Jet Reconstruction

and applications…

Mateusz Ploskon

Outline

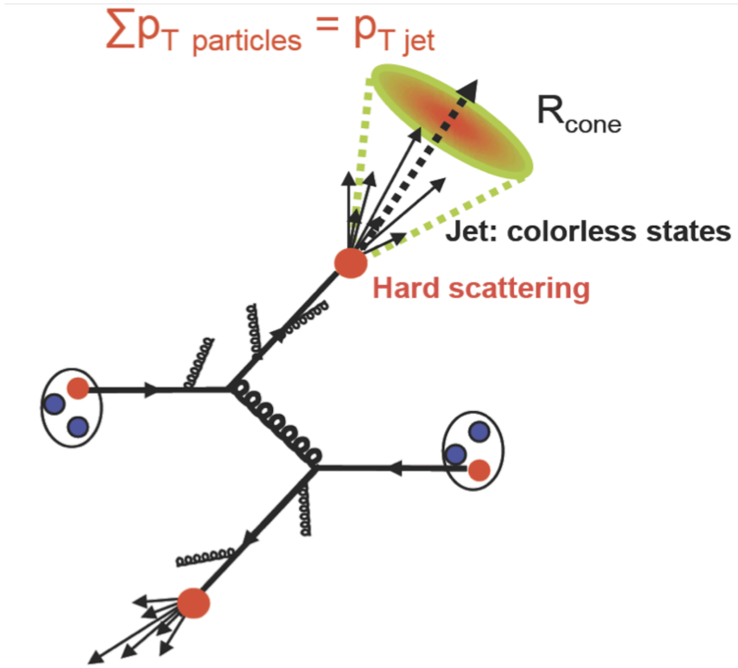
- What is a jet and what does it mean to reconstruct it?
- Jets in elementary, hadronic and HI collisions
- Why to reconstruct jets?
- Utilizing jets in heavy-ion collisions
- Jet related observables
- Outlook

What is a jet?

A spray of collimated showers/particles

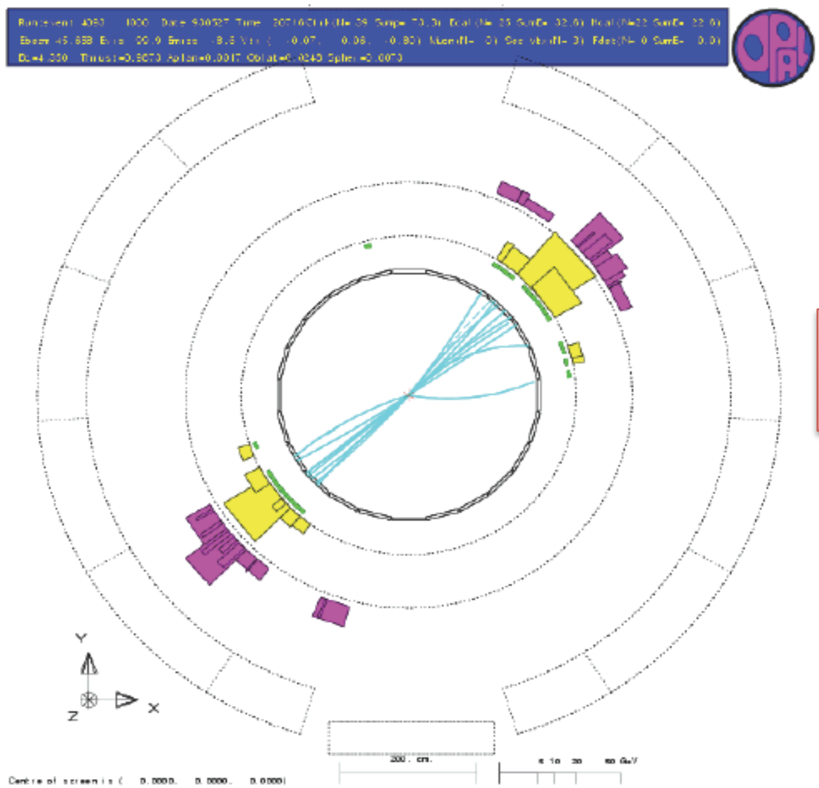
- Hardly ever better defined...

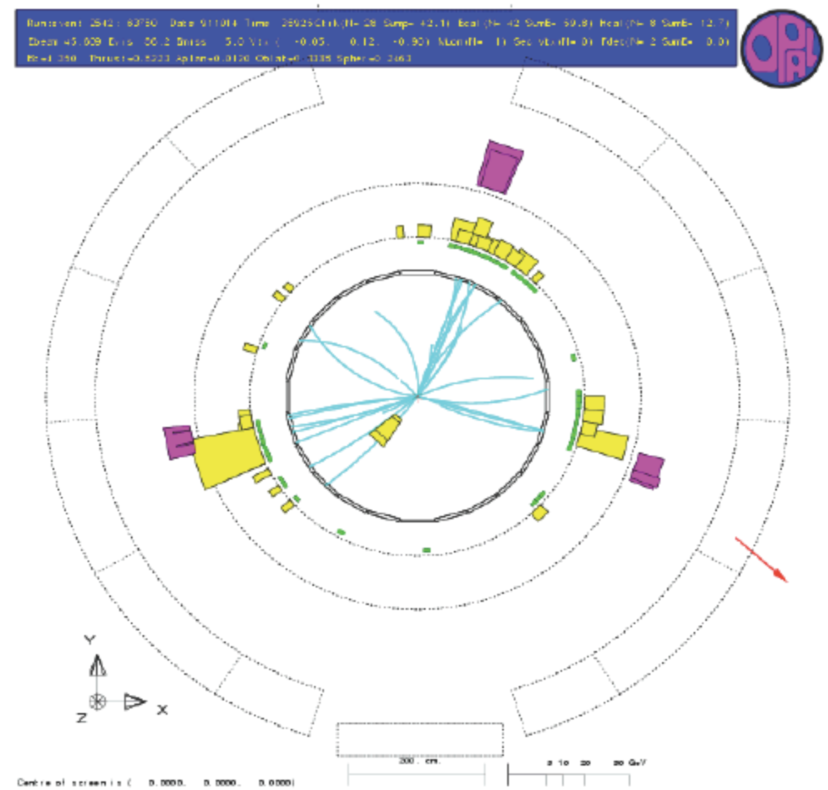
- Direct indication of fragmenting parton
- **Good assumption**: approximate parton/jet energy by reconstructing energy of individual particles/ constituents
- Jets (unlike single hadrons) are objects which are "better" understood/calculable within pQCD



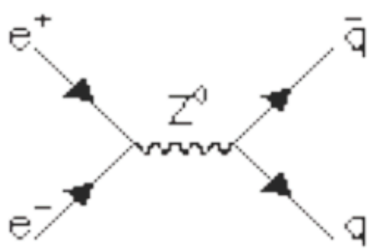
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

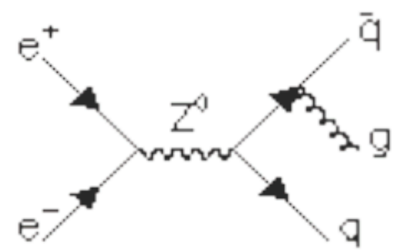
Jets at collider experiments





LEP





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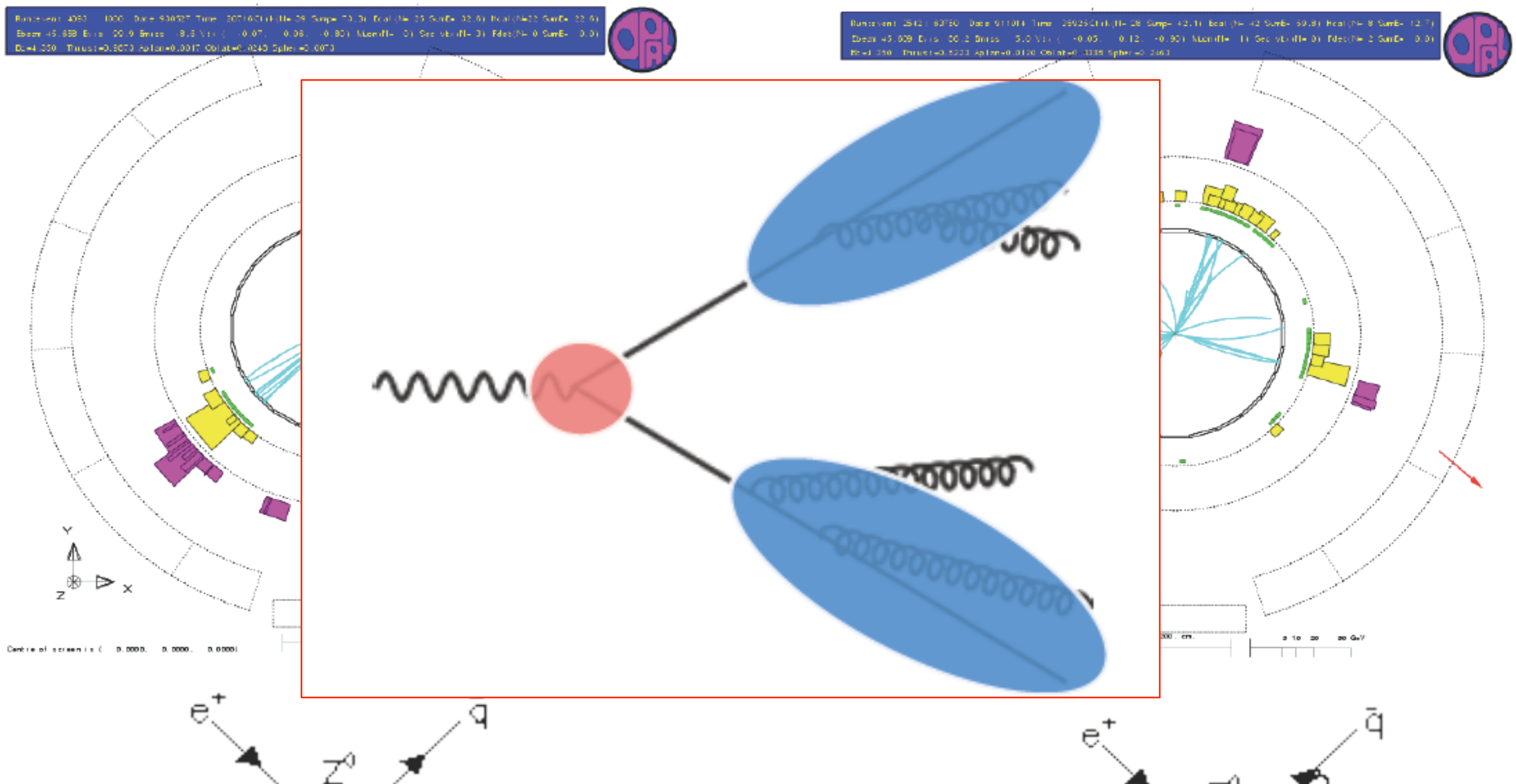
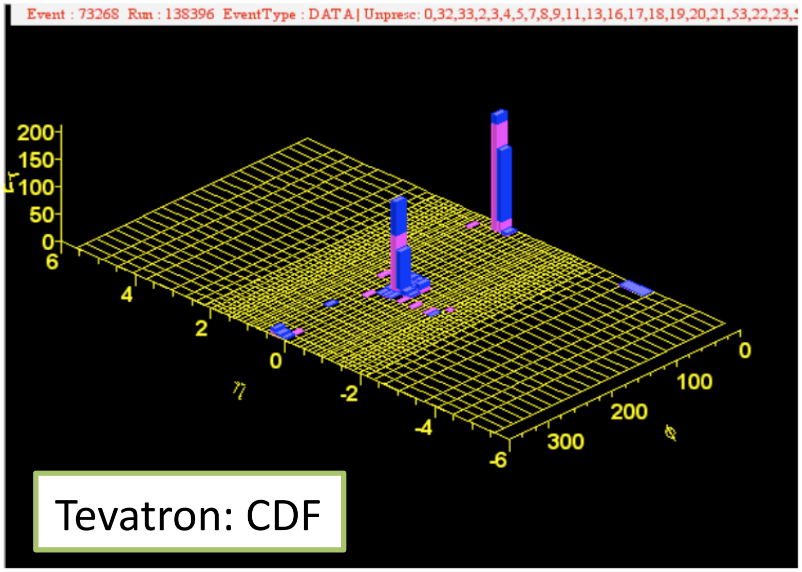


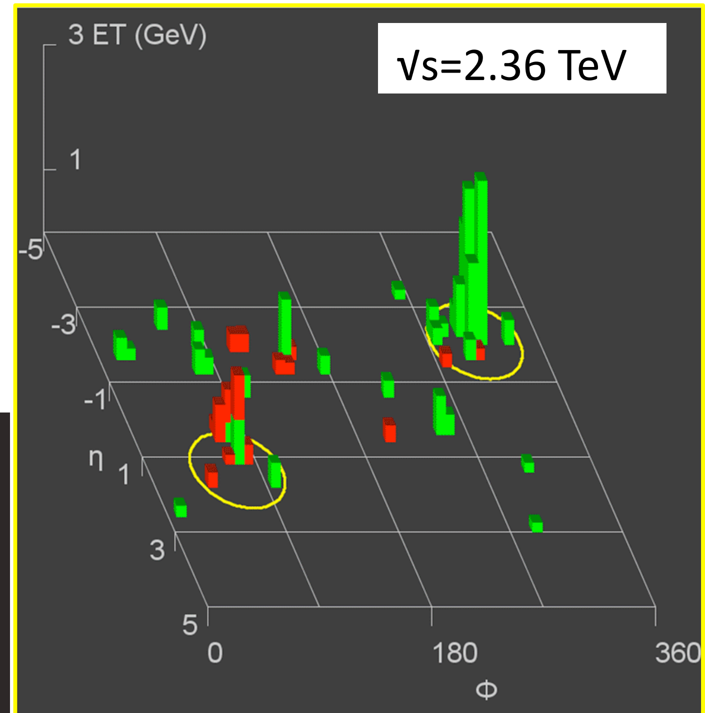
$$\sigma(e^+ + e-) = \sigma(e^+ + e-) \otimes J_1 \otimes J_2$$

Tevatron, RHIC and already at LHC

These are hadron colliders!

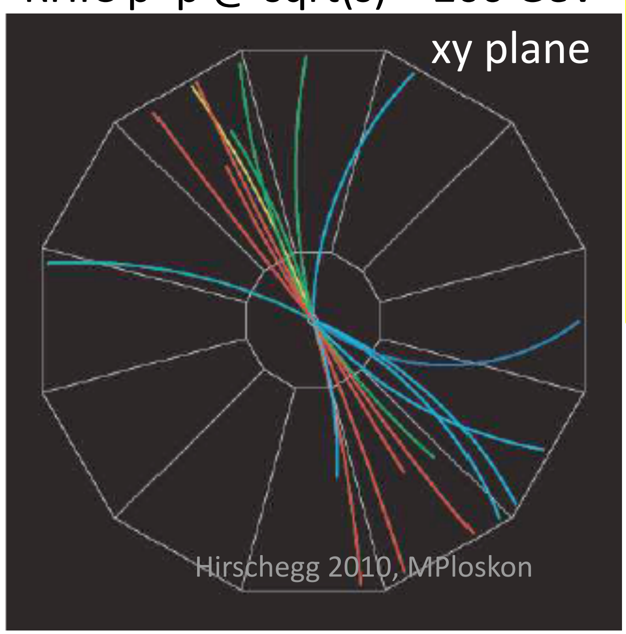


ATLAS Nov/Dec 2009



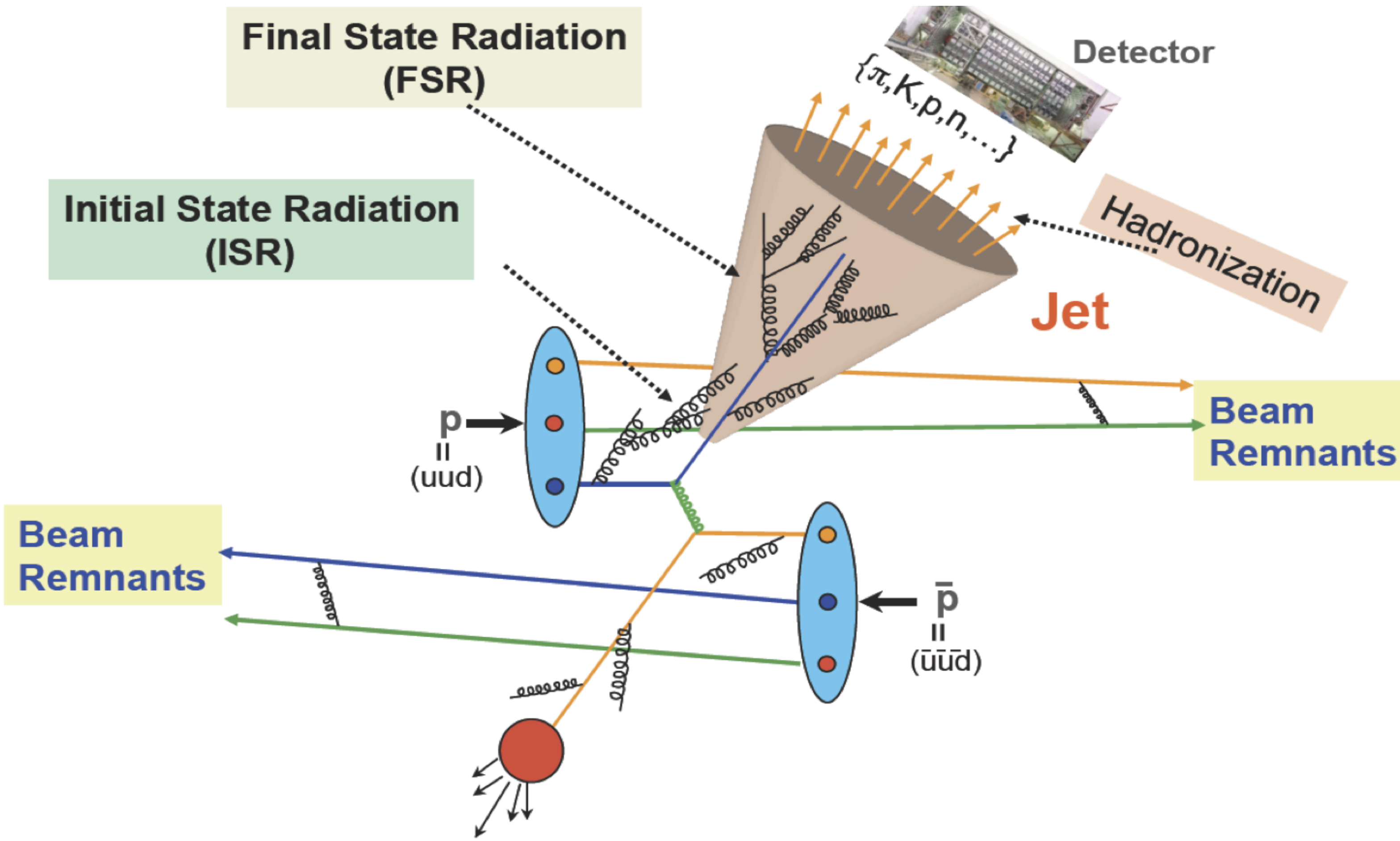
Jet1: E_T (EM scale)~ 16 GeV, $\eta = -2.1$
Jet2: E_T (EM scale) ~ 6 GeV, $\eta = 1.4$

RHIC p+p @ sqrt(s) = 200 GeV



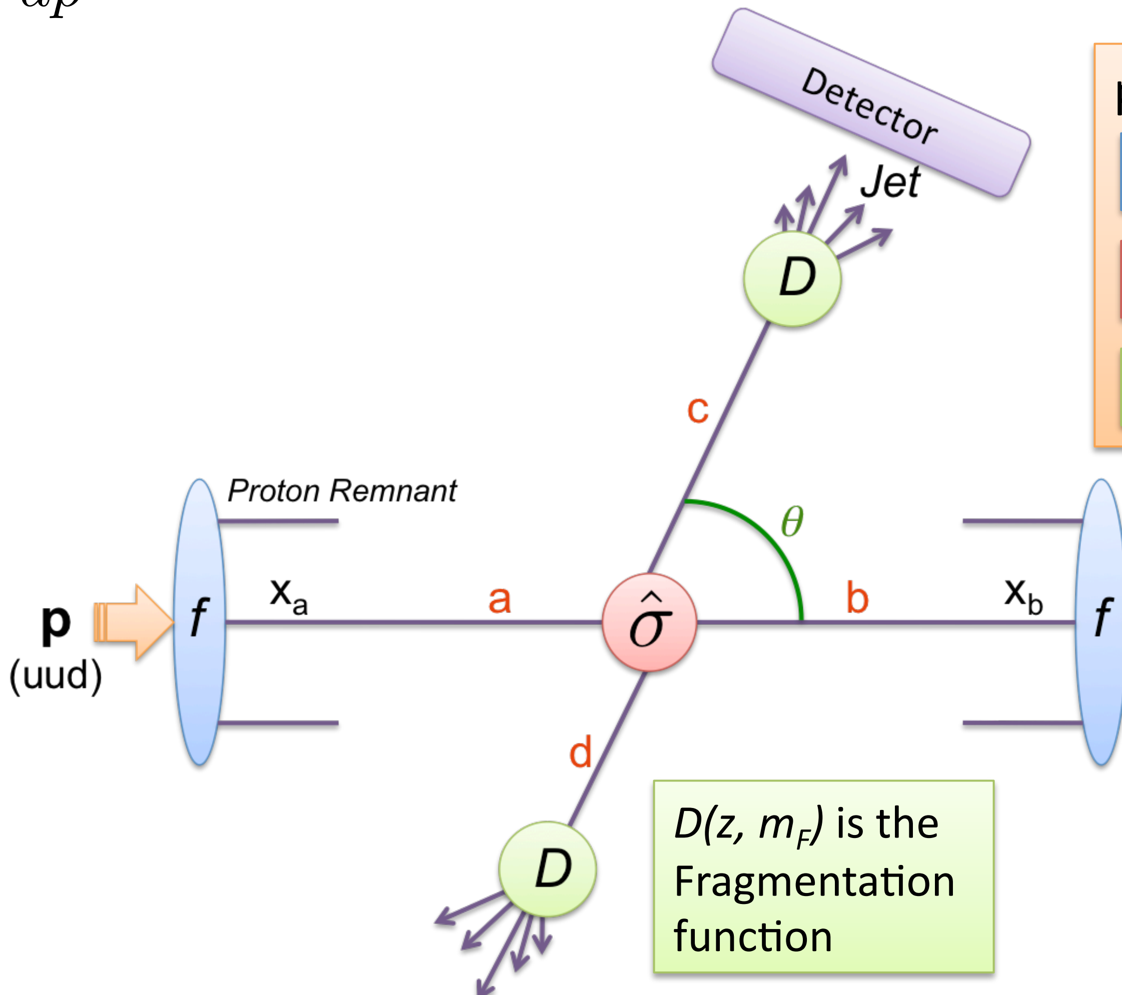
STAR TPC Event Display

What really happens in hadronic collisions…



Hadronic collisions and pQCD

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a,Q^2) \otimes f_{b/B}(x_b,Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c,Q^2)$$

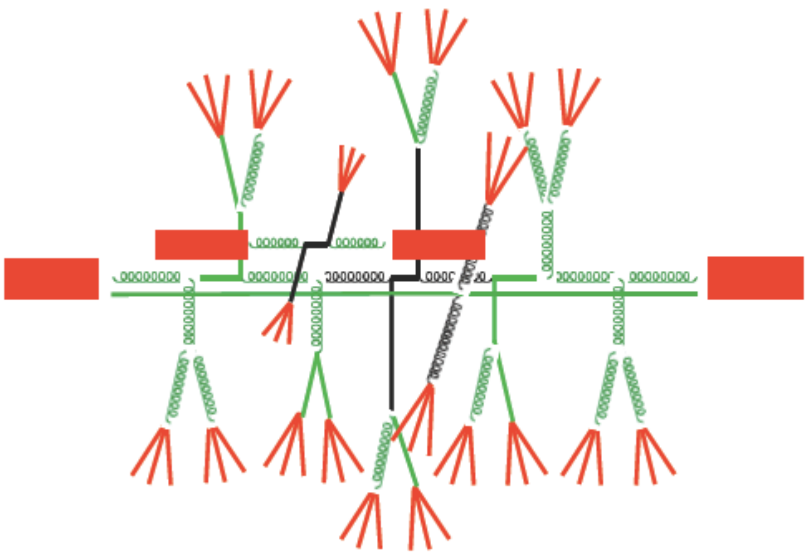


pQCD factorization:

- parton distribution fn $f_{a/A}$
- partonic cross section
- fragmentation fn $D_{h/c}$

D(z, m_F) is the Fragmentation function

Hadronic collisions and interaction at different scales



- Distance scale set by $d \sim 1/s$
- Distance scale set by $d \sim 1/m_J$
- Distance scale set by $d \sim 1/\Lambda$
- Various scales involved

Theory needs to answer how to isolate perturbative piece (jet finding algorithm has to identify it).

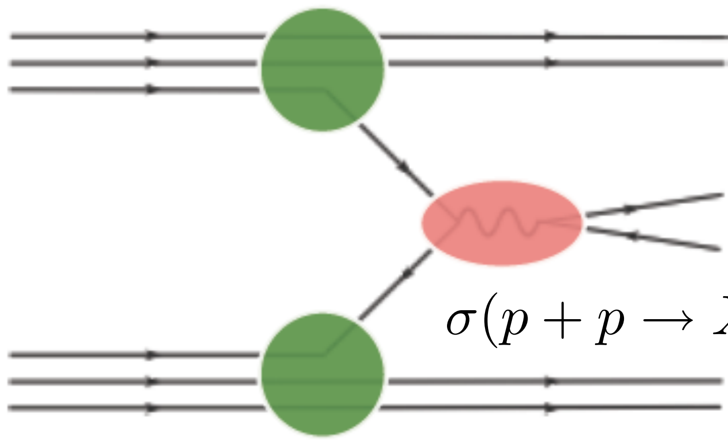
Why jets?

- Complete jet reconstruction (in terms of energy flow at a given resolution scale)
  - Significantly reduces uncertainties (fragmentation)
  - Allows for much better comparison/understanding of experimental results with theory

$$\frac{d\sigma}{dp_T} = (PDF) \otimes (hard\ x - sec) \otimes (fragmentation)$$

$$\frac{d\sigma}{dp_T} = (PDF) \otimes (hard\ x - sec)$$

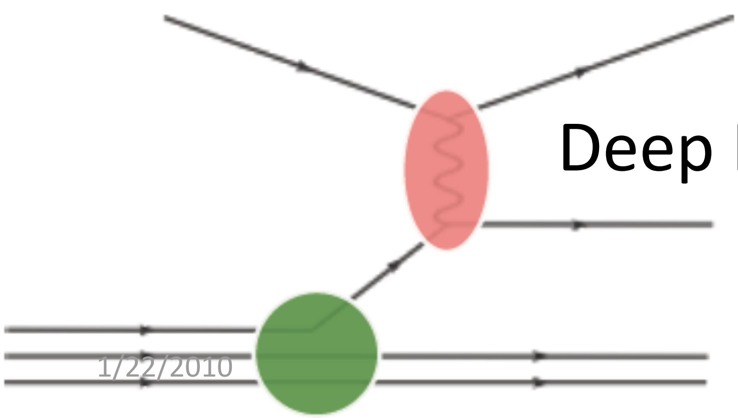
Examples of h-h processes calculable within pQCD



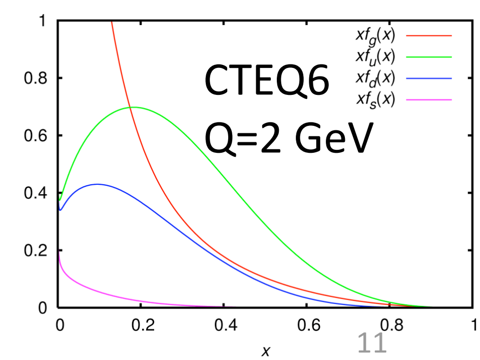
Drell-Yan

$$\sigma(p+p \rightarrow X + e^{+} + e-) = f_q \otimes f_q \otimes \sigma(q+q \rightarrow e^{+} + e-)$$

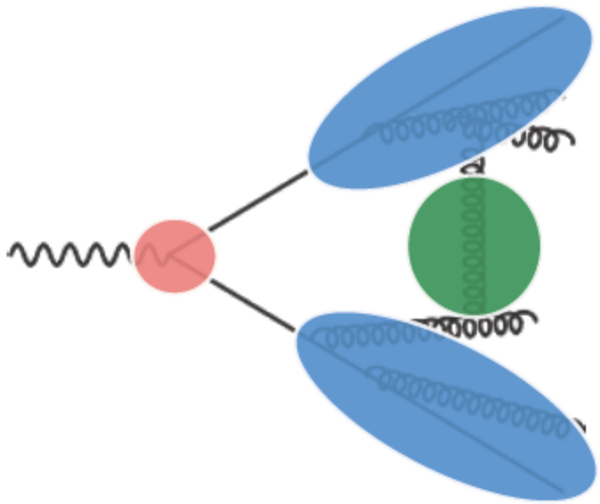
$$\sigma(p+e^{-} \rightarrow X + e-) = f_q \otimes \sigma(q+e^{-} \rightarrow q + e-)$$



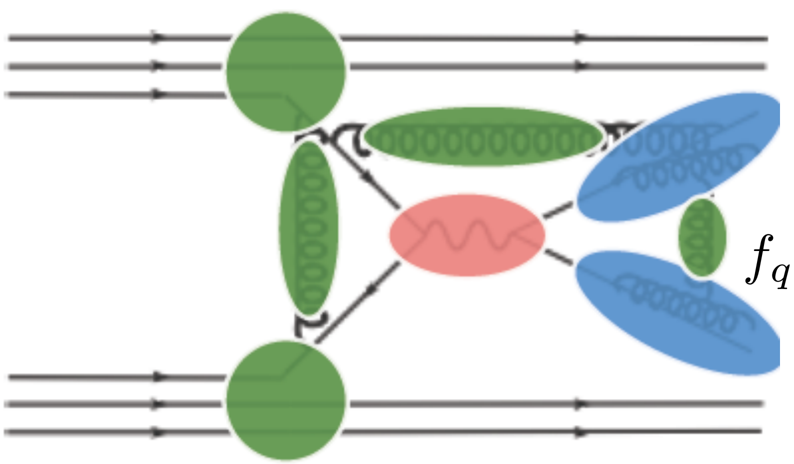
Deep Inelastic Scattering



Event shape studies



$$\sigma(e^+ + e^- \rightarrow hadrons) =$$
$$\sigma(e^+ + e^- \rightarrow q + q) \otimes J_1 \otimes J_2 \otimes \boxed{S}$$



$$\sigma(p^+ + p^- \rightarrow jets) =$$
$$f_q \otimes f_q \otimes \sigma(q^+ + q^- \rightarrow q + q) \otimes J_1 \otimes J_2 \otimes \boxed{S}$$

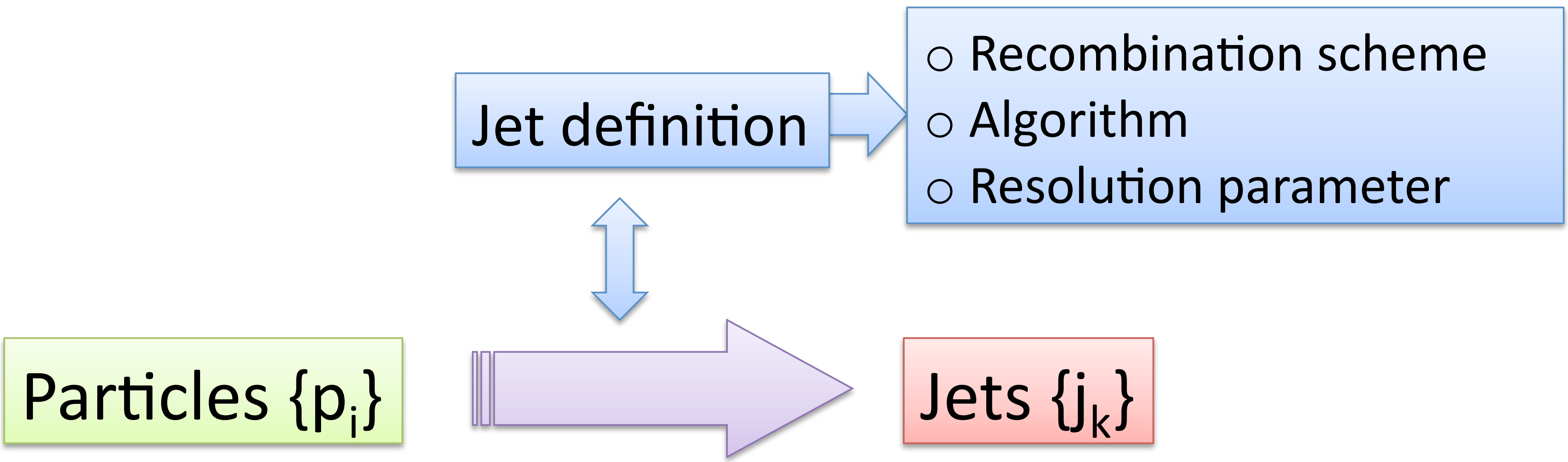
Focus of this talk

$$\sigma(h + h \rightarrow jet + X) =$$
$$f_q \otimes f_q \otimes \sigma(q + q \rightarrow jet + X) \otimes J$$

Properties of jet finding
-> Jet definition

Finding jets

Finding jets



Note: jets=hard partons, however definition of a parton in terms of a jet is ambiguous -> multiple jet definitions.

Optimum jet finder algorithm

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Tevatron 1990

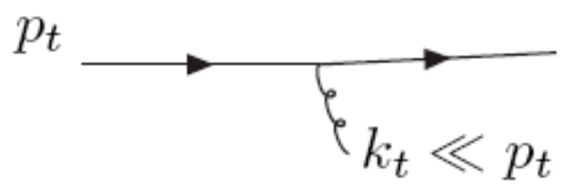
QCD divergences and jet finders

QCD probability for gluon bremsstrahlung at angle θ and $\perp$-mom. k_t:

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:

Collinear



Soft

For pQCD to make sense, the (hard) jets should not change when

- one has a collinear splitting
  i.e. replaces one parton by two at the same place (η, ϕ)
- one has a soft emission *i.e.* adds a very soft gluon

More on jet finders

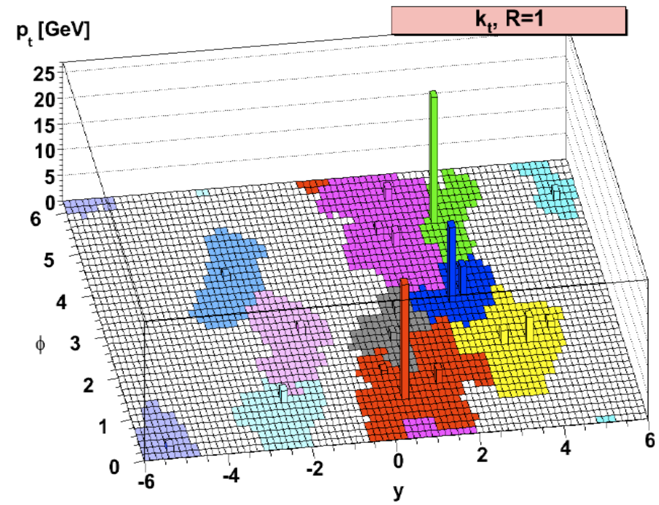
- Some "bad" jet properties
  - Multiplicity (not well understood in theory and not easily measured)
  - Charge (pair from vacuum dilutes significance; fractional q charge)
- Jet equivalence:

$$J(\overrightarrow{p}_{partons}) \approx J(\overrightarrow{p}_{shower}) \approx J(\overrightarrow{p}_{hadrons}) \approx J(\overrightarrow{p}_{cells/tracks})$$

- Jets are four-vectors with mass
  - *modulo p-recombination scheme*
- Different algorithms give/may different answers
  - However, if analysis is very sensitive to algorithm – something must be wrong(!) – *still a learning curve in HI*
- Jet size is process dependent(!) – need theory input on optimal size (resolution parameter).

Modern algorithms

- Colinear and infrared safe
- Improved performance
- Rigorous definition of jet area
- Different algorithms -> different response to the underlying event
  - Developed for uniform bg subtraction (pile-up) at LHC



M. Cacciari, G. Salam, G. Soyez

$$p_T^{jet} = p_T^{cluster} - \rho \times Area$$

Two main classes of algorithms: recombination (kt, Cambridge/Aachen, anti-kt) and cone (Mid point cone, CDF, SIScone)

Example: Kt-like algorithms

1.1 k_t jet algorithm

The definition of the inclusive k_t jet algorithm that is coded is as follows:

1. For each pair of particles i, j work out the k_t distance

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\, \Delta R_{ij}^2 / R^2 \quad (1)$$

   with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where k_{ti}, y_i and ϕ_i are the transverse momentum, rapidity and azimuth of particle i and R is a jet-radius parameter usually taken of order 1; for each parton i also work out the beam distance $d_{iB} = k_{ti}^2$.

2. Find the minimum $d_{\min}$ of all the d_{ij}, d_{iB}. If $d_{\min}$ is a d_{ij} merge particles i and j into a single particle, summing their four-momenta (this is E-scheme recombination); if it is a d_{iB} then declare particle i to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.

Anti-kt: k_t^2 is replaced by k_t^{-1}

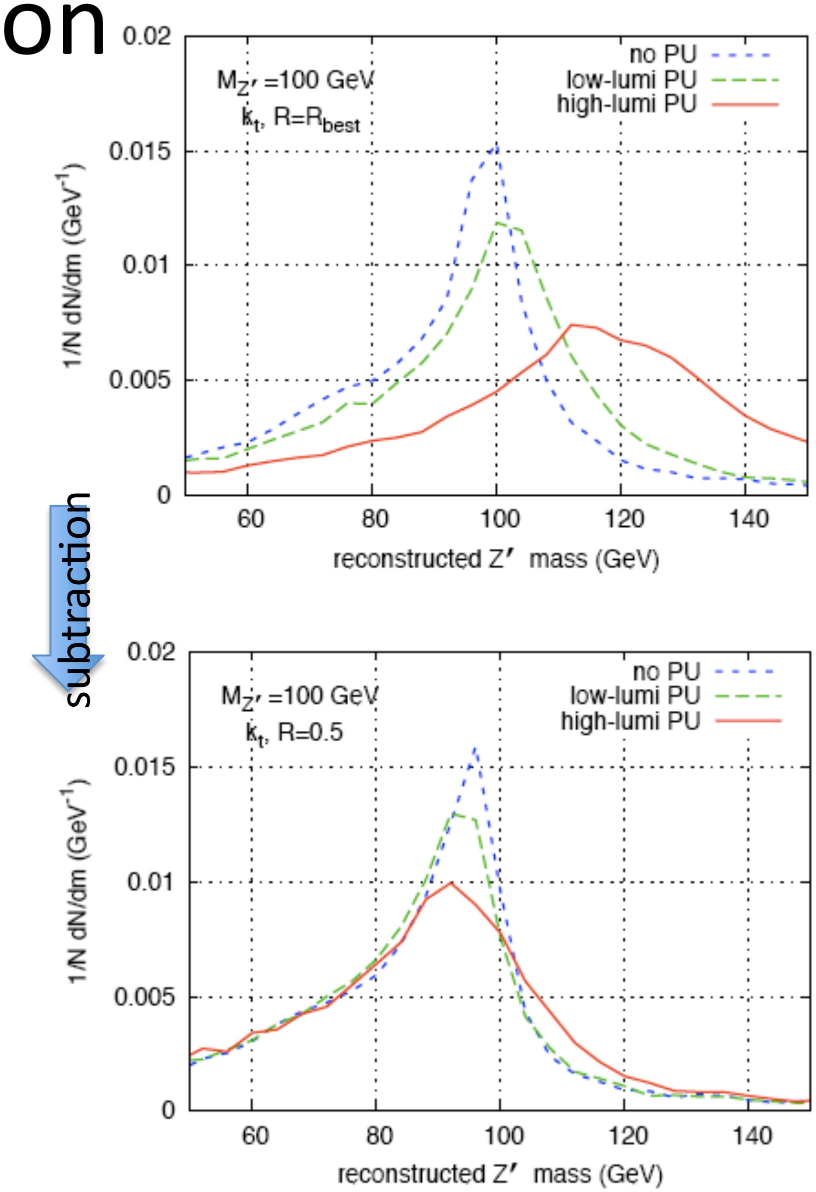
M. Cacciari, G. P. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]

Background subtraction

$$p_T^{jet} = p_T^{cluster} - \rho \times Area$$

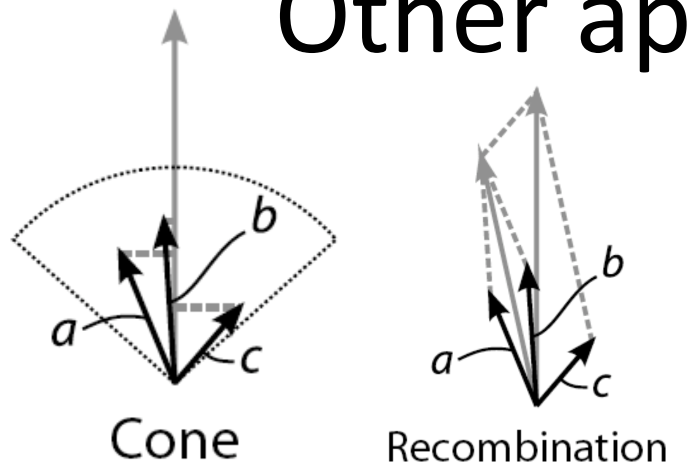
$$p_T^{jet} = p_T^{true} \otimes \delta\rho$$

- ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm
- A: area of the jet – measured using number of artificially injected infinitely soft particles of finite *"size"* into an event that are clustered into the jet
- δρ: uncertainty due to noise fluctuations – non-uniformity of the event background

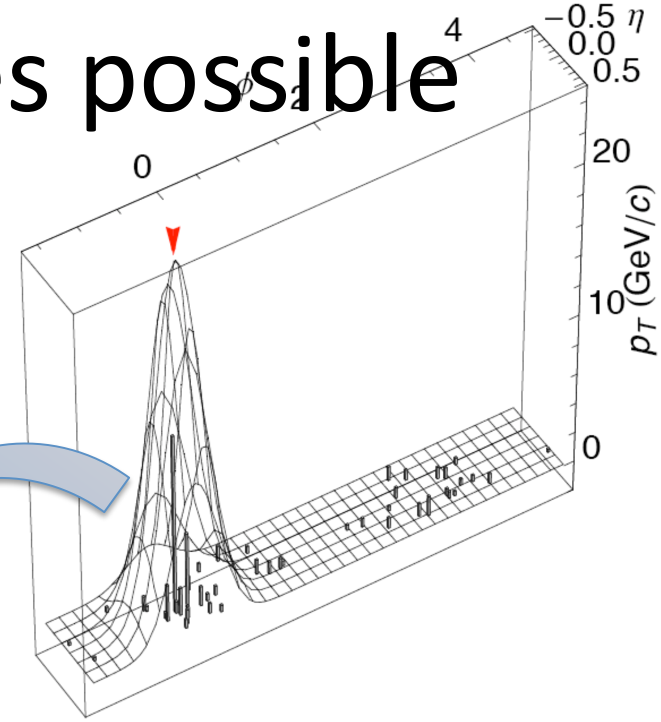


M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

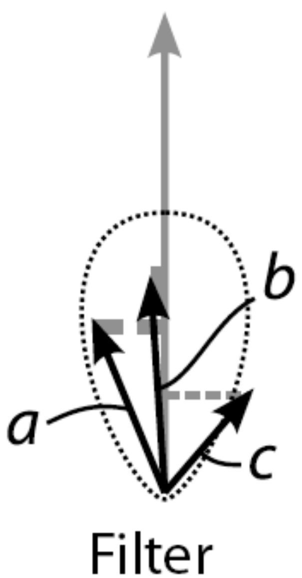
Other approaches possible



Yui Shi Lai, arXiv:0806.1499, QM 2009



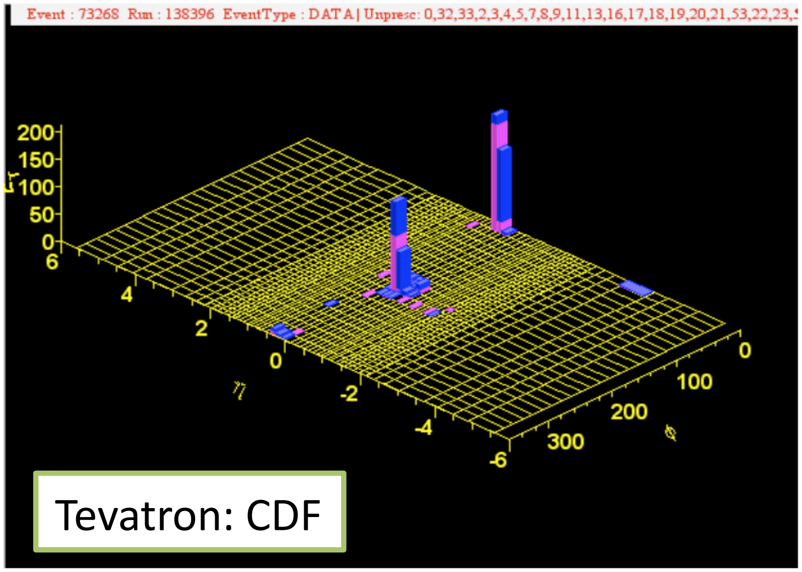
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta',\varphi') \exp\left[-\frac{(\eta-\eta')^2+(\varphi-\varphi')^2}{2\sigma^2}\right] = \text{max!}$$



- Seedless, infrared and collinear safe
- Optimizes S/B (focus on the "core" of the jet)
- Robust against background

Results from PHENIX

Tevatron, RHIC and already at LHC



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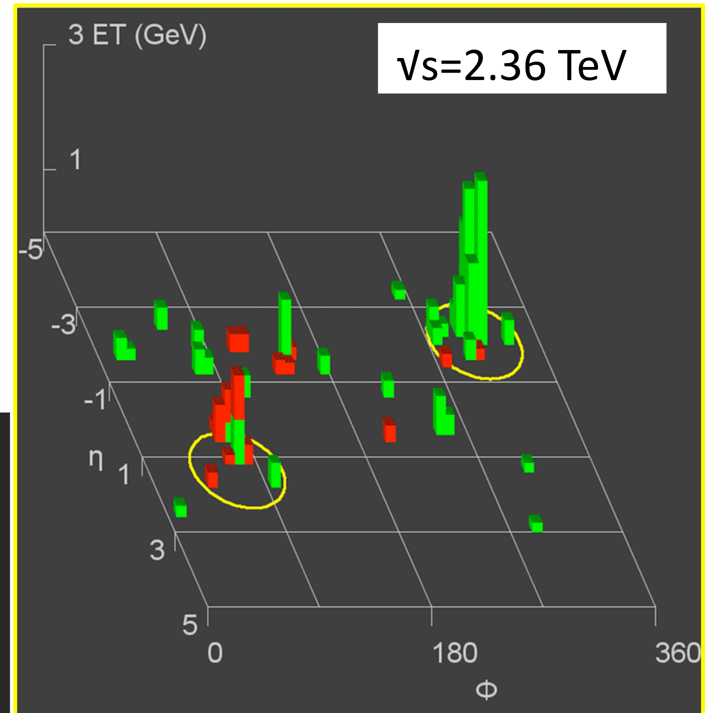

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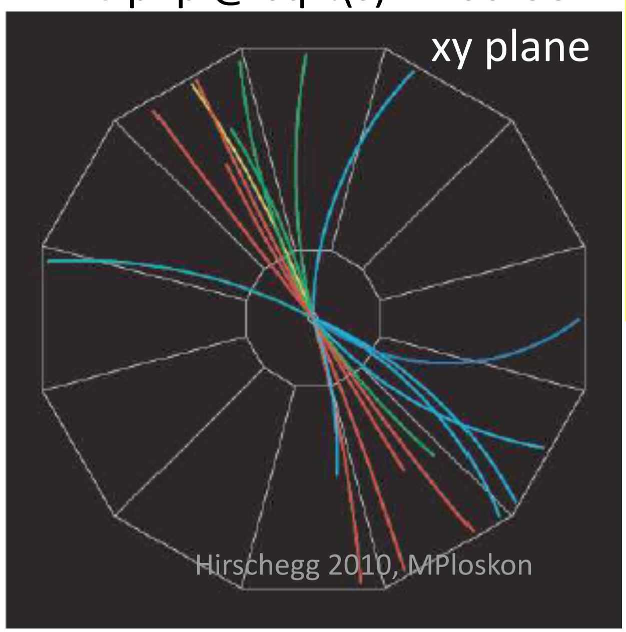
STAR TPC Event Display

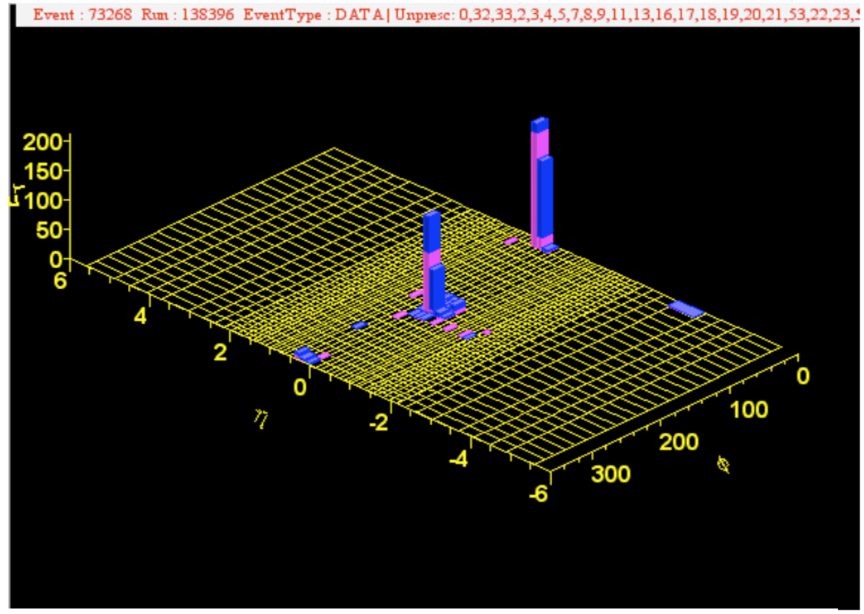


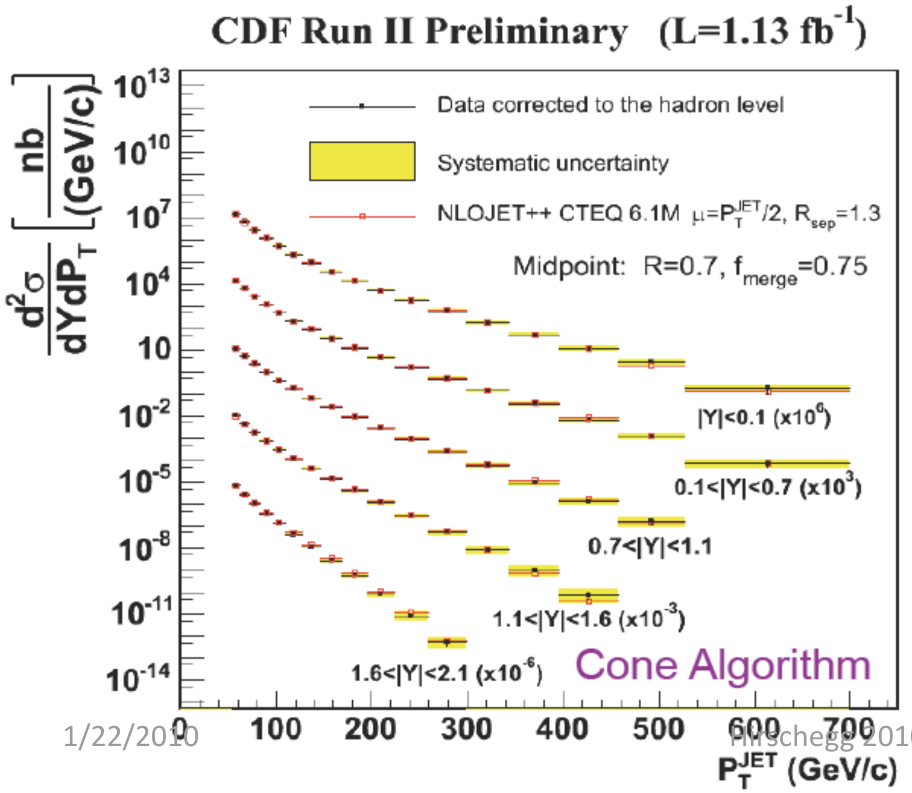
Testing/exercising the theory…

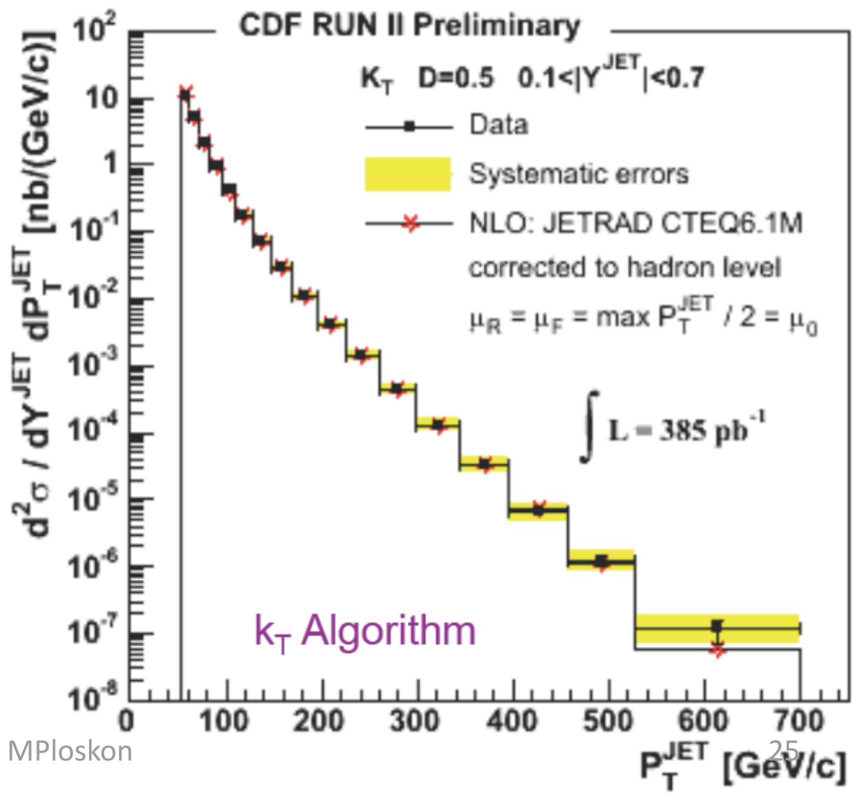
Tevatron

Very good agreement with NLO pQCD

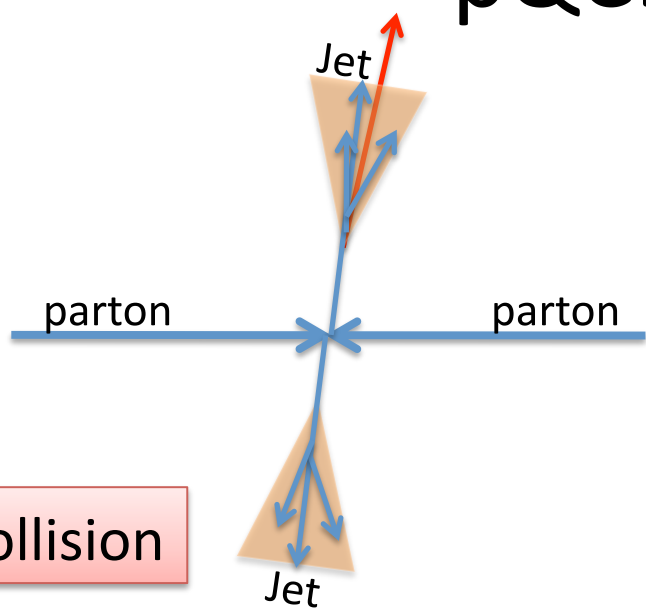
Multiple algorithms used converging to consistent results







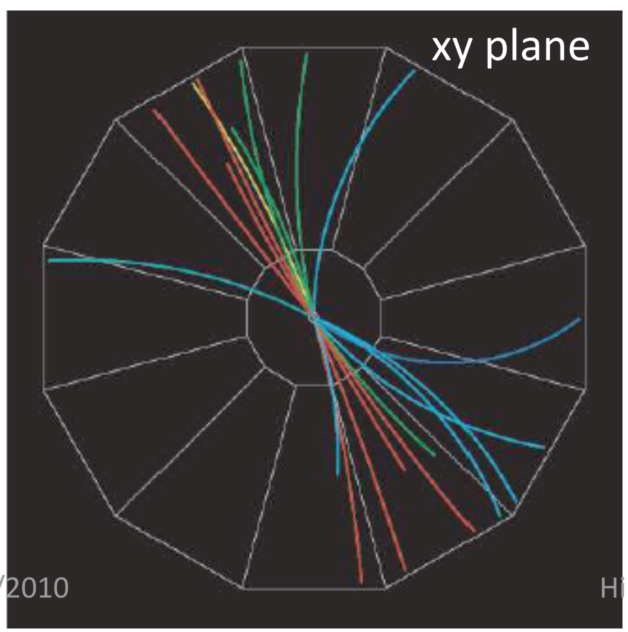
pQCD at RHIC

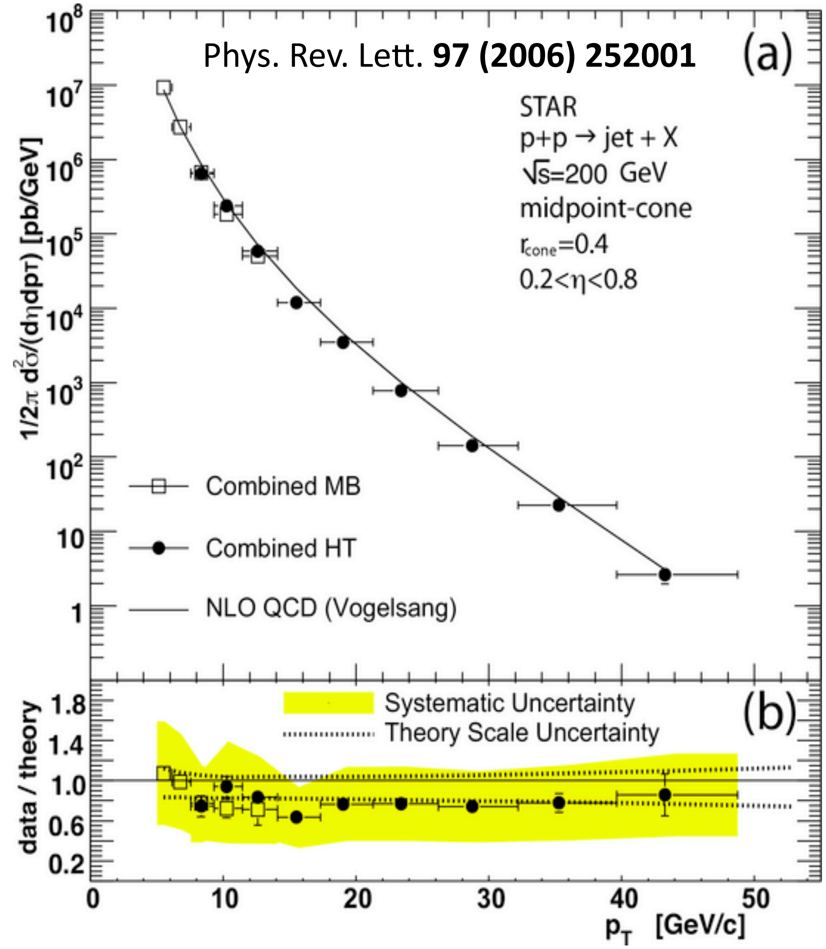


p+p collision

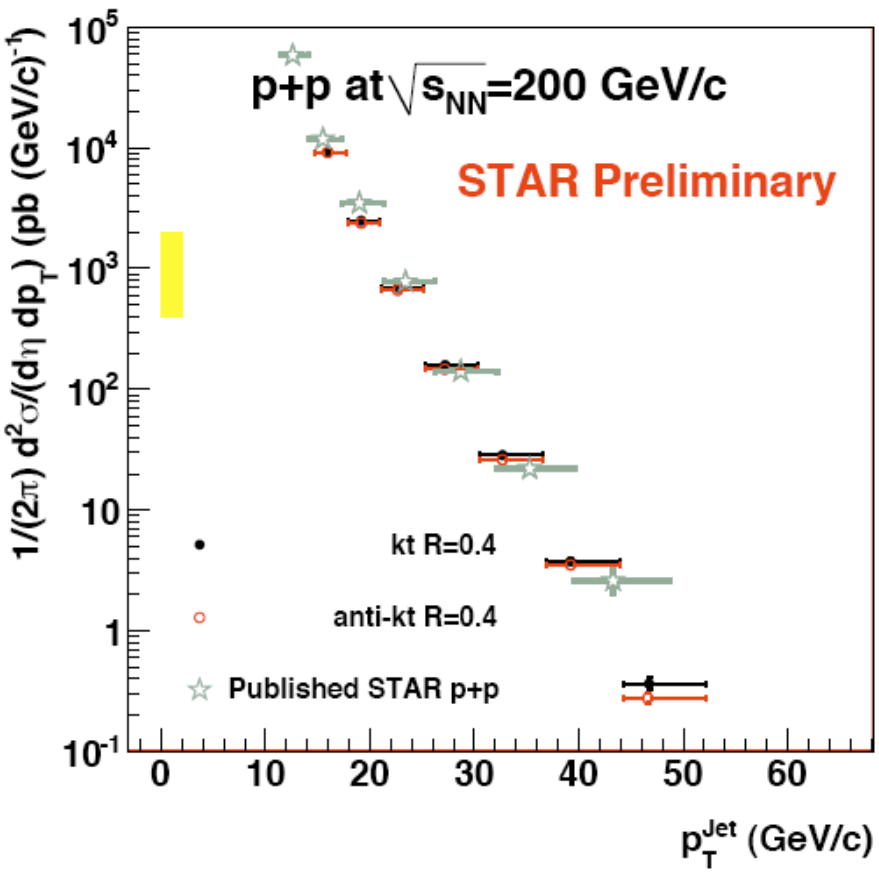
$$d\sigma \propto (PDF) \otimes (HARD)$$

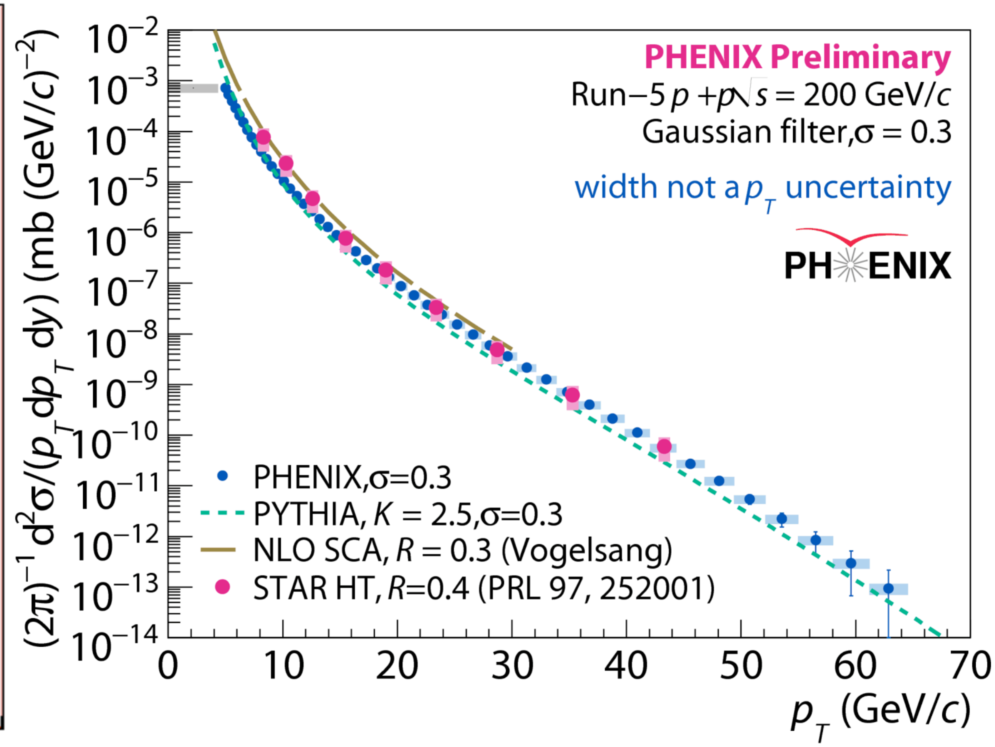
STAR TPC Event Display





Jet cross-sections in p+p at RHIC





p+p: Cross-section ratio R=0.2/R=0.4

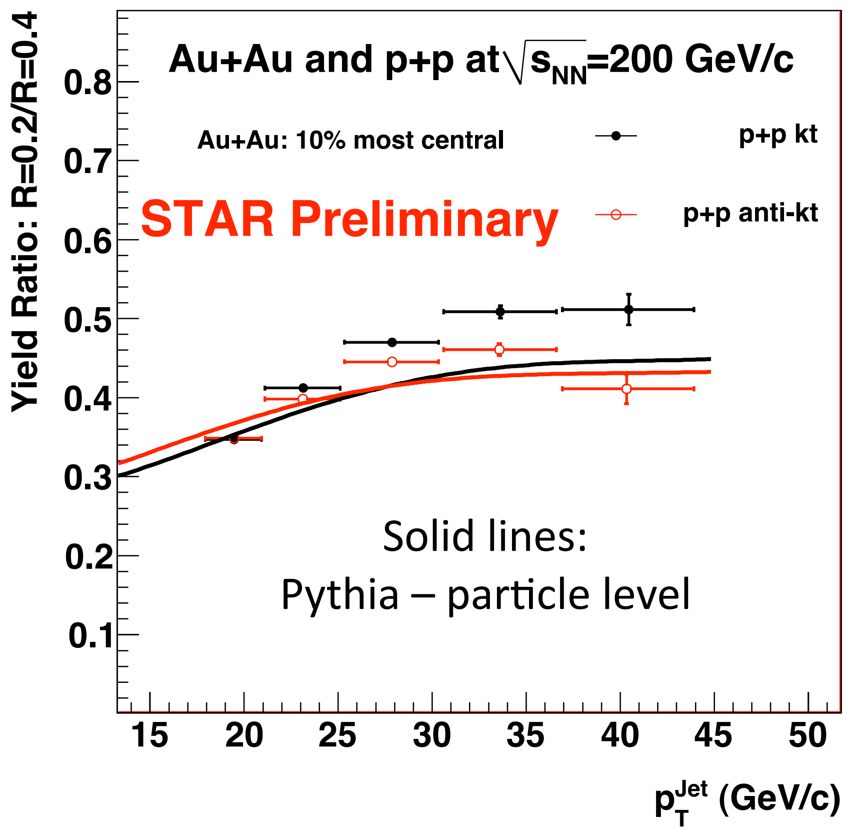
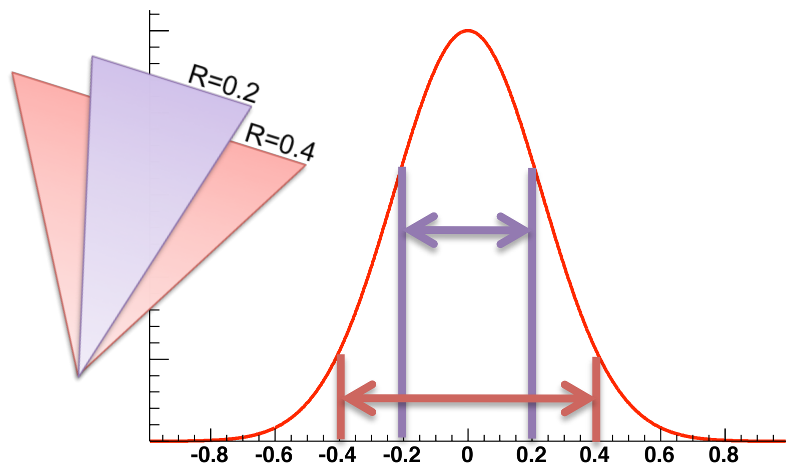
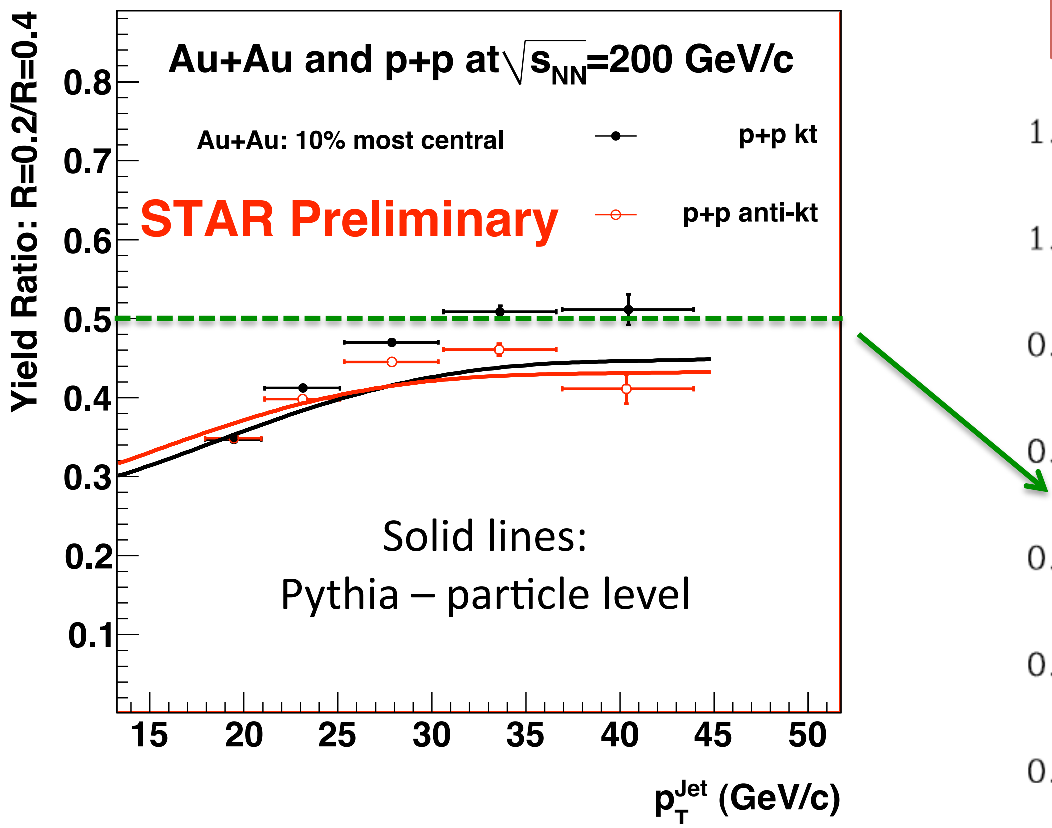


Illustration: Gaussian 1D profile



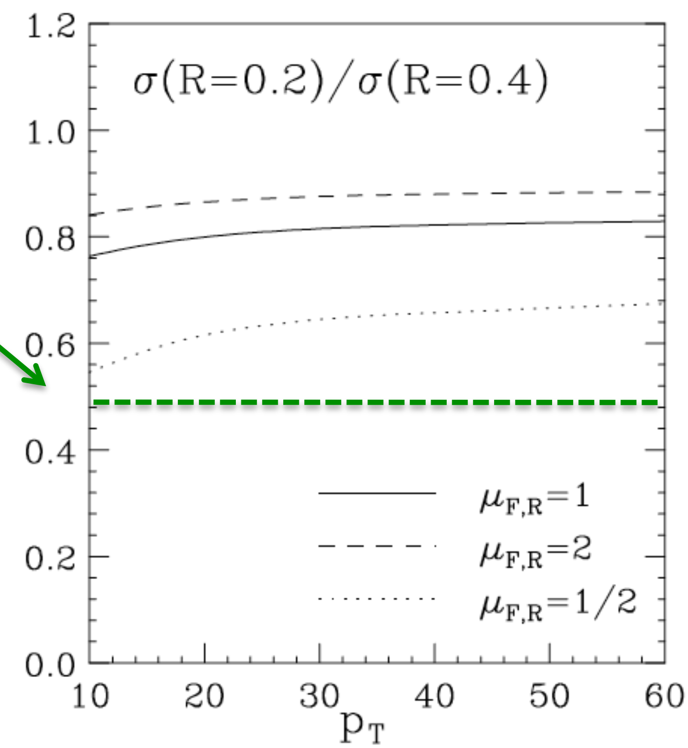
p+p: "Narrowing" of the jet structure with increasing jet energy

p+p: cross-section ratio R=0.2/R=0.4



Narrowing of structure with increasing energy

NLO Calculation
W. Vogelsang – priv. comm. 2009



NLO: narrower jet profile
→hadronization effects?

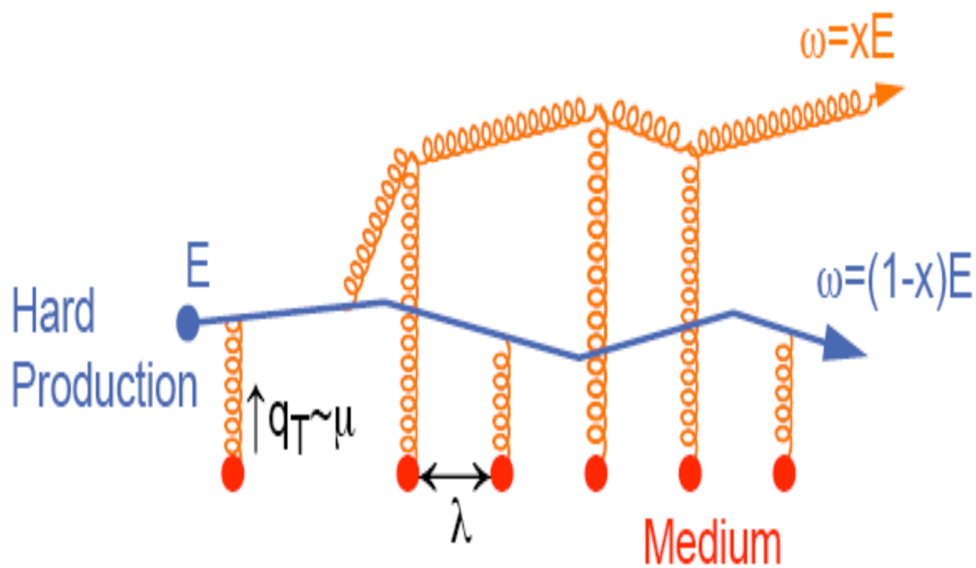
What happens in HI collisions?

Jet-medium interaction

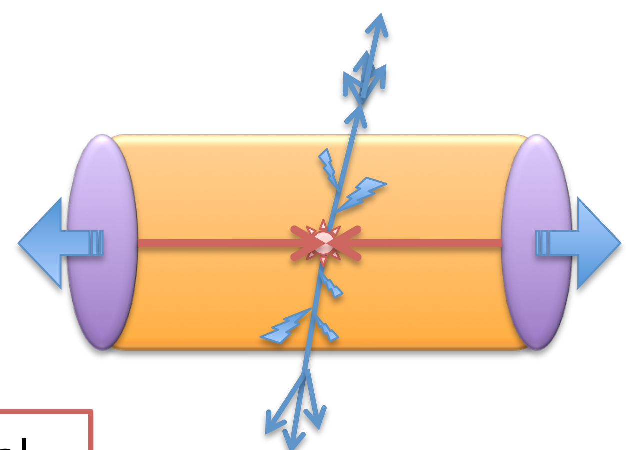
QED: Bremsstrahlung is dominant energy loss mechanism at high energy limit

QCD: High energy partons lose energy via gluon radiation (QCD bremsstrahlung)

Medium characterized by the transport coefficient qhat: squared momentum transfer per unit length (mean free path)

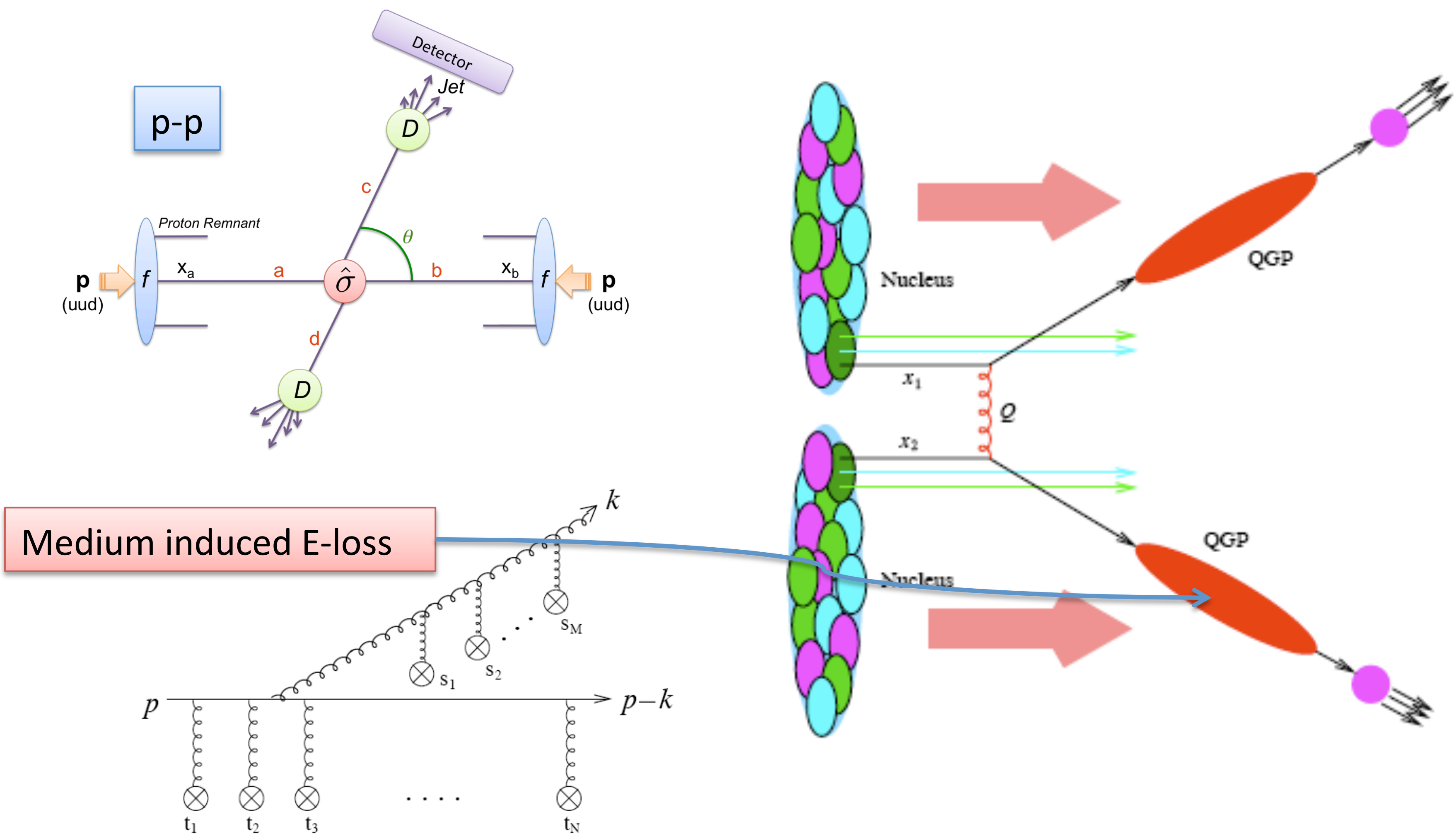


$$\hat{q} \sim \mu^2/\lambda$$



Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

Factorization in HI collisions

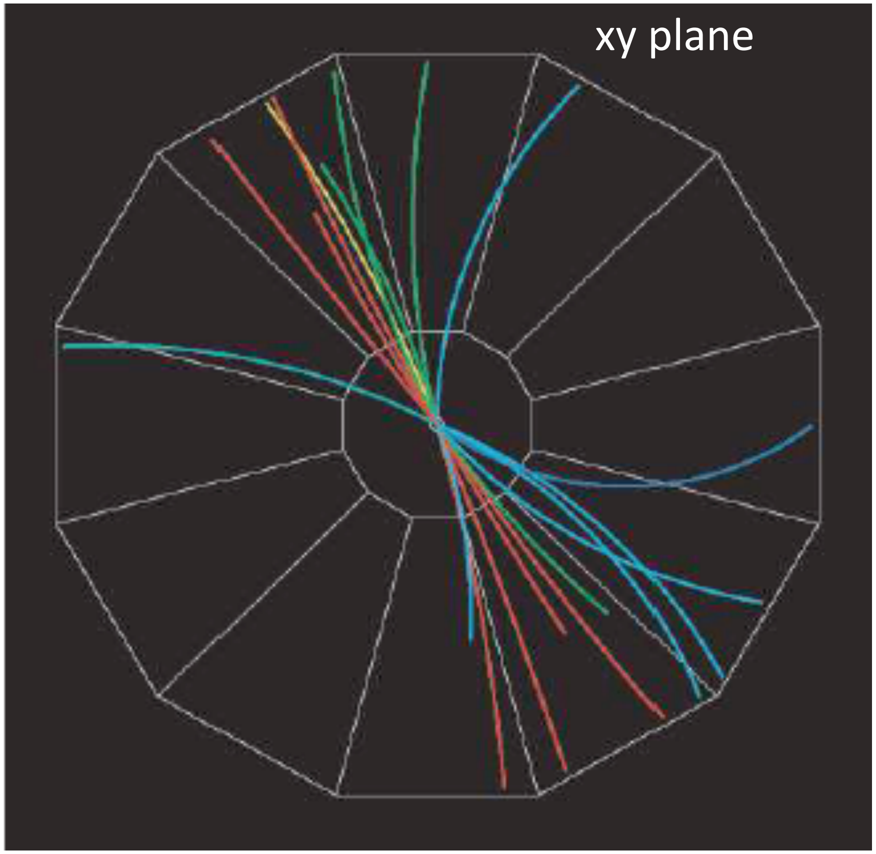


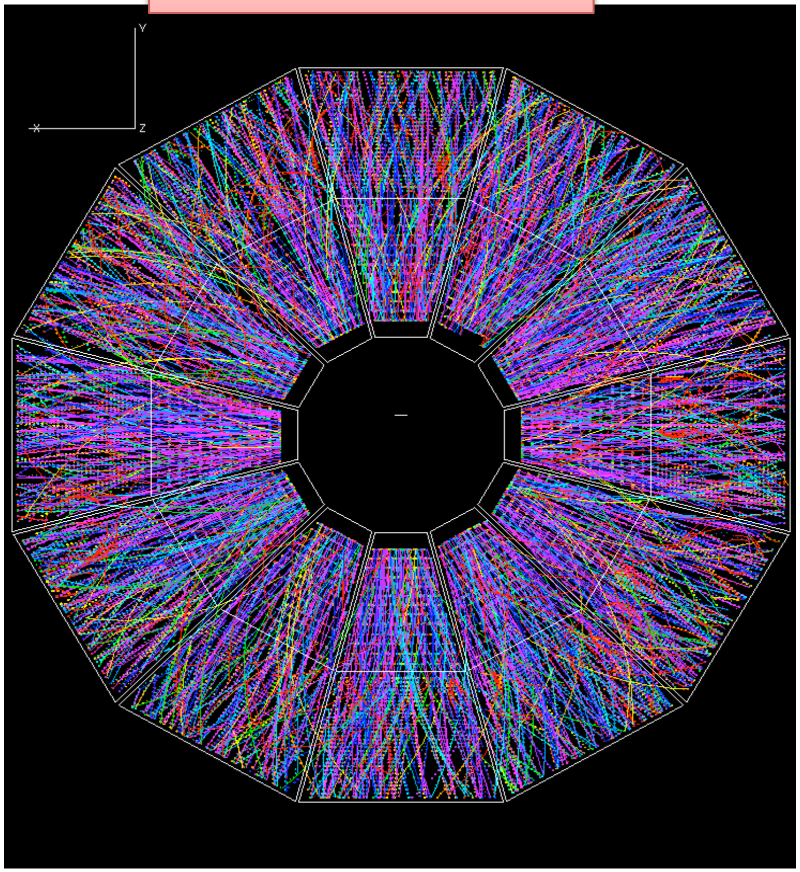
Finding jets?

p+p Collision

Au+Au Collision

STAR TPC Event Display



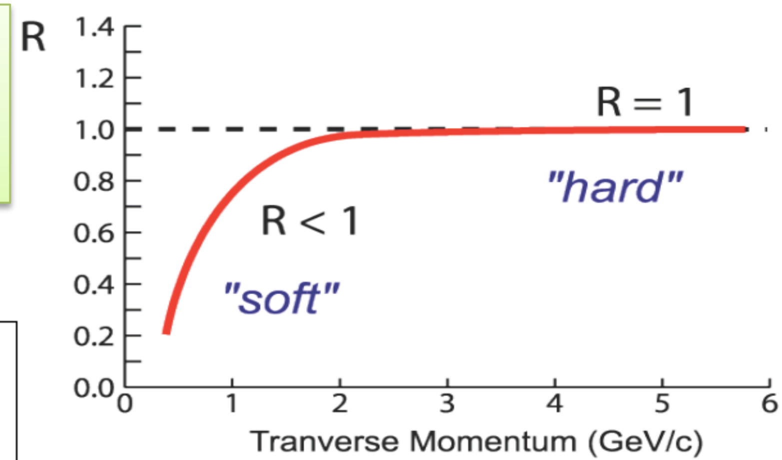


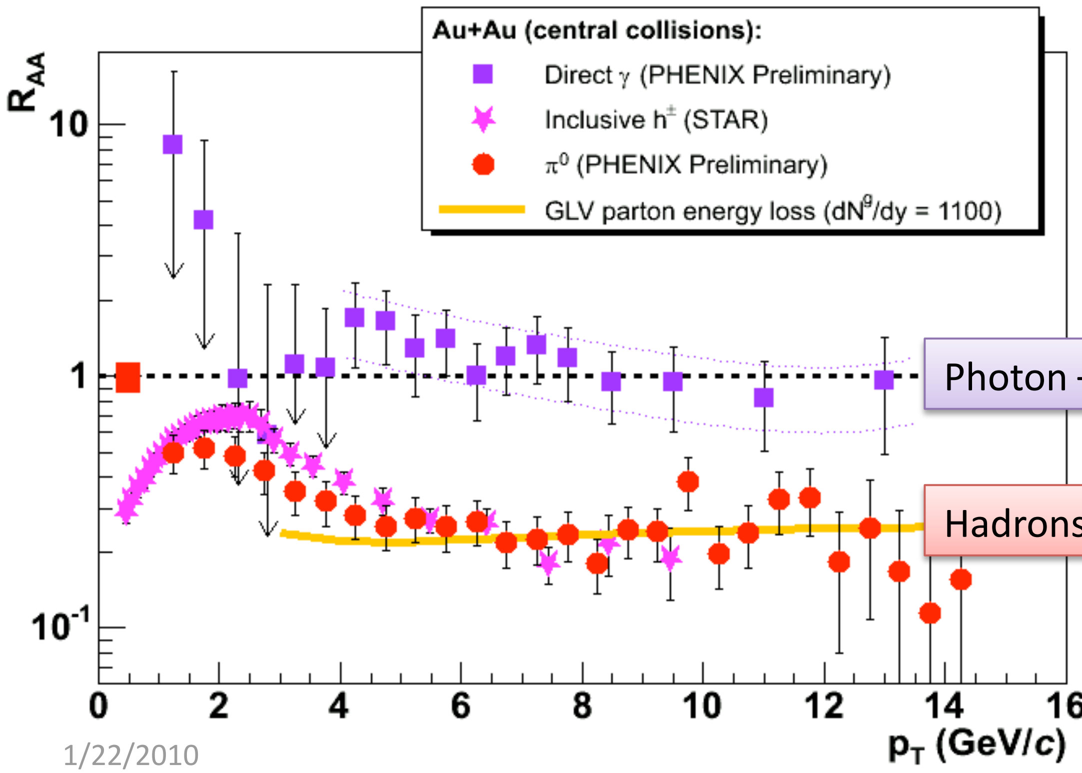
Jet quenching via hadron suppression

$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

$$T_{AB} =< N_{bin} > /\sigma^{pp}_{inel}$$

No “effect”:
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

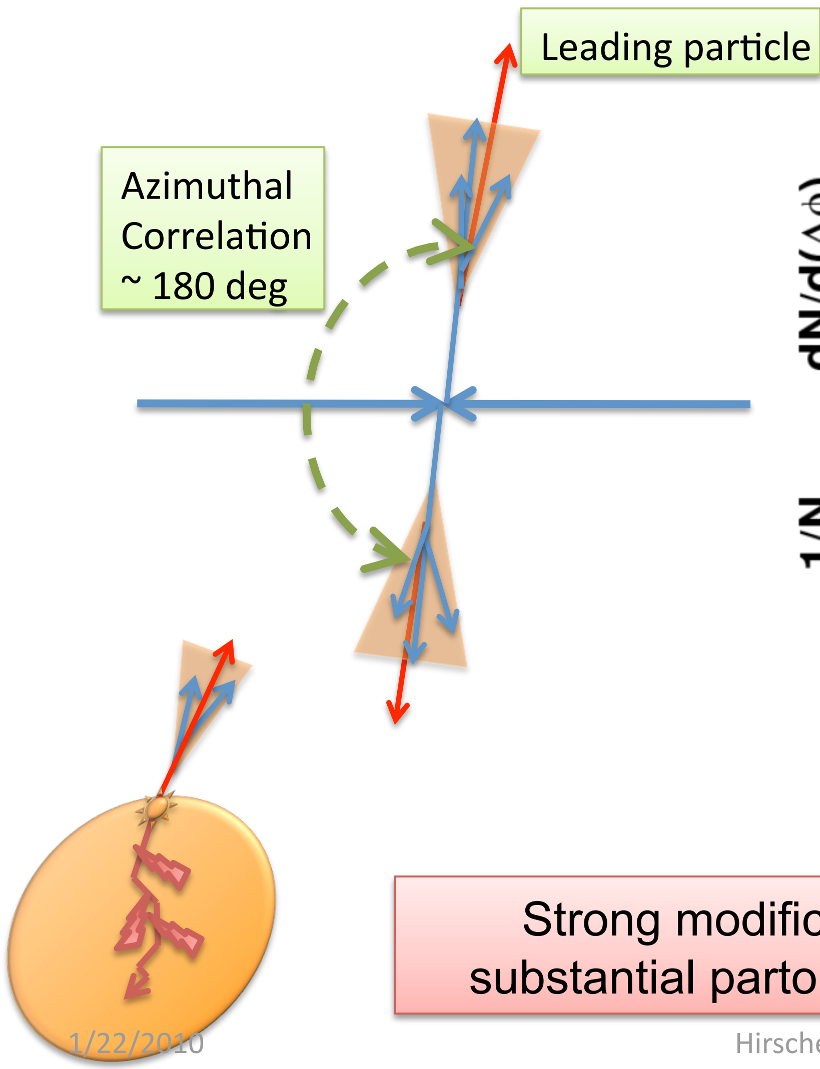




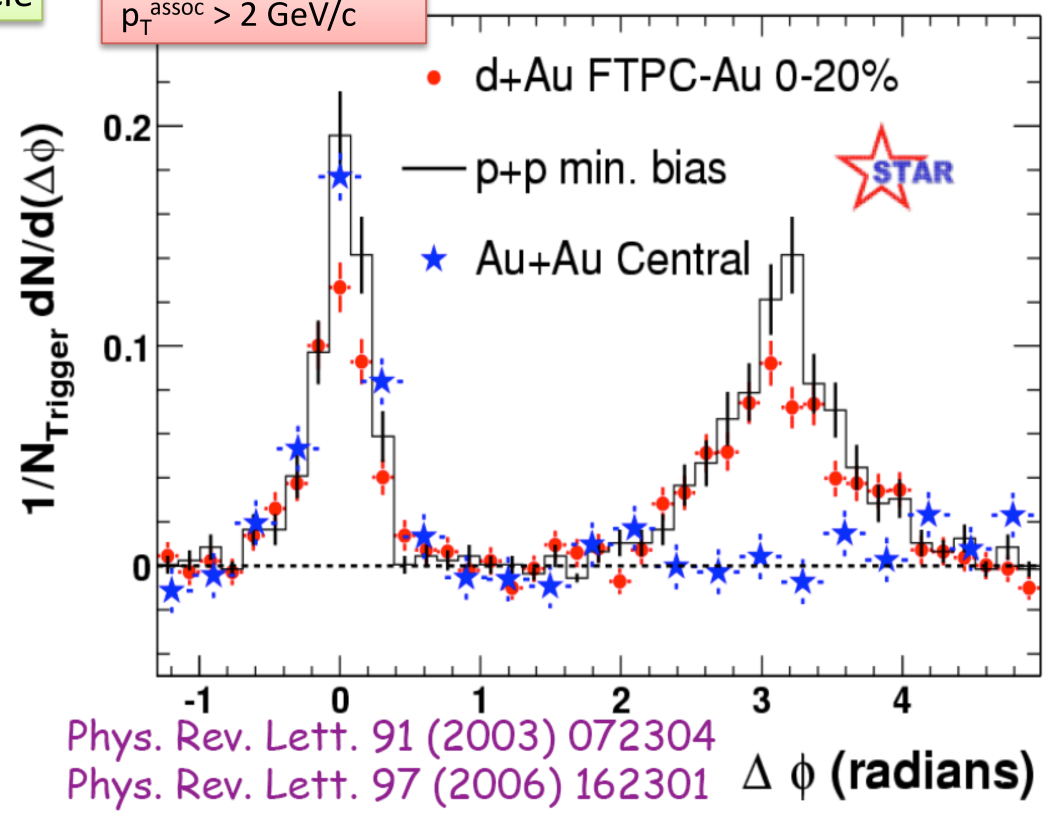
Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppression

Jet quenching: recoil jet suppression via leading hadron azimuthal correlations



4< p_T^{trig} < 6 GeV/c
p_T^{assoc} > 2 GeV/c

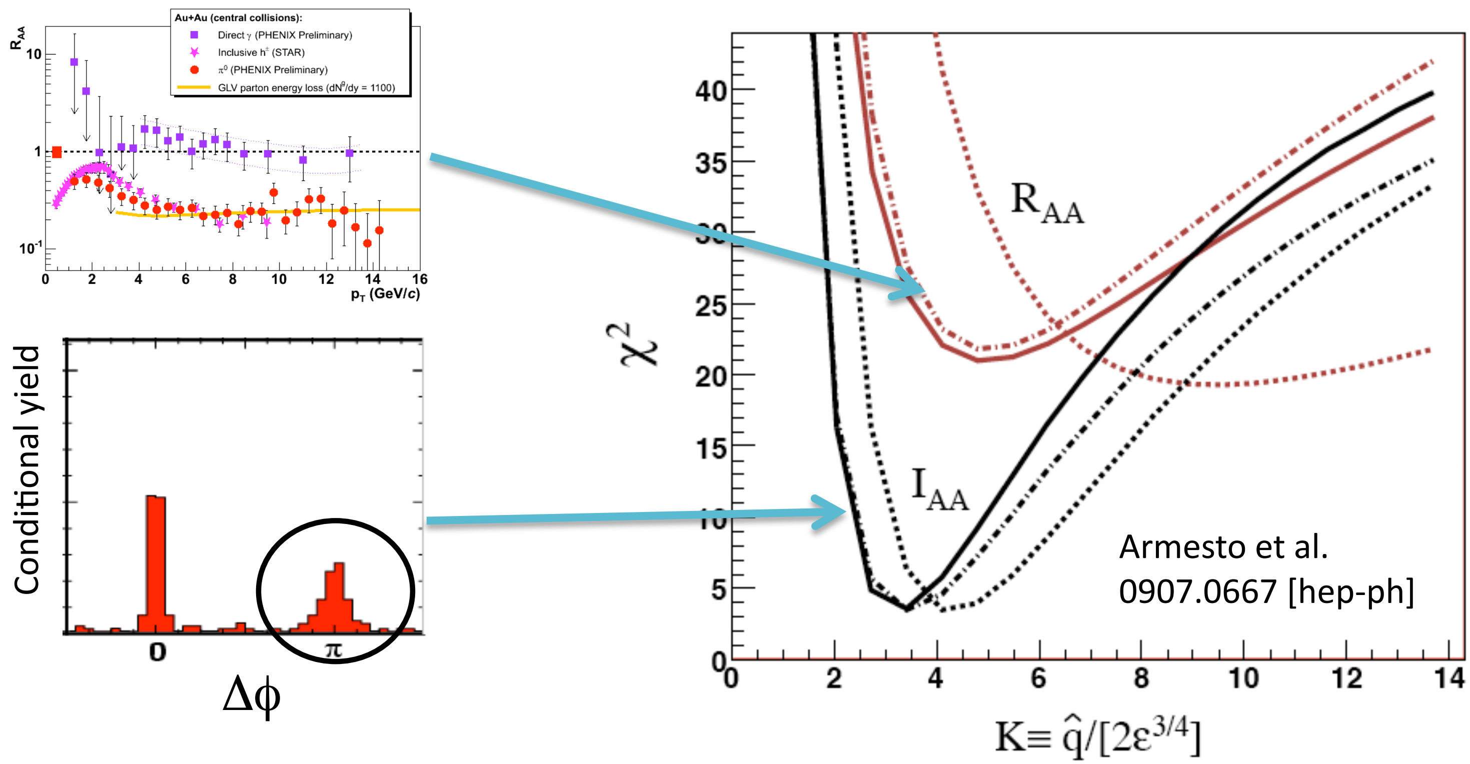


Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Strong modification of the recoil-jet indicates substantial partonic interaction within the medium

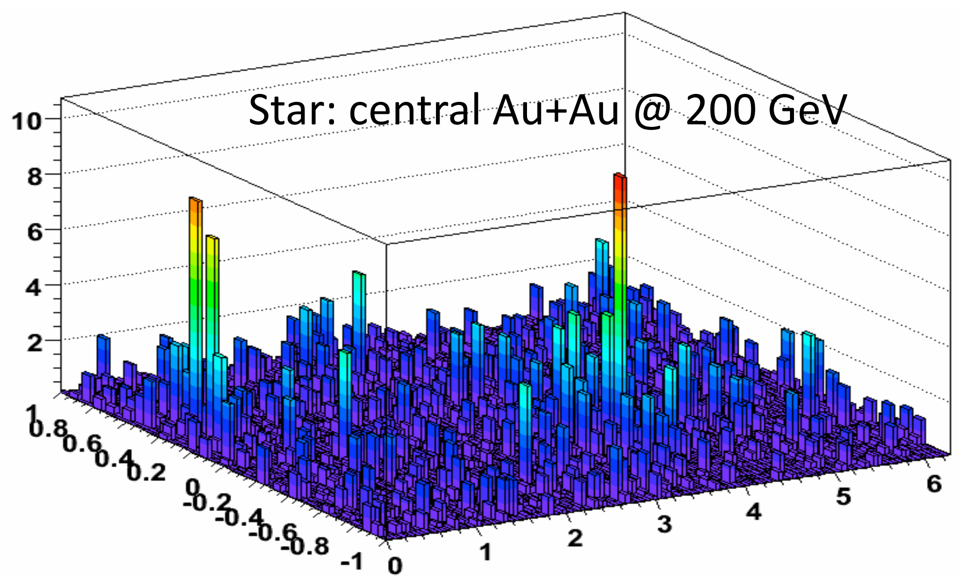
High p_T hadrons: quantitative analysis

Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

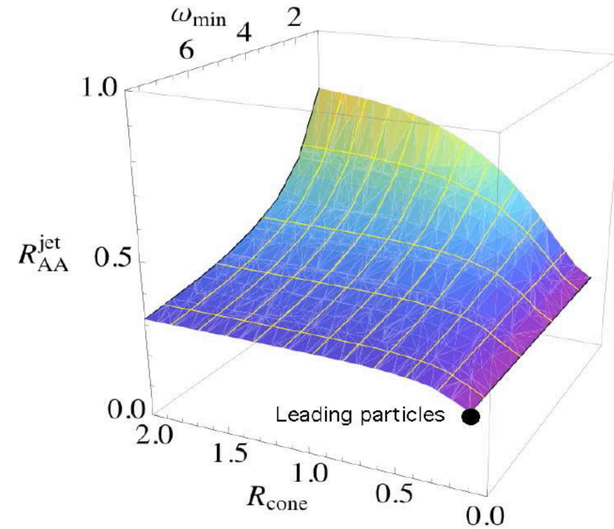


- Reasonably self-consistent fit of independent observables
- Main limitation is the accuracy of the theory
- So what is missing? ….

Towards the full jet reconstruction in HI collisions



Complete Jet Reconstruction in Heavy Ion Collisions: why bother?



Jet quenching is a *partonic* proces

➔obscured by hadronization

High p_T hadron triggers bias towards non-interacting jets

➔suppresses the jet population that interacts the most

➔no access to dynamics of energy loss

Soft hadron correlations (p_T<few GeV/c) are difficult to interpret as QCD jets

➔requires strong analysis and modeling assumptions

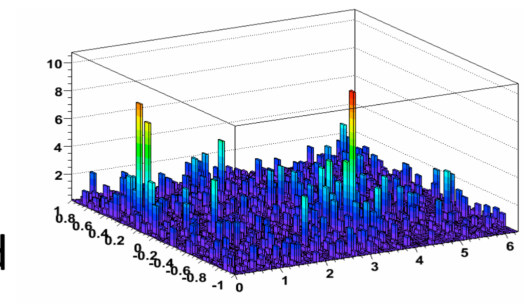
➔ no clear connection to theory

Goal of full jet reconstruction: integrate over hadronic degrees of freedom to measure medium-induced jet modifications at the *partonic* level ➔ much more detailed connection to theory

HI Jet Reconstruction: strategy

What we have learned over the past two years:
"anti-quenching" biases lurk everywhere!

1. Detector level trigger (high-pT single particle)
2. Seeded reconstruction algorithms
3. Track and tower p_T cuts to suppress background



No shortcuts: we have to face the full event background and its fluctuations head-on

- complex interplay between event background and jet signal

Need multiple *independent* background correction schemes to assess systematics

- more is better than few, but must be independent
- no shortcuts: corrections depend on observable

HI Jet Reconstruction: observables

Note: in HI collisions we should very little rely on kinematics since E is smeared. Counting is more robust!

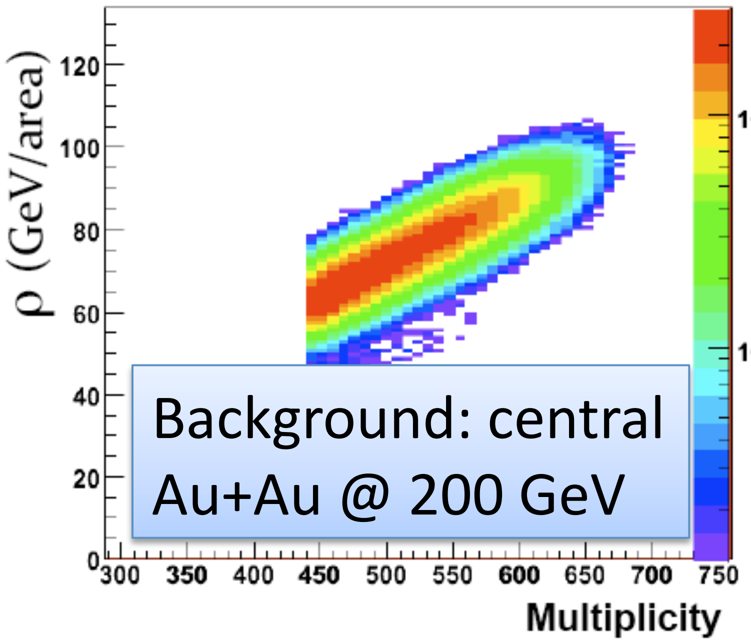
Primary observables (jets):

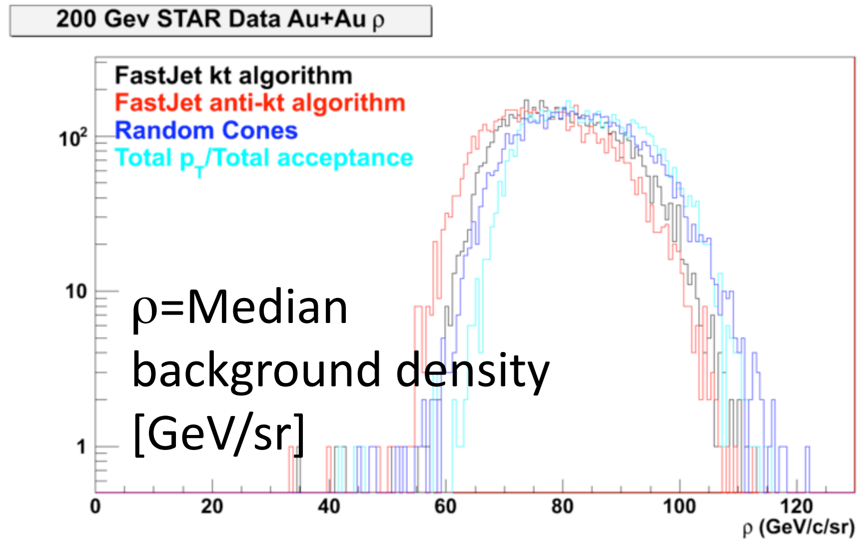
- Cross sections vs p+p
- Cross sections vs R: Energy redistribution (aka jet broadening)
- h+jet and jet+jet coincidences
- subjet distributions
- ....

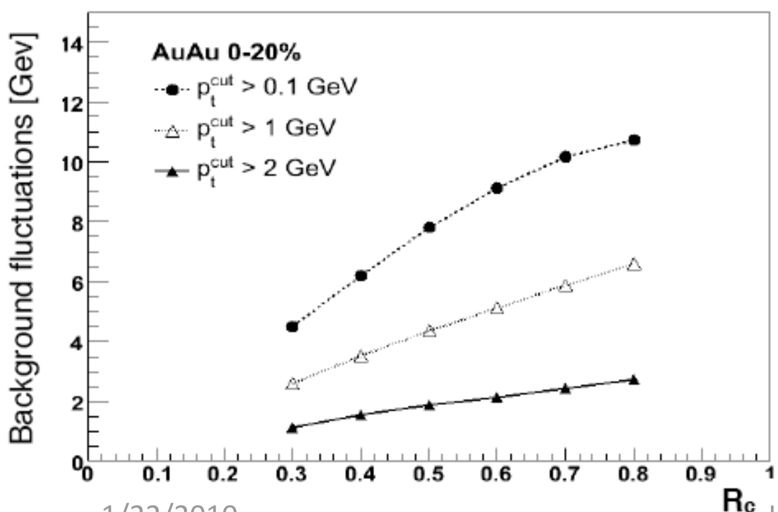
Secondary observables (hadrons):

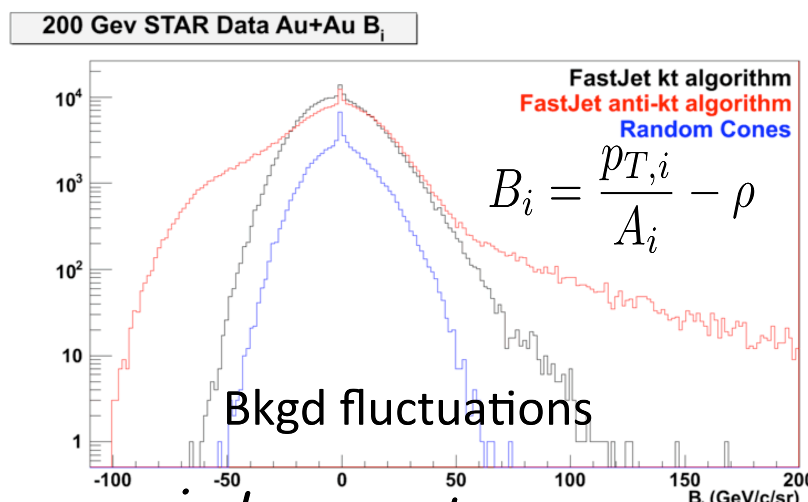
- longitudinal momentum distributions (which are not "fragmentation functions")
- Transverse momentum distributions (j_T)
- .....

Background characterization









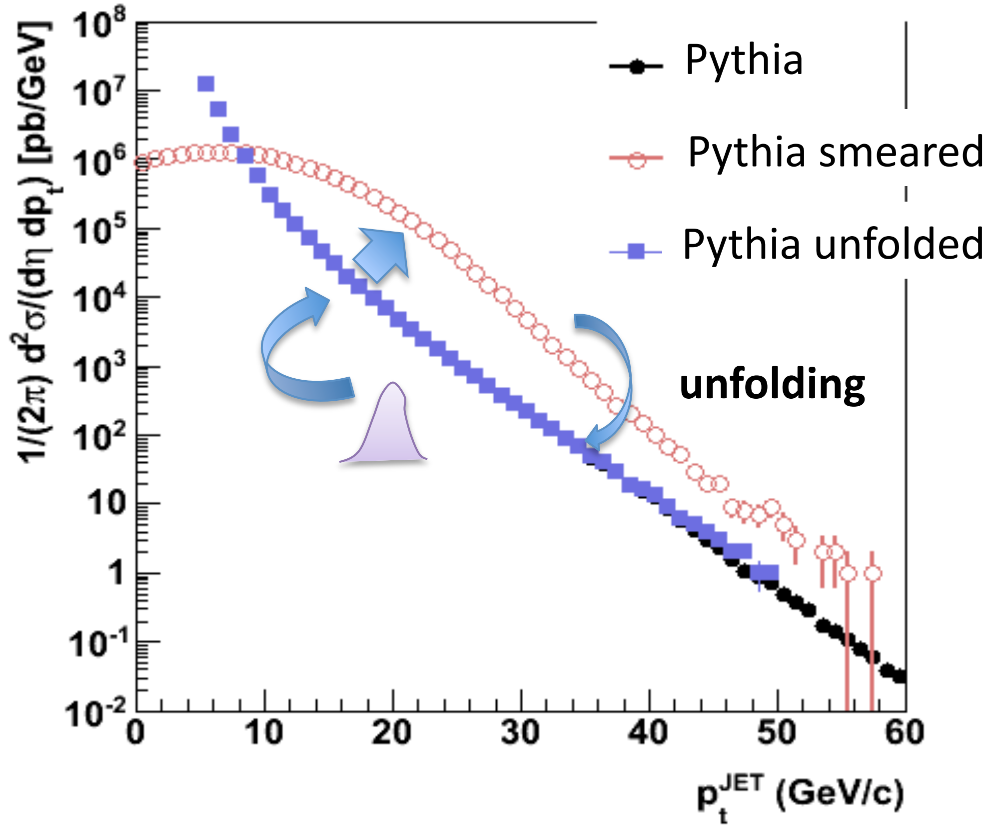
$$p_T^{jet} = p_T^{true} \otimes \delta\rho$$

Spectrum unfolding

Background non-uniformity (fluctuations) and energy resolution introduce pT-smearing

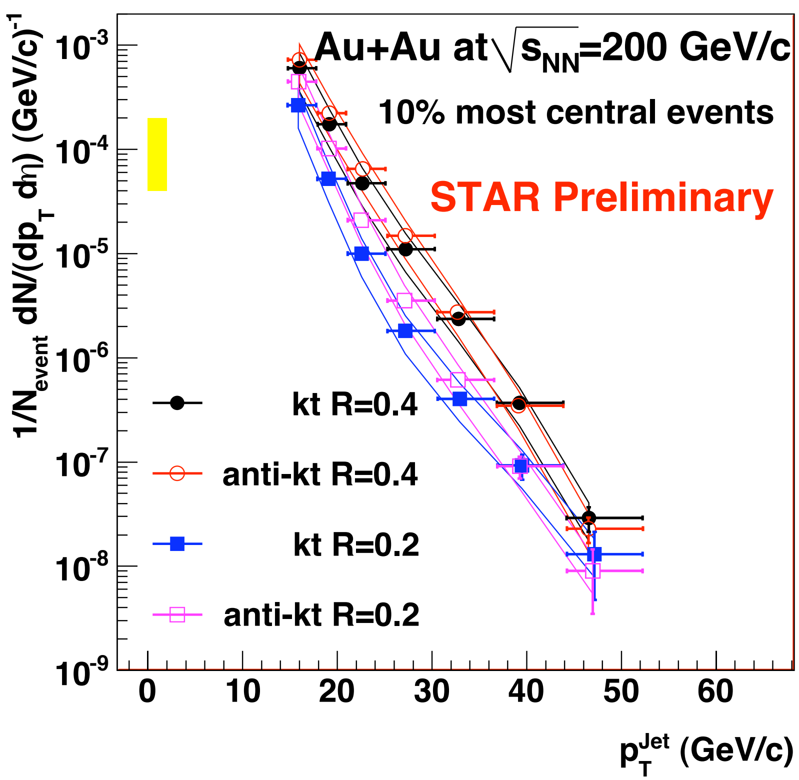
Correct via “unfolding”: inversion of full bin-migration matrix

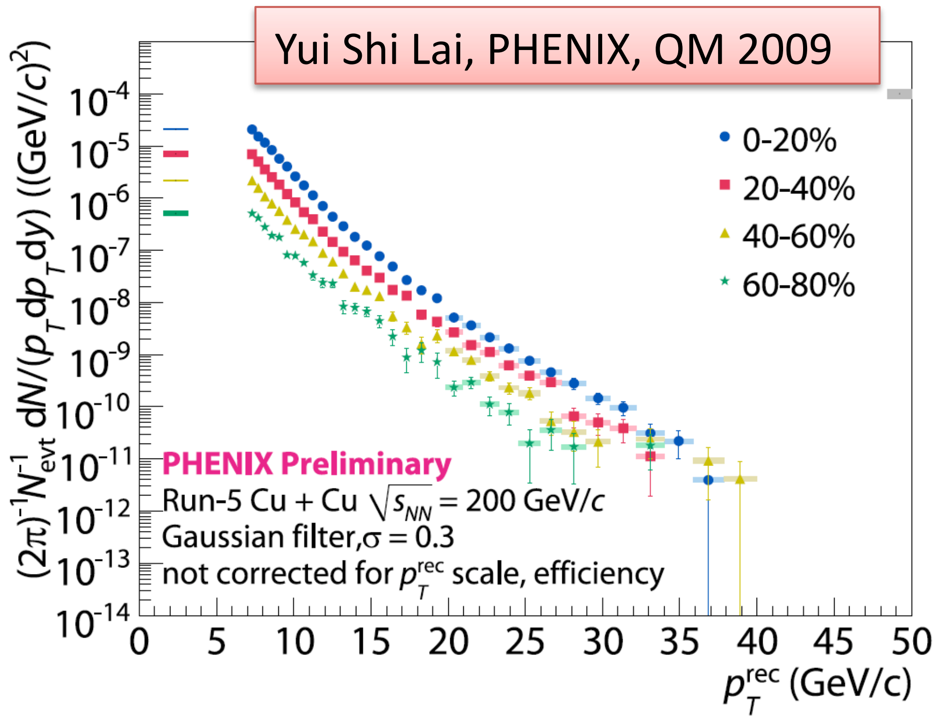
Check numerical stability of procedure using jet spectrum shape from PYTHIA



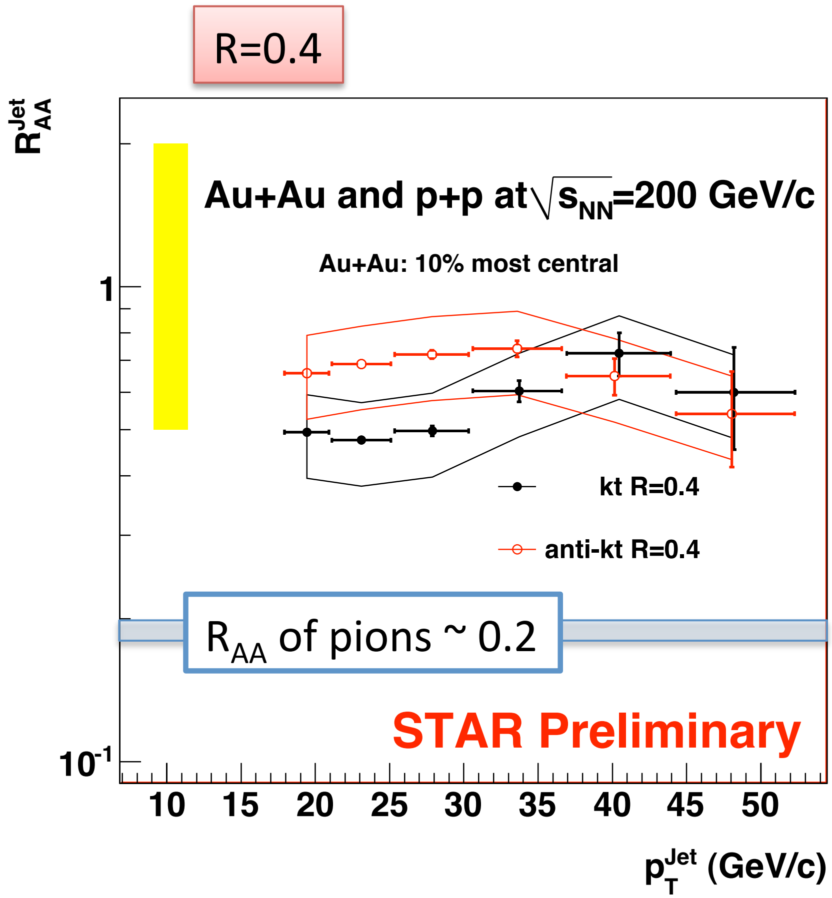
Procedure must be numerically stable
Correction depends critically on background model
→ main systematic uncertainty for HI

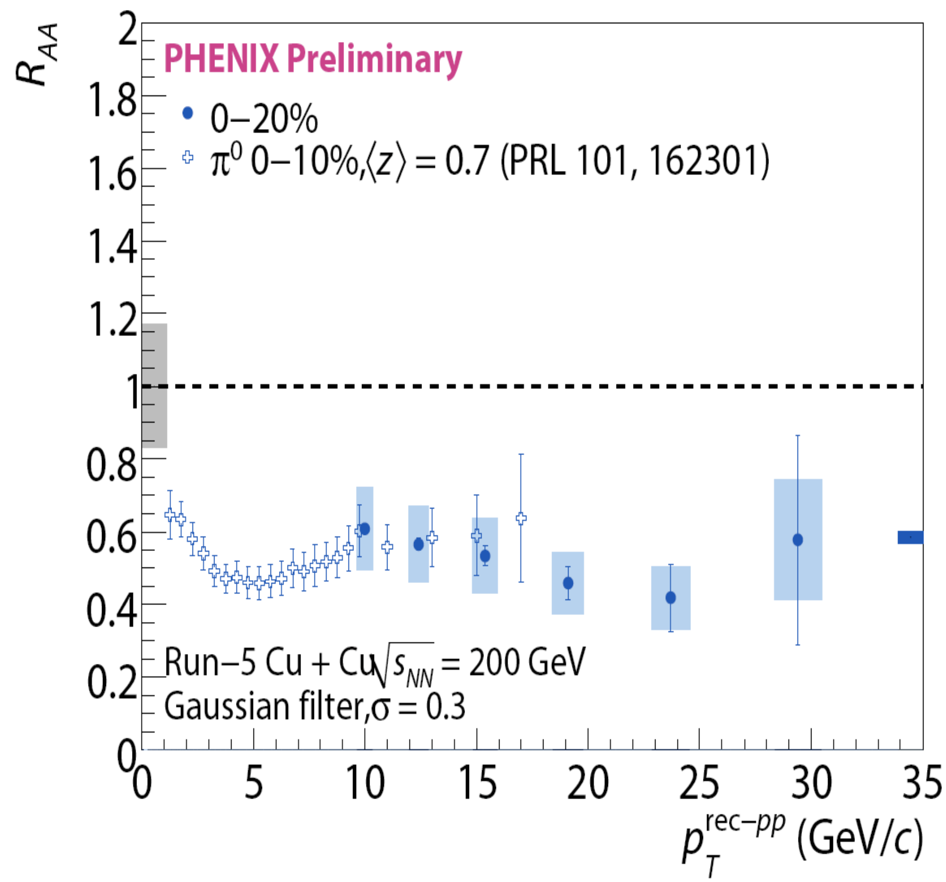
Jet production cross-sections in HI Collisions at RHIC





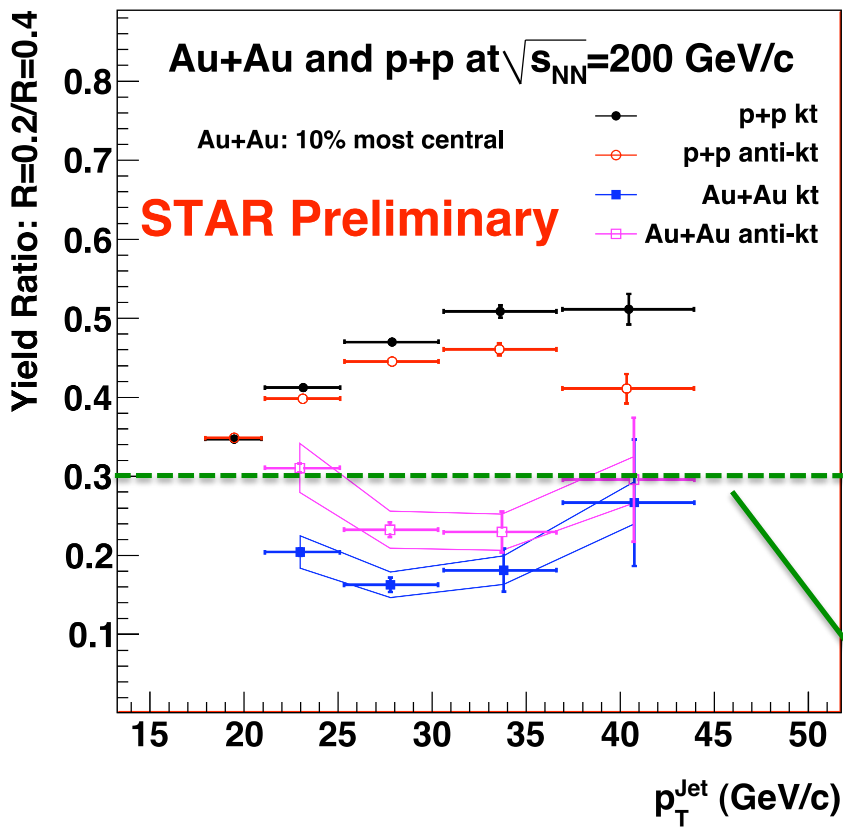
Current result : jet R_{AA}



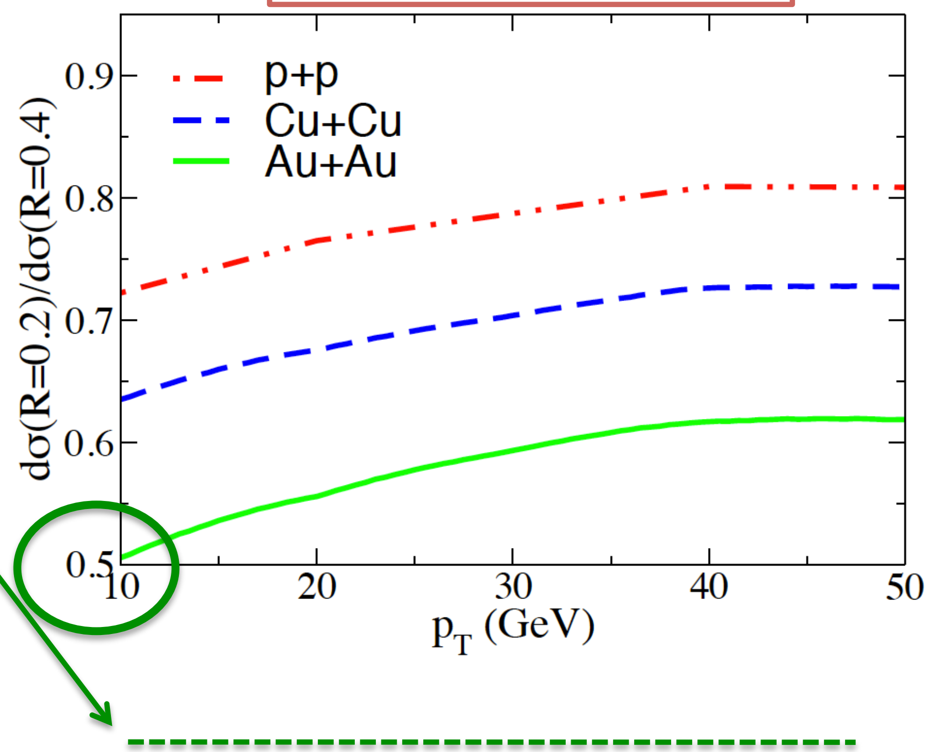


- R_{AA} < 1 : full jet cross-section not recovered ➔jet broadening
- But systematically difficult measurement

Au+Au: cross-section ratio R=0.2/R=0.4



NLO Calculation
B.-W. Zhang and I. Vitev
priv. comm. 2009



Stronger broadening seen in measurement than NLO calculation…
➔strong hadronization effects? (that would be unfortunate)

Calculations and models of jet quenching and jet reconstruction

TECHQM: energy loss in a static "QGP Brick"

Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma "Brick"
(Outline Version II)

TEC-HQM Collaboration
The Earth, Solar System, Milky Way, Virgo Supercluster, Universe
(Dated: January 8, 2010)

This is the second draft of the outline of a report describing the comparison of various pQCD based formalisms treating the energy loss of hard partons in a thermal quark-gluon plasma for a simplified geometry. Specifically, we compare the predictions of the WHDG and ASW, and Higher Twist (HT) formalisms in the opacity expansion, and of the BDMPS–Z and AMY formalisms in the multiple soft scattering approximation.

- All analytical approaches represented:
  GLV/WHDG, ASW, HT, AMY
- Exercise has explored systematically the limitations of all approaches due to soft and collinear approximations (known previously but not via model-to-model comparisons)

Solutions:
- NLO calculations
- Monte Carlo codes (modifications of PYTHIA and HERWIG)

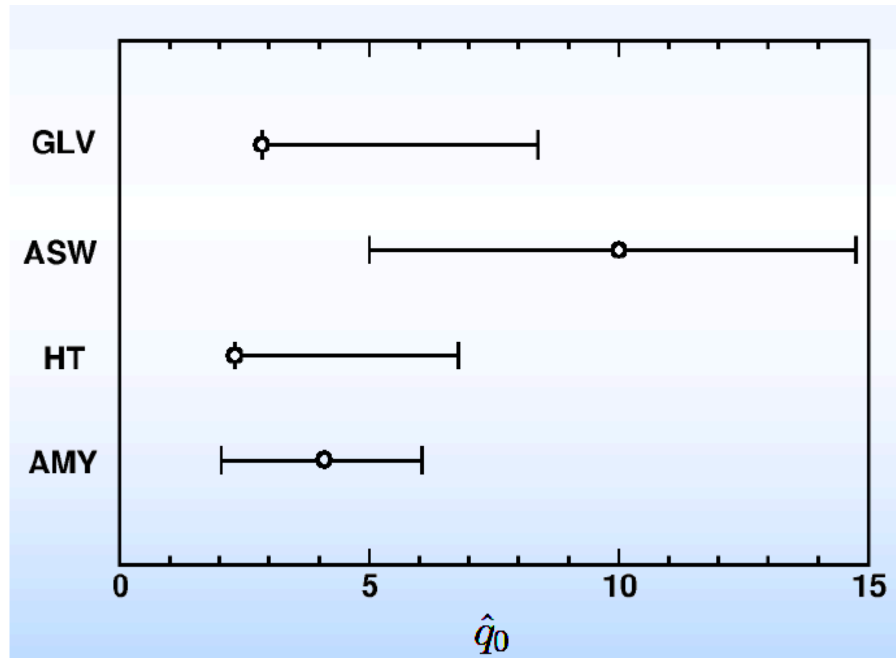
Jet quenching analytic approaches: theory uncertainties

Will Horowitz (TECHQM/CATHIE workshop Dec ‘09)

https://wiki.bnl.gov/TECHQM/index.php/CATHIE/TECHQM_Dec_14-18:_Parallel_Session_on_Jet_Quenching

Same QGP brick for all models:

Systematic uncertainty on qhat due to soft and colinear approximations



- “Central” values disagree by a factor of several, but within realistic uncertainty band
- This clarifies the “qhat puzzle”

New theory development: Jet quenching Monte Carlos

- HIJING (Heavy Ion Jet INteraction Generator)
  X.-N. Wang, M. Gyulassy, Phys.Rev.D44:3501-3516,1991.
- JEWEL (Jet Evolution With Energy Loss)
  K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, Eur.Phys.J.C60:617-632,2009.
  K. Zapp, J. Stachel, U.A. Wiedemann, Phys.Rev.Lett.103:152302,2009.
- MARTINI (Modular Algorithm for Relativistic Treatment of Heavy IoN Interactions)
  B. Schenke, C.Gale, S. Jeon, Phys.Rev.C80:054913,2009.
- PQM (Parton Quenching Model)
  A. Dainese, C. Loizides, G. Paic, Eur.Phys.J.C38:461-474,2005.
- PYQUEN/HYDJET/HYDJET++ (HYDrodynamics plus JETs)
  I.P. Lokhtin, A.M. Snigirev, J.Phys.G34:S999-1004,2007.
  I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, I. Arsene, K. Tywoniuk, Comput.Phys.Commun.180:779-799,2009.
- Q-PYTHIA / Q-HERWIG
  N. Armesto, L. Cunqueiro, C.A. Salgado, Eur.Phys.J.C63:679-690,2009.
  N. Armesto, G. Corcella, L. Cunqueiro, C.A. Salgado, JHEP 0911:122,2009.
- YaJEM (Yet another Jet Energy-Loss Model)
  T. Renk, arXiv:0808.1803, Phys.Rev.C78:034908,2008.

https://wiki.bnl.gov/TECHQM/index.php/CATHIE/TECHQM_Dec_14-18:_Parallel_Session_on_Jet_Quenching

Modeling jet quenching by modified splitting function

JEWEL, YaJEM use Salgado/Wiedemann ansatz:

Fit to high p_T pion suppression

$$P_{a\to bc}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \to \frac{4}{3}\left(\frac{2(1+f_{\mathrm{med}})}{1-z} - (1+z)\right)$$

qPYTHIA, qHERWIG use ASW quenching weights

$$P_{\mathrm{tot}}(z) = P_{\mathrm{vac}}(z) + \Delta P\,,$$

$$\Delta P = \Delta P(z,t,\hat{q},L,E) = \frac{2\pi k_T^2}{\alpha_s}\frac{dI^{\mathrm{med}}}{dz\,dk_T^2}$$

Modeling jet quenching by modified splitting function

JEWEL, YaJEM use Salgado/Wiedemann ansatz:

Fit to high p_T pion suppression

$$P_{a\to bc}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \to \frac{4}{3}\left(\frac{2(1+f_{\mathrm{med}})}{1 \ldots} \; [illegible] \; z)\right)$$

Straight forward application of jet algorithms.
Either on parton or particle level.

qPYTHIA, q[illegible] quenching weights

$$P_{\mathrm{tot}}(z) = P_{\mathrm{vac}}(z) + \Delta P\,,$$

$$\Delta P = \Delta P(z,t,\hat{q},L,E) = \frac{2\pi k_T^2}{\alpha_s}\frac{dI^{\mathrm{med}}}{dz\,dk_T^2}$$

NLO E-Loss calculations and jet finding

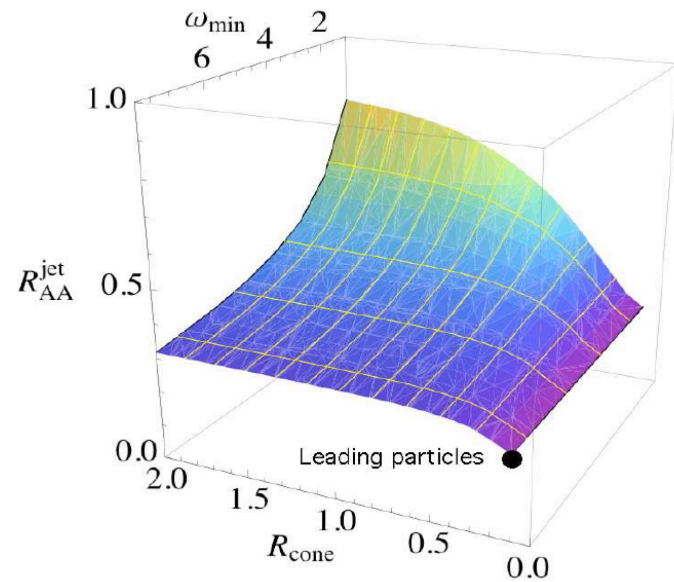
GLV medium induced radiation: number of scatterings, momentum transfers, color current propagators, coherence phases (LPM)…

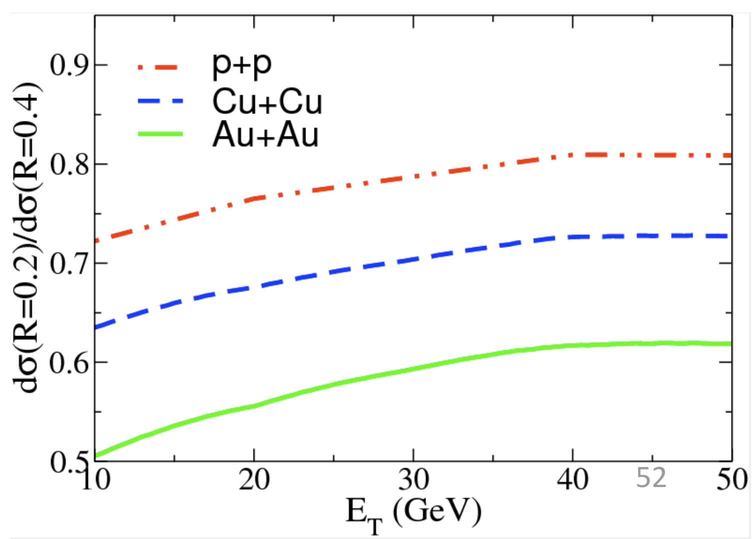
Jet cross-sections:

$$\frac{d\sigma^{\rm jet}}{dE_T dy} = \frac{1}{2!}\int d\{E_T,y,\phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T,y,\phi\}_2} S_2(\{E_T,y,\phi\}_2) + \frac{1}{3!}\int d\{E_T,y,\phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T,y,\phi\}_3} S_3(\{E_T,y,\phi\}_3)$$

S_2 and S_3 contain jet finding algorithm (phase space constraints identifying jet with its parent parton)

[I. Vitev, B.-W. Zhang arXiv:0910.1090v1 [hep-ph]]
and refs there





Eur. Phys. J. C (2009) 63: 679–690
DOI 10.1140/epjc/s10052-009-1133-9

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

Q-PYTHIA: a medium-modified implementation of final state radiation

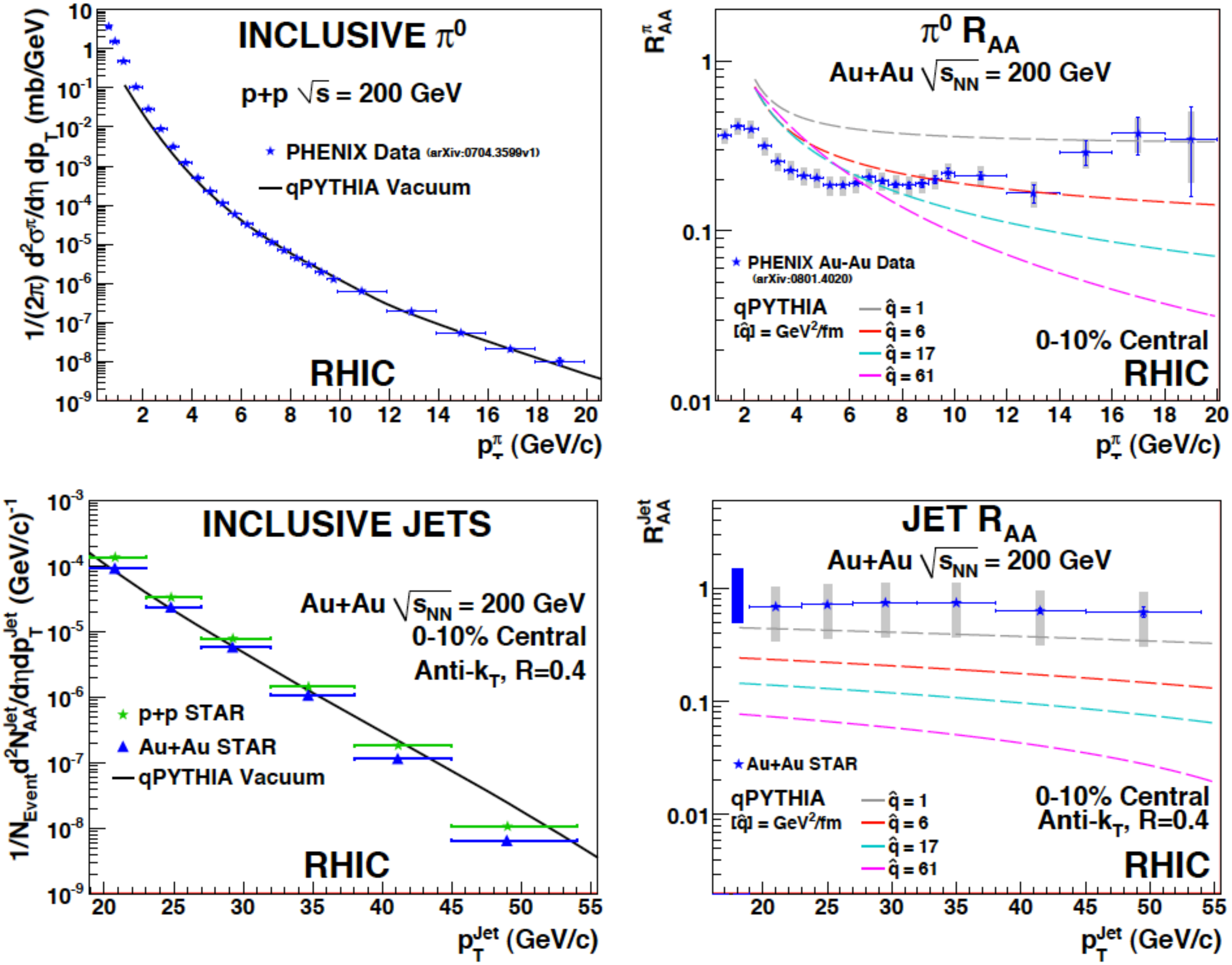
Néstor Armesto[1,a], **Leticia Cunqueiro**[2,b], **Carlos A. Salgado**[1,c]

[1]Departamento de Física de Partículas and IGFAE, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Galicia, Spain
[2]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, 00044 Frascati (Roma), Italy

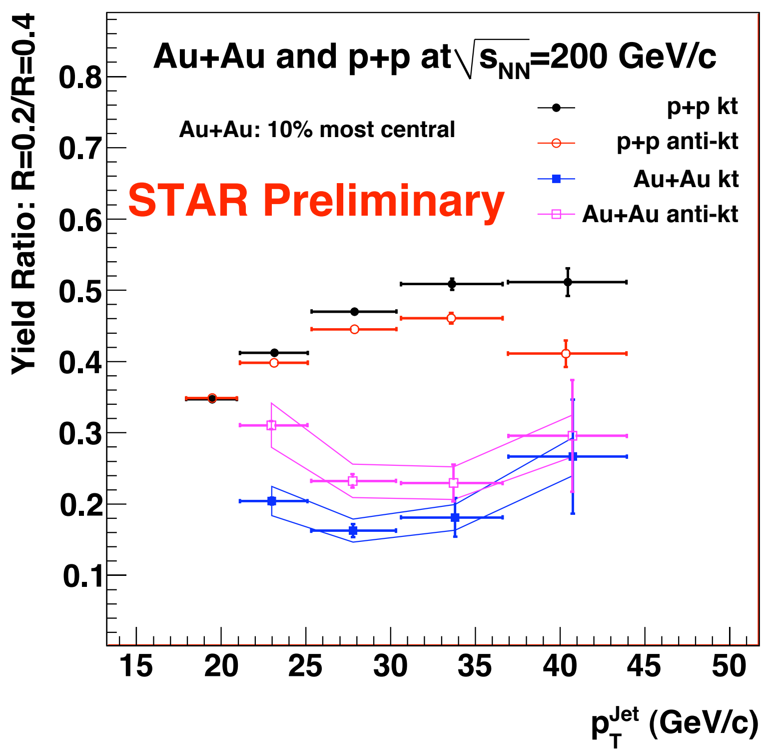
qPYTHIA is the only publically released code at present…

qPYTHIA vs RHIC data I

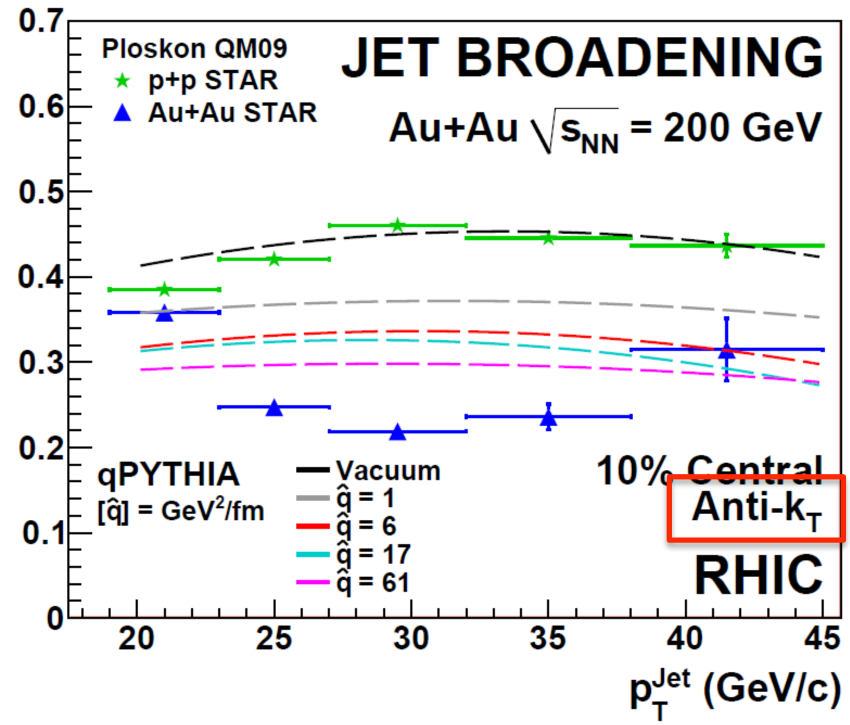
B. Fenton-Olsen, LBNL



qPYTHIA vs STAR data II



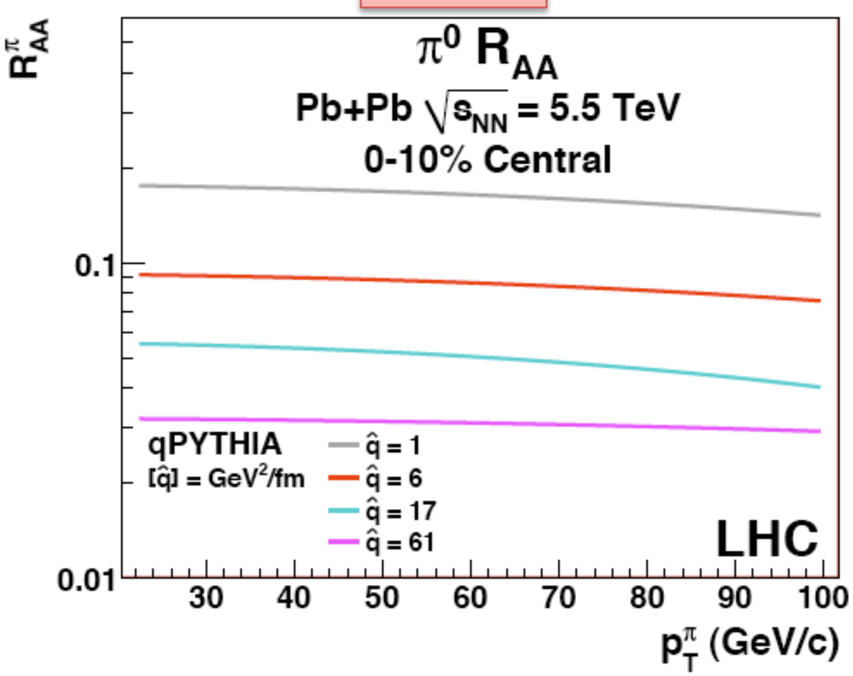
B. Fenton-Olsen, LBNL



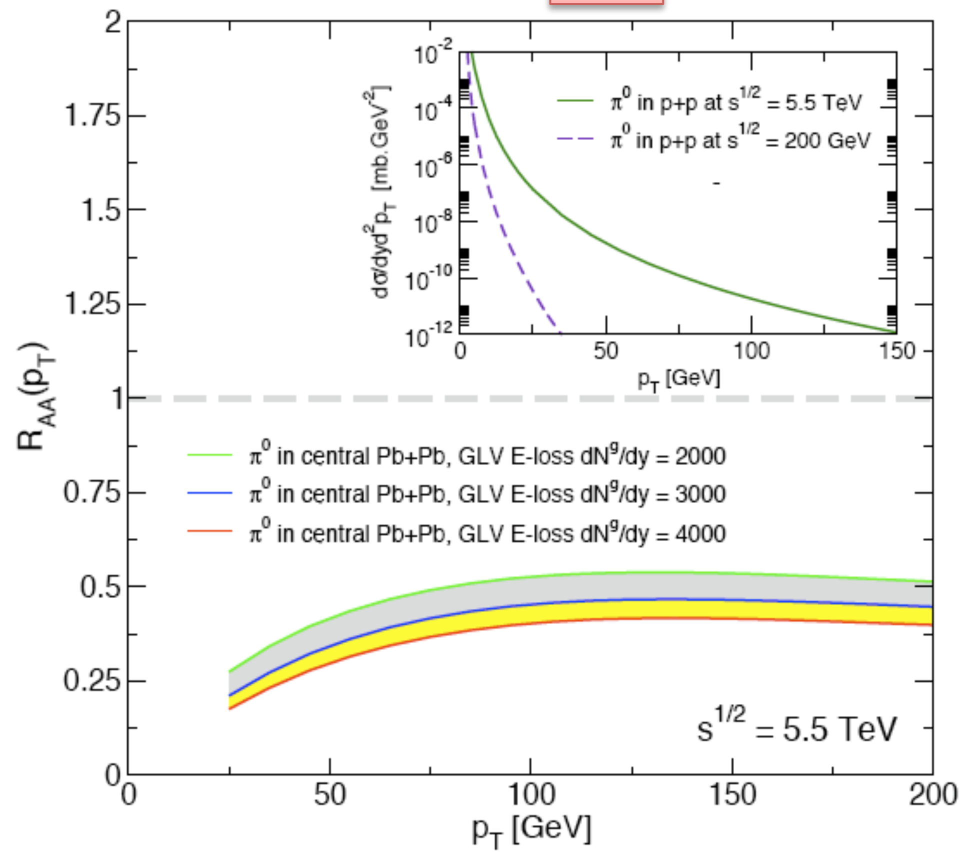
qPYTHIA predicts more suppression (smaller R_{AA}) and less broadening that observed

High-pT hadron suppression at LHC

qPythia

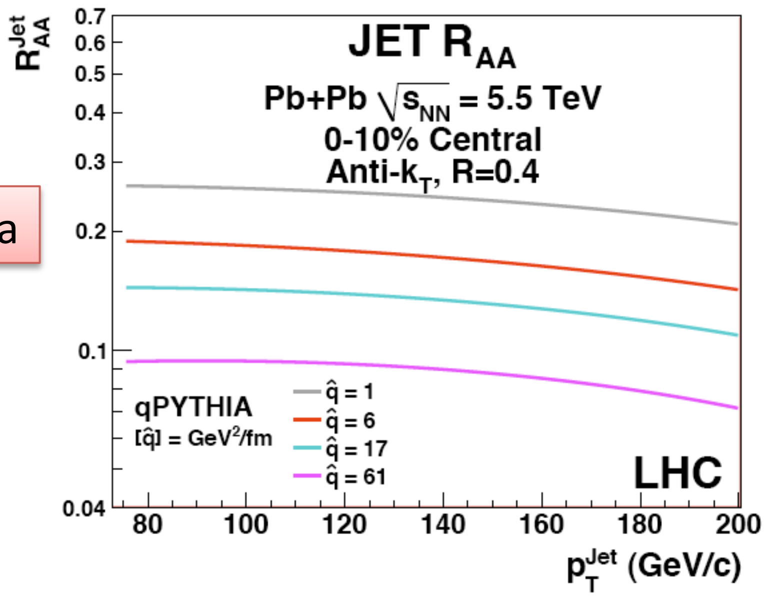


GLV

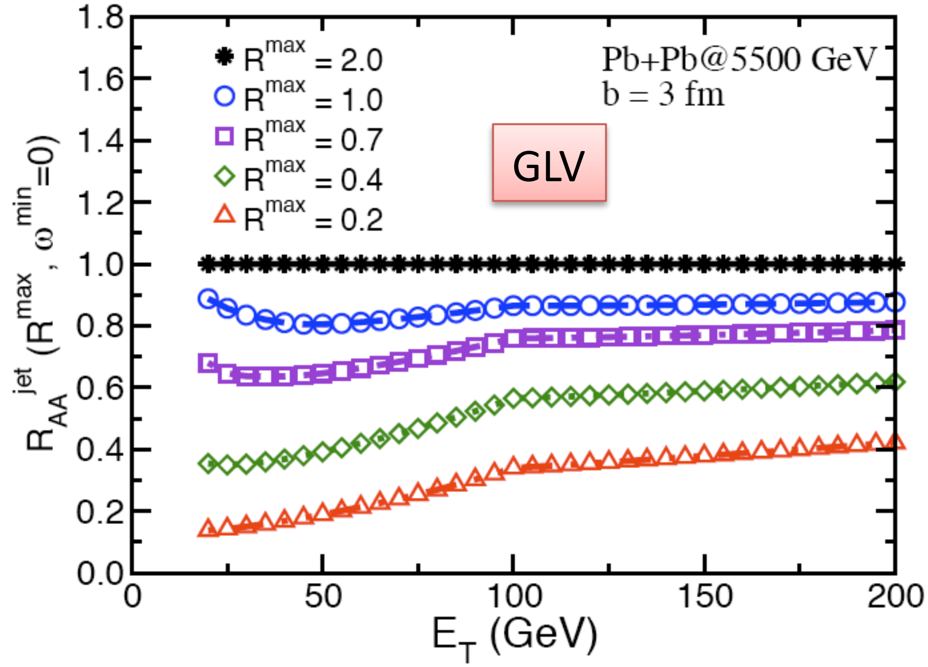


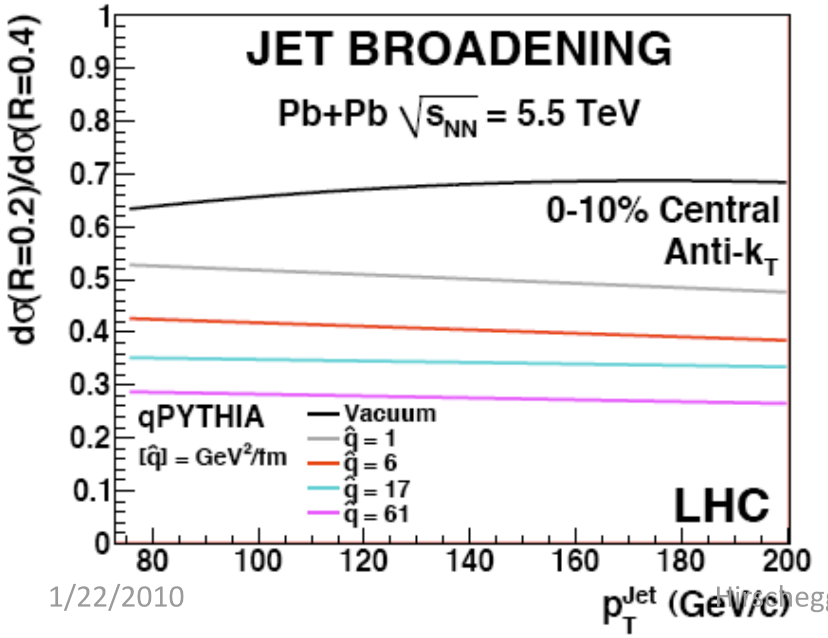
Jet quenching signals at LHC

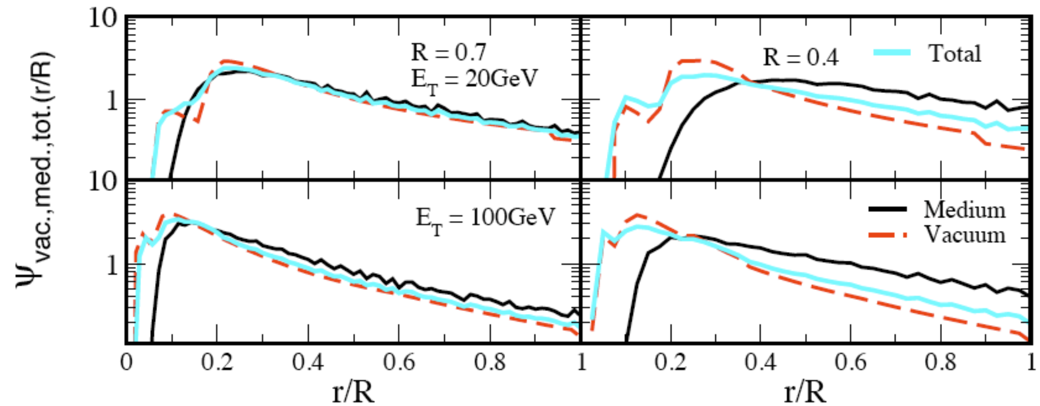
qPythia



GLV





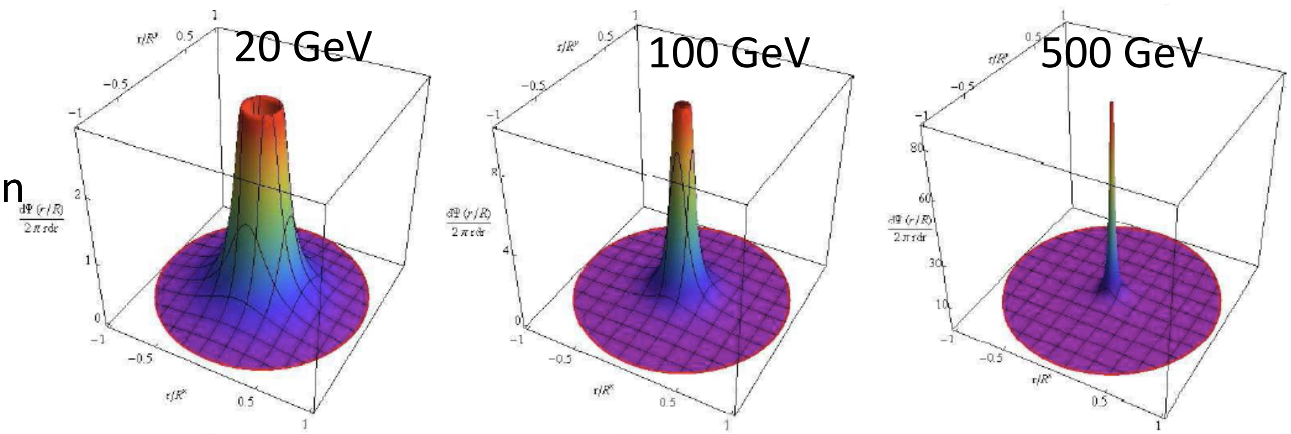


Further jet measurements

Not possible w/o full jet reconstruction(!)

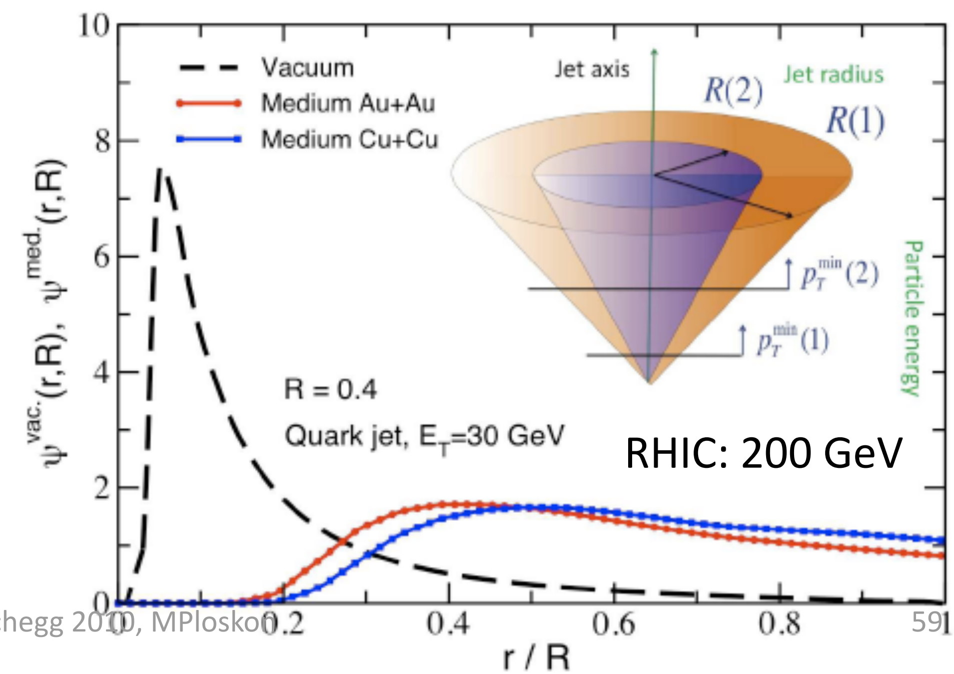
Jet shapes

LHC/
Tevatron



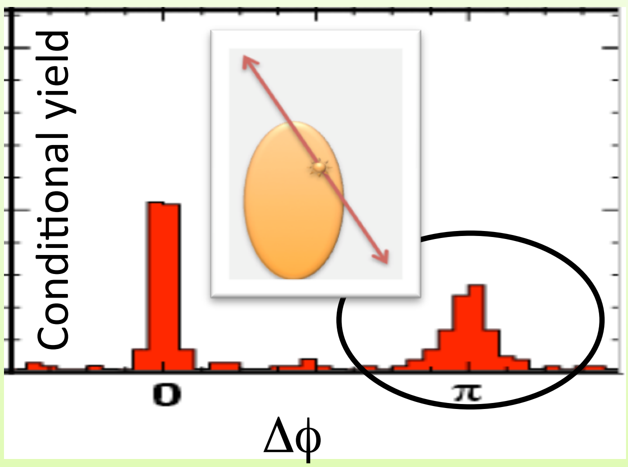
$$\psi(r,R) = \frac{d}{dr}\left\{ \frac{\sum_i E_{T_i}\theta(r - R_{i,\text{jet}})}{\sum_i E_{T_i}\theta(R - R_{i,\text{jet}})} \right\}$$

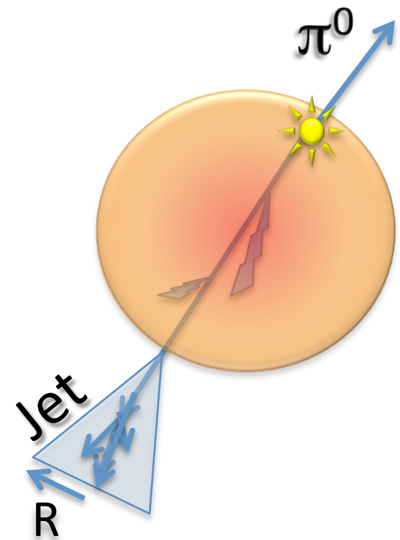
[I. Vitev, B.-W. Zhang arXiv:0910.1090v1 [hep-ph]]()

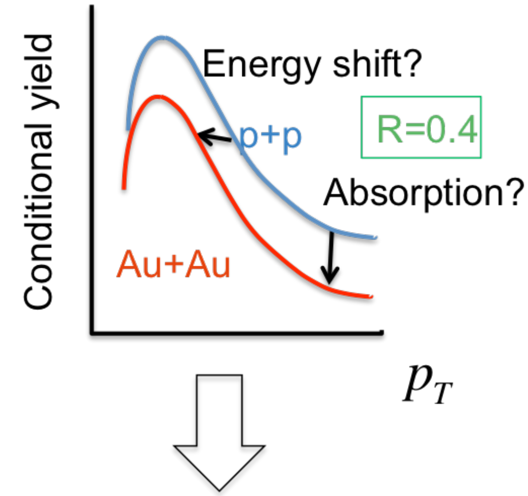


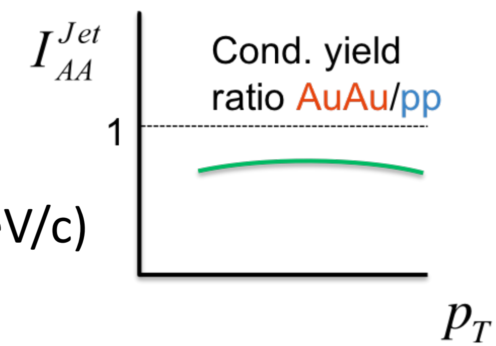
Hadron+jet coincidence

STAR high pT dihadrons: bias towards non-interacting jet population





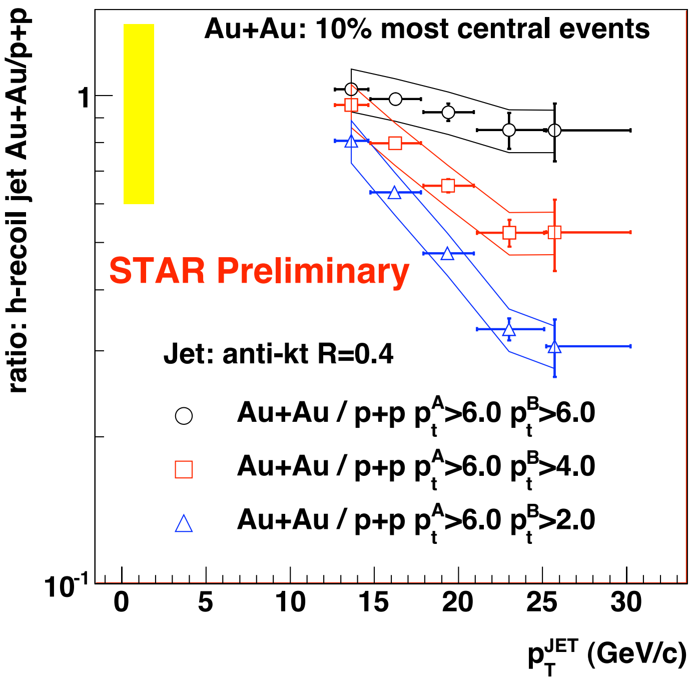


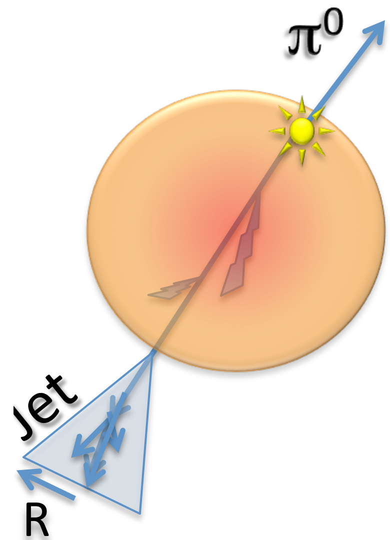


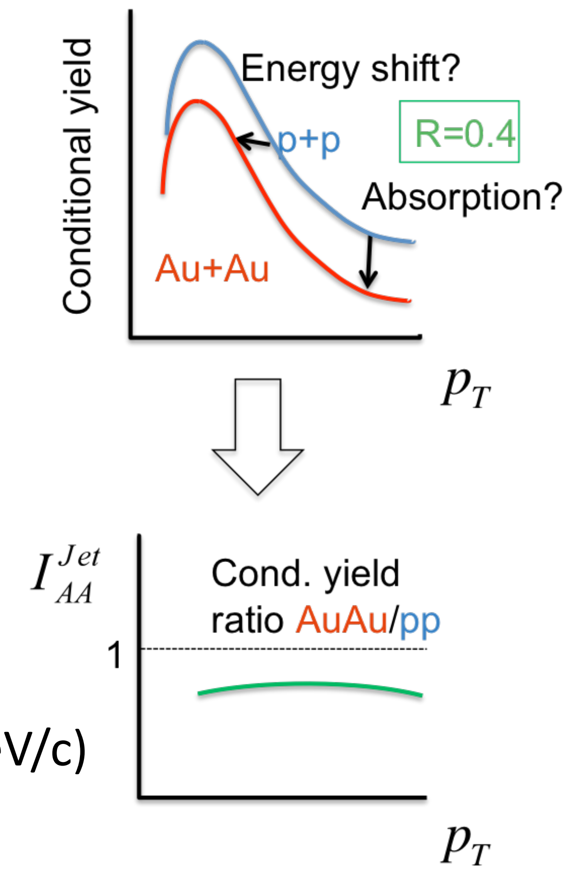
- Trigger on hard, leading π^0 (p_T>6 GeV/c)
  - 3x3 tower cluster in BEMC
- Construct spectrum of recoil jets
  - normalized per di-hadron trigger

This event selection will ***maximize*** the recoil path length distribution in matter

Hadron+jet coincidence







- Trigger on hard, leading π^0 (p_T>6 GeV/c)
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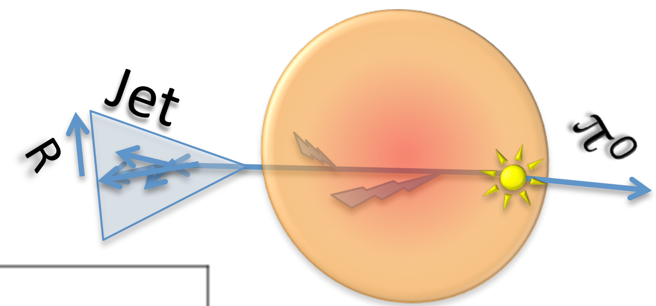
  - normalized per di-hadron trigger

> This event selection will ***maximize*** the recoil path length distribution in matter

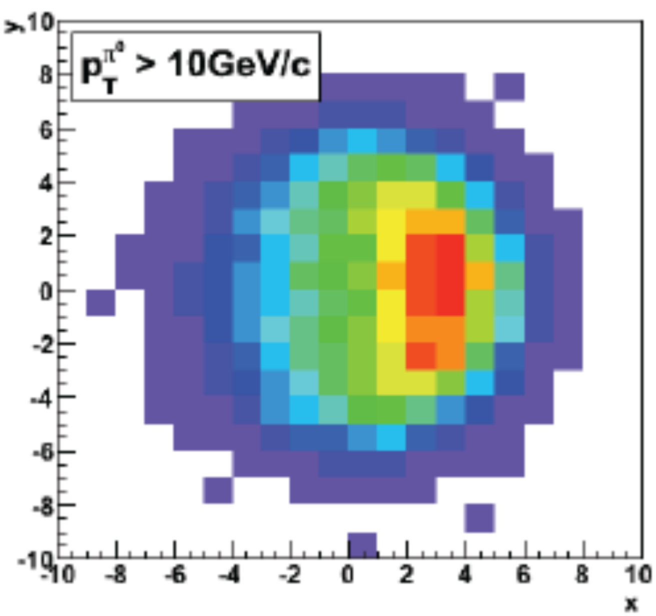
qPYTHIA: geometric bias of high p_T hadron production

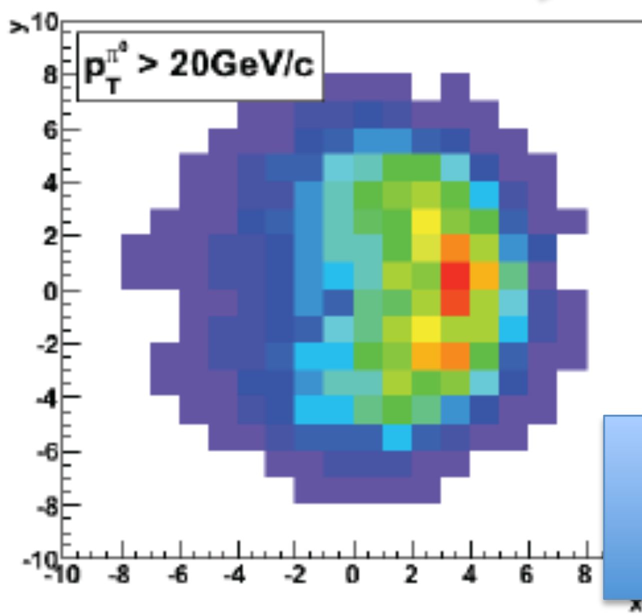
Distribution of vertices generating high p_T pion trigger in x-direction

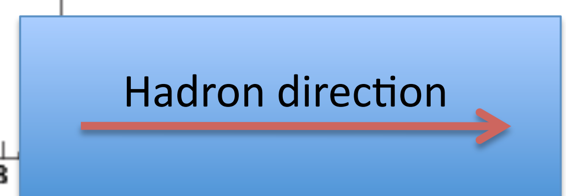
Pb+Pb 5.5 TeV
qhat=50 GeV^2/fm



Hiroki Yokoyama, Tsukuba

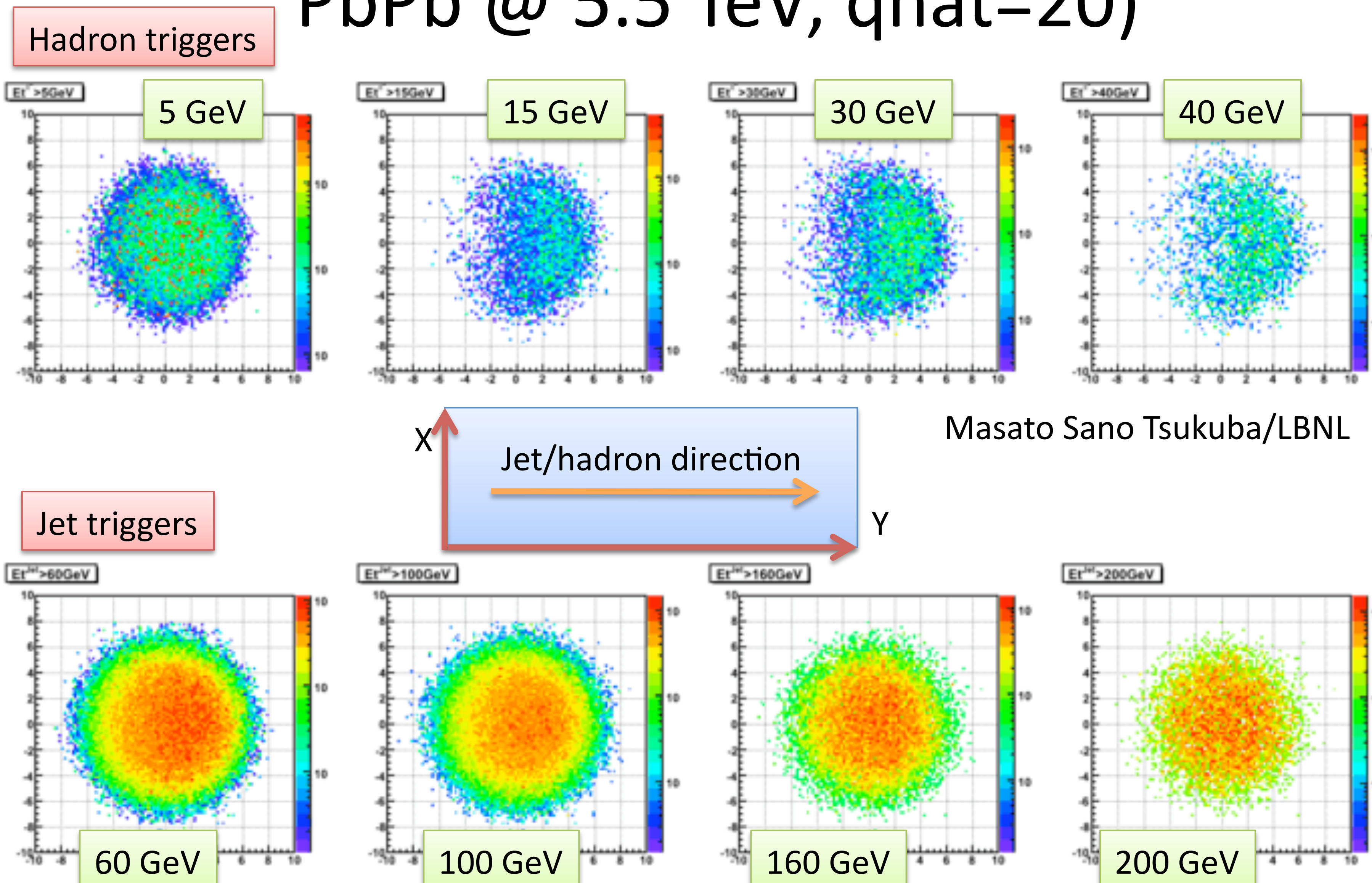






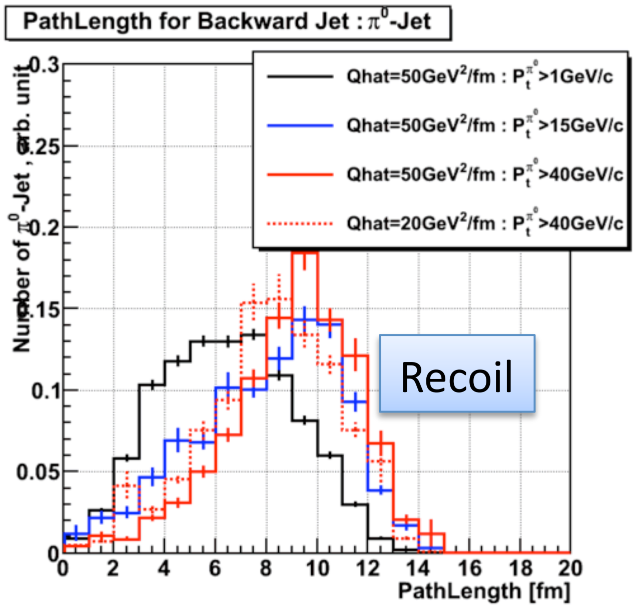
Comparison to STAR data in progress…

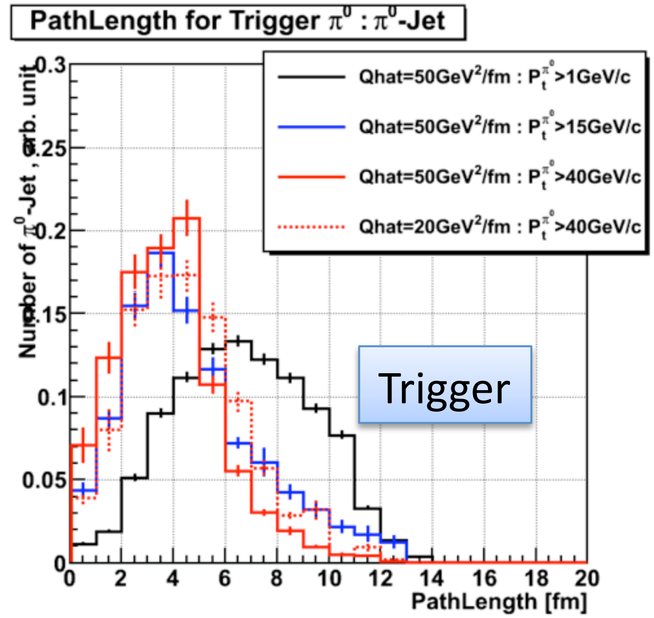
High-pT hadron bias (LHC: central PbPb @ 5.5 TeV; qhat=20)



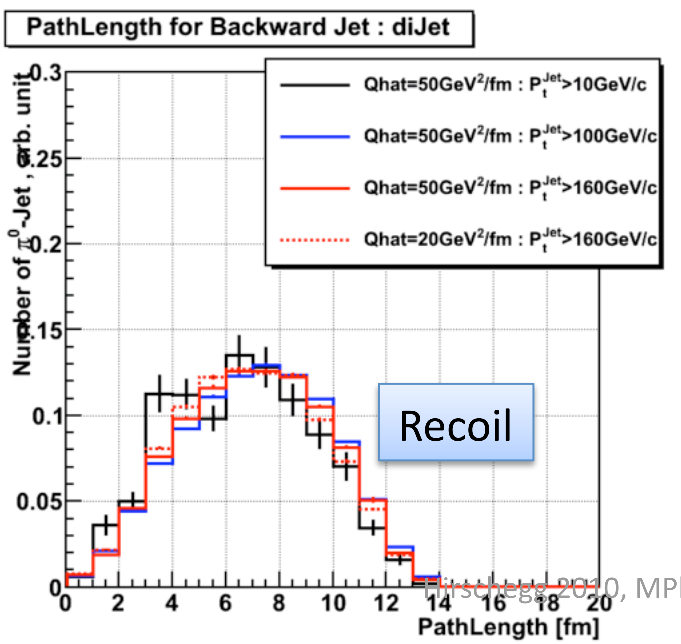
Path lengths: high-pT hadron vs jet trigger

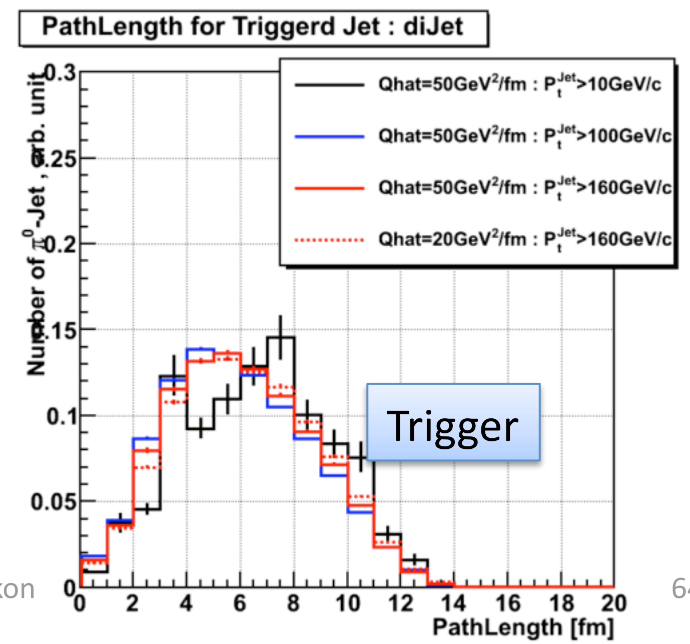
π^0-Jet:
->surface bias



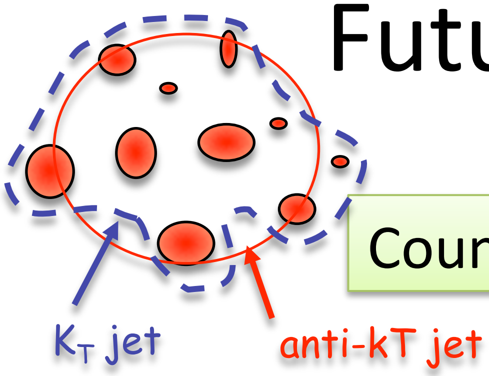


Jet-Jet:
complete
exploration
of path lengths

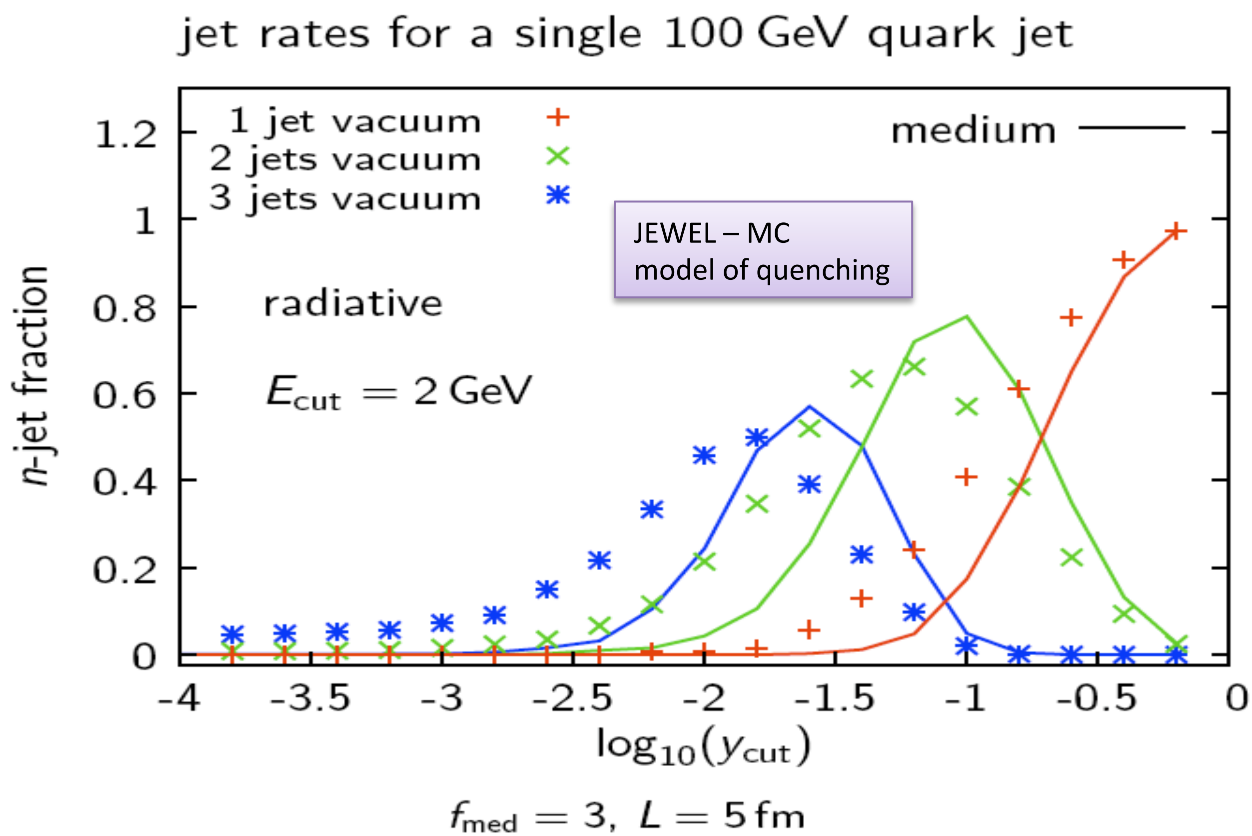




Future measurement: subjets



Count sub-jets when $y_{ij} > y_{cut}$: $y_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_{\rm cm}^2$



JEWEL – MC
model of quenching

Subjet distributions:

+ Insensitive to hadronization
+ Quenching signal with bg suppressing pt cut

- Suffer from energy irresolutions:

$$-log_{10}(f_{corr}^2)$$

where

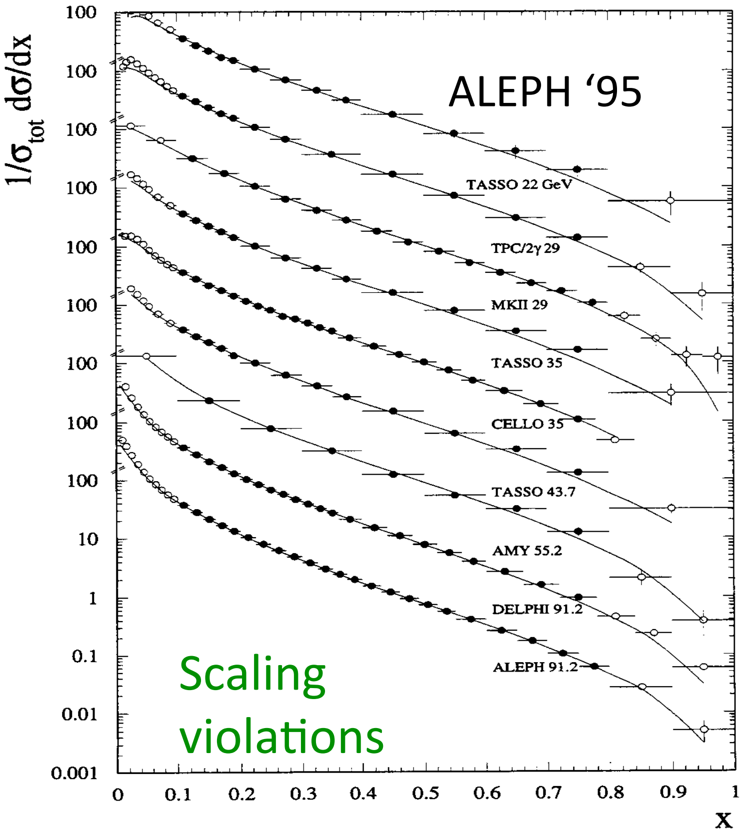
$$f_{corr} = E_{jet}^{true} / E_{jet}^{measured}$$

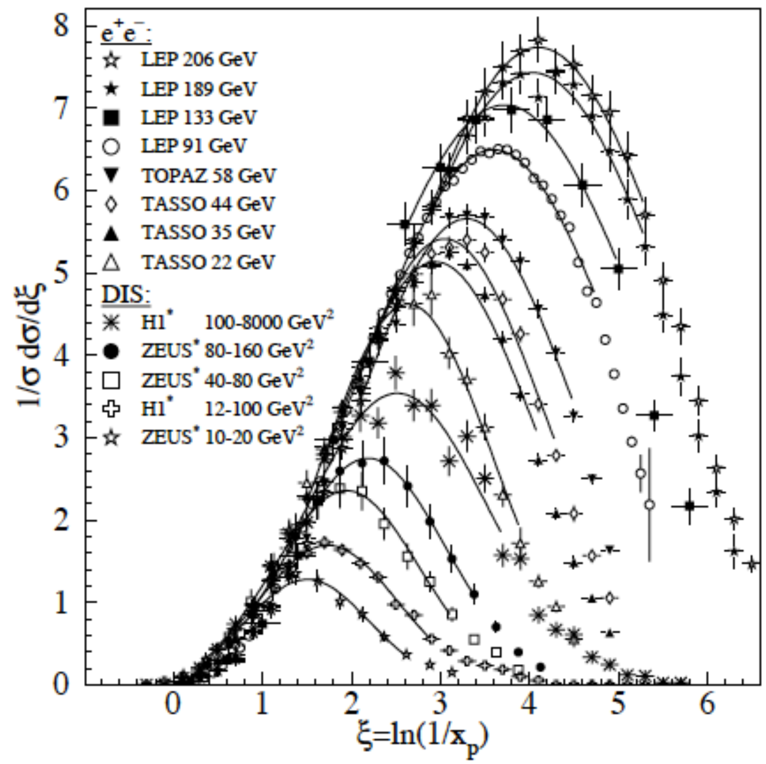
C. Zapp et al.
arXiv:0804.3568 [hep-ph]

Properties of the Fragmentation Function

- Universal (independent of collision system)
- Scale dependence ➔ DGLAP evolution
- Dependence on partonic species (g vs q vs Q)

Fragmentation Functions in e^+e^-





MLLA:

$$z = p_{L|jet}^{hadron} / p^{Jet}$$

peak position $\xi_p \simeq \frac{1}{4} ln \left(\frac{s}{\Lambda^2} \right)$

$$\xi = ln(E^{Jet} / p_{hadron})$$

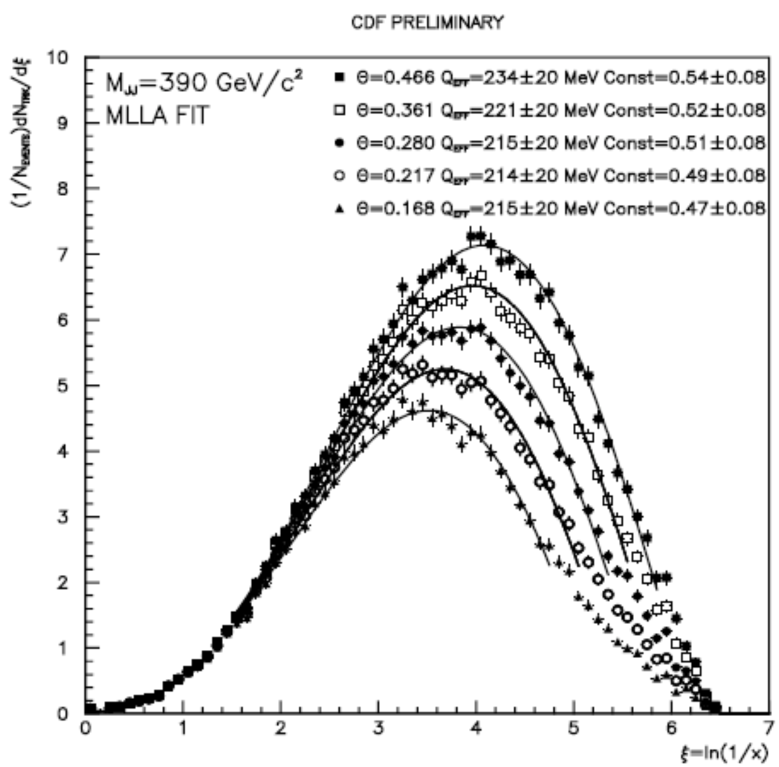
Gaussian width $\sigma \propto \left[ln \left(\frac{s}{\Lambda^2} \right) \right]^{\frac{3}{4}}$

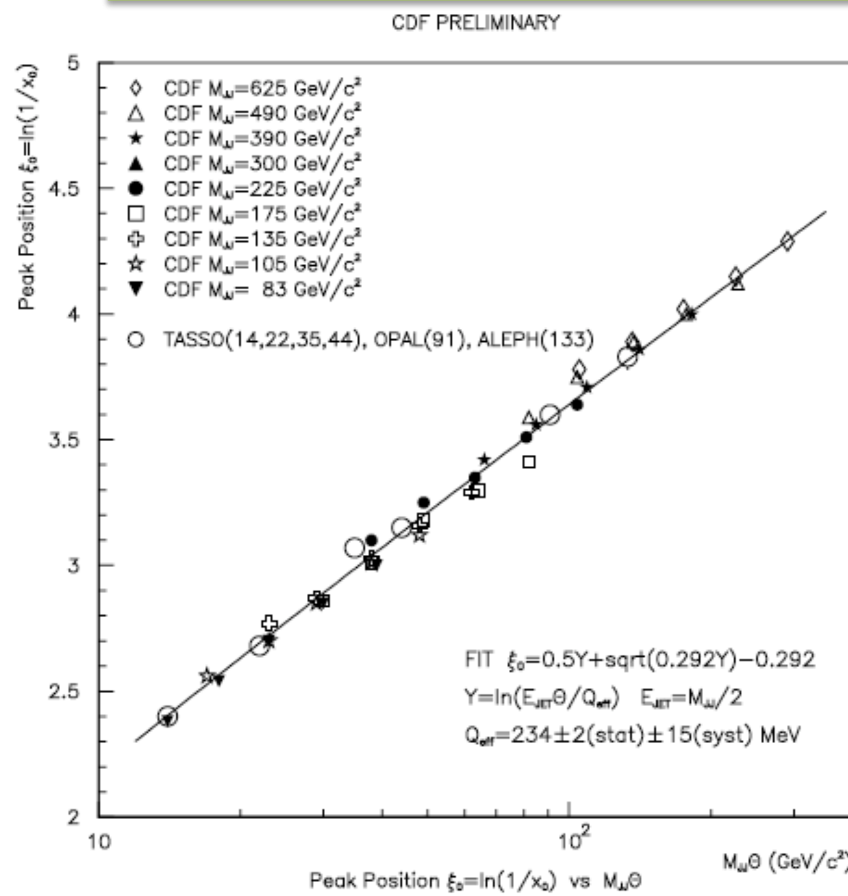
Tevatron circa 2000 A.D.

Note: these are not fragmentation functions –
Rather: hadronic momentum distributions in jets

Why not FFs?

- No evidence that they are universal
- No unambiguous definition of scale Q^2
  - ➔What is evolution equation?
- Complex and unknown mixture of partonic species

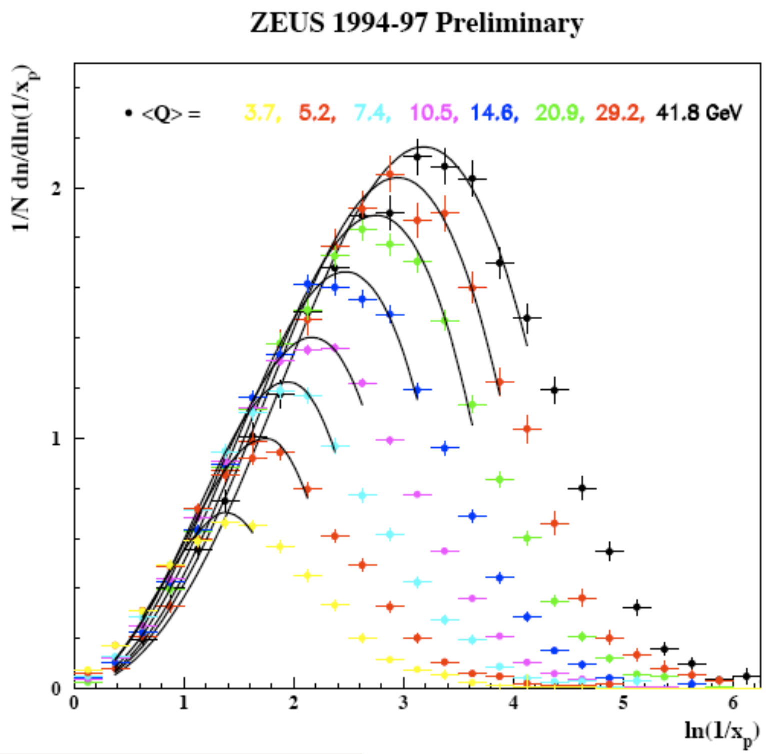


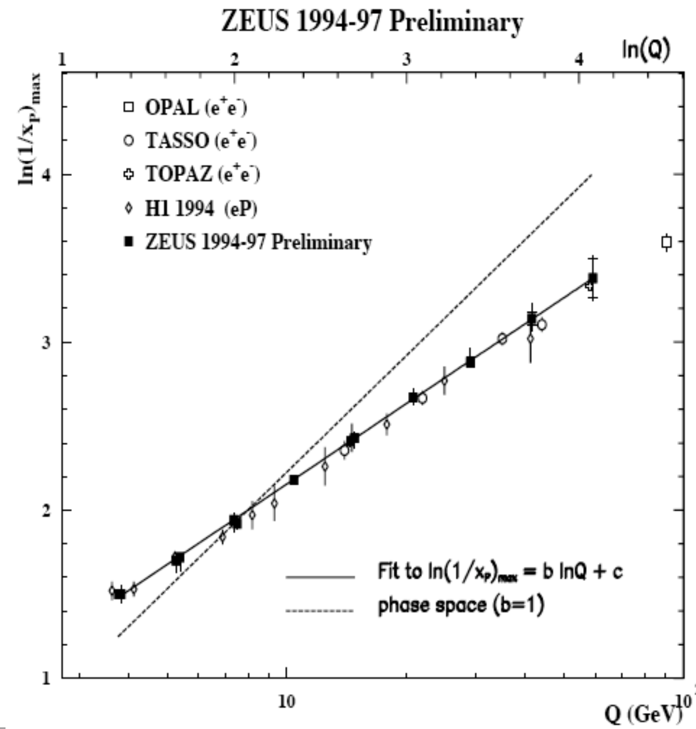


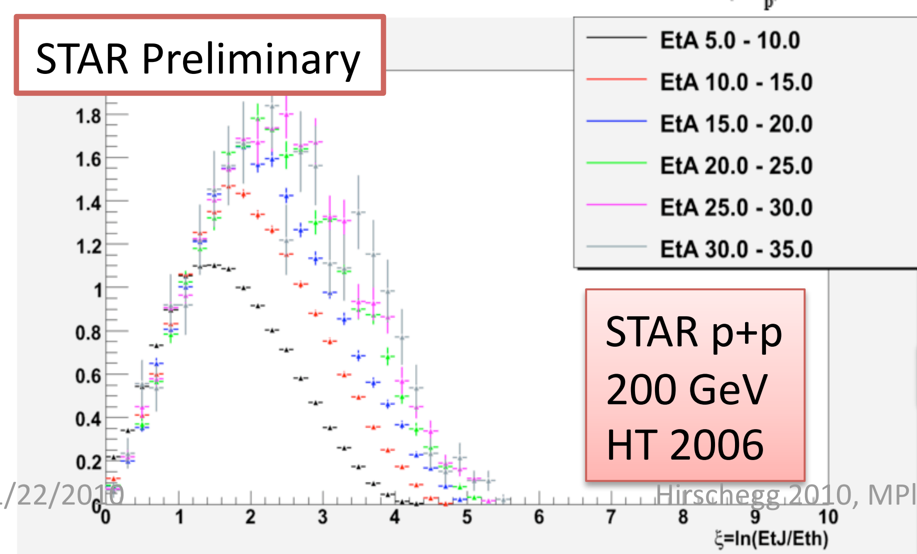
Dijet events: $E_{jet} = M_{jj}/2,\ Y = \ln\left(\frac{E_{jet}\cdot\theta_{cone}}{Q_{eff}}\right),\ \xi = \ln\frac{E_{jet}}{p_{trk}}$

$$Q_{eff} \equiv Q_0 = \Lambda_{QCD}$$

Hadrons in jets @ RHIC



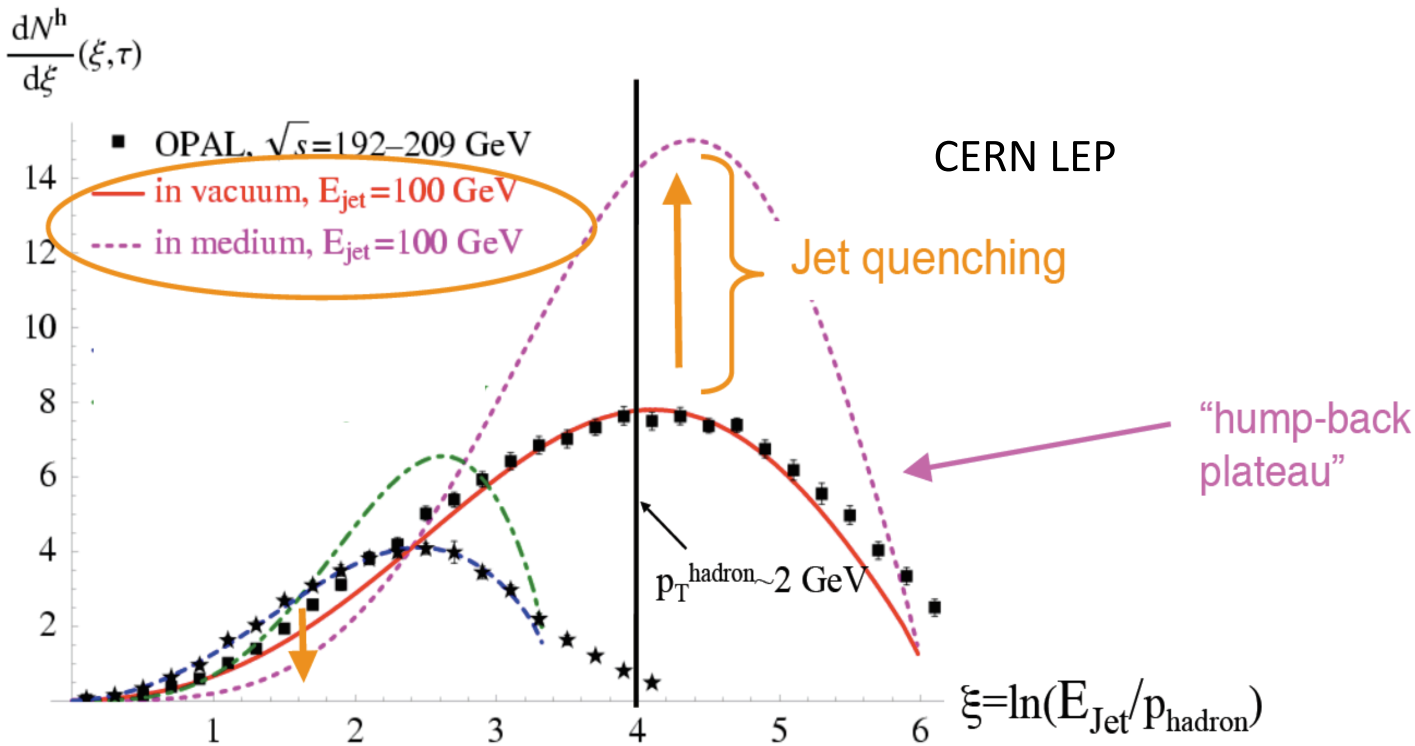




$$\xi \cdot \xi_{\max} \equiv \log(1/x_p)_{\max}$$

Test?

Why to measure fragmentation patterns in HI collisions?



Outlook

Complete jet reconstruction promises qualitatively new insight into jet interactions in matter

→major focus of RHIC II and LHC HI programs
→has stimulated significant new theory activity

But significant technical issues for systematically well-controlled measurements

→main issue: HI background characterization
→high backgrounds expected also in high luminosity p+p at LHC

Hadronic collisions and pQCD

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a,Q^2) \otimes f_{b/B}(x_b,Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c,Q^2)$$