QCD at hadron colliders

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Outline

Introduction:

Focus on current (Tevatron)
and future (LHC) hadron colliders

High pT pQCD phenomena & issues:

PDF measurement
Jet Physics
Underlying Event
Multi-parton dynamics
Perspective for LHC

Summary:

Tevatron, proton-anti-proton,
$\sqrt{s}$ = 1.96 TeV (Fermilab)

LHC, proton-proton,
$\sqrt{s}$ = 14 TeV (CERN)

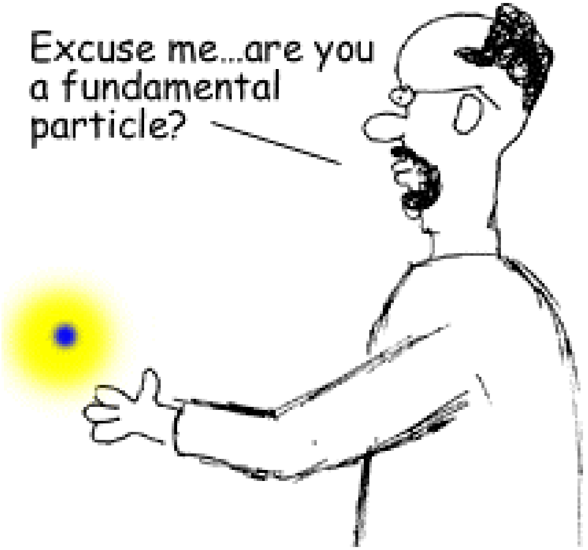
Fundamental tests of QCD

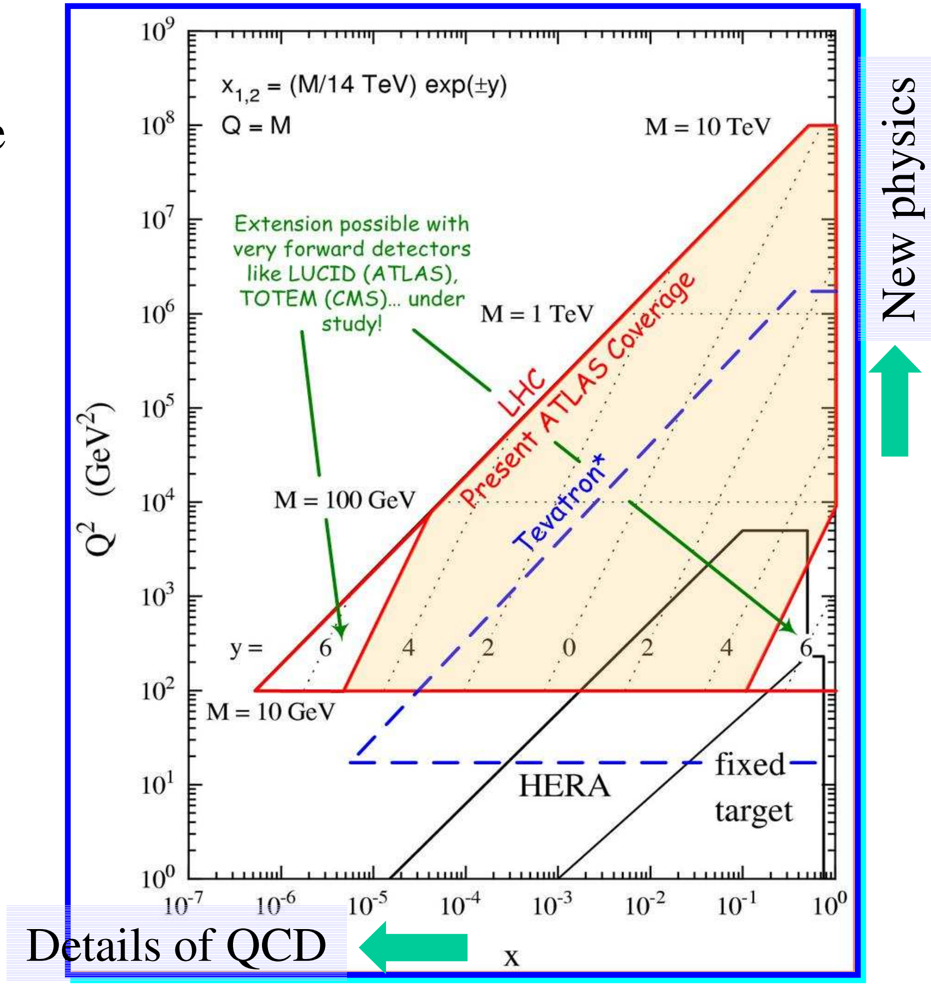
Probing hadron(proton) structure:

Tevatron and LHC can explore the structure of protons over the wide range of high x and Q^2 in PDF.

Understanding QCD phenomena:

What is the parton nature?





W. Stirling, LHCC Workshop "Theory of LHC Processes" (1998)
*annotation from J. Huston, Talk @ ATLAS Standard Model WG Meeting (Feb. 2004)

QCD at hadron colliders

TEVATRON $\sqrt{s} = 1.96 TeV \quad p\bar{p}$

L=5x10^{31} cm^{-2} s^{-1}

process	evts/s
W→e ν	0.1
Z→e e	0.02
t t	3x10^{-5}
JET 20	2x10^{3} (1250)
JET 50	25 (50)
JET100	0.5

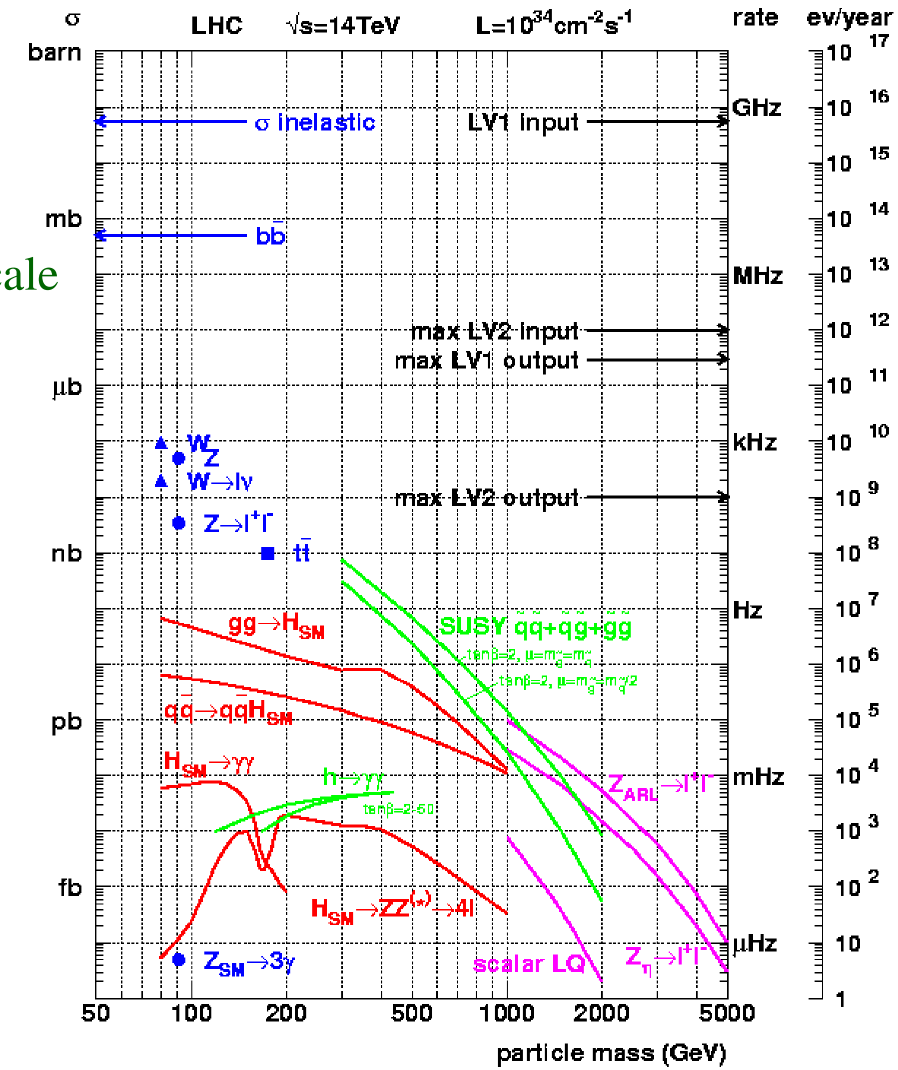
prescale

LHC $\sqrt{s} = 14 TeV \quad pp$

L=~10^{34} cm^{-2} s^{-1}

process	evts/s
W→e ν	~200
Z→e e	~20
t t	~10
JET 100	~10^{4}

Source of background!!

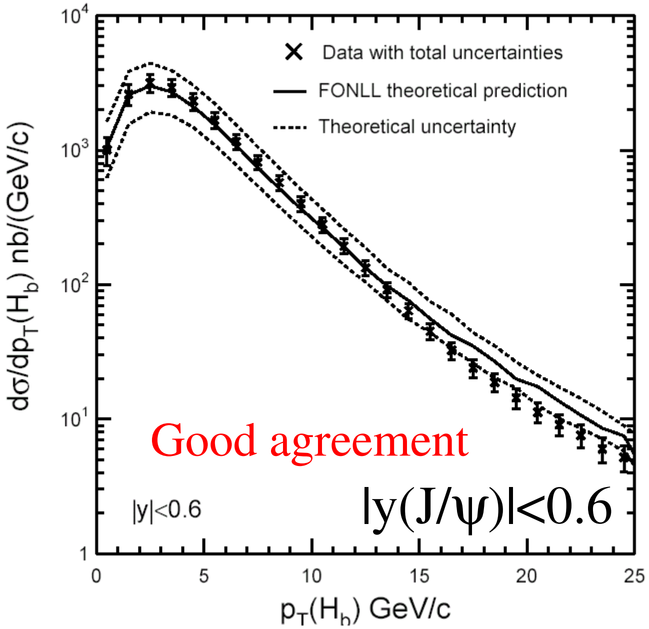


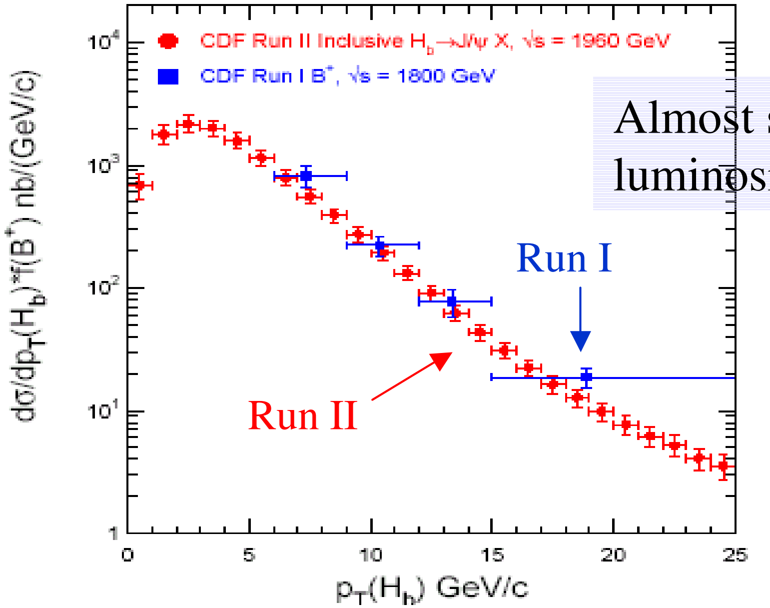
Remarkable success of QCD

Total inclusive single b-hadron (H_b) cross section

$$\sigma(p\bar{p} \to H_b X, |y| < 0.6) = 17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\ \mu\text{b}$$

Now, factor 2-3 discrepancy was recovered by theory, while the data was significantly increased in Run II.





Almost same luminosity

Theory: much improved hadronization correction.

Experment: much increased data. Thanks vertex trigger.

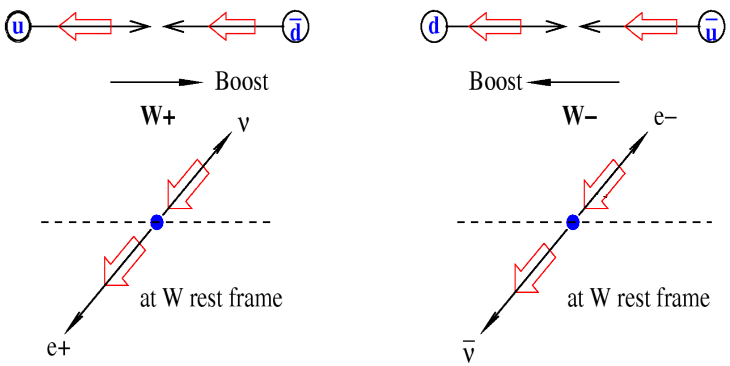
Cont.

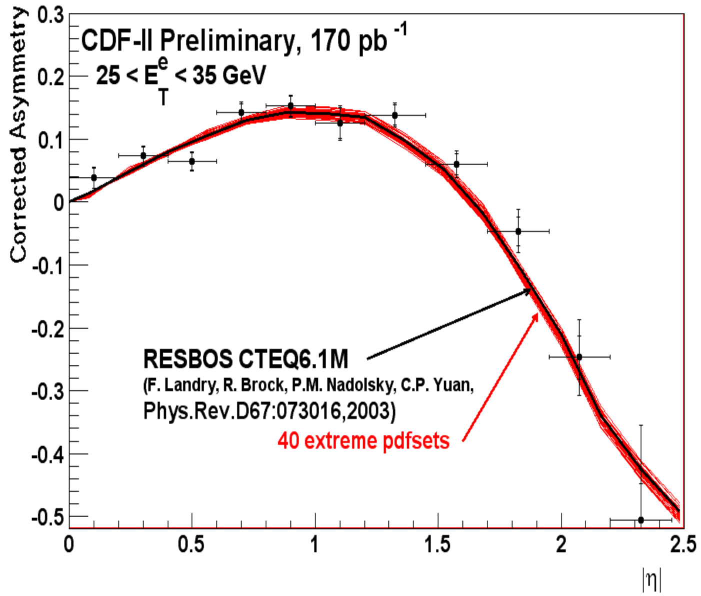
W charge asymmetry:

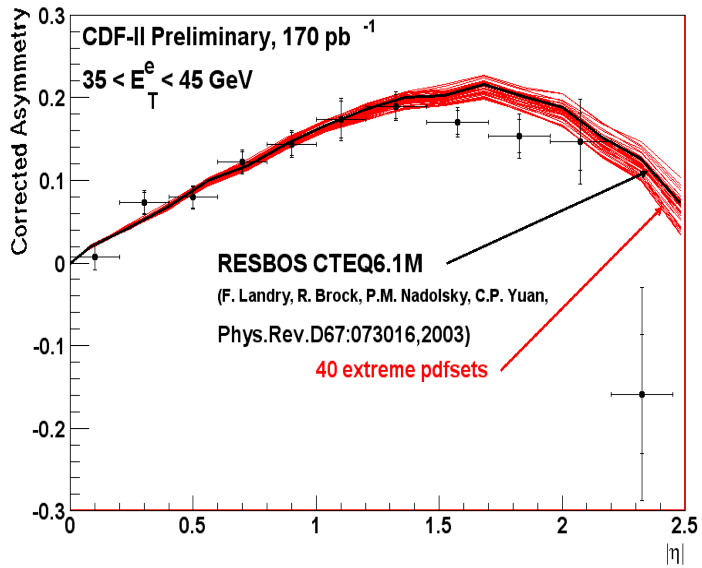
Sensitive to u/d component in PDF.

$$A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e}$$

$$\sim \frac{d(x)}{u(x)}$$







Exp : Charge ID in forward region.
(Silicon standalone tracking)

Theo: PDF uncertainty.
(strict test of PDF in forward region)

Results from CDF

Regardless of high statistics, not so many results from QCD…

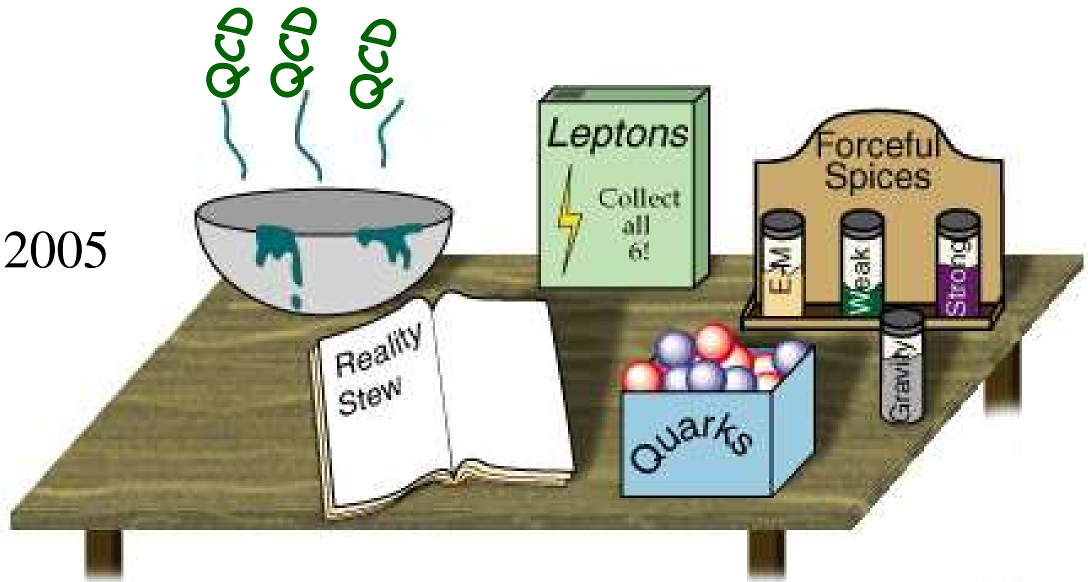
Number of papers (PRL&PRD) from CDF (CDF Run II),

31 (10) (B)
10 (6) (Electroweak)
25 (5) (Top)
14 (1) (QCD)
30 (5) (Exotic)

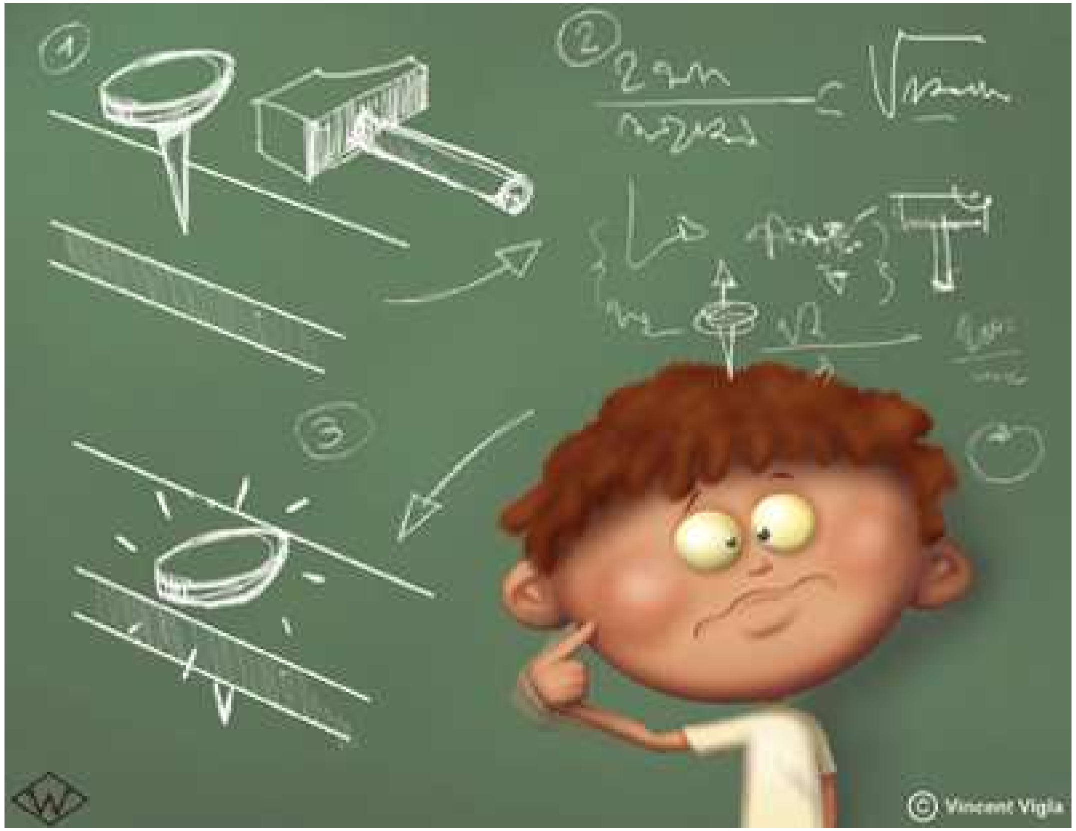
Total 110 (27) Mar.2005

Run II

Note: "QCD" means high p_T pQCD. Clearly, we see slow time dependence for published QCD results.



Why so difficult?



Event topology at hadron colliders

Event topology is assumed to consist of typically three independent (mostly QCD) physics (no interference).

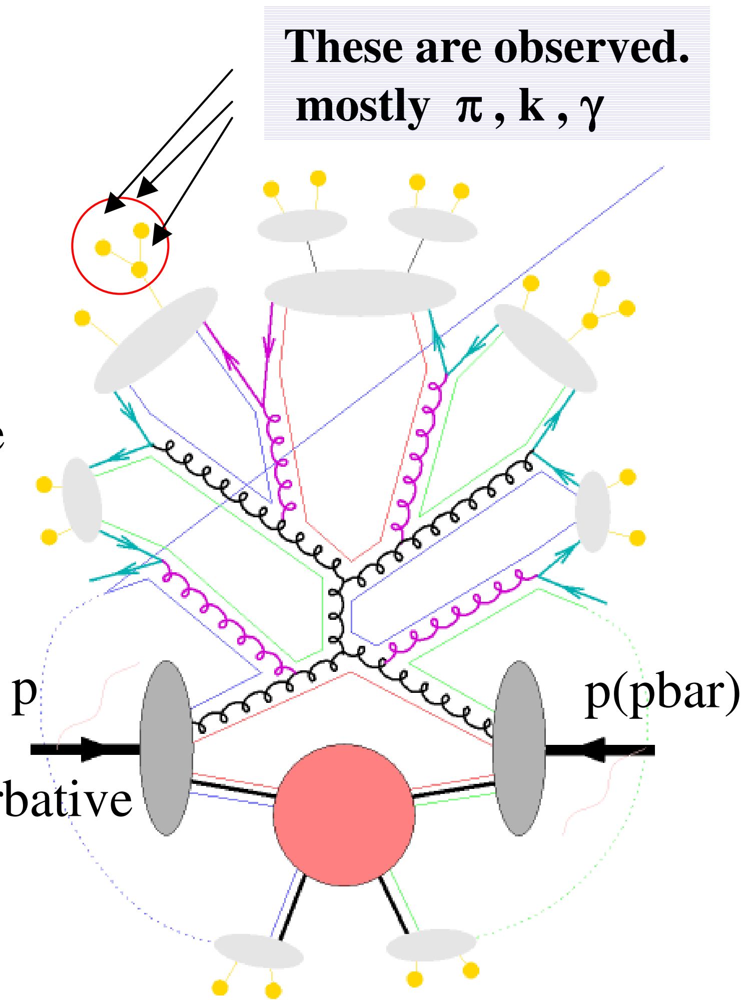
Hard interaction :
 supplied by ME,
 scale stabilities (Q^2).
PDF and shower evolution:
 respect to PDF,
 ordering variables (m , θ , pT).

} perturbative

Q^2 ↓

Formed hadrons :
 non-perturbative gluon splitting,
 color singlet object,
 cluster → hadrons,
 hadron decay.

} non-perturbative



Jet production

Definition of a "jet" : (hep-ex/0005012)

"a collimated spray of high energy hadrons"

⇒ small dependence of the fragmentation.

For quantitative studies, it should be equivalent to

(Theory) what we think a "jet" is, and

(Experiment) what we can accurately measure.

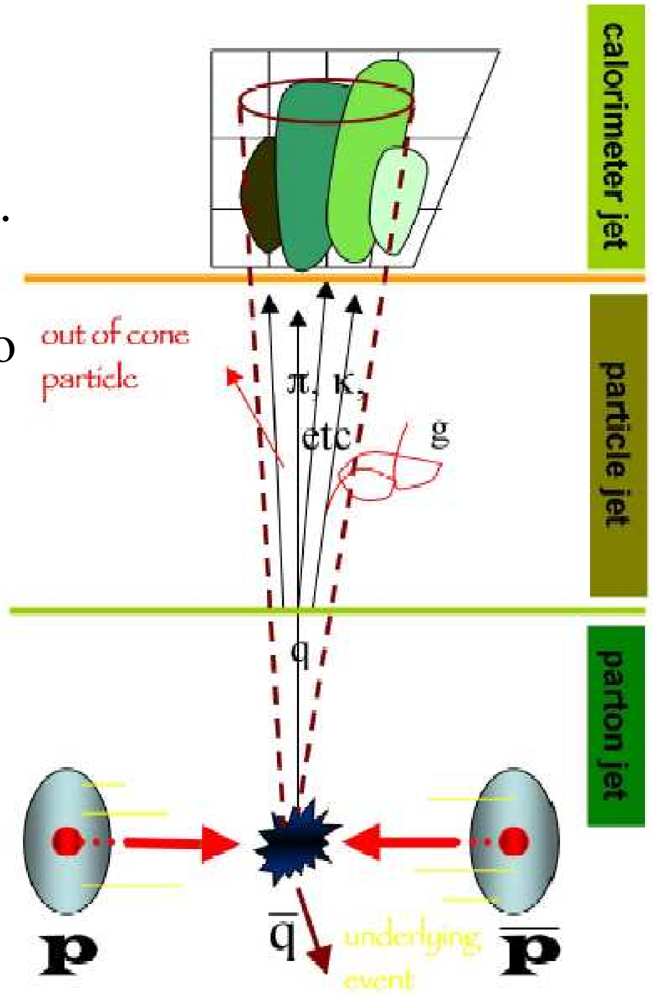
⇒ Jet Algorithm

Each level, algorithm should be the same.

Two types of jet algorithms have been used.

Cone algorithms (Geometry basis)

k_T algorithm (4-memomentun basis)



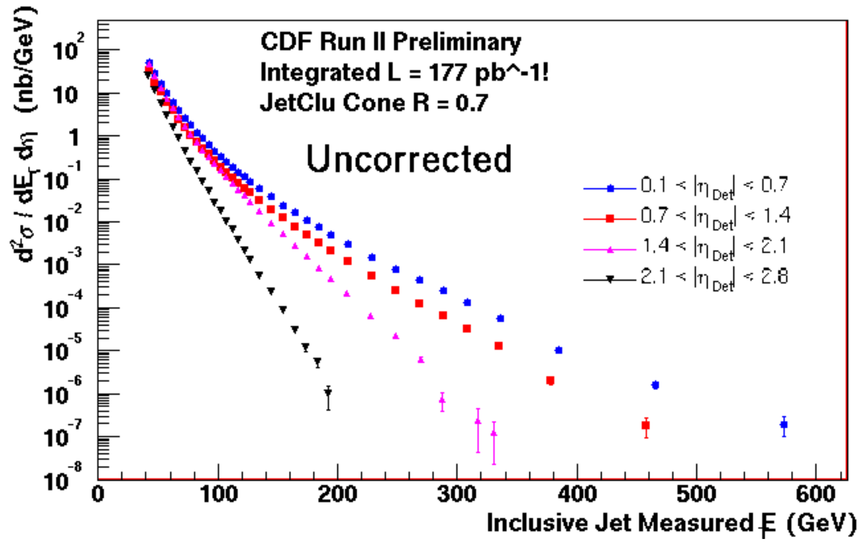
Inclusive Jet Cross Section

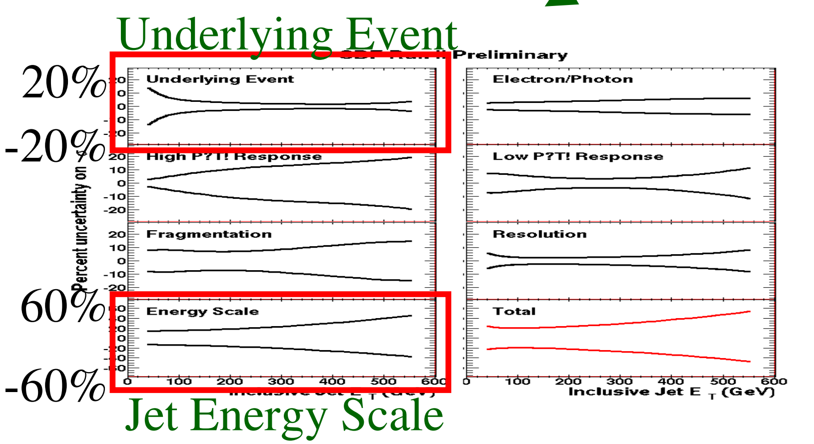
Jets were measured 4 different range of η with $E_T > 40$ GeV.

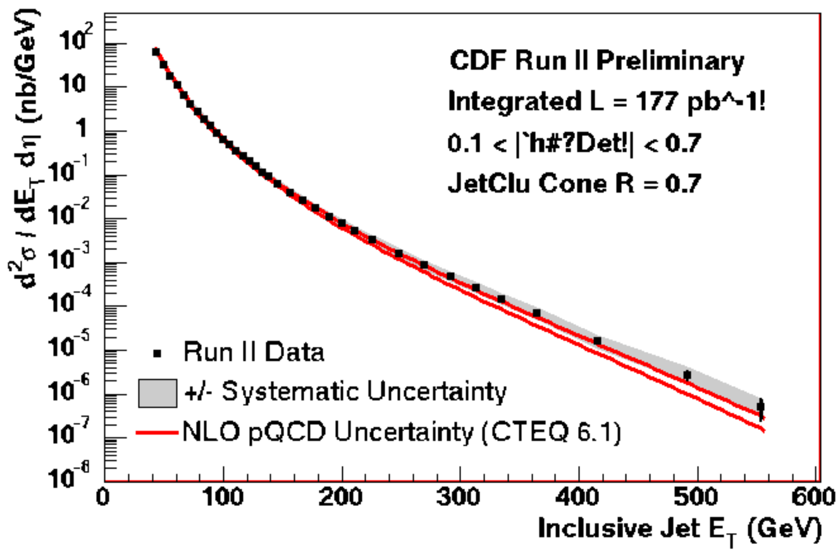
Run I style Cone Jet Algorithm was used (Cone size = 0.7).

Compared with theory in the central region ($0.1 < \eta < 0.7$).

Both systematic uncertainties for Data and Theory are applied.







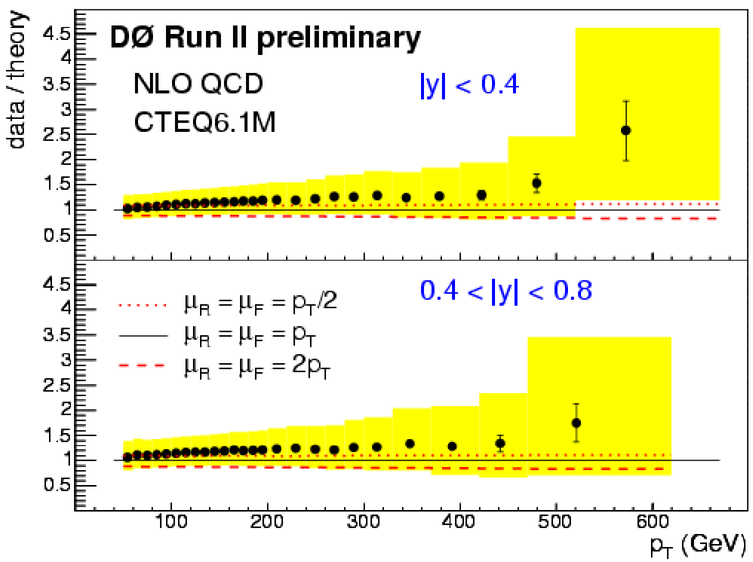
Comparison Data with Theory

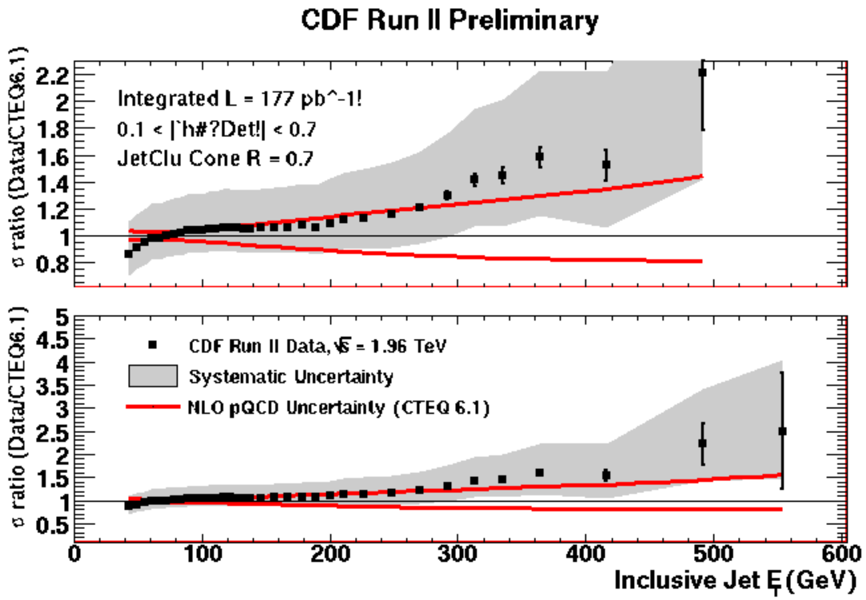
Déjà vu : High E_T excess again??

In Run I, similar behavior was observed. CTEQ5HJ

Data size are 2-3 times larger than that of Run I exp.

CDF and D0 use different cone algorithms.





CTEQ v.s. MRST

It is known fact that MRST was not suitable to describe Tevatron jet data at high x region.

MRST parameterization : $q(x,Q^2) = Ax^2(1+c\sqrt{x}+dx)(1-x)^b$

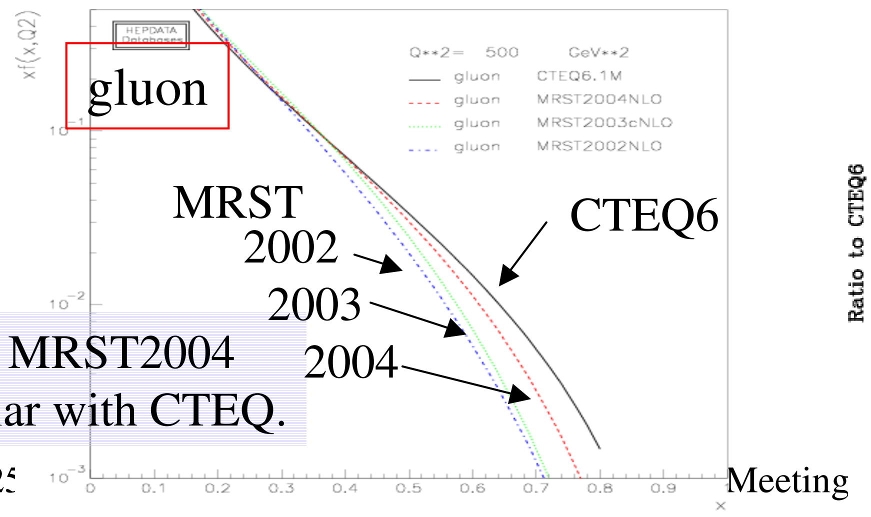
CTEQ parameterization : $q(x,Q^2) = A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+A_4 x)^{A_5}$

Conversion of DIS to MSbar satisfies:

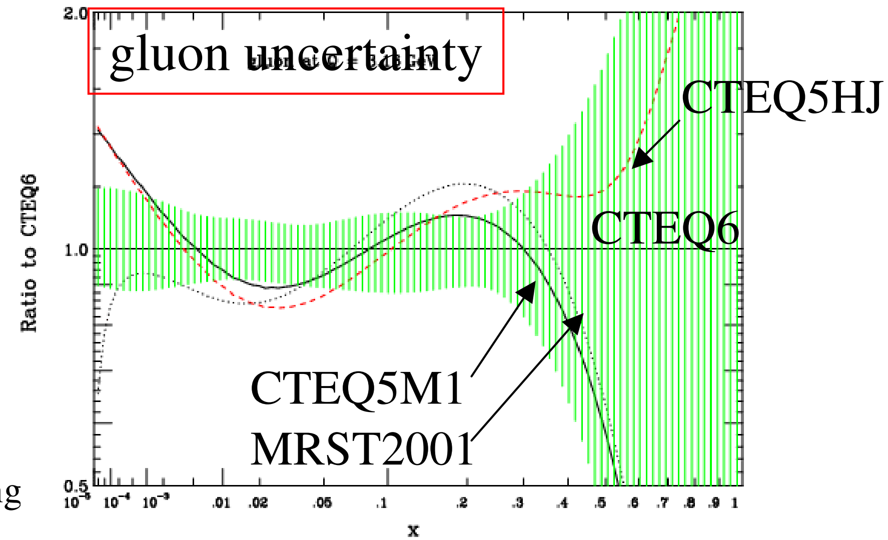
$$q^{DIS} = q^{\overline{MS}} + C_q^{\overline{MS}} \otimes q^{\overline{MS}} + C_g^{\overline{MS}} \otimes g^{\overline{MS}}$$

$$g^{DIS} = g^{\overline{MS}} - C_q^{\overline{MS}} \otimes q^{\overline{MS}} - C_g^{\overline{MS}} \otimes g^{\overline{MS}}$$

The DIS quark(gluon) gets harder(softer) at high x region.



Recent MRST2004 is similar with CTEQ.



Incl. Jet prod. xsec with k_T-clustering

k_T algorithm:

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}, \quad d_i = (P_{T,i})^2$$

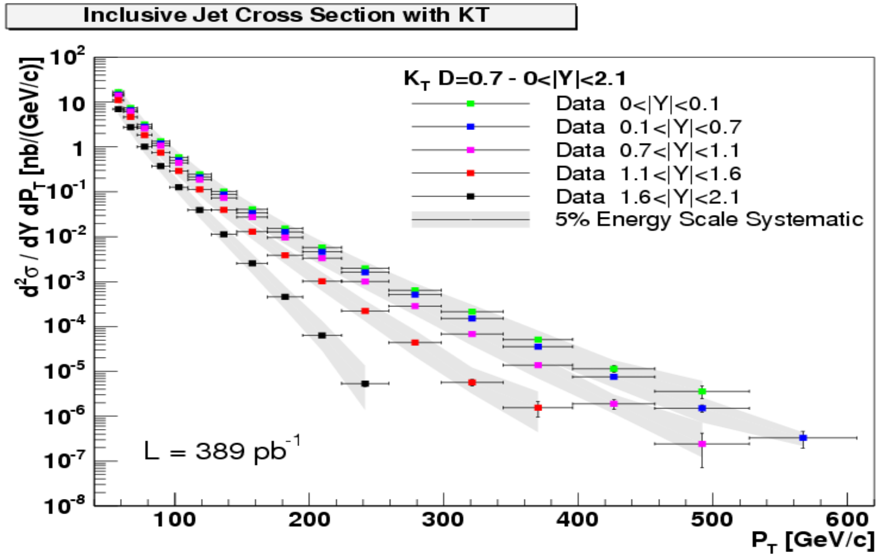
The k_T algorithm has a great feature:

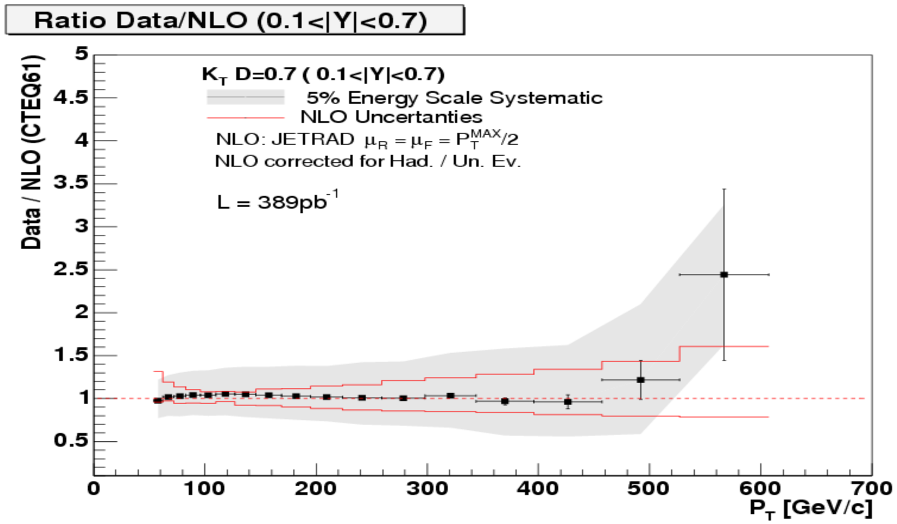
- infrared/collinear safe,
- no merging/splitting requirement,
- preferred by theory.

Jet energy correction strongly depends on the simulations.
$E_T > 75$ GeV is required.
Not corrected using data.

Similar behavior with Cone algorithm, but better description than Cone Algo.

Why?? Work in progress.





Summary for inclusive jet measurement

High E_T excess in data is observed although it is still within jet energy uncertainty. The measurement was the same as that of Run I exp.
The similar behavior has been observed since Run I exp.

Experiment:

Implementation of Cone Jet Algorithm:

Common agreement was concluded in Run II Jet WG.

- Midpoint Algorithm will be future standard.
- Re-do jet measurement again.

Implementation of k_T-Algorithm:

First measurement at CDF is shown. Still under development.

- no jet energy corrections / discrepancy between data/MC
- much CPU time (can not use as Trigger),
- no b-tagging algorithm using k_T .

Theory:

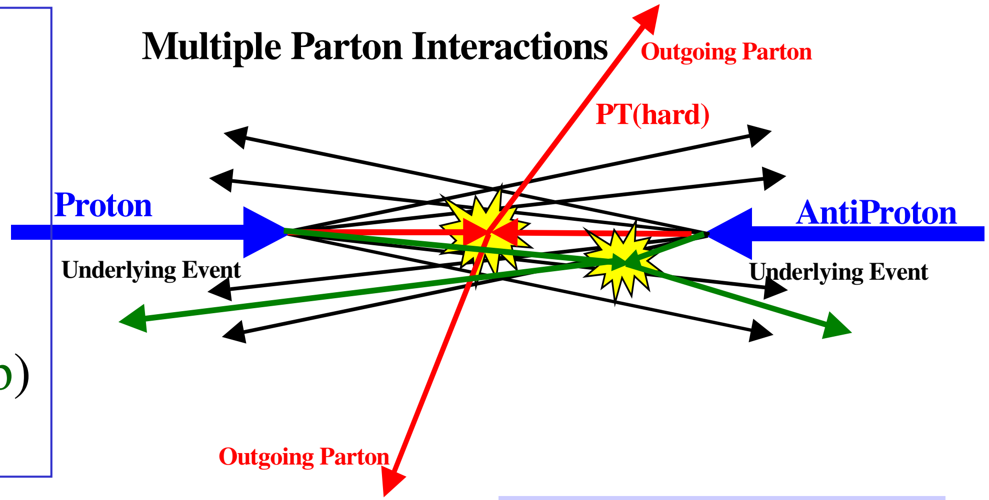
PDF: Recent MRST gets closer to CTEQ.

Underlying Event

Underlying Event (UE) = (Whole Event) – (Hard part)

There assume to be several (incoherent) phenomena in a collision.

Hard interaction (ME)
Final State Radiation (FSR)
Initial State Radiation (ISR)
Multiple Parton Interaction (MPI)
Beam-Beam Remnants (BBR)
Additional p pbar collisions (pile-up)
Minimum Bias collisions (MB)



Tuning by Rick Field (CDF) is MPI + BBR.

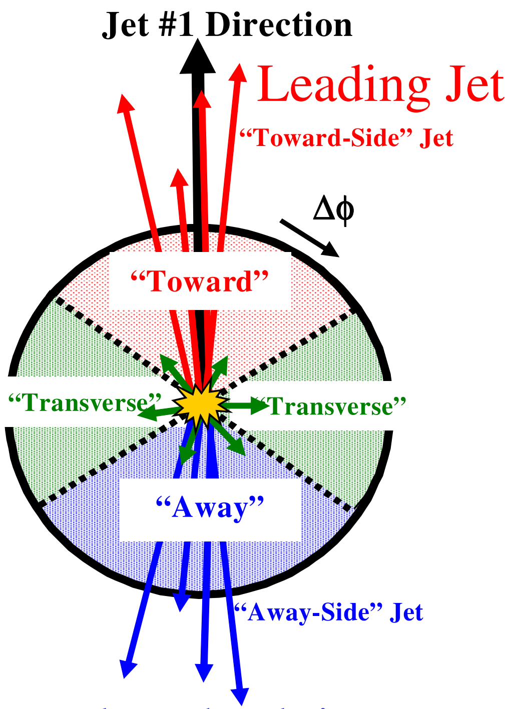
Common source of all measurements

People interests may be ME (perturbative theory).
Jet energy correction will cover FSR.

ISR is really matter…

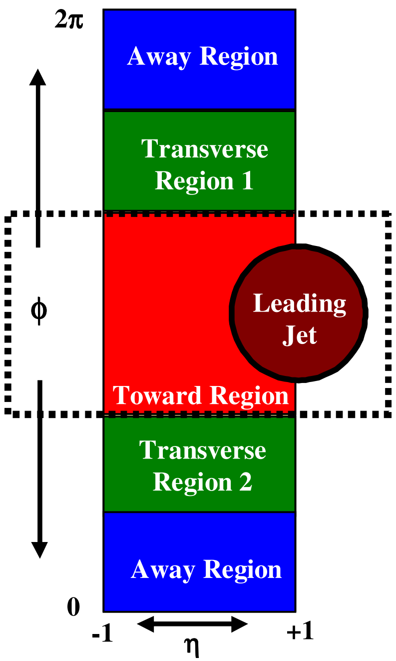
Looking at Transverse region

The “Transverse” regions are sensitive to the underlying events, where the transverse regions are defined by the Leading Jet.



Back-to-back jet

If E_T(jet#2)/E_T(jet#1) > 0.8



Define three regions with respect to Leading Jet (JetClu, R=0.7, $|\eta| < 2.$) :

“Toward” $\Rightarrow |\Delta\phi|<60^o$

“Away” $\Rightarrow |\Delta\phi|>120^o$

“Transverse” $\Rightarrow 60^o > |\Delta\phi| < 120^o$

Transverse Region:

Charged Particle Δϕ Correlations

$p_T > 0.5$ GeV/c $|\eta| < 1$

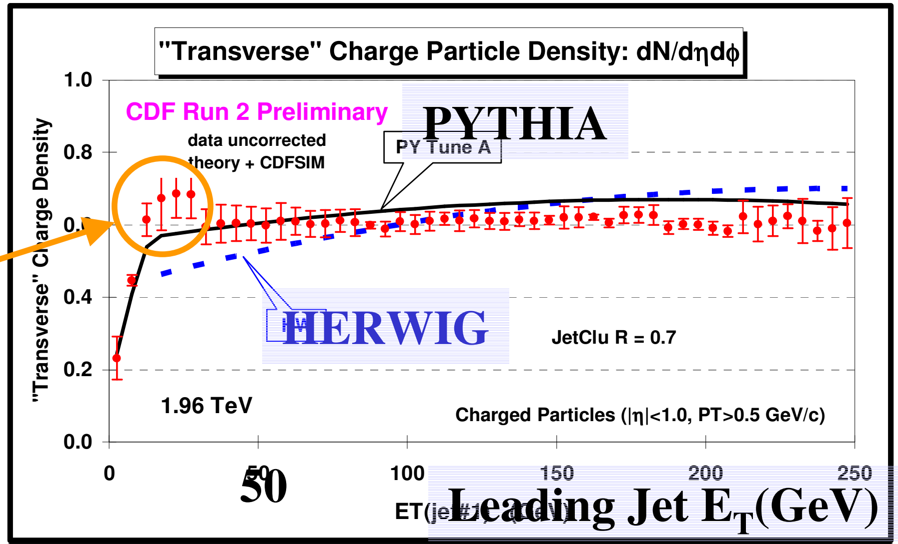
➡ Neutral component is estimated by global ratio.

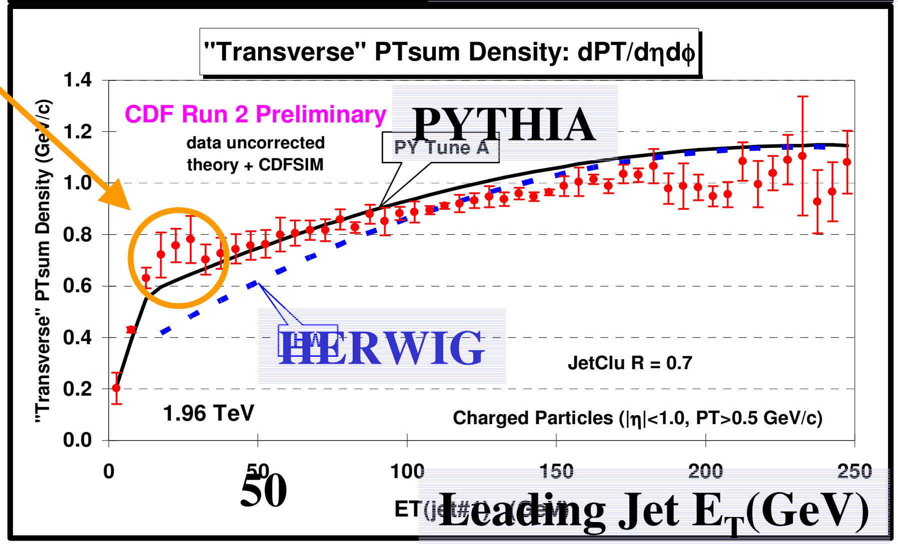
Charged particles in Transverse region

In "Transverse" region, look at
 Charged Particle Density (above)
 P_T Sum Density (below)

I asked "What's this?"

Rick said : "Don't ask me!"





PYTHIA (tune A) is better description than HERWIG.

Underlying event tuning looks work well at Tevatron. How about LHC?

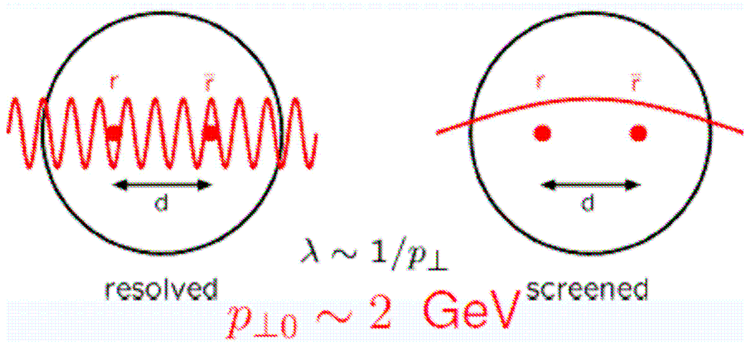
Model of Multiple Interaction

Multiple Interaction (MI) must exist (hadrons are composite).

There are existing models for MI, but still need to investigate new models toward LHC.

➡ Very important effect in LHC.

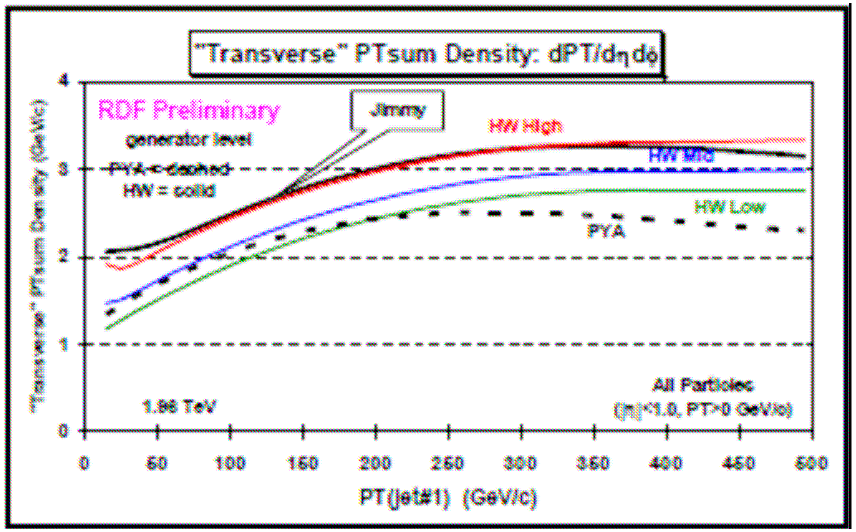
The idea is to put hard 2-2 process in a proton with Eikonal Hard Scattering Models (developed by HERA).



New models from PYTHIA and HERWIG :

(PYTHIA) : new p_T ordered parton shower and MI (hep-ph/0408302)

(HERWIG) : using matter distribution in the proton (hep-ph/9601371)



Common problem : Q^2 dependence

too many particles in high E_T region.

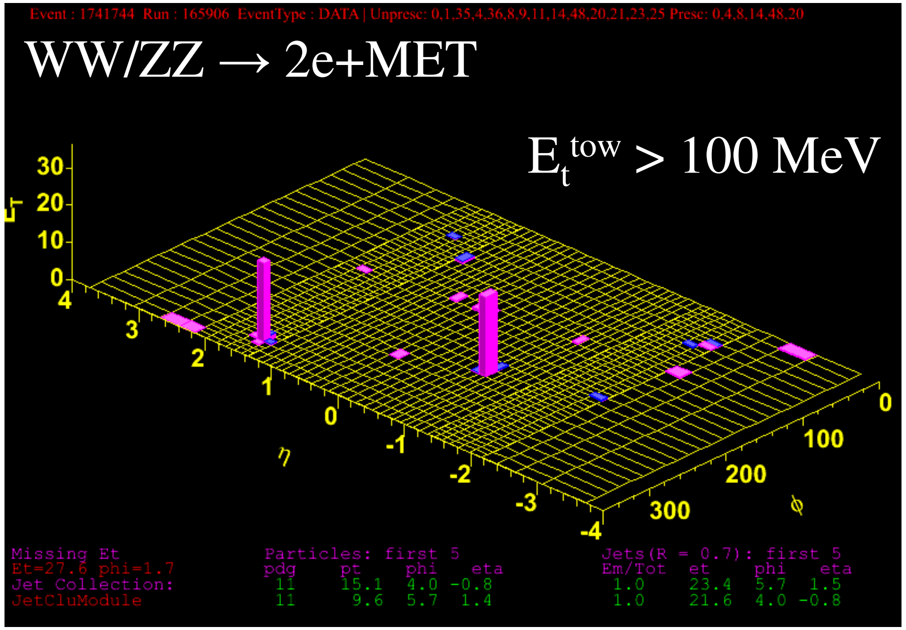
Tevatron data is NOT so!!!

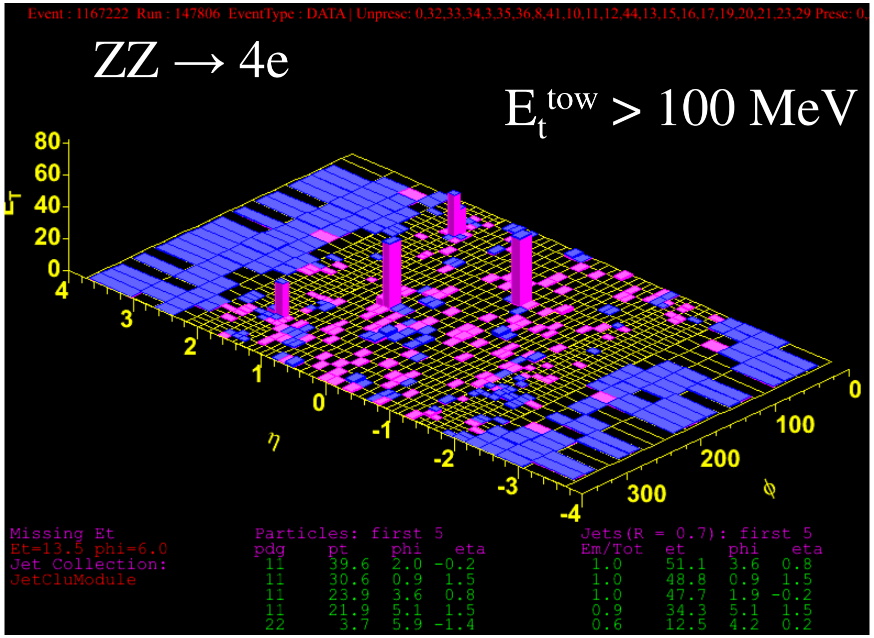
Super clean event (from CDF data)

High Q^2 scattering event.

Super clean event!

White pomeron?? New physics??
(hep-ph/0405190)





Reasonable with MC underlying event prediction.

Summary for Underlying Event

Underlying Events are tuned in Run II data. Only charged particles are tuned. The modeling by PYTHIA describes better than HERWIG one.

Experiment:

- E_T Sum (with neutral component) does not match with MC. (Data have more energy.) This effect is approximately ~800MeV in Cone R=0.7.
- We see a dependence of offline software version.

Theory:

- New models are proposed toward to LHC physics.
- Putting a hard 2-2 QCD process in Multiple Interaction is tunable to fit Tevatron data. However Q^2 dependence is inherited in high E_T region, which is not favored in Tevatron data.
- What happens at LHC?

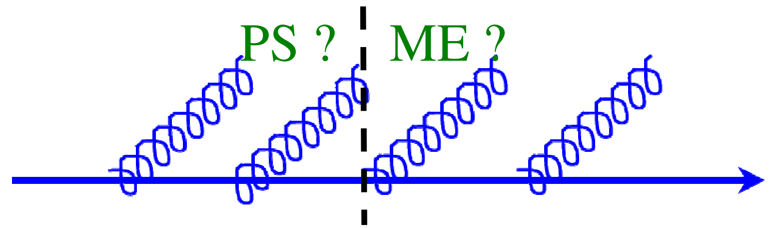
Dynamics of multi-particle final state

Most of new physics processes have a multi-parton final state from their particle decays. ⟹ Ex. Higgs/SUSY : multi-leptons/jets configurations.

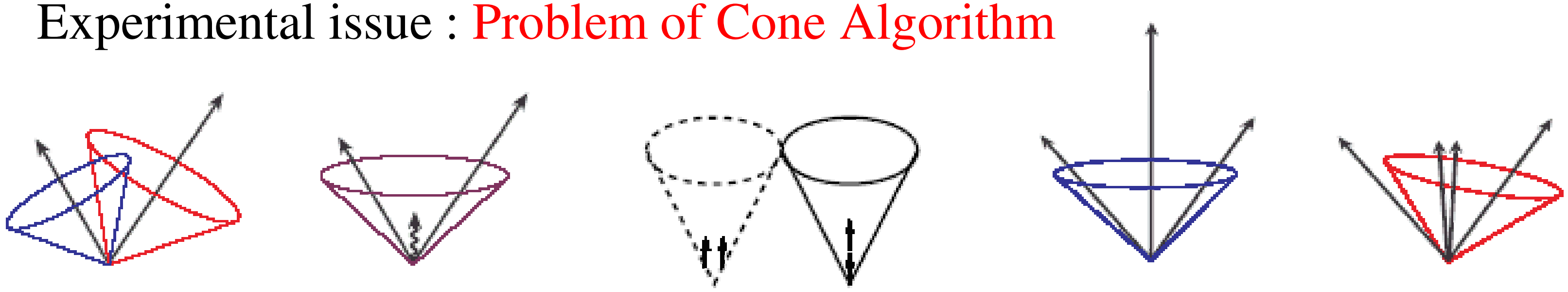
There are two aspects of

Theoretical issue : Double counting problem

“ How do we define “hardness” in the event?? ”



Experimental issue : Problem of Cone Algorithm



infrared sensitivity
(soft gluon radiation merges jets)

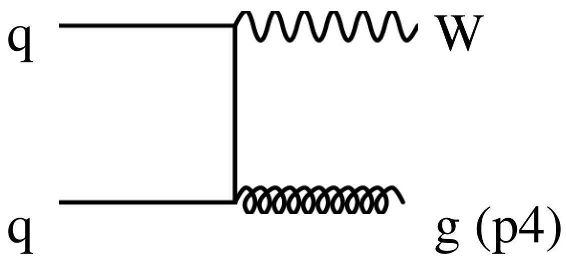
collinear sensitivity (1)
(signal split into two towers below threshold)

collinear sensitivity (2)
(sensitive to E_t ordering of seeds)

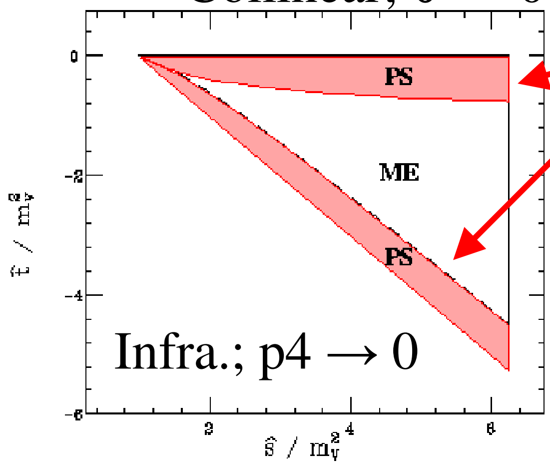
Phase space of ME and PS

Overlapped phase space between “hard” and “soft” part.

ME approach is responsible to “hard” part,
PS approach is responsible to “soft” part.

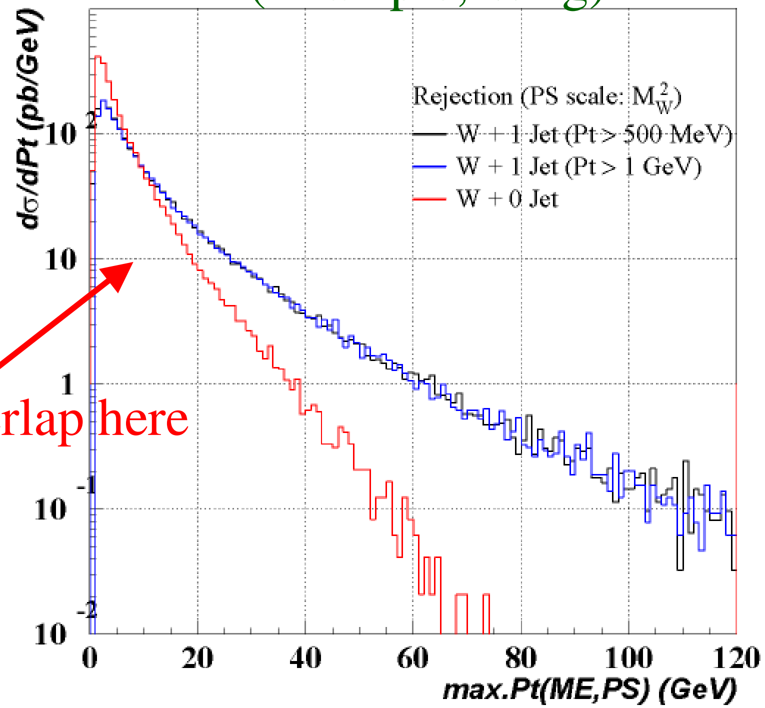


Collinear; $\theta \to 0$



Overlap here

(Example, W+g)



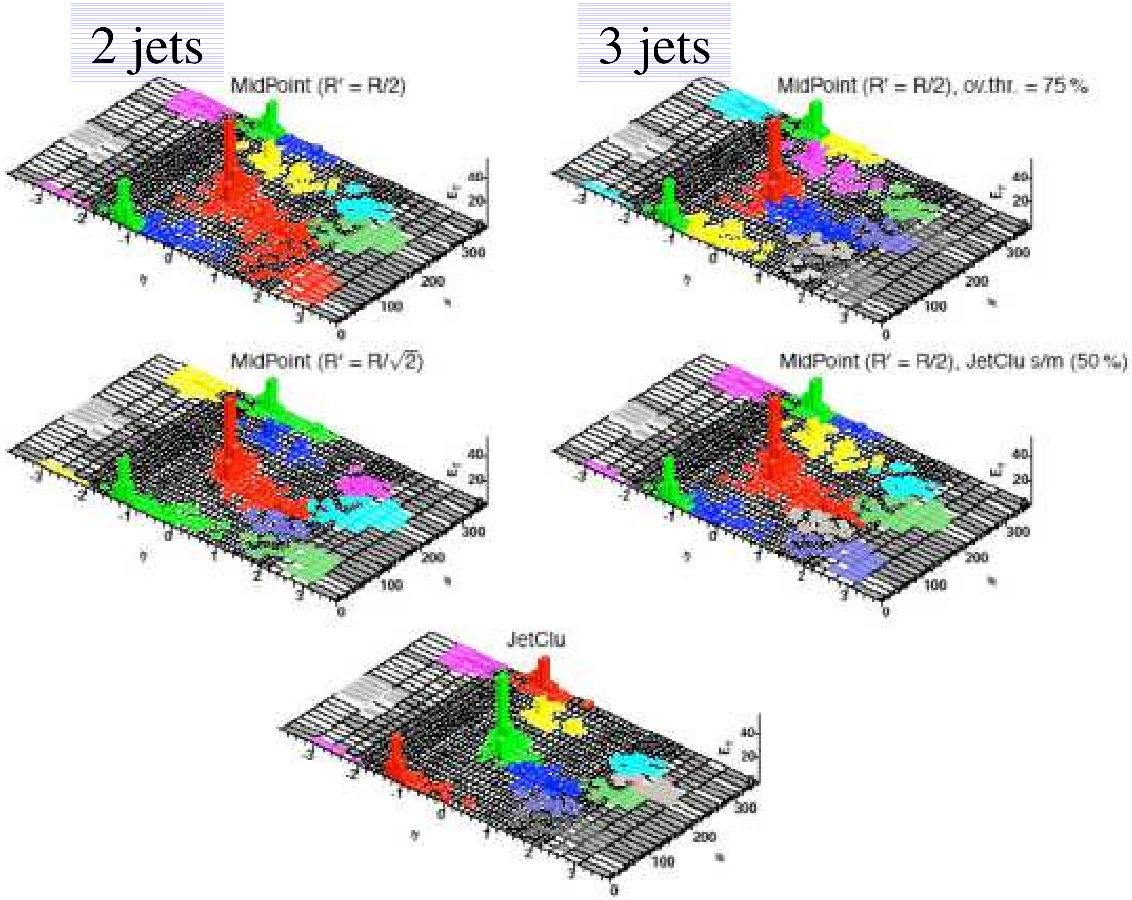
PS does not make high pt partons.

Problem of Cone Algorithm

Merging/splitting parameter (R_{sep} & f) is free parameter.

Lego plots are showing how is the jet counting affected by various merging and splitting parameters.

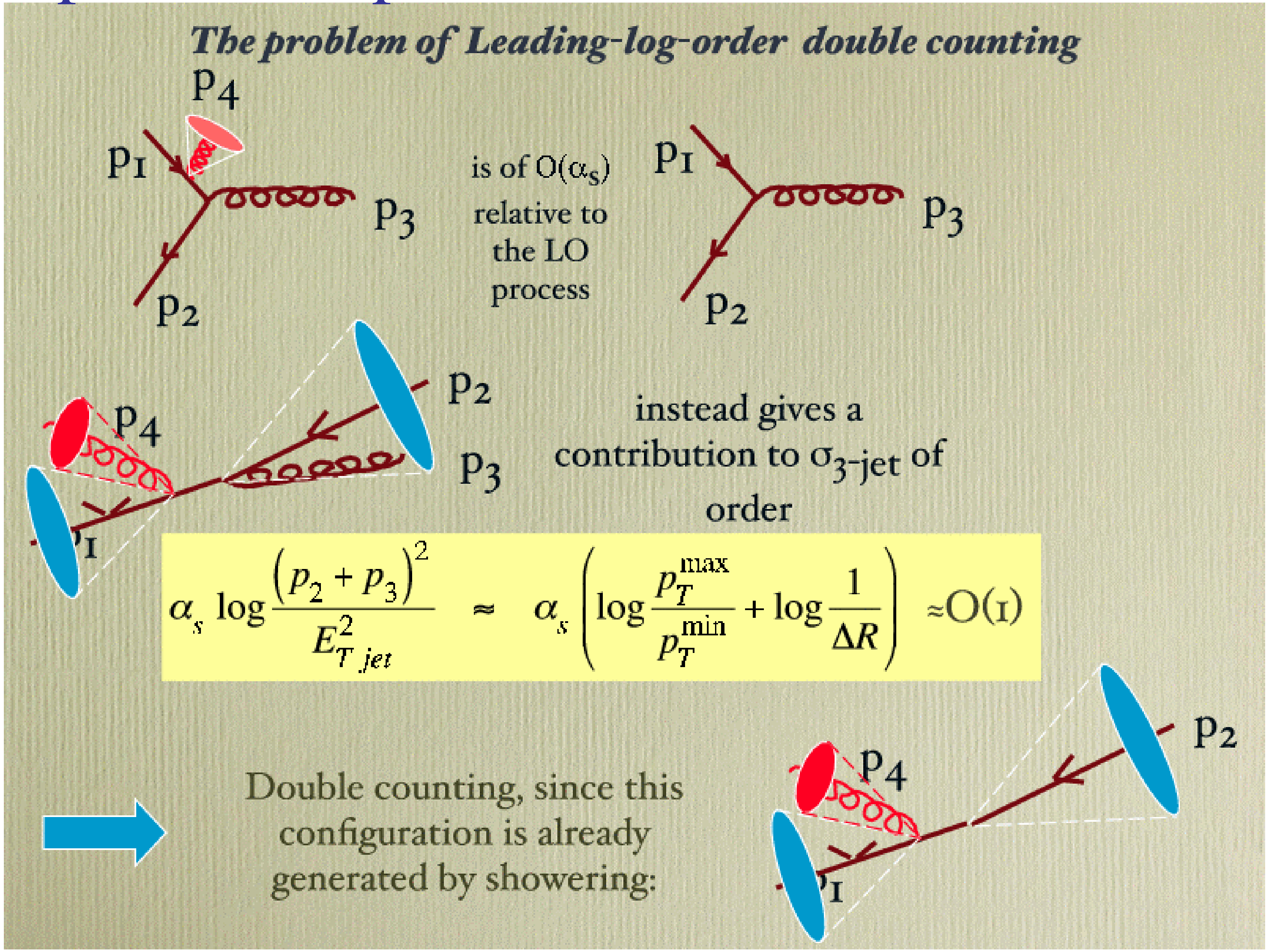
Jet E_T also varies.



Big problem:

Number of jets are very affected by this parameter.

Complex Example



Parton-Jet Matching

Naïve Prescription :

Constrain Theoretical and Experimental ambiguity at the same time.

MLM matching (M.L.Mangano) :

Require events matched parton with hadron-jet.

complicated phase space.

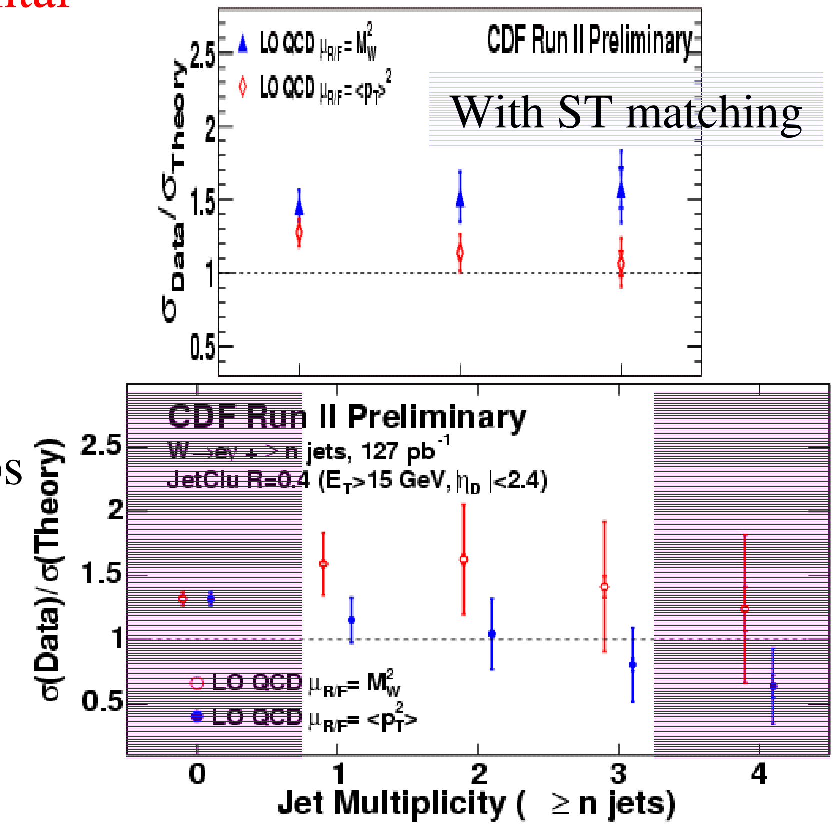
ST matching (S.Tsuno) :

Require phase space one parton drops into one jet with 95% probability.

simple phase space, but may underestimate.

With matching requirement, there is no unphysical cut dependence (ΔR cut).

W+jets process at CDF II



With ST matching

Without matching ($\Delta R > 0.2$)

CKKW and LL-subtraction method

CKKW method:

S.Catani etal, JHEP 11(2001)063

"Describe a hard part in term of soft (parton shower) interactions."

Leading-Log (LL) subtraction:

MC@NLO:

S.Frixione etal, JHEP 0308(2003)007

GRACE-NLO:

Y.Kurihara etal, Nucl.Phys.B654(2003)301

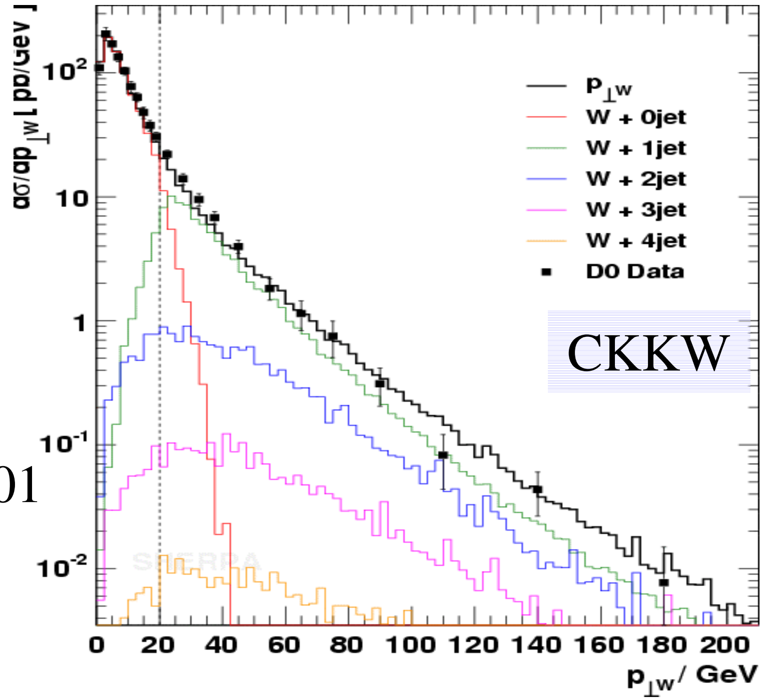
"Calculate the hard part truncated by LL-term (parton shower)."

PDFs suitable for MC:

J.C.Collins etal, JHEP 6(2002)018

"Take correct scheme."

W p_T distribution



$P(\sigma_{W+0jet})+P(\sigma_{W+1jet})+P(\sigma_{W+2jets})+P(\sigma_{W+3jets})+P(\sigma_{W+4jets})$

Summary for multi-parton dynamics

Understand of multi-parton configuration is very important for the background estimation for new physics searches or ELWK precision measurements rather than the pure QCD studies, because they(searches) often require multi-jets or complicated event topology.

Experiment:

- For QCD study, note that there is no (reliable) result of measurements using multi-jets configuration at hadron colliders. Our knowledge is still poor what we should measure.
- On the other hand, we can not get out of the QCD background for new physics searches or precision measurements. Better theoretical description is better… (apple and apple)

Theory:

- We had a big progress. CKKW method illuminates the structure of multi-parton dynamics. Recent development of NLO calculation is also applause.

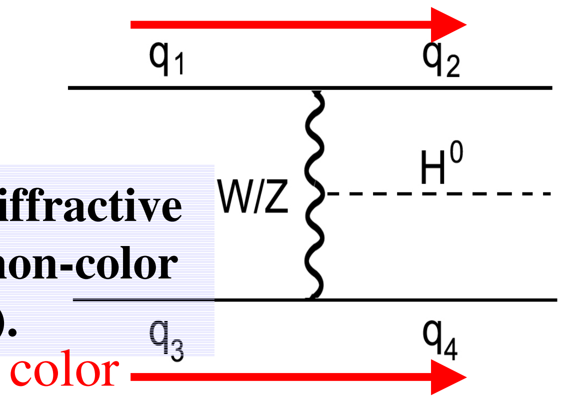
Perspective of QCD in LHC

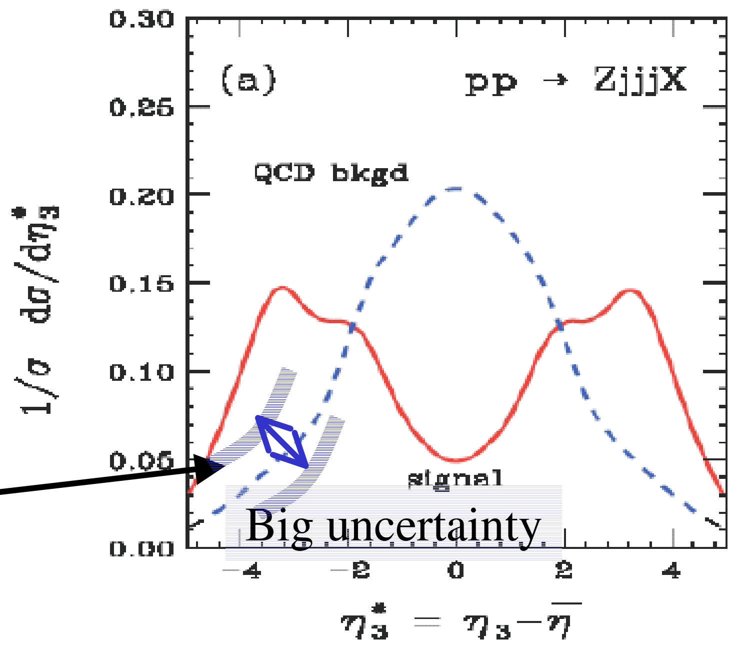
Vector Boson Fusion (VBF) Higgs production is expected to have a strong discovery potential in low mass region ($100 < M_H < 160$).

Its unique signature throws a tough question in QCD :

Presence of forward-backward jets with large rapidity separation.
Suppression of gluon radiation in central rapidity region.

Such as diffractive process (non-color exchange).





We have never measured the tail structure.

How do we model QCD background shape??

Central Jet veto is key.

Zeppenfeld plot

Look at third E_T jet balancing between leading and secondary jets.

$$\eta_3^* = \eta_3 - \frac{\eta_1 + \eta_2}{2}$$

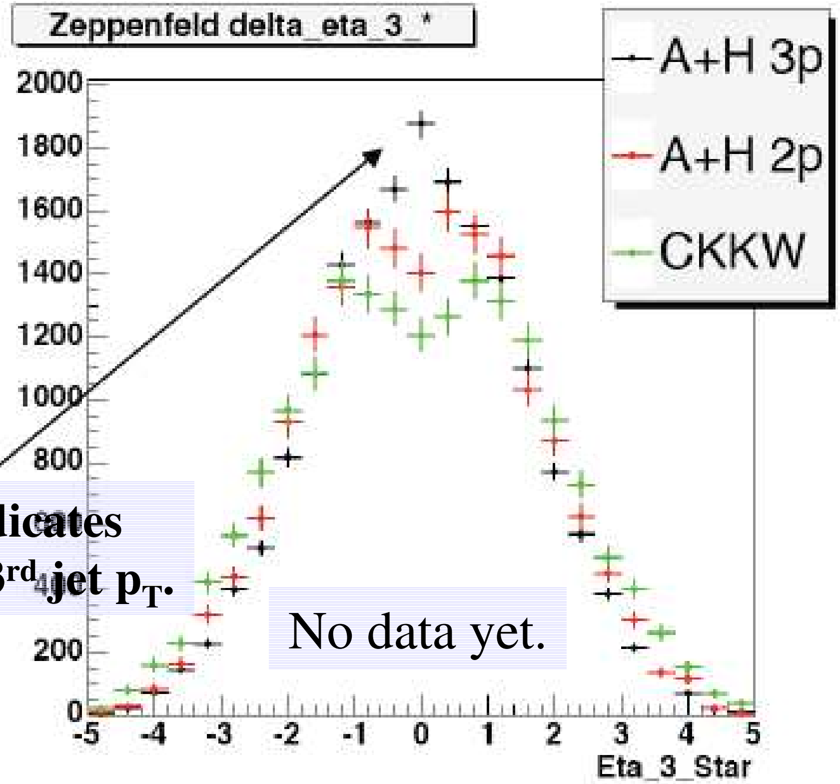
where, 3rd jet can be softer.

Compare with Tevatron W+ (≥3) jets to see how does it look like.

Tagged & 3rd jet E_T > 8 GeV for $\Delta\eta_{12}$>1

- ME W+3jets + PS (p_T > 8GeV)
- ME W+2jets + PS (p_T > 8GeV)
- CKKW

Normalized same area



This peak indicates just a cut of 3rd jet p_T.

No data yet.

Anyway, something will happen at Tevatron.

Conclusion

In sense that QCD events must be checked by ALL analysis,

QCD has been the most strictly tested theory at hadron colliders.

We (Theory and Experiment) tackle to reduce the measurement/theoretical uncertainties. PDF and Jet are a key to understand high p_T pQCD phenomena.

Multi-parton (jet) dynamics just began in consideration. Note that every QCD results are inclusive measurements. The multi-parton configuration in Theory and Experiment will be much improved in the current Tevatron exp. and future LHC.

Many are on-going:

Uncovered topics so far :

photon production; γ-jet , W(jj)γ

Drell-Yan ; Z(ll)-jet

etc…