Tirana workshop,
Physics dept, Tirana University
September 26 and 27th, 2016

The Standard Model and the LHC

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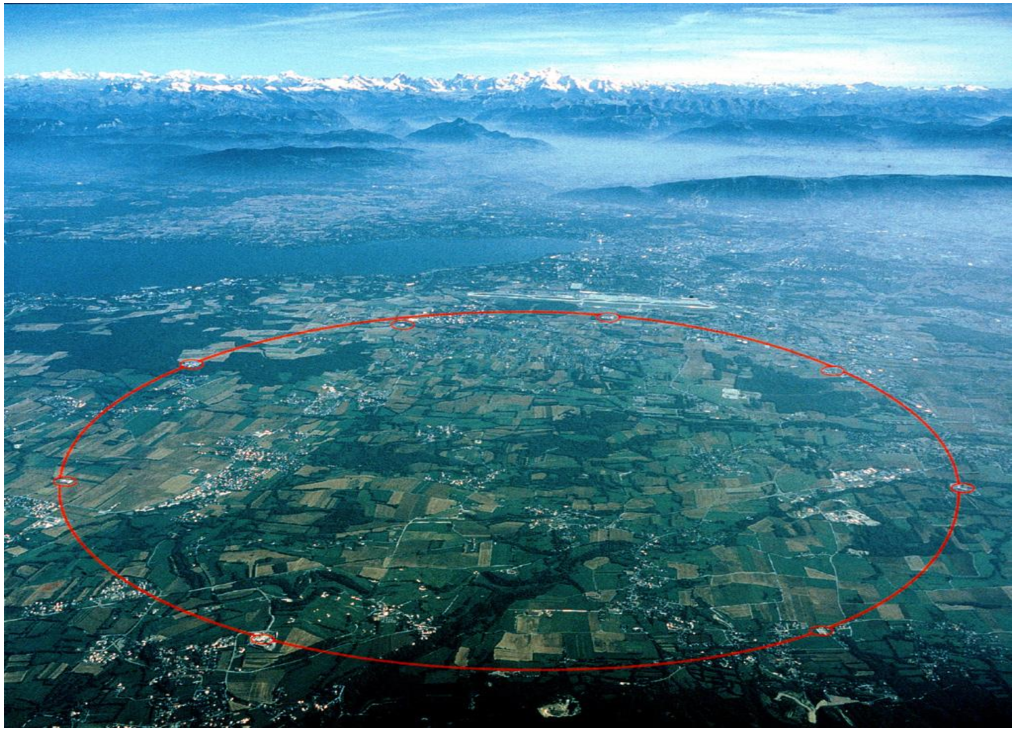
CEN Saclay/IRFU/SPP and CERN/Ph

introduction on the LHC and CMS
testing the Standard Model at the LHC,
up to the discovery of the Higgs boson
beyond the Standard Model searches at the LHC
what next?

Looking for the Higgs: The Large Hadron Collider - genesis of the project



The LHC project started at the initiative (and with the daring!!) of C. Rubbia

The Aachen Conference in October 1990 marked the start-up, since then work on the collider and magnets, various detector designs and understanding physics issues went on without let-up

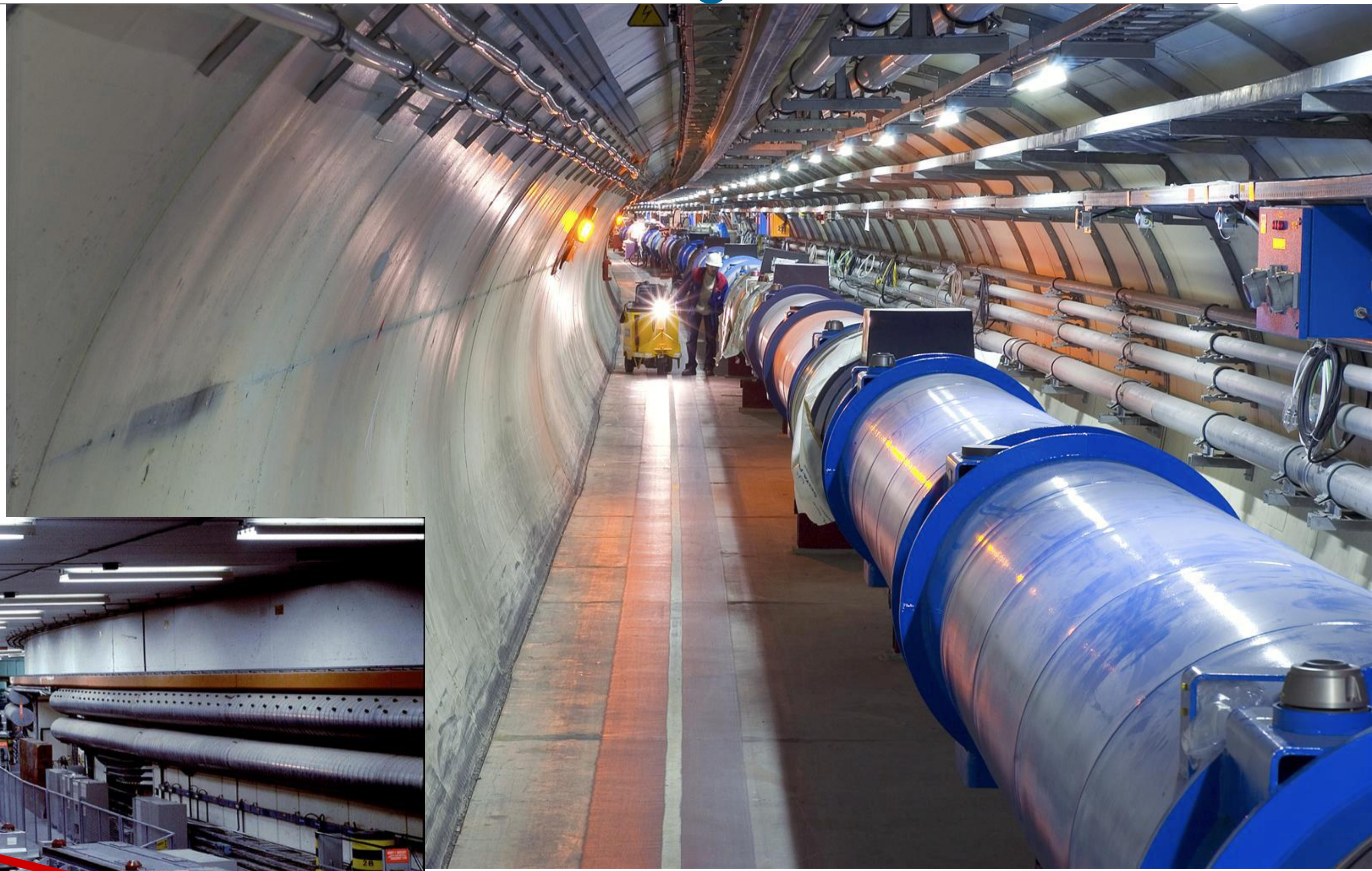
→ Scientifico-diplomatic trips in 1990/91/92 to Japan, India, Russia, USA, Canada etc

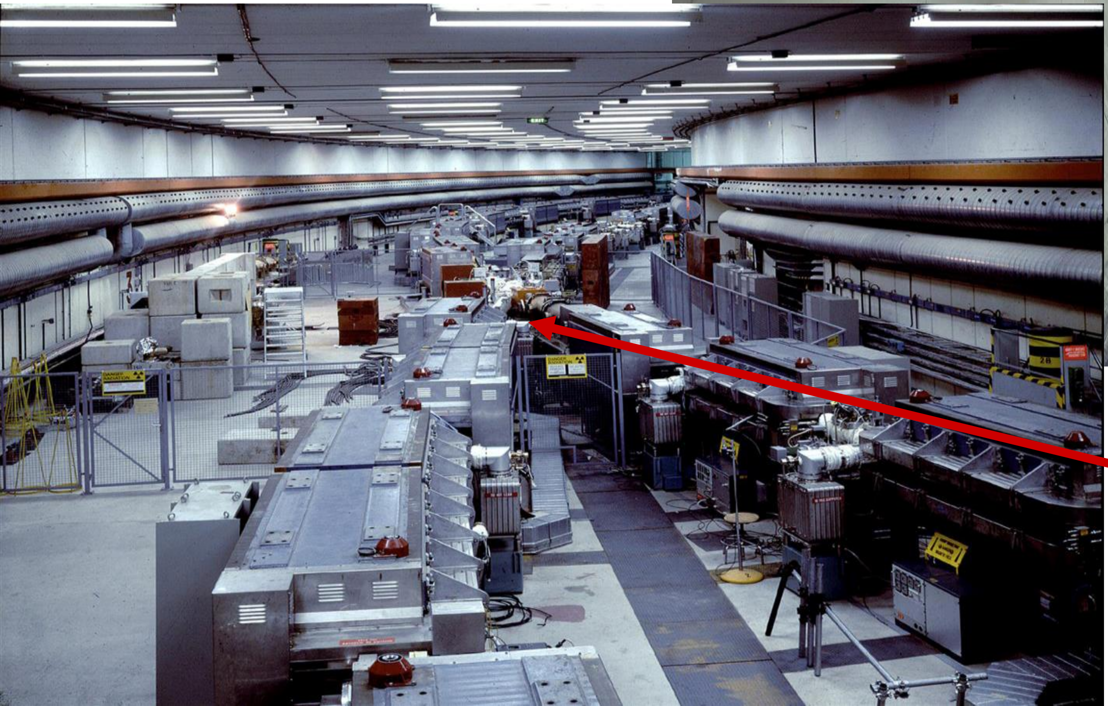
LHC vs SSC: Rubbia's arguments: savings!

- existing LEP tunnel ~1 GCHF
- existing infrastructure at CERN (PS. SPS, etc) ~ 1 GCHF
- "two-in-one" scheme for dipoles saves ~ half the cost of magnet ~ 0.7 to 1 GCHF

thus overall LHC cost ~ 3 GCHF ←

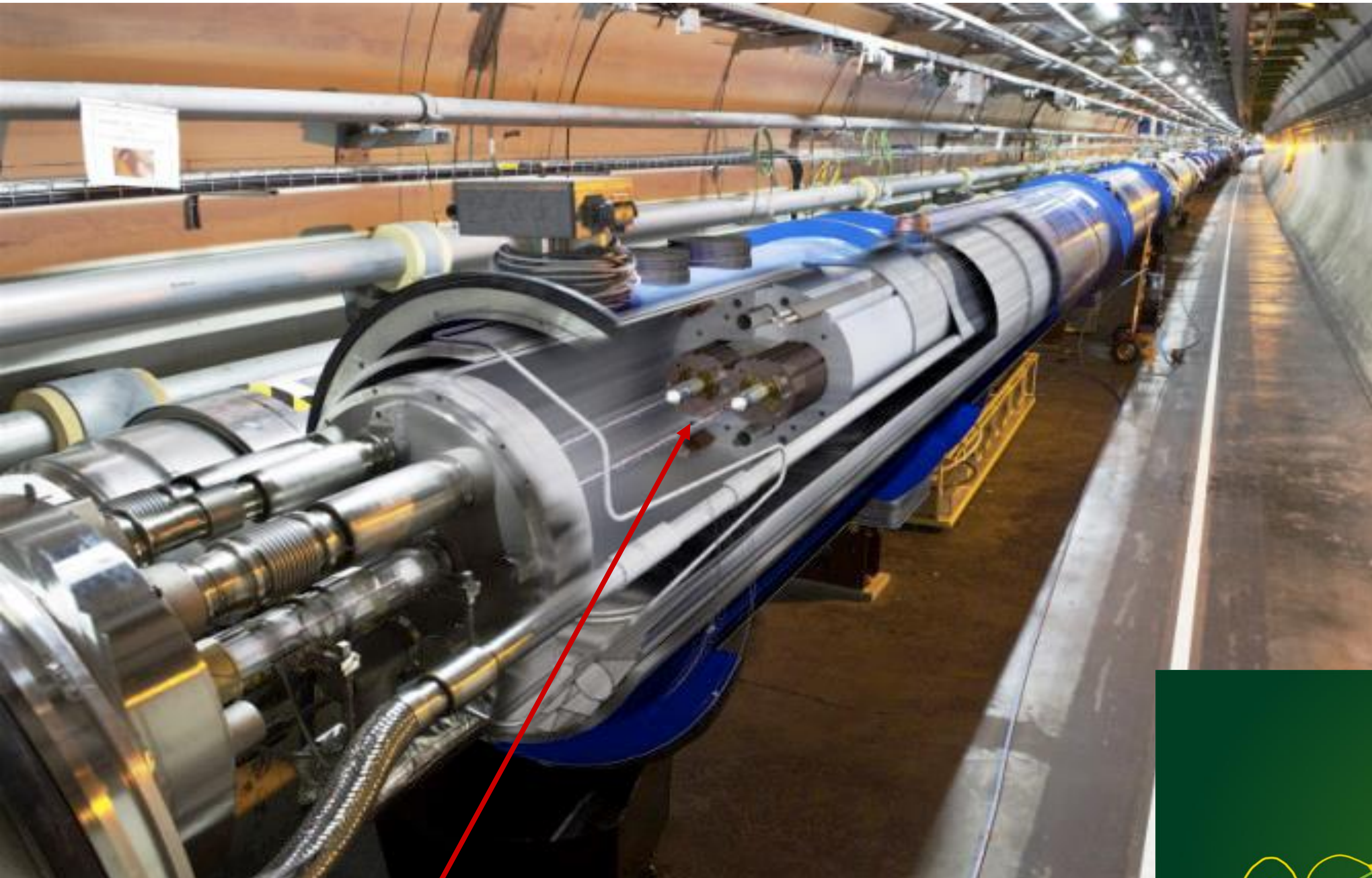
The LHC - a single set of magnets in the tunnel
thanks to the “two-in-one” magnet scheme





the ISR - a typical proton-proton collider;
ISABELLE and the SSC were of same design

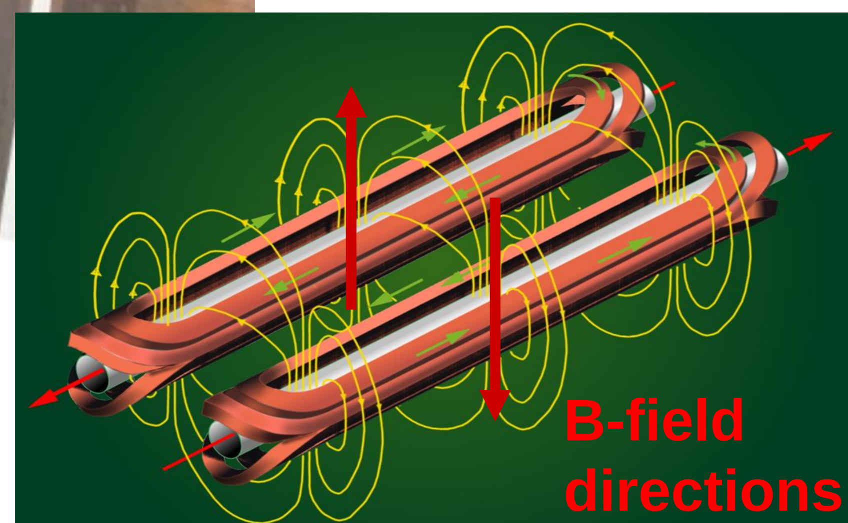
The LHC tunnel - a single set of magnets thanks to the “two-in-one” magnet scheme - II



The magnets have to be aligned with 100μm precision over the 27 km circumference!

Vacuum in the beam pipe as on the Moon!

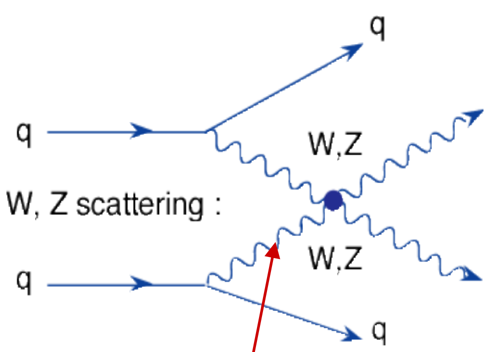
Magnetic field lines

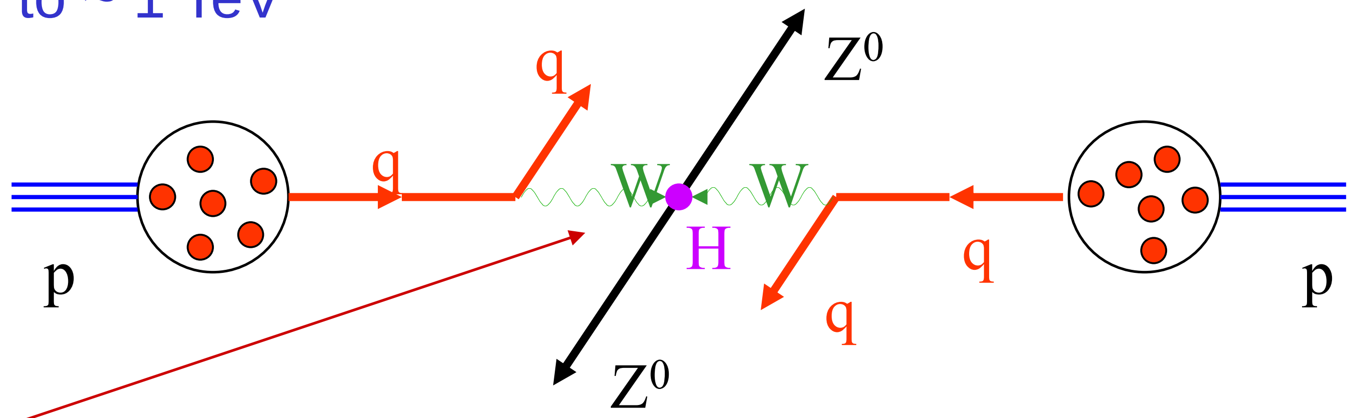


the two-in-one magnet
40.000 tons of material at -271 ^{0}C
The coldest place in the Univers!

The LHC: required energy and luminosity

- To solve e-w symmetry breaking need to study W_L-W_L scattering at a centre of mass energy of up to ~ 1 TeV





E_W ~ 500 GeV

E_{quark} ~ 1 TeV

E_{proton} ~ 6 TeV ➡ required LHC energy: pp collisions at ~ 6 + 6 TeV

- Event Rate = Luminosity x Cross-section x Branching Ratio = L x σ x BR

e.g. H(1TeV) → ZZ → 2e+2μ or 4e or 4μ

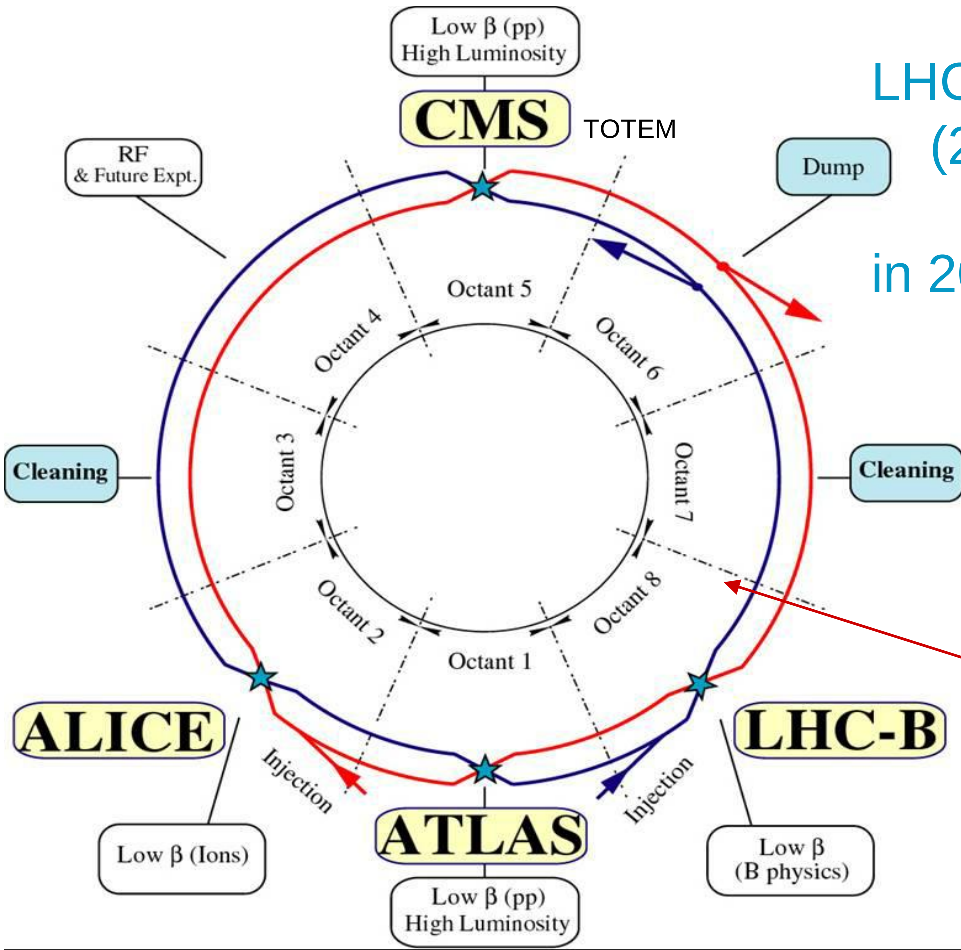
For 10 events/year = 10^{34}x10^{7}x10^{-37}x10^{-3} !! ➡ required L ~ 10^{34} cm^{-2} s^{-1}

- Luminosity, gives the number of proton-proton collisions taking place per sec.

For L = 10^{34}cm^{-2}s^{-1} and σ(pp) ~ 100 mb ➡ rate = 10^{9}/sec !!!

The Large Hadron Collider – overview

~ 65% of the 27 km long circumference covered with 1232 2-in-1 superconducting dipoles of 14.3m length operated at 1.9 ºK giving a field of B = 8.3T , altogether 1200 tons of superconducting cable and 40.000 tons of material at 1.9 ºK superfluid He temperature!.



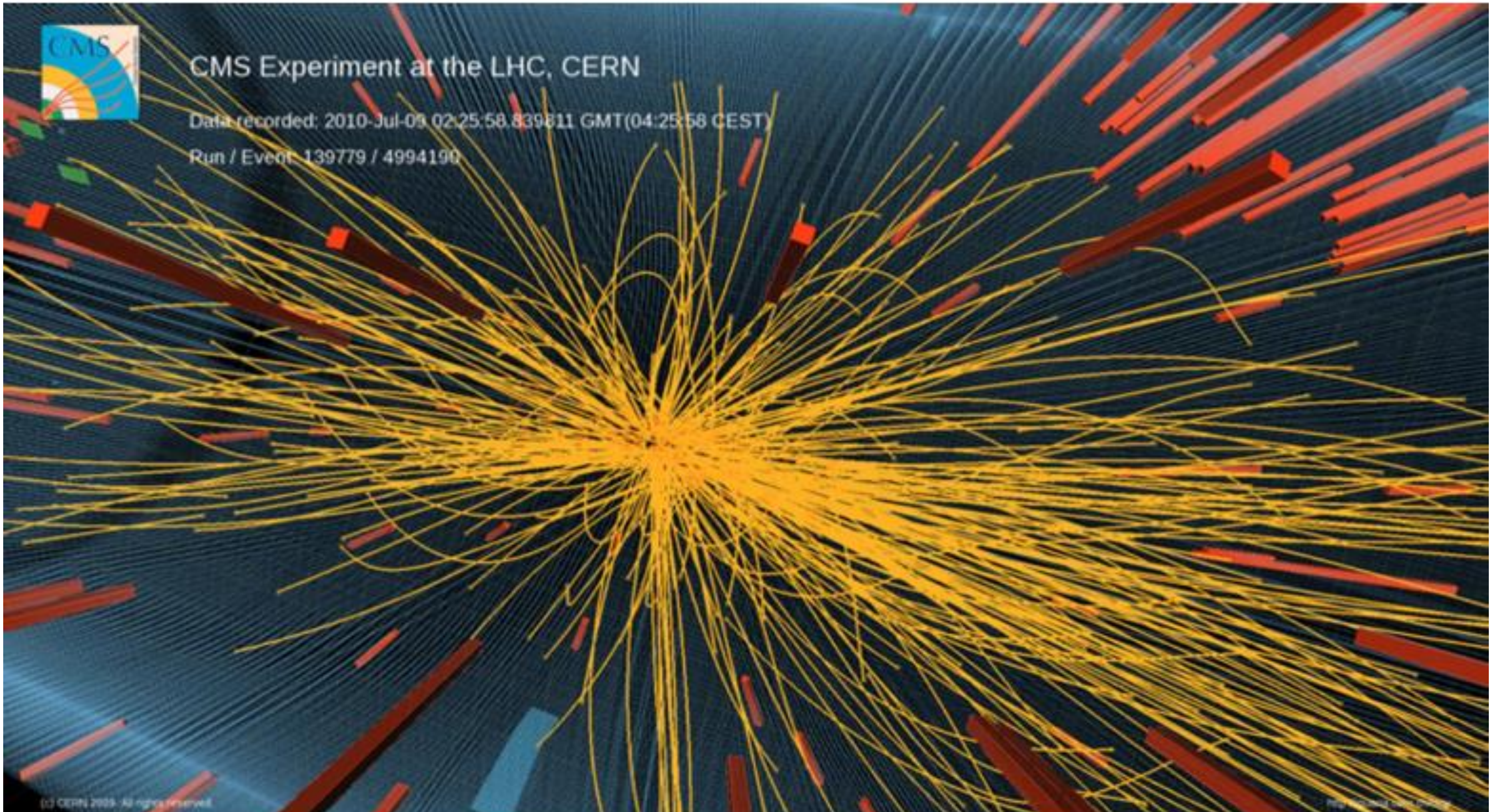
LHC(2012) pp	8.000 GeV	$\sim 7\times10^{33}$ cm^{-2} s^{-1}
(2015) PbPb	5.000(NN) GeV	$\sim 10^{27}$ cm^{-2} s^{-1}
in 2016 pp:	13.000 GeV	$\sim 1.2\times10^{34}$ cm^{-2} s^{-1}
in ~2025:	13.000 GeV	$\sim 10^{35}$ cm^{-2} s^{-1}

p = ReB

A typical proton-proton collision at the LHC,
there are ~ one billion such collisions per second

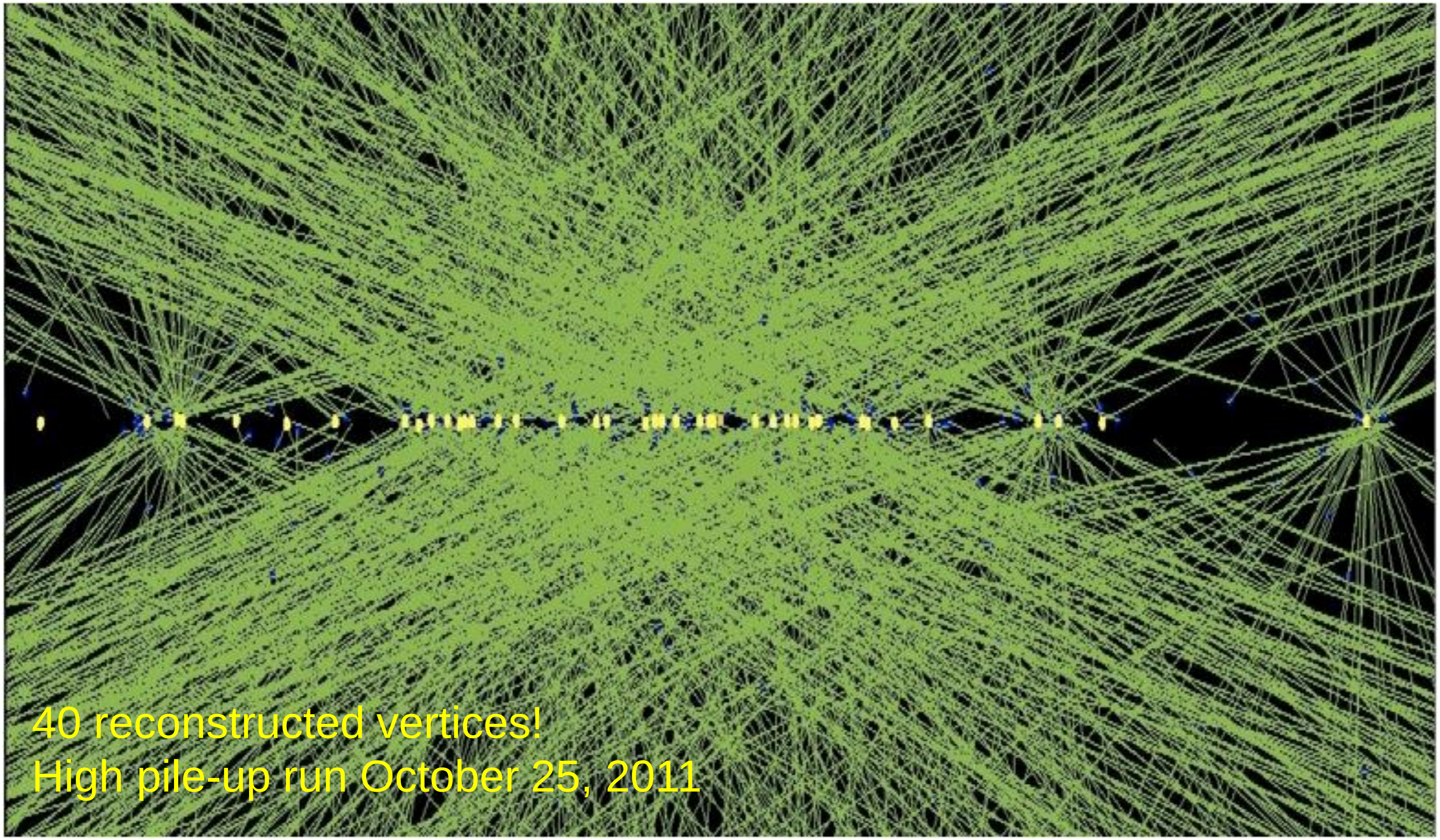
(in reality they are clustered by~25 every 25nseconds – pile-up)

Expected Higgs boson production rate is less than one in a billion pp colisions!



LHC operation in 2012 : pile-up, up to ~ 30 (50 nsec bunch spacing),

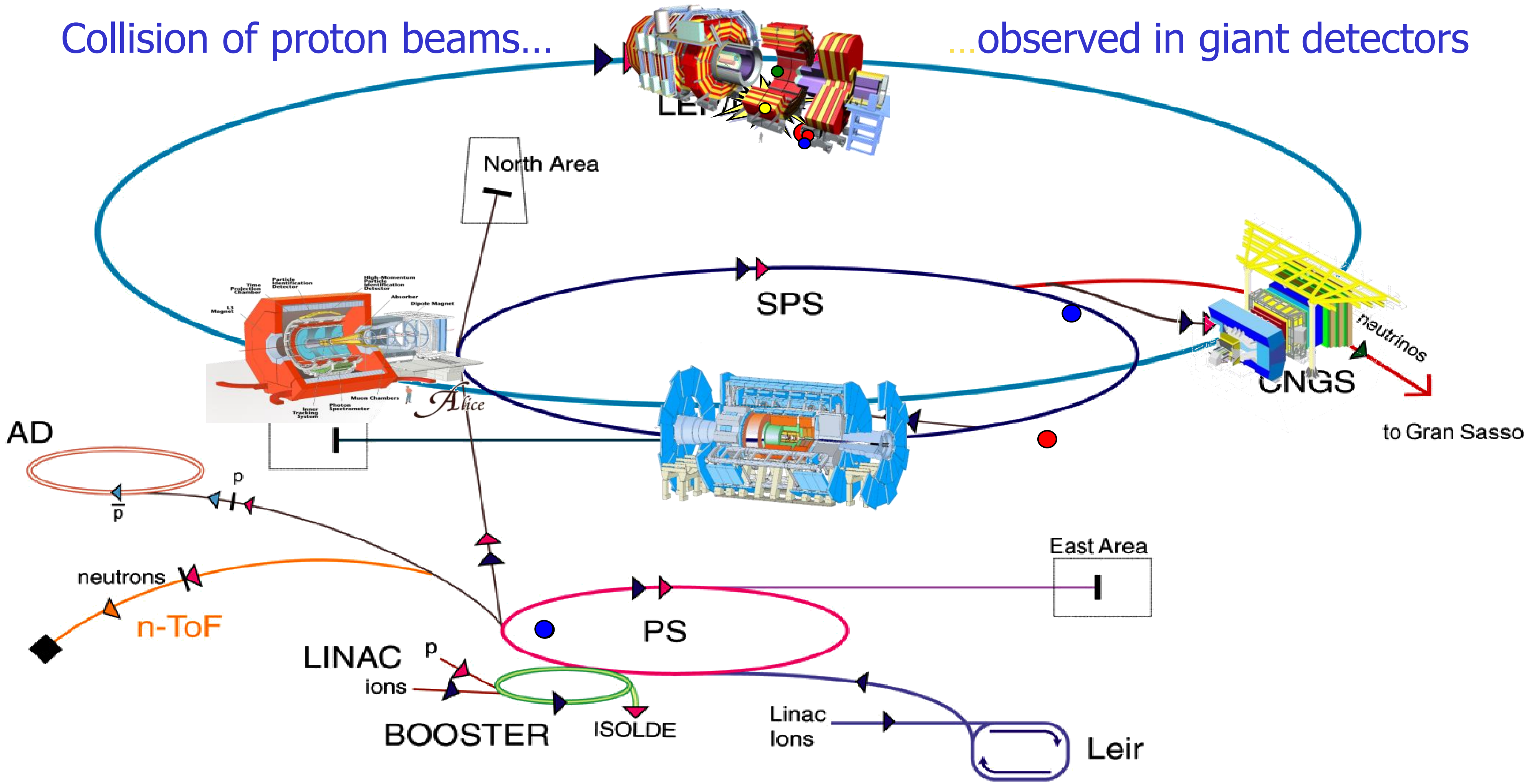
in 2016 we have ~ 45 pile-ups (25 nsec spacing)



In HL-LHC phase (~5x10^{34}cm^{-2}s^{-1})we expect to go to ~150 pile-ups per crossing!

The Large Hadron Collider and experiments

Collision of proton beams… …observed in giant detectors

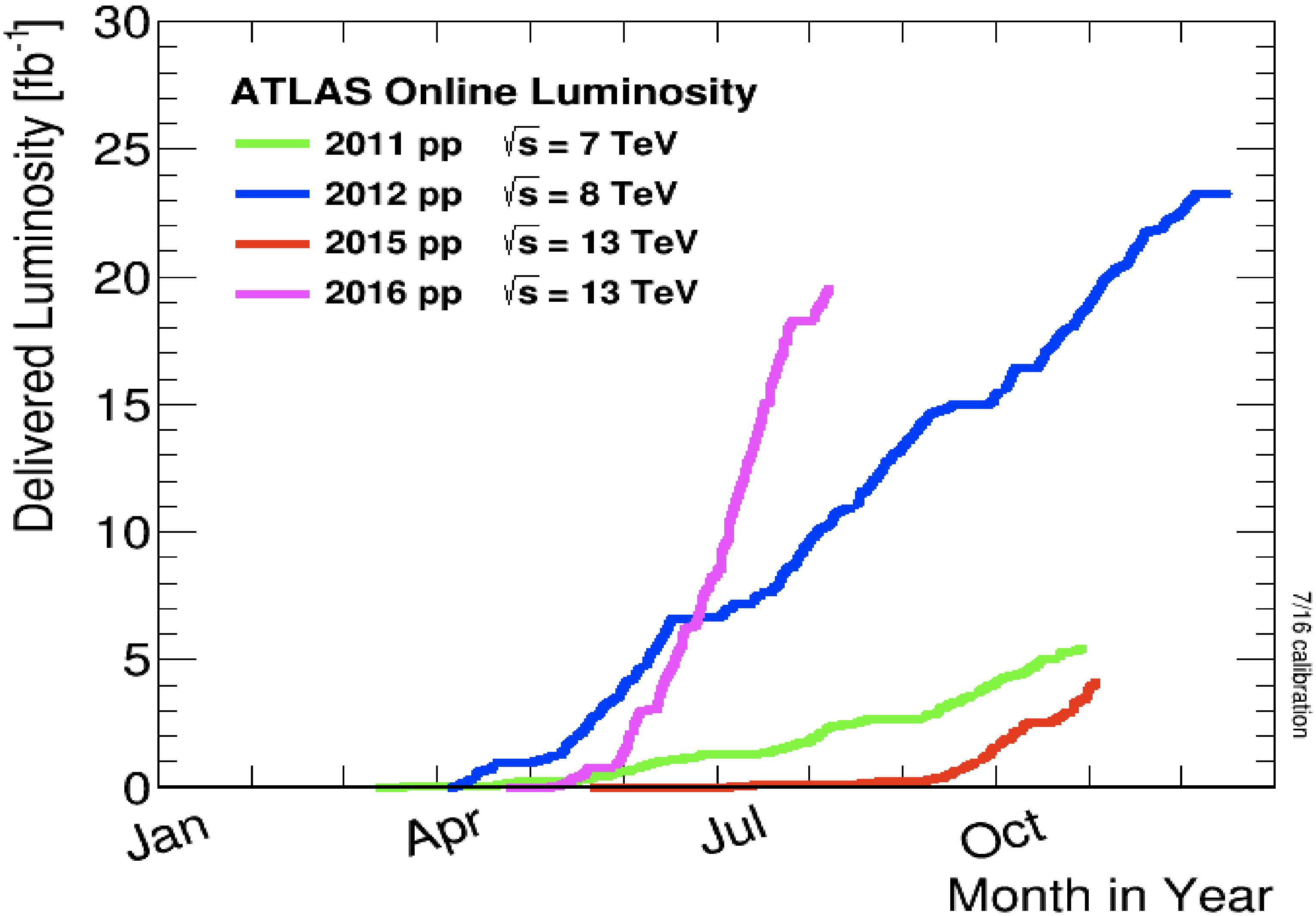


p (proton)
ion
neutron
p̄ (antiproton)
proton/antiproton conversion
neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso

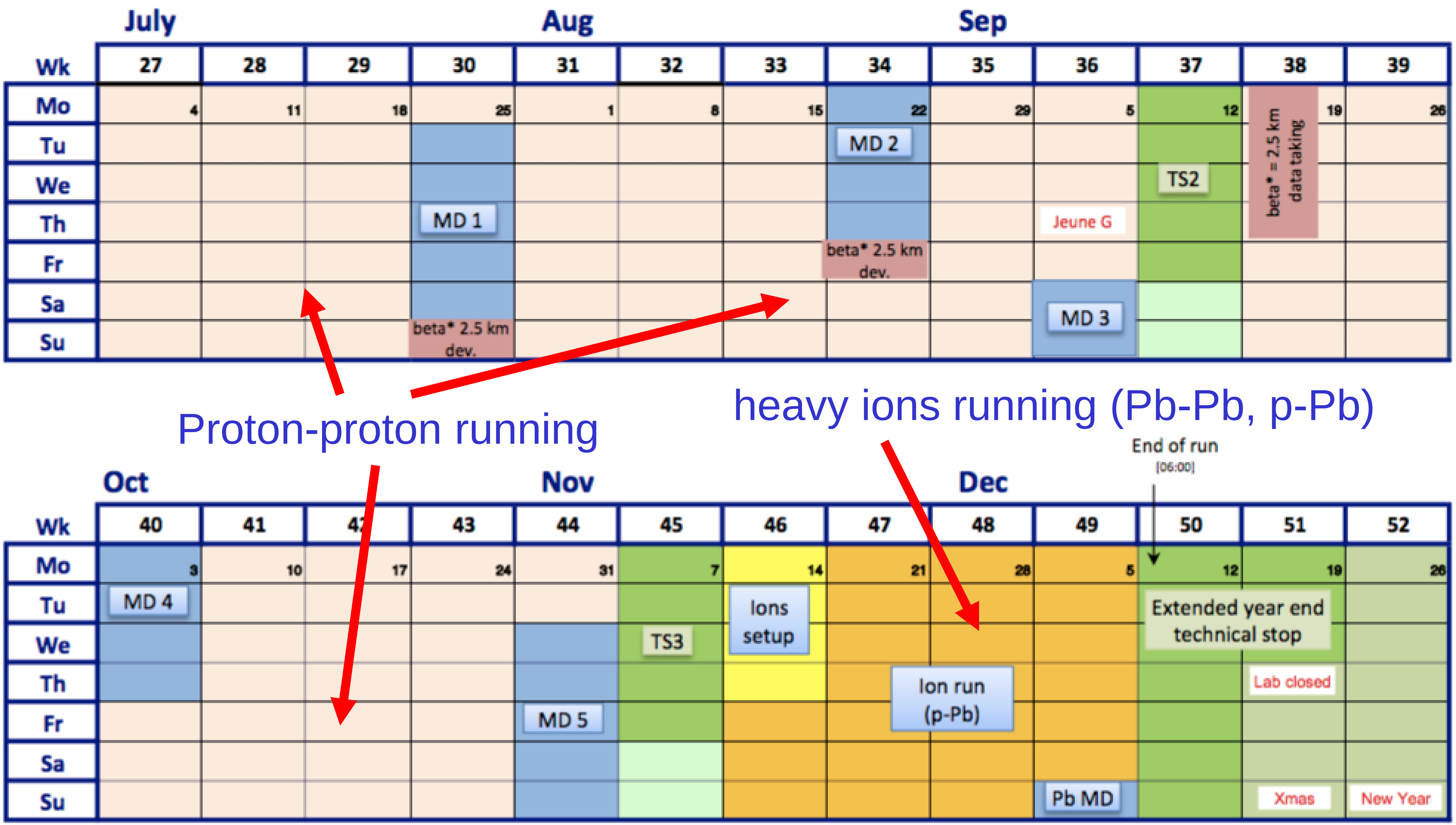
ATLAS and CMS proton-proton luminosities, from 2011 till mid-July 2016



Notice rate in 2016!

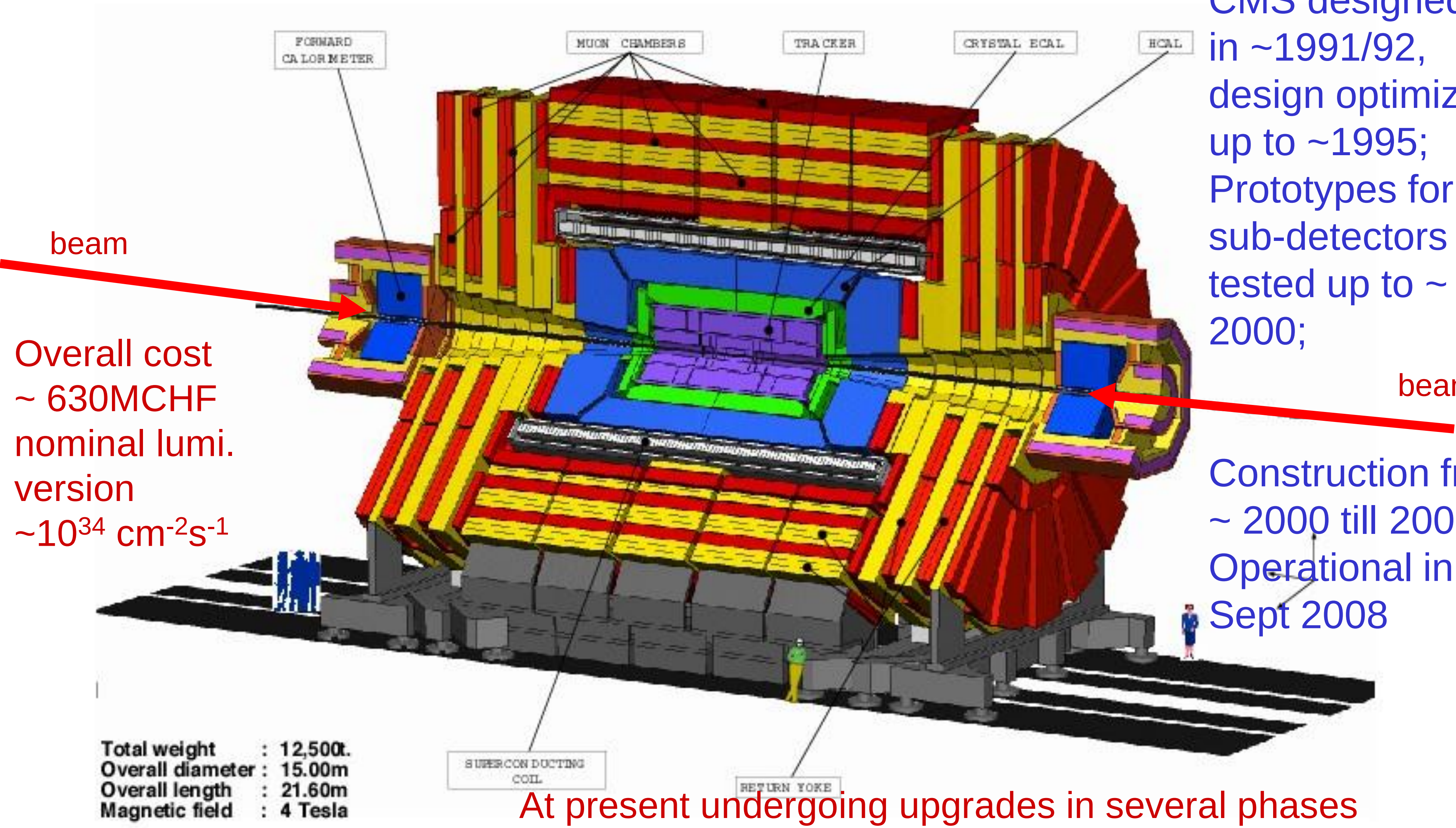
For 2016 alltogether we expect ~35 - 40fb^{-1}

Current (September 1st) LHC schedule for 2016



The CMS (Compact Muon Solenoid) detector

CMS designed in ~1991/92, design optimized up to ~1995; Prototypes for sub-detectors tested up to ~ 2000;



Overall cost ~ 630MCHF nominal lumi. version $\sim 10^{34}$ cm^{-2}s^{-1}

Construction from ~ 2000 till 2008 Operational in Sept 2008

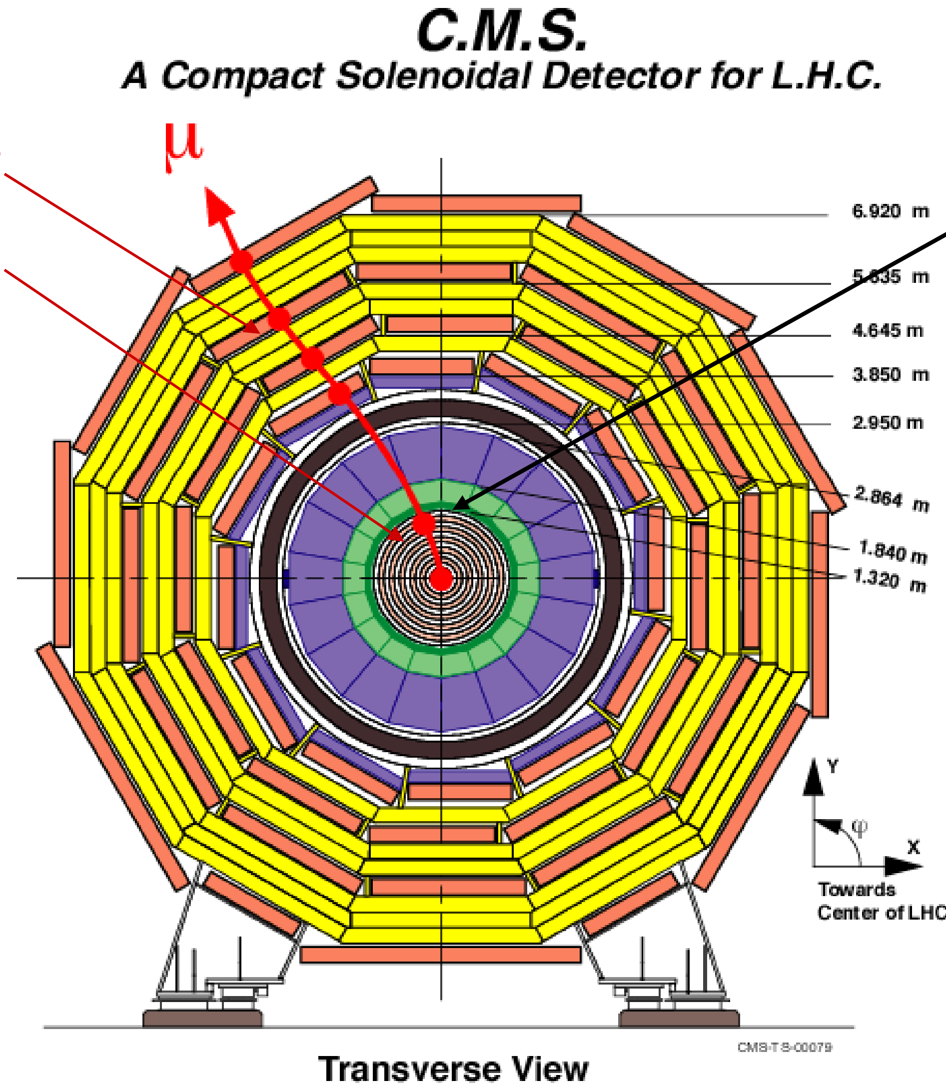
At present undergoing upgrades in several phases to face conditions of HL-LHC running ($\sim 10^{35}$ cm^{-2}s^{-1})

CMS in transverse view - basic design

B ~ 2 Tesla

B = 4 Tesla

Total bending power on a muon ~ 16Tm



p = reB

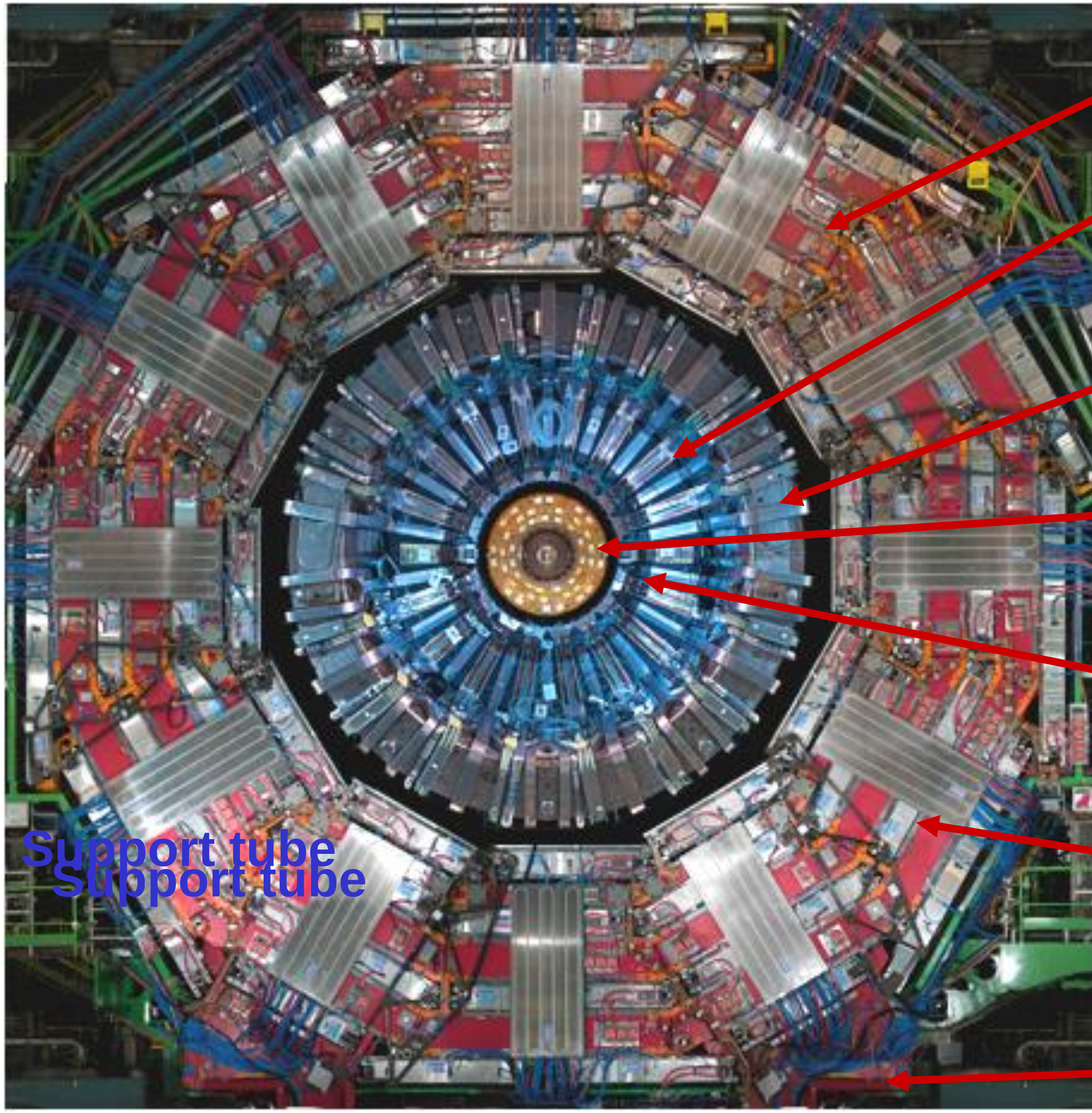
momentum resolution from curvature:

$$\Delta p/p \sim \varepsilon\, p / (\sqrt{n}\; B\, l^2)$$

ε= resolution on point measurement
n = number of points measured per track
l = useful track length
B = magnetic field

The goal is to identify and measure all particles produced at the interaction point

LHC experiments are really international endeavors! CMS for example:



Support tube

Flux return yoke
Germany,Russia,Chekia,Japan

Hadron calorimeter
USA,Russia,Ukraina,Turkey,Iran, India,Hungary

Solenoid magnet
France,Italy,Switzerland,Finland, Croatia,UK,Japan,CERN

Tracking system
Germany,Italy,France,Belgium,USA Finland,Switzerland,CERN…..

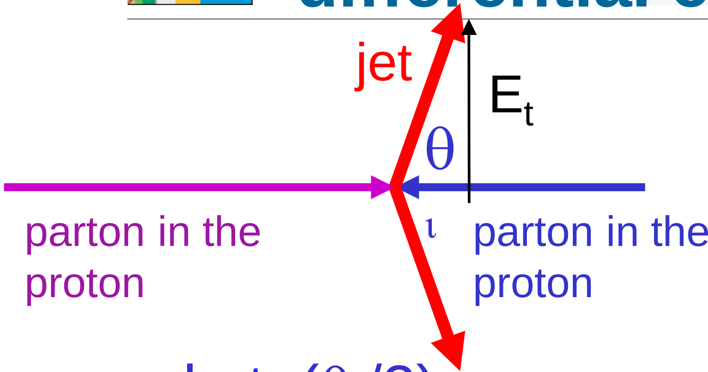
Electromagnetic calorimeter
Russia,China, France,Italy,Japan, UK,Switzerland,Greece,Taiwan

Muon system
Italy,Germany,Spain,USA,Russia, Bulgaria,Belgium,Korea,Pakistan,CERN

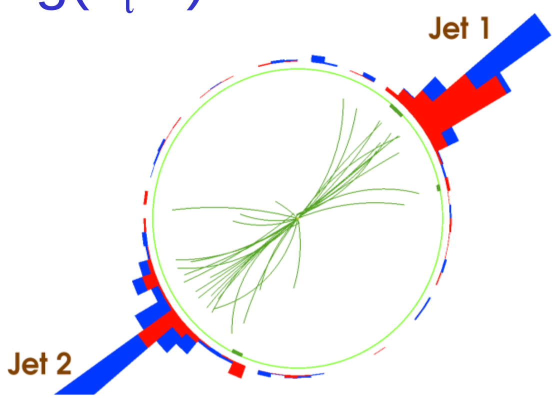
Support system
China,Pakistan,USA

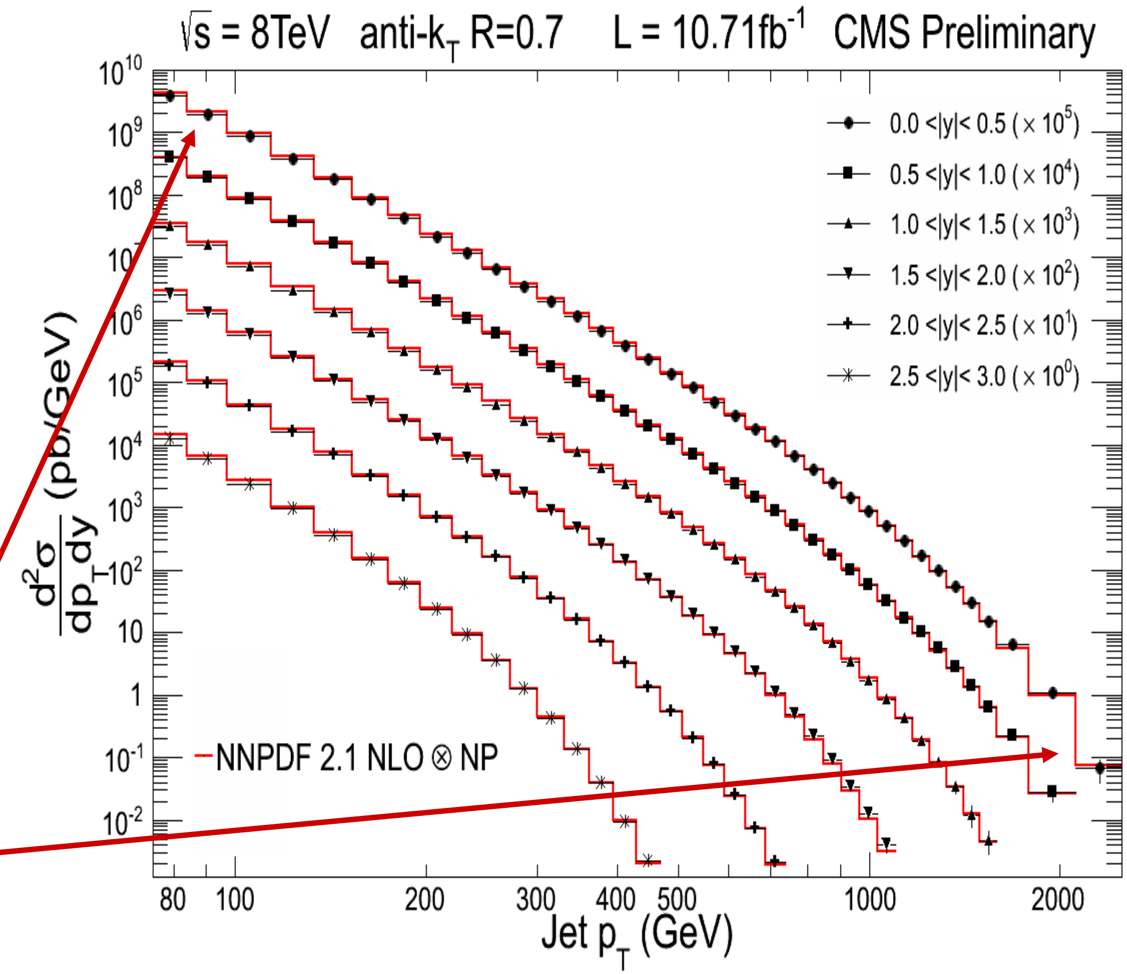
SM Physics
jets, W, Z, top, Higgs boson

Among first LHC results: Inclusive single jet double-differential cross section at 8 TeV



$y_j = -\ln tg(\theta_\iota/2)$





10-12 orders of variation in magnitude in cross section!!

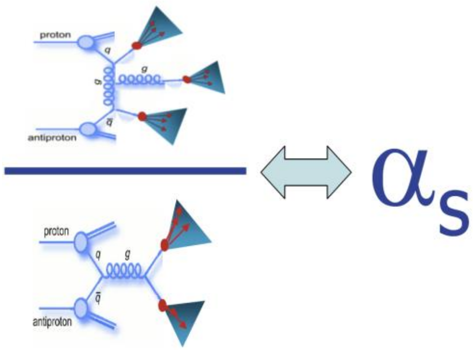
Total uncertainty 50-10% dominated by JES

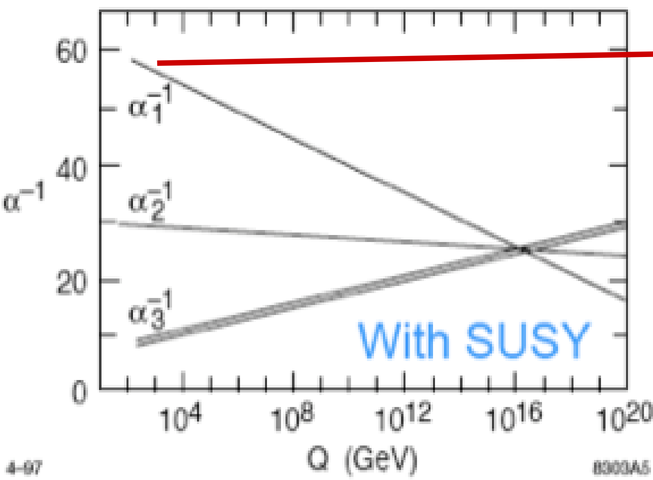
Good agreement between data and NLO pQCD with various PDFs

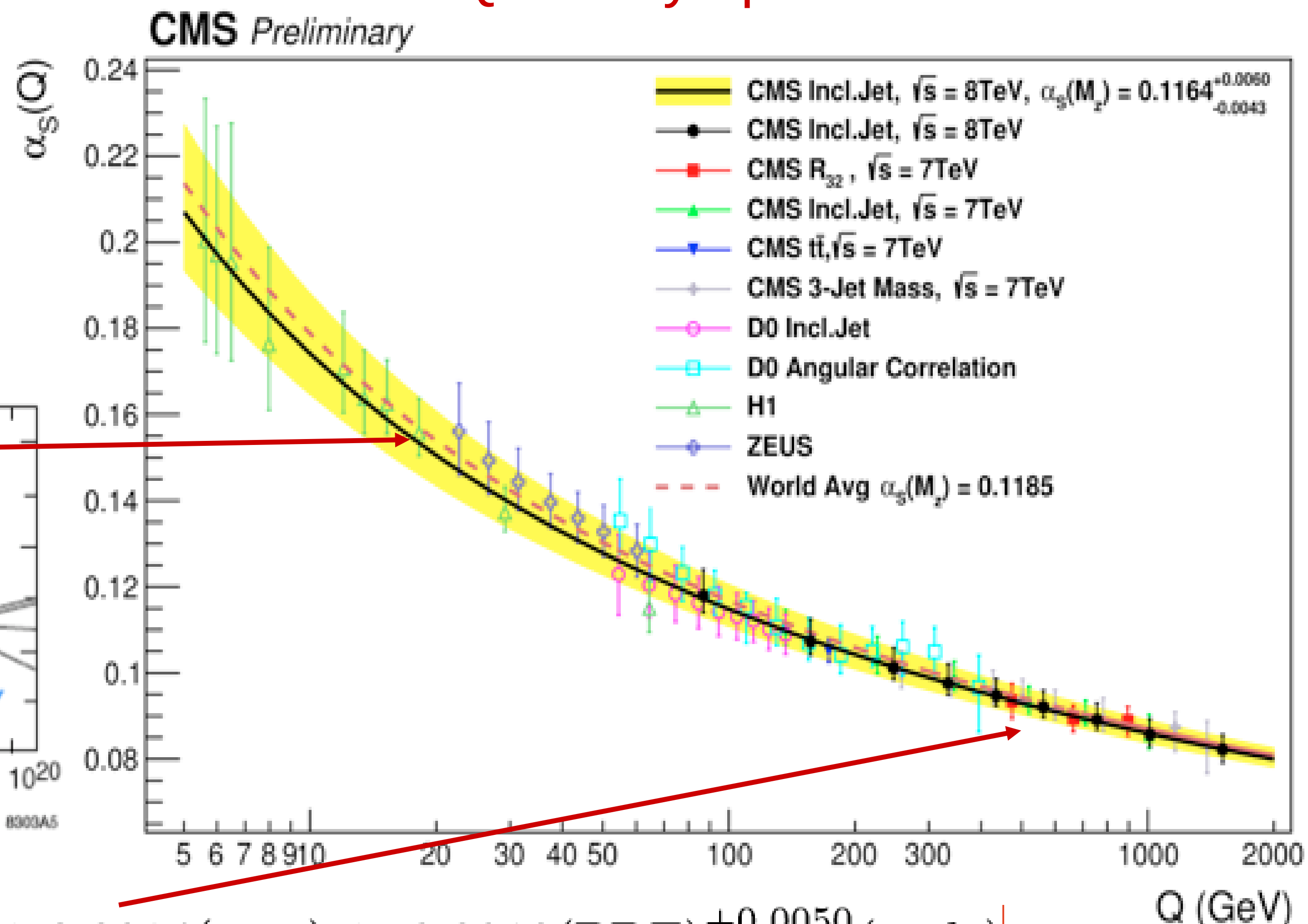
newest studies extend beyond jet-E_t of 2 TeV

3-jet to 2-jet cross section ratio and the evolution of the strong coupling constant $\alpha_s(Q)$

test of QCD asymptotic freedom in SM



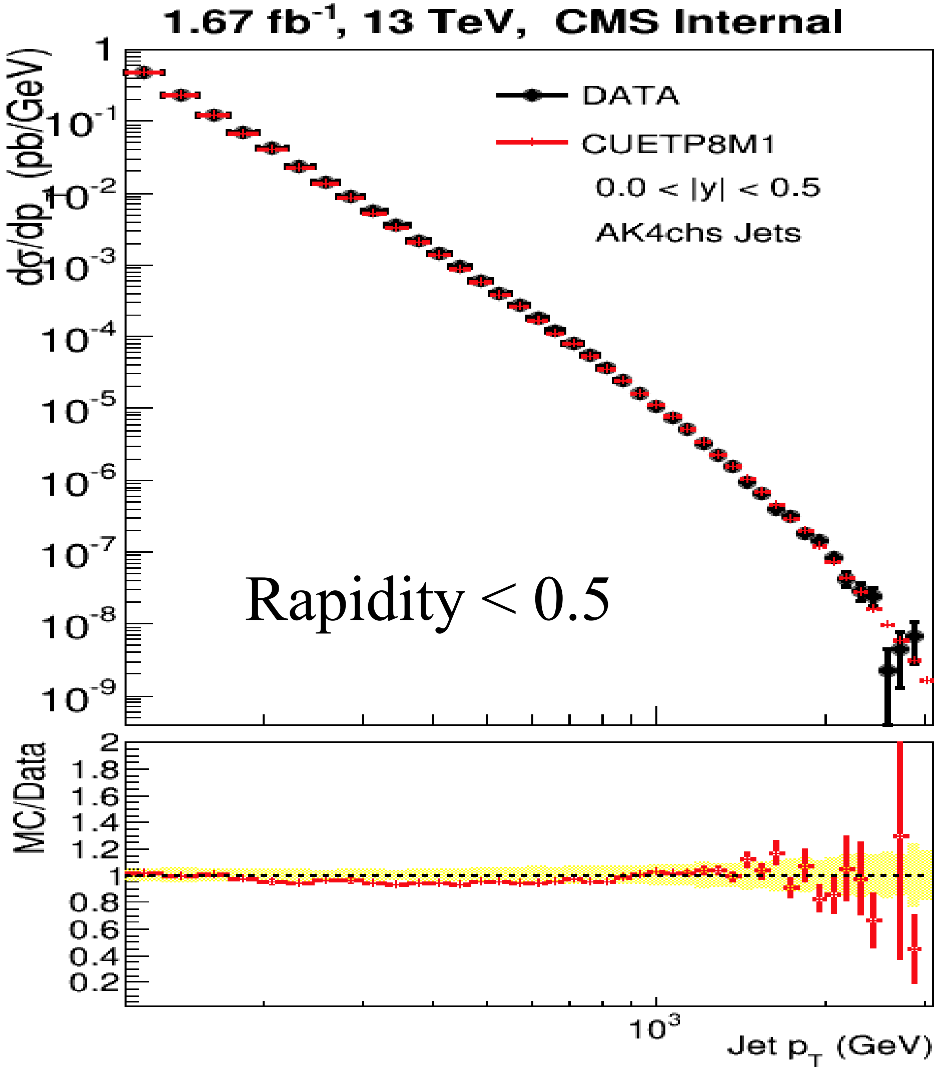


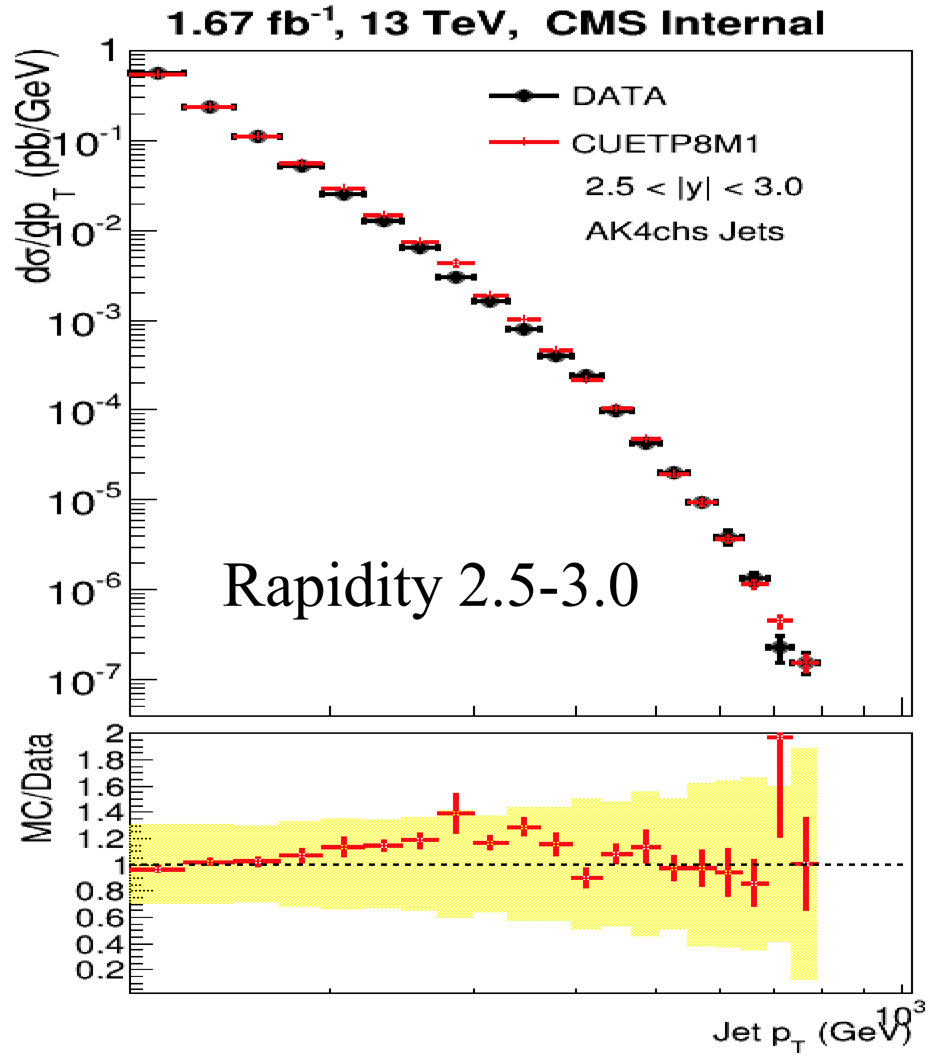


$$\alpha_s(M_Z) = 0.1148 \pm 0.0014(\text{exp.}) \pm 0.0018(\text{PDF})^{+0.0050}_{-0.0000}(\text{scale})$$

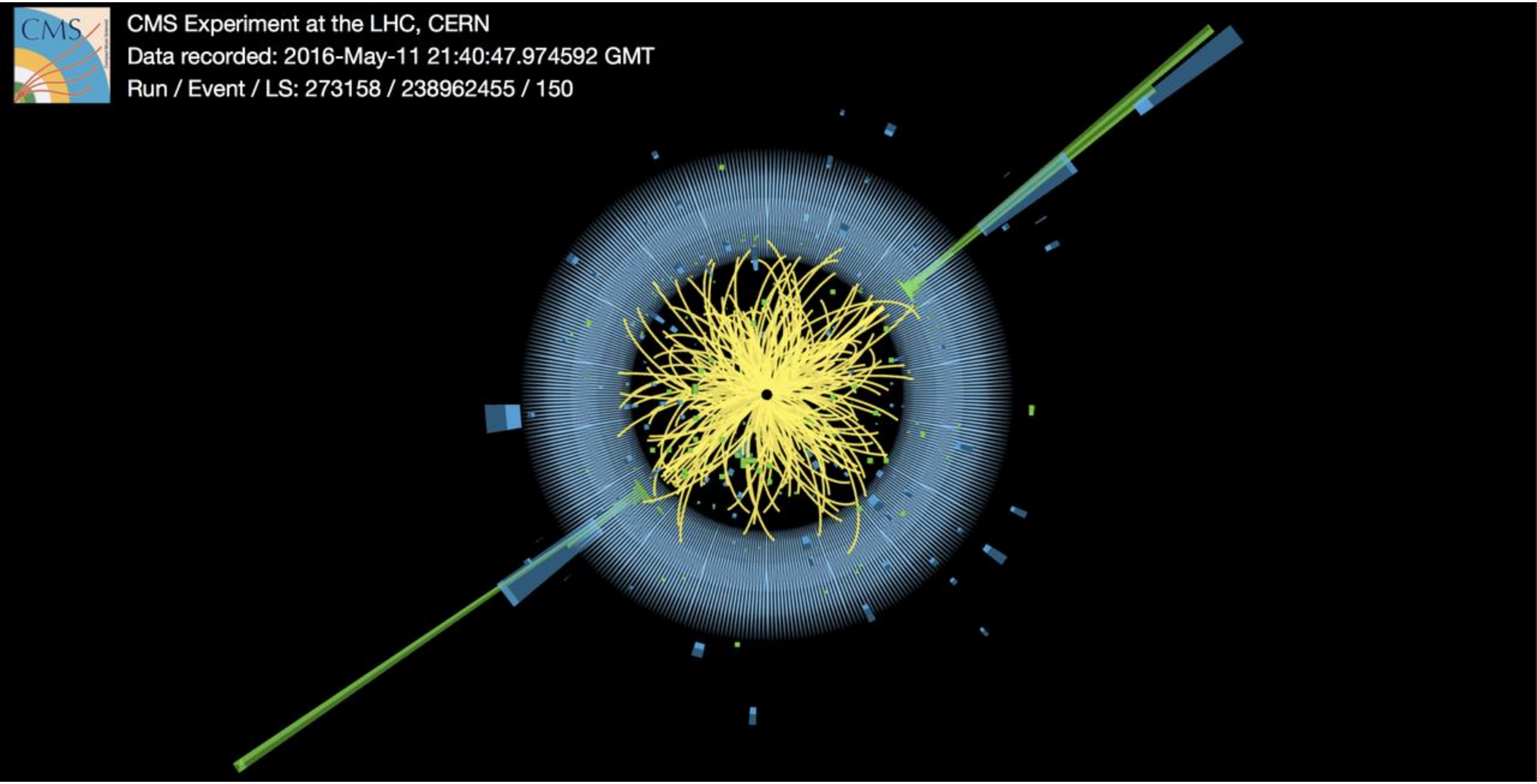
Jets at 13 TeV, CMS, 2015 data, 1.6 fb^{-1}

2015 25 ns data: extend up to 3 TeV, improve precision in p_T tail, perform α_S fit and study its evolution vs Q



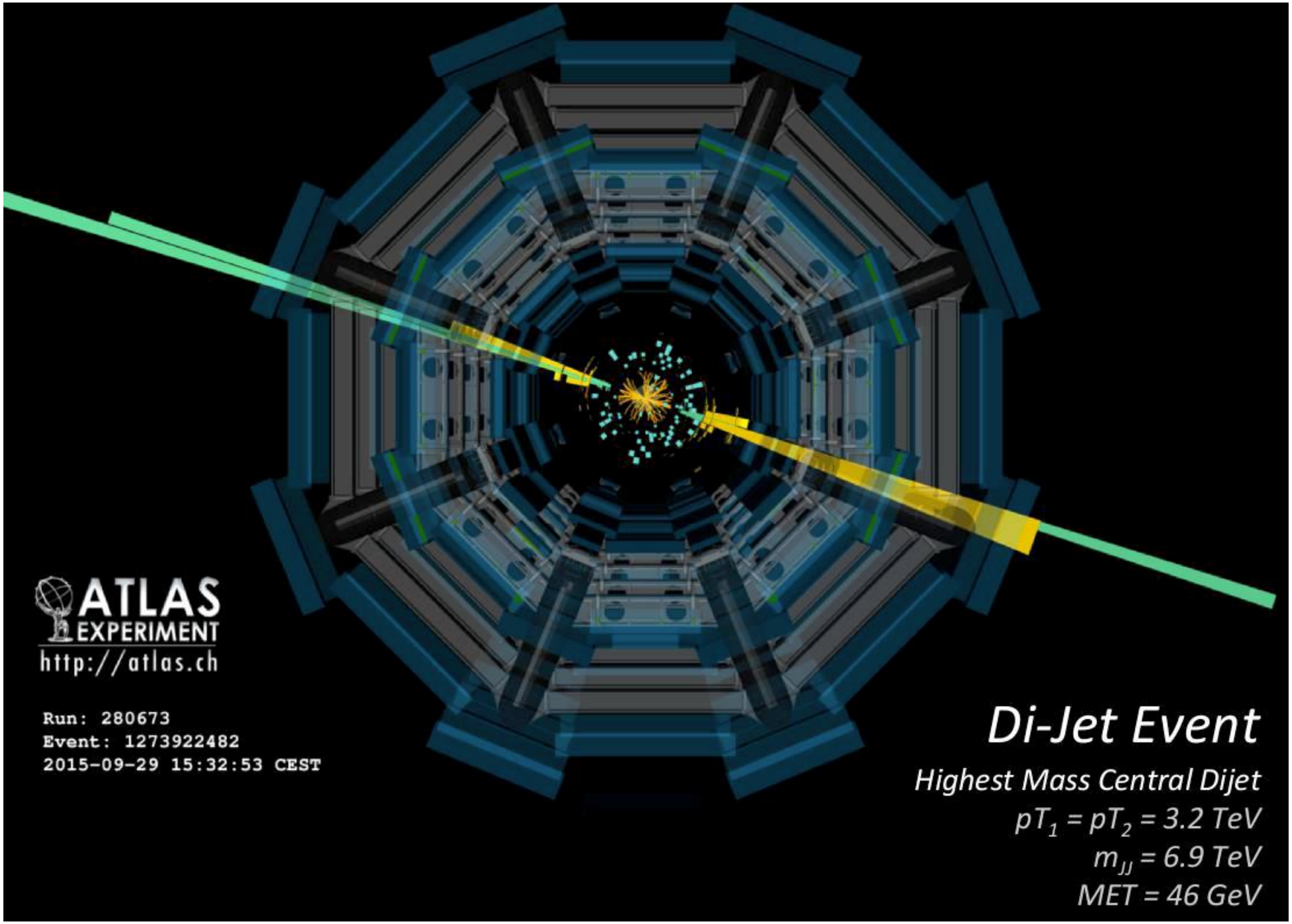


Dijet event in CMS, 13 TeV

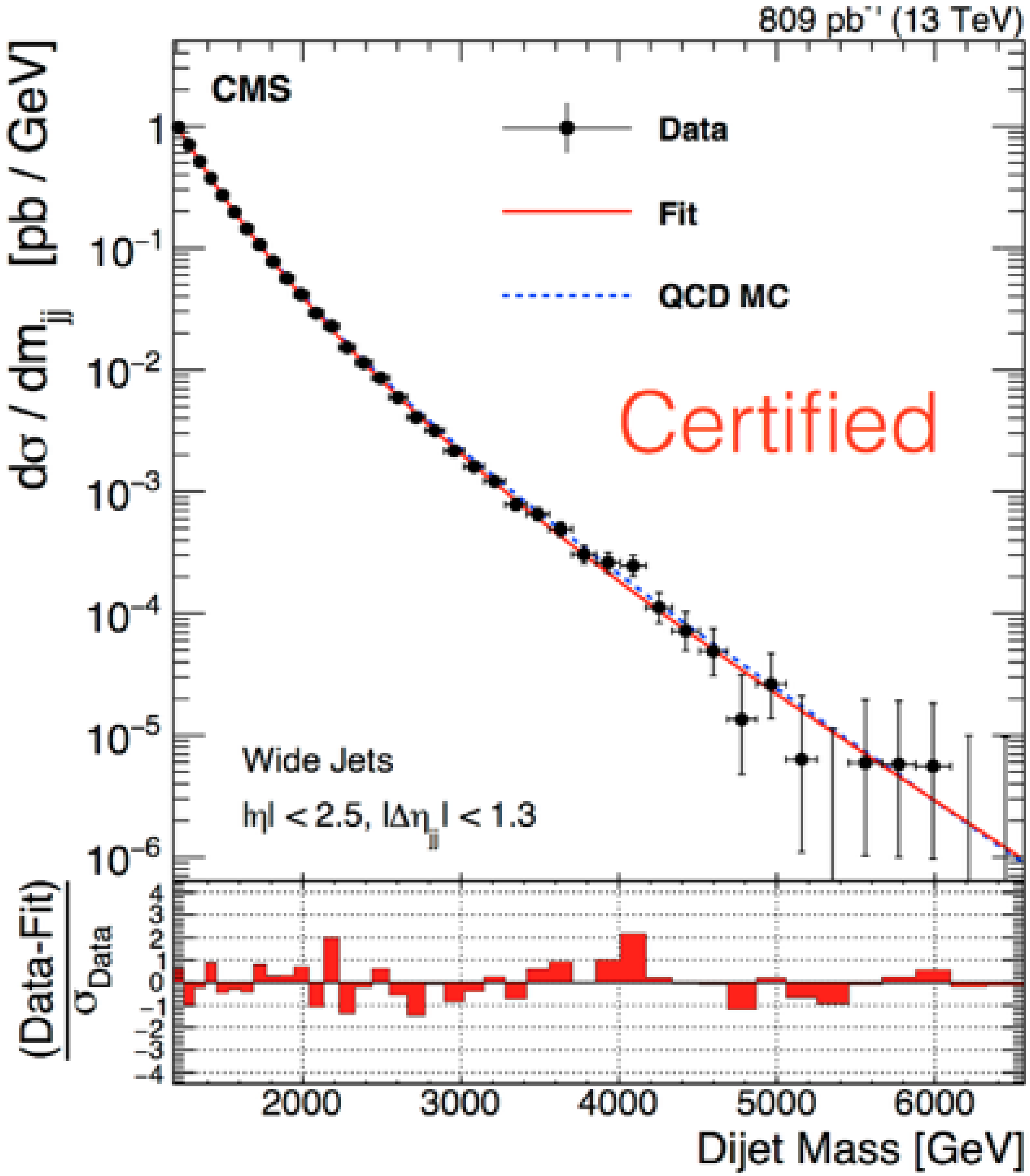


Dijet event in ATLAS at 13 TeV, 2016 data

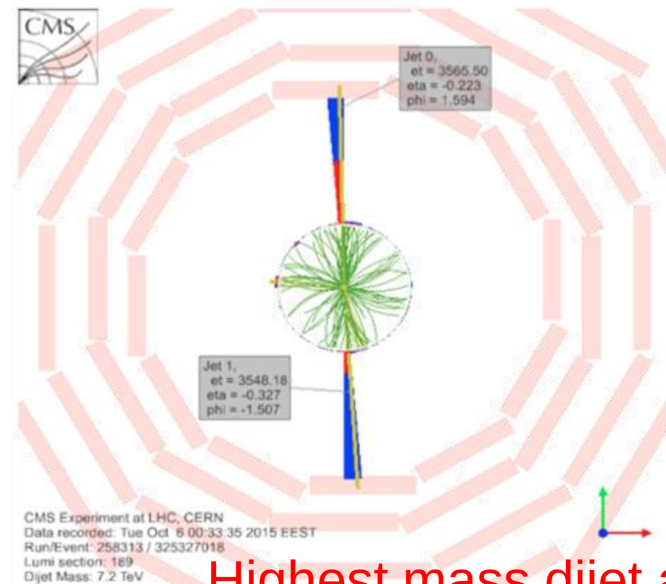
Large increase in cross section for high mass states going from 8 TeV to 13 TeV



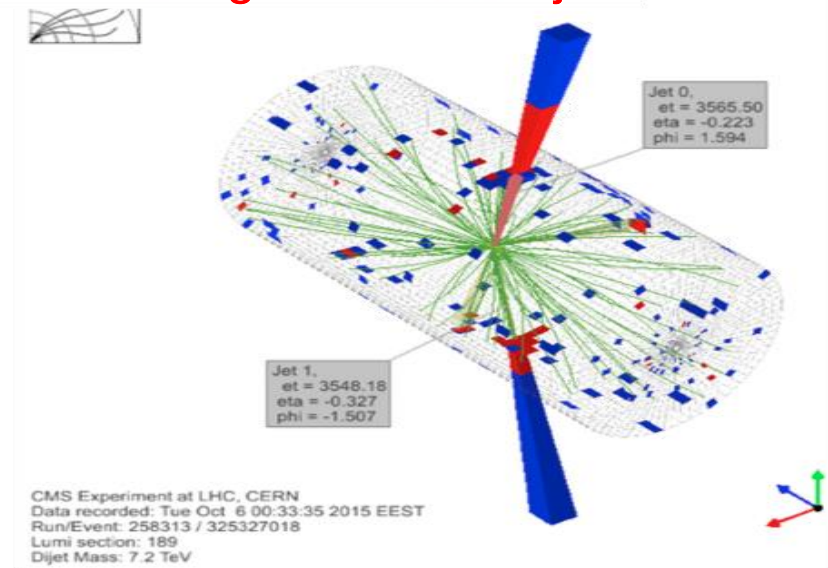
Early 13 TeV data, 800 pb^{-1} – dijets effective mass



- very-well balanced dijet event

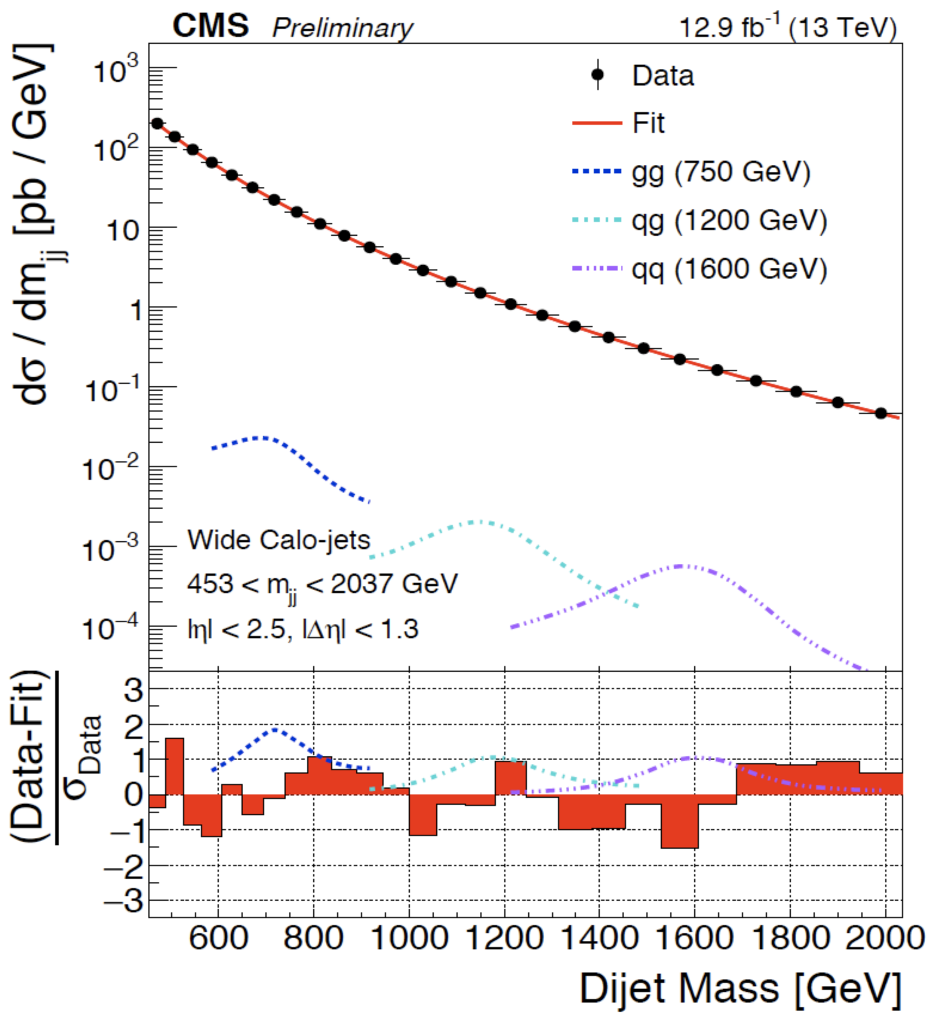


Highest mass dijet at 7.2 TeV

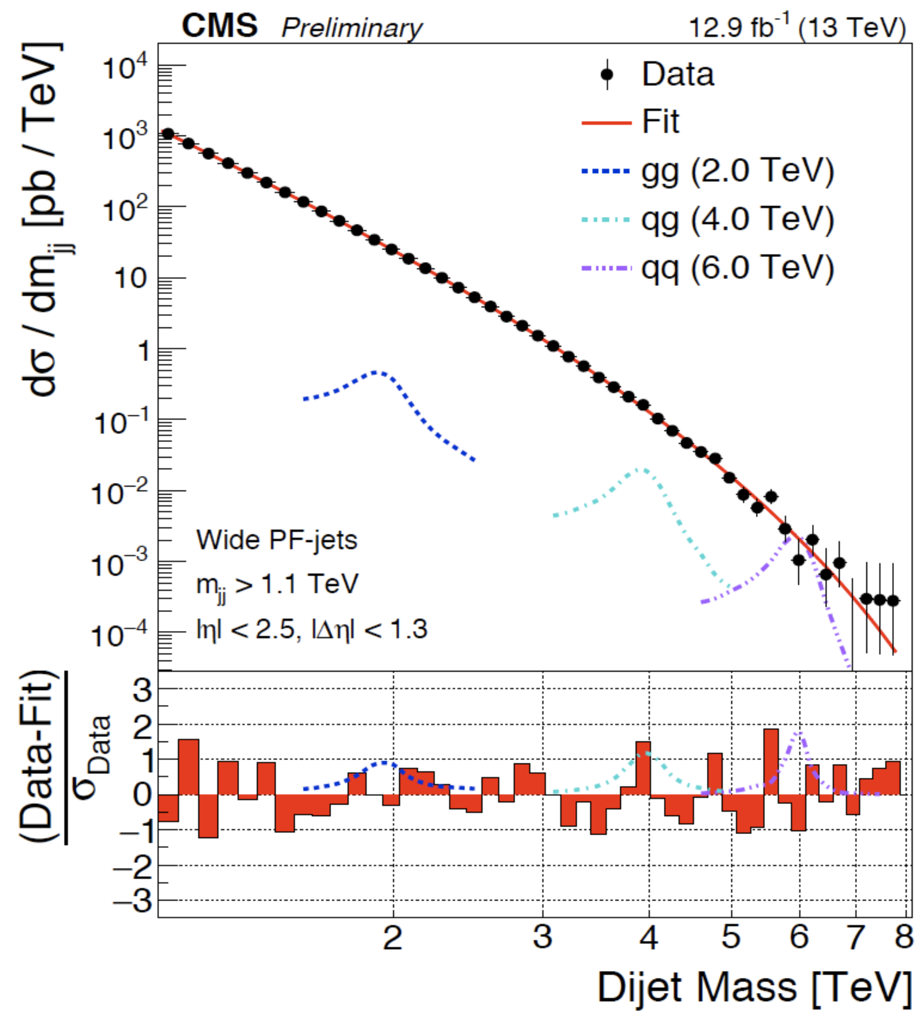


Searches in dijet final states, CMS 13 TeV, 13 fb^{-1}

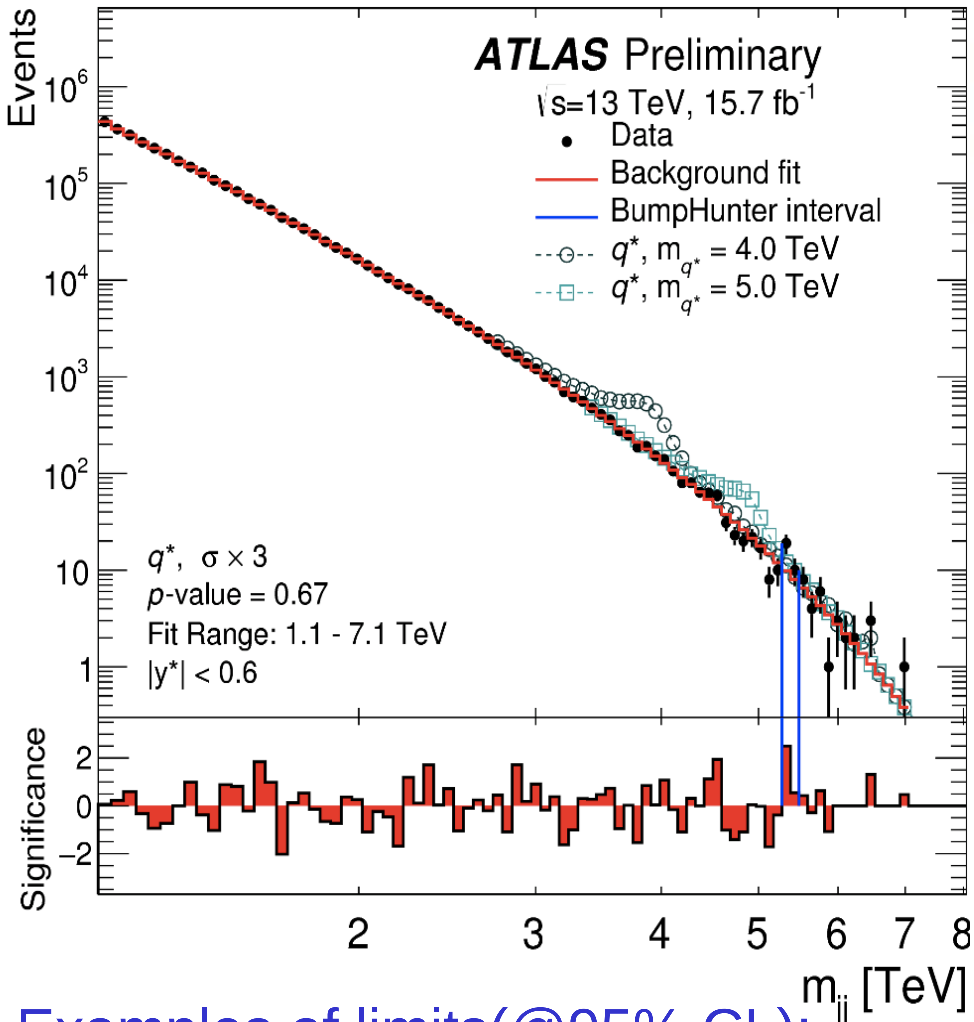
Low mass Analysis

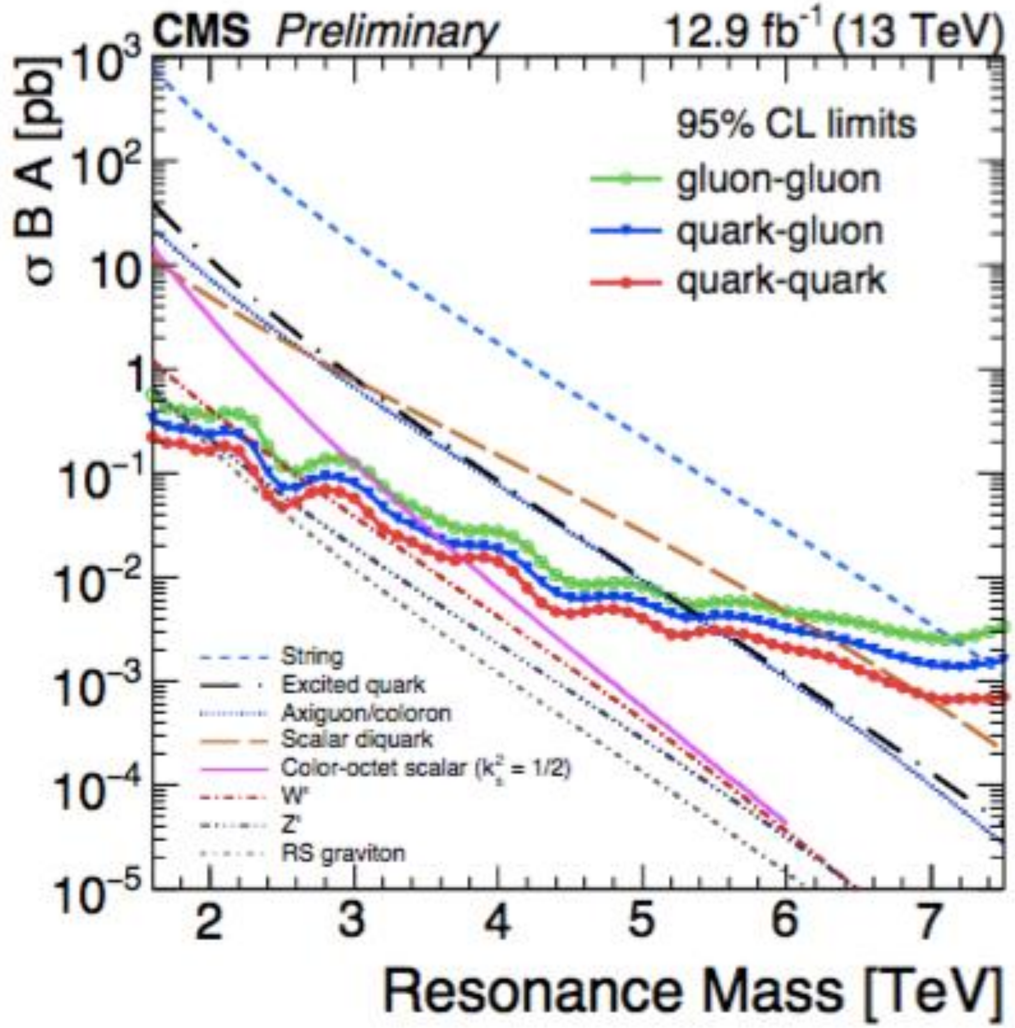


High mass Analysis



Dijets - search for resonances, 2016 data, ~13fb^{-1}



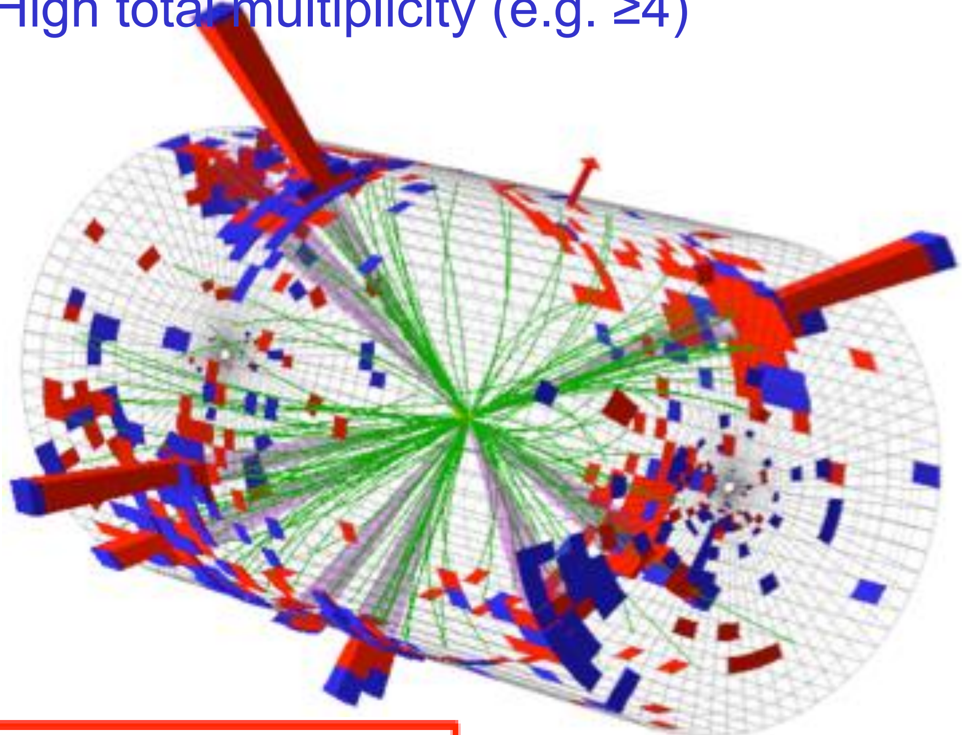


Examples of limits(@95% CL):
m(q*) > 5.6 TeV (ATLAS Run-1: 4.1 TeV)
Z' > 1.5 TeV

Strongest limit:
STRING resonances excluded up to 7.4 TeV

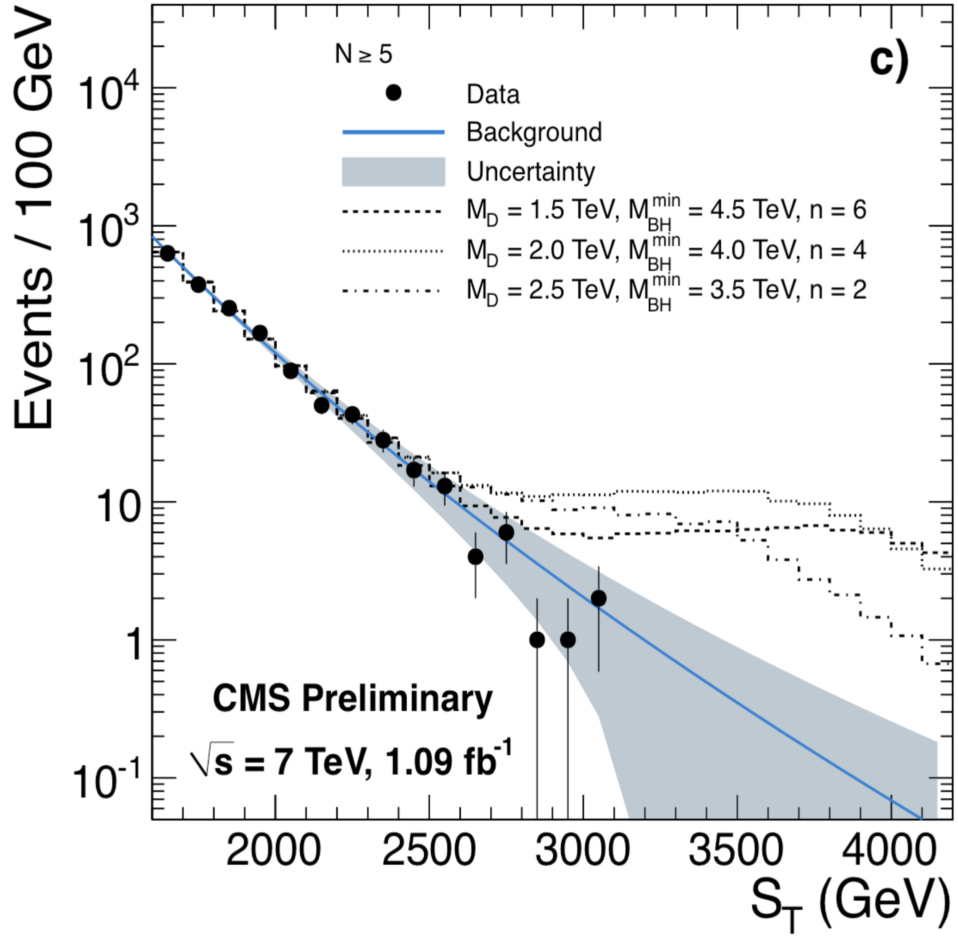
Microscopic quantum Black Holes - 7 TeV results

BH production in ADD model
(large flat extra spatial dimensions)
- Democratic and isotropic decay
- High ST events (total transverse energy)
- High total multiplicity (e.g. ≥4)



10 Jet event, S_T = 1.1 TeV

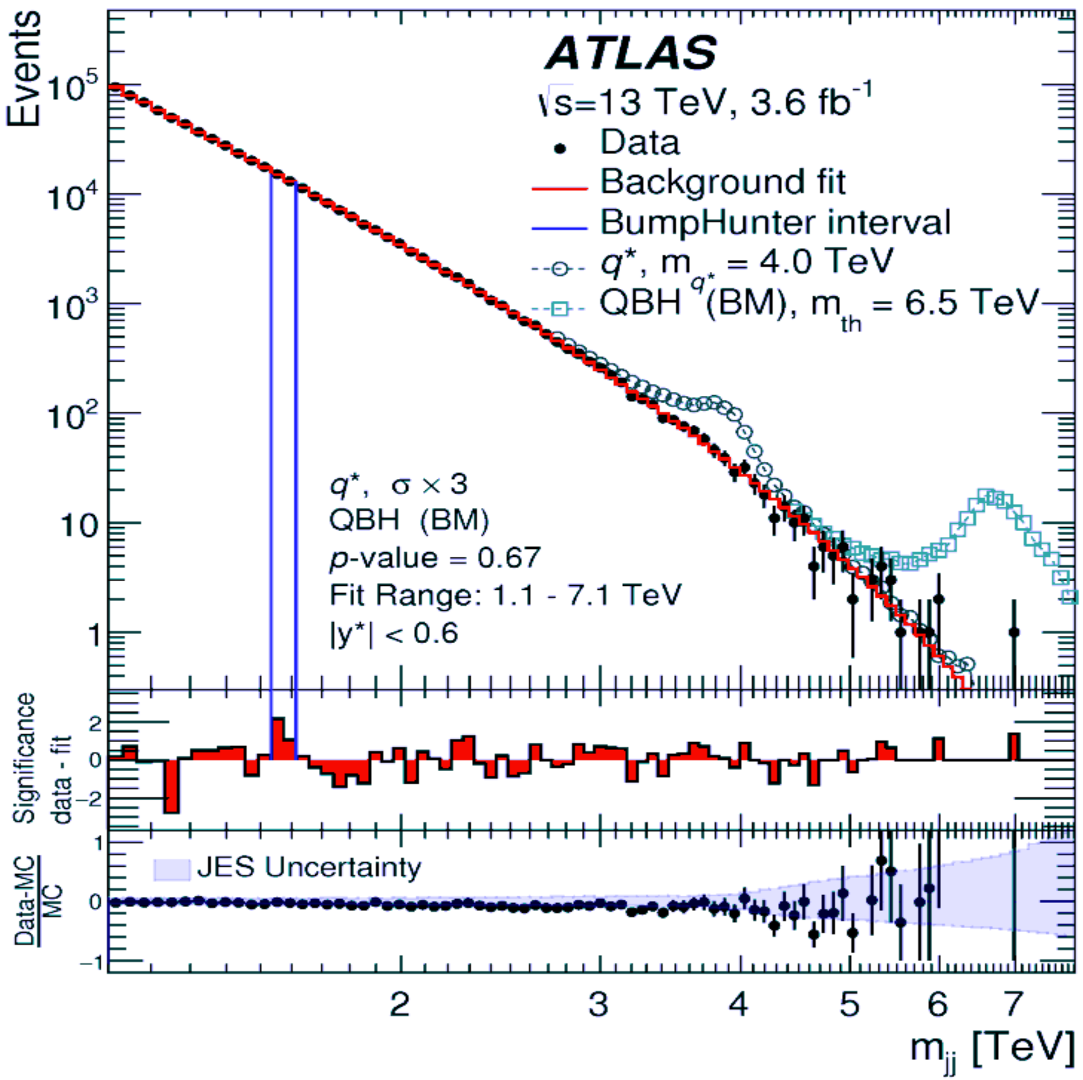
Microscopic black hole evaporation:
Events with large transverse energy sum, S_T



Limits on Black hole
> 4 – 5 TeV @ 95% C

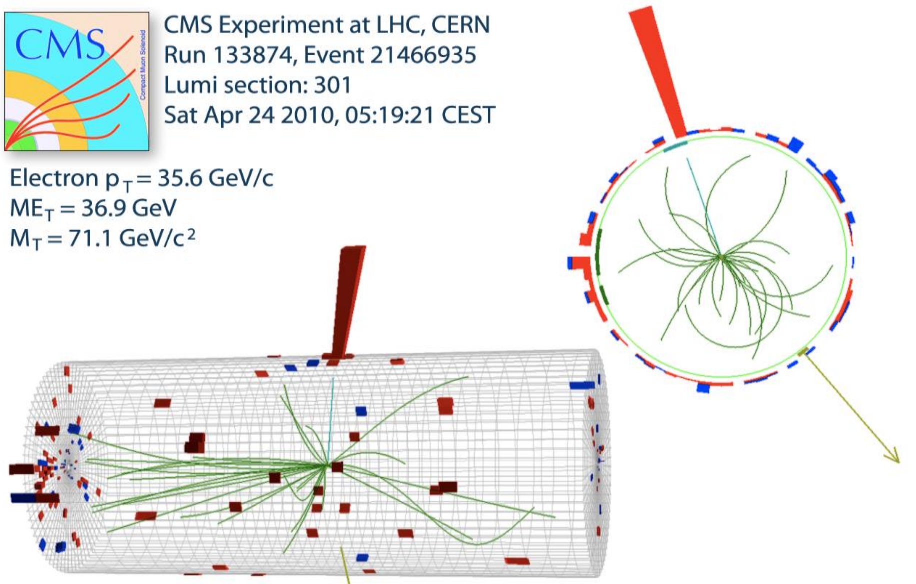
ATLAS, searches with jets at 13 TeV, 2016, ~ 3fb^{-1}

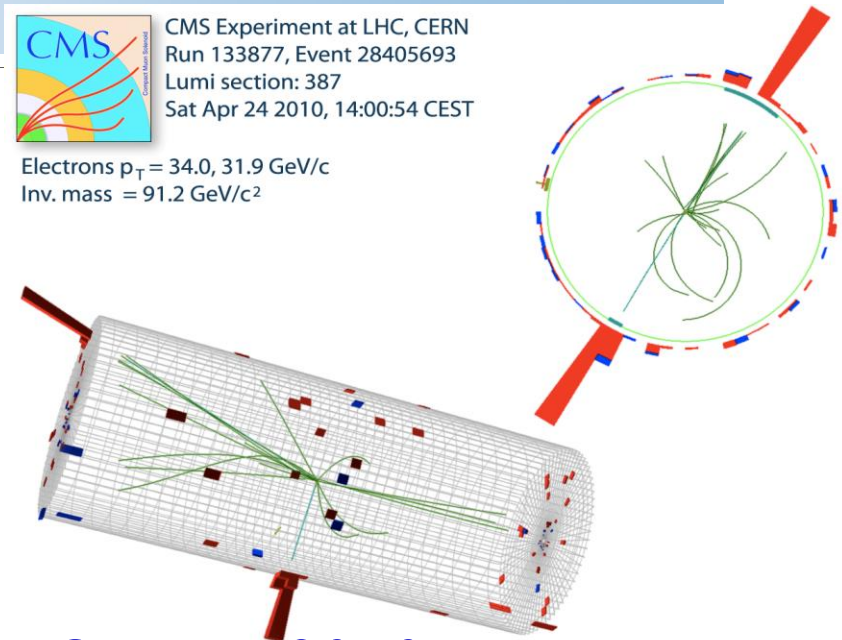
Search for resonances decaying to two jets. No significant excess seen.
Limits on quantum black holes, excited quarks, W’, Z’ models



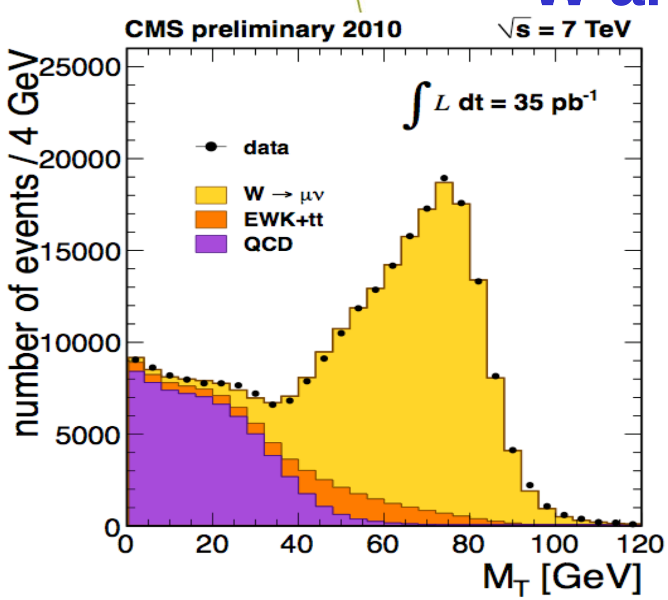
Search for thermal black holes
Signal region : 3 to 8 jets
Signal region at high HT
No significan excess, limits on threshold mass ~ 9 TeV

First W → eν and Z → e⁺e⁻ events in LHC, April 2010



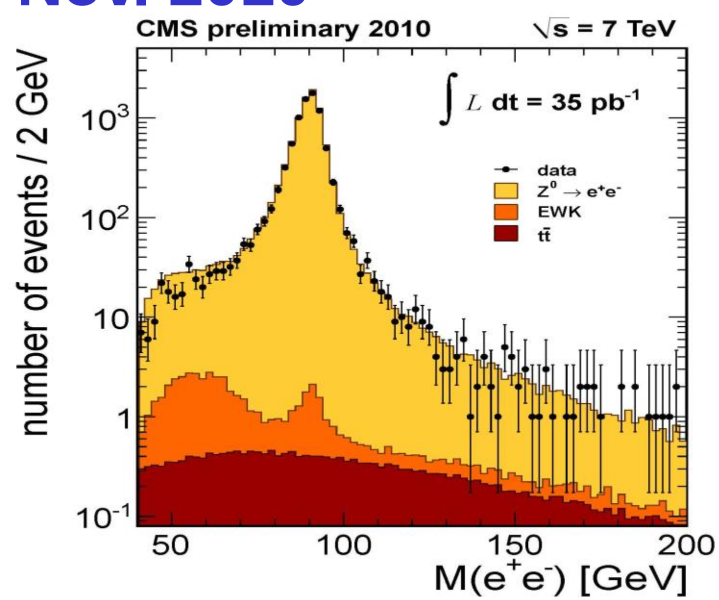


W and Z spectra in CMS, Nov. 2010



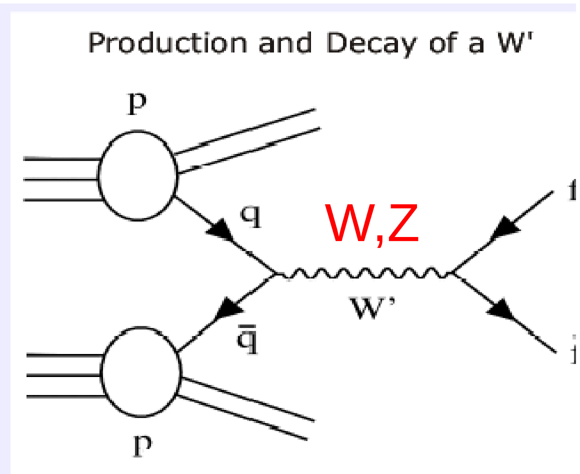
By end-2012 we had ~150.000.000 W and ~15.000.000 Z decaying leptonically!!

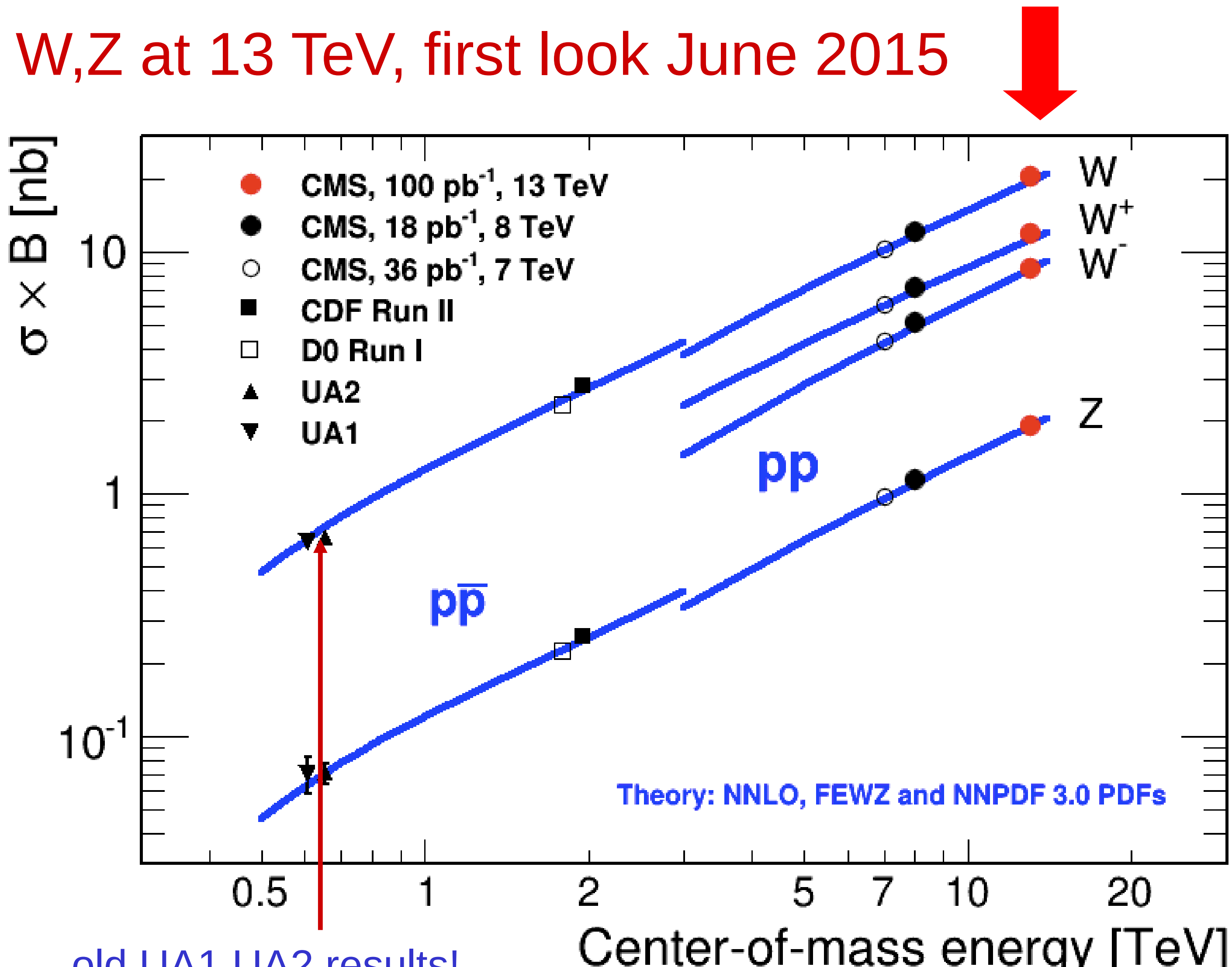
Note progress since first W, Z!



W, Z production cross sections, testing QCD
from the CERN pp-bar collider to the Tevatron and the LHC

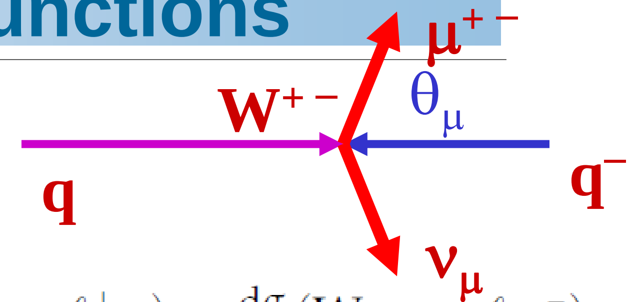
W,Z at 13 TeV, first look June 2015





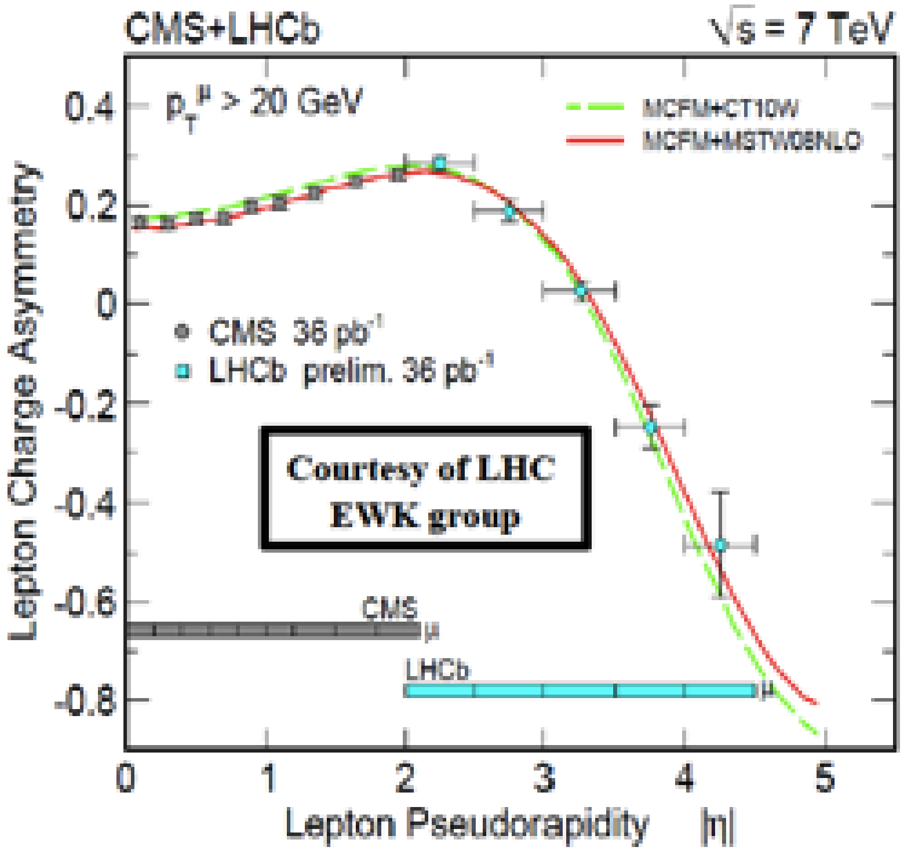
old UA1,UA2 results!

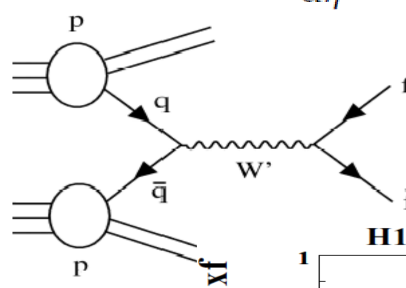
W^{+-} charge asymmetry, CMS and LHCb, - constraining proton structure functions

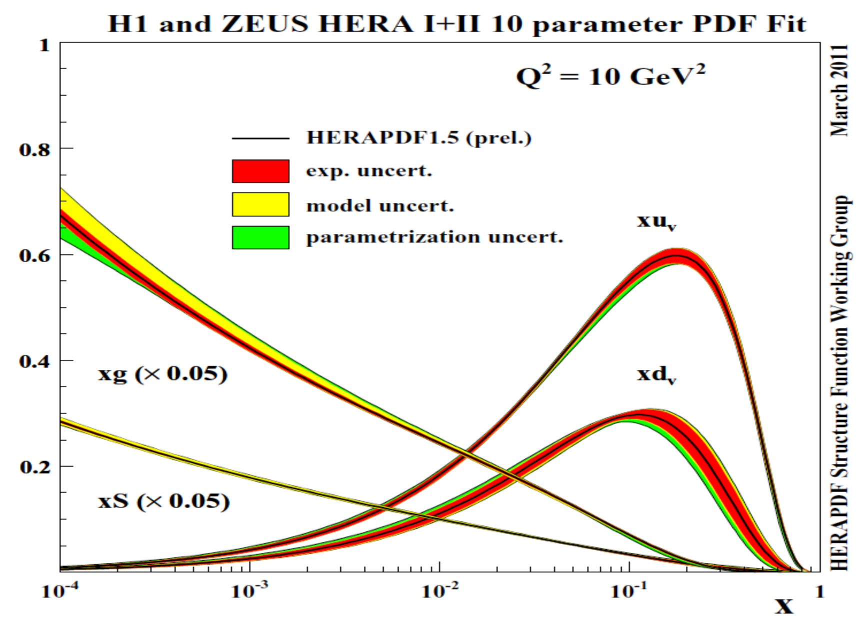


$W^{+-} \to \mu^{+-}\,\nu$ charge asymmetry vs η_μ
combining CMS and LHCb data

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



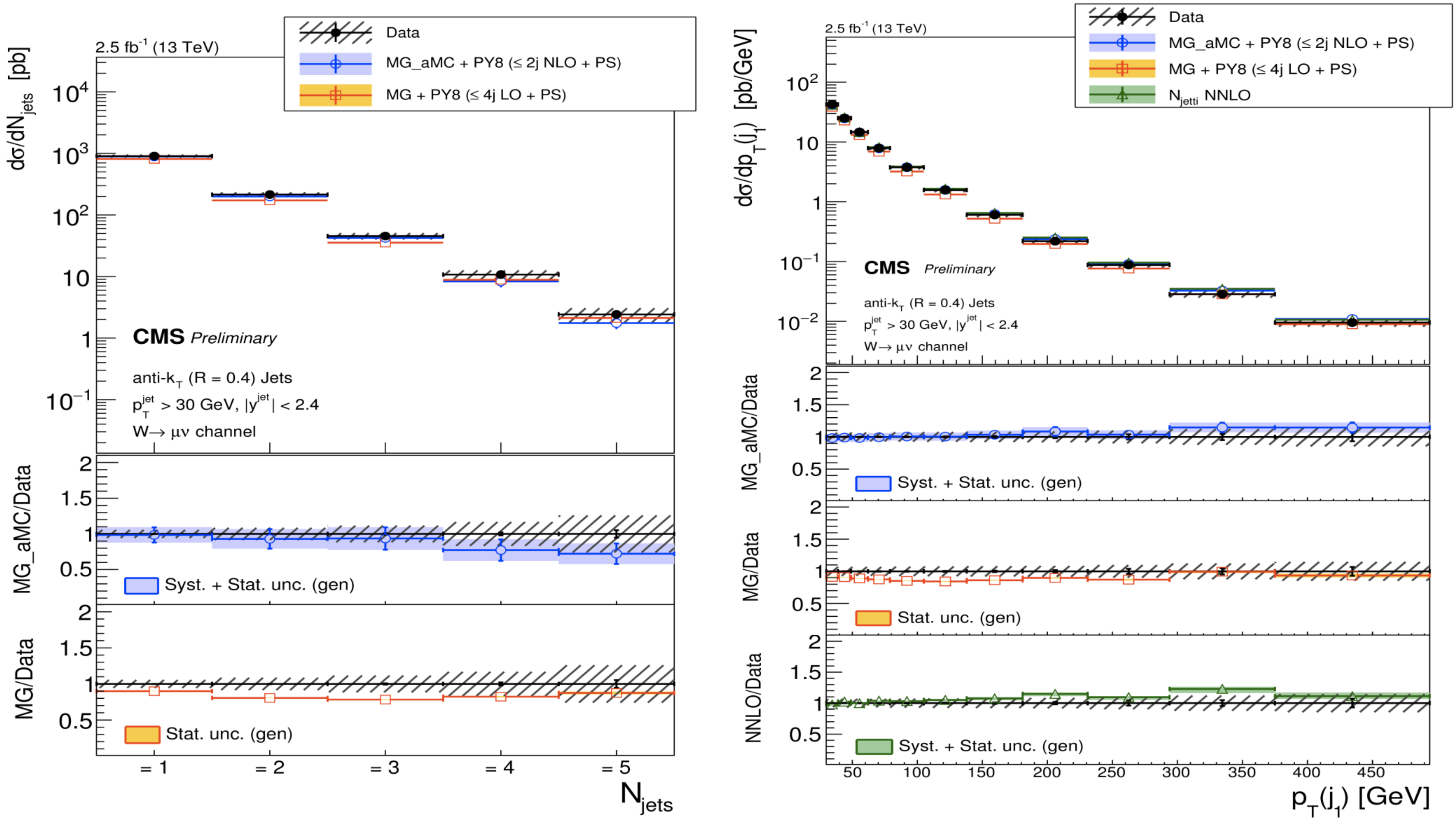


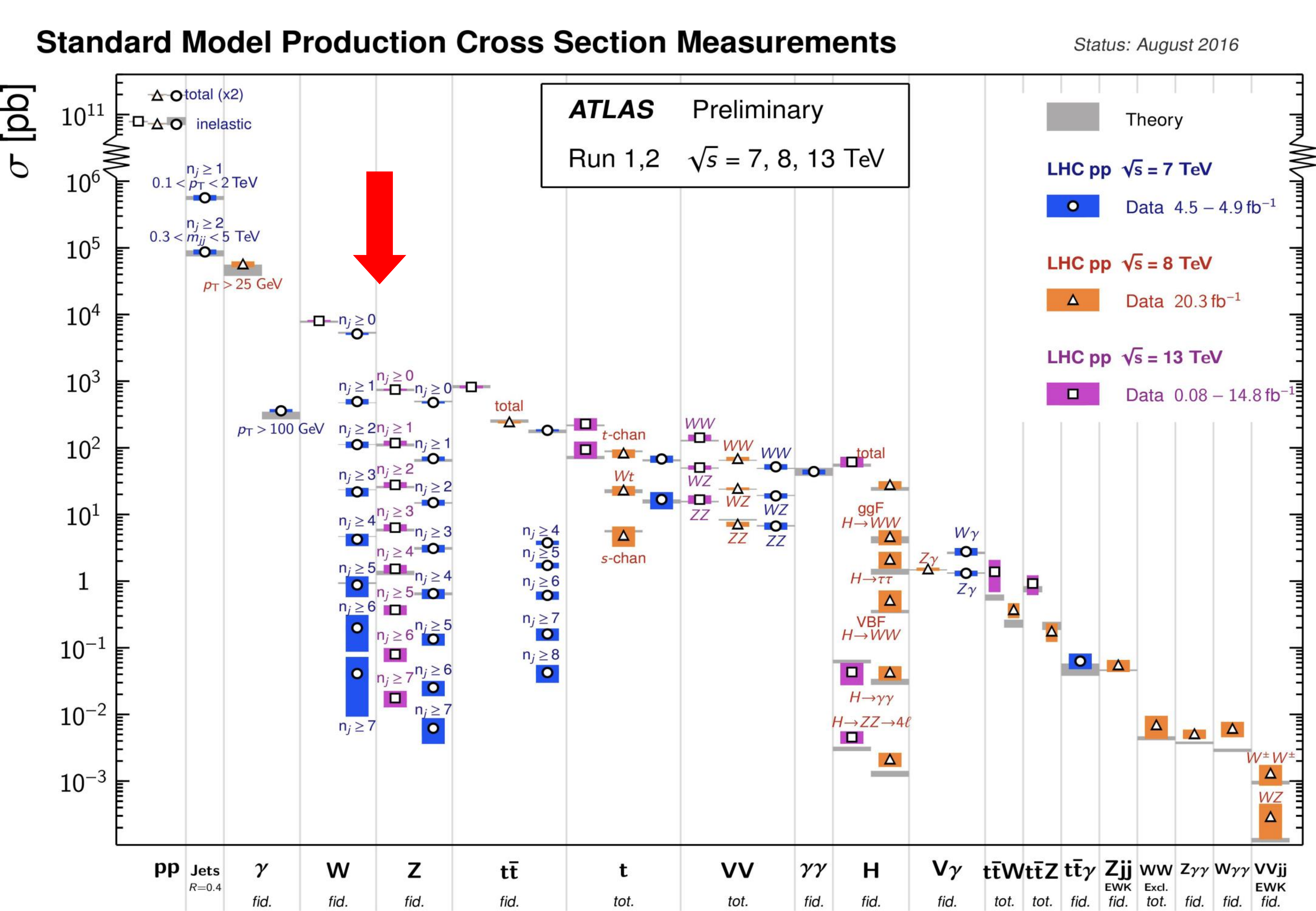


$\eta_\mu = -\ln \mathrm{tg}(\theta_\mu/2)$

W(→ μν) + jets, 13 TeV, CMS

Measurement of the differential cross section W(μν)+jets CMS, 2.5fb^{-1}, 13 TeV, compared with NNLO for one inclusive jet and NLO for all inclusive jet spectra.

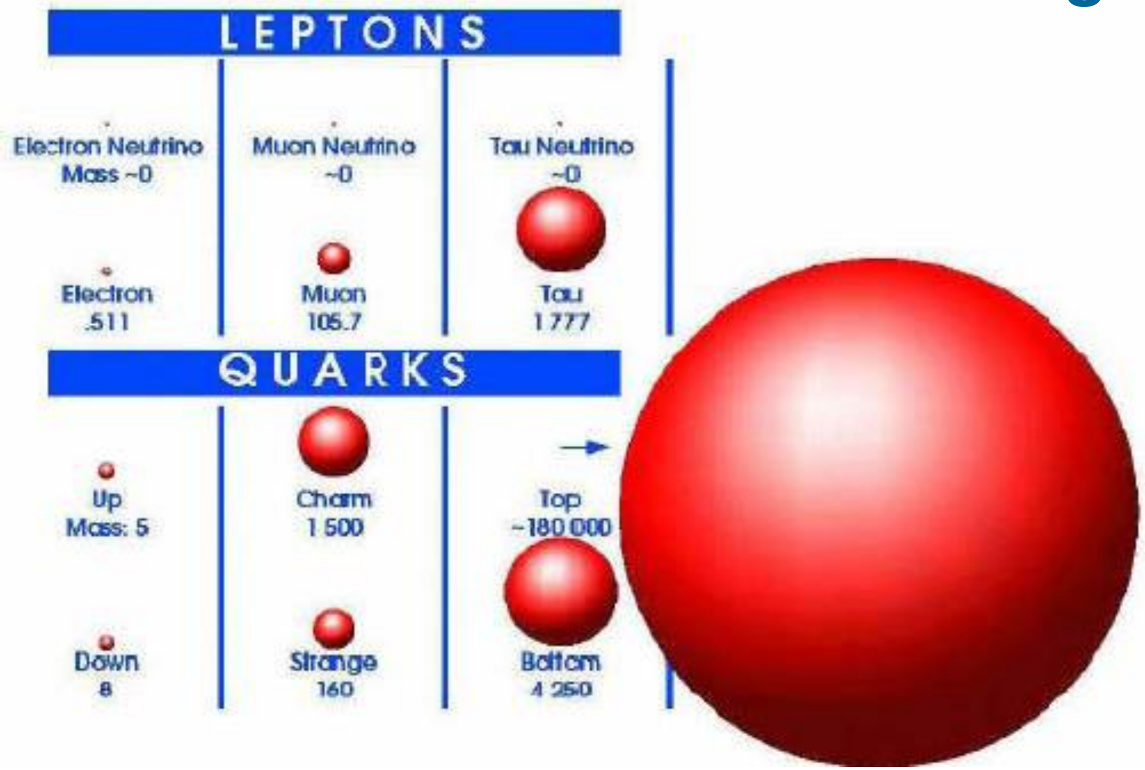


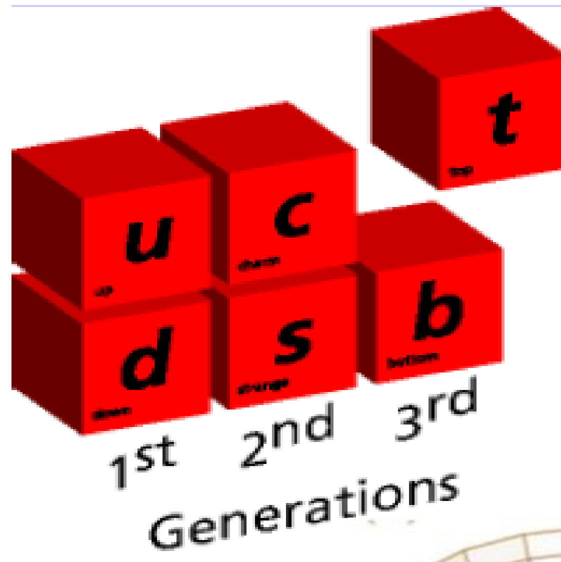


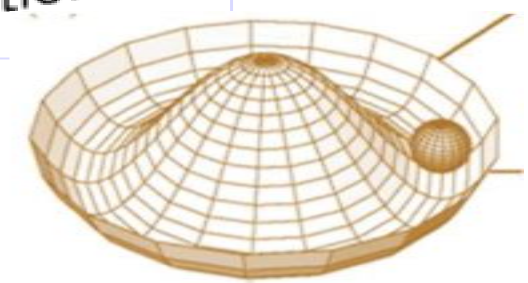
Standard Model Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 14.8 fb⁻¹
σ [pb]
total (x2)
inelastic
n_j ≥ 1 0.1 < p_T < 2 TeV
n_j ≥ 2 0.3 < m_jj < 5 TeV
p_T > 25 GeV
p_T > 100 GeV
total
t-chan
Wt
s-chan
WW
WZ
ZZ
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
W±W±
WZ
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
VVjj EWK fid.

Top quark physics
- some aspects

Study of the top quark: one of the main goals of the LHC







$g_{Hff} = m_f/v$

V μ^2 λ

At nominal energy and luminosity LHC produces about 1 top-antitop pair second!

The LHC could be called a ‘top factoty’!

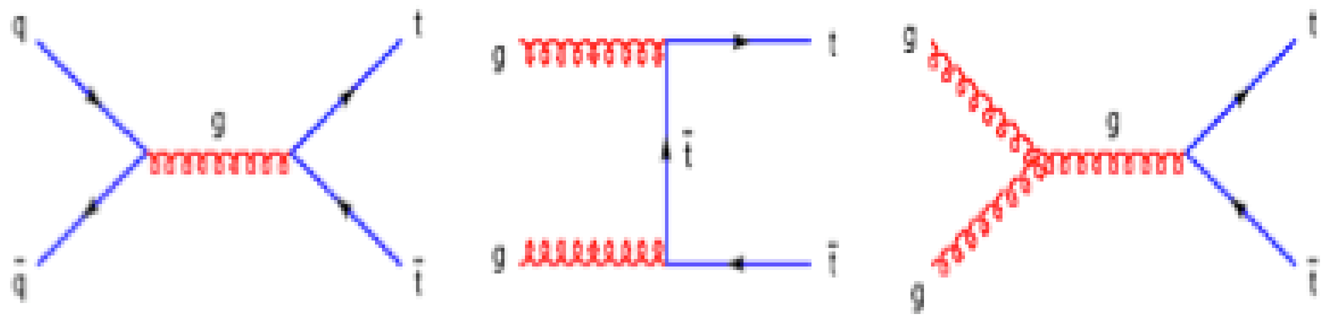
Top quark physics after the Higgs discovery:

– Special role in EWSB mechanism?

– Does it play a role in non-SM physics?

Top at the LHC, production and decays for ex. top $\rightarrow$ lepton + jets final states

tt-bar production diagrams, some….

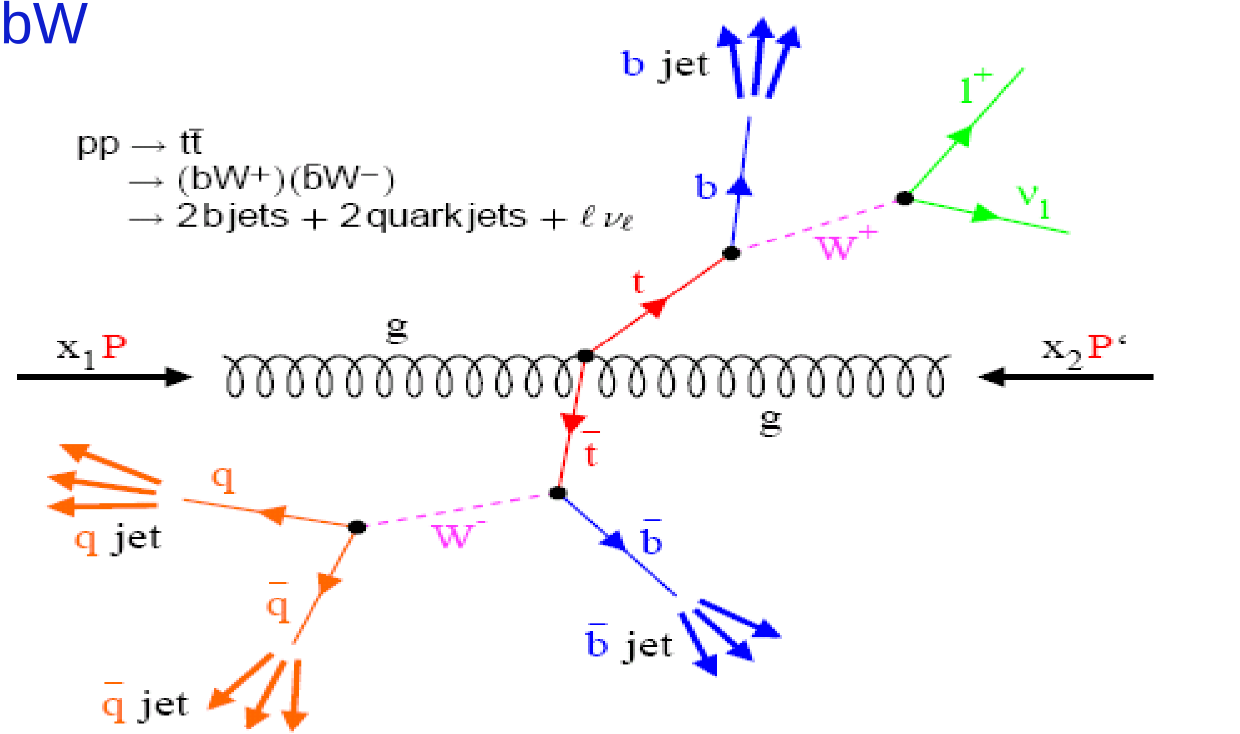


+…..

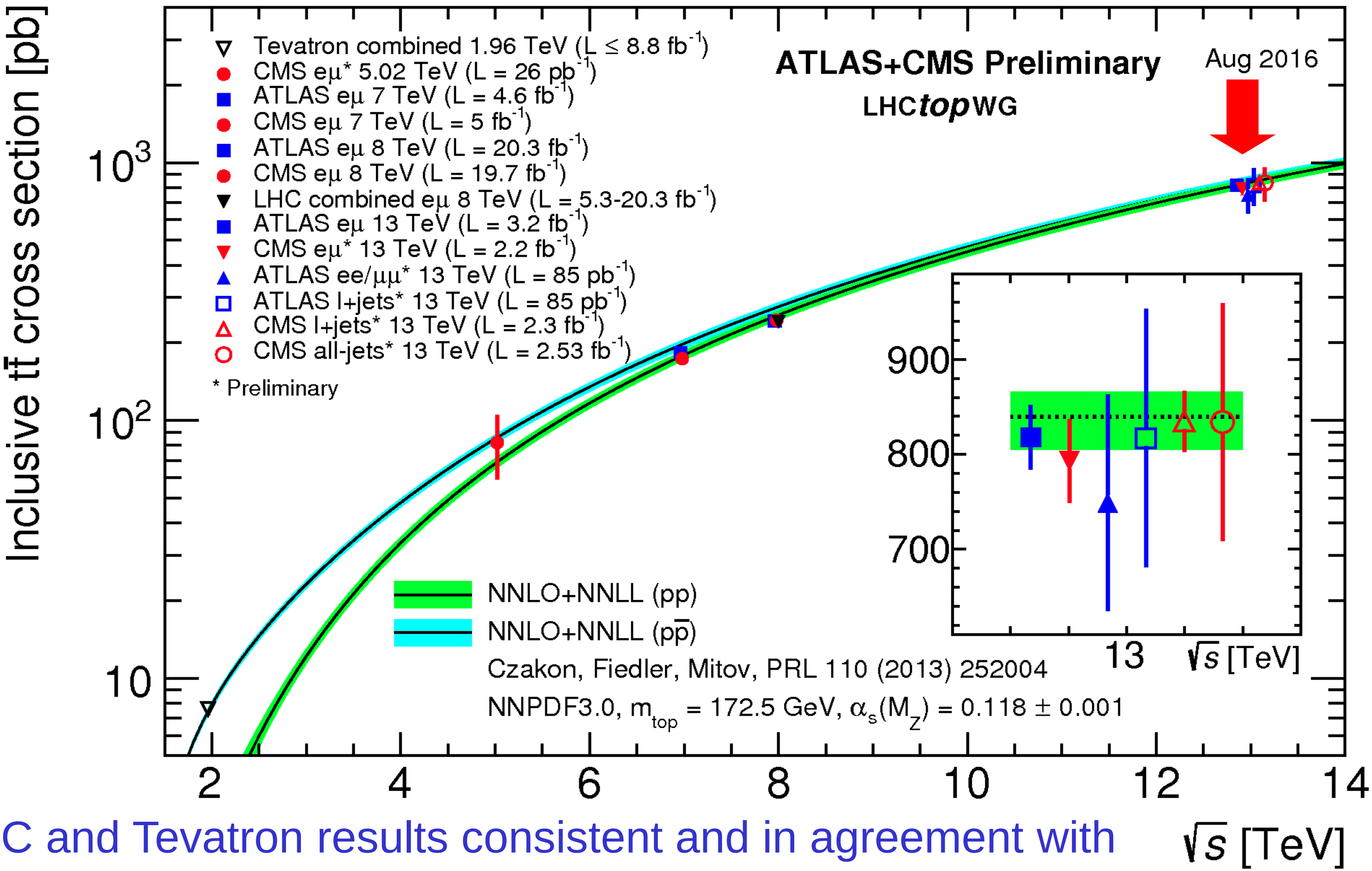
Top decay in the SM: t $\rightarrow$ bW

tt-bar event decay topology in «sigle lepton mode »:

tt $\rightarrow$ bWbW $\rightarrow$ blvbqq

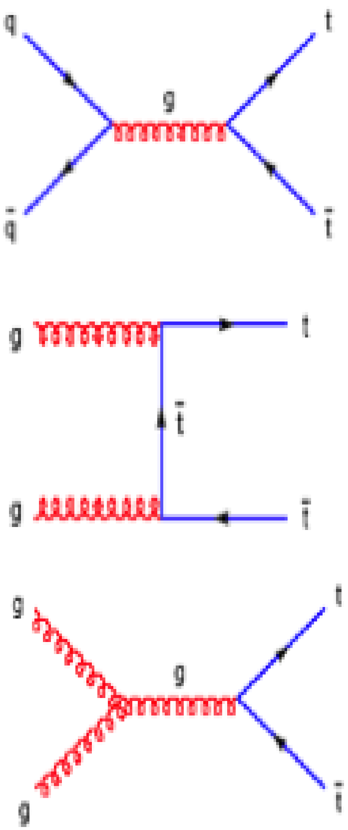


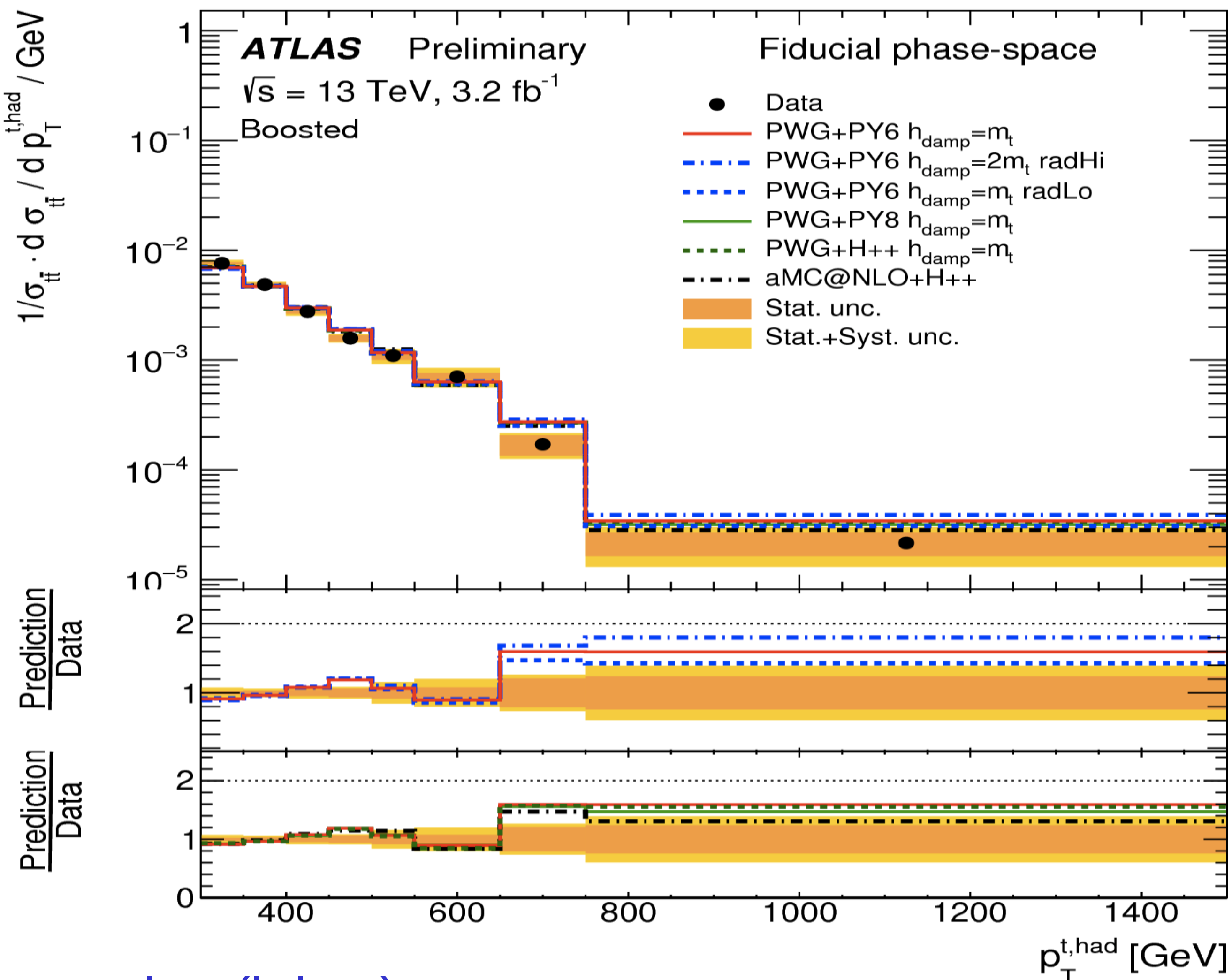
Top pair production cross-sections, up to 13 TeV



LHC and Tevatron results consistent and in agreement with NNLO+NNLL over a large range of center-of-mass energies

tt-bar differential cross section, ATLAS, 13 TeV - testing QCD



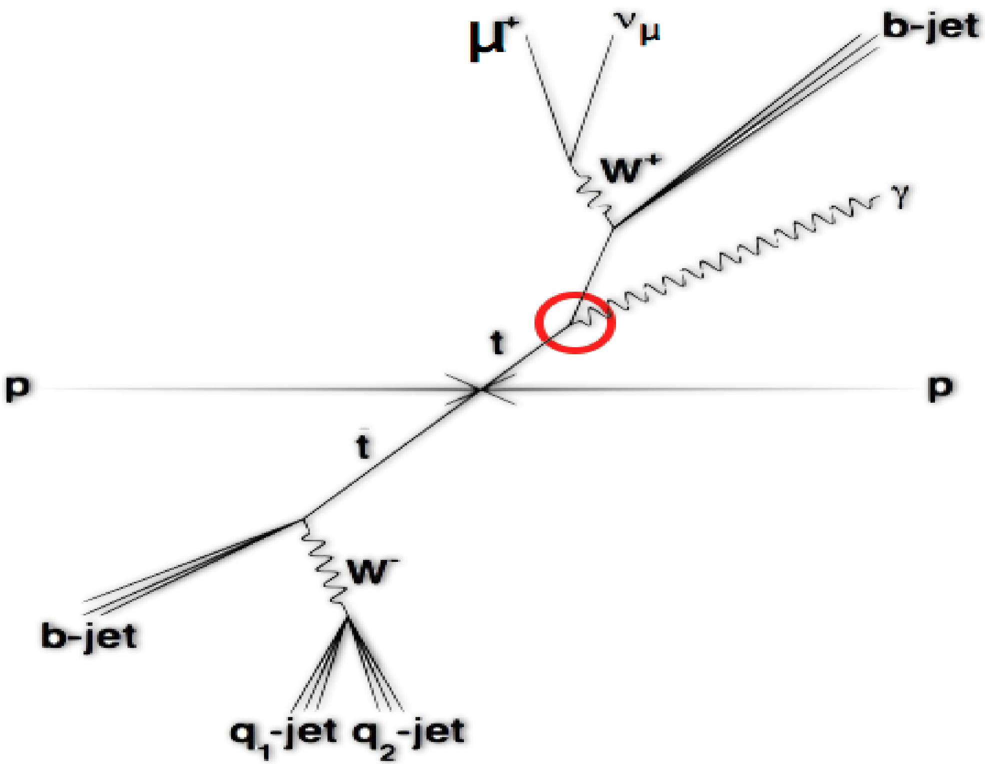


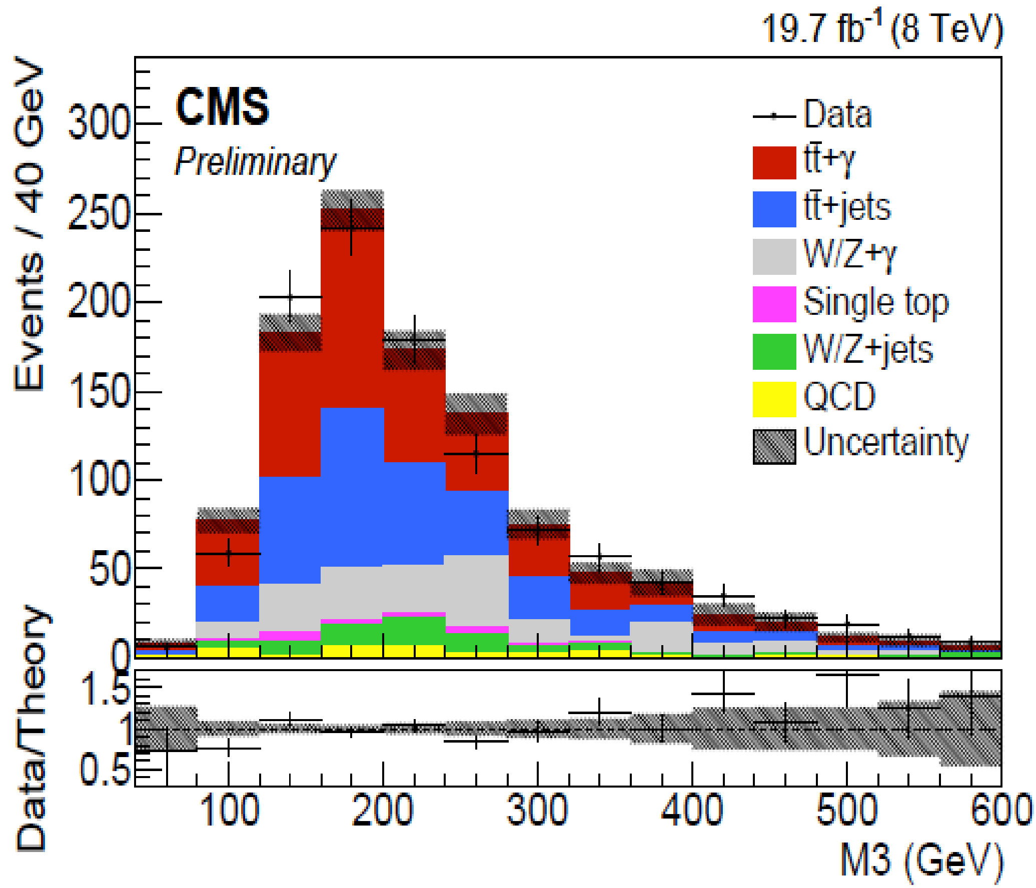
Differential tt cross section (l+jets):

ATLAS, 3.2 fb^{-1}, 13TeV, tops resolved and boosted.

Top properties, charge, status in 2013 and final results at 8 TeV

semi-muonic tt + photon





tt+γ $\Delta R(\gamma,\text{jet}) > 0.1$ and $p_T(\gamma) > 2\text{GeV}$

$\sigma(tt+\gamma) = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})$ pb

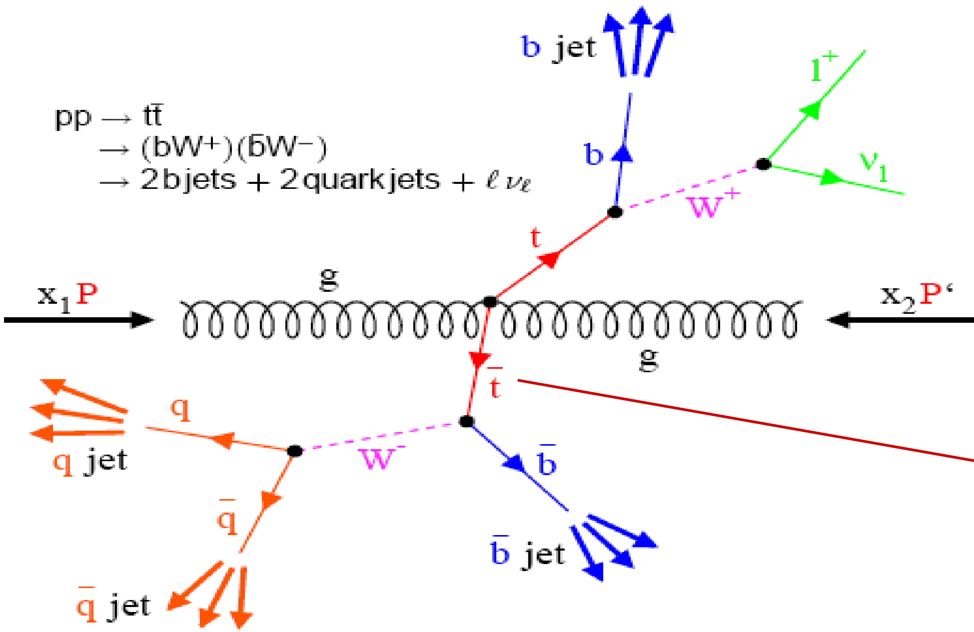
theory: 1.8 ± 0.5 pb

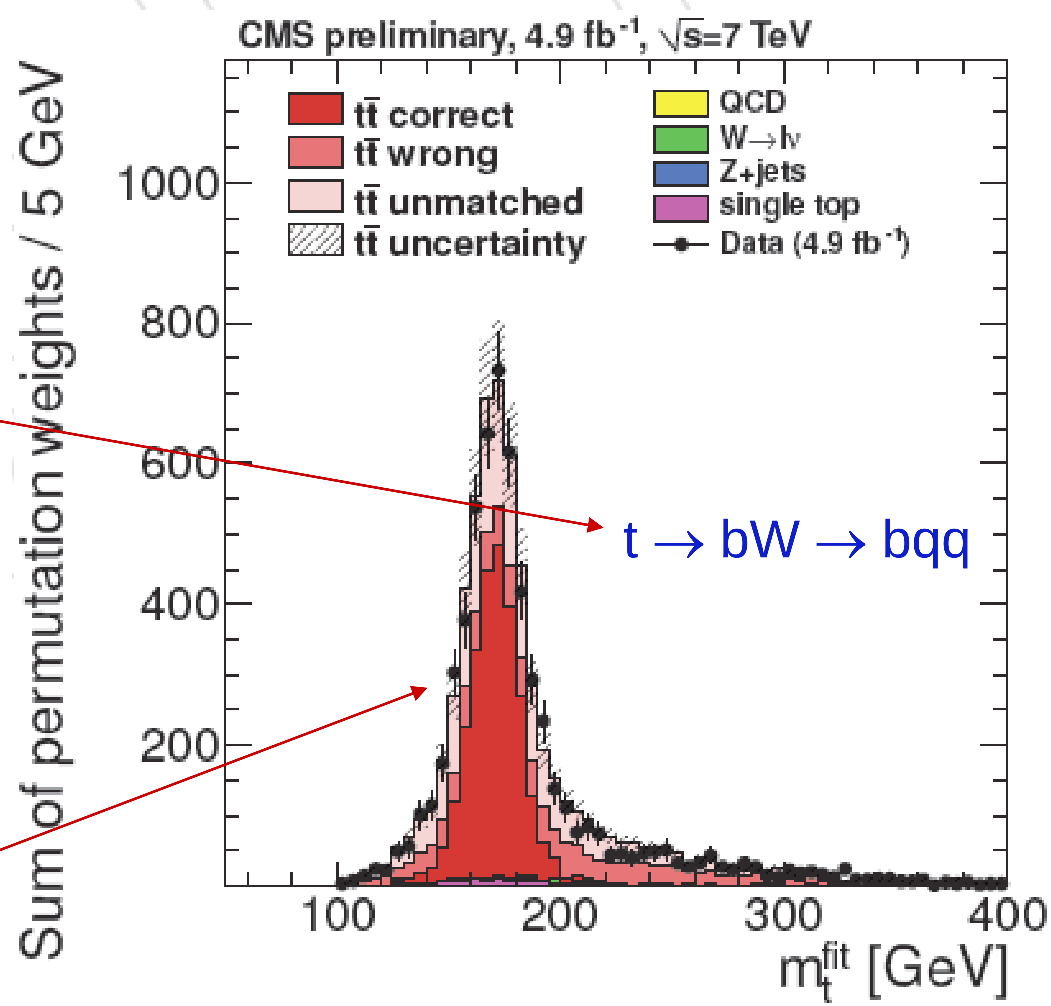
l+jets

- Ratio ttγ/tt in fiducial region
- 21% precision

Top mass - from the semileptonic mode, the most appropriate one for mass…..

$t\bar{t} \to bW\, bW \to bl\nu\, bqq$

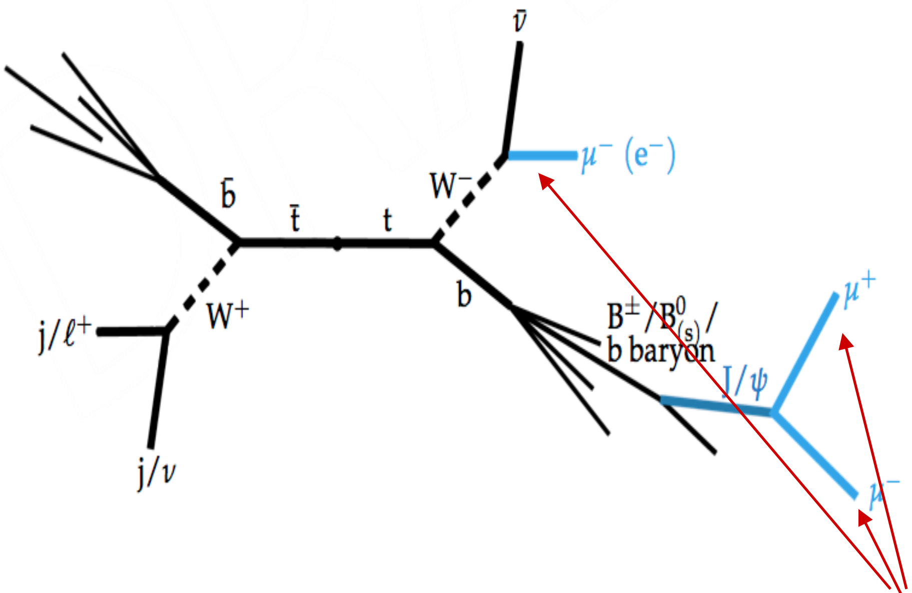


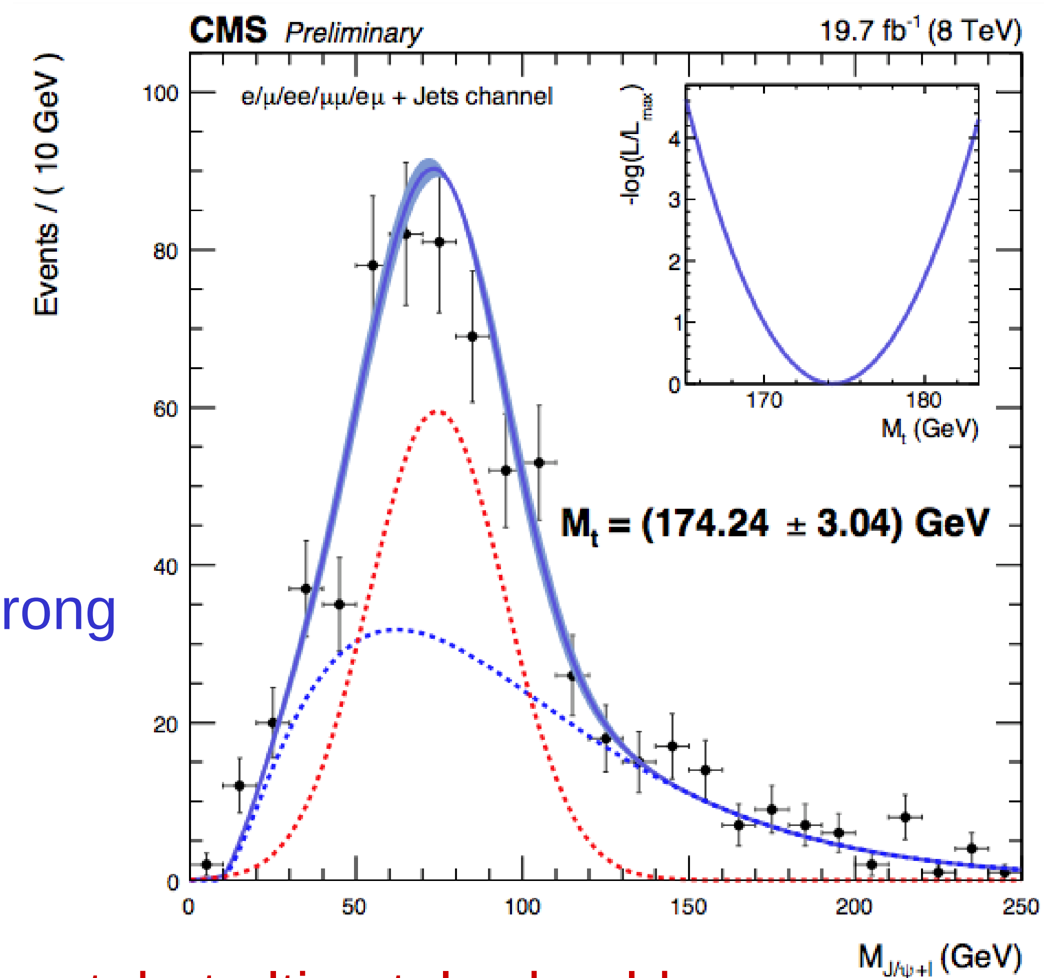


$t \to bW \to bqq$

CMS average : 172.6 ± 0.1 ± 0.7 GeV

Top mass in top pairs with J/psi in b-decay chain, 3-lepton final states, at 8 TeV

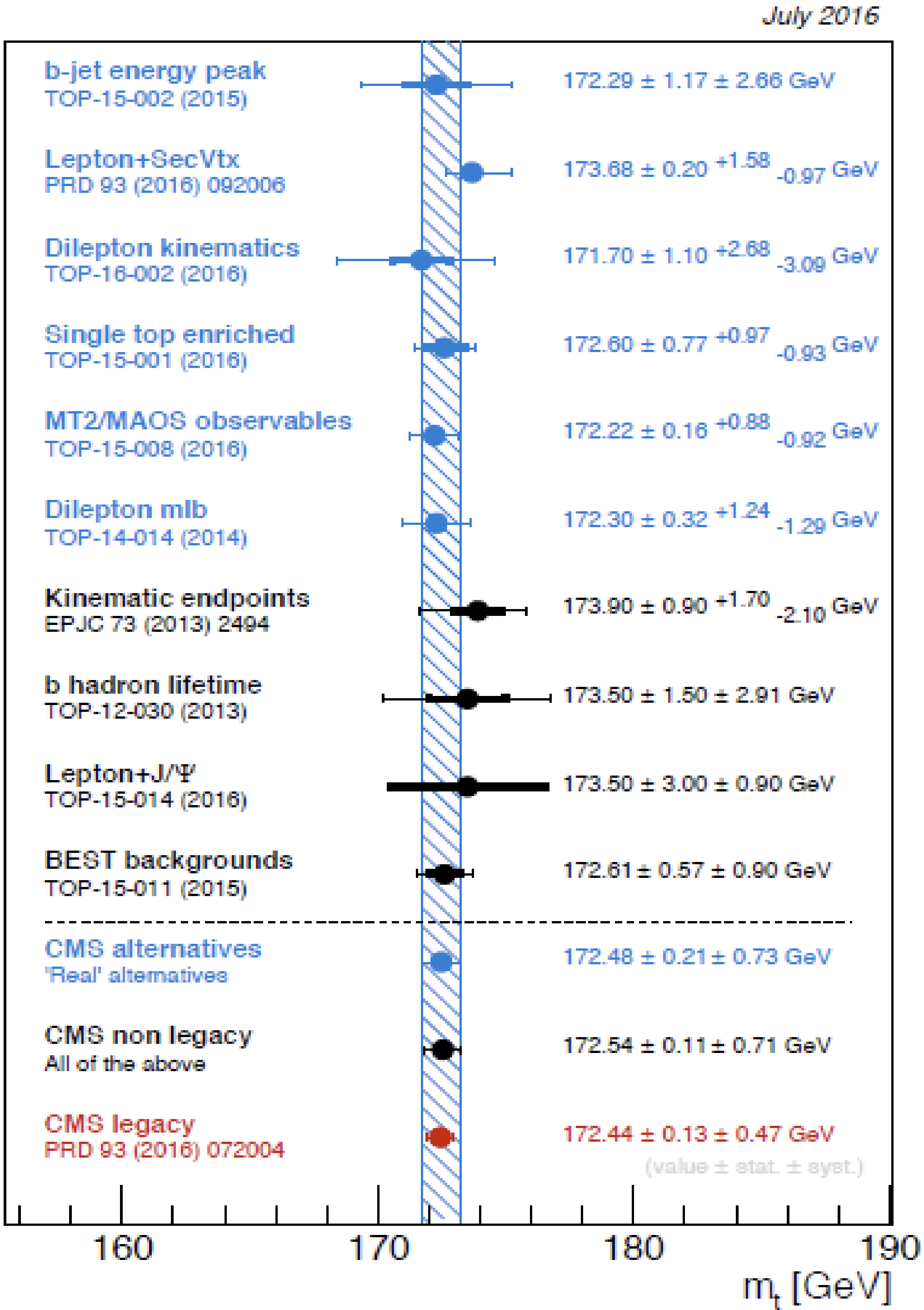




Using the correlation between the 3-prong mass and the top quark mass
An old idea, first application of CMSNOTE-2006-058

measurement statistics limited at present, but ultimately should provide the most precise measurement

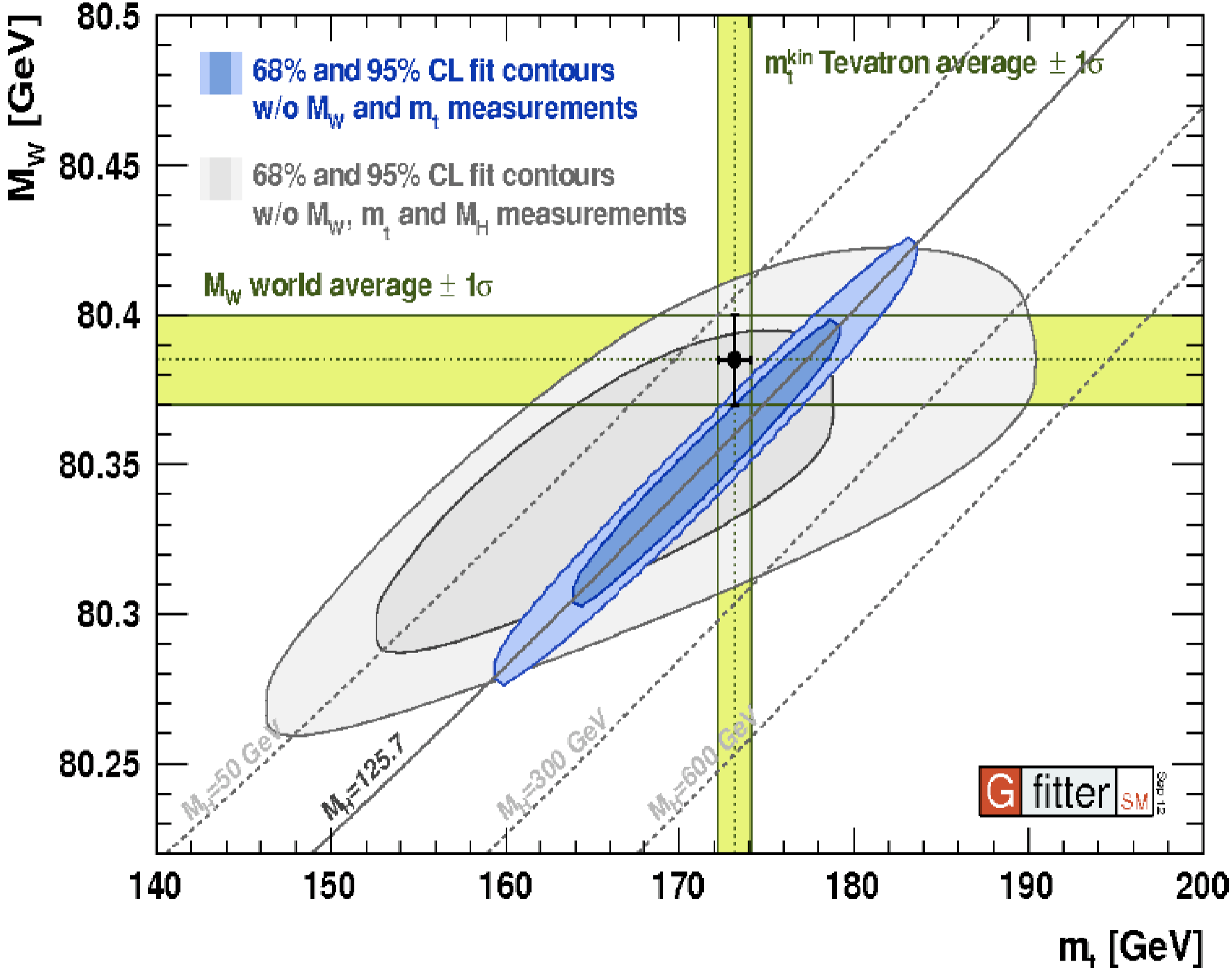
CMS, top mass measurements, status September 2016



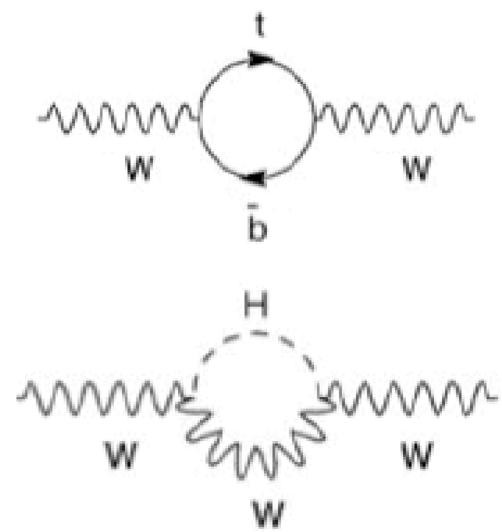
- We have the best mass measurementin the world (by combining the best analyses per channel), TOP-14-022, Phys. Rev. D 93, 072004 (2016)

- We have several "alternative measurements", not meant to be competitive but complementary

Testing the coherence of the Standard Model - importance of precision measurements of W, top and Higgs masses

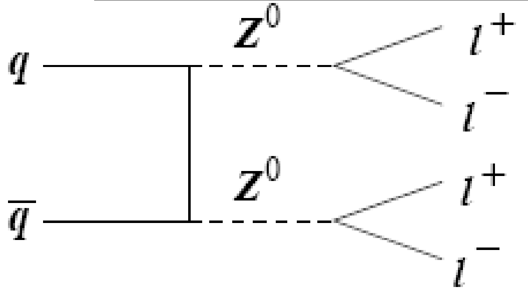


W mass correlated to the Higgs and top masses

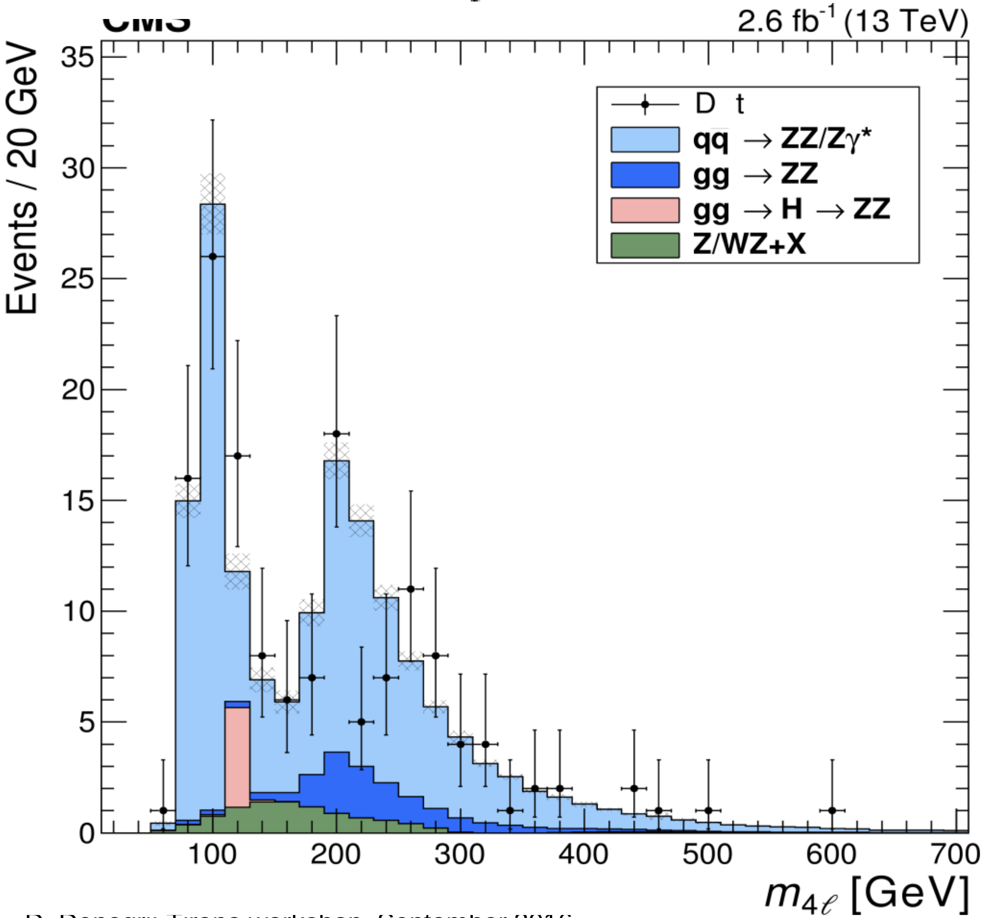


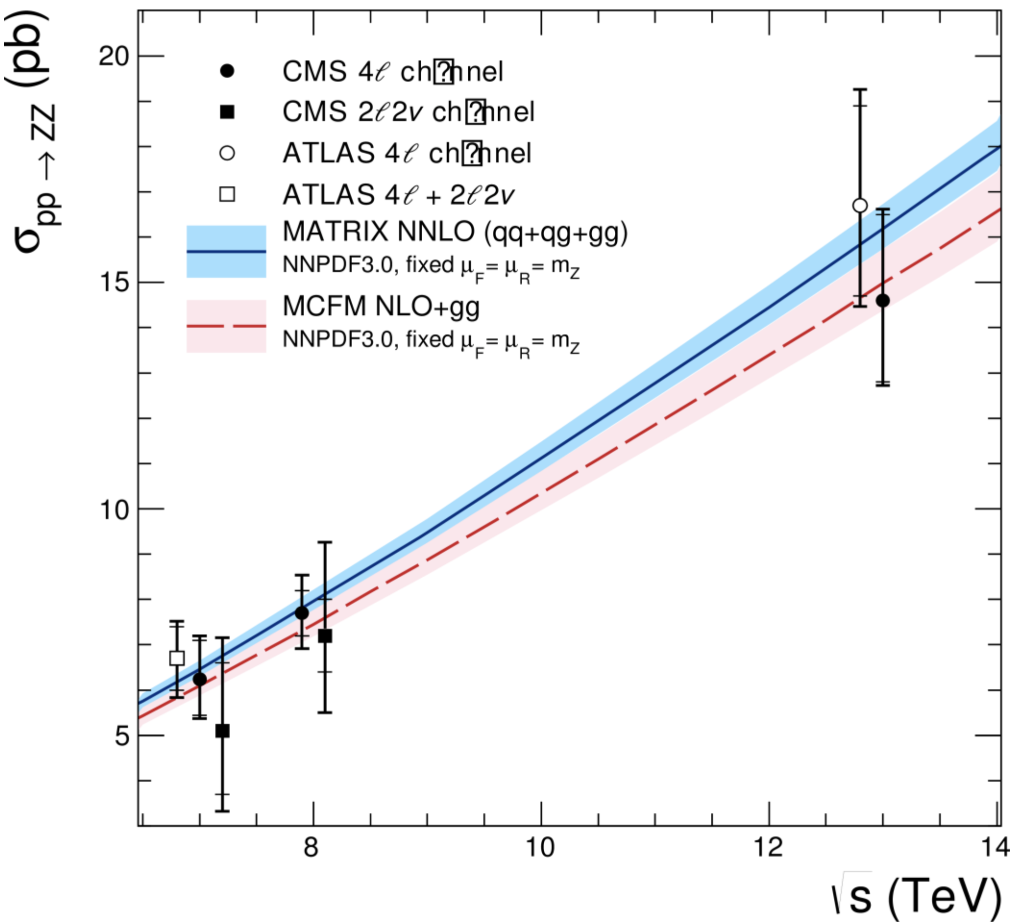
Electroweak measurements
- di-boson channels

ZZ → 4 leptons, 13 TeV, CMS, summer 2016



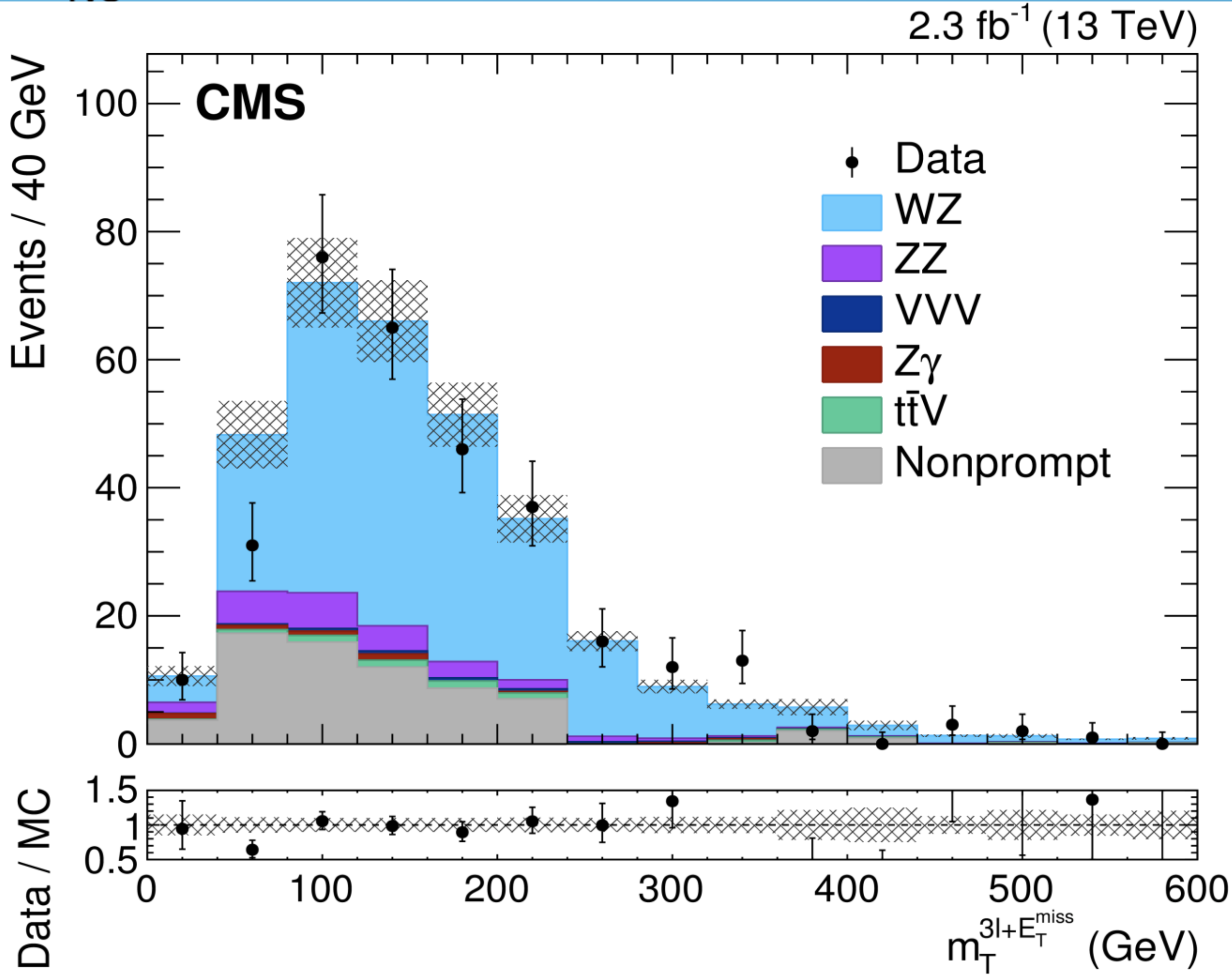
Measurement of ZZ→ lll'l'
CMS, 2.6fb^{-1}, 13 TeV
$\sigma(ZZ) = 14.6^{+1.9}_{-1.8}(st)^{+0.5}_{-0.3}(sy) \pm 0.2(th) \pm 0.4(lu)$ pb
NNLO: $15.0^{+0.7}_{-0.6} \pm 0.2$ pb
~14% precision, statistically limited

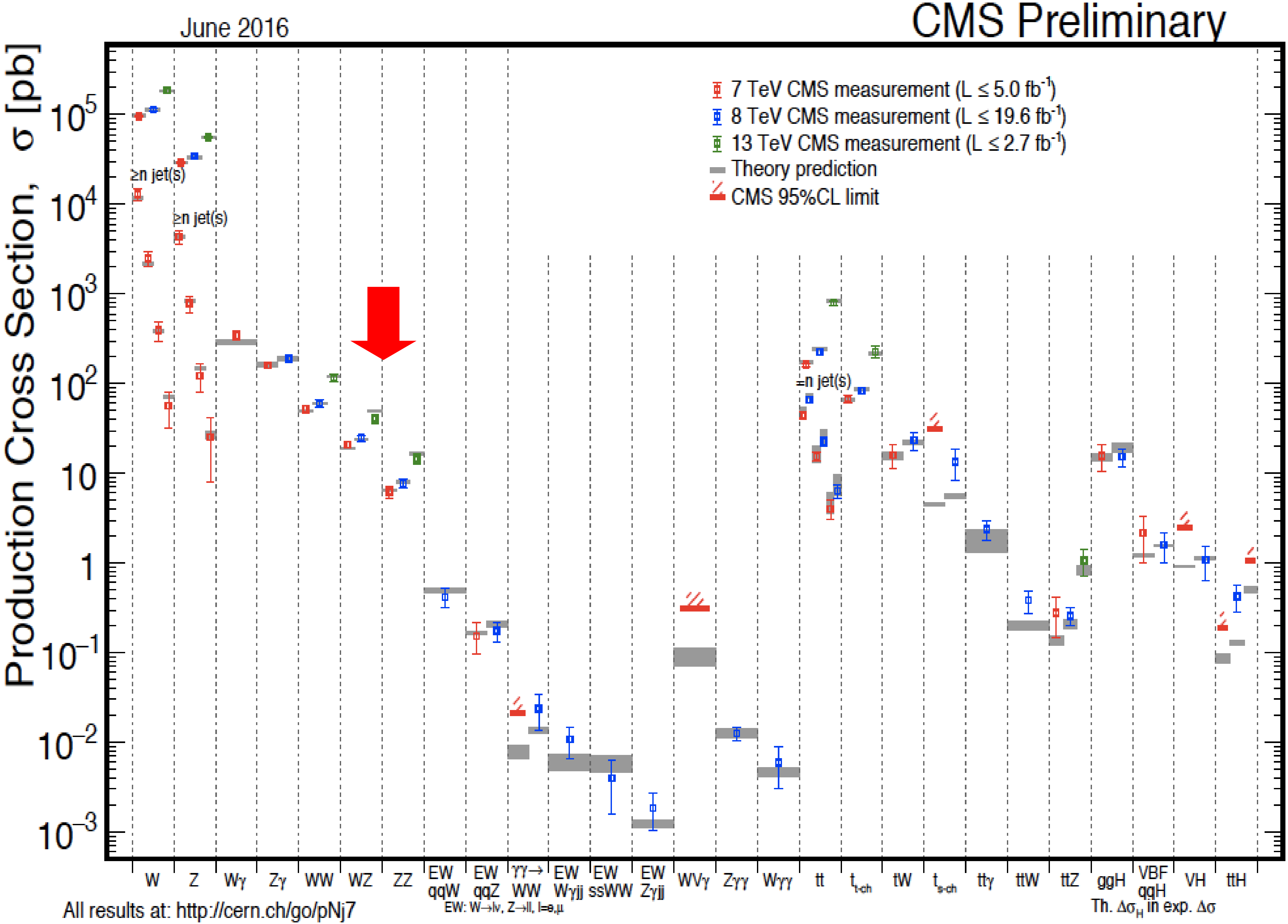




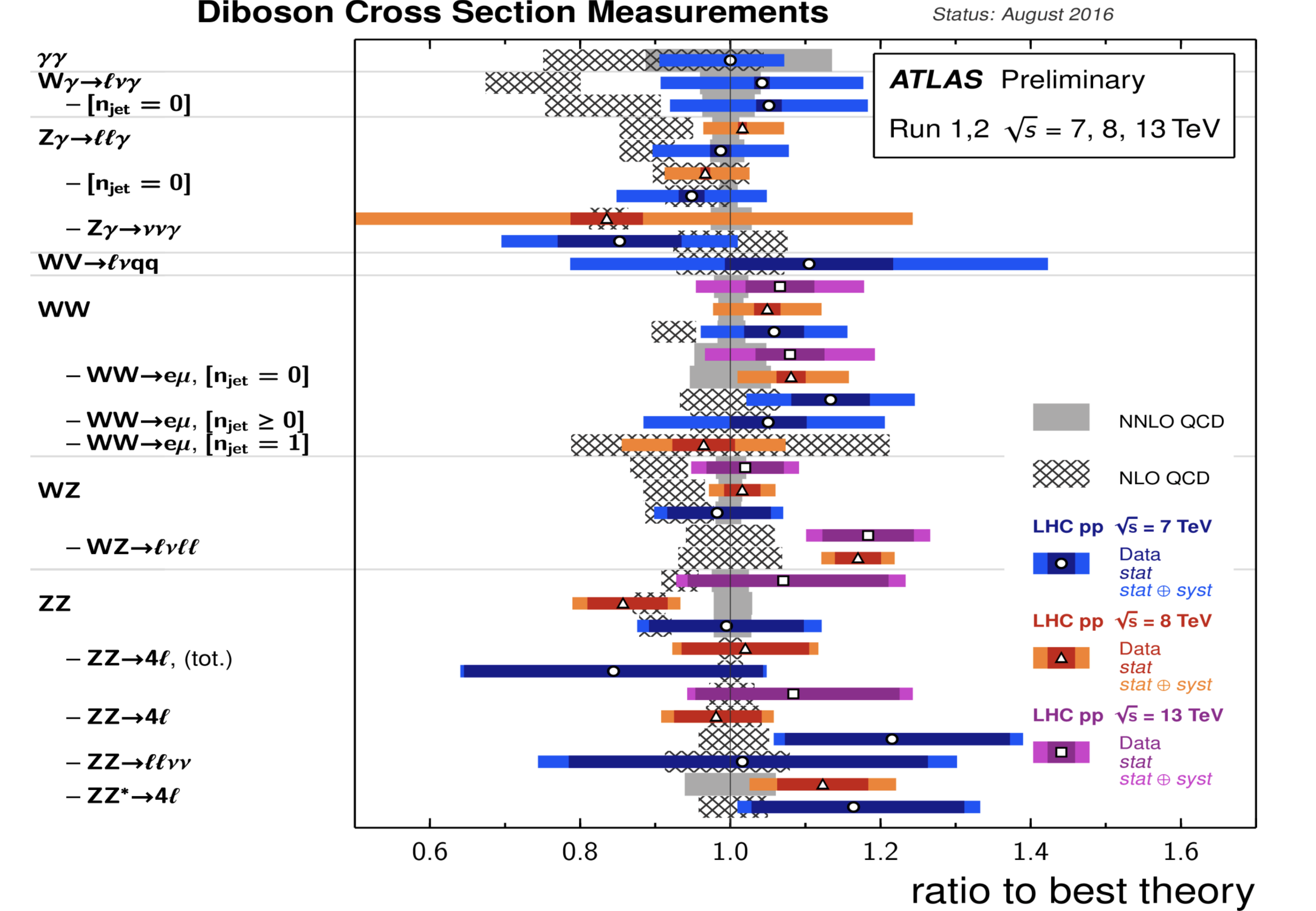
WZ → 3 leptons, 13 TeV, CMS, summer 2016

Measurement of WZ→ lνl'l'
CMS, 2.3fb^{-1}, 13 TeV
$\sigma(WZ) = 39.9 \pm 3.2(stat)^{+2.9}_{-3.1}(syst) \pm 0.4(theo) \pm 1.3(lumi)$ pb
NNLO: $50.0^{+1.1}_{-1.0}$ pb



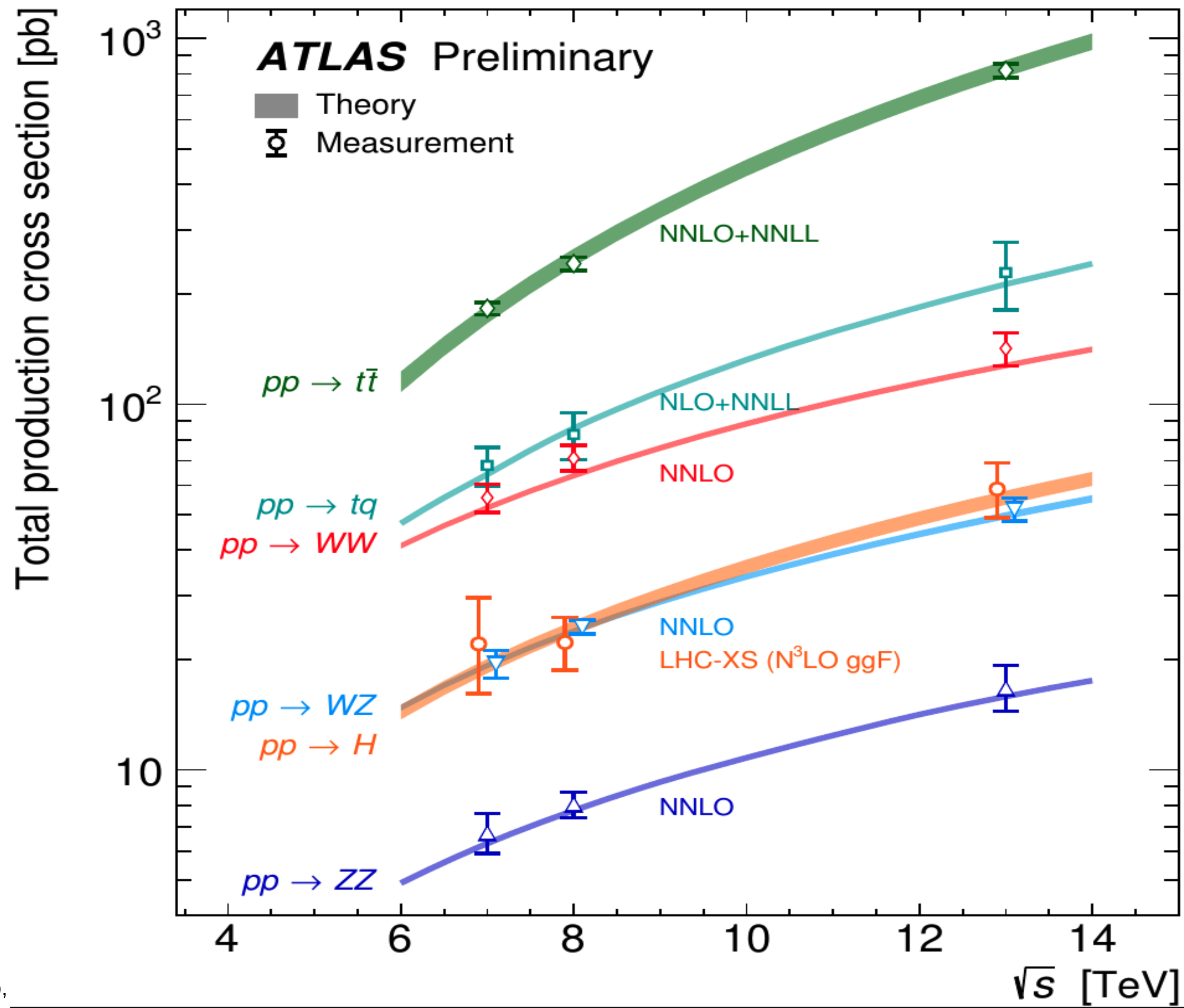


June 2016
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 2.7 fb-1)
Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW Wγjj
EW ssWW
EW Zγjj
WVγ
Zγγ
Wγγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7



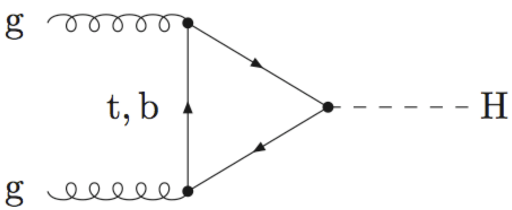
Diboson Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
γγ
Wγ→ℓνγ
– [njet = 0]
Zγ→ℓℓγ
– [njet = 0]
– Zγ→ννγ
WV→ℓνqq
WW
– WW→eμ, [njet = 0]
– WW→eμ, [njet ≥ 0]
– WW→eμ, [njet = 1]
WZ
– WZ→ℓνℓℓ
ZZ
– ZZ→4ℓ, (tot.)
– ZZ→4ℓ
– ZZ→ℓℓνν
– ZZ*→4ℓ
NNLO QCD
NLO QCD
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6
ratio to best theory

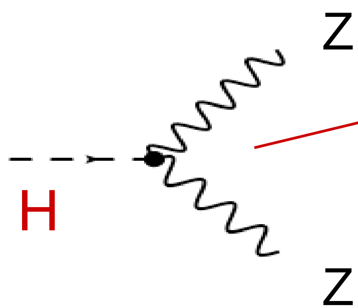
SM cross section summary, ATLAS, energy dependence 7, 8, 13 TeV

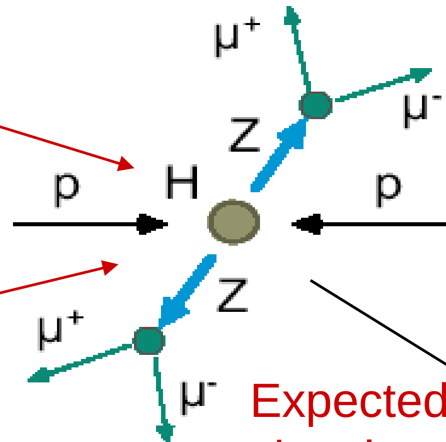


the Higgs…..

Production and detection of the Higgs in CMS - if m_H ~ 150 GeV (H ⟶ ZZ/ZZ* ⟶ 4 leptons) - expectations from 1992!

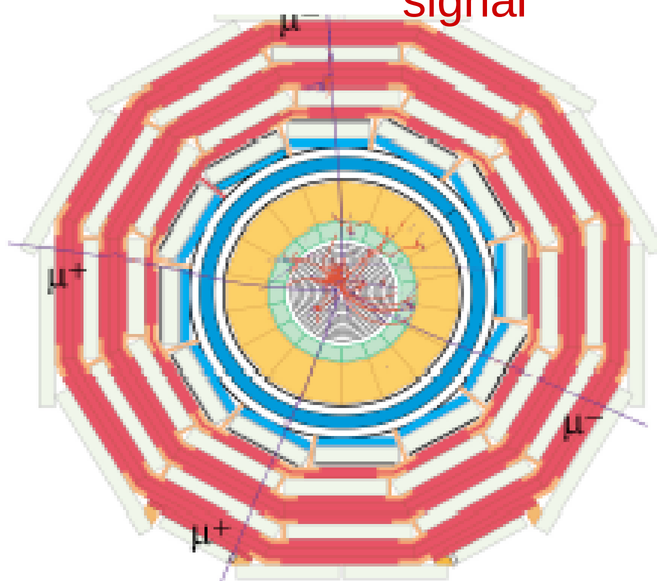




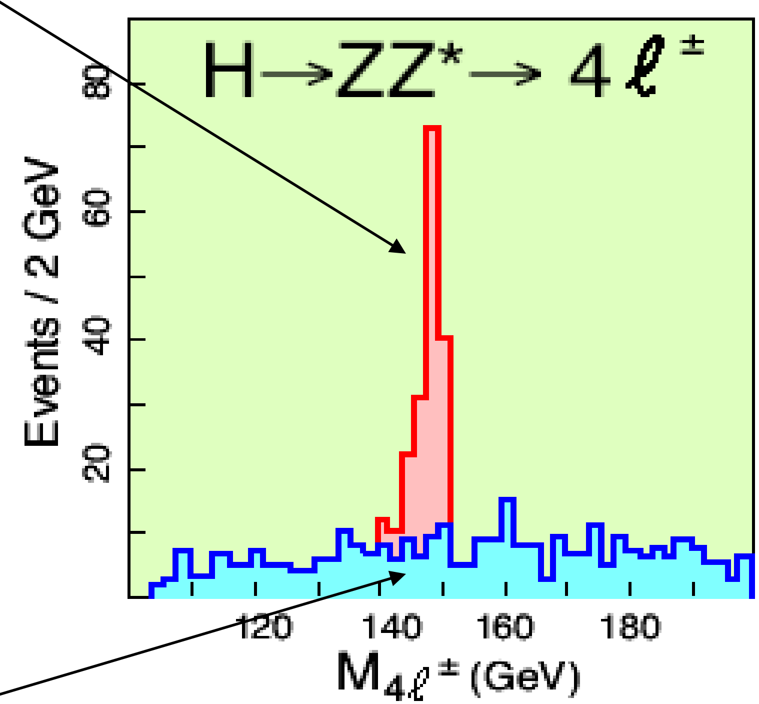


Expectations for signal and background if the Higgs has a mass ~ 150 GeV
Similar situation in the mass range ~ 130 - ~ 400 GeV

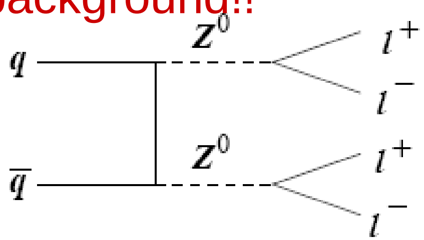
Expected Higgs signal



M_{Higgs} = 150 GeV

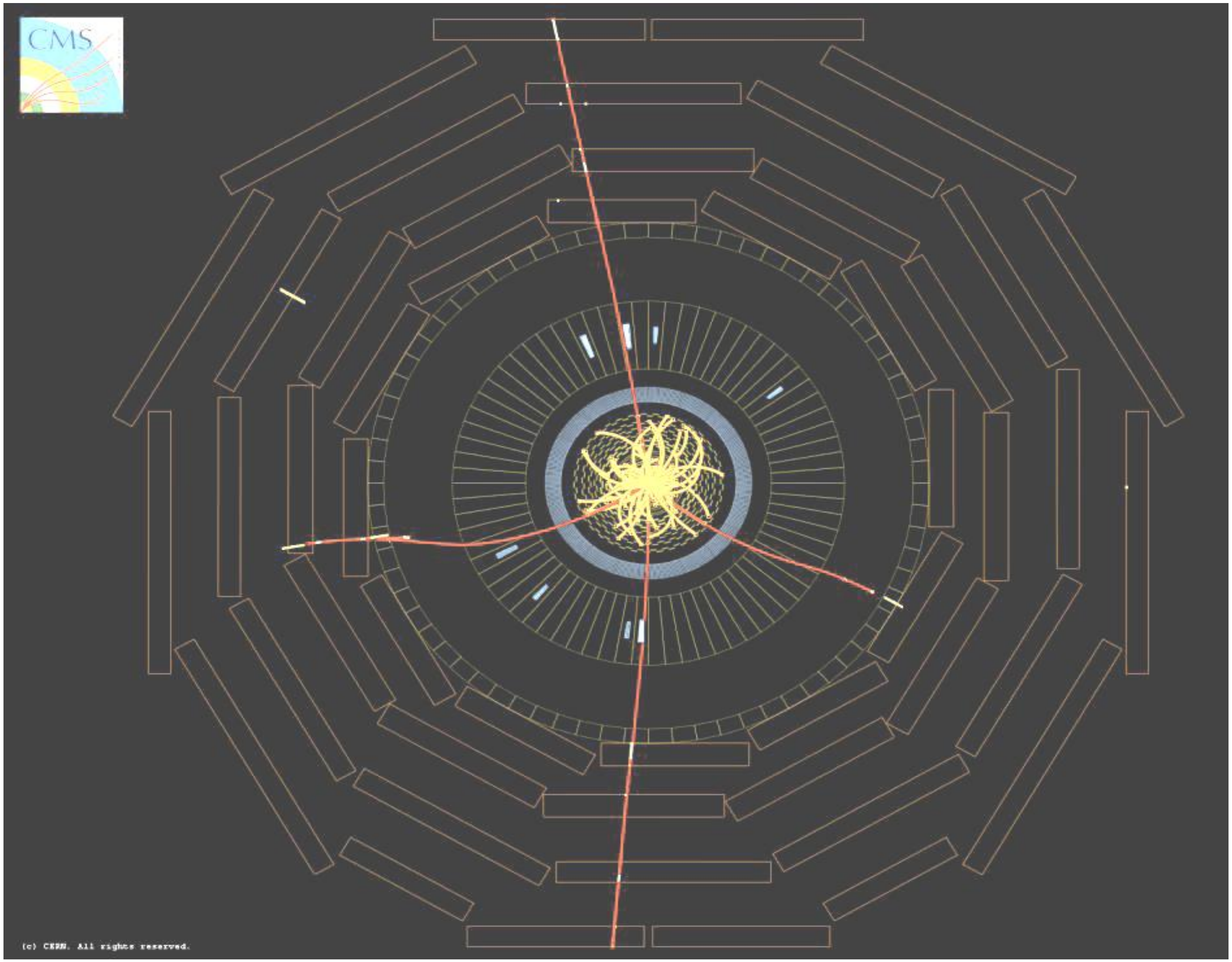


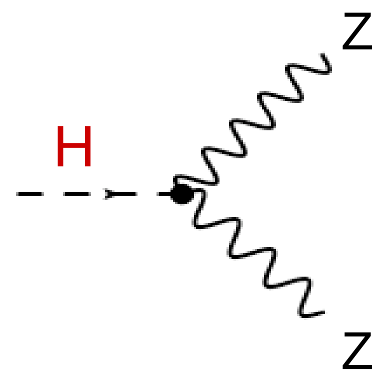
Electroweak ZZ background!!

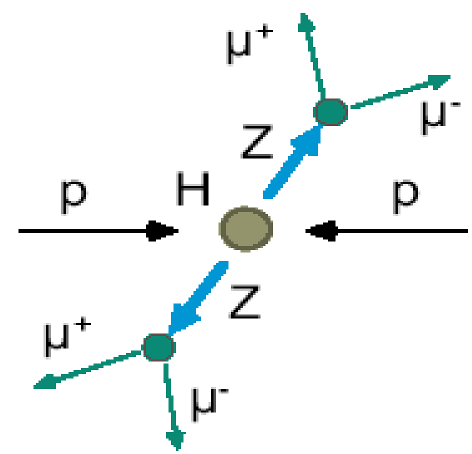


Electroweak ZZ background

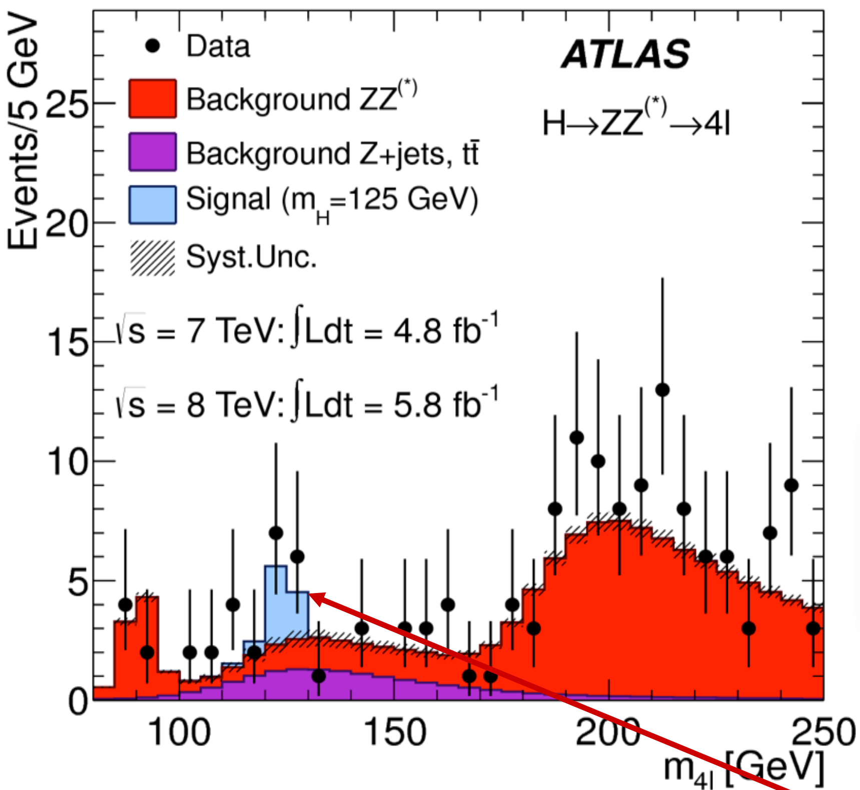
$H \to ZZ \to \mu\mu\mu\mu$ candidate event in CMS, $\sqrt{s}$ = 8 TeV data, 2012

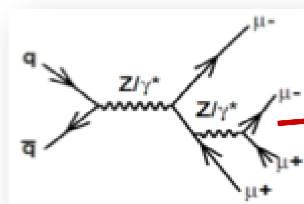


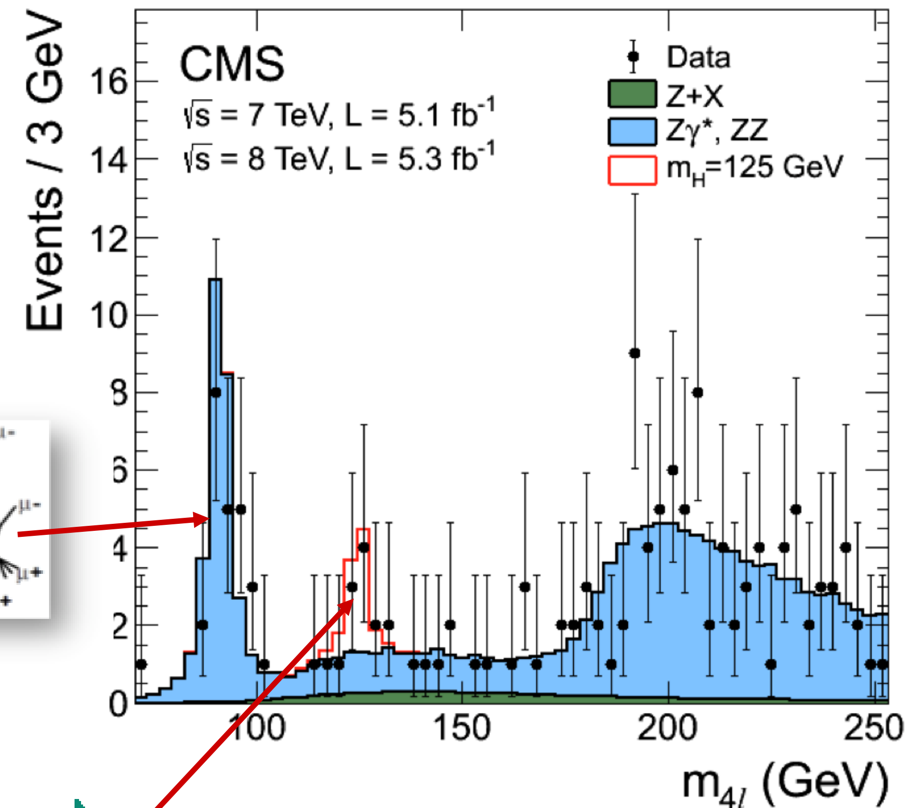


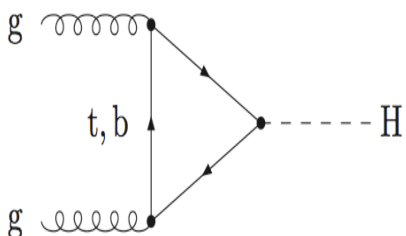


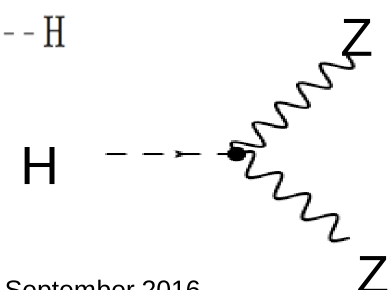
Higgs decay to 4 leptons, ATLAS and CMS, July 4th 2012 - discovery

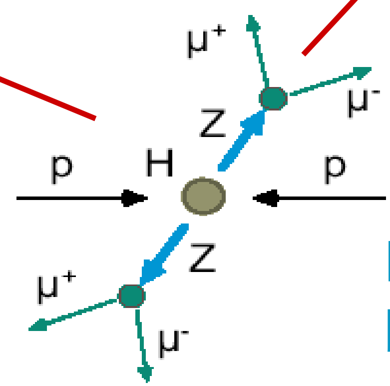






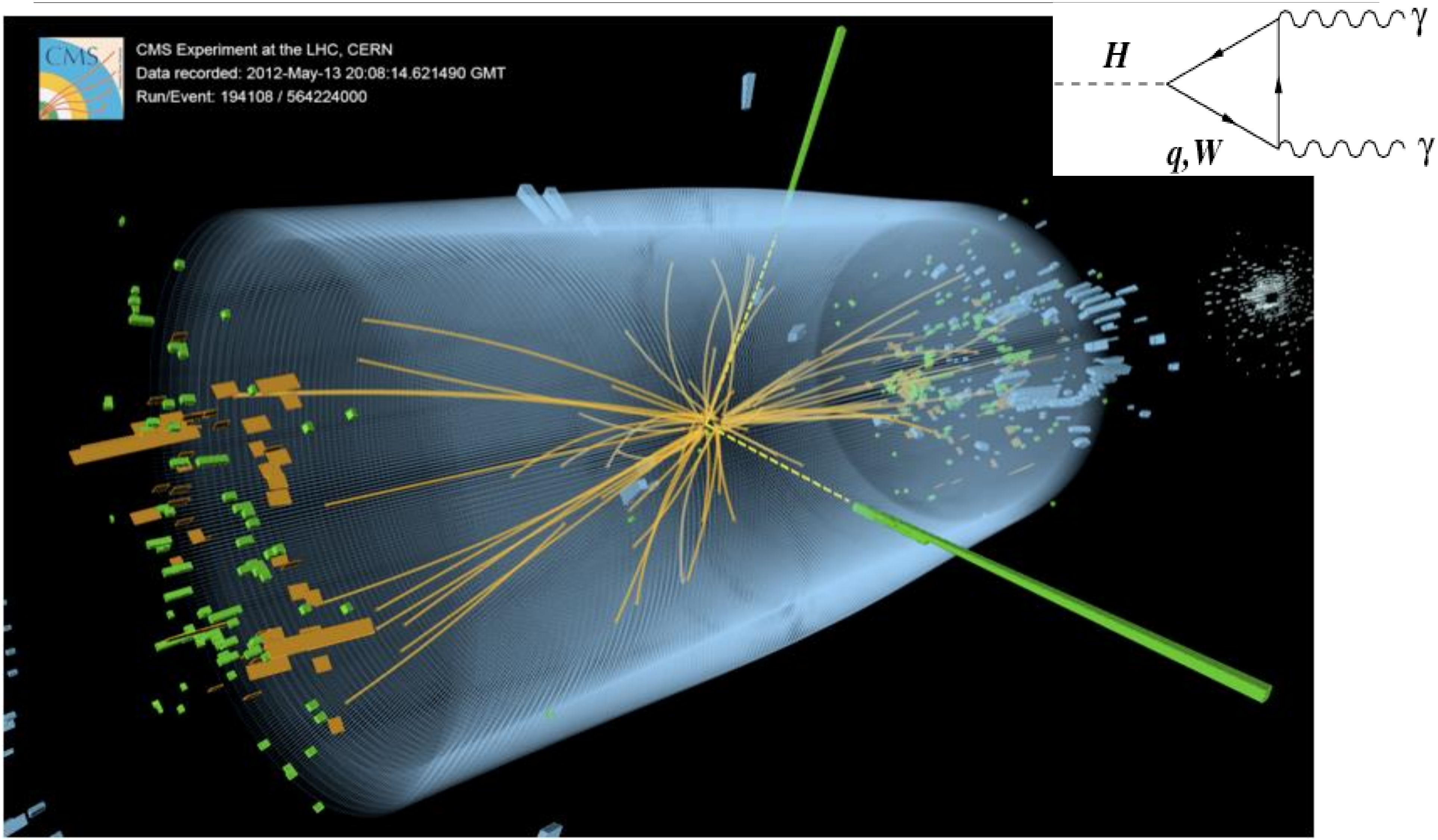






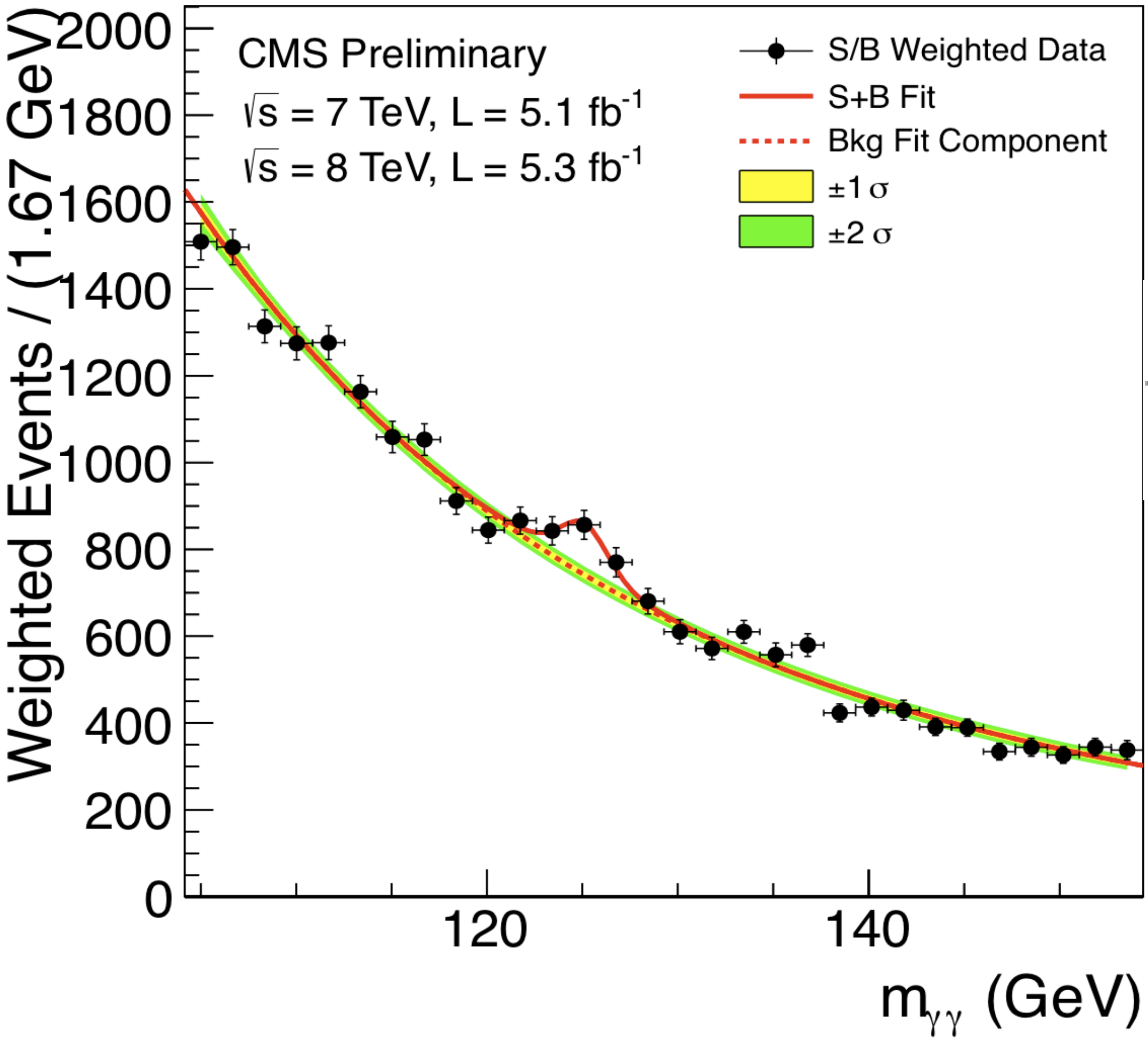
Notice these modest beginnings! As for W, Z!

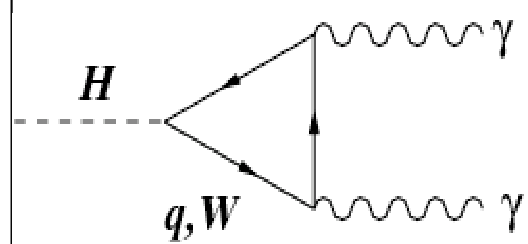
$H \rightarrow \gamma\gamma$ candidate in CMS



$$m^2_{\gamma\gamma} = 2\, E_1 E_2\, (1 - \cos\theta_{12})$$

H $\longrightarrow$ γγ in CMS, July 2012





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The Nobel Prize in Physics 2013

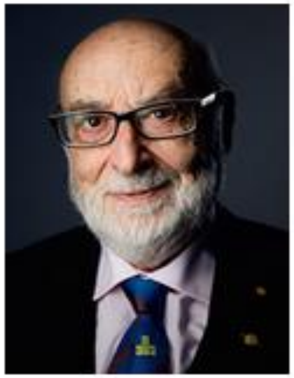


Photo: A. Mahmoud
François Englert
Prize share: 1/2

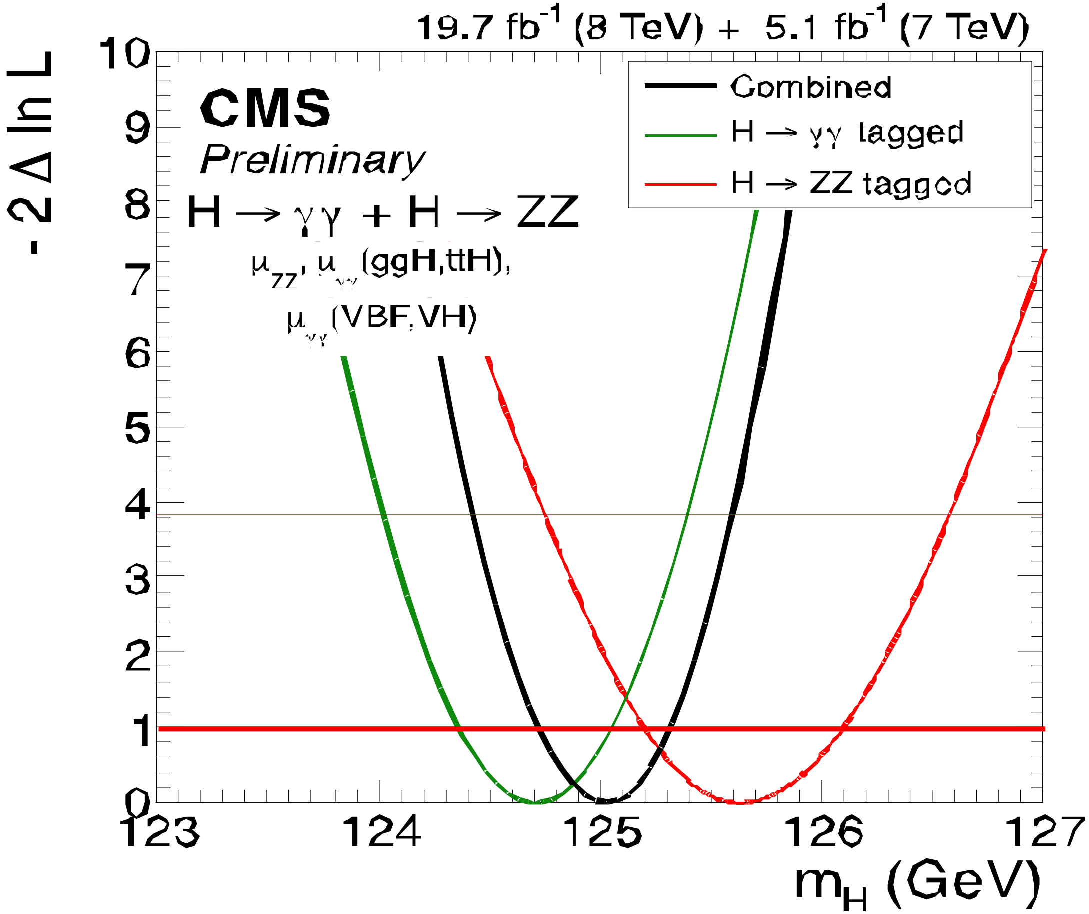
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

What is the mass?

Measure the mass through high precision channels

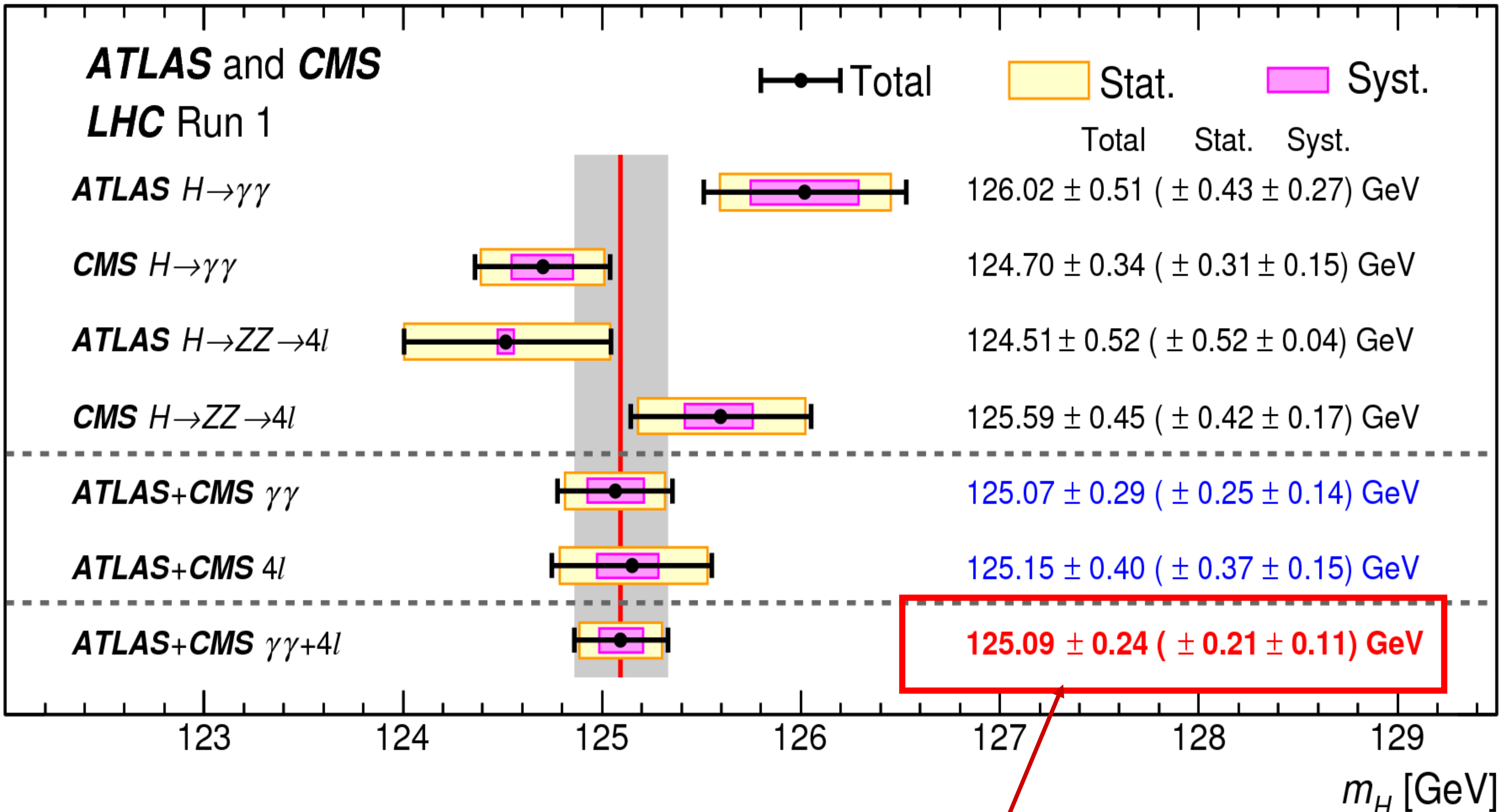
$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$



$m_H = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})\ \text{GeV}$ $\quad m_H = 125.03 \pm^{0.26}_{0.27}\ (\text{stat}) \pm^{0.13}_{0.15}\ (\text{syst})\ \text{GeV}$

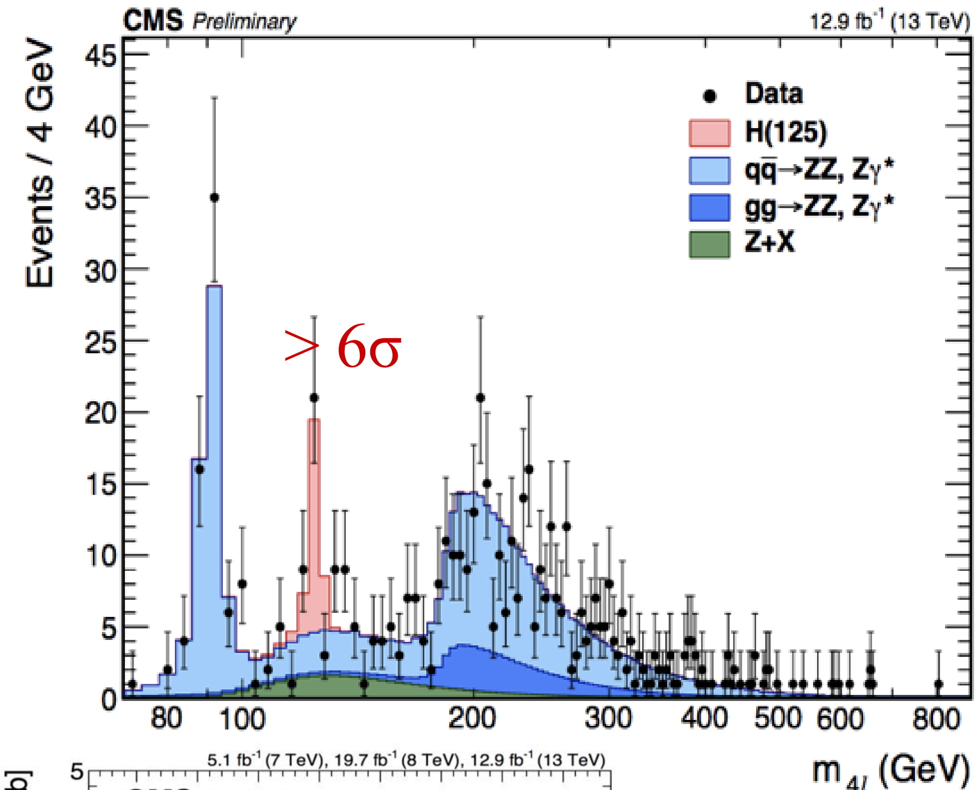
for ATLAS and CMS

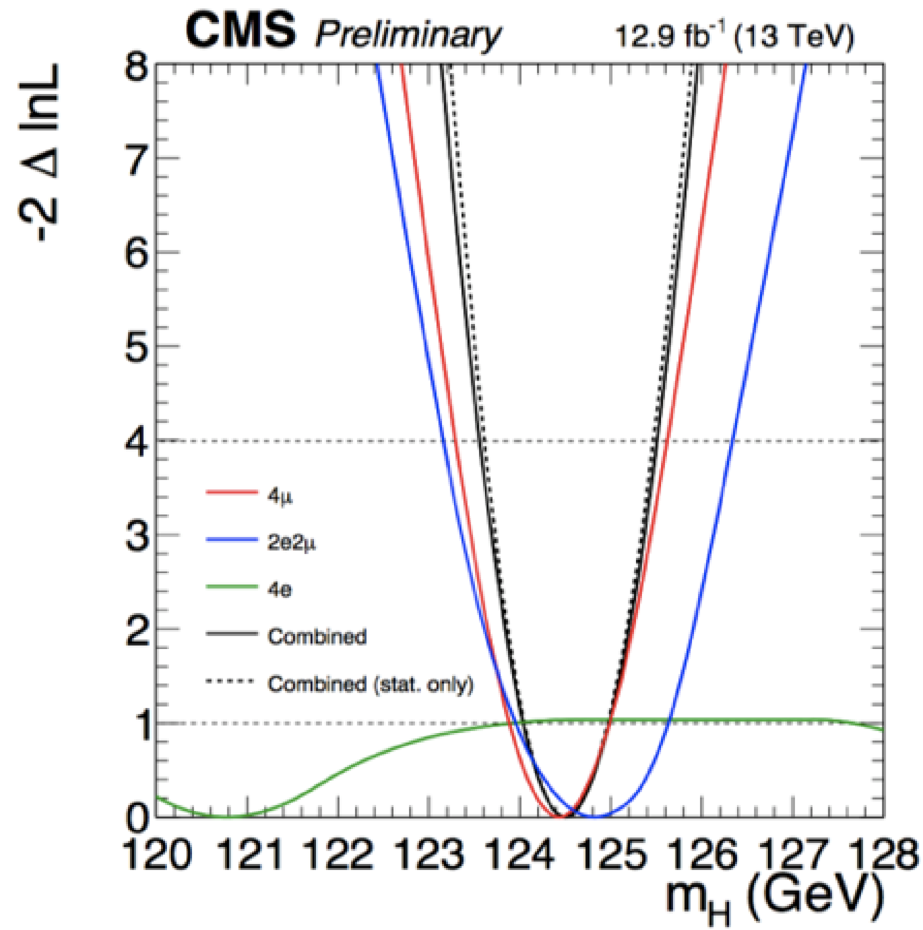
ATLAS + CMS combination on Higgs mass, final run1 analysis, April 2015

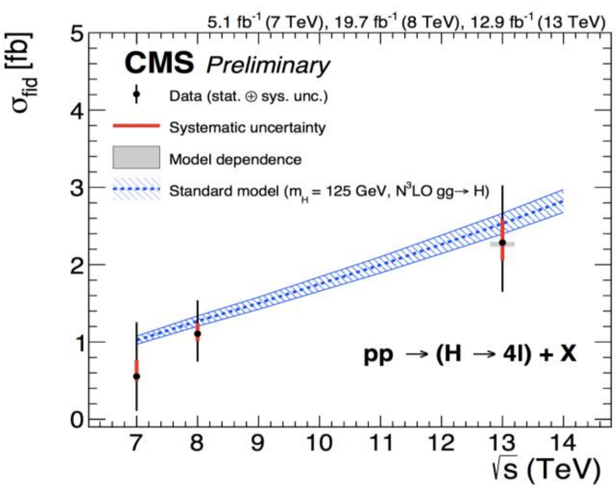


precision of ~2 pro mille!!

$H \rightarrow$ 4 leptons, Sept-15th 2016, CMS, 13 fb^{-1}



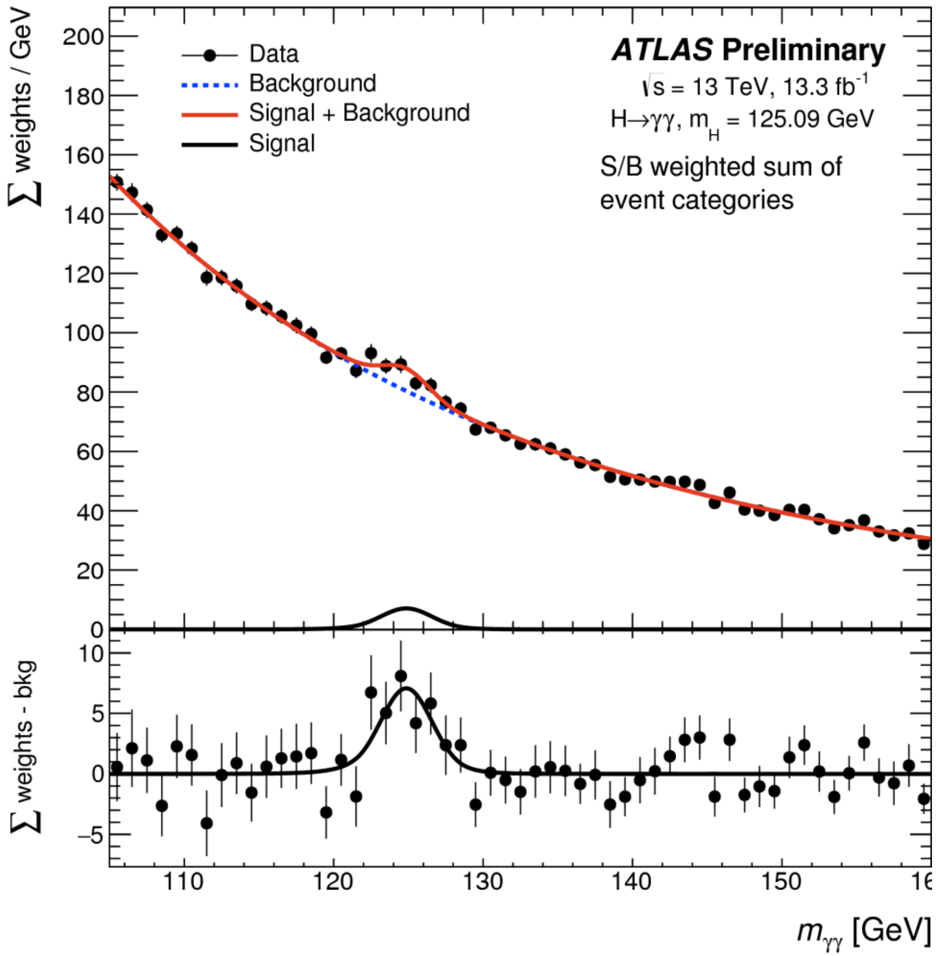


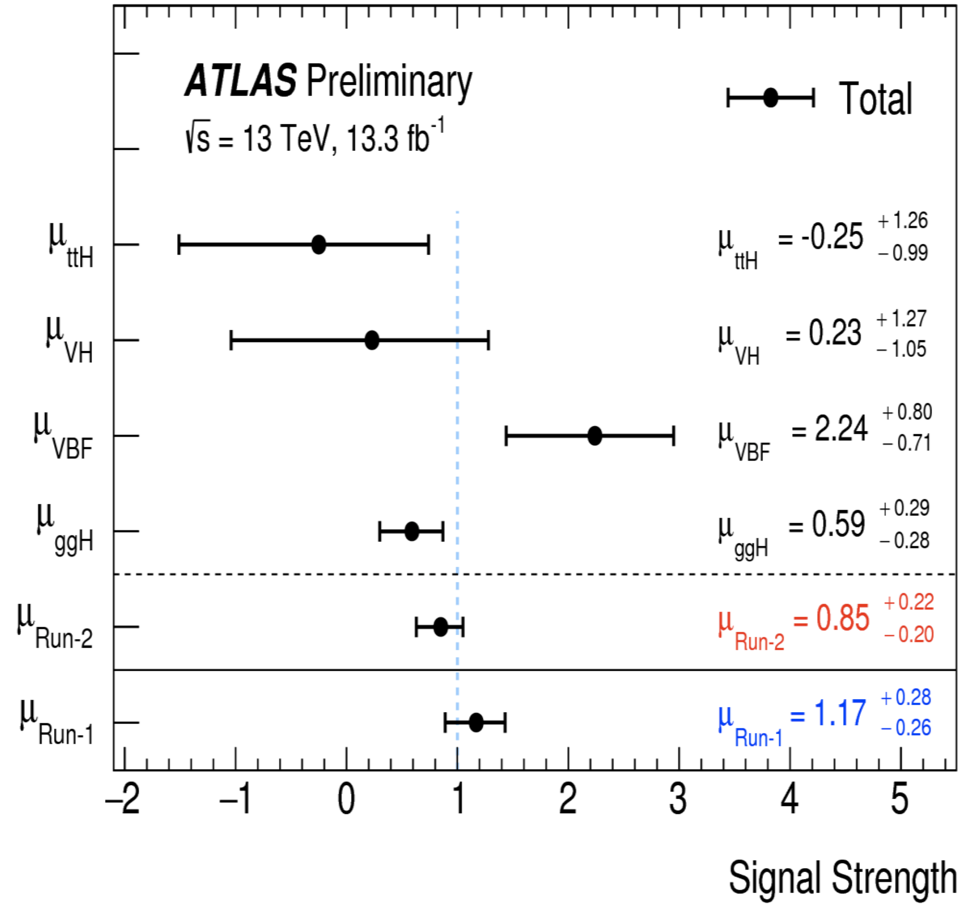


$$m_{\rm H} = 124.50^{+0.48}_{-0.46}\ {\rm GeV} = 124.50^{+0.47}_{-0.45}({\rm stat.})^{+0.13}_{-0.11}({\rm sys.})\ {\rm GeV}$$

$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$

$H \rightarrow \gamma\gamma$, 13 TeV, 13fb^{-1}, ATLAS, August 2016

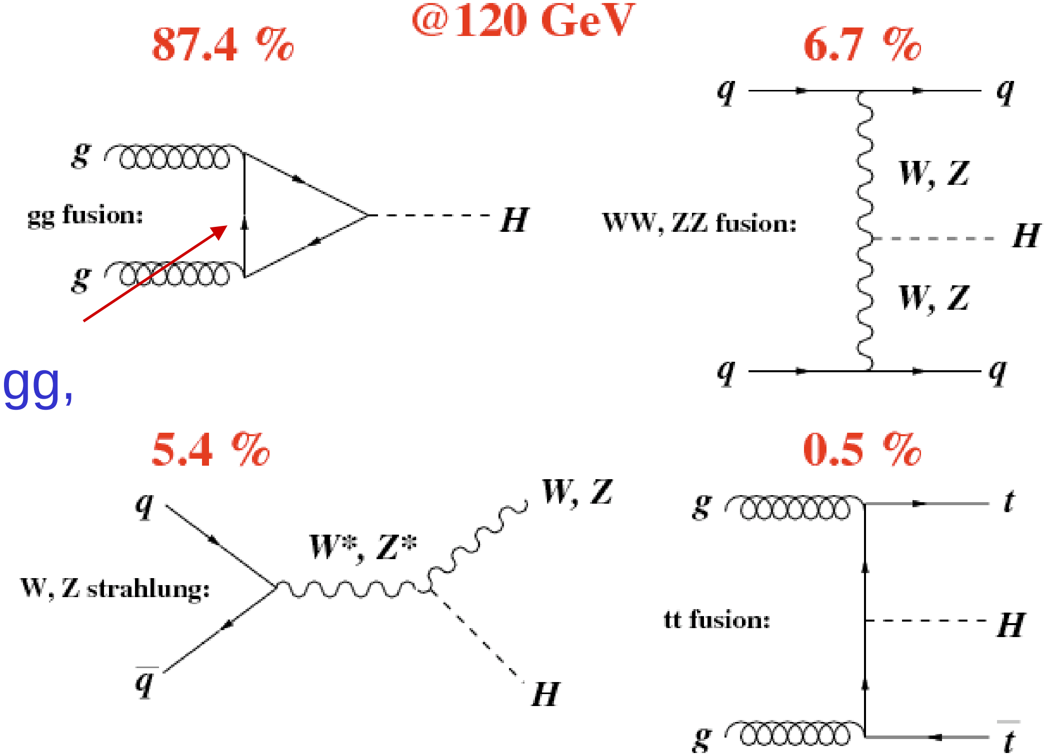




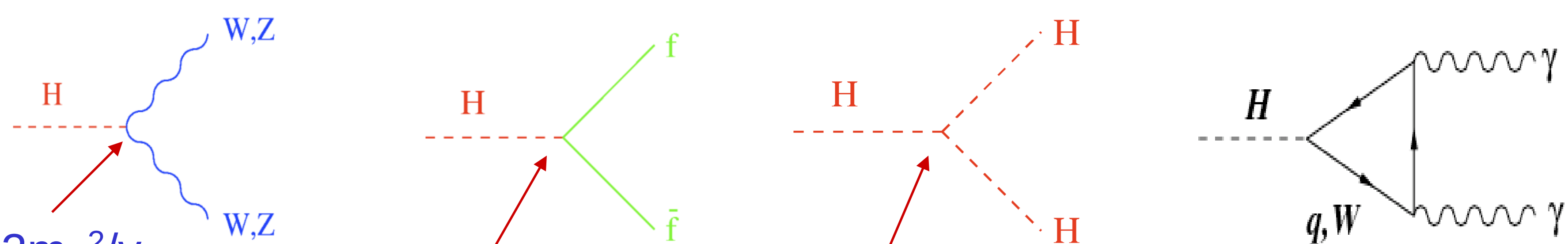
13 TeV	Fiducial σ (fb)	SM prediction (fb)
ATLAS (13.3 fb^{-1})	43.2±14.9(stat)±4.9(syst)	62.8+3.4-4.4 (N3LO+XH)

Higgs production mechanisms and decay modes

@120 GeV



indirect coupling to gg,
top in the loop



$g_{HVV} = 2m_V^2/v$

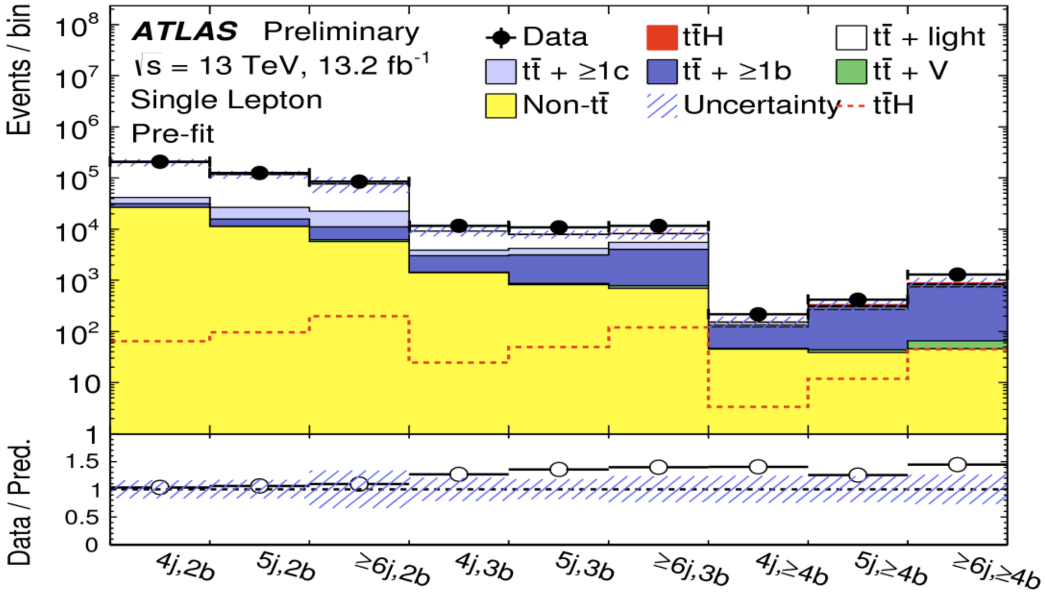
$g_{HWW} = g\ m_W$

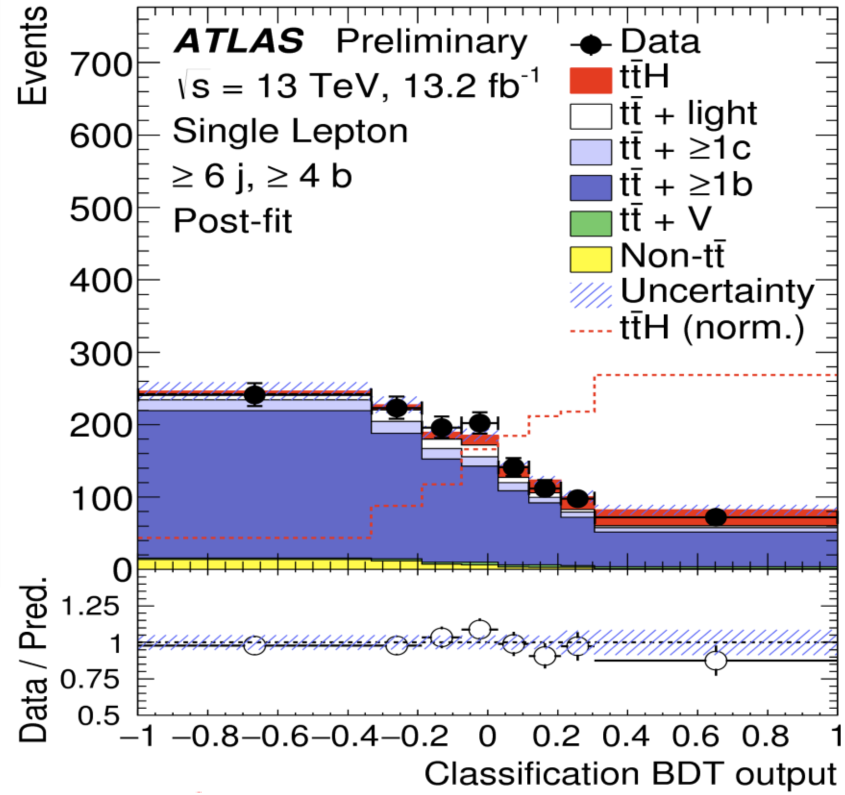
$g_{Hff} = m_f/v$

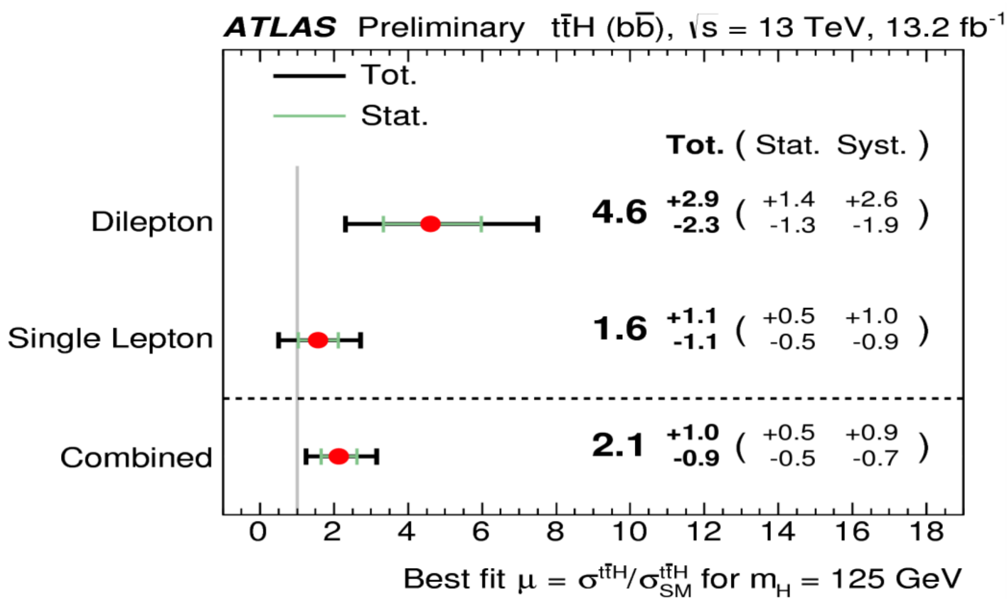
$g_{HHH} = 3m_H^2/v$

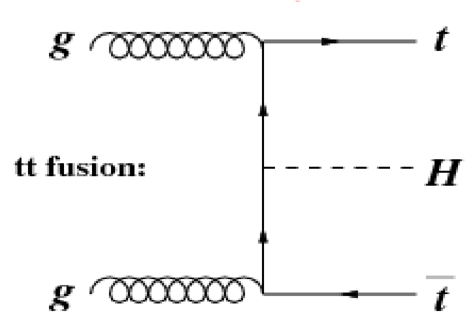
indirect coupling to $\gamma\gamma$

ttH(H → bb) - important channel, measures directly Higgs coupling to top



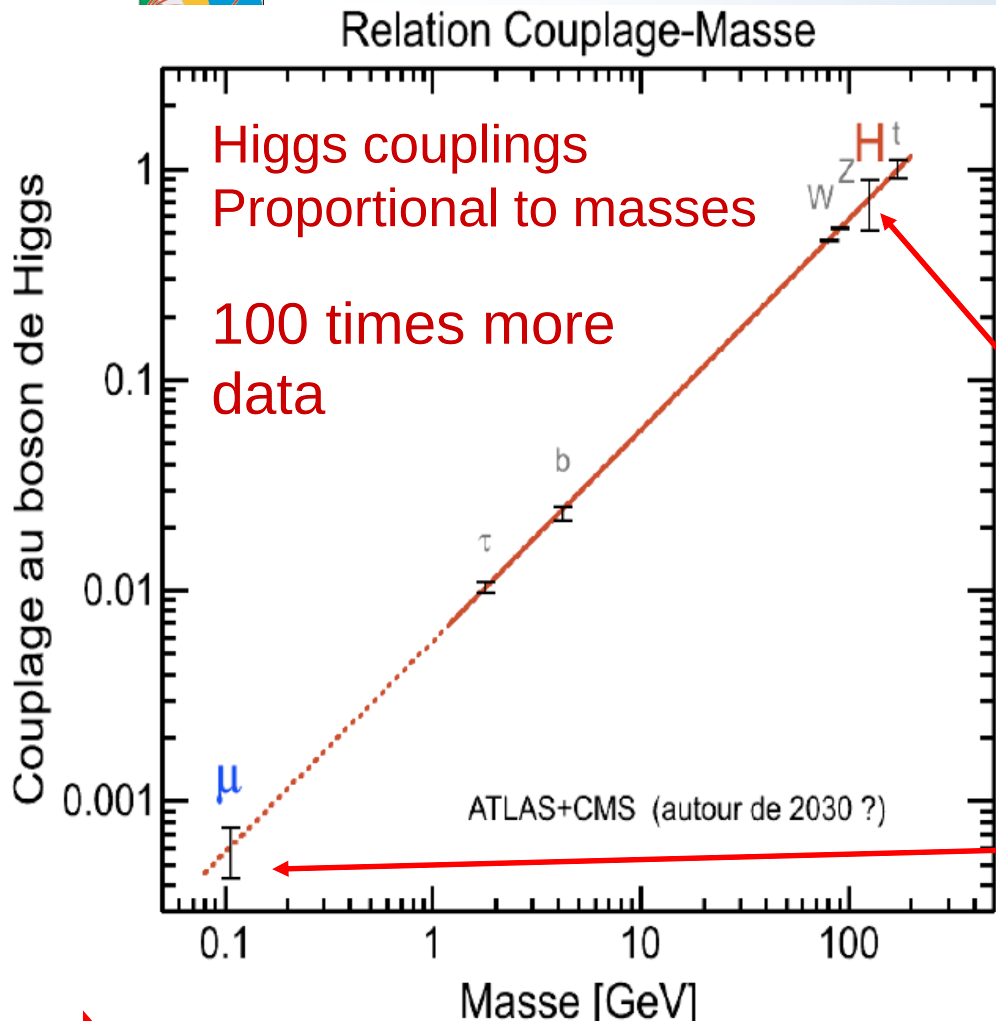






First result from ATLAS, $13.2fb^{-1}$, 13 TeV.

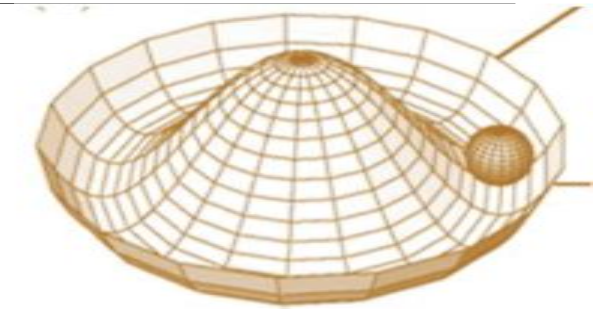
Higgs couplings - future up to HL-LHC and 3000fb^{-1}



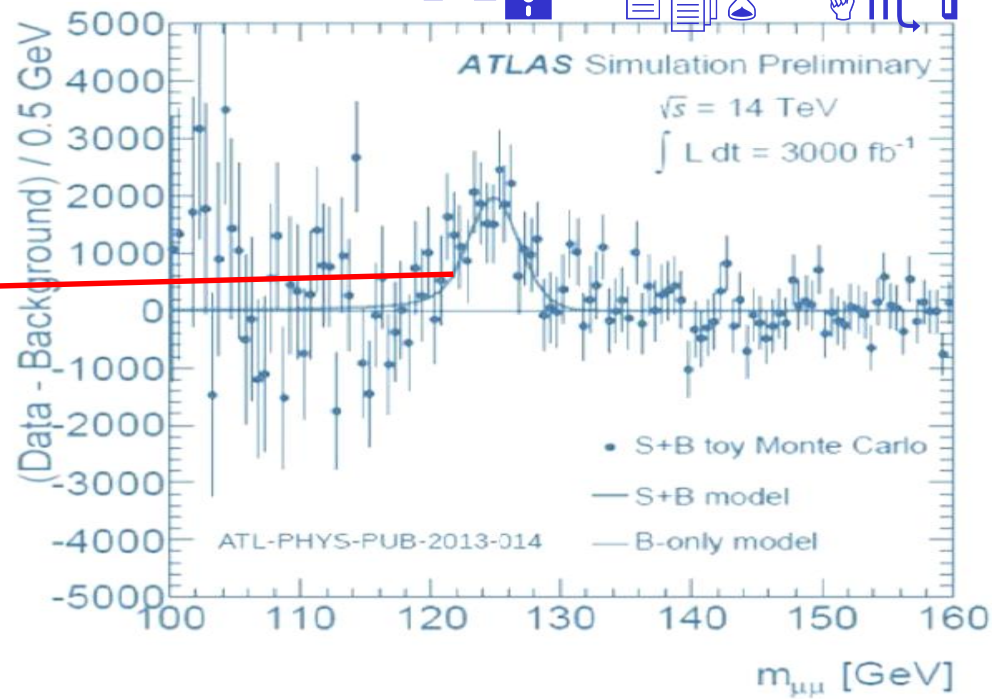
$g_{Hff} = m_f/v$

$g_{HHH} = 3m_H^2/v$

$g_{HVV} = 2m_V^2/v$



Higgs self-coupling and Higgs potential



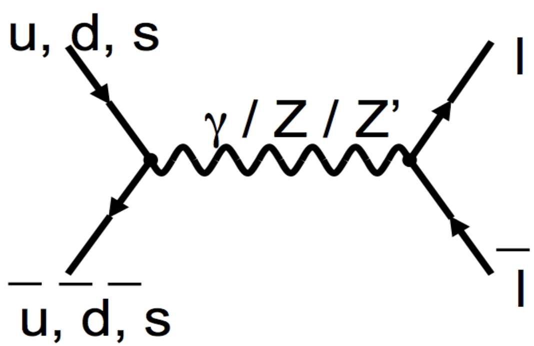
With 3000fb^{-1} data at 13 TeV (by ~ 2025) couplings to 8 particles, including coupling to muons

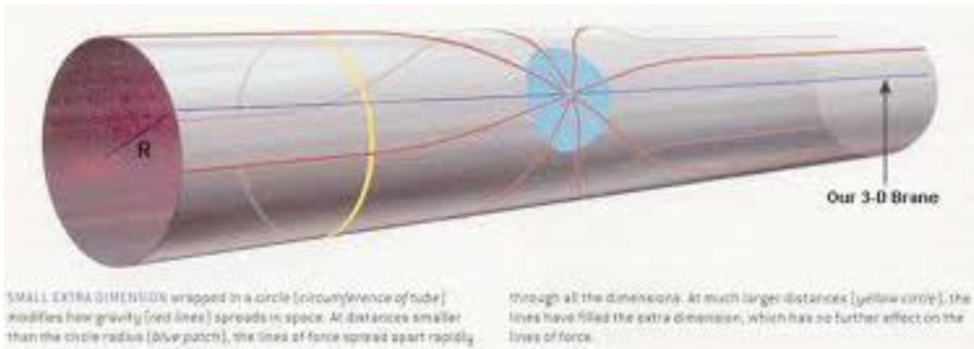
Looking further for physics beyond the Standard Model

- diphotons
- dilepton pairs, Z', W' etc
- SUSY
- DM…..

Searches for heavy dilepton or diphoton resonances, extra dimensions

Search for excesses in invariant mass spectra:
- Predicted by several BSM models with extended gauge symmetries
- Z' and W' with SM-like couplings
- Kaluza-Klein excitations from RS model of extra dimensions
- E6 models
- Technicolor
- ……….



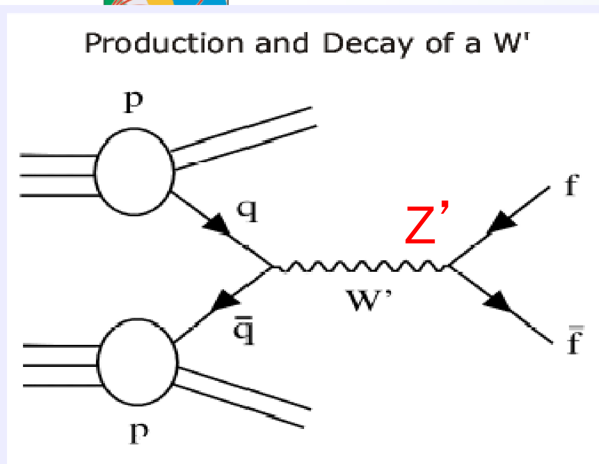


$$M_{Pl}^2 \sim M_D^{2+n} R^n$$

• Searches for non-resonant excess in kinematic distributions and mass spectra
• Predicted by many Extra Dimension Models
- Universal Extra Dimensions (UED), RS etc

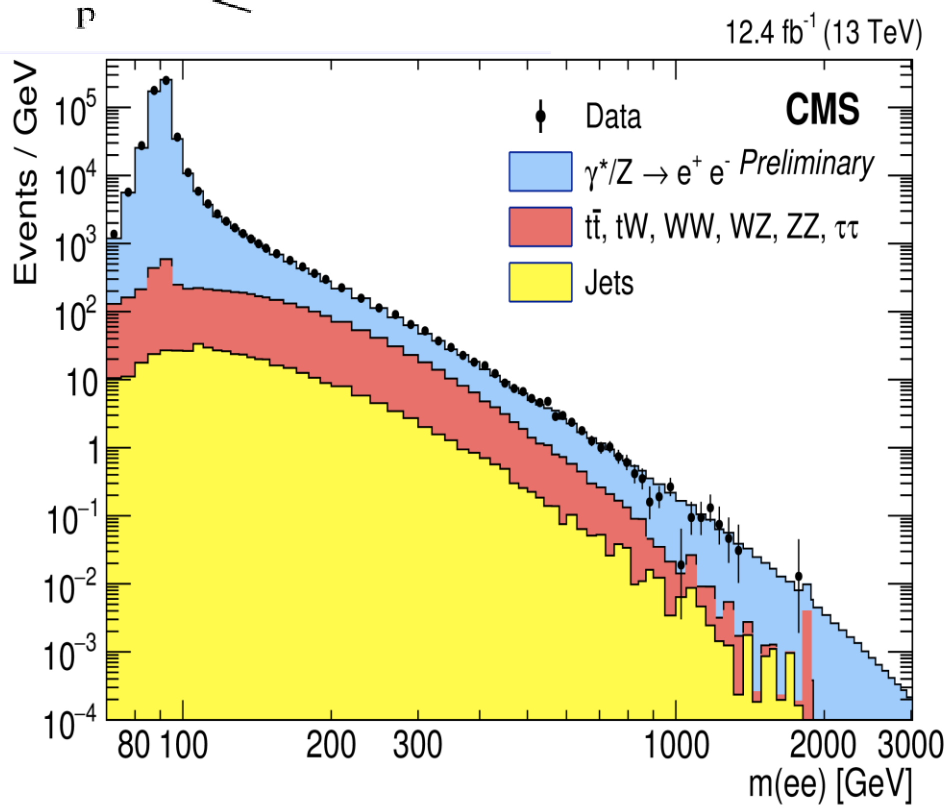
Drell-Yan (e+e-) pairs, ATLAS and CMS, 13 TeV search for heavy Z' $\to l^+l^-$

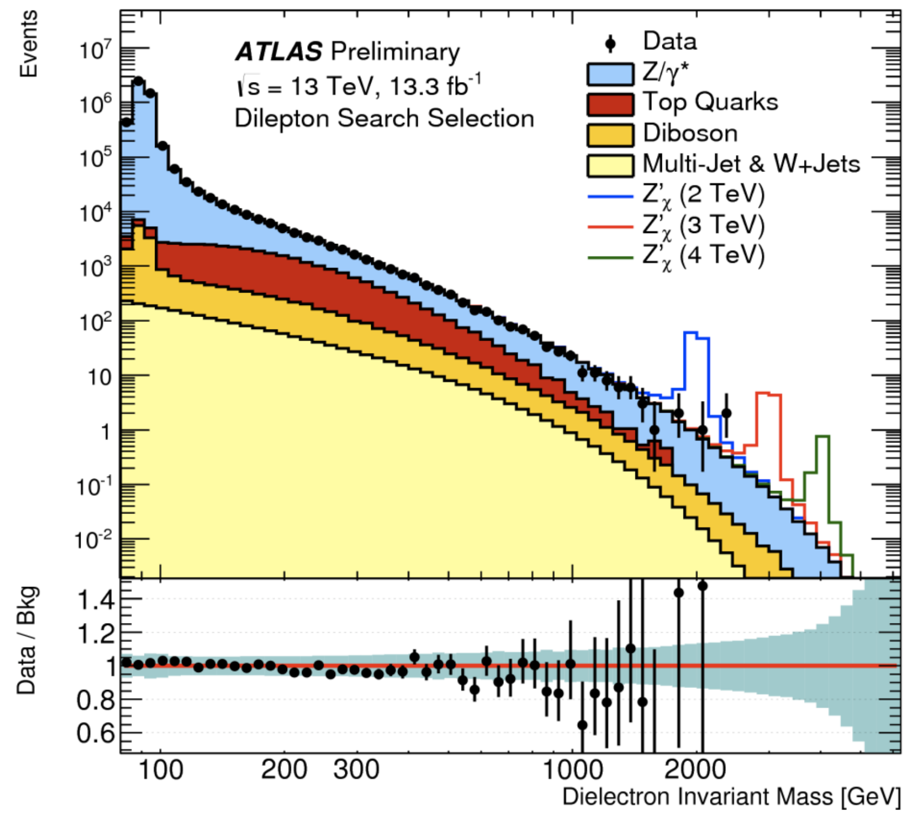
new gauge boson or KK excitation



New limit in SSM:

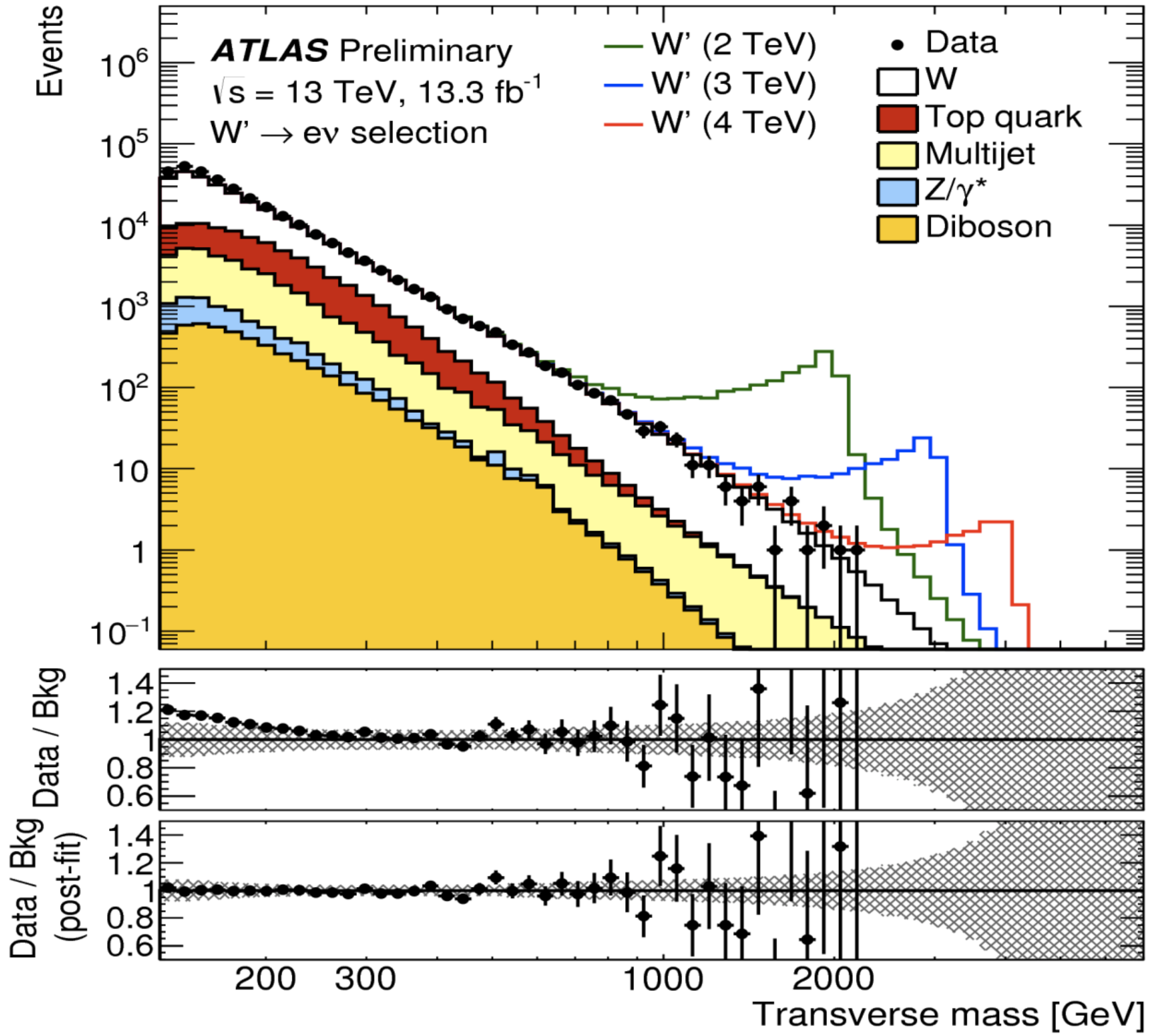
$Z'_{SSM} > 4$ TeV

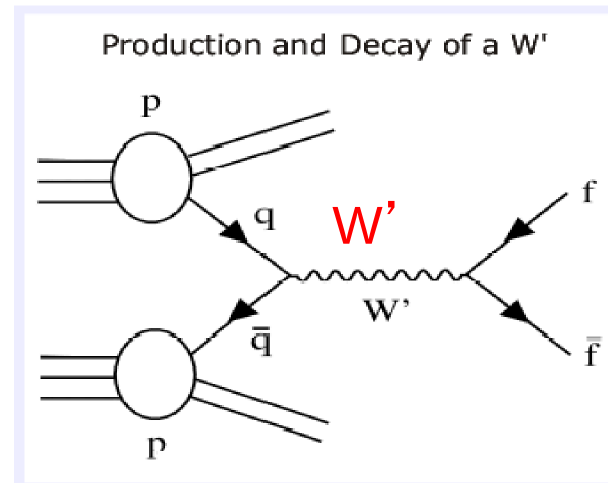




Search for heavy W' in the W' → lepton + $E_t^{missing}$ channel, 13 TeV data,

new gauge boson or KK excitation

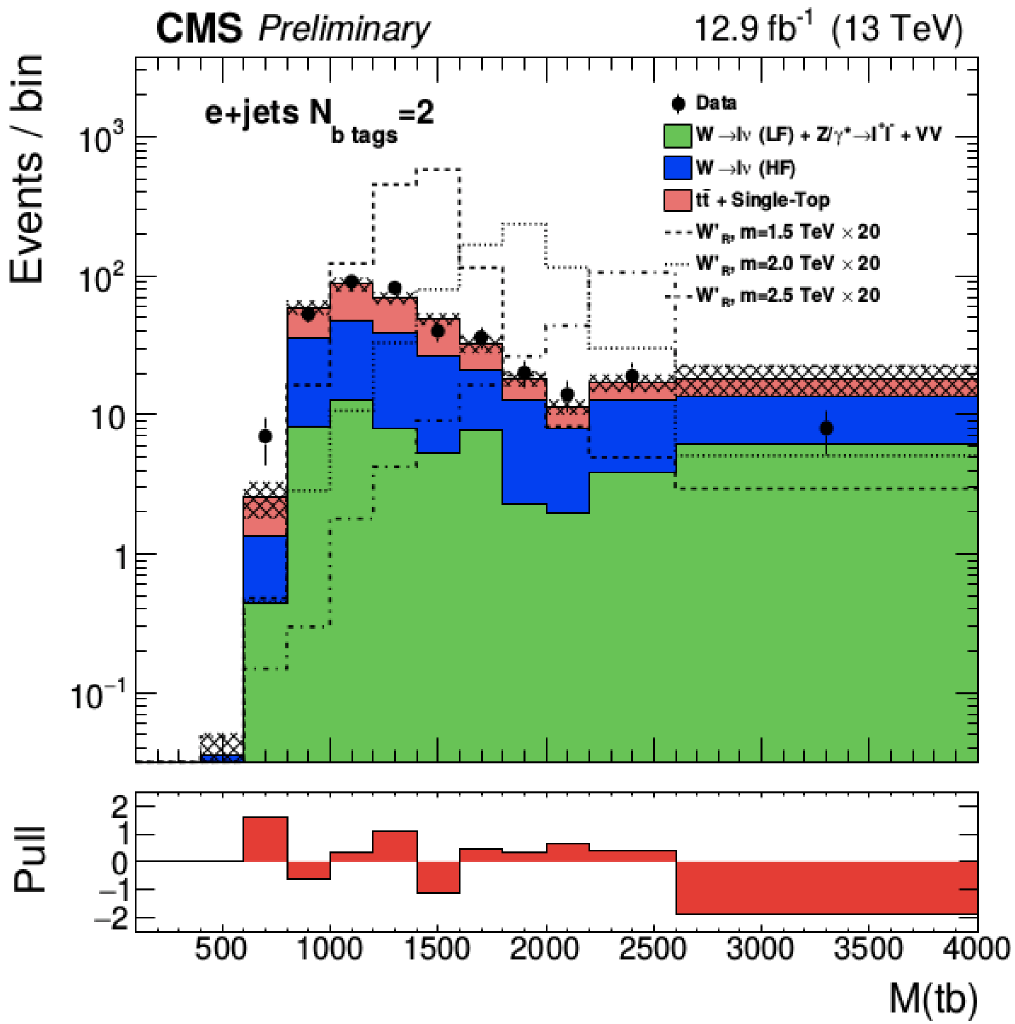


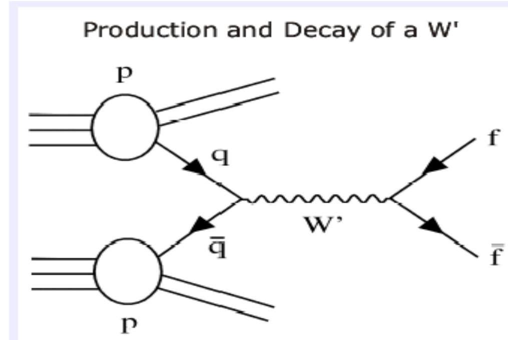


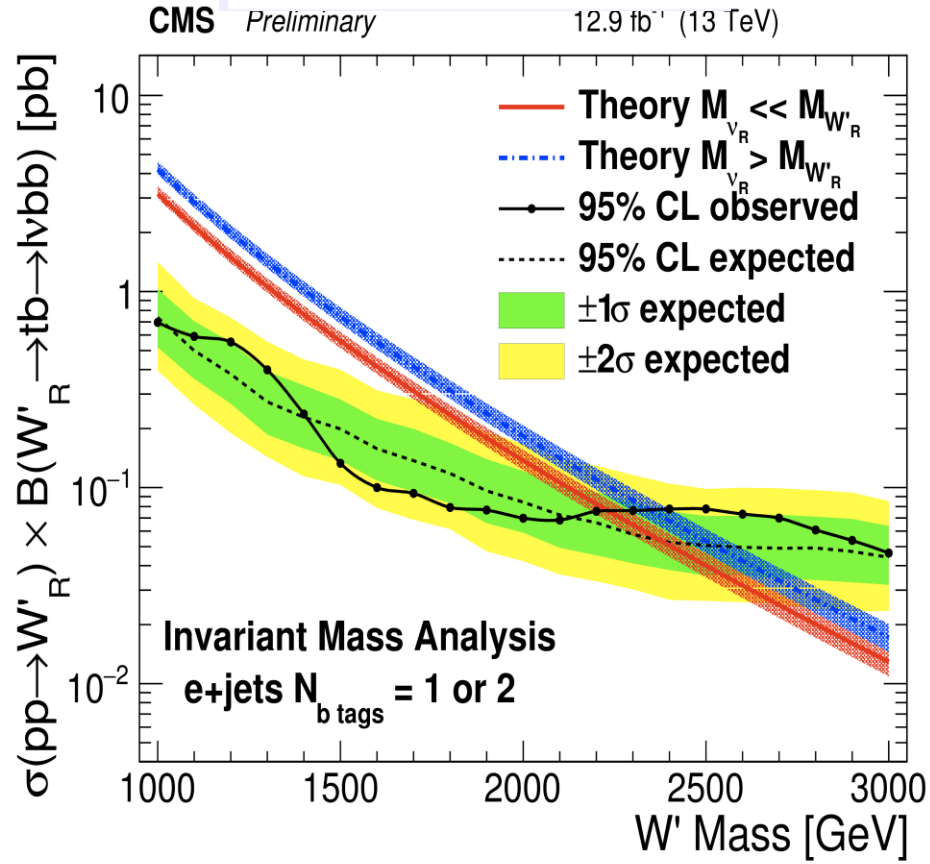
New limit in SSM:

SSM W' > 4.74 TeV

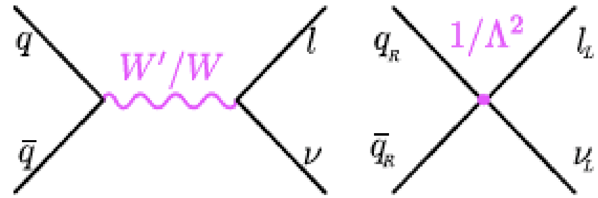
Search for W' in the W' → tb channel, 13 TeV data, summer 2016







Models with e + $E_t^{missing}$, HL-LHC expectations

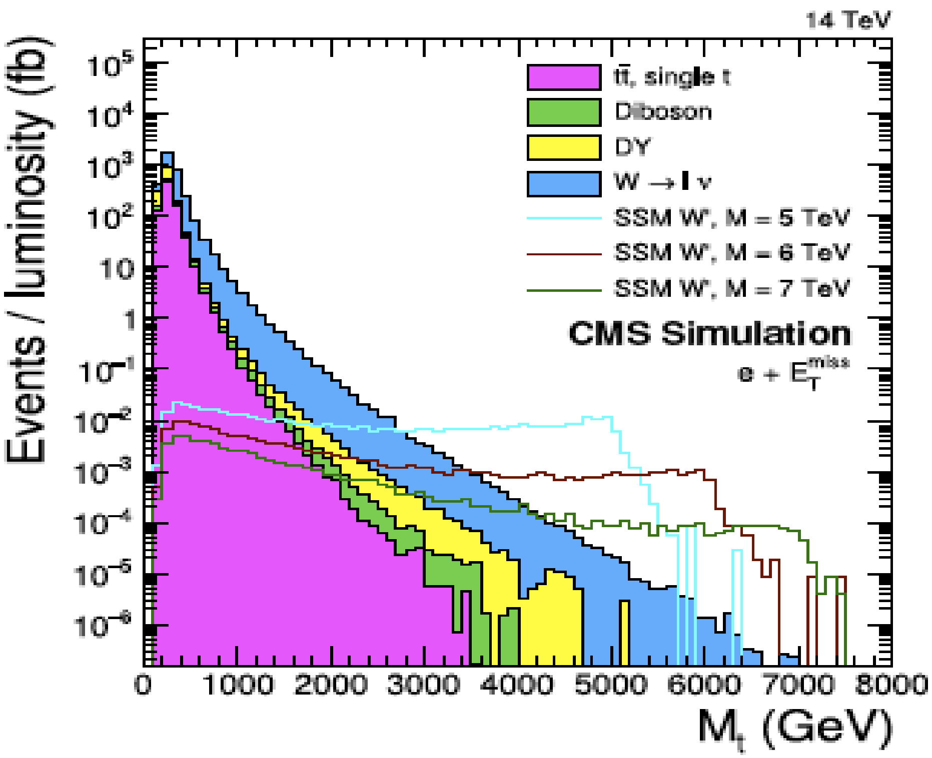


Several BSM models predict signal in lepton+MET

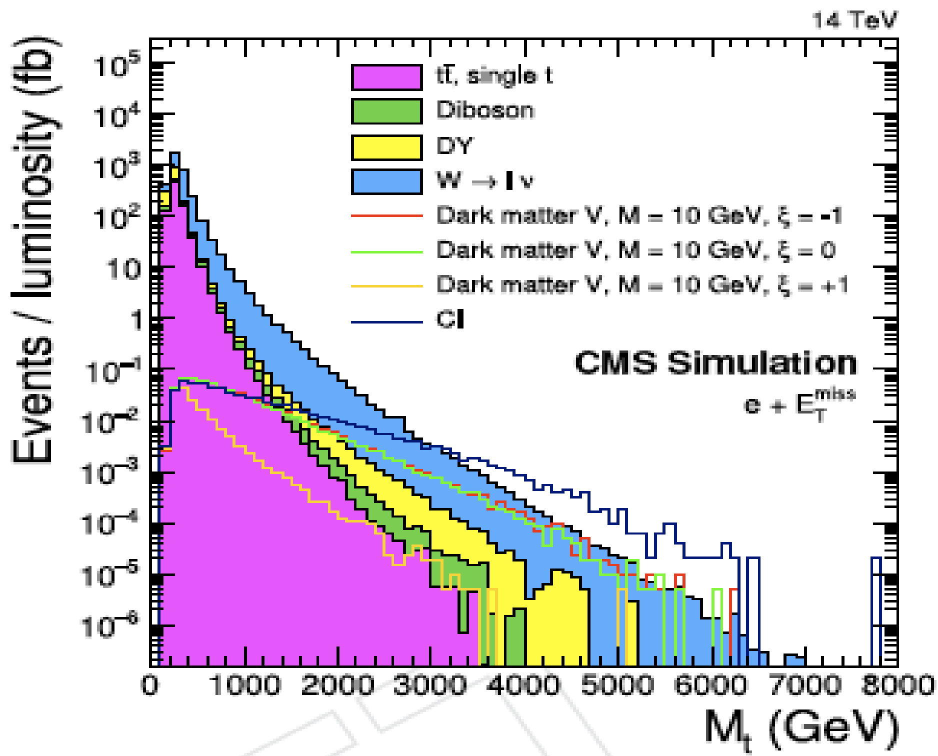
•W´ signal with characteristic Jacobian peak (still visible in electron channel)

•Other models, contact interaction (CI) and DM, xsec not defined by theory but depends on free model parameter L.

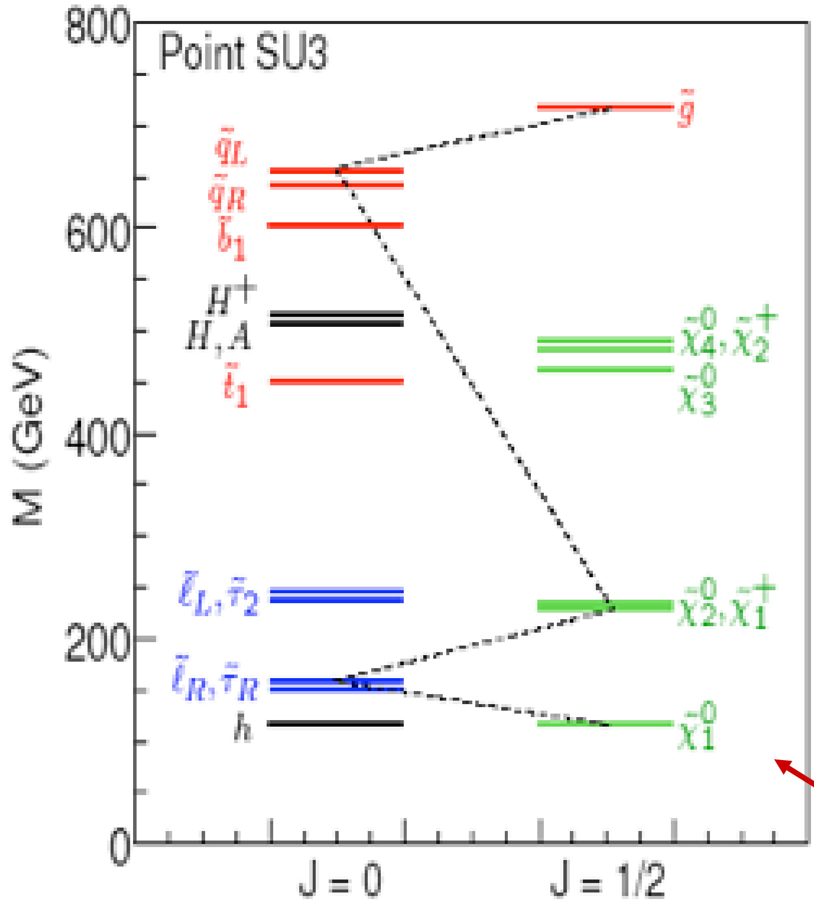
W´ scaled to theorectial xsec

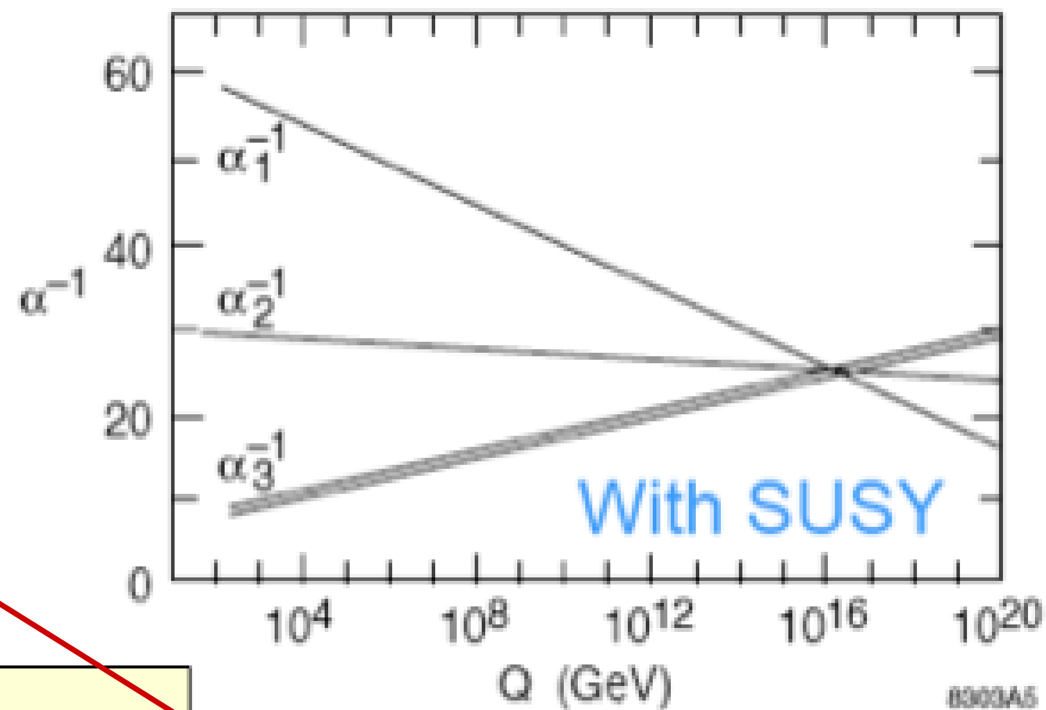


Distributions scaled to 1 fb.

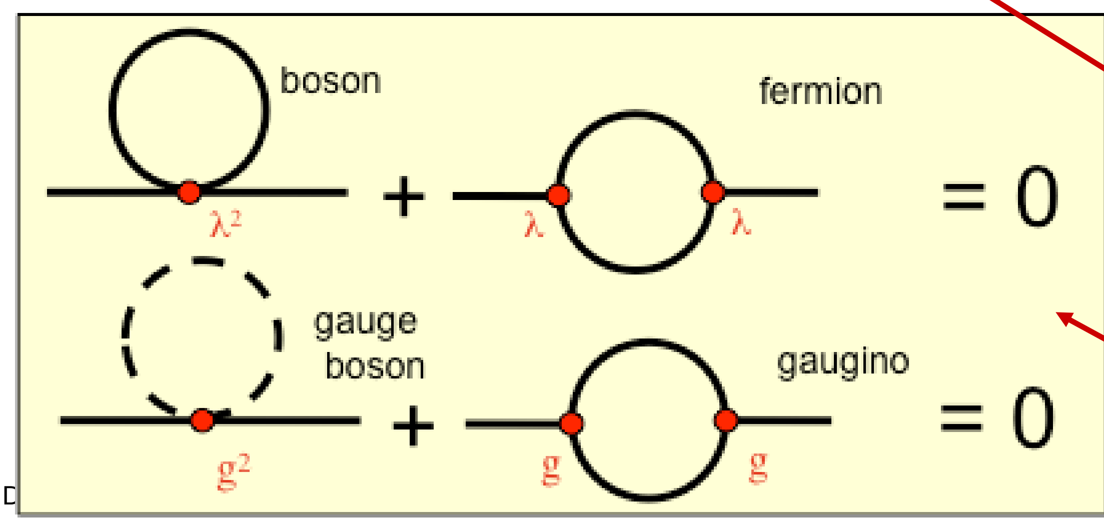


SUSY - could solve a number of problems at ew scale





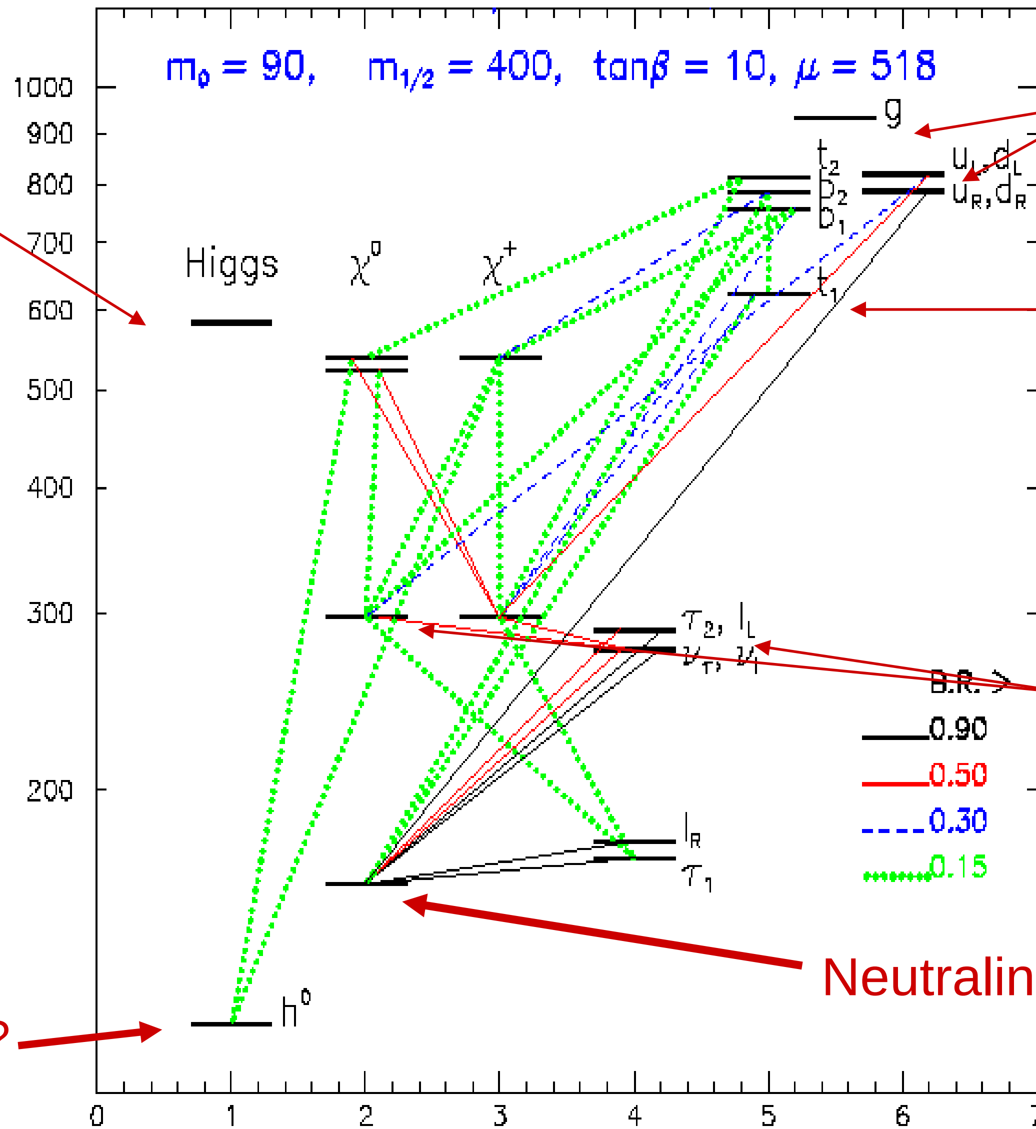
Possibly the DM particle….



Stabilizes Higgs boson mass

Supersymmetry - a typical mass spectrum

four are here
A,H,H^+H^-
direct searches
give no sign yet



produced by strong interactions
direct searches give no sign yet, might be > 2TeV

Stop - produced by strong interactions
could be much lighter than all others sis (>~ 500 GeV)
no sign yet

produced also by ew interactions, no sign yet

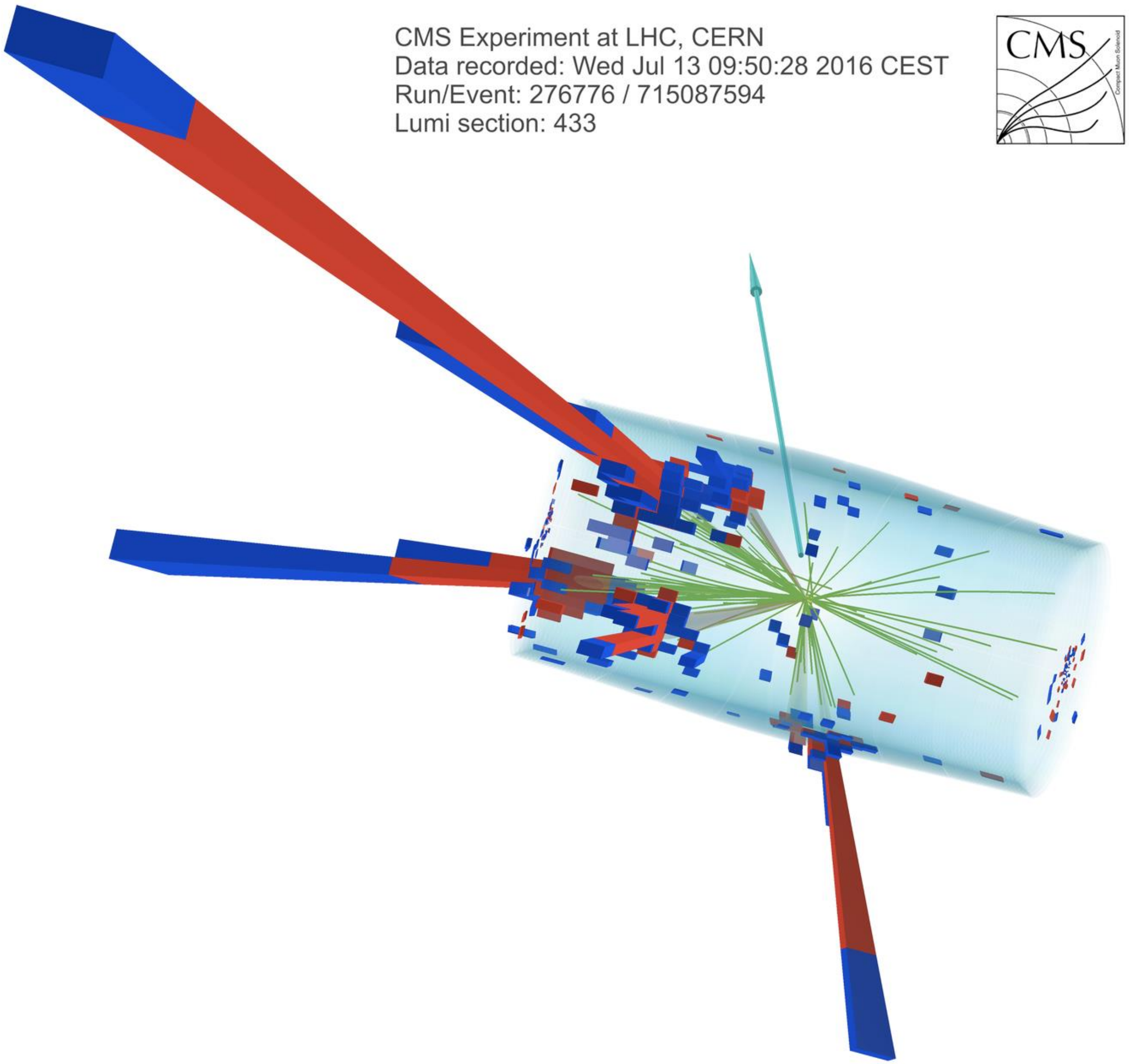
Neutralino-1, LSP - DM candidate

$\tilde{\chi}_1^0$

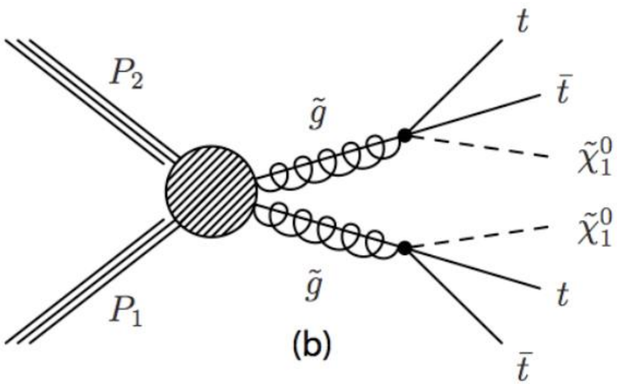
the 125 GeV one?
possibly….

…l' objet de toutes nos pensées

Badly unbalanced SUSY-candidate-type event



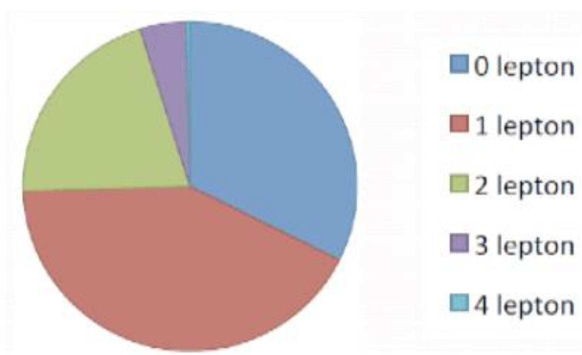
SUSY searches in CMS, gluino to top, 8 TeV

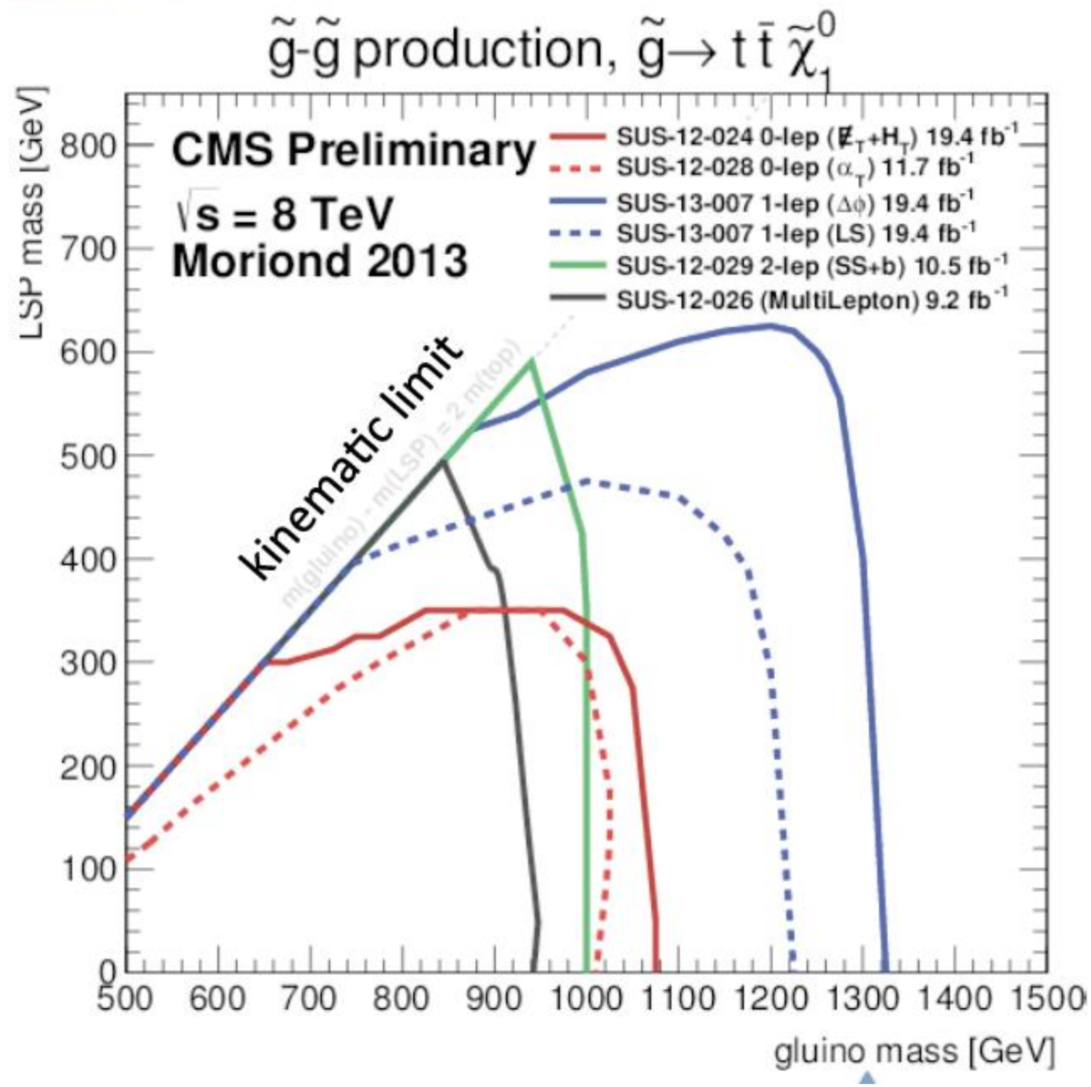


- Assumptions:

  $m_{\tilde{t}} > m_{\tilde{g}}$

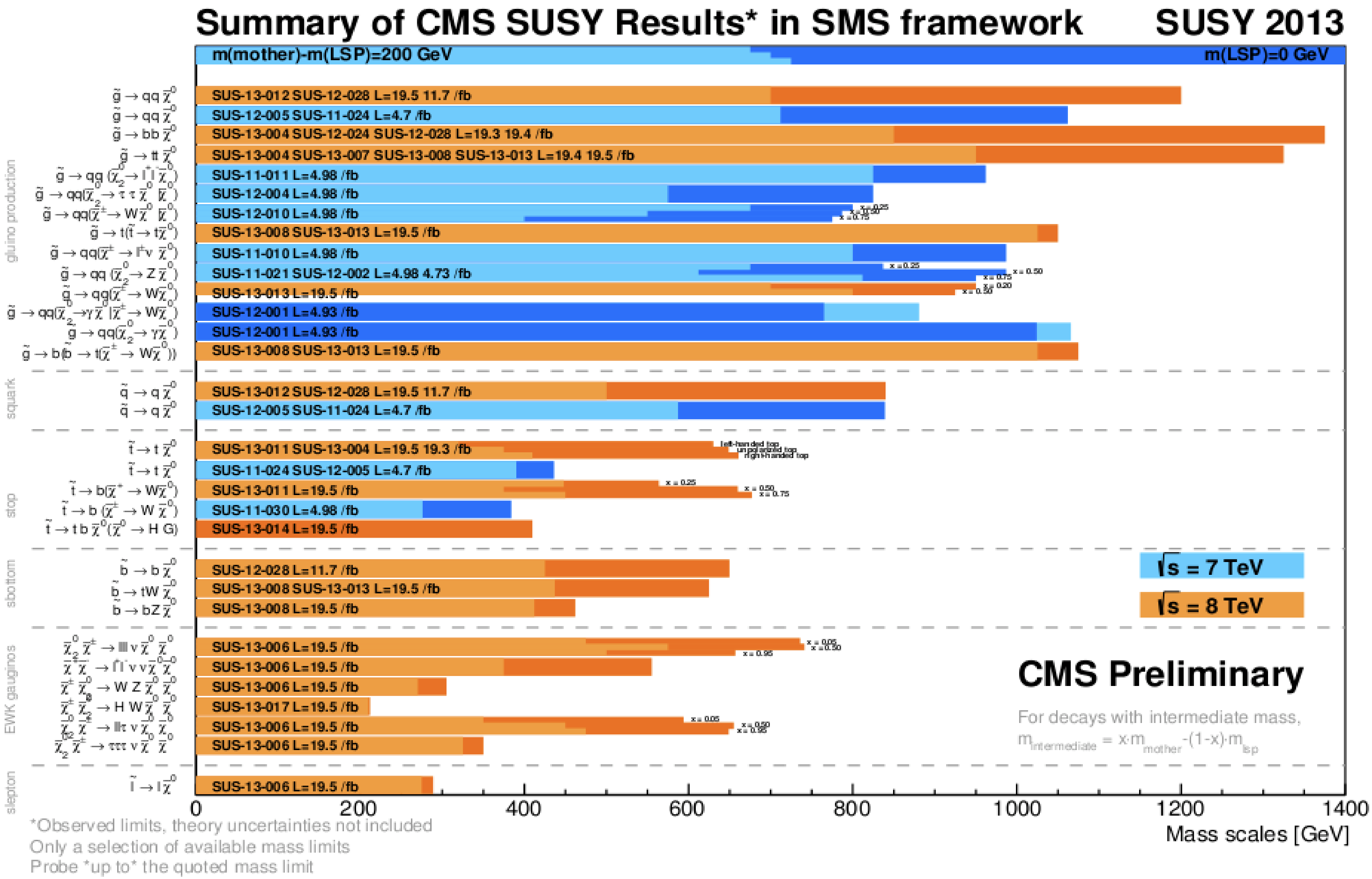
  $\mathrm{BR}(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0) = 100\%$



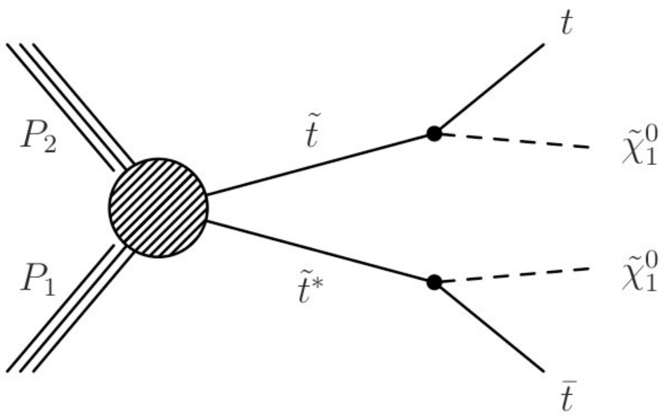


Gluinos with mass < 1.3 TeV excluded…

SUSY status in 2013 - RPC

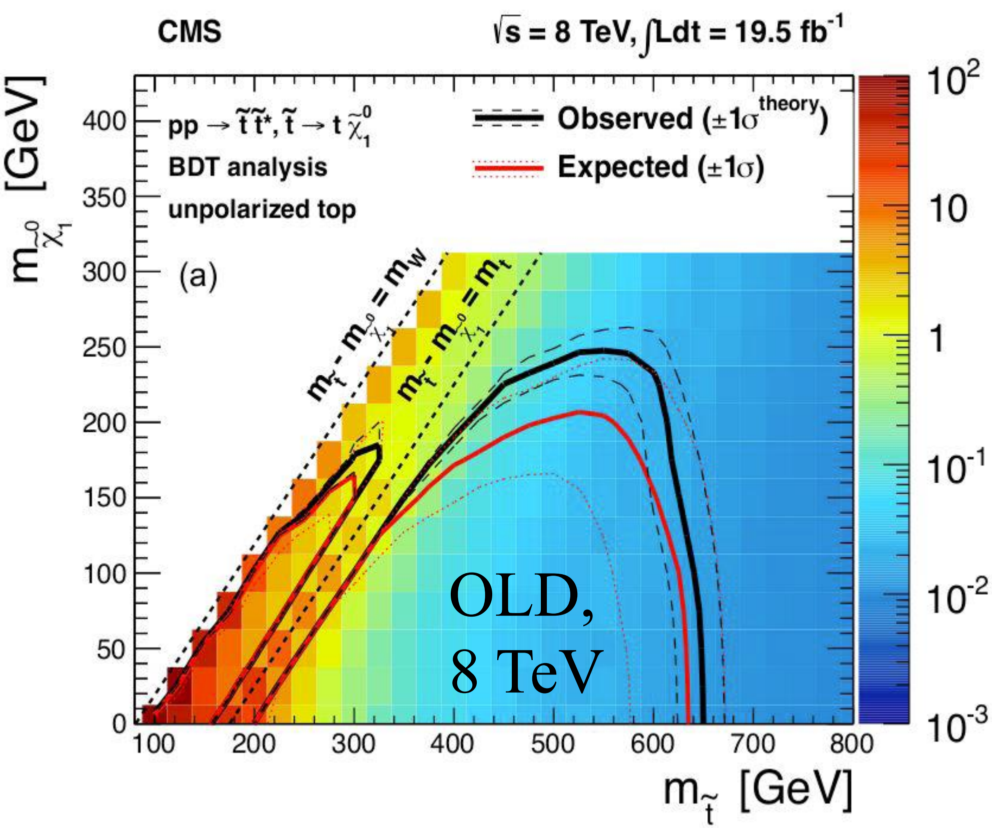


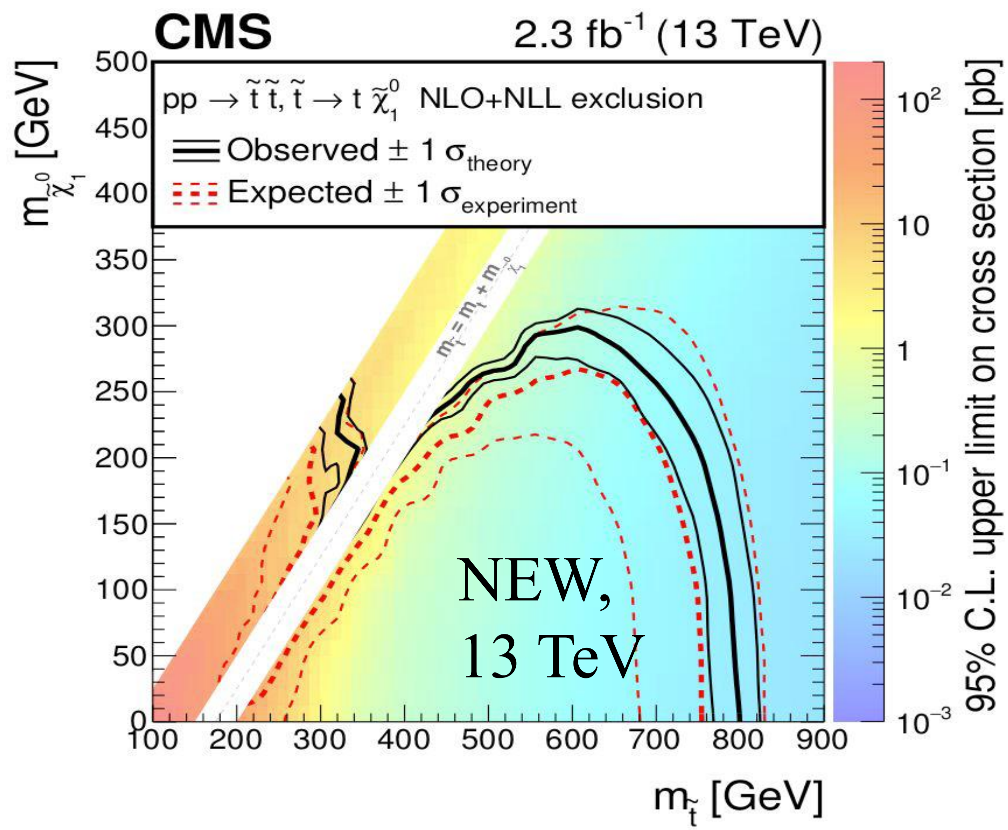
SUSY studies at 13 TeV, stop studies



T2tt,
T2bb,
T2qq

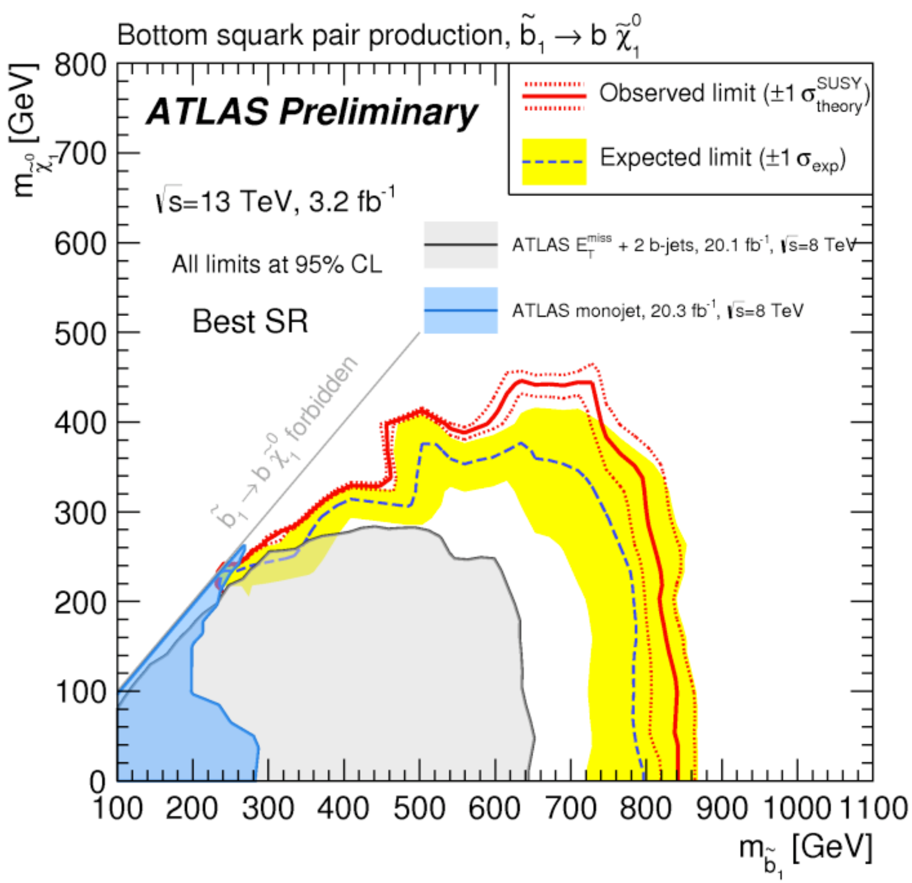
- Many regions, defined by HT, MT2, Njet(≥1), Nb,pTjet
- Final sample, refined treatments, T2tt/T2bb/T2qq interpretation added

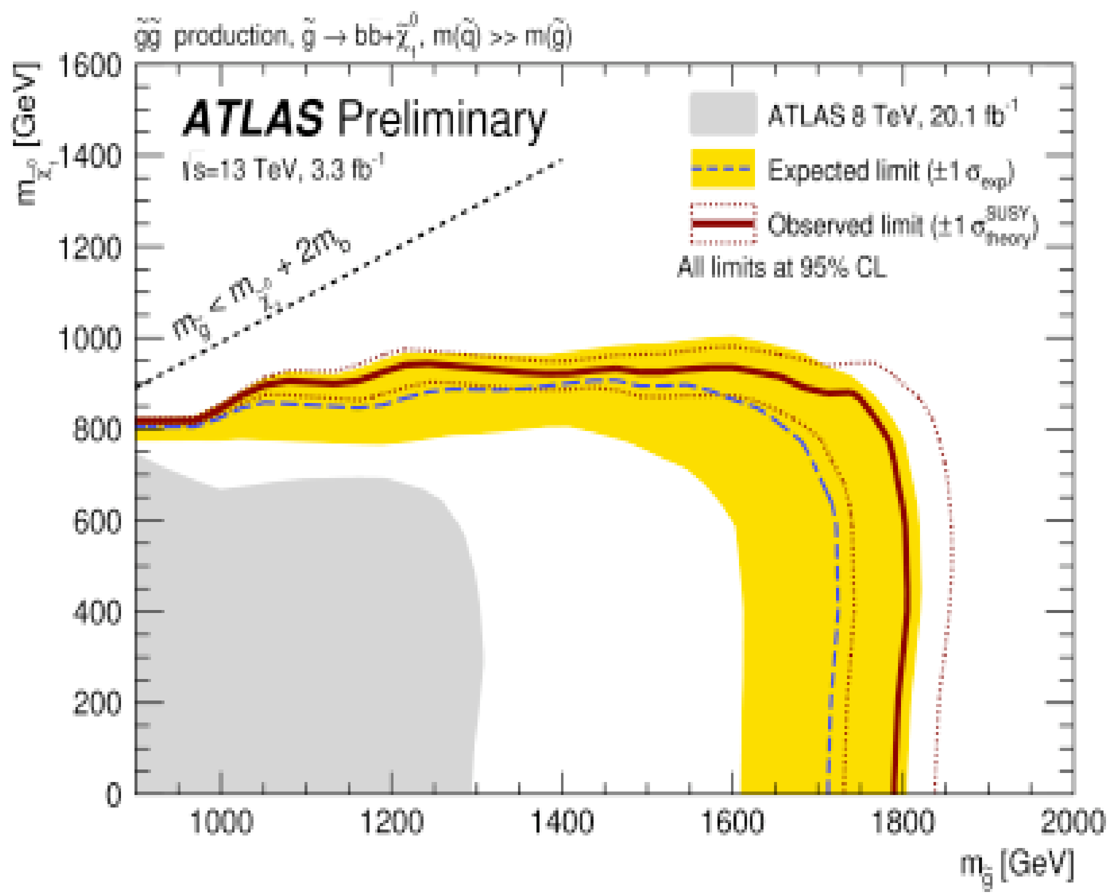




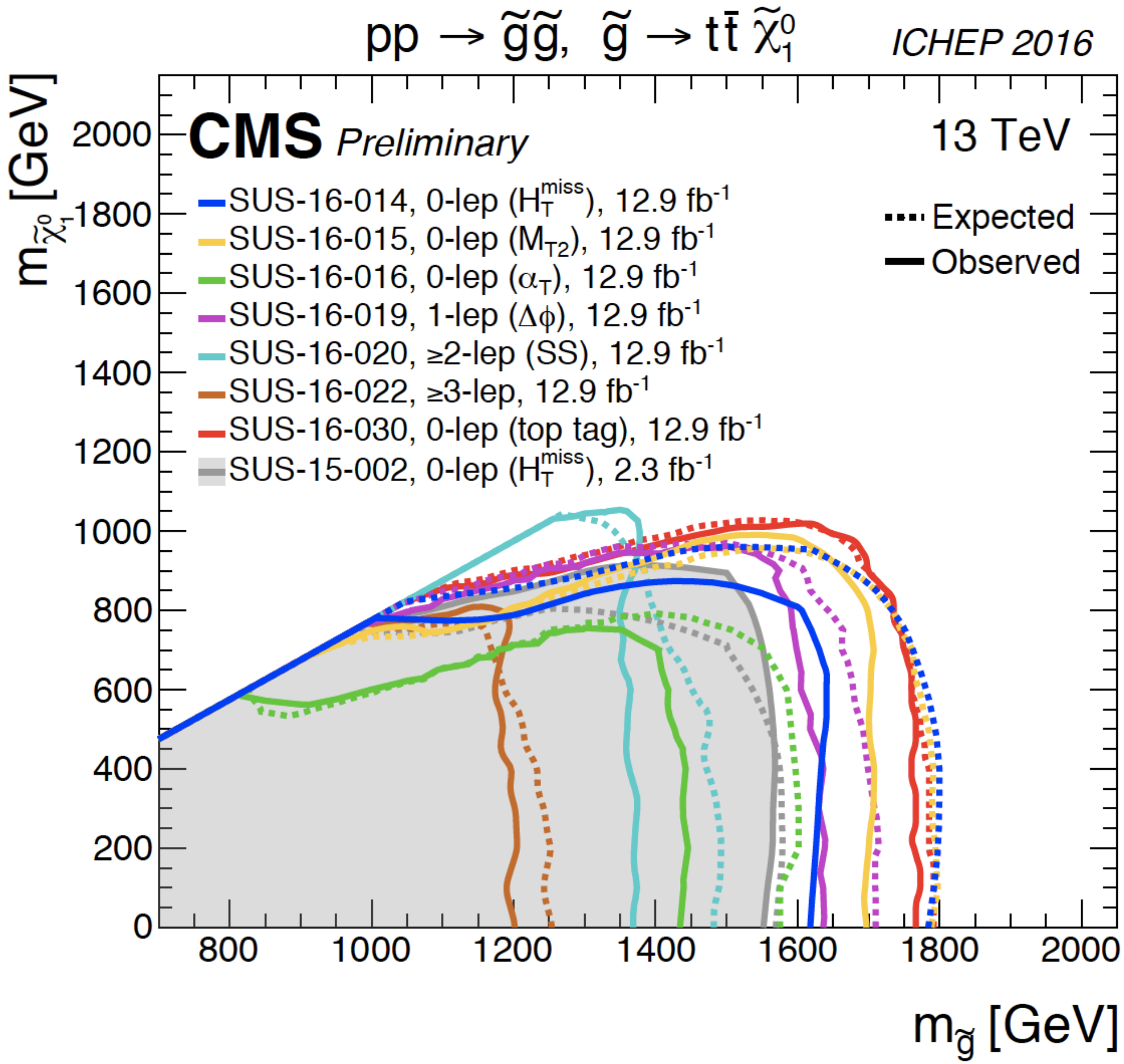
SUSY searches, 13 TeV, ATLAS, sbottom, gluinos versus neutralino-1 exclusion plots

Large gains in terms of cross sections for massive particle production in going from 8 to 13 TeV collision energy
For squarks/gluinos of ~1.5 TeV the gain is factor of 35!

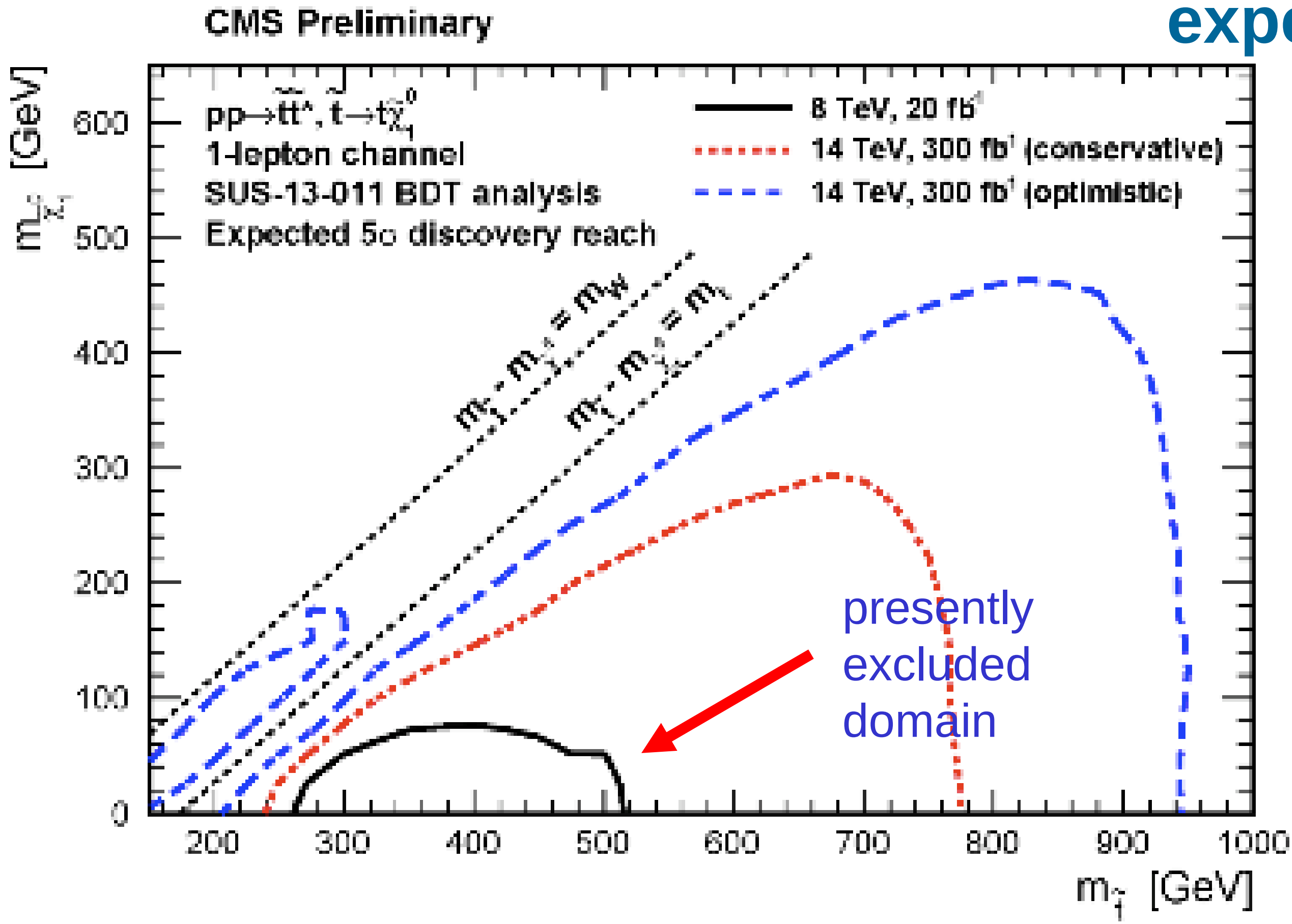




Limits on gluinos and neutralinos, CMS, mid 2016



Stop perspectives….14 TeV LHC, 300 fb^{-1} expected in ~2022



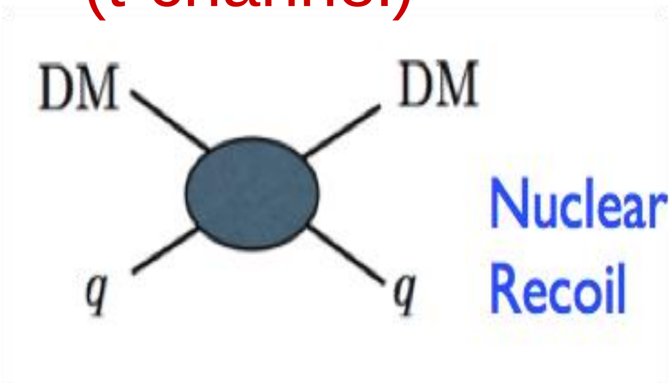
If the 125 GeV Higgs is in fact the h from MSSM, then stop is likely in the ~0.5 -1 TeV range (other squarks being ~ >`2-3 TeV)

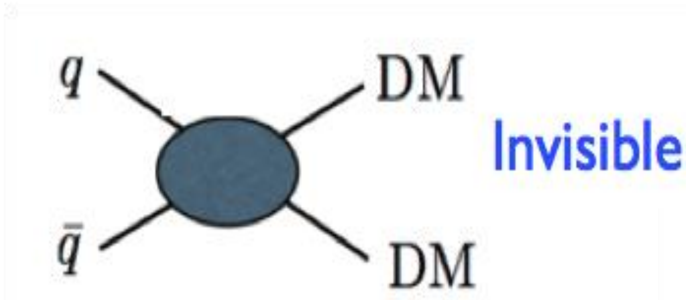
With ~14 TeV, stop could be discovered up to ~950 GeV with 300 fb^{-1}

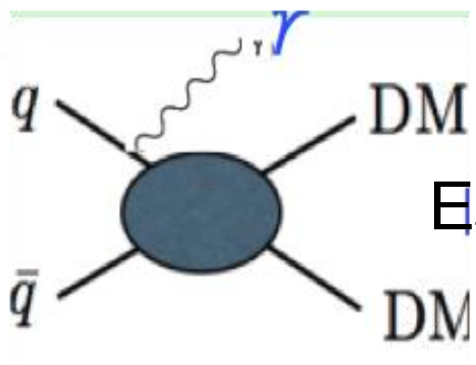
Dark Matter searches, direct vs collider searches

Direct searches
elastic scattering
(t-channel)

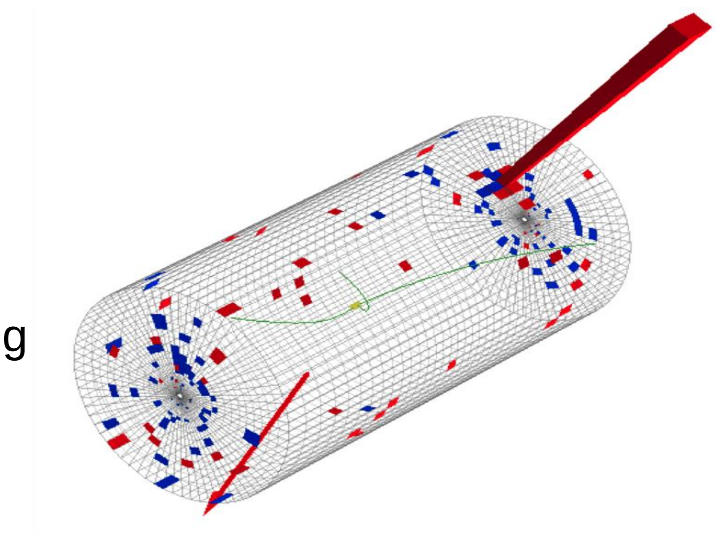
Collider searches
Pair production
(s-channel)







$E_t^{missing}$



radiation of a photon - or gluon - in the initial state makes the process visible

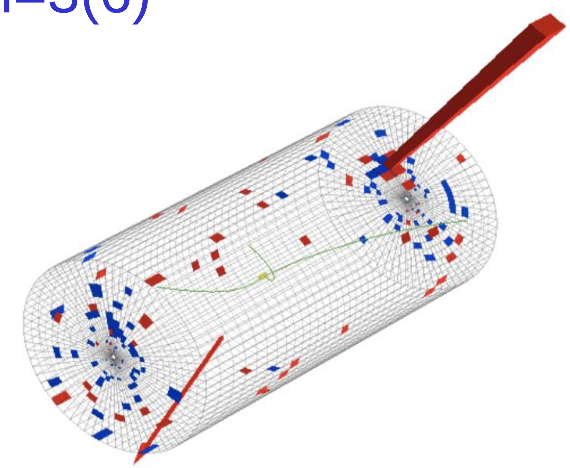
Search for mono-jets and mono-photons, 7TeV

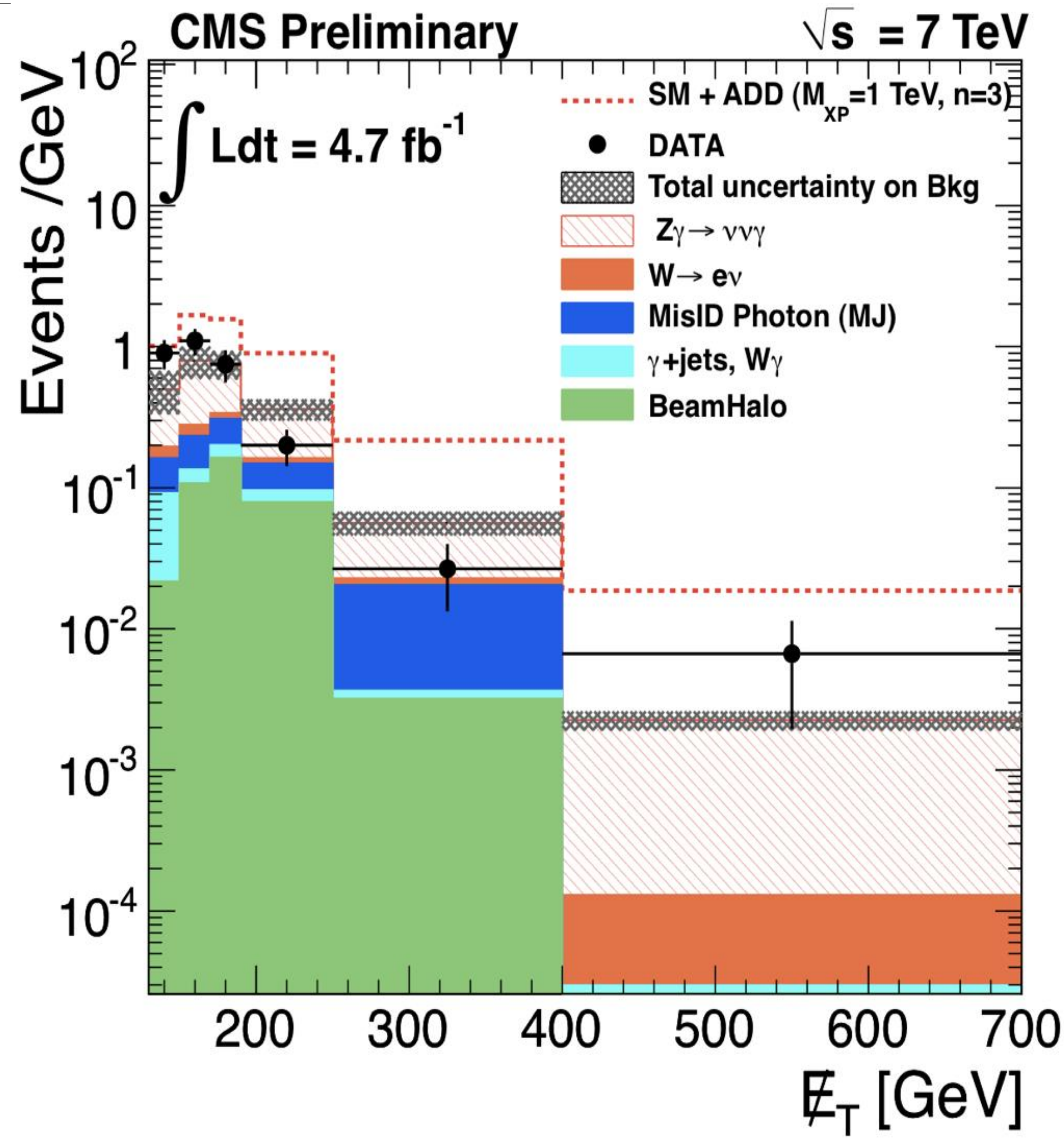
Search the gamma+MET and jet+MET data

- Look for evidence of Dark Matter production Or extra dimensions

Monojet: ADD limits set > 4 TeV for n = 2

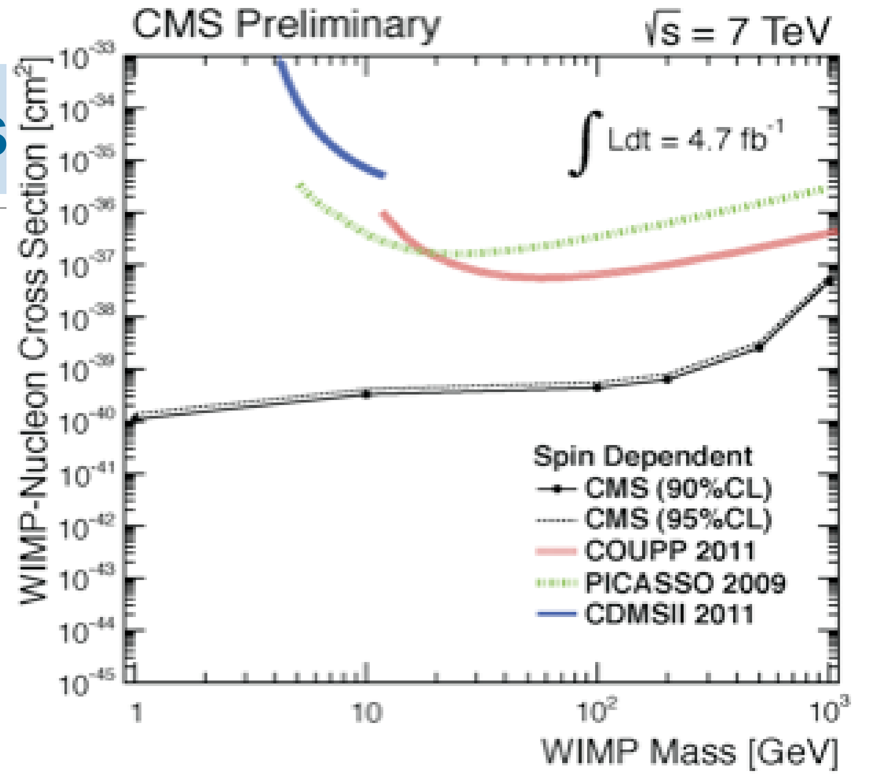
Monophoton: > 1.59 (1.66) TeV for n=3(6)

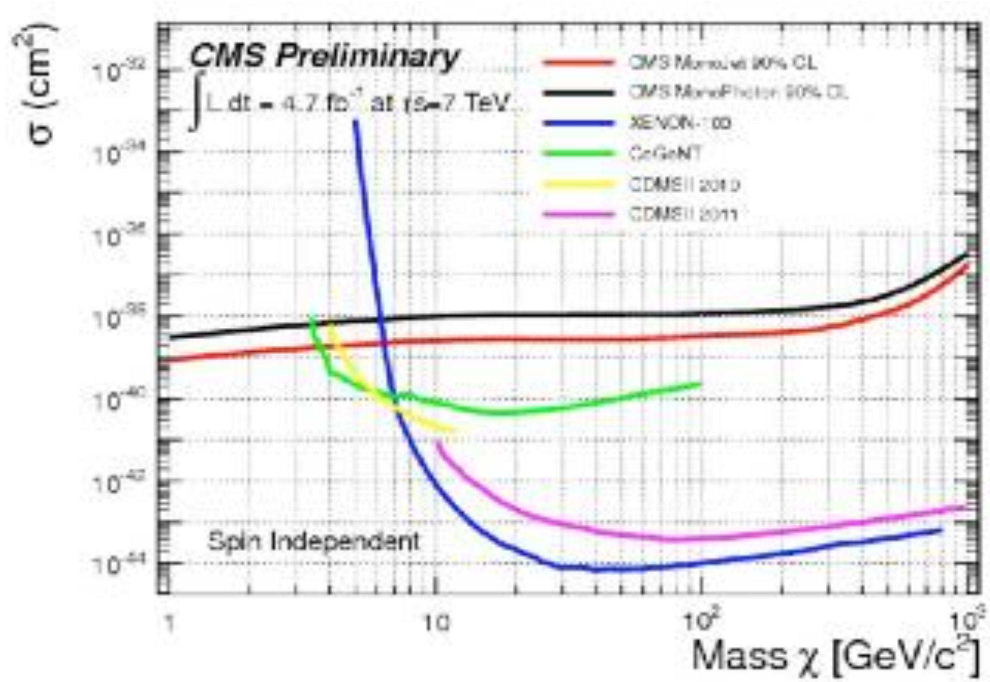


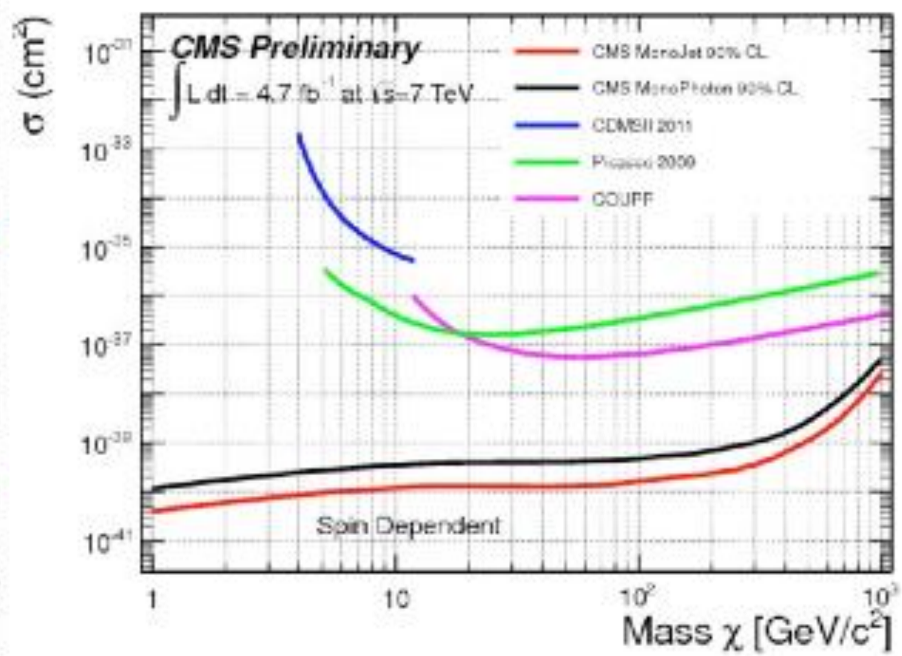


DM searches - early limits

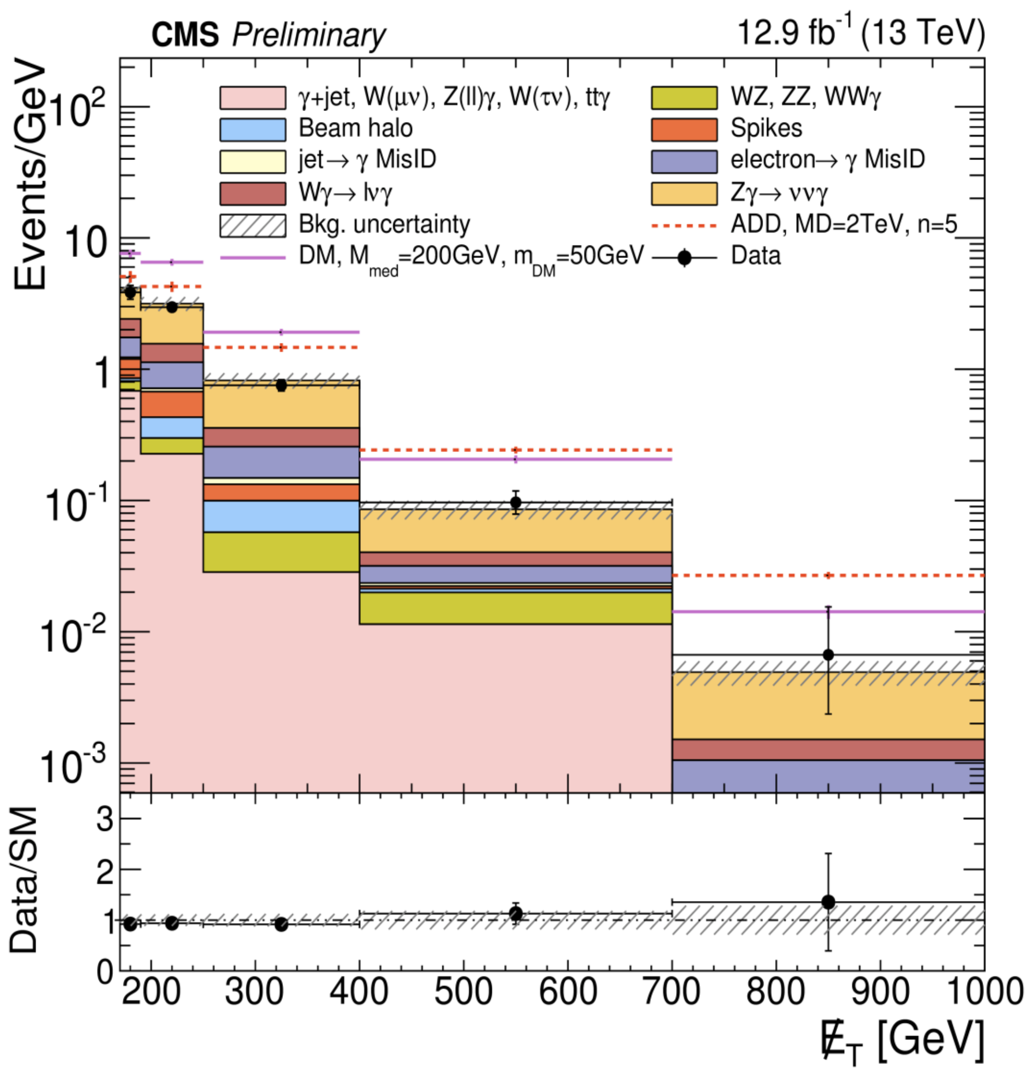
- Monojet (EXO-11-059) and monophoton (EXO-11-096) analyses probing models with extra dimensions and dark matter
- Best limits on DM with spin-dependent couplings to date

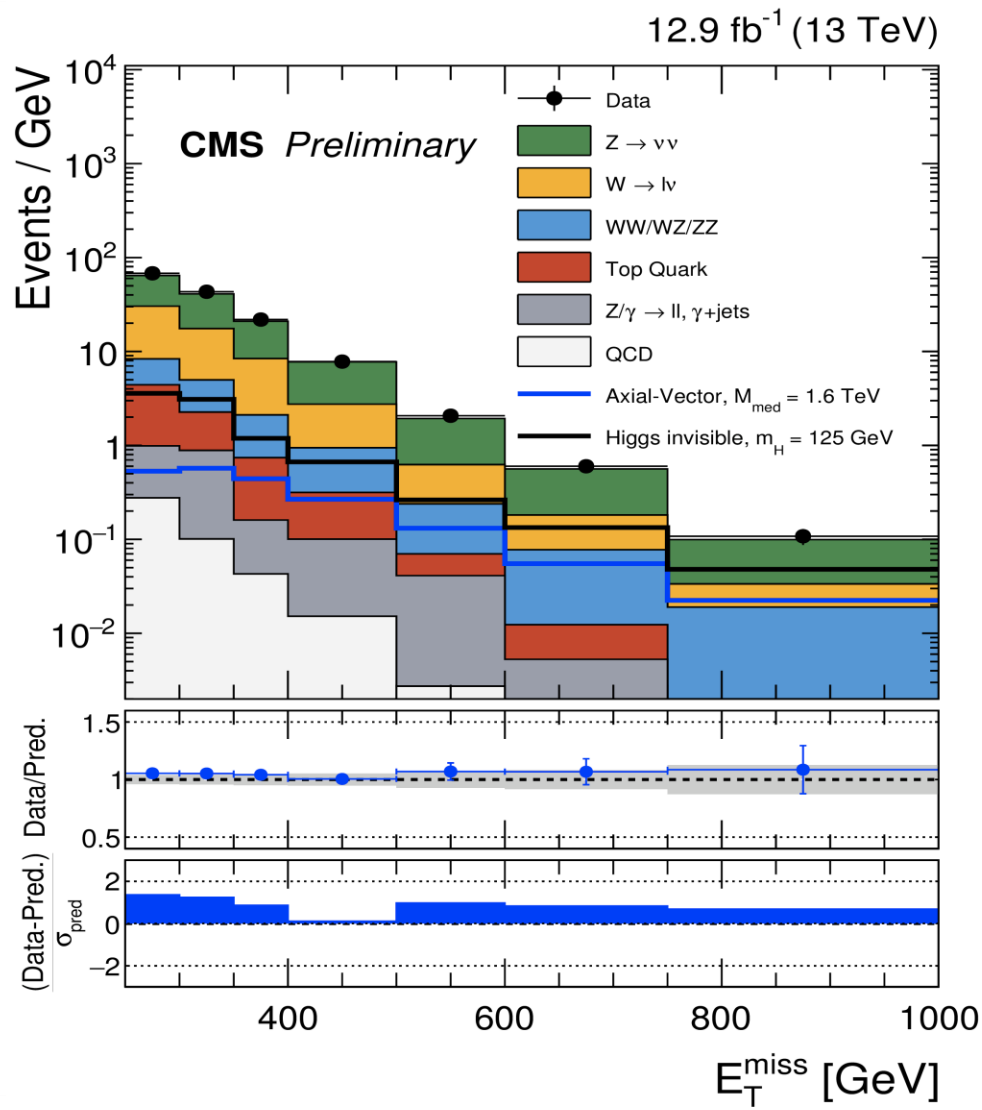






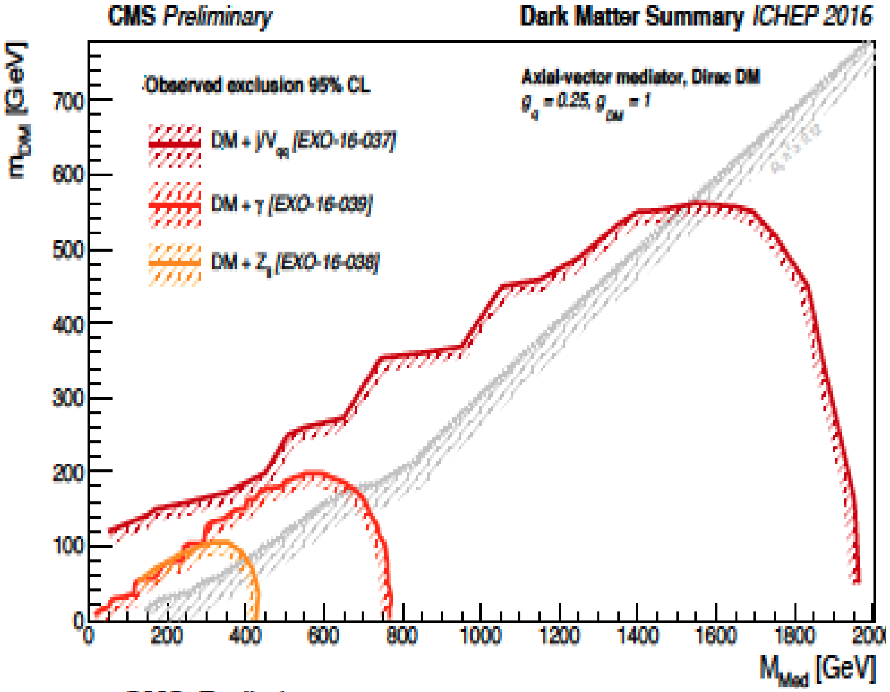
Dark Matter searches in mono-photons and mono-jets, CMS, 13 TeV, summer 2016 studies

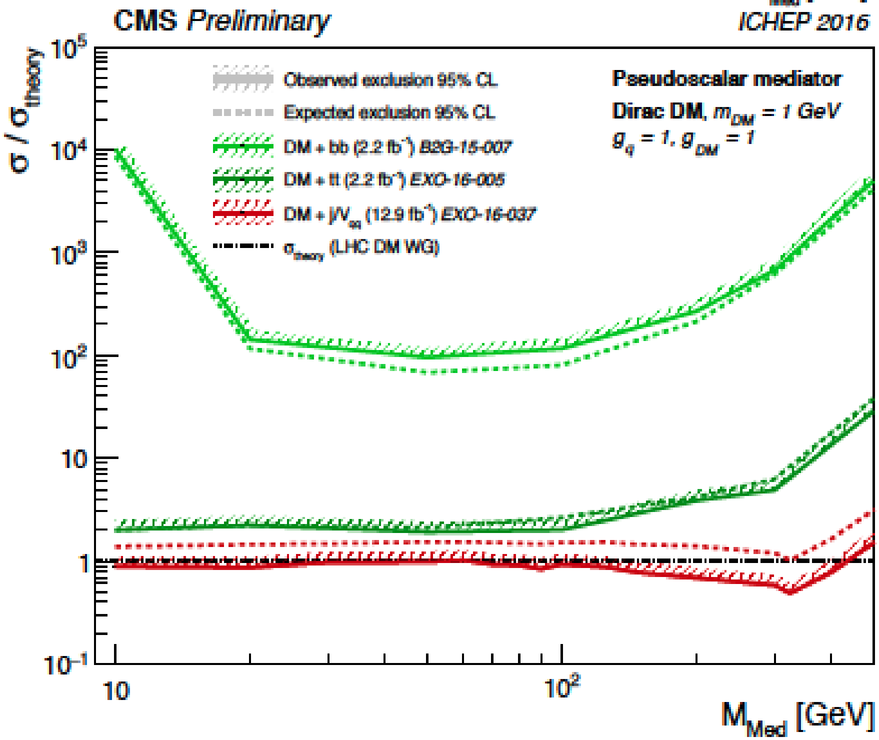


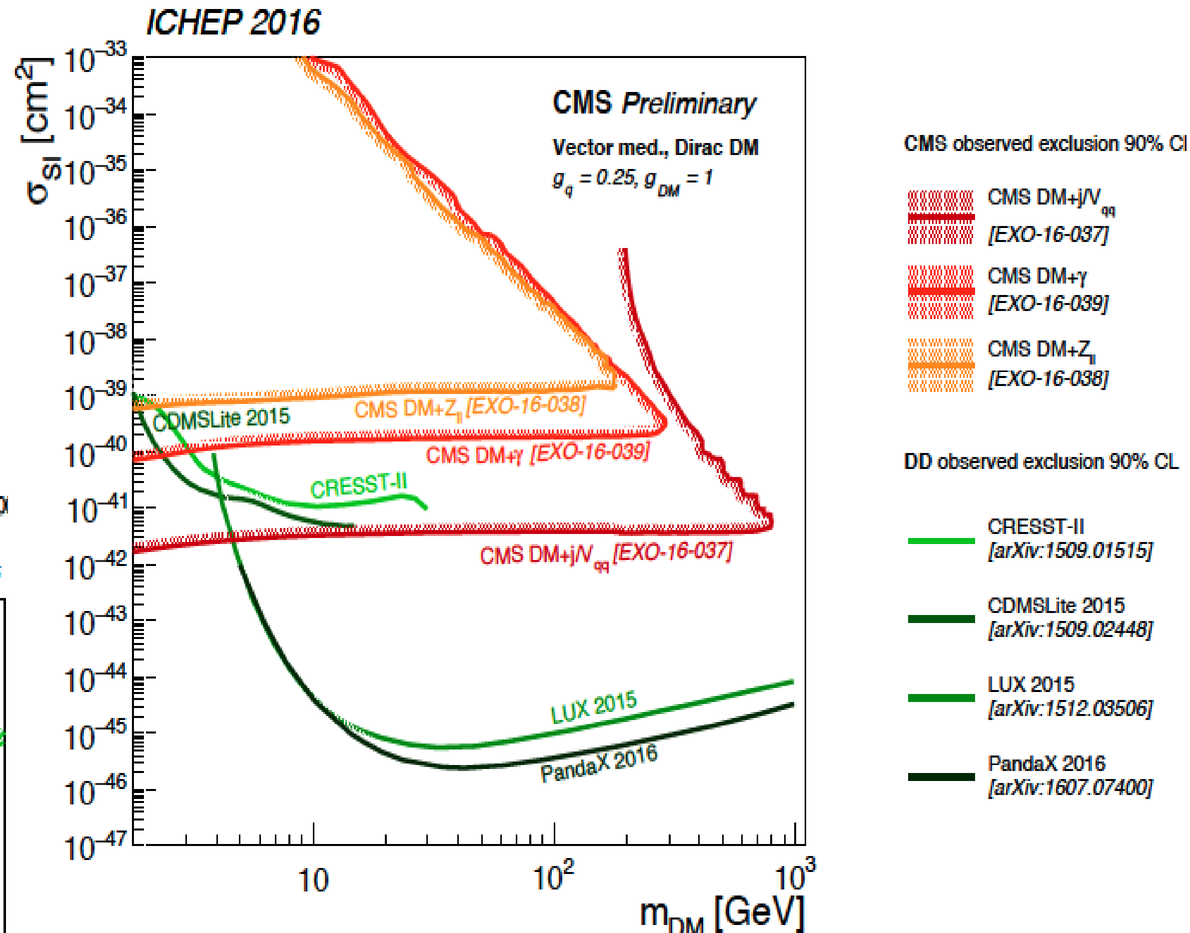


No excess seen!

DM at LHC, mid-2016 status



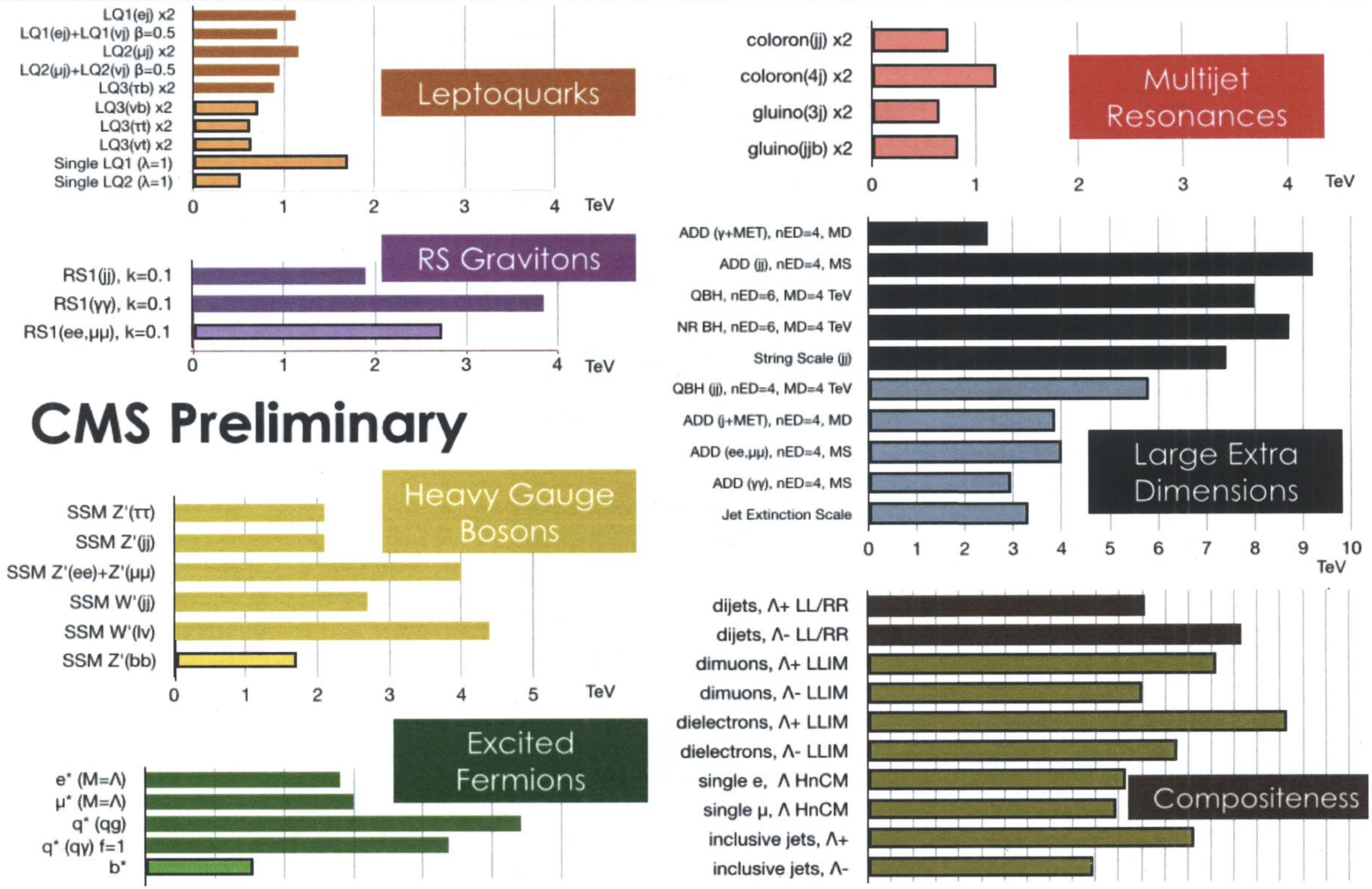




A coherent picture of DM:

- No significant excess observed so far
- DM mass exclusion up to ~550 GeV
- Vector Mediator mass exclusion up to 1.95 TeV

Exotic searches

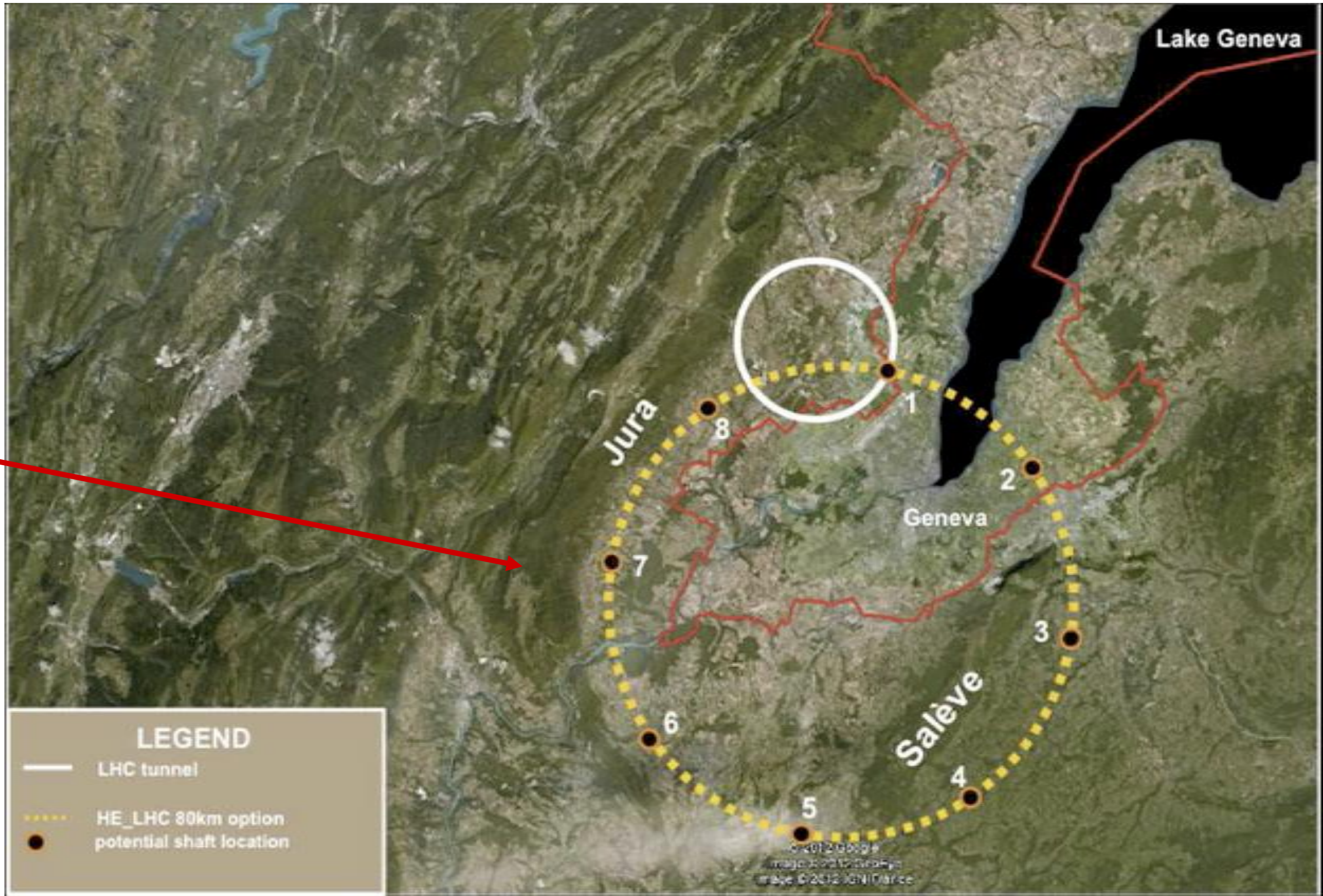


Many searches met or exceeded the sensitivity of Run 1

Possible very long-term future (~2035/40) - FCC project

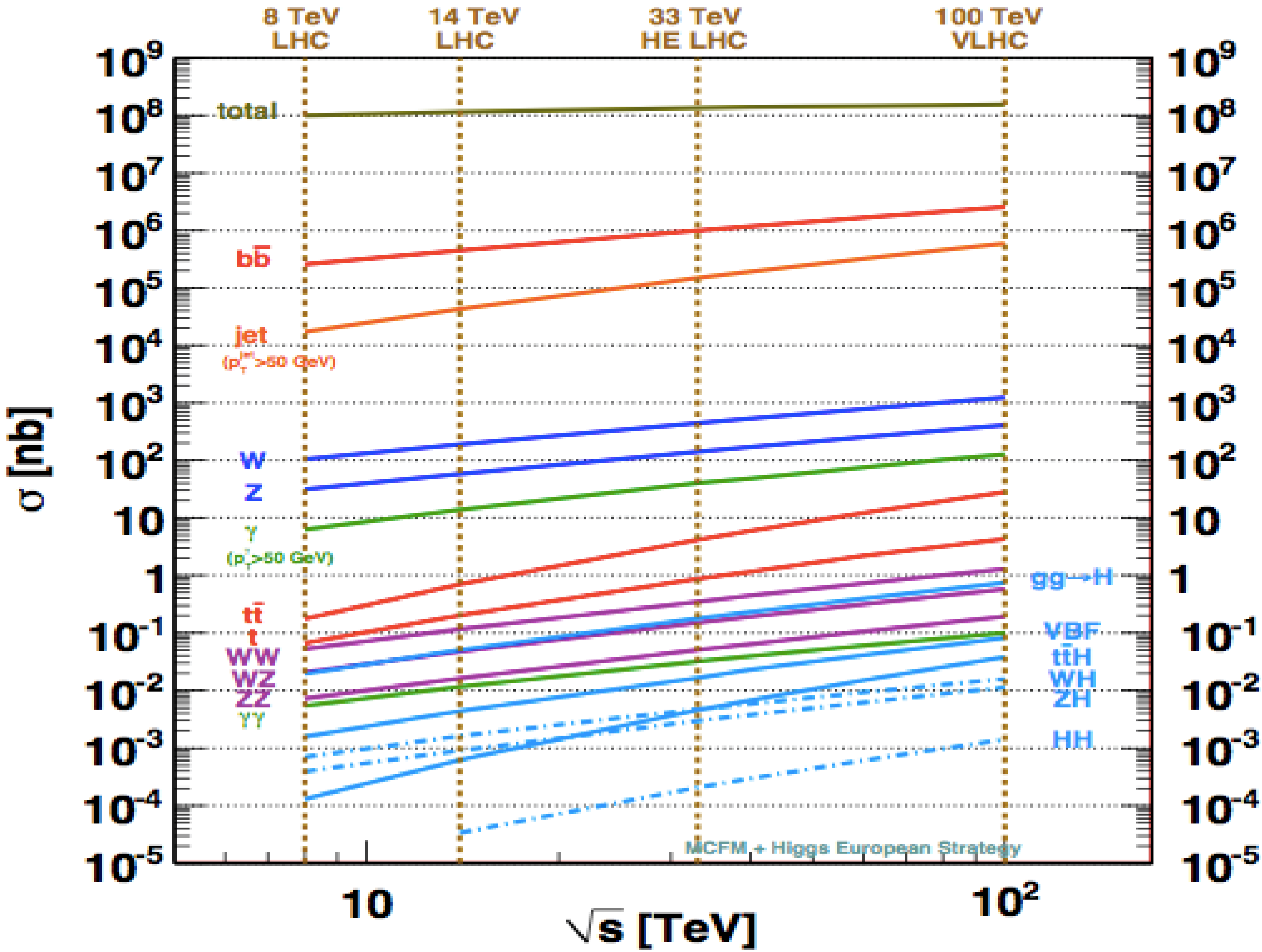
An Ultra Large Collider to reach 100 TeV in pp mode, an order of magnitude larger then LHC, with an e^+e^- initial phase at ~350 GeV, potential for e-p and Pb-Pb - the FCC project. Projects at the technology frontier at level of design studies and generating requiring/motivating ambitious R&D efforts

An 80-100 km tunnel encompassing all of the Geneva area….

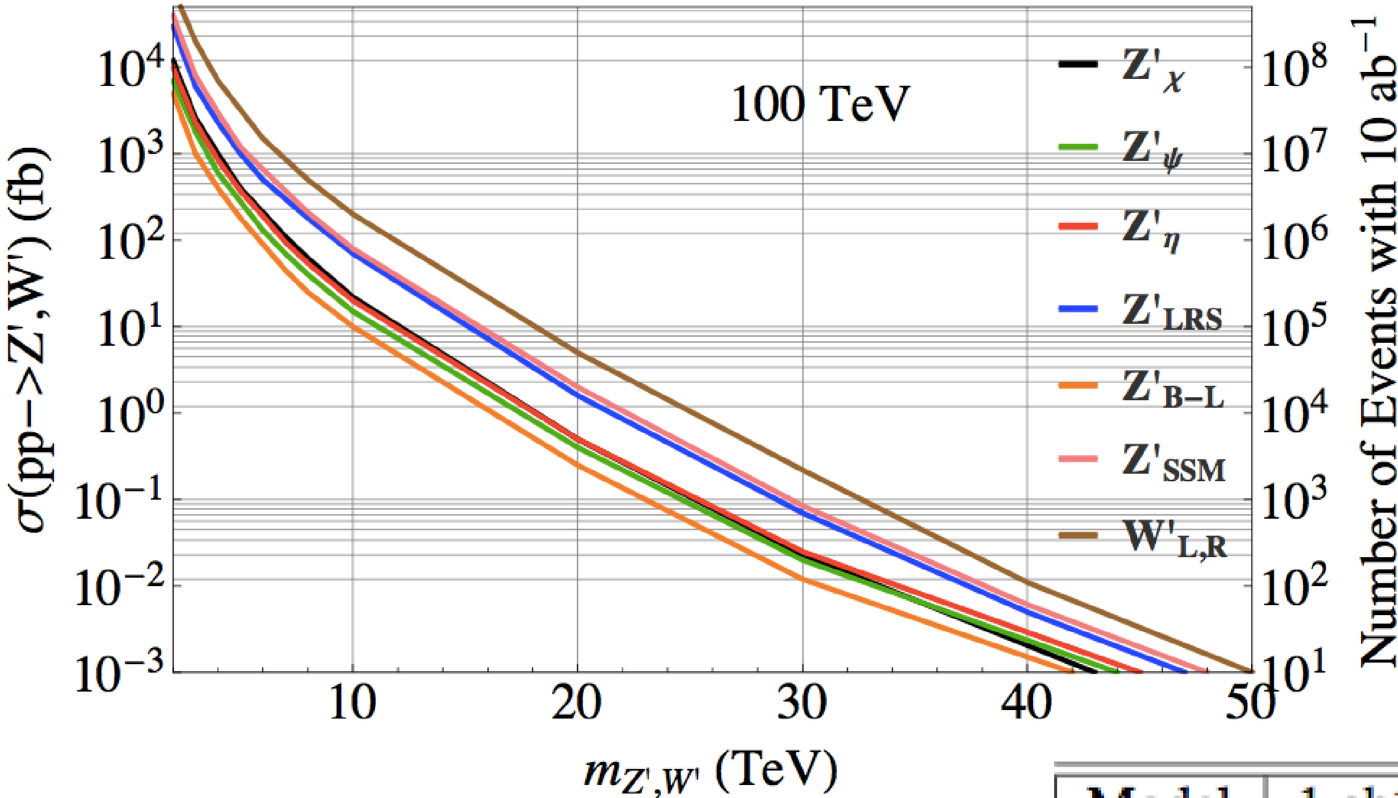


There are also the ILC, CLIC….projects

FCC-hh main cross sections



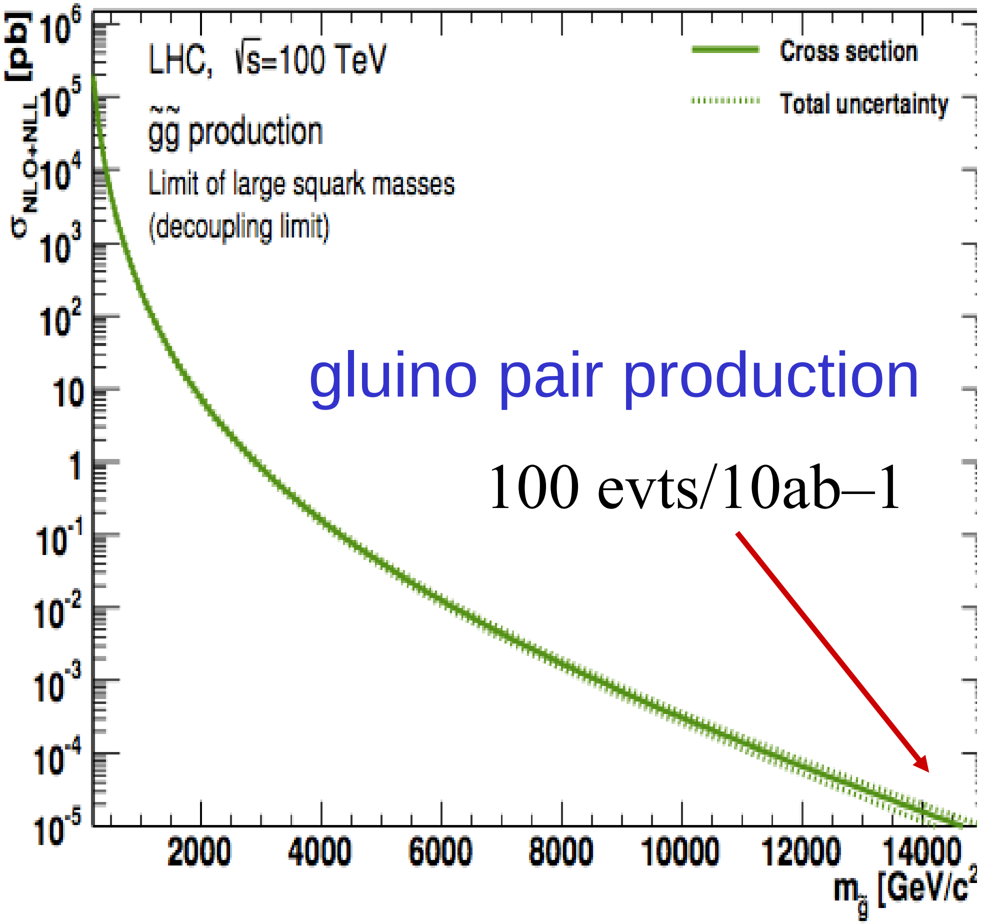
New weak gauge interactions, Fcc-hh reach with 10 atob^{-1}

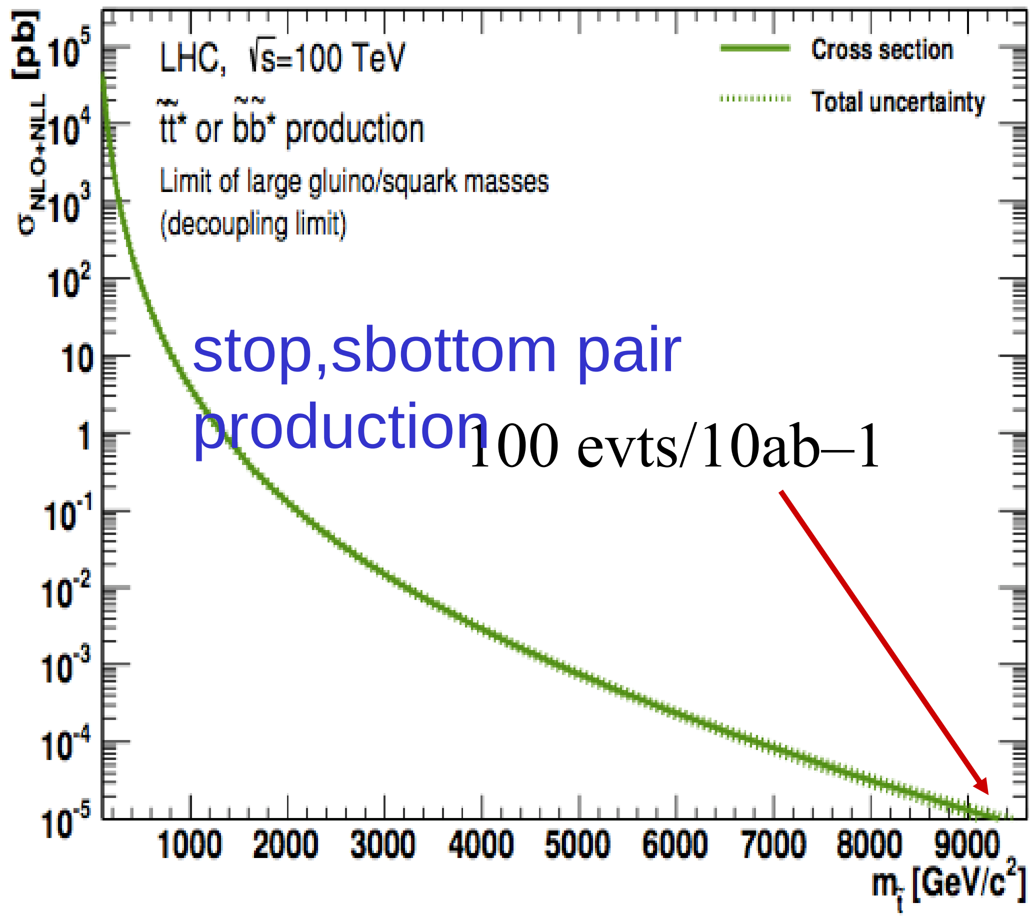


Model	1 ab^{-1}	10 ab^{-1}	100 ab^{-1}
SSM	23.8	33.3	41.3
LRM	22.6	31.5	39.5
ψ	20.1	29.1	37.2
χ	22.7	30.6	38.2
η	20.3	29.8	38.0
I	22.4	29.2	36.2

Discovery reach
T.Rizzo, arXiv:1403.5465

SUSY production at 100 TeV, Fcc-hh mass reach for gluinos, stops, sbottoms





Conclusions

The LHC is an incredible technological and scientific endeavor - on a world-wide scale - and a great success

The experiments ATLAS, CMS, ALICE and LHCb are all operating very successfully. The physics results up to now are magnificent, discovery of the Higgs, beautiful and detailed studies in EWK, QCD and B-physics, rare decay modes, QGP studies etc

In 2016 LHC started operating at 13 TeV; many technical challenges overcome. Near future: clarification of the Higgs (is it THE Higgs boson or a A Higgs from an extentionn of the SM), but the main task is to look for physics beyond the Standard Model, looking for SUSY etc especially so in the HL-LHC phase.

The particle physics community is already working on long-term options/projects to take over in ~ 20-30 years from now