Chris Quigg Symposium

Predicting MB & UE at the LHC

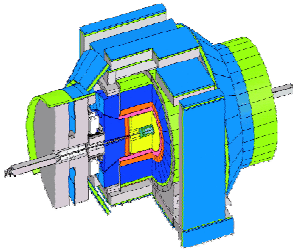
Rick Field

University of Florida

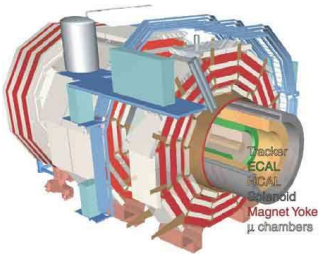
Quantum Chromo-Dynamics

Outline of Talk

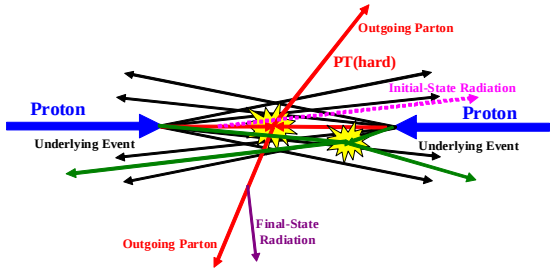
- The inelastic non-diffractive cross section.
- The "underlying event" in a hard scattering process.
- The QCD Monte-Carlo model tunes.
- Relationship between the "underlying event" in a hard scattering process and "min-bias" collisions.
- "Min-Bias" and the "underlying event" at the LHC.



CDF Run 2



CMS at the LHC



UE&MB@CMS

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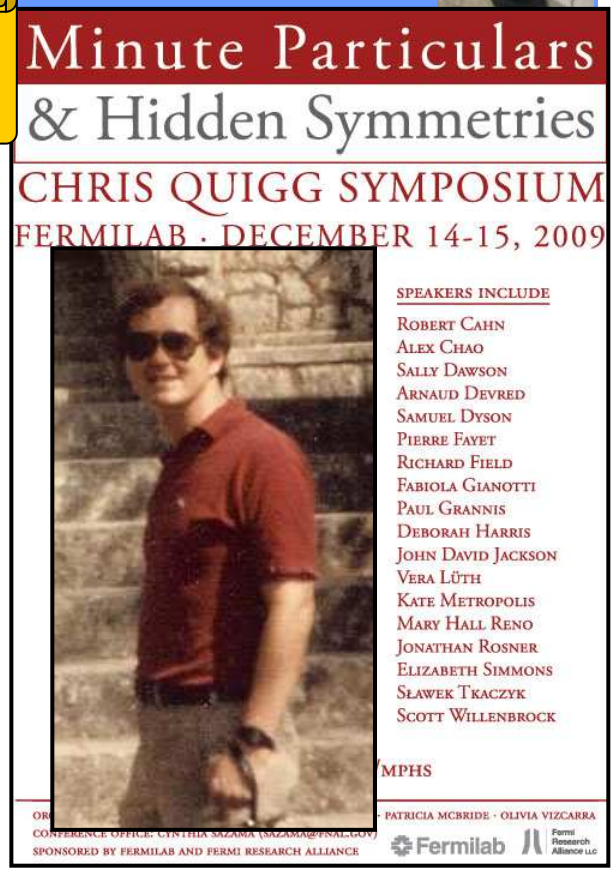

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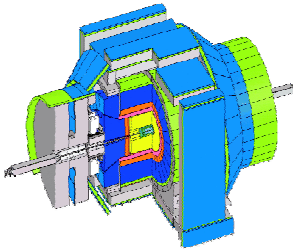

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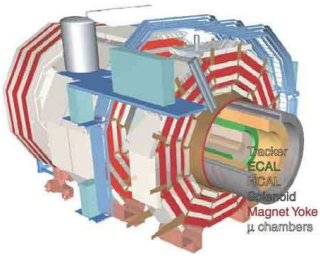
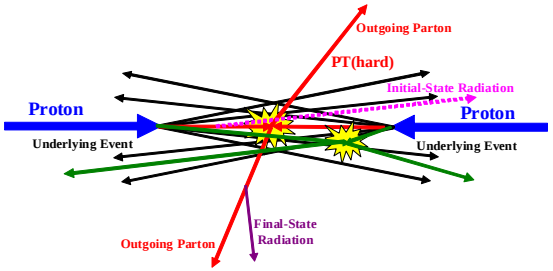
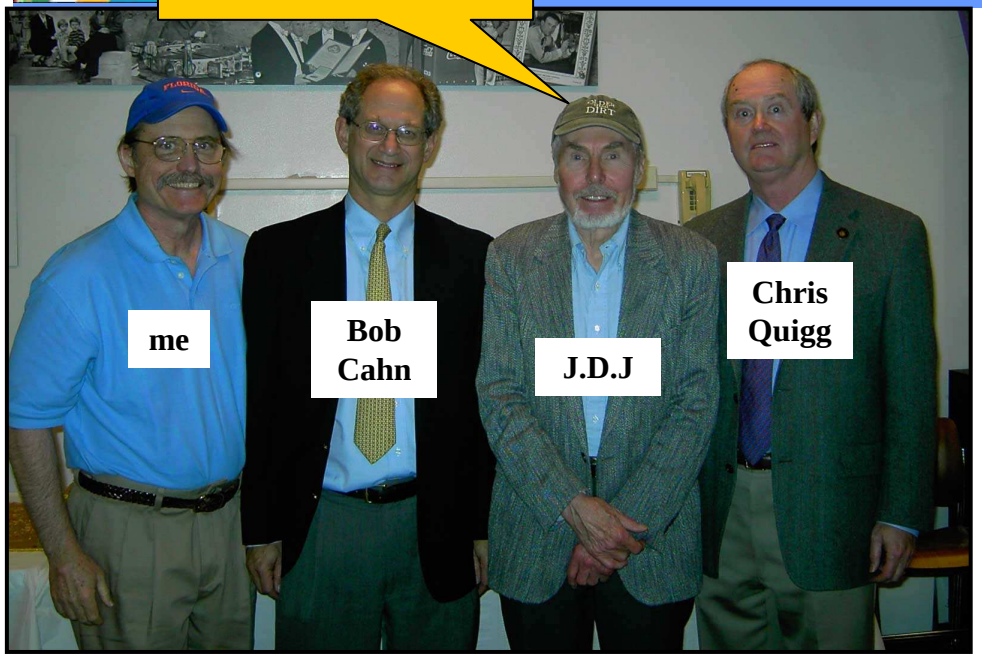


CMS at the LHC



UE&MB@CMS

J.D.J. Students



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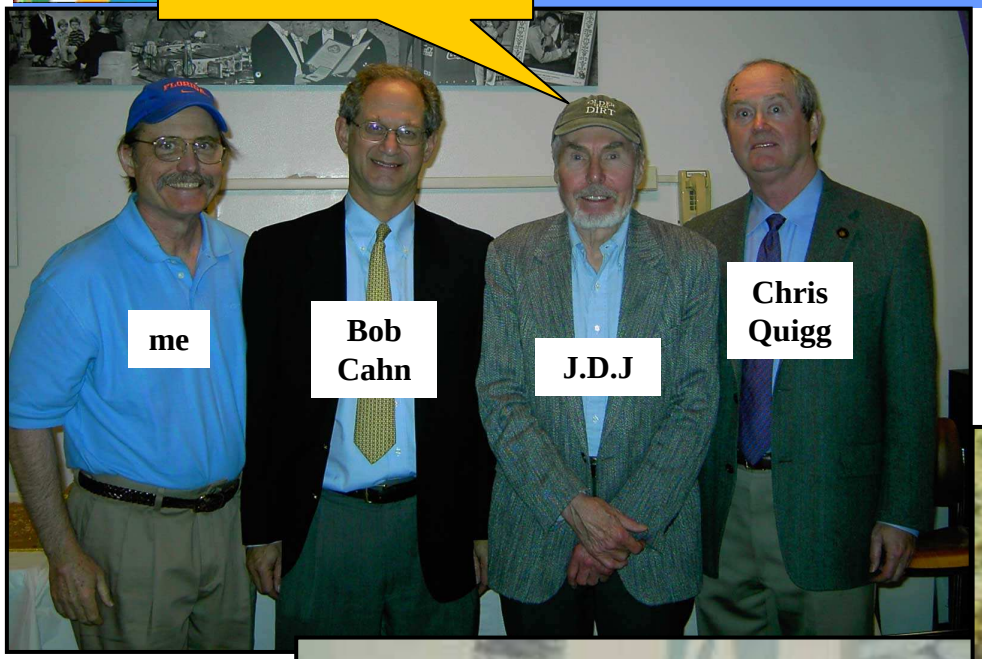
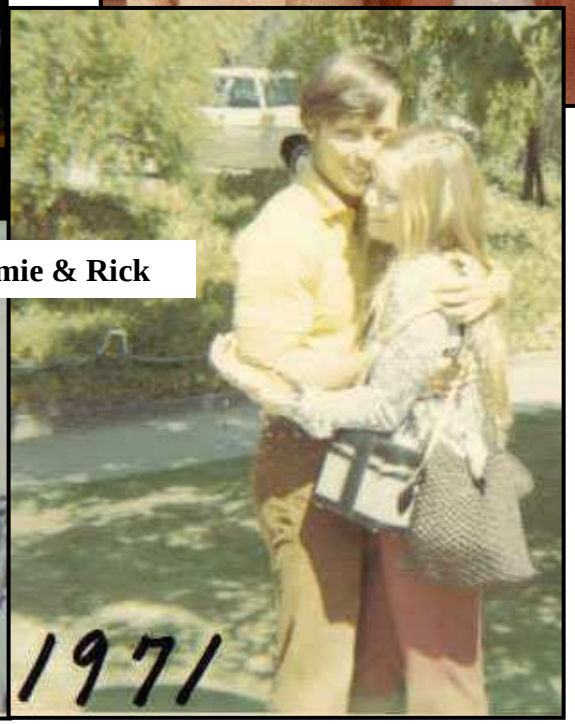
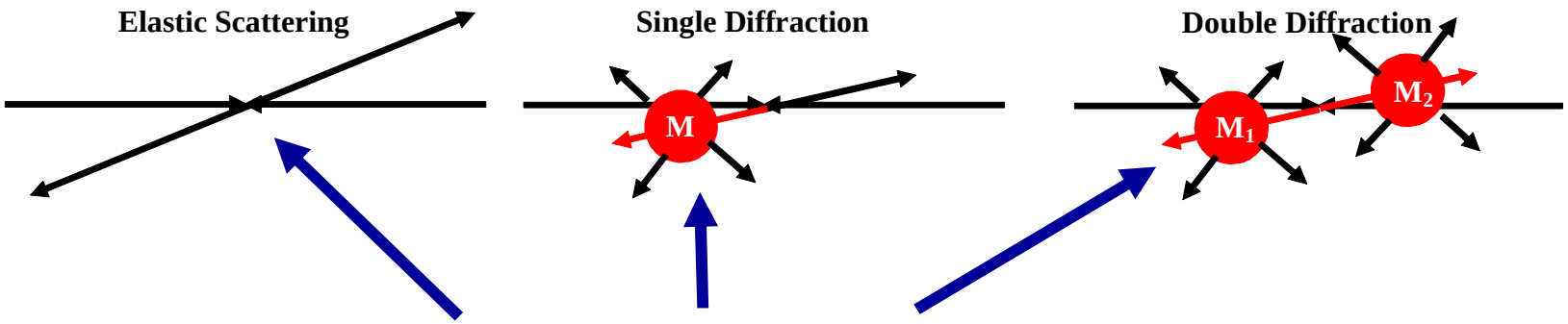




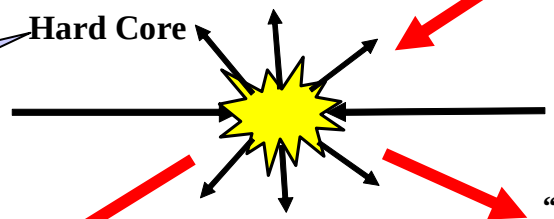
Proton-Proton Collisions

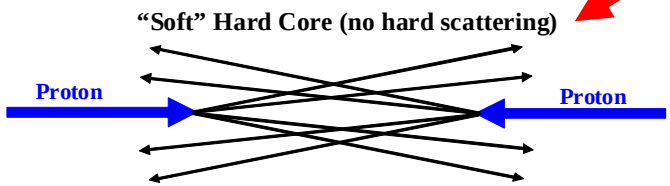


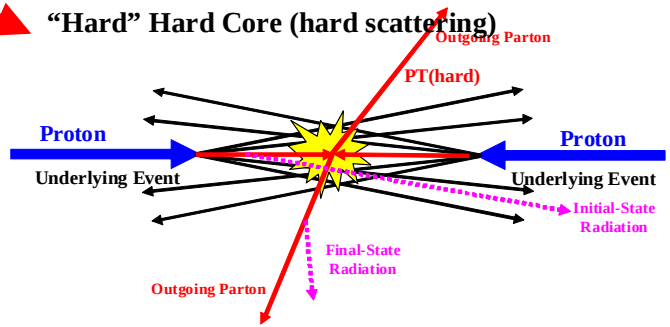
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND}$$

"Inelastic Non-Diffractive Component"

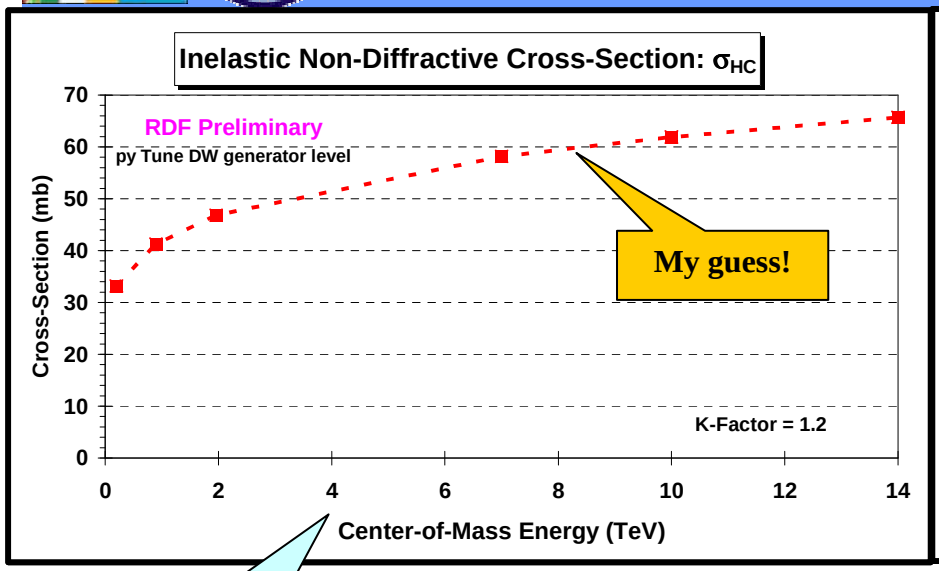
The "hard core" component contains both "hard" and "soft" collisions.

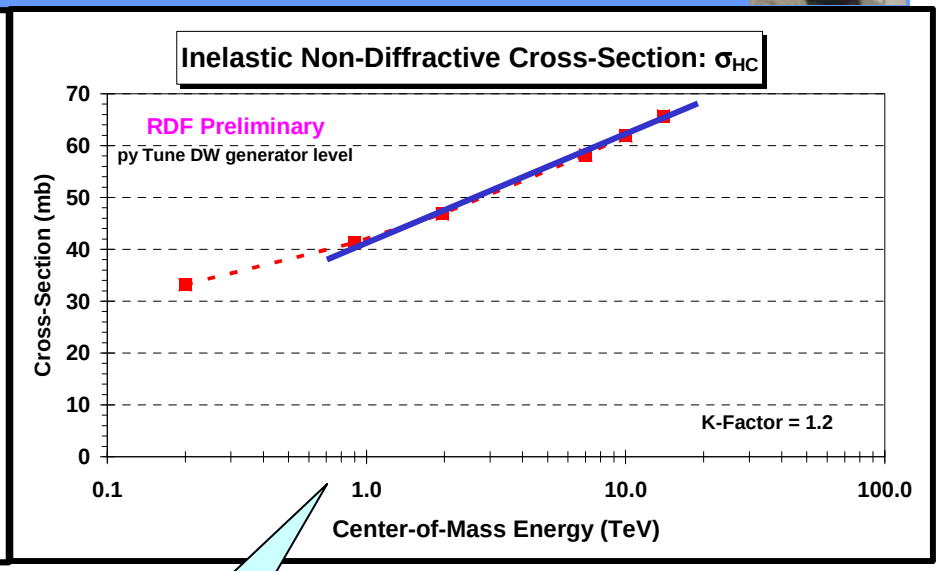






Inelastic Non-Diffractive Cross-Section





Linear scale!

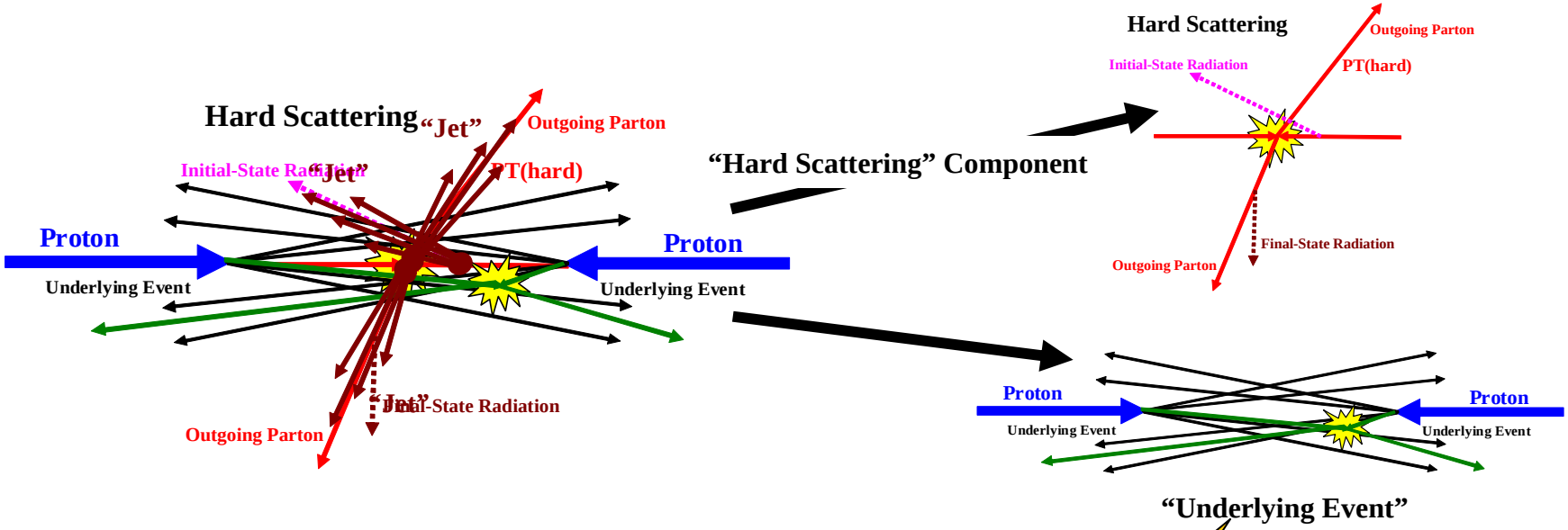
Log scale!

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

- **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

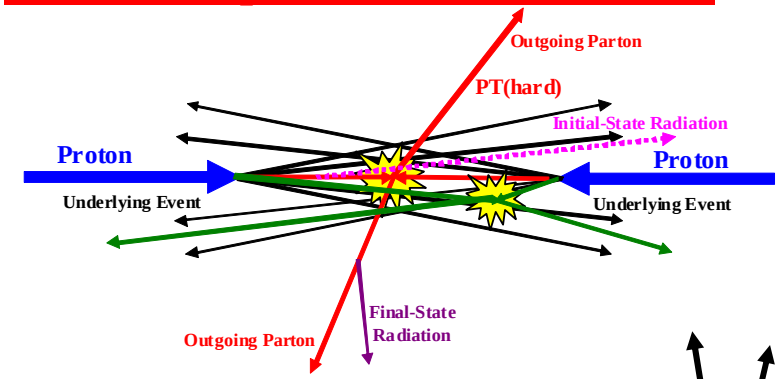


- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scatter[illegible]g and add initial and final-state gluon radiation (in the leading log approximation or modified leadin[illegible] approximation).
- The "underlying event" consists of the "beam-beam remnants" and [illegible] articles 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!

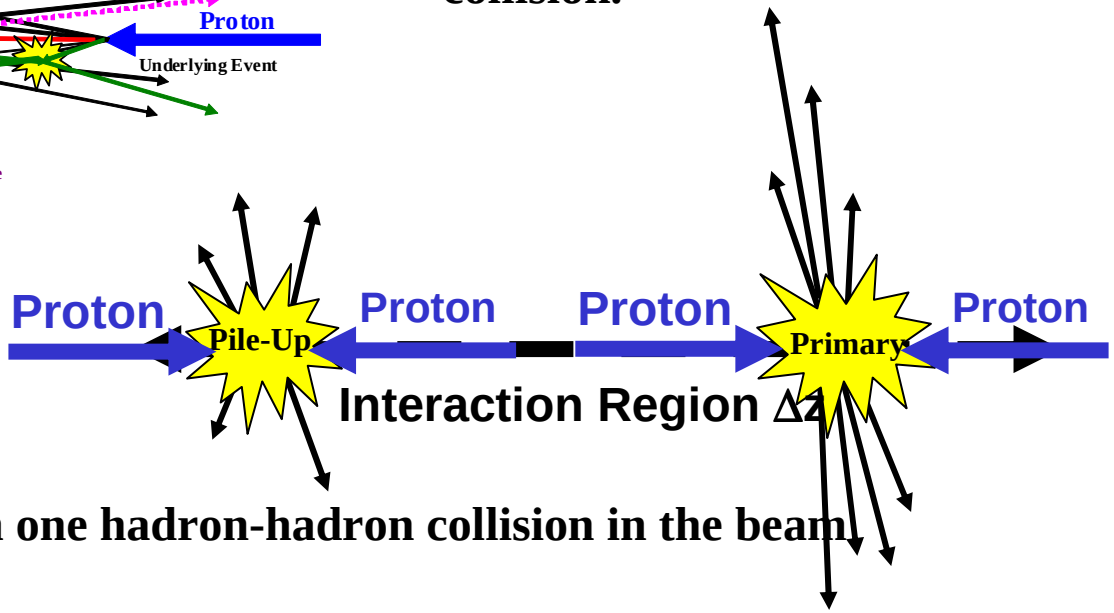
MPI, Pile-Up, and Overlap

MPI: Multiple Parton Interactions



- **MPI: Additional 2-to-2 parton-parton scatterings within a single hadron-hadron collision.**

Pile-Up

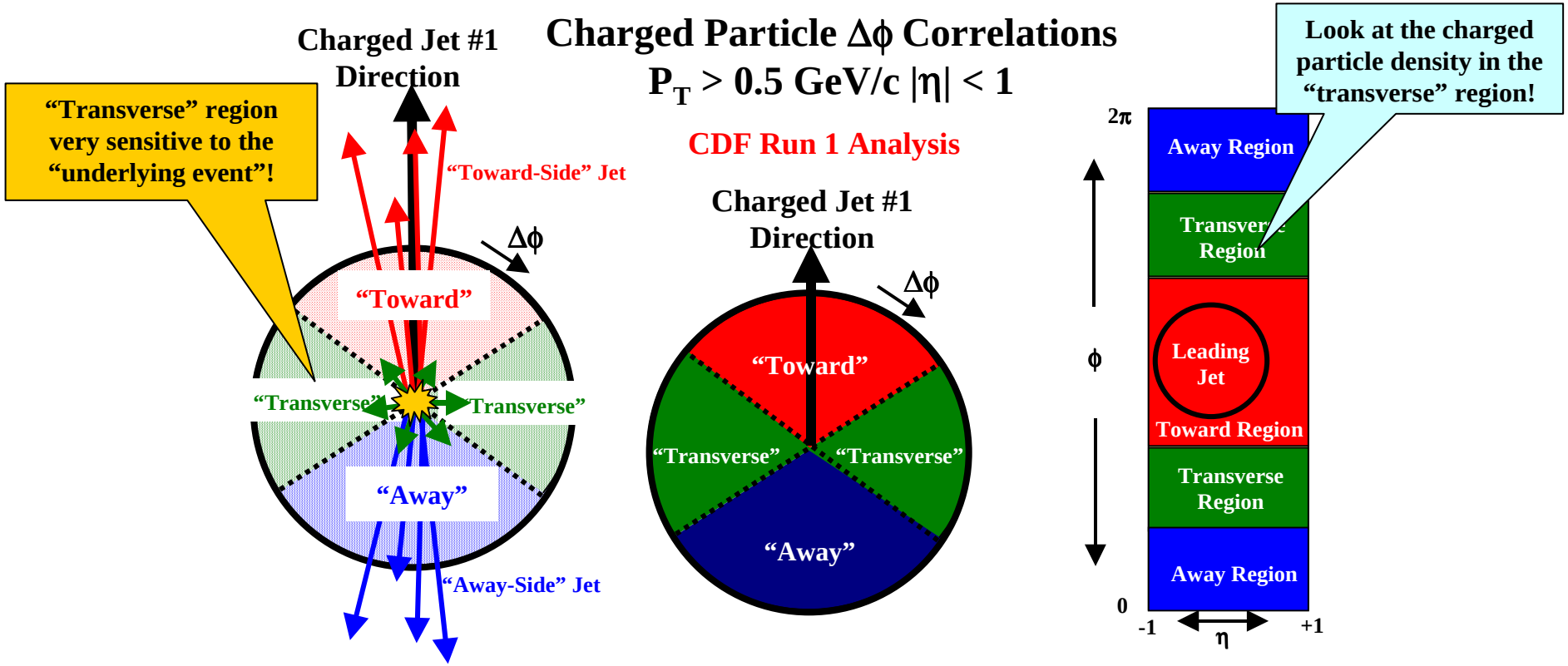


- **Pile-Up: More than one hadron-hadron collision in the beam crossing.**

Overlap

- **Overlap: An experimental timing issue where a hadron-hadron collision from the next beam crossing gets included in the hadron-hadron collision from the current beam crossing because the next crossing happened before the event could be read out.**

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



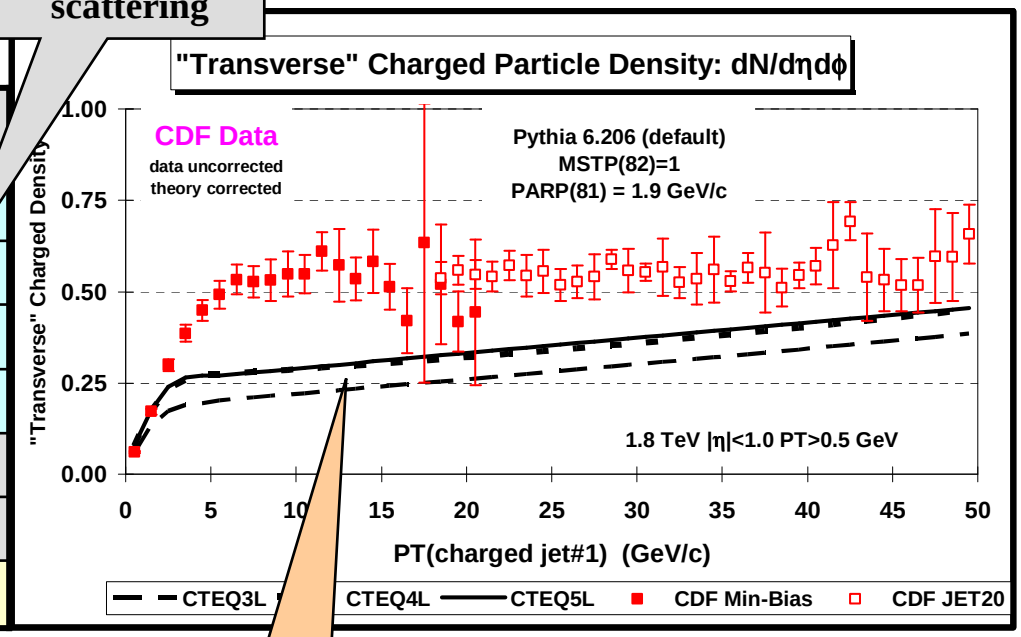
- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same size in η-ϕ space, $\Delta\eta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

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)

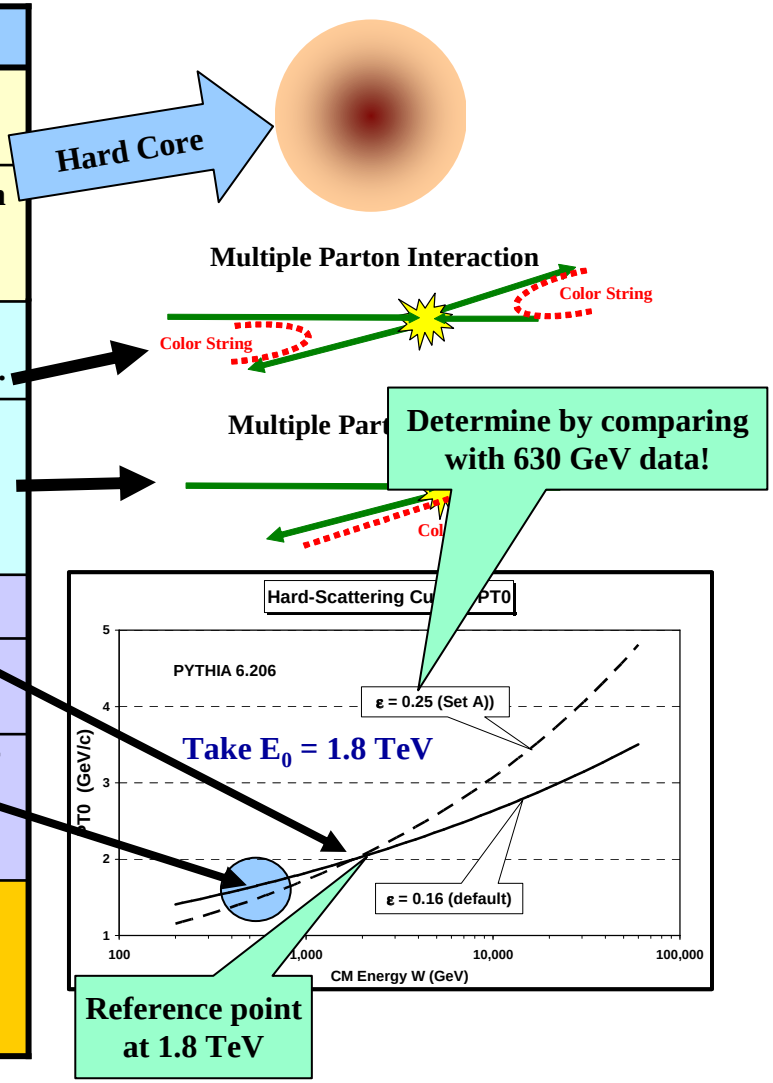
Default parameters give very poor description of the "underlying event"!

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!

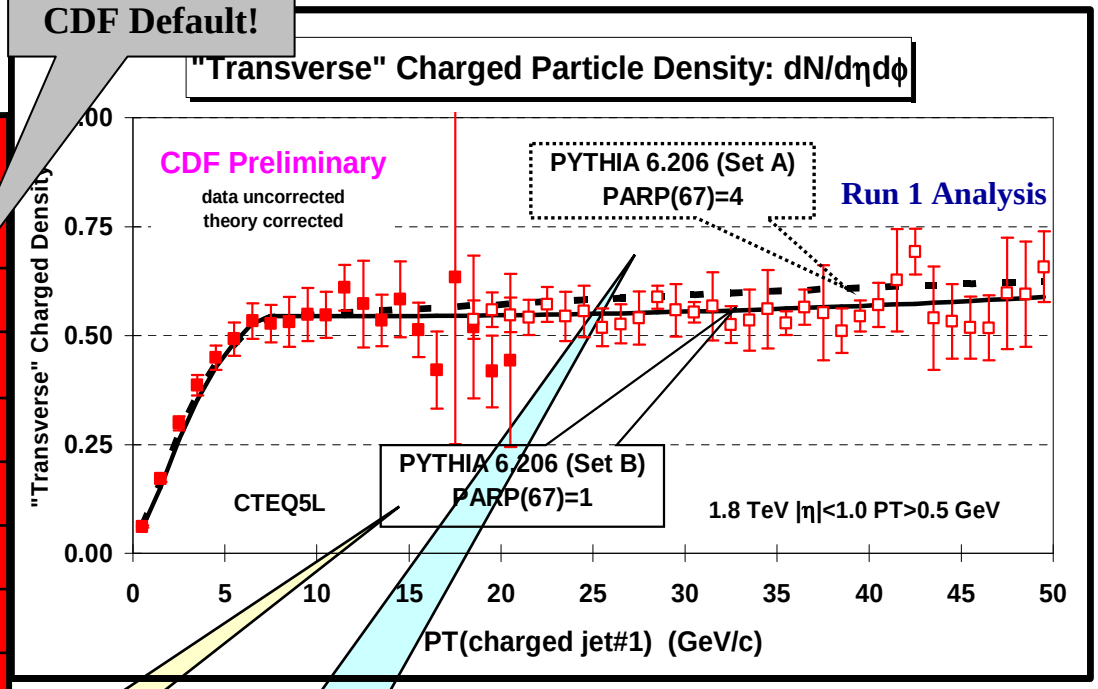


Run 1 PYTHIA Tune A

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!

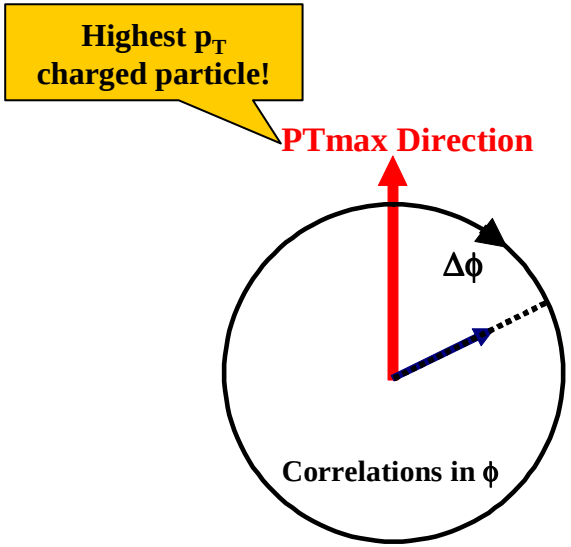


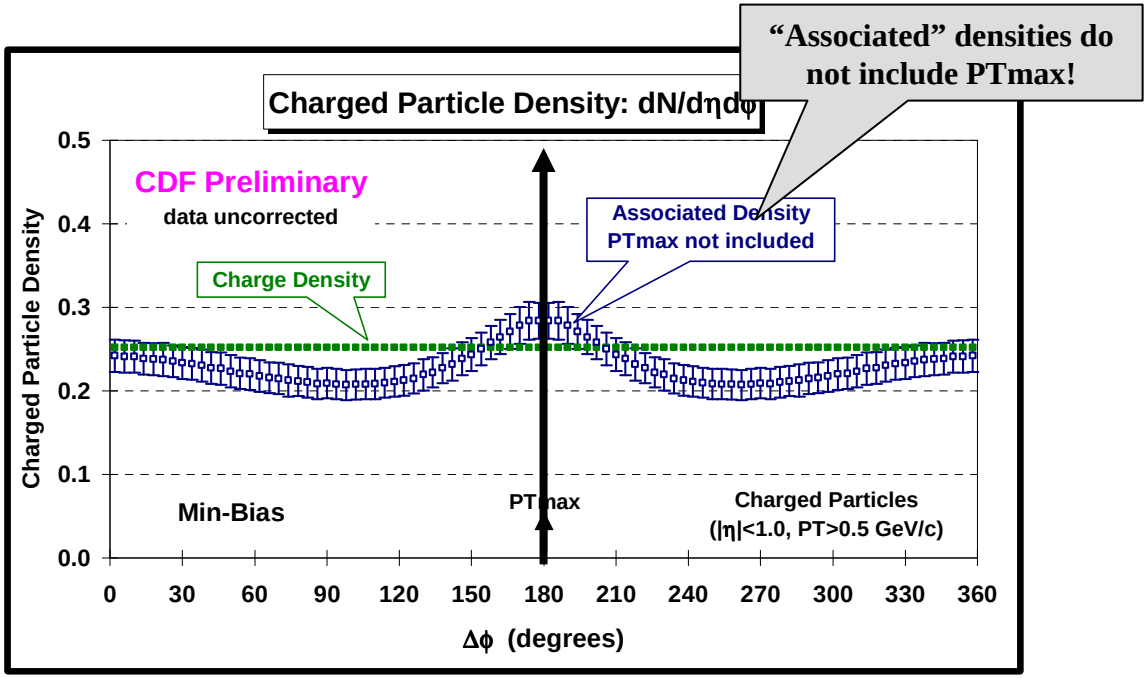
➡ **Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

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

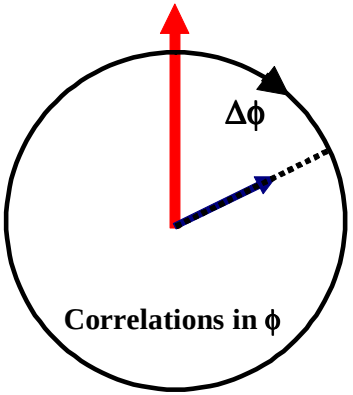




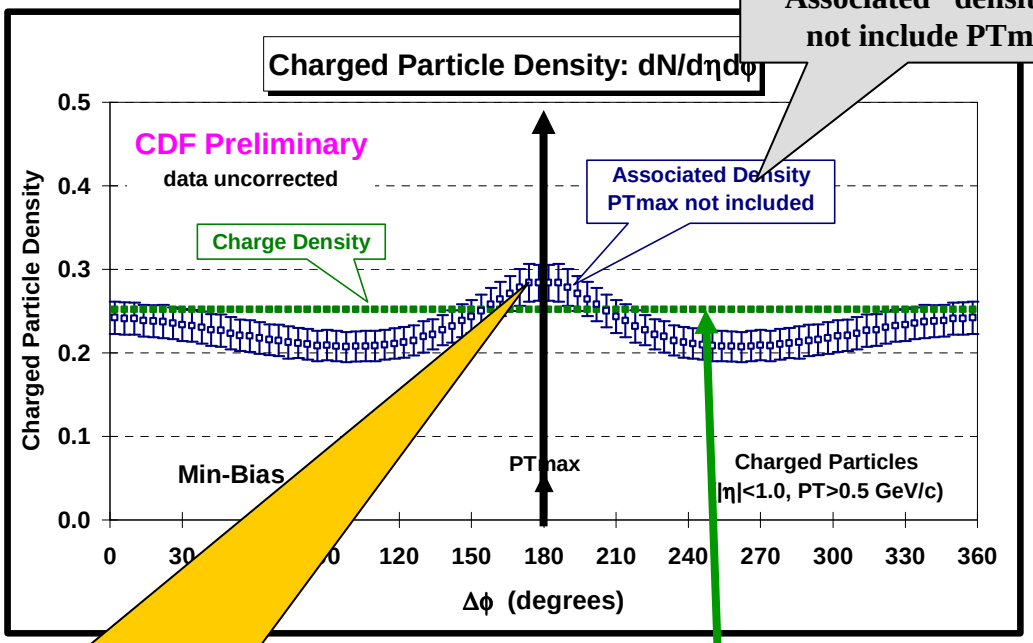
- Use the **maximum p_T charged particle in the event, PTmax**, to define a direction and look at the the "associated" density, $dN_{chg}/d\eta d\phi$, in **"min-bias" collisions** (p_T > 0.5 GeV/c, |η| < 1).
- Shows the data on the **Δϕ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, 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!

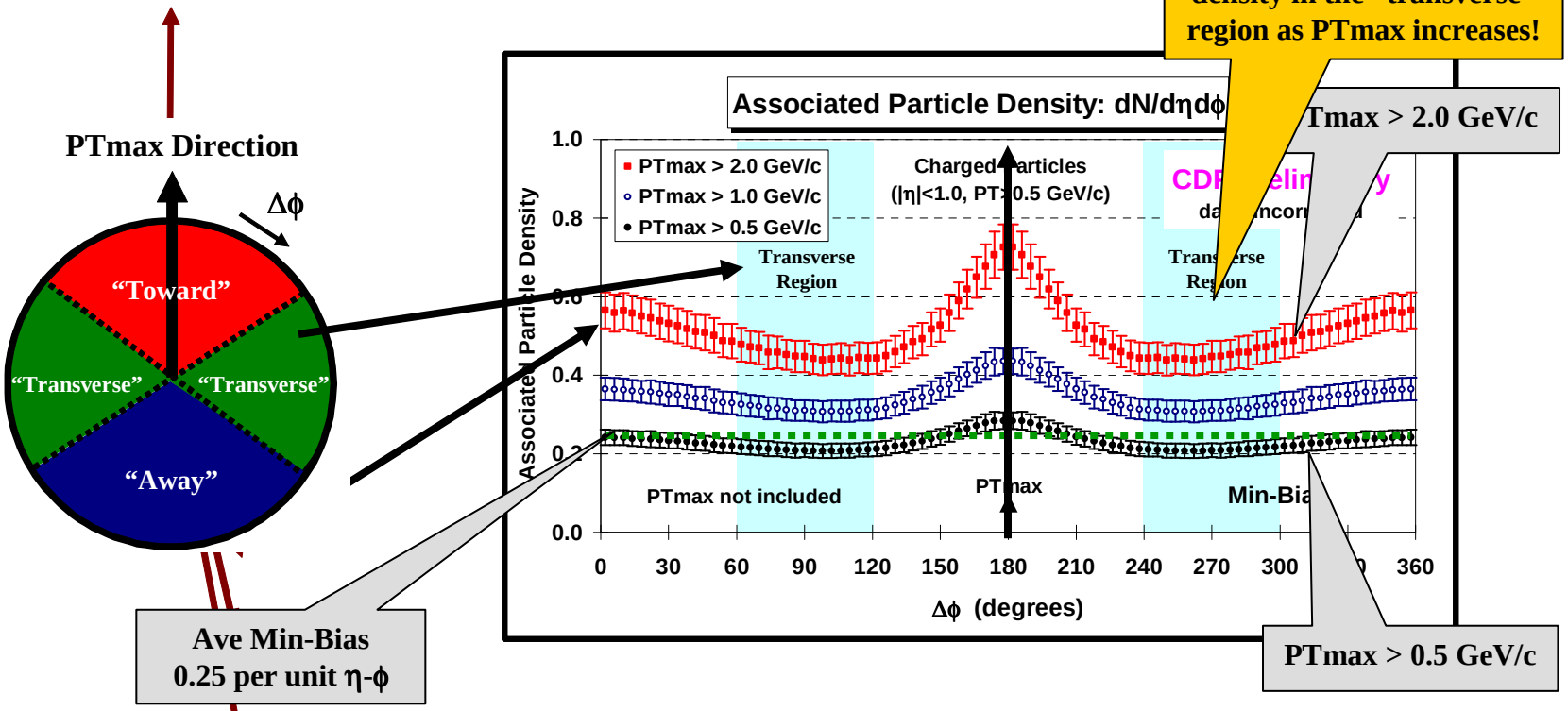


It is more probable to find a particle accompanying PTmax than it is to find a particle in the central region!

- Use the m[illegible] event, PTmax, to define a direction and look at the the [illegible]in-bias" collisions (p_T > 0.5 GeV/c, |η| < 1).
- Shows the [illegible]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.

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

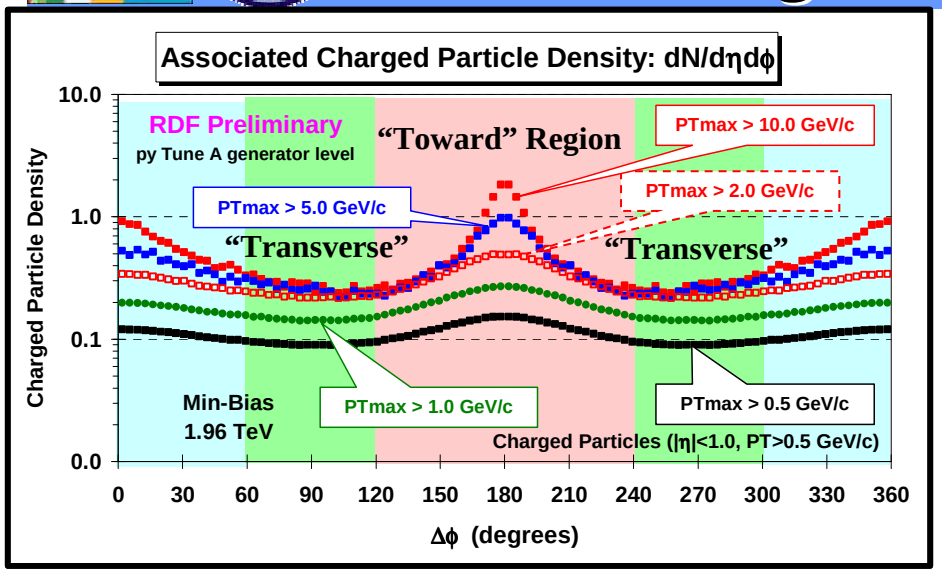
Rapid rise in the particle density in the "transverse" region as PTmax increases!

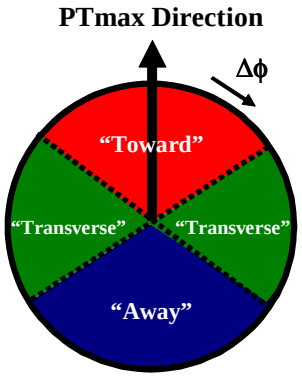


- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.

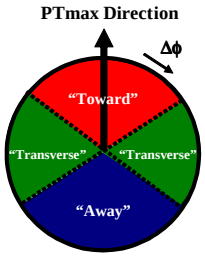
- Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).

Min-Bias "Associated" Charged Particle Density



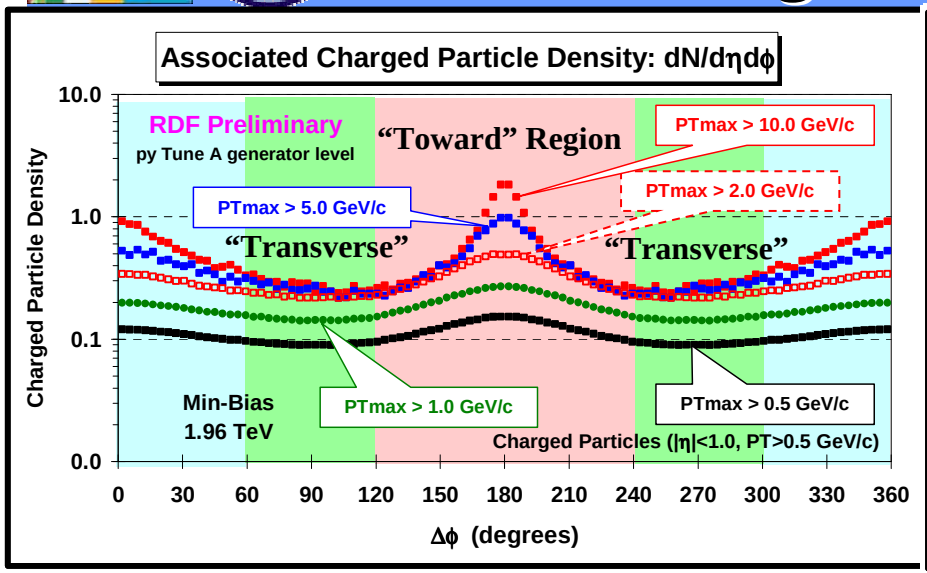


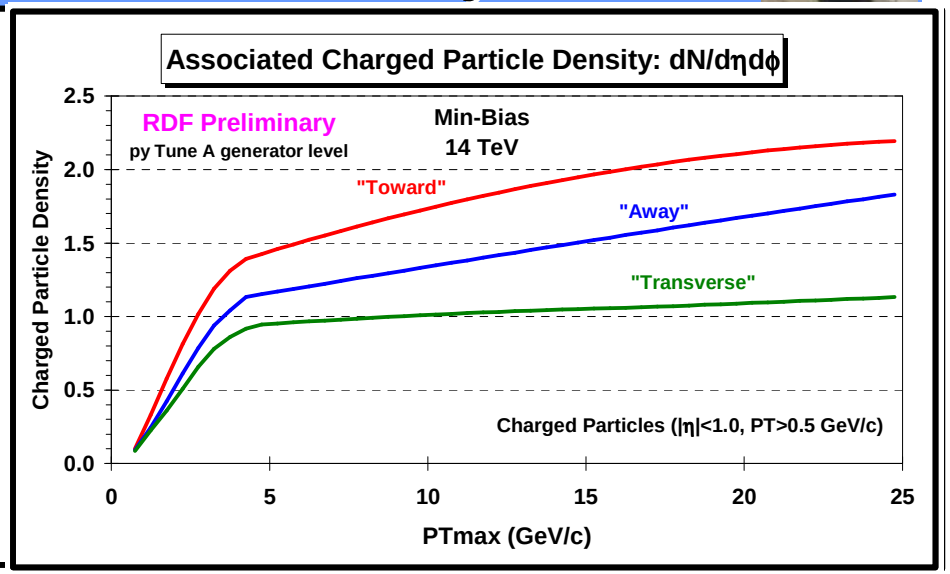
➡ **Shows the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events at 1.96 TeV with PTmax > 0.5, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune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





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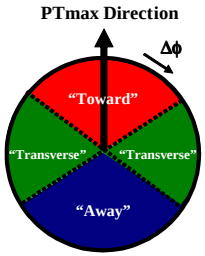
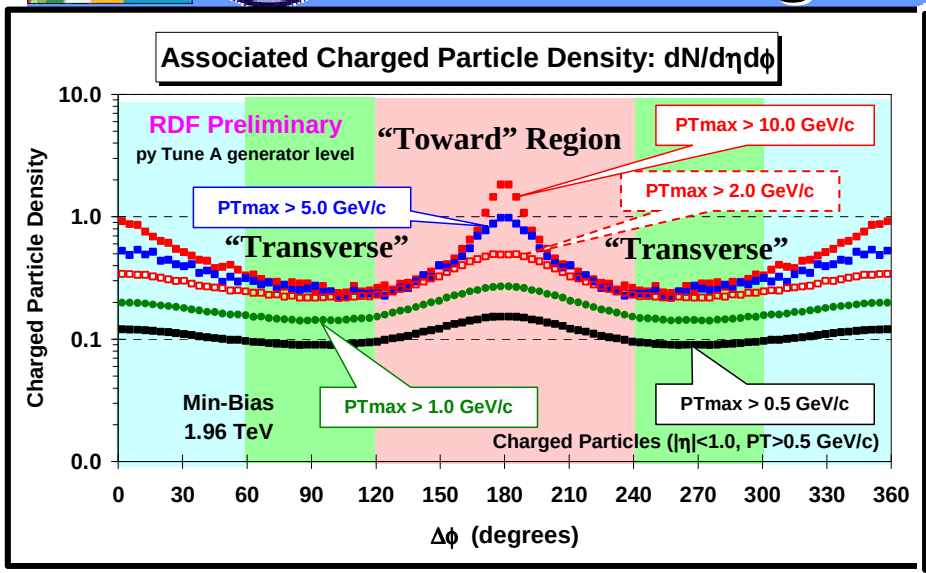
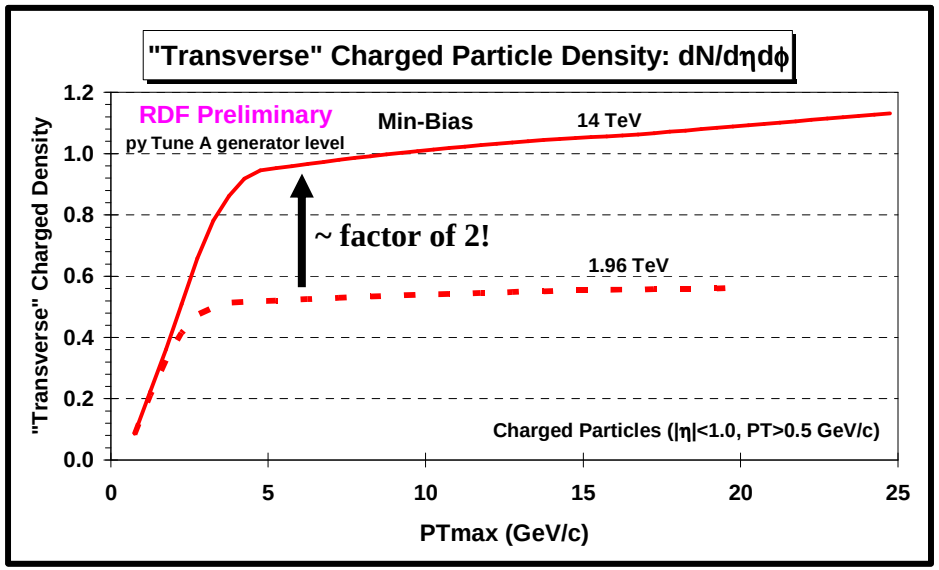


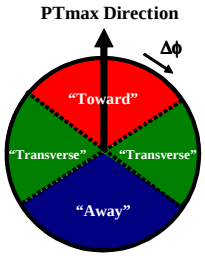
➡ **Shows the "associated" charged particle density in the "toward", "away" and "transverse" regions as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 1.96 TeV from PYTHIA Tune A (generator level).**

Min-Bias "Associated" Charged Particle Density



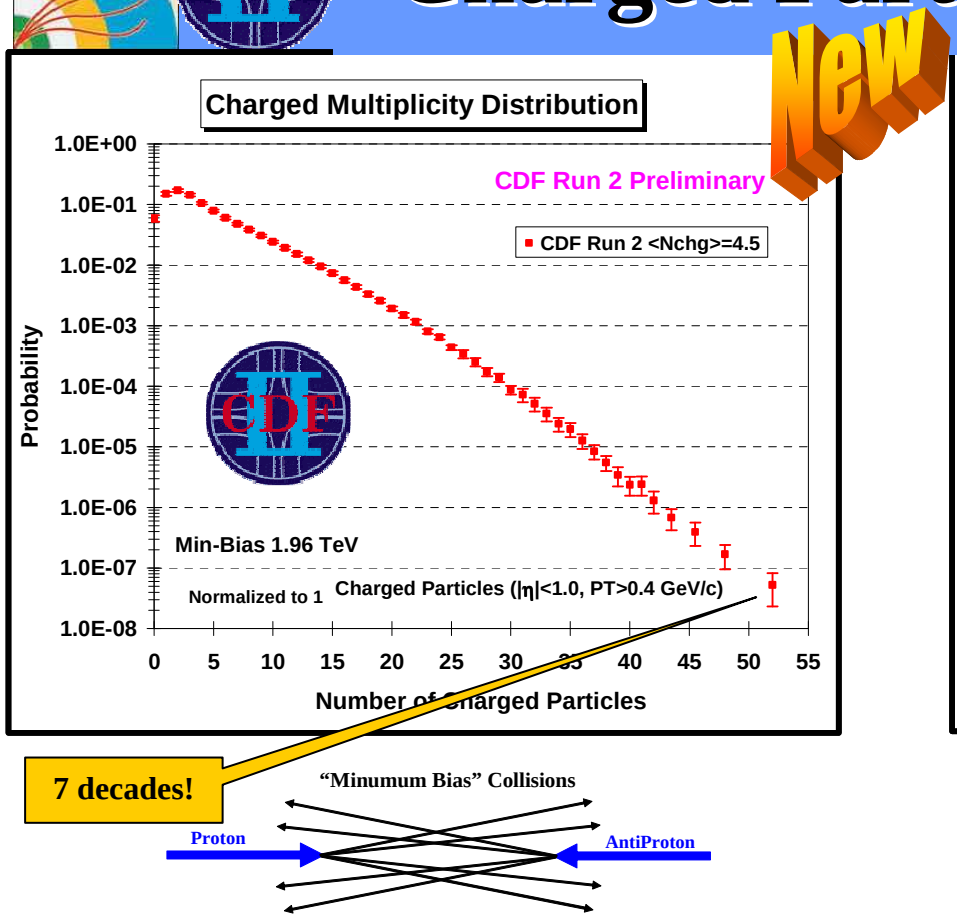


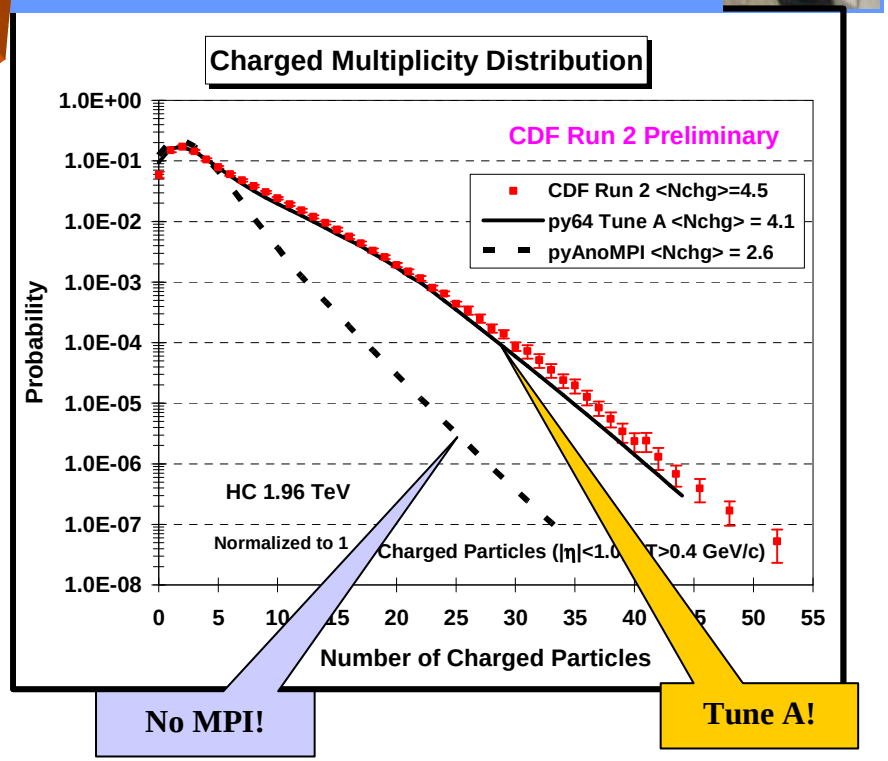
- **Shows the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events at 1.96 TeV with PTmax > 0.5, 1.0, 2.0, 5.0, and 10.0 GeV/c from PYTHIA Tune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

Charged Particle Multiplicity

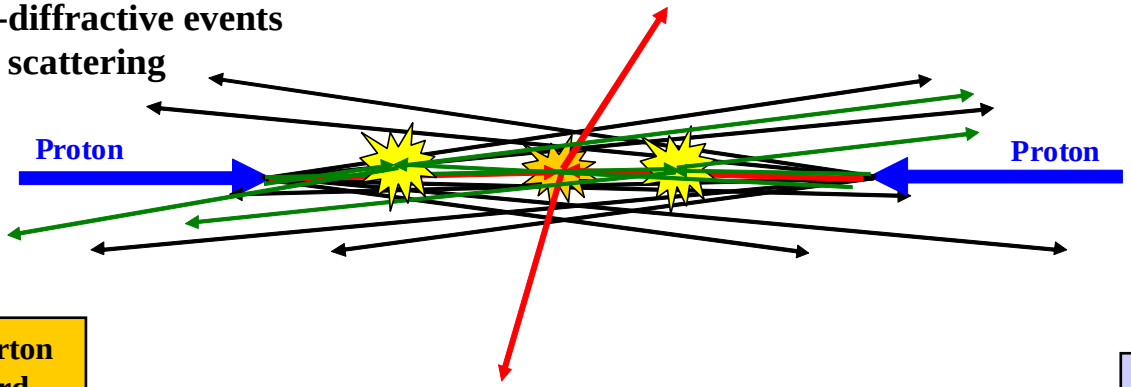




- **Data at 1.96 TeV on the charged particle multiplicity (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2.**
- **The data are compared with PYTHIA Tune A and Tune A without multiple parton interactions (pyAnoMPI).**

The "Underlying Event"

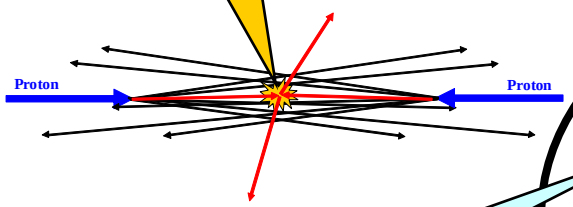
Select inelastic non-diffractive events that contain a hard scattering

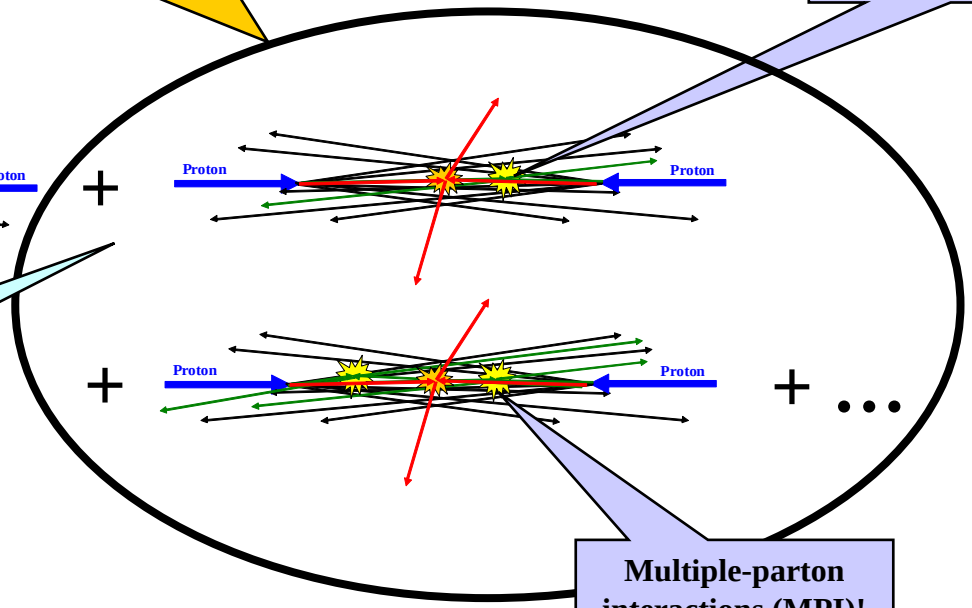


Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

The "underlying-event" (UE)!

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

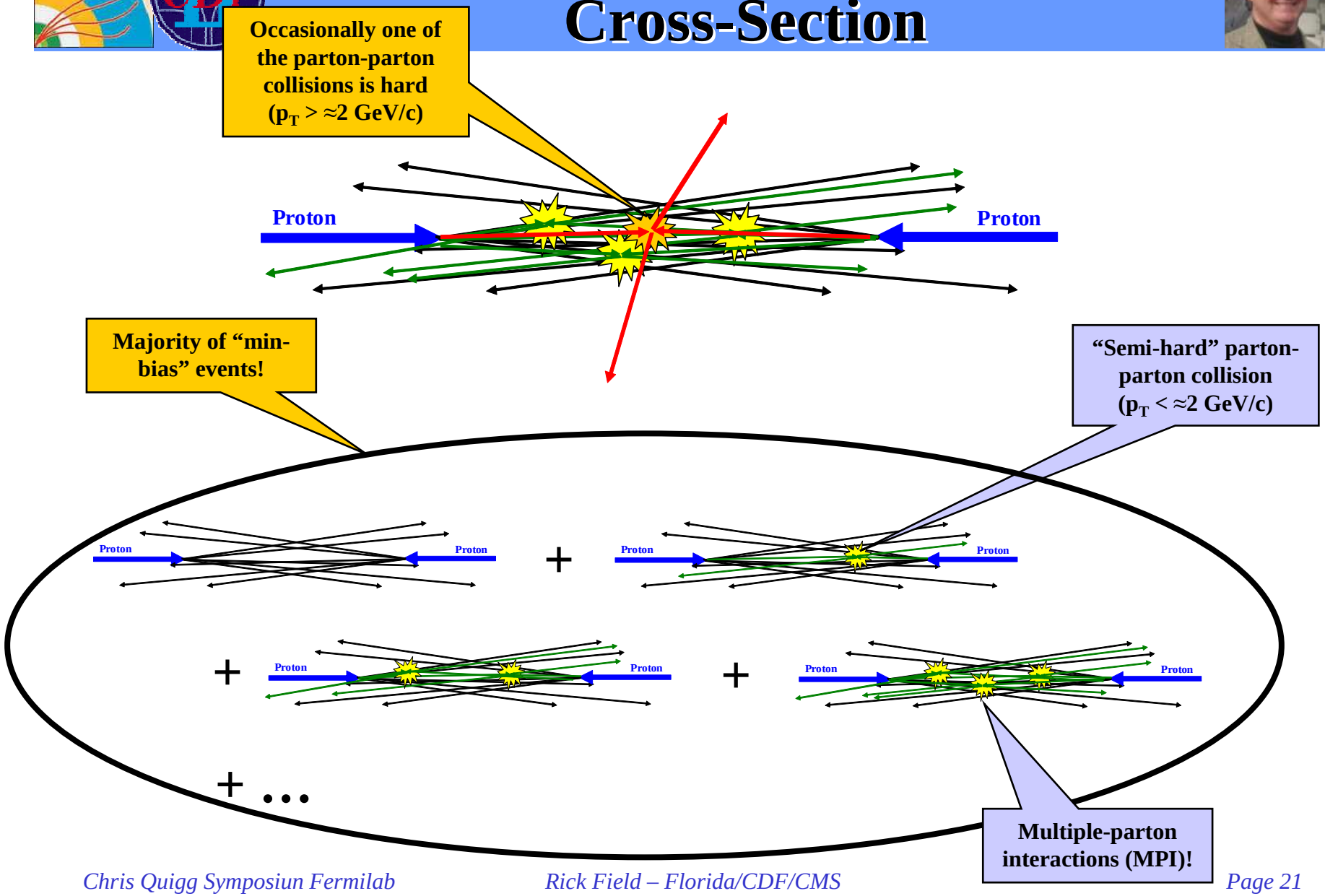




Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

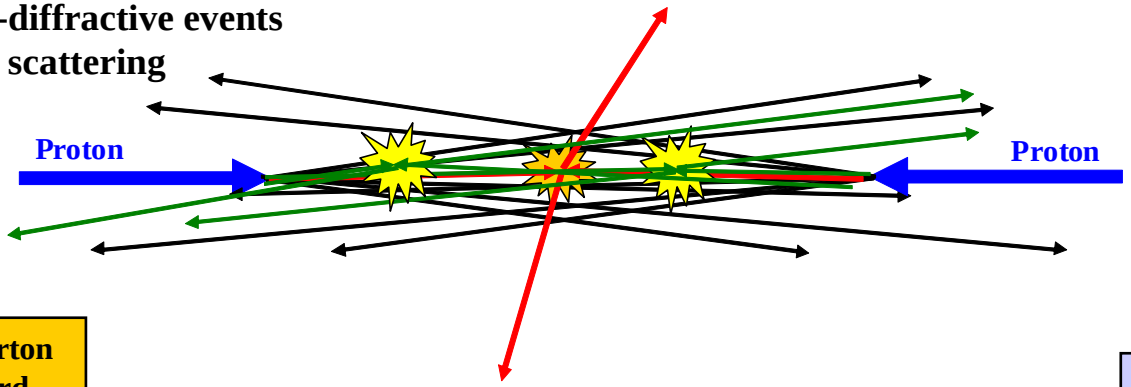
Multiple-parton interactions (MPI)!

The Inelastic Non-Diffractive Cross-Section



The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering



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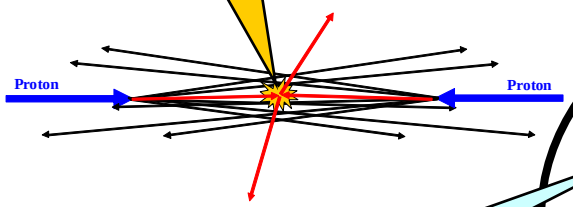
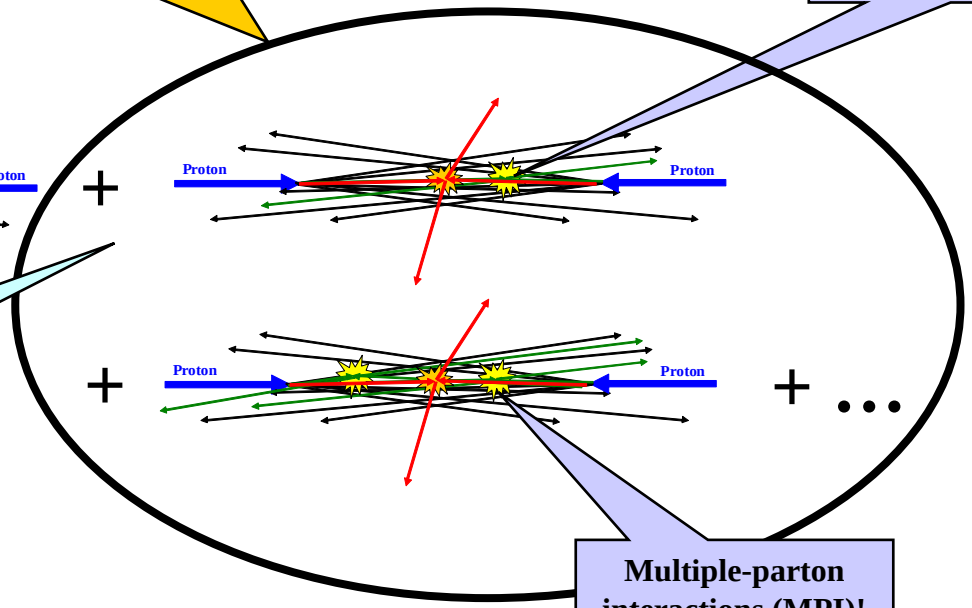
"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)

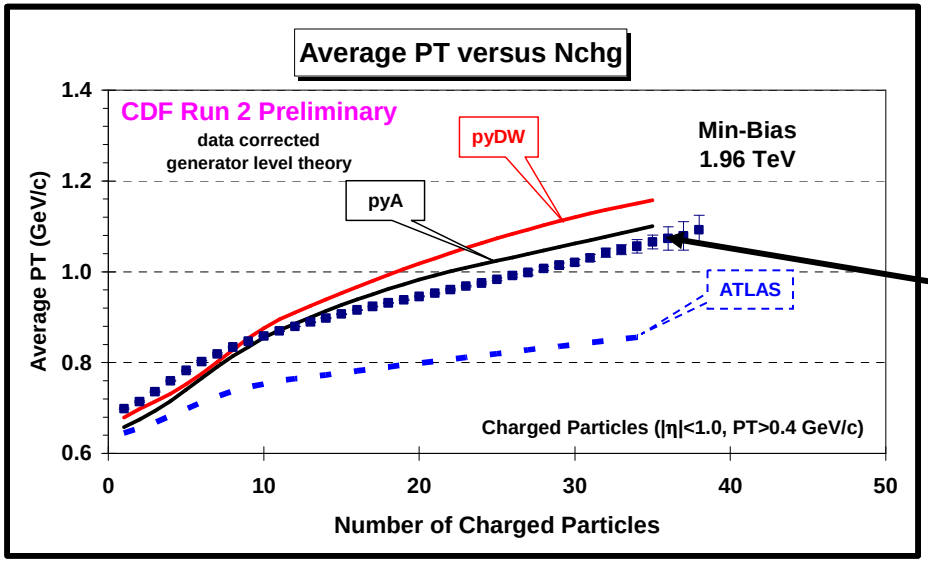


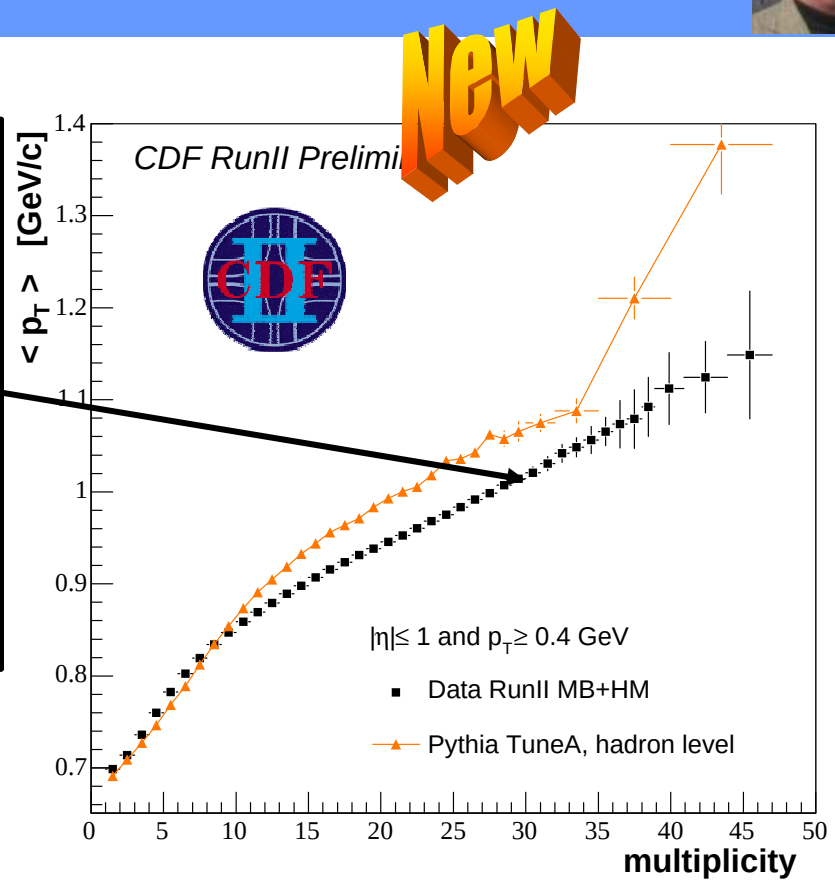


Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

Multiple-parton interactions (MPI)!

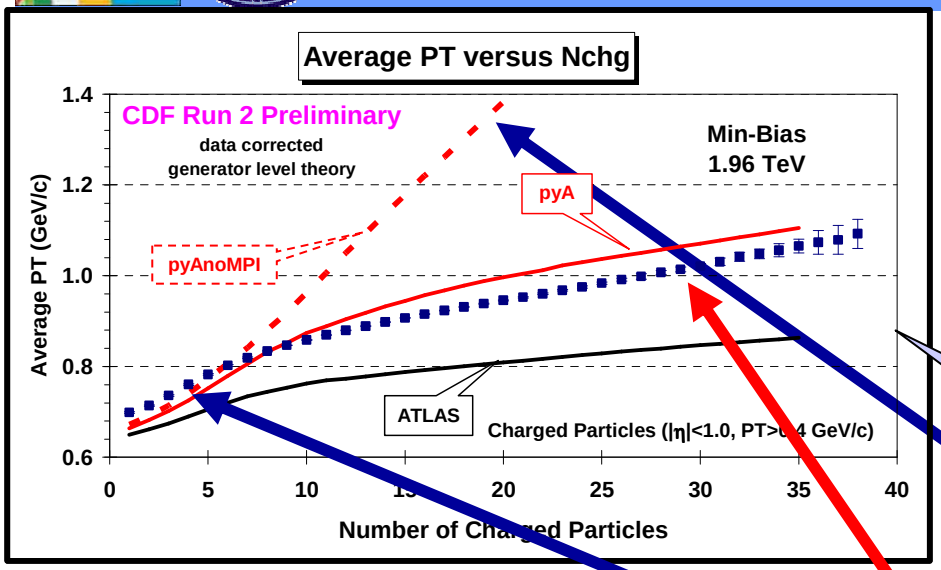
Min-Bias Correlations





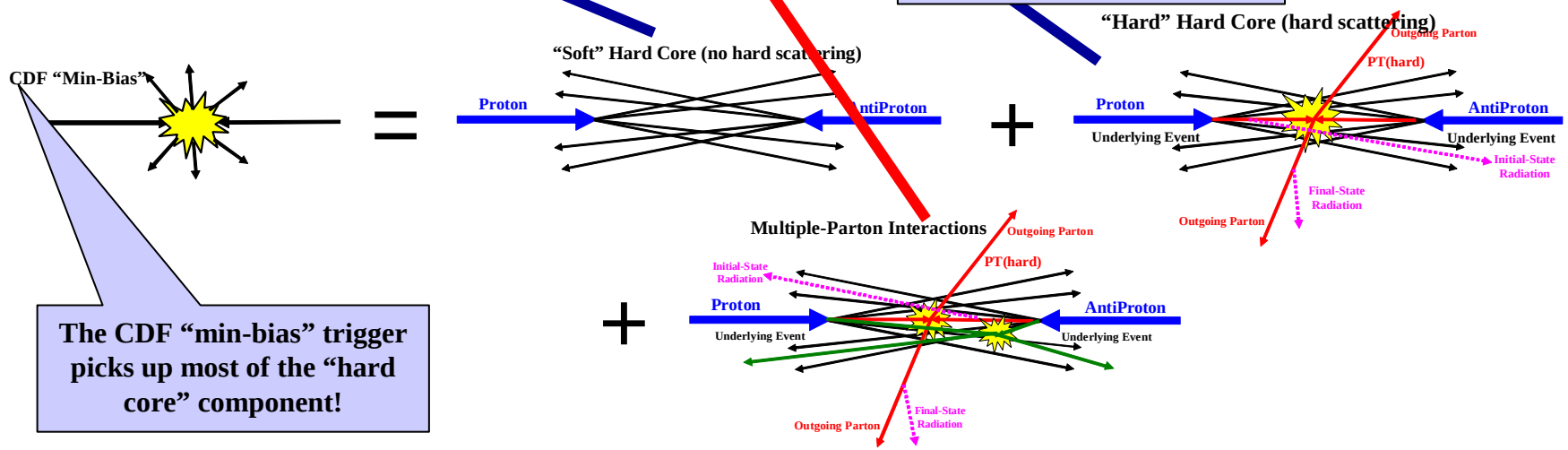
➡ **Data at 1.96 TeV on the average p_T of charged particles versus the number of charged particles (p_T > 0.4 GeV/c, |η| < 1) for "min-bias" collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A at the particle level (*i.e.* generator level).**

Min-Bias: Average PT versus Nchg



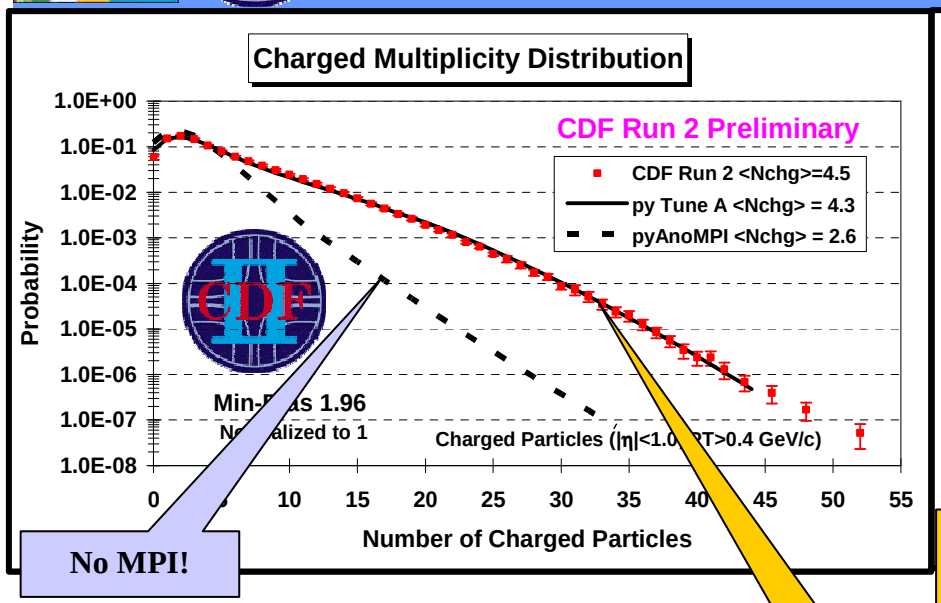
- Beam-beam remnants (*i.e.* soft hard core) produces low multiplicity and small $<p_T>$ with $<p_T>$ independent of the multiplicity.
- Hard scattering (with no MPI) produces large multiplicity and large $<p_T>$.
- Hard scattering (with MPI) produces large multiplicity and medium $<p_T>$.

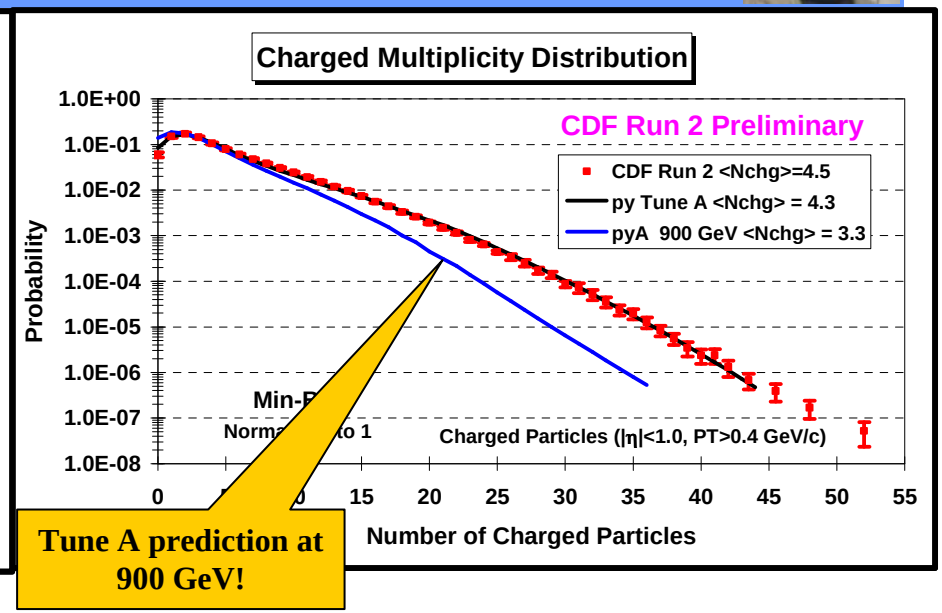
This observable is sensitive to the MPI tuning!



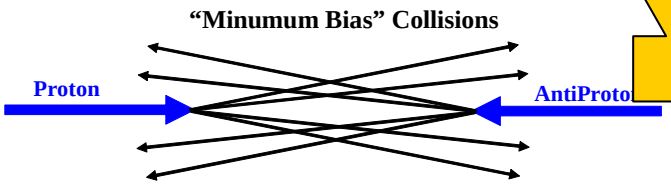
The CDF "min-bias" trigger picks up most of the "hard core" component!

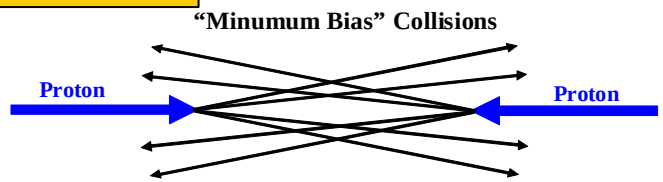
Charged Particle Multiplicity





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).
- Prediction from PYTHIA Tune A for proton-proton collisions at 900 GeV.

Peter's Pythia Tunes WEBsite

Peter's Pyth

February 2009 © P

Navigate these pages by using the menu to the lef
become available, and as the available data increas
comparison of a small number of tunes to available
but look for links at the top of each page for compar

Apr 2009: Full descriptions and parameters of the "P
MPI workshop proceedings)
Dec 2007: Some interesting min-bias distributions fo
Houches workshop proceedings)

The tunes currently available on the plots are (numb

Tunes using Q2-ordered model

- 100: **A**: Rick Field's Tune A to Tevatron Underl
shower models, with a double-gaussian matte
near-maximal color correlations. [Oct 2002]
- 103: **DW**: Rick Field's Tune DW to Tevatron U
to Tune A, but has 2 GeV of primordial kT and
initial-state radiation (i.e., more ISR radiation).
correlations. [Apr 2006]
- 104: **DWT**: Variant of DW using the Pythia 6.2
agreement with Tevatron energy scaling quant
- 106: **ATLAS-DC2** ("Rome"): first ATLAS tune c
framework. Does not give very good agreemen
- 107: **A-CR**: variant of Tune A using the Pythia
new "color annealing" color reconnection mod
an example of strong color reconnections. [Ma
- 108: **D6**: Rick Field's Tune D6 to Tevatron data
- 110: **A-Pro**: Tune A with LEP tune from Profes
- 113: **DW-Pro**: Tune DW with LEP tune from P
- 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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Oct 2008]
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CTEQ6L1 PDFs. [Feb 2009]

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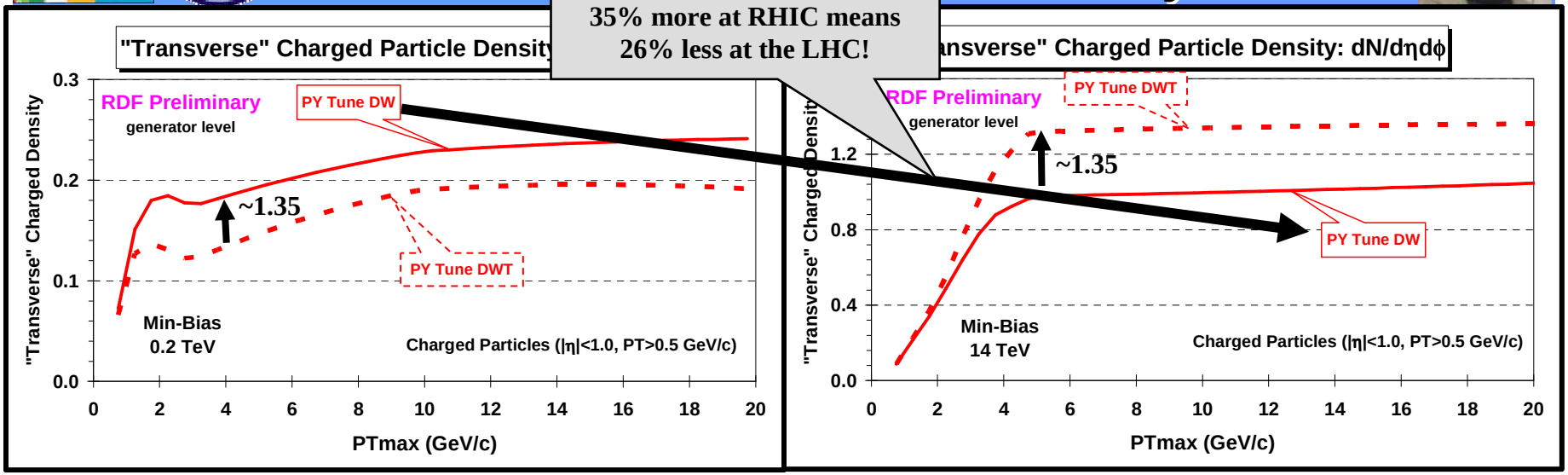
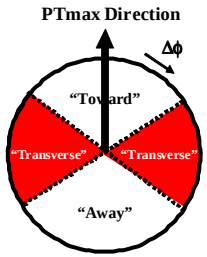
E framework made with

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

Min-Bias "Associated" Charged Particle Density

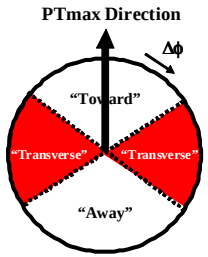


RHIC



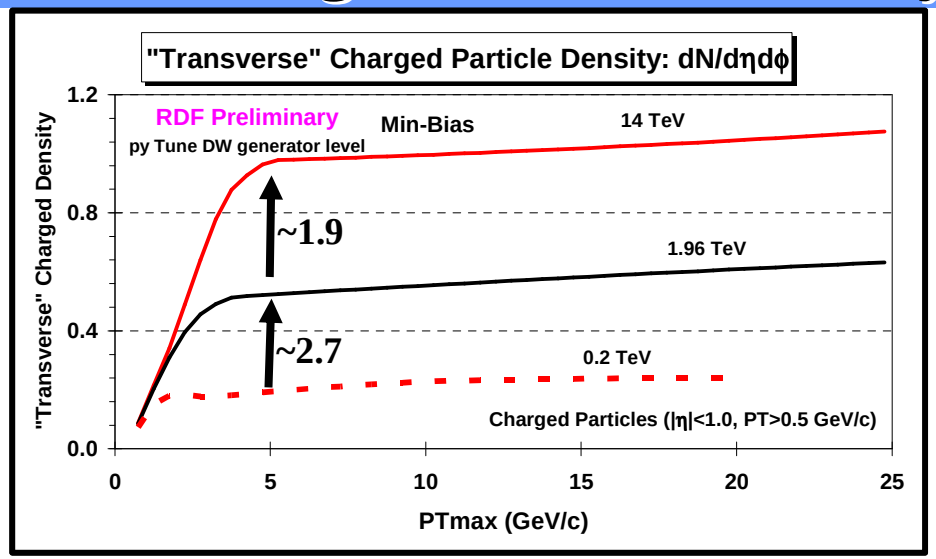
0.2 TeV → 14 TeV
(~factor of 70 increase)

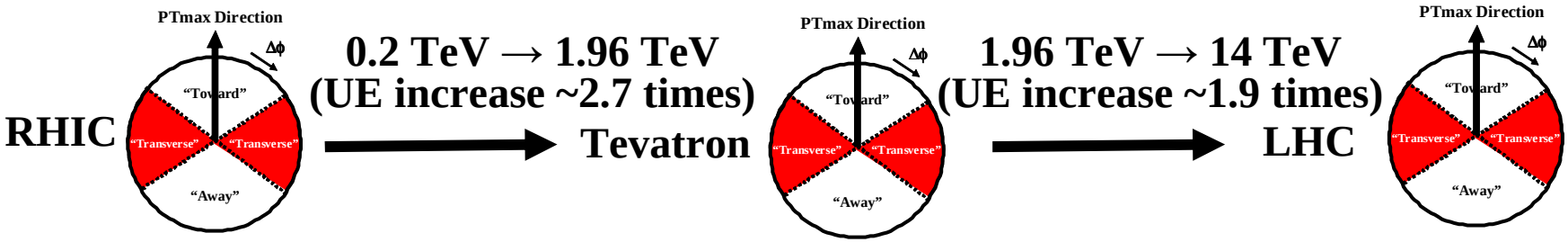
LHC



➡ **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





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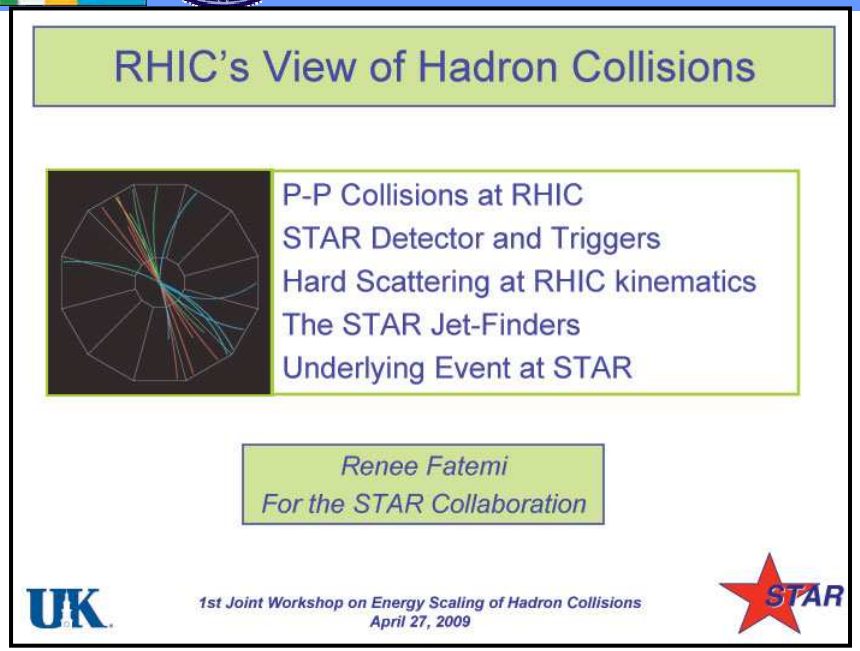
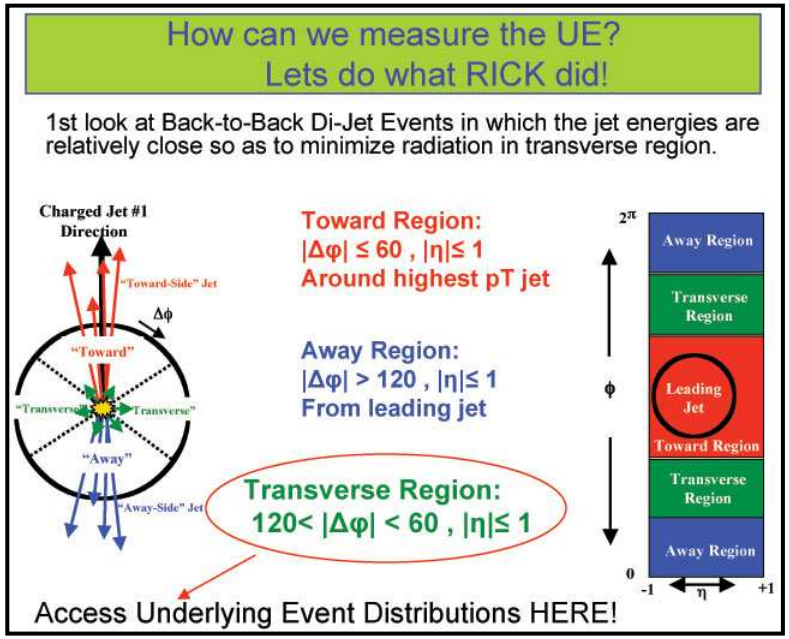
The "Underlying Event" at STAR

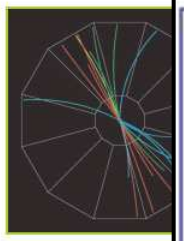




➡ **At STAR they have measured the "underlying event at W = 200 GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.**

The "Underlying Event" at STAR

RHIC



UK

ergies are
egion.

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!)

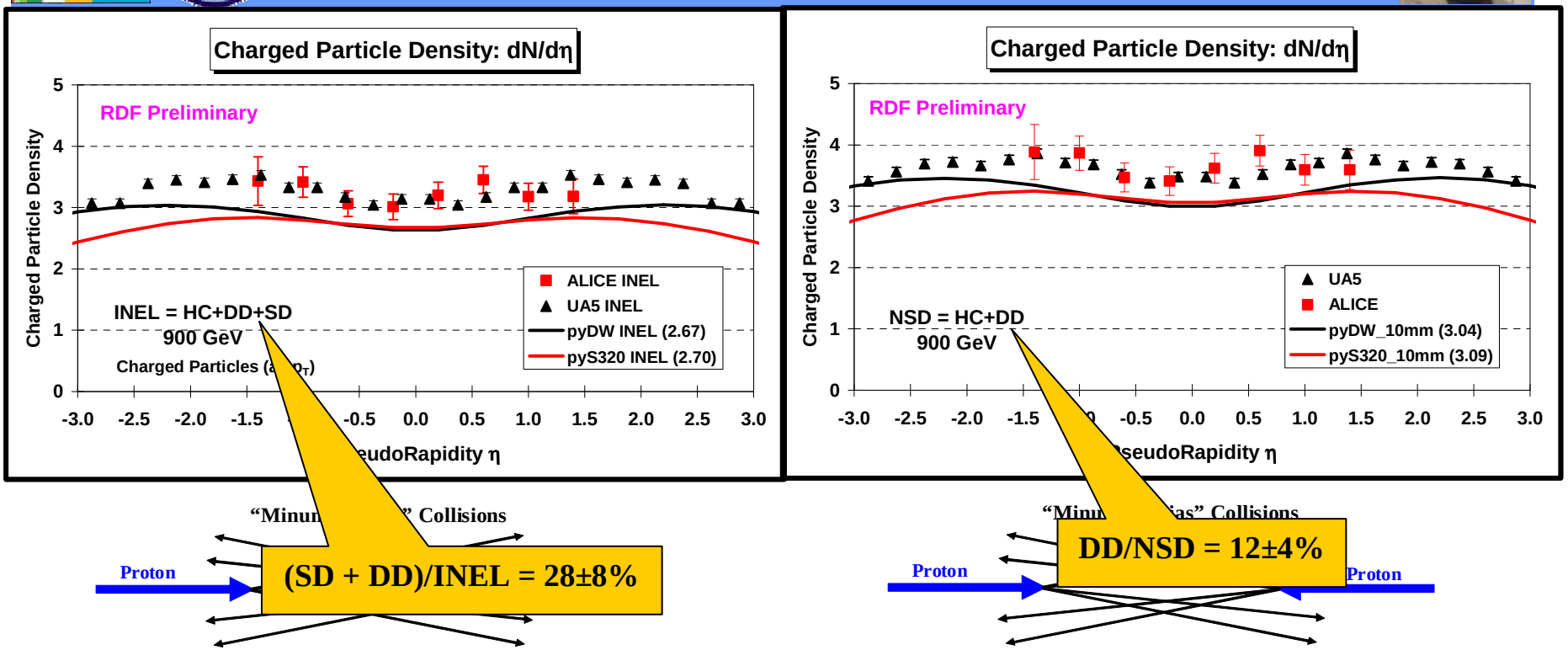
VI. Underlying Event distributions in general smaller than those at CDF. Tower & Track Multiplicities are the exception, but this may be due to the 0.2 (STAR) versus 0.5 GeV (CDF) pT/Et cut-off.

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.

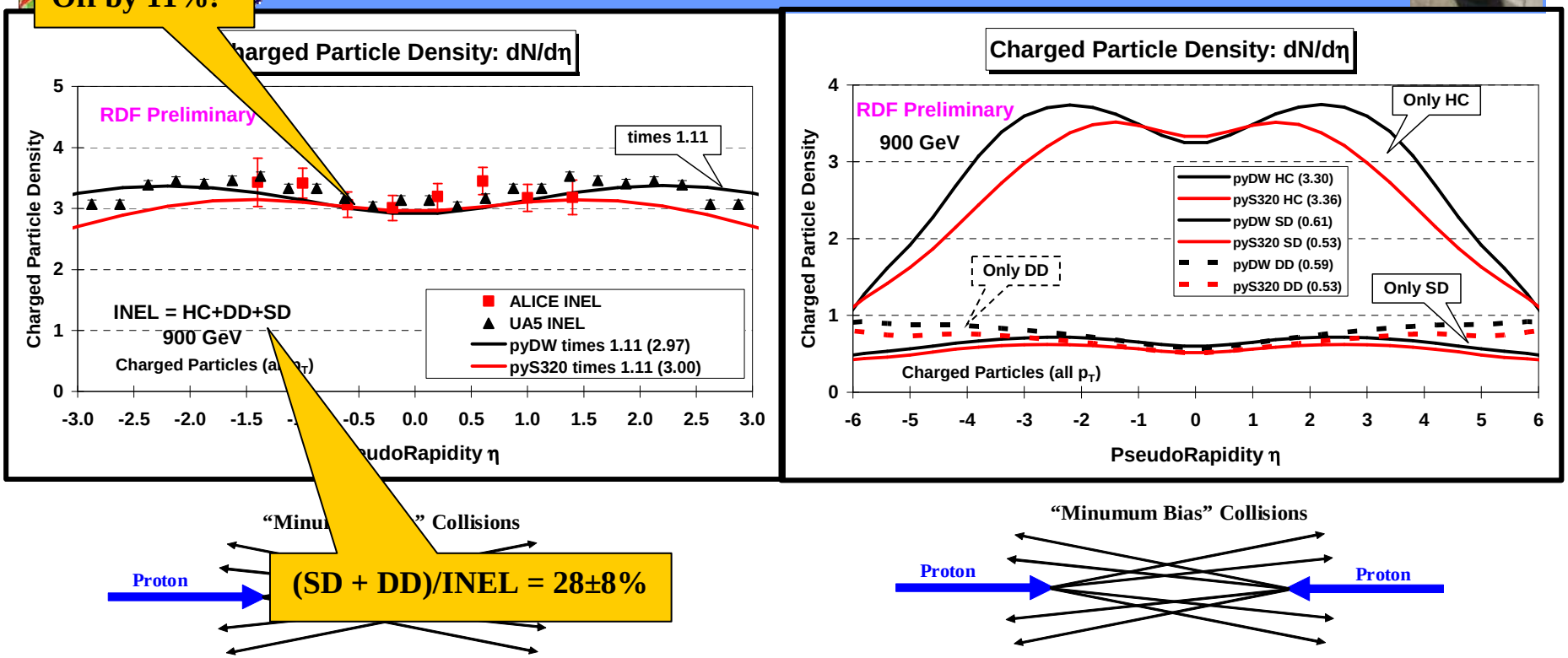
➡ **At STAR** **2 GeV)**
and comp

LHC Predictions: 900 GeV



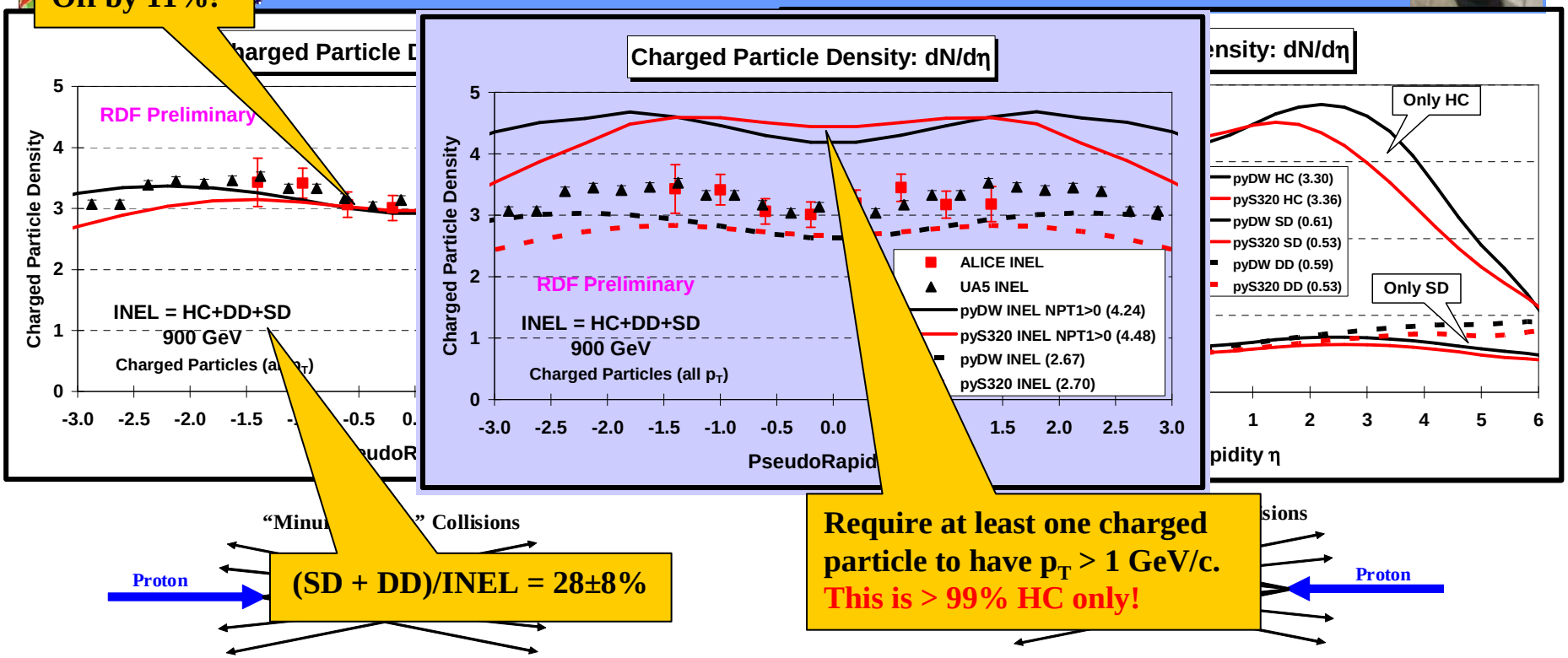
➡ **Compares the 900 GeV data with my favorite PYTHIA Tunes (Tune DW and Tune S320 Perugia 0). Tune DW uses the old Q^2-ordered parton shower and the old MPI model. Tune S320 uses the new p_T-ordered parton shower and the new MPI model. The numbers in parentheses are the average value of dN/dη for the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



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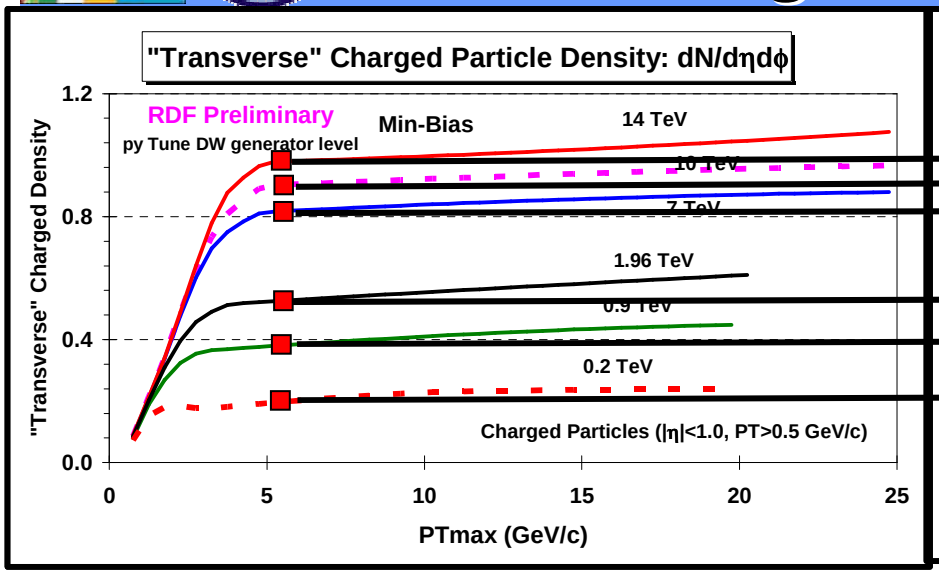
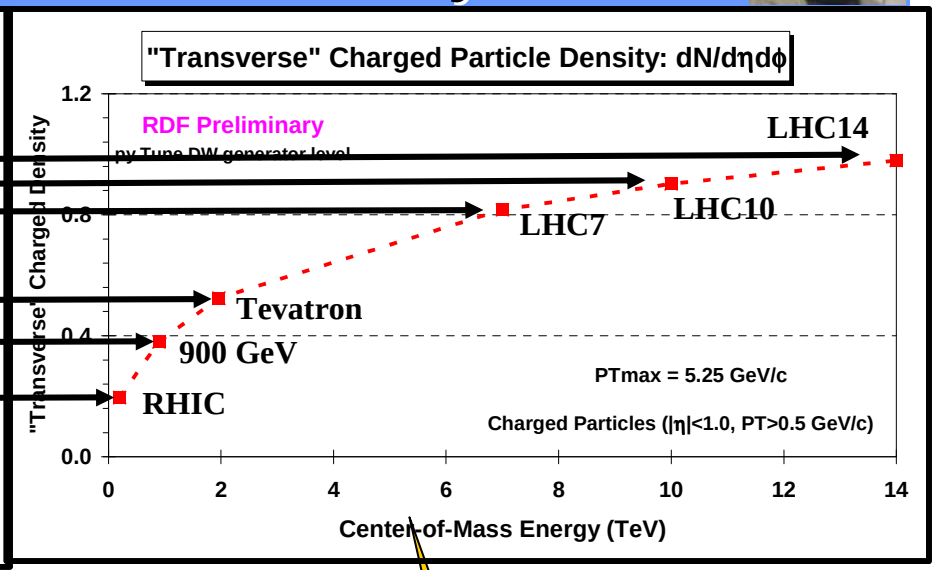
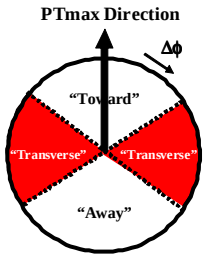
Min-Bias "Associated" Charged Particle Density

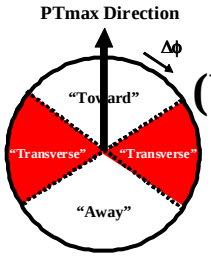




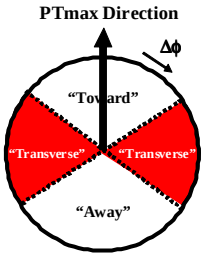
RHIC



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



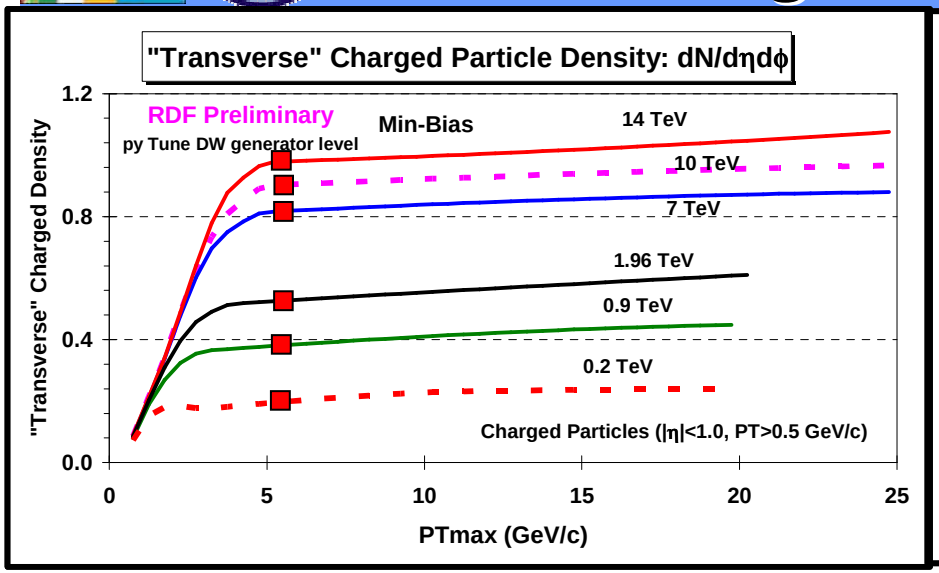
1.96 TeV → 14 TeV (UE increase ~1.9 times) → **LHC**

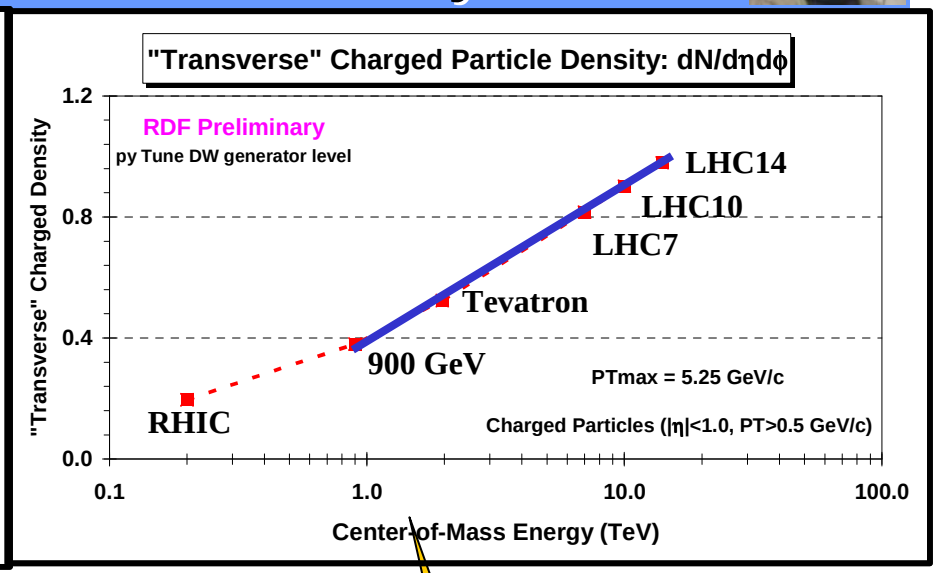


Linear scale!

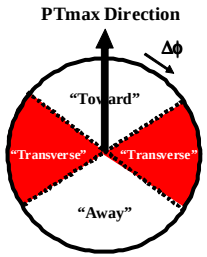
➡ **Shows the "associated" charged particle density in the "transverse" region a[illegible] function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-[illegible]s" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tu[illegible] article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

Min-Bias "Associated" Charged Particle Density





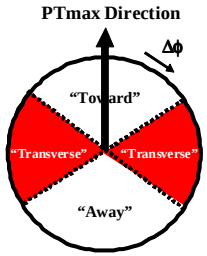
LHC7



7 TeV → 14 TeV
(UE increase ~20%)

Linear on a log plot!

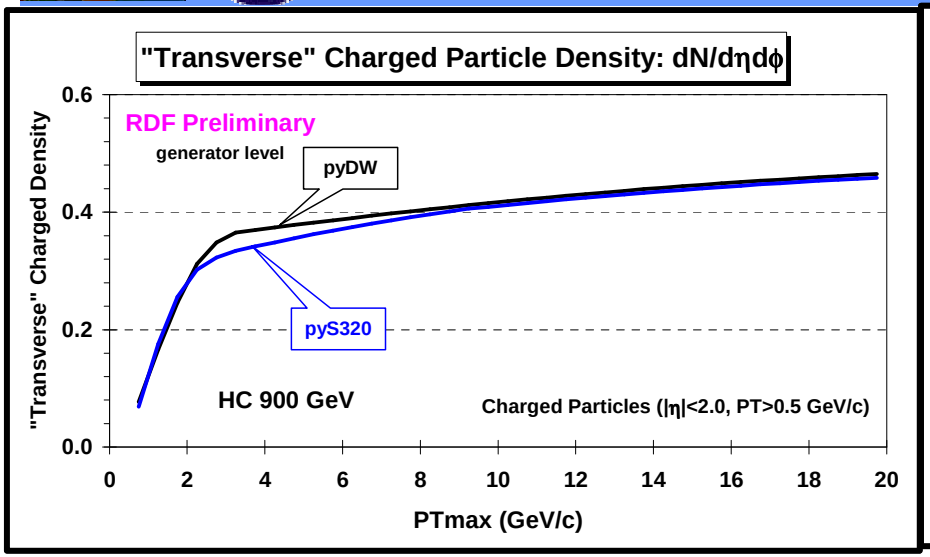
LHC14

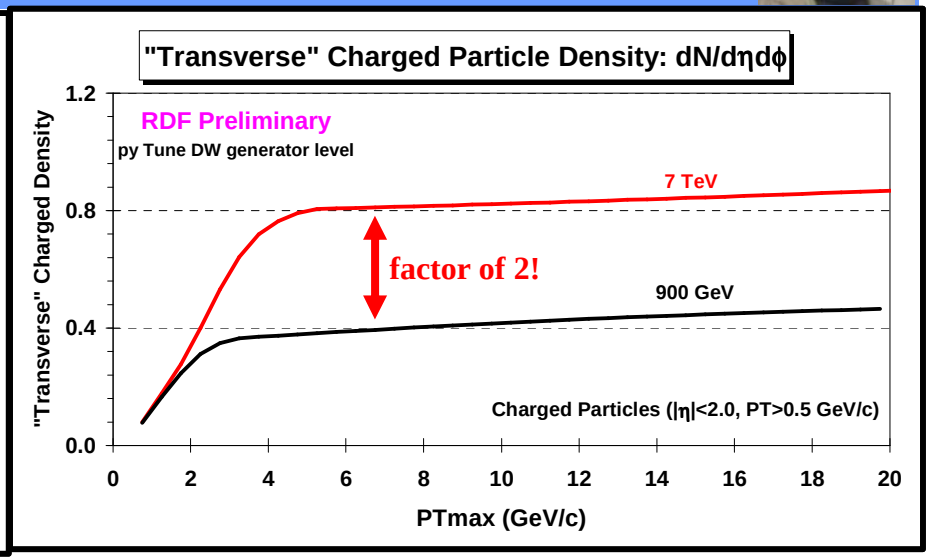


Log scale!

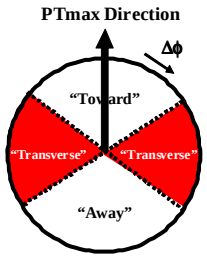
➡ **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.*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

"Transverse" Charge Density



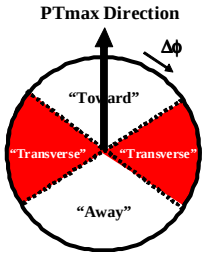


LHC 900 GeV



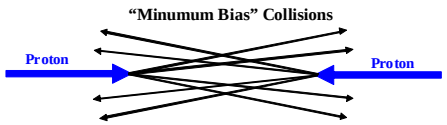
900 GeV → 7 TeV
(UE increase ~ factor of 2.1)

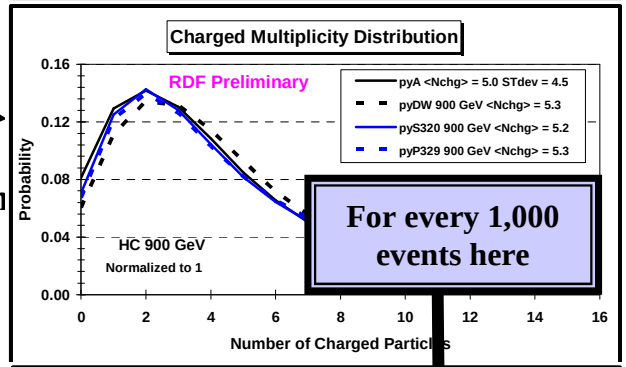
LHC 7 TeV



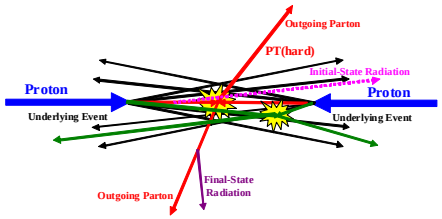
➡ **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) at 900 GeV as defined by PTmax from PYTHIA Tune DW and Tune S320 at the particle level (*i.e.* generator level).**

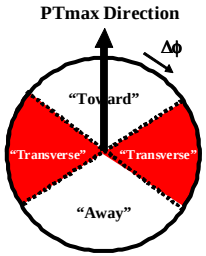
Important 900 GeV Measurements

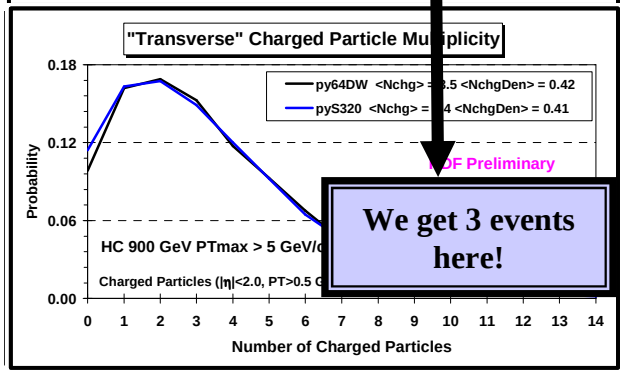




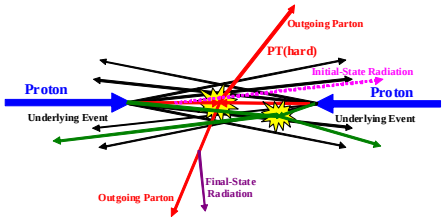
- **The amount of activity in "min-bias" collisions (multiplicity distribution p_T distribution, PTsum distribution, dNchg/dη).**

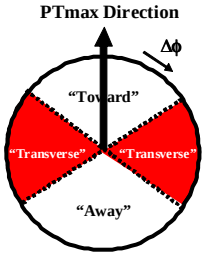


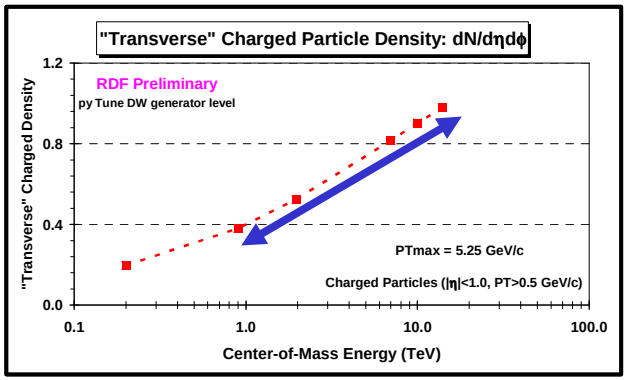




- **The amount of activity in the "underlying event" in hard scattering events ("transverse" Nchg distribution, "transverse" p_T distribution, "transverse" PTsum distribution for events with PTmax > 5 GeV/c).**

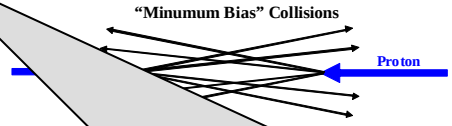


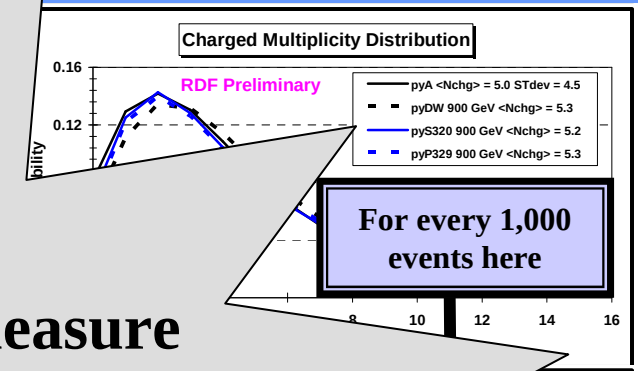




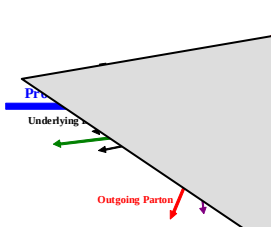
- **We should map out the energy dependence of the "underlying event" in a hard scattering process from 900 GeV to 14 TeV!**

Important 900 GeV Measurements

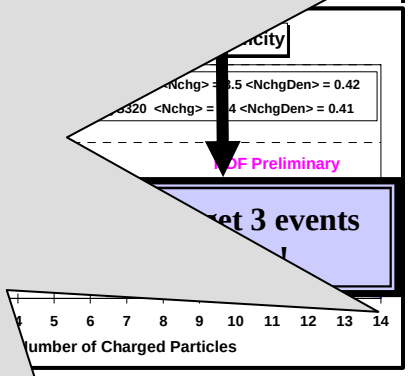




- The amount of act… ias" co… p_T distribution, PTsu…

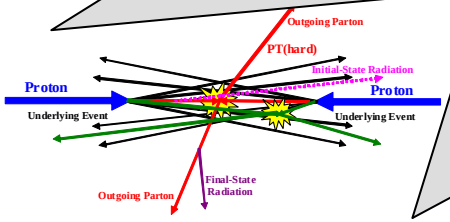


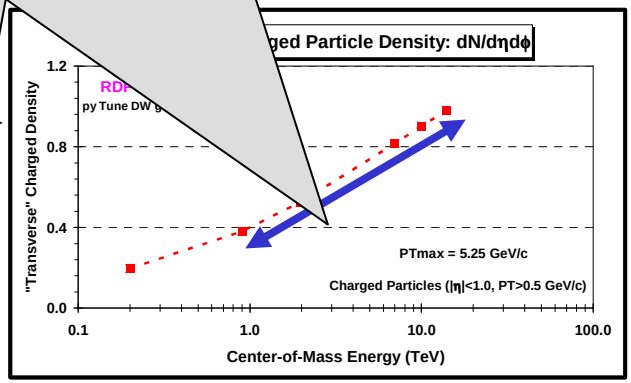
For every 1,000 events here



- The amount of activ… events ("transve… "transverse"…

et 3 events



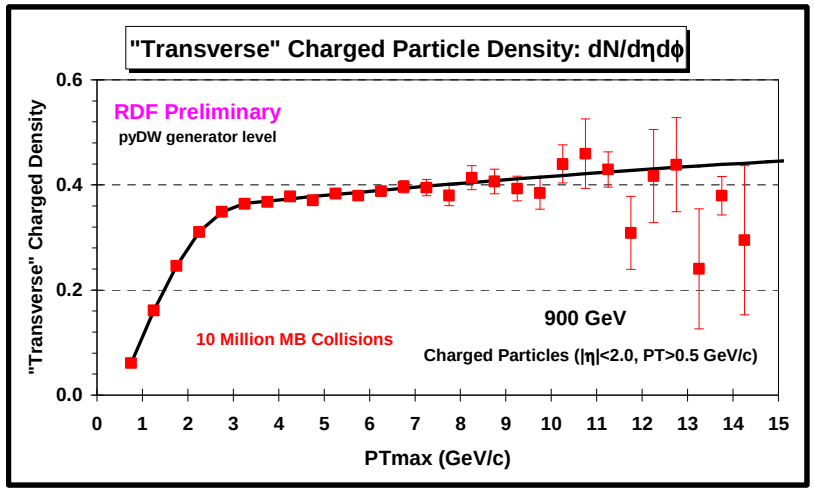


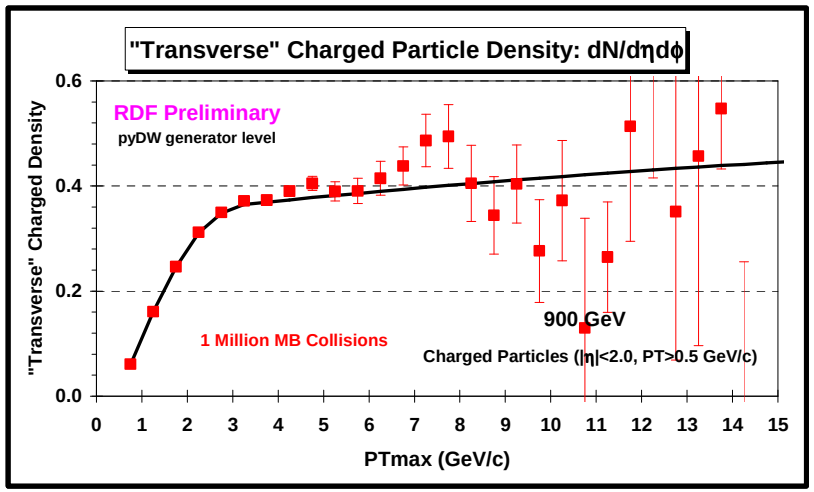
It is very important to measure BOTH "min-bias" and the and the "underlying event" at 900 GeV!

To do this we need to collect about 5,000,000 CMS min-bias triggers!

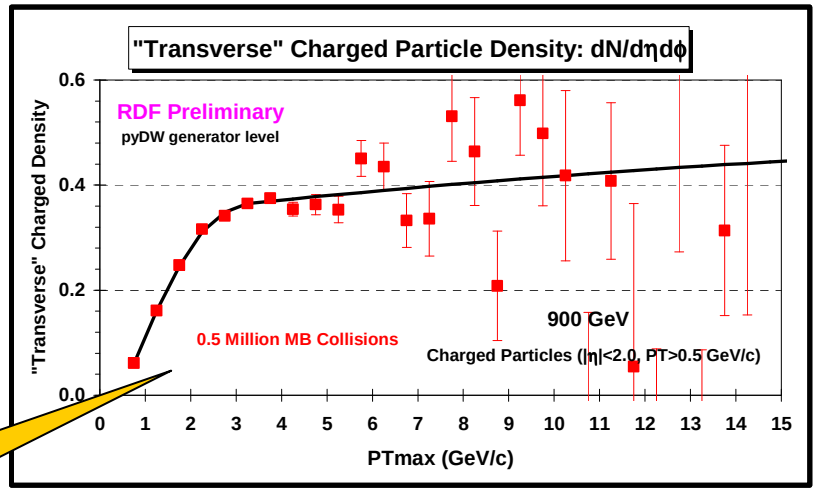
- We should map out the energy dependenc… he "underlying event" in a hard scattering process from 9… GeV to 14 TeV!

The "Underlying Event" at 900 GeV





- **Show how well we could measure the "transverse" charged particle density versus PTmax with 10 M, 1 M, and 0.5 M "min-bias" (MB) events collected by CMS. Assumes that for all the events that the tracker is working well! The goal is to see how well the data (red squares) agree with the QCD MC prediction (black curve).**



Unfortunately, looks like this is all we will get!