Lecture III

Jet quenching in high-energy heavy-ion collisions

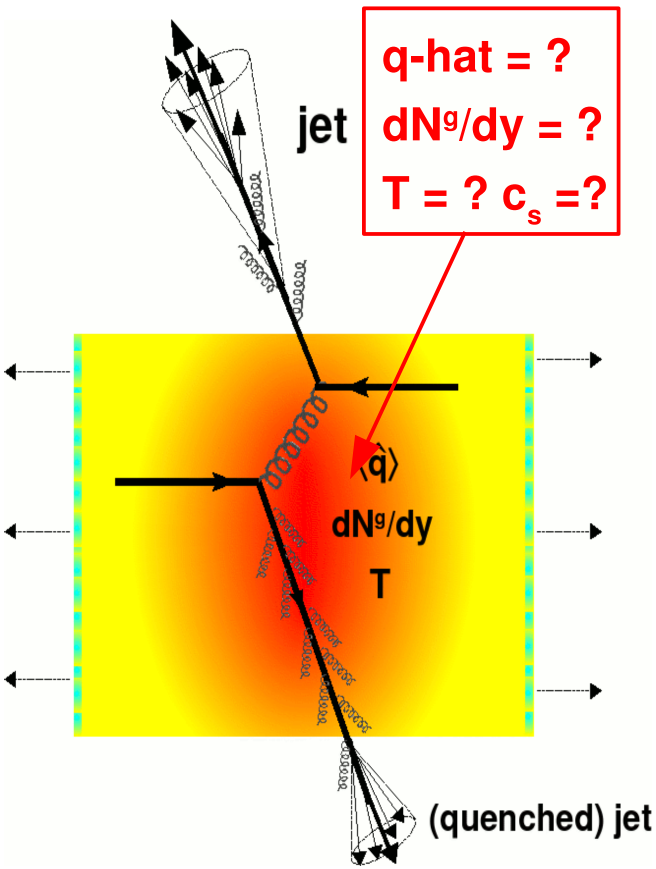
International School QGP & HIC

Torino, Dec. 8th - 13th 2008

David d'Enterria

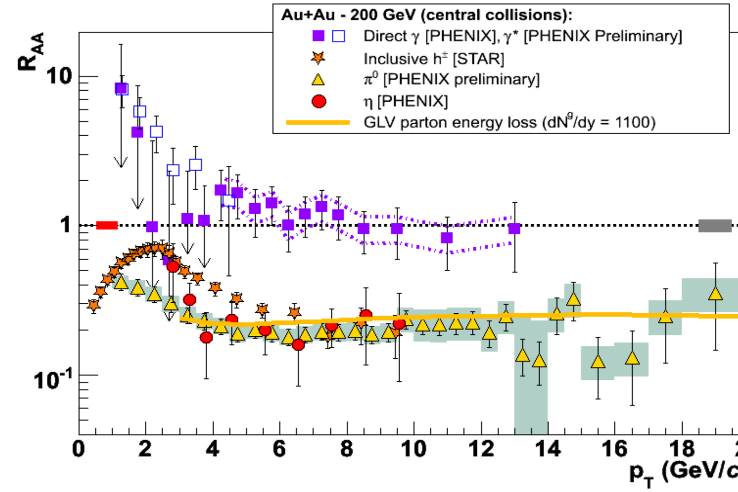
Massachusetts Institute of Technology

Overview

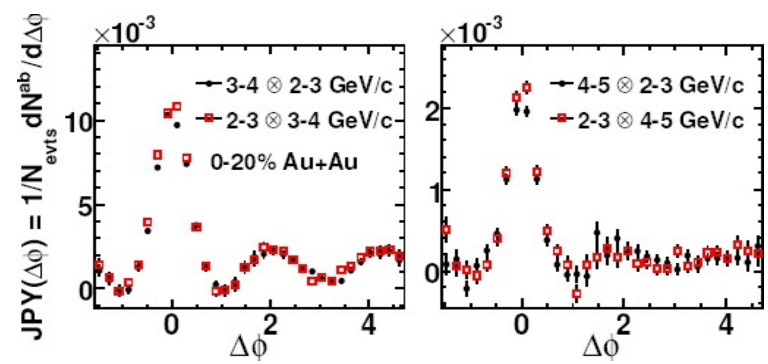


Hot/dense QCD matter properties via "jet quenching"

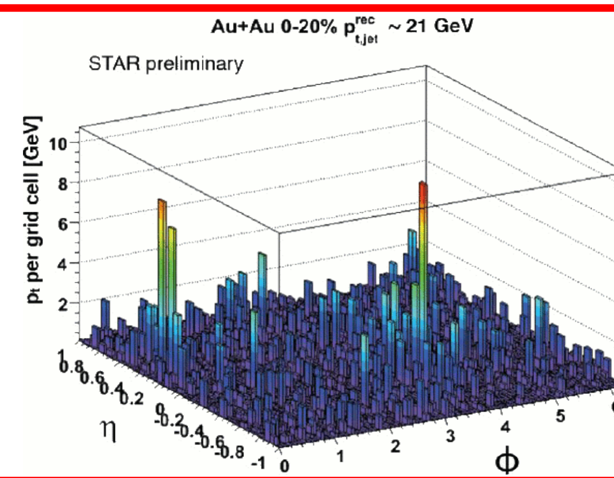
- Suppressed high-p_T hadron spectra:



- Modified high-p_T dihadron Δφ-η correlations:

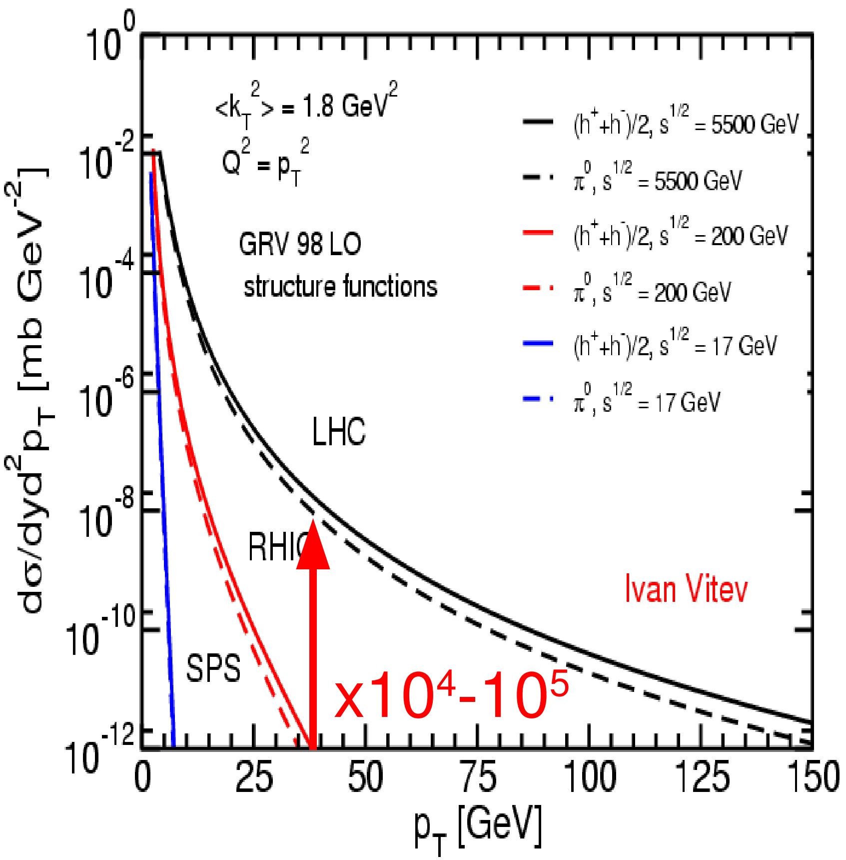


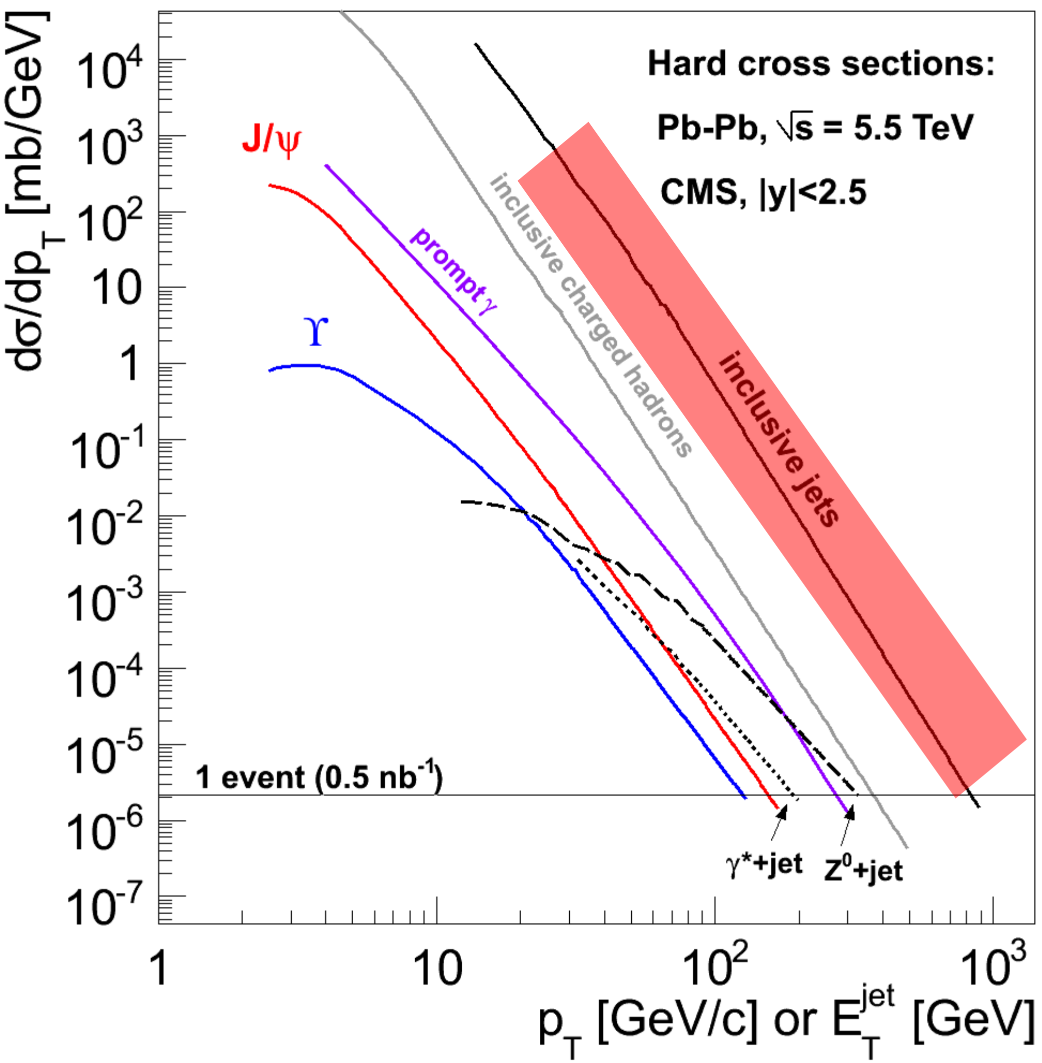
- Full jet reco, γ-jet, modified FFs:



Jets: RHIC vs. LHC

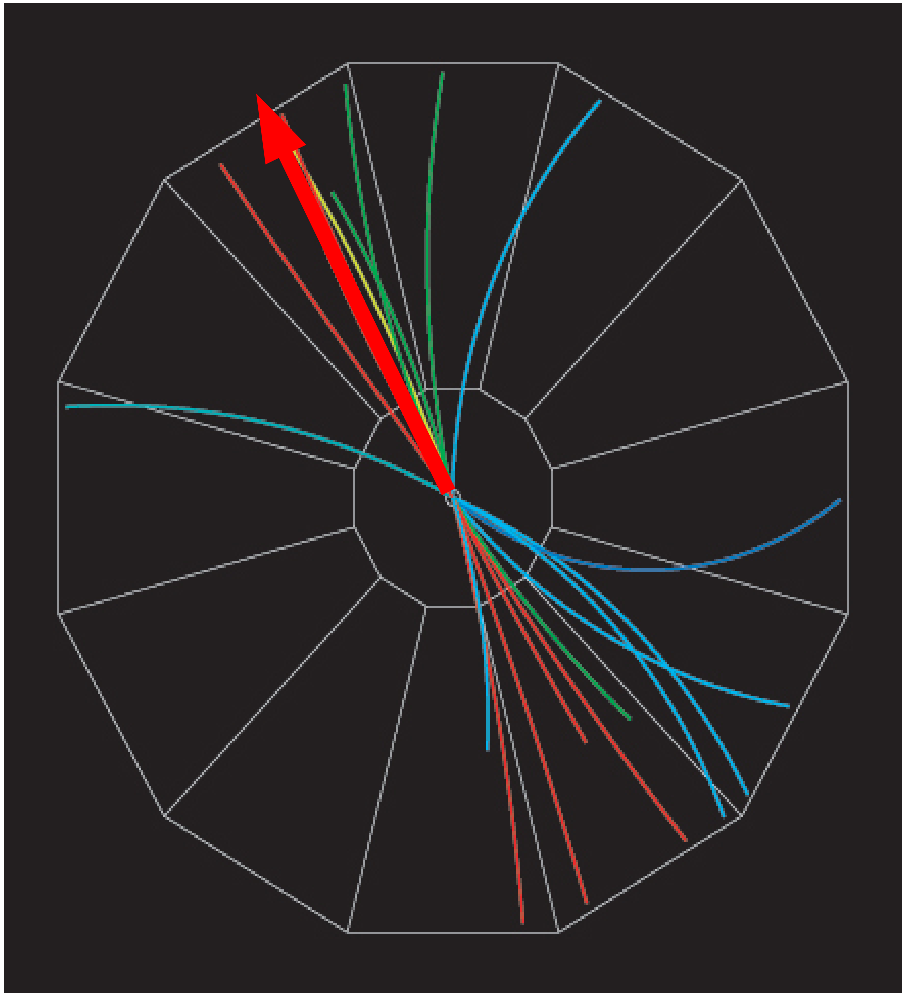
- Cross-sections for jet production will be huge at the LHC (E_T^{max}~1 TeV)
- Detectors designed (large acceptance, trigger) to measure them.

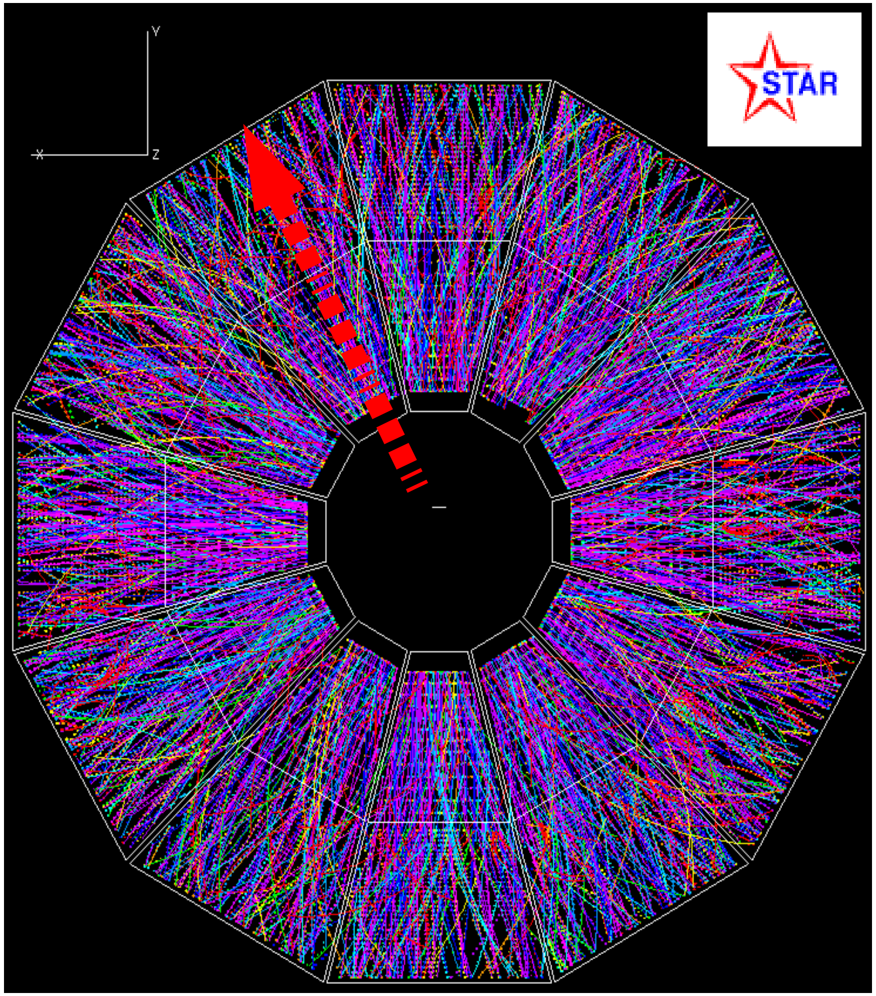




III. Jet reconstruction, γ jet, fragmentation functions

Jet quenching via high-p_T leading hadrons

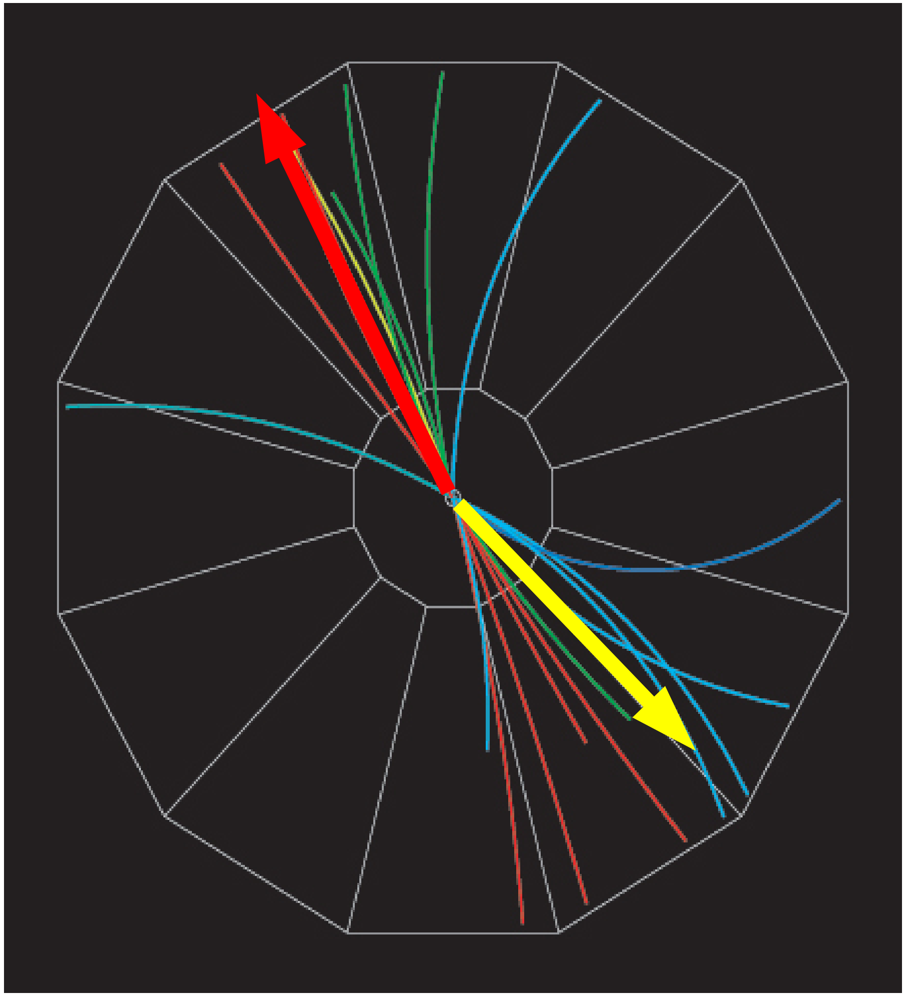




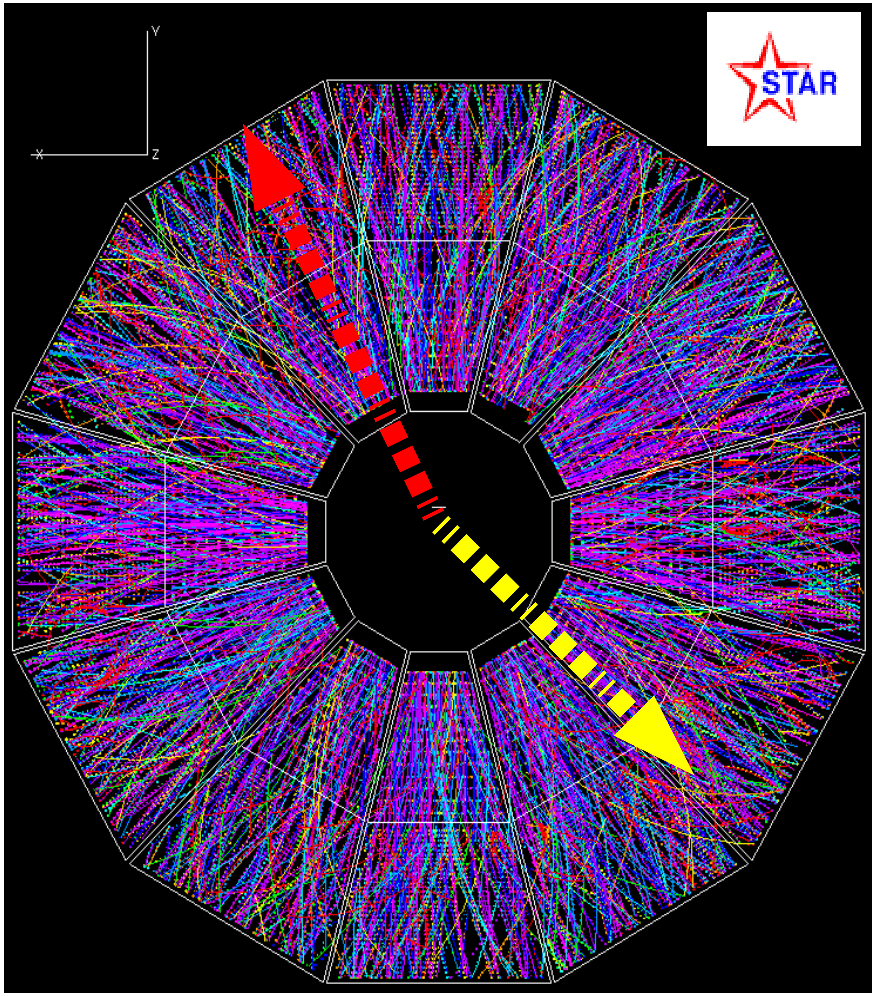
p+p →jet+jet [$\sqrt{s}$ = 200 GeV]

Au+Au → X [$\sqrt{s_{NN}}$ = 200 GeV]

Jet quenching via high-p_T dihadron ϕ correlations

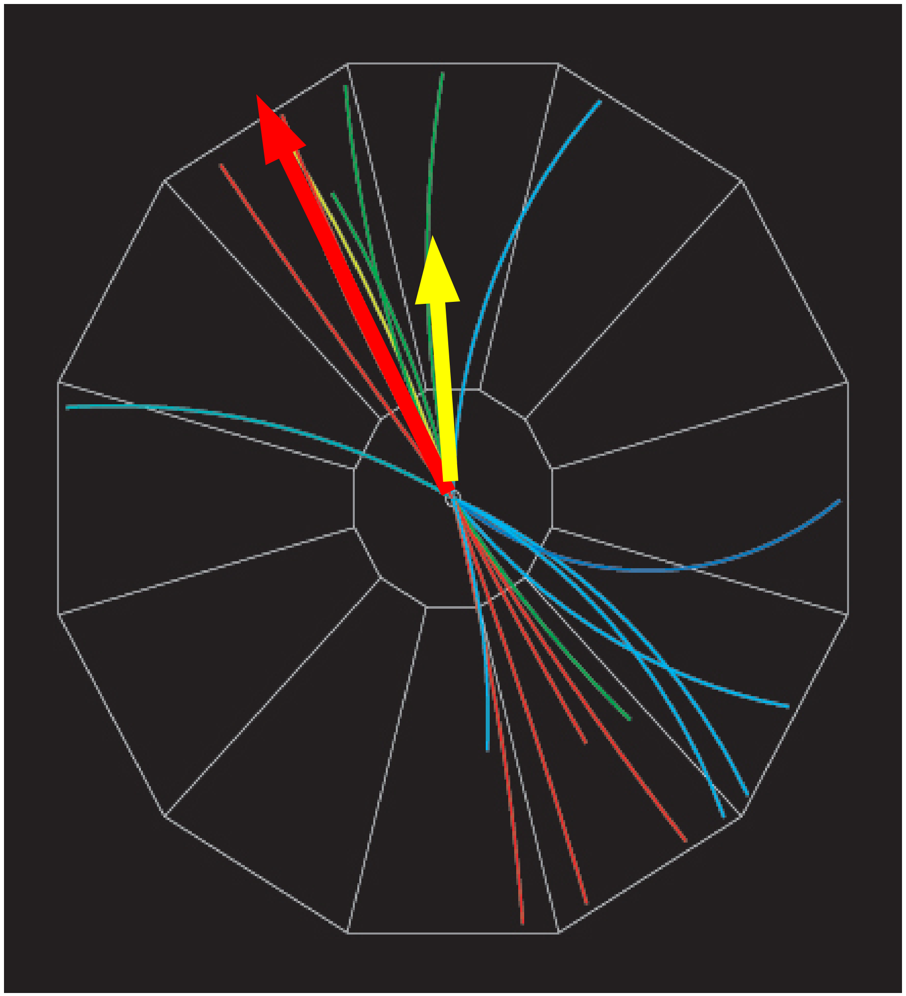


$p+p \rightarrow$jet+jet [$\sqrt{s}$ = 200 GeV]

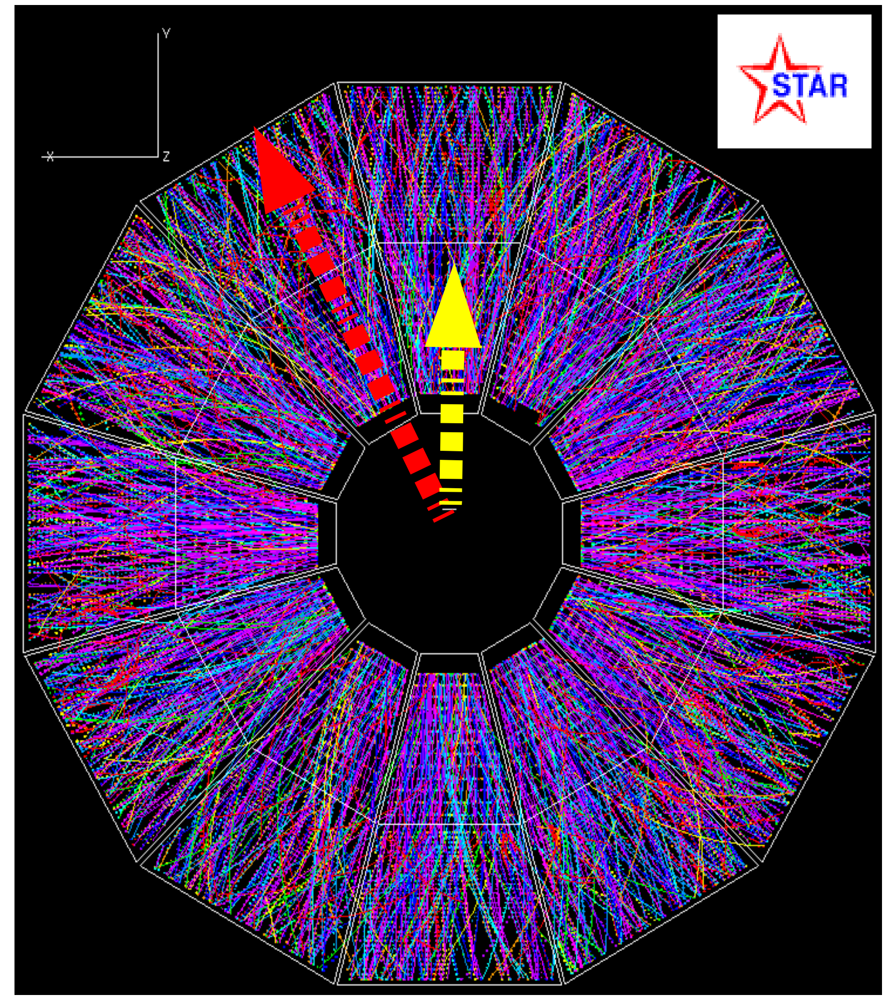


Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]

Jet quenching via high-p_T dihadron ϕ correlations

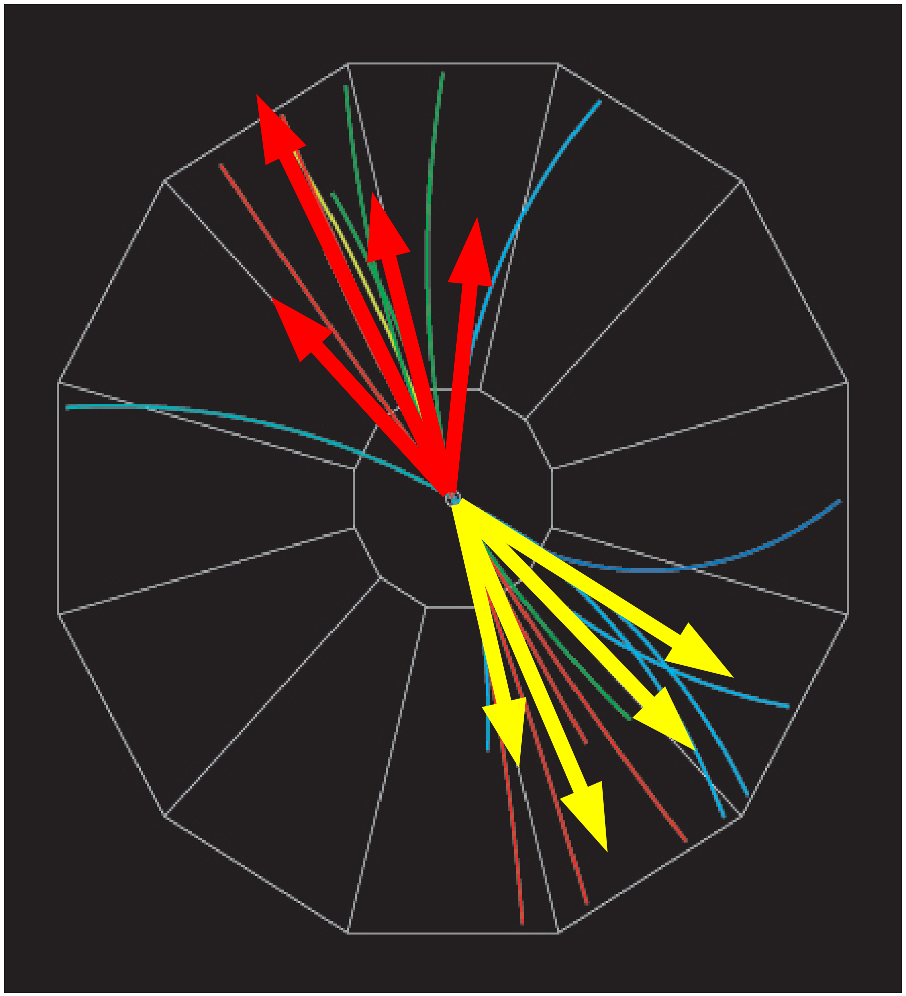


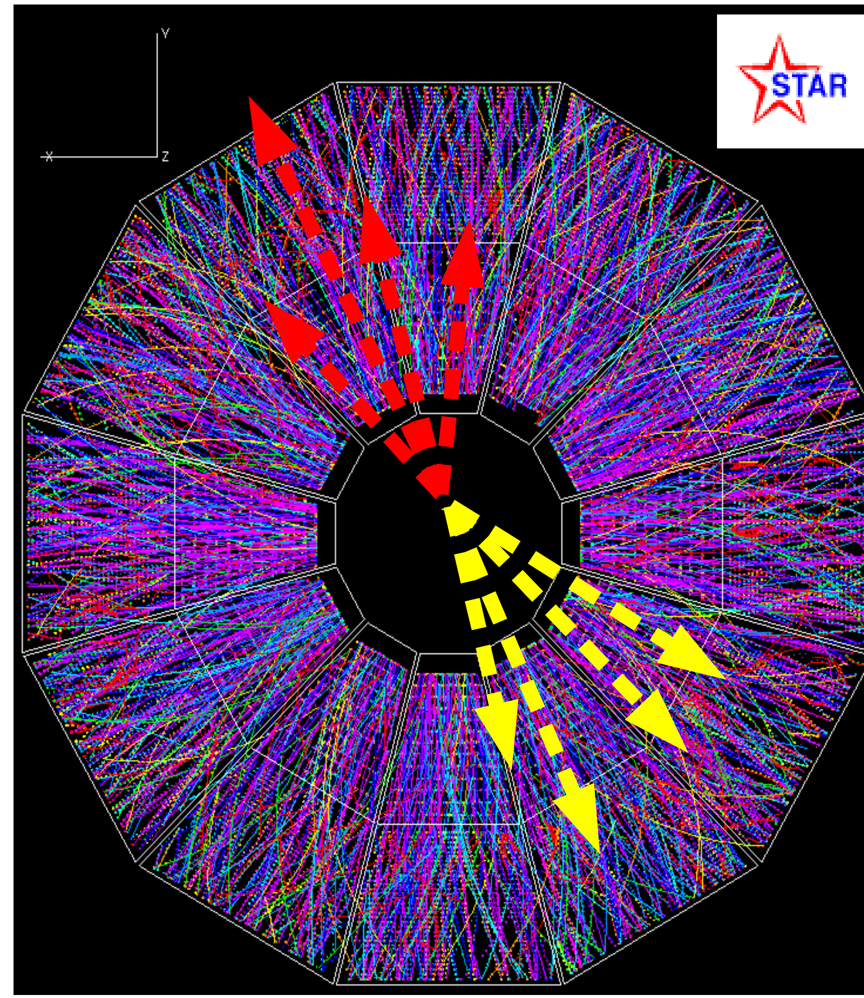
$p+p \rightarrow$jet+jet [$\sqrt{s}$ = 200 GeV]



Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]

Jet quenching via full-jet reco & gamma-jet



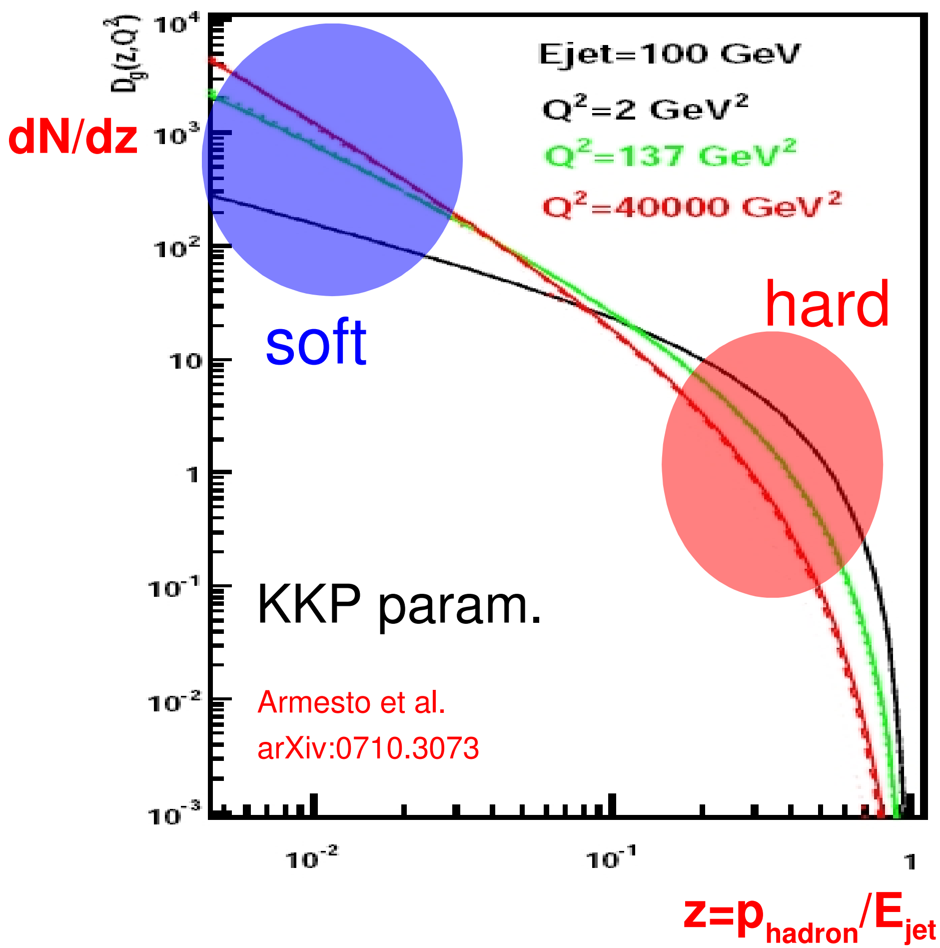


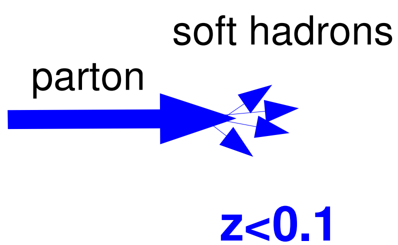
p+p →jet+jet [√s = 200 GeV]

Au+Au → X [$\sqrt{s_{NN}}$ = 200 GeV]

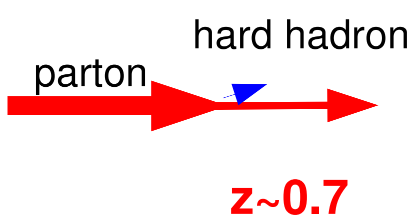
Fragmentation Functions (FF)

- FF: Probability that a hadron h takes mom. fraction $z = p_{had}/p_{parton}$ of parent parton.
- FFs for (u,d,s,g → π,k,p,h) obtained from e^+e^- data parametrizations.
- FFs evolution follows DGLAP (parton splitting) eqs.: fitted at one scale Q, can be extrapolated to any other Q' (>1 GeV).





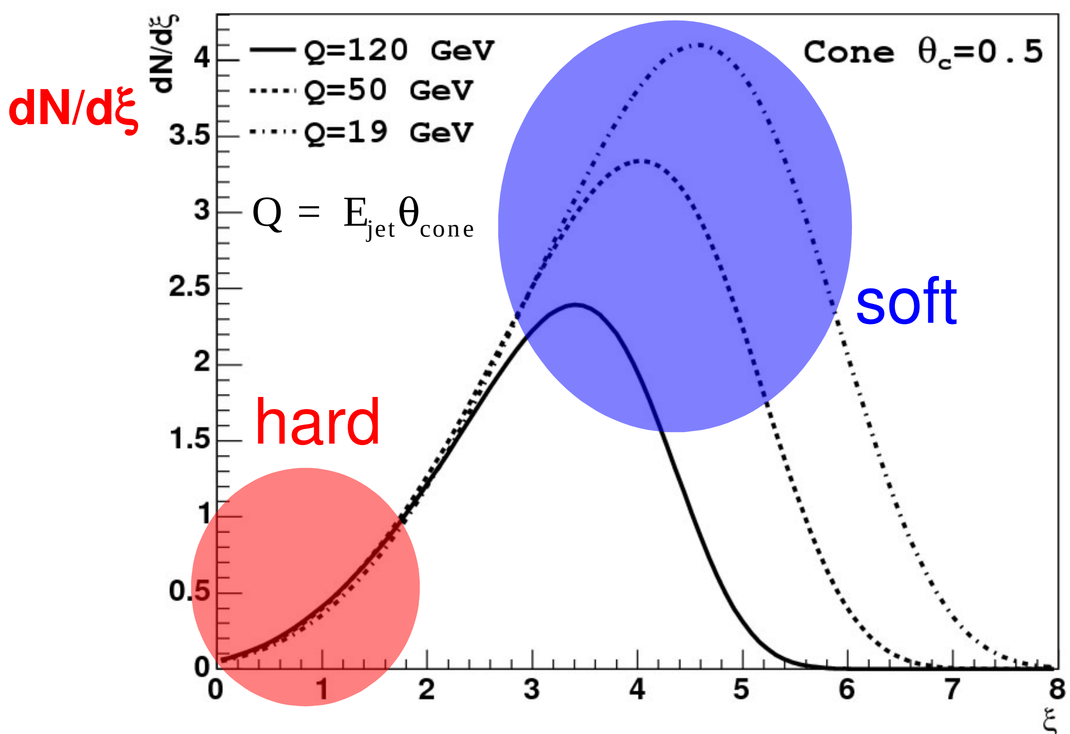
Most of fragmentation hadrons have a small fraction of the parent parton momentum.



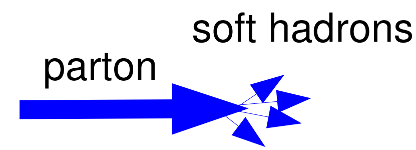
High-z "leading" hadrons (z~0.5-0.7) dominate high-p_T hadron spectra

Fragmentation Functions (MLLA)

- Fragmentation functions in the Modified-Leading-Log Approximation are computed with emphasis in the low-z (soft) region of the parton fragmentation.
- (Next-to-)MLLA = Framework to calculate/resum QCD emission diagrams (and interferences) down to non-perturbative scales $Q_{eff} \sim \Lambda_{QCD} \sim 200$ MeV.



$\xi = -\log(p_{hadron}/E_{jet}) = \log(p_{jet}/E_{hadron})$



low z = large ξ

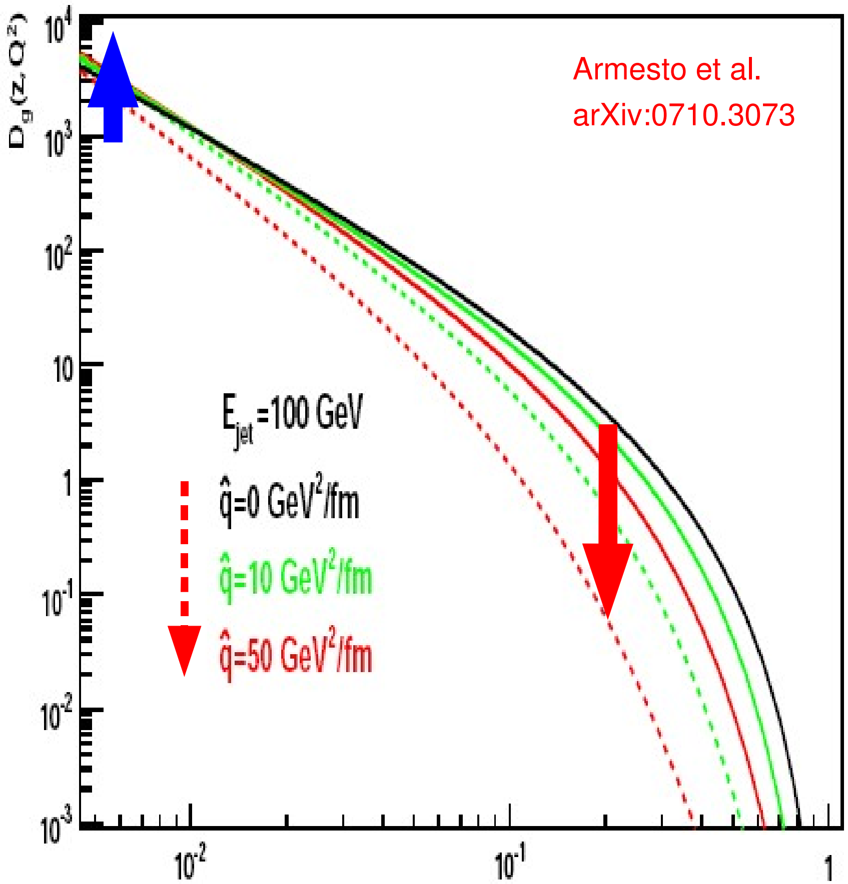
MLLA allows to calculate: jet shapes, jet multiplicities, k_T correlations in jets, ...

Mueller (1983)
Dokshitzer, Troyan (1984)
Malaza, Webber (1984), ...

Medium-modified Fragmentation Functions (FFs)

- Radiative energy loss in a hot/dense QCD medium shifts parton energy from high-z to low-z hadrons: leading-hadron suppression.

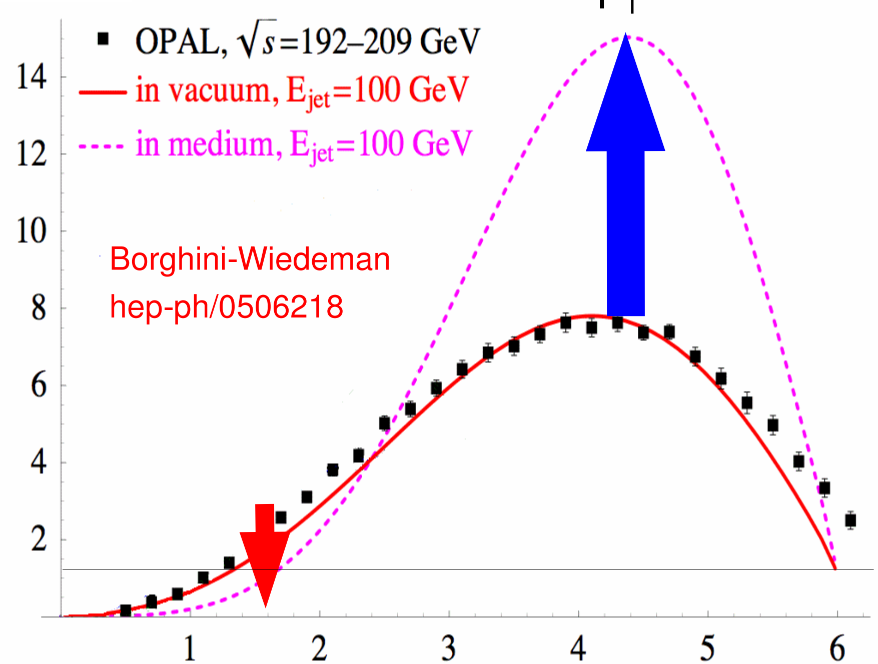
dN/dz: FF(z,$\hat{q}$)



$z=p_{hadron}/E_{jet}$

dN/dξ

Quenching increases low-p_T hadrons

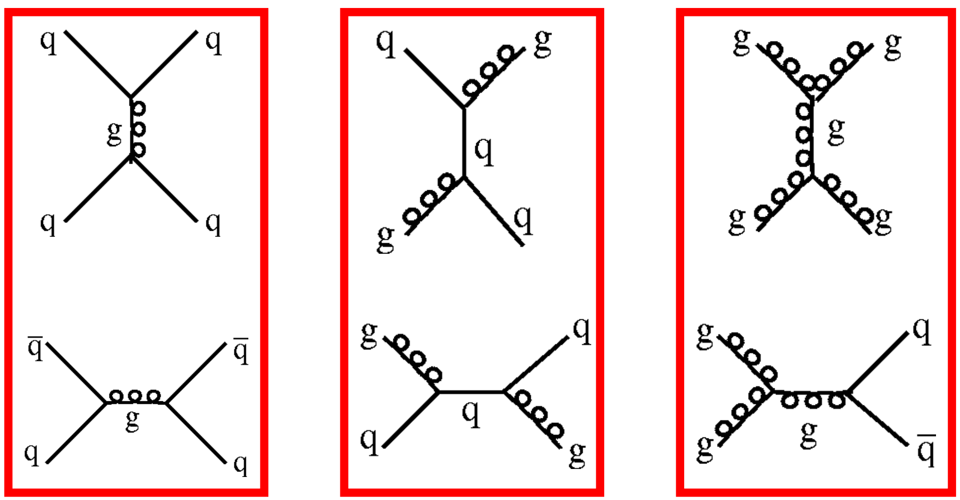


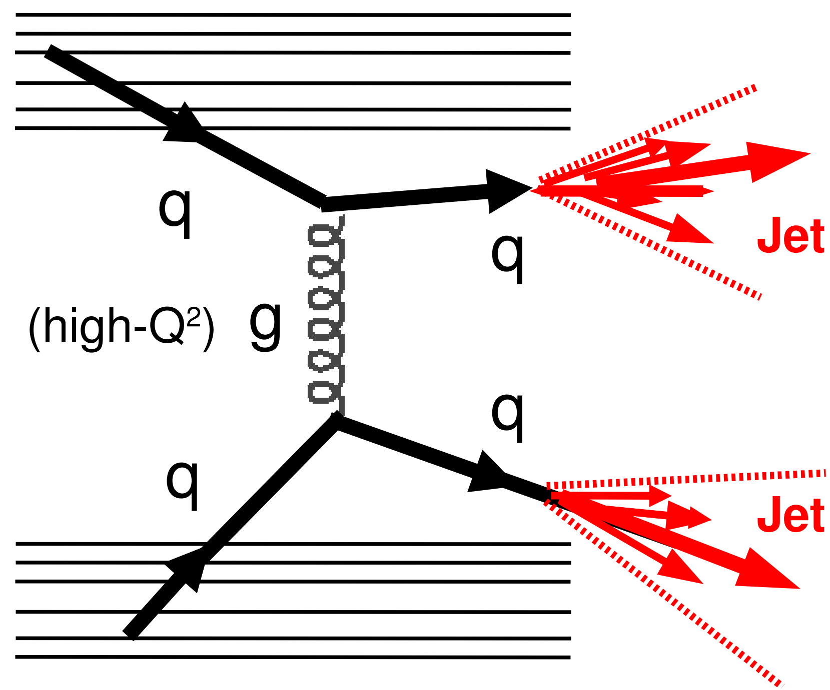
Quenching decreases high-p_T hadrons

$\xi=\log(E_T/p_T)$

Jets in hadronic collisions

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (or in the decay of a heavy particle)
- Jet production processes (leading order):



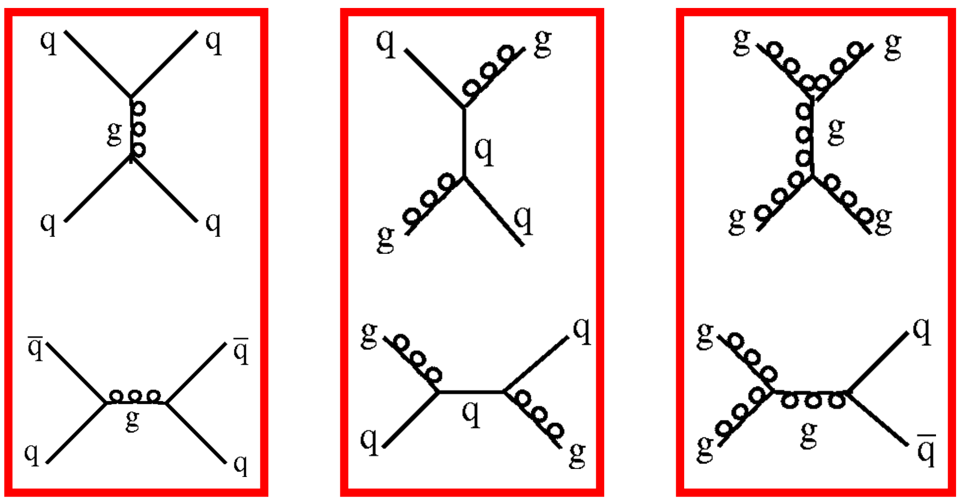


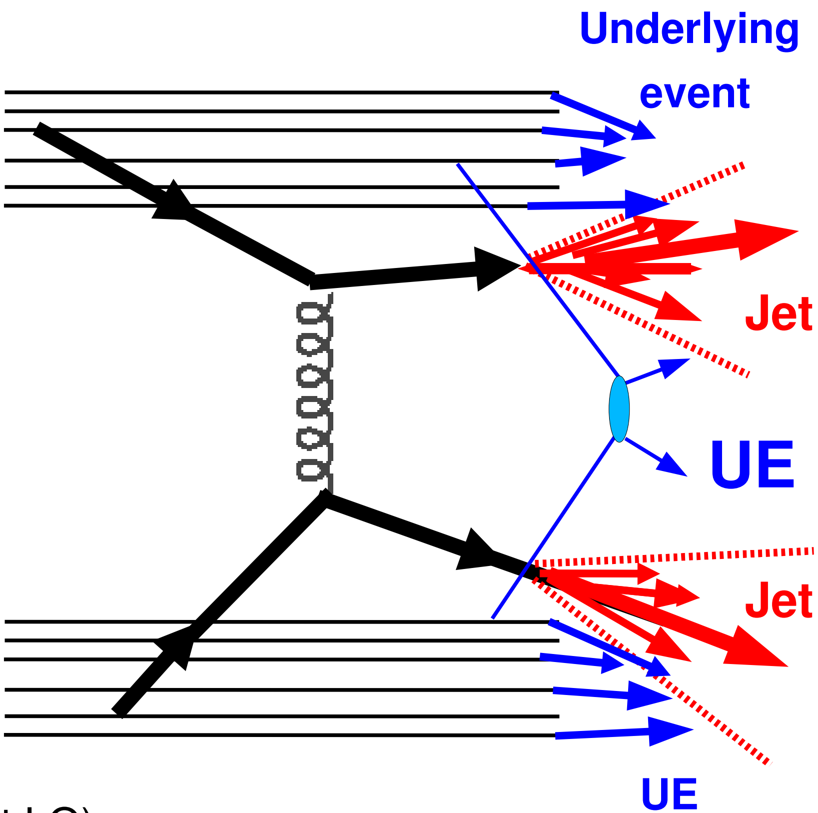
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in hadronic collisions: Underlying Event

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg.
- Jet production processes (leading order):



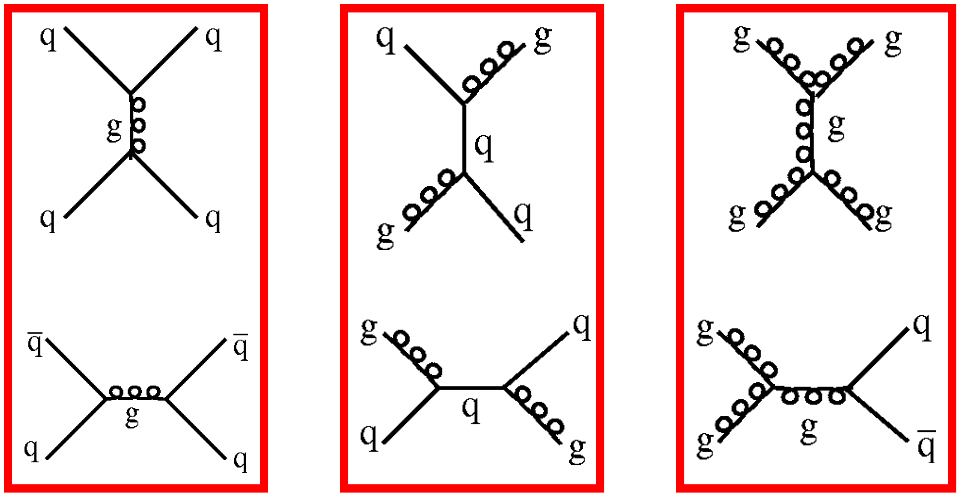


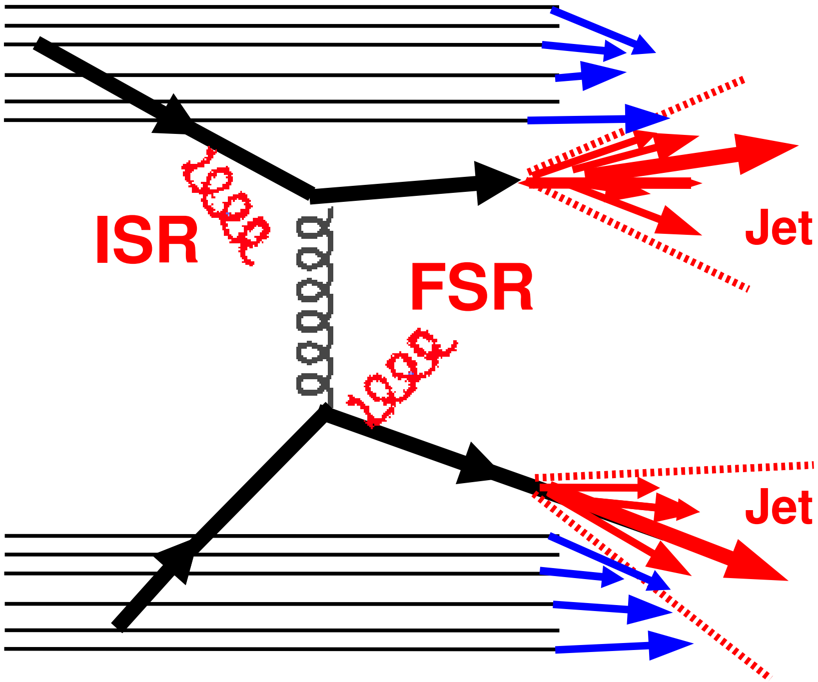
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in hadronic collisions: Initial- & Final-state Rad.

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg.
- Jet production processes (leading order):



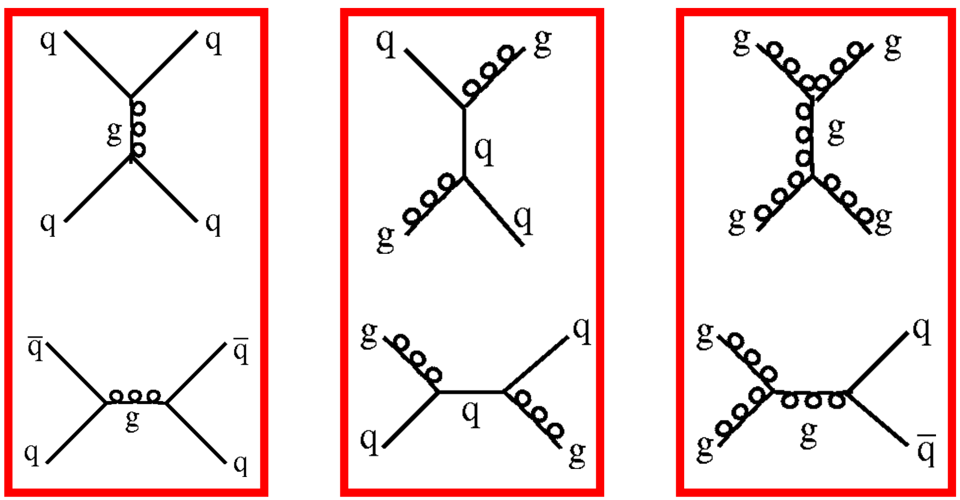


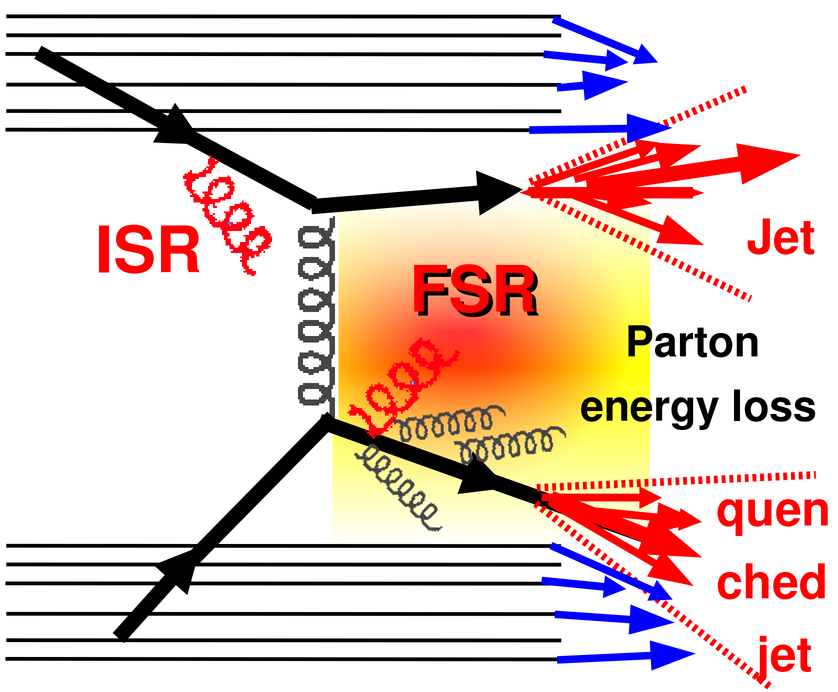
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in nucleus-nucleus collisions: enhanced FSR

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg.
- Jet production processes (leading order):





Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

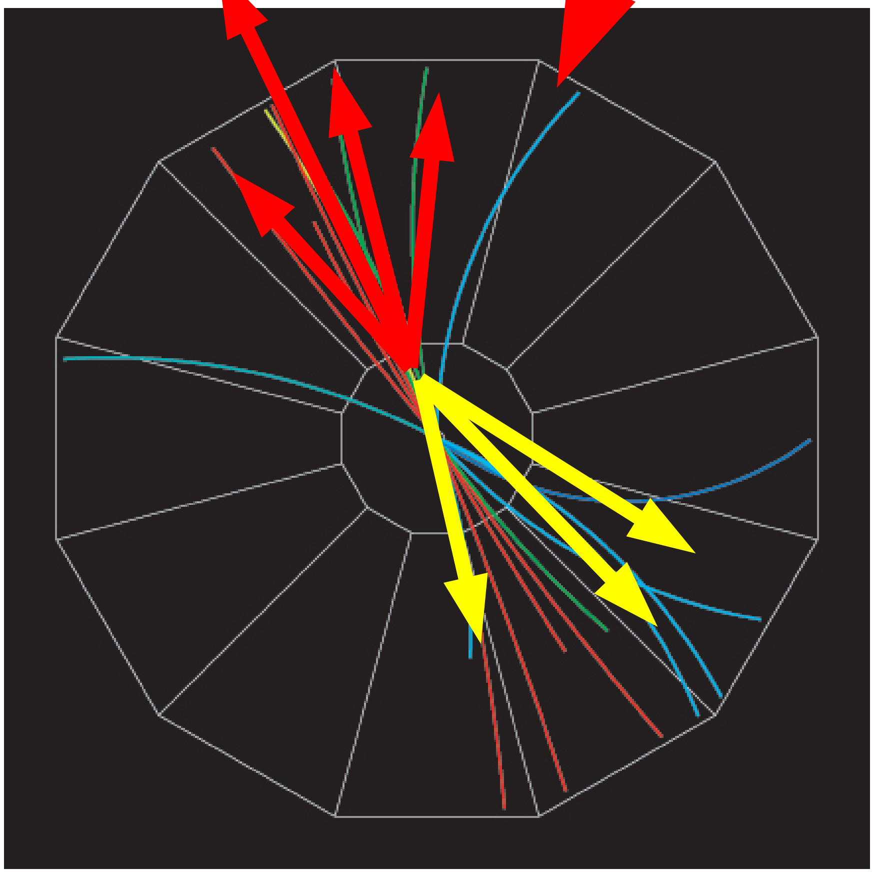
- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

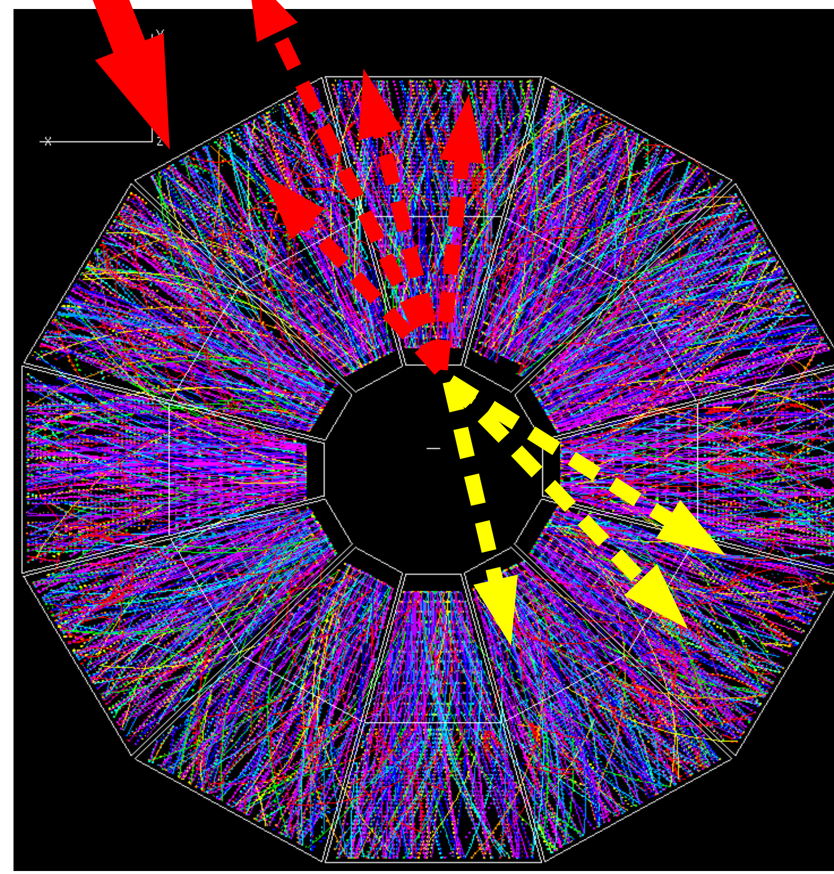
Jet reconstruction

- How does one reconstruct this ? in this environment ?

(Jet algorithms)

(UE bckgd subtraction)
(Jet energy corrections)





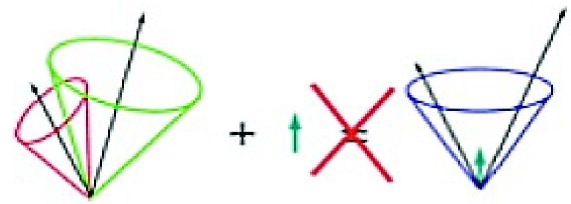
p+p $\rightarrow$jet+jet [$\sqrt{s}$ = 200 GeV]

Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]

Jet reconstruction in heavy-ions

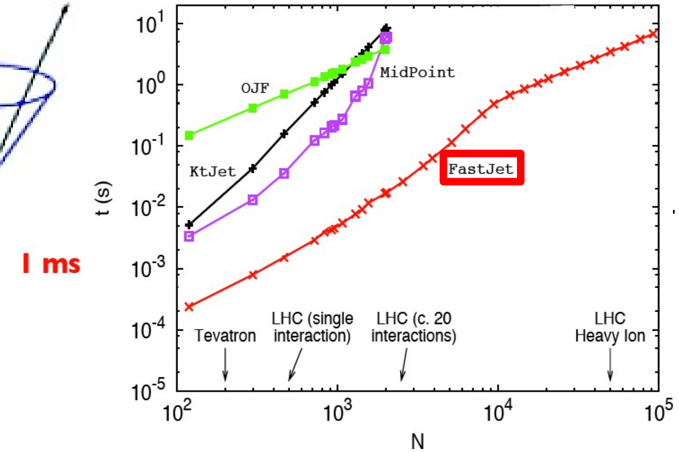
Not an easy business ...

- Step I: Clustering algorithm



- Infrared & collinear safe
- Speed [N_{tot}~$O(10^4)$]

❤ FastkT, SISCone, ...

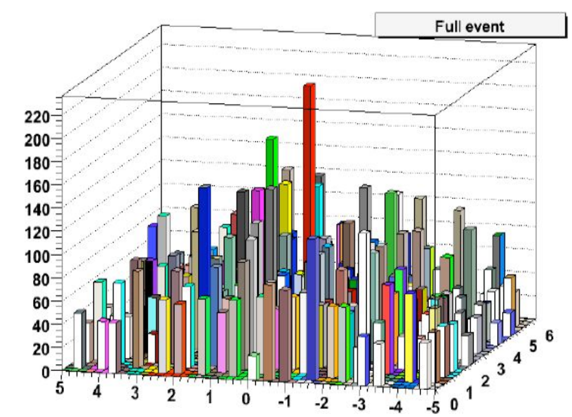


- Step II: Background subtraction

UE~$\pi R^2 \cdot 1/(2\pi) \cdot dE_T/dy$, dE_T^{LHC}/dy~1 TeV

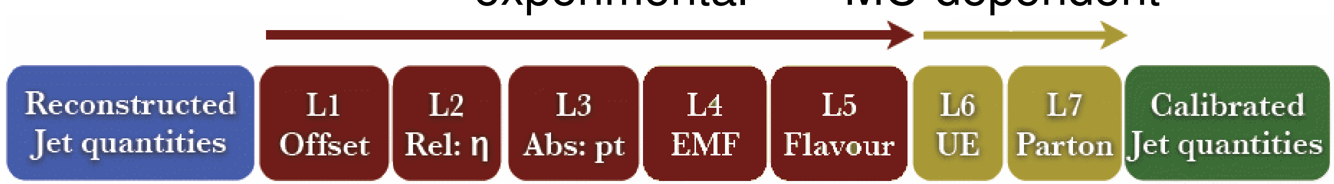
❤ Diff. techniques available now

UE (R=0.4) ~ 80 GeV (& fluctuating !)



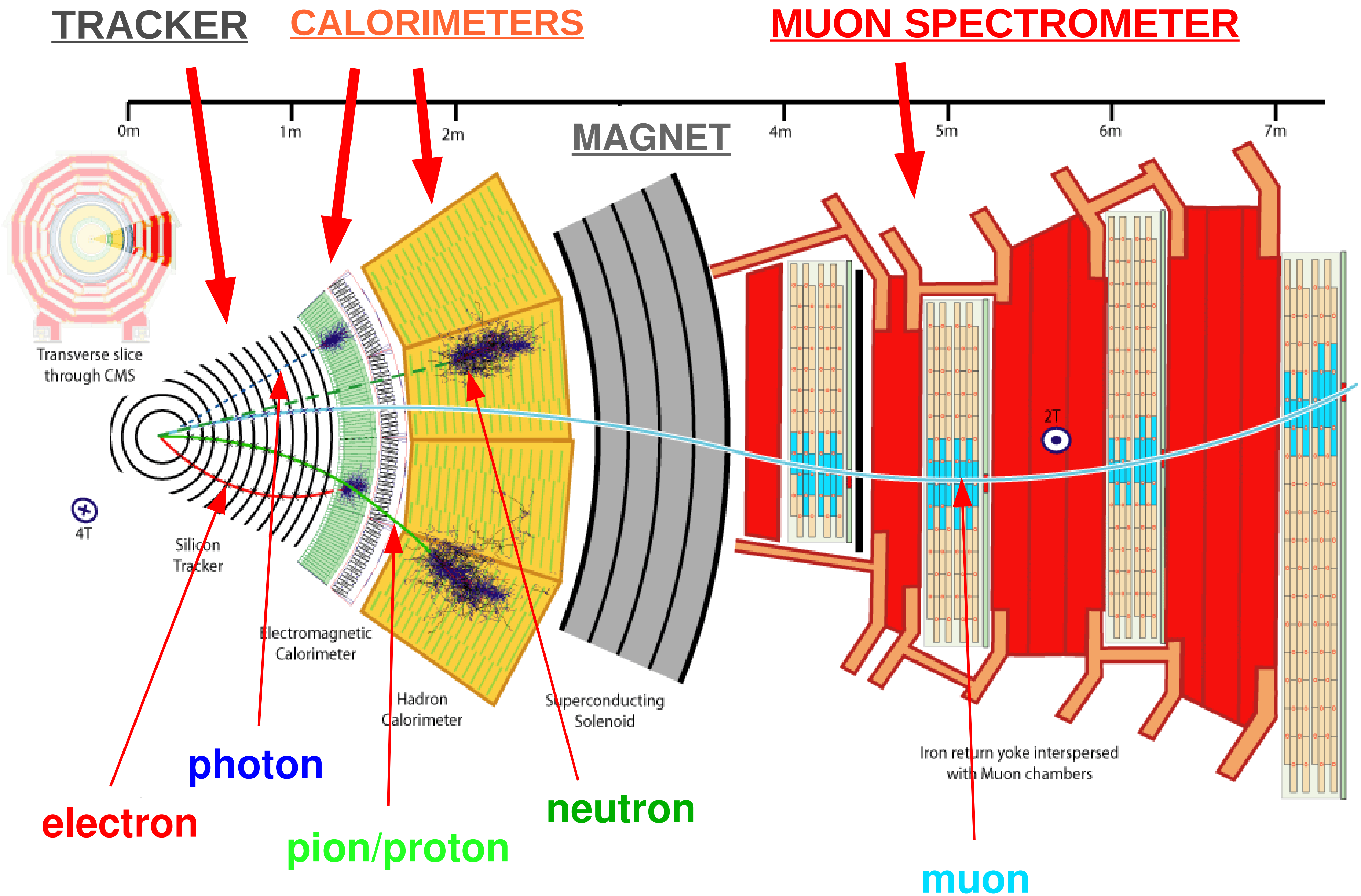
- Step III: Jet corrections

experimental MC-dependent

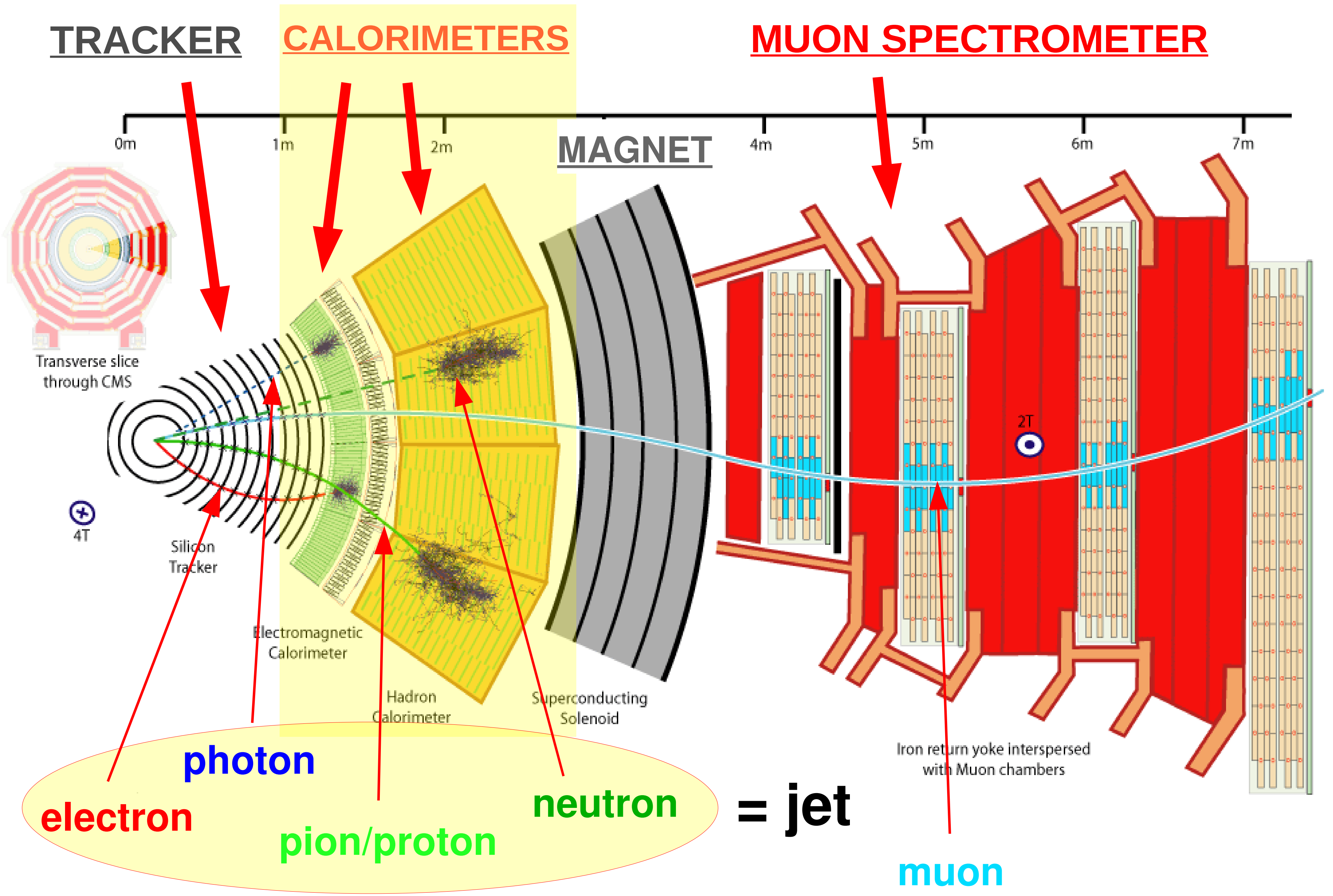


- Data-driven (model-independent) jet energy calibration needed !

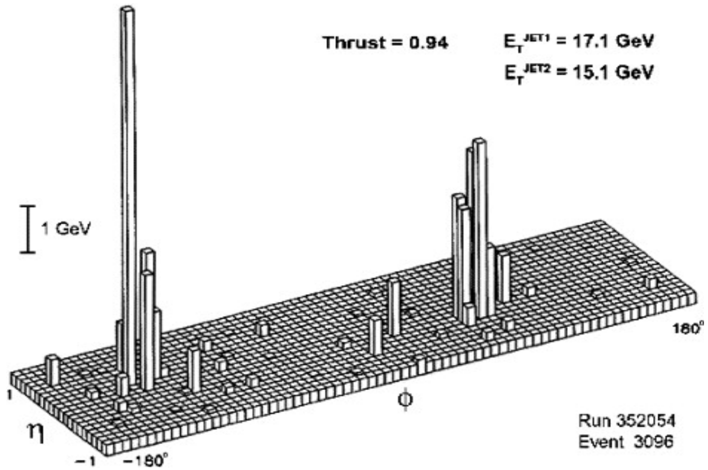
Particle measurements in a collider detector



Jet measurements in a collider detector

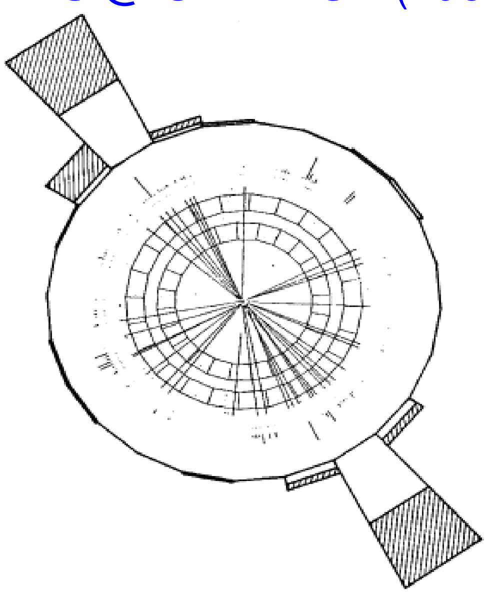


Jet lego plot η-ϕ energy in calorimeters



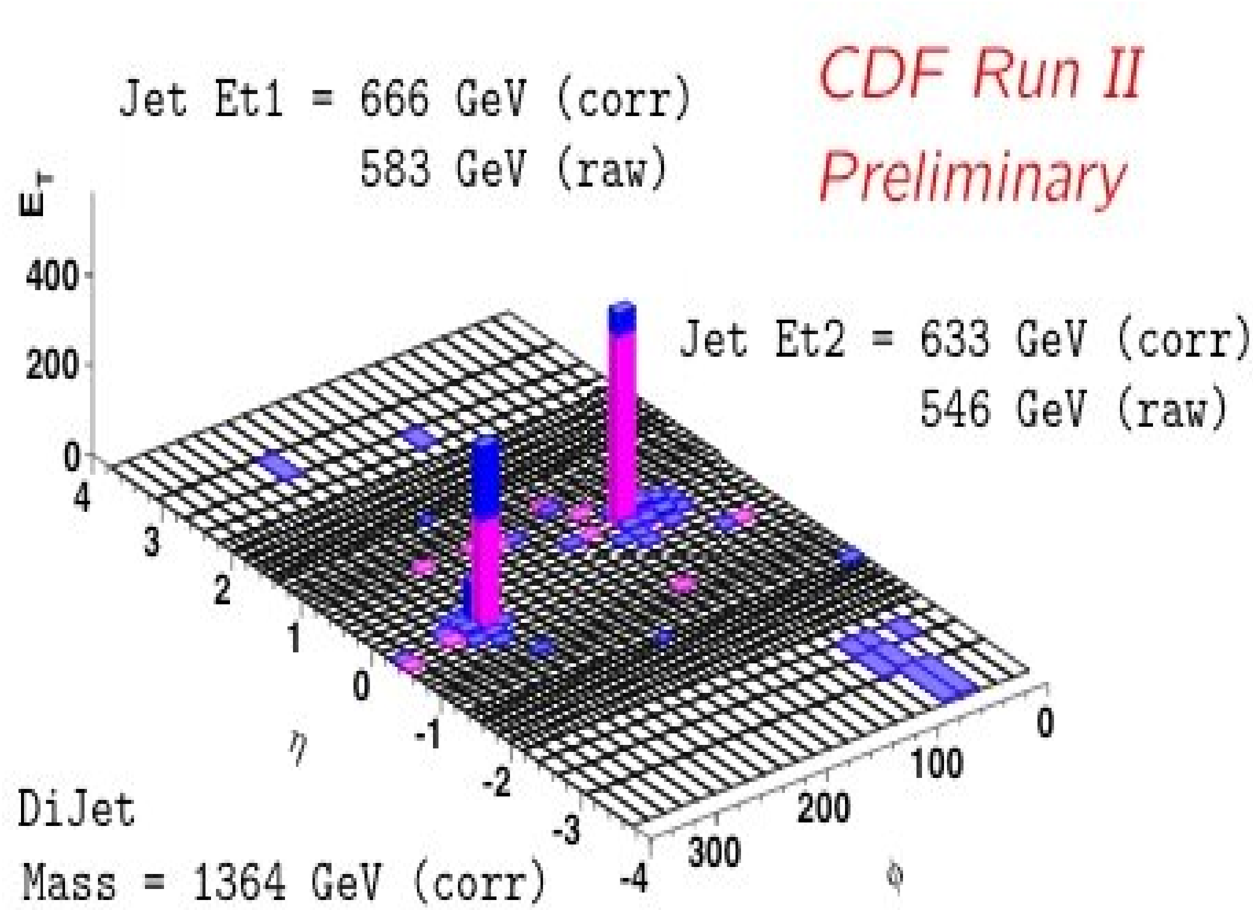
p+p → jet+jet [√s = 63 GeV]

AFS @ CERN-ISR (1982)



p+pbar → jet+jet [√s = 560 GeV]

UA2 @ CERN-SppS (1983)



p+pbar → jet+jet [√s=1.96 TeV]

CDF @ Tevatron (2001)

Step I: Jet algorithms (general)

- Calorimeter-level jet:

  EXP: a collection of 4-vectors based on calorimeter towers (what one measures in the detector).

- Hadron-level jet:

  TH: a collection of hadrons after parton hadronization.

  Non-perturbative processes:

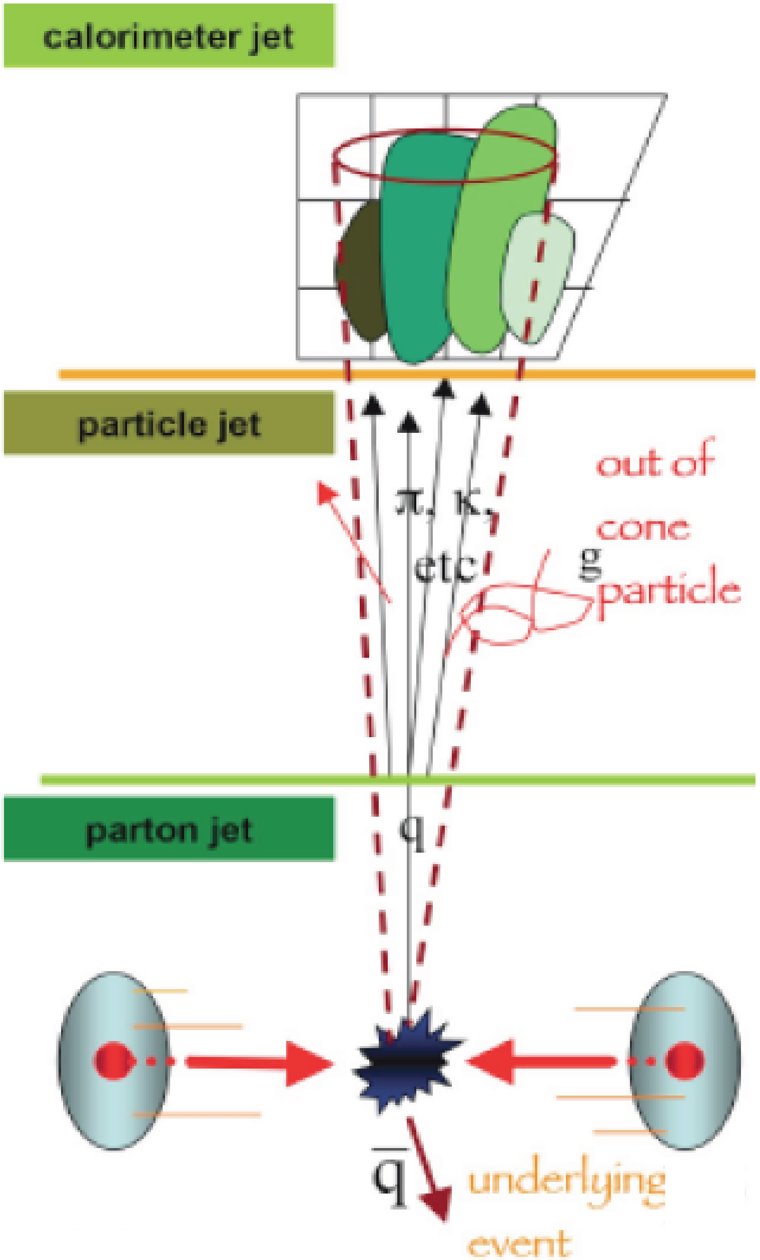
  rely on data-tuned MC.

- Parton-level jet:

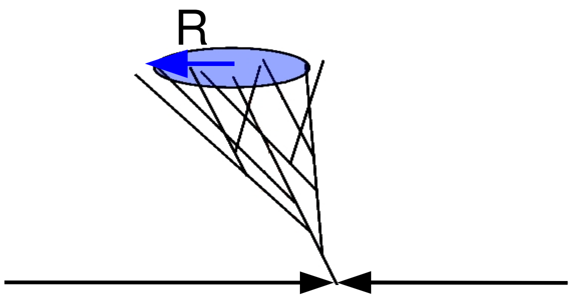
  TH: what one calculates (pQCD)

- Need to associate final-state particles with initial parton:

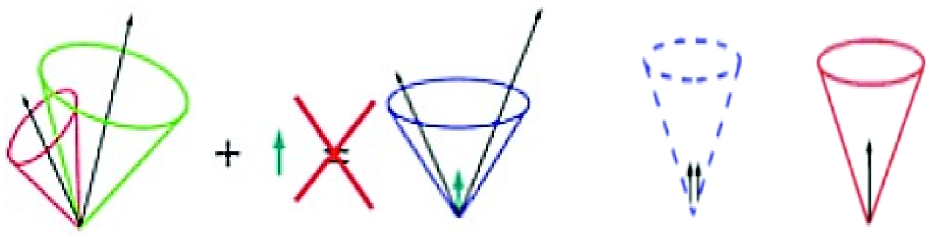
  - No unique way of doing this !
  - Jet algorithms



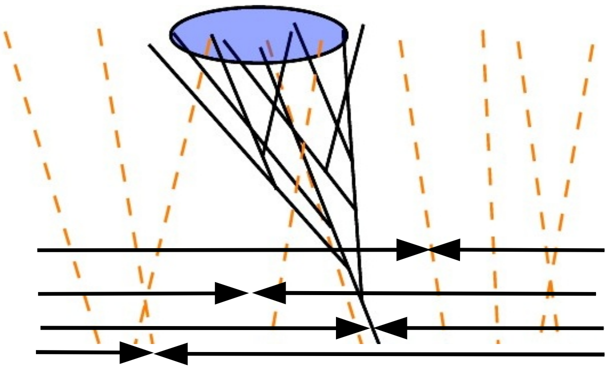
Step I: Jet algorithms (general)



- Goal: Combine hadrons into jets, according to a given "distance" (radius).
- Requirements:
  - infrared & collinear safe: soft-emission & collinear splitting must not change jets
  - applicable at parton & hadron level: direct comparison of data & pQCD



- Plus, in addition ...
  - not too sensitive to non-perturbative effects: hadronisation, underlying event, pile-up (p-p)
  - realistically applicable at detector level (e.g. not too slow)



Step I: Jet algorithms (basics)

- Two main types of jet algorithms:

(1) Cone-type:

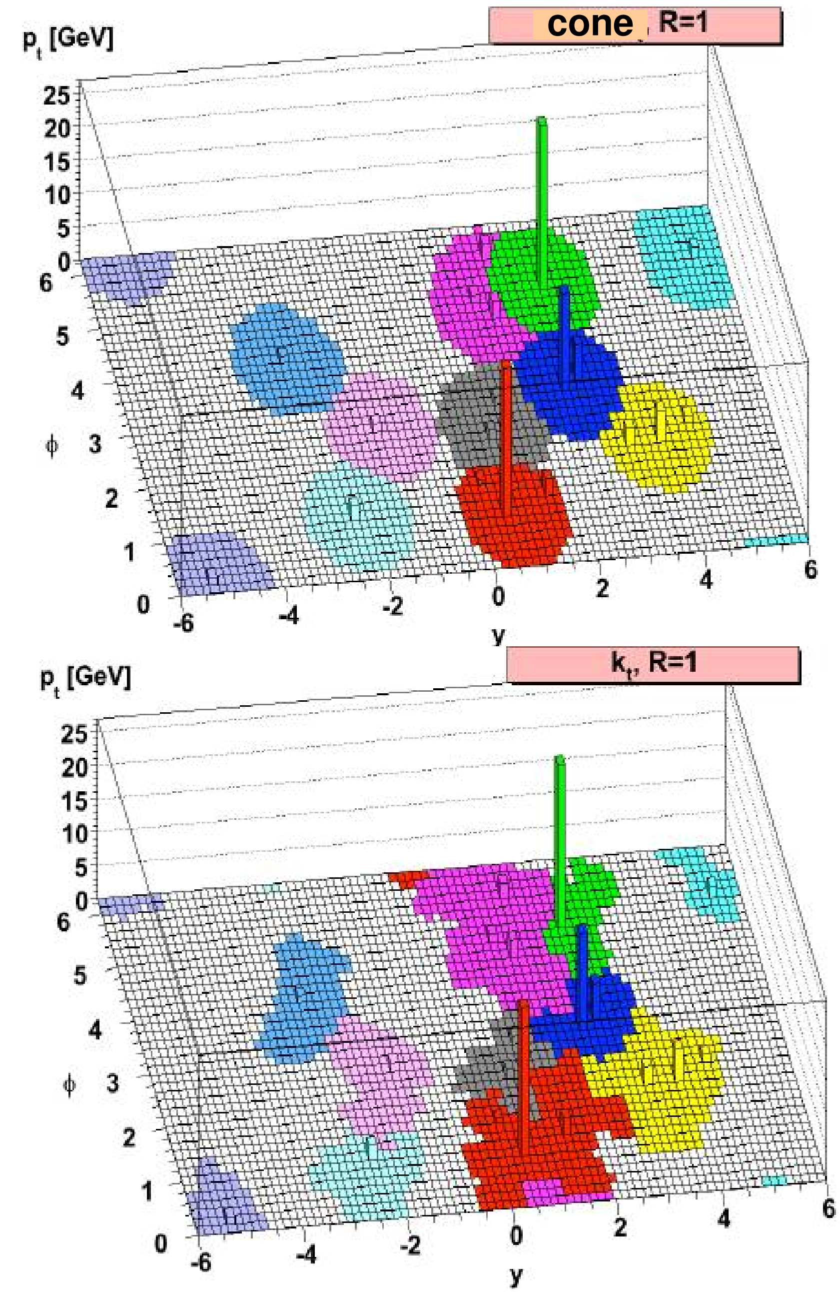
- "Top-down": Identify energy flow into pre-defined cones of radius R
- JetClu, ILCA/MidPoint, ICone, SISCone, ...

  Mainly used at the Tevatron.

(2) Sequential clustering:

- "Bottom-up": Pair-wise successive recombinations of closest hadron in k_T, (next closest, ...) up to distance D.
- kt, Cambridge/Aachen, Jade, ...

  Widely used at LEP & HERA.



Step I: Jet algorithms (basics)

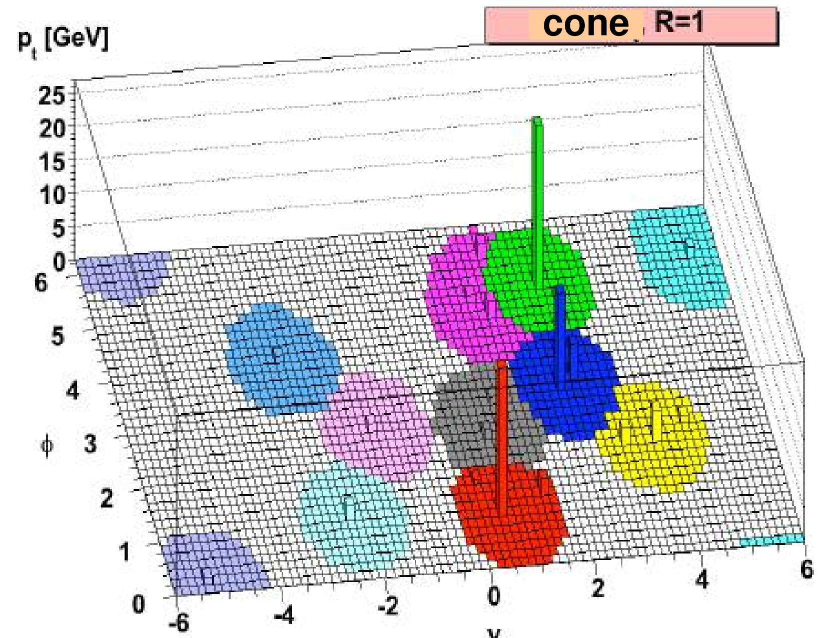
- Two main types of jet algorithms:

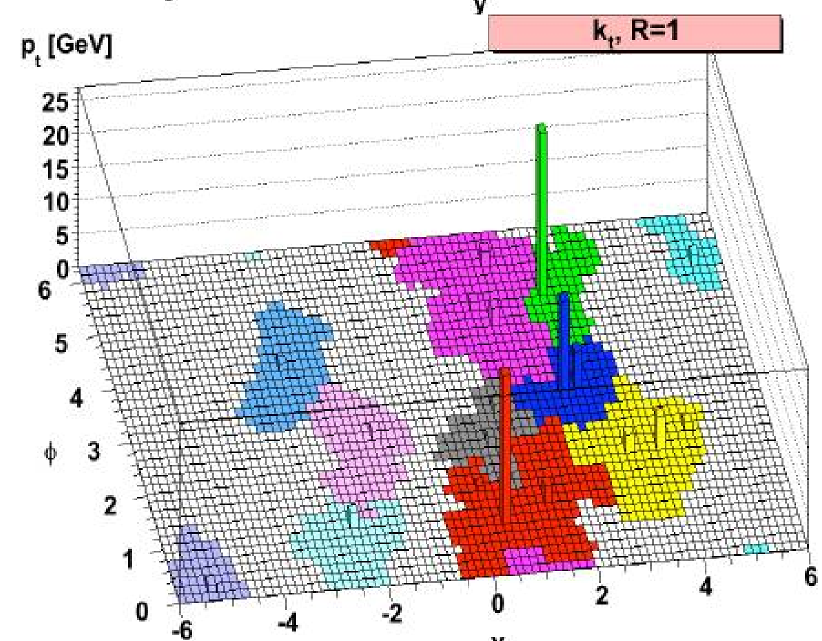
(1) Cone-type:

- ♥ Fast (easy to implement in triggers).
- ♥ UE corrections easier
- ☹ Detailed definition can be messy (seeds, split/merge), dark towers, ...
- ☹ Infrared/collinear safety not guaranteed

(2) Sequential clustering:

- ♥ Infrared & collinear safe
- ♥ More "realistic": mimick (backwards) QCD shower branching dynamics.
- ☹ (Used to be) slow.
- ☹ UE subtraction trickier.





Step I: Jet algorithms (speed)

- Time taken to cluster N particles.
- "Normal" kt: Very slow for large N (~N^3).

  fast-kt & Cam/Aachen kt: Very fast (~N ln N).

  SISCone: ~N^2 ln N

M.Cacciari & G.Salam PLB (2007)

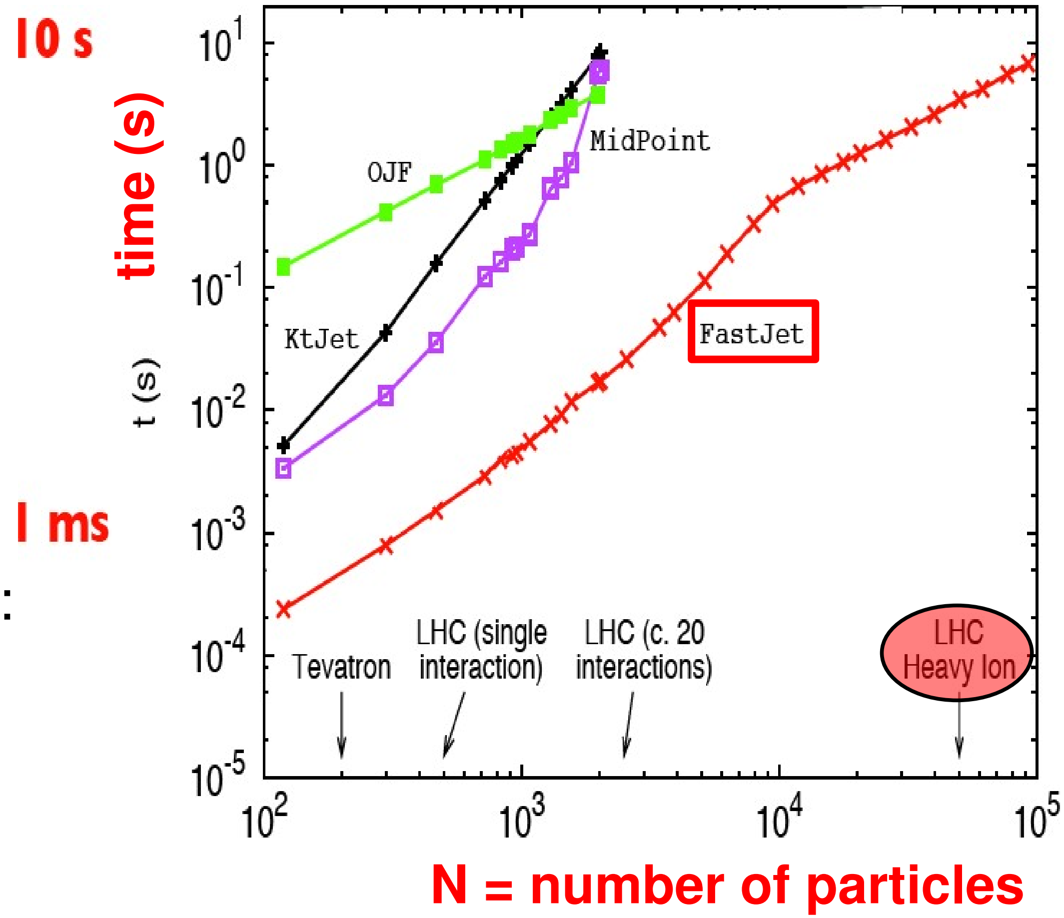
fast-Kt:

- (based on Voronoi diagrams)
- Speed at small-N:

  ~2 orders of magnitude gain wrt. $\mathcal{O}(N^2)$ implementation

- Speed at large-N (heavy-ions):

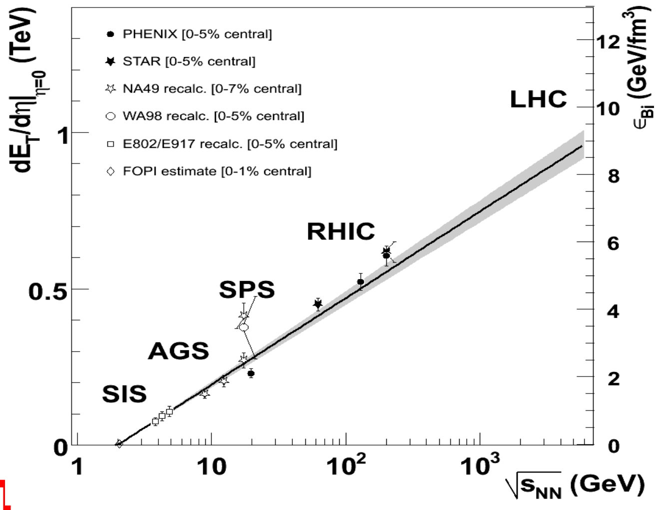
  $\mathcal{O}$(1 sec) rather than 1 day !



Step II: Underlying event subtraction (Pb-Pb LHC)

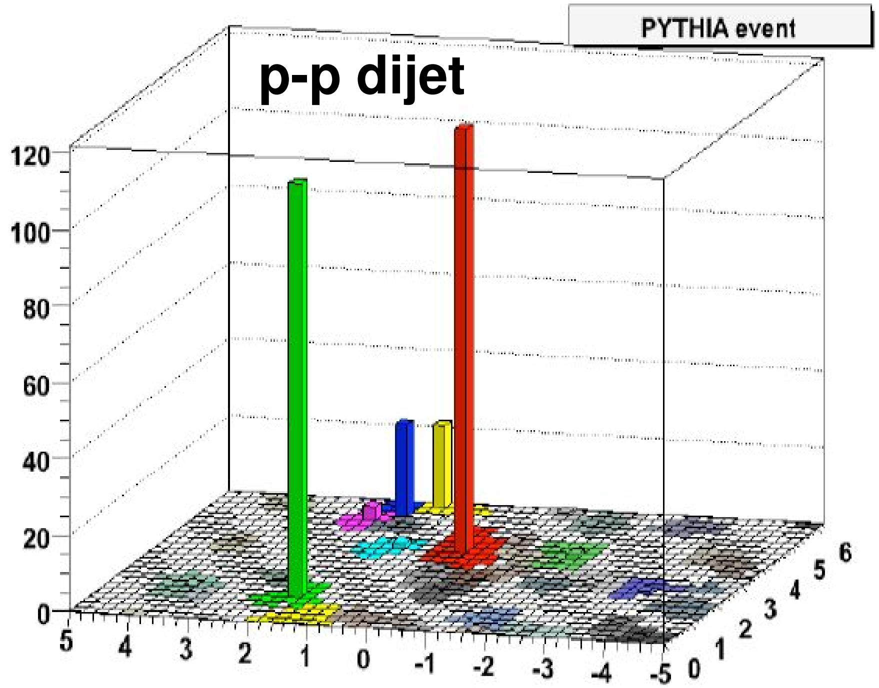
- Huge Pb-Pb soft background at the LHC :

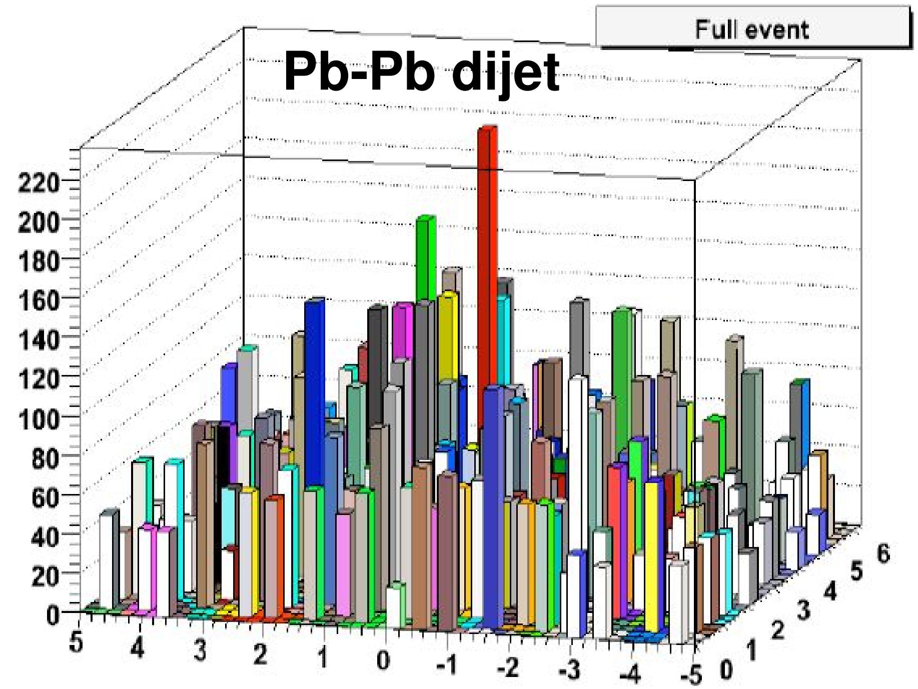
  $dE_T^{LHC}/d\eta$ ~ 1 TeV at η=0



- Background-E_T inside jet of cone R=0.4:

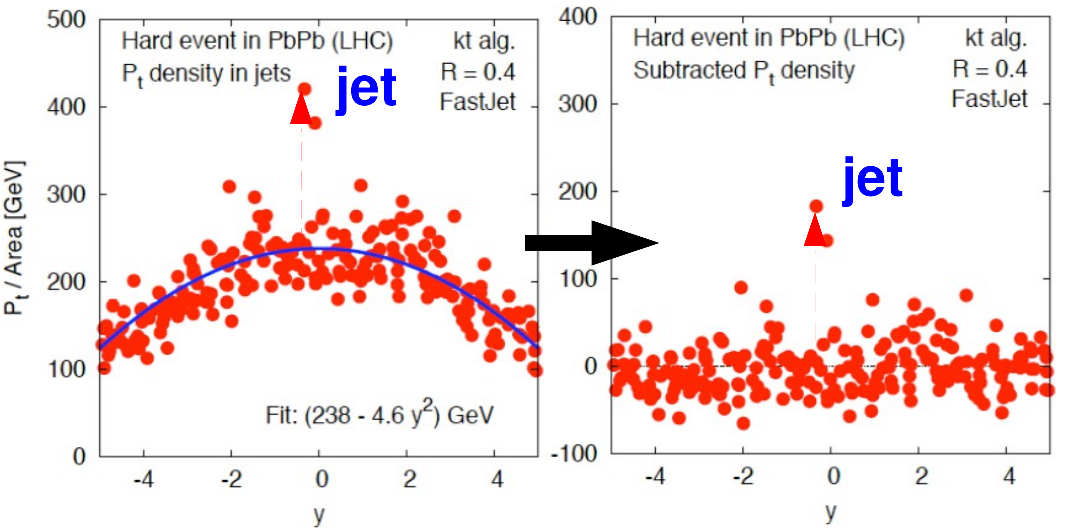
$$UE(R=0.4) \sim \pi R^2 \cdot 1/(2\pi) \cdot dE_T/dy \sim 75\ \text{GeV !!}$$ (fluctuating !)

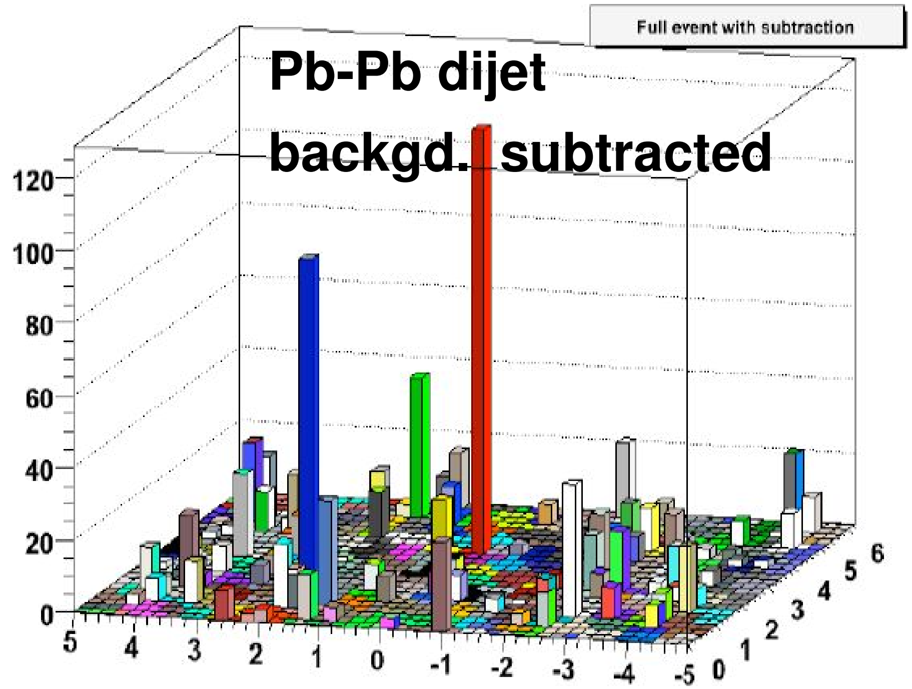




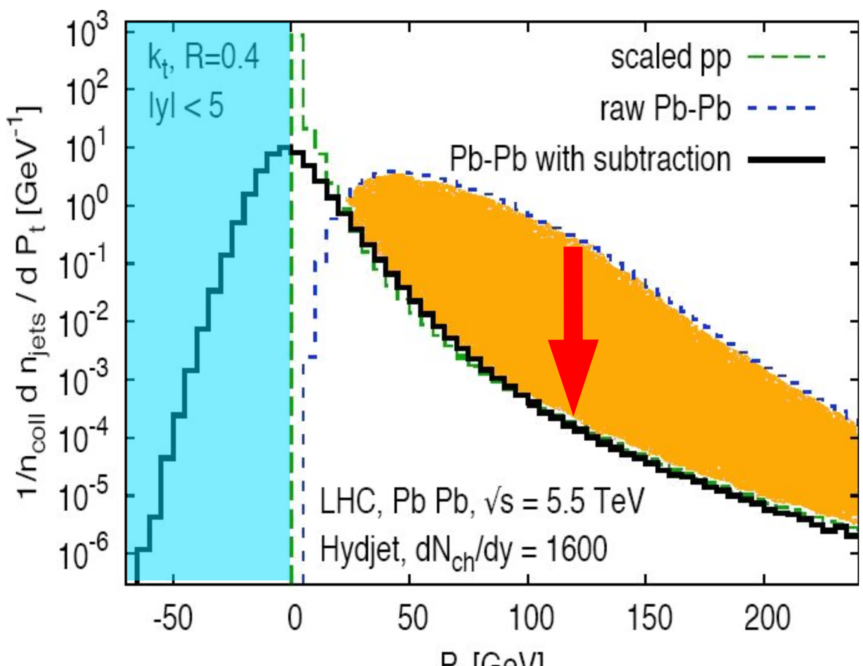
Step II: UE subtraction (fastJet)

- fastJet implementation:
  - fit $p_T(y)$/area for background
  - subtract it for each jet

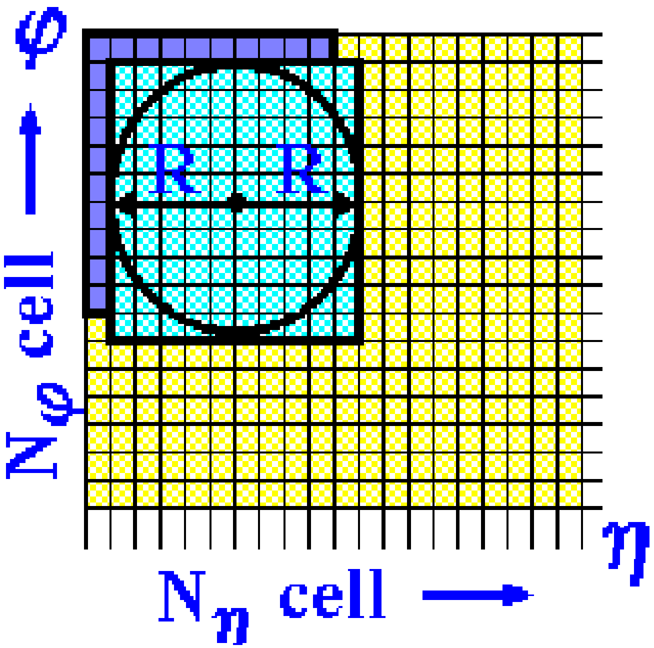




- Final Pb-Pb jet spectrum:



Step II: UE subtraction (ICone)



Iterative event-by-event background subtraction:

- Calculate $<E_T^{tower}(\eta)>$, $D^{tower}(\eta)$ in η rings.
- Subtract for all E_T^{tower} tower energies:

$$E_T^{tower} = E_T^{tower} - E_t^{pile\text{-}up}$$

$$E_t^{pile\text{-}up} = <E_T^{tower}(\eta)> + D^{tower}(\eta)$$

- Negative tower energies are replaced by zero

- Find jets with $E_T^{jet} > E_t^{cut}$ using std. iterative cone algo with new tower energies
- Recalculate background energy with towers outside the jet cone.
- Recalculate tower energy with new pile up energy.
- Final jets are found with the same iterative cone algorithm:

$$E_T^{Jet} = E_T^{cone} - E_t^{pile\text{-}up\ new}$$

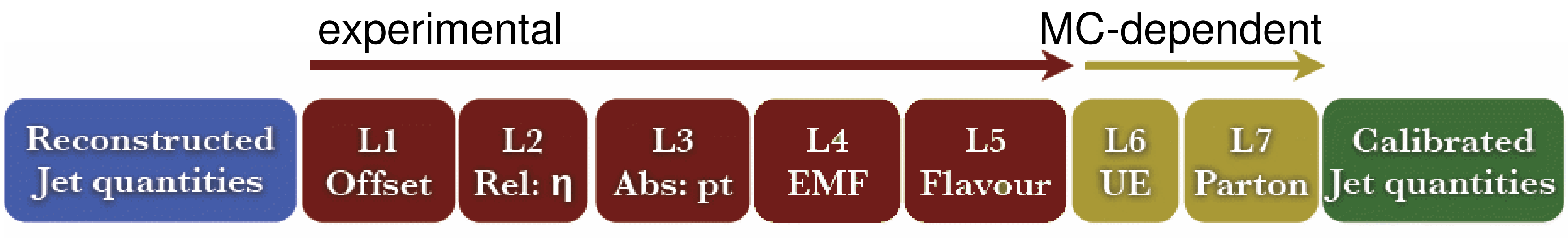
Step II: UE subtraction (ICone)

- Search for the particle with the highest transverse energy (seed).
- Use its spatial coordinates to define the axis of the jet candidate.
- Define a cone on the ϕ-η plane with a radius of R (e.g. R=0.4).
- Find final state particles inside which are closer to the jet axis than R.
- Redefine the the jet with the help of these particles:

$$E_{T,jet} = \sum_i E_T^i \qquad \eta_{jet} = \frac{1}{E_{T,jet}} \sum_i E_i^i \eta^i \qquad \varphi_{jet} = \frac{1}{E_{T,jet}} \sum_i E_T^i \eta^i$$

- If the alteration of the jet axis is less than a predefined value, then the jet is found and their particles are removed
- Otherwise return to step 4

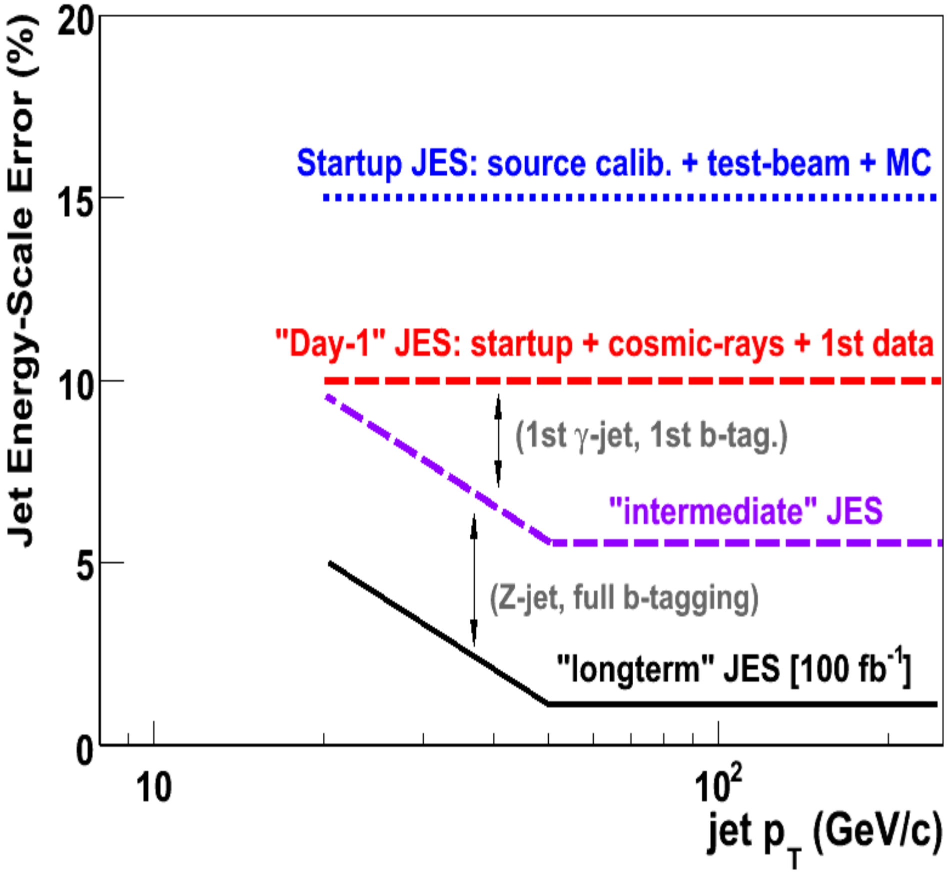
Step III: Jet energy corrections

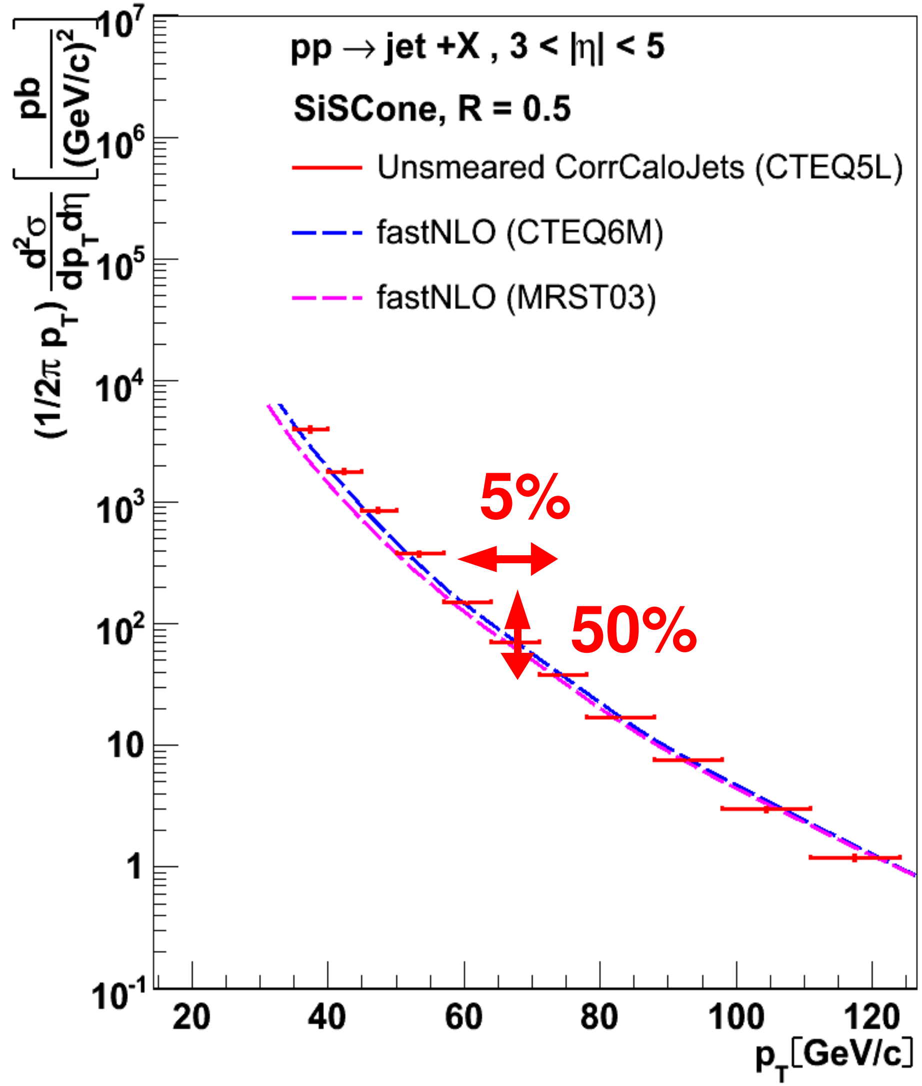


- Data-driven corrections:
  - L1-L4: Relative (η) & absolute energy scale, electromagnetic fraction
    [Main source of uncertainty ! (see next)]
  - L5: Flavour separation (gluon, quark) feasible in heavy-ions ?
  - Obtained in dijet & γ-jet balancing in proton-proton collisions.
  - No serious experiment trusts just on Monte Carlo for this !
- MC-dependent corrections:
  - Underlying-event: Depends on modeling of initial- & final-state radiation & multi-parton interactions. The observable we are after !
    Use at least 2 jet-quenching MCs e.g. PYQUEN (large out-of-cone elastic E_{loss}) and Q-PYTHIA (BDPMS-based)
  - Hadronization: Parton-to-hadron vacuum fragmentation. Use 2 types of MCs: string (Q-PYTHIA) and cluster (Q-HERWIG) fragmentation

Step III: Jet Energy Scale

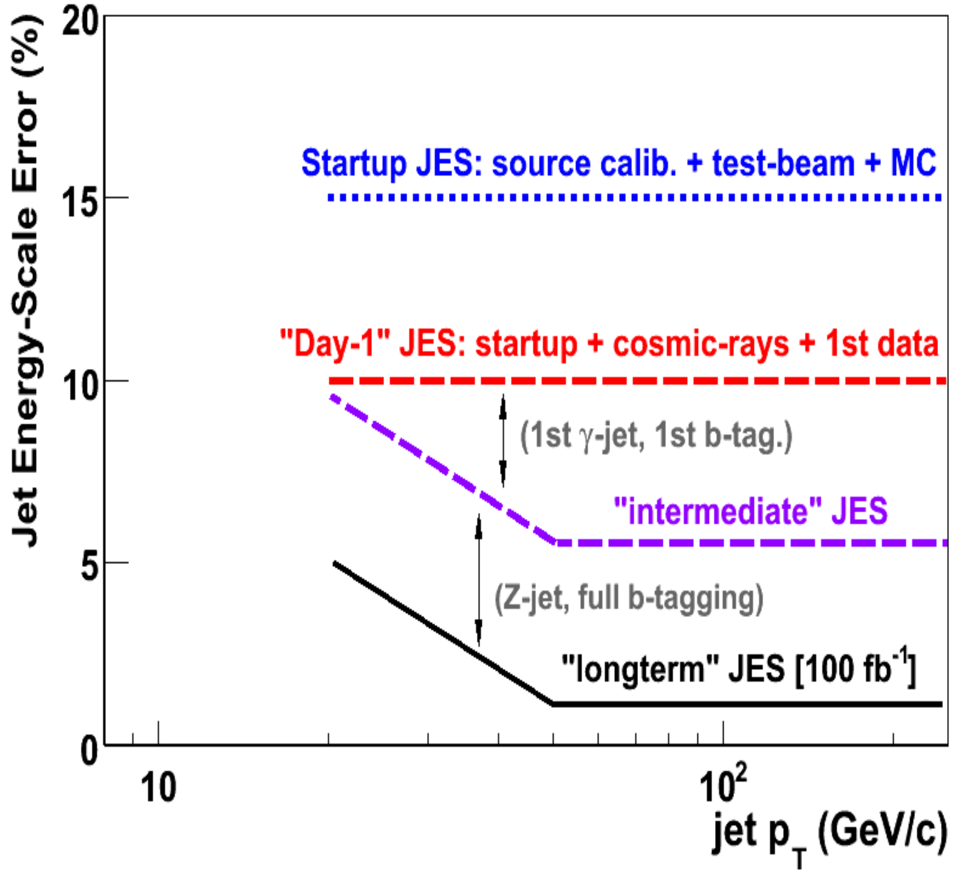
- ~5% uncertainties in jet-energy propagate into ~50% uncertainties in E_T (steeply falling) spectrum !
- Example: p+p -> fwd jet+X

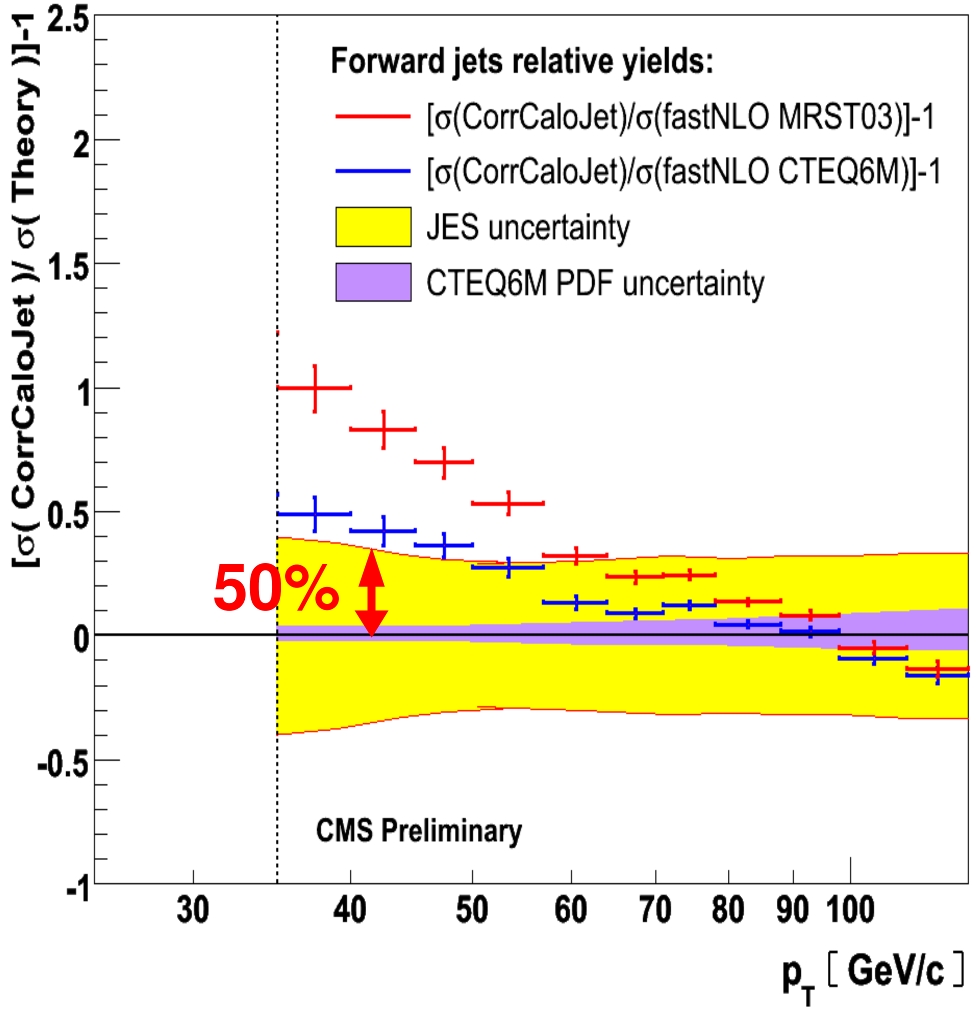




Step III: Jet Energy Scale

- ~5% uncertainties in jet-energy propagate into ~50% uncertainties in E_T (steeply falling) spectrum !
- Example: p+p -> fwd jet+X



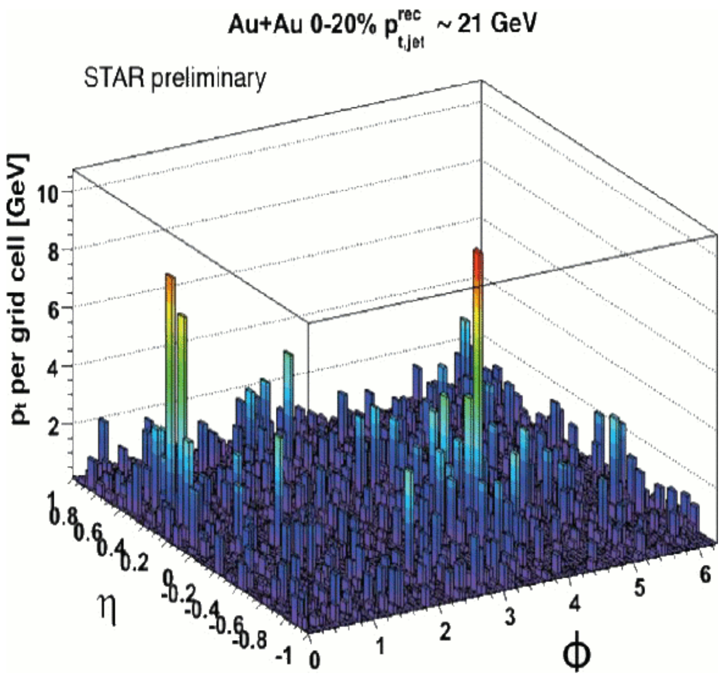


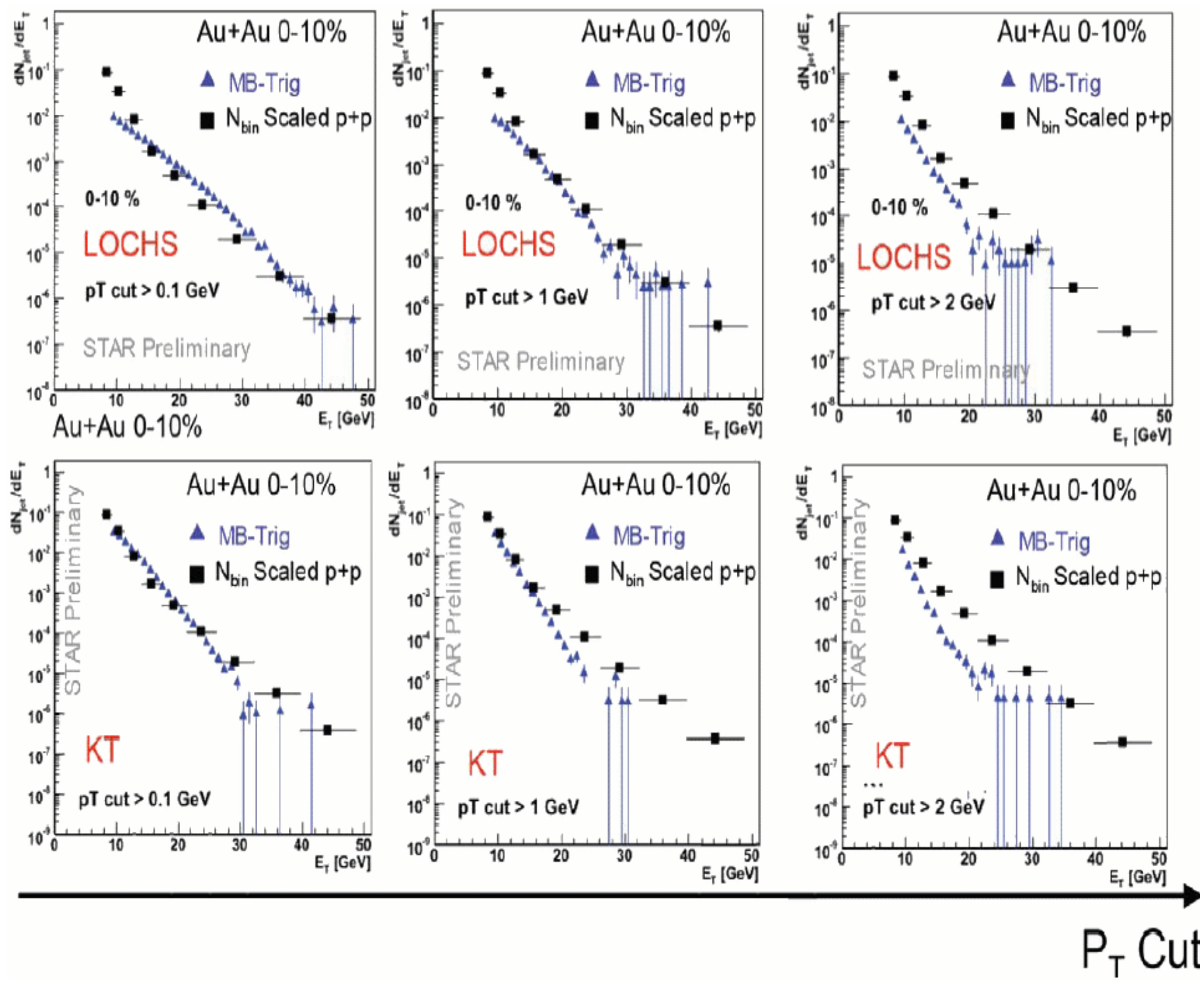
Jet reco example: STAR (AuAu, 200 GeV)

- STAR jet-reco proof-of-principle !

J.Putschke, S.Salur, HP08

AuAu→ jet + X, 200 GeV

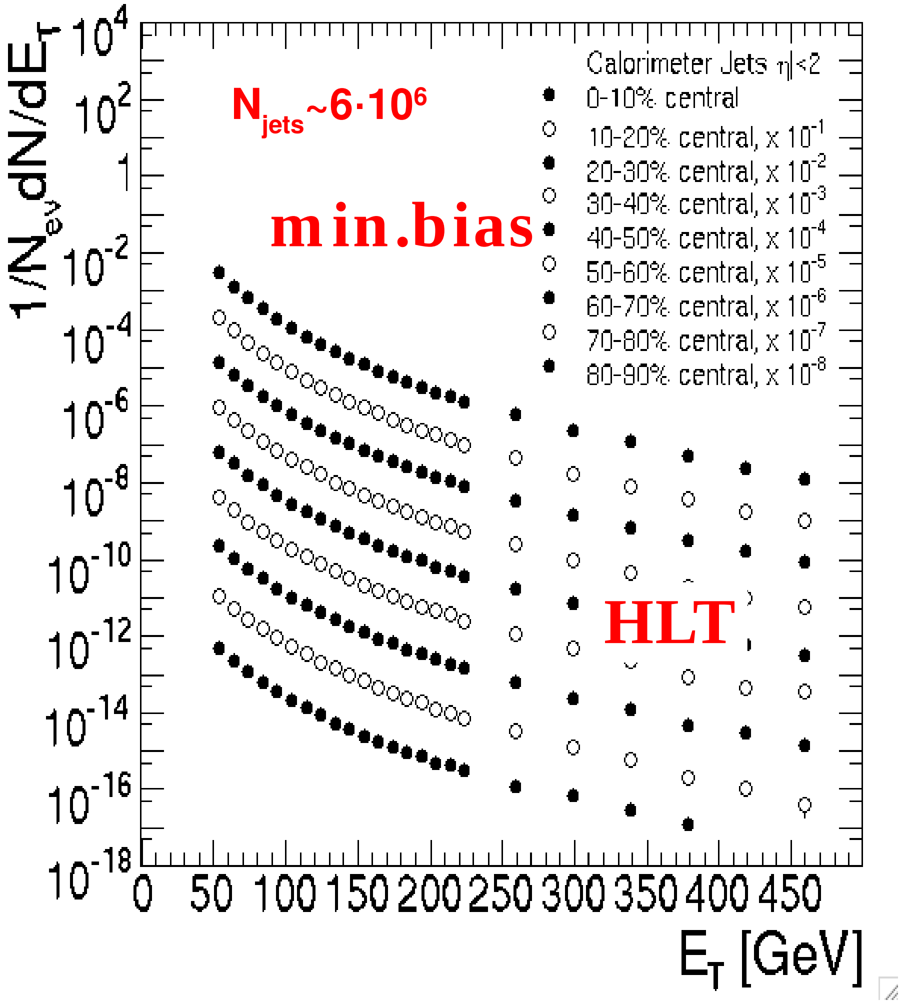


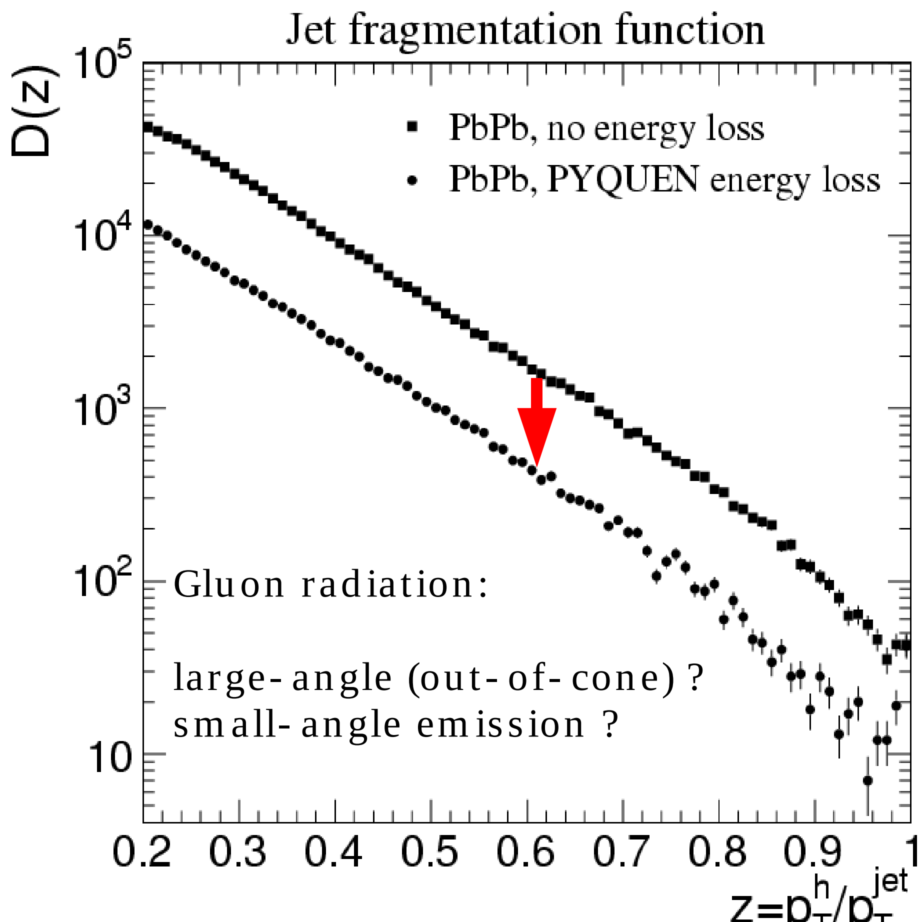


- Promising start ... but missing (and/or MC-dependent) jet energy corrections

Jet reco example: CMS full-sim (PbPb, 5.5 TeV)

- Jet spectra up to E_T~ 0.5 TeV (PbPb, 0.5 nb^{-1}, HLT-triggered).
- Combined with inclusive hadron p_T: Detailed studies of medium-modified (quenched) jet Fragmentation Functions possible.





I. Lokhtin et al., PLB567 (03)39

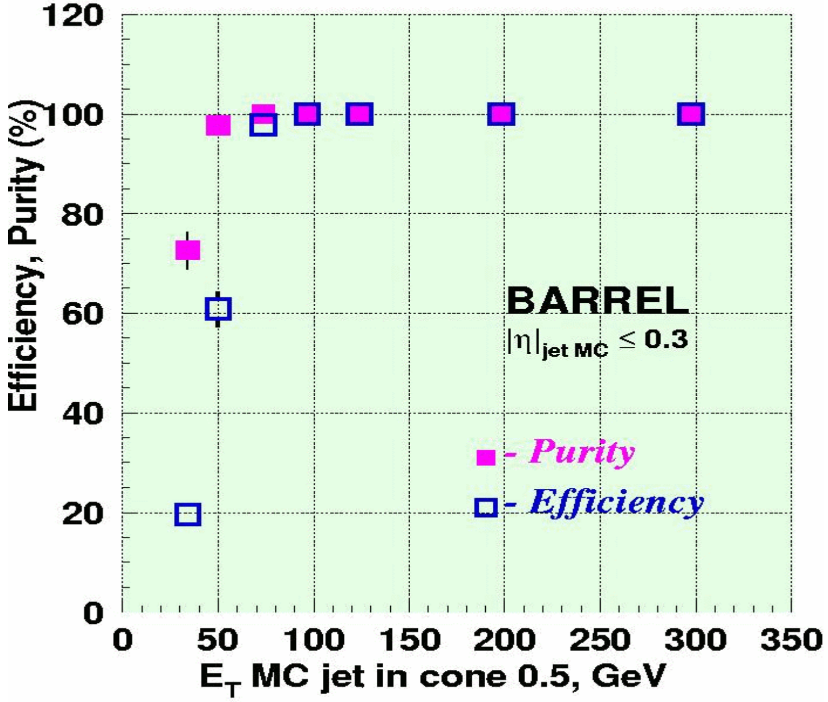
Jet reco performances: CMS (full sim)

Iterative-cone (R=0.5) + backgd. subtraction (dN_{ch}/dy=5000)

- Efficiency, purity

  High effic./purity for

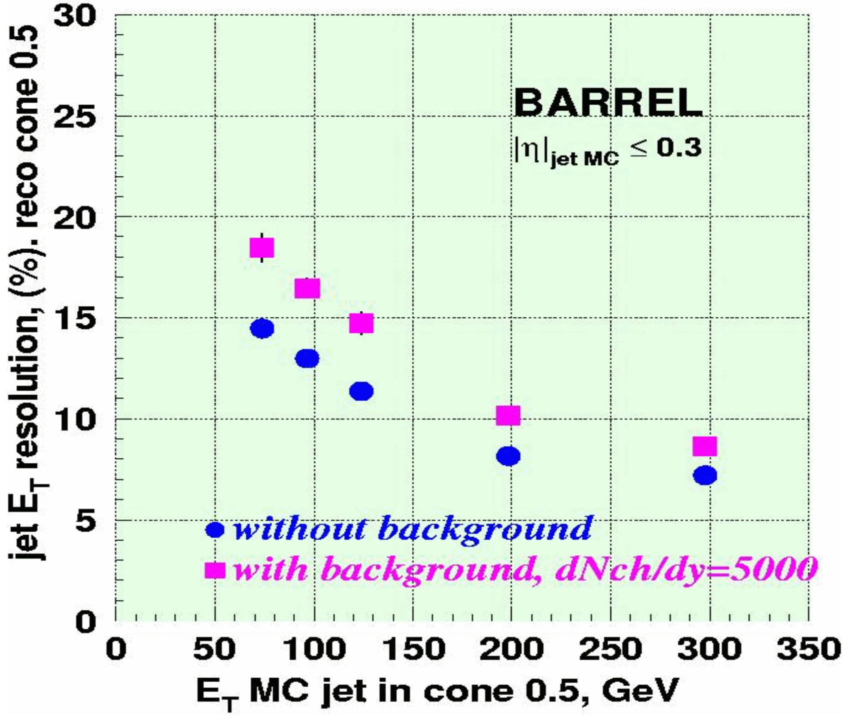
  E_T > 50 GeV/c



- Energy resolution

  $\sigma_E/E<15\%$ for

  E_T>100 GeV

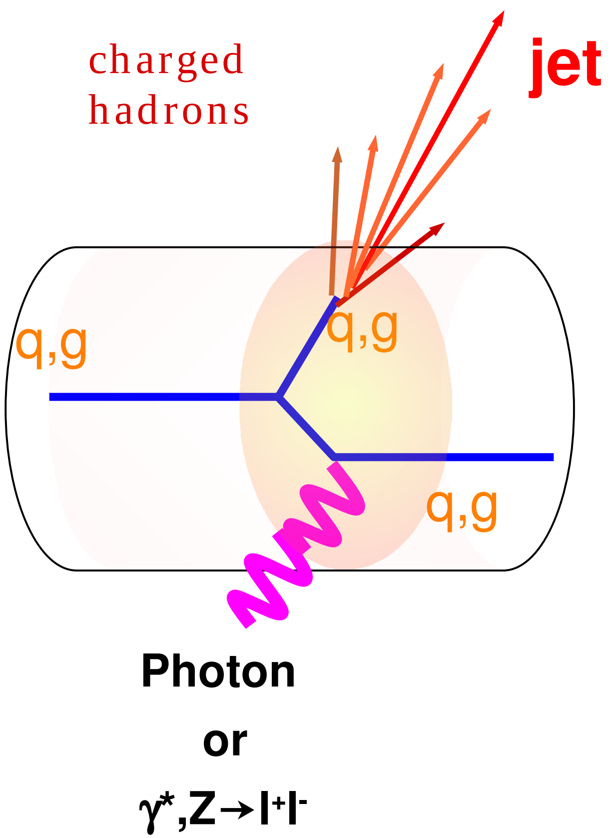


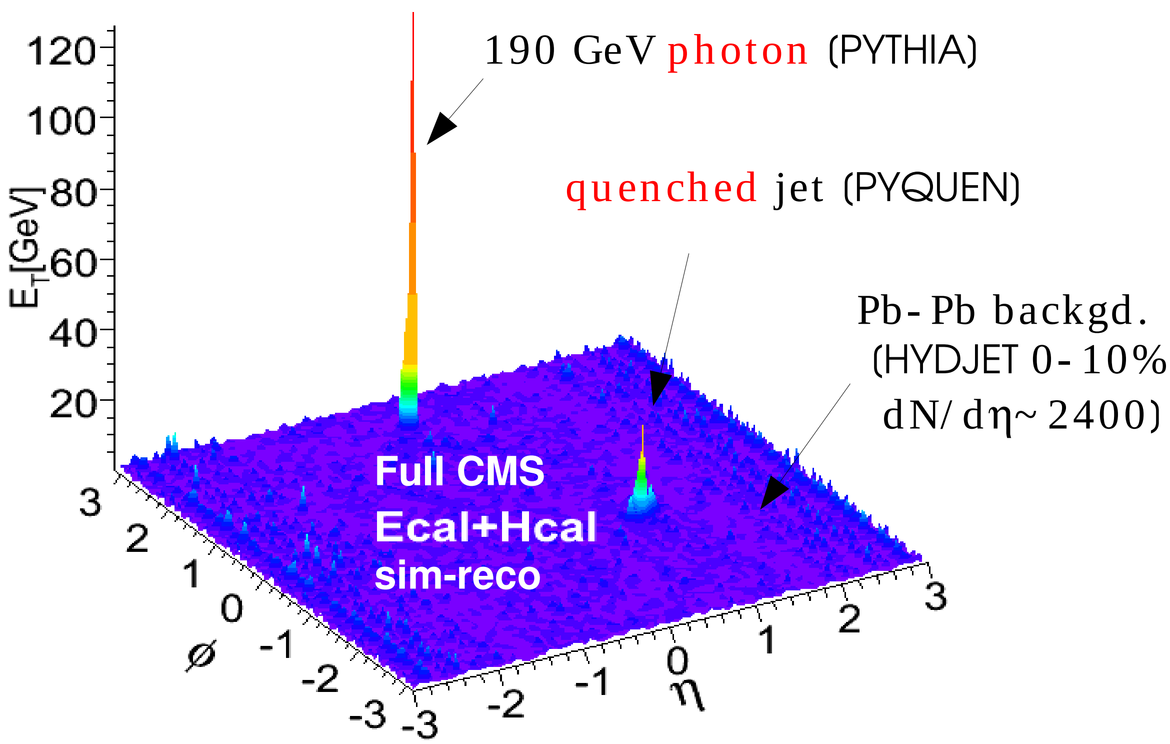
Jet balancing with γ or Z

- Calibrate jet-energy loss with unaffected back-to-back gauge bosons (γ,γ*,Z):

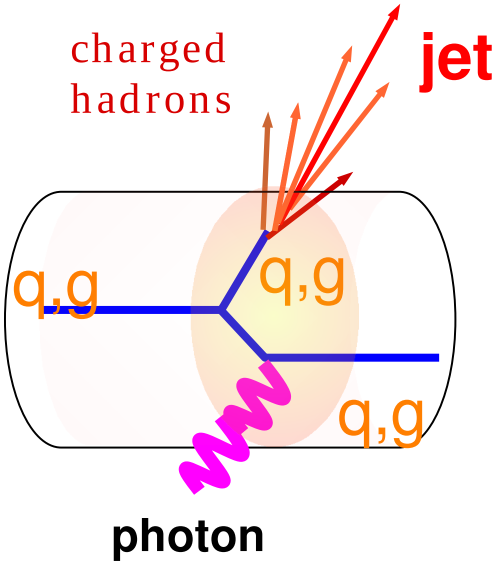
  energy of γ,Z = energy of parton at vertex (before energy loss).

- γ,Z-events in Pb-Pb allow one to determine medium-modified Fragmentation-Functions correlating away-side hadrons with parent-parton (=photon) energy





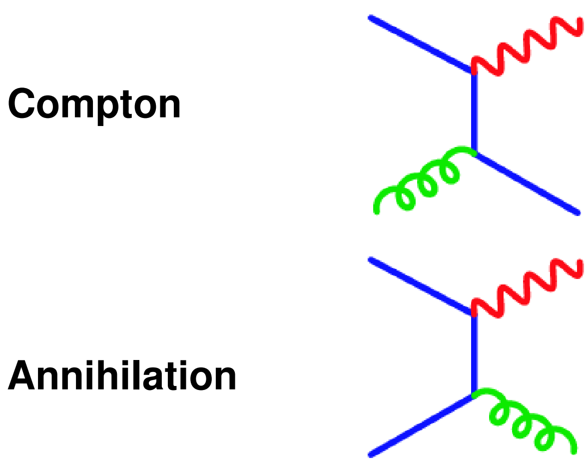
γ – jet in Pb-Pb at 5.5 TeV (CMS)



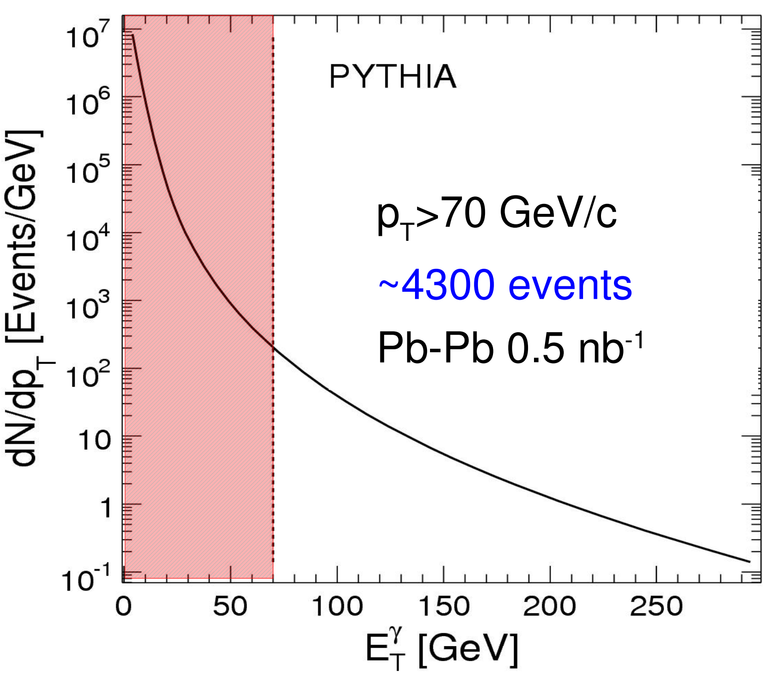
Challenging measurement !

- Isolated γ, $|\eta|<2$, $R_{isol}<0.5$ → parton E_T
- Back-to-back jet $|\eta|<2$, $|\Delta\phi_{j\text{-}g}|>3$ → away-side axis
- Tracks ($|\eta|<2.5$, $R_{jet}<0.5$) → fragment hadron p_T
- Construct FF: away-side hadron yields vs. $z=p_T^{hadron}/E_T^{photon}$

LO diagrams (back-to-back):



- Expected CMS γ-jet statistics

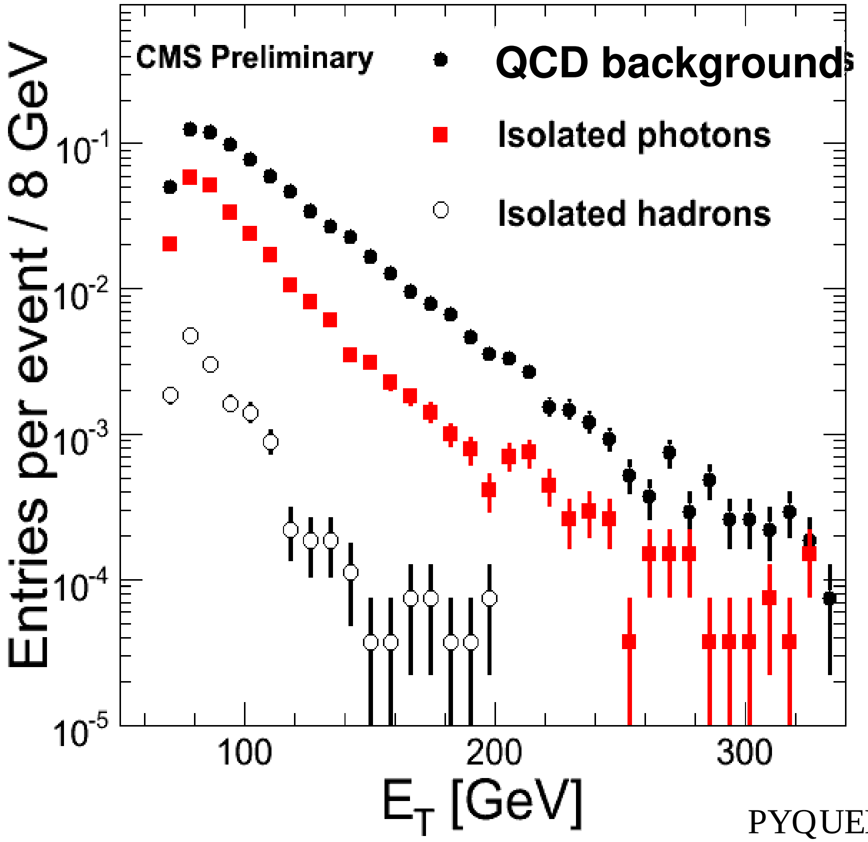


γ – jet in Pb-Pb at 5.5 TeV (CMS): photon reco

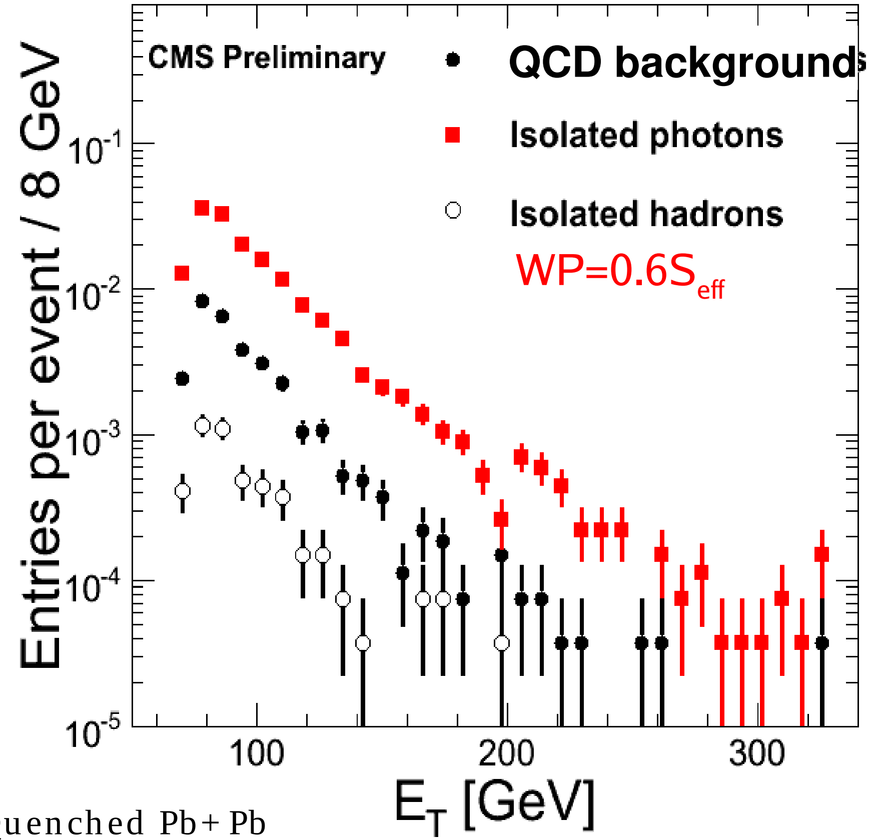
- Photon identification: Look for EM-like clusters in EM Cal. (shower-shape vars.)
- Isolated photon: Impose no hadronic activity (above a given p_T) in tracker/HAD Cal.
- Multi-variate-Analysis (MVA, "Fisher LD") of 21 variables.

photon isolation/shape cuts improve S/B by factor ~15

Before cuts: S/B=0.3



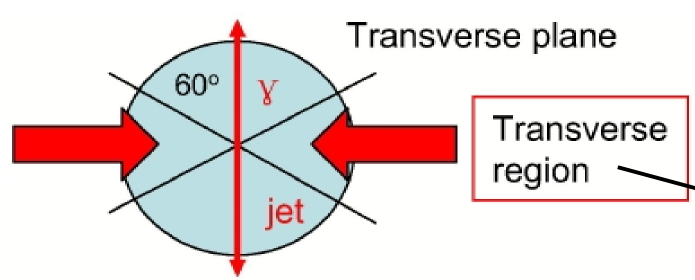
After cuts: S/B=4.5



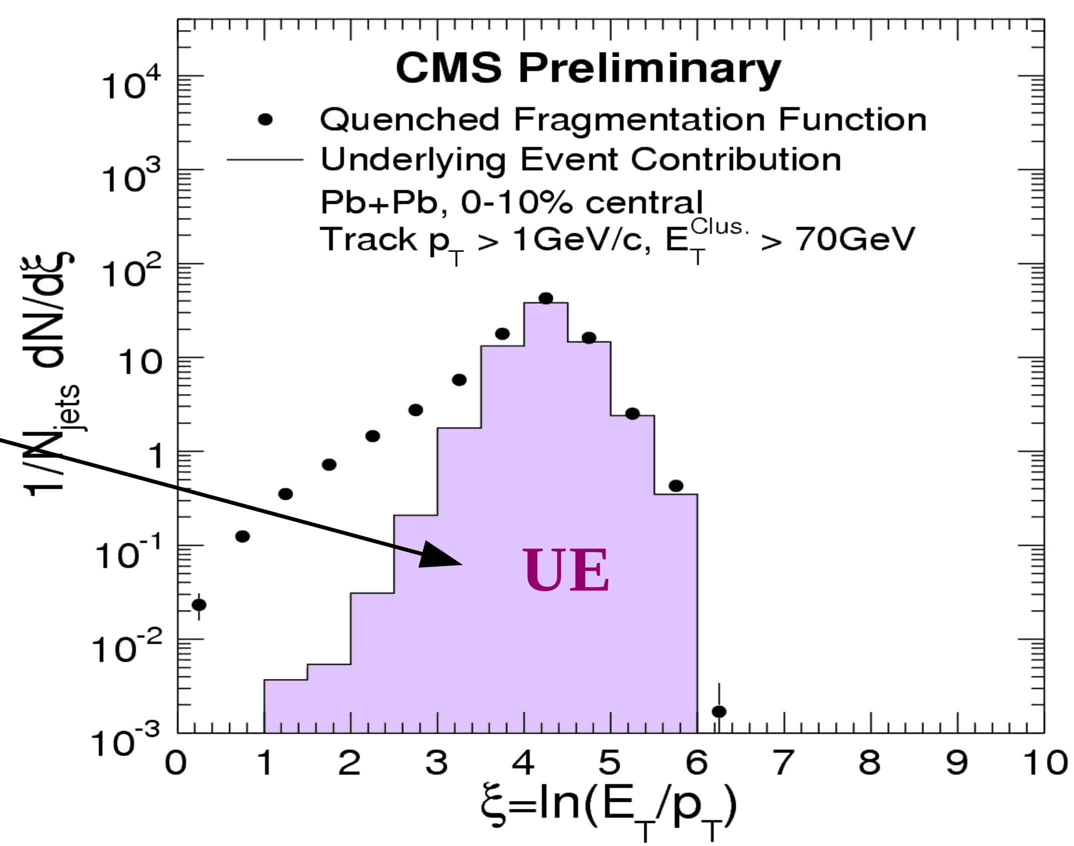
PYQUEN/ Quenched Pb+Pb

γ – jet in Pb-Pb at 5.5 TeV (CMS): UE

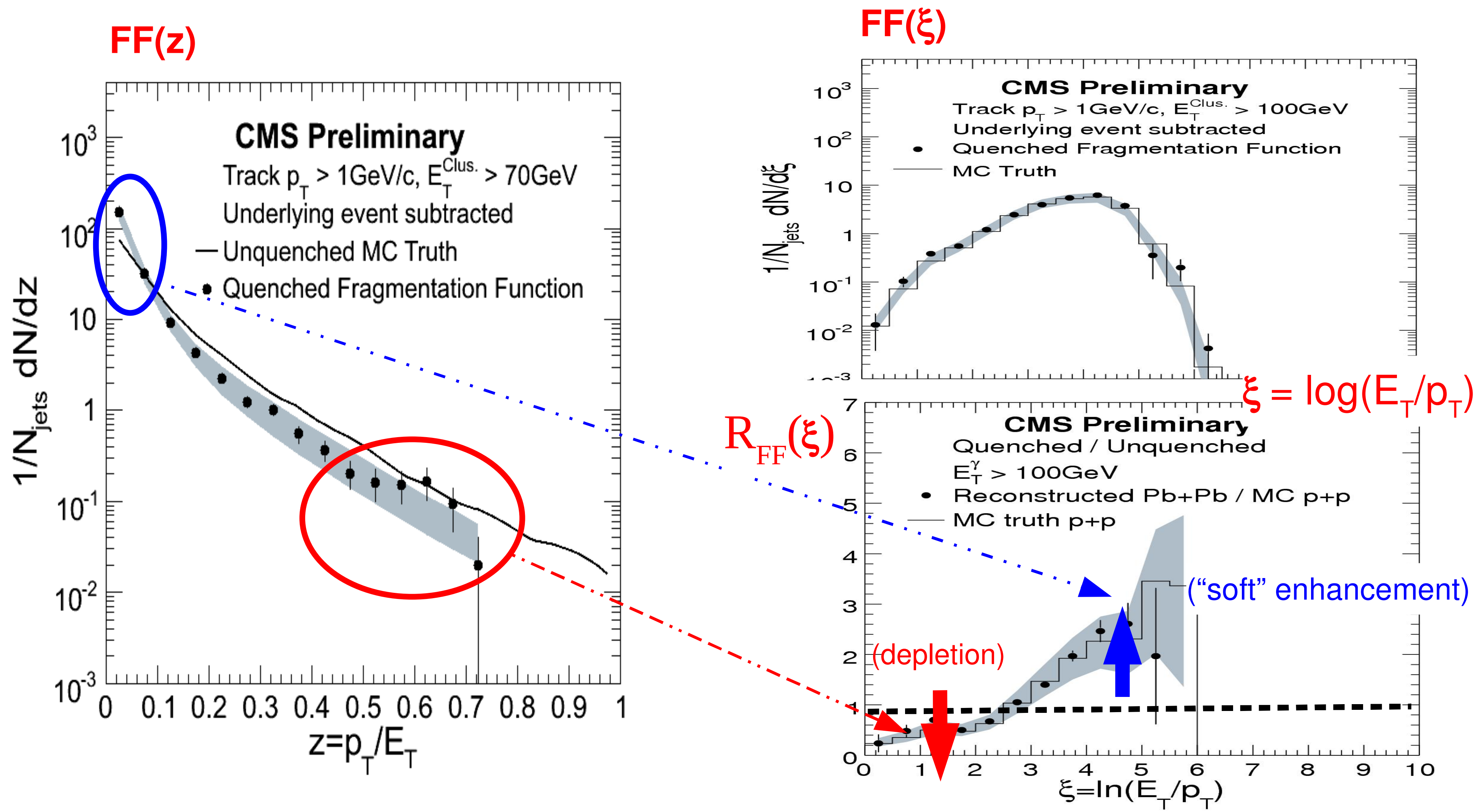
- Underlying Event background: contamination of low-z region of FF.
- Subtraction using hadrons within R=0.5 cone transverse to jet axis:



FF(z): dN/dξ



γ – jet in Pb-Pb (CMS): medium FFs



- Medium FFs measurable for $z<0.7$ (or $0.2 < \xi < 5$) with high significance
- Syst. uncertainties dominated by (low) away-side jet reco effic. 30-70 GeV

Jet reco, γ jet, medium FFs: Summary

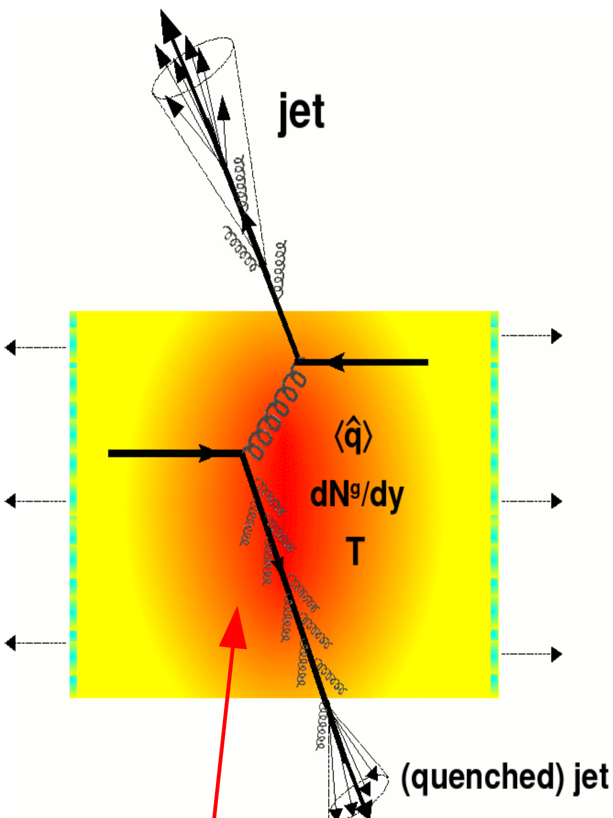
- Full jet reconstruction is the ultimate tool to study "jet quenching" in high-energy A-A collisions.
- Not yet exploited at RHIC (low yields) but very common at the LHC.
- Jet reconstruction algorithms & UE background subtraction presented
- gamma-jet will be an excellent tool to study medium-modified FFs:

⇒ obtain q-hat parameter

⇒ Radiation in hot/dense QCD matter: small- vs. large-angle gluon emission

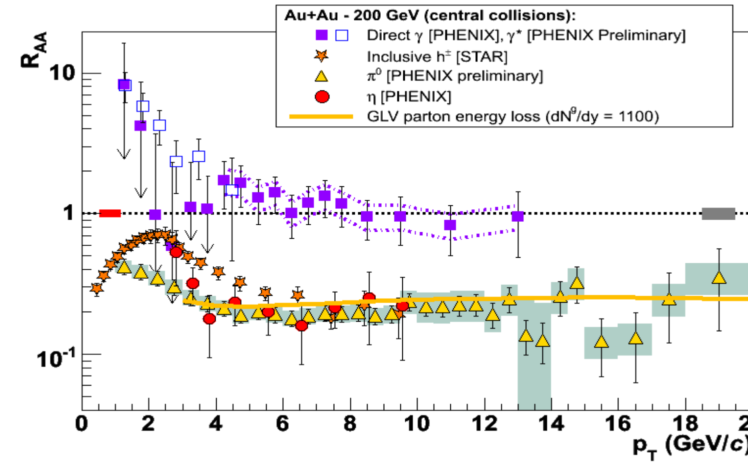
Jet quenching summary

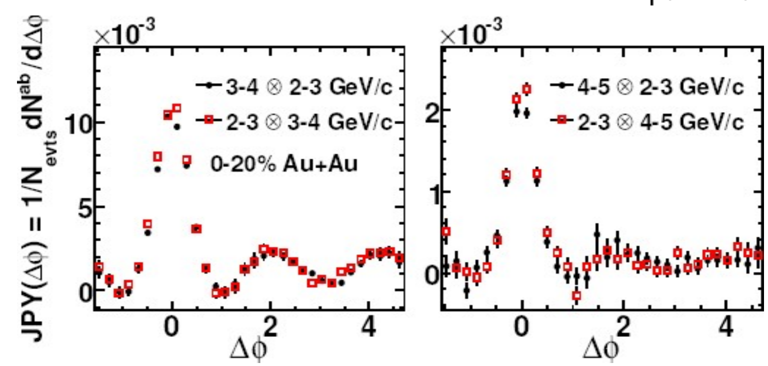
Hot/dense QCD matter tomography



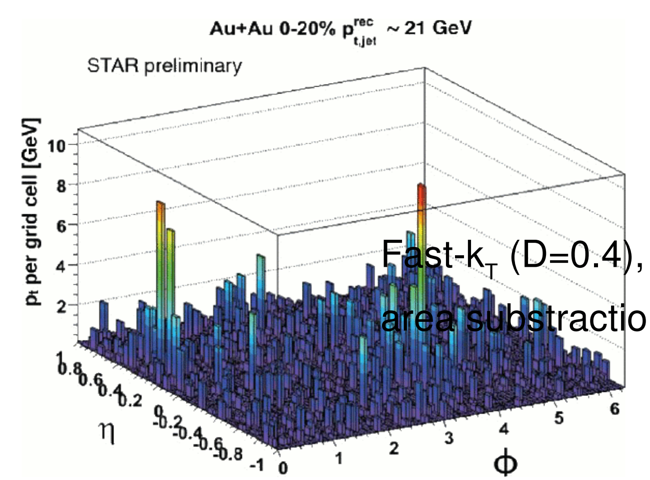
$\hat{q}$ ~13 GeV²/fm
dN^g/dy = 1400
T~0.4 GeV
c_s~0.3 (?)

- High-p_T hadron spectra (R_{AA}) & dihadron correlations (I_{AA}): parton E_{loss} models
  - Most of observables well reproduced.





- Full jet reco, γ-jet, medium modified Ffs:
  - Tools available for jet reco & bckgd. subtraction
  - Data-driven jet corrections (do not rely on MC alone !)



Backup slides

NLLA + LHPD: hadron momenta in jets

Momentum distribution

of charged particles in jets

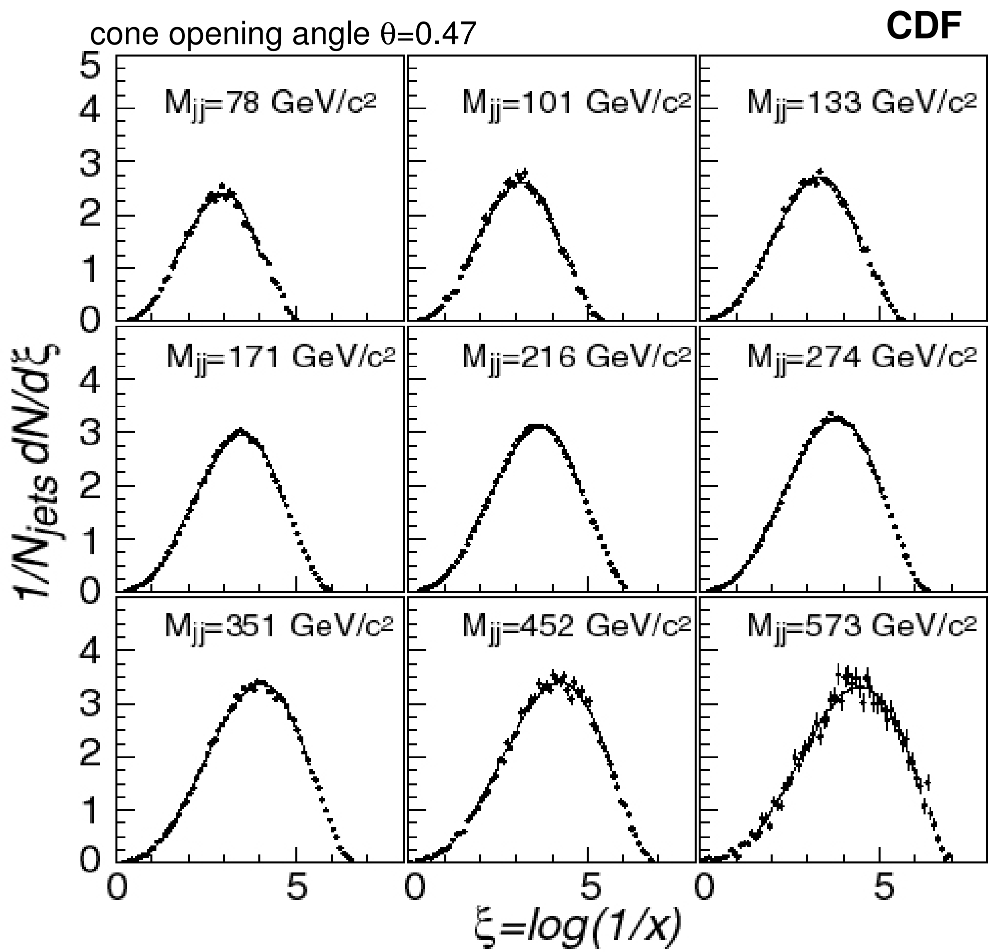
- dijet events with well-balanced E_T
- 15-30° cone around dijet axis

Two parameter fit (MLLA+LPHD)

- works surprisingly well in a wide range of dijet masses
- MLLA Q_{eff} = 230±40 MeV

  k_T-cutoff can be set as low as Λ_{QCD}
- $K_{LPHD(\pm)} = 0.56 \pm 0.10$

  $N_{hadrons} \approx N_{partons}$



$$x = \frac{p_{particle}}{E_{jet}} \qquad \xi = \ln(1/x) = \ln\left(\frac{E_{jet}}{p_{particle}}\right)$$

NLLA+LHPD: particle multiplicity (gluon vs quark jets)

LLA and NLLA: $r = N_{gluon} / N_{quark} = 9/4 = 2.25$

n NLLA: r = 1.4-1.8, depending on the energy scale

di-jet and γ-jet events have very different fractions of q/g-jets

→ multiplicities in quark and gluon jets can be resolved

Results agree with n NLLA

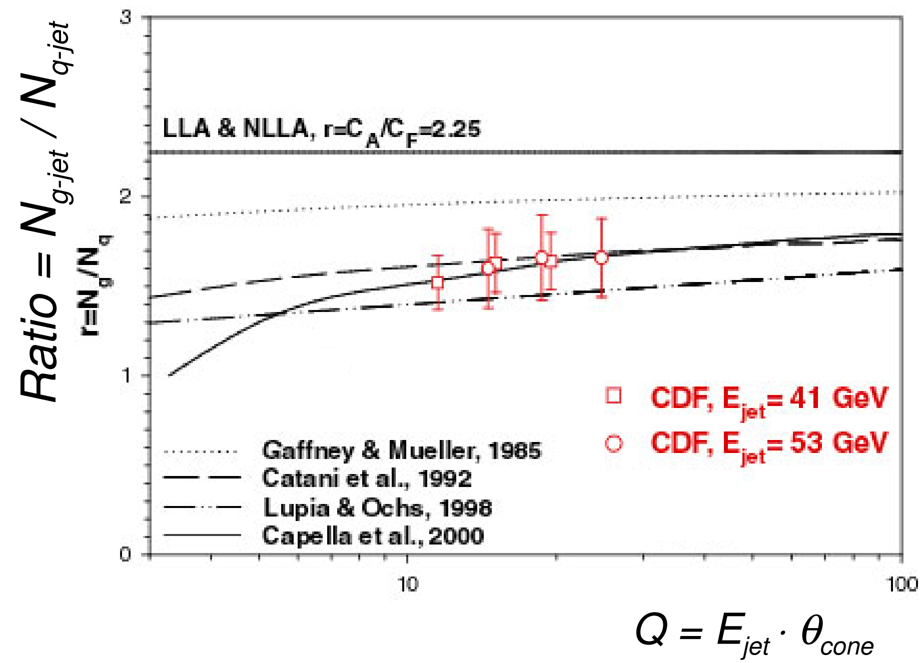
$r = 1.64 \pm 0.17$

at Q~20 GeV

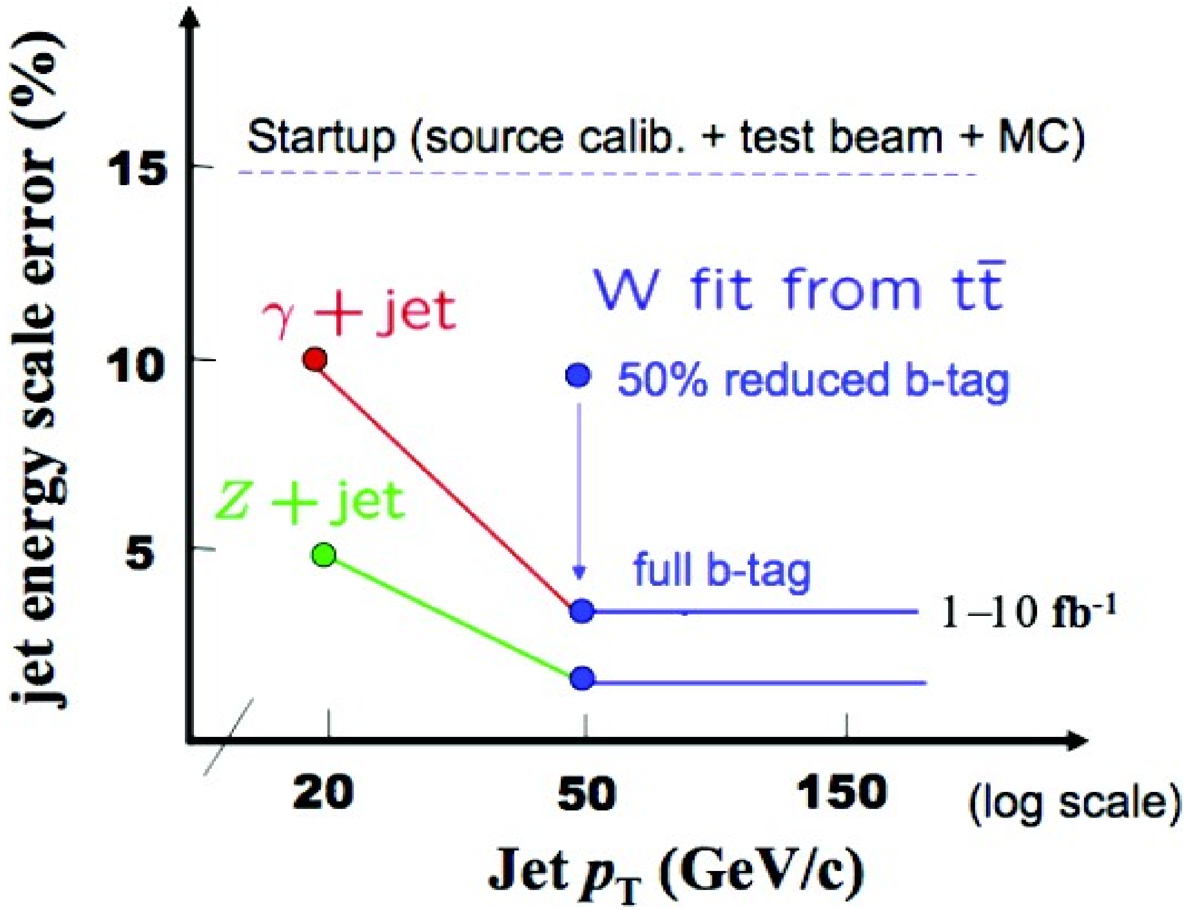
Most recent LEP result (OPAL)

$r = 1.51 \pm 0.04$

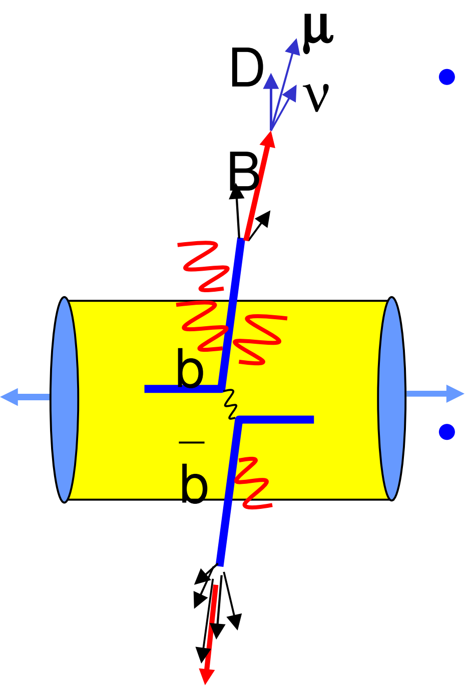
at Q~90 GeV



Jet calibration (p-p)



b-Jet fragmentation



- Radiative energy loss is different for heavy and light quarks.

  Y.L.Dokshitzer and D.E. Kharzeev, hep-ph/0106202

- Reconstruct Jets, tag heavy quark (c,b)-Jets by:
  - Hadronic decay:
    - secondary vertices from charged tracks
  - Leptonic decay:
    - muons with displaced vertices

- compare jet shapes/properties of heavy quark jets and of light quark jets.
  - Exploit parton mass dependence to study parton energy loss mechanism.

Jets in hadronic collisions: discovery (SppS)

Jets seen first in e+e- at PETRA (early 1970s)

- 23 December 1982

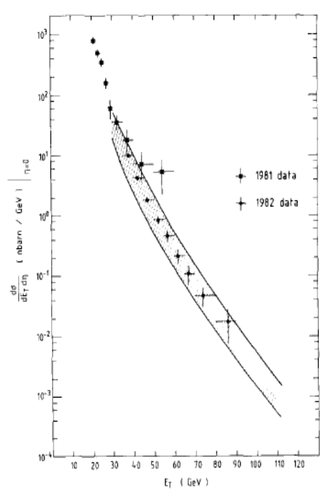
  We measure the inclusive jet cross section with transverse energy up to 60 GeV and the two jet mass up to 120 GeV

  UA1 collab., PLB 123B, 115 (1983)

- 17 August 1983

  A more detailed study out to E_T~100 GeV

  UA1 collaboration, PLB 132B, 214 (1983)



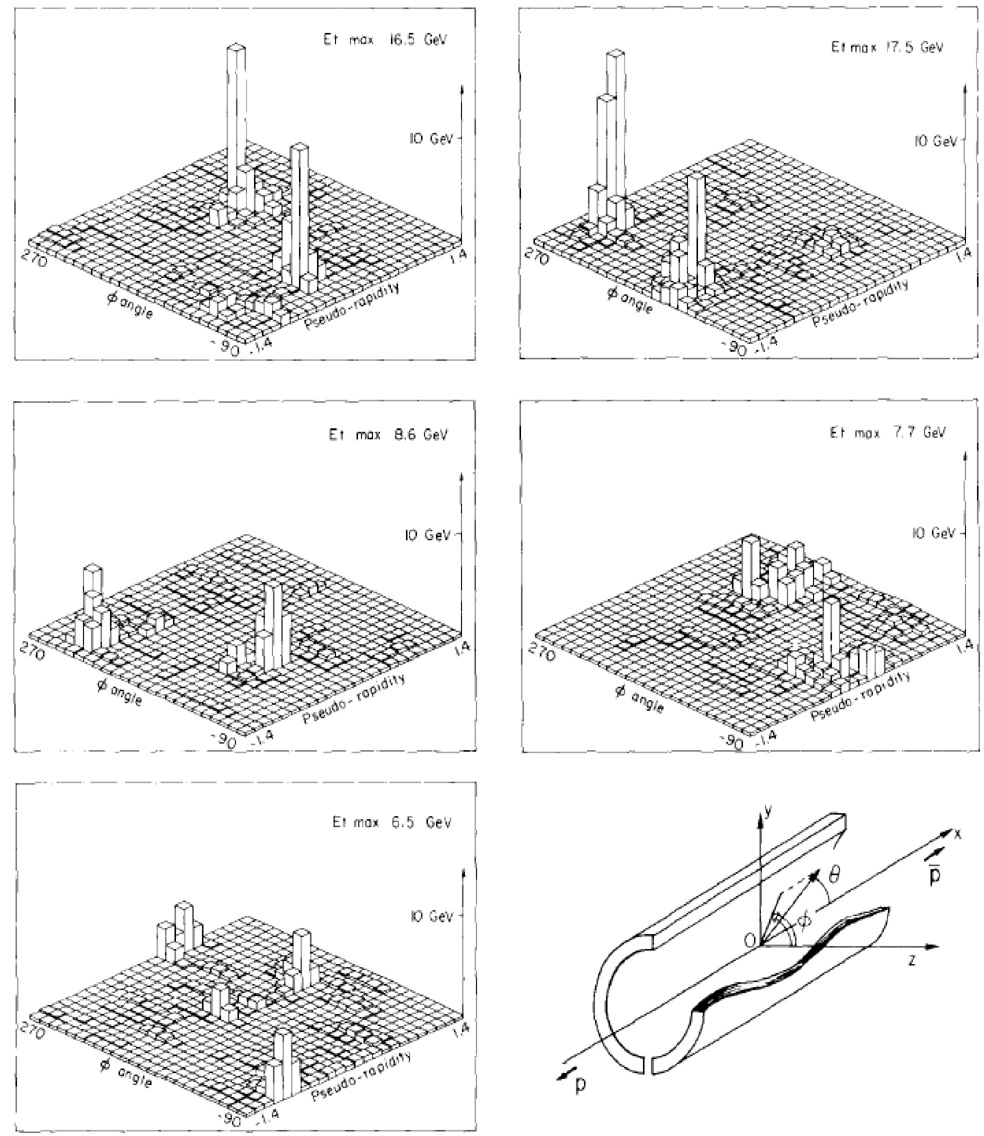


Fig. 3. Distribution of transverse energy versus azimuth ϕ and pseudo-rapidity η, for the five events with the highest ΣE_T.