[CMS PAS QCD-10-001],now [Eur. Phys. J. *C70* (2010) 555–572]
and [CMS PAS QCD-10-010]

CMS results on underlying event structure

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On behalf of the CMS collaboration

Outline:

→ Introduction
→ Methodology and experimental overview
→ Event and track selection
→ MC description
→ Results for leading object methodology at 7TeV and 900GeV
→ Improvements in MC tunning
→ First look at Jet Area/Median approach
→ Conclusions and 'coming soon'

Introduction

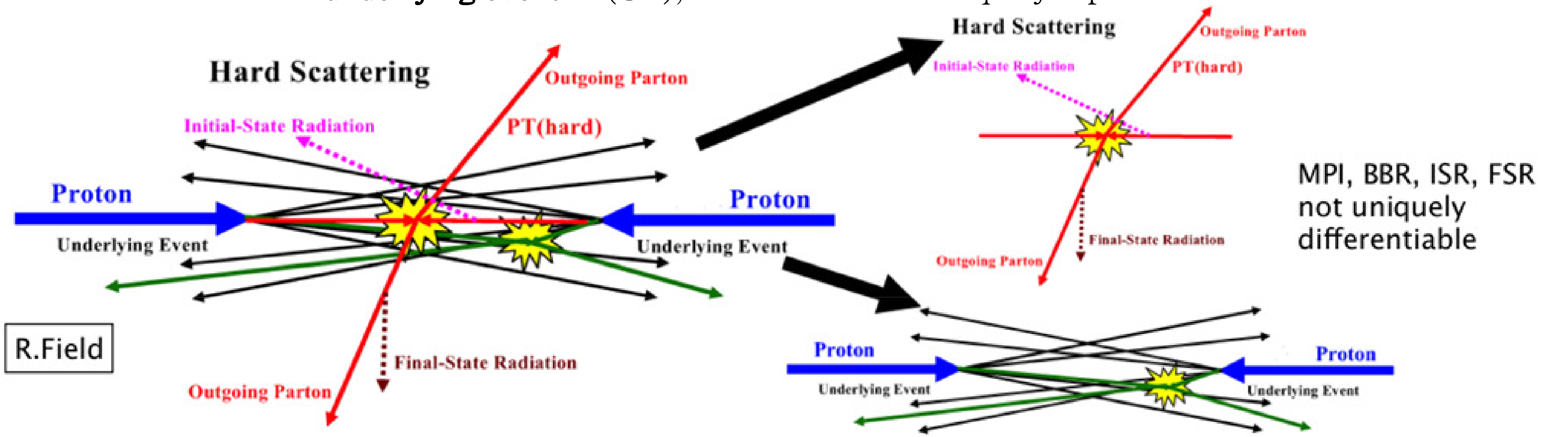
In hard processes the hadronic final states of hadron-hadron interactions can be described as the superposition of several contributions:

→ products of the **partonic hard scattering** (including **initial and final state radiation**);

→ hadrons produced in additional **multiple parton interactions** (**MPI**);

→ "**beam-beam remnants**" (**BBR**) resulting from the hadronization of the partonic constituents that did not participate in other scatters.

MPI and BBR form the "**underlying event**" (**UE**), which cannot be uniquely separated from initial and final state ra(



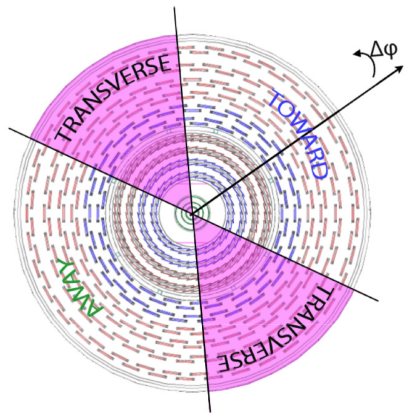
- UE dynamics is **not fully understood** (e.g. centre-of-mass energy dependence);
- A good description of UE properties is **crucial** for precision measurements of Standard Model processes and the search for new physics at the CERN Large Hadron Collider (LHC)

Methodology

[CMS PAS QCD-10-001],now [Eur. Phys. J. *C70* (2010) 555–572]
and [CMS PAS QCD-10-010]

- Same approach as CDF studies:

  Phys. Rev. **D65** (2002) 092002 , *Phys. Rev.* **D70** (2004) 072002



Lead. obj. direction

transverse section of the silicon tracker sub-detector

- An **energy scale** in the event is determined by the "leading" (highest in p_T) object:

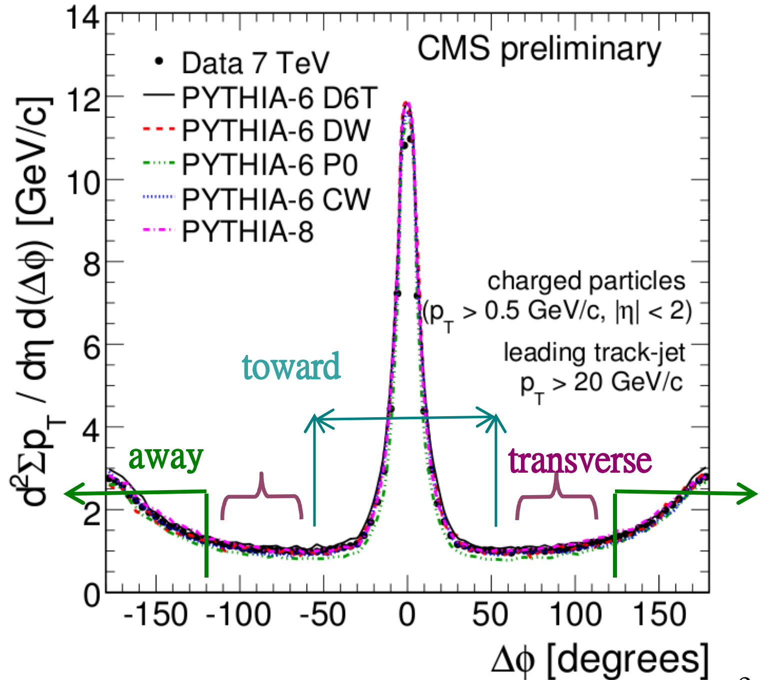
  → Leading **track-jet** (clustering tracks, SIScone algorithm)

  - The leading object is expected to reflect the direction of the partons produced in hard interaction;

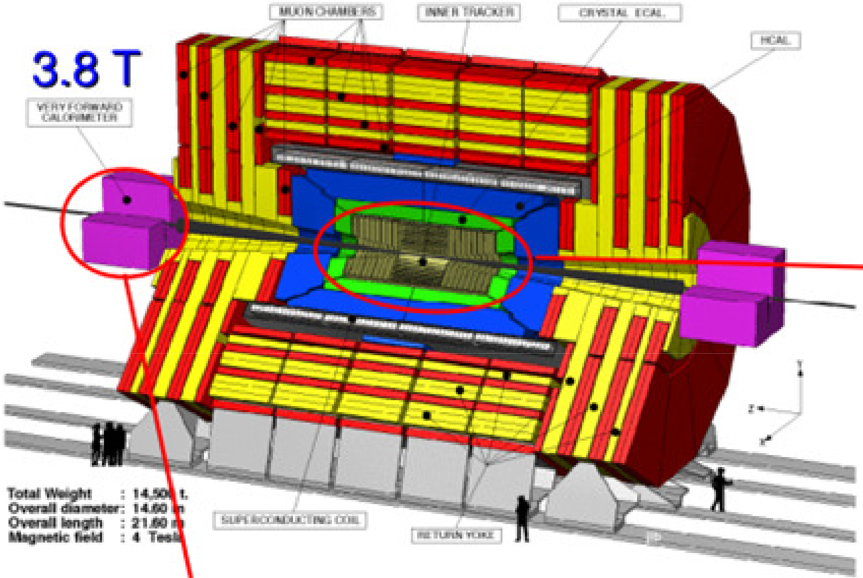
  - 3 topological regions are determined from the azimuthal difference w.r.t. the leading object :
    - → toward : dominated by the hard parton-parton scattering and radiation
    - → away : as above
    - → transverse : suited for UE studies !

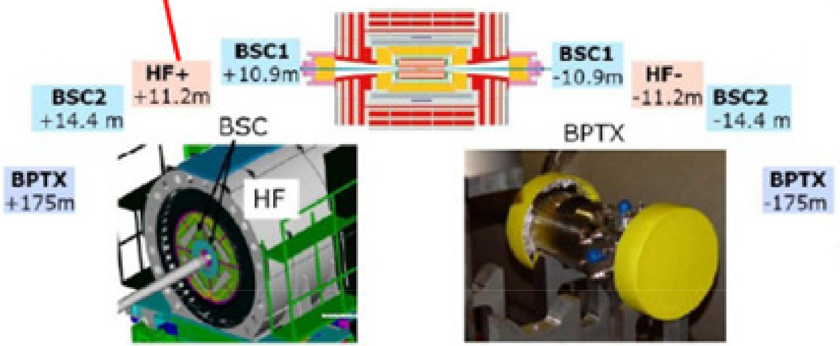
- Observables built from **charged tracks:**
  - : charged multiplicity density
  - : p_T sum density

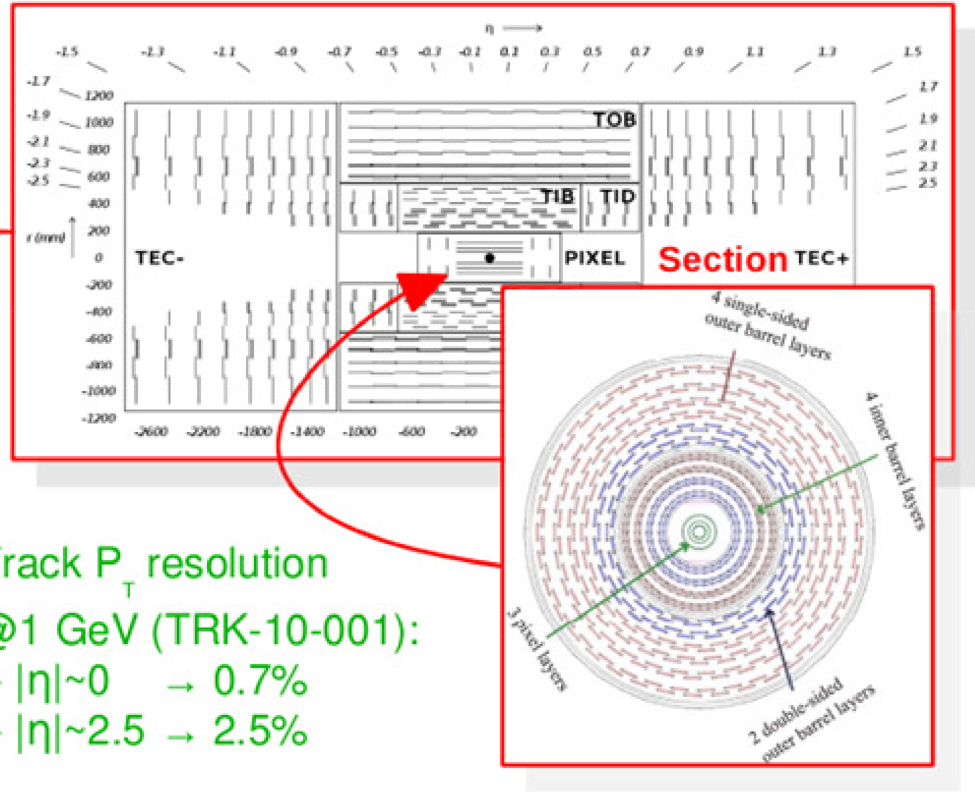
Topological regions description:



Experimental overview







Track P_T resolution

@1 GeV (TRK-10-001):

- $|\eta|\sim 0 \rightarrow 0.7\%$
- $|\eta|\sim 2.5 \rightarrow 2.5\%$

[CMS PAS TRK-10-001 sub. for publ.]

Beam Scintillator Counters
- ± 10.86m from interaction point
- Hit and coincidence rates (beam-halo rejection)

⟶ 96.3% efficiency for MIPs and time resolution of 3ns

Beam Pick-up **T**iming for the e**X**periments (175m from IP)
- Bunch structure
- Timing of beam

Time resolution better 2ns!

Data Aquisition:
- 900GeV, 2009 data
- 7TeV, up to May 2010

Event and track selection

(tables reported for 900GeV data)

- **Trigger: coincidence of both *Beam Pick-up Timing for eXperiments* (BPTX) and *Beam Scintillator Counters* (BSC)**
- **Good primary vertex**
- **Presence of leading object**

Event selection	Data [nb. events]	Data [%]	MC [%]
triggered	255 122	100	100
+ 1 primary vertex	239 038	93.7	92.9
+ 15 cm vertex z window	238 977	93.7	92.8
+ at least 3 tracks associated	230 611	90.4	88.7
leading track, $p_T > 0.5\,\mathrm{GeV}/c$	216 215	93.8	93.2
$p_T > 1.0\,\mathrm{GeV}/c$	131 421	60.8	55.0
$p_T > 2.0\,\mathrm{GeV}/c$	28 210	21.5	19.5
leading track-jet, $p_T > 1.0\,\mathrm{GeV}/c$	155 005	67.2	62.9
$p_T > 3.0\,\mathrm{GeV}/c$	24 928	16.1	15.9

ZeroBias events used for cross-checking efficiencies in data and MC

Good agreement in DATA VS MC comparison

- **Kinematic region for tracker acceptance and good tracking performances**
- **Association of tracks to primary vertex**
- **Additional quality cut**

Track selection	Data [nb. tracks]	Data [%]	MC [%]
reconstruction algorithm	4 004 923	100	100
$+\ p_T > 0.5\,\mathrm{GeV}/c$	1 707 998	42.6	44.0
$+\ \|\eta\| < 2.5$	1 689 910	98.9	98.7
$+\ \|\eta\| < 2$	1 399 344	82.8	81.5
$+\ d_{xy}/\sigma(d_{xy}) < 5$	1 235 193	88.3	88.8
$+\ d_z/\sigma(d_z) < 5$	1 204 979	97.6	97.9
$+\ \sigma(p_T)/p_T < 5\%$	1 168 530	97.0	96.9
Total	1 168 530	29.2	29.8

Final efficiency ~ 90%, fake rates ~ 2% at central rapidity (from Simulation)

MC description

- We present 7TeV and 900GeV **reconstructed data** in comparison with different MC predictions after **full detector simulation**;
- Tunes of the PYTHIA generator (version 6.420): **D6T**, **DW**, **Perugia-0 (P0)**, **CW**
- Pythia 8 (different model! only one tune along the lines of P0): version 8.135

PYTHIA **regularization** of the formal divergence of the leading order partonic scattering amplitude as the final state parton transverse momentum p_T approaches 0:

$$\begin{cases} 1/\hat{p}_T^{\,4} \rightarrow 1/(\hat{p}_T^{\,2} + \hat{p}_{T_0}^{\,2})^2 \\ \hat{p}_T(\sqrt{s}) = \hat{p}_{T_0}(\sqrt{s_0}) \cdot (\sqrt{s}/\sqrt{s_0})^{\epsilon} \end{cases}$$

Regularization: can be interpreted as inverse of effective color screening length

energy dependence

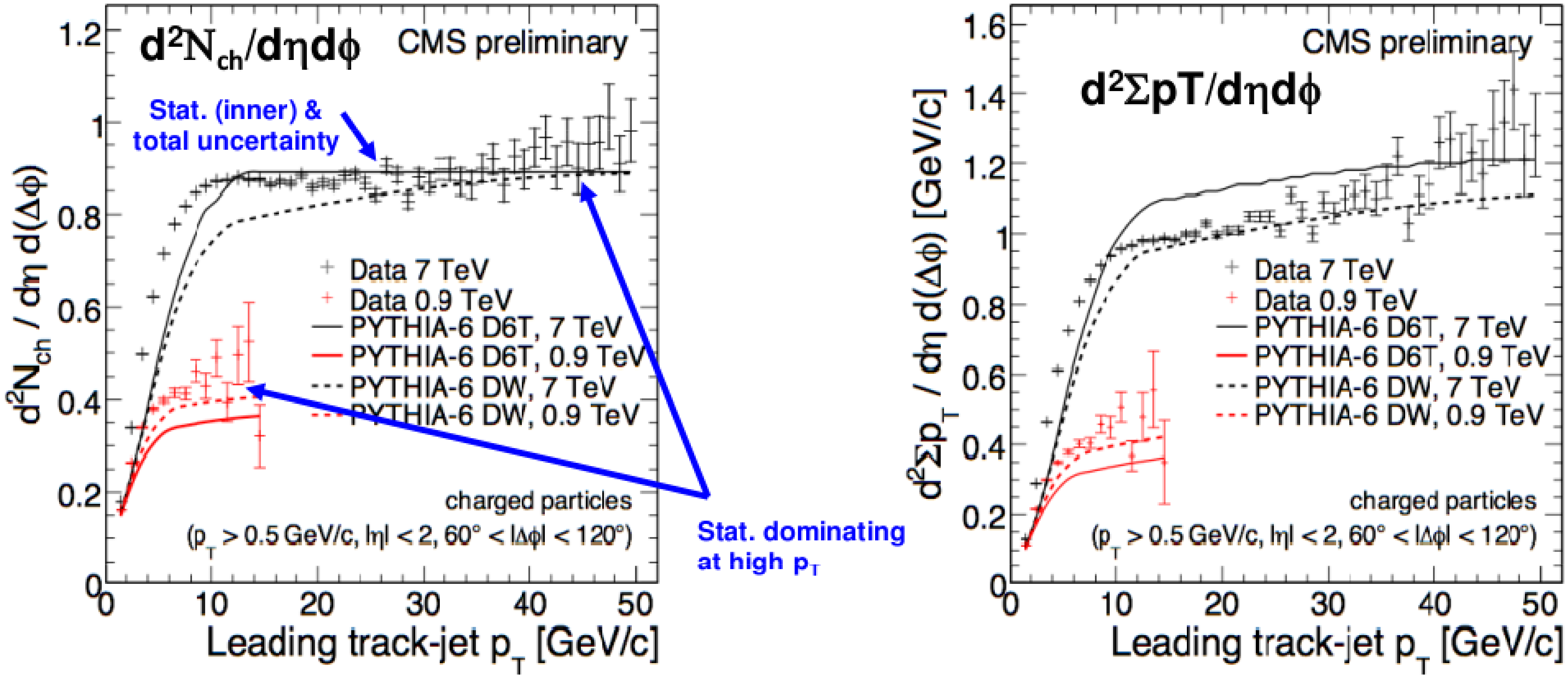
Reference value: e.g. at CDF $\sqrt{s_0} = 1.8\,\mathrm{TeV}$, $\hat{p}_{T_0} = 2.0\,\mathrm{GeV}/c$

- Same parameter regularize **both MPI and hard scattering**: more MPI activity is predicted for smaller values of p_T^0

Tune	p_T^0(1.8TeV)	ϵ	details
D6T	**1.8 GeV/c**	**0.16**	**Consider ATLAS and LHCb studies on multiplicity at SPS; CTEQ6LL Parton distributions**
DW	1.9 GeV/c	0.25	Consider 630GeV & 1.8TeV CDF resultsCTEQ5L parton distributions
P0	**2 GeV/c**	**0.26**	**As above + New PYTHIA MPI model; PT ordered showers;**
CW	**1.8 GeV/c**	**0.3**	Ad hoc for 900GeV CMS data, maximizing MPI but still compatible with Tevatron; default PYTHIA color reconnection; Parton distributions CTEQ5L

Densities in the transverse region

7 TeV and 900 GeV results for the reference charged multiplicity density and ΣpT density profiles including both D6T and DW predictions.

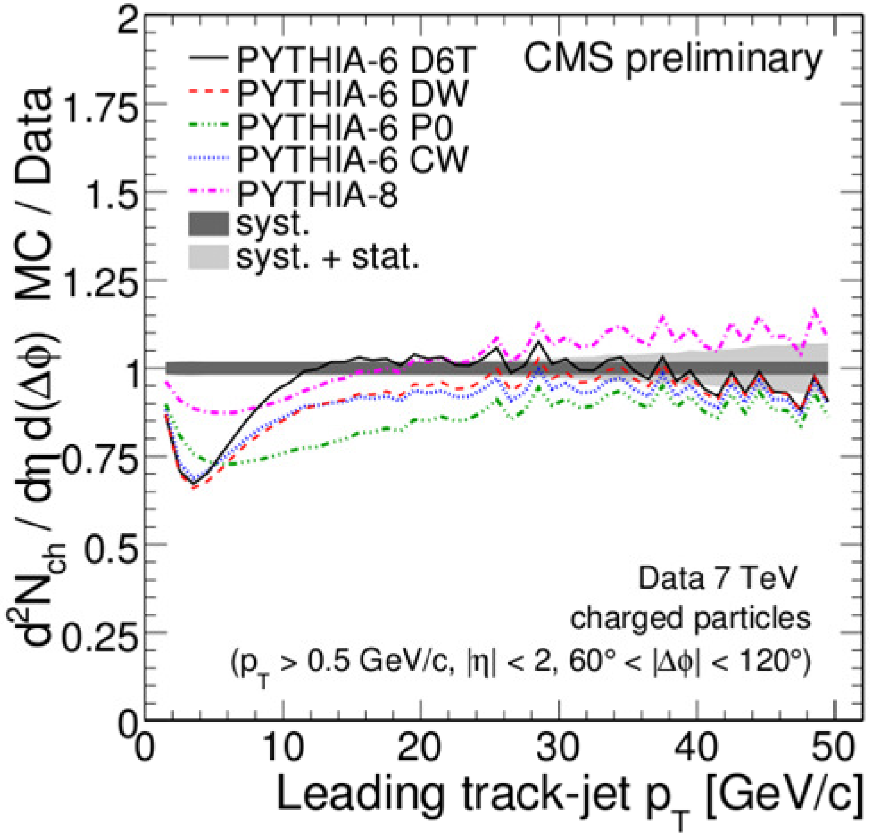


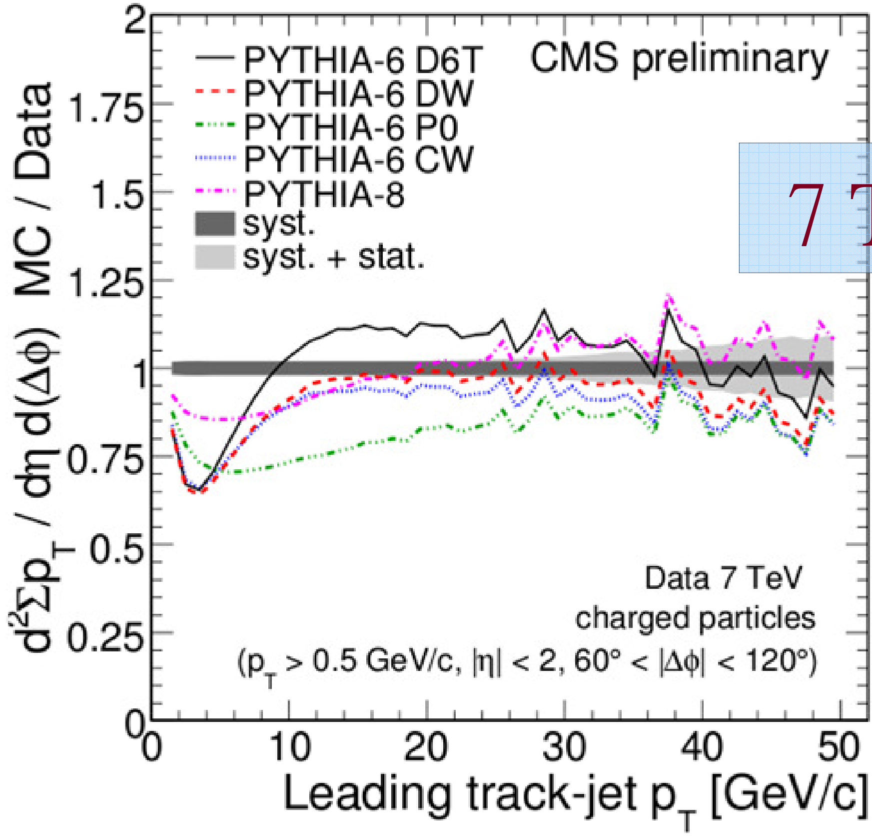
Fast rise for pT < 8 GeV/c (4 GeV/c), attributed mainly to the **increase of MPI activity**, followed by a **Plateau-like region** with ≈ constant average number of selected particles and a slow increase of ΣpT, in a **saturation regime**.

Increase of the activity with √s also corroborates MPIs (growth with PDFs).

Densities in the transverse region

Comparison with more tunes, at 7TeV:

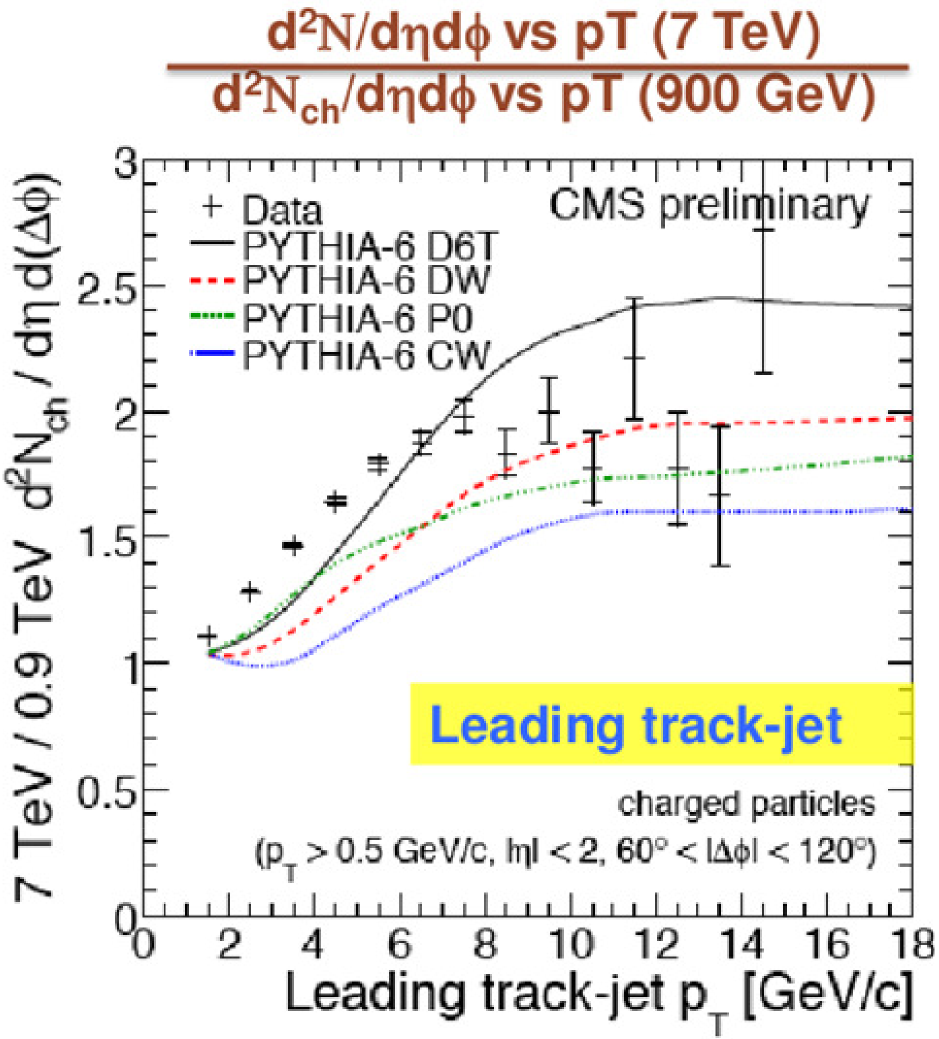


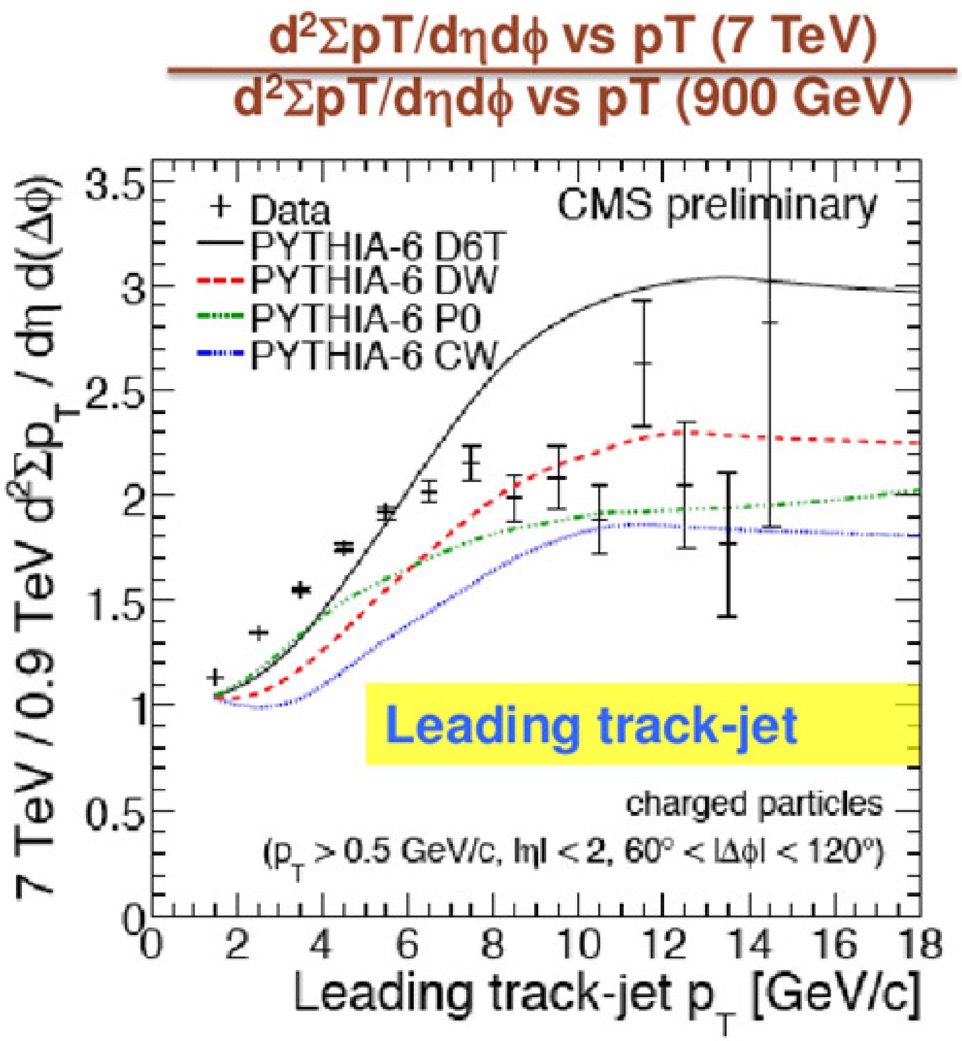


7 TeV

- PYTHIA-8 more successful than the other tunes at the lowest pT values.
- In the higher pT region (for pT>~8GeV/c), the flattening of the distributions is described by **D6T,** CW and DW;
- the increase of activity with increasing leading track-jet p T observed for P0 and for PYTHIA-8 is significantly too large, with P0 predictions being systematically below the data.

Comparisons between 7TeV and 900GeV



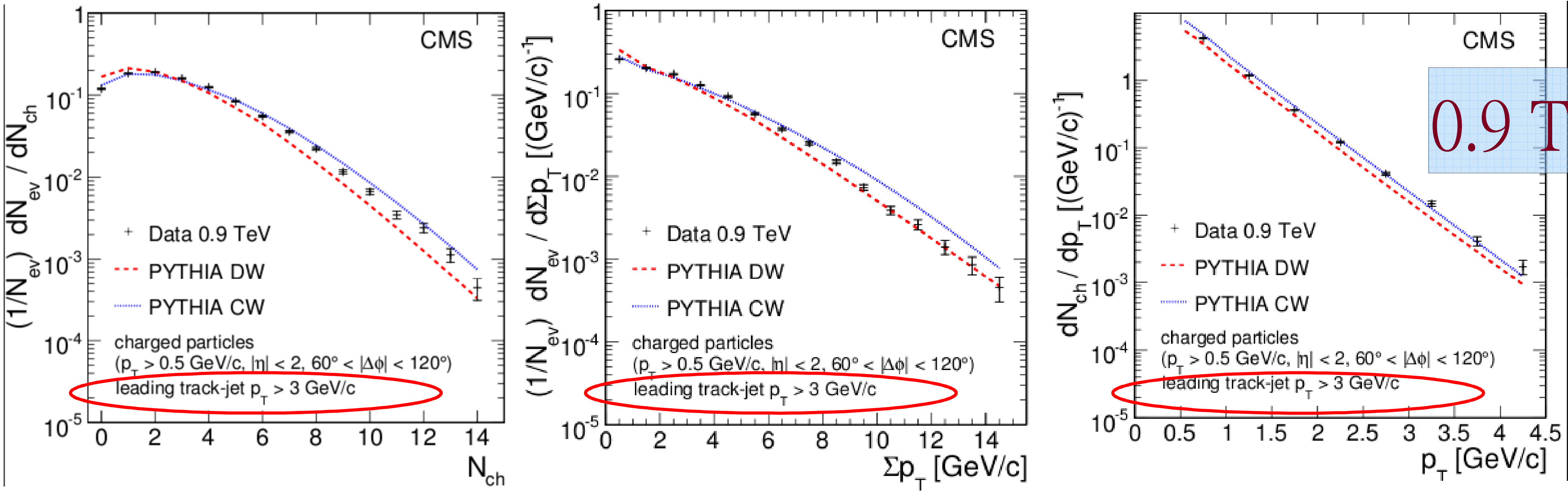


Poor description of the rise. **P0** has the worst shape. **CW** underestimates the plateau regions. **D6T**, with slower energy dependency of the p_T cut-off, overestimates the plateau regions.

N_{chg}, p_T, p_T in the transverse region

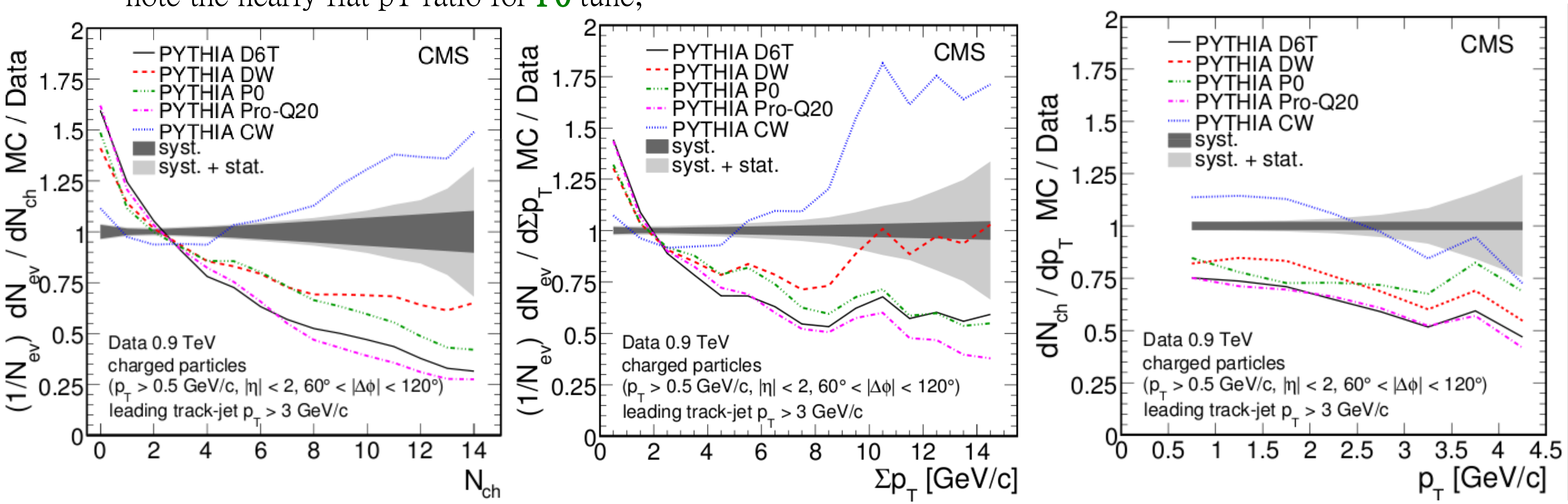
Minimal scale threshold

0.9 TeV



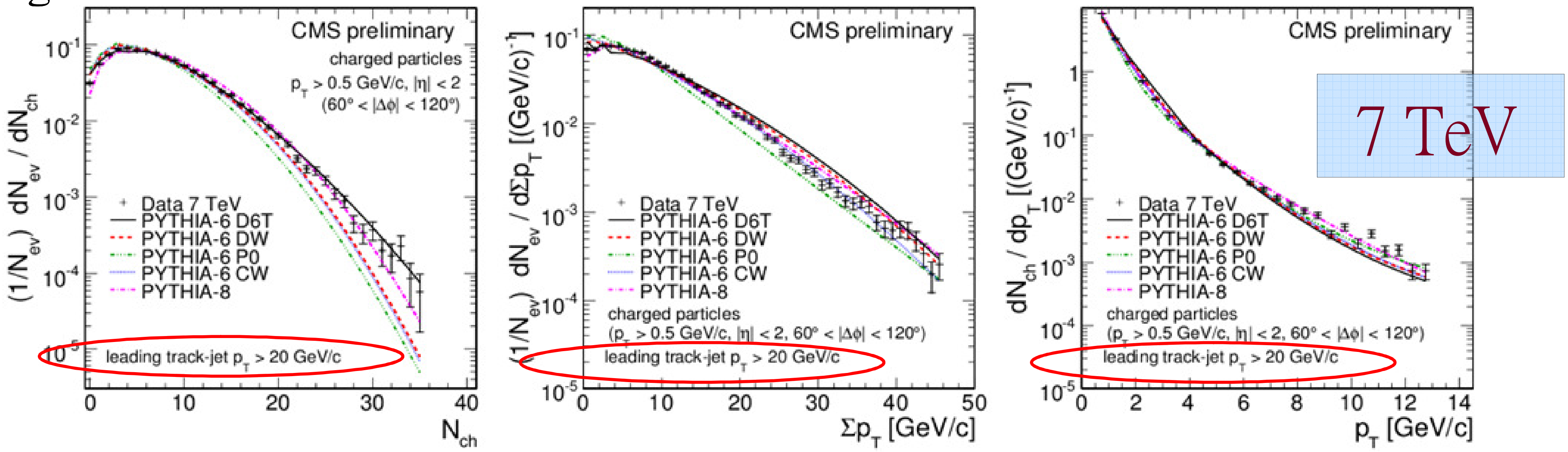
→ CW and DW tunes bracketing data over most of the experimental range;

→ note the nearly flat pT ratio for P0 tune;



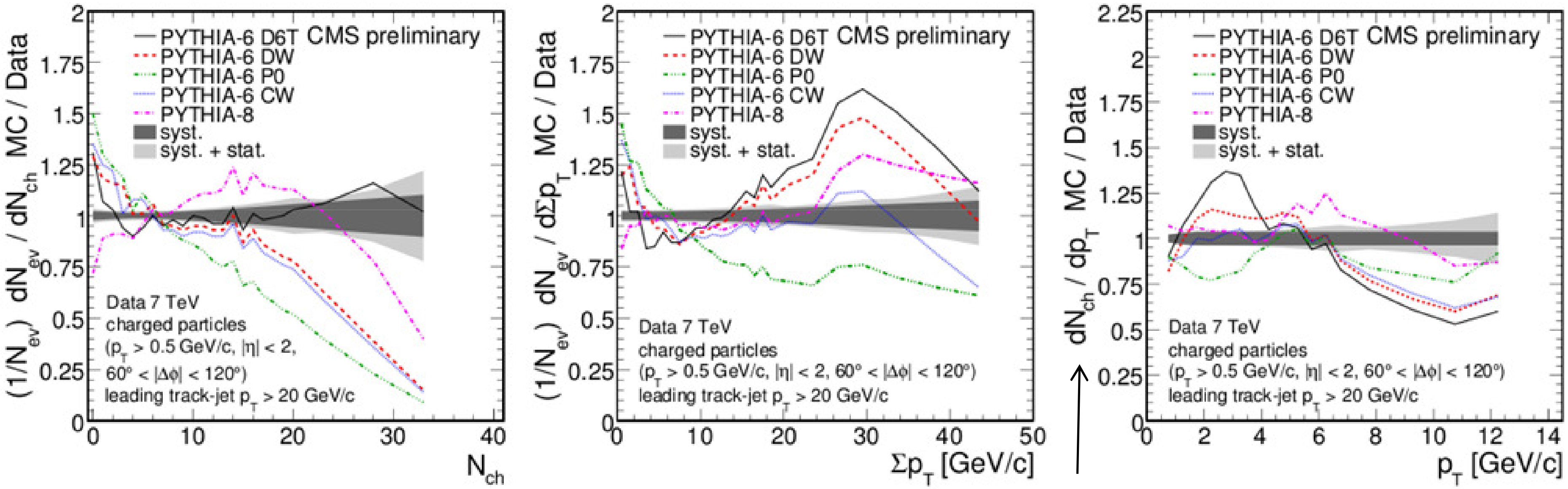
N_{chg}, p_T, p_T in the transverse region

Minimal scale threshold



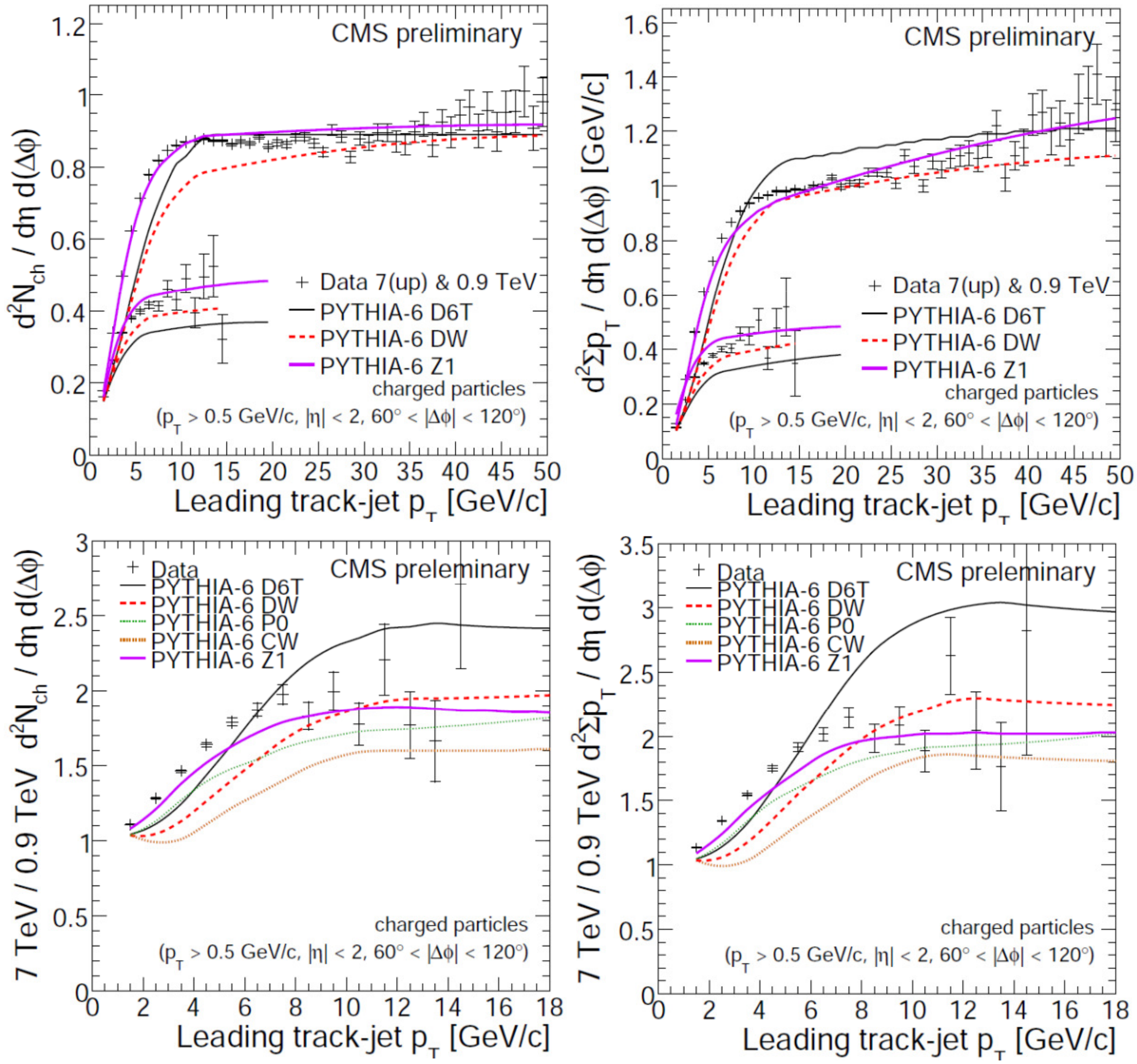
distributions extending up to quite large values of the selected observables:

quite well described overall by the various MC models, over several orders of magnitude.



remarkable similarity for pT spectra between all models and excellent agreement with the data (exception of D6T below 4 GeV/c): in particular by **tune P0,** whereas this model strongly underestimates the tail of the multiplicity and $\sum p_T$ distributions.

Recent developments: Z1 tune



- new CMS PYTHIA 6.4 tune using the new p_T-ordered parton showers and the new MPI;
- pdfs CTEQ5L ;
- PARP(82) = 1.932 (MPI Cut-off) ;
- PARP(90) = 0.275 (MPI Energy Extrapolation)

Pretty good job of fitting data at 900GeV and 7TeV
... BUT:
Slightly overestimating CDF 1.96TeV data
[backup slides]

Systematics uncertainties

- Detailed treatment of various sources of systematics:

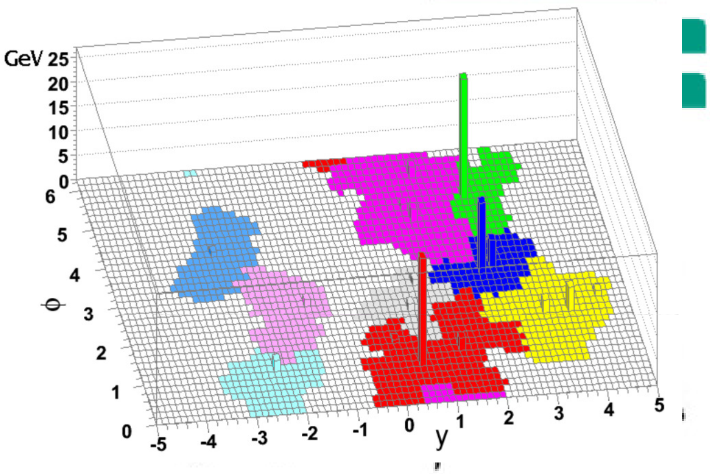
→ **Track selection**: evaluated by applying various sets of cuts and comparing their effects onto data and simulated events;
→ Contribution from a **mis-aligned scenario**;
→ Effects for a different tracker **material budget description**;
→ **Background contamination**: it has been accounted for the underestimation in MC simulation for K^0_S and Λ^0 production as well as photon conversions;
→ **Trigger**-related systematic uncertainty verified by means of alternative trigger set up (from Hadronic Forward subdetector)
→ Effects of run-by-run change in **inactive tracker channels**
→ Effects of different **beamspot position simulation**

- Different contributions summarized for all the distributions of the analysis in reference points (table for 7TeV, relative uncertainties):

	track sel.	tracker align.	tracker mater.	bg. cont.	trigger	vtx sel.	beam spot	total (%)
$d^2N_{ch}/d\eta d(\Delta\phi)$ ($p_T = 20\,GeV/c$)	0.5	0.3	1.0	0.8	0.3	1.0	0.3	1.8
$d^2\Sigma p_T/d\eta d(\Delta\phi)$ ($p_T = 20\,GeV/c$)	0.6	0.3	1.0	0.8	0.3	1.2	0.3	2.0
dN_{ev}/dN_{ch} ($N_{ch} = 4$)	0.3	0.3	0.6	0.5	0.3	0.4	0.2	1.0
$dN_{ev}/d\Sigma p_T$ ($\Sigma p_T = 4.5\,GeV/c$)	0.3	0.2	0.9	0.7	0.3	0.4	0.2	1.3
dN_{ch}/dp_T ($p_T = 1\,GeV/c$)	0.5	0.5	1.0	0.8	0.3	1.7	0.3	2.3

Jet Area/median method

[CMS PAS QCD-10-005]



- Use track-jets, kt R=0.6 algorithm – Infrared and collinear safe
- Relies on active jet-area concept
  - Add grid of artificial soft objects (pt~10^{-100} GeV) called *ghosts*
  - Cluster them with physical tracks
    - → Infra-red: physics does not vary!
  - Area of jet proportional to the contained ghosts

- Underlying activity estimator

$$\rho' = \underset{j \in \text{physical jets}}{\text{median}} \left[\left\{ \frac{p_{Tj}}{A_j} \right\} \right] \cdot C \quad C = \frac{\sum_{j \in \text{physical jets}} A_j}{A_{tot}}$$

- Occupancy "C":
  - Recovers "empty" events (900 GeV) dominated by *ghost-jets*

(**median** being less sensitiv to outliers)

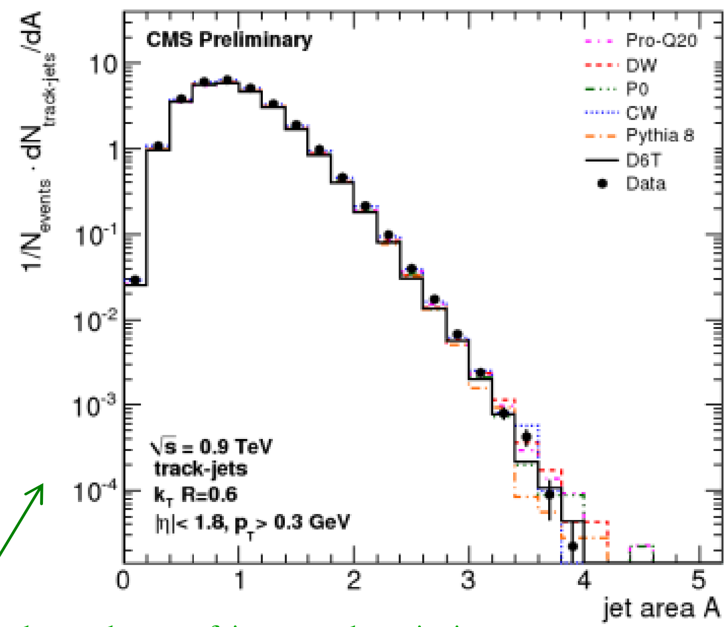
- Complementary to traditional approach
  - UE measured with infrared and collinear safe quantities
  - Look at all the event (not only transverse region)
  - No need for leading object!
- Fundamental for pile-up and UE jet energy corrections

Areas with FastJet www.fastjet.fr

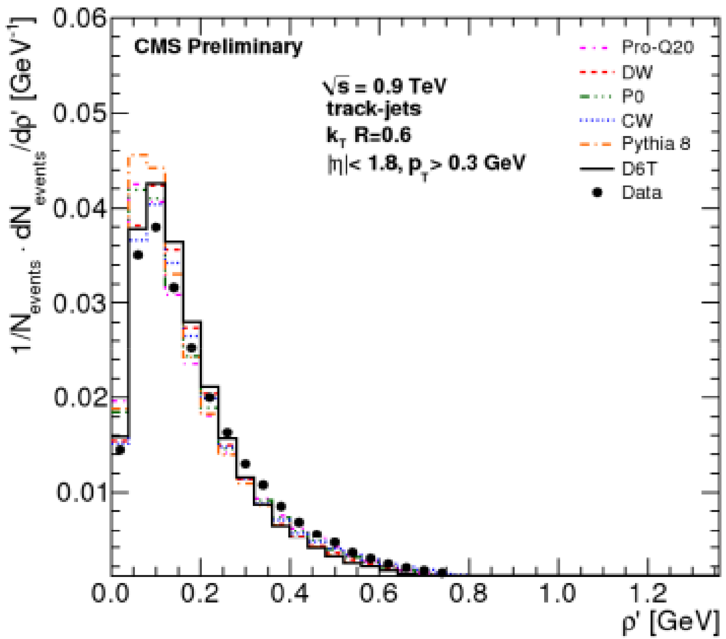
Areas of kt jets are not round. They depend on the surrounding topology

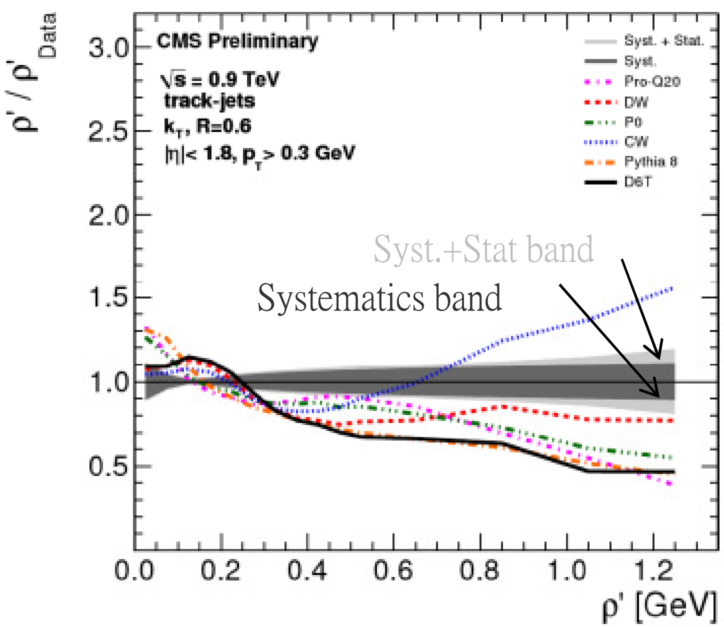
Based on the paper: "On the characterisation of the underlying event" JHEP04(2010)065; M. Cacciari, G. Salam, S. Sapeta.

Jet Area/median: 900GeV results



Tune independence of jet area description





Event & Track Selection identical to the traditional UE measurement at 900 GeV, only differences →

pT track > 0.3 GeV instead of 0.5 GeV
|η| track < 2.3 instead of 2.5
|η| track-jet < 1.8 instead of 2.0

- Complementary UE approach
- Consistent with traditional patterns
- Towards UE and pile-up jet energy corrections

Conclusions and *'coming soon'*

→ Studied the production of charged particles with pT>0.5GeV/c and $|\eta| < 2$ at the LHC, in *pp* collisions at sqrt(s)=7TeV and 900GeV, in the presence of a hard scale (transverse momentum of the leading track-jet, up to 50 GeV/c for 7TeV). Particular attention devoted to the '*transverse region*', most appropriate for the study of the underlying event.

→ Observed strong growth of the UE activity with increasing leading track-jet pT followed above ~8GeV/c (4GeV) for 7TeV (900GeV) by a saturation region with nearly constant multiplicity and small $\sum p_T$ increase.

→ Strong growth of the hadronic activity in the transverse region also observed, for the same value of the leading track-jet pT, with increasing centre-of-mass energy, by comparing data taken by the CMS detector at sqrt(s) = 0.9 and 7 TeV

→ Predictions of several tunes of the PYTHIA program version 6 and of the new version 8, after full detector simulation, have been compared to the data. Simulations describe the gross features of the data but they often fail in details, except for the strongly falling pT distribution. In particular, no PYTHIA-6 model is able to reproduce at 7TeV the fast rise of UE activity with increasing leading track-jet pT , while the plateau-like saturation region is reproduced with variable success, both in shape and in normalization.
A relatively strong dependence of p_{T0} , as in tune DW (with eps= 0.25), compared to a lower value as in tune D6T (eps= 0.16), is preferred.

→ First application on 900GeV data of Jet Area/median approach: sensitiveness to UE description

→ To be soon presented: results fully unfolded (by Bayesian approach) for reconstruction effects, reaching higher event scales for both data collected at 0.9 and 7TeV due to large increase in statistics.

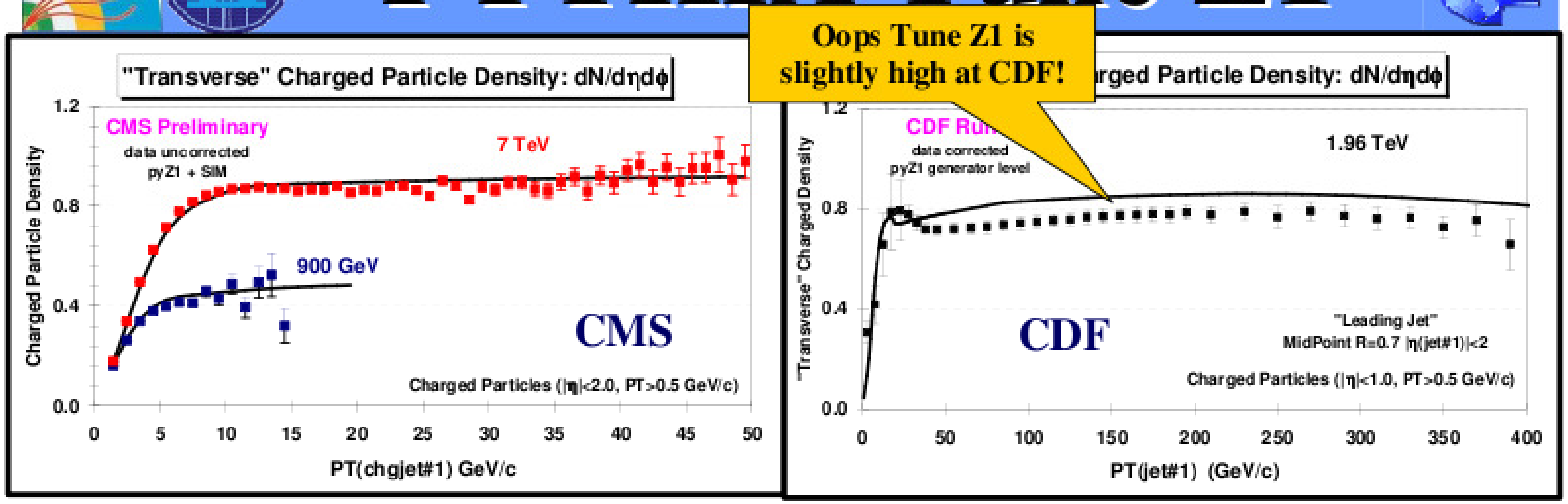
additionals

PYTHIA Tune Z1

Parameters not shown are the PYTHIA 6.4 defaults!

Parameter	Tune Z1 (R. Field CMS)	Tune AMBT1 (ATLAS)
Parton Distribution Function	CTEQ5L	LO*
PARP(82) – MPI Cut-off	1.932	2.292
PARP(89) – Reference energy, E0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.25
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6

PYTHIA Tune Z1



- **CMS preliminary data at 900 GeV and 7 TeV** on the "transverse" charged particle density, dN/dηdφ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA **Tune Z1** after detector simulation.
- **CDF published data at 1.96 TeV** on the "transverse" charged particle density, dN/dηdφ, as defined by the leading calorimeter jet (jet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1.0$. The data are corrected and compared with PYTHIA **Tune Z1** at the generator level.

Jet Area/median: 900GeV systematics

- Very similar treatment as for UE classical approach already shown:

Systematic Effect	Size	Size Estimation Method
Tracker material budget: $\pm 5\%$	0.2%	Constant value independent of ρ'
Minimal z separation between multiple vertices: (10 ± 5) cm	0.5%	
Maximal track $\|\eta\|$: 2.3 ± 0.2	0.5%	
Significances of track impact parameters: $(5 \pm 1)\sigma$	0.5%	
Maximal track p_{T} uncertainty $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$: $(5 \pm 2)\%$	0.4%	
Track-jet p_{T} resolution: 5%	0.5%	
Tracker alignment	0.6%	Derived bin-by-bin in ρ' from fit (Quoted at rho'~1.2, maximal effects)
Tracker map of non-operational channels	2.3%	
Data - MC track efficiency & fake rate mismatch: $\pm 2\%$	6.0%	
Minimal track p_{T}: (300 ± 30) MeV	5.8%	
Track-jet response shift: $\pm 1.7\%$	5.6%	
Trigger efficiency bias	3.1%	

Jet Area/median method

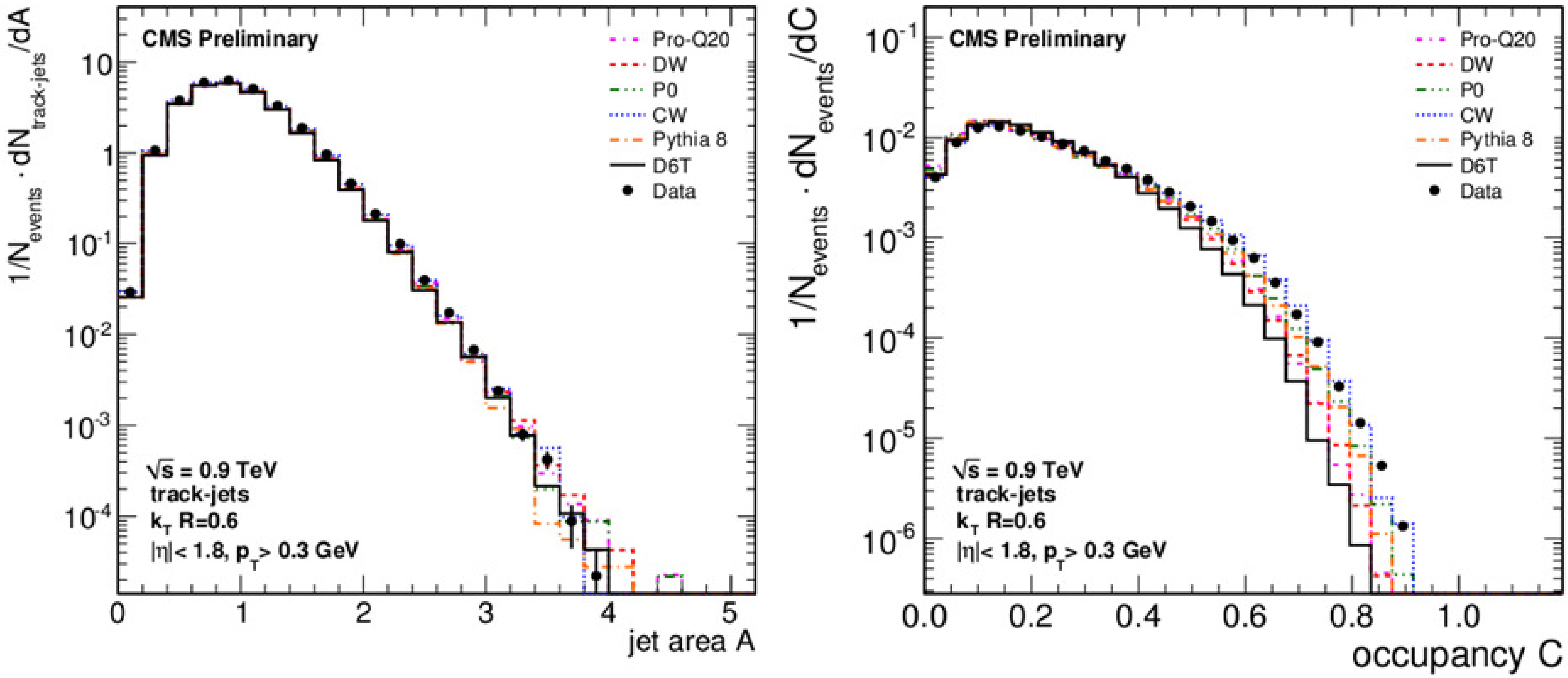


Figure 3: Normalized jet area distribution (left) and area occupancy (right) of track-jets in data (black circles) and for different PYTHIA 6 tunes and PYTHIA 8 default tune: higher track multiplicities are reflected by higher numbers of track-jets and also by larger occupancies due to the better area coverage.

Jet Area/median method

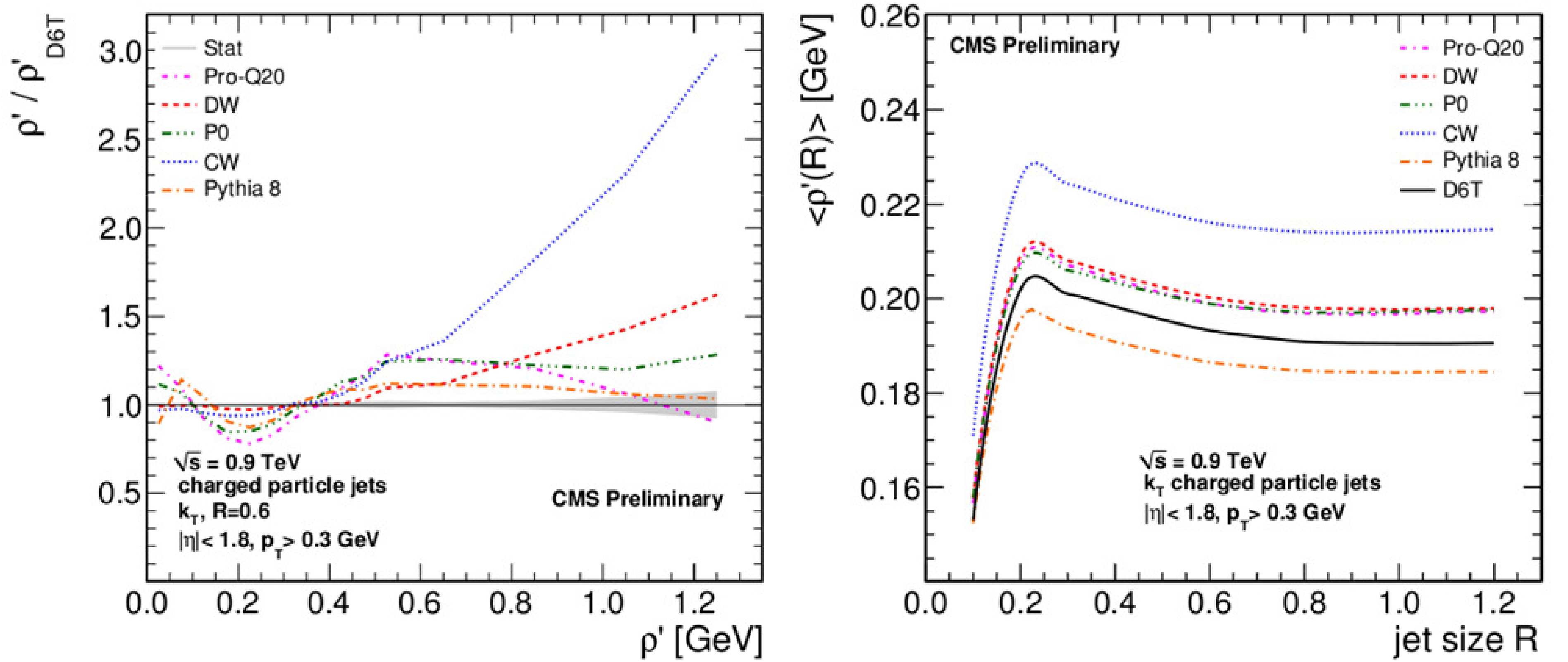


Figure 4: Median of jet p_T over area of charged particle jets for the different PYTHIA 6 tunes and PYTHIA 8 default tune relative to PYTHIA 6 tune D6T (left). The light-gray shaded band corresponds to the statistical uncertainty. Dependence of the mean of the ρ' distribution for the different tunes on the jet size R with charged particle jets (right).