2.62	3.00	59.759	9.18
	20.0	5.257	3.19	30.00	67.982	13.32
L=5 fm	0.12	3.924	2.30	0.15	53.401	6.90
	0.30	4.512	2.82	0.40	59.174	9.10
	0.90	5.354	3.56	3.00	69.689	14.70
				50.00	87.929	26.44

Results for the brick II



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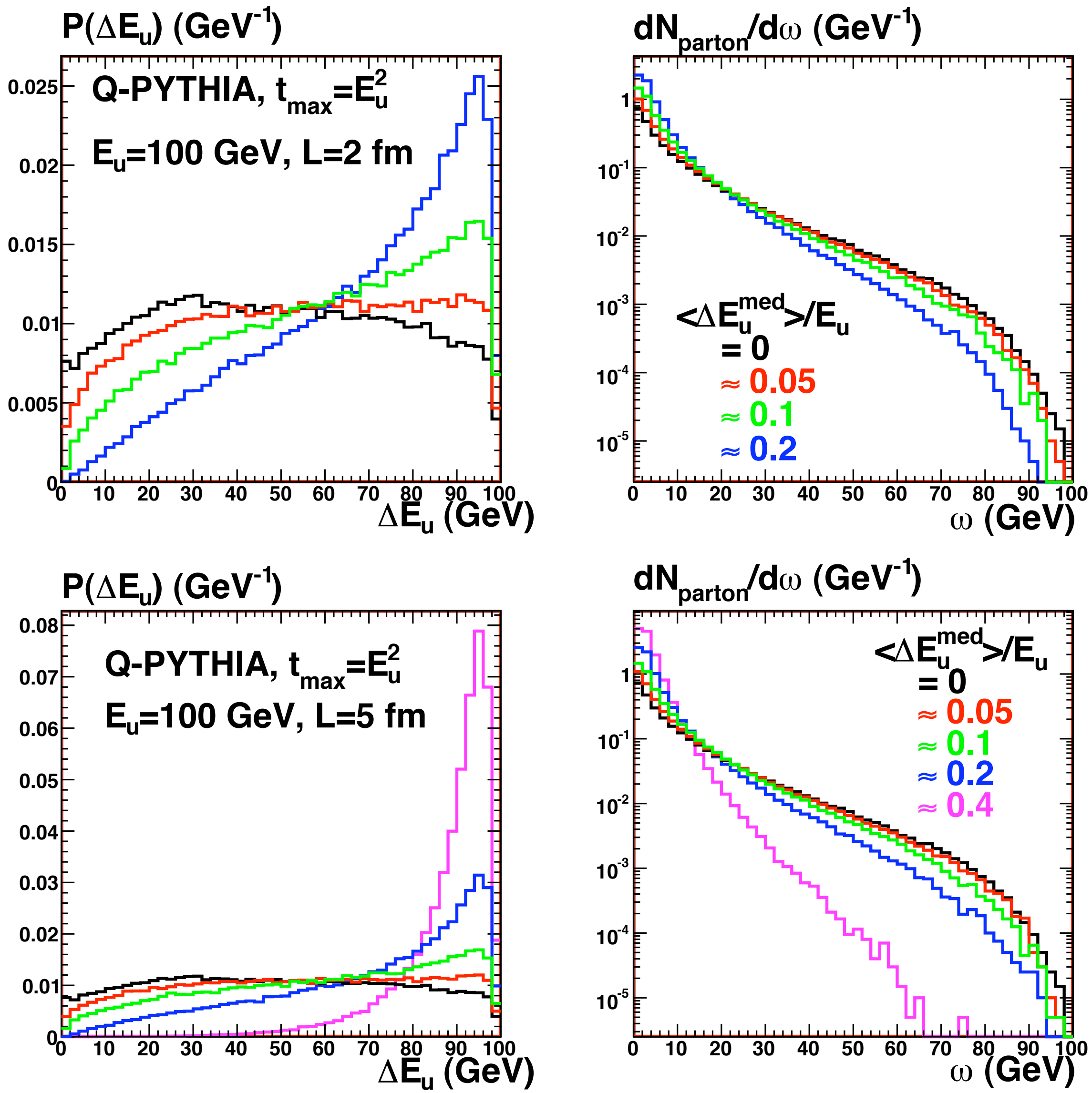

Summary

- Modified splitting functions in PYTHIA & HERWIG
  - Vacuum and medium treated on the same footing
  - Role of virtuality; energy conservation; length; ...
- Allows phenomenological studies in experimental conditions
- Publicly available code Q-PYTHIA v1.0.1 at Q@MC site:

  http://igfae.usc.es/QatMC