

# Recent Results from CMS Experiment at LHC

**Bora Isildak**  
for the CMS Collaboration



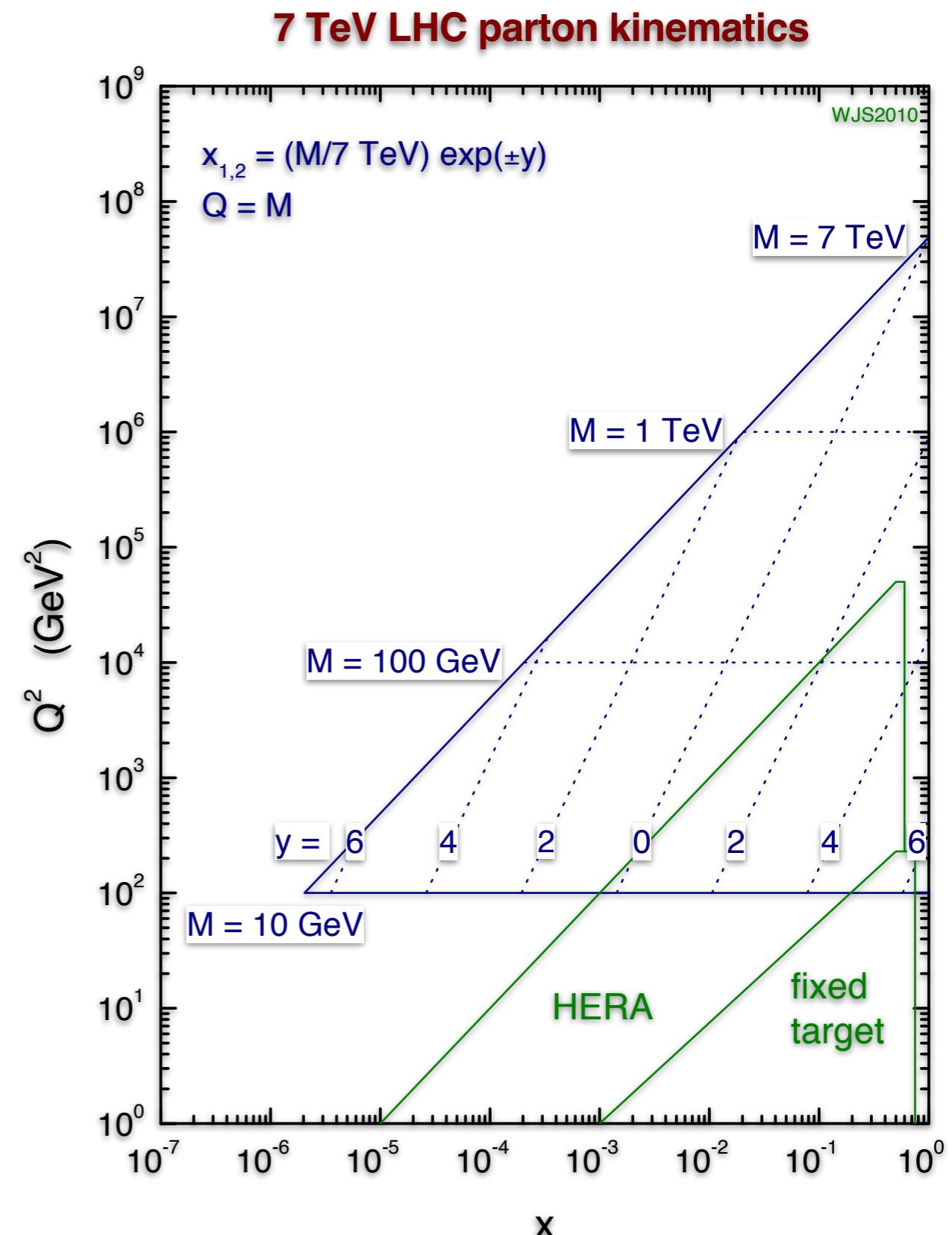
**QCD@Work: International Workshop on QCD - Theory and  
Experiment, 16-19 Jun 2014, Giovinazzo (Italy)**

# Outline

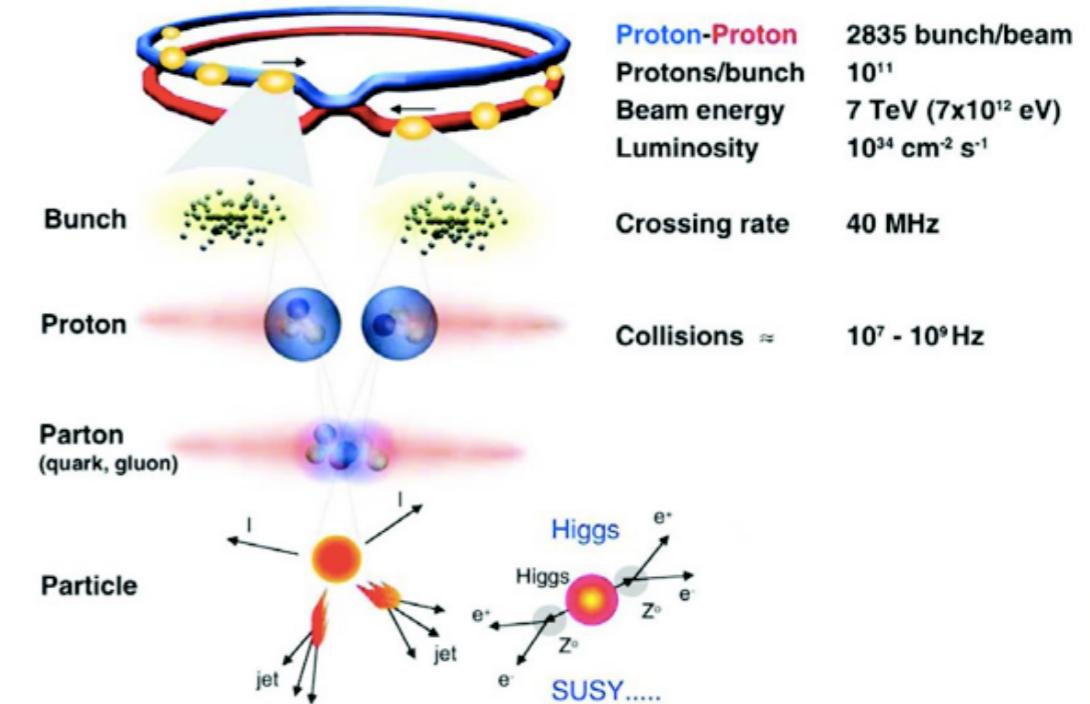
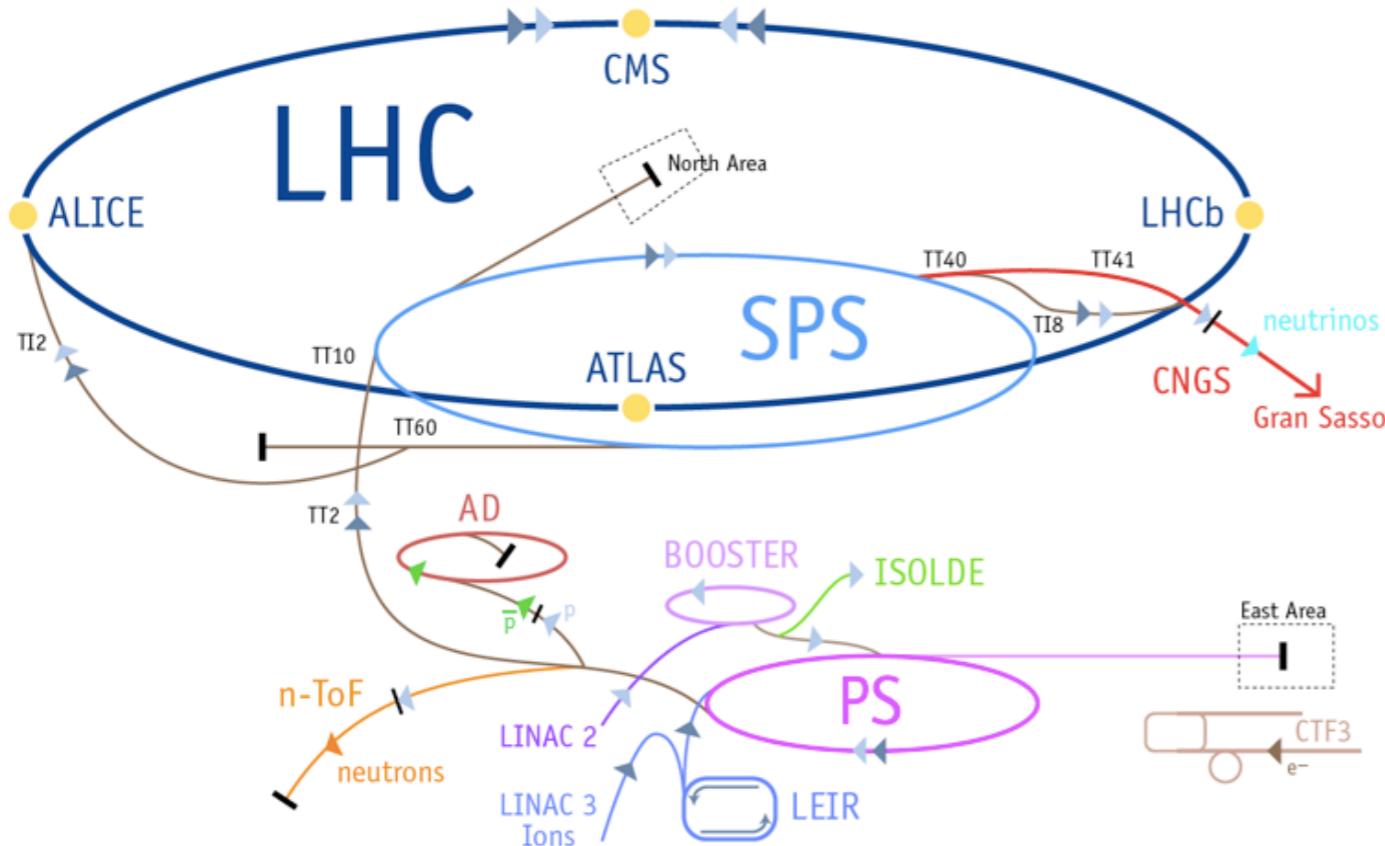
- Introduction
- CMS Experiment (Quick)
- Jet Reconstruction and Calibration
- Importance of QCD
- Higgs Discovery
- Cross Section Measurements (outlook)
  - Some SM-QCD Physics Results
  - New Physics?
    - Search for narrow resonances in dijet mass spectrum
    - Jet extinction in inclusive jet- $pT$  spectrum
  - Conclusions

# Introduction

- QCD processes are dominant in pp collisions at LHC they affect all measurements; as signal or as background must be understood in detail
- LHC pp collisions covers an extensive and unexplored kinematic region
- A more precise knowledge of QCD is important for new-physics searches
- multijet production is important for SUSY searches



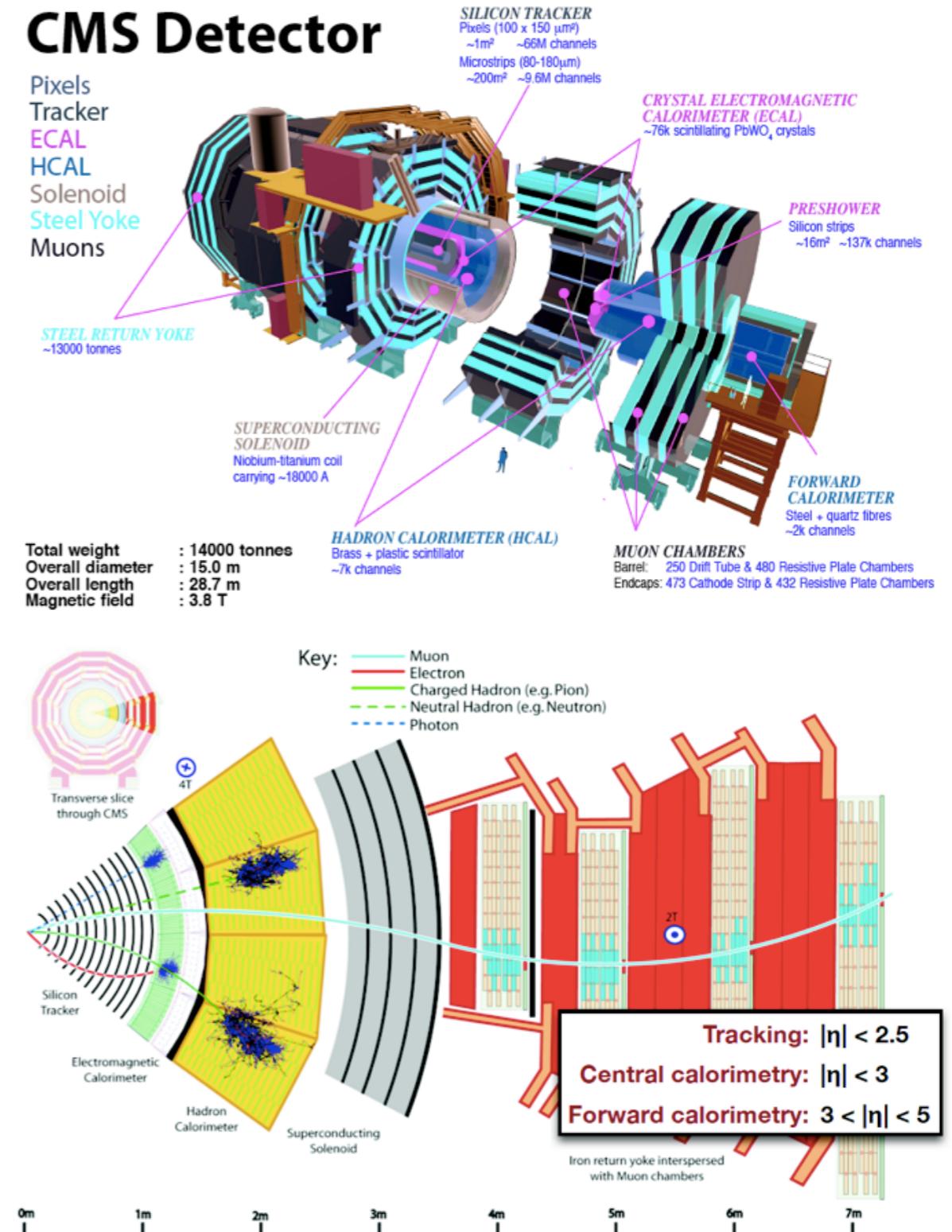
# Large Hadron Collider



- The LHC is the world's largest and the most powerful collider (run at 7 TeV and 8 TeV so far)
- Located in the existing LEP tunnel between 50 and 175 m underground with 26.7 km circumference long.
- The LHC hosts four main detectors (ALICE, ATLAS, CMS, LHCb).
- The first  $p\bar{p}$  collision in March 2010, the first  $Pb-Pb$  collision in November 2010, and the first p- $Pb$  collisions in September 2012

# CMS Detector

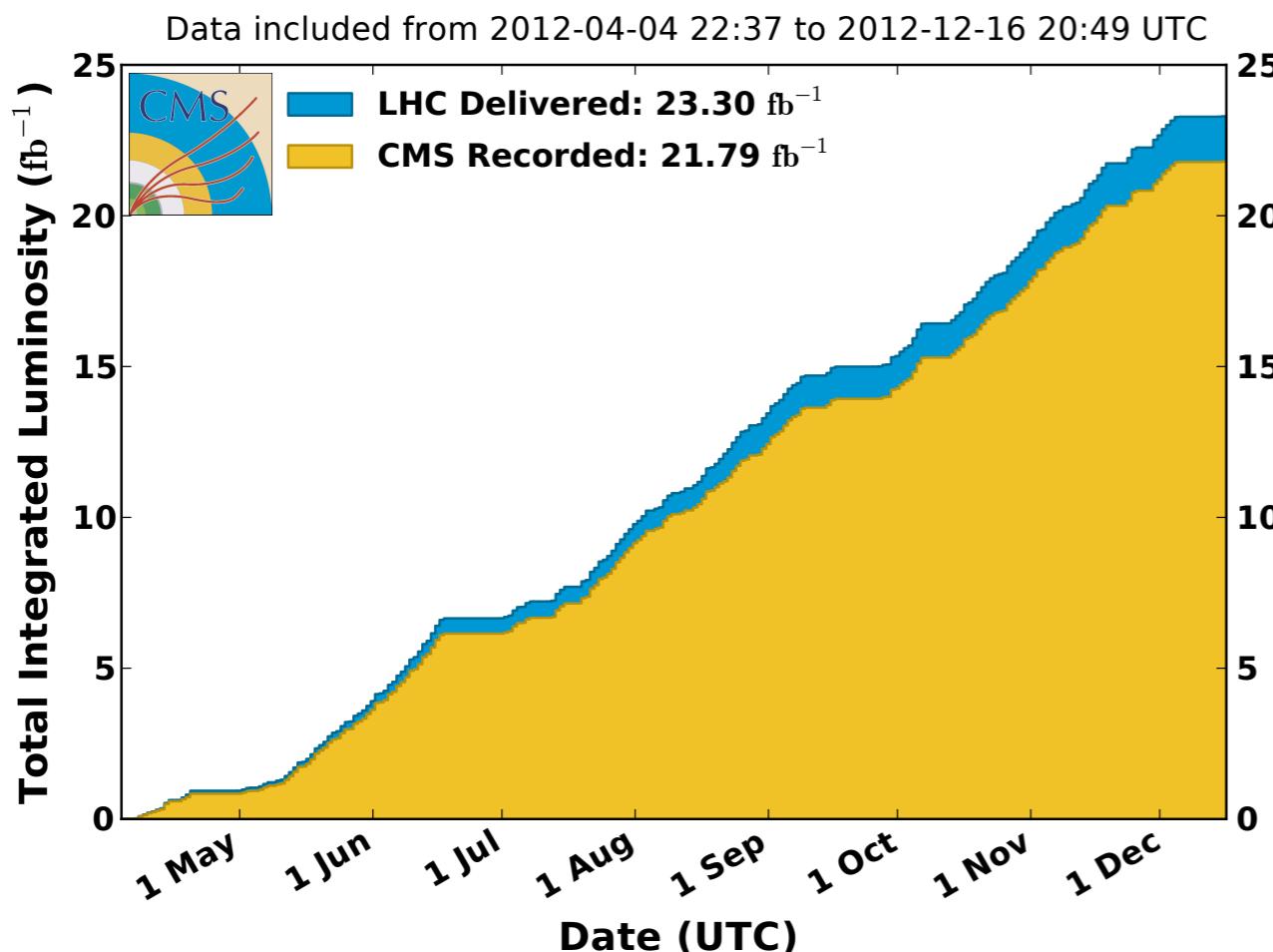
- The Compact Muon Solenoid (CMS) is a multi purpose detector at the LHC.
- The CMS detector design is similar to the structure of an onion.
- CMS consists of several layers of each one which is specialised to measure and identify different classes of particles.
- The detector requirements for CMS
  - Good muon identification and momentum resolution,
  - Good charged particle momentum resolution and reconstruction efficiency in the inner tracker,
  - Good electromagnetic energy resolution, good diphoton and dielectron mass resolution,
  - Good MET and dijet mass resolution.



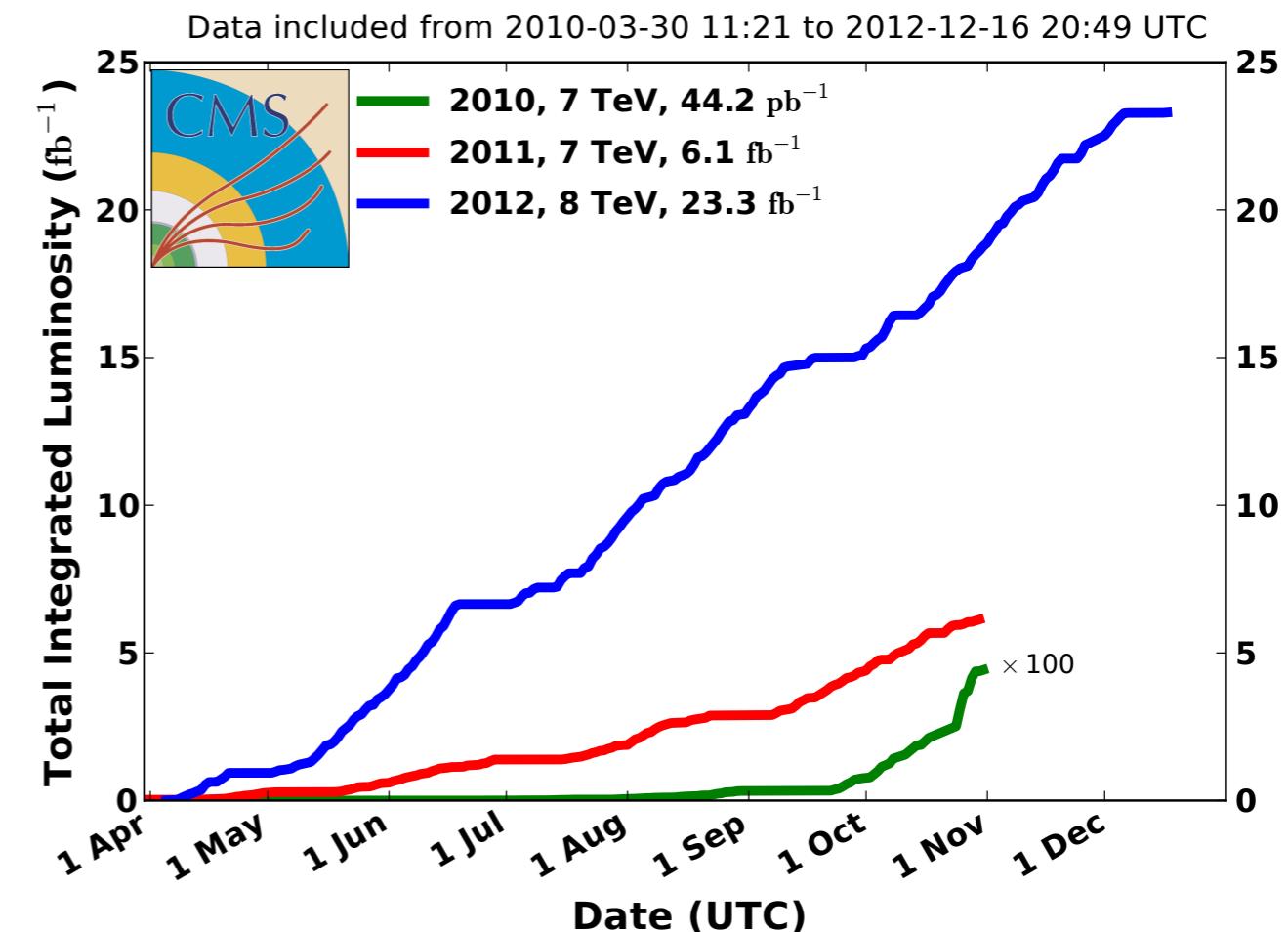
# CMS Detector

## Collisions throughout the years

**CMS Integrated Luminosity, pp, 2012,  $\sqrt{s} = 8 \text{ TeV}$**



**CMS Integrated Luminosity, pp**



Very successful LHC operations in 2010-2012  
 8 TeV: Challenging environment  
 Very high pile-up, new techniques

13 TeV in 2015  
 LHC may exceed design luminosity and  
 run at higher than design pile-up

# CMS Detector

1/10 of the Collaborators



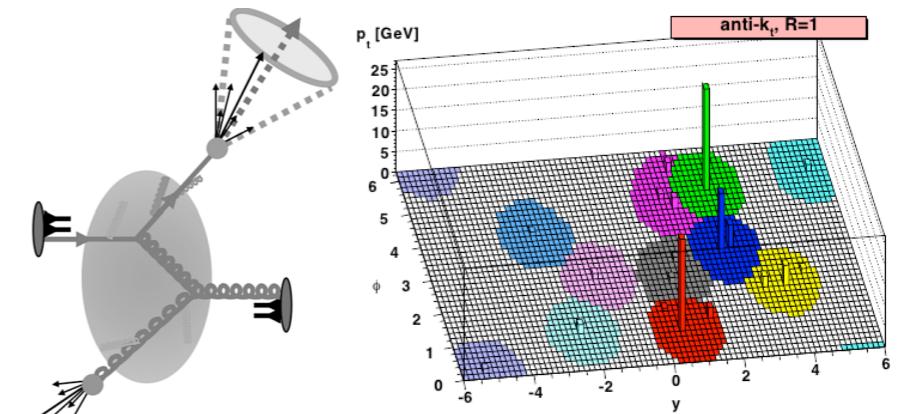
# Jet Reconstruction

Jets are the experimental signatures of quarks and gluons  
Invaluable objects to probe QCD

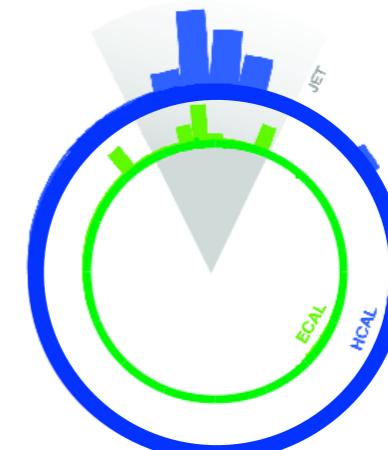
- It is an object that is clustered out of collimated spray of particles by using a set of mathematical rules

$$d_{ij} = p_{T,i}^{2p} \quad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

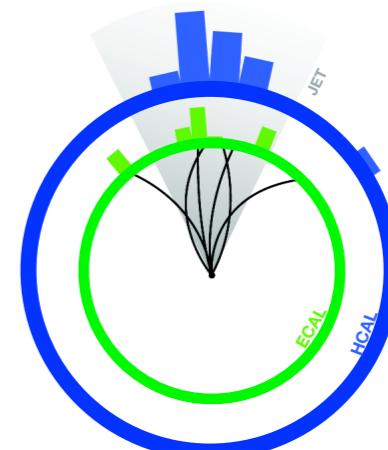
- CMS's default jet reconstruction algorithm is “anti- $k_T$  jet” algorithm with  $p=-1$  in the expression above
  - successive recombination (belongs to the  $k_T$  family)
  - infrared and collinear safe
  - geometrically cone-like (some round shape in the  $y\text{-}\phi$  plane)
  - tends to cluster around the hard energy depositions
- The jet reconstruction in CMS follows the “E-Scheme”
  - addition of Lorentz vectors
  - massless particles  $\rightarrow$  massive jets



Calorimeter Jets



Particle Flow Jets



calorimeter towers or  
particle-flow  
candidates

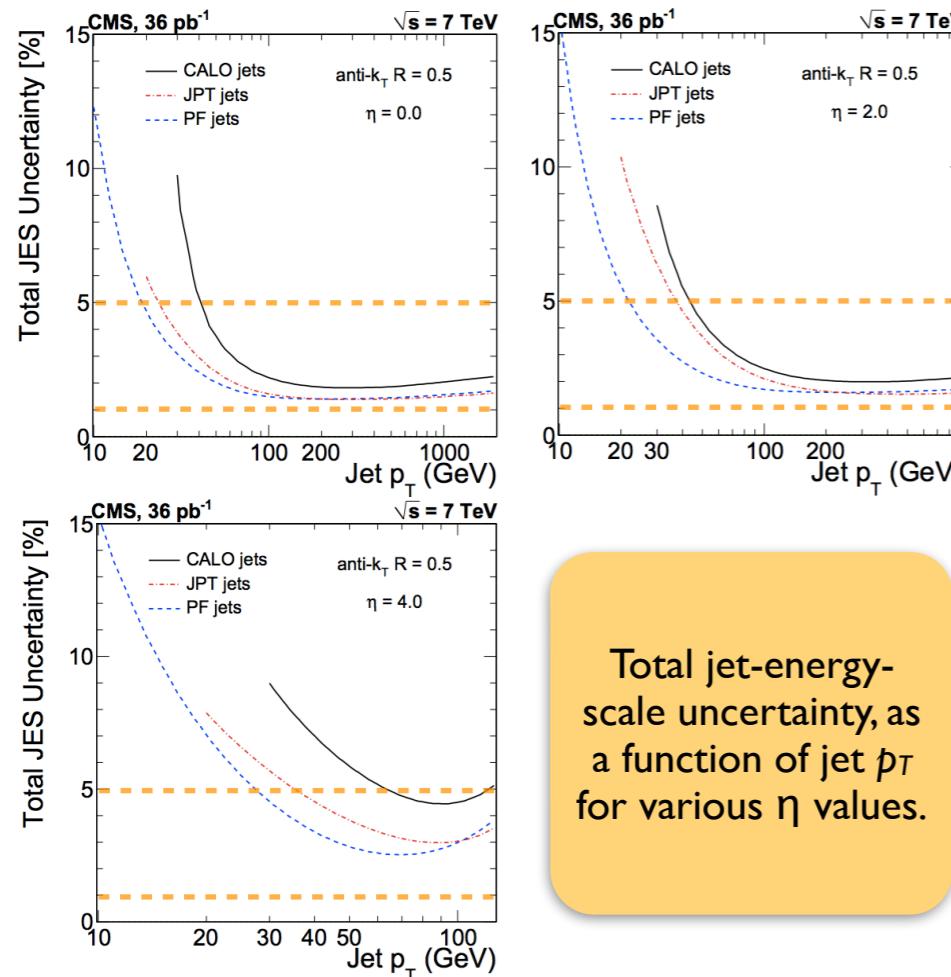
Jet clustering algorithm

CaloJets or  
PF Jets

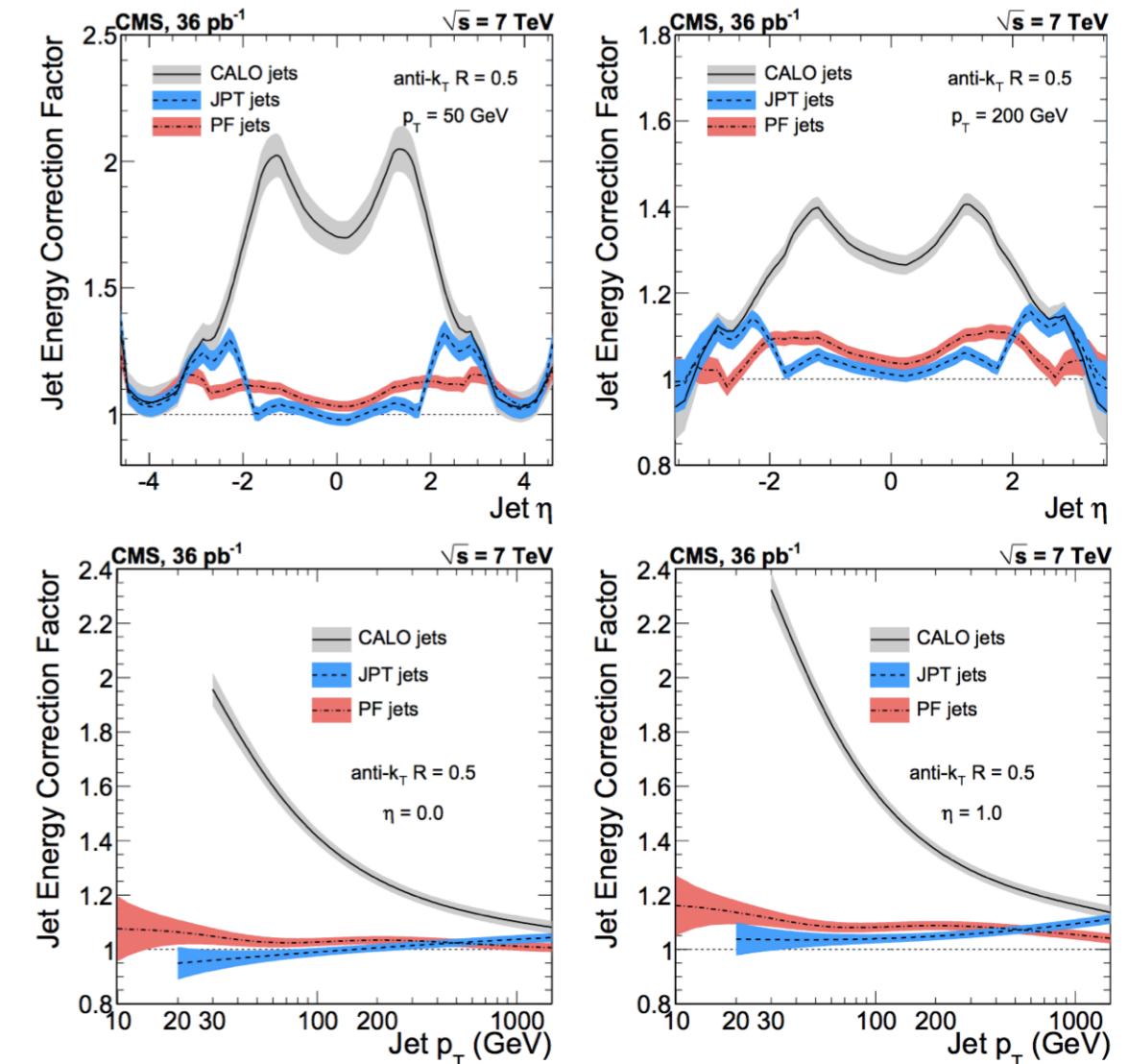
# Jet Reconstruction and Calibration

J. Instrum. 6 (2011) P11002

- Jet Energy Calibration
- Factorized approach is used like in Tevatron
  - offset correction
  - relative correction
  - absolute JEC scale determined with  $Z \rightarrow \mu^+ \mu^- + \text{jet}$ ,  $Z \rightarrow e^+ e^- + \text{jet}/\gamma + \text{jet}$



Total jet-energy-scale uncertainty, as a function of jet  $p_T$  for various  $\eta$  values.



Jet Calibration vs.  $\eta$  is better than 0.5% in  $|\eta_{\text{jet}}| < 2$  region

- pile-up corrections becomes important
- dijet  $p_T$  balance
- MPF method adopted from D $\phi$

# Importance of QCD Knowledge



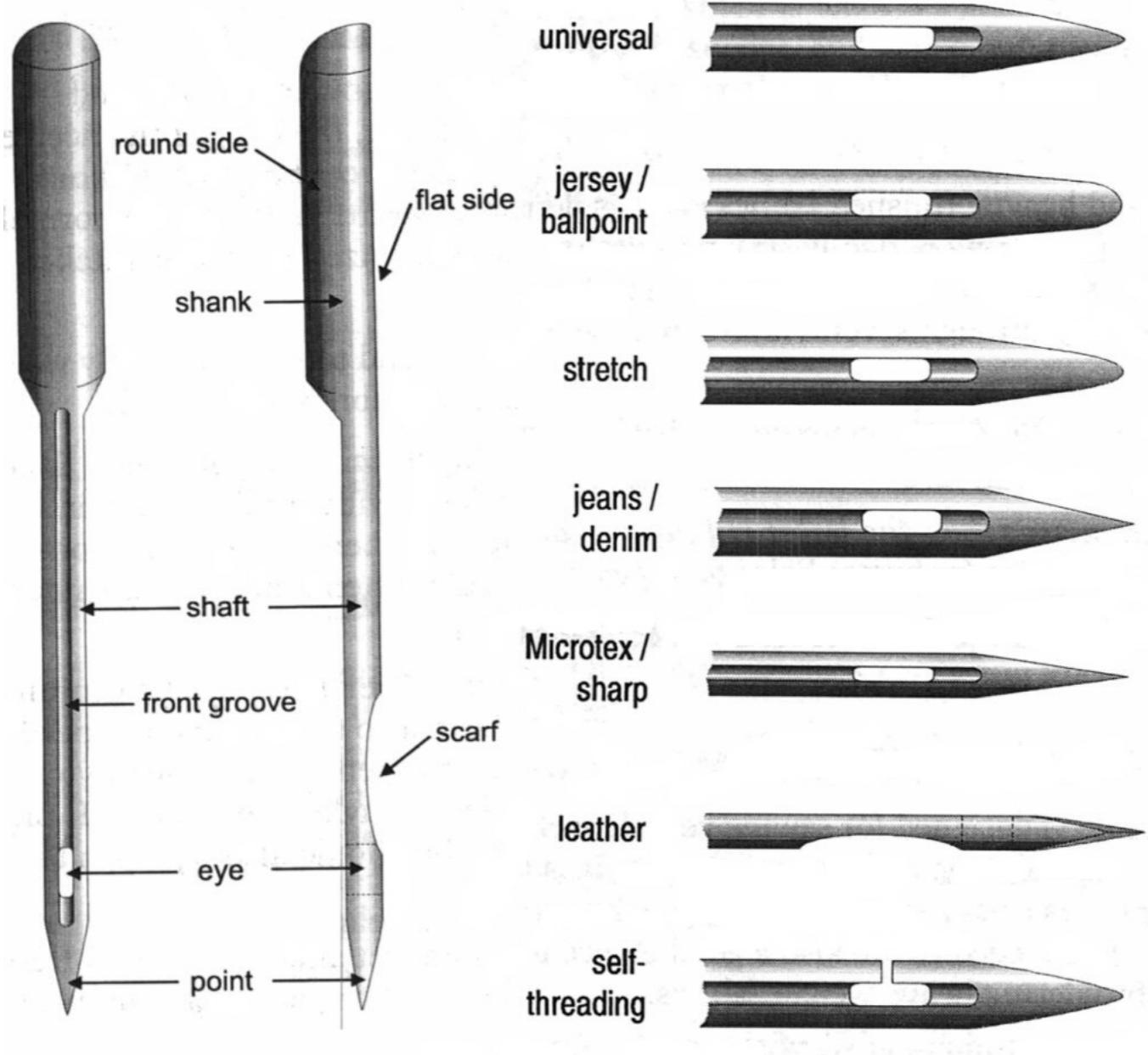
**Famous Analogy  
HEPEx Searches - searching for a needle in a haystack!**

# Importance of QCD Knowledge



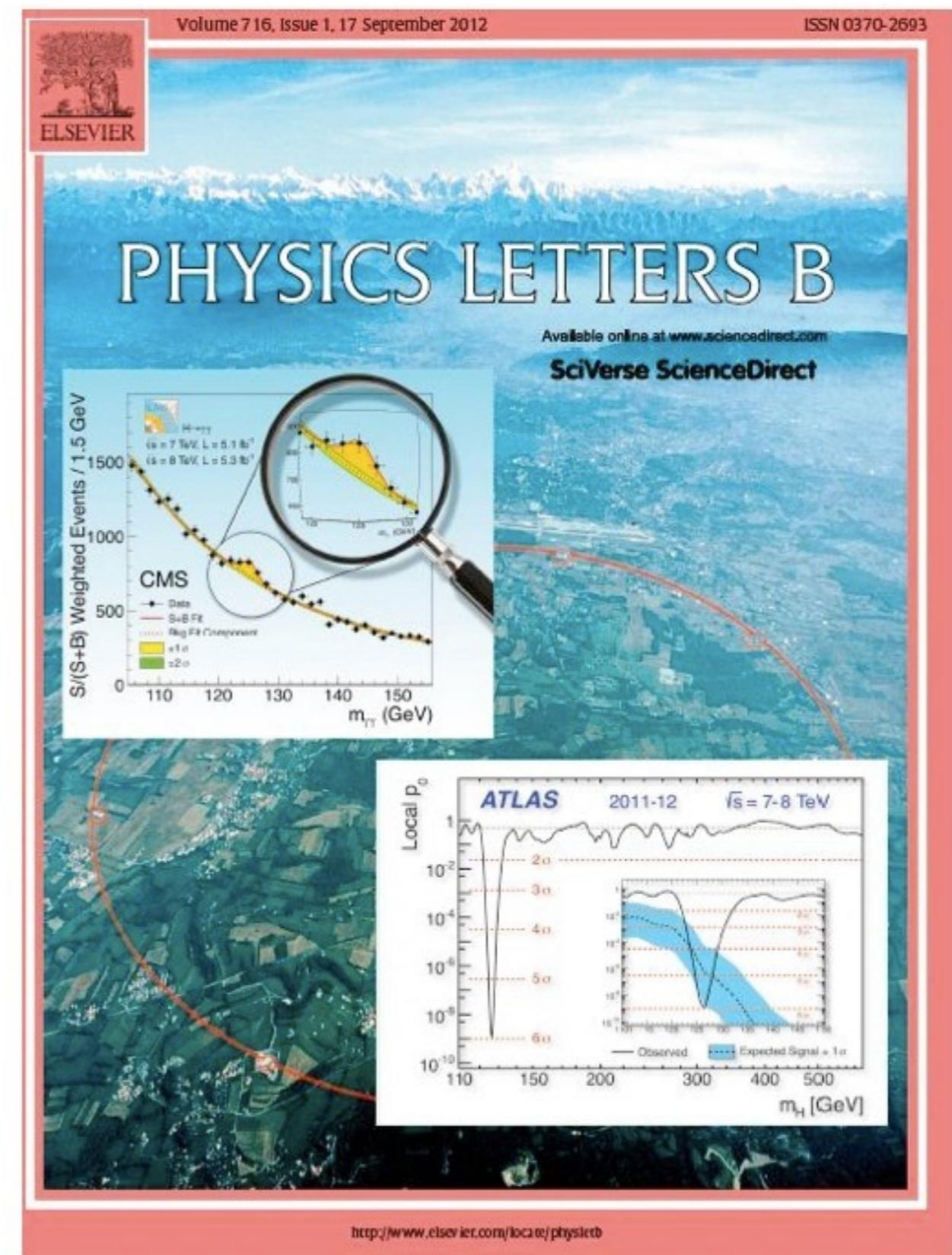
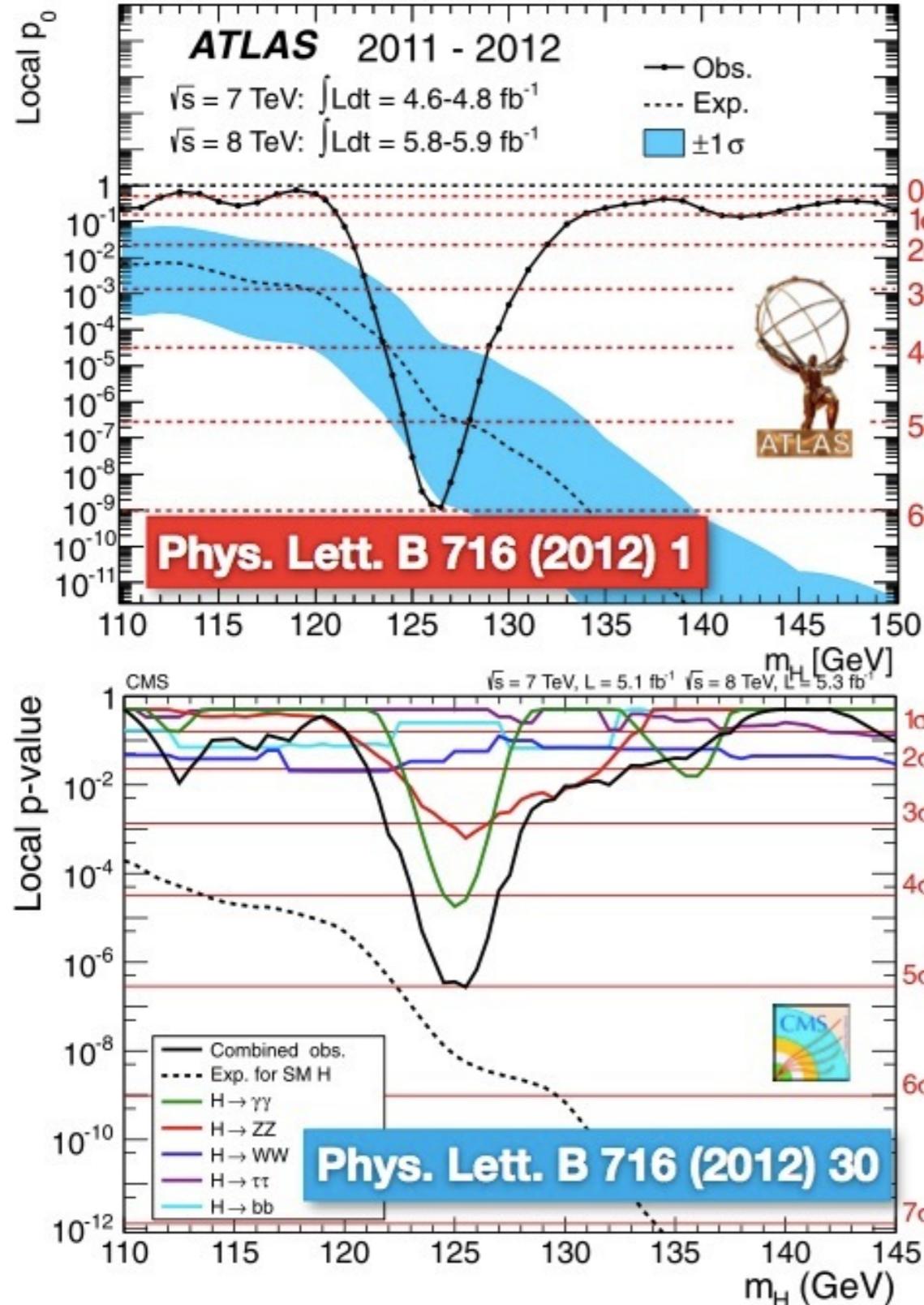
**Actually,  
searching for a specific needle in a needle stack!**

# Importance of QCD Knowledge



Type of needles.  
Their details.  
Only then, we can  
recognise the new  
needles in the stack.

# Higgs Discovery at CMS (sine qua non)



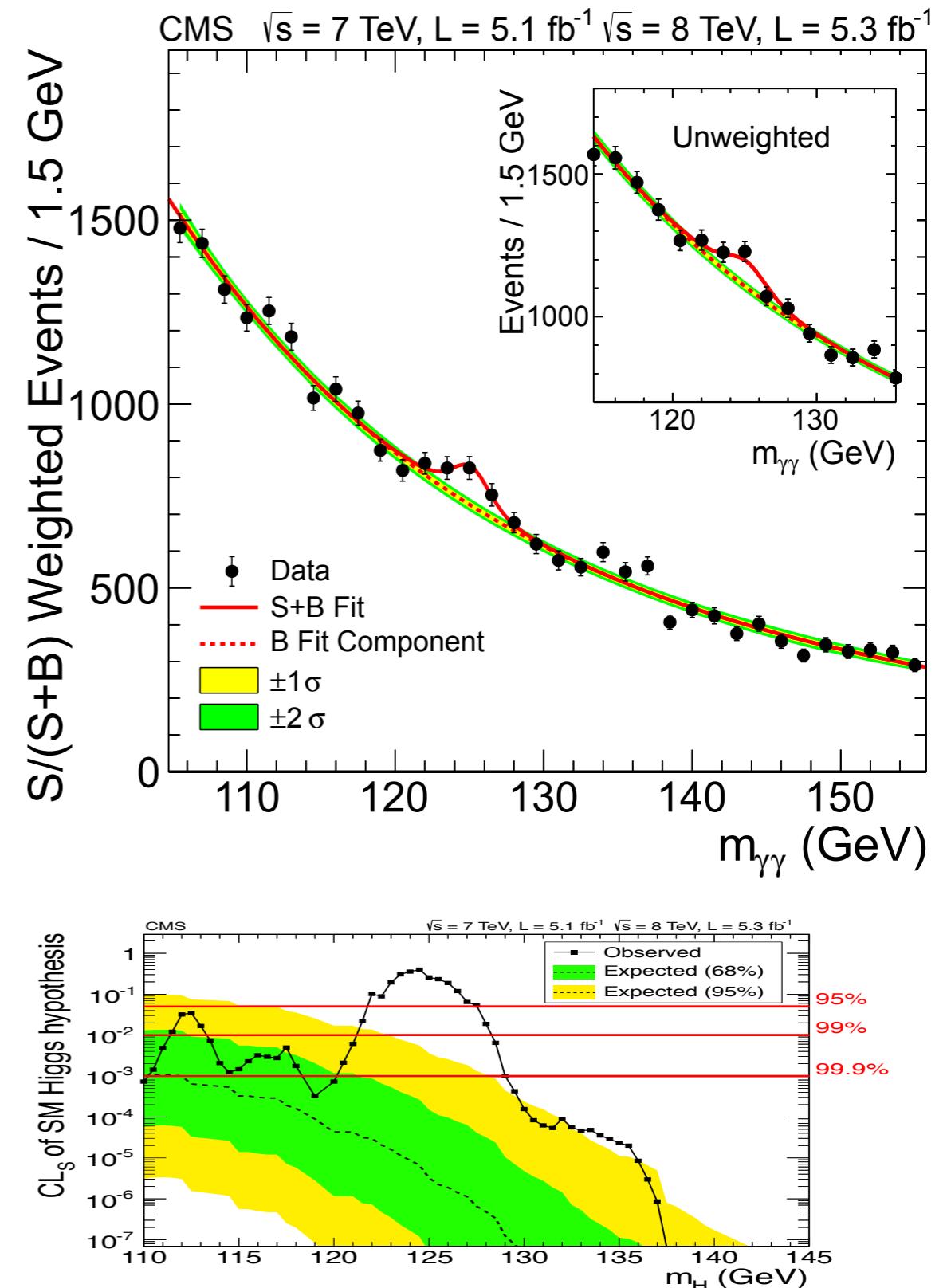
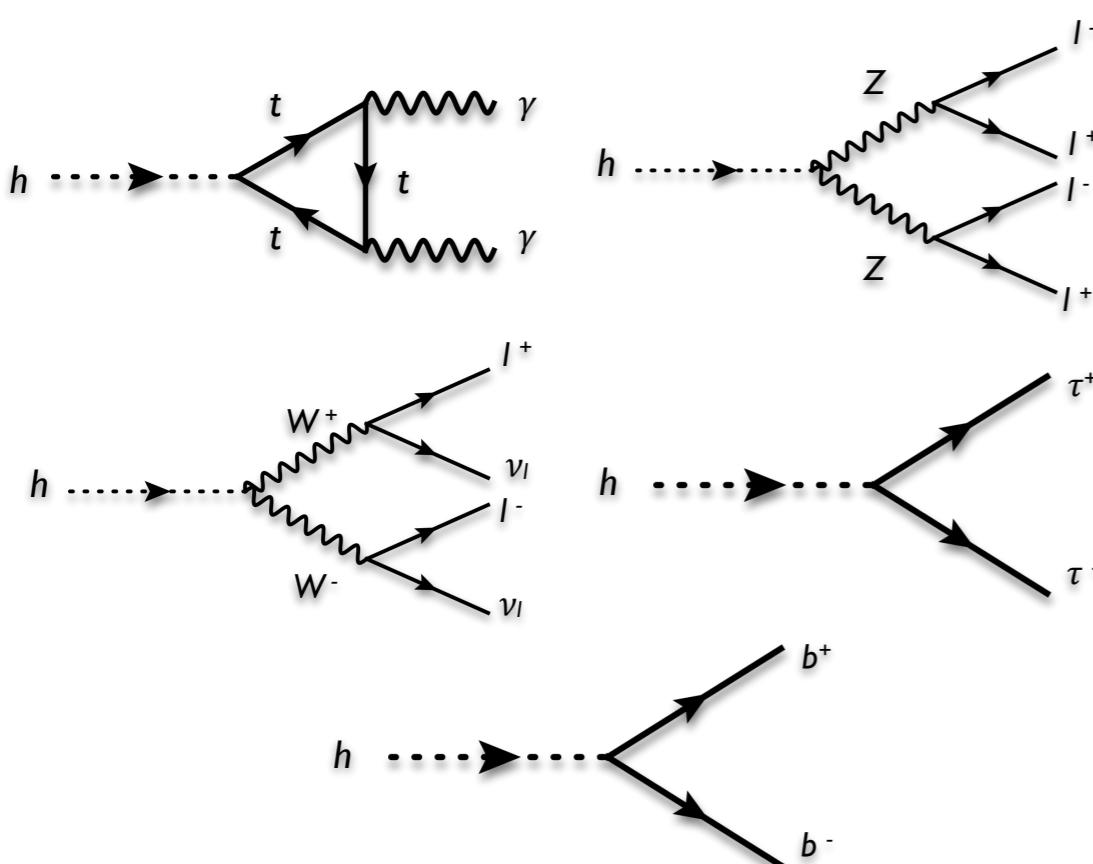
# Higgs Discovery at CMS (sine qua non)

Phys. Lett. B 716 (2012) 30-61

in five decay modes;

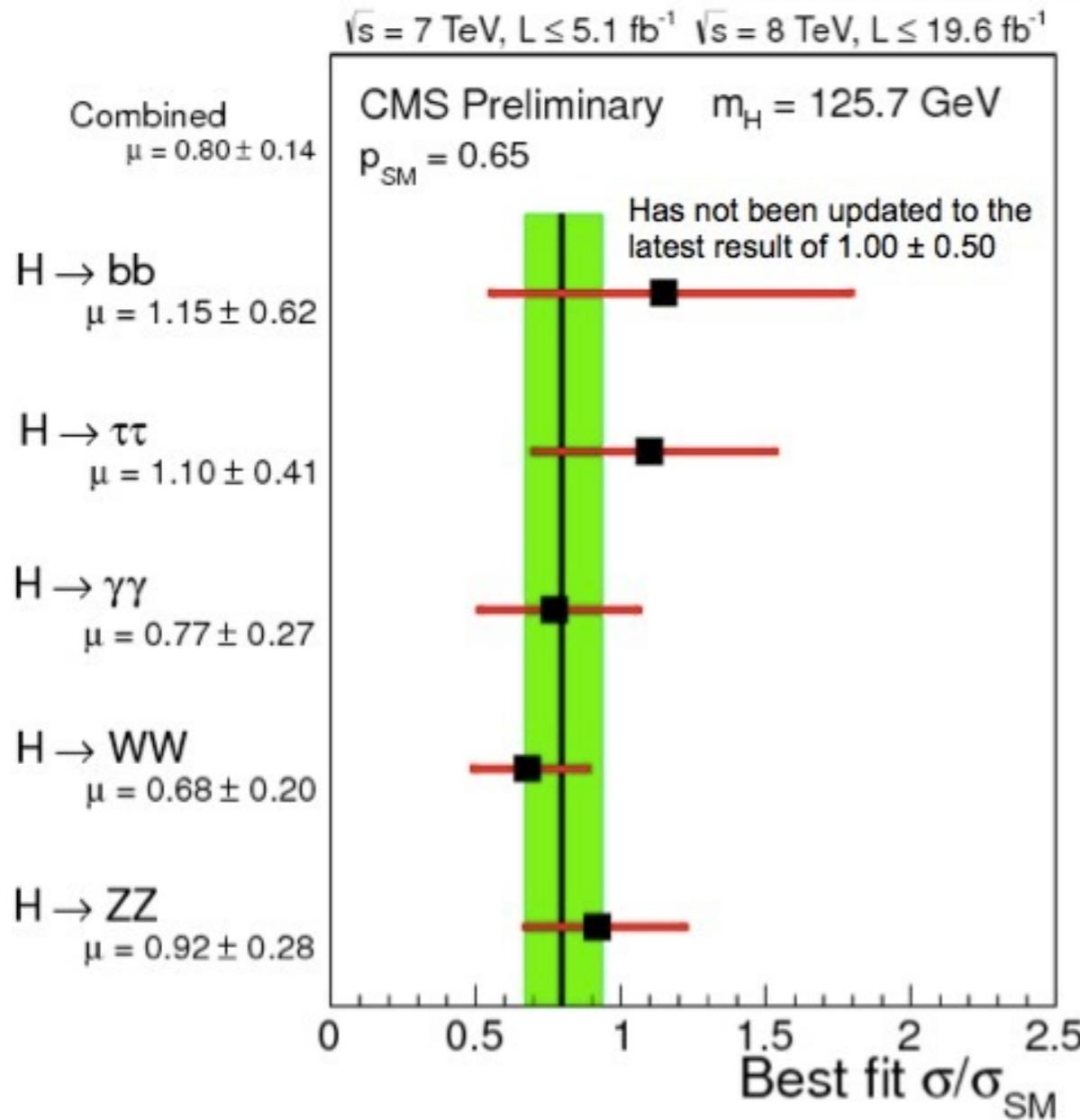
$H \rightarrow \gamma\gamma, ZZ, W^+W^-, \tau^+\tau^-, \text{ and } bb$

An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV.



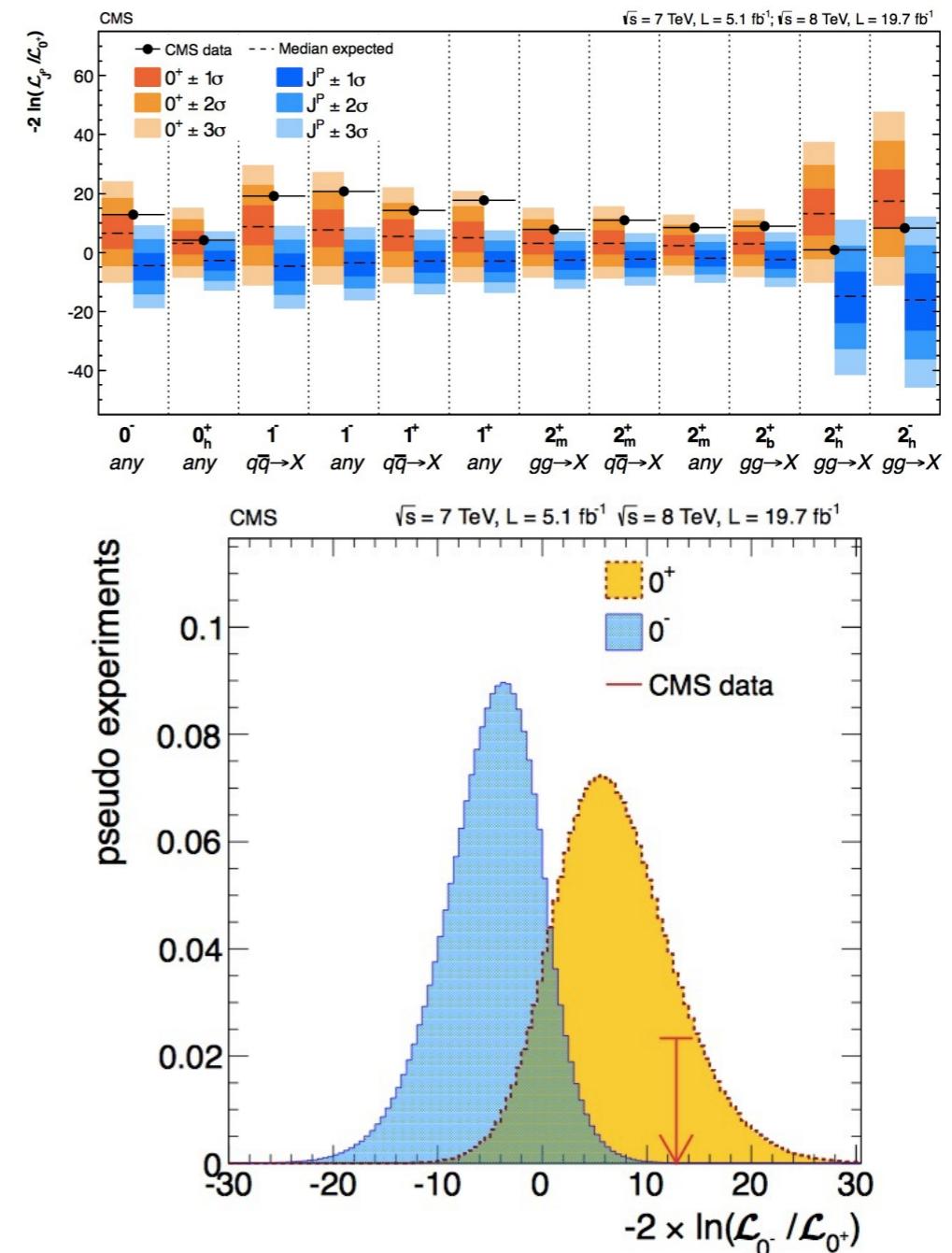
# Higgs Discovery at CMS (sine qua non)

## signal strengths

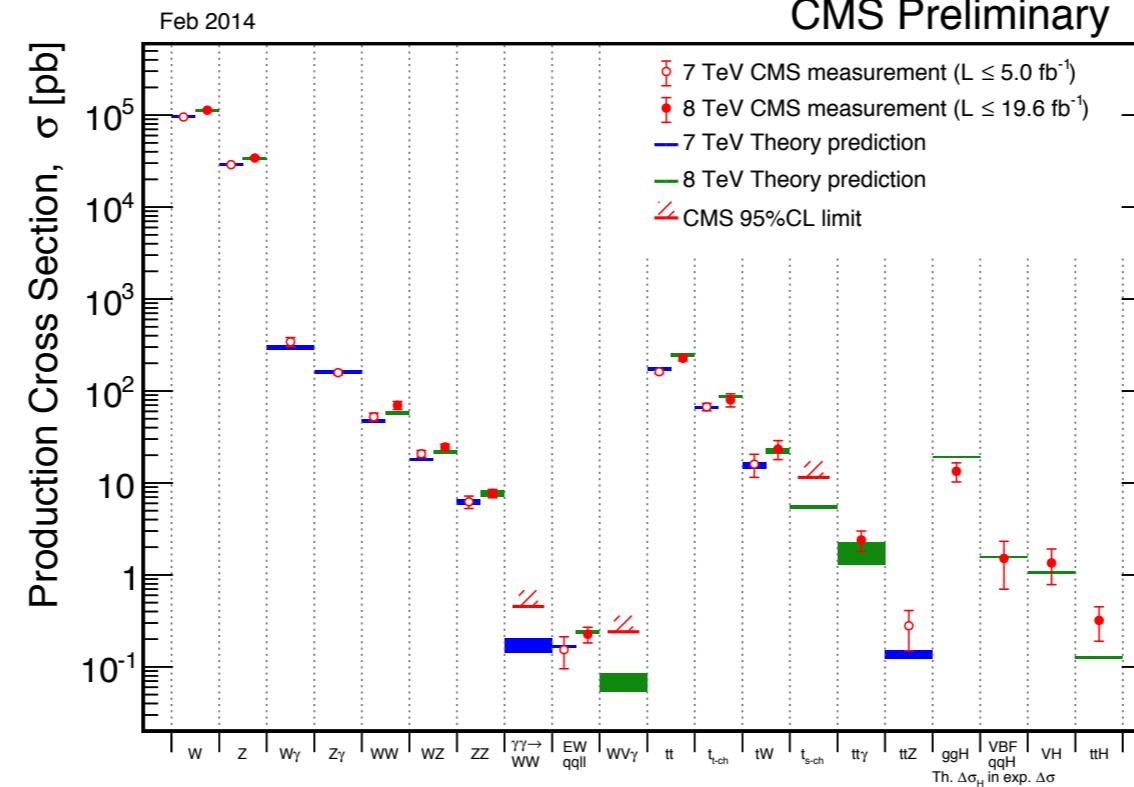
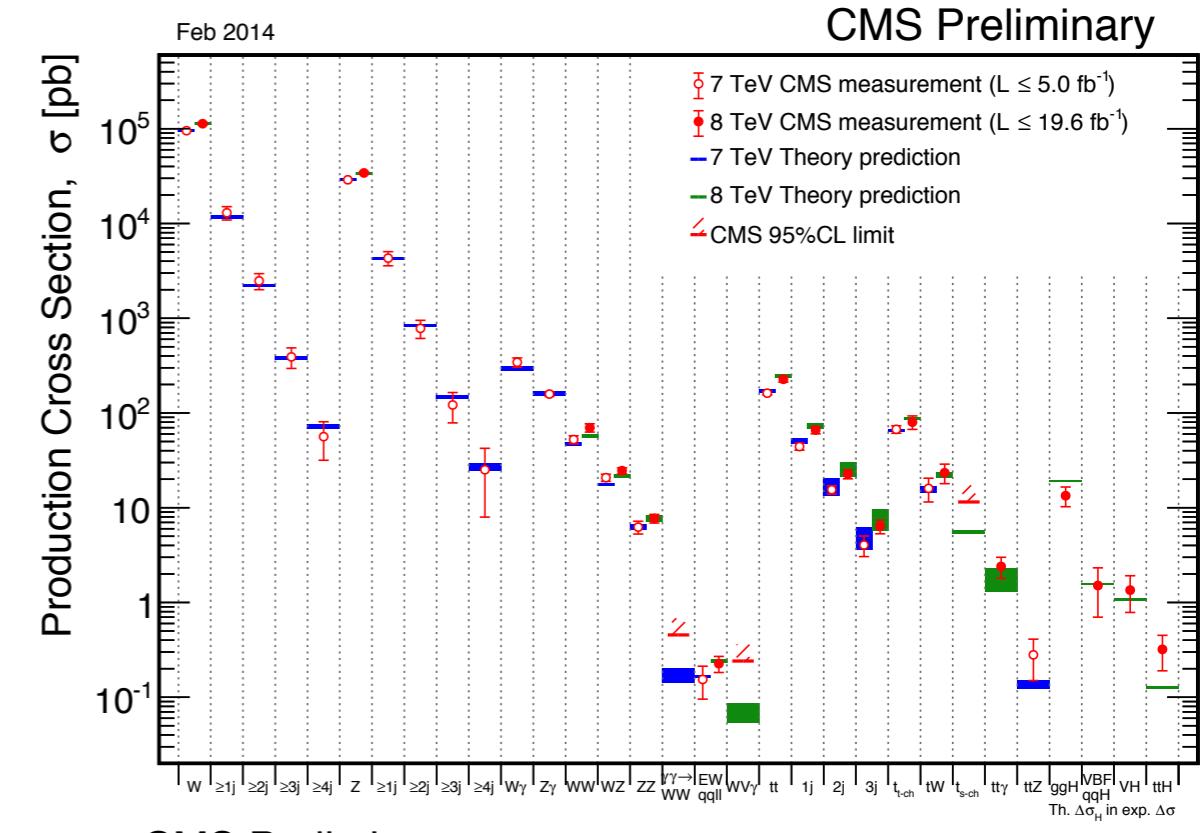
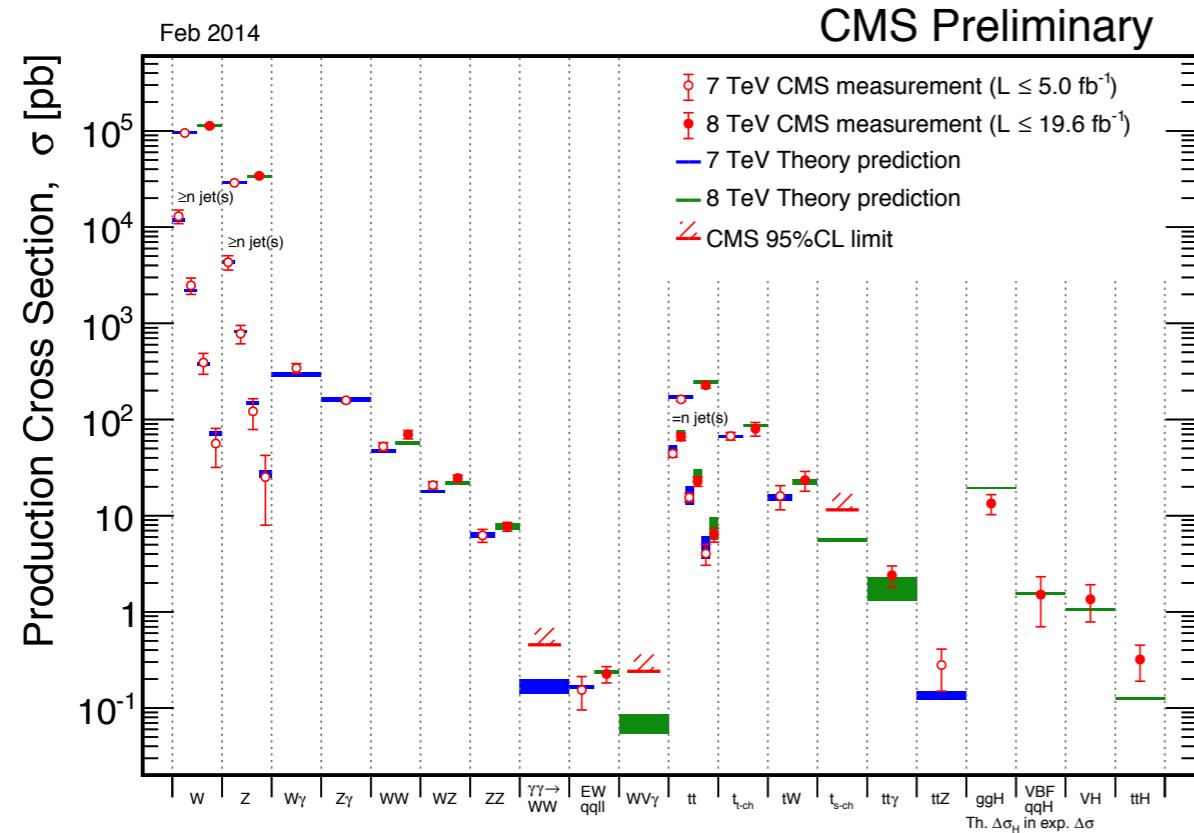


## Higgs spin and parity

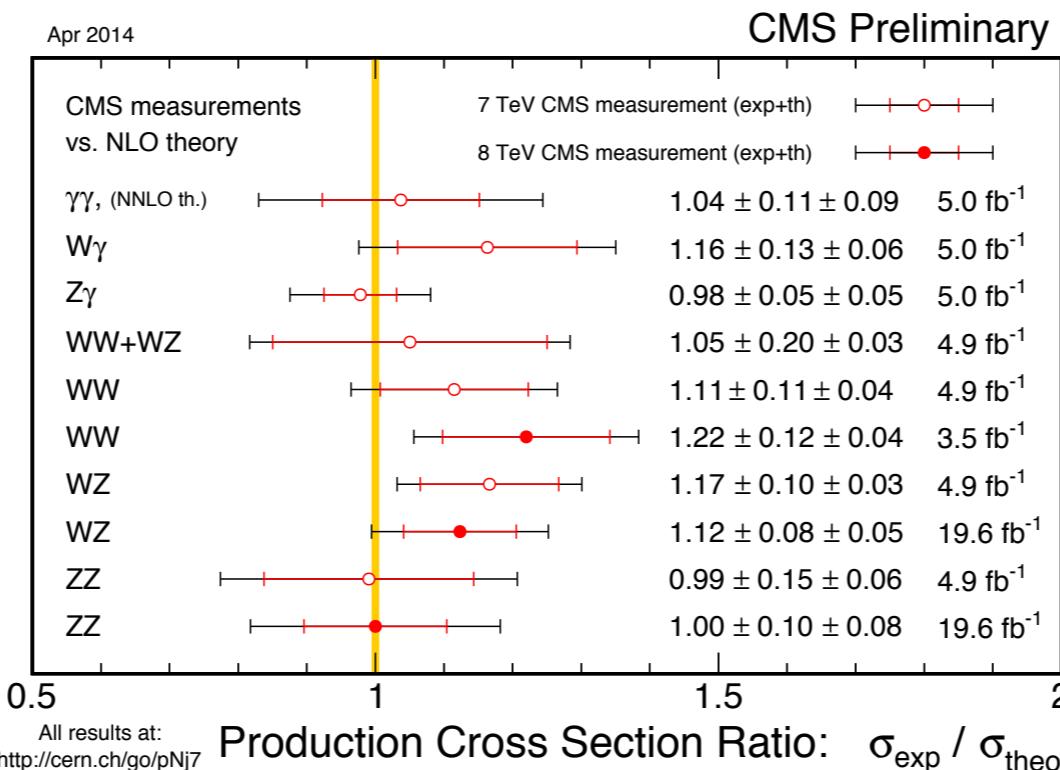
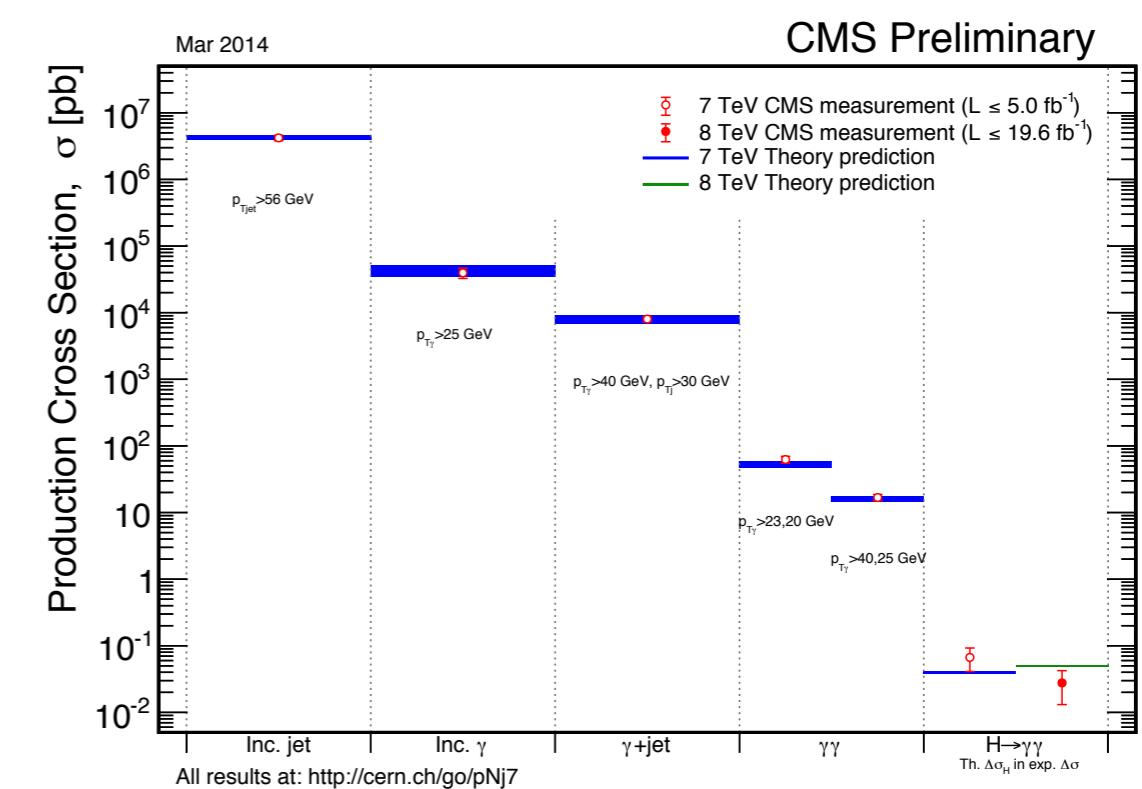
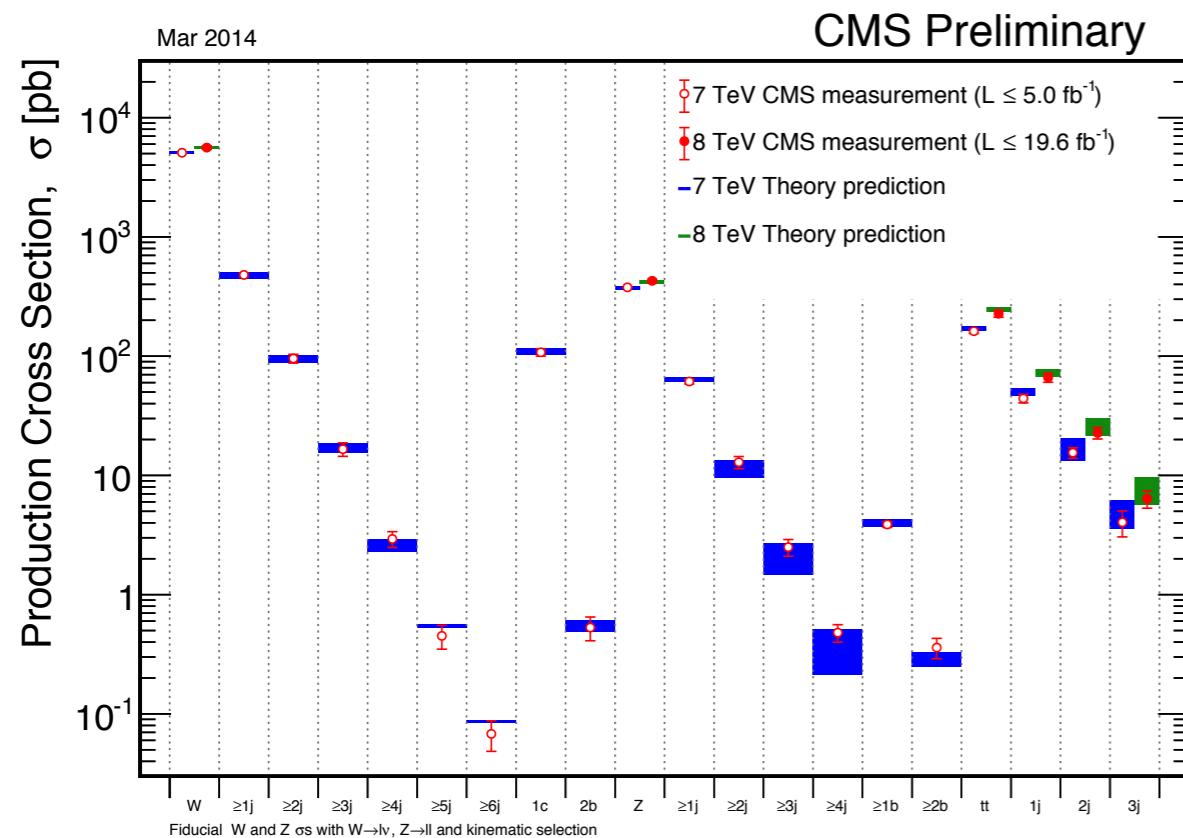
$J^{PC} = 0^{++}$  is preferred over the alternatives



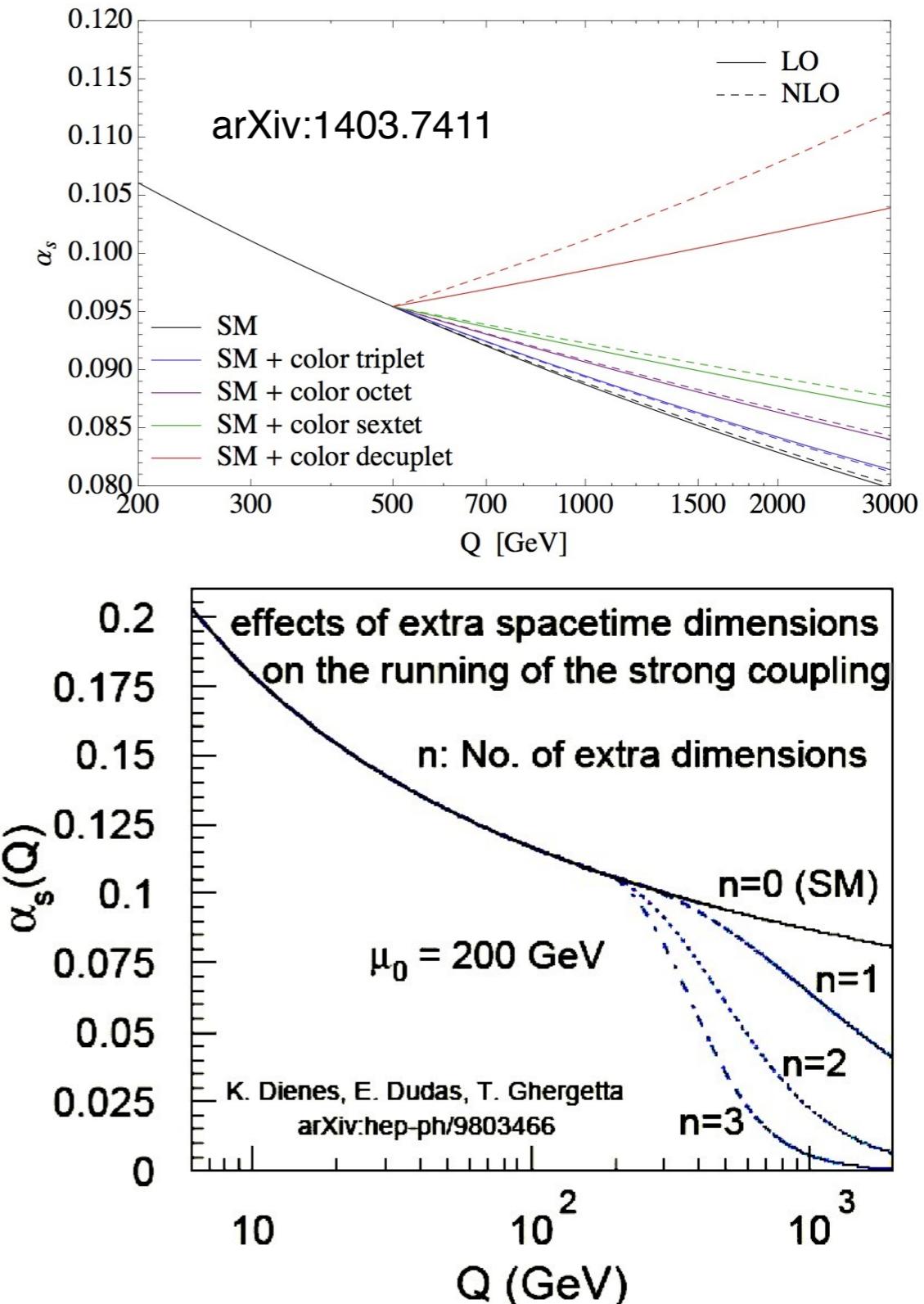
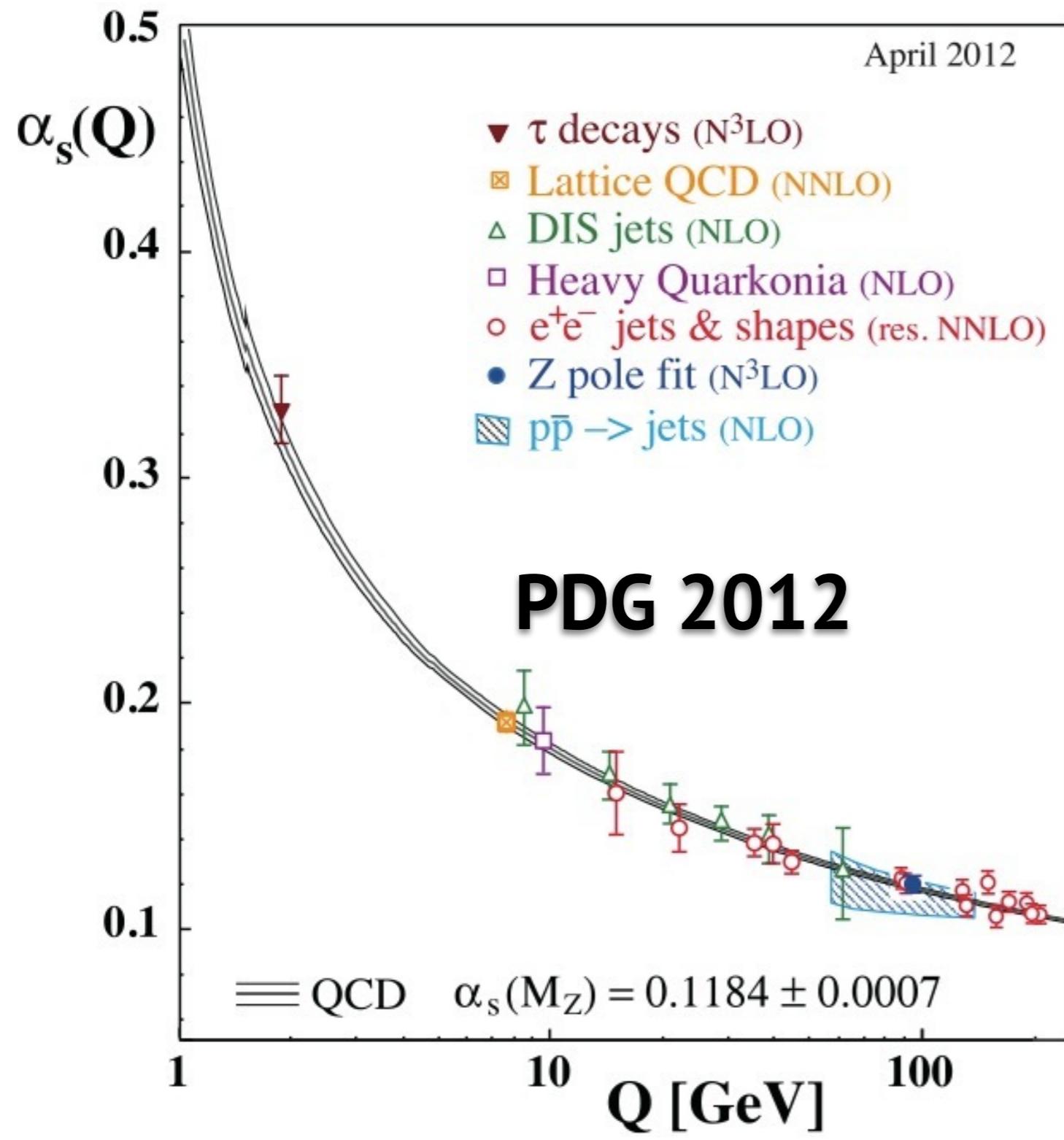
# CMS Cross Section Measurements



# CMS Cross Section Measurements

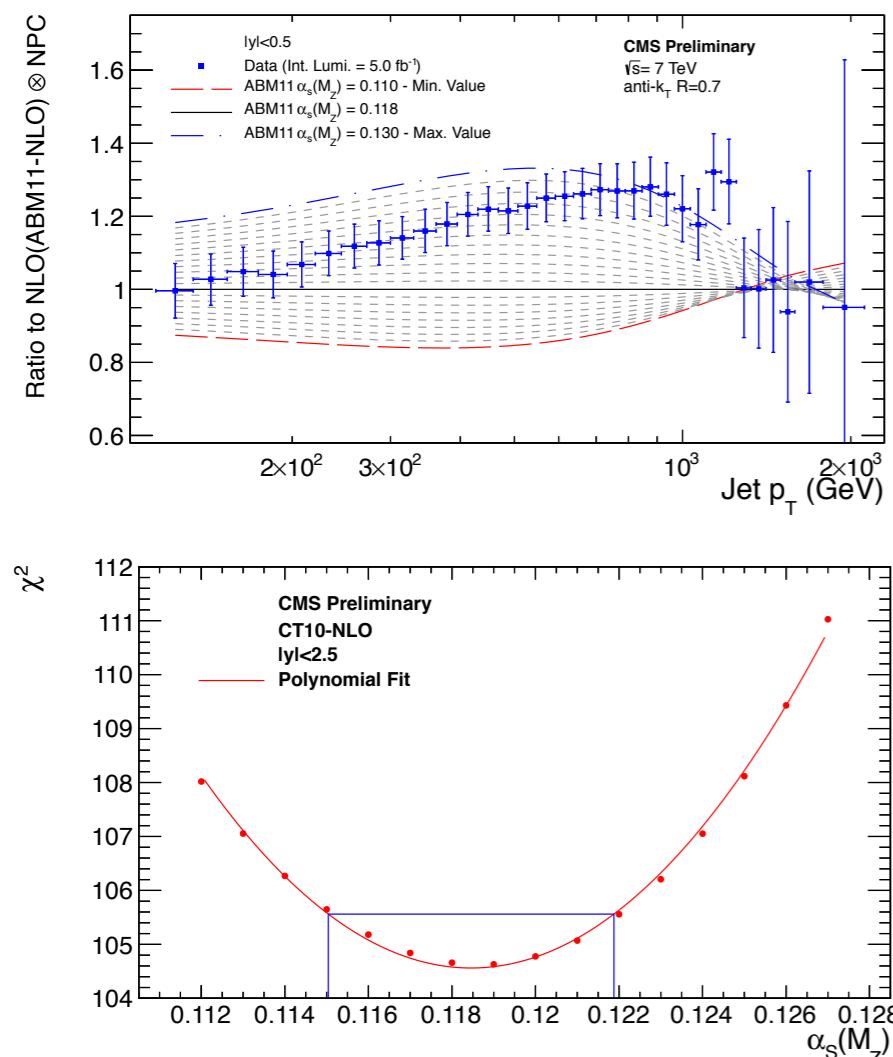


# Sensitivity of Strong Coupling



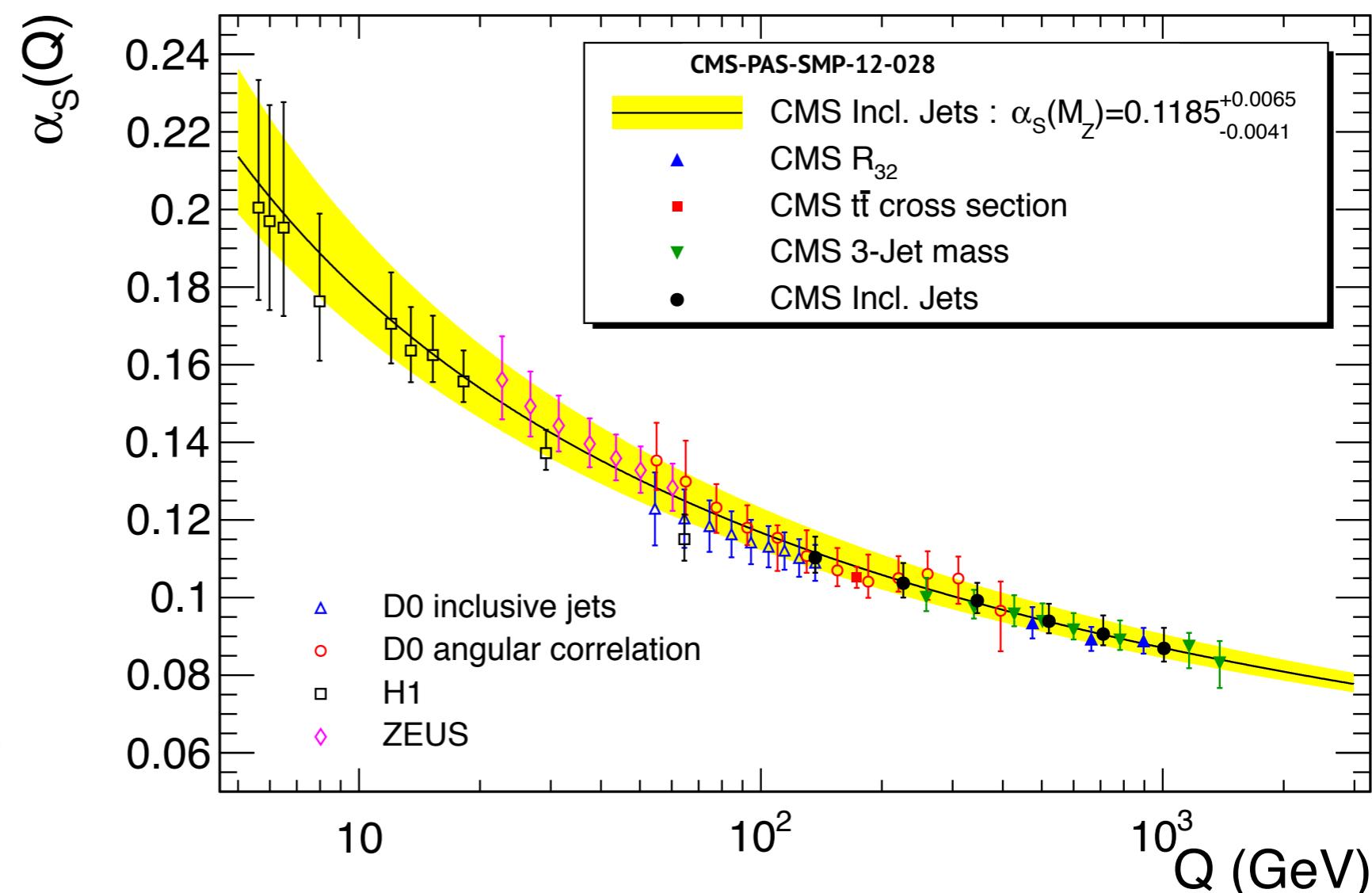
# Strong Coupling ( $\alpha_s(Q)$ ) Results

CMS-PAS-SMP-12-028



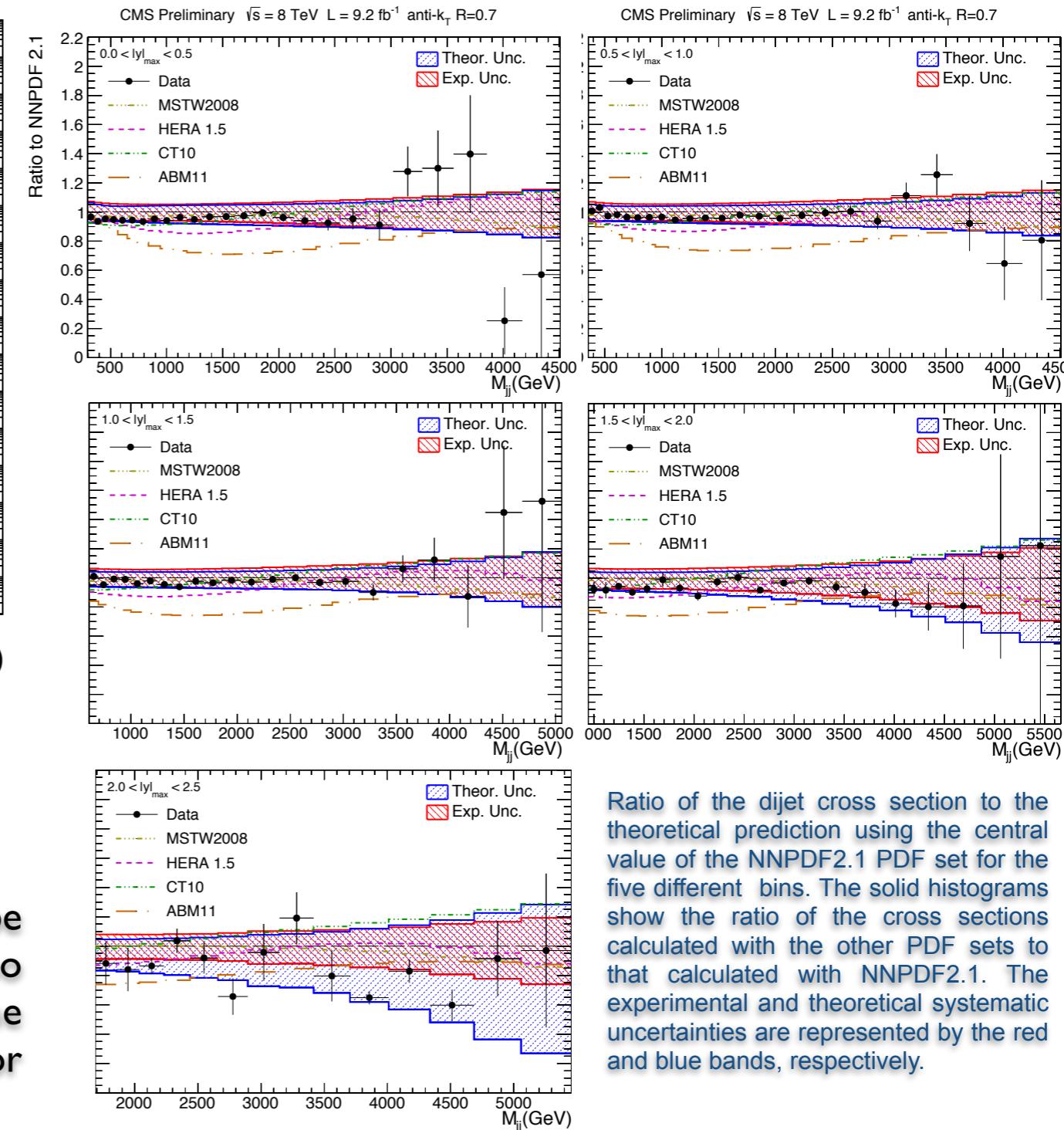
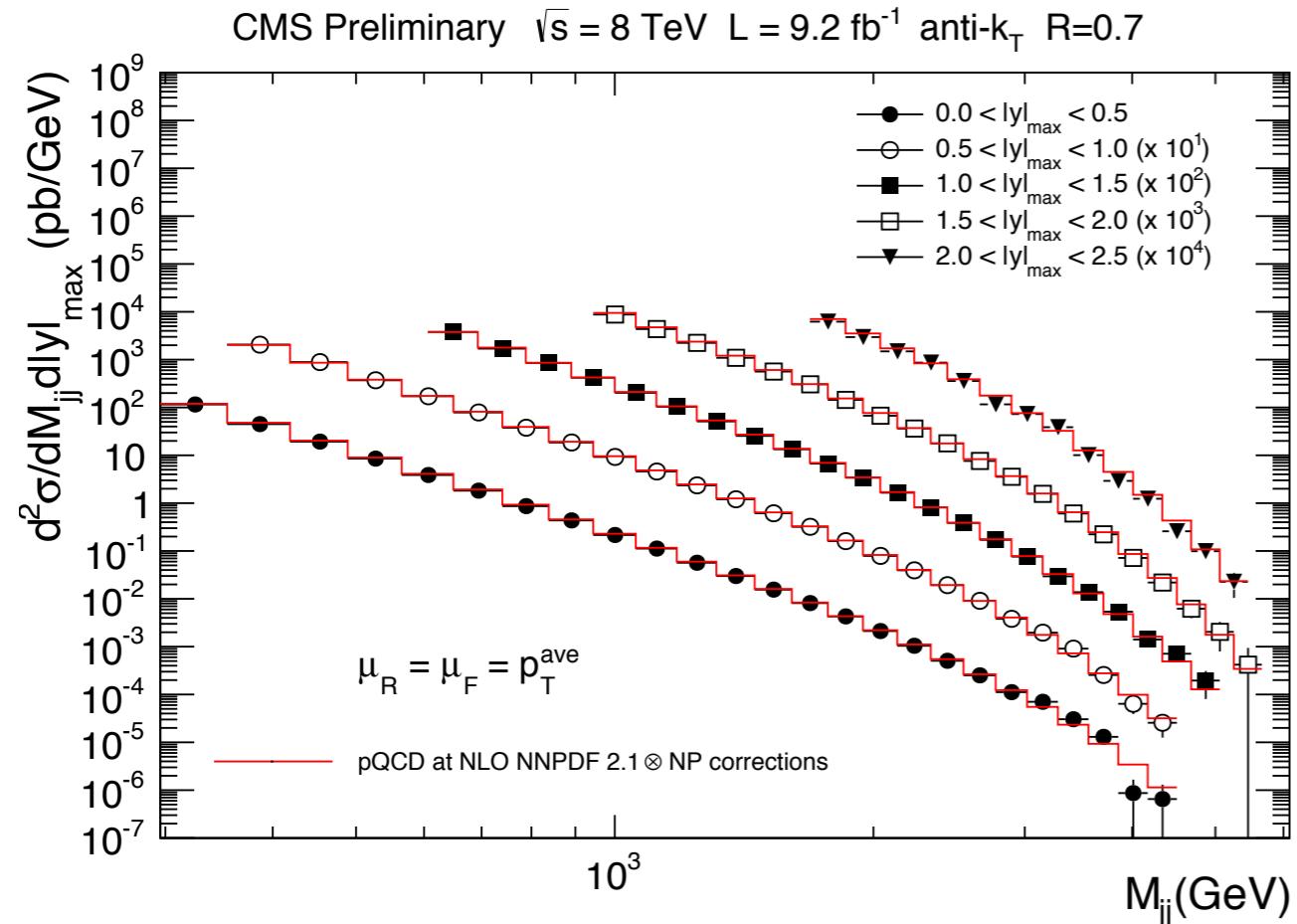
Using predictions from theory at next-to-leading order, complemented with electroweak corrections, the strong coupling constant is determined from the inclusive jet cross section to be

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\text{exp.}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0055}_{-0.0022}(\text{scale})$$



# Dijet Mass Production Cross Section at 8 TeV

CMS-PAS-SMP-14-002



The invariant mass of the two jets can be given in terms of proton momentum fractions  $x_{1,2}$

The dijet cross section as a function of  $M_{jj}^2$  can be precisely calculated in perturbative QCD and it also allows sensitive searches for physics beyond the Standard Model, such as dijet narrow resonances or contact interaction searches.

Ratio of the dijet cross section to the theoretical prediction using the central value of the NNPDF2.1 PDF set for the five different bins. The solid histograms show the ratio of the cross sections calculated with the other PDF sets to that calculated with NNPDF2.1. The experimental and theoretical systematic uncertainties are represented by the red and blue bands, respectively.

# Z boson and b jets cross section

arXiv:1402.1521v1

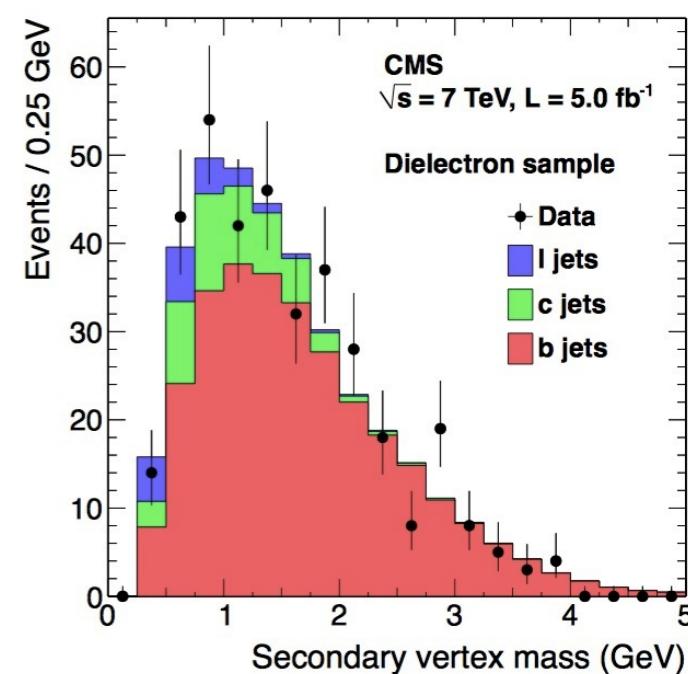
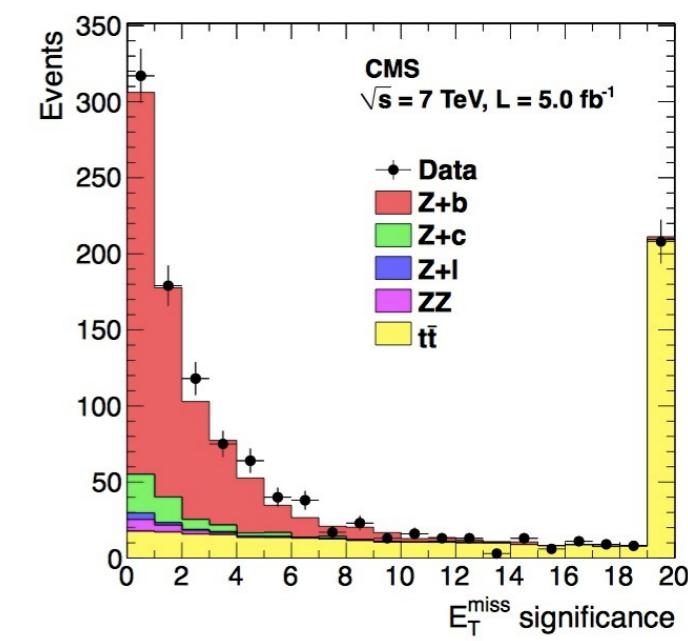
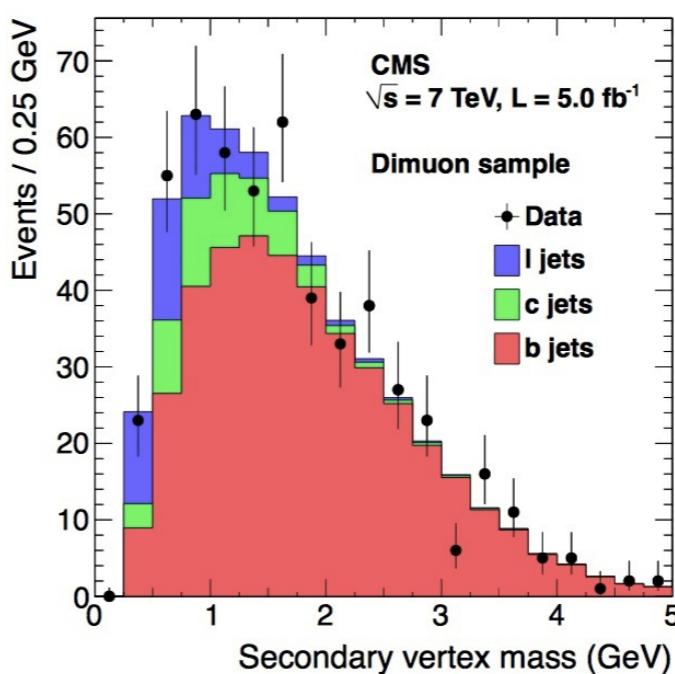
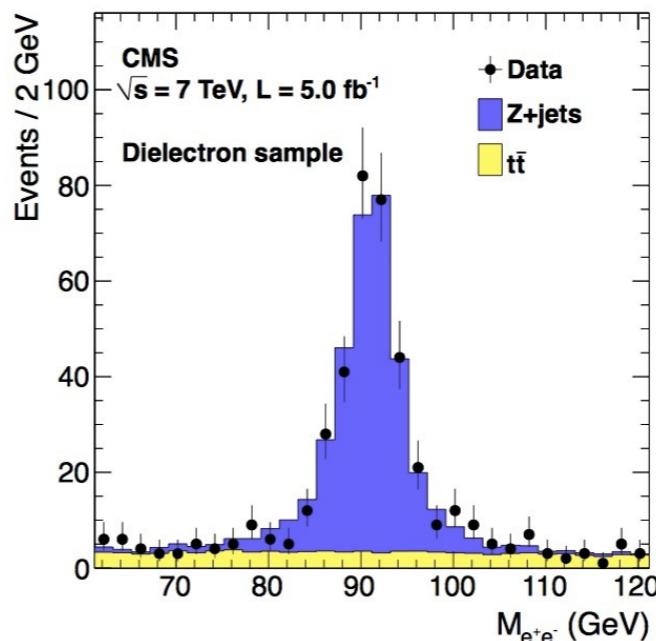
Invariant mass of the b-jet pair ( $M_{bb}$ ) , in Z+2b-jets final state, is used in the study of the Higgs boson produced in association with a Z boson and decaying into two b jets, in the Z(H)H(bb) final state.

Understanding the details of the kinematics is important in the search for undiscovered particles as well as for the study of the newly discovered Higgs boson in similar topologies.

To account for migrations between different b-jet multiplicities, a  $2 \times 2$  matrix equation is

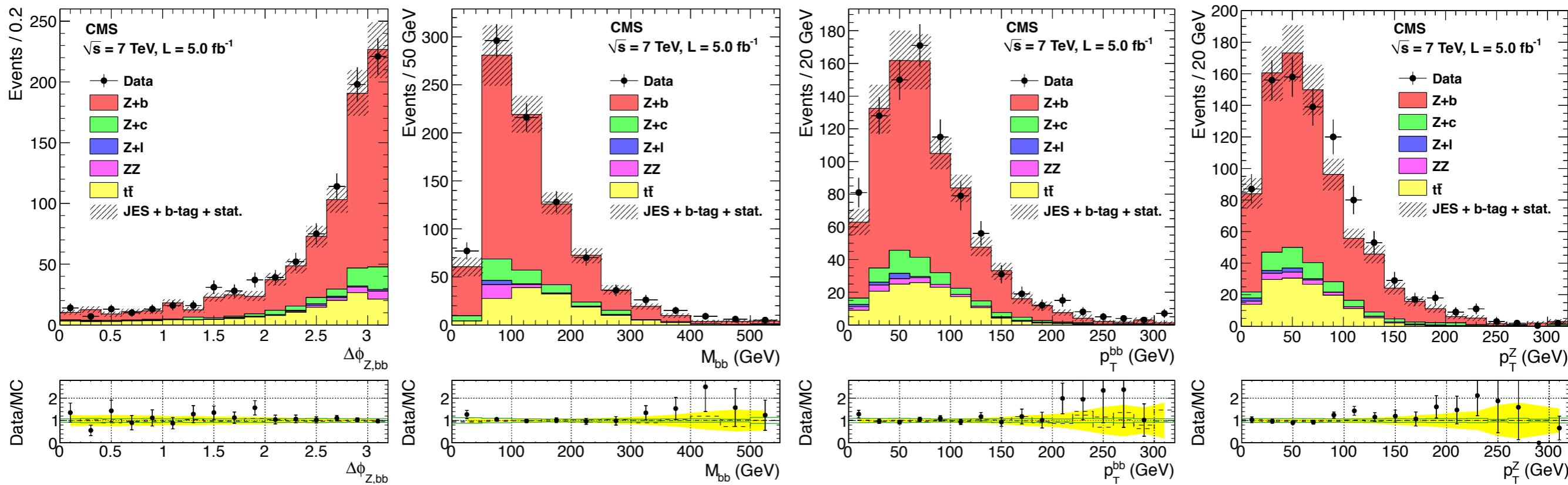
$$\begin{pmatrix} \sigma_{Z+1b} \\ \sigma_{Z+2b} \end{pmatrix} = \frac{1}{\mathcal{L}} \times \varepsilon_r^{-1} \times \varepsilon_l^{-1} \times \varepsilon_b^{-1} \times \varepsilon_m^{-1} \times \begin{pmatrix} N_{sig}^{Z+1b} \\ N_{sig}^{Z+2b} \end{pmatrix}$$

- Simple Secondary Vertex' (SSV) b-tagging
- 1% mistagging
- 55% b-tag efficiency



# Z boson and b jets cross section

arXiv:1402.1521v1



**Measured cross sections and expectations from MADGRAPH, MCFM and aMC@NLO:**

Cross section	Measured	MADGRAPH (5F)	aMC@NLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMC@NLO (4F)
$\sigma_{Z+1b}$ (pb)	$3.52 \pm 0.02 \pm 0.20$	$3.66 \pm 0.22$	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
$\sigma_{Z+2b}$ (pb)	$0.36 \pm 0.01 \pm 0.07$	$0.37 \pm 0.07$	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
$\sigma_{Z+b}$ (pb)	$3.88 \pm 0.02 \pm 0.22$	$4.03 \pm 0.24$	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b}/Z+j$ (%)	$5.15 \pm 0.03 \pm 0.25$	$5.35 \pm 0.11$	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

# $\gamma + \text{jets}$ differential cross section

arXiv:1311.6141v1

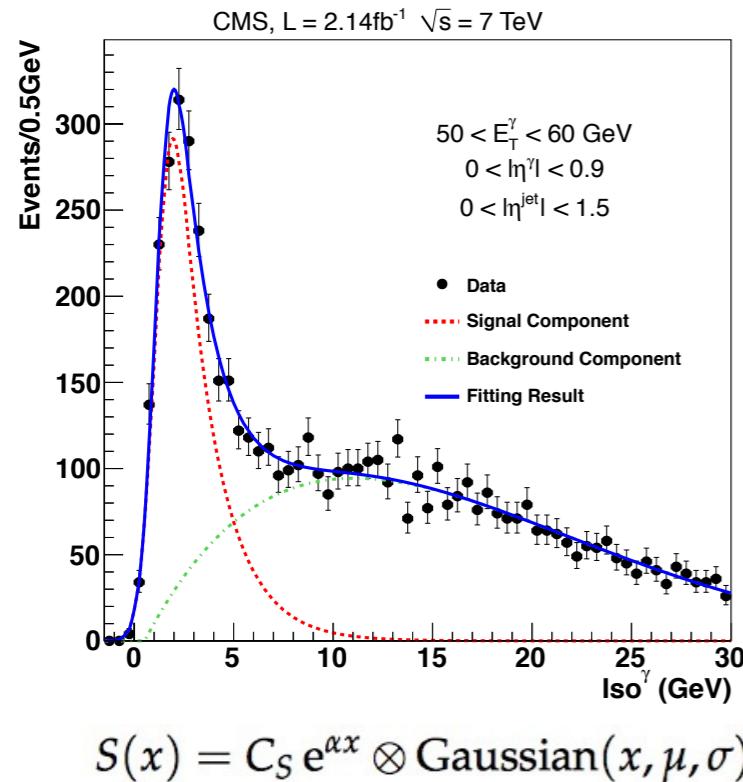
## a direct probe of quantum chromodynamics (QCD)

Measurement of the triple differential cross section,

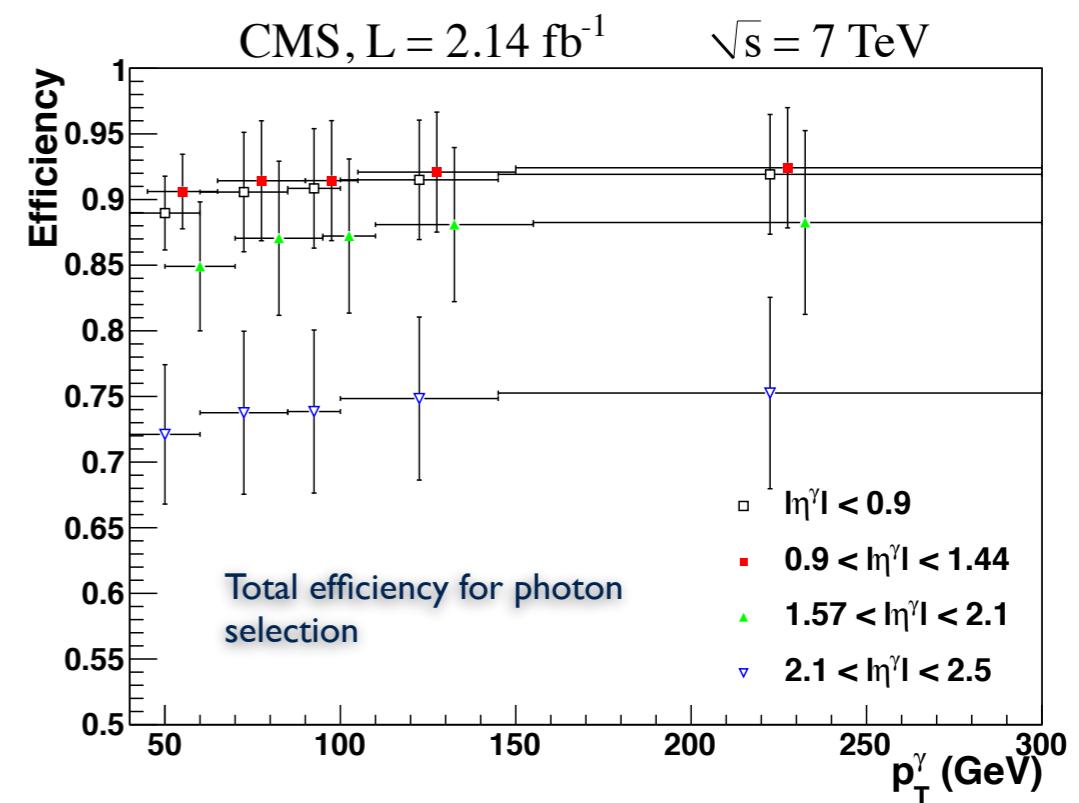
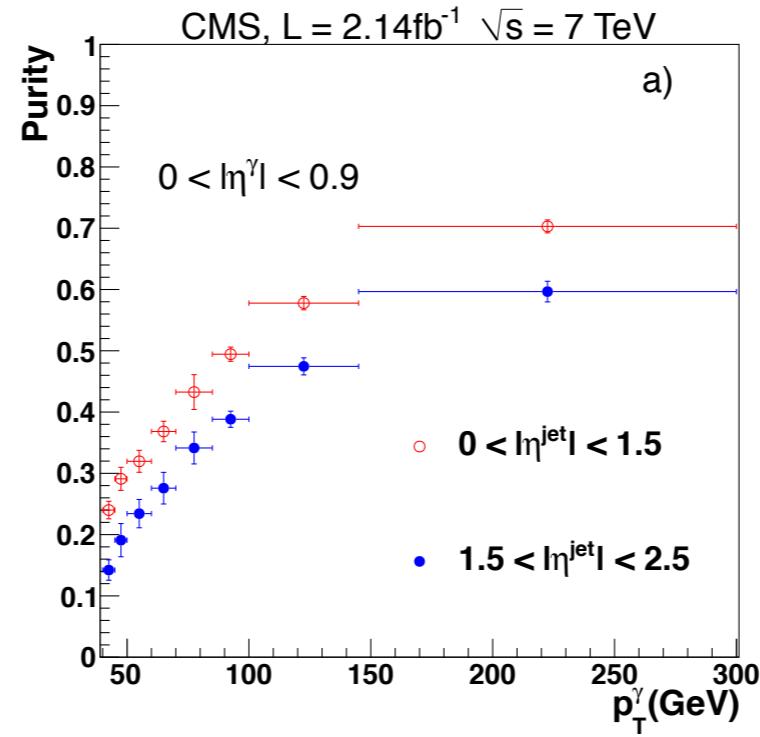
$$\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{\text{jets}}}$$

in photon+jets final states using a data sample from proton-proton collisions at 7 TeV is presented. This sample corresponds to an integrated luminosity of  $2.14 \text{ fb}^{-1}$  collected by the CMS detector at the LHC

Template fitting method for purity calculation



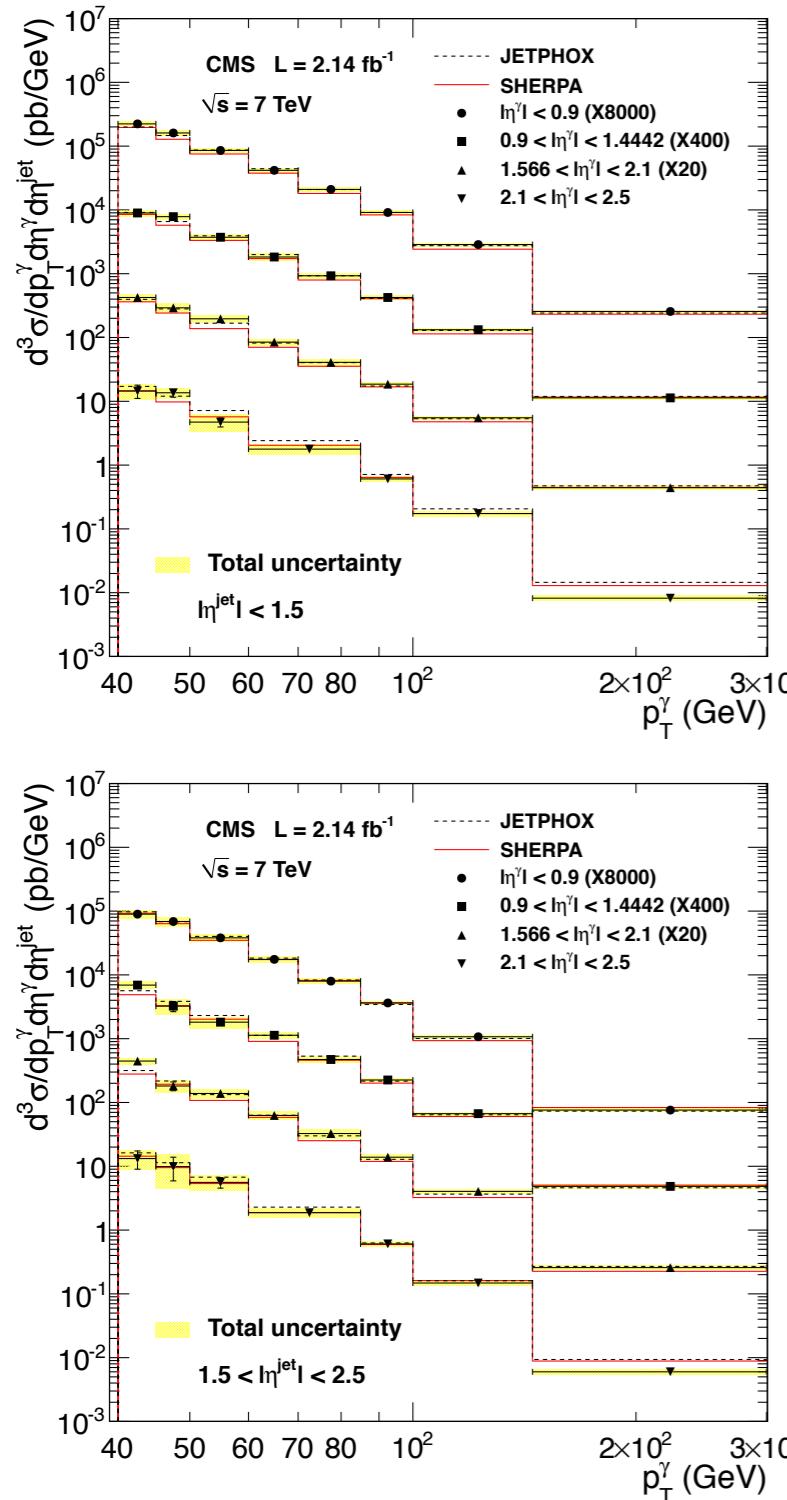
Purity Results



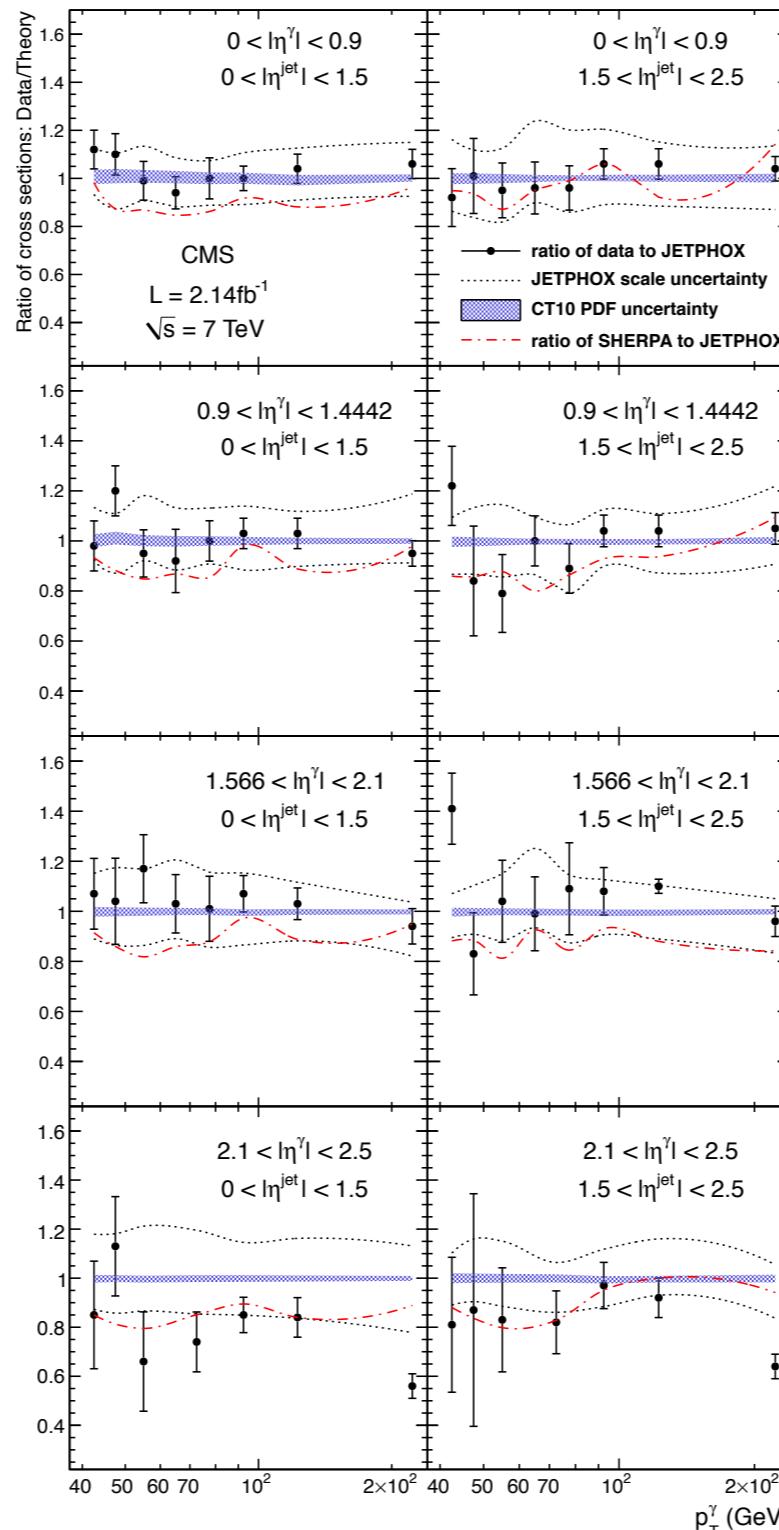
# $\gamma + \text{jets}$ differential cross section

arXiv:1311.6141v1

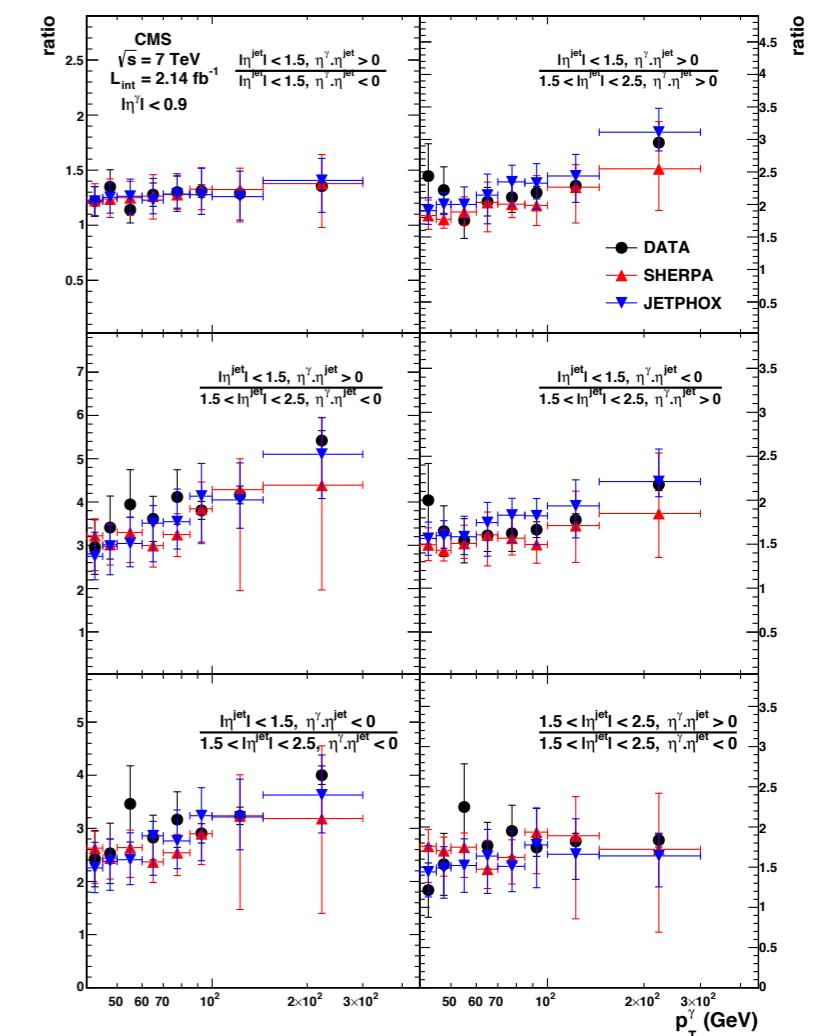
Cross section



The ratios of the measured triple-differential cross section to the NLO prediction



Ratios of the measured triple-differential cross section between various photon and jet orientations



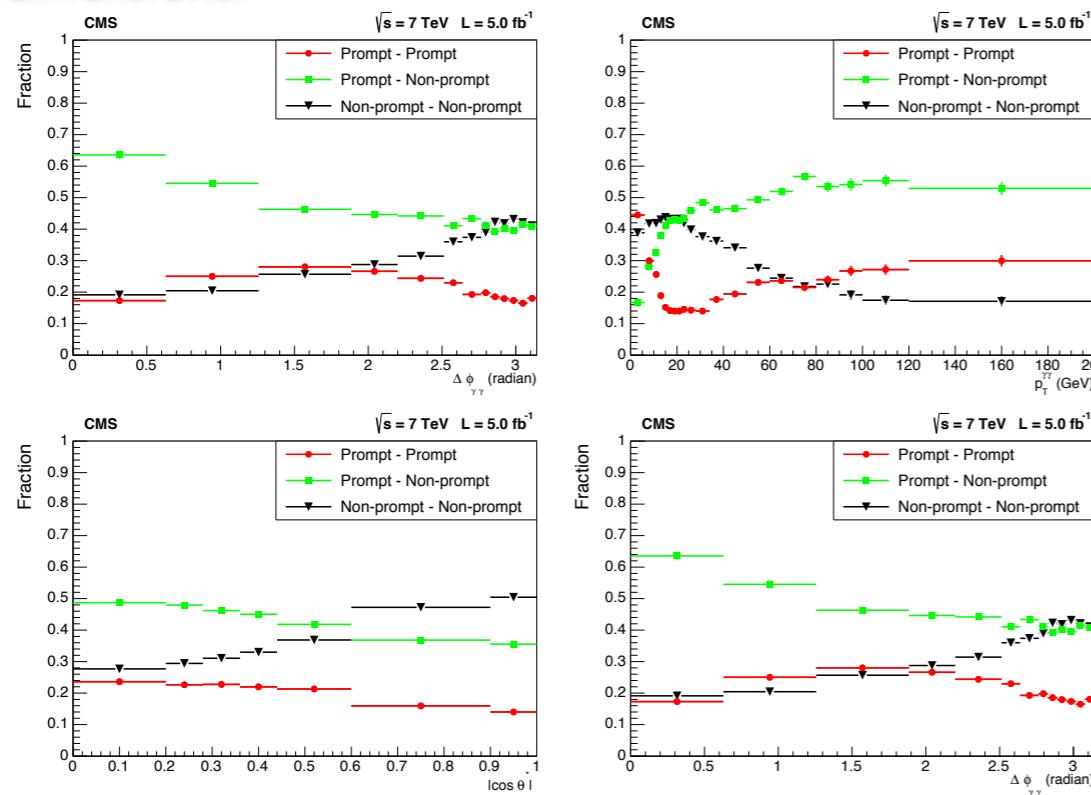
The measurements are compared to theoretical predictions from the SHERPA leading-order QCD Monte Carlo event generator and the next-to-leading-order perturbative QCD calculation from JETPHOX.

The predictions are found to be consistent with the data over most of the examined kinematic region.

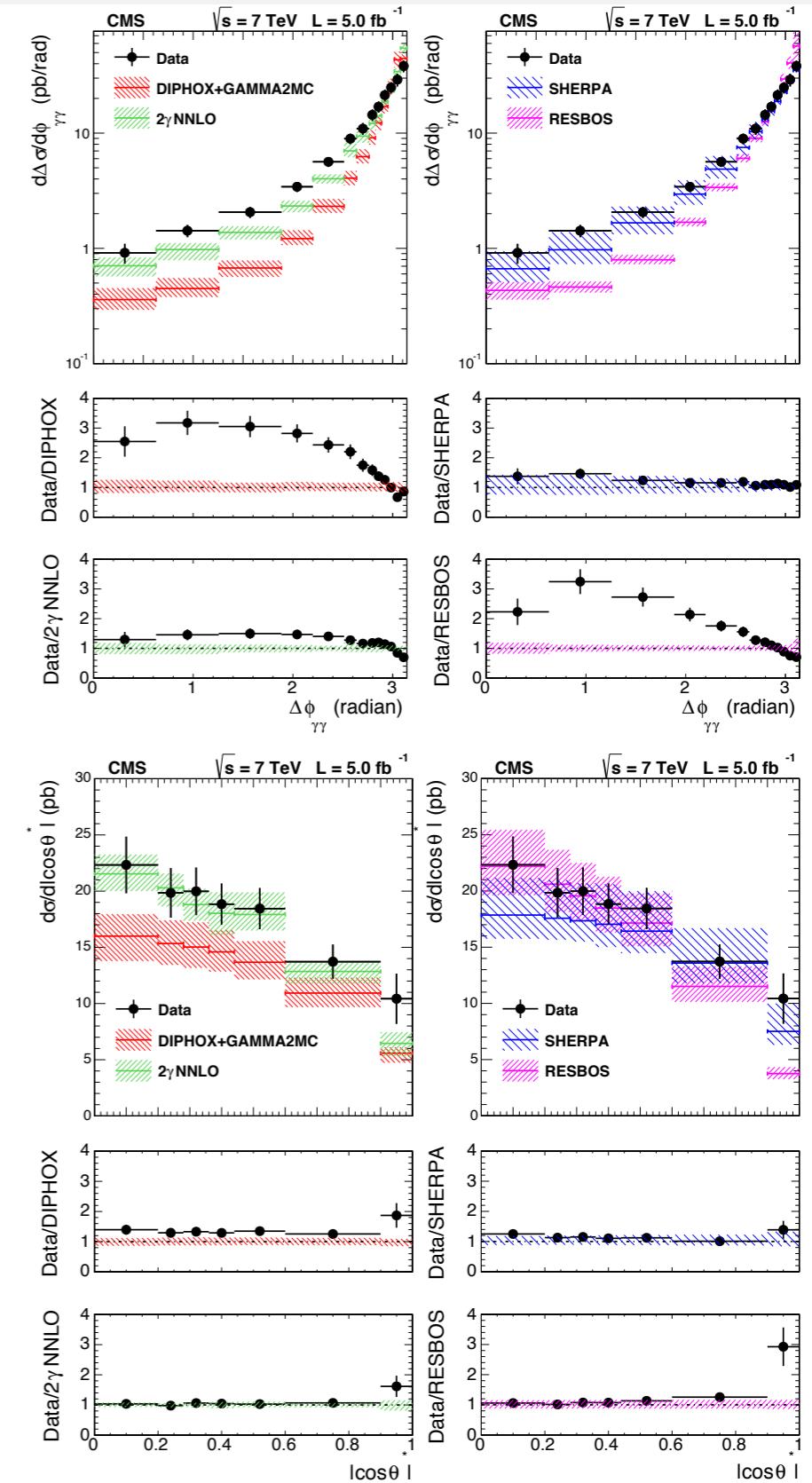
# $\gamma+\gamma$ differential cross section

arXiv:1405.7225v1

- Constitutes the major source of background in the diphoton decay channel of the newly discovered Higgs boson
- As well as to searches for physics beyond the standard model. New physics processes may also appear as non-resonant deviations in the spectrum (events with large MET, as in gauge-mediated SUSY breaking or in models of universal extra dimensions).
- Alternatively, some models predict narrow resonances, such as the graviton in the Randall–Sundrum model for warped extra dimensions.

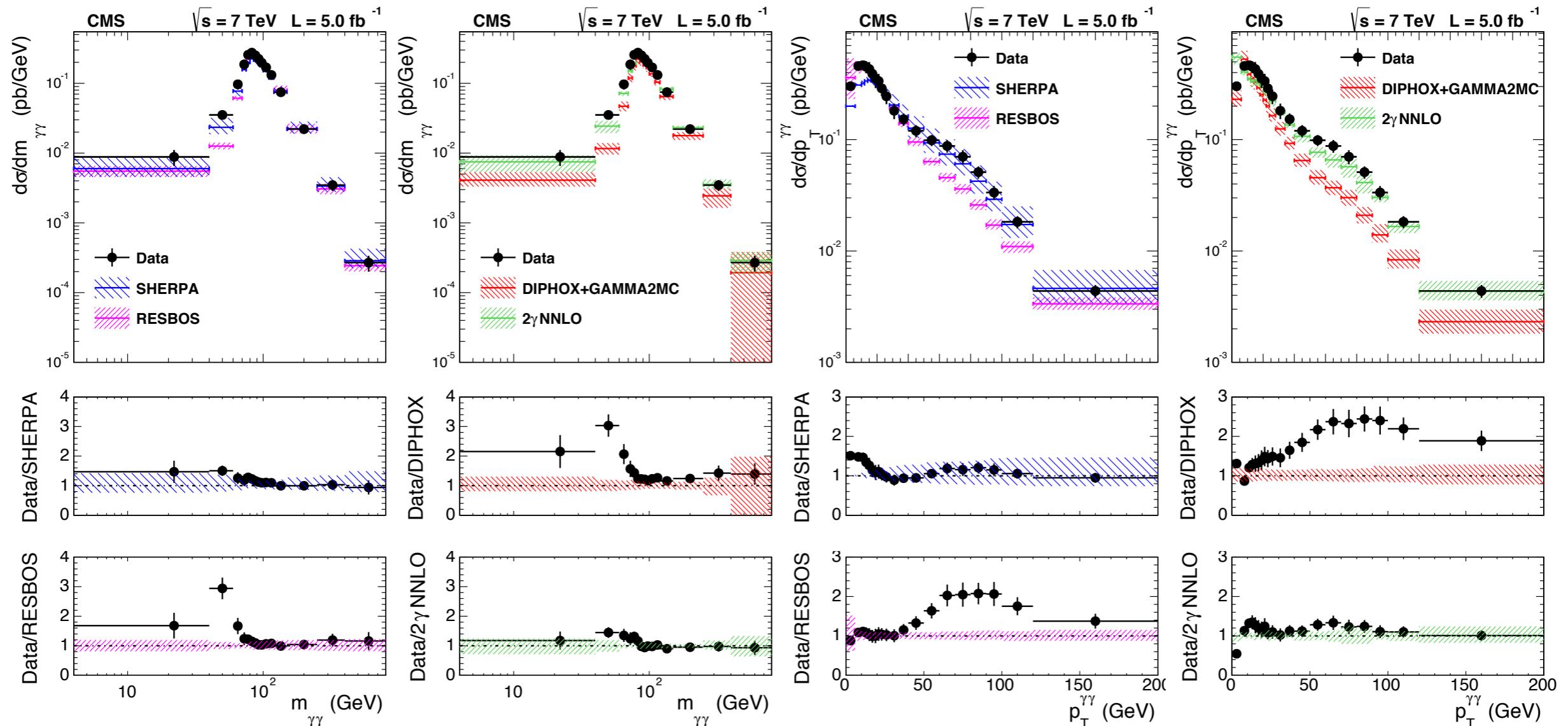


Fractions of prompt-prompt, prompt-non-prompt and non-prompt-non-prompt components as a function of the differential variables in the whole acceptance of the analysis. Uncertainties are statistical only.



# $\gamma + \gamma$ differential cross section

arXiv:1405.7225v1



The total cross section measured in data for the phase space defined above is:  
 $\sigma = 17.2 \pm 0.2 \text{ (stat.)} \pm 1.9 \text{ (syst.)} \pm 0.4 \text{ (lum.)} \text{ pb}$ ,  
compared with

$\sigma_{\text{NNLO}}(2\gamma\text{NNLO}) = 16.2(+1.5)(-1.3) \text{ (scale) pb}$   
 $(\text{DIPHOX} + \text{GAMMA2MC}) = 12.8(+1.6)(-1.5) \text{ (scale)}(+0.6)(-0.8) \text{ (pdf+}\alpha_s\text{) pb}$ ,  
 $\sigma_{\text{NLO}}(\text{RESBOS}) = 14.9(+2.2)(-1.7) \text{ (scale)} \pm 0.6 \text{ (pdf+}\alpha_S\text{) pb}$ ,  
 $\sigma_{\text{LO}}(\text{SHERPA}) = 15.2(+3.2)(-1.9) \text{ (scale) pb}$ .

# VZ production cross section in VZ → Vbb-bar decay channel

arXiv:1403.3047v1

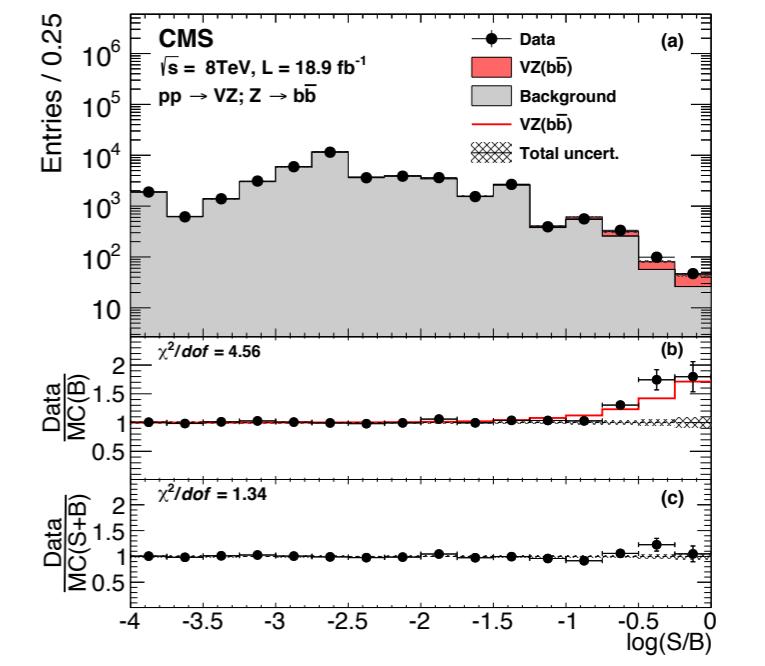
In pp collisions at  $\sqrt{s} = 8$  TeV, the predicted cross sections are  $\sigma(pp \rightarrow WZ) = 22.3 \pm 1.1$  pb and  $\sigma(pp \rightarrow ZZ) = 7.7 \pm 0.4$  pb at next-to-leading order (NLO) in quantum chromodynamics (QCD)

One Z boson decays to b-tagged jets. The other gauge boson, either W or Z detected through its leptonic decay (either  $W \rightarrow e\nu$ ,  $\mu\nu$  or  $Z \rightarrow e^+e^-$ ,  $\mu^+\mu^-$ , or  $\nu\nu$ )

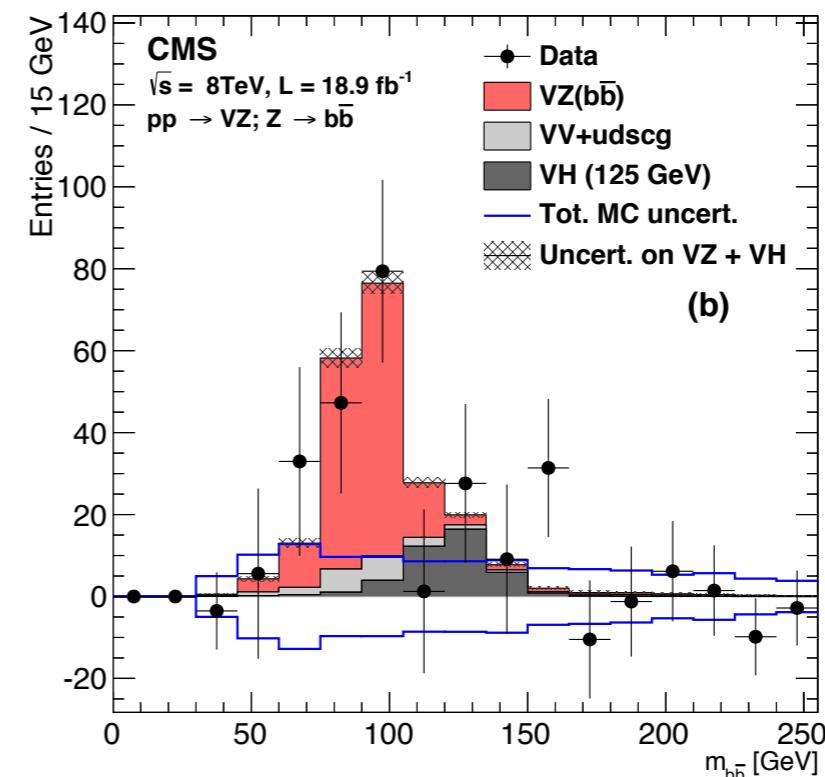
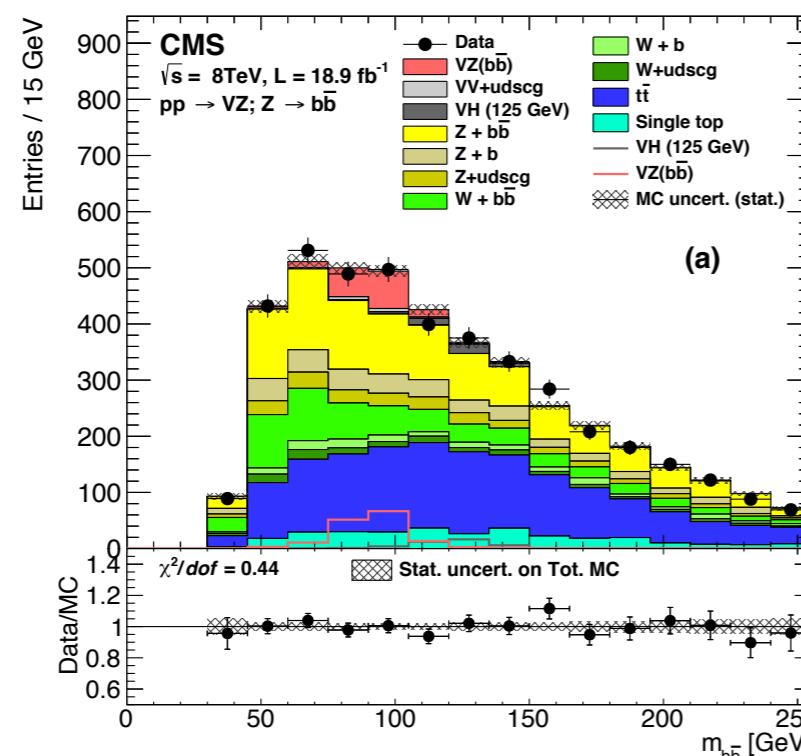
Measurement of the triple differential cross section,

$$\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{jets}}$$

in photon+jets final states using a data sample from proton proton collisions at TeV is presented. This sample corresponds to an integrated luminosity of 2.14 collected by the CMS detector at the LHC

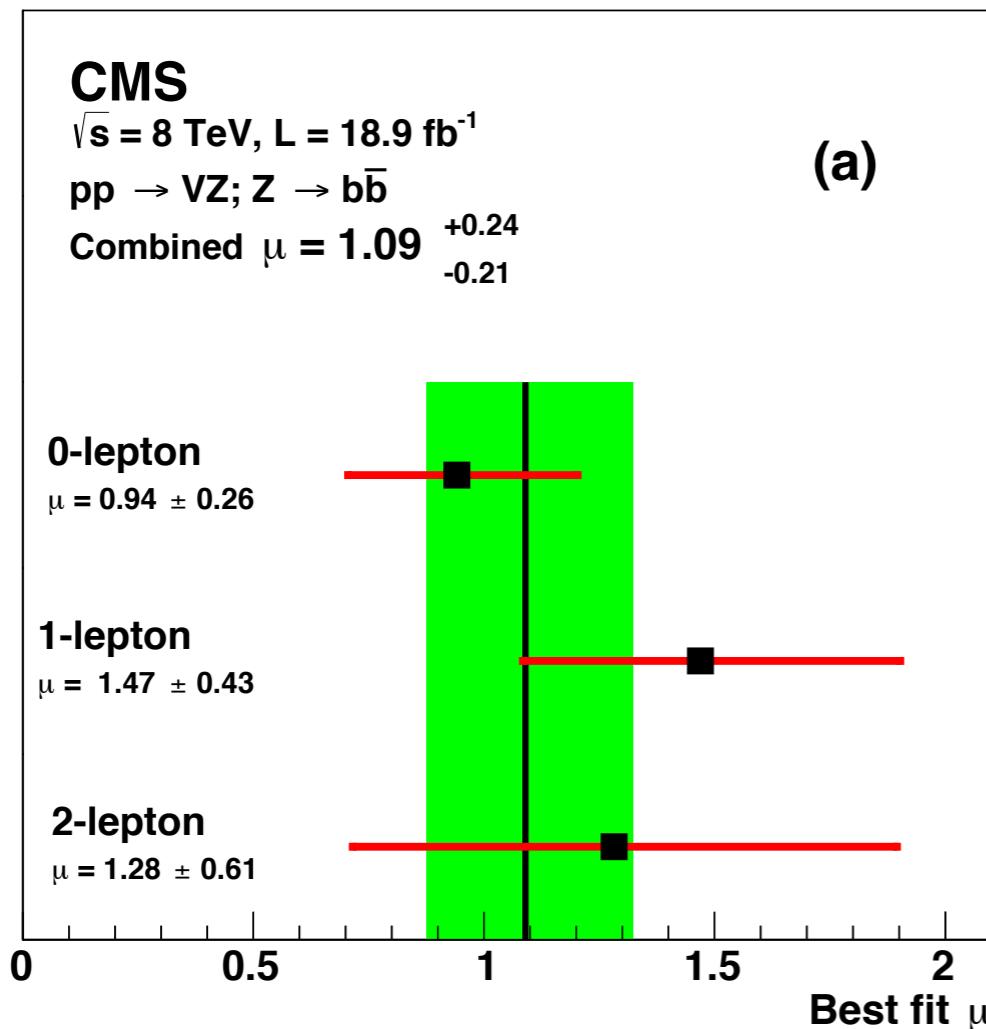


Combination of all channels into a single distribution.

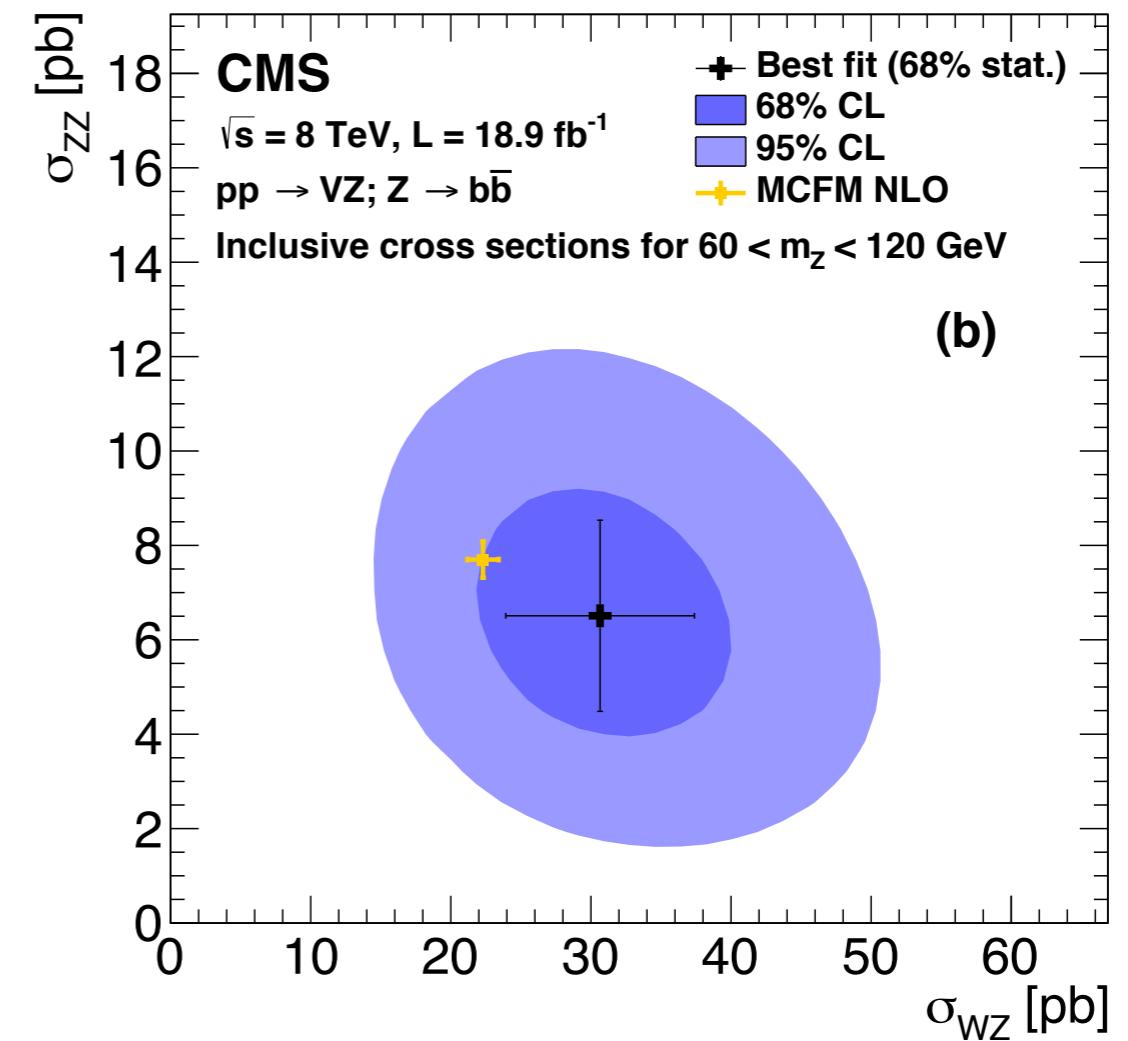


## VZ production cross section in VZ → Vbb-bar decay channel

arXiv:1403.3047v1



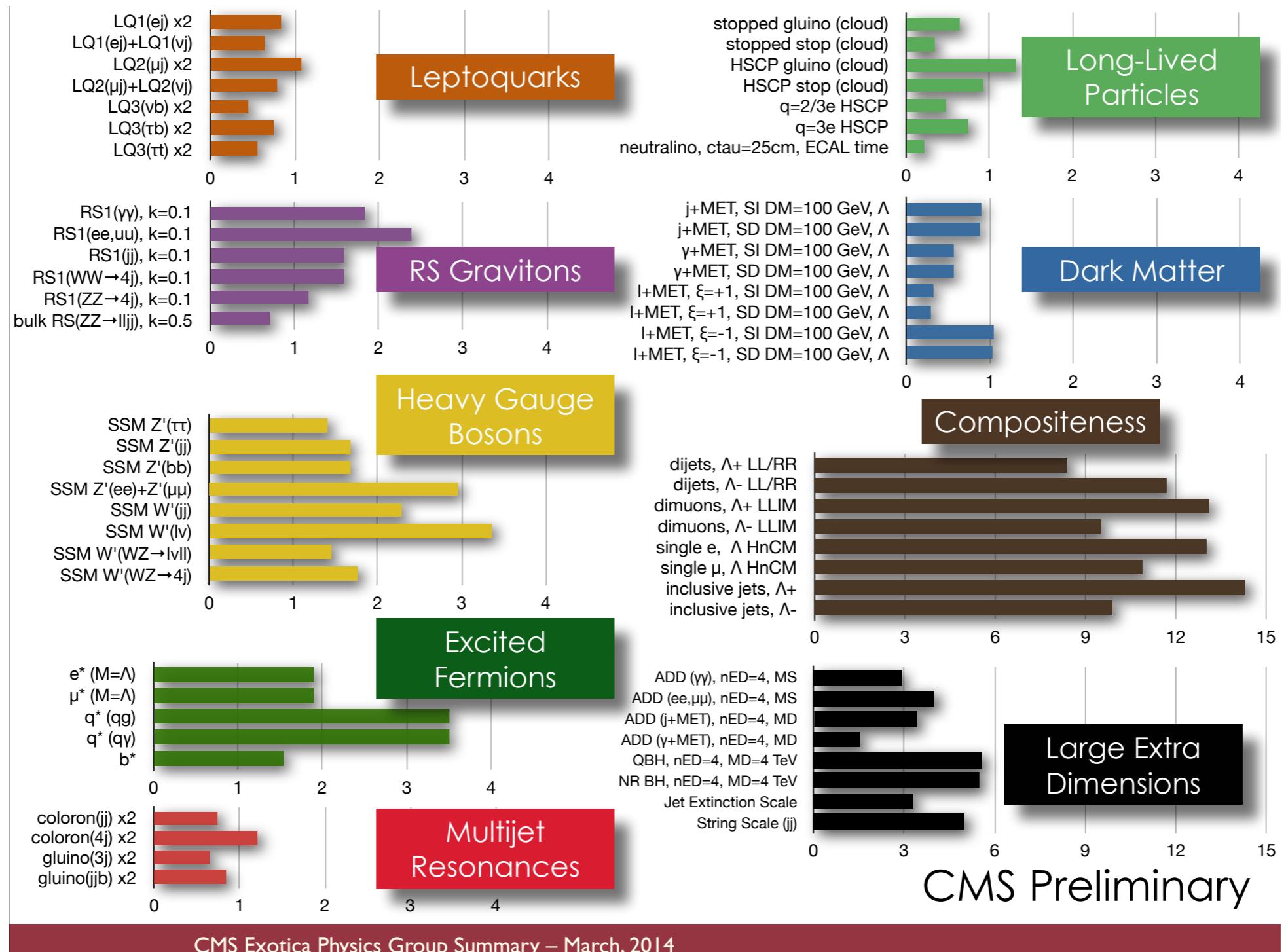
The best-fit value of the production cross section for VZ production, relative to the standard model cross section



The 68% & 95% CL contour regions for the WZ-ZZ production cross-sections.

The total cross sections, defined for  $60 < M_Z < 120 \text{ GeV}$ , are found to be  $\sigma(\text{pp} \rightarrow \text{WZ}) = 30.7 \pm 9.3 \text{ (stat.)} \pm 7.1 \text{ (syst.)} \pm 4.1 \text{ (th.)} \pm 1.0 \text{ (lum.)} \text{ pb}$  and  $\sigma(\text{pp} \rightarrow \text{ZZ}) = 6.5 \pm 1.7 \text{ (stat.)} \pm 1.0 \text{ (syst.)} \pm 0.9 \text{ (th.)} \pm 0.2 \text{ (lum.)} \text{ pb}$ .

# New Physics?

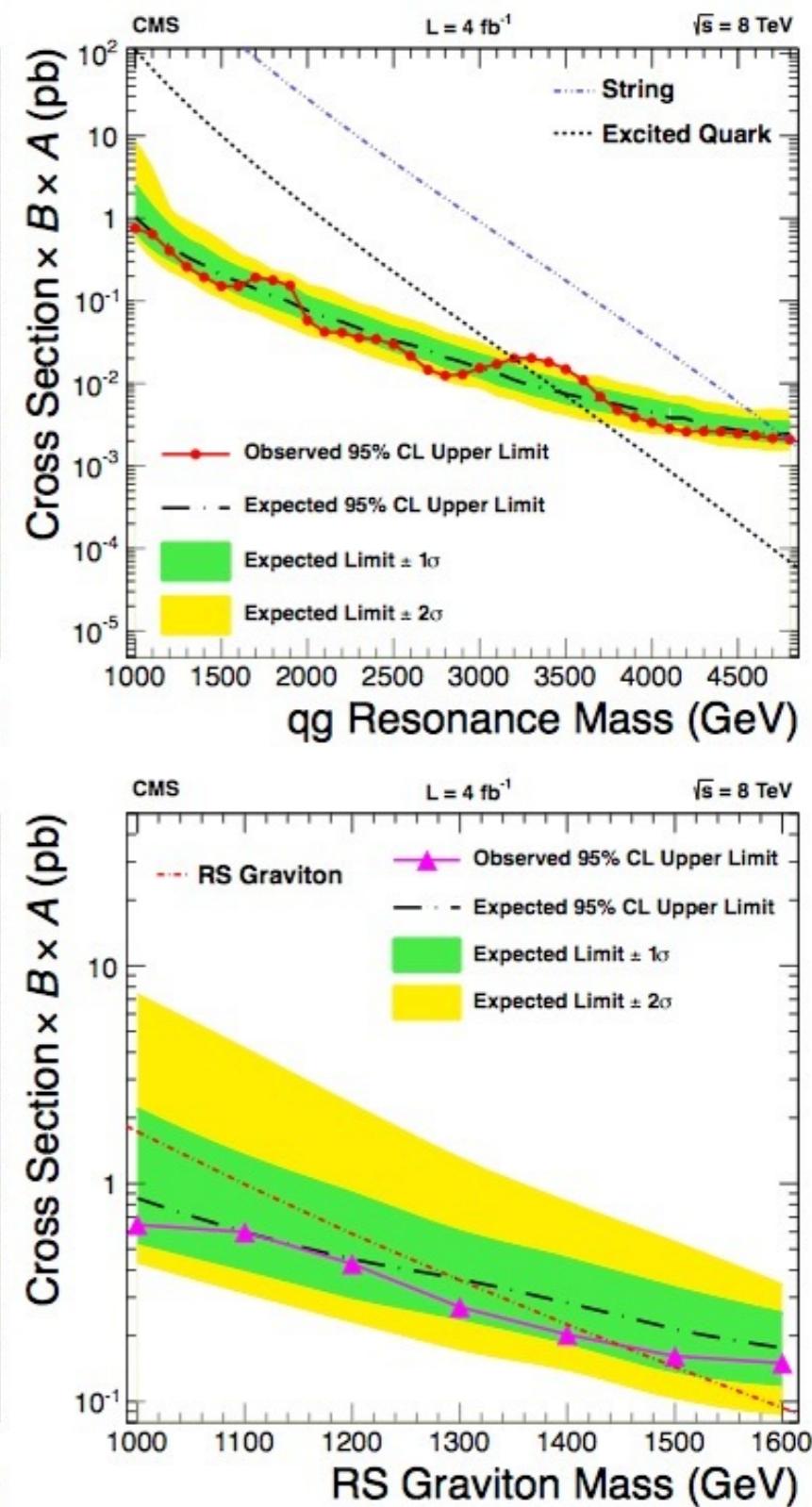
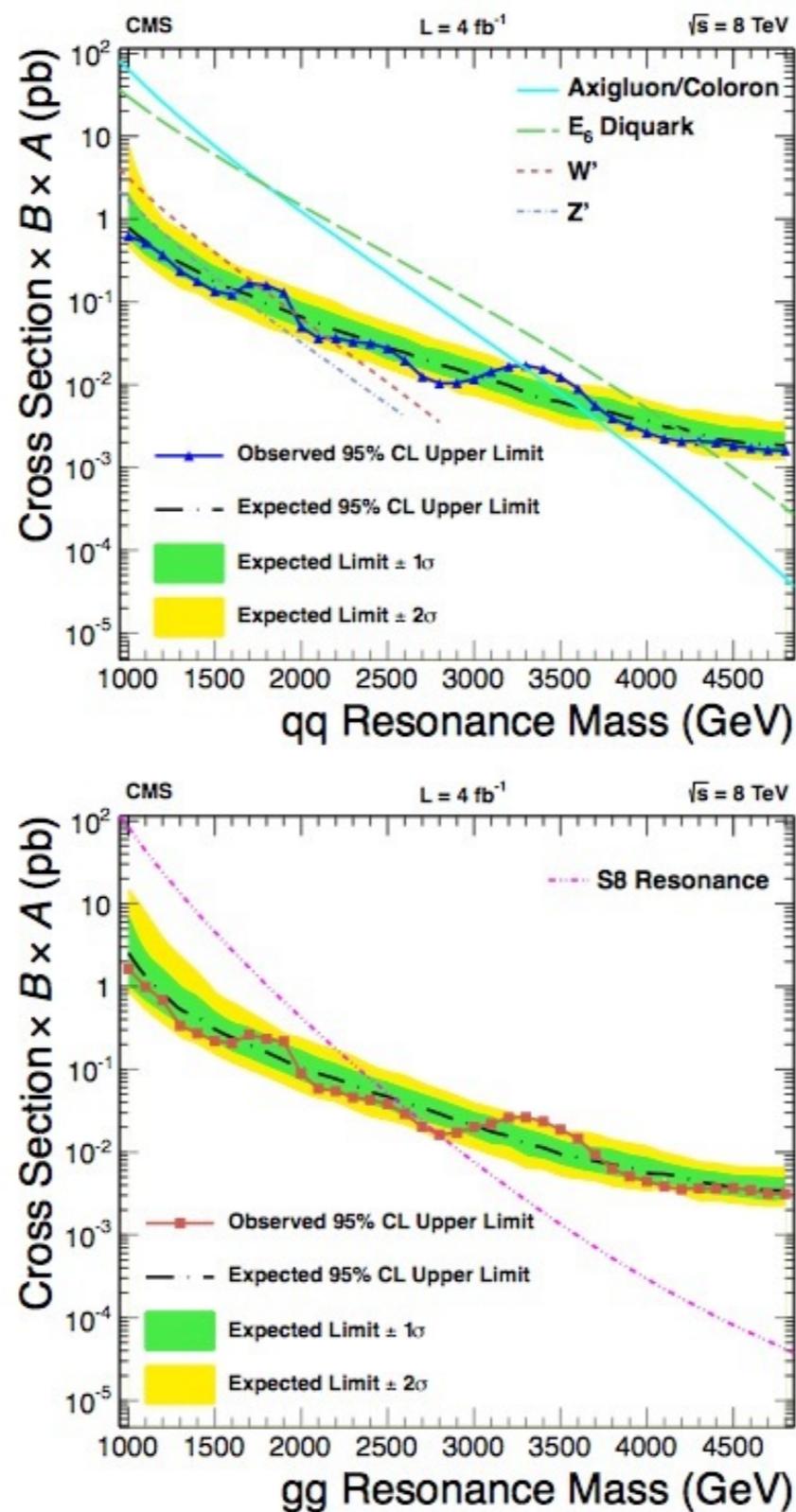
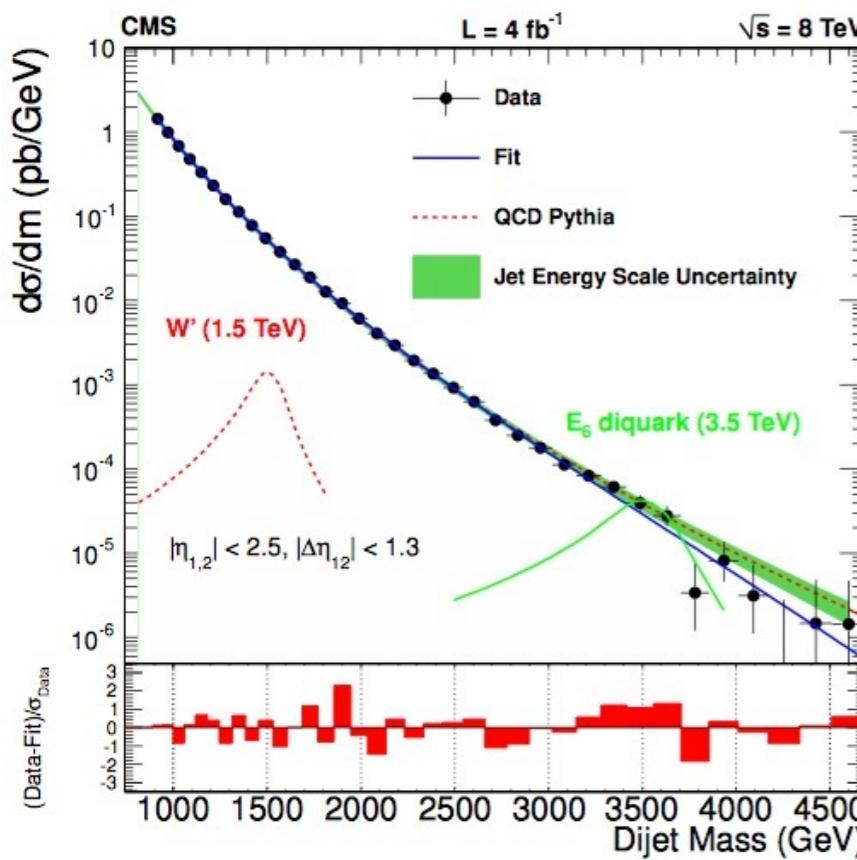


Needles we are looking for. No sign of any new type YET!

# New Physics? Dijet Spectrum

Phys. Rev. D 87 (2013) 114015

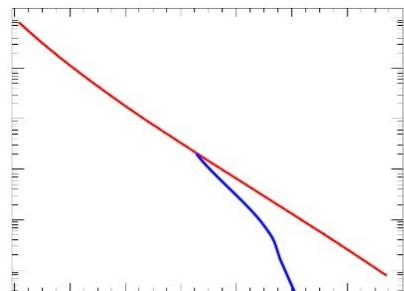
any bump in QCD?



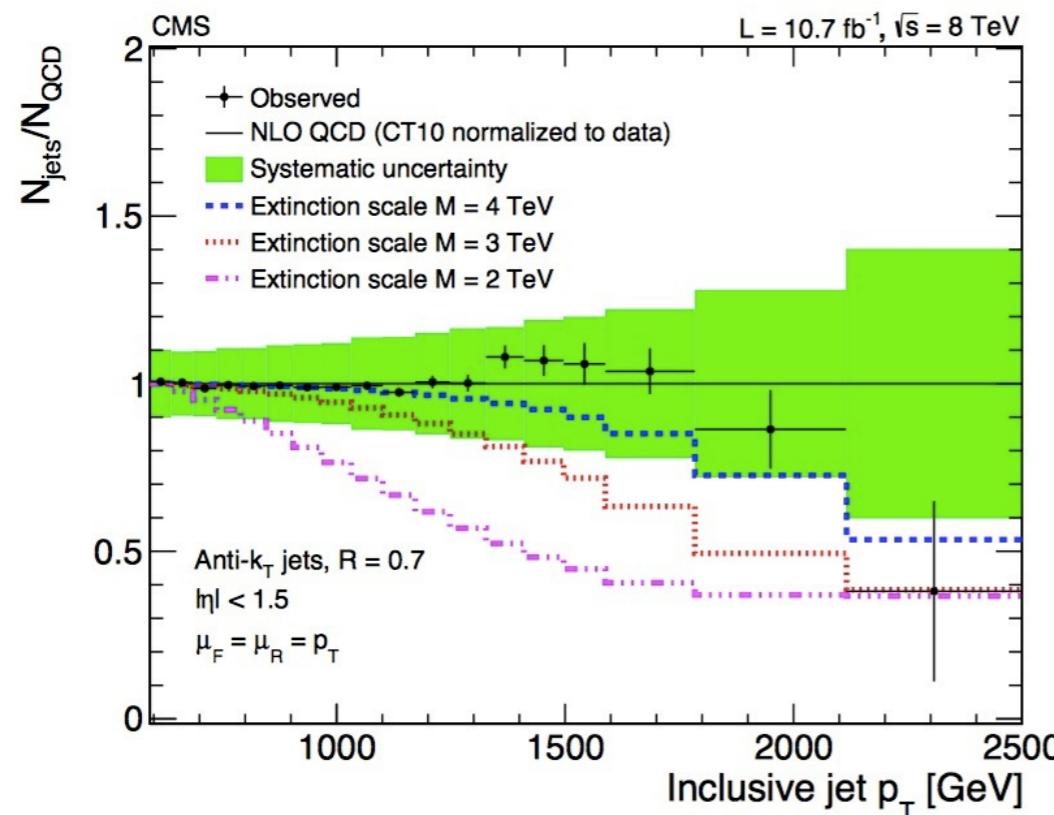
# New Physics? Jet Extinction

arXiv:1405.7653v1

## or a deficit?



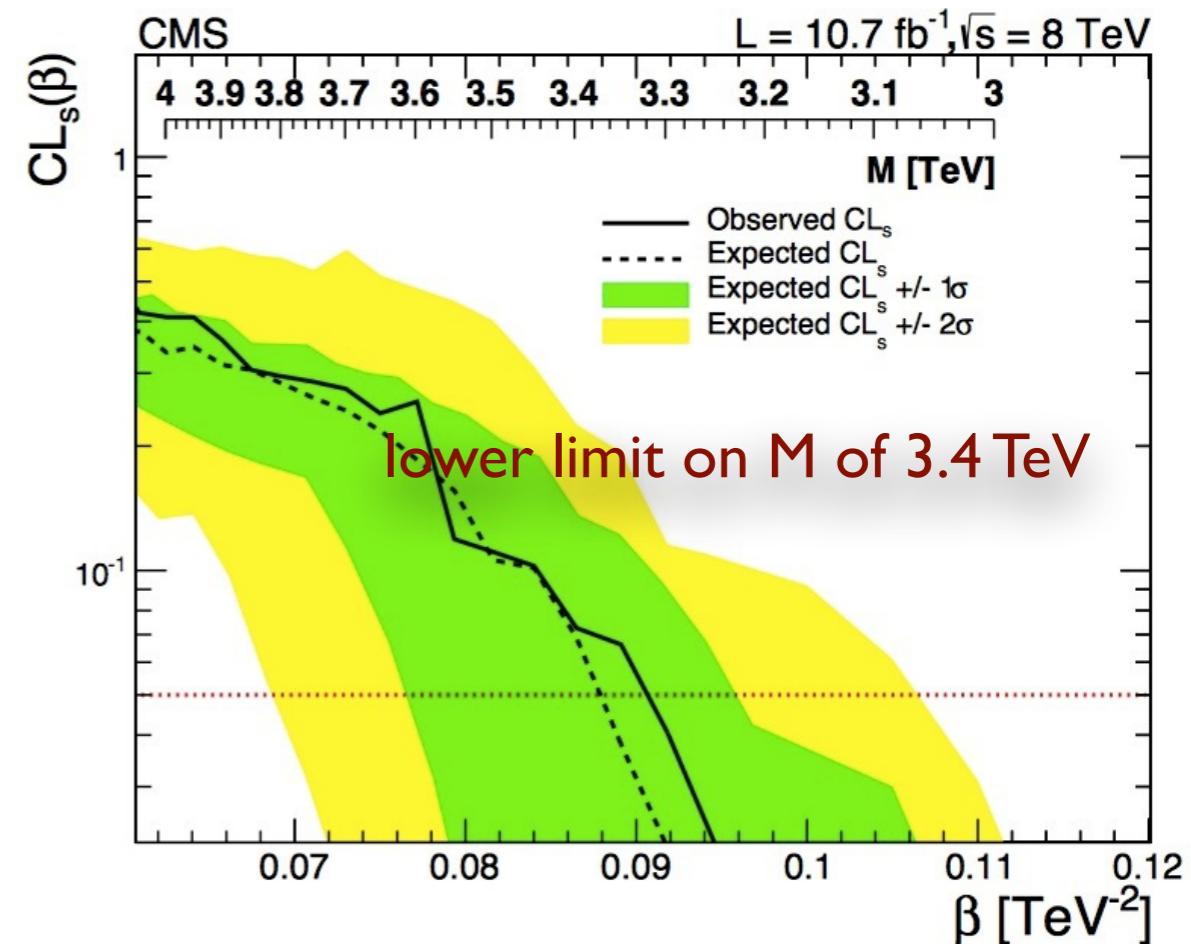
$$\beta = \frac{1}{M^2}$$

 $M$  : equivalent to the modified Planck scale

Quantum gravity suggests that hard short distance scattering processes are highly suppressed for center of mass scattering energies beyond the fundamental Planck scale.

If this scale is close to the electroweak scale non-perturbative quantum gravity effects could be manifest as an extinction of high transverse momentum jets at the LHC.

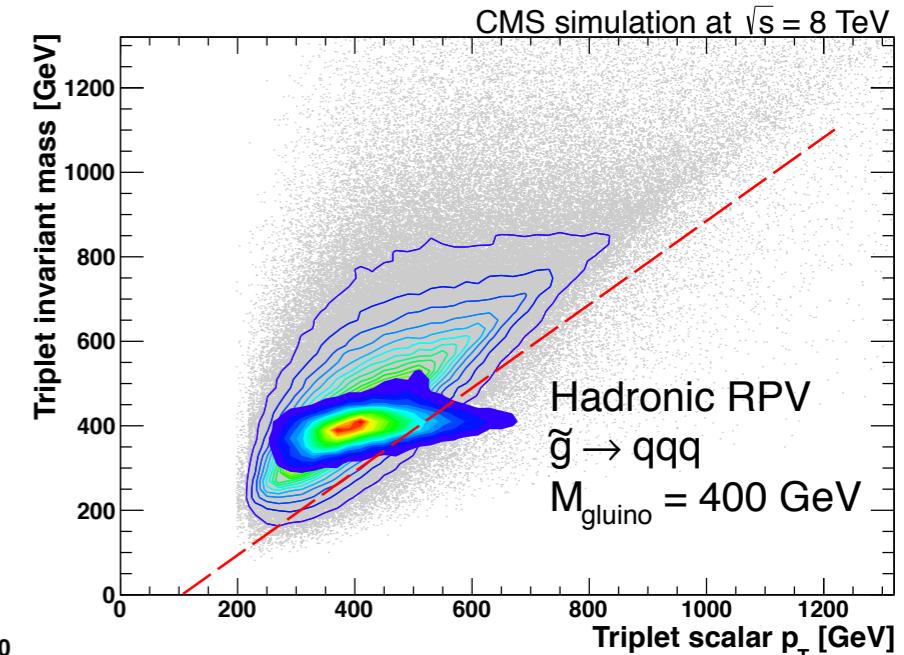
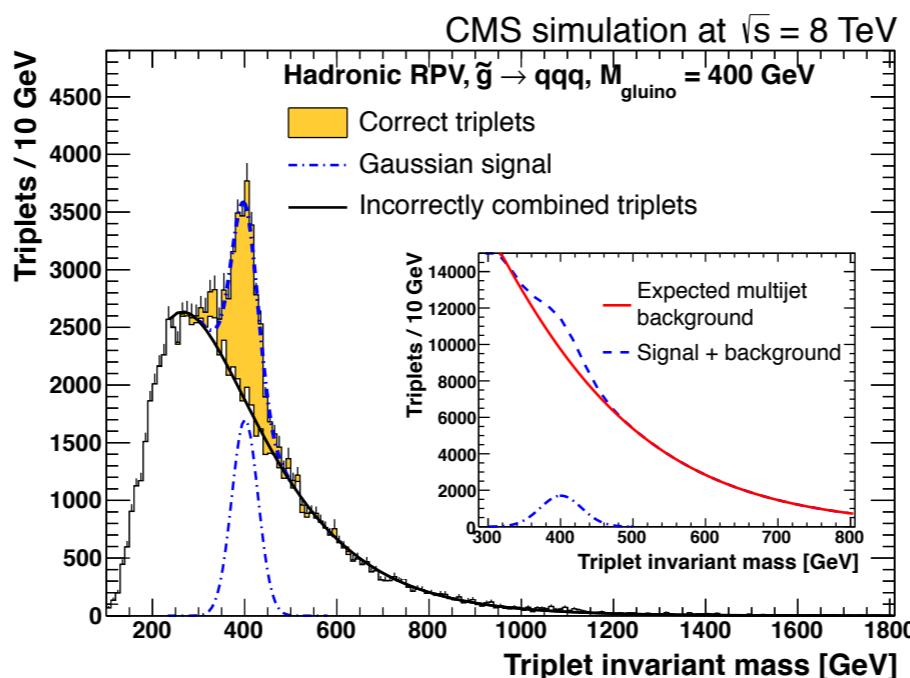
If  $M \rightarrow \infty, \beta \rightarrow 0$  where the SM assumption that Planck scale is at too high



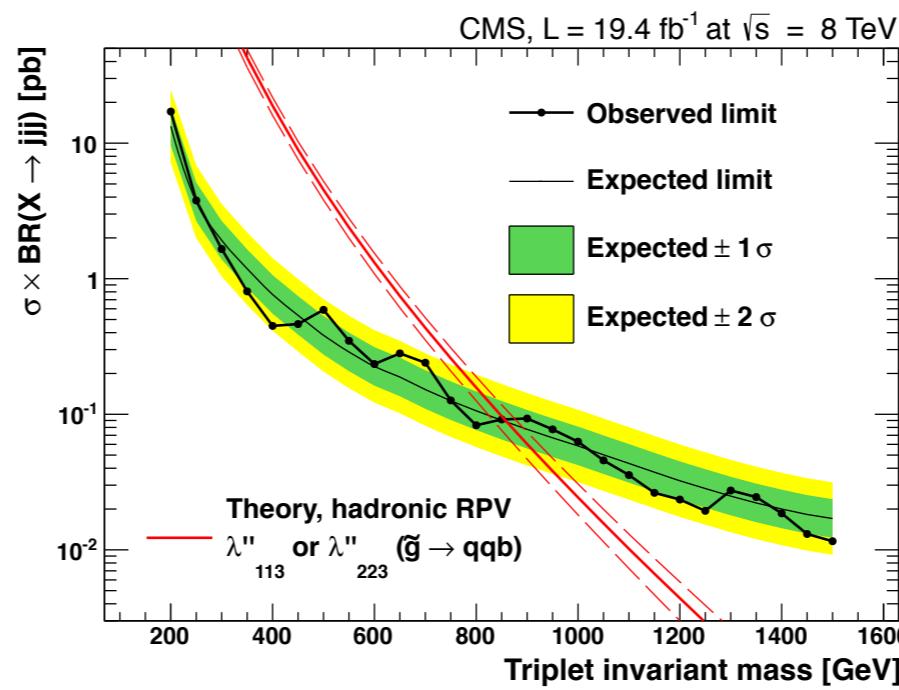
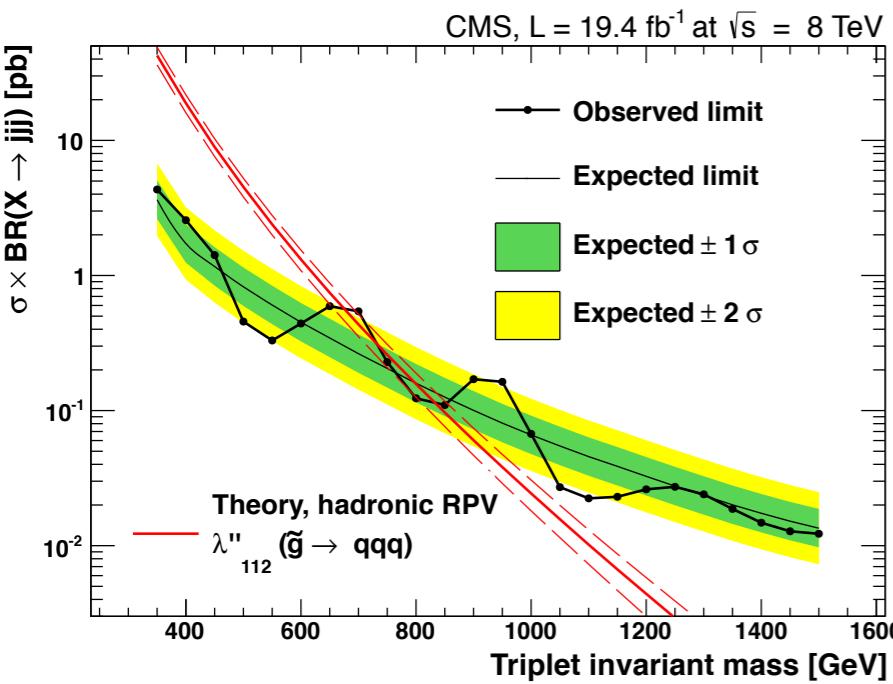
# New Physics? Three Jet Resonances

Physics Letters B 730 (2014) 193–214

The signal models explored assume R-parity-violating (RPV) supersymmetric gluino pair production and have final states with either only light-flavour jets or both light- and heavy-flavour jets



Gluino production and decay are simulated using the Pythia [22] event generator (v6.424), with each gluino decaying to three quarks through the  $\lambda''(udd)$  quark RPV coupling



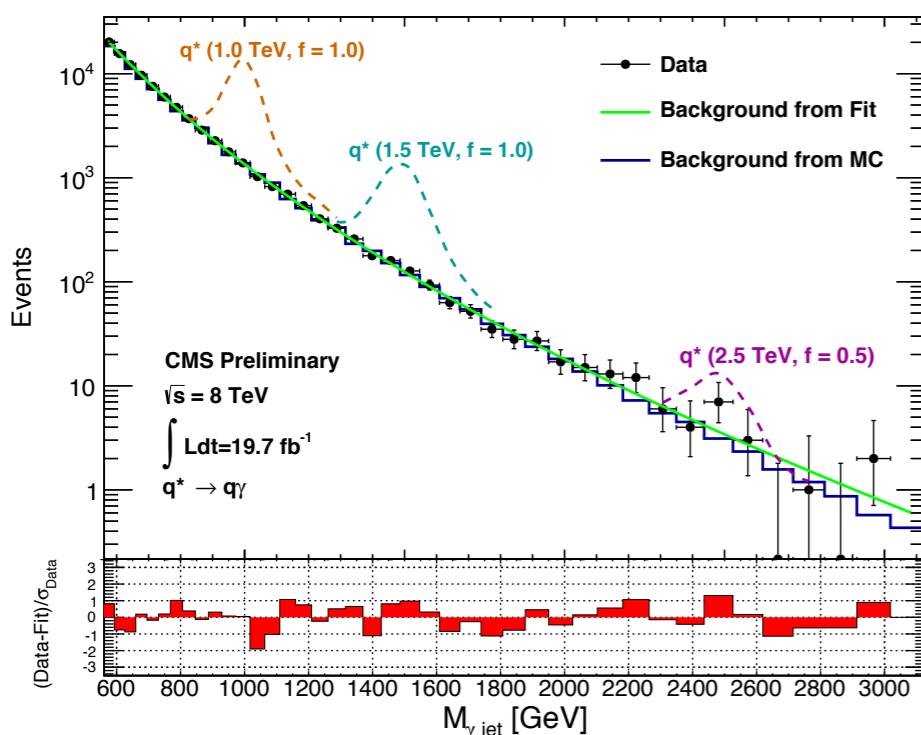
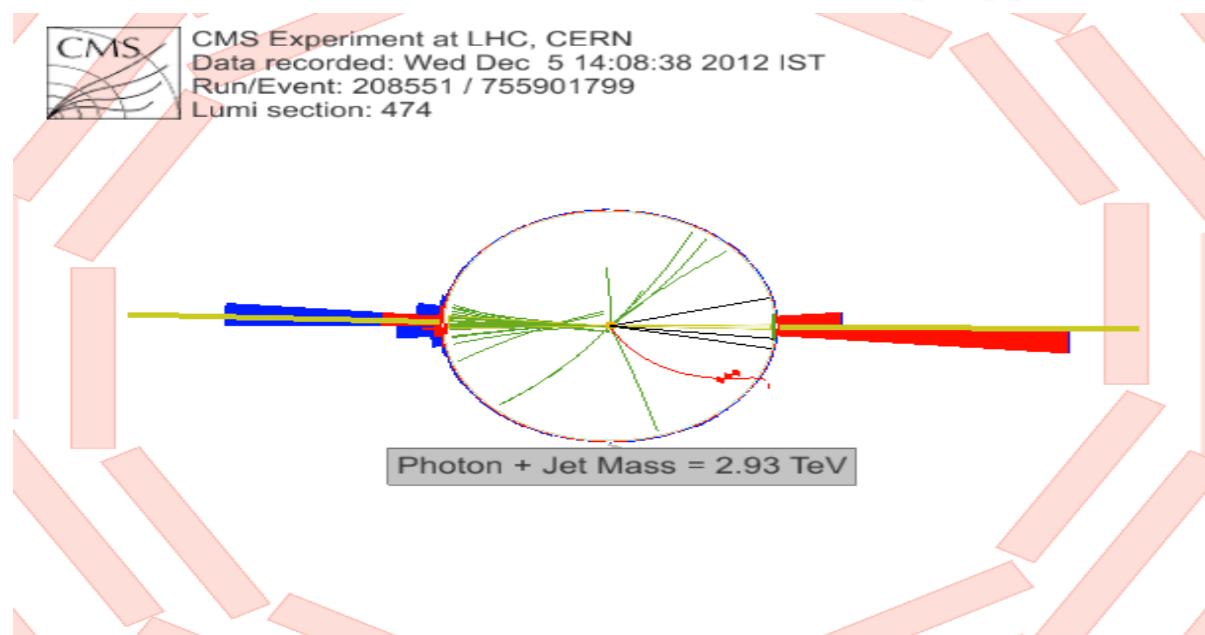
The production of gluinos undergoing RPV decay into light-flavour jets has been excluded at the 95% CL for masses below 650 GeV. Gluinos that include a heavy-flavour jet in their decay have been excluded at 95% CL for masses between 200 and 835 GeV, which is the most stringent limit to date for this model of gluino decay.

# New Physics? Excited Quarks ( $q^*$ )

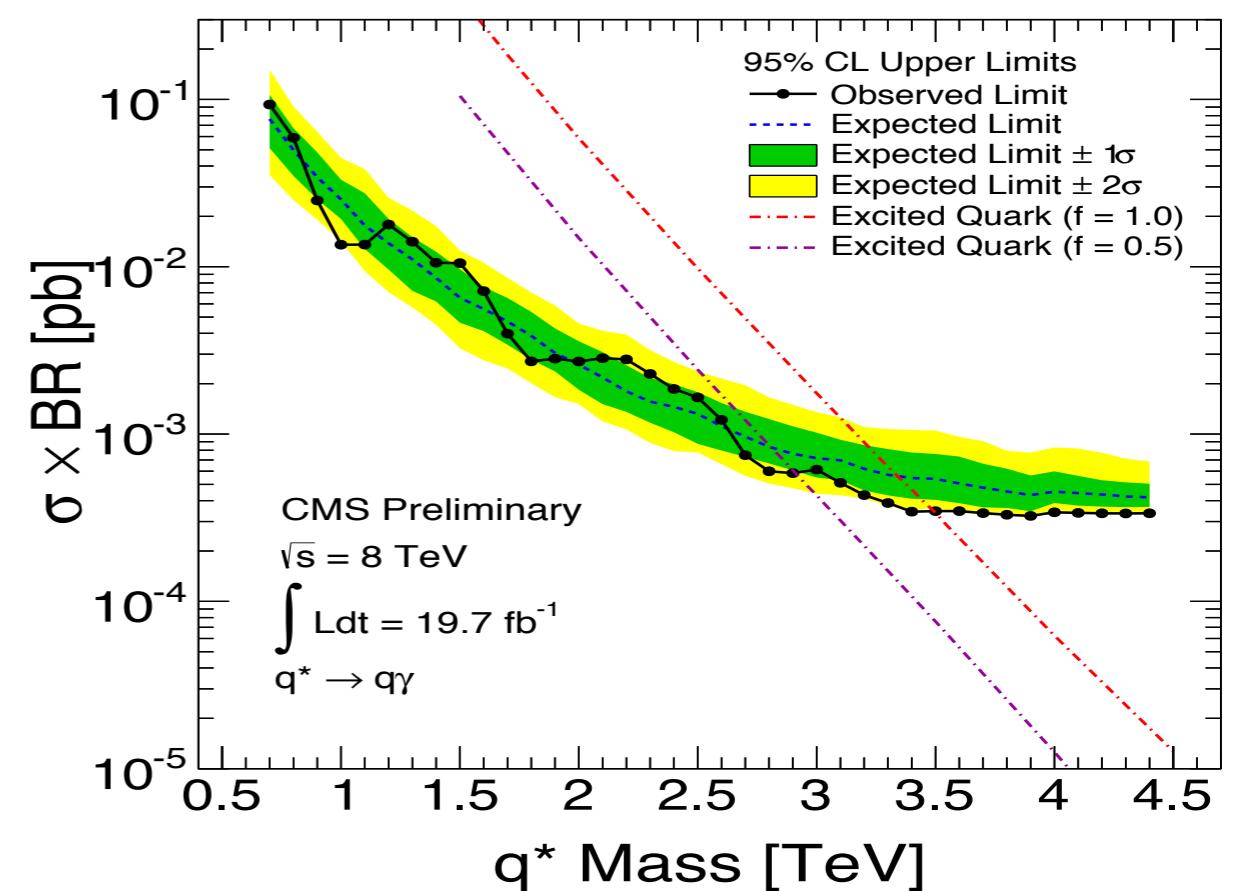
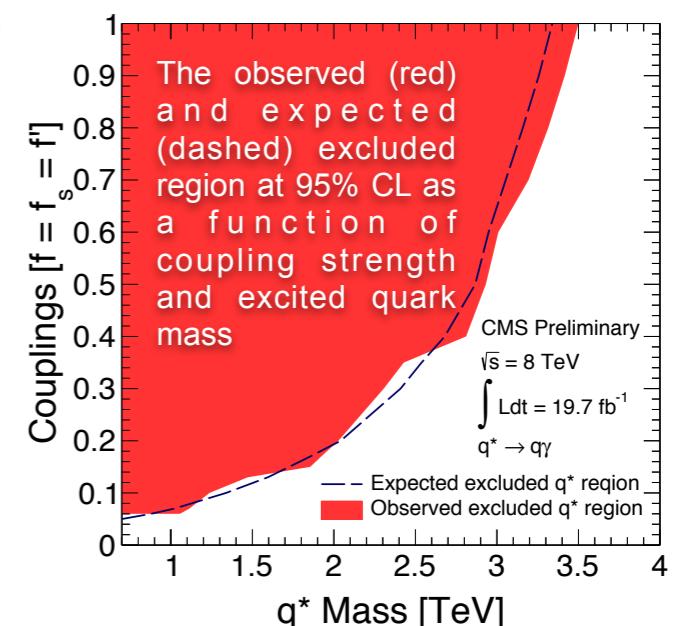
CMS-PAS-EXO-13-003

A search for excited quarks ( $q^*$ ) decaying into a  $\gamma +$  jet final state at  $\sqrt{s} = 8$  TeV

Event display of the highest invariant mass  $\gamma +$  jet candidate with mass of 2.93 TeV observed in data in the  $\rho - \phi$  plane.

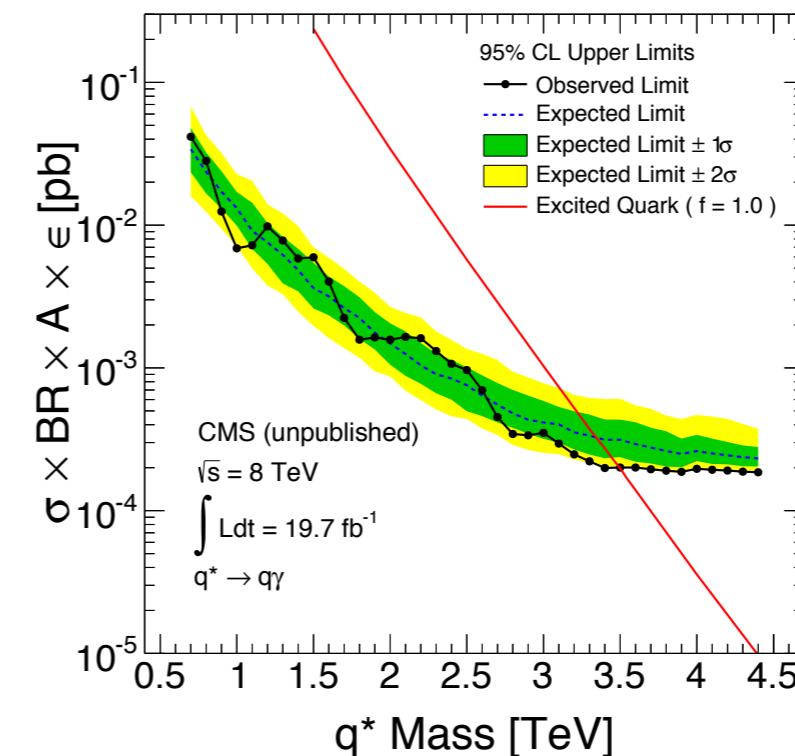
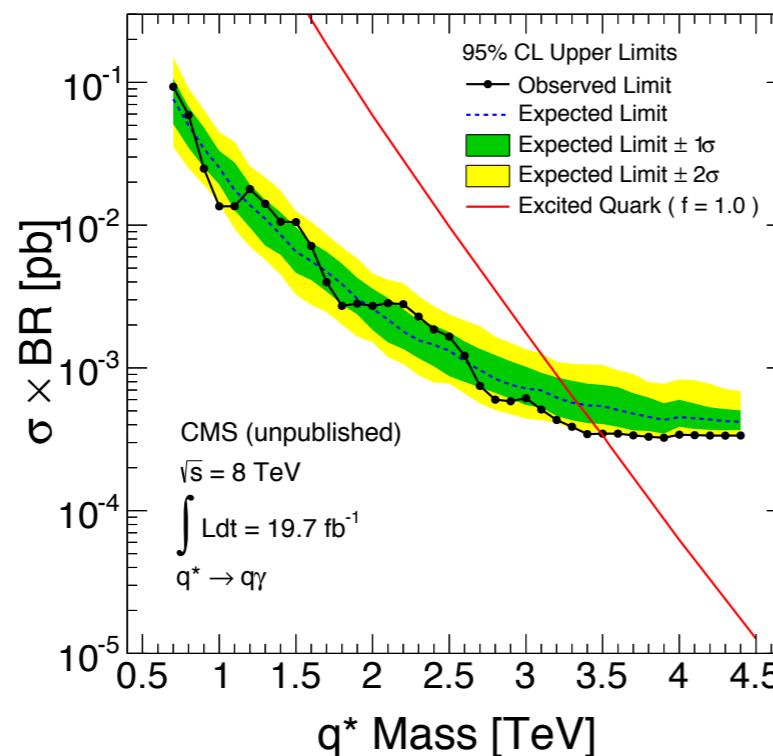
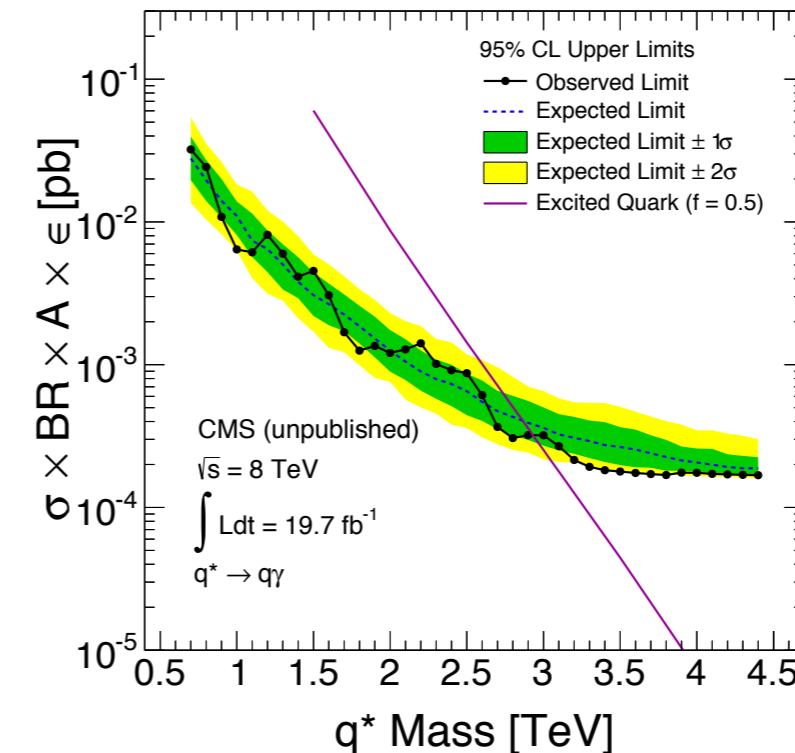
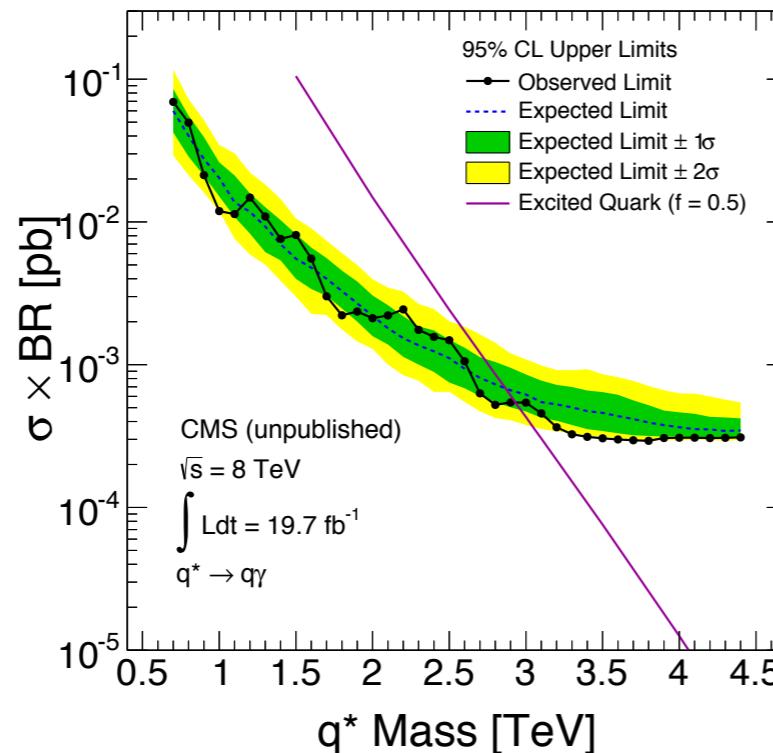


We exclude at 95% CL excited quarks with  $0.7 < M_{q^*} < 3.5$  TeV



# New Physics? Excited Quarks ( $q^*$ )

CMS-PAS-EXO-13-003



# Conclusions

- CMS has completed a very large number of analyses with  $p\bar{p}$  collisions at 7 & 8 TeV
- Excellent understanding of the detector has been achieved, even at high pile-up conditions!
- The level of the precision of Standard Model measurements are quite high
  - important constraints on theory ingredients (e.g. PDFs) and backgrounds to Higgs studies and new physics searches
  - no signs of new physics (non-SM physics) (YET/STILL)
- Many results have been published and lots of is going to be published soon.

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

