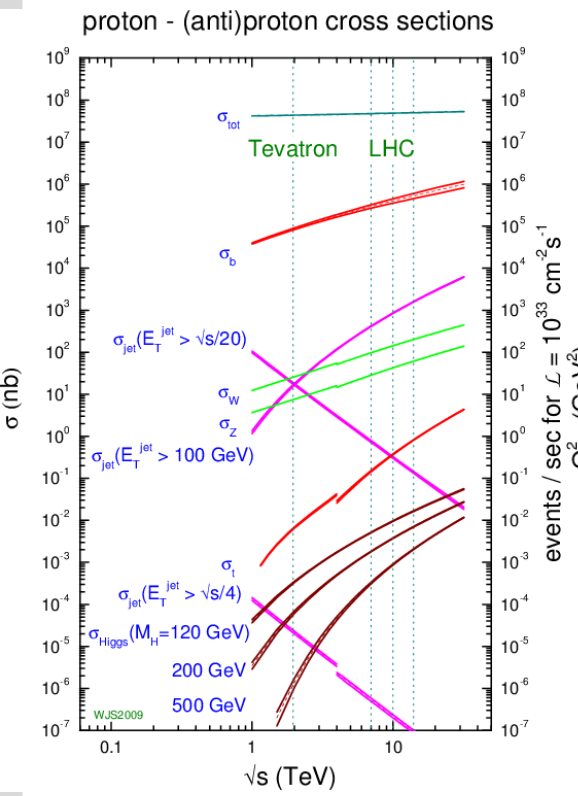
Karlsruhe Institute of Technology

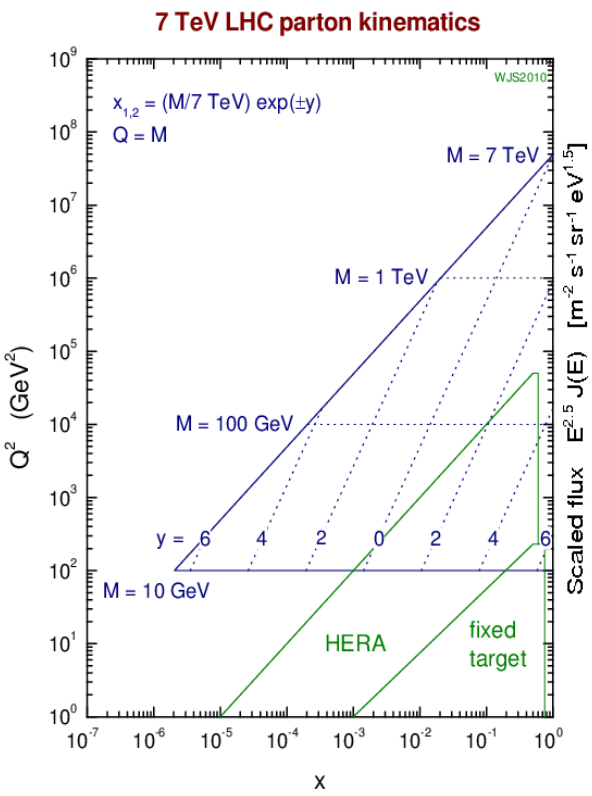
# QCD and forward results from CMS

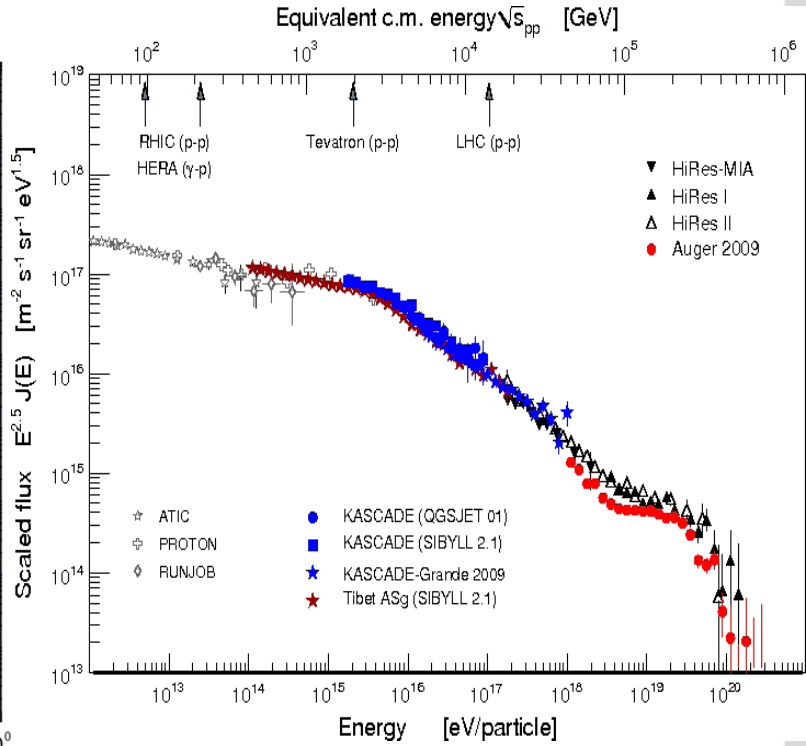
**Igor Katkov**

On behalf of the CMS Collaboration

# (Yet another) Motivation

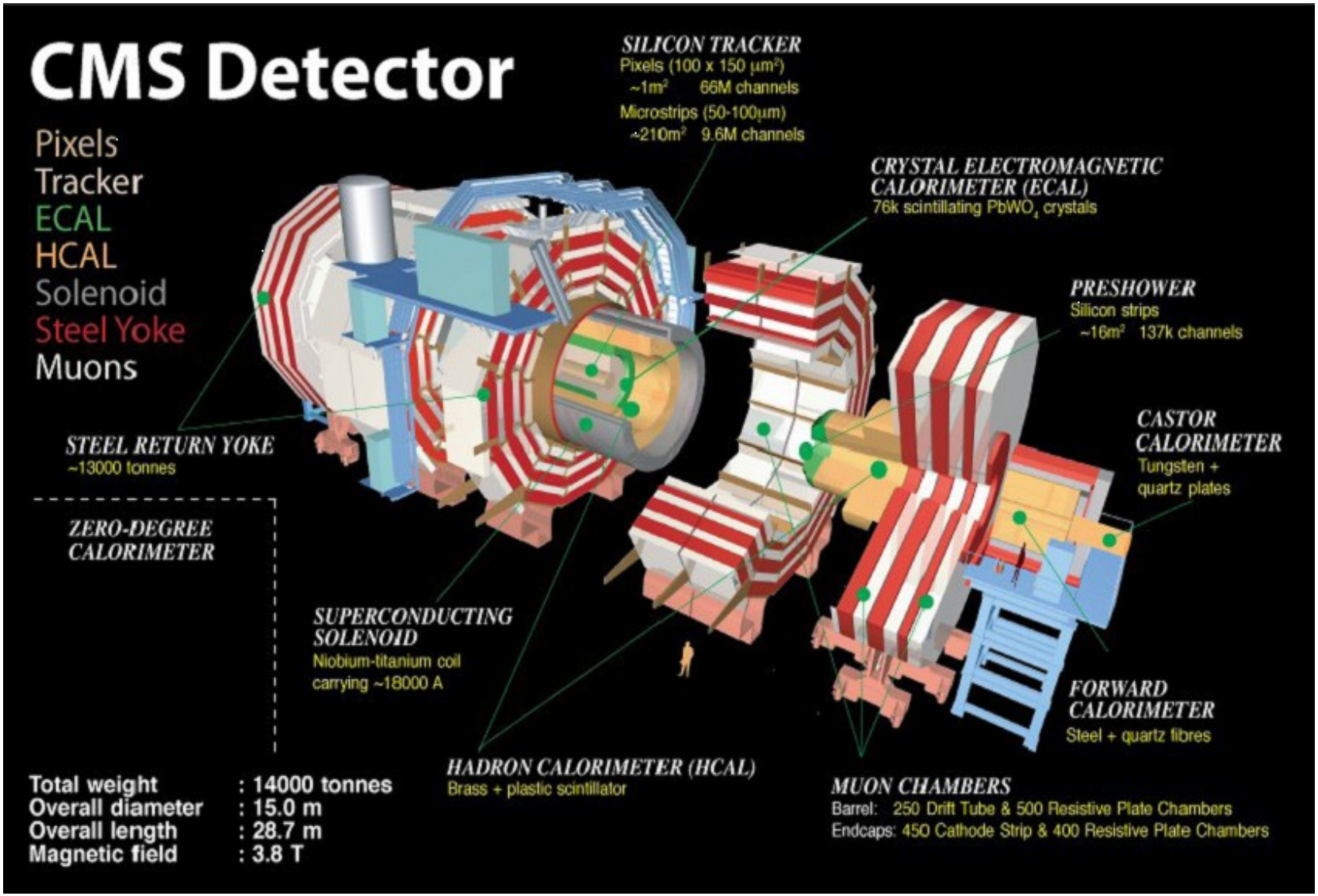


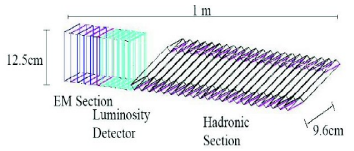

- Understanding of QCD at new energy frontier

www.hep.phy.cam.ac.uk/~wjs
Astroparticle Physics 35 (2011) 98


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
CASTOR CALORIMETER
Tungsten + quartz plates
STEEL RETURN YOKE
~13000 tonnes
ZERO-DEGREE CALORIMETER
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

# CMS forward detectors

ZDC (|η| > 8.1)




Rotating

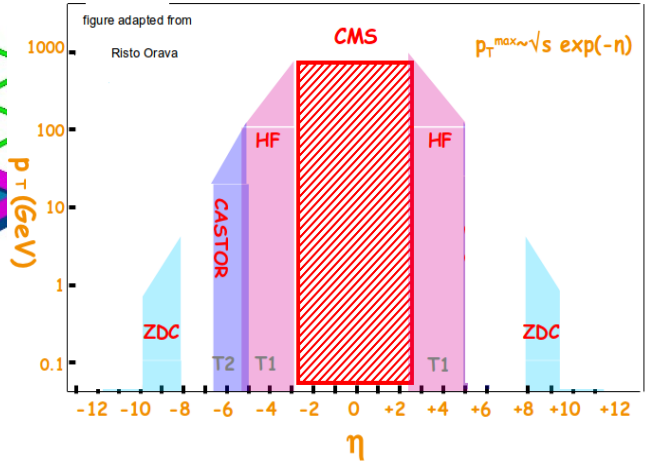
Collar

HF (3 < |η| < 5)

TOTEM/ T1

CASTOR ( -6.6< η< -5.2 )

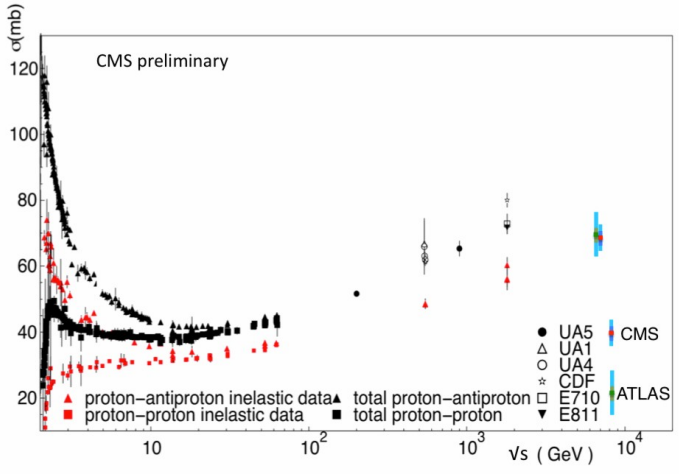
T2



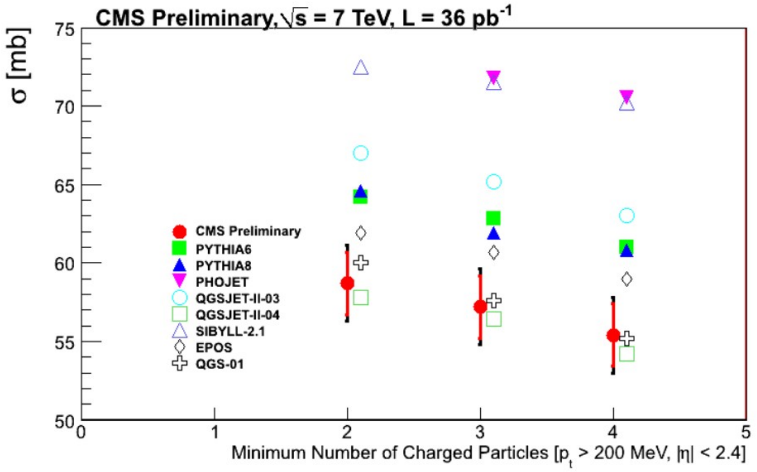

- Cherenkov/quartz calorimetry in the forward region (HF @ 11.2m / CASTORcal @ 14.4m / ZDC @ 140m) to meet design challenges

# Total inelastic cross section: turn pile-up into advantage to measure fundamental quantity

CMS PAS FWD-11-001

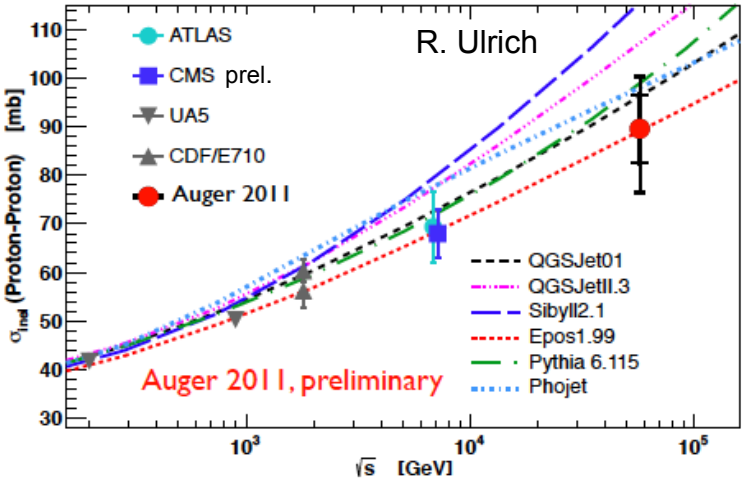



Courtesy of arXiv:1102.1949

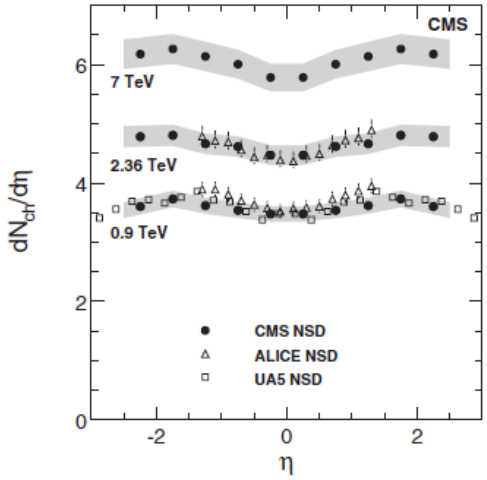


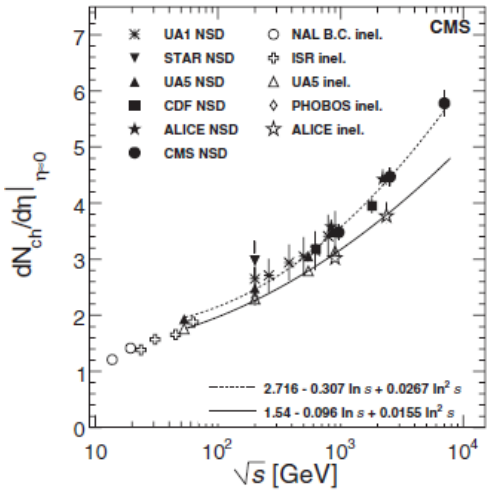

- Vertex multiplicity in bins of $L_{inst}$
- Correct for vtx efficiency for at least N central particles
- Derive σ from fit assuming Poisson dependence of pile-up vs lumi
- Extrapolate to total σ with MC

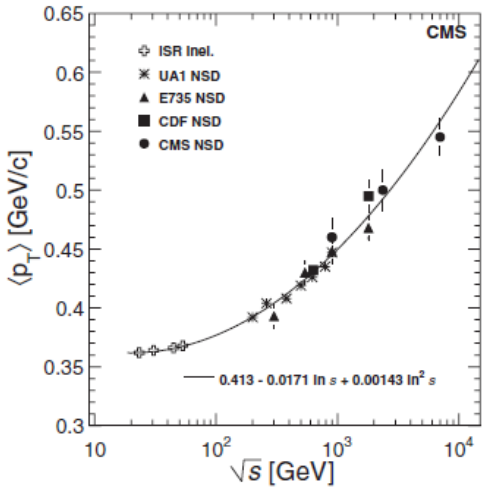
$$\sigma_{inel} = 68 \pm 2.0(syst.) \pm 2.4(lumi) \pm 4(ext.)$$

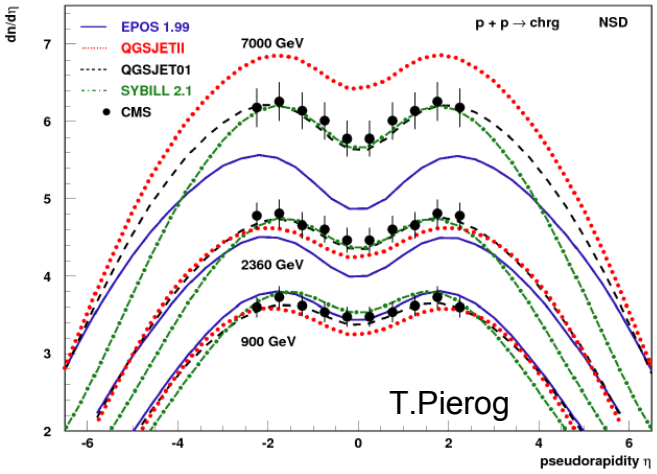


# Single charged particle spectra



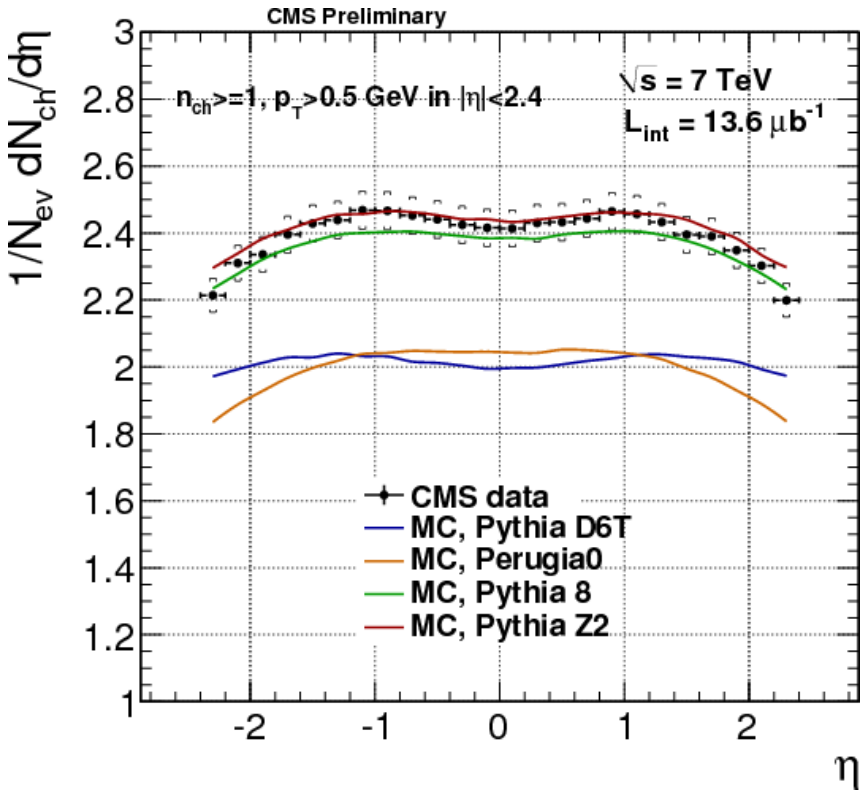



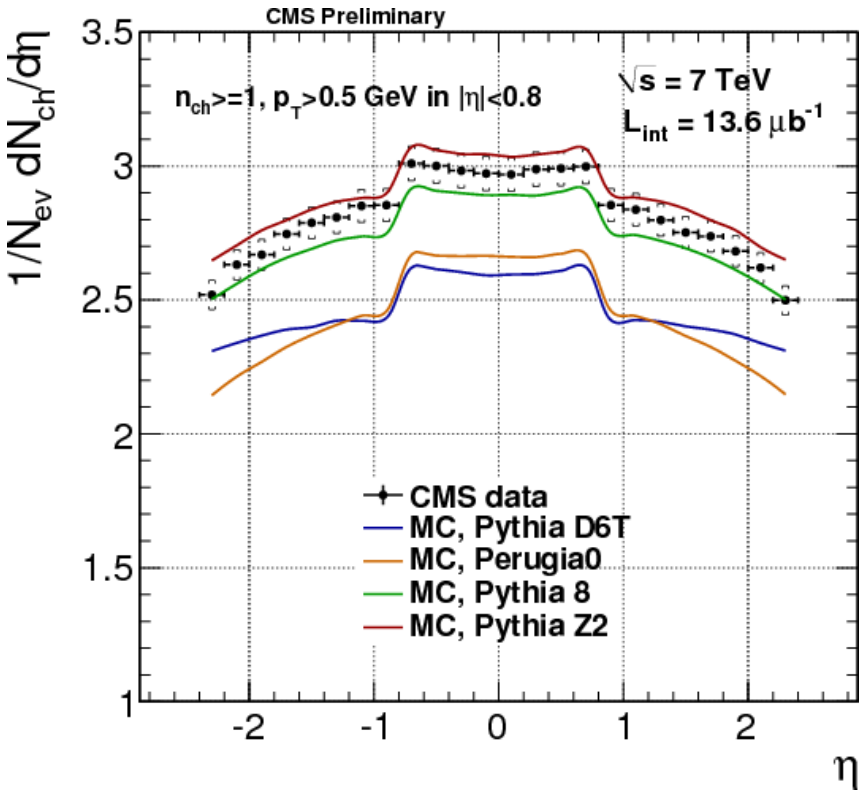




- Measurements for different experiments in agreement
- Spectra steeply increasing with energy
- NSD ↔ model dependence

PRL 105 (2010) 022002

# Single charged particle spectra ($n_{ch}$ >=1)

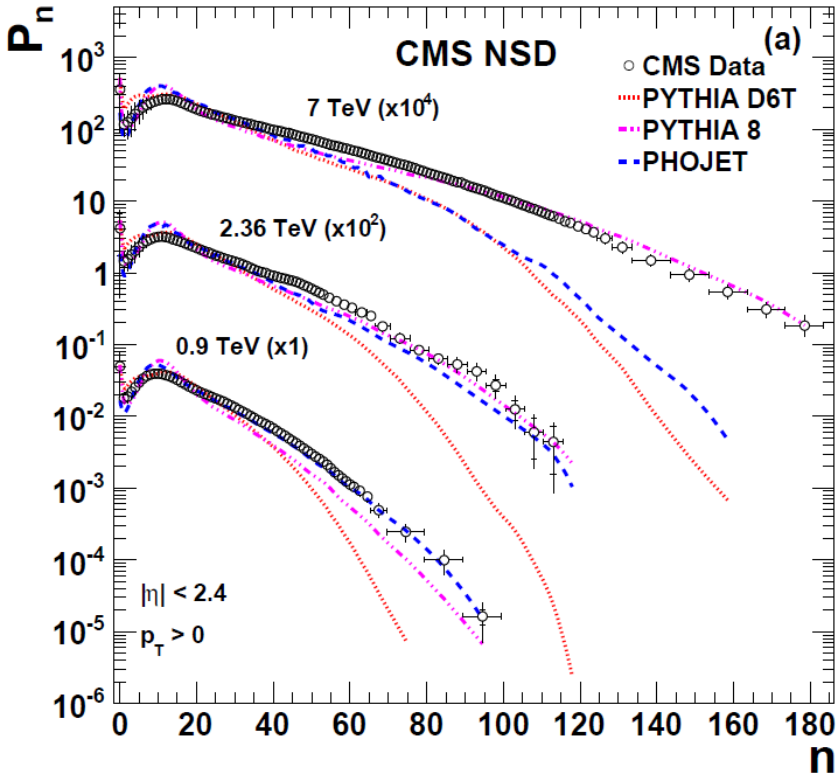


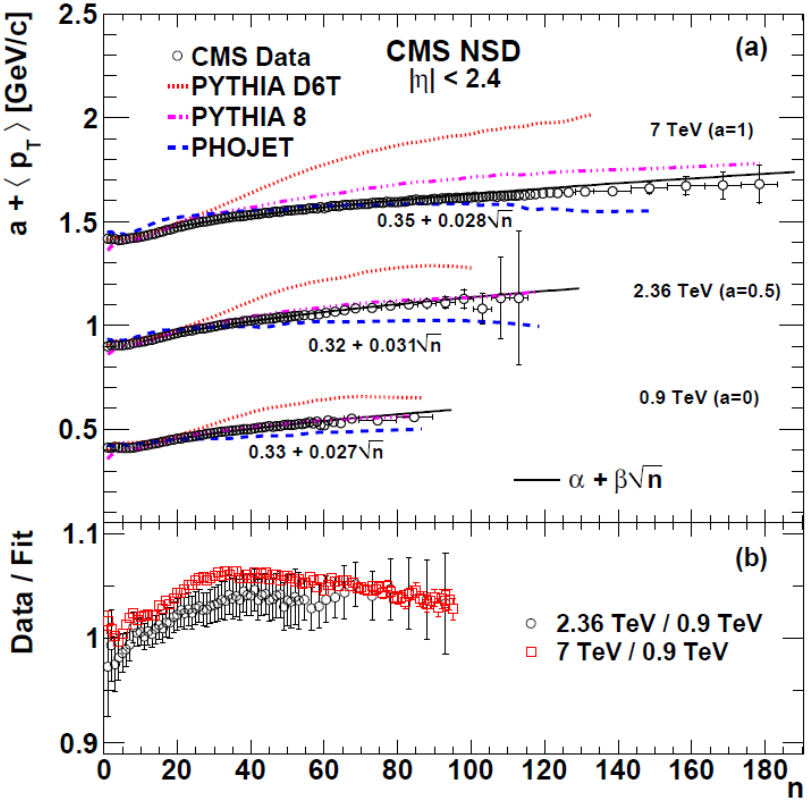




- Reduce model dependence for comparisons / tuning
- Pre-LHC tunes fail

CMS PAPER QCD-10-024

# Charged particle multiplicities

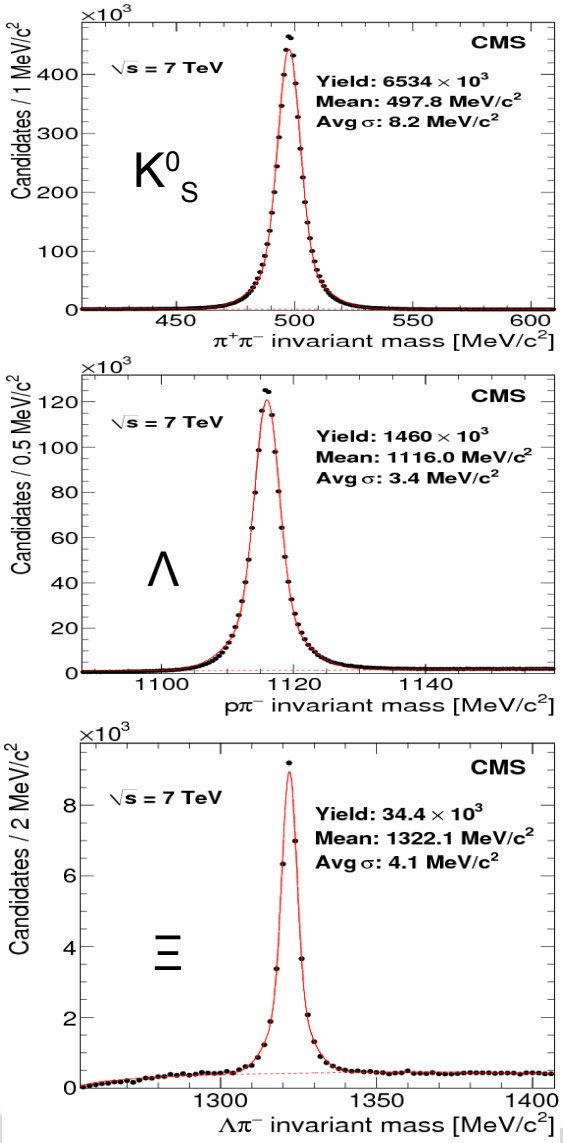


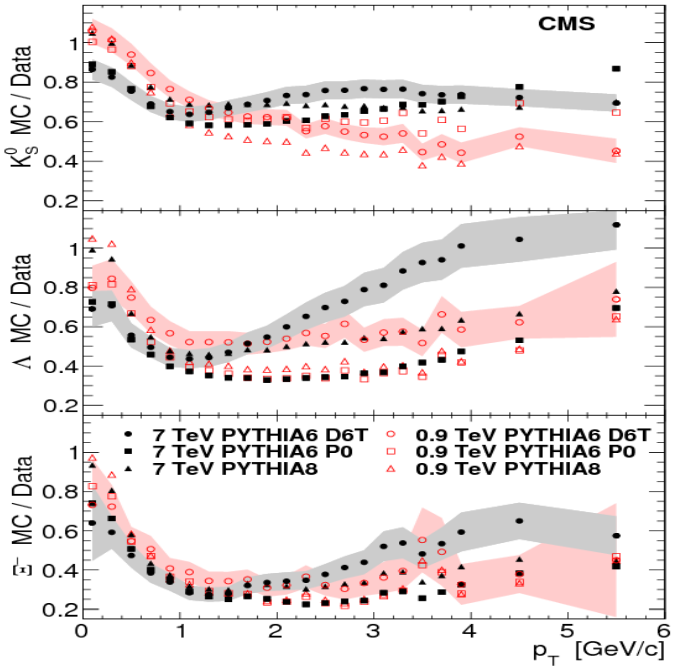



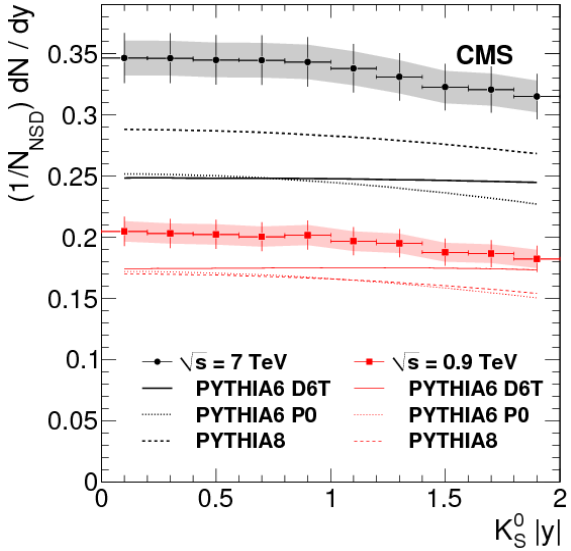

- Information on many “tunable” aspects: diffraction, MPI, saturation
- No model can describe energy dependence; multiplicity and average transverse momentum at the same time

JHEP 01 (2011) 079

# Identified particle spectra: strange particle production



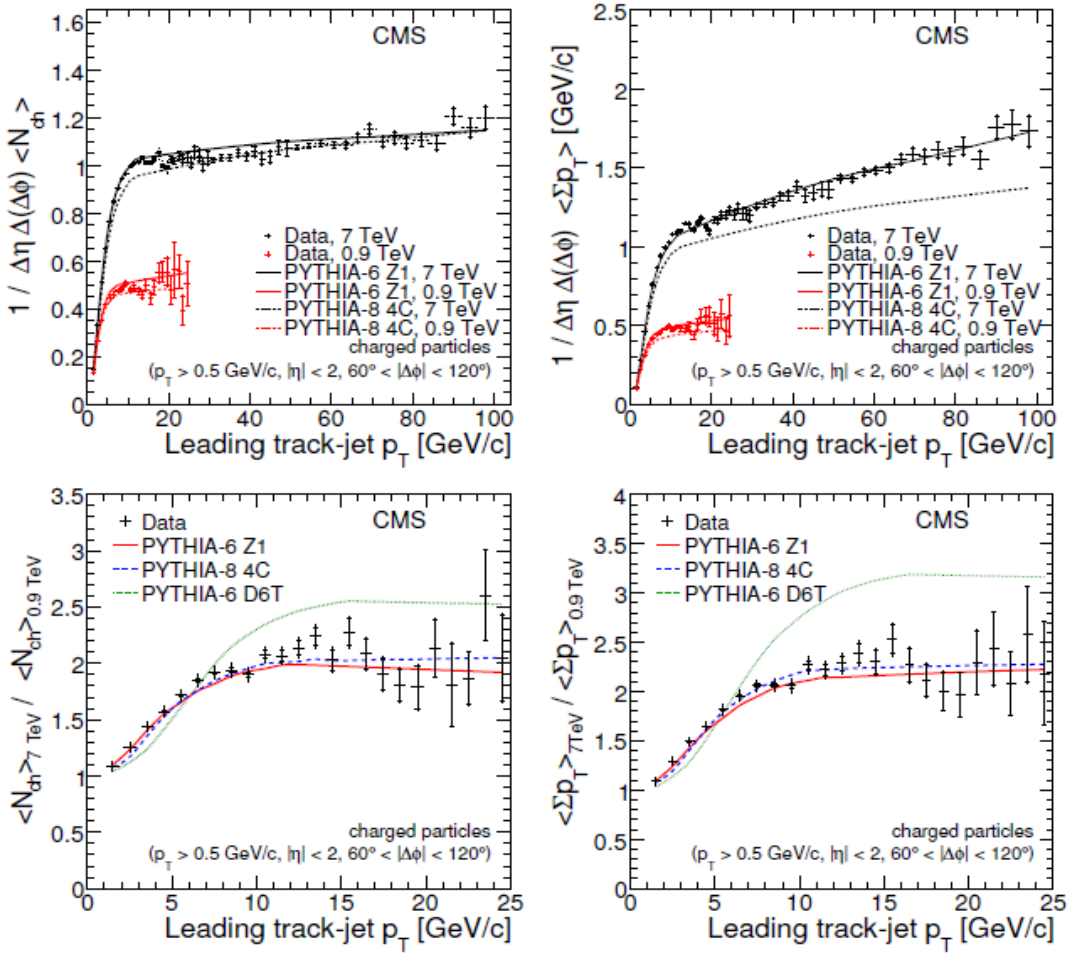



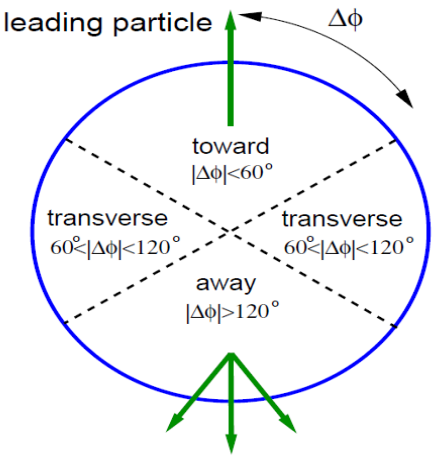




- Strangeness / baryon production
- MC undershoots data, especially for $\Xi^-$, up to factor 3 at 7 TeV

JHEP05(2011)064

# (Classical) Underlying event studies

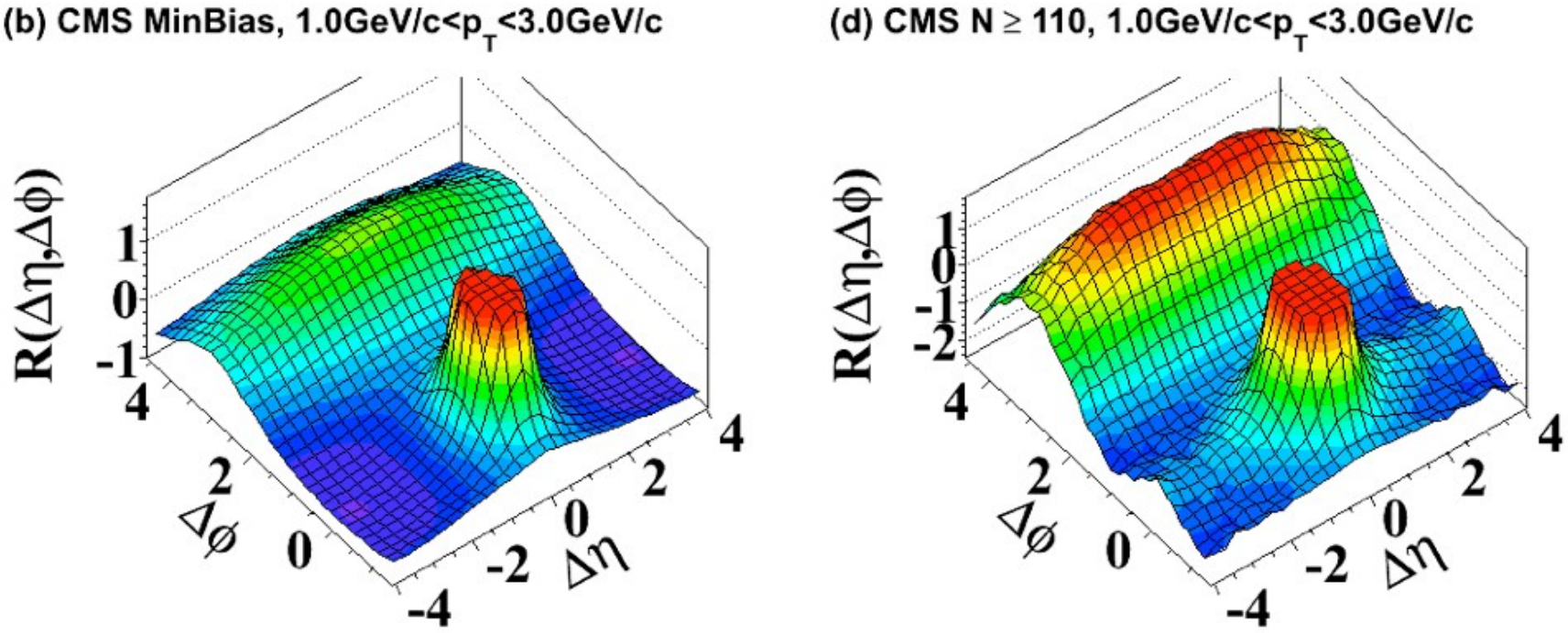



- Strong increase of UE activity from 0.9 to 7 TeV
- Well described by parton shower MC tunes...
- But what about Tevatron data at the same time

JHEP09(2011)109

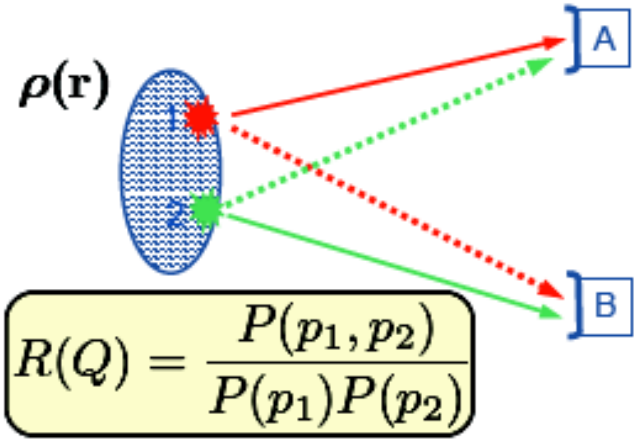
# Correlations: “ridge effect”

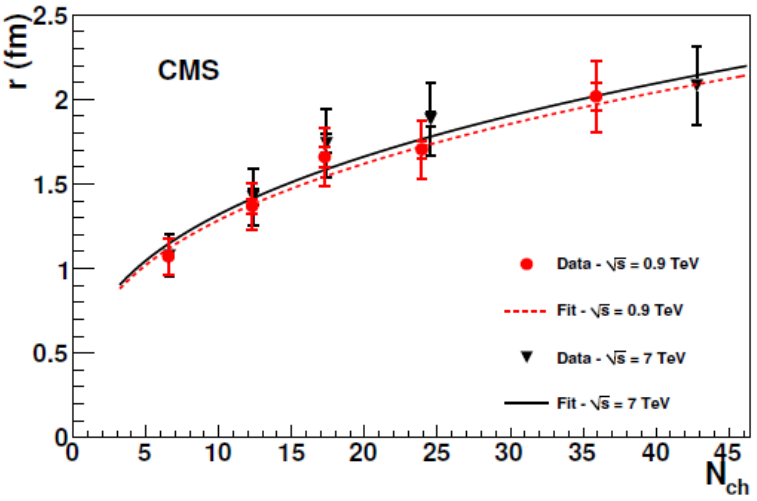


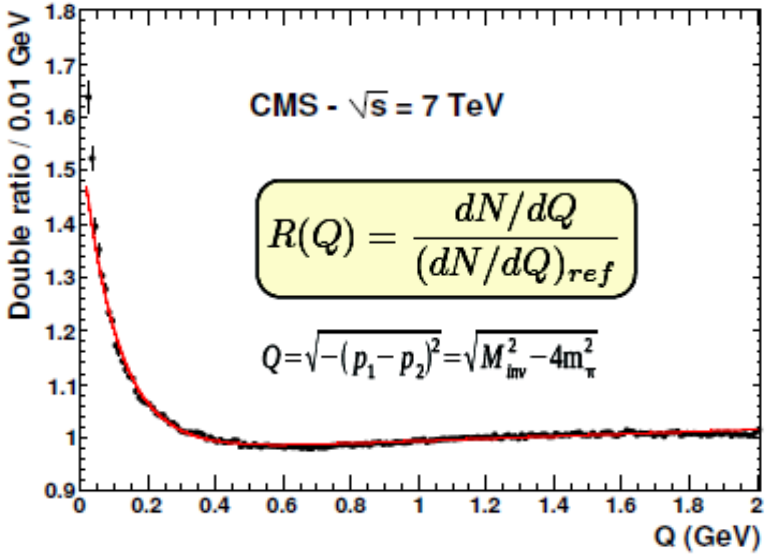

- Measurements motivated by effect observed in HI collisions at RHIC
- Long-range, near-side angular correlations in high multiplicity pp events at intermediate $p_T$ (ridge at $\Delta\varphi \sim 0$)
- Not in usual HEP MC models; hydrodynamical nature like in HI?

JHEP 09 (2010) 091

# Bose-Einstein correlations



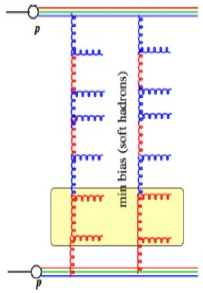



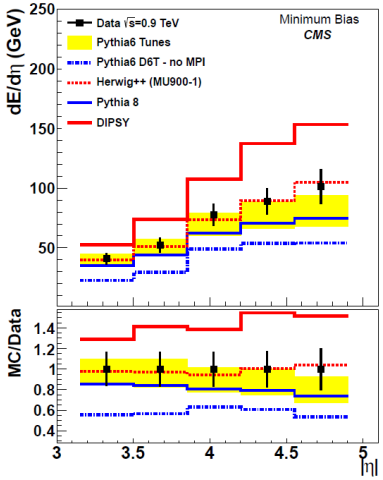



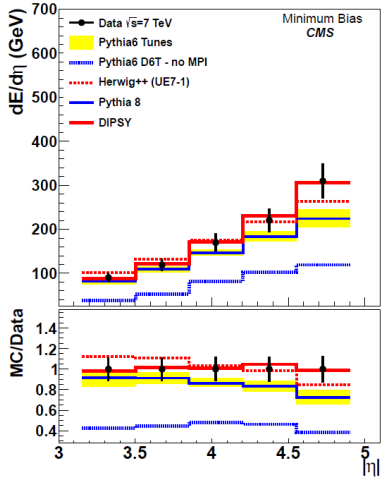

- Effective emission region grows with multiplicity; energy scaling

JHEP05(2011)029

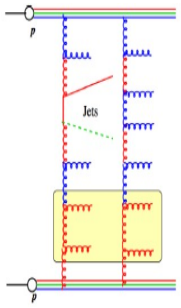
# Forward energy flow

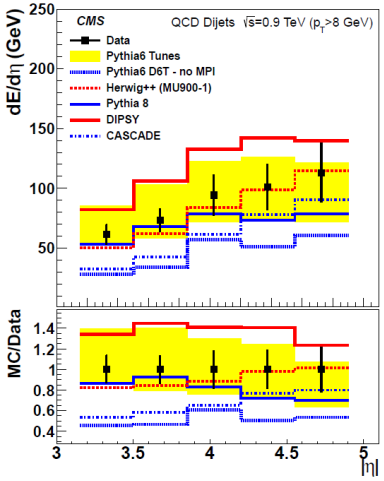


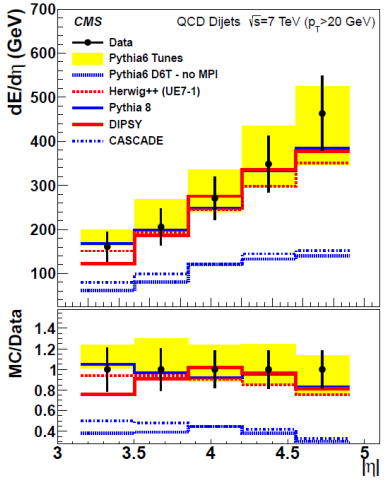



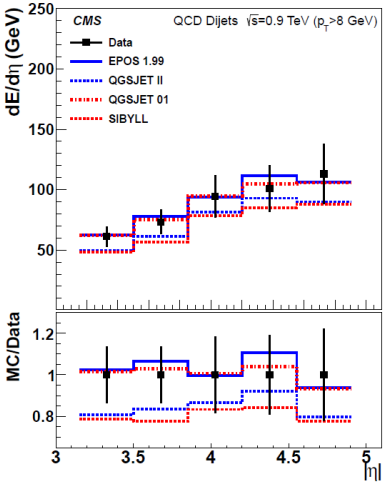



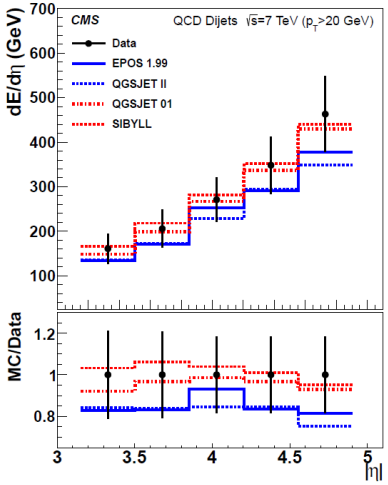

- Strong rise of energy flow with energy
- Energy flow increase for dijets
- Without MPI models fail
- Cosmic ray models best



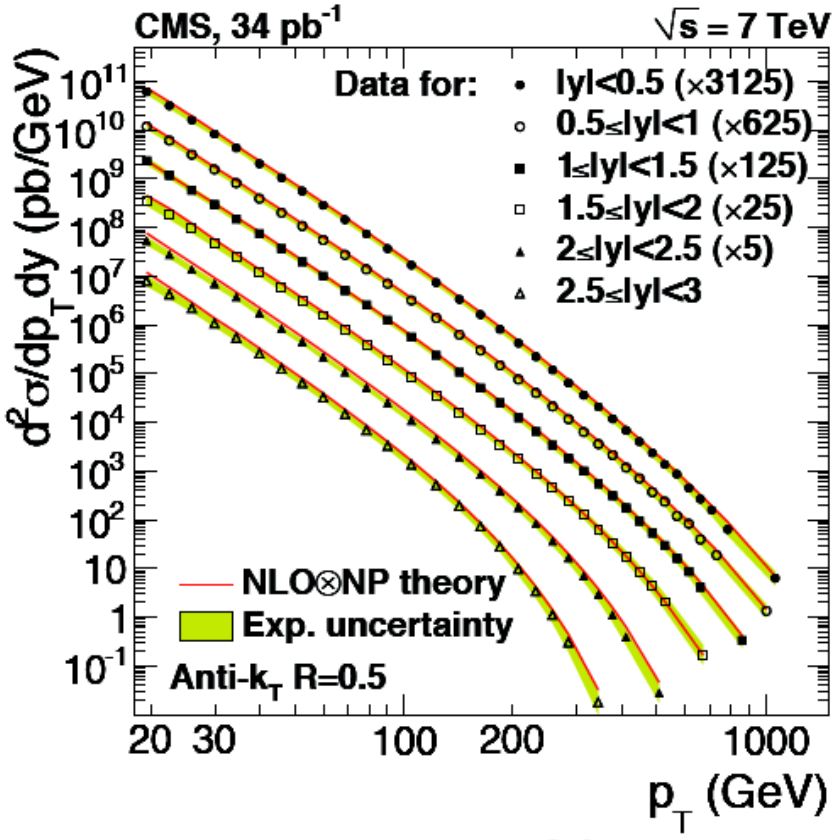




cdsweb.cern.ch/record/1386739 / arXiv:1110.0211 / CMS PAPER FWD-10-011

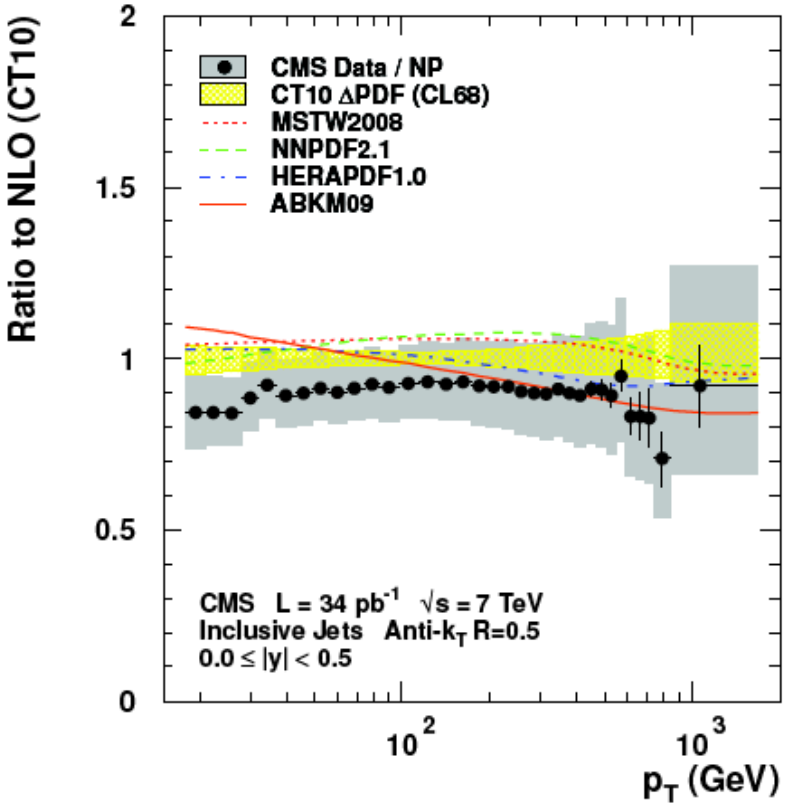
# Double differential inclusive jet cross sections for central rapidities

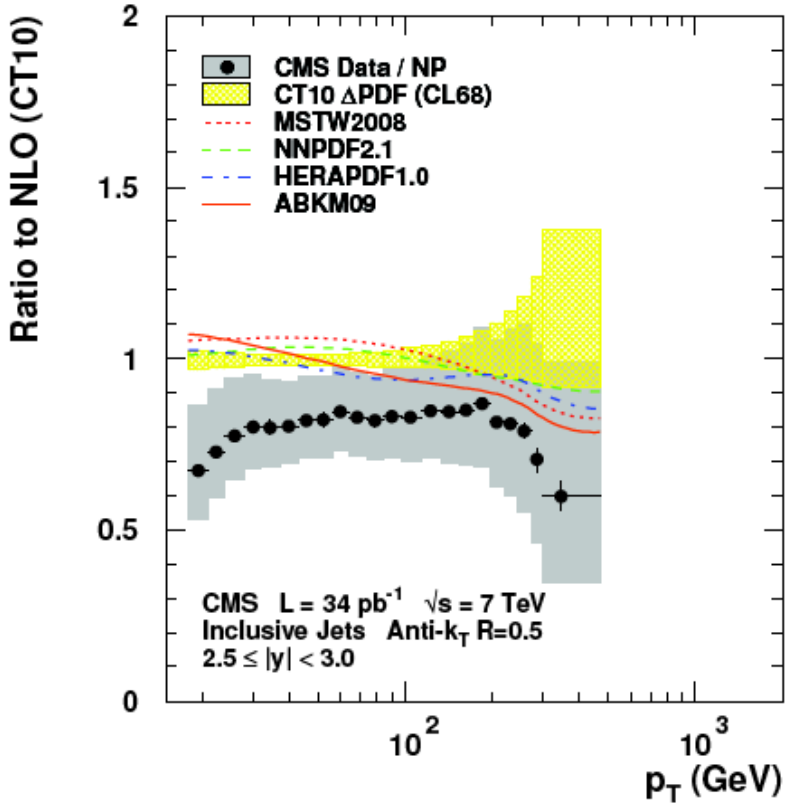
- Anti-$k_T$ particle flow jets with R = 0.5
- Measured wide range in $p_T$
- Simple bin-by-bin correction
- Compared to NLOJet++ (fastNLO)




PRL 107 (2011) 132001

# Inclusive jets: comparisons to PDFs

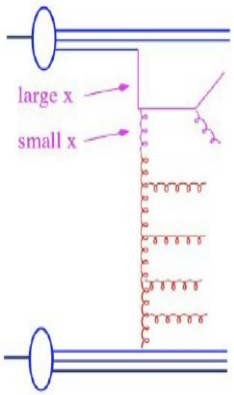


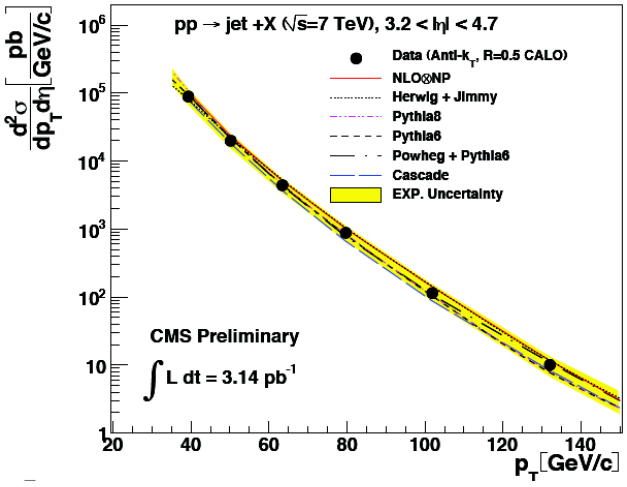



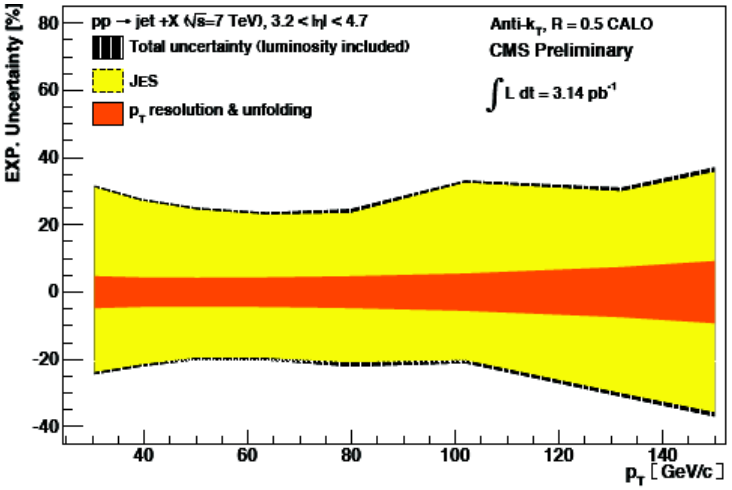

- Better agreement in central rapidity bins and at higher $p_T$

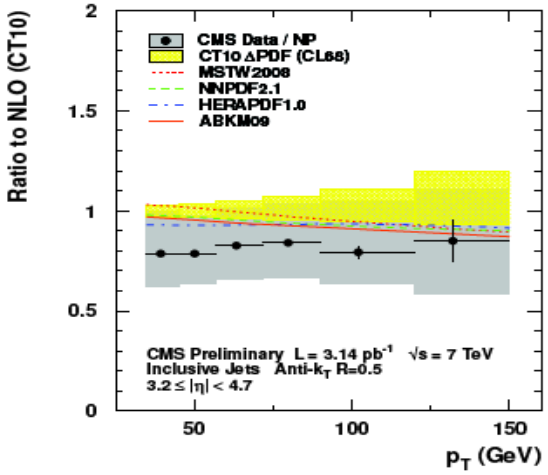
CMS-NOTE-2011-004

# Inclusive forward jets



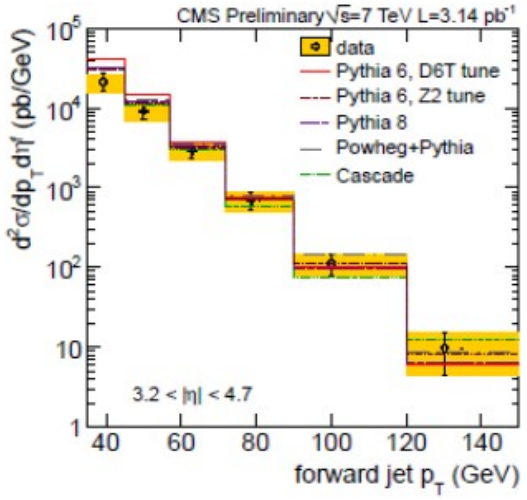



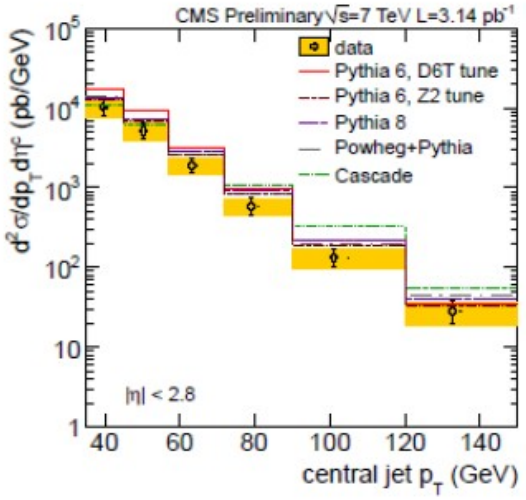



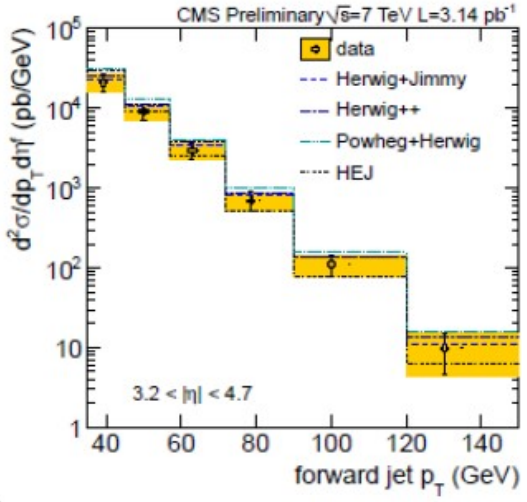

- In reasonable agreement with predictions within large JES uncertainties

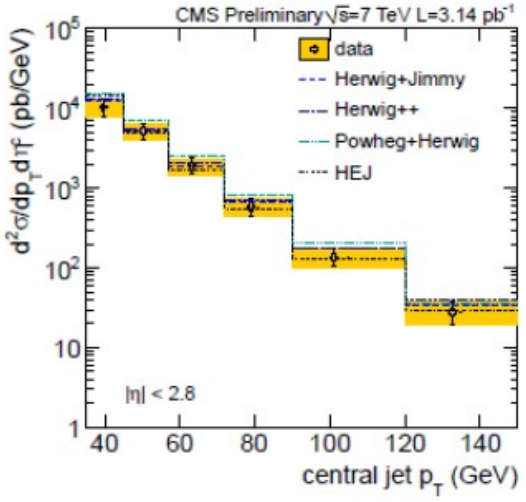
CMS PAS FWD-10-003

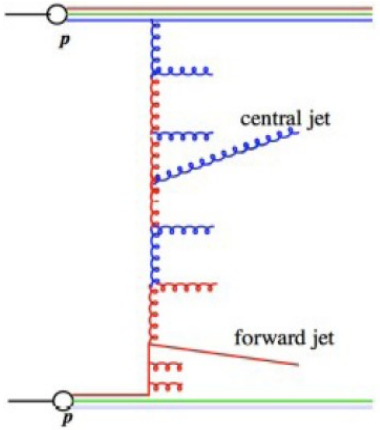
# Forward-central jets



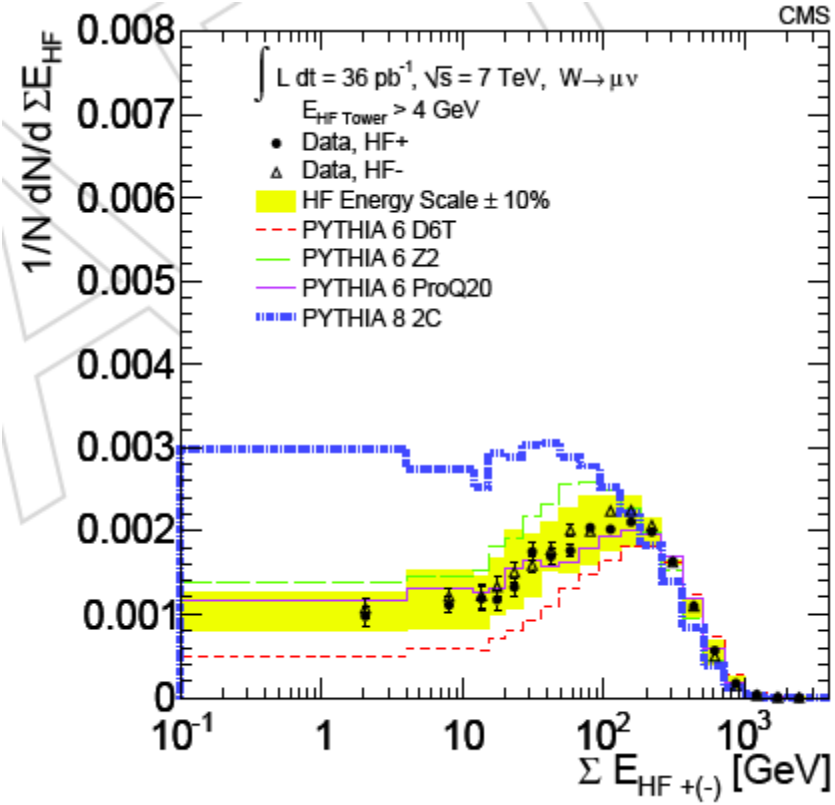



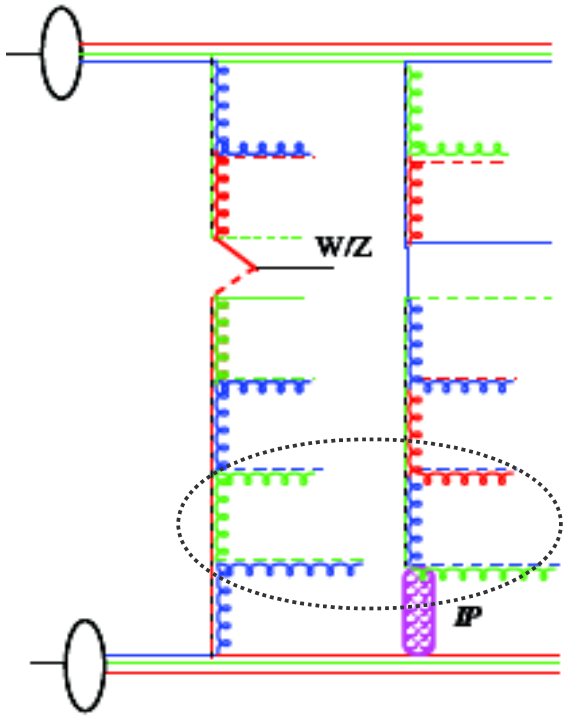




- BFKL vs DGLAP
- Wide spread in predictions
- Correlations pose a challenge for description

CMS PAS FWD-10-006

# Energy flow with W/Z production

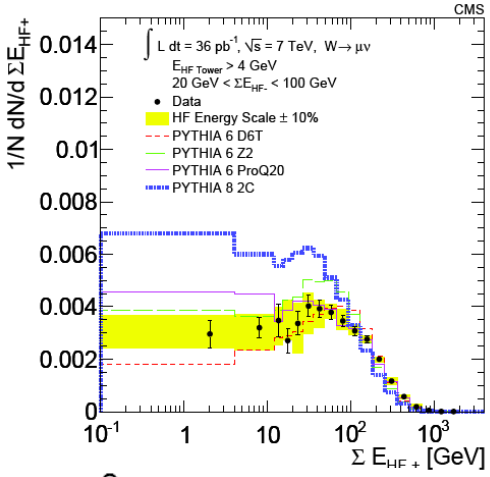


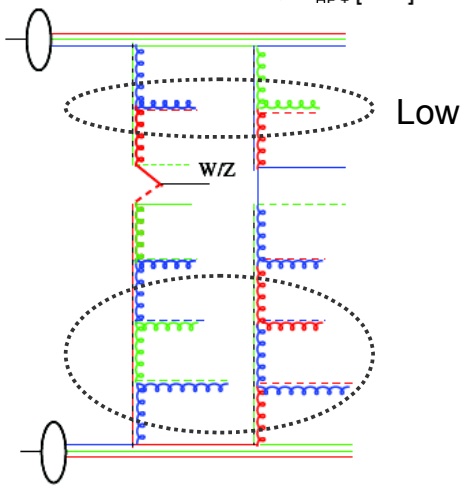




- Explore underlying event / MPI in event / diffraction

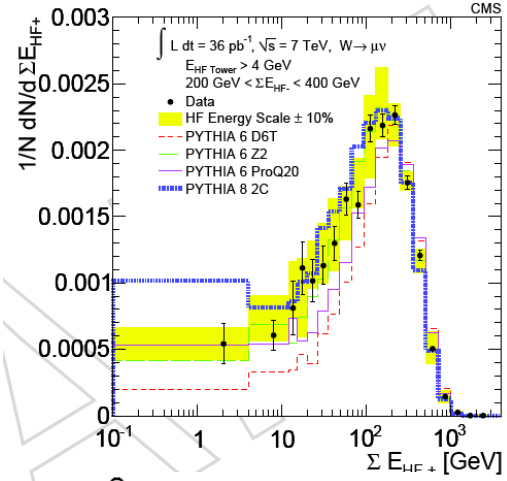
CMS PAPER FWD-10-008

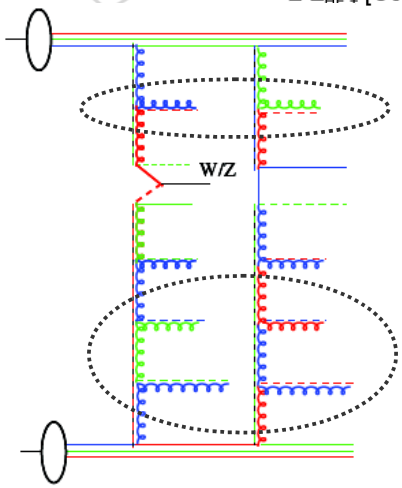
# Energy flow with W/Z production (cont'd)



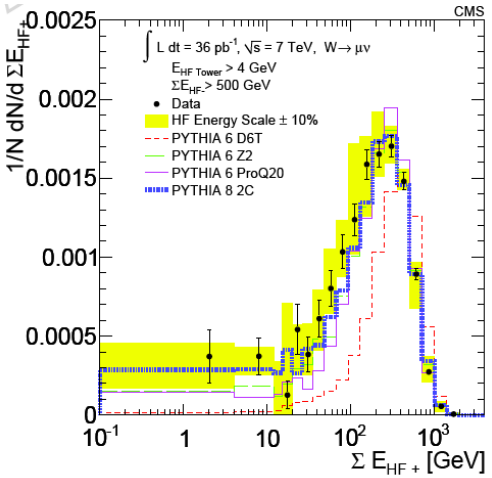



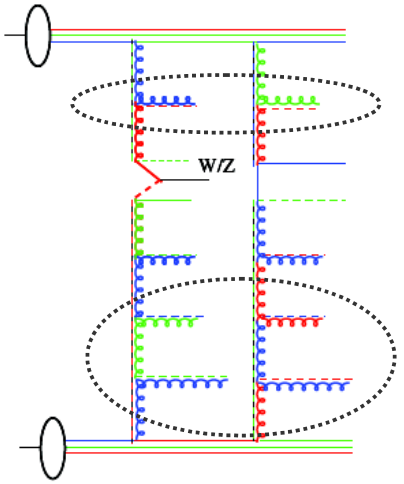

Low




Medium

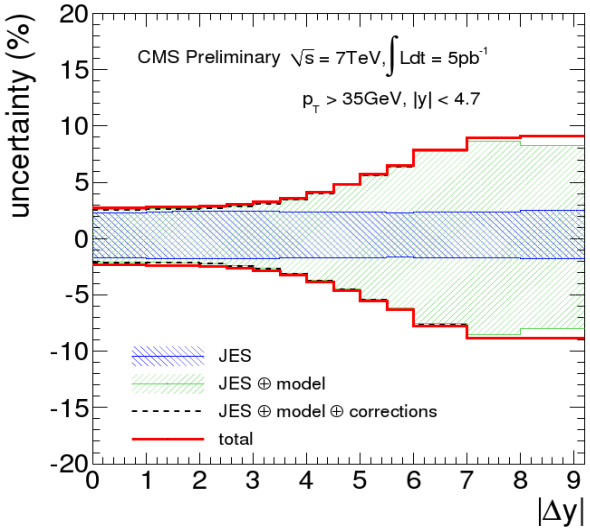


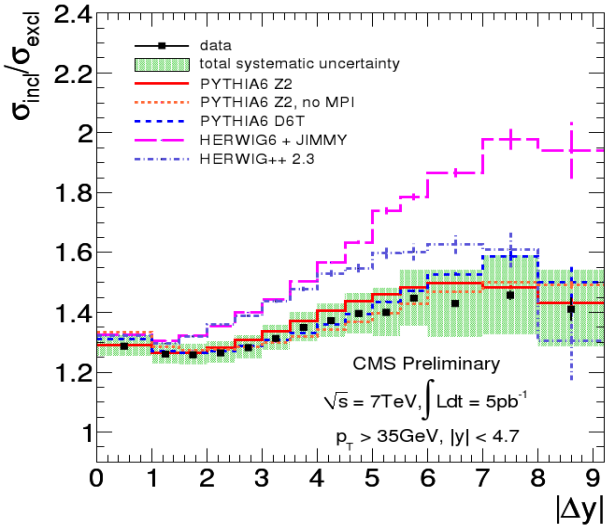




High

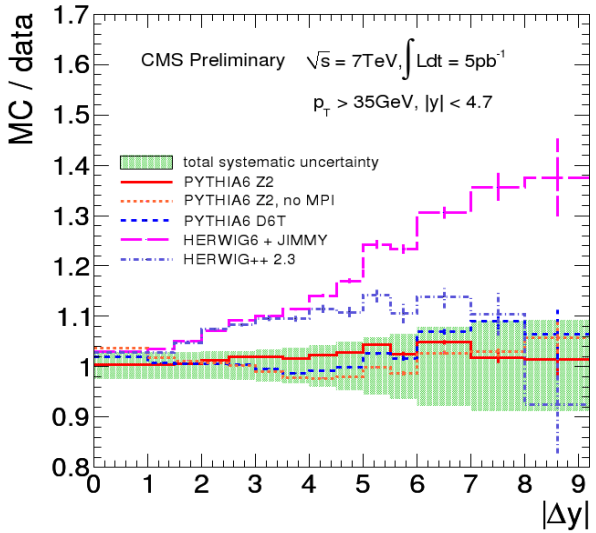
- Forward/backward strongly correlated; not well modeled

# Inclusive to exclusive di-jet ratio

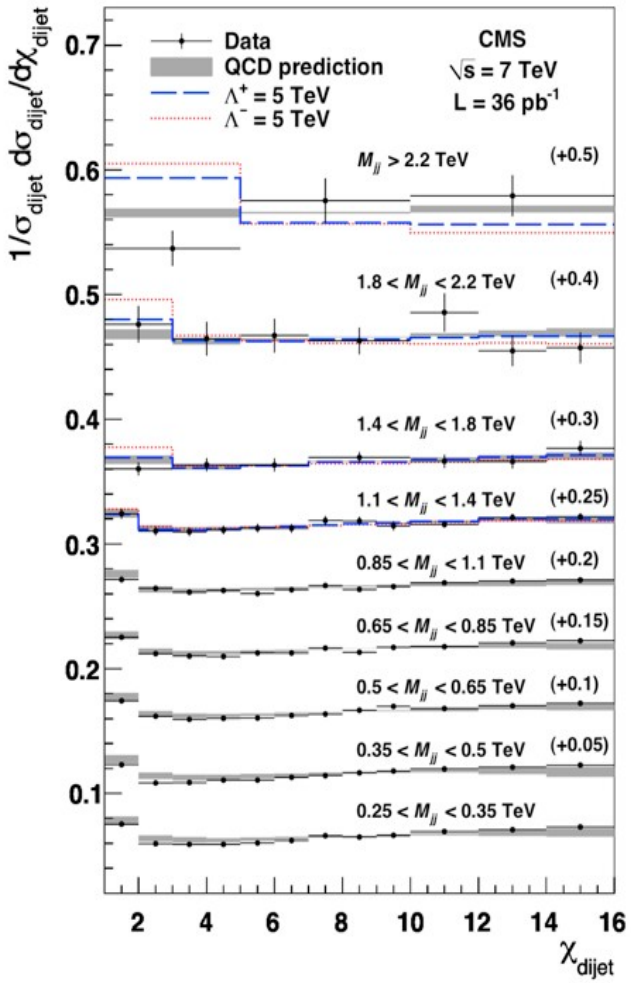


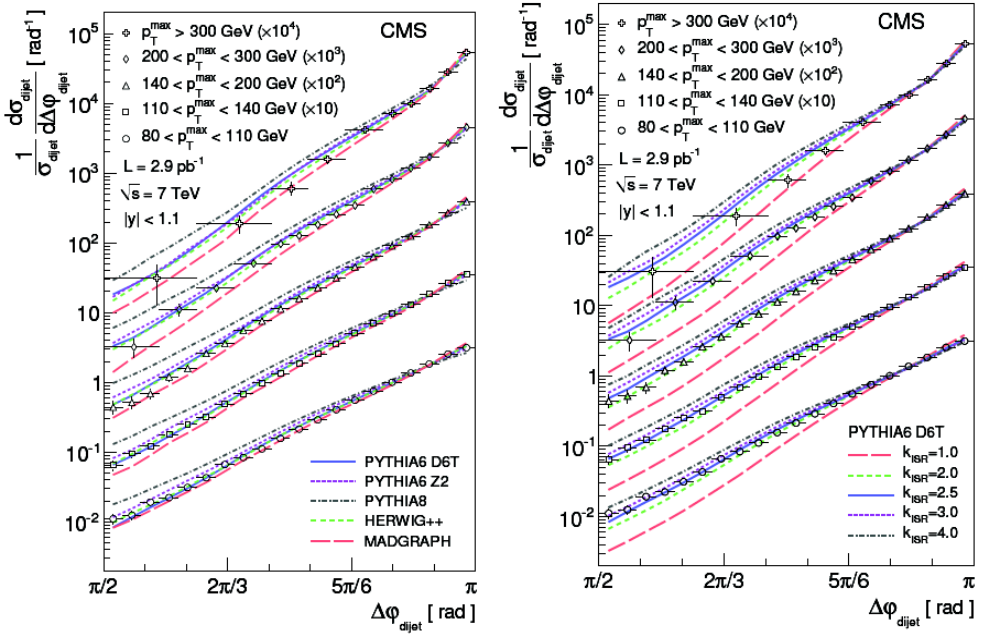




- Large rapidity separation to proble effects beyond DGLAP
- Rise of R = $\sigma_{incl}$ / $\sigma_{excl}$ with Δy as phase space for parton emission opens
- In agreement with PYTHIA6 predictions within uncertainties



# Double differential di-jet distributions

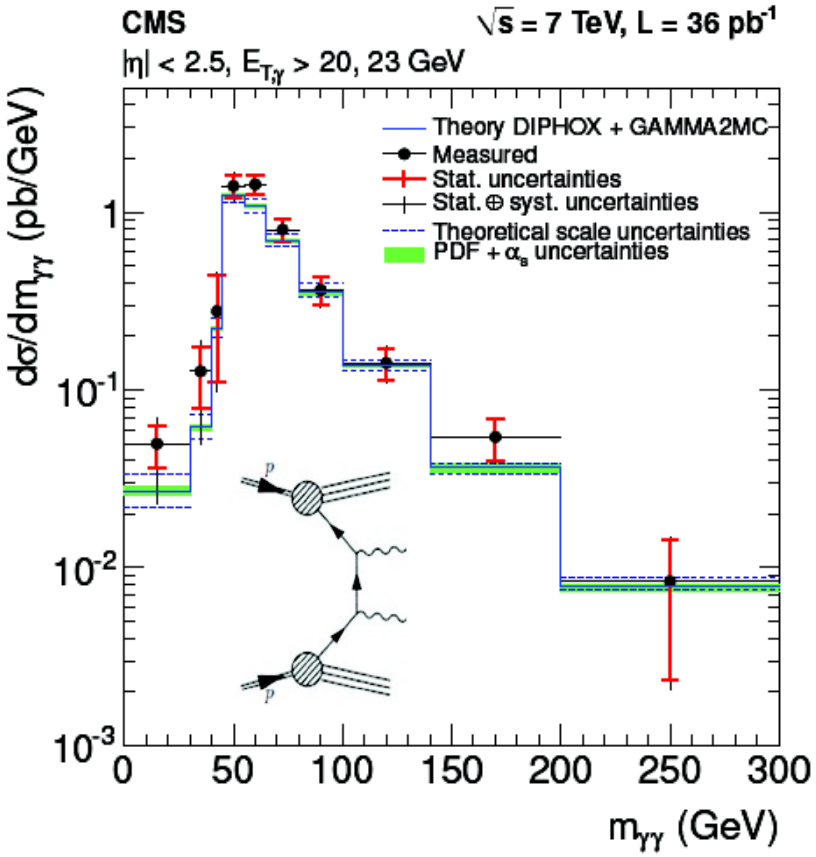


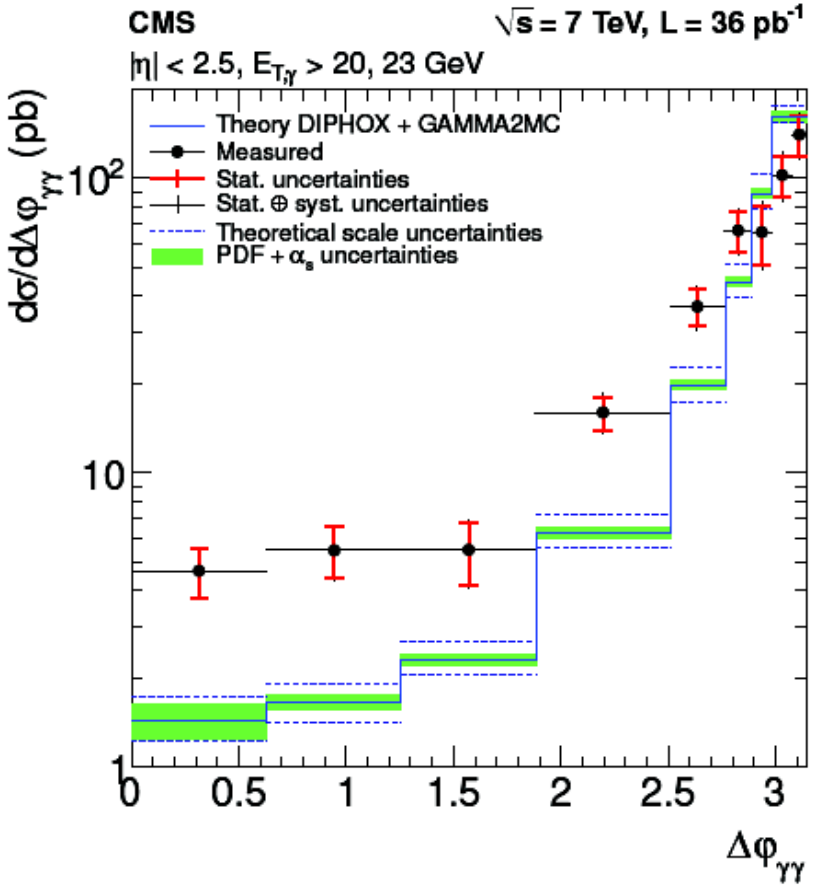




- Stringent test of QCD, sensitivity to new physics
- pQCD @ NLO and parton shower MC describe data, sensitivity to modeling of ISR

PRL 106 (2011) 201804
PRL 106 (2011) 122003

# Di-photon cross sections




- Irreducible background to H → γγ
- Measured cross section underestimated at low Δφ, low masses

# Summary

- Wide spectrum of QCD measurements performed at LHC energies offered to public allowing further tests in the unique kinematic regime
- Reasonable description for inclusive measurements; (de)correlations in several cases pose a challenge
- Especially high-$p_T$ analyses can profit from huge data sample of 2011 as pile-up is not a big issue
- Soft QCD/forward studies need e.g. dedicated low lumi runs to extend their data samples

# BACKUP

# Acknowledgments


- X. Janssen
- H. Jung
- K. Kousouris
- G. Safronov

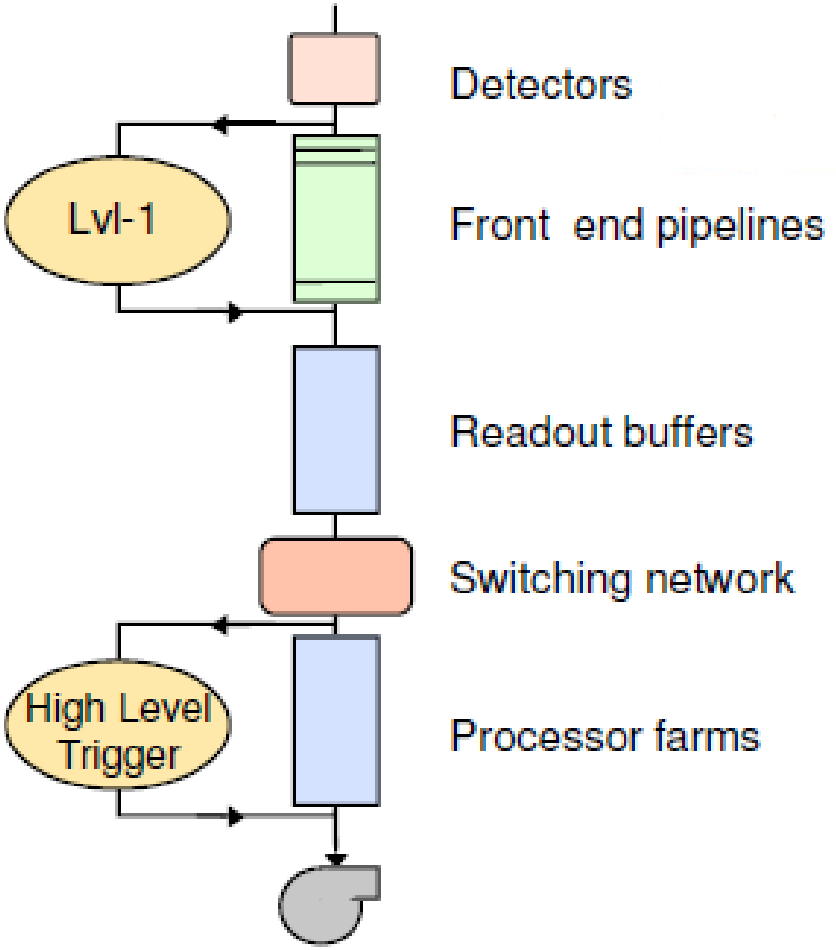
# Two level trigger system

- < 100 kHz @ L1, O(100) Hz @ HLT

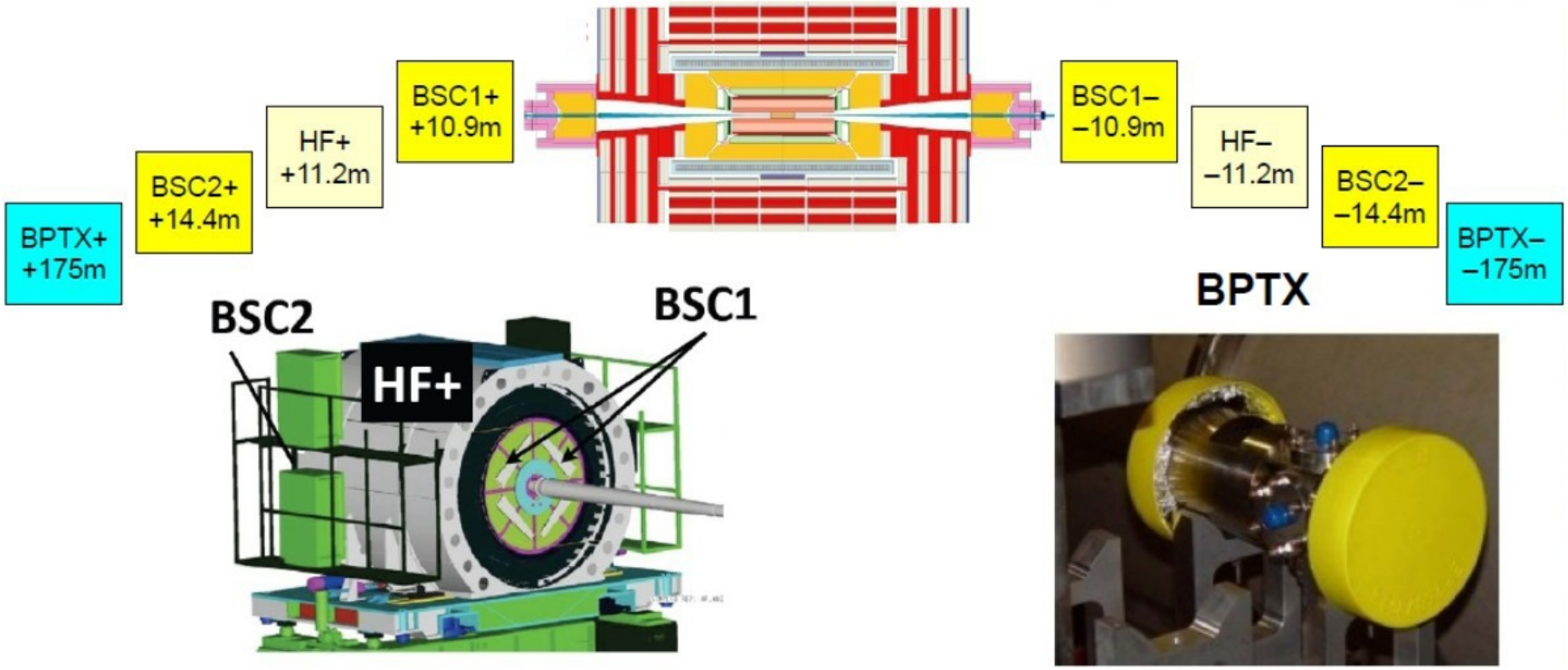
(two SW levels: μ+CALO only ↔ full detector including TRK)

- In 2011 10-fold increase from peak instantaneous lumi of ~0.2 / nb / s ($2 \times 10^{32}$ / $cm^2$ / s) in 2010

- Quickly evolved from triggering on mainly Minimum/Zero Bias (threshold based) to sophisticated trigger menus (combining fully reconstructed objects)

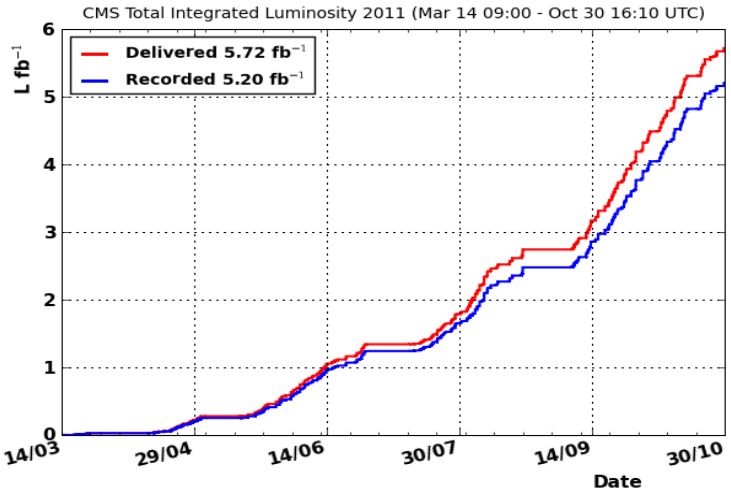


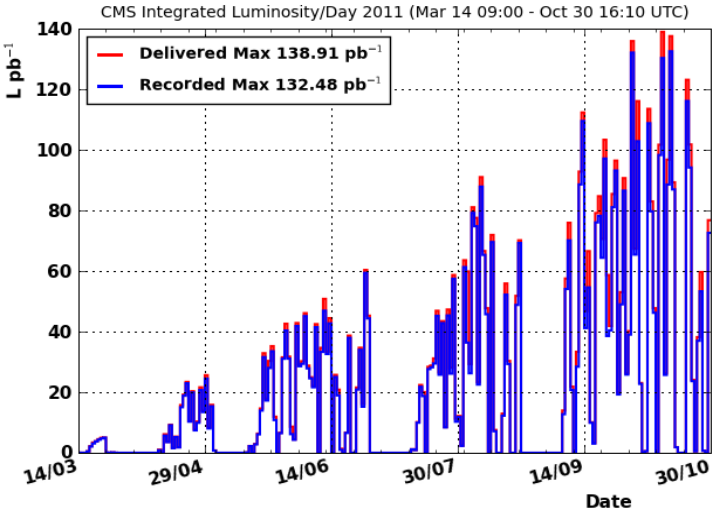
# Minimum Bias Triggers

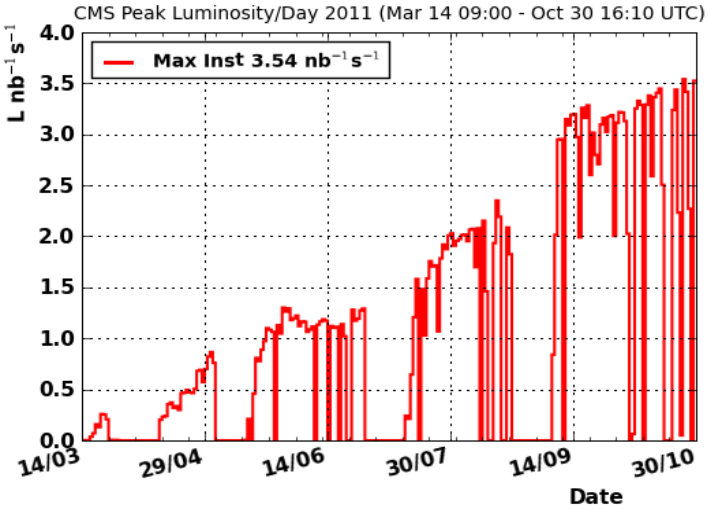



- Beam scintillation counter: info on hits and coincidence signals
- Beam Pick-up Timing for eXperiments: precise info on structure and timing of LHC beams
- BSC + BPTX → minimum bias (beam halo/gas/splash, high multiplicity) triggering / monitoring for pp and HI

# Fantastic LHC and CMS as well




- In 2009 ~10/μb @ 900 GeV c.m.e.,
  ~0.5/μb @ 2360 GeV
- In 2010 <40/pb @ 7 TeV still at low pile-up
- In 2011 recorded ~5.2/fb @ 7 TeV pp
  (and 250/nb @ 2.76 TeV) with good efficiency
- Pile-up: 2 – 4 extra interactions per crossing in
  2010, 5 – 8 (and up to ~ 16) in 2011

# Monte Carlo models / tunes

- Partonic cross section regularised via cut-off

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

- More MPI activity is predicted for smaller values of pt0
- Considered mainly PYTHIA-6 tunes consistent with UE measurements by CDF which favour pt0 = 2.0 GeV for √s0 = 1.8 TeV
- Tunes DW, P0, Pro-Q20: $\varepsilon$ = 0.25 in agreement with CDF data at √s = 630 GeV and 1.8 TeV (DW pt0 = 1.90 GeV)
- Tune D6T: $\varepsilon$ = 0.16 motivated by the measurements of charged particle multiplicities by UA5 at SppS collider (pt0 = 1.84 GeV)
- Tunes P0, Pro-Q20 use LEP results to describe hadron fragmentation at high *z*
- Tune P0 and PYTHIA-8: new PYTHIA MPI model interleaved with parton showering
- PYTHIA-6 includes only soft diffraction, while PYTHIA-8 includes simulation of hard diffraction
- PHOJET: alternative event generator, differs in underlying dynamical model for particle production, based on the dual-parton model with multi-Pomeron exchanges

# Monte Carlo models

- CASCADE: CCFM evolution with off-shell matrix elements
- JIMMY generator for multiple interactions, close integration with HERWIG
- POWHEG: interface NLO calculations to shower Monte Carlo programs
- High Energy Jets (HEJ) generator for multi-jet processes with focus on (non-collinear) radiative corrections
- Cosmic ray models:

**Older models:**

Glauber based, different mostly in remnants+diffraction, for example:
**QGSJet01** *(Kalmykov, Ostapchenko)*
**SIBYLL** *(Engel, Gaisser, Lipari, Stanev)*

**Recent models:**

**QGSJetII** *(Ostapchenko)*
Theory++, Optimized for cosmic rays

**EPOS** *(Werner, Pierog)*
Phenomenology++
Optimized for LHC, RHIC (and cosmic rays)

# Diffractive event displays

- Exclusive J/ψ → μ μ

•Trigger on HLT_L1DoubleMuOpen or HLT_L1DoubleMuOpen_Tight

•Require good vertex with exactly 2 opposite-sign muons (TMLastStationAngular tight ID)

•No other tracks in the event

•< 5 calorimeter towers over noise threshold

•No activity above threshold in the Zero Degree Calorimeter

$$\Delta\phi(\mu\mu)/\pi > 0.9, \quad \Delta p_T(\mu\mu) < 1.5 \text{ GeV}$$

- Diffractive dijet

**Event selection with HLT_JET15U trigger**

**Require good vertex, loose jet ID**

**Anti-kt jet algorithm with R=0.5**

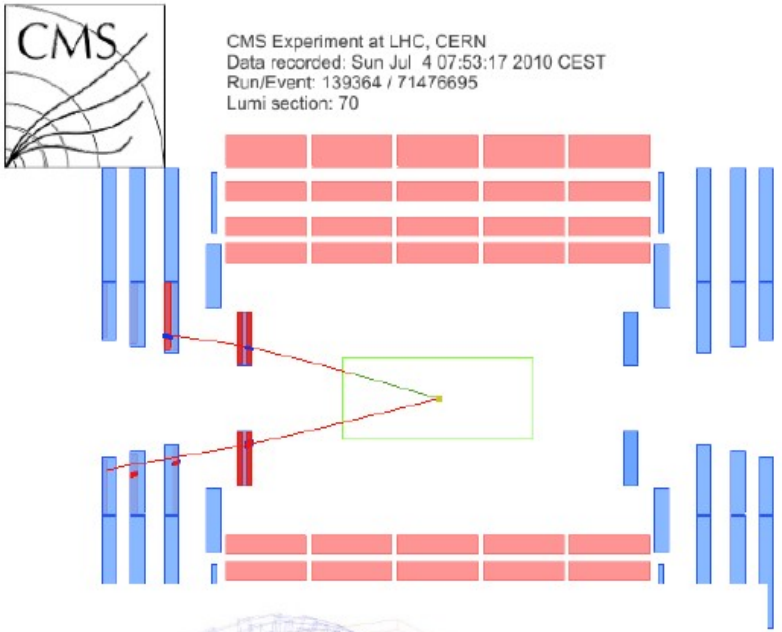
**$P_T$(jet1) > 30 GeV, $P_T$(jet2) > 20 GeV**

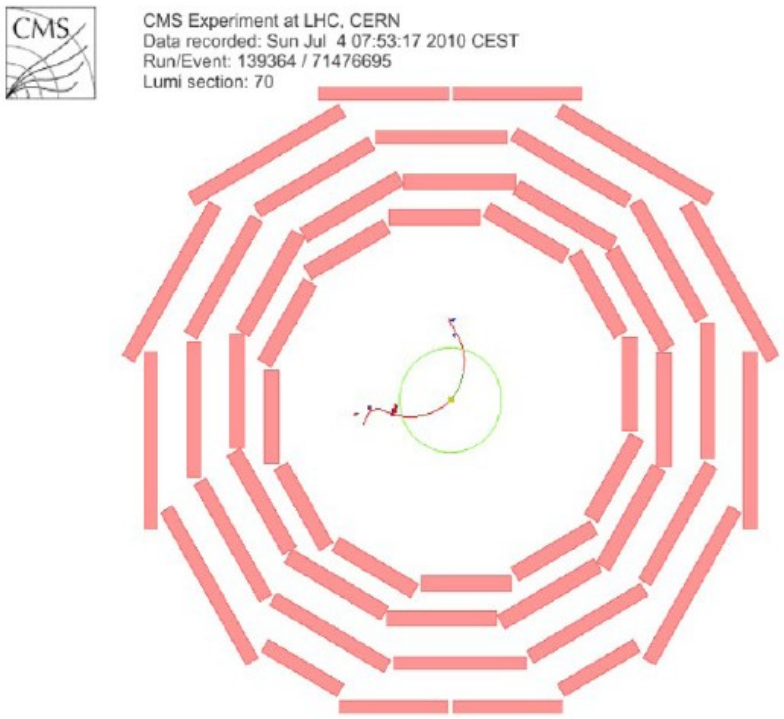
**Diffractive selection:**

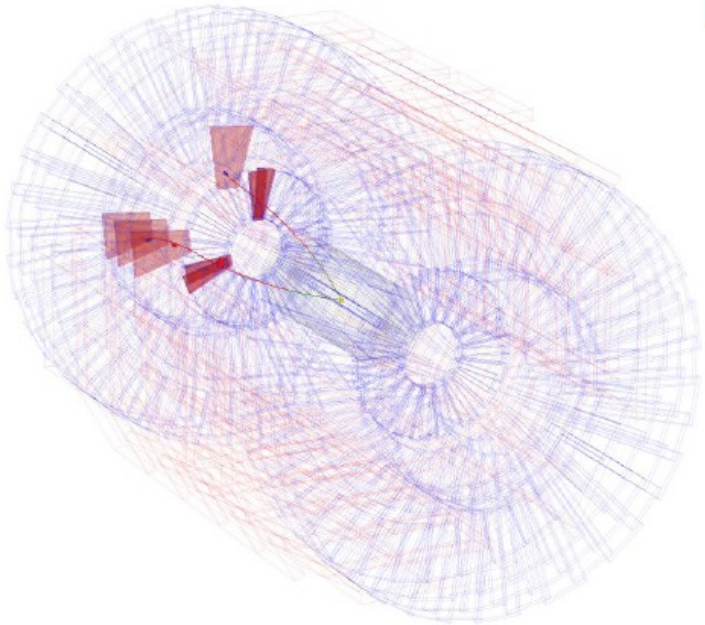
**No energy deposition in HF with E>4 GeV**

- Diffractive W → μ ν

- **Diffractive Selection:**
  - No energy deposit in HF (LRG, Calo Tower Energy > 4 GeV)
- **Event display options:**
  - Barrel: Calo Tower Energy > 1.5 GeV
  - Endcaps: Calo Tower Energy > 2 GeV
  - Forward: Calo Tower Energy > 4 GeV
  - Tracks: p_T > 500 MeV



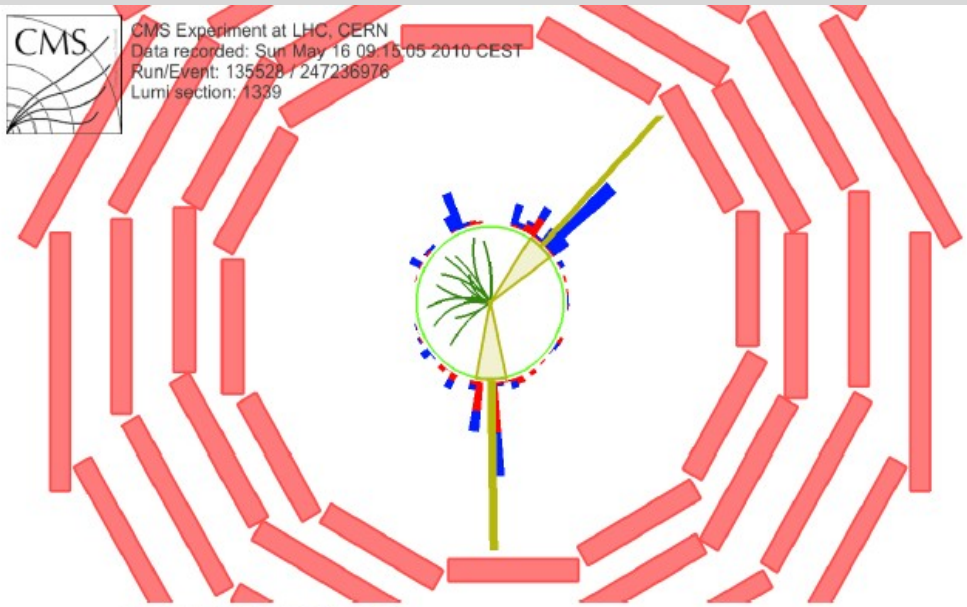



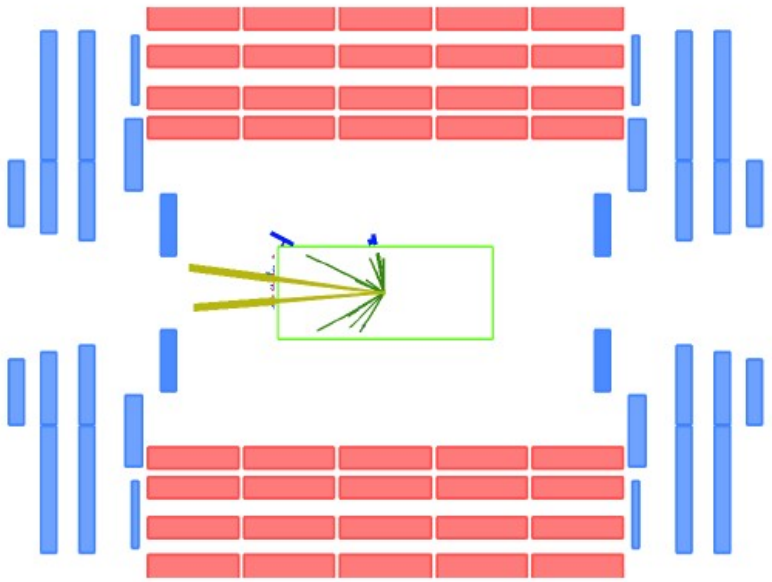



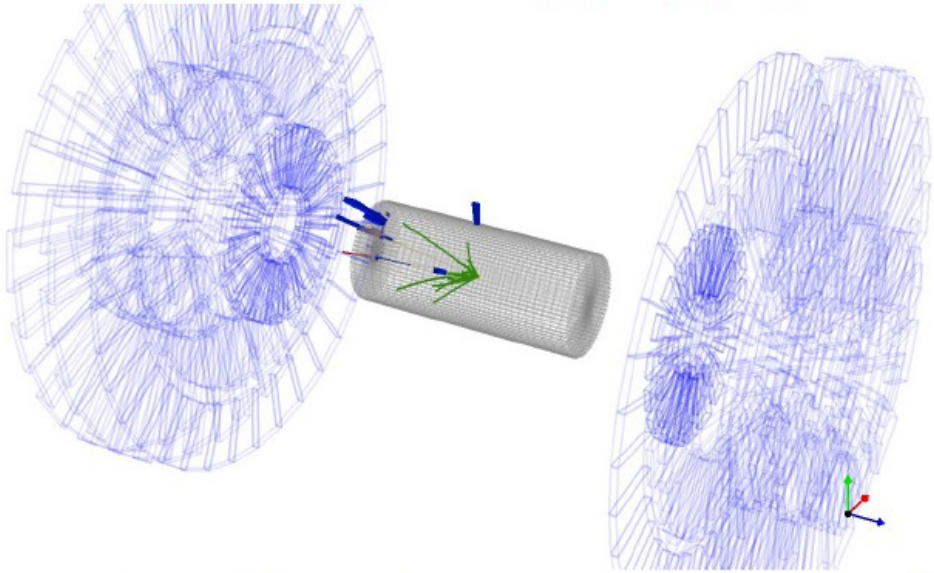
$$
\begin{aligned}
m &= 3.05 \pm 0.03 \text{ GeV} \\
\frac{\Delta\phi}{\pi} &= 0.98 \\
\Delta p_T &= 0.05 \text{GeV}
\end{aligned}
$$

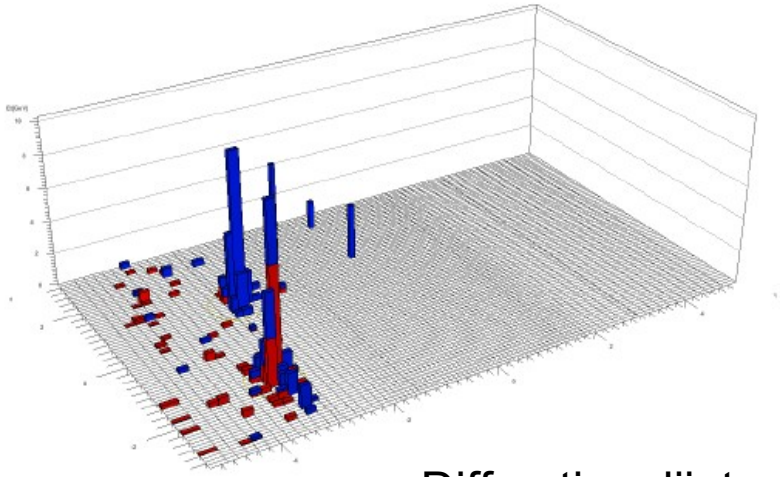
$$
\begin{aligned}
\text{track: } p_T &> 0 \text{ GeV} \\
\text{HCAL: } E &> 4 \text{ GeV} \\
\text{ECAL: } E &> 2.5 \text{ GeV}
\end{aligned}
$$

Exclusive J/ψ → μ μ



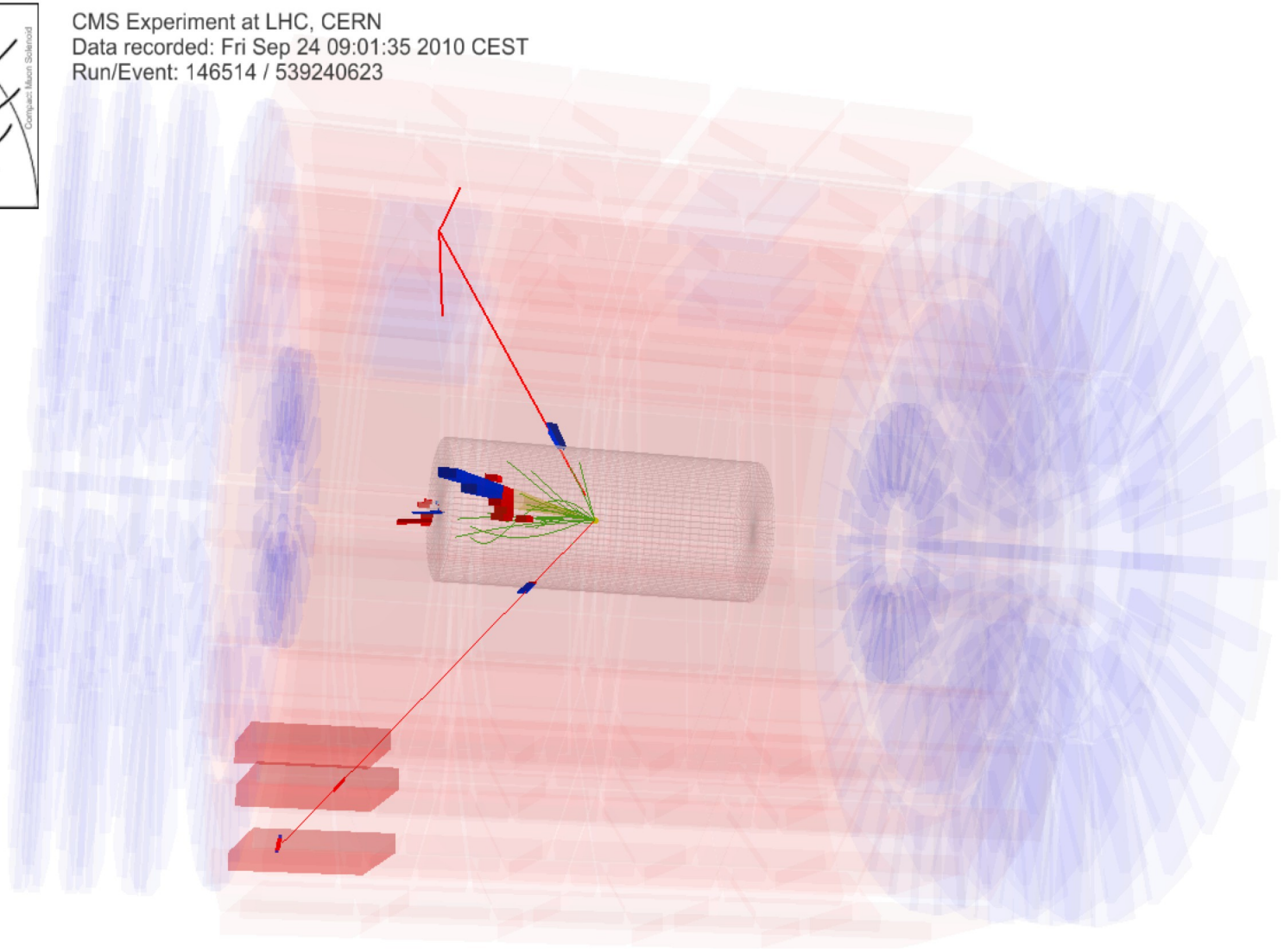




Diffractive dijet

$E(\eta < 3.0) > 1.5$ GeV $\quad p_T(\text{track}) > 0.5$ GeV
$E(\eta \geq 3.0) > 2.0$ GeV

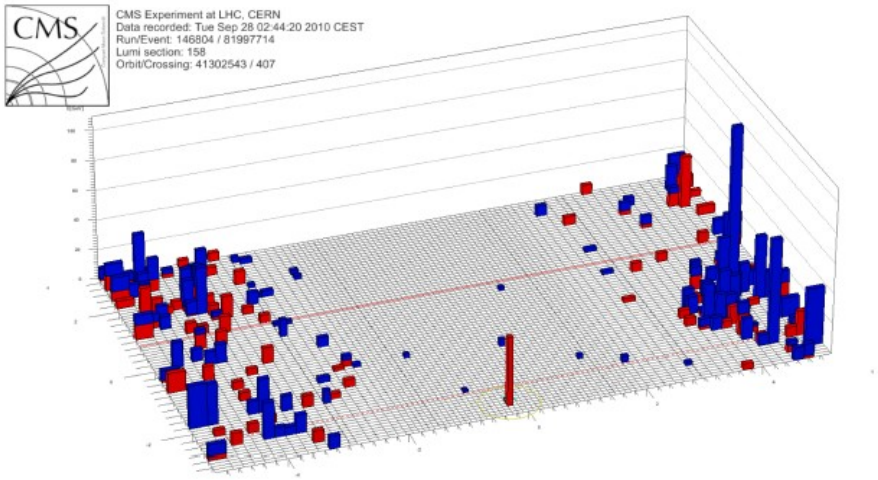
$p_T(\text{jet1}) = 41.2$ GeV, $\quad p_T(\text{jet2}) = 31.9$ GeV
$\eta(\text{jet1}) = -2.8$, $\quad \eta(\text{jet2}) = -3.3$

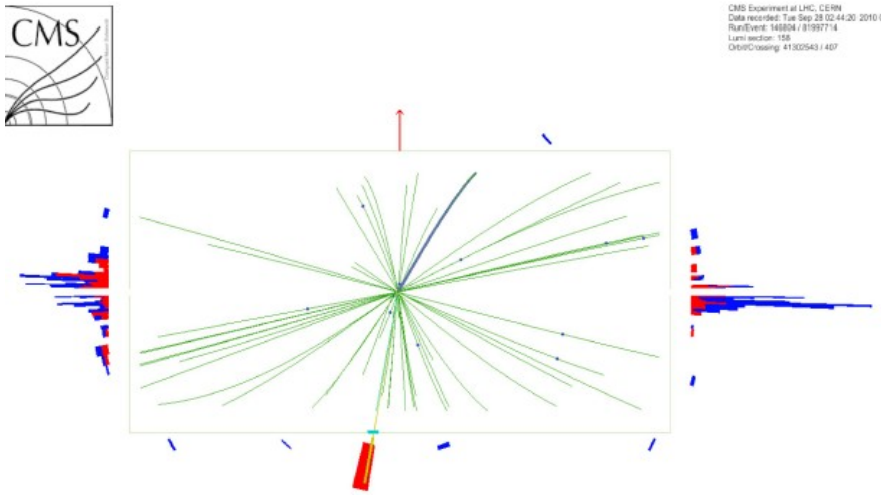



Diffractive W → μ ν

# W/Z events w/o rapidity gap

W -> e nu



Z -> mu mu