Jet finding – a quick guide

A free speech exercise

Outline

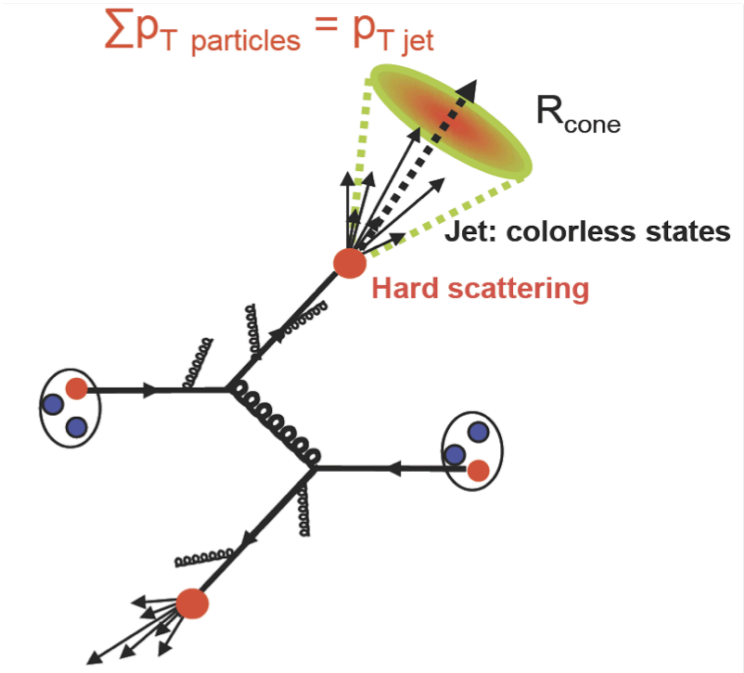
- What is a jet and what does it mean to reconstruct it? Why to reconstruct jets?
- Jets in elementary, hadronic collisions
- Jet finders and different jet definitions
- Backgrounds? Pile-up, underlying event, heavy-ion activity
- Summary

What is a jet?

A spray of collimated showers/particles

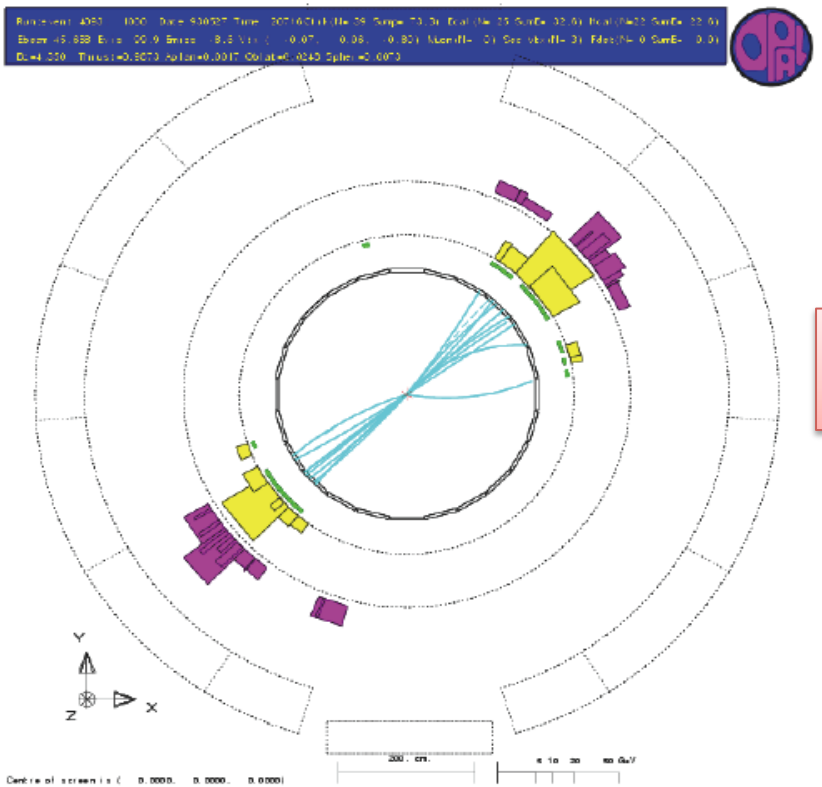
- Hardly ever better defined...

- 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

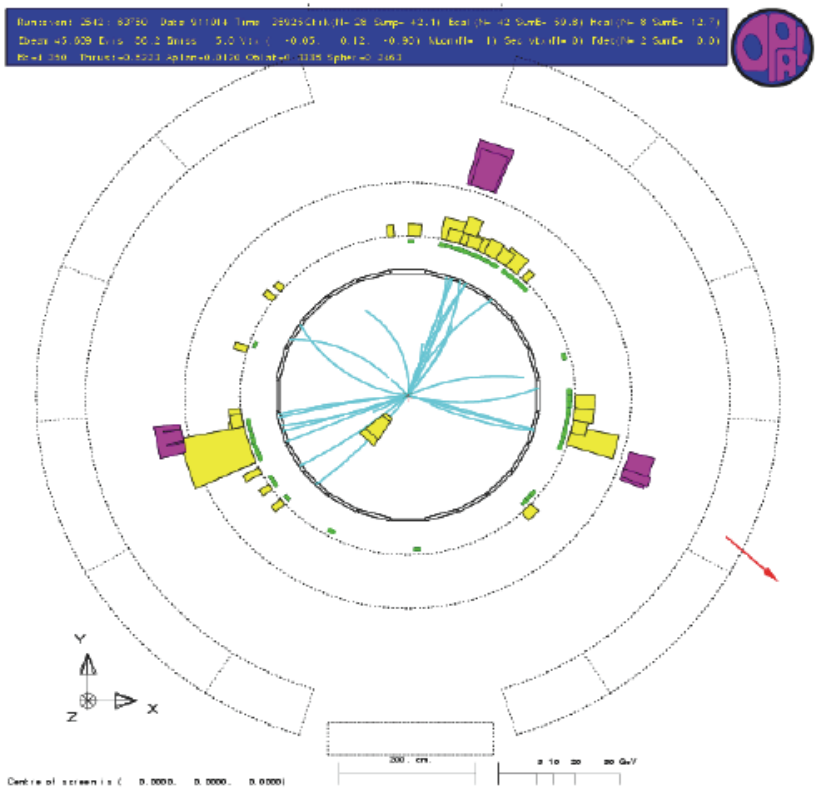


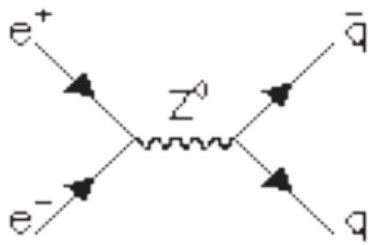
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

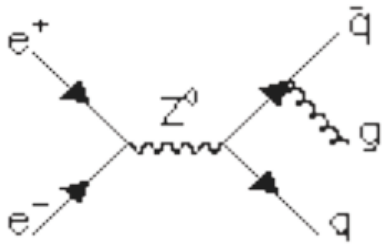
Jets at collider experiments



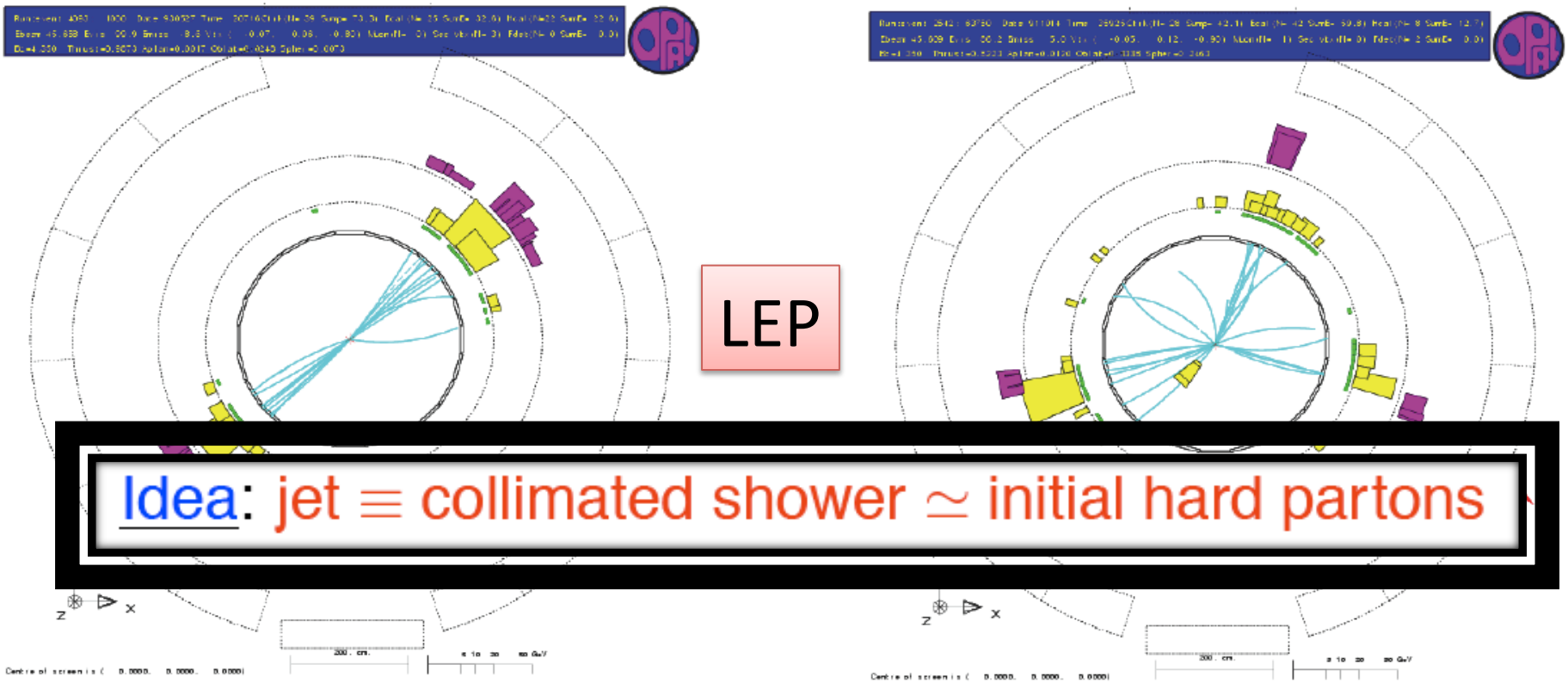
LEP



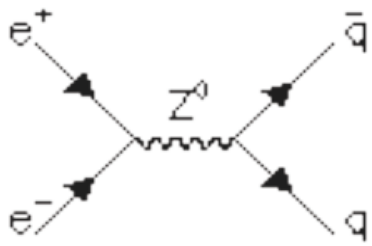


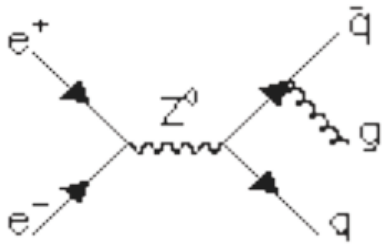


Jets at collider experiments



Idea: jet ≡ collimated shower ≃ initial hard partons





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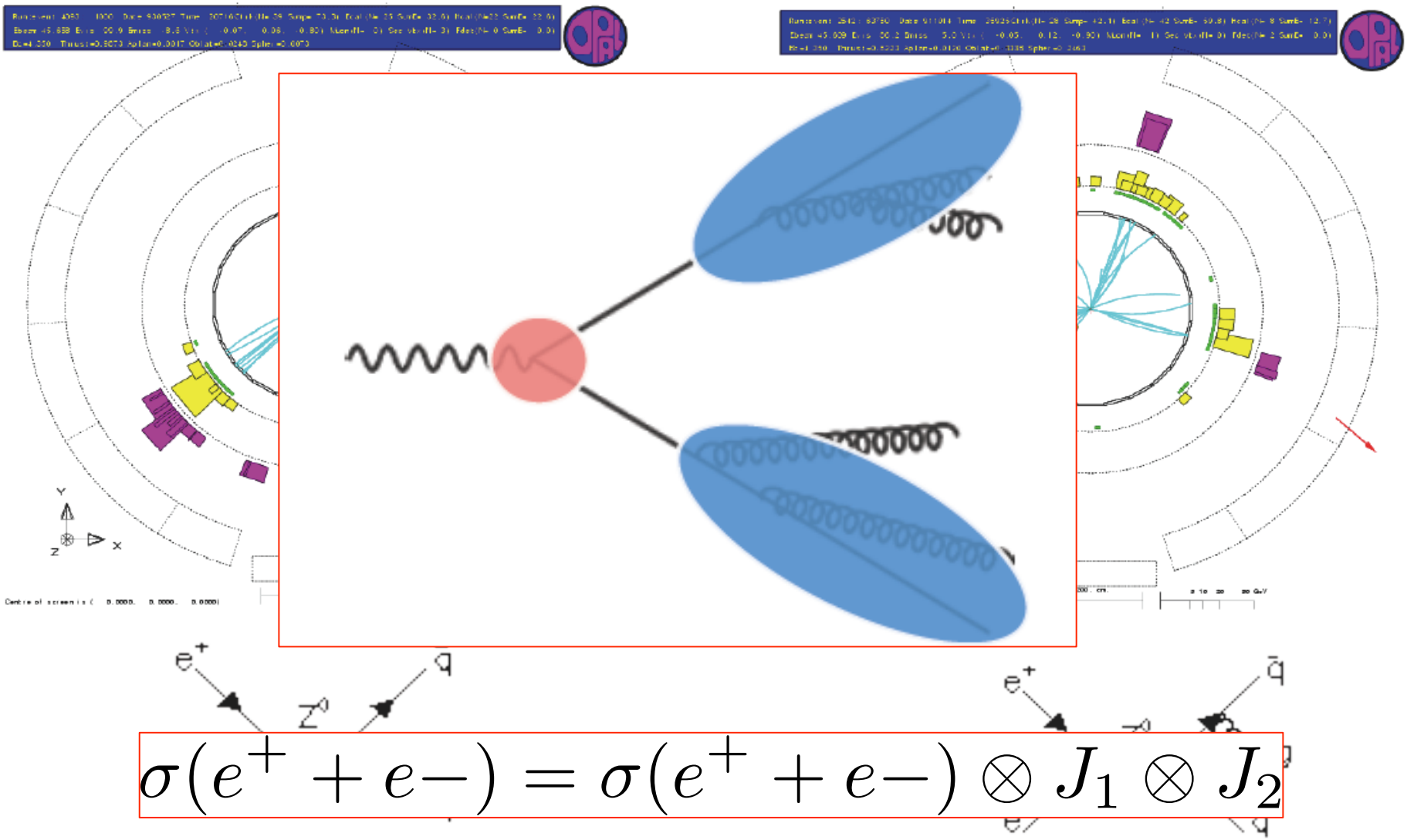
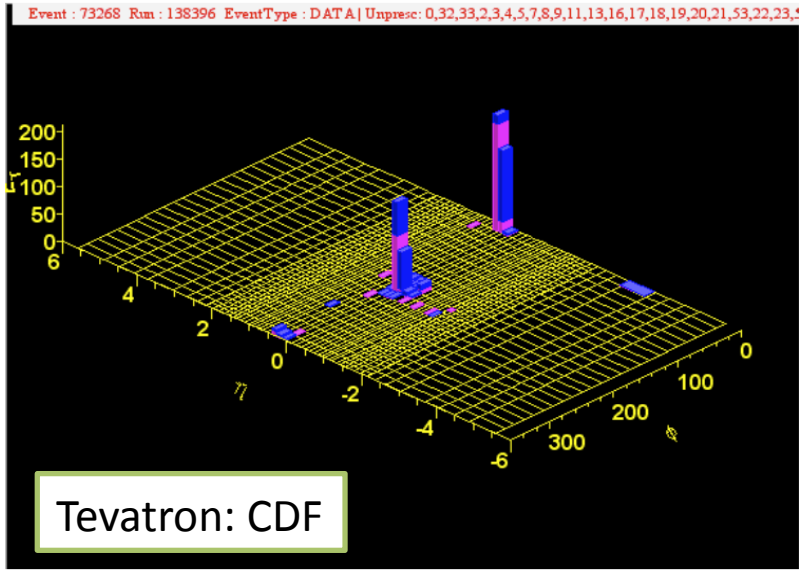


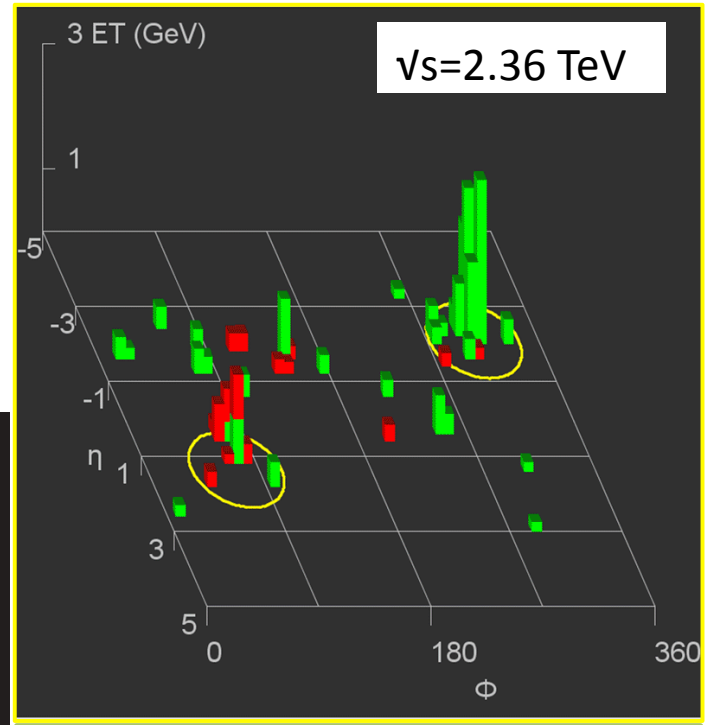
$$\sigma(e^+ + e-) = \sigma(e^+ + e-) \otimes J_1 \otimes J_2$$

Tevatron, RHIC and already at LHC



These are hadron colliders!

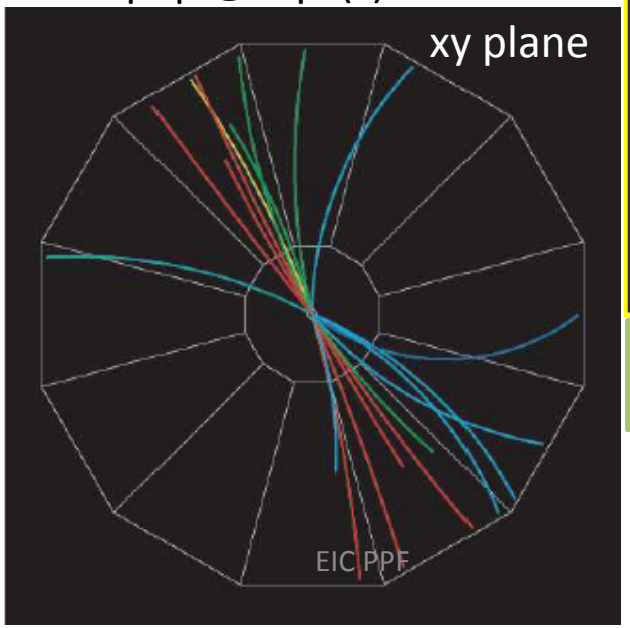
ATLAS Nov/Dec 2009



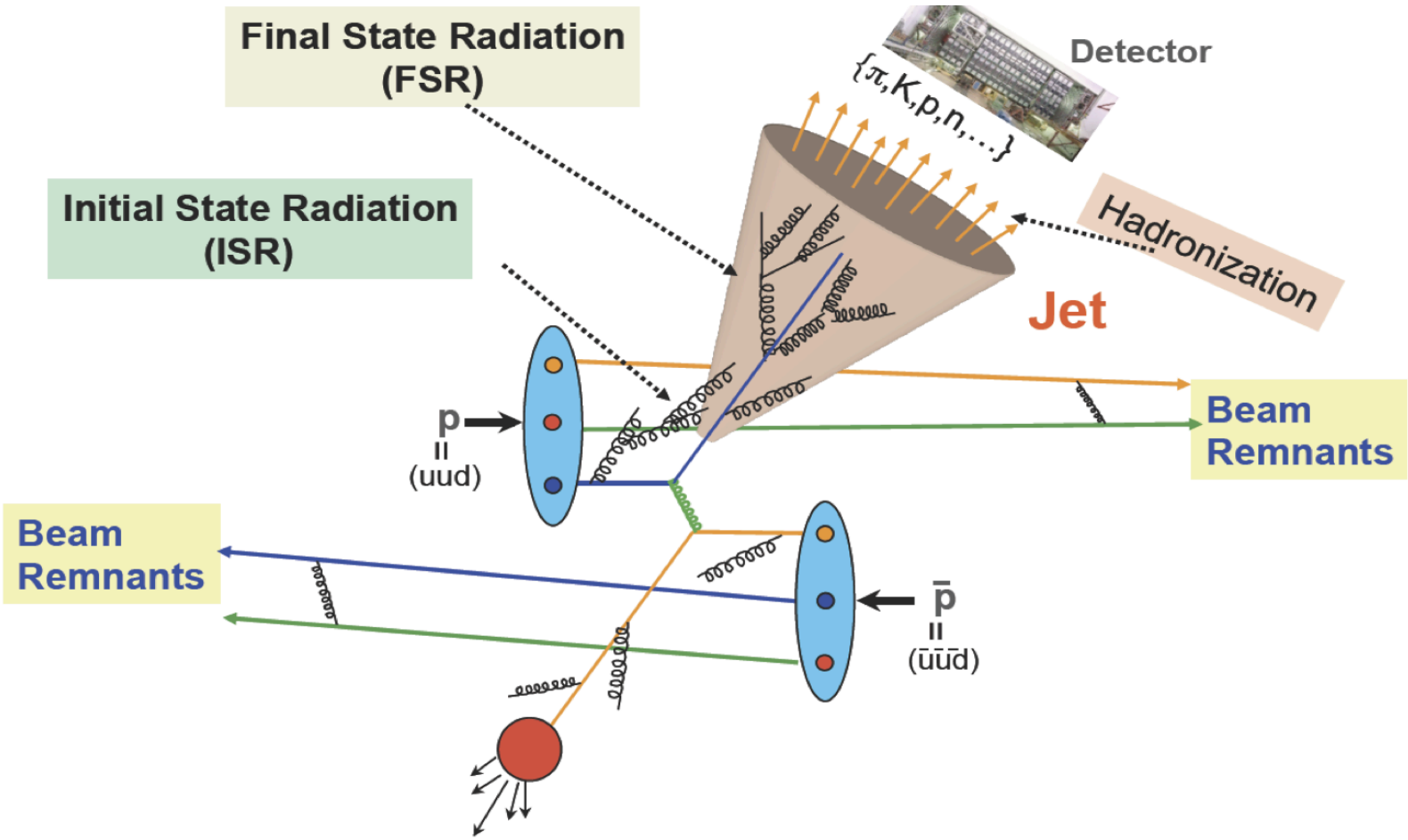
Jet1: E_T (EM scale)~ 16 GeV, $\eta = -2.1$
Jet2: E_T (EM scale) ~ 6 GeV, $\eta = 1.4$

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

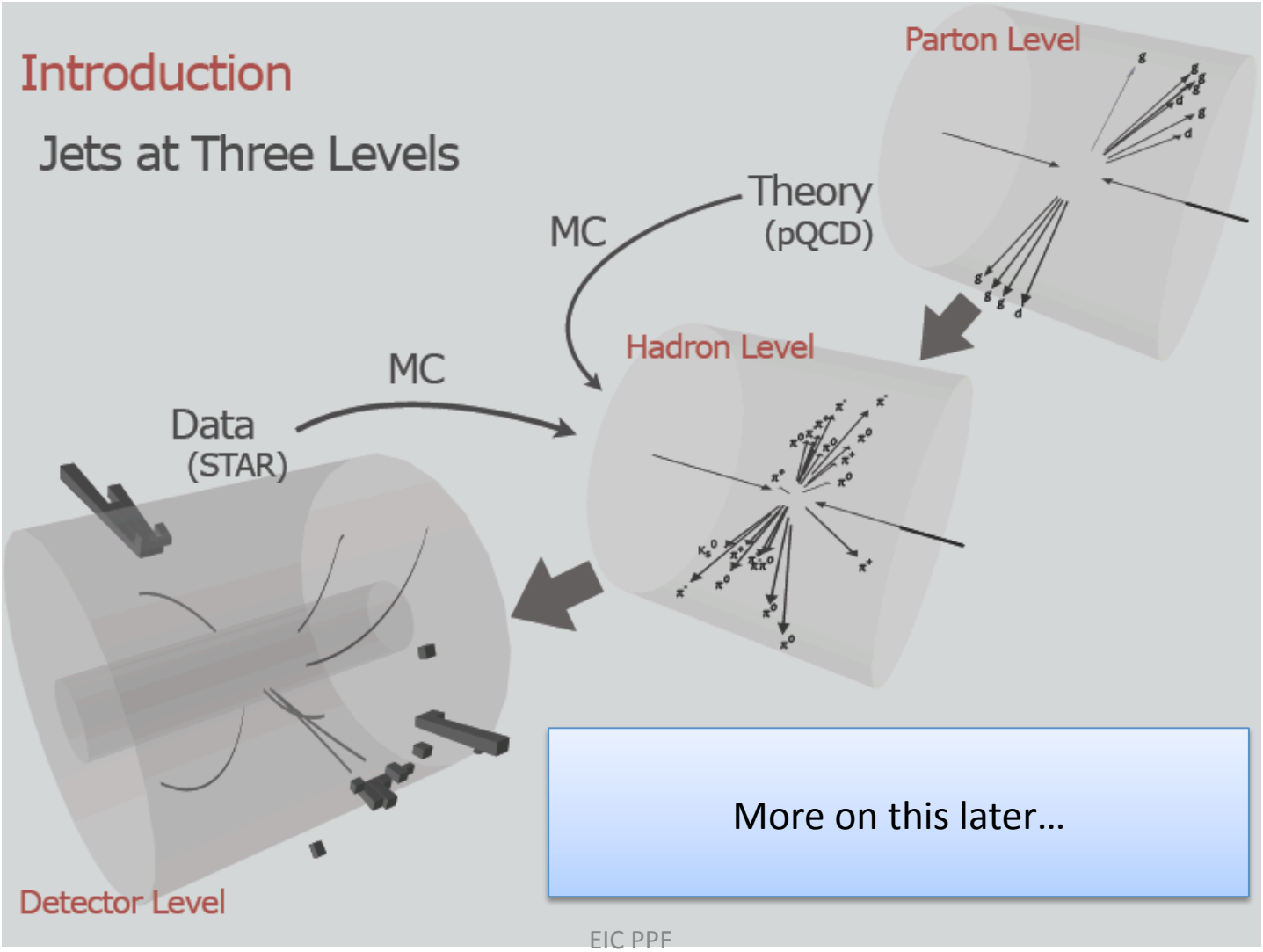
STAR TPC Event Display



What really happens in hadronic collisions…



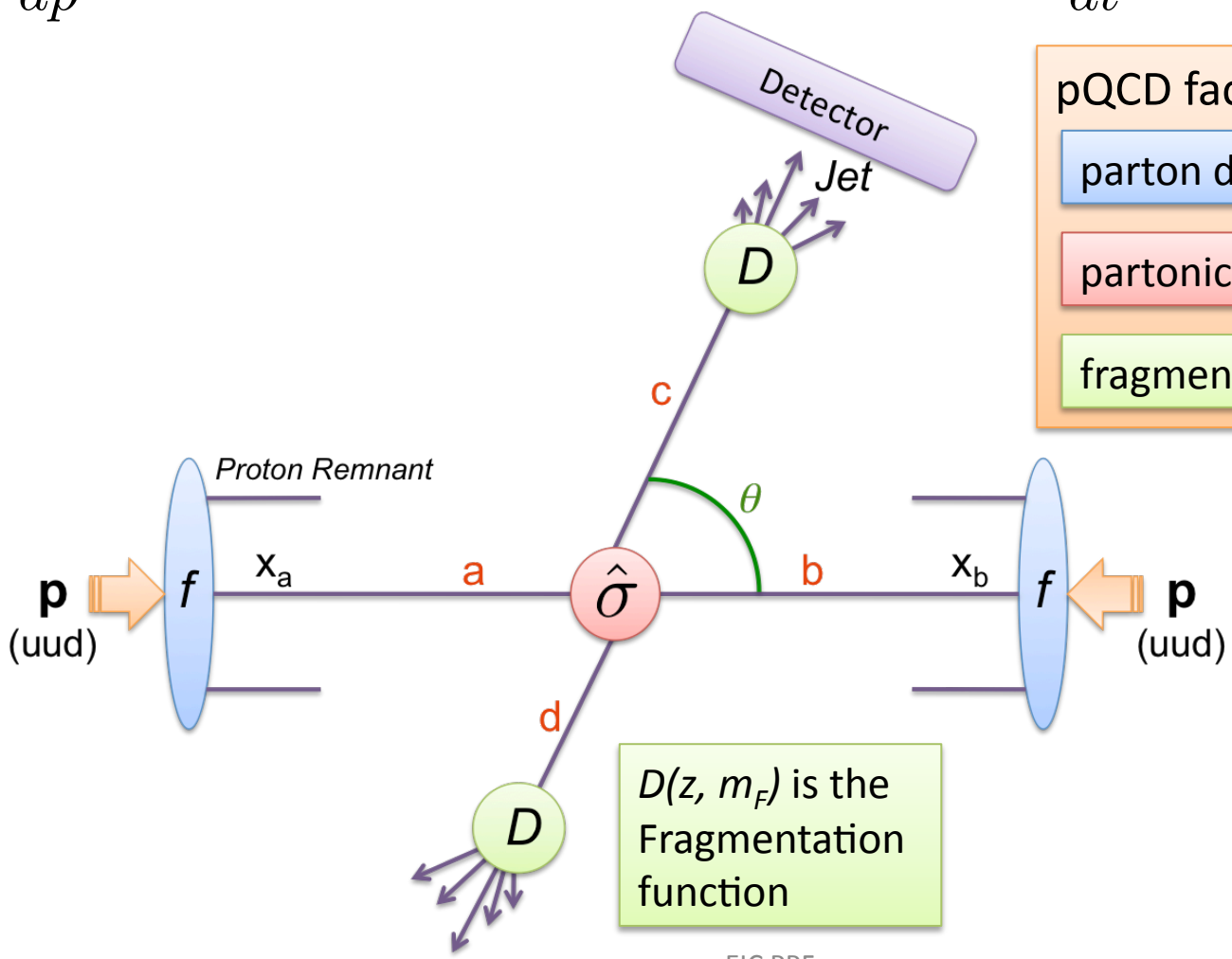
Jets at different “levels”



More on this later…

Hadronic collisions and pQCD

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

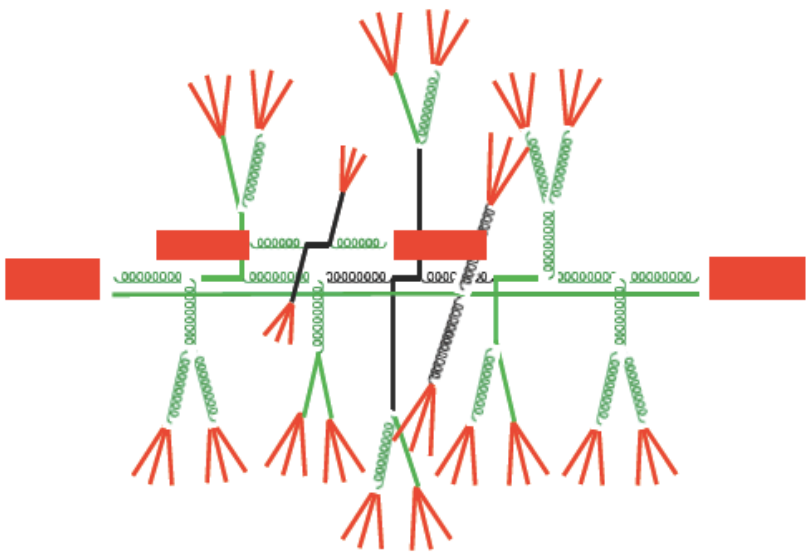


pQCD factorization:

- 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).

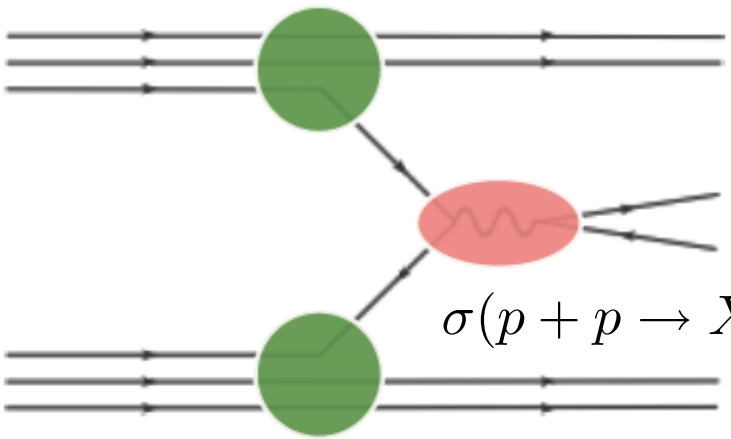
Why jets?

- 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

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

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

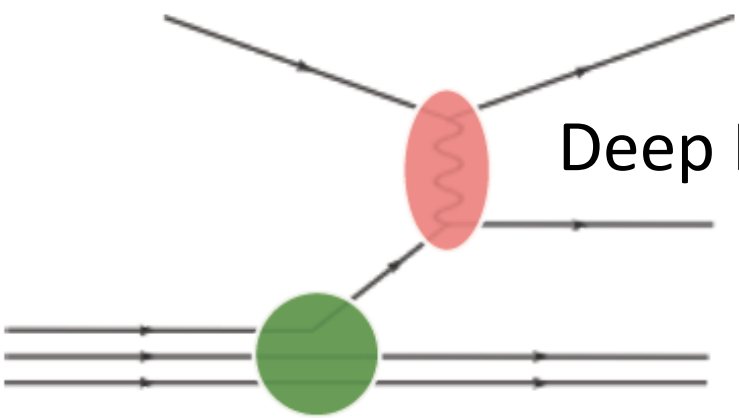
Examples of processes calculable within pQCD



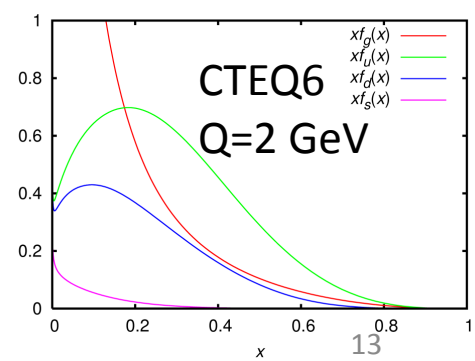
Drell-Yan

$$\sigma(p+p \to X + e^+ + e-) = f_q \otimes f_q \otimes \sigma(q+q \to e^+ + e-)$$

$$\sigma(p+e^- \to X + e-) = f_q \otimes \sigma(q+e^- \to q + e-)$$

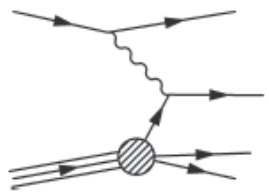


Deep Inelastic Scattering



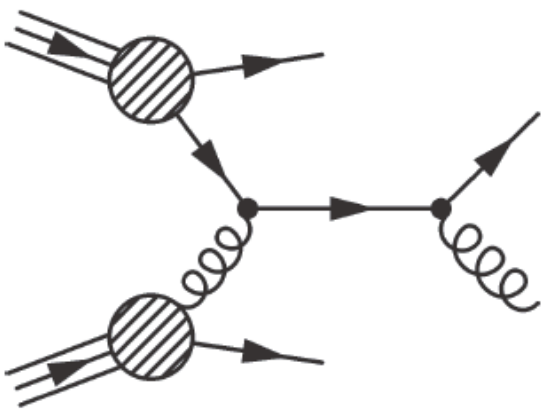
Examples of processes calculable within pQCD

In DIS, parton-level kinematics can be always determined



$$x = \frac{Q^2}{2M\nu}$$

In pp, not unless two outgoing partons are measured

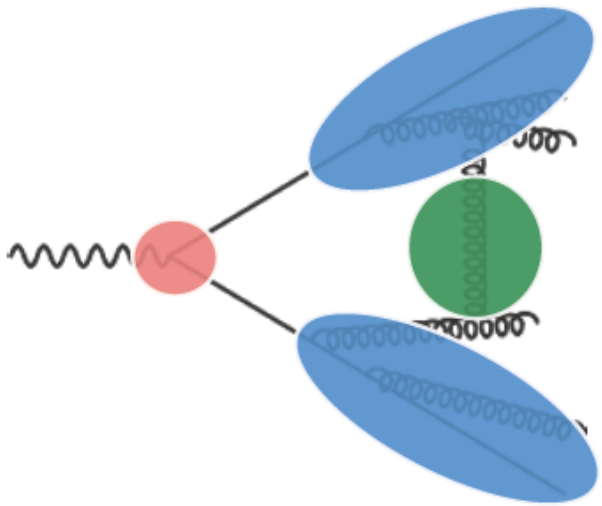


$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{\eta_3} + e^{\eta_4} \right)$$

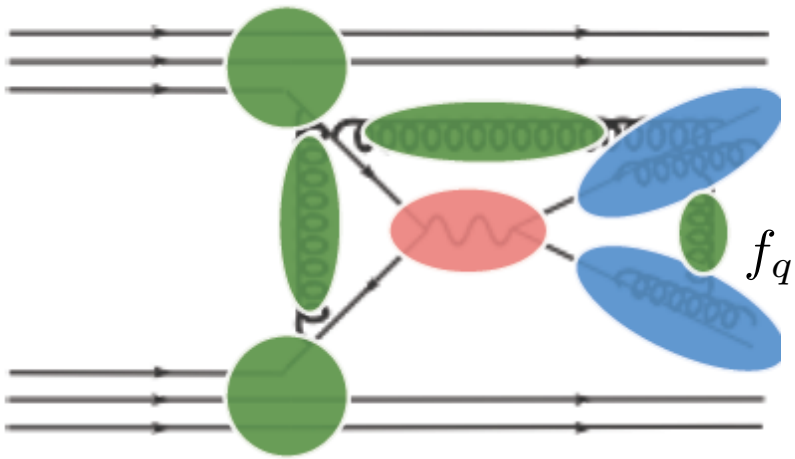
$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-\eta_3} + e^{-\eta_4}\right)$$

can be estimated from dijets

Event shape studies



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



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

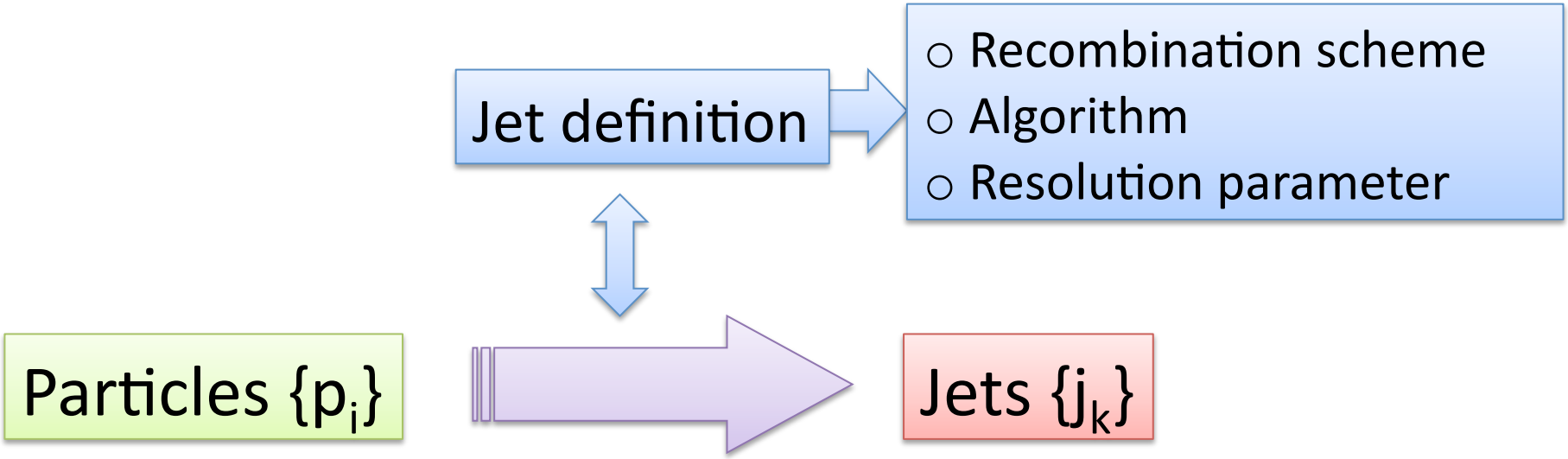
Focus of this talk

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

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

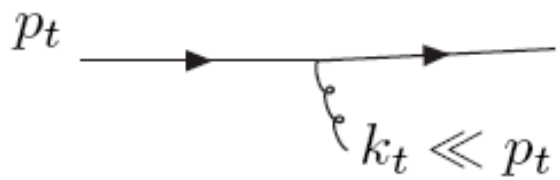
QCD divergences and jet finders

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

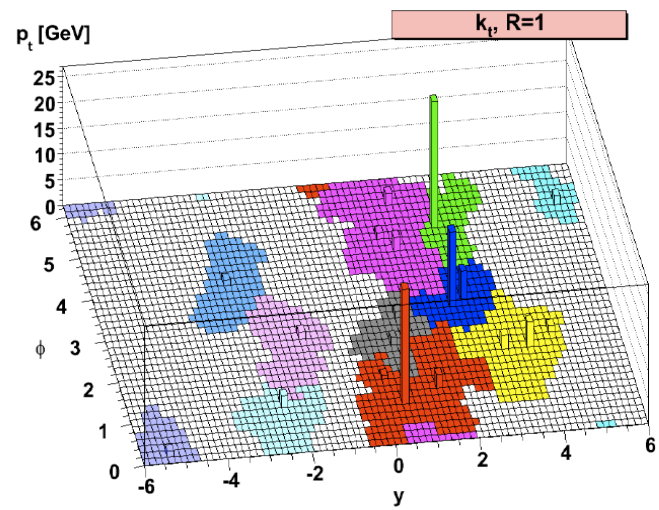
- Some "bad" jet properties
  - Multiplicity (not well understood in theory and not easily measured)
  - Charge (pair from vacuum dilutes significance; fractional q charge)
- Jet equivalence:

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

- 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

- Collinear 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)

Jet algorithms - summary

Summary

FASTJET

Unsafe

- CMS Iterative Cone
- ATLAS Cone
- CDF JetClu
- CDF MidPoint
- D0 run II Cone

Safe

- k_t
- Cambridge/Aachen
- anti-k_t
- SISCone

Impact

Observable	Last meaningful order
Inclusive jet cross section	NLO
3 jet cross section	LO (NLO in NLOJet)
$W/Z/H$ + 2 jet cross sect.	LO (NLO in MCFM)
jet masses in 3 jets	none (LO in NLOJet)

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

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

   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 $d_{iB} = k_{ti}^2$.

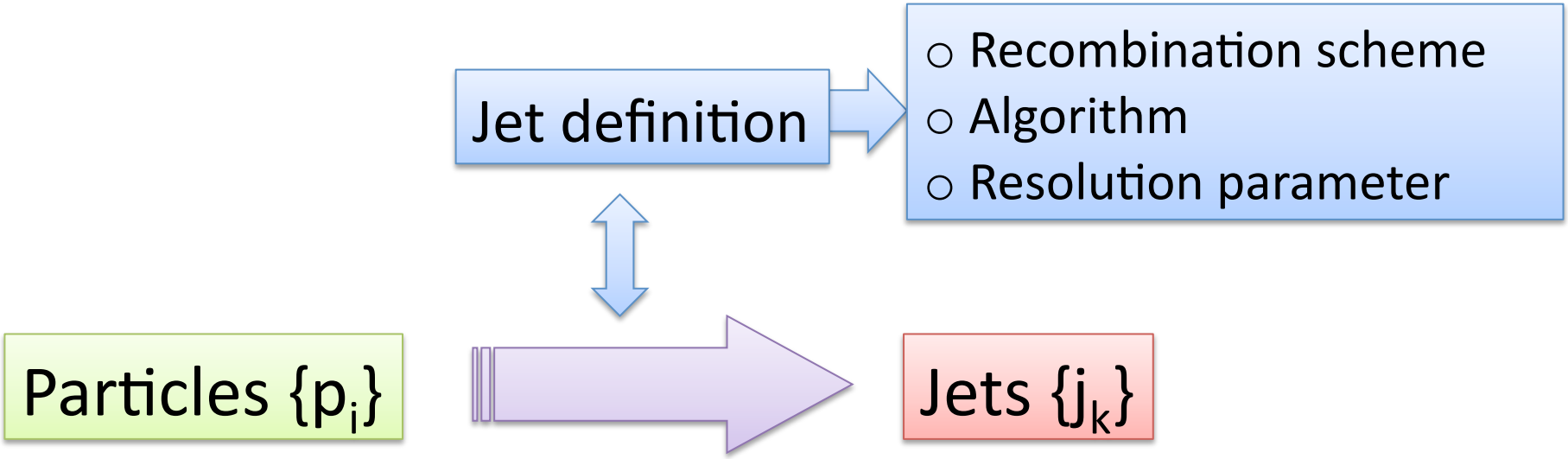
2. Find the minimum $d_{\min}$ of all the d_{ij}, d_{iB}. If $d_{\min}$ is a d_{ij} merge particles i and j into a single particle, summing their four-momenta (this is E-scheme recombination); if it is a d_{iB} then declare particle i to be a final jet and remove it from the list.

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]

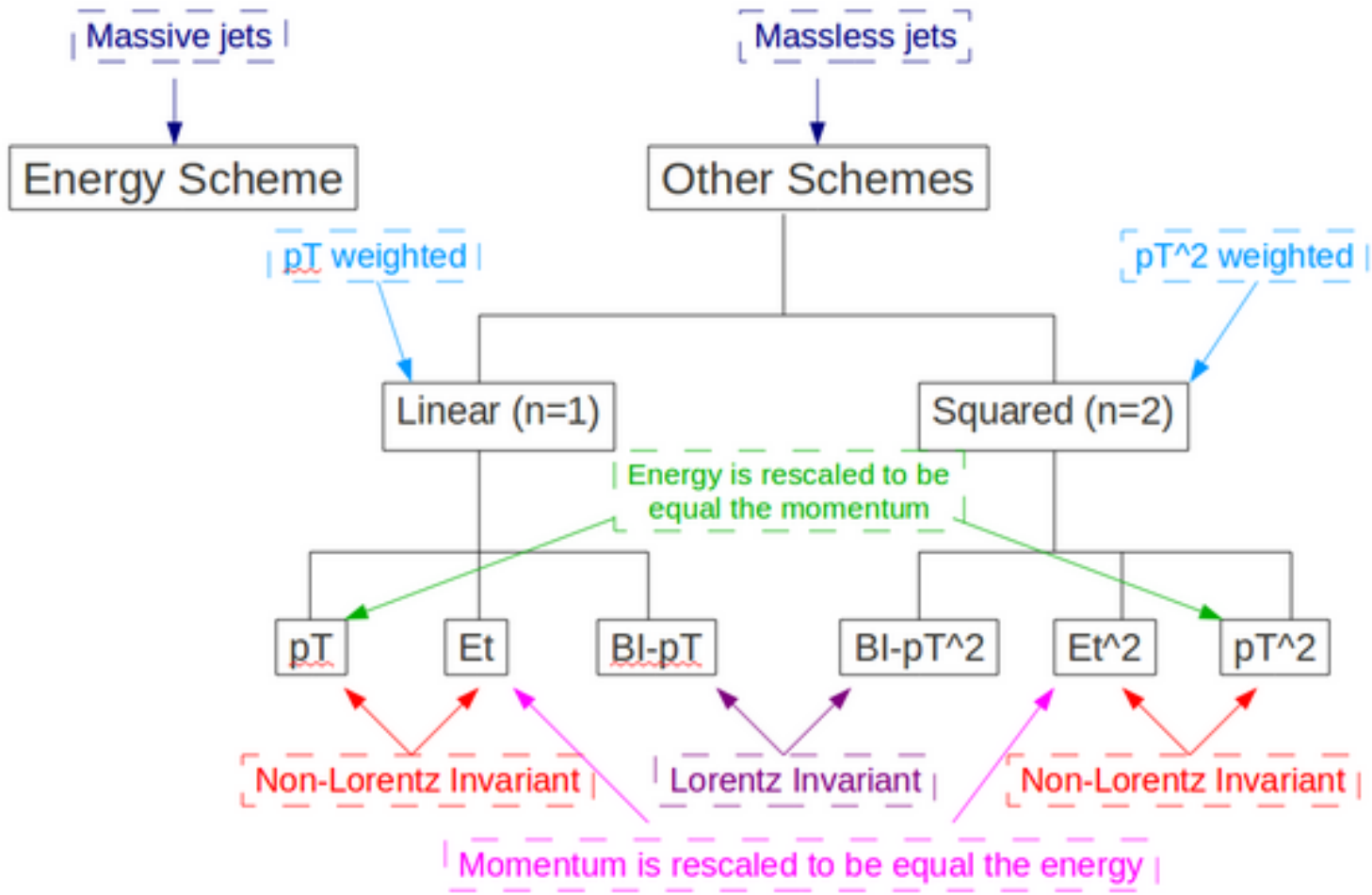
Finding jets



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

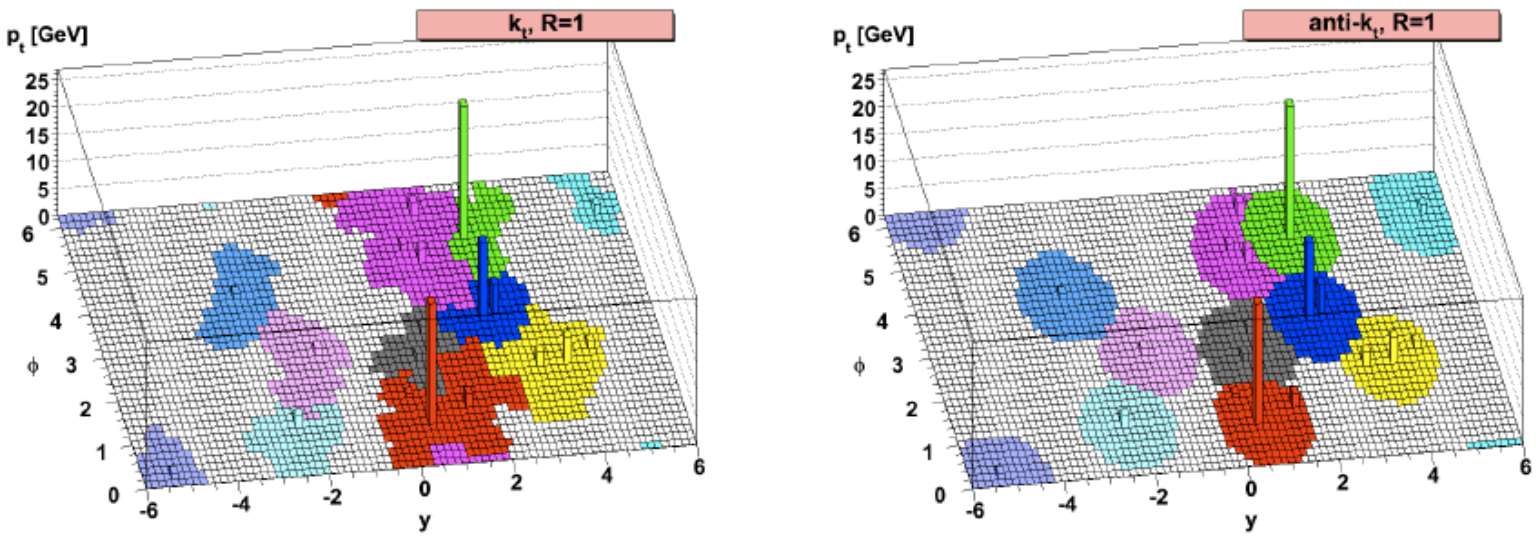
So, what is a recombination scheme?

-> at each step of algorithm one has a choice how to cluster/recombine the particles/objects into a resulting “jet”



Different jet finders – different structures – again: jet definition!

k_t | anti-k_t



Example: perturbative expansion of areas (at order α_s)

$$\langle \mathcal{A}(p_t, R) \rangle = \mathcal{A}_0 + \frac{C_{F,A}}{b_0 \pi} \pi R^2 \, d \, \log \left(\frac{\alpha_s(Q_0)}{\alpha_s(R p_t)} \right)$$

FASTJET

- area $\neq \pi R^2$, area $\neq$ const.

$Q_0 \equiv$ IR regulator $\propto$ background density

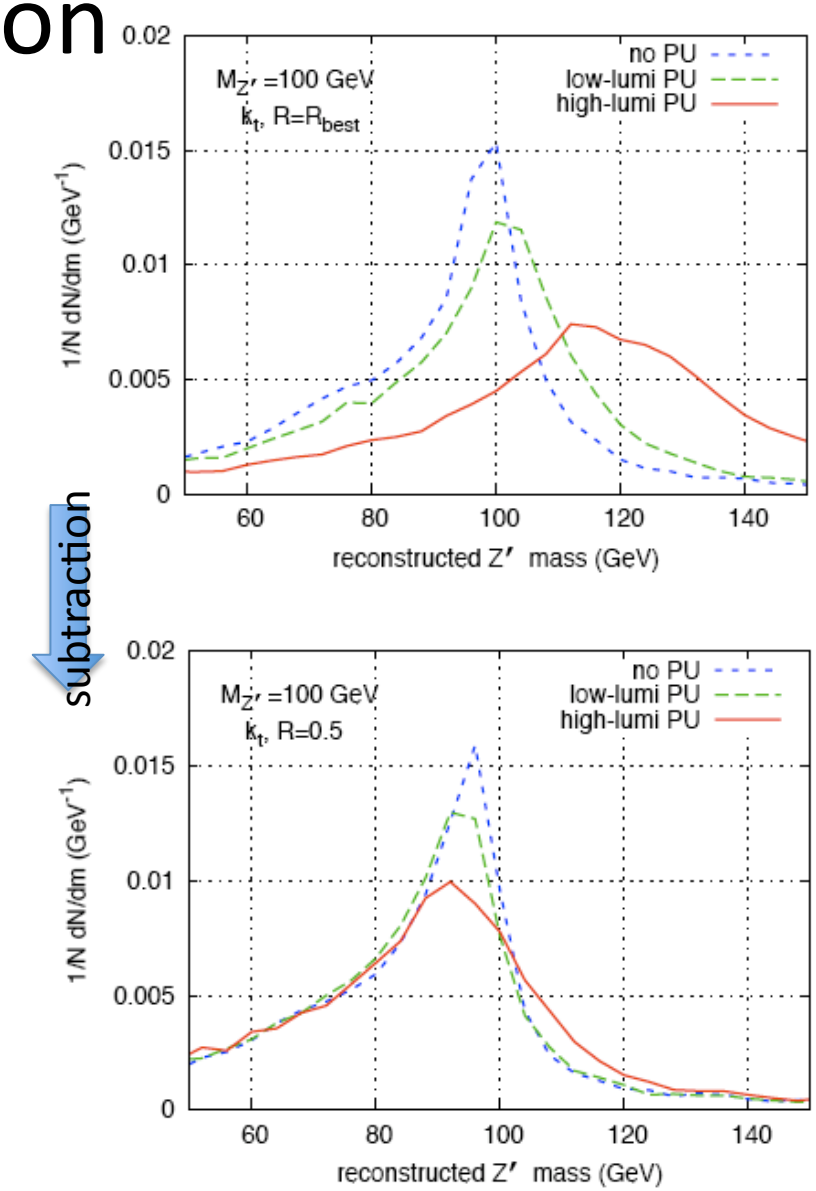
Background subtraction

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

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

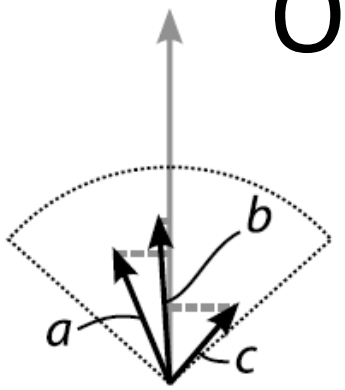
- ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm
- A: area of the jet – measured using number of artificially injected infinitely soft particles of finite *"size"* into an event that are clustered into the jet
- δρ: uncertainty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

NOTE: ρ can be estimated in several ways!

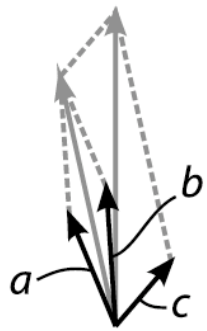


M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

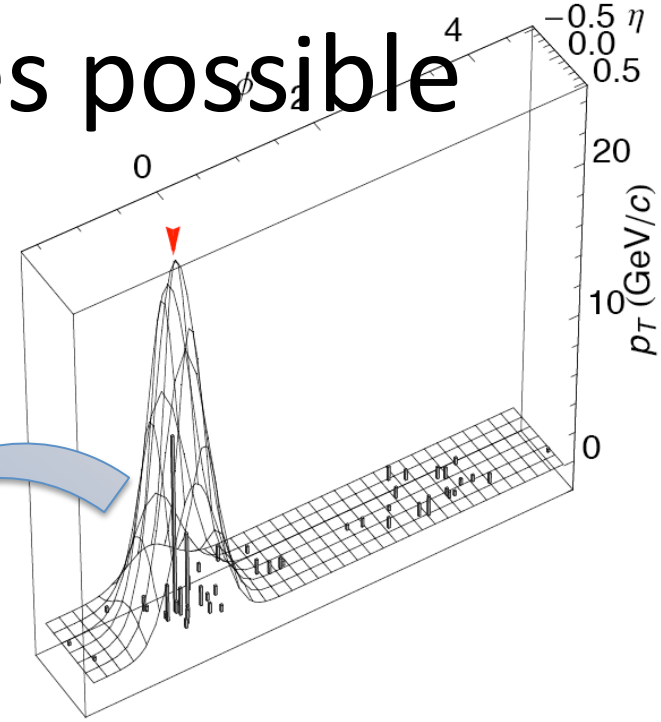
Other approaches possible



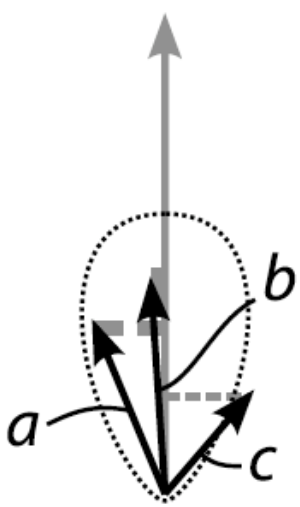
Cone



Recombination



Yui Shi Lai, arXiv:0806.1499, QM 2009



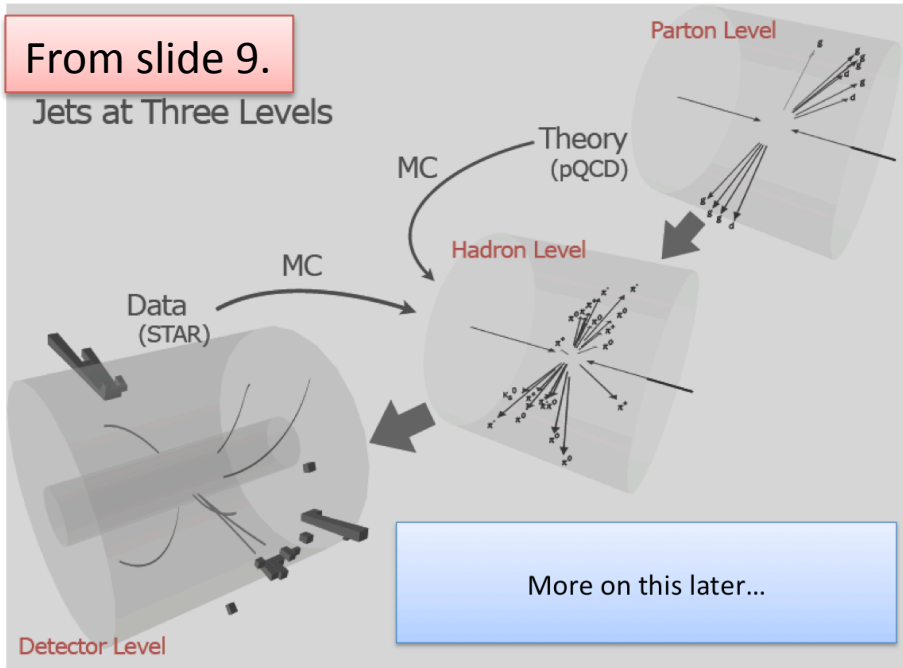
Filter

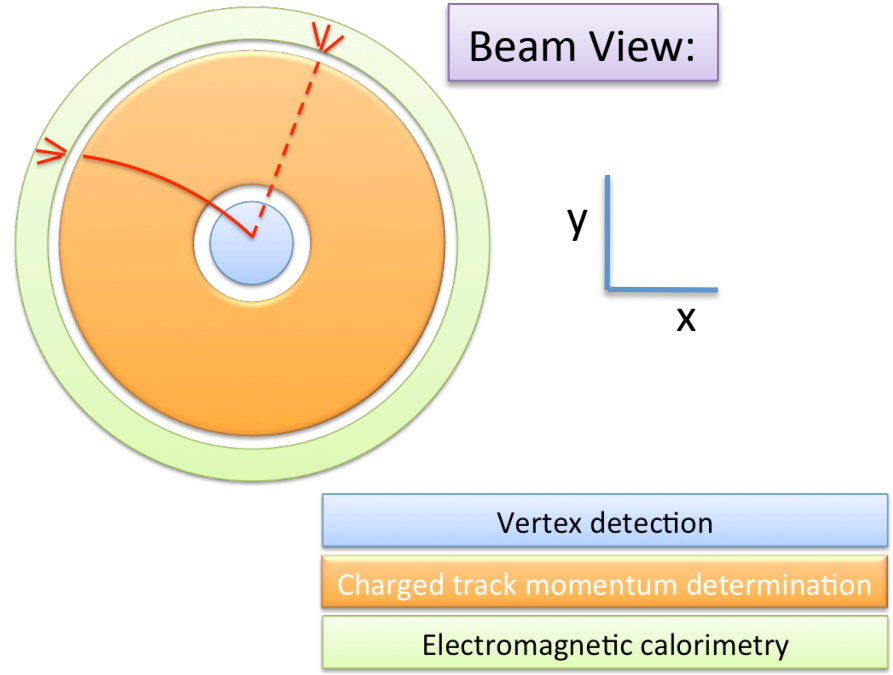
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta',\varphi') \exp\left[-\frac{(\eta-\eta')^2+(\varphi-\varphi')^2}{2\sigma^2}\right] = \text{max!}$$

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

Results from PHENIX

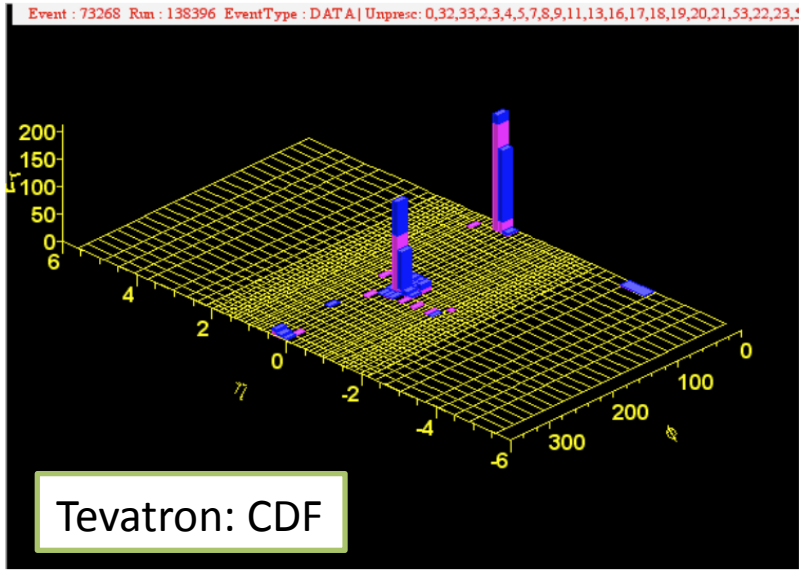
What to “put” in to the jet finder? - experimental issue





Make sure you do not “measure/use” the same energy twice!
STAR example: charged hadrons from TPC also shower into EMC (with a certain P)!

Tevatron, RHIC and already at LHC



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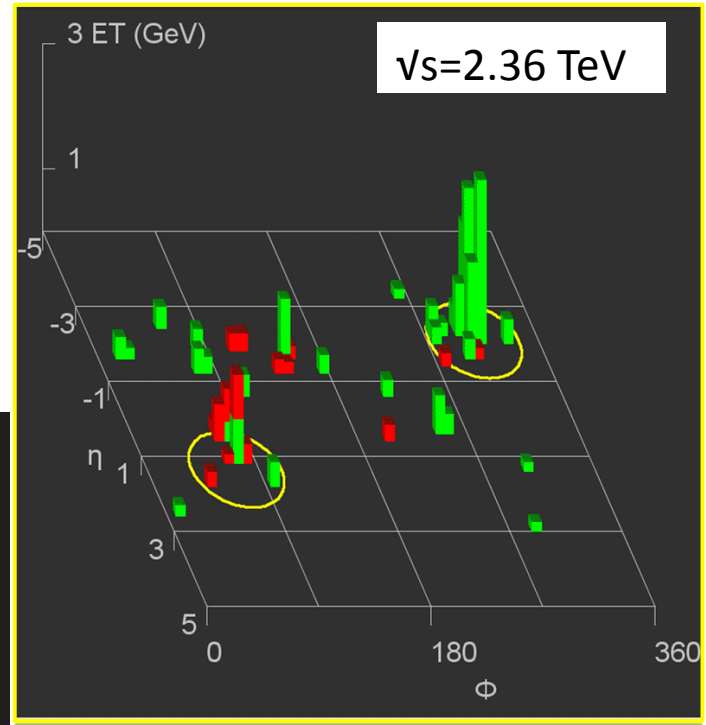

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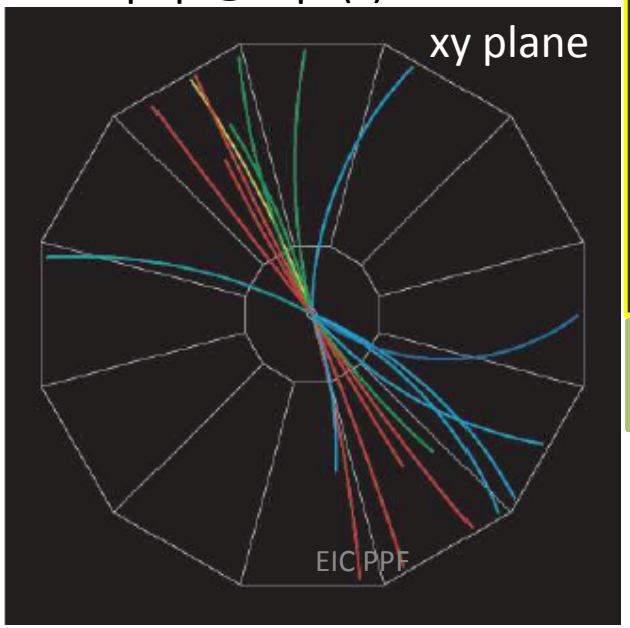
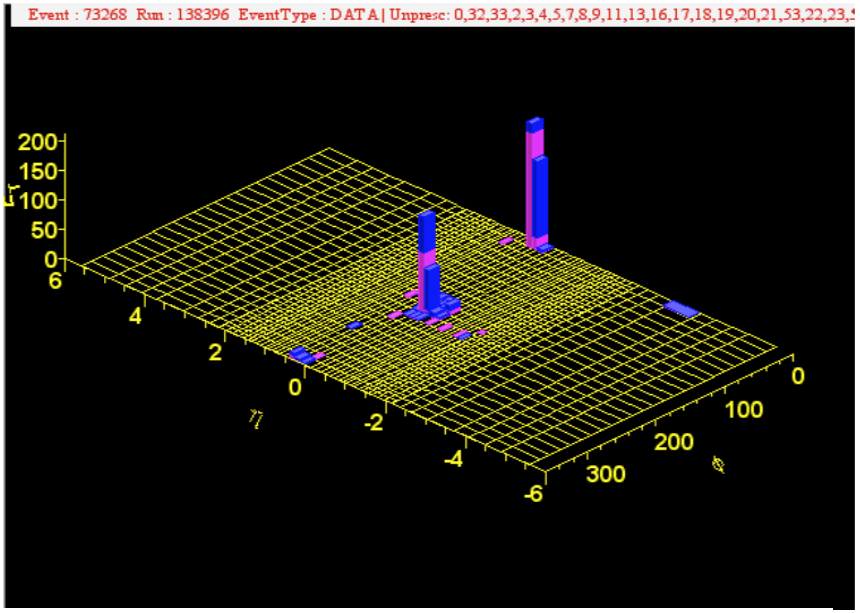


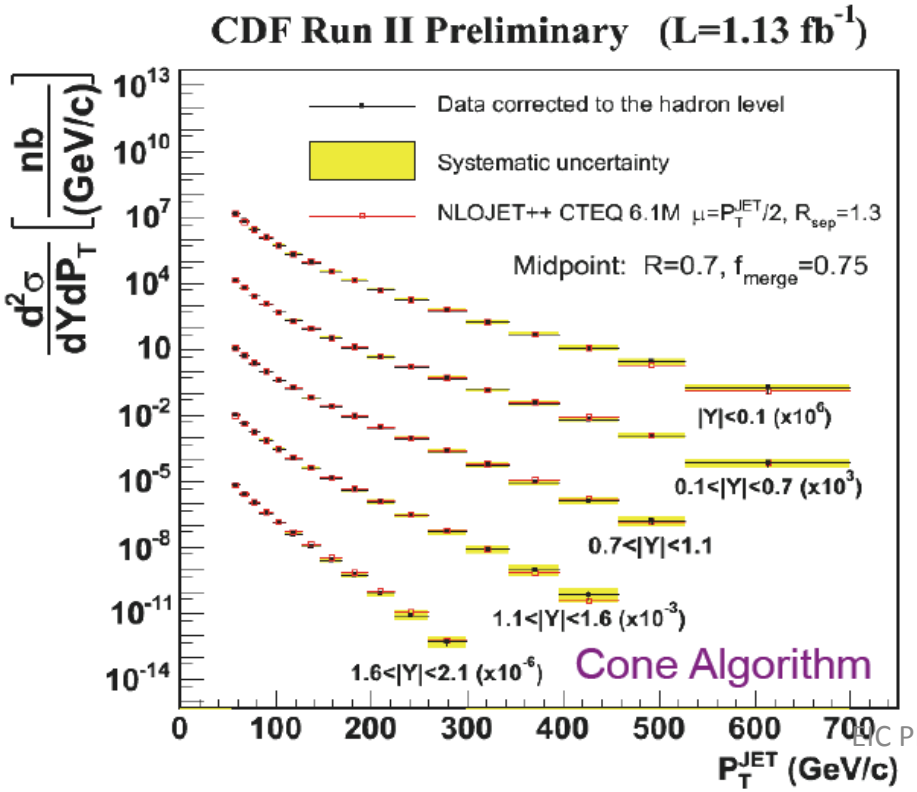
Testing/exercising pQCD…

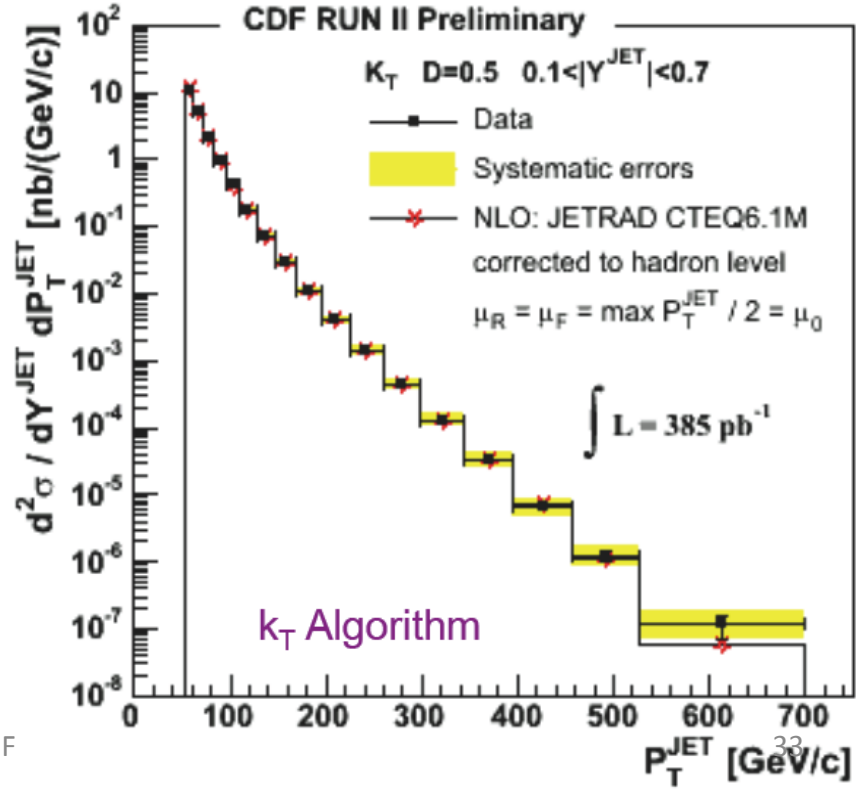
Tevatron

Very good agreement with NLO pQCD

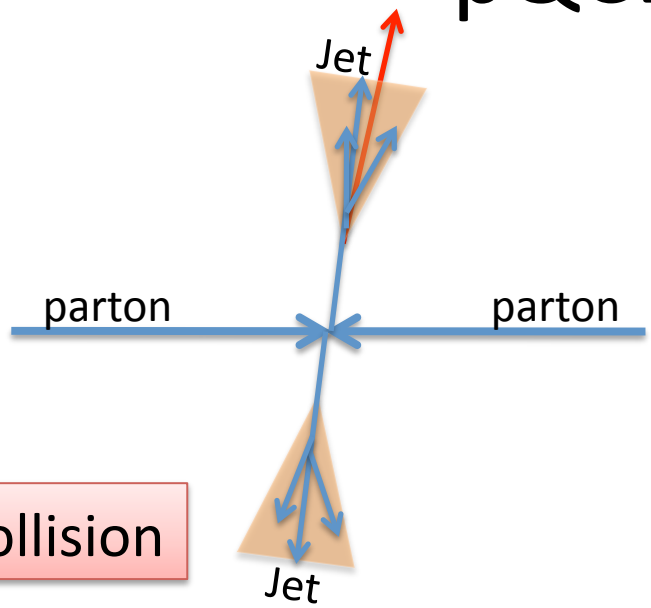
Multiple algorithms used converging to consistent results





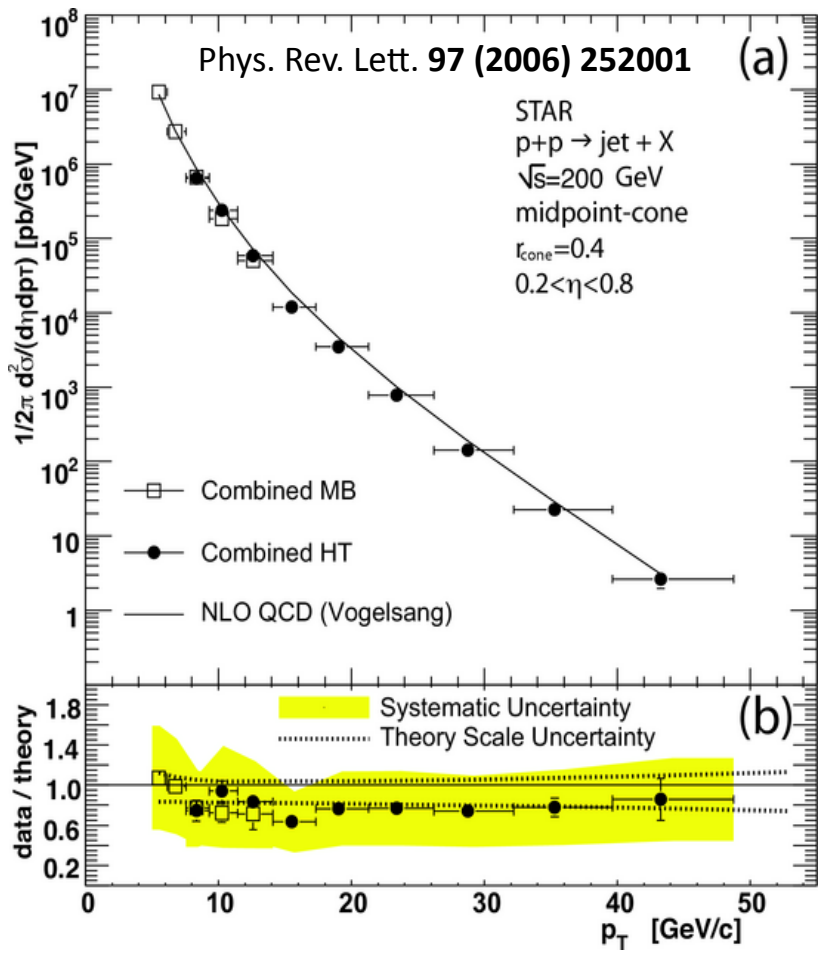


pQCD at RHIC

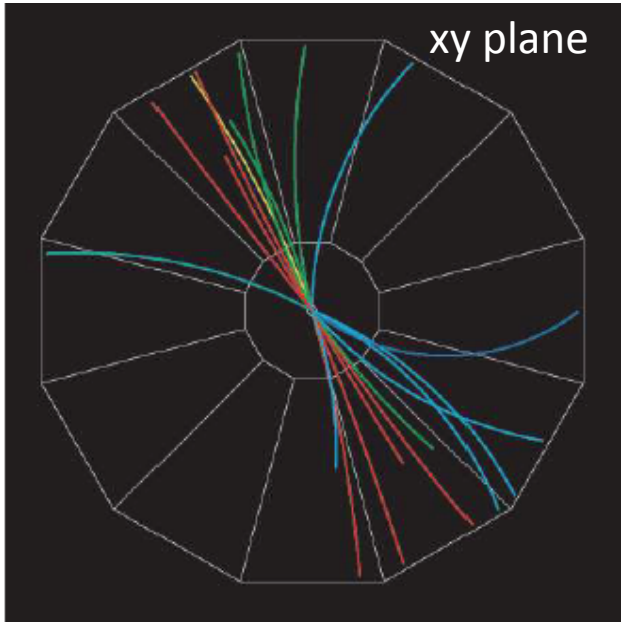


p+p collision

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



STAR TPC Event Display



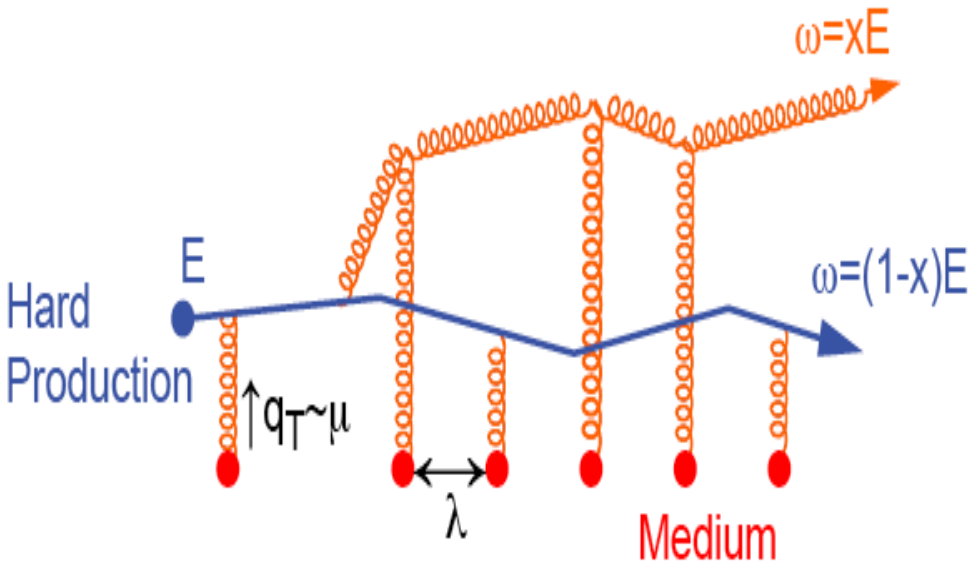
What happens in HI collisions?

Jet-medium interaction

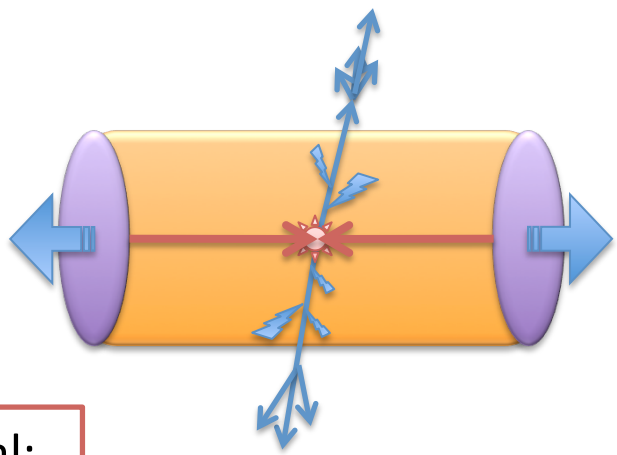
QED: Bremsstrahlung is dominant energy loss mechanism at high energy limit

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)

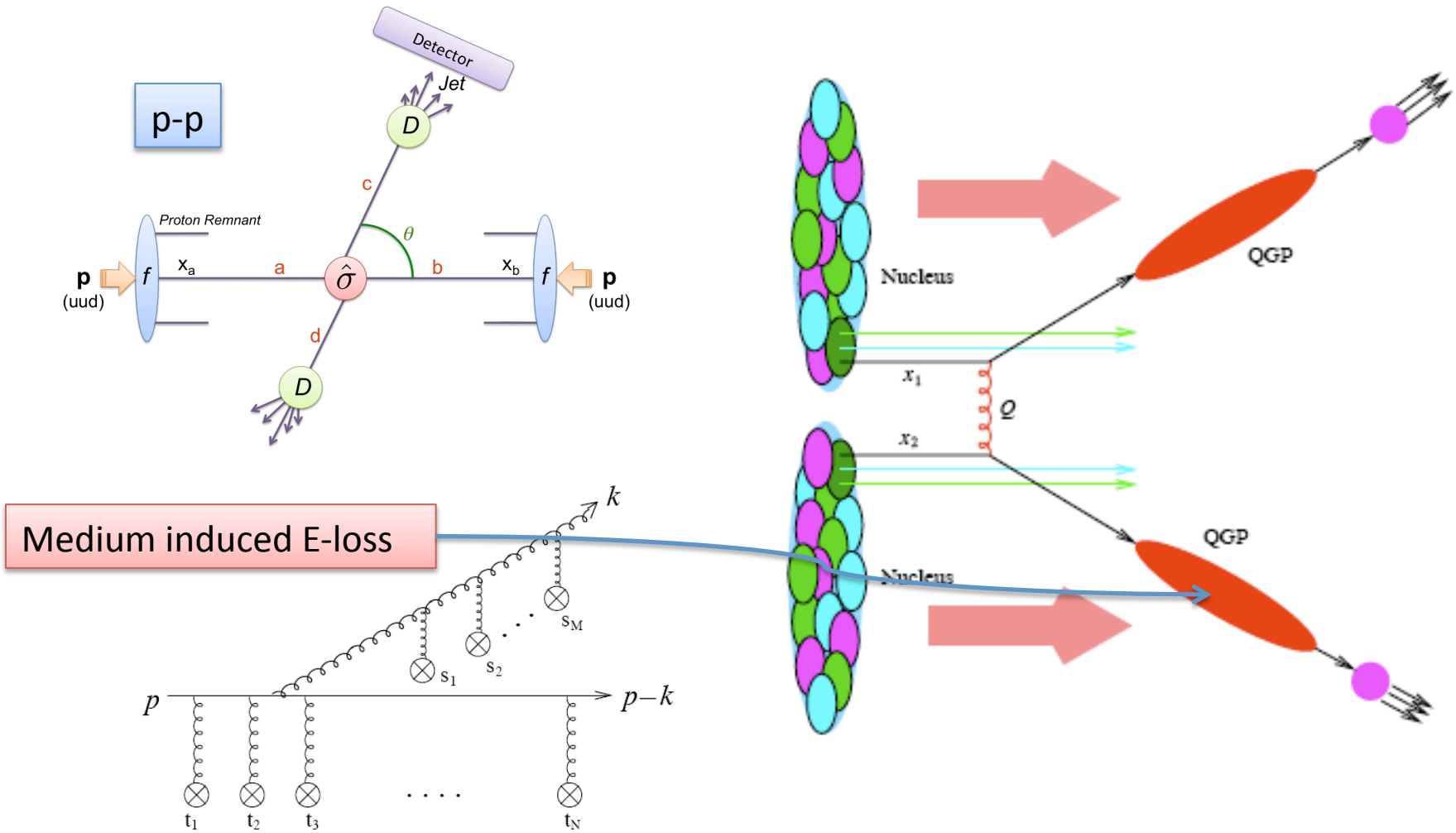


$$\hat{q} \sim \mu^2/\lambda$$

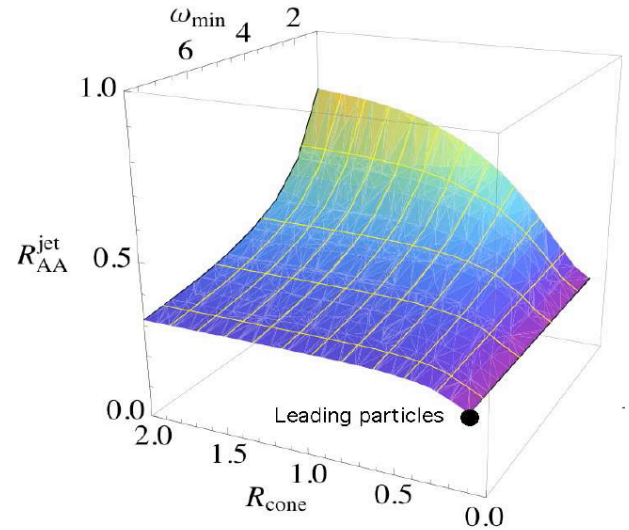


Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

Factorization in HI collisions



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

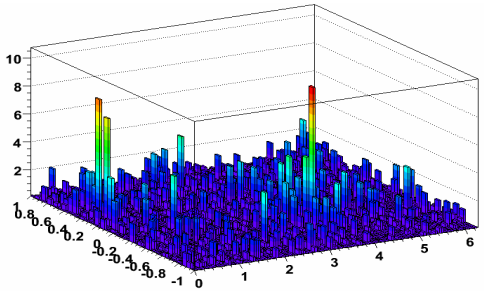
Goal of full jet reconstruction: integrate over hadronic degrees of freedom to measure medium-induced jet modifications at the *partonic* level ➔ much more detailed connection to theory

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

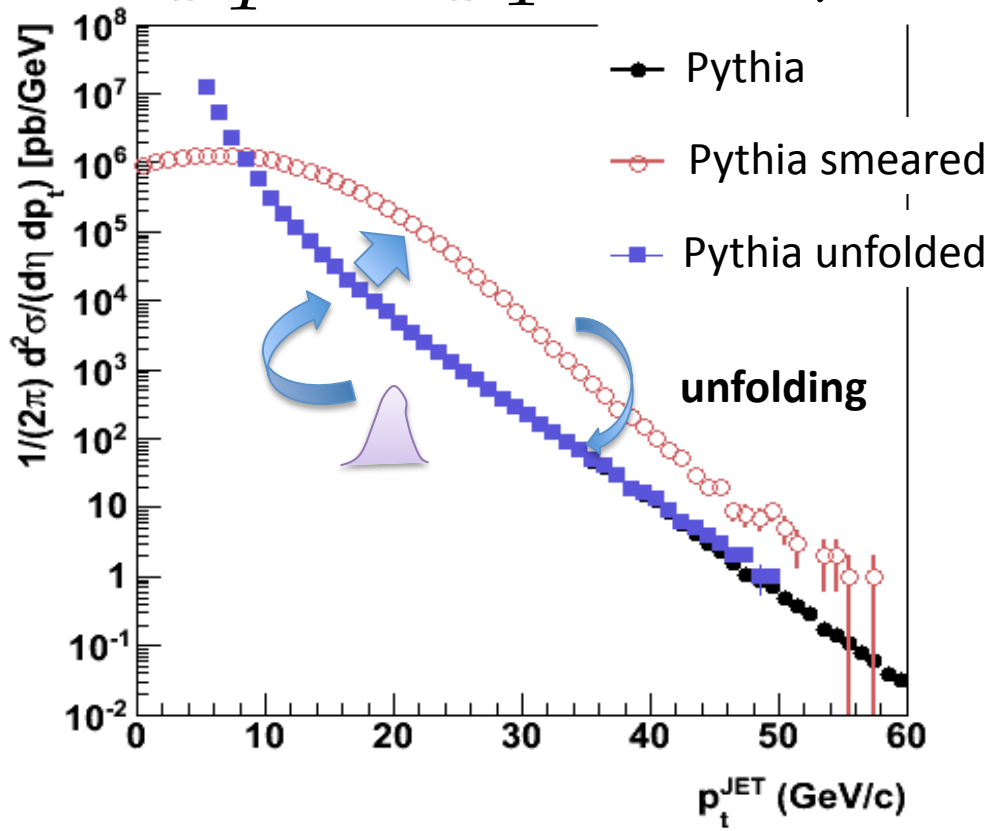
Jet pT irresolution due to HI background

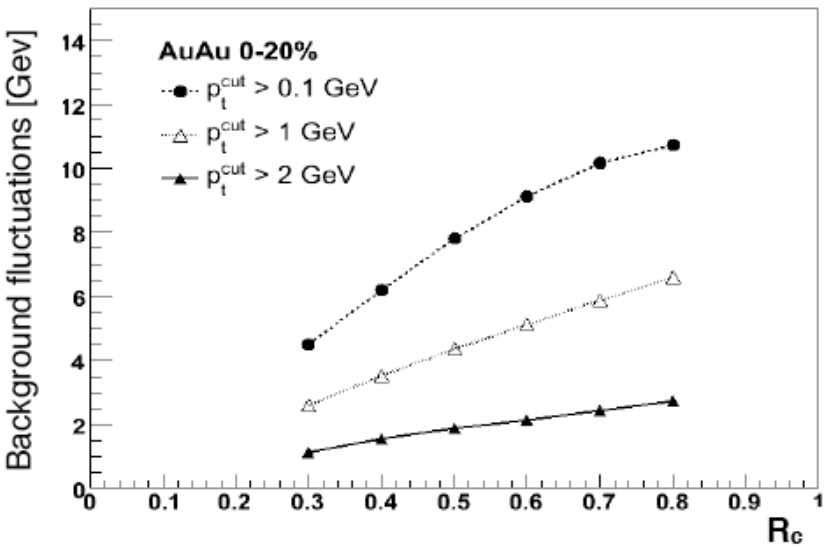
Background non-uniformity (fluctuations) and energy resolution introduce pT-smearing

Correct via "unfolding": inversion of full bin-migration matrix

Check numerical stability of procedure using jet spectrum shape from PYTHIA

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





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

NLO E-Loss calculations and jet finding

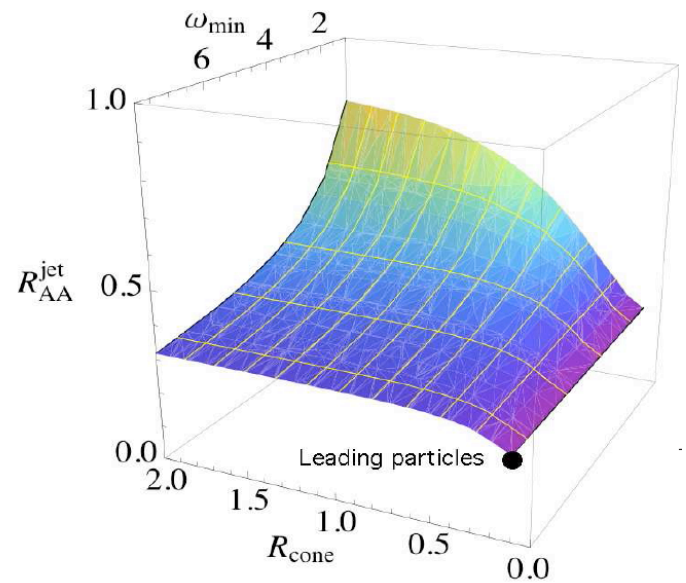
GLV medium induced radiation: number of scatterings, momentum transfers, color current propagators, coherence phases (LPM)…

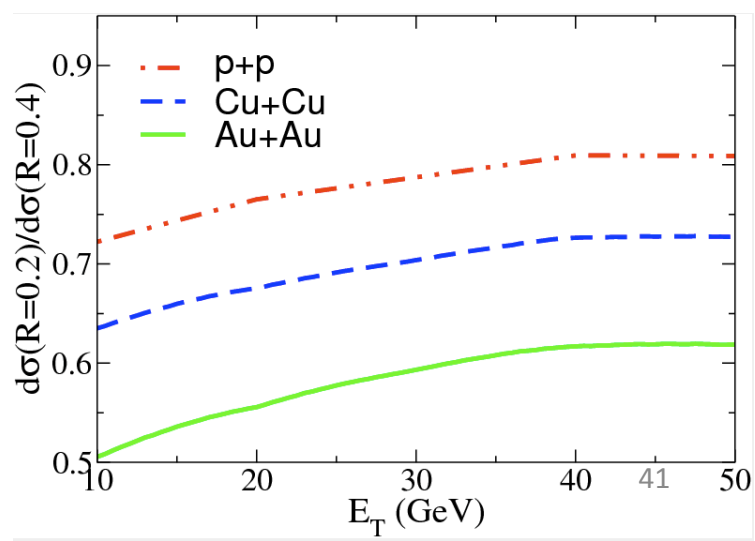
Jet cross-sections:

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

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 (one of the previous HITs)



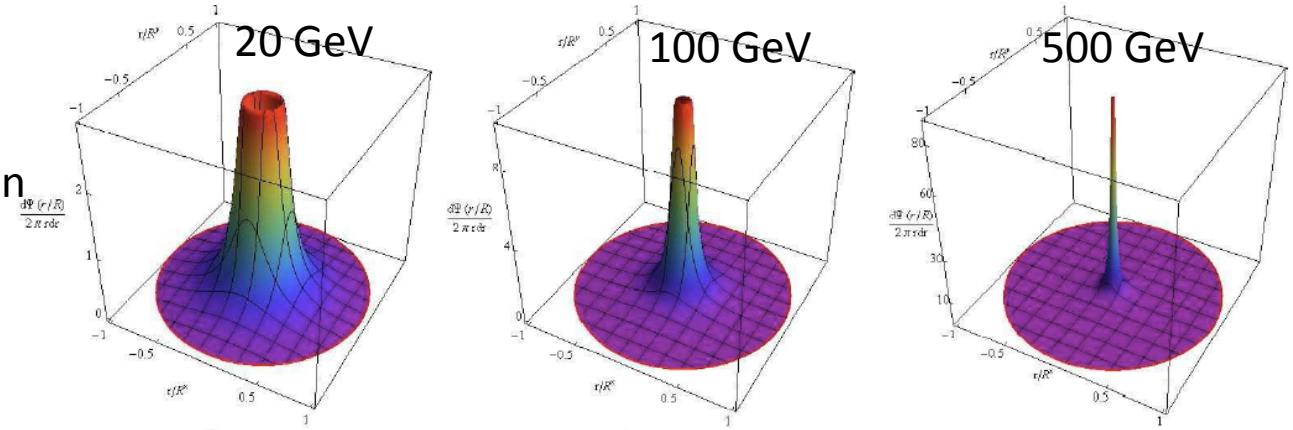


Further jet measurements

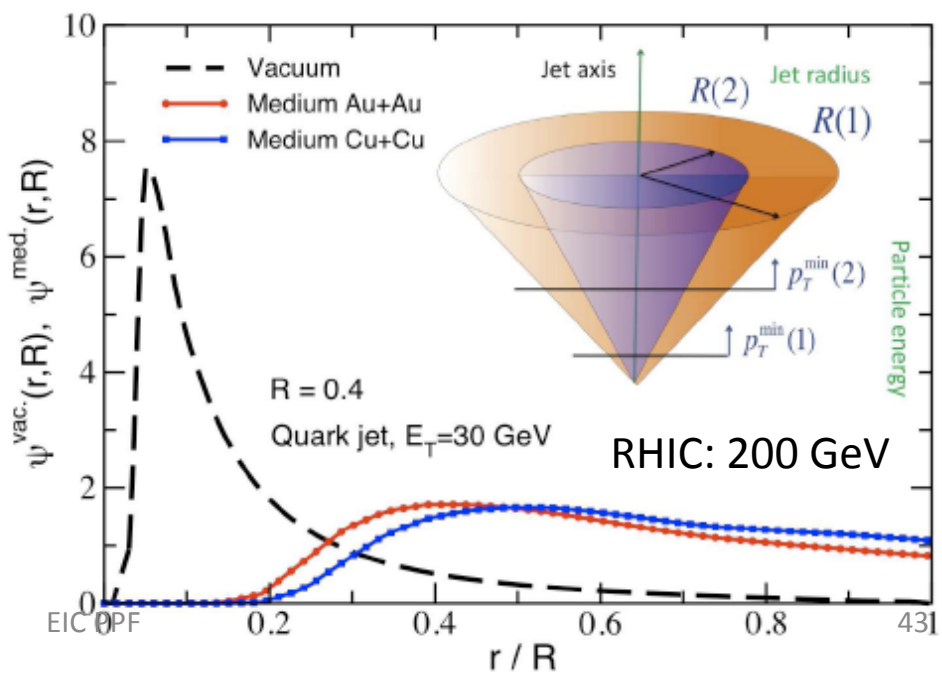
Not possible w/o full jet reconstruction(!)

Jet shapes

LHC/
Tevatron

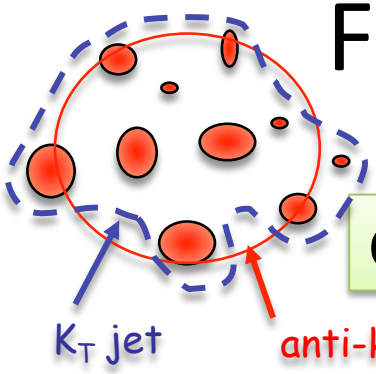


$$\psi(r,R) = \frac{d}{dr}\left\{\frac{\sum_i E_{T_i}\theta(r - R_{i,\text{jet}})}{\sum_i E_{T_i}\theta(R - R_{i,\text{jet}})}\right\}$$

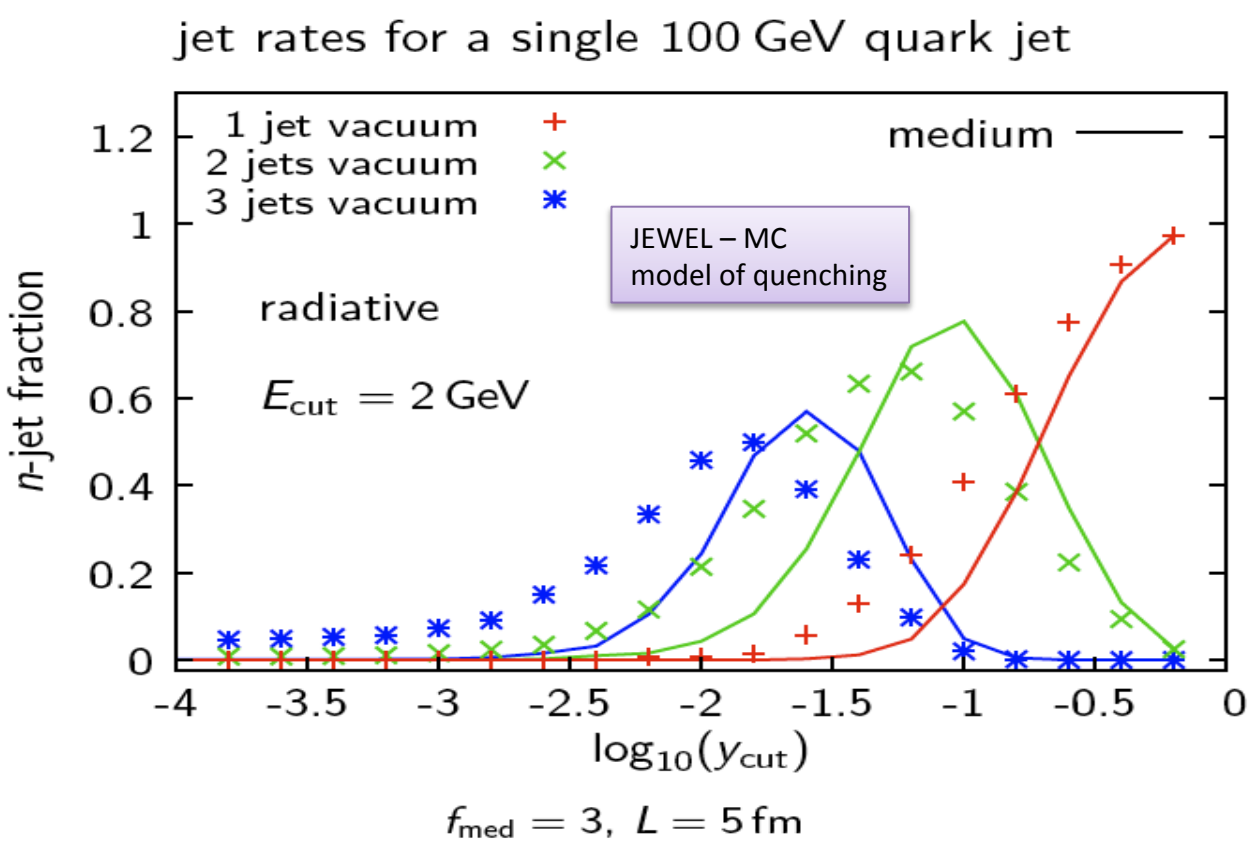


[I. Vitev, B.-W. Zhang arXiv:0910.1090v1 [hep-ph]]

Future measurement: subjets



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



Subjet distributions:

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

- Suffer from energy irresolutions:

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

where

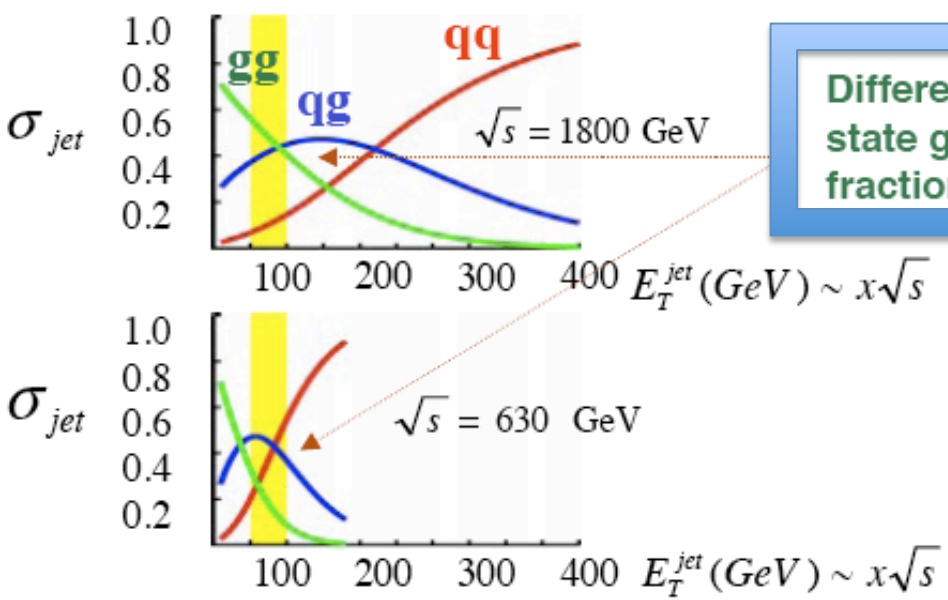
$$f_{corr} = E_{jet}^{true}/E_{jet}^{measured}$$

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

Subjets at Tevatron(D0)

- Reclustering (re-run of a kt algor) on a jet -> recombination into n-subjets separated by y_{min} cut -> used for q-g jet discrimination

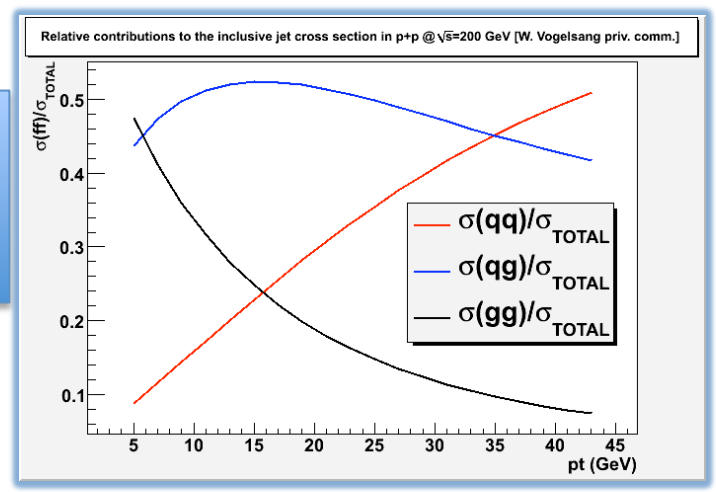
- Basic Idea:
  - Compare the subjet multiplicity of jets with same E_T and η at center of mass energies 630 and 1800 GeV



Different final state gluon fraction

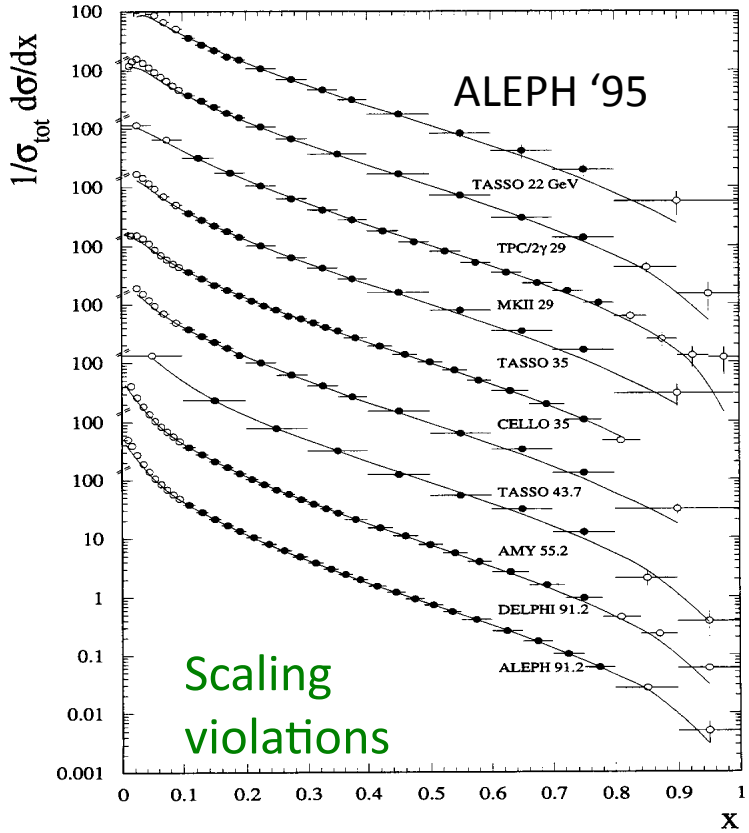
hep-ph/0704.1677

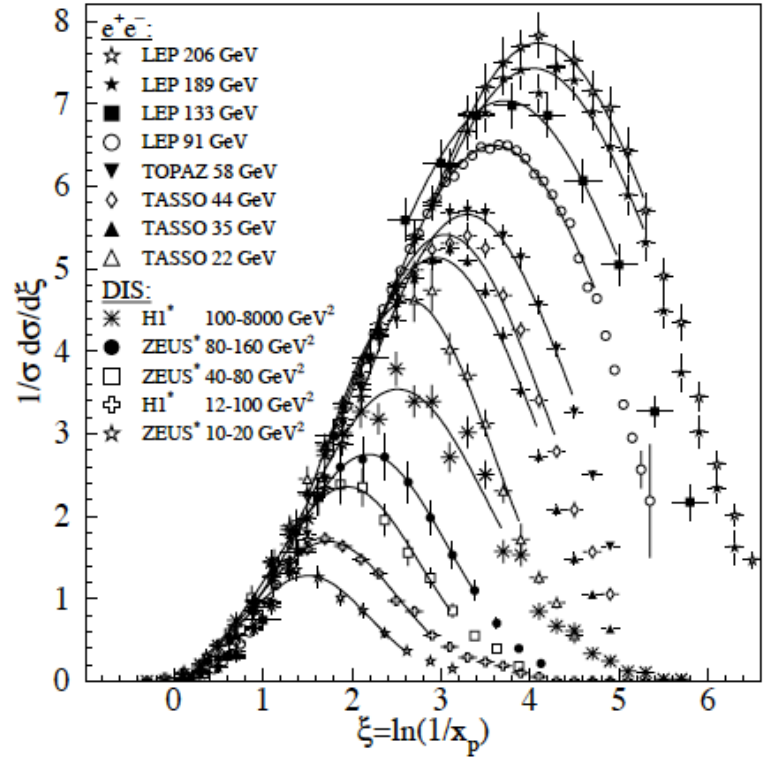
Vogelsang: pp @ 200 GeV



What about pp@130;500 GeV ?
Probably to small diff in σ(ff) ?

Fragmentation Functions in e^+e^-





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

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

MLLA:

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

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

Summary

- Jets ~ partonic kinematics
- Advanced jet finders:
  - http://www.lpthe.jussieu.fr/~salam/fastjet/
- Systematic effects are important
  - Jet energy scale and jet energy resolution
  - R – the resolution parameter and the jet definition – know what you measure and how it corresponds to theory
- Jet observables robustness is the key
  - Not obscured by hadronization
- Avoid biases: seed bias, kinematic cuts etc