Jets at Hadron Colliders

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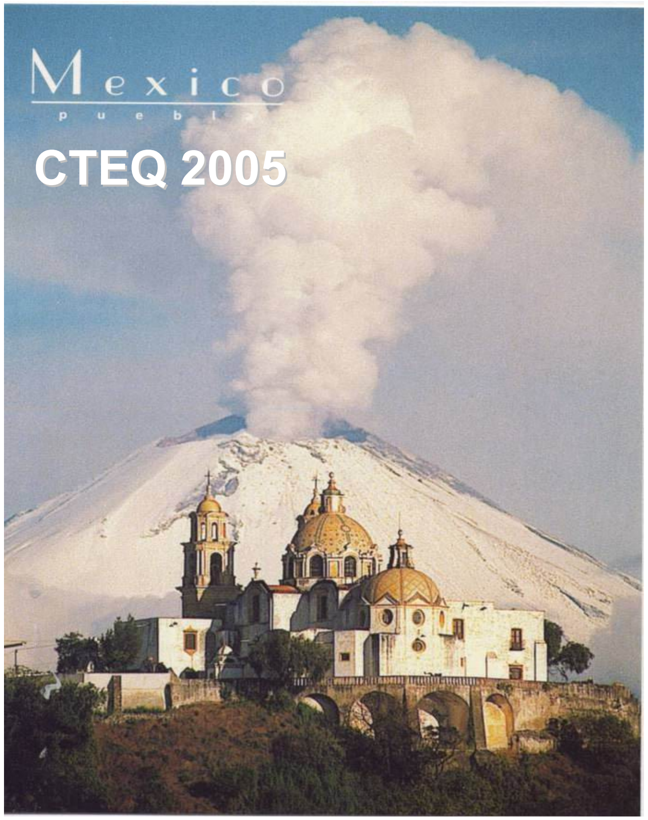
(CDF and CMS Collaborations)



Outline

- Introduction: what is jet physics and why bother?
- Hadron Colliders
- Detectors at Hadron Colliders
- What is a jet, after all?
- Jet Physics:
  - jet production (X+jets)
  - jet structure
  - jets as a probe of GQP
  - jet pollution
- Summary: all you need to remember

Jet Physics in SM and Beyond

SM Physics with jets
- jet production (X+jets)
  → QCD at large energy scales

SM Physics of jets
- jet structure
  → QCD at small energy scales

SM Physics using jets as a probe
- jet propagation through Quark-Gluon Plasma
  → QCD of dense states

QCD and Jets are the key to New Physics
- new physics is likely to be born in a QCD process
- new physics often results in jets in final states
- most of the time, QCD is the major background

Jet Physics Challenges

QCD foundations are well understood, but:

- Theoretically, QCD calculus remains to be a challenge, both at
  - at large energy scales, despite of α_s being relatively small (~0.1)
  - and even more so at low energy scales where α_s diverges

- Experimentally, Jets
  - are a mess by themselves (hard to have a firm grip on them)
  - and contaminate other otherwise would-be clean tools (γ, e, μ, τ, $\not{E}_T$)

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Hadron Colliders

- ISR (Intersecting Storage Rings) at CERN
- Sp$\bar{p}$S (Super Proton-Antiproton Synchrotron) at CERN
- Tevatron at Fermilab
- LHC (Large Hadron Collider) at CERN

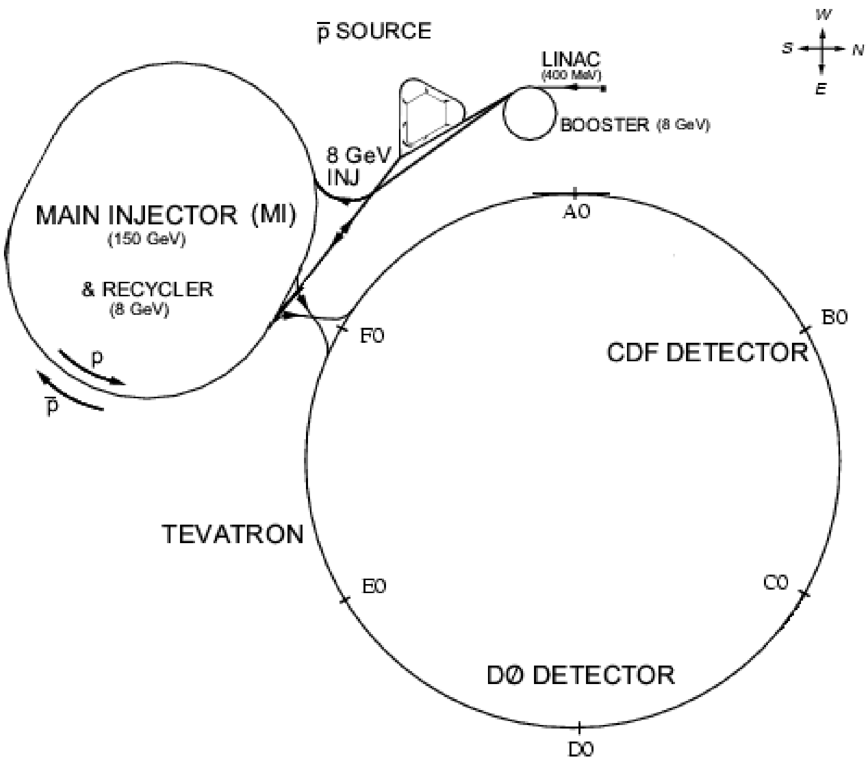
Collider	Years	Particles	CoM Energy	Max Luminosity
ISR	1971-1984	pp	60 GeV	2×10^{32} cm^{-2}s^{-1}
Sp$\bar{p}$S	1981-1990	p$\bar{p}$	600 GeV	6×10^{30} cm^{-2}s^{-1}
Tevatron	1987-2009	p$\bar{p}$	2 TeV	10^{32} cm^{-2}s^{-1}
LHC	2007-	pp	14 TeV	10^{34} cm^{-2}s^{-1}

- RHIC (Relativistic Heavy Ion Collider) at Brookhaven

RHIC	2000-...	A+A	$2\times100\times$N GeV	10^{27} cm^{-2}s^{-1}

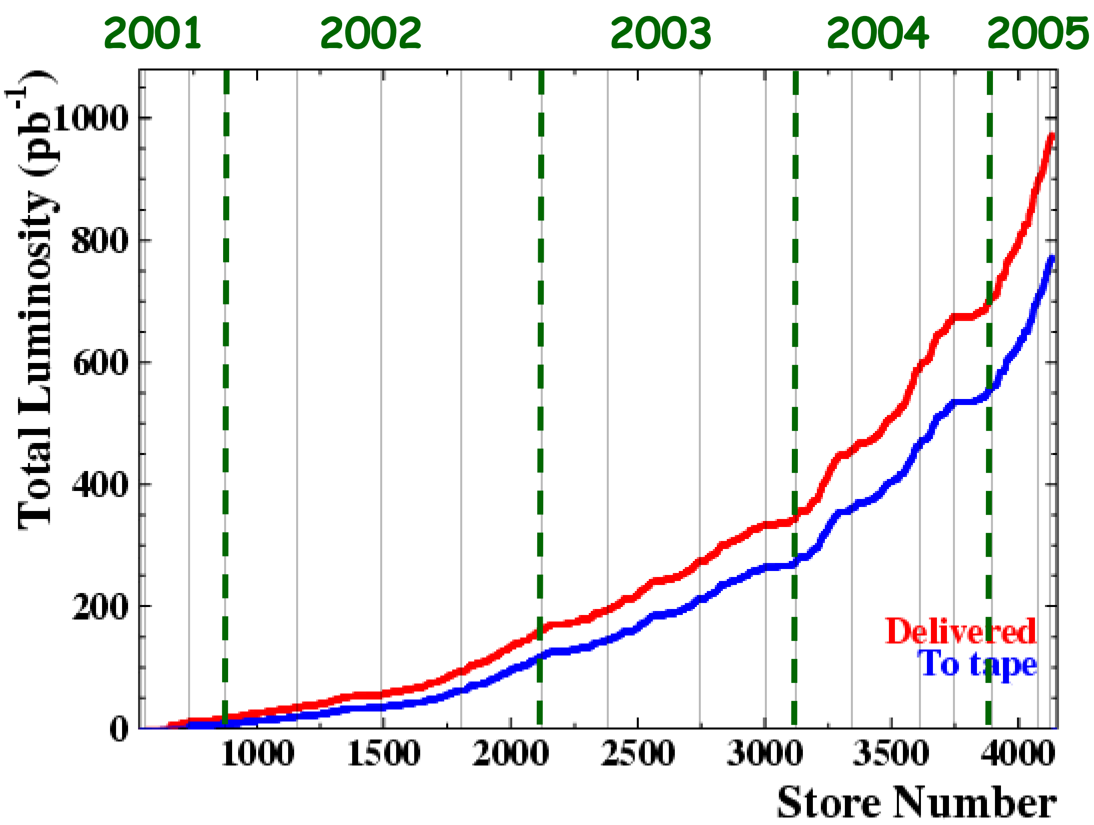
Tevatron accelerator complex

Tevatron accelerator complex



- Negatively ionized hydrogen gas enters linear accelerator (400MeV).
- Ions pass through carbon foil to remove electrons.
- Booster accelerates protons to 8GeV
- Protons enter MI—accelerated to 150GeV.
- Protons from MI used to produce antiprotons
- Antiprotons sent to MI—accelerated to 150GeV
- Protons and antiprotons injected into the main ring and accelerated to 980 GeV

Tevatron accelerator complex



Run I

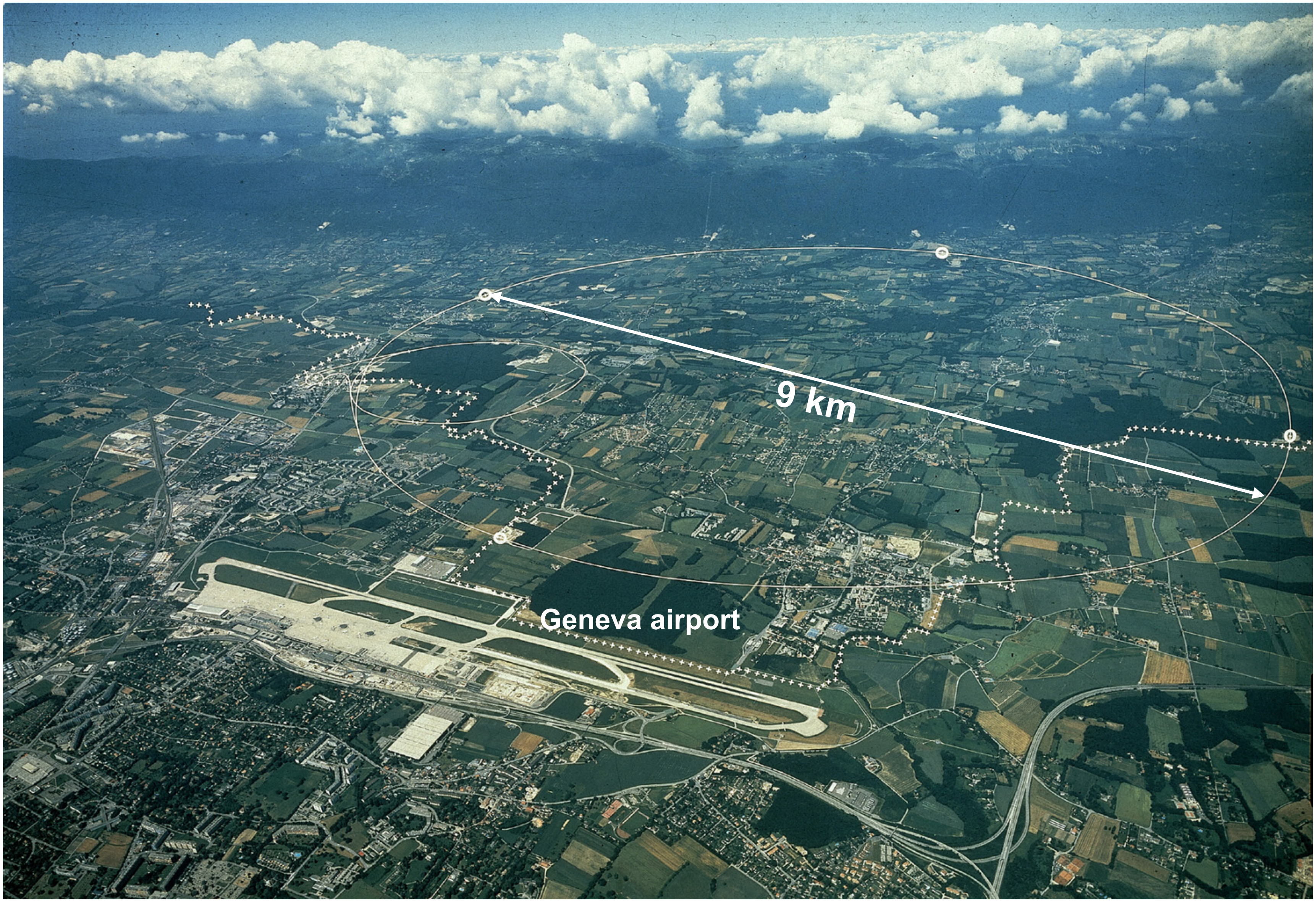
- 1992-1996
- CoM Energy 1.8 TeV
- Max L = 2×10^{31} cm^{-2} s^{-1}
- Int. L = 0.1 fb^{-1}

Run II

- 2001-2009
- CoM Energy 1.96 TeV
- Int. L = 4-8 fb^{-1} (by 2009)

- So far:
  - Max L: ~10^{32} cm^{-2} s^{-1}
  - Integral L: ~1 fb^{-1}

Large Hadron Collider



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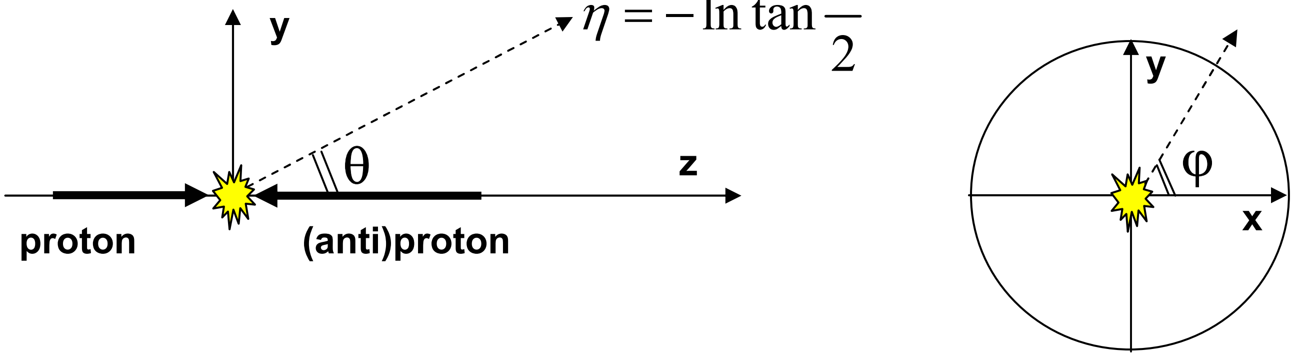
Hadron Collider Detector: Coordinates



$$\eta = -\ln \tan \frac{\theta}{2}$$

φ – azimuthal angle

η – pseudorapidity

- **η=0 (θ=90°)** **η=1 (θ=40°)** **η=2 (θ=15°)**
- **soft particles are approxumately uniformly distributed along η**
- **hard-scattered partons may have a boost along the beam line, but $\Delta\eta = \eta_1 - \eta_2$ remains Lorentz-invariant with respect to such boosts and is related to the polar scattering angle in the center of mass of scattered partons**
- **in central region $\eta<1$: $\Delta\eta \sim \Delta\theta_{LAB}$**

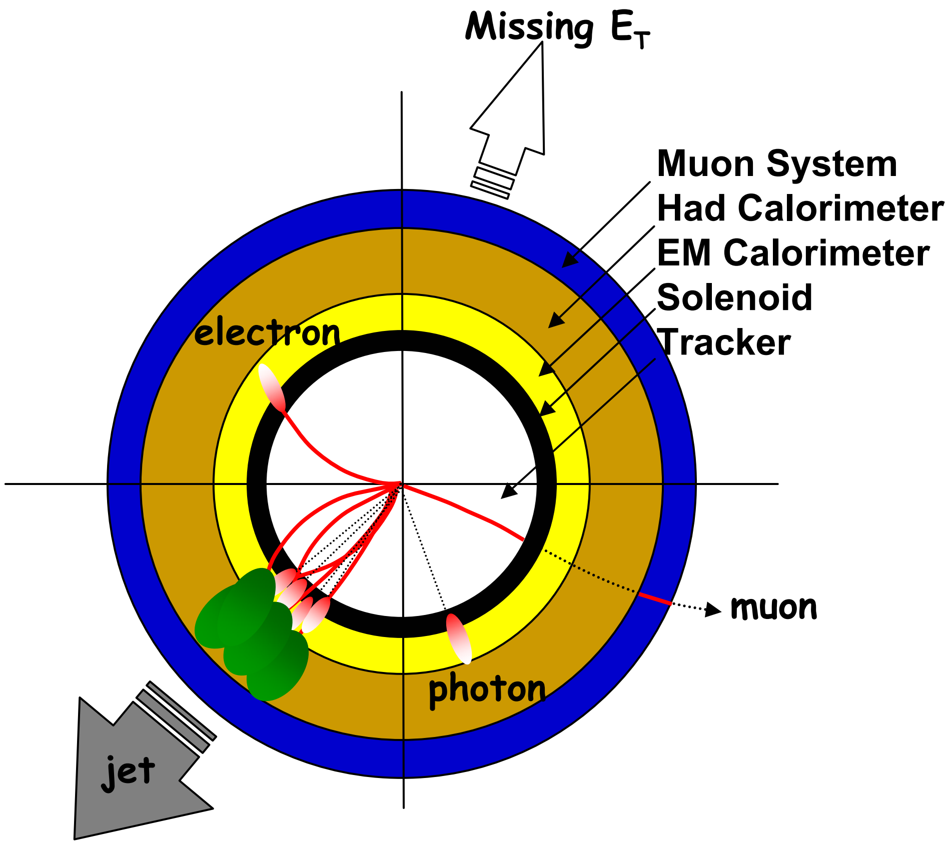
Hadron Collider Detector: Concept

Detector:

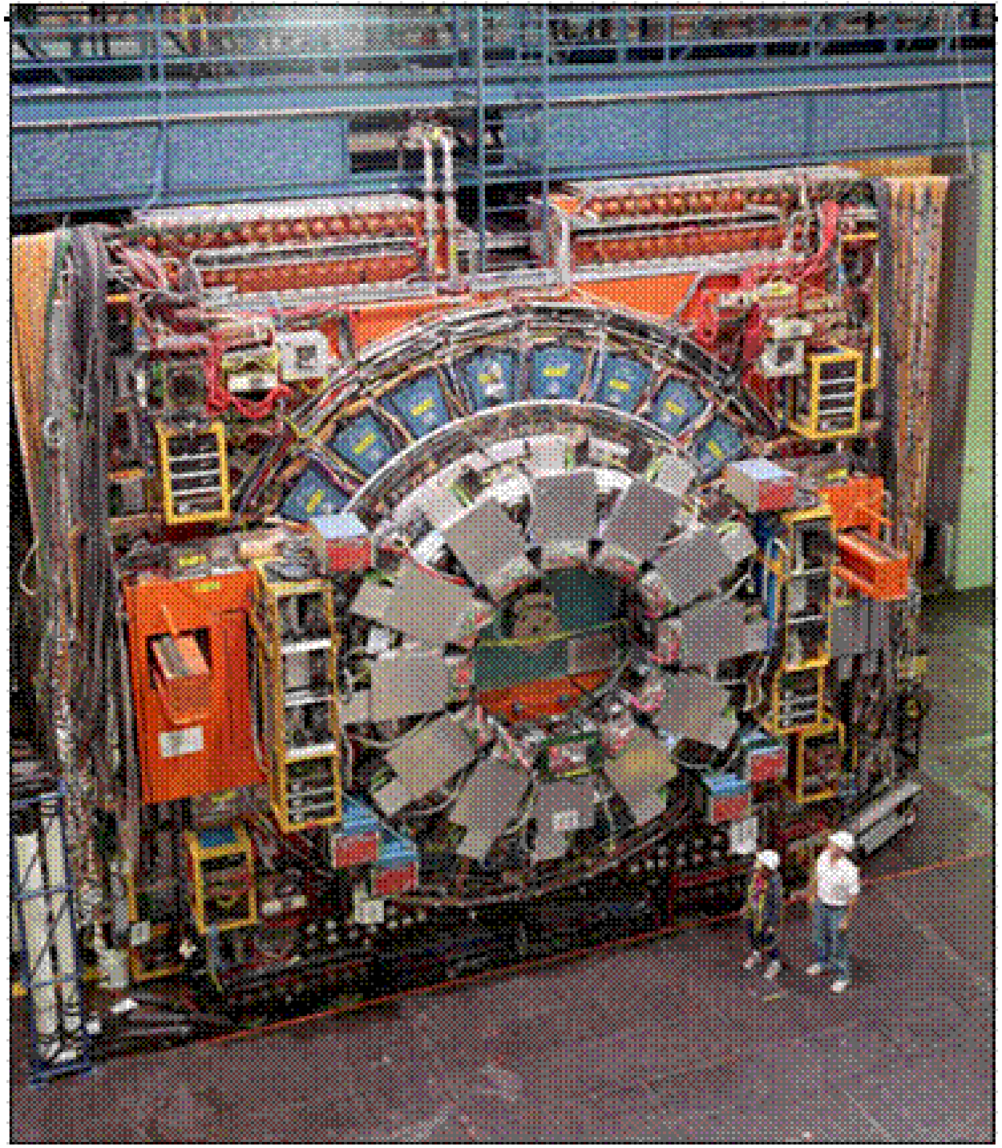
- solenoid
- inner tracker
- em calorimeter
- had calorimeter
- muon system

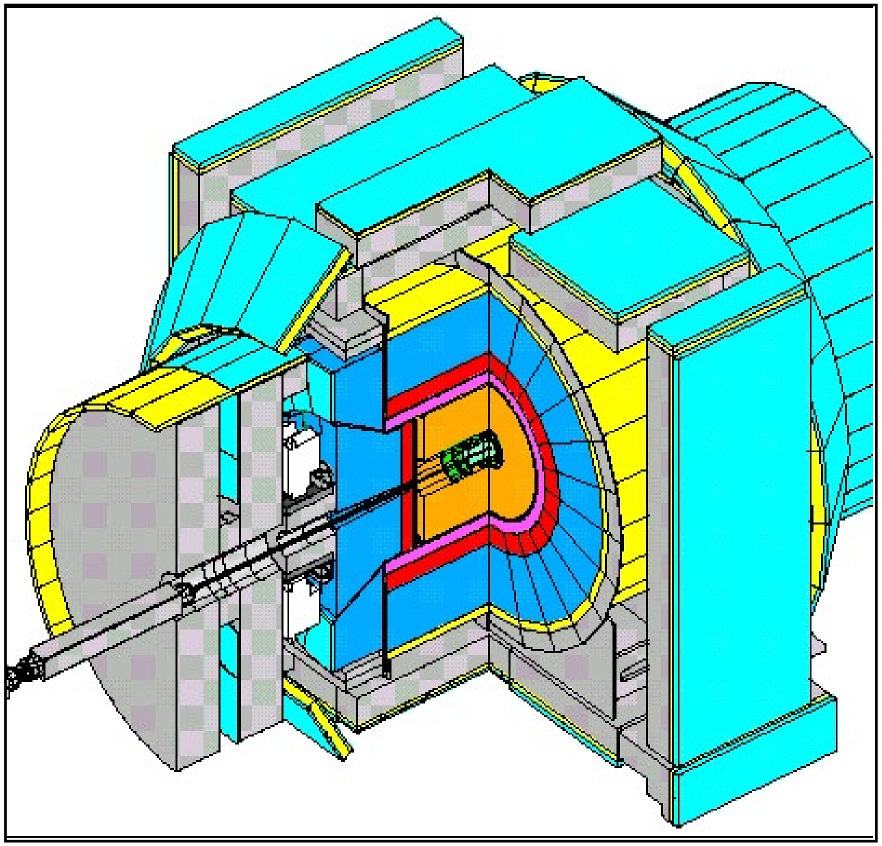
Primary Physics Objects:

- electron
- photon
- hadron jet
- individual charged hadron
- muon
- missing E_T



Hadron Collider Detector: CDF (example)





- 3d vertex coverage: $|\eta|<2$
- Tracking coverage: $|\eta|<2$
- Calorimeter coverage: $|\eta|<3.6$
- Mini-plug calorimeter: $3.6<|\eta|<5.1$
- Muon coverage: $|\eta|<1.5$

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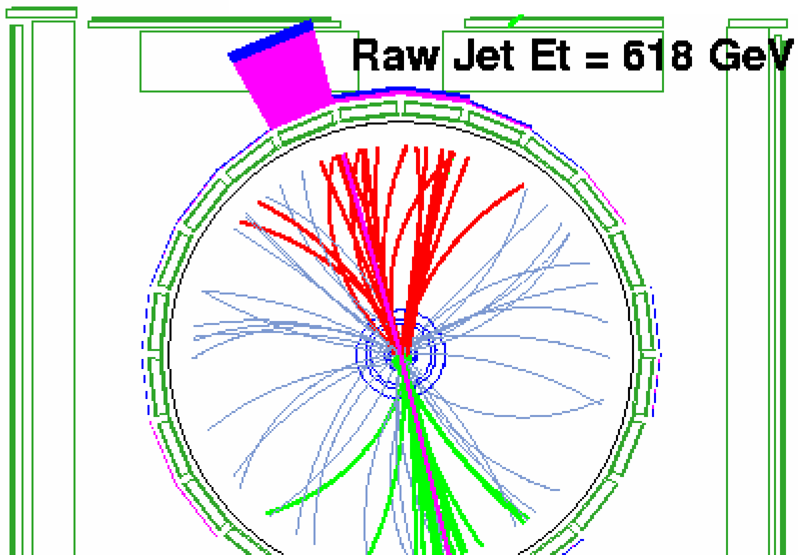
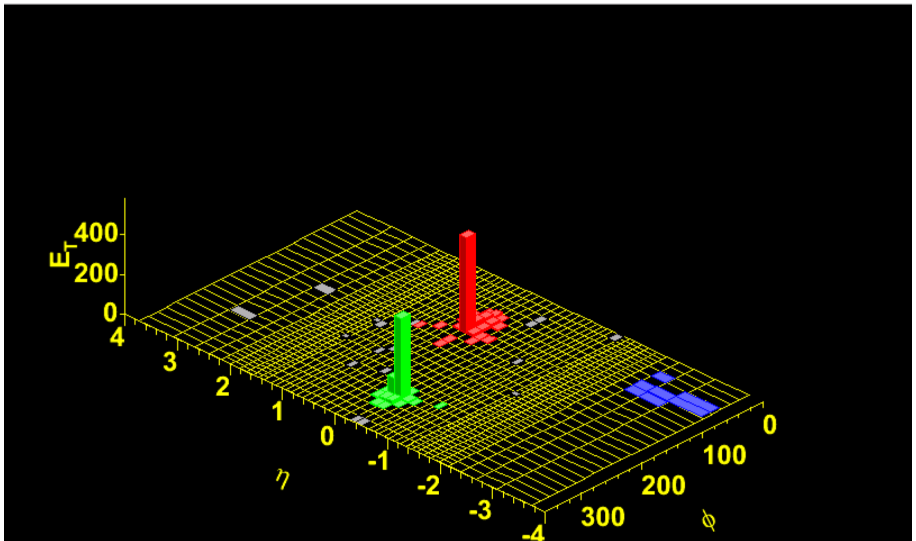
Jet: what is it?

Two jets as seen by CDF detector
(event with the highest E_T jet)

TRACKER: axial view



CALORIMETERS: unfolded (η, ϕ)–plane



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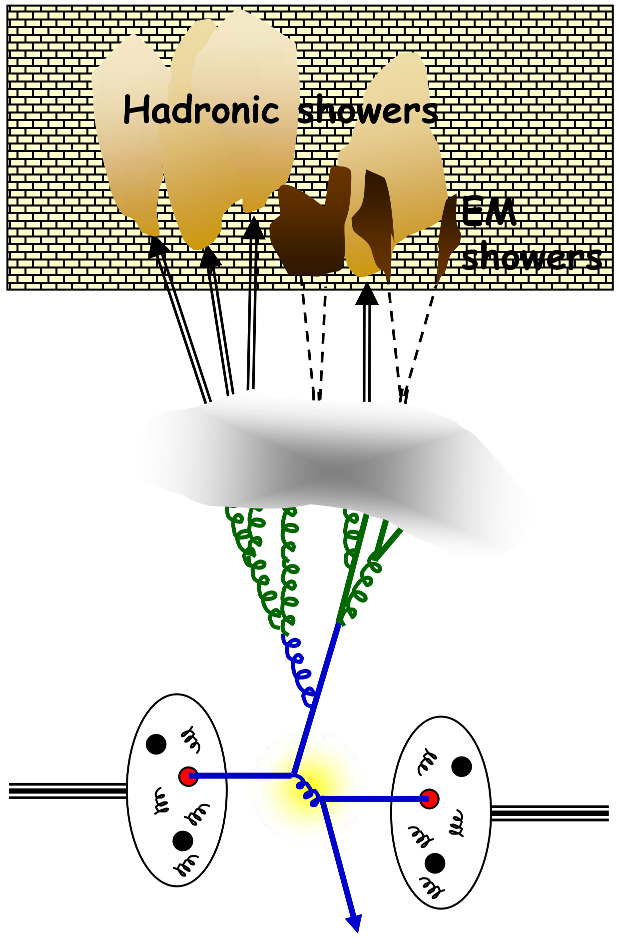
Don’t believe your eyes:
JET IS A MESSY OBJECT

Jet: from birth to death



EACH STAGE IS FULL OF UNCERTAINTIES

Pick two partons and their momenta
- parton density functions, PDF

Hard Scattering: 2 → X
- exact matrix element at LO
- some known at NLO,...

Soft final state radiation
- approximate resummation in all orders of pQCD: LLA (leading log approximation), NLLA

Hadronization
- phenomenological models

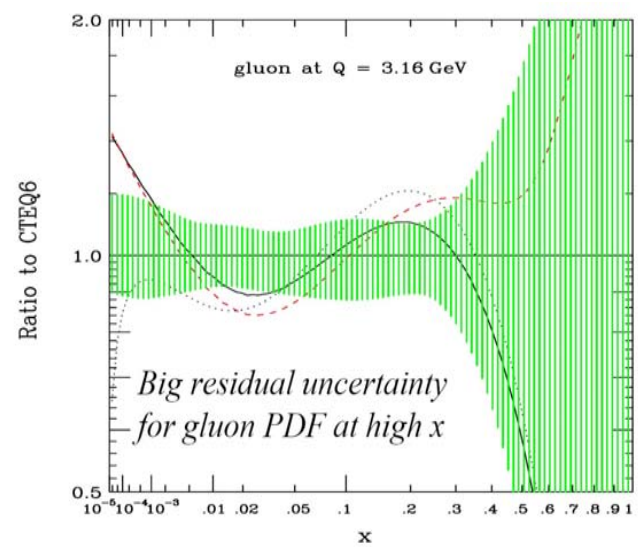
Calorimeter response
- electromagnetic shower for photons
- hadronic shower for “stable” hadrons

Jet identification (and corrections)
- jet finding algorithms

Jet: Parton Density Functions

PDF $f_a(x, Q)$ – parton probability density function to find parton a with momentum $p=xP$, where

- a—quark (or antiquark) of particular flavor or gluon
- P—proton/antiproton momentum
- Q—transferred momentum



PDFs

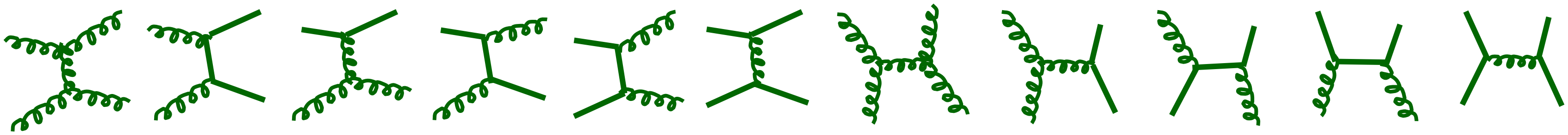
- not calculable from first principles
- pQCD does predict Q-dependence
- obtained from global fits (ee, ep, pp, etc)
  - — uncertainties; very large for g(x) at large x
  - — beware of the vicious circle:

    PDFs are obtained from data and then
    re-used in data analyses to judge on agreement of theory and experiment

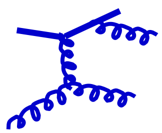
Jet: Exact Matrix Element (e.g., inclusive jets)

- LO ($2 \rightarrow 2$, $\sim\alpha^2$) is available: jet = parton

  Sample of LO diagrams:

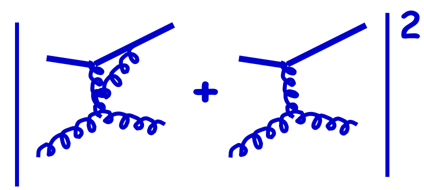


- NLO ($2 \rightarrow 2$ and $2 \rightarrow 3$, $\sim\alpha^3$) is available: jet = 1 or 2 partons



\+ . . .

Interference



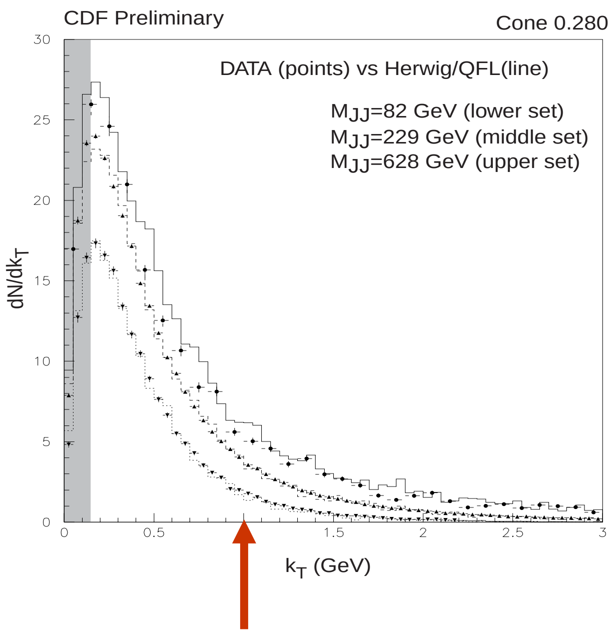
\+ . . .

- NNLO: "soon to become available" for many years…

- Is NLO good enough?
  - NLO is very far from the actual multiplicity of particles in jets
  - Merging criteria on whether 2 partons in NLO form one or two jets may be quite different from the experimental definitions: more phenomenological parameters
  - NLO x-section remains sensitive to the choices of renormalization scale

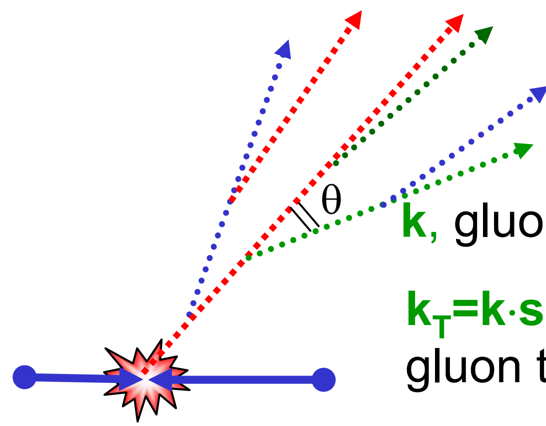
Jets: more soft radiation?

k_T distribution of particles in jets



1 GeV

From data we know that most particles have k_T<1 GeV



k, gluon momentum

k_T=k·sinθ
gluon transverse momentum

Differential probabilities of gluon emission:

$$dw \sim \alpha_S \frac{dk}{k}\frac{dk_T}{k_T}, \qquad \alpha_S = \frac{2\pi}{9\ln\left(k_T / \Lambda_{QCD}\right)}$$

any hope?

Perturbative methods at k_T<1 GeV are doubtful:
- **α_s becomes large**
- **also, notice diverging terms**

Jet: Leading Log Resummations

If we push k_T cutoff scale Q_{cutoff} low:

- α_s gets larger
- colinear/soft divergences lead to large log terms:

probability to emit n partons: $p(n) \sim \alpha_s^n \left(C_0 \ln^{2n} \frac{E_{jet}}{Q_{cutoff}} + C_1 \ln^{2n-1} \frac{E_{jet}}{Q_{cutoff}} + \ldots \right)$

- multi-gluon production becomes inevitable at Q~10 GeV! (E_{jet}~100)
- resummation techniques in all orders are a-must
- fortunately, theorists managed to account for and resum all orders with the leading-log (C_0) and next-to-leading-log (C_1) precision:
  - LLA Leading-Log Approximation
  - NLLA Next-to-Leading-Log Approximation
    - ~ NOTE: some beyond-NLL terms are often included in calculations, which may result in various flavors of NLLA, depending on what was included

Jet: Hadronization

Transition from parton shower to hadrons—theory does not exist

- hopefully, hadrons inherit partons' properties...
  Local Parton Hadron Duality Hypothesis

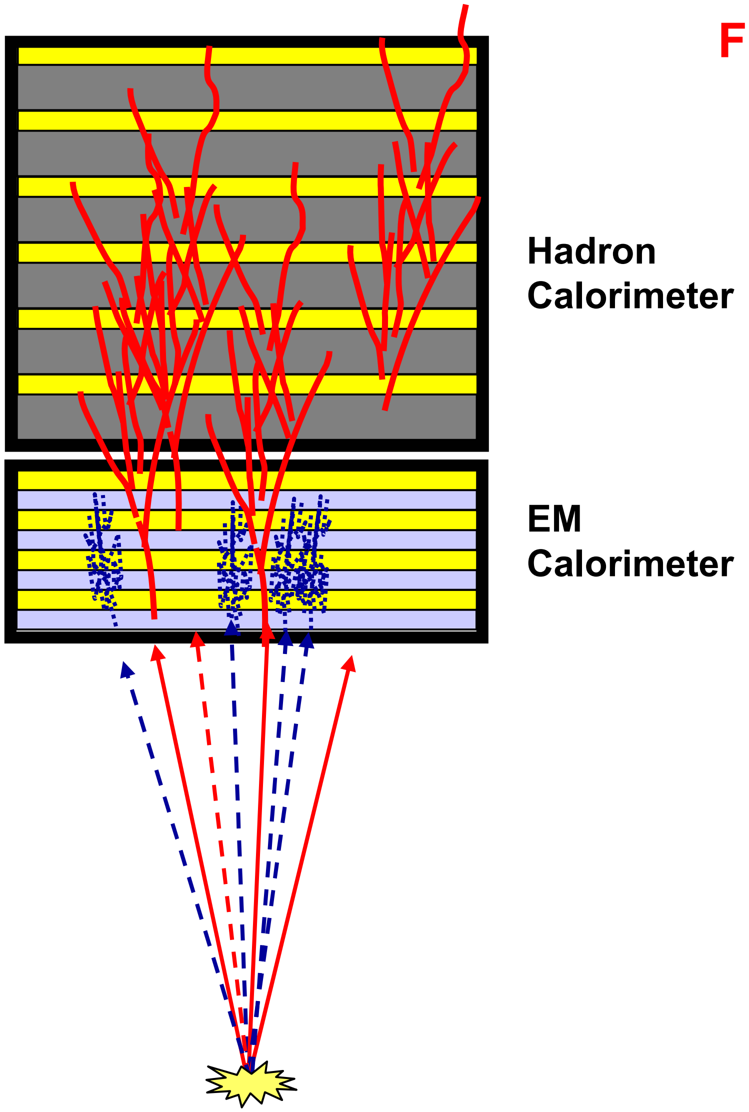
- To make parton-hadron connection closer, can we push Q_{cutoff} to Λ_{QCD}?
  Yes, e.g. Modified LLA, or MLLA (actually, NLLA + some extra terms)

- Naively, MLLA+LPHD would imply:
  - $N_{hadrons} = K * N_{partons}$ with K~1
  - momentum distribution of hadrons = that of partons
  - parton-parton correlations (momentum, multiplicity): do they survive hadronization?

Transition from parton shower to hadrons—Monte Carlo Generators

- stop parton shower development at Q_{cutoff} ~ 1 GeV
- and then do hadronization
  - completely phenomenological
  - different MC Generators do it differently!
  - with many tuning parameters to match data...

Jet: Detector Response

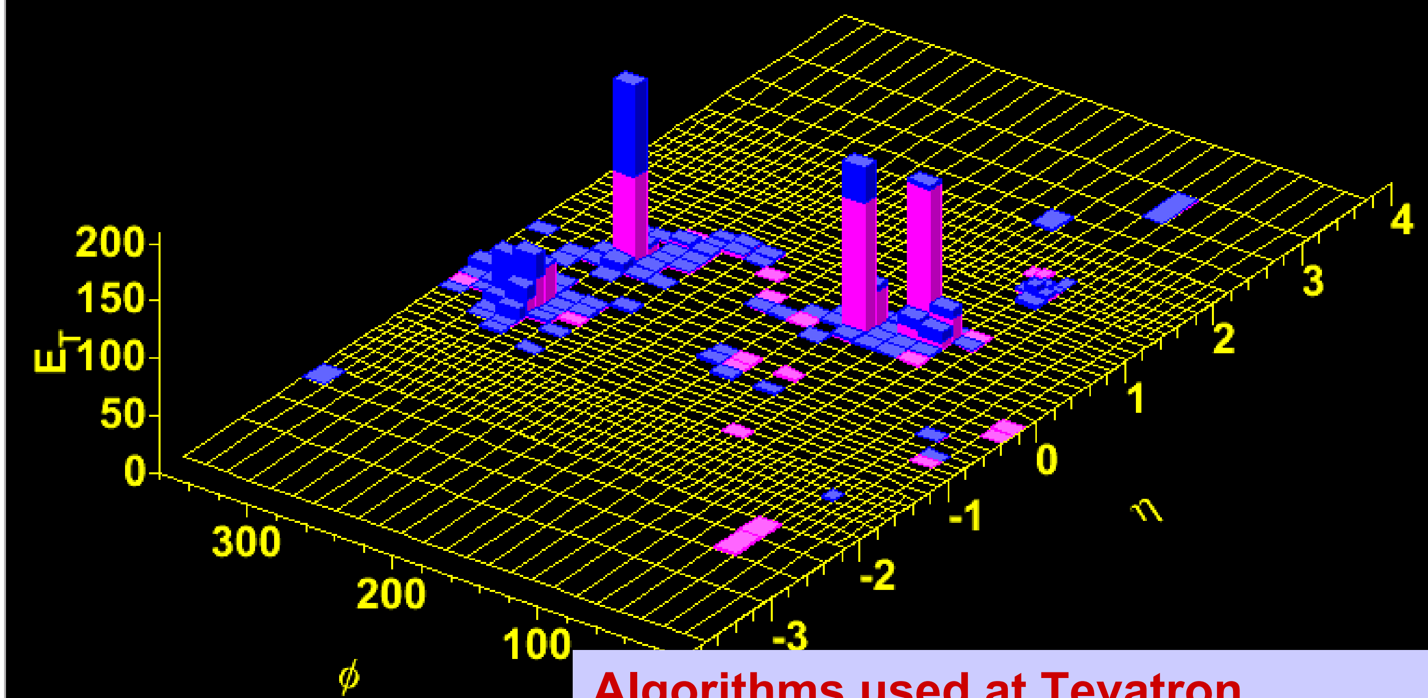


Fluctuations, fluctuations, fluctuations...

- jet: mostly $\pi^{\pm}$, π^{0} ($\pi^{0}\rightarrow\gamma\gamma$), ~10% K, few p/n
  number of particles and their relative composition fluctuate wildly
- em shower is dense, short, with intrinsic fluctuations
- had shower is broad and long, with large intrinsic fluctuations
- sampling technology (passive/active media) adds non-negligible fluctuations
- EM Cal response on hadrons is larger than that of Had Cal (different sampling density): varying starting point of had shower gives large fluctuations in the response

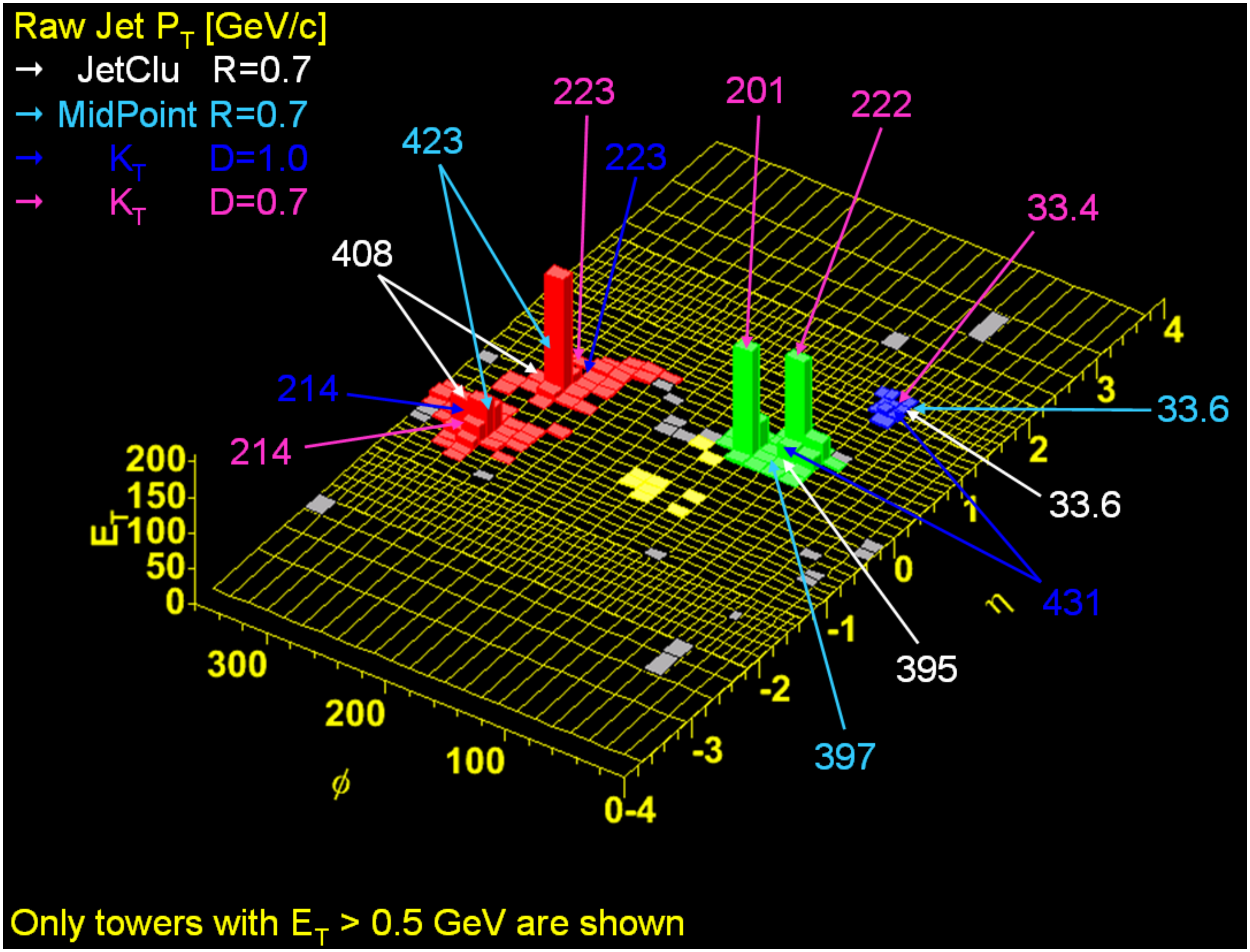
Jet Finding Algorithms

How many jets are out there?



Algorithms used at Tevatron
- Cone, MidPoint Cone, kT
- each comes with a free parameter
- and some other variations (flavors)

So, how many jets are out there?



Jet: How well can we measure it, after all?

Before getting to the answer:

- **corrections:**
  - out-of-cone losses
  - UE contribution subtraction
  - is it a clean cut?

- **calibration:**
  - test beam
  - jet-jet energy balance
  - jet-photon energy balance
  - are they all directly applicable?

Net Result:

- **Jet Energy Resolution (stochastic):**

$$\frac{\delta E_T}{E_T} \approx \frac{70\%}{\sqrt{E_T(GeV)}} \oplus 6\%$$

- **Absolute Scale Uncertainty (systematic):**

$$\frac{\delta E_T}{E_T} \approx 5\%$$

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Jet Physics at Hadron Colliders

- **Physics with jets (jet production)**
  - Jets (inclusive, dijets, Njets)
  - Heavy flavor jets
  - V+jets (W, Z, γ)
  - Diffractive jets
  - Multi Parton Interaction jets
- **Physics of jets**
  - q/g jet differences
  - particle momentum distributions
- **Jets as a probe of QGP**
  - jet quenching at RHIC
- **Jet pollution**
  - photon fakes
  - lepton fakes

Inclusive jet production

$$p + \overline{p} \rightarrow Jet(E_T, \eta) + X$$

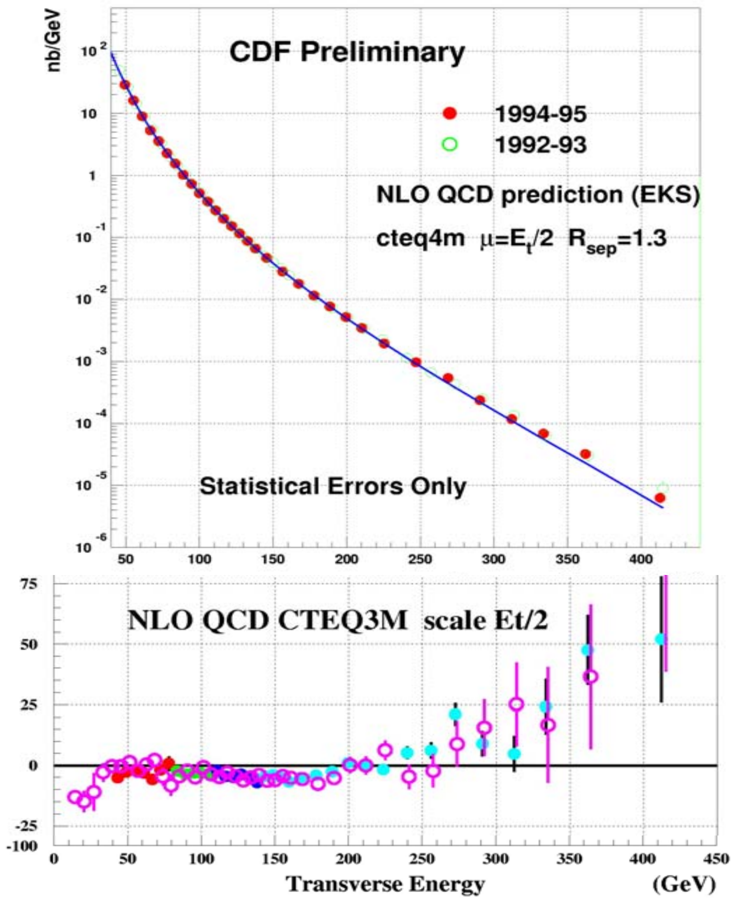
With only two variables in the game, we may want to and do choose to study

- **E_T differential x-section: $d\sigma/dE_T$**
- **for different η-bins…**

Inclusive jet production: Run I story…

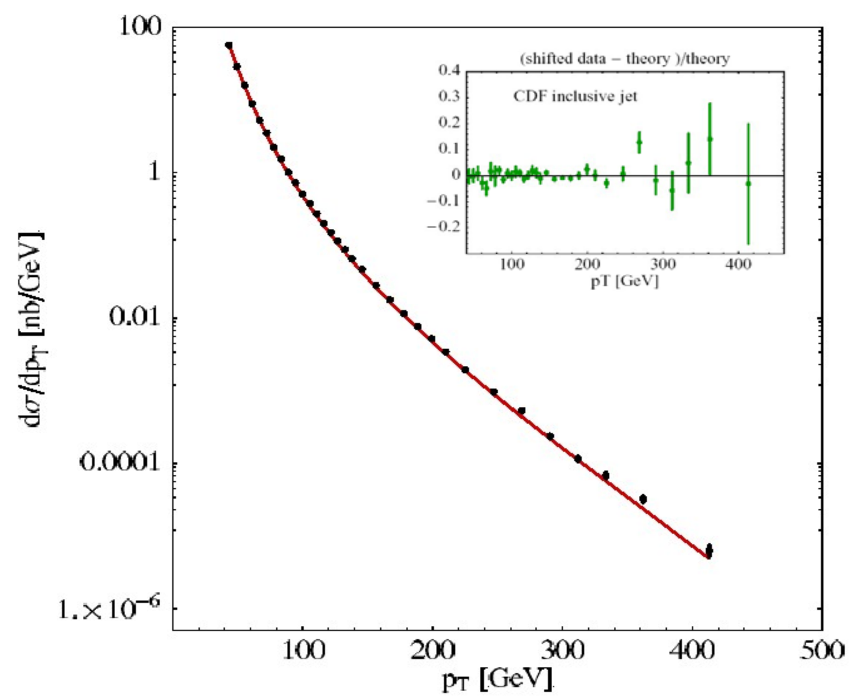
Run I data and NLO+CTEQ3M

- Excess at high E_T?
- Quark compositness?



Run I data and NLO+CTEQ6M

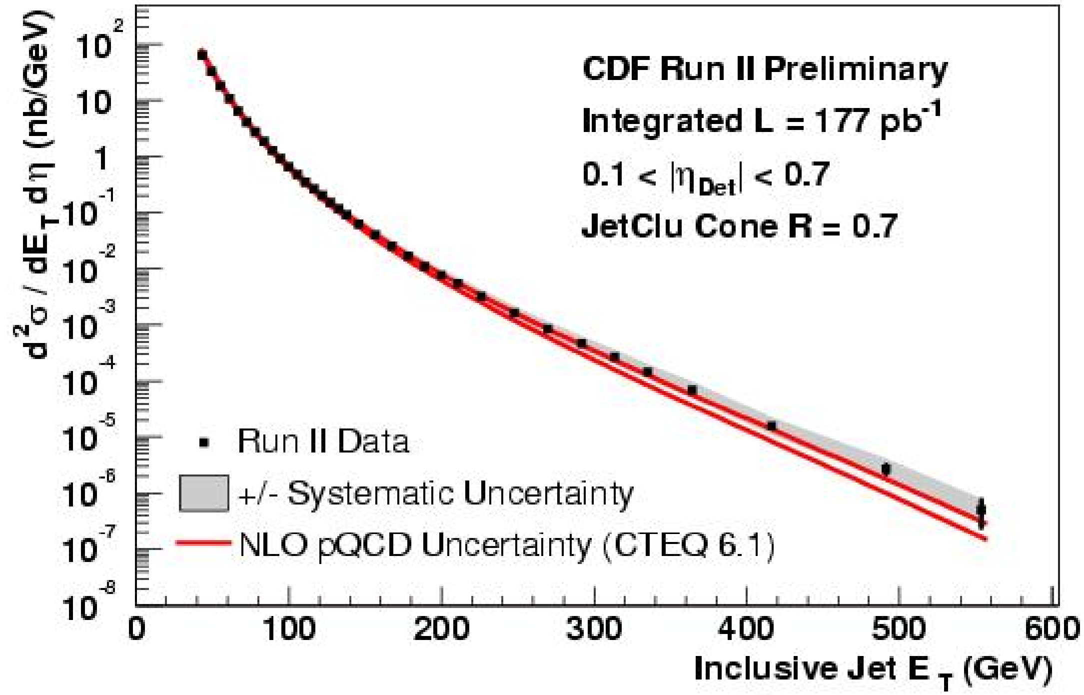
- CTEQ6:
  - New Data: H1, ZEUS, D0 (vs. η!), CDF
  - New methods: Systematic errors included
  - New features: Errors are available
- no excess, anymore?

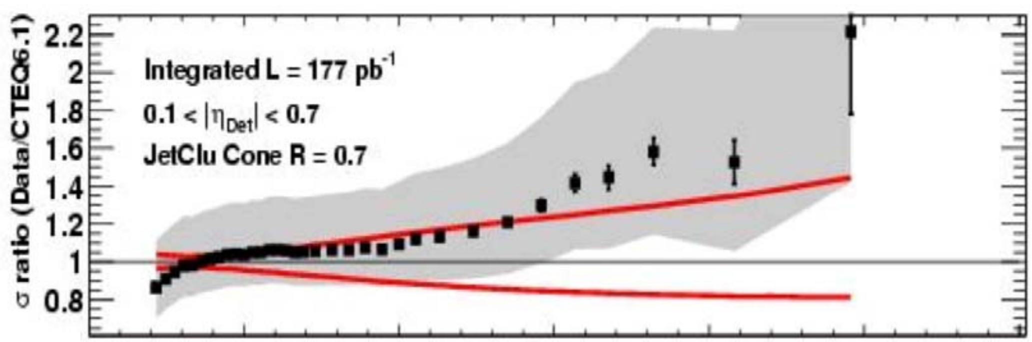


Inclusive jet production: Run II data vs NLO

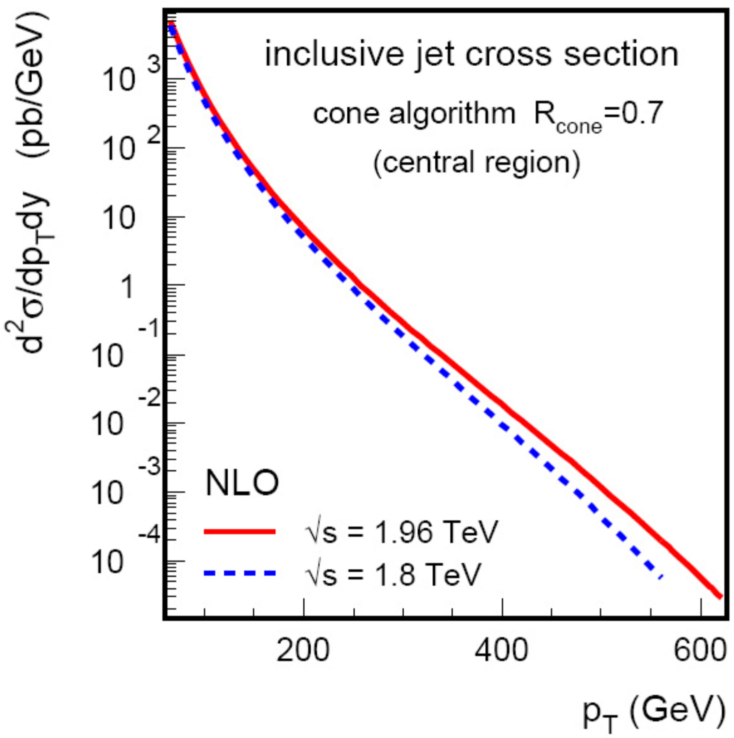
Run II data and theory:

- reasonable agreement with NLO+CTEQ6.1
- déjà vu:
  "high-E_T excess" again?
- ~20% dip at lower E_T? (not present in Run I)
- must beat systematic errors down:
  - Theory: PDFs
  - Experiment: energy scale

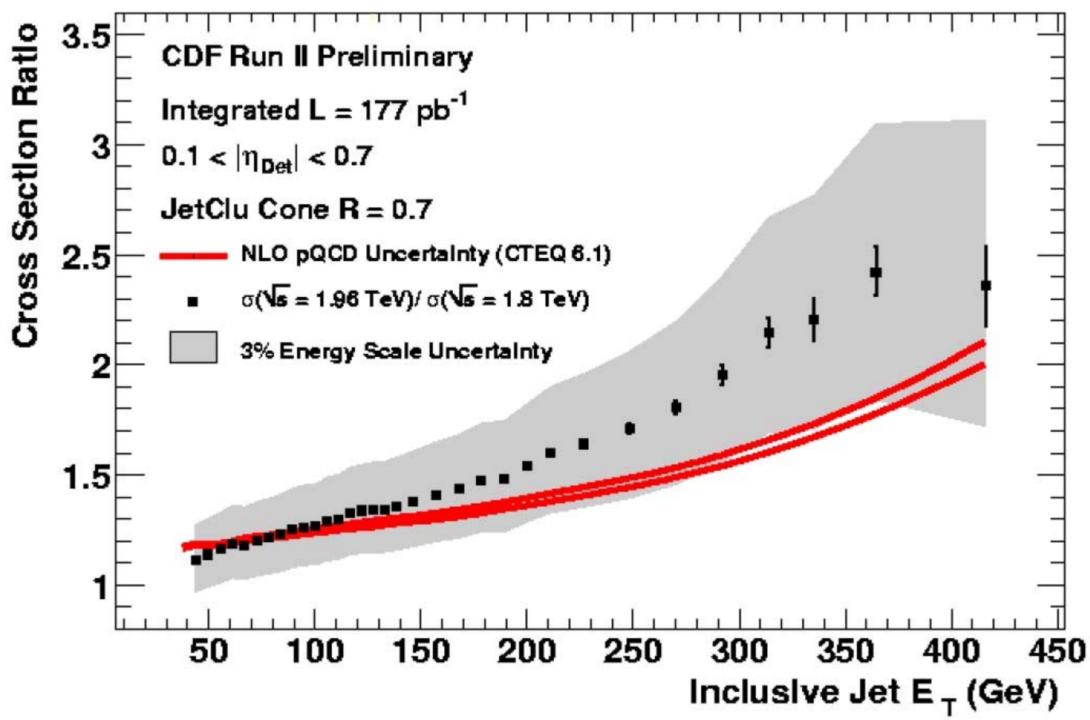




Inclusive jet production: Run II vs Run I



σ(Run II) / σ(Run I)

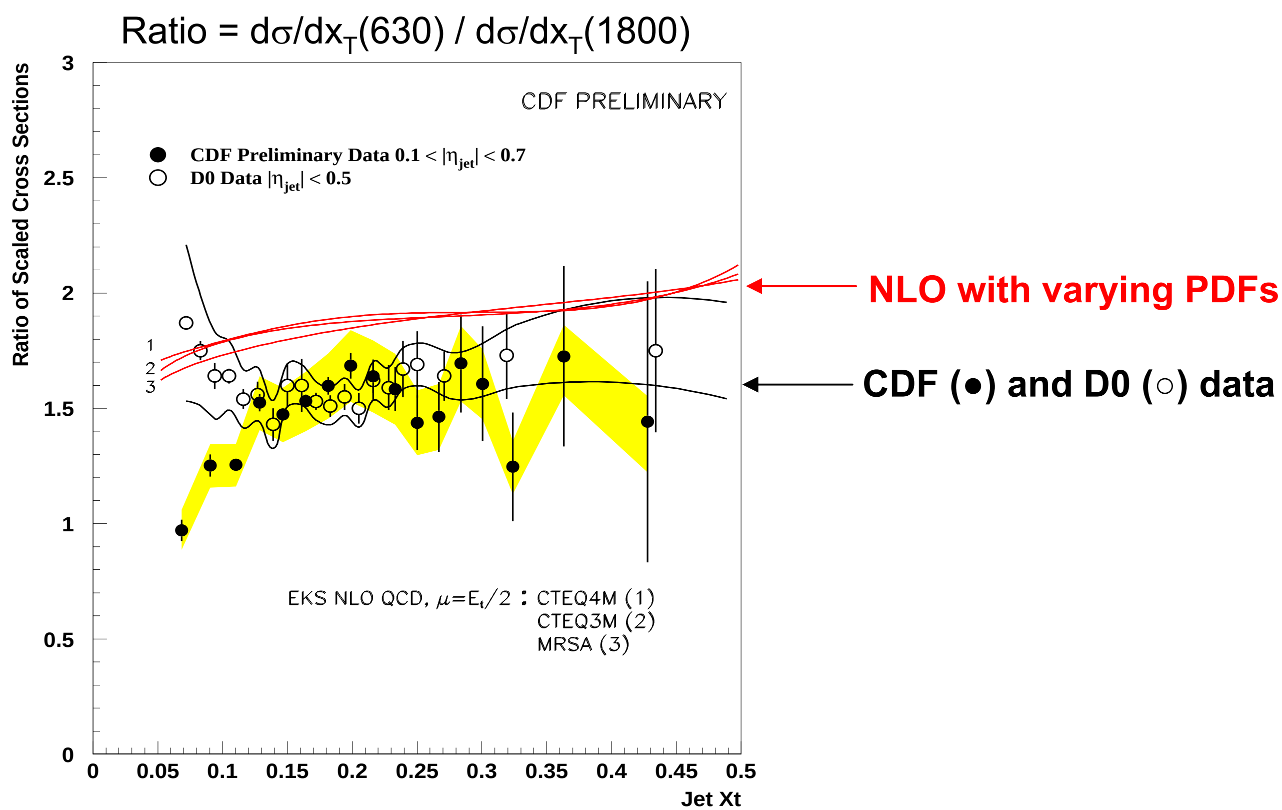


- **PDF uncertainties largely cancel out...**
- **The Run II – Run I discrepancy remains, but within energy scale errors that become really annoying…**

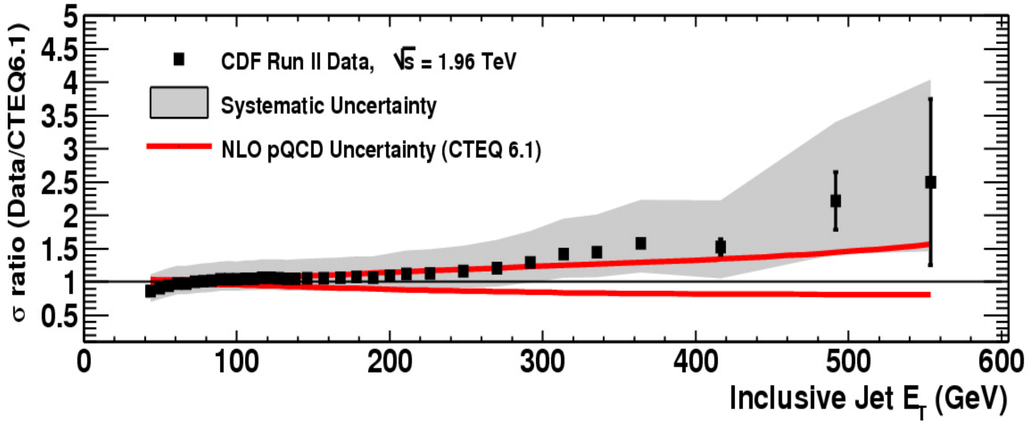
Tevatron: 1.8 TeV vs 630 GeV

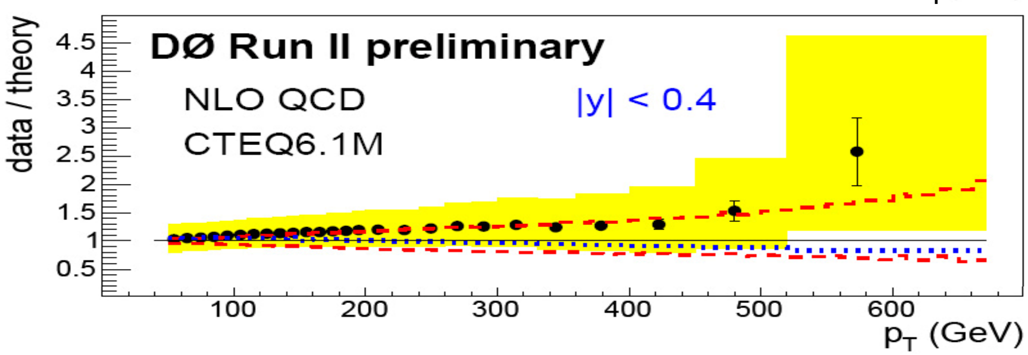
Déjà vu again?

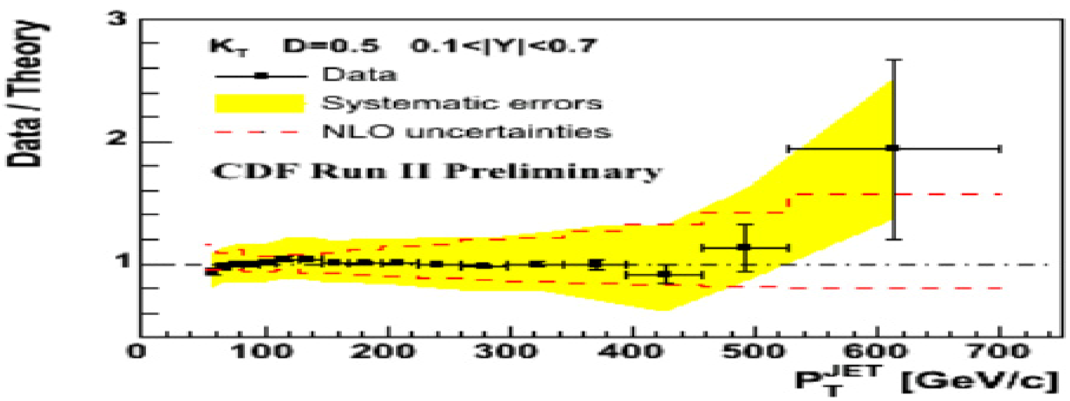
- the current discrepancy "$d\sigma/dE_T(1.96)$ vs. $d\sigma/dE_T(1.8)$" is disturbingly similar to
- the past discrepancy "$d\sigma/dx_T(1.8)$ vs. $d\sigma/dx_T(0.63)$"



Cone vs. MidPoint Cone vs. K_T algorithms







RUN II PRELIMINARY RESULTS

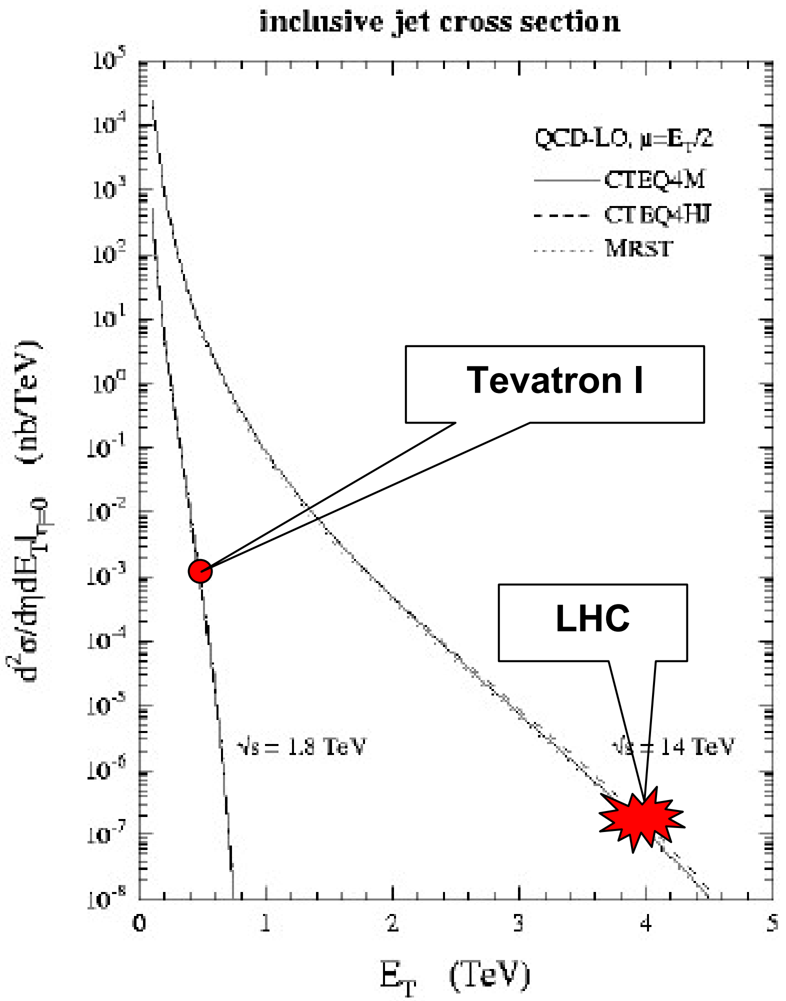
Cone (Run I Cone)
CDF, L=177 pb^{-1}

MidPoint Cone (Run II Cone)
D0, L=378 pb-1

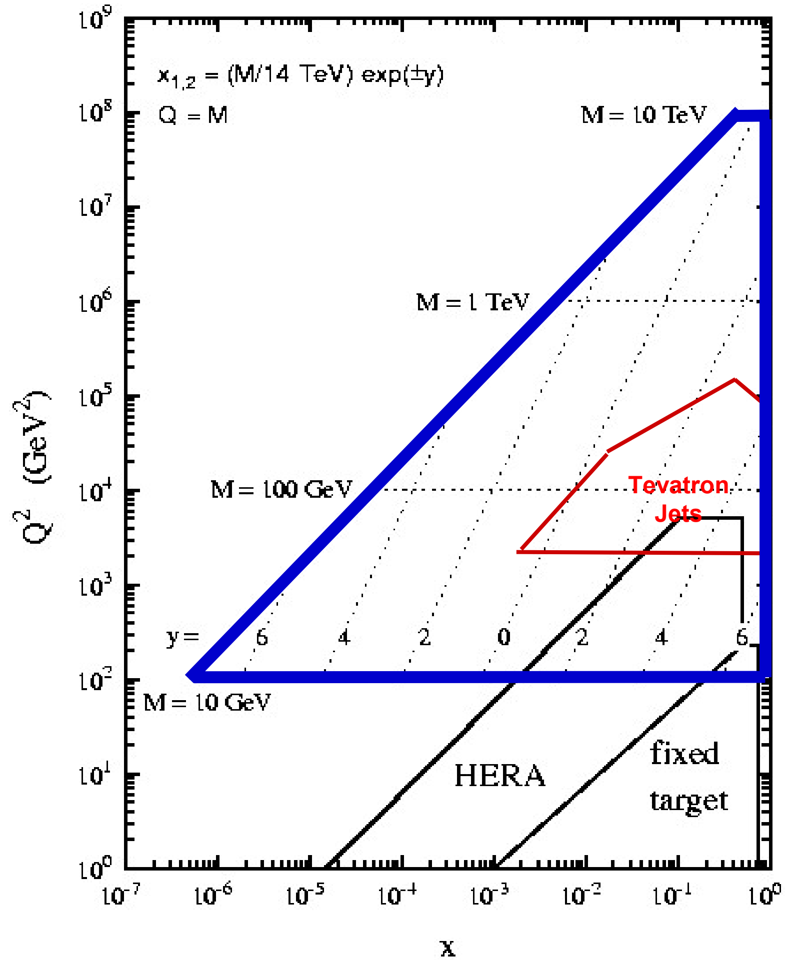
K_T
CDF, L=385 pb^{-1}

Jets at LHC

Jets up to E_T=4 TeV



Huge (x,Q²) range



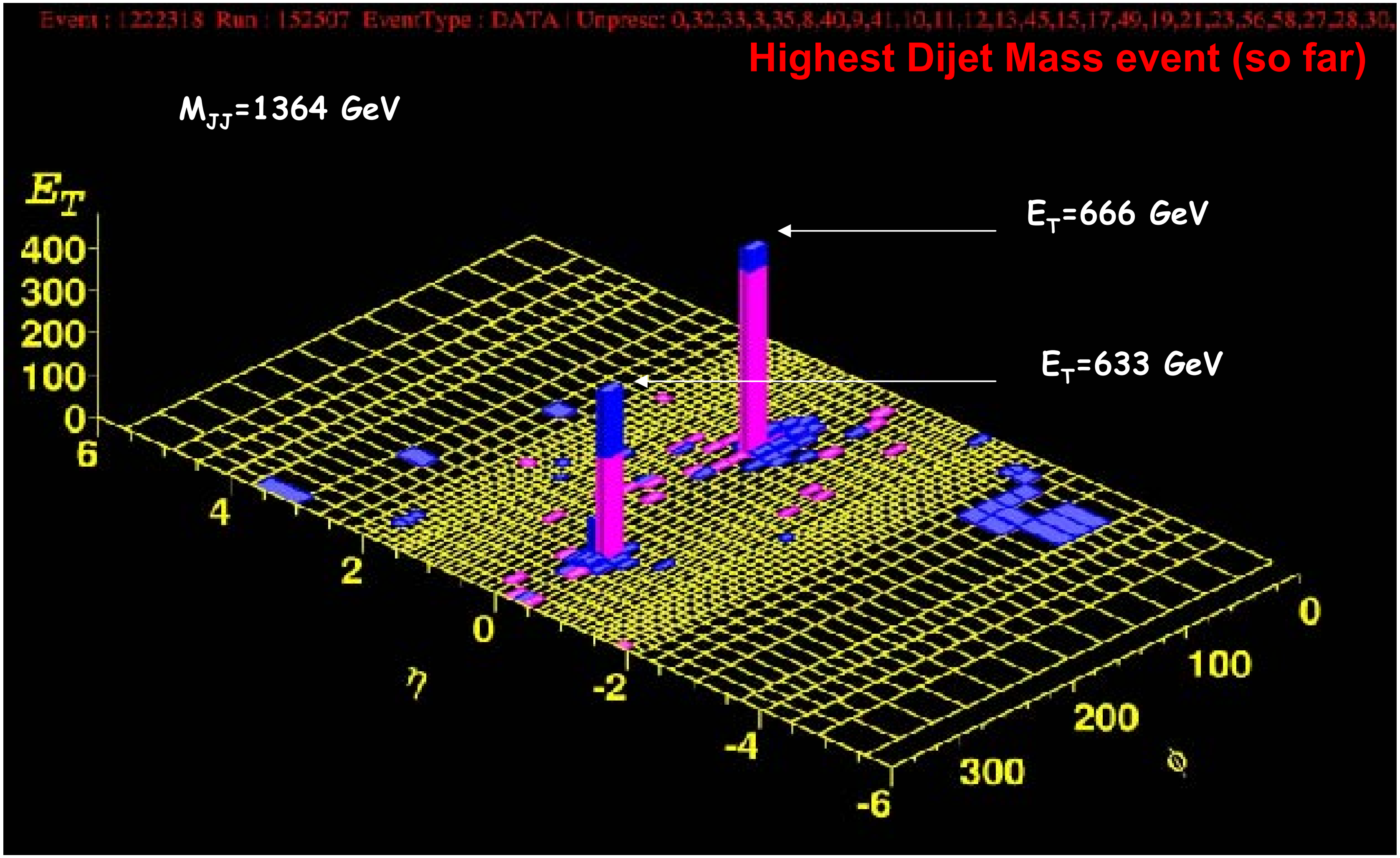
Dijet production

$$p + \overline{p} \rightarrow Jet_1 + Jet_2 + X$$

With 5 independent variables in the game (E_1, η_1, E_2, η_2, $\Delta\phi_{12}$), one might want to look at:

- **dijet mass M_{JJ} (differential x-section)**
- **dijet axis polar angle θ_{cm} in dijet CoM frame (distribution)**
- **azimuthal angle $\Delta\phi_{12}$ (distribution)**
- **…**

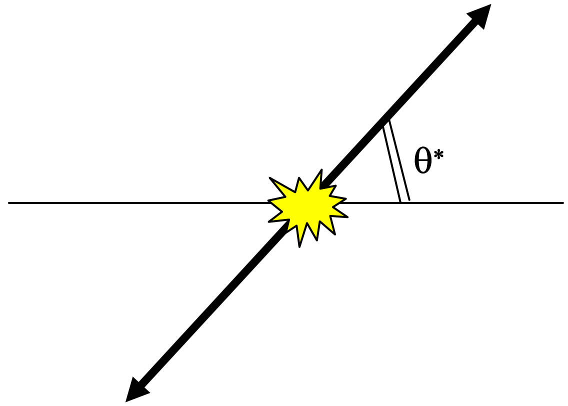
Dijets


Highest Dijet Mass event (so far)
M_{JJ}=1364 GeV
E_T=666 GeV
E_T=633 GeV
E_T
400
300
200
100
0
6
4
2
0
η
-2
-4
-6
0
100
200
300
φ

Dijets: polar angle (I)

Dijet polar angle distribution can disentangle whether the high E_T access is due to

- **quark substructure: new physics!**
- **or enhanced PDF $f(x)$ at large x:**
  g(x) at large x is poorly constrained



θ^* – smaller polar angle in dijet center of mass frame

Enhanced PDF $f(x)$ at large x

- **increased $d\sigma/dE_T$ at high E_T (and $d\sigma/dM_{JJ}$ at high M_{JJ})**
- **unchanged forward angular distribution**
  characteristic of t-channel exchange a la Rutherford scattering: $dN/d\theta \sim 1/\sin^4(\theta/2)$

$$\chi = \frac{1+\cos\theta^*}{1\text{-}\cos\theta^*} = e^{|\eta_1 - \eta_2|}$$

Quark substructure results in

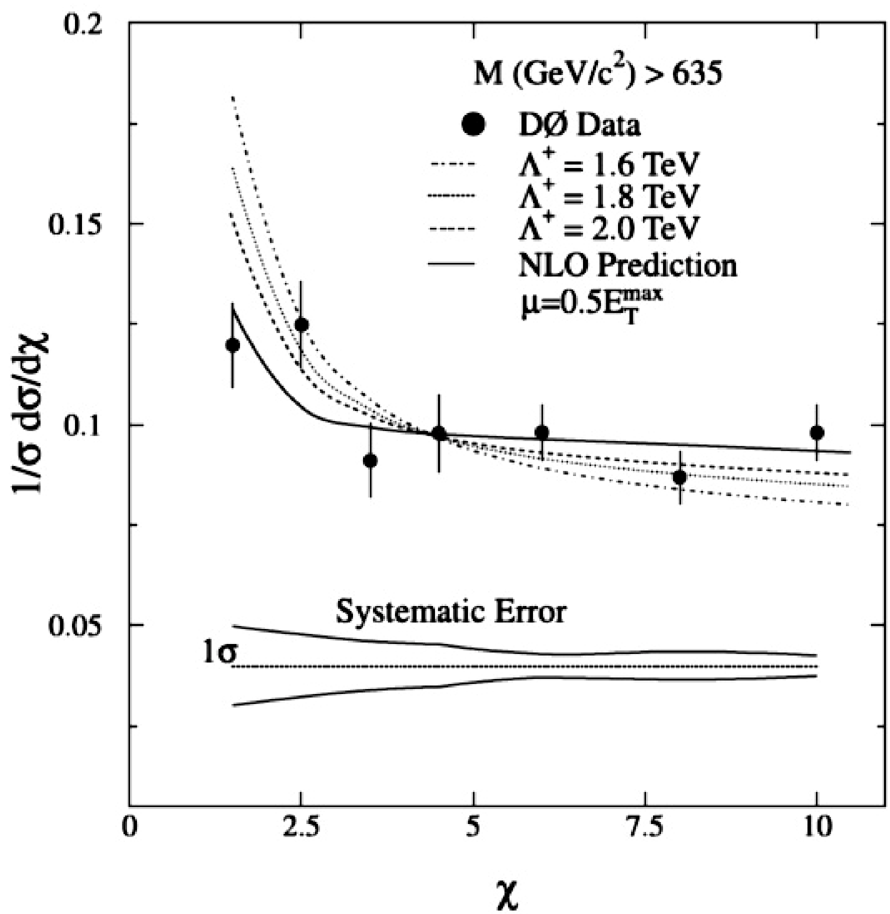
- **increased $d\sigma/dE_T$ at high E_T (and $d\sigma/dM_{JJ}$ at high M_{JJ})**
- **more central angular distribution**

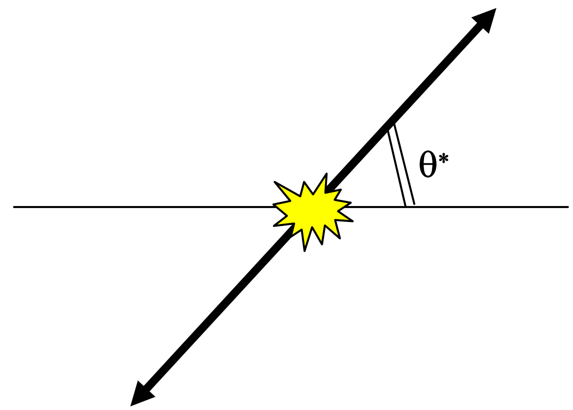
$\frac{dN}{d\chi}$ distribution is ~flat for Rutherford scattering

Dijets: polar angle (II)

Run I Compositness limit: Λ > 2 TeV

cf. ultimate LHC reach >30 TeV



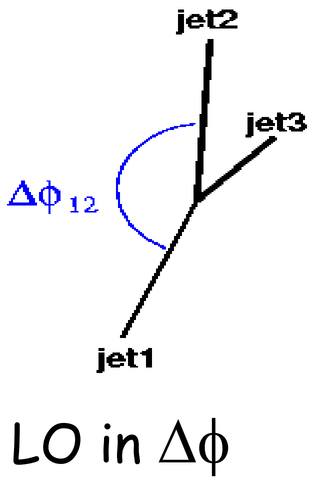


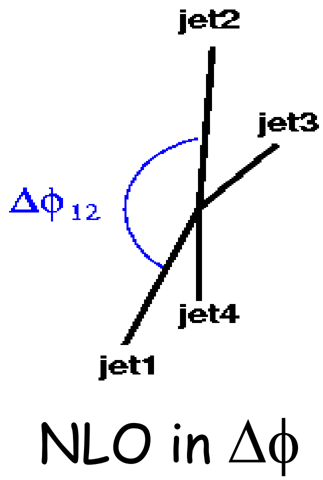
θ^* – smaller polar angle in dijet center of mass frame

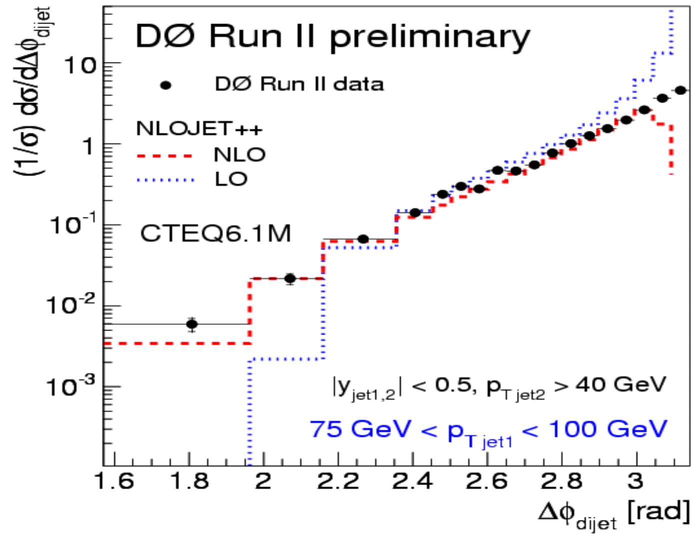
$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*} = e^{|\eta_1 - \eta_2|}$$

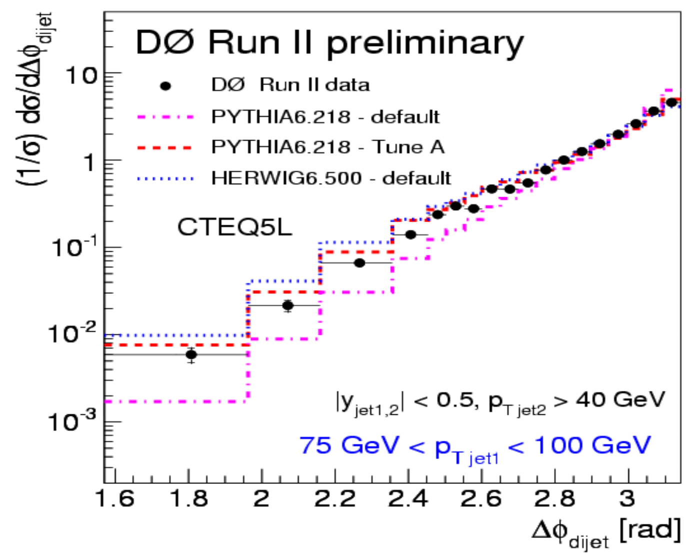
$\frac{dN}{d\chi}$ distribution is ~flat for Rutherford scattering

Dijets: azimuthal angle $\Delta\phi_{12}$









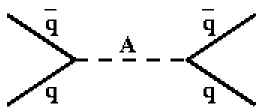
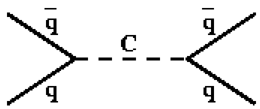
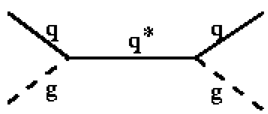
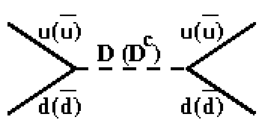
- LO is very poor at $\Delta\phi\sim\pi/2$ and $\Delta\phi\sim\pi$
- NLO fixes $\Delta\phi\sim\pi/2$, but still no good at $\Delta\phi\sim\pi$

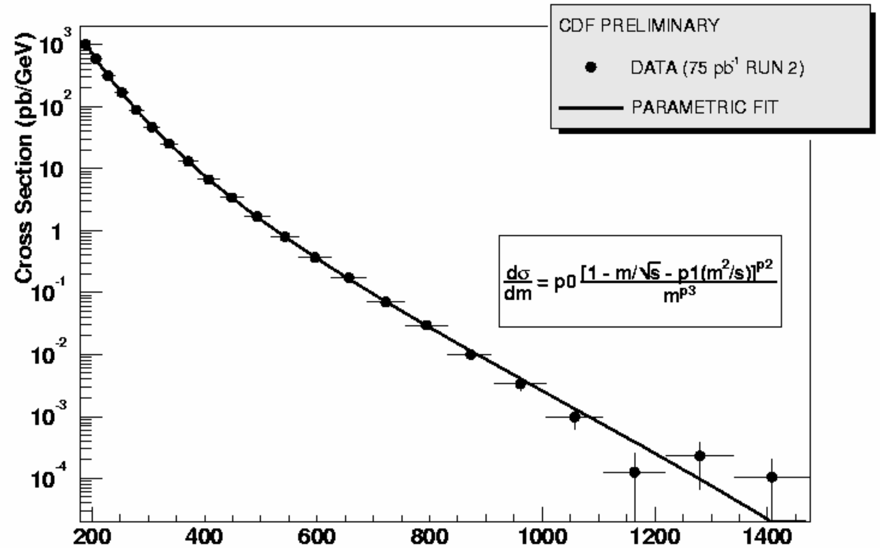
* Herwig is quite good everywhere
* Pythia is too low at $\Delta\phi\sim\pi/2$ (needs ISR enhancement)

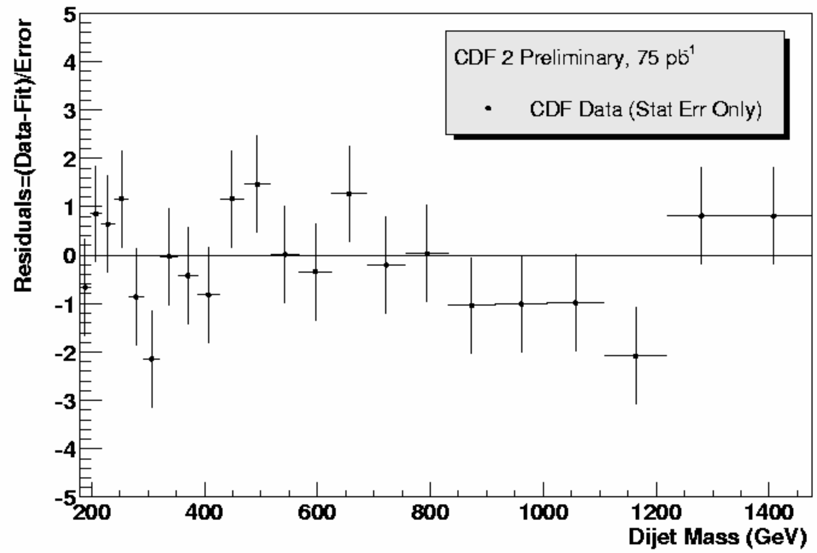
Dijet spin-off: any narrow resonances in M_{JJ}?

Plausible new physics scenarios leading to narrow dijet resonances:

New Particles That Decay to Dijets

Model	Particle	Production/Decay	J^P(color) & $\Gamma/2$
Chiral Color SU(3)L x SU(3)R	Axigluon A		1^+(8) .05 M
Extended Technicolor	Coloron C		1^- (8) .05 M
Composite Fermions	Excited Quark q*		$1/2^+$(3) .02 M
Superstring Inspired E6 Models	Diquarks D, D^c		$0^+(\bar{3})$ .004 M





→Any bumps over a smooth line fit?

Nope: many models are excluded with mass in the range 200-1000 GeV

3-, 4-, 5-, 6-jet production

$$p + \overline{p} \rightarrow N \;\; Jets + X$$

Run I:

- **all independent kinematical distributions with up to 6 jets in the final states were checked for consistency with QCD**
- **no discrepancies outside of the experimental and theoretical systematic uncertainties were found**

Jets at Hadron Colliders

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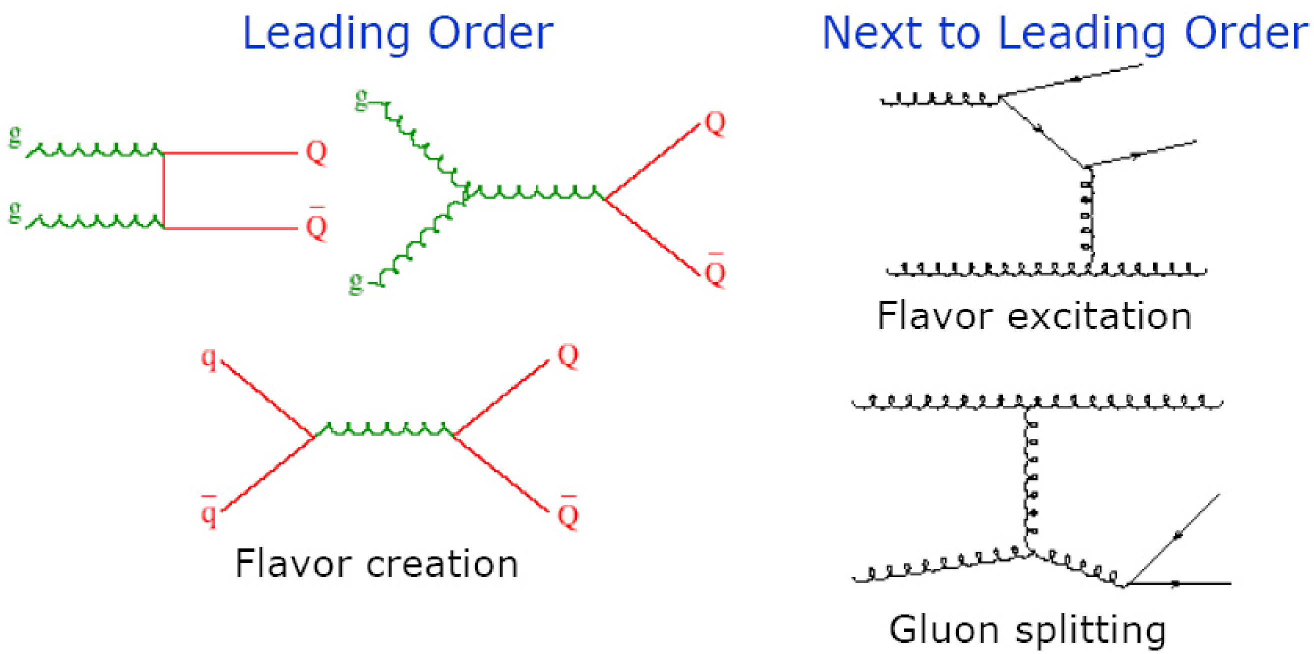
  - lepton fakes

b-jet production



- **Cross section is known up to NLLO + LLA resummation**
- **Understanding of the phenomenological B-meson fragmentation function is critical for evaluating B-tagging efficiency**

b-jet tagging

Method

- Jets with tracks forming displaced vertex

b-tagging efficiency: ~40%

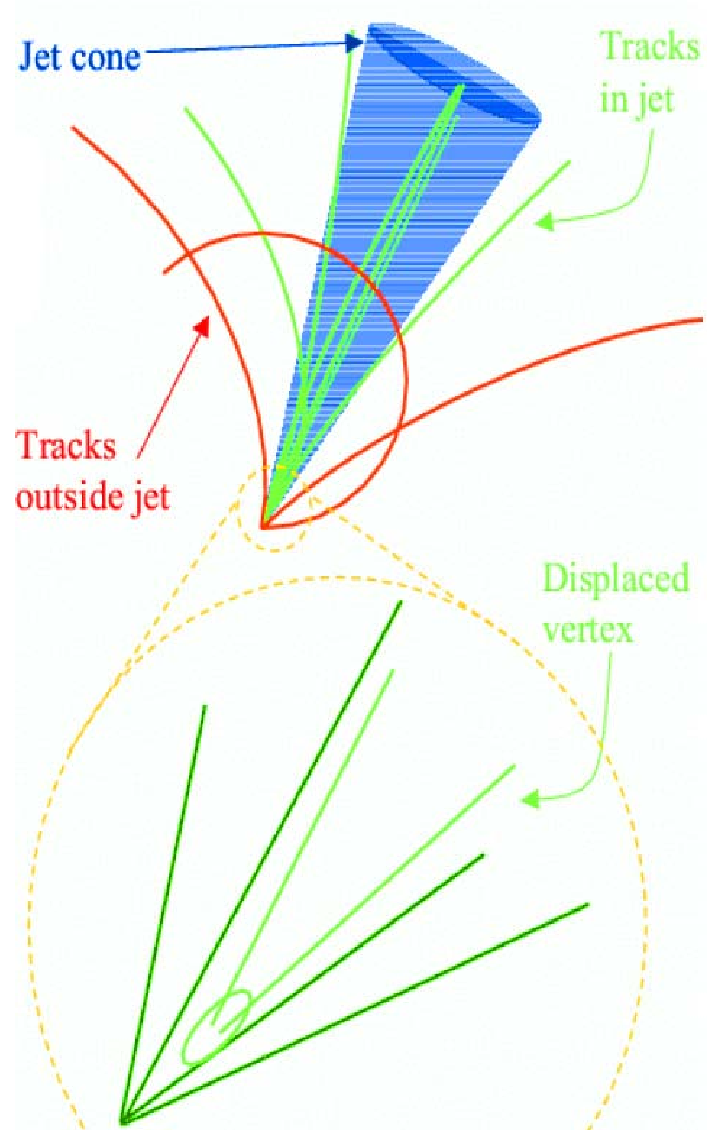
- decay length distribution $e^{-L/\lambda}$ peaks at 0

b-tagging purity: ~30%

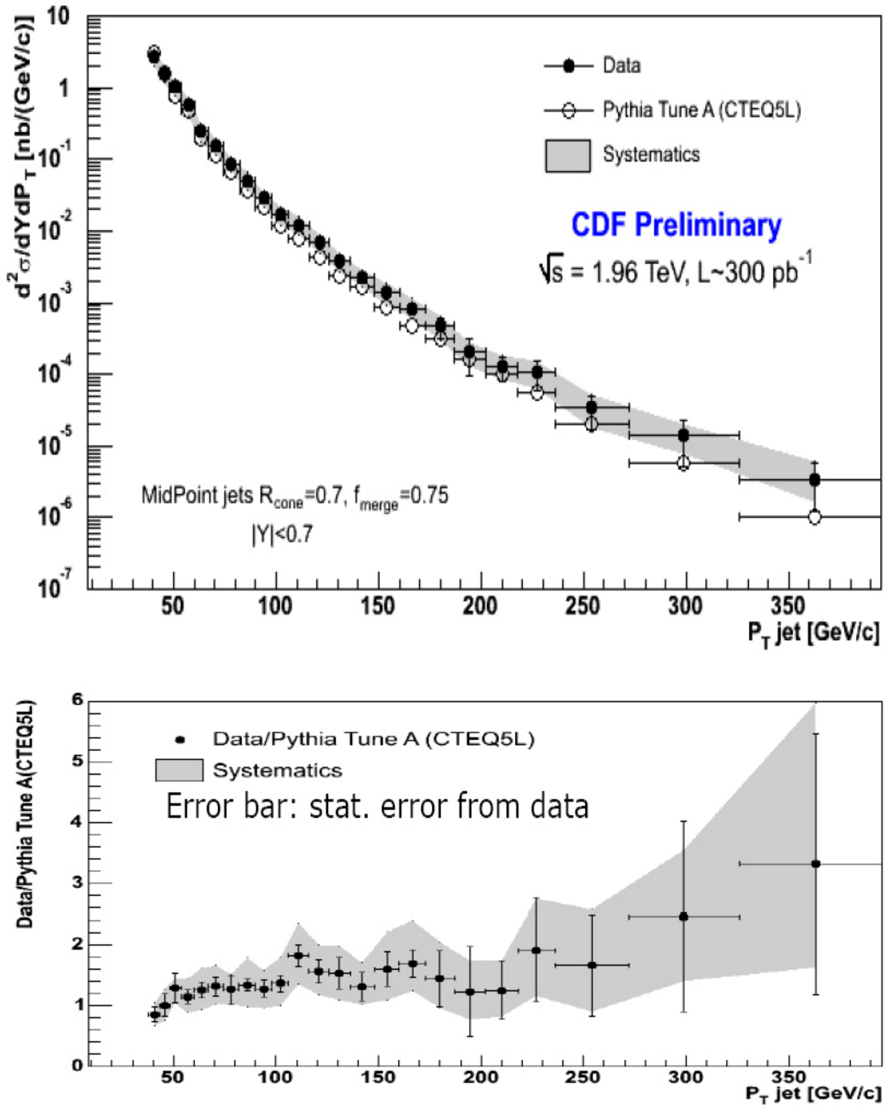
- c-jets
- q/g jets with mis-id or mis-measurements
- invariant mass formed by displaced tracks can be used to evaluate purity

Other Methods used:

- hadronic (combined with displaced vertex)
  - inclusive, $H_b \rightarrow J/\psi + X$
  - exclusive, e.g. $B^+ \rightarrow J/\psi + K^+$
- semi-leptonic:
  - $H_b \rightarrow \mu + X$



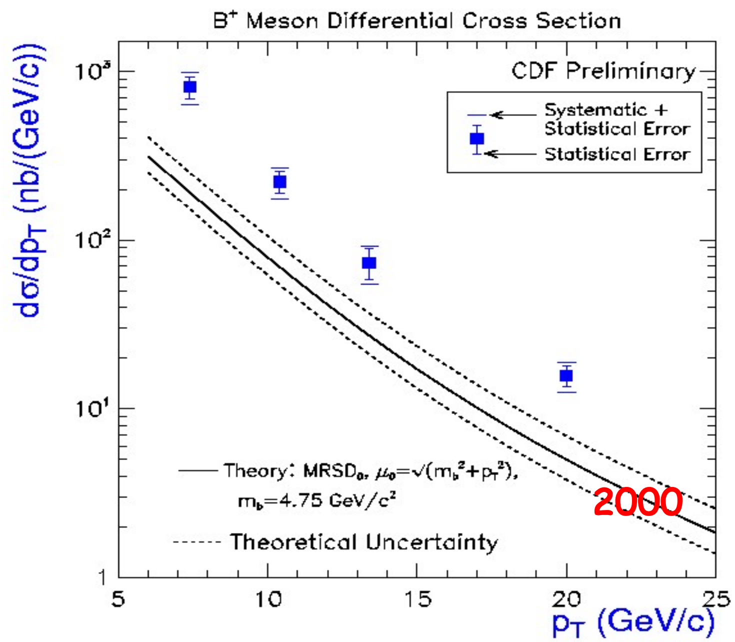
b-jet production

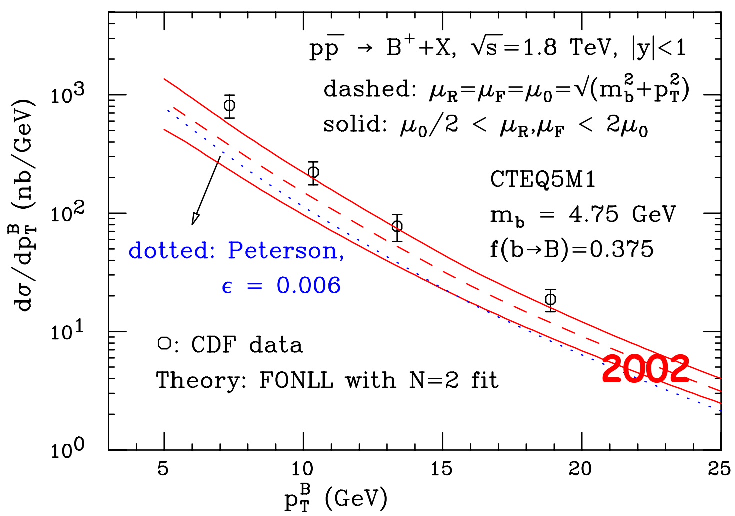


b-jet production:

- ~3% of all jets (almost P_T independent)
- agrees with pQCD
  - Pythia Monte Carlo = LO: data/LO ~ 1.4 (as expected)
  - NLO comparison is forthcoming

b-production: Run I controversy (1)





Experiment vs Theory in Run I

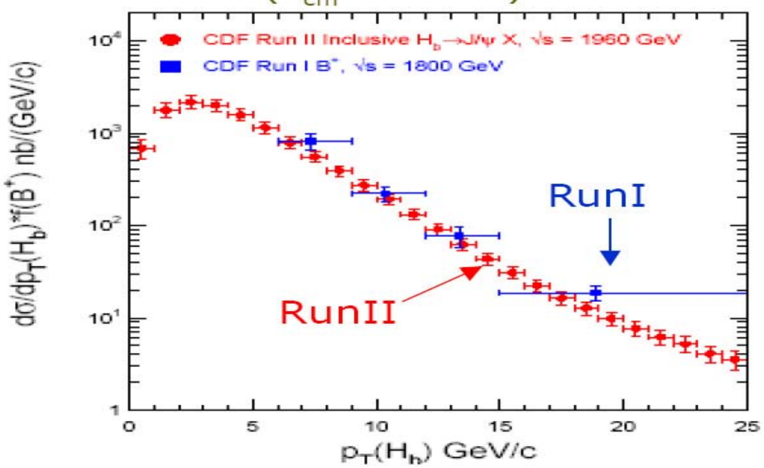
- data/theory ~ 3 (excess? exciting!)

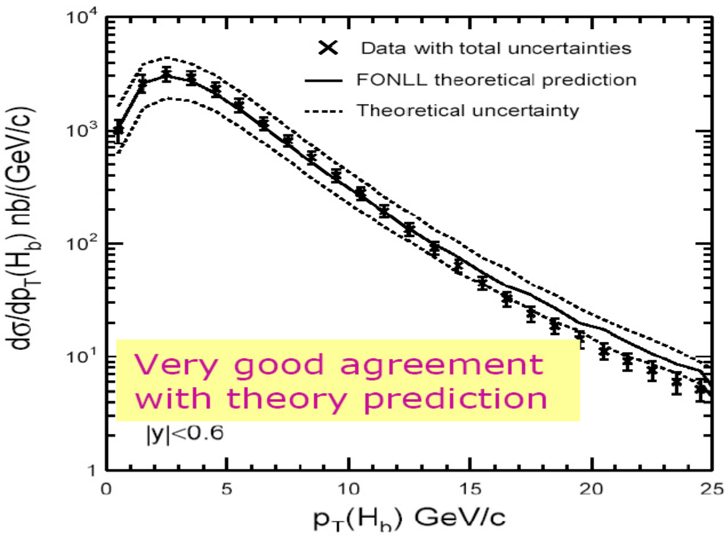
Theory since Run I:

- Fixed Order NLO + LL resummation became available
- b-quark fragmentation function updated (LEP data input)
- more resent PDFs

b-production: Run I controversy (2)

comparison with RunI data
$|y(H_b)| < 1$, σ(RunII) multiplied
by B^+ fragmentation=0.4
(E_{cm} rescaled)





Experiment vs Theory in Run I

- data/theory ~ 3 (excess? exciting!)

Theory since Run I:

- Fixed Order NLO + LL resummation became available
- b-quark fragmentation function updated (LEP data input)
- more resent PDFs

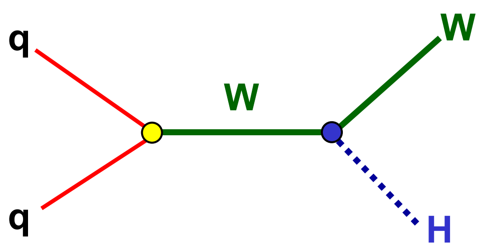
Experiment since Run I

- Run I results: not changed
- Run II agrees with Run I

Experiment vs Theory now

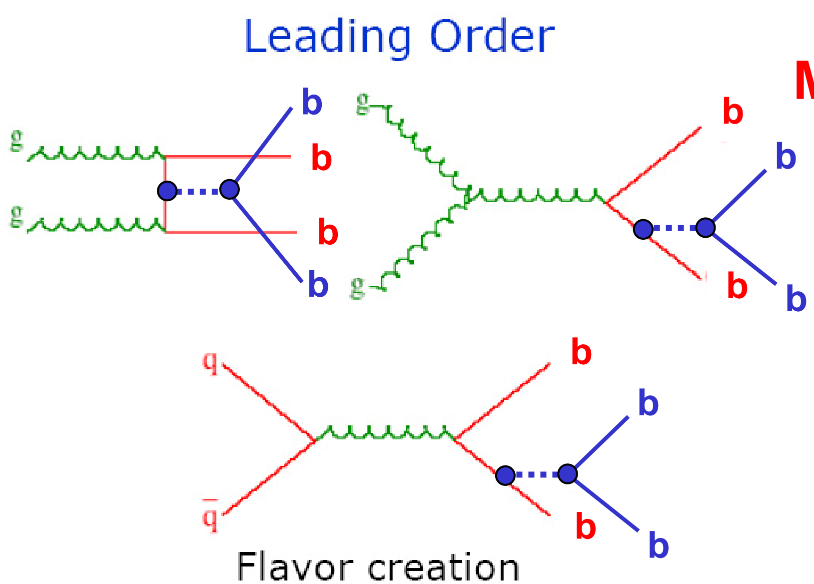
- coexist in peace (boring...)

b-jet production spin-off: Search for Higgs



SM Higgs

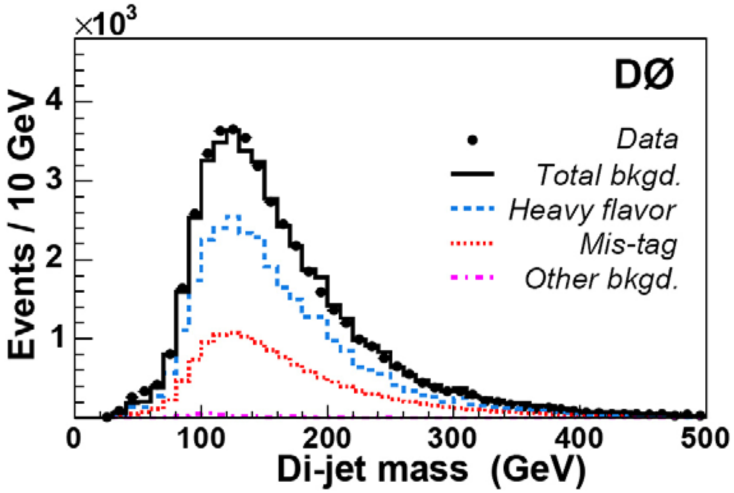
- likes to couple to heavy particles:
  ZH, WH are best bets, if any at all,
  for discovering SM Higgs at Tevatron
  (t is the best, but hard to produce)
- H->bb is the dominant decay channel



MSSM Higgs (in most of parameter space)

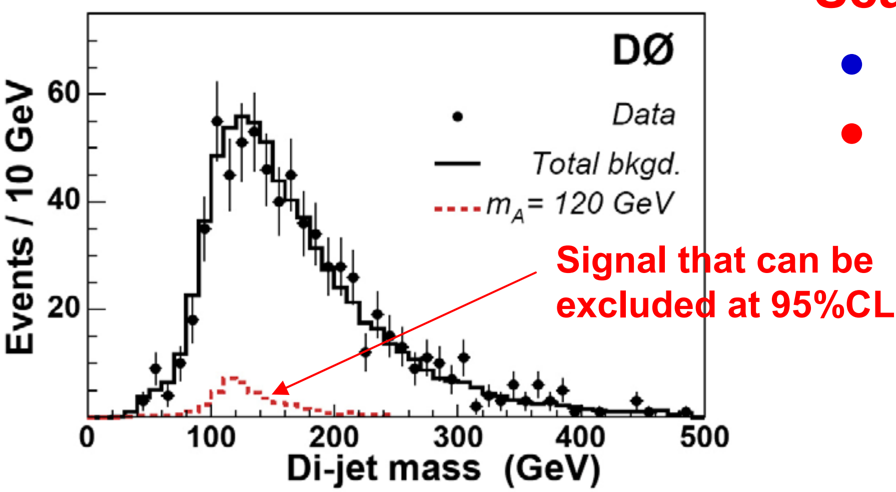
- Z and W couplings suppressed
- coupling to down-fermions enhanced:
  bbH production cross section is large
- H->bb still the dominant decay channel
- Look for multi b-jets!

b-jet production spin-off: Search for Higgs



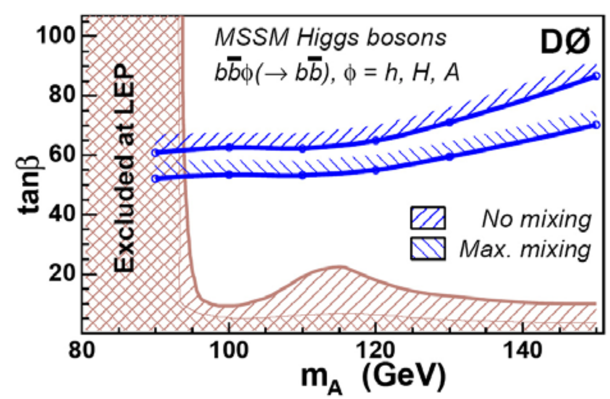
Calibrate your analysis on 2 b-jet events

- **heavy flavor bkgd: QCD bbj+X**
- **mistag: QCD jjj+X**
- **other bkgd: Zj, tt, bbbb, etc.**



Search for Higgs in bbb+X

- **note: 4^{th} b-jet is allowed to be missed**
- **no excess seen: No Nobel Prize (yet)**



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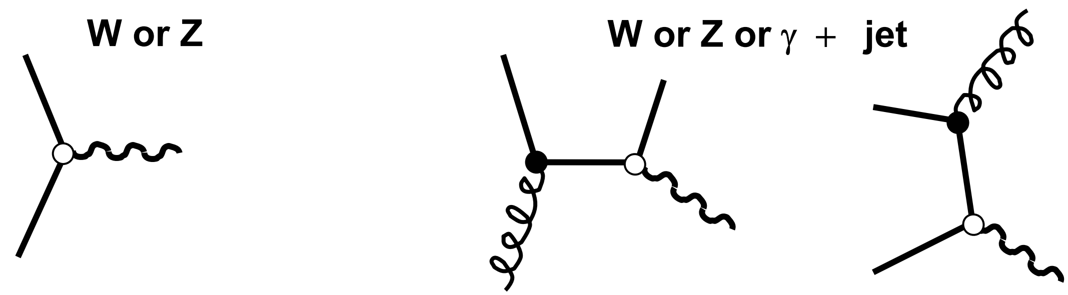
EWK vector bosons (W, Z, γ) + jets

Examples of LO diagrams



- Smaller subset of diagrams, different mix of initial partons: PDF contribute differently as compared to the plain jet production

Theory (on example of W):

- W inclusive: can be generated at NNLO level
- W + 1 jet: NLO level
- W + 2, 3, 4 jets: LO level

Notes:

- Inclusive distributions are not affected by jet finding uncertainties
- W/Z/γ identification algorithms have their own caveats…

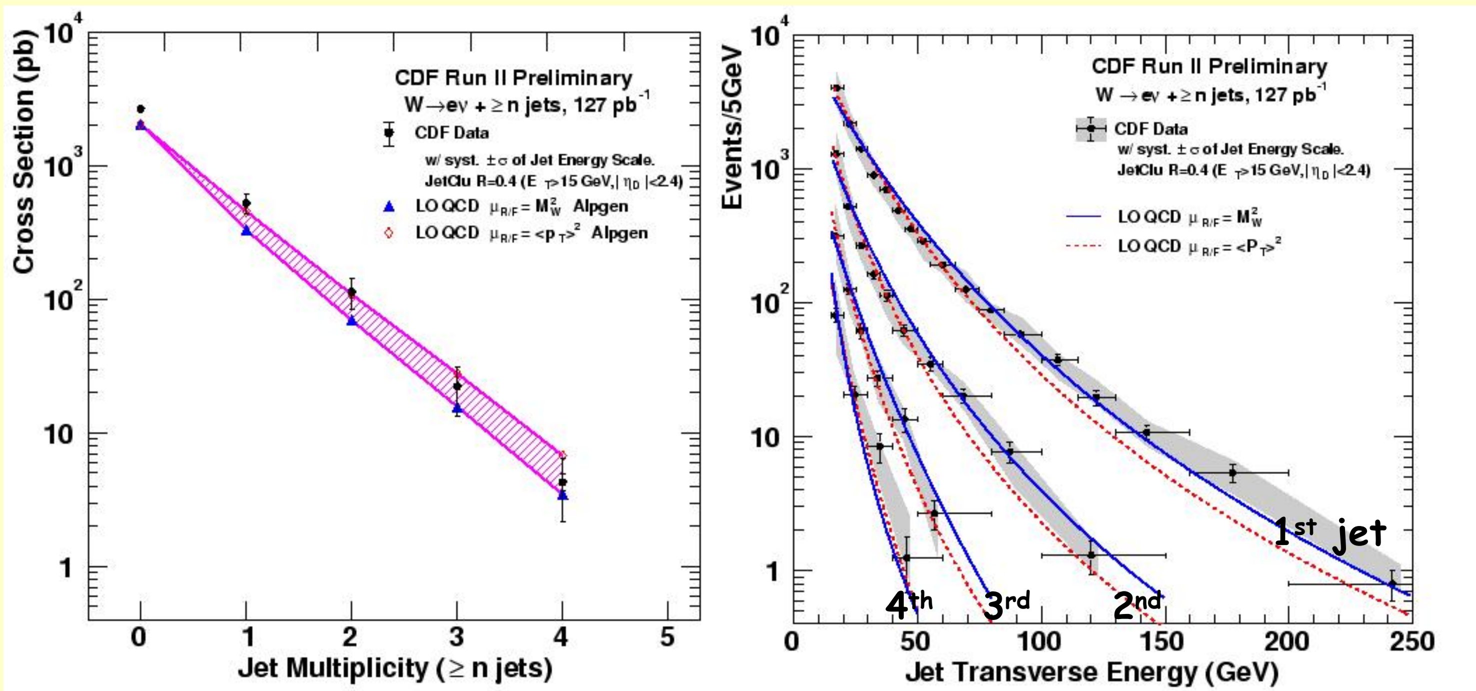
W + jets

Inclusive $\sigma(W) \times Br(W \to e\nu)$

	Run I (1.8 TeV)	Run II (1.96 TeV)	
CDF:	2.38±0.24 nb	2.64±0.18 nb	
LO:	1.76	1.94	LO is significantly off
NLO:	2.41	2.64	NLO works quite well
NNLO:	2.50	2.73	NNLO makes little difference

$\sigma(W + \geq N\ jets) \times Br(W \to e\nu)$:

LO QCD works fairly well



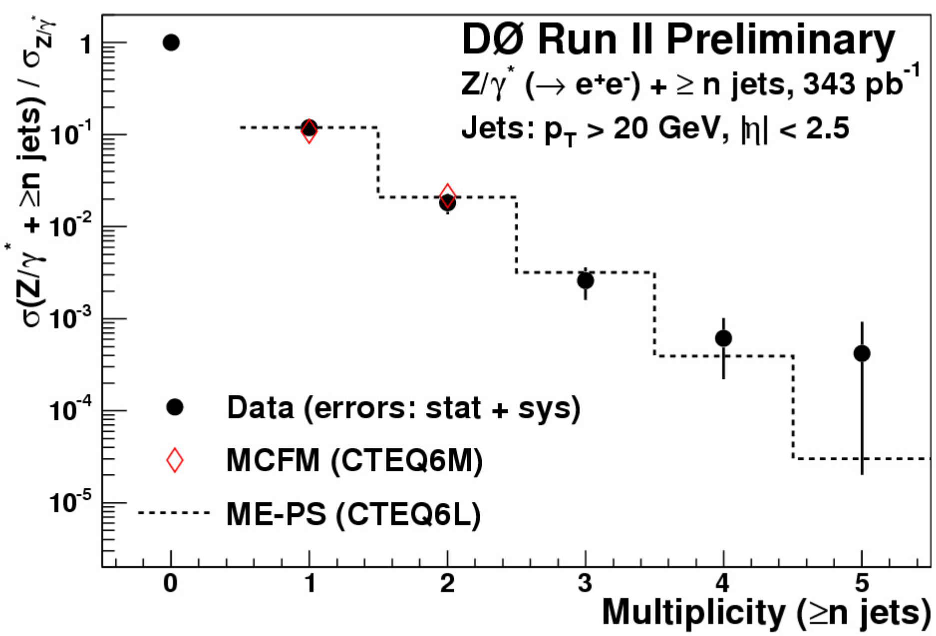
Z + jets

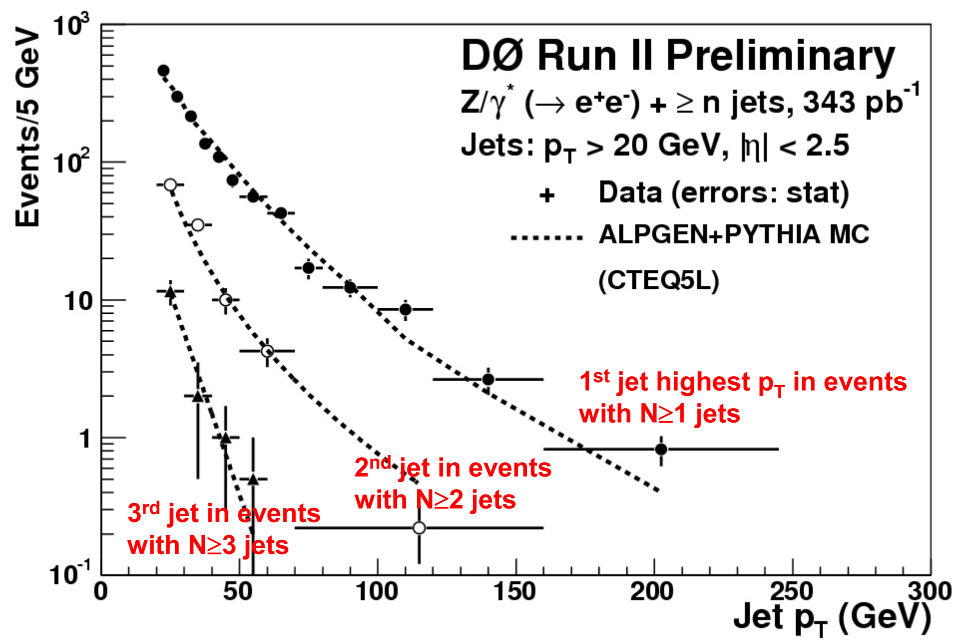
Ratio σ(Z + ≥N jets) / σ(Z) agrees well with

- LO Matrix Element (MadGraph) + Parton Shower (Pythia)
- MCFM (NLO total x-section)

Jet P_T in Z+jets events agrees well with

- LO Matrix Element (ALPGEN) + Parton Shower (Pythia)

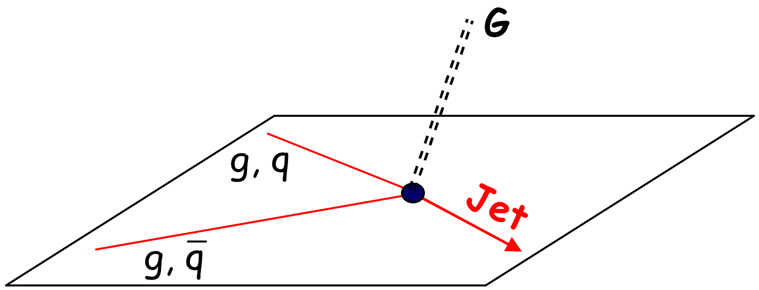




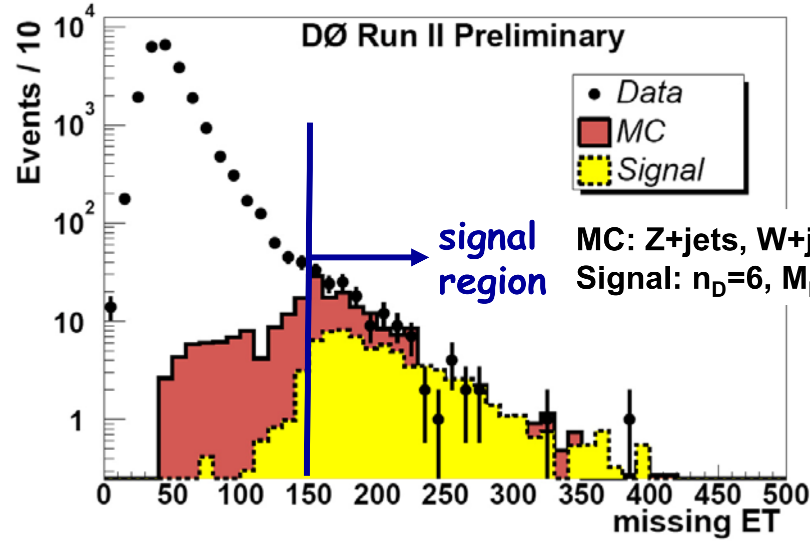
Z+jet spin-off: Extra Dimension searches

Large Extra Dimensions (ADD)

Arkani-Hamed, Dimopoulos, Dvali, Phys Lett B429 (98)



$$p+\overline{p} \rightarrow Jet + \not{E}_T$$



Leading Jet P_T>150 GeV $|\eta|$<1
No e/μ candidates
MET>150 GeV

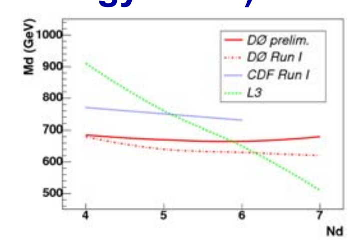
Main background:

$$p+\overline{p} \rightarrow Z + Jet + X$$

$$Z \rightarrow \nu\overline{\nu}$$

After additional cuts on isolation, 2nd jet E_T<50 GeV

- Expected Background:
  N_B = 100±6(stat)±8(theory) +50%-30% (jet energy scale)
- Data: N = 63



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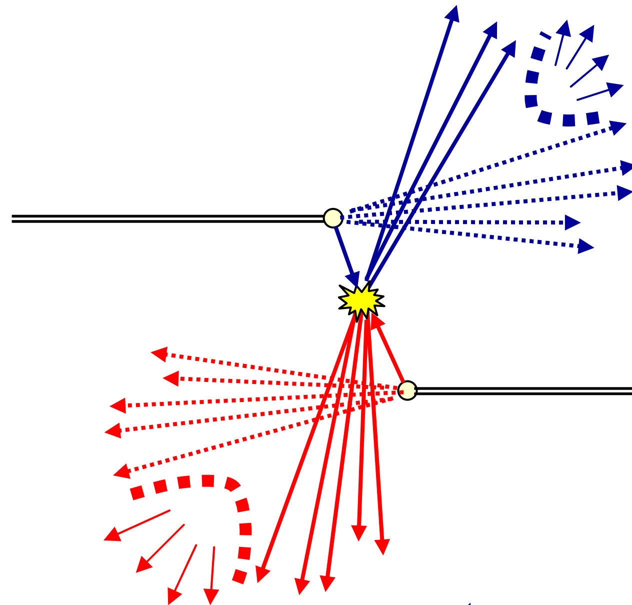
Diffractive Dijets

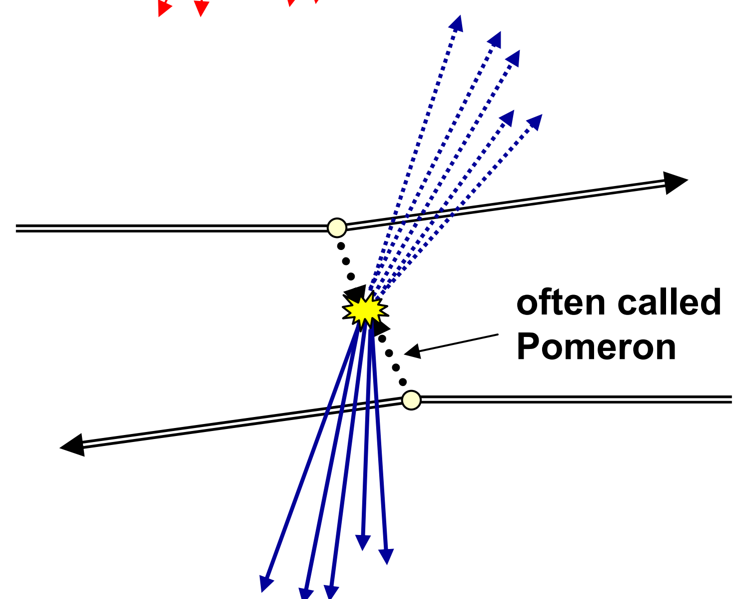
Typical parton-parton interaction

- two partons scatter and produce two jets
- proton and antiproton remnants carry on along the beam line and produce forward-backward debris
- color strings between outgoing hard-scattered partons and spectator partons break resulting in flow of particles between jets and beam line

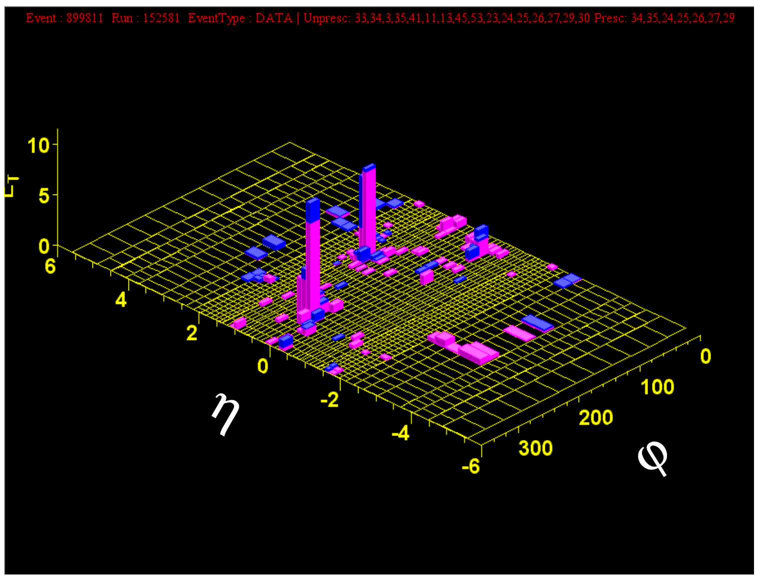


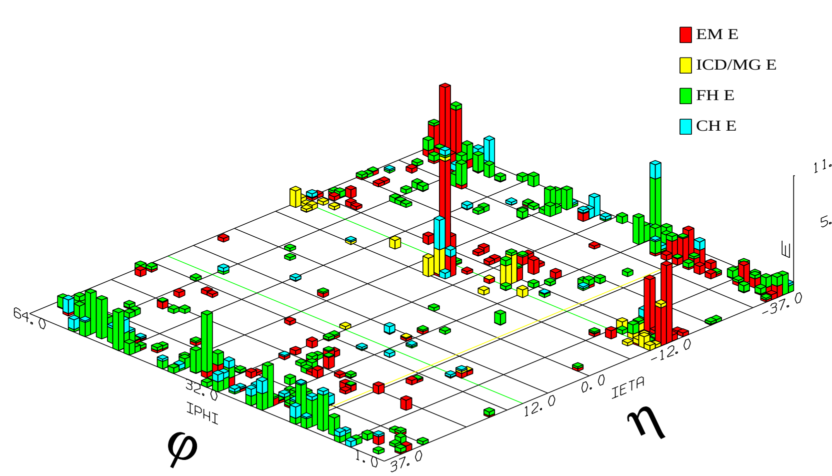
Typical diffractive interaction

- one or both protons remain intact
- whatever protons exchange with has quantum numbers of vacuum, but still must have QCD as an underlying theory
  - diffractive cross section is relatively large
  - hadrons/jets readily produced in such events
- no color strings between outgoing partons and protons are formed resulting in
  - characteristic rapidity gaps (intervals of pseudo-rapidity unpopulated with any particles)



Double Pomeron Exchange Dijet fraction

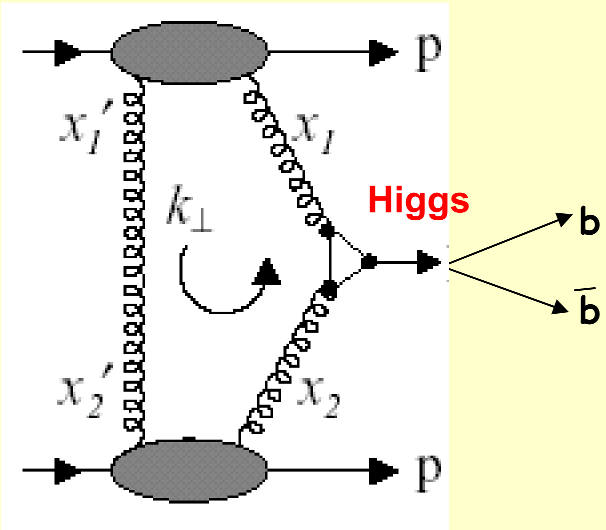




$$\frac{\text{"Double Pomeron Exchange" Dijets}}{\text{Non-Diffractive Dijets}} \sim 10\% \quad (E_{T2} > 7\text{ GeV})$$

Diffraction dijets: new twist (diffractive Higgs?)

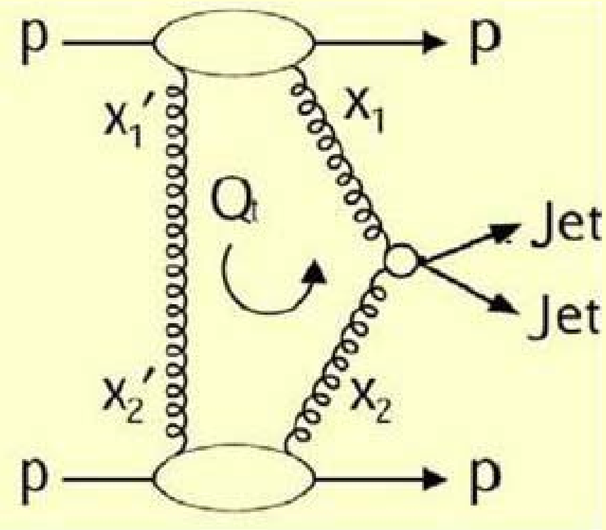
Khoze, Martin, Ryskin (2002):



Clean Signal at LHC

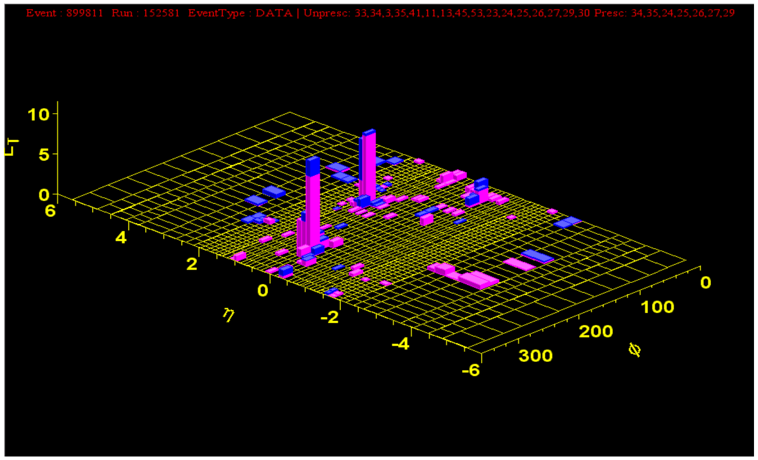
- $\sigma \sim 3$ pb
  30 events in 1 yr at $L=10^{33}$
- Signal/Bkgd ~ 3

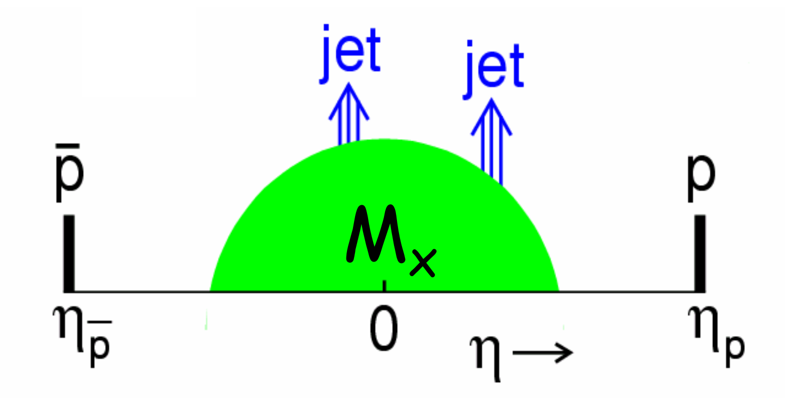
We can check the model at Tevatron!



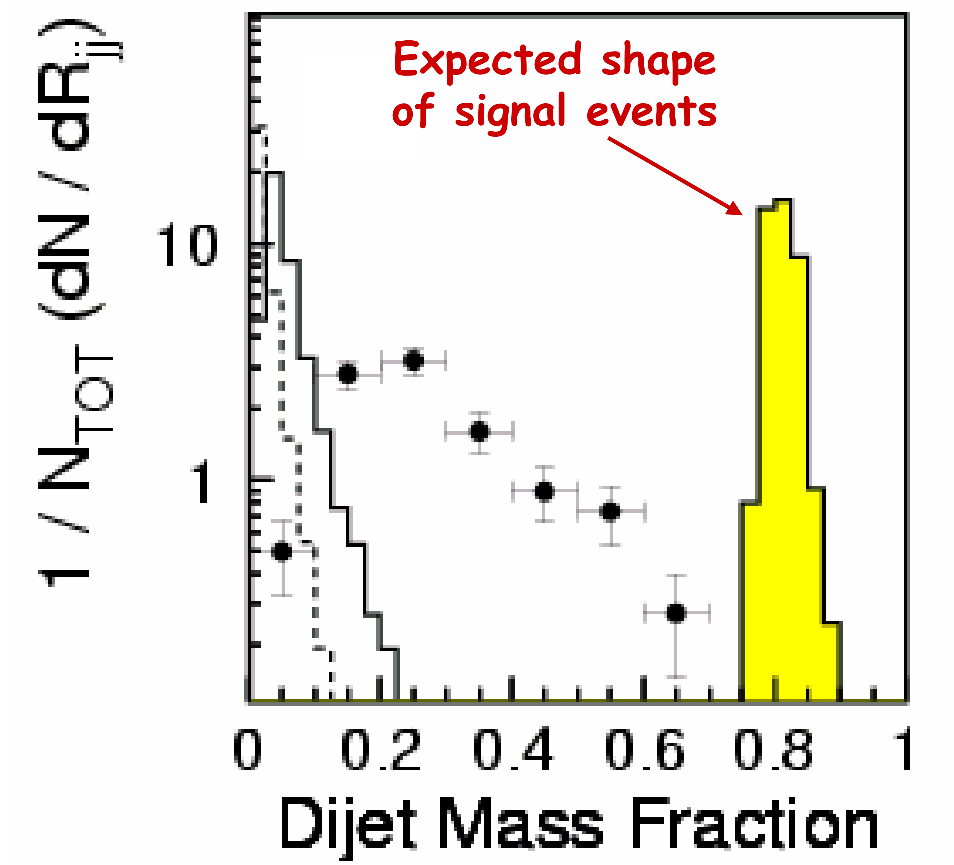
- $\sigma \sim 40$ pb (E_T>25 GeV),
  with factor of 2 uncertainty
- ~100% gg jets

Diffractive Exclusive Dijets?



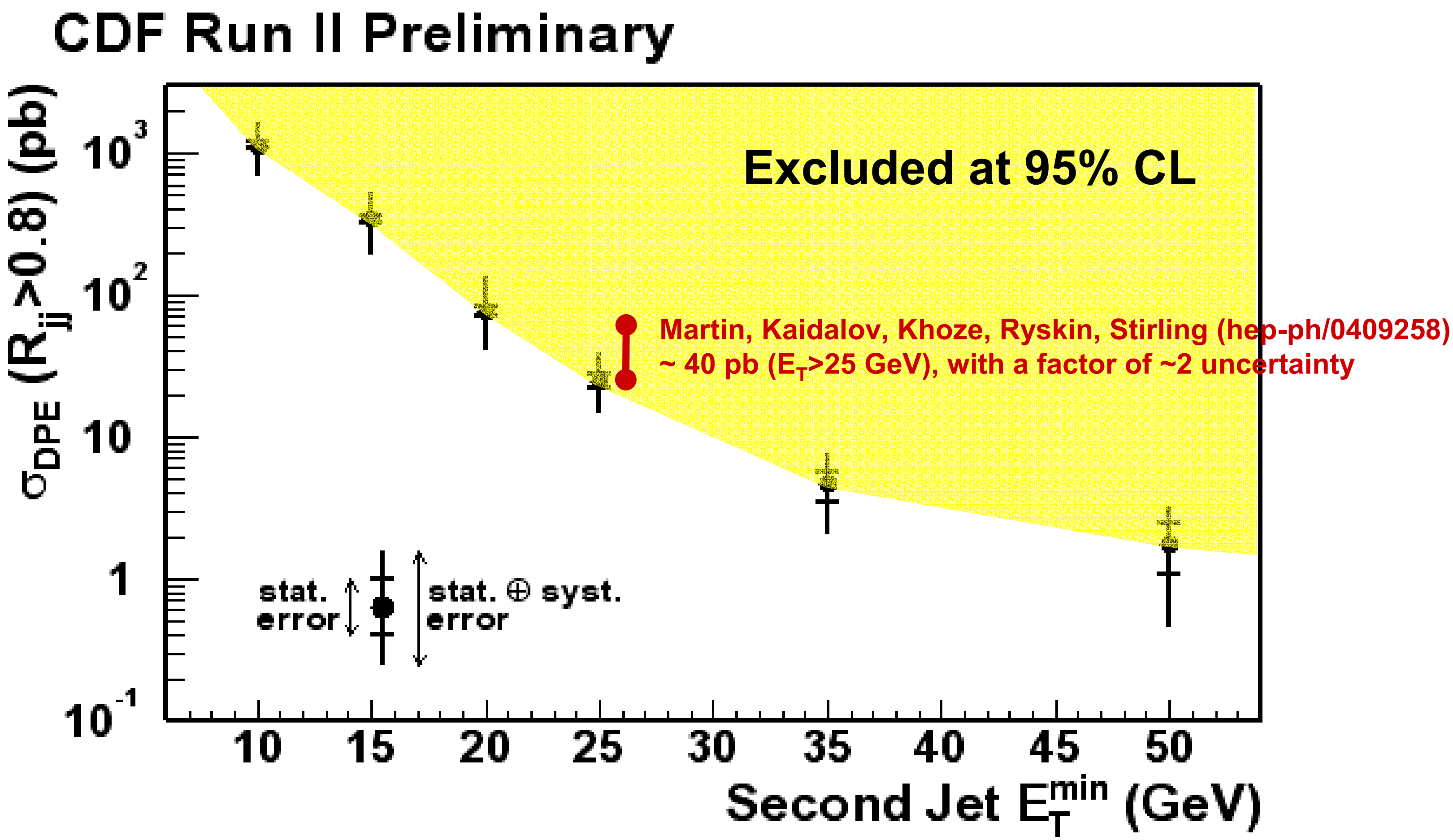


Dijet Mass Fraction $R_{jj} = \dfrac{M_{jj}}{M_x}$



Jets at Hadron Colliders

Diffractive Exclusive Dijets: so does it check?



More statistics is needed...

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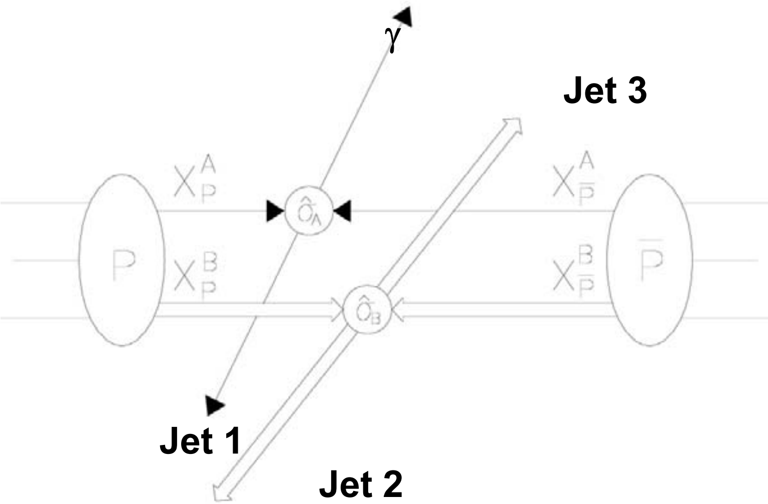
Jets from Multi-Parton Interactions



Process *a*:

- γ-jet: cross section σ_a

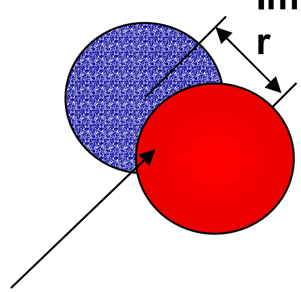
Process *b*:

- dijet: cross section σ_b

Double-parton scattering in single pp collision:

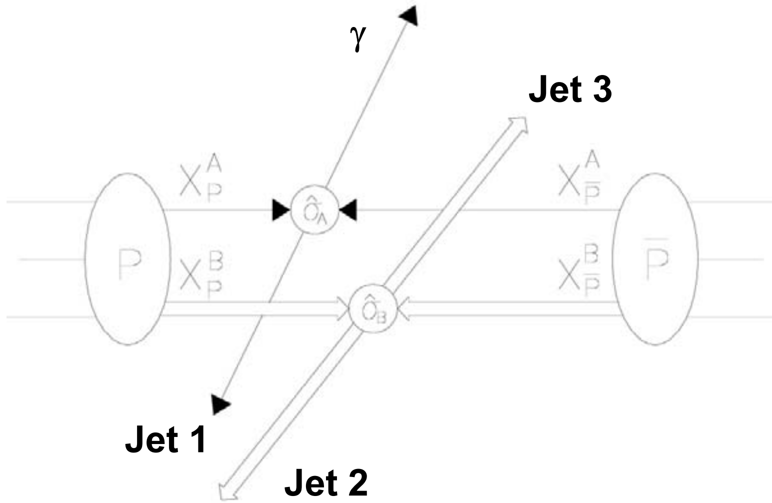
- (γ-jet) + (dijet)
- cross section σ_{ab}

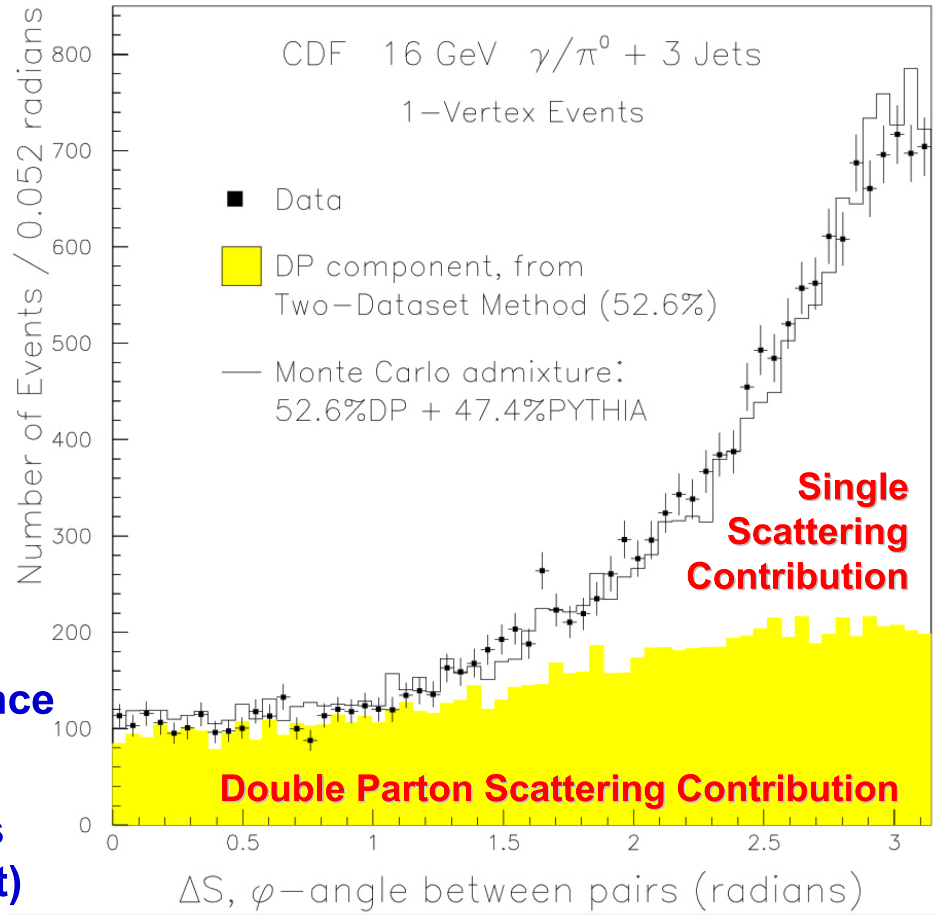
$$\sigma_{ab} = \frac{\sigma_a \sigma_b}{\sigma_{eff}}$$



- σ_{eff} characterizes
  - transverse proton size and density of partons
  - clumping of partons together
    (the smaller σ_{eff}, the clumpier the structure is)
  - x_1-x_2 correlations for combined pdf $f(x_1, x_2)$:
    (should σ_{eff} be x-dependent, it would be a tale tell sign of two-parton correlations)
- if partons are uniformly distributed in a sphere of radius r, related to the total non-diffractive inelastic cross section ~50 mb, then
  - σ_{eff} ~ 11 mb

Jets from Multi-Parton Interactions





Signal selection:

- **3 jets and photon**
- **match γ-jet and jet-jet by best E_T balance**

Double (γj + jj) vs single (3jγ)

- **The best discriminating distribution is Δφ-angle between P_T(γ-jet) and P_T(dijet)**
  - **$P_T \neq 0$ due to NLO contributions**
  - **P_T directions do not correlate for two nearly independent interactions**
  - **and strongly correlate for single interaction (tend to be back to back)**

1) $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
   (consistent with no spatial clumpiness)
2) No parton-parton momentum correlations seen

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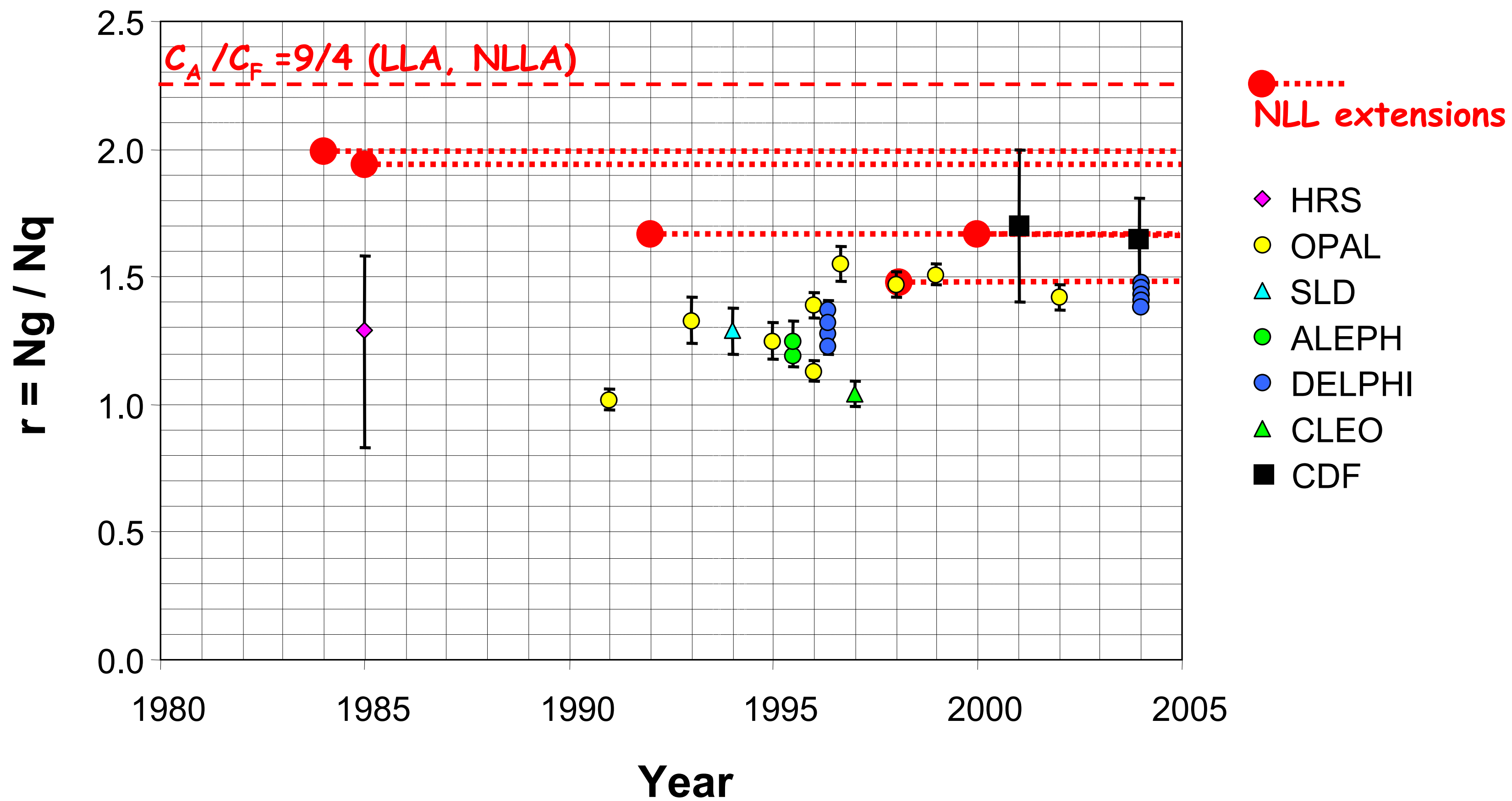
Jet Fragmentation: Gluon vs. Quark Jets in Historical Perspective

Ratio $r = N_{ch}(\text{gluon jet}) / N_{ch}(\text{quark jet})$

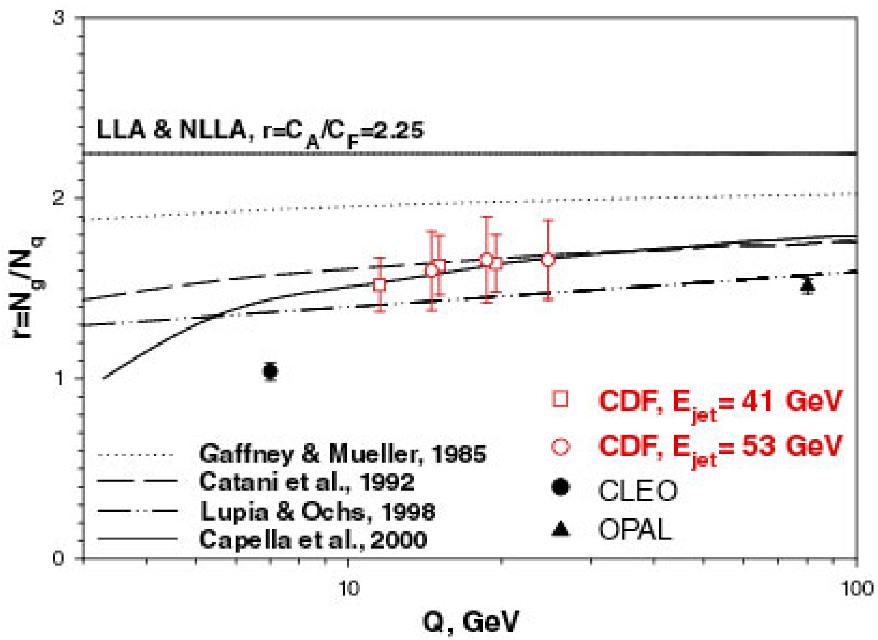


Jet Fragmentation: Gluon vs Quark jets

Difference of Particle Multiplicities in Gluon and Quark jets:

$r = N_{hadrons}$(gluon jet) / $N_{hadrons}$(quark jet)

- **calculations (for partons):**
  - various extensions of NLLA: r=1.5-1.7 (depends on $Q=E_{jet}\cdot\theta_{cone}$)
- **data: 15+ papers from e^+e^-**
  - r=1.0-1.5 (not all self-consistent)
- **CDF analysis:**
  - dijet events with M_{jj}~100 GeV gluon jet fraction ~60%
  - γ-jet events with $M_{\gamma j}$~100 GeV gluon fraction ~20%
  - measure N_{jj} and $N_{\gamma j}$ inside 15-30° cone around jet axis
  - resolve for N_g, N_q and their ratio, **RESULT: r ~ 1.6±0.2**



Jet Fragmentation: momenta, multiplicities

Momentum distribution of charged particles in jets

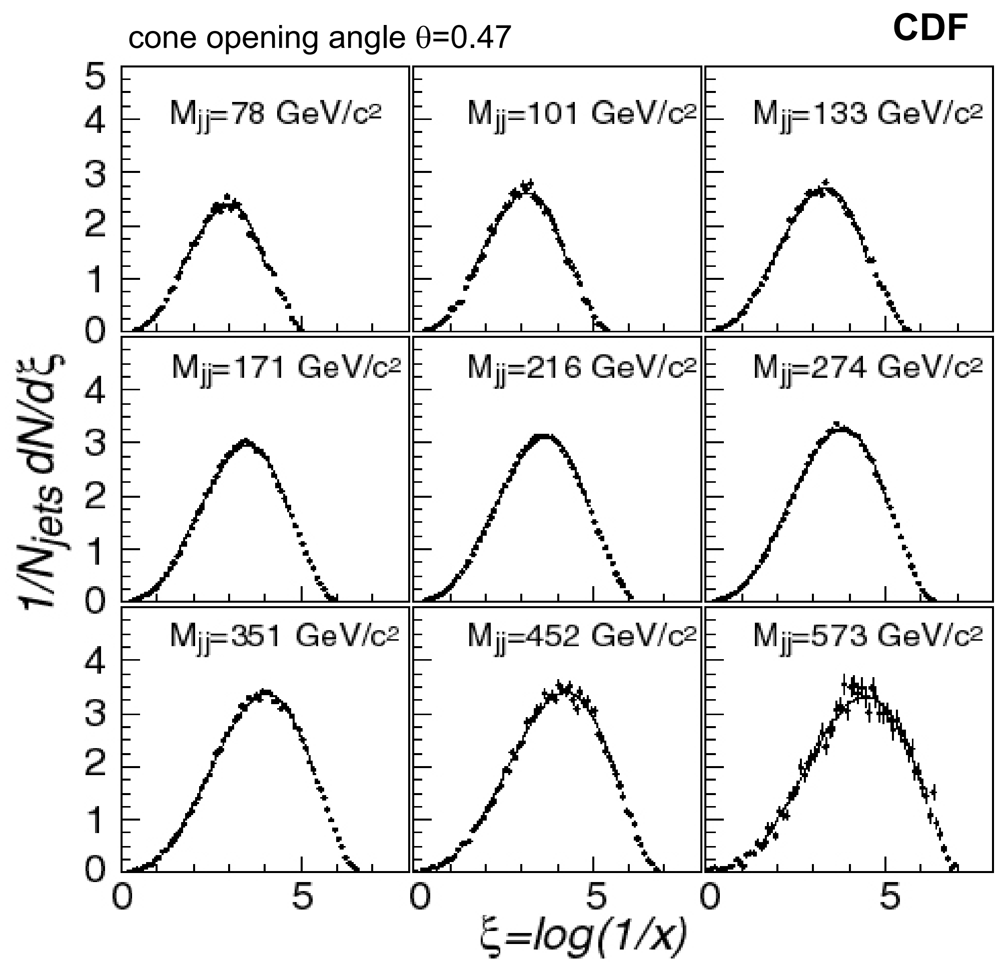
- dijet events with well-balanced E_T
- 15-30° cone around dijet axis

Two parameter fit (MLLA+LPHD):

- works surprisingly well in <u>wide range of dijet masses</u>

- MLLA Q_{eff} = 230±40 MeV
  ☞ k_T-cutoff can be set as low as Λ_{QCD}

- $K_{LPHD(\pm)}$ = 0.56 ± 0.10
  ☞ $N_{hadrons} \approx N_{partons}$



$$x = \frac{p_{particle}}{E_{jet}}$$

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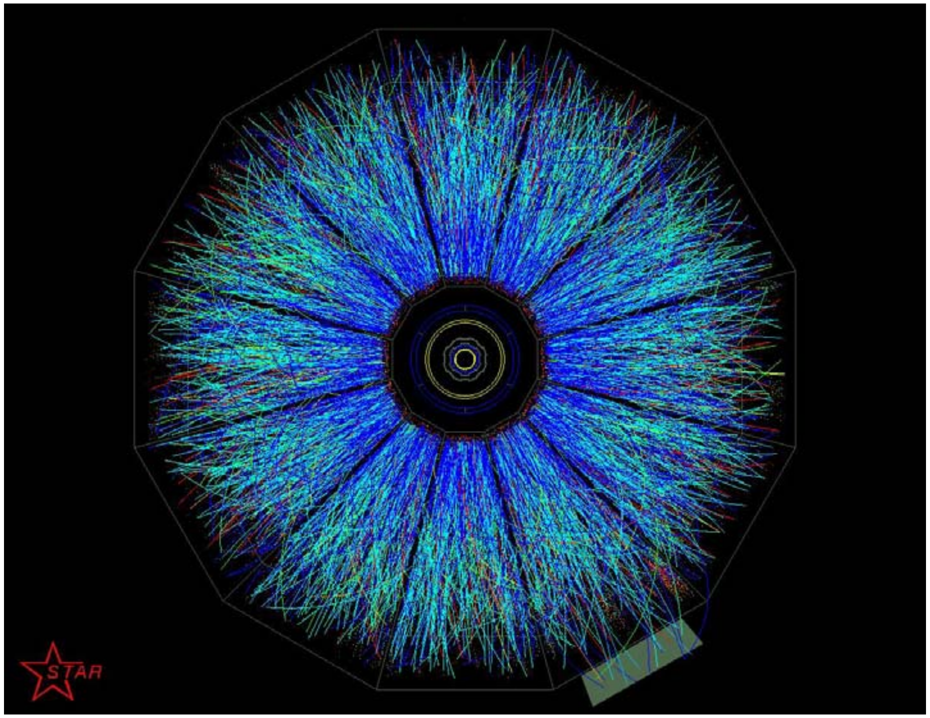
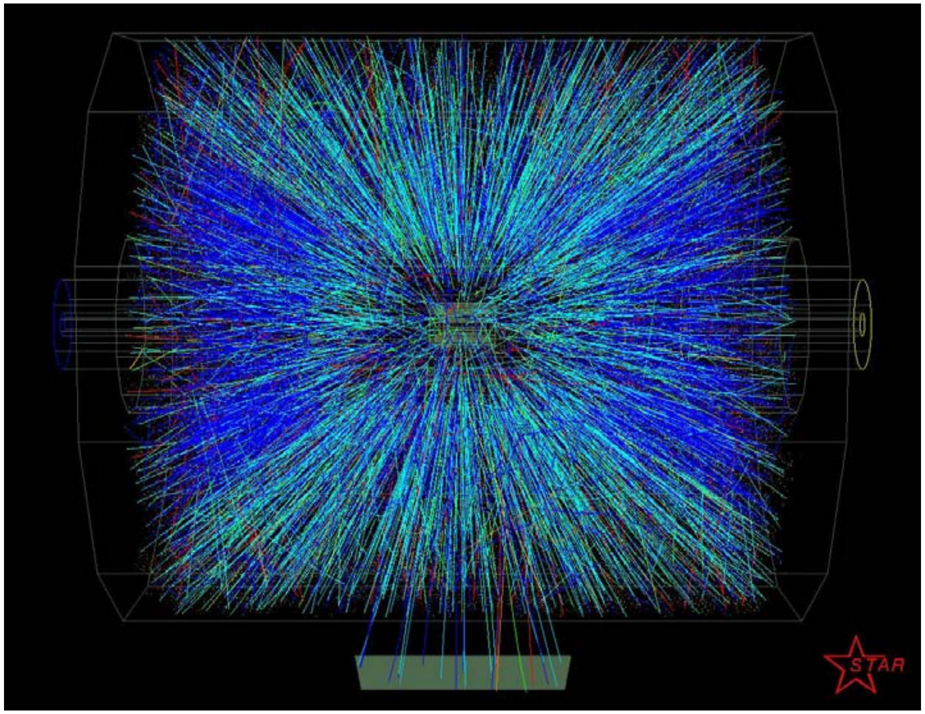
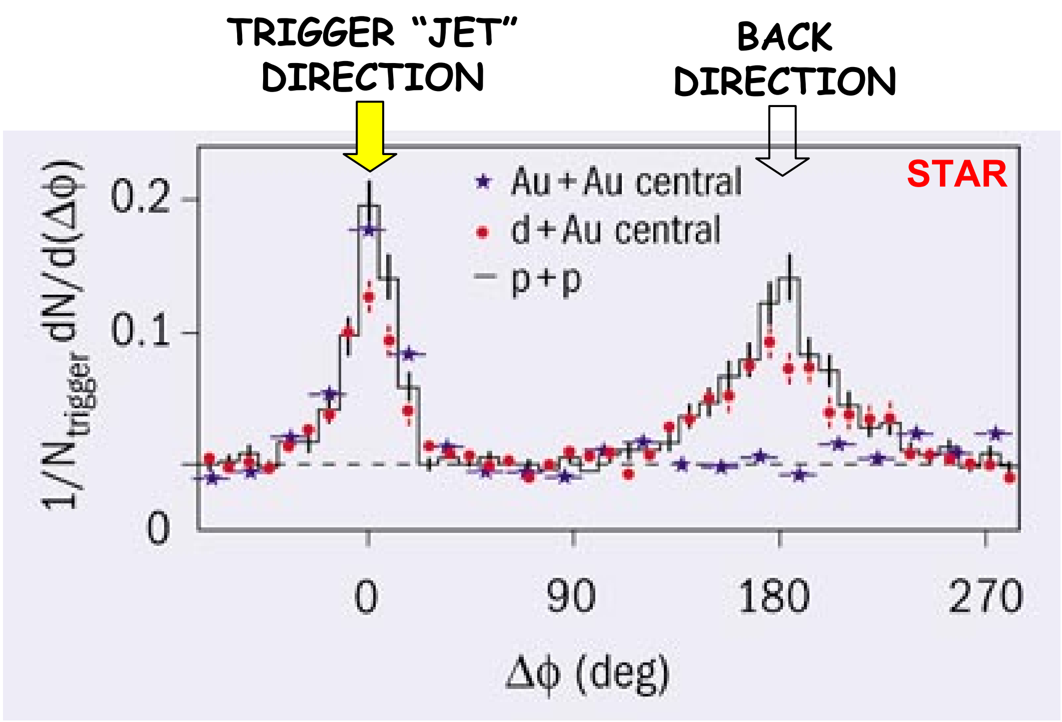
Jet Physics: RHIC



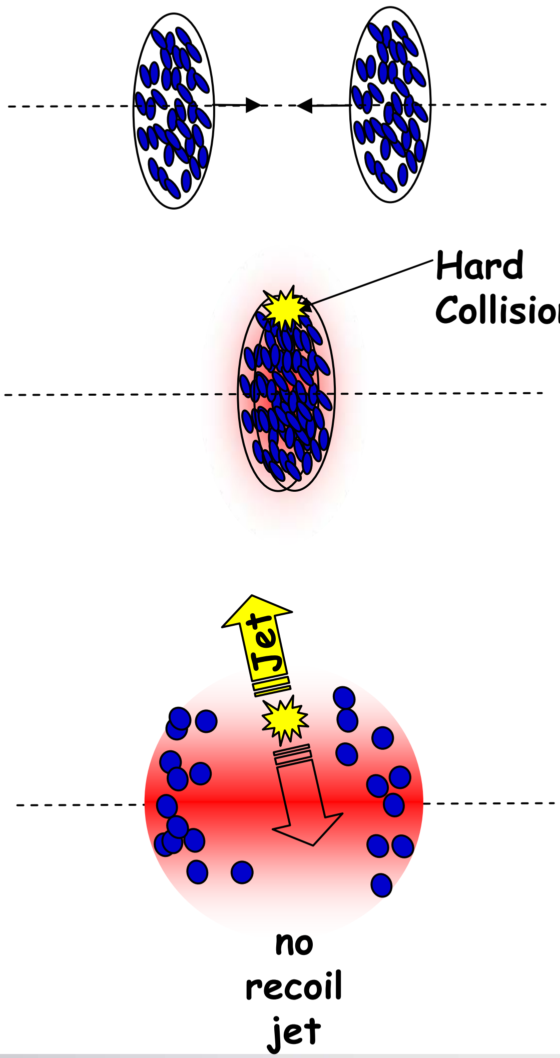


RHIC: Jets as a probe of QGP (I)

Jet Quenching—sign of Quark-Gluon Plasma?



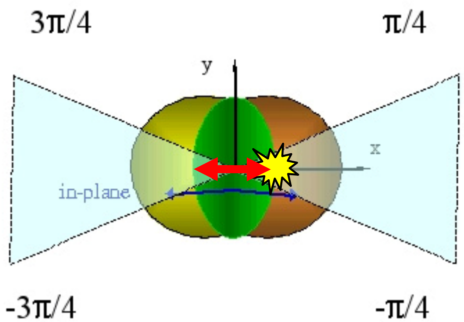
Tracks with pT>2 GeV

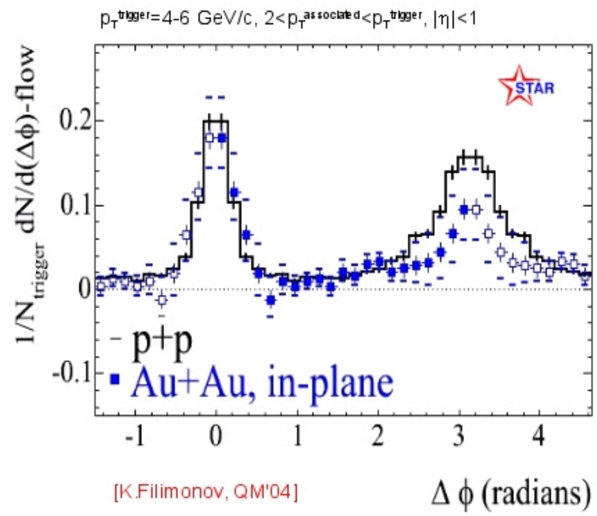


RHIC: Jets as a probe of QGP (II)

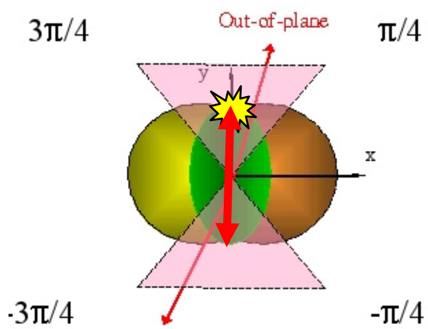
Absorption dependence on the path in GQP

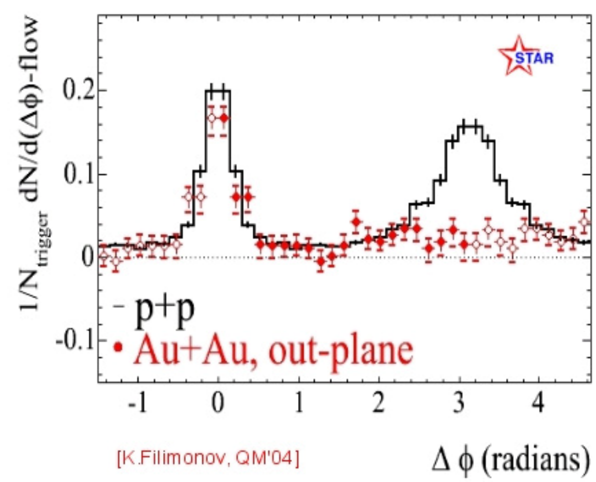
axial view
(non-central collisions)





small suppression





large suppression

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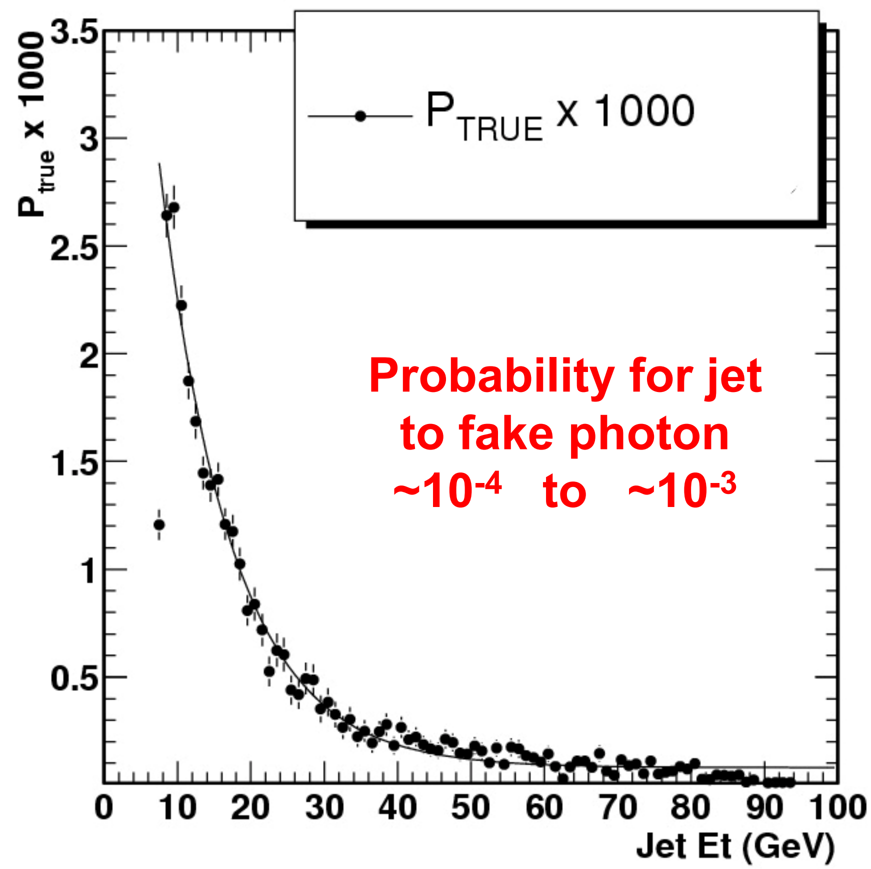
Jet Pollution: fake photons

Photon id:

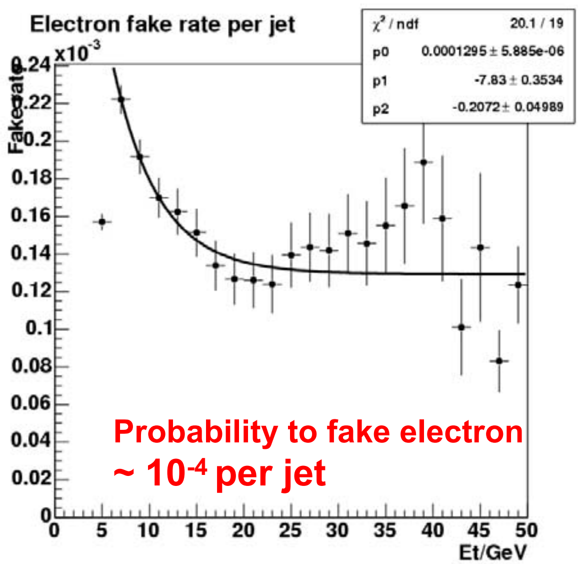
- EM Cluster:
  - $E_T > 7$ GeV
  - HAD/EM < $0.055+0.00045E_T$
  - 0 or 1 track with $p_T<1+0.005E_T$
- Energy in Isolation Cone $\Delta R=0.4$ (excluding EM Cluster)
  - Cal Energy < $2+0.005E_T$
  - Track Energy < $5+0.005E_T$
- Shower shape
  - $\chi^2<20$ (transverse profile at the depth of shower maximum)

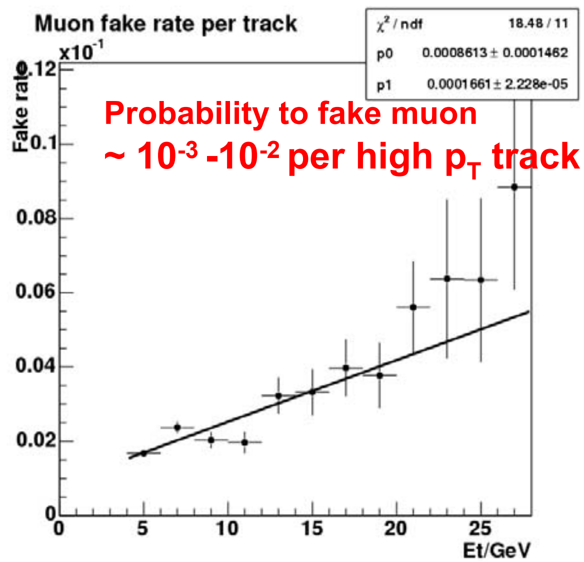


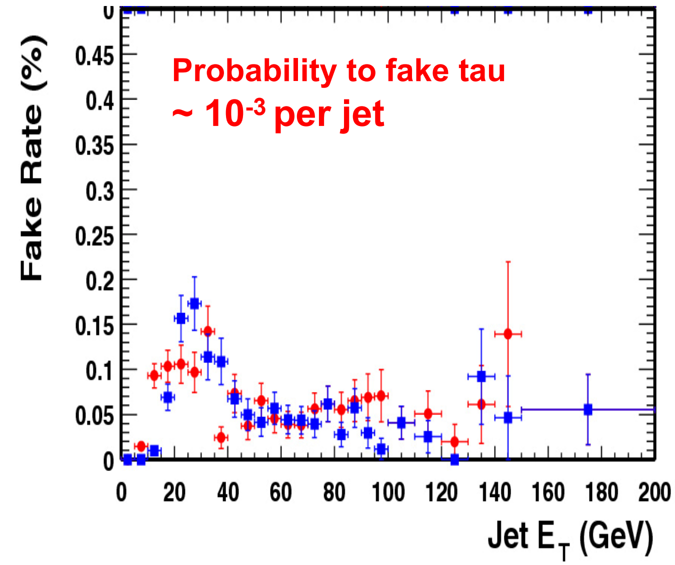
Jet faking photon:

- via fragmentation fluctuation
  - one prompt π^0
  - very few and soft $\pi^{\pm}$, π^0 in $\Delta R=0.4$

Jet Pollution: leptons







Electron:

- source of mis-id
  - fragmentation:

    $\pi^{\pm}$-π^{0} overlap with low isolation energy

Muon:

- source of mis-id
  - fragmentation:

    π/K decays

    b-jets ($B \to \mu + X$)

    punchthrough

    all with low isolation energy

Tau (hadronic):

- source of mis-id
  - fragmentation:

    1-3 prompt π's with low isolation energy

Conclusions

Jet Physics:

- jets + X production
- jet structure
- jets as a probe of GQP
- jet pollution to non-jet specific analyses—jets are everyone's business
  (even if you search for SUSY in Same-Sign di-Muon channel and could not care less of jets...)

Jets and New Physics:

- Understanding jet physics is the key for discovering phenomena beyond the Standard Model at hadron colliders

Jets and Standard Model:

- QCD, being simple underneath, is very reach with diverse phenomena (compare to condense matter physics, all of which stems from plain EM)