LHC@BNL Workshop

Early QCD Measurements at the LHC

Rick Field

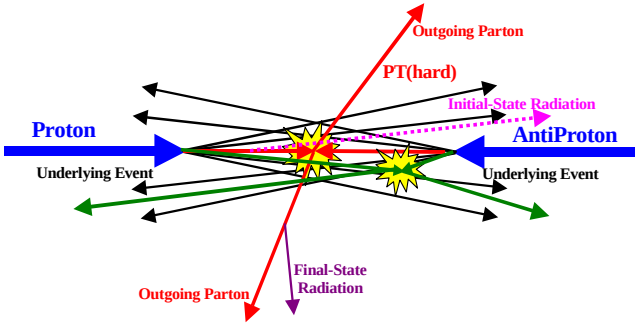
University of Florida

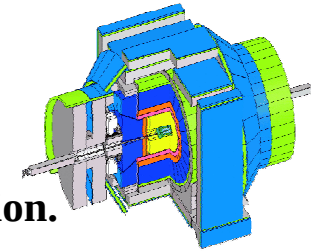
BNL February 7, 2010

Outline of Talk

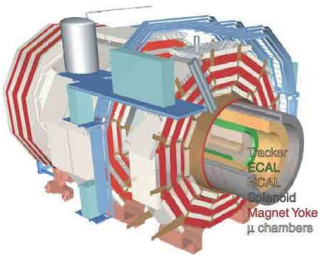
- The inelastic non-diffractive cross section.
- What is the "underlying event"?
- The QCD Monte-Carlo Model tunes.
- The Pythia MPI energy scaling parameter PARP(90).
- Extrapolations from the Tevatron to RHIC and the LHC.
- The "underlying event" at STAR.
- Min-Bias and the "underlying event".
- The "underlying event" in Drell-Yan production.
- LHC predictions!
- Summary & Conclusions.

Quantum Chromo-Dynamics





CDF Run 2



CMS at the LHC

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- The Pyth
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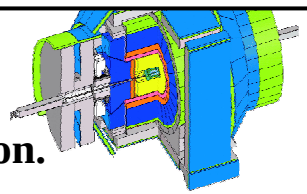
- The "und
- Min-Bias and the "underlying event".
- The "underlying event" in Drell-Yan production.
- LHC predictions!
- Summary & Conclusions.

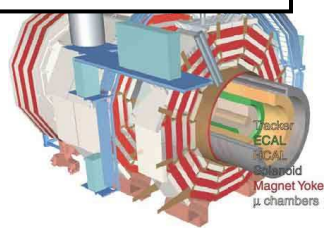
Amplitude Analysis of the Reaction $K^-p \to \pi^- Y^{*+}(1385)$†

M. Aguilar-Benitez,* S. U. Chung, R. L. Eisner, and R. D. Field
Brookhaven National Laboratory, Upton, New York 11973
(Received 19 June 1972)

We present a model-independent amplitude analysis of the reaction $K^-p \to \pi^- Y^{*+}(1385)$ at 3.9 and 4.6 GeV/c incident momenta. By observing the two-step decay of the $Y^{*+}(1385)$ we determine the magnitudes and two relative phases of the four independent transversity amplitudes which describe the reaction. These amplitudes are found to be in rough agreement with the predictions of the naive quark model; however, the predictions do not hold exactly.

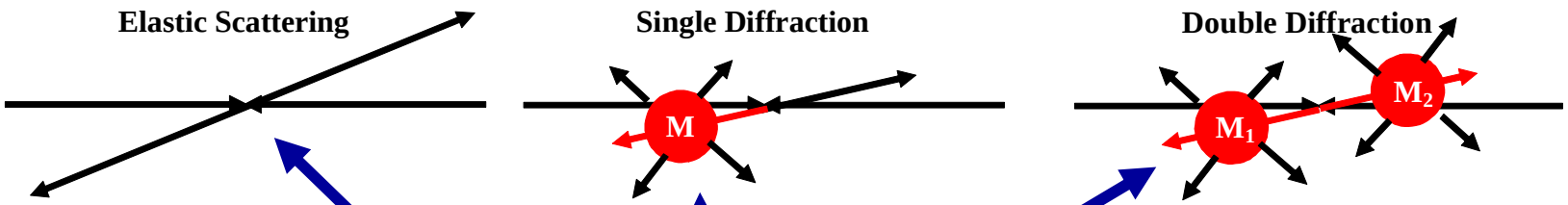


CDF Run 2



CMS at the LHC

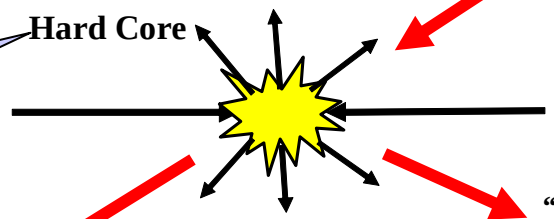
Proton-Proton Collisions

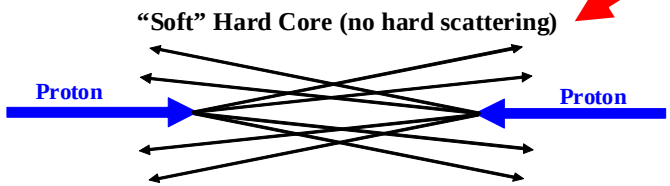


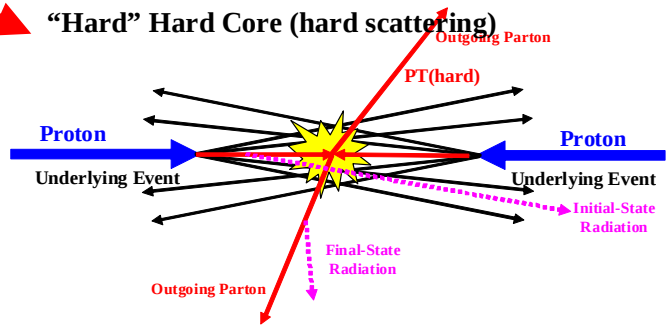
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND}$$

"Inelastic Non-Diffractive Component"

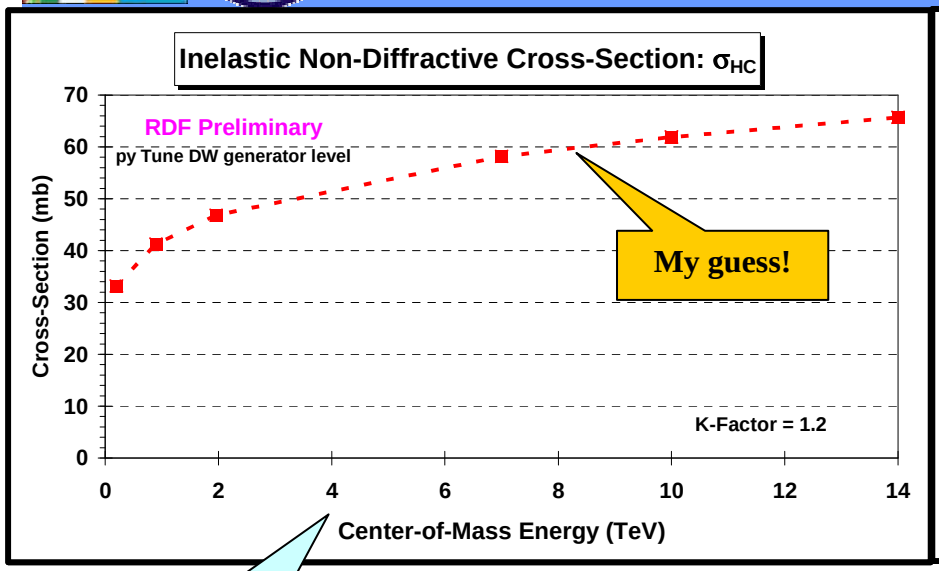
The "hard core" component contains both "hard" and "soft" collisions.

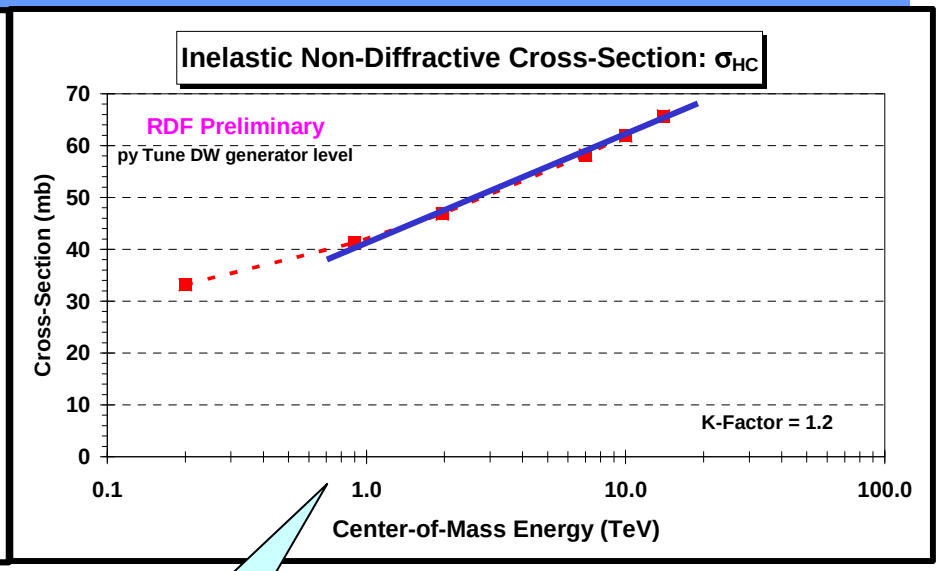






Inelastic Non-Diffractive Cross-Section





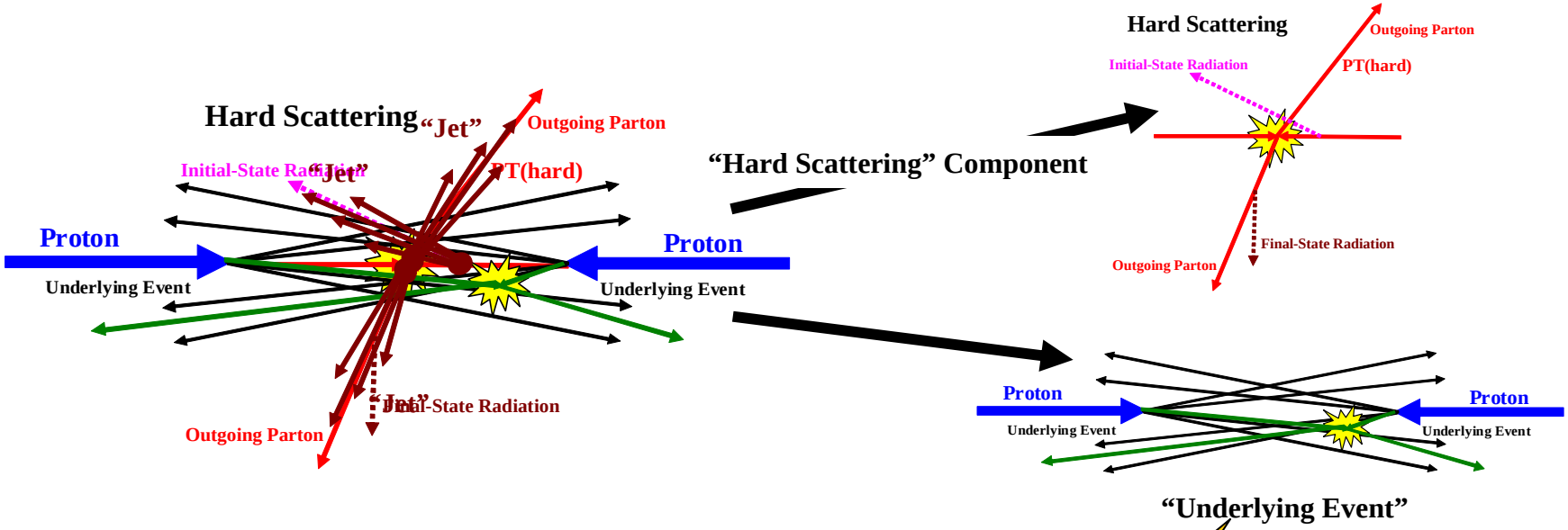
Linear scale!

Log scale!

$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND}$$

- The inelastic non-diffractive cross section versus center-of-mass energy from PYTHIA (×1.2).
- σ_{HC} varies slowly. Only a 13% increase between 7 TeV (≈ 58 mb) and 14 teV (≈ 66 mb).
  Linear on a log scale!

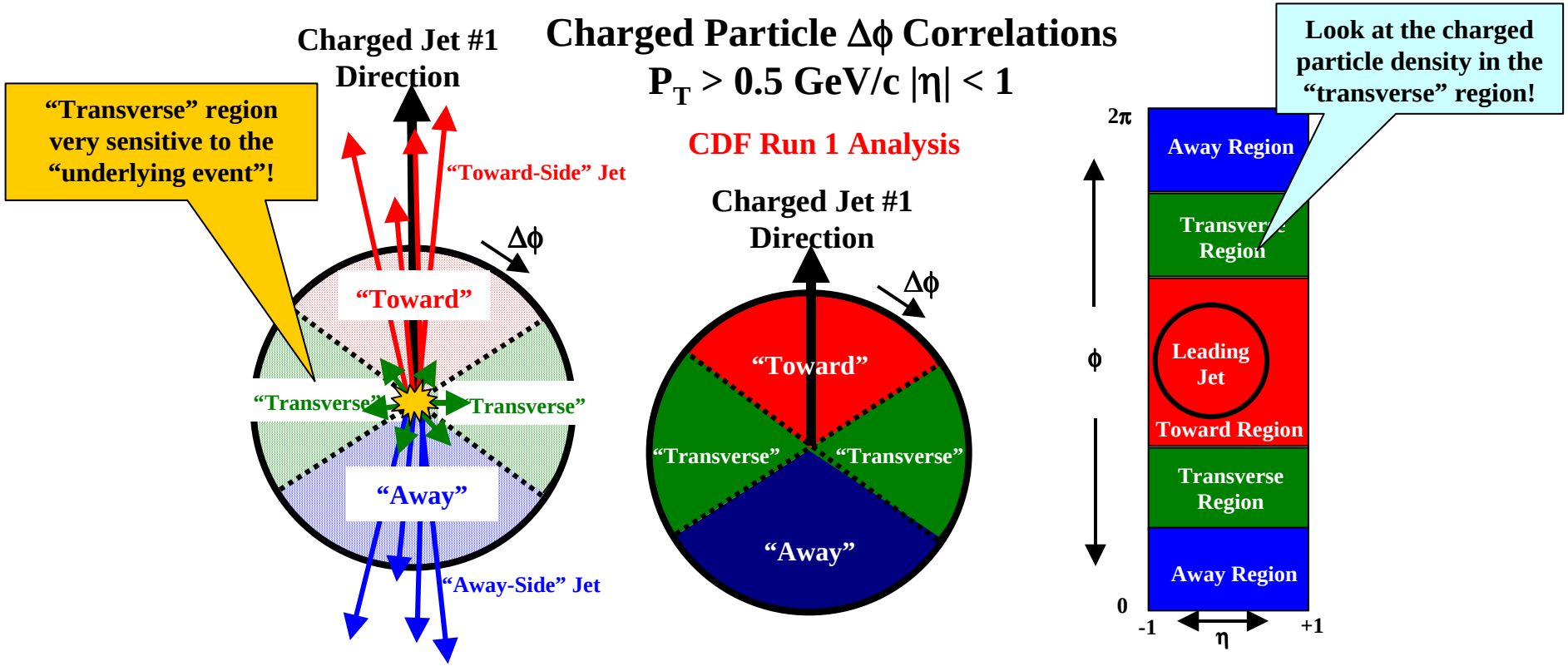
QCD Monte-Carlo Models: High Transverse Momentum Jets



- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scatter[illegible]g and add initial and final-state gluon radiation (in the leading log approximation or modified leadin[illegible] approximation).
- The "underlying event" consists of the "beam-beam remnants" and [illegible] articles arising from soft or semi-soft multiple parton interactions (MPI).
- Of course the outgoing colored parton[illegible]bly "underlying event" observables receive contributions fron[illegible]

The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

CDF Run 1: Evolution of Charged Jets "Underlying Event"



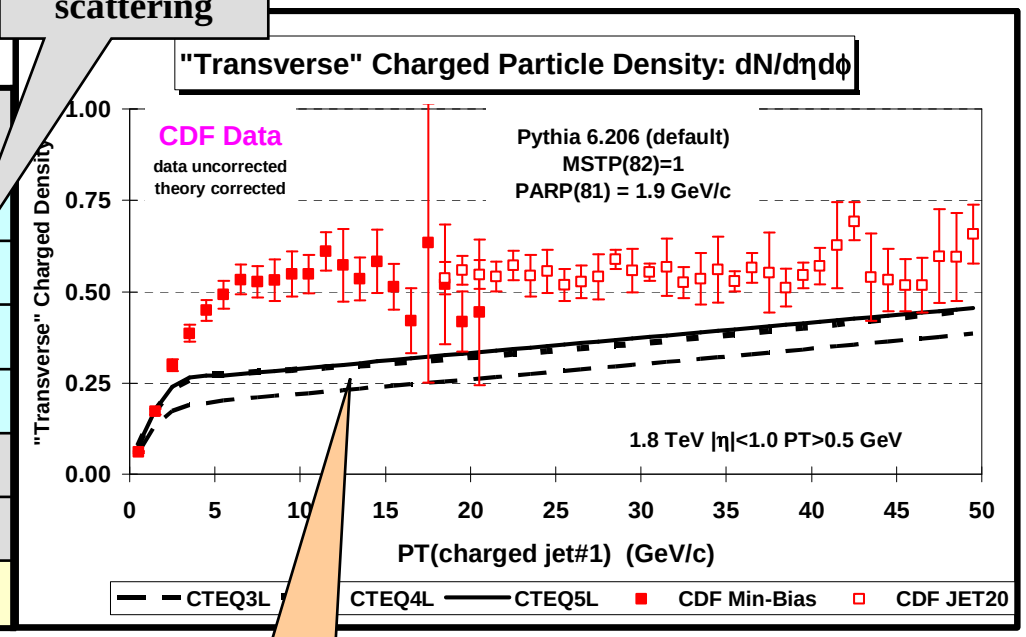
- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same size in η-ϕ space, $\Delta\eta x \Delta\phi = 2x120^o = 4\pi/3$.

PYTHIA 6.206 Defaults

PYTHIA default parameters

Parameter	6.115	6.125	6.158	6.206
MSTP(81)	1	1	1	1
MSTP(82)	1	1	1	1
PARP(81)	1.4	1.9	1.9	1.9
PARP(82)	1.55	2.1	2.1	1.9
PARP(89)		1,000	1,000	1,000
PARP(90)		0.16	0.16	0.16
PARP(67)	4.0	4.0	1.0	1.0

MPI constant probability scattering



➡ **Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.206 (P_T(hard) > 0) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.**

Note Change
PARP(67) = 4.0 (< 6.138)
PARP(67) = 1.0 (> 6.138)

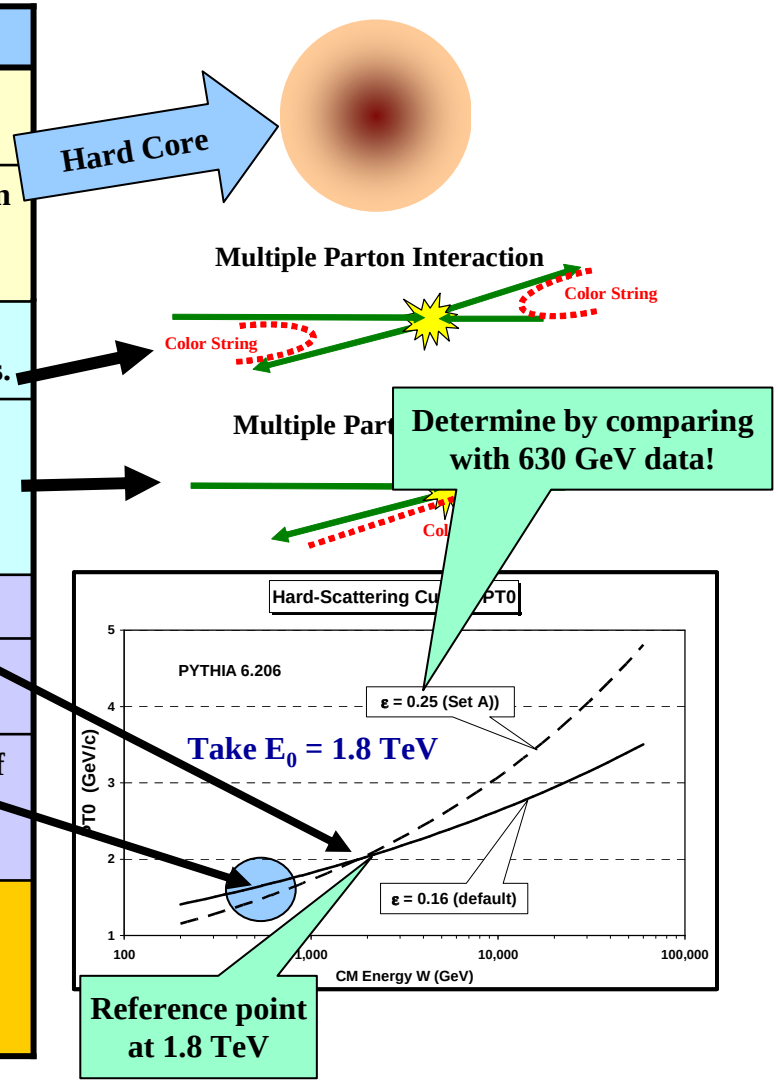
Default parameters give very poor description of the "underlying event"!

Tuning PYTHIA:
Multiple Parton Interaction Parameters

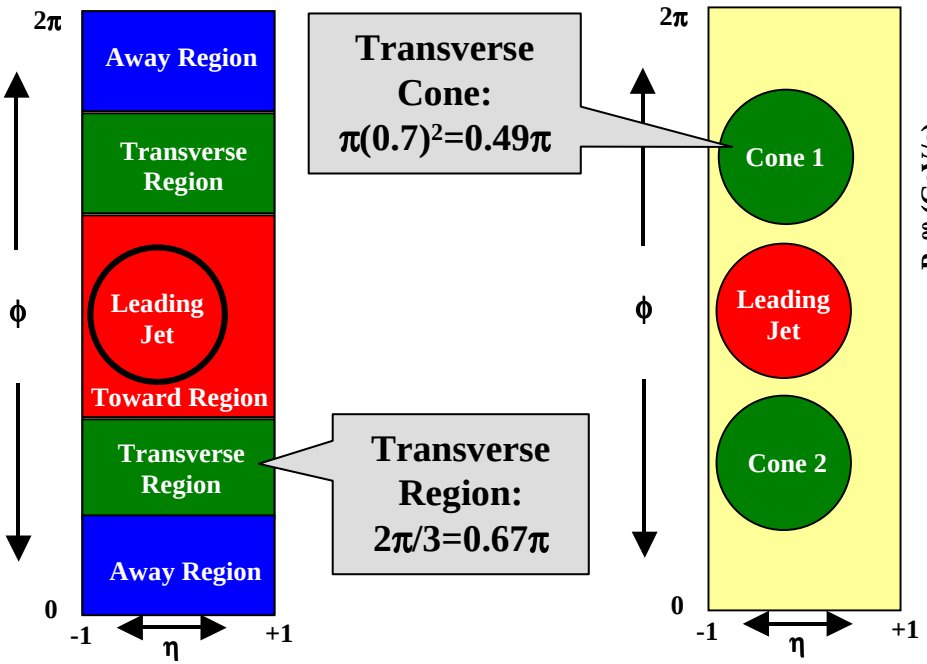
Parameter	Default	Description
PARP(83)	0.5	Double-Gaussian: Fraction of total hadronic matter within PARP(84)
PARP(84)	0.2	Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter
PARP(85)	0.33	Pr[illegible] uces two gluons w[illegible] nearest neighbors.
PARP(86)	0.66	Prob[illegible] luons eit[illegible] s des[illegible] closed [illegible] loop. [illegible] ists of [illegible]ark-antiqua[illegible]s.
PARP(89)	1 Te[illegible]	Determin[illegible] reference energy E_0.
PARP(82)	[illegible].9 GeV/c	The c[illegible]off P_{T0} that regulates the 2-to-2 sc[illegible]ring divergence $1/PT^4 \rightarrow 1/(PT^2+P_{T0}^2)^2$
PARP(90)	0.16	Determines the energy dependence of the cut-off P_{T0} as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{\varepsilon}$ with ε = PARP(90)
PARP(67)	1.0	A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

Determines the energy dependence of the MPI!

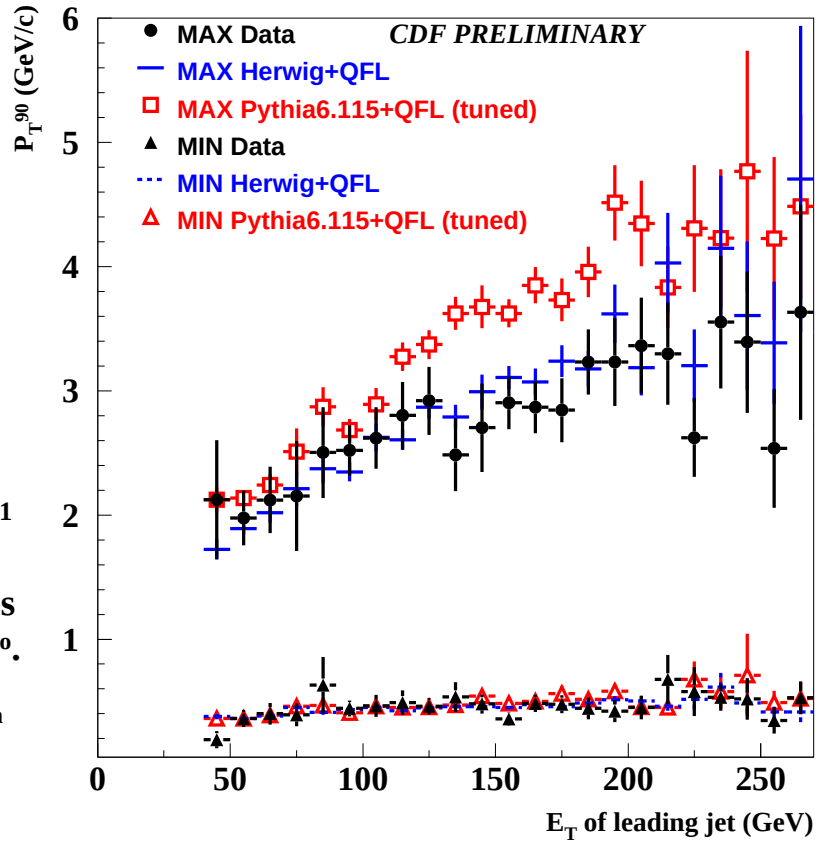
Affects the amount of initial-state radiation!



"Transverse" Cones vs "Transverse" Regions

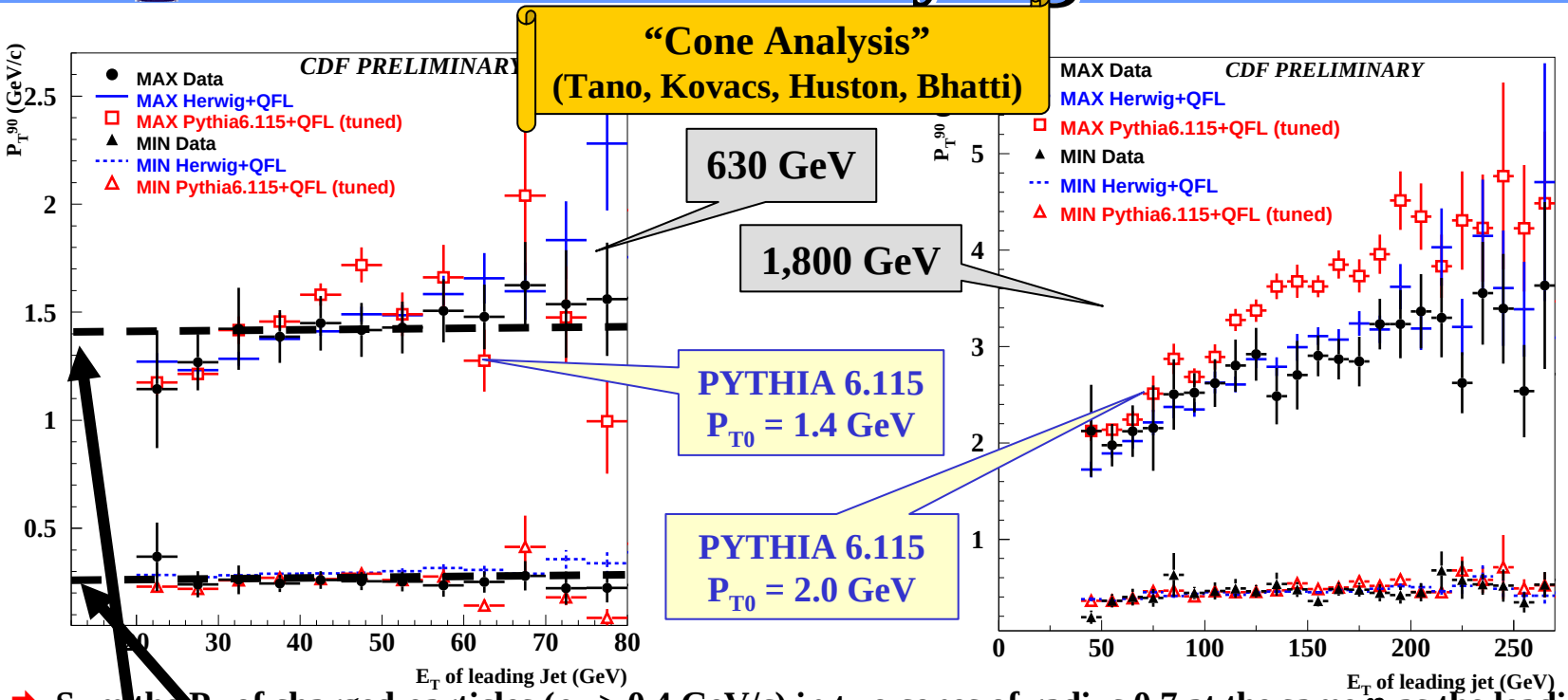


"Cone Analysis"
(Tano, Kovacs, Huston, Bhatti)



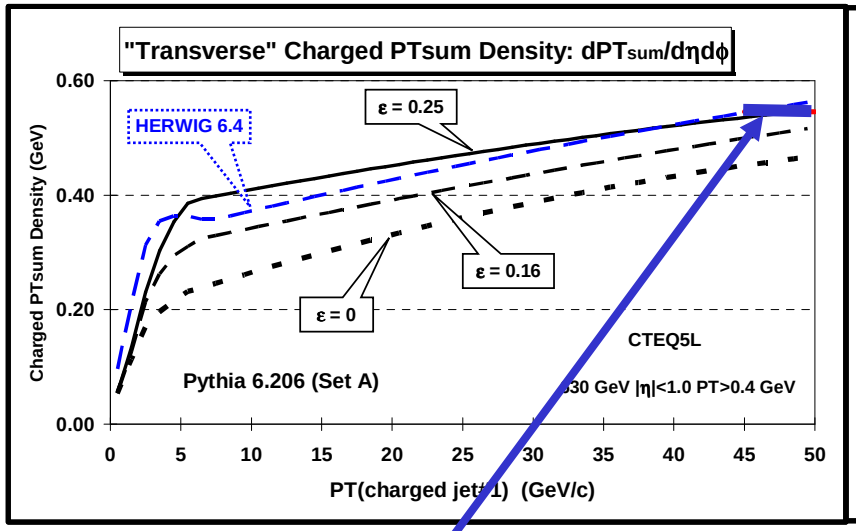
- Sum the P_T of charged particles in two cones of radius 0.7 at the same η as the leading jet but with $|\Delta\Phi| = 90^o$.
- Plot the cone with the maximum and minimum PT_{sum} versus the E_T of the leading (calorimeter) jet.

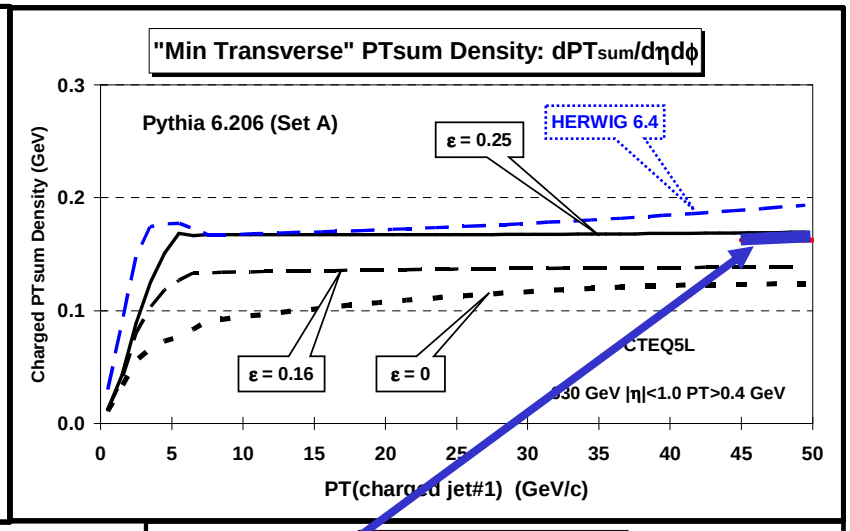
Energy Dependence of the "Underlying Event"



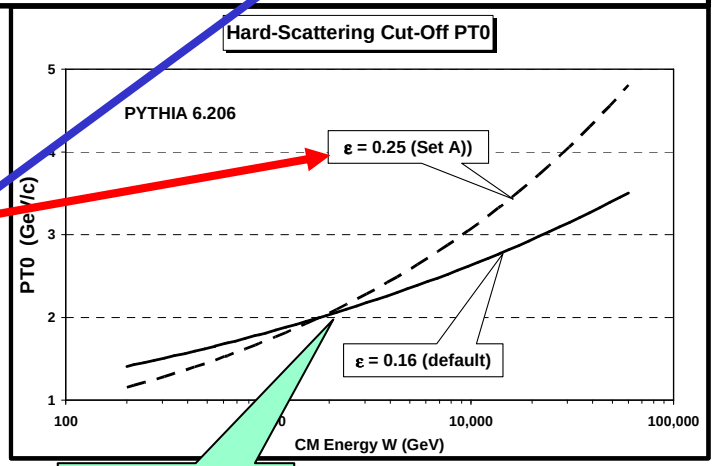
- Sum the P_T of charged particles (p_T > 0.4 GeV/c) in two cones of radius 0.7 at the same η as the leading jet but with $|\Delta\Phi| = 90^o$. Plot the cone with the maximum and minimum PT_{sum} versus the E_T of the leading (calorimeter) jet.
- Note that PYTHIA 6.115 is tuned at 630 GeV with P_{T0} = 1.4 GeV and at 1,800 GeV with P_{T0} = 2.0 GeV. This implies that a = PARP(90) should be around 0.30 instead of the 0.16 (default).
- For the MIN cone 0.25 GeV/c in radius R = 0.7 implies a PT_{sum} density of $dPT_{sum}/d\eta d\phi$ = 0.16 GeV/c and 1.4 GeV/c in the MAX cone implies $dPT_{sum}/d\eta d\phi$ = 0.91 GeV/c (average PT_{sum} density of 0.54 GeV/c per unit η-ϕ).

"Transverse" Charged Densities
Energy Dependence





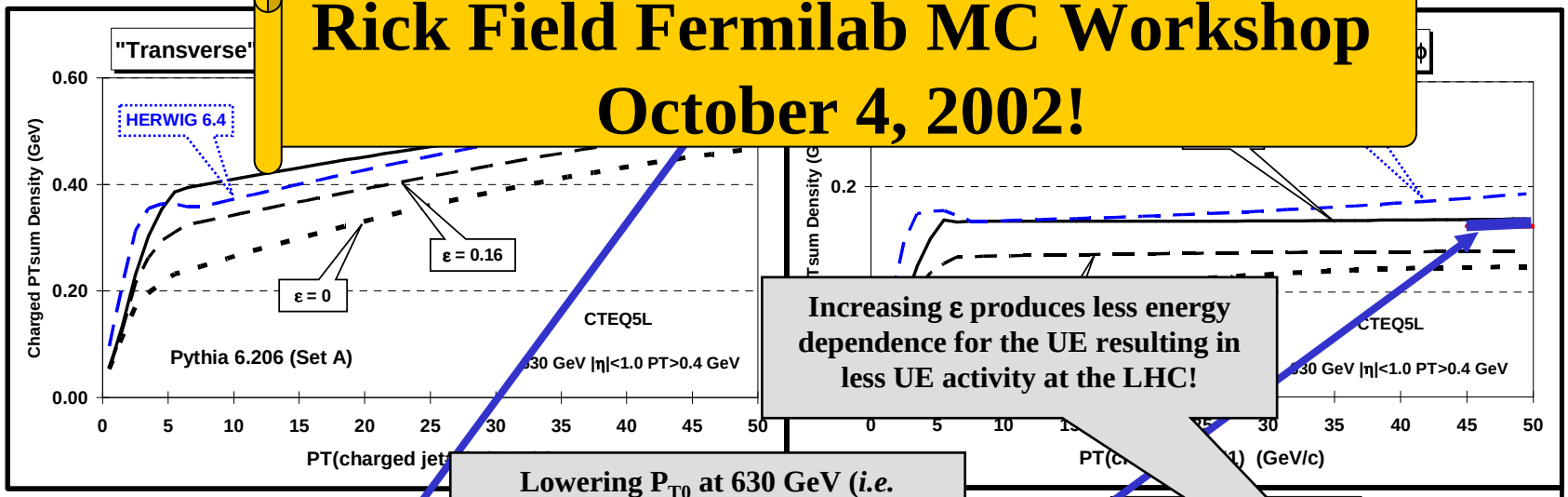
- Shows the "transverse" charged PT_{sum} density ($|\eta|<1$, $P_T>0.4$ GeV) versus P_T(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).
- Also shown are the PT_{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti "transverse" cone analysis at 630 GeV.



Reference point
E_0 = 1.8 TeV

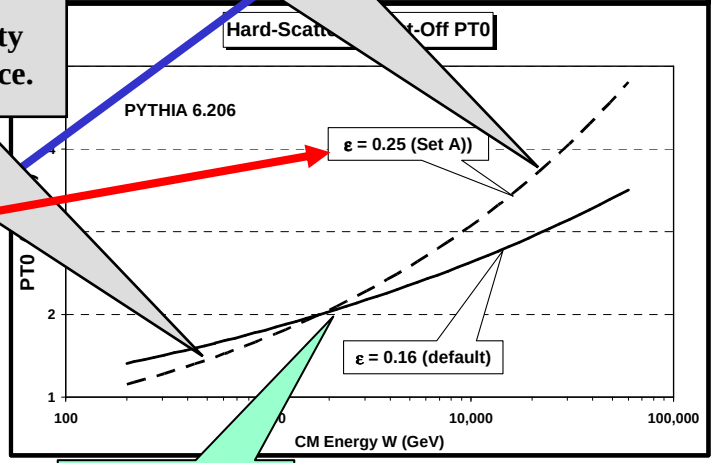
"Transverse" Charged Densities
Energy Dependence

Rick Field Fermilab MC Workshop
October 4, 2002!



Increasing ε produces less energy dependence for the UE resulting in less UE activity at the LHC!

Lowering P_{T0} at 630 GeV (*i.e.* increasing ε) increases UE activity resulting in less energy dependence.



Reference point E_0 = 1.8 TeV

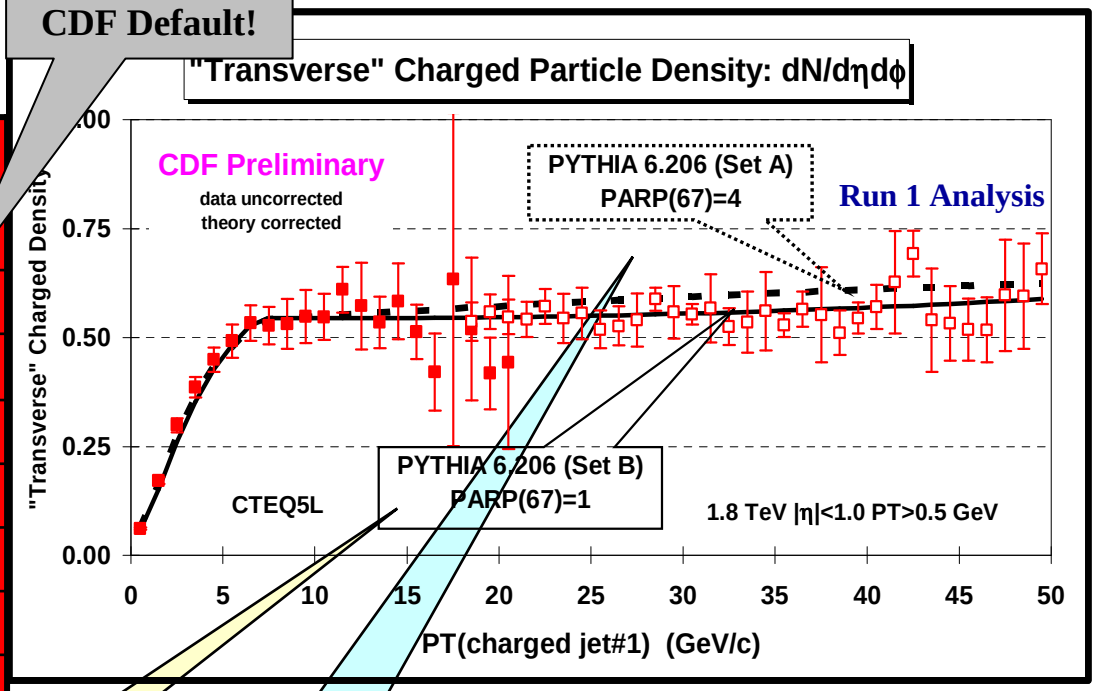
- Shows the "transverse" ch
  (|η|<1, P_T>0.4 GeV) versus
  GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).
- Also shown are the PT_{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti "transverse" cone analysis at 630 GeV.

Run 1 PYTHIA Tune A

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0

CDF Default!



➡ **Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

CDF Run 1 $P_T(Z)$

PYTHIA 6.2 CTEQ5L

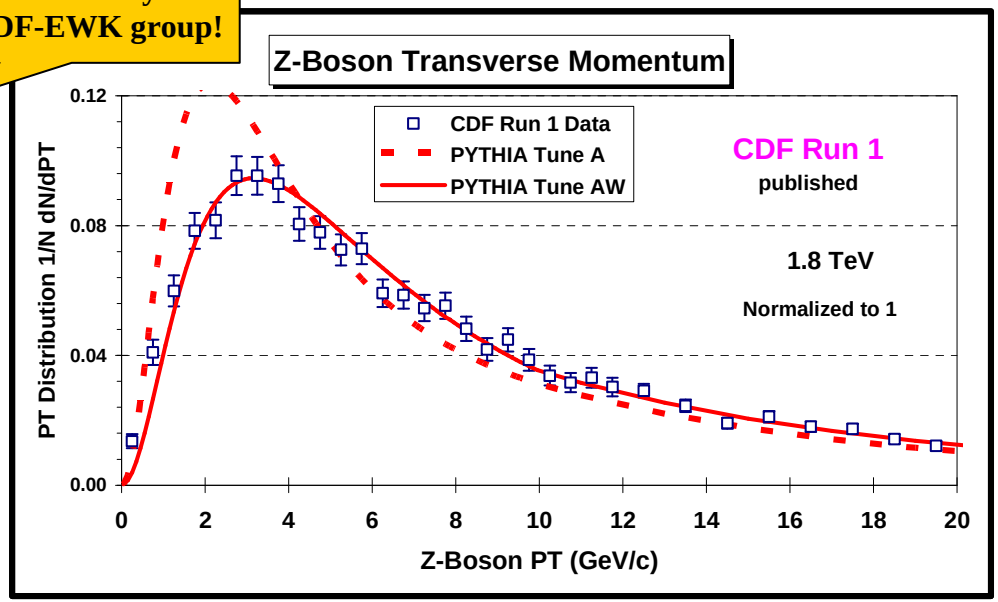
Tune used by the CDF-EWK group!

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

UE Parameters

ISR Parameters

Intrensic KT



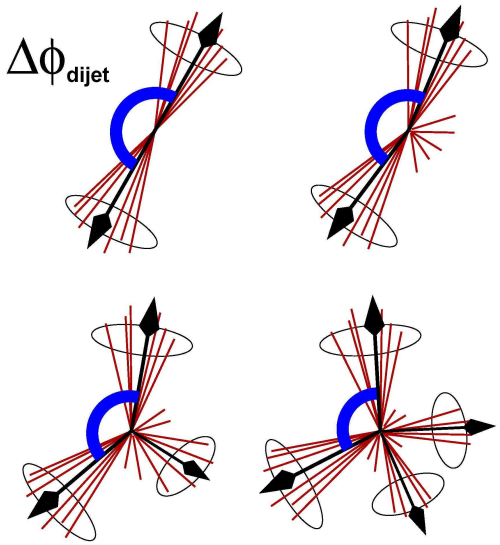
➡ **Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune A ($\langle p_T(Z)\rangle = 9.7$ GeV/c), and PYTHIA Tune AW ($\langle p_T(Z)\rangle = 11.7$ GeV/c).**

Effective Q cut-off, below which space-like showers are not evolved.

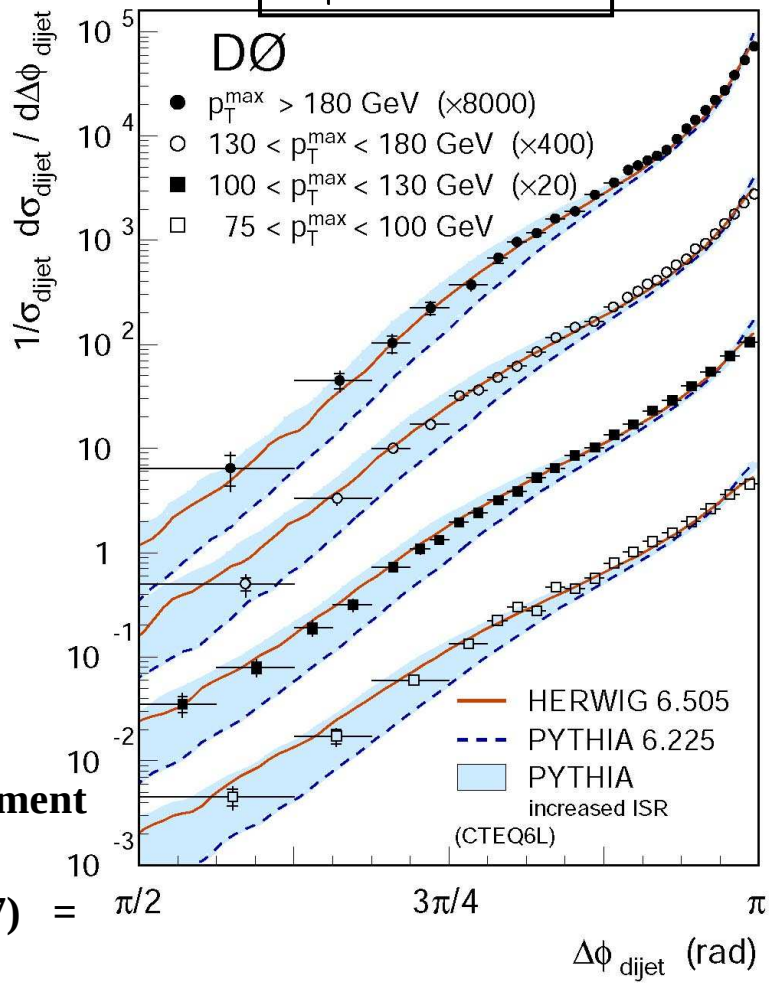
The $Q^2 = k_T^2$ in α_s for space-like showers is scaled by PARP(64)!

Jet-Jet Correlations (DØ)

Jet#1-Jet#2 Δϕ Distribution



Δϕ Jet#1-Jet#2



- **MidPoint Cone Algorithm (R = 0.7, f_{merge} = 0.5)**
- **$\mathcal{L}$ = 150 pb^{-1} (Phys. Rev. Lett. 94 221801 (2005))**
- **Data/NLO agreement good. Data/HERWIG agreement good.**
- **Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A, best fit 2.5).**

CDF Run 1 $P_T(Z)$

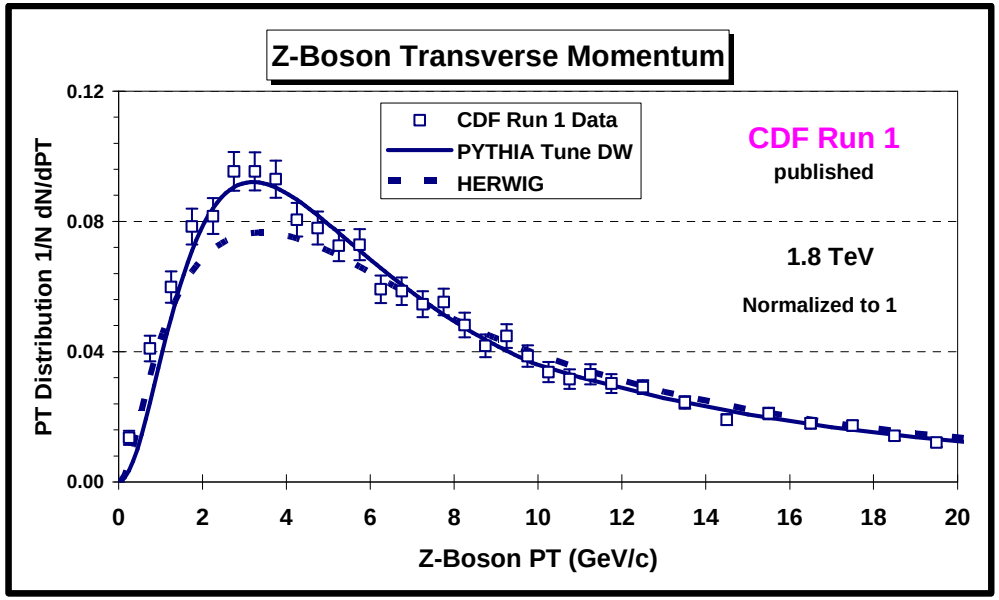
PYTHIA 6.2 CTEQ5L

Parameter	Tune DW	Tune AW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.25	1.25
PARP(64)	0.2	0.2
PARP(67)	2.5	4.0
MSTP(91)	1	1
PARP(91)	2.1	2.1
PARP(93)	15.0	[illegible]

UE Parameters

ISR Parameters

Intrensic KT



➡ **Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune DW, and HERWIG.**

Tune DW uses D0's perfered value of PARP(67)!

Tune DW has a lower value of PARP(67) and slightly more MPI!

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

ISR Parameter

Intrinsic KT

Parameter	Tune AW	Tune DW	Tune D6
PDF	CTEQ5L	CTEQ5L	CTEQ6L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	2.0 GeV	1.9 GeV	1.8 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	1.8 TeV
PARP(90)	0.25	0.25	0.25
PARP(62)	1.25	1.25	1.25
PARP(64)	0.2	0.2	0.2
PARP(67)	4.0	2.5	2.5
MSTP(91)	1	1	1
PARP(91)	2.1	2.1	2.1
PARP(93)	15.0	15.0	15.0

Uses CTEQ6L

Tune A energy dependence!

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

ISR Parameter

Intrinsic KT

ATLAS energy dependence!

Parameter	Tune DWT	Tune D6T	ATLAS
PDF	CTEQ5L	CTEQ6L	CTEQ5L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	1.9409 GeV	1.8387 GeV	1.8 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.5
PARP(85)	1.0	1.0	0.33
PARP(86)	1.0	1.0	0.66
PARP(89)	1.96 TeV	1.96 TeV	1.0 TeV
PARP(90)	0.16	0.16	0.16
PARP(62)	1.25	1.25	1.0
PARP(64)	0.2	0.2	1.0
PARP(67)	2.5	2.5	1.0
MSTP(91)	1	1	1
PARP(91)	2.1	2.1	1.0
PARP(93)	15.0	15.0	5.0

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

Parameter	Tune DWT	Tune D6T	ATLAS
PDF	CTEQ5L	CTEQ6L	CTEQ5L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP( )	1.9409 GeV	1.8387 GeV	1.8 GeV
	0.5		0.5
	0.4		.5
	1.0		.33
	1.0	1.	66
PARP(9)	1.96 TeV	1.96 TeV	1.0 TeV
PARP(90)	0.16	0.16	0.16
PARP(62)	1.25	1.25	1.0
PARP(64)	0.7	0.2	1.0
PARP(6		2.5	1.0
MSTP(91)		1	
PARP(9		2.1	
PARP( )		15.0	

Tune A

Tune AW

Tune B

Tune BW

Tune D

Tune DW

Tune D6

Tune D6T
CMS

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

Parameter	Tune	WT	Tune D6T
PDF	CT		CTEQ6L
MSTP(81)			1
(82)			4
PARP(			
MSTI			
PAR			2.
PA			15.0

Tune A

Tune D

Tune D6

Tune D6T
CMS

These are "old" PYTHIA 6.2 tunes!

There are new 6.420 tunes by
Peter Skands (Tune S320, update of S0)
Peter Skands (Tune N324, N0CR)
Hendrik Hoeth (Tune P329, "Professor")

Peter's Pythia Tunes WEBsite

Peter's Pythia Plots

February 2009 © P. Z. Skands

Navigate these pages by using the menu to the left. More plots will be added, as new tunes become available, and as the available data increases. The default for each topic is a comparison of a small number of tunes to available data (or just to each other if no data exists), but look for links at the top of each page for comparisons with more models.

Apr 2009: Full descriptions and parameters of the "Perugia" tunes (submitted to the Perugia MPI workshop proceedings)
Dec 2007: Some interesting min-bias distributions for early LHC runs (submitted to the 2007 Les Houches workshop proceedings)

The tunes currently available on the plots are (numbered as in PYTUNE):

Tunes using Q2-ordered model

- 100: **A**: Rick Field's Tune A to Tevatron Underlying-Event Data. Uses the "old" UE and shower models, with a double-gaussian matter profile, 1 GeV of primordial kT, and near-maximal color correlations. [Oct 2002]
- 103: **DW**: Rick Field's Tune DW to Tevatron Underlying-Event and Drell-Yan Data. Similar to Tune A, but has 2 GeV of primordial kT and uses a very small renormalization scale for initial-state radiation (i.e., more ISR radiation). It also has completely maximal color correlations. [Apr 2006]
- 104: **DWT**: Variant of DW using the Pythia 6.2 default collider energy scaling (has worse agreement with Tevatron energy scaling quantities than DW). [Apr 2006]
- 106: **ATLAS-DC2** ("Rome"): first ATLAS tune of the Q2-ordered showers and old UE framework. Does not give very good agreement with Tevatron min-bias quantities.
- 107: **A-CR**: variant of Tune A using the Pythia 6.2 default color connections but with the new "color annealing" color reconnection model applied as an afterburner. Is intended as an example of strong color reconnections. [Mar 2007]
- 108: **D6**: Rick Field's Tune D6 to Tevatron data, using CTEQ6L1 PDFs.
- 110: **A-Pro**: Tune A with LEP tune from Professor. [Oct 2008]
- 113: **DW-Pro**: Tune DW with LEP tune from Professor. [Oct 2008]
- 114: **DWT-Pro**: Tune DWT with LEP tune from Professor. [Oct 2008]
- 116: **ATLAS-DC2-Pro**: ATLAS-DC2 with LEP tune from Professor. [Oct 2008]
- 117: **A-CR-Pro**: Tune A-CR with LEP tune from Professor. [Oct 2008]
- 118: **D6-Pro**: Tune D6 with LEP tune from Professor. [Oct 2008]
- 129: **Pro-Q20**: Tune of the Q2-ordered showers and old UE framework made with Professor, an automated tuning tool. [Feb 2009]

Tunes intermediate between Q2- and pT-ordered models

- 201: **A-PT**: Retune of Tune A with pT-ordered final-state showers. [Mar 2007]
- 211: **A-PT-Pro**: Tune A-PT with LEP tune from Professor. [Oct 2008]
- 221: **Perugia A-PT**: "Perugia" update of A-PT-Pro. [Feb 2009]
- 226: **Perugia A6-PT**: "Perugia" update of A-PT-Pro, using CTEQ6L1 PDFs. [Feb 2009]

Tunes using pT-ordered model

- 300: **S0**: First Sandhoff-Skands Tune of the "new" UE and shower framework, with a smoother matter profile than Tune A, 2 GeV of primordial kT, and "colour annealing" color reconnections. Uses the default Pythia energy scaling rather than that of Tune A. [Apr 2006]
- 303: **S0A**: A variant of S0 which is identical to S0 at the Tevatron, but which uses the Tune A energy scaling of the UE activity. [Apr 2006]
- 304: **NOCR**: Sandhoff-Skands "best try" without color reconnections. Gives less good agreement with Tevatron data. [Apr 2006]
- 306: **ATLAS-CSC**: first ATLAS tune of the pT-ordered showers and new UE framework. Does not give very good agreement with Tevatron min-bias quantities.
- 313: **S0A-Pro**: A variant of S0A revamped with a comprehensive retune of the fragmentation parameters to LEP data (by the "Professor" tool, hence the name). [Oct 2008]
- 314: **NOCR-Pro**: NOCR with LEP tune from Professor. [Oct 2008]
- 320: **Perugia 0**: "Perugia" update of S0-Pro. [Feb 2009]
- 321: **Perugia HARD**: Systematically "hard" variant of Perugia 0. [Feb 2009]
- 322: **Perugia SOFT**: Systematically "soft" variant of Perugia 0. [Feb 2009]
- 323: **Perugia 3**: Variant of Perugia 0 with different ISR/MPI balance and different collider energy scaling. [Feb 2009]
- 324: **Perugia NOCR**: "Perugia" update of NOCR-Pro. [Feb 2009]
- 325: **Perugia X**: Variant of Perugia 0 using MRST LO* PDFs. [Feb 2009]
- 326: **Perugia 6**: Variant of Perugia 0 using CTEQ6L1 PDFs. [Feb 2009]
- 329: **Pro-pT0**: Tune of the pT-ordered showers and new UE framework made with Professor, an automated tuning tool. [Feb 2009]

➡ **http://home.fnal.gov/~skands/leshouches-plots/**

Peter's Pythia Tunes WEBsite

Peter's Pyth

February 2009 © P

Navigate these pages by using the menu to the lef
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Tunes using Q2-ordered model

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- 114: **DWT-Pro**: Tune DWT with LEP tune from
- 116: **ATLAS-DC2-Pro**: ATLAS-DC2 with LEP t

Parameter	Type	S0A-Pro	P-0	P-HARD	P-SOFT	P-3	P-NOCR	P-X	P-6
MSTP(51)	PDF	7	7	7	7	7	7	20650	10042
MSTP(52)	PDF	1	1	1	1	1	1	2	2
MSTP(64)	ISR	2	3	3	2	3	3	3	3
PARP(64)	ISR	1.0	1.0	0.25	2.0	1.0	1.0	2.0	1.0
MSTP(67)	ISR	2	2	2	2	2	2	2	2
PARP(67)	ISR	4.0	1.0	4.0	0.5	1.0	1.0	1.0	1.0
MSTP(70)	ISR	2	2	0	1	0	2	2	2
PARP(62)	ISR	-	-	1.25	-	1.25	-	-	-
PARP(81)	ISR	-	-	-	1.5	-	-	-	-
MSTP(72)	ISR	0	1	1	0	2	1	1	1
PARP(71)	FSR	4.0	2.0	4.0	1.0	2.0	2.0	2.0	2.0
PARJ(81)	FSR	0.257	0.257	0.3	0.2	0.257	0.257	0.257	0.257
PARJ(82)	FSR	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
MSTP(81)	UE	21	21	21	21	21	21	21	21
PARP(82)	UE	1.85	2.0	2.3	1.9	2.2	1.95	2.2	1.95
PARP(89)	UE	1800	1800	1800	1800	1800	1800	1800	1800
PARP(90)	UE	0.25	0.26	0.30	0.24	0.32	0.24	0.23	0.22
MSTP(82)	UE	5	5	5	5	5	5	5	5
PARP(83)	UE	1.6	1.7	1.7	1.5	1.7	1.8	1.7	1.7
MSTP(88)	BR	0	0	0	0	0	0	0	0
PARP(79)	BR	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
PARP(80)	BR	0.01	0.05	0.01	0.05	0.03	0.01	0.05	0.05
MSTP(91)	BR	1	1	1	1	1	1	1	1
PARP(91)	BR	2.0	2.0	1.0	2.0	1.5	2.0	2.0	2.0
PARP(93)	BR	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
MSTP(95)	CR	6	6	6	6	6	6	6	6
PARP(78)	CR	0.2	0.33	0.37	0.15	0.35	0.0	0.33	0.33
PARP(77)	CR	0.0	0.9	0.4	0.5	0.6	0.0	0.9	0.9
MSTJ(11)	HAD	5	5	5	5	5	5	5	5
PARJ(21)	HAD	0.313	0.313	0.34	0.28	0.313	0.313	0.313	0.313
PARJ(41)	HAD	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
PARJ(4								1.2	1.2
PARJ(46)	HAD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PARJ(47)	HAD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

PS, Proceedings of the Perugia MPI Workshop 2008

[Oct 2008]
2008]
framework made with

pT-ordered models

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CTEQ6L1 PDFs. [Feb 2009]

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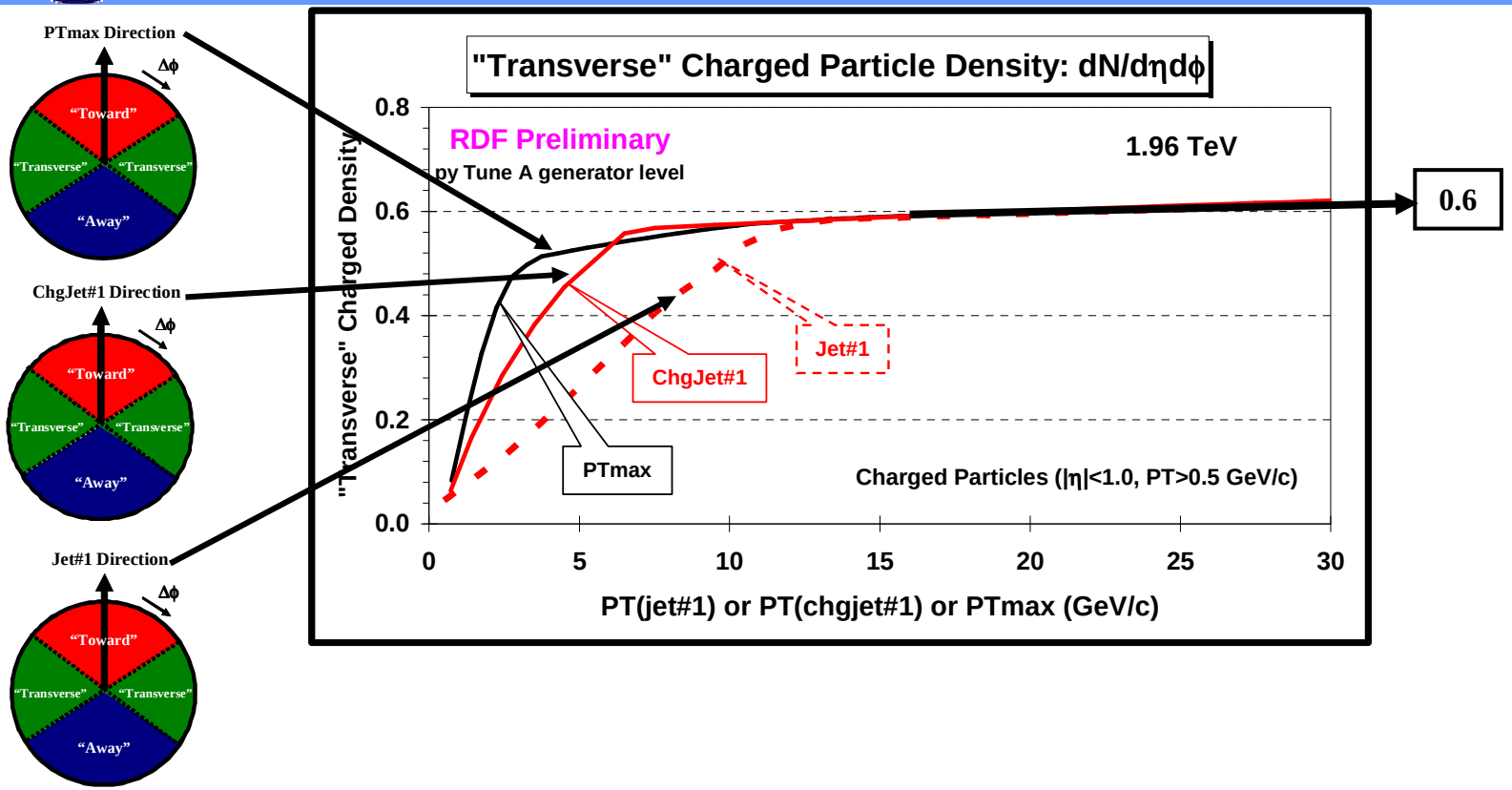
balance and different collider

2009]
s. [Feb 2009]
. [Feb 2009]
E framework made with

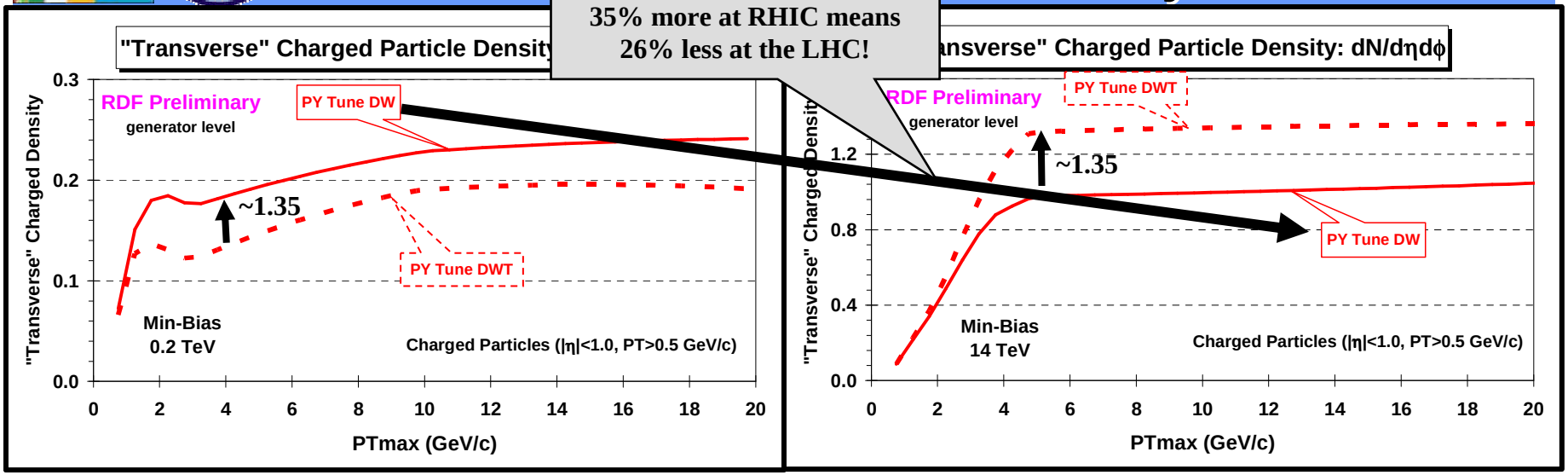
➡ **http://home.fnal.gov/~skands/leshouches-plots/**

"Transverse" Charged Density

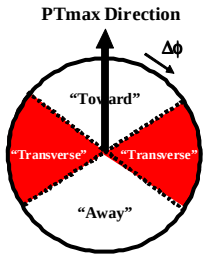


- **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 1) at 1.96 TeV as defined by PTmax, PT(chgjet#1), and PT(jet#1) from PYTHIA Tune A at the particle level (*i.e.* generator level).**

Min-Bias "Associated" Charged Particle Density

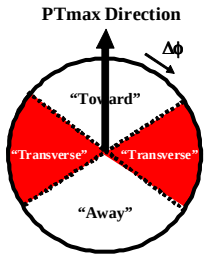


RHIC



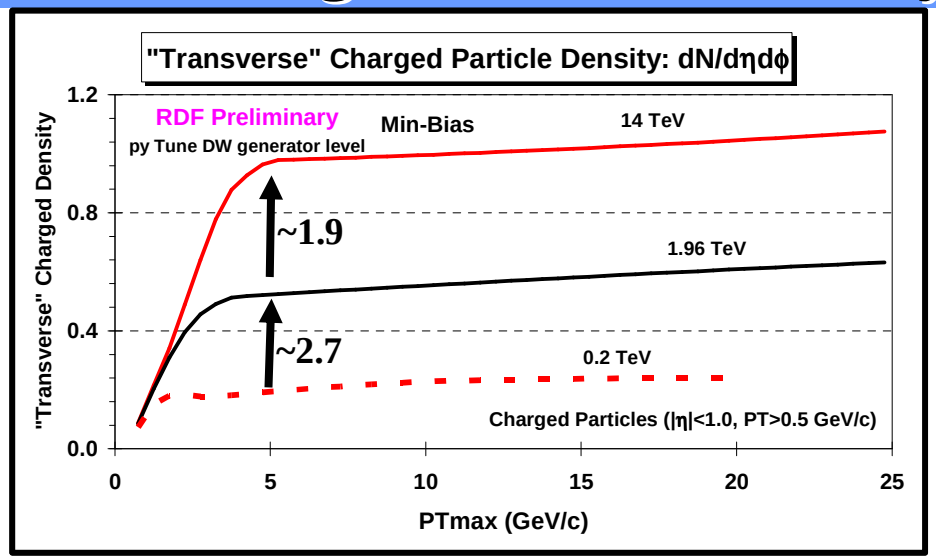
0.2 TeV → 14 TeV
(~factor of 70 increase)

LHC

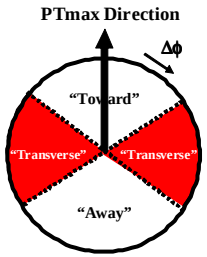


➡ **Shows the "associated" charged particle density in the "transverse" regions as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV and 14 TeV from PYTHIA Tune DW and Tune DWT at the particle level (*i.e.* generator level). The STAR data from RHIC favors Tune DW!**

Min-Bias "Associated" Charged Particle Density

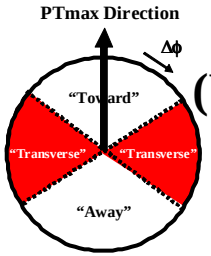


RHIC



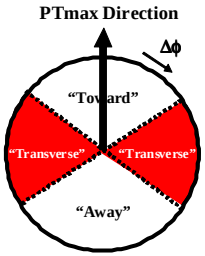
0.2 TeV → 1.96 TeV (UE increase ~2.7 times)

Tevatron



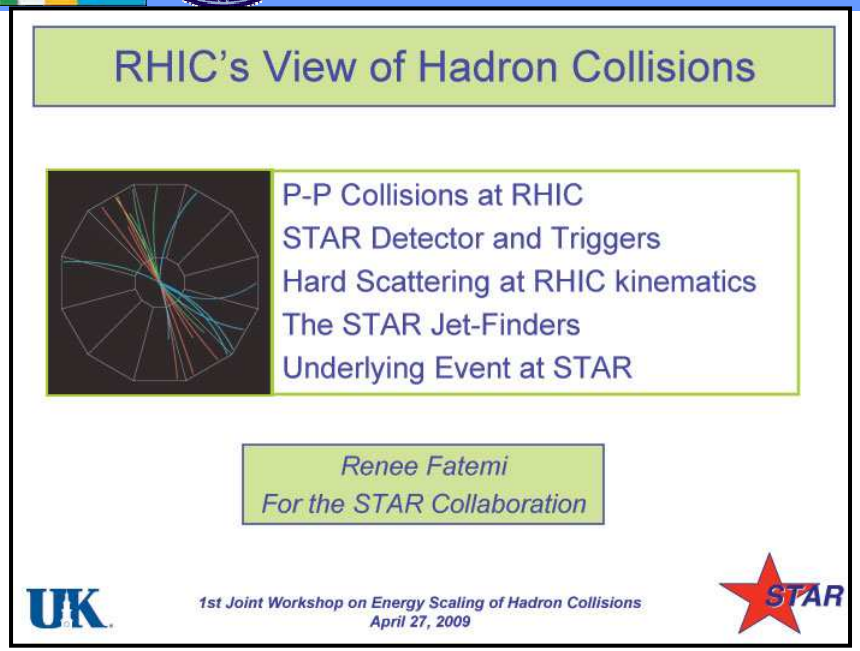
1.96 TeV → 14 TeV (UE increase ~1.9 times)

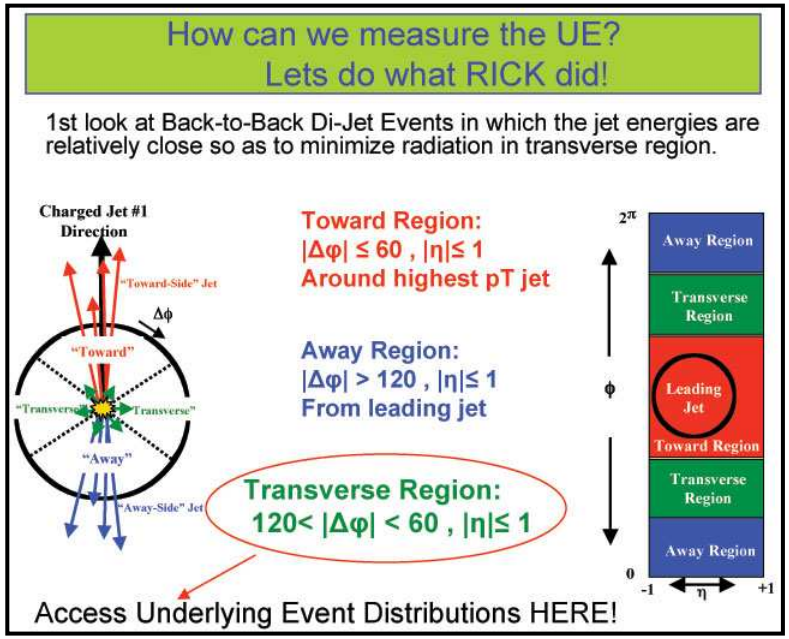
LHC



- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 1.96 TeV and 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.* generator level).**

The "Underlying Event" at STAR





➡ **At STAR they have measured the "underlying event at W = 200 GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.**

The "Underlying Event" at STAR

Conclusions

I. Hadron Collisions at RHIC take place at an order of magnitude smaller $\sqrt{s}$ than the Tevatron. Nevertheless, jets are observed and reconstructed down to pT=5 GeV and are well described by pQCD

II. Comparisons between several jetfinders reveal consistent results

III. Interest in the Underlying Event at RHIC Kinematics is driven by the need for jet energy scale corrections as well as pure physics interests (see talks by M. Lisa and H. Caines)

IV. UE at RHIC appears to be independent of jet pT and decoupled from hard interaction

V. CDF Tune A provides an excellent description of the UE at $\sqrt{s}$ =200 GeV (thanks Rick!)

VI. Underlying Event distributions in general smaller than those at CDF. Tower & Track Multiplicities are the exception, but this may be due to the 0.2 (STAR) versus 0.5 GeV (CDF) pT/Et cut-off.

VII. For a cone jet with R=0.7 UE contributes 0.5-0.9 GeV.

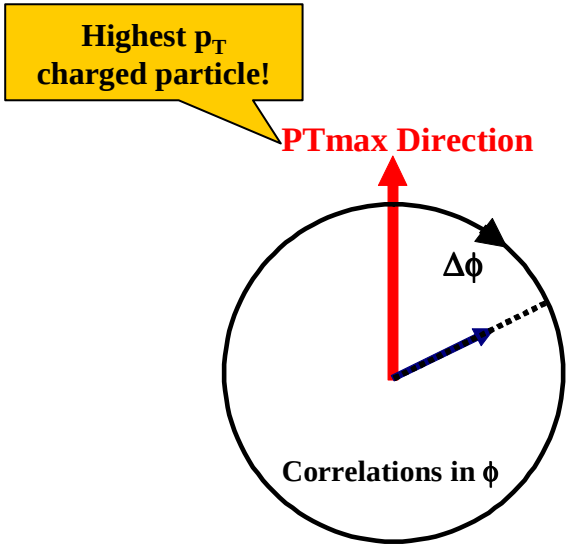
VIII. Comparison of Leading Jet and Back-to-Back distributions indicate that large angle radiation contributions are small at RHIC energies.

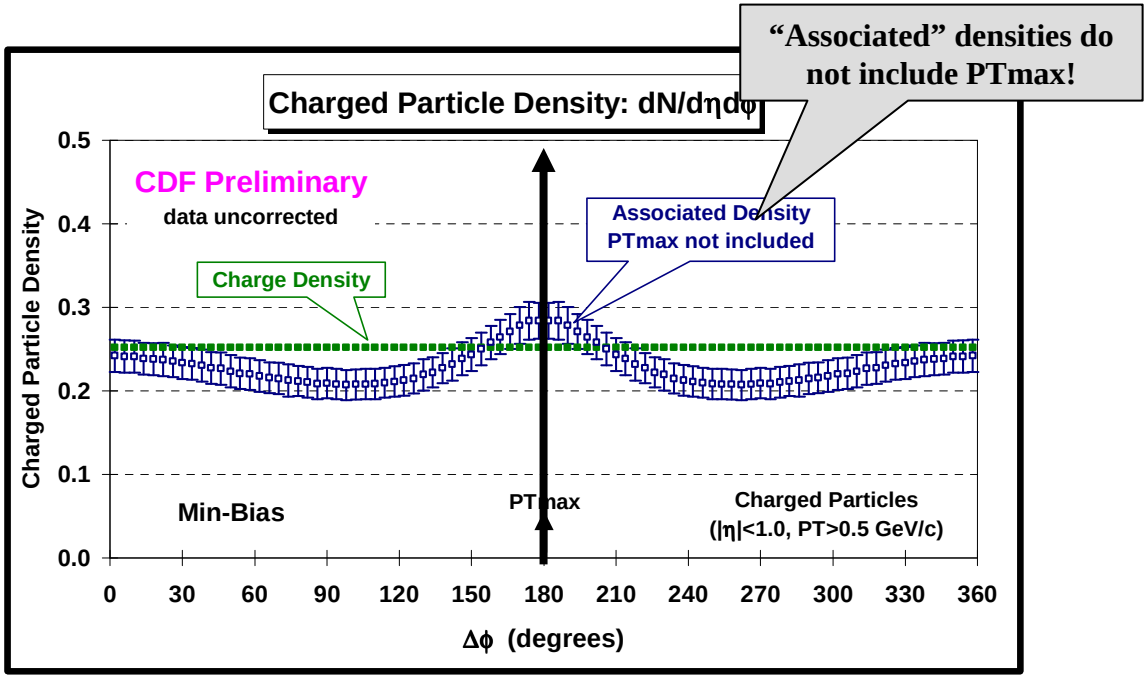
➡ **At STAR**

and comp

2 GeV)

CDF Run 1 Min-Bias "Associated" Charged Particle Density

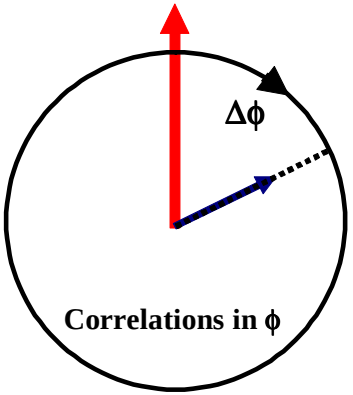




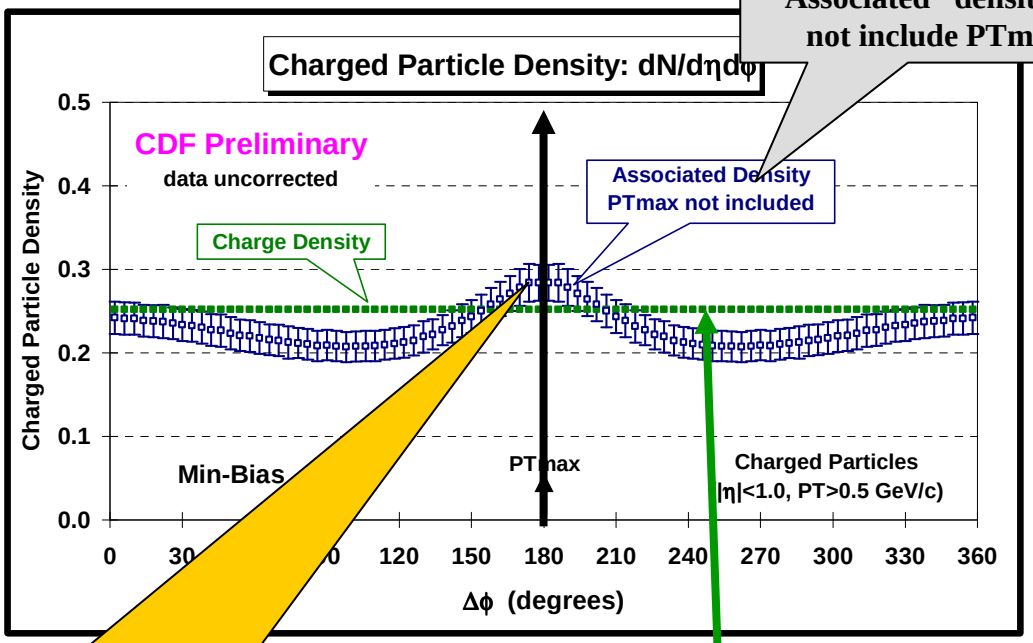
- Use the **maximum p_T charged particle in the event, PTmax**, to define a direction and look at the the "associated" density, $dN_{chg}/d\eta d\phi$, in **"min-bias" collisions** (p_T > 0.5 GeV/c, |η| < 1).
- Shows the data on the **Δϕ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for **"min-bias" events**. **Also shown is the average charged particle density, $dN_{chg}/d\eta d\phi$, for "min-bias" events**.

CDF Run 1 Min-Bias "Associated" Charged Particle Density

Highest p_T charged particle!



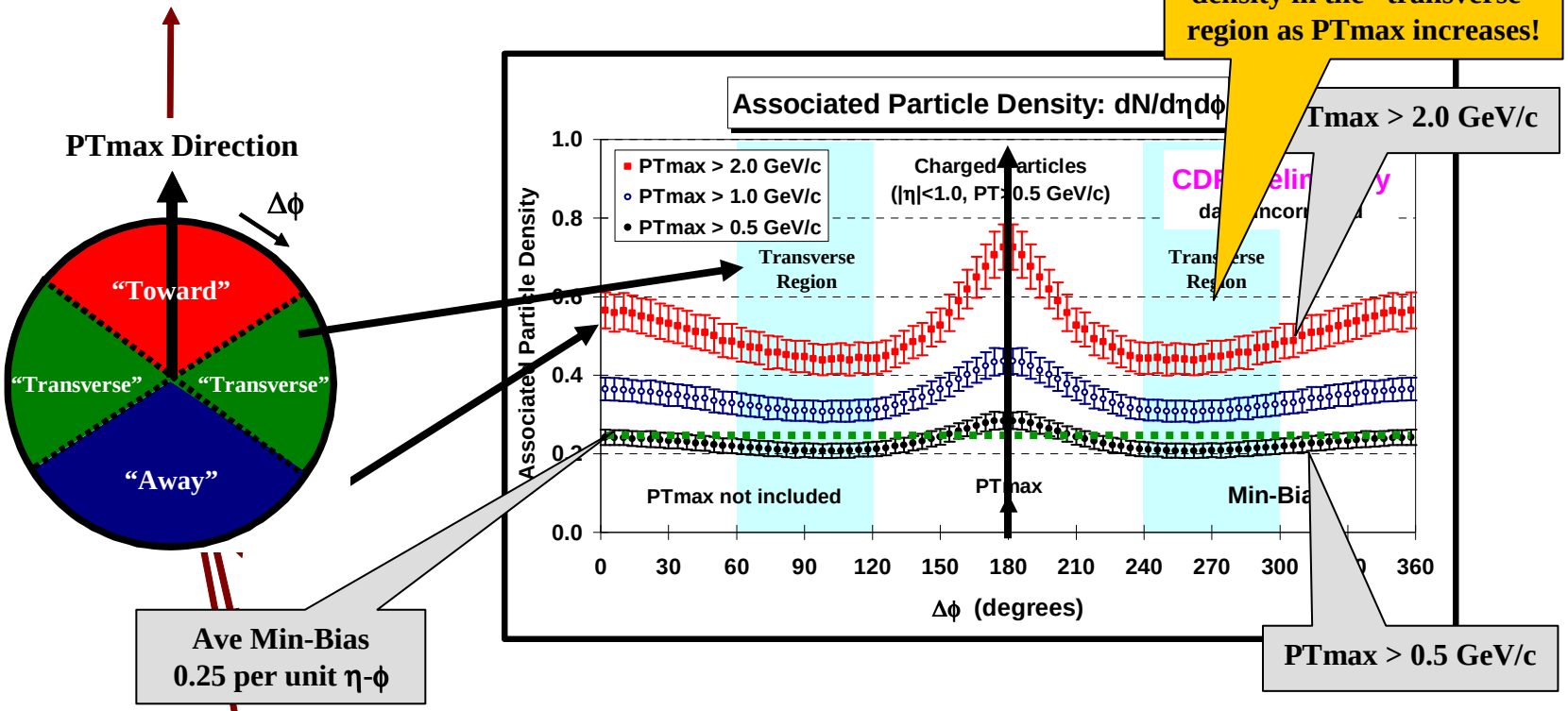
"Associated" densities do not include PTmax!



- Use the m charged par event, PTmax, to define a direction and look at the the in-bias" collisions (p_T > 0.5 GeV/c, |η| < 1).
- Shows the ciated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events. Also shown is the average charged particle density, $dN_{chg}/d\eta d\phi$, for "min-bias" events.

It is more probable to find a particle accompanying PTmax than it is to find a particle in the central region!

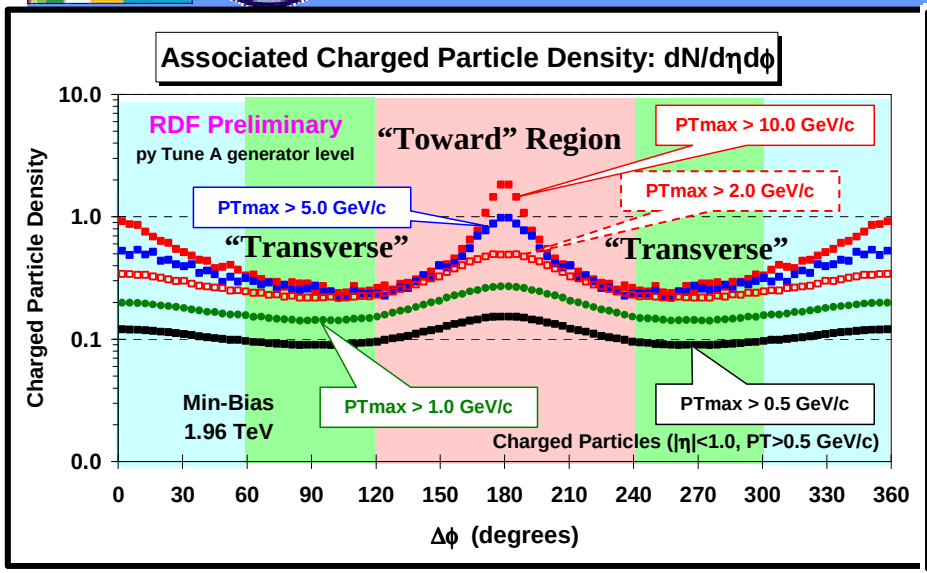
CDF Run 1 Min-Bias "Associated" Charged Particle Density

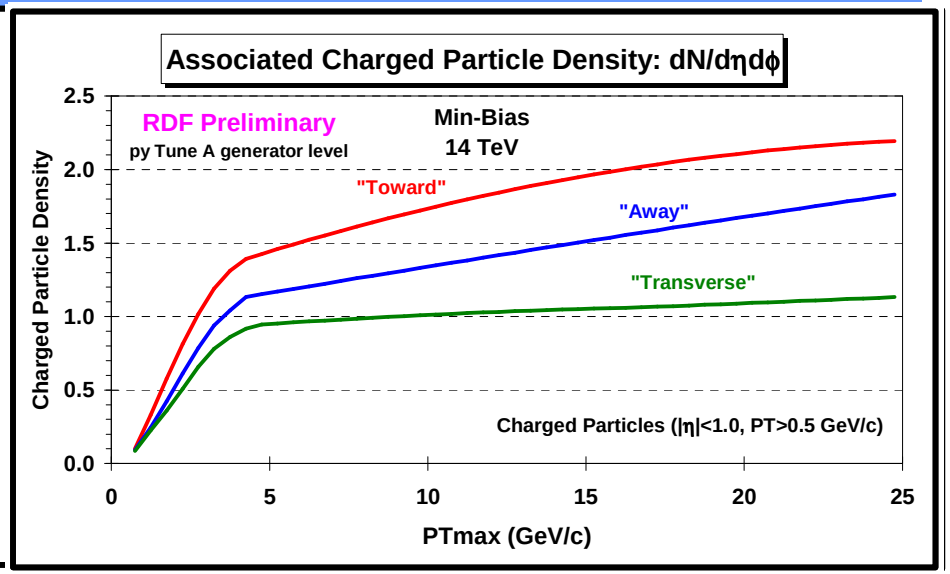


- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.

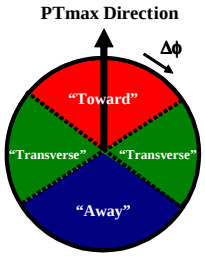
- Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).

"Associated" Charged Particle Density



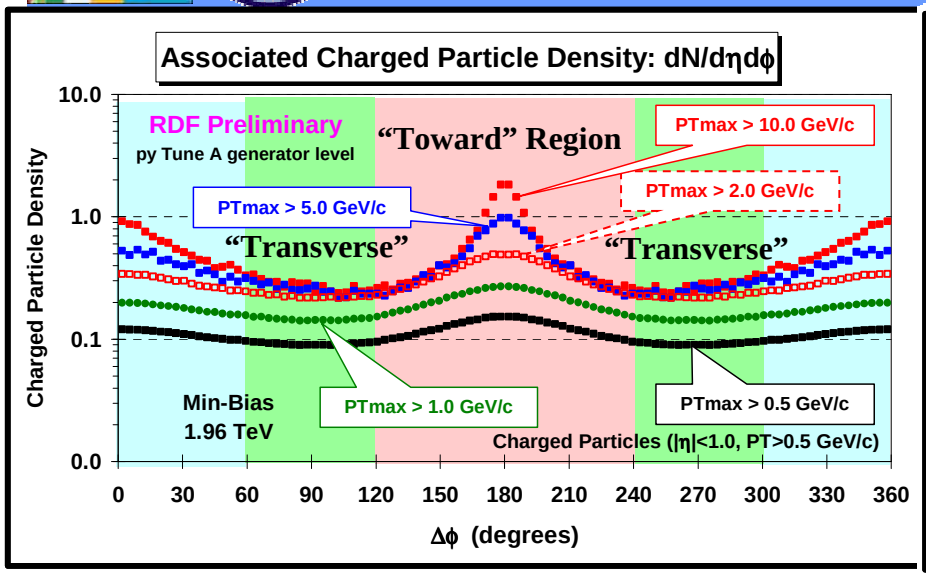


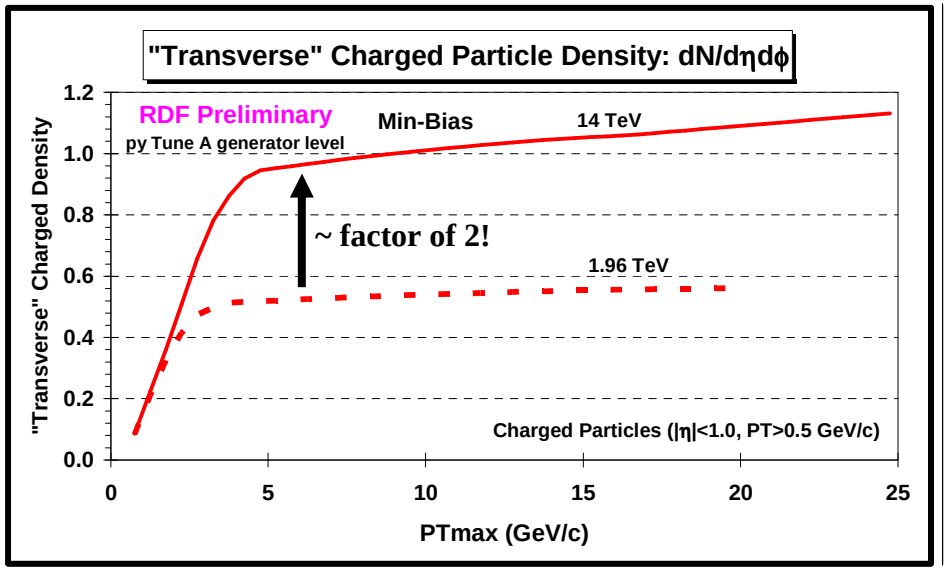
➡ **Shows the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events at 1.96 TeV with PTmax > 0.5, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune A (generator level).**



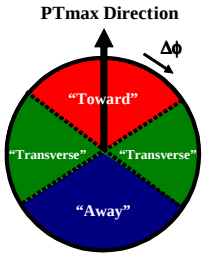
➡ **Shows the "associated" charged particle density in the "toward", "away" and "transverse" regions as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 1.96 TeV from PYTHIA Tune A (generator level).**

"Associated" Charged Particle Density



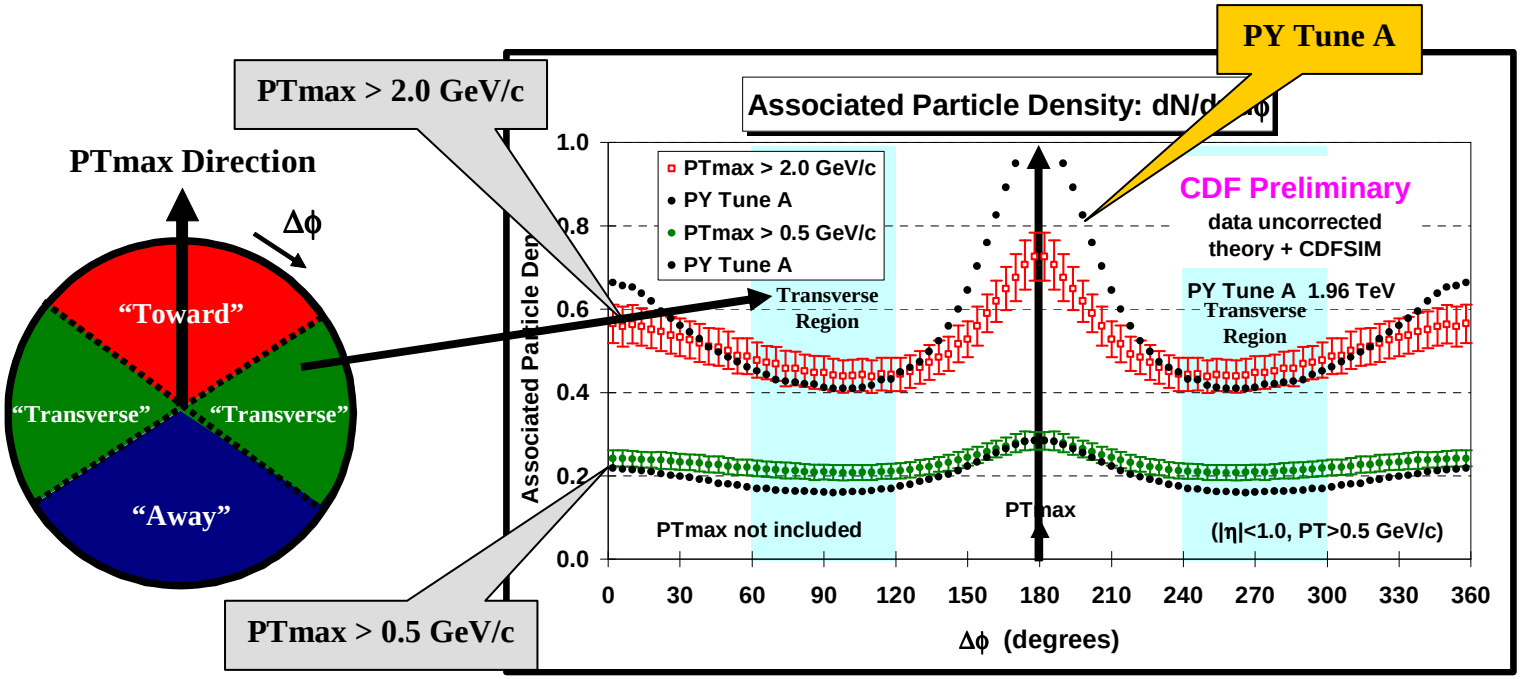


➡ **Shows the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events at 1.96 TeV with PTmax > 0.5, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune A (generator level).**



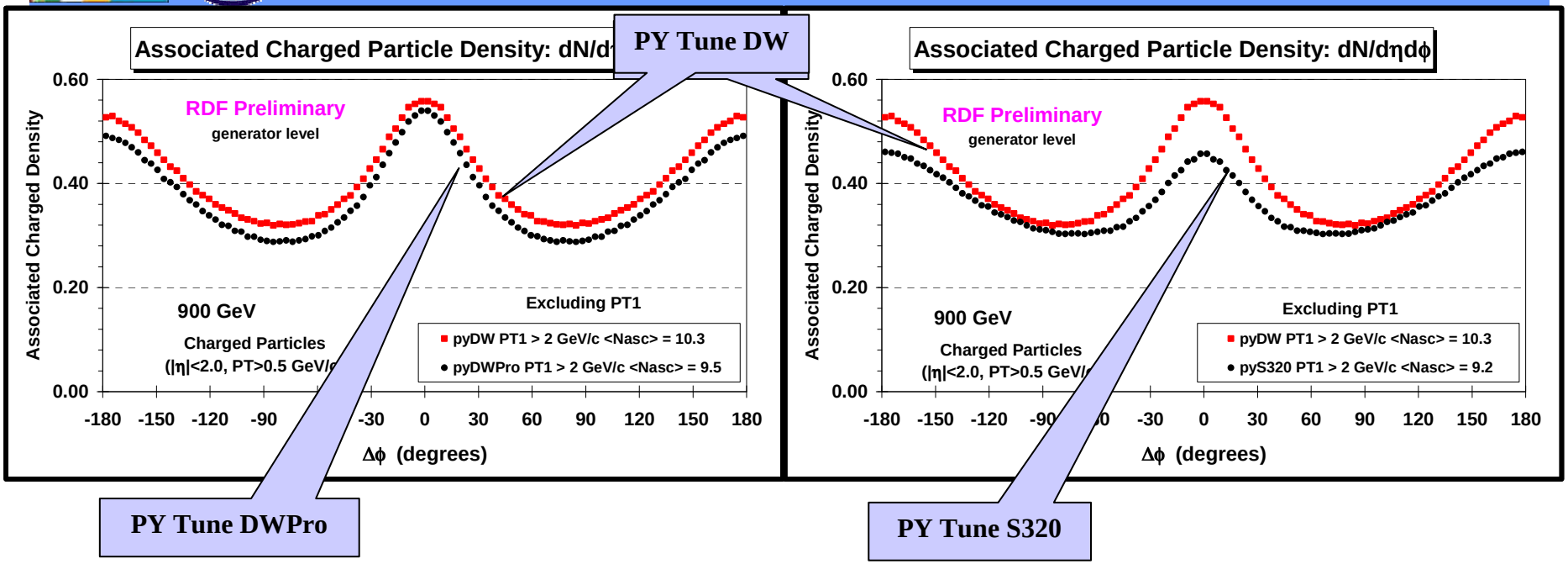
➡ **Shows the "associated" charged particle density in the "toward", "away" and "transverse" regions as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 1.96 TeV from PYTHIA Tune A (generator level).**

Min-Bias "Associated" Charged Particle Density



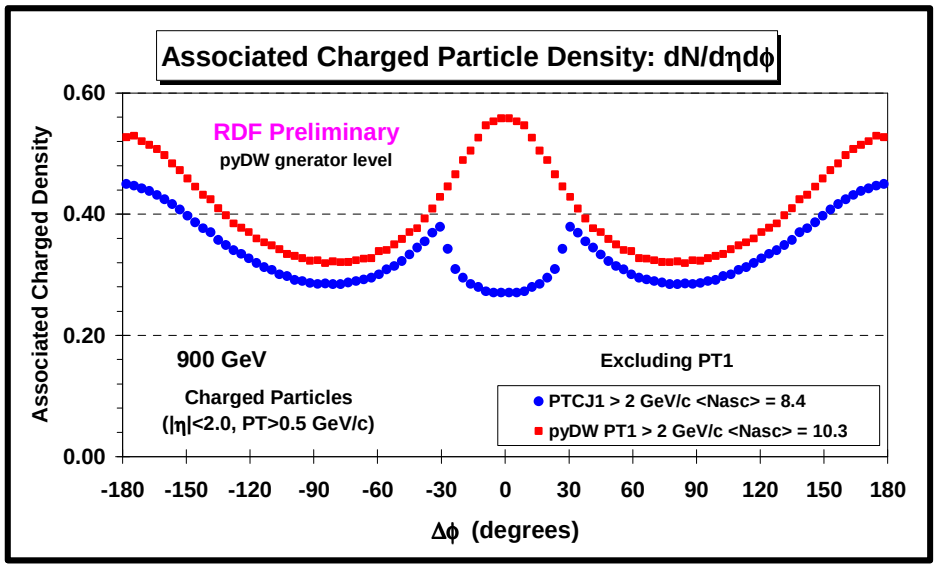
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA Tune A (after CDFSIM).
- PYTHIA Tune A predicts a larger correlation than is seen in the "min-bias" data (*i.e.* Tune A "min-bias" is a bit too "jetty").

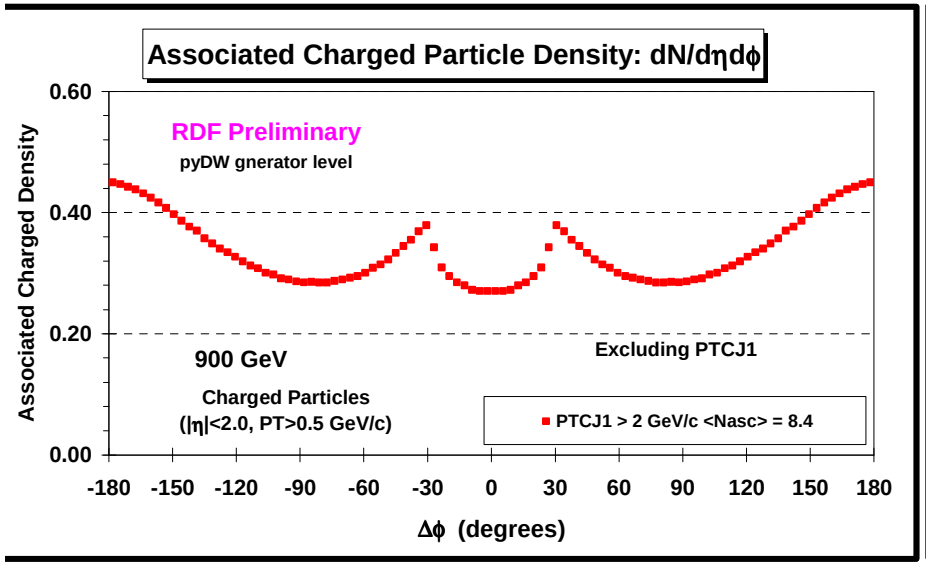
"Associated" Charged Particle Density



- **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 2, *not including PTmax*) relative to PTmax at 900 GeV with PTmax > 2.0 GeV/c from PYTHIA Tune DW, Tune DWPro, and Tune S320 (generator level).**

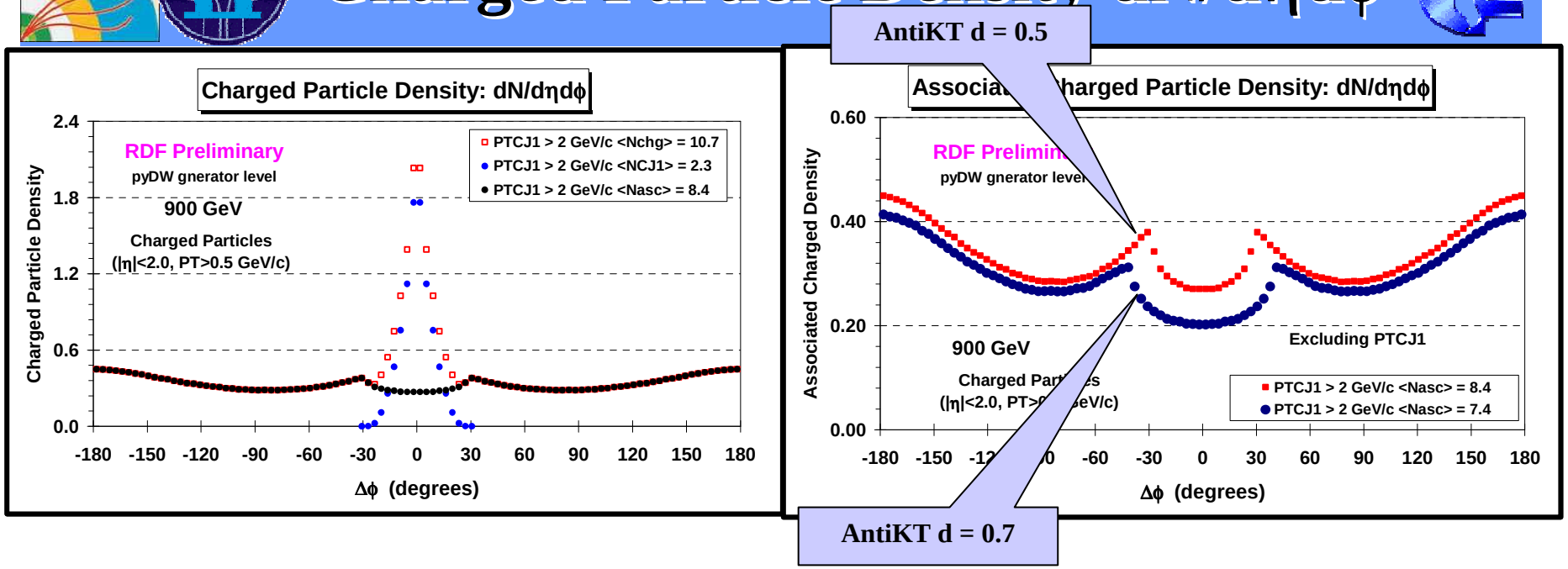
Charged Particle Density dN/dηdϕ





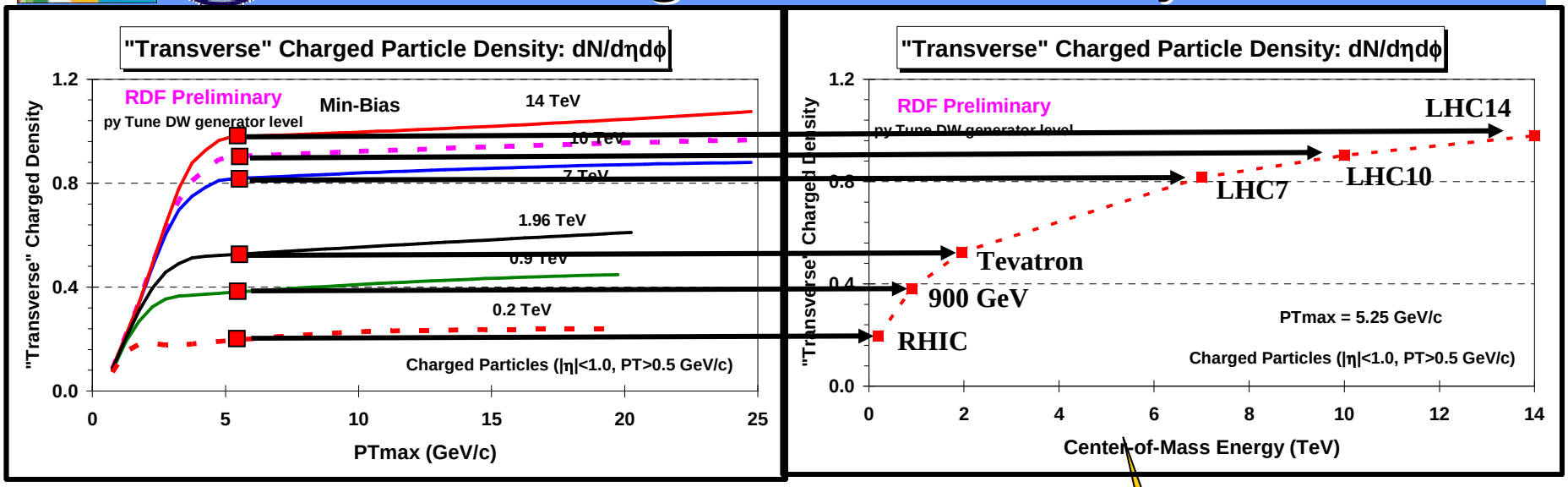
- **Shows the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 2, *not including PTmax*) relative to PTmax (rotated to 180°) at 900 GeV with PTmax > 2.0 GeV/c from PYTHIA Tune DW.**
- **Shows the Δϕ dependence of the "overall" and "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 2, *including all particles*) relative to the leading charged particle jet (Anti-KT, d = 0.5) at 900 GeV with PTmax > 2.0 GeV/c from PYTHIA Tune DW (generator level).**

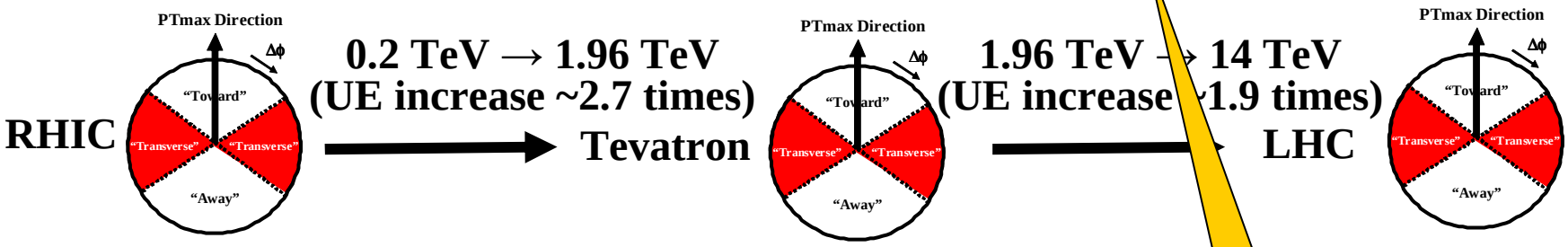
Charged Particle Density dN/dηdϕ



➡ **Shows the Δϕ dependence of the "overall" and "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 2, *including all particles*) relative to the leading charged particle jet (Anti-KT, d = 0.5) at 900 GeV with PTmax > 2.0 GeV/c from PYTHIA Tune DW (generator level).**

Min-Bias "Associated" Charged Particle Density

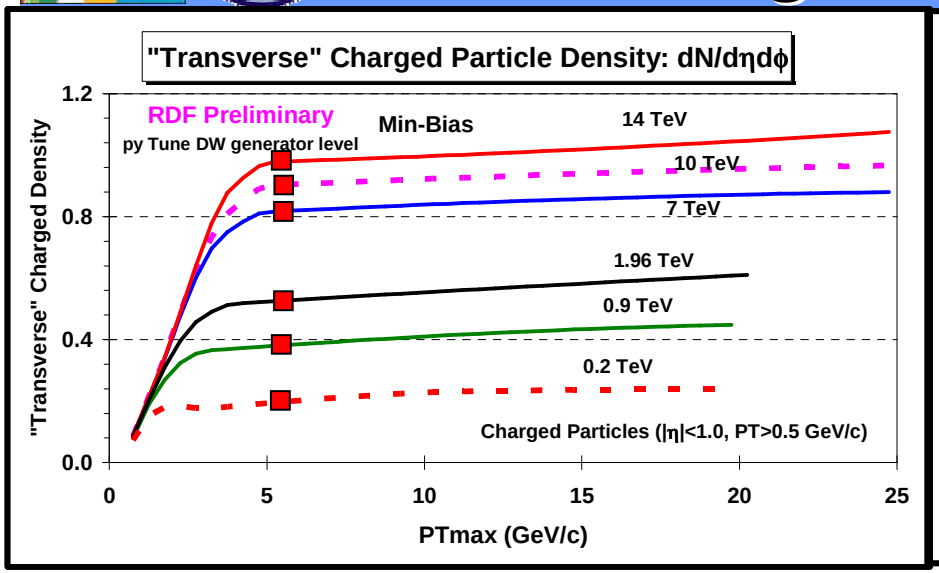


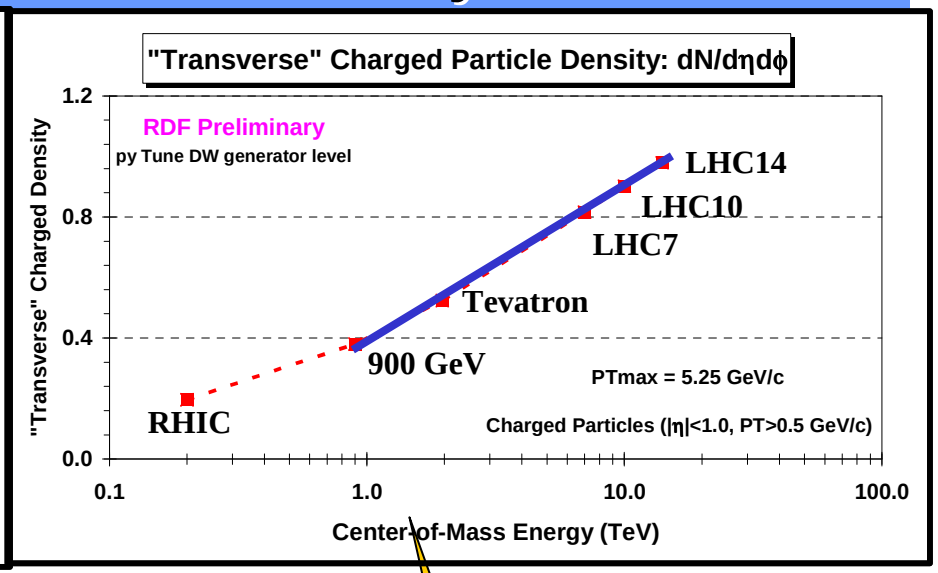


Linear scale!

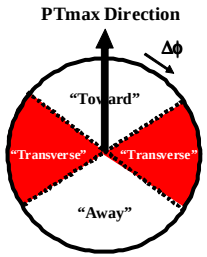
- Shows the "associated" charged particle density in the "transverse" region a[illegible] function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min[illegible]s" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tu[illegible] article level (*i.e.* generator level).

Min-Bias "Associated" Charged Particle Density





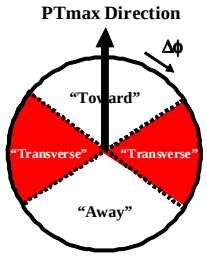
LHC7



7 TeV → 14 TeV
(UE increase ~20%)

Linear on a log plot!

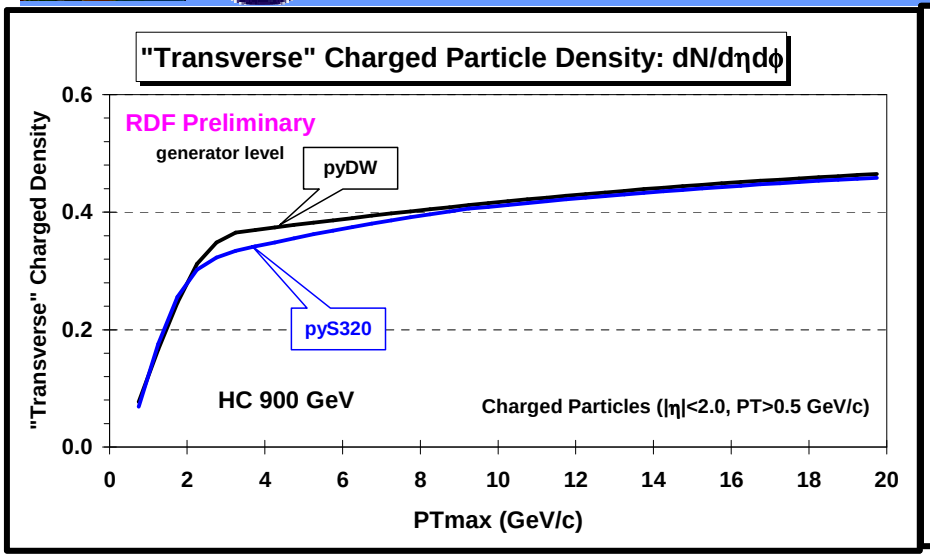
LHC14

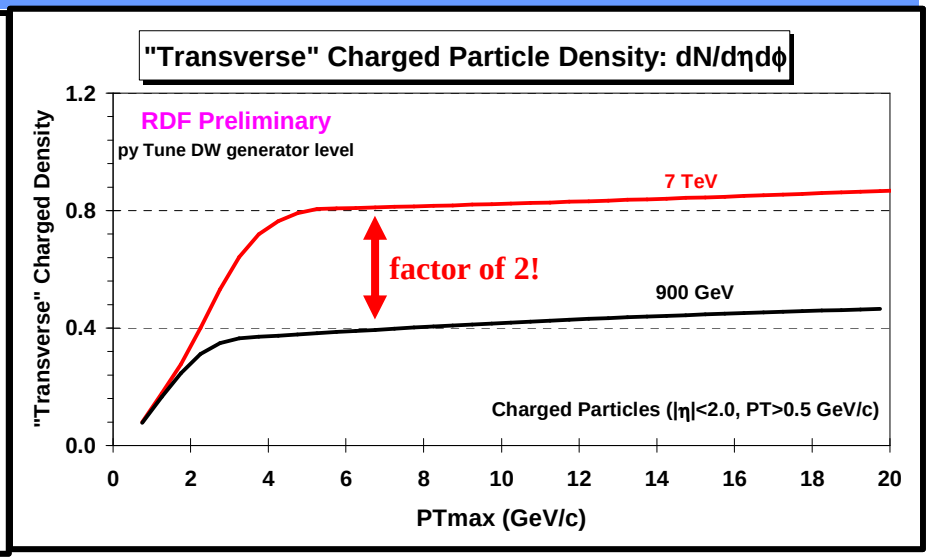


Log scale!

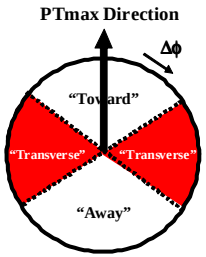
➡ **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.* generator level).**

"Transverse" Charge Density



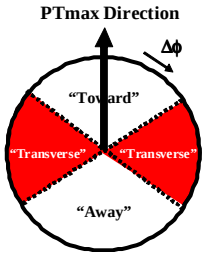


LHC 900 GeV



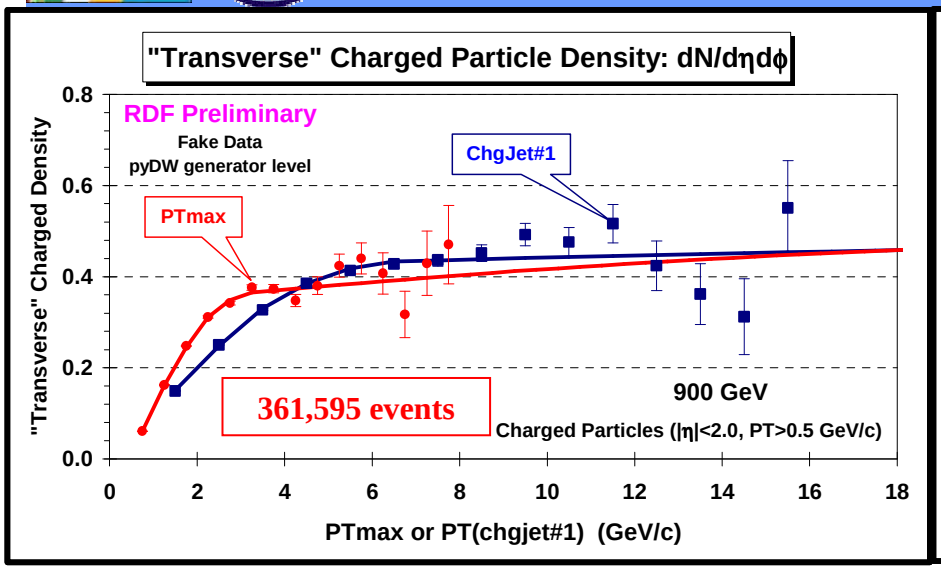
900 GeV → 7 TeV
(UE increase ~ factor of 2.1)

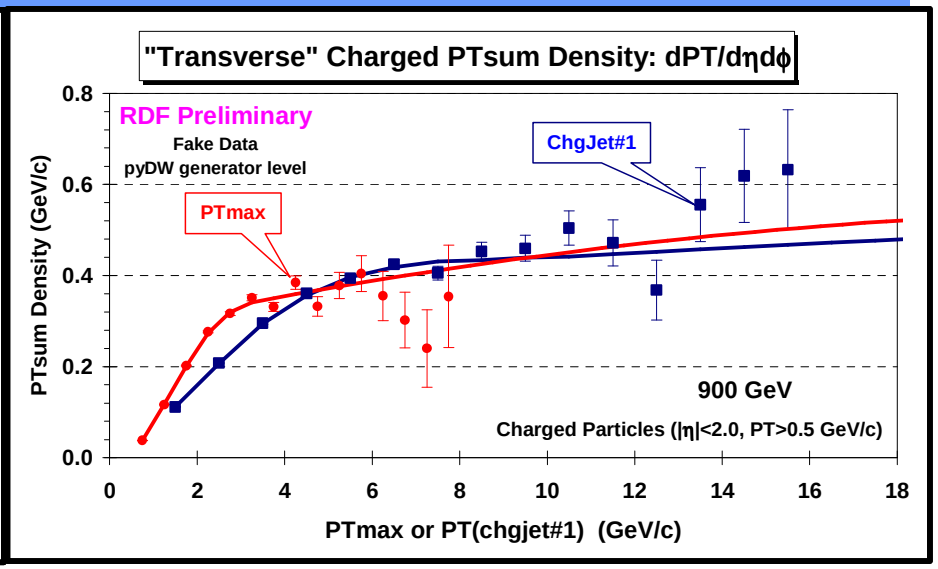
LHC 7 TeV



- **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) at 900 GeV as defined by PTmax from PYTHIA Tune DW and Tune S320 at the particle level (*i.e.* generator level).**

"Transverse" Charged Particle Density

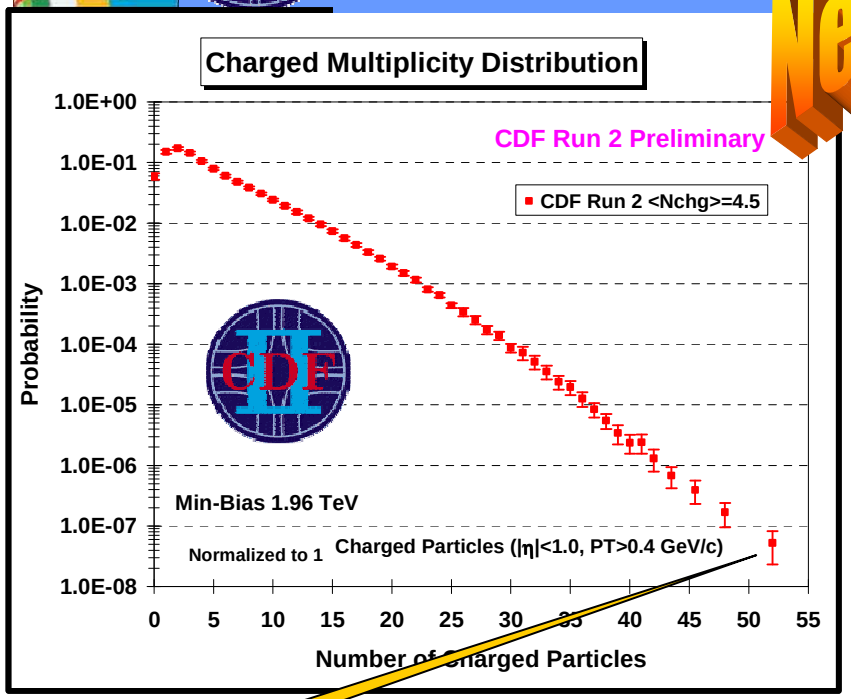




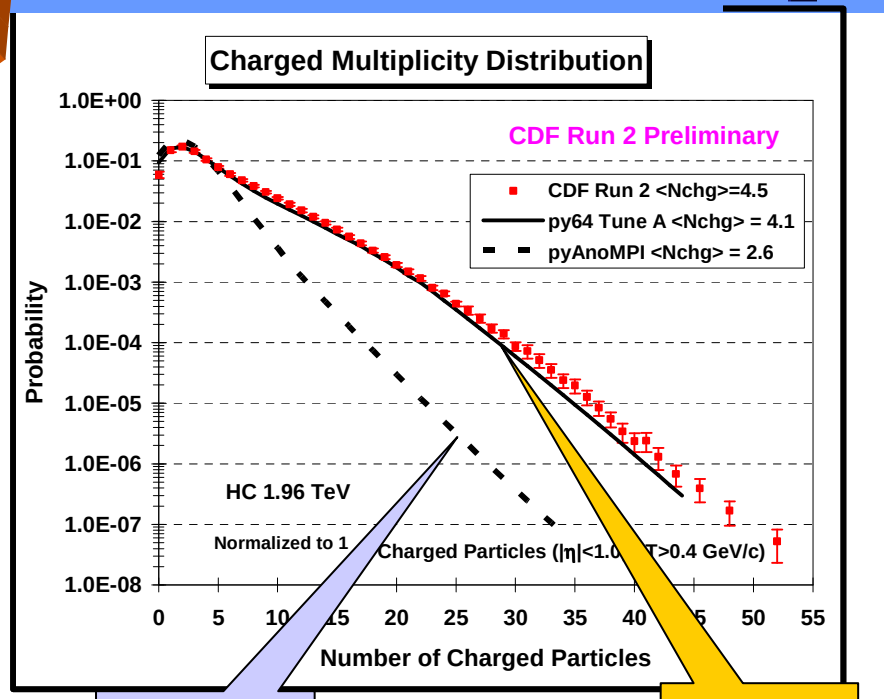
- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

- **Fake data (from MC) at 900 GeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

Charged Particle Multiplicity



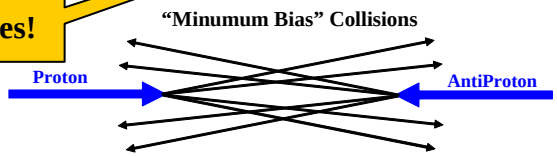
New



7 decades!

No MPI!

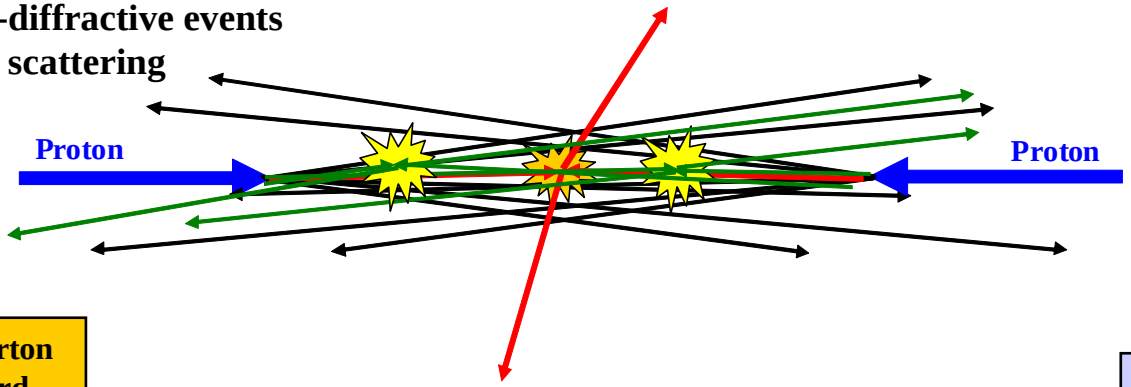
Tune A!



- Data at 1.96 TeV on the charged particle multiplicity (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2.
- The data are compared with PYTHIA Tune A and Tune A without multiple parton interactions (pyAnoMPI).

The "Underlying Event"

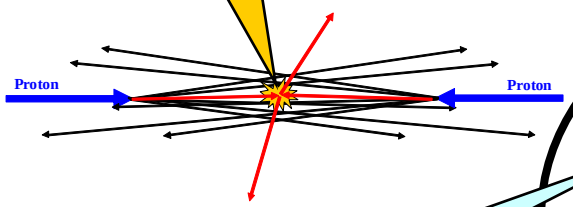
Select inelastic non-diffractive events that contain a hard scattering

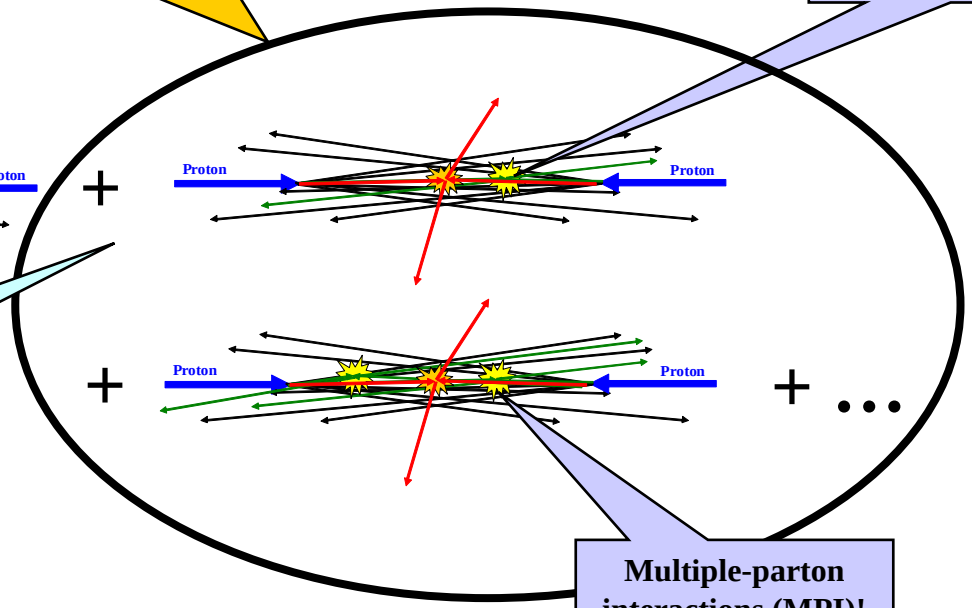


Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

The "underlying-event" (UE)!

"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)

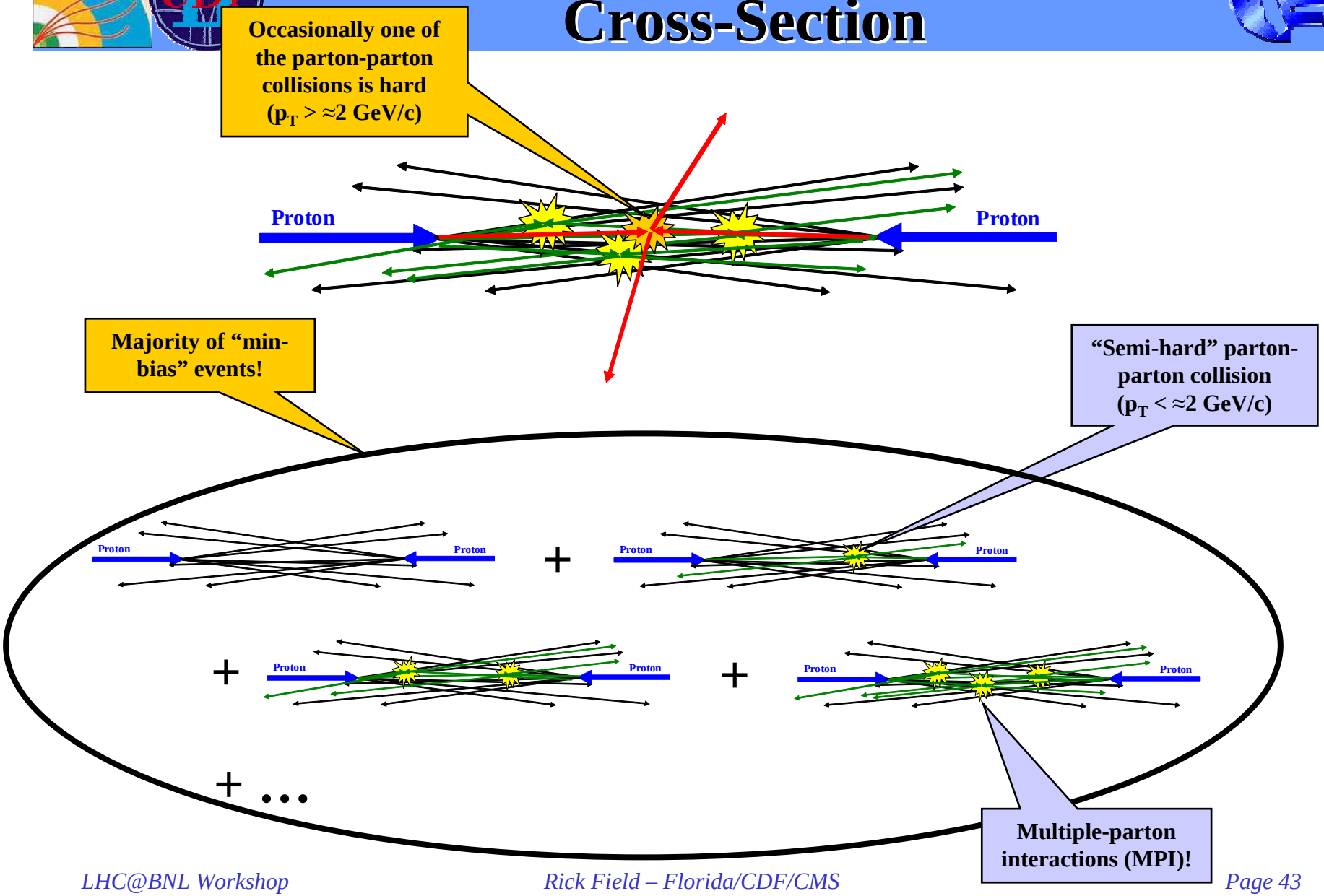




Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

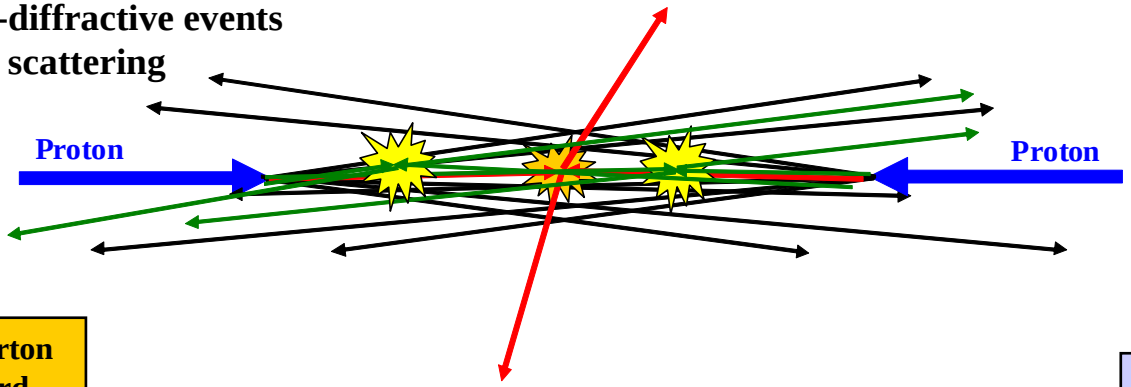
Multiple-parton interactions (MPI)!

The Inelastic Non-Diffractive Cross-Section



The "Underlying Event"

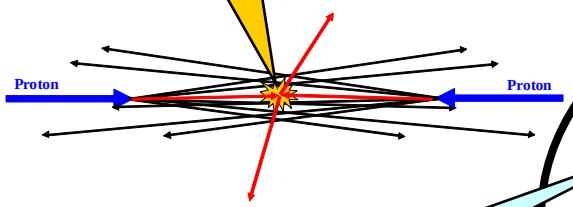
Select inelastic non-diffractive events that contain a hard scattering

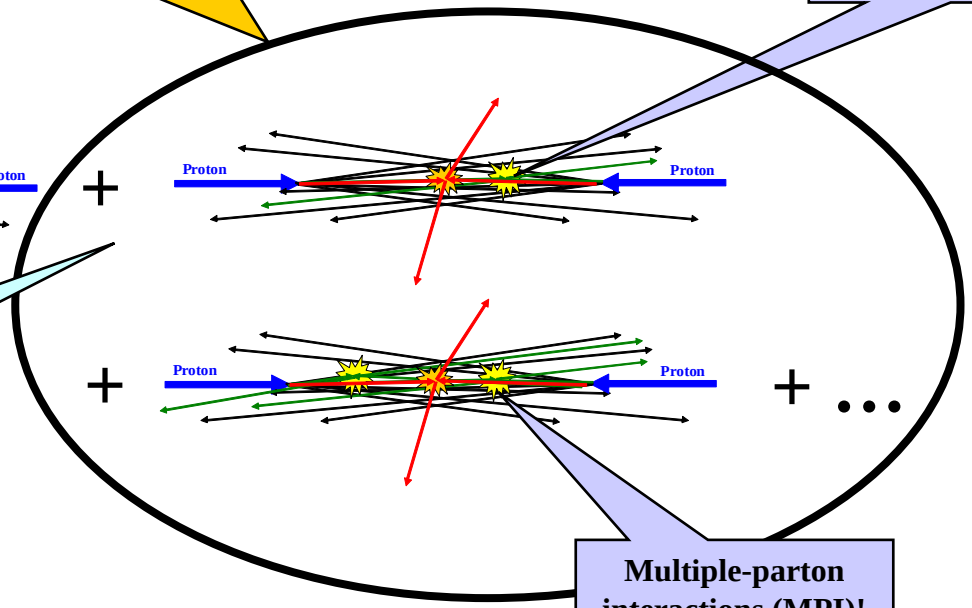


Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

The "underlying-event" (UE)!

"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)

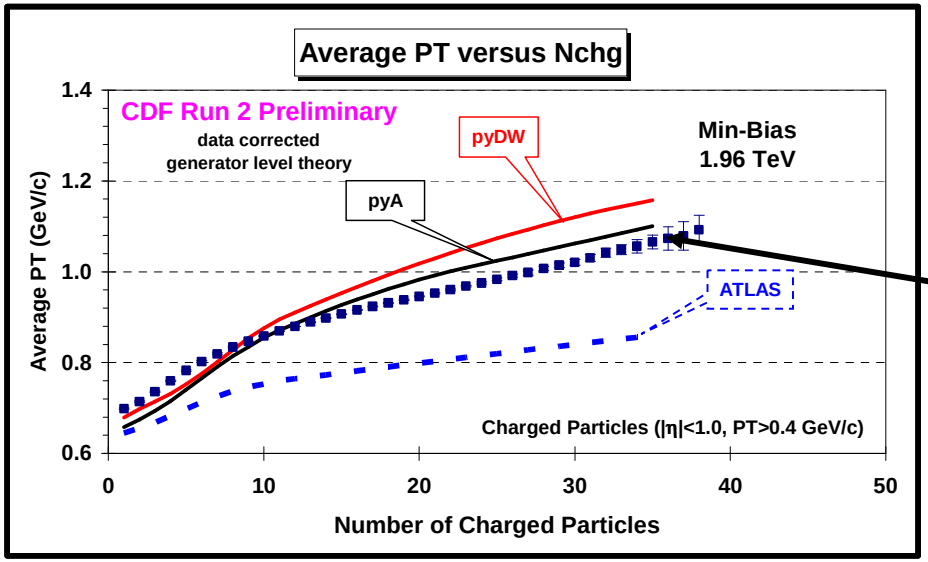


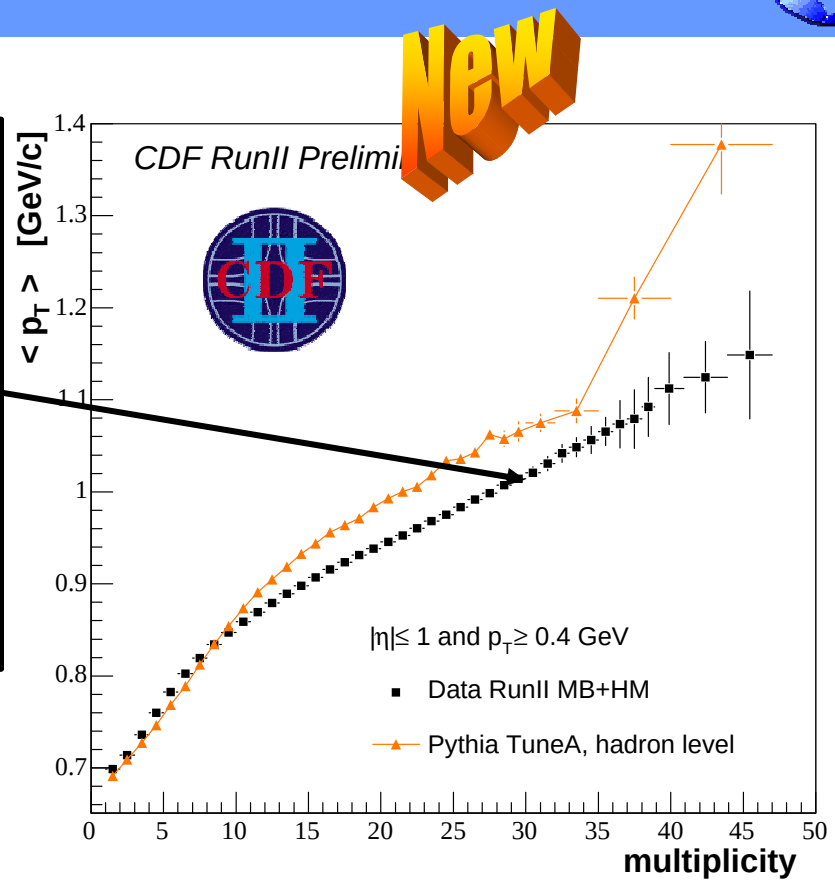


Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

Multiple-parton interactions (MPI)!

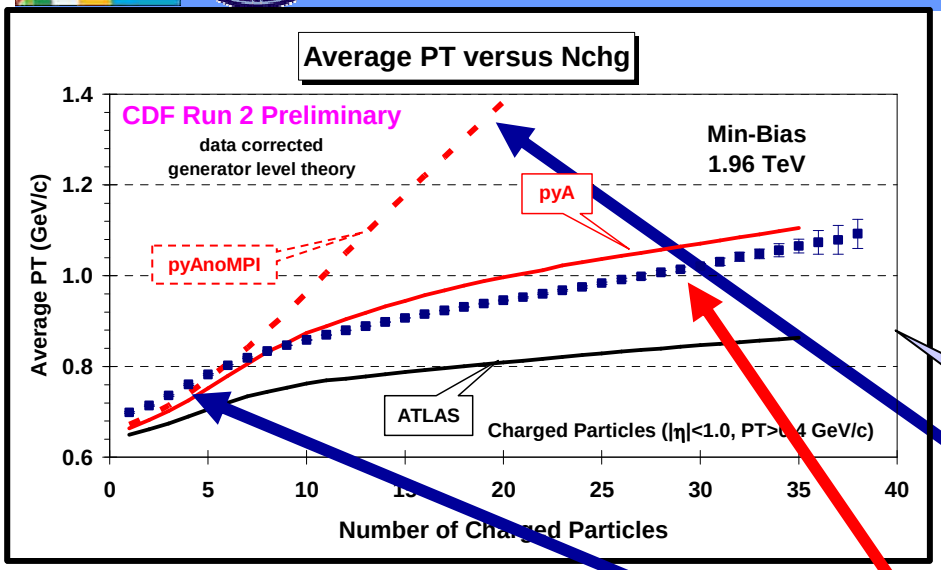
Min-Bias Correlations





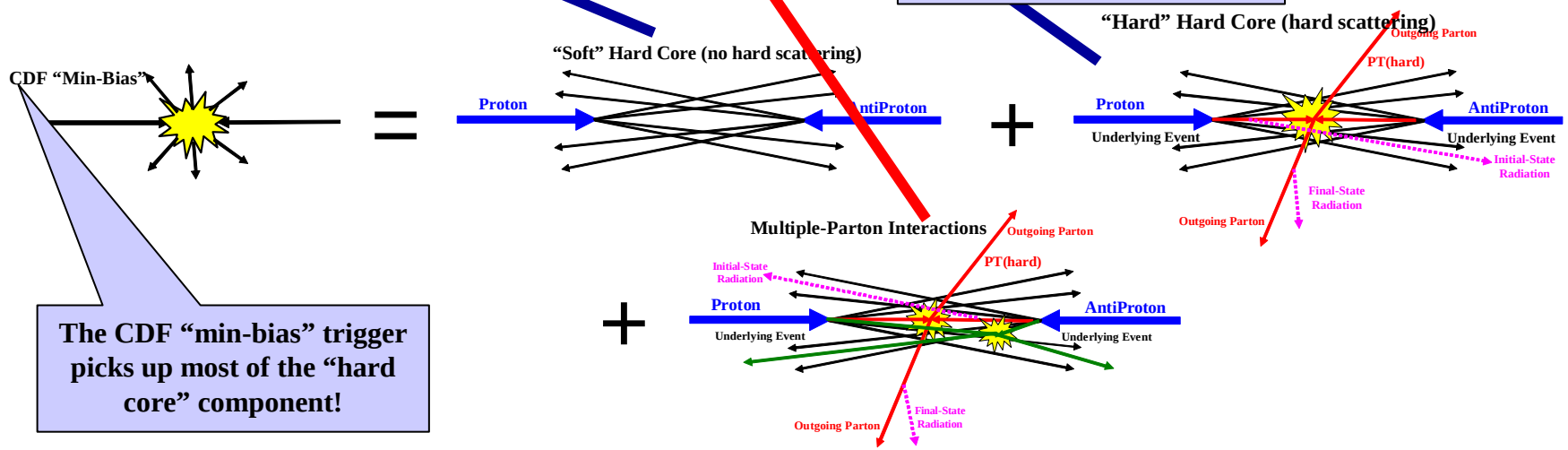
➡ **Data at 1.96 TeV on the average p_T of charged particles versus the number of charged particles (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A at the particle level (*i.e.* generator level).**

Min-Bias: Average PT versus Nchg



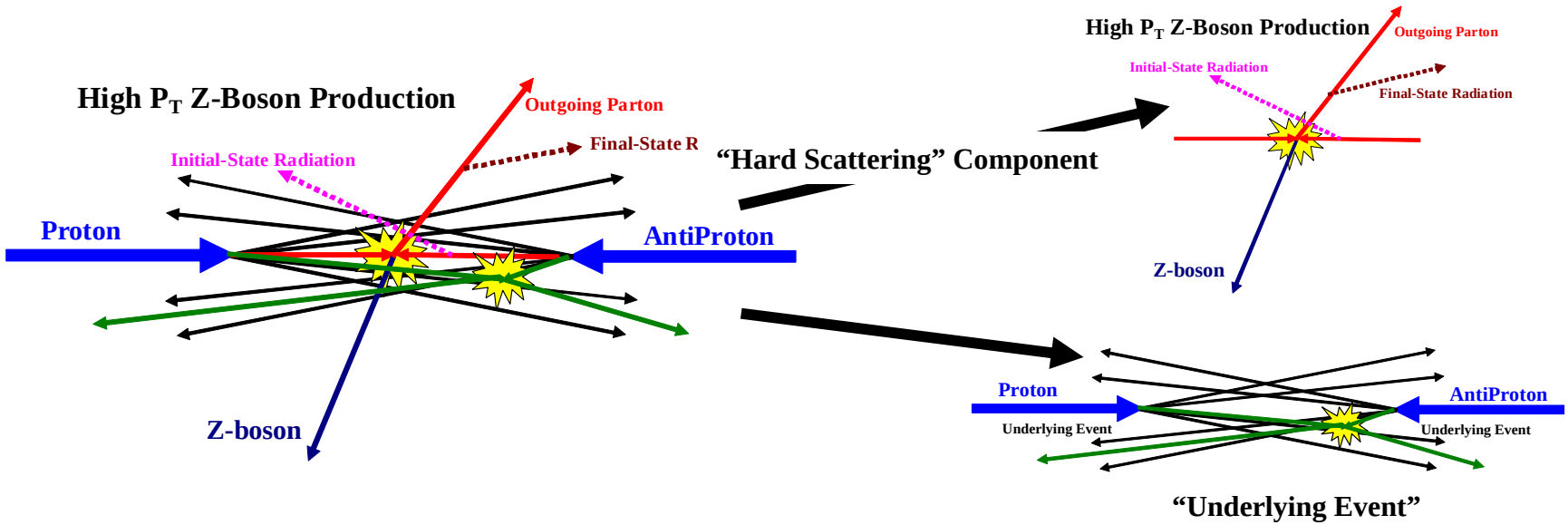
- Beam-beam remnants (*i.e.* soft hard core) produces low multiplicity and small $<p_T>$ with $<p_T>$ independent of the multiplicity.
- Hard scattering (with no MPI) produces large multiplicity and large $<p_T>$.
- Hard scattering (with MPI) produces large multiplicity and medium $<p_T>$.

This observable is sensitive to the MPI tuning!



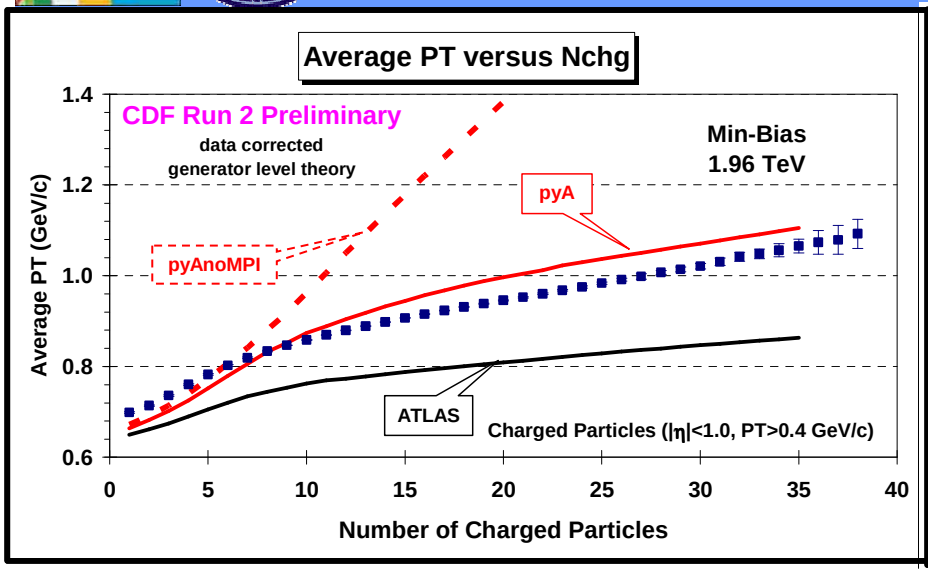
The CDF "min-bias" trigger picks up most of the "hard core" component!

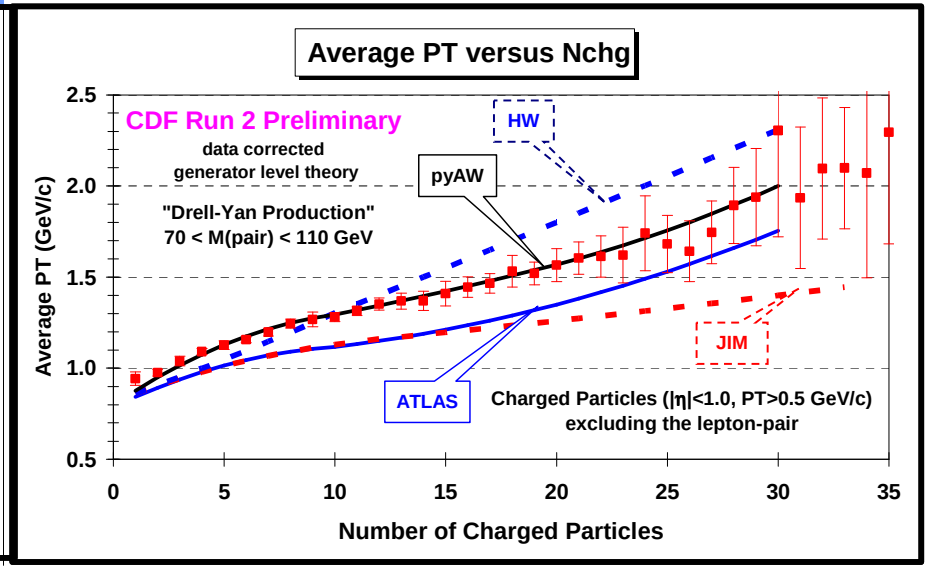
QCD Monte-Carlo Models: Lepton-Pair Production

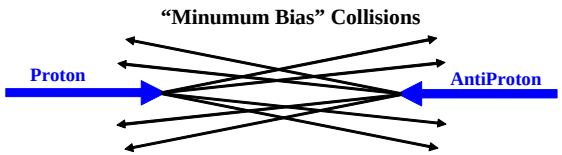


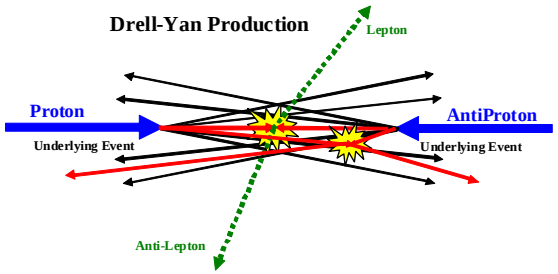
- Start with the perturbative Drell-Yan muon pair production and add initial-state gluon radiation (in the leading log approximation or modified leading log approximation).
- The "underlying event" consists of the "beam-beam remnants" and from particles arising from soft or semi-soft multiple parton interactions (MPI).
- Of course the outgoing colored partons fragment into hadron "jet" and inevitably "underlying event" observables receive contributions from initial-state radiation.

Average PT versus Nchg





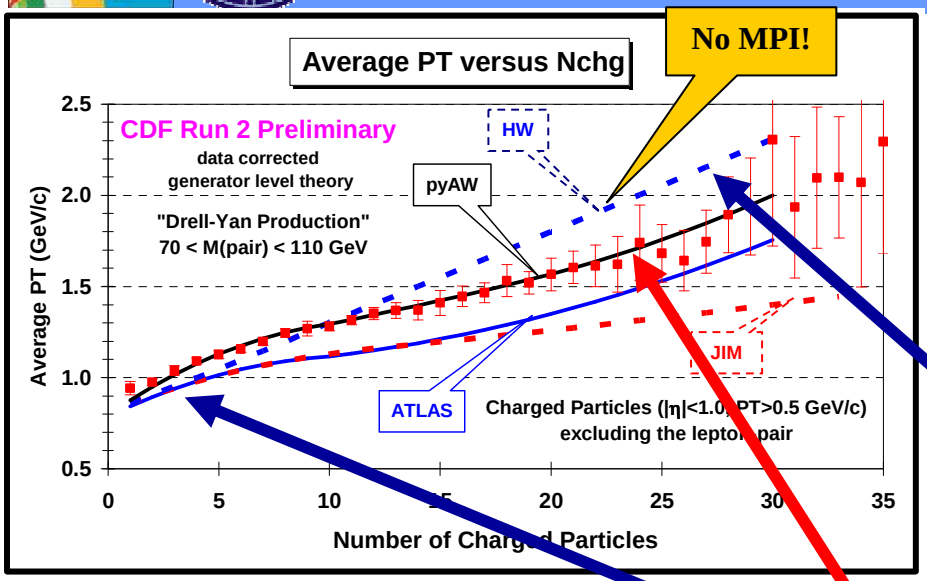




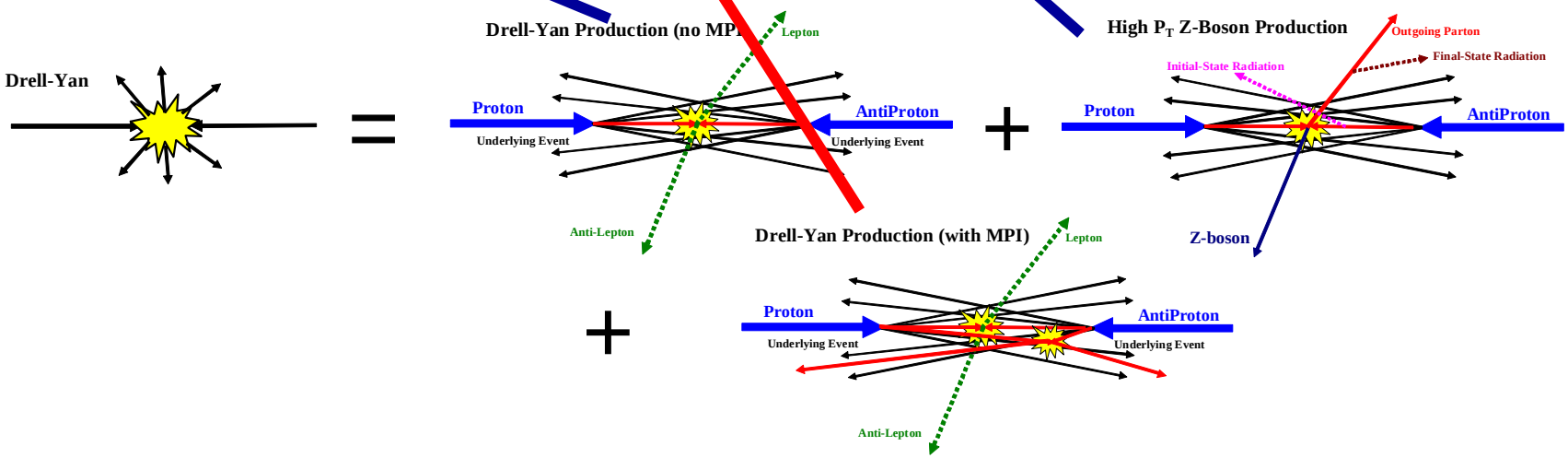
- **Data at 1.96 TeV on the average p_T of charged particles versus the number of charged particles (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2. The data are corrected to the particle leveland are compared with PYTHIA Tune A, Tune DW, and the ATLAS tune at the particle level (*i.e.* generator level).**

- **Particle level predictions for the average p_T of charged particles versus the number of charged particles (p_T > 0.5 GeV/c, |η| < 1, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV) at CDF Run 2.**

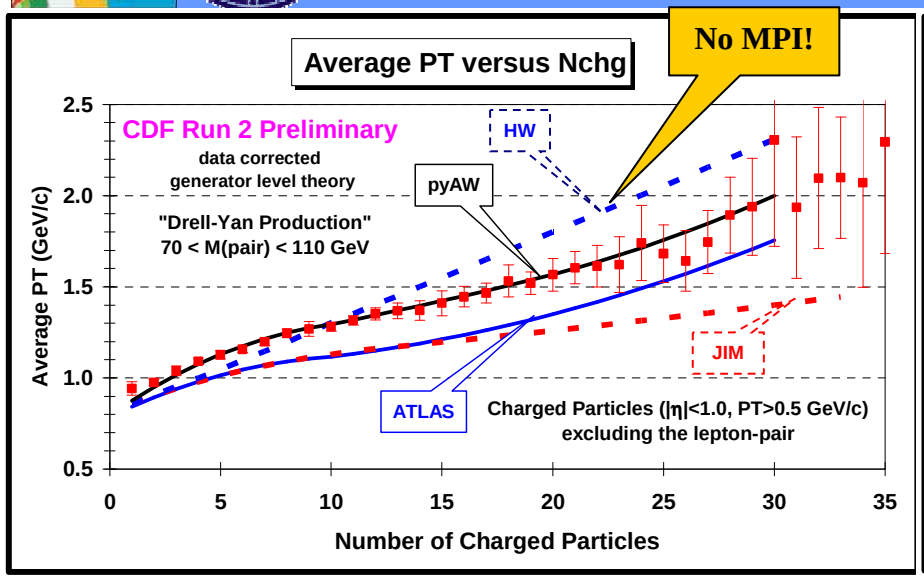
Average PT versus Nchg

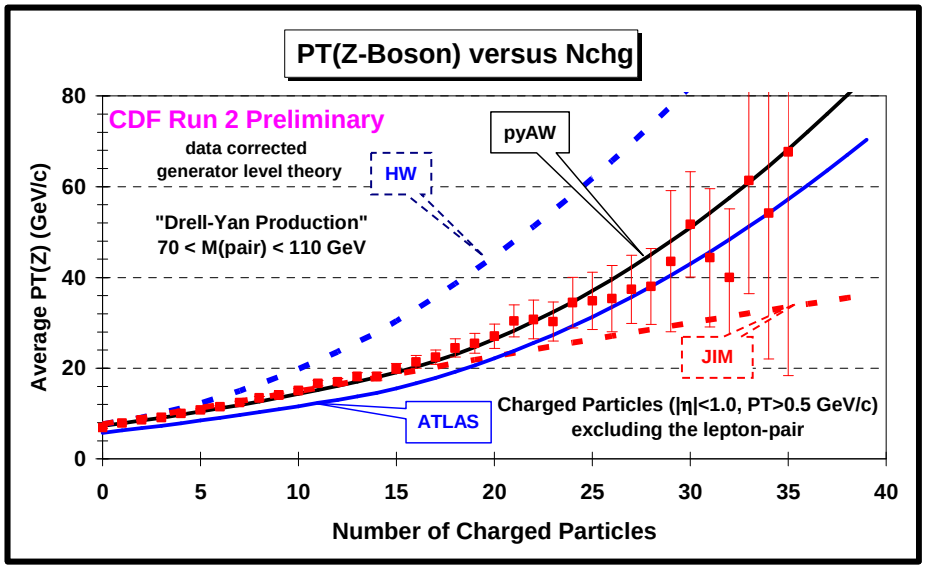


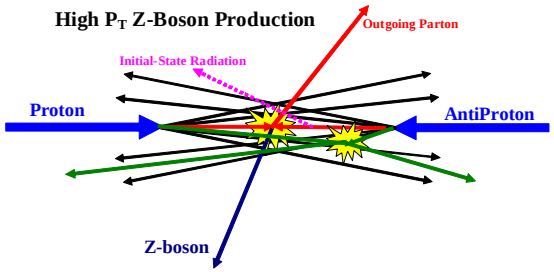
- Z-boson production (with low $p_T(Z)$ and no MPI) produces low multiplicity and small $\langle p_T \rangle$.
- High p_T Z-boson production produces large multiplicity and high $\langle p_T \rangle$.
- Z-boson production (with MPI) produces large multiplicity and medium $\langle p_T \rangle$.



Average PT(Z) versus Nchg



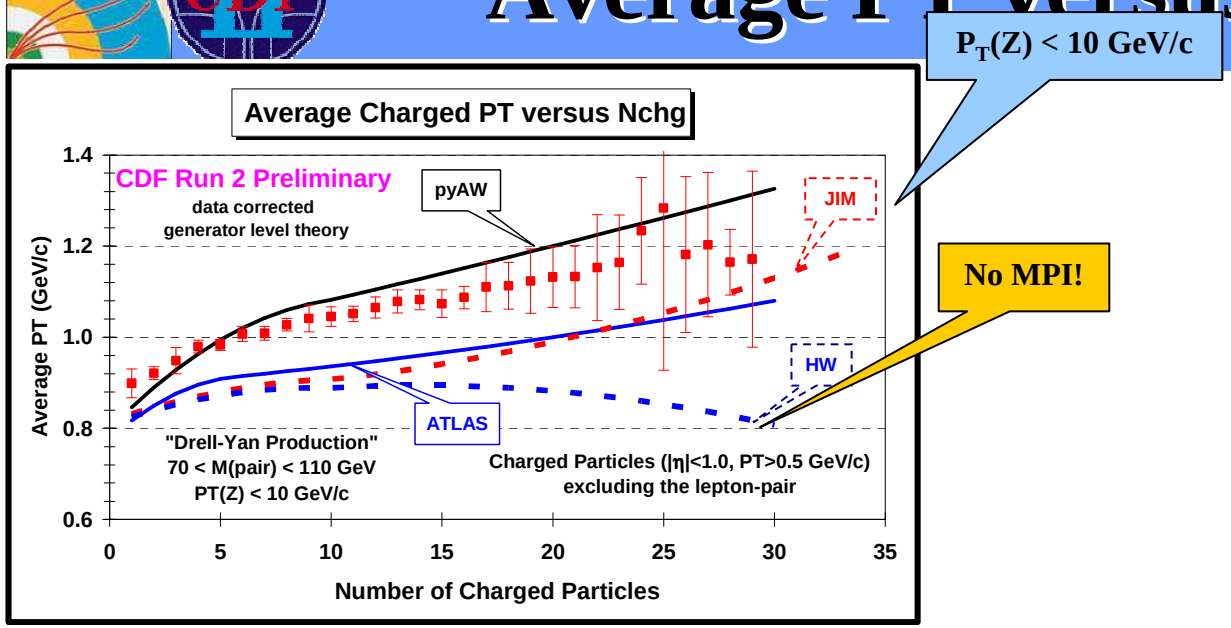




➡ **Predictions for the average P_T(Z-Boson) versus the number of charged particles (p_T > 0.5 GeV/c, |η| < 1, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV) at CDF Run 2.**

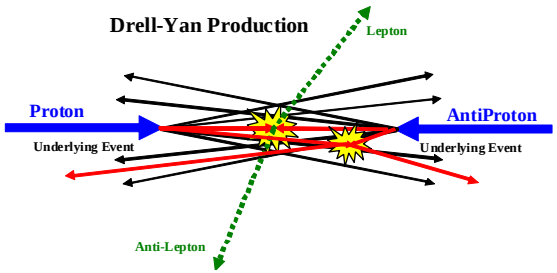
➡ **Data on the average p_T of charged particles versus the number of charged particles (p_T > 0.5 GeV/c, |η| < 1, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (*i.e.* generator level).**

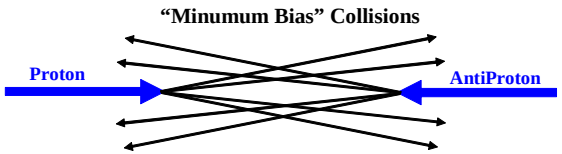
Average PT versus Nchg



$P_T(Z) < 10$ GeV/c

No MPI!

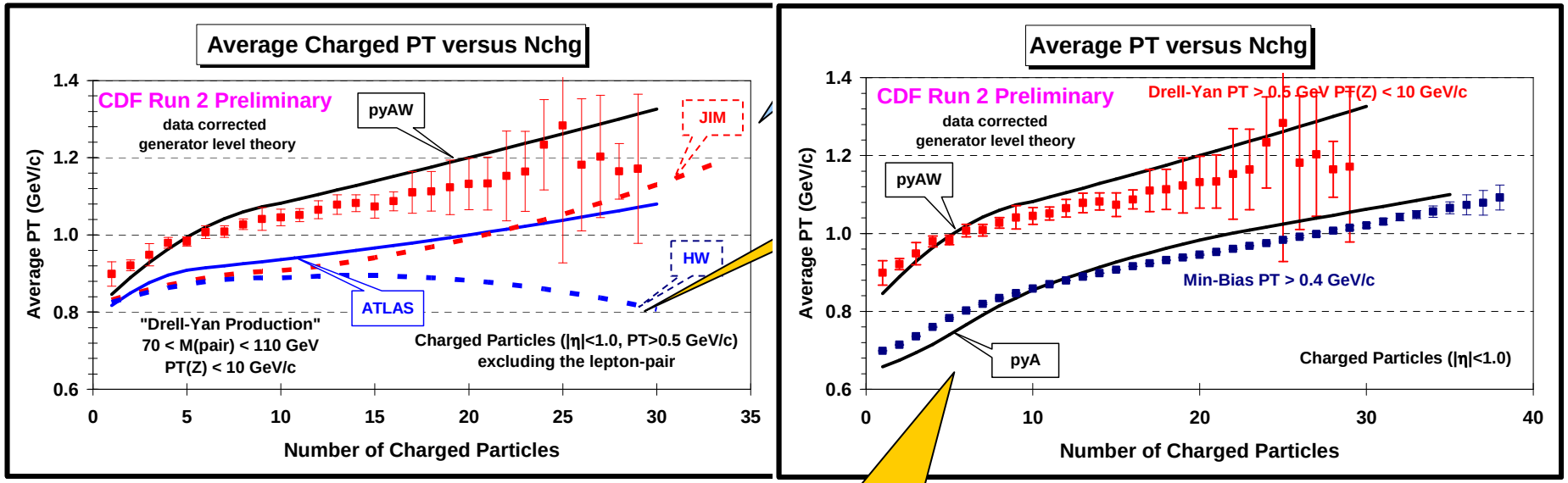


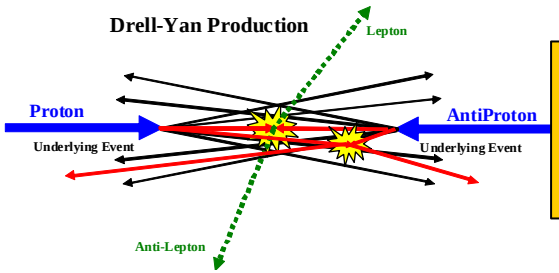


➡ **Data the average p_T of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV, P_T(pair) < 10 GeV/c) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (*i.e.* generator level).**

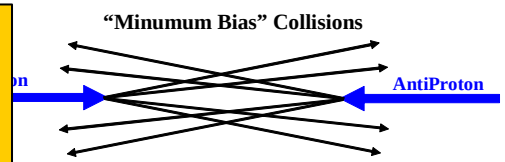
Average PT versus Nchg

$P_T(Z) < 10$ GeV/c



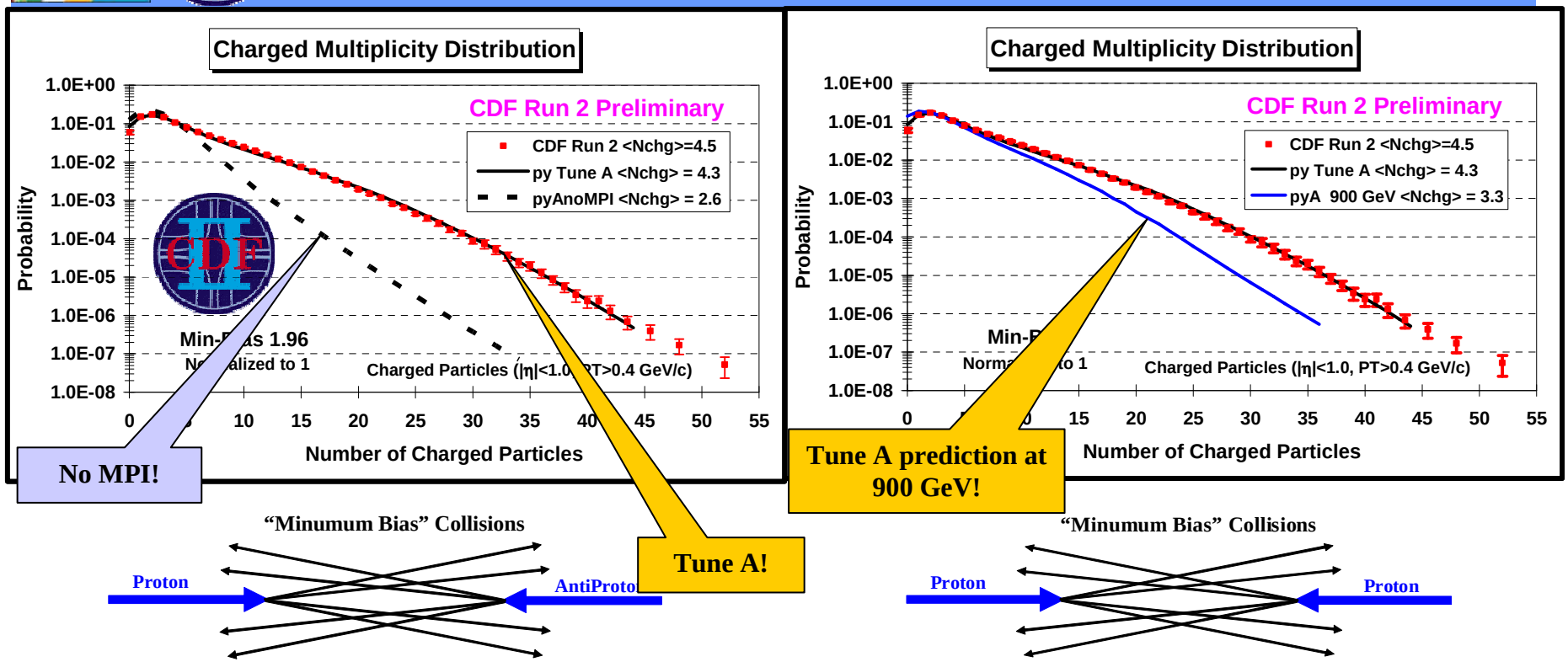


Remarkably similar behavior! Perhaps indicating that MPI playing an important role in both processes.



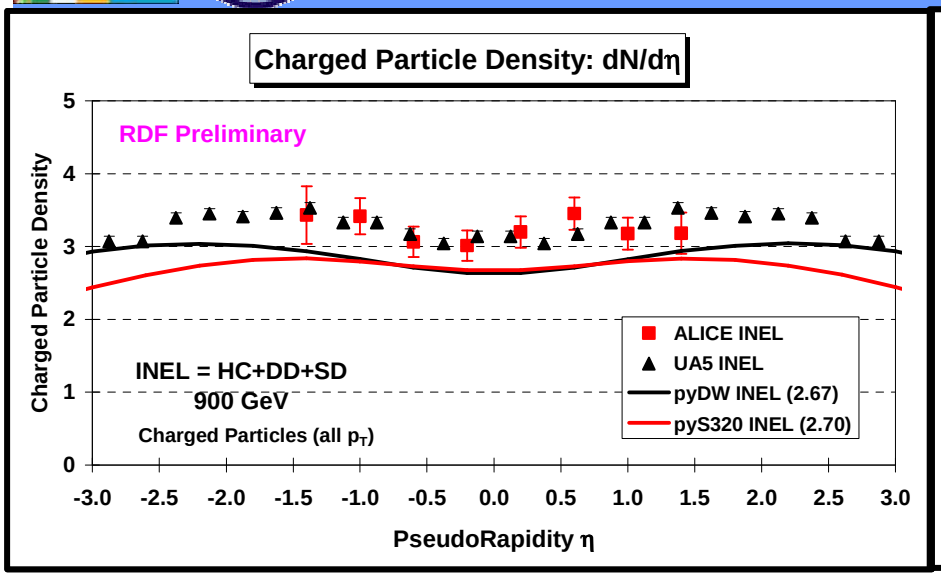
➡ **Data the average p_T of charged particles versus the number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, excluding the lepton-pair) for for Drell-Yan production (70 < M(pair) < 110 GeV, P_T(pair) < 10 GeV/c) at CDF Run 2. The data are corrected to the particle level and are compared with various Monte-Carlo tunes at the particle level (*i.e.* generator level).**

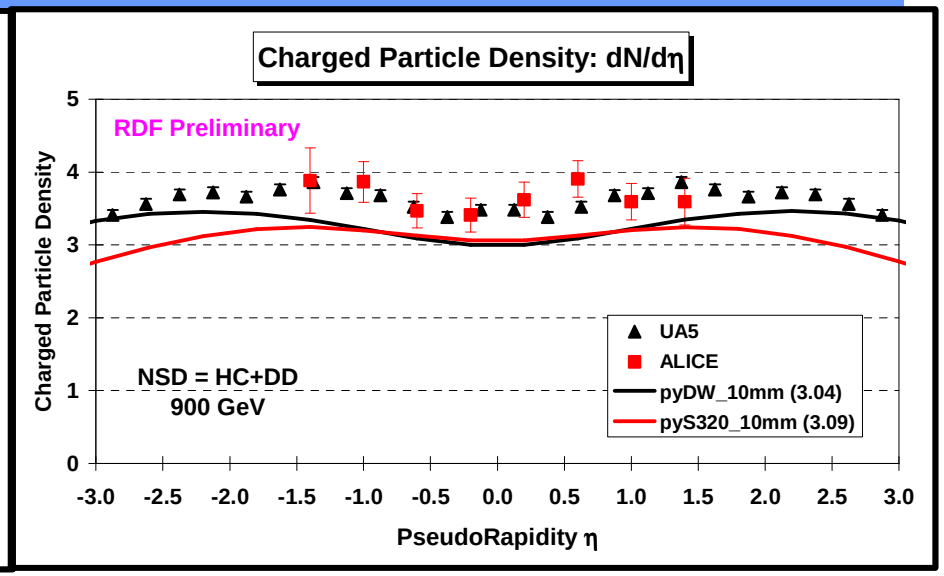
Charged Particle Multiplicity

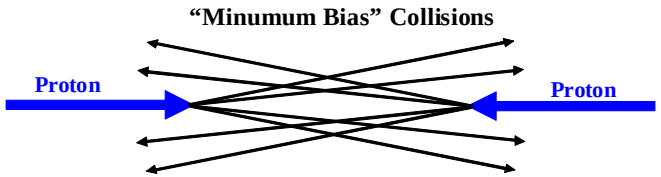


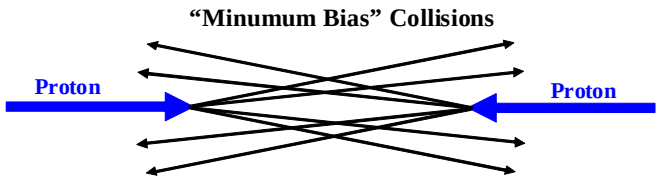
- Data at 1.96 TeV on the charged particle multiplicity (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2.
- The data are compared with PYTHIA Tune A and Tune A without multiple parton interactions (pyAnoMPI).
- Prediction from PYTHIA Tune A for proton-proton collisions at 900 GeV.

LHC Predictions: 900 GeV



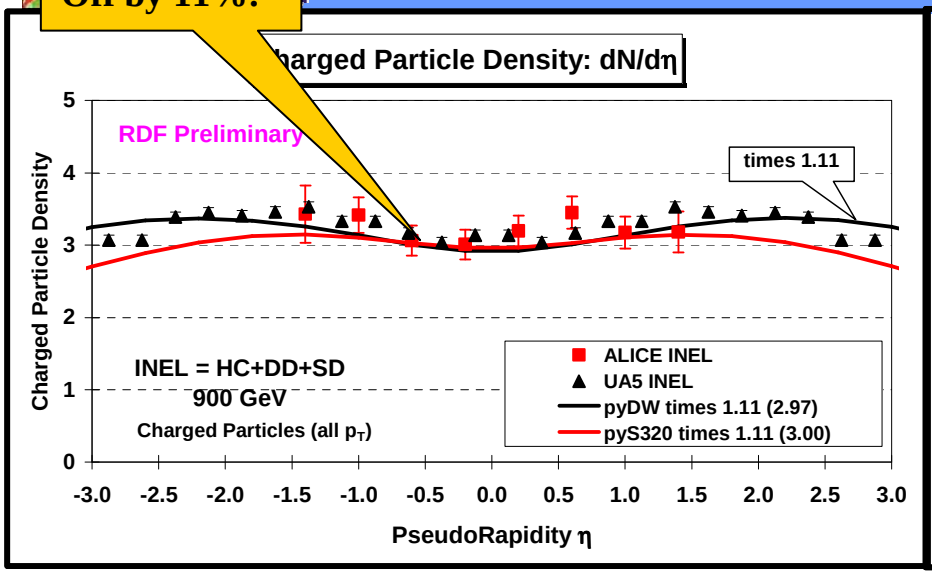


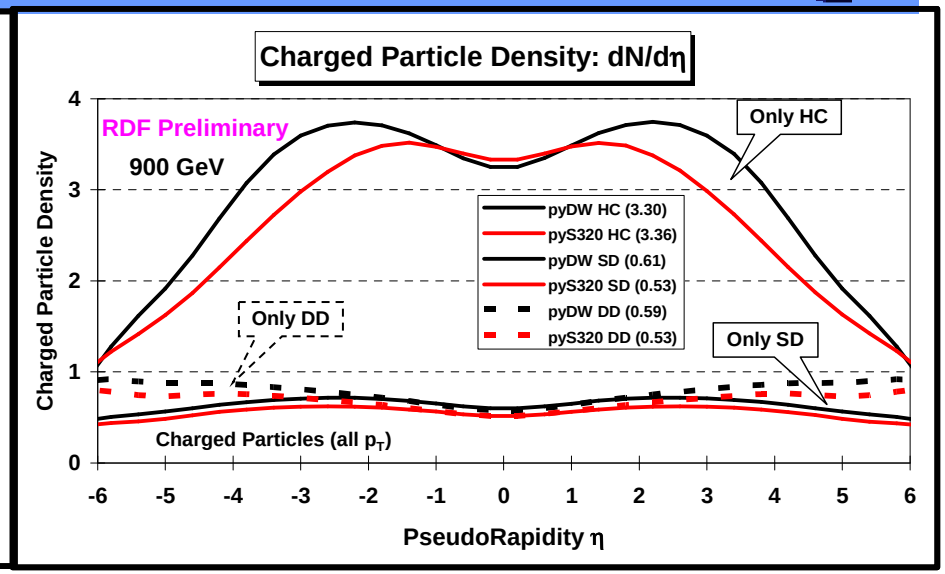


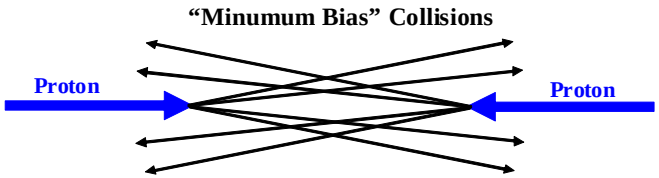


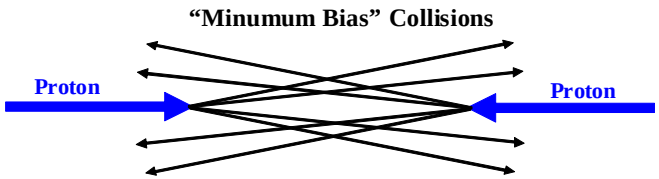
➡ **Compares the 900 GeV data with my favorite PYTHIA Tunes (Tune DW and Tune S320 Perugia 0). Tune DW uses the old Q^2-ordered parton shower and the old MPI model. Tune S320 uses the new p_T-ordered parton shower and the new MPI model. The numbers in parentheses are the average value of dN/dη for the region $|\eta| < 0.6$.**

LHC Predictions: 900 GeV



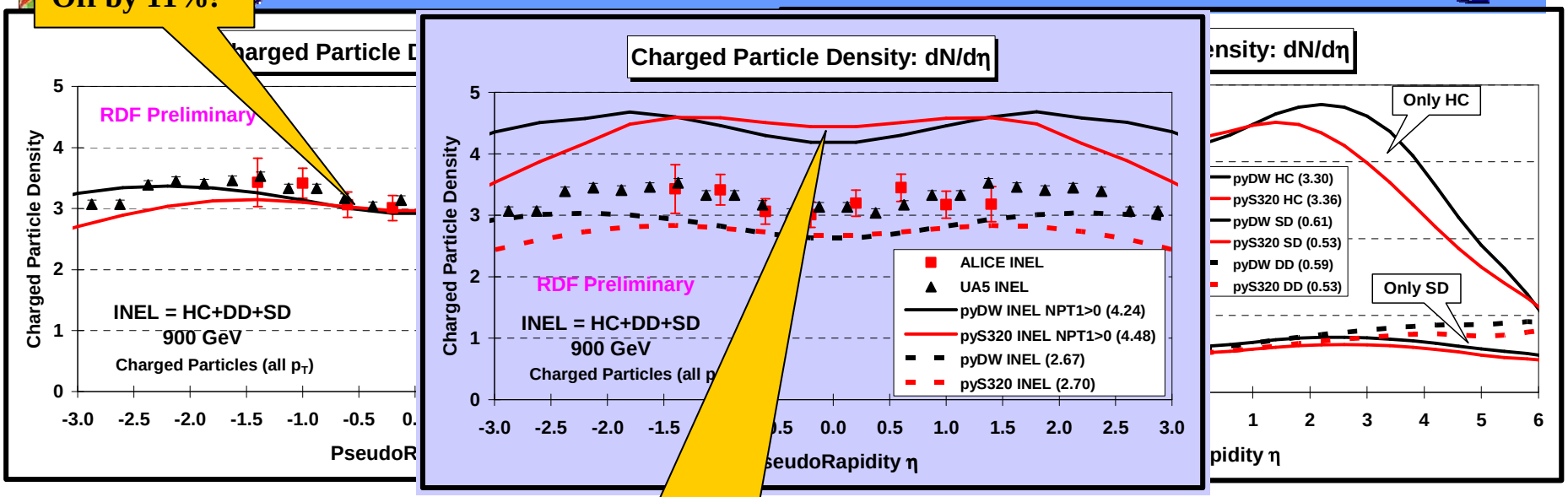






➡ **Shows the individual HC, DD, and SD predictions of PYTHIA Tune DW and Tune S320 Perugia 0. The numbers in parentheses are the average value of dN/dη for the region |η| < 0.6. I do not trust PYTHIA to model correctly the DD and SD contributions! I would like to know how well these tunes model the HC component. We need to look at observables where only HC contributes!**

LHC Predictions: 900 GeV

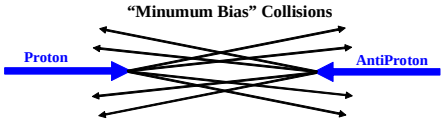


Require at least one charged particle to have $p_T > 1$ GeV/c. This is > 99% HC only!

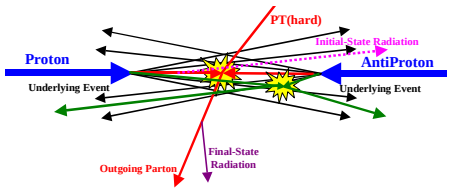
➡ **Shows the individual HC, DD, and SD predictions of PYTHIA Tune DW and Tune S320 Perugia 0. The numbers in parentheses are the average value of dN/dη for the region |η| < 0.6. I do not trust PYTHIA to model correctly the DD and SD contributions! I would like to know how well these tunes model the HC component. We need to look at observables where only HC contributes!**

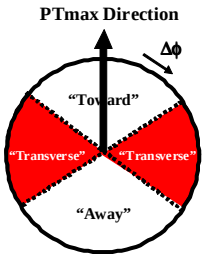
LHC Predictions

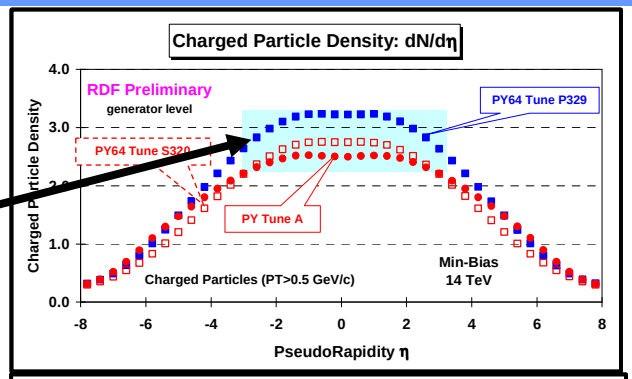
I believe because of the STAR analysis we are now in a position to make some predictions at the LHC!



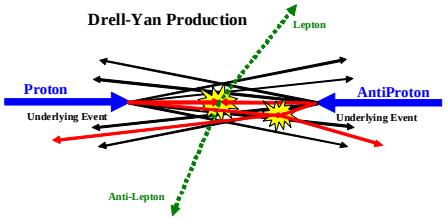
➡ **The amount of activity in "min-bias" collisions.**

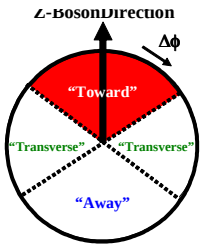


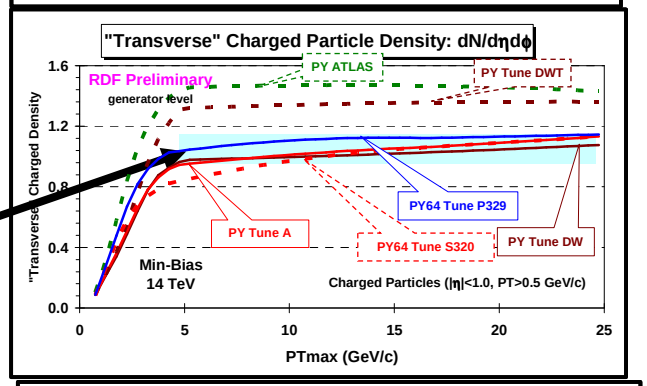




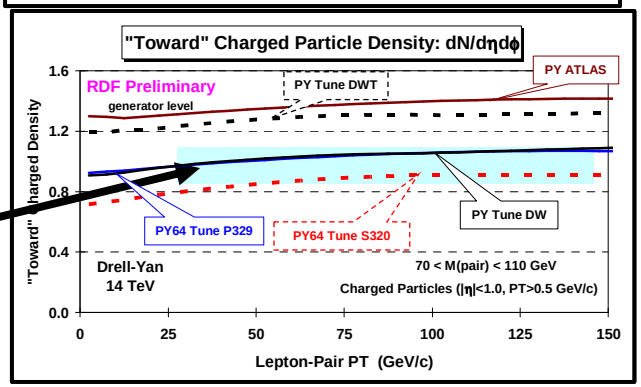
➡ **The amount of activity in the "underlying event" in hard scattering events.**





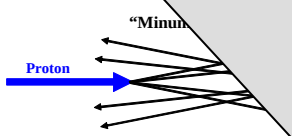


➡ **The amount of activity in the "underlying event" in Drell-Yan events.**

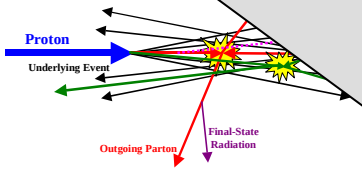


LHC Predictions

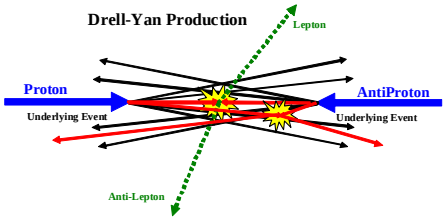
I believe because of the STAR analysis we are now in a position to make some predictions for the LHC!

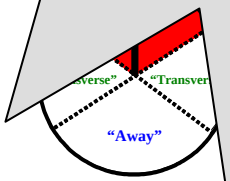


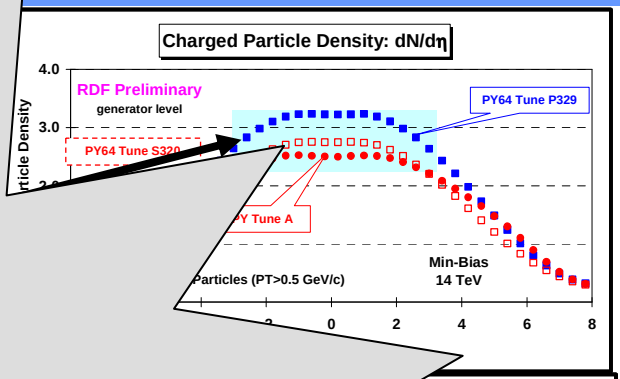
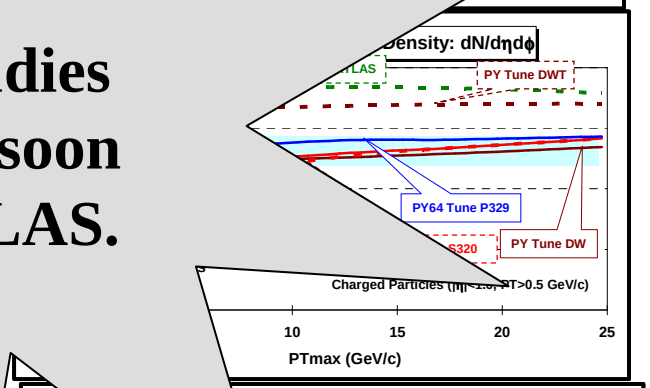
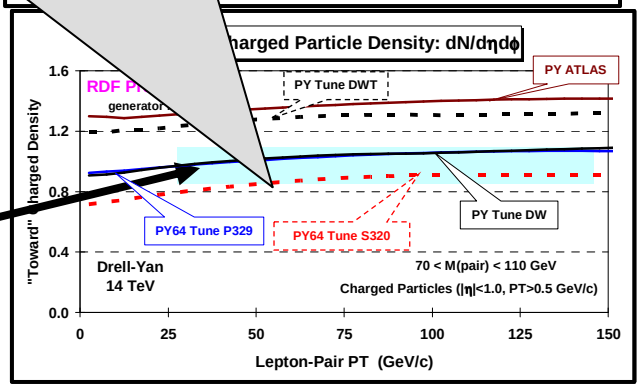
- **The amount of activity in "min**



- **The amount of acti scattering eve**





- **The amount of activity in the "underlying ev" in Drell-Yan events.**

Stay tuned! UE studies at 900 GeV coming soon from CMS and ATLAS.