QCD, EWK and Top results from CMS

… on a river of discovery

MARTIJN MULDERS (CERN)

FOR THE CMS COLLABORATION

MANAUS AMAZONAS, AUGUST 3, 2015

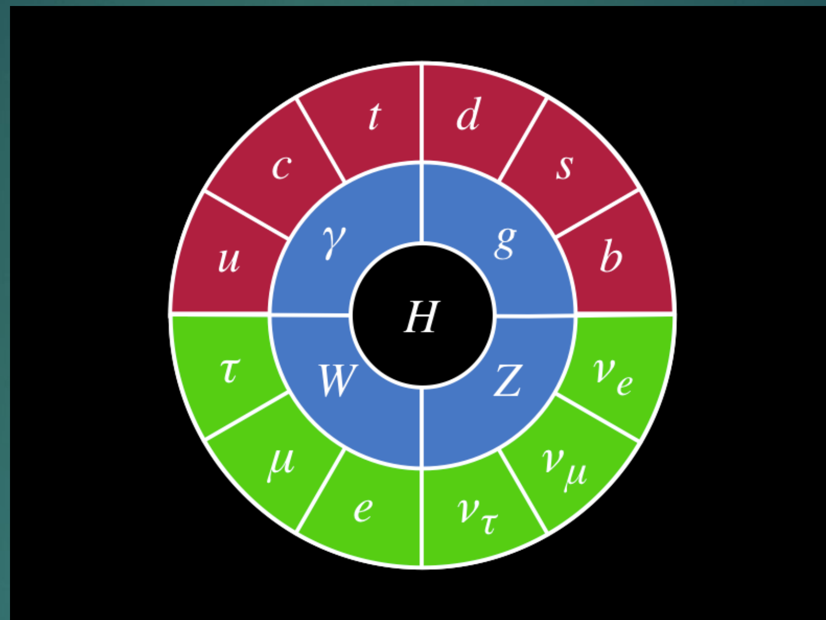
ATLAS: dedicated talks on Thursday
D. Lopez (EWK + QCD)
A. Paramonov (Top)

On a River of Discovery…

… success of the expedition relies
crucially on a reliable Map
and the best possible tools..!

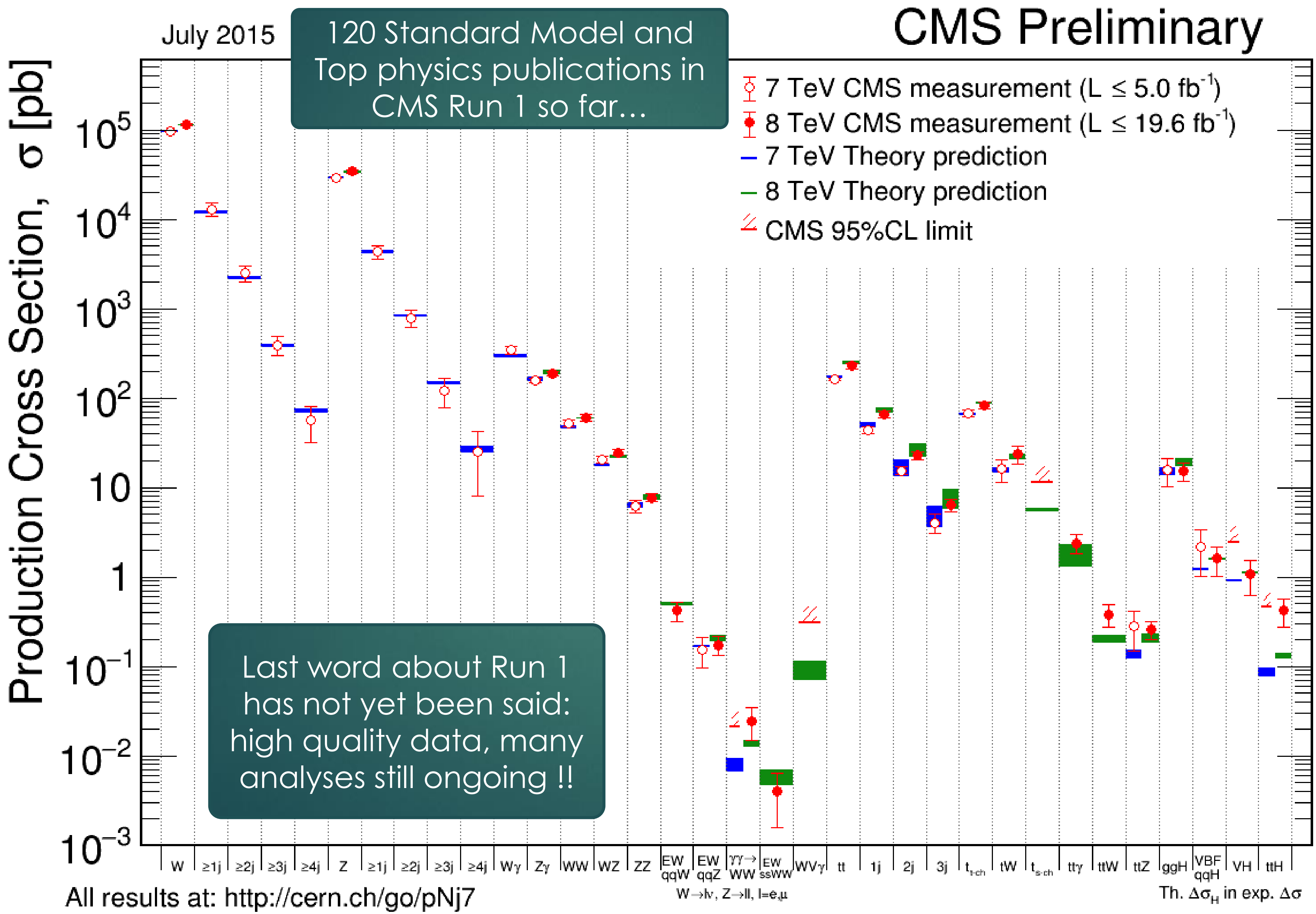
(including a magnet)

The Standard Model "Map"



- The preferred choice of particle explorers !
- Incredibly successful at describing all known elementary particles and forces
- Thoroughly reviewed, updated and completed during the LHC Run 1 "expedition"

Success of the Standard Model in Run 1:



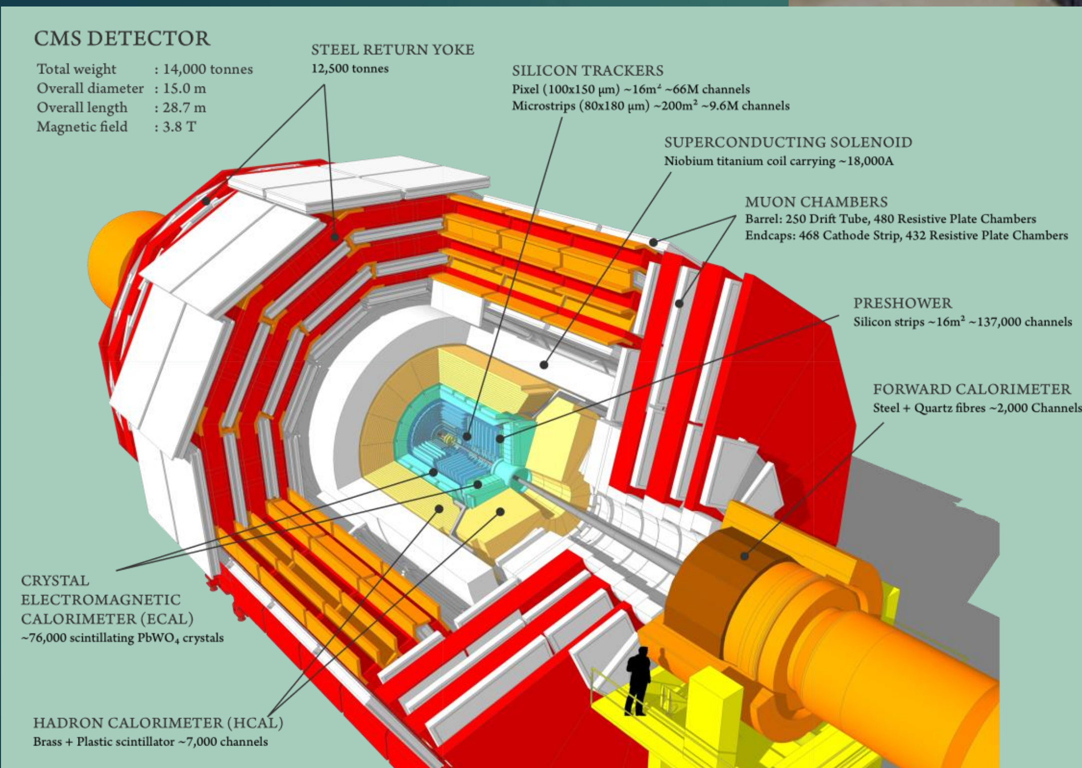
120 Standard Model and Top physics publications in CMS Run 1 so far…

Last word about Run 1 has not yet been said: high quality data, many analyses still ongoing !!

Focus on recent highlights:

- CMS LOGBOOK from our First Expedition (Run 1)
  - Strong Force (QCD, jets, alpha_s, pdfs, MC Tools)
  - Electroweak Precision Measurements
  - More about Top quarks, Anomalous Couplings, Rare decays
- Preparations for the Second Expedition (Run 2)
  - A very first look

CMS detector
(Compact Muon Solenoid)



Itaipu dam
(Iguaçu, Brazil)

height x length: 15 x 29 m | 200 x 7900 m

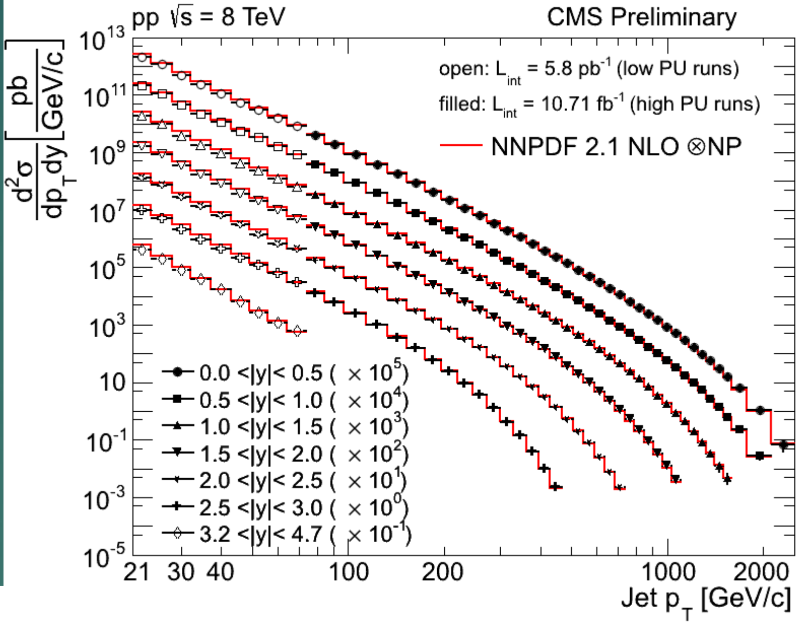
max energy stored: 2.5 GJ | == 0.2 s of Itaipu production

Steel used: 1 x  | 380 x 

Precision QCD

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

- State-of-the-art theory + MC models:
  - NNLO calculations
  - NLO + Parton Shower → MC tools
  - NLO QCD + EWK corrections
- Precise measurements of Jets, W+jets, Z+jets, ttbar + jets, di-bosons, ttV, single top, …



NNLO calculations important at least for the following cases:

1) Benchmark processes measured with high accuracy

- ✅ $e^+e^- \to 3$ jets
- ✅ pp → W, Z
- ✅ $pp \to t\bar{t}$
- (✅) pp → 2 jets
  - ↘ towards completion

2) Processes with large NLO corrections

- ✅ pp→H
  - ↘ even N3LO known now
- ✅ pp→H+jet
- ✅ pp→HH

3) Important backgrounds for Higgs and NP searches

- ✅ pp→γγ
- ✅ pp→Wγ, Zγ
- ✅ pp→WW
  - ↘ NNLO reduces tension with ATLAS data **+ CMS**
- ✅ pp→ZZ
- ❌ pp→WZ
- ✅ pp→W(Z)+jet

Grazzini, EPS HEP 2015

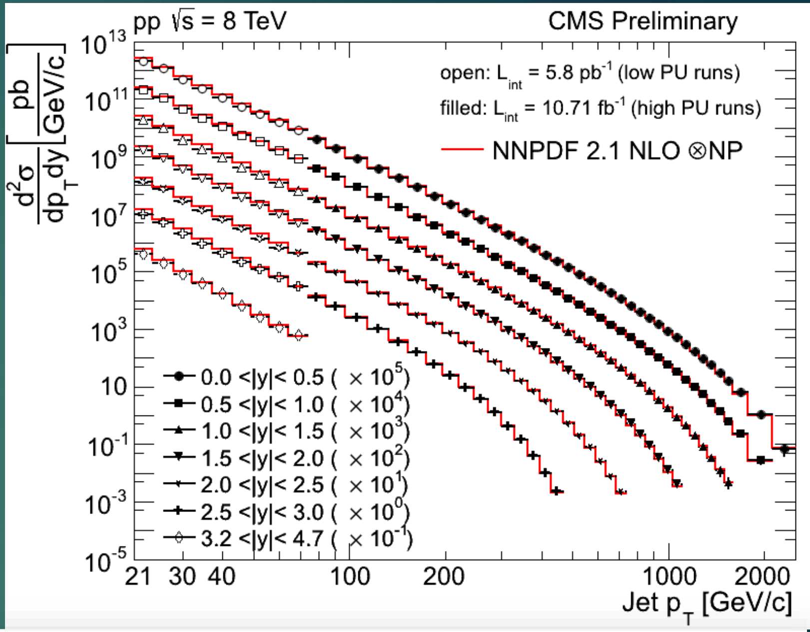
This allows to:

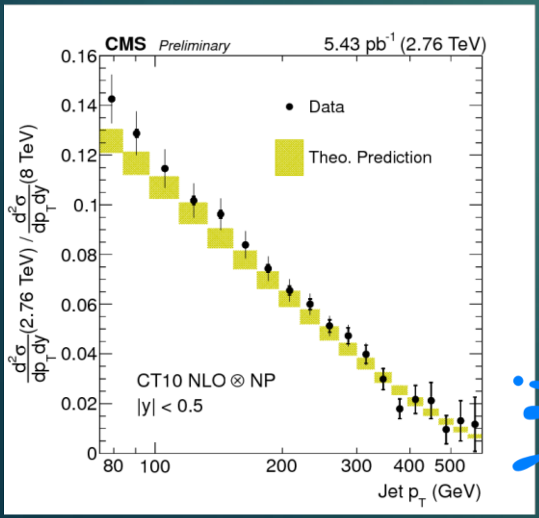
- Constrain PDFs
- Tune MC parameters
- Measure alpha_s
- Model backgrounds for Higgs and BSM physics

Inclusive Jets

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012

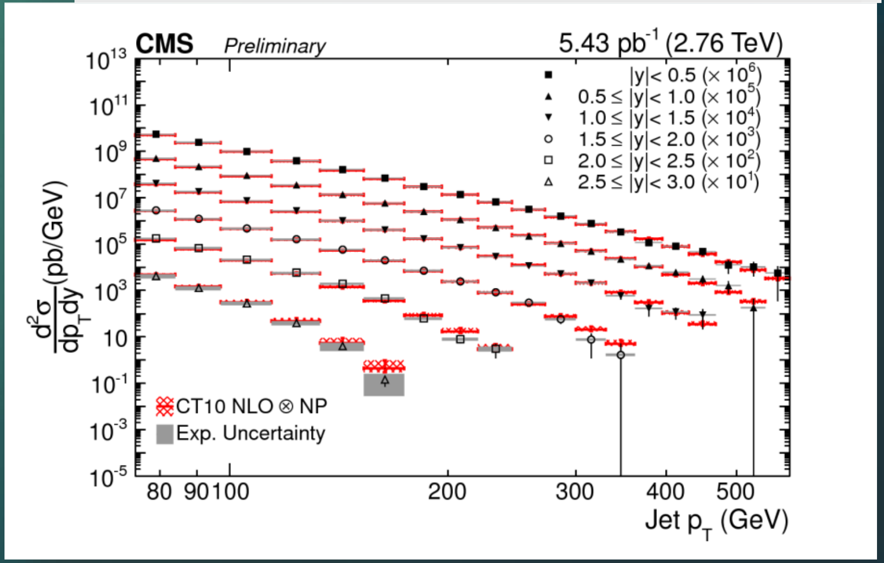
- Fixed-order NLO prediction folded with non-perturbative corrections agrees with data over 2 decades in energy and 13 orders of magnitude in cross section !
- Will improve q, g PDFs at high x
- New: same analysis at 2.76 TeV (5 /pb)
- Exp. (jet energy scale, luminosity) and theory uncertainties reduced in ratio:





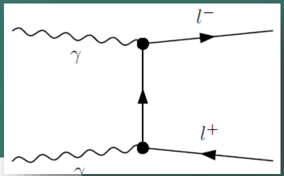
$$\frac{2.76\ TeV}{8\ TeV}$$

CMS-PAS-SMP-14-017



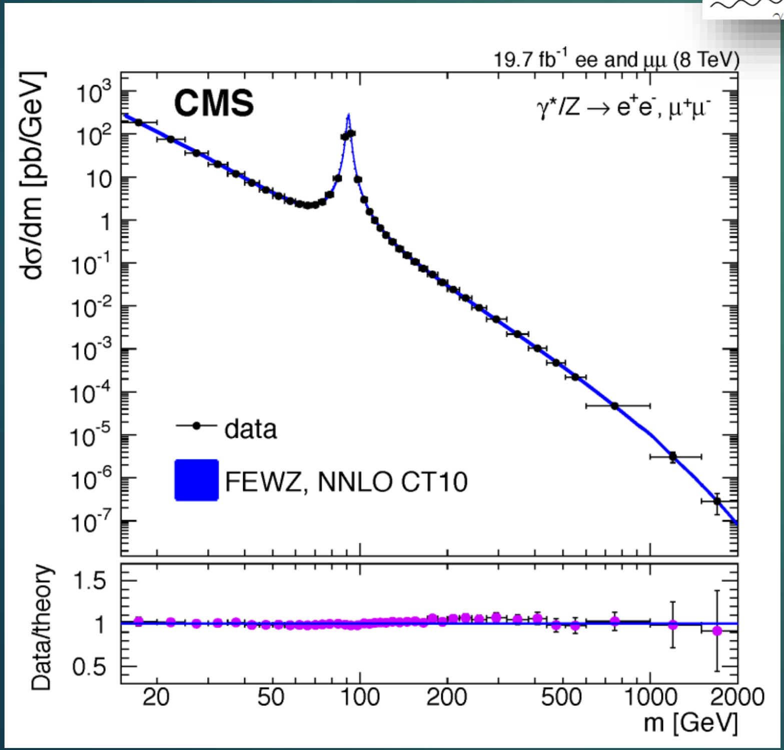
Drell-Yan Cross Section

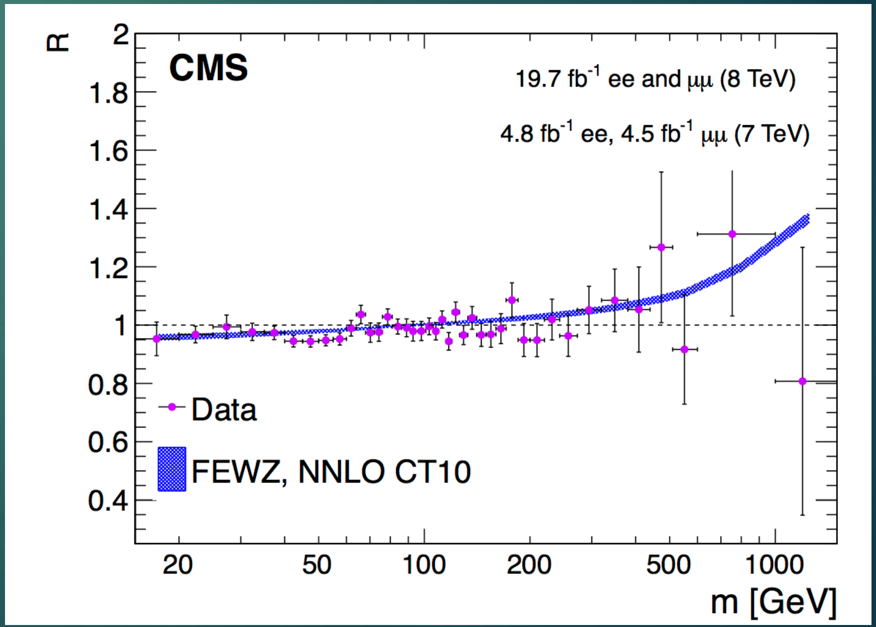
- Cross section vs. dilepton mass now measured at 8 TeV, from 15-2000 GeV in mass
- Compared to NNLO QCD + NLO EWK corrections (+ including $\gamma\gamma \rightarrow l^+ l^-$)



- Differential double ratios $(1/\sigma Z)(d\sigma/dm)$ 8TeV / $(1/\sigma Z)(d\sigma/dm)$ 7TeV measured for the first time

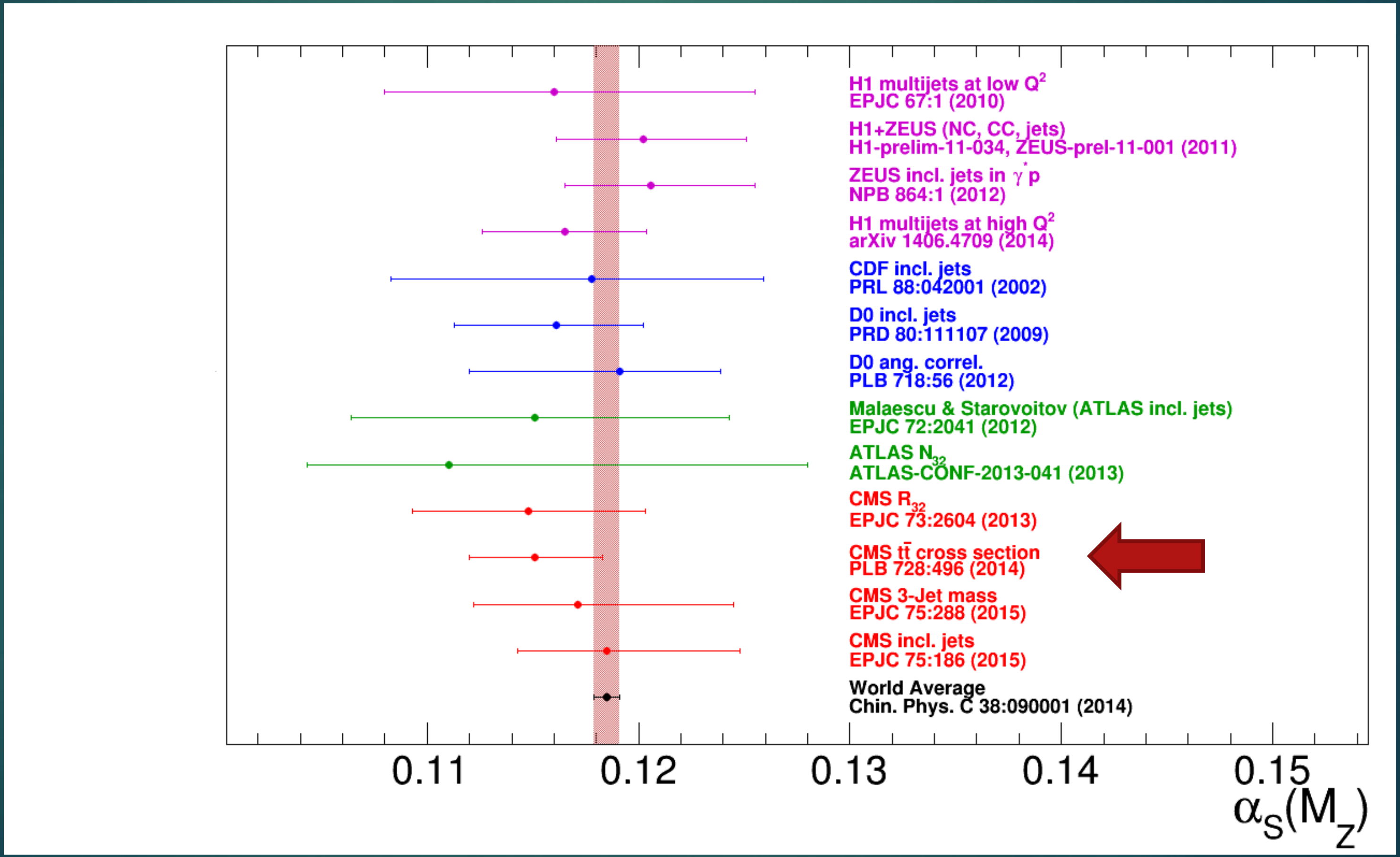
EPJC 75 (2015) 147



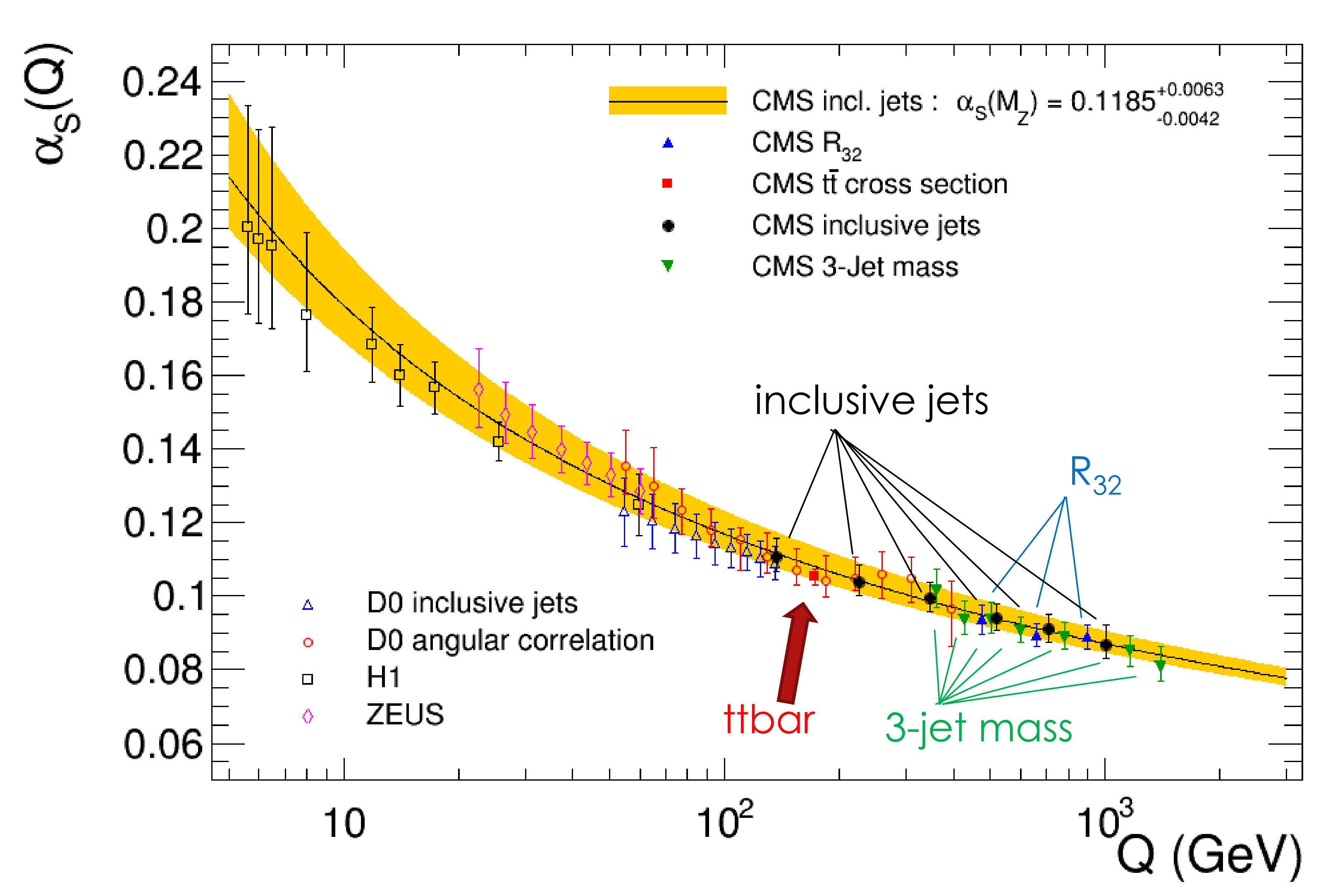


Strong coupling: overview

- Hadron collider data agrees with the PDG world average → note: most precise hadron collider result from ttbar …!



Strong coupling: overview

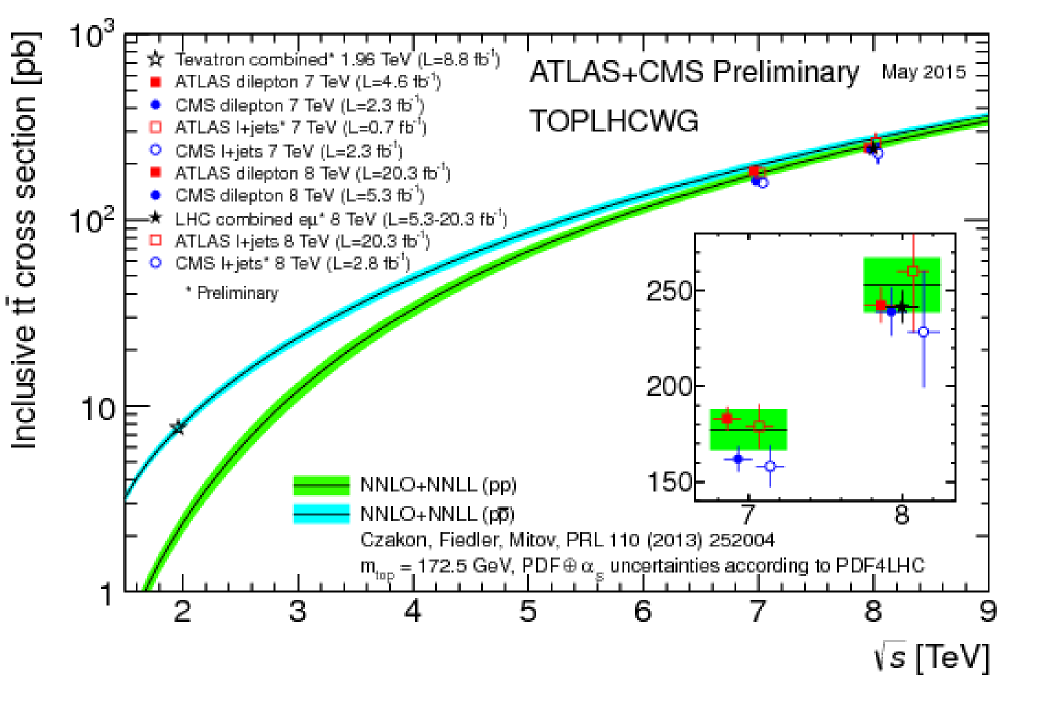


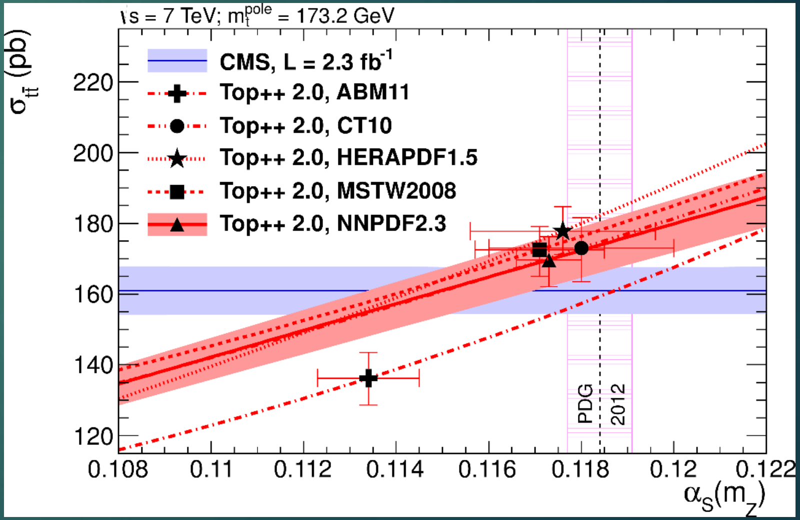
Top pair cross section

- Most precise results from di-lepton decay channel
- In agreement with NNLO+NNLL QCD predictions for m_{top} ~172.5 GeV

Czakon, Fiedler, Mitov PRL 110 (2013) 252004

- Allowed first extraction of α_s at hadron collider with NNLO precision -- agrees with PDG at 3x worse error (CMS 7 TeV)
- Experimental and theoretical (scale, pdf) uncertainties similar in size (3-5%)





[PLB 728 (2014) 496-517](#)

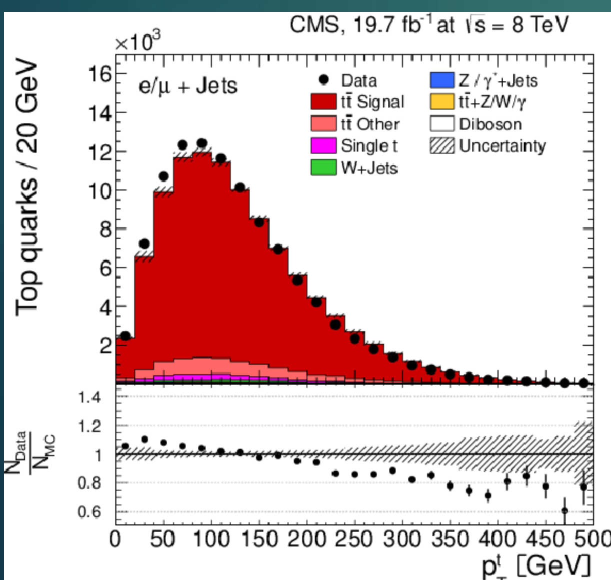
[Corrigendum: PLB 738 (2014) 526-528]

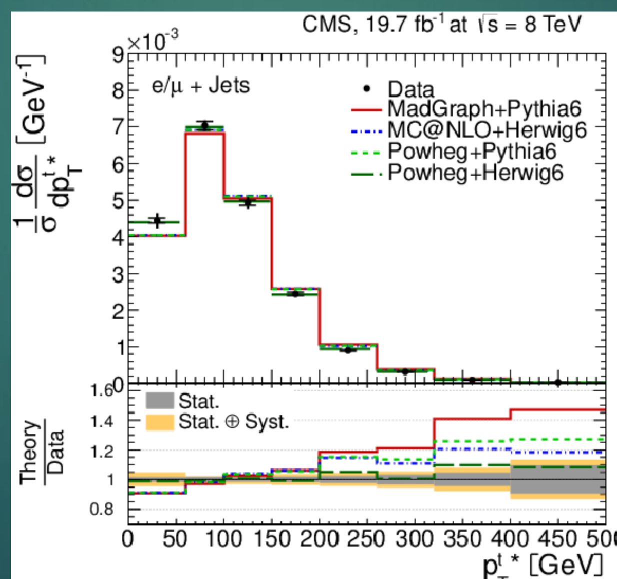
Differential ttbar production at 8 TeV

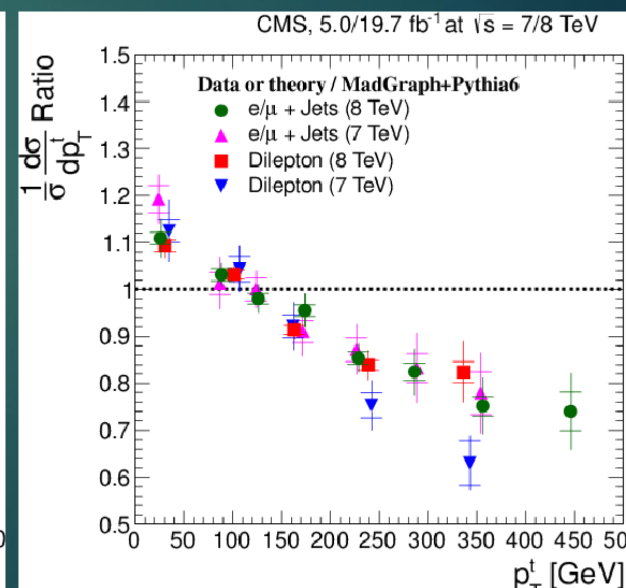
arXiv:1505.04480

- Full Run 1 data; distributions vs p_T and η of (b-)jets, leptons, top and tt
- Generally good agreement with (N)LO ME+PS predictions, except:
- p_T (top) is softer in data than in LO and NLO predictions; will be interesting to compare to future differential NNLO+NNLL calculations

= important uncertainty for top measurements, and ttH background





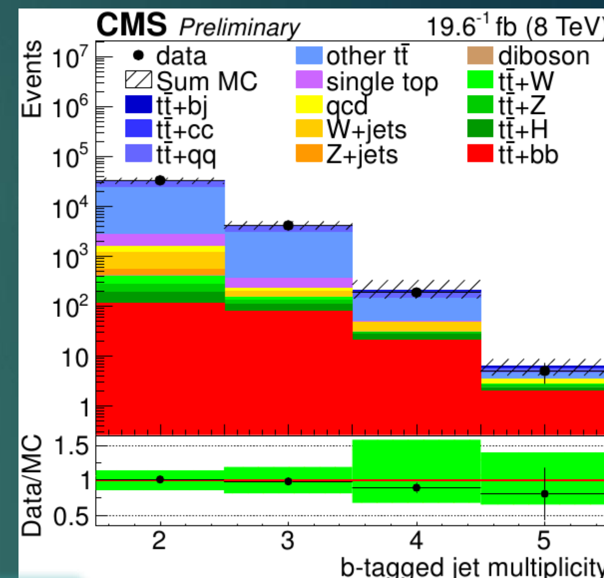


Heavy flavor production

- Production of extra jets, in particular also heavy flavor (c or b), extremely important
- Background for Higgs and BSM physics
- [Not covered here: many results on V+jets, Vb, Vbb, Wc, tt+jets]

- New CMS 8 TeV: tt+bb in l+jets channel (pT jets > 40 GeV, η < 2.5)
- Multivariate analysis, template fit
- Result provided with corrections to level before / after parton shower:

CMS-PAS-TOP-13-016



	$\sigma(t\bar{t}b\bar{b})$	$\sigma(t\bar{t}jj)$	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
hardB:			
this analysis	271 fb ± 40%	23.1 pb ± 16%	0.012 ± 34%
theory NLO$^{(arXiv:1403.2046)}$	229 fb $^{+18\%}_{-24\%}$	21.0 pb $^{+15\%}_{-13\%}$	0.011 $^{+39\%}_{-13\%}$
MadGraph+pythia	174 fb ± 28%	24.3 pb ± 20%	0.007 ± 10%
hadronB:			
this analysis	348 fb ± 38%	23.1 pb ± 16%	0.015 ± 32%
CMS dilepton$^{(arXiv:1411.5621)}$	360 fb ± 36%	16.1 pb ± 14%	0.022 ± 29%
MadGraph+pythia	216 fb ± 35%	24.3 pb ± 20%	0.009 ± 14%

→ consistent with NLO

→ 1.5 – 2x MG+Pythia

+30% from gluon → bb

→ ~consistent with di-lepton channel

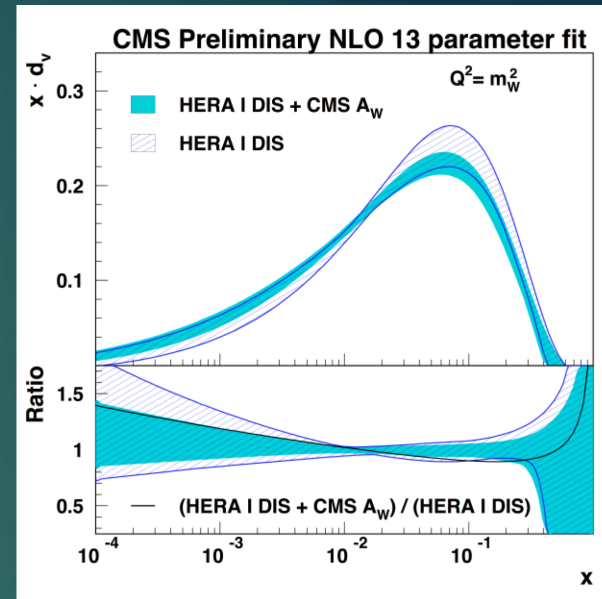
Charge Asymmetry

CMS-PAS-SMP-14-022

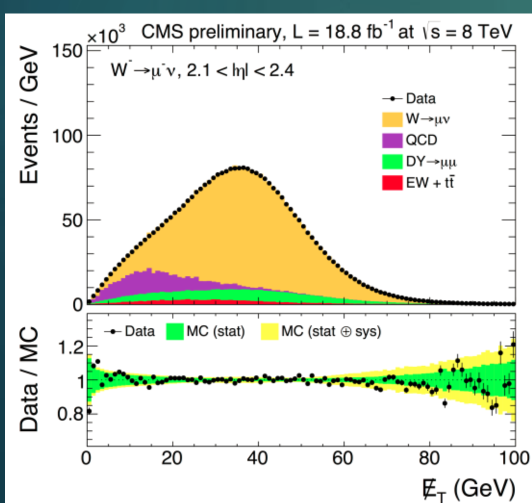
- 8 TeV – muon channel
- W charge asymmetry with 8 TeV data (more up than down in proton → expect more W+ than W-)
- Provides additional constraints for PDFs in range ~ 0.001 < x < 0.1

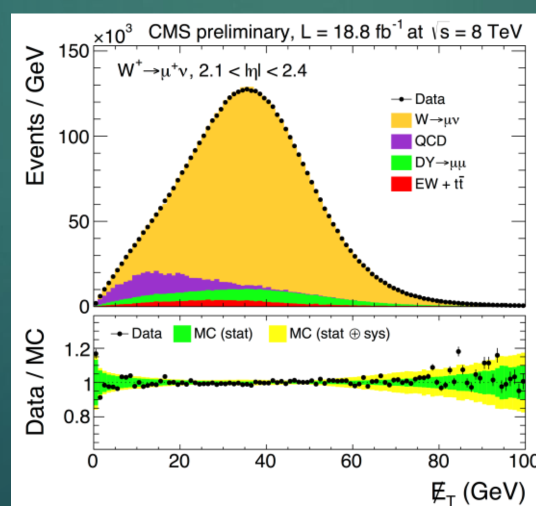
$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\overline{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\overline{\nu})}$$

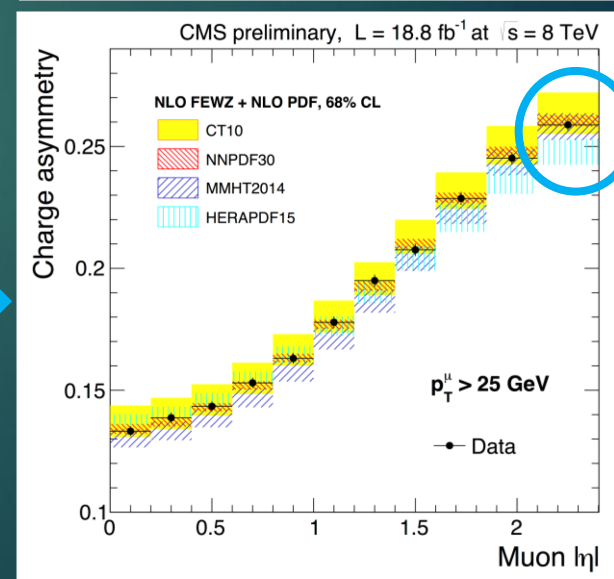
NEW!



eg 2.1< |η| < 2.4 :







Charge Asymmetry in ttbar

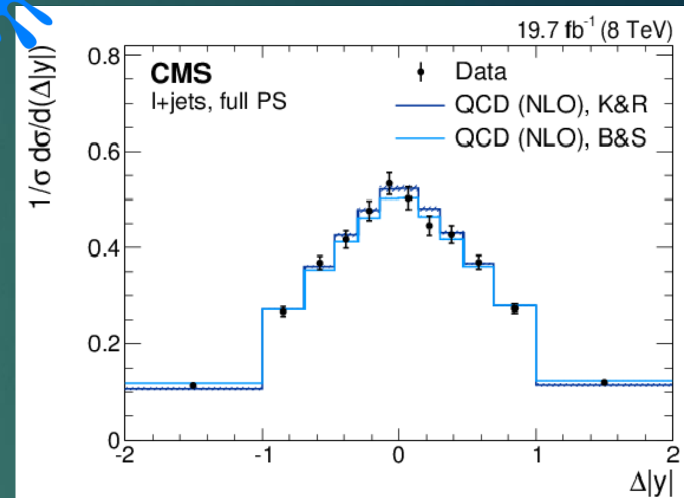
NEW!

arXiv:1507.03119

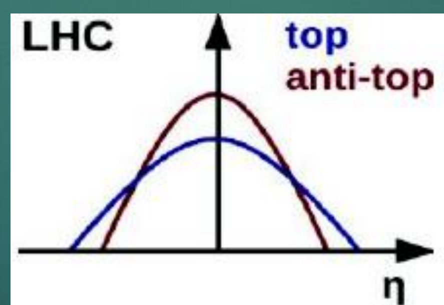
- ISR/FSR interference, LO-NLO interference induces small SM asymmetry in production rapidity
- Enhanced at NNLO, see "Resolving the Tevatron top quark A_{FB} puzzle"
  Czakon, Fiedler, Mitov, PRL 115, 052001 (2015)
- New CMS 8 TeV:
  A_C = +0.001 ± 0.0068 (stat) ± 0.0037 (syst)

  (NLO QCD: 0.010 - 0.011)

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

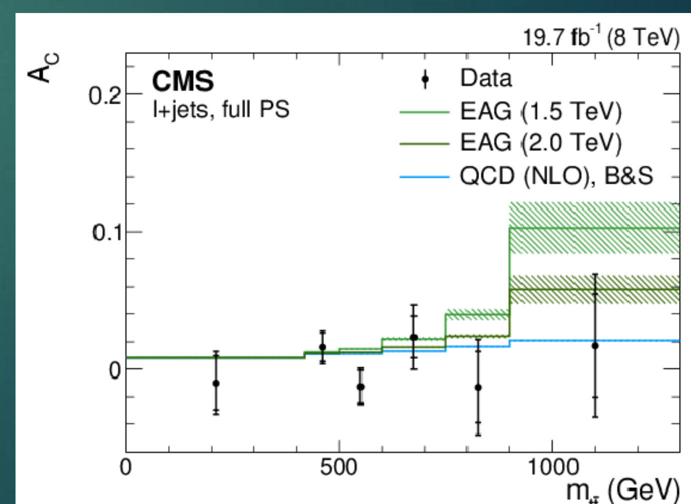


- Also differentially in y(tt), p_T(tt), and m(tt)



- Exotic tt interactions would modify A_C vs. mass: 1.5 TeV effective axial-vector gluon coupling excluded

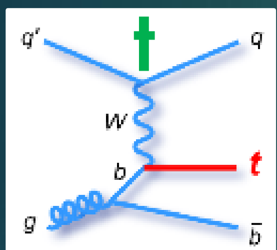
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

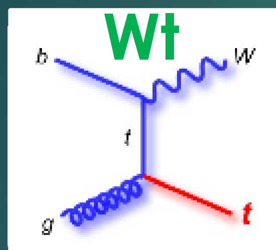


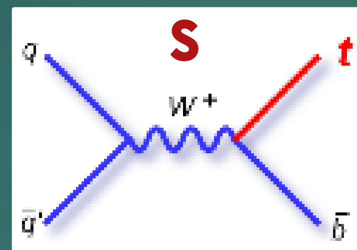
Electroweak Top Production

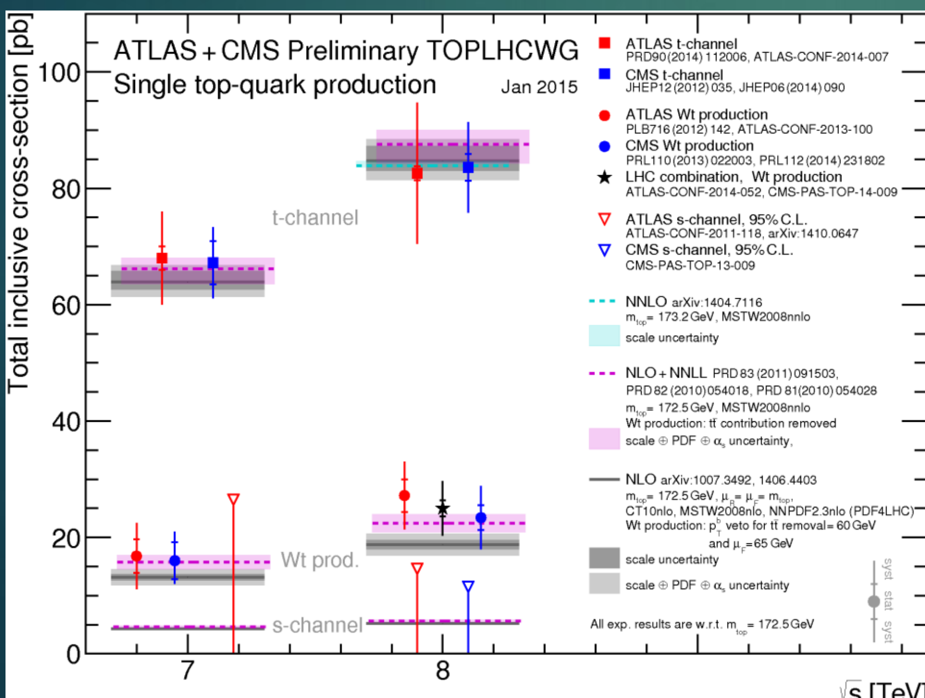
- 3 production modes (at LO)

observed | observed

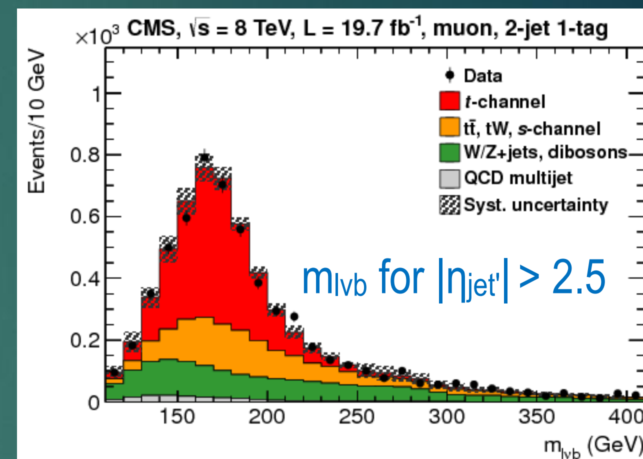








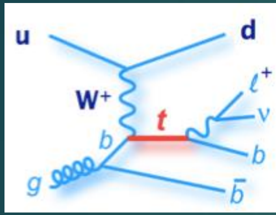
- t-channel single top: abundant and fairly pure

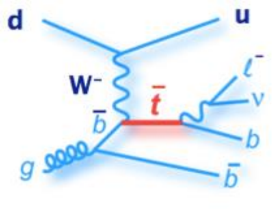


- Suitable for top quark property measurements: polarization, W helicity, V_{tb}, anomalous couplings, charge asymmetry, mass… (more in Run 2)

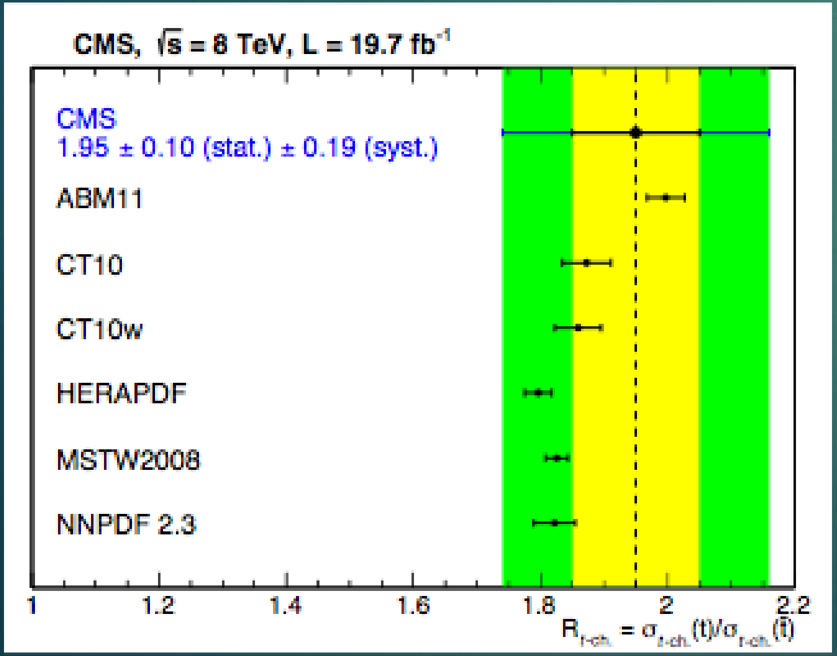
Charge Asymmetry and V_{tb} in Single Top

top | anti-top

2 x 

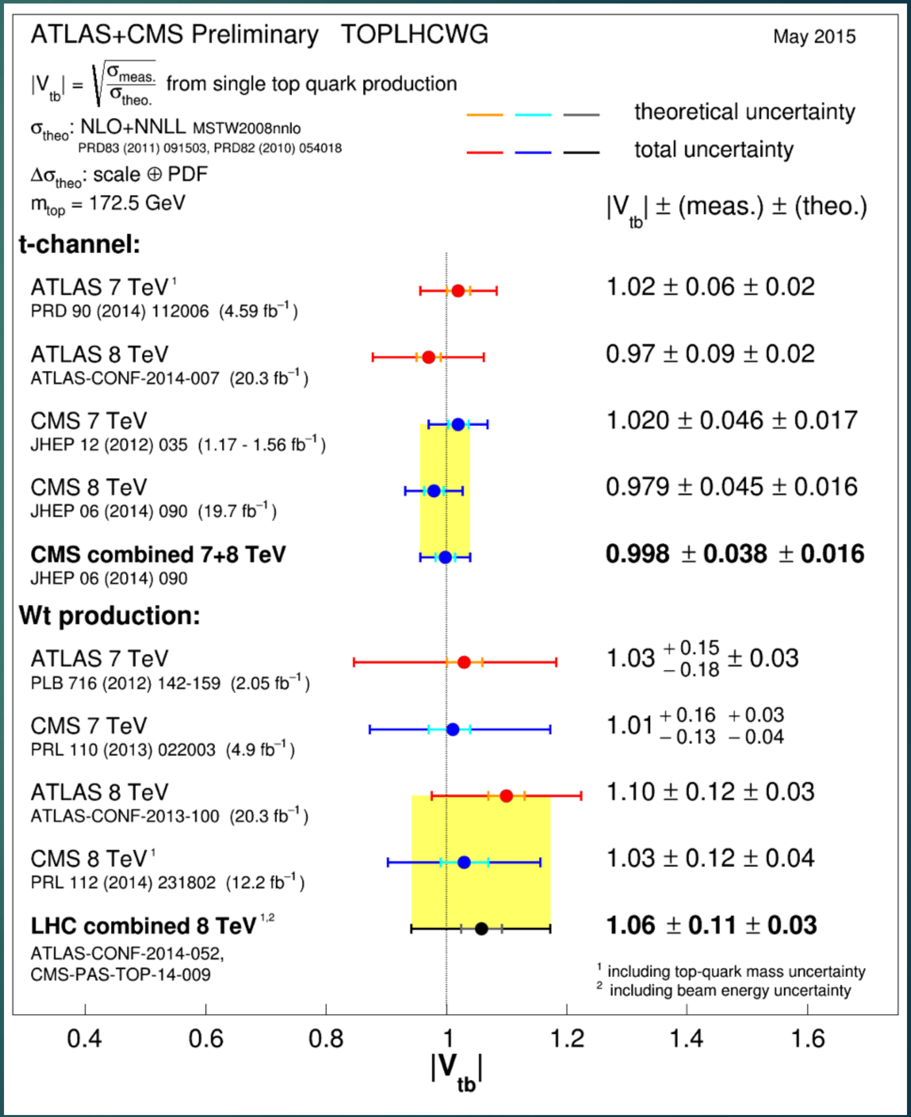


- t-channel: as for W, expect charge asymmetry with 2x more **u** than **d** in PDF



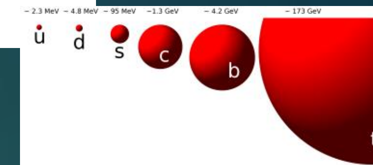
JHEP 06 (2014) 090

- Directly measure Vtb coupling:



Top is special

CMS 20 years



$1/m_t$ < $1/\Gamma_t$ < $1/\Lambda_{QCD}$ < m_t/Λ^2_{QCD}

Production time < Lifetime < Hadronization time < Spin decorrelation time

Production & Decay can be factorized (to good approx.)

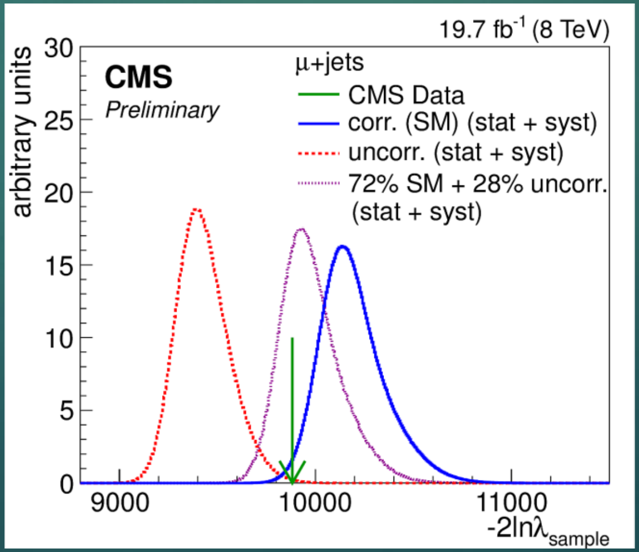
Allows study of "bare quark" properties, in particular spin information

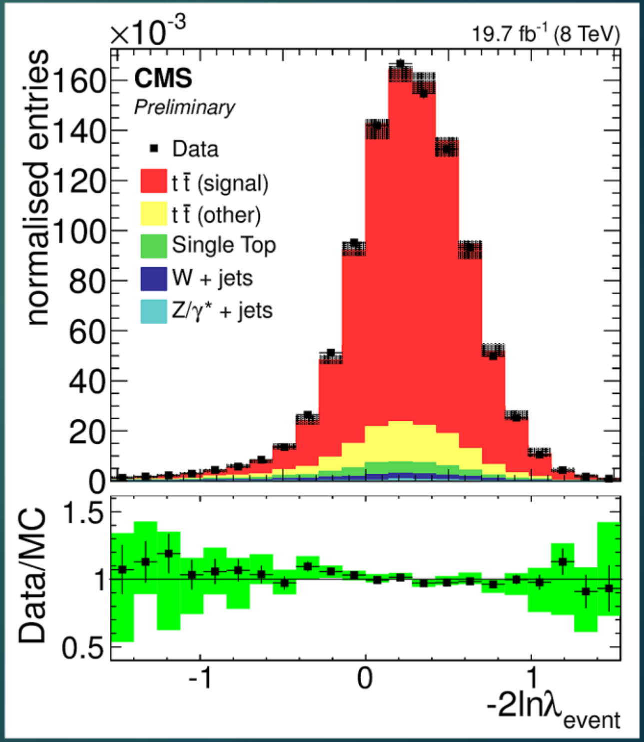
- Heaviest known elementary particle (Y_t ~1)
- Decays before it hadronizes or can form bound states
- Couples to all known forces..!
- Unique laboratory for precision QCD, quark EWK properties, EWK symmetry breaking, flavor studies, window to New Physics ?

Top spin correlations

CMS-PAS-TOP-13-015

- Measurement in μ+jets channel at 8 TeV
- Matrix Element method full 4-vector information of top quark decay products for improved statistical precision
- SM correlation preferred over uncorrelated hypothesis
- $f_{corr} = 72 \pm 9(\text{stat})^{+15}_{-13}(\text{syst})\ \%$
- Most precise result in lepton+jets channel

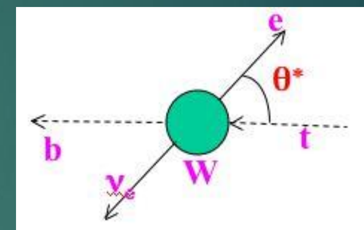




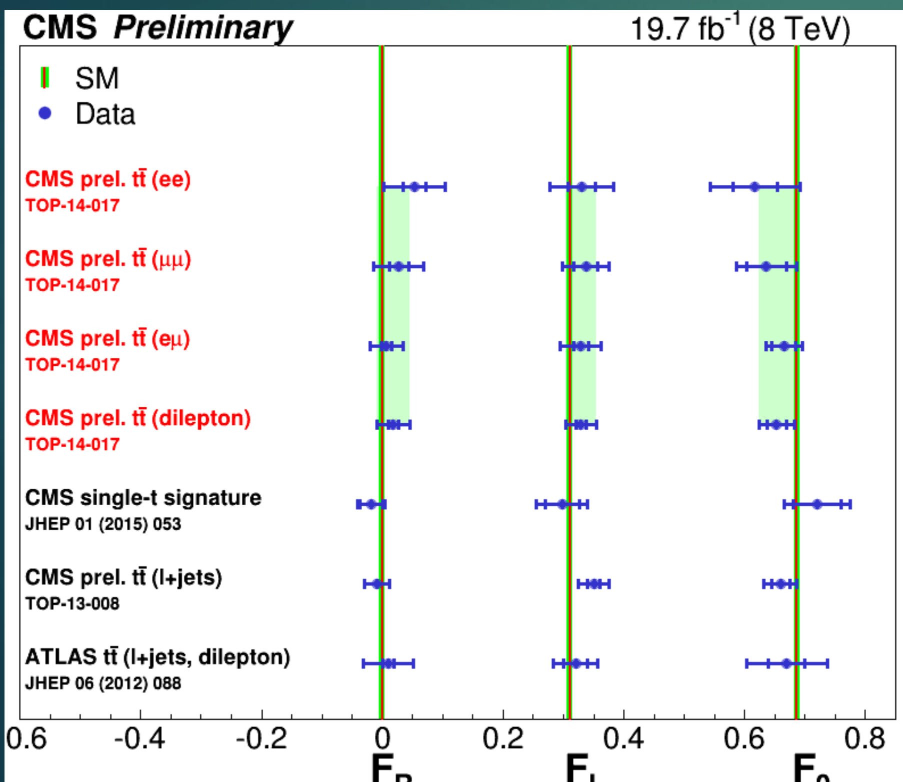
See also:
7 TeV dilepton channel
PRL 112 (2014) 182001

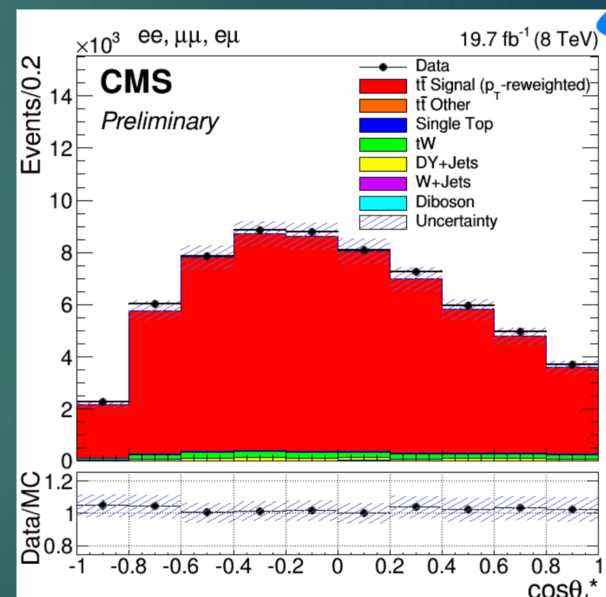
W helicity in ttbar

- New: di-lepton channel, 8 TeV
- Most precise in di-lepton channel
- In agreement with SM expectation



NEW!

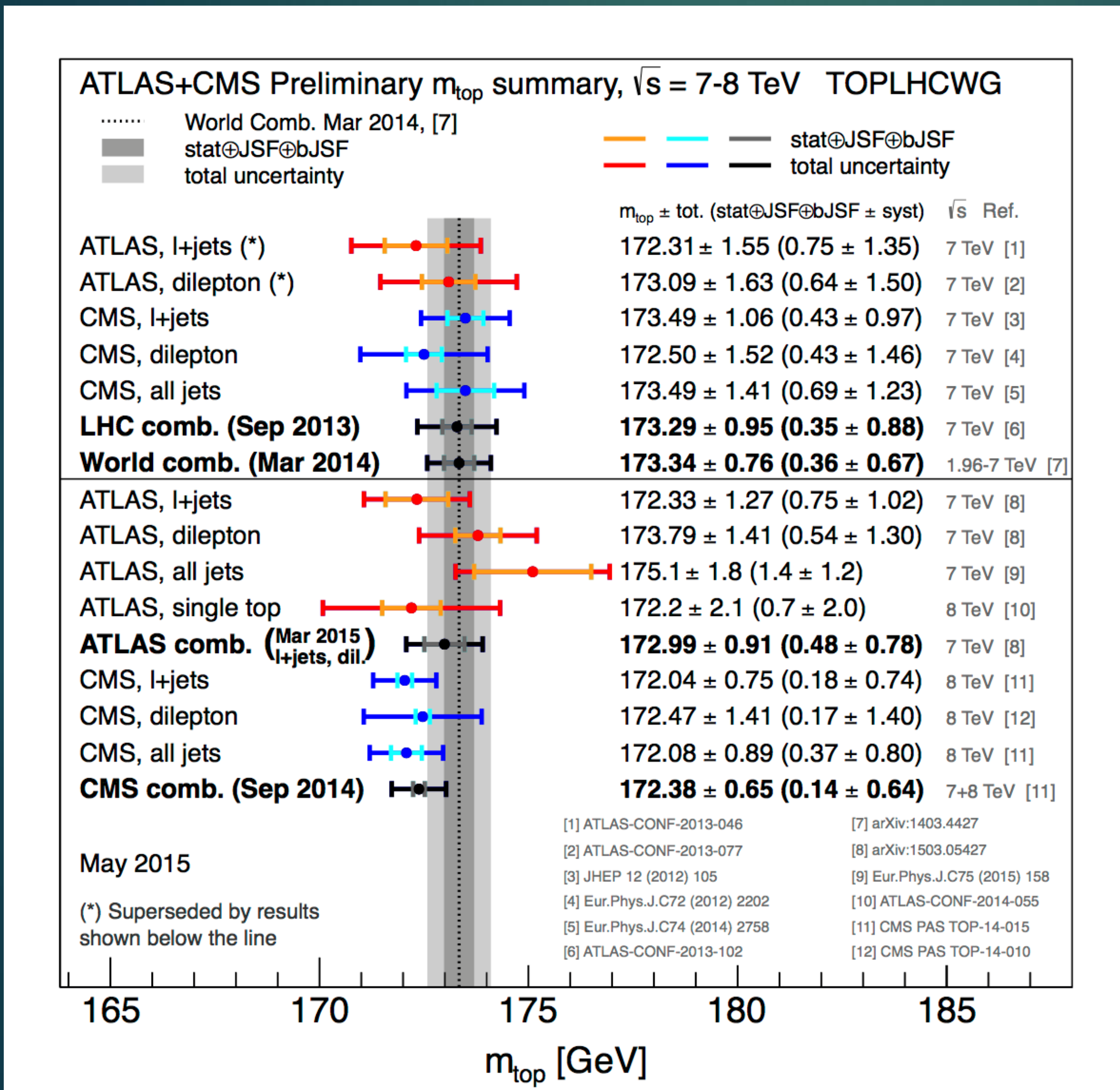




CMS-PAS-TOP-14-017

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0$$

Top Mass (from invariant mass)



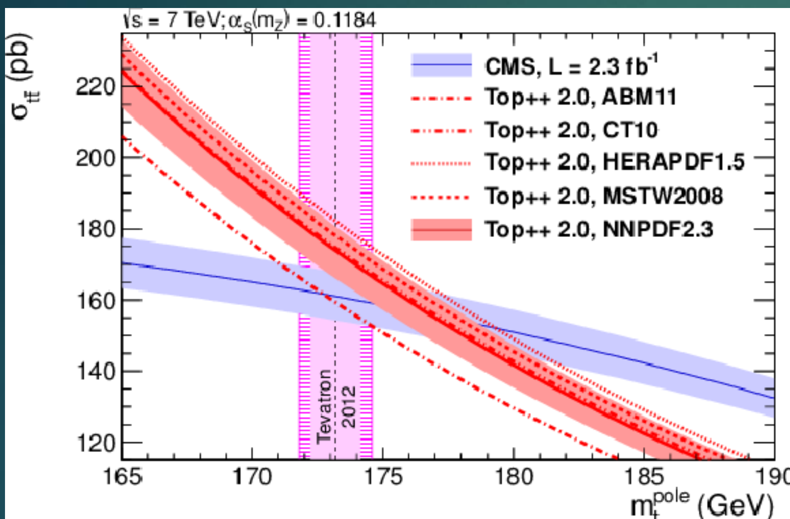
- Overall consistency observed between experiments, channels and collider energies
- Some tension for latest combinations:

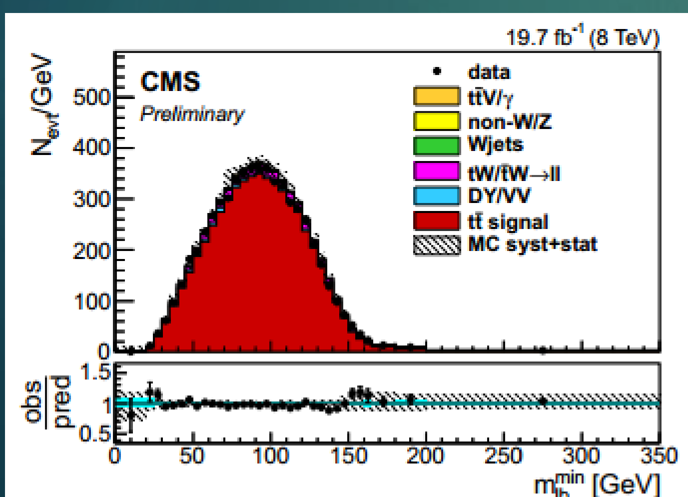
Tevatron	174.34 ± 0.64 GeV
CMS :	172.38 ± 0.65 GeV
ATLAS	172.99 ± 0.91 GeV

- Sub-GeV precision, even for some single results
- MC mass parameter extracted – no formal link with proper QFT renormalized m_{top}!

Top Mass (other observables)

[PLB 728 (2014) 496-517](#)
[Corrigendum: PLB 738 (2014) 526-528]



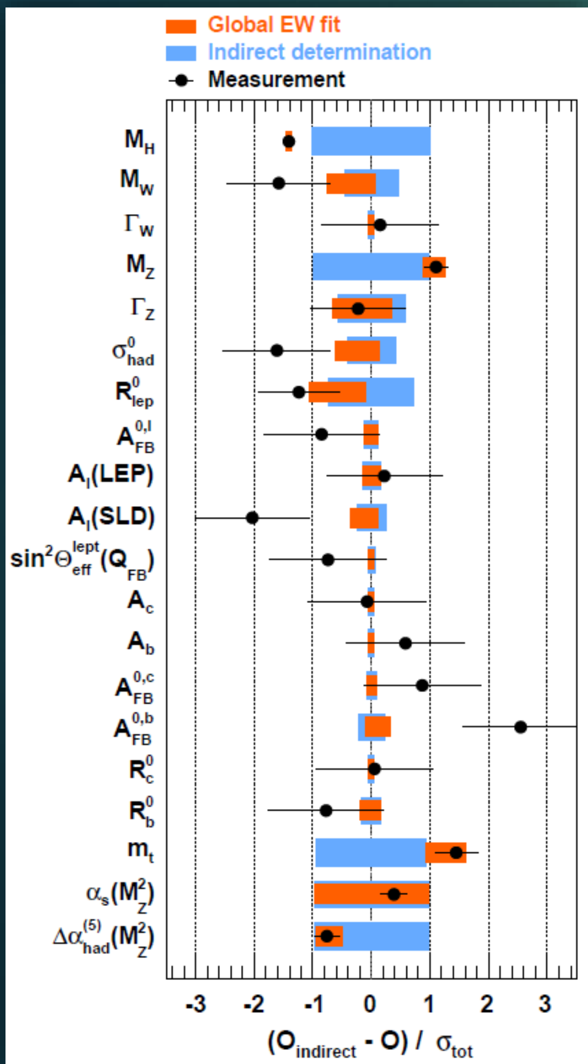


CMS-PAS-TOP-14-014

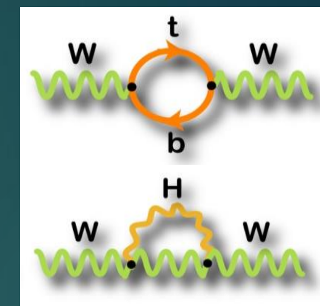
1. Pole mass from cross-section (a_s fixed to PDG value) → first result at NNLO precision $m_t^{pole} = 176.7^{+3.0}_{-2.8}$ GeV
2. M_{lb} spectrum → to allow well-defined top mass extraction from theory prediction
3. Lxy method → B hadron decay length (tracking only) CMS-PAS-TOP-12-030
4. Lepton kinematic endpoints → mass defined purely from kinematic formula (no MC, no QCD) EPJC 73 (2013)2494

Electroweak Fit

EWK fit at NNLO:



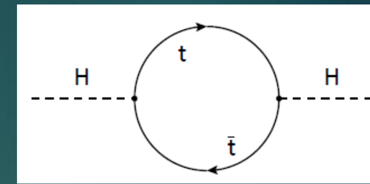
$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$



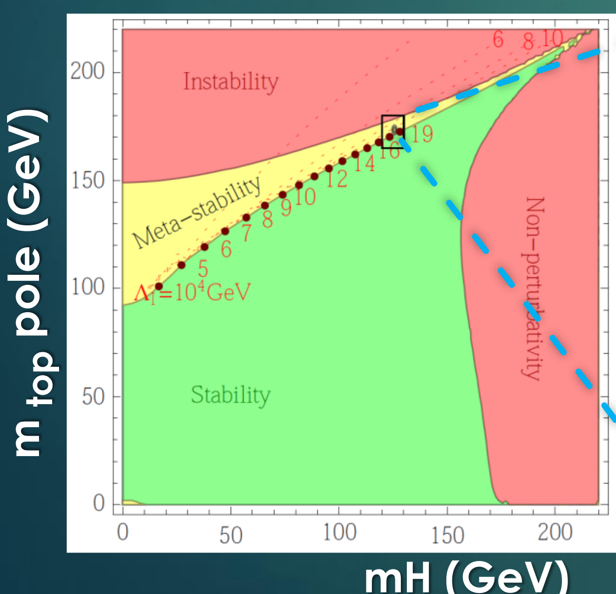
- With mH, all parameters of SM EWK sector measured precisely
- Overconstrained: consistency check of the Standard Model + search for hints of BSM
- Overall very good fit
- Main experimental uncertainty is from mW
- New EWK (+Higgs) measurements from LHC (and beyond) will allow more precise tests

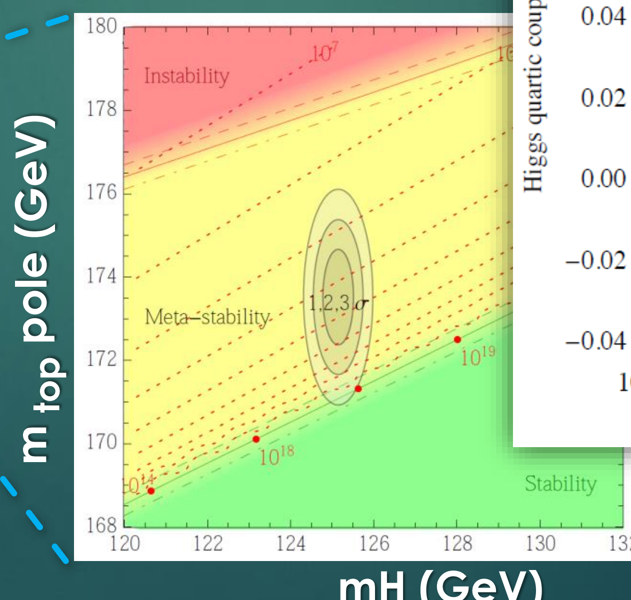
http://arxiv.org/abs/1407.3792
EPJC 74 (2014) 3046

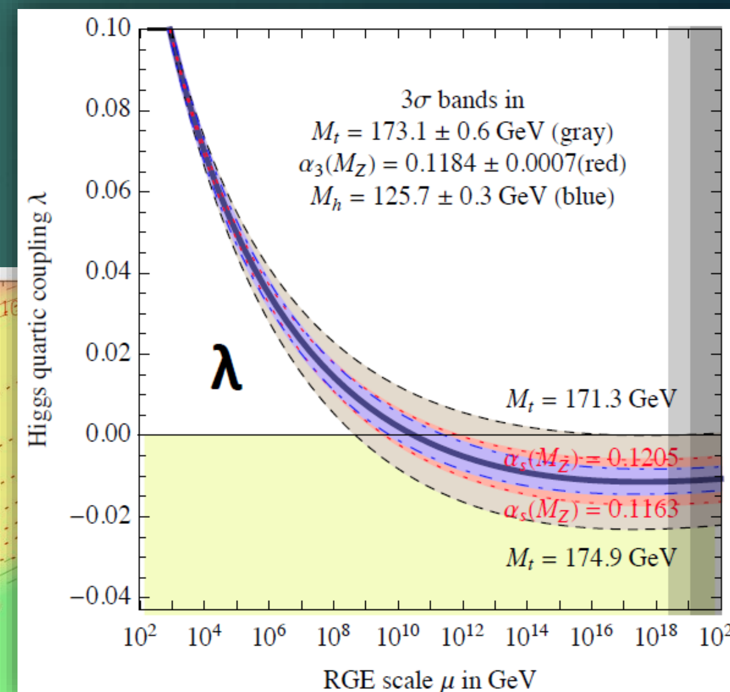
Vacuum Stability



- Evolution of Higgs quartic coupling λ , and of the corresponding Higgs potential depends strongly on top mass through radiative corrections … main uncertainty is from top mass
- Surprise fact from Run 1: with current Higgs and Top mass, EWK vacuum is <u>surprisingly stable</u>: on border between stability and meta-stability
- No requirement for New Physics to be "around the corner" …

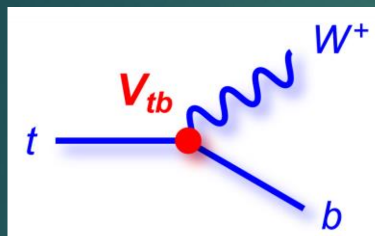


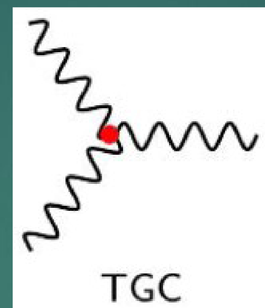


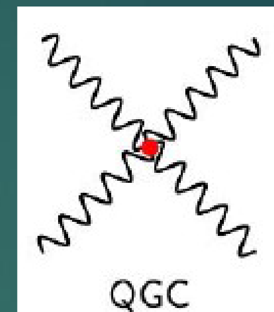


<u>Degrassi et al, JHEP 1208 (2012) 098</u>

Anomalous Couplings







- Single Top, and (EWK) di-boson / tri-boson production at LHC Run 1 allow detailed study of top and Vector Boson couplings
- Effect of New Physics at a scale Λ can be described with higher-dimensional operators in effective field theory:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \ldots$$

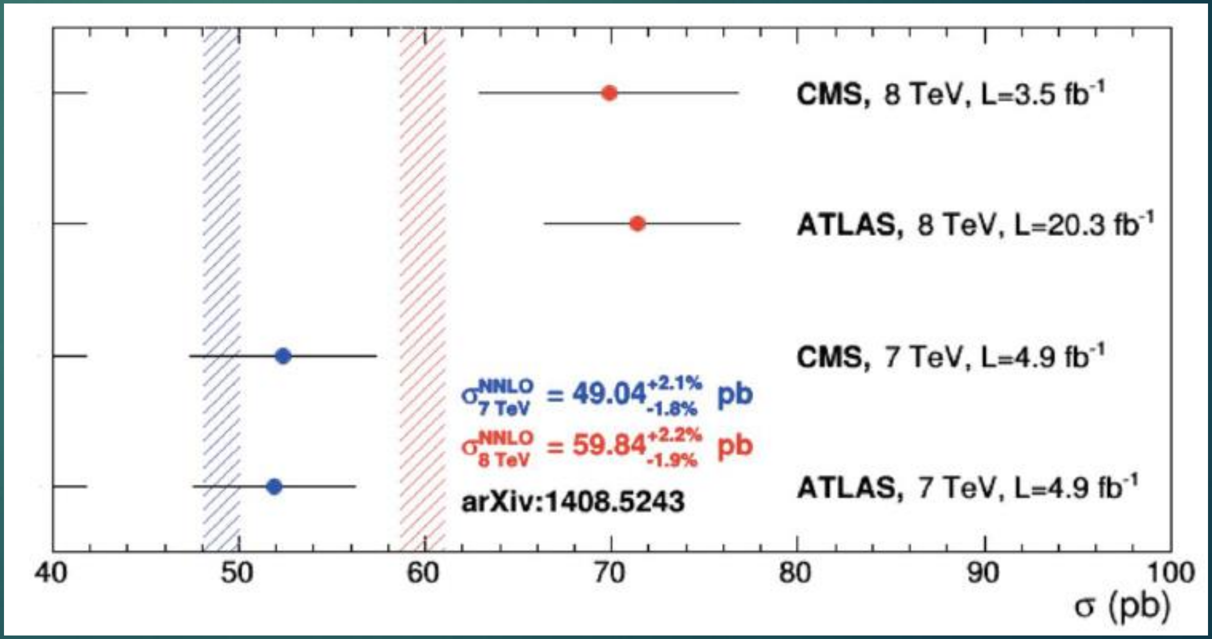
- Dimension 6 and 8 operators are the most relevant
- Equivalence to description in terms of anomalous TGCs and QGCs

  See eg C. Degrande et al Annals Phys. 335 (2013) 21-32

- So far: no evidence of any deviations from the Standard Model

Di-bosons

- Di-boson events at LHC Run 1: bread and butter of EWK physics
- Studied in many production and decay channels
- Allows to probe Gauge couplings (TGCs) with great precision
- Previously: tension between observed WW cross section and NLO prediction (~20% effect ~ 2 sigma in ATLAS and CMS)



WW production cross section

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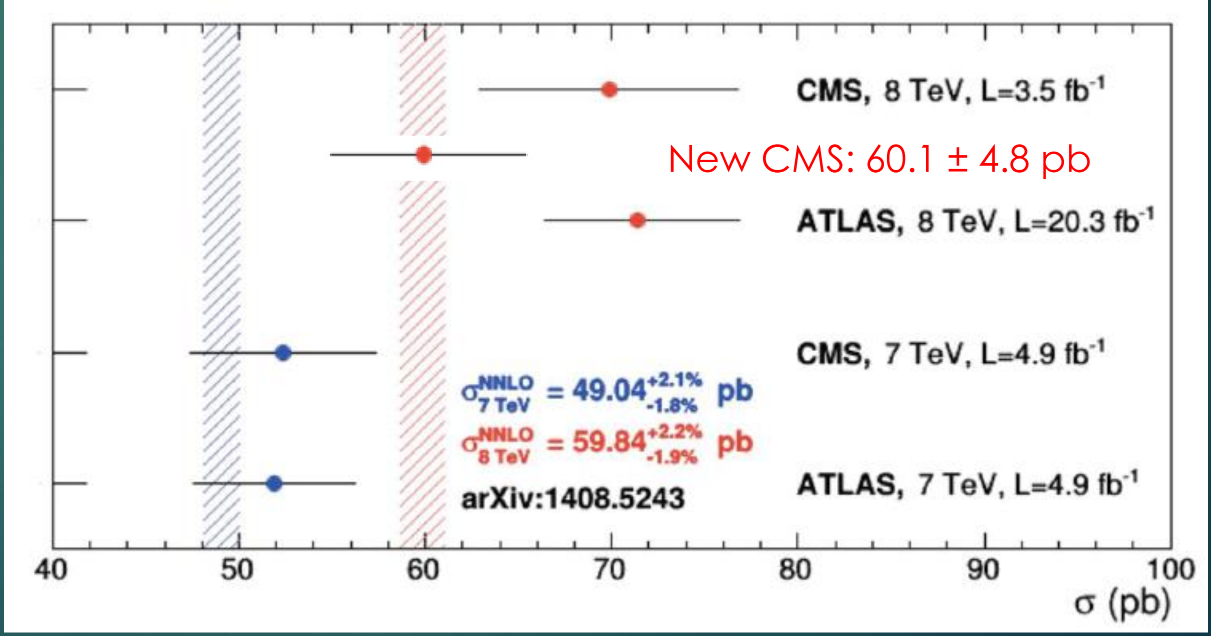
- NNLO reduced tension

arXiv 1507.03268

- New: CMS (8 TeV) consistent with NNLO prediction



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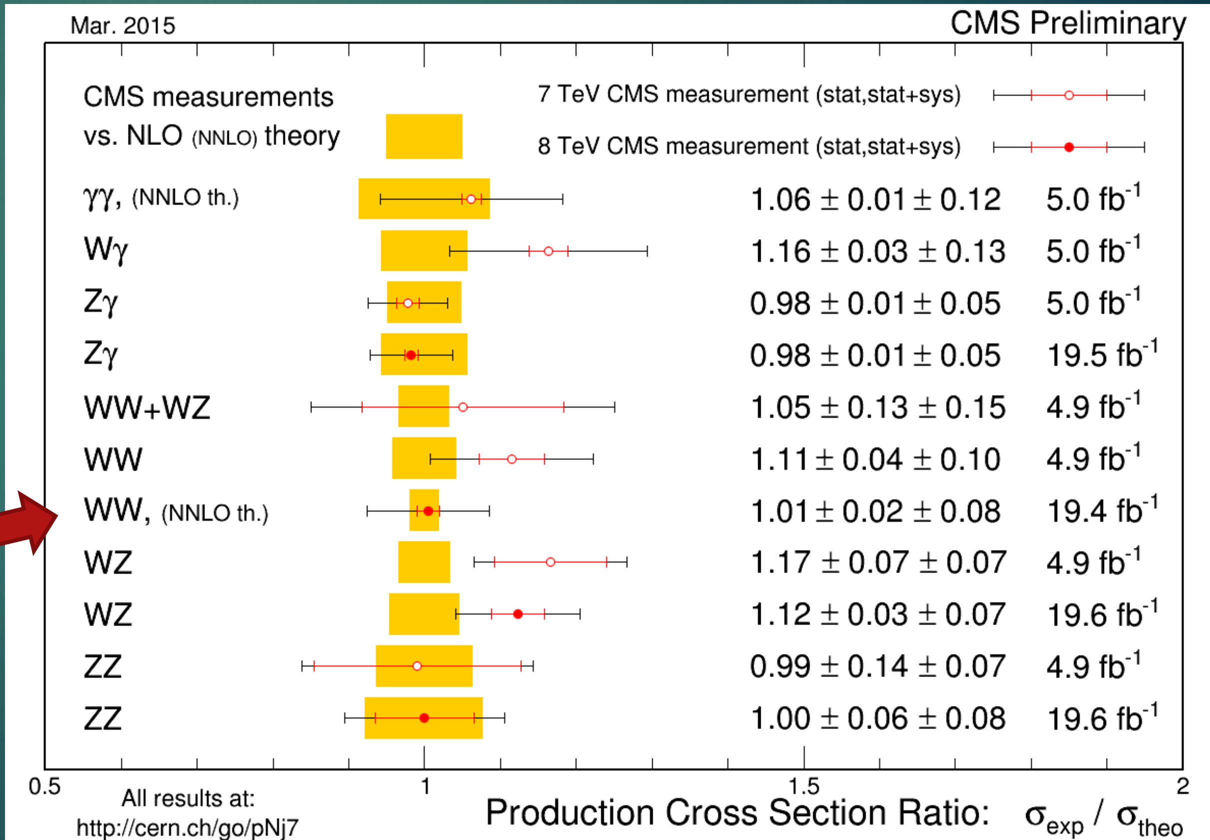
- Previously: tension between observed WW cross section and NLO prediction
- NNLO reduced tension

NEW!

arXiv 1507.03268

- New: CMS (8 TeV) consistent with NNLO prediction
- No discrepancies > 2σ (in CMS)

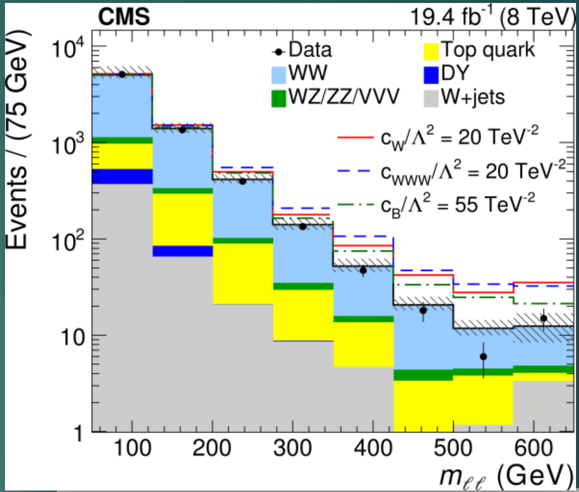


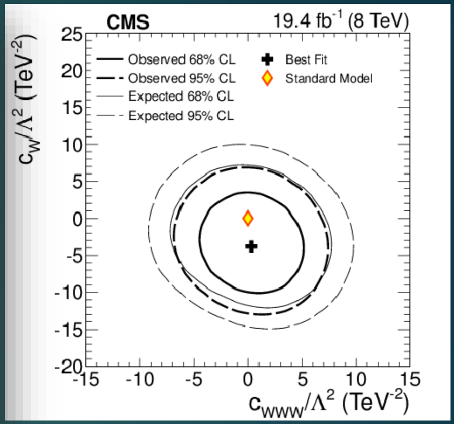
Anomalous TGCs

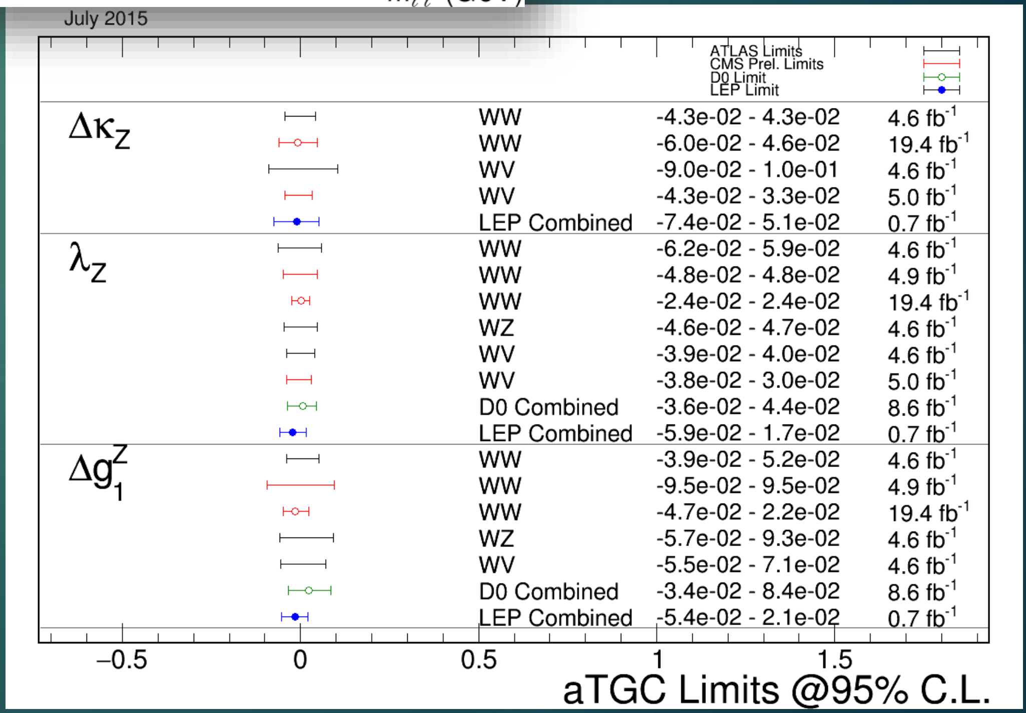
arXiv 1507.03268

NEW!

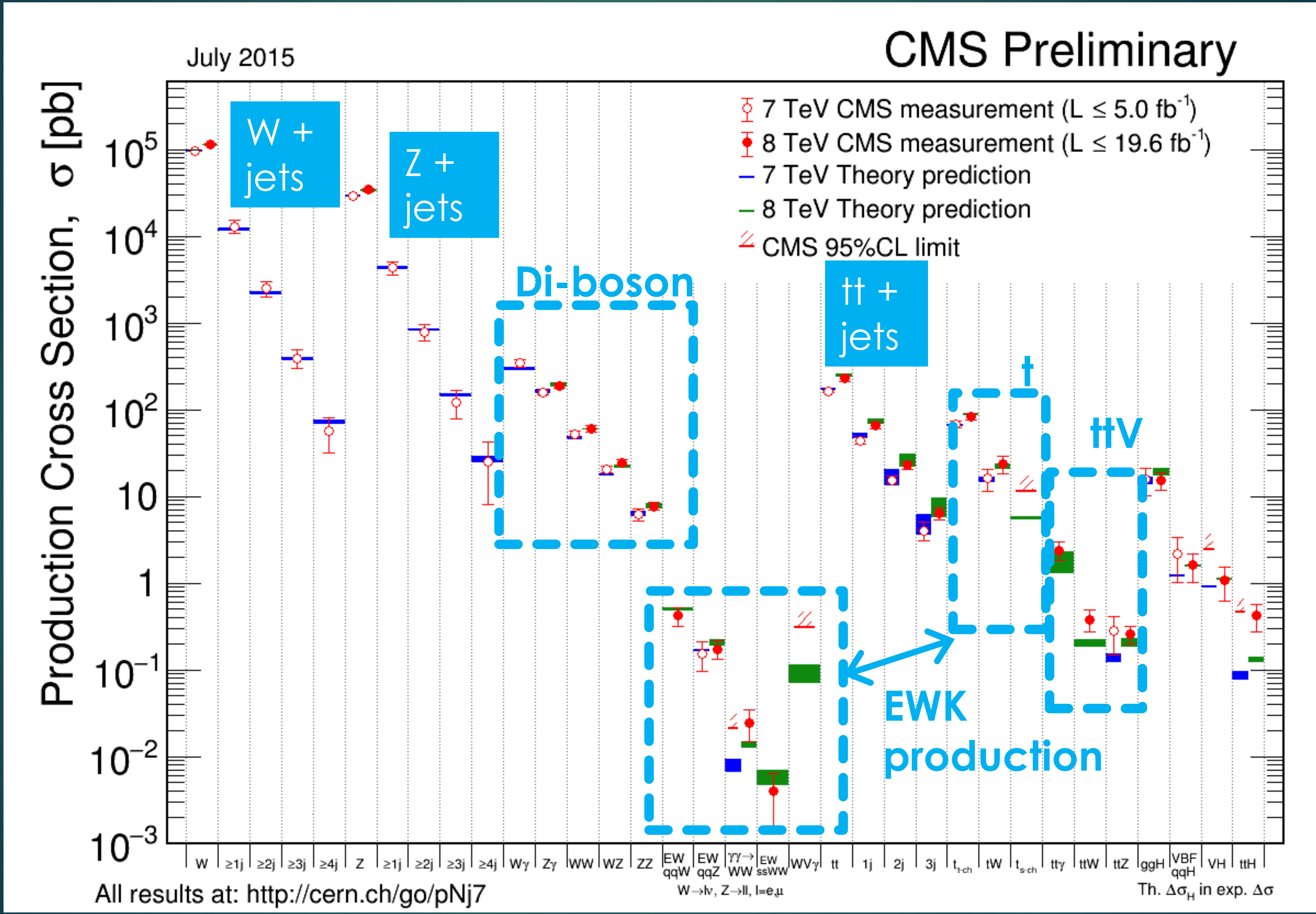
- WW: no sign of anomalous effects in high-mass tail $m_{\ell\ell}$
- LHC limits competitive in charged TGC couplings
- The WV final state is slightly more sensitive than WW →
- For more info on neutral aTGC and aQGCs see: http://cern.ch/go/kMP8



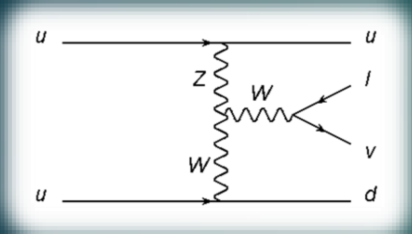




On to more 'exotic' processes:



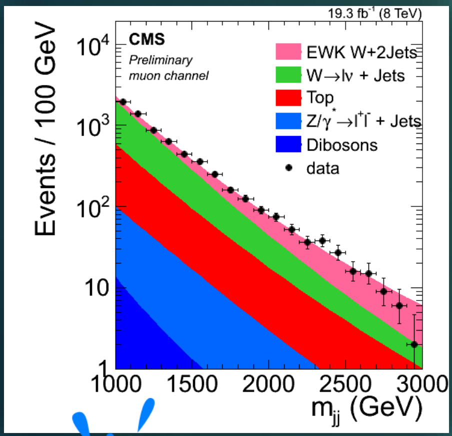
Triple-boson and EWK di-boson production



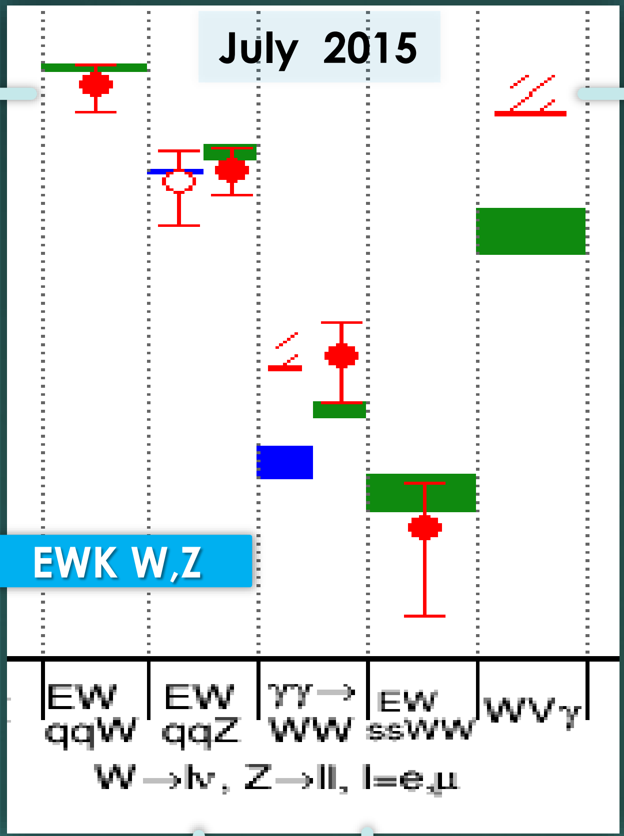
+ other diagrams

- EWK qqW, agrees with NLO prediction

CMS-PAS-SMP-13-012

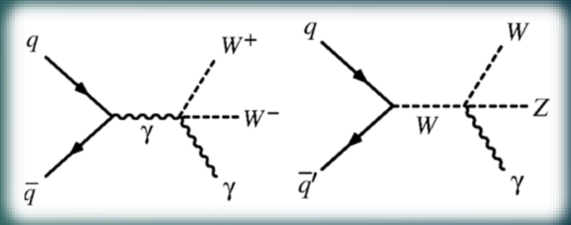


NEW!



VV scattering

EPJC 75 (2015) 66



PRD 90 (2014) 032008

- Triple-boson production
- Limit: 3.4 x SM prediction
- First constraints on 8-dim operator, and aQGCs

- First studies of vector boson scattering
- See talk by Dilson de Jesus Damião this afternoon

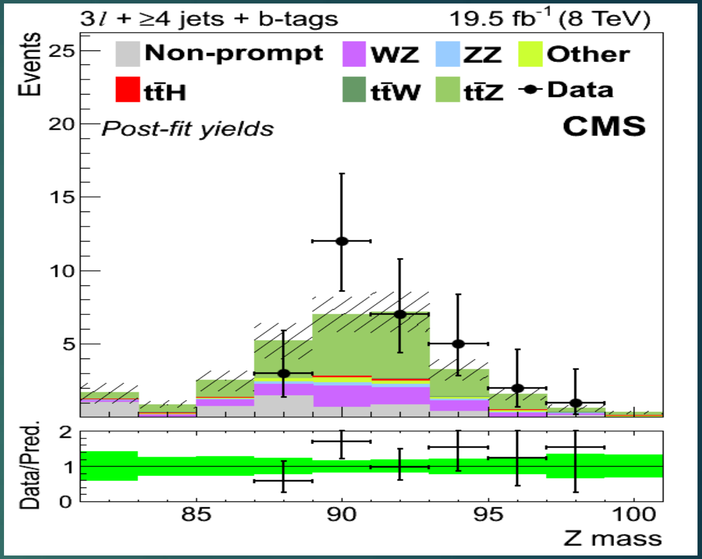
ttZ, ttW

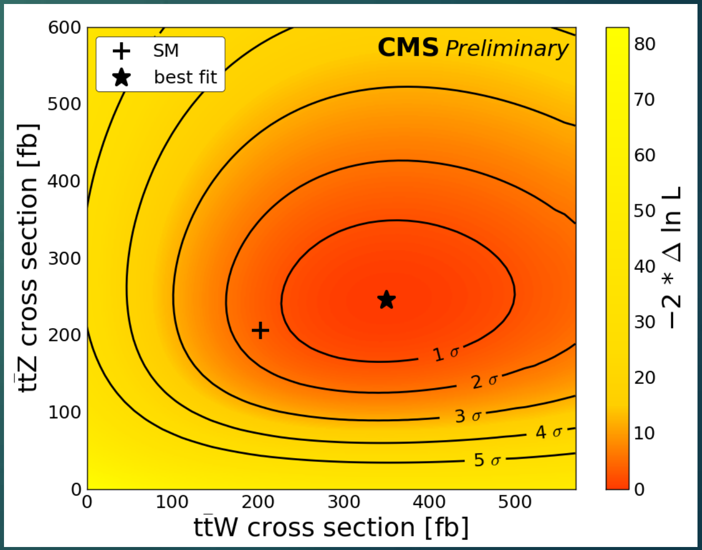
NEW!

CMS-PAS-TOP-14-021

- Combining signatures with 2, 3 or 4 leptons and b-jets
- ttW significance 4.8 σ (3.5 σ expected)
- ttZ significance 6.4 σ (5.7 σ expected)
- Measured cross-sections allow to put constraints on 5 anomalous dimension-6 operators:

operator	best fit point(s)	1σ CL	2σ CL
$\bar{c}_{uB}$	-0.07 and 0.07	{-0.11, 0.11}	{-0.14, 0.14}
$\bar{c}'_{HQ}$	0.12	{-0.07, 0.18}	{-0.33, -0.24} and {-0.02, 0.23}
$\bar{c}_{HQ}$	-0.09 and 0.41	{-0.22, 0.08} and {0.24, 0.54}	{-0.31, 0.63}
$\bar{c}_{Hu}$	-0.47 and 0.13	{-0.60, -0.23} and {-0.11, 0.26}	{-0.71, 0.37}
$\bar{c}_{3W}$	-0.28 and 0.28	{-0.36, -0.18} and {0.18, 0.36}	{-0.43, 0.43}





Rare (FCNC) top decays

- SM: FCNC decays expected to be extremely rare Br ~O(10^{-15})
- → Any observation == New Physics !!

- t → Zc : Br < 0.05 %

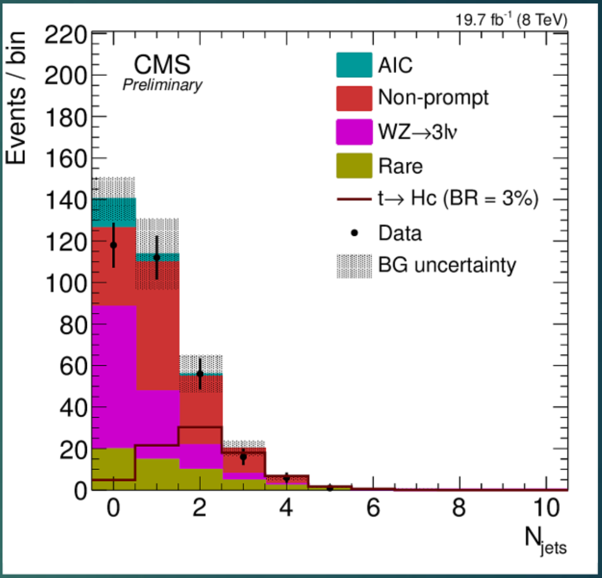
PRL 112 (2014) 171802 , PLB 718 (2013) 1252

- t → Hc (lepton channels):

  Br < 0.93 % observed

  0.89% expected

NEW!



CMS-PAS-TOP-13-017

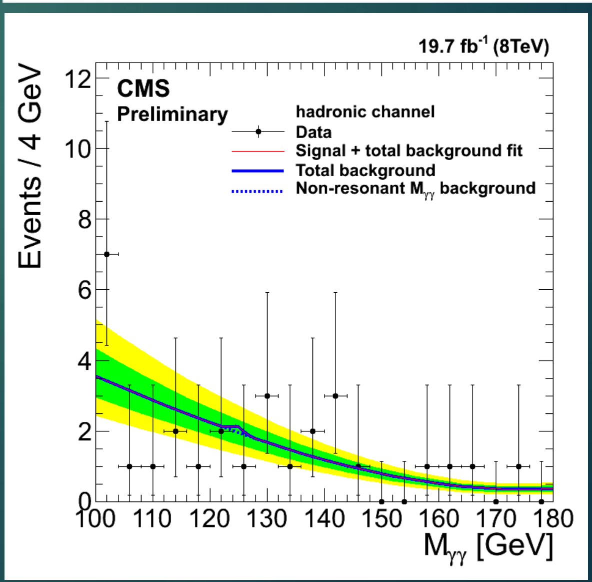
- t → Hc(u) with H → γγ :

  Br < 0.47 (0.42) % observed

  0.71 (0.65) % expected

NEW!

[at 95% CL]

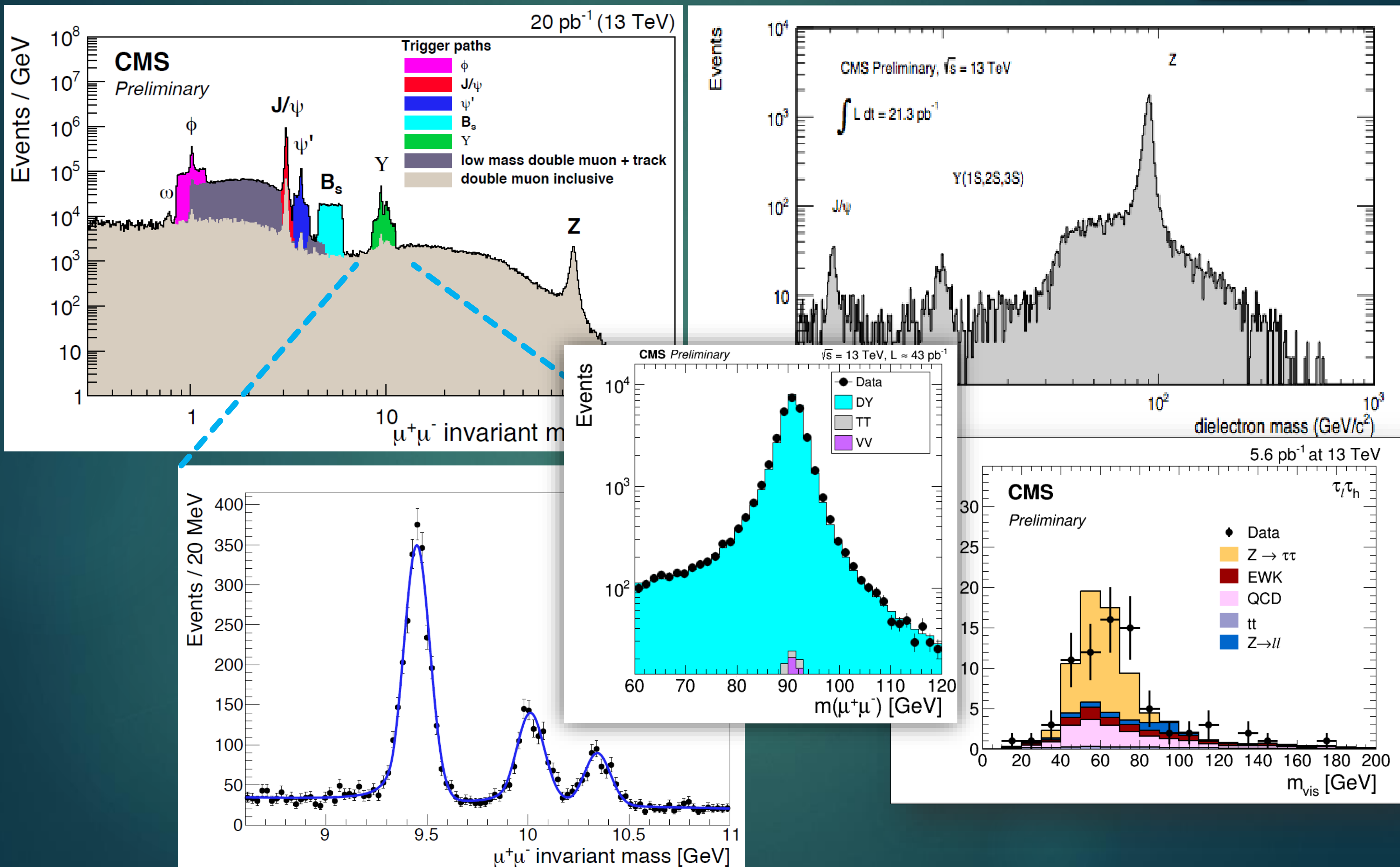


CMS-PAS-TOP-14-019

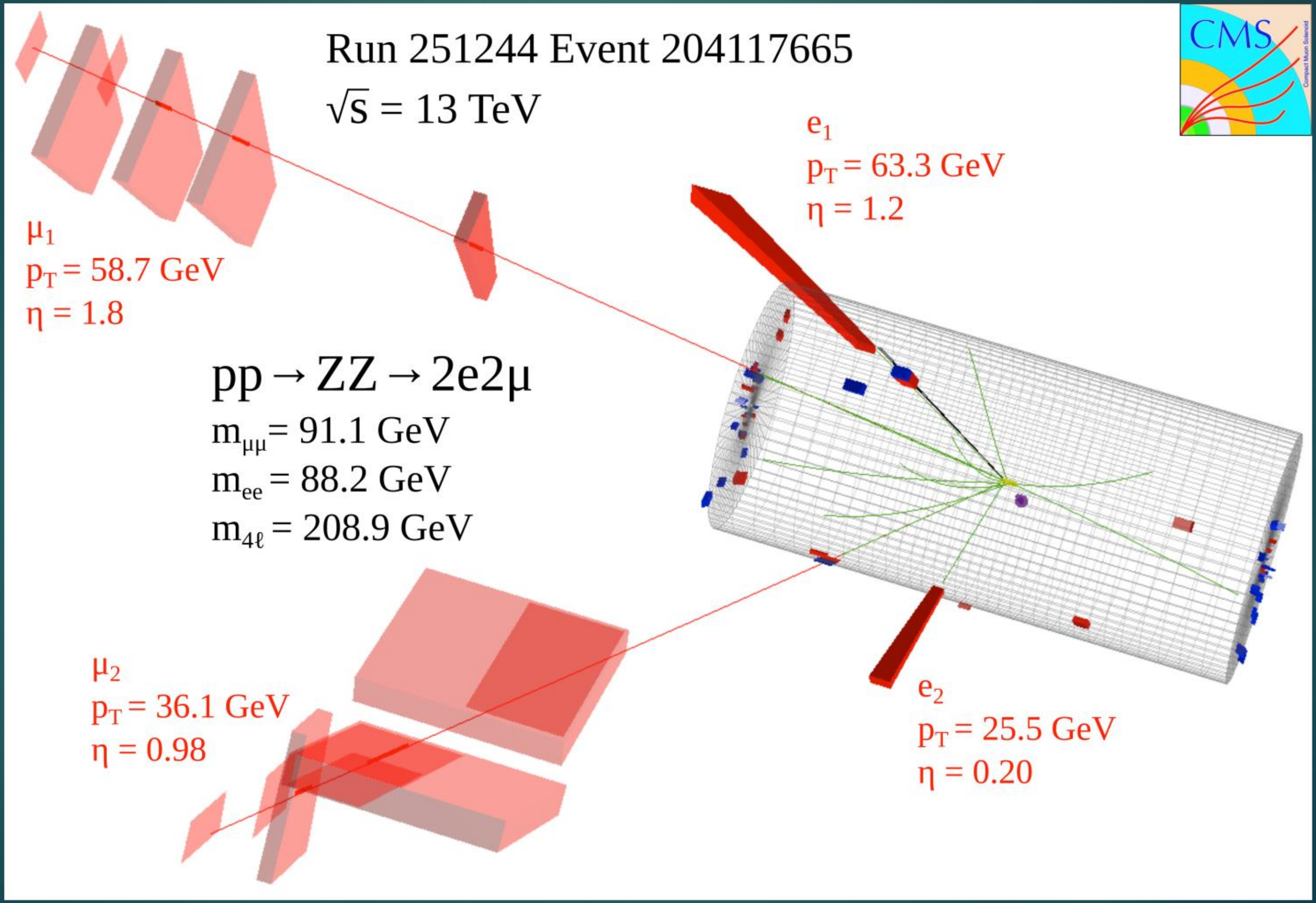
Summary Run 1 Expedition

- Tera-scale production of jets, vector bosons, top
- Standard Model Map verified, updated, completed → accurate and possibly stable up to high scales !
- New processes (besides Higgs): tW, ttV, EWK production of Z and W, first signs of WW scattering
- Testing beyond NLO QCD: NLO+PS, NNLO, NLO EWK… Array of new tools ready for Run 2 !!

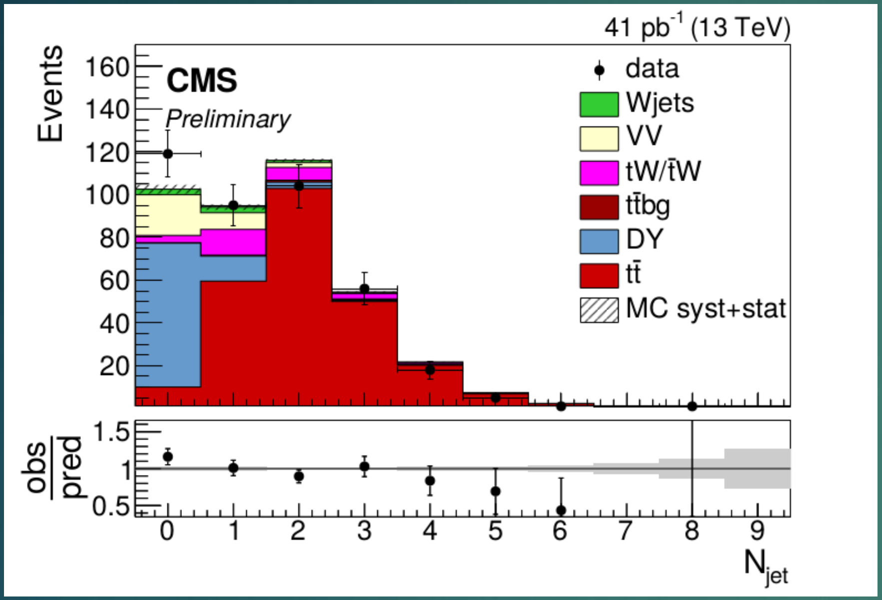
First look at 13 TeV:

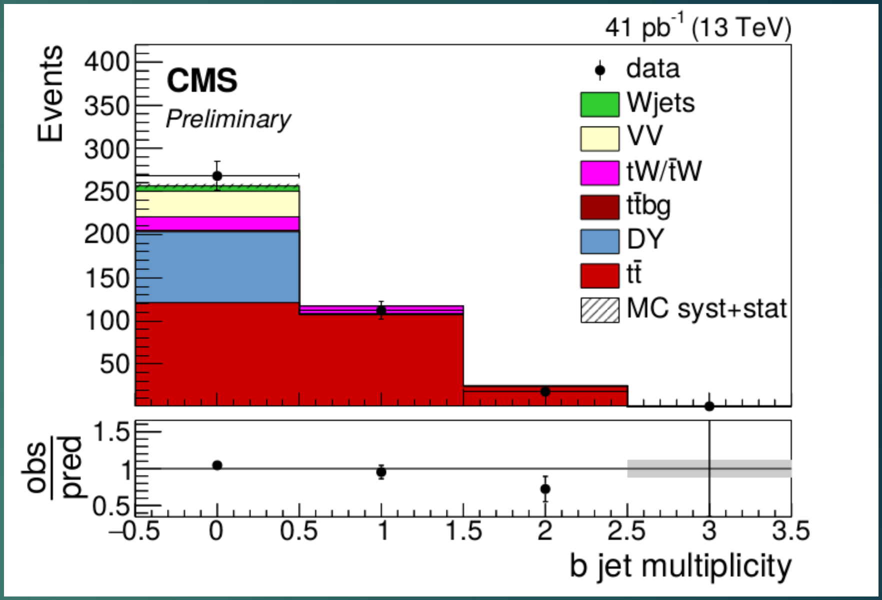


A di-boson candidate:



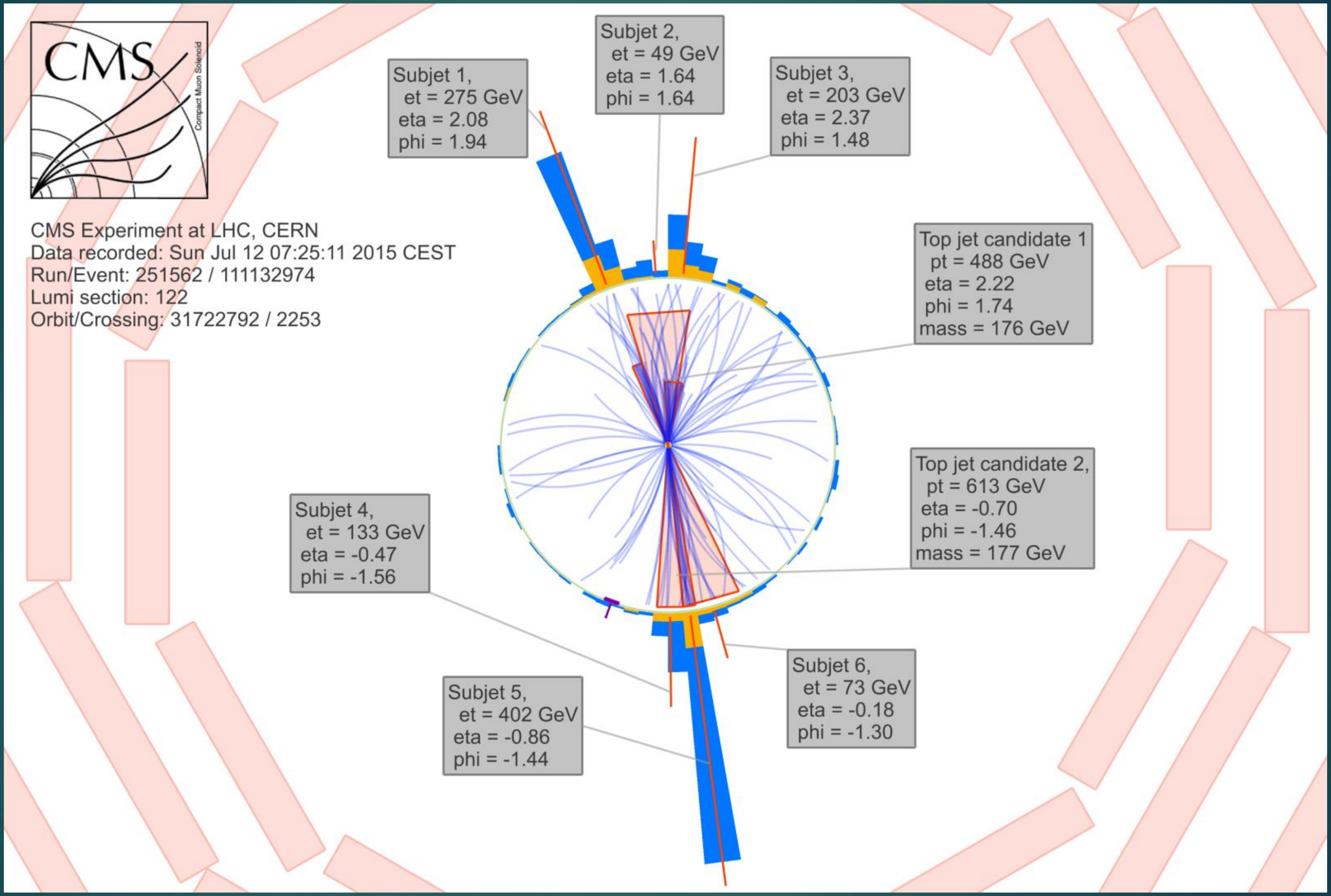
Top as expected, at 13 TeV:





Distribution of the number of hadronic jets with p_T>30 GeV, $|\eta|$<2.4 (left) and jets passing the tight threshold on the b-tagging discriminant (right) for events containing one isolated muon (p_T> 20 GeV, $|\eta|$<2.4, passing tight identification criteria) and one isolated electron (p_T> 20 GeV, $|\eta|$<2.4, excluding barrel-endcap gap, passing medium identification criteria) with opposite charge, forming an invariant mass greater than 50 GeV

Boosted ttbar (m_{tt}=2.49 TeV)

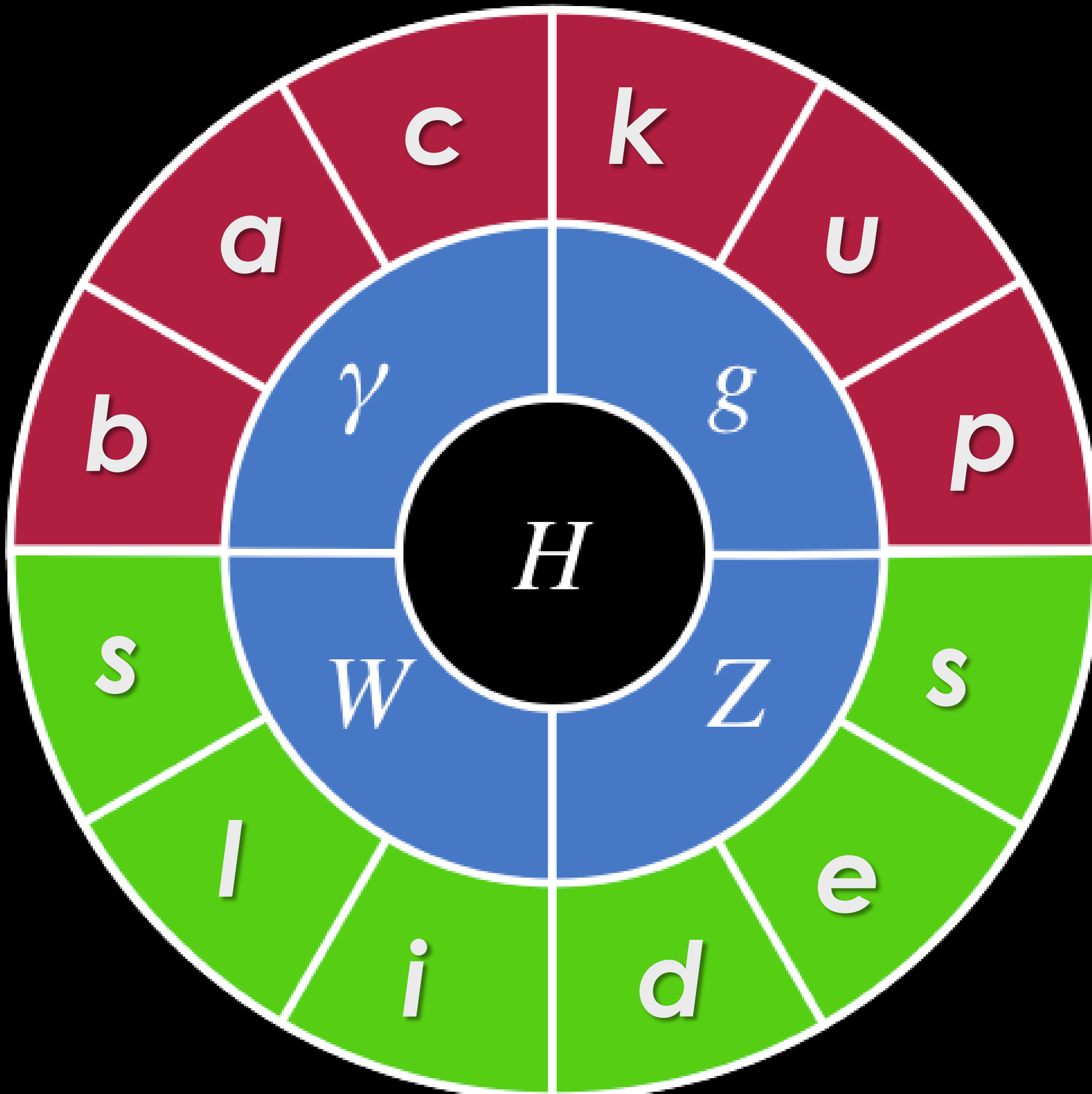


m(topjet1)=177 GeV, pt(topjet1)=0.61 TeV
m(topjet2)=176 GeV, pT(topjet2)=0.49 TeV

6 subjets,
1 b-tagged subjet

Voltzberg Bump Hunt, Surinam, 1981

Ready for a New Adventure !


b
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More information

- New CMS publications page:

http://cms-results.web.cern.ch/cms-results/public-results/publications/

- Standard Model Results:

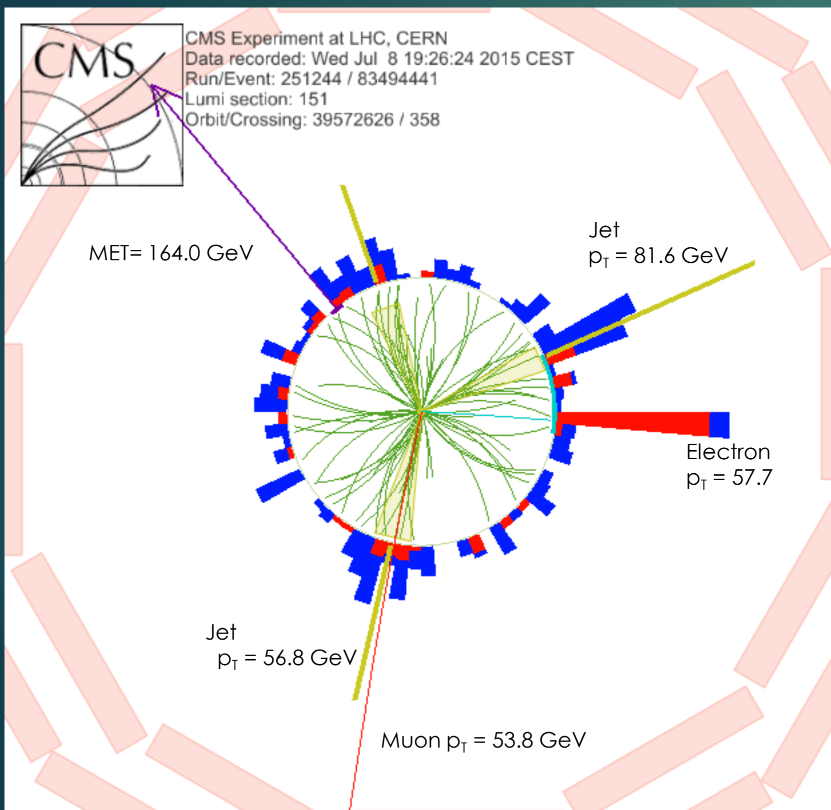
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

- Top Physics Results:

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

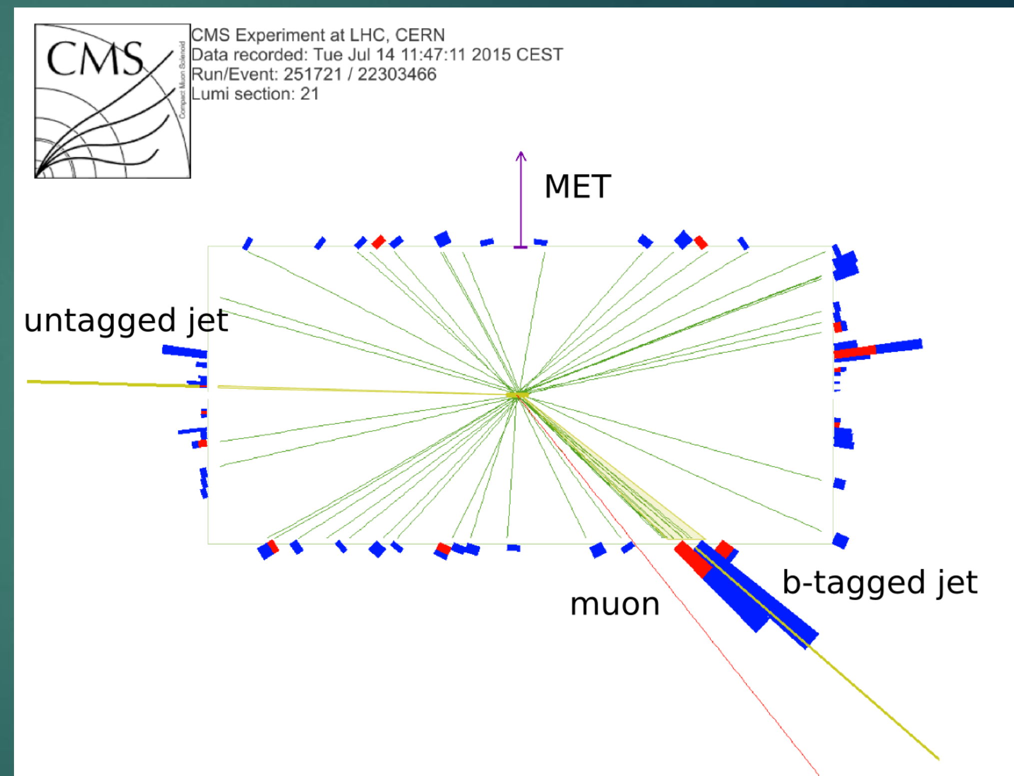
Top candidate events:

ttbar eμ bb



- One isolated muon, one isolated electron and two b-tagged hadronic jets.

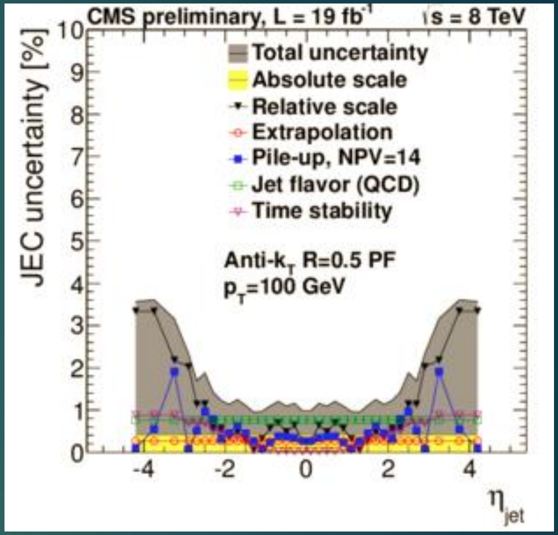
single top t-channel

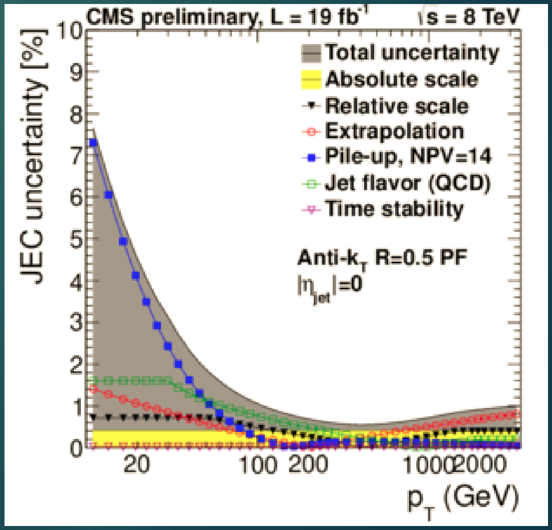


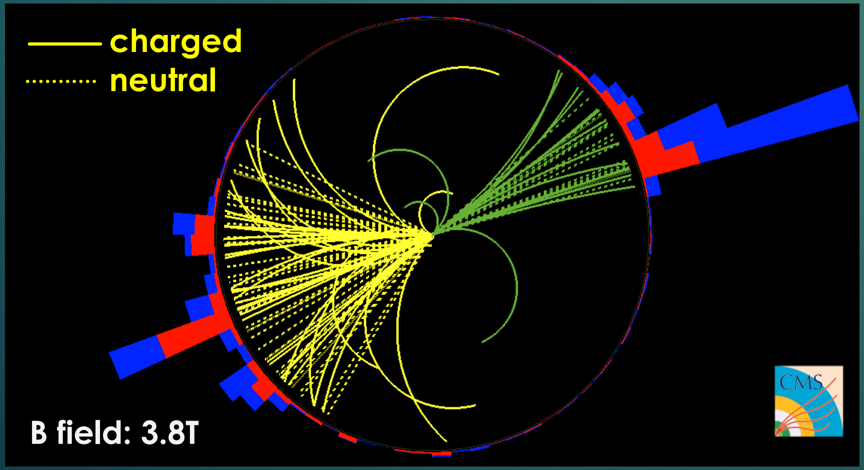
- One isolated muon, one b-tagged central jet, one forward jet |η| = 4.7 Reconstructed top mass: 177 GeV

Jet reconstruction in CMS

- Anti-kt clustering algorithm common to most all results (R = 0.5 and 0.7 at CMS)
- CMS Particle Flow Jets (PF Jets): Clustering of particle flow candidates constructed by combining information from all sub-detector systems
- Jet energy scale (8 teV) ~1% in barrel 100 GeV and above !



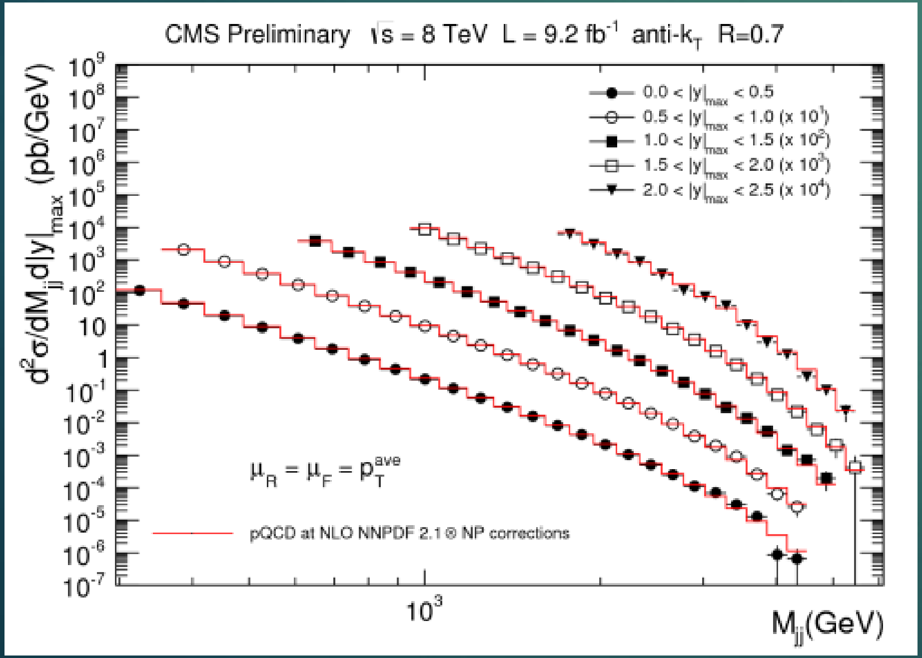


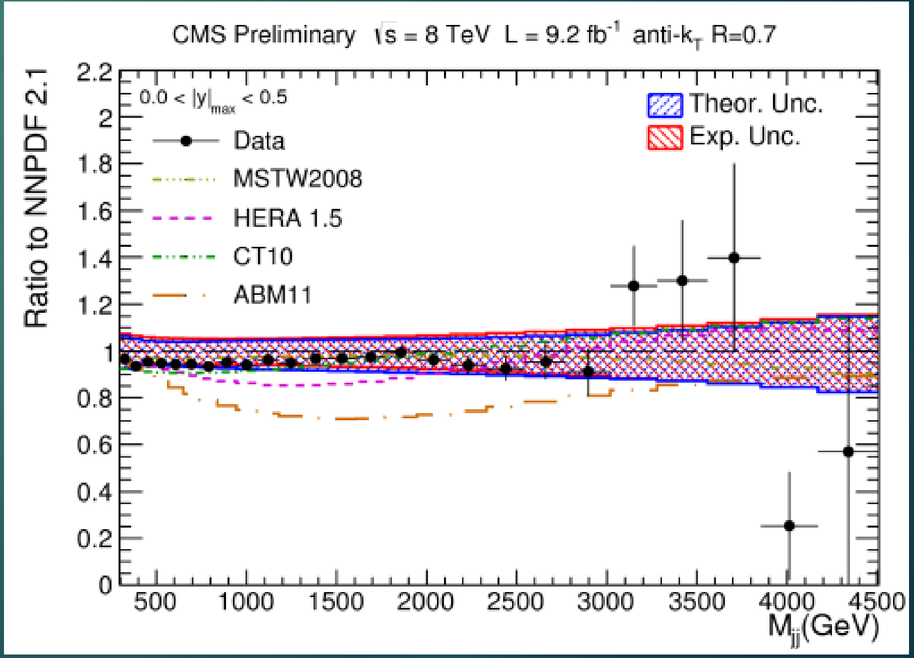


Di-jet production

- Dijet predictions at 7 TeV and 8 TeV also consistent with data
- Events up to about 5 TeV (… this will go fast at 13 TeV !)

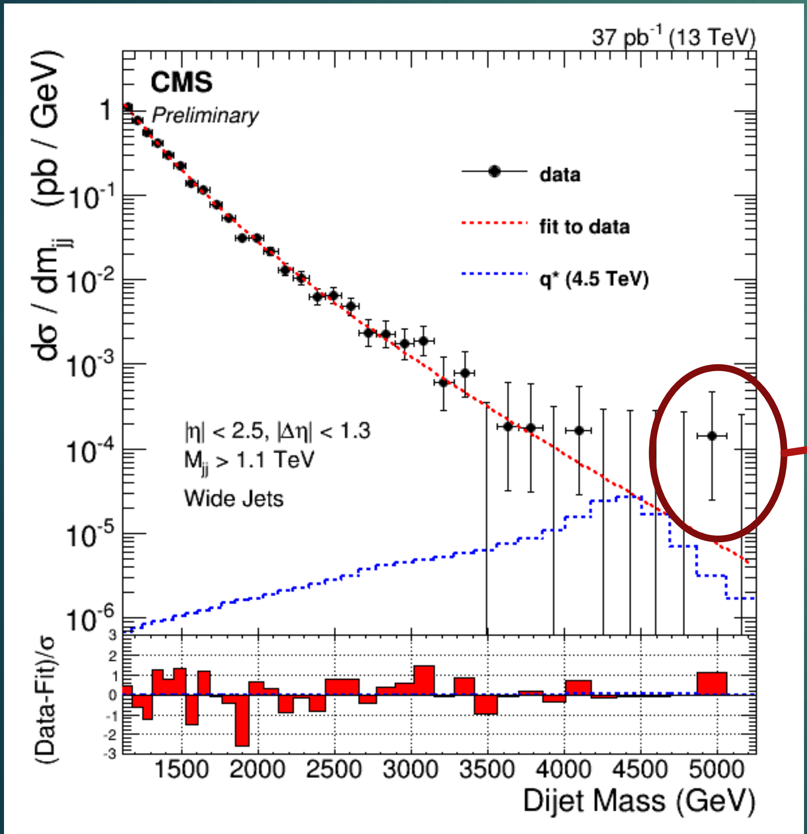
CMS-PAS-SMP-14-002

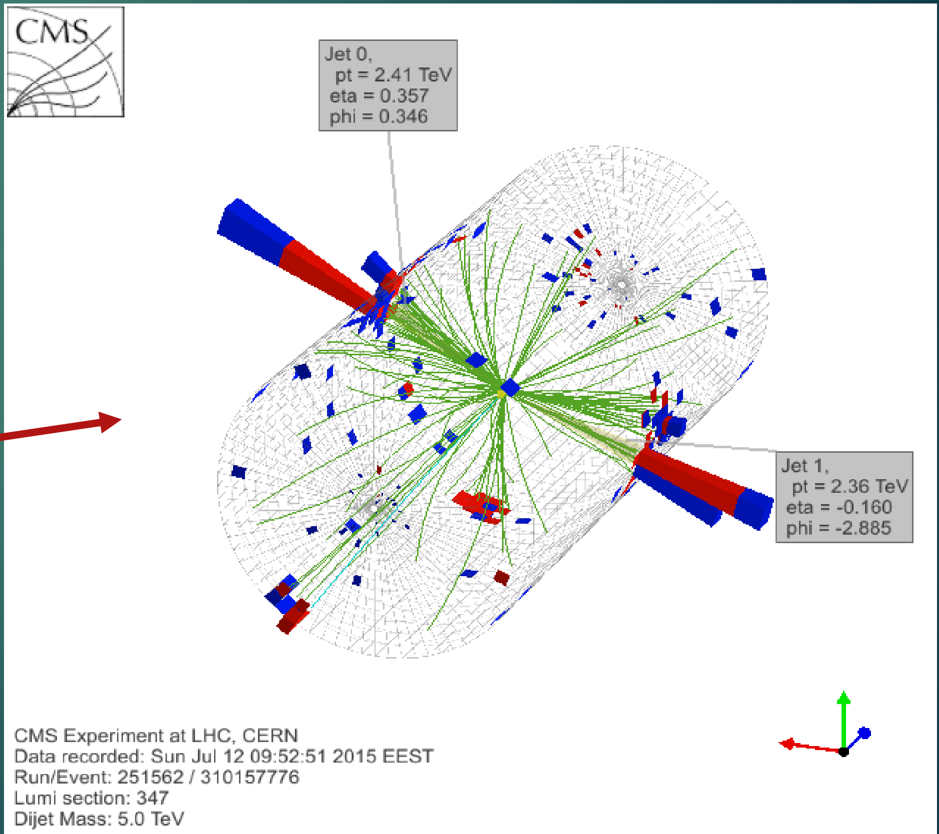




Di-jet event at 13 TeV

- First look at 13 TeV data – 37 pb^{-1} analyzed
- Red dashed line is 4-parameter fit to data
- Highest di-jet invariant mass ~ 4.8 TeV (wide jets)
- No sign of deviations from Standard Model so far…



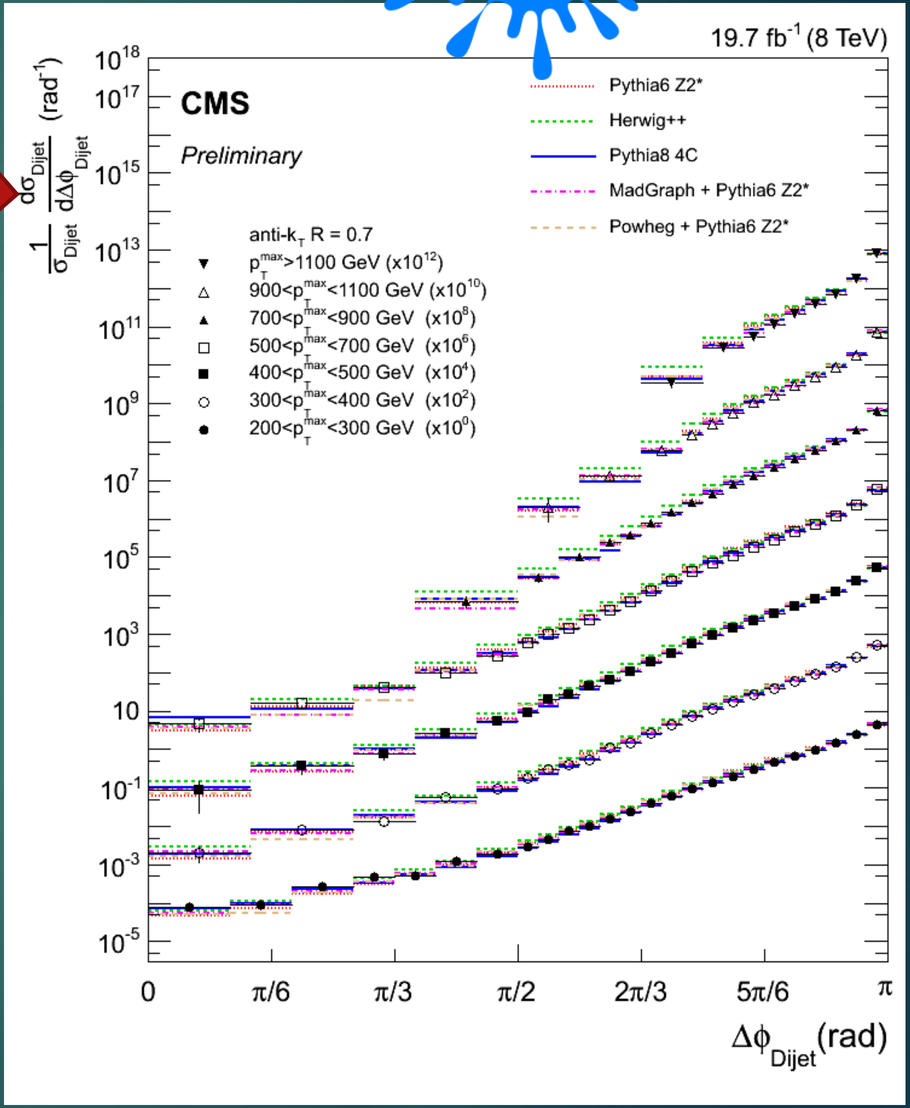


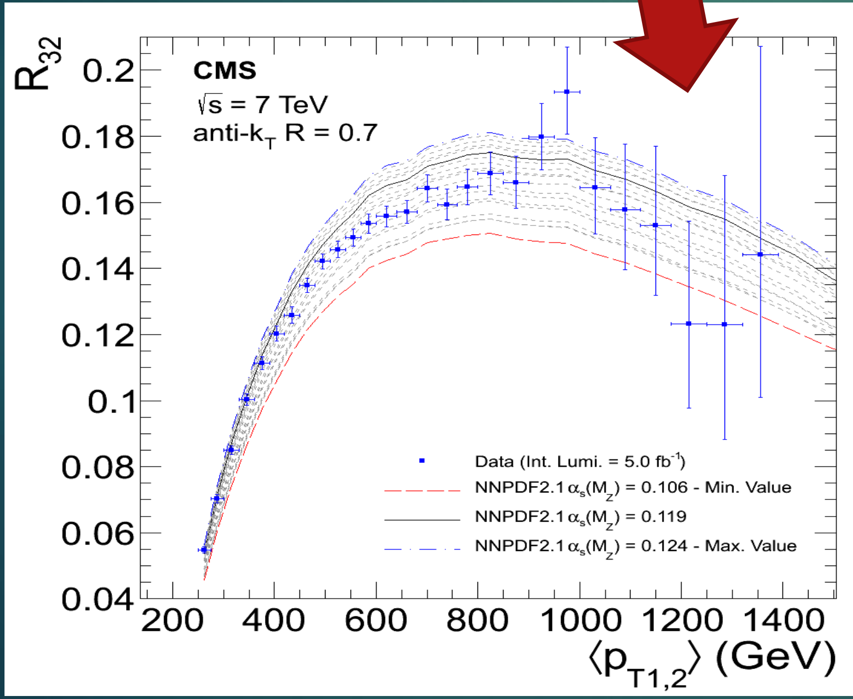
More jets

- Di-jet azimuthal decorrelations with full 8 TeV data set
- R_{32} : 3-jet to 2-jet ratio (7 TeV) → measure alpha_s

CMS-PAS-SMP-14-015

NEW!





EPJC 73 (2013) 2604