The study of Multiple Parton Interactions processes in CMS

**Filippo Ambroglini,
Paolo Bartalini,
Florian Bechtel,
Livio Fano',
Rick Field,
Khristian Kotov,
Daniele Treleani,
…**

(see also "credits" in the last slide)

HERA/LHC WG MEETING, October 31st 2007

MPI research program in CMS

Mostly conducted in the CMS PH QCD group (K. Rabbertz)

1) **Underlying Event in Jet and Drell-Yan Events at the LHC**
2) **Extension of (1) to Diffractive Topologies**
3) **Minimum Bias at the LHC (Multiplicities, P_T spectra)**
4) **Double Parton Scattering at the LHC**
5) **Tuning of Monte Carlo Models based on (1), (2) and (3)**

Today updates on:
Pythia tunes, UE feasibility in jet topologies, Minijets

\+ related CMS contributions:

1) **Validation of double high PT interactions in Pythia 8 (F. Bechtel)**
2) **Simulation of Quarkonia production in CMS (A. Kraan)**

See also previous HERA/LHC contributions from L.Fano', D.Treleani, K.Borras

MB & UE: Definitions and status

Minimum Bias

The generic single particle-particle interactions

Underlying Event (UE)

Everything except the leading hard scattering component of the collision

UE ≠ MB but some aspects & concepts are similar:

Phenomenological study of Multiplicity & P_T of charged tracks

-> Can go very low in P_T

-> Straightforward association to the primary vertex

PHENOMENOLOGY

- MB: CDF, UA5. Charged multiplicities and PT distributions, $dN/d\eta d\phi$ at $\eta=0$
- UE: CDF. Charged and PT densities far from the jet region

pQCD Models

MPI (multiple parton interactions)

Extend the perturbative QCD to soft regime, particularly adequate to describe both MB and UE observables

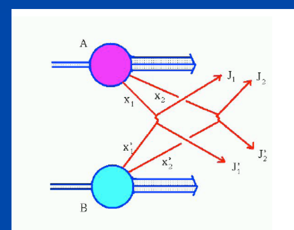
pQCD Models

ISR, FSR, SPECTATORS…
Not enough to account for the observed multiplicities & P_T spectra !!!

→

The Pythia solution:
[T. Sjöstrand et al. PRD 36 (1987) 2019]
Multiple Parton Interactions (MPI)
(now available in other general purpose MCs: Herwig/Jimmy, Sherpa, etc.)

Inspired by observations of double high P_T scatterings



Main Parameter: P_T cut-off P_{T0}

$$\sigma(\widehat{P}_T) \rightarrow \sigma(\widehat{P}_T) \cdot \frac{(\widehat{P}_T)^4}{((\widehat{P}_{T0})^2 + (\widehat{P}_T)^2)^2}$$

(dampening also describes quarkonia x-sections)

- ✓ **Cross Section Regularization for $P_T \rightarrow 0$**
- ✓ **P_{T0} can be interpreted as inverse of effective colour screening length**
- ✓ **Controls the number of interactions hence the Multiplicity: $< N_{int} > = \sigma_{parton\text{-}parton} / \sigma_{proton\text{-}proton}$**

Emphasis on the Energy-dependence of the parameters.
CDF, UA5 MB Phenomenology favors exponent behavior
CGC Theory favors constant behavior [G.Gustafson & G.Miu]

Details in backup slides

Models with Varying impact parameter between the colliding hadrons better describe shapes

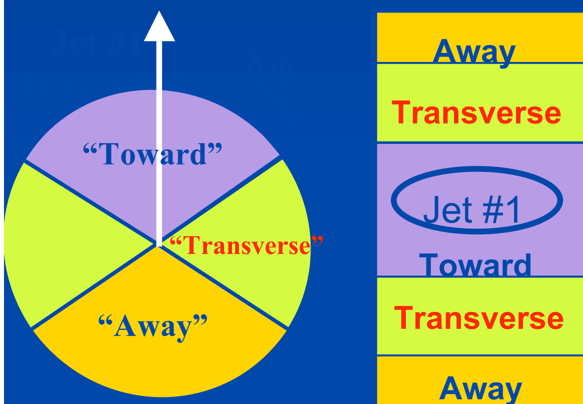
UE: CMS measurement plan at the LHC

[CMS Note 2006/067]
CMS PTDR vol. 2
(SM_QCD section)

From charged jet (using MB and jet triggers)

Topological structure of p-p collision from charged tracks

Charged jet definition -> ICA with massless charged tracks as input



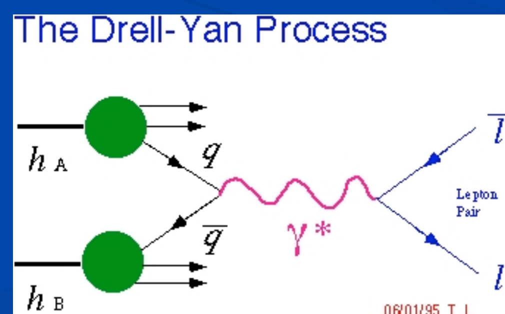
The leading Charged jet defines a direction in the ϕ plane

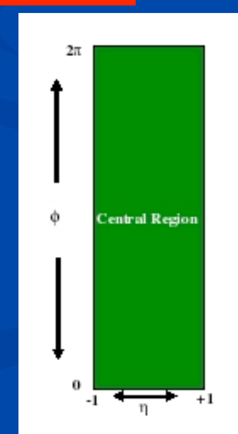
The transverse region is particularly sensitive to the UE

Main observables:
+ $dN/d\eta d\phi$, charged density
+ $d(PT_{sum})/d\eta d\phi$, energy density

From D-Y muon pair production
(using muon triggers)

observables are the same but
defined in all the ϕ plane





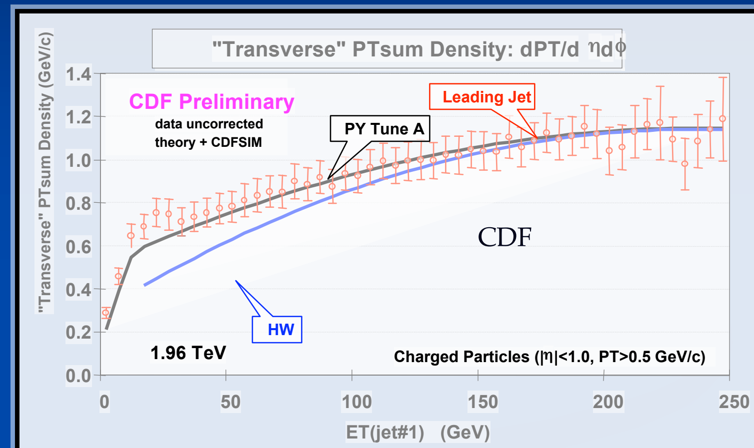
Tunes

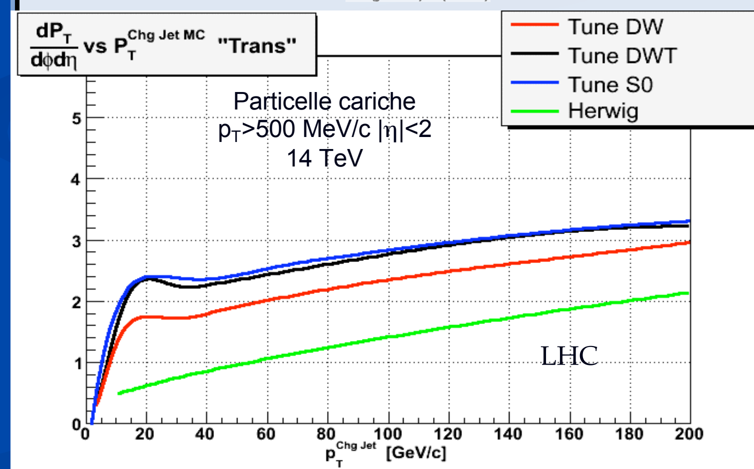
Generators setup used
(further details in backup slides)
+ Pythia Tune DW (ε=.125)
OLD MPI, IP CORRELATIONS
+ Pythia Tune DWT (ε=0.08)
DW with default PT-cut-off evolution
+ Pythia Tune S0 (ε=0.08)
P.Skands, New MPI, more correlations
+ HERWIG

All these Pythia Tunes describe the UE@Tevatron.
Herwig without MPI almost ruled out
(Useful reference)

$$P_{T0} = P_{T0}^{TUN}\left(\frac{\sqrt{s}}{TUN\ E}\right)^{2\varepsilon}$$

$d(PT_{sum})/d\eta d\phi$

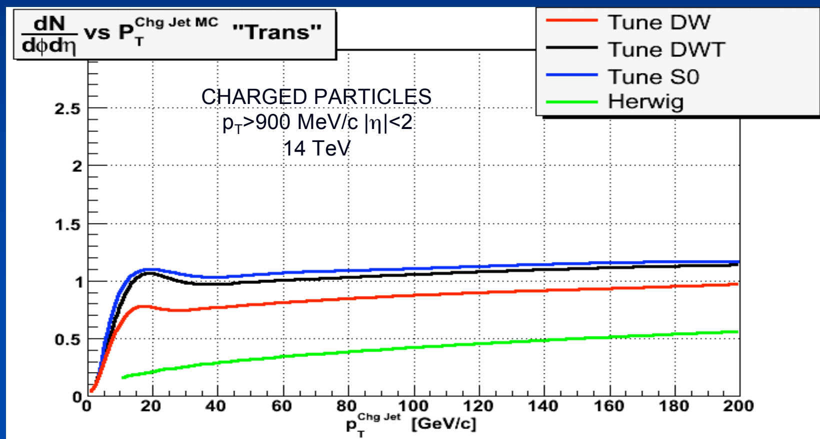




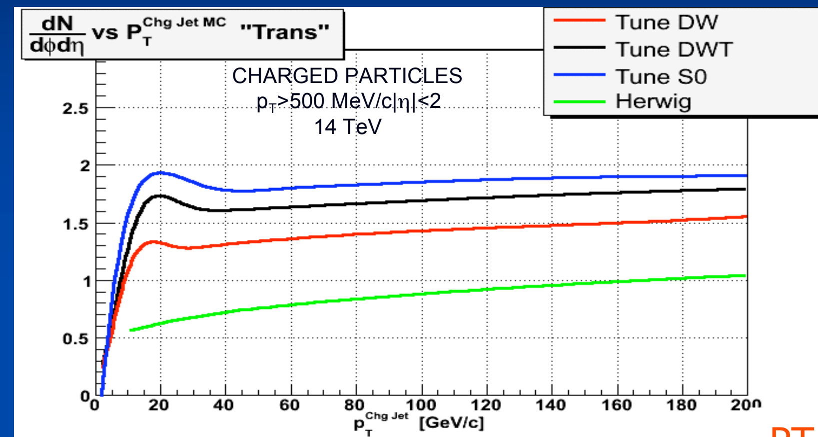
Sensitive differences at the LHC: but cannot rely just on one distribution !

Generator level studies

UE $dN/d\eta d\phi$ PT threshold at 500 MeV enhances differences between DWT and S0

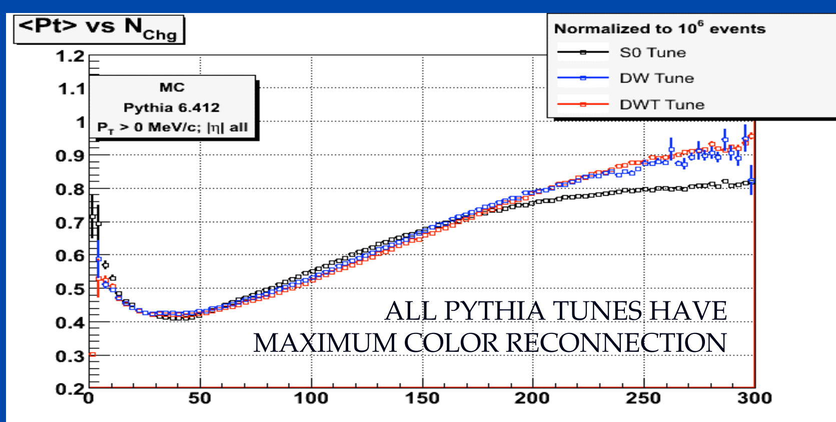


PT

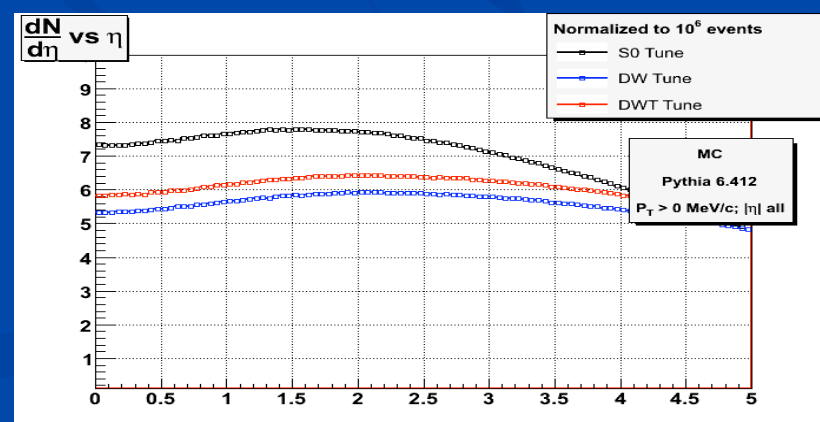


PT

Further discrimination power from MB observables



Nchg



η

UE: Bottom Line

The detector level simulation is almost complete
Soon published results for 10pb^{-1} with some original methodologies (usage of ratios to reduce systematics).

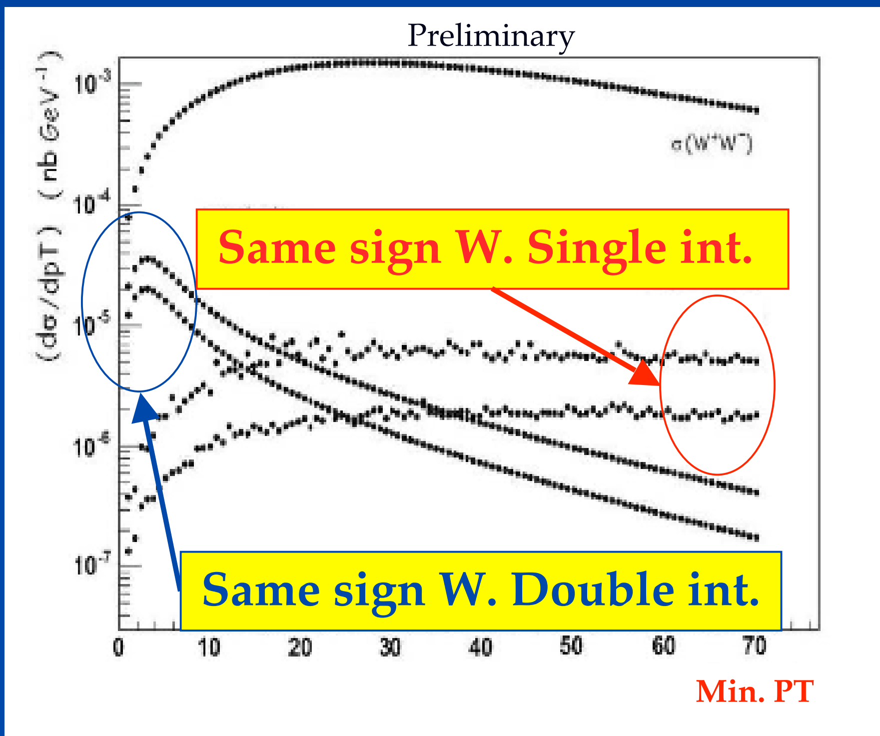
UE: Plans

Complete the feasibility studies for the UE measurement.

Switch soon to Fast KT for both charged jet reconstruction and definition of UE observables

The MPI challenge at the LHC

THE ULTIMATE GOAL WOULD BE TO ACHIEVE A UNIFORM DESCRIPTION FOR **HIGH P_T** AND **LOW P_T** MPI phenomena



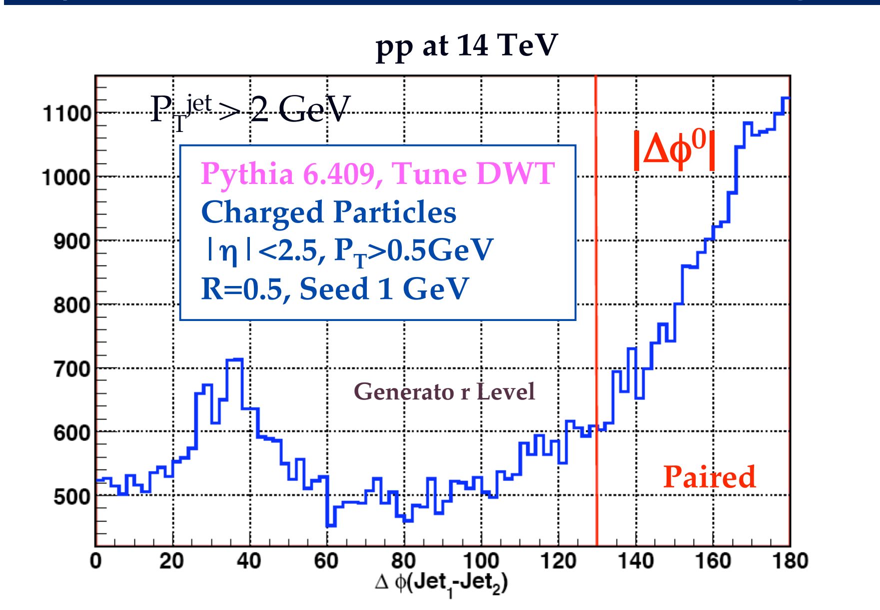
HOW?

- **Standard MB & UE measurements (along the lines of the CDF experience)**
- **3j + γ (idem)**
- **Counting pairs of same sign W** NEW
- **Counting pairs of mini-charged jets in MB interactions** NEW

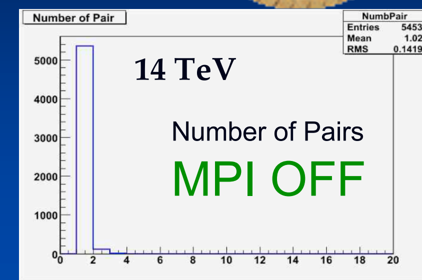
[See contribution of D.Treleani to the last meeting of the HERA/LHC w/s]

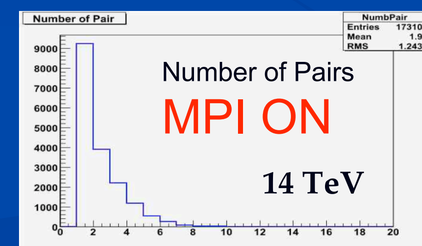
Quoting MPIs with paired MiniJets

$\Delta\phi$ distribution for the two most energetic charged Mini-Jets of the events



Pairing Algorithm:
- MiniJets ordered in decreasing P_T
- Start from the first
- Paired = jet with closest PT that satisfies the condition $|\Delta\phi^0|<|\Delta\phi|$





The idea of the measurement is to study the Rates for a given number N of Mini-Jet Pairs above a given P_T threshold -> Infrared Safe Quantity

$$\langle N\rangle\sigma_H = \sigma_S \quad \text{and} \quad \frac{1}{2}\langle N(N-1)\rangle\sigma_H = \sigma_D \qquad \langle N(N-1)\rangle = \langle N\rangle^2\frac{\sigma_H}{\sigma_{eff}}$$

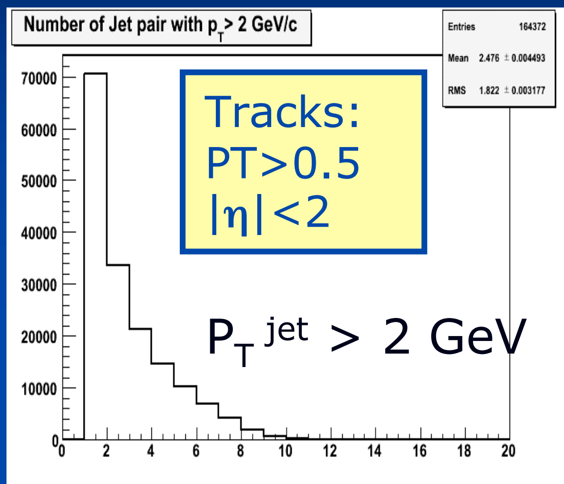
Where $\sigma_{inel} = \sigma_{soft} + \sigma_H$

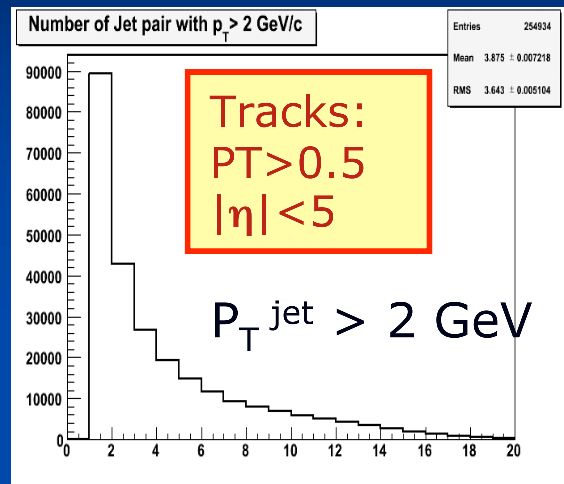
"S" = Single Interactions, "D" = Double Interactions, "H" = Hard

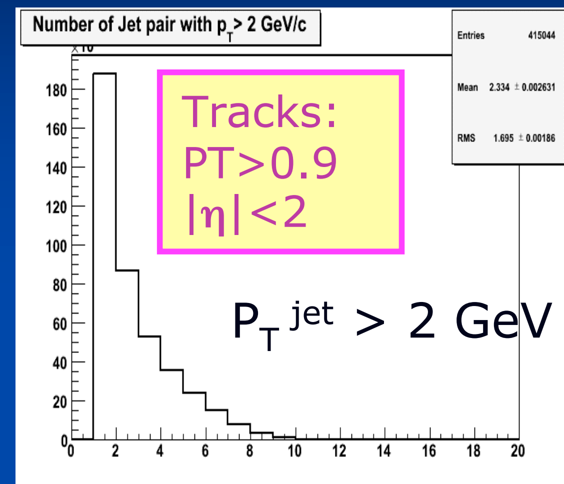
$\sigma_{eff}(P_T)$ contains the information on the spatial distribution of partons

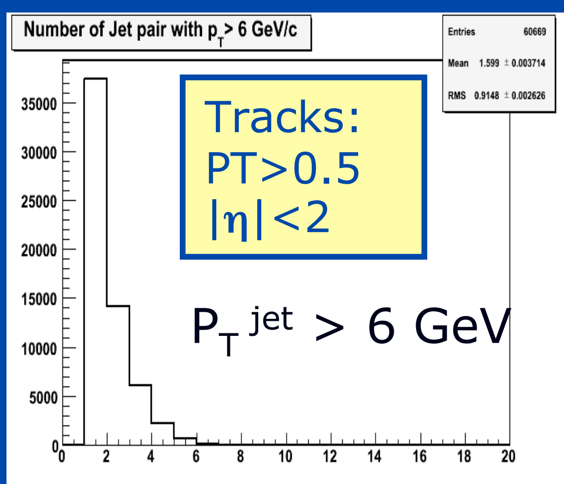
Quoting MPIs with paired MiniJets

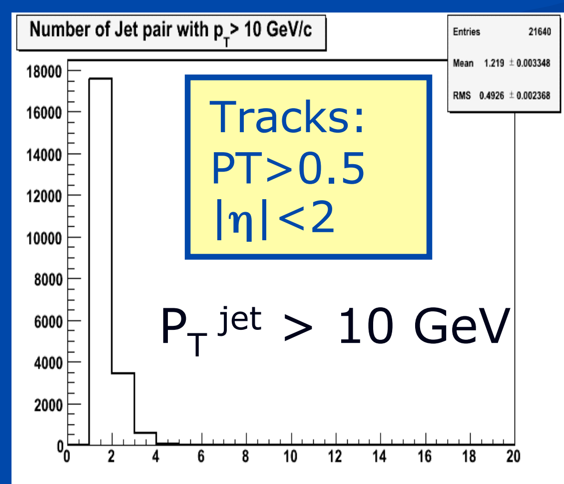
N = Number of jet pairs for different η ranges, P_T^{track}, P_T^{jet}

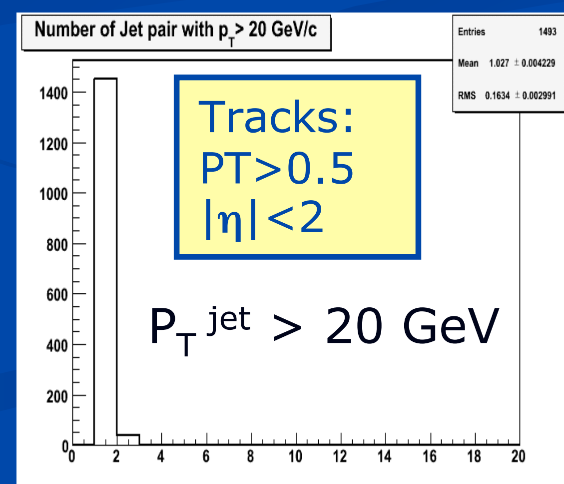








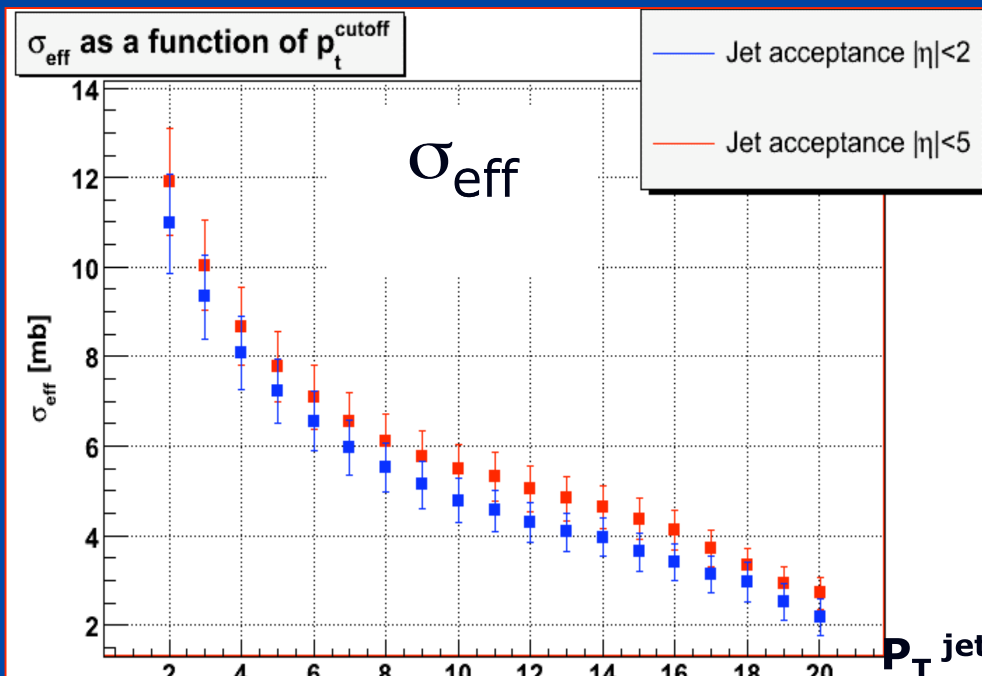


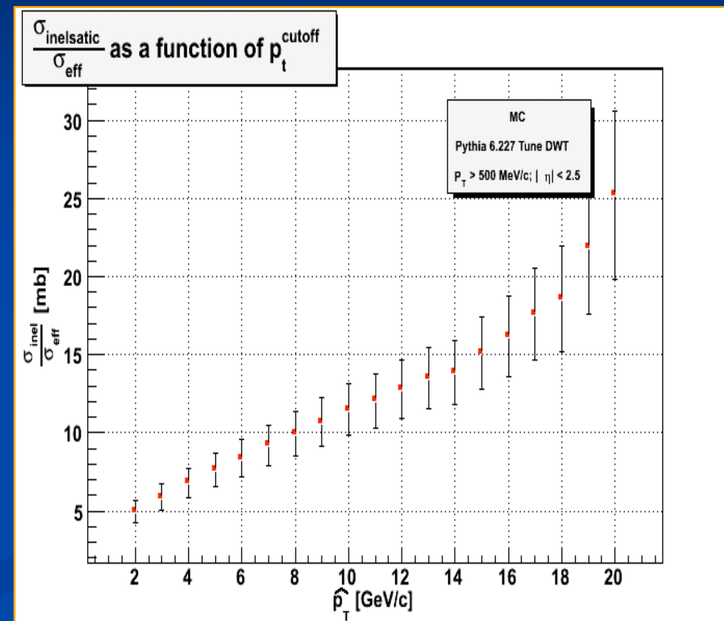


N deeply depends on acceptance & efficiency

Quoting MPIs with paired MiniJets

$$\langle N\rangle\sigma_H=\sigma_S \quad \text{and} \quad \frac{1}{2}\langle N(N-1)\rangle\sigma_H=\sigma_D \qquad \langle N(N-1)\rangle = \langle N\rangle^2\frac{\sigma_H}{\sigma_{eff}}$$





Enhancement in the probability of additional interactions

σ_{eff} doesn't depend on acceptance & efficiency (also from theory)

Mini-jets: Bottom Line

Given the progress reported in soft track reconstruction the Generator level studies look very promising!

The efficiency and acceptance independent measurement of σ_{eff} is the first priority

Mini-jets: Plans

Complete the feasibility studies at the reconstruction level

Evaluate different clustering algorithms (along the lines of the UE analysis)

From Rick…

From: Rick Field <rfield@phys.ufl.edu>
Date: October 31, 2007 1:03:18 PM GMT+01:00
To: Paolo Bartalini Paolo.Bartalini@cern.ch

Hi Paolo,

Please tell the people at the meeting that I wish I could have come. I will especially miss the dinners at the German restaurant we went to last time. Also tell them that I am working hard at getting corrected data to them to use in tuning and improving the Monte-Carlo models. I have almost completed analyses on Leading Jet, Charged jet, Inclusive 2-jet, and Exclusive 2-jet topologies. I am beginning the "pre-blessing" and "blessing" process tomorrow and I should have data for them by Christmas.

Credits

Livio Fano',
Filippo Ambroglini,
Florian Bechtel,
Khristian Kotov,
Rick Field,
Daniele Treleani,
Klaus Rabbertz,
Kerstin Borras,
Hannes Jung,
Sylvia Eckermann,
Guenther Dissertori,
Alexey Drozdetskiy,
Monika Grothe,
Michele Arneodo,
Torbjorn Sjostrand,
Aneta Iordanova,
Richard Hollis,
Craig Buttar
etc…

BACKUP

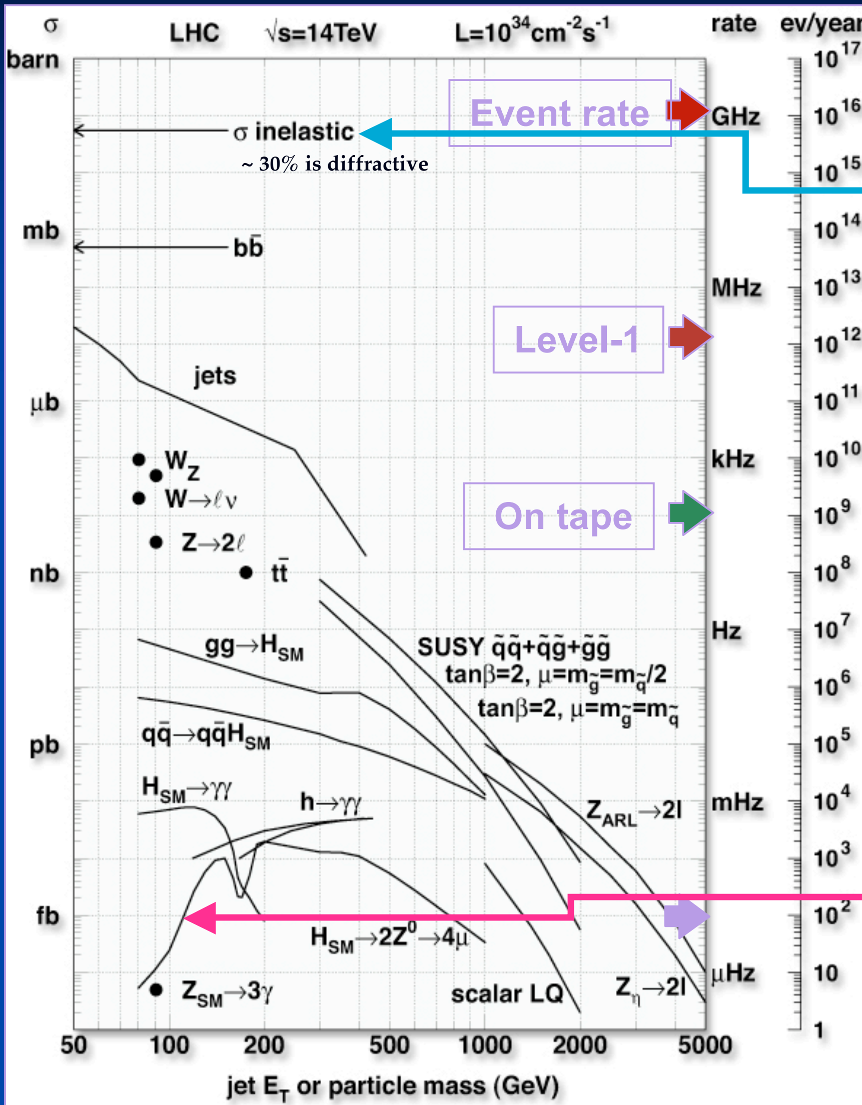
Pythia CTEQ5L Tunes

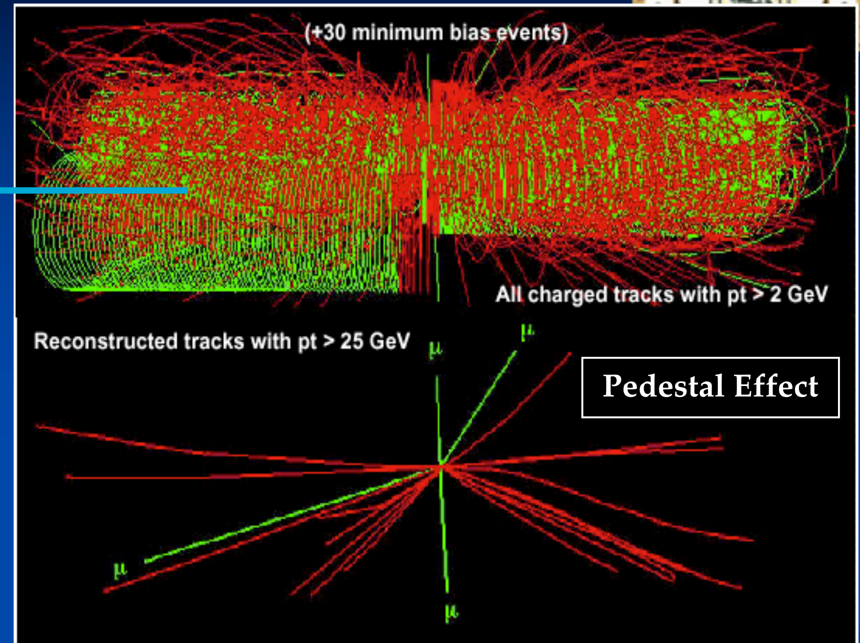
Parameter (PYTHIA v.6412+)	A	ATLAS	DW	DWT	S0
UE model MSTP(81)	1	1	1	1	21
UE infrared regularisation scale PARP(82)	2.0	1.8	1.9	1.9409	1.85
UE scaling power with $\sqrt{s}$ PARP(90)	0.25	0.16	0.25	0.16	0.16
UE hadron transverse mass distribution MSTP(82)	4	4	4	4	5
UE parameter 1 PARP(83)	0.5	0.5	0.5	0.5	1.6
UE parameter 2 PARP(84)	0.4	0.5	0.4	0.4	n/a
UE total gg fraction PARP(86)	0.95	0.66	1.0	1.0	n/a
ISR infrared cutoff PARP(62)	1.0	1.0	1.25	1.25	(= PARP(82))
ISR renormalisation scale prefactor PARP(64)	1.0	1.0	0.2	0.2	1.0
ISR Q^2_{max} factor PARP(67)	4.0	1.0	2.5	2.5	n/a
ISR infrared regularisation scheme MSTP(70)	n/a	n/a	n/a	n/a	2
ISR FSR off ISR scheme MSTP(72)	n/a	n/a	n/a	n/a	0
FSR model MSTJ(41)	2	2	2	2	(p_T − *ordered*)
FSR Λ_{QCD} PARJ(81)	0.29	0.29	0.29	0.29	0.14
BR colour scheme MSTP(89)	n/a	n/a	n/a	n/a	1
BR composite x enhancement factor PARP(79)	n/a	n/a	n/a	n/a	2
BR primordial k_T width $<|k_T|>$ PARP(91)	1.0	1.0	2.1	2.1	n/a
BR primordial k_T UV cutoff PARP(93)	5.0	5.0	15.0	15.0	5.0
CR model MSTP(95)	n/a	n/a	n/a	n/a	6
CR strength ξ_R PARP(78)	n/a	n/a	n/a	n/a	0.2
CR gg fraction (old model) PARP(85)	0.9	0.33	1.0	1.0	n/a

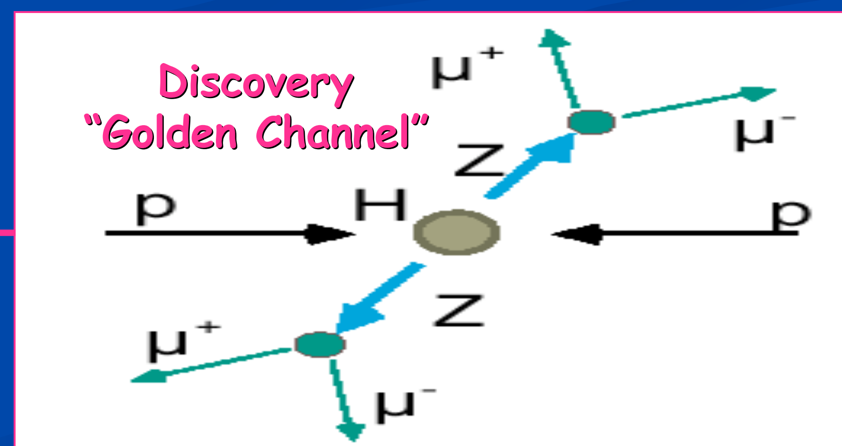
Table 3.1: PYTHIA parameters, divided into main categories: UE (underlying event), ISR (initial state radiation), FSR (final state radiation), BR (beam remnants), and CR (colour reconnections). The UE reference energy for all models is PARP(89)=1800GeV, and all dimensionful parameters are given in units of GeV.

$PT0 = PT0(Ecm/E0)^{PARP(90)}$

Final States at the LHC







Definitions & Terminology

- **Minimum Bias (MB)**
  - The generic single particle-particle interactions.
  - Elastic + Inelastic (including Diffractive). ~ 100 mb @ LHC.
    - → Soft. Low P_T, low Multiplicity..
  - What we would observe with a fully inclusive detector/trigger.
  - At the LHC, several MB interactions can take place in a single beam crossing. $<N_{int}> = L_{inst} * \sigma$.
    - → MB seen if "interesting" Triggered interaction also produced.
    - → Pile-up effect.
    - Tracking detectors help to separate the different primary vertices.
    - Possible overlap of clusters in calorimeters. Need energy flow.

- **Underlying Event (UE)**
  - All the activity from a single particle-particle interaction on top of the "interesting" process.
    - Initial State Radiation (ISR).
    - Final State Radiation (FSR).
    - Spectators.
    - … Not enough! What else ??? (Will see in a moment…).
  - The UE is correlated to its "interesting" process.
    - Share the same primary vertex.
    - Events with high P_T jets or heavy particles have more underlying activity →Pedestal effect.
      - Sometimes useful! Ex. Vertex reconstruction in $H \rightarrow \gamma\gamma$.
  - UE ≠ MB but some aspects & concepts are similar.
    - Phenomenological study of Multiplicity & P_T of charged tracks.

Motivations

- Study of "soft" QCD
  - Exploring Fundamental aspects of hadron-hadron collisions
    - Structure of Hadrons, Factorization of interactions
    - Energy dependence of cross sections and charged multiplicities

Regge: $s^{\alpha_P(s) - 1}$ Froissard bound: $(\ln s)^2$

$\alpha_P(s) - 1 = 0.12$ [Kaidalov '91]

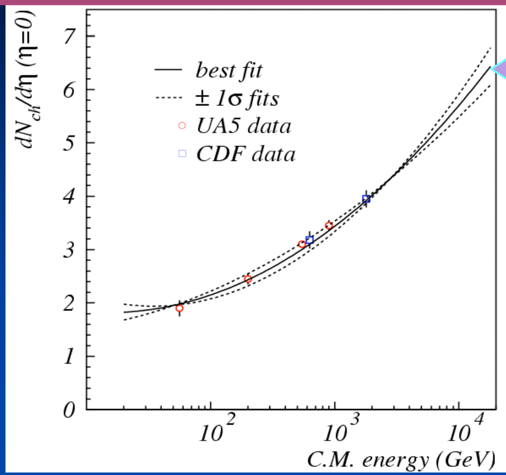
→ Tuning of Monte Carlo Models

→ Understanding the detector
  - Occupancies, Backgrounds, etc.

→ Calibration of major physics tools
  - Jet Energy, Missing Energy, Jet Vetoes, Vertex Reconstruction, Photon/Lepton Isolation

MB: Average Charged Multiplicity at $\eta=0$

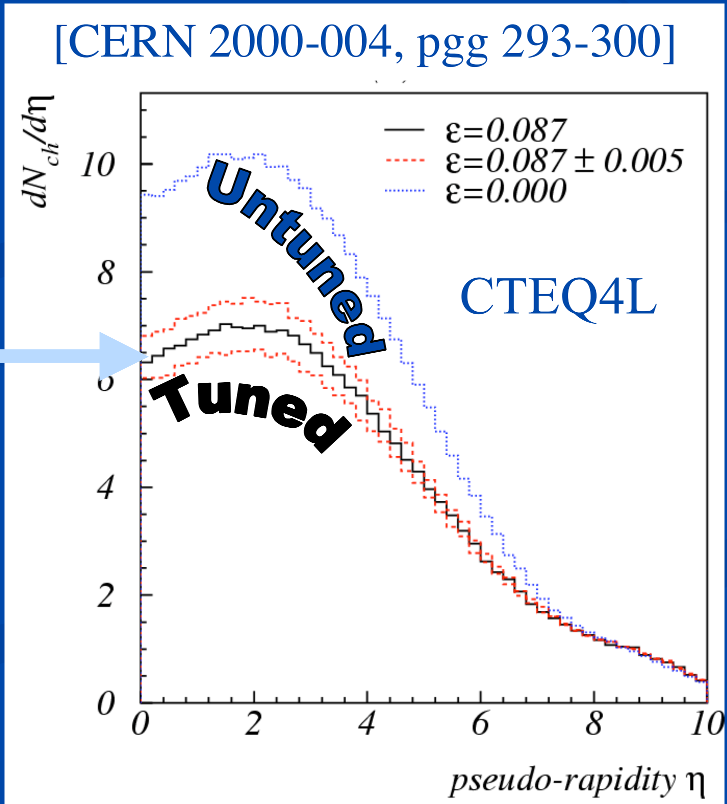
[CERN 2000-004, pgg 293-300]



Extrapolation to the LHC Energy

- UA5 at √s = 53, 200, 546, 900 GeV [Z. Phys. C 33 (1986) 1]
- CDF at √s = 630, 1800 GeV [PRD 41 (1989) 2330]

Agreement With Phenomenological Fit



- "post Hera" PDFs have increased color screening at low x ?

  $x\,g(x,Q^2) \rightarrow x^{-\varepsilon}$ for $x \rightarrow 0$

- P_T cut-off adjusted to reproduce the measured multiplicity for each PDF
- P_T cut-off fitted with exponential function

$$P_{T0} = P_{T0}^{LHC}\left(\frac{\sqrt{s}}{14\ TeV}\right)^{2\varepsilon}$$

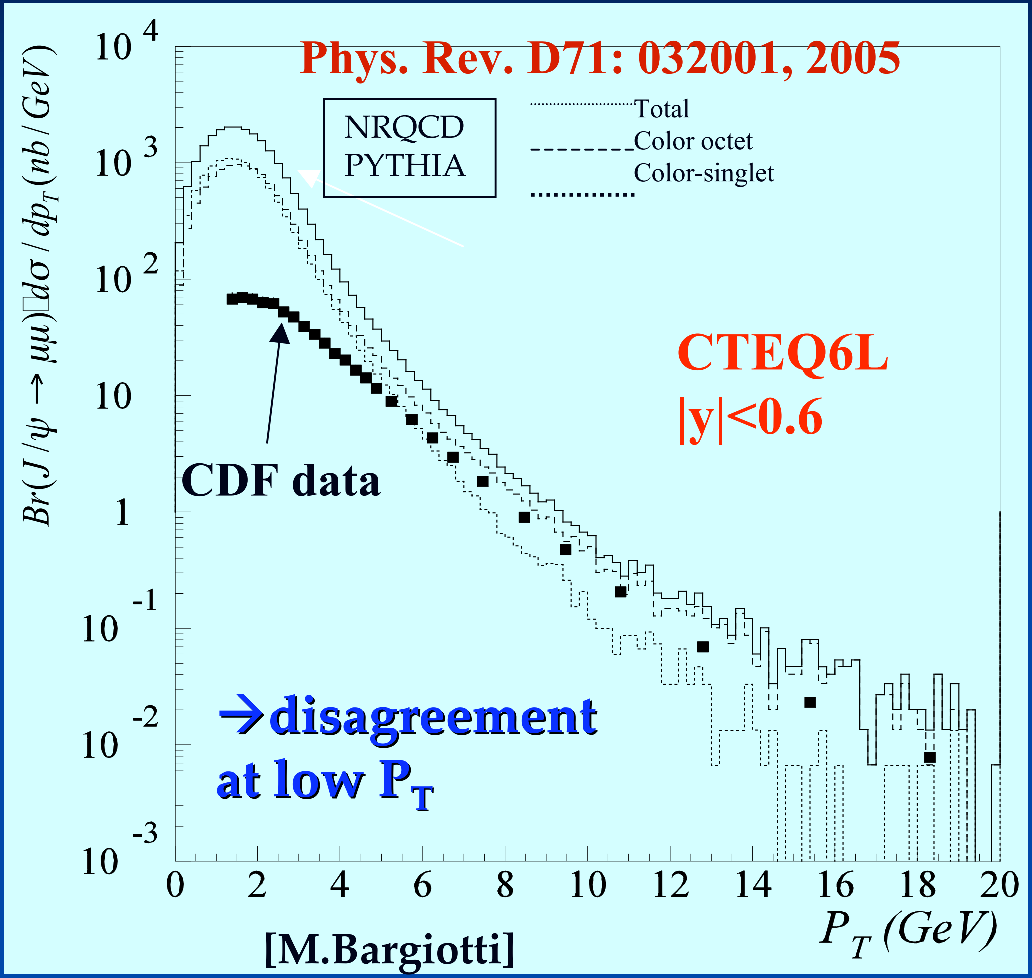
Side Note on the energy dependency of the P_T cut-off

G.Gustafson & G.Miu
rather suggest energy independency of the P_T cut-off.

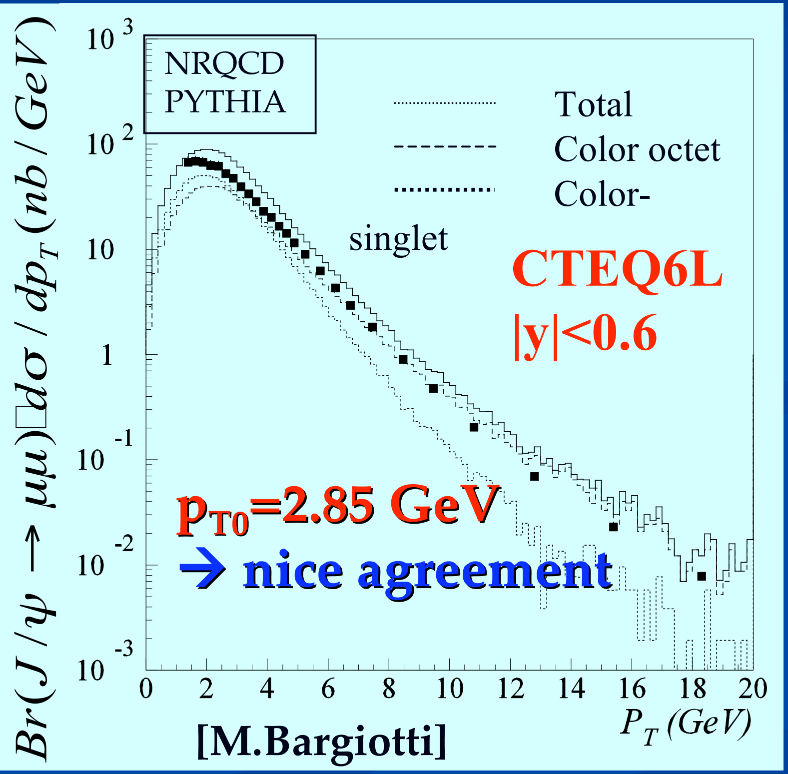
Minijets and transverse energy flow in high-energy collisions.
[Phys.Rev.D63:034004,2001]

Hadronic collisions in the linked dipole chain model.
[Phys.Rev.D67:034020,2003]

Quarkonia also prefers dampening...



$$\sigma(\widehat{P}_T) \to \sigma(\widehat{P}_T) \cdot \frac{(\widehat{P}_T)^4}{((\widehat{P}_{T0})^2 + (\widehat{P}_T)^2)^2}$$



Regularization natural: gluon exchange in the t channel $d\sigma / dP_T^2 \sim 1/ dP_T^4$

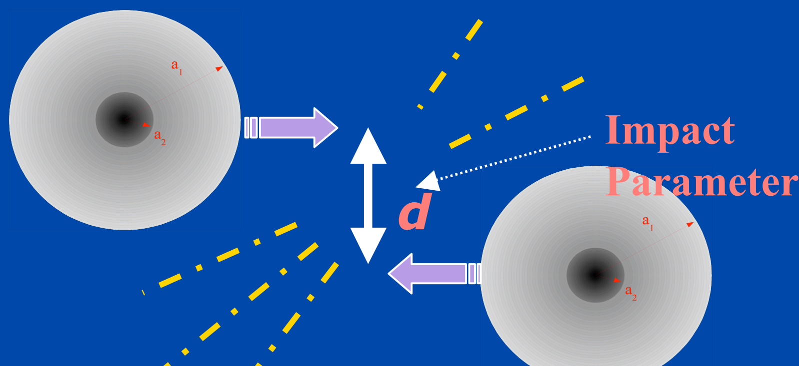
Let's assume universality: same P_{T0} of MPI, same energy dependency!

MB: Charged Multiplicity Distribution

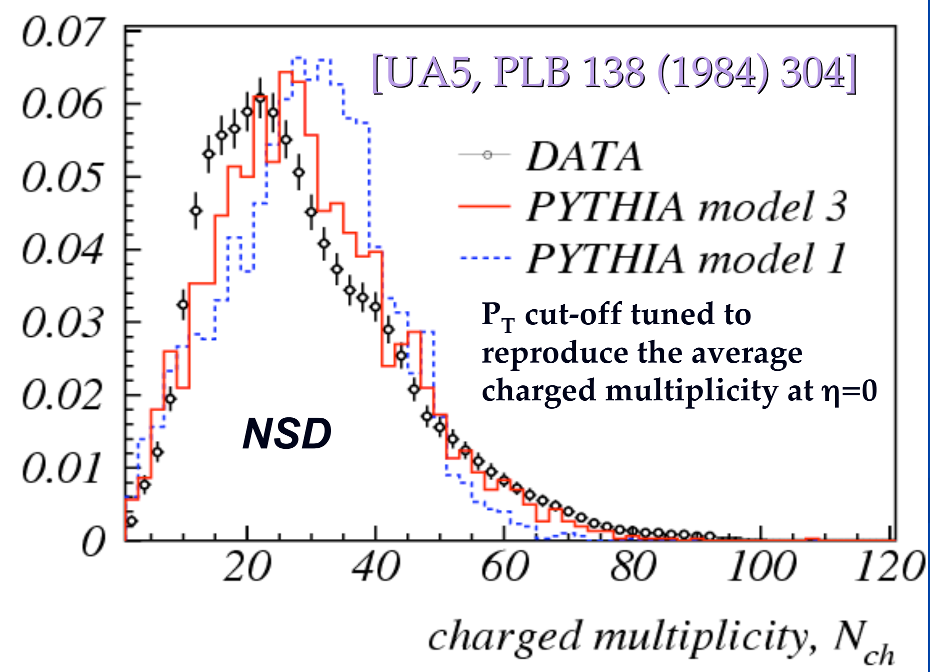
Choice of the multiple interaction model:

- All hadron collisions equivalent (MSTP(82)=1)
  - → Abrupt turn off of the cross section at P_T cut-off
  - → All the partonic interactions equivalent
- Varying impact parameter between the colliding hadrons.
  - → Continuous turn off of the cross section at P_T cut-off
  - → Correlated partonic interactions.
  - → Hadronic matter described by one (MSTP(82)=3) or two (MSTP(82)=4) Gaussian(s)

Model with Varying impact parameter between the colliding hadrons; hadronic matter is described by Gaussians



Introduce IP correlations in Multiple Parton Interactions → Pedestal Effect

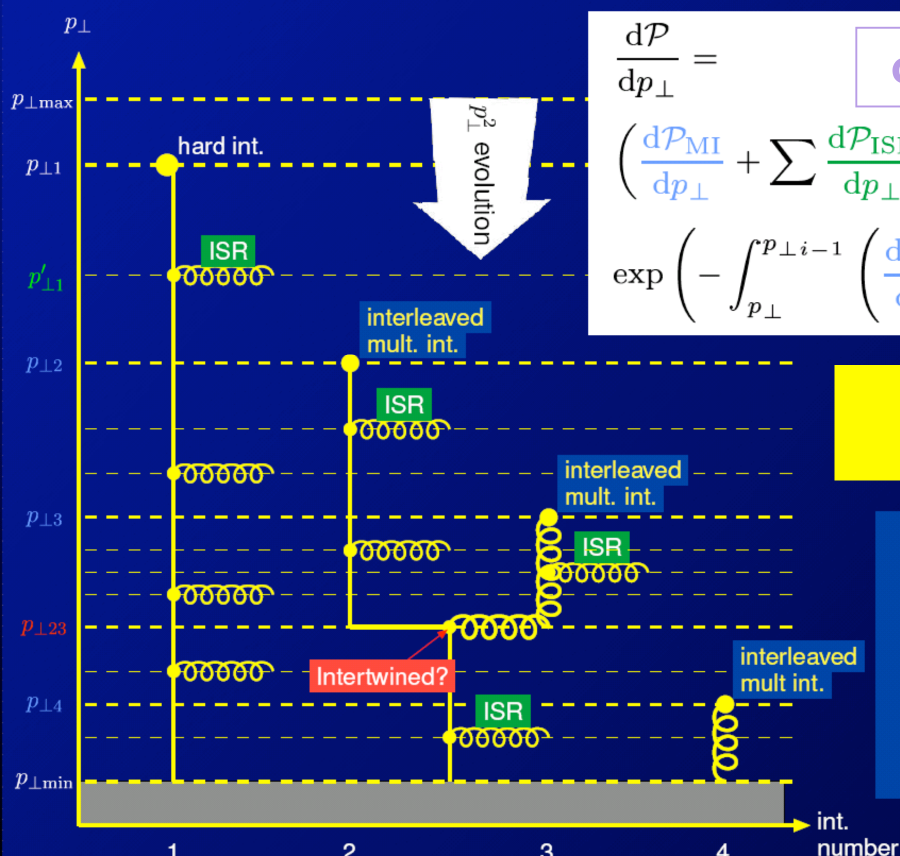


"Interleaved evolution" with multiple interactions

T. Sjöstrand & P. Skands - Eur.Phys.J.C39(2005)129 + JHEP03(2004)053

The new picture: start at the most inclusive level, $2 \to 2$.

Add exclusivity progressively by evolving *everything* downwards.



$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

optional from Pythia 6.3

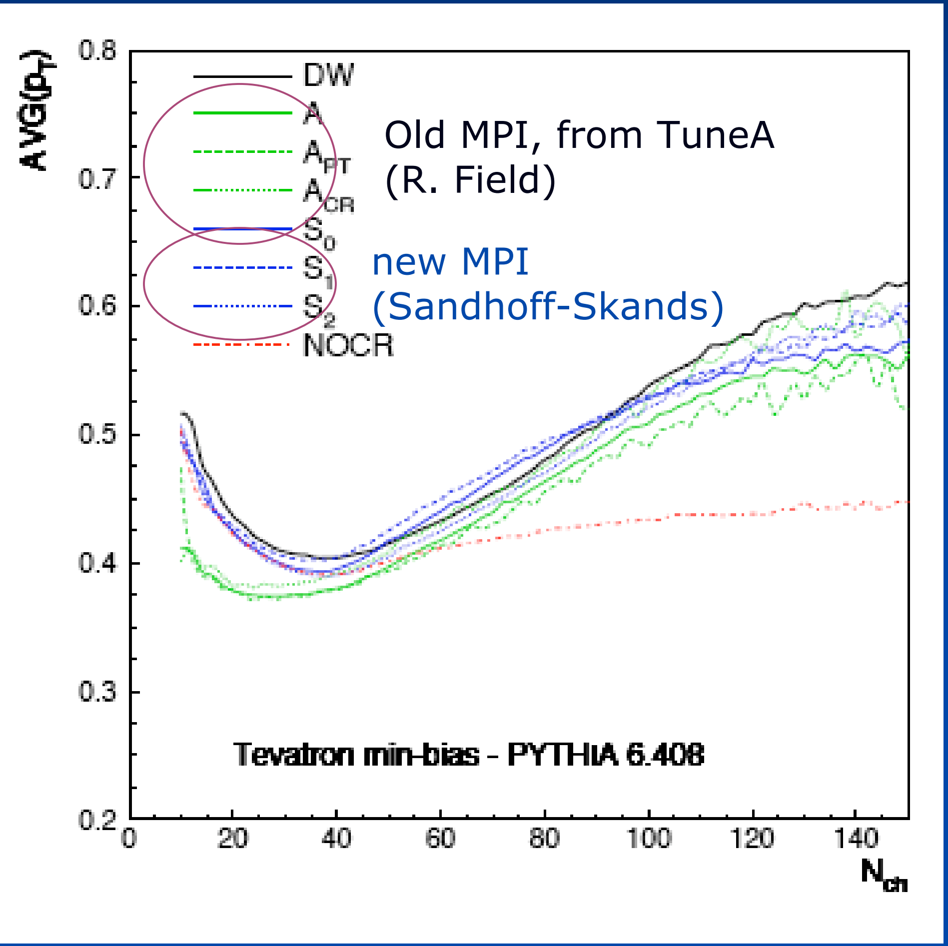
→Underlying Event
(separate LARGE topic now …)

~ "Finegraining"

→ correlations between all perturbative activity at successively smaller scales

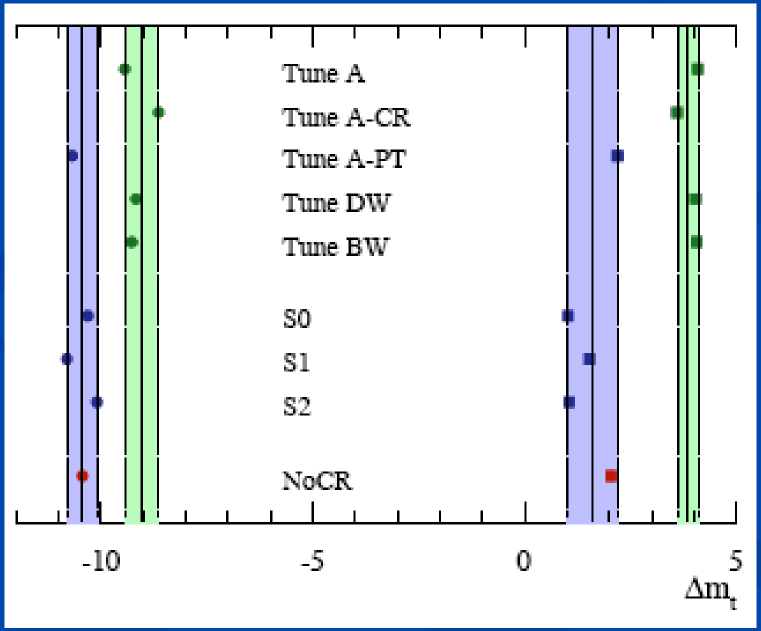
[P.Skands]

MB: Further observables sensitive to the differences between the models: <P_T> vs Multiplicity



[P.Skands, D.Wielke, hep/ph 0703081]

Effect on the top mass for different models (new/old Pythia MPI) and reconnections scenarios



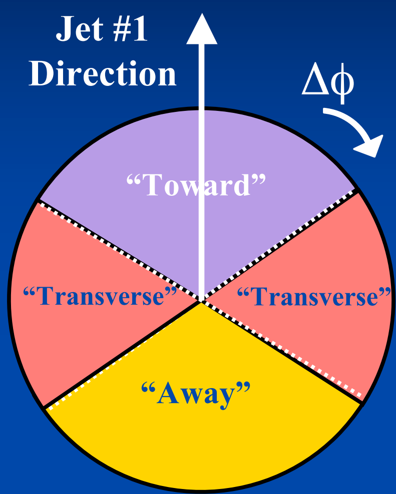
Further information on tunings in back-up slides

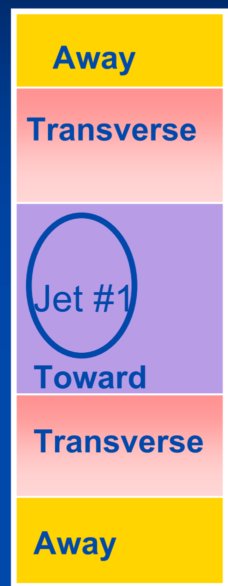
MB Phenomenology: Bottom Line

- Comparisons between Pythia and experimental data (UA5, CDF) demonstrate that Multiple Parton Interaction models are successful in reproducing the charged track multiplicity spectrum in minimum bias events.
- With the "post-HERA" PDFs, there's strong indication for exponential running of the P_T cut-off in MPI. Predictions made at larger energies (ex. LHC) with fixed P_T cut-off are most likely to overestimate the multiplicity observables.
- The shape of the charged multiplicity distribution is well described by "varying impact parameter" MPI models with Gaussian matter distributions inside the protons.

Basic Underlying Event Observables

[R.Field et al., PRD 65 (2003) 092002]



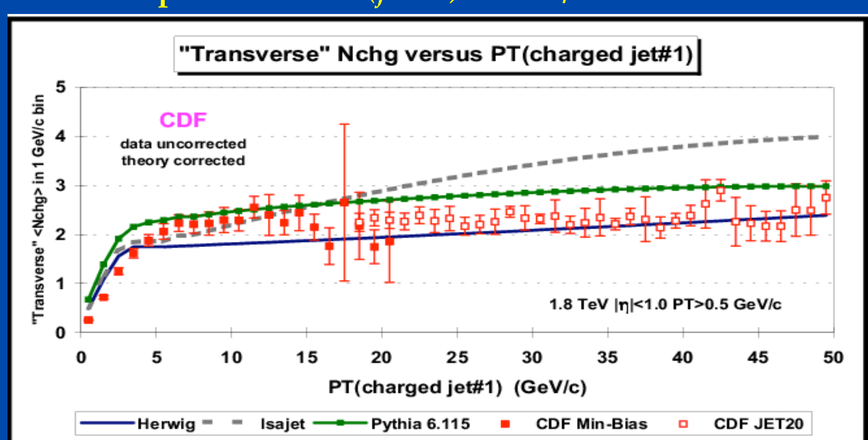


- "Charged jet" definition with *R=0.7*
- Assign all charged particles (P_T> 0.5 GeV/c) and |η|<1 to a jet

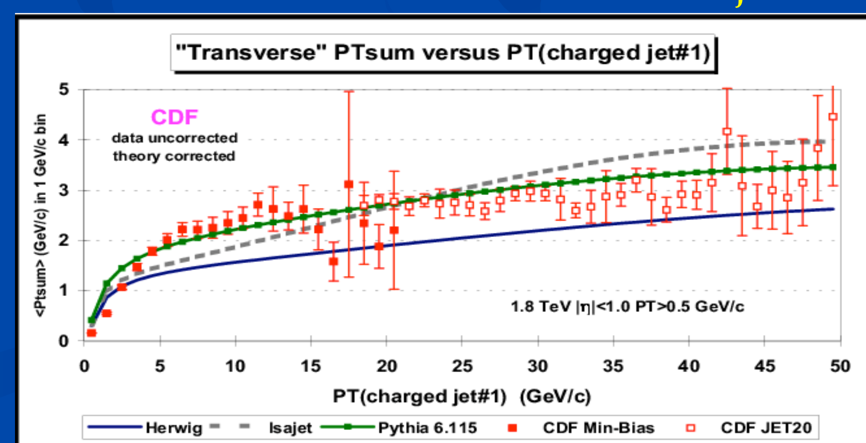
In the three different zones define:
- Charged Multiplicity
- ΣP_T (charged tracks)

Transverse regions are expected to be sensitive to the Underlying Event

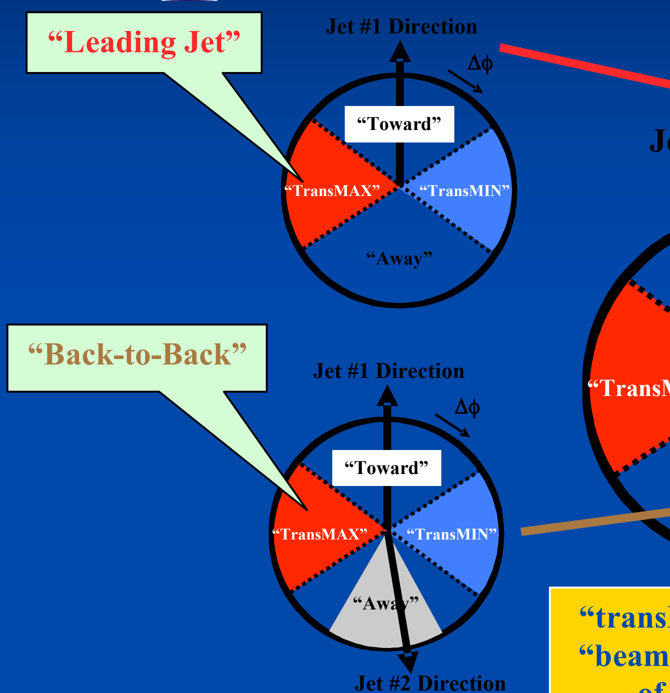
Rapid growth and then constant plateau for *PT(jet#1)*>5GeV/c

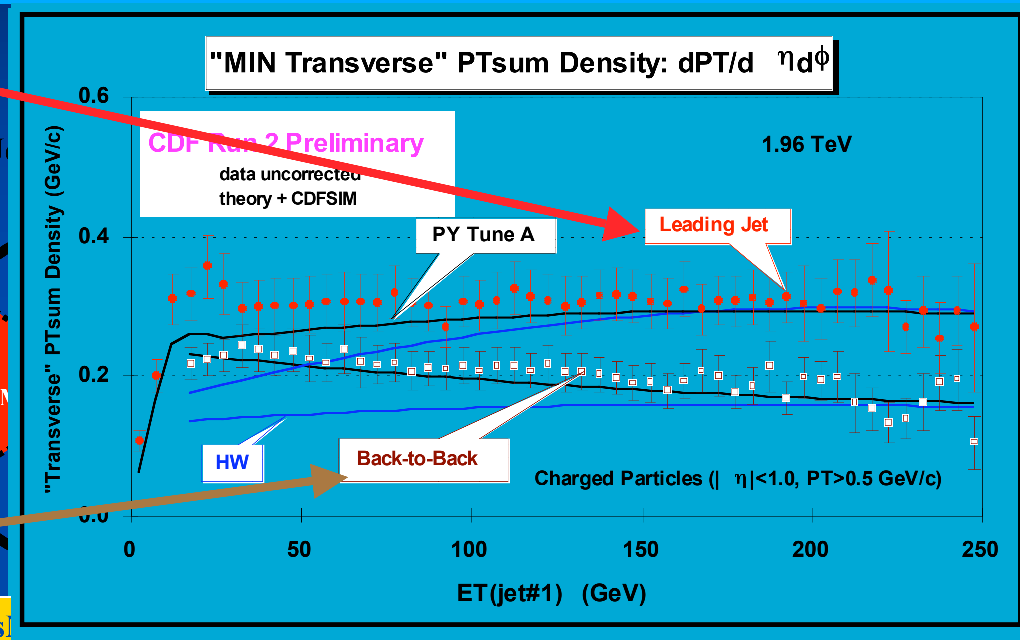


Smooth connection between Minimum bias and jet events



…IE: “TransMIN” PTsum Densit… versus E_T(jet#1)





“transl…
“beam-beam remnant” component
of the “underlying event”!

- Use the leading jet to define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged particle density.
- Shows the “transMIN” PTsum density, dPTsum/dηdφ, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus E_T(jet#1) for “Leading Jet” and “Back-to-Back” events.

[R.Field]

CDF UE Studies: Bottom Line

- **CDF Examines the jet event structure looking at Toward, Away and Transverse regions in azimuth for central rapidities**

- **The Transverse region is expected to be particularly sensitive to the underlying event**

- **The CDF underlying event data in the Transverse region can be described with appropriate tunings for the PYTHIA Multiple Partonic Interactions models, other models missing MPI (HERWIG, ISAJET) fail to reproduce the charged multiplicity and P_T spectra**

- **Sensitivity to the beam remnant and multiple interactions components of the underlying event in the "Transverse" region can be enhanced selecting back to back jet topologies**

MPI with correlated interactions <-> Pedestal Effect