Latest CMS Results at LHC and Physics Prospects

J. Alcaraz (CIEMAT - Madrid)

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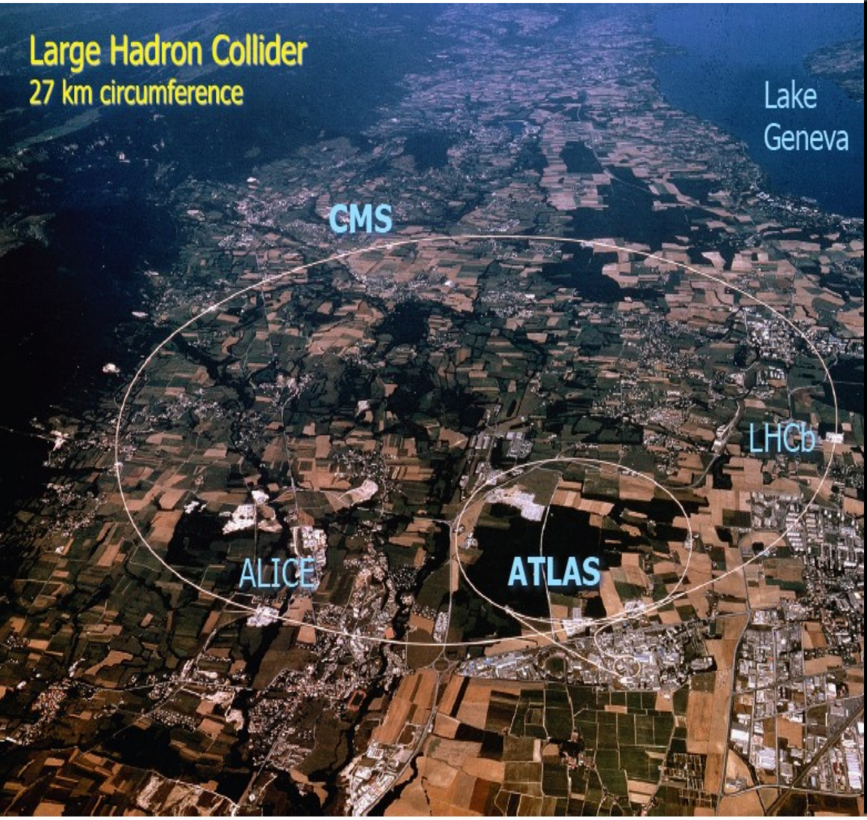
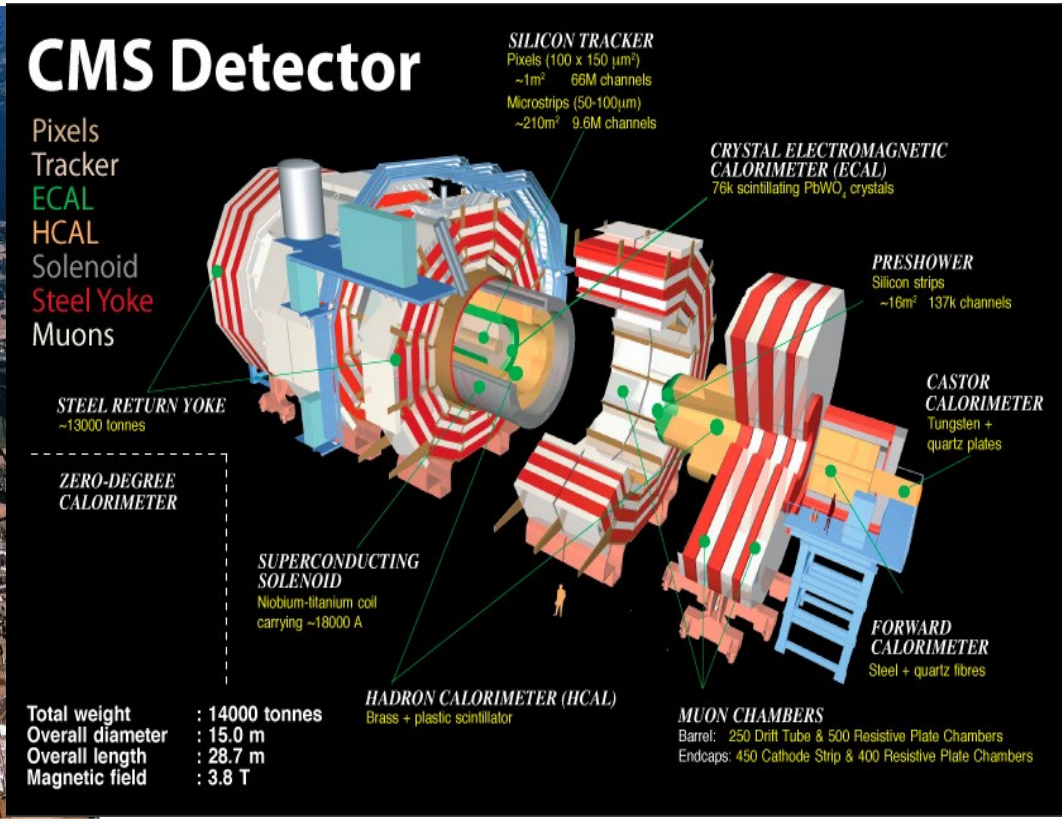
Outline

- CMS experiment status and current performance
- Early physics: first analyses, EWK and top physics. Early searches
- Physics prospects (2010-2012)

The LHC and CMS





- First collisions recorded in 2009
- Current running conditions: $\sqrt{s} = 7$ TeV, $L > 10^{32}\ cm^{-2}\ s^{-1}$
- CMS is one of the two multi-purpose experiments at the LHC

The CMS design: goals

- Good muon identification and momentum resolution:
  - Redundant measurements and redundant trigger systems
  - $\Delta M_{\mu\mu} / M_{\mu\mu} \approx 1\%$ at 100 GeV
  - Unambiguous determination of the charge for $p^T_\mu < 1$ TeV

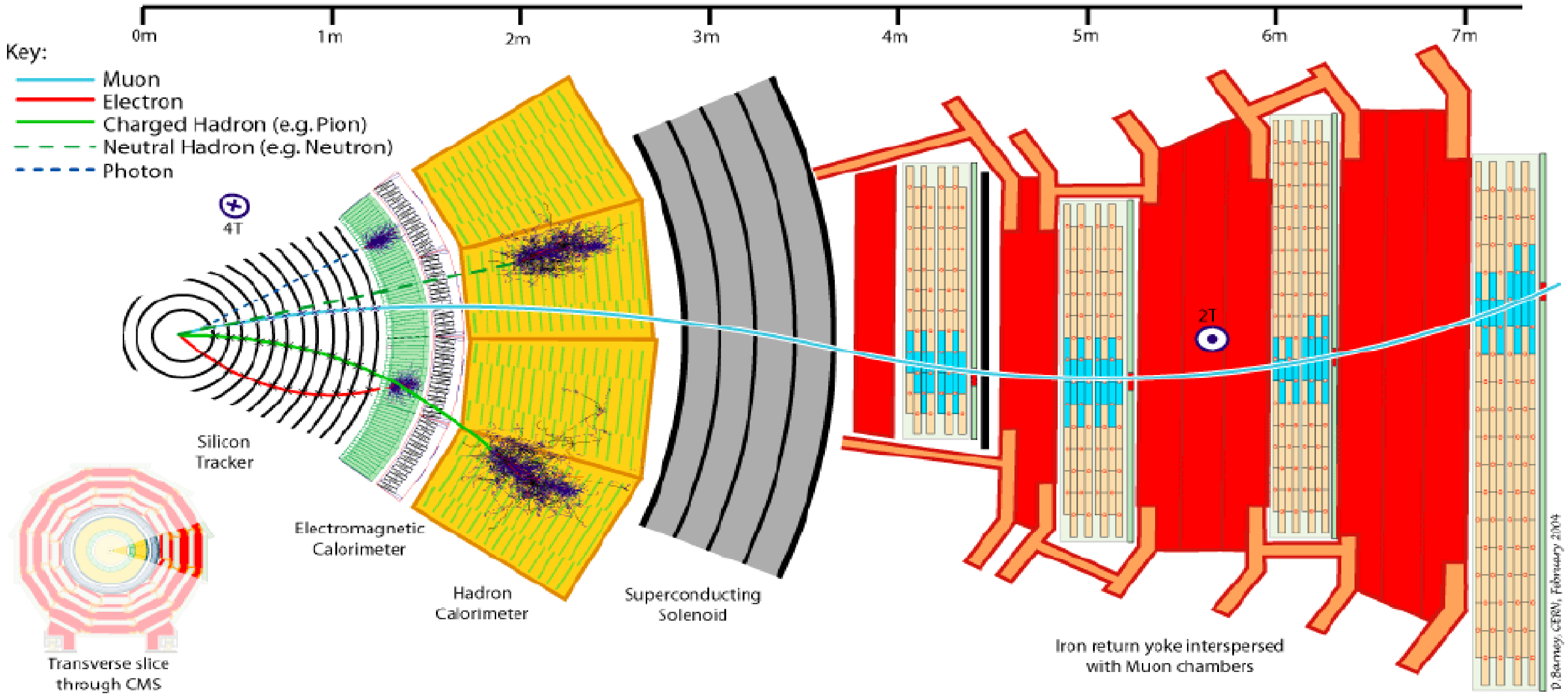
- Precise and efficient inner tracking, including vertex capabilities:
  - Efficient triggering and offline tagging of taus and b-jets
  - Pixel detectors close to the interaction region

- Good electromagnetic identification and photon/electron energy resolution:
  - $\Delta M_{ee} / M_{ee}$, $\Delta M_{\gamma\gamma} / M_{\gamma\gamma} \approx 1\%$ at 100 GeV
  - Large coverage and good granularity, π^0 rejection

- Good jet and missing transverse energy resolution:
  - Hermetic coverage, fine lateral segmentation

The CMS way...

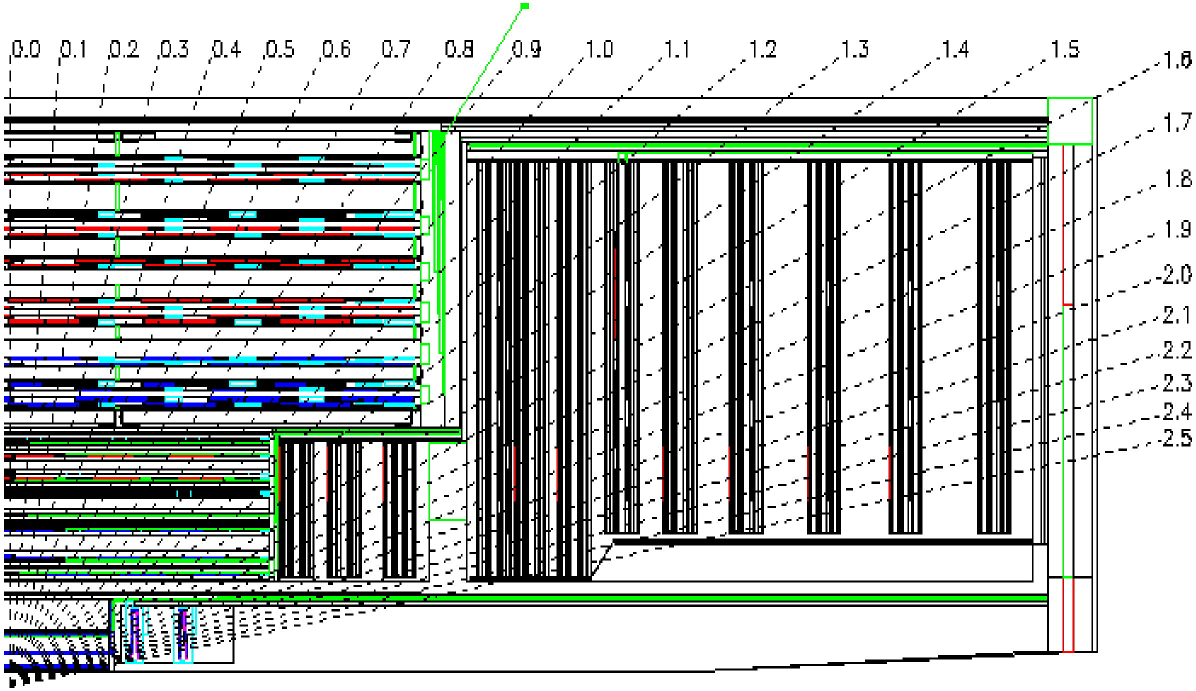
'Compact' and fully 'solenoidal' design

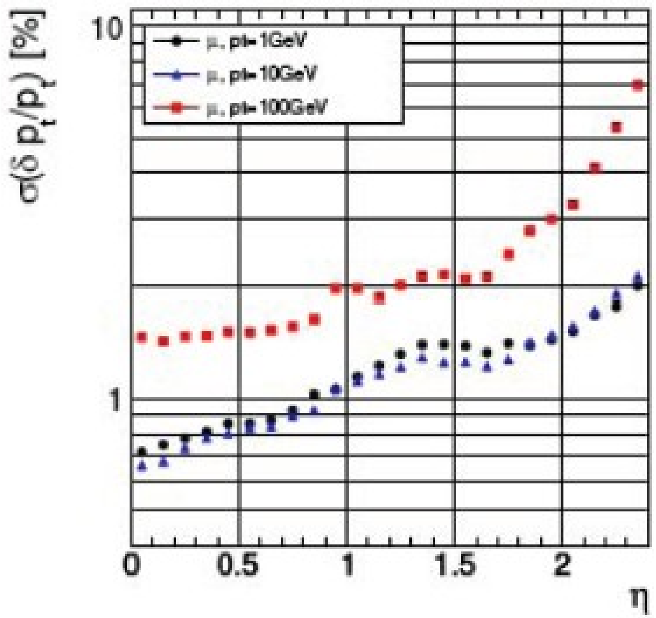


• All central tracking and calorimetry contained inside a superconducting solenoid (B=3.8 T, L = 13 m, r = 3m) => large BL^2

• Iron yoke instrumented to host the muon spectrometer => Measurement of muon momentum thanks to the saturation of the iron

CMS inner tracking system

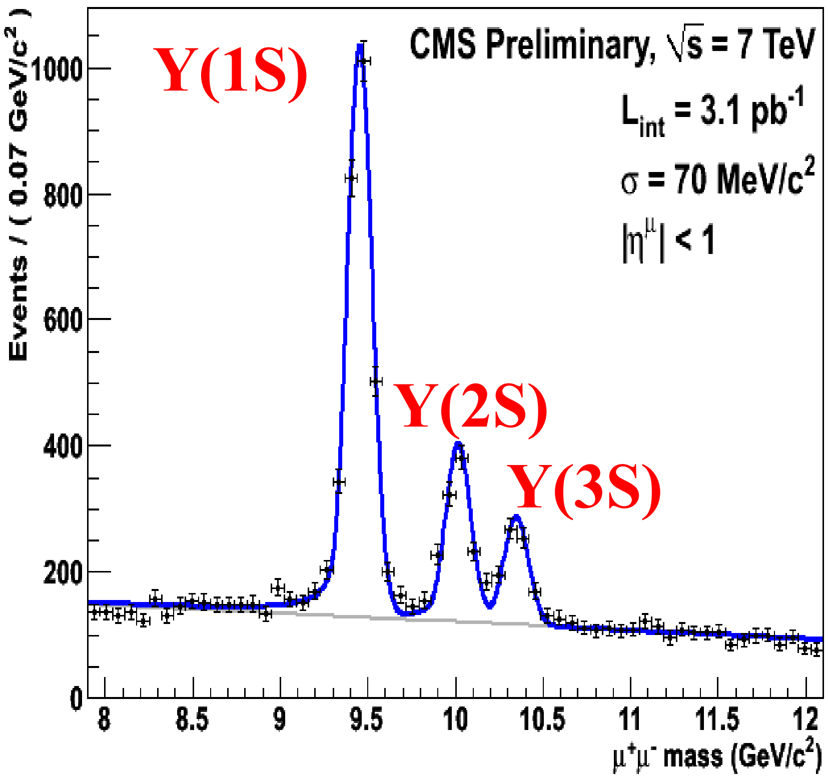


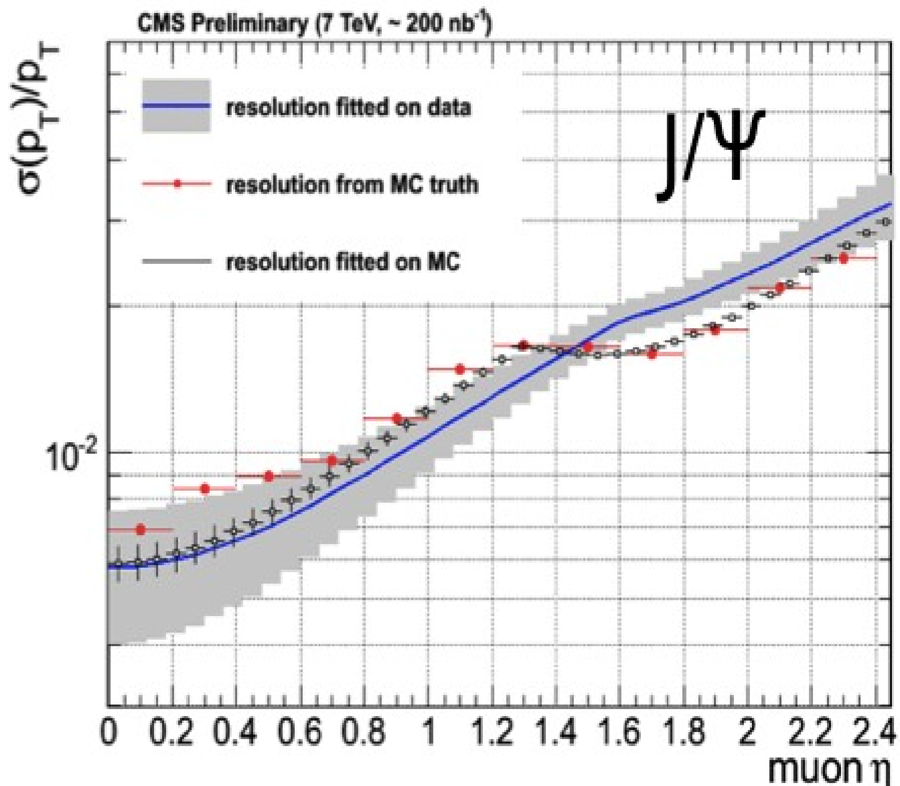


A huge, ultra-precise silicon tracker system:

- For $p_T \leq 100$ GeV, $\Delta p_T / p_T \approx 0.5$-2% ($|\eta|<1.6$)
  - Muon resolution dominated by inner tracking resolution for $p_T < \approx 100$ GeV
- $\Delta d_{xy} \approx 10$ μm resolution at very high p_T
- $\Delta z \approx 20$-40 μm resolution at very high p_T ($|\eta|<2$)

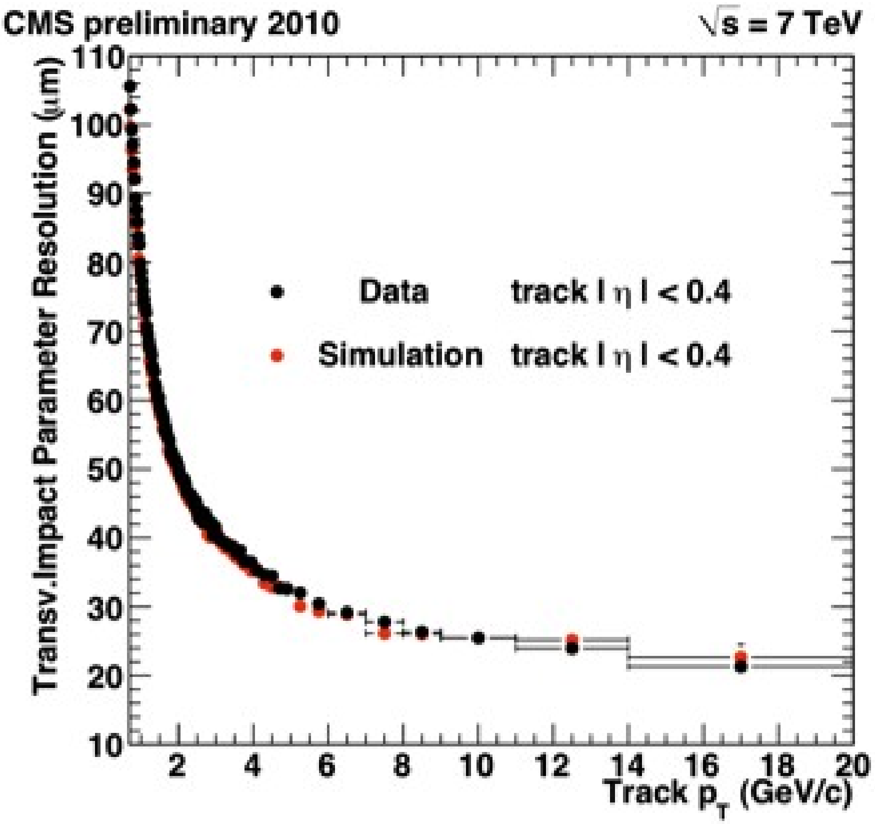
CMS: tracking performance

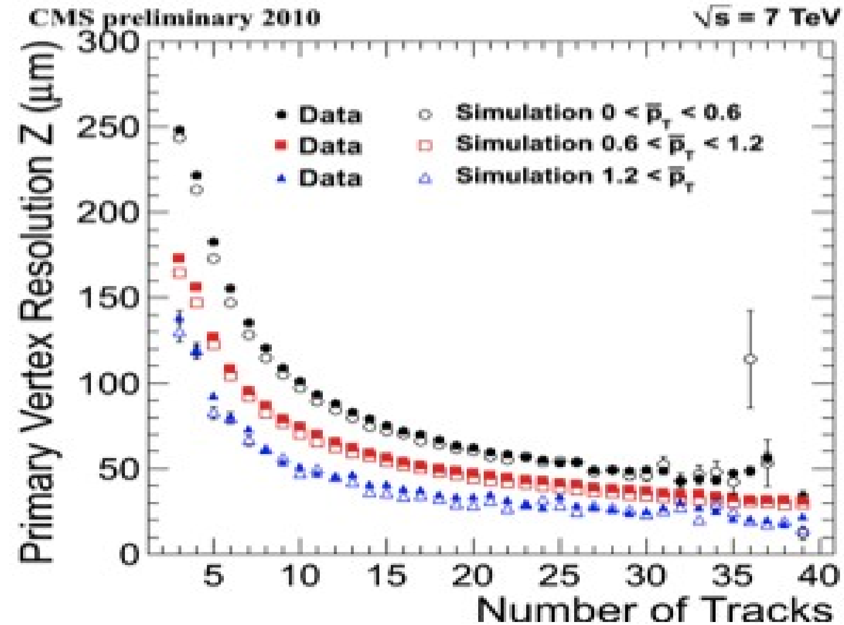


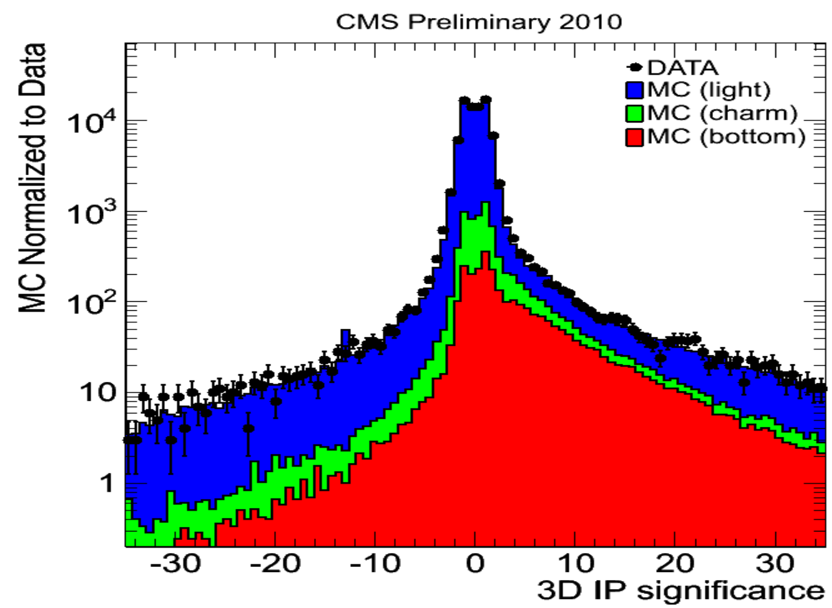


- Tracker resolution working 'almost' as in the simulation
- Resolutions extracted directly from data (narrow resonance widths)

CMS: tracking performance



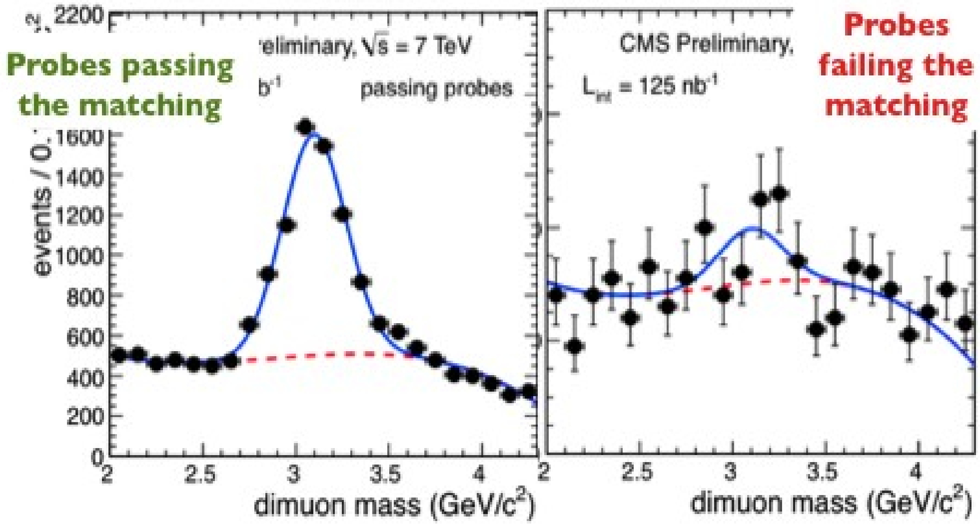




- High accuracy of impact parameter and vertex measurements, in reasonable agreement with simulations => b-tagging already operational !!

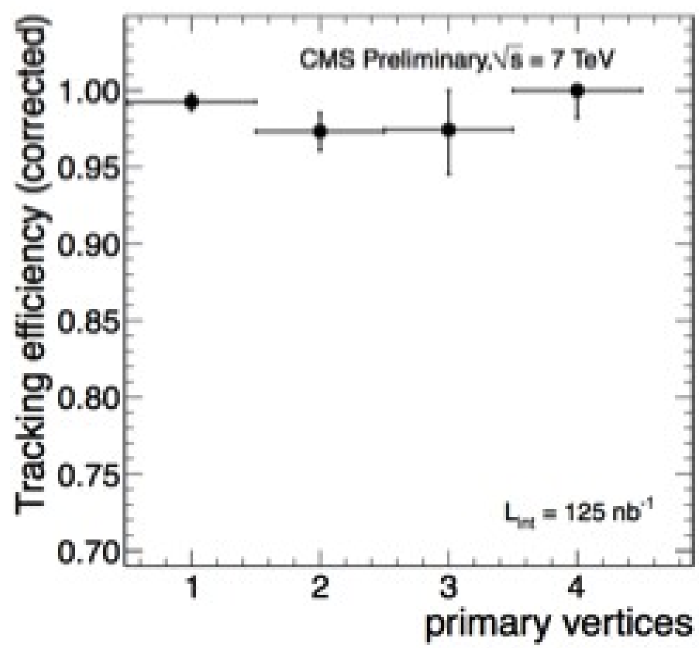
CMS: tracking performance

J/Psi Tag and probe



Region	Data Eff. (%)	Sim Eff. (%)	Data/Sim
$0.0 \le \lvert\eta\rvert < 1.1$	$100.0^{+0.0}_{-0.3}$	$100.0^{+0.0}_{-0.1}$	$1.000^{+0.001}_{-0.003}$
$1.1 \le \lvert\eta\rvert < 1.6$	$99.2^{+0.8}_{-1.0}$	$99.8^{+0.1}_{-0.1}$	$0.994^{+0.009}_{-0.010}$
$1.6 \le \lvert\eta\rvert < 2.1$	$97.6^{+0.9}_{-1.0}$	$99.3^{+0.1}_{-0.1}$	$0.983^{+0.009}_{-0.010}$
$2.1 \le \lvert\eta\rvert < 2.4$	$98.5^{+1.5}_{-1.6}$	$97.6^{+0.2}_{-0.2}$	$1.010^{+0.015}_{-0.016}$
Combined	$98.8^{+0.5}_{-0.5}$	$99.2^{+0.1}_{-0.1}$	$0.996^{+0.005}_{-0.005}$

- Very high efficiency of tracking (measured also in data on J/Ψ samples). Even in the presence of pileup!

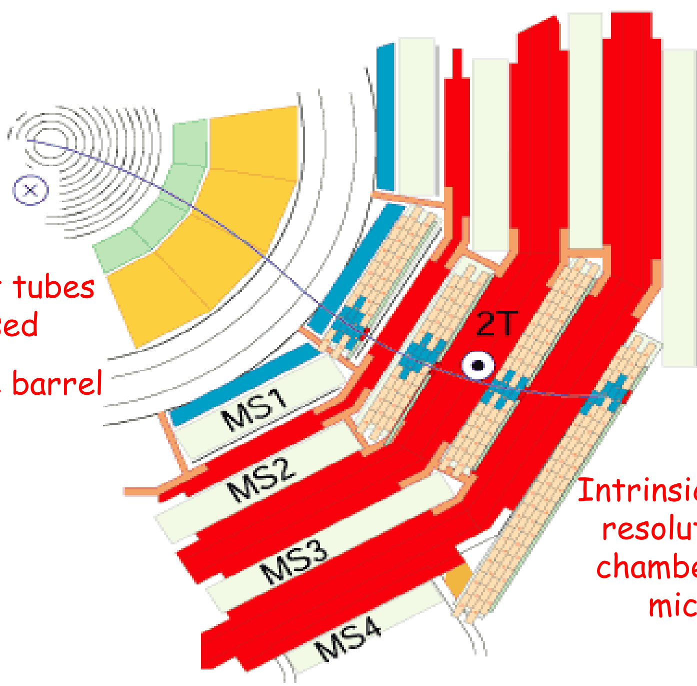


CMS: a special muon system

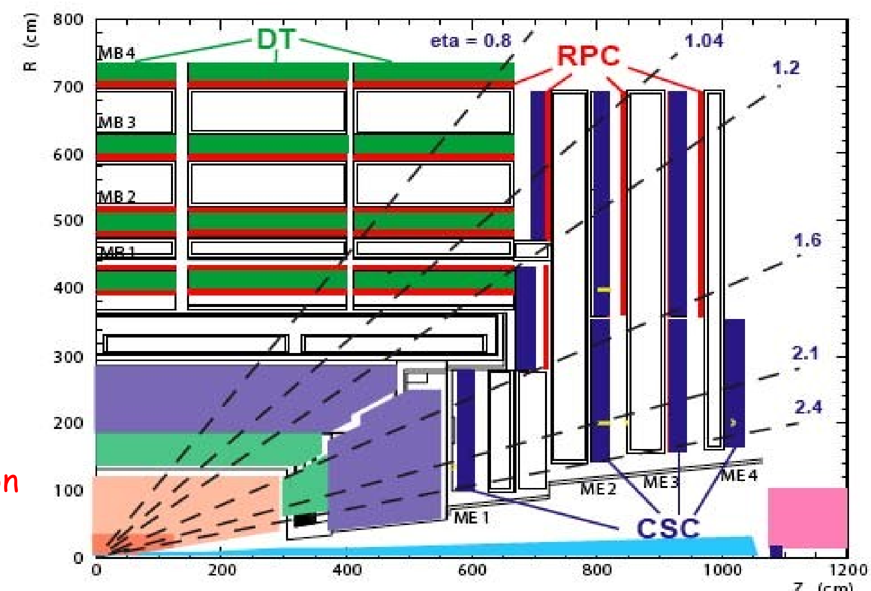
- The CMS muon system (barrel and also endcap) is optimized for:
  - Robust, efficient and redundant muon triggering system (chambers+RPCs)
  - Efficient muon identification and reconstruction (|η|<2.4, redundant coverage)
  - Precise measurement (< 10%) for TeV momenta (good alignment + level arm)

Drift tubes used

in the barrel



Intrinsic position resolution per chamber ~ 100 microns

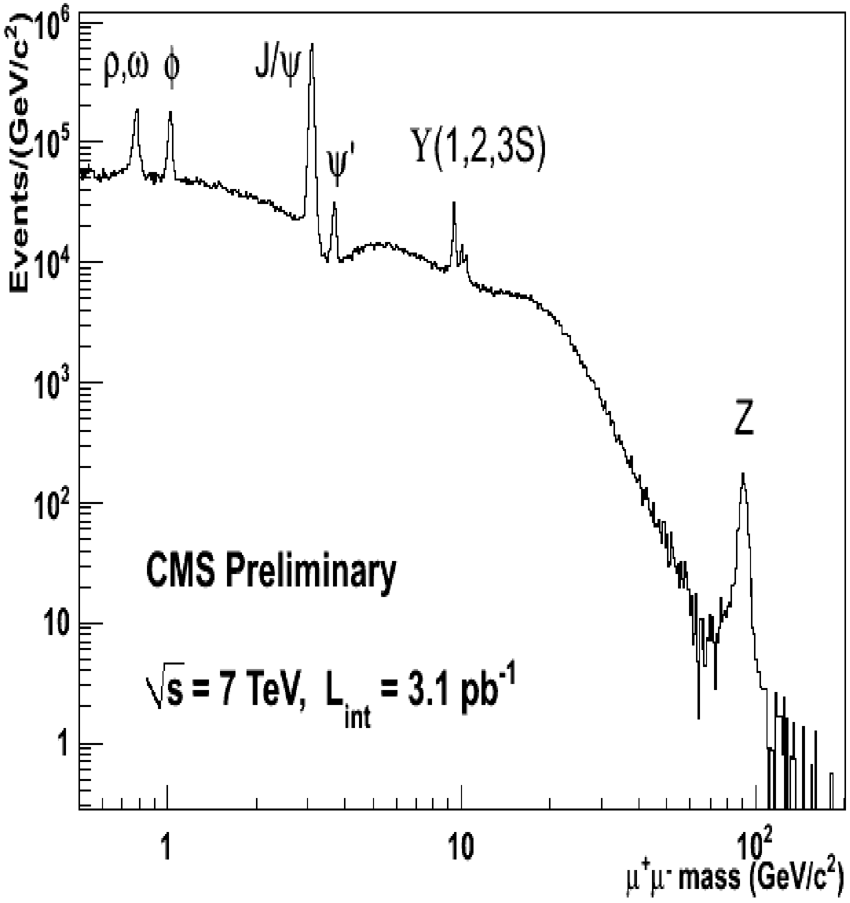


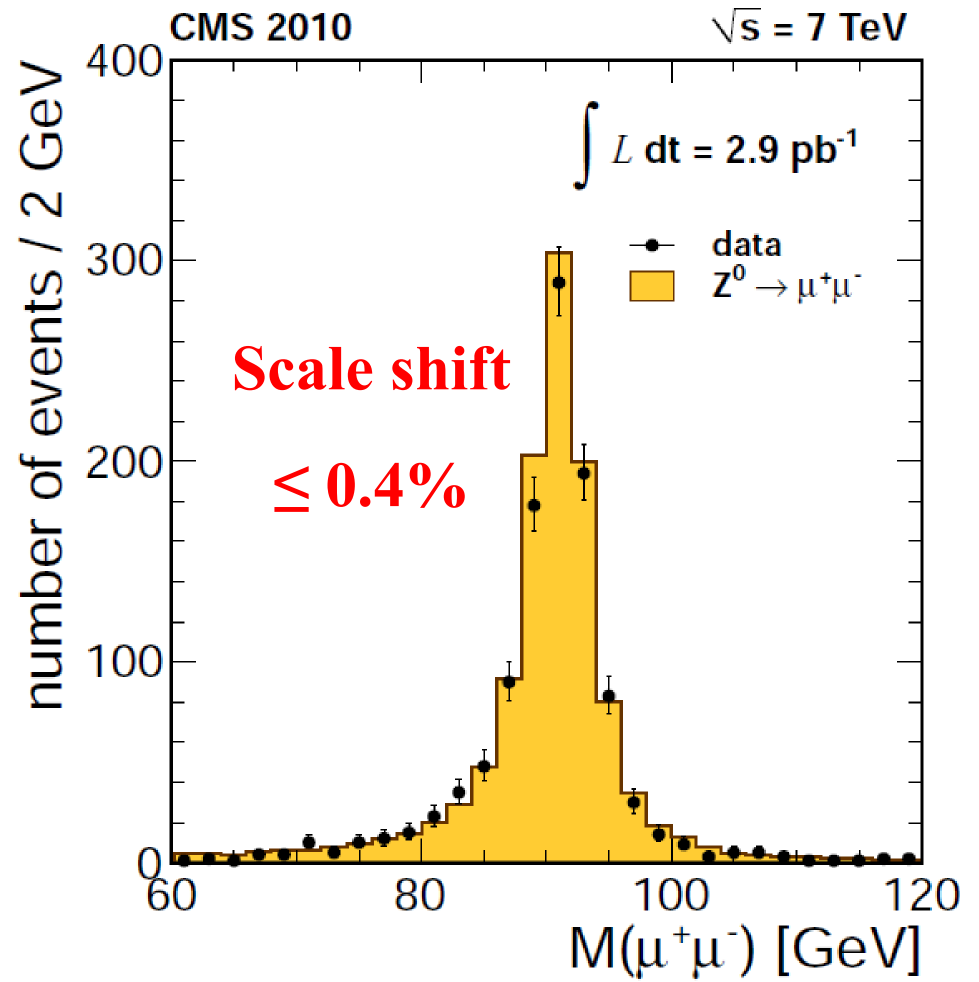
Cathode Strip Chambers (CSC) used in the end-caps

RPCs for fast timing and trigger response

CMS: muons

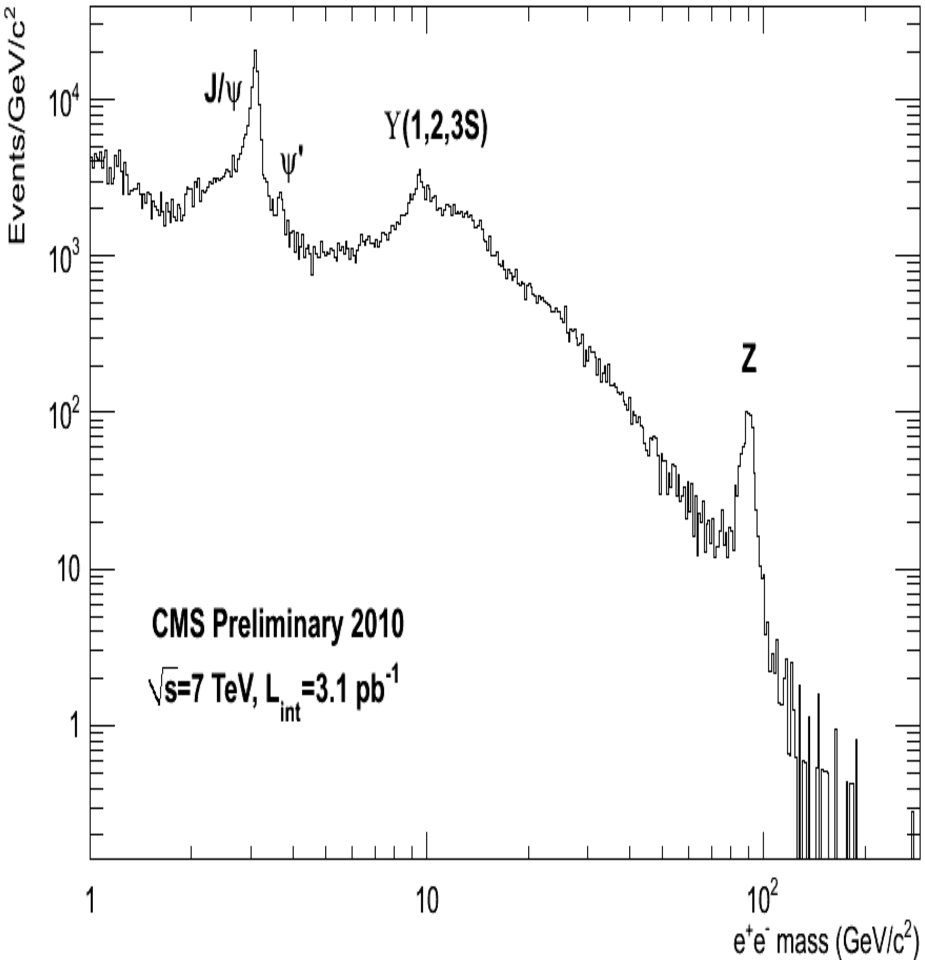
Finally:

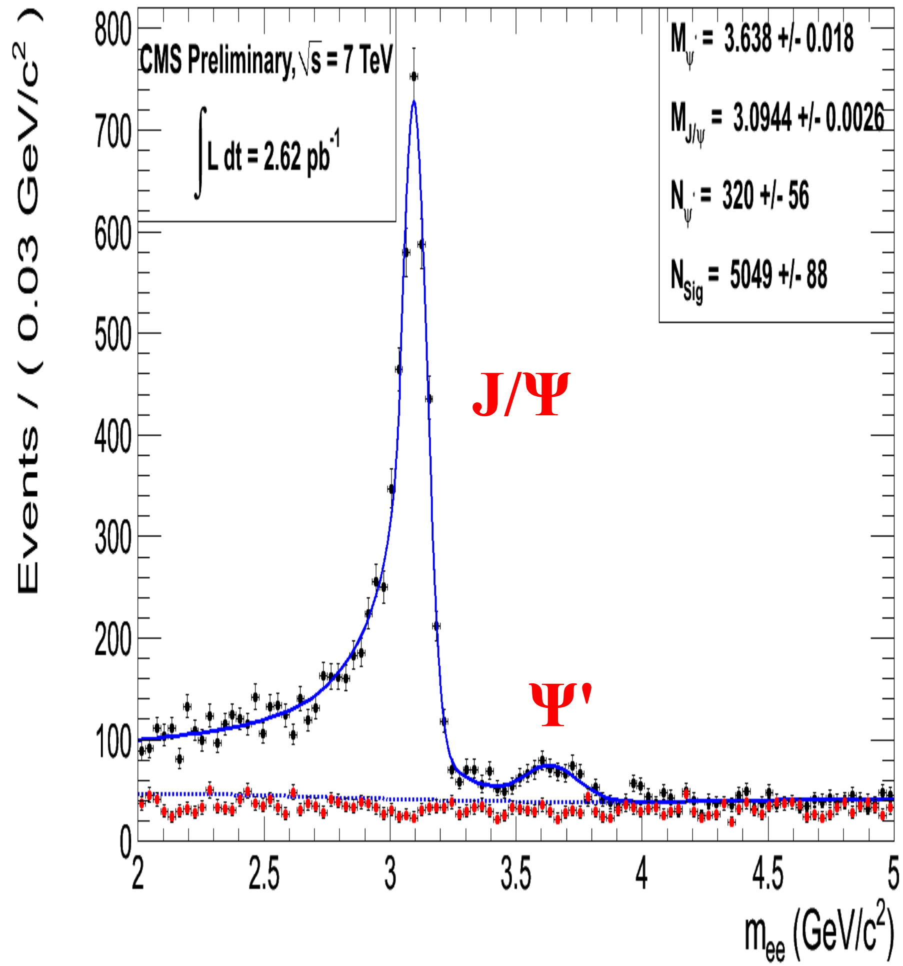




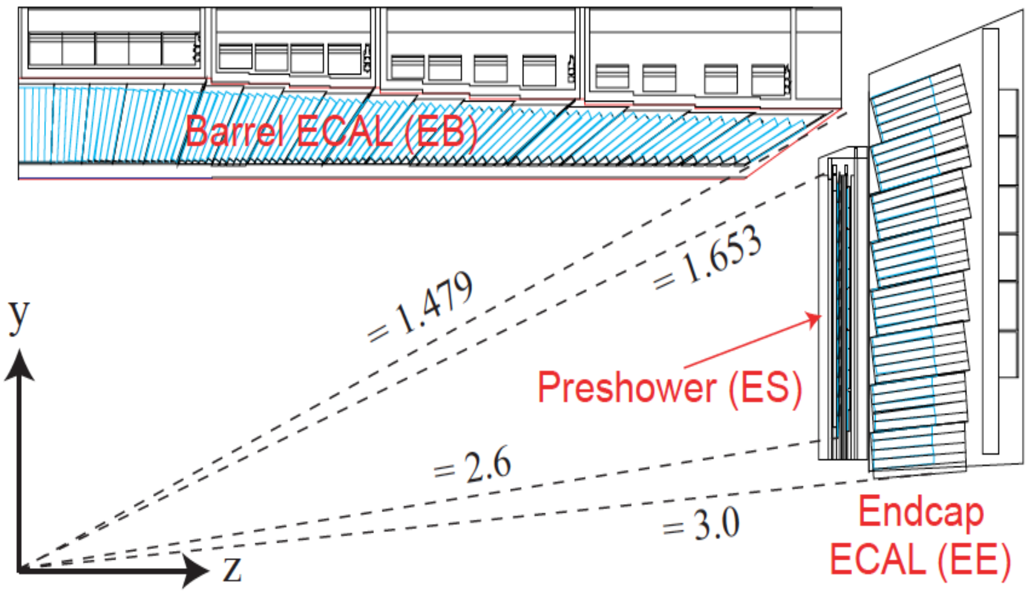
CMS: electrons/photons

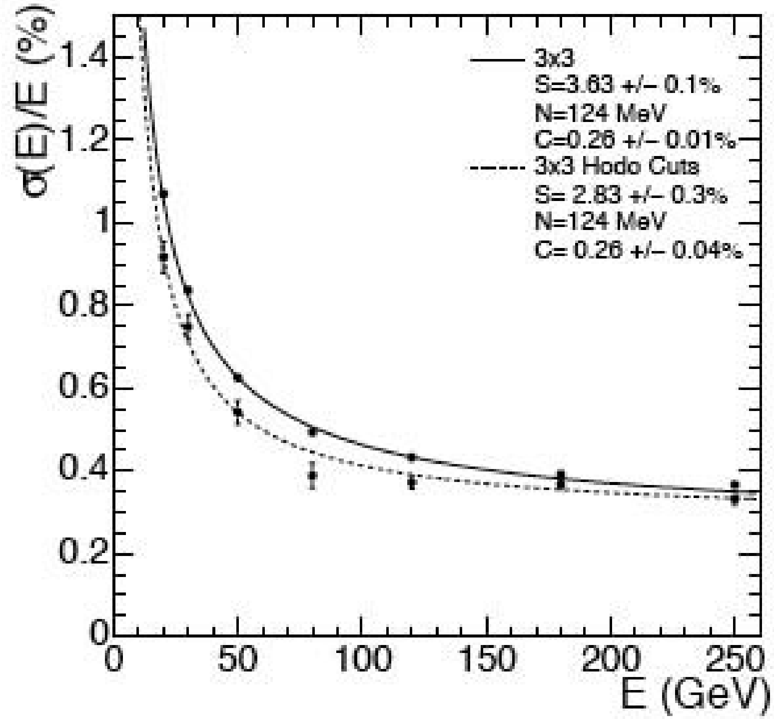
We also have good electromagnetic resolution in CMS:





CMS Electromagnetic Calorimeter



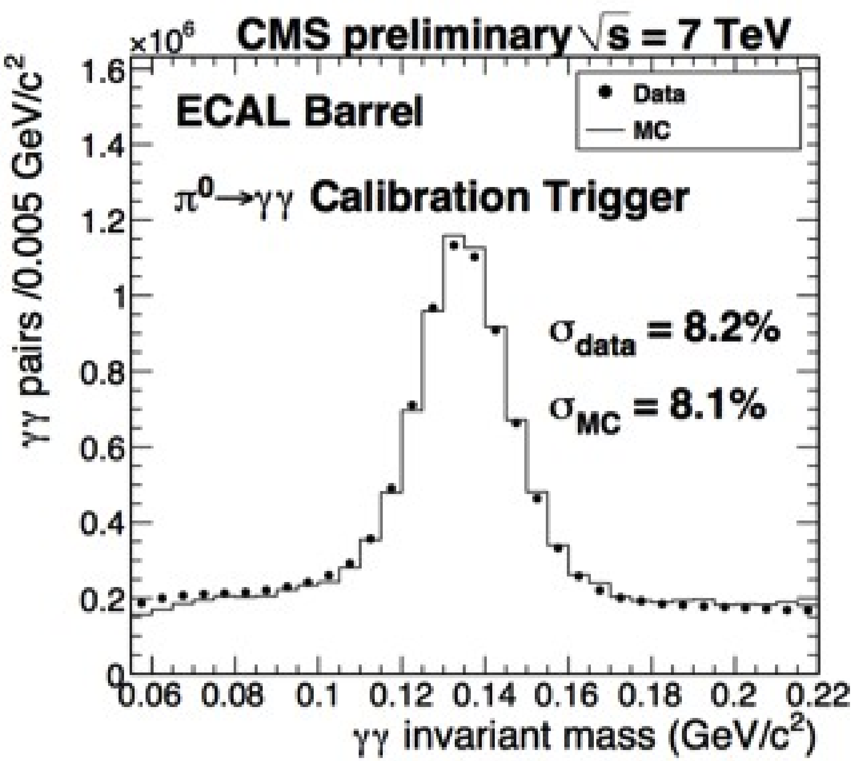


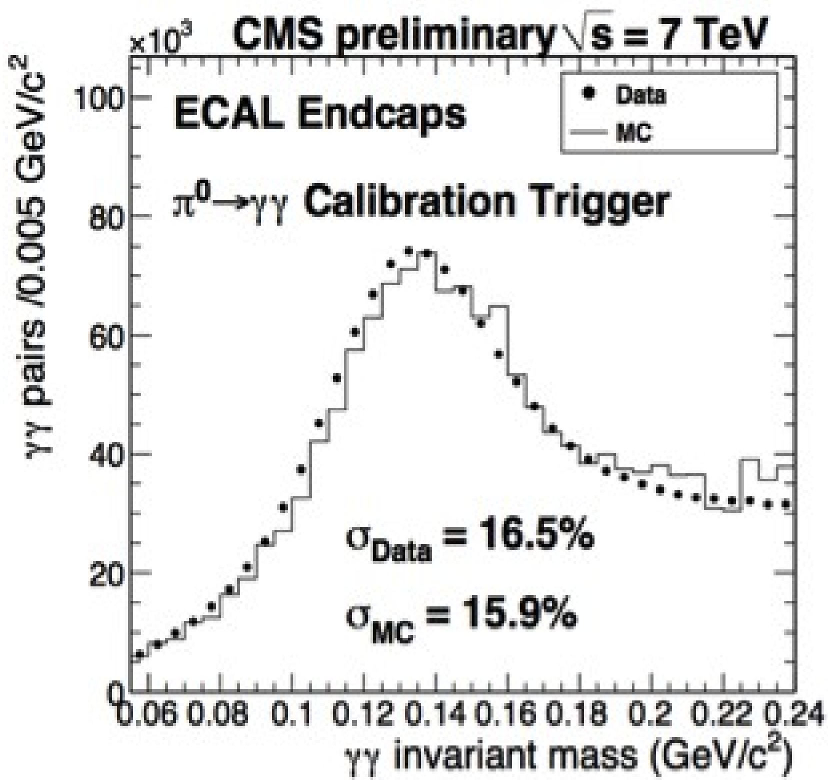
- A crystal calorimeter ($PbWO_4$): extremely good resolution (stochastic term ≈ 2.8% at 1 GeV), low noise (noise term ≈ 120 MeV), good uniformity/intercalibration (uniformity ≈ 0.3% from test-beam studies):

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.3\%)^2 \qquad \text{(E in GeV)}$$

CMS: electrons/photons

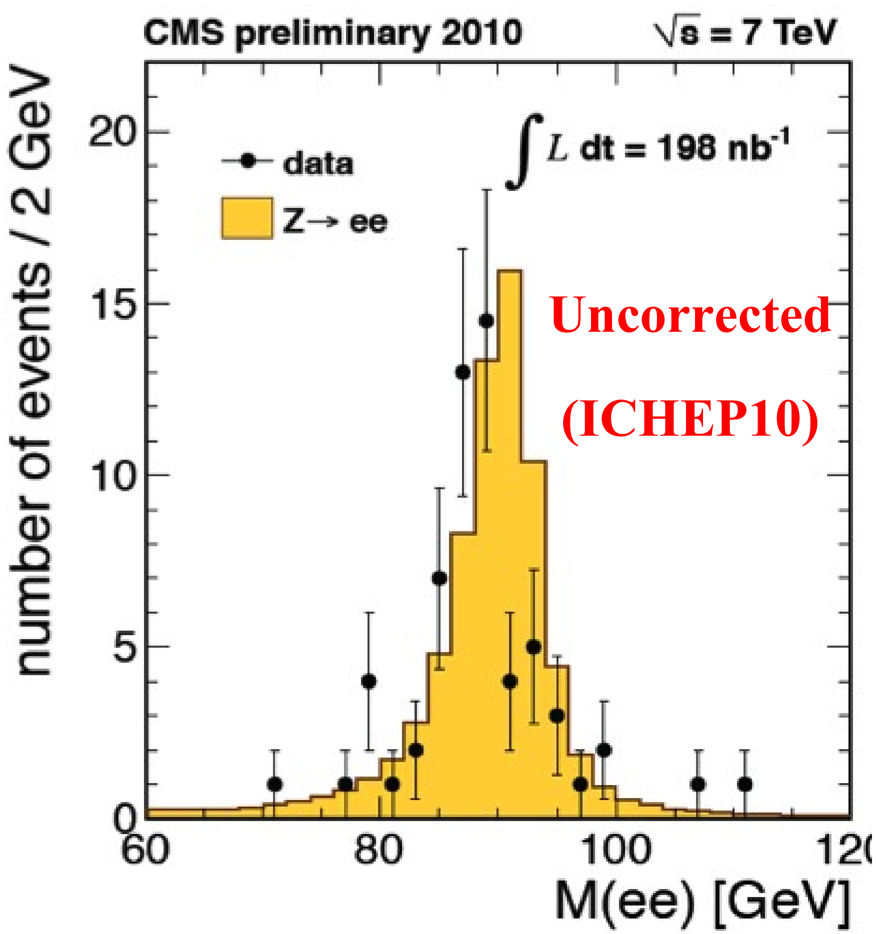
… down to low energies

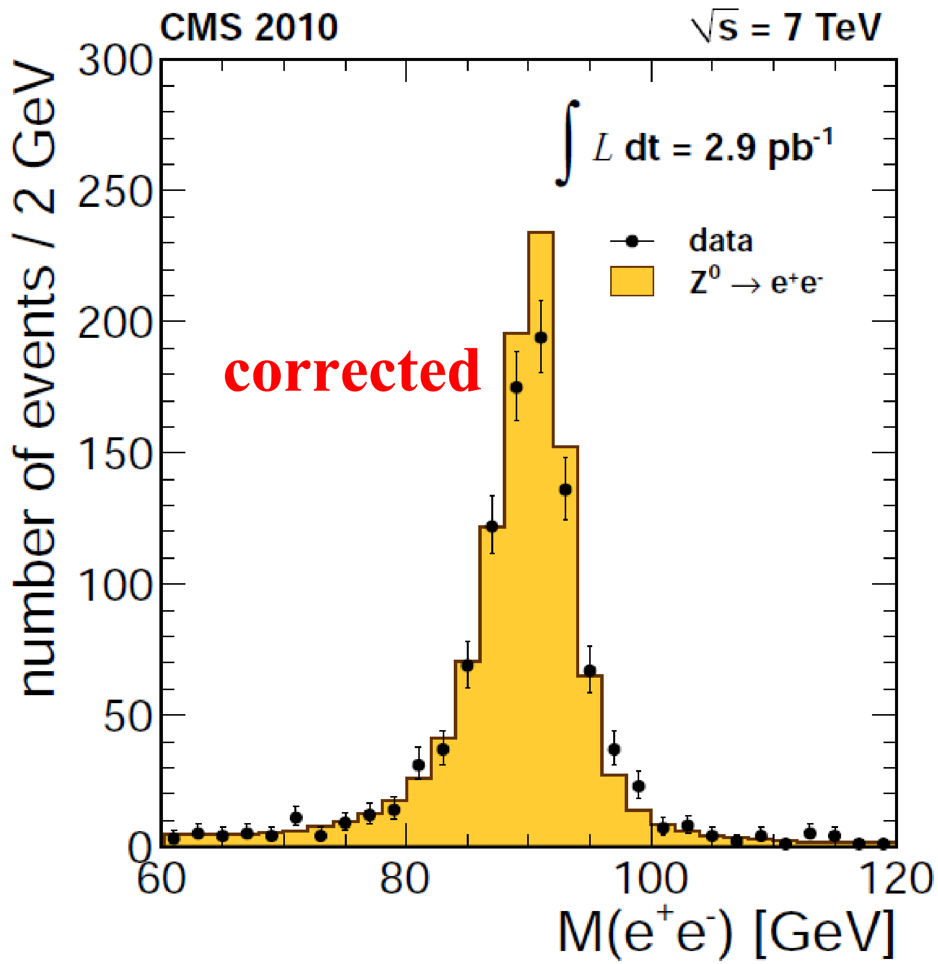




Good agreement with expectations

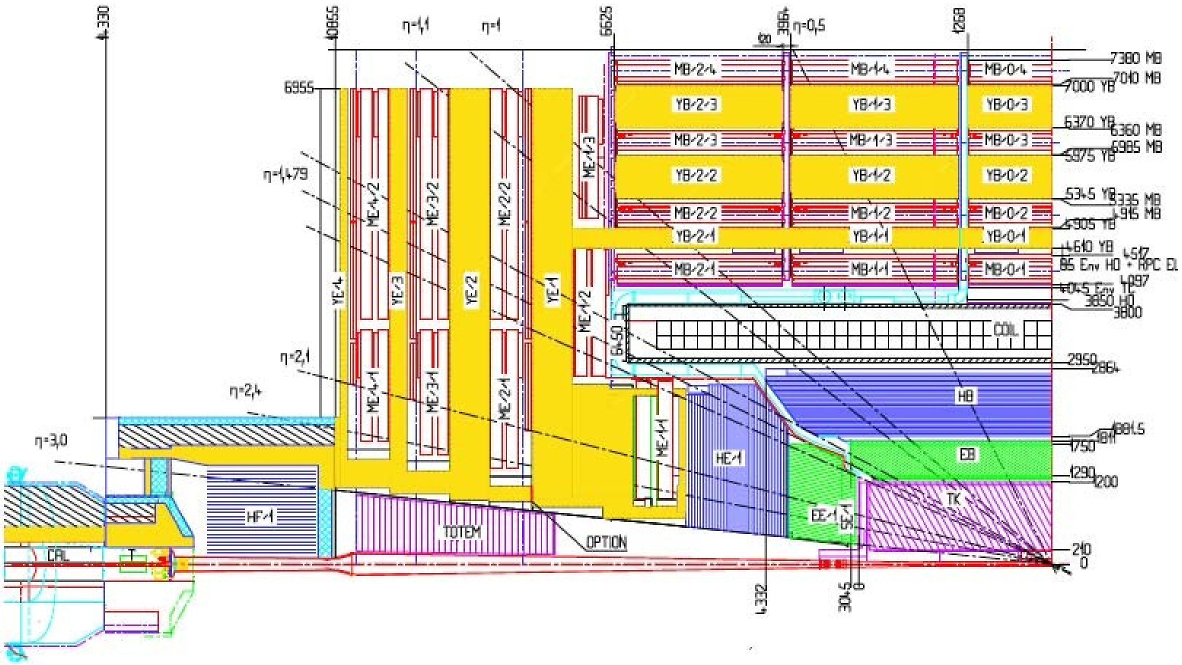
CMS: electrons/photons





At high E_T the scale in the barrel region is now set by the π^0 calibration (correct to 1%); 3% shift in the endcap region

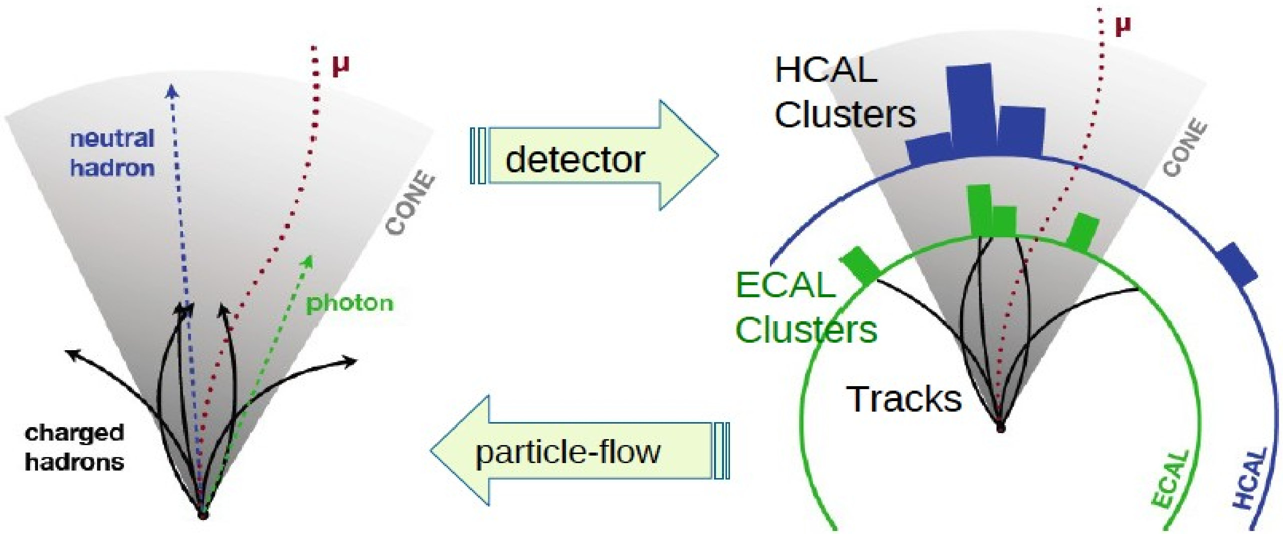
CMS Hadronic Calorimetry



- Scintillator-brass/steel tile calorimeter: compact, hermetic, good segmentation and coverage (|η|<5.2)
- Jet angular resolution ~ 20 (30) mrad in φ (θ) at $E_T \geq 100$ GeV
- Jet transverse energy resolution (using ECAL+HCAL only, barrel):

$$\left(\frac{\sigma}{E_T}\right)^2 = \left(\frac{1.25}{\sqrt{E_T}}\right)^2 + \left(\frac{5.6}{E_T}\right)^2 + (3.3\%)^2$$

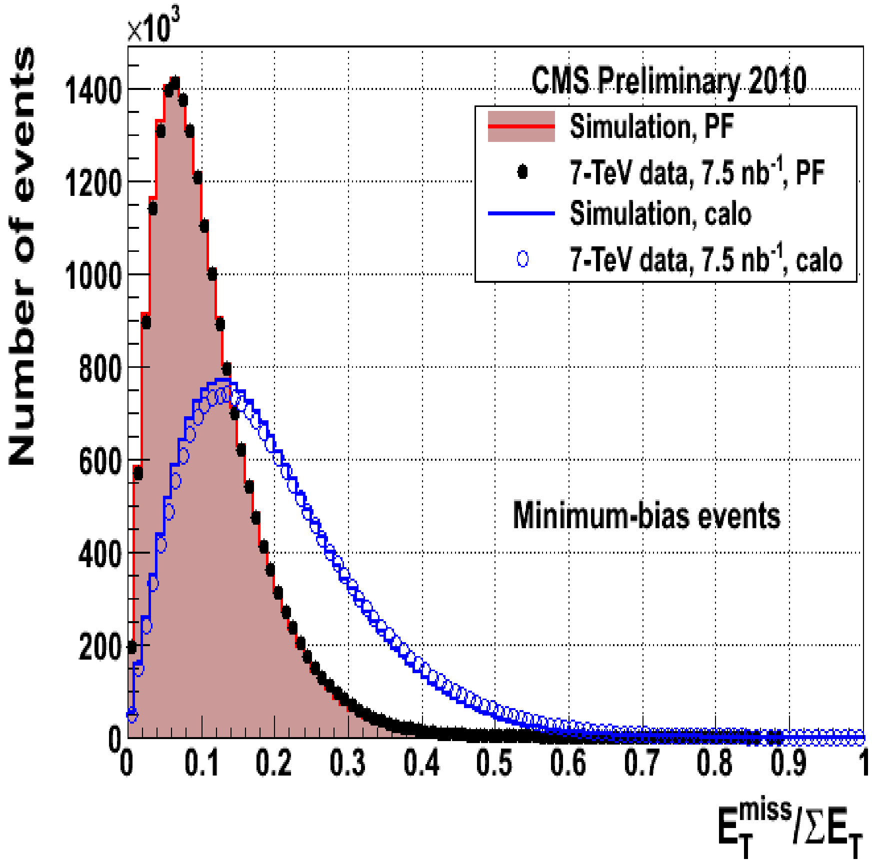
CMS: particle-flow techniques

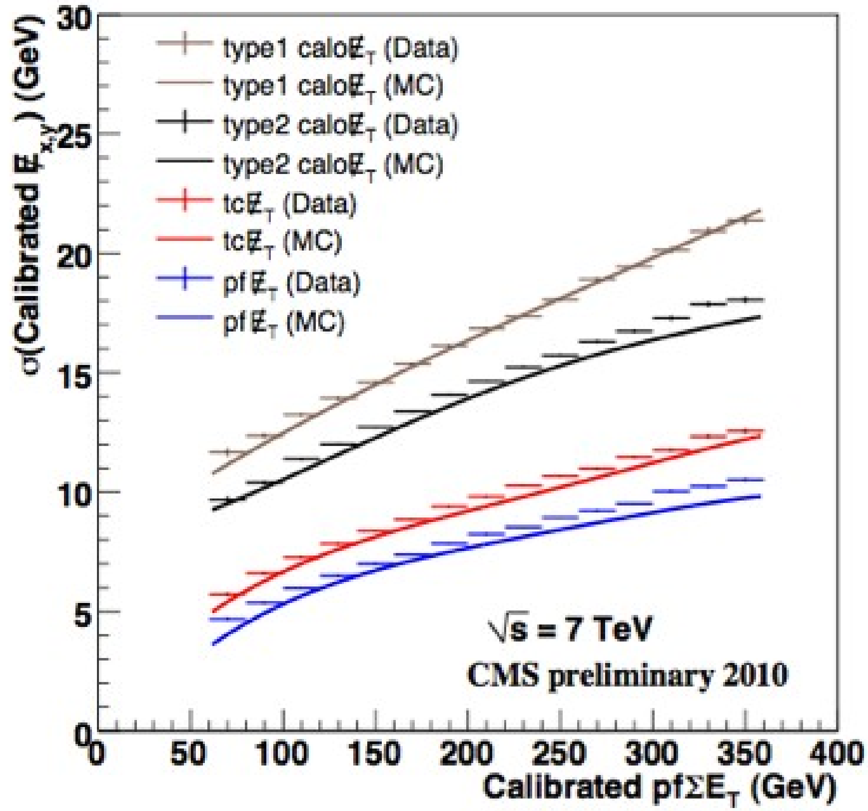


- In CMS, charged particles get well separated due to the huge tracker volume and the high magnetic field (3.8 T)
- CMS has an excellent tracking resolution, able to go to down to very low momenta (~few hundred MeVs)
- CMS has also an excellent electromagnetic calorimeter with good granularity
- In multijet events, only 10% of the energy corresponds to neutral (stable) hadrons

Big improvement in energy resolution and identification using particle-flow techniques

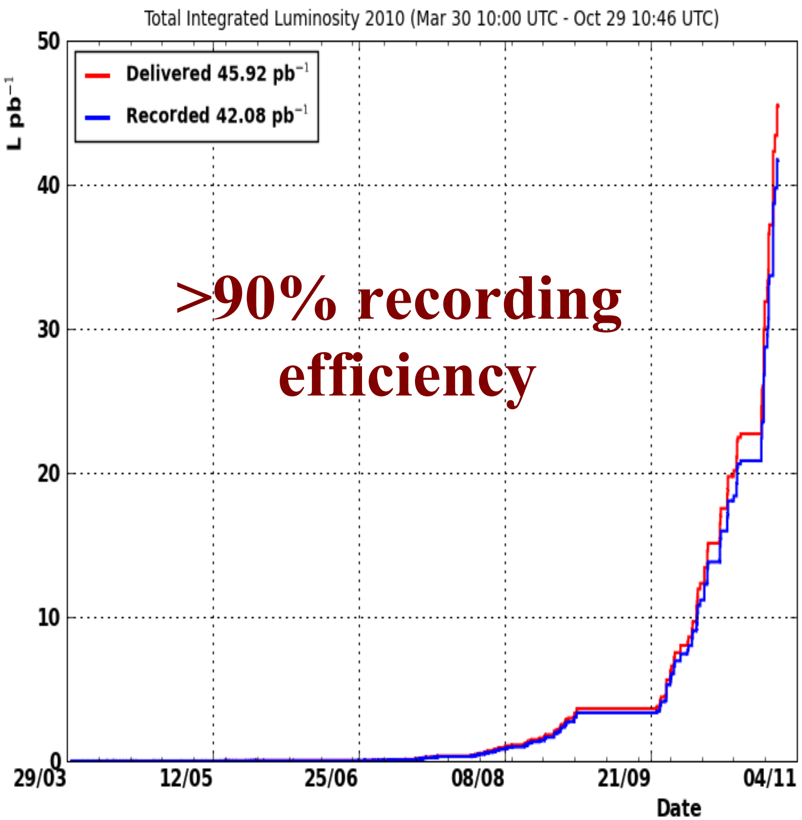
CMS: particle-flow techniques

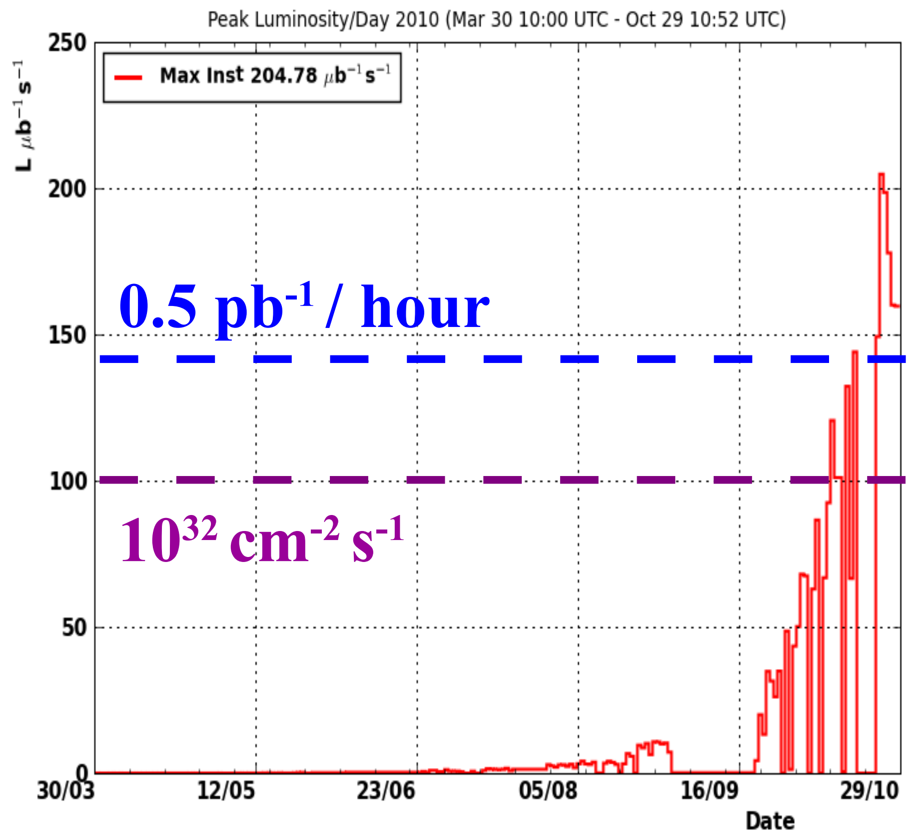




- Factor of two improvement in energy resolution with respect to measurements using calorimeter information only.

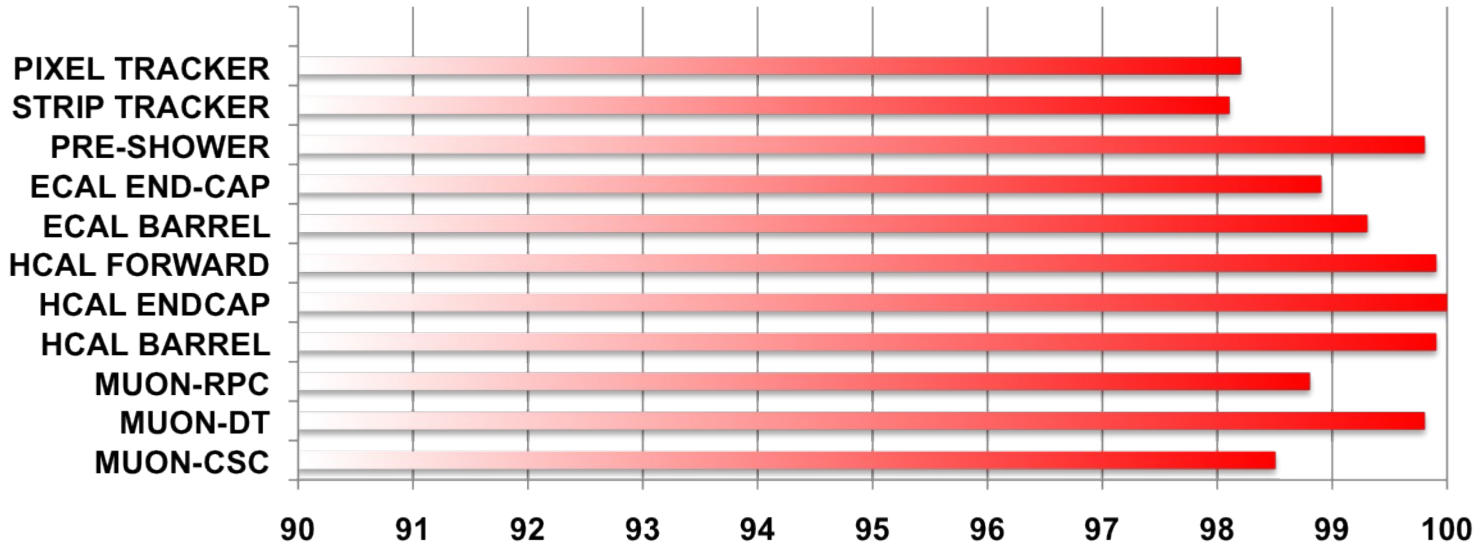
CMS is taking data ...





- Already ~ 45 pb^{-1} delivered, ~40 pb^{-1} collected.
- Also in essentially 'nominal' conditions: Level-1 trigger rates > 50 kHz, HLT rates > 300 Hz, and in the presence of pileup.

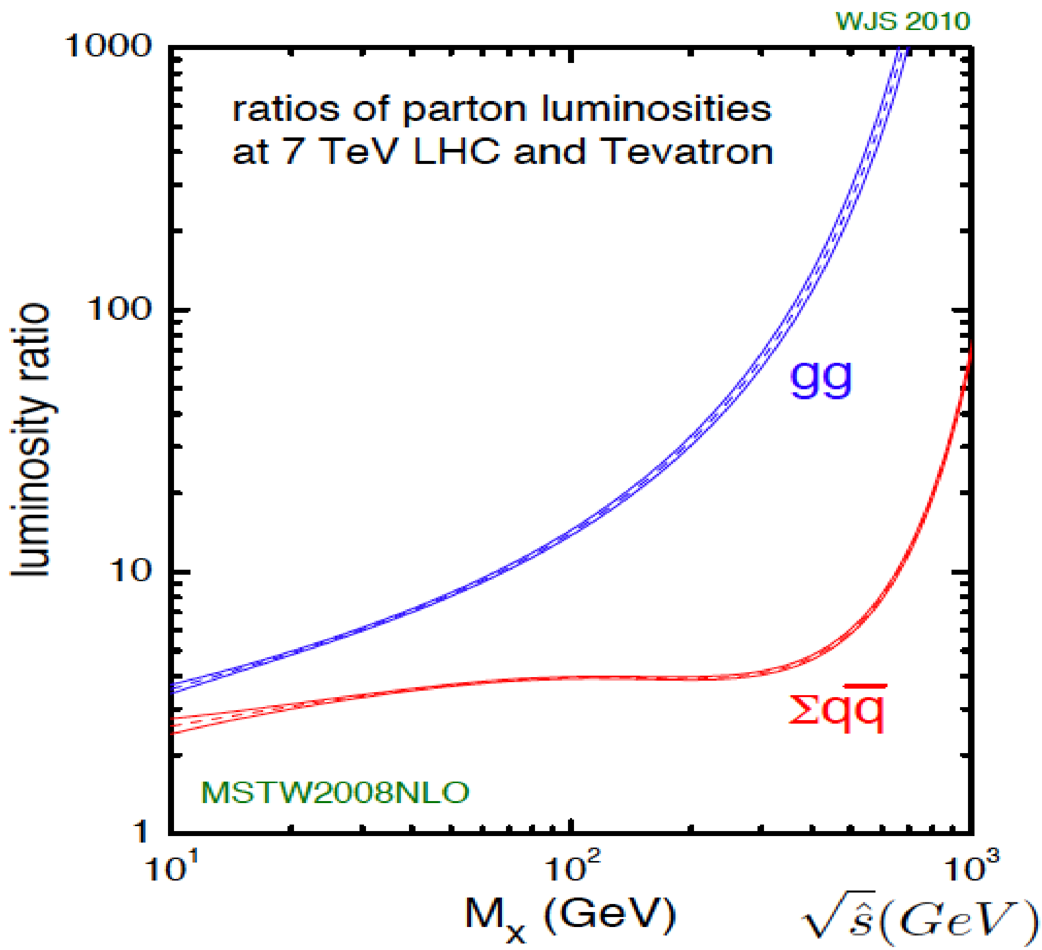
CMS is taking data ...



	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

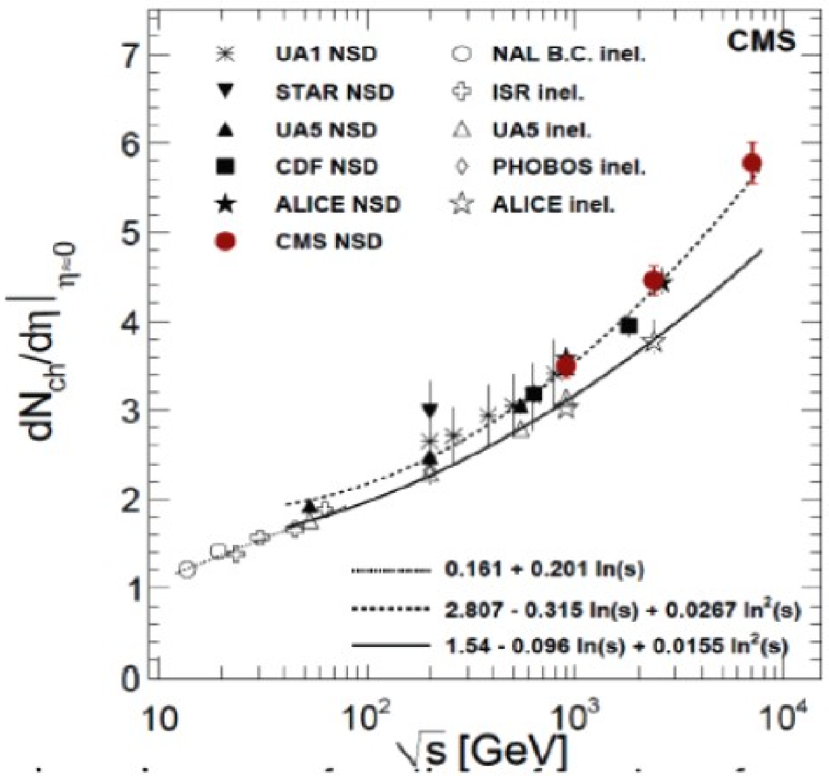
CMS fully operational at > 98% level

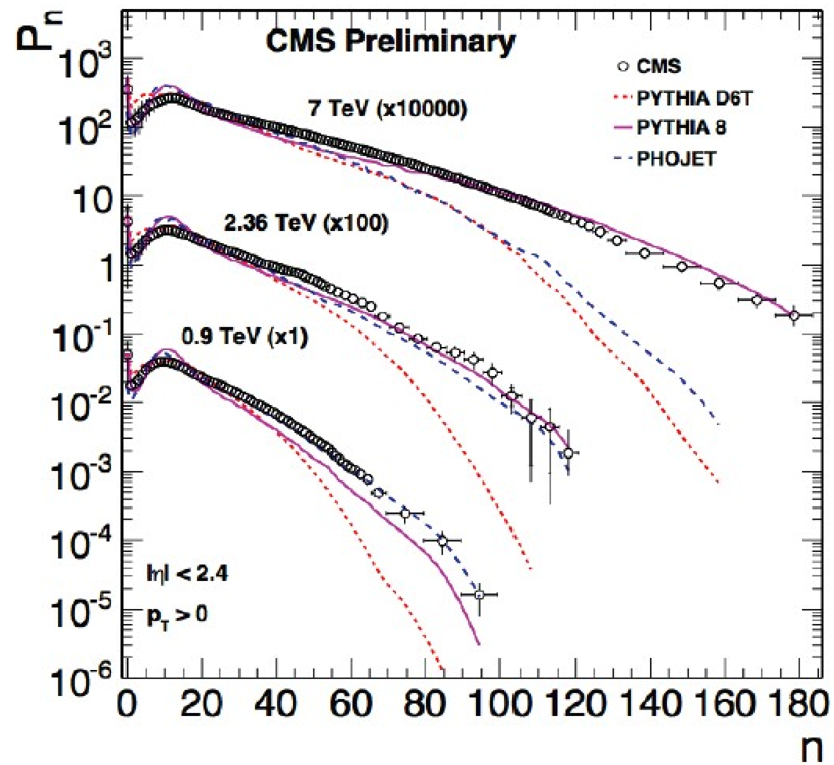
The LHC at √s = 7 TeV



- The LHC at √s= 7 TeV offers (with respect to Tevatron):
  - Higher center-of-mass energy → access to new physics scales, even with very low luminosities
  - ~ 10 times more gluon-gluon initial state → top factory, more Higgs cross section, also larger QCD backgrounds
  - ~ 3 times more $q\overline{q'}$ initial state → larger W/Z production in general (inclusive or associated)

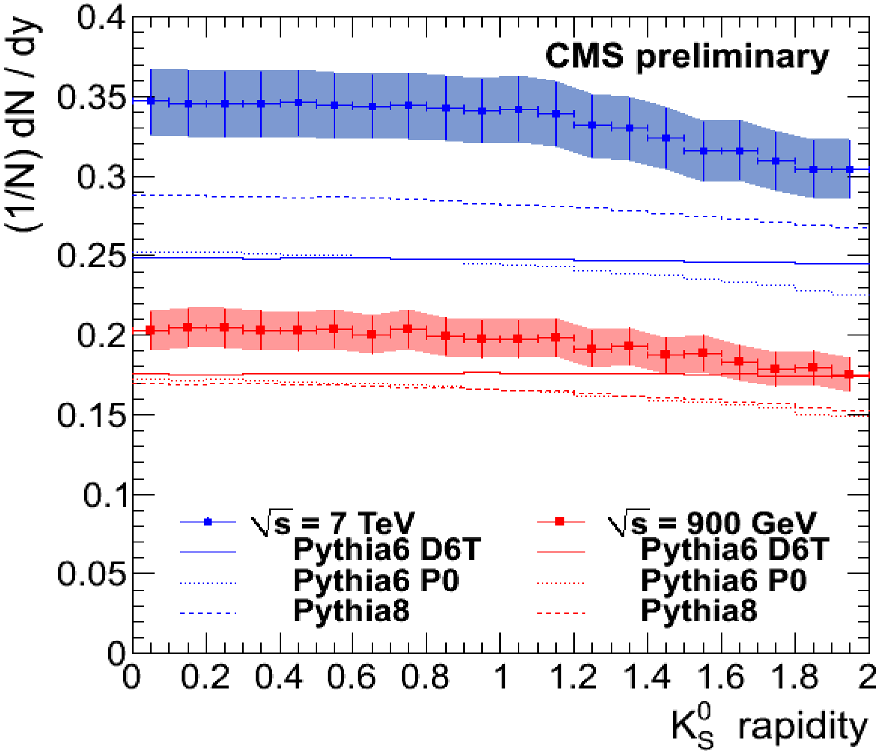
CMS physics results: QCD, low p_T

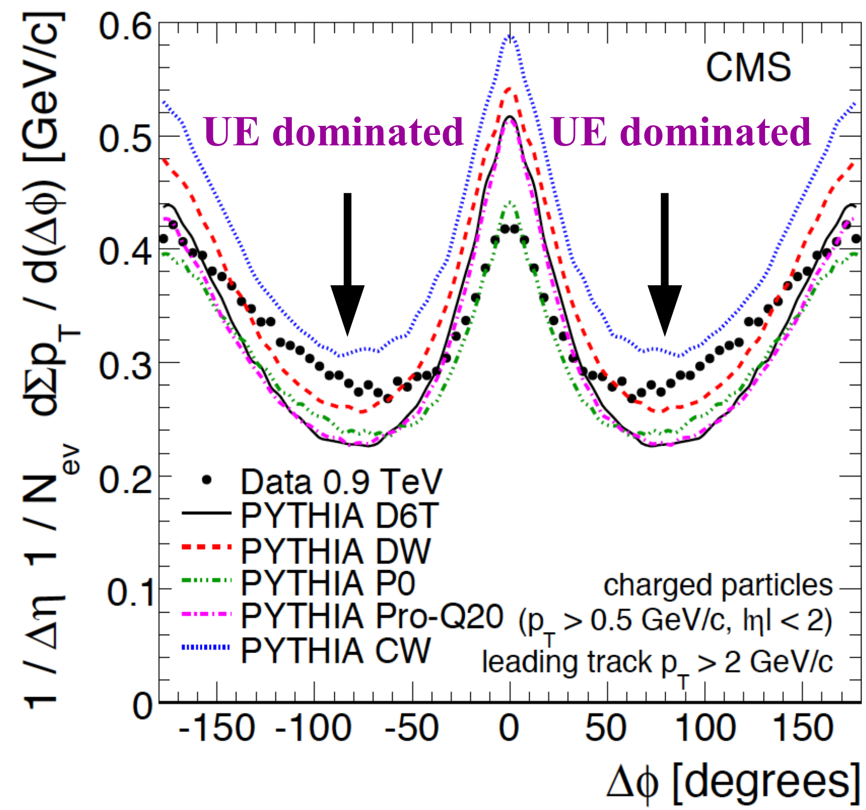




- Steeper rise in particle density than what most models predict.
- More discrepancies in the low p_T region of the spectrum. p_T < 500 MeV
- A more detail model tuning is required (although the implications for high-p_T physics are marginal)

CMS physics results: strangeness, underlying event properties, ...



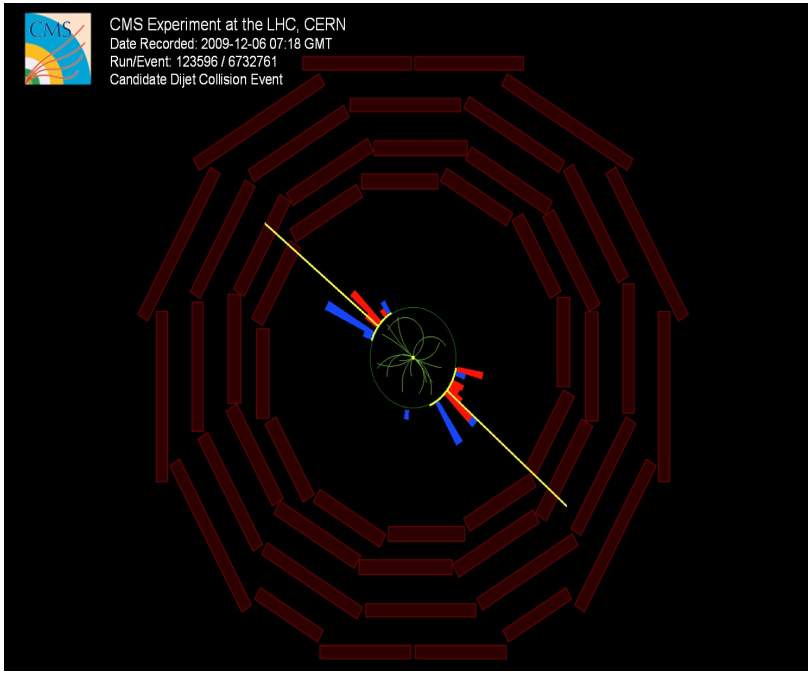


- Usual MC settings predict less strange-quark production than what is seen.
- Underlying event activity does not match extrapolations from Tevatron. Also confirmed by other experiments. New tunings going on...

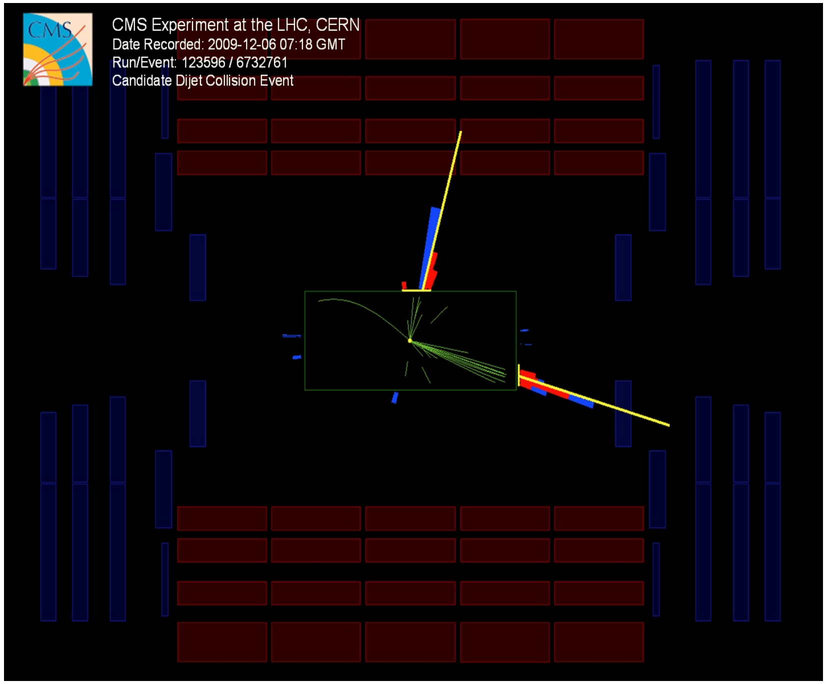
CMS physics results: the 'ridge'

TWO-PARTICLE CORRELATIONS AS A FUNCTION OF THE AZIMUTHAL ($\Delta\Phi$) AND PSEUDO-RAPIDITY ($\Delta\eta$) SEPARATION

Dijet-like events: transverse plane



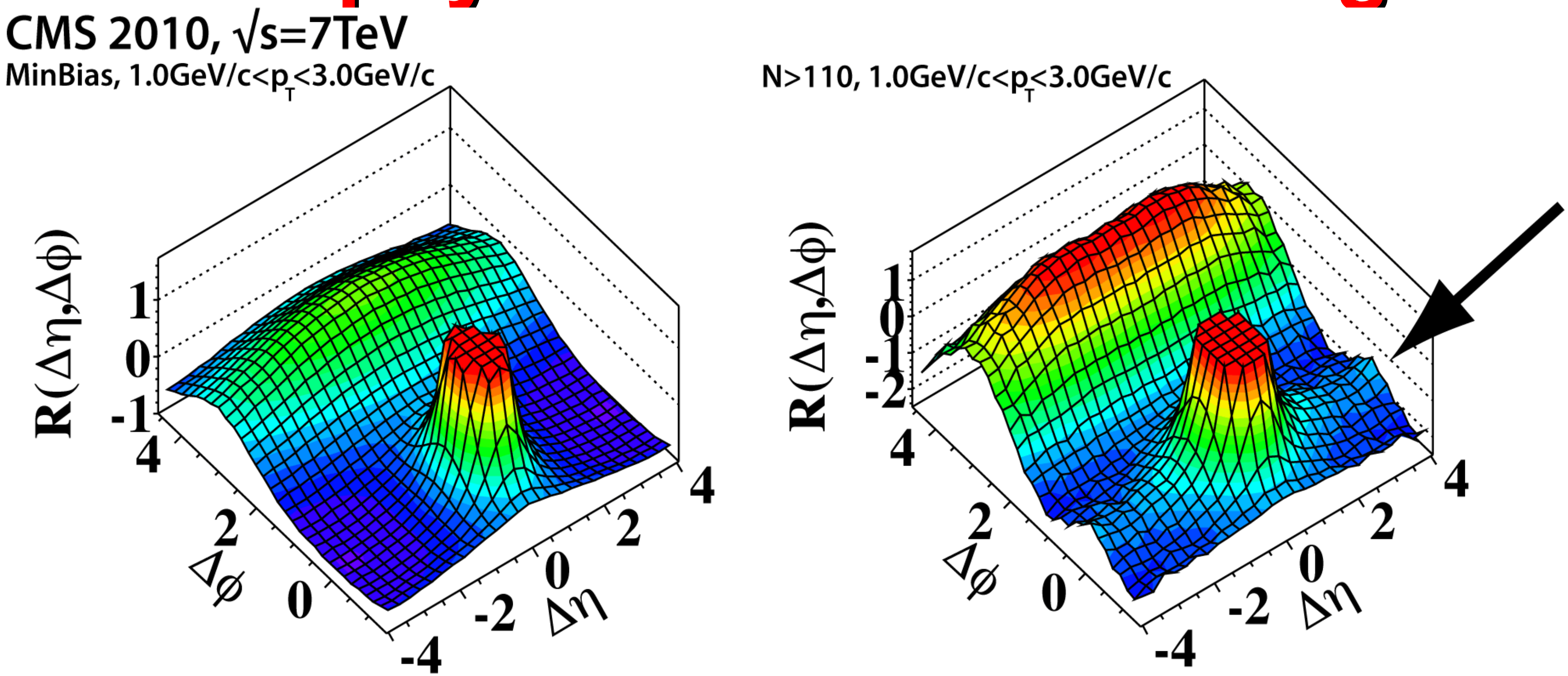
Dijet-like events: longitudinal plane



Correlations are large at $\Delta\Phi \approx 0$, $\Delta\eta \approx 0$

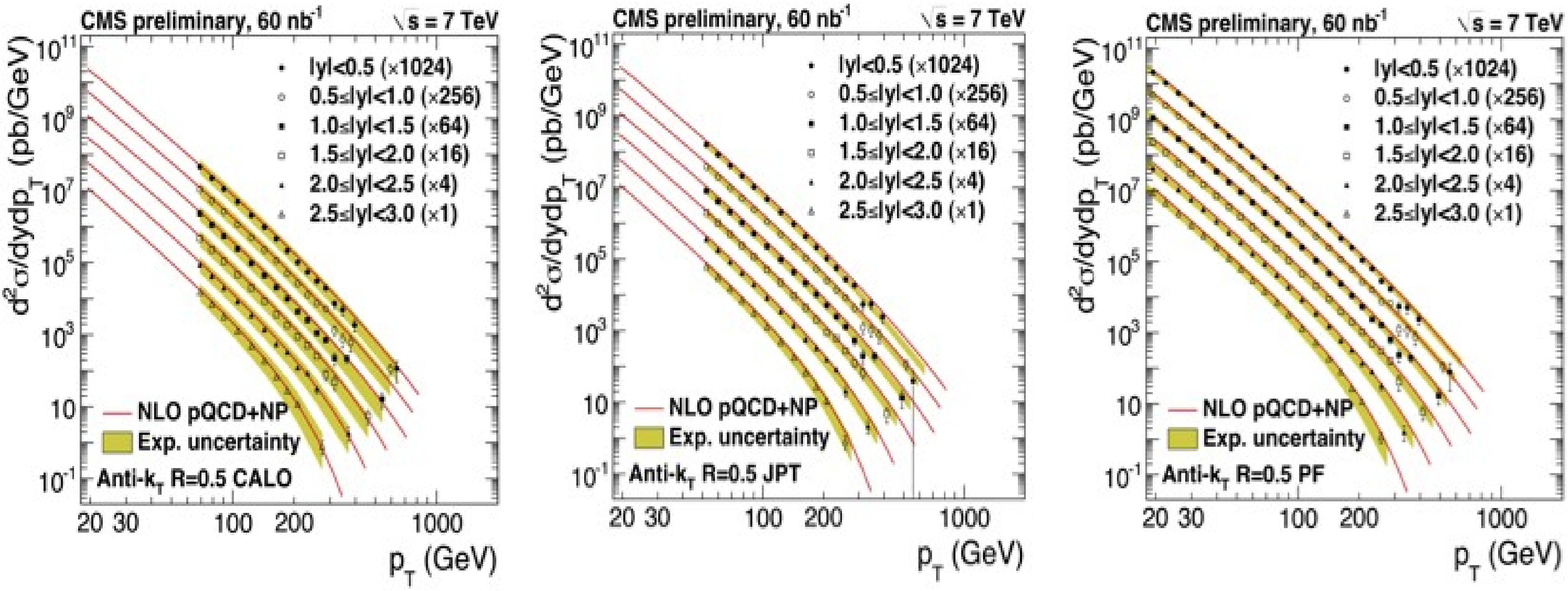
Correlations are large at $\Delta\Phi \approx \pi$, any $\Delta\eta$

CMS physics results: the 'ridge'



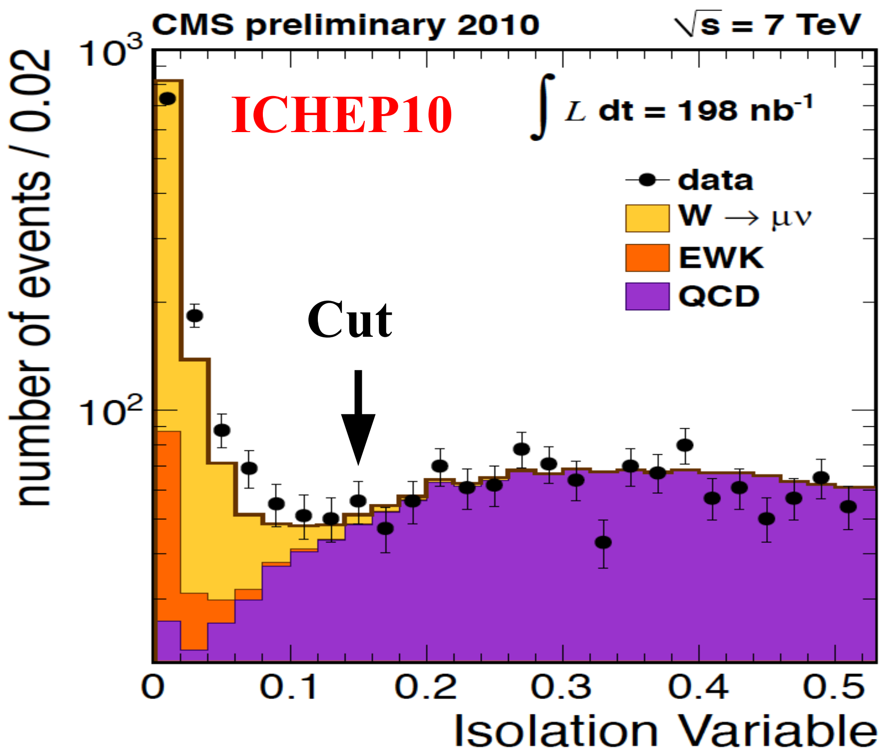
- Unexpected correlation between pairs of particles with ΔΦ≈0 and any Δη
- Not reproduced by our reference Monte Carlos (PYTHIA, …)
- Similar effects have been seen in Heavy Ion experiments
- Physics origin not understood yet. More studies going on...

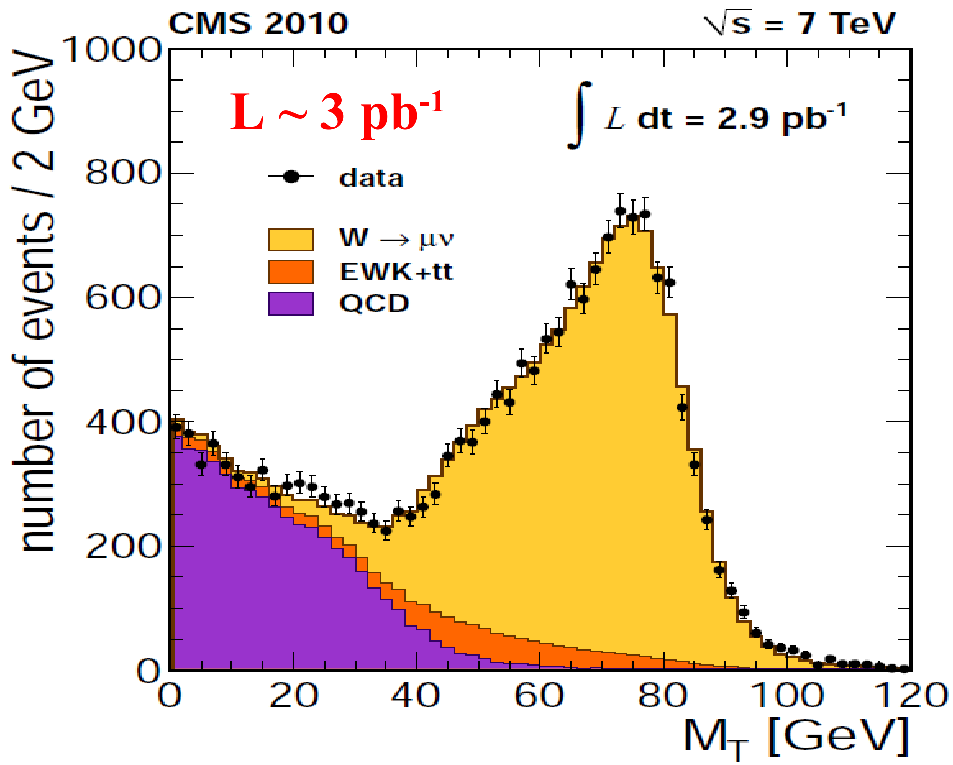
CMS physics results: high p_T



- Results in good agreement with NLO predictions
- For all types of jets (CALO: calorimetric jets, JPT: jets track-corrected, PF: particle-flow jets). Particle-flow jets allow to probe efficiently much lower transverse momenta (> 18 GeV)

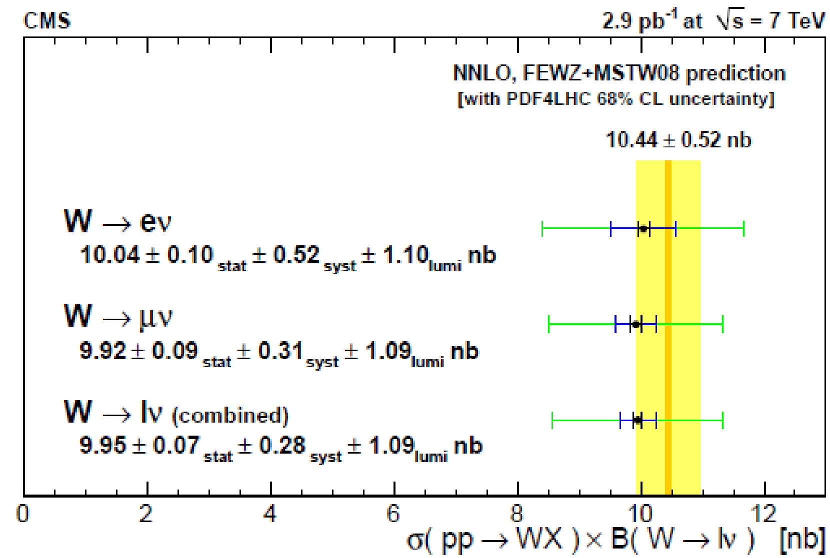
CMS physics results: EWK

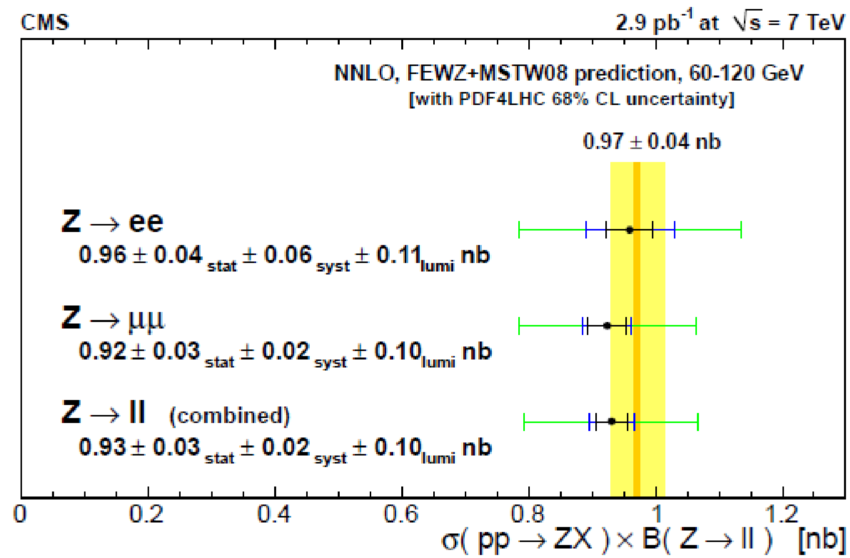


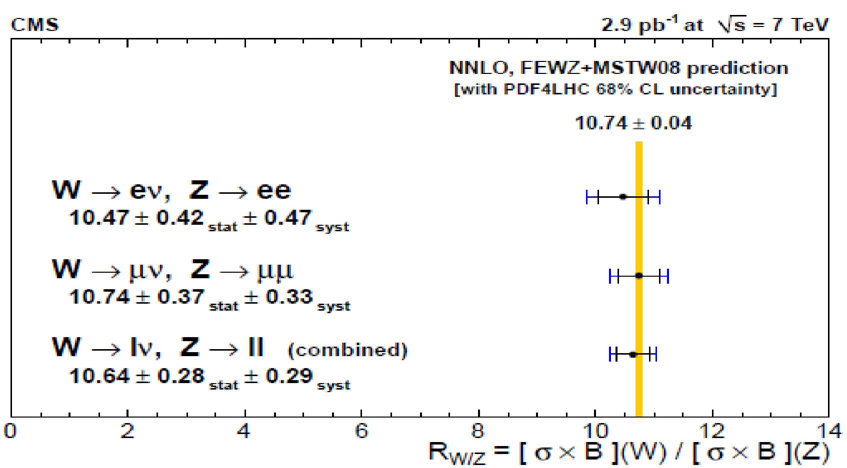


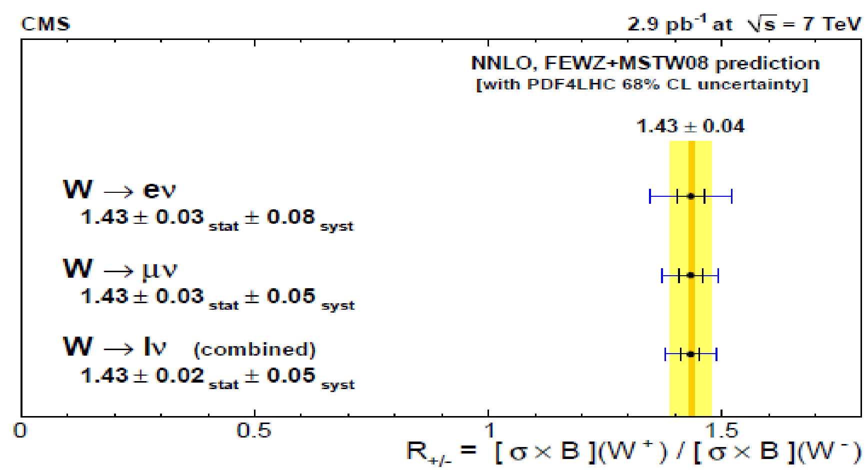
- Very 'direct' and unbiased selection in CMS: 1) high p_T (>20 GeV), isolated leptons; b) fit M_T (or missing E_T) distributions.
- Efficiencies, resolutions, signal and background shapes studied / extracted from data.

CMS physics results: EWK



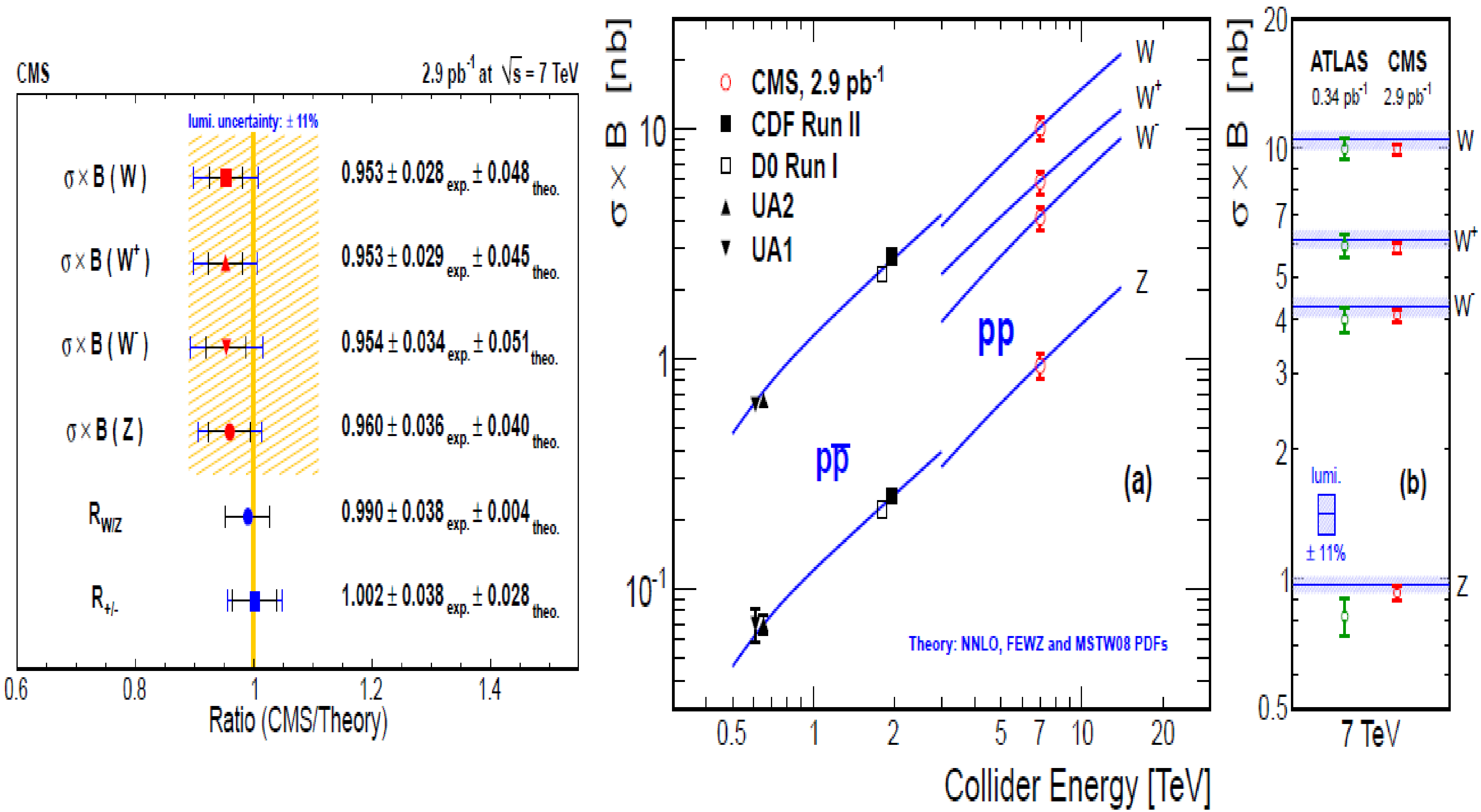






- First EWK results presented at ICHEP. Important benchmark for many future studies: V+jets, background for searches, … Good agreement with the SM expectations

CMS physics results: EWK

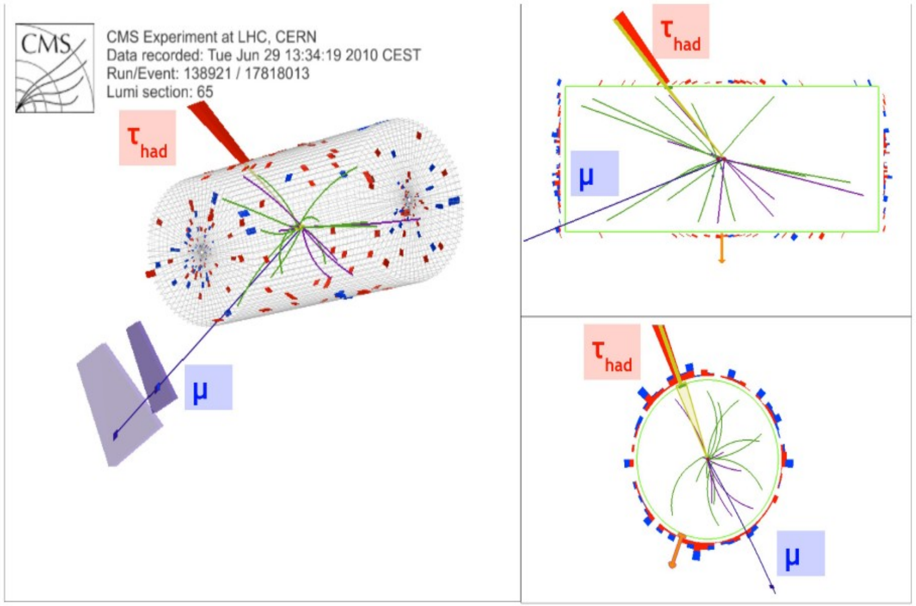


- Paper with L = 2.9 pb^{-1} : hep-ex:1012.2466, imminent publication in JHEP

CMS physics results: Taus

Z → tau tau → mu +tau$_{had}$ (one prong+pi0 tau)

Visible Mass (WP 75%)

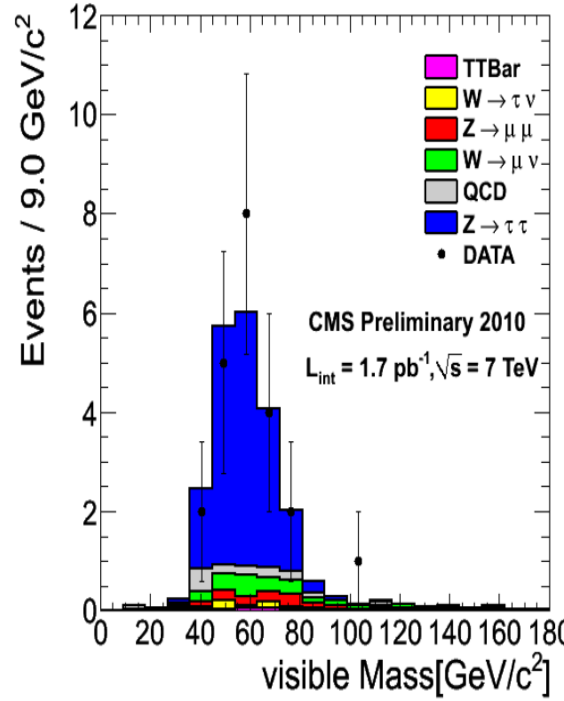


μ p_T = 22.8 GeV/c

τ_{had} E_T = 32.9 GeV

Vis. Mass = 60.8 GeV/c^2
M_T(μ,MET) = 10.1 GeV

Selections as in ICHEP PFT-10-004 PAS

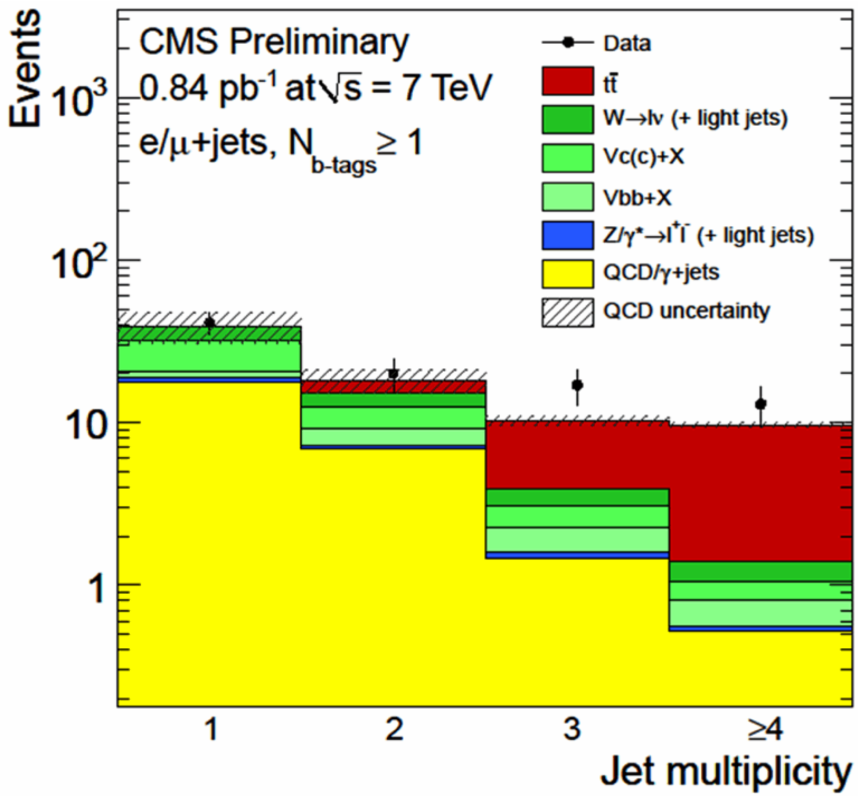


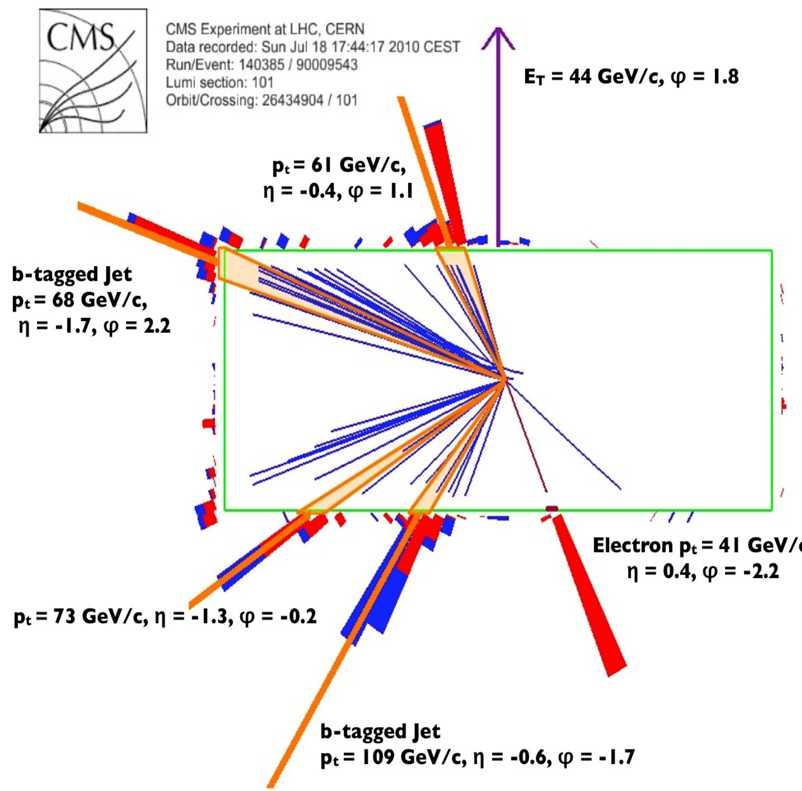
WP 75

- **Mu Pt > 15 GeV/c**
- **Rel Comb PF Iso < 0.1**
- **Tau Pt > 20 GeV/c**
- **HPS Loose Isolation**

- This is an example of the power of particle-flow techniques in CMS
- Visible tau signal in Z-> tau tau production with just 1.7 pb^{-1} of data !!
- This is an important benchmark measurement for key new particle searches like H-> tau tau, for instance!

CMS physics results: $t\bar{t}$ production

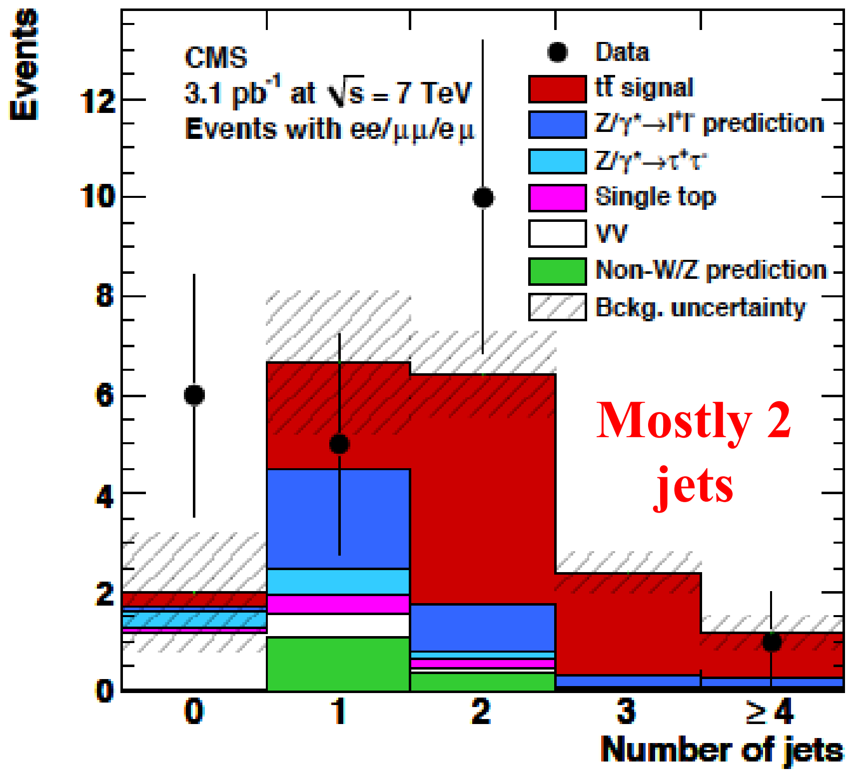


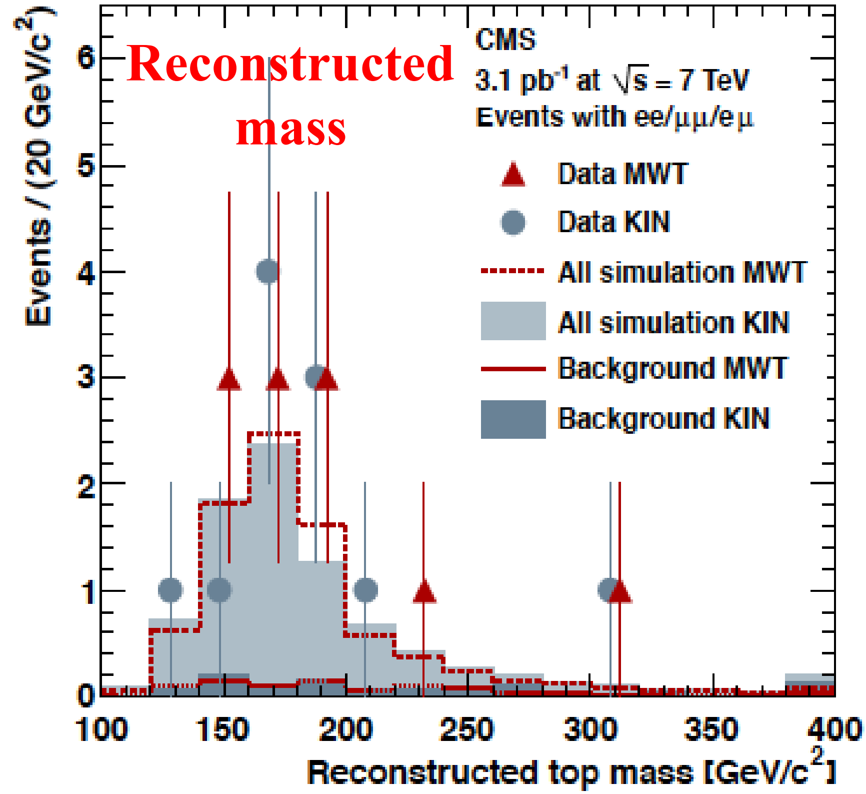


- Study of $t\bar{t} \rightarrow bq\bar{q}'\ \bar{b}l\nu$ with just 0.84 pb^{-1} : high-pt, isolated lepton and at least one b-tagged jet (secondary vertex tagger with ≥ 2 tracks: ~ 80% efficiency with small fake rate)
- 30 events observed with ≥ 3 jets, over a predicted background of ~ 5 events

TOP SIGNAL ESTABLISHED !!

CMS physics results: $t\bar{t}$ production



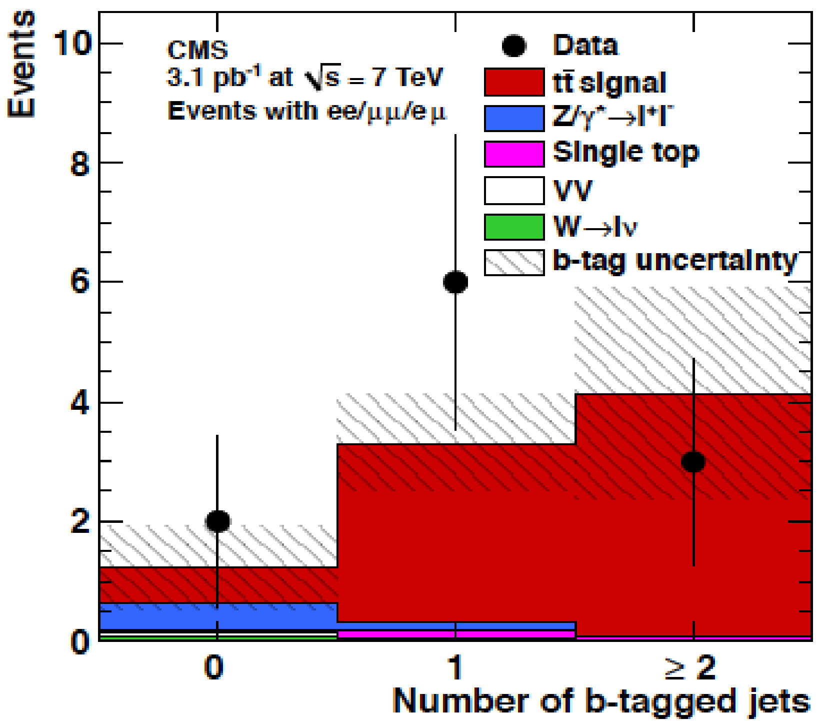


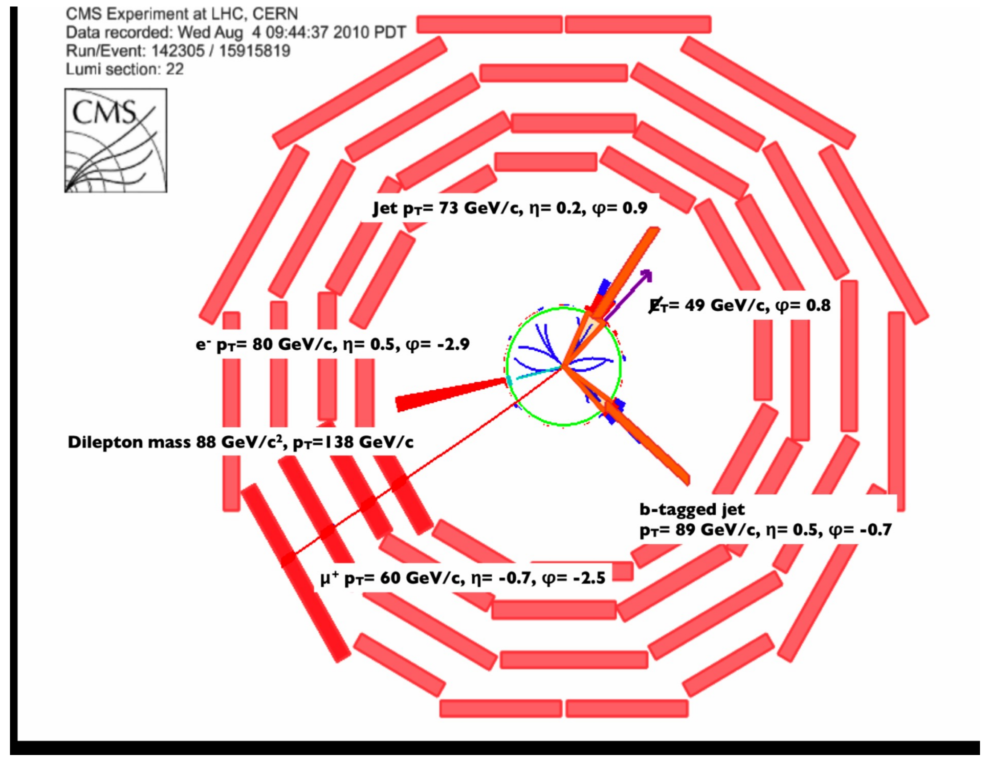
First top-quark published result at the LHC: measurement of the $t\bar{t}$ cross section in the di-leptonic channel: $t\bar{t} \rightarrow bl\bar{\nu}\ \bar{b}l\nu$

- Selection: two isolated high-p_T leptons (electrons or muons), missing E_T (>20-30 GeV, depending on the channel), at least two hard jets (E_T > 30 GeV)

CMS physics results: $t\bar{t}$ production

$$\sigma(pp \to t\bar{t}) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})\ \text{pb.}$$

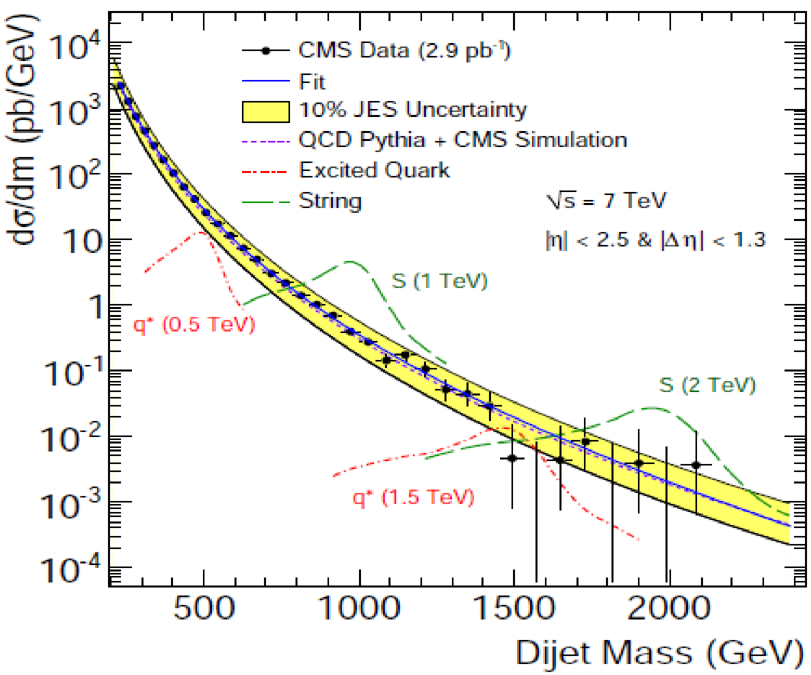


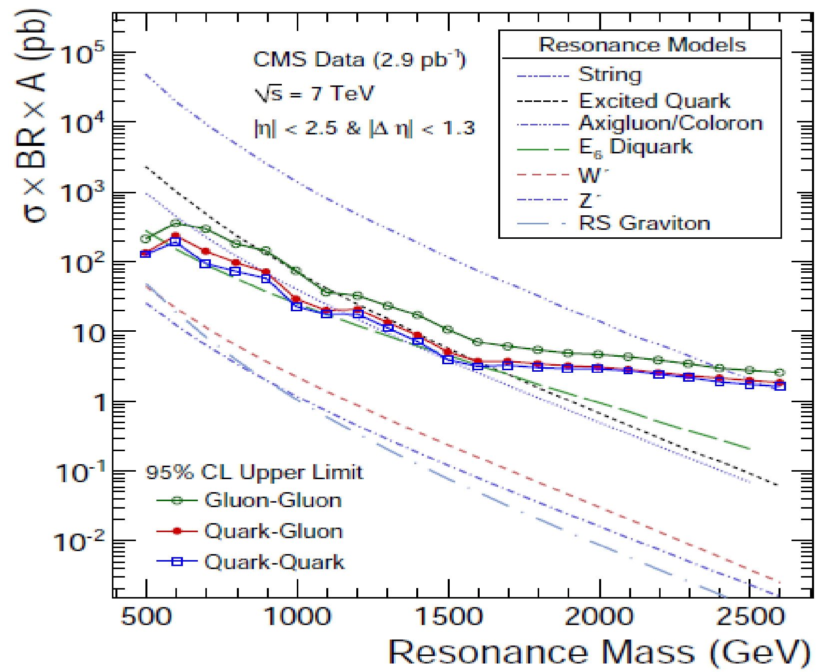


B-tagging cross-check of the consistency of the observed signal with $t\bar{t}$ production (but not used in the selection and measurement)

CMS physics results: searches

- Jet searches: two ways to observe a convincing signal of new physics in di-jet events:
  - a) Search for unexpected resonant production in di-jet systems



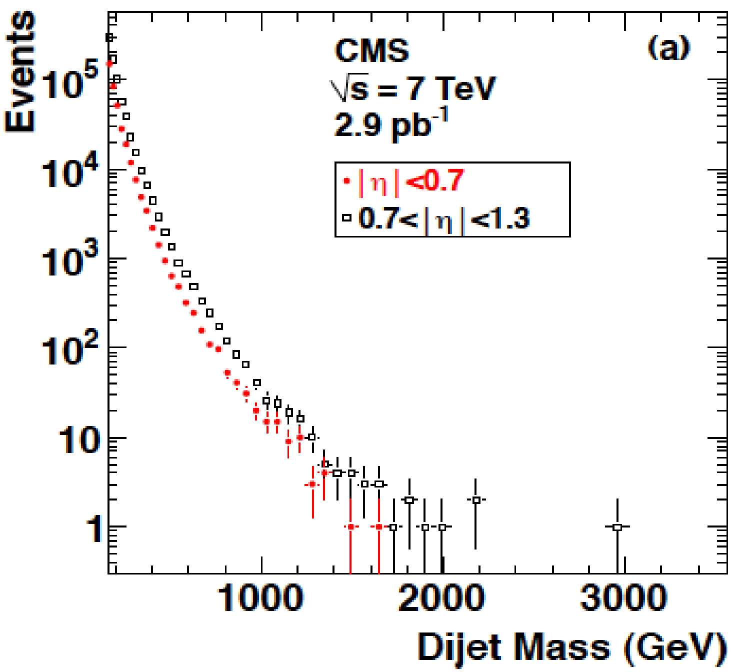


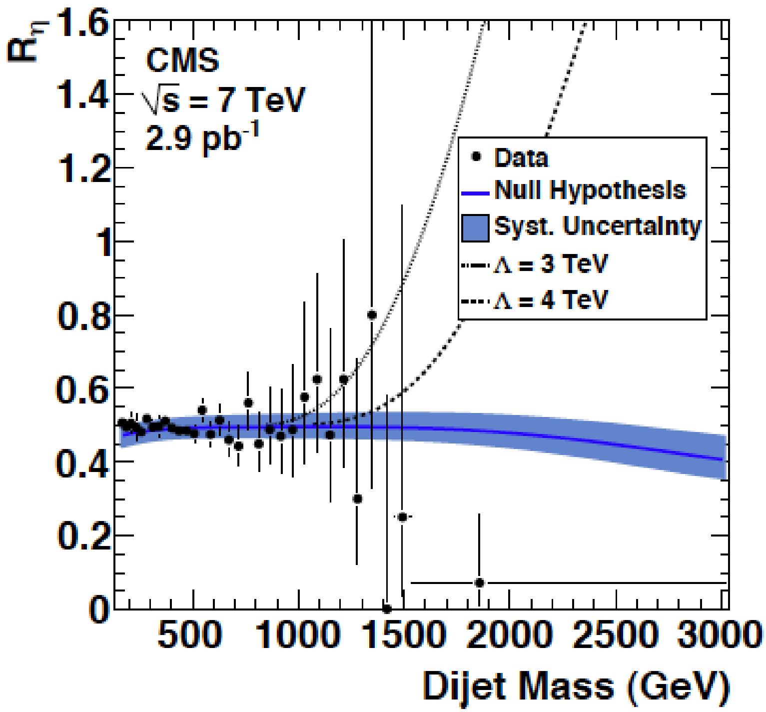
- Here we can see the power of increasing √s. Tevatron limits already superseded: string resonances (>2.5 TeV), excited quarks (>1.58 TeV), axi-gluons (>1.52 TeV), E_6 di-quarks (>1.60 TeV). Published in PRL (Phys. Rev. Lett. 105, 211801 (2010))

CMS physics results: searches

- Jet searches: two ways to observe a convincing signal of new physics in di-jet events:
  - b) Search for an excess of jet product in the central region with respect to non-central region:

$$R_{\eta} = N(|\eta|<0.7) / N(0.7<|\eta|<1.3)$$

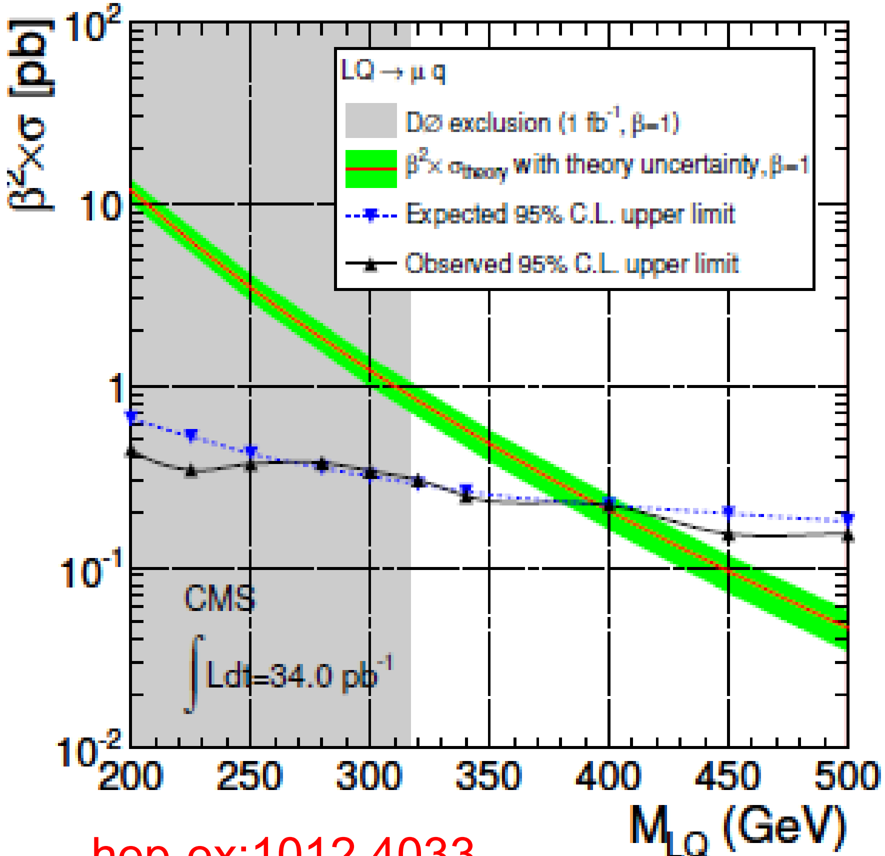




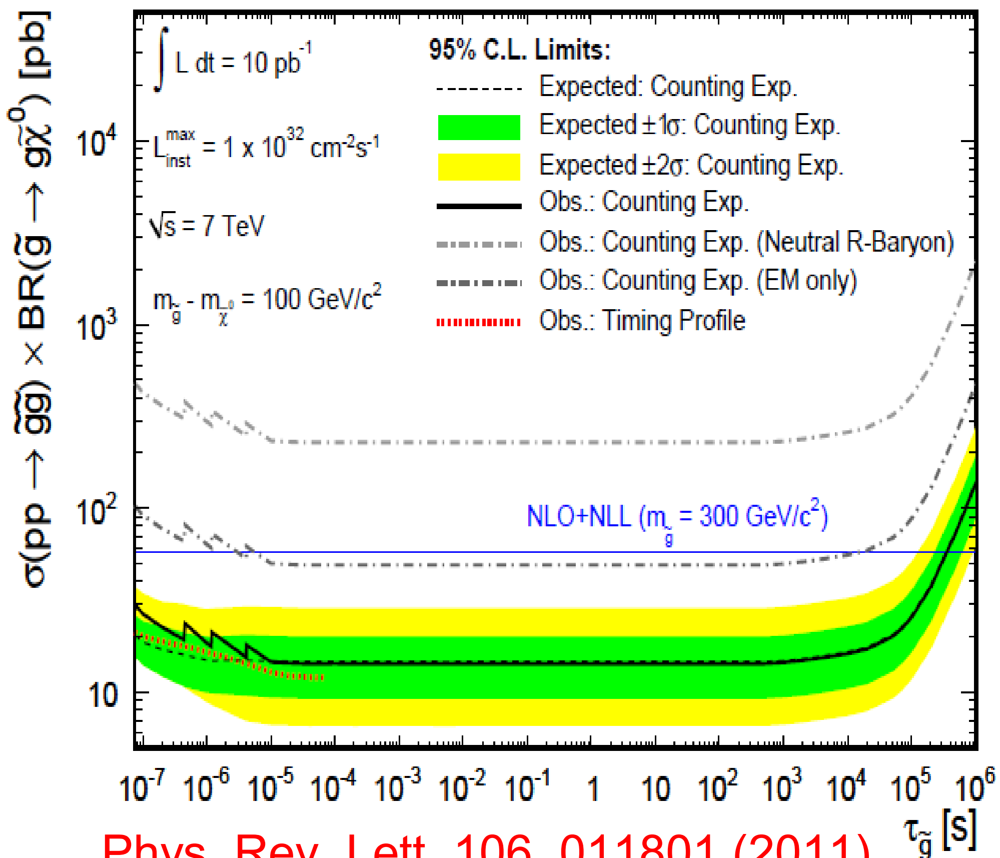
Compositeness scales < 4.0 TeV excluded: Phys. Rev. Lett. 105, 262001 (2010))

CMS physics results: searches

- More 'exotic' searches at hadron colliders: leptoquarks. heavy stable charged particles, stopped gluinos, ...



hep-ex:1012.4033



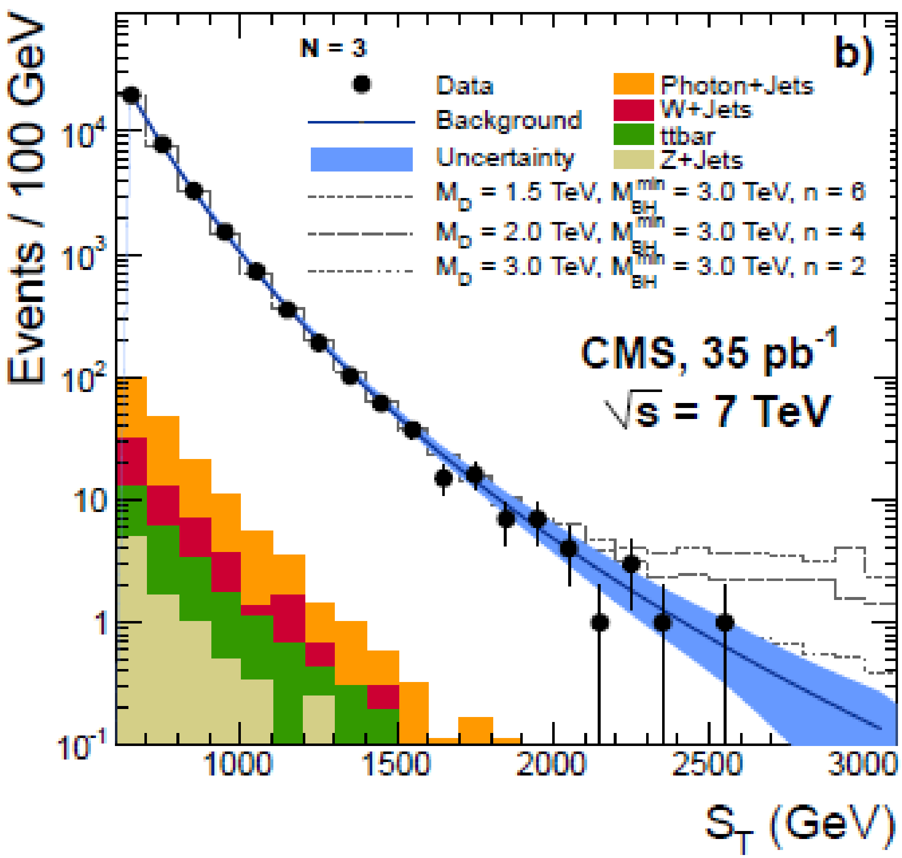
Phys. Rev. Lett. 106, 011801 (2011)

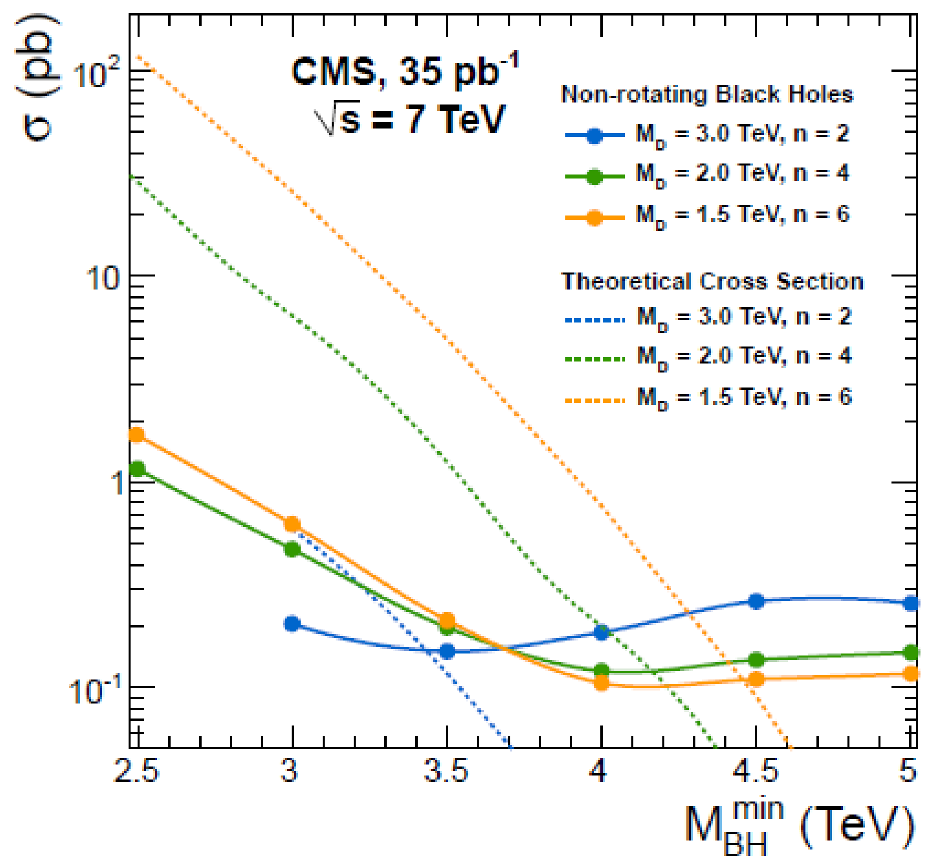
Already extending Tevatron limits with present luminosities...

CMS physics results: searches

- Microscopic black holes, ...

hep-ex:1012.3375

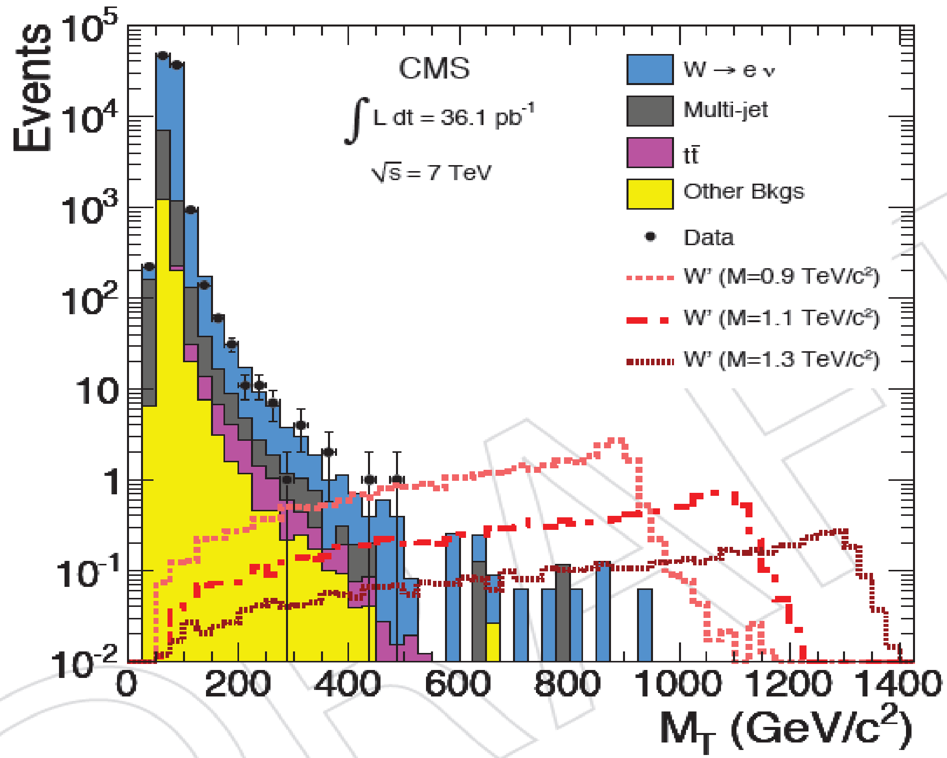


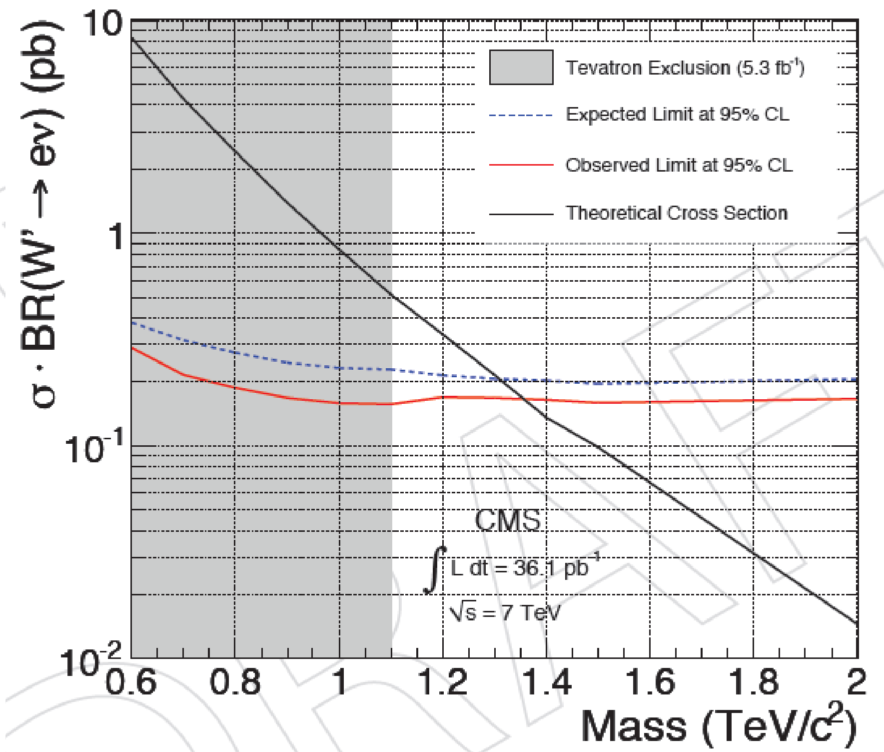


No black holes from gravity at the TeV scale
(lower limits on mass in the 3.5-4.5 TeV range)

CMS physics results: searches

- New gauge bosons, ...

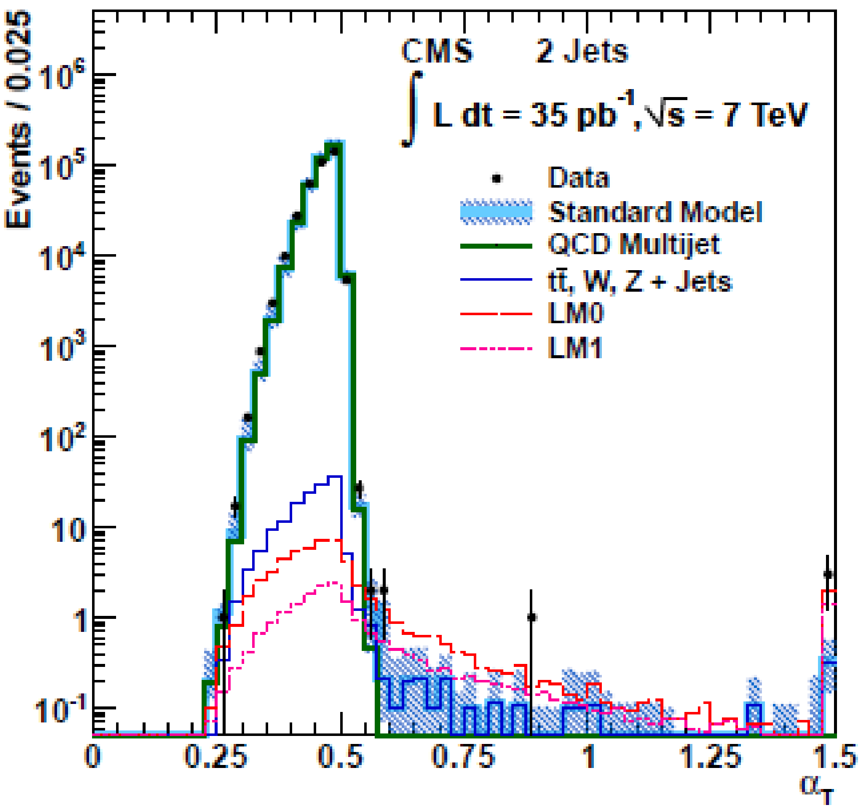




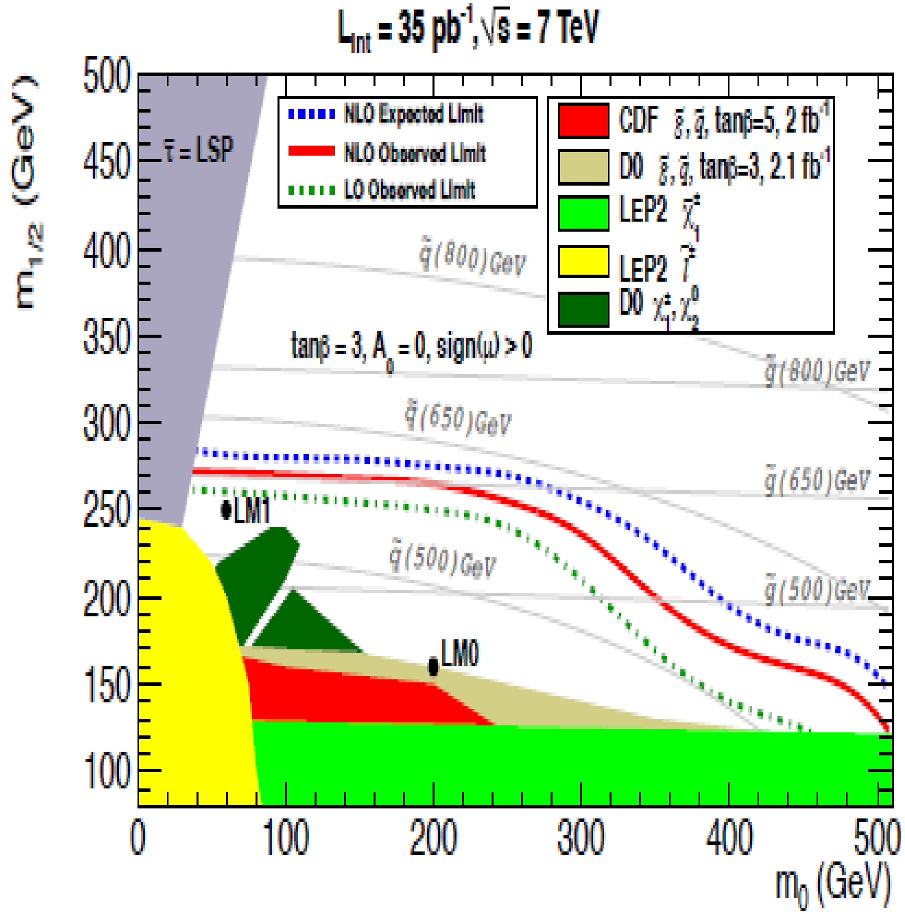
No extra W gauge bosons found; electron results already published (M<1.36 TeV, hep:ex:1012.5945), muon and combined results imminent

No extra Z gauge bosons found in M<850-1150 GeV (depending on the model); electron+muon results already sent for publication (CERN-PH-EP-2011-002)

CMS results: SUSY



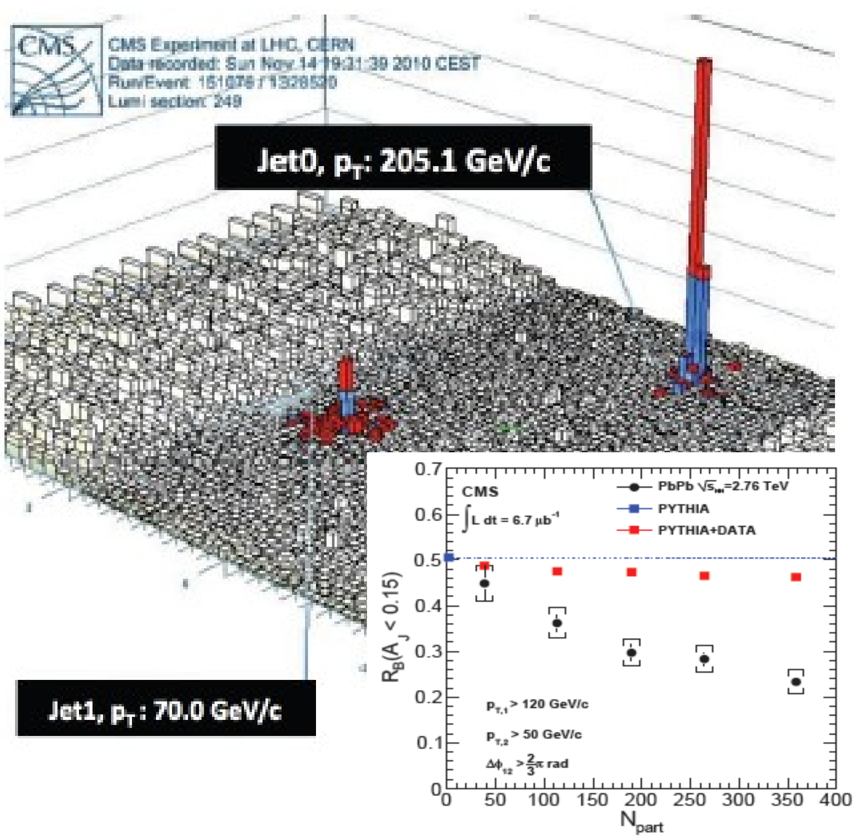
$\alpha_T = E_T^{j2} / M_T$



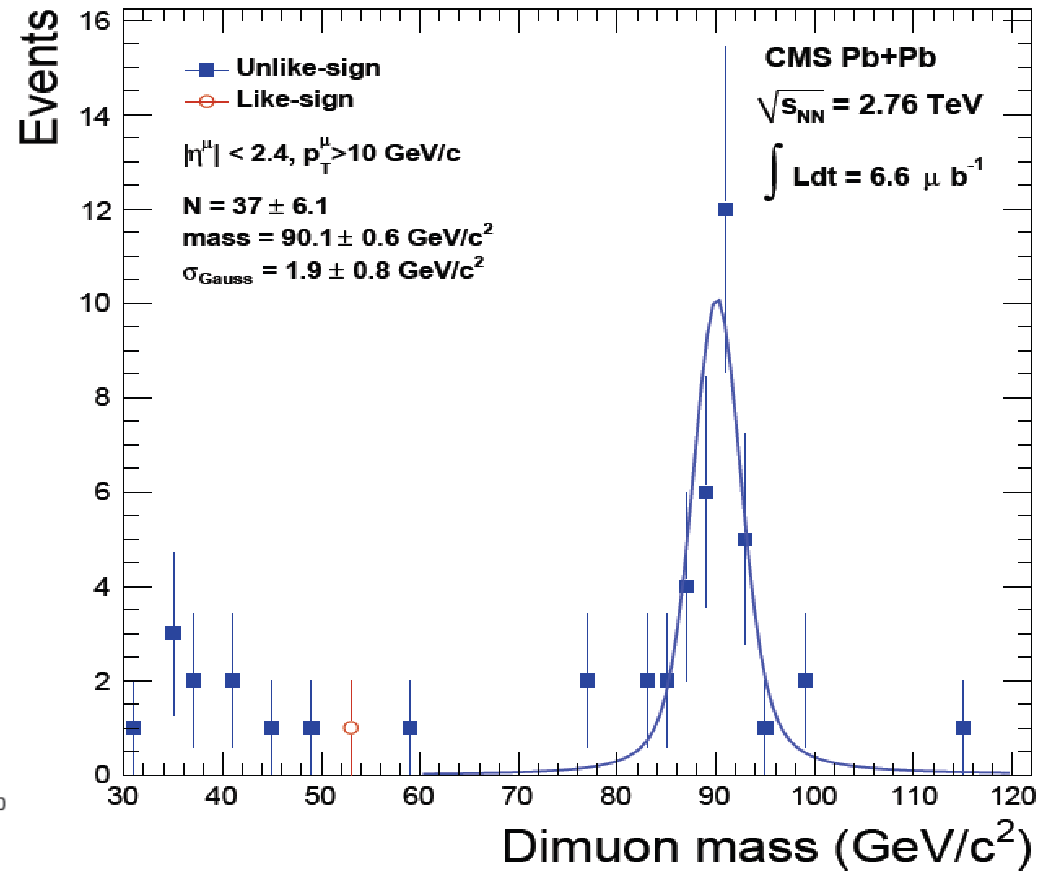
CERN-PH-EP-2010-084

- 36 pb^{-1} is enough to improve over past experiments...
- Data-driven methids used to control SM backgrounds

CMS results: Heavy Ion Run



Jet quenching:
CERN-PH-EP-2011-001

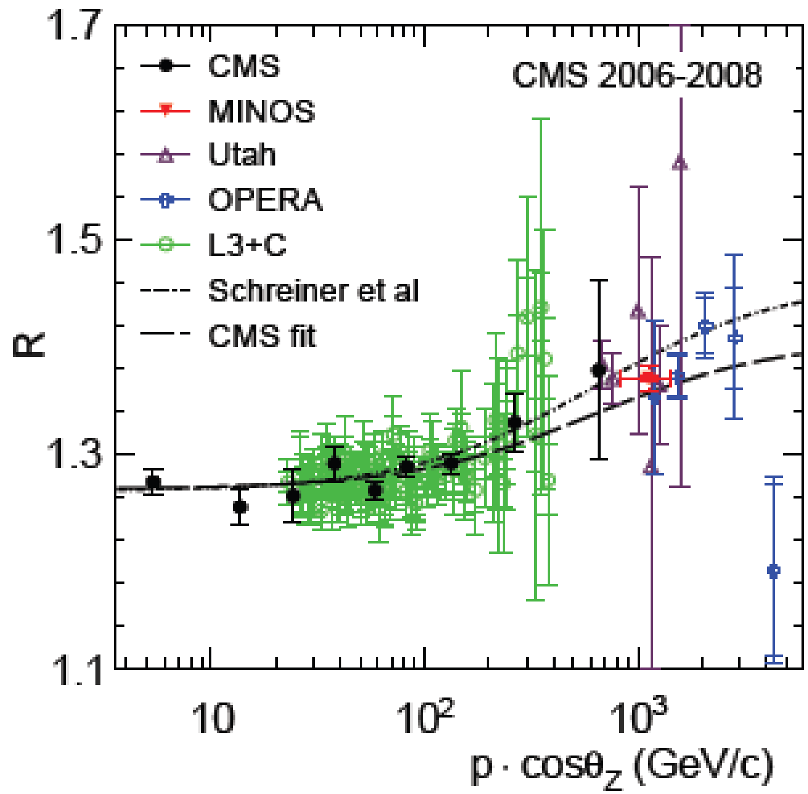


First observation of Z events in Heavy Ion collisions: CERN-PH-EP-2011-003

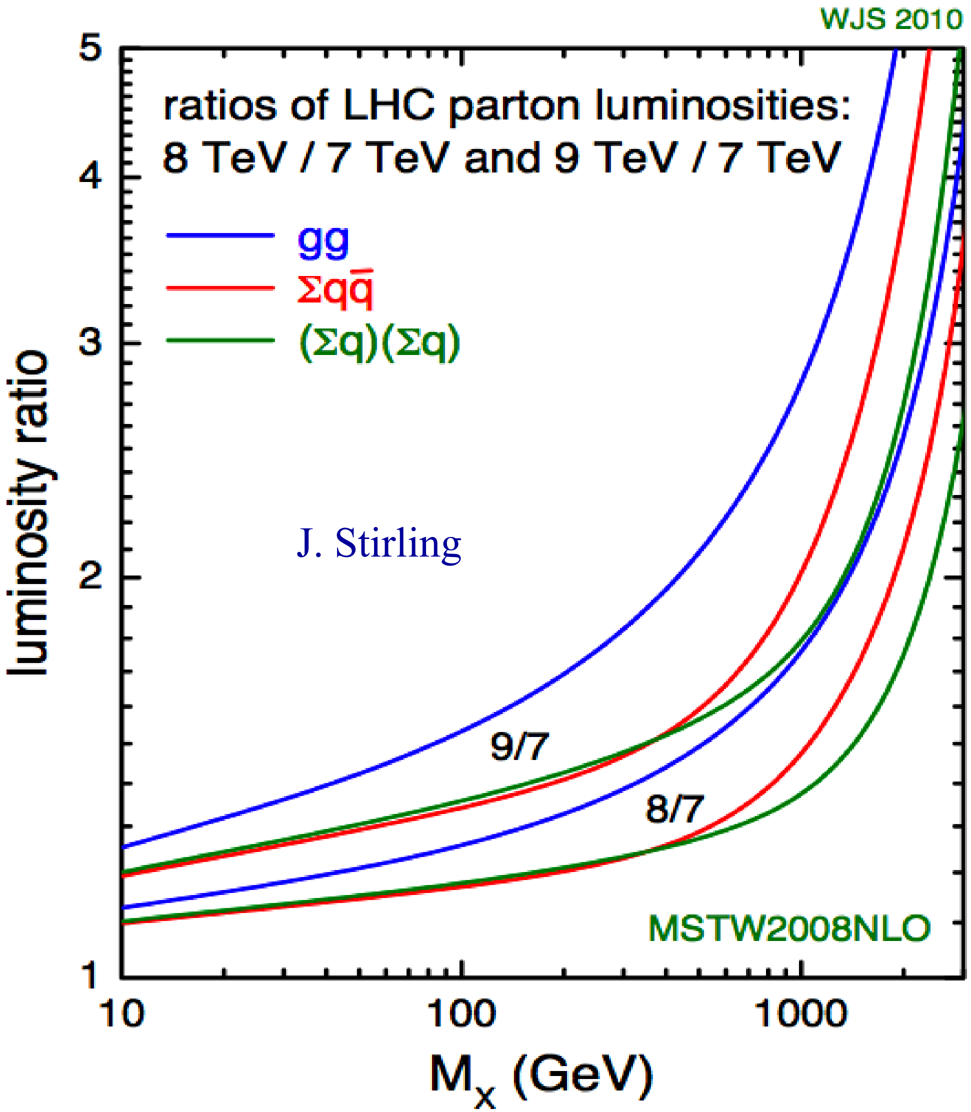
- Pb-Pb collisions at 2.76 TeV / nucleon, 6.7 μb^{-1} collected in late 2010
- Plenty of new interesting effects in this dense environment

CMS results ...

- I am still missing many important results:
  - Non-collision results (for instance the Measurement of the Muon Charge Ratio → it turned out to be also useful to understand how to control the muon resolution at the TeV scale)
  - Coming papers related with the Higgs search:
    - Observation of WW production
    - Limits on H->WW in the presence of a fourth fermion generation
    - Limits on supesymmetric Higgses for high tan(beta) in the ($b\bar{b}$ →) H->tau tau channel (already improving Tevatron limits for m_A< 350 GeV)
  - ~ 20 papers already published, and ~ 20 papers in the queue, and even more going on but not yet at the final stage, ...



The LHC at $\sqrt{s}$ = 8-9 TeV



- It is likely that the LHC be able to run in 2011-2012 at a higher center-of-mass energy and collect ≥ 5 fb^{-1} per experiment (still to be confirmed).
- Again, improvements due to the rise in center-of-mass energy are kind of expected
- This implies more work on the experimental side (new prospect studies, simulations, ...), but it is welcome :)

CMS prospects: Higgs searches

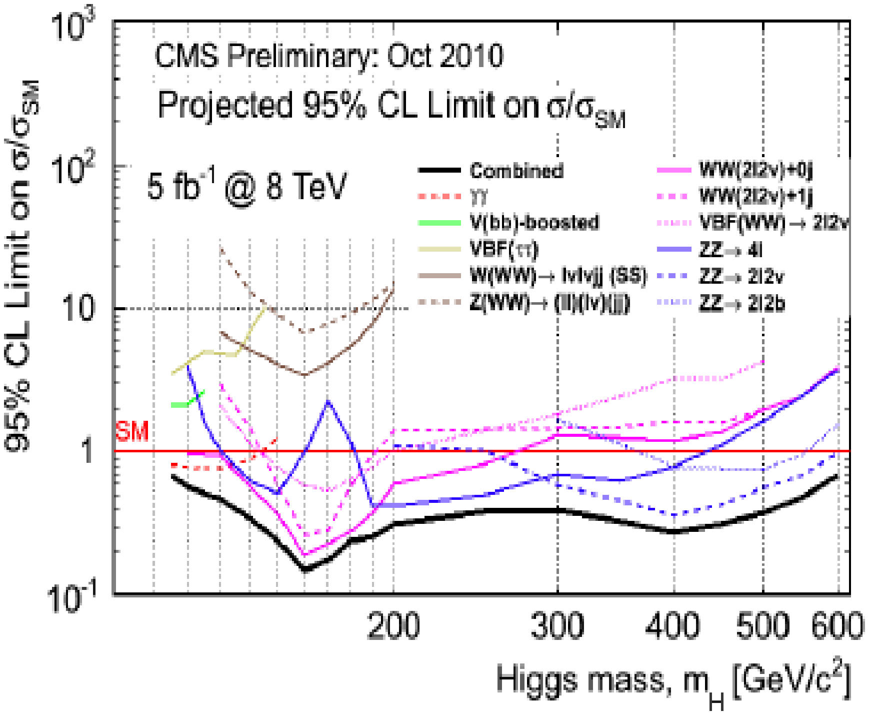
- Here √s is not the relevant quantity; much more integrated luminosity is necessary. One loses gg->H going from √s=14 TeV to √s=7 TeV (factor of 4)
- Improvements over previous estimates: add channels with potential sensitivity (à la Tevatron), not just `golden' ones (since detector performance is optimal)

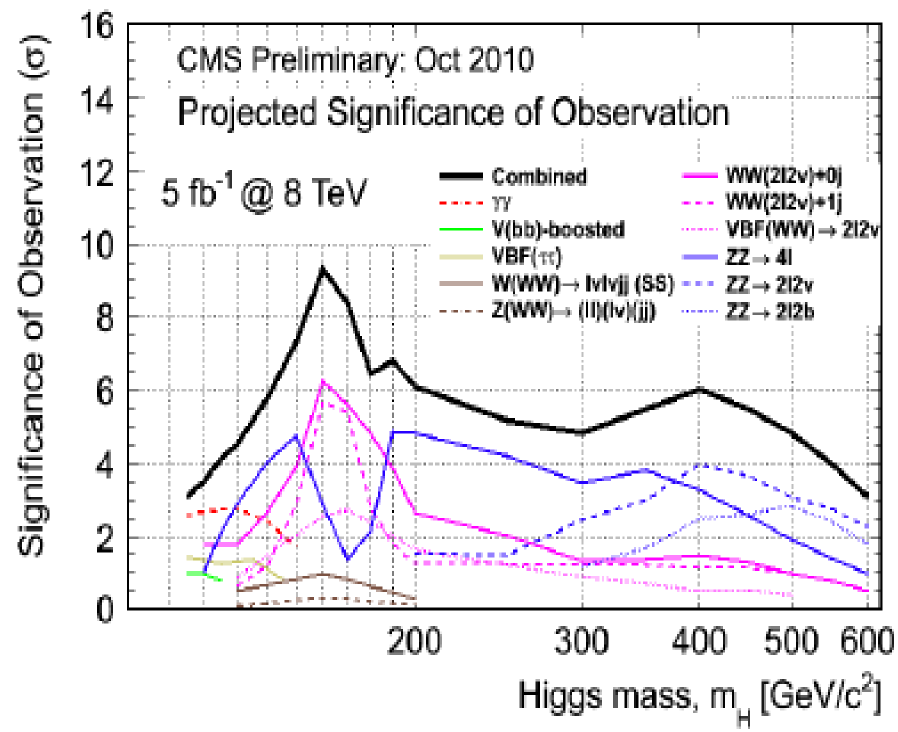
Channels included:	Mass range Studied (GeV)
$H \rightarrow \gamma\gamma$	115-150
VBF $H \rightarrow \tau\tau$	115-145
VH, $H \rightarrow bb$ (highly boosted)	115-125
VH, $H \rightarrow WW \rightarrow l\nu jj$	130-200
$H \rightarrow WW \rightarrow 2l2\nu$ + 0/1 jets	120-600
VBF $H \rightarrow WW \rightarrow 2l2\nu$	130-500
$H \rightarrow ZZ \rightarrow 4l$	120-600
$H \rightarrow ZZ \rightarrow 2l2\nu$	200-600
$H \rightarrow ZZ \rightarrow 2l2b$	300-600

All analyses are cut-and-count

CMS prospects: Higgs searches

- Improvements over previous estimates: add channels with potential sensitivity (à la Tevatron), not just `golden' ones (detector performance is optimal)

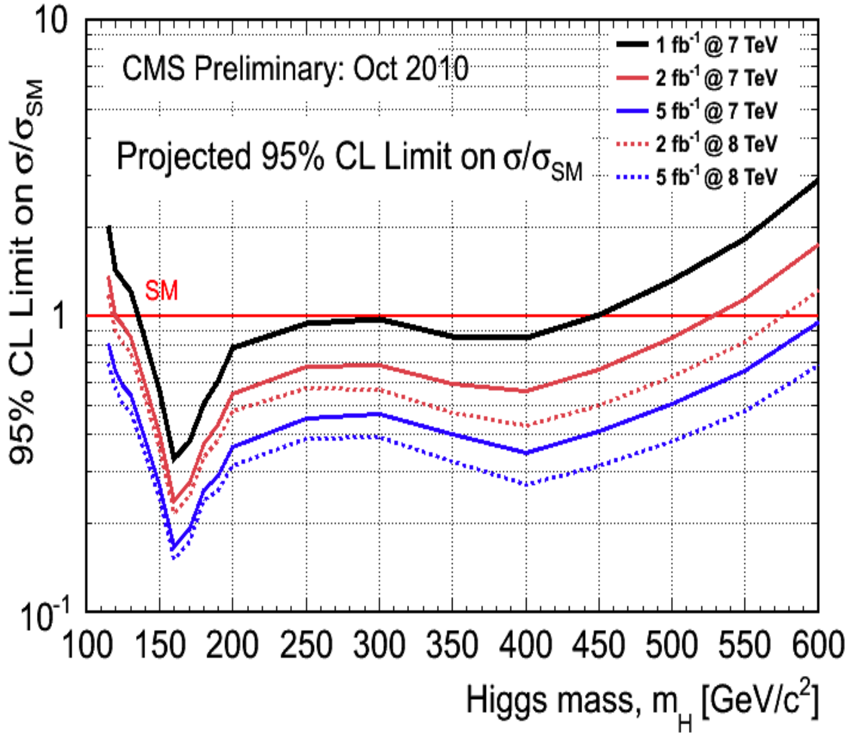


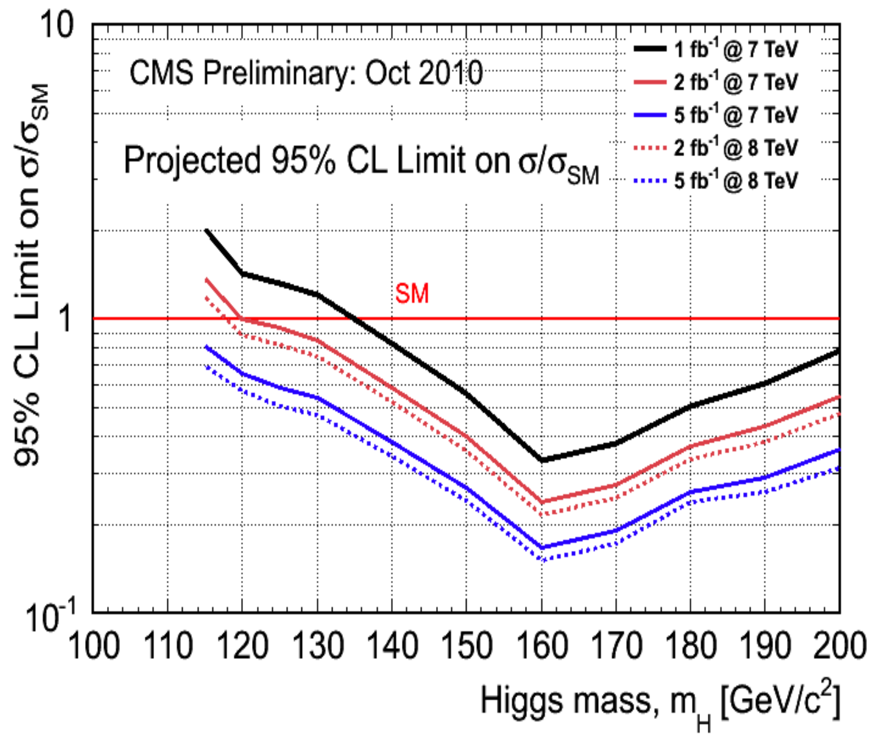


5 fb^{-1} would be enough to exclude all the relevant Higgs mass range, or get an 'observation' at >3 standard deviations

CMS prospects: Higgs searches

- Improvements over previous estimates: add channels with potential sensitivity (à la Tevatron), not just `golden' ones (since detector performance is optimal)





7 TeV, 1 fb^{-1}: exclusion sensitivity: m_H = 135-450 GeV

"ATLAS+CMS" (2 x CMS): m_H = 120-525 GeV

Conclusions

- CMS is in good shape:
  - More than 40 pb^{-1} data collected at $\sqrt{s}$=7 TeV, with >90% efficiency
  - The detector performance is almost ideal, even at this early stage. Many sophisticated improvements already in place (particle-flow techniques, for instance)
- EWK and $t\bar{t}$ cross sections already measured
  - In good agreement with the SM
  - These are important benchmarks for futures precision studies and new physics searches
- Already with this luminosity (≤ 40 pb^{-1}) CMS is able to go beyond past experiments in many new physics searches
- With ≥ 5 fb^{-1} per experiment LHC should be able to exclude/discover the SM Higgs over the whole relevant range of possible masses

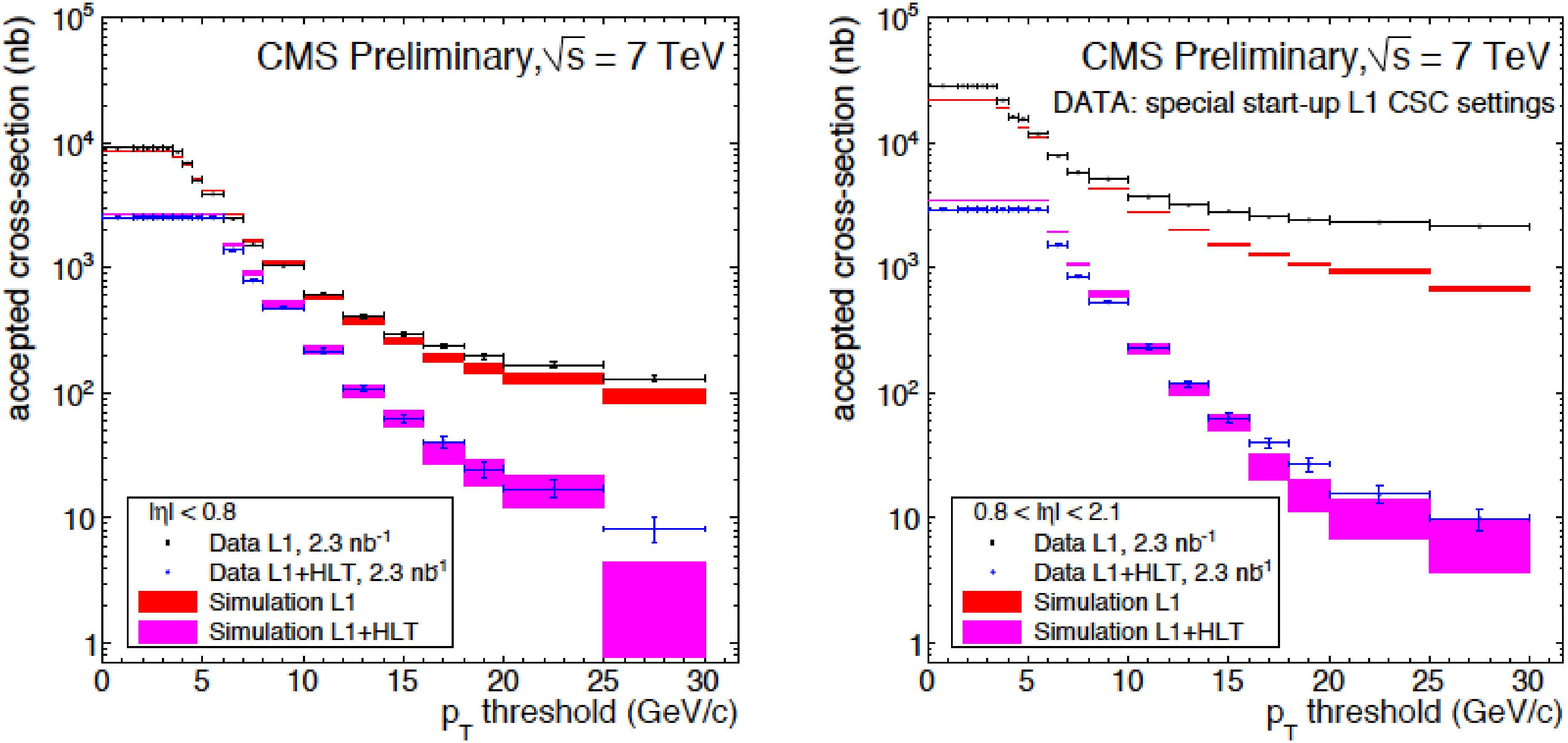
CMS is actively analyzing the latest data and eagerly waiting for an even more exciting 2011 LHC year!

- But the amount of work needed is still HUGE!

BACKUP

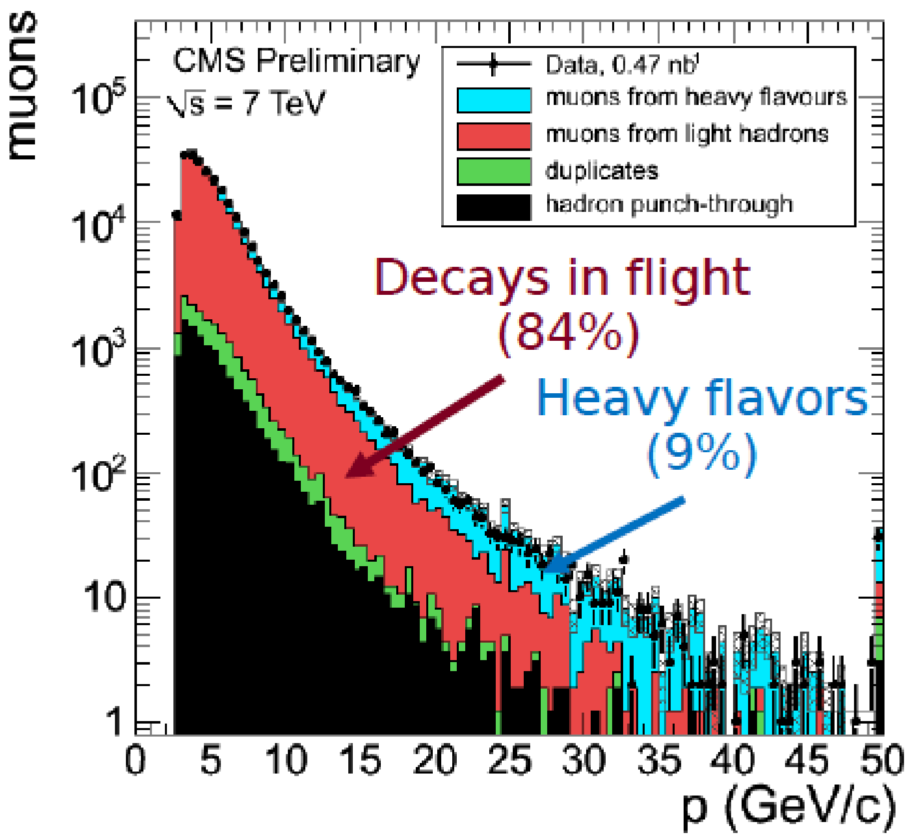
CMS: muons

The main role of the CMS muon system for p_T< 200 GeV or so is to provide efficient and reliable trigger information ...



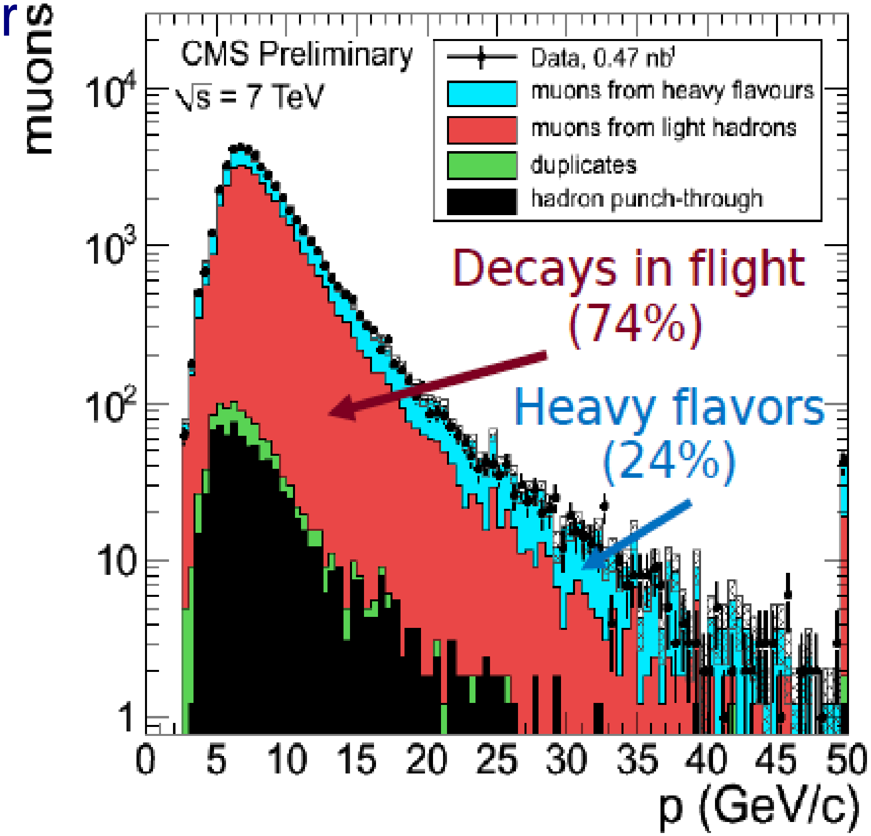
CMS: muons

… and efficient and reliable muon identification with a good understanding of the different background components (decays-in-flight, hr



Muons tracker-driven

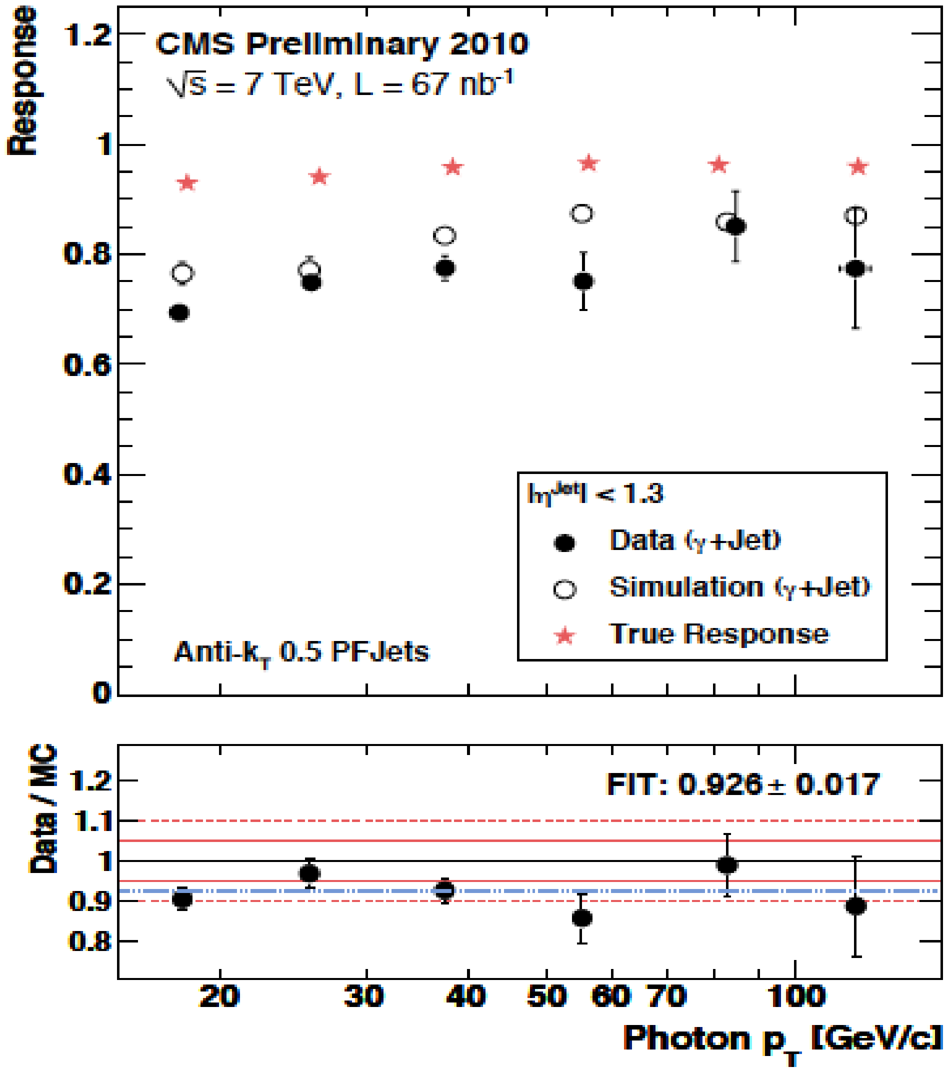
(>=1 chamber segments matched)



Muons muon-chamber driven

(>= two chamber segments)

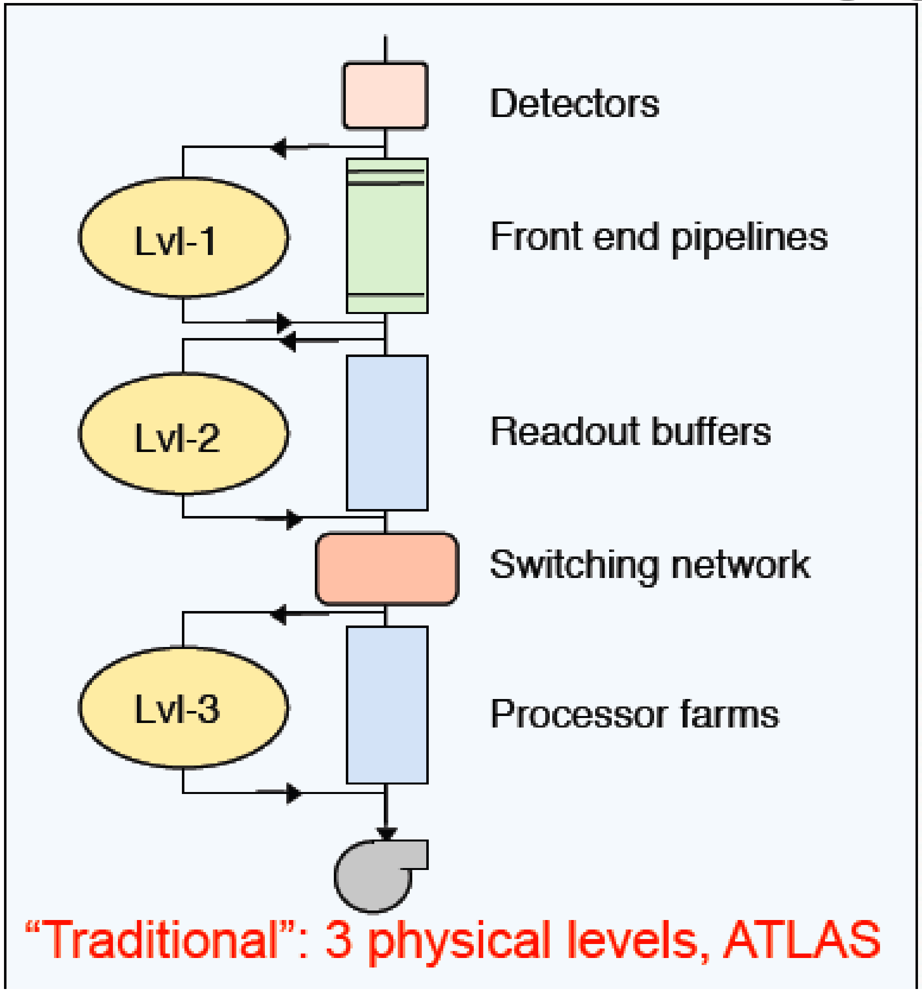
CMS: particle-flow techniques

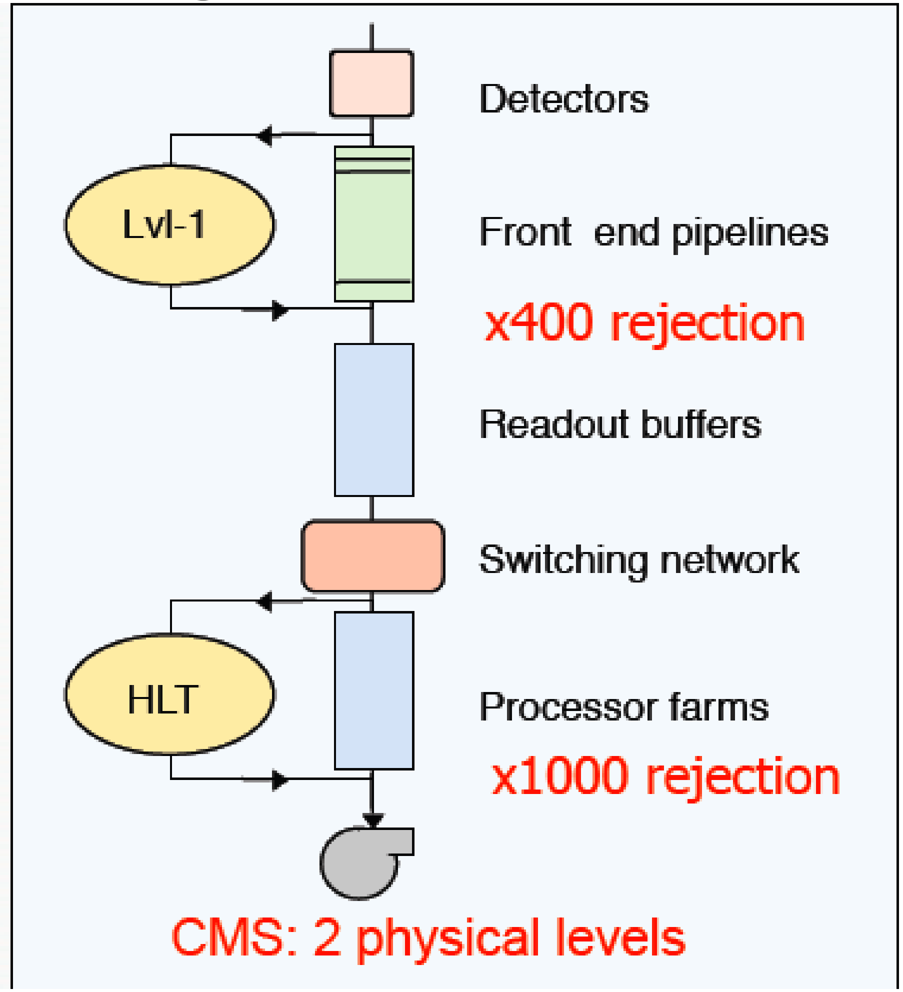


Photon + jet samples

- And, since particles are identified almost one-by-one, calorimeter corrections in the jet response, as well as scale energy corrections, are smaller in a particle-flow approach
- The approach also allows improvements in the particle identification step: bremsstrahlung, conversions, ...
- Everything suggests that the PFlow response is uniform in energy, in reasonable agreement with simulations, and with scale variations not larger than 5%.

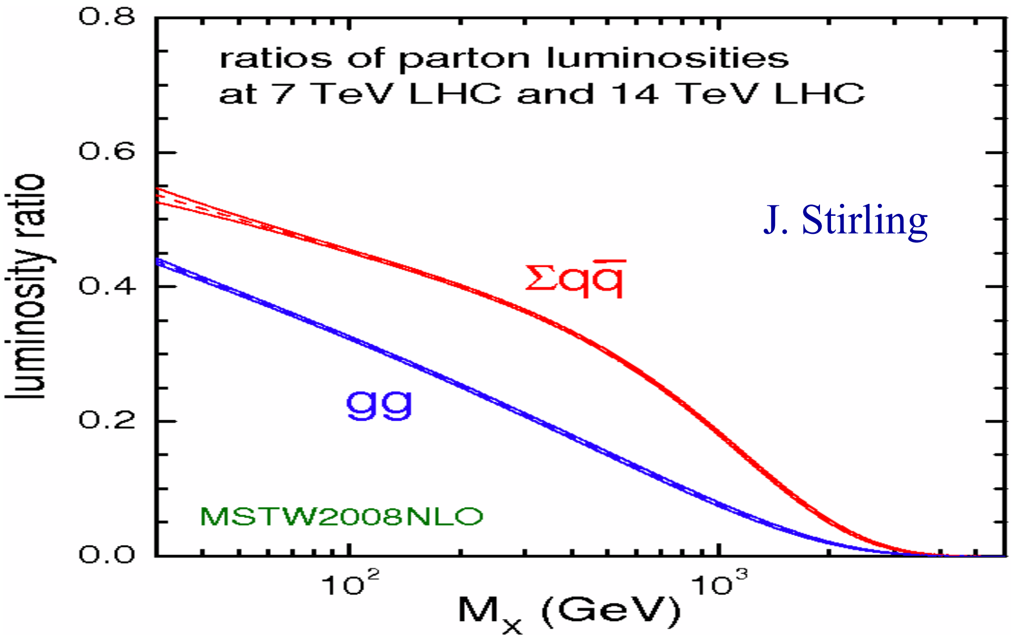
CMS Trigger system

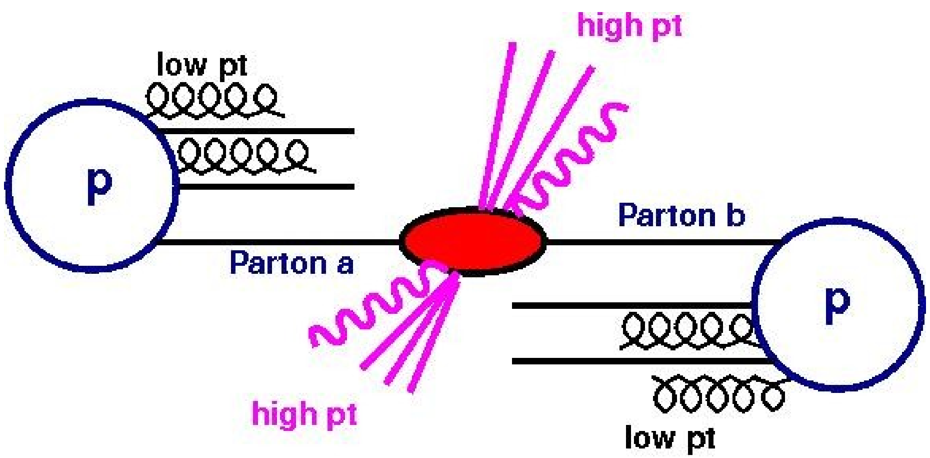




- Challenging, but allows to be dependent on ``software'' and use fully (more precise) reconstructed information at earlier stages..

LHC: √s=7 TeV vs √s=14 TeV



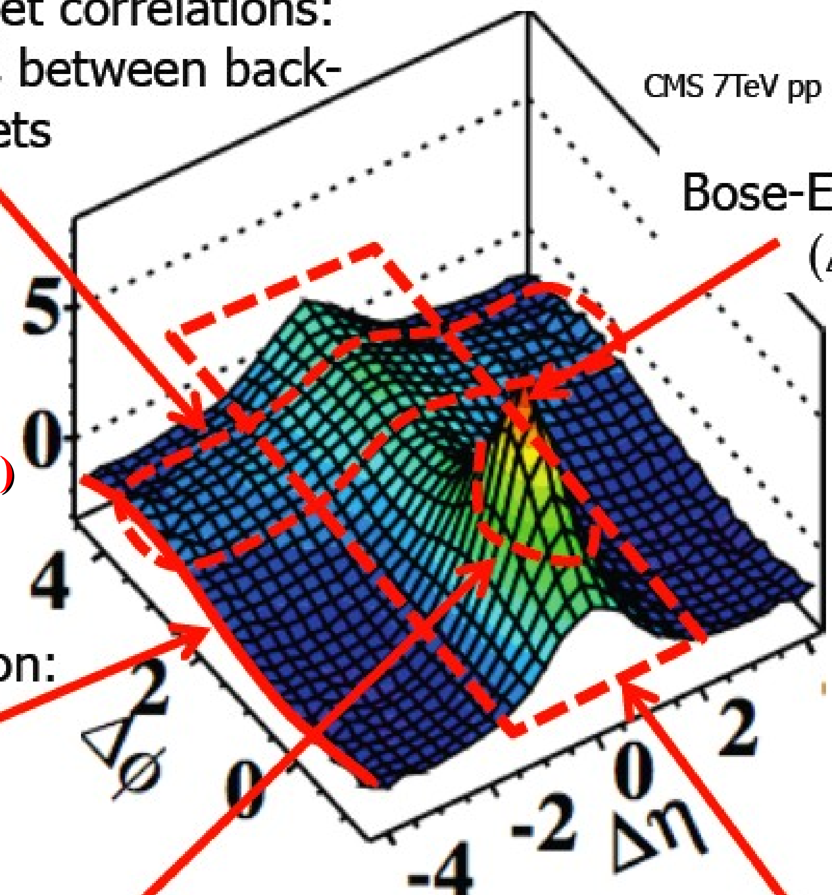


- Major changes with respect to √s = 14 TeV:
  - Cross sections reduced by a factor of three or so:
    - W/Z cross sections ~ 50% (slightly compensated by larger acceptance at lower rapidities)
    - Ttbar cross section ~ 25%
    - Higgs (m=200 GeV) ~ 25%
- Strong reduction of the energy reach for high masses and energy scales
  - Z' resonance (m~1 TeV) ~ 20%
  - One order of magnitude less reach for new physics effects at scales of ≥ 2 TeV
- Subtler effects:
  - Less gluon-gluon relative to qqbar hard interactions (PDF effect)

CMS physics results: the 'ridge'

"Away-side" ($\Delta\phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets

TWO-PARTICLE CORRELATIONS AS A FUNCTION OF THE AZIMUTHAL ($\Delta\Phi$) AND PSEUDO-RAPIDITY ($\Delta\eta$) SEPARATION



Bose-Einstein correlations:
$(\Delta\phi, \Delta\eta) \sim (0,0)$

Momentum conservation:
$\sim -\cos(\Delta\phi)$

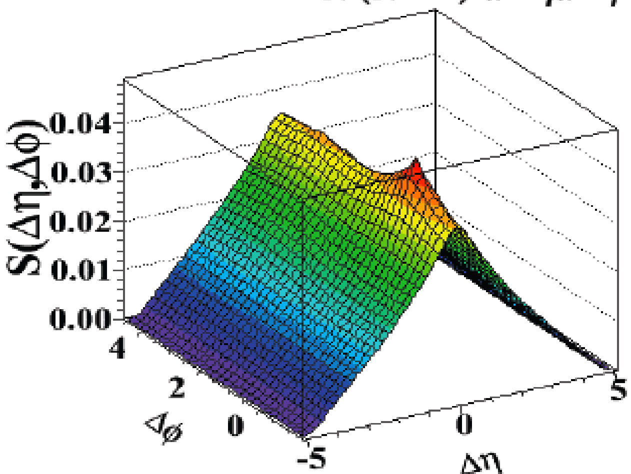
"Near-side" ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

Short-range correlations ($\Delta\eta < 2$):
Resonances, string fragmentation, "clusters"

CMS physics results: the 'ridge'

Signal distribution:

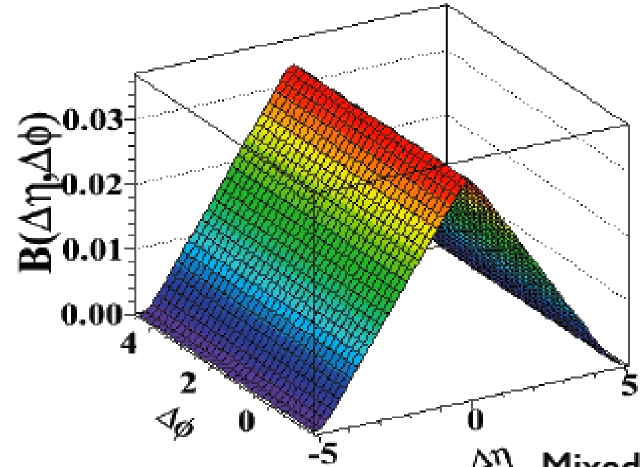
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Same event pairs

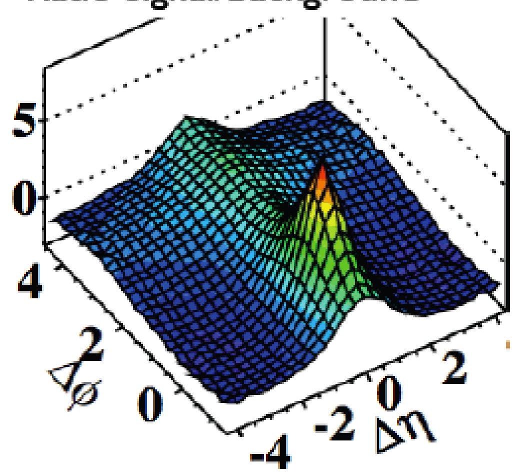
Background distribution:

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



Mixed event pairs

Ratio Signal/Background



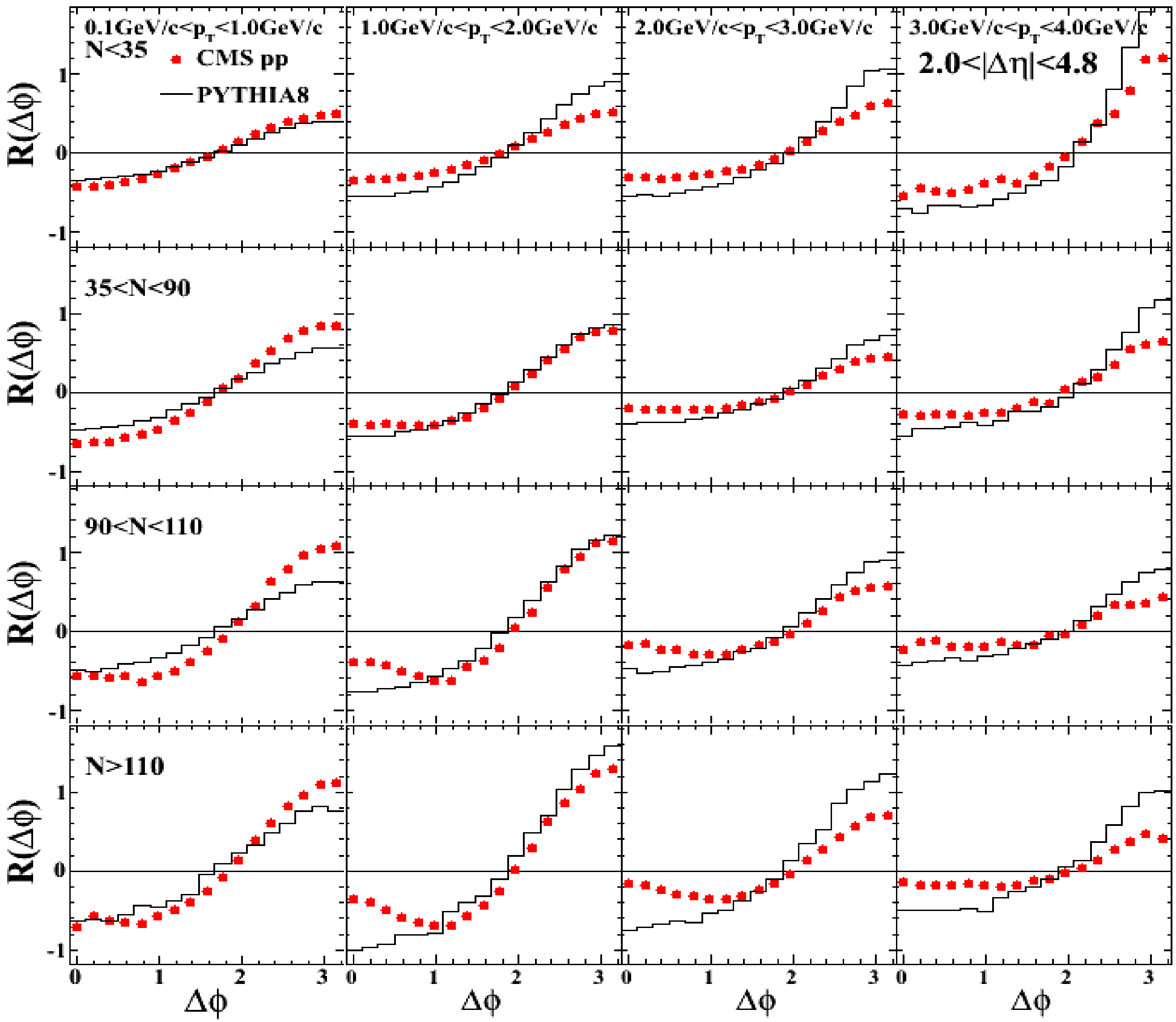
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

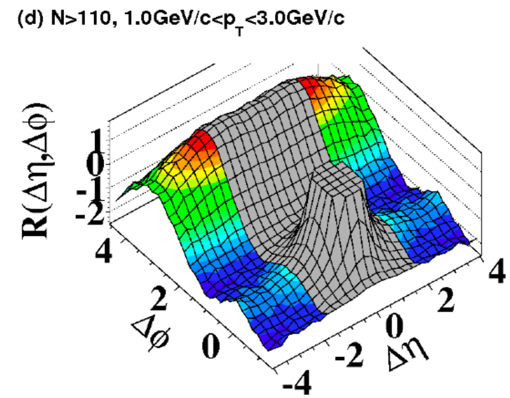
p_T-inclusive two-particle angular correlations in min bias collisions

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

CMS pp 7TeV

CMS physics results: the 'ridge'

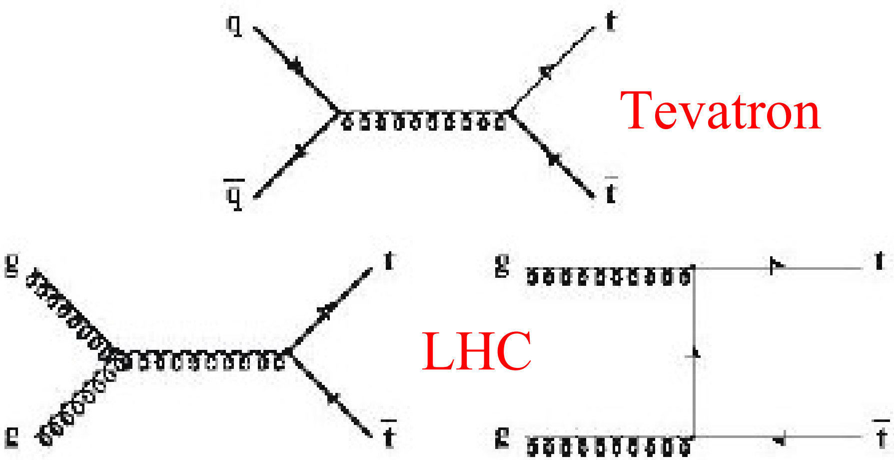


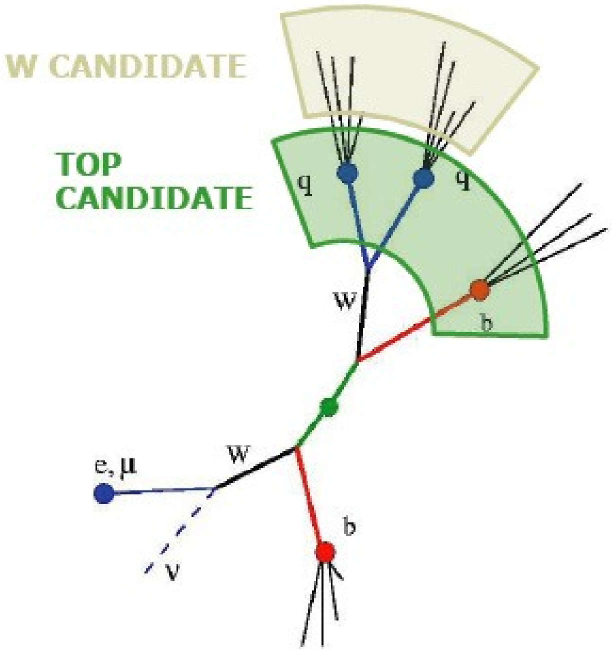


| Δ η | > 2 region selected Maximum correlation for 1 < p_T < 3 GeV and high multiplicities (>90)

Top production

- Top production is huge at the LHC: At √s=7 TeV, σ ~ 150 pb, dominant process is gg->ttbar , rate ~ 20 times Tevatron for the same luminosity.





- Understanding top production => understanding the whole detector: lepton identification, resolutions, isolation, jets, missing energy, b-tagging, ... => spin-offs: jet scale calibration, b-tagging efficiencies,...

CMS prospects: Higgs searches in various luminosity/energy scenarios