Monte Carlo simulations of hard probes

Many thanks to: all MC speakers and authors
+ Leticia Cunqueiro, Abhijit Majumder, Liliana Apolinario

Marta Verweij (CERN)

September 2016
Hard Probes, Wuhan

Why do we need MCs?

Many experimental observables are not calculable from first principles or too complicated

Allow theoretical and experimental studies of complex multiparticle physics

Study the effect of a certain phenomenon on specific observables in case analytically not possible

For interpretation of experimental measurements

To improve precision of experimental data

All this requires theory-experiment interaction

Improving data quality with help from MCs

Feasibility studies – predict rate of certain process + quenching sensitivity for a observable

Simulate background – analysis strategy design

Study detector requirements – for new facilities and upgrades

Study detector resolution and efficiency
→ for example: quenching uncertainty on jet energy scale

Full MC event in vacuum

Hard scattering

Initial state radiation (ISR)

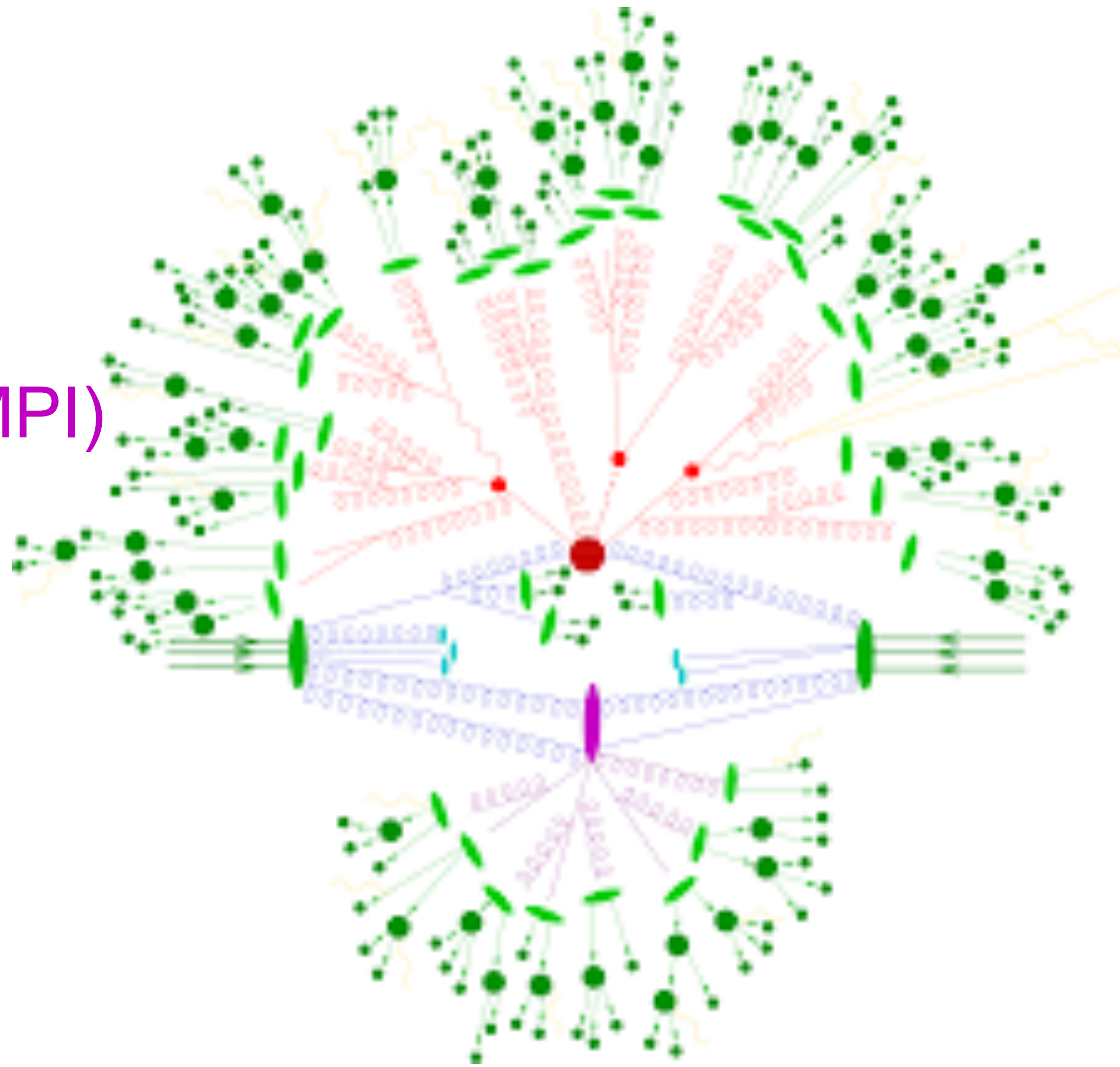
Multi parton interactions (MPI)

Final state radiation (FSR)

Color reconnections

Hadronization

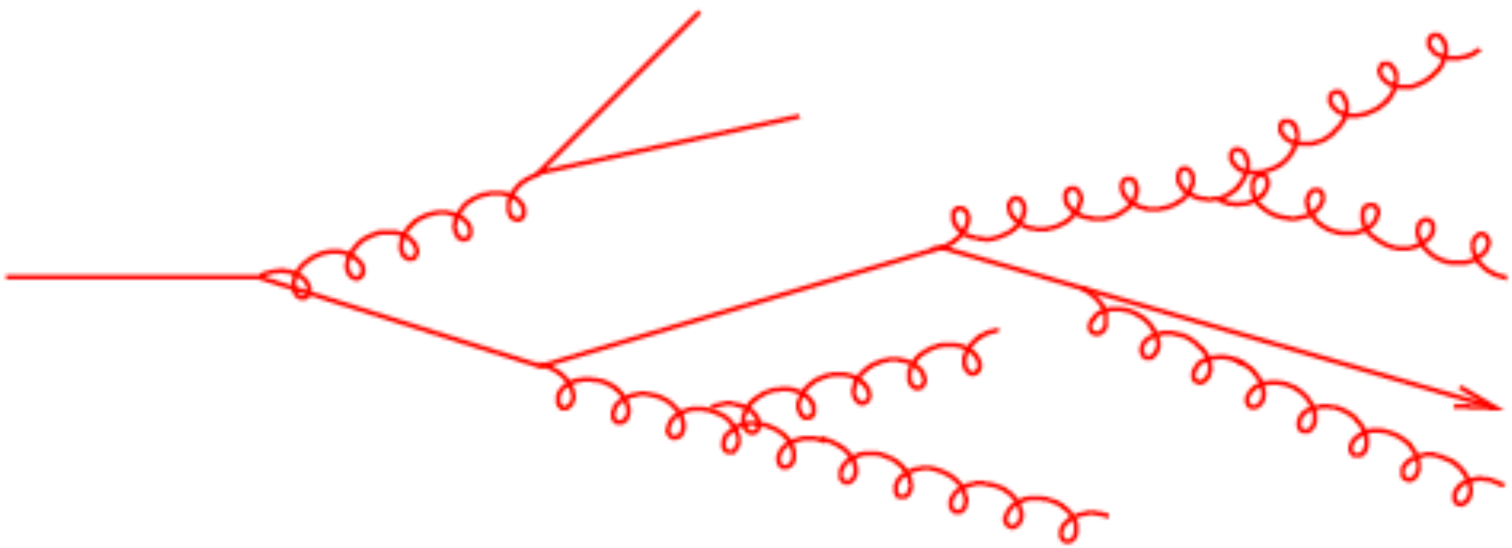
…



QCD Parton shower in vacuum

Probabilistic process. (cross section is not affected)
Collinear factorization → DGLAP evolution ($Q_1 > Q_2 > Q_3 \ldots$)
Altarelli-Parisi splitting functions describe 1→ 2 splitting process

Key difference between the various generators is the evolution variable: virtuality Q^2, transverse momentum k_T, angle θ
→ All the same in the collinear limit



MC ingredients for hard processes

Hard jet production – matrix elements
→The same for vacuum and quenched MC

Final state parton shower
→ pp: resummation of collinear logarithms (LL)
→ AA: quenching implementation – model dependent

Initial state parton shower
→ pp: similar to final state parton shower
→ AA: nPDFs, otherwise unchanged

Hadronisation
→ pp: non-perturbative effect – modeled
→ AA: assumed outside medium, but no proof

Round table

Saturday afternoon

Discussion about the basic principles of jet quenching MC implementation

- Hybrid strong/weak coupling model
- Linear Boltzmann Transport model
- QPYTHIA
- MATTER
- MARTINI
- JEWEL

pQCD based radiative energy loss

AdS/CFT based energy loss

References to models in backup

Round table

Saturday afternoon

Discussion about the basic principles of jet quenching MC implementation

- Hybrid strong/weak coupling model – Daniel Pablos
- Linear Boltzmann Transport model – Tan Luo
- QPYTHIA – Liliana Apolinario
- MATTER – Michael Kordell
- MARTINI – Sangyong Jeon
- JEWEL

5 representatives of MC models gave us a quick overview of their model. Discussion afterwards

pQCD based radiative energy loss

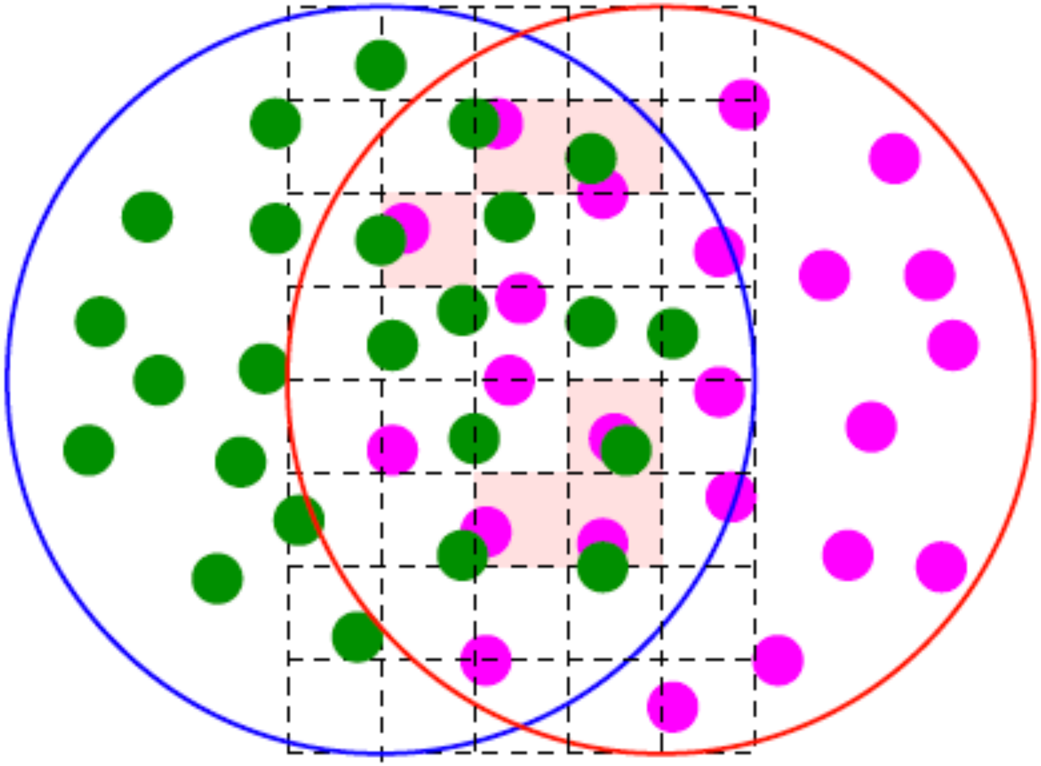
AdS/CFT based energy loss

References to models in backup

Hard jet production

Hard parton production for all models according to LO or NLO
Glauber Ncoll profile

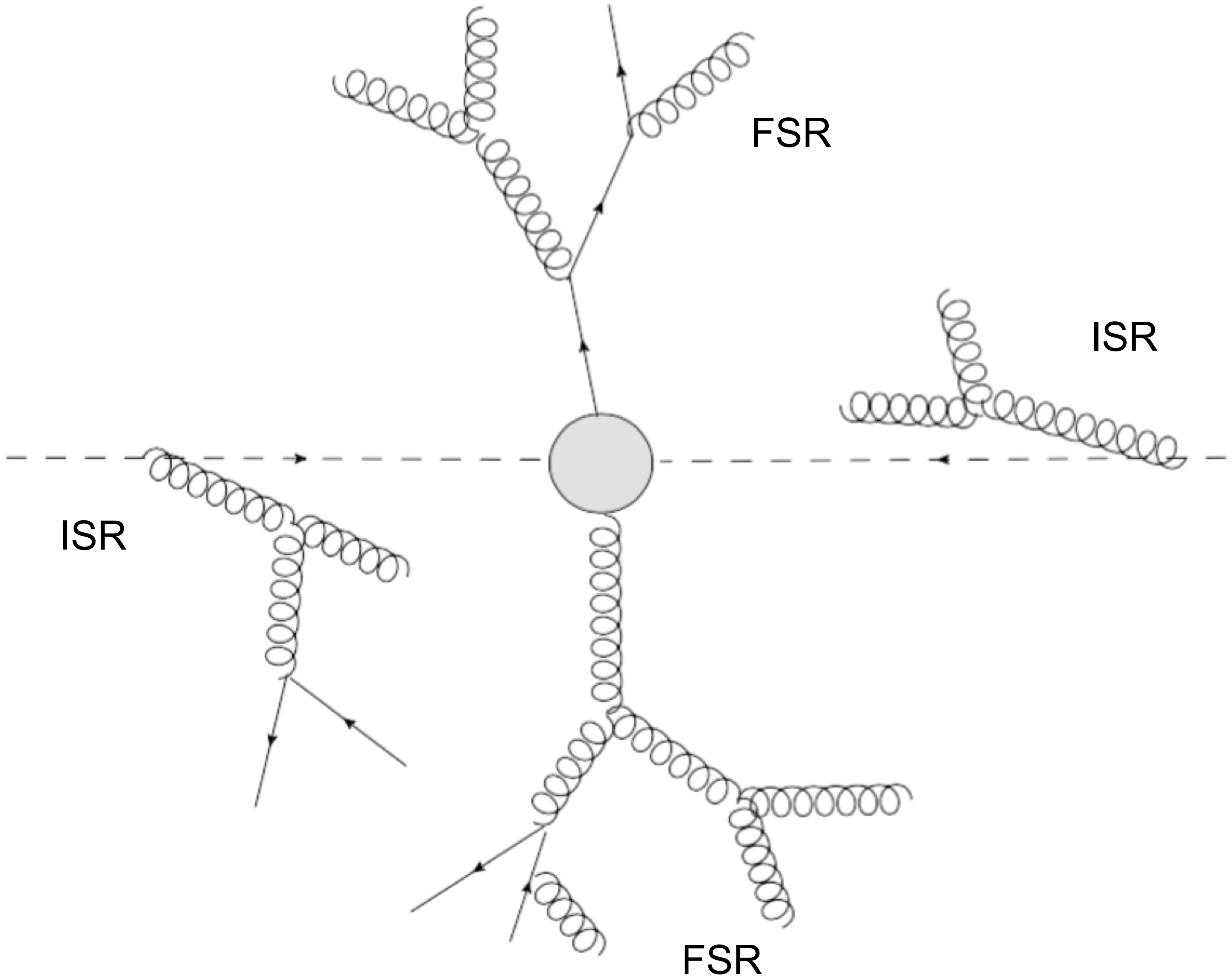
Parton has to be assigned a position in space-time coordinates which map to a medium



Medium and parton evolve in space-time during parton shower

MC Parton Shower

This is where jet quenching is implemented



MC Parton Shower

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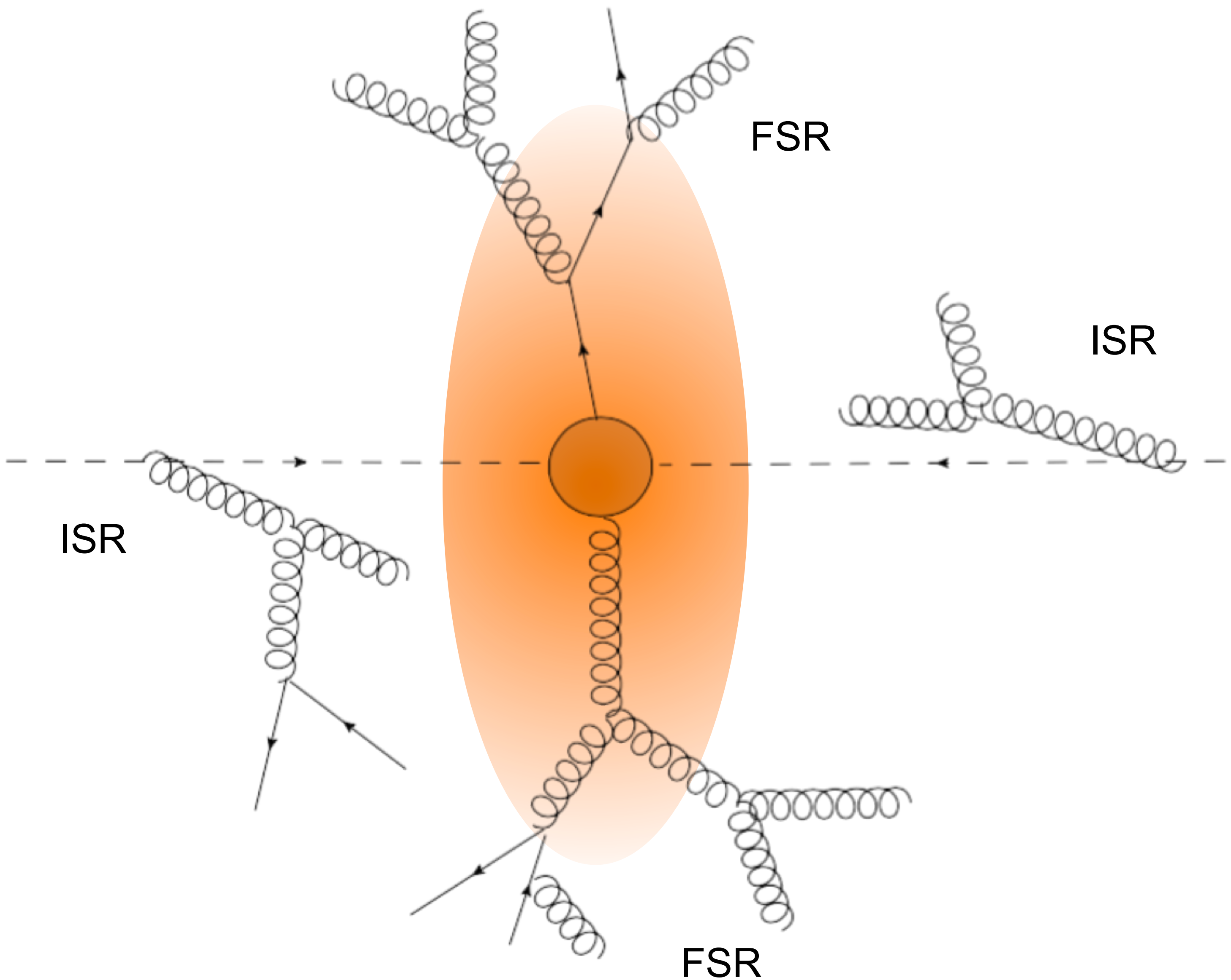
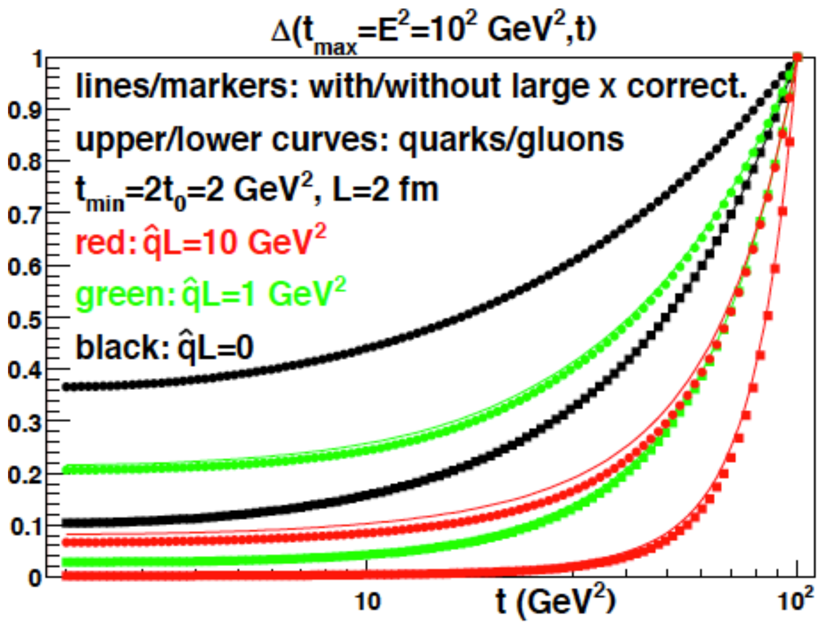


Sudakov with medium modified splitting

Implemented in QPYTHIA, MARTINI, MATTER, YAJEM-BW



$$dP(t,z) = \frac{\alpha_s}{2\pi} P^{tot}(z)\Delta(t_0,t)dz\frac{dt}{t}$$

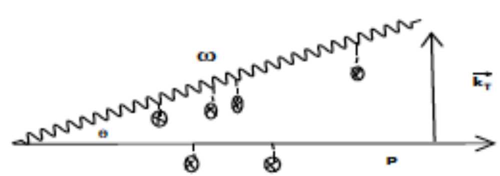
Evolution variable

Sudakov form factor

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

Contains information about local medium properties
L: Medium length
q̂: Transport coefficient

Evolution of Sudakov form factor in QPYTHIA
→Enhancement of splitting probability



Energy-momentum conservation within shower

arXiv:0907.1014
arXiv:0909.5118

Medium modified splitting

Implemented in QPYTHIA, MARTINI, MATTER, YAJEM-BW

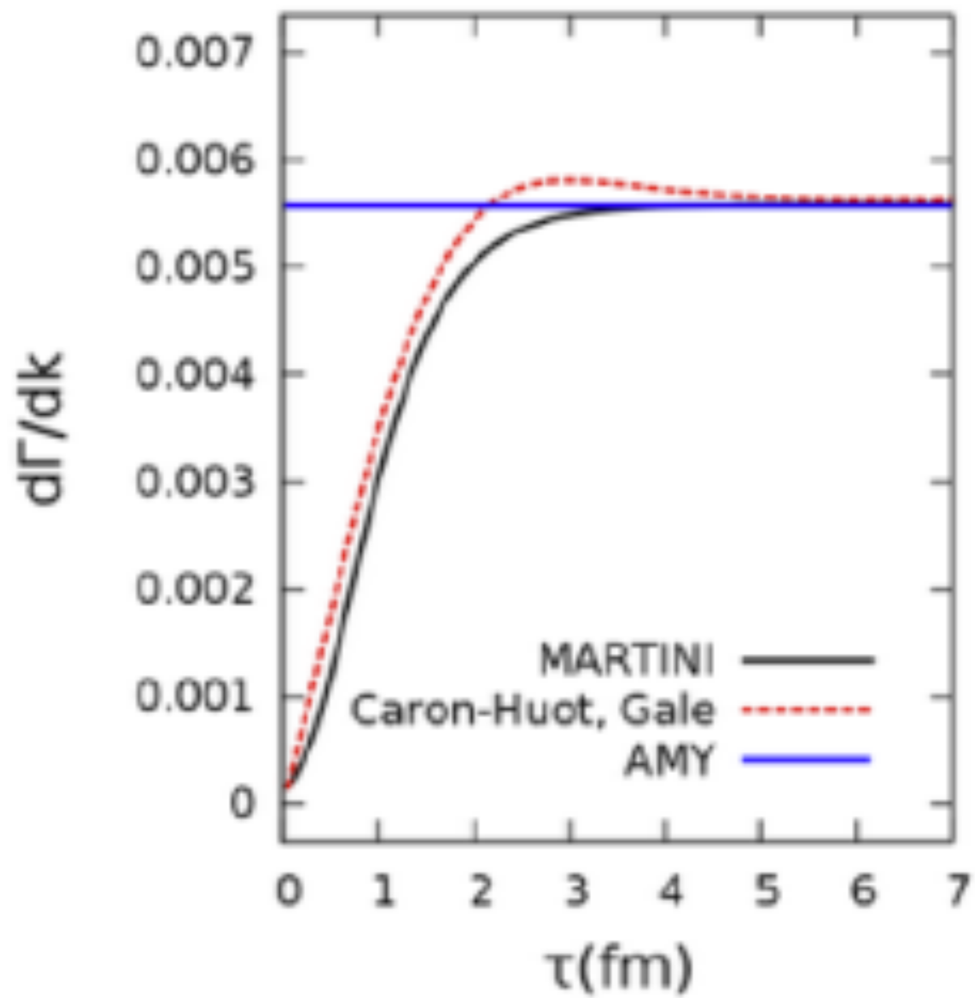
Includes elastic, radiative and conversion processes
Relative contributions controlled by weights

Total interaction probability given by local conditions

$$P = \sum_i \Delta t_{local} \int dk \frac{d\Gamma_i}{dk}$$

Radiative: emission rate from AMY

C. Park, M.Sc Thesis, McGill (2015)



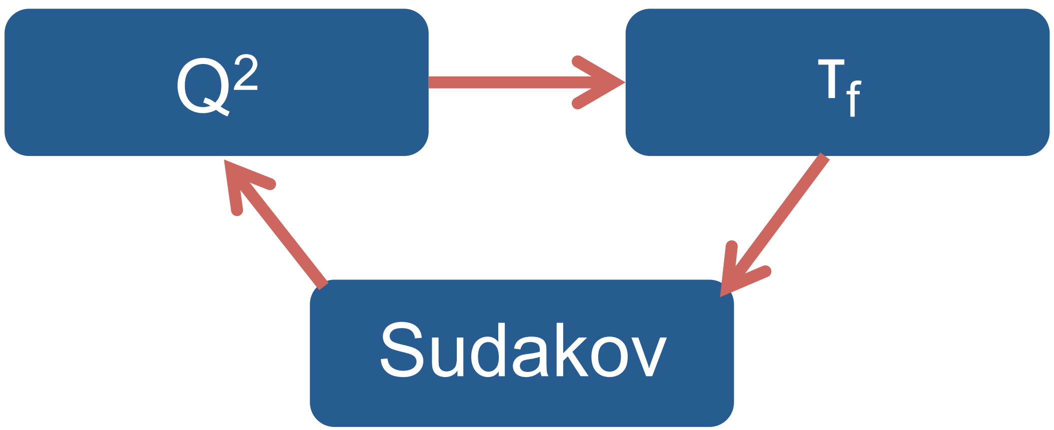
arXiv:0909.2037, arXiv:0911.4470

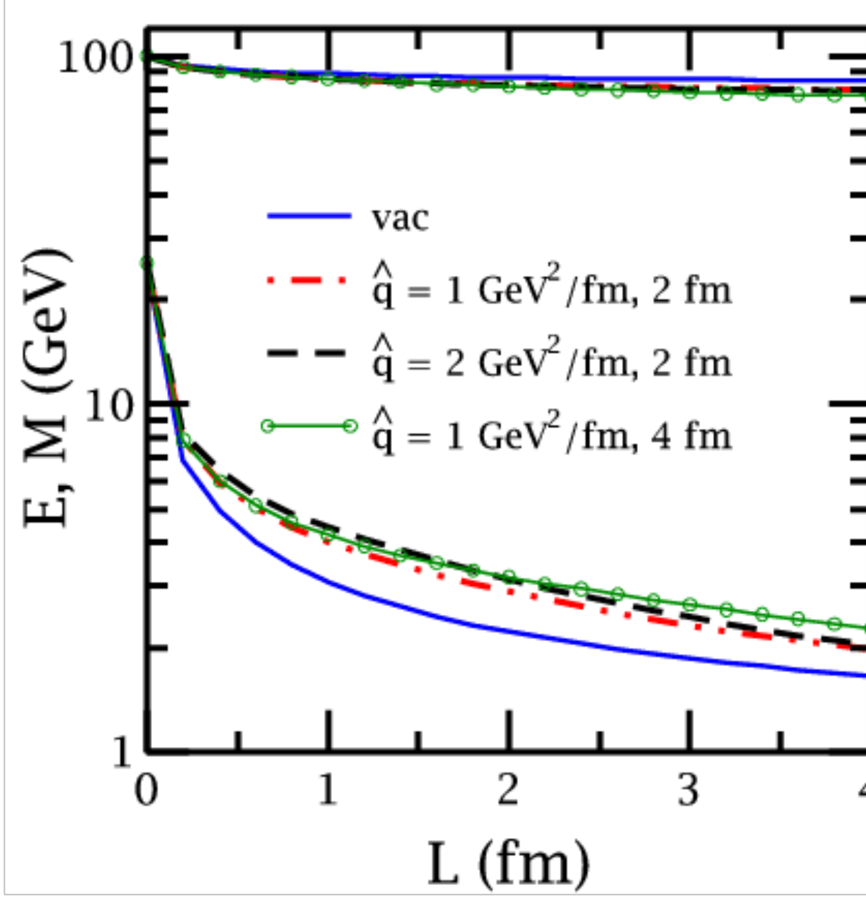
Sudakov with medium modified splitting

Implemented in QPYTHIA, MARTINI, MATTER, YAJEM-BW

Modified virtuality evolution
Radiative energy loss: higher twist
Few scatterings per emission limit

Sudakov form factor modified





Phys.Rev. C93 (2016)

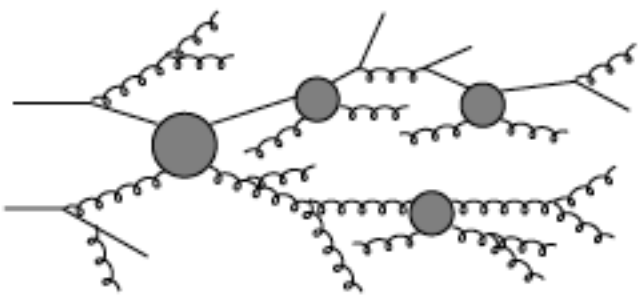
arXiv:1301.5323

$$S_\zeta(Q_0^2,Q^2) = \exp[-\int_{2Q_0^2}^{Q^2}\frac{d\mu^2}{\mu^2}\frac{\alpha_s(\mu^2)}{2\pi} * \int_{Q_0/Q}^{1-Q_0/Q} dy P_{qg}(y)\{1+\int_{\zeta_i^-}^{\zeta_i^- +\tau^-} d\zeta K_{p^-,\mu^2}\}]$$

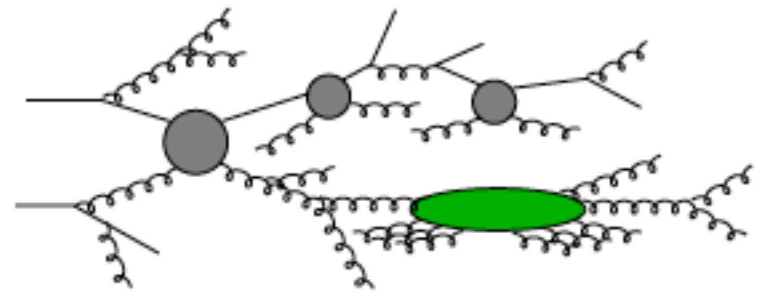
JEWEL

Scattering of partons with medium
→ Same as hard scatter but now incoming parton is from medium
Using infrared continuation (2→2) of matrix element (ME)
Generates elastic and inelastic processes

Scatterings with medium



Scatterings with medium + LPM effect



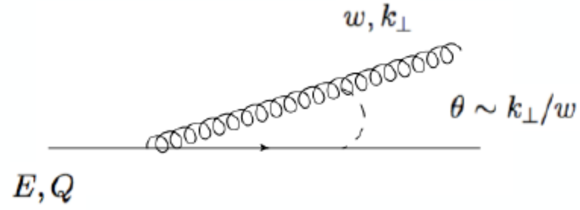
Formation time: determines which emission is realised

LPM interference: governed by formation times

arXiv:1212.1599
arXiv:1111.6838

[Figures by K. Zapp – Subatech Seminar]

HYBRID



Parton shower production perturbative process

→ use full Pythia8 parton shower + space-time through formation time of vacuum splittings ($\tau_f = \omega/k_t^2 = 2E/Q^2$)

Interaction with medium strongly coupled – holography

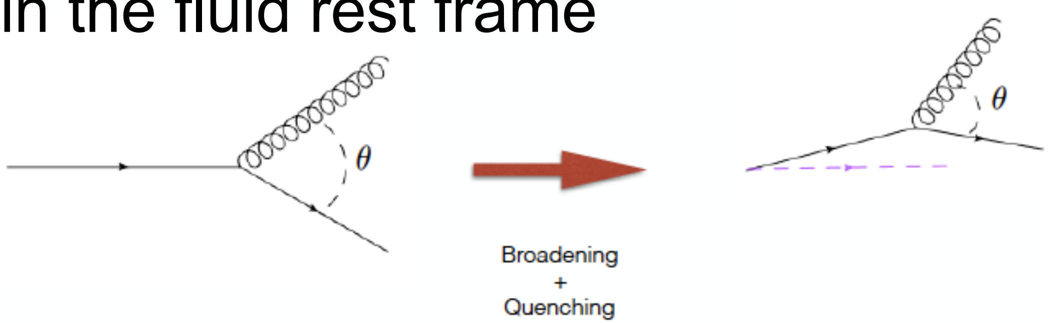
→ Each parton in vacuum shower interacts with medium leading to energy loss

→ Energy loss rate from holography

$$\frac{1}{E_{\text{in}}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\text{stop}}^2}\frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

$$x_{\text{stop}} = \frac{1}{2\,\kappa_{\text{sc}}}\frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

Broadening: transverse kicks in the fluid rest frame



Additional tool: Coherence by using resolution parameter

arXiv:1405.3864,1508.00815,1609.05842

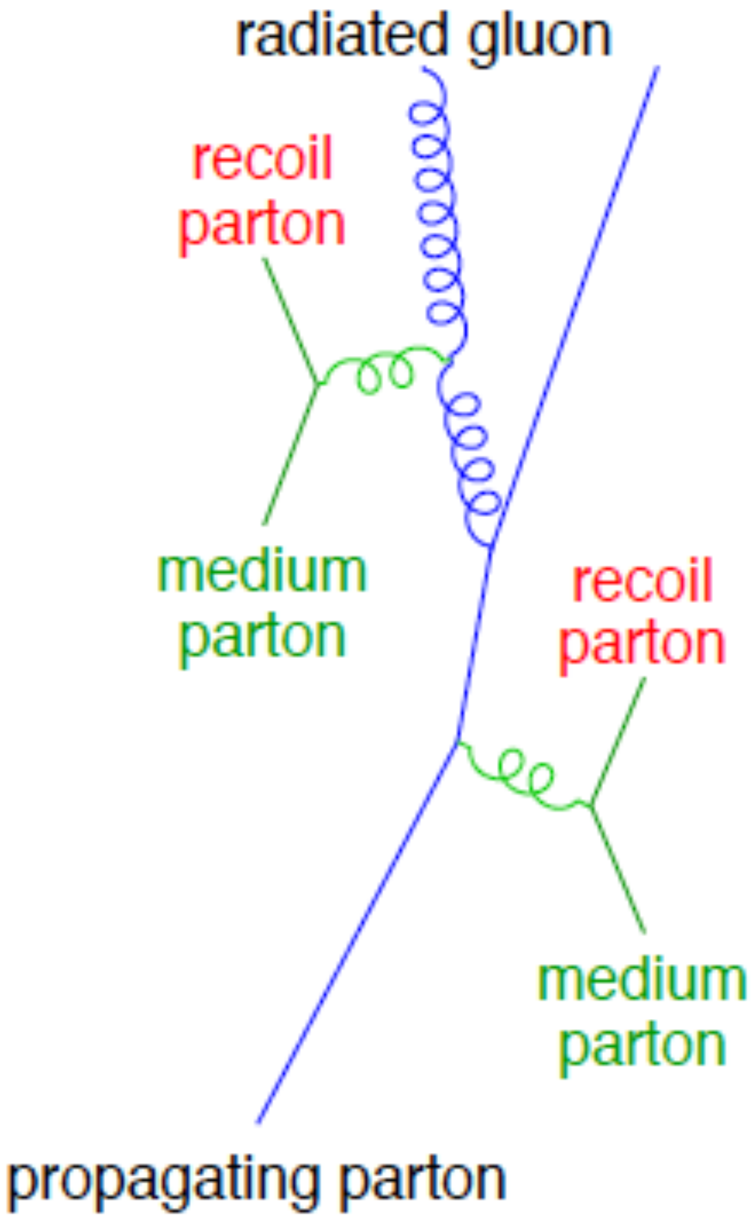
Medium response - JEWEL recoil

Jets modify the 'background' close to it
- Partons in jet scatter with partonic constituents of medium

Consequence: energy-momentum leakage from parton shower

Need recoil partons to conserve energy-momentum
→ recoil partons also carry momentum from medium

Subtraction technique developed to subtract scattering centers which don't belong to parton shower
[R.K. Elayavalli, Saturday]



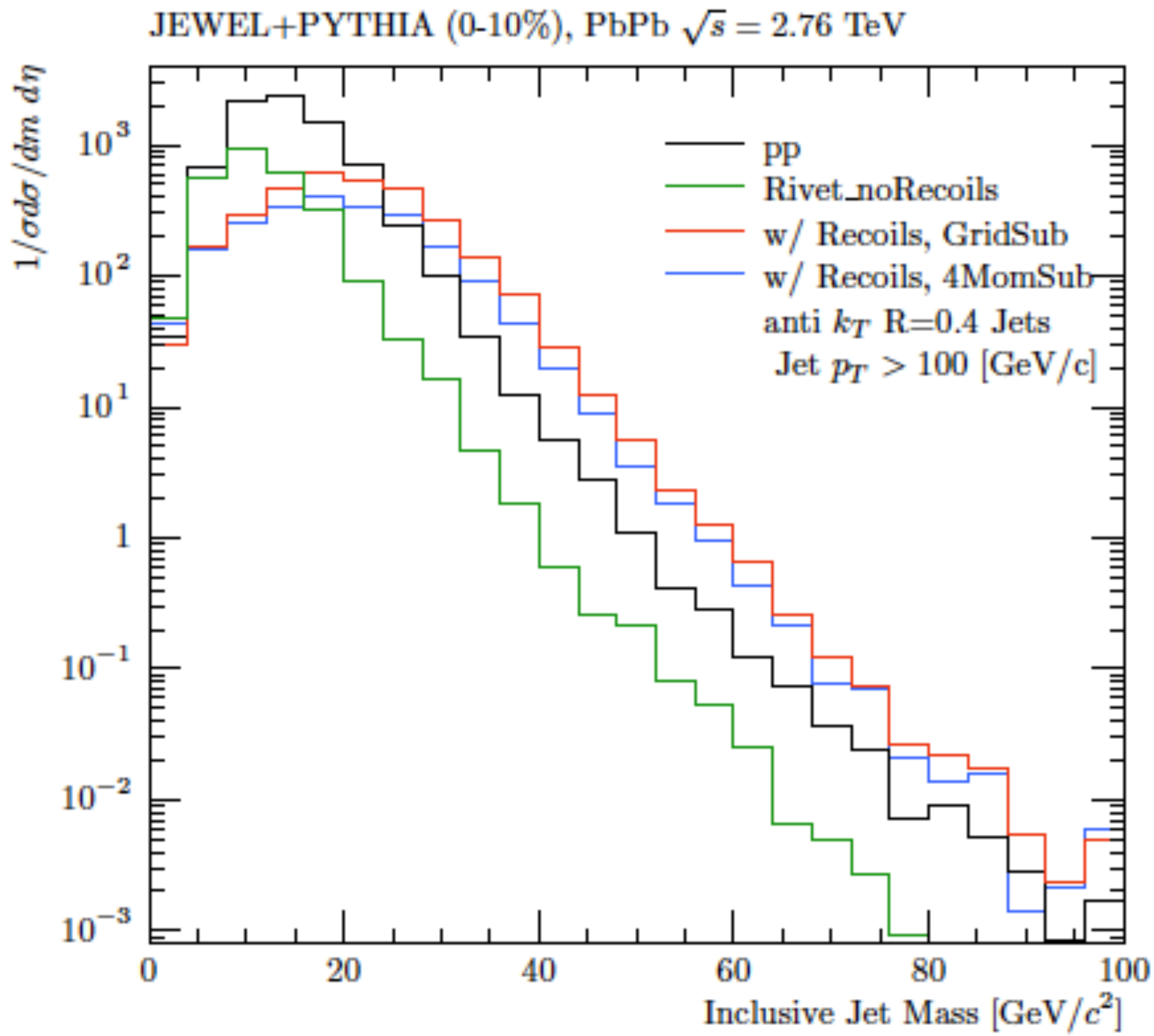
Medium response - JEWEL recoil

Two extremes:
- No recoil
- With recoil
  but no scattering of recoil partons with medium

Recoil has large effect on jet mass

What if recoil partons would interact with the medium?
→ Brownian motion
Expect jet mass to decrease

Effect of recoil on jet mass



[R.K. Elayavalli, Saturday]

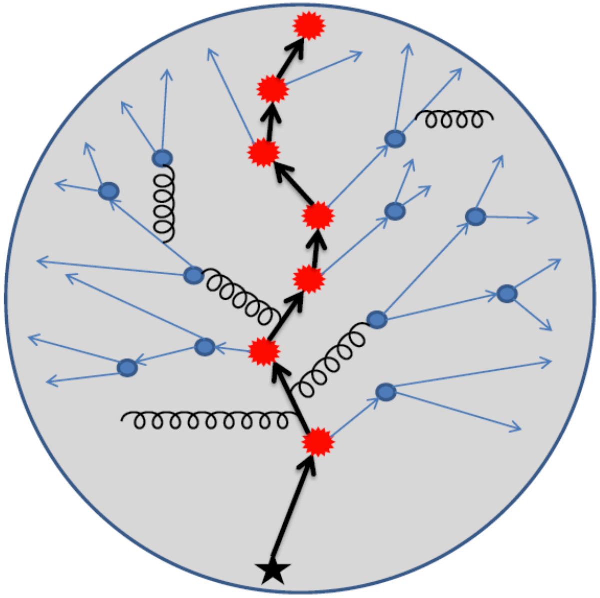
Medium response in LBT

Medium excitation

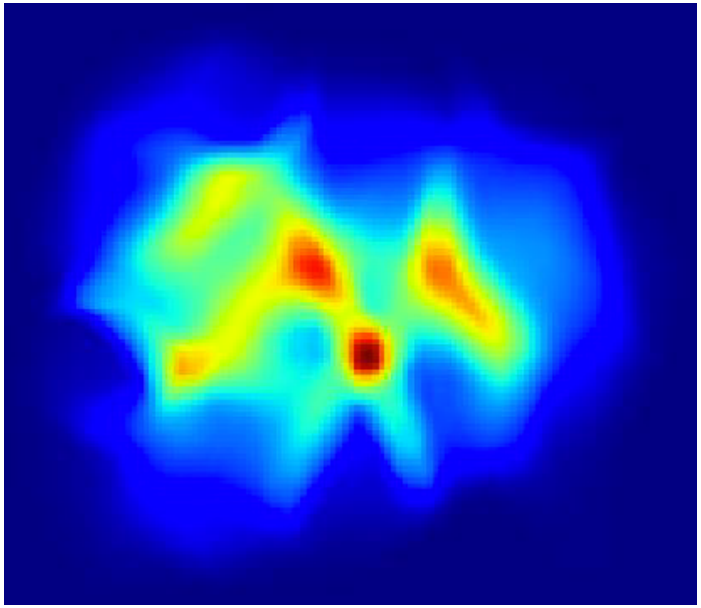
Jet-induced medium partons are propagated through medium and included in jet reconstruction

Also keep track of the modified medium

Jet



Medium



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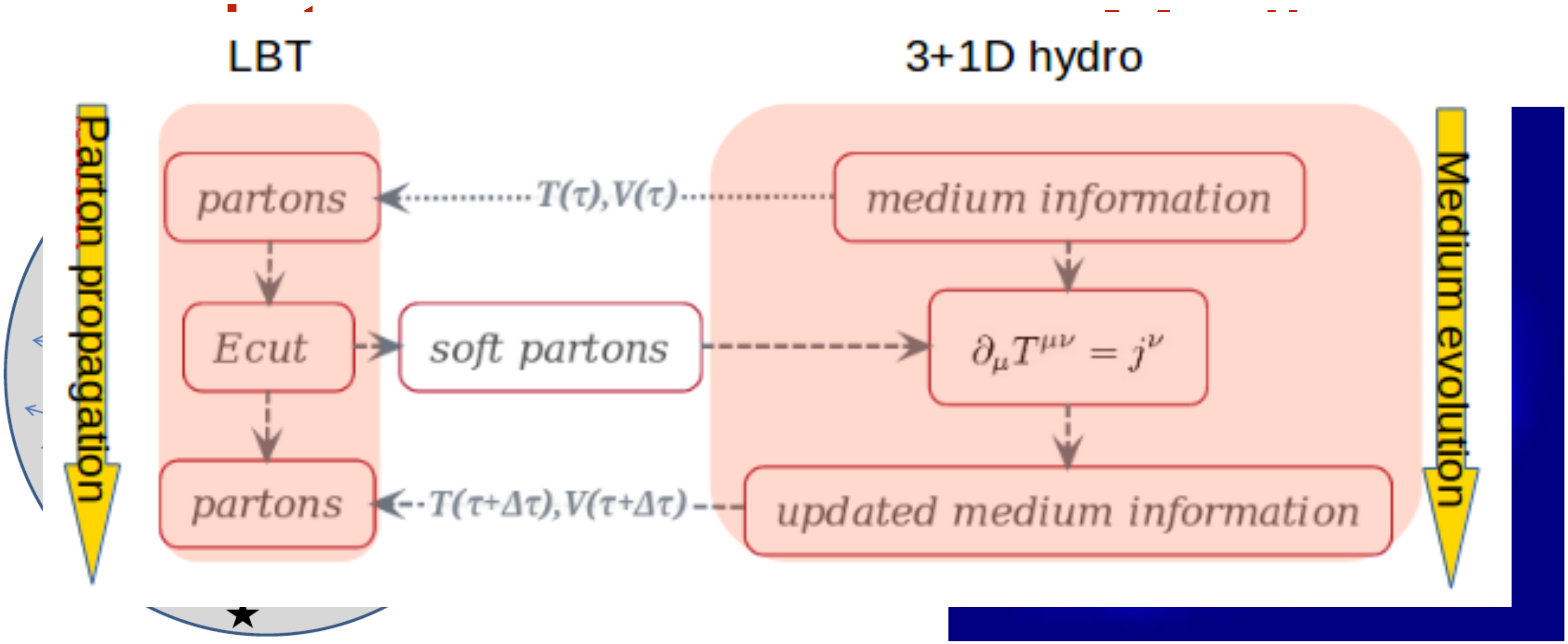

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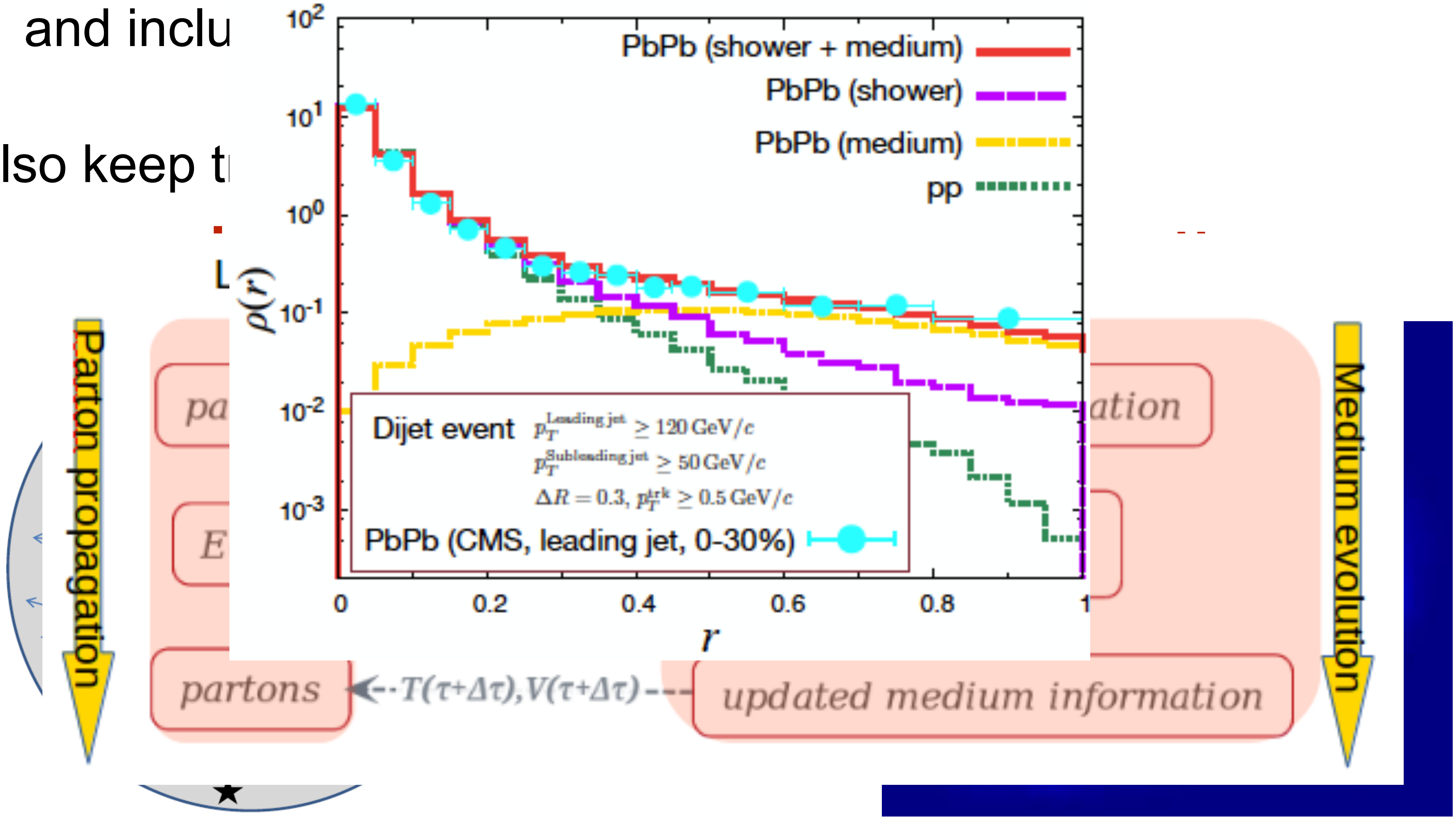
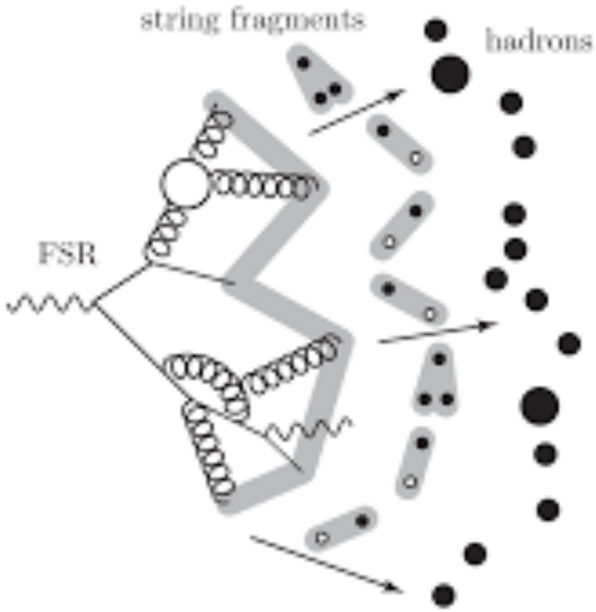


Hadronisation



All models assume hadronisation in vacuum
→ Uncertain if this is correct → large uncertainty

Hadronisation

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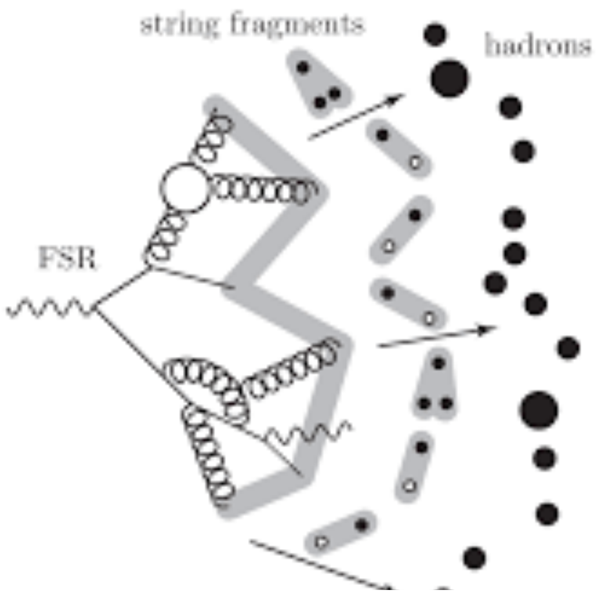
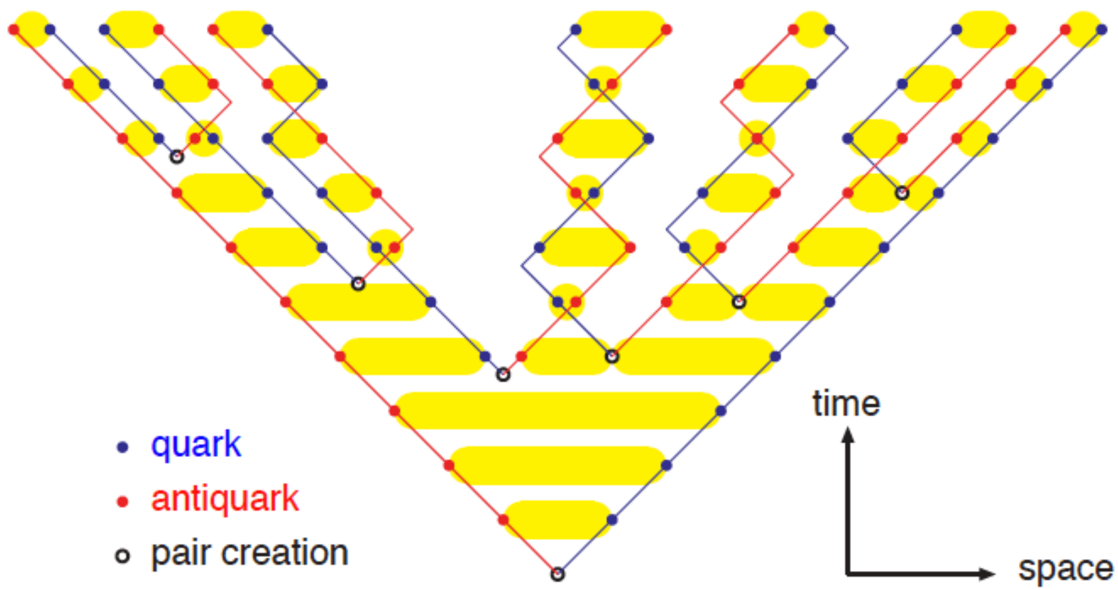
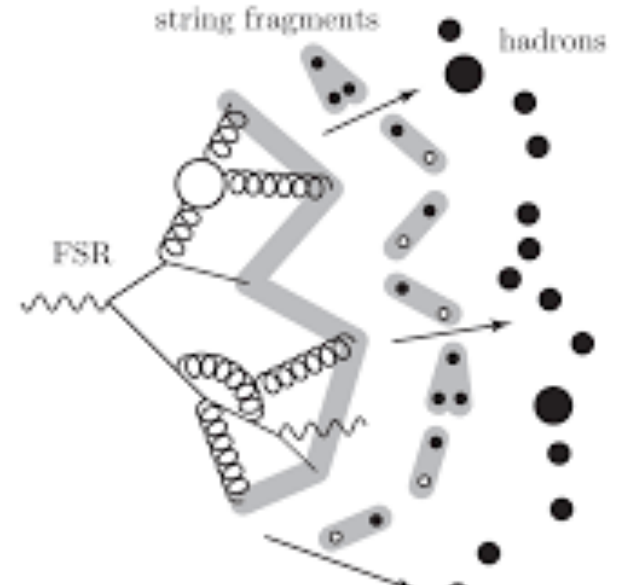
Hadronisation is a non-perturbative process

- Vacuum generators: modeled based on experimental data
- Jet quenching MCs: almost all Lund string fragmentation model. Same as vacuum MC





Hadronisation



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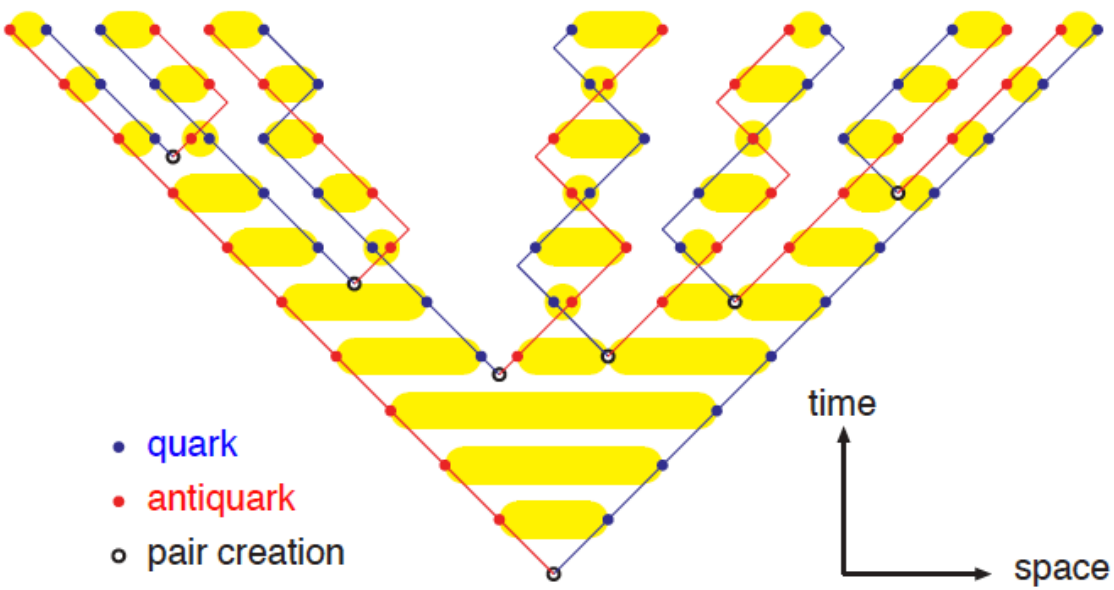


Open questions:

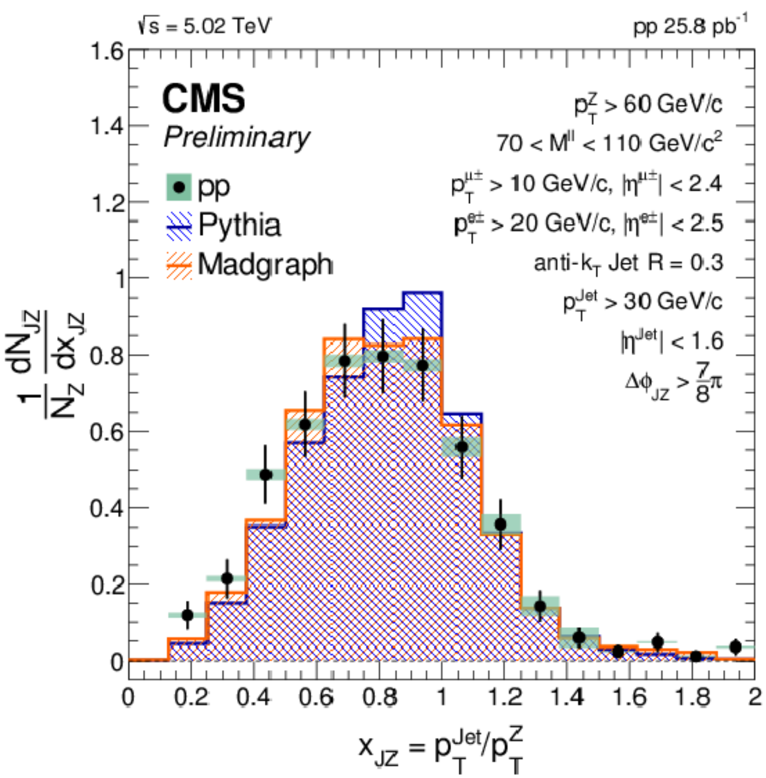
- How to deal with medium changing color structure?
- Interplay between jet and medium hadronisation?
- What if hadronisation starts in the medium?

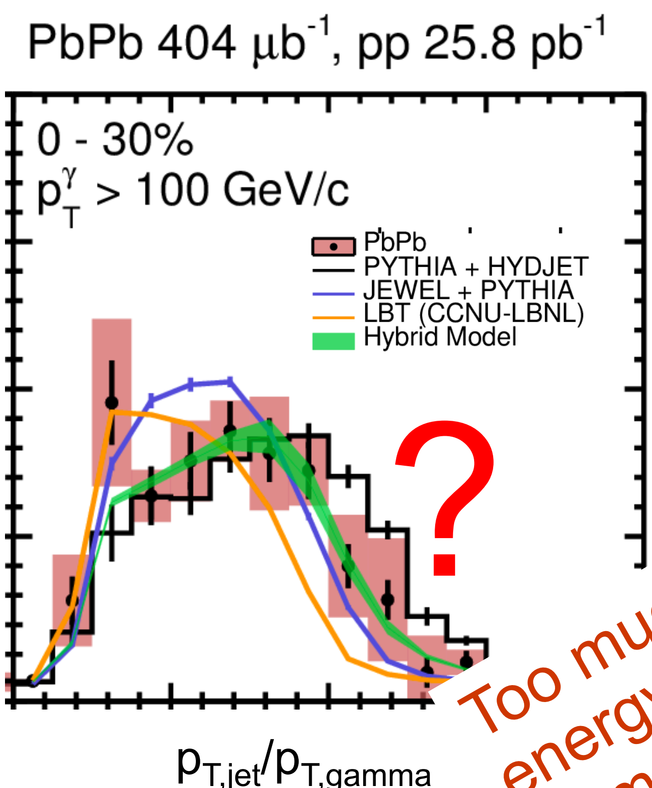
Vacuum baseline

Some models use PYTHIA6, others PYTHIA8: all LO

For inclusive measurement not very important

It matters for correlation observables (X-jet, jet-X, jet-jet)
→ if baseline wrong, comparison of PbPb with quenched MC not very meaningful





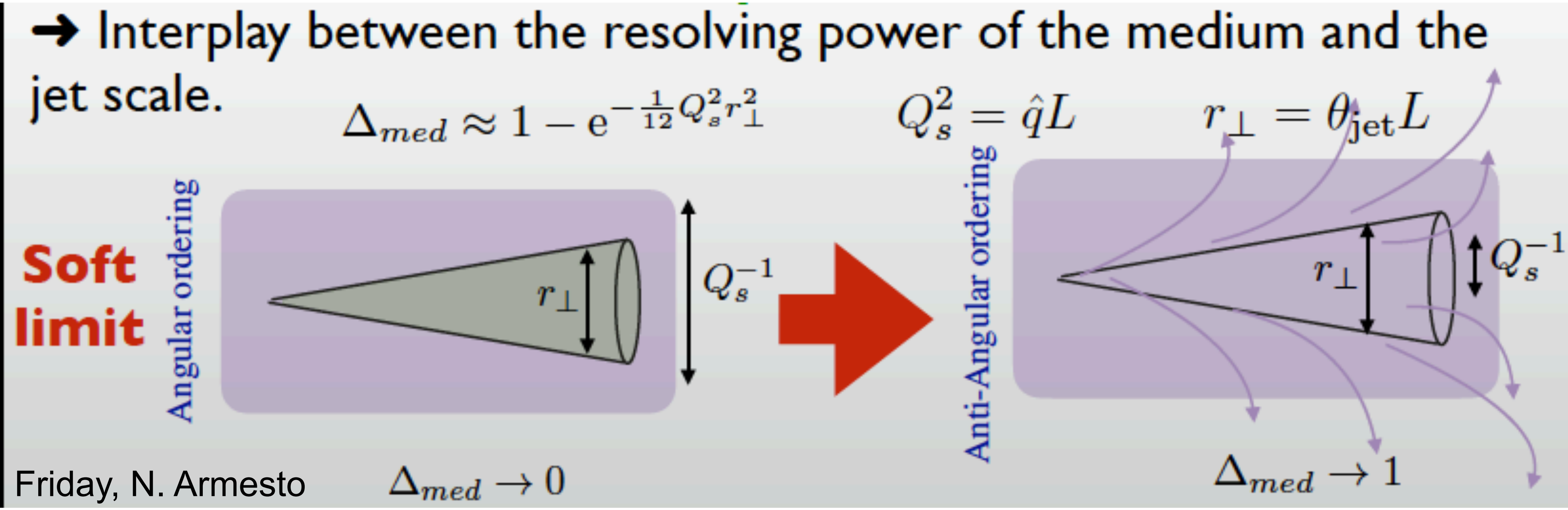
Too much energy loss for all models?

Limitations

From the round table discussion

We learned a lot since the first jet quenching MCs appeared
→ Newly derived phenomena can be implemented

One of the discussed items:
- Coherence: not all partons radiate independently



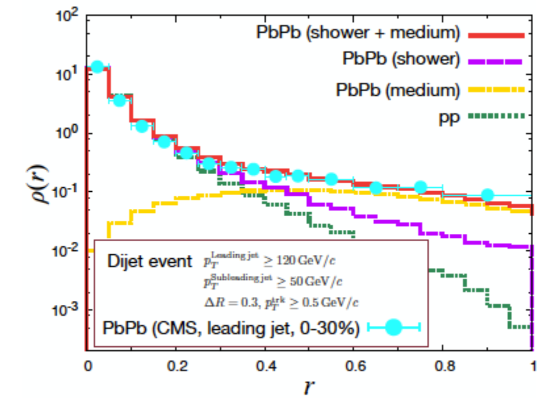
not implemented in any model - but analytical prescription ready
(in hybrid model crude phenomenological approximation)

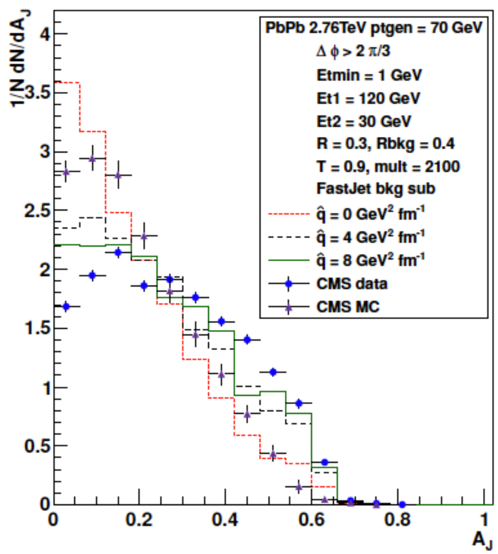
Data vs MC

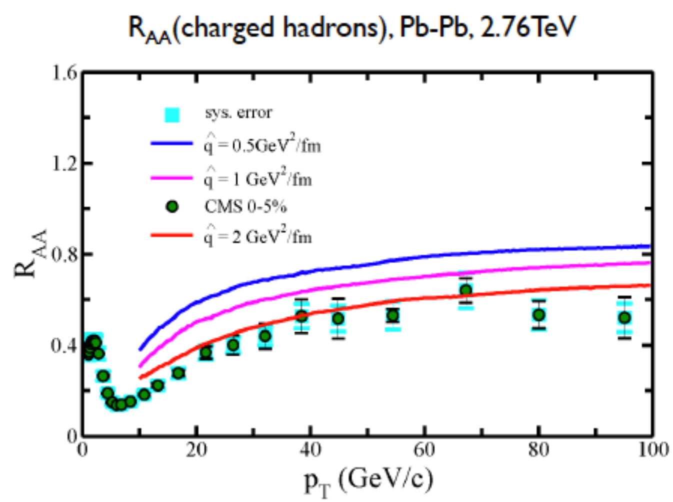
Rich phenomenology by comparing jet quenching MCs with data

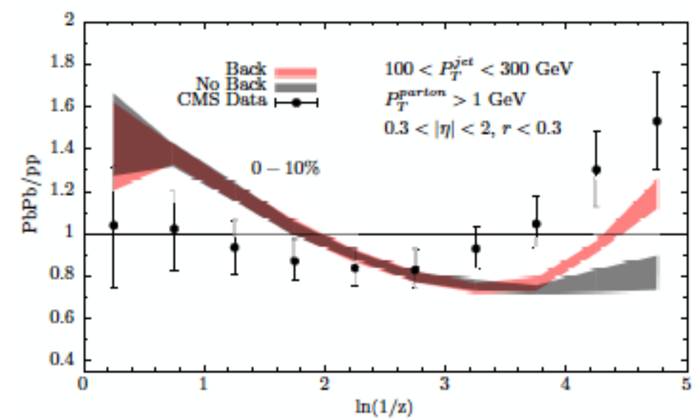
→ Some models get ruled out or sometimes fixed

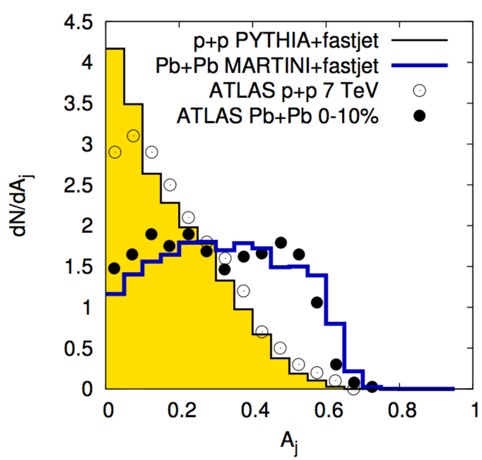
Too much to go through in a systematic manner

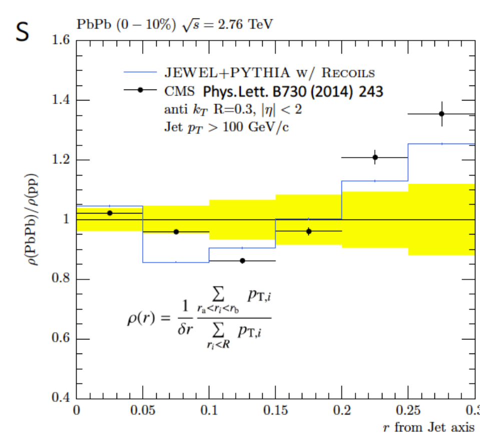


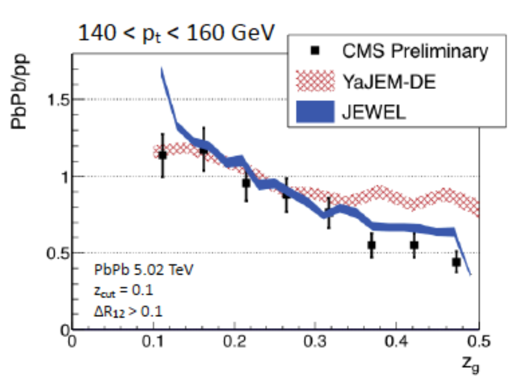


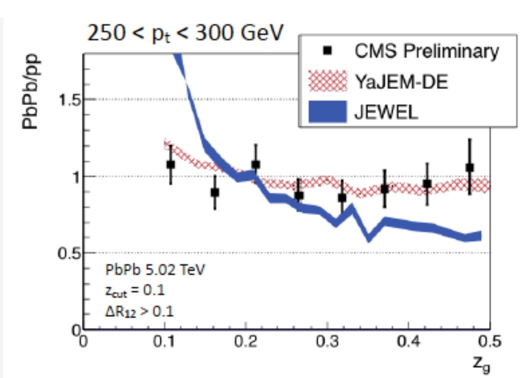












References

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MARTINI: arXiv:0909.2037, arXiv:0911.4470

JEWEL: arXiv:1111.6838, arXiv:1212.1599

LBT: arXiv:1503.03313, arXiv:1605.06447

MATTER: arXiv:1301.5323

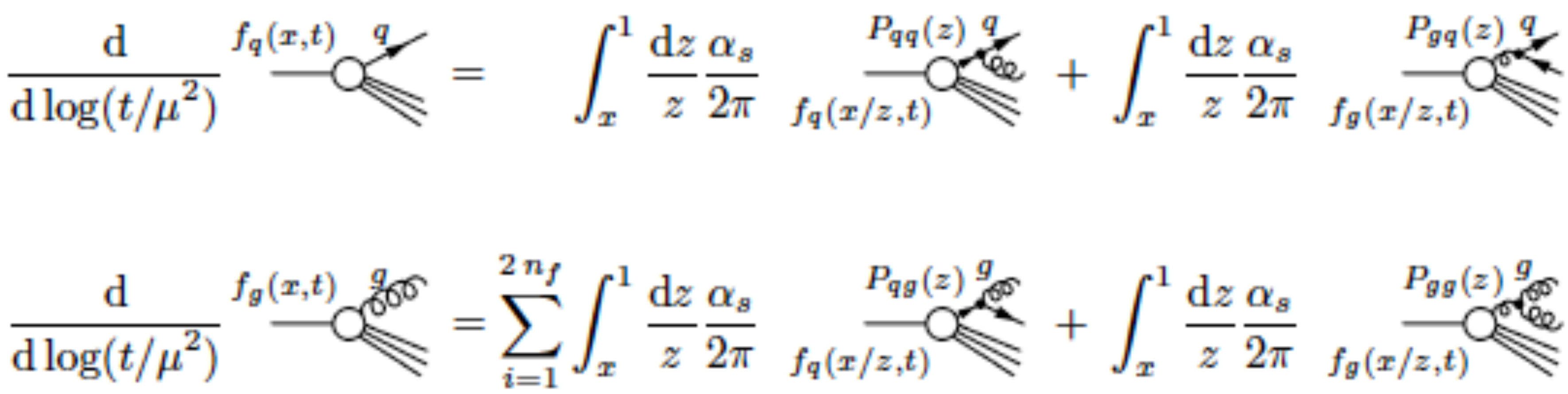
backup

QCD Parton shower in vacuum

Collinear factorization → DGLAP evolution

Altarelli-Parisi splitting function describe 1→ 2 splitting process

Vacuum recoil scheme: spectators absorb the recoil
- if splitter has zero on-shell mass, kinetic energy is absorbed from spectator



DGLAP evolution of PDFs. Ref: S. Hocke arXiv:1411.4085

Existing MCs

HYDJET++/PYQUEN

- Energy loss kernel inspired by BDMPS
- Generates full HI events (including soft particle production)

HIJING

- Medium induced parton splitting process
- Generates full HI events (including soft particle production)

QPYTHIA (+ QHERWIG)

- Medium-enhanced splitting probability. Dynamical scattering centers.
- Only parton shower + hadronization

MARTINI

- Based on AMY energy loss kernel + elastic scatterings
- Only parton shower + hadronization

Existing MCs

JEWEL

ME into infrared limit. Unified description of ME+PS emissions. Elastic scatterings

Only parton shower + hadronization

YAJEM

Parton gains virtuality through interactions with the medium

Only parton shower + hadronization

MATTER++

Higher twist energy loss. Space-time evolution

Only parton shower + hadronization

LBT

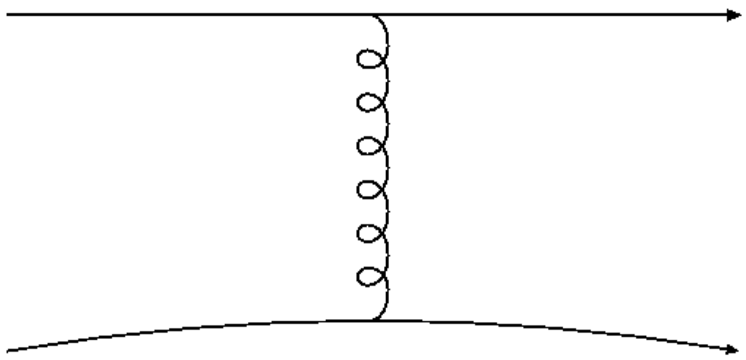
Only parton shower + hadronization

Hybrid

Only parton shower + hadronization

Radiative and collisional scatterings

Collisional / elastic



Radiative