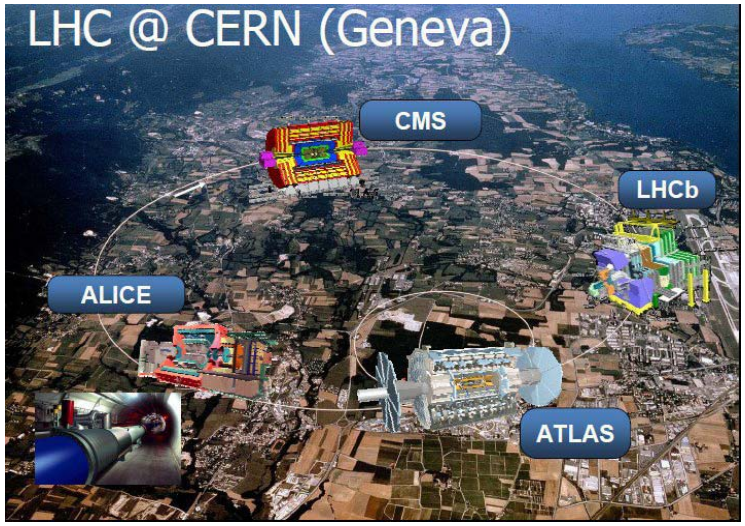
# Overview of the CMS experiment results at the LHC




Silvia Costantini
Ghent University
On behalf of the CMS Collaboration

Crimea 2011
3-10 September 2011

# CMS achievements and results

Top Physics: see talk by Jérémie Lellouch

Higgs Searches: talk by Antonio Branca

Heavy Flavour Physics: talk by Nicola Pozzobon

This talk will not cover Heavy Ion Physics

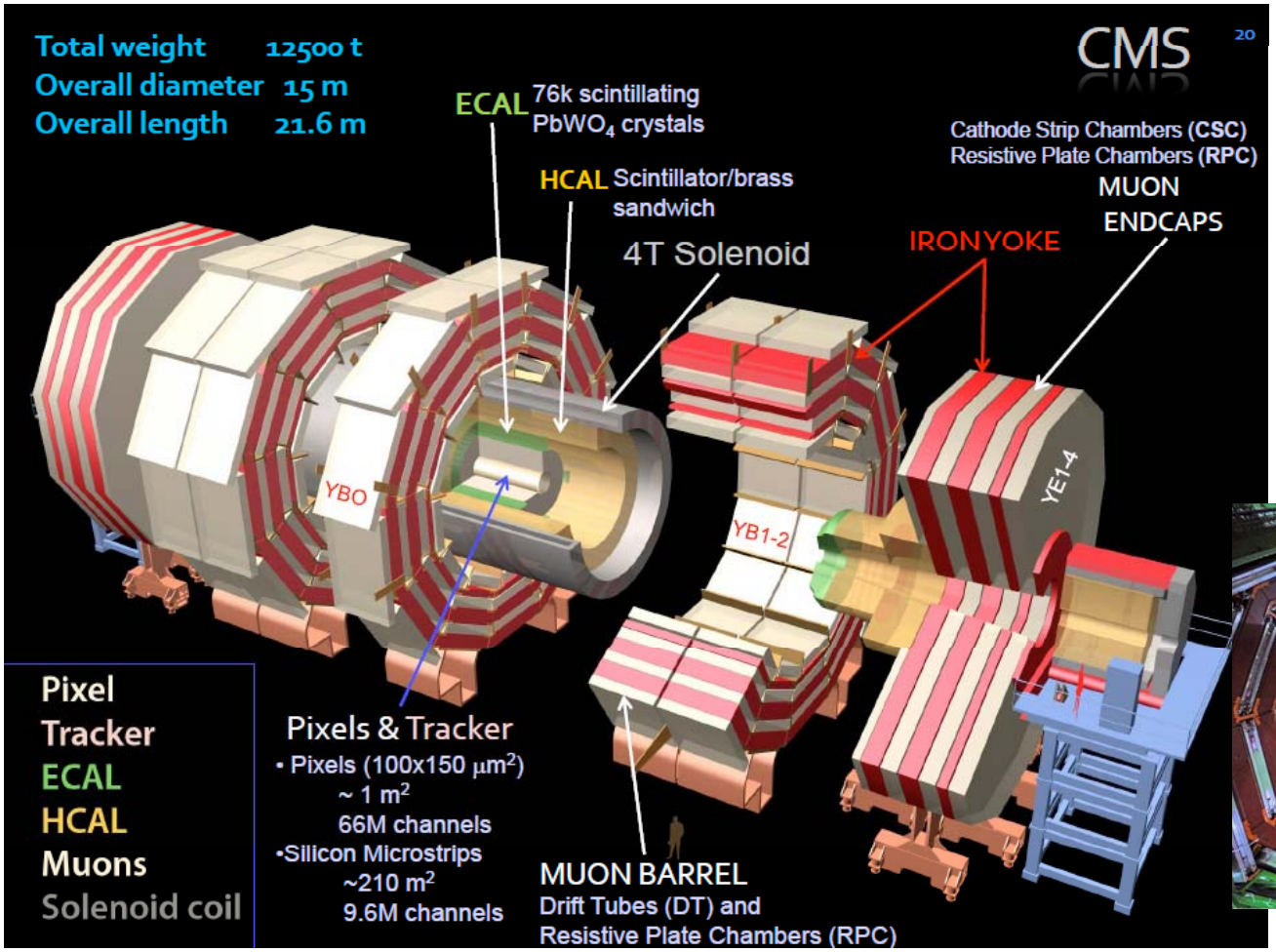
- 2011 operation
- QCD Physics
- EWK Physics (mainly W and Z)
- Searches for New Physics

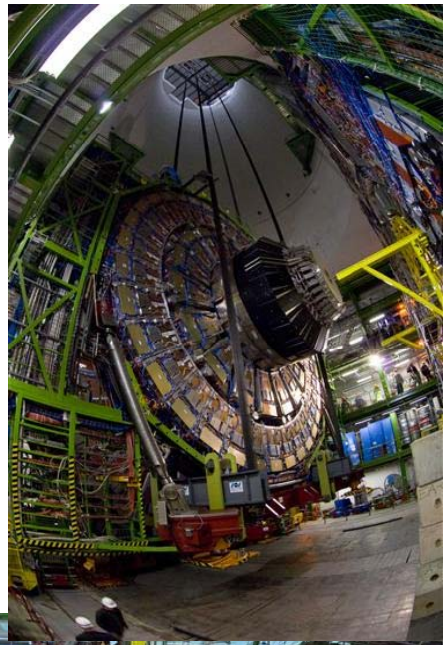
**More at:**

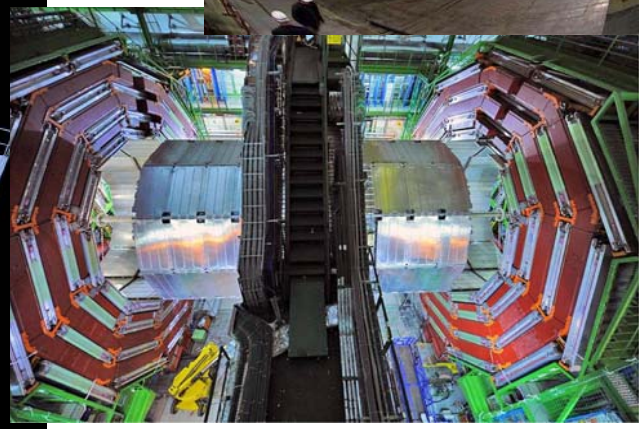
**https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults**

# The CMS Collaboration

**~3400 scientists and engineers (including ~840 students) from 173 institutes in 40 countries**





**http://cms.cern.ch**

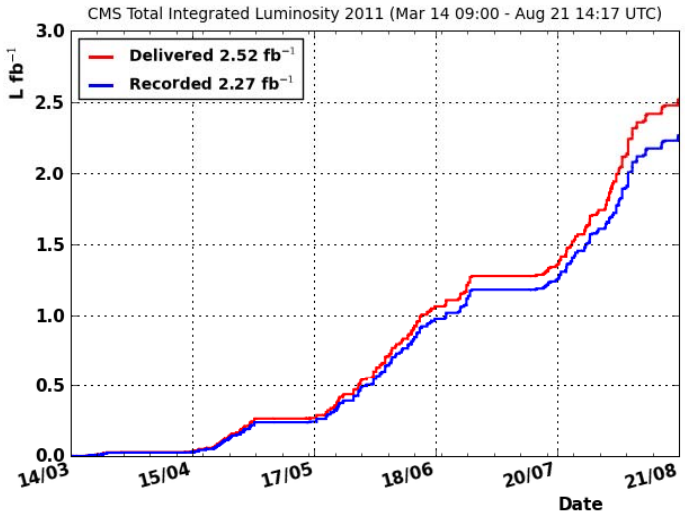
# LHC/CMS operations pp@√s=7TeV 2011

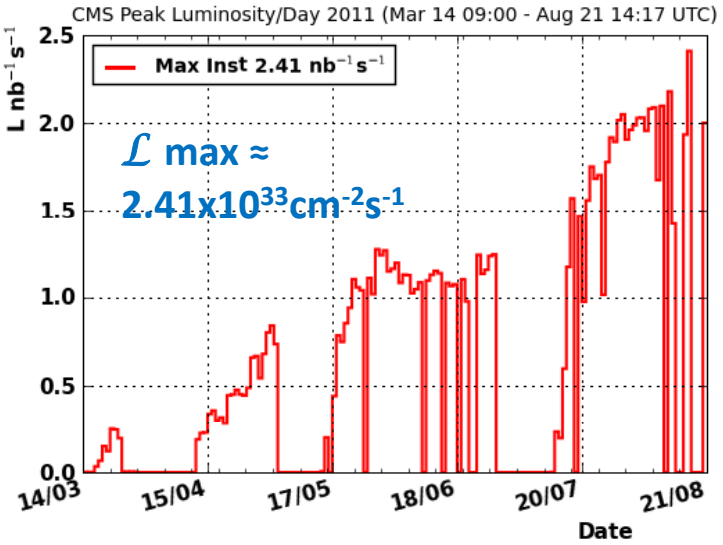
**2.52 fb$^{-1}$** delivered by LHC and **2.27 fb$^{-1}$** recorded by CMS (as of Aug. 21).
2010 @ 7 TeV : ~36 pb$^{-1}$

Overall data taking efficiency **~90%.**

**Average fraction of operational channels per subsystem >98.5%**

| | |
|---|---|
| RPC | 98.5 |
| CSC | 98.3 |
| DT | 99.4 |
| HF | 99.9 |
| HE | 100.0 |
| HB | 99.9 |
| ES | 95.9 |
| EE | 98.6 |
| EB | 99.1 |
| STRIP | 97.8 |
| PIXEL | 96.9 |

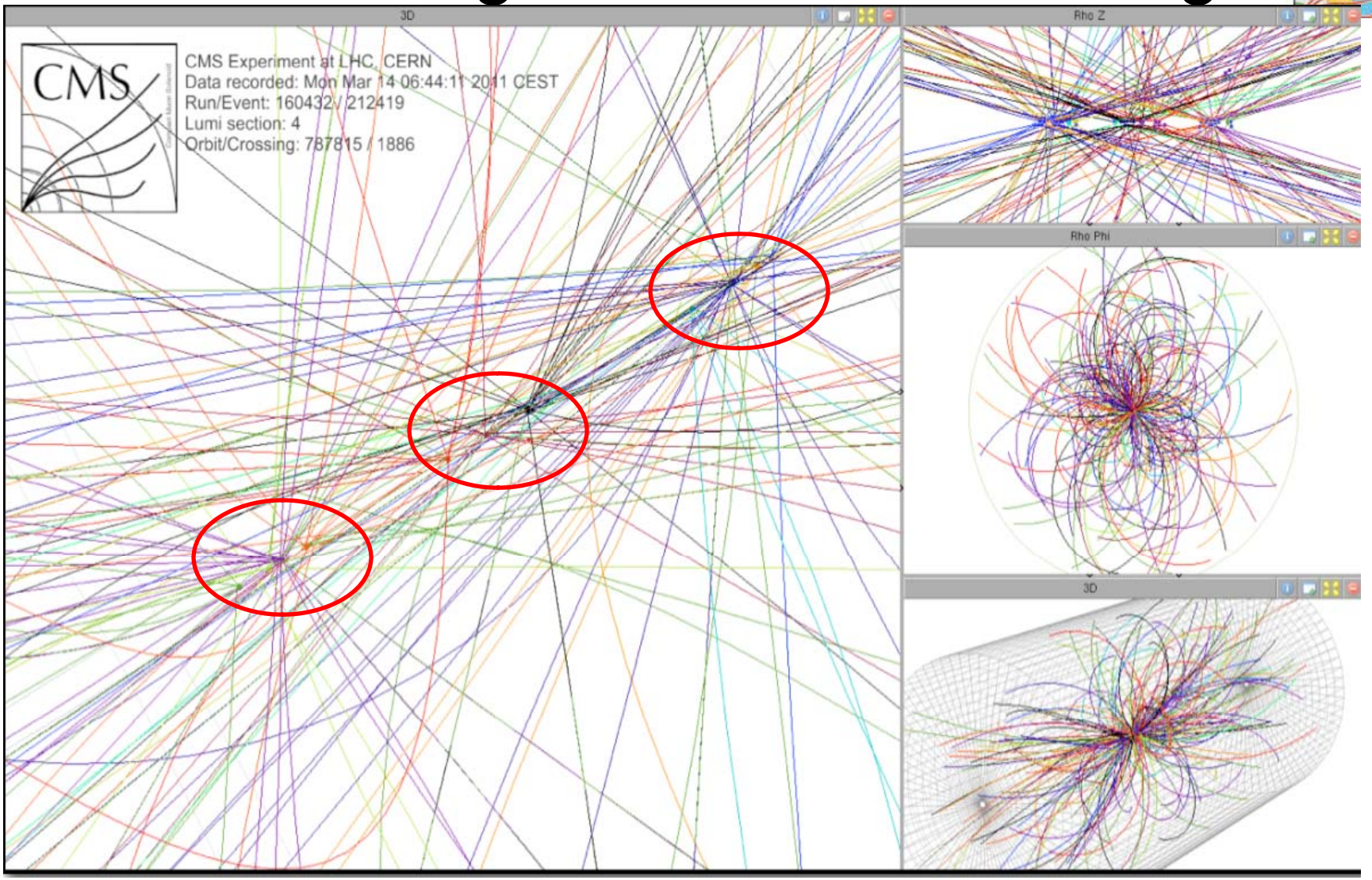



- **Instantaneous luminosity above $2 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$**

**Certified** data for physics: **Golden 93%, Muon 96%.**

# The challenge of 2011 data taking




At nominal luminosity (**$10^{34}$ cm$^{-2}$s$^{-1}$**) 25 inelastic collisions will be superimposed to the interesting events (**pileup**)

# DAQ/L1/HLT running smoothly at >$10^{33}$

## Typical operating conditions (pp)

- **At start of fill: Lumi ~1.7x$10^{33}$,**
- **~9 events per BX ev size~450kB**
- **Level-1 rate ~60 kHz, 50% HLT CPU**
- **3-400 Hz recording**
- **Central DAQ availability ~99%**

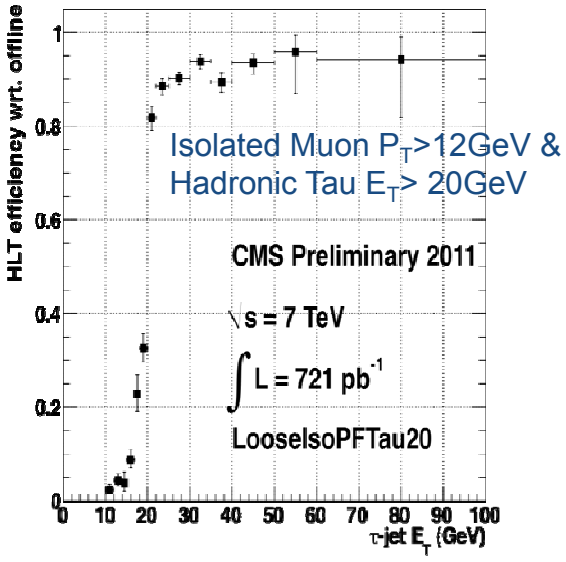
## Pile-up as expected in terms of event size

DAQ Limitations for further increase of the PU
Total size < ~1MByte.
**With 25PU** (~750kByte): OK.

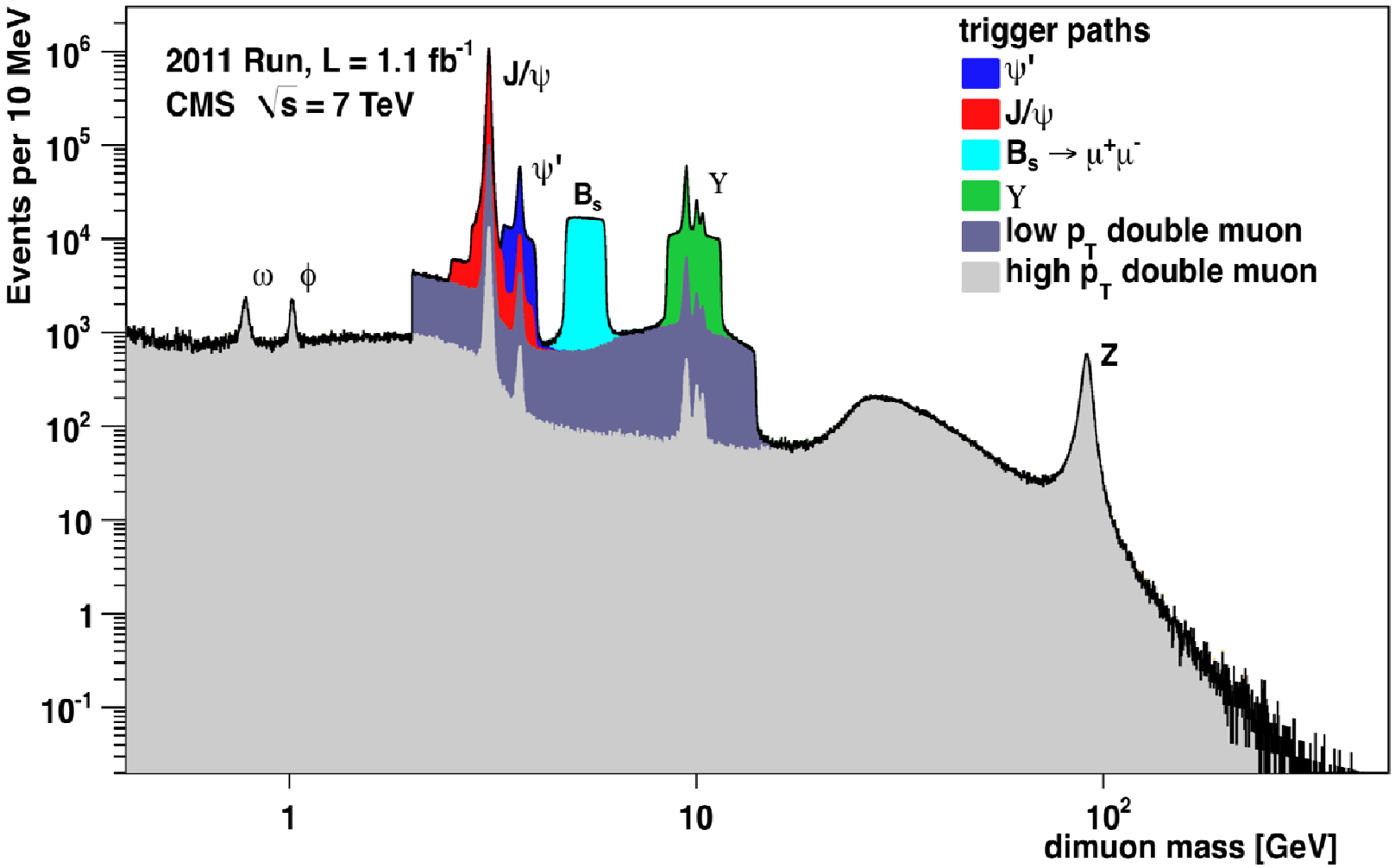
## L1 trigger menus:

- L1 trigger menus optimized to cope with the
- luminosity increase from $10^{32}$ to 5x$10^{33}$ $cm^{-2}s^{-1}$.
- Increased importance of multi-object triggers

**Moderate rate dependence on pile-up: f**or 25 pile-up events we expect ~20% additional rate.
**HLT Trigger menus from 2x$10^{32}$ to 2x$10^{33}$**
Single object triggers for electrons, photons, muons, jets, total energy, & missing transverse energy.
Over 200 **multi-object triggers** including tau and b-jet triggers.
**Effect of pile-up understood and mitigated.**



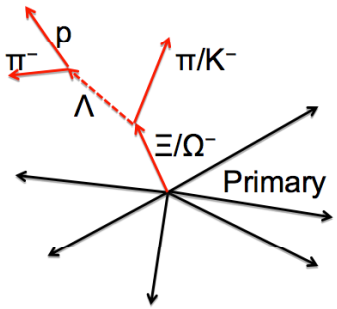
# Triggering on di-muons at $10^{32}$-$10^{33}$ with CMS



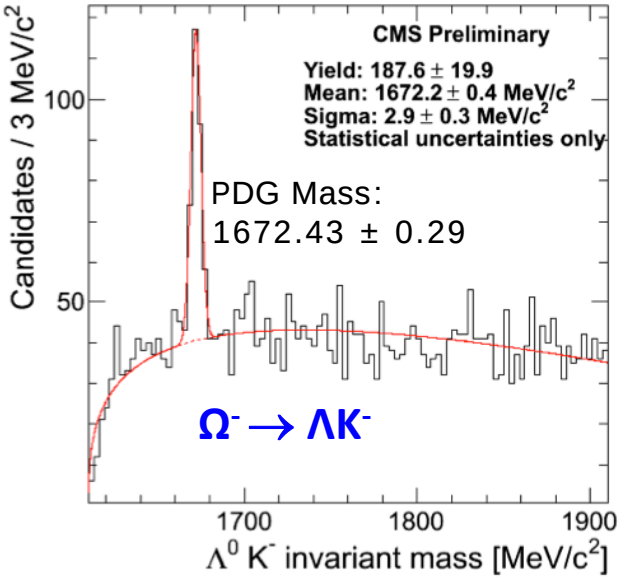

Dimuon mass distribution obtained from overlapping several trigger paths.

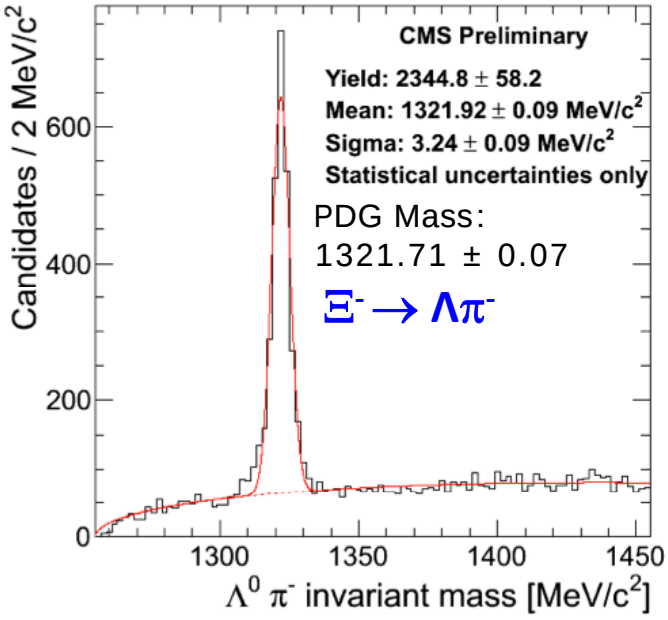
# Low mass resonances

- Tracks displaced from primary vertex ($d_{3D} > 3\sigma$)
- Common displaced vertex ($L_{3D} > 10\sigma$)



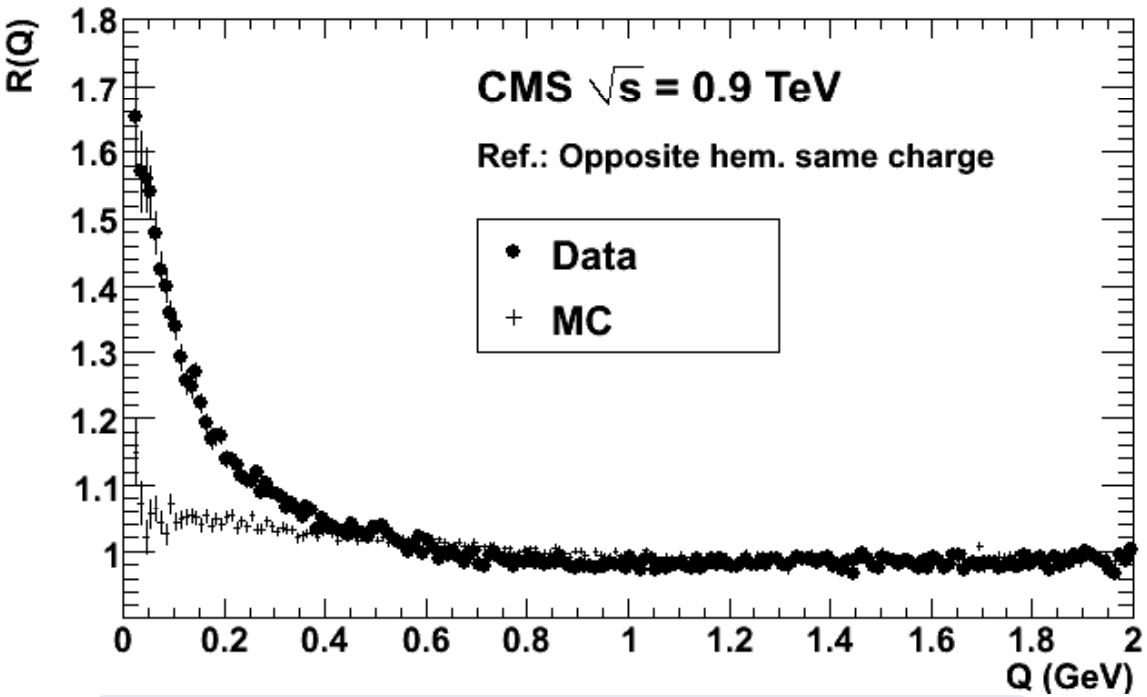

Invariant mass distribution for different combinations ($\Omega^{\pm} \to \Lambda K^{\pm}$ or $\Xi^{\pm} \to \Lambda\pi^{\pm}$ ) fit to a common vertex.



# Bose-Einstein Correlations

Phys. Rev. Lett. : 105 (2010) , pp. 032001




- The signal is observed in the form of an enhancement of pairs of same-sign charged particles with small relative four-momentum.

- The size of the correlated particle emission region is seen to increase significantly with the particle multiplicity of the event.

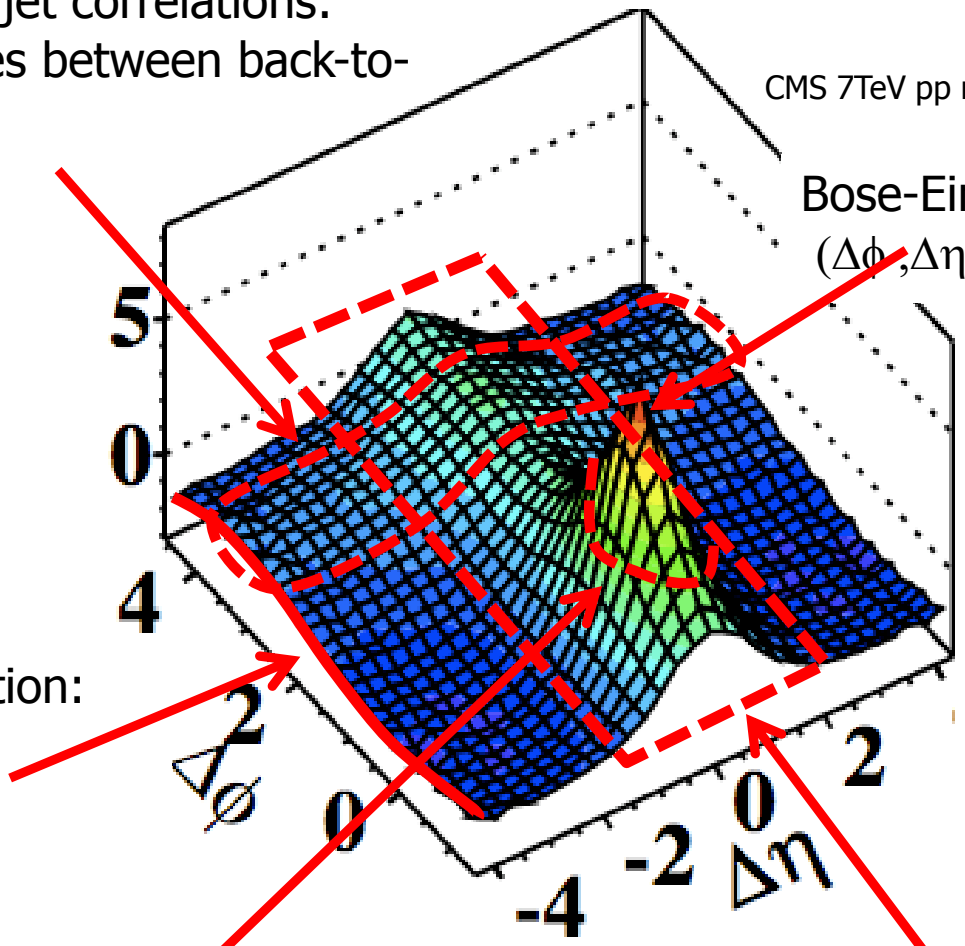
Correlation is studied using the ratio R between join probability of emission of a pair of bosons and the individual probabilities.

$$R = \frac{P(p_1,p_2)}{P(p_1)\ P(p_2)}$$

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{m_{inv}^2 - 4m_\pi^2}$$

# Angular Correlation Functions

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




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

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

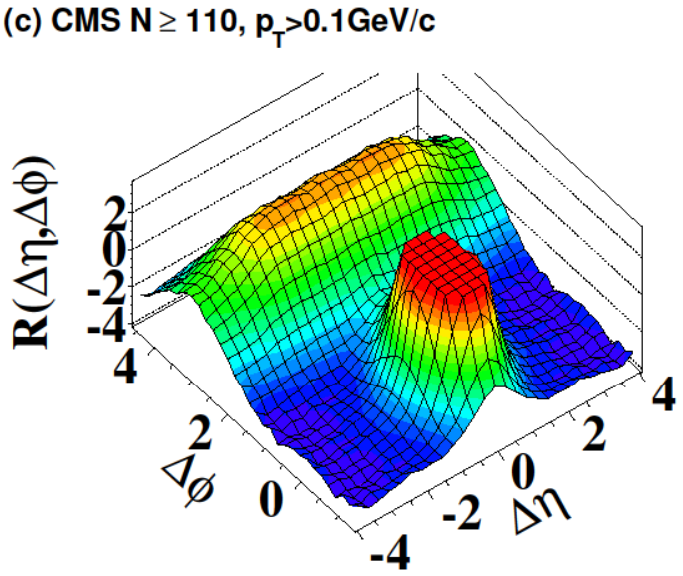
"Near-side" ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

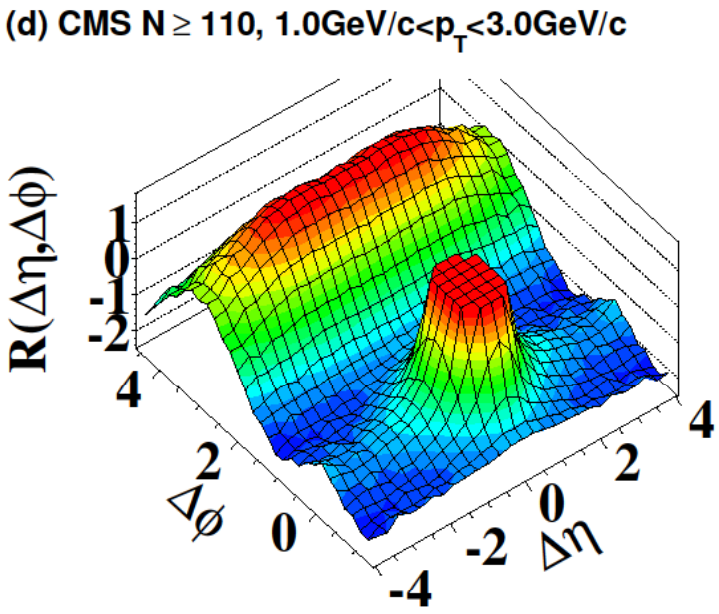
Short-range correlations ($\Delta\eta < 2$):
Resonances, string fragmentation, "clusters"

# Long-range near-side correlations in high multiplicity events (N>110)

J. High Energy Phys. 09 (2010) 091

- ridge-like structure at the near-side ( $\Delta\varphi=0$) in pp collisions
- enhancement is most evident in the intermediate transverse momentum range 1 < pT < 3 GeV/c
- similar correlation in relativistic heavy ion data



# Jets: Inclusive jet cross sections

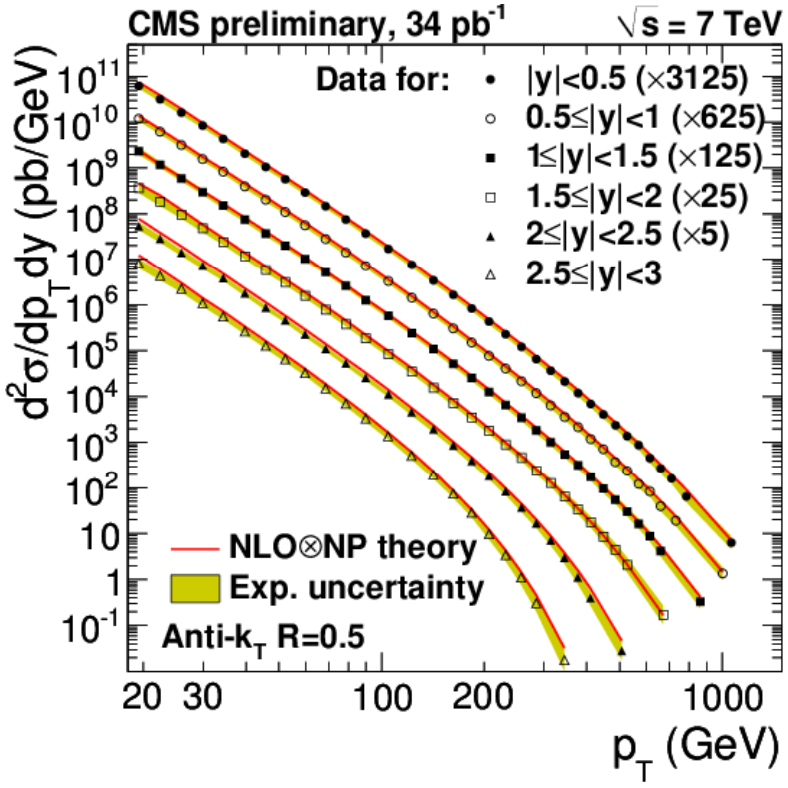
CMS-PAS-QCD-2010-011, accepted by PRL  Ph.Lett. B 702 (2011) 336

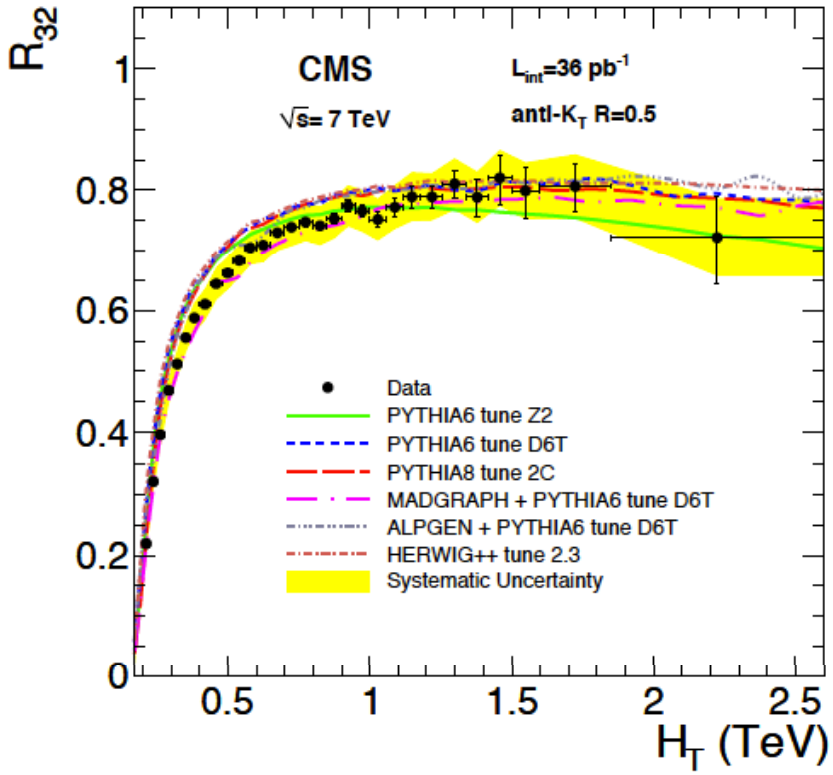
Jet pT 18-1100 GeV
Rapidity < 3

Agreement with NLO pert. QCD predictions

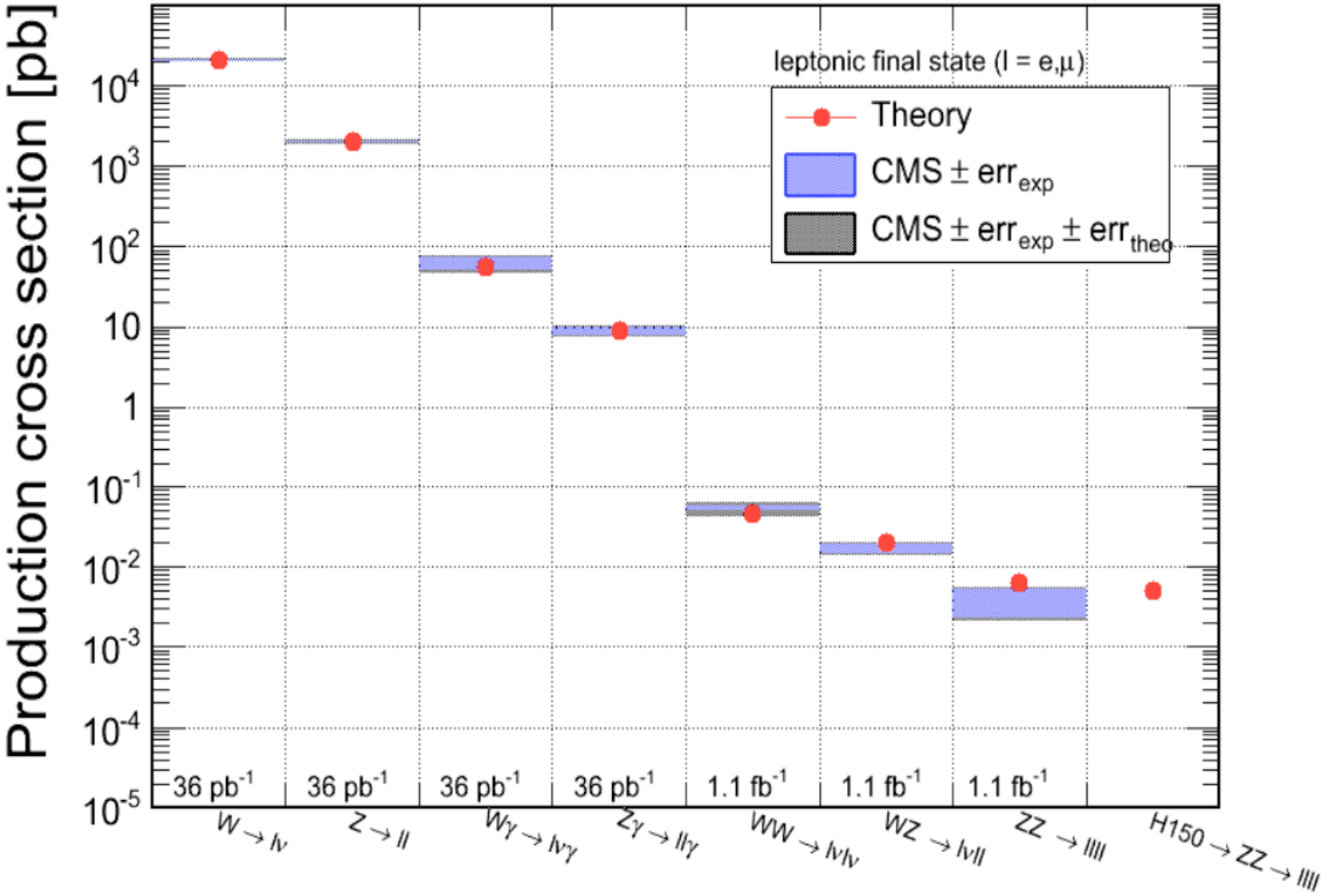
$R_{32}$ = ratio 3 jets/2 jets events

Extends to HT range not explored before



# EWK bosons and di-bosons

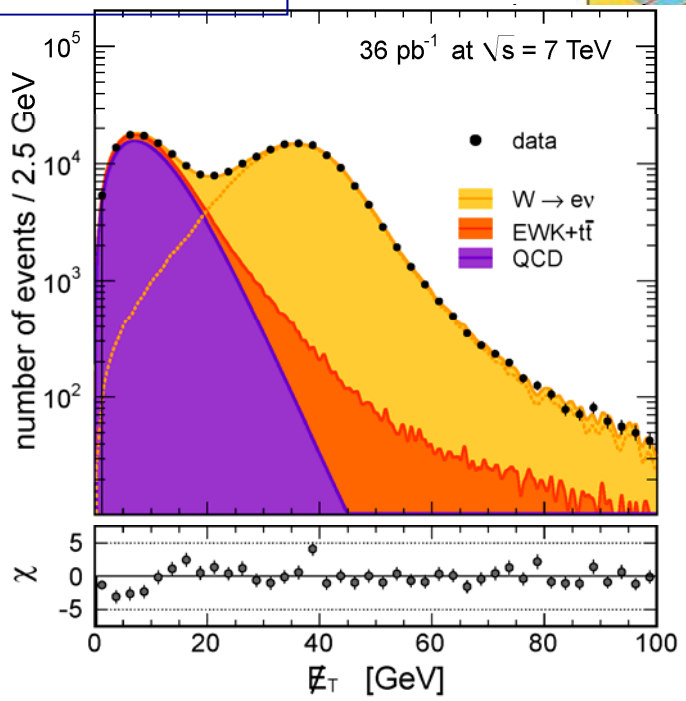


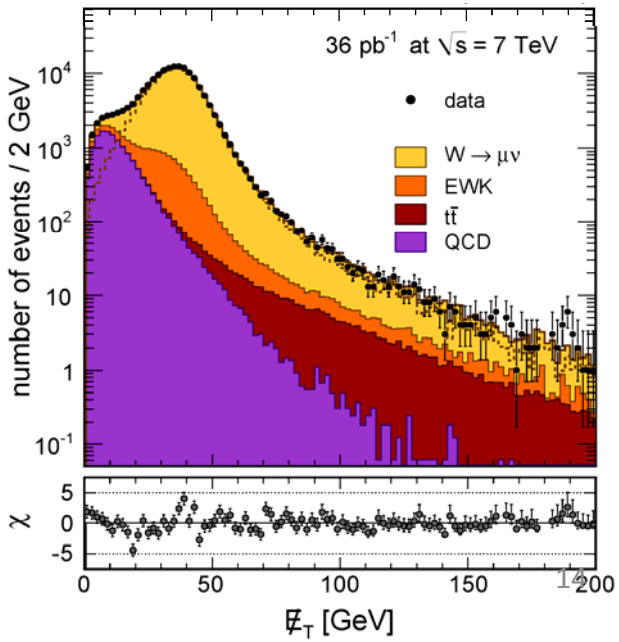
CMS-PAS-EWK-2010-005

# W inclusive production

Simple W pre-selection in CMS:
- Loose single-lepton (m,e) triggers
- High pT (>25 GeV) lepton in trigger/detector fiducial volume
- Isolated leptons. Use transverse activity / lepton pT in a DR<0.3 cone
- Dilepton veto

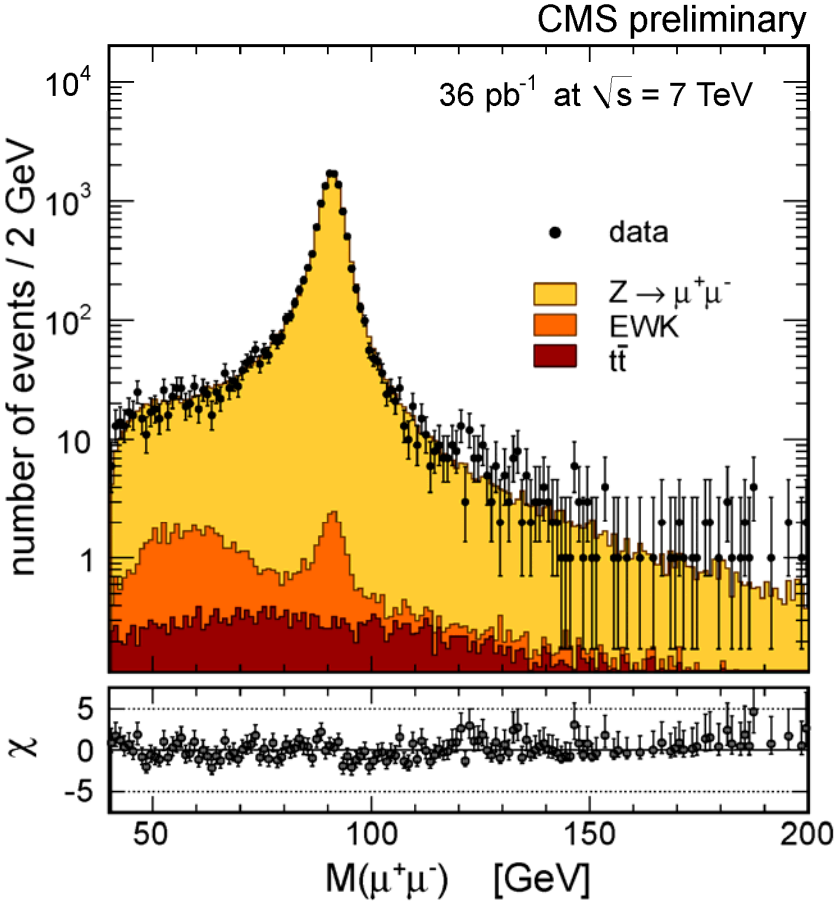
Cross section measurement strategy:
- Fit missing ET distributions for W+ and W- (no cut applied, to avoid biases)
- Efficiencies, resolutions, signal and background shapes studied/extracted from data



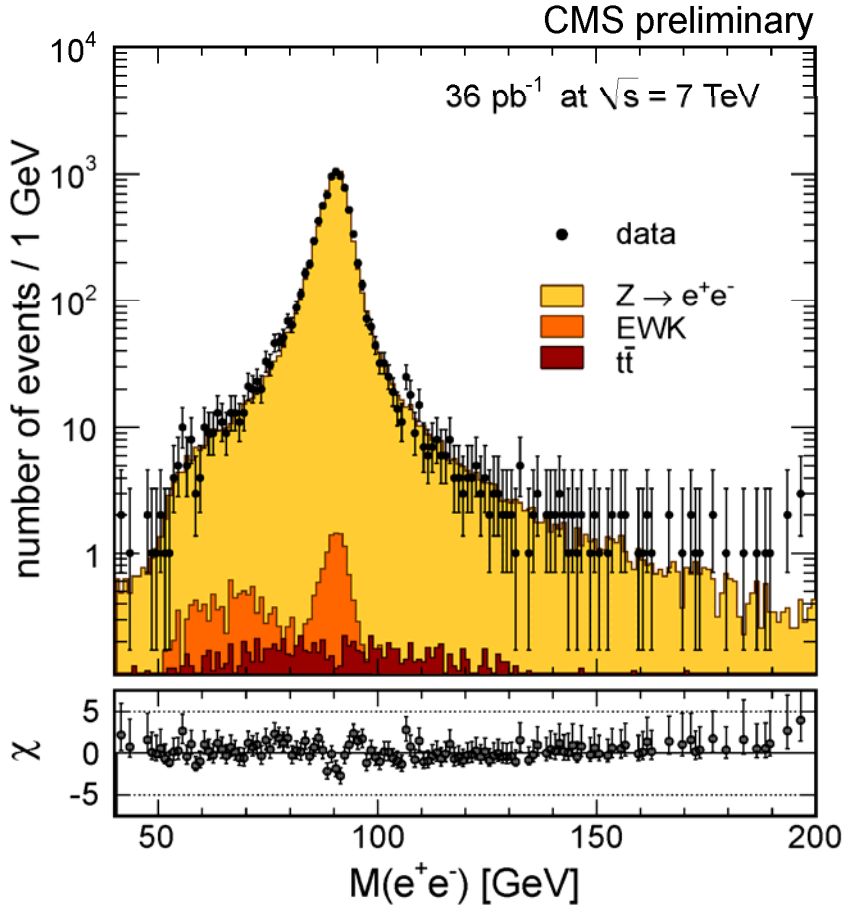



CMS-PAS-EWK-2010-005

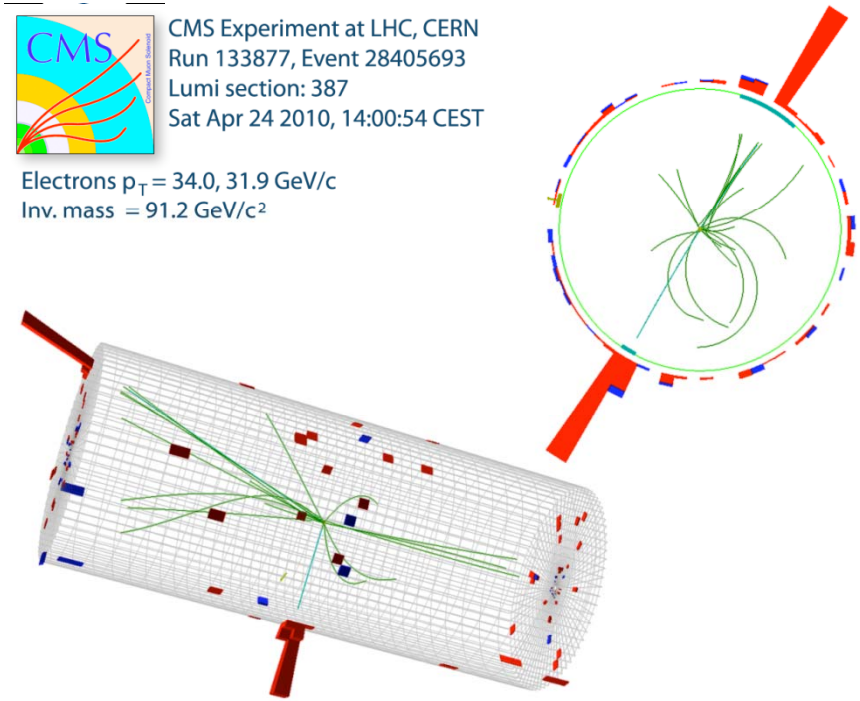
# Z → μμ




# Z → ee

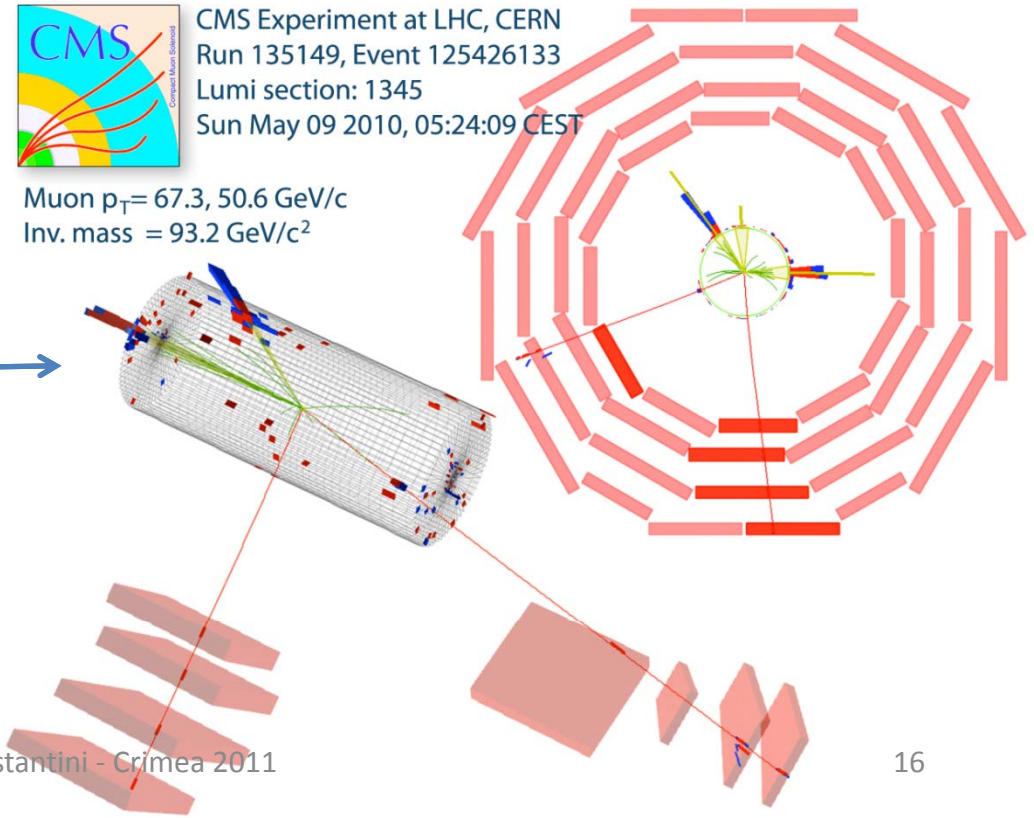



Very low expected background (log scale)



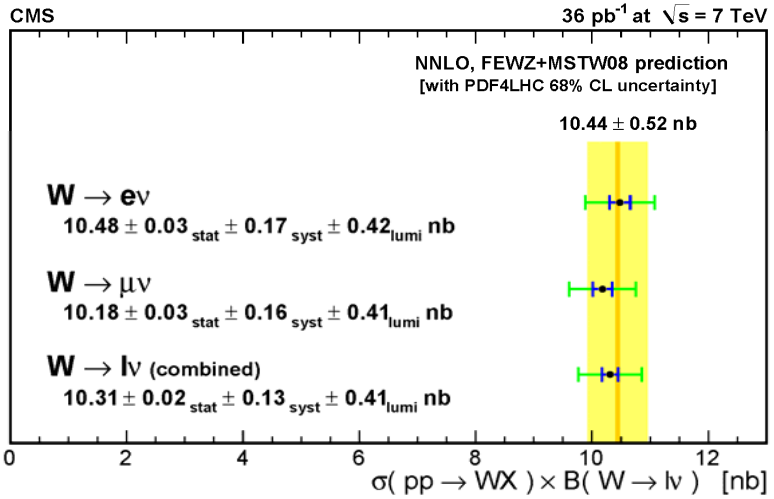

$Z \rightarrow ee$

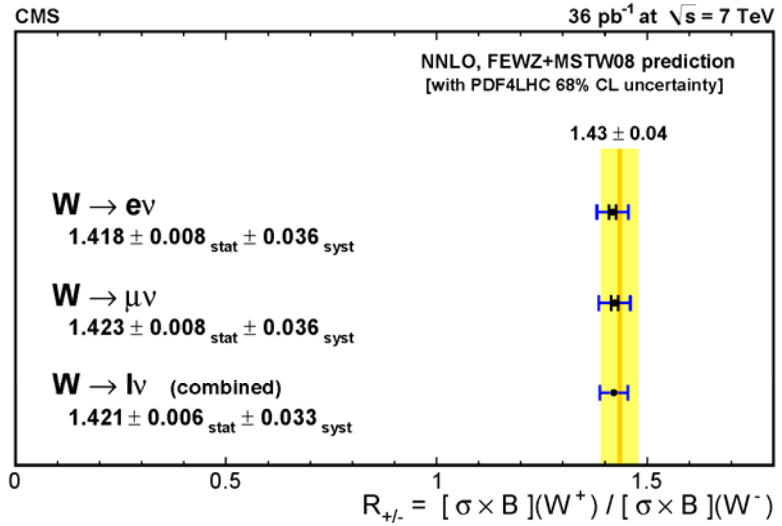
$Z \rightarrow \mu\mu$

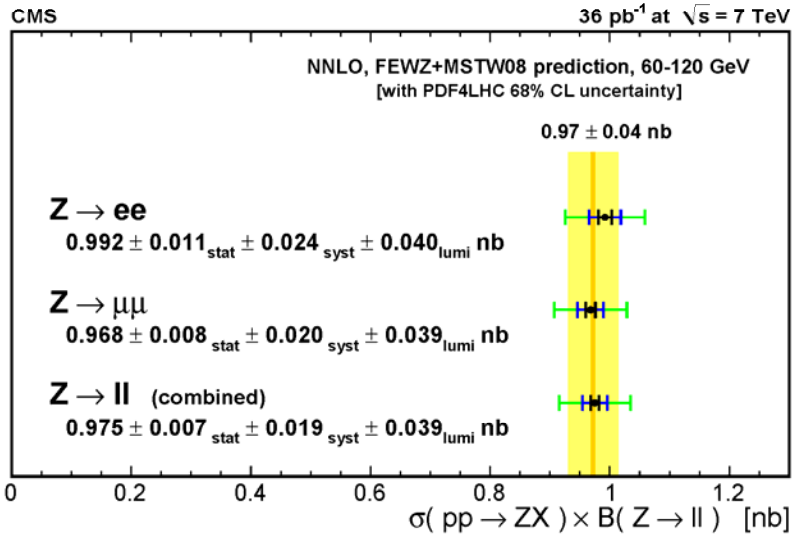


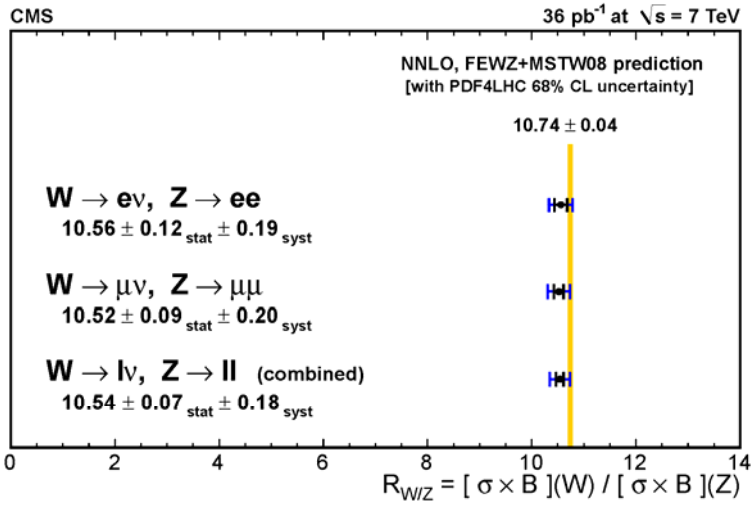
# W/Z inclusive results

## cross-section measurements

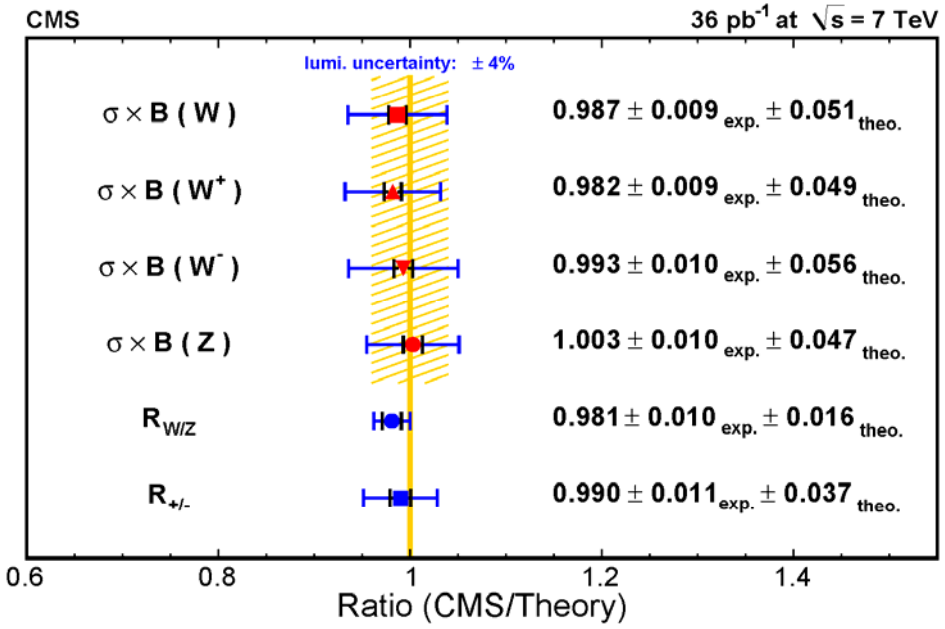


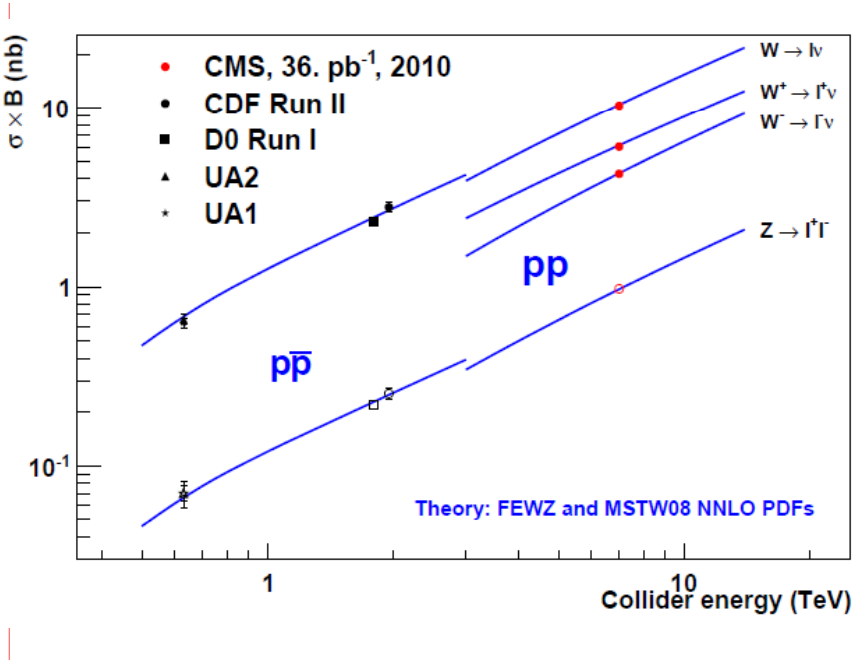



# W/Z inclusive results



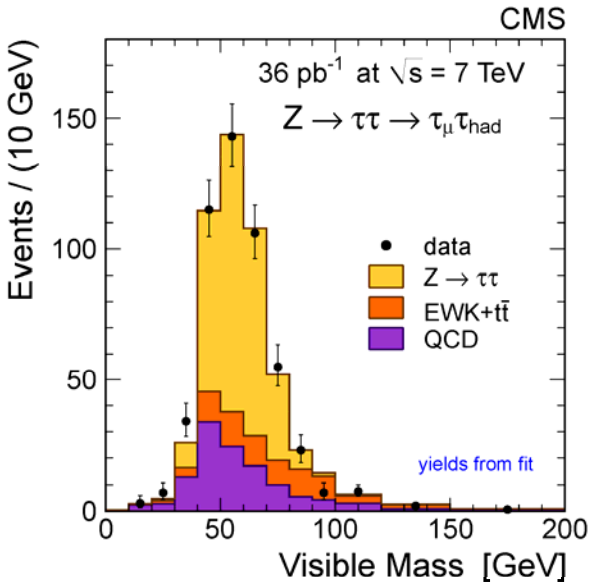

**Good agreement with NNLO theory expectations**

# $Z \rightarrow \tau\tau$

CMS-PAS-EWK-2010-013, **arXiv:1104.1617**

•Important benchmark measurement for new particle searches like MSSM Higgs (with H → tt)

•Big improvements in tau identification in CMS with respect to PTDR expectations. New methods able to improve the identification of exclusive hadronic modes




Channels with hadronic taus:
$Z \rightarrow \tau\tau \rightarrow$
$\mu + \tau$ had,
$e + \tau$ had

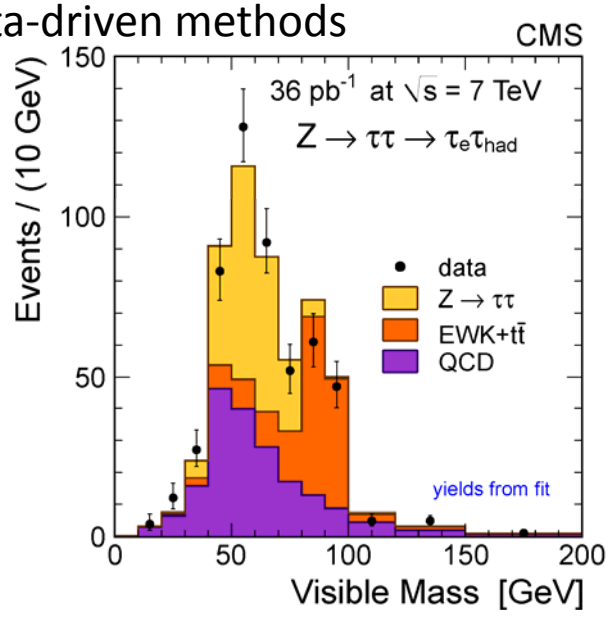
QCD backgrounds with muons (b →μ, decays in flight, ...)

• Typical selection cuts for tau EWK measurements:

- pT(isolated lepton) > 15 GeV
- pT(isolated had. tau) > 20 GeV

• MT (lepton,MET)< 40-50 GeV

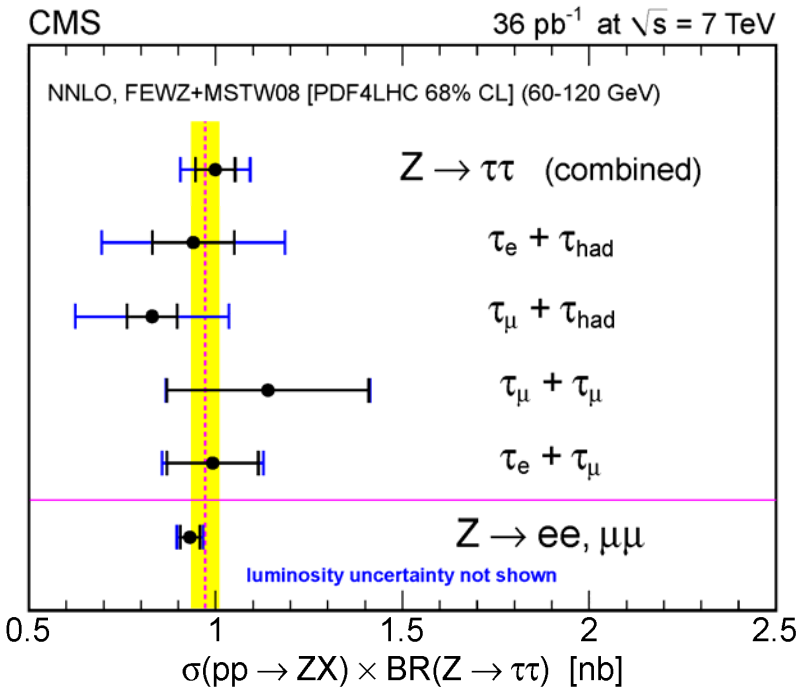
• Special effort to determine most efficiencies and backgrounds using data-driven methods

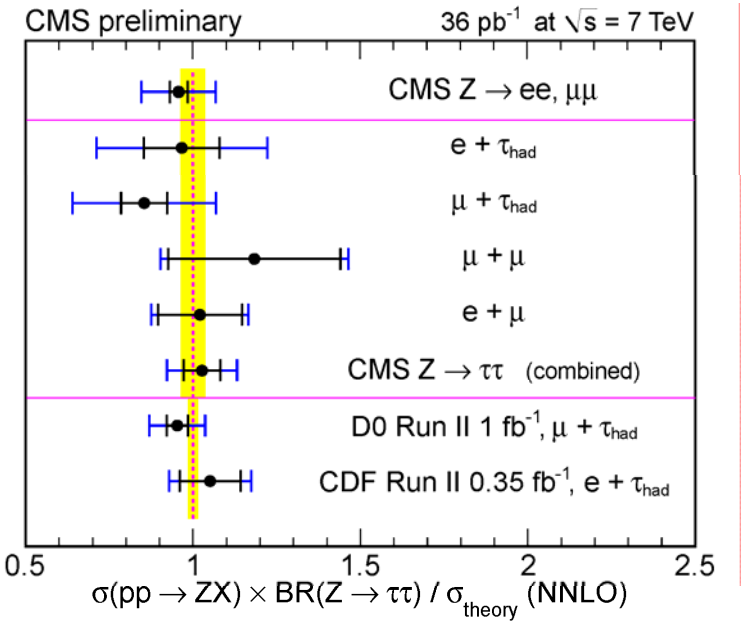



Non-negligible EWK background
QCD contamination (fake electrons)

# $Z \rightarrow \tau\tau$

CMS-PAS-EWK-2010-013

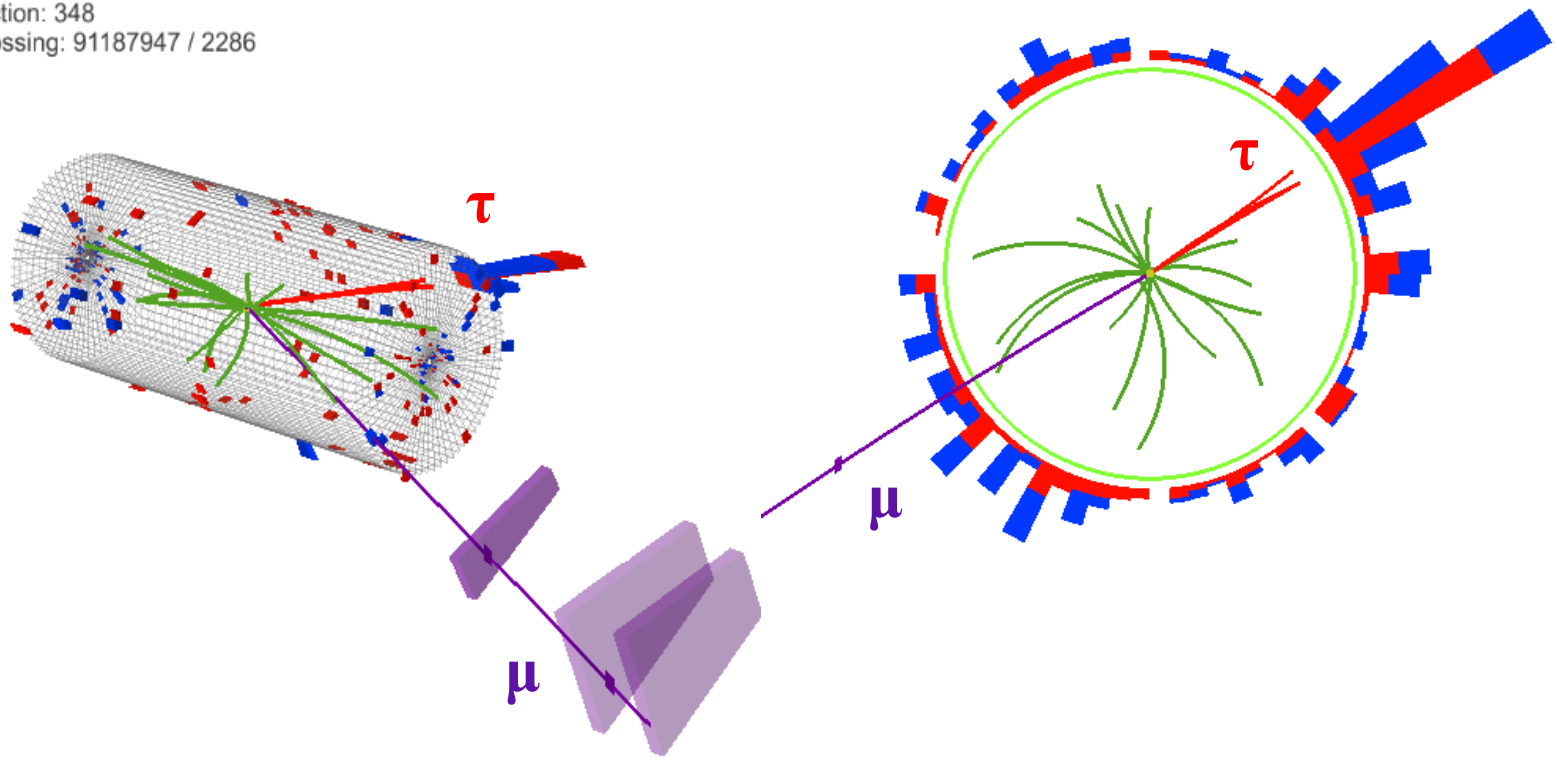



CMS results: consistent with Z → ee, μμ measurements.
Similar precision as the Tevatron with just 36 $pb^{-1}$

# $Z \rightarrow$ tau tau $\rightarrow$ mu + $tau_{had}$ (3-prong tau)

CMS Experiment at LHC, CERN
Data recorded: Sun Aug 15 03:57:48 2010 CEST
Run/Event: 142971 / 323188785
Lumi section: 348
Orbit/Crossing: 91187947 / 2286



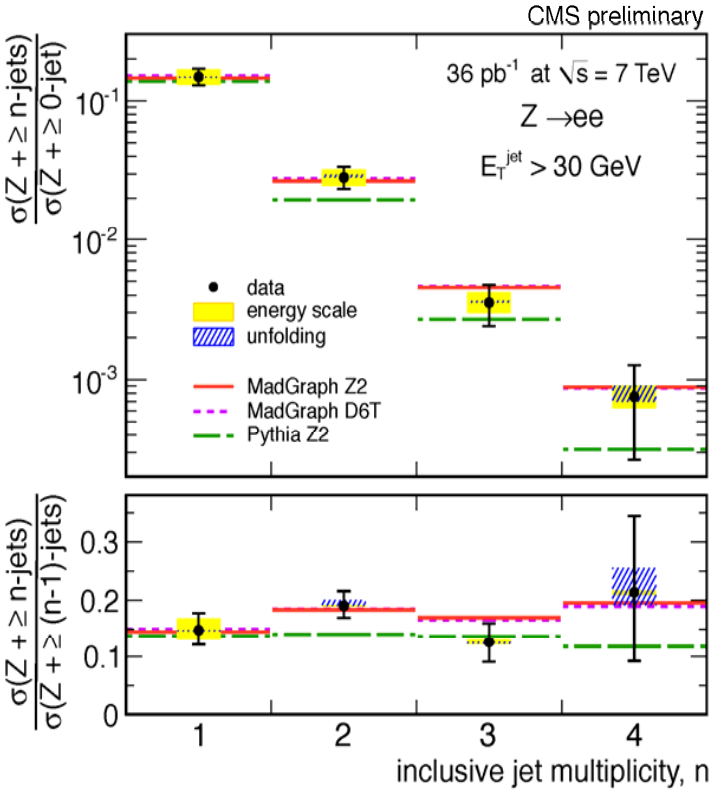

μ Pt = 32.4 GeV/c
η = 1.7

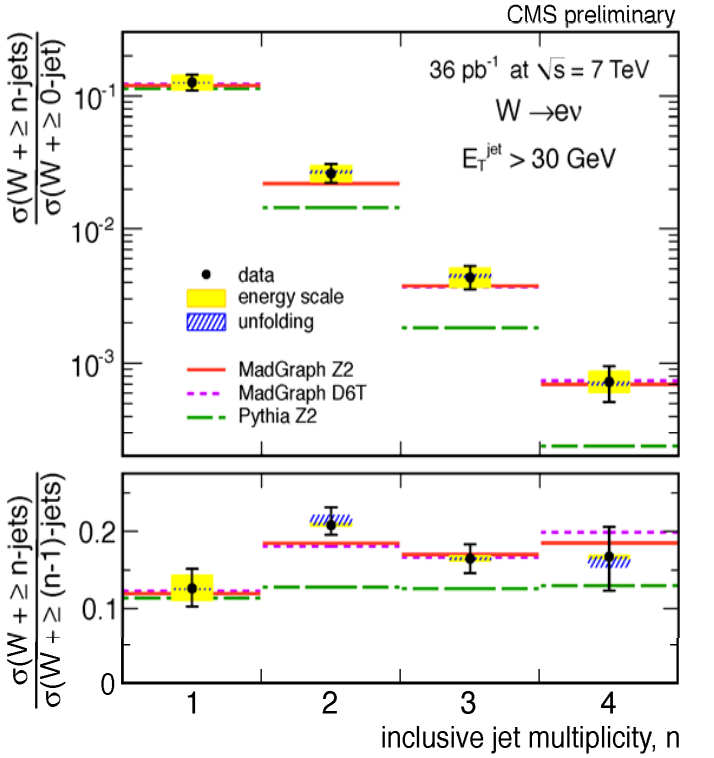
τ Pt = 37.4 GeV/c
η = 1.5
Mass = 1.2GeV/$c^2$

Vis. Mass= 70 GeV/$c^2$
$M_T$(μ,MET) =4.1 GeV

# W/Z+jets

**CMS PAS EWK-10-012**



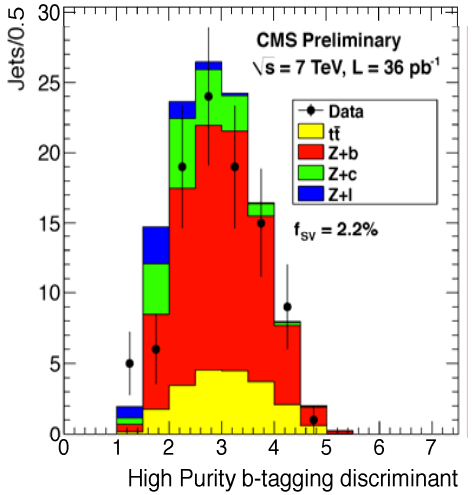




- Results agree with the expectations from MADGRAPH
- PYTHIA does not agree with the data (only expected to describe up to 1 hard jet + soft/collinear radiation - LO+ME reweighting)

# Z+b-jet, W+c-jet

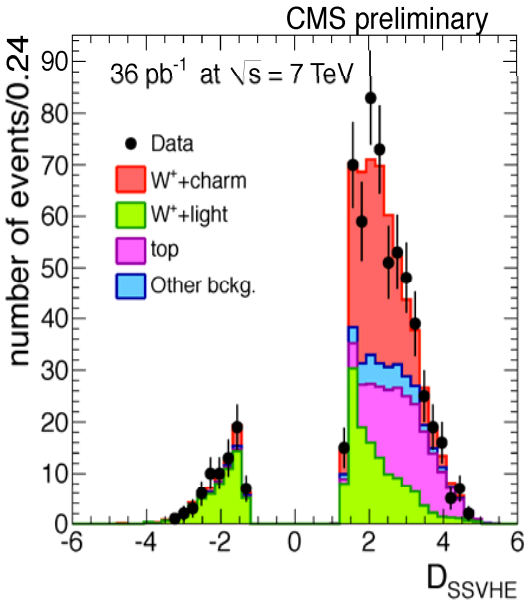
CMS PAS EWK-10-015

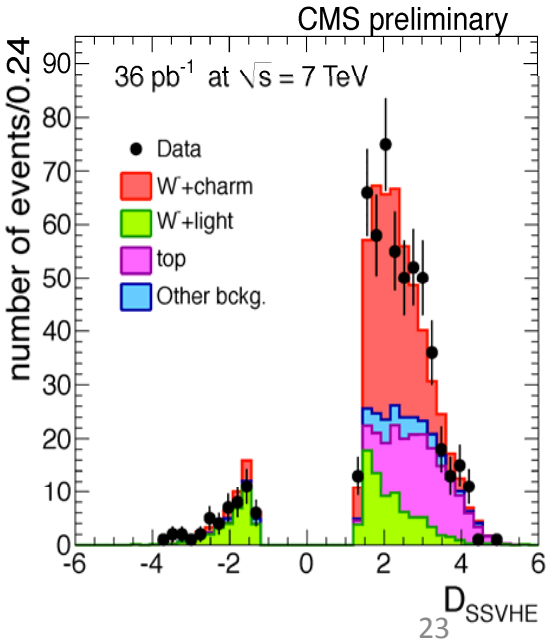
CMS PAS EWK-11-013




- **Process dominated by s-bar g → $W^+$ c-bar and sg→ $W^-$ c . It can probe s and s-bar content of proton.**
- Select W+≥1 jet events in muon channel
  - $M_T$ > 50 GeV to reject QCD background
  - Jet $E_T$ > 20 GeV
  - Require SV with ≥2 associated tracks and significantly displaced from PV
- B-tagging descriminant variable $D_{SSVHE}$ built from flight distance between PV and SV

$\sigma(Z+b)/\sigma(Z+j) = 0.054 \pm 0.016$
$(0.046 \pm 0.014)$ for $Z \rightarrow ee(Z \rightarrow \mu\mu)$
In agreement with NLO



# Di-bosons: WW, WZ, ZZ.

With 2011 data updated measurement of the $W^+W^-$ cross section and first measurements of the WZ, ZZ production cross sections at 7TeV.

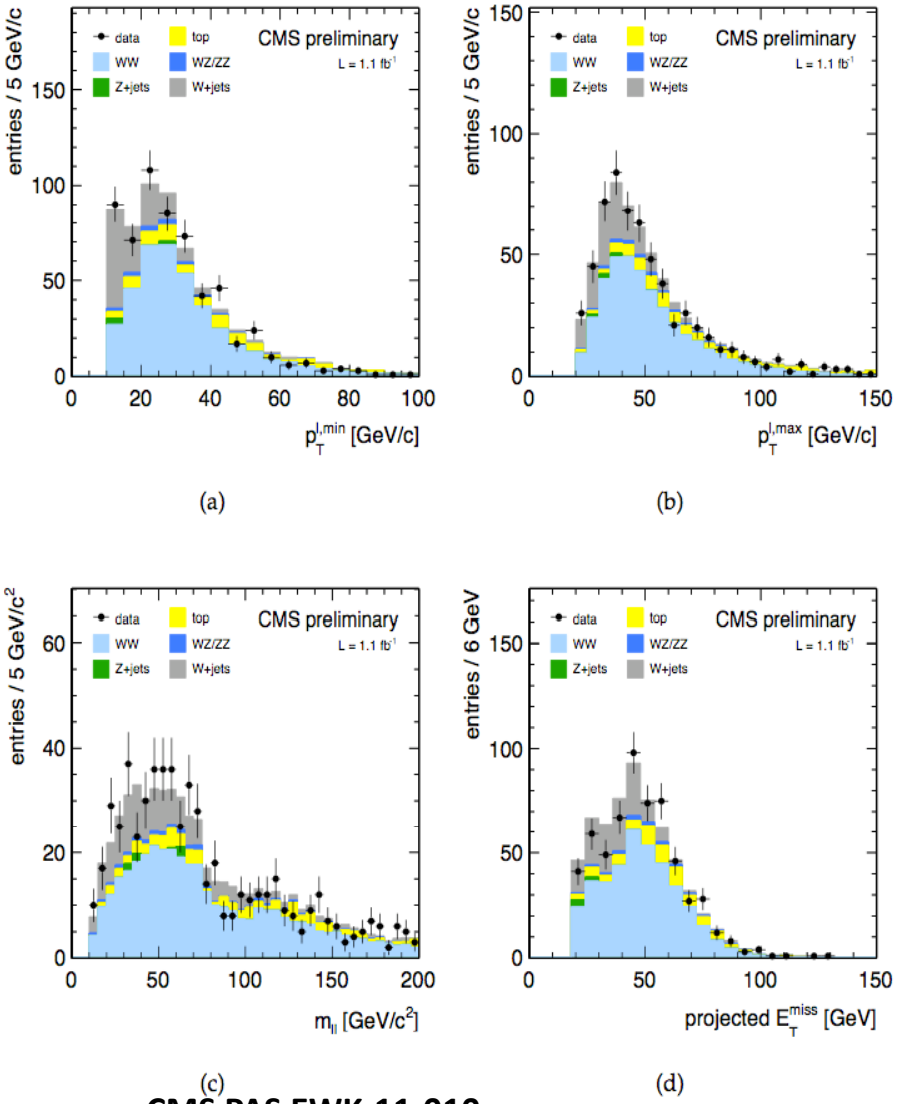
**$\sigma(pp \rightarrow W^+W^- + X) = 55.3 \pm 3.3(stat.) \pm 6.9$ (syst.) $\pm$ 3.3 (lumi.) pb.**

**$\sigma(pp \rightarrow WZ + X) = 17.0 \pm 2.4(stat.) \pm 1.1$ (syst.) $\pm$ 1.0 ( lumi.) pb.**

**$\sigma(pp \rightarrow ZZ + X) = 3.8 +1.5(stat.) \pm 0.2$ (syst.) $\pm$ 0.2 ( lumi.) pb.**

All measured values are consistent with the standard model predictions.

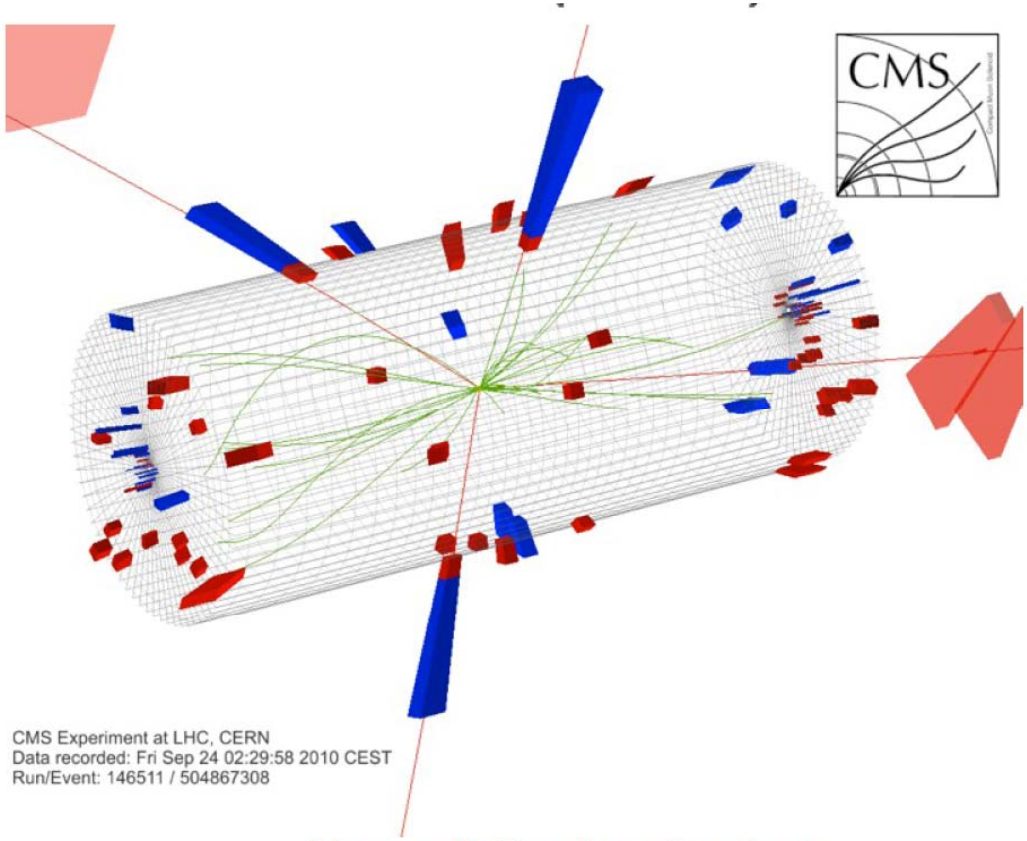
Data driven methods are used to understand the background.




**CMS PAS EWK-11-010**

# First candidate ZZ →4μ

$\mu_0 + \mu_1$: 92.15 GeV (total($Z$) $p_T$ 26.5 GeV, $\phi$ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total($Z$) $p_T$ 29.4 GeV, $\phi$ +.06),




No explicit cut on tracks $p_T$

# SUSY Search Strategy

| 0-leptons | 1-lepton | OSDL | SSDL | ≥3 leptons | 2-photons | γ+lepton |
|---|---|---|---|---|---|---|
| Jets + MET | Single lepton + Jets + MET | Opposite-sign di-lepton + jets + MET | Same-sign di-lepton + jets + MET | Multi-lepton | Di-photon + jet + MET | Photon + lepton + MET |


- **Basic analysis strategy:**

- Focus on topology using different kinematic observables
  - So that types of SM bkg and detector strong assets drive the searches

- Use well understood CMS 'objects'
  - Leptons, photons, jets, MET; Particle Flow to increase sensitivity everywhere

- Use data driven background whenever possible

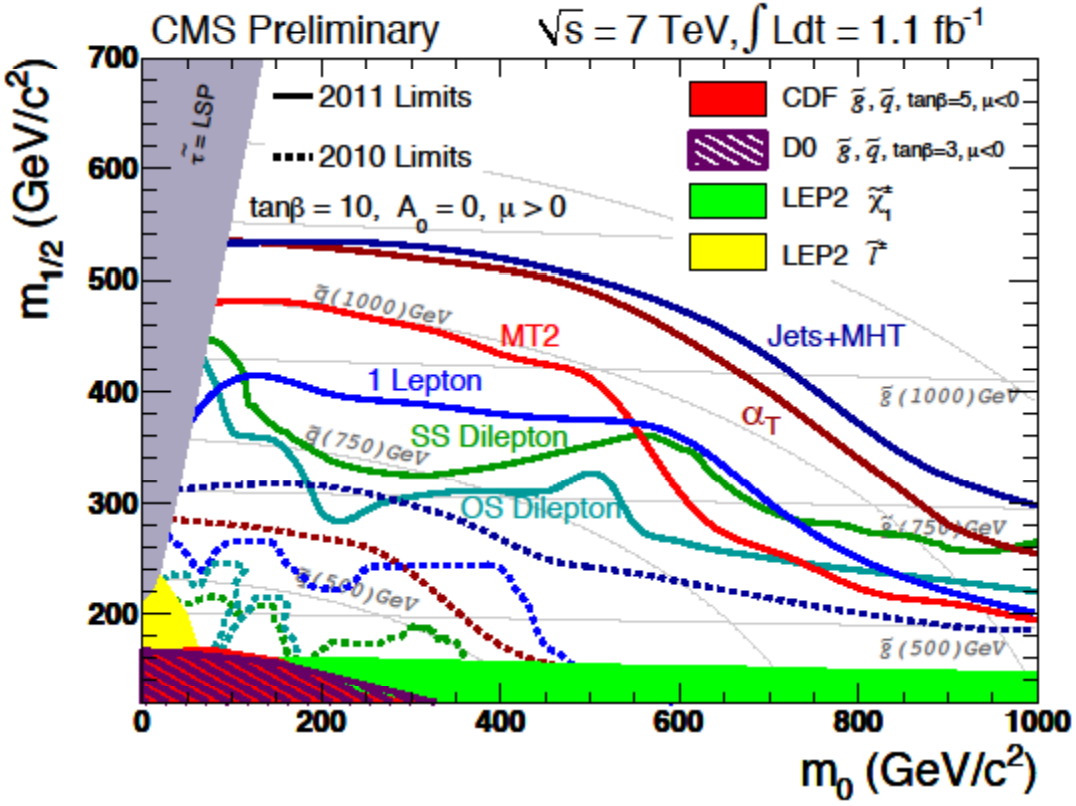
- Full results at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

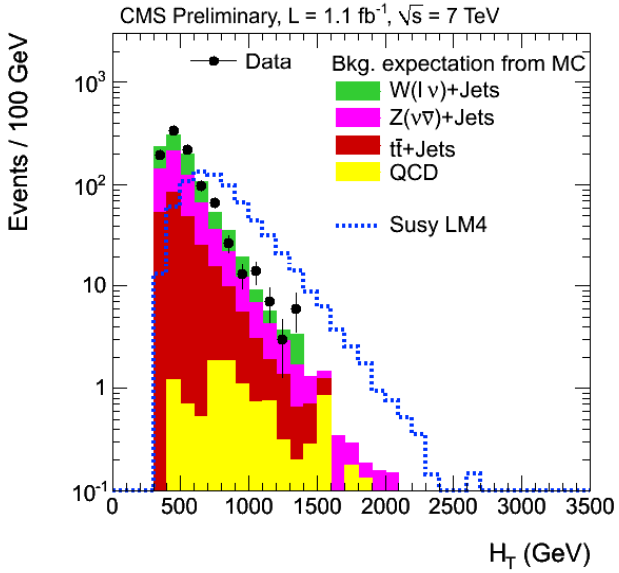
# Major 2011 results with 1 $fb^{-1}$

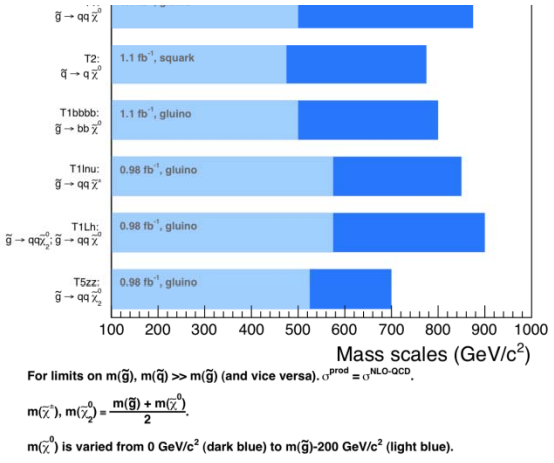
| | | | |
|---|---|---|---|
| Search for supersymmetry in all-hadronic events with αT | SUS11003 | PAS-SUS-11-003 | 1.1/fb |
| Search for supersymmetry in all-hadronic events with missing energy | SUS11004 | PAS-SUS-11-004 | 1.1/fb |
| Search for supersymmetry in all-hadronic events with MT2 | SUS11005 | PAS-SUS-11-005 | 1.1/fb |
| Search for supersymmetry with photons, jets and MET | SUS11009 | PAS-SUS-11-009 | 1.1/fb |
| Search for new physics with same-sign isolated dilepton events with jets and missing energy | SUS11010 | PAS-SUS-11-010 | 0.98/fb |
| Search for new physics in events with opposite-sign dileptons and missing transverse energy | SUS11011 | PAS-SUS-11-011 | 0.98/fb |
| Search for New Physics in Events with a Z Boson and Missing Transverse Energy | SUS11017 | PAS-SUS-11-017 | 0.98/fb |
| Search for Physics Beyond the Standard Model in Z + MET + Jets events at the LHC | SUS11012 | PAS-SUS-11-012 | 191/pb |

# Progress on SUSY

CMS Combined Exclusion Plot




**Limits well beyond LEP/Tevatron reach**

**Within the constrained SSM models CMS is crossing the border of excluding gluinos and squarks up to 1TeV and beyond.**

# Exotica

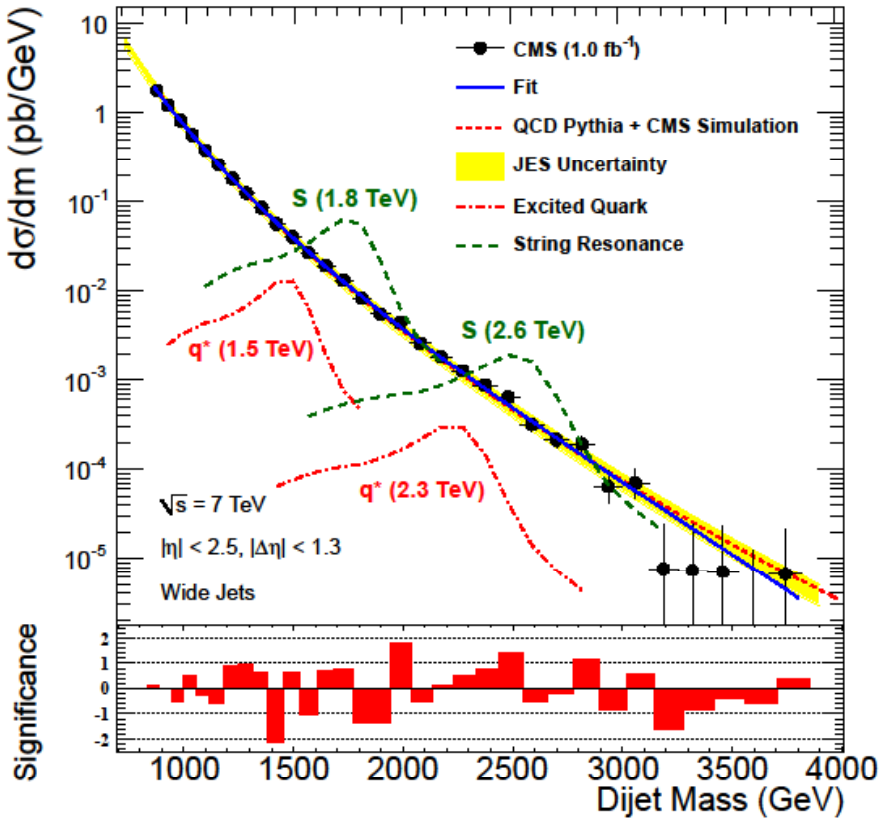
**Plenty of new results with ~1 fb$^{-1}$:**
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

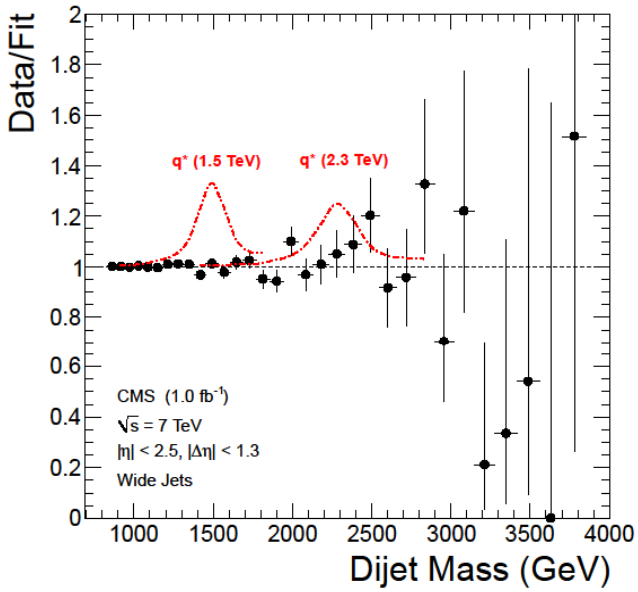
| | | | | |
|---|---|---|---|---|
| Search for Resonances in the Dijet Mass Spectrum from 7 TeV pp Collisions at CMS | 1107.4771 (hep-ex) | 1/fb | Submitted to PLB | EXO11015 |

| | | | |
|---|---|---|---|
| Search for Long-Lived Exotica Decaying to Displaced Leptons | EXO11004 | | 1.1/fb |
| Search for Extra Dimension in Monojets + MET | EXO11059 | PAS EXO-11-059 | 1.1/fb |
| Search for heavy narrow resonances decaying to ttbar (mu+jets) | EXO11055 | PAS EXO-11-055 | 1.1/fb |
| Search for a Heavy Bottom-like Quark | EXO11036 | PAS EXO-11-036 | 1.1/fb |
| Search for Search for W' (or techni-rho) to WZ | EXO11041 | PAS-EXO-11-041 | 1.2/fb |
| Search for Extra Dimensions in Diphoton Events | EXO11038 | PAS EXO-11-038 | 1.1/fb |
| Search for Extra Dimensions in Monophoton Events | EXO11058 | PAS-EXO-11-058 | 1.1/fb |
| Search for Extra Dimensions in Dimuon Events | EXO11039 | PAS-EXO-11-039 | 1.2/fb |
| Search for t' to bW (dilepton channel) | EXO11050 | PAS EXO-11-050 | 1.1/fb |
| Search for Z' to ttbar (boosted tops) | EXO11006 | PAS EXO-11-006 | 0.9/fb |
| Search for t' to bW (l+j channel) | EXO11051 | PAS EXO-11-051 | 0.8/fb |
| Search for Resonances to Dileptons | EXO11019 | PAS EXO-11-019 | 1.1/fb |
| Search for W' to e,mu | EXO11024 | PAS EXO-11-024 | 1.1/fb |
| Search for Stopped HSCPs | EXO11020 | PAS EXO-11-020 | 0.9/fb |
| Search for HSCPs | EXO11022 | PAS EXO-11-022 | 1.1/fb |
| Search for Black Holes | EXO11071 | PAS EXO-11-071 | 1.1/fb |
| Search for a Heavy Neutrino | EXO11002 | PAS EXO-11-002 | 0.2/fb |
| Search for T/t' to tZ | EXO11005 | PAS EXO-11-005 | 0.2/fb |

# Search for narrow di-jet resonances

1107.4771 (hep-ex) CMS PAS EXO-11-005




The data exclude at 95% C.L.:

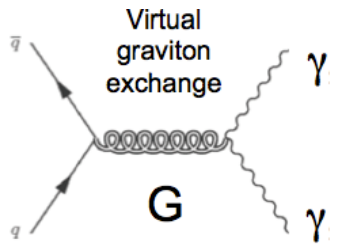
- string resonances with mass < 4.00 TeV
- $E_6$ diquarks with mass < 3.52 TeV
- excited quarks with mass < 2.49 TeV
- axigluons and colorons with mass < 2.47 TeV
- W' bosons with mass < 1.51 TeV

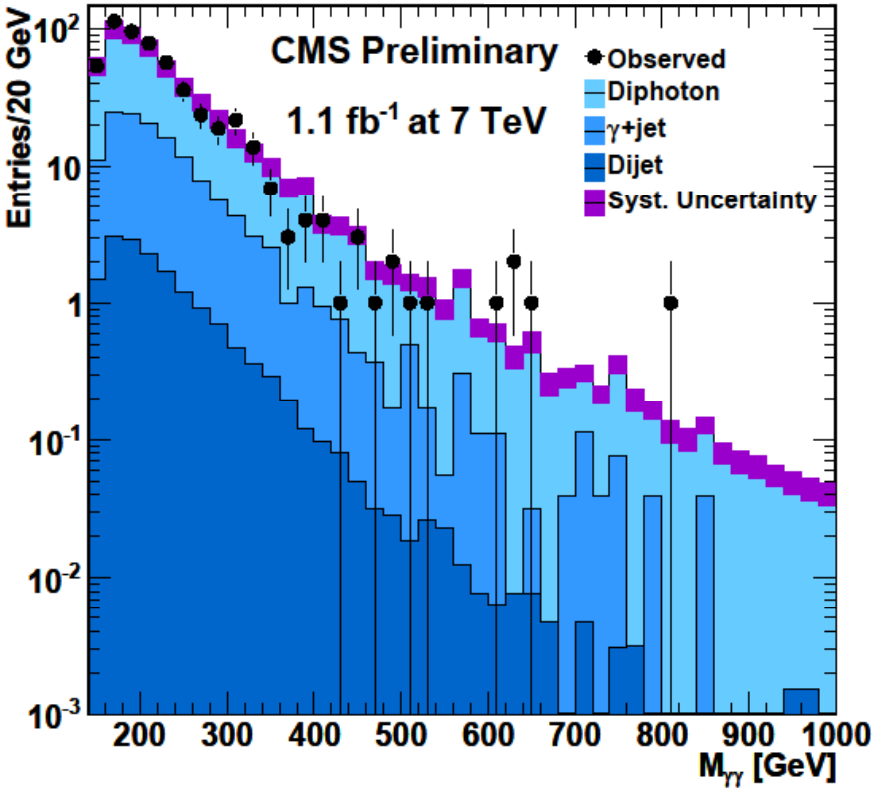
# Extra dimensions in $\gamma\gamma$

CMS PAS EXO-11-038

Resonant and non-resonant diphoton production considered

- Require two high energy isolated photons, with $M_{\gamma\gamma} > 140$ GeV
- $E_T > 70$ GeV
- Use barrel photons only($|\eta| < 1.44$, to ensure highest purity



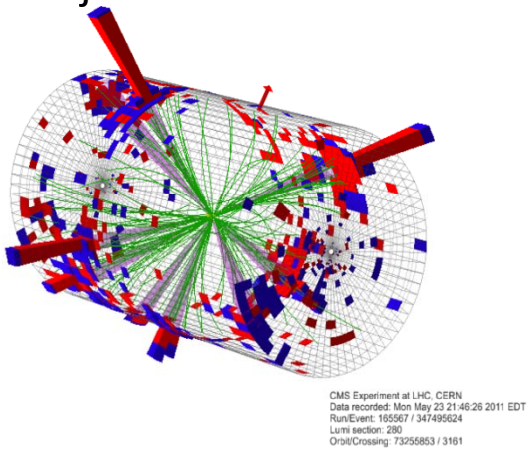

| Process | Diphoton Invariant Mass Range [TeV] | | | |
|---|---|---|---|---|
| | [0.14,0.2] | [0.2,0.5] | [0.5,0.8] | [0.8, ∞) |
| Multijet | 7 ± 3 | 9 ± 3 | 0.1 ± 0.1 | 0.003 ± 0.001 |
| $\gamma$ + jet | 53 ± 8 | 67 ± 10 | 1.5 ± 0.2 | 0.19 ± 0.04 |
| Diphoton | 185 ± 33 | 205 ± 37 | 7.6 ± 1.4 | 1.1 ± 0.2 |
| Total Backgrounds | 245 ± 35 | 283 ± 39 | 9.2 ± 1.4 | 1.3 ± 0.2 |
| Observed | 263 | 276 | 6 | 1 |

Lower limits on Effective Planck scale in the range 2.2-3.7 TeV (for nED = 2-7)

# Microscopic Black Holes

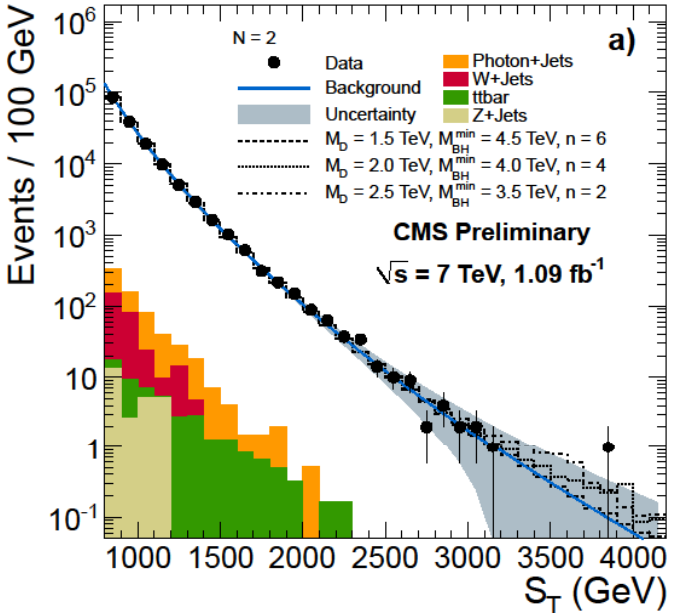
CMS PAS EXO-11-038

9-jet candidate event



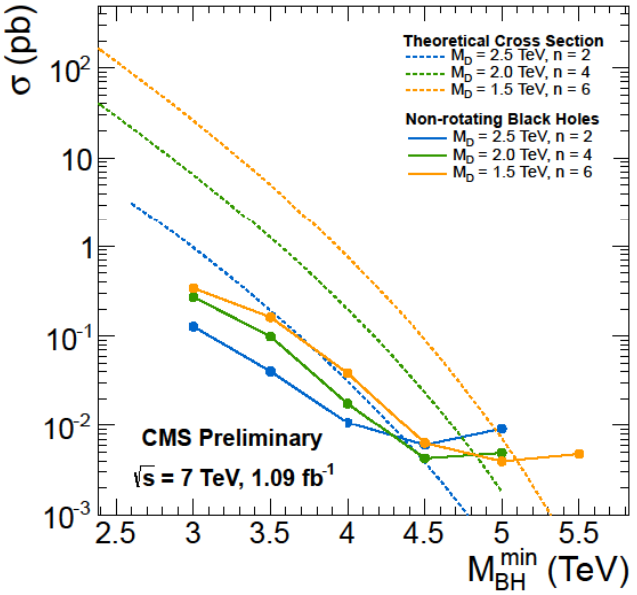

Look for excess in $S_T$, scalar sum of all sizeable (E>50 GeV) 'objects' (jets, leptons, photons, MET)

Bkg: mostly multijet QCD




Spectacular typical signal from an evaporating black hole:

- large total transverse energy
- multiple energetic jets, leptons, and photons

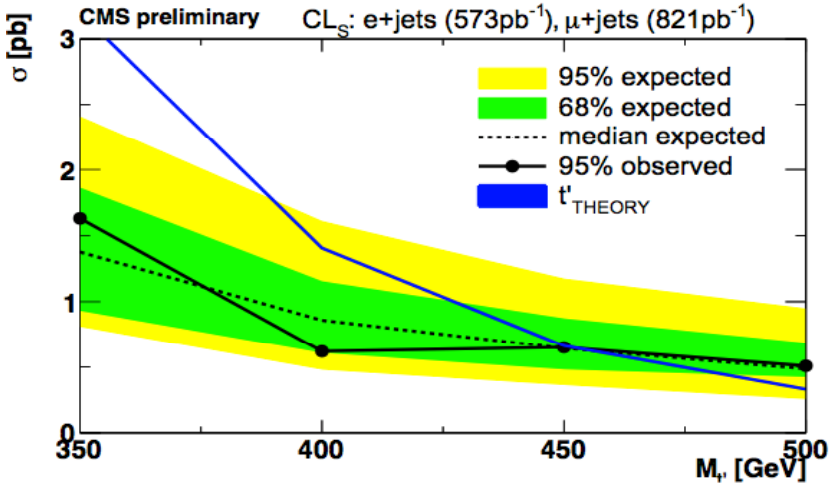



- Model-independent limits on new physics production in high-multiplicity energetic final states
- Model-specific limits on semi-classical black hole masses in the 4 -5 TeV range for a variety of model parameters.

# 4th generation quarks

**CMS PAS-EXO-11-051**

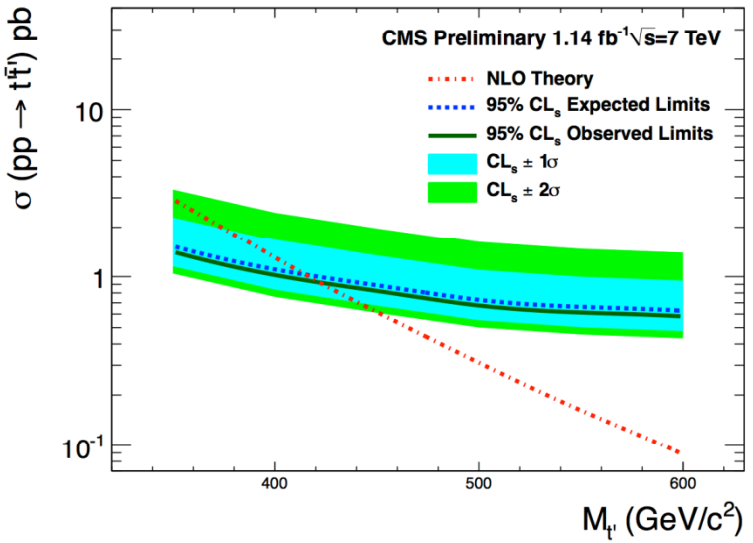
$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$



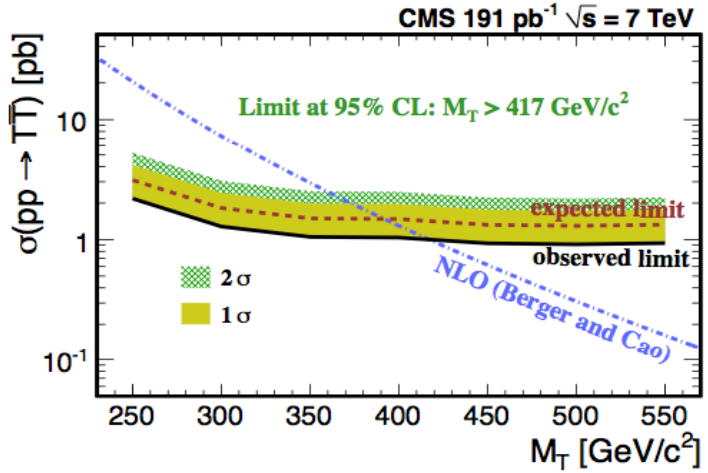

t' mass > 450 GeV at 95% CL (semileptonic)

**CMS PAS-EXO-11-050**

$t'\bar{t}' \rightarrow bW^+\bar{b}W^- \rightarrow b\ell^+\nu\,\bar{b}\ell^-\bar{\nu}$




t' mass > 422 GeV at 95% CL (dileptonic)



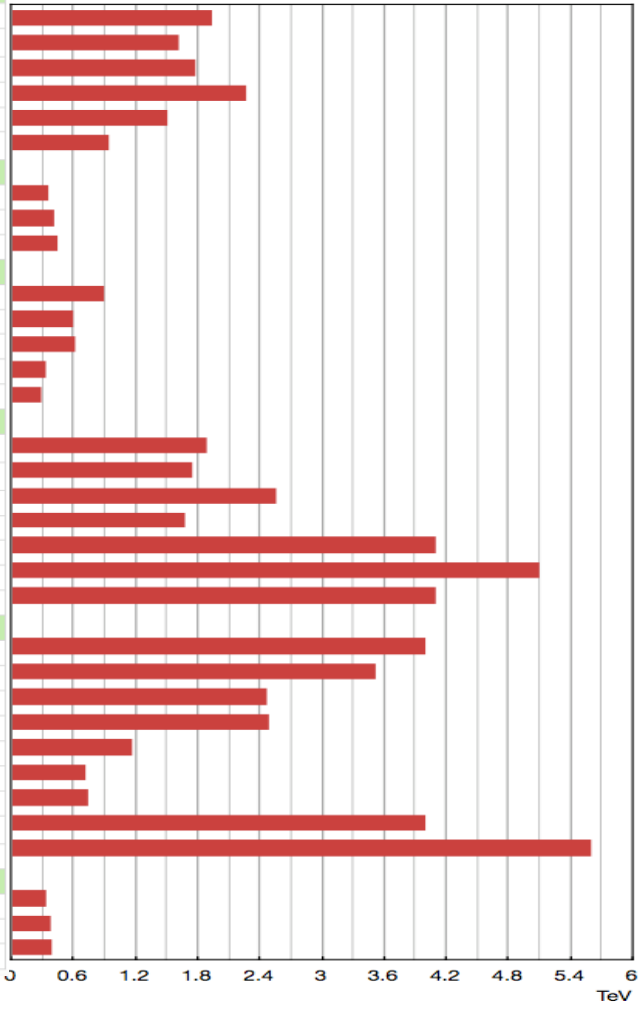

**CMS PAS-EXO-11-005**

Top-like T/t' → tZ

t' mass > 422 GeV at 95% CL (T/t' → tZ)

# Summary of CMS EXO searches

| | Limits in TeV | |
|---|---|---|
| | Heavy Bosons | |
| $Z'_{SSM}$ ll | 1.94 | 2011 |
| $Z'_{\psi}$ ll | 1.62 | 2011 |
| $G_{KK}$ ll k/M = 0.1 | 1.78 | 2011 |
| W' lν | 2.27 | 2011 |
| W' dijet | 1.51 | 2011 |
| $G_{KK}$ γγ k/M = 0.1 (2010) | 0.945 | 2010 |
| | 4th Generation | |
| $M_{b'}$, b' ⇒ tW (2010) | 0.361 | 2010 |
| $M_{t'}$, t' ⇒ tZ (100%) | 0.417 | 2011 |
| $M_{t'}$, t' ⇒ bW (100%), l+jets | 0.45 | 2011 |
| | Heavy Stable Particles | |
| $M_{gluino}$, HSCP | 0.899 | 2011 |
| $M_{gluino}$, Stopped Gluino | 0.601 | 2011 |
| $M_{stop}$, HSCP | 0.620 | 2011 |
| $M_{stop}$, Stopped Gluino | 0.337 | 2011 |
| $M_{stau}$, HSCP | 0.293 | 2011 |
| | Large Extra Dimensions | |
| $M_S$, γγ, GRW (2010) | 1.89 | 2010 |
| $M_S$, μμ, GRW (2010) | 1.75 | 2010 |
| $M_D$, monojet, $n_{ED}$ = 2 (2010) | 2.56 | 2010 |
| $M_D$, monojet, $n_{ED}$ = 6 (2010) | 1.68 | 2010 |
| $M_{BH}$, rotating, $M_D$=3.5 TeV, $n_{ED}$ = 2 | 4.1 | 2011 |
| $M_{BH}$, non-rot, $M_D$=1.5 TeV, $n_{ED}$ = 6 | 5.1 | 2011 |
| String Ball M, $M_D$=2.1, $M_s$=1.7, $g_s$=0.4 | 4.1 | 2011 |
| | Compositeness and Contact Interactions | |
| String Resonances | 4.0 | 2011 |
| $E_6$ diquarks | 3.52 | 2011 |
| Axigluon/Coloron | 2.47 | 2011 |
| q* , dijet | 2.49 | 2011 |
| q* , boosted Z | 1.17 | 2010 |
| e*, Λ = 2 TeV | 0.720 | 2010 |
| μ*, Λ = 2 TeV | 0.745 | 2010 |
| C.I. Λ , dijet mass (3 $pb^{-1}$) | 4.0 | 2010 |
| C.I. Λ , X analysis | 5.6 | 2010 |
| | LeptoQuark | |
| LQ1, β=0.5 (2010) | 0.340 | 2010 |
| LQ1, β=1.0 (2010) | 0.384 | 2010 |
| LQ2, β=1.0 (2010) | 0.394 | 2010 |



# Conclusions

- CMS is in good operating conditions and seems to be able to cope well with the challenge of instantaneous luminosity higher than $10^{33}cm^{-2}s^{-1}$.

- Plenty of new physics results are being published. No evidence for BSM physics so far.

- I didn't mention many other very interesting analyses
- CMS Public Physics Results at:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults