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Possible first observation of proton-proton phenomenology at LHC with CMS

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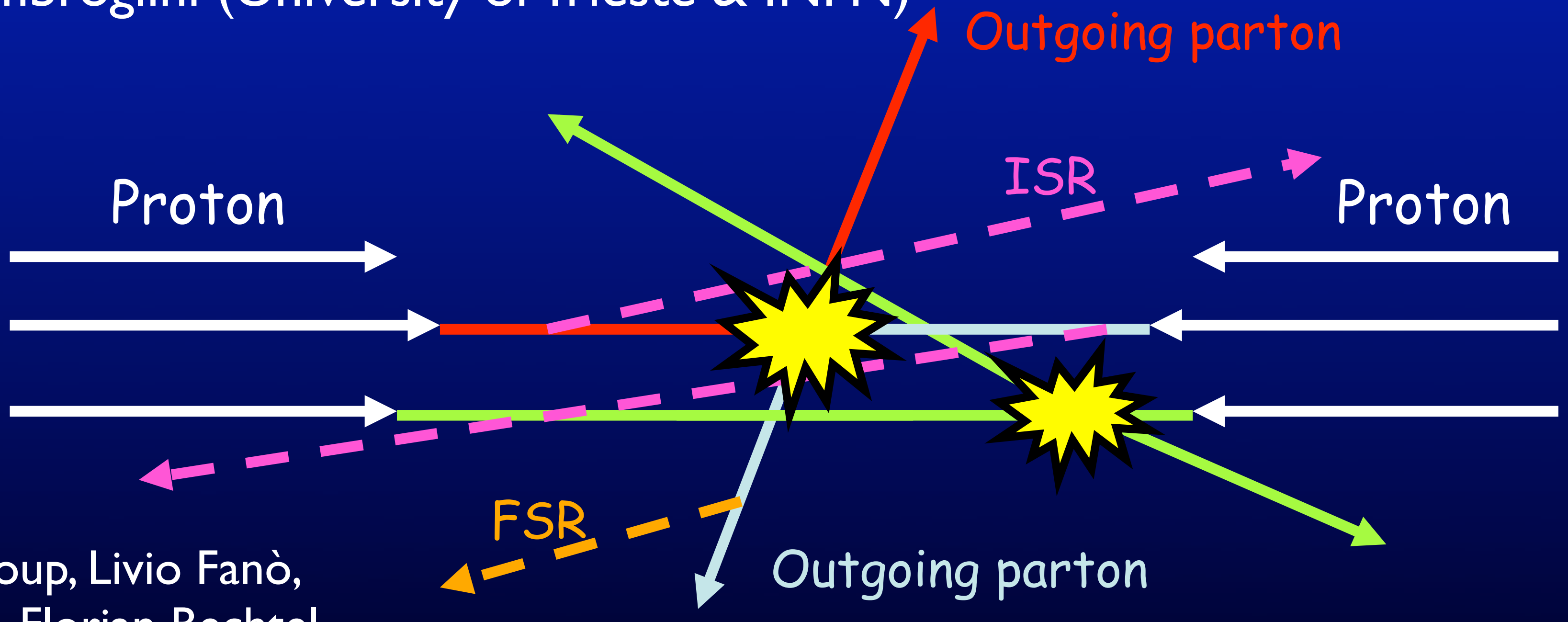
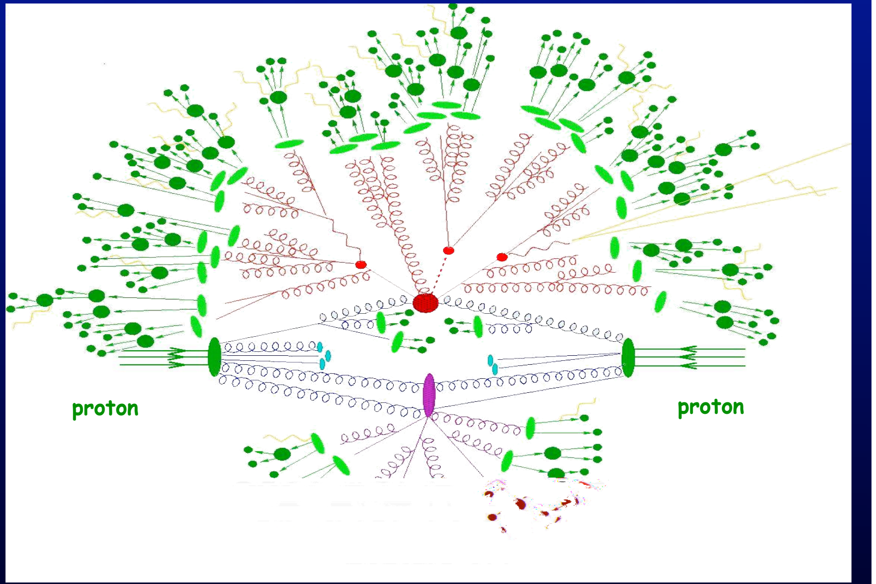


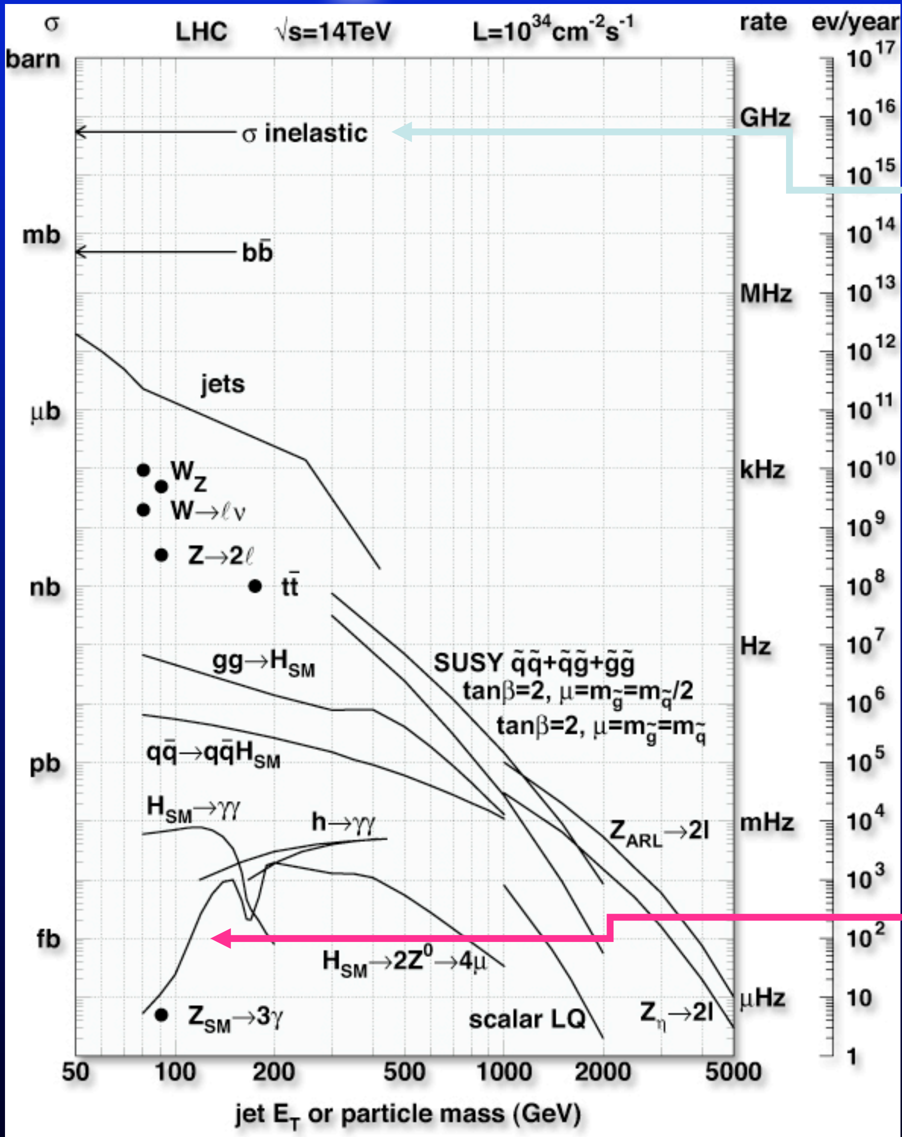
Thanks to:
CMS QCD group, Livio Fanò, Paolo Bartalini, Florian Bechtel, Lucia Garbini, Rick Field, Daniele Treleani, Ferenc Sikler, Peter Skands, et al.

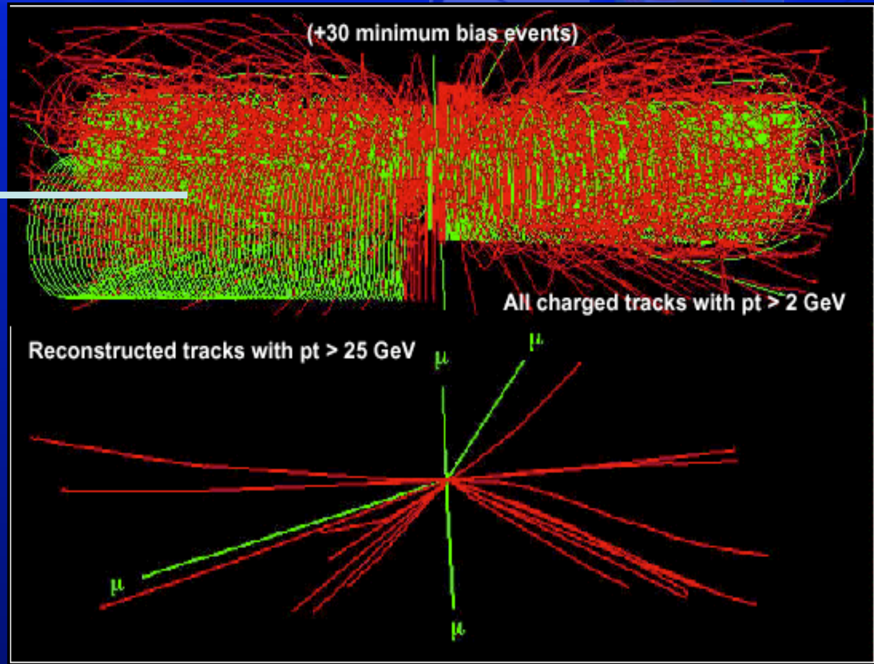
Outlook

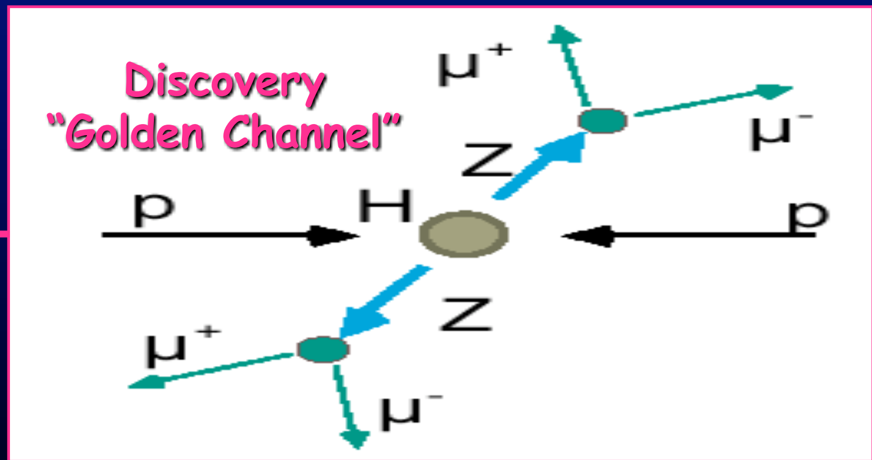
- Introduction to Large Hadron Collider environment
- Underlying Event (UE) Minimum Bias (MB) and Multiple Partonics Interactions (MPI)
  - Introduction (try to speak the same language)
- QCD models and experimental results
- CMS QCD early physics
  - Minimum Bias
  - Underlying Event
  - MPI:
    - Mini Jets
    - Double parton scattering



Final state at Large Hadron Collider





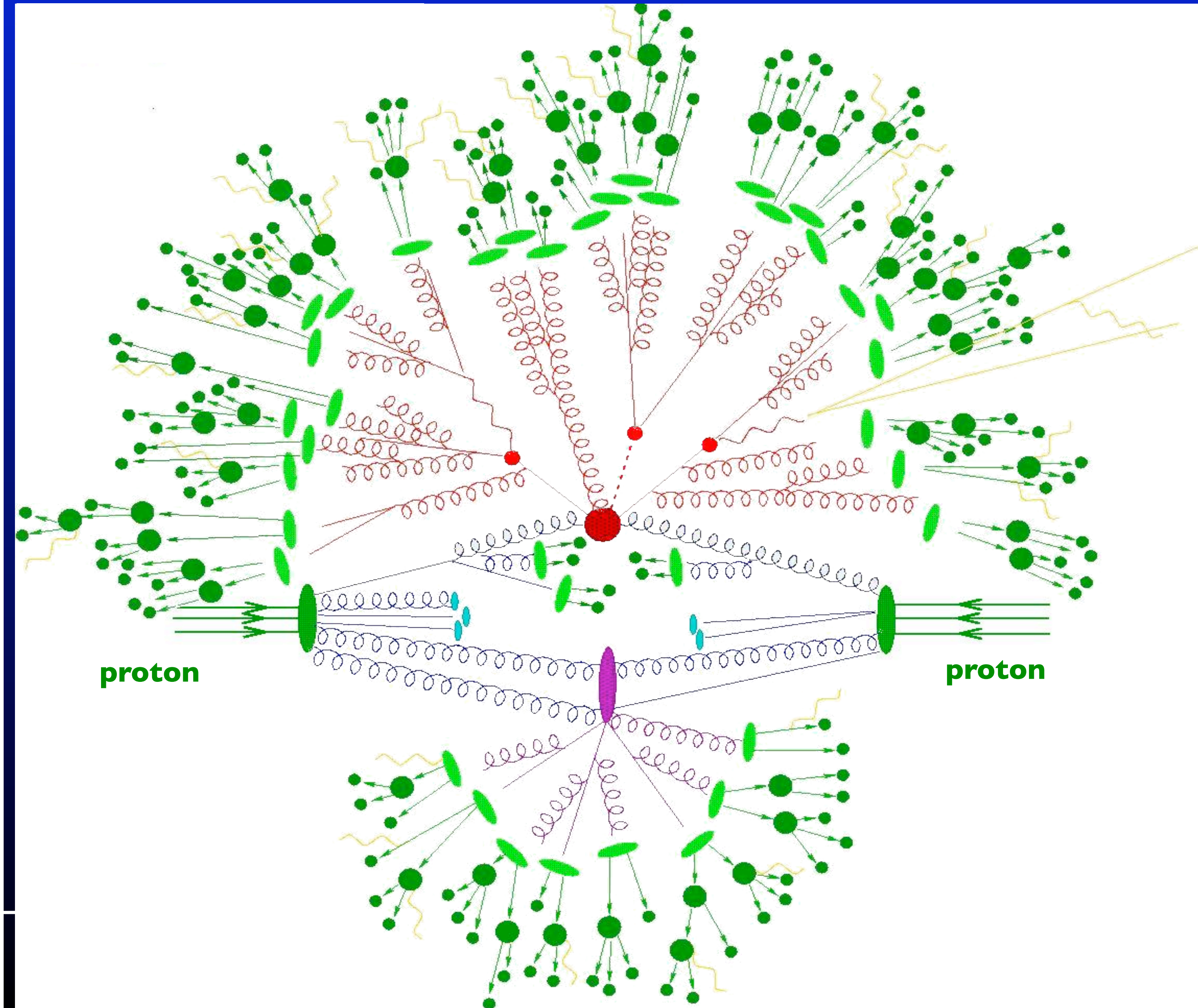


Final state at Large Hadron Collider

At the LHC essentially all physics will arise from quark and gluon interactions (small and large transverse momentum)

- Hard Process (*High pT*) well described by perturbative QCD
- Soft Interactions (*Low pT*): require phenomenological models
  - Dominant processes at the LHC (Minimum Bias)

p-p interaction @ LHC



Hard Interaction

ISR and FSR

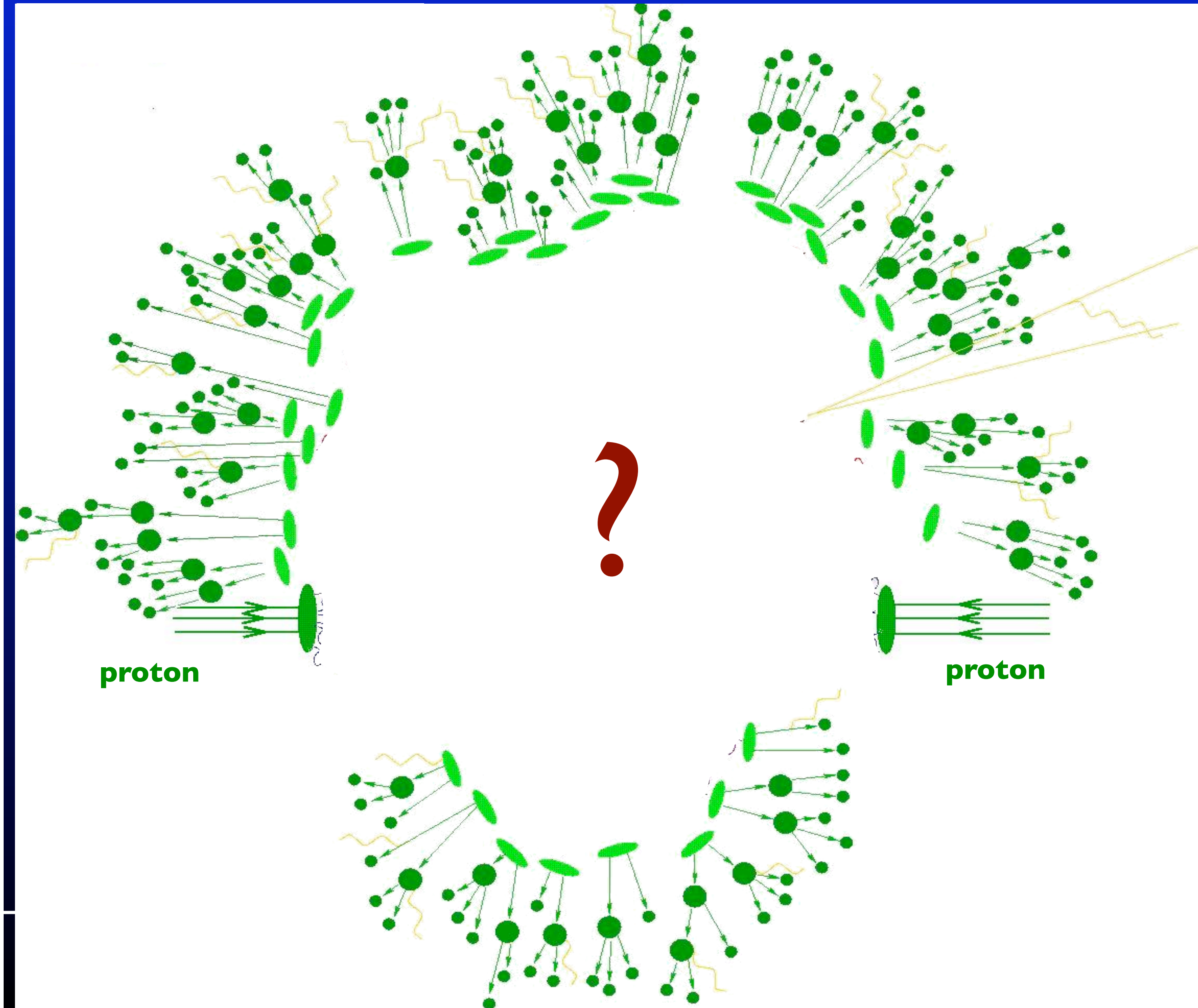
Jet

Fragmentation and Hadronization

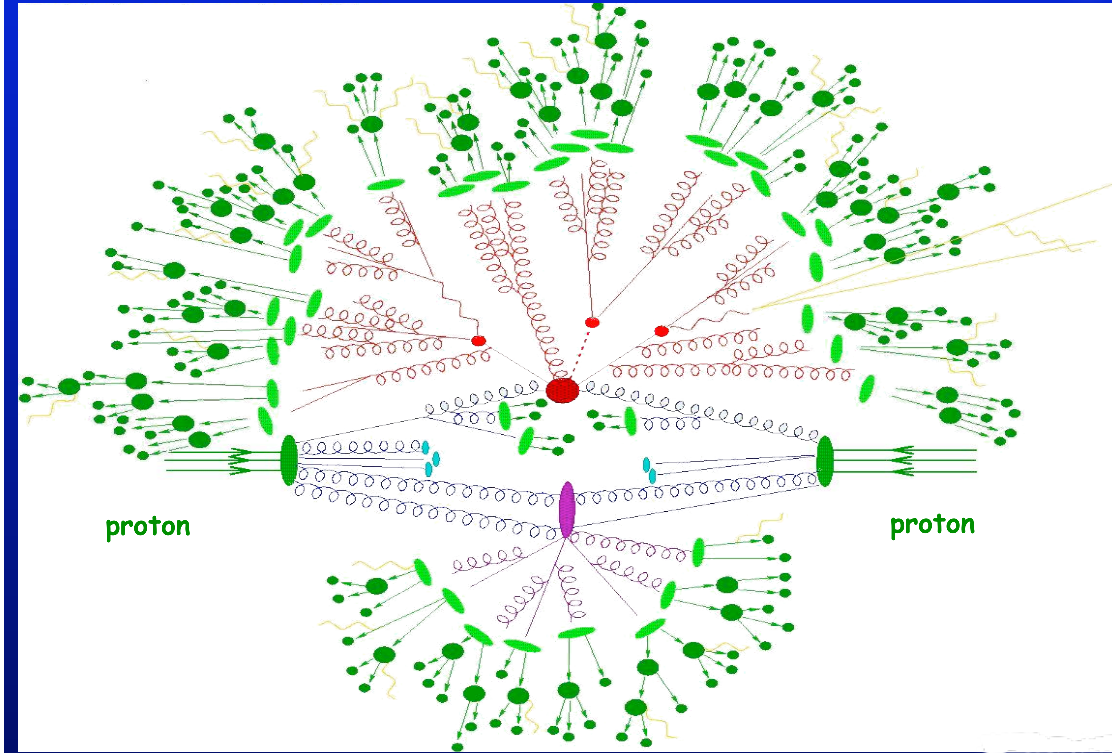
MPI

Beam Remnant

p-p interaction @ LHC



Minimum Bias e Underlying Event



Minimum Bias

Generic proton-proton interaction

Elastic + Inelastic ~ 100 mb @ LHC.

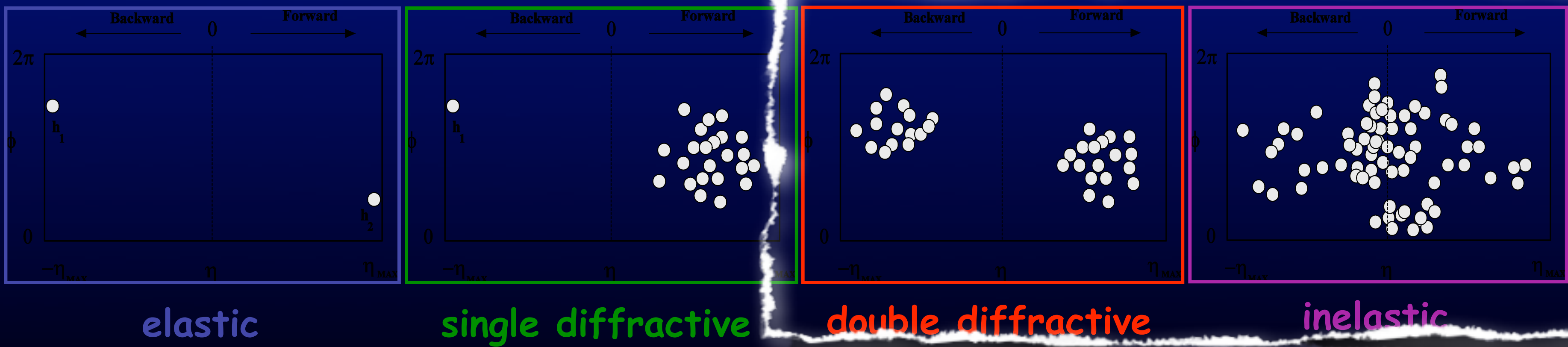
- Soft. Low P_T, low Multiplicity.

At LHC, many MB interactions can take place in the same bunch crossing.

$<N_{int}> = L_{inst} * \sigma/f$.

- MB can be recorded together with other interactions that can activate the trigger.
- Pile-Up.

What can be observed with a detector/trigger fully inclusive.



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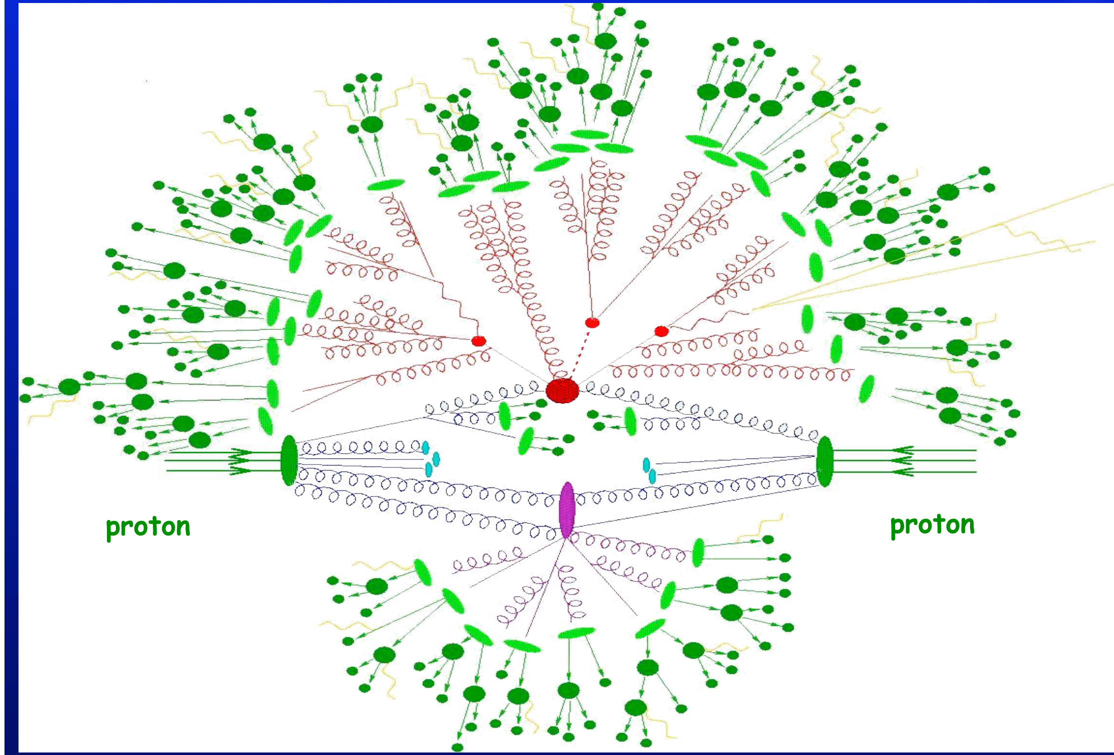

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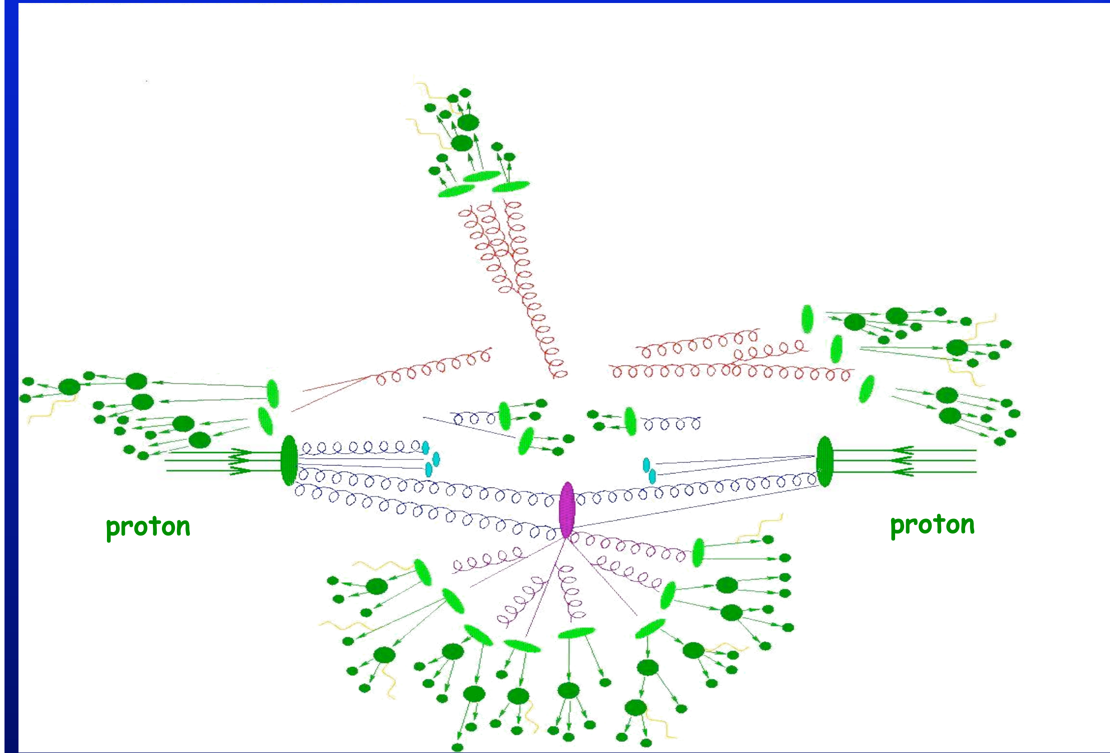
Minimum Bias e Underlying Event



Underlying Event

- All the activity of a single parton-parton interaction that is on top of the "interesting" process.
  - Initial State Radiation (ISR).
  - Final State Radiation (FSR).
  - Spectators.
  - MPI multiple parton interaction
- UE is correlated with the "interesting" process.
  - Share the same vertex.
  - The UE activity grows up with the energy scale of the main interaction
    - Pedestal effect.
  - UE studies can also help understand various physics phenomena!
    - Vertex reconstruction for H->γγ. γ.

Motivation

Exploring Fundamental aspects of hadron-hadron collisions

Describe QCD@LHC in the best way

- Not enough to rescale conclusions from Tevatron to 14 TeV
- [different Q^2, x range and energy dependence of the cut-offs]

Structure of hadrons

- Factorization of interactions
- spin offs on other relevant physics

Impact on the search of new physics

The understanding of the MB and transition of pQCD and soft QCD

- Important for Higgs in VBF and in general
- for all the channels that using the the jet veto and fwd jet tag

Calibration of major physics tools

Low, medium and high-PT QCD affected by "surrounding" processes which affect:

- Pile up understanding, jet energy, isolation performances,
- vertexing, detector response, High-PT background…

Tuning of Monte Carlo Models

Both not-perturbative and perturbative aspects

- Remnants, I-FSR radiation, MPI…
- (UE activity, mini-jet, hard scattering, double scattering)

Understanding the detector

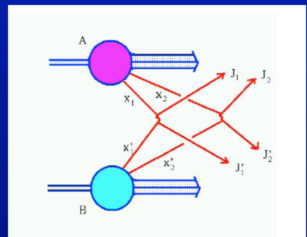
- occupancies, background, …

Theory/Models of pp interactions

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

The Pythia solution:
Multiple Parton Interactions (MPI)
(now available in other general purpose MCs: Herwig/Jimmy, Sherpa, etc.)

Inspired by observations of double high P_T scatterings



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

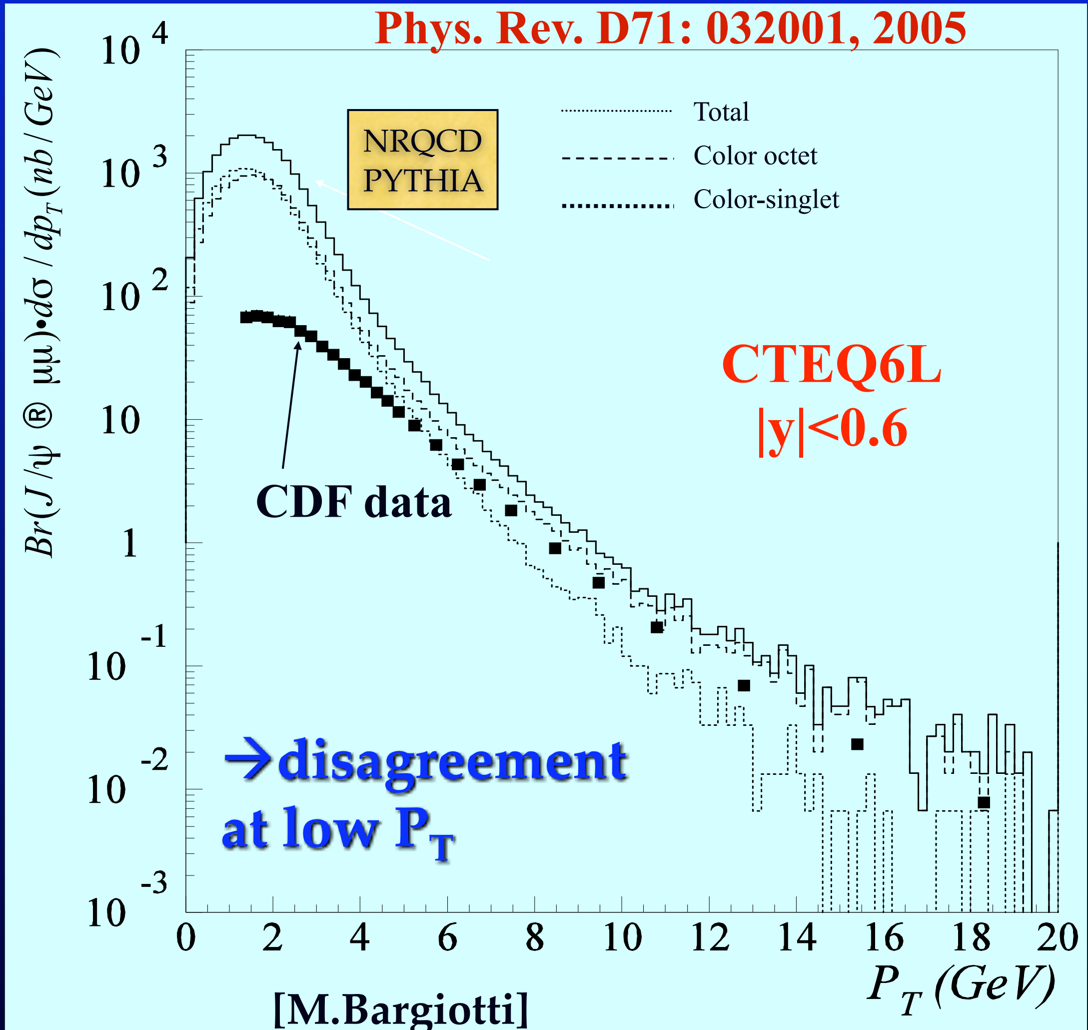
- ✓ **Cross Section Regularization for P_T -> 0**
- ✓ **P_{T0} can be interpreted as inverse of effective colour screening length**
- ✓ **Controls the number of interactions hence the Multiplicity:**

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

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

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

Also Quarkonia prefer dampening



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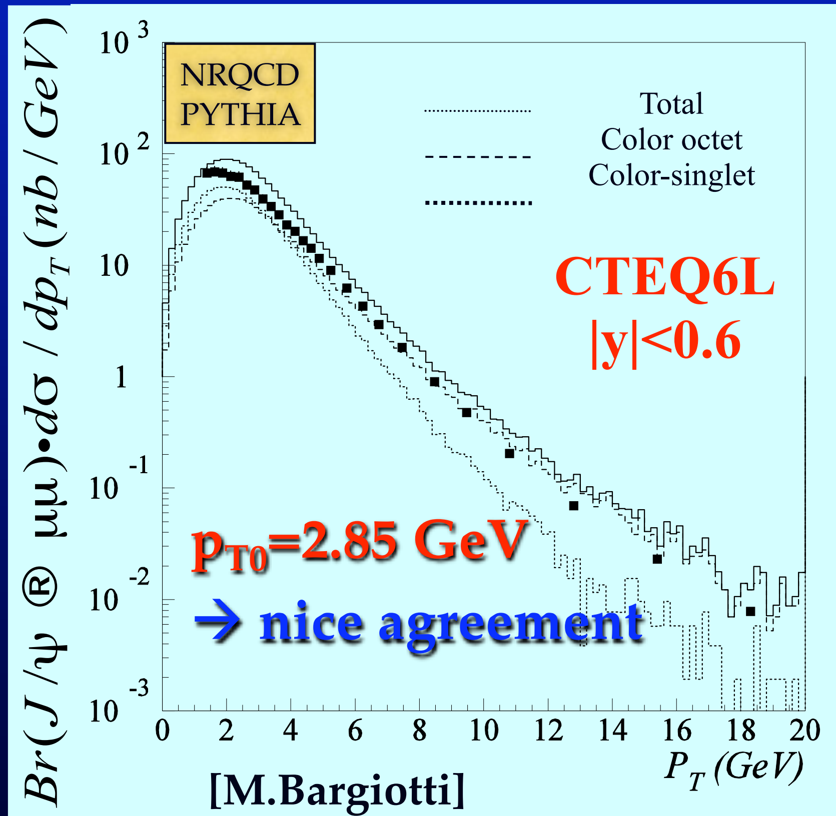

Regularization natural: gluon exchange in the t channel $d/dP_T^2 \sim 1/dP_T^4$

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

Pythia models

[P. Skands]

MPI Models in Pythia 6.4

- **Old Model: Pythia 6.2 and Pythia 6.4**
  - "Hard Interaction" + **virtuality-ordered** ISR + FSR
  - p_T-ordered MPI: **no ISR/FSR**
  - Momentum and color explicitly conserved
  - Color connections: **PARP(85:86) → 1** in Rick Field's Tunes
  - No explicit color reconnections

MPI create kinks on existing strings, rather than new strings

- **New Model: Pythia 6.4 and Pythia 8**
  - "Hard Interaction" + **p_T-ordered** ISR + FSR
  - p_T-ordered MPI + **p_T-ordered** ISR + FSR
    - ISR and FSR have **dipole kinematics**
    - **"Interleaved"** with evolution of hard interaction in one common sequence
  - Momentum, color, and **flavor** explicitly conserverd
  - Color connections: random or ordered
  - Toy Model of Color reconnections: **"color annealing"**

Hard System + MPI allowed to undergo color reconnections

Peter Skands

Color Connections, Multijets - 7

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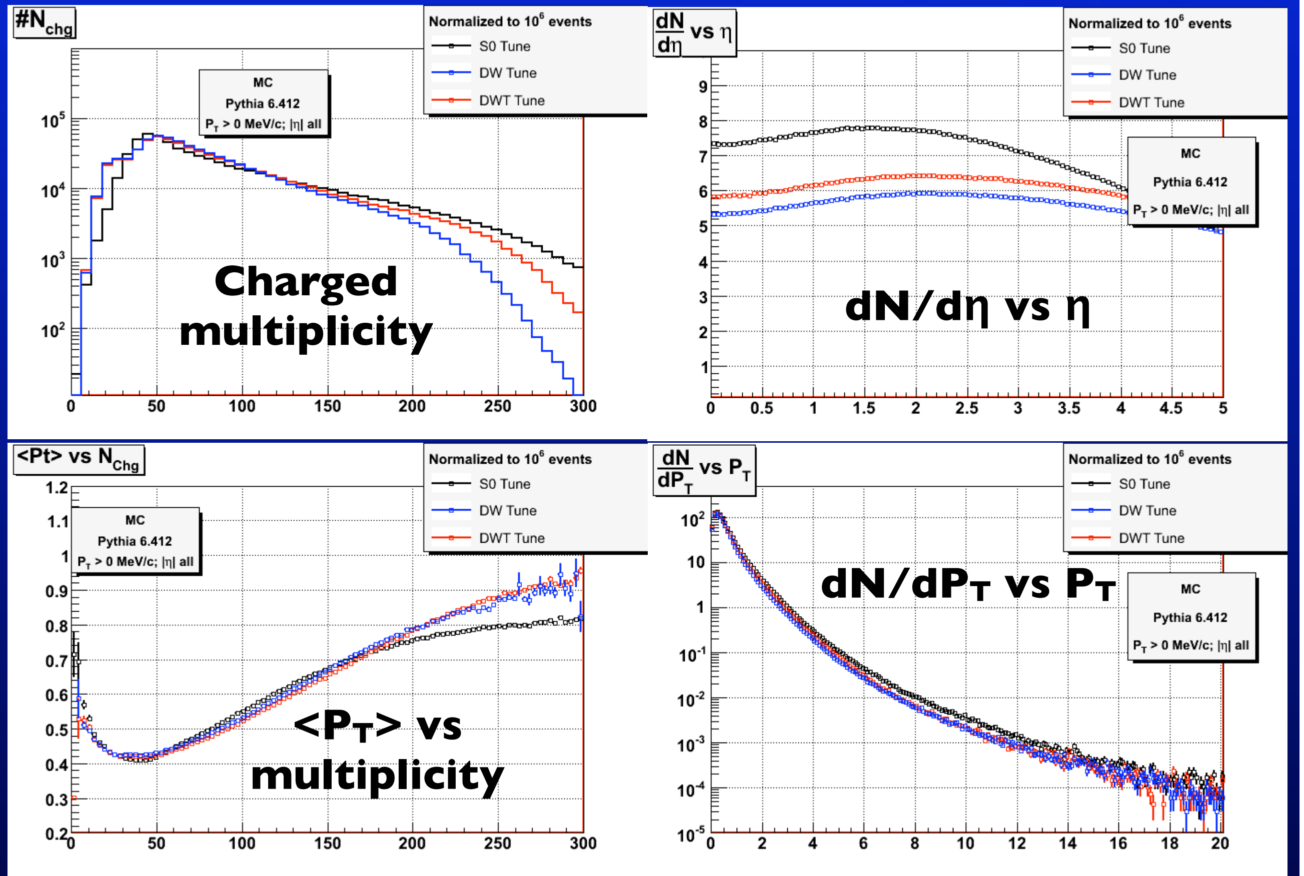
Pythia Tune

Pythia Tune DW
(from Tune A)
OLD MPI model,
IP CORRELATIONS
Pythia Tune DWT
DW and
default PT-cut-off evolution
Pythia Tune S0
New MPI, more correlations

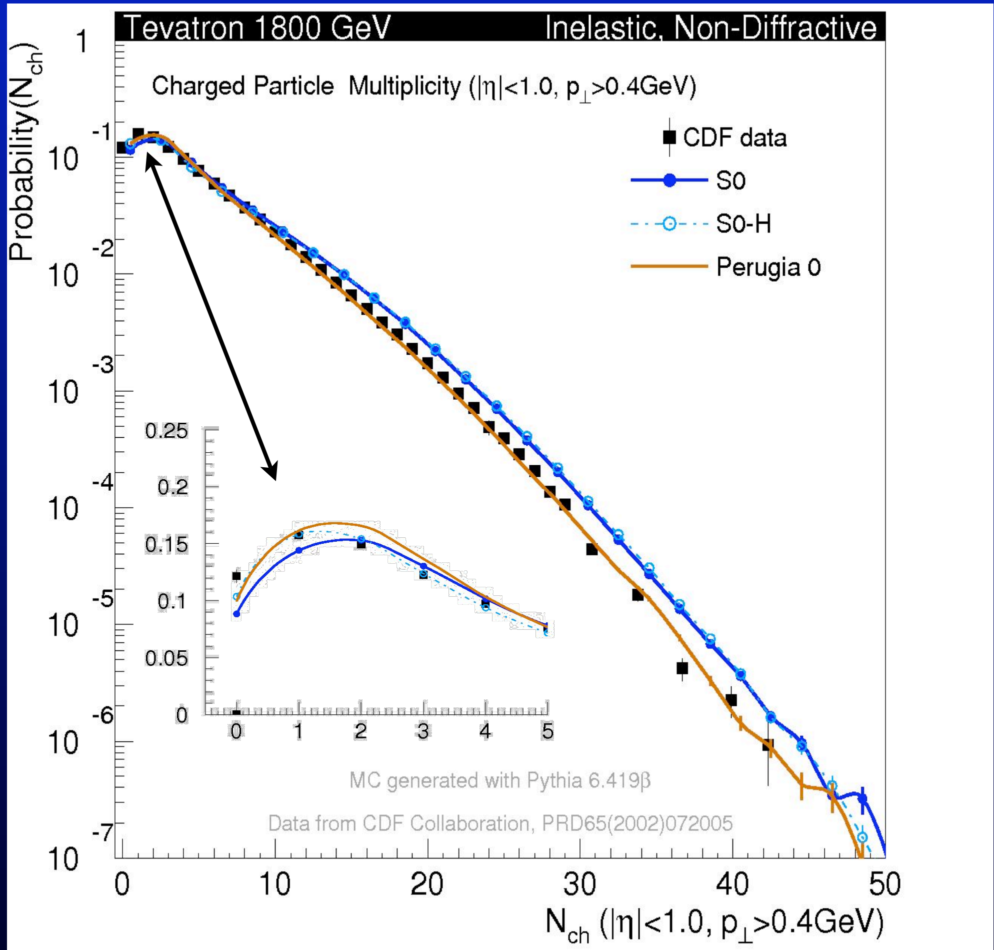


All these Pythia Tunes describe the UE@Tevatron, but show several
differences extrapolating to LHC energy
not enough to re-scale conclusions to 14 TeV.

Pythia Tune

[P. Skands]

- Perugia Tunes
  - First parameterization of new model using both Tevatron and LEP data
  - First attempt of taking into account the systematics.
  - Use a data-driven approach.



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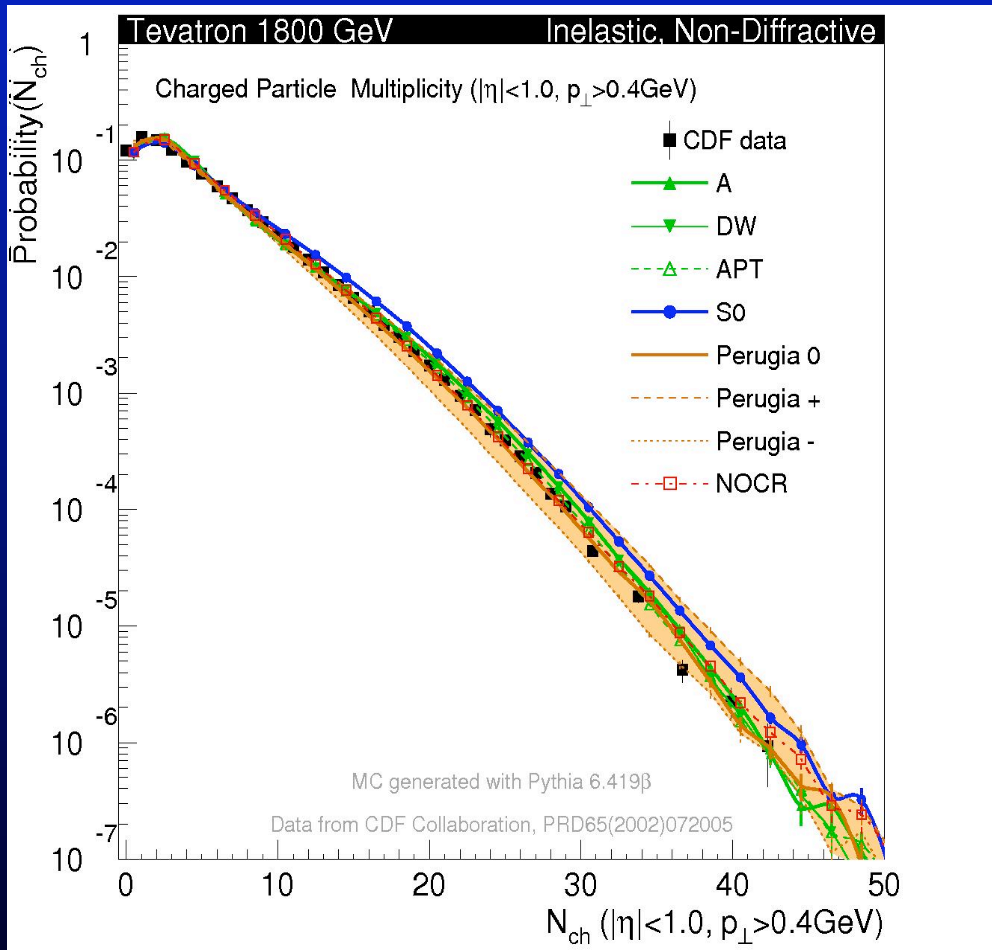

Pythia Tune

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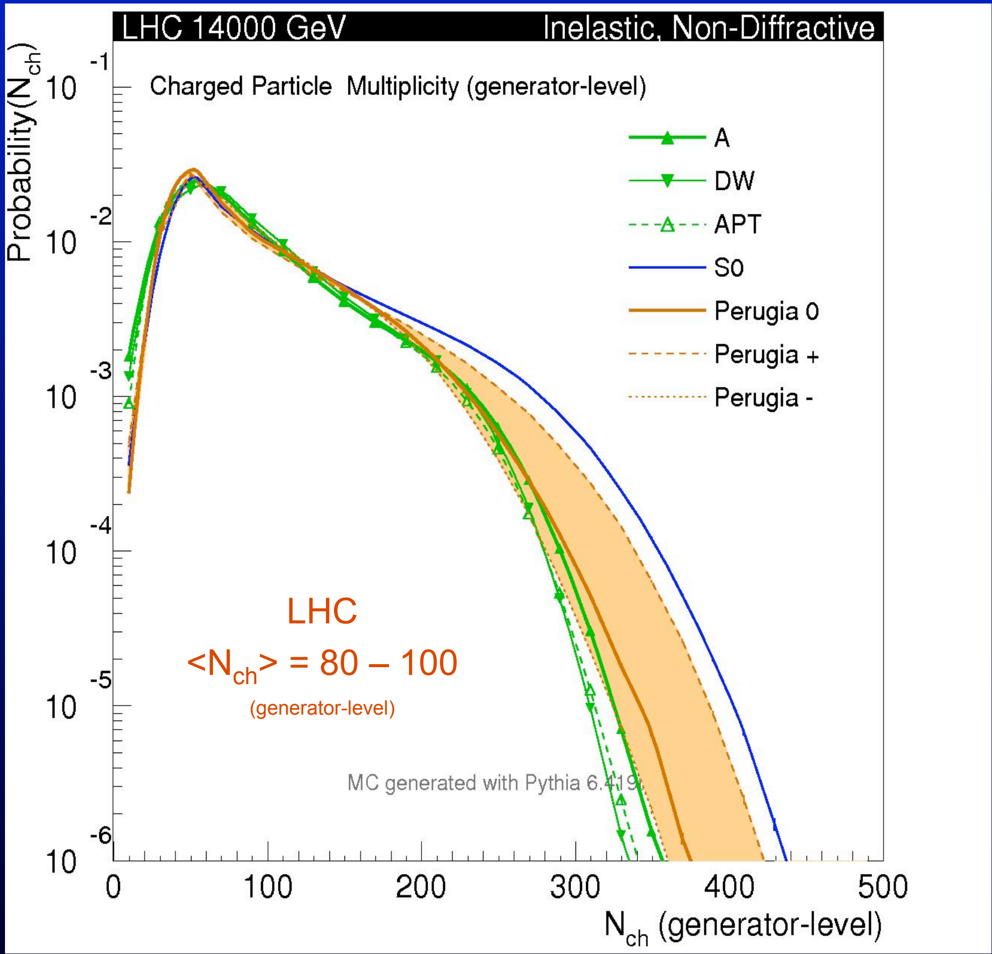
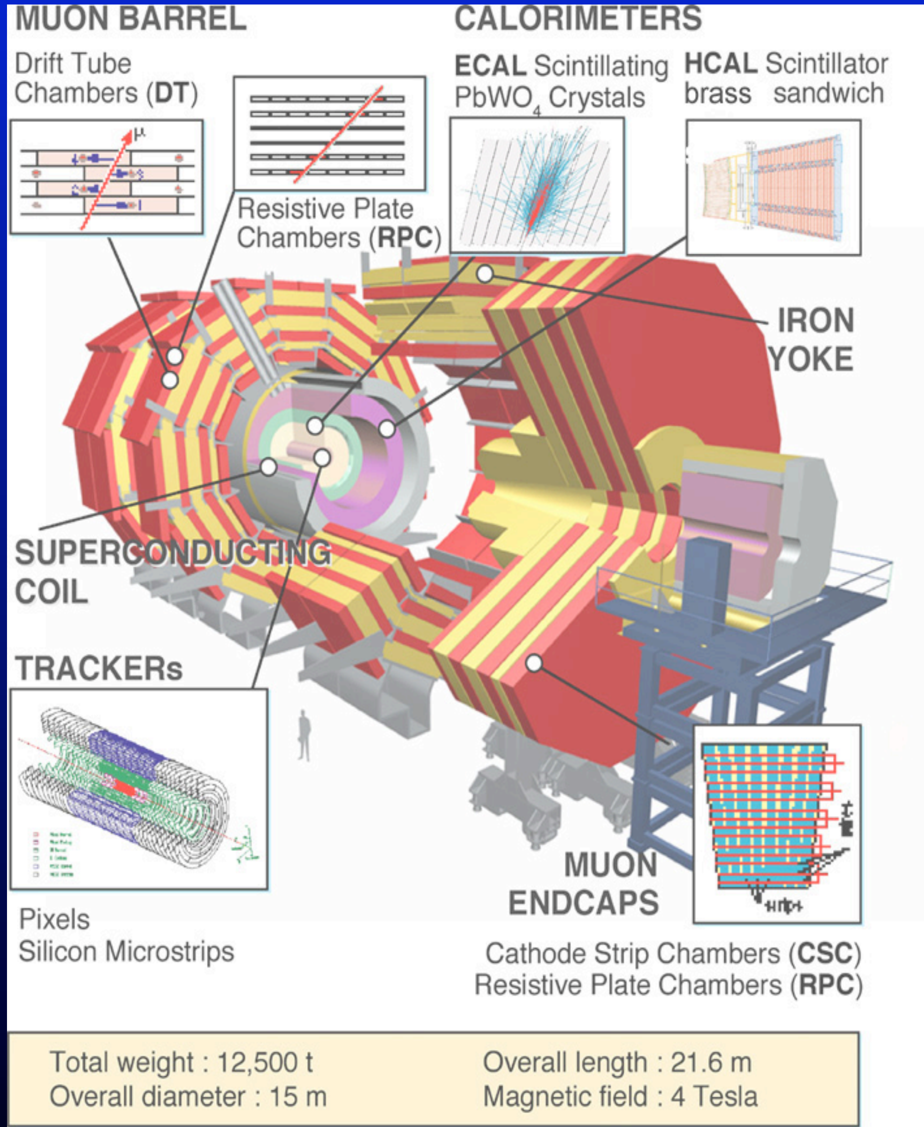


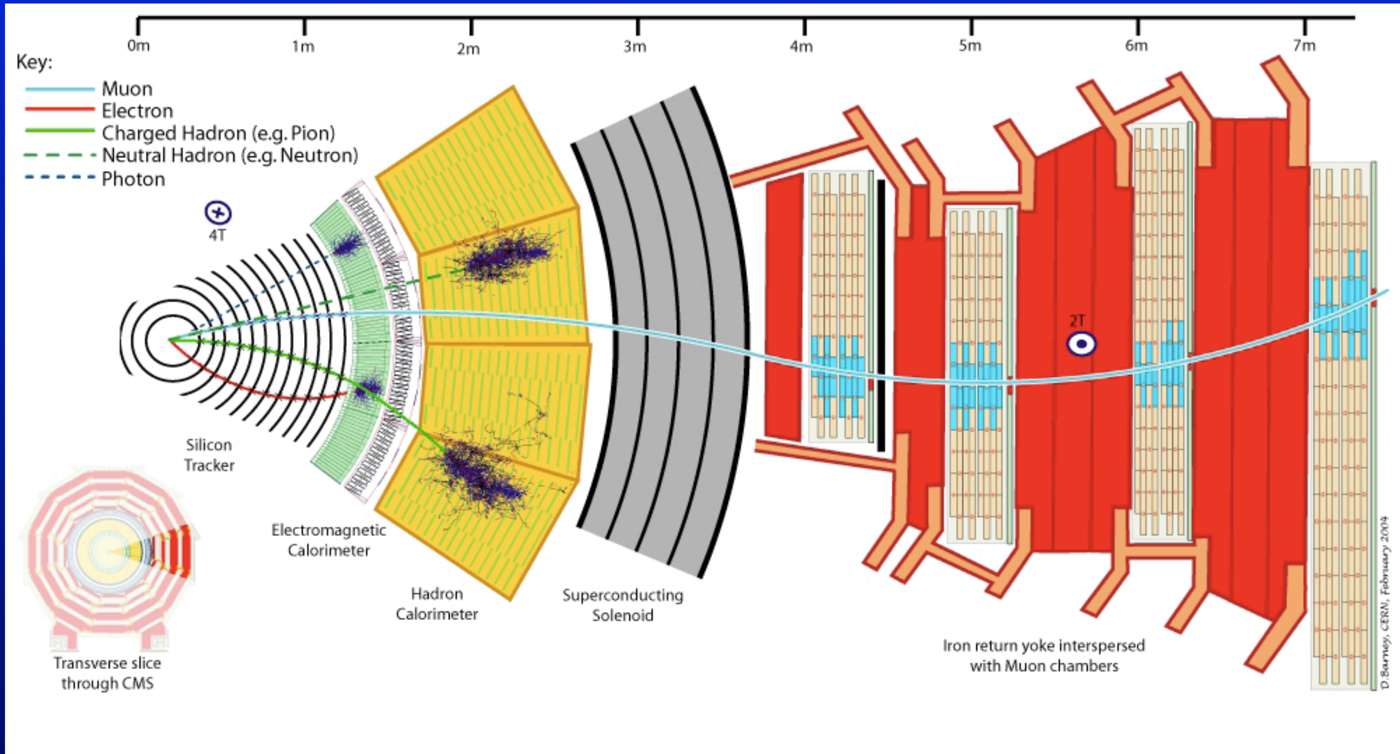
Experimental approach

- Study the Minimum Bias interaction
  - Study the MPI with "macroscopic" variables like charged multiplicity
  - We obtain indication on the energy dependencies of P_T cut-off
- Study the Underlying Event
  - Quantify the activity of process simultaneous to the hard interaction
    - Impact also in the understanding of the detector and to calibrate the tools for discovery
  - Study the MPI in the low-p_T kinematic region
- Study the Double Parton Scattering
  - We move the study of MPI from low p_T to high p_T kinematic region

CMS detector



CMS detector



- Silicon tracker: pixels and strips (|η| < 2.4)
- Muon chambers (|η| < 2.4)
- Electromagnetic (|η| < 3) and hadronic (|η| < 5) calorimeters
- Extension with forward detectors (CASTOR 5.3 < |η| < 6.6, ZDC |η| > 8.3)

$$\frac{\sigma}{p_\perp} = 15\%\, p_\perp[\mathrm{TeV}] + 0.5\%$$

$$\frac{\sigma}{E} \approx \frac{2.7\%}{\sqrt{E}} \oplus 0.5\%$$

$$\frac{\sigma}{E} \approx \frac{90\%}{\sqrt{E}} \oplus 7\%;$$

We can measure leptons (e, μ), hadrons (π, K, p), charged and neutrals (n,γ)

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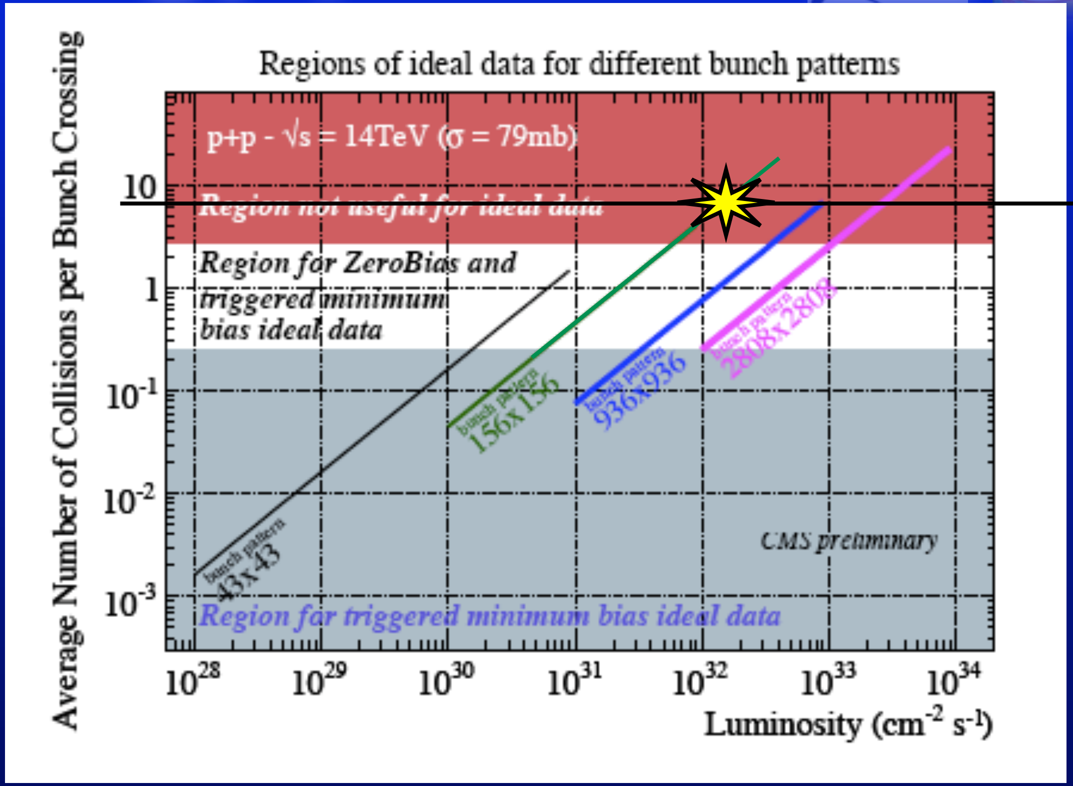
MB legacy from previous experiment

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.

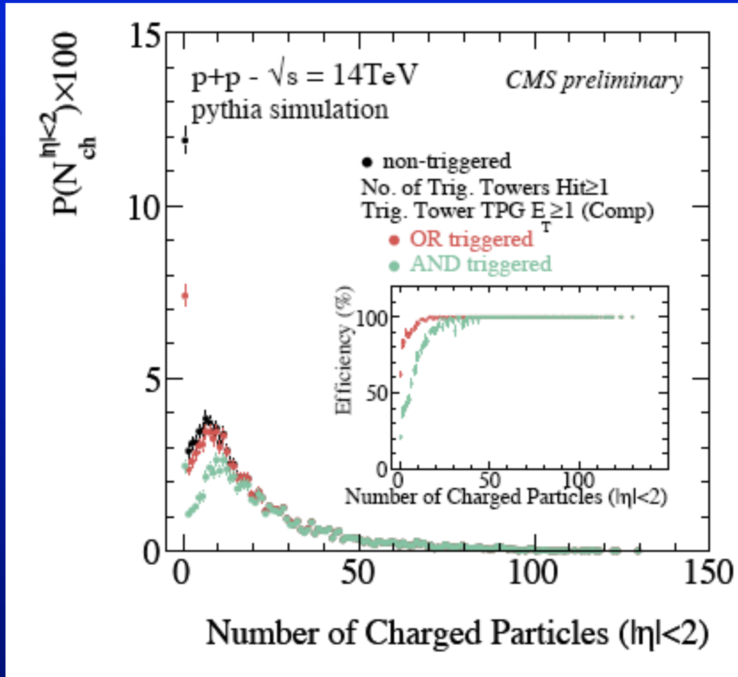
The shape of the charged multiplicity distribution is well described by "varying impact parameter" MPI models with Gaussian matter distributions inside the protons.

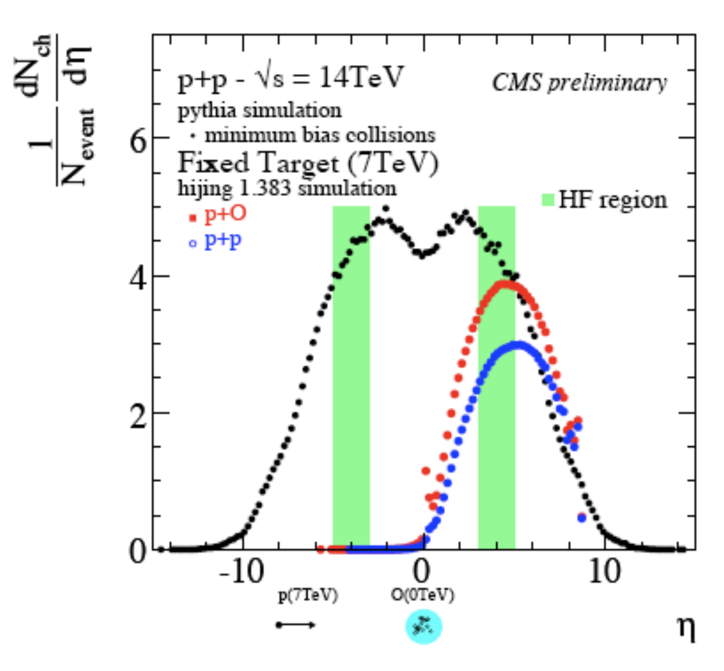
Trigger strategy for MB



- Random trigger, Level-1
  - zero bias: trigger on crossing of filled bunches
  - optimal for moderate intensity, heavily prescaled
- At least one track in the pixel detector, HLT
  - very low bias, optimal for very low intensity running (e.g. @ 900 GeV)
  - efficiencies: 88% IN; 99% ND, 69% DD, 59% SD (@ 14 TeV)
  - can be completed by offline vertex trigger

Forward Calorimeter strategy

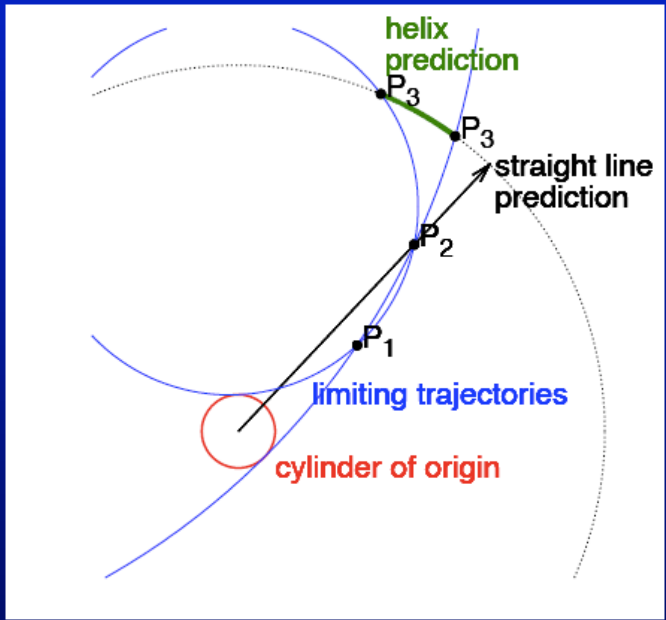


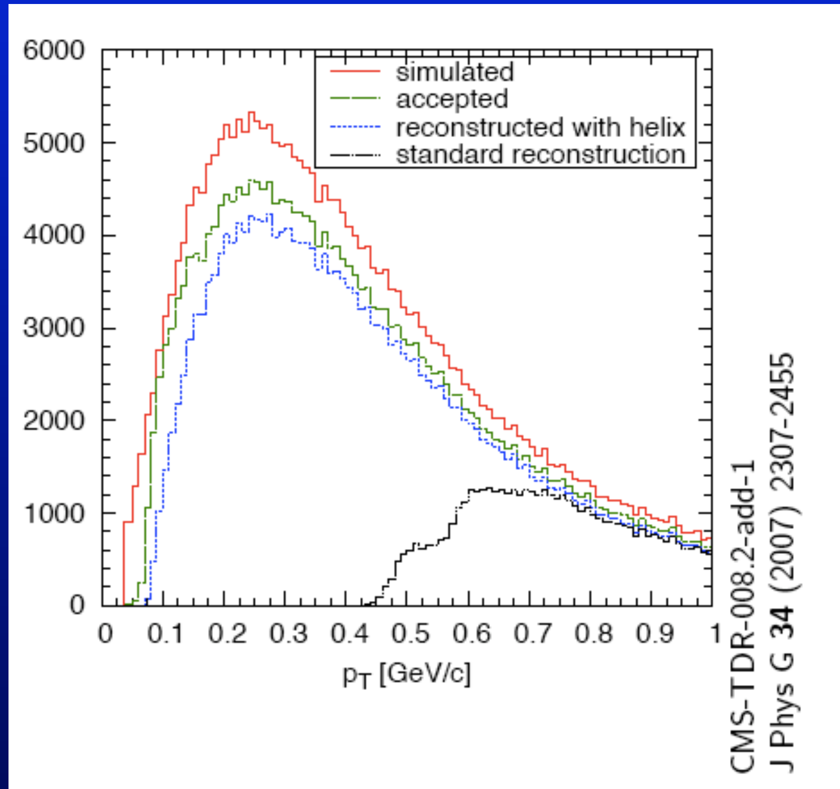


- count towers with E_T > 1GeV in the forward calorimeters (HF, 3< |η| <5)
- require hits on one side (OR triggered) efficiency: 89% IN (@ 900 GeV); 97% ND, 79% DD, 71% SD (@ 900 GeV)
- require hits on both sides (AND triggered) less efficient (59% IN), but not sensitive to beam-gas background
- Usability of triggers depend on bunch pattern and luminosity

Tools for measurements

Low-pT tracking

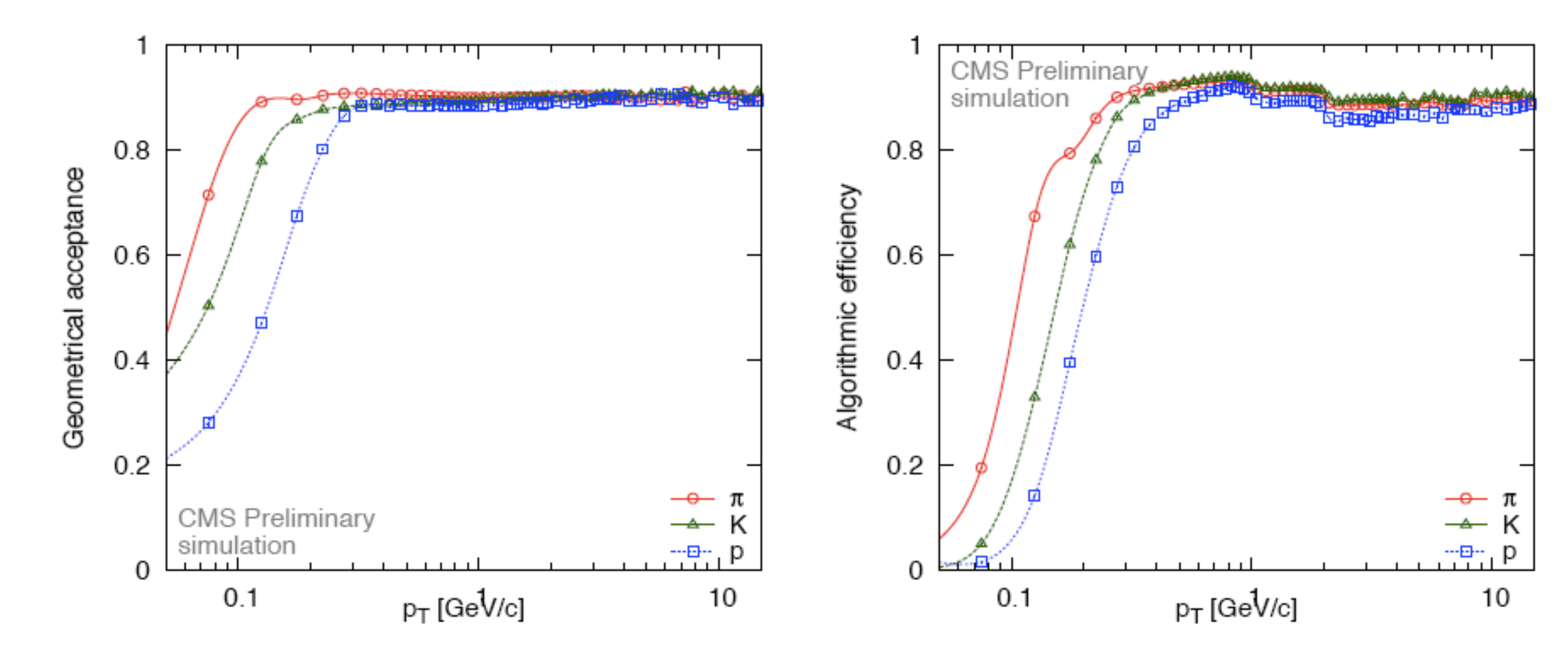




[F. Sikler]

- Modified method
  - Hit pair finding, then prediction for the third hit
  - "origin": the track must come from the cylinder of origin
  - "minimum": the p_T of the track must be above the minimal value
  - "third": the track must be able to reach the third layer (barrel or endcap)

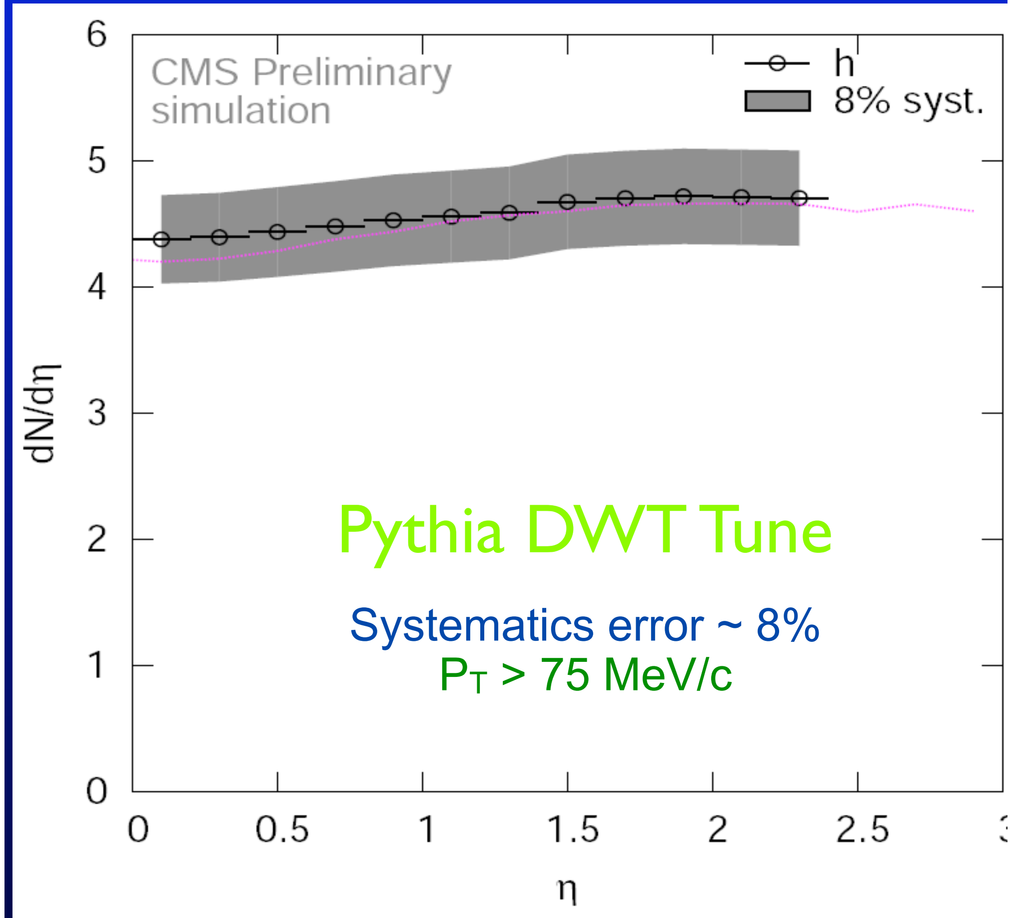
Tools for measurements

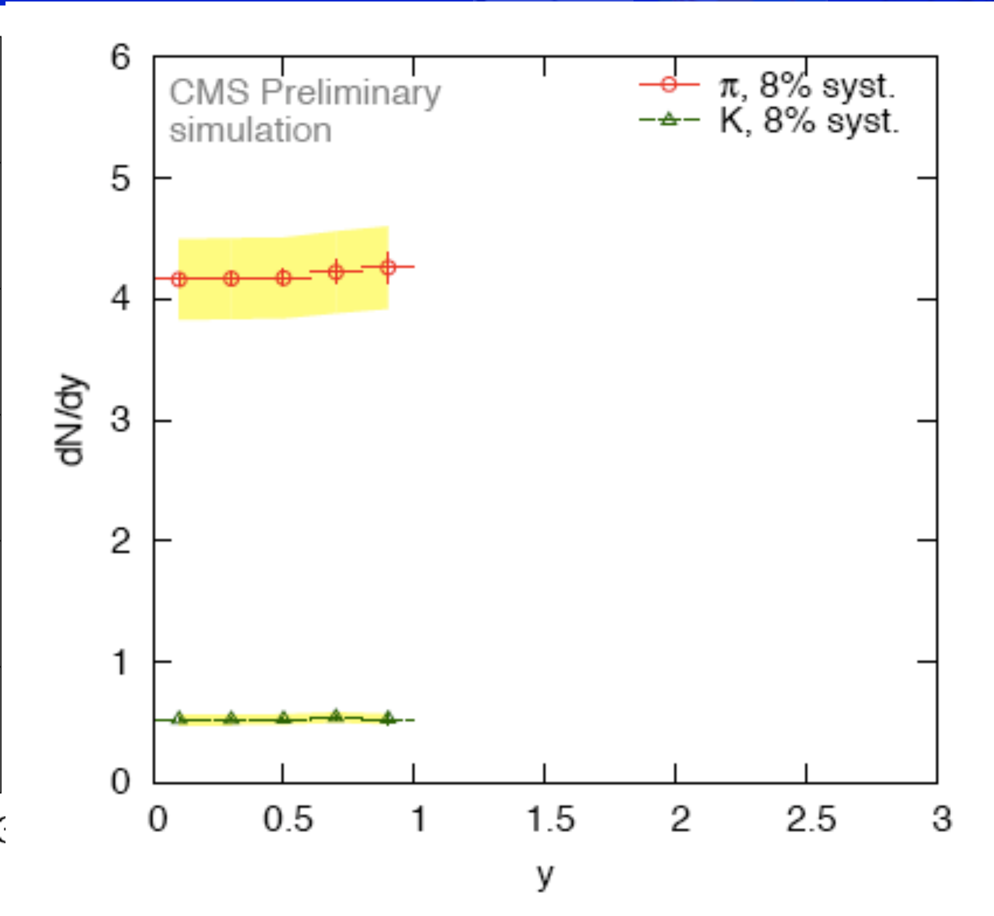


[F. Sikler]

Different for low pT for particles with different mass
Steps at 1 and 2 GeV/c are due to stricter requirements (points on track)

Minimum Bias ad LHC

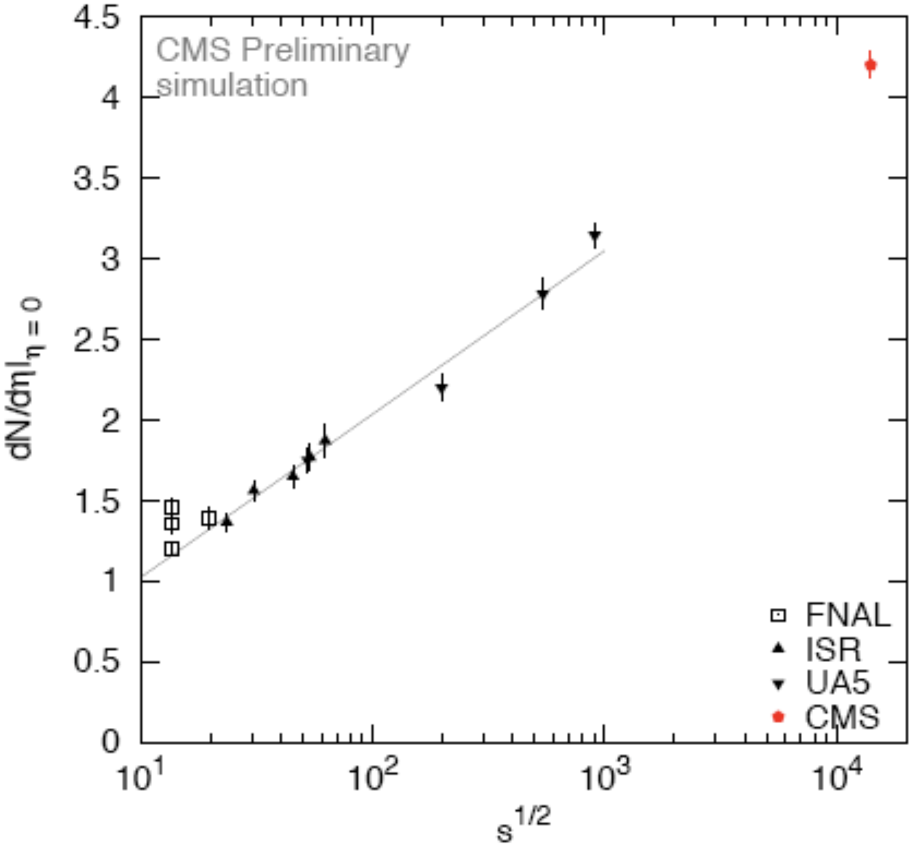


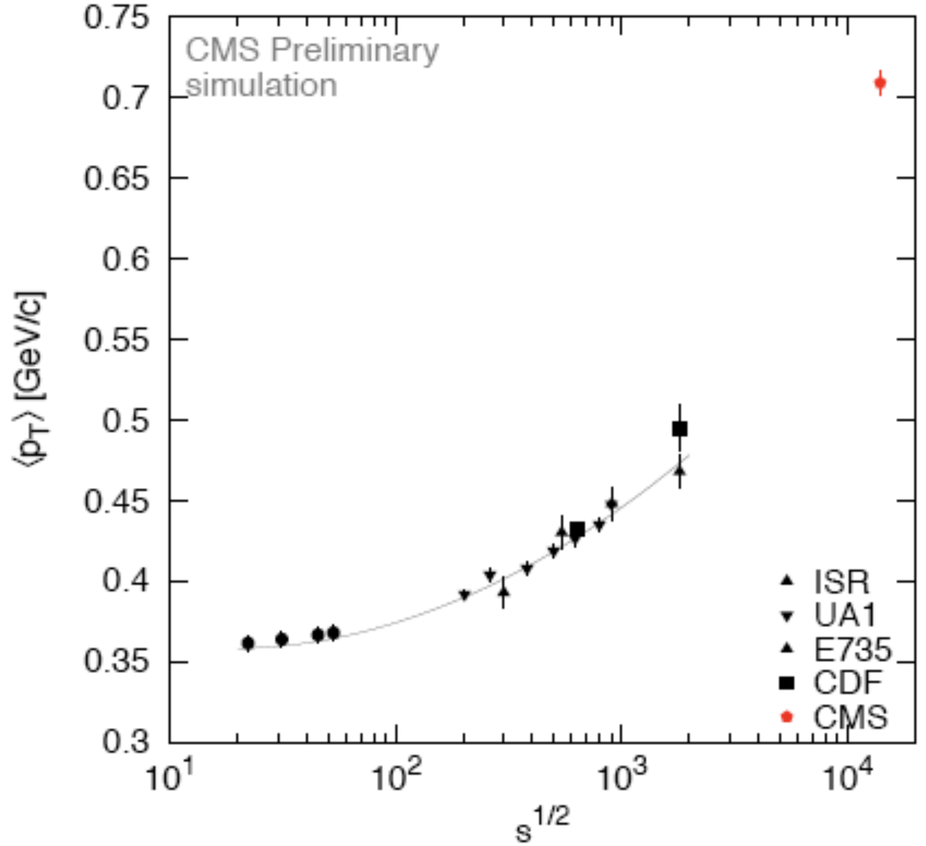


[F. Sikler]

The acceptance of the tracker limits the accessible η/y range, total number of produced charged particles cannot be measured

Minimum Bias ad LHC





Comparison to lower energy measurements: FNAL, ISR, UA1, UA5, E735, CDF

We can verify if $dN/d\eta|_{\eta=0}$ continues its linear increase in $\log\sqrt{s}$

A strong, non-linear increase of $<p_T>$ is expected

[F. Sikler]

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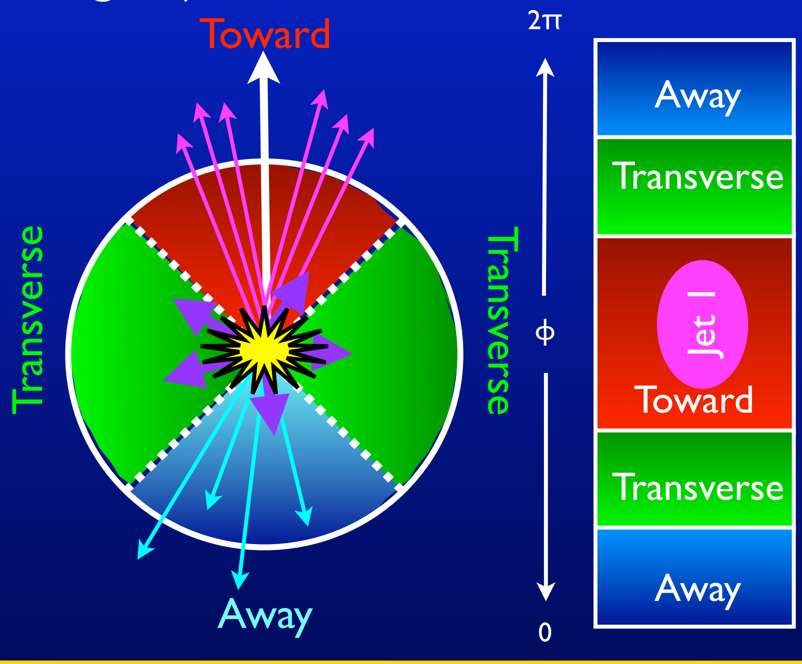
Measurment of UE with CMS

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 observable:

- **$dN/d\eta d\varphi$, charged density vs P_T Jet#1**
- **$d(PT_{sum})/d\eta d\varphi$, energy density vs P_T Jet#1**

Components of UE:

- Initial State Radiation (ISR)
- Final State Radiation (FSR)
- Spectators
- MPI

Why Study Underlying Event:

- Quantify the activity of process simultaneous to the hard interaction
- Study the MPI in the low-p_T

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UE legacy from previous experiment

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

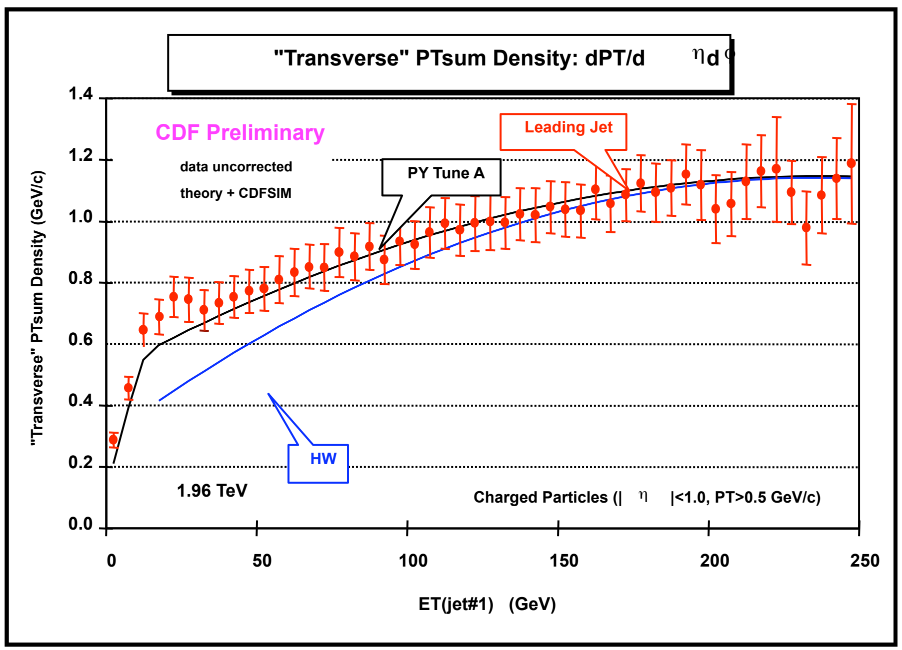
The Transverse region is expected to be particularly sensitive to the underlying event

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

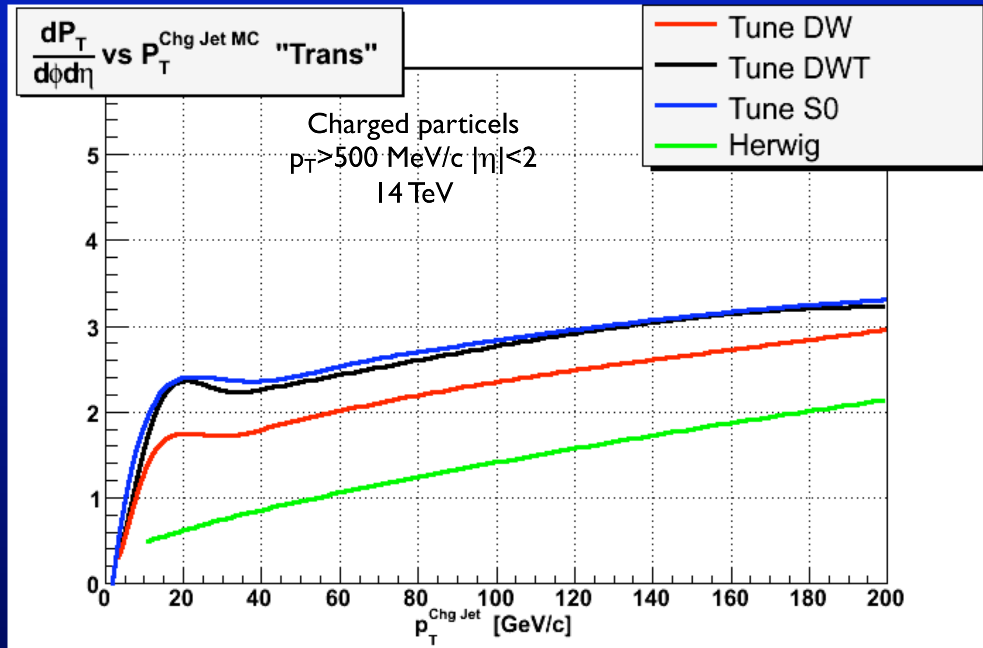
Sensitivity to the beam remnant and multiple interactions components of the underlying event in the “Transverse” region can be enhanced selecting back to back jet topologies

Generator level comparison between Tevatron and LHC

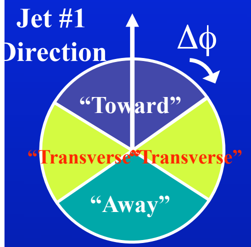
Tevatron



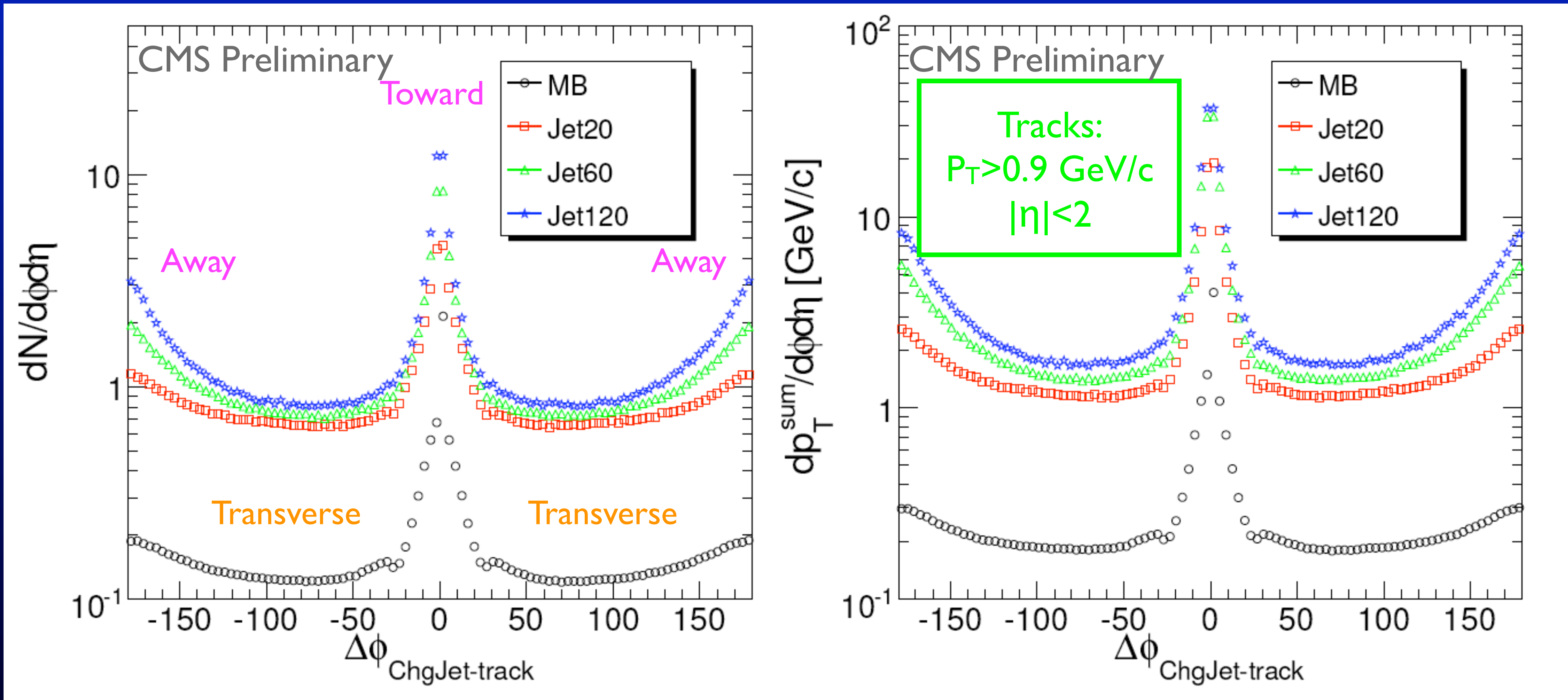
LHC



Why transverse region

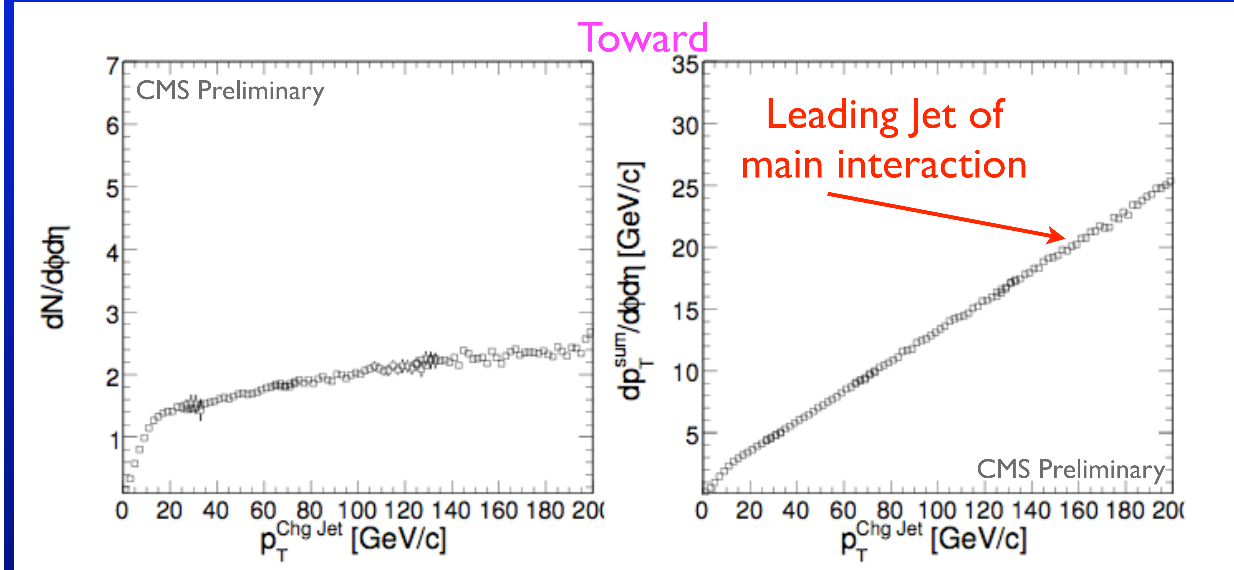


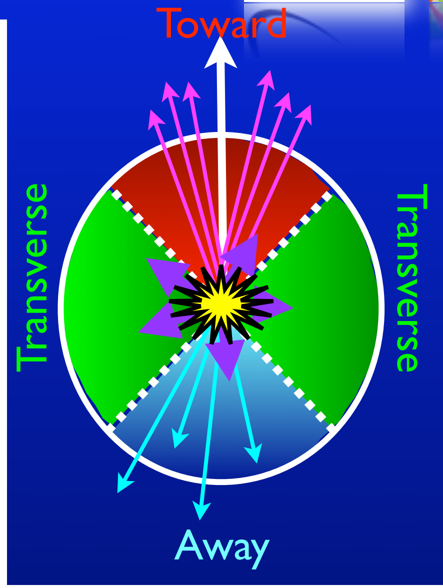
UE observable vs Δφ between tracks and leading charged Jet



CMS Physics Analysis Summary QCD-07-003

Activity in the different regions



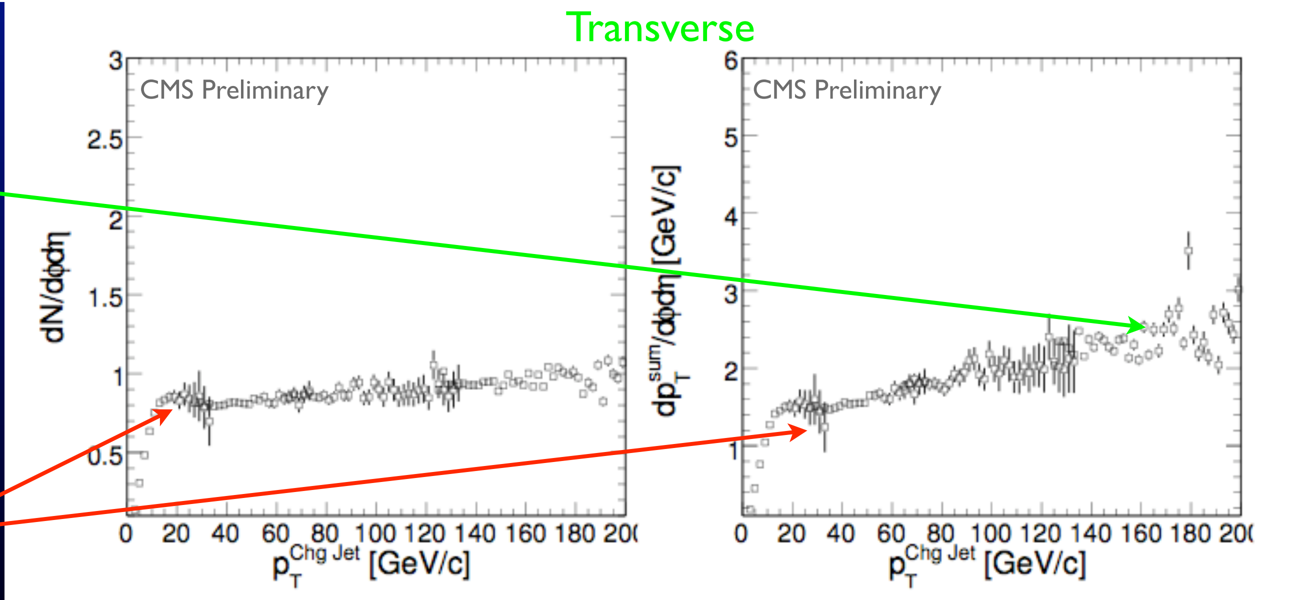


Tracks:
P_T>0.9 GeV/c
|η|<2

CMS Physics Analysis Summary QCD-07-003

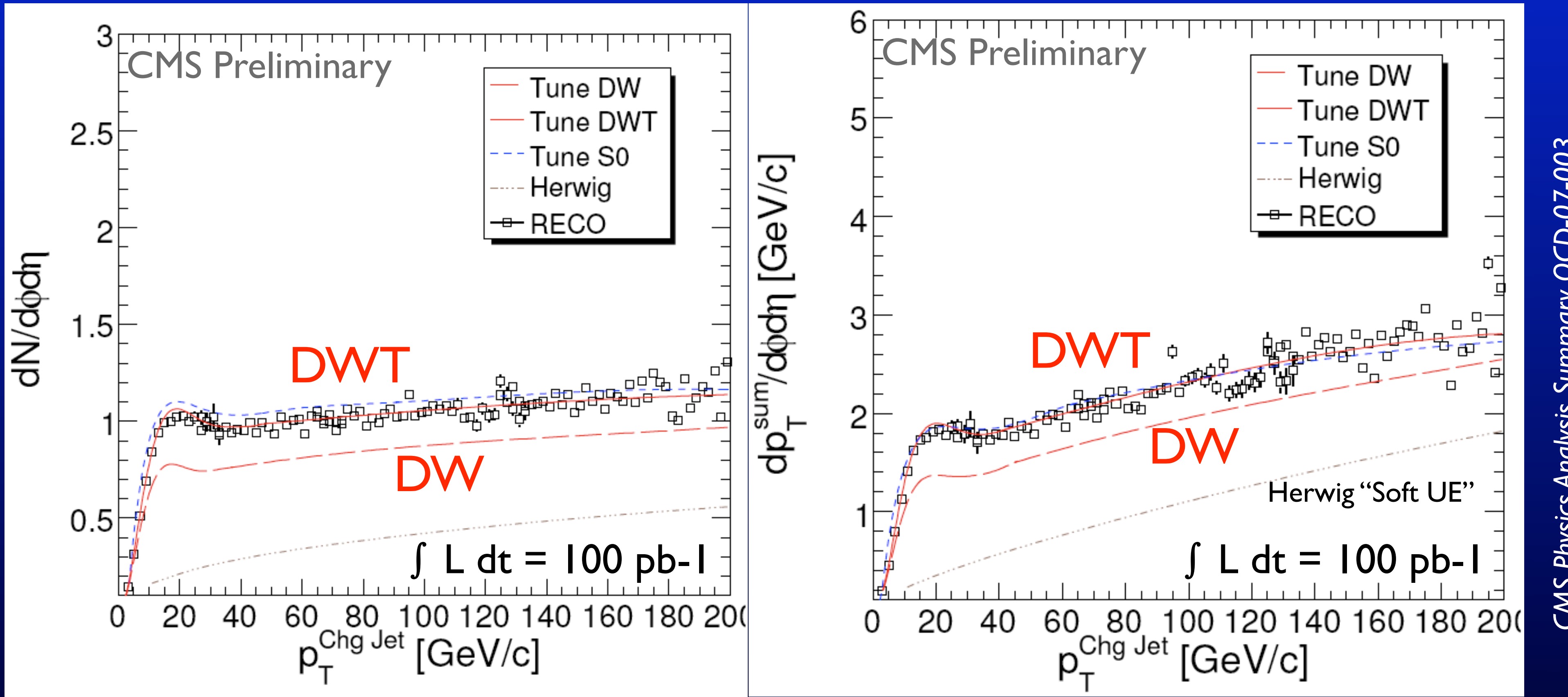
The rise after 80 GeV/c in the energy density is essentially due to the ISR and FSR

The plateau is reached immediately (~20 GeV)
The UE activity saturates very soon



Charged Jets

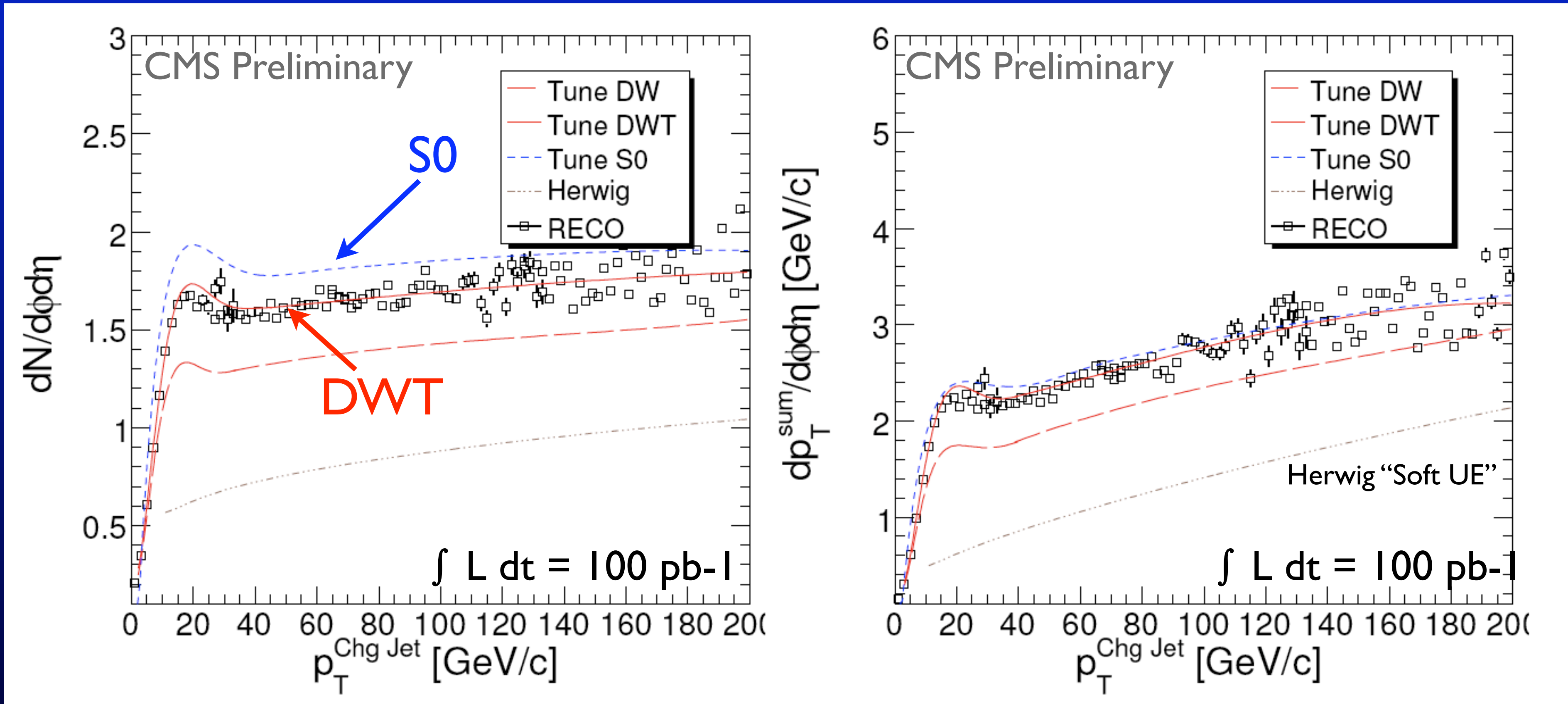
Select charged tracks in | η | < 2 with pT > 0.9 GeV/c



discriminate DW against DWT

Charged Jets

Select charged tracks in | η | < 2 with pT > 0.5 GeV/c



CMS Physics Analysis Summary QCD-07-003

discriminate DWT against S0

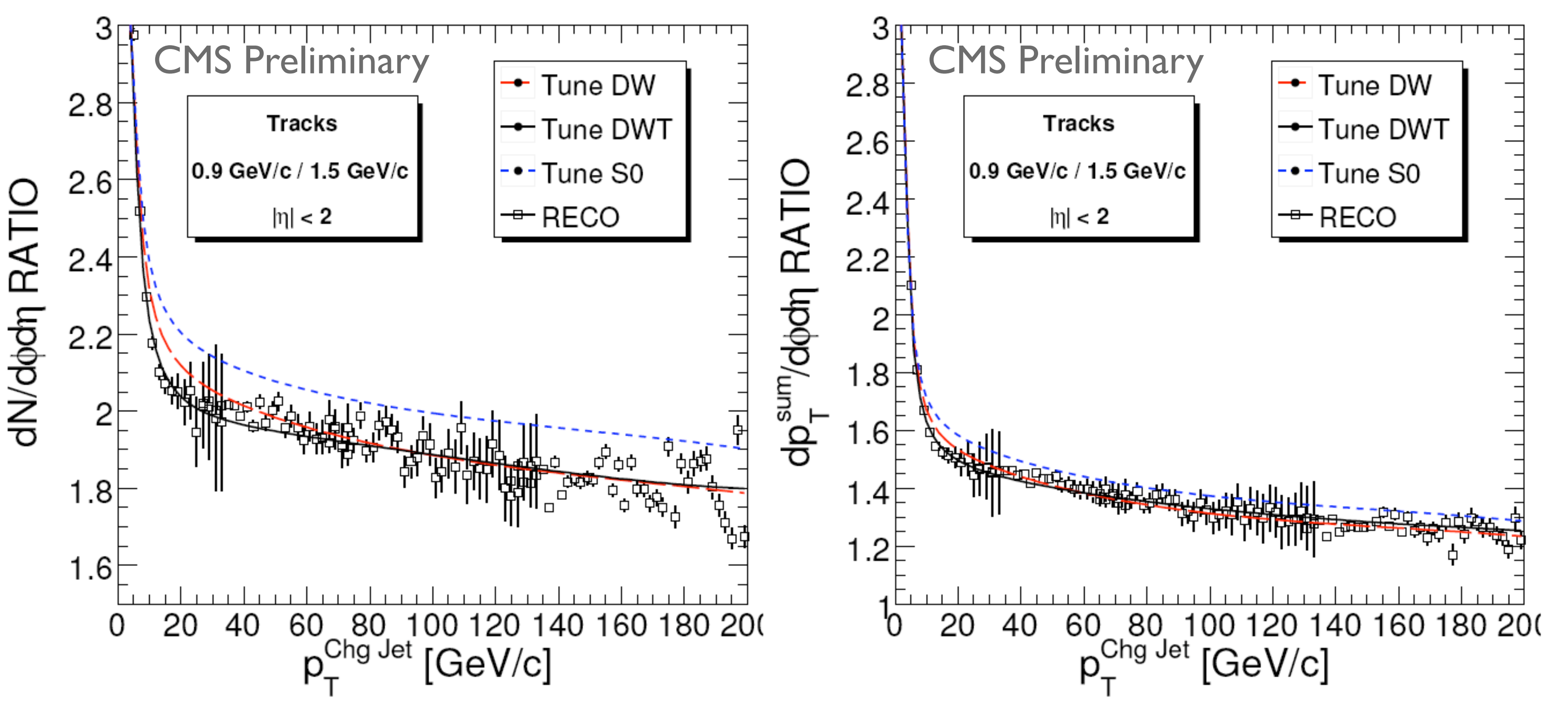
Charged Jets: Ratio

Ratios between uncorrected UE-observables:

UE-density(pT(track) > 0.9 GeV/c) / UE-density(pT(track) > 1.5 GeV/c)

No additional track reconstruction corrections needed!

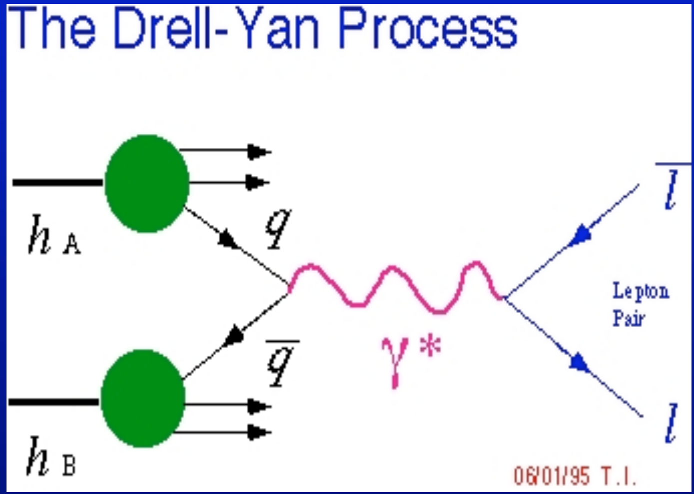
track reconstruction performance uniform in pT for pT > 0.9 GeV/c

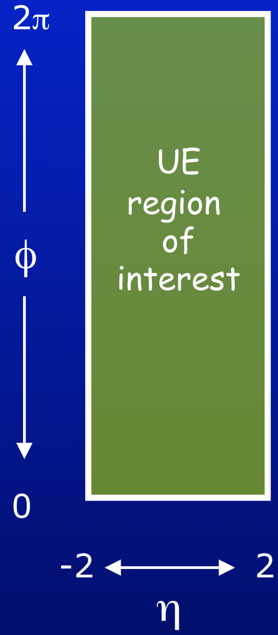


CMS Physics Analysis Summary QCD-07-003

discriminate DW/DWT against S0

UE @ LHC... new strategy





From D-Y muon pair production

(using muon triggers)

observables are the same but defined in all the ϕ plane

(after removing the μ pairs everything else is UE)

Main observables:

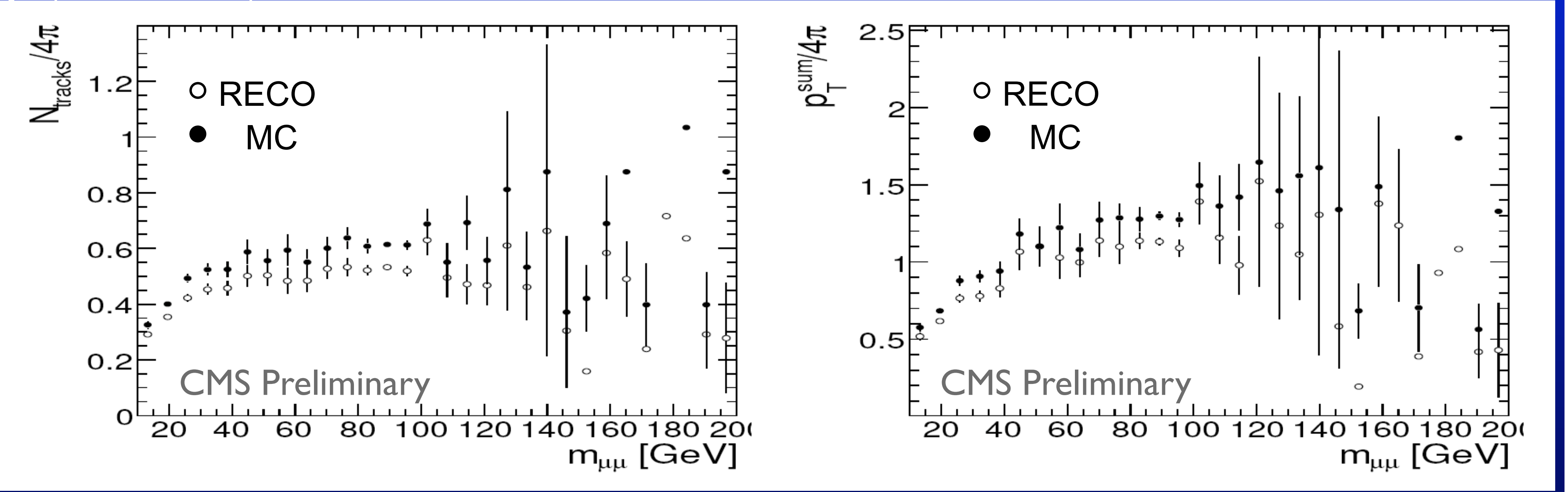
- $dN/d\eta d\phi$, charged density
- $d(PT_{sum})/d\eta d\phi$, energy density

Using D-Y electron pair??

Study the UE directly on Top and/or Higgs??

Drell-Yan

J. Phys. G: Nucl. Part. Phys. 34 995-1579



Lack of statistics for M(μ,μ) out of Z mass peak.
(error bars dominated by MC statistics, arbitrary luminosity)
Good agreement with MC prediction:
differences compatible with expected corrections from di-muon mass calibration, efficiency of charged track reconstruction and fake rate.

Experimental approach

- Study the Minimum Bias interaction
  - Study the MPI with "macroscopic" variables like charged multiplicity
  - We obtain indication on the energy dependencies of P_T cut-off
- Study the Underlying Event
  - Quantify the activity of process simultaneous to the hard interaction
    - Impact also in the understanding of the detector and to calibrate the tools for discovery
  - Study the MPI in the low-p_T kinematic region
- Study the Double Parton Scattering
  - We move the study of MPI from low p_T to high p_T kinematic region

Double Parton scattering

Double high P_T interactions observed by AFS, UA2, CDF and now D0!!!

[CDF Collab, Phys. Rev. Lett. 79, 584 (1997)]
[http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/QCD/Q13/]

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.

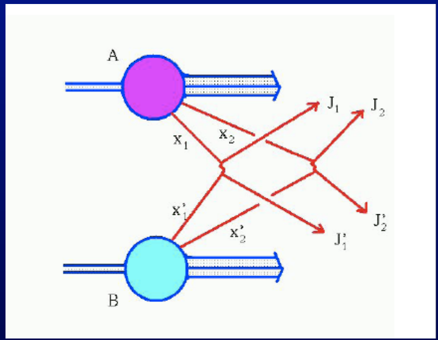
σ_{eff} contains the information on the spatial distribution of partons

Possible analysis strategy

$3j + \gamma$
-Reproduce results of CDF and now D0

New

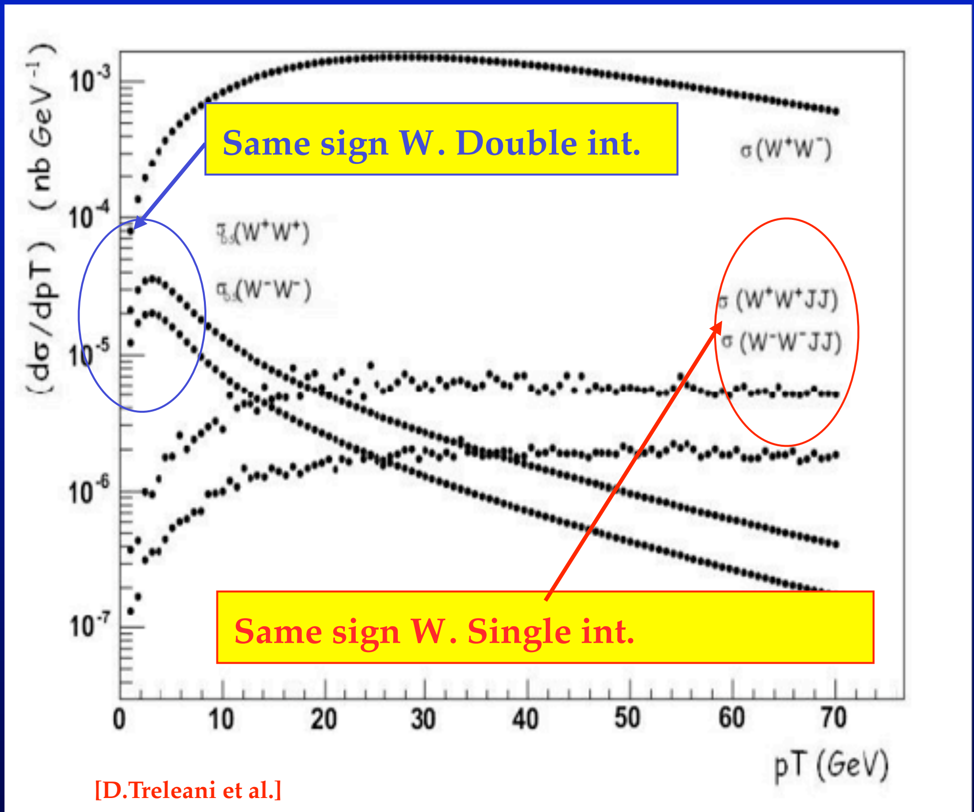
Counting same sign W pairs
Counting pairs of charged mini-jets in MB events



Counting the pairs of mini-jets we can quantify directly the number of MPI

We move the study of MPI from low p_T to high p_T

Implication of DP and MPI at LHC



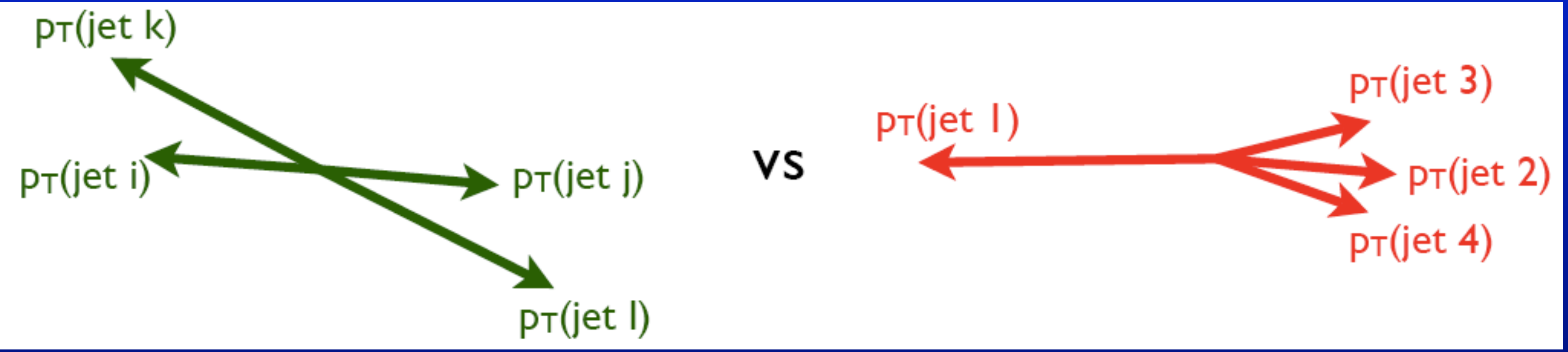
We cannot neglect the DP as additional sources of background for relevant process:

- HW
- W(Z)+jets, W(Z)b+jets, W(Z)bb+jets
- tt→llbb, tb →bbln
- bb+jets
- final state with multi jets (p_T^{min}~20,30 GeV)

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

DPS Analysis strategy

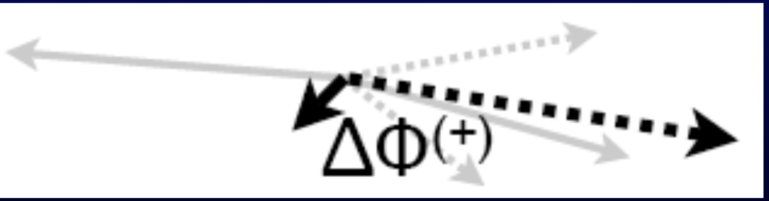
We have to distinguish among these two situations



Following the CDF approach we identify the jets pair using this variable

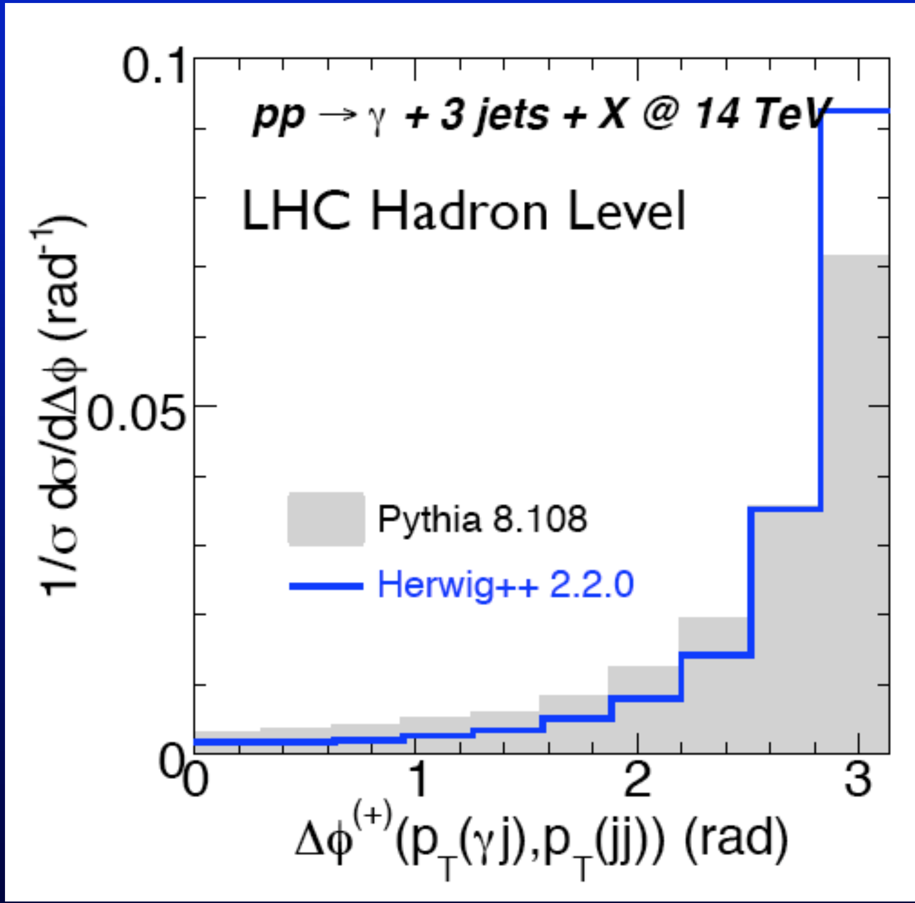
$$\min\left(\frac{|\vec{p}_{Ti}+\vec{p}_{Tj}|^2}{|\vec{p}_{Ti}|+|\vec{p}_{Tj}|}+\frac{|\vec{p}_{Tk}+\vec{p}_{Tl}|^2}{|\vec{p}_{Tk}|+|\vec{p}_{Tl}|}\right)$$

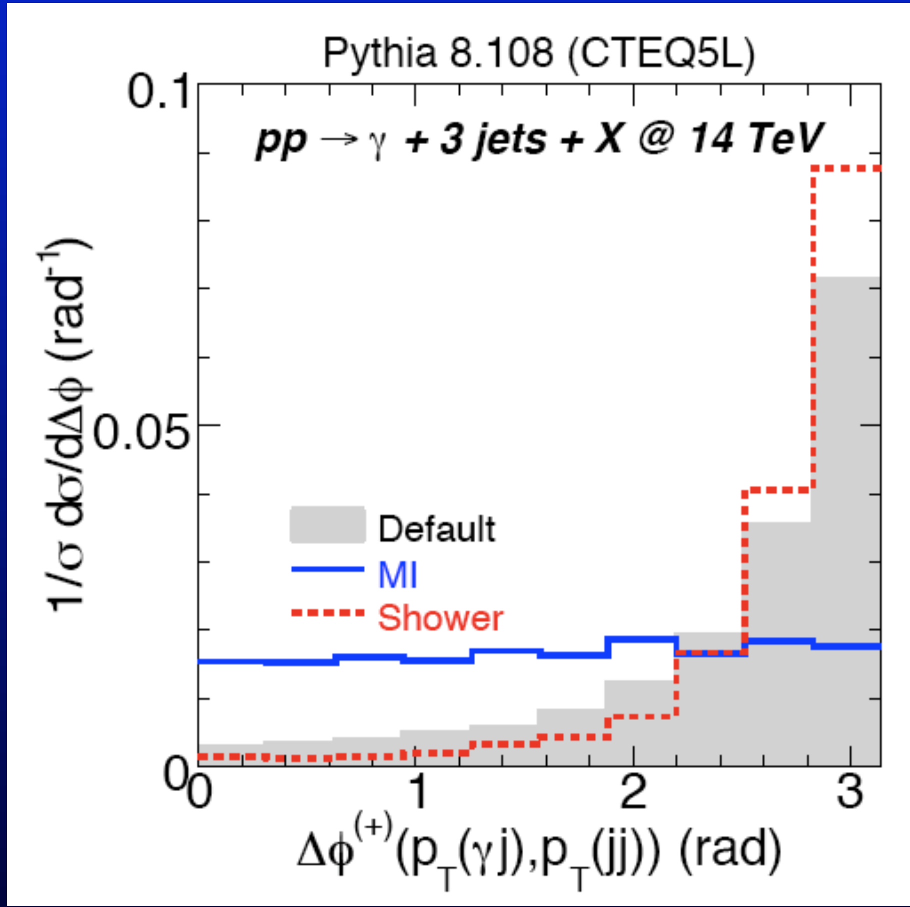
Study $\Delta\Phi^{(+)}$ between $\mathbf{p}_{T1} + \mathbf{p}_{T2}$ and $\mathbf{p}_{T3} + \mathbf{p}_{T4}$



Results obtained with new Pythia 8

[F. Bechtel]

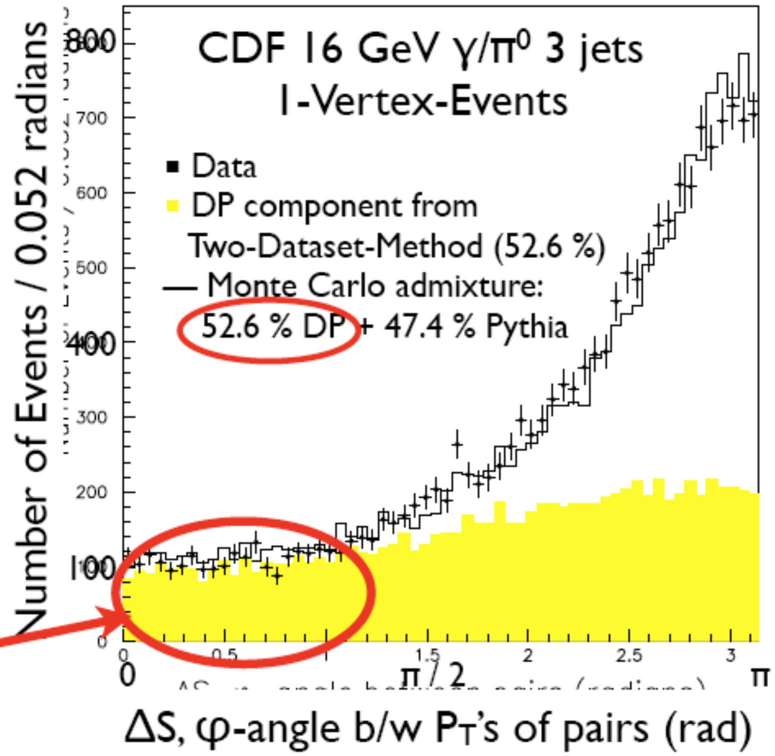




γ + 3 Jet analysis (CDF)

Tevatron Results

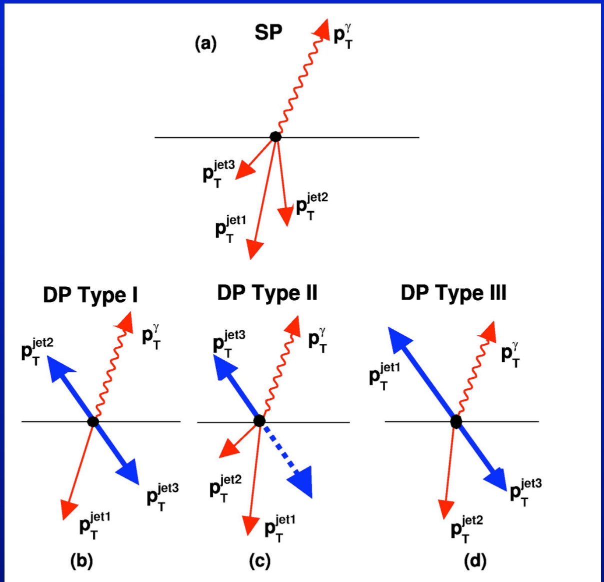
- **CDF analysis**
  - Choose pairs which minimize event imbalance
  - study $\Delta\varphi$ (ΔS) between $p_{T\gamma}$ + p_{T1} and p_{T2} + p_{T3}
- **DPS model: admixture**
  - Pythia, MPI switched off
  - add sum of min-bias and γ+jet datasets
- **Need double-parton component to describe the data**



florian.bechtel@desy.de MPI @ LHC 08, Perugia, October 2008 7

Tevatron: σ_{eff} = 11 mb Treleani, Phys.Rev.D76:076006,2007

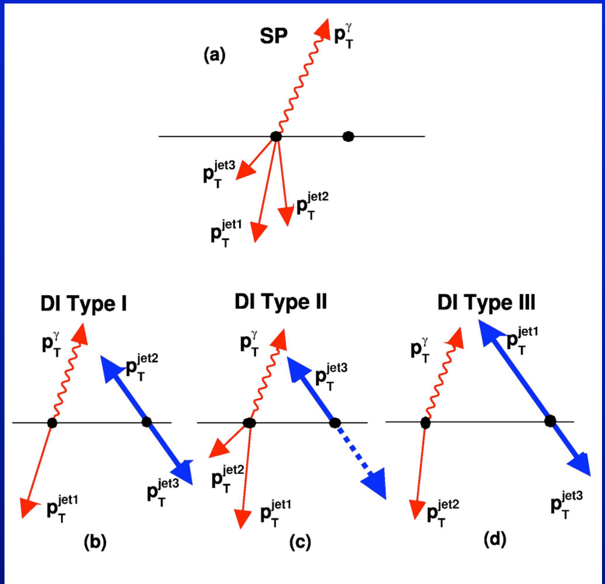
γ + 3 Jet analysis (D0)



These are the event topologies considered for the analysis

-> identical to the CDF topologies

γ + 3 Jet analysis (D0)



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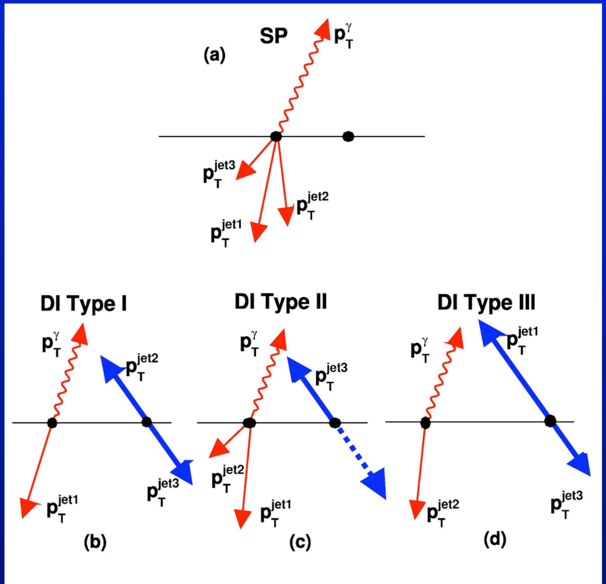
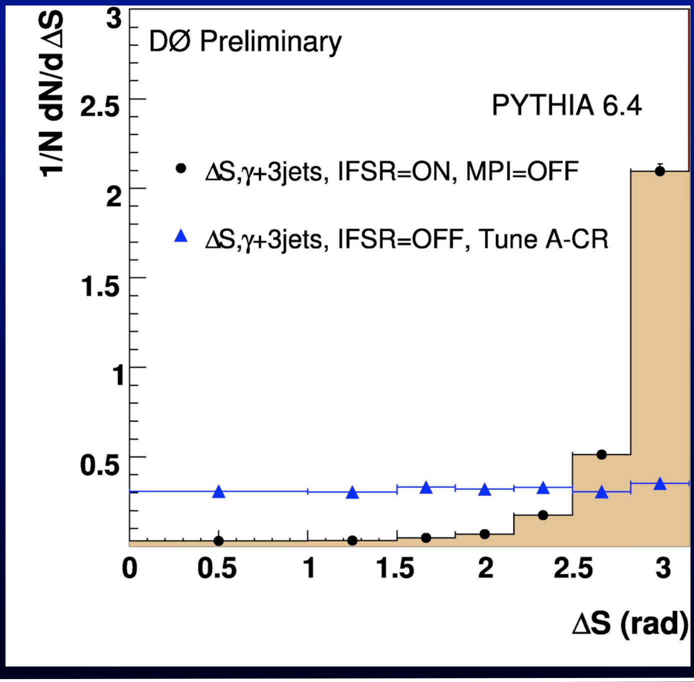
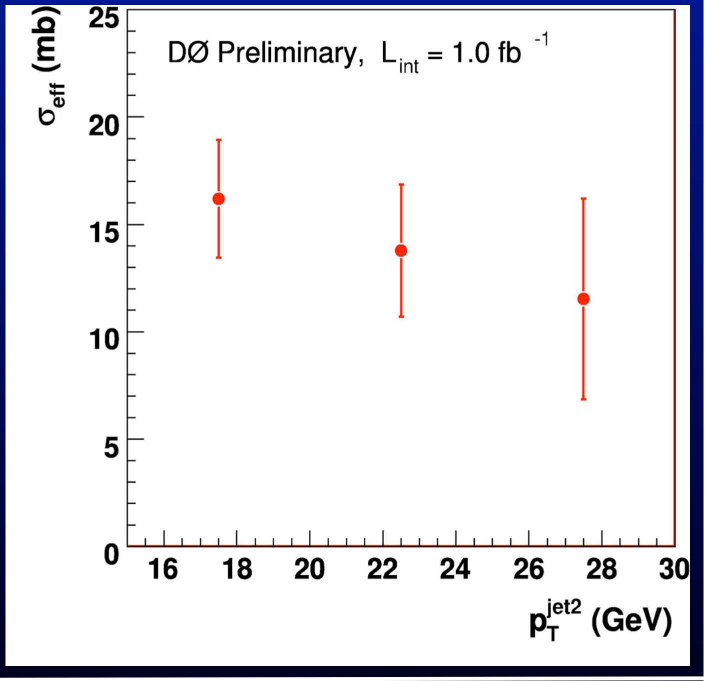
γ + 3 Jet analysis (D0)



The D0 results are close to the original from CDF...
maybe also this analysis have the same problem





Mini-Jets analysis

[D. Treleani]

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

$$< N > \sigma_{hard} = \sigma_S$$

$$\frac{1}{2} < N(N-1) > \sigma_{hard} = \sigma_D$$

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

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

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

Mini-Jets analysis

[D. Treleani]

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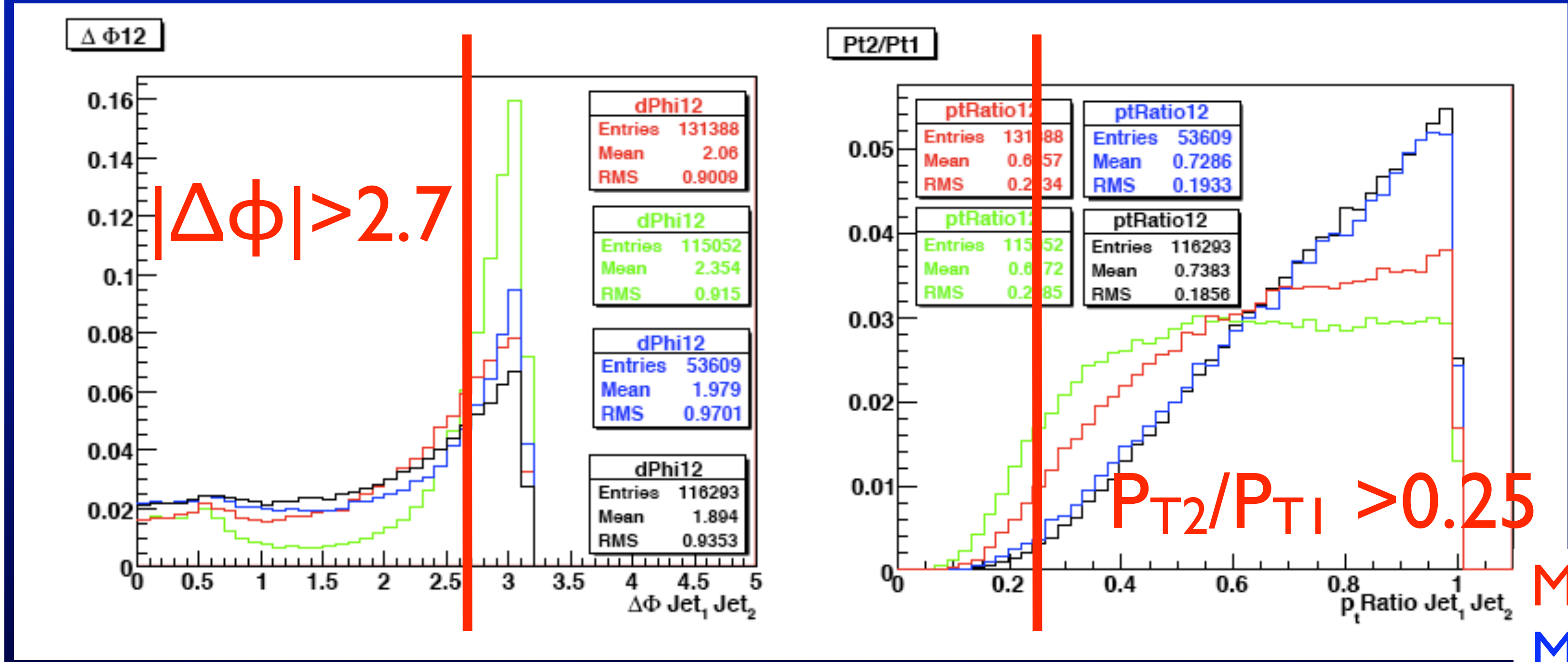
$$\langle \mathbf{N}(\mathbf{N}-\mathbf{1})\rangle = \langle \mathbf{N}\rangle^{\mathbf{2}} \frac{\sigma_{\mathbf{hard}}}{\sigma_{\mathbf{eff}}}$$

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

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

Jets pairing

To count the number of MPI we count the pair of mini-jet
Mini-jet are jet built using as input the charged particles only (tracks) and with a very low P_T threshold



MPI off RAD on
MPI on RAD off
MPI off RAD off
MPI on RAD on

filippo.ambroglini@cern.ch

Jets pairing

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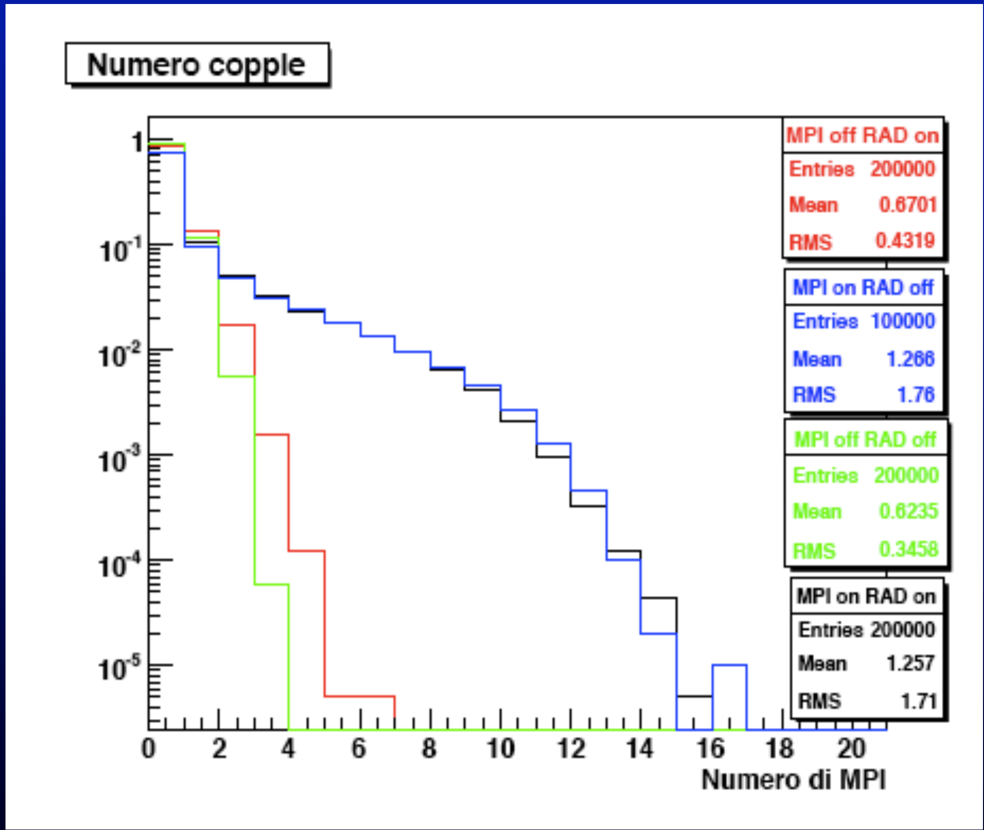
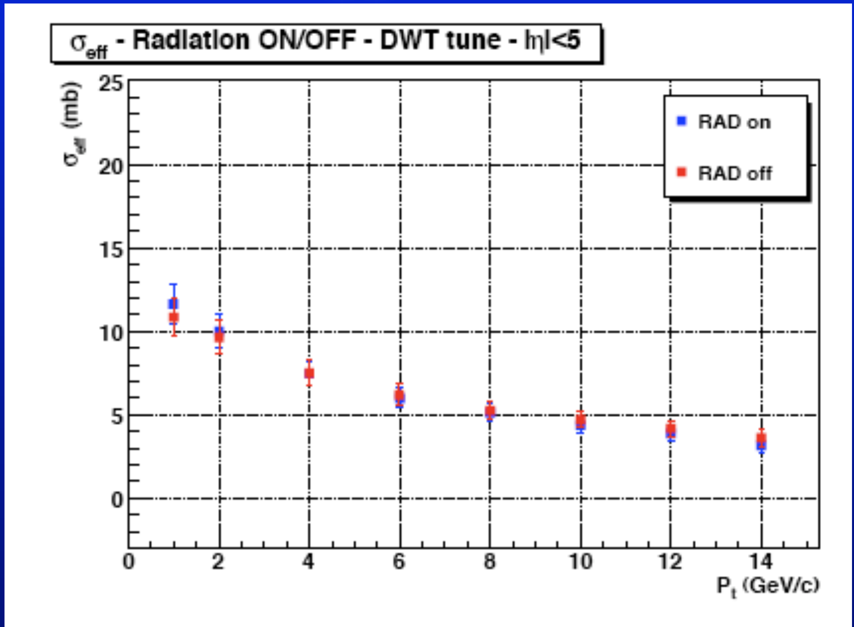
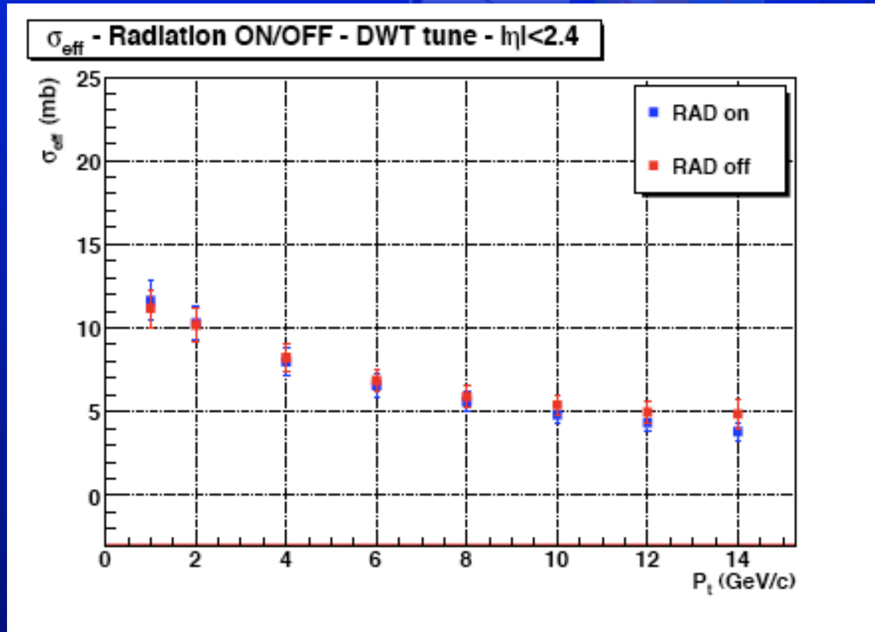


MPI off RAD on
MPI on RAD off
MPI off RAD off
MPI on RAD on

σ_{eff} estimation



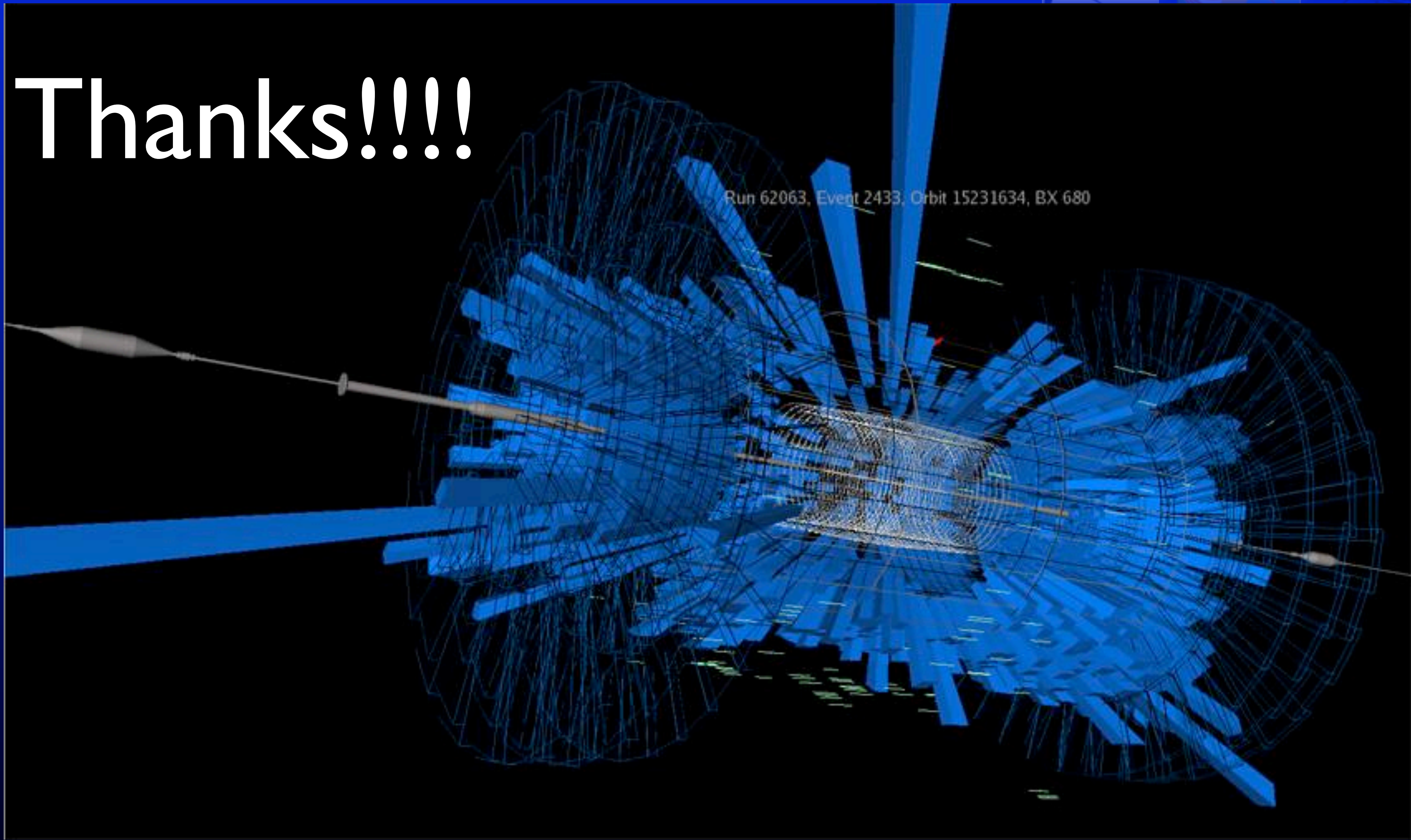


With this analysis the σ_{eff} is not sensitive to the radiation and is also independent from the geometrical acceptance

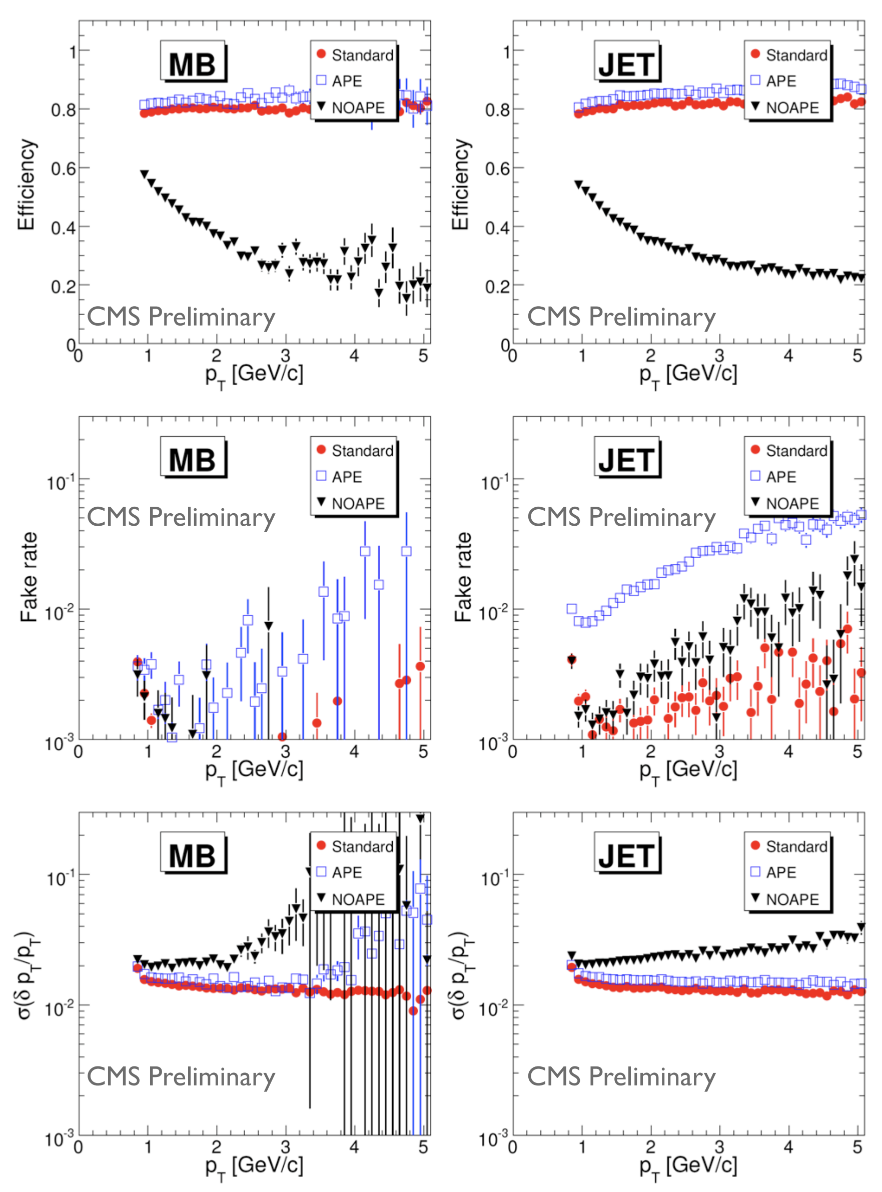
$$\sigma_{DP} \equiv m \frac{\sigma_A \sigma_B}{2\sigma_{eff}}.$$

$\sigma_B /(2\sigma_{eff})$ represent the probability of having B interaction starting from A interaction

Thanks!!!!



Tracker performance



$\int L\,dt = 1\ pb^{-1}$

Ideal aligned detector

Misaligned

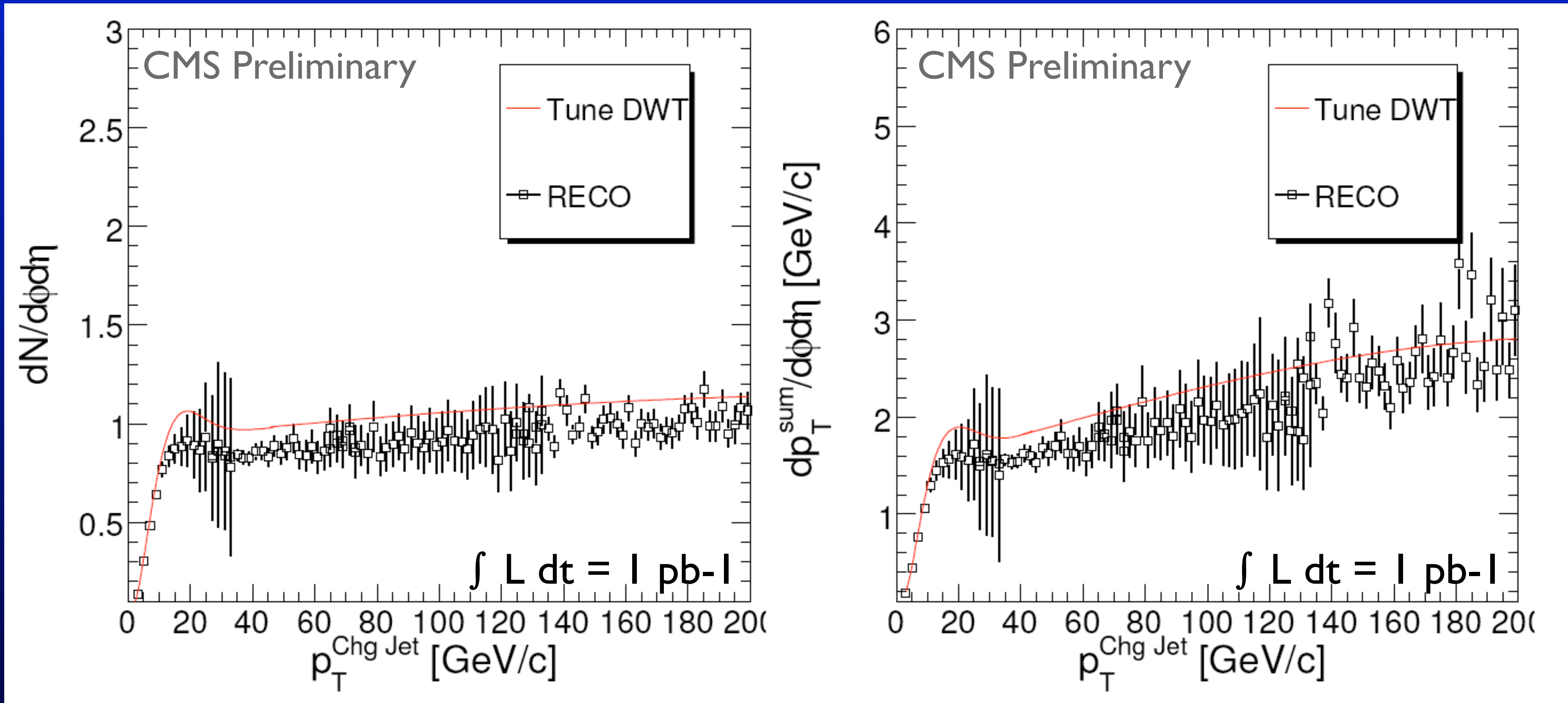
Misaligned + APE (Alignment Position Error)

- Efficiency and fake performances are recovered using APE (additional error to the hit in order to take into account alignment precision)
- Transverse momentum resolution partially recovered
- Higher efficiency with APE is due to the Multiple Scattering (MS) effect recovered by a larger search window

CMS Physics Analysis Summary QCD-07-003

Charged Jet (1pb-1)

Select charged tracks in | η | < 2 with P_T > 0.9 GeV/c



[uncorrected data]

CMS Physics Analysis Summary QCD-07-003

Recovering the tracking at startup assures the possibility to build UE observables from first days of data taking and start building correction functions