(Q-PYTHIA: a) Monte Carlo Framework for Jet Quenching

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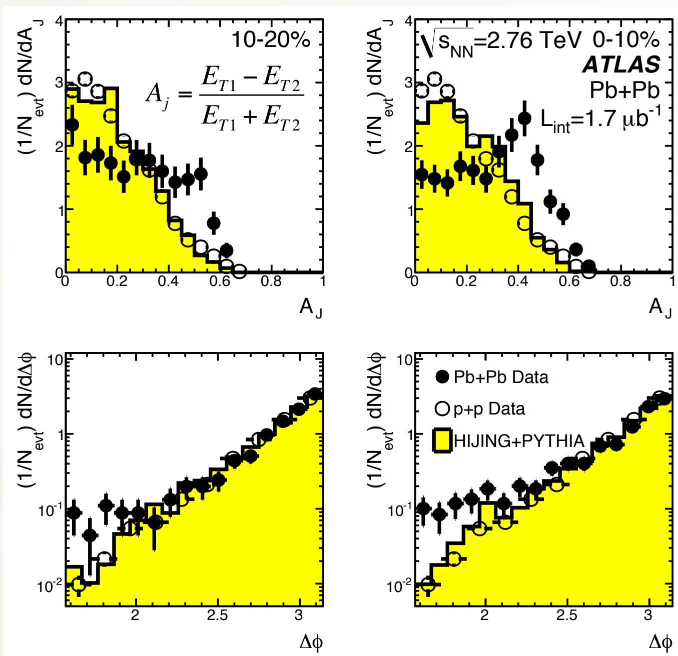
High-pt Probes of High Density QCD at the LHC

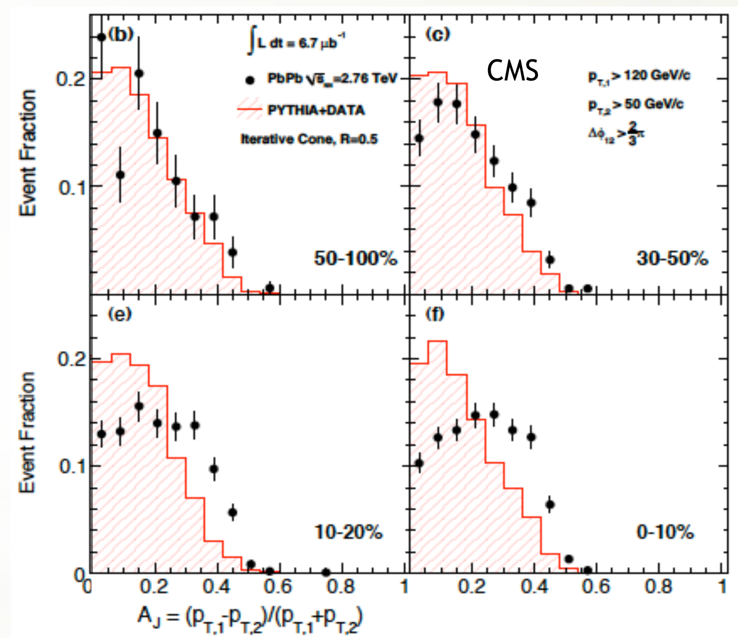
May 30th - June 1st, 2011

École Polytechnique, Palaiseau

Introduction

- Jet Quenching has been established as a fundamental tool to study hot matter in HIC: already at the LHC!!!





Di-jet Asymmetry

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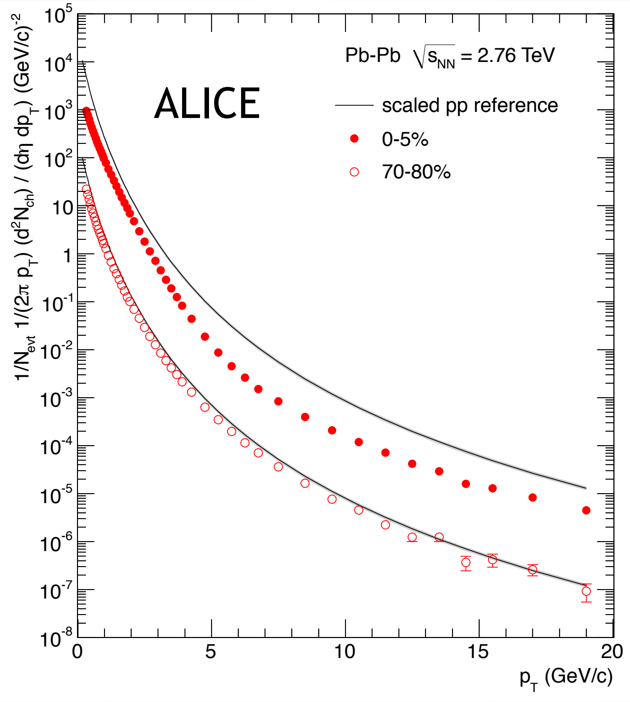
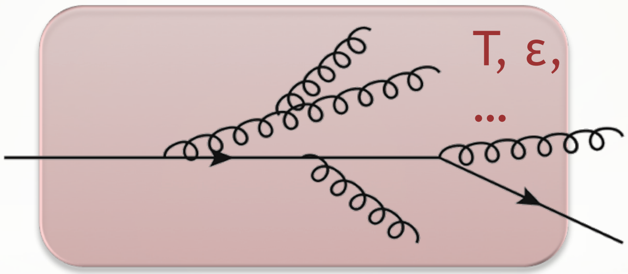


Suppression of high-pT spectrum

Introduction

- How does the medium modify a jet?
  - Radiative energy loss of a high-energy parton
    - Modification of the standard QCD radiation pattern
  - Energy loss ⟷ T, ε, ..



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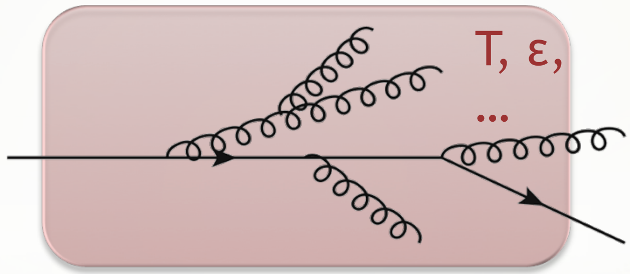

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  - high-energy approximation
  - assumptions on multiple emissions

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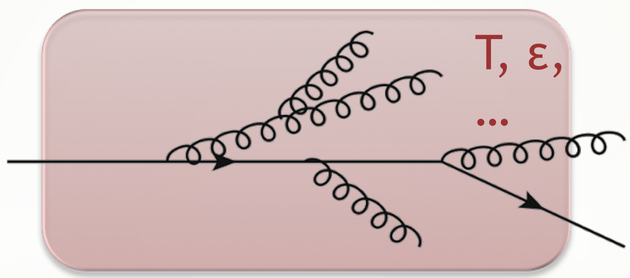
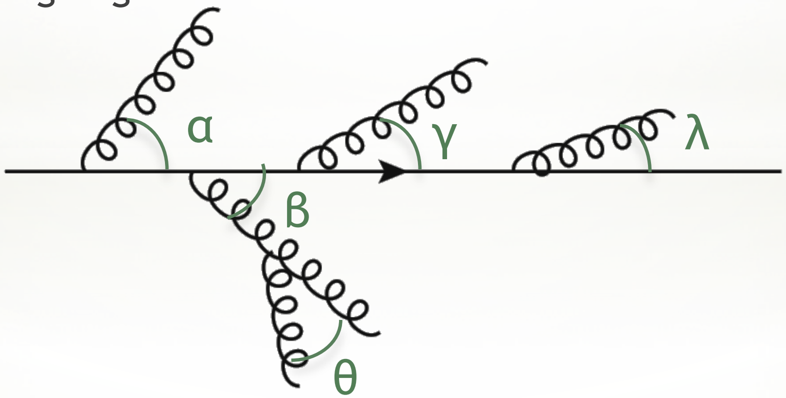


- Analytic existing formalisms (BDMPS/ASW/GLV, AMY, HT) rely on:
  - high-energy approximation
  - assumptions on multiple emissions

→ Monte Carlo (PYQUEN, YaJem, Q-PYTHIA/HERWIG, HIJING, MARTINI,...)

Jet Formation

- Vacuum (PYTHIA, HERWIG, SHERPA):
  - Process of branching characterized by $P_{a\rightarrow bc}$: splitting functions
  - Each parton characterized by some virtuality scale, Q^2 ($t=m^2$, p_t^2, θ: all of them equivalent at high energies)
  - Evolution downwards in Q^2 ('time' ordering)
  - Color coherence effects essential
    - Ordering of subsequent independent emissions in terms of decreasing angle



$\alpha > \beta > \gamma > \lambda$

$\beta > \theta$

Jet Formation

- Medium (Q-PYTHIA):
  - Medium-induced gluon radiation taken as the main ingredient
  - Presence of a medium
    - Time should play a role as an ordering variable
    - Ordering variable for multiple gluon emission?
      - Assume $Q^2 = m^2$ but eventually correct for the finite formation time of the gluons
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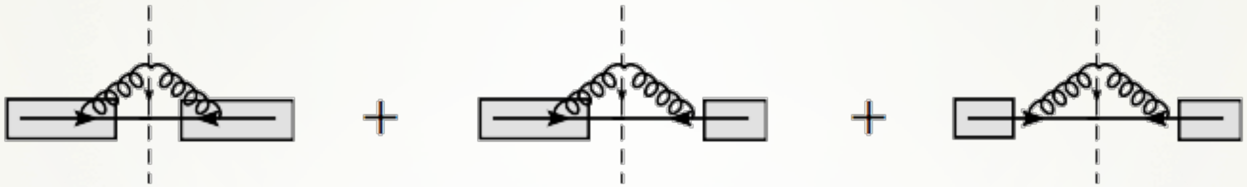
    - Independence of multiple gluon emission when re-scattering with the medium as in vacuum
  - Does not consider:
    - Recoil (elastic energy loss)
    - Modification of the color structure of the shower by exchanges with the medium
    - Back-reaction
    - In-medium hadronization

Splitting Functions

- Total medium-induced radiation spectrum



$$\frac{dI^{\rm tot}}{dz\, d\mathbf{p}_T^2} = \frac{dI^{\rm vac}}{dz\, d\mathbf{p}_T^2} + \frac{dI^{\rm med}}{dz\, d\mathbf{p}_T^2}$$

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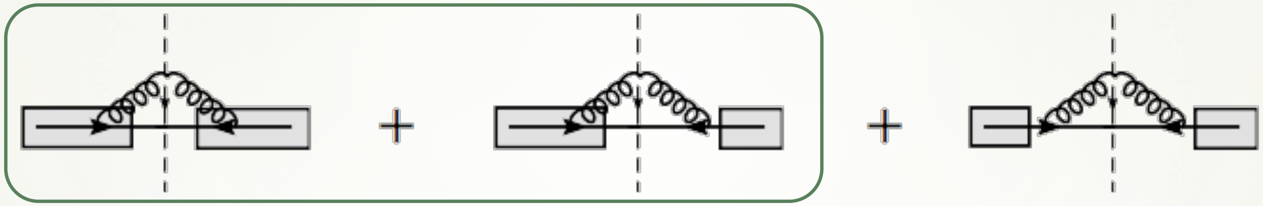

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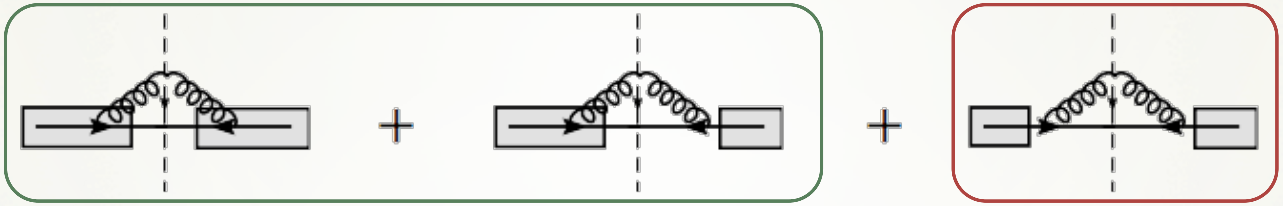

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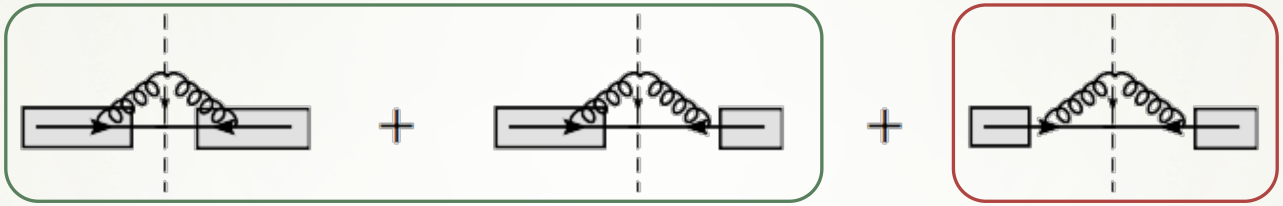

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- Analogy with the soft limit of the vacuum part: define medium-modified part of the splitting function as:

$$\Delta P(z,t) \simeq \frac{2\pi t}{\alpha_s}\frac{dI^{\text{med}}}{dzdt}$$

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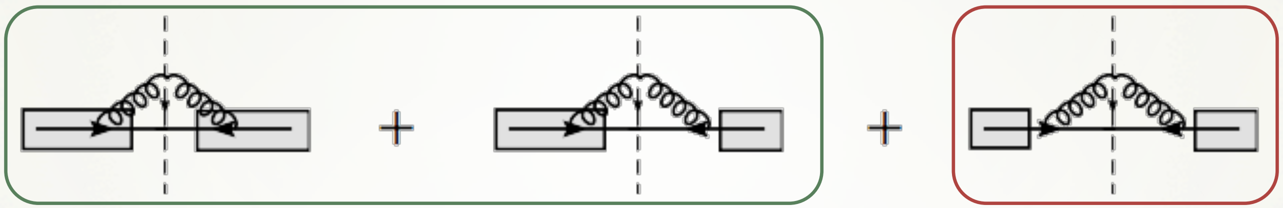

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  - Extension to hard emission as in vacuum

Sudakov Form Factor

- Implementation of the t-ordered final state radiation routine in PYTHIA:
  - Probabilistic interpretation of DGLAP evolution:

$$D(x,t) = \underbrace{\Delta(t) D(x,t_0)}_{\text{No splitting between } t_0 \text{ and } t} + \underbrace{\Delta(t) \int_{t_0}^{t} \frac{dt_1}{t_1} \frac{1}{\Delta(t_1)} \int \frac{dz}{z} P(z) D\left(\frac{x}{z}, t_1\right)}_{\text{Contribution when some finite amount of radiation is present}}$$

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  - Sudakov form factor: probability not to branch while evolving from scale t_0 to t_1

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$$P_{\text{tot}}(z) = P_{\text{vac}}(z) + \Delta P(z, t, \hat{q}, L, E)$$

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- Medium-modified Sudakov factor

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$\hat{q}$

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Transformed ⇓ into

$$\boxed{\omega_c = \frac{1}{2}\hat{q}L^2} \qquad \boxed{\hat{q}L}$$

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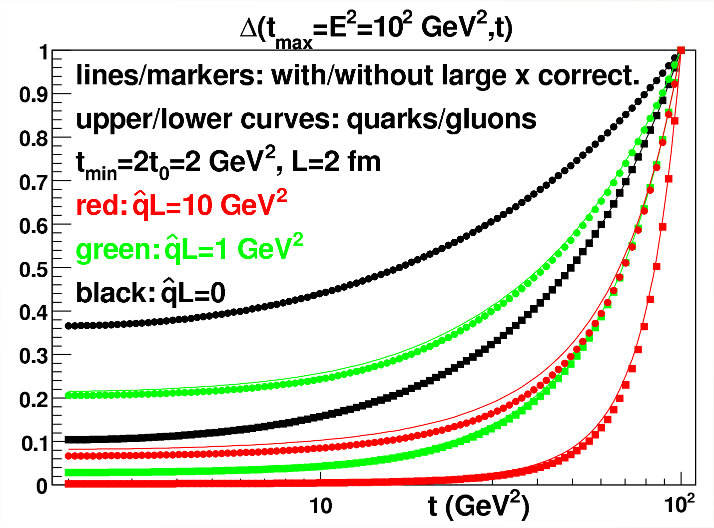
Suppression of the Sudakov: more radiation in medium than in vacuum



[Armesto, Cunqueiro, Salgado, Xiang]

Program

- Q-PYTHIA is the usual PYTHIA-6.1.18 with a modified final-state radiation:
  - Only modification: t-ordered FSR routine PYSHOW
    - Additional auxiliary routines (black box) + two routines that can be modified by the user:

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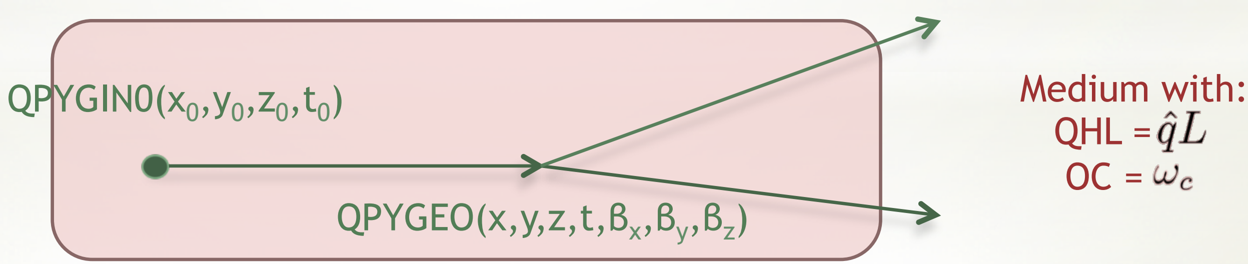
    - Additional auxiliary routines (black box) + two routines that can be modified by the user:
      - QPYGIN0(x_0,y_0,z_0,t_0): user specifies the position and time of the hard scattering, to be called once per NN collision
      - QPYGEO(x,y,z,t,β_x,β_y,β_z,QHL,OC) computes the parameters (QHL,OC) for a parton located at (x,y,z,t) moving along the direction defined by (β_x,β_y,β_z); medium to be specified by the user (some defaults available)



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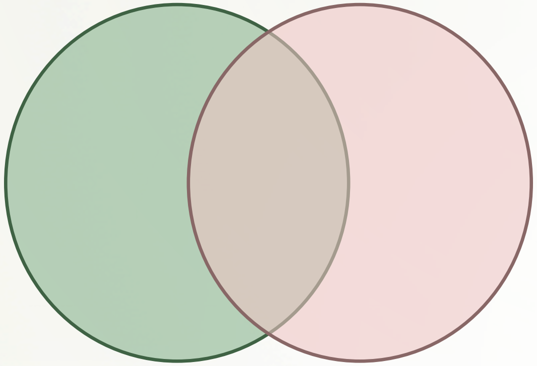

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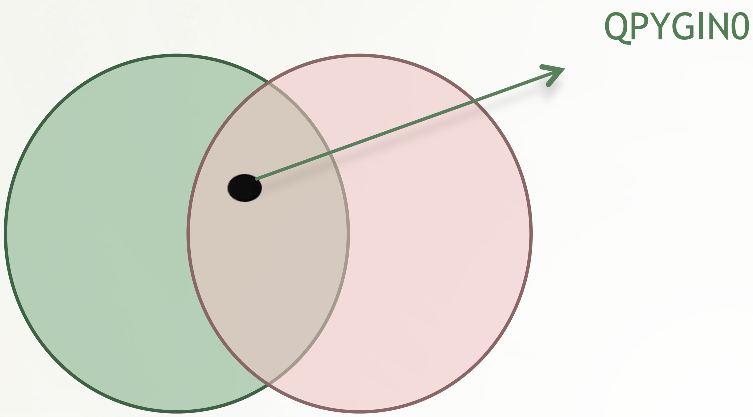

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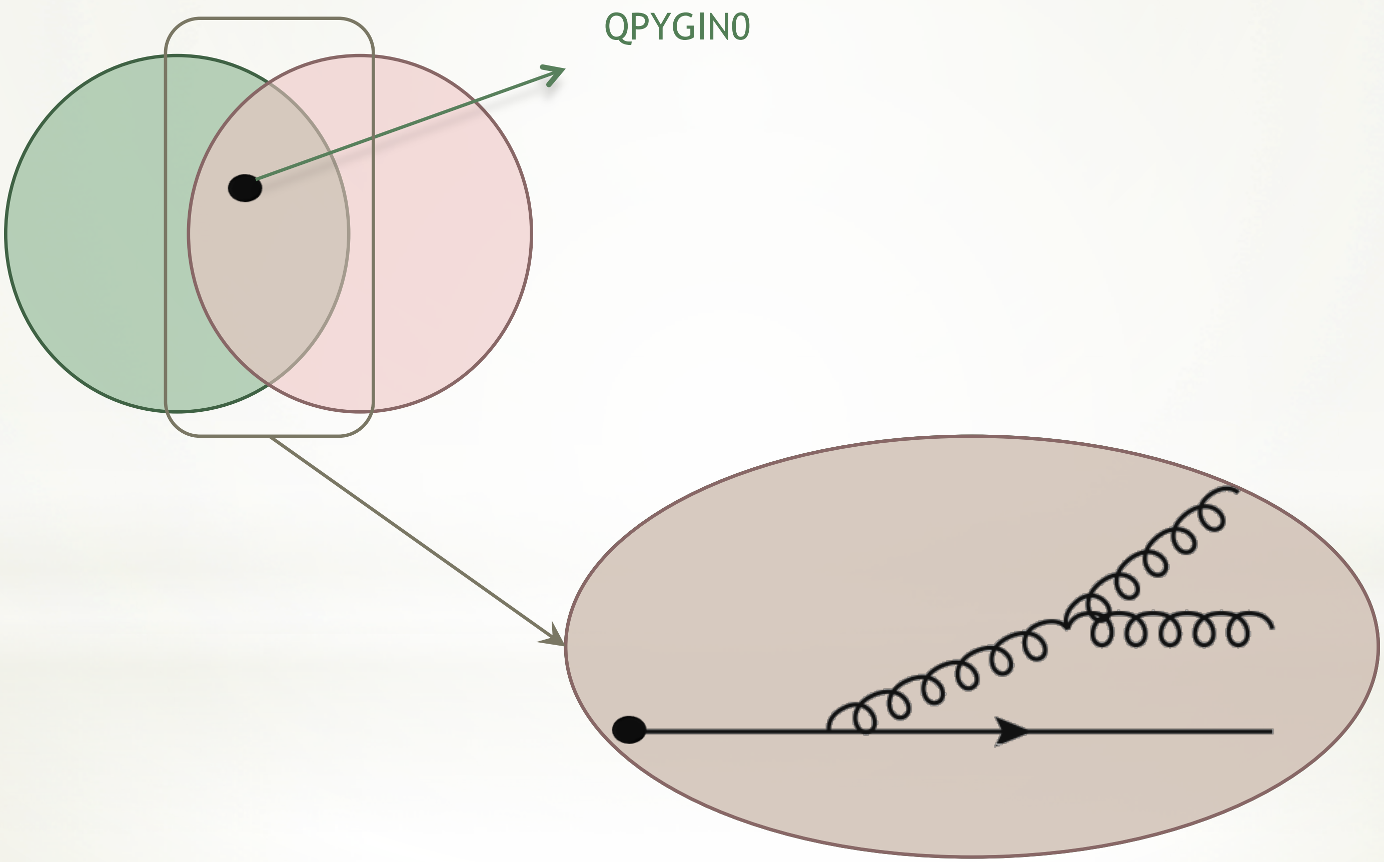

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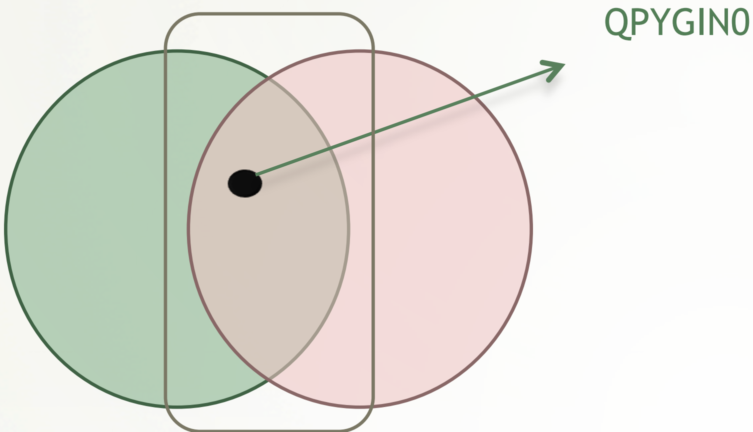
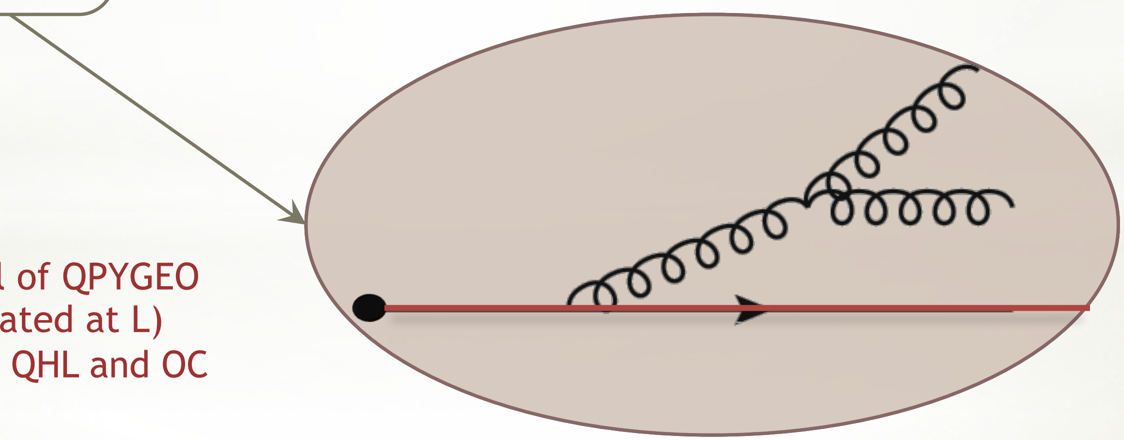


First call of QPYGEO
(evaluated at L)
Compute QHL and OC



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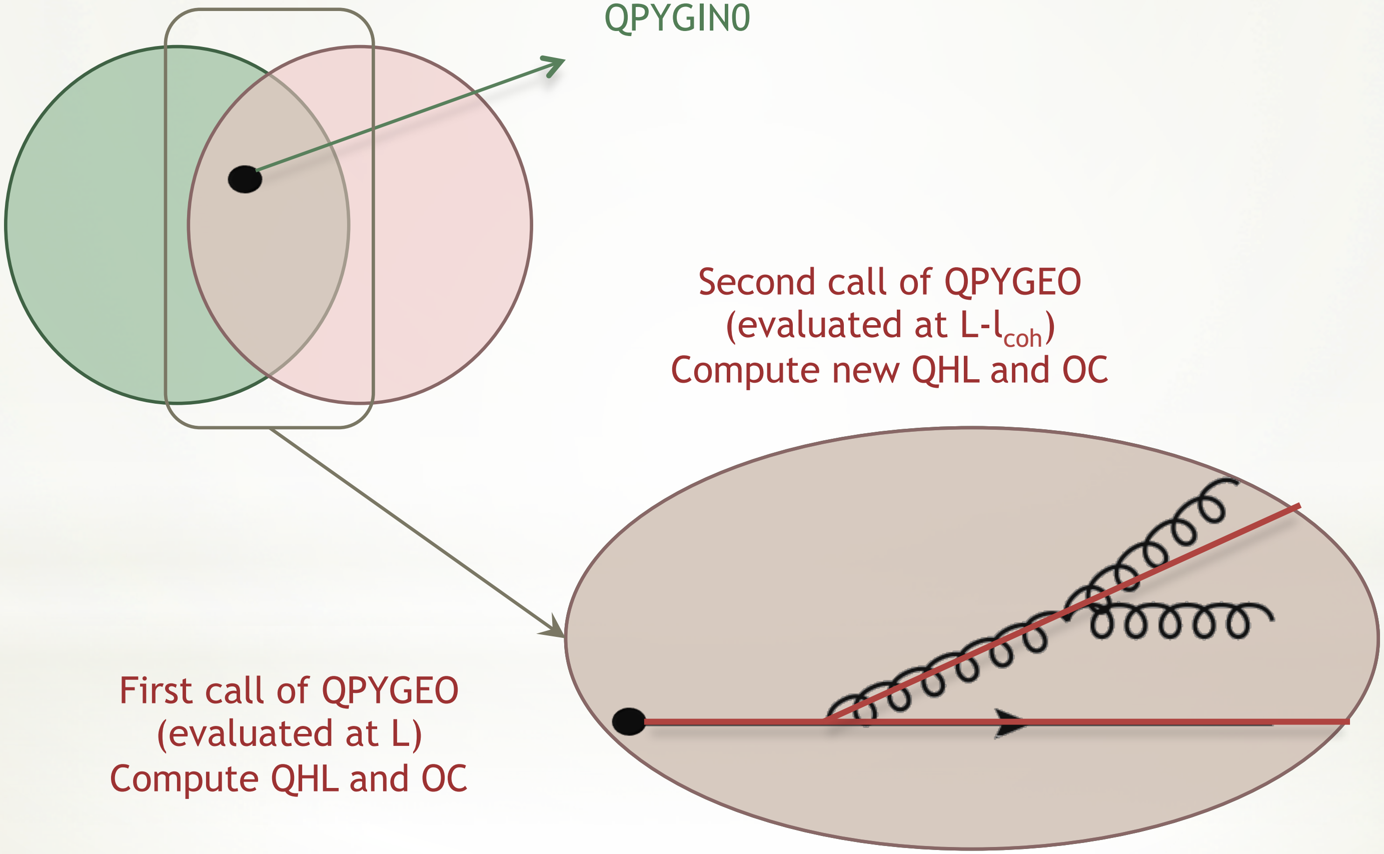

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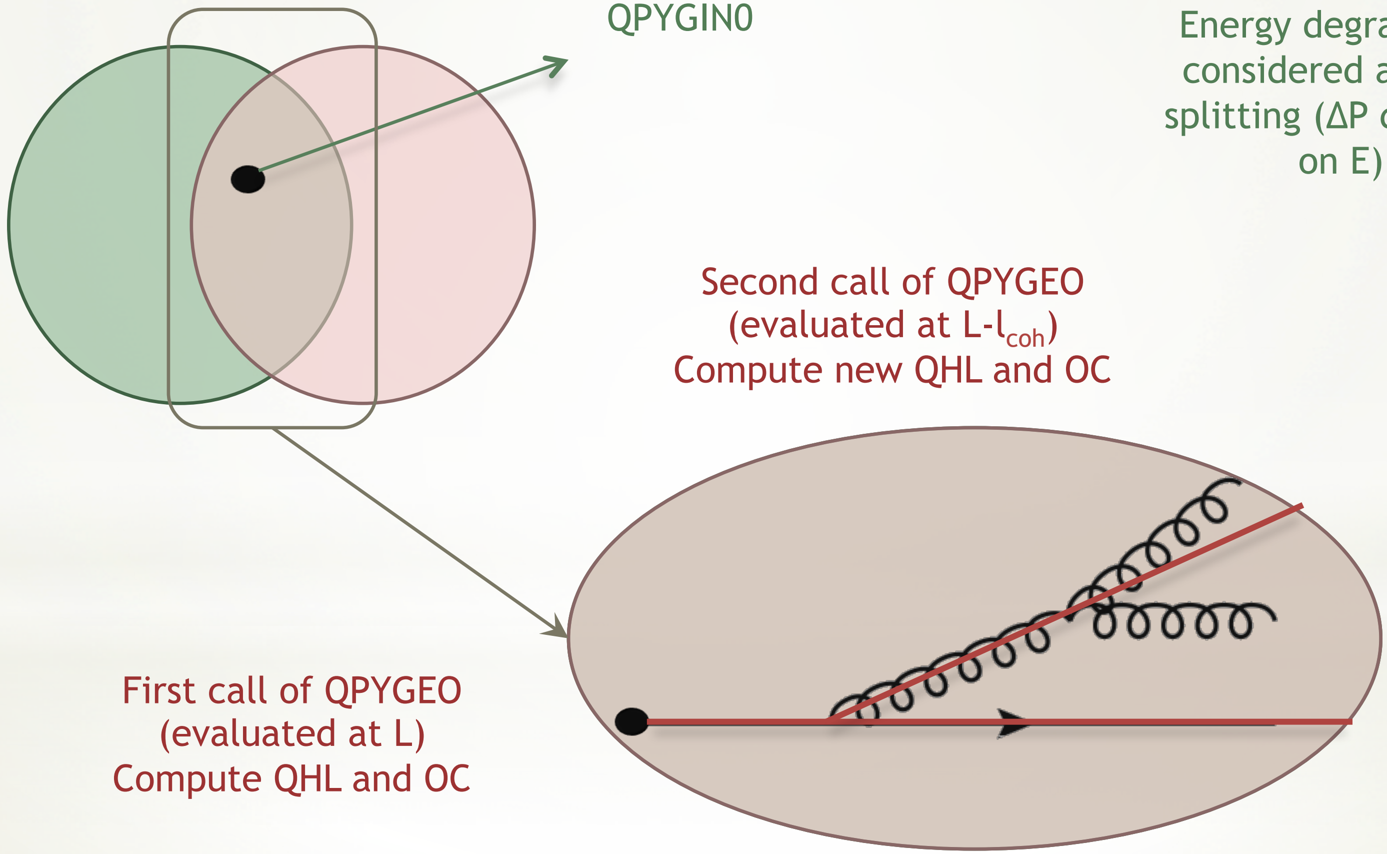
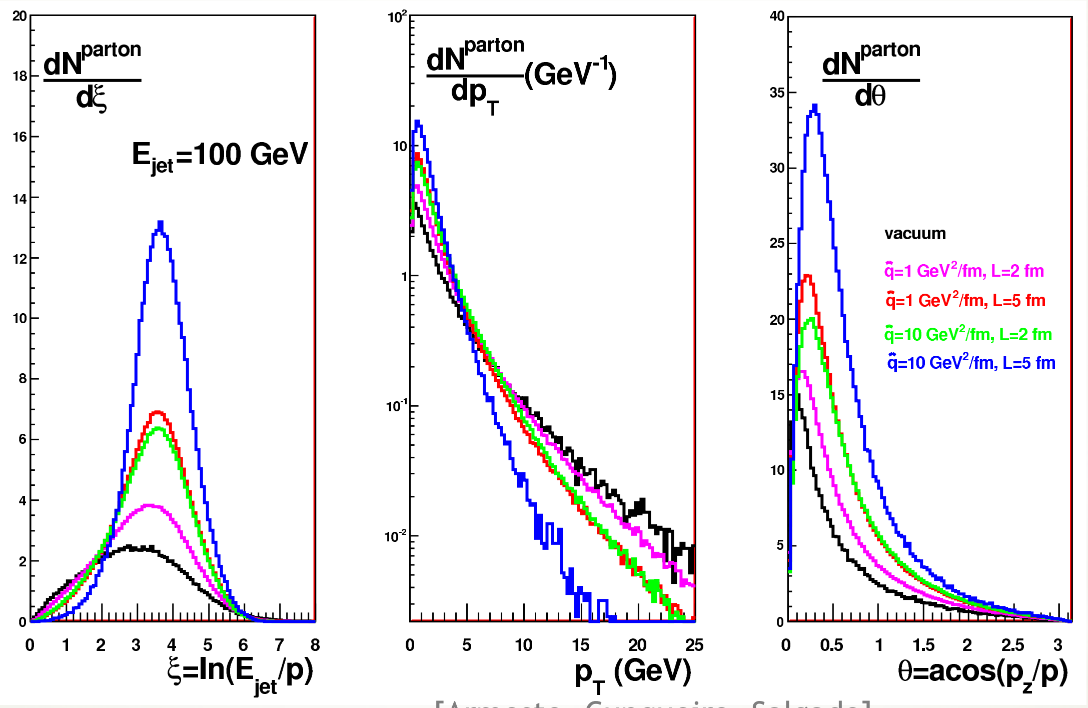


Moreover:
Energy degradation considered at each splitting (ΔP depends on E)

Results

- Results at parton level:



[Armesto, Cunqueiro, Salgado]

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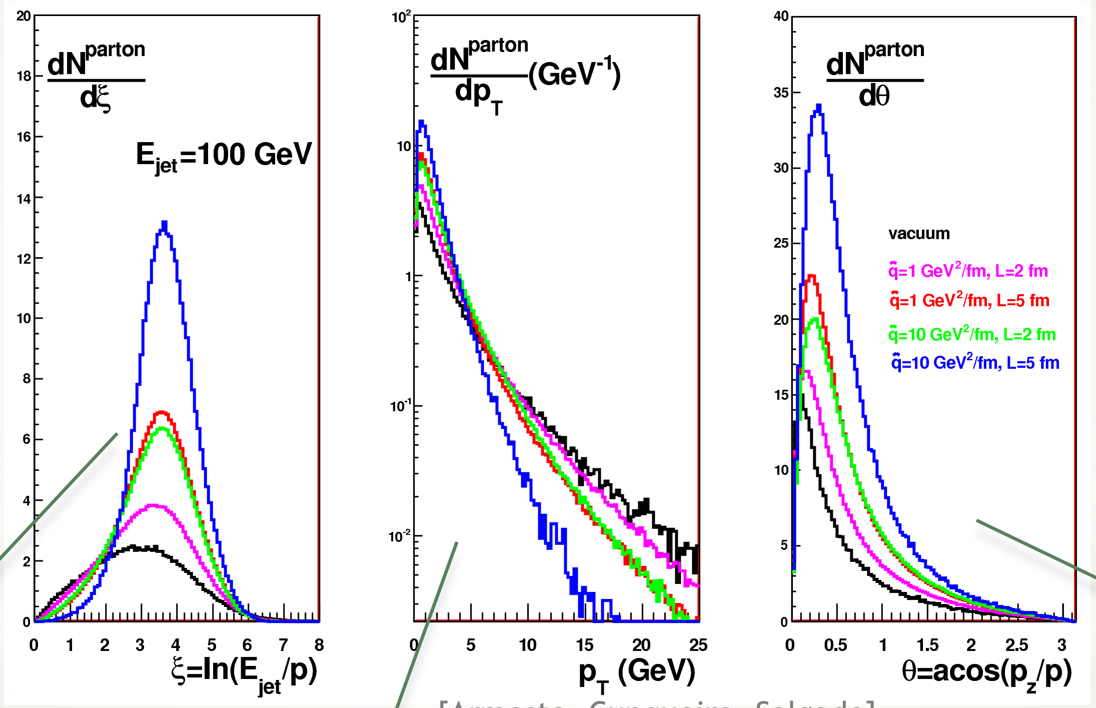


[Armesto, Cunqueiro, Salgado]

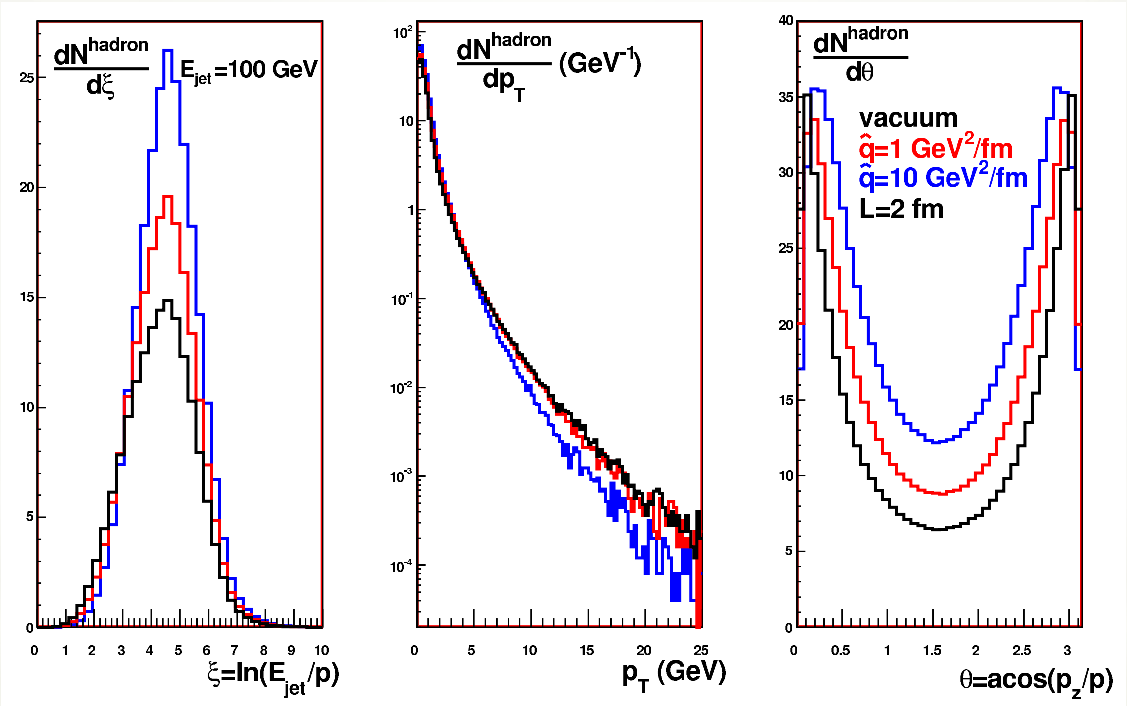
Suppresion of low-ξ particles
Enhancement of large-ξ

Supression of high-pT particles (E conservation) and enhancement of intermediate-pT

Broadening of angular distribution

Results

- Results at hadron level:

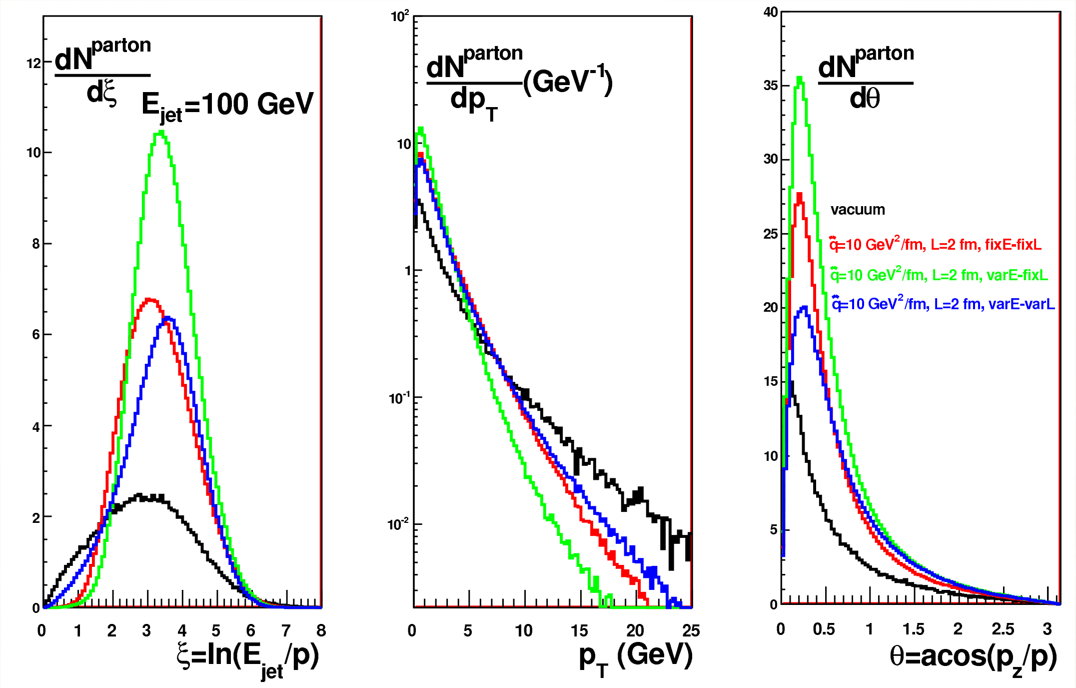


[Armesto, Cunqueiro, Salgado]

Medium effects are diminished by hadronization: low momentum partons do not produce hadrons

Results

✦Medium length and energy degradation effects on evolution

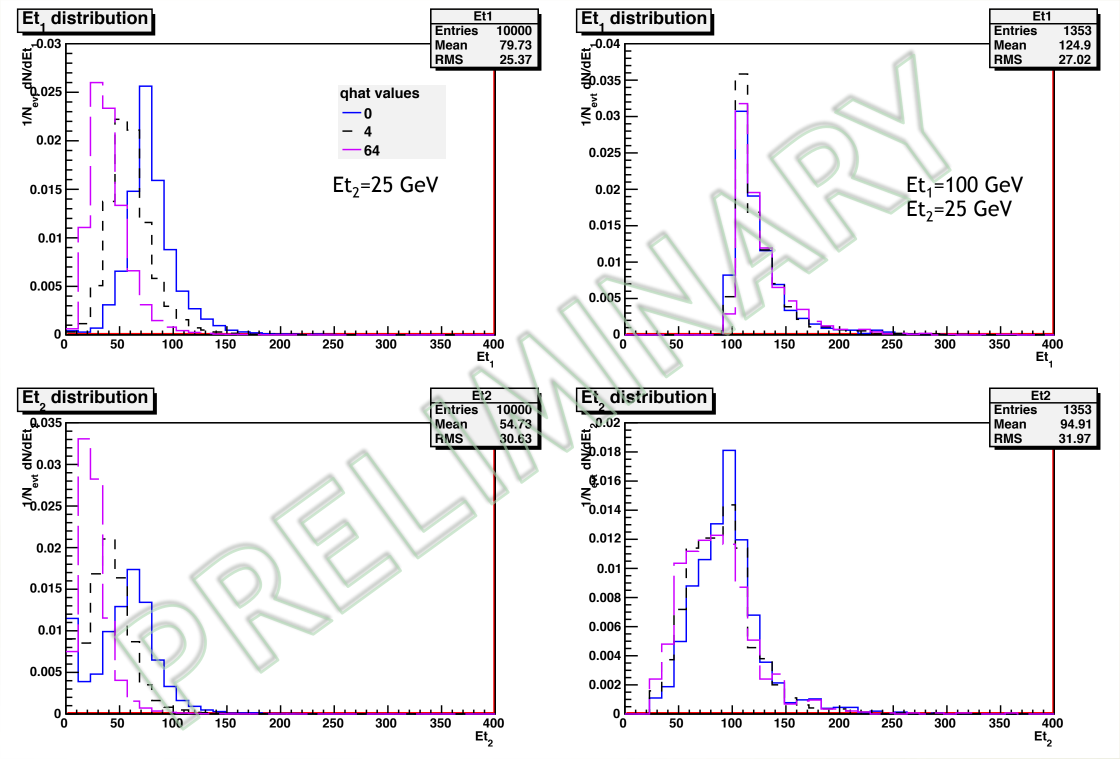


[Armesto, Cunqueiro, Salgado]

Medium effects are largest considering energy degradation but no evolution in length

Results

- Some on-going studies on jets:
  - Problems/Difficulties on the theory side:
    - Cut in p_T and definition of MC truth



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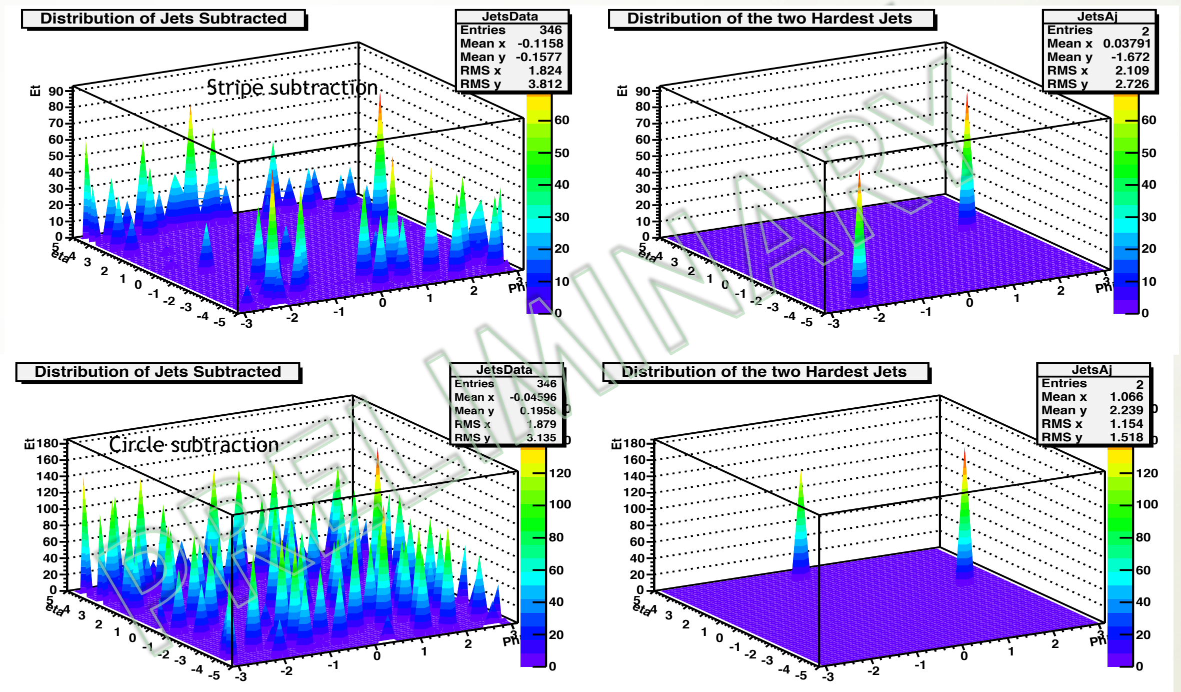

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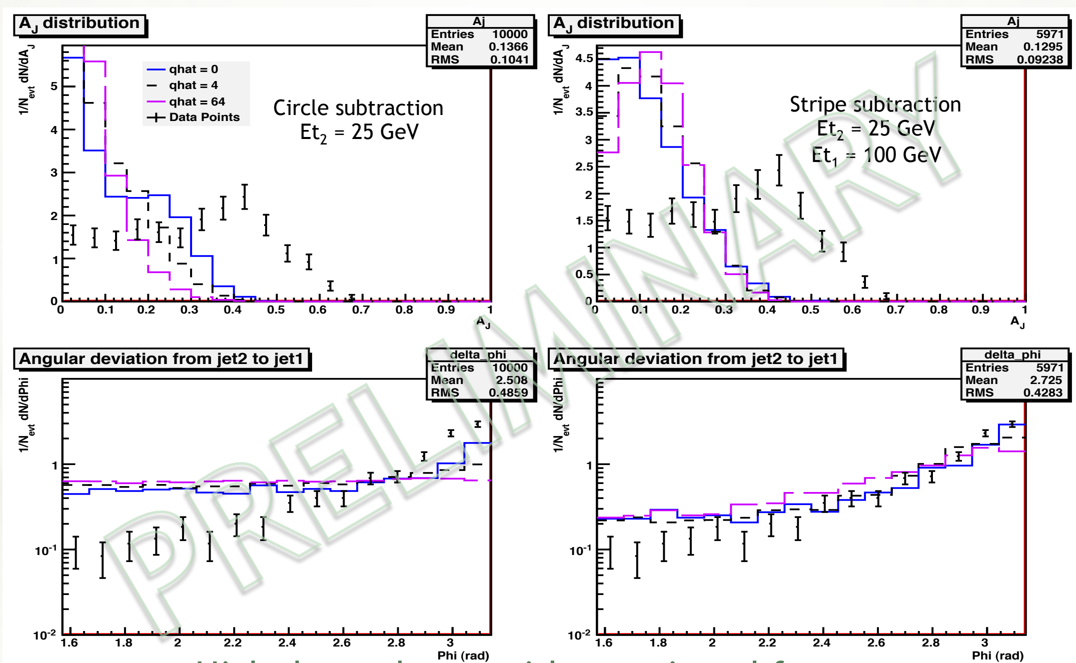
See also:
Cacciari, Salam, Soyez, 2011
He, Vitev, Zhang, 2011
Lokhtin, Belyaev, Snigirev, 2011

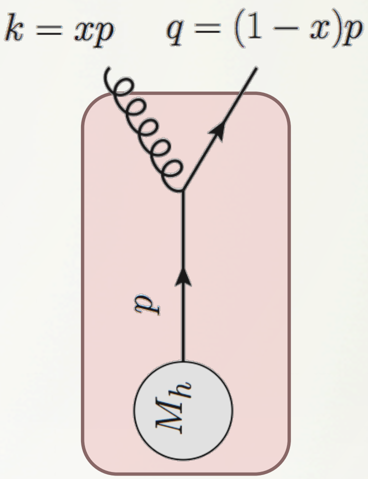


High dependence with mentioned factors

On-going Improvements

- Medium-induced gluon radiation spectrum only for small-x

$$\omega \frac{dI^{med}}{d\omega d^2\mathbf{k}_\perp}\bigg|_{x\to 0} = \frac{\alpha_s C_F}{(2\pi)^2\omega} 2\mathrm{Re}\left\{ \frac{1}{\omega}\int dy_+ d\bar{y}_+ d\mathbf{x}_\perp \mathrm{e}^{-i\mathbf{k}_\perp\cdot\mathbf{x}_\perp}\mathrm{e}^{-\frac{1}{2}\int d\xi n(\xi)\sigma(\mathbf{x}_\perp)} \frac{\partial}{\partial\mathbf{y}_\perp}\frac{\partial}{\partial\mathbf{x}_\perp}\mathcal{K}(y_+,\mathbf{y}_\perp=\mathbf{0};\bar{y}_+,\mathbf{x}_\perp) + 2\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp{}^2}\int dy_+ d\mathbf{x}_\perp \mathrm{e}^{-i\mathbf{x}_\perp\cdot\mathbf{k}_\perp}\frac{\partial}{\partial\mathbf{y}_\perp}\mathcal{K}(y_+,\mathbf{y}_\perp=\mathbf{0};L_+,\mathbf{x}_\perp)\right\}$$



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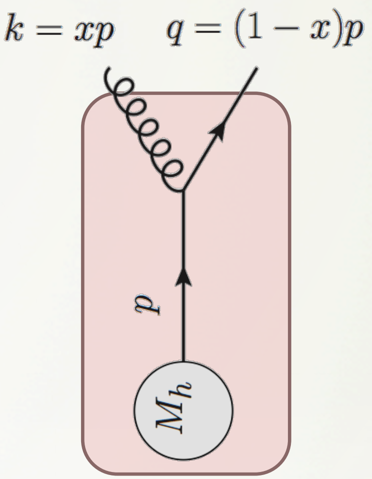

- Medium modified splitting functions extended by comparison with the vacuum ones
  - e.g: q➔q

$$x = 1 - z$$

$$P_{vac}(z) \simeq \frac{2C_F}{1-z}$$

Results

$$P_{q\leftarrow q}(z) = 2C_F\frac{1+z^2}{1-z}$$

Vacuum SF

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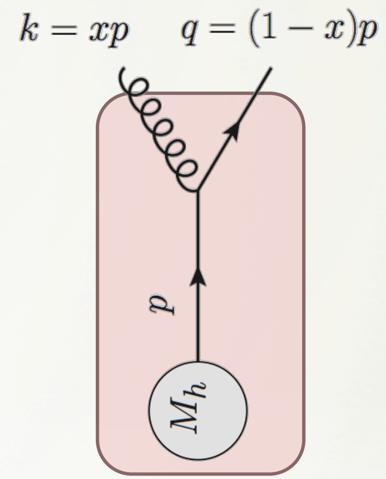

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Vacuum SF

➔

$$(1+z^2)P_{vac}$$

$$(1+z^2)\Delta P$$

On-going Improvements

- Instead of extending, compute the radiation spectrum in the opposite limit (x~1):

$$q_+ \frac{dI^{med}}{dq_+ d^2q_\perp}\bigg|_{x\to 1} = \frac{\alpha_s C_F}{2\pi^2}\frac{1-x}{p_+}\mathrm{Re}\left\{\frac{1}{p_+}\int dy_+ d\bar{y}_+ d\mathbf{x}_\perp \mathrm{e}^{-i\mathbf{q}_\perp\cdot\mathbf{x}_\perp}\mathrm{e}^{-\frac{1}{2}\int_{\bar{y}_+}^{L_+} d\xi n(\xi)\sigma(\mathbf{x}_\perp)}\right.$$
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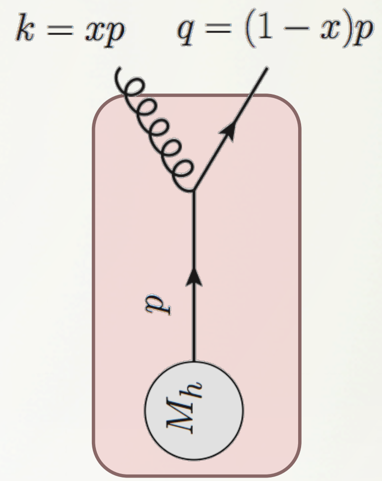

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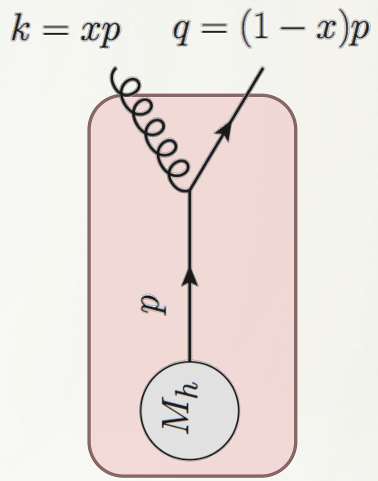

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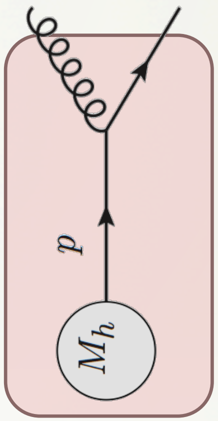

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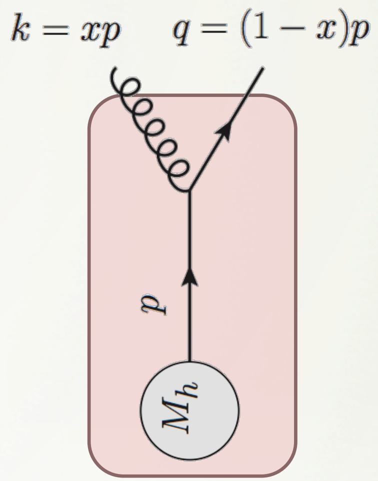

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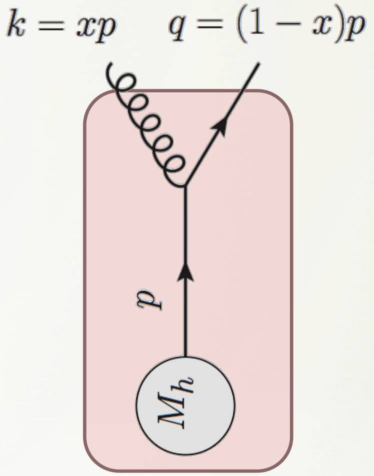

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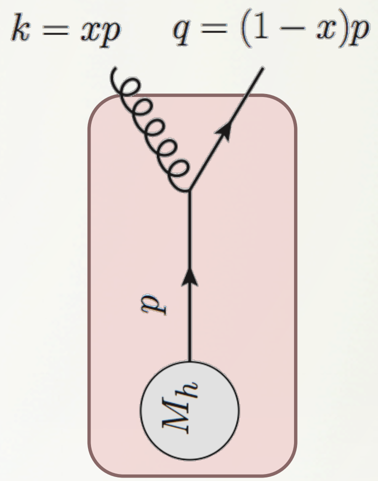

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- Include corrections in the Q-PYTHIA by matching the two functions

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  - Avoid compilation
  - Options for QPYGIN0 (overlap)

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Future

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- Q-PYTHIA download:
  - http://igfae.usc.es/qatmc/

END

Thanks!