The Abdus Salam
International Centre for Theoretical Physics

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International Atomic Energy Agency

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**International Workshop on QCD at Cosmic Energies III**

***28 May - 1 June, 2007***

**Lecture Notes**

P. Bartalini
*University of Florida, USA*

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

# Minimum Bias (MB), Underlying Events (UE) and More at the LHC

## *the interplays between "low" $P_T$ and "high" $P_T$ processes*

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

**Paolo Bartalini**
**(University of Florida, CMS)**

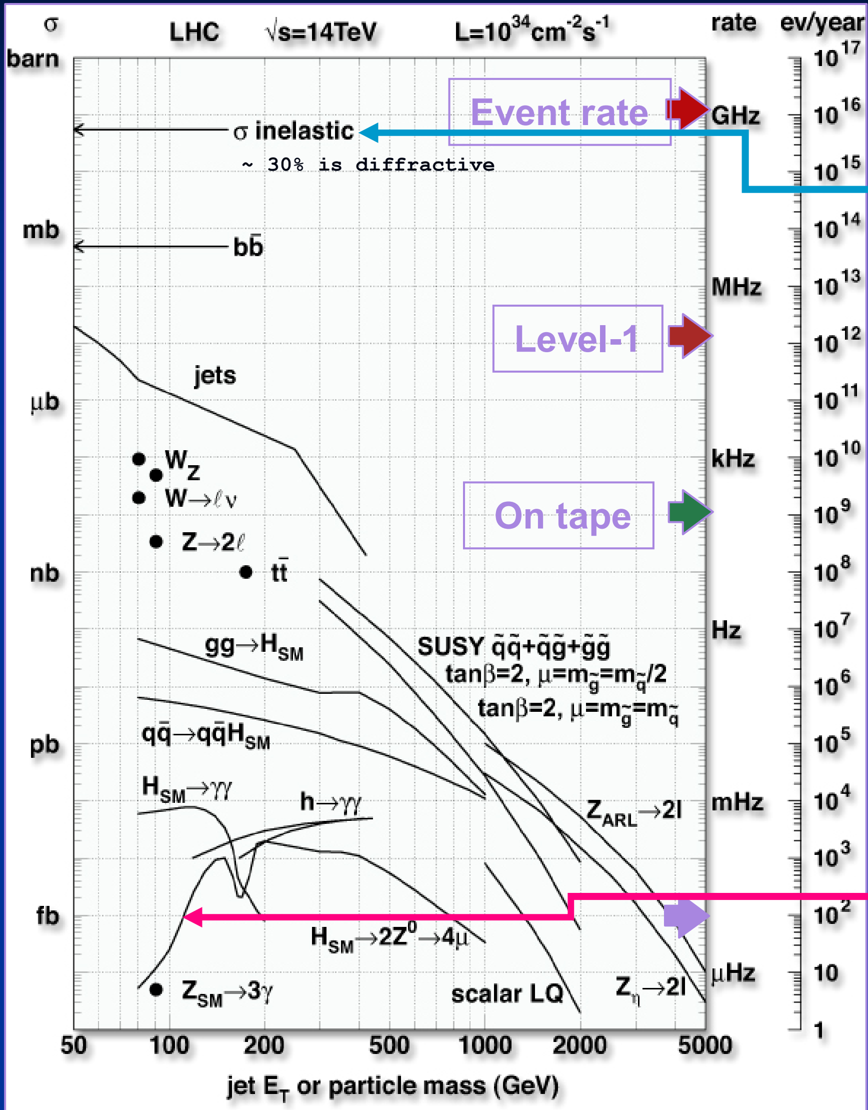
Strictly connected to the contribution of Valentina Avati (May 30th)

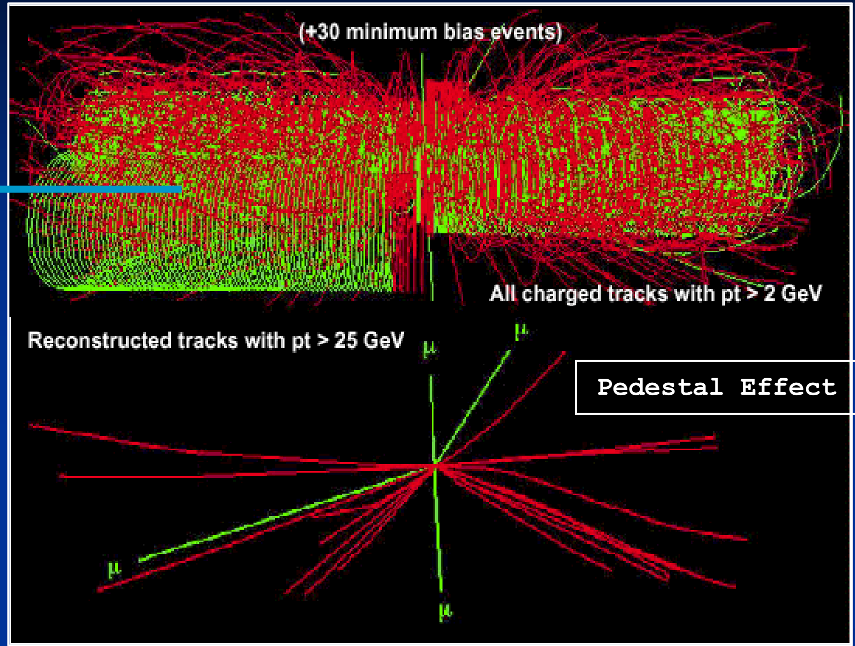
# Minimum Bias (MB), Underlying Events (UE) and More at the LHC

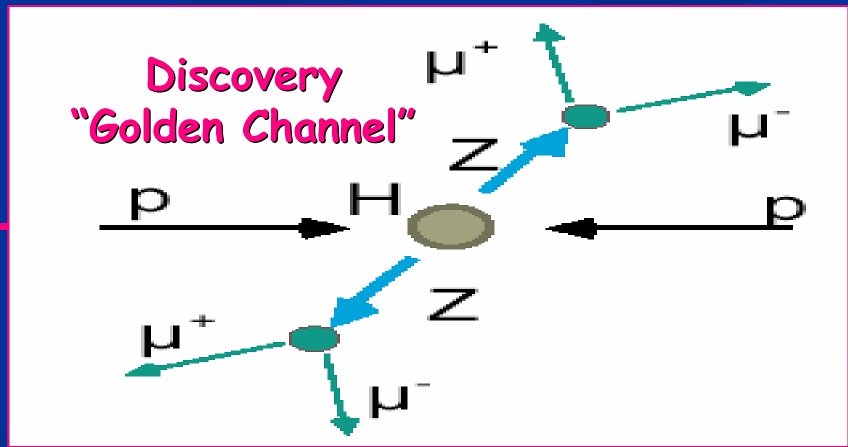
## Outline

1) Introduction / Definition of the Physics Processes
2) Multiple Partonic Interactions (MPI) Models
3) Review of the older MB&UE Phenomenology
4) The LHC Challenge: Unification of High & Low PT MPIs
5) The LHC Start-up Scenario
6) CMS Detectors & Triggers
7) CMS MB&UE Feasibility Studies
8) Interplays with Diffraction

# Final States at the Large Hadron Collider



# 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. $\langle N_{int} \rangle = L_{inst} * \sigma$.
    → 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 $H \to \gamma\gamma$.
  - 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: $(\ln^2 s)$

$\alpha_P(s) - 1 = 0.12$ [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

# pQCD Models

❖ **Underlying Event (UE)**

Everything except the hard scattering component of the collision

ISR, FSR, SPECTATORS…

Not enough!!!

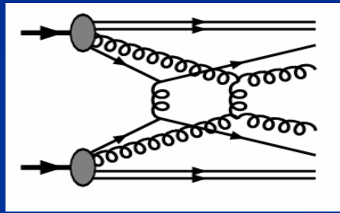
→

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)**

✓ **Cross Section Regularization for $P_T \rightarrow 0$**

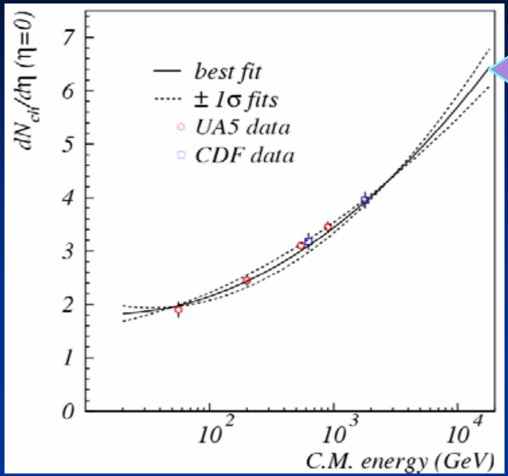
✓ **$P_{T0}$ can be interpreted as inverse of effective colour screening length**

✓ **Controls the number of interactions hence the Multiplicity:**

$$< N_{int} > = \sigma_{parton\text{-}parton} / \sigma_{proton\text{-}proton}$$

Tuning for the LHC:
Emphasis on the Energy-dependence of the parameters.

# MB: Average Charged Multiplicity (Central Region)

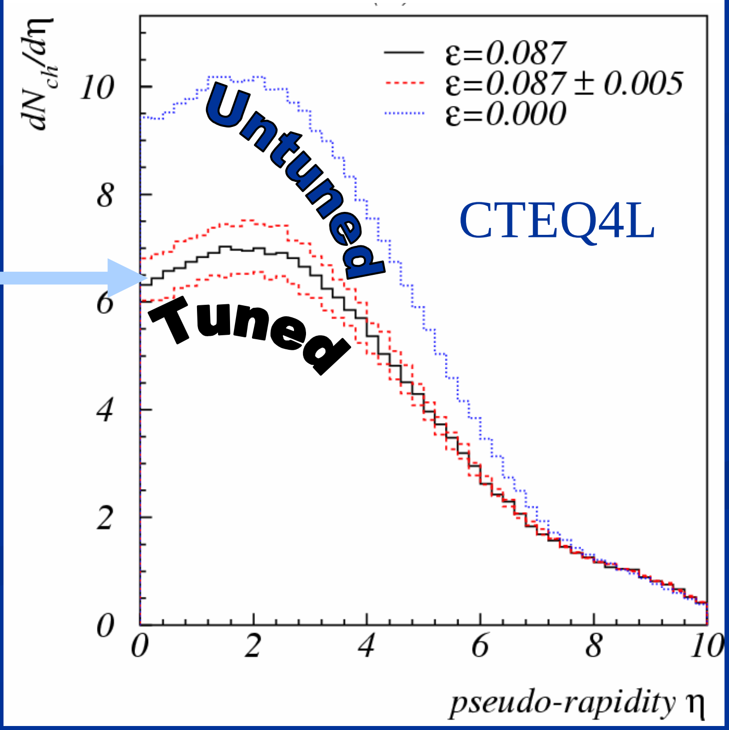



Extrapolation to the LHC Energy

[CERN 2000-004, pgg 293-300]

- 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

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

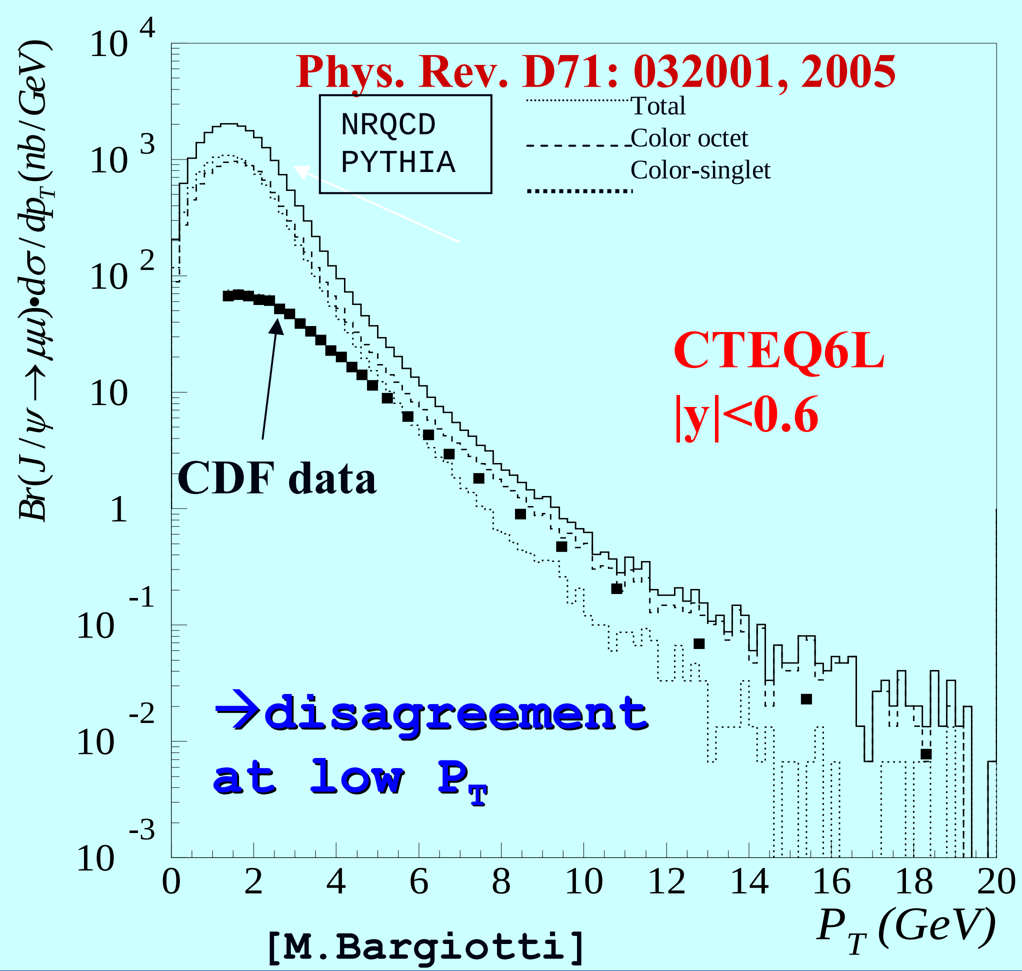
# Side Note on the energy dependency of the $P_T$ cut-off

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

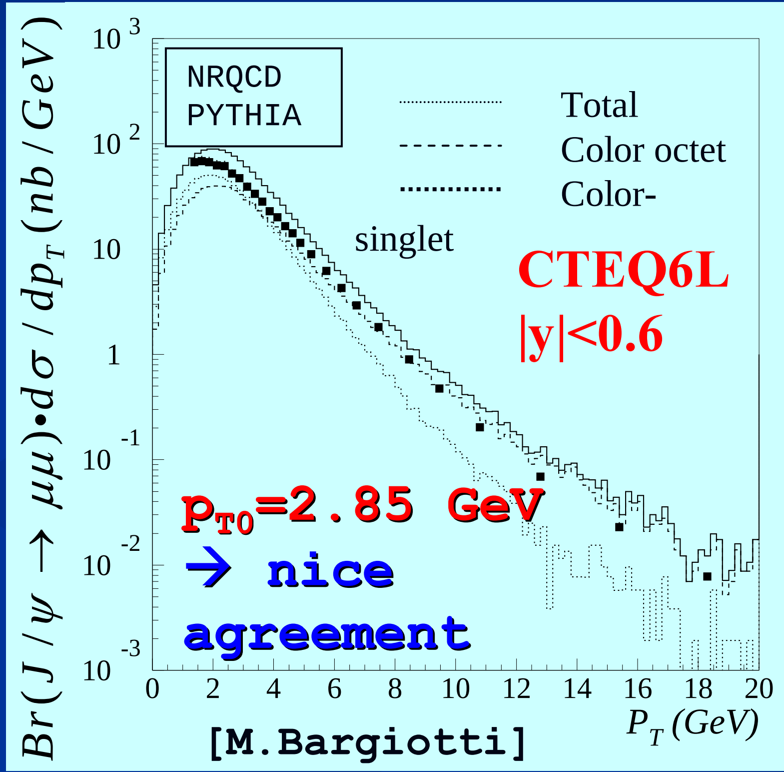
Minijets and transverse energy flow in high-energy collisions.
[Phys.Rev.D63:034004,2001]

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

# Quarkonia also prefers dampening...




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




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

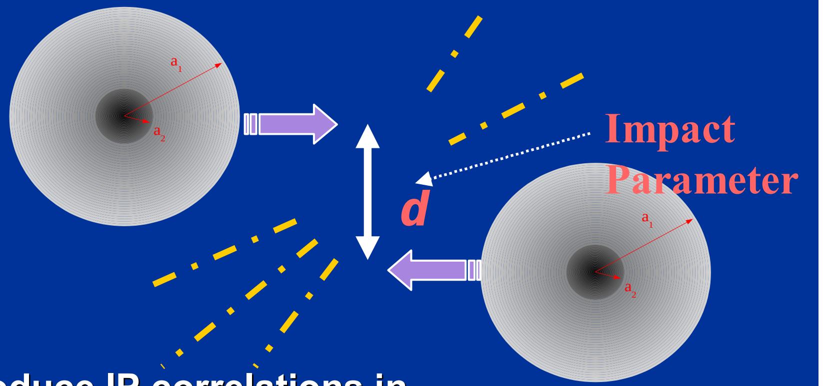
Let's assume universality: same PT0 of MPI, same energy dependency!

# MB: Charged Multiplicity Distribution

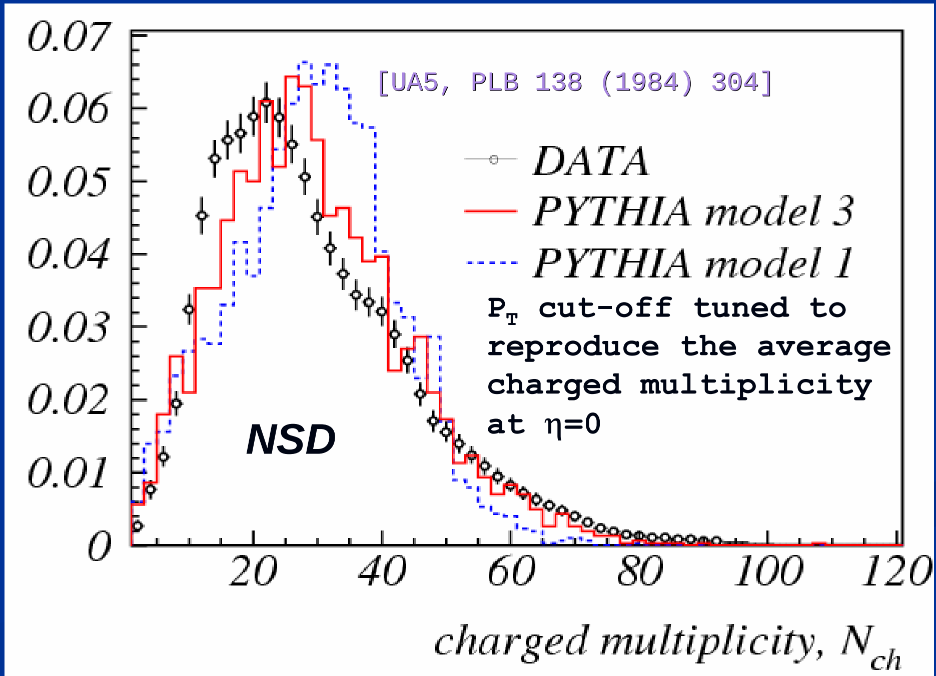
**Choice of the multiple interaction model:**

- 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 can be described by Gaussians**




Introduce IP correlations in Multiple Parton Interactions → Pedestal Effect

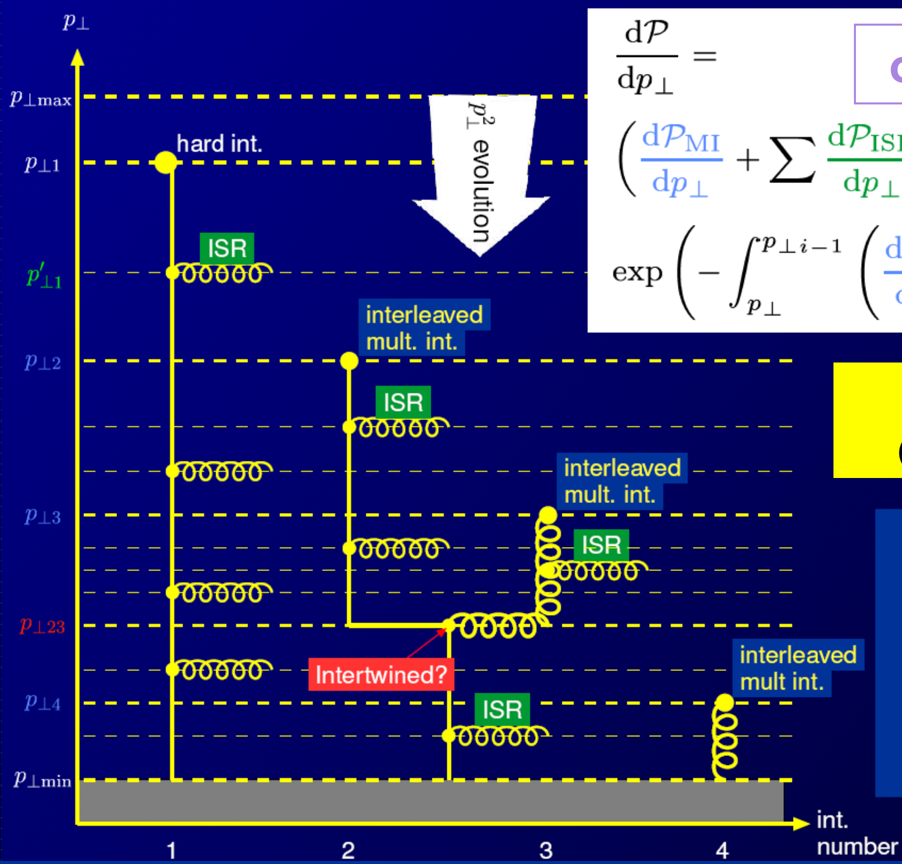


# “Interleaved evolution” with multiple interactions

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.




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

optional from Pythia 6.3

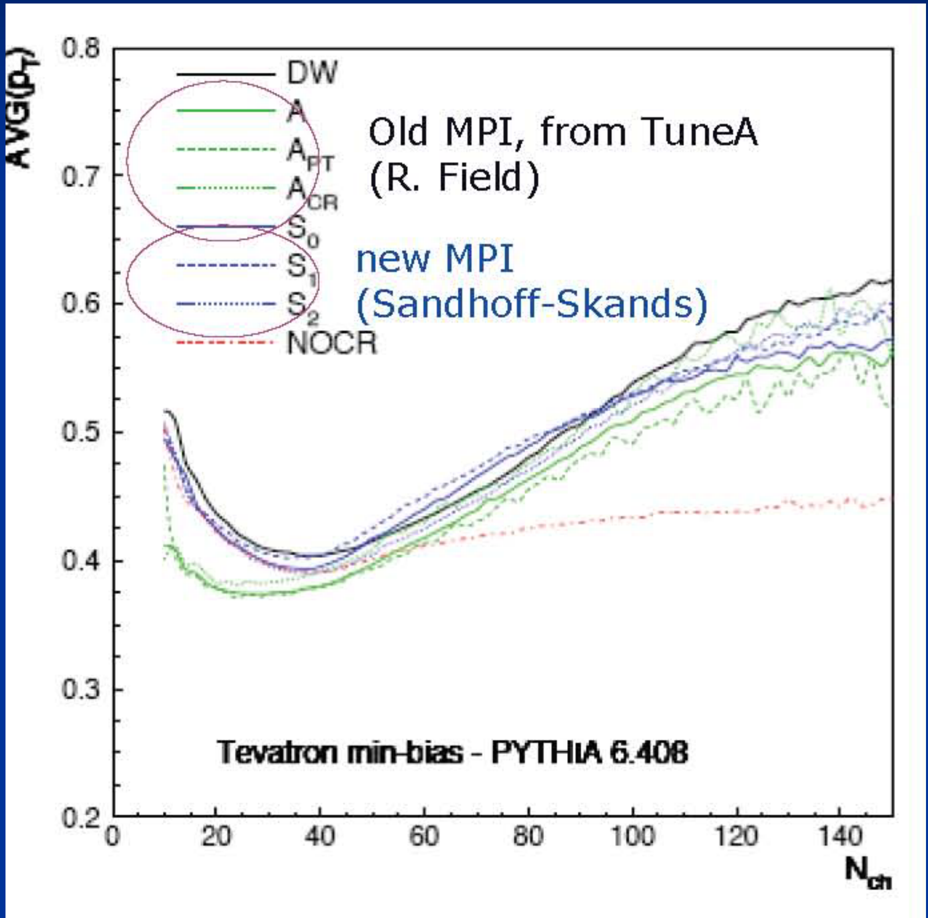
→Underlying Event
(separate LARGE topic now …)

~ “Finegraining”

→ correlations between all perturbative activity at successively smaller scales

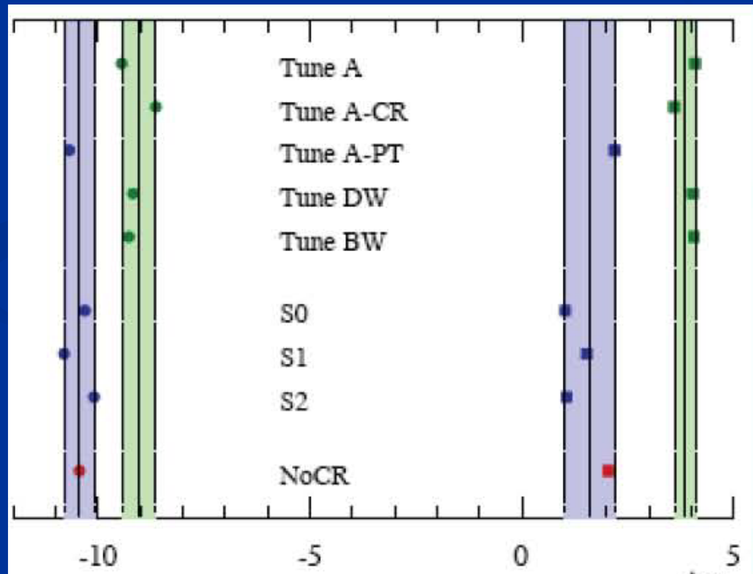
[P.Skands]

# 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



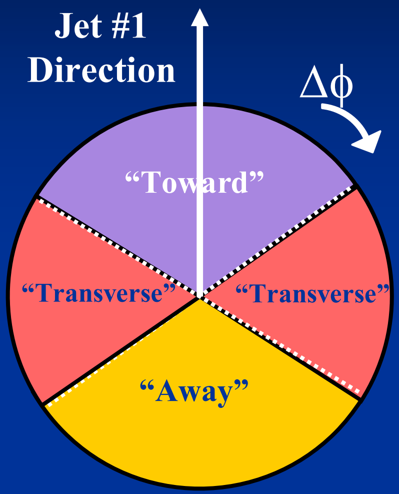

**Further information on tunings in back-up slides**

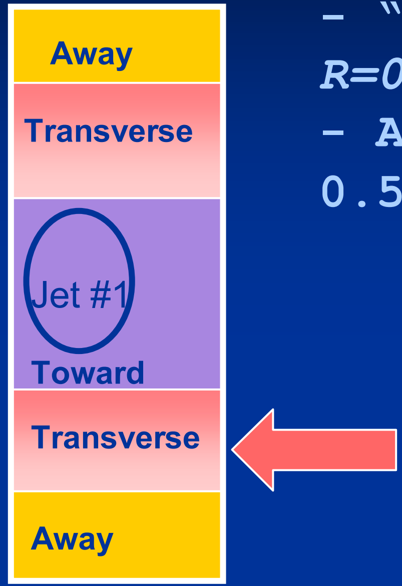
# MB Phenomenology: Bottom Line

- 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]



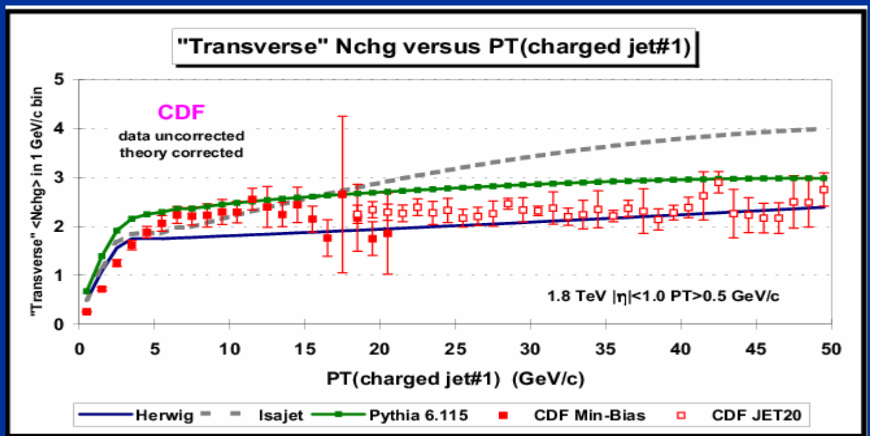

- "Charged jet" definition with *R=0.7*
- Assign all charged particles ($P_T$> 0.5 GeV/c) and |η|<1 to a jet

In the three different zones define:

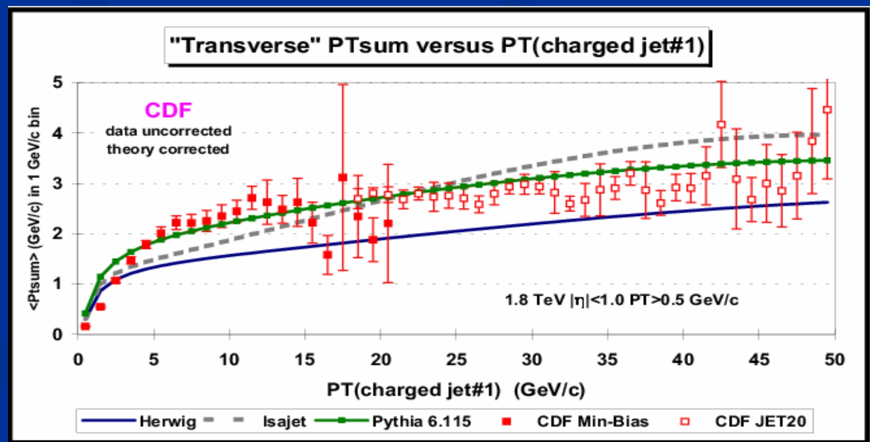
- Charged Multiplicity
- $\Sigma$ $P_T$ (charged tracks)

Transverse regions are expected to be sensitive to the Underlying Event

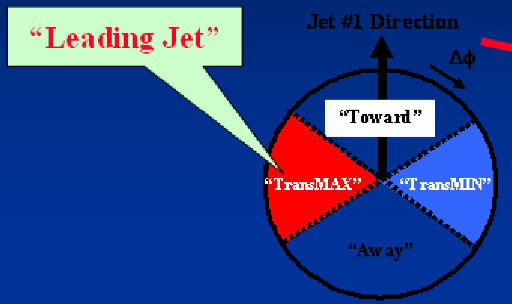
Rapid growth and then constant plateau for *PT1*>5GeV/c

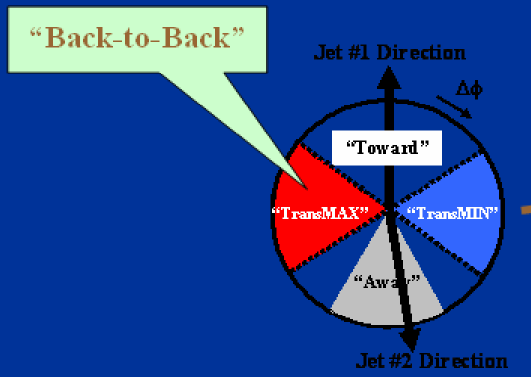


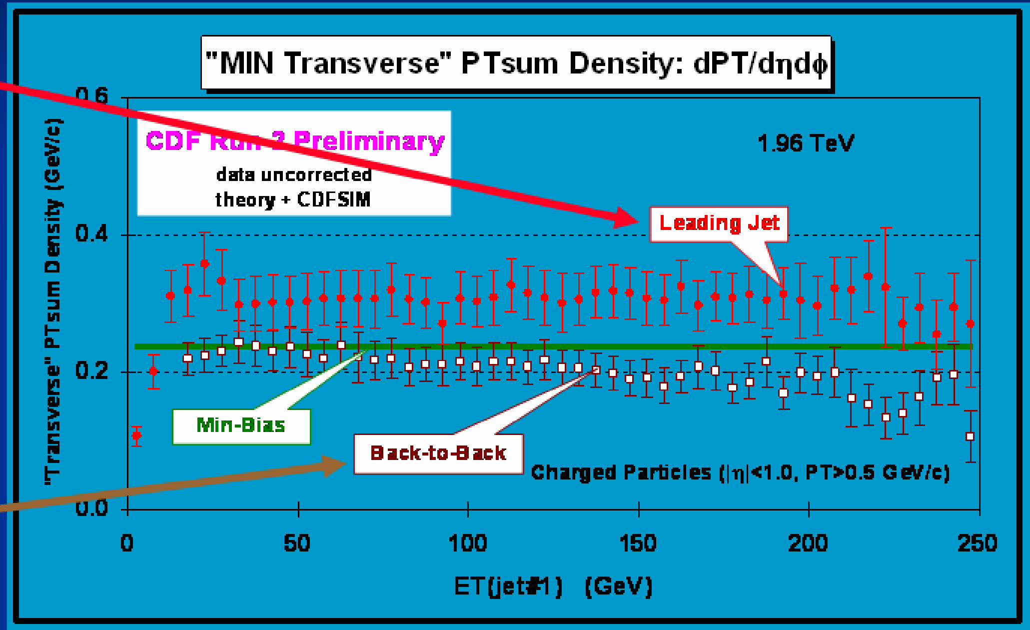

Smooth connection between Minimum bias and jet events



# UE: "TransMIN" PTsum Density versus $E_T$(jet#1)




"transMIN" is very sensitive to the "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" charge particle density, dNchg/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]

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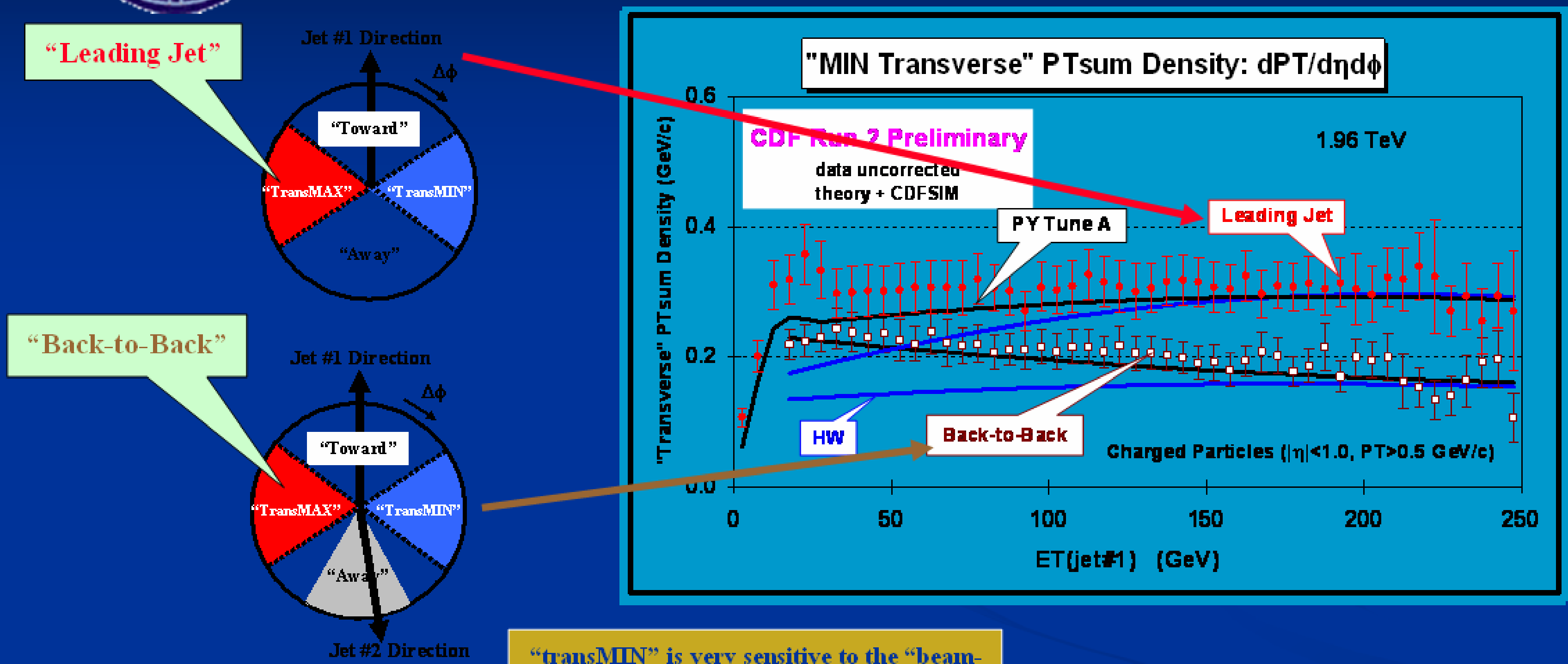


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# CDF UE Studies: Bottom Line

- 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

# MPI: Just a successful MB&UE model or rather a real feature of nature ?

**Double high $P_T$ interactions observed by AFS, UA2, CDF!!!**

[CDF Collab, Phys. Rev. Lett. 79, 584 (1997)]

In the simplest model, DP produces a final state that mimics a combination of two independent scatterings.

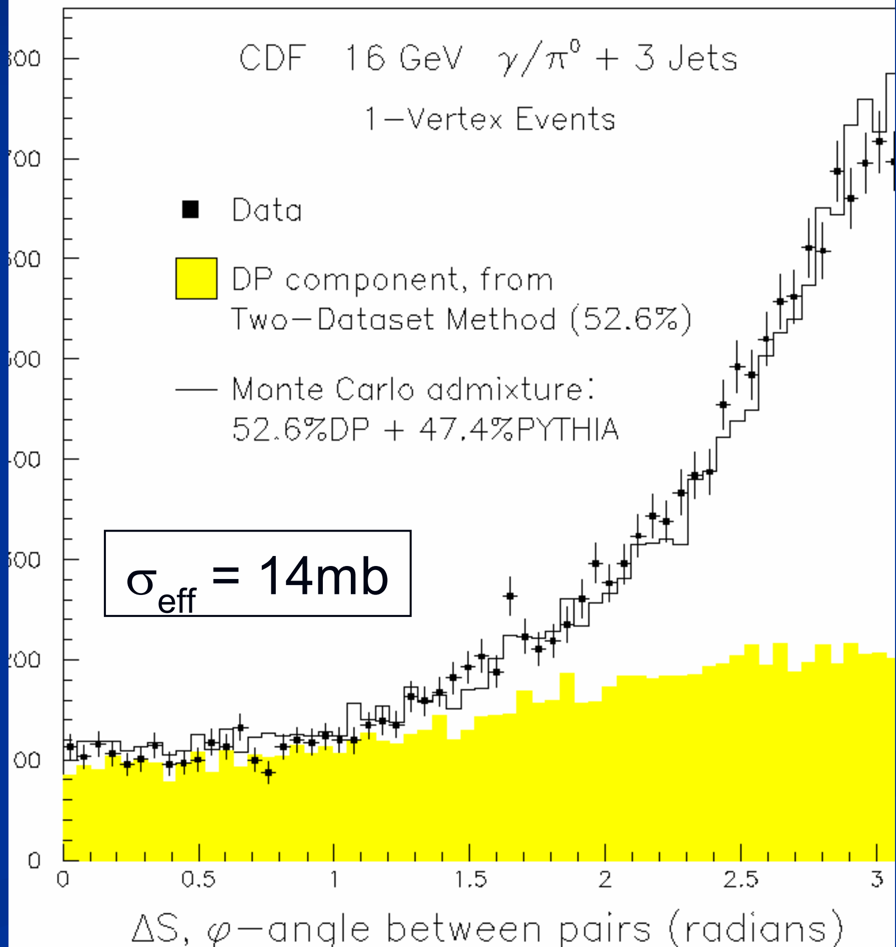
$$\sigma_{DP} \equiv m \frac{\sigma_A \sigma_B}{2\sigma_{eff}}.$$

m=2 for distinguishable scatterings
m=1 for indistinguishable scatterings

$\sigma_B/(2\sigma_{eff})$ is the probability of hard scattering B taking place given A, and this will be larger or smaller depending on the parton spatial density.

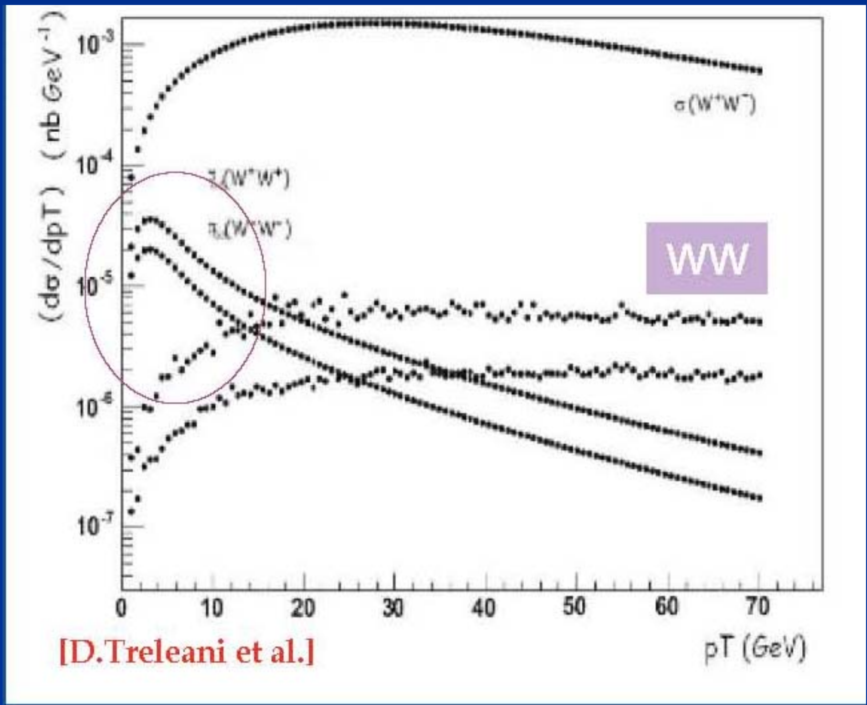
$\sigma_{eff}$ contains the information on the spatial distribution of partons

[Paoti Chang Fermilab Conf-97-175-E]



# The MPI Challenges for the LHC

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




**HOW?**

- **3j + γ**
- **Standard MB & UE measurements** (along the lines of the CDF experience)

**NEW**

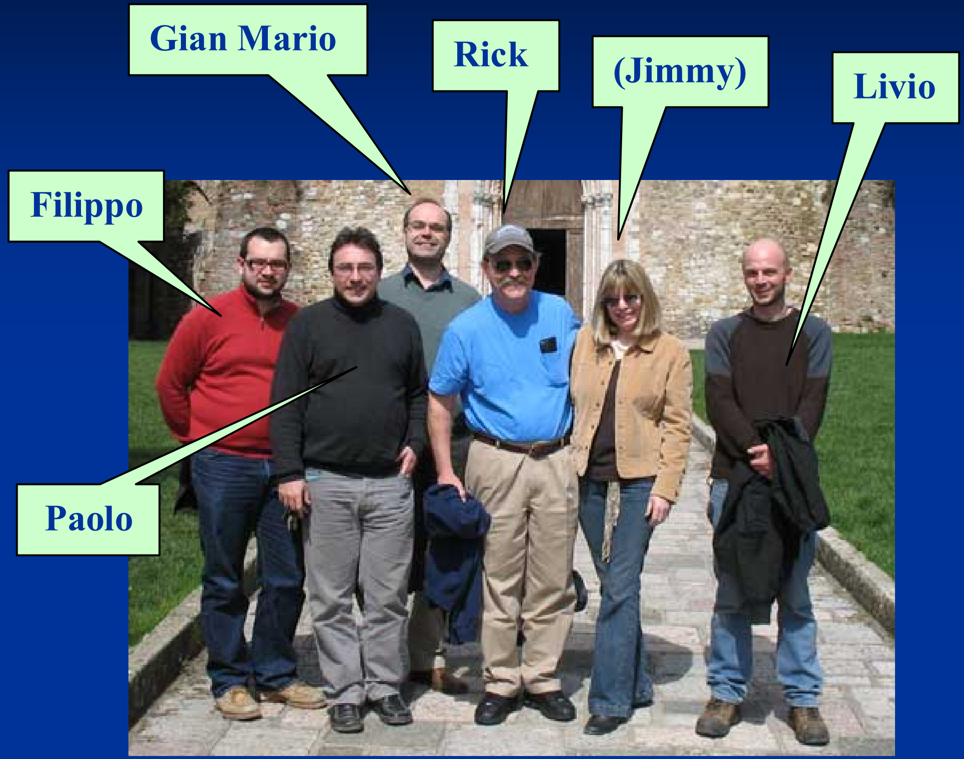
- **Counting pairs of same sign W**

**NEW**

- **Counting pairs of mini-charged jets in MB interactions**

[Treleani et al. Int.J.Mod.Phys.A20:4462-4468 (2005). Phys. Rev. D 72, 034022 (2005).]

# The MB&UE@CMS Task Force




*Perugia, Italy, March 2006*

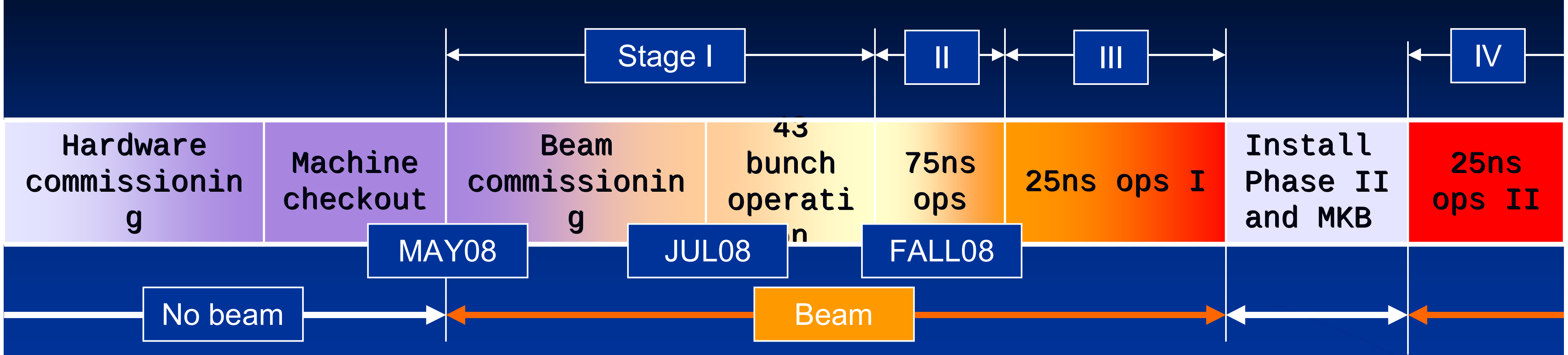
*Florian*

*Khristian*

*Daniele*

*Darin*

# *Staged commissioning plan for protons (R. Bailey)*



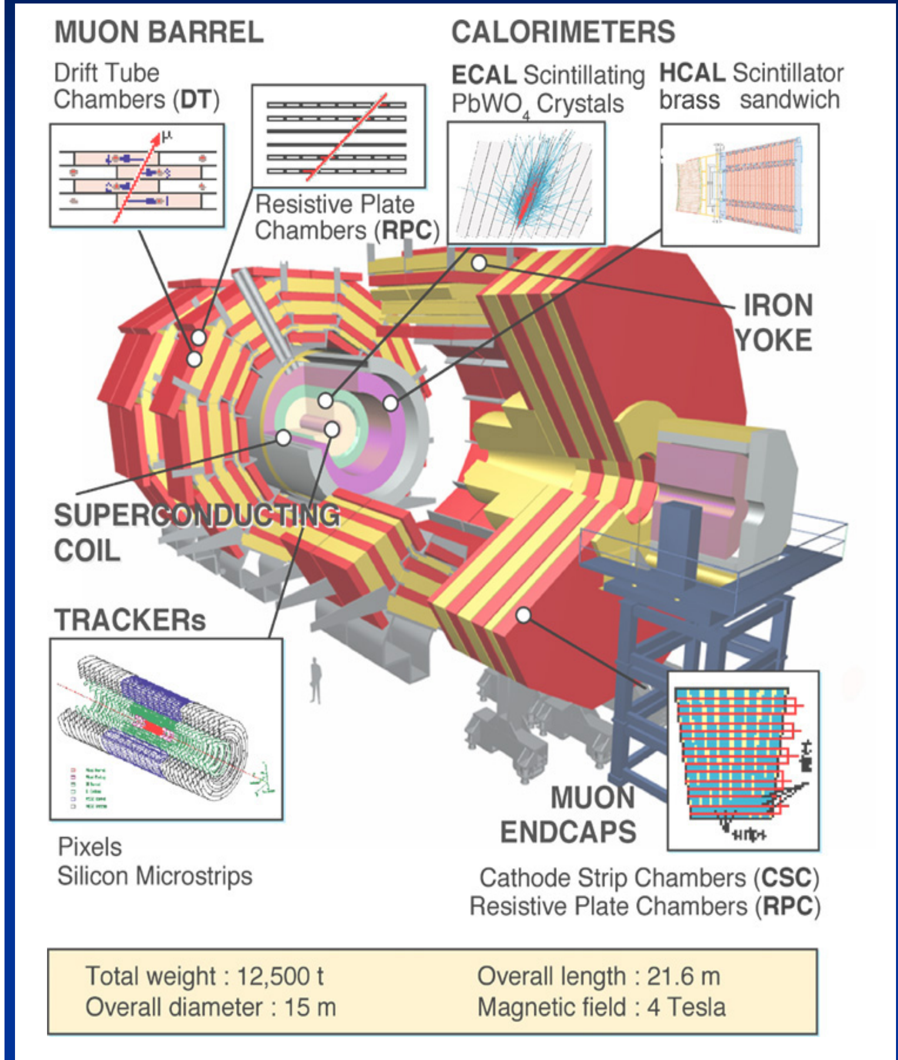

- Pilot physics run
  - First collisions
  - 43 bunches, no crossing angle, no squeeze, moderate intensities
  - Expected performance ~$10^{31}$ $cm^{-2}$ $s^{-1}$ at ~1 event/crossing
  - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
  - Performance limit $10^{32}$ $cm^{-2}$ $s^{-1}$ (event pileup)
- 75ns operation
  - Establish multi-bunch operation, moderate intensities
  - Relaxed machine parameters (squeeze and crossing angle)
  - Expected performance ~$10^{32}$ $cm^{-2}$ $s^{-1}$ at ~1 event/crossing (FALL08)
  - Push squeeze and crossing angle
  - Performance limit $10^{33}$ $cm^{-2}$ $s^{-1}$ (event pileup)
- 25ns operation I
  - Nominal crossing angle
  - Push squeeze
  - Increase intensity to 50% nominal
  - Performance limit 2 $10^{33}$ $cm^{-2}$ $s^{-1}$
- 25ns operation II
  - Push towards nominal performance

900 GeV runs also scheduled

[P. Lebrun, Elba07]

# CMS Design features

## Detectors




**Long 4 Tesla Solenoid containing Tracker, ECAL and HCAL**
**Tracking up to $\eta$ ~ 2.4**
**$\mu$ system in return iron**
**First $\mu$ chamber just after Solenoid (max. sagitta)**
**Big lever arm for Pt measurement**

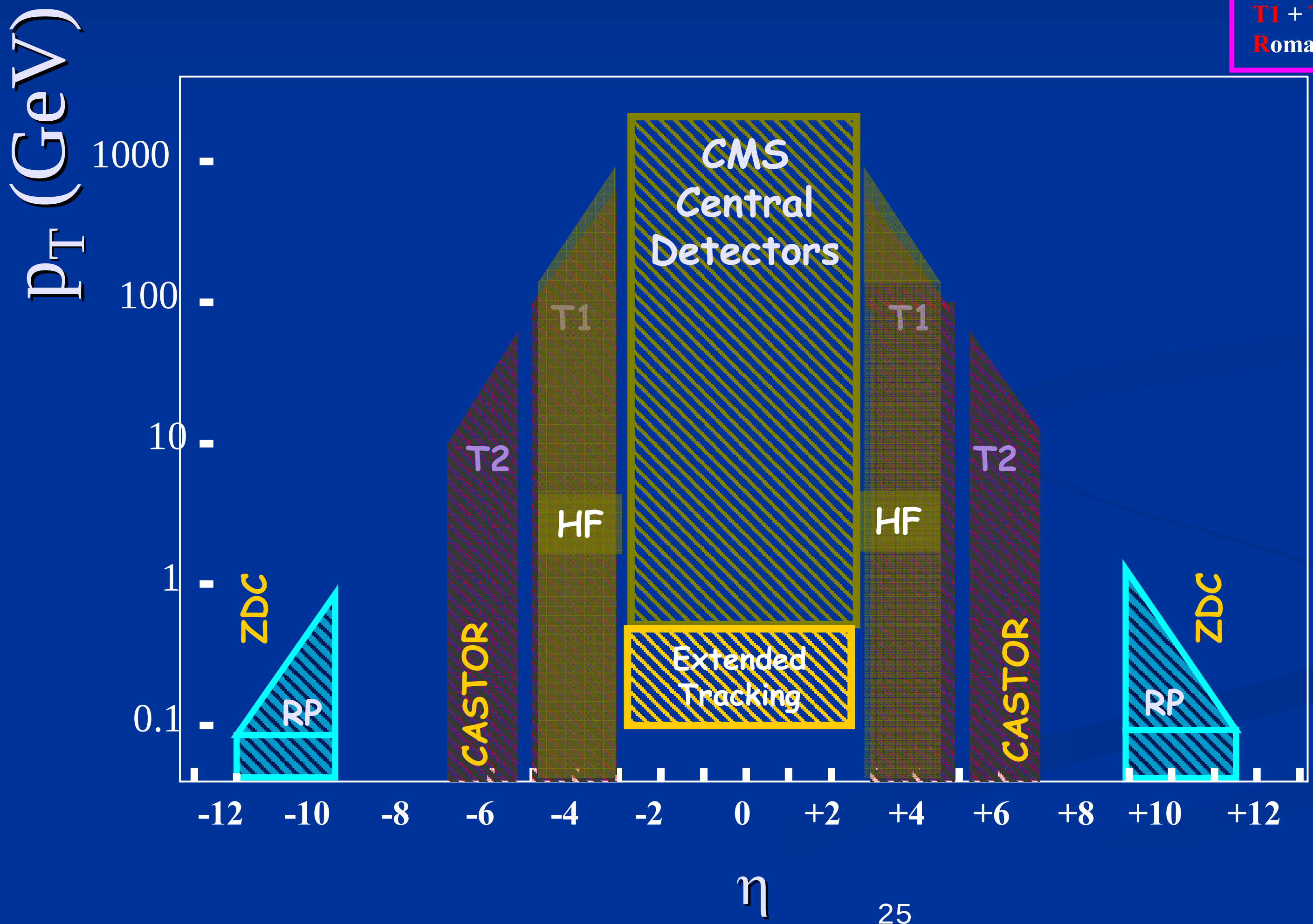
| | |
|---|---|
| Event Rates: | ~$10^9$ Hz |
| Event size: | ~1 MByte |
| Level-1 Output | 100kHz |
| Mass storage | $10^2$Hz |
| Event Selection: | ~$1/10^{13}$ |

# CMS performances

- basic performance numbers
  - HCAL resolution $\frac{\sigma}{E} \approx \frac{90\%}{\sqrt{E}} \oplus 7\%;$
  - ECAL resolution $\frac{\sigma}{E} \approx \frac{2.7\%}{\sqrt{E}} \oplus 0.5\%$
  - Tracker resolution $\frac{\sigma}{p_\perp} = 15\% \, p_\perp[\mathrm{TeV}] + 0.5\%$
  - Calorimeter-Jet E-resolution $\frac{\sigma}{E_T} \approx \frac{125\%}{\sqrt{E_T}} \oplus 3.3\% \oplus \frac{5.6\%}{E_T}$
- Remember : CMS design choice: optimize performance for muon/track momentum resolution and electromagnetic energy resolution....
- now working on: **Particle Flow**
  - combine in optimal way information from all subsystems
  - should considerably improve resolution, especially at low jet $p_T$

# TOTEM+CMS: $p_T$-$\eta$ coverage

**CMS Forward detectors:**
**Hadron Forward Calorimeter HF: $3 \leq |\eta| \leq 5$**
**Castor Calorimeter: $5.2 \leq |\eta| \leq 6.5$**
**Beam Scintillation counters BSC**
**Zero-Degree Calorimeter ZDC**
**TOTEM detectors:**
**T1 (CSC) in CMS endcaps, T2 (GEM) behind HF**
**T1 + T2: $3 \leq |\eta| \leq 6.8$**
**Roman Pots with Si det. up to 220 m**



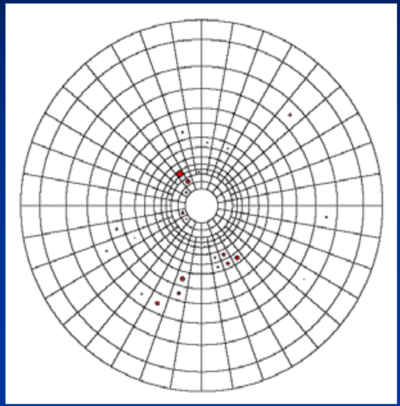

$p_T^{max} \sim \sqrt{s} \exp(-\eta)$

# MB Trigger

## Idea: Based on Hadron Forward (HF) Calorimeter

[HI addendum to CMS PTDR]

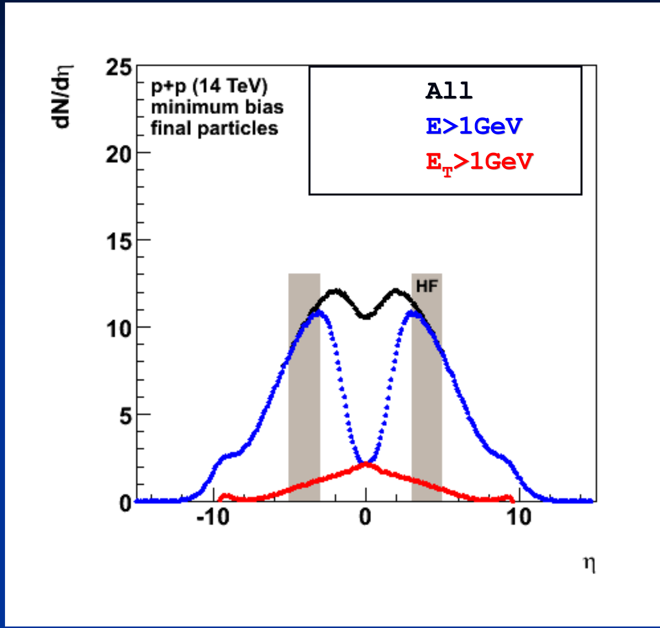
**1 pp interaction:**



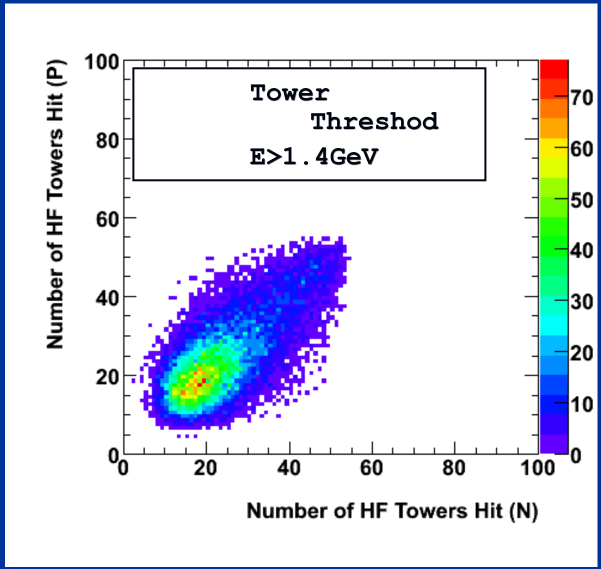
$3<|\eta|<5$

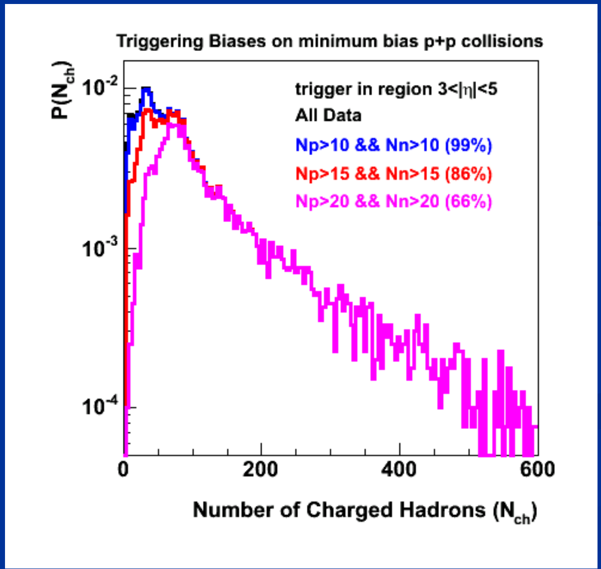
18 wedges/side

0.175x0.175 towers




Using towers or single cells fired

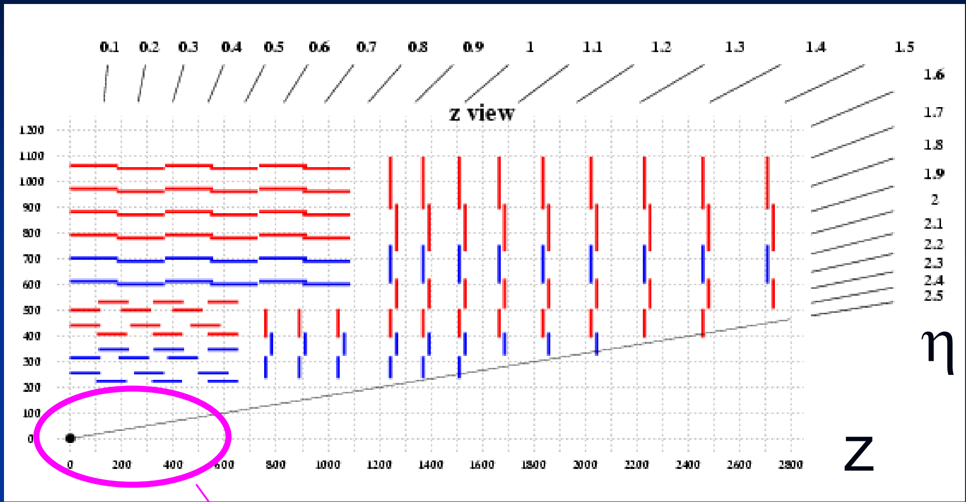


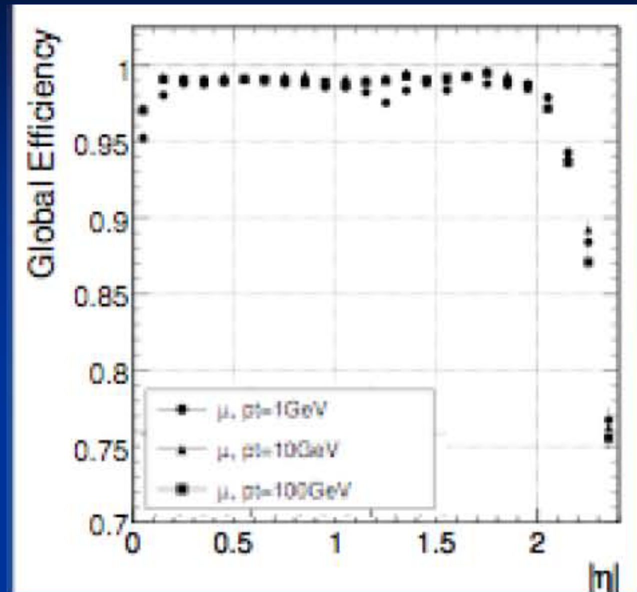



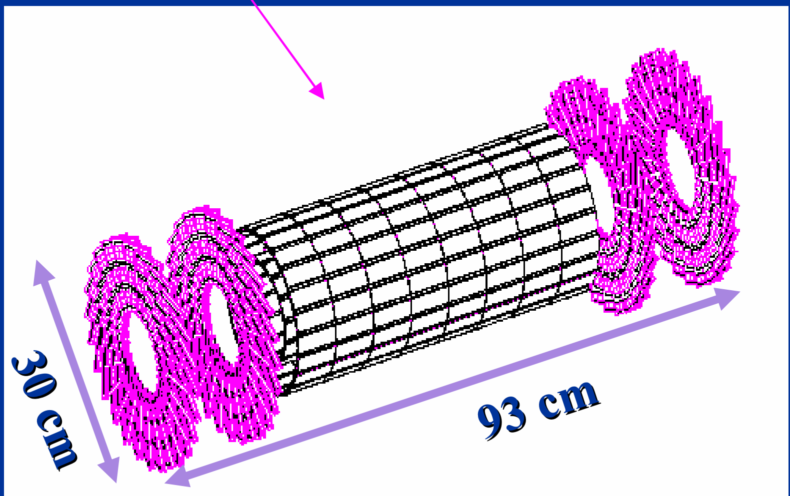

Cut on the number of calorimeter cells
>10 cells hit
99% efficient
>10 forward cells and
>10 backward cells

>15 → 86%
>20 → 66%

# The CMS Tracker



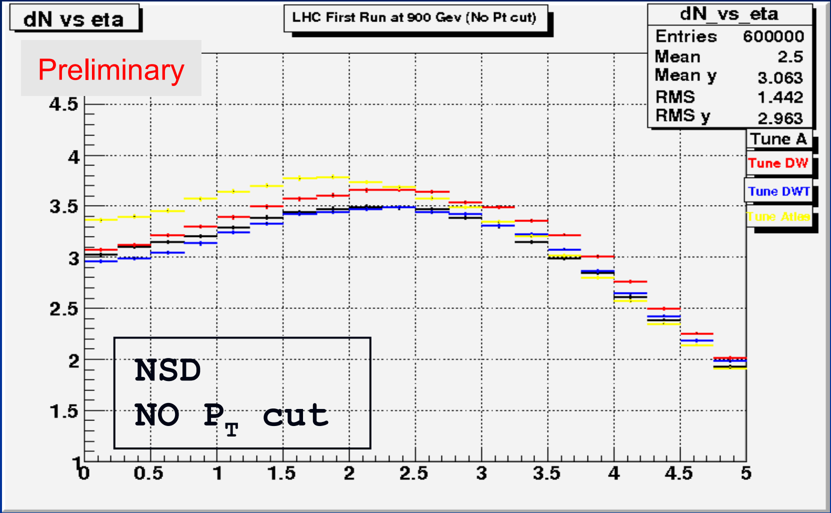




**Three Pixel Hits**
**Ten to Fourteen Silicon μ–Strip Measurement Layers**
**Radius ~ 110 cm, Length ~ 270 cm**
**1.90mm sagitta for 100 GeV Pt track**
**150 * 150 $\mu m^2$ Pixels**
**320 μm thick Si for R < 60cm, Strip ~ 10cm, Pitch 81-123 μm**
**500 μm thick Si for R > 60cm, Strip ~ 20cm, Pitch 123-183 μm**

"Standard" Tracking:
$|\eta| < 2.4$
$P_T > 0.9$ GeV

Occupancy < $10^{-4}$
Track Reconstruction Exploits Pixel Seeding

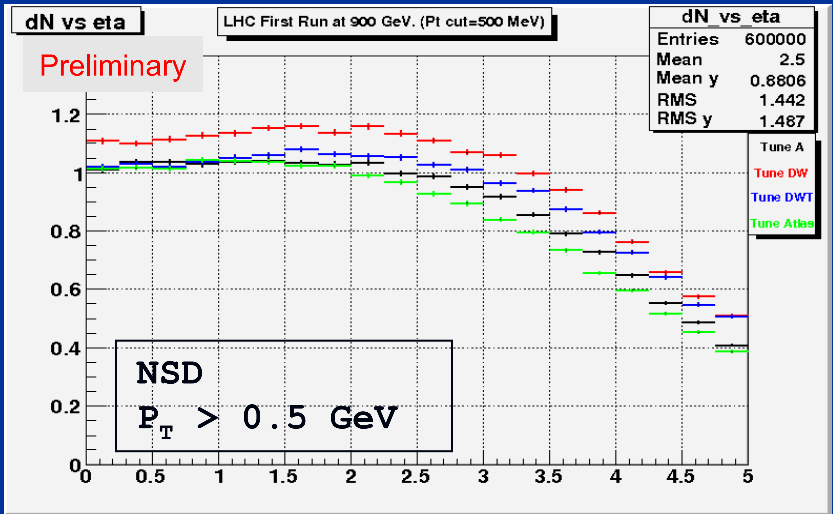
# MB: Pseudorapidity distribution of charged tracks in LHC runs at sqrt(s) = 900GeV

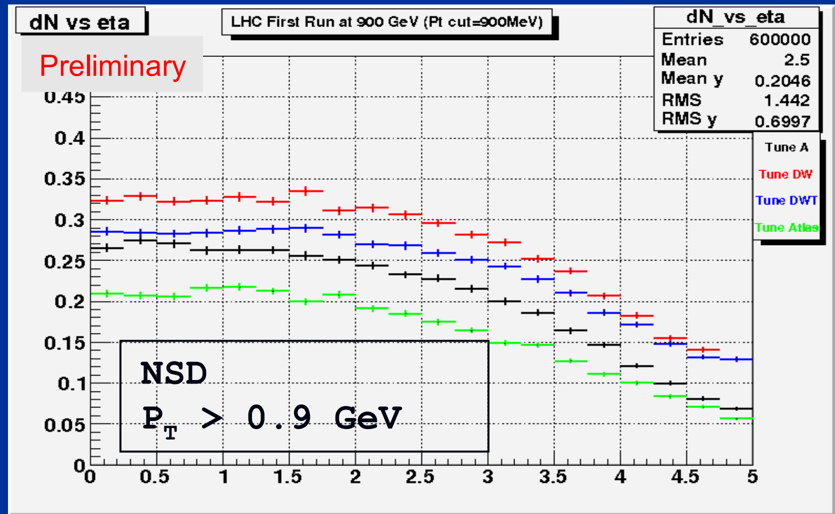



Predictions according to 4 different Pythia Tunes (Details of Tunes in Back-up slides)

For the charged multiplicity in the central ragion ($\eta = 0$) we have:

| PT Cut | Tune ATLAS | TuneDWT |
|---|---|---|
| 0 | ~3.4 | ~3 |
| 500 MeV | ~1 | ~1 |
| 900 MeV | ~0.22 | ~0.29 |

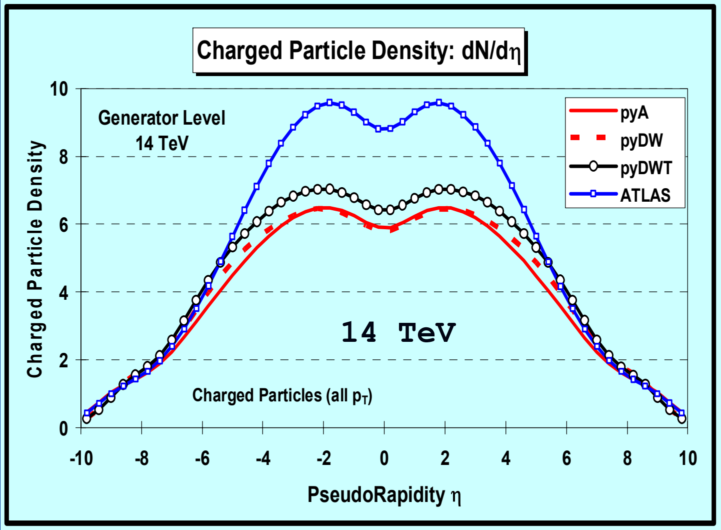


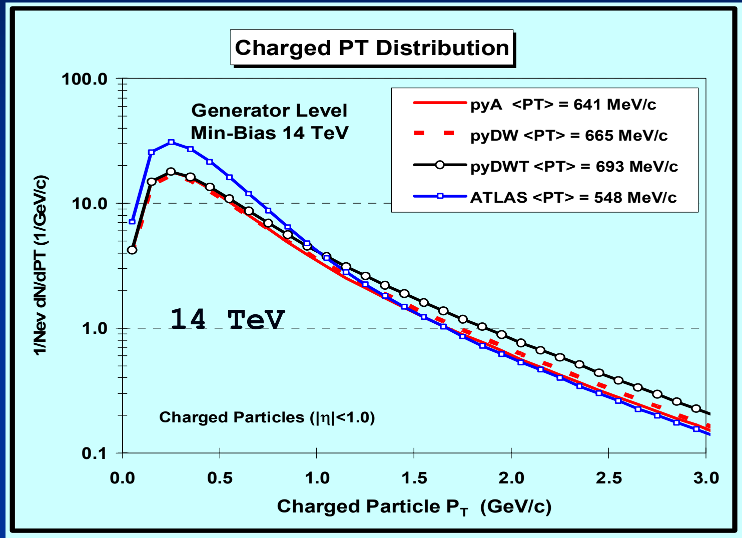




Warning: The “Standard” CMS Tracking (PT>0.9 GeV) Would Reconstruct Max ~ 10% of the tracks!

# Measuring central MB (&UE) activity - soft tracking

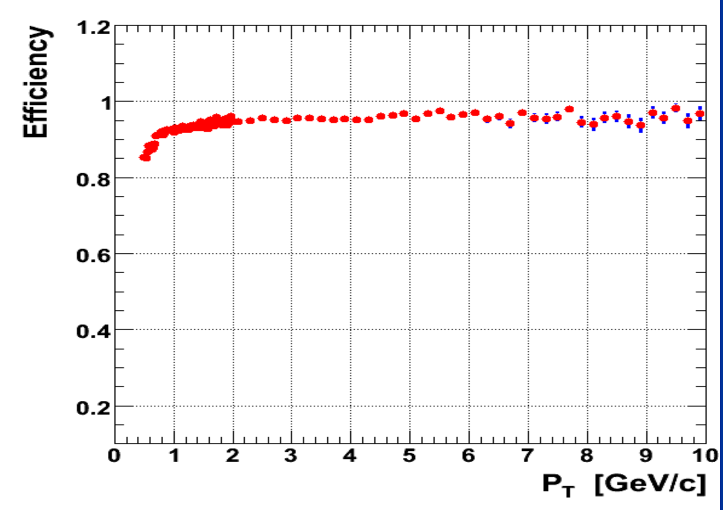
| $\sigma_{tot}$ | $= \sigma_{Elastic}$ | $+ \sigma_{SD}$ | $+ \sigma_{DD}$ | $+ \sigma_{HardCore}$ | |
|---|---|---|---|---|---|
| (14 TeV) | ~20 mb | ~15 mb | ~10 mb | ~55 mb | = ~100 mb |

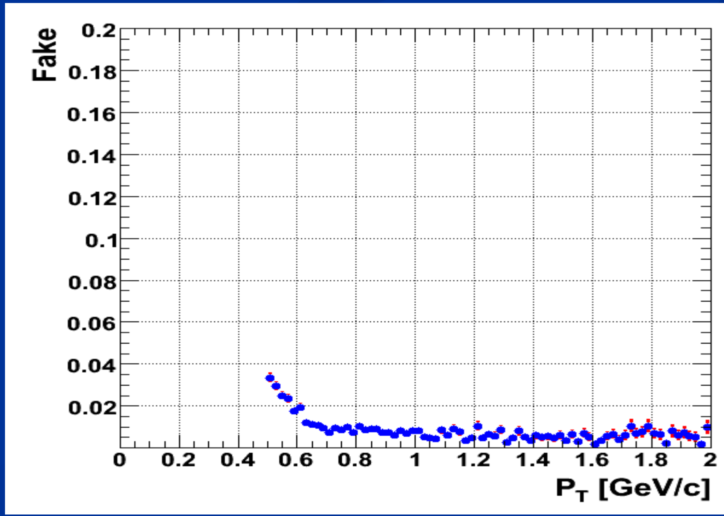



Details of Tunes in Backup Slides

Reconstructing MB&UE observables heavily rely on the tracking performances: low PT thresholds, low fake rates, high efficiencies

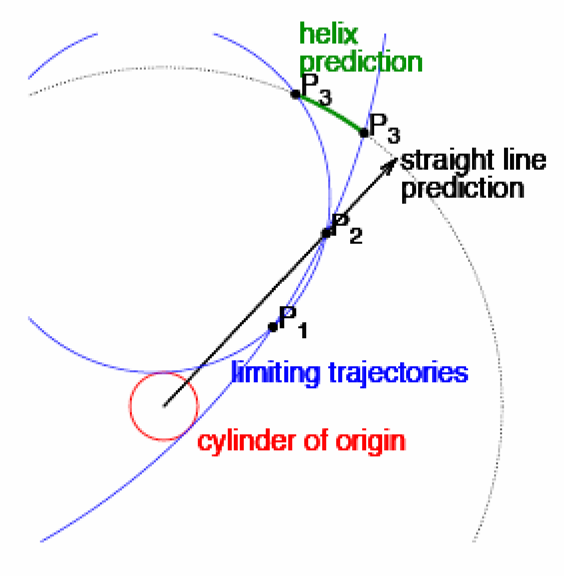


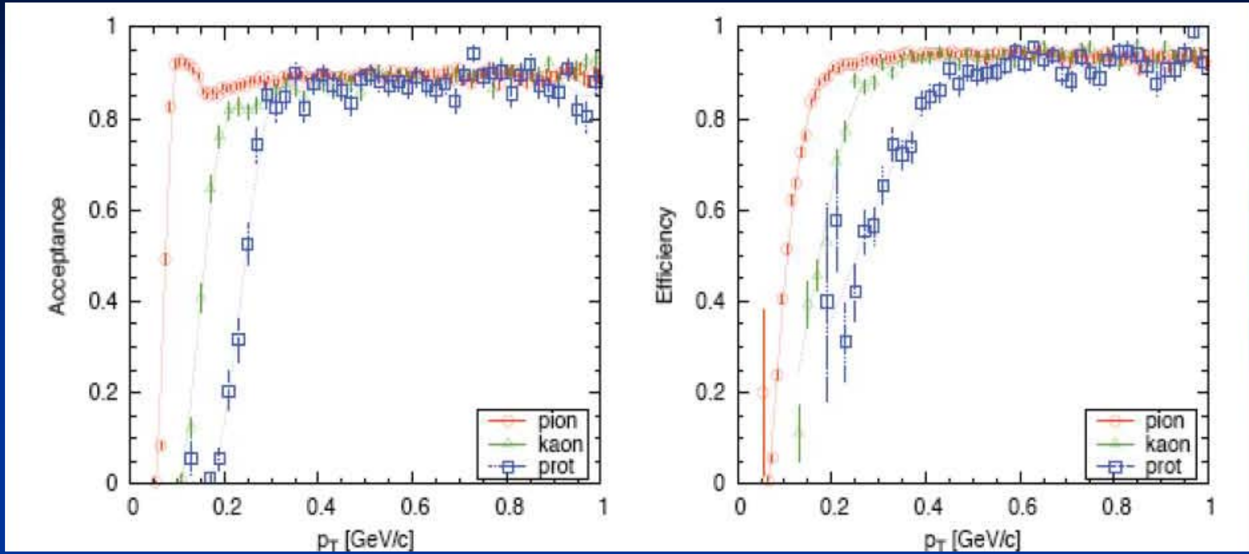




Standard tracking with modified seeding extend to ~500 MeV

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

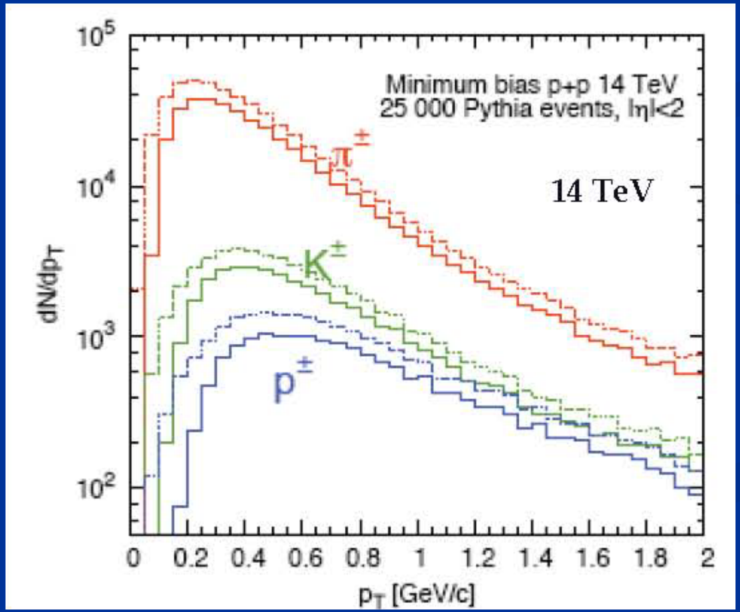
# Measuring central MB (&UE) activity - very soft tracking

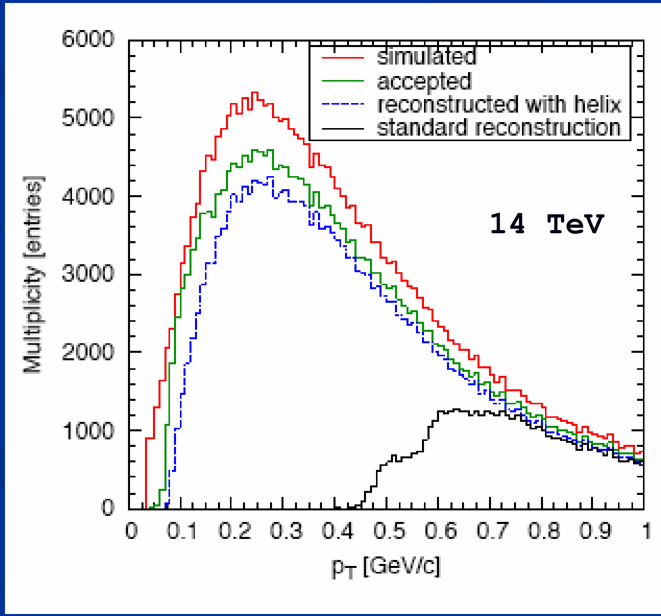



Tracklets:
Only pixel triplets:
down to 150 MeV !

[F.Sikler et al. hep-ph/0702193]
& HI addendum to CMS PTDR

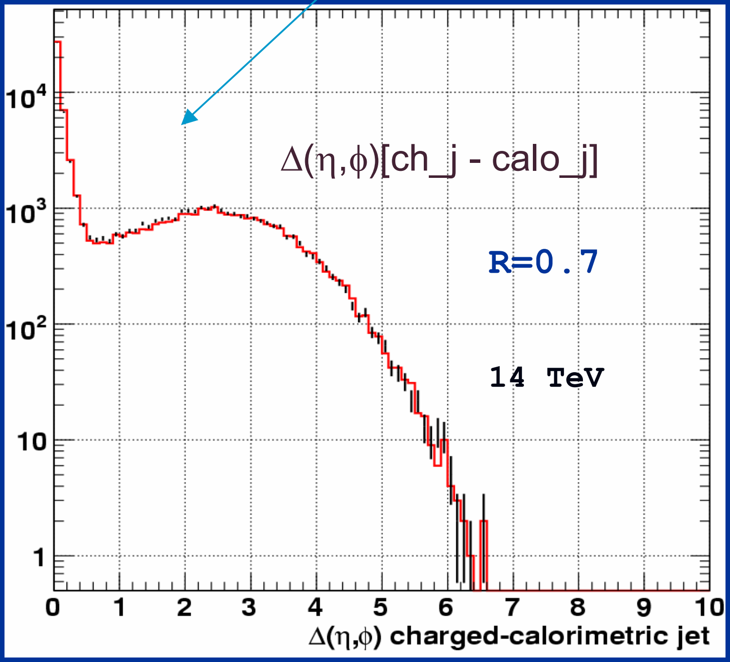


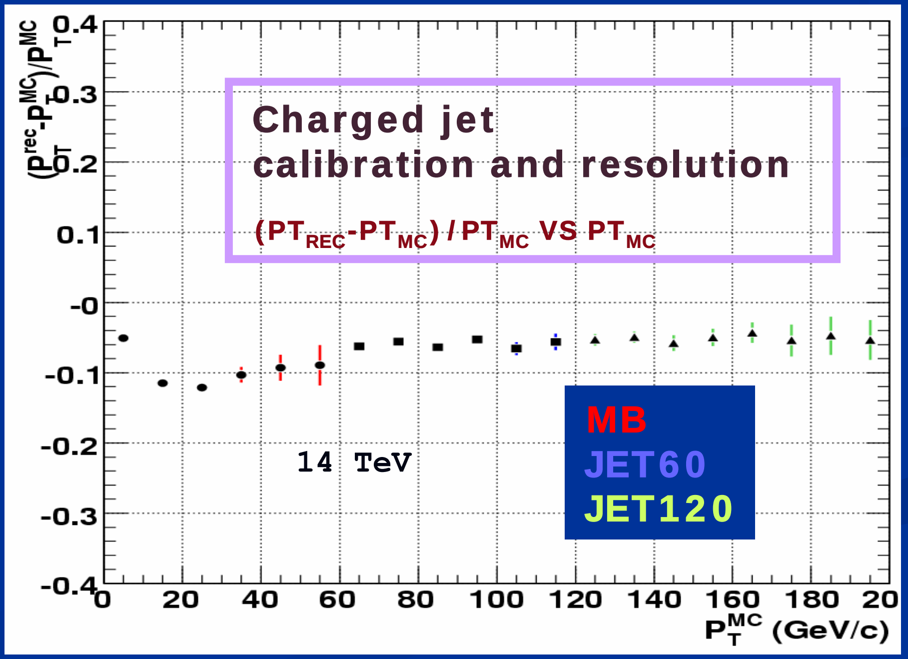



# Charged Jet definition and performances

Charged jet definition:
Iterative Cone Algorithm (ICA) with massless charged tracks as input

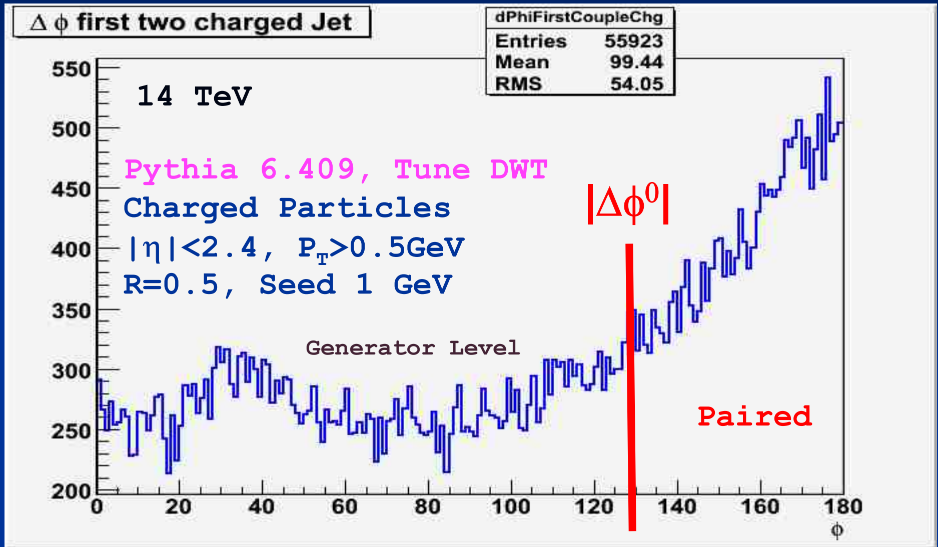
$\Delta(\eta,\phi)$
**leading Calorimetric - leading Charged Jet (on MB sample)**



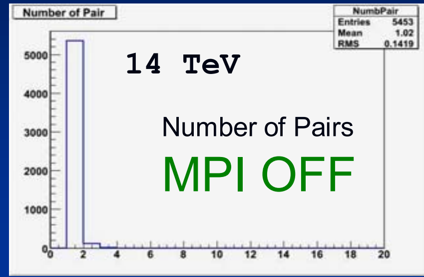



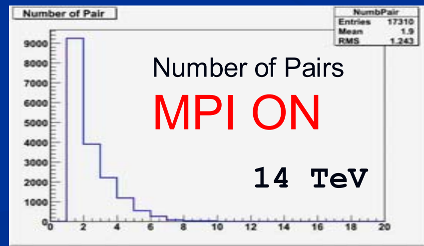
# MB: Quoting MPI through paired MiniJets

$\Delta\phi$ 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

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

[D.Treleani, CMS]

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

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

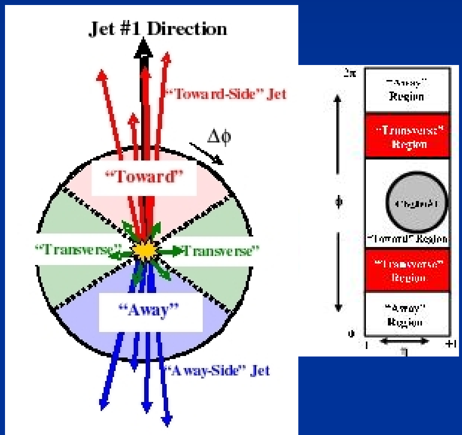
# UE: measurement plan at the LHC

[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



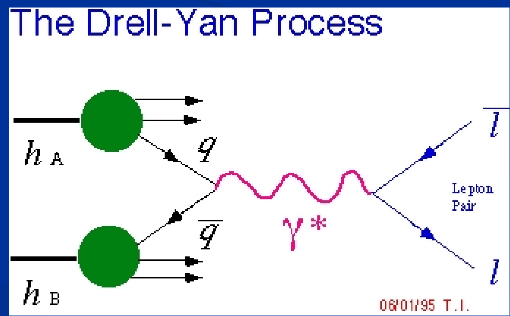

The leading Charged jet defines a direction in the $\phi$ plane

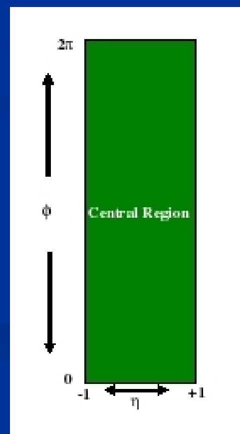
The transverse region is particularly sensitive to the UE

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 $\phi$ plane

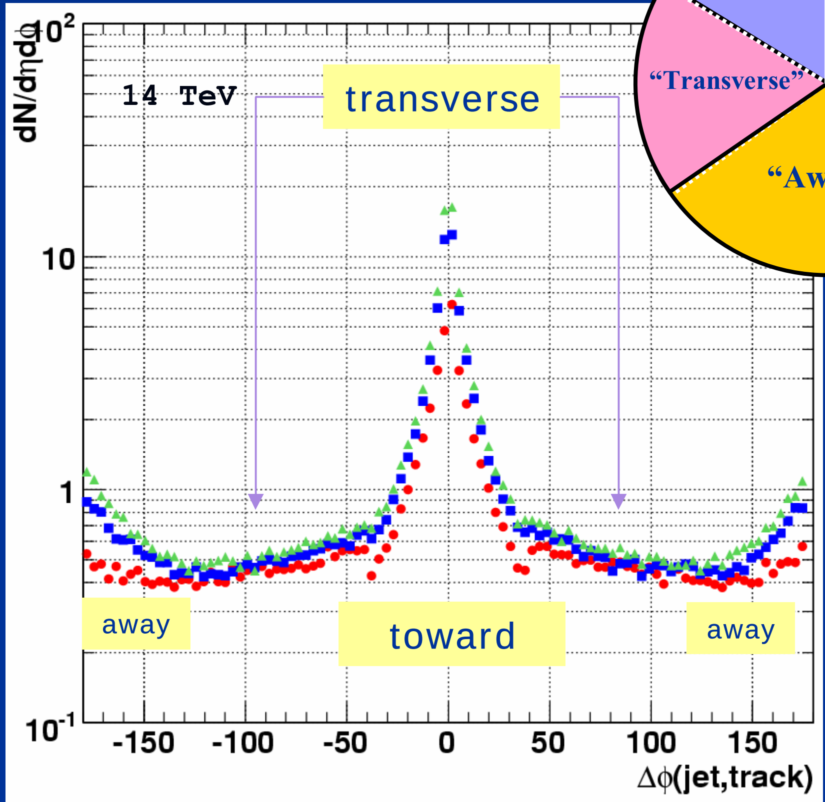


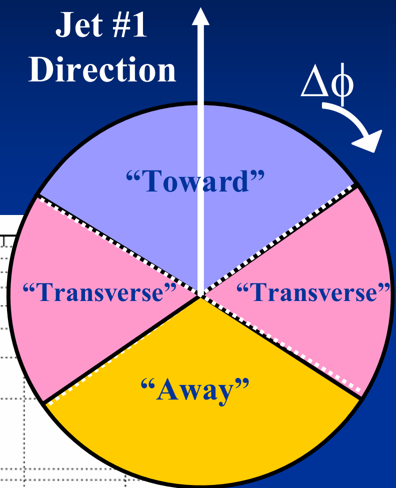



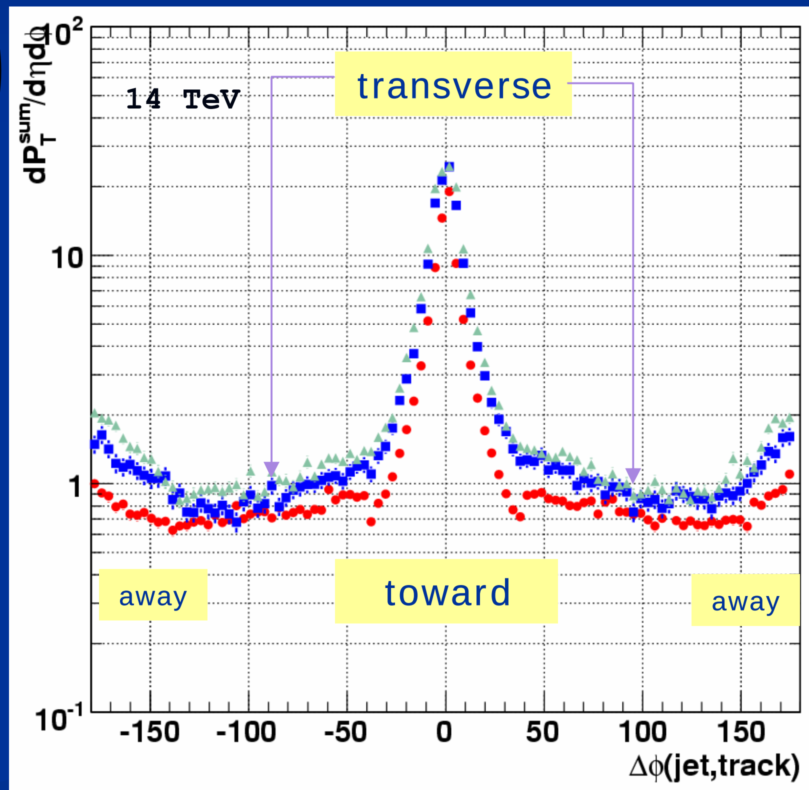

(after removing the $\mu$ pairs everything else is UE)

# UE: Reconstruction studies: Activity vs distance to charged jet

pp at sqrt(s)=14 TeV



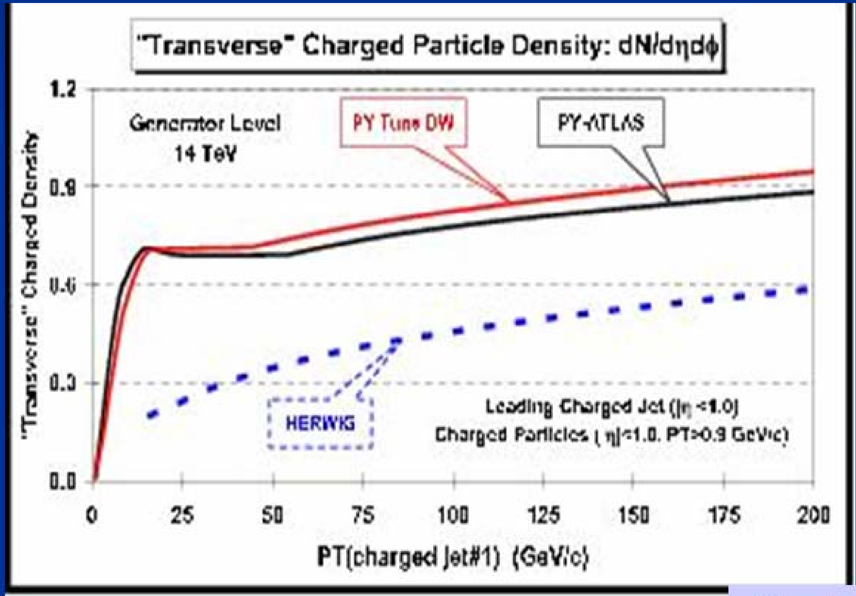




MB
JET60
JET120

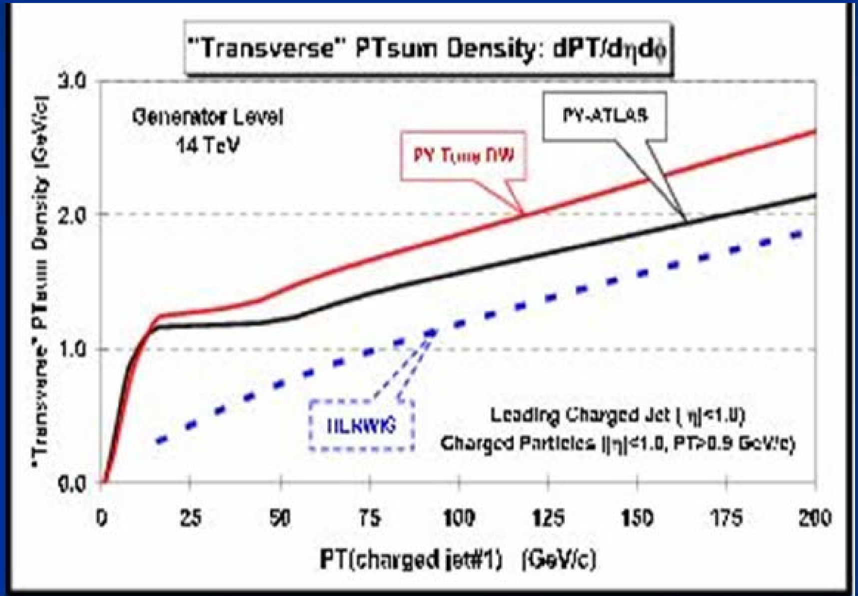
Charged tracks with PT>0.9 and |η|<1

# UE@CMS: Reconstruction studies charged jet: transverse region

pp at sqrt(s)=14 TeV




PT_ch_jet1

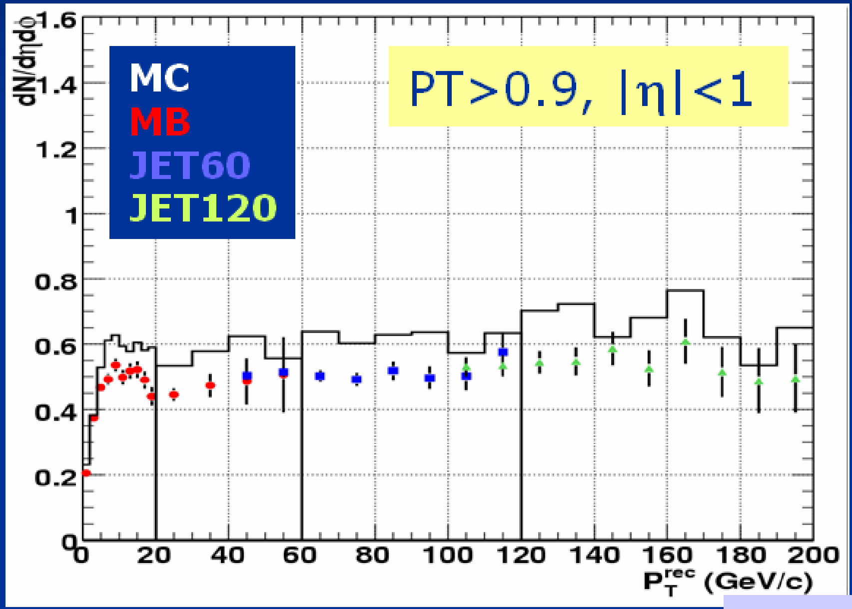



PT_ch_jet1

# UE@CMS: Reconstruction studies charged jet: transverse region

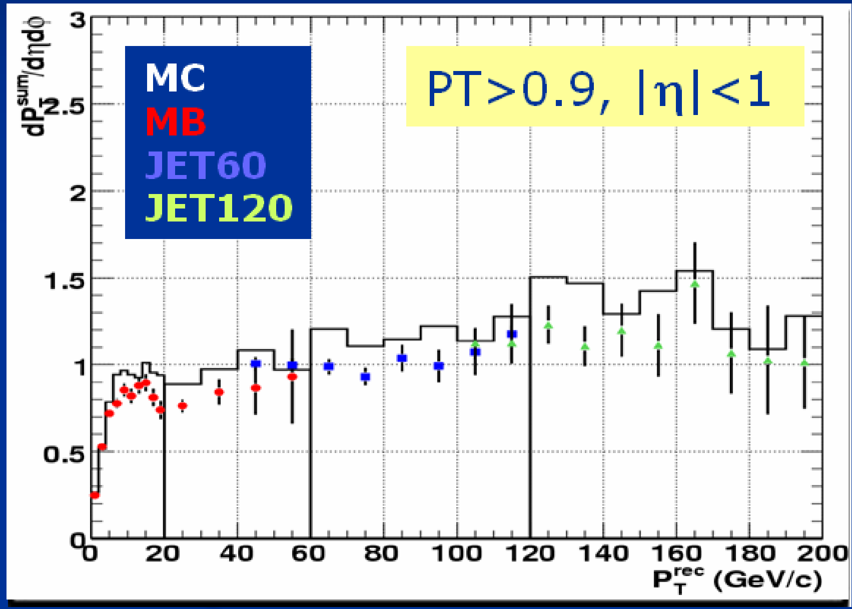
pp at sqrt(s)=14 TeV

**$dN_{ch}/d\eta d\phi$ VS PT_ch_jet1**




PT_ch_jet1

**$dPT_{sum}/d\eta d\phi$ VS PT_ch_jet1**




PT_ch_jet1

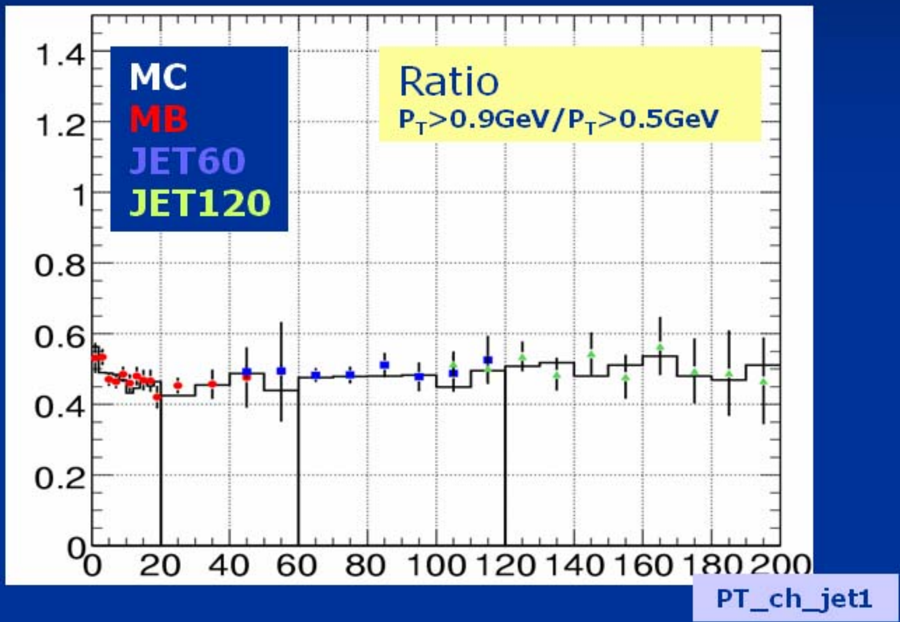
Good RECO/MC agreement in shape

Differences compatible with the expected corrections from charged jet PT calibration, charged tracks innefficiencies and fake rate

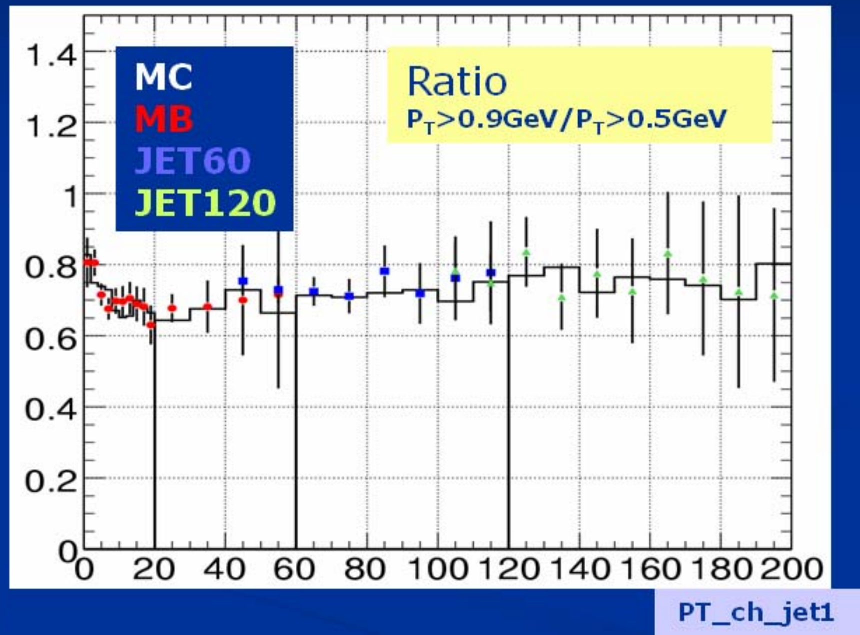
# UE@CMS: Reconstruction studies charged jet: transverse region

pp at sqrt(s)=14 TeV

**$dN_{ch}/d\eta d\phi$ VS PT_ch_jet1**




**$dPT_{sum}/d\eta d\phi$ VS PT_ch_jet1**




Good RECO/MC agreement in shape

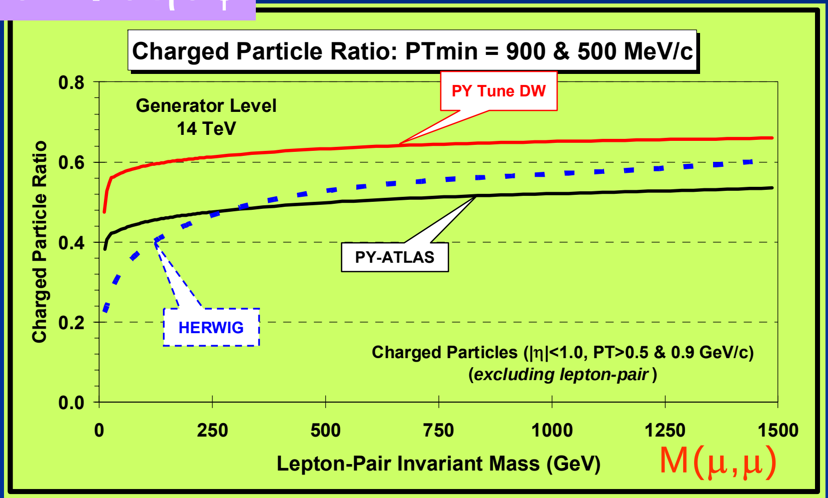
Differences compatible with the expected corrections from charged jet PT calibration, charged tracks innefficiencies and fake rate

RECO/MC Differences absorb in the ratio, no need to apply corrections!
Emphasis on the reconstruction of soft tracks...

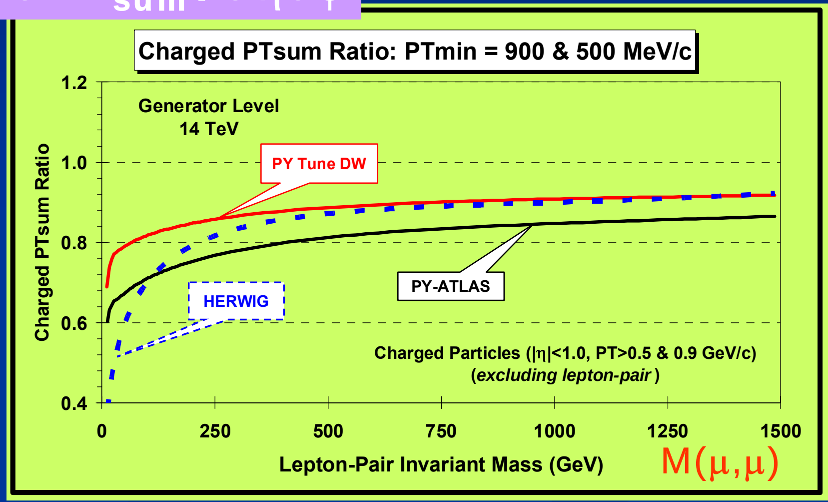
# UE@CMS: Generator level studies – Drell Yan

pp at sqrt(s)=14 TeV

**dN / dηdφ**




**$dPT_{sum}$ / dηdφ**




**Ratio $P_T$>0.9GeV / $P_T$>0.5GeV ($P_T$ tracks threshold)**

Ratio observables are sensitive to differences between models !!!

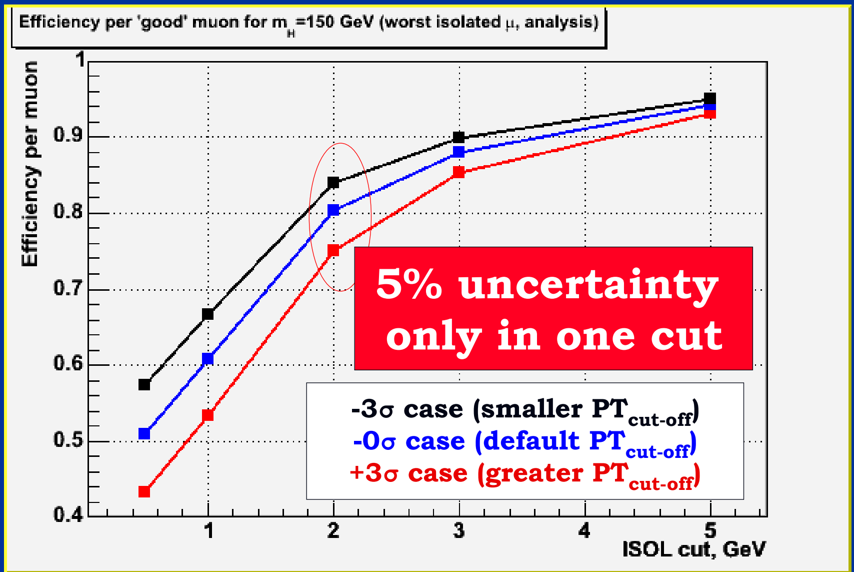
- ❖ Here we don't concentrate on MC tuning, however we adopt reference models/parameters: → For further information see Back-up slides

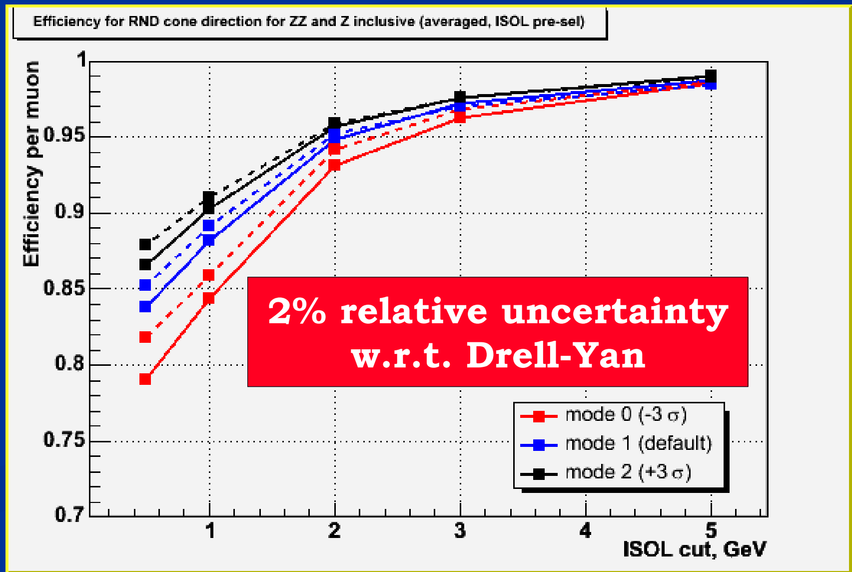
# UE: Application to muon isolation in H→4μ search (suppression of tt and Zbb backgrounds)

1. How well can we predict the isolation cut efficiency using the current Monte Carlo generators?
2. Can we calibrate the isolation cut efficiency using the experimental data themselves and, if yes, would the associated experimental systematic errors be smaller than the Monte Carlo based theoretical uncertainties?

Isolation parameter is a sum of $P_T$ of tracks inside a cone $dR(\eta,\varphi) = 0.3$ ($P_T$ of considered tracks > 0.8 GeV)

Random cone direction: all the calculations for isolation observable done for uniformly distributed random directions in event instead of directions for 'real' muons.



## selections for $L=10^{32}$

**MB trigger**

1) prescaling by a factor $4*10^7$ an HF trigger with high efficiency (e.g.: at least 10 cells fired in + and - detector)
-> 1 Hz

2) using a jet trigger requiring L1 calo jet with $E_T>25$ -> 5.8 MHz -> prescaled $6*10^6$
-> 1 Hz

**JET60/JET120** (altready defined in tables)

JET60: $E_T>25$(L1) ->prescaled by 2'000(0.146 KHz) -> $E_T>60$ (HLT) -> 2.8 Hz

JET120: $E_T>60$(L1) -> prescaled by 40 (0.097 KHz) -> $E_T>120$ (HLT) -> 2.4 Hz

**DI-MUONS**

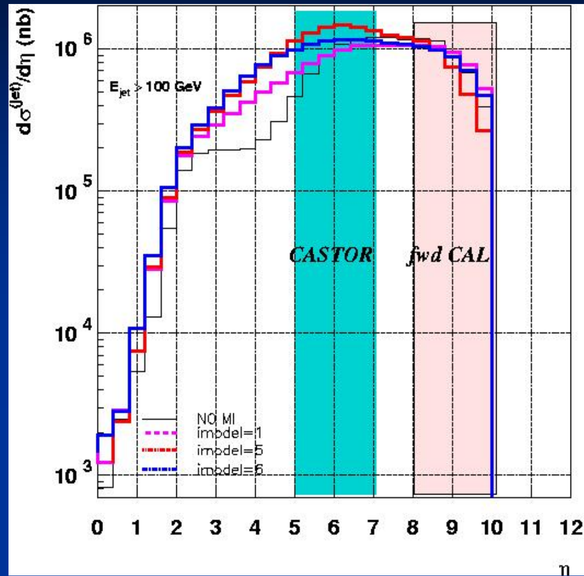
2 muons with $P_T>3$ GeV -> 200 Hz -> prescaled by 200
-> 1 Hz

background from quarkonia is in ~ 1/10 events
due to QCD contribution, the "signal" will be
in less than 1/200 events

In this case the problem will be the signal/background separation:
+ higher thresholds -> reduced M_inv range which can be explored
+ isolation request -> could introduce a bias in the UE measurements

**Generator Level Studies with Pythia 6.4x**

## Jet x-sec at forward rapidities

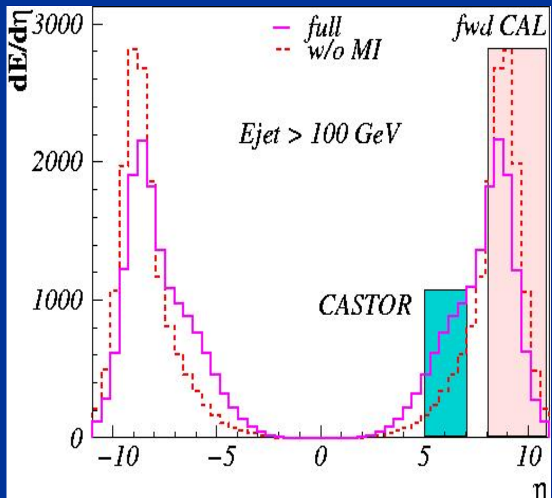


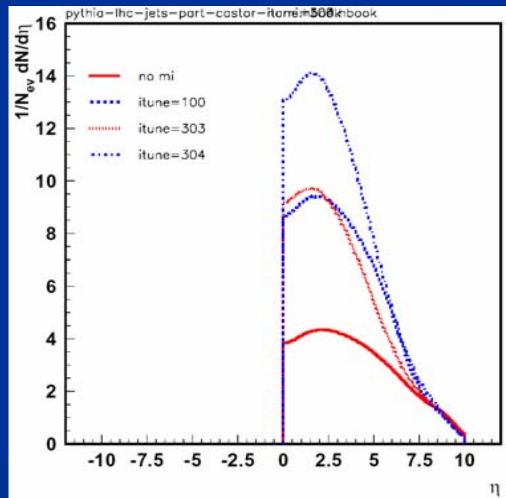

Understanding the dynamics measuring correlations between different rapidity ranges:

- forward to very forward
- forward to central

## energy flow

The energy taken by the beam remnant depends on the MPI Tune.




## Particle flow

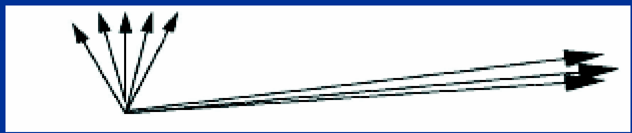
Would the central measurement benefit from triggering on CASTOR ?

→ For further information on the tunes see Back-up slides

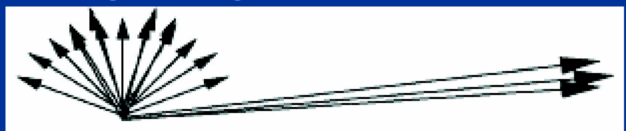
## Long range correlations

**central** **forward**


**no correlation**



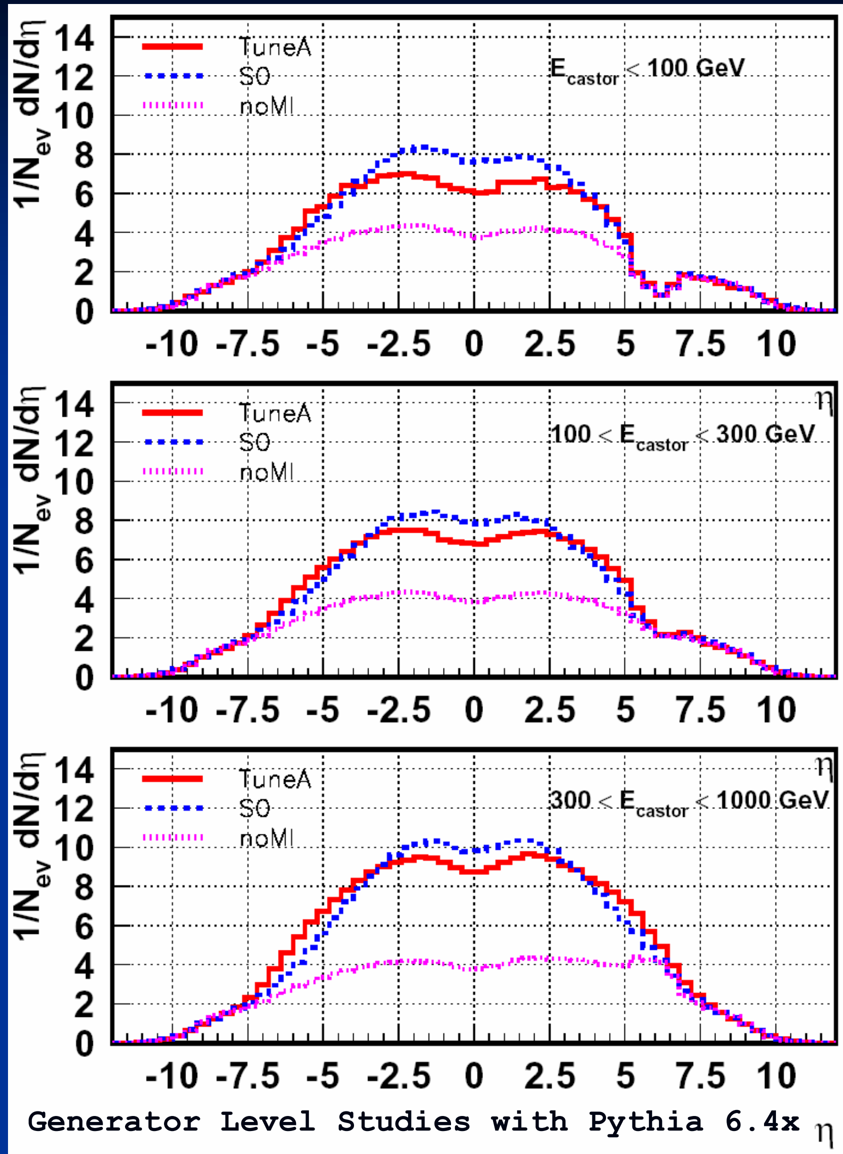
**long range correlation**



Pythia without MI -> no correlation

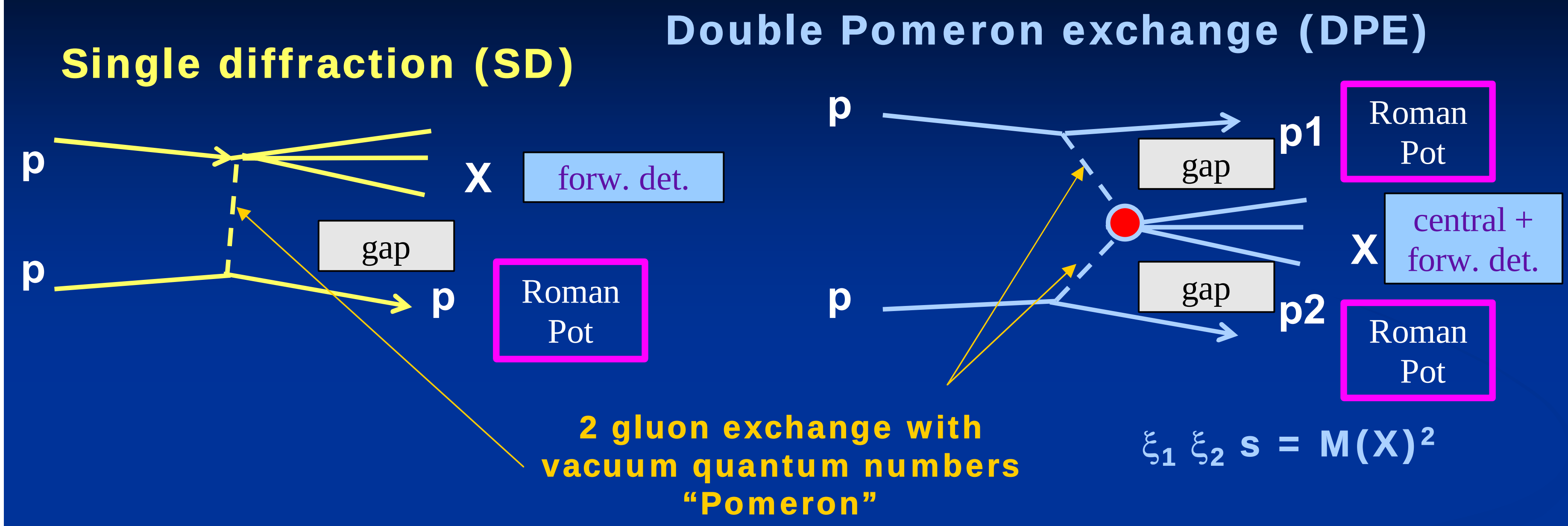
Pythia with MI:

Long range correlations, trigger enhancing differences in the central region




→ For further information on the Tunes see Back-up slides

# Diffraction at the LHC




- Single + Double diffractives ~ 1/3 of the inelastic cross section at the LHC
- Processes can be hard or soft, scale given by X
- Scattered proton(s) & momentum loss (ξ) measured in Roman Pot detectors along beam line
- Large Rapidity Gaps (LRG) between the scattered proton(s) and X

✓ Measure fundamental quantities of soft QCD: SD and DPE inclusive cross sections, their s, t, $M_X$ dependences

✓ X includes jets, W's, Z's, Higgs: hard processes calculable in pQCD

✓ Give info on proton structure (dPDFs and GPDs), QCD at high parton densities, multi-parton interactions, discovery physics

# CMS and TOTEM: a common diffractive physics program

Using near-beam detectors at 220m from the IP [CERN/LHCC 2006-039]

Further forward options currently under investigation by the FP420 R&D project (detectors at 420 m from the IP)

Nominal LHC beam optics, $\beta^* = 0.5$m:
TOTEM: $0.02 < \xi < 0.2$
FP420: $0.002 < \xi < 0.02$

**Accessible physics depends on instantaneous & integrated luminosity**

**"Low Luminosity"** i.e $< 10^{32}$ cm$^{-2}$s$^{-1}$. Integrated lumi a few 100 pb$^{-1}$ to < 1 fb$^{-1}$
Pile-up negligible (Can see LRG, forward protons associated to PV)

- Measure inclusive SD and DPE cross sections and their Mx dependence
- In addition to running at nominal LHC optics ($\beta^*=0.5$m) few days of running with $\beta^*=90$m @ $10^{31}$ cm$^{-2}$s$^{-1}$, with much improved coverage for diffractive events.

**"Intermediate Luminosity"** i.e $> 10^{32}$ cm$^{-2}$s$^{-1}$. Integrated lumi 1 to few fb$^{-1}$
Pile-up not negligible (Cannot see LRG, issue with associating protons to PVs)

- Measure SD and DPE in presence of hard scale (dijets, vector bosons, heavy quarks)

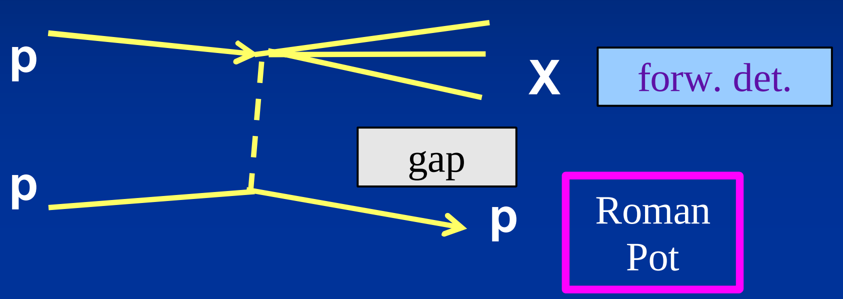
**"High Luminosity"** i.e $> 10^{33}$ cm$^{-2}$s$^{-1}$. Integrated lumi several tens fb$^{-1}$
High Pile-up rate (Same as above and even more challenging…)

- Search for the SM or MSSM Higgs in central exclusive production

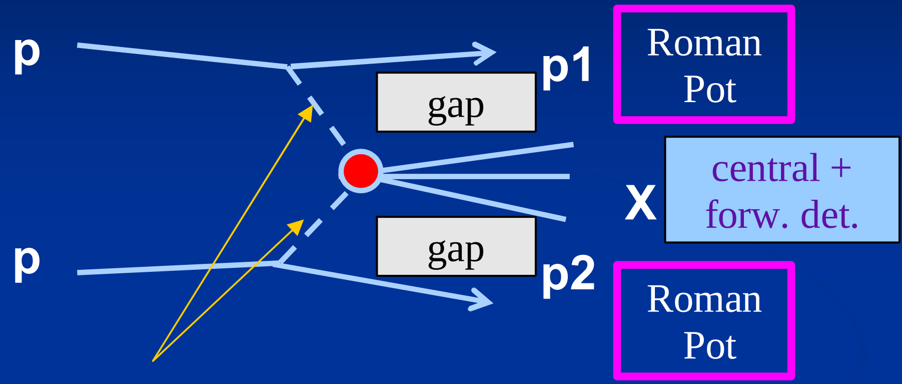
At intermediate to high lumi also rich program of $\gamma\gamma$ and $\gamma$p physics (QED)

# UE in Hard Diffractive Topologies

**Single diffraction (SD)**




**Double Pomeron exchange (DPE)**




Scale given by **X** → `Study UE(`$M_X$`)`

By definition **MPI** in diffractive events are strongly suppressed

The **Beam Remnant** component is also strongly suppressed
(at least in the hemispheres with surviving protons)

→ **The Underlying Event in Diffractives, if correctly identified, should be mostly contributed by ISR and FSR**

# Interplays Between Multiple Interactions and Hard Diffraction at the LHC

- Handle on soft multiple parton-parton interactions in hard diffractive events
  - Breaking of factorization in hard diffraction
    - Survival probability of protons and LRG ~ $e^{-<N_{int}>}$

Where $< N_{int} > = \sigma_{parton\text{-}parton} / \sigma_{inel\ proton\text{-}proton}$

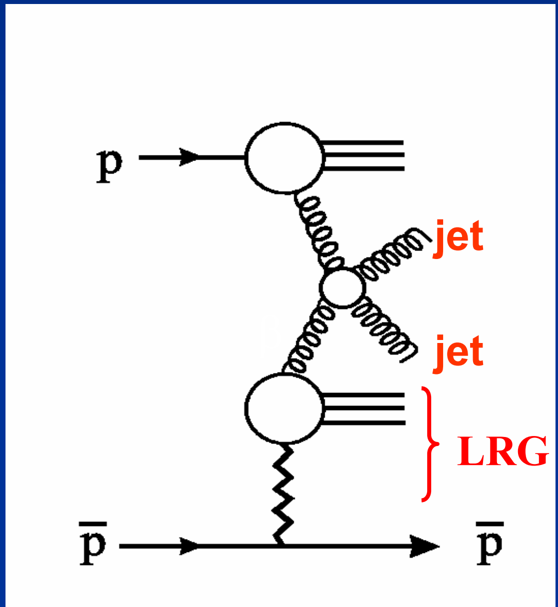
| [R.Field] | σ parton-parton at 1.96 TeV | σ parton-parton at 14 TeV |
|---|---|---|
| Tune A | 309.7 mb | 484.0 mb |
| Tune DW | 351.7 mb | 549.2 mb |
| Tune DWT | 351.7 mb | 829.1 mb |

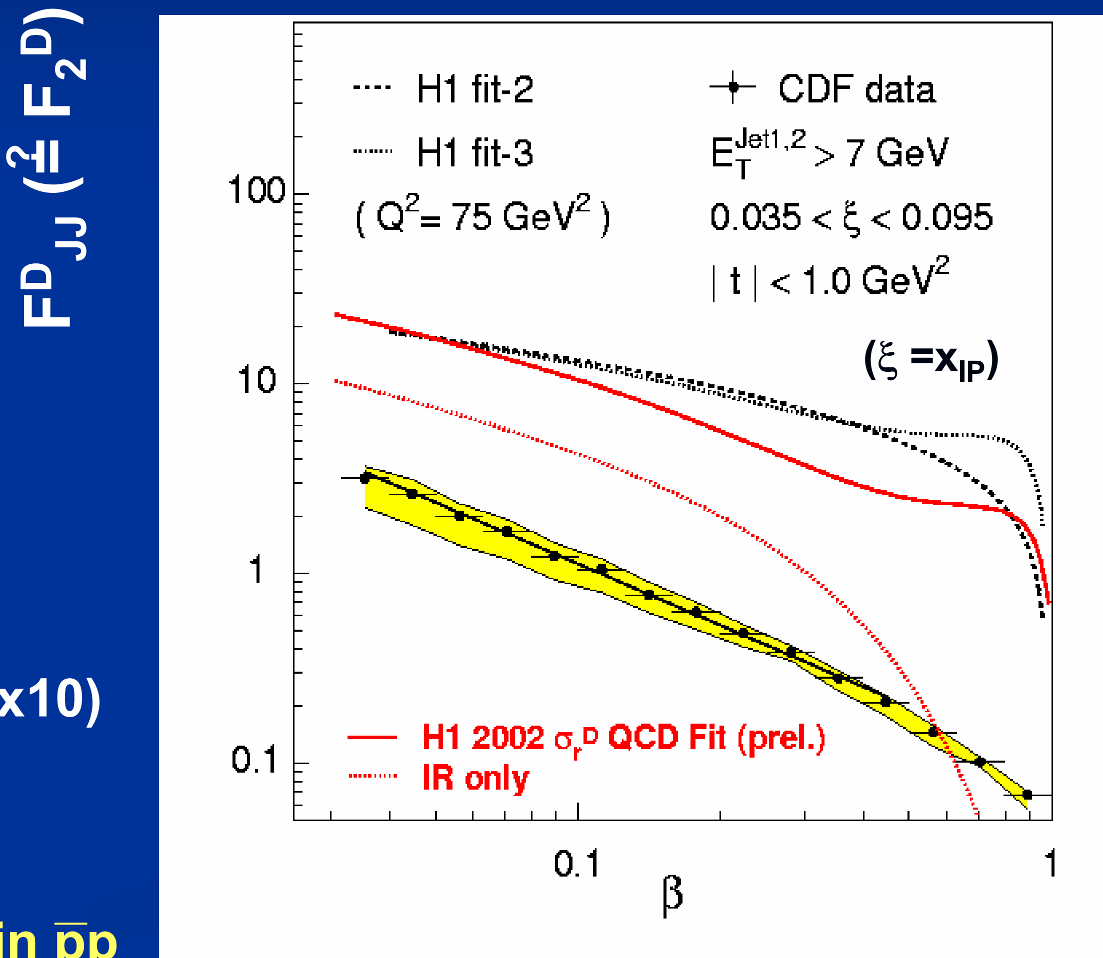
~ 100 mb

- Experimentally, there are at least two ways to extract info from data
  - Extrapolate the dPDFs measured at HERA and Tevatron and compare the resulting cross section predictions for the LHC with the cross sections measured at the LHC
  - Measure $F_2^D$, via e.g. dijet production, in SD and DPE and compare
    - The difference is a measure of hard diffractive factorization breaking and hence of multiple parton-parton interactions

# Test factorization in $p\bar{p}$ events

**Factorization of diffractive PDFs not expected to hold for $\bar{p}p$ & pp scatterings – indeed it does not:**




**Normalisation discrepancy (x10)**
**(depends on √s [CDF, D0])**

➡ **Hard scattering factorization violated in $\bar{p}p$**

[M.Arneodo]

# Challenges for selecting diffraction at the LHC

1) PILE-UP (PU)
2) TRIGGER (next slide)

The tracker detectors achieve very good PU vertex separation capabilities
Vertex resolution along the beam axis: ~ 50 $\mu$m
Association of forward protons to their vertex is much more challenging!

Proton acceptance of the RPs on either side is:
220m: 0.055 protons per PU event
420m: 0.012 protons per PU event

At $L = 2 \times 10^{32}$ $cm^{-2}s^{-1}$ fake DPE probability for 420*420 coincidence ~$10^{-3}$
Feasibility Figures for Diffraction Physics at the LHC Deteriorates!

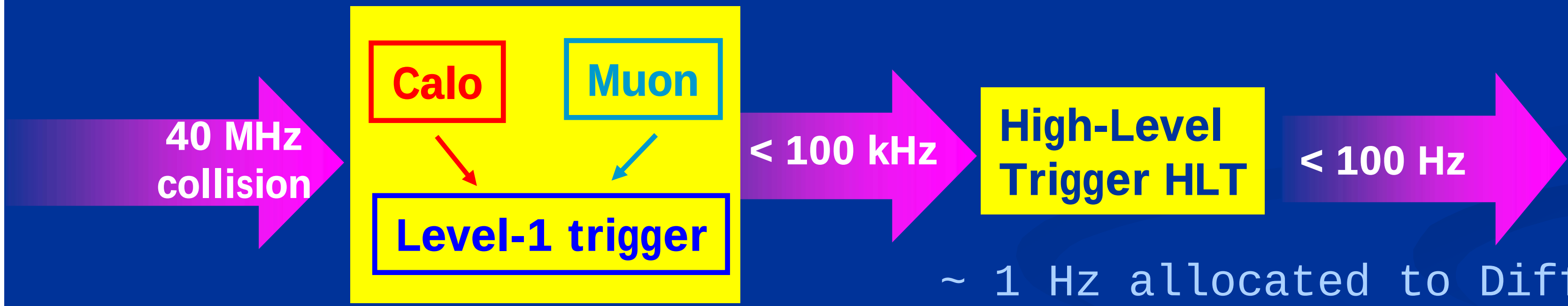
Problem can be sorted out with good time-resolution forward detectors:
$L \sim 10^{32}$ $cm^{-2}s^{-1}$. PV spacing ~ 1 cm. needed time resolution ~ 10 ps
$L > 10^{33}$ $cm^{-2}s^{-1}$. PV spacing ~ 1 mm. needed time resolution ~ 1 ps

# *Trigger (I)*

→ CMS trigger thresholds for nominal LHC running too high for diffractive events

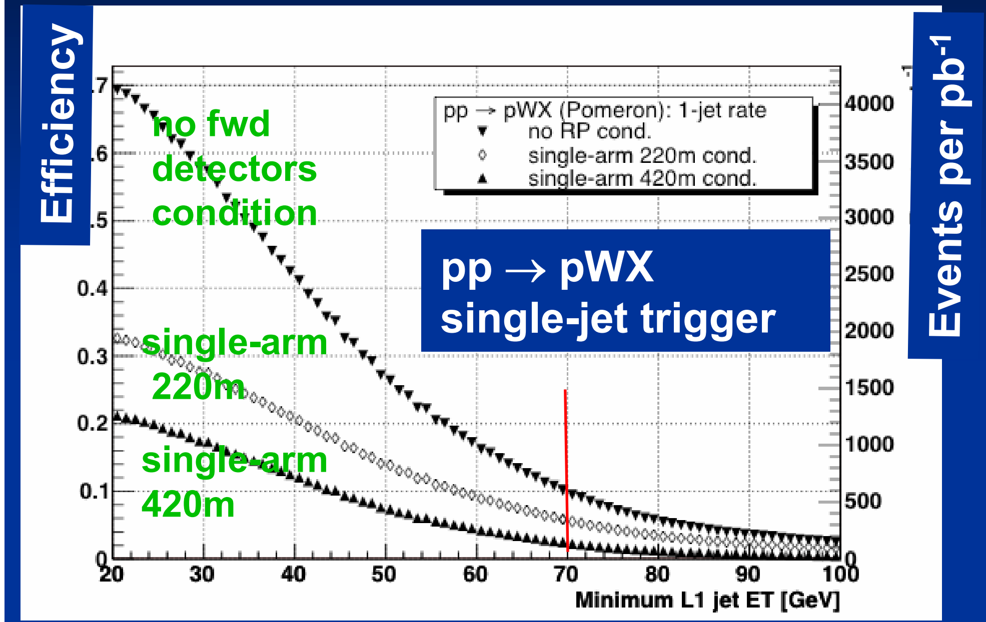
→ Use information of forward detectors to lower in particular CMS jet trigger thresholds

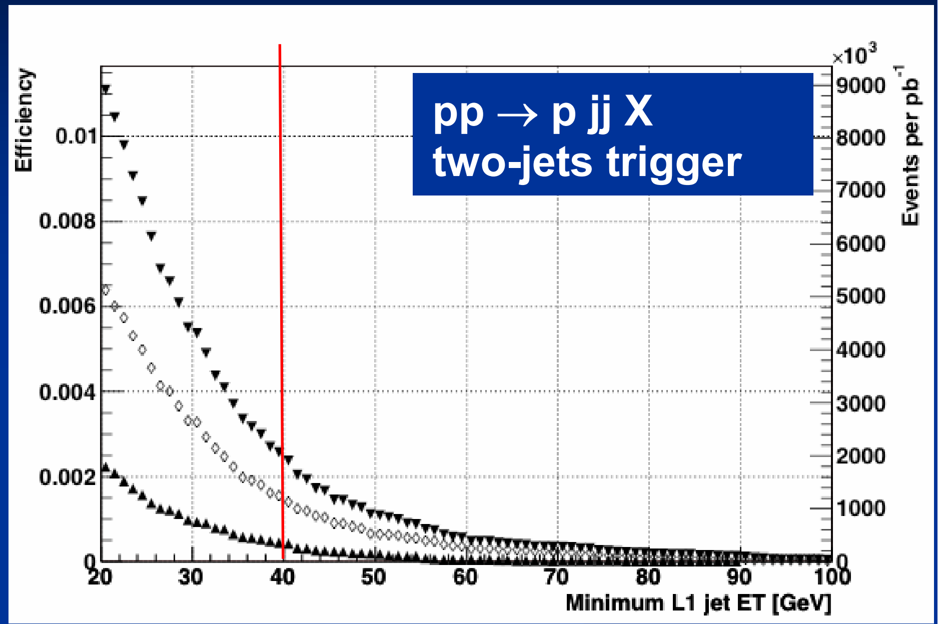
→ The CMS trigger menus now foresee a **dedicated diffractive trigger stream with 1% of the total bandwidth on L1 and HLT** (1 kHz and 1 Hz)




~ 1 Hz allocated to Diffraction

# Trigger (II)




**L1 trigger threshold [GeV]**

Attention: Gap survival probability not taken into account
Normalized to number of events with $0.001 < \xi < 0.2$
for proton and, in 2-jet case, with jets with $p_T > 10$GeV

At $2 \times 10^{33}$ cm$^{-1}$ s$^{-1}$ without any additional condition on fwd detectors:

L1 1-jet trigger threshold O(150 GeV)
L1 2-jet trigger threshold O(100 GeV)

# Strategy of the Two-jets Trigger

| Lumi nosity $[cm^{-2}s^{-1}]$ | # Pile-up events per bunch crossing | L1 2-jet rate [kHz] for $E_T > 40$GeV per jet | Total reduc tion needed | Reduction when requiring track in RP detectors at 220 m | |
|---|---|---|---|---|---|
| | | | | | $\xi < 0.1$ |
| $1 \times 10^{32}$ | 0 | 2.6 | 2 | 370 | |
| $1 \times 10^{33}$ | 3.5 | 26 | 20 | 7 | 15 |
| $2 \times 10^{33}$ | 7 | 52 | 40 | 4 | 10 |

**single-sided 220m condition**
without and with cut on $\xi$

Achievable total reduction: 10 (single-sided 220m) x 2 (jet iso) x 2 (2 jets same hemisphere as p) = 40

**Adding L1 conditions on the near-beam detectors provides a rate reduction sufficient to lower the 2-jet threshold to 40 GeV per jet while still meeting the CMS L1 bandwidth limits for luminosities up to 2x $10^{33}$ $cm^{-1}$ $s^{-1}$**

Much less of a problem is triggering with muons, where L1 threshold for 2-muons is 3 GeV

# CMS MB&UE Feasibility Studies
# Bottom Line

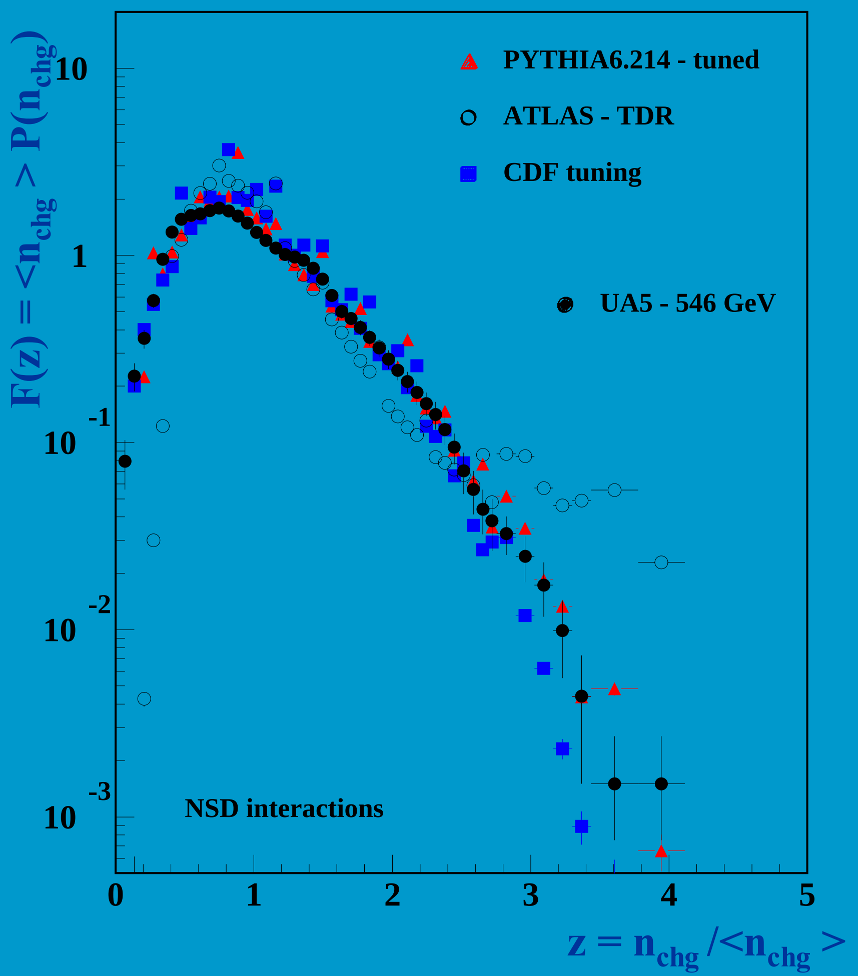
- CMS will measure a large variety of processes dealing with multiple partonic interactions in both low and high $P_T$ regimes
  - MB&UE: some new ideas
    - Extension of MB measurements to mini-jets
    - Extension of UE measurements to Drell Yan → Test of UE universality
    - Ratios between observables made with different $P_T$ min of ch. tracks

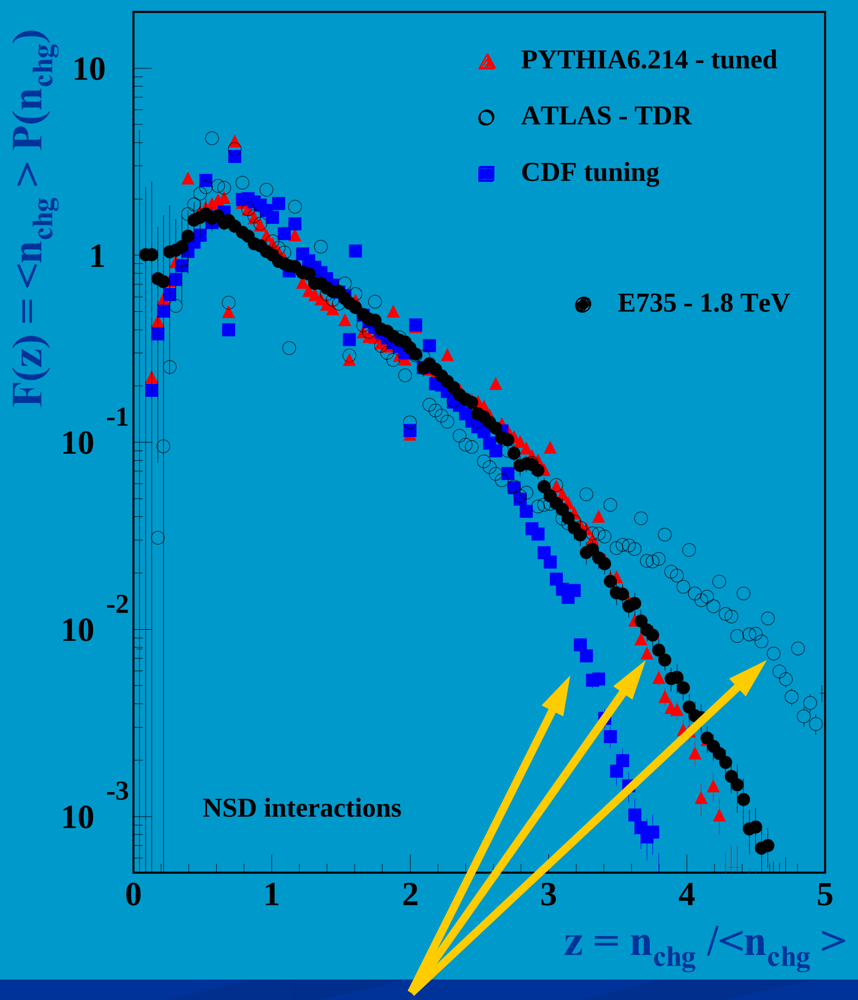
    → Emphasis on charged track / charged jet reconstruction
  - Interplays with Diffraction at the LHC
    - Soft diffractives are a substantial part of the MB
    - Multiple partonic interactions determine factorization breaking, disappearance of protons and rapidity gaps
    - Measurement of SD and DPE cross sections with a hard scale

    → Emphasis on trigger and on rejection of backgrounds from pile-up

# BACKUP

# MB: KNO Distributions at UA5 and E735



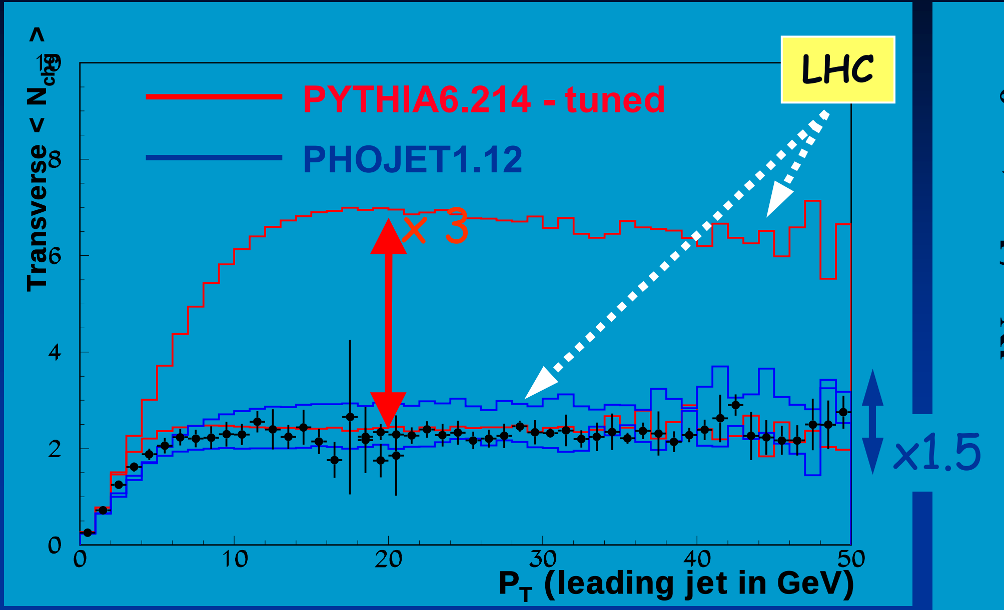



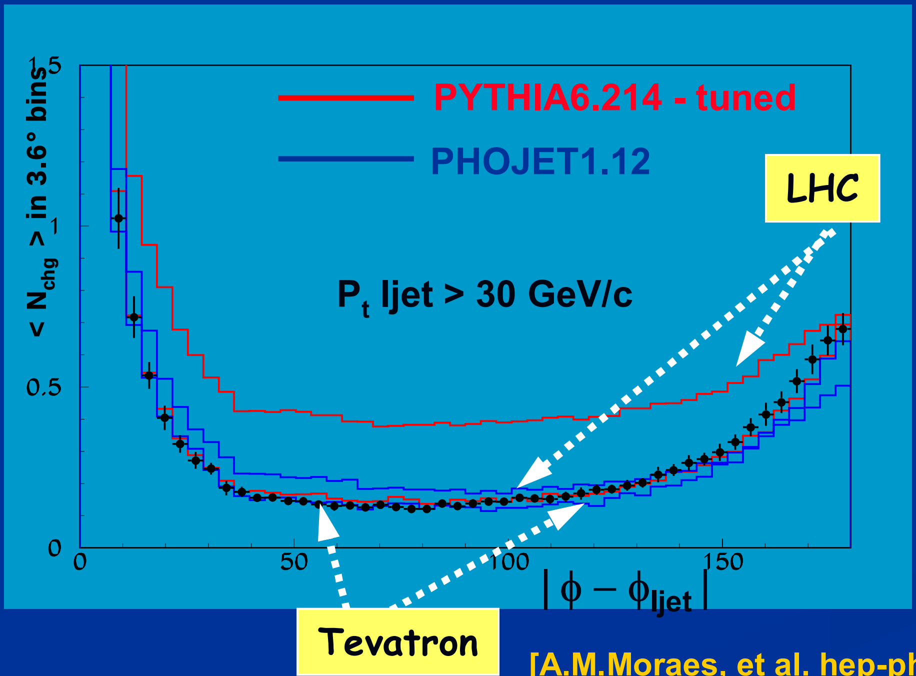

**KNO Scaling** [Koba, Nielsen, Olesen, Nucl. Rev. B40 (1972) 371]

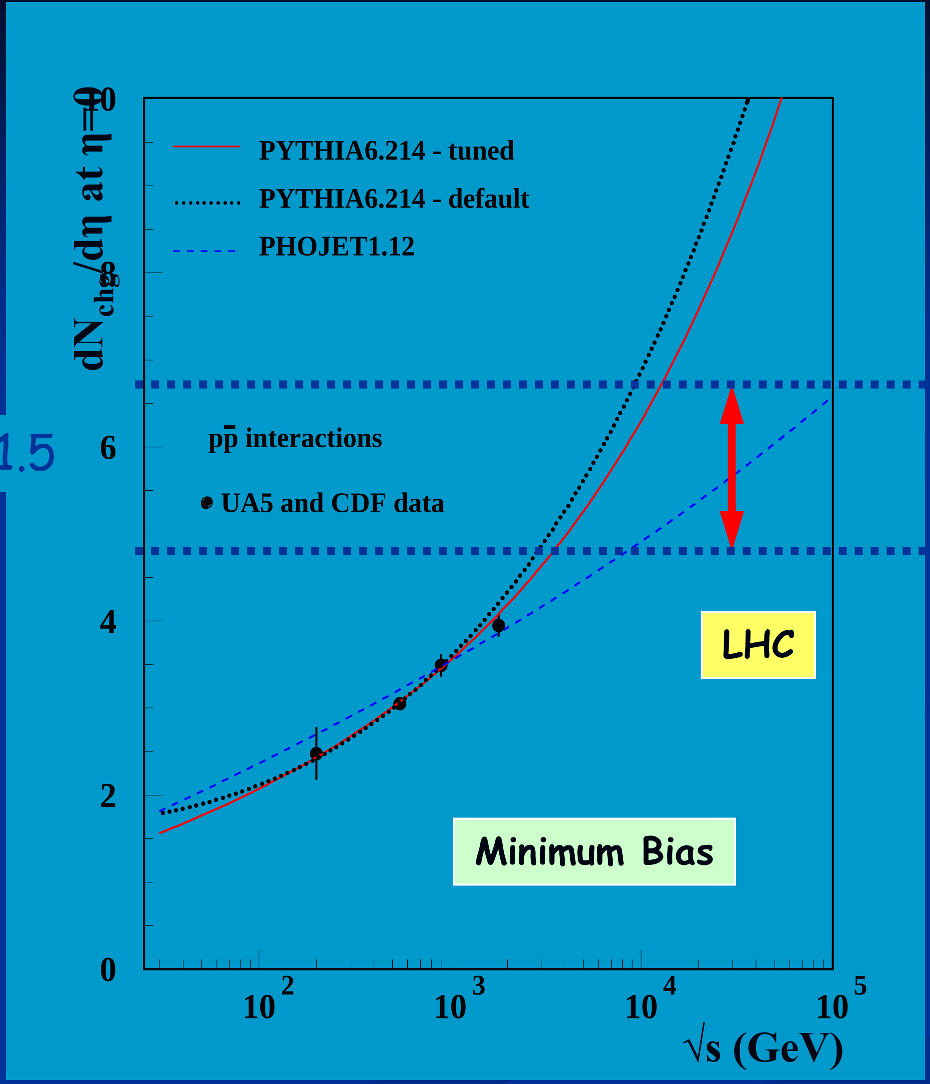
[A.M.Moraes, C.Buttar and I.Dawson, hep-ph/0403100, pgg 8-16]

High-multiplicity events are described differently by each tuning

# ATLAS: UE & MB predictions at the LHC and comparisons with ppbar




- PYTHIA models favour $\ln^2(s)$
- PHOJET suggests a $\ln(s)$ dependence.

[A.M.Moraes, et al. hep-ph/0403100, pgg 8-16]

# LHC predictions: pp collisions at $\sqrt{s}$ = 14 TeV

| Observable | PYTHIA6.214 – tuned | PHOJET1.12 | Δ% |
|---|---|---|---|
| $\sigma_{tot}$ (mb) | 101.5 | 119.1 | 17.3 |
| $\sigma_{elas}$ (mb) | 22.5 | 34.5 | 53.3 |
| $\sigma_{NSD}$ (mb) | 65.7 | 73.8 | 12.3 |
| *Minimum bias Predictions* | | | |
| $<n_{chg}>$ | 91.0 | 69.6 | 30.7 |
| $dN_{chg}/d\eta$ plaeau for $\|\eta\|<2.5$ | ~ 7.0 | ~ 5.5 | 27.3 |
| $dN_{chg}/d\eta$ at $\eta = 0$ | 6.8 | 5.1 | 33.3 |
| $<pT>$ at $\eta = 0$ (GeV) | 0.55 | 0.64 | 16.3 |
| $n_{tot}$ ($\|\eta\|<15$) | 158.4 | 115.1 | 37.6 |
| $n_{tot}$ ($\|\eta\|<2.5$) | 60.9 | 45.5 | 33.8 |
| *Underlying Event Predictions* | | | |
| $<N_{chg}>$ $pT_{ljet}$ > 10 GeV | ~ 6.5 | ~ 3.0 | ~ 115 |
| $<pT_{sum}>$ $pT_{ljet}$ > 10 GeV | ~ 7.5 | ~ 3.5 | ~ 115 |
| $dN_{chg}/d\eta$ $pT_{ljet}$ > 10 GeV | ~ 29.0 | ~ 13.3 | ~ 125 |
| UE/Min-bias $pT_{ljet}$ > 10 GeV | ~ 4 | ~ 2 | ~ 100 |

# PYTHIA 6.2 Tunes [R.Field]

Use LO $\alpha_s$ with $\Lambda$ = 192 MeV!

K-factor (Sjöstrand)

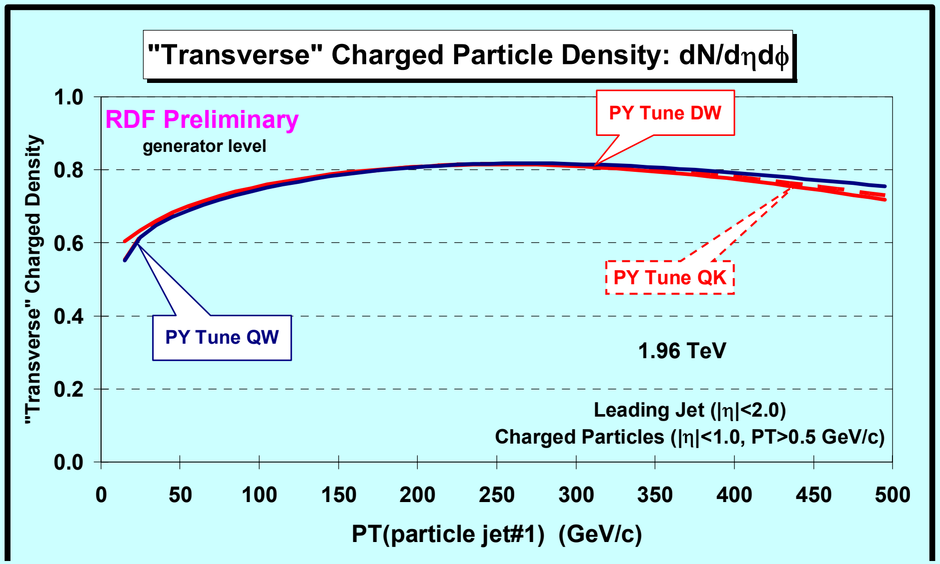
UE Parameters

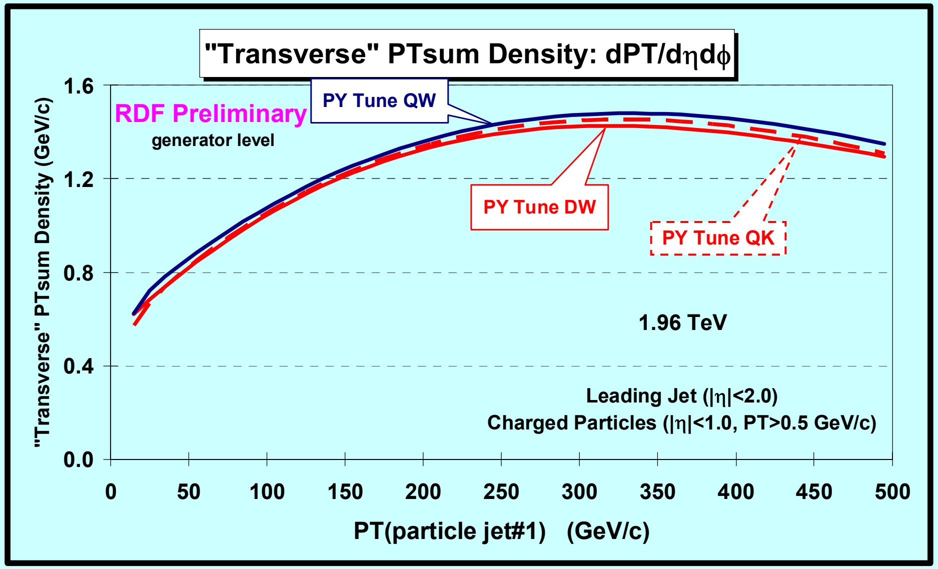
ISR Parameter

Intrensic KT

| Parameter | Tune DW | Tune DWT | ATLAS | Tune QW | Tune QWT | Tune QK | Tune QKT |
|---|---|---|---|---|---|---|---|
| PDF | CTEQ5L | CTEQ5L | CTEQ5L | CTEQ6.1 | CTEQ6.1 | CTEQ6.1 | CTEQ6.1 |
| MSTP(2) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| MSTP(33) | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| PARP(31) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.8 | 1.8 |
| MSTP(81) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| MSTP(82) | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| PARP(82) | 1.9 GeV | 1.9409 GeV | 1.8 GeV | 1.1 GeV | 1.1237 GeV | 1.9 GeV | 1.9409 GeV |
| PARP(83) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| PARP(84) | 0.4 | 0.4 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 |
| PARP(85) | 1.0 | 1.0 | 0.33 | 1.0 | 1.0 | 1.0 | 1.0 |
| PARP(86) | 1.0 | 1.0 | 0.66 | 1.0 | 1.0 | 1.0 | 1.0 |
| PARP(89) | 1.8 TeV | 1.96 TeV | 1.0 TeV | 1.8 TeV | 1.96 TeV | 1.8 TeV | 1.96 TeV |
| PARP(90) | 0.25 | 0.16 | 0.16 | 0.25 | 0.16 | 0.25 | 0.16 |
| PARP(62) | 1.25 | 1.25 | 1.0 | 1.25 | 1.25 | 1.25 | 1.25 |
| PARP(64) | 0.2 | 0.2 | 1.0 | 0.2 | 0.2 | 0.2 | 0.2 |
| PARP(67) | 2.5 | 2.5 | 1.0 | 2.5 | 2.5 | 2.5 | 2.5 |
| MSTP(91) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| PARP(91) | 2.1 | 2.1 | 1.0 | 2.1 | 2.1 | 2.1 | 2.1 |
| PARP(93) | 15.0 | 15.0 | 5.0 | 15.0 | 15.0 | 15.0 | 15.0 |

# PYTHIA 6.2 Tunes [R.Field]

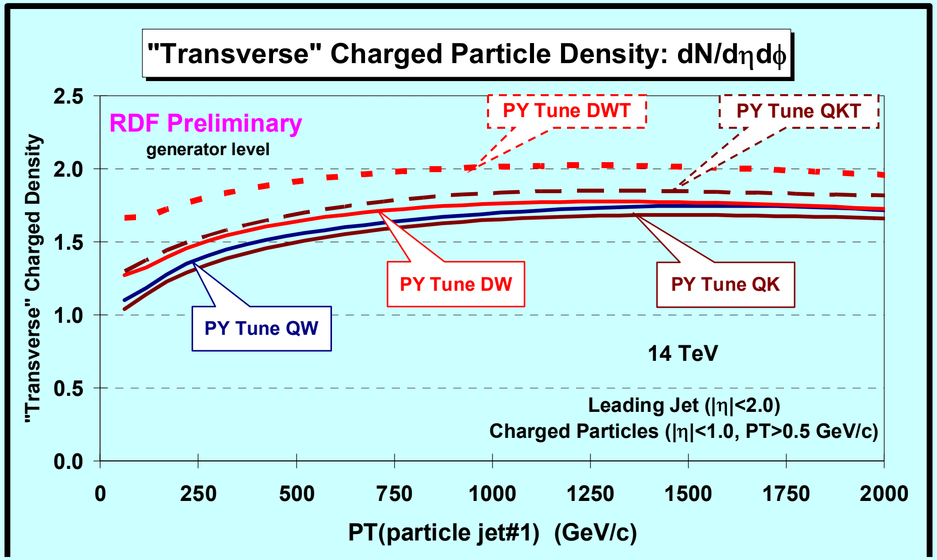


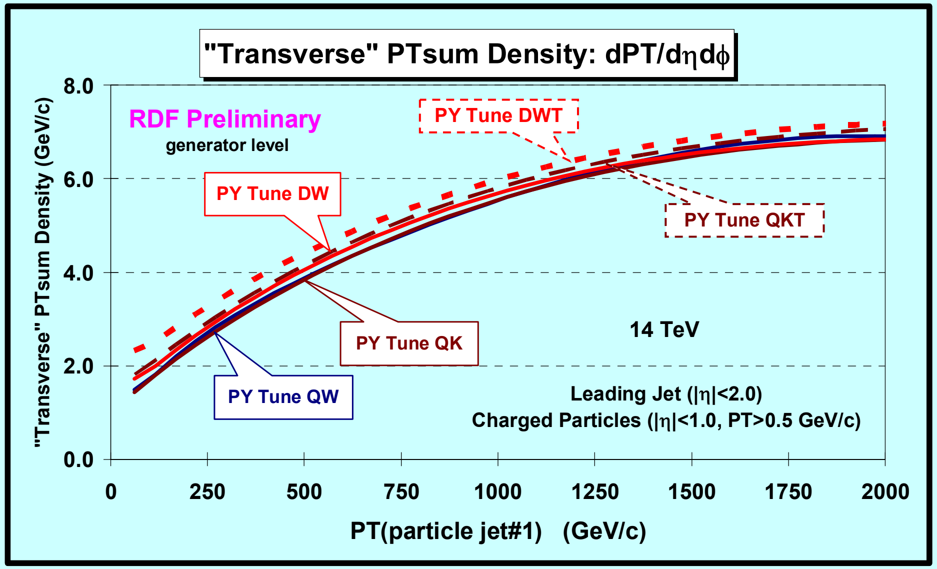




| | 1.96 TeV | | 14 TeV | |
|---|---|---|---|---|
| | $P_{T0}$ (MPI) GeV | σ (MPI) mb | $P_{T0}$ (MPI) GeV | σ (MPI) mb |
| Tune DW | 1.9409 | 351.7 | 3.1730 | 549.2 |
| Tune DWT | 1.9409 | 351.7 | 2.6091 | 829.1 |
| ATLAS | 2.0 | 324.5 | 2.7457 | 768.0 |
| Tune QW | 1.1237 | 296.5 | 1.8370 | 568.7 |
| Tune QK | 1.9409 | 259.5 | 3.1730 | 422.0 |
| Tune QKT | 1.9409 | 259.5 | 2.6091 | 588.0 |

- Remember the $p_T$ cut-off, $P_{T0}$, of the MPI cross section is energy dependent and given by $P_{T0}(E_{cm}) = PARP(82) \times (E_{cm}/E_0)^{\varepsilon}$ with $\varepsilon = PARP(90)$ and $E_0 = PARP(89)$.
- Average charged particle density and PTsum density in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $P_T$(jet#1) at 1.96 TeV for PY Tune DW, Tune QW, and Tune QK.

# PYTHIA 6.2 Tunes [R.Field]




| | 1.96 TeV | | 14 TeV | |
|---|---|---|---|---|
| | $P_{T0}$(MPI) GeV | σ(MPI) mb | $P_{T0}$(MPI) GeV | σ(MPI) mb |
| Tune DW | 1.9409 | 351.7 | 3.1730 | 549.2 |
| Tune DWT | 1.9409 | 351.7 | 2.6091 | 829.1 |
| ATLAS | 2.0 | 324.5 | 2.7457 | 768.0 |
| Tune QW | 1.1237 | 296.5 | 1.8370 | 568.7 |
| Tune QK | 1.9409 | 259.5 | 3.1730 | 422.0 |
| Tune QKT | 1.9409 | 259.5 | 2.6091 | 588.0 |

- Average charged particle density and PTsum density in the “transverse” region ($p_T$ > 0.5 GeV/c, |η| < 1) versus $P_T$(jet#1) at 14 TeV for PY Tune DW, Tune DWT, Tune QW, Tune QK, and Tune QKT.

# "New" MPI Tunes $A_{PT}$, $S_0$, $S_1$, $S_2$ [P.Skands]

| Parameter (PYTHIA v.6408+) | | DW | A | $A_{PT}$ | $A_{CR}$ | $S_0$ | $S_1$ | $S_2$ | NOCR |
|---|---|---|---|---|---|---|---|---|---|
| UE model | MSTP(81) | 1 ('old' [17]) | | | | 21 ('new' [20]) | | | |
| UE infrared regularisation scale (at $\sqrt{s} = 1800$ GeV) | PARP(82) | 1.9 | 2.0 | 2.1 | 2.0 | 1.85 | 2.1 | 1.9 | 2.05 |
| -"-, scaling power with $\sqrt{s}$ | PARP(90) | 0.25 ('fast') | | | | 0.16 ('slow') | | | |
| UE hadron transverse mass distribution | MSTP(82) | 4 ('double Gaussian') | | | | 5 ('ExpOfPow') | | | |
| -"- parameter 1 | PARP(83) | 0.5 | | | | 1.6 | 1.4 | 1.2 | 1.8 |
| -"- parameter 2 | PARP(84) | 0.4 | | | | n/a | | | |
| UE total $gg$ fraction | PARP(86) | 1.0 | 0.95 | 0.95 | 0.66 | n/a | | | |
| ISR infrared cutoff | PARP(62) | 1.25 | 1.0 | 1.0 | 1.0 | ($\equiv$ PARP(82) ) | | | |
| ISR renormalisation scale prefactor | PARP(64) | 0.2 | 1.0 | 1.0 | 1.0 | 1.0 | | | |
| ISR $Q^2_{\rm max}$ factor | PARP(67) | 2.5 | 4.0 | 4.0 | 4.0 | n/a | | | |
| ISR infrared regularisation scheme | MSTP(70) | n/a | | | | 2 | 0 | 2 | 2 |
| ISR FSR off ISR scheme | MSTP(72) | n/a | | | | 0 | 1 | 0 | 0 |
| FSR model | MSTJ(41) | 2 | 2 | 12 | 2 | ($p_\perp$-ordered) | | | |
| FSR $\Lambda_{\rm QCD}$ | PARJ(81) | 0.29 | 0.29 | 0.14 | 0.29 | 0.14 | | | |
| BR colour scheme | MSTP(89) | n/a | | | | 1 | 1 | 1 | 2 |
| BR composite $x$ enhancement factor | PARP(79) | n/a | | | | 2 | 2 | 2 | 3 |
| BR primordial $k_T$ width $\langle\vert k_T\vert\rangle$ | PARP(91) | 2.1 | 1.0 | 1.0 | 1.0 | n/a | | | |
| BR primordial $k_T$ UV cutoff | PARP(93) | 15.0 | 5.0 | 5.0 | 5.0 | 5.0 | | | |
| CR model | MSTP(95) | n/a | | | 6 | 6 | 2 | 4 | 1 |
| CR strength $\xi_R$ | PARP(78) | n/a | | | 0.25 | 0.2 | 0.35 | 0.15 | 0.0 |
| CR $gg$ fraction (old model) | PARP(85) | 1.0 | 0.9 | 0.9 | 0.0 | n/a | | | |

[T.Sjostrand]

# PYTUNE

Minimum bias + Underlying event tunes conveniently setup with `CALL PYTUNE(MODEL)`, where possible `MODEL` values are

| | | |
|---|---|---|
| Old UE, $Q^2$-ordered showers | | |
| 100 | A | Rick Field's Tune A |
| 101 | AW | Rick Field's Tune AW |
| 102 | BW | Rick Field's Tune BW |
| 103 | DW | Rick Field's Tune DW |
| 104 | DWT | Rick Field's Tune DW with slower UE energy scaling |
| 105 | QW | Rick Field's Tune QW (NB: needs CTEQ6.1 PDF's) |
| 106 | ATLAS | Arthur Moraes' ATLAS tune |
| 107 | ACR | Tune A modified with annealing CR |
| New UE, $Q^2$-ordered showers | | |
| 200 | IM 1 | Intermediate 1: annealing CR |
| New UE, interleaved pT-ordered showers, annealing CR | | |
| 300 | S0 | Sandhoff-Skands Tune 0 |
| 301 | S1 | Sandhoff-Skands Tune 1 |
| 302 | S2 | Sandhoff-Skands Tune 2 |
| 303 | S0A | S0 with "Tune A" UE energy scaling |
| 304 | NOCR | New UE "best try" without colour reconnections |
| 305 | Old | New UE, original (primitive) colour reconnections |

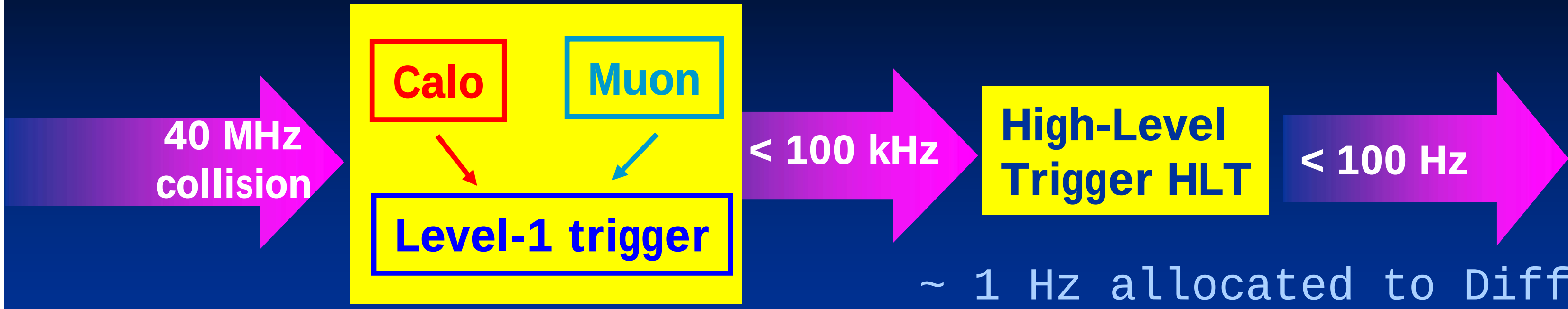
# Study of SD W production at the LHC Start-up with 10 $pb^{-1}$

- Look at $W \to \mu\nu$, $W \to e\nu$
- Assume no forward detectors (Castor, ZDC, Totem) beyond HF, $|\eta|<5$
- Assume no pile-up
- No diffractive triggers (i.e. $W \to l\nu$ selected by lepton trigger)
- Assumed cross sections ($W \to \mu\nu$):
  Diffractive: 75 pb → expect 750 events per 10 $pb^{-1}$ [Cox, Forshaw]
  Inclusive: 17.5 nb → expect 175 kevents per 10 $pb^{-1}$

  ie diffractive component about 0.5% of total
  this assumes "rapidity gap survival probability" of 0.05
  [Khoze, Martin, Ryskin, PLB 643 (2006) 93]
- Follow the procedure used at Fermilab by CDF and D0:
  CDF: Run 1a, 1b, $W \to e\nu$ [PRL78(1997)2698]
  D0: based on 85 $pb^{-1}$ in Run 1b ($W \to e\nu$) [PLB574 (2003)169]

[M.Arneodo]

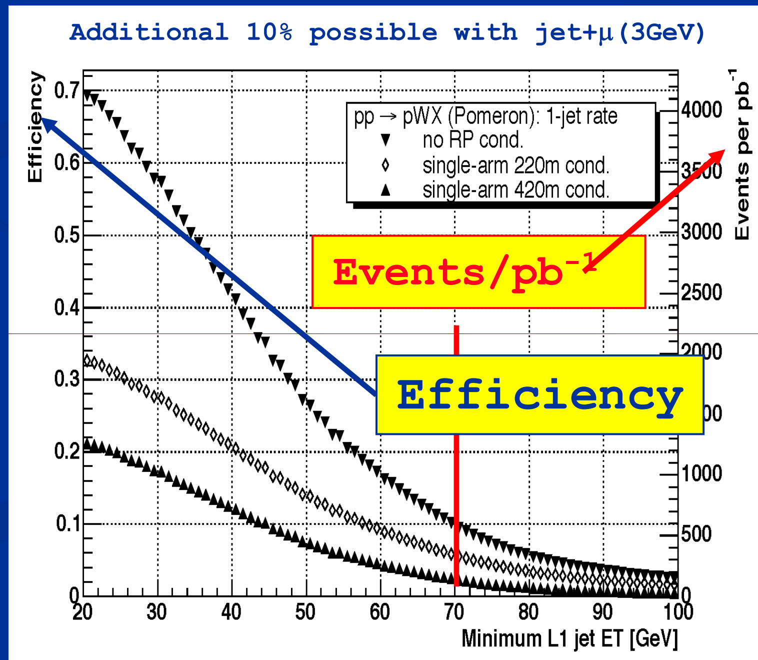
# Diffractive Triggers




**Example of Trigger Performances for SD process: W production**

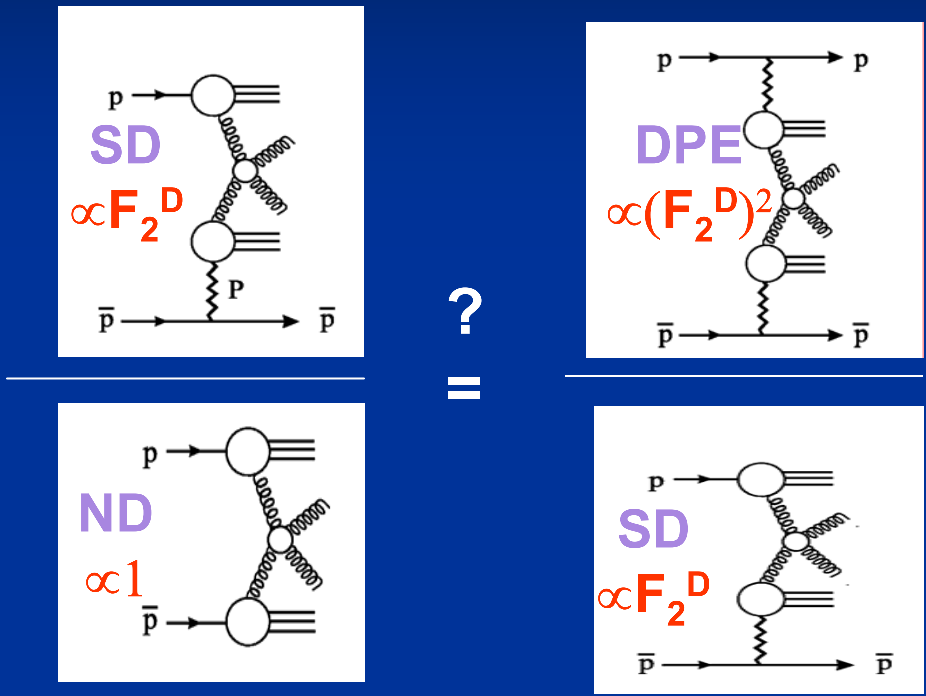
**L1 single-jet rate for central jets ($|\eta|<2.5$) @ L1 jet $E_T$ cutoff of 70 GeV and single arm 220m condition with $\xi<0.1$ for Lumi $2 \times 10^{33}$ $cm^{-2}$ $s^{-1}$: ~1 kHz**
**-> Can collect ~ 300 SD W / $pb^{-1}$**

**Rates for SD prod of Z and dijets also quoted**

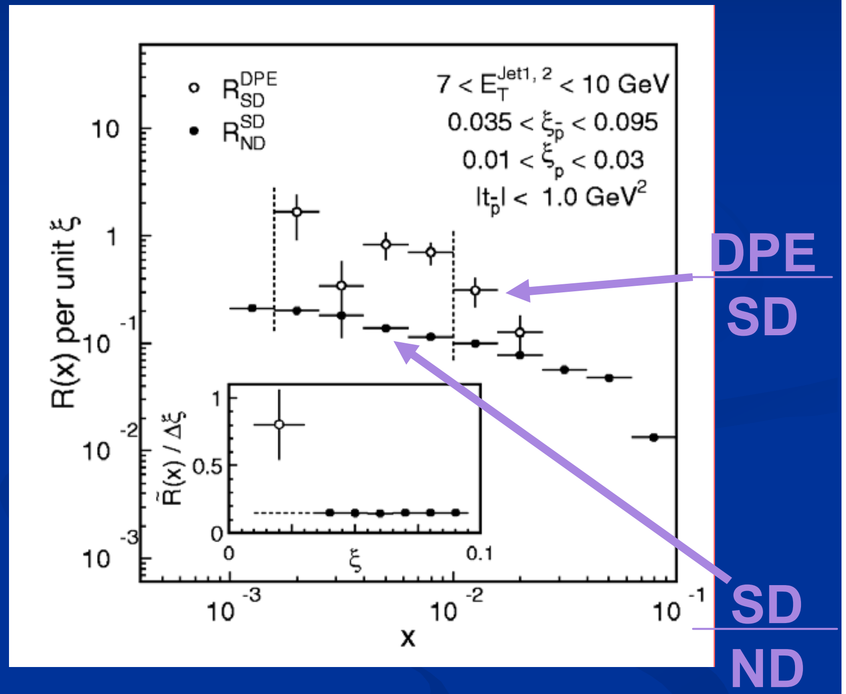


# Test factorization in $\bar{p}p$ events

**Even within the $\bar{p}p$ data alone hard diffractive factorization does not hold:**




CDF

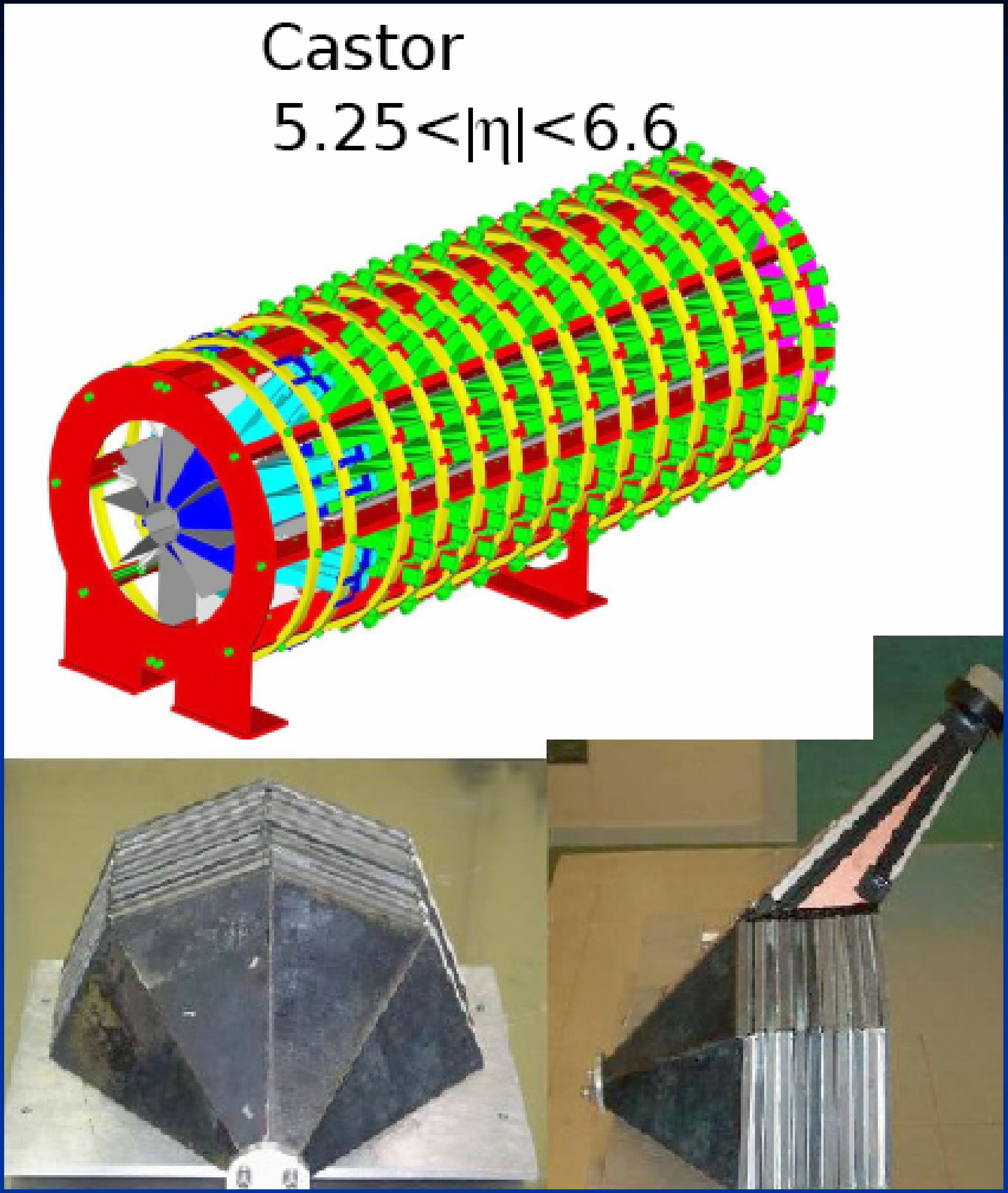



$$\frac{SD}{ND} \Big/ \frac{DPE}{SD} = 0.19 \pm 0.07 \ (\neq 1\ !)$$

Probability for 2 LRGs > (probability for 1 LRG)$^2$,
ie get different $F_2^D$ from 1 LRG and 2 LRG events

→ **Hard scattering factorization violated**

[M.Arneodo]




Tungsten + Quartz plates
EM + Had sections

$E > 100$ GeV
$\sigma(E)/E < 3\%\ e,\gamma$
$< 18\%\ \pi$