Jets in heavy-ion collisions at RHIC and LHC

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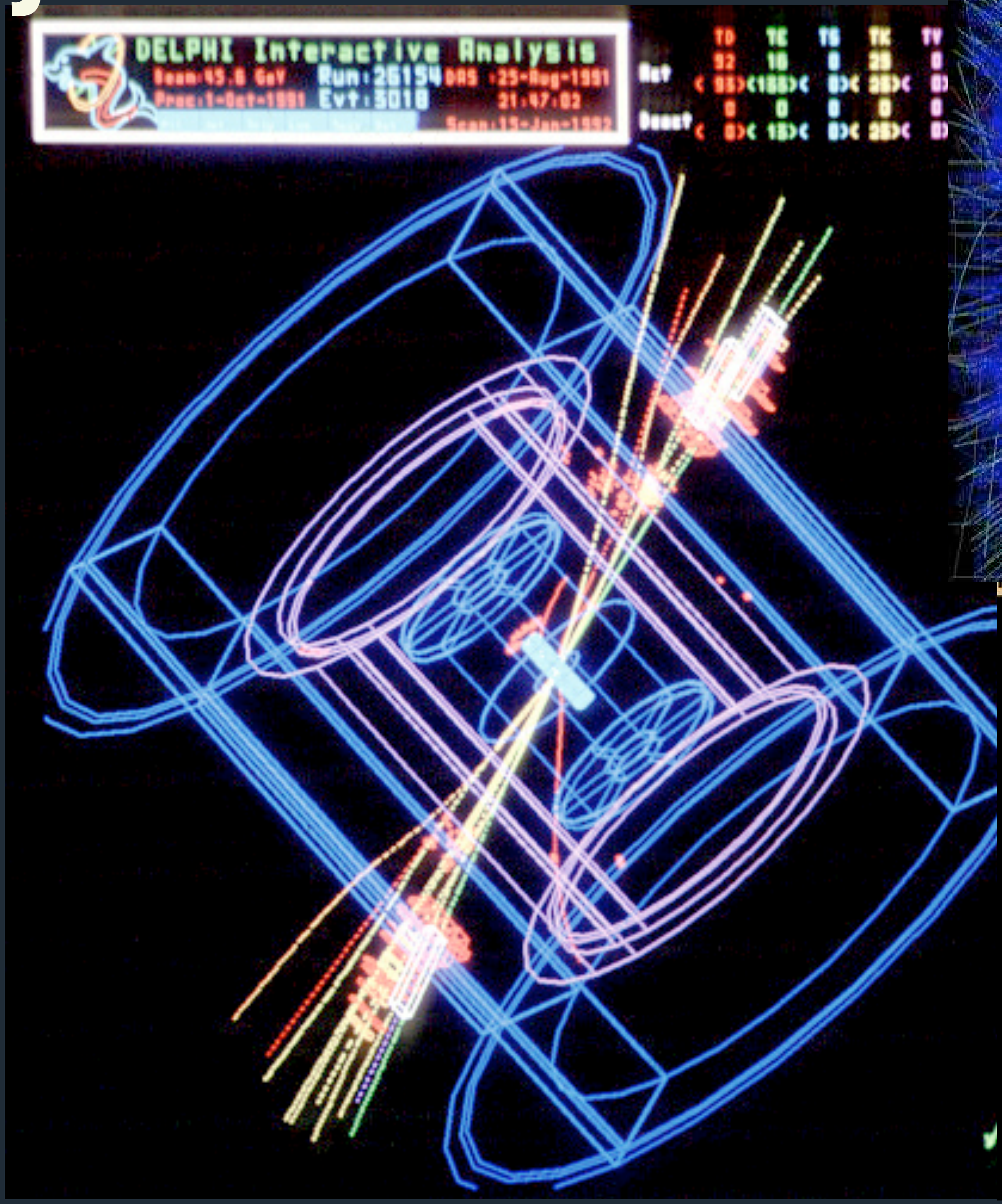
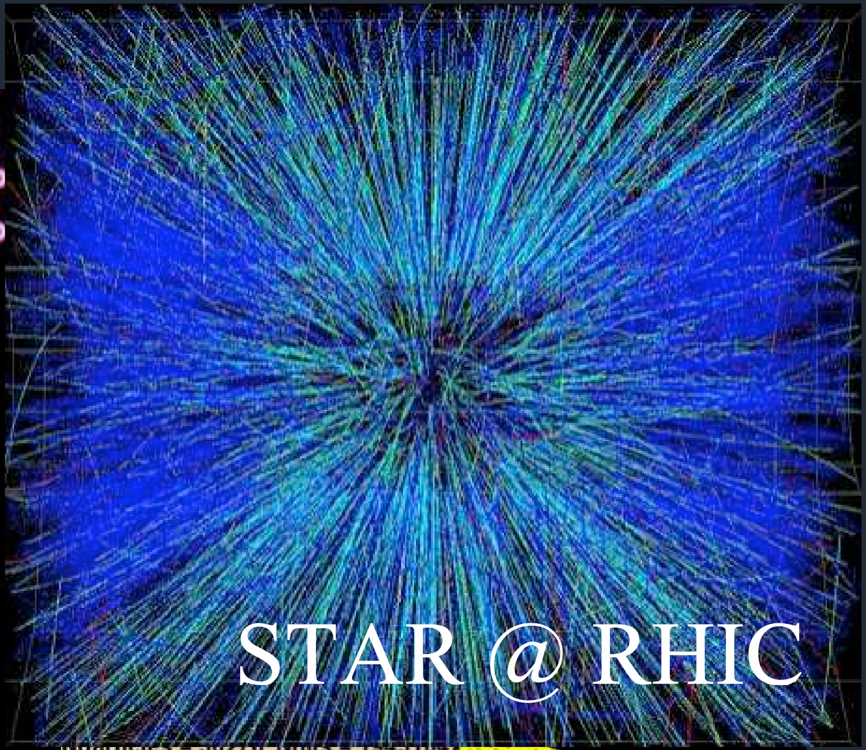
Summary from Lect. 1, 2 & 3

- DIS and jets
  - Evolution equation - gluon radiation
- Factorization in QCD: PDFs & FF universal
- Particle propagation in medium
- Jet quenching phenomenology: $\hat{q}$
  - Inclusive observables measured at RHIC

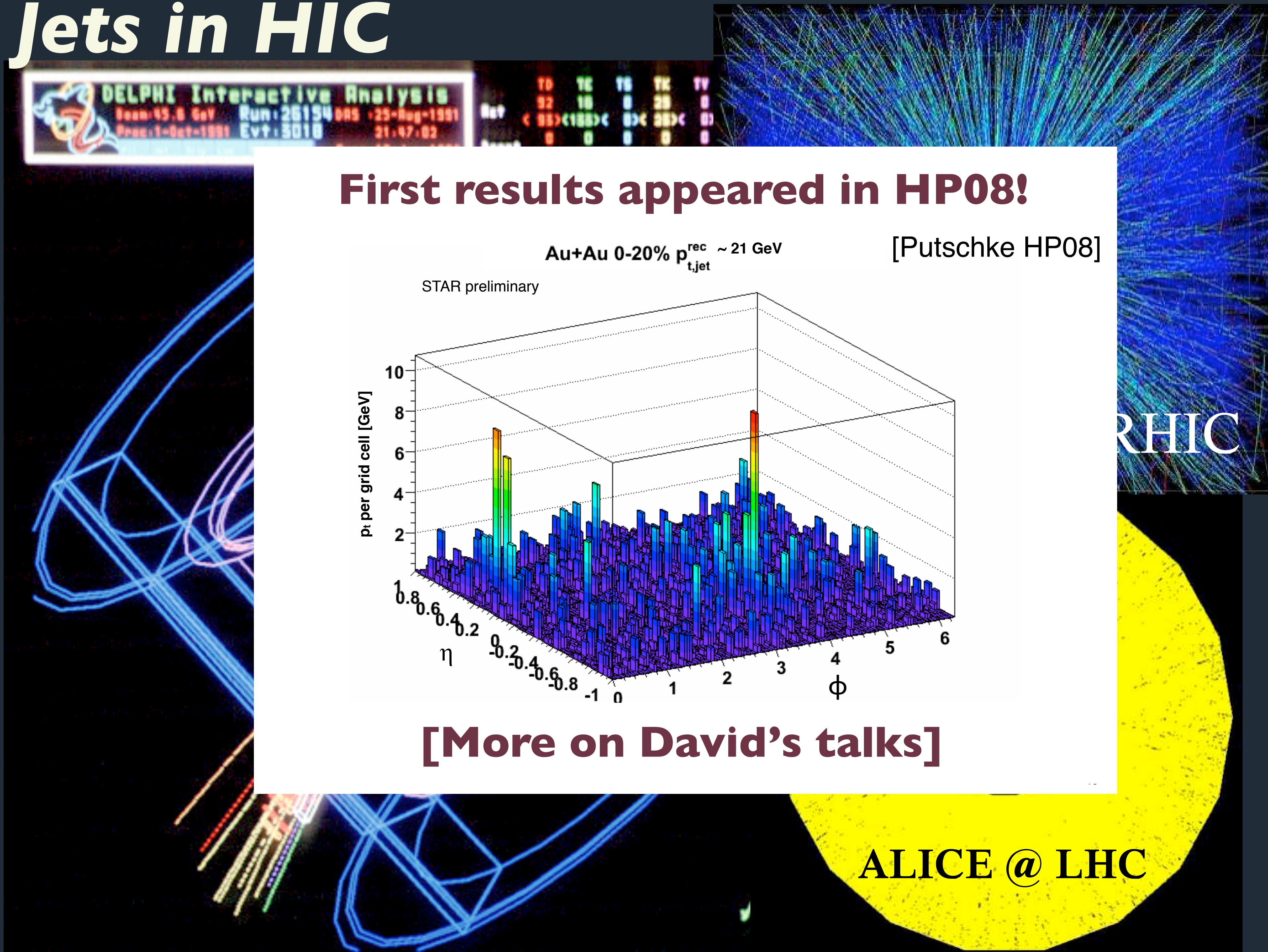
Jets in HIC


DELPHI Interactive Analysis
Run:26154
Evt:3018


STAR @ RHIC

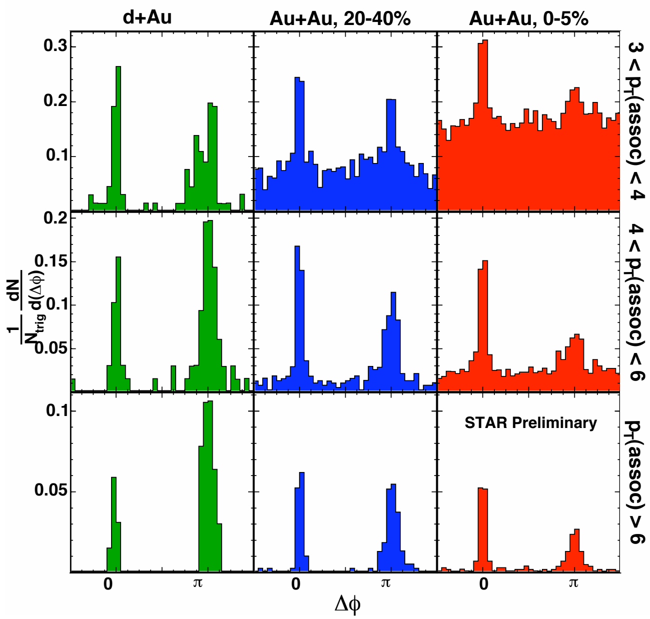

ALICE @ LHC

Jets in HIC



DELPHI Interactive Analysis
First results appeared in HP08!
[Putschke HP08]
Au+Au 0-20% $p_{t,jet}^{rec}$ ~ 21 GeV
STAR preliminary
p_t per grid cell [GeV]
η
ϕ
[More on David's talks]
RHIC
ALICE @ LHC

Jet studies in HIC



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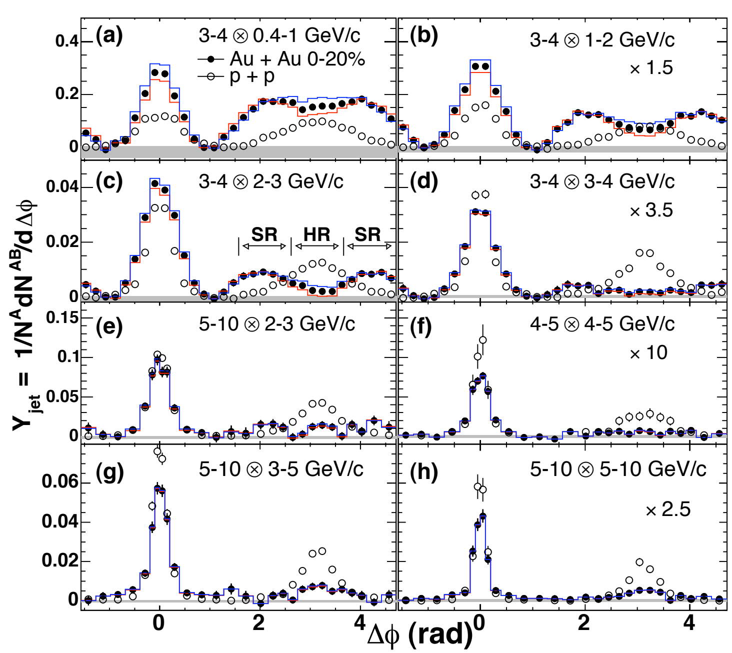

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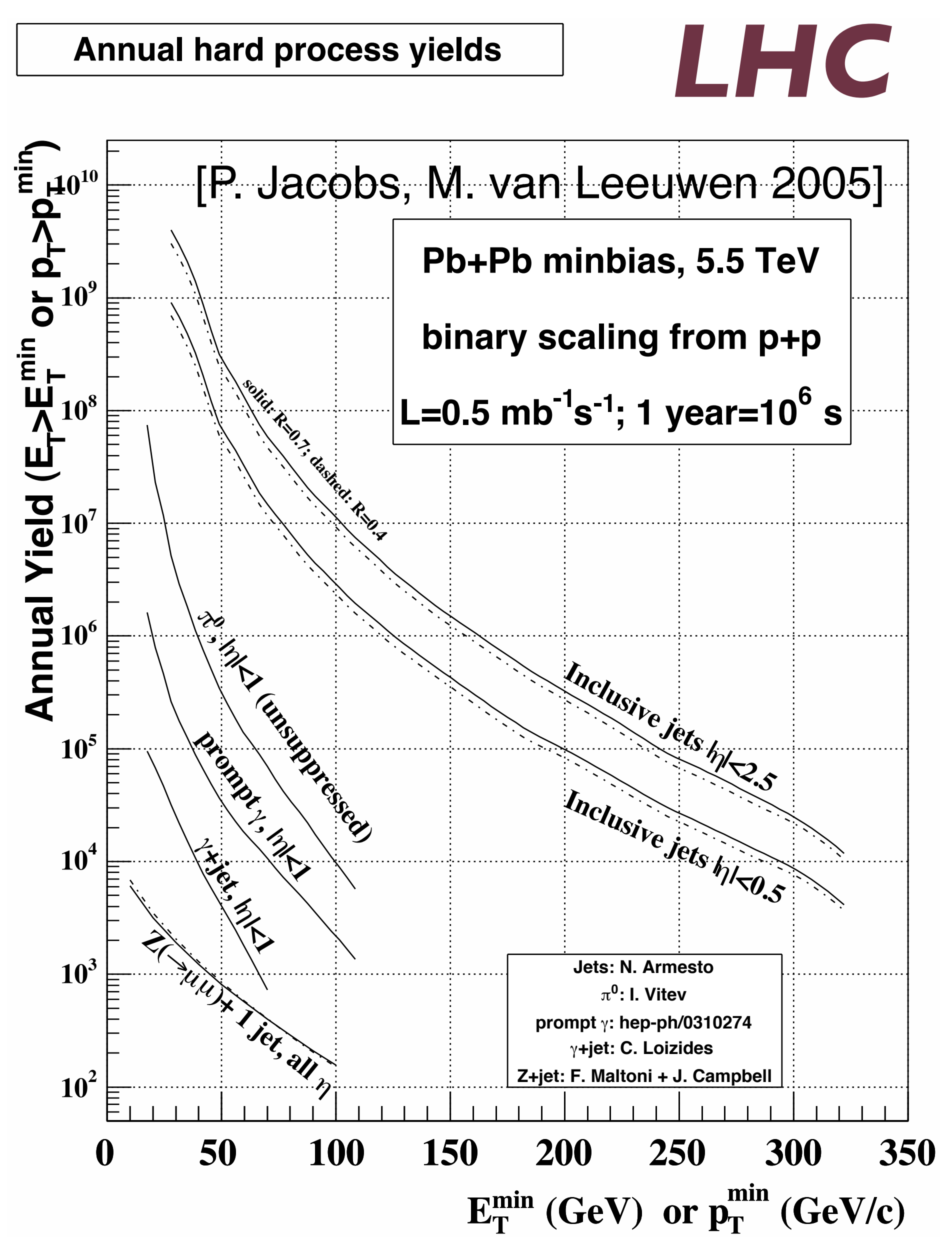

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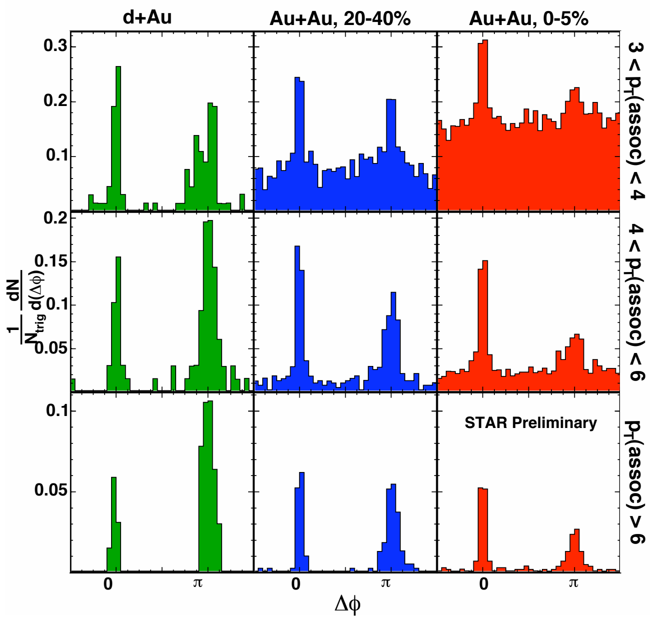

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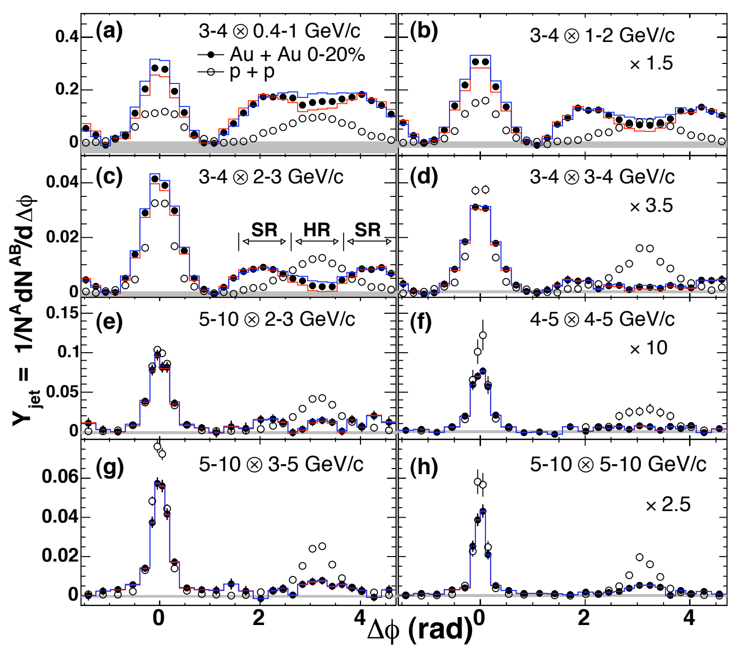

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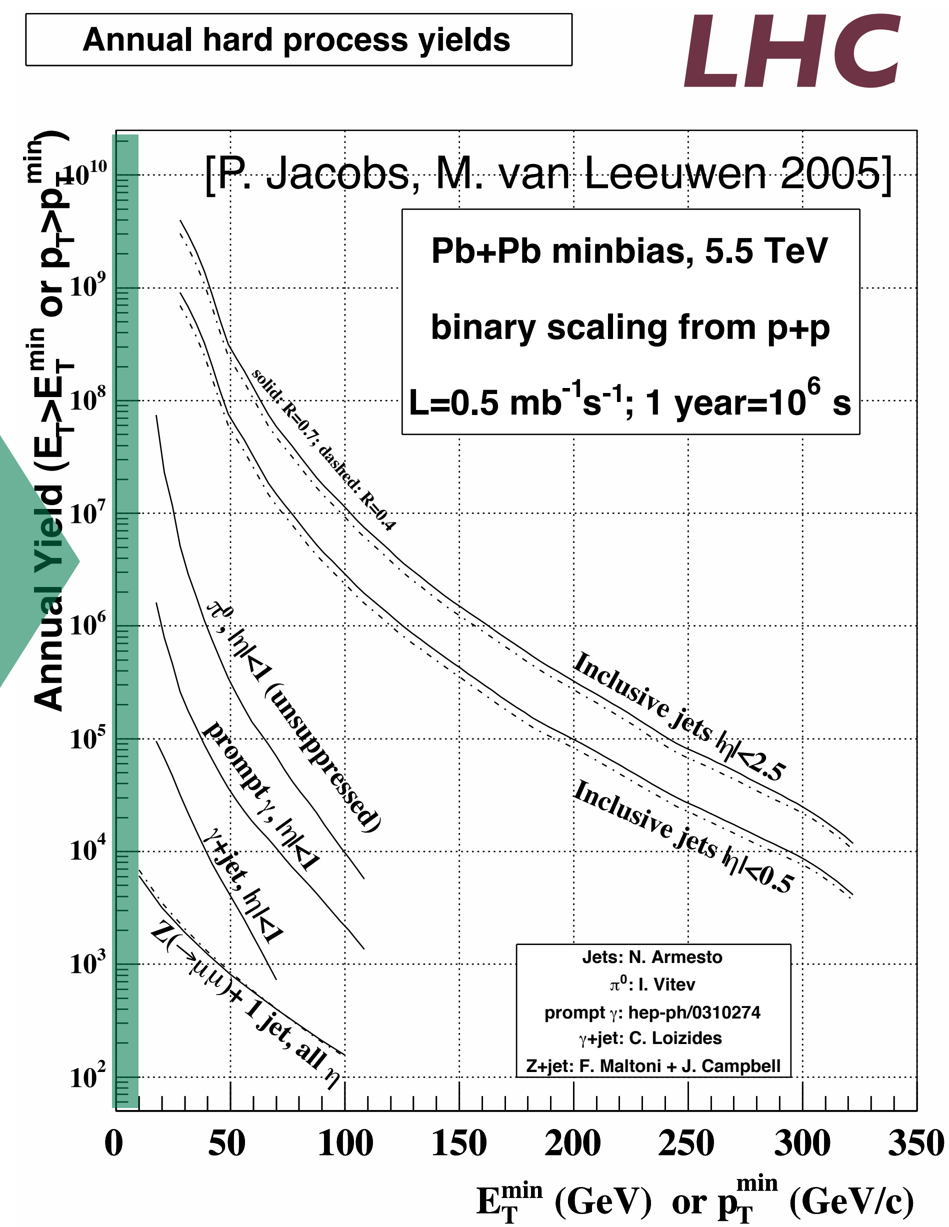
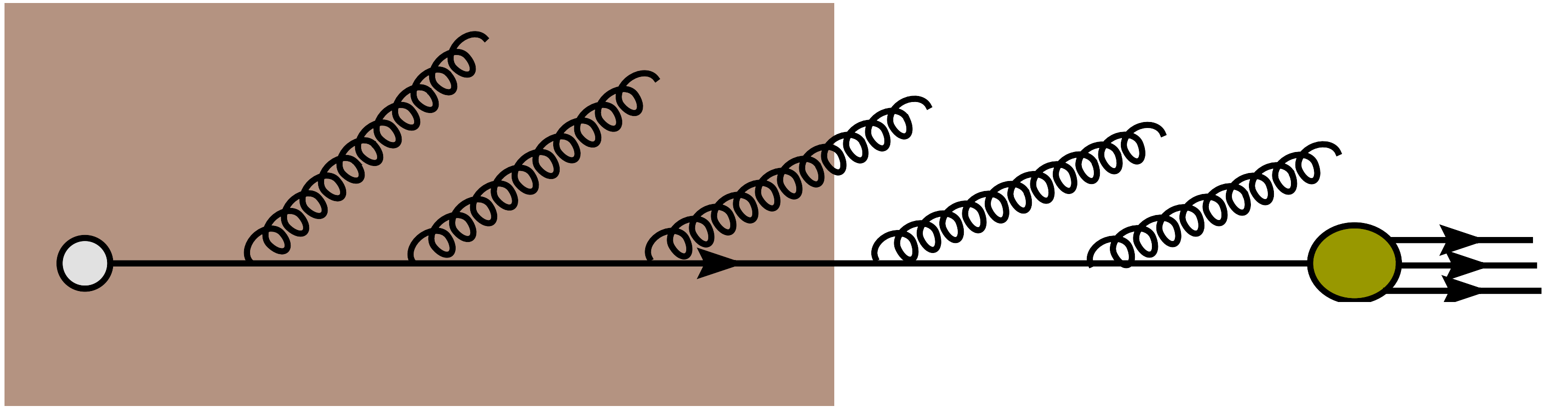


Independent gluon emision

- Vacuum and medum-induced gluon radiation treated separately
  - Medium-radiation first
  - Medium produces only energy loss
    (no modification of the evolution)
  - Independent gluon emission approximation - Poisson distribution



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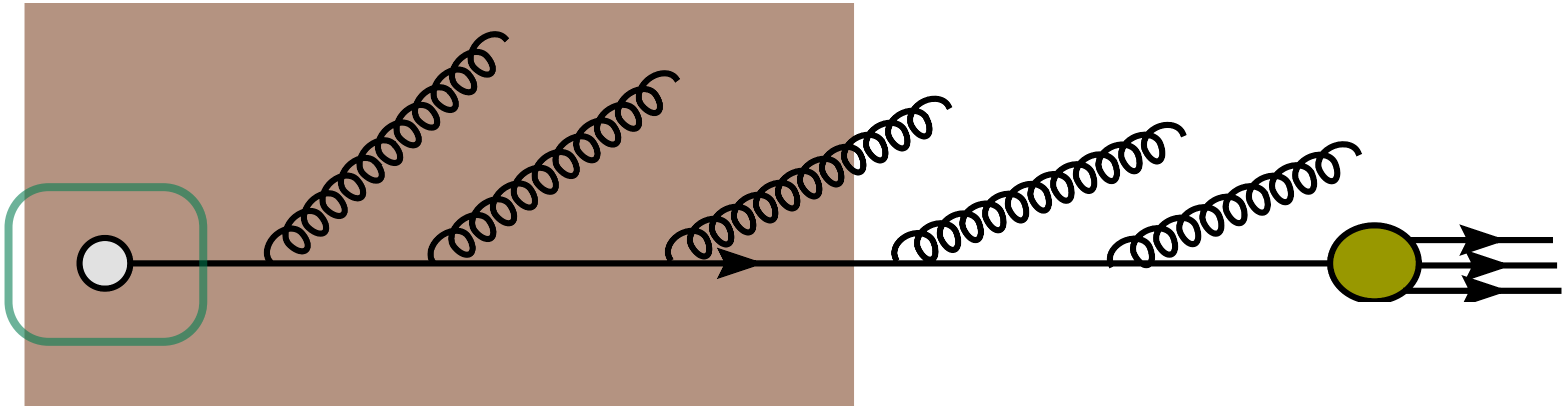
Hard Process



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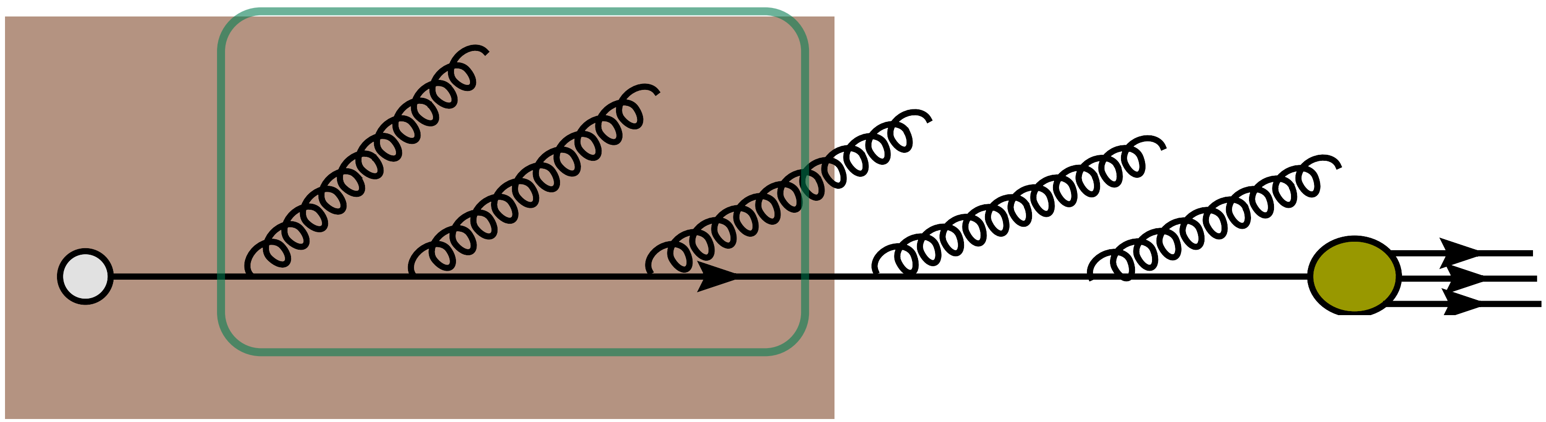
Medium-induced gluon radiation



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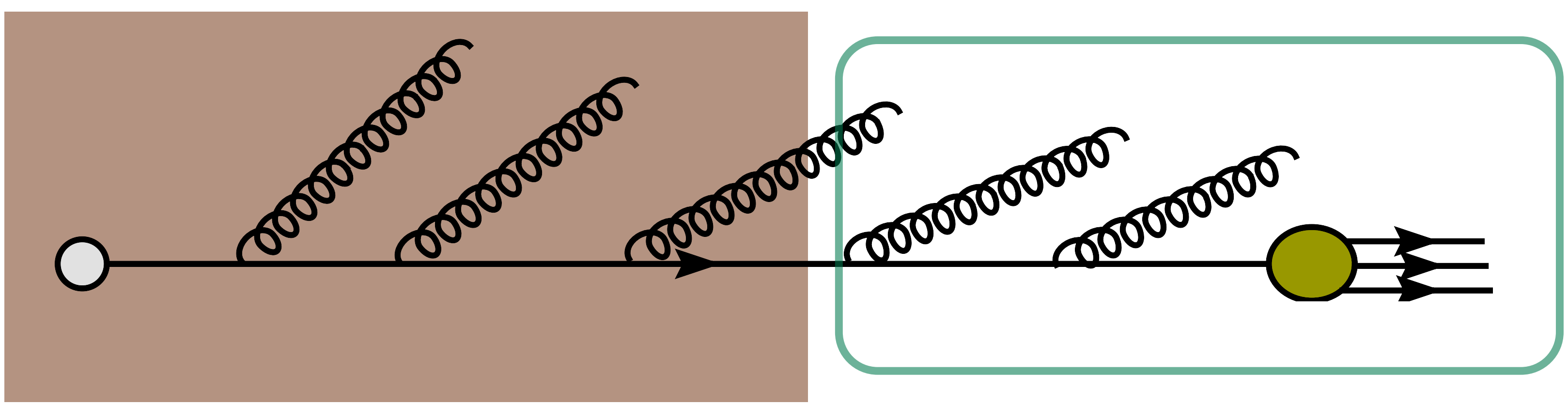
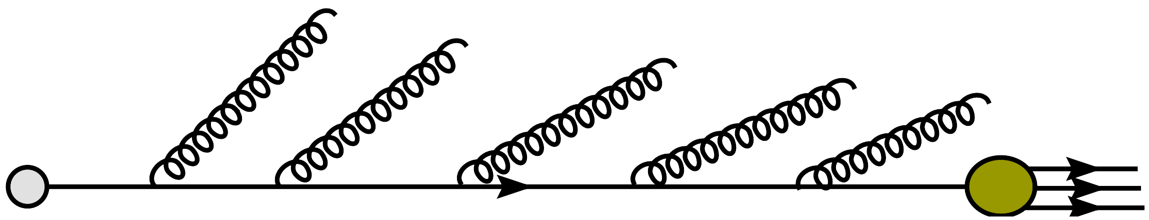
DGLAP vacuum evolution and hadronization



An improved medium-evolution?

- Recall evolution in vacuum
  - First order gives divergencies - leading contributions
  - n-gluon emission has enhancement factor $\mathcal{O}\left(\left[\alpha_s \log Q^2\right]\right)^n$
  - Resuming these contributions gives evolution eqs. (DGLAP)



- Multiple gluon emission can be computed in vacuum

  [see e.g. Peskin, Schroeder: *Introduction to QFT*]
  - Not computed up to now in the medium *
  - Medium effects enhanced by $\alpha_s L \simeq \alpha_s A^{1/3}$
  - Independent gluon emission (QW) is a model implementation

*[see, however, Kovchegov, Jalilian-Marian 2004; Baier, Kovner, Nardi, Wiedemann 2005]

Jets and new developments

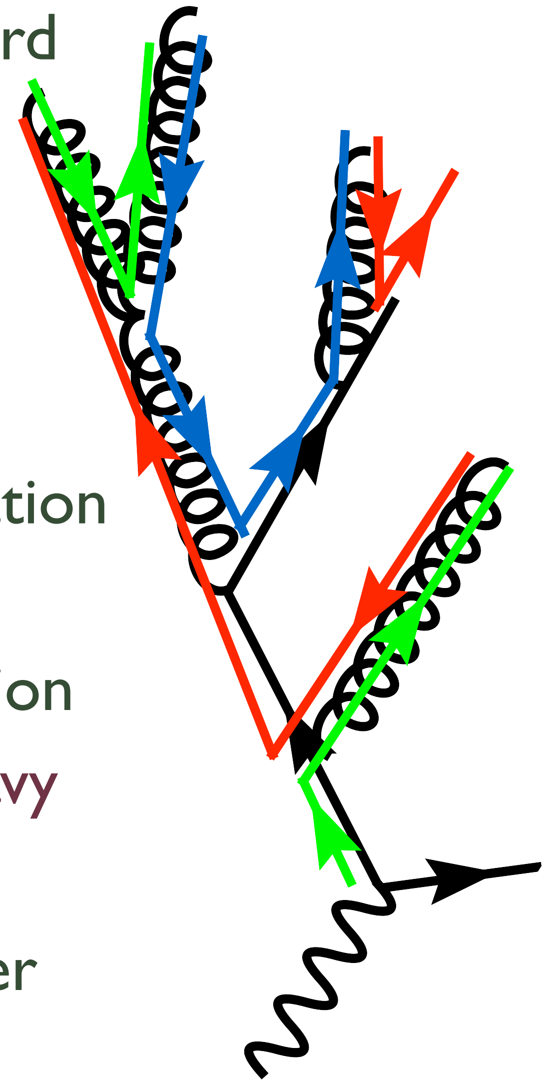
- **Exploratory studies up to now**
- **One main goal: to have a Monte Carlo implementation**
  - *Armesto, Corcella, Cunqueiro, Salgado (also Xiang) **
  - *Zapp, Ingelman, Rathsman, Stachel, Wiedemann*

    (also Borghini, Sapeta)
  - *Lokhtin, Petrushanko, Snigirev, Teplov ...*
  - *Renk*

* *Discussed here.*

Modifications of jet evolution I

- ⇛ Gluon multiplication is a building block of the hard cross sections
- ⇛ Medium-induced gluon radiation
  - Larger multiplicities
  - Modified jet structures (broadening...)
- ⇛ Non-eikonal corrections to the partons propagation in medium (a.k.a collisional E loss)
- ⇛ Modification of the non-perturbative hadronization
  - Some hints at RHIC (baryon/meson ratio, heavy quarks? [David's favorite ;-)])
- ⇛ Modification of the color structure of the shower evolution



Modifications of jet evolution II

- In the vacuum, DGLAP evolution describes the parton shower
- 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

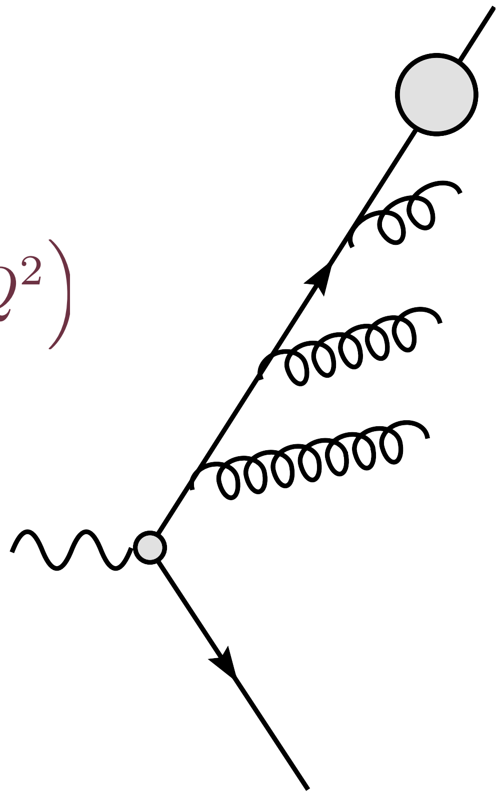
- DGLAP evolution for FF in vacuum

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

- Probabilistic interpretation

$$d\mathcal{P}(z,k_\perp^2) = \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)\ dz dk_\perp^2$$

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



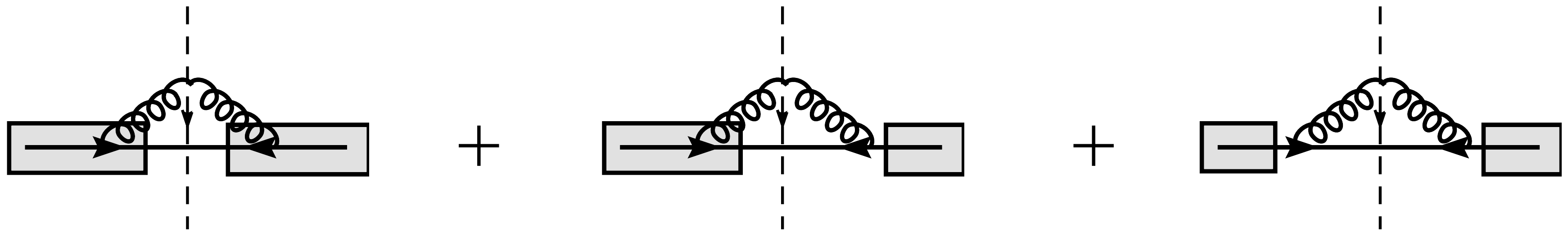
- Define a medium-modified splitting probability

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

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

Medium-modified splittings

⇛ Remember that the total gluon radiation has vacuum+medium



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

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

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

[Polosa, Salgado 2006; Armesto, Cunqueiro, Salgado, Xiang 2007]

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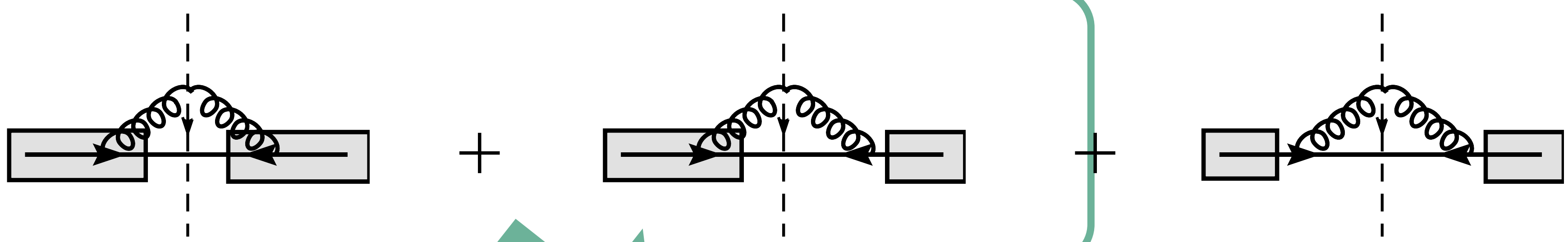

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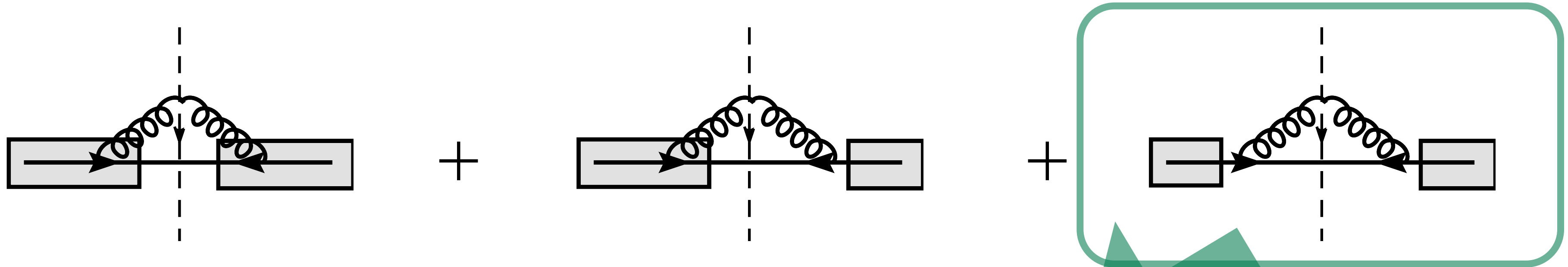

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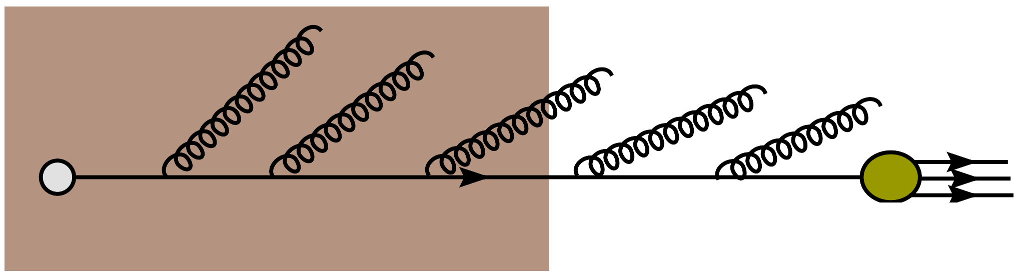
Medium-modified evolution

- So, the new evolution equation containing the medium terms

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

- The modification is known from the medium-induced radiation
- We need to specify the initial conditions
  - Take the vacuum FF as initial conditions (KKP set)
  - All the medium-effects are built by the evolution



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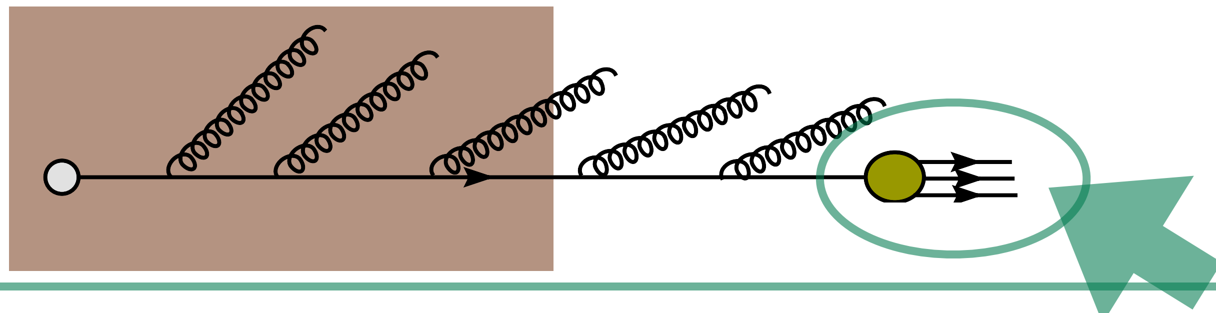

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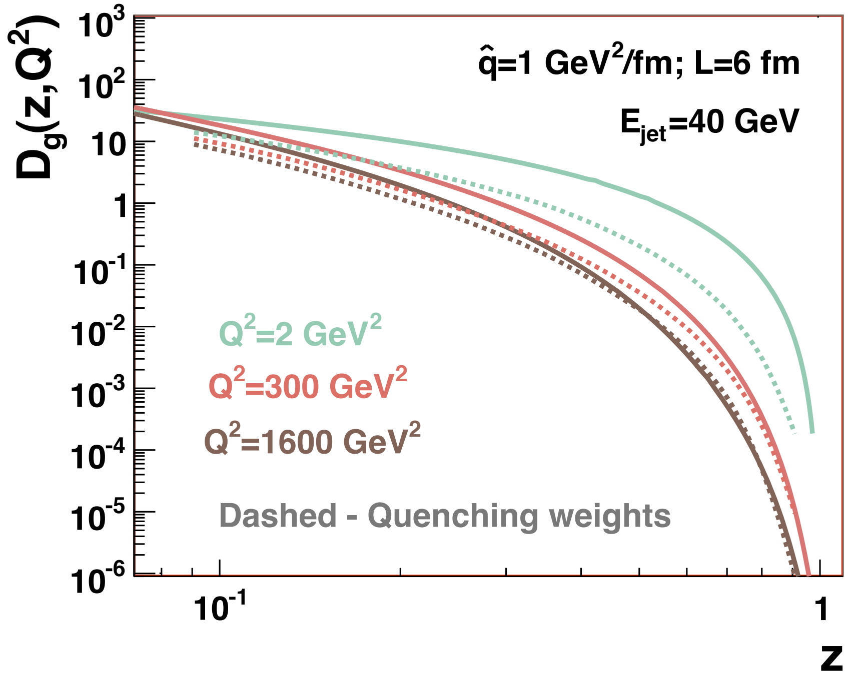
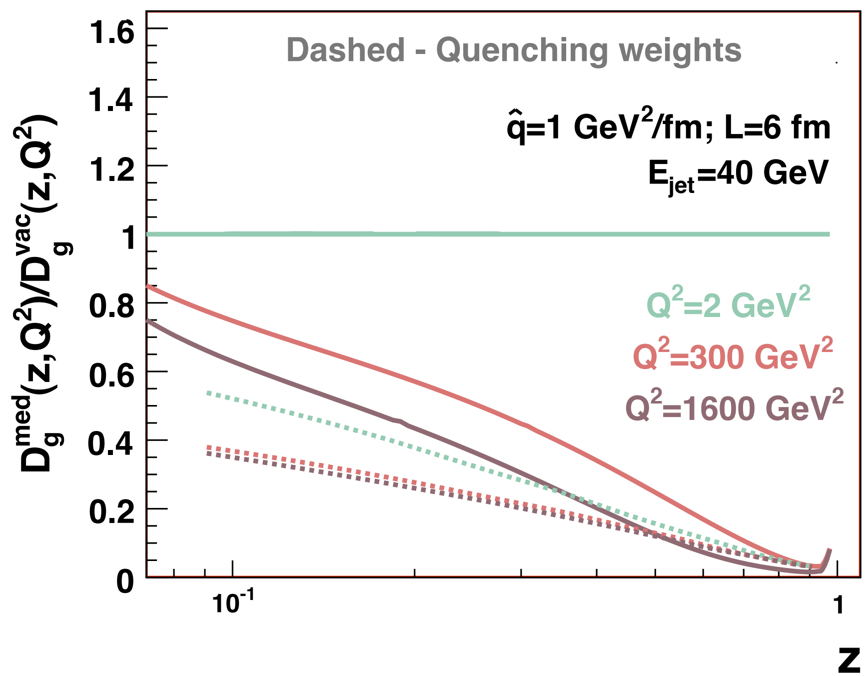
Results: numerical solution of the evolution

- Initial conditions: no effect at $Q_0 = 2$ GeV - vacuum KKP FF taken





- Softening of the fragmentation functions - energy loss
- Agreement with QW framework when $Q^2 \simeq E^2_{\rm jet}$
- QW overestimates suppression when $Q^2 \ll E^2_{\rm jet}$

[Armesto, Cunqueiro, Salgado, Xiang 2007]

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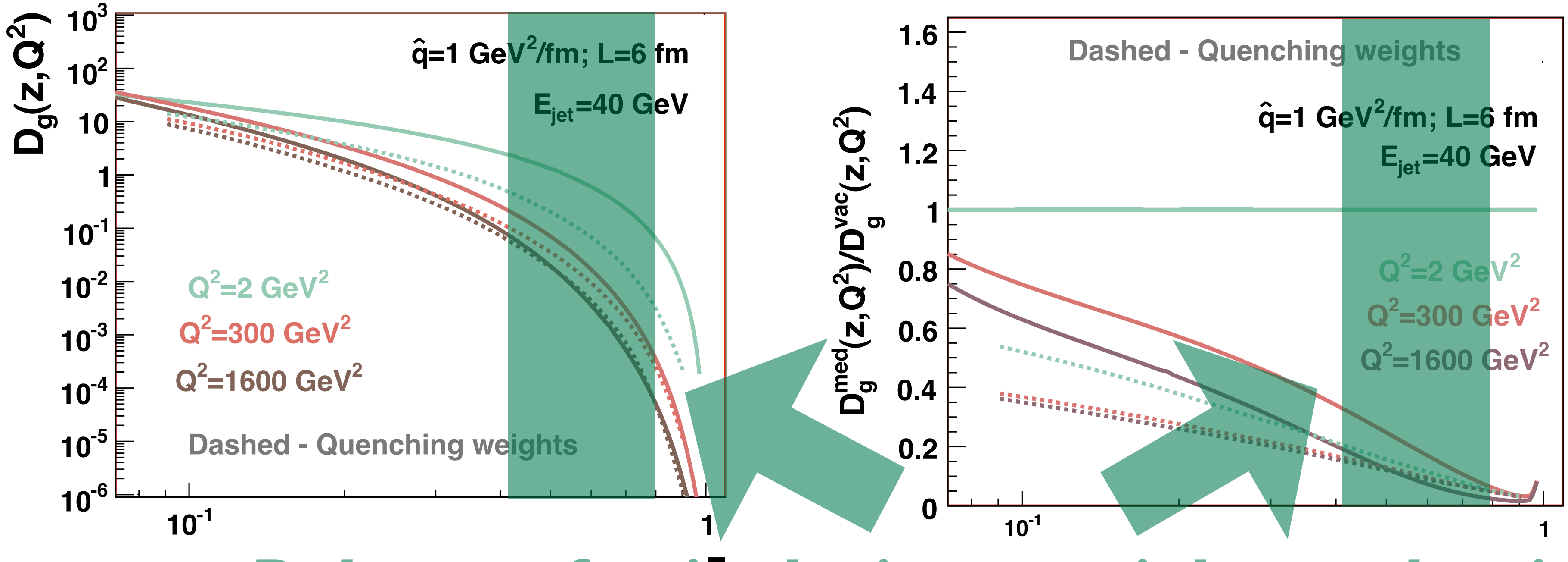

Relevant for inclusive particle production

- Softening of the fragmentation functions - energy loss
- Agreement with QW framework when $Q^2 \simeq E_{\rm jet}^2$
- QW overestimates suppression when $Q^2 \ll E_{\rm jet}^2$

[Armesto, Cunqueiro, Salgado, Xiang 2007]

Monte Carlo implementation

Sudakov prescription

⇛ Integral formulation of DGLAP (equivalent at LO in α_s)

$$f(x,t) = \Delta(t) f(x,t_0) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t')$$

⇛ Probability of no radiation between two scales

➘ Sudakov form factor

$$\Delta(t) \equiv \exp\left[- \int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P(z) \right]$$

⇛ The probability of one splitting

$$d\mathcal{P}(t,z) = \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P(z) \Delta(t)$$

⇛ Probabilistic interpretation well suited for MC event generators

Sudakov prescription (cont')

$$f(x,t) = \Delta(t) f(x,t_0) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t')$$

This part tells when nothing has happen from $t_0 \to t$

This part tells that one splitting took place at t'

So, the probability of just one splitting from two scales $t_0 \to t$:

$$d\mathcal{P}(t,z) = \frac{dt}{t}\, dz\, \frac{\alpha_s}{2\pi} P(z)\, \Delta(t_{\max}, t)$$

Sudakov prescription (cont')

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Monte Carlo implementation

⇛ This probabilistic approach is the basis of most MC codes

↘ HERWIG, PYTHIA, SHERPA, ...

How does it work?

1) First, decide whether there is branching from an initial t_1 to t_2

i) $\Delta(t_2)/\Delta(t_1)$ is the probability of no (resolvable) branching

ii) $\mathcal{R}$ is a random number generated by the program

iii) Generate t_2 with

$$\frac{\Delta(t_2)}{\Delta(t_1)} = \mathcal{R}$$

2) For this branching, decide the fraction of momentum $z = x_2/x_1$

$$\int_\epsilon^{x_2/x_1} dz\, \frac{\alpha_s}{2\pi} P(z) = \mathcal{R}' \int_\epsilon^{1-\epsilon} dz\, \frac{\alpha_s}{2\pi} P(z)$$

3) Repeat 1) and 2) until a cut-off scale t_0 is reached

How?

⇛ Many different methods to chose a variable according to a distribution

↘ Example: Hit or miss method

1. Chose

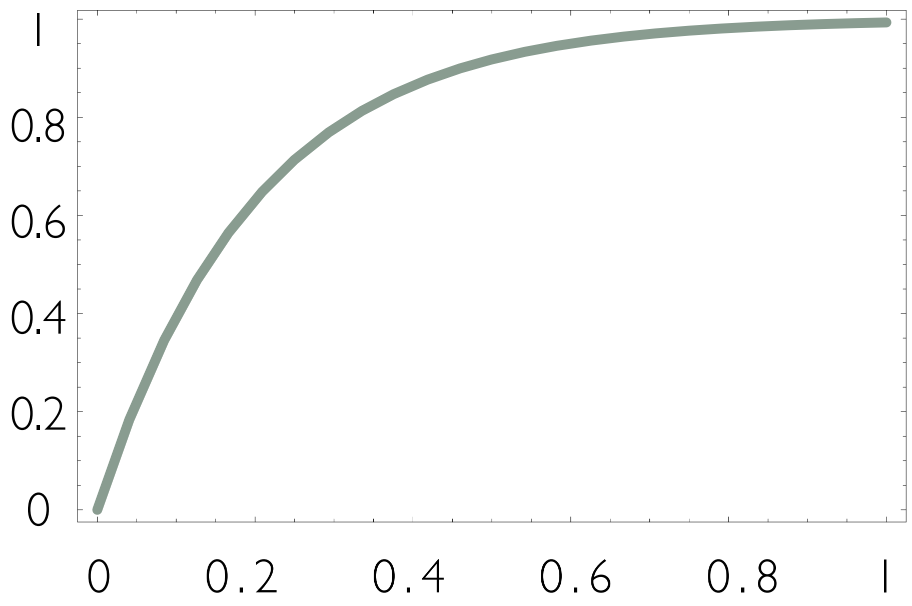
$$x = x_{\rm min} + (x_{\rm max} - x_{\rm min})\mathcal{R}$$

2. If

$$f(x) \leq \mathcal{R}' \, f_{\rm max}$$

reject the value and start at 1.

$\mathcal{R}$, $\mathcal{R}'$ random numbers between 0 and 1



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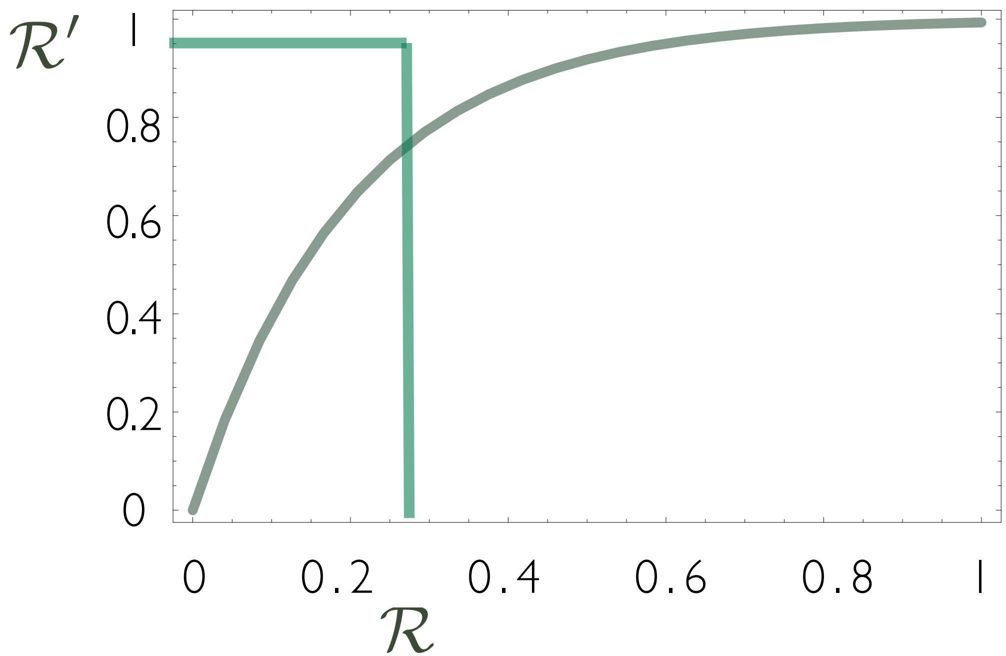

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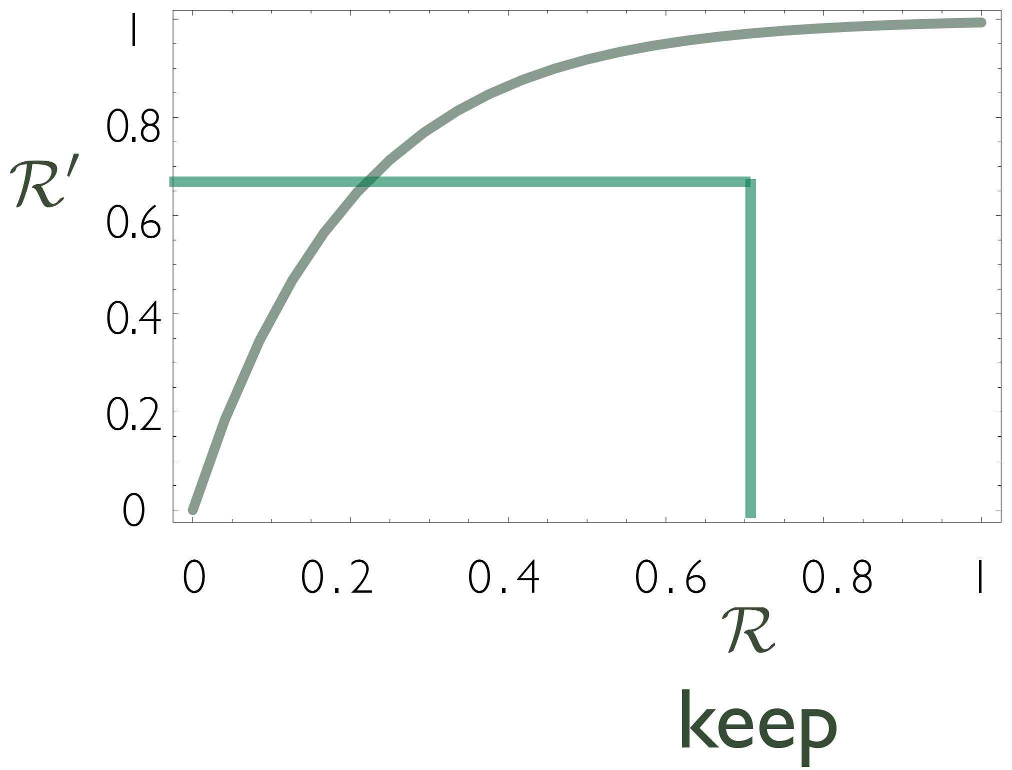
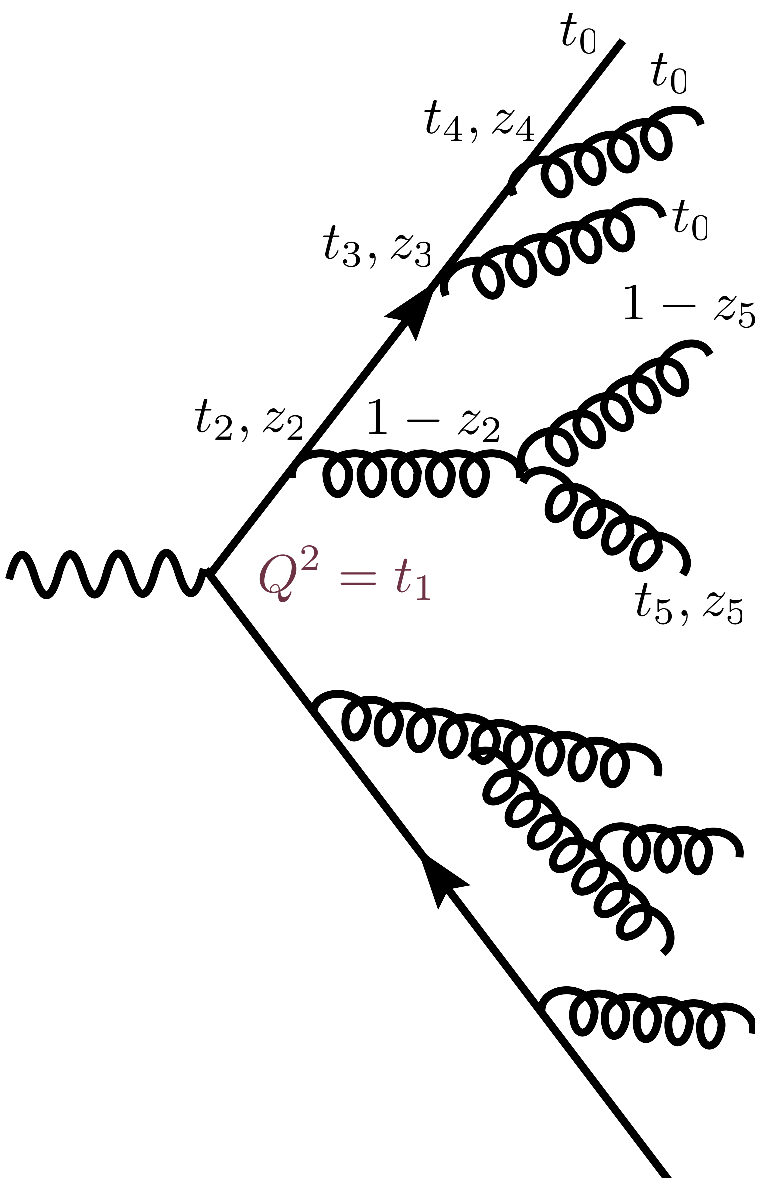


Branching process



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

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)

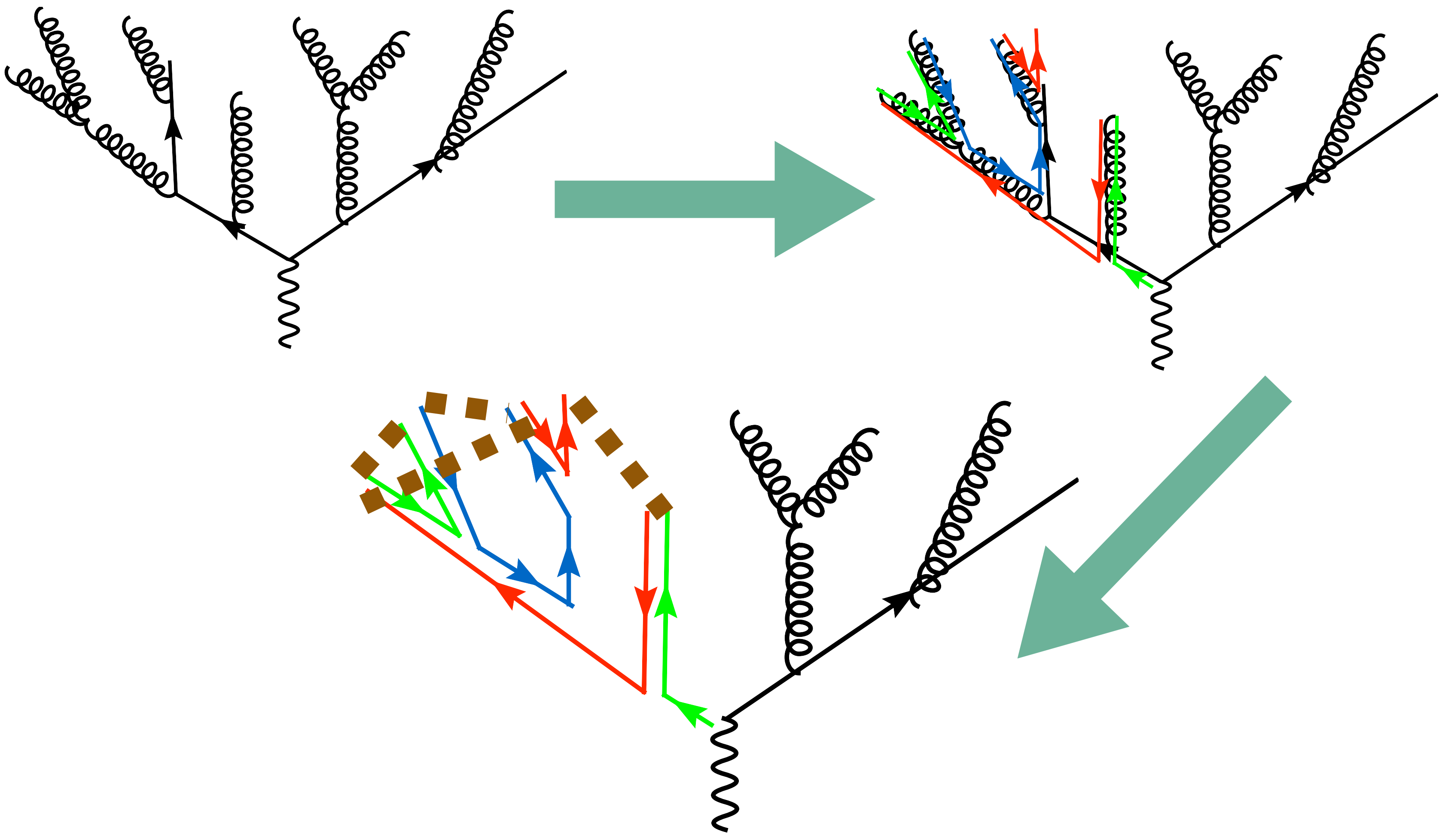
  i) No branching is found with $t < t_0$

    → Branching stops

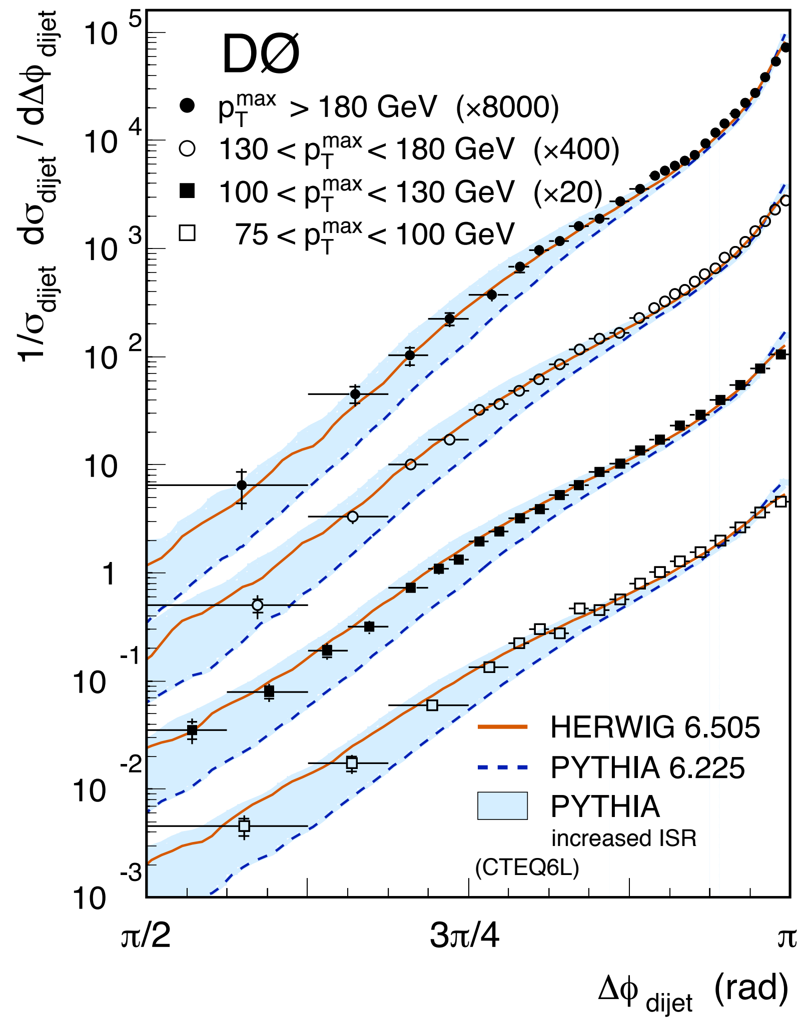
4) Distribution of gluons in the final state has to be hadronized

Color connections

- Each parton splitting modifies the color structure
  - PYTHIA then reconnects the colors to form and decay strings



Comparison with data

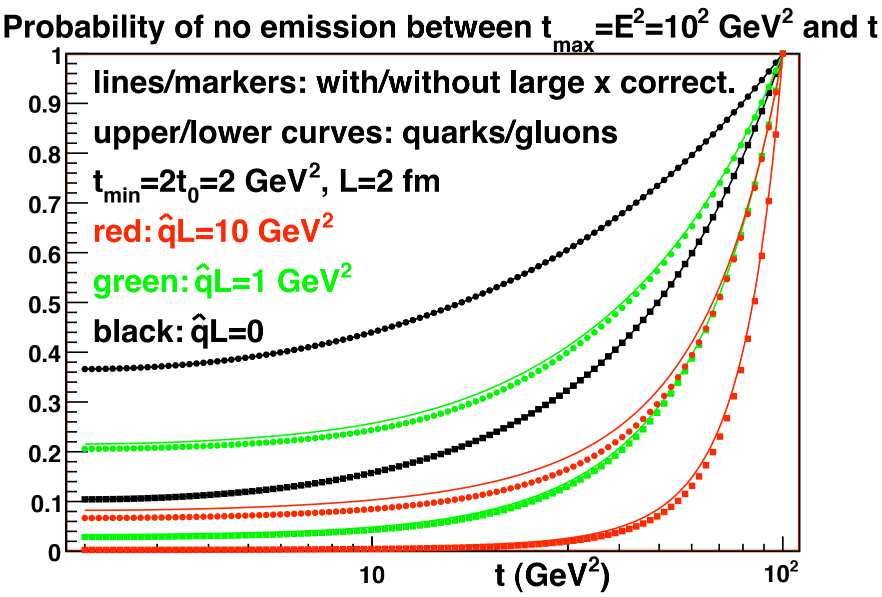


Di-jet azimuthal decorrelation at the Tevatron

Including the medium terms

- Sudakov form factor with medium-modified splitting probability

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} \left[P(z) + \Delta P(z, t', \hat{q}, L)\right]\right]$$



E=10 GeV

[Armesto, Cunqueiro, Salgado, Xiang 2007]

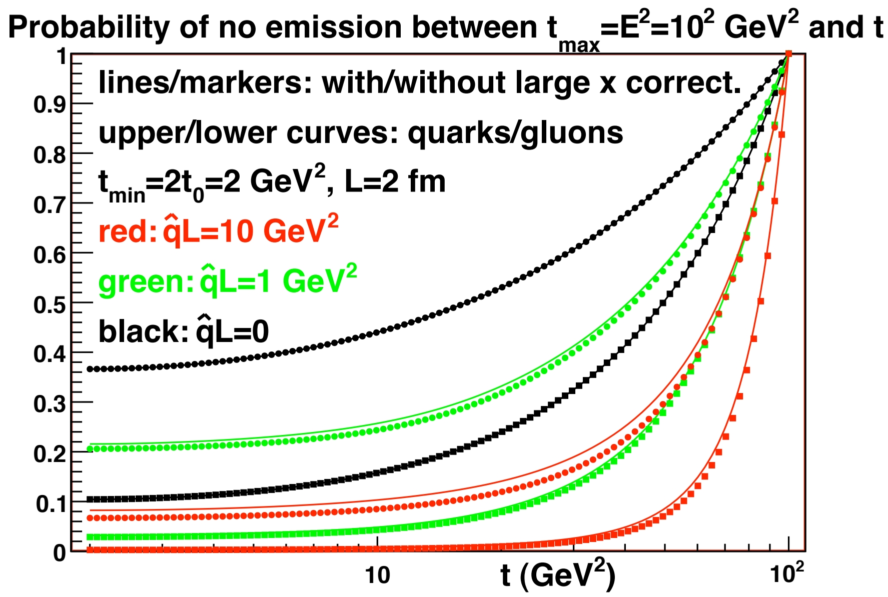
- The medium terms suppress the Sudakov
  - **More radiation in medium than in vacuum**

Including the medium terms

⇛ Sudakov form factor with medium-modified splitting probability

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\,\frac{\alpha_s}{2\pi}\left[P(z)+\Delta P(z,t',\hat{q},L)\right]\right]$$

The medium is here



E=10 GeV

[Armesto, Cunqueiro, Salgado, Xiang 2007]

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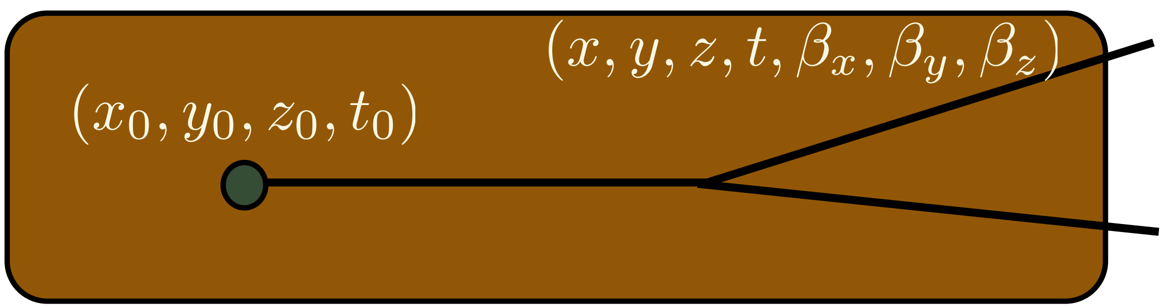
More radiation in medium than in vacuum

The program

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

[Notice, however, that this is <u>not</u> 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 $(x, y, z, t, \beta_x, \beta_y, \beta_z)$



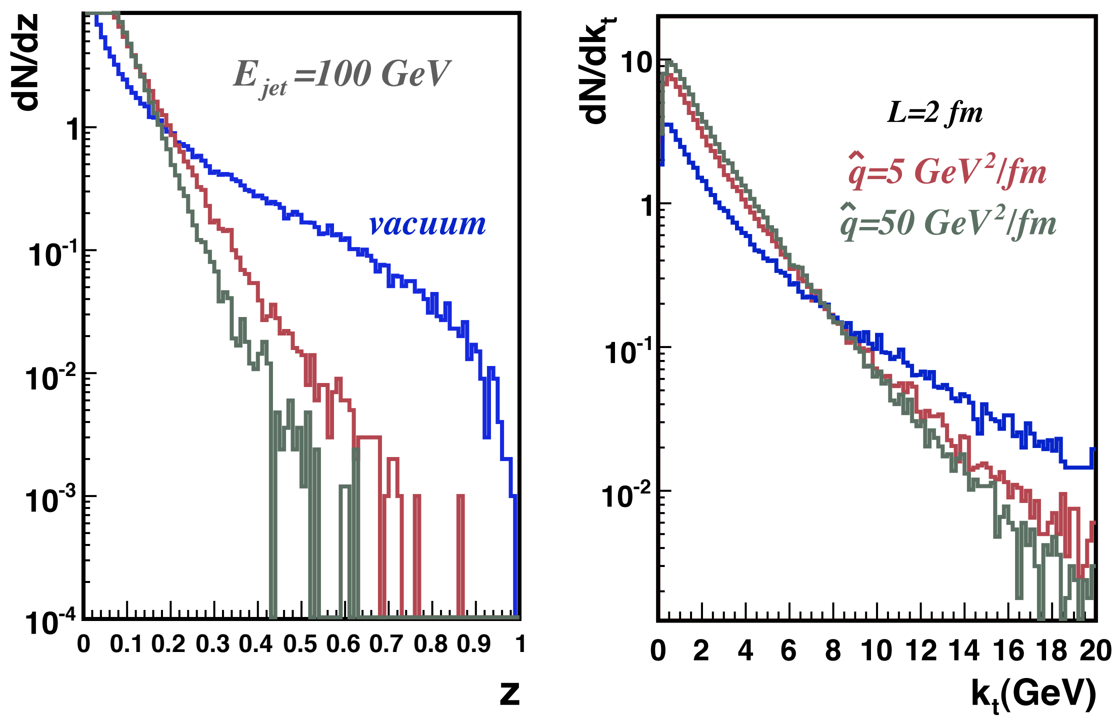
Routines QPYGIN and QPYGEO

```
      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,AA2,BBX,BBY,BBZ
C     Example valid for both frames coinciding
      x0=0.d0 ! fm
      y0=0.d0 ! fm
      z0=0.d0 ! fm
      t0=0.d0 ! fm
```

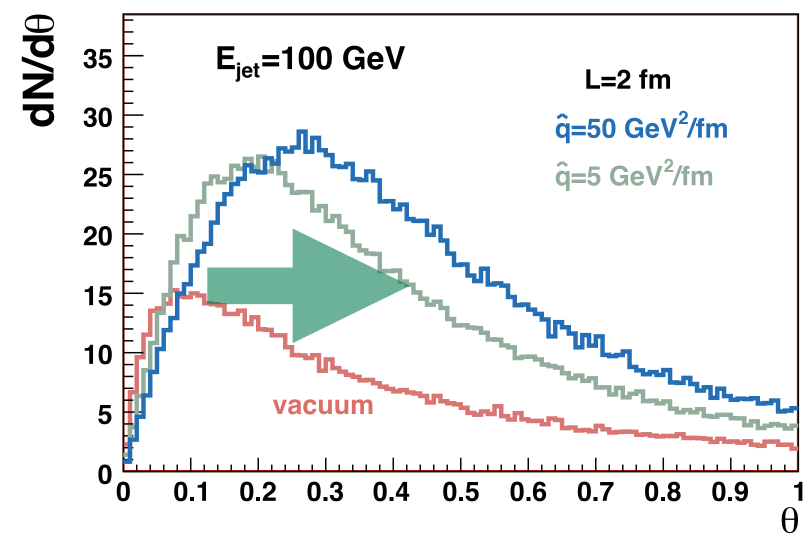
```
      SUBROUTINE QPYGEO(X,Y,Z,T,BX,BY,BZ,QHL,OC)
C     USER-DEFINED ROUTINE:
C     The values of qhatL and omegac have to be computed
C     by the user, using his preferred medium model, in
C     this routine, which takes as input the position
C     x,y,z,t of the parton to branch, the trajectory
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).
```

Results from an implementation in Pythia

Fragmentation function



Angular distribution

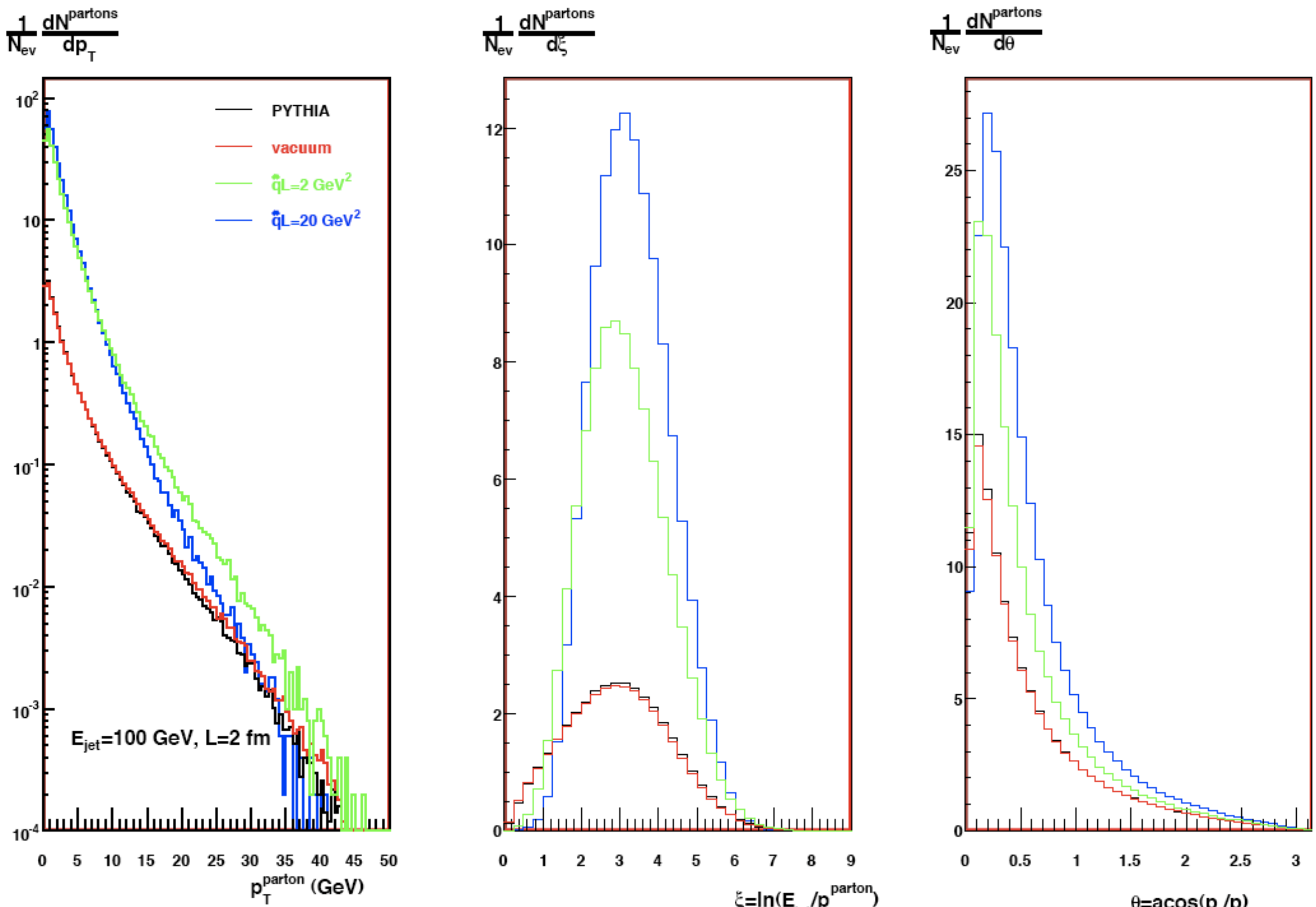


⇒ Main medium-modifications in agreement with expectations

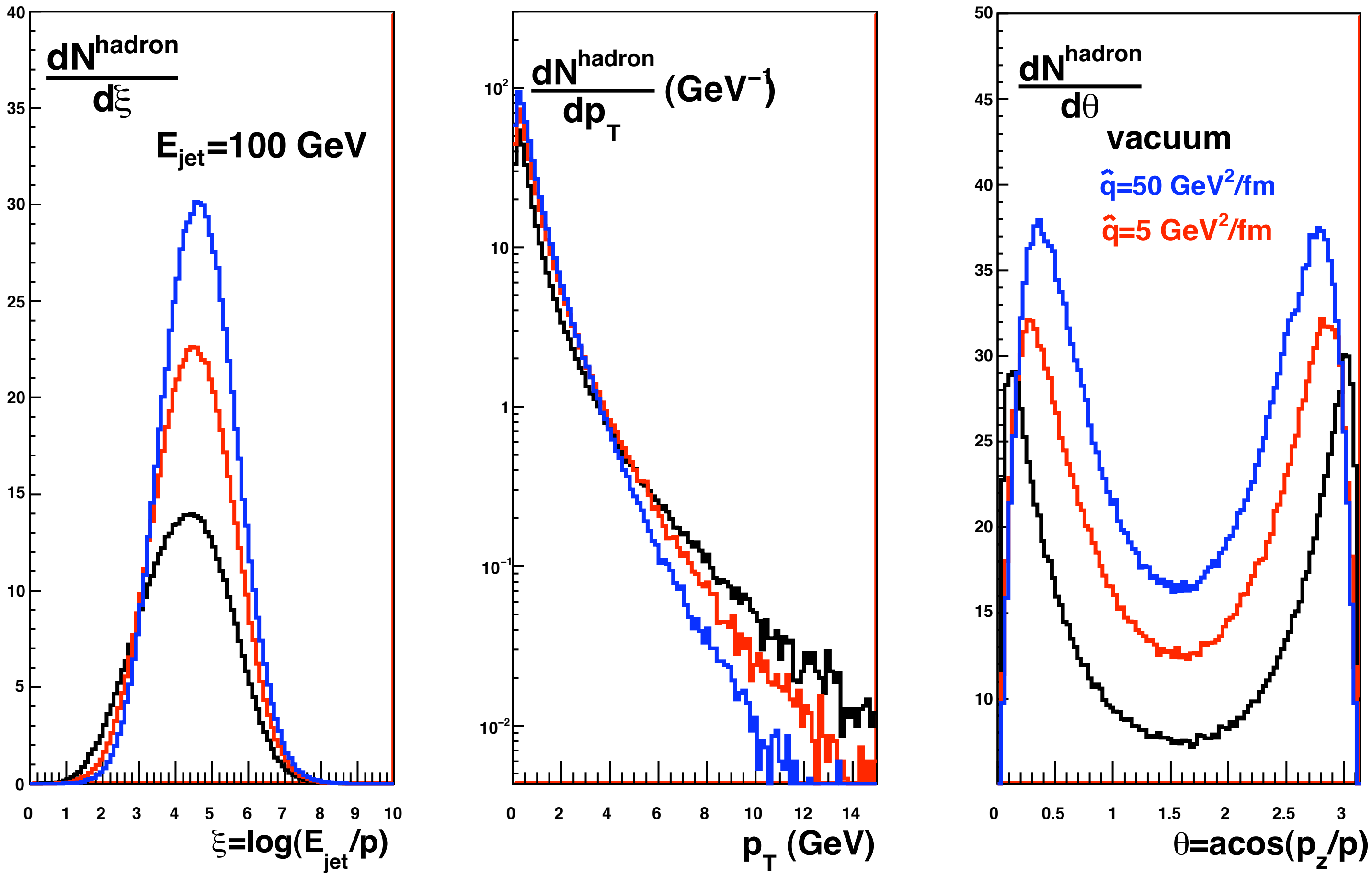
- Particle spectrum softens (energy loss)
- Larger emission angles (jet broadening)
- Larger multiplicity

[Armesto, Corcella, Cunqueiro, Salgado in preparation]

More results



Results including hadronization



⇛ Effects are reduced by hadronization

⇛ Comparison of different hadronization models is important:

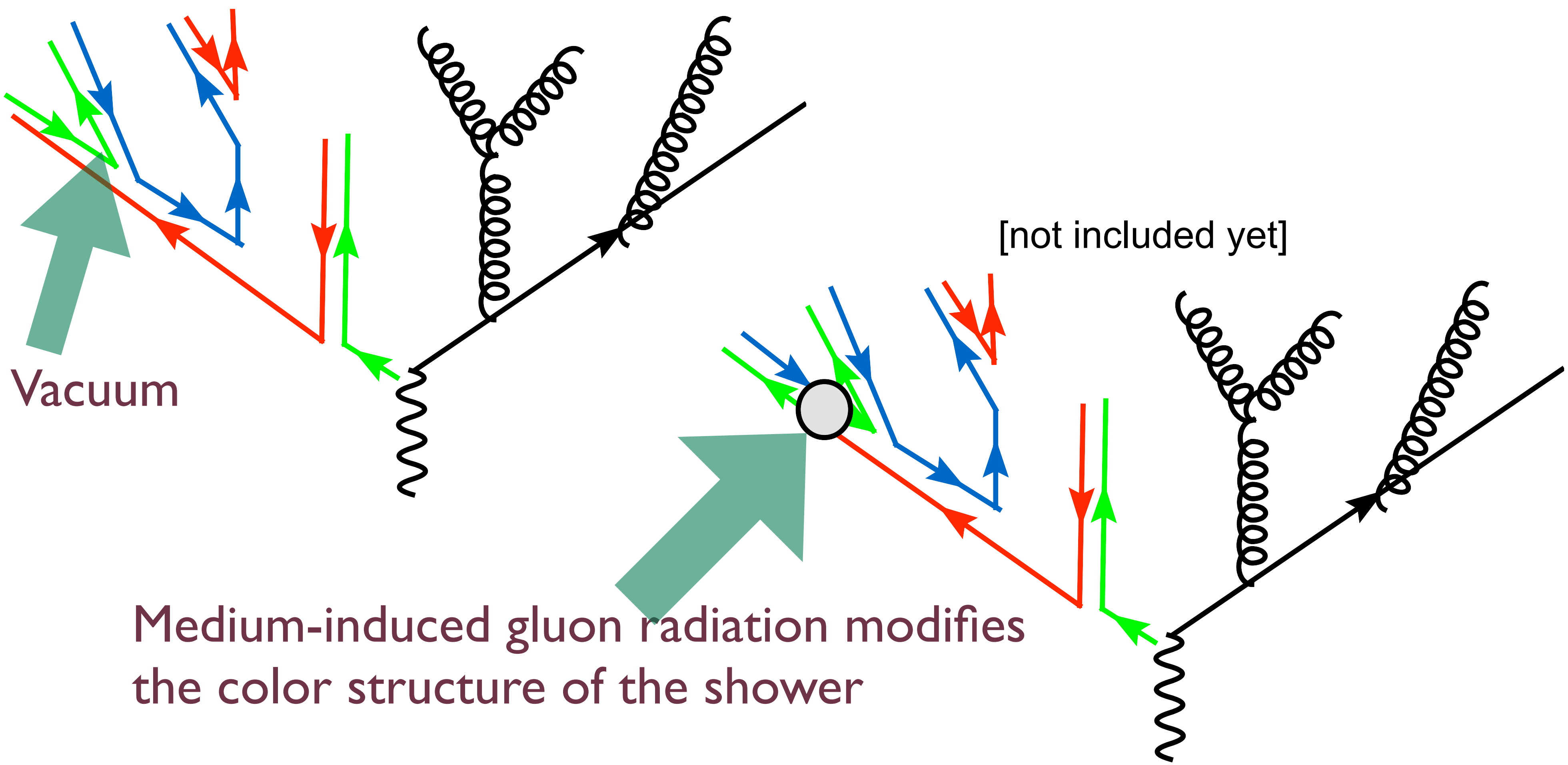
PYTHIA (string fragmentation) vs HERWIG (cluster hadronization)

Different effects

- More radiation
  - Energy loss: leading particle suppression
  - Multiplicity increases
- Different angular dependence
  - Broadening from medium but partial compensation from multiplicity enhancement
- Role of hadronization?

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



From the Sudakov to the QW

- The QW can be obtained as a particular case of the Sudakov prescription we have just presented
  - Start from the DGLAP eq. in integral form

$$D(x,t) = \Delta(t)D(x,t_0) + \Delta(t)\int_{t_0}^{t}\frac{dt_1}{t_1}\frac{1}{\Delta(t_1)}\int\frac{dz}{z}P(z)D\left(\frac{x}{z},t_1\right)$$

- Now write the iterative solution (discretize t)

$$\begin{aligned}
D(x,t) &= \Delta(t)D(x,t_0) + \Delta(t)\sum_{n=1}^{\infty}\int_{t_0}^{t}\frac{dt_1}{t_1}\int_{t_0}^{t_1}\frac{dt_2}{t_2}\cdots\int_{t_0}^{t_{n-1}}\frac{dt_n}{t_n}\int\frac{dz_1}{z_1}\int\frac{dz_2}{z_2}\cdots\int\frac{dz_n}{z_n}\\
&\times P(z_1)P(z_2)\cdots P(z_n)D\left(\frac{x}{z_1z_2\cdots z_n},t_0\right)\\
&= \Delta(t)D(x,t_0) + \Delta(t)\int\frac{d\epsilon}{1-\epsilon}\sum_{n=1}^{\infty}\int_{t_0}^{t}\frac{dt_1}{t_1}\int_{t_0}^{t_1}\frac{dt_2}{t_2}\cdots\int_{t_0}^{t_{n-1}}\frac{dt_n}{t_n}\prod_{i=1}^{n}\int dz_i\,P(z_i)\\
&\times \delta\left(z_1z_2\cdots z_n-[1-\epsilon]\right)D\left(\frac{x}{1-\epsilon},t_0\right).
\end{aligned}$$

From the Sudakov to the QW II

⇛ In the limit of soft radiation

$$D(x,t) \simeq \Delta(t) D(x,t_0) + \Delta(t) \int \frac{d\epsilon}{1-\epsilon} \sum_{n=1}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int_{t_0}^{t} \frac{dt_i}{t_i} \int dz_i \, P(z_i) \times \delta\left(\epsilon - \sum_{j=1}^{n} x_j\right) D\left(\frac{x}{1-\epsilon}, t_0\right).$$

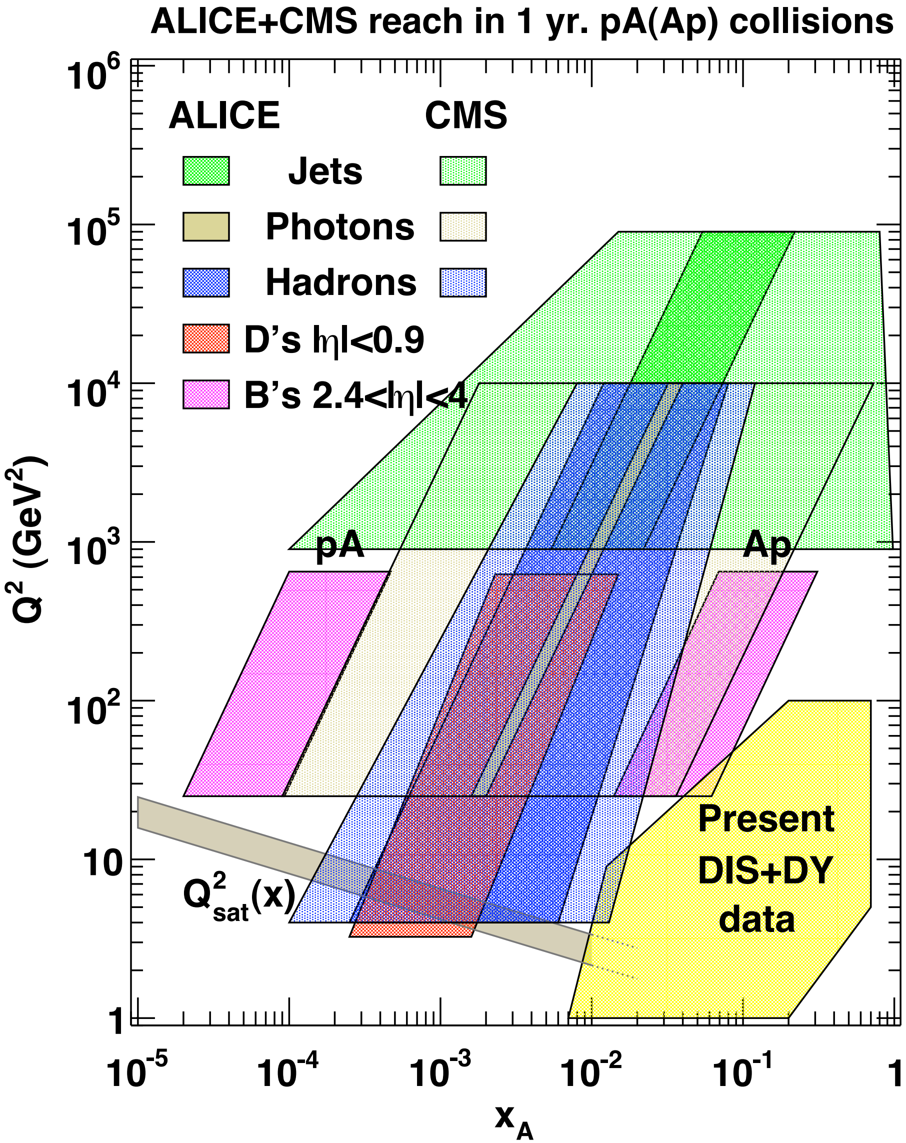
⇛ Taking $P(z) = P^{\rm vac}(z) + \Delta P(z), \quad \Delta(t) = \Delta^{\rm vac}(t)\Delta^{\rm med}(t),$

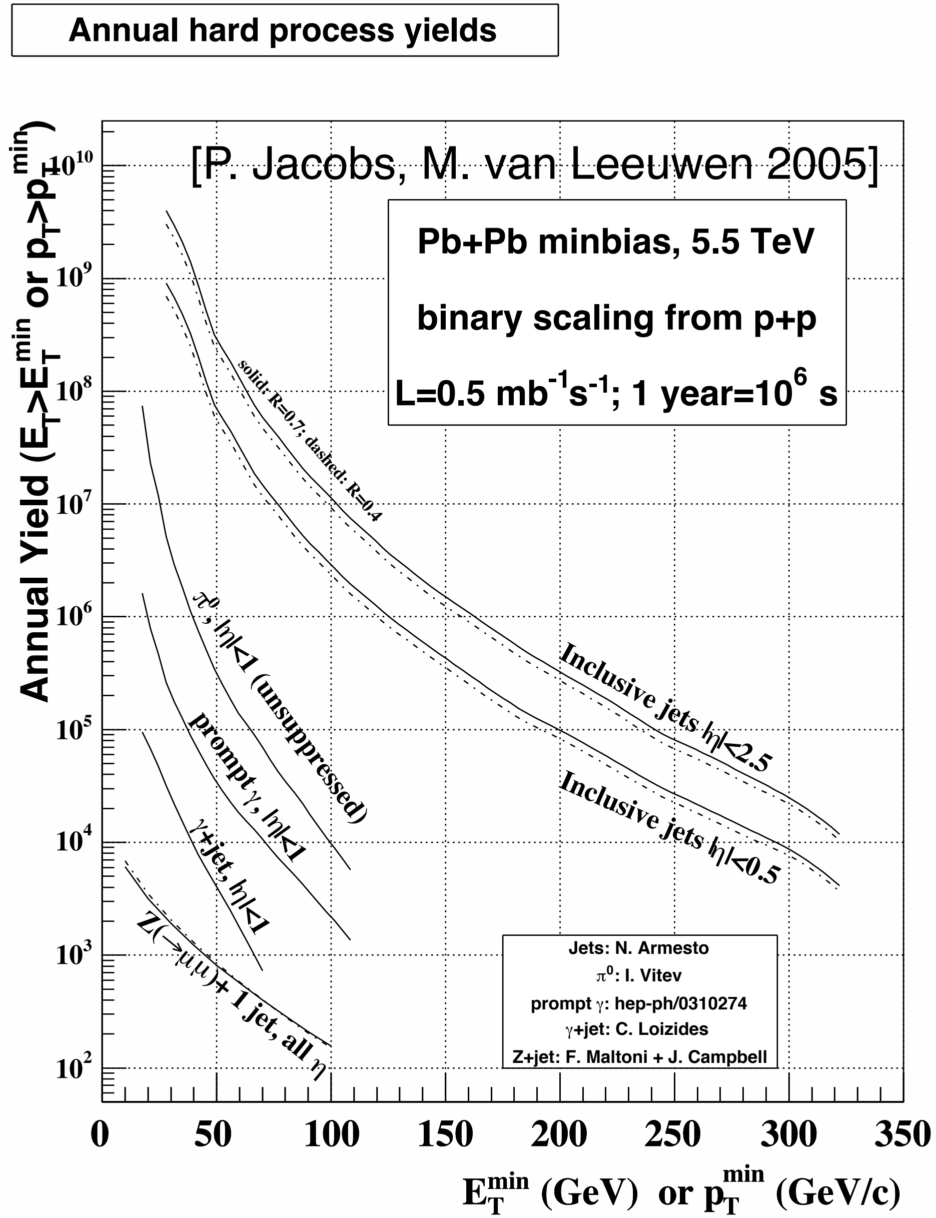
$$\begin{aligned} D(x,t) \quad &\simeq \quad \Delta^{\rm med}(t) D^{\rm vac}(x,t) + \Delta^{\rm med}(t) \int \frac{d\epsilon}{1-\epsilon} \sum_{n=1}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int_{t_0}^{t} \frac{dt_i}{t_i} \int dz_i \, \Delta P(z_i) \\ &\times \quad \delta\left(\epsilon - \sum_{j=1}^{n} x_j\right) D^{\rm vac}\left(\frac{x}{1-\epsilon}, t\right) \end{aligned}$$

⇛ Which can be written in terms of the usual QW

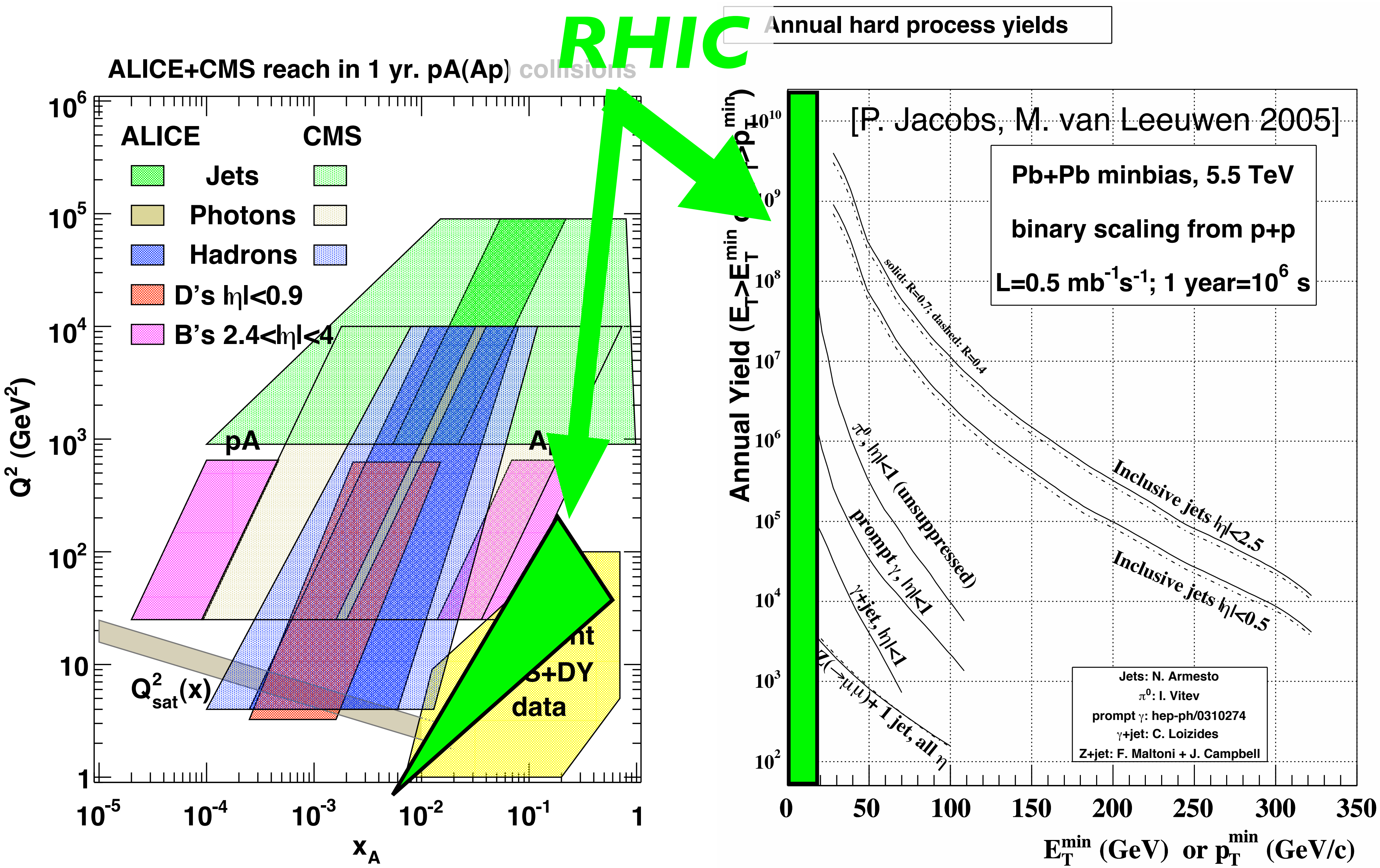
$$D(x,t) \simeq p_0 \, D^{\rm vac}(x,t) + \int \frac{d\epsilon}{1-\epsilon} \, p(\epsilon) \, D^{\rm vac}\left(\frac{x}{1-\epsilon}, t\right)$$

New regimes at the LHC

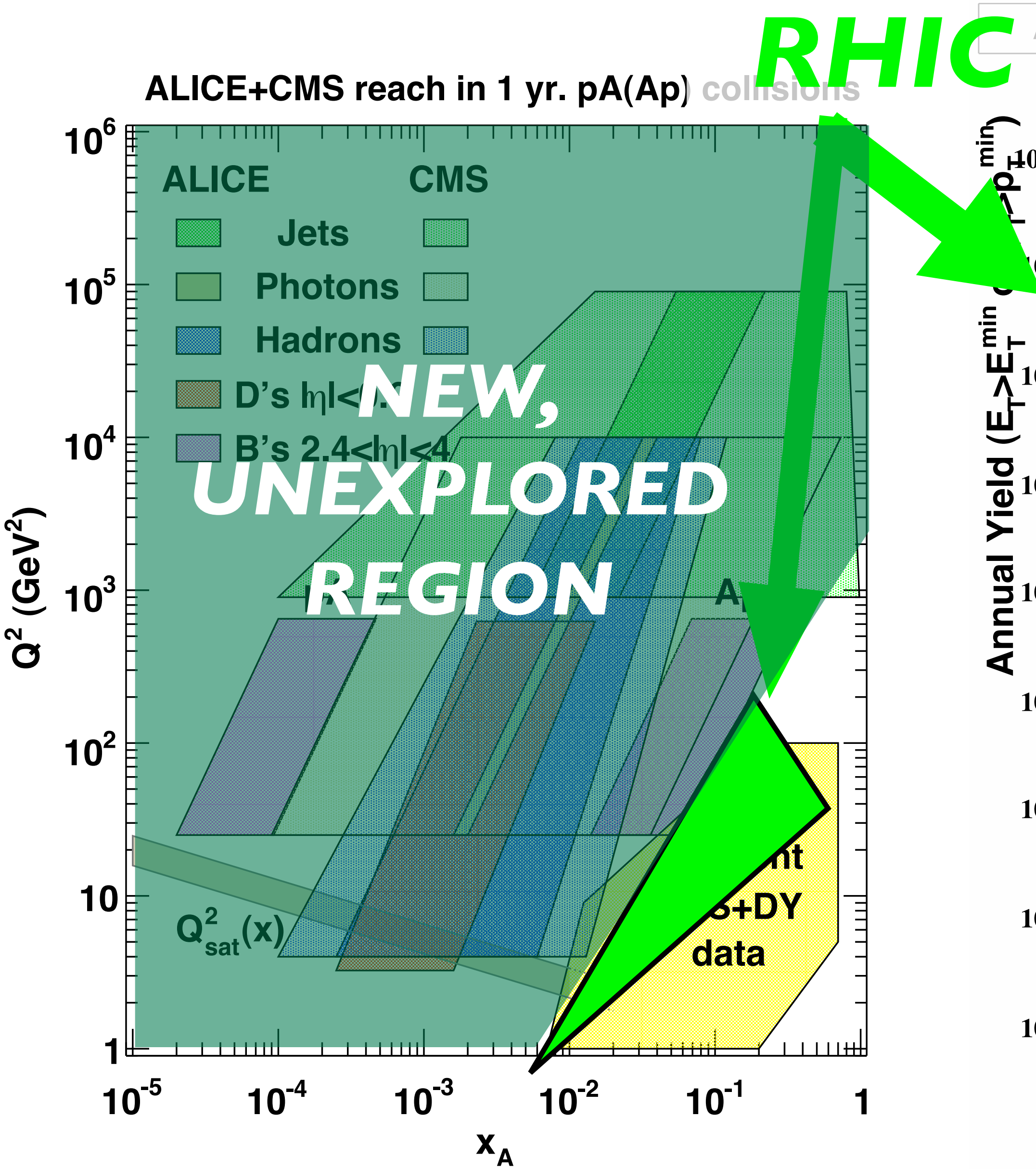


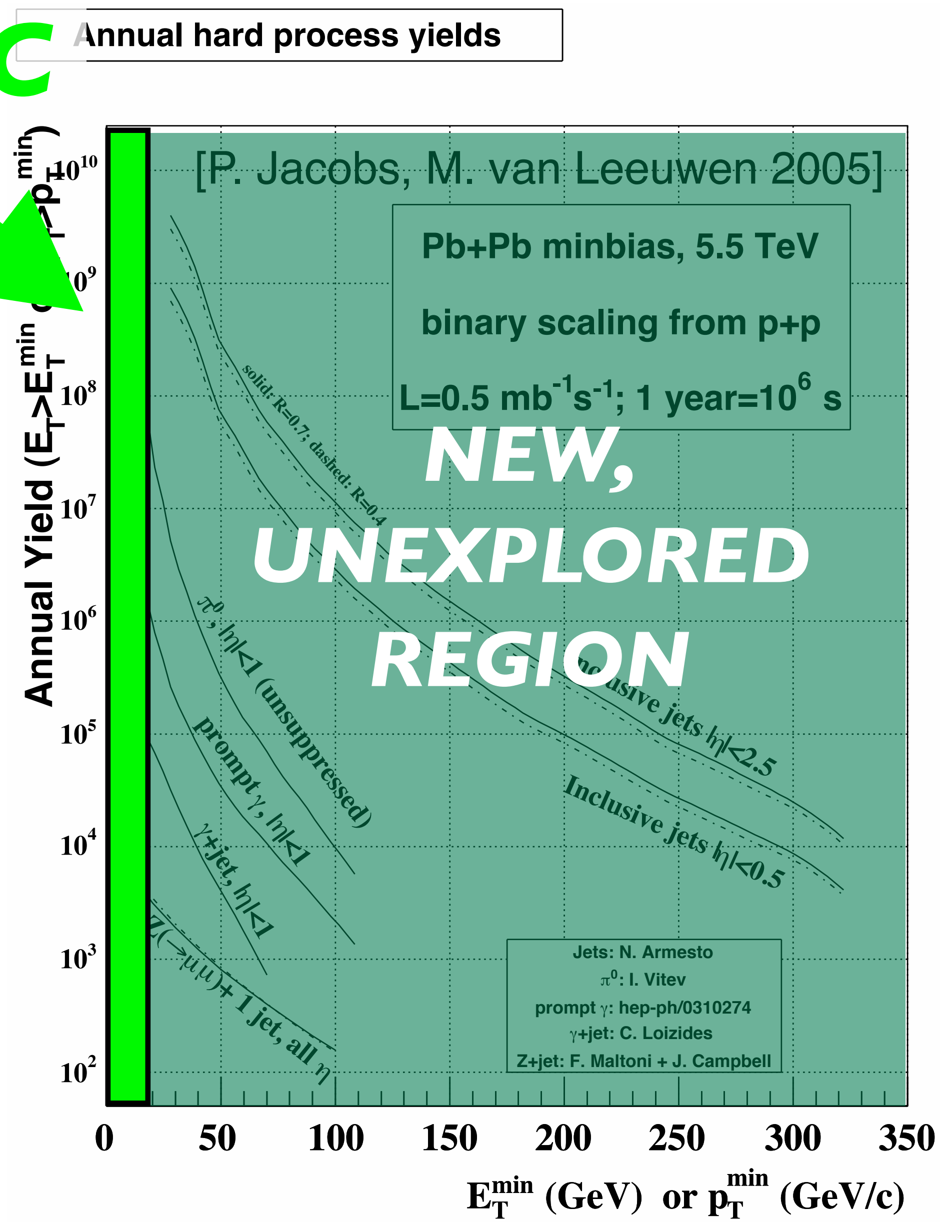


New regimes at the LHC



New regimes at the LHC





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

Summary

- We have supplemented the splitting functions with a medium term (à la BDMPS - ASW)
  - Vacuum and medium treated on the same footing
  - Role of virtuality; energy conservation; length; ...
- Implementation in PYTHIA (and HERWIG)
  - Modification of the shower routine PYSHOW
  - The rest is standard PYTHIA
- Many issues still to be clarified in TH/PH/EX
- Publicly available code Q-PYTHIA v1.0 at Q@MC site:

http://igfae.usc.es/QatMC