Investigation of the underlying event (and multi parton scattering) in pp collisions at the LHC with CMS

How soft QCD can prepare the ground for the interpretation of some rare SM backgrounds

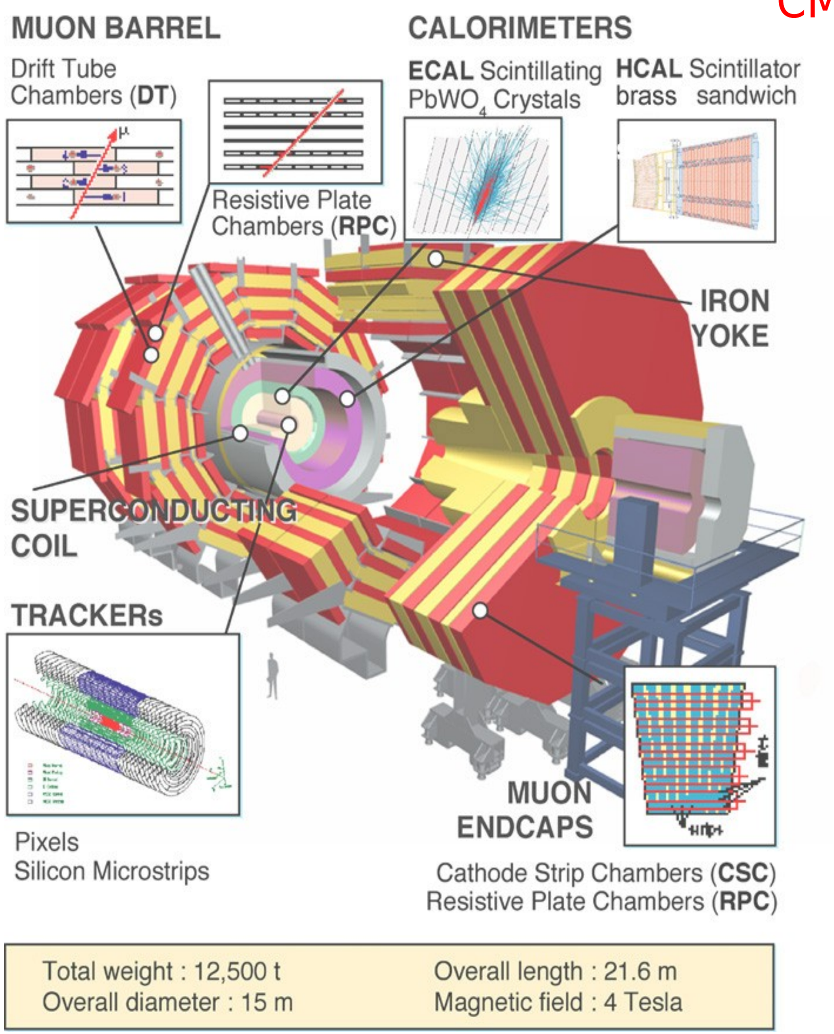
Summer Institute on QCD, Heavy Flavours and Higgs physics

Frascati, June 27th 2012

Paolo Bartalini
(National Taiwan University)

CMS Design features

Detectors



CMS design choice: optimize performance for muon / track momentum resolution (and electromagnetic energy resolution)

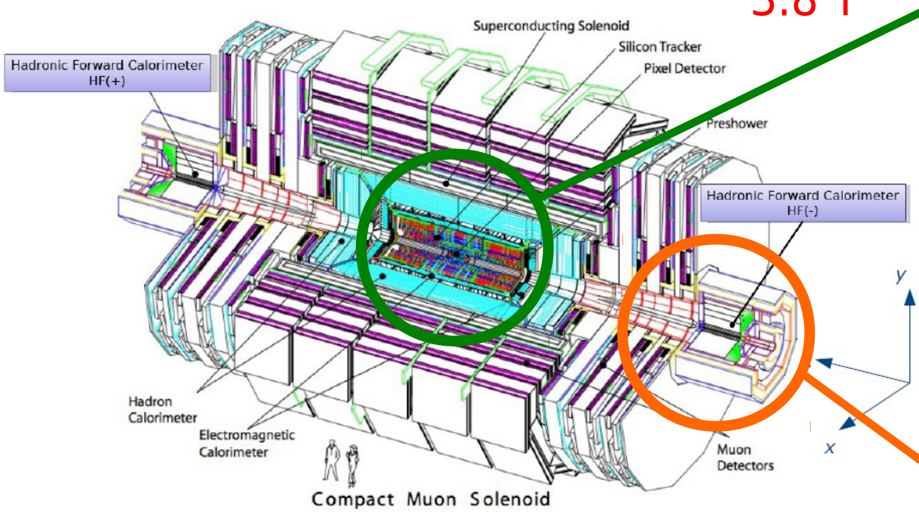
Long 4 Tesla Solenoid containing Tracker, ECAL and HCAL
Tracking up to η ~ 2.4
μ system in return iron
First μ chamber just after Solenoid (max. sagitta)
Big lever arm for PT measurement

Event Rates:	~109 Hz
Event size:	~1 MByte
Level-1 Output	~100kHz
Mass storage	~102Hz
Event Selection:	~1/1013

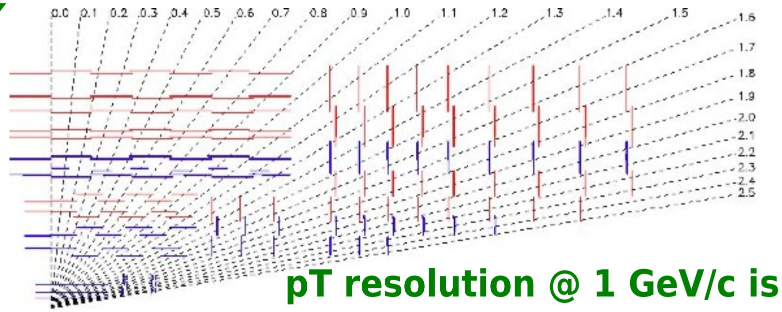
Measuring tracks in CMS

CMS Detector

3.8 T



CMS Tracker



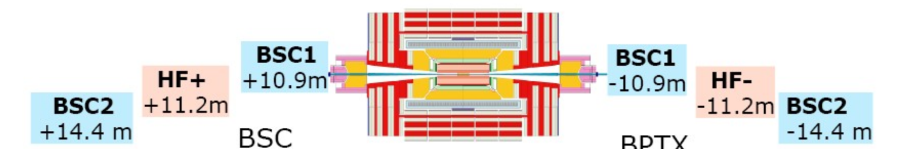
pT resolution @ 1 GeV/c is:
0.7% at *η = 0 and*
2% at $|\eta|$ = 2.5

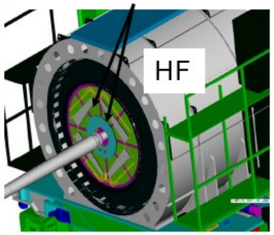
"CMS Tracking Performance Results from early LHC Operation", [Eur. Phys. J. C70 (2010) 1165-1192]

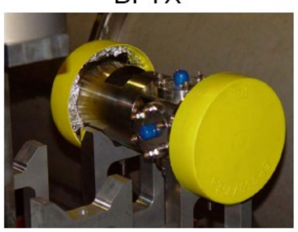
Beam Scintillator Counters (BSC) 96.3% efficiency for MIPs and time resolution of 3 ns.

Beam Pick-up Timing for eXperiments (BPTX) time resolution better than 0.2 ns.

Trigger System







Hadron Forward:

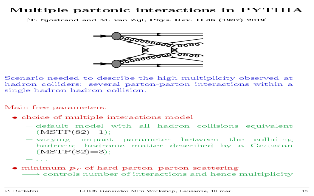
- @11.2m from interaction point
- rapidity coverage: $3 < |\eta| < 5$
- Steel absorbers/ quartz fibers (Long +short fibers)
- 0.175x0.175 η/φ segmentation

pQCD Models

RADIATION, SPECTATORS…
not enough to account for
the observed multiplicities
& pT 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 PT scatterings


Multiple partonic interactions in PYTHIA
[T. Sjöstrand and M. van Zijl, Phys. Rev. D 36 (1987) 2019]

Scenario needed to describe the high multiplicity observed at hadron colliders: several parton-parton interactions within a single hadron-hadron collision.

Main free parameters:
- choice of multiple interactions model
  - default model with all hadron collisions equivalent (MSTP(82)=1);
  - varying impact parameter between the colliding hadrons; hadronic matter described by a Gaussian (MSTP(82)=3);
  - …
- minimum p_T of hard parton–parton scattering
  ⟶ controls number of interactions and hence multiplicity

P. Bartalini LHCb Generator Mini Workshop, Lausanne, 10 mar. 16

Main Parameter: PT cut-off PT0

along the lines of the Pythia **underlying event** formalism:

$$\sigma(\widehat{P_T}) \rightarrow \sigma(\widehat{P_T}) \cdot \frac{(\widehat{P_T})^4}{((\widehat{P_{T0}})^2 + (\widehat{P_T})^2)^2}$$

$$\widehat{P_{T0}}(s) = \widehat{P_{T0}}(s_0) \cdot \left(\frac{s}{s_0}\right)^{\epsilon}$$

$$\epsilon = PARP(90)/2 \approx 0.08$$

B(J/ψ→μμ) dσ / dp (

(dampening)

- Cross Section Regularization for PT→0.
- PT0 can be interpreted as inverse of effective colour screening length.
- Controls the number of interactions hence the Multiplicity: **< Nint > = σparton-parton / σproton proton**

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

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

  x g(x,Q2) ∝ x-λ /2 for x → 0

PT0s' = PT0s (√s' / √s)ε

Pythia Tunes in CMS

PRE-LHC

- Pythia 6 Virtuality ordered showers, old MPIs
- **CTEQ5L** pre-LHC Tune **DW(T)**
- **CTEQ6LL** pre-LHC Tune **D6(T)**
  - **[arXiv:1003.4220]**
- Describe UE and other very important observables at Tevatron like pT(heavy bosons) and Jet azimuthal decorrelation
- Pythia 6 new MPIs with interleaved pT-ordered showers **(MORE RADIATION, LESS MPIs)**
- **CTEQ5L** LHC Tune **Z1** uses Professor AMBT1 LEP fragm. & ATLAS Min Bias: **Updated Color Rec.**
- **CTEQ6LL** LHC Tune **Z2** **inherits MPI parameters from Z1 → retuned in Z2***
  - **[arXiv:1012.5104, arXiv:1010.3558v1]**

POST-LHC

- Pythia 8, brand new MPI model, inteleaved pT-ordered showers
- **CTEQ6LL** Tevatron **Tune 2C** describes the relevant Tevatron phenomenology
- **CTEQ6LL** LHC **Tune 4C** describes ATLAS MB & UE (leading track)
  - **[arXiv:1011.1759]**

pT0LHC = pT0Tevatron (√sLHC / √sTevatron)$^{\varepsilon}$

Where ε = PARP(90) or MultipleInteractions:EcmPow

DW, Z1, Z2 → **large ε ≈ 0.24 - 0.30 (CTEQ5L**, **CTEQ6LL** for Z2)

T versions (for example D6T) 2C, 4C, Z2* → **small ε ≈ 0.16 - 0.21 (CTEQ6LL)**

Still no coherent description of Tevatron and LHC

Underlying Event measurements @ CMS

QCD-10-001: "First Measurement of the Underlying Event Activity at the LHC with √s = 0.9 TeV". Eur. Phys. J. C 70 (2010) 555-572.

QCD-10-010: "Measurement of the Underlying Event Activity at the LHC with √s = 7 TeV and Comparison with √s = 0.9 TeV". JHEP 1109, 109 (2011).

QCD-10-021: "Measurement of the Underlying Event Activity with the Jet Area/Median Approach at 7 TeV and comparison to 0.9 TeV". CERN-PH-EP-2012-152, submitted to JHEP.

QCD-11-012: "Measurement of the Underlying Event Activity in the Drell-Yan process in proton-proton collisions at √s = 7 TeV". CERN-PH-EP-2012-085, arXiv:1204.1411v1, submitted to Eur. Phys. J. C.

FWD-10-008: "Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at 7 TeV. ". Eur.Phys.J. C72 (2012) 1839.

FWD-10-011: "Measurement of energy flow at large pseudorapidities in pp collisions at √s = 0.9 and 7 TeV". JHEP 1111 (2011) 148, Erratum-ibid. 1202 (2012) 055.

FWD-11-003: "Study of the Underlying Event at Forward Rapidity in Proton-Proton Collisions at the LHC". CDS Record: 1434458.

"There would not be a vertex in $H \to \gamma\gamma$ events without the Underlying Event…"

Actually UE is interesting per se! Handle on soft MPI.

…

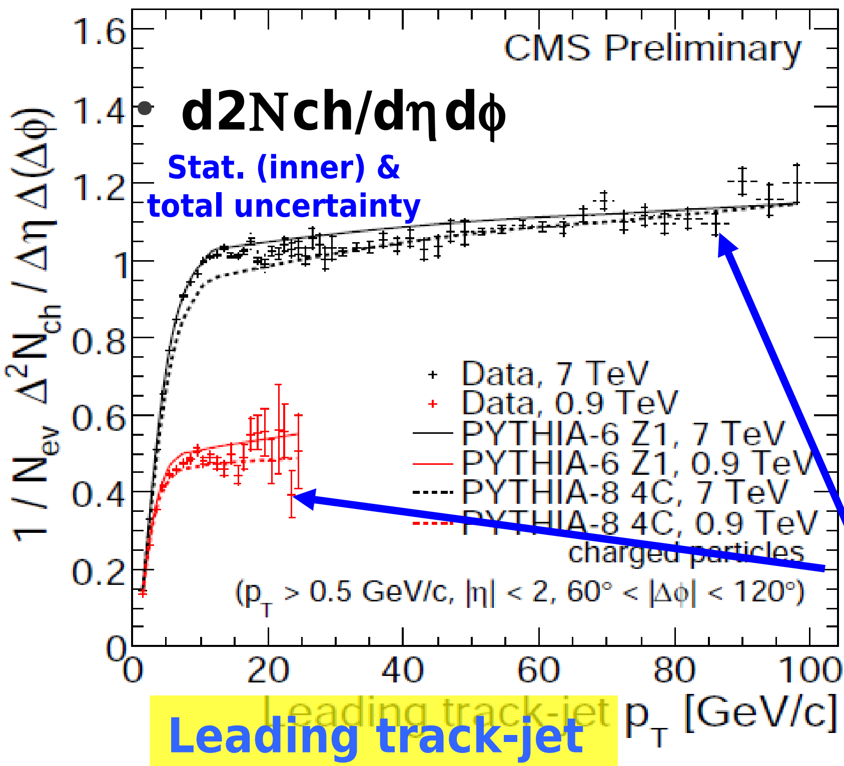
QCD- (or FWD-) XX-YYY: …

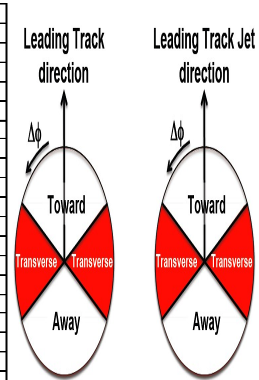
[FWD-XX-YYY]

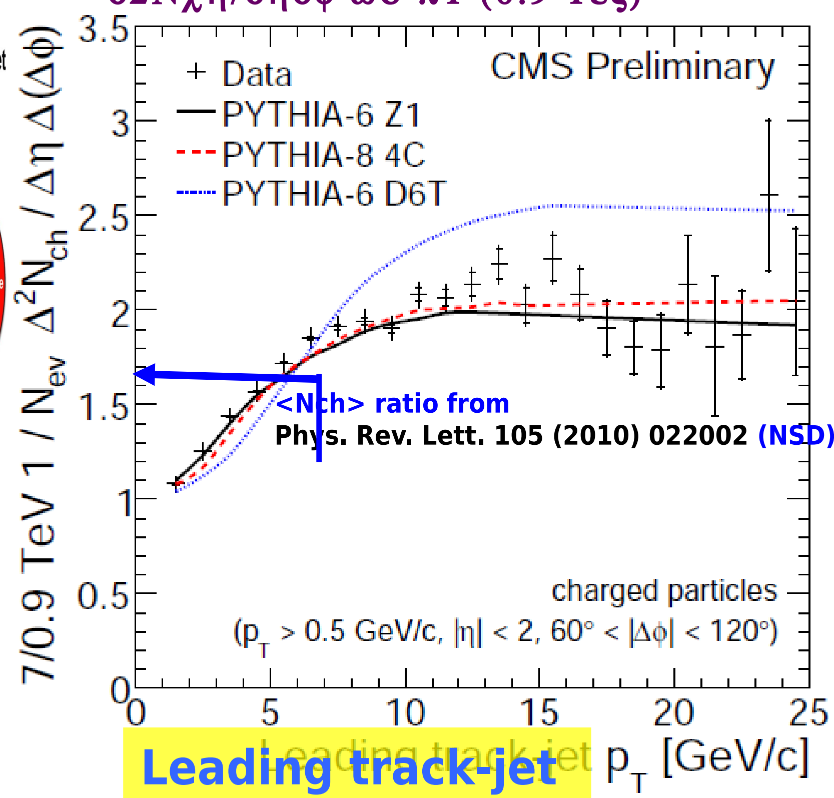
UE in Jets: Densities in the Transverse Region

7 TeV and 0.9 TeV results for the reference charged multiplicity density profiles including Z1 (solid) and 4C (dashed) MC predictions.

- d2Nχη/δηδφ ϖσ πT (7 Τες)
- δ2Nχη/δηδφ ϖσ πT (0.9 Τες)







Fast rise for pT < 8 GeV/c (4 GeV/c), attributed mainly to the **increase of MPI activity**, followed by a **Plateau-like region** with ≈ constant average number of selected particles in a **saturation regime**.

A factor 2 UE increase going from 0.9 TeV to 7 TeV to be compared with 1.66 for MB.

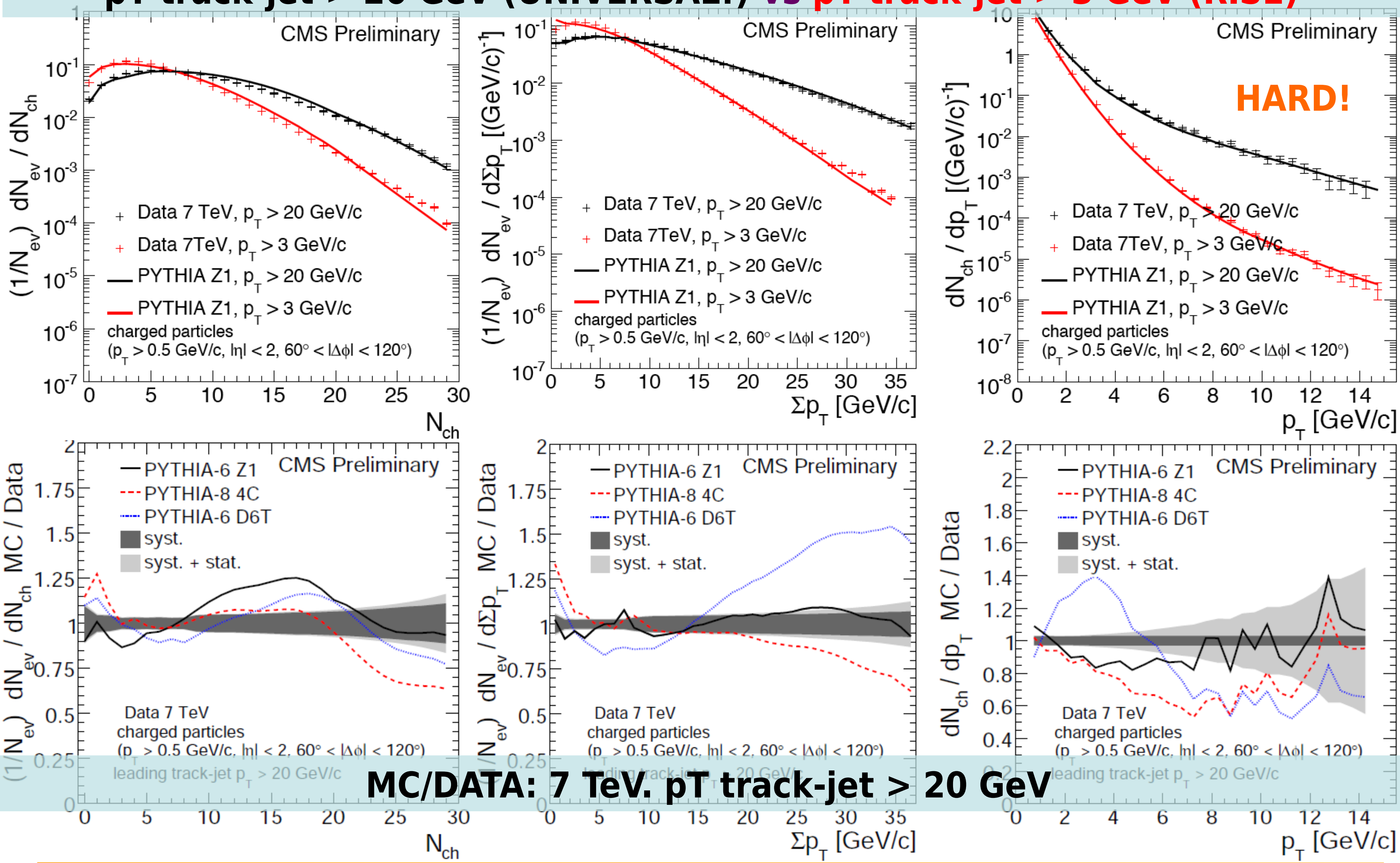
See interpretation of M.Strikman et al. Phys. Rev. **D83 (2011) 054012**

more details in back-up sli

Nota bene: corrected distributions!

UE in Jets: √s = 7 TeV. Nch, Σ(pT) and pT in Transverse Region

pT track-jet > 20 GeV (UNIVERSAL!) vs pT track-jet > 3 GeV (RISE)

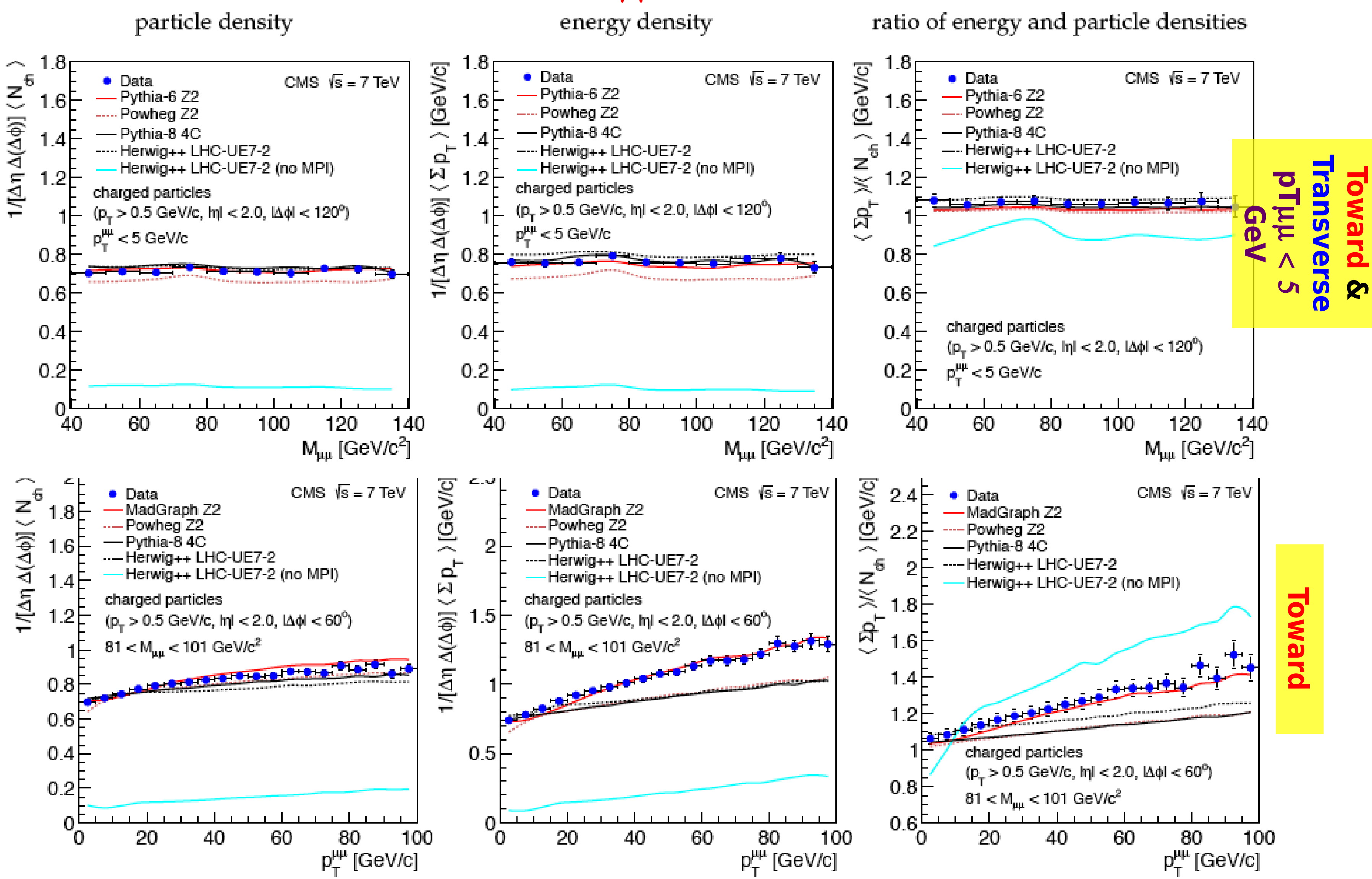


MC/DATA: 7 TeV. pT track-jet > 20 GeV

[QCD-10-001, QCD-10-010]

UE activity in Drell-Yan events (μμ)

81 GeV < Mμμ < 101 GeV



[QCD-11-012]

UE activity in Drell-Yan events (μμ)

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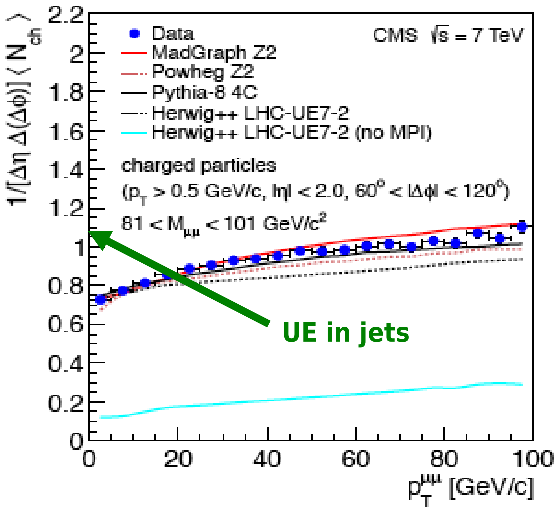
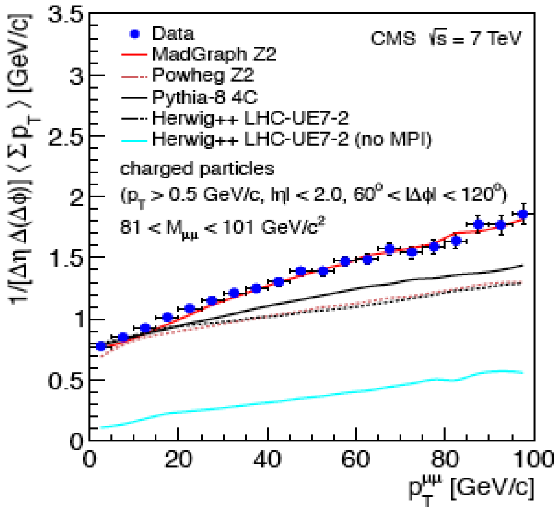
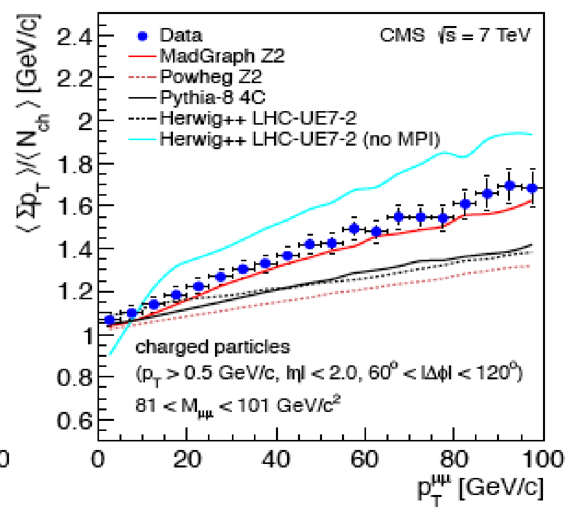


particle density



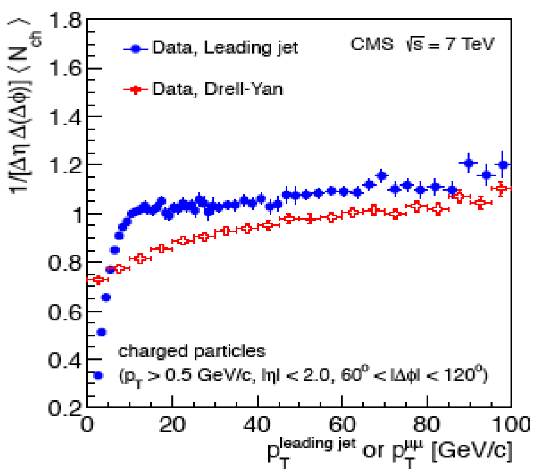
energy density



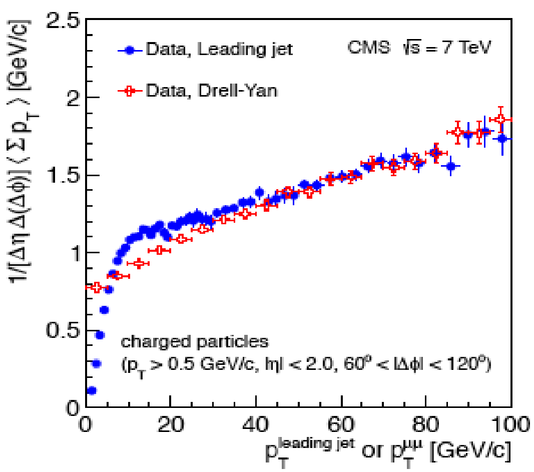
ratio of energy and particle densities

Transverse

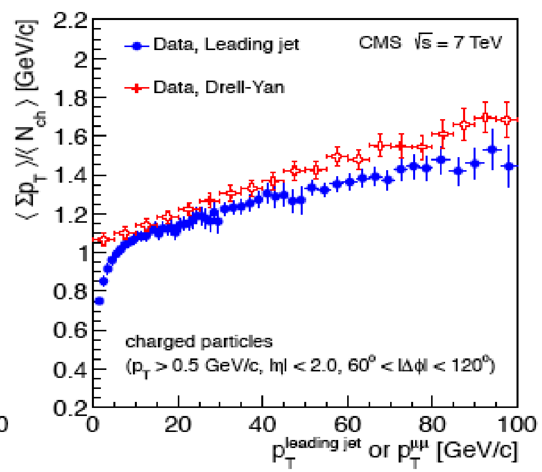
particle density



energy density



ratio of energy and particle densities



Transverse

[QCD-11-012]

MPI vs Generalized Parton Distributions

"Transverse nucleon structure and diagnostics of hard parton-parton processes at LHC".
[M.Strikman @ Northwest Terascale w/s and **Phys. Rev. D83 (2011) 054012**]

Gluon transverse size decreases with increase of x

$<\rho 2>$g from analysis of GPDs from J/ψ photo production

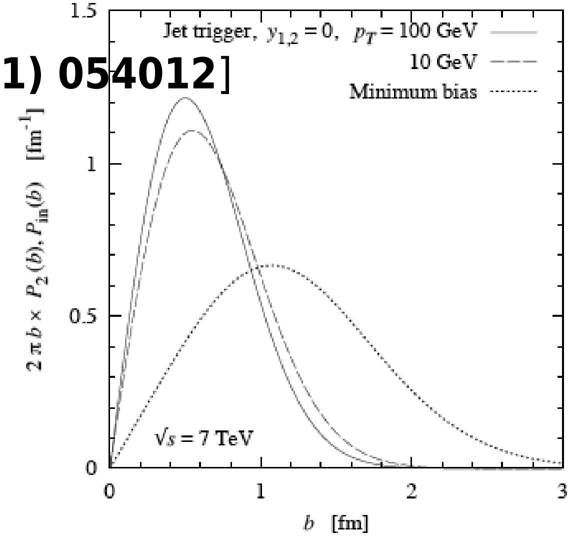
Transverse size of large x partons is mu
smaller than the transverse range of soft strong interactions

$$\langle \rho^2 \rangle_g = \frac{\partial}{\partial t} \frac{G(x.t)}{G(x,0)}$$

$$\langle \rho^2 (x > 10^{-2} \rangle \ll R^2_{soft}$$

⇓

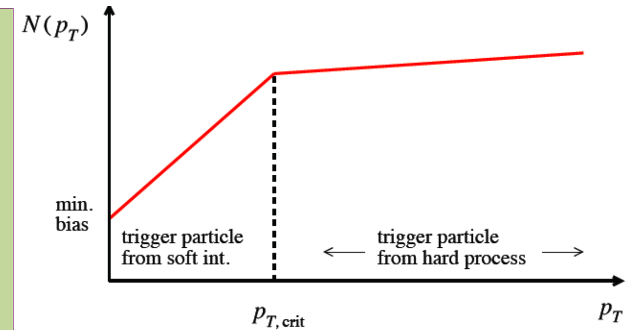
Two scale picture



Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2}$ = 0, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).

Also explains general features of UE @ hadron colliders

$<\rho 2>$g $<$ $<\rho 2>$q explains
UE in DY $<$ UE in Jets



A new approach to UE: Jet Area/Median

Based on the paper: "On the characterization of the underlying event"; JHEP04(2010)065; M. Cacciari, G. Salam, S. Sapeta.

The underlying event activity is given by ρ=median{pT/A}. (less sensitive to outliers!)

To estimate the jet area η–ϕ cells are filled by ghost deposits of O(10-100 GeV).

- FastJet [arXiv:hep-ph/0512210] essential to speed up the calculation.
- 0.9 TeV: ghost jets dominate the median!!!
- CMS Adjusted observable for low occupancy:

kT jets

$$\rho' = \underset{j \in physical\ jets}{median}\left[\left\{\frac{p_{T,j}}{A_j}\right\}\right] * C$$

$$C = \frac{\Sigma_j A_j}{A_{tot}}$$

Tracks: pT > 0.3 GeV

|η| < 2.3

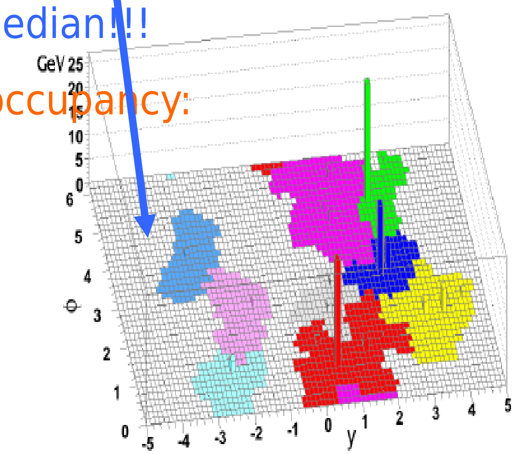
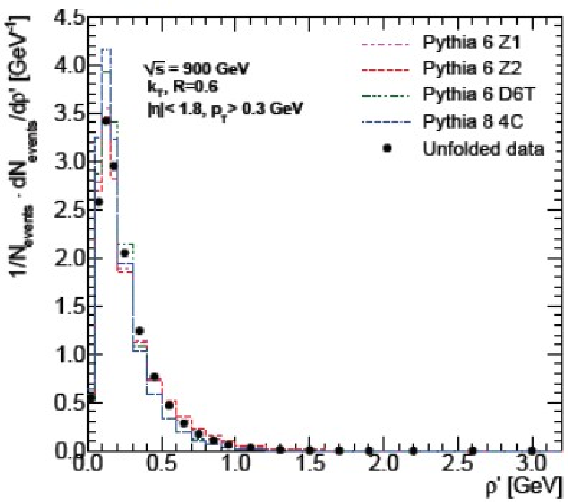
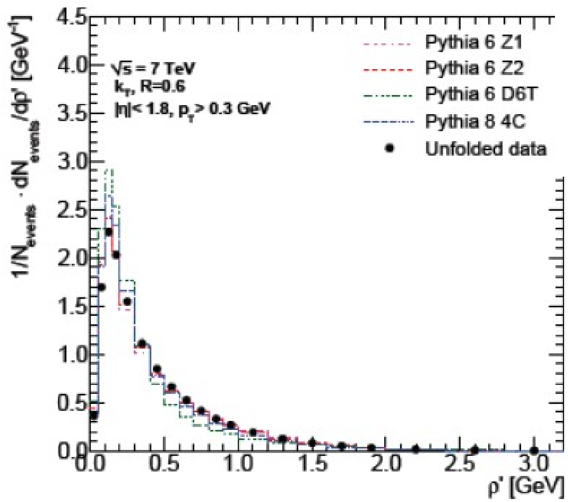


Figure 4: Active area for the same event as in figure 3, once again clustered with the k_t algorithm and $R = 1$. Only the areas of the hard jets have been shaded — the pure 'ghost' jets are not shown.





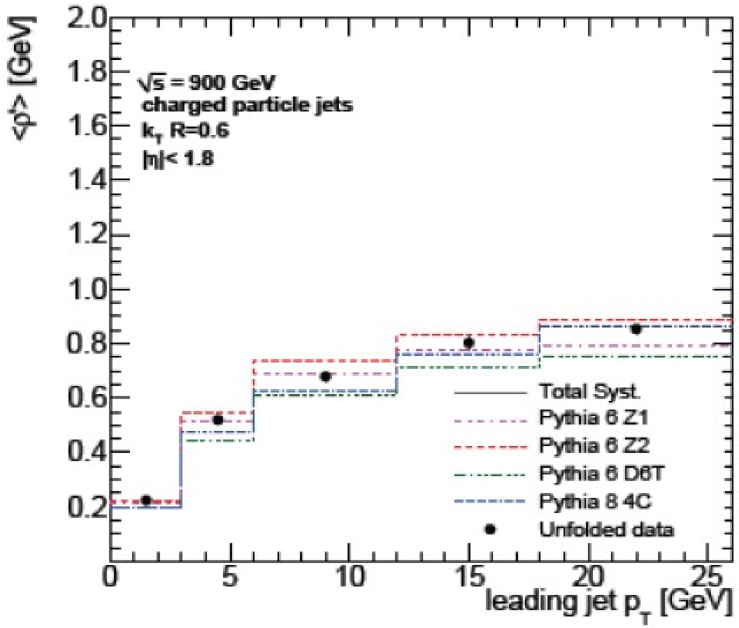
Clear sensitivity to the differences between the Models / Tunes

[QCD-10-021]

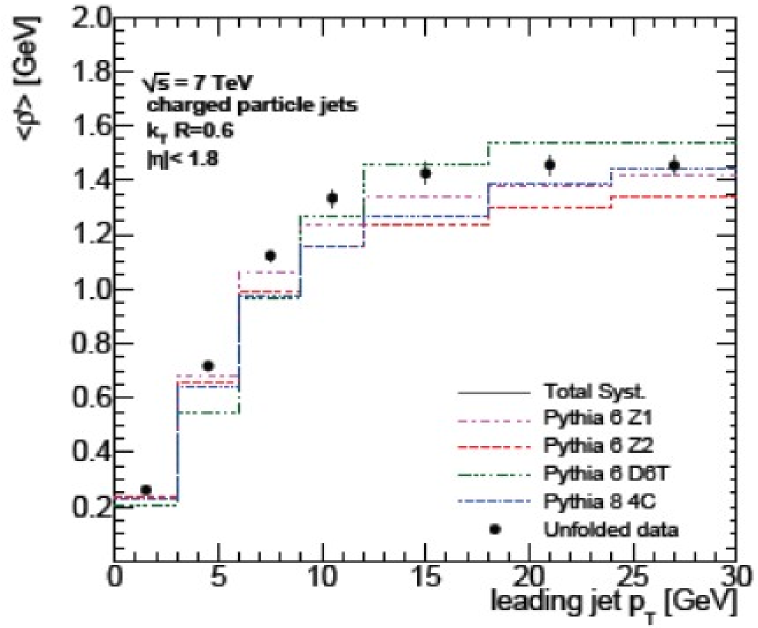
A new approach to UE: Jet Area/Median

The energy evolution of the new Underlying Event observables shows similar qualitative features with respect to the traditional approaches used to quote the UE activity (i.e. charged multiplicity and charged transverse momentum densities).

√s = 0.9 TeV



√s = 7 TeV



[QCD-10-021]

Energy flow in the forward region

- Measurement relies on the energy flow in the Hadron Forward Calorimeter ($3.15 < \eta < 4.9$) in the presence of events “triggered” by a more central activity (M

Test of central-forward correlations

- Corrected data

  - Distributions studied:

$$E_{FLOW}(dijet) = \frac{1}{N_{dijet}} \frac{\Delta E}{\Delta \eta}(dijet)$$

$$E_{FLOW}(minbias) = \frac{1}{N_{minbias}} \frac{\Delta E}{\Delta \eta}(minbias)$$

- Two different √s included: 0.9 and 7 TeV

Definition of di-Jet samples: $|\eta| < 2.5, |\Delta\varphi_{jet1,jet2} - \pi| < 1$

  - pT Calo Jet > 8 GeV at 0.9 TeV
  - pT Calo Jet >20 GeV at 7 TeV

MB event selection: At least one charged particle in both the forward and the backward regions. (Single Diffractives events suppressed)

[FWD-10-011]

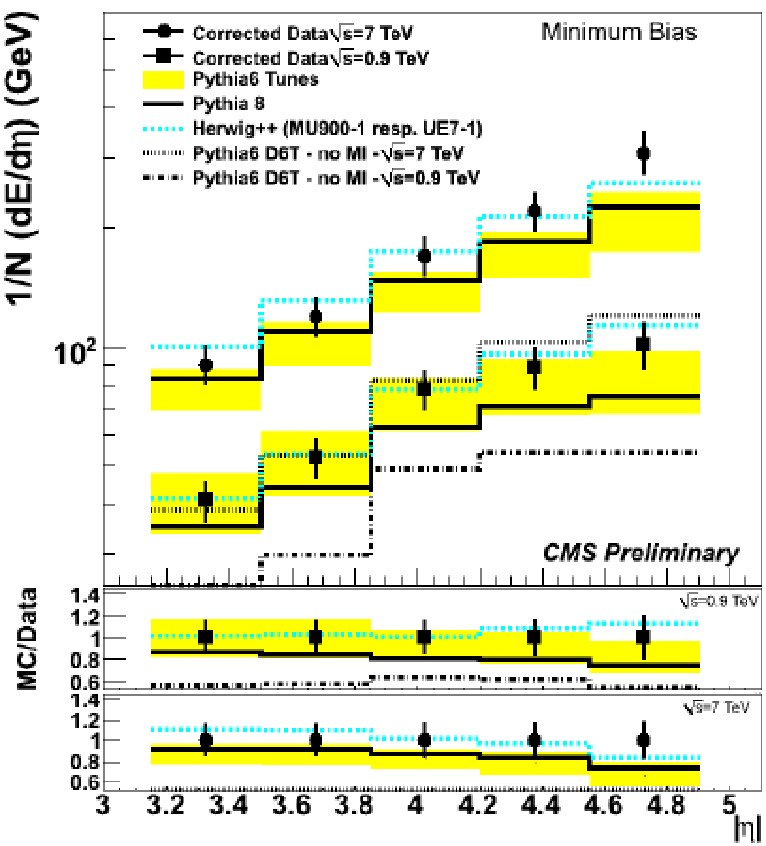
Energy flow in the forward region

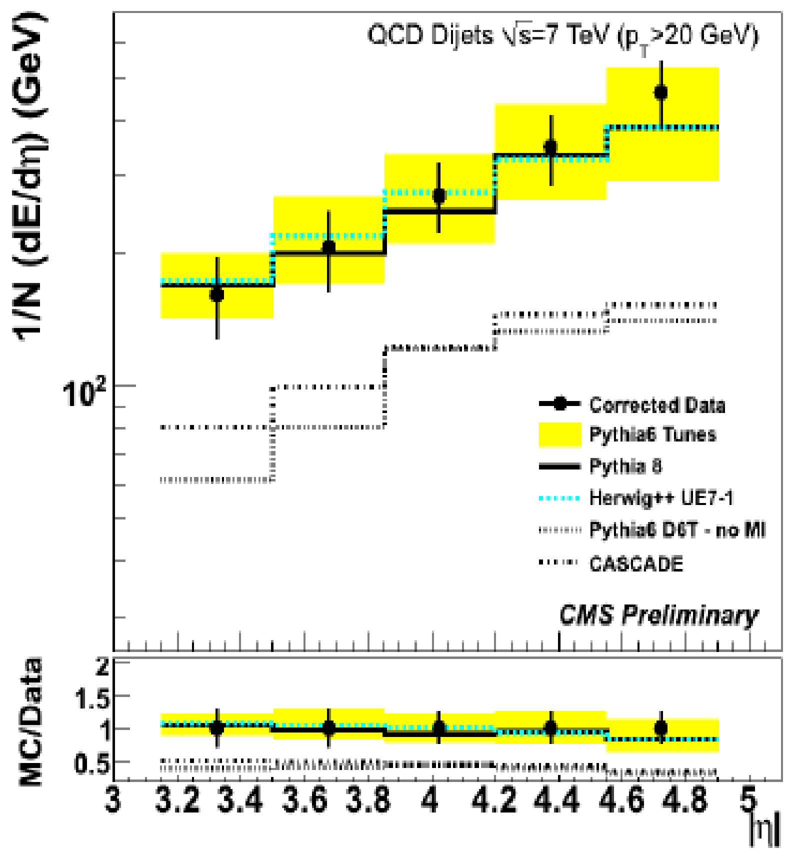
Energy flow increases with the scale (MB vs di-jet) & √s:

- Effect attributed mainly to MPI.

Pattern very similar with respect to the traditional UE measurement from both a quantitative and a qualitative point of view.

Energy flow also increases with η (close to beam remnant)





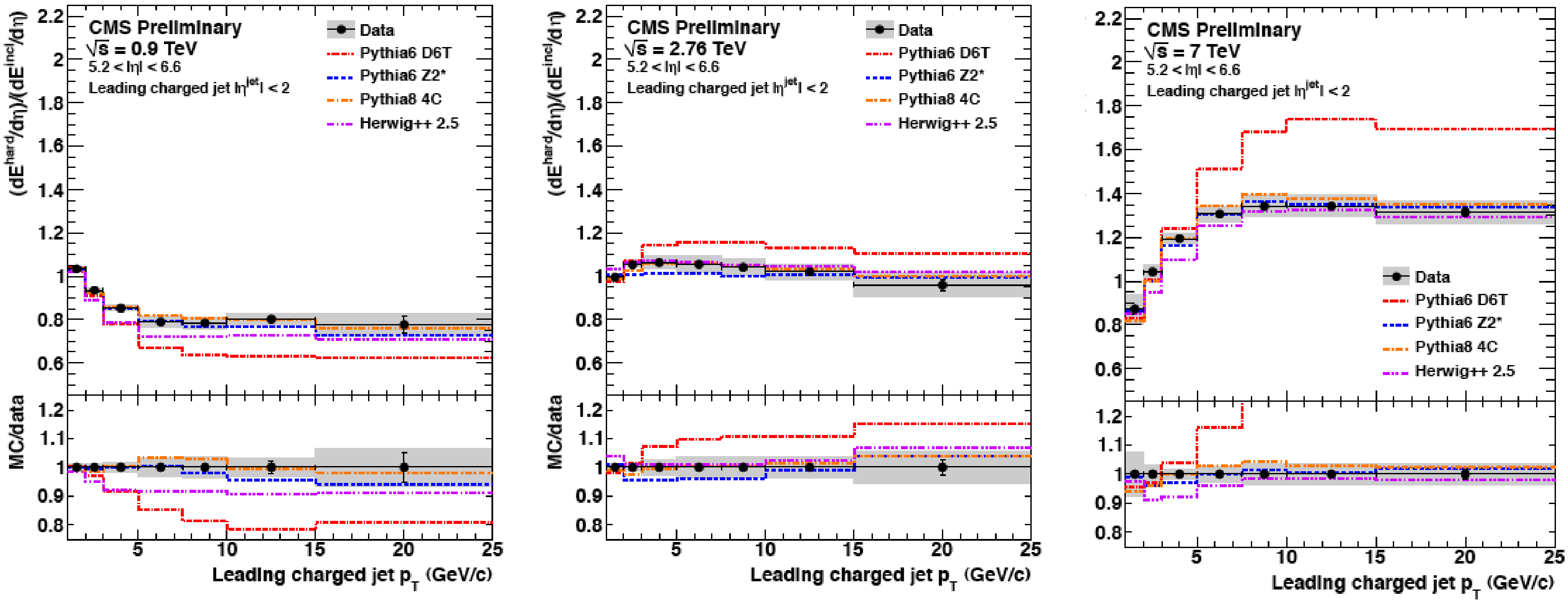
Cascade Kt-factorization based MC, no MPI.

Compared to the traditional UE measurements, we draw slightly different conclusions for what concerns the agreement of the MC models & tunes

[FWD-10-011]

Energy flow in the VERY forward region

$\sqrt{s}$ = 0.9 TeV **$\sqrt{s}$ = 2.76 TeV** **$\sqrt{s}$ = 7 TeV**



Energy deposited in CASTOR (5.2 < |η| < *6.6) for events* with a charged particle jet in the central pseudorapidity region |ηjet| < *2, as a* function of charged particle jet transverse momentum pT *(normalized to the average energy in inclusive events)*

- pT evolution of observable changes trend with √s (decreasing at low √s, increasing at high √s)
- Post LHC models adopting pT-ordered showers are favored by data (agreement within 5-10%)
- Good agreement also for ***EPOS 1.99, QGSJET01, QGSJETII-03, SIBYLL 2.1*** (within 20%)

Underlying Event measurements @ CMS

Jets: Traditional UE study in the central pseudorapidity region relying on tracks

Increase of the activities with the scale of the interactions and with √s corroborates MPIs, which saturate at a modest energy scale.

- **UE in di-jet events is ≈ universal.**

Jets: First measurement of the UE with Jet Area/Median approach.

Original methodology developed to handle events with low particle multiplicity.

MB/Jets: energy flow studies on the forward and very forward regions relying on the Hadron Forward and on the CASTOR calorimeters.

Enhanced sensitiveness to the beam remnant component of the UE.

Challenging test of pp general purpose and cosmic rays MC models. Good performances of pT-ordered showers.

Drell-Yan: first measurement of the Underlying Event at the LHC with √s = 7 TeV.

MPI saturated. Radiative increases of UE activity with pT di-lepton. Constant vs Mdi-lepton. Min activity around 80% with respect to the plateau in jet events.

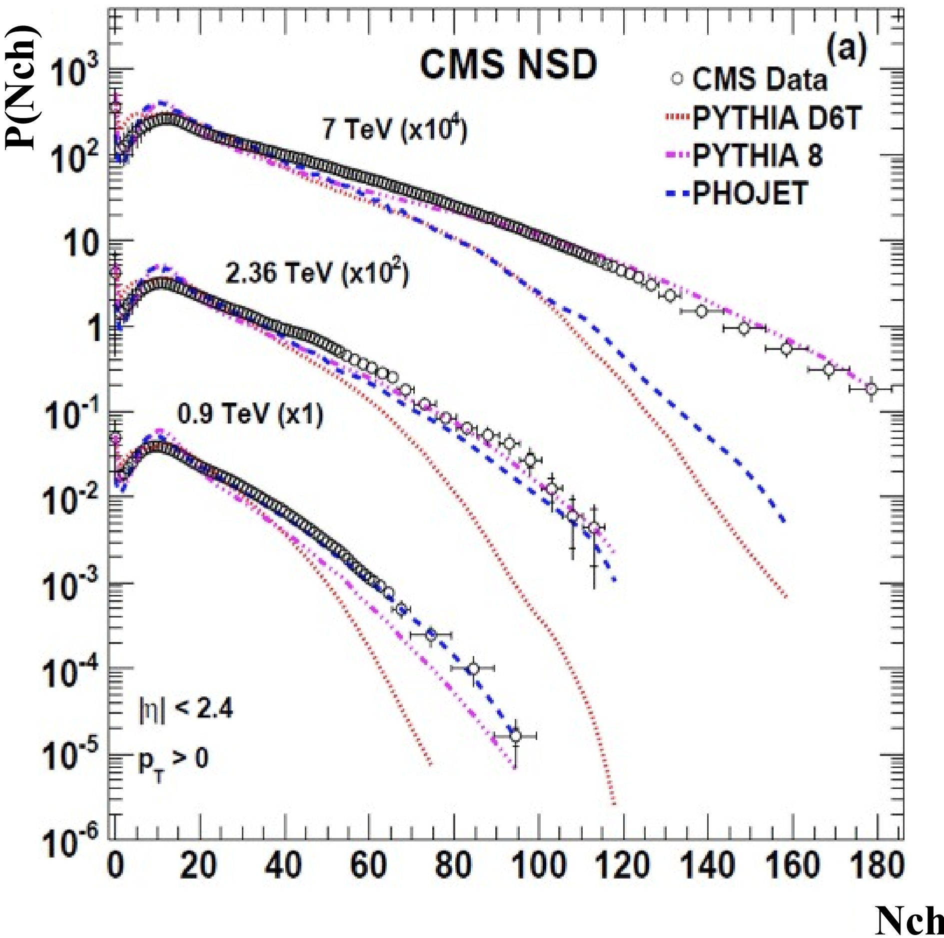
UE in Drell-Yan w.r.t. Jet Interpretation in the context of the GPDF.

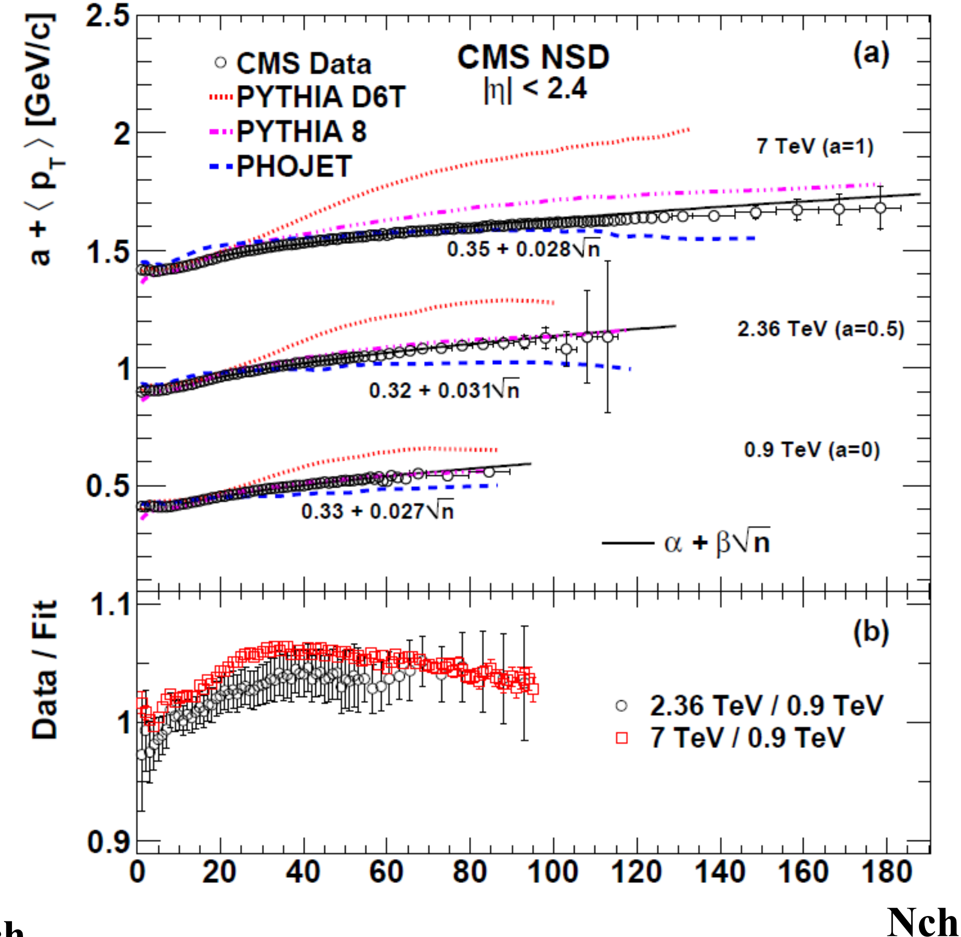
[QCD-10-001, QCD-10-010, QCD-10-005, etc.]

PART II

Multiple Parton Interactions and Multiplicity Highlights

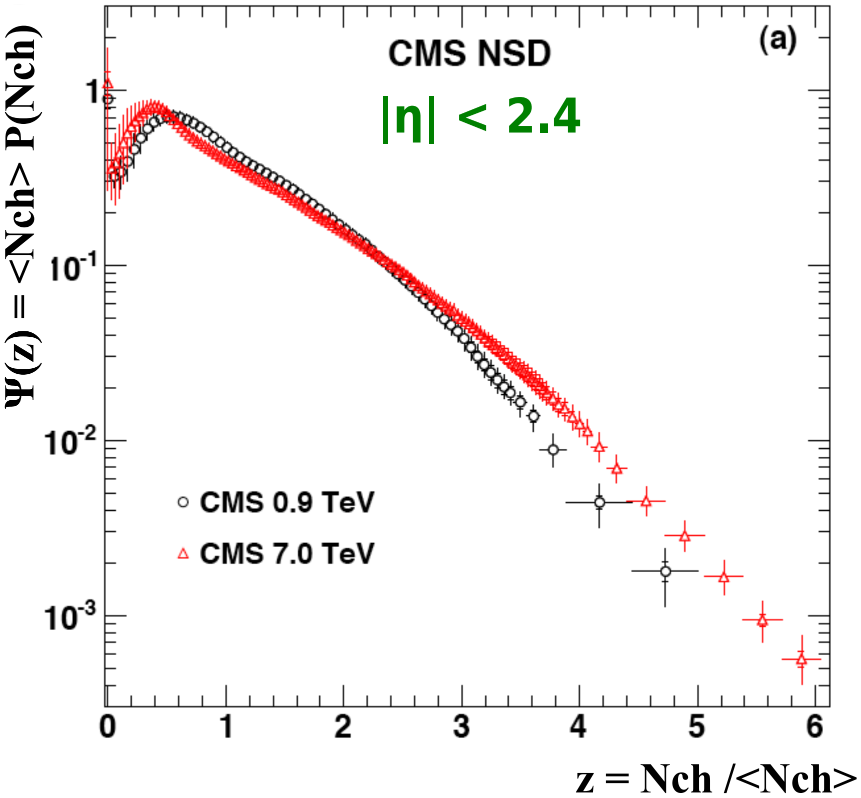
Charged multiplicity Nch

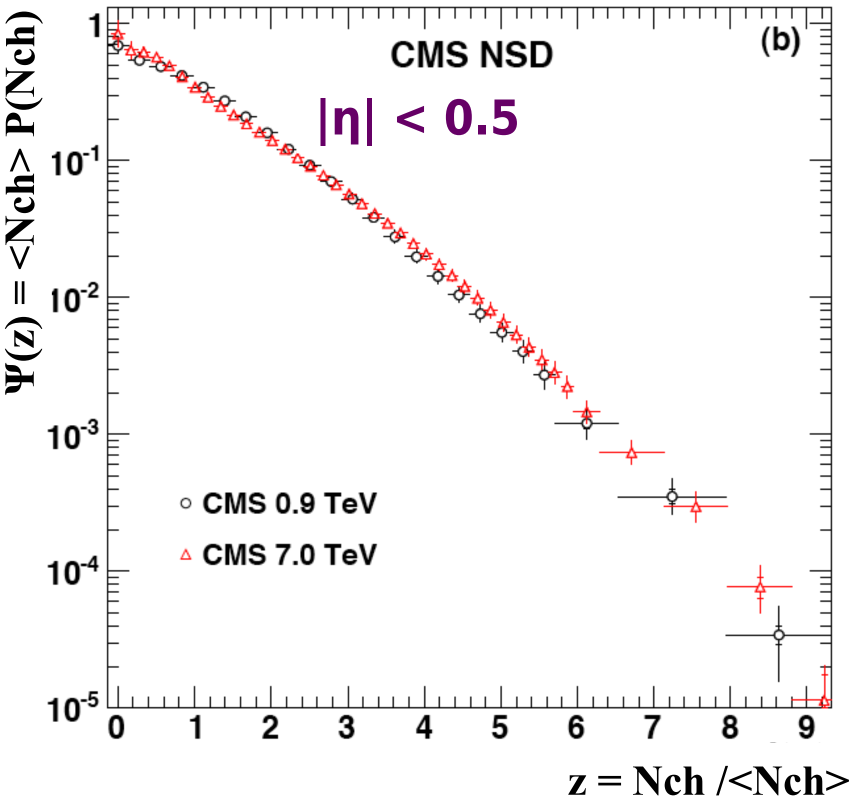




Charged particle multiplicities in Non Single Diffractive (NSD) events.
P(Nch) = probability to produce Nch charged particles.
Large multiplicity tail observed at 7 TeV. **<pT> vs Nch scales with energy.**

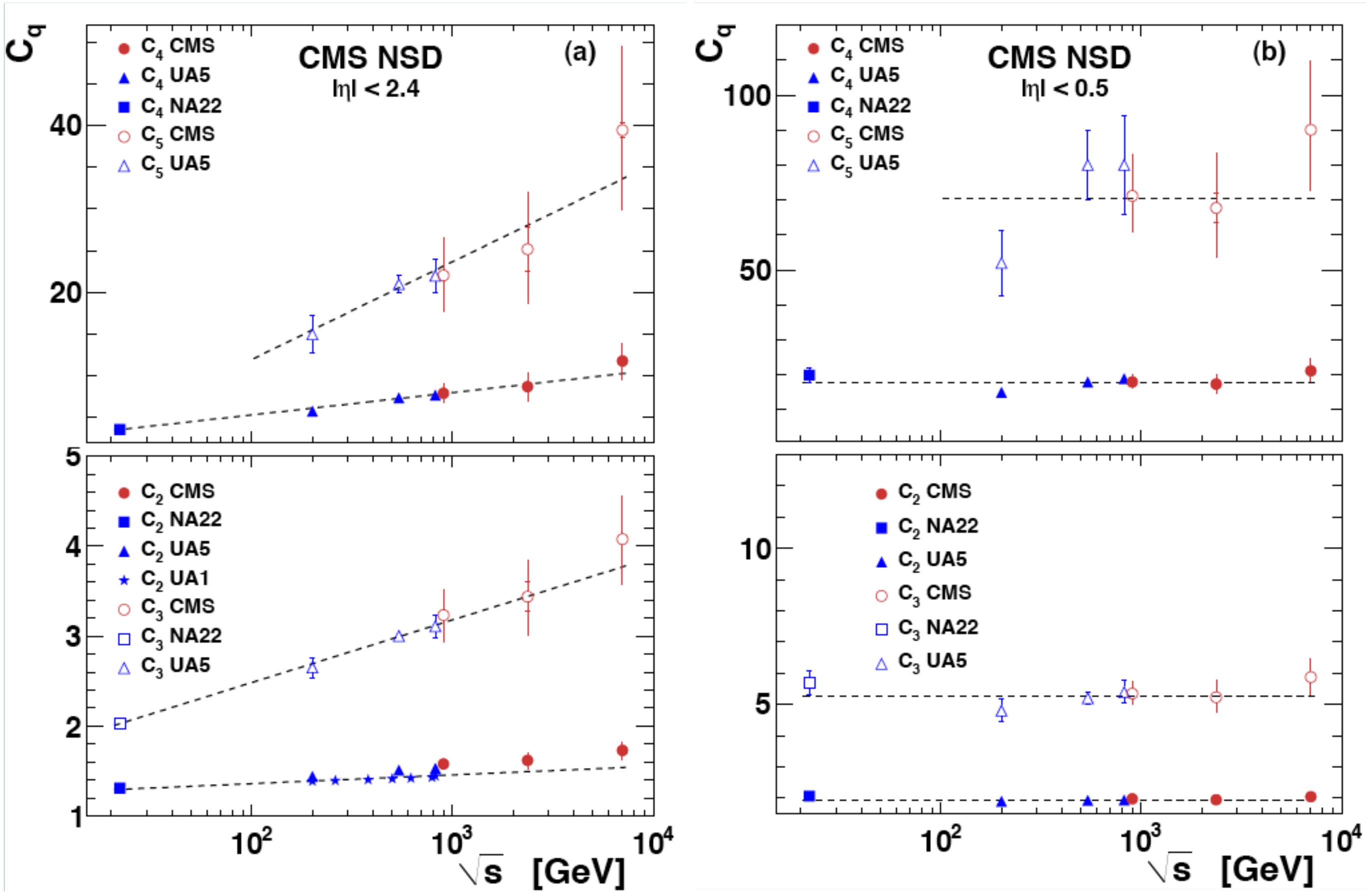
Violation of the KNO scaling





) Scaling [Koba, Nielsen, Olesen, Nucl. Rev. B40 (1972) 371].
ation already reported by UA5 (and comparing ISR, SPS, Tevatron).
S confirms violation for |η|<2.4. Sensitive effect in the tails (large z = Nch /<Nch>
erpretation: connected to the presence of Multiple Parton Interactions.

Normalized order-q moments Cq = <Nch>q/<Nchq>



√s dependence of the normalized moments Cq of the multiplicity distribution for:

(a) |η| < 2.4 and

(b) |η| < 0.5

(a) ln(s) linear fits

(b) constant fits

If KNO scaling holds, also Cq are independent from √s.

Violation sensitive for |η|< 2.4, i.e. large pseudo-rapidity.

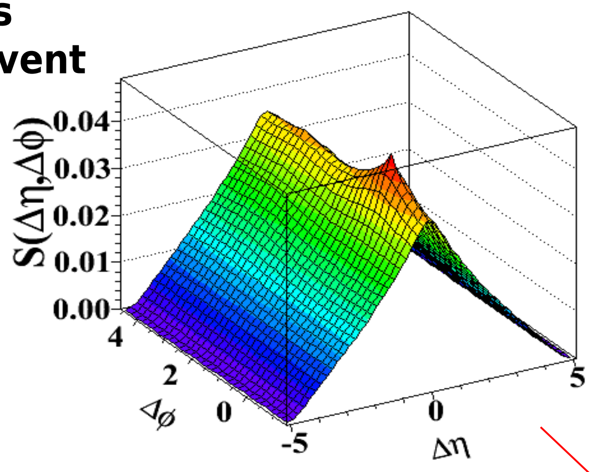
No clear violation for |η|< 0.5 at least up to the order 4.

Definition of di-hadron correlation function

Signal distribution:

$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)} \frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$

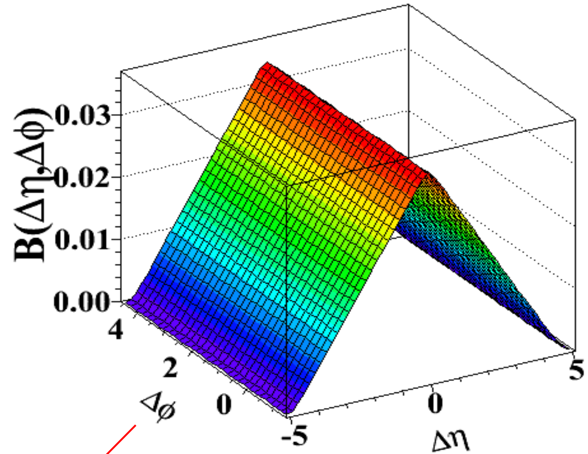
Particle pairs from same event



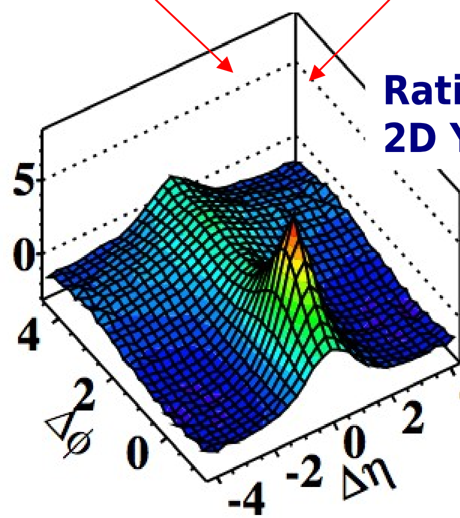
Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2} \frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$

Pairs from mixed events



$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



Ratio Signal/Background = Associated 2D Y

$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_{bins}$$

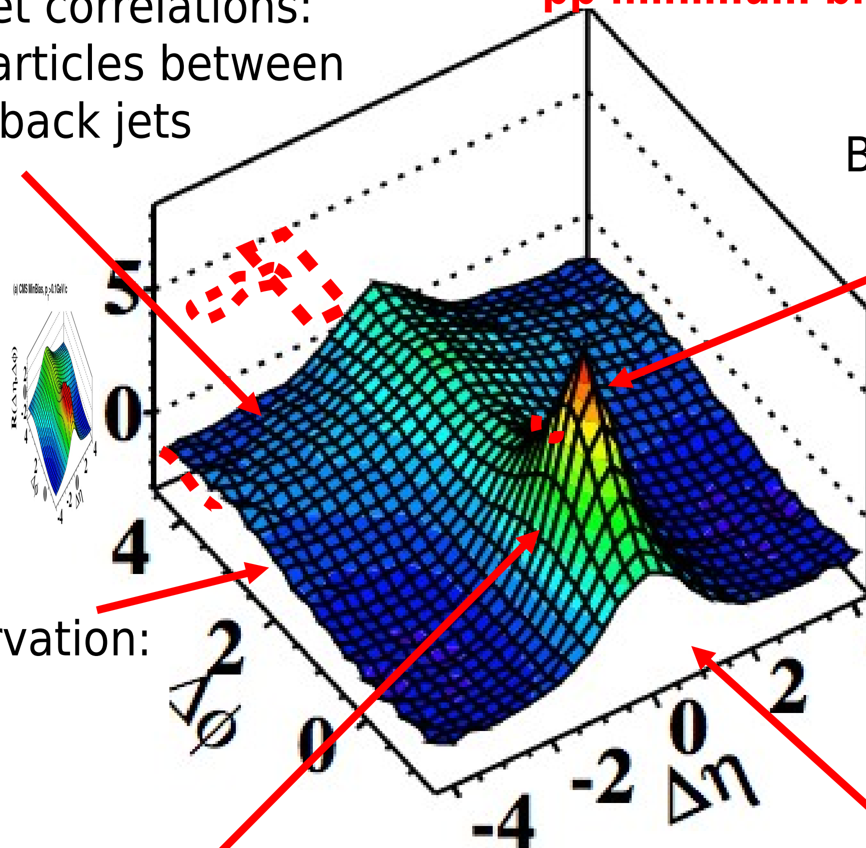
Can specify selected pair of trigger (pTtrig) and associated (pTassoc) particle pT ranges.

Long and short range correlations

pp minimum bias events √s = 7 TeV

"Away-side" jet correlations:
Correlation of particles between
back-to-back jets

Bose-Einstein correlations:
(Δφ,Δη) ~ (0,0)



Momentum conservation:
~ cos(Δφ)

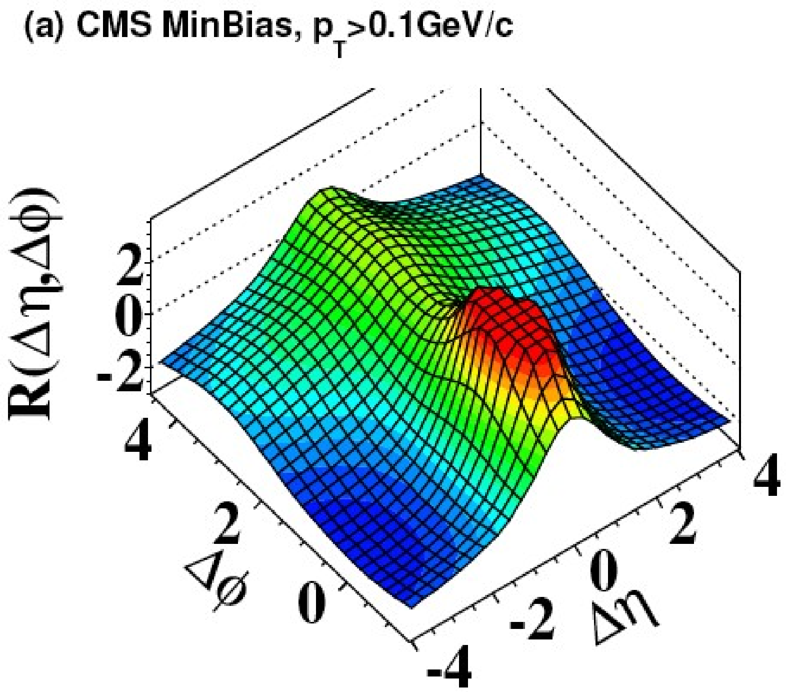
"Near-side", Δφ~ 0 jet peak:
Correlation of particles
within a single jet

Short-range correlations (|Δη| < 2):
Resonances, string or cluster fragmentation

Associated 2D Yields for Particles with PT > 0.1 GeV

pp interactions at 7 TeV

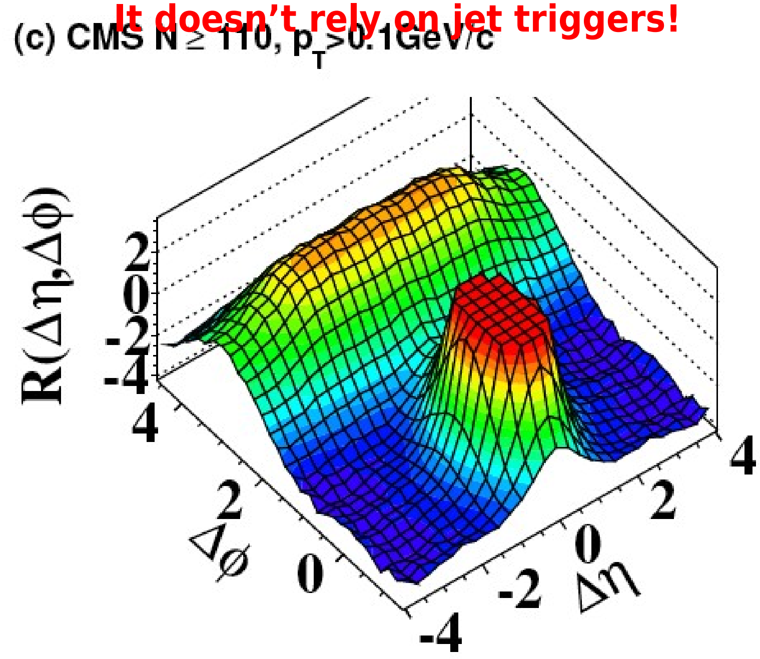
MinBias



High Multiplicity (N>110)

Special trigger developed to collect these rare O(10-5) events.

It doesn't rely on jet triggers!



jet peak is cut for better visibility of the correlations.

peak correlations with away-side – stronger in the high multiplicity events (more jet event

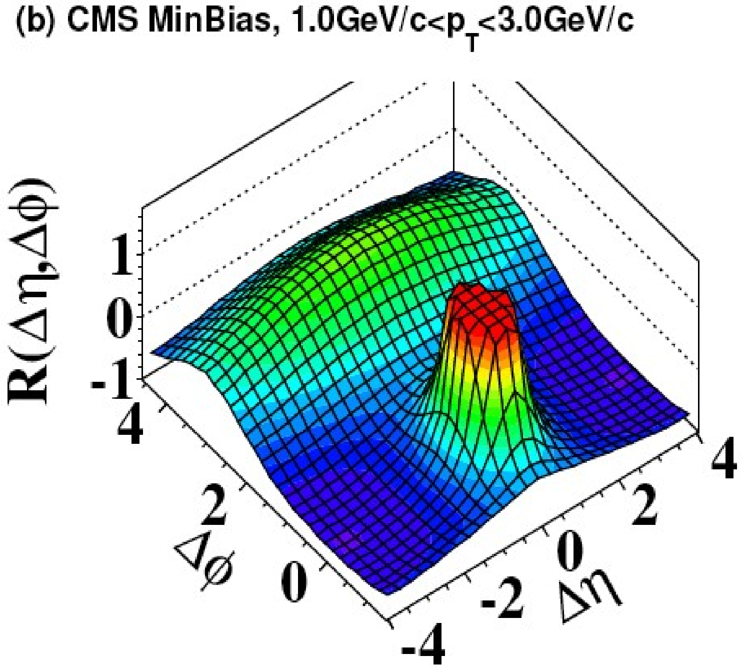
significant "new" structure seen in the high multiplicity events.

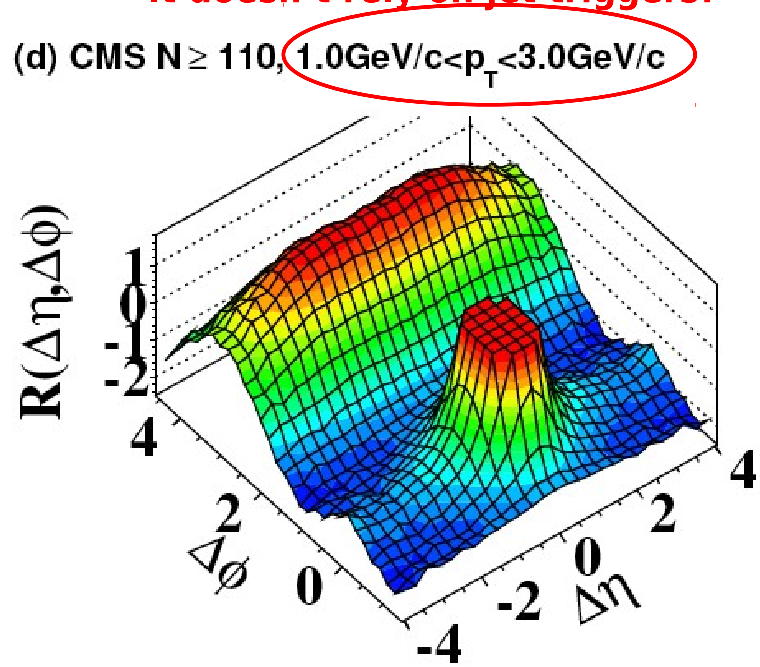
Associated 2D Yields for Particles with 1.0 < PT < 3 GeV

MinBias

High Multiplicity (N>110)

Special trigger developed to collect these rare O(10-5) events.
It doesn't rely on jet triggers!



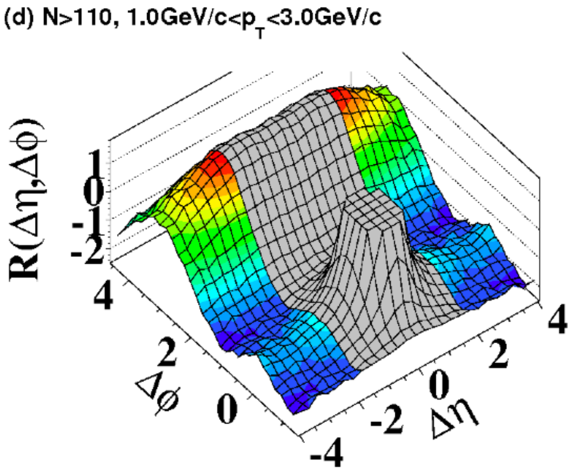


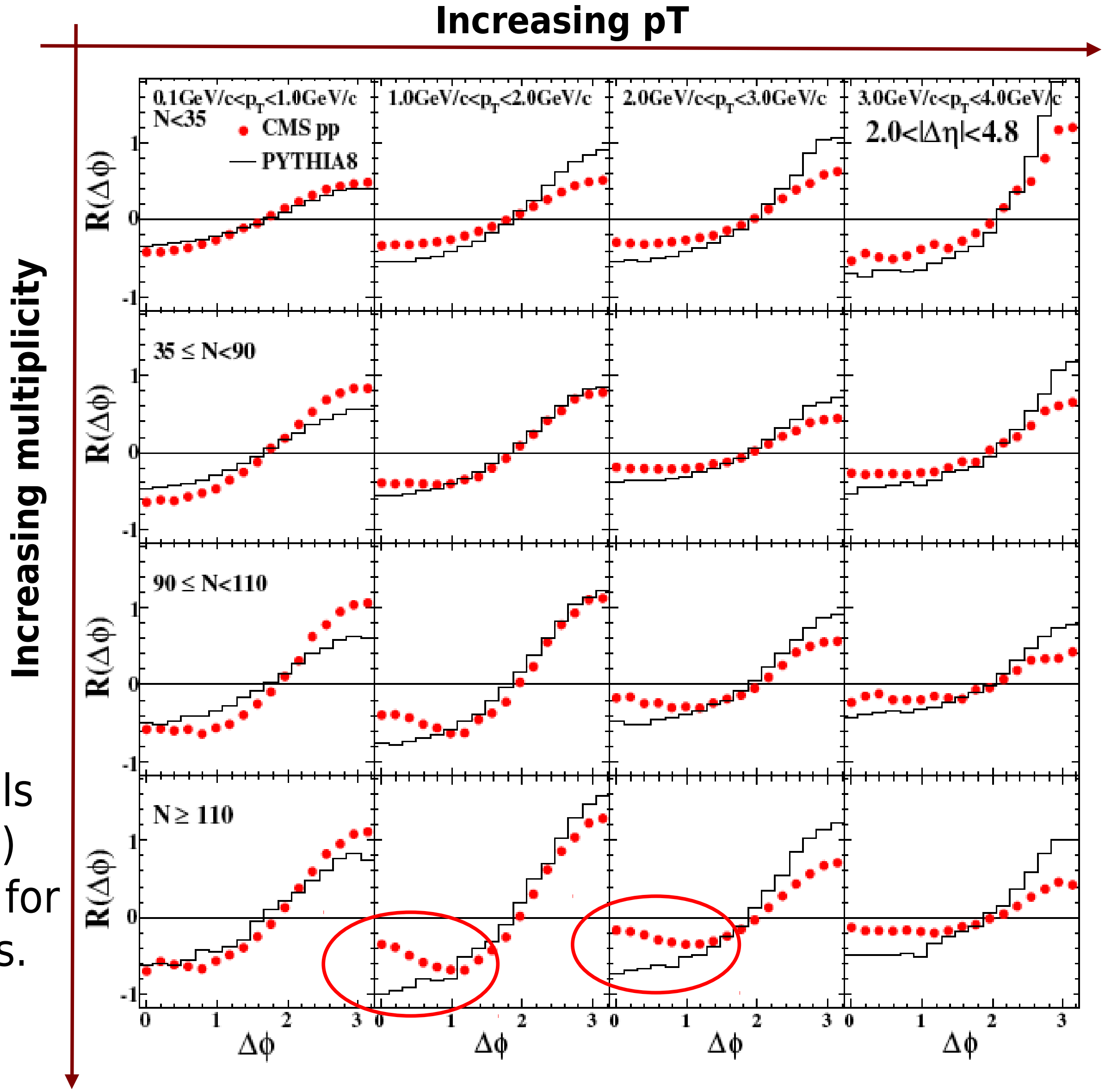
iting pT of particles to 1<pT<3 GeV

- Gives a stronger correlation between the away region and the jet region in both MB and high multiplicity events.
- Gives a pronounced structure at large Δη around ΔΦ=0 in the high multiplicity eve

Associated 1D yields in bins of pT and Nch

Long range:
Project 2 < |Δη| < 4.8 onto Δφ:





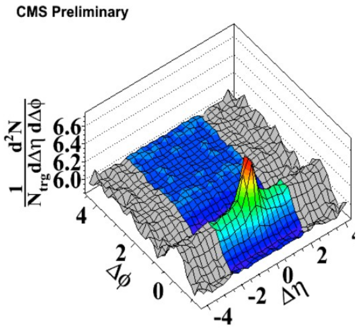
Ridge most pronounced for high multiplicity events and at 1 < pT < 3 GeV.

No ridge seen in tested MC models (Pythia 8, Pythia6, Herwig++, etc.)

Several interpretations proposed for this HI-like effect in pp interactions.

[QCD-10-002, HIN-11-006]

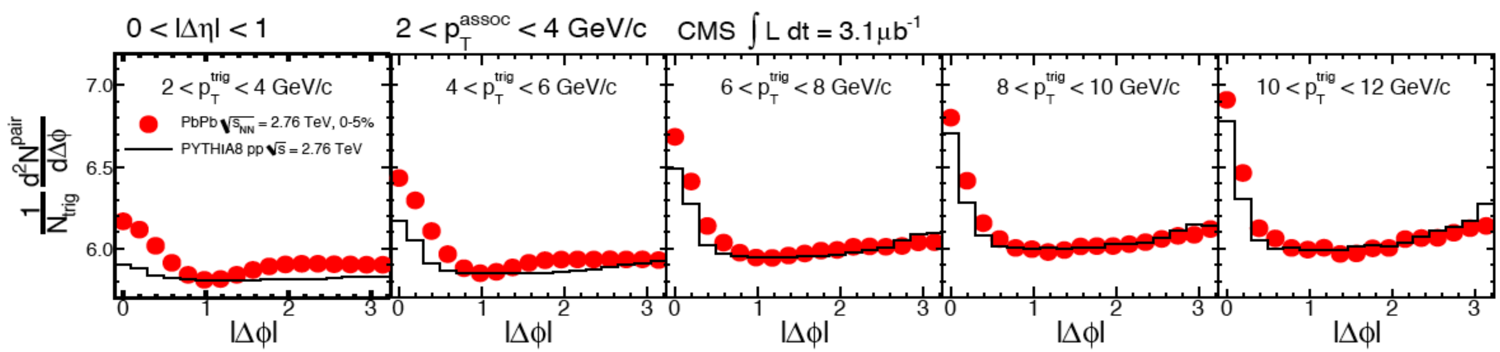
Short and Long Range Correlations in PbPb (√sNN = 2.76 TeV)

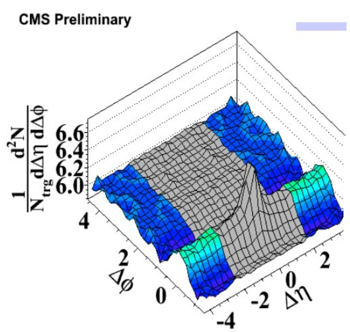


Ridge seen in Heavy Ion collsions.

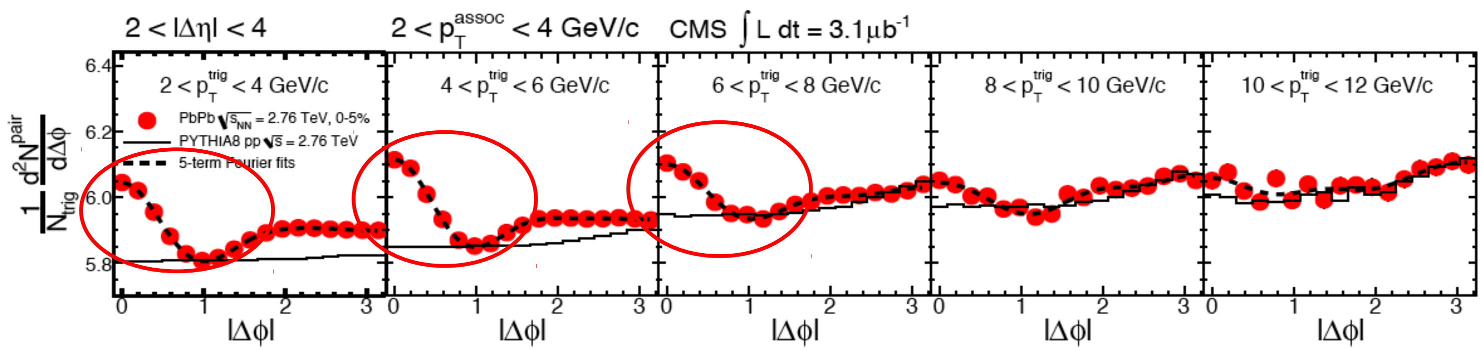
Centrality 0-5%

Short range (0 < |Δη| < 1)





Long range (2 < |Δη| < 4)



long range correlations studied for different pTtrig.
nge correlations: large deviation from predictions (No ridge in MC).
ffect maximal for pTtrig ≈ 2-6 GeV then it does disappear beyond 10 GeV! (als

[HIN-11-001]

(Soft) Multiple Parton Intractions highlights @ LHC

Charged multiplicity measurements:

CMS confirms large multiplicity tails and KNO violation more pronounced at high energies.

- à On the other hand MPI models have been invented to describe large multiplicity tails and KNO violation at SPS.

UE Measurements in Jets:

Steep rise followed by plateau. Indication of two different regimes (two scale picture). MPI rise dominates at low pT, radiation rise dominates at higher pT.

 UE in di-jet events is ≈ universal.

UE Measurements in Drell-Yan:

MPI saturated. Radiative increases of UE activity with pT di-lepton.

Constant vs Mdi-lepton.

 Min activity around 80% with respect to the plateau in jet events.

Evidence of MPI effects provided also in terms of Forward-Central correlations.

MPI play a major role in the “ridge” effect at the LHC.

PART III

Multiple Parton Interactions measurements at high p
i.e. the Double Parton Scattering

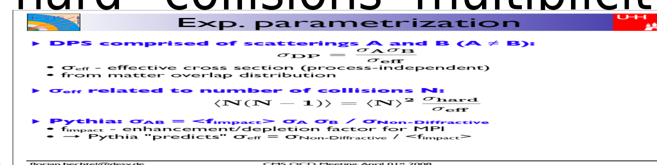
MPI: from “soft” to “hard”

- **σ(A+B) = m * σ(A) * σ(B) / σeff** (m = ½ for identical interactions, m = 1 otherwise)
  - σeff ≈ (process,) scale and √s independent

P(B|A) = P(B) * (σinel/σeff)

[D.Treleani et al. rich bibliography]

- For A = B, σeff related to the momenta of the “hard” collisions’ multiplicity:



- σeff (Tevatron) ≈ 11 mb [Treleani et al., PRD76:076006,2007] from CDF 3jet+γ.

- Pythia: σeff = σNon-Diffractive / <fimpact>
  - where fimpact is tune dependent σeff (Tevatron) ≈ 20÷30 mb

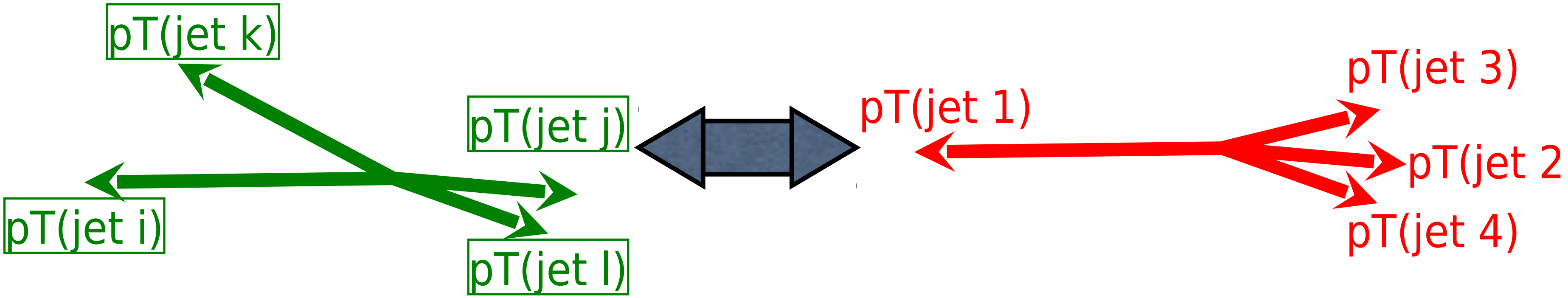
DPS Strongly underestimated in the models? Can DPS be measured at the LHC ?
What are the relationships beween “soft” and “hard” MPI measurements?
Which are the impacts on LHC searches? Particularly relevant for the multi fb-1 analyses

DPS / MPI studies in CMS: **Target 4th MPI w/s (fall 2012)**

- DPS in 3 jet + γ events at 7 TeV.
- DPS in 2-b-jets + 2-jets.
- DPS in Z + di-jet events.
- DPS in W + di-jet events.
- Same sign W production.
- Double J/Ψ production.
- Double Υ.
- Rapidity gap suppression…

Double Parton Scattering in 4 “objects” topologies

Disentangle double-parton-scattering from bremsstrahlung



- No correlation (DPS) vs Strong correlation (SPS)

Define different correlation angles between jet pairs:

AFS solution:

- Study Δφ between pT1 - pT2 and pT3 - pT4

CDF solution:

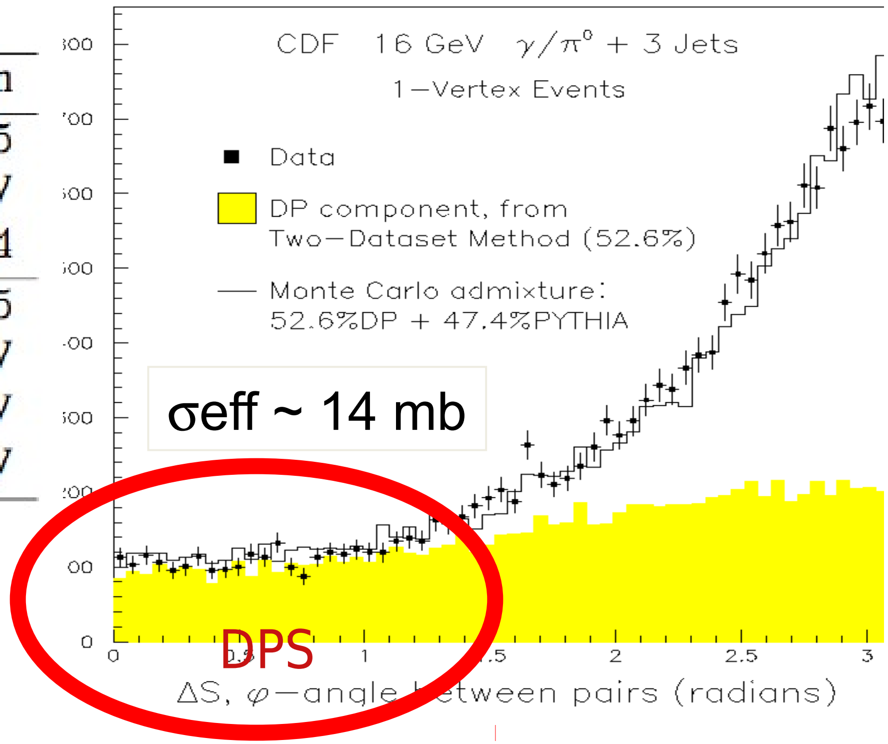
- Study Δφ between pT1 + pT2 and pT3 + pT4 (CDF nomenclature: ΔS)

Measurement of DPS @ Tevatron (3jet + γ)

Double high PT interactions observed by AFS, UA2, CDF, D0!!!

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

	CDF	LHC extrapolation
Photon	$\|\eta\| \leq 1.1$	$\|\eta\| \leq 2.5$
	$E_T \geq 16$ GeV	$E_T \geq 50$ GeV
	Cone $R = 0.7$	$k_\perp$ $D = 0.4$
Jets	$\|\eta\| \leq 4.2$	$\|\eta\| \leq 5$
	$E_T \geq 5$ GeV	$E_T \geq 20$ GeV
	$E_{T4} < 5$ GeV	$E_{T4} < 10$ GeV
	$E_{T2}, E_{T3} < 7$ GeV	$E_{T2}, E_{T3} < 30$ GeV

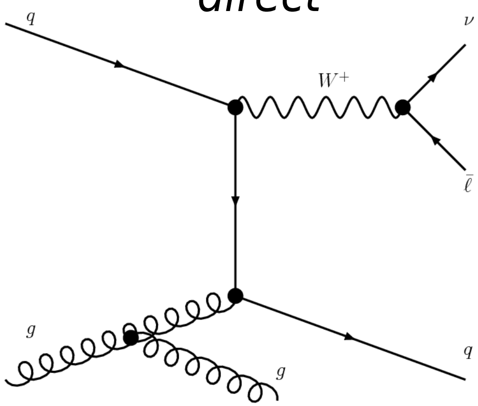


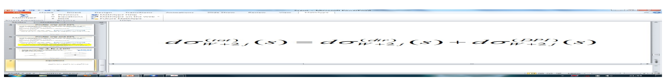
σeff ~ 16 mb [D0 collaboration Phys.Rev. D81 (2010) 052012]

W → lν + 2 jets

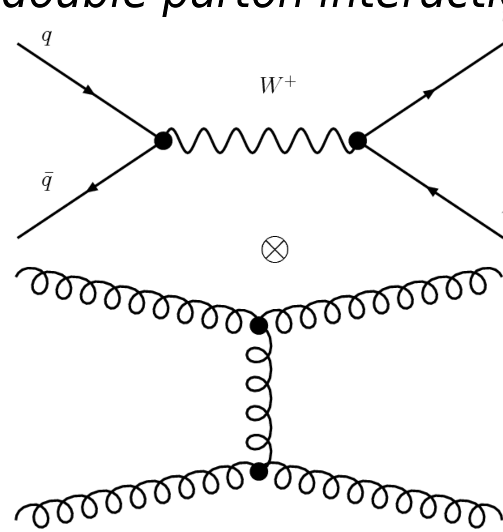
ATLAS-CONF-2011-160

direct

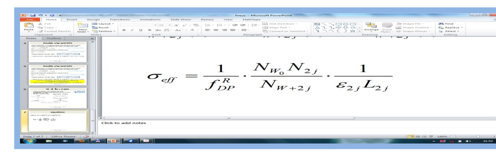




double parton interaction



$$f^{R}_{DP} = \frac{N_{W_0+2j_{DPI}}}{N_{W+2j}}$$



- measure fraction of *W0 + 2jDPI* in the *W+2jet* sample (fRDP)
  - use difference in kinematics (pT, ...)
- *σeff*

W selection
Single lepton trigger
1 lepton (e, μ) pT > 20 GeV, η < 2.5
MET > 25 GeV, mT > 40 GeV
2 jets, pT > 20 GeV, |y| < 2.8

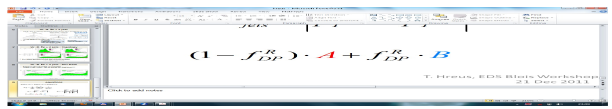
Jet selection
(Minimum bias trigger used to measure di-jet x-section alone)
2 jets, pT > 20 GeV, |y| < 2.8

W → lν + 2 jets : DPS Rate

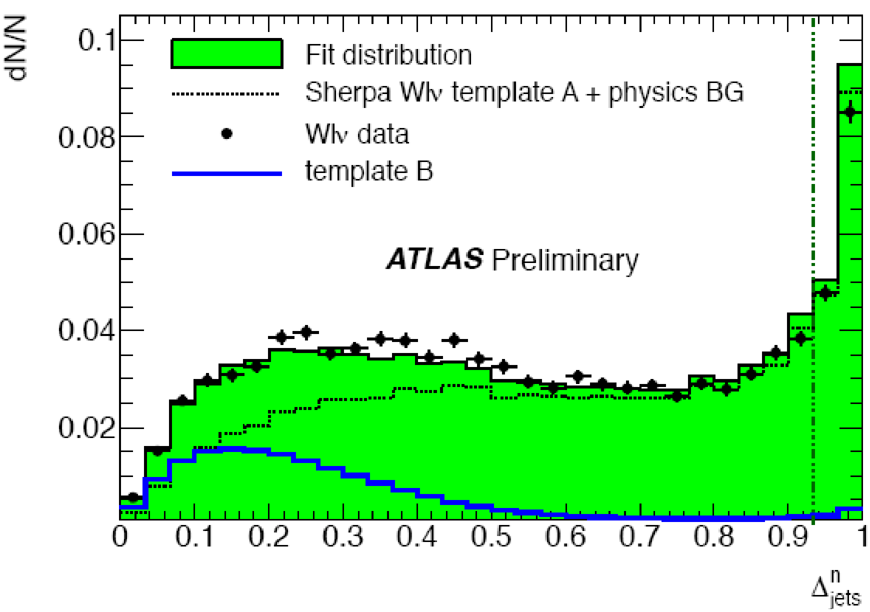
ATLAS-CONF-2011-160

- Extraction of fRDP using fit to data with two templates
- Template A (non DPS sample): both jets originate from the primary sca
- Template B (a DPS sample) : both jets originate from the DPS scatter

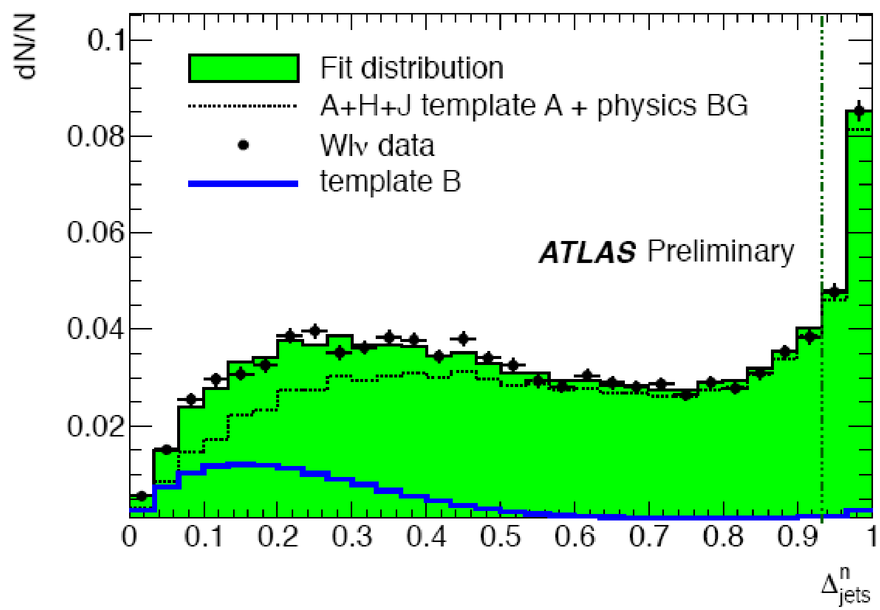
$$\Delta^n_{jets} = \frac{\left| \vec{p}_T^{\,J1} + \vec{p}_T^{\,J2} \right|}{\left| \vec{p}_T^{\,J1} \right| + \left| \vec{p}_T^{\,J2} \right|}$$



X^2/N_{dof} 1.4, $f^R_{DP} = 0.18$

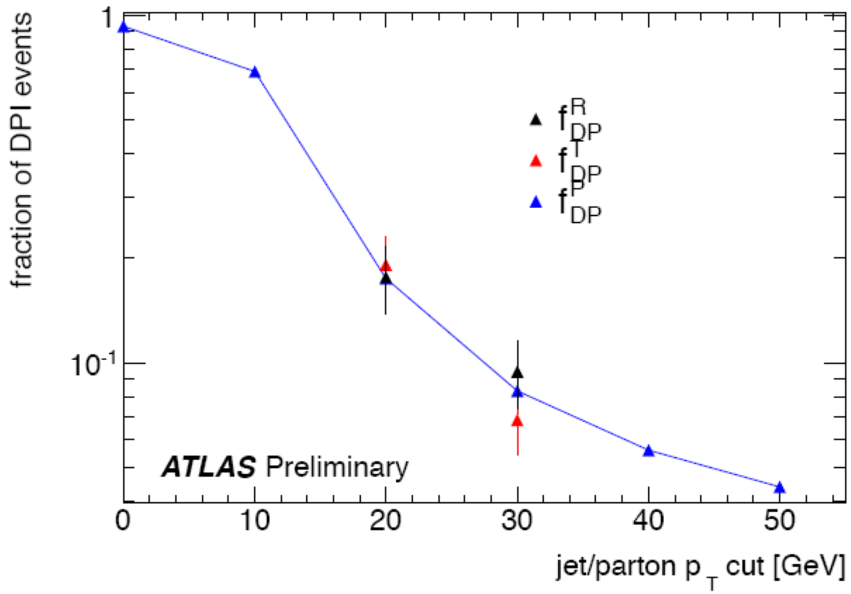


X^2/N_{dof}=0.9, $f^R_{DP} = 0.14$



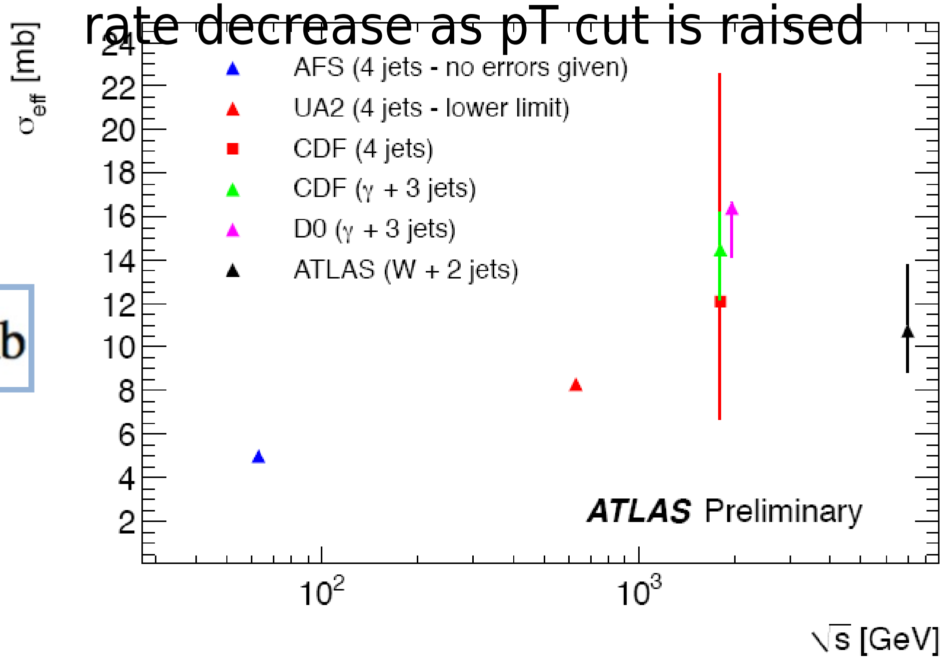
$$f^R_{DP} = 0.16 \pm 0.01 \text{ (stat.)} \pm 0.03 \text{ (sys.)}$$

W □ lν + 2 jets : σeff



- extracted component of DPS at the reco level (fRDP) is a good estimator of the value of fPDP at parton level

- both predicted and extracted DPS rate decrease as pT cut is raised

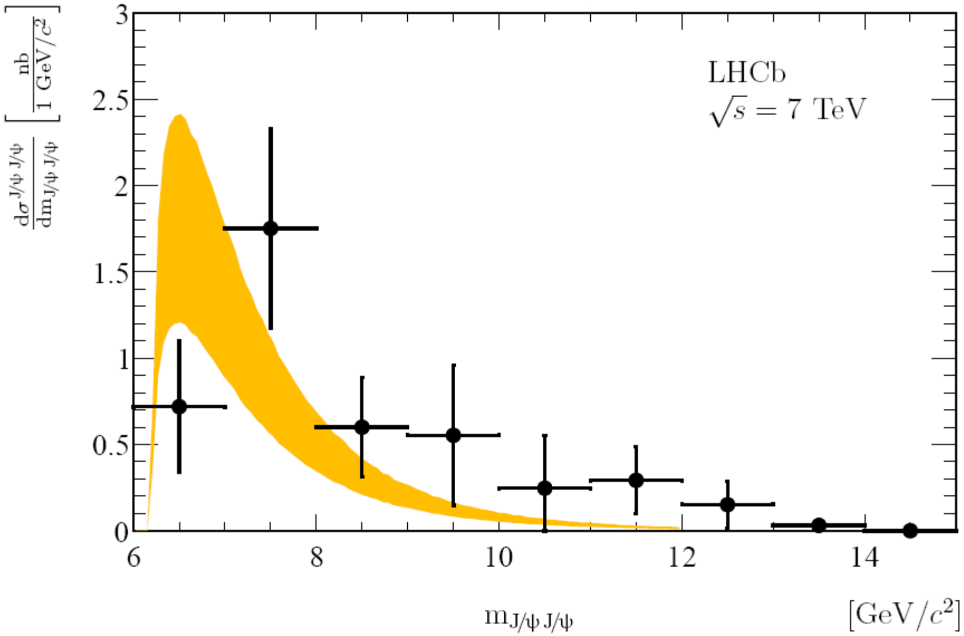


$$\sigma_{\text{eff}}(7\,\text{TeV}) = 11 \pm 1\ (\text{stat.})\ ^{+3}_{-2}\ (\text{sys.})\ \text{mb}$$

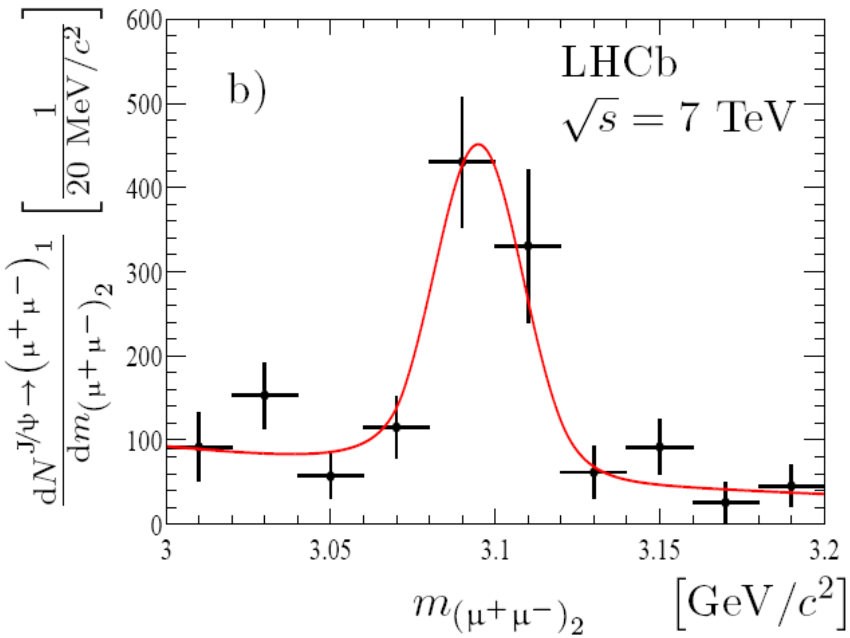
- *σeff* consistent with Tevatron results
- *s*-dependence not excluded

Double J/ψ Production

[arXiv 1109.0963 [hep-ex]]



Corrected event yield: N = 672 ± 129



Prediction of σJ/ψJ/ψ includes direct production and freed down from ψ(2S), but no DPS

Measured cross-section (6σ excess):

σJ/ψJ/ψ = 5.1 +- 1.0 (stat) +- 1.1 (syst) nb

reasonable agreement between data and theory

 contribution from DPS?

J/ψ candidates ordered with increasing pT.
Fit: *double-sided Crystal Ball function*

pTμ > 650 MeV (μ+μ– channel)
3.0 < mμ+μ– < 3.2 GeV
2 < yJ/ψ < 4.5
pTJ/ψ < 10 GeV

Double J/ψ and DPS

Using σeff formulation, we can obtain estimation of the contribution from the double parton scattering (single J/ψ production cross-section was measured by LHCb):

$$\sigma_{\rm DPS}^{J/\psi\, J/\psi} = \frac{1}{2}\frac{\sigma_{\rm SPS}^{J/\psi}\,\sigma_{\rm SPS}^{J/\psi}}{\sigma_{\rm eff}} \simeq 2.0\ {\rm nb}$$

S.P. Baranov, A.M. Snigirev, N.P. Zotov [Phys. Lett. B 705 (2011) 116–119]

Cross-section through the standard gg→2J/ψ mechanism gives:

$$\sigma_{\rm SPS}^{J/\psi\, J/\psi} = 4.15\ {\rm nb}$$

A.V. Berezhnoy, A.K. Likhoded, A.V. Luchnsky, A.A. Novoselov, [arXiv:1101.5881]

Theoretical prediction from both modes : $\sigma_{\rm SPS}^{J/\psi\, J/\psi} + \sigma_{\rm DPS}^{J/\psi\, J/\psi} = 6.15\ {\rm nb}$

- close to the σJ/ψJ/ψ cross-section measured by LHCb (σJ/ψJ/ψ = 5.1 +-

A hint of the evidence to the double parton scattering in the double J/ψ production!

- Large TH uncertainties (αs scale, J/ψ wave function, gluon distr.,…) give factor 2-3

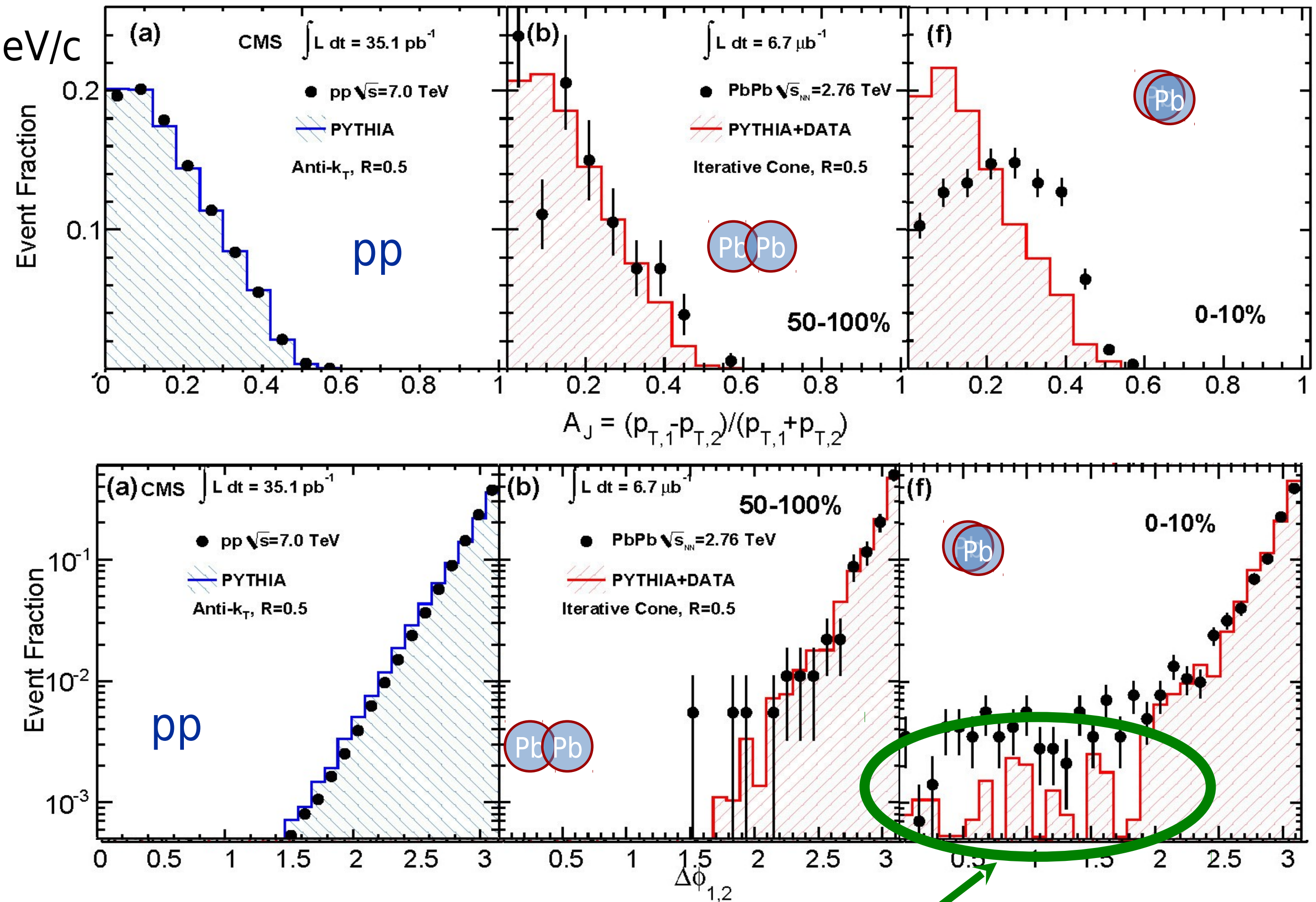
HI: Jet quenching via large dijet energy imbalance & hard MPI

Dijets, calorimeters only

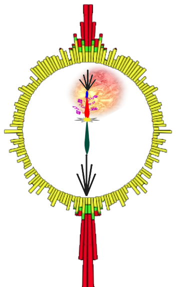
Leading pT>120 GeV/c

Sub-leading pT>50 GeV/c

pp PbPb, 50 - 100% PbPb 0 - 10%



pT imbalance, increasing with centrality



Back-to-back $\Delta\phi\sim\pi$ for all centralities

arXiv:1102.1957

Multiple Hard Parton Scattering!

Relevant literature (2011)

Keyword MULTIPLE PARTON INTERACTIONS (MPI)

1) Disentangling correlations in Multiple Parton Interactions
By Giorgio Calucci, Daniele Treleani.
arXiv:1009.5881 [hep-ph].
Phys.Rev. D83 (2011) 016012.

TH

2) Multiple parton interactions and forward double pion production in pp and dA scattering
By Mark Strikman, Werner Vogelsang.
arXiv:1009.6123 [hep-ph].
Phys.Rev. D83 (2011) 034029.

HI vs pp

3) Multiple Parton Interactions in Z+ jets production at the LHC. A comparison of factorized and non-factorized double parton distribution functions
By Ezio Maina.
arXiv:1010.5674 [hep-ph].
JHEP 1101 (2011) 061.

LHC hard/soft

4) Multiple Parton Interactions Studies at CMS
By Paolo Bartalini, Livio Fano'.
arXiv:1103.6201 [hep-ex].

5) Azimuthal decorrelations and multiple parton interactions in photon+2 jet and photon+3 jet events in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV
By D0 Collaboration (Victor Mukhamedovich Abazov et al.).
arXiv:1101.1509 [hep-ex].
Phys.Rev. D83 (2011) 052008.

Tevatron hard/soft

6) Soft multiple parton interactions as seen in multiplicity distributions at Tevatron and LHC
By I.M. Dremin, V.A. Nechitailo.
arXiv:1106.4959 [hep-ph].
Phys.Rev. D84 (2011) 034026.

Relevant literature (2011) continued

Keyword DOUBLE PARTON SCATTERING (DPS)

) Double Parton Splitting Diagrams and Interference and Correlation Effects in Double Parton Scattering
y Jonathan R. Gaunt.
rXiv:1110.1536 [hep-ph].

) Double Parton Scattering Singularity in One-Loop Integrals
y Jonathan R. Gaunt, W.James Stirling.
rXiv:1103.1888 [hep-ph].
IEP 1106 (2011) 048.

TH

) Probing double parton scattering with leptonic final states at the LHC
y Jonathan R. Gaunt, C.H. Kom, A. Kulesza, W.J. Stirling.
rXiv:1110.1174 [hep-ph].

DPS@LHC
In final states with leptons

) A Fresh look at double parton scattering
y M.G. Ryskin, A.M. Snigirev.
rXiv:1103.3495 [hep-ph].
hys.Rev. D83 (2011) 114047.

2 Jets + 2 b-Jets

) Investigations of Double Parton Scattering: Example of $pp \rightarrow b \bar{b} \rm{jet~jet} X$
y Edmond L. Berger.
rXiv:1106.0078 [hep-ph].

Relevant literature (2011) continued

Keyword DOUBLE PARTON SCATTERING (DPS)

) Prospects for observation of double parton scattering with four-muon final states at LHCb
y C.H. Kom, A. Kulesza, W.J. Stirling.
rXiv:1109.0309 [hep-ph].

) Pair production of J/psi as a probe of double parton scattering at LHCb
y C.H. Kom, A. Kulesza, W.J. Stirling.
rXiv:1105.4186 [hep-ph].
hys.Rev.Lett. 107 (2011) 082002.

LHCb

QUARKONIA

) Double parton scattering as a source of quarkonia pairs in LHCb
y Alexey Novoselov.
rXiv:1106.2184 [hep-ph].

) Double heavy meson production through double parton scattering in hadronic collisions
y S.P. Baranov, A.M. Snigirev, N.P. Zotov.
rXiv:1105.6276 [hep-ph].

0) Calculation of W b bbar Production via Double Parton Scattering at the LHC
y Edmond L. Berger, C.B. Jackson, Seth Quackenbush, Gabe Shaughnessy.
rXiv:1107.3150 [hep-ph].

W + 2b-jets

1) LHC Sensitivity to Wbb Production via Double Parton Scattering
y Seth Quackenbush, Edmond L. Berger, C.B. Jackson, Gabe Shaughnessy.
rXiv:1109.6271 [hep-ph].

Relevant literature (2012) preliminary

Keyword DOUBLE PARTON SCATTERING (DPS)

Double parton scattering in double logarithm approximation of perturbative QCD
M.G. Ryskin (St. Petersburg, INP), A.M. Snigirev (SINP, Moscow). Mar 2012. 7 pp.
e-Print: **arXiv:1203.2330**

What is Double Parton Scattering?
Aneesh V. Manohar, Wouter J. Waalewijn, . Feb 2012. 5pp. Temporary entry
e-Print: **arXiv:1202.5034**

A QCD Analysis of Double Parton Scattering: Color Correlations, Interference Effects and Evolution.
Aneesh V. Manohar, Wouter J. Waalewijn, . Feb 2012. 24pp. Temporary entry
e-Print: **arXiv:1202.3794**

Connection to the DPS theory

- **σ(A+B)= m * σ(A) * σ(B) / σeff** (m = ½ for identical interactions, m = 1 otherwise)
- The effective x-section (σeff) should be regarded as the most natural link to the theory.
- √s and scale (in)dependency should not be assumed, it should be rather tested/measured although the first benchmark measurements should focus on simple working points.
- Initial process dependency is studied regarding the global picture of DPS measurements.
- The relationship applies to inclusive measurements only!

Get rid of those cuts which selects "one and only one" additional interaction!!! Triple, interactions should be retained as well.

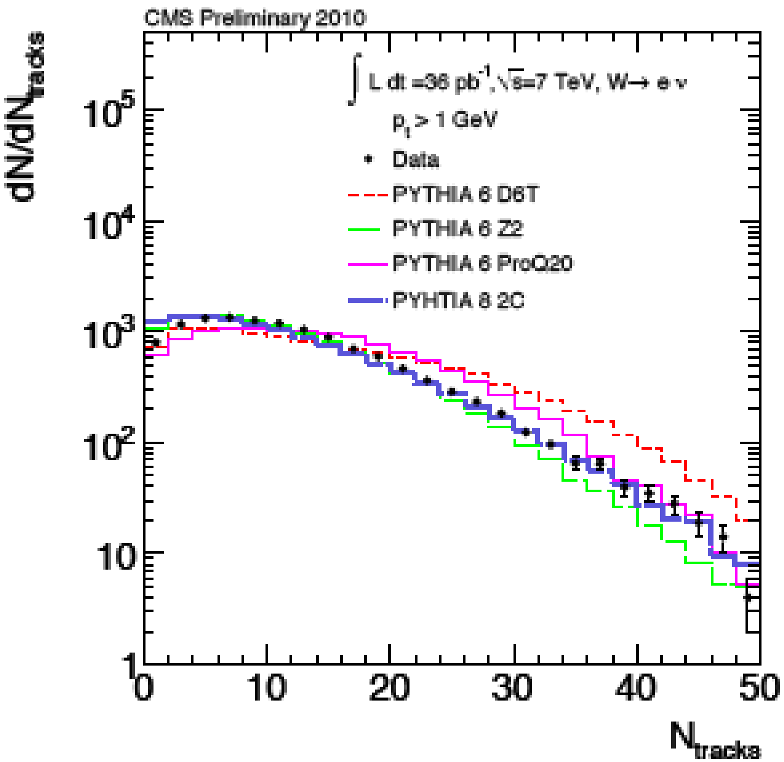
- Alternative relationships apply to exclusive measurements [Treleani et al.]

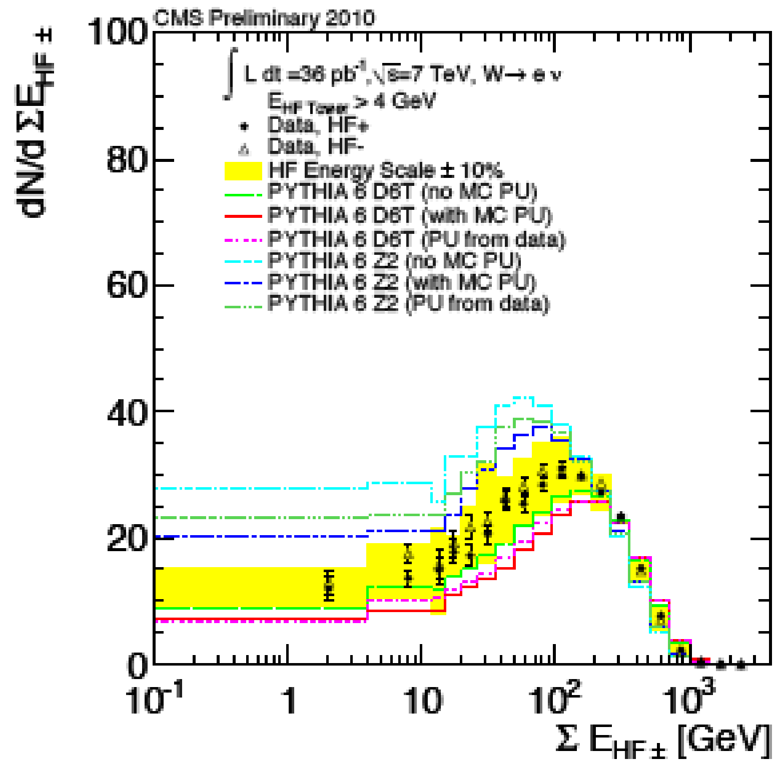
MC matters, it is the only way to define SIGNAL and BACKGROUNDS in DPS analyses

- It is desirable to have more generator level studies: how DPS signals are diluted?
- At the same time it is ESSENTIAL to use appropriate DPS SIGNAL (Pythia8, Herwig++).
- BACKGROUND **IS NOT** MPI OFF (or DPS off) **IT IS RATHER** "2nd interaction below a given pT"

FWD / BACKUP

Energy flow in W (and Z) events



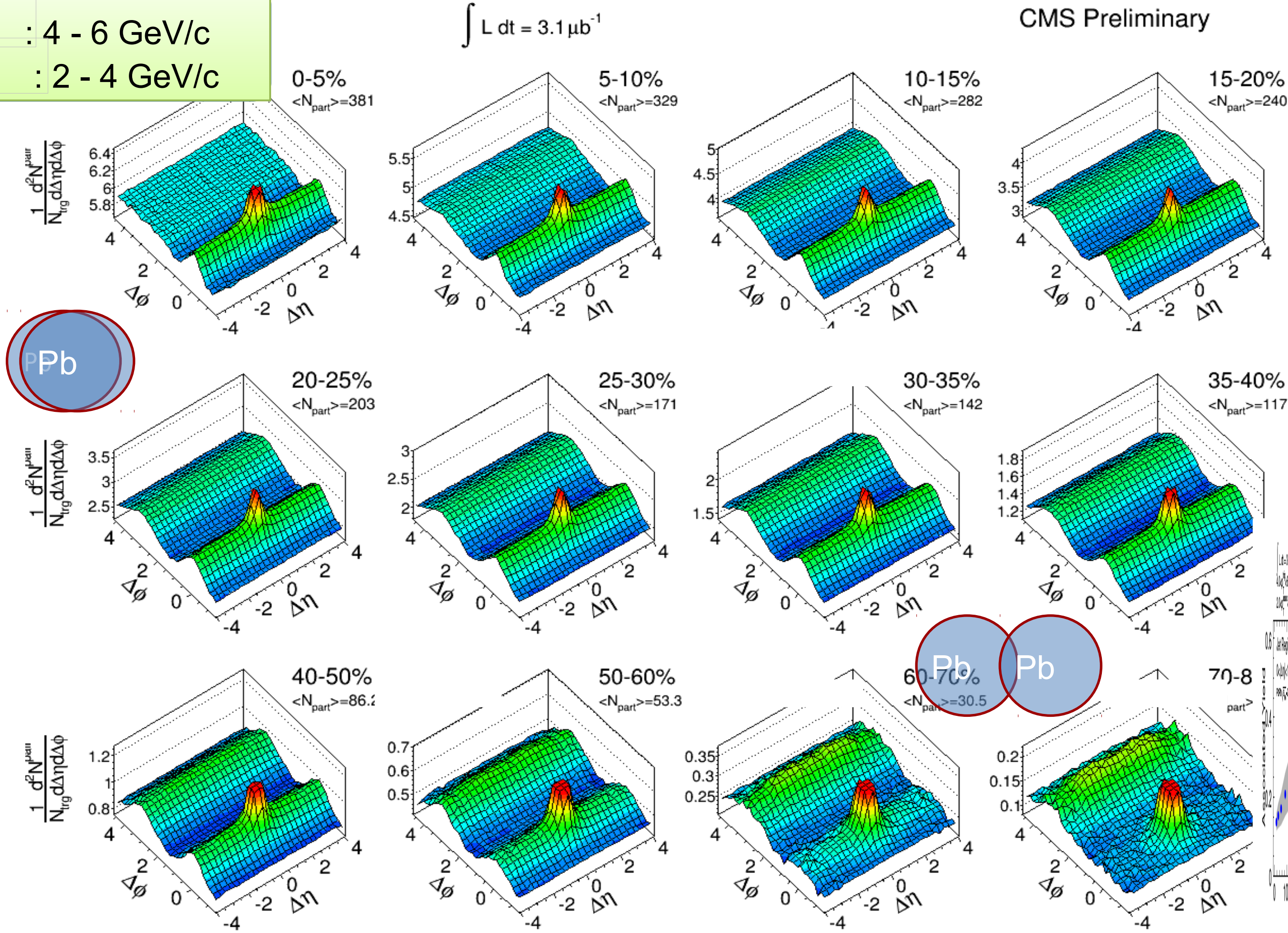


W selected requiring leptonic decays:
pT(l) > 25 GeV, Missing Energy ET> 30 GeV, Minv(l,ET) > 60 GeV.
Investigating both central tracks and forward energy.
Conclusions similar for Z events.
Further studies selecting events with Large Rapidity Gaps (not shown here)

Centrality effect and elliptic flow subtraction

Centrality dependence of correlations in PbPb (√sNN = 2.76 TeV)

: 4 - 6 GeV/c
: 2 - 4 GeV/c



Associated hadron yields of the ridge structure are studied before and after explicit subtraction of the