Studying the Underlying Event at the Tevatron

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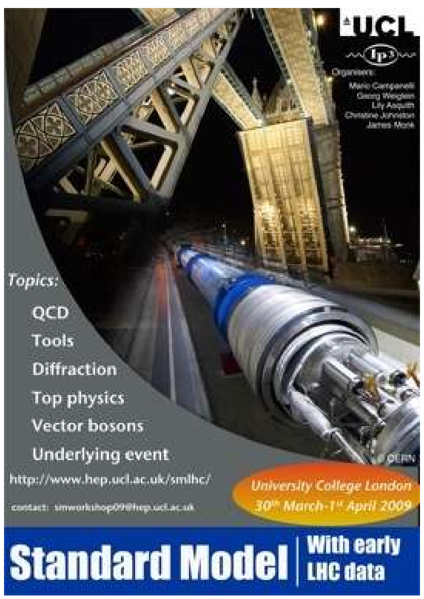
(On behalf of the CDF Collaboration)



1st April, 2009
University College London

Motivation:

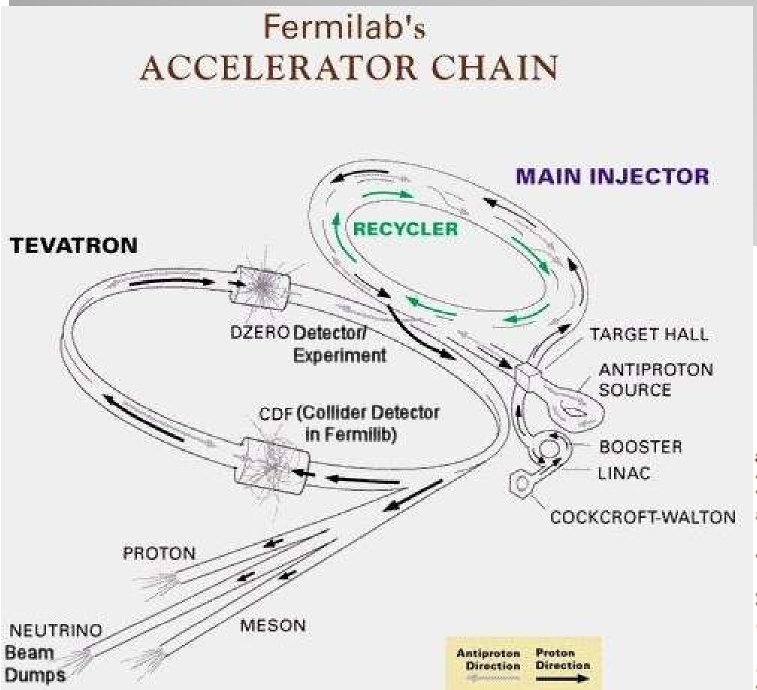
- Need to be able to simulate "ordinary" QCD and "Standard Model" events at the collider.

- Finding "new" physics requires a good understanding of the "old" Physics (Not only to have a good model of the hard scattering part of the process but also of "underlying event").

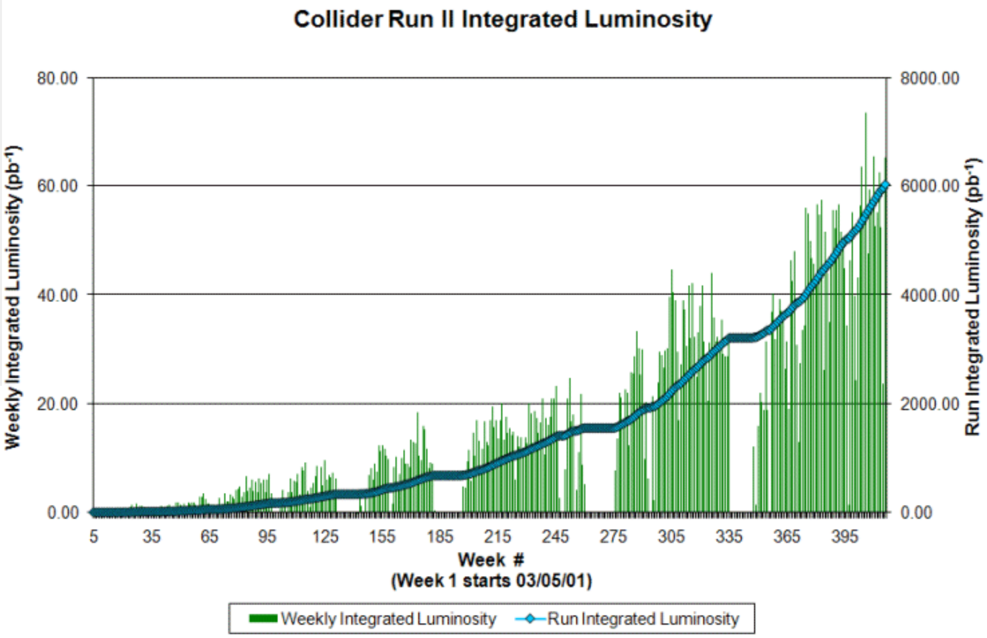
Outline

- “Underlying Event”
- Looking at the observables sensitive to the Underlying Event
- Looking ahead to the LHC

TeVatron

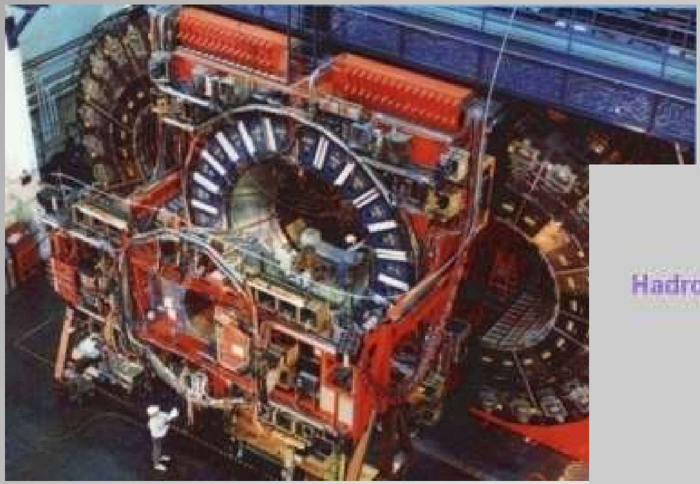


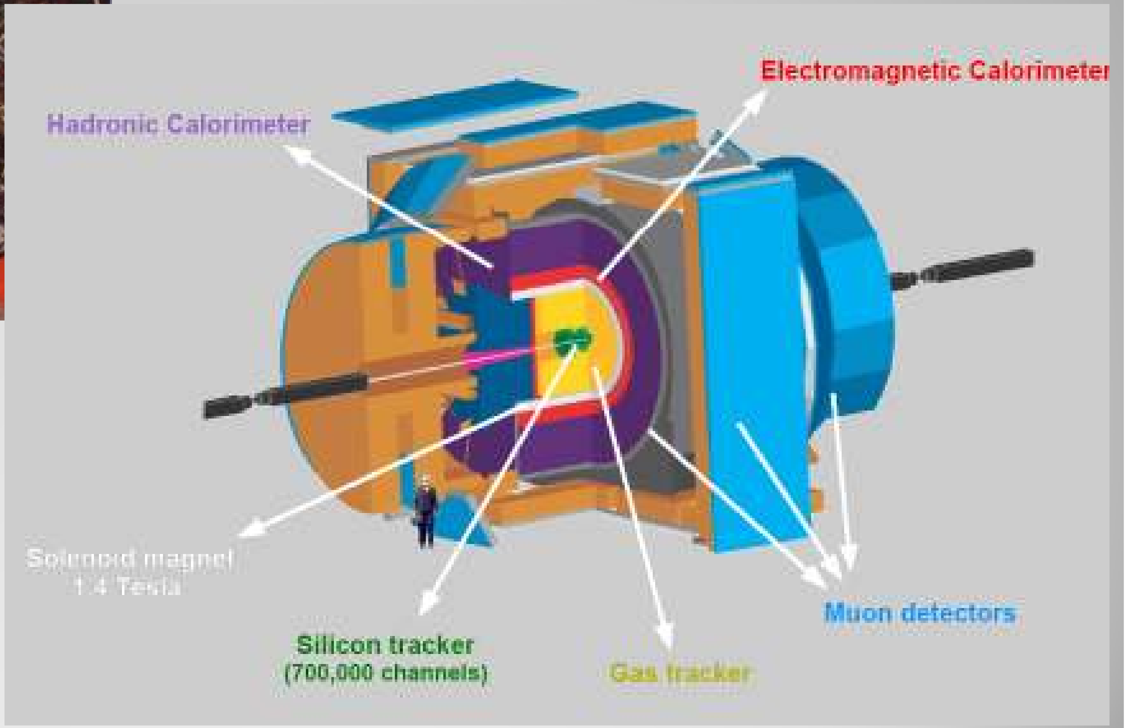
Fermilab's
ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO Detector/ Experiment
TARGET HALL
ANTIPROTON SOURCE
CDF (Collider Detector in Fermilib)
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO Beam Dumps
MESON
Antiproton Direction
Proton Direction



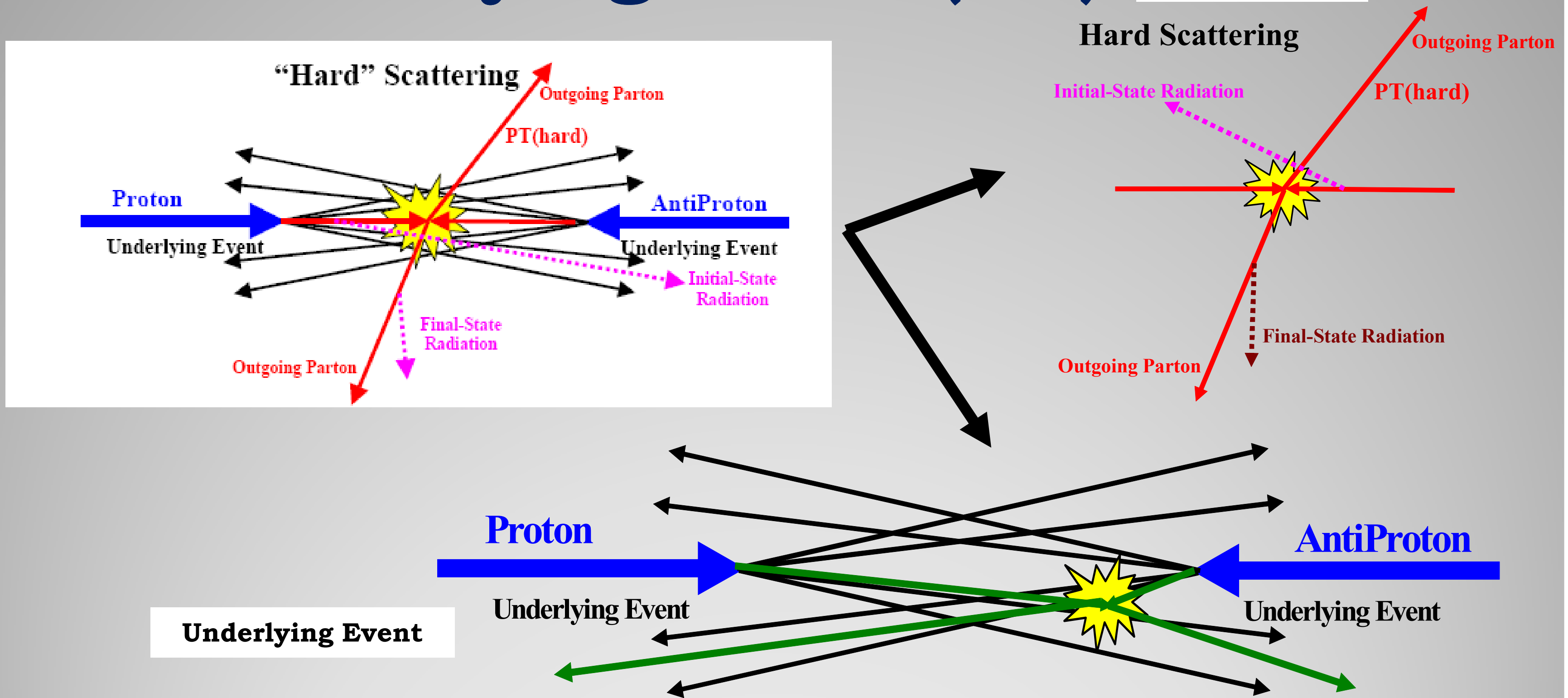
Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb⁻¹)
Run Integrated Luminosity (pb⁻¹)
0.00
20.00
40.00
60.00
80.00
2000.00
4000.00
6000.00
8000.00
5 35 65 95 125 155 185 215 245 275 305 335 365 395
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

Collider Detector at Fermilab (CDF)





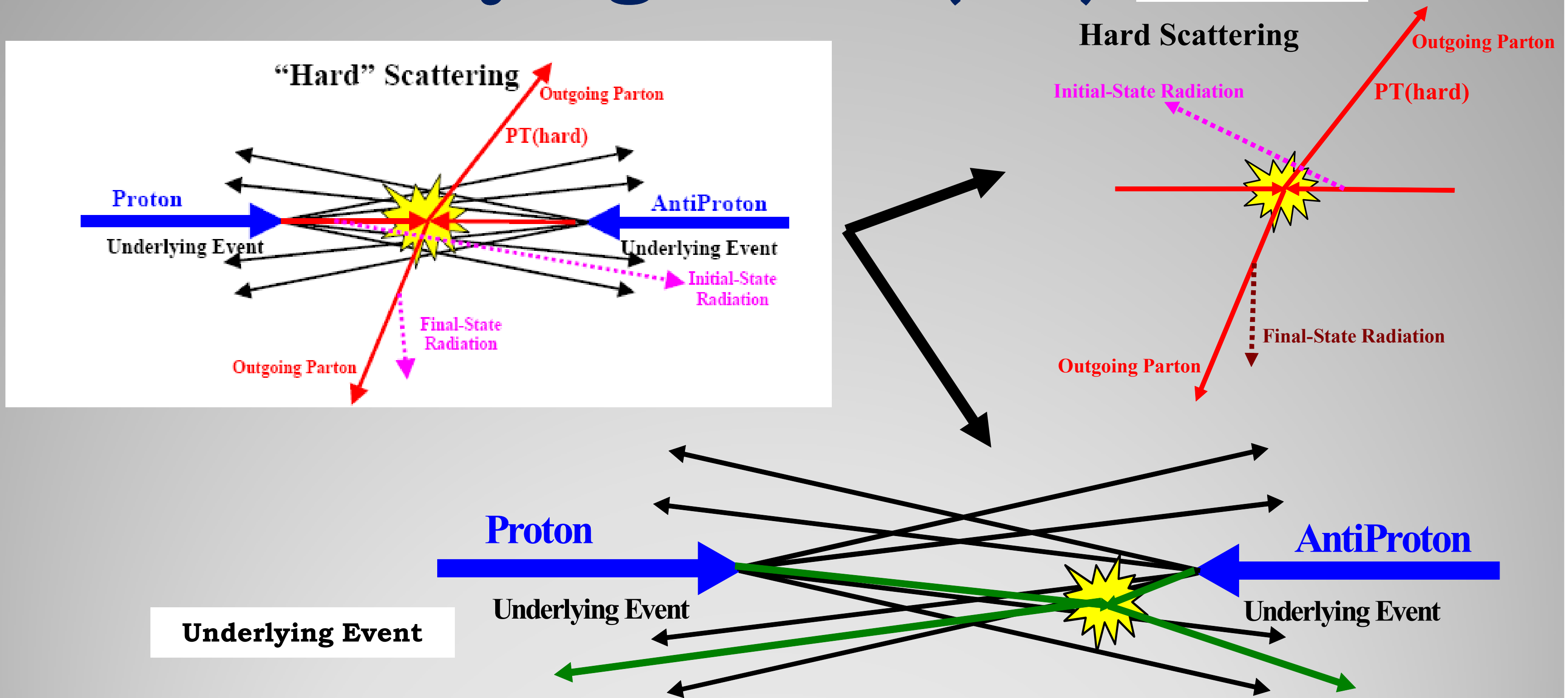
The Underlying Event (UE)



Everything except the two outgoing hard scattered components.
Beam-beam remnants (BBR), multiple parton interactions (MPI) …

The Underlying Event (UE)

Hard Scattering Component



From an experimental point of view, on an event by event basis, it is impossible to separate these two components.

So what is the problem with the Underlying Event ?

- The process of interest at hadron colliders are mostly the hard scattering events.
- These hard scattering events are contaminated by the underlying event.
- The underlying event is an **unavoidable background** to most collider observables.
- Increasing luminosity implies more hadronic collisions – which also complicates things. ***(pile-up)***
- The underlying event is not well understood since **non-perturbative physics** is involved.

Measuring it is important in …

- Precision measurements of hard interactions where soft effects need to be subtracted.

- Jet cross-section, missing energy, isolation cuts, top mass …

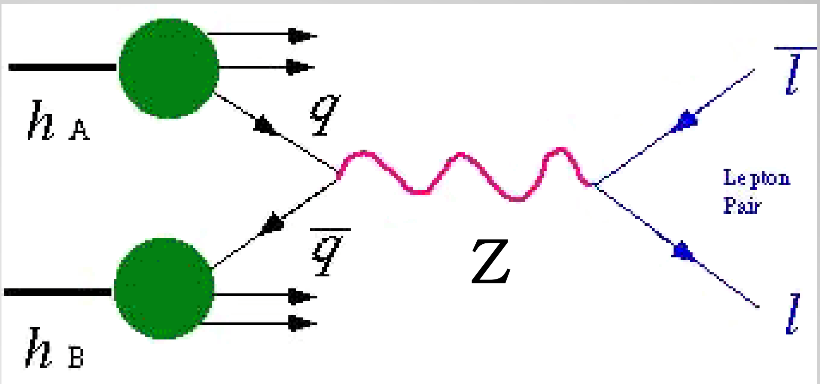
- *QCD Monte-Carlo tuning.* See Stefan's talk

Higher the precision, higher the accuracy of physics measurements.

Underlying Event Studies at CDF

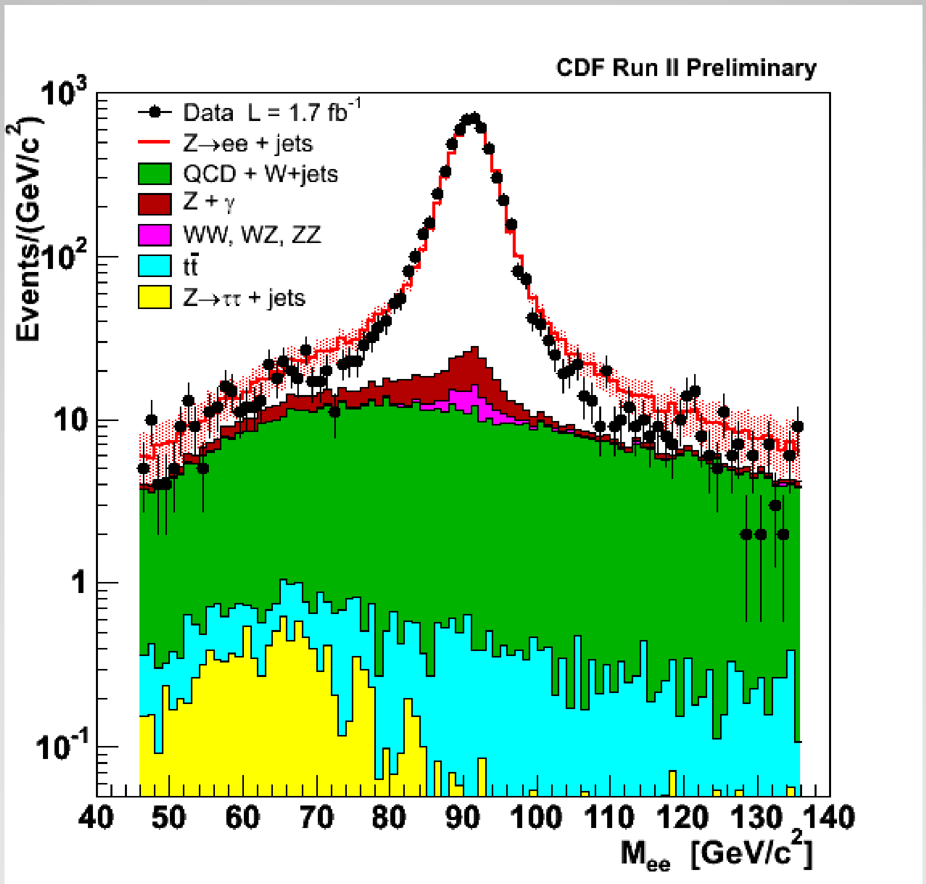
Earlier: Leading Jet events corresponding to the leading calorimeter jet (MidPoint R = 0.7) in the region $|\eta| < 2$ with no other conditions.

New:
Drell-Yan process

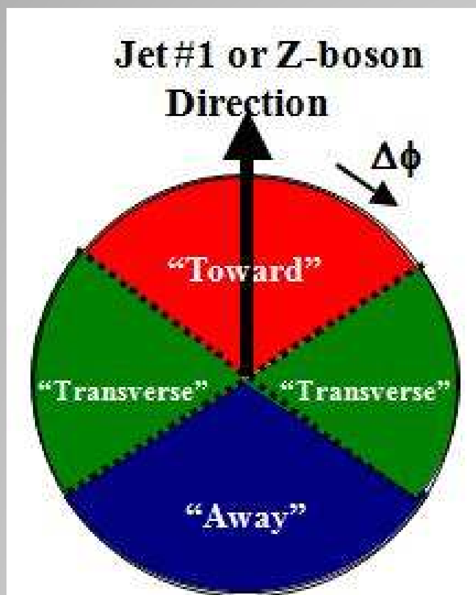


- Charged particles with: $p_T > 0.5$ GeV/c and $|\eta| < 1$
- Using events with the lepton pair invariant mass in the Z region: $70 < M(ll) < 110$ GeV/c^2

Negligible Background at "Z"



Dividing up the Central Region

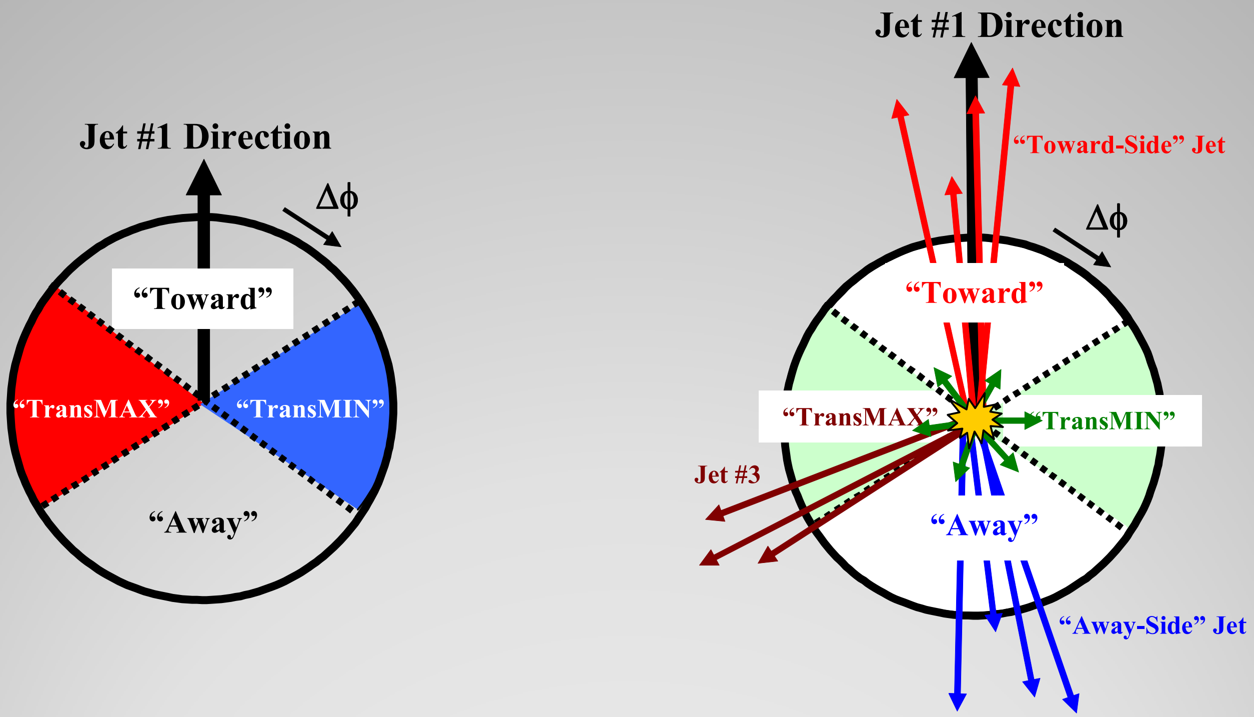


We define –

- $|\Delta\phi| < 60^o$ as **Toward**
- $60^o < |\Delta\phi| < 120^o$ as **Transverse**
- $|\Delta\phi| > 120^o$ as **Away**

Azimuthal angle $\Delta\phi$ relative to the leading calorimeter jet (or the Z-boson)

TransMAX, MIN, DIF Regions



- TransMIN sensitive to the soft BBR component
- TransDIF (TransMAX-TransMIN) sensitive to the hard scattering component (*i.e.* ISR/FSR)

Analysis Aim

- The goal of the analysis was to produce data on the **underlying event** that is **corrected** to the particle level so that it can be used to **tune** the QCD Monte-Carlo models without requiring CDF detector simulation.
- Compare with Leading Jet results
- Generally by looking at the measurements sensitive to the underlying event, we would be able to **better constrain** our underlying event models.

Analysis Strategy

- **High p_T** Electron and Muon Data, yielding ~65,000 electron and muon (oppositely charged) pairs each, passing all selection cuts.
- Charged Particles with **p_T > 0.5 GeV/c and $|\eta|$ <1**
- Using events with the lepton pair invariant mass in the Z region: **70 GeV/c^2 < M(ll) < 110 GeV/c^2**
- Errors coming both from **statistical and systematic** (due to lepton selection and charged particle selection) sources.

Observables

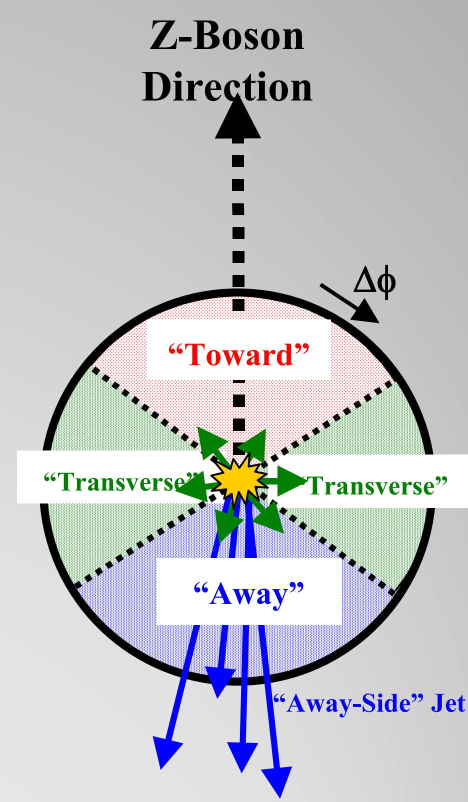
Observable	Particle Level	Detector Level
Lepton Pair P_T	P_T of the Lepton Pair.	P_T of the Lepton Pair, formed by at least one "Tight" Lepton.
No of Charged	Number of charged particles ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$)	Number of "good" charged tracks ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$)
P_T Sum	Scalar P_T sum of charged particles ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$)	Scalar P_T sum of "good" charged tracks ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$)
$< P_T >$	Average P_T of charged particles ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$) Require at least 1 charged particle	Average P_T of "good" charged tracks ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$) Require at least 1 charged track
P_T Max	Maximum P_T of charged particle ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$) Require at least 1 charged particle	Maximum P_T of "good" charged tracks ($P_T > 0.5$ GeV/c, $\|\eta\| < 1$) Require at least 1 "good" charged track

Z-Boson Production at Tevatron

Single Z Bosons are produced with large p_T via the ordinary QCD sub processes:

$$qg \rightarrow Zq, \; q\bar{q} \rightarrow Zg, \; \bar{q}g \rightarrow Z\bar{q}$$

They generate additional gluons via bremsstrahlung – resulting in multi-parton final states **fragmenting into hadrons** and forming **away-side jets**.



	CDF (pb)	NNLO (pb)
$\sigma(Z\rightarrow l^+l^-)$	254.9±3.3(stat)±4.6(sys)±15.2(lum)	252.3±5.0

CDF: Phys. Rev. Lett. 94, 091803 (2005)
NNLO Theory: Stirling, Van Neerven

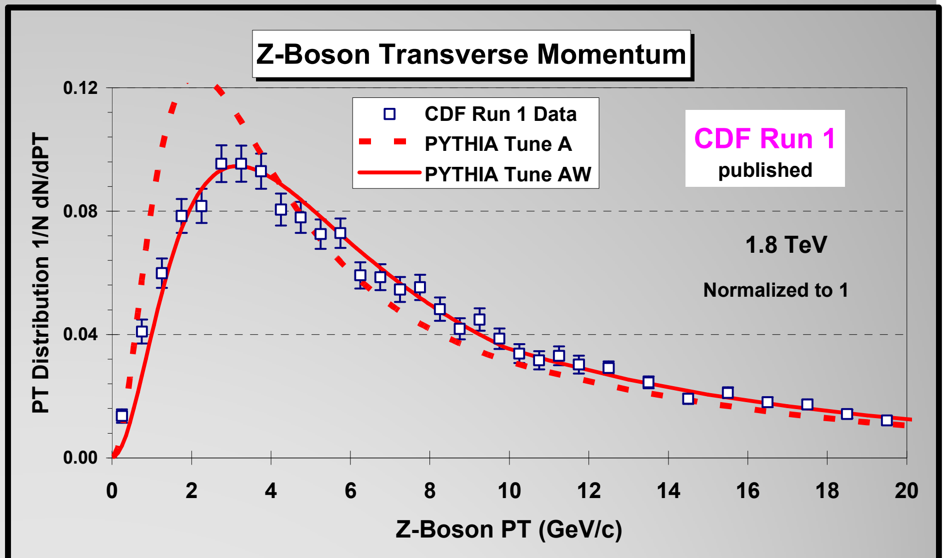
CDF Run 1 Tune (PYTHIA 6.2 CTEQ5L)

UE Parameters

ISR Parameters

Intrinsic KT

Parameter	Tune A	Tune AW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	2.0 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	0.9
PARP(86)	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	4.0
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(93)	5.0	15.0



Both tunes reveal a remarkably good agreement of the data and PYTHIA.

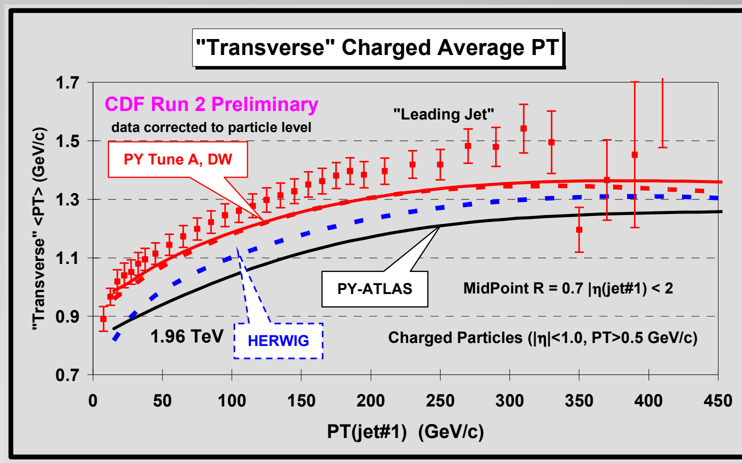
CDF Run 2 Tune (PYTHIA 6.206 CTEQ5L)

UE Parameters

ISR Parameters

Intrensic KT

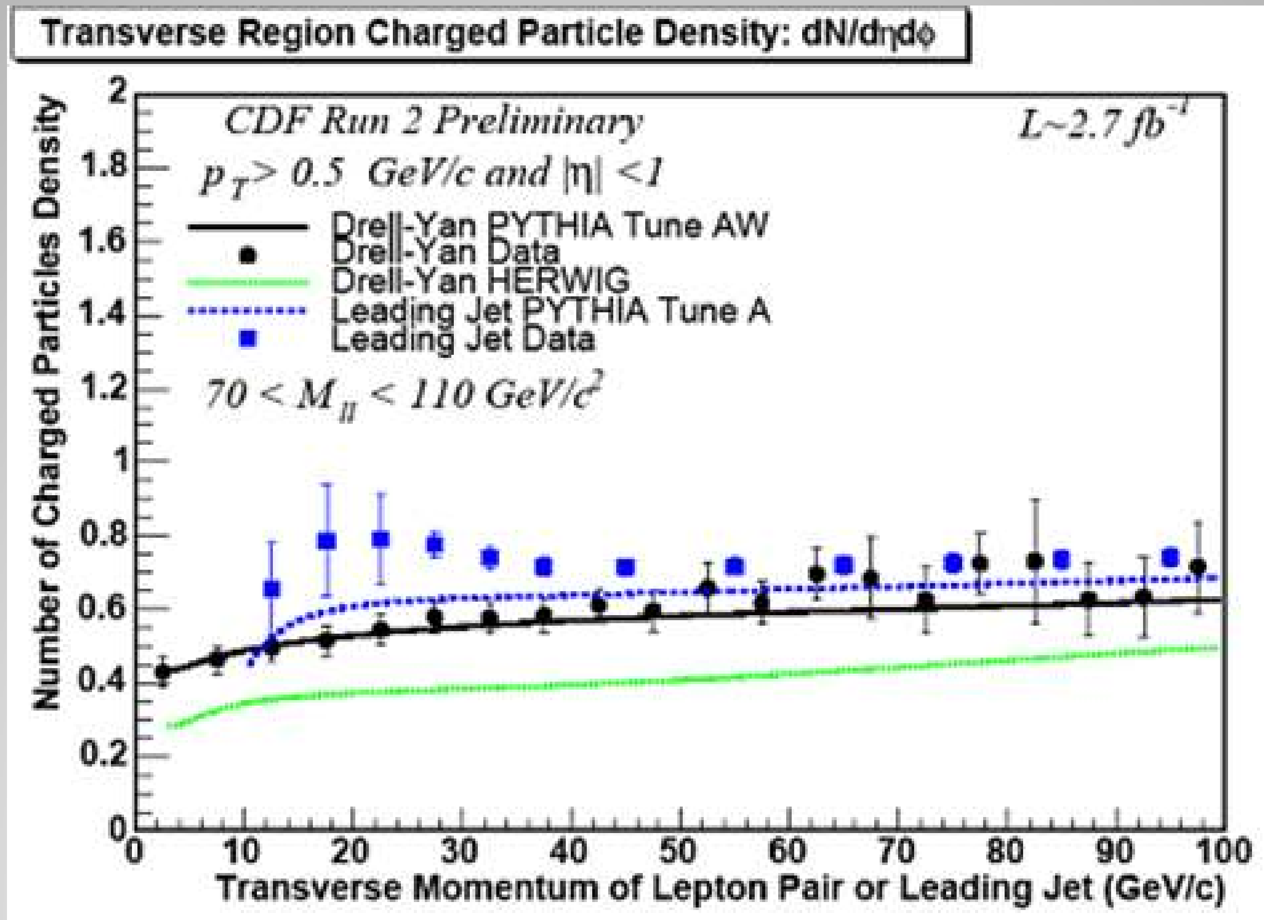
Parameter	Tune A	Tune DW	Tune DWT
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	2.0 GeV	1.9 GeV	1.9409 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4
PARP(85)	0.9	1.0	1.0
PARP(86)	0.95	1.0	1.0
PARP(89)	1.8 TeV	1.8 TeV	1.96 TeV
PARP(90)	0.25	0.25	0.16
PARP(62)	1.0	1.25	1.25
PARP(64)	1.0	0.2	0.2
PARP(67)	4.0	2.5	2.5
MSTP(91)	1	1	1
PARP(91)	1.0	2.1	2.1
PARP(93)	5.0	15.0	15.0



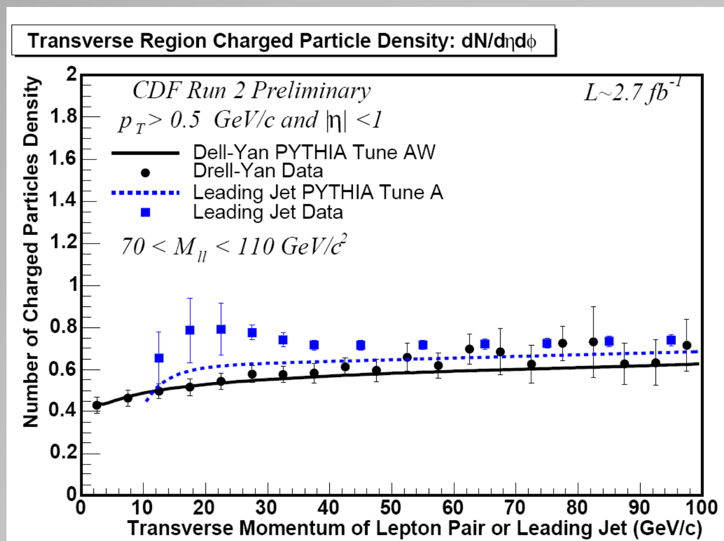
PYTHIA Tune DW is very similar to Tune A except that it fits the CDF $P_T(Z)$ distribution and it uses the DØ prefered value of PARP(67) = 2.5.

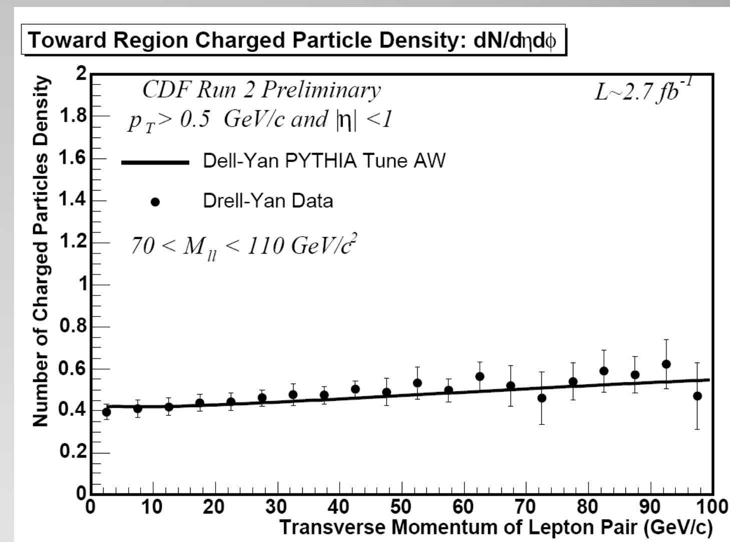
Results (I): The underlying event observables as a function of the lepton pair p_T

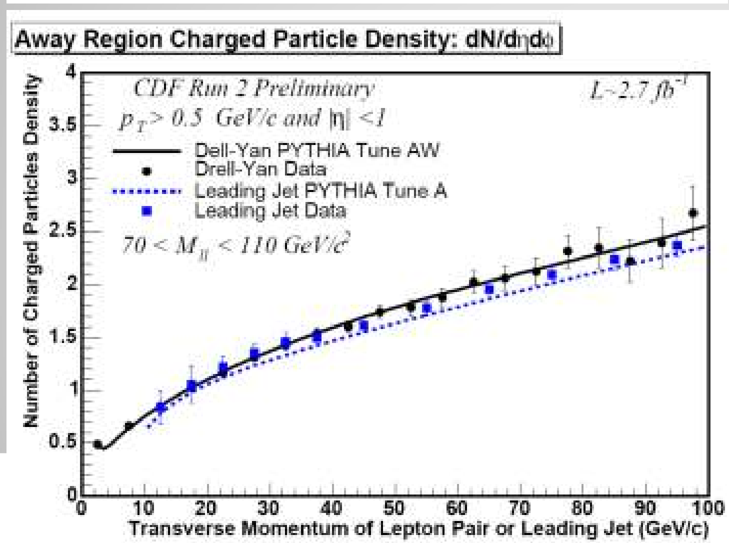
Charged Particle Multiplicity

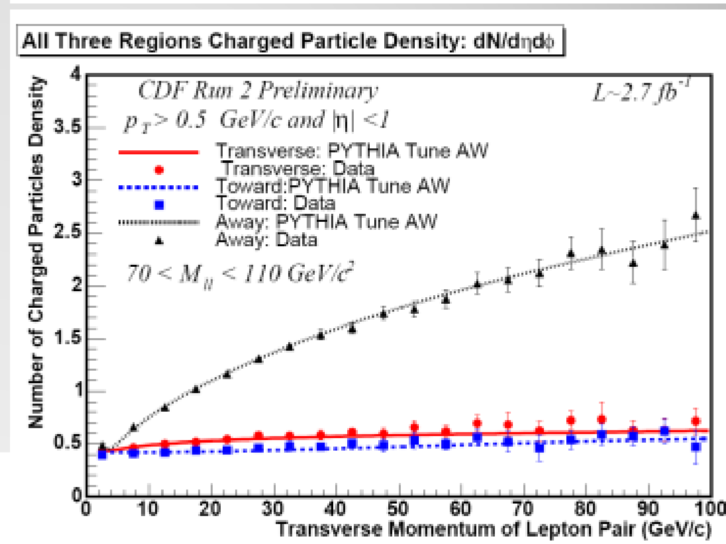


Charged Particle Multiplicity (I)

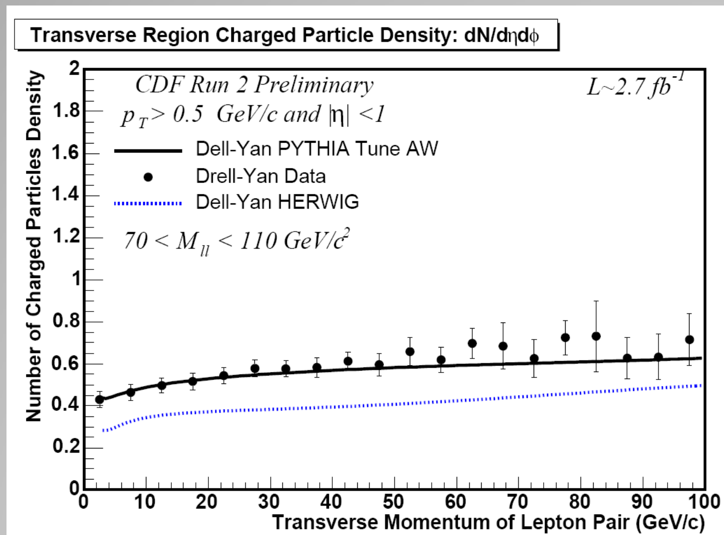


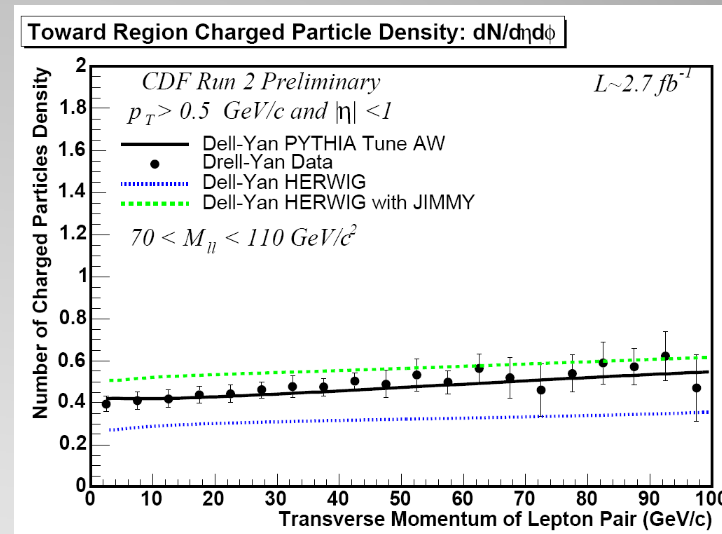


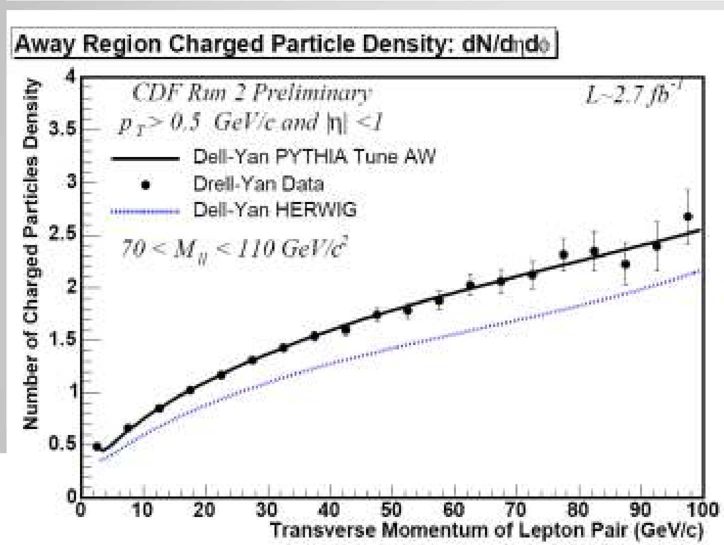


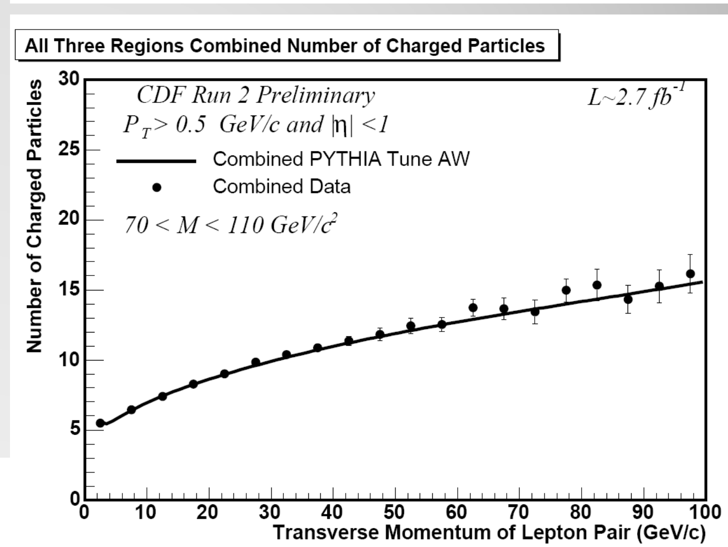


Charged Particle Multiplicity (II)

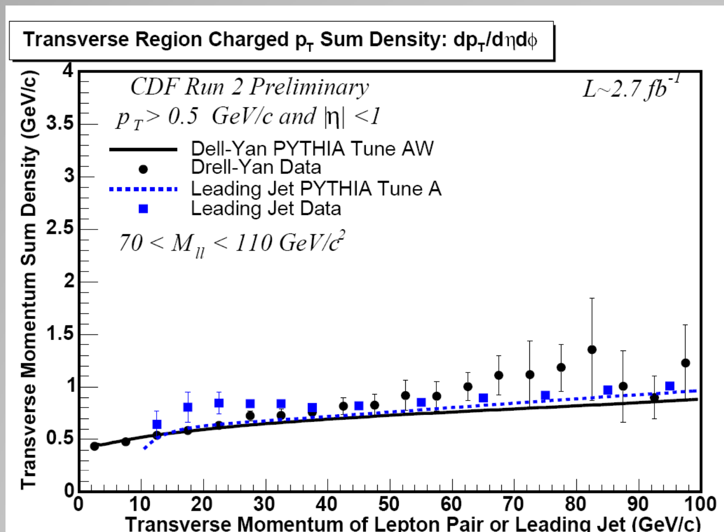


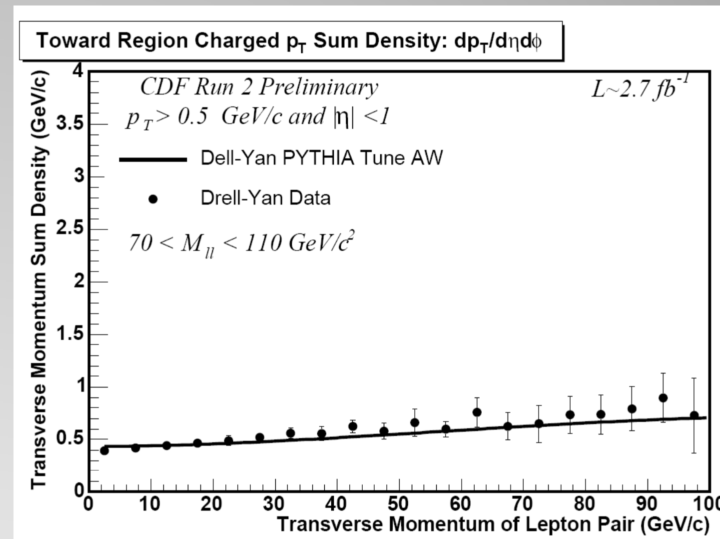


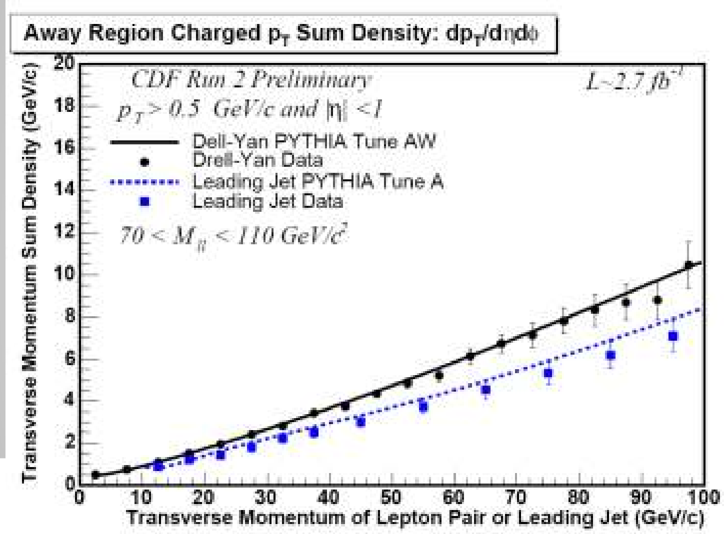


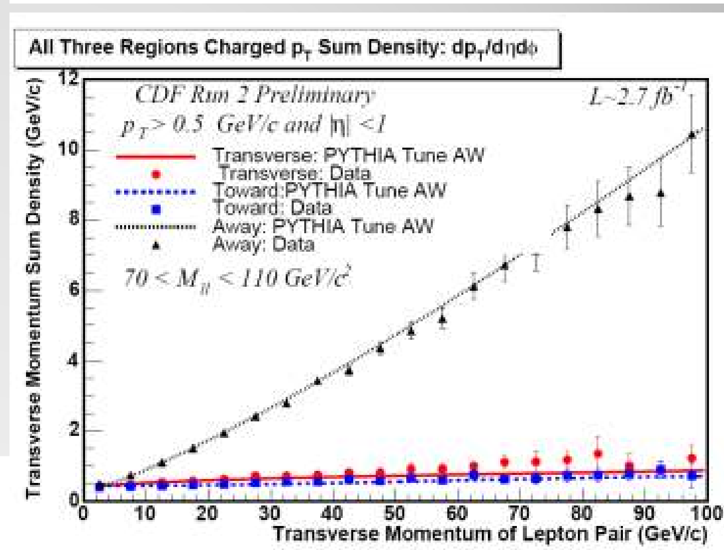


Charged Transverse Momentum Sum (I)

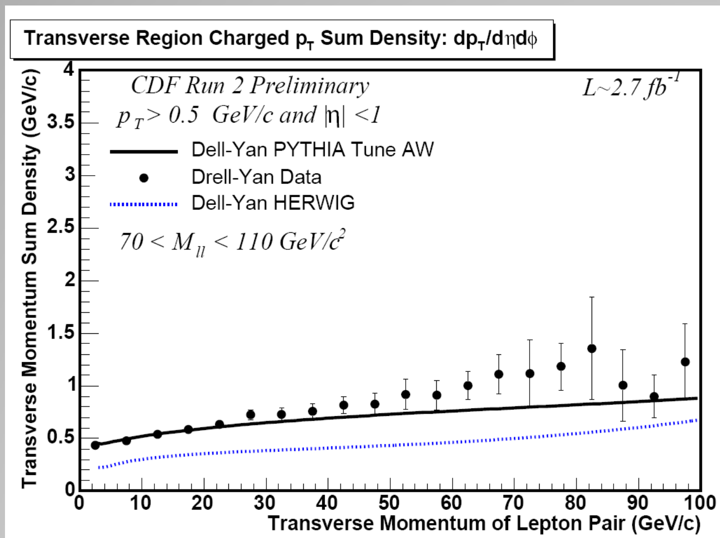


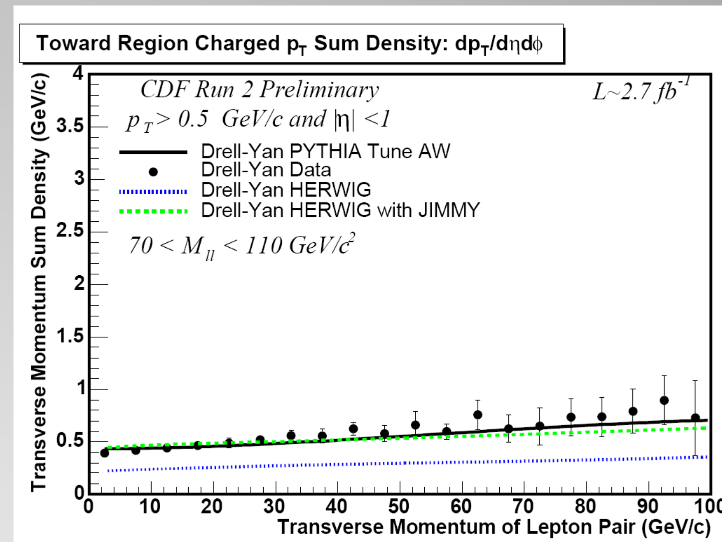


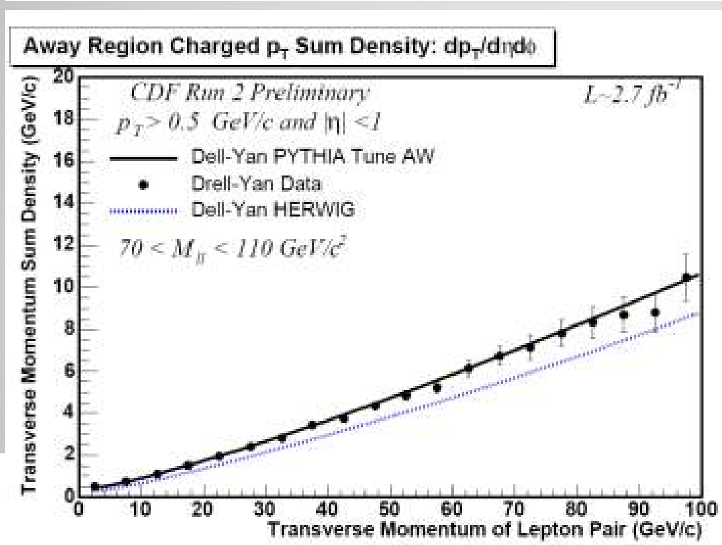


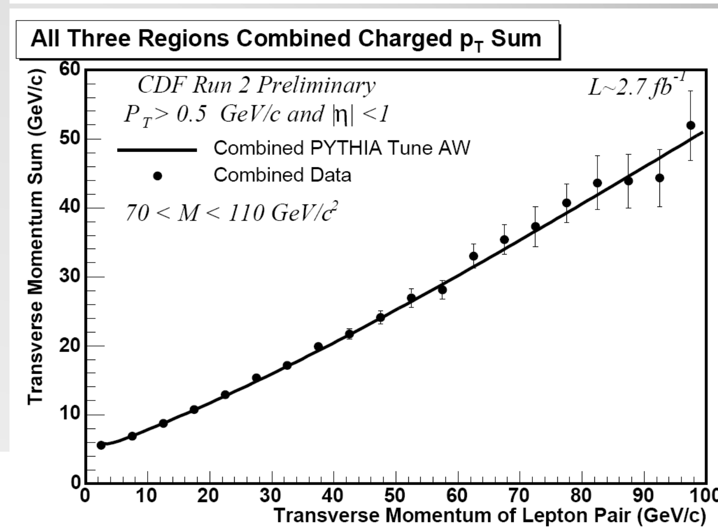


Charged Transverse Momentum Sum (II)

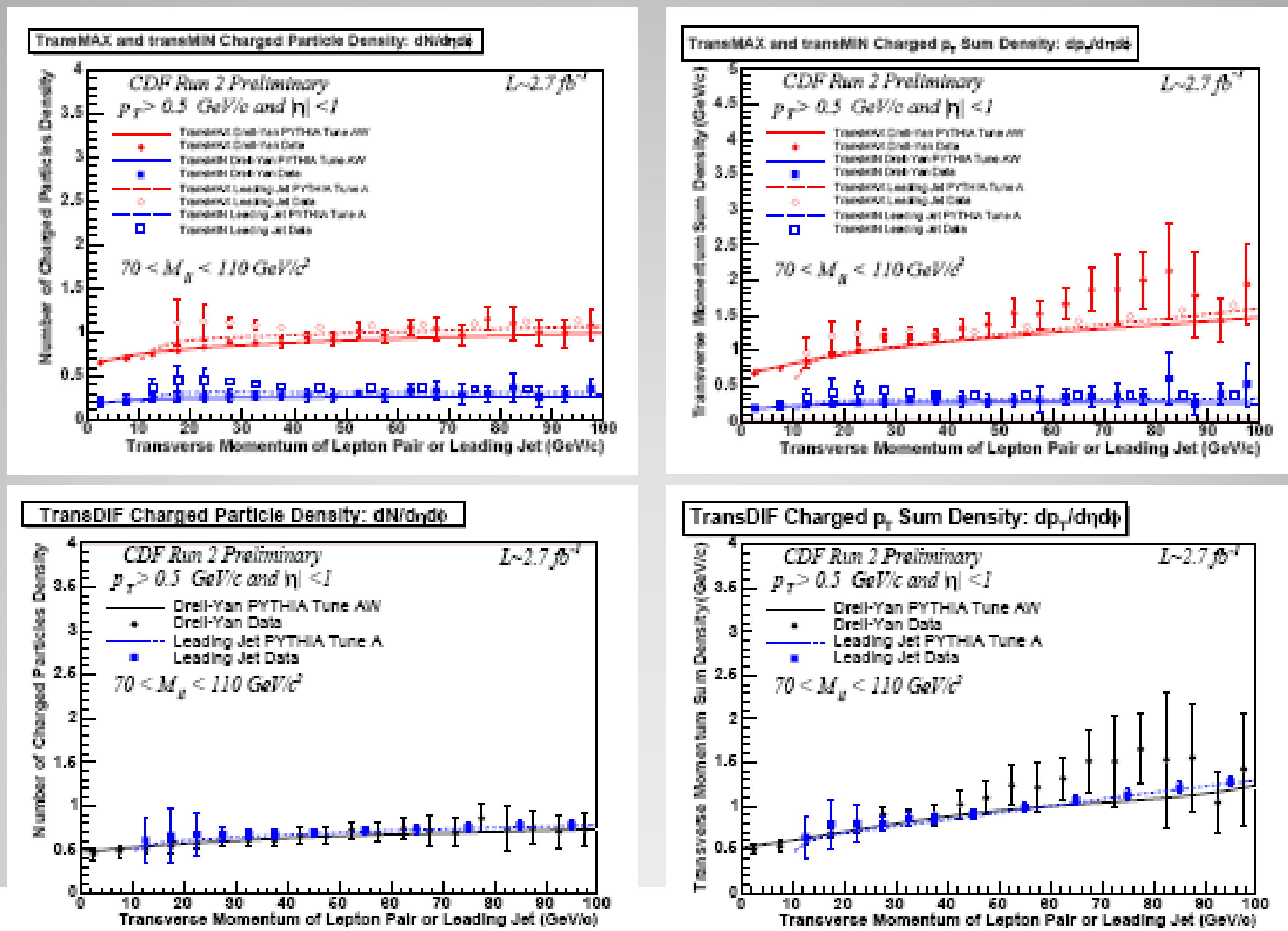




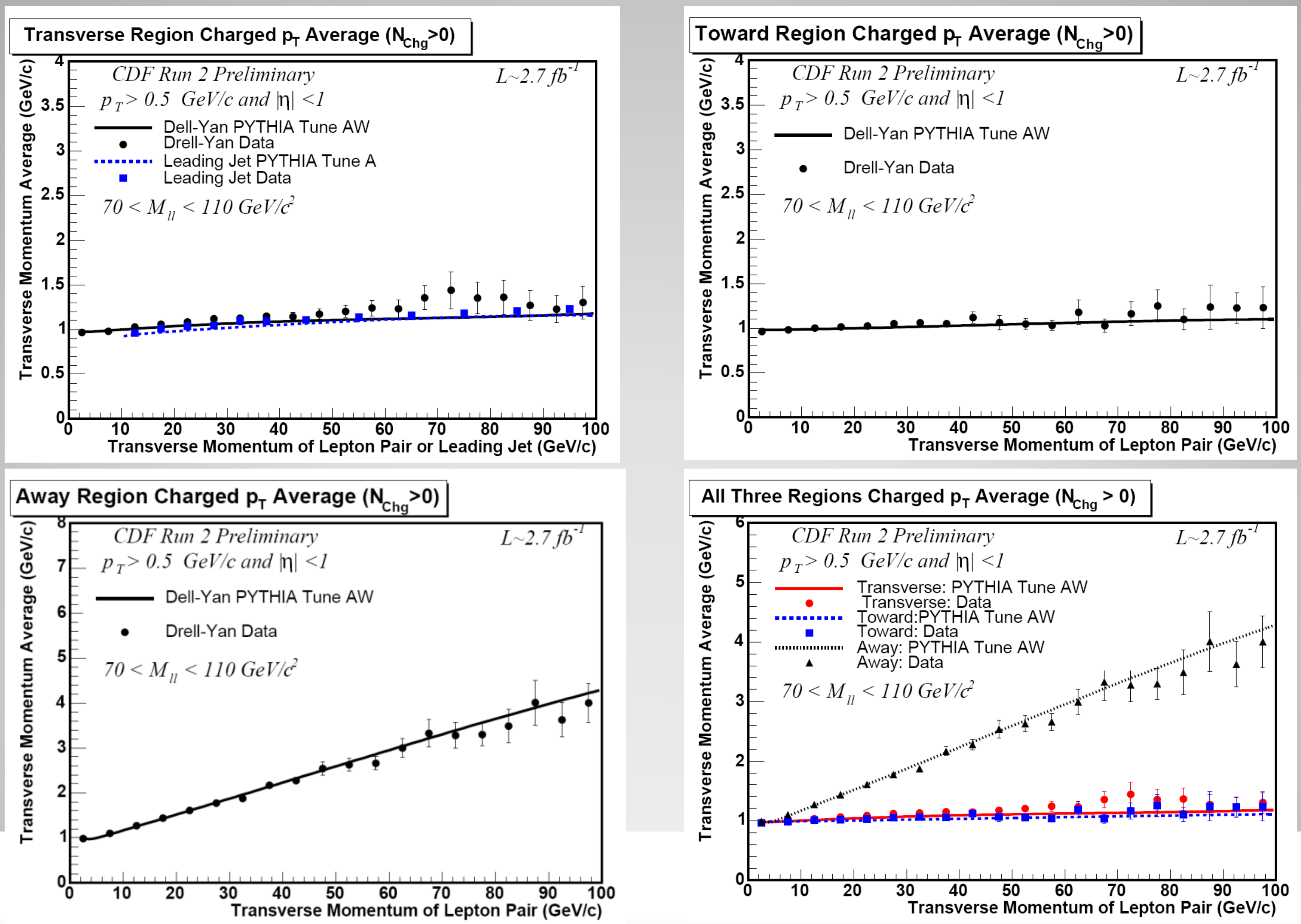




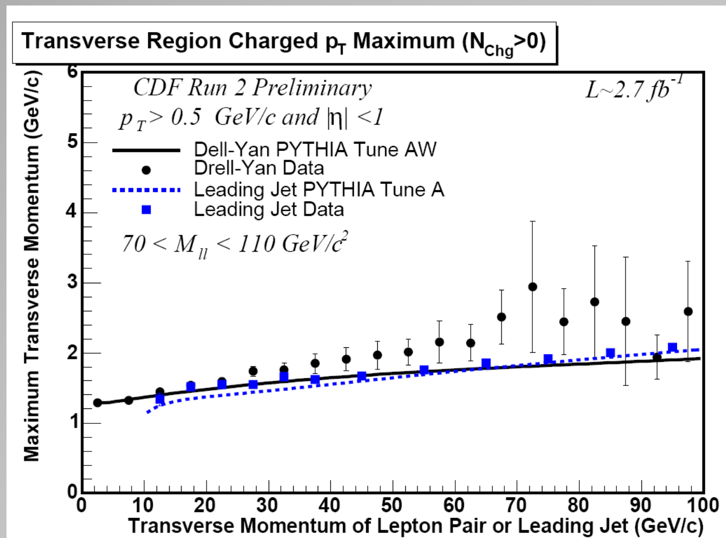
TransMAX, MIN, DIF Regions

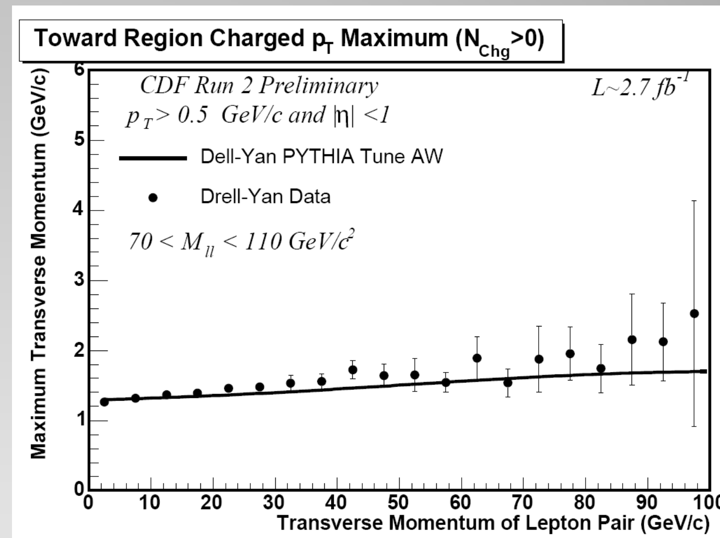


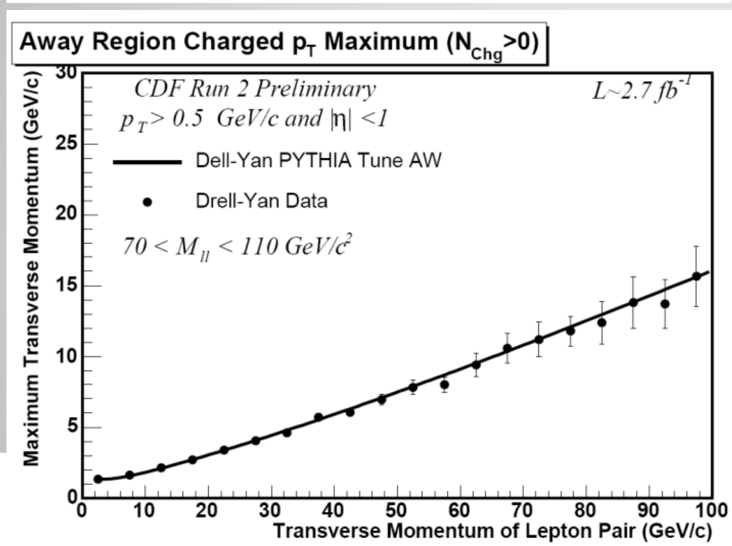
Charged Transverse Momentum Average

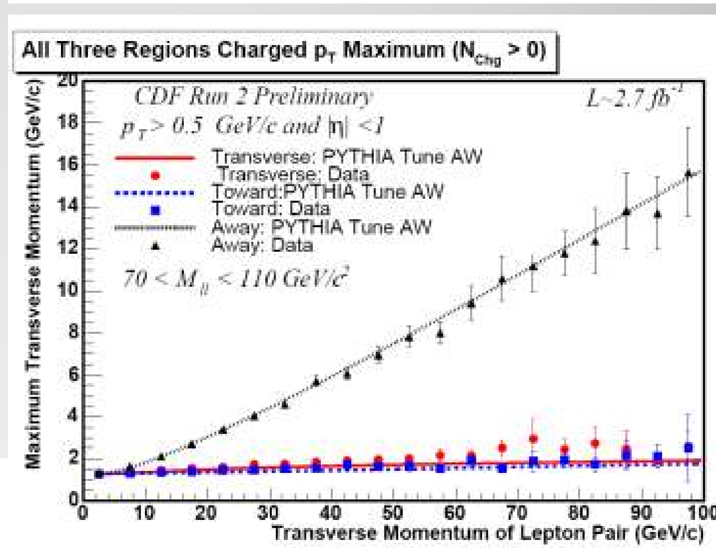


Charged Transverse Momentum Maximum





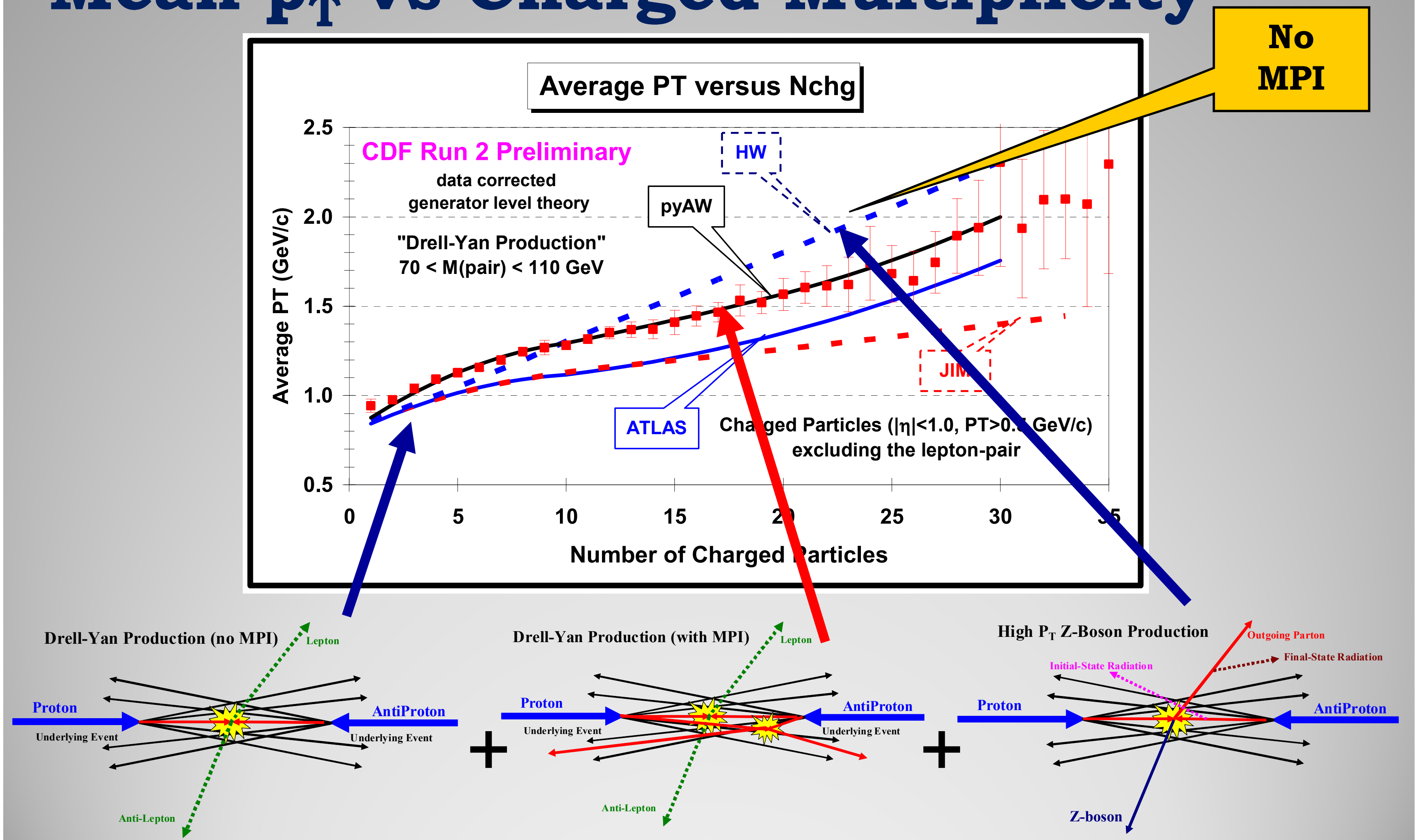




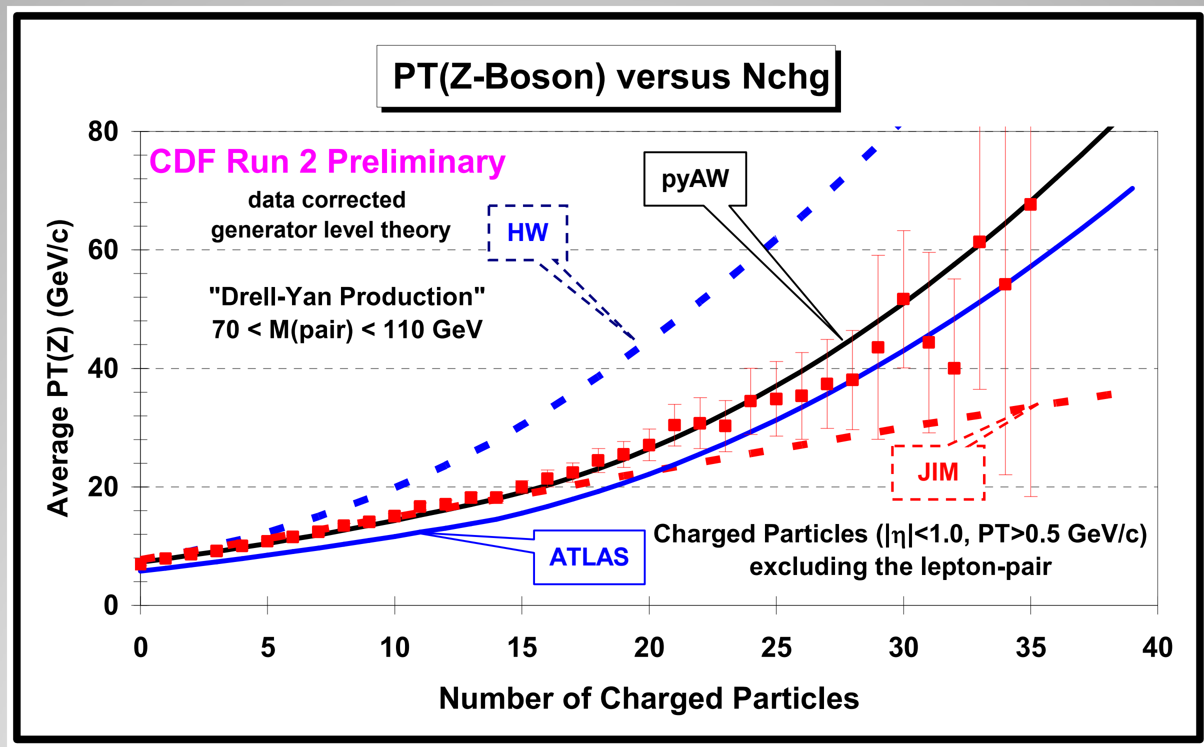
Results (II): Correlation between mean p_T of the charged particles against the charged particle multiplicity

$\langle p_T \rangle$ versus N_{chg} is a measure of the amount of **hard versus soft** processes contributing and it is **sensitive** to the modeling of the multiple-parton interactions.

Mean p_T vs Charged Multiplicity



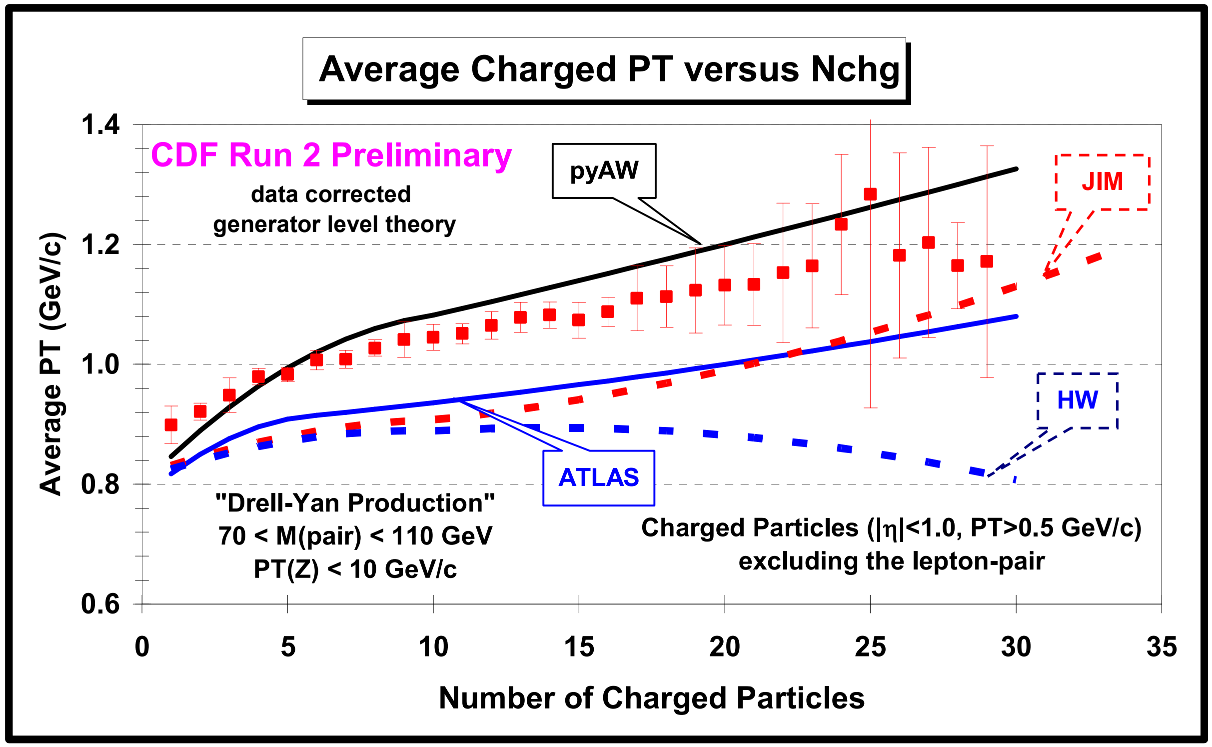
Mean p_T vs Charged Multiplicity



Large N_{chg} implies high p_T jets (i.e. hard 2→2 scattering). Without MPI the only way to get large N_{chg} is to have a very hard 2→2 scattering.

Mean p_T vs Charged Multiplicity

$P_T(Z) < 10$ GeV/c



Multiple-parton interactions provides another mechanism for producing large multiplicities that are harder than the beam-beam remnants, but not as hard as the primary Z +jet hard scattering.

Moving Forward to LHC

- The UE measurement plan at the LHC benefits from the solid experience of the CDF studies.
- Predictions on the amount of activity in transverse region at the LHC are based on extrapolations from lower energy data (mostly from the Tevatron).
- All the UE models have to be tested and adjusted at the LHC, in particular we know very little about the energy dependents of MPI in going from the Tevatron to the LHC.

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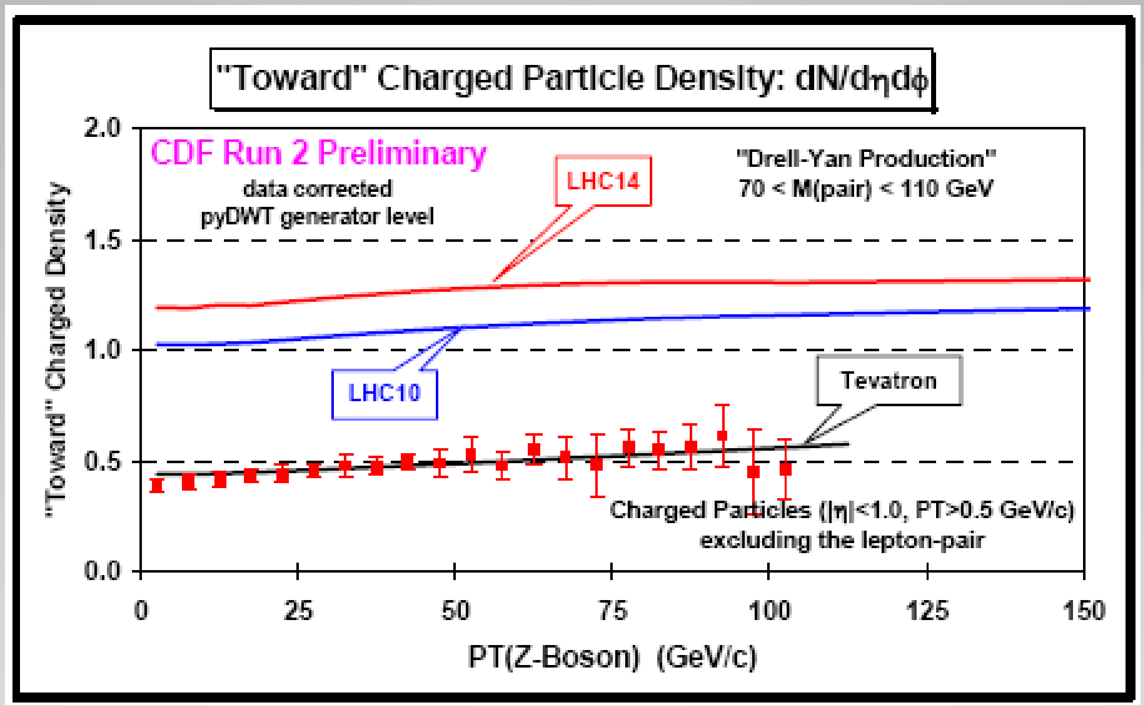
Few hundred pb^{-1} integrated luminosity in first year – enough Z's to look at the UE with Drell-Yan / Z+jets …

Moving Forward to LHC



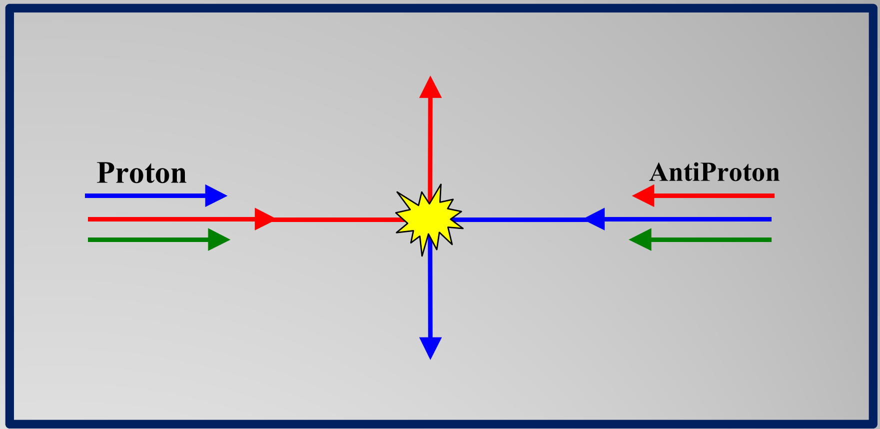
Underlying Event much more active at LHC

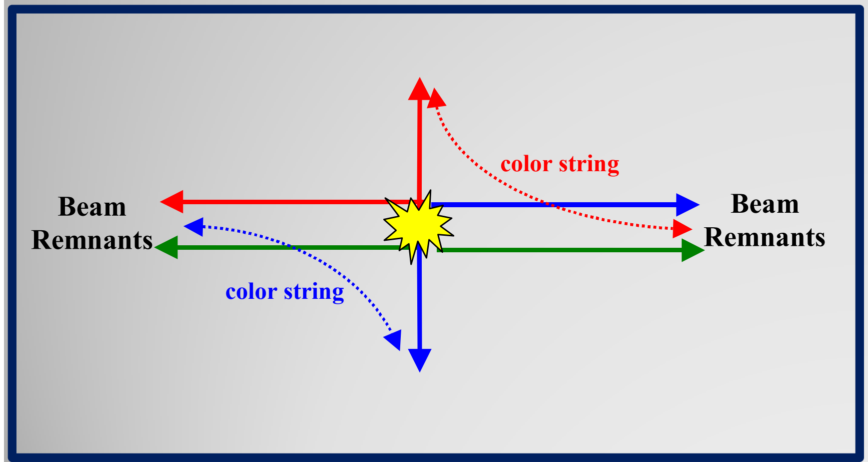
Conclusions

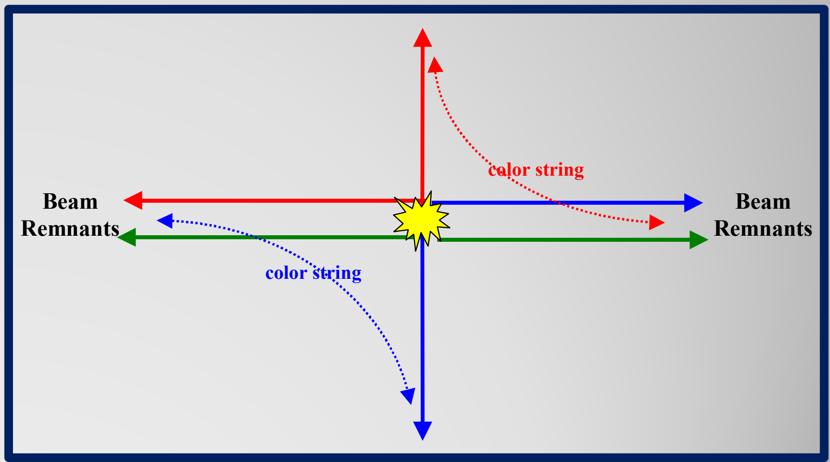
- Observed excellent agreement with PYTHIA tune AW predictions.
- Close match with leading jet underlying event results –underlying event models (BBR part) independent of hard scattering event?
- By looking at the correlation between $\langle p_T \rangle$ and charged multiplicity, we can discriminate between different contributing subprocesses.

As seen in Madison, WI

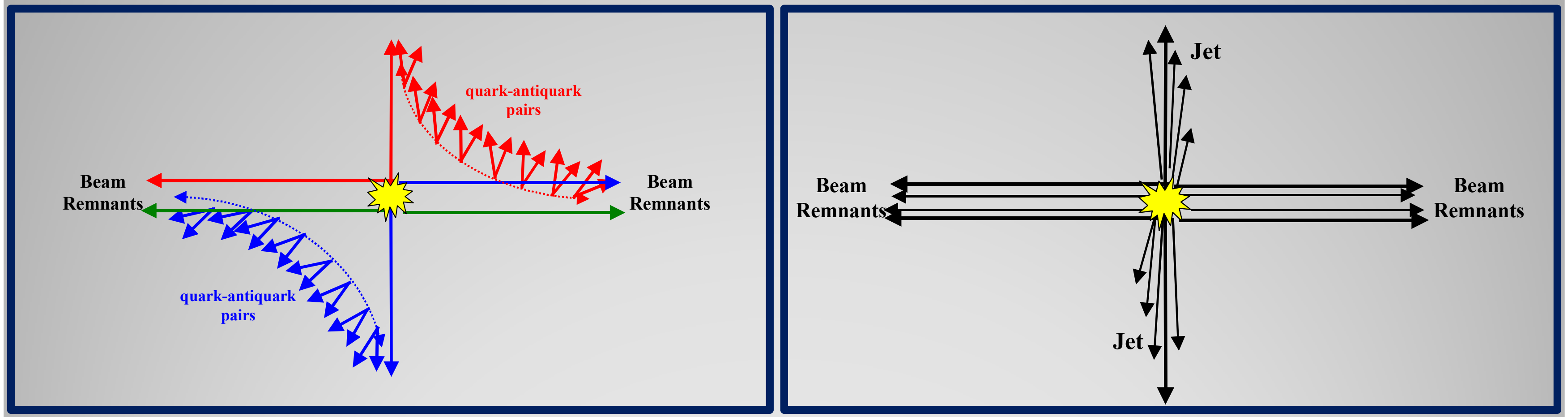
Monte-Carlo Simulation of Hadron-Hadron Collisions







Monte-Carlo Simulation of Hadron-Hadron Collisions



The resulting event consists of hadrons and leptons in the form of two large transverse momentum outgoing jets plus the beam-beam remnants.

PYTHIA

For underlying event studies, the only tool we have is to compare the data and the **predictions** from various Monte Carlo event generators, i.e. PYTHIA.

Apollo's priestess, Pythia, performing the duty of the oracle

PYTHIA has "knobs" which can be *tuned* to obtain an optimal description of the data.

PYTHIA Parameters

PYTHIA UE Parameter	Definition
MSTP(81)	MPI on/off
MSTP(82)	3 / 4: resp. single or double gaussian hadronic matter distribution in the p / pbar
PARP(67)	ISR Max Scale Factor
PARP(82)	MPI pT cut-off
PARP(83)	Warm-Core: parp(83)% of matter in radius parp(84)
PARP(84)	Warm-Core: ”
PARP(85)	prob. that an additional interaction in the MPI formalism gives two gluons, with colour connections to NN in momentum space
PARP(86)	prob. that an additional interaction in the MPI formalism gives two gluons, either as described in PARP(85) or as a closed gluon loop. Remaining fraction is supposed to consist of qqbar pairs.
PARP(89)	ref. energy scale
PARP(90)	energy rescaling term for PARP(81-82)~E_{CM}^PARP(90)

PYTHIA Parameters

PYTHIA UE Parameter	Definition
MSTP(81)	MPI on/off
MSTP(82)	3 / 4: resp. single or double gaussian hadronic matter distribution in the p / pbar
PARP(67)	ISR Max Scale Factor
PARP(82)	MPI pT cut-off

- PYTHIA uses MPI to enhance the UE.
- Multiple parton interaction more likely in a hard (central) collision.
- ISR Max Scale Factor affects the amount of initial-state radiation.
- Increasing the cut-off decreases the multiple parton interaction.