LHC Physics overview

What has been achieved ? (with a CMS knowledge bias …)

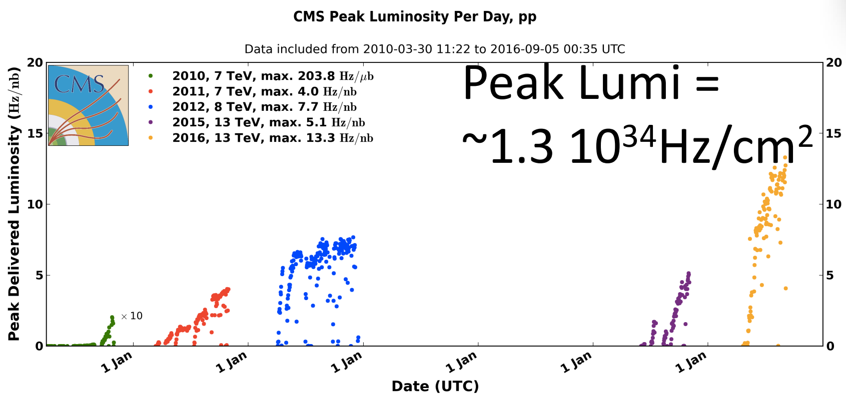
What is the focus of the near and far future ?

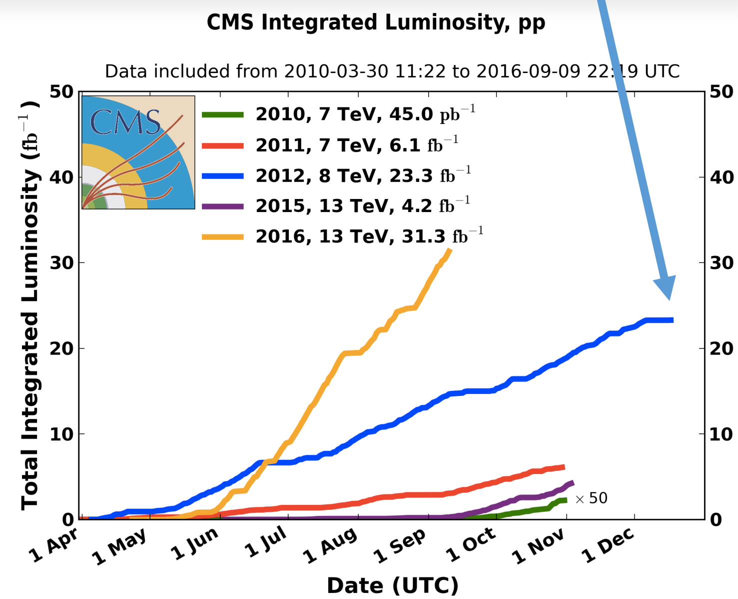
T. Camporesi, CERN EP Department

Setting the scene

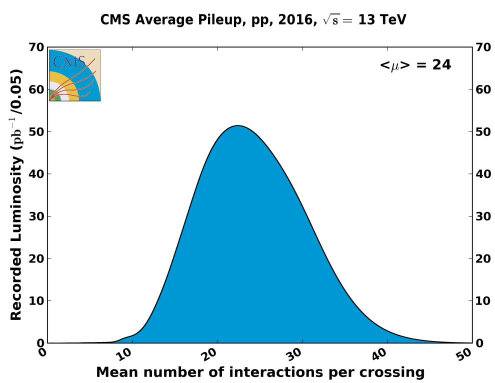
- Thanks to the accelerator teams of CERN, the LHC has exceeded even the most optimistic performance estimates

The estimate prior to the start of the 2016 campaign were to achieve something similar to the previous best (2012)



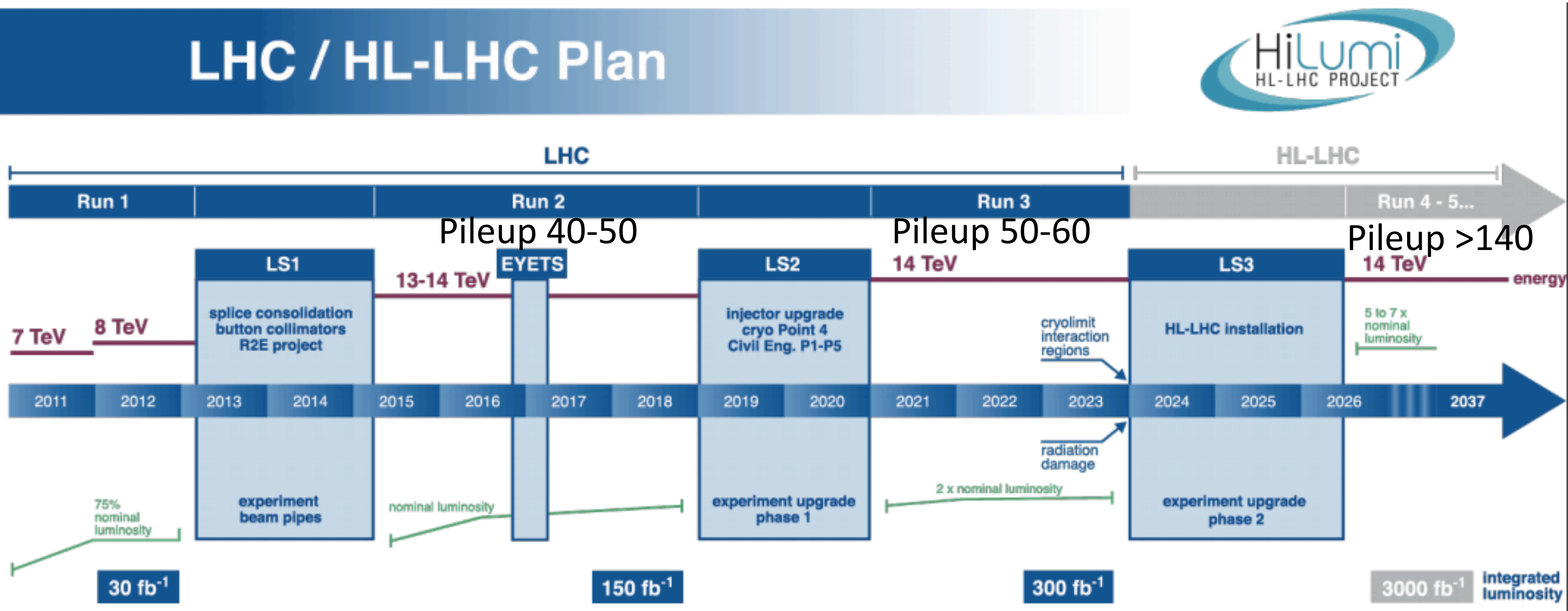


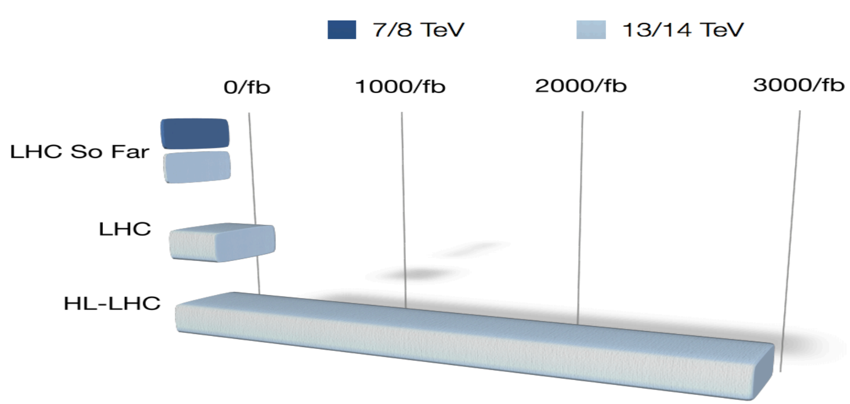
Pileup distribution for the 13 TeV data shown here



CMS livetime ~95% and > 94% of logged data usable for any physics analysis

Setting the scene





The main LHC chapters of the LHC Physics book

Standard Model studies

- QCD: Forward physics and High Pt
- Electroweak
- Flavour

Higgs Physics

Beyond the Standard Model searches

- SUSY
- Exotica

Heavy Ions: apologies for not being able in the time allocated to cover this rich area

QCD forward (and soft) Physics

- LHC has proven its ability to enhance our understanding in this area which is ~difficult from the experimental point of view
- Does not like high pileup… but it can do great things with little lumi
- Measurements are important to constrain modelling and calculations
- Examples of achievements:
  - Particle correlations studied ...and surprise found: ‘The ridge’
  - Undelying event studies: often not recognized enough for its fundamental role in most of the other LHC studies
  - Bose-Einstein correlations (still an active area of understanding)
  - $dN/d\eta$: the first publication when new energy range and a integral metric of our understanding of PP collisions
  - Specific studies of particle spectra
  - Future prospects: integration of Roman Pots detectors and ability to perform high purity studies of $\gamma\gamma$, WW and pure gluon production

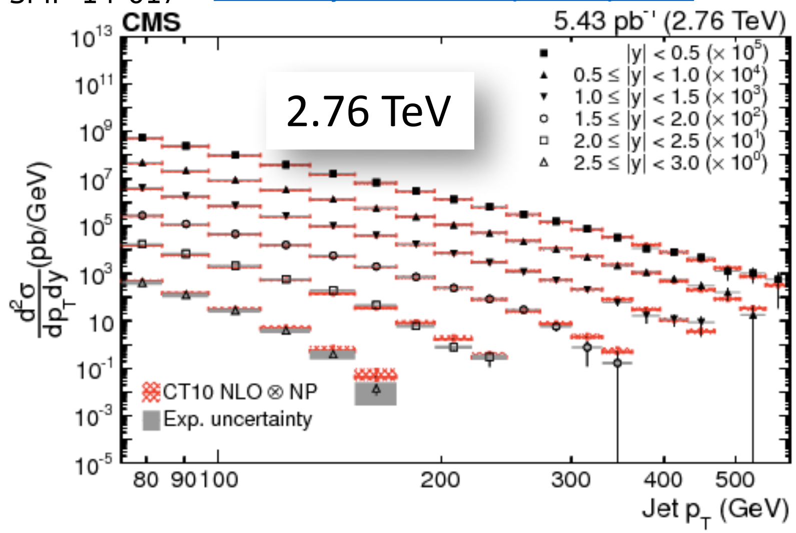
QCD hard

- Detailed studies of jet multiplicities at several energies (2.76,7,8 13 TeV) providing remarkable feedback to Theorists and MC simulations and helping improving the knowledge of the PDFs
- Detailed study of jet correlations, forward and Central production
- Measurement of AlphaS (and its running) from jet production
- Jet production mechanisms in associations with electroweak bosons
- Ongoing are studies of charm and b jets
- Inclusive studies which can help constrain radiation models
- The interaction with theory has been extraordinary: 'unexpected' achievements like NNLO (and beyond) calculations and hadronization models are being checked more and more precisely
- The future will see more of the same
- It is hard to imagine that there will be much left to explore once the first few hundred fb^{-1} are collected.

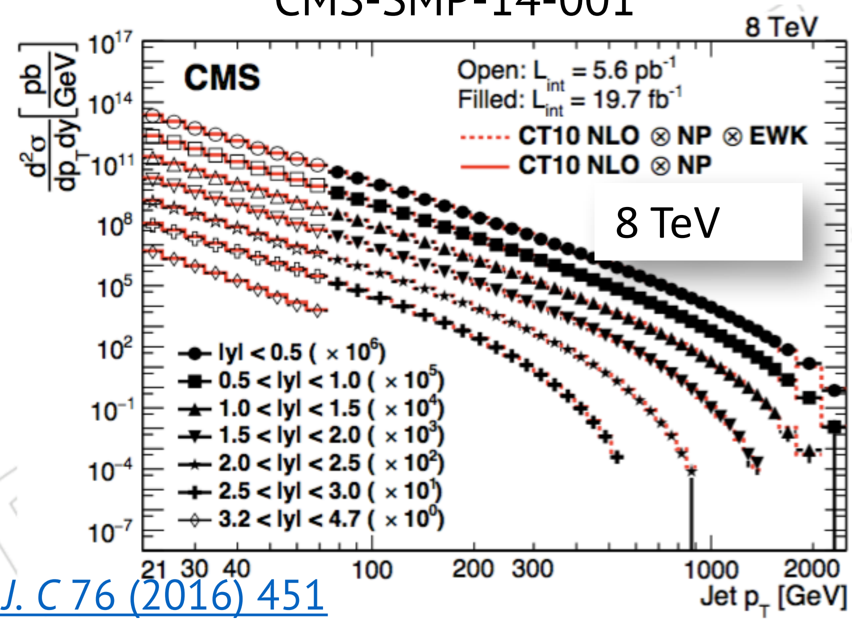
Some examples

CMS-SMP-14-017

Eur. Phys. J. C 76 (2016) 265



CMS-SMP-14-001



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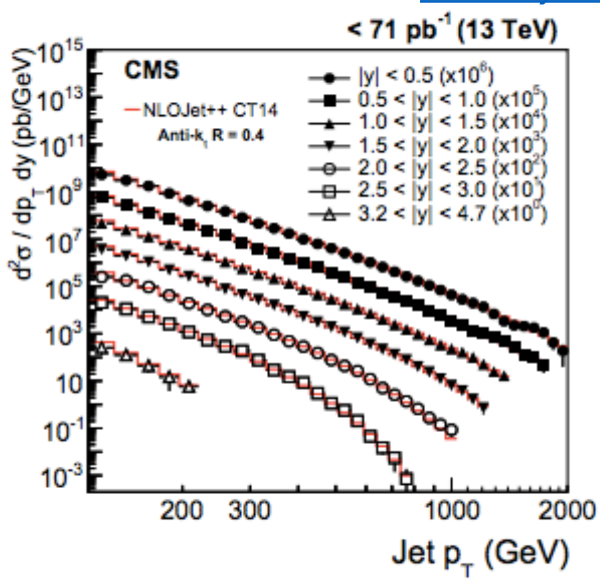
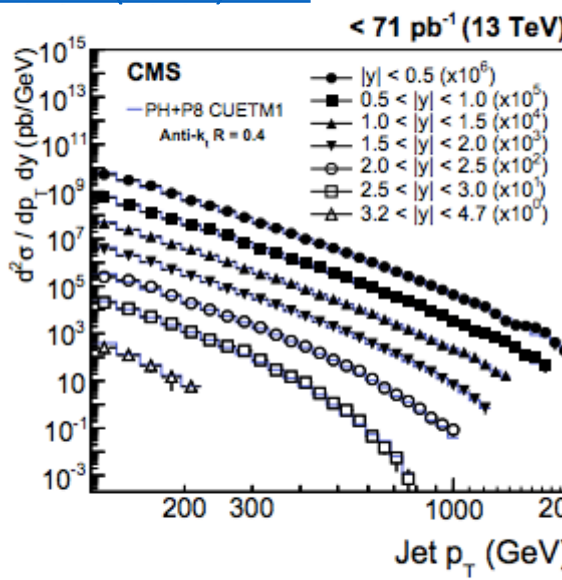




13 TeV

Jet cross section ratio and α_S

SMP-14-001

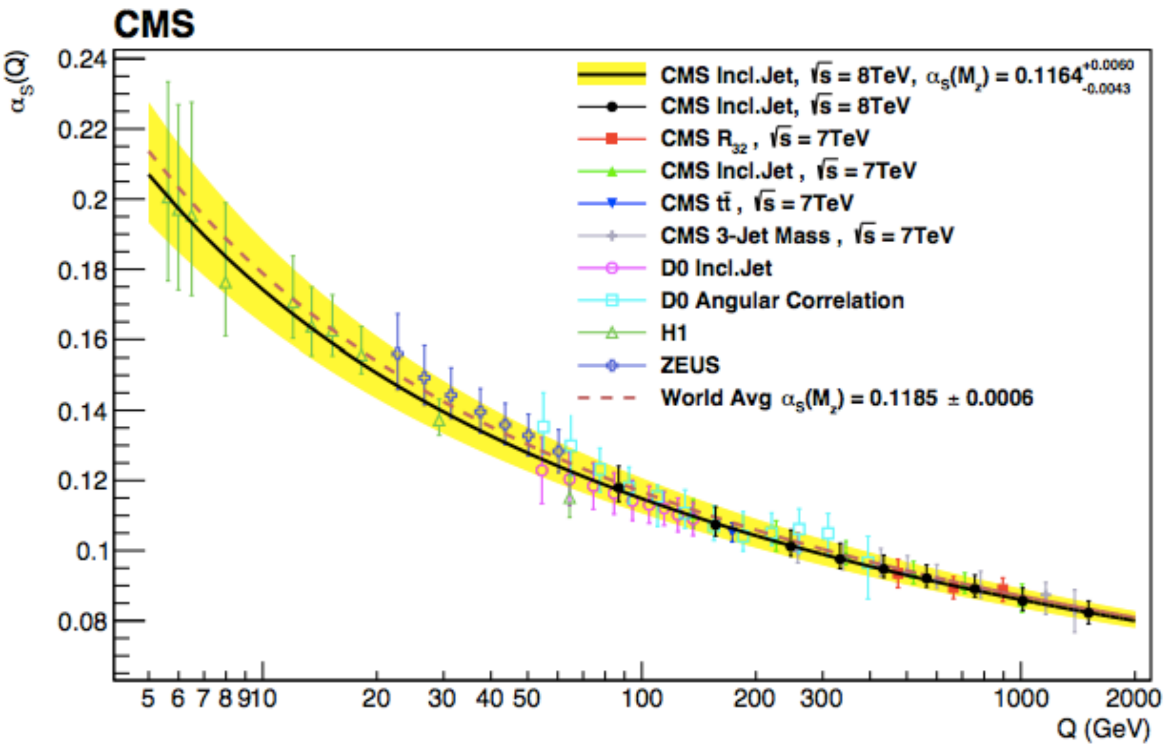


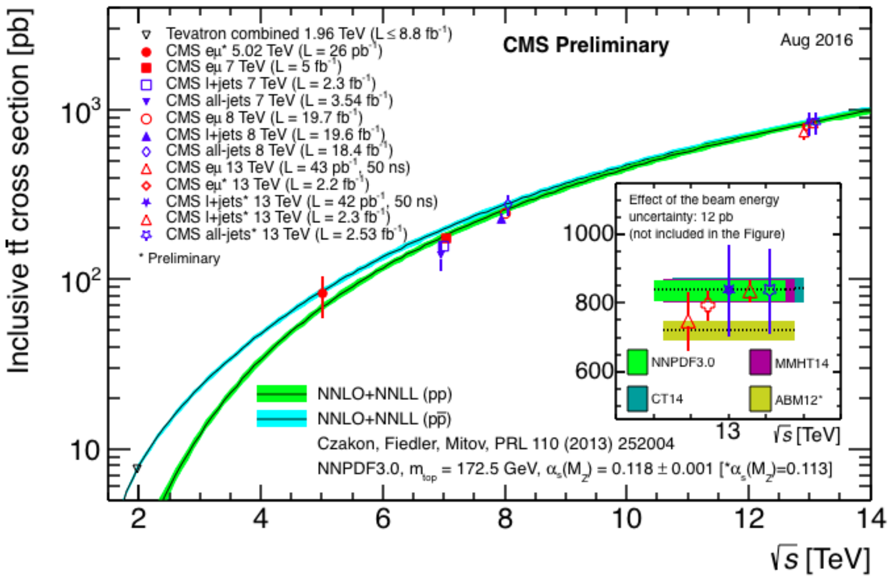
Figure 13: The running $\alpha_S(Q)$ as a function of the scale Q is shown, as obtained by using the CT10 NLO PDF set. The solid line and the uncertainty band are obtained by evolving the extracted $\alpha_S(M_Z)$ values by using the 2-loop 5-flavour renormalization group equations. The dashed line represents the evolution of the world average value. The black dots in the figure show the numbers obtained from the $\sqrt{s} = 8$ TeV inclusive jet measurement. Results from other CMS [53–55], D0 [49, 50], H1 [56, 57], and ZEUS [58] measurements are superimposed.

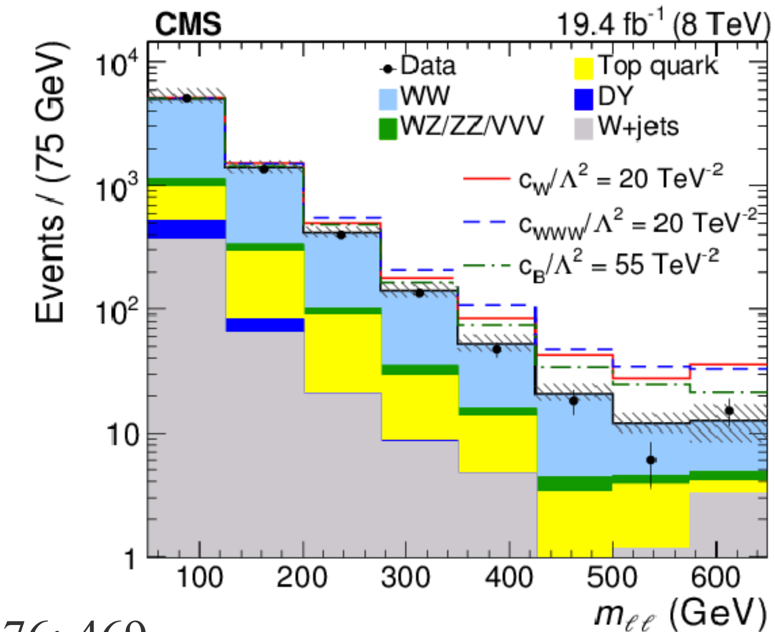
Electroweak

- The experiments have delivered increasingly precise measurements of single, double boson cross sections
- Triple boson production are setting improved limits on Anomalous Gauge Coupling
- The top sector has seen a bountiful of fundamental measurement exploiting fully the fact that LHC is above a TOP factory
  - Very precise Single top measurements
  - Top pair production measured at several PP energy
  - First measurements of associated production of top pairs and bosons has been performed
  - Top decay electroweak asymmetries have been measured
- Electroweak induced asymmetries in W decays have been precisely precisely measured over a large rapidity intervals allowing major constraints on PDFs

Some achievements

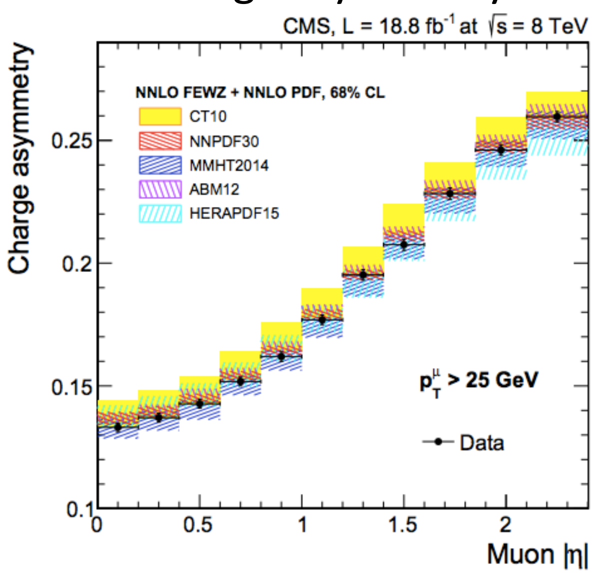
Will BSM physics be detected via EWeak bosons?

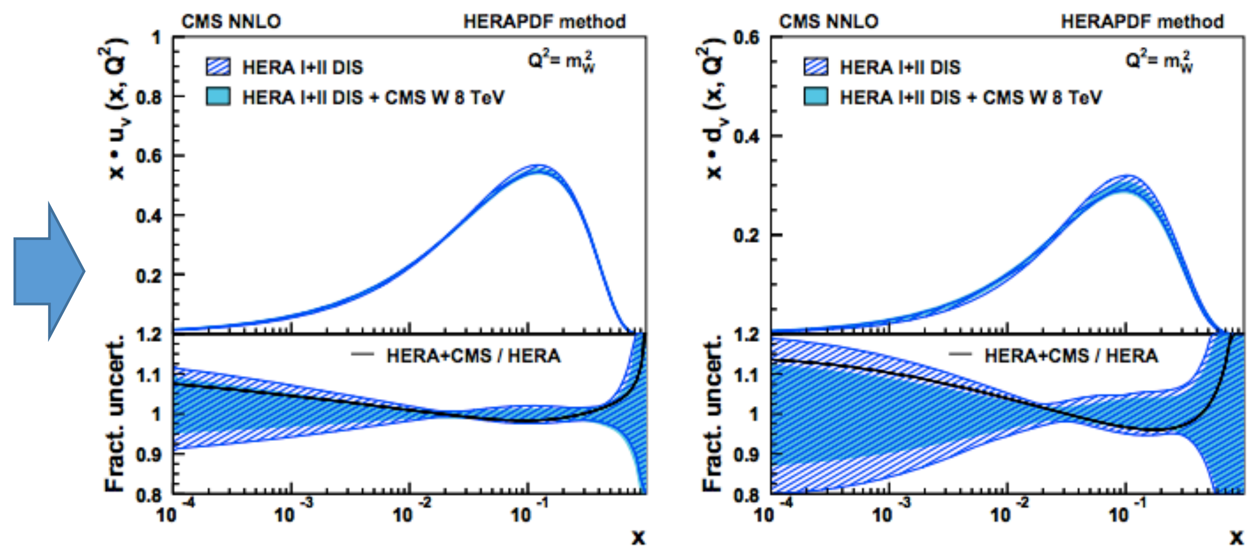




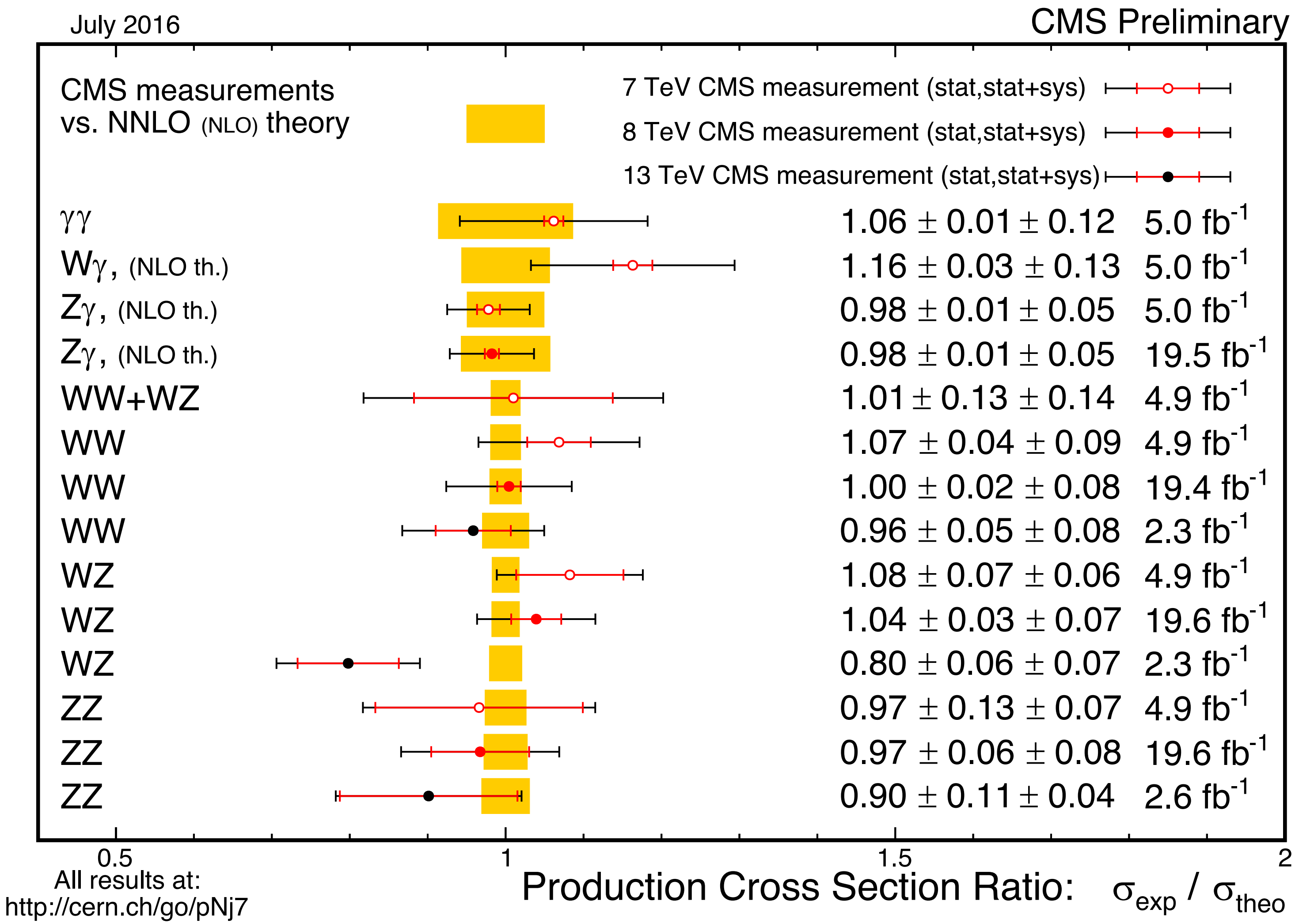
W charge asymmetry

Eur. Phys. J. C (2016) 76: 469.

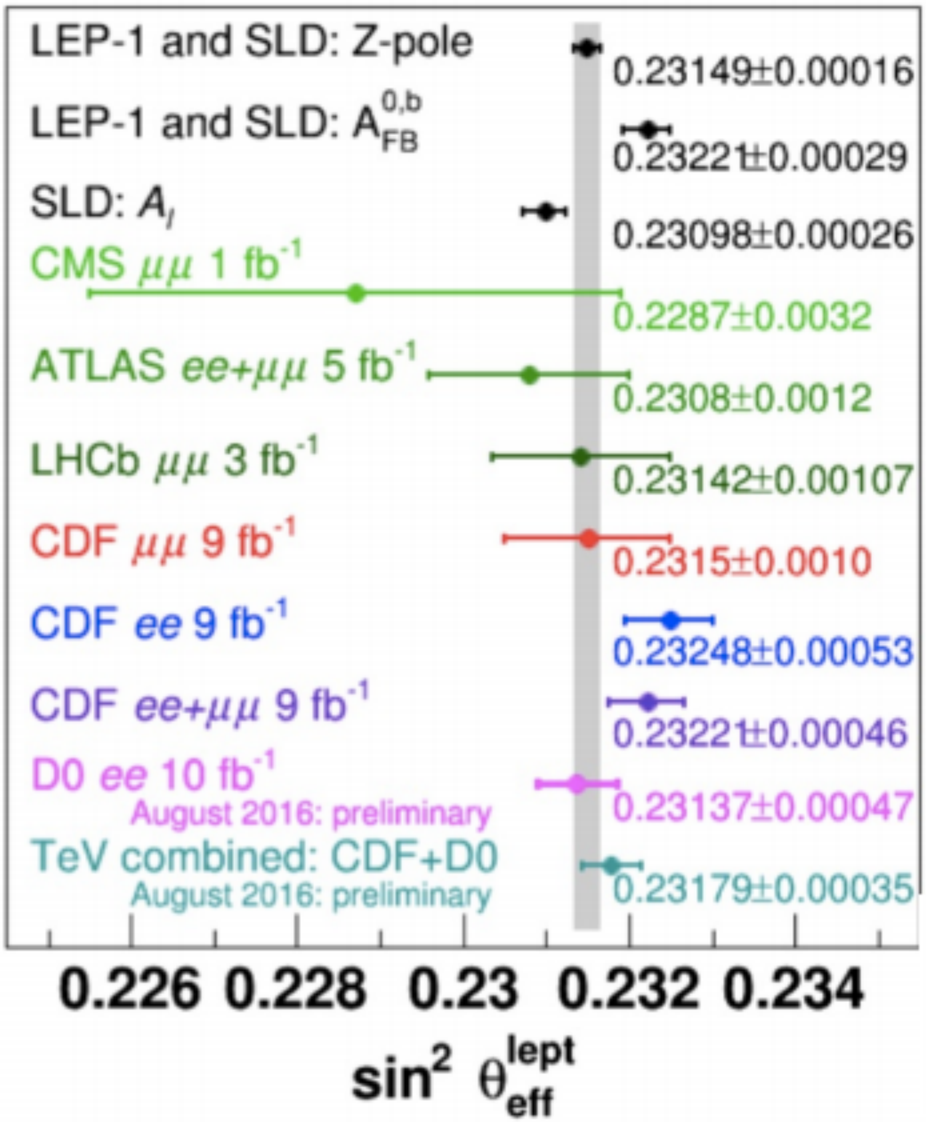




Measuring with increasing precision



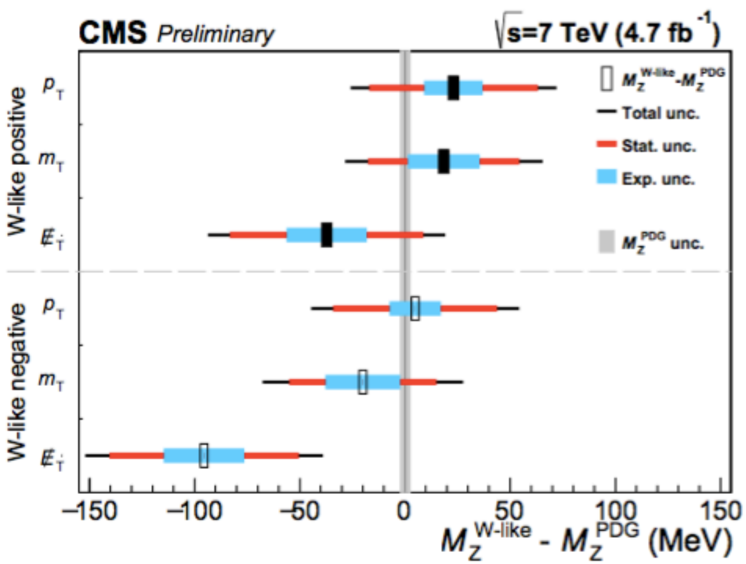
To the heart of EW



CMS and ATLAS need large stats to overcome initial pp state dilution of charge asymmetry, but there is no show stopper to aim to match the precision of LEP/SLD and possibly contribute to the understanding of the A_{FB} vs A_l discrepancy
Will be hard , might take generations of students..but probably worth it

The big challenge: M_W

- The goal of matching or even exceeding the Tevatron precision for M_W (16 Mev) has been a dream since the beginning of LHC…
- The dream (after few generations of students and given the potential for theoretical progress in Eweak corrections calculation) might become true: recent exercise to calculate M_Z using M_W like approach seems to indicate that the quality of the LHC detectors (and especially of its tracking) are such that the goal of matching/exceeding the precision of Tevatron is not out of reach. Eweak corrections precisions at the level a few MeV are as well in sight.



$$M_Z^{W\text{like}} = 91206 \pm 36\ (\text{stat.}) \pm 30\ (\text{syst.})\ \text{MeV}$$

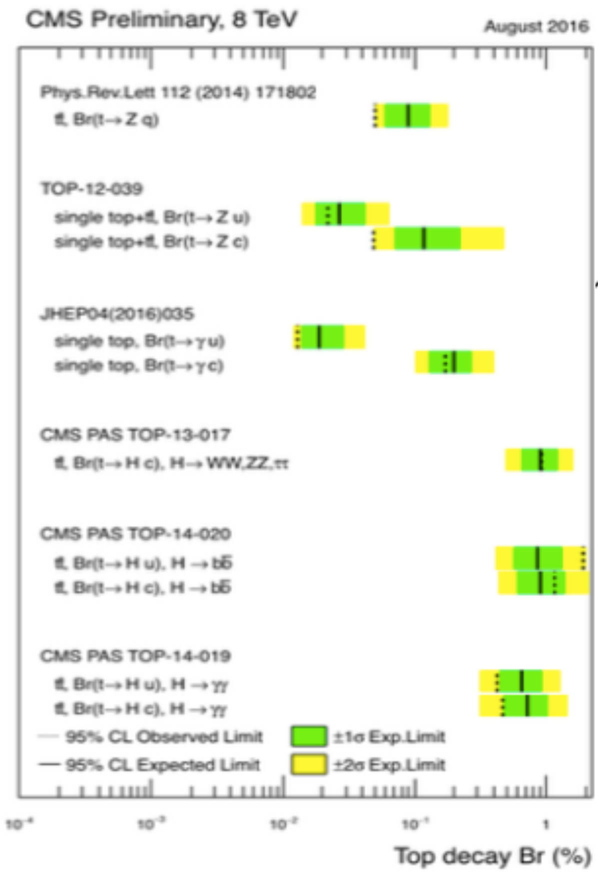
Vector Boson Scattering

- VBS will be an area of measurement until the end of LHC
- Besides a closure test of the Standard model is also one of the precision physics measurement with the highest potential to unveil BSM hints
  - It will give access to possible anomalous triple and quartic Gauge couplings
  - Longitudinal W scattering is the key verification to see if the Higgs alone is sufficient to regularize the possibly divergent cross section
- Understanding the SM behaviour of VBS will also be a major asset in many searches which are using VBS production of new physics to beat down the backgrounds

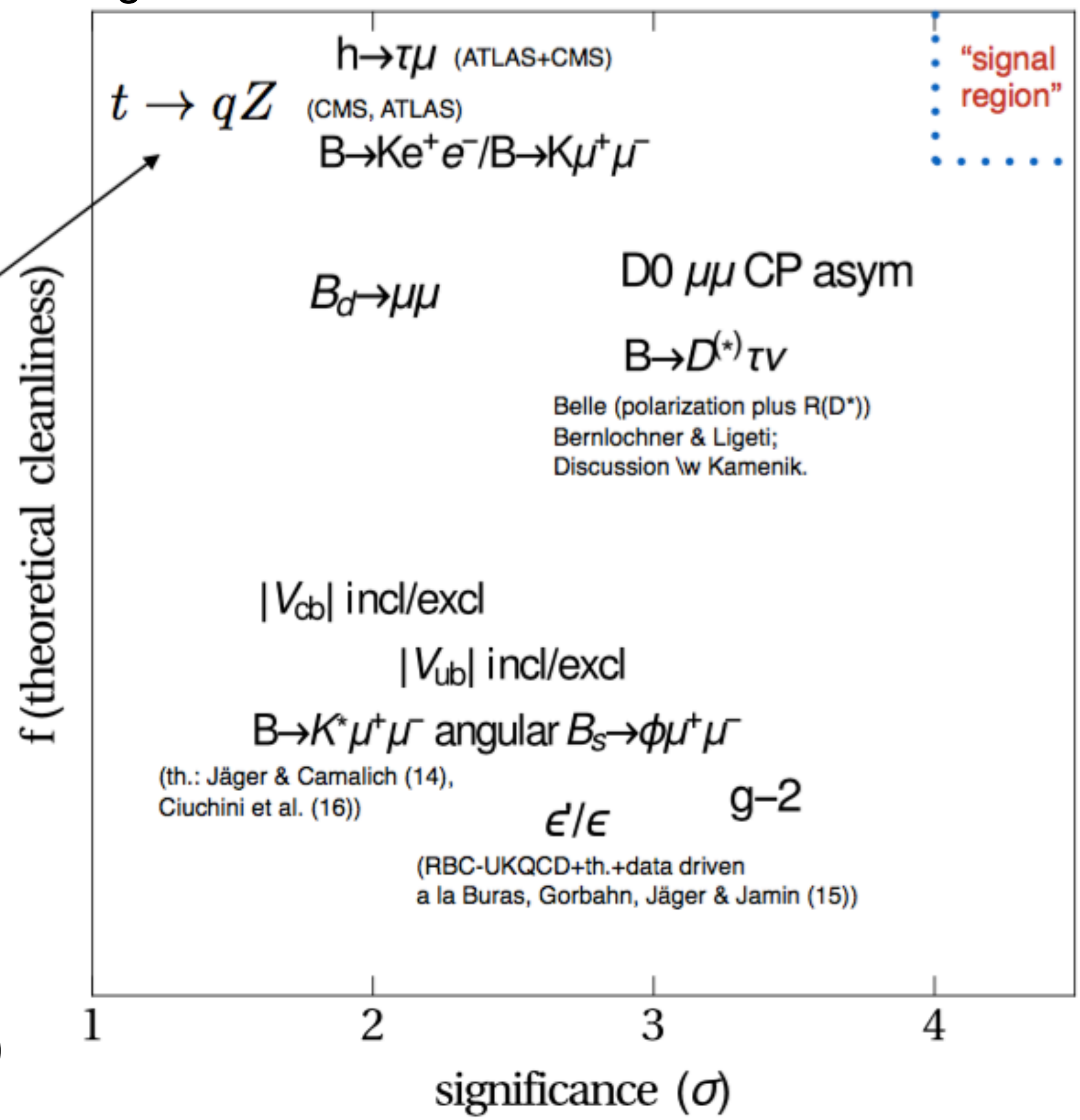
Exploiting the TOP factory

- Exploring the coupling of the Top to W, Z,H and analyze it in the framework of EFT deviations
- improve precision of (differential) top quark production cross-sections, also in multiple dimensions, to constrain PDFs and to continue to be a driving force and testing ground for new improved higher-order QCD calculations and sophisticated new MC generators
- look for rare production processes, such as tttt or even 6-top production
- The staggering statistics can be appreciated if one thinks that at 3 ab^{-1} will have order of 10^8 events triggered with one top fully reconstructed and charge-tagged and can do
  - look for FCNC in rare decays such as t-->Zq , t-->Hq
  - Will have 10^7 W to τ decays (can study lepton universality in W decays)
  - Can study W to charm decays
  - Study rare W decays
  - Have a sample of 10^8 charged tagged b hadrons

Flavour: the land of fluctuations



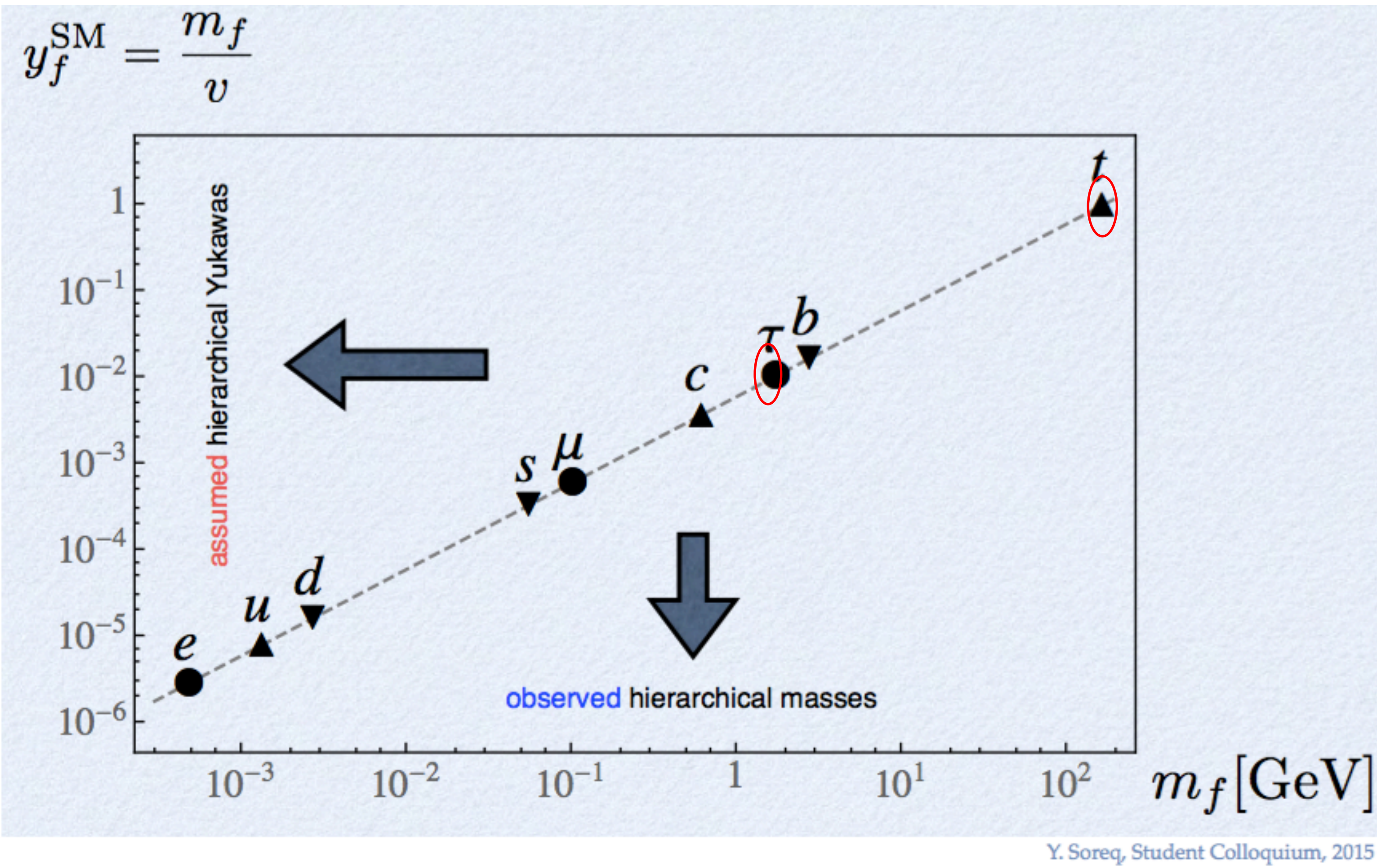
Ligeti: 1606.02756



Modified Ligeti Plot from
Gilad Perez (SEARCH 2016)

Flavour: studying the origins

Is this the right picture ?
For τ and top so far ~ ok
μ_τ=1.1±0.24
μ_{top}~ 2.0±0.4 (theory comb ATLAS-CMS)



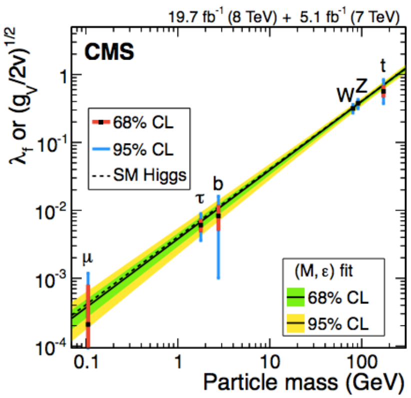
Higgs physics

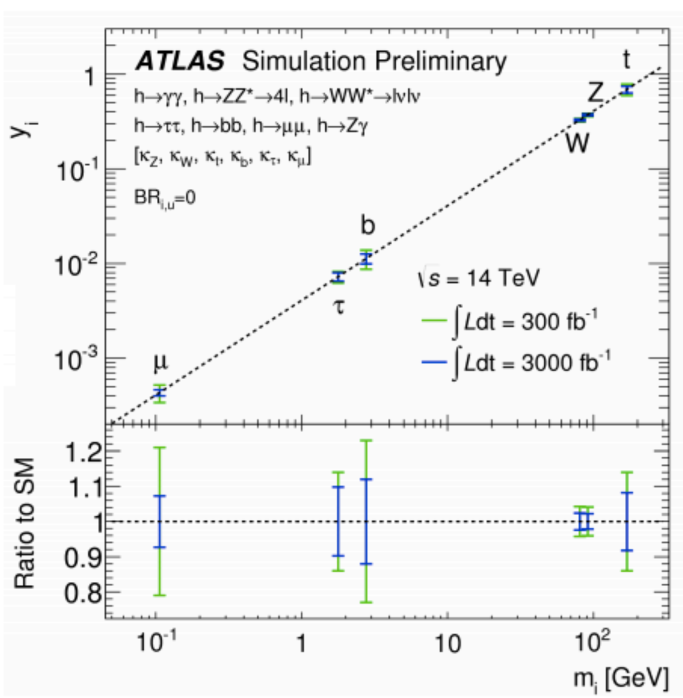
- Higgs physics and Std Model measurements are the main program of the LHC future
- Obviously we are keen to be sensitive to new physics: this can be achieved by precision or by looking in areas of increased sensitivity
- Production calculation precision improved a lot

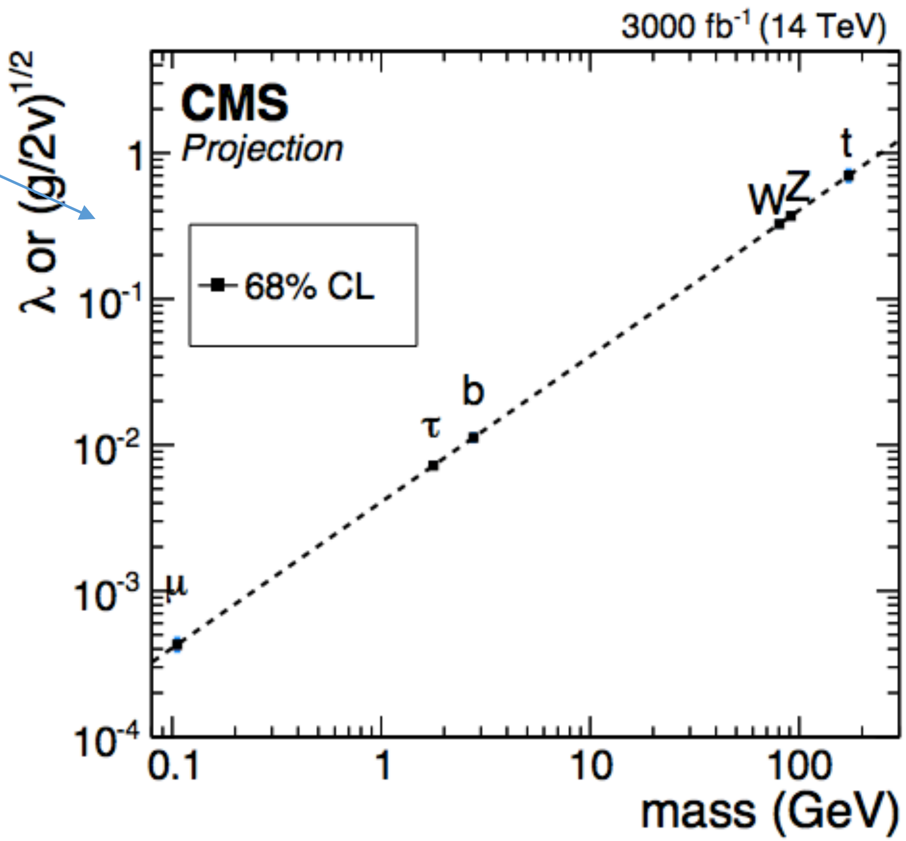
H+0 jet	N^3LO	O(3-5 %)	10 pb	fully inclusive
H+1 jet	N^2LO	O(7%)	7 pb	fully exclusive; Higgs decays, infinite mass limit
H+2 jet	NLO	O(20%)	1.5 pb	matched/merged
H+3 jet	NLO	O(20%)	0.4 pb	matched/merged/almost
WBF	N^2LO	O(1%)	1.5 pb	exclusive, no VBF cuts
WBF	N^2LO	O(5%)	0.2 pb	exclusive, VBF cuts
ZH, WH	N^2LO	O(2-3%)	O(1) pb	decays to bottom quarks
ttH	NLO	O(5%)	0.2pb	decays, off-shell effects

Higgs Physics precision

We want to go from this to this



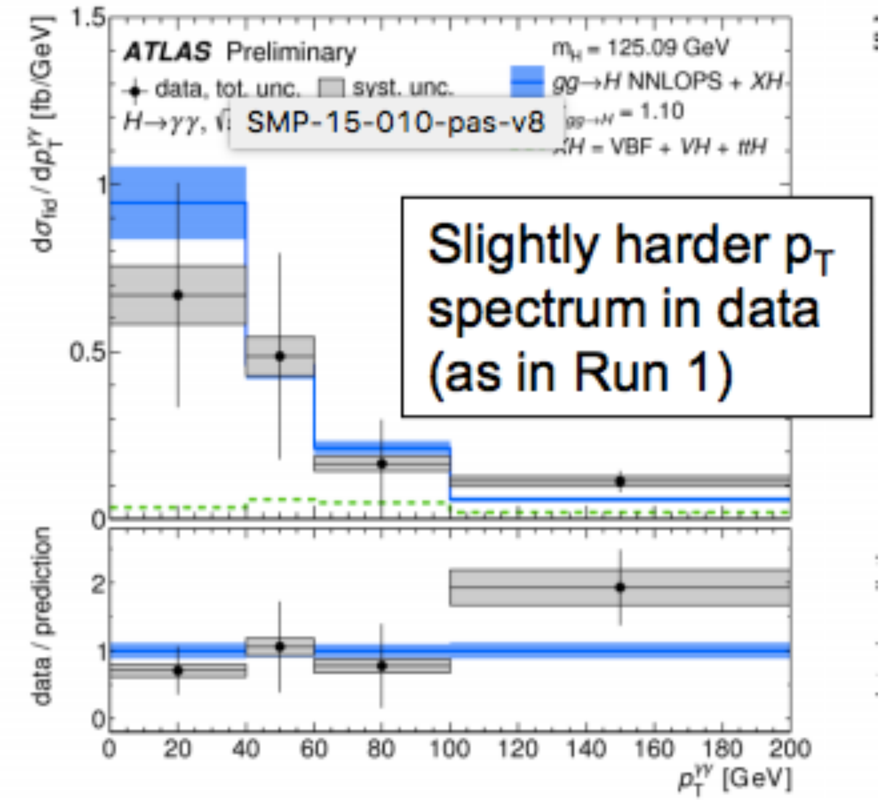




But seeing new physics will be hard …

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Higgs Physics precision

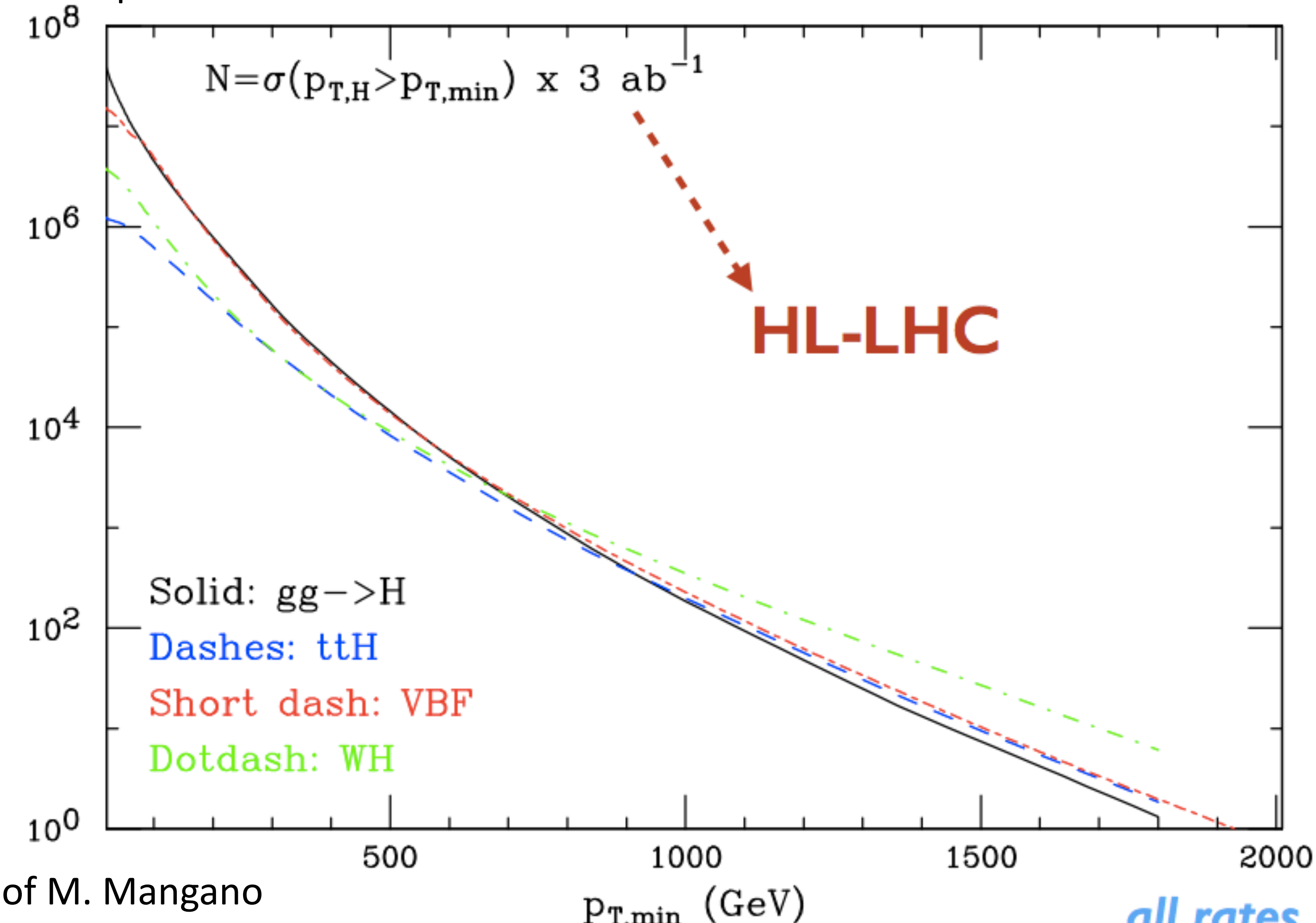


Differential distributions might reveal deviations: statistics (300 fb^{-1}) will start probing expected values

Higher statistics will improve systematics understanding, allow better S/N selections etc.

Higgs Physics High sensitivity

High Pt might reveal surprises and is directly sensitive to production mechanism

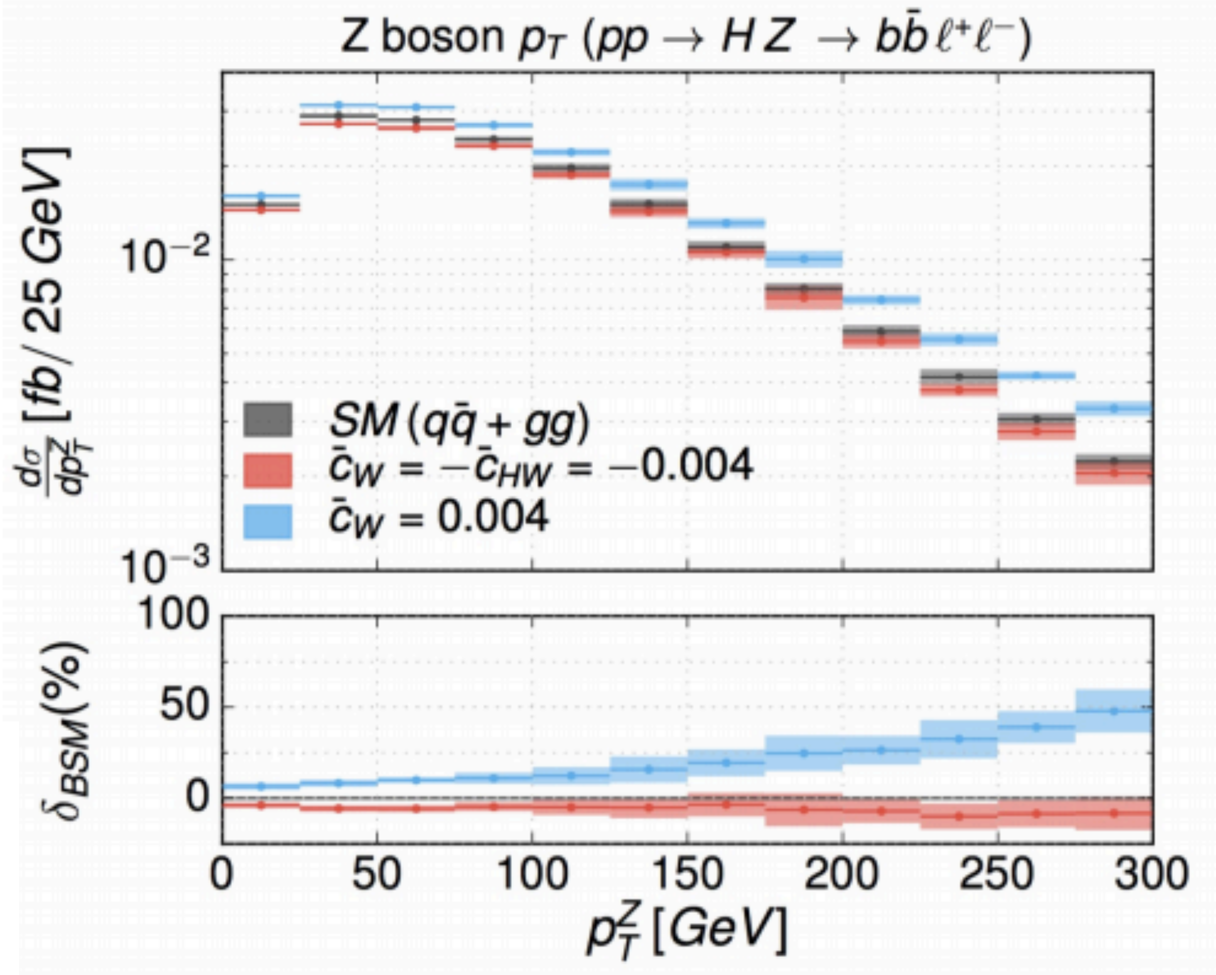


Courtesy of M. Mangano

all rates LO

Higgs physics High sensitivity

Sensitive to Higher Dim operators



Mimasu, Sanz, Williams, arXiv:1512.02572v

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

Di higgs search

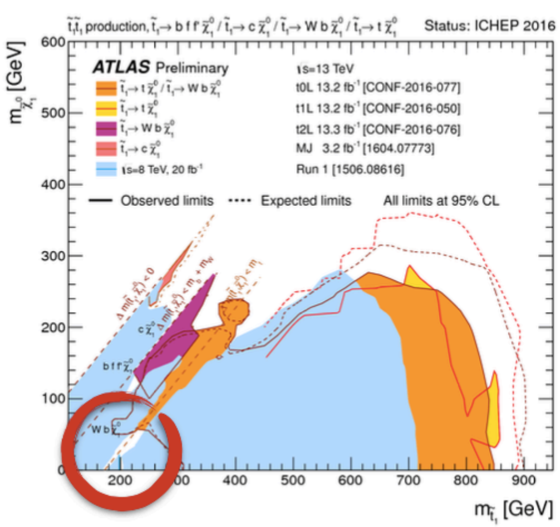
- A key measurement for the global LHC program …
- Good coverage by the experiment already now: good perspective for the future

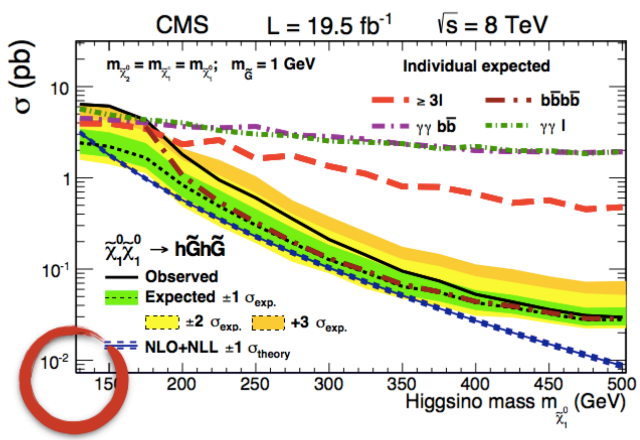
	Resonant	Non-resonant
bbbb	CMS ATLAS	CMS ATLAS
bbττ	CMS	CMS
bbWW	CMS	CMS
bbγγ	CMS ATLAS	CMS ATLAS
γγWW	ATLAS	ATLAS

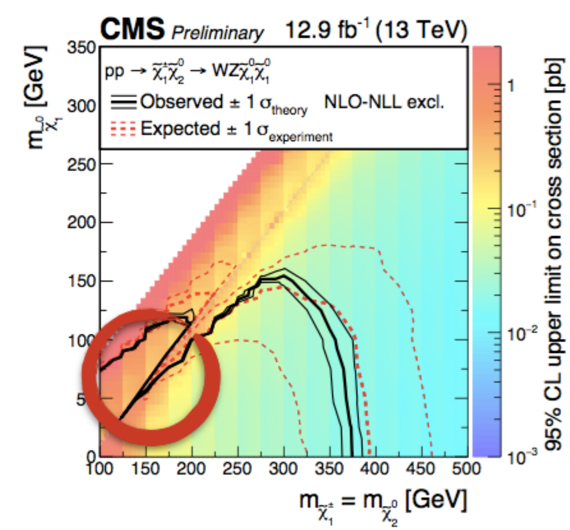
CMS PAS released just after ICHEP   CMS New for ICHEP!

SUSY

- There are no low hanging fruits
- Why is it still a favored BSM scenario?
  - Hierarchy Problem
  - Gauge Coupling Unification
  - WIMP miracle
- Strong SUSY production is close to saturate limits, electroweak still being explored
- Holes remaining in ’degenerate areas’ (e.g. stop degenerate with top): may be discovery is hidden in high precision SM measurements?



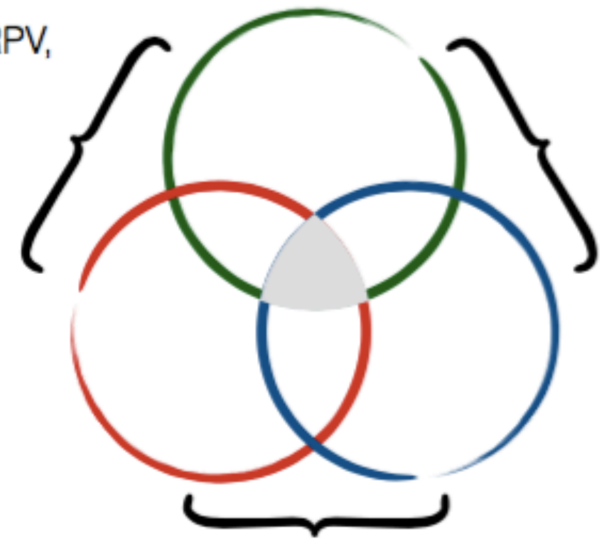




SUSY

Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>



Naturalness & Dark Matter

- Additional states near weak scale (sgluon, KK resonances, …)
- Higgs properties
- <Your idea here>

Unification & Dark Matter

- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Borrowed from N. Craig, SEARCH 2016

scenari

- In NM1, the sleptons are light, with $m(\tilde{\ell}_L) \approx m(\tilde{\tau}_1) \approx 430\,\text{GeV}$, and furthermore $m(\tilde{\chi}_1^0) < m(\tilde{\ell}_L) < m(\tilde{\chi}_2^0)$. (In NM2 and NM3, the sleptons are effectively decoupled.) This pattern of neutralino and slepton masses leads leads to the $m_{\ell^+\ell^-}$ dilepton edge signature originating from the cascade process $\tilde{\chi}_2^0 \to \tilde{\ell}_L^{\pm}\ell^{\mp}, \tilde{\ell}_L^{\pm} \to \ell^{\pm}\tilde{\chi}_1^0$. (The direct decays $\tilde{\chi}_2^0 \to \text{Z/H}\tilde{\chi}_1^0$ are suppressed by a small mass splitting between the two neutralinos.)
- In NM2, both $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ are Wino-like, with masses around 530 GeV, leading to a large $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ pair production cross section. For the $\tilde{\chi}_2^0$, the decay $\tilde{\chi}_2^0 \to \text{H}\tilde{\chi}_1^0$ is dominant, while $\tilde{\chi}_1^{\pm} \to \text{W}^{\pm}\tilde{\chi}_1^0$ has a 100% branching fraction. These decays provide a powerful signature that can be used to search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production.
- In, NM3 the LSP $\tilde{\chi}_1^0$ is higgsino-like with a mass of around 200 GeV, and the dominant $\tilde{t}_1$ decays are $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $\tilde{t}_1 \to t\tilde{\chi}_2^0$. This leads to a spectacular signature for gluino pair production with four top quarks and large $\not\!\!E_T$.

10.3.2.2 Stau coannihilation model (STC)

In the stau coannihilation model [258], all of the sleptons and sneutrinos are light, and the $\tilde{\tau}_1$ and $\tilde{\chi}_1^0$ masses are nearly degenerate, with $m(\tilde{\tau}_1) = 194\,\text{GeV}$ and $m(\tilde{\chi}_1^0) = 187\,\text{GeV}$). The mass degeneracy of the $\tilde{\tau}_1$ and the $\tilde{\chi}_1^0$ allows efficient co-annihilation of dark matter to lower the predicted relic density to its observed value.

10.3.2.3 Stop coannhilation model (STOC)

The stop coannihilation [259, 260] model STOC is also formulated in the cMSSM parameter space. In this model, $m(\tilde{t}_1) \approx 400\,\text{GeV}$ is very low, and the top squark is nearly degenerate with the $\tilde{\chi}_1^0$, which is bino-like. As a consequence, the direct top squark pair production cross section is enormous, $\sigma(\tilde{t}\tilde{t}^*) \approx 2.1$ pb. The top squark decays are effectively invisible, however, because they proceed via the loop process $\tilde{t} \to c\tilde{\chi}_1^0$, in which the daughter charm jet is extremely soft due to the small mass splitting between $\tilde{t}_1$ and $\tilde{\chi}_1^0$. Nevertheless, if the $\tilde{t}_1$-pair system is boosted against a hard jet from initial-state radiation, the process is experimentally accessible in the single jet + $\not\!\!E_T$ signature, as in monojet searches [261].

Discovery can come early …or late

Explored:

- 9 different experimental signatures.
- 5 different types of SUSY models.

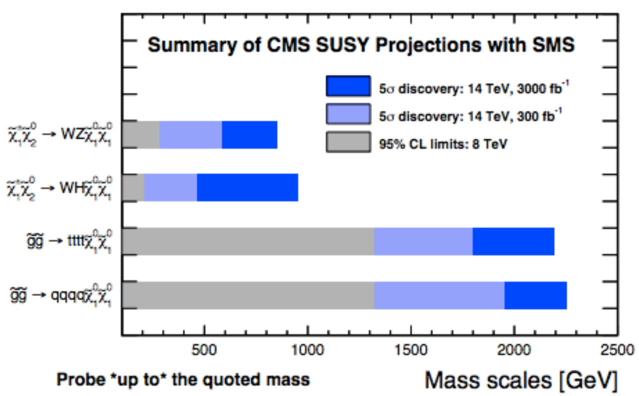
There are scenarios where the full statistics of Hi Lumi LHC will be needed to reach 5σ

Exploring SUSY model space →

Exploring experimental signature space ↓

Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300					
	3000					
all-hadronic (MT2) search	300					
	3000					
all-hadronic $\tilde{b}_1$ search	300					
	3000					
1-lepton $\tilde{t}_1$ search	300					
	3000					
monojet $\tilde{t}_1$ search	300					
	3000					
$m_{\ell^+\ell^-}$ kinematic edge	300					
	3000					
multilepton + b-tag search	300					
	3000					
multilepton search	300					
	3000					
ewkino WH search	300					
	3000					

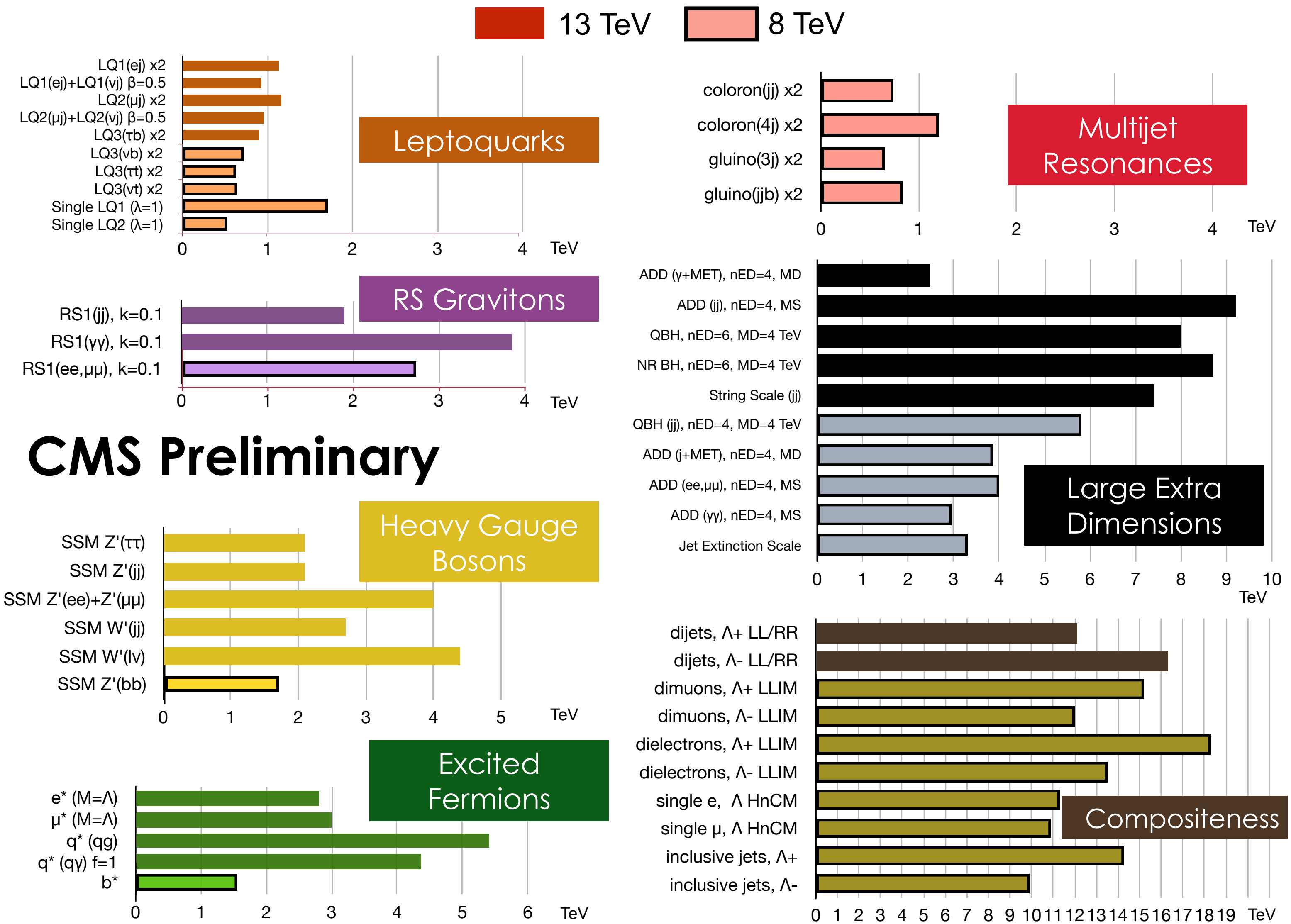
$< 3\sigma$ | $3 - 5\sigma$ | $> 5\sigma$



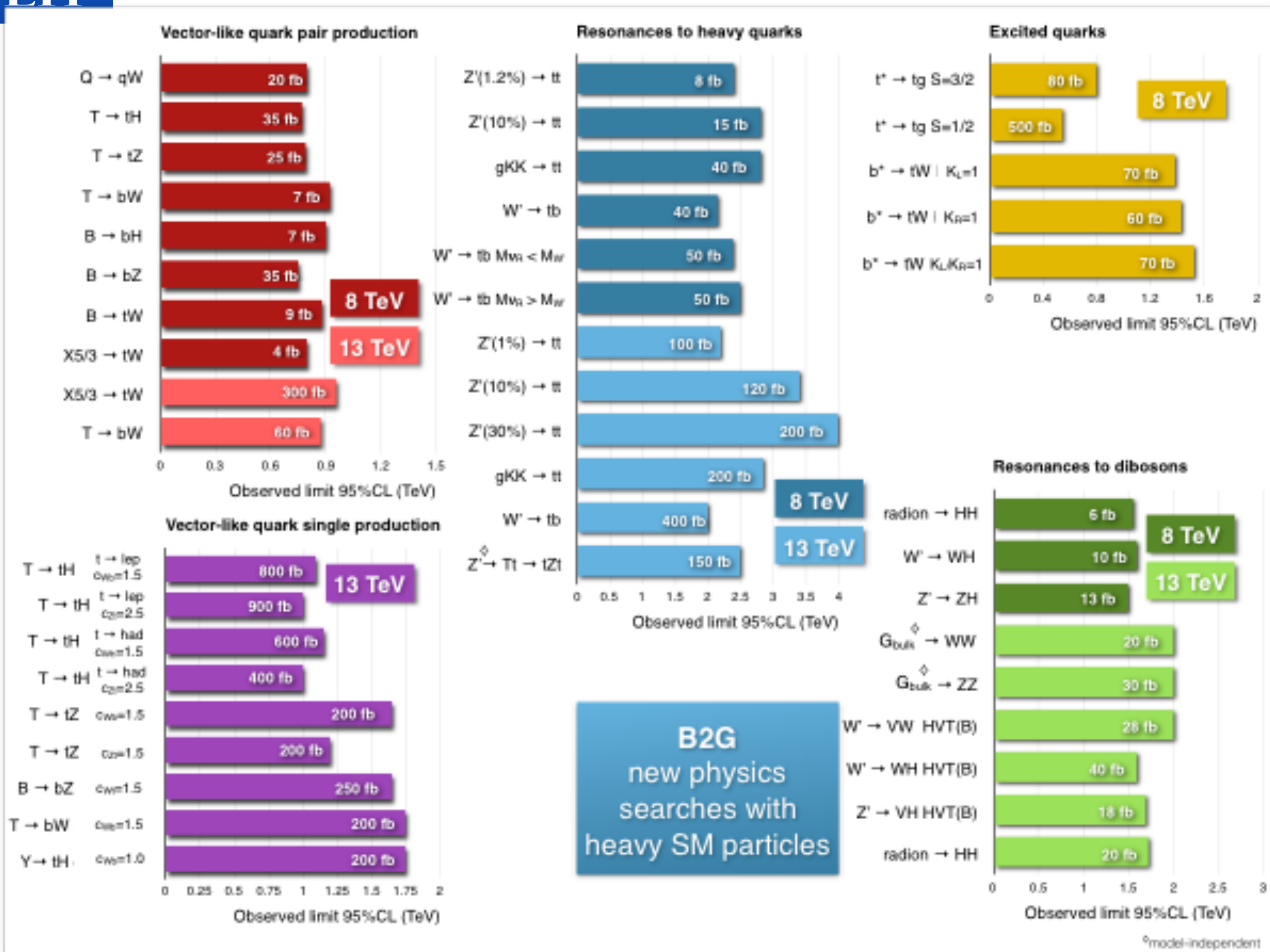
Exotica

- No significant deviations found so far from SM expectation
- Now it is exciting time: integrated lumi doubling times are short and the time until LS2 will be prime time for discoveries
- Major effort will have to put in maintaining sensitivity to long lived particles (decaying far from the vertex , possibly out of the tracker volume)
- Major focus is on Dark matter motivated searches

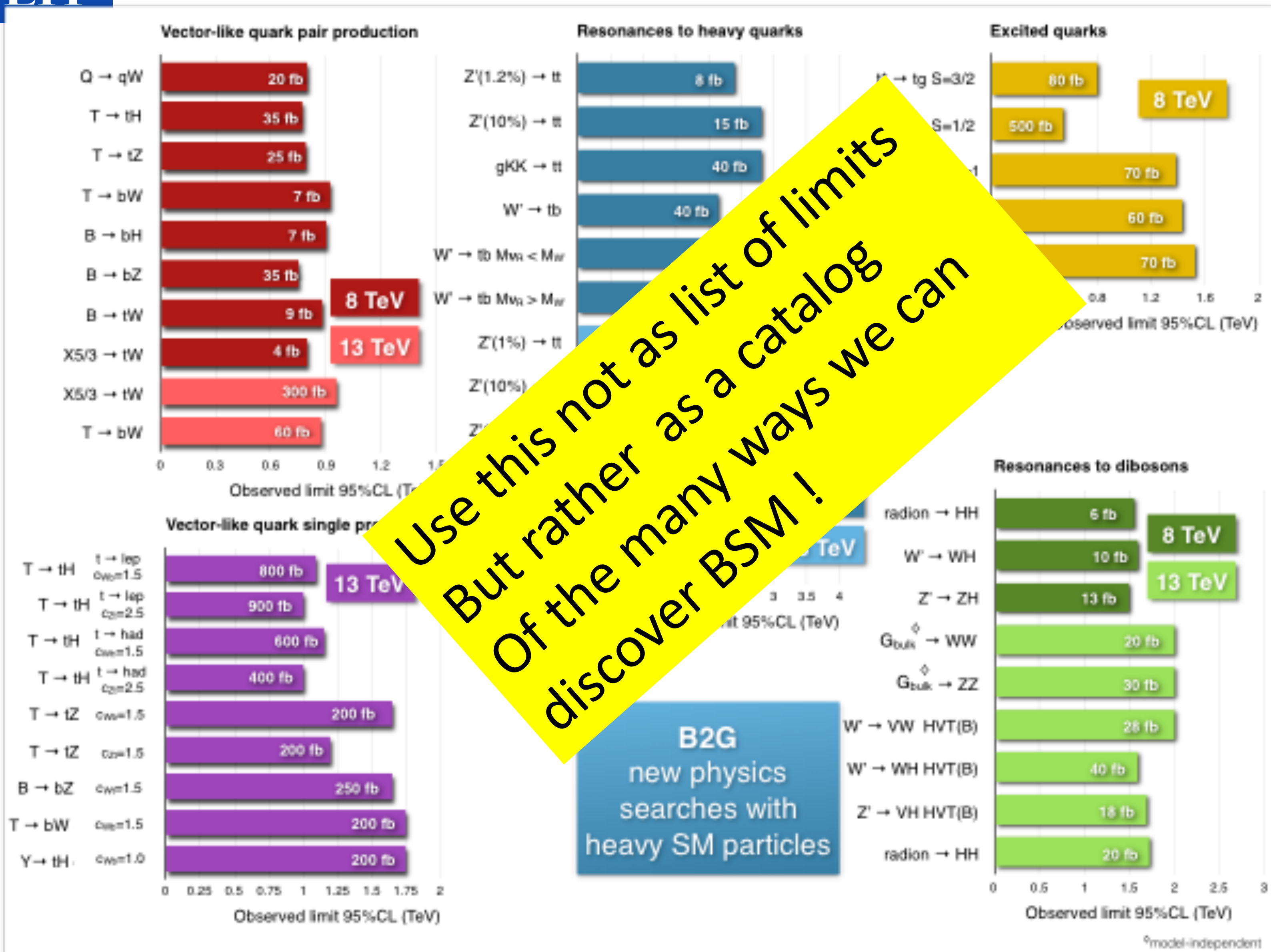
Exotica searches summary (i)



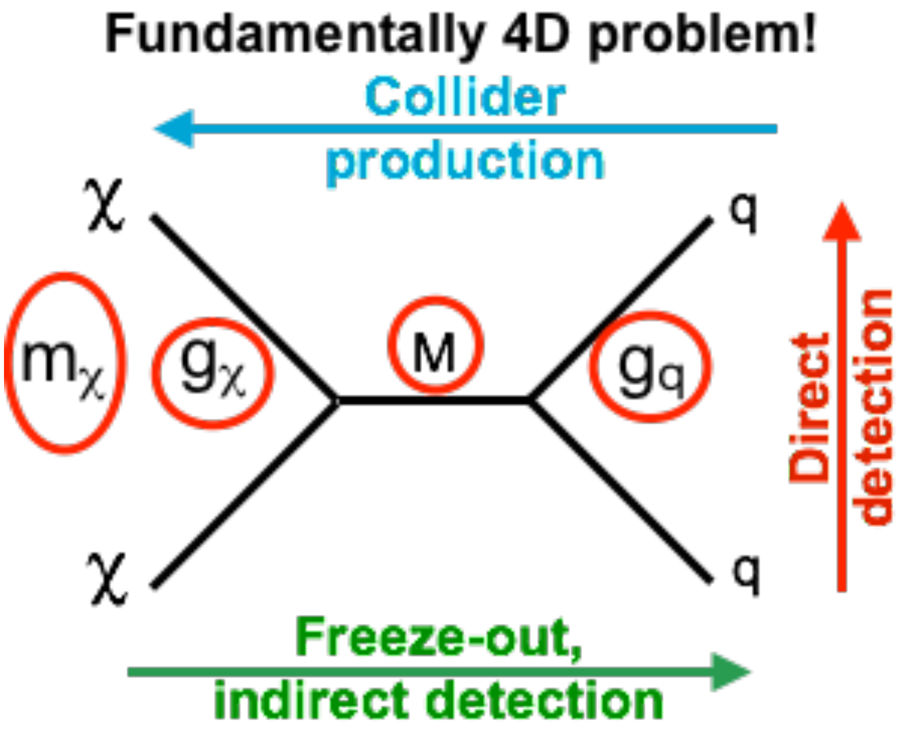
Exotica searches summary ii)



Exotica searches summary ii)



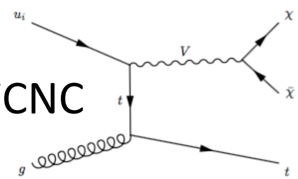
Dark Matter searches

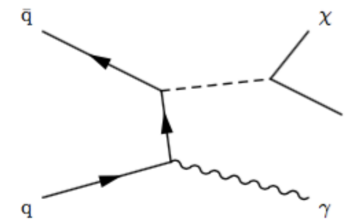


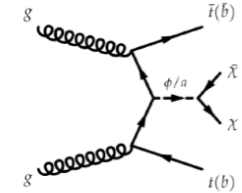
Our search mapped in terms of DM mass and Mediator mass

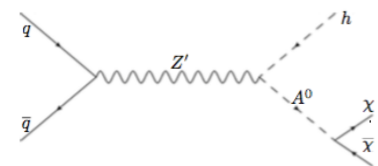
Dark Matter search

FCNC

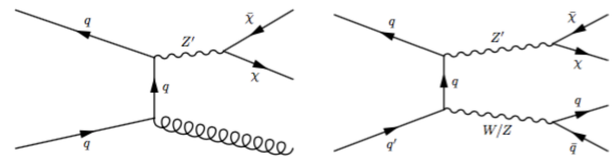


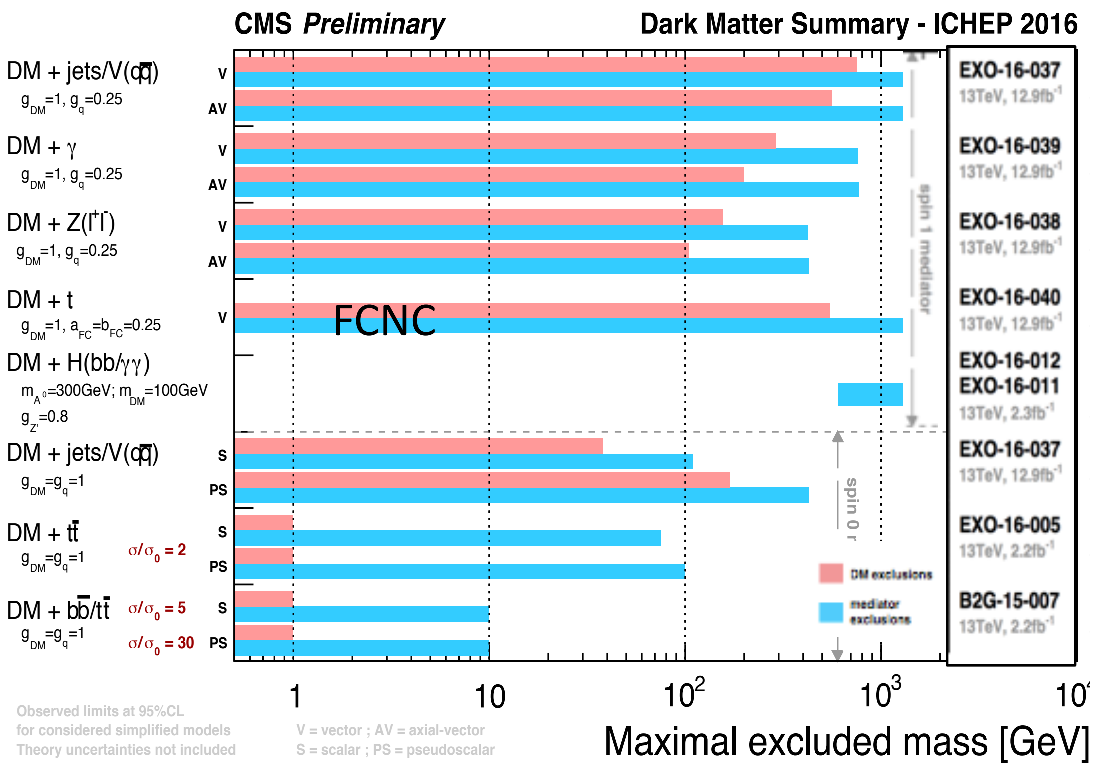


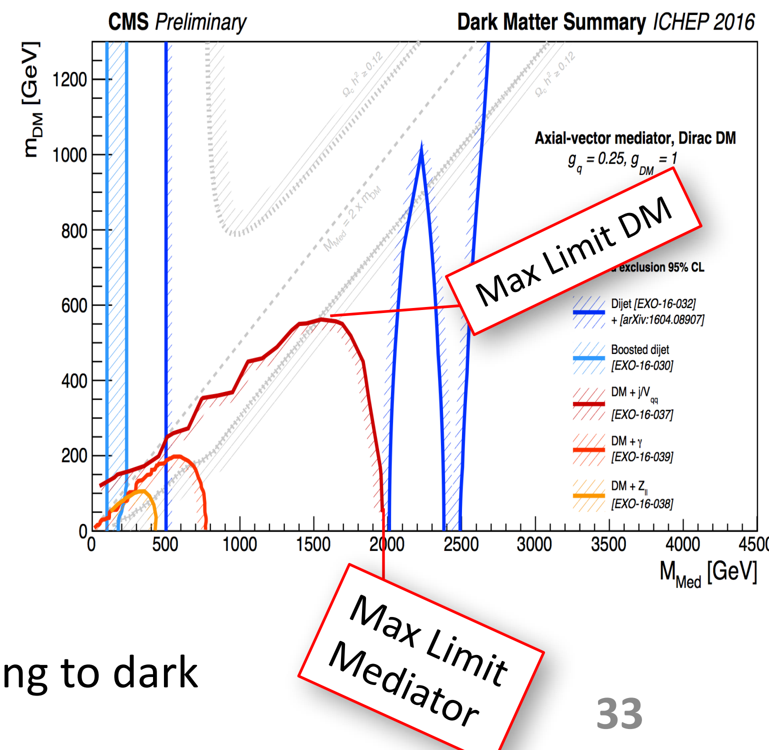




Basic idea: search of mono-object recoiling against MET







Summary of all Dark Matter Searches in Run II

Max and Min Limits on mediator search (blue) decaying to dark matter (red)

Summary

- LHC and the experiments are performing beyond expectations
- The research program is extremely rich:
  - so far the initial measurements of the SM parameters in the new energy ranges have been performed. The recent breakthrough in the theoretical calculations are going to stimulate higher precision measurements
  - The search for new physics has been the main focus of the PP experiments… No success so far, but we have just started scratching the surface of the LHC potential
- The future looks bright: the LHC performance is such that the estimates of Integrated lumi (which a couple of years ago were looking very optimistic) are realistic, and the experiments are collecting data effectively and producing high quality results

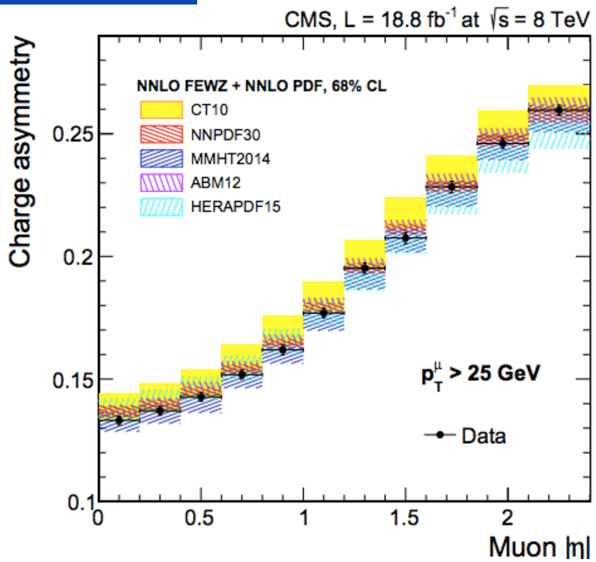
Backup

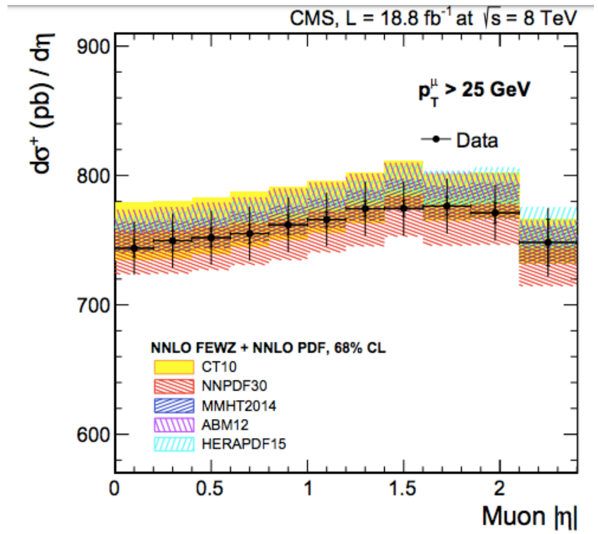
Amazing progress in last years on the theory side: NNLO and N3LO

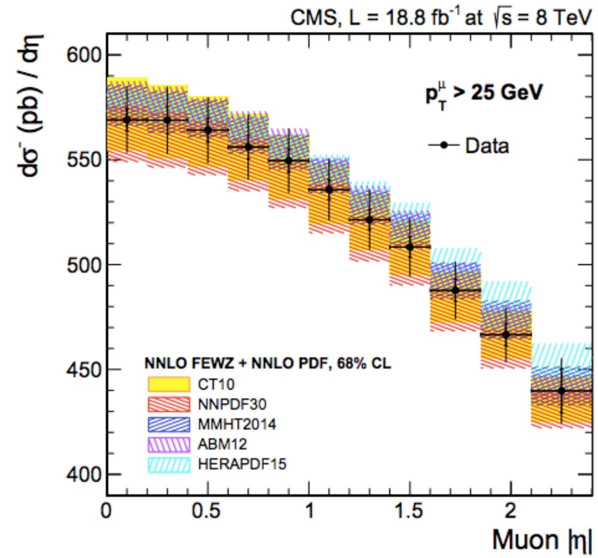
dijets	O(3%)	gluon-gluon, gluon-quark	PDFs, strong couplings, BSM
H+0 jet	O(3-5 %)	fully inclusive (N3LO)	Higgs couplings
H+1 jet	O(7%)	fully exclusive; Higgs decays, infinite mass tops	Higgs couplings, Higgs p_t, structure for the ggH vertex.
tT pair	O(4%)	fully exclusive, stable tops	top cross section, mass, p_t, FB asymmetry, PDFs, BSM
single top	O(1%)	fully exclusive, top decays, t-channel	V_{tb}, width, PDFs
WBF	O(1%)	exclusive, VBF cuts	Higgs couplings
W+j	O(1%)	fully exclusive, decays	PDFs
Z+j	O(1-3%)	decays, off-shell effects	PDFs
ZH	O(3-5 %)	decays to bb at NLO	Higgs couplings (H-> bb)
ZZ	O(4%)	fully exclusive	Trilinear gauge couplings, BSM
WW	O(3%)	fully exclusive	Trilinear gauge couplings, BSM
top decay	O(1-2 %)	exclusive	Top couplings
H -> bb	O(1-2 %)	exclusive, massless	Higgs couplings, boosted

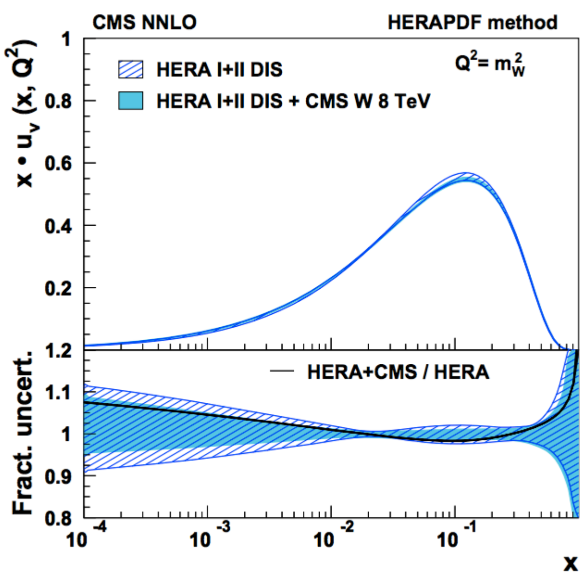
W differential cross section and charge asymmetry (II)

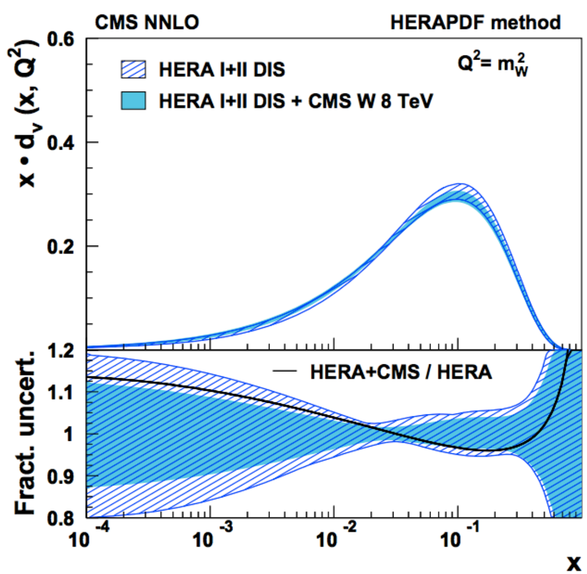
Eur. Phys. J. C (2016) 76: 469.











Drell-Yan differential cross sections

http://dx.doi.org/10.1016/j.physletb.2015.07.065 SMP-13-013

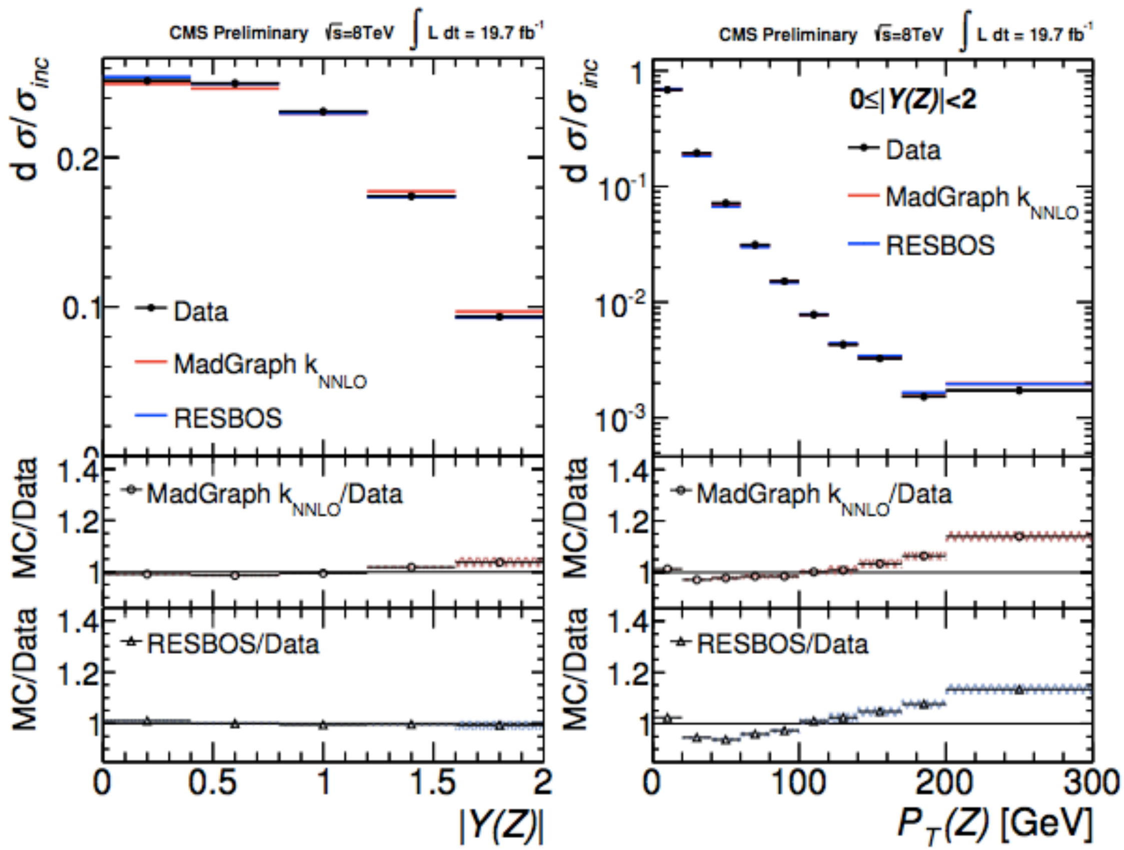
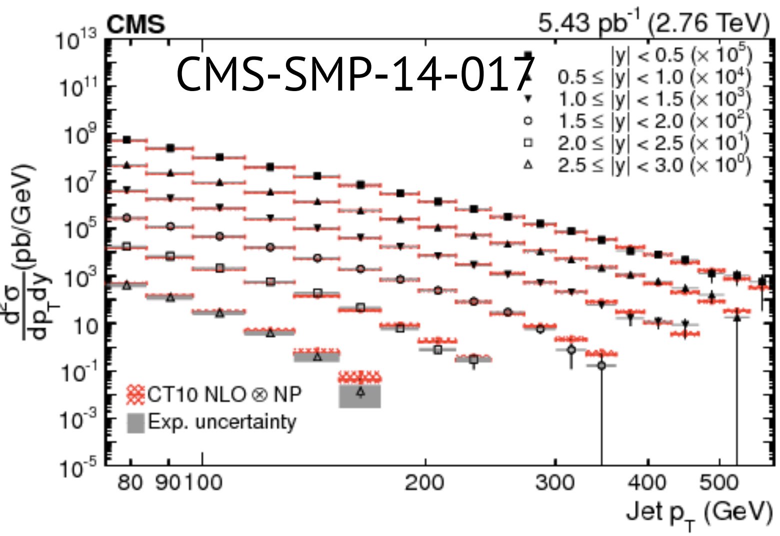


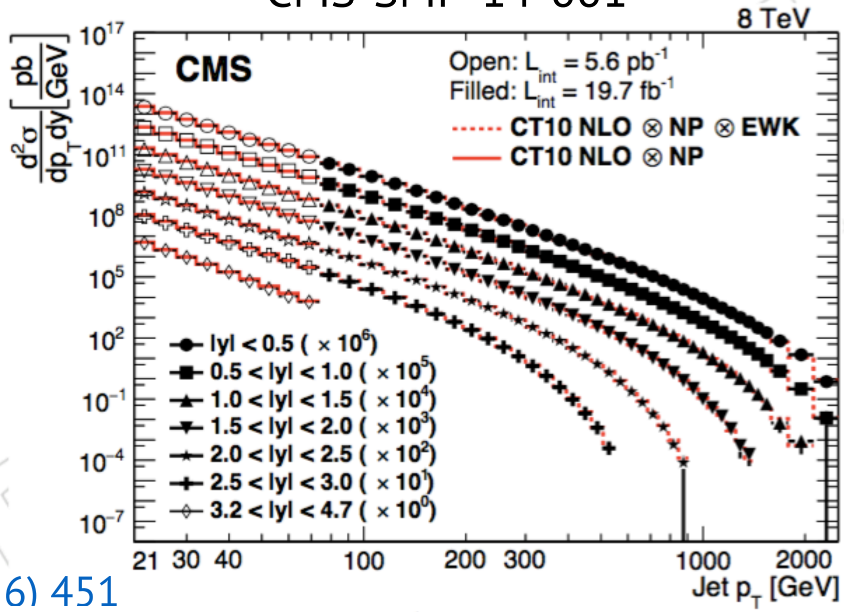
Figure 2: The Z-boson cross section, normalized to the inclusive cross section, as a function of $P_T(Z)$ and $|Y(Z)|$, compared to predictions of simulation from MADGRAPH normalized to NNLO (red symbols) and RESBOS (blue symbols). MADGRAPH uses the CTEQ6L1 PDF and for RESBOS CT10nnlo is used.

Inclusive jet cross section

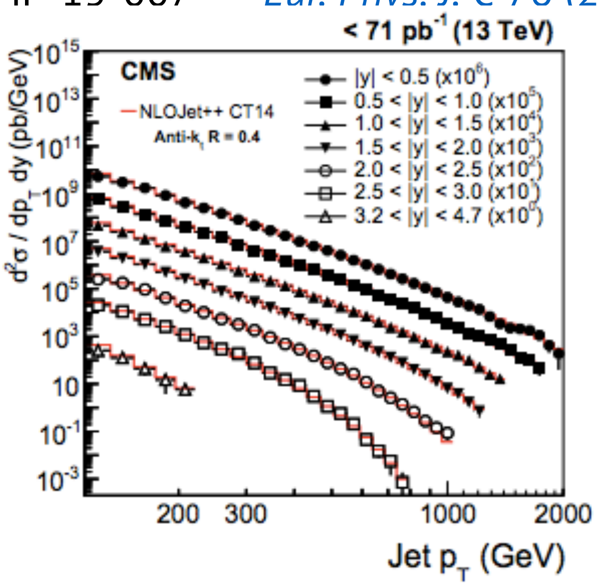
Eur. Phys. J. C 76 (2016) 265

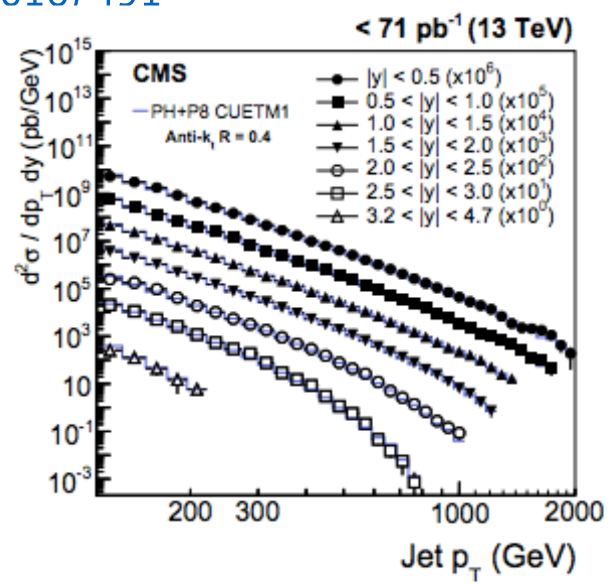


CMS-SMP-14-001

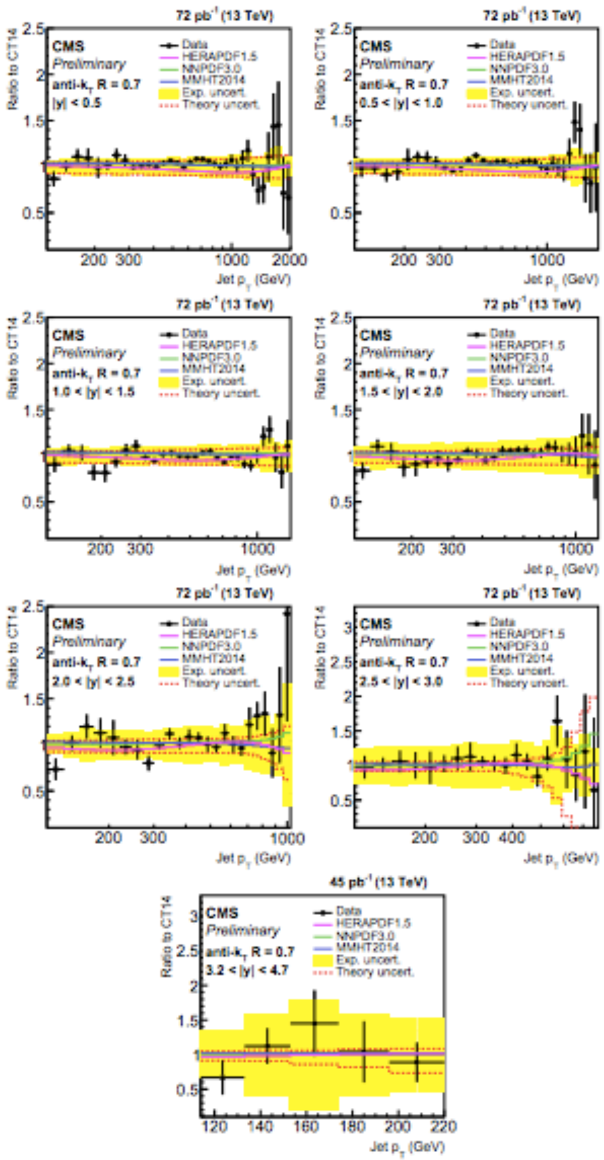


SMP-15-007 *Eur. Phys. J. C 76 (2016) 451*





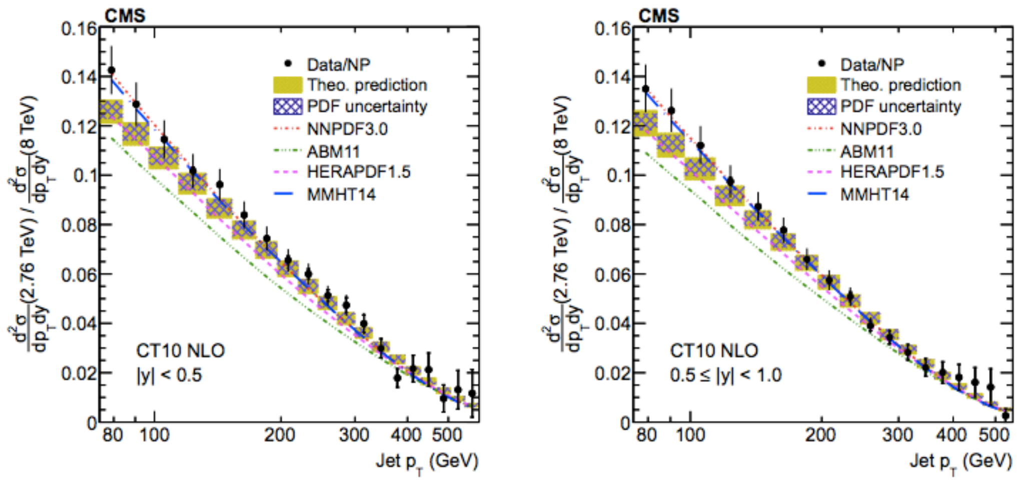
Jet Cross section 13 TeV



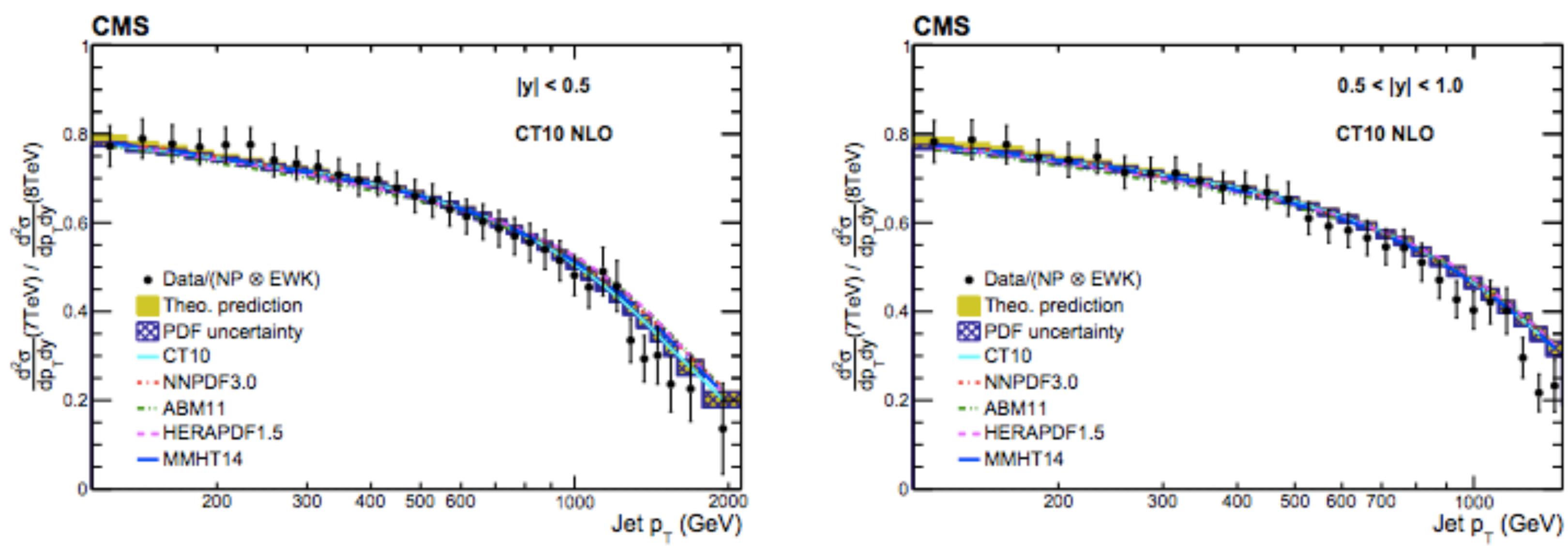
Jet cross sections are understood at High energy as well as at low energy

Jet cross section ratio and α_S

SMP-14-001



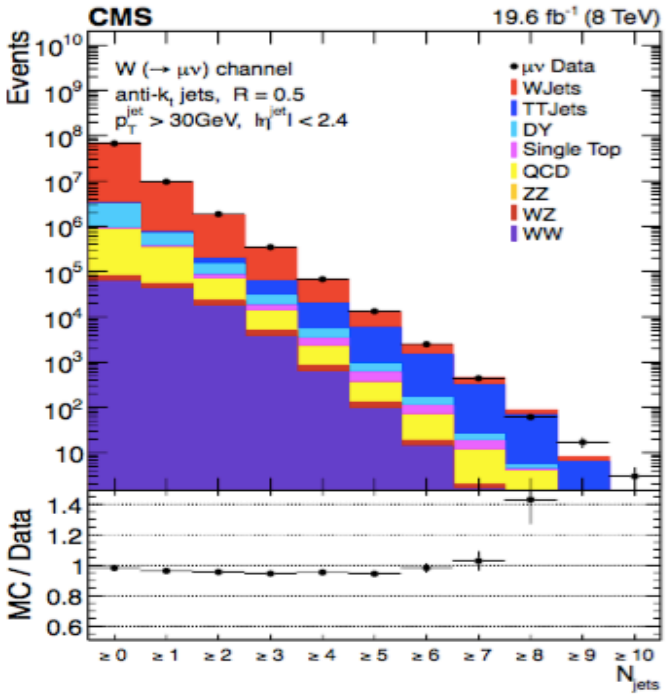
7 TeV/8 TeV

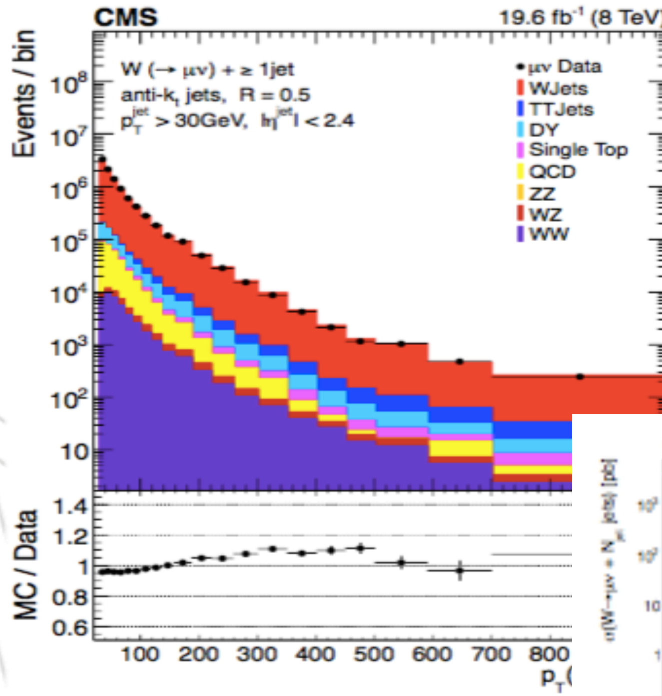


Jet production study (and modelling)

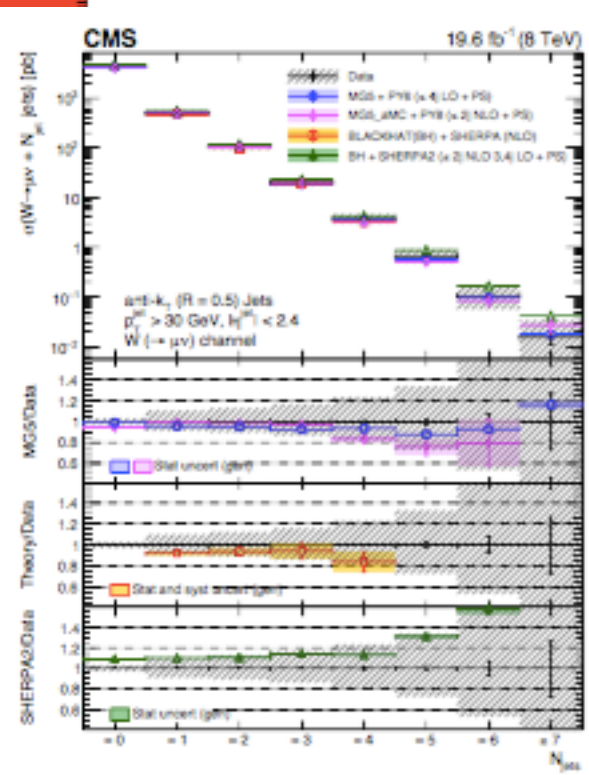
W + jets (8TeV)

SMP-14-023





Leading Jet in W+jet events

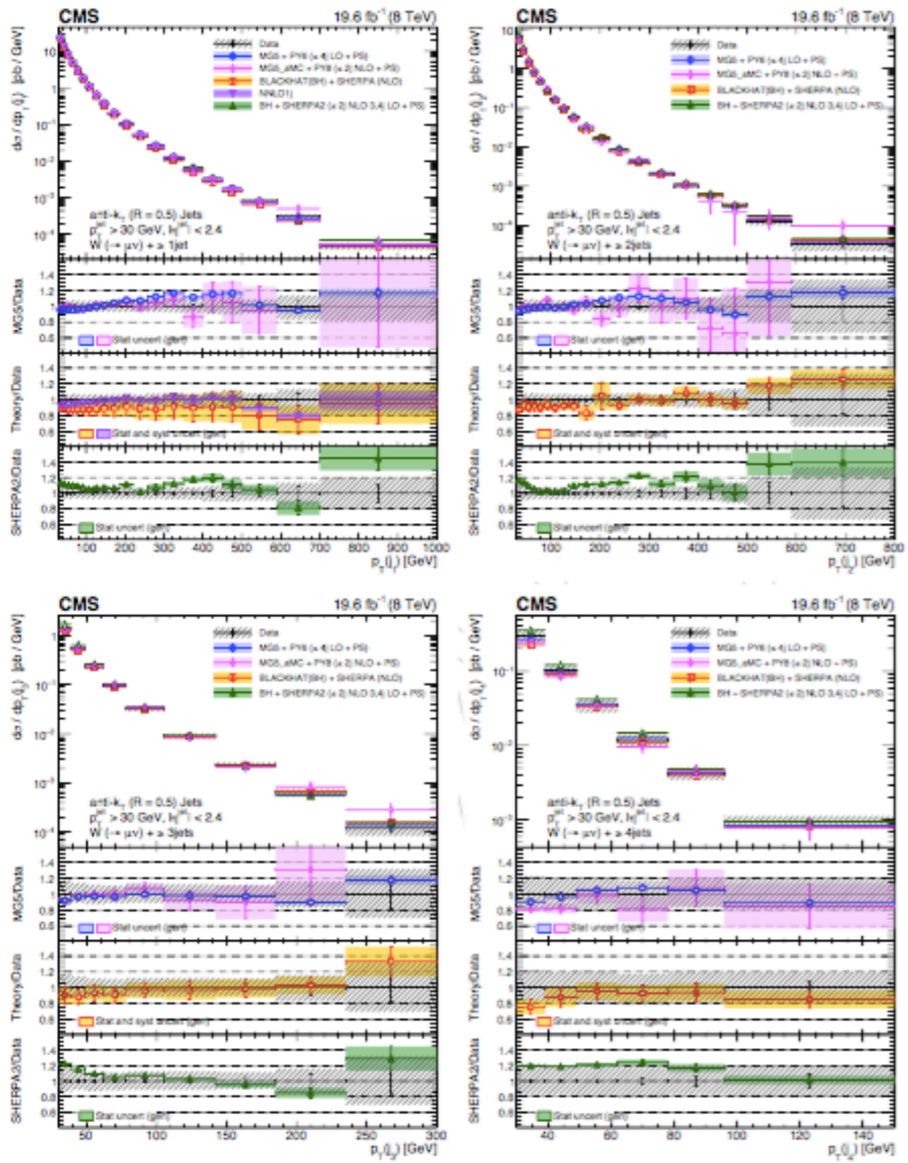


Exclusive Cross section compared
To generators

W + jets (8TeV)

SMP-14-023

Cross sections differential in the transverse momenta of the four leading jets, compared to the predictions of MadGraph, MadGraph5 aMC@NLO, Sherpa 2, Black- Hat+sherpa, and NNLO inclusive one-jet production (indicated as NNLO1j). Black- Hat+sherpa and NNLO1j are corrected for hadronization and multiple-parton interaction effects. Black circular markers with the gray hatched band represent the unfolded data mea- surements and their total uncertainties.

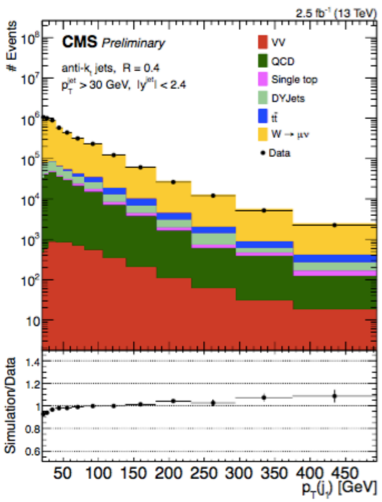


W + jets (13 TeV)

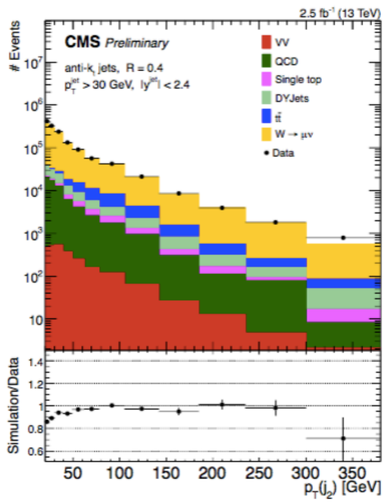
CMS PAS SMP-16-005

Exclusive Cross section

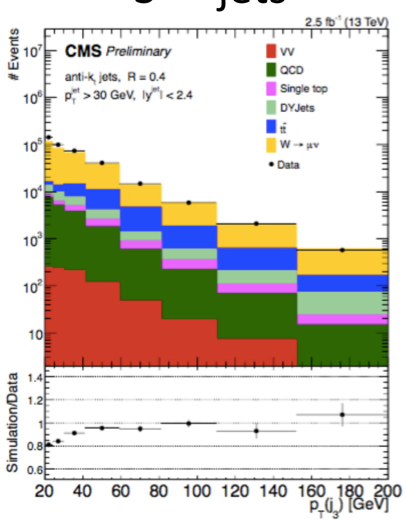
1st jets

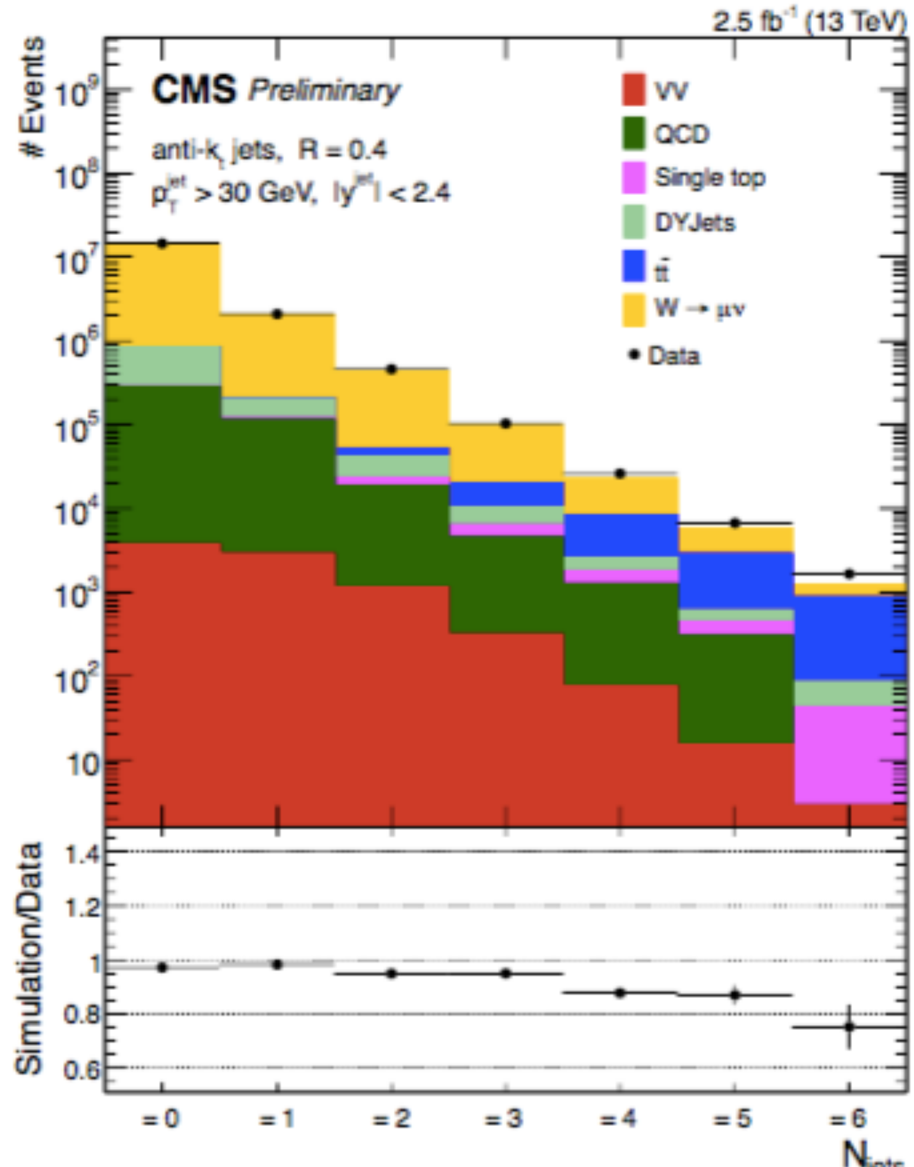


2nd jets



3rd jets



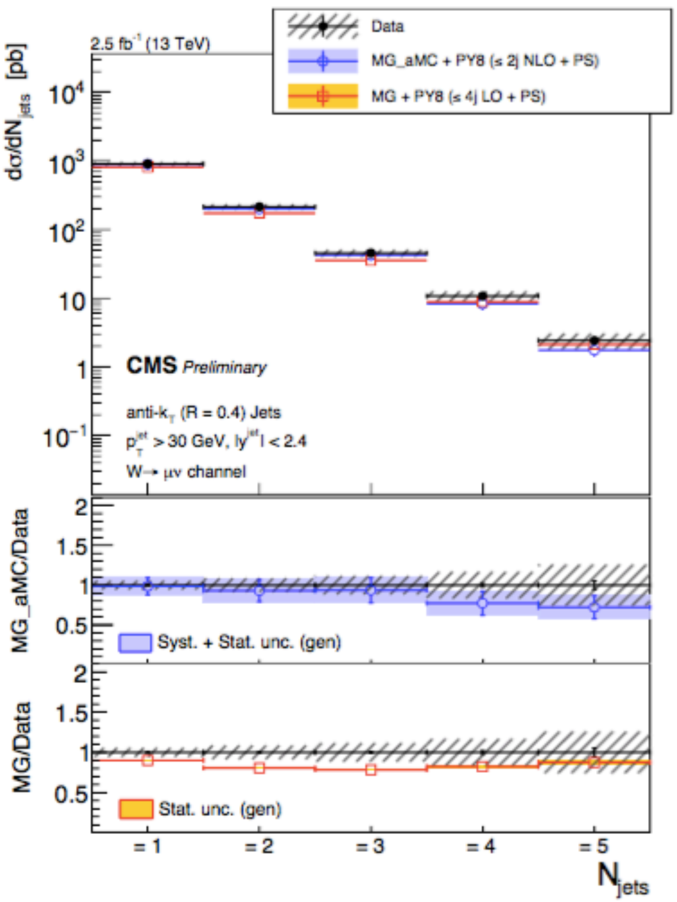


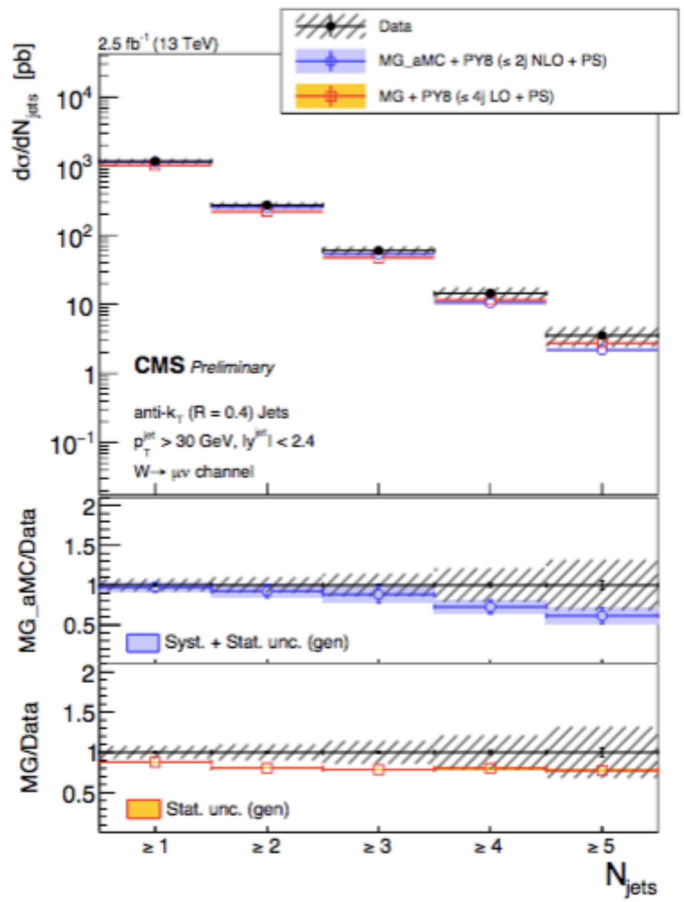
W + jets (13 TeV)

CMS PAS SMP-16-005

Exclusive cross section — Inclusive cross section

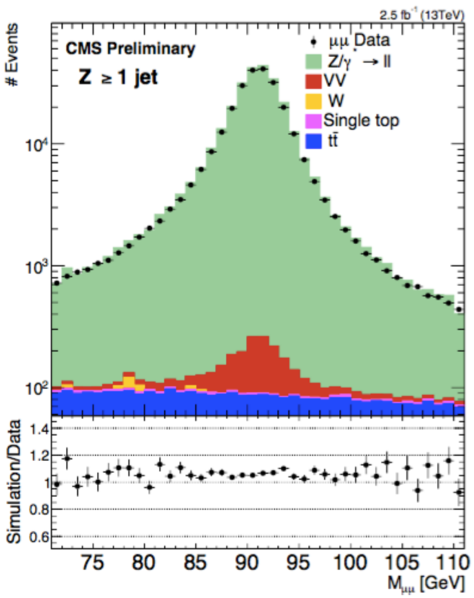
compared to the predictions of MG aMC FxFx and MG aMC

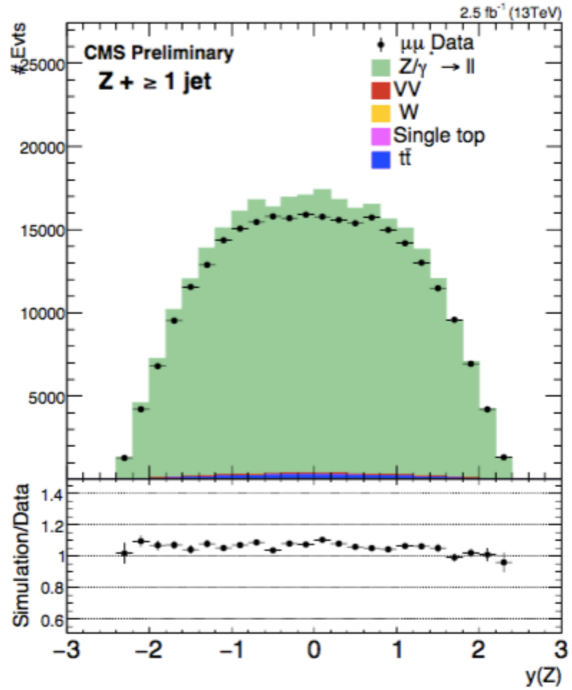


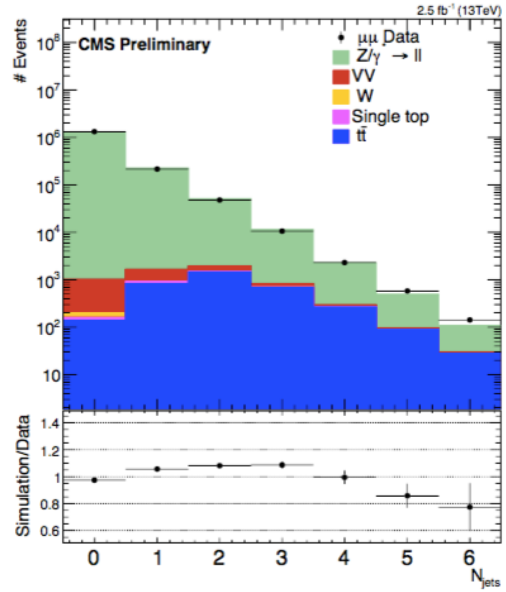


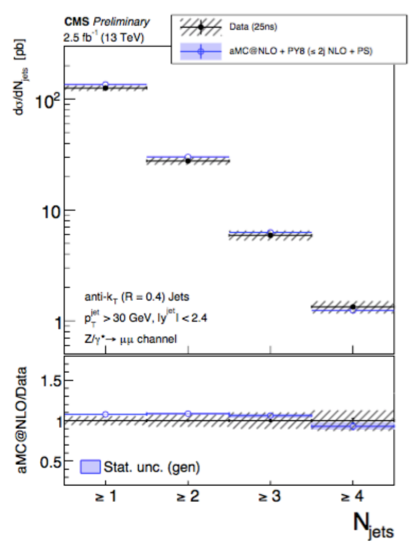
Z+jets (13 TeV)

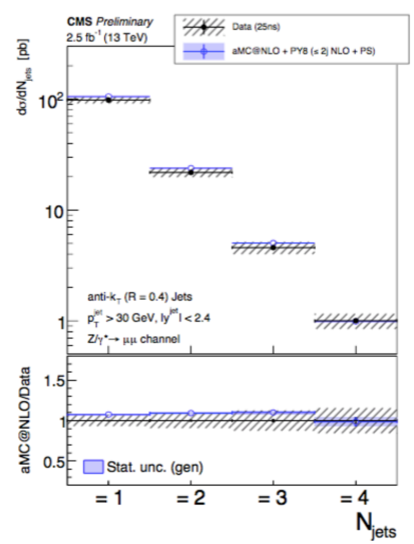
CMS PAS SMP-15-010









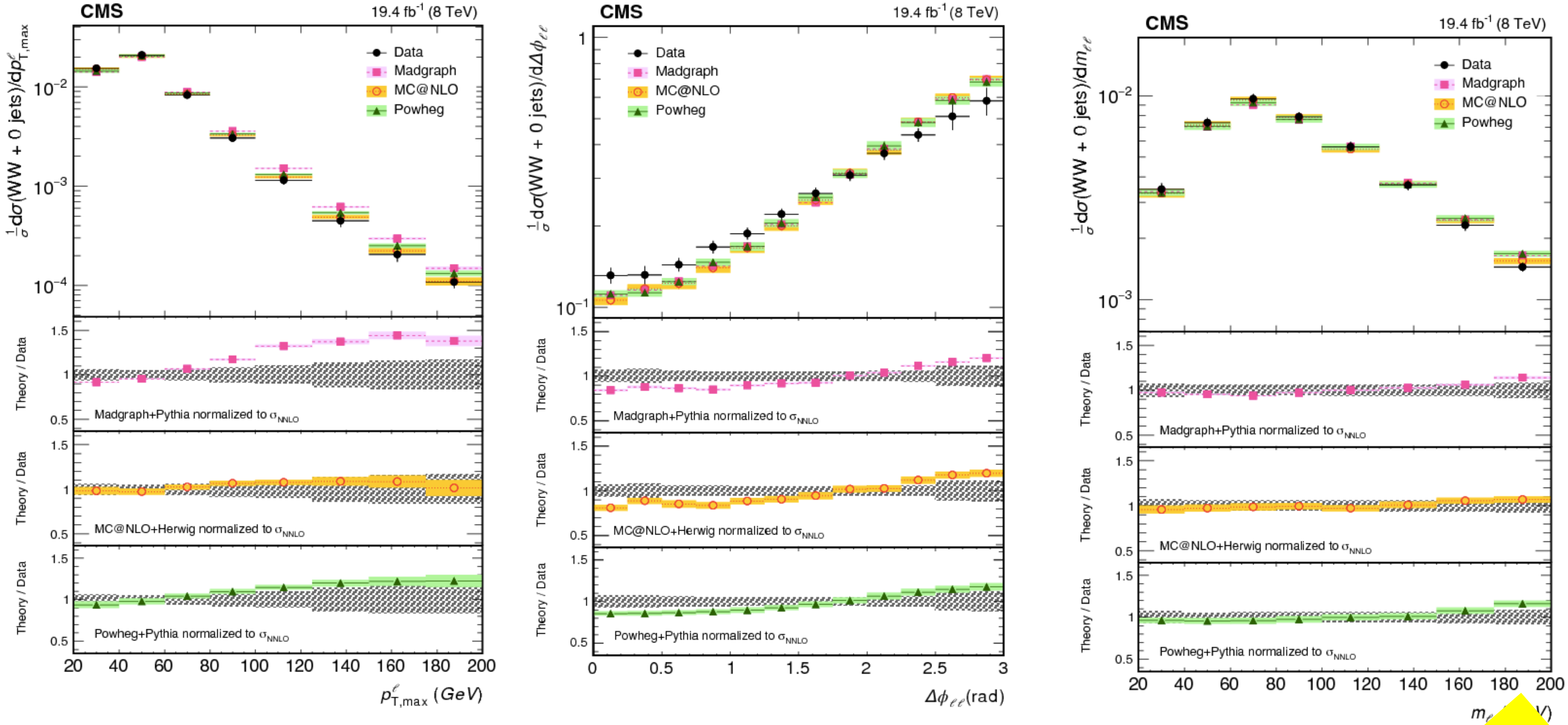


Di-boson cross sections…the success of NNLO

WW (8TeV)

CMS-SMP-14-016

[Eur. Phys. J. C 76 (2016) 401]



$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat}) \pm 3.2\,(\text{exp}) \pm 3.1\,(\text{theo})$$

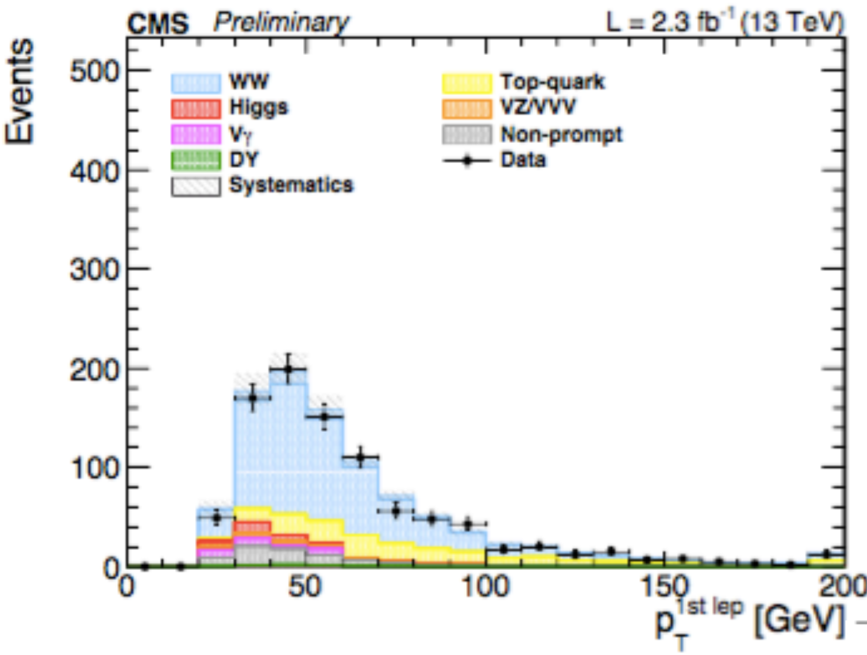
$$\pm 1.6\,(\text{lumi})\,\text{pb} = 60.1 \pm 4.8\,\text{pb}.$$

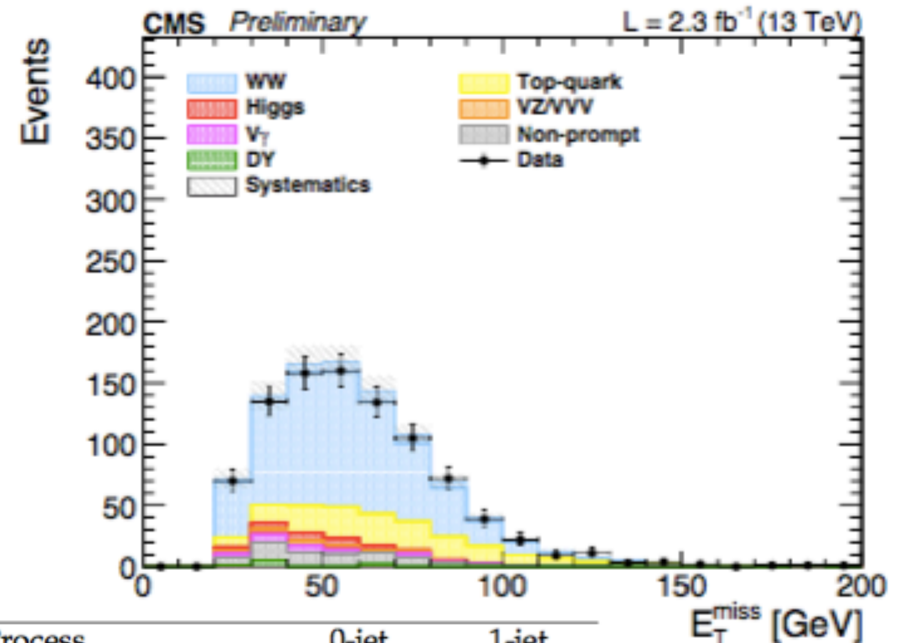
NNLO theoretical prediction of $59.8^{+1.3}_{-1.1}$ pb

A tribute to precise calculations

WW cross section (13TeV)

CMS PAS SMP-16-006





Process	0-jet	1-jet
$qq \to W^+W^-$	585 ± 38	228 ± 19
$gg \to W^+W^-$	51 ± 8	25 ± 4
W^+W^-	636 ± 40	253 ± 20
ZZ + WZ	16 ± 1	15 ± 1
Top-quark	177 ± 18	338 ± 34
$Z/\gamma^* \to \ell^+\ell^-$	3 ± 4	31 ± 7
$W\gamma^*$	8 ± 2	6 ± 2
$W\gamma$	25 ± 4	30 ± 5
Non-prompt	70 ± 19	33 ± 10
Higgs	25 ± 2	14 ± 1
Total bkg.	324 ± 27	467 ± 37
W^+W^- + Total bkg.	961 ± 49	720 ± 42
Data	927	719

Stat exp syst th syst lumi

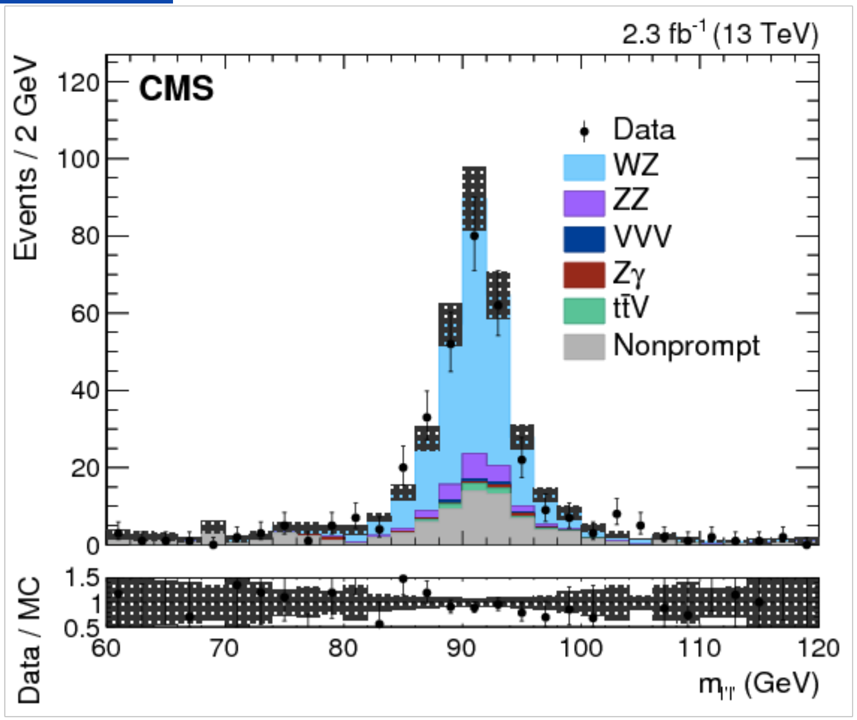
$$115.3 \pm 5.8 \pm 5.7 \pm 6.4 \pm 3.6 \quad \text{pb}$$

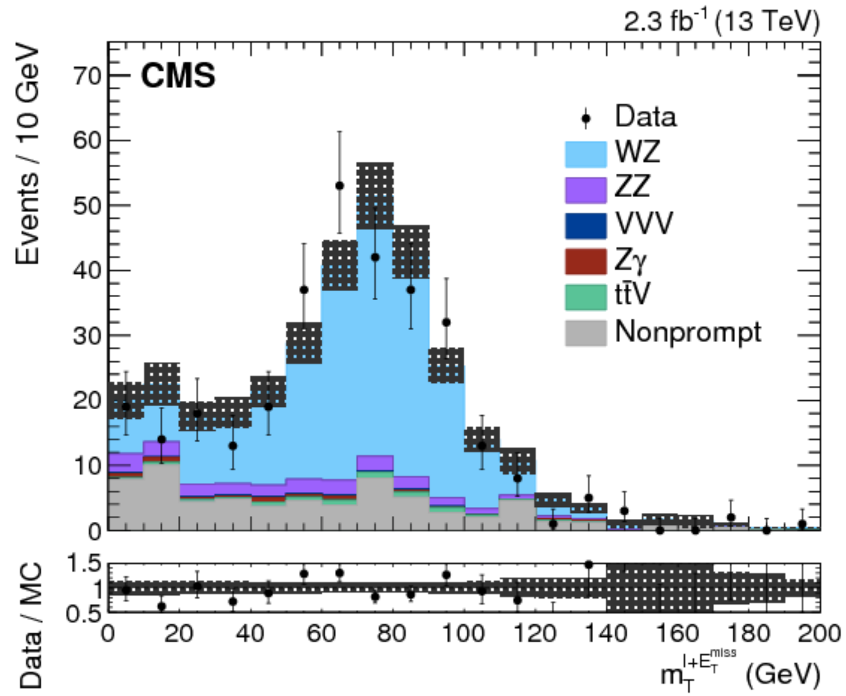
$$\sigma^{\mathrm{NNLO}}(pp \to W^+W^-) = 120.3 \pm 3.6 \text{ pb}$$

WZ (13 TeV)

CMS-SMP-16-002

arXiv:1607.06943





$$\sigma(pp \to WZ) = 39.9 \pm 3.2\,(\text{stat})^{+2.9}_{-3.1}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 1.3\,(\text{lumi})\,\text{pb}.$$

expected $44.9^{+2.2}_{-1.8}\,(\text{scale}) \pm 0.7\,(\text{PDF})\,\text{pb}$

ZZ (13 TeV)

CMS-SMP-16-001

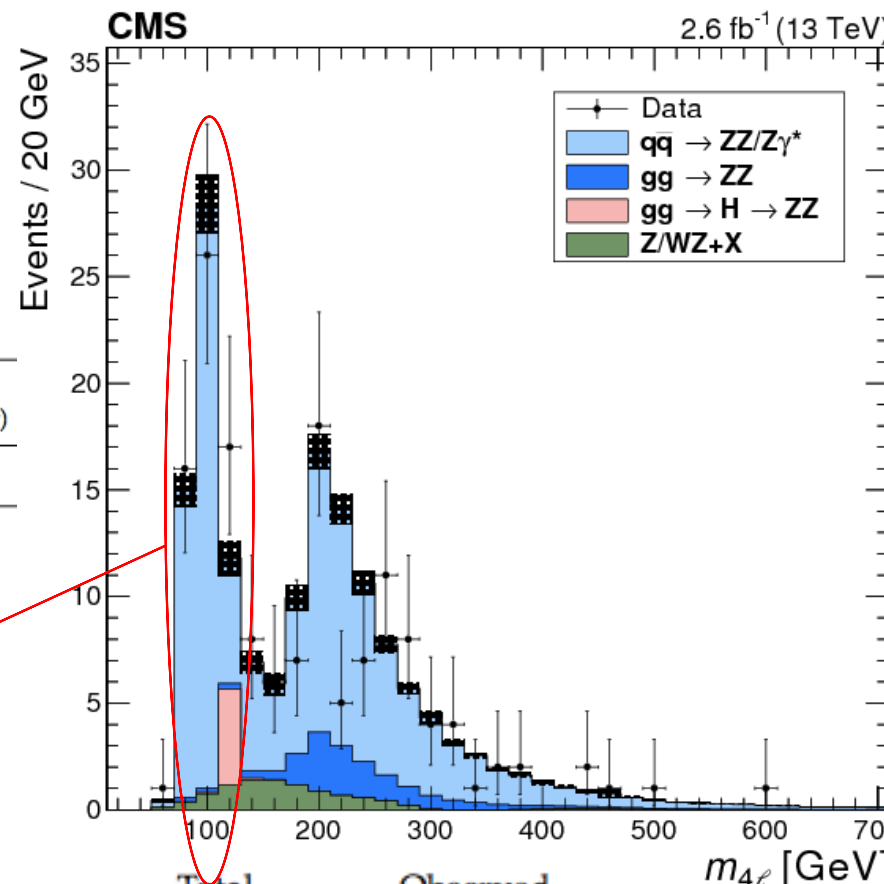
arXiv:1607.08834

Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\mathrm{GeV}$, $p_T^{\ell_2} > 10\,\mathrm{GeV}$, $p_T^{\ell_{3,4}} > 5\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$, $m_{\ell^+\ell^-} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair)
$Z \to \ell^+\ell^-\ell'^+\ell'^-$	$m_{Z_1} > 40\,\mathrm{GeV}$ $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100\,\mathrm{GeV}$
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$60 < m_{Z_1}, m_{Z_2} < 120\,\mathrm{GeV}$

The measured cross sections are

$$\sigma_{\mathrm{fid}}(pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-) = 30.5^{+5.2}_{-4.7}\,(\mathrm{stat})^{+1.8}_{-1.4}\,(\mathrm{syst}) \pm 0.8\,(\mathrm{lumi})\ \mathrm{fb},$$

$$\sigma_{\mathrm{fid}}(pp \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-) = 34.8^{+4.6}_{-4.2}\,(\mathrm{stat})^{+1.2}_{-0.8}\,(\mathrm{syst}) \pm 0.9\,(\mathrm{lumi})\ \mathrm{fb}.$$



$80<M_{4l}<100$

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$16.88 \pm 0.14 \pm 0.62$	$0.31 \pm 0.30 \pm 0.12$	$17.19 \pm 0.33 \pm 0.63$	17
$2e2\mu$	$15.88 \pm 0.14 \pm 0.87$	$0.37 \pm 0.27 \pm 0.15$	$16.25 \pm 0.31 \pm 0.88$	16
4e	$5.58 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.08$	$5.78 \pm 0.13 \pm 0.53$	6
Total	$38.33 \pm 0.21 \pm 1.19$	$0.89 \pm 0.42 \pm 0.22$	$39.22 \pm 0.47 \pm 1.21$	39

ZZ (13TeV)

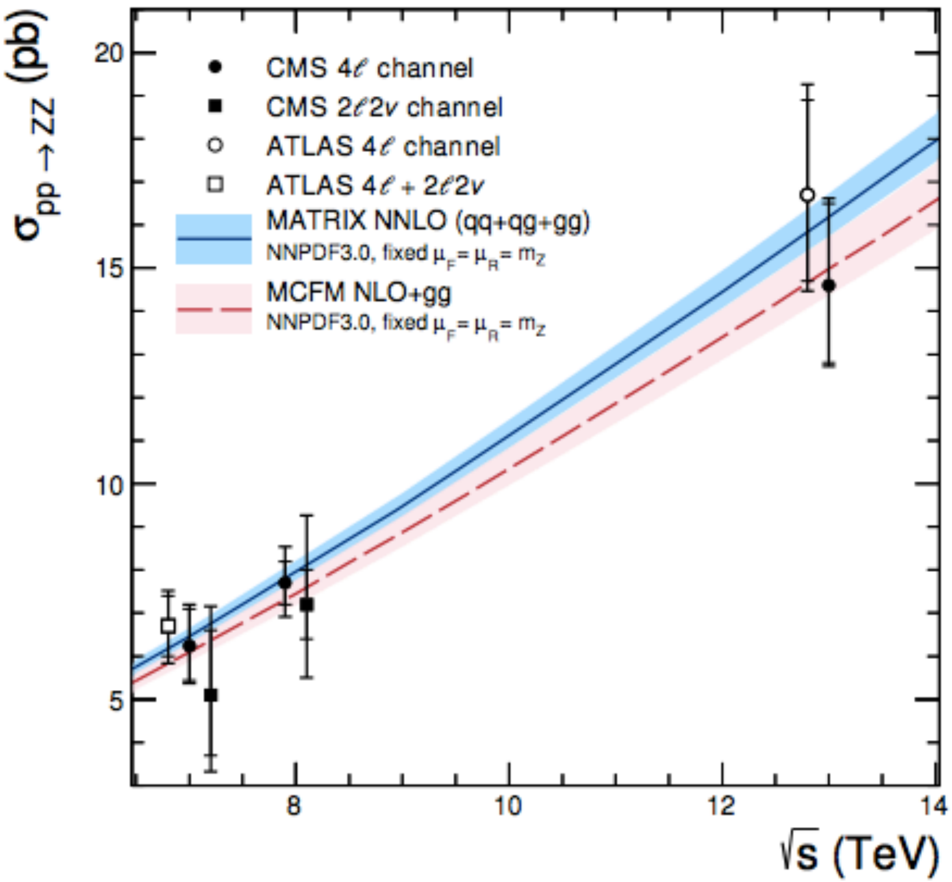
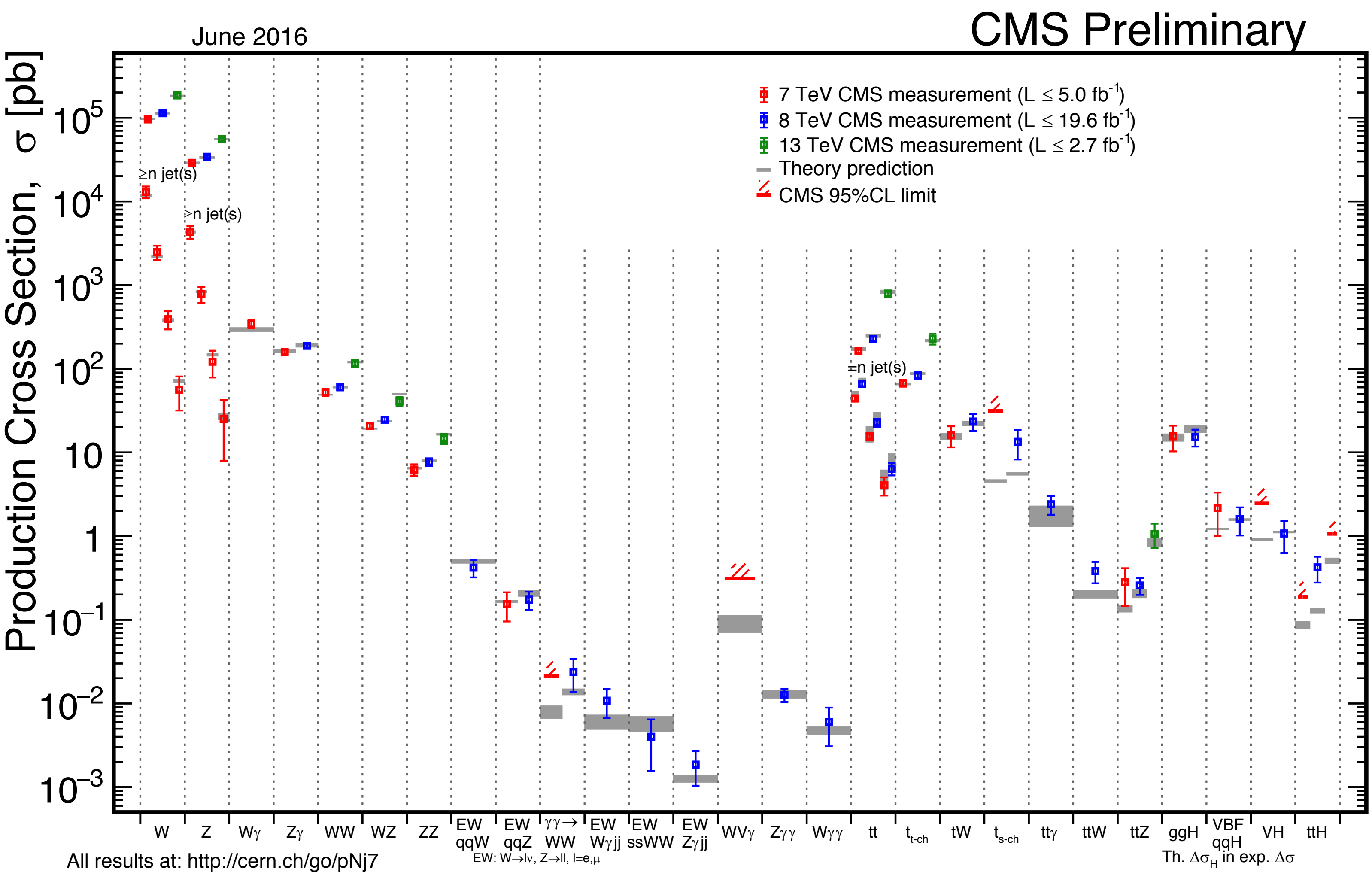
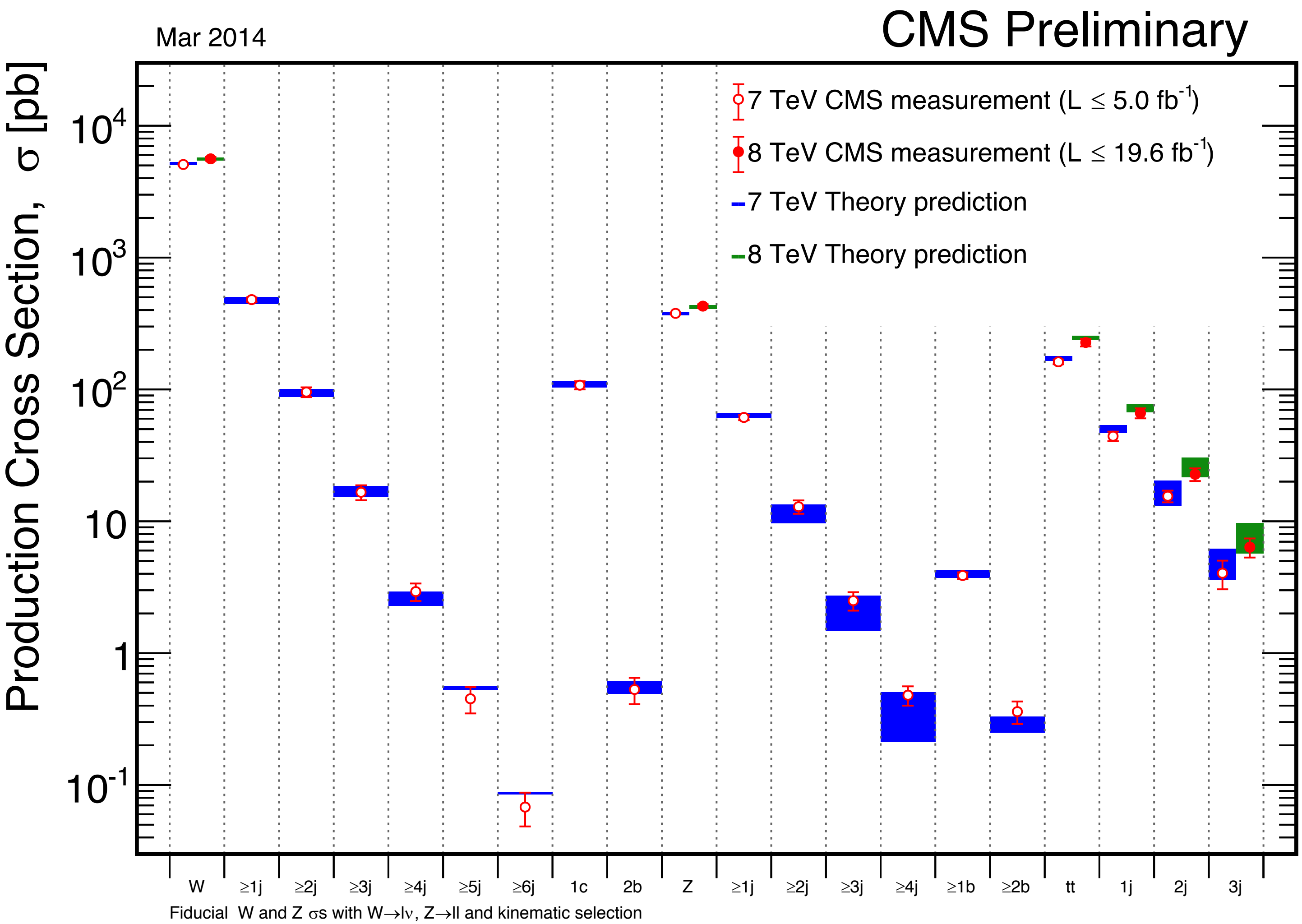


Figure 5: The total ZZ cross section as a function of the proton-proton center-of-mass energy. Results from the CMS and ATLAS experiments are compared to predictions from MATRIX and MCFM with NNPDF3.0 PDF sets and fixed scales $\mu_F = \mu_R = m_Z$.

Covering the ground

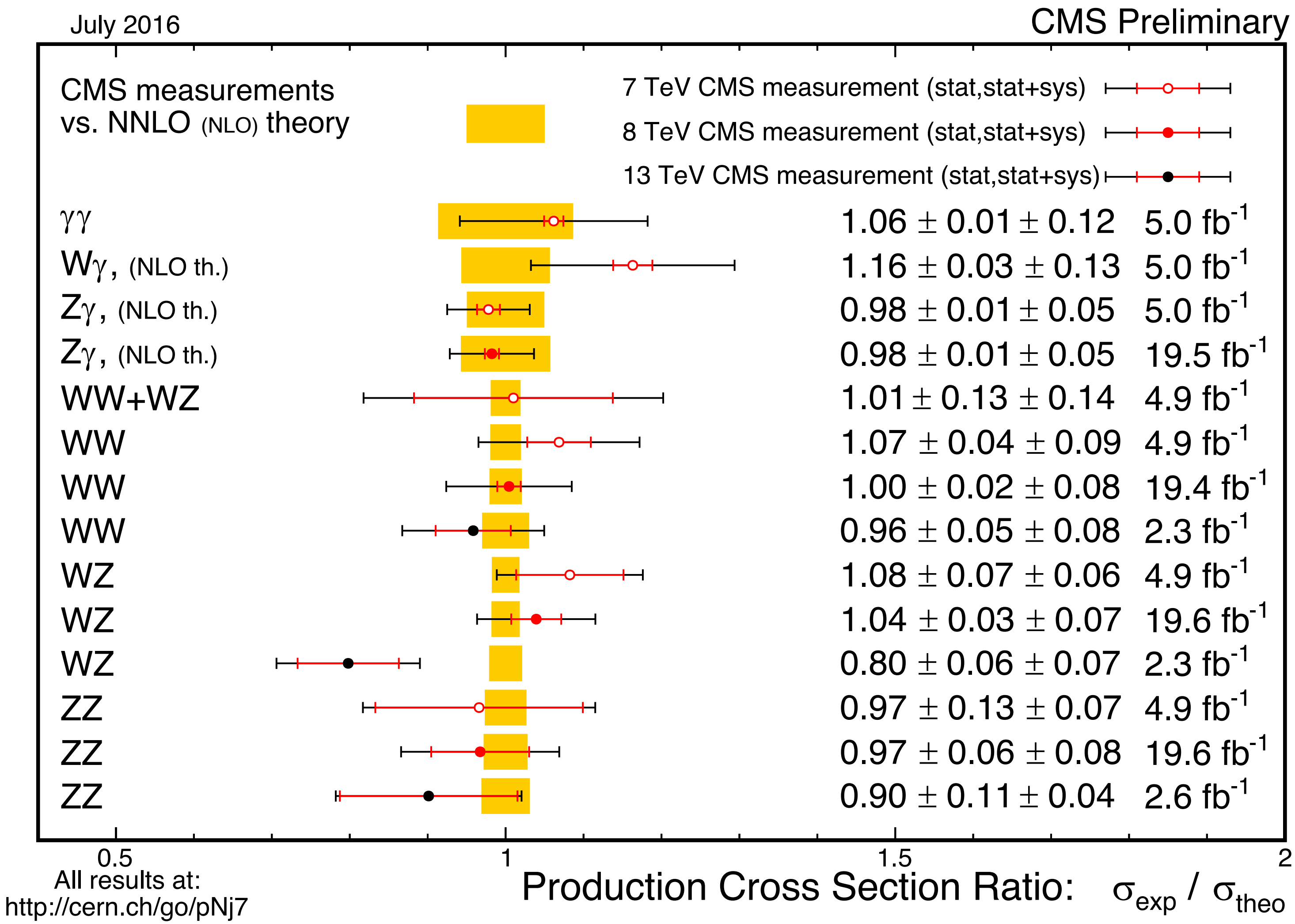


W/Z +x



Mar 2014
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)
7 TeV Theory prediction
8 TeV Theory prediction
W
≥1j
≥2j
≥3j
≥4j
≥5j
≥6j
1c
2b
Z
≥1j
≥2j
≥3j
≥4j
≥1b
≥2b
tt
1j
2j
3j
Fiducial W and Z σs with W→lν, Z→ll and kinematic selection

Dibosons

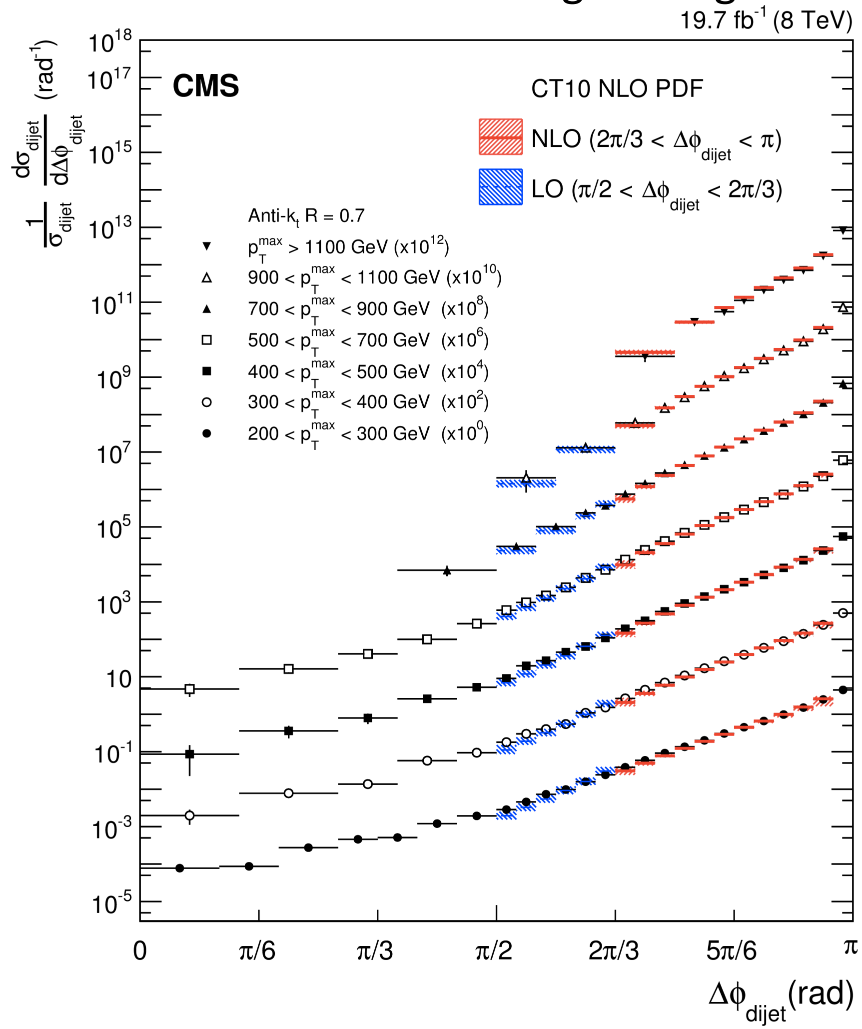

July 2016
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ
Wγ, (NLO th.)
Zγ, (NLO th.)
Zγ, (NLO th.)
WW+WZ
WW
WW
WW
WZ
WZ
WZ
ZZ
ZZ
ZZ
1.06 ± 0.01 ± 0.12 5.0 fb-1
1.16 ± 0.03 ± 0.13 5.0 fb-1
0.98 ± 0.01 ± 0.05 5.0 fb-1
0.98 ± 0.01 ± 0.05 19.5 fb-1
1.01 ± 0.13 ± 0.14 4.9 fb-1
1.07 ± 0.04 ± 0.09 4.9 fb-1
1.00 ± 0.02 ± 0.08 19.4 fb-1
0.96 ± 0.05 ± 0.08 2.3 fb-1
1.08 ± 0.07 ± 0.06 4.9 fb-1
1.04 ± 0.03 ± 0.07 19.6 fb-1
0.80 ± 0.06 ± 0.07 2.3 fb-1
0.97 ± 0.13 ± 0.07 4.9 fb-1
0.97 ± 0.06 ± 0.08 19.6 fb-1
0.90 ± 0.11 ± 0.04 2.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

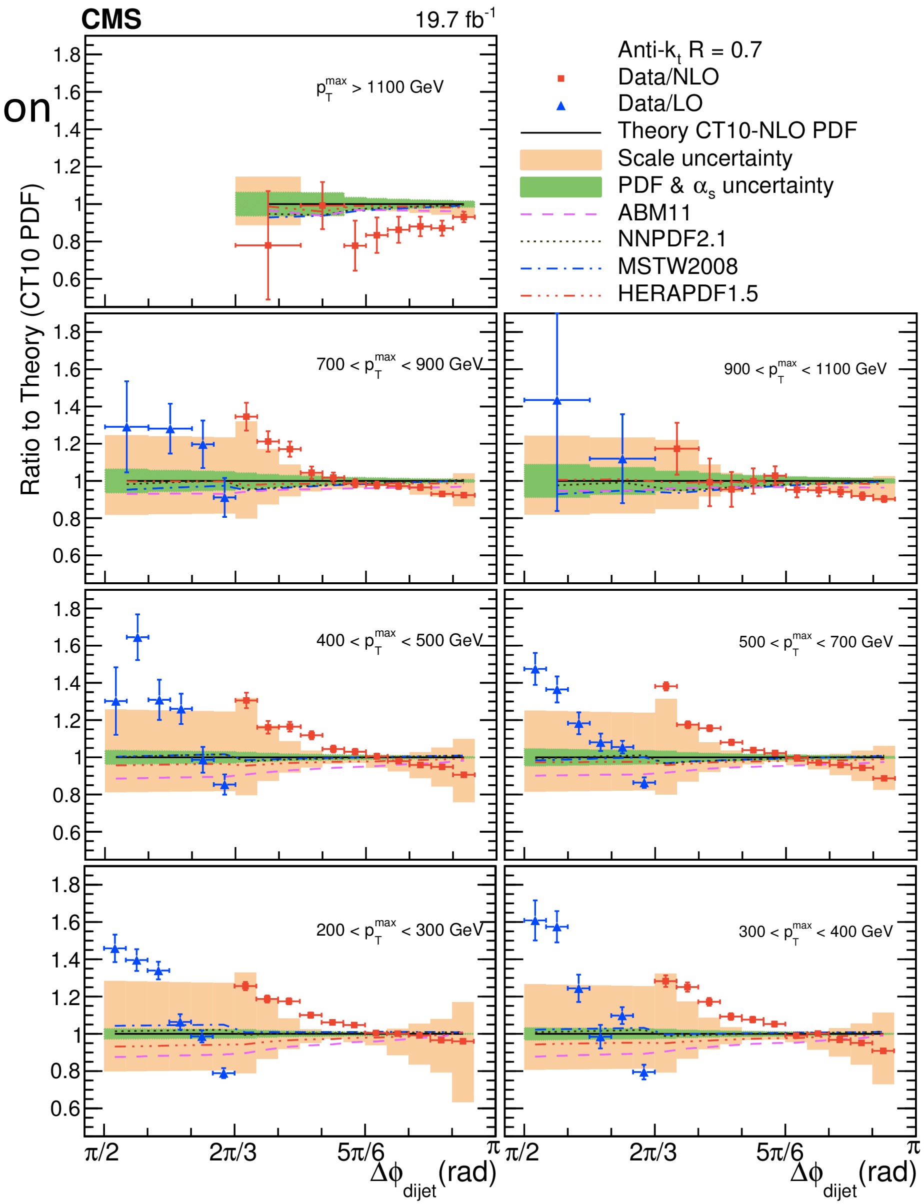
Jets: central production

CMS-SMP-14-015

Calculations performed with NLOJET++(V4.1.3)

Normalized in EACH Pt range to avg X-section



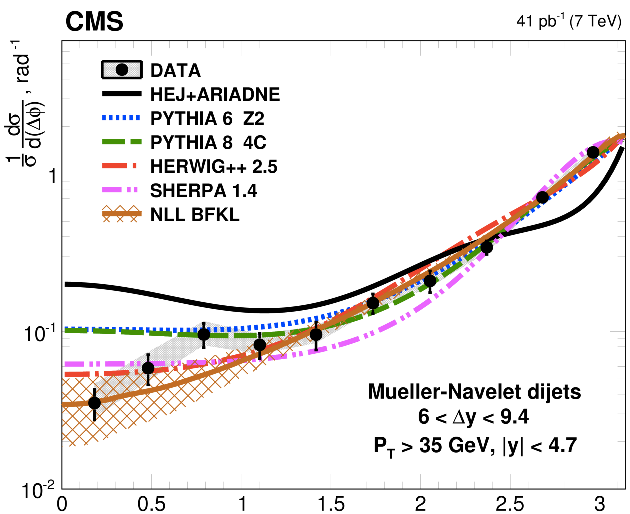


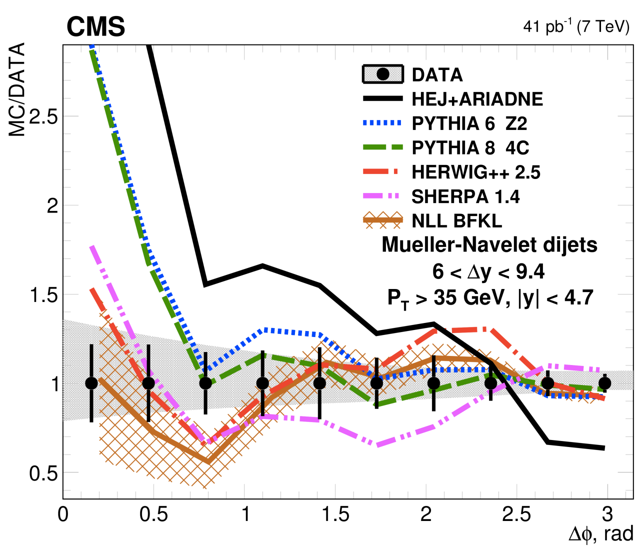
Jets: forward production

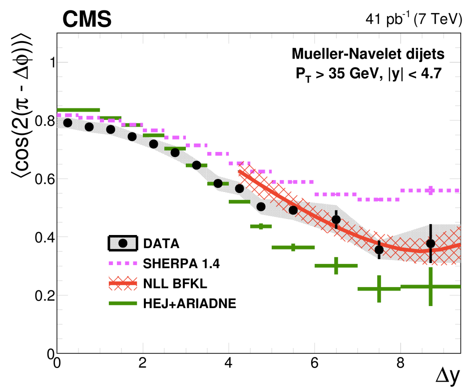
CMS-FSQ-12-002

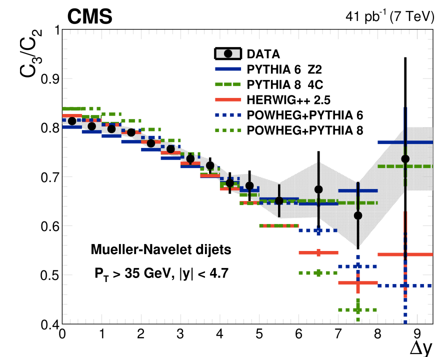
Mueller-Navelet Azimuthal decorrelation study: $P_t$jets> 35 GeV, ΔY up to 9.4

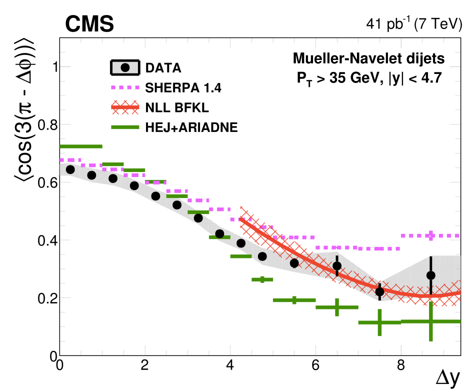
http://arxiv.org/pdf/1601.06713.pdf

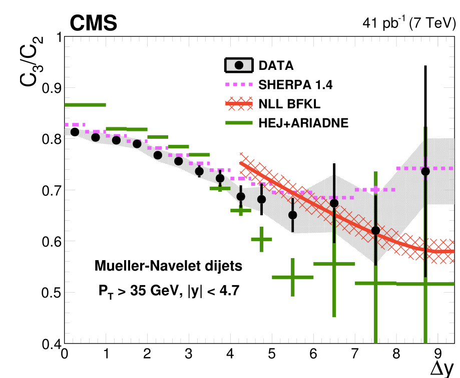










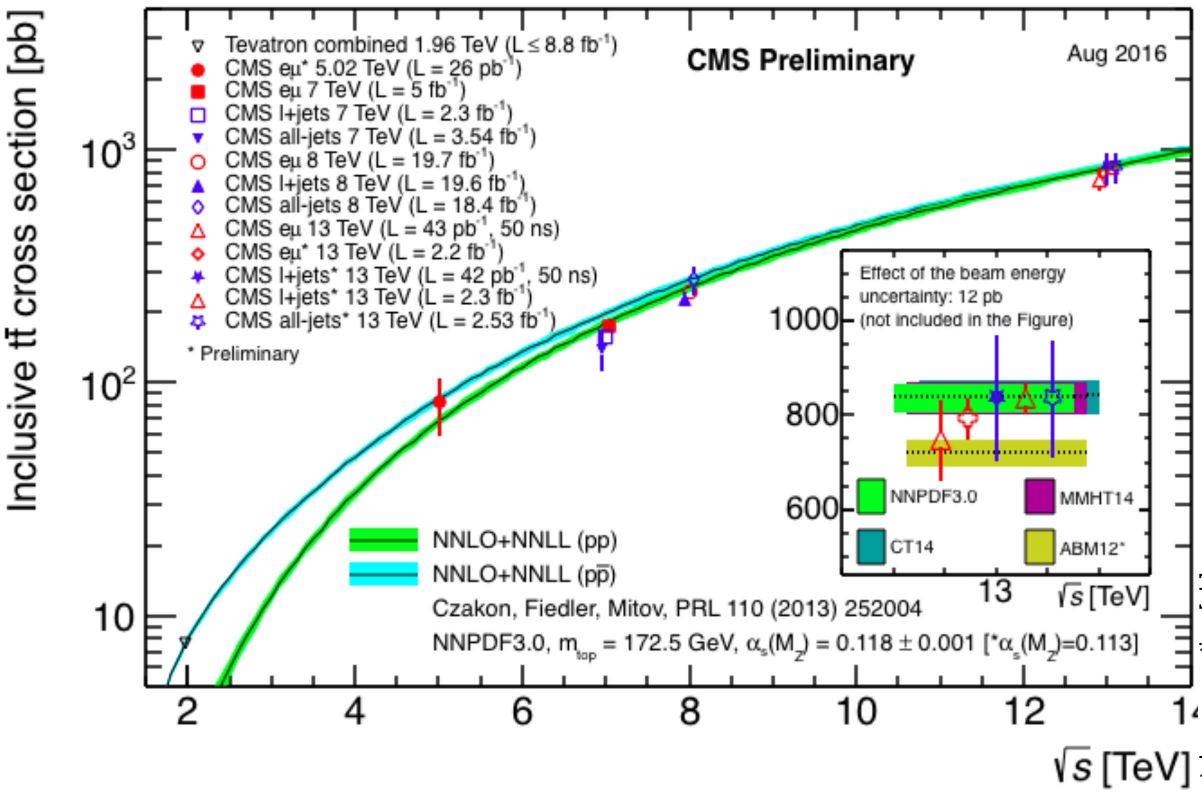


The kinematical domain of the present study lies in between the regions described by the DGLAP and BFKL approaches

LHC : a TOP factory

LHC : a Top quark factory

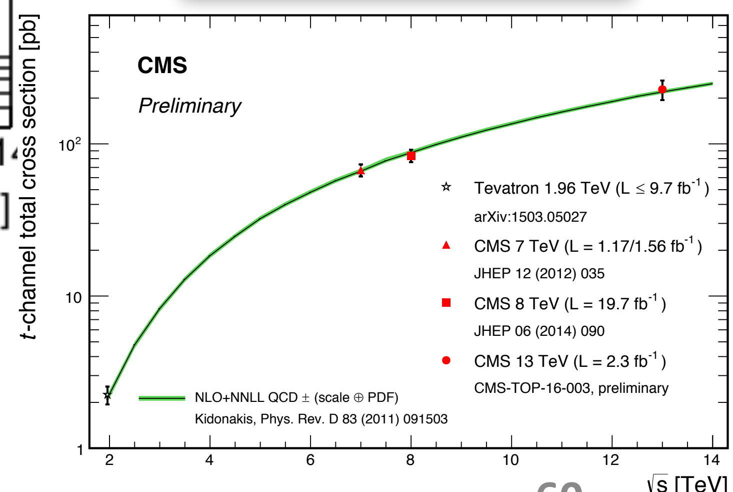
CMS PAS TOP-16-006



ttbar cross section
Measured at 4 different energies

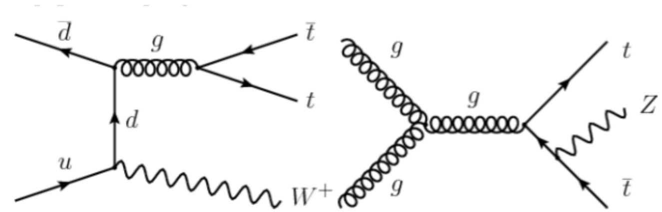
CMS PAS TOP-16-003

Single top cross section



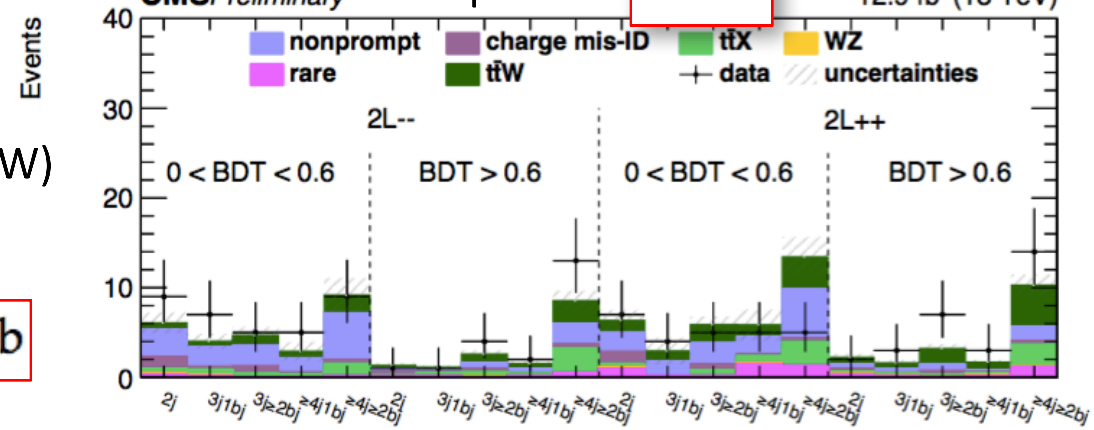
Top pairs + W/Z

TOP-16-017



2 leptons

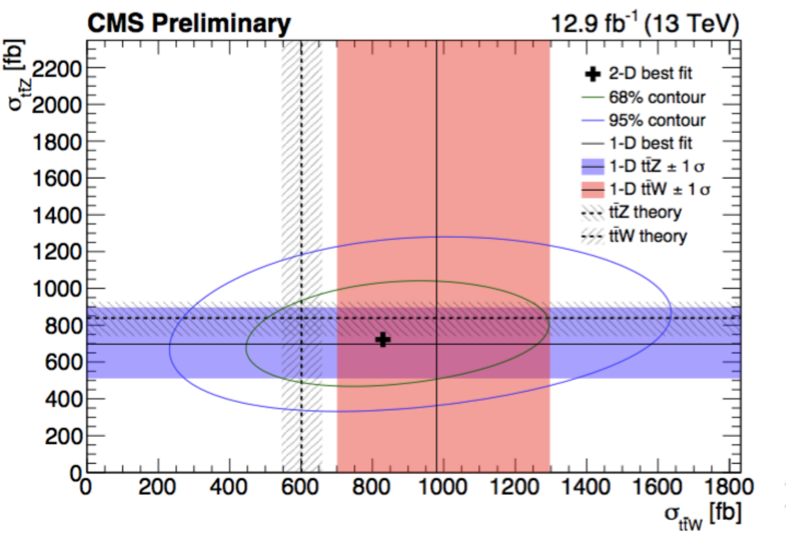
ttW



Select event with 2 SameSign leptons(TTW) or 3 or 4 leptons (TTZ)

$$\sigma(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}(\text{stat.})^{+0.14}_{-0.12}(\text{sys.})\ \text{pb}$$

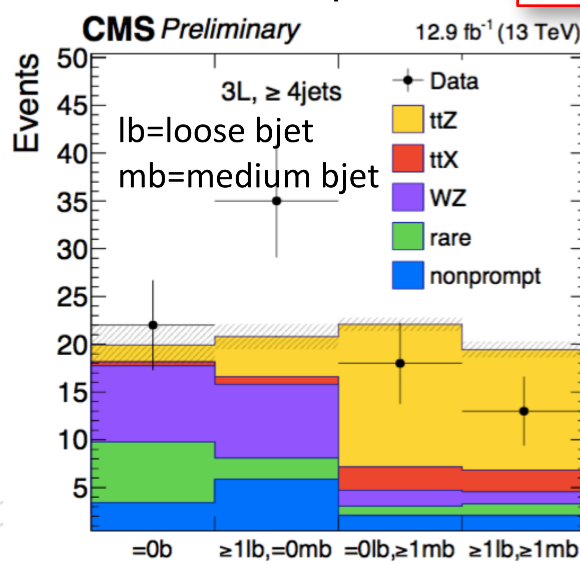
$$\sigma(t\bar{t}W) = 0.98^{+0.23}_{-0.22}(\text{stat.})^{+0.22}_{-0.18}(\text{sys.})\ \text{pb}$$

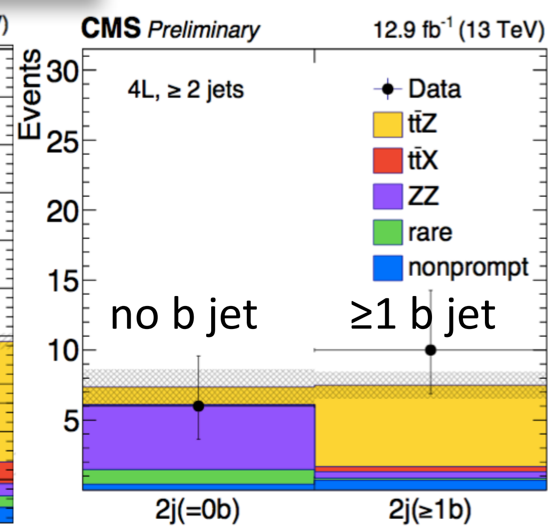


3 leptons

ttZ

4 leptons





The main goal of LHC : Higgs physics

HIG-16-033

Higgs re-discovery: $H \to ZZ \to 4\ell$

at m_H=125.09 GeV

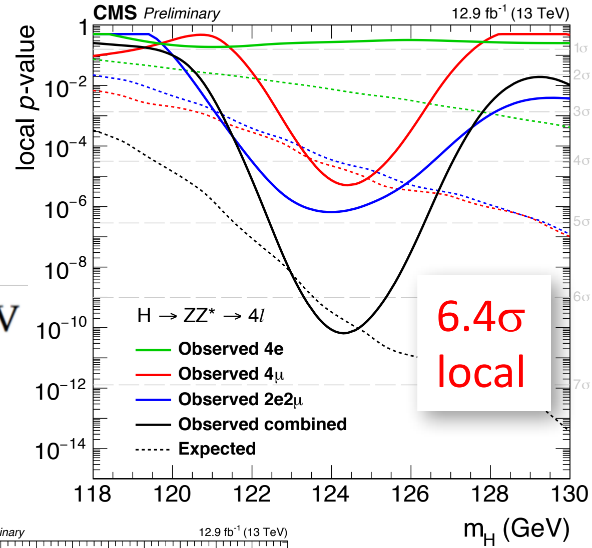
$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$

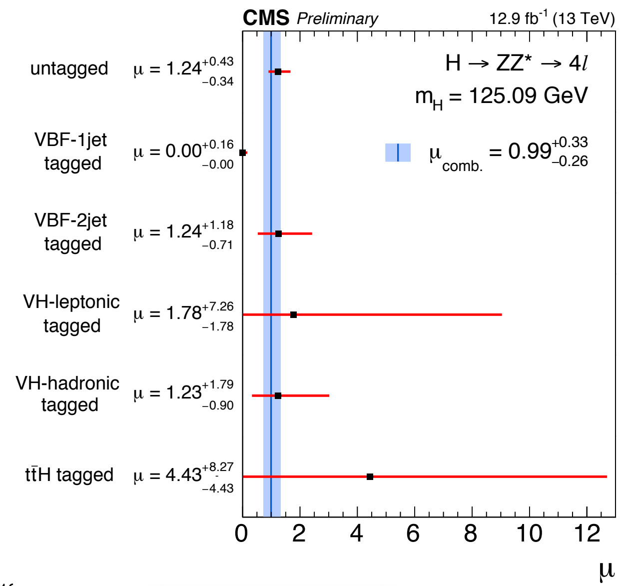
Profiling all nuisances and μ

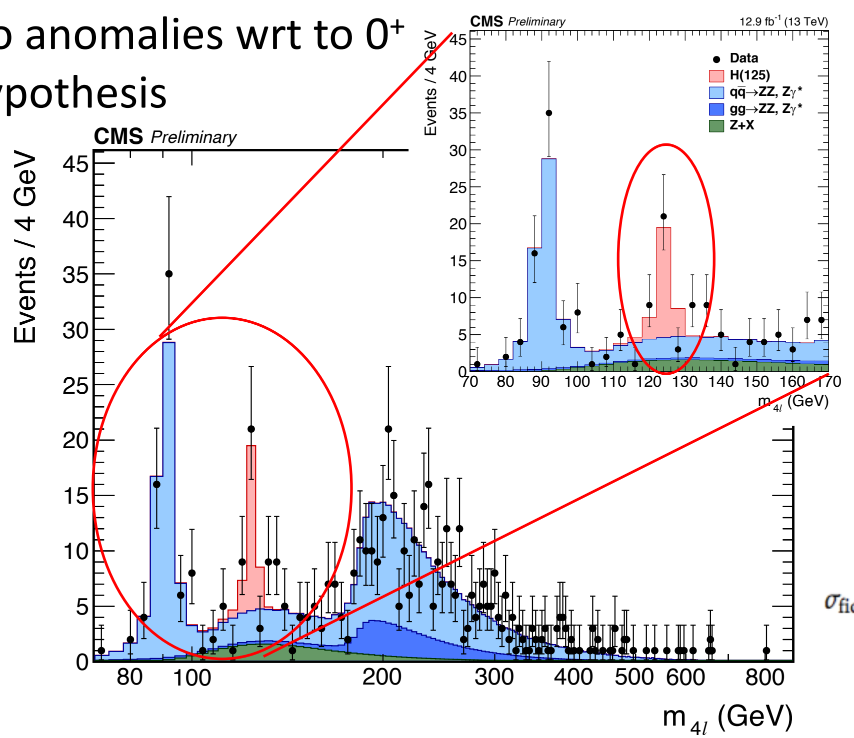
$m_H = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$ GeV

Γ_H<41 MeV (comparing off-shell and on-shell)

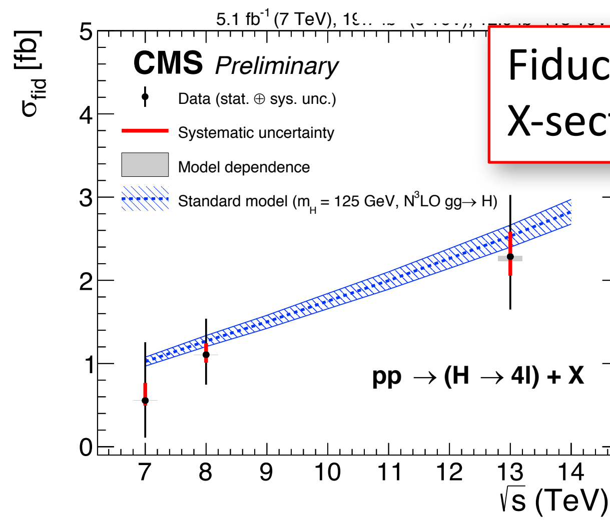
No anomalies wrt to 0^+ hypothesis







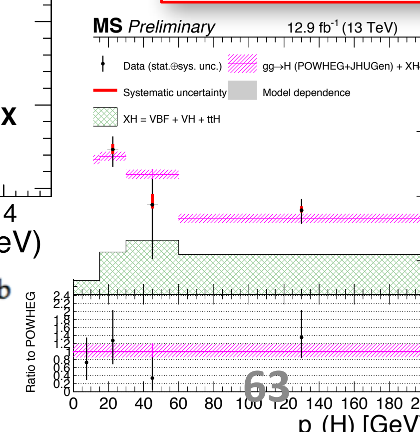
Fiducial X-section



$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})$ fb

$\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13$ fb

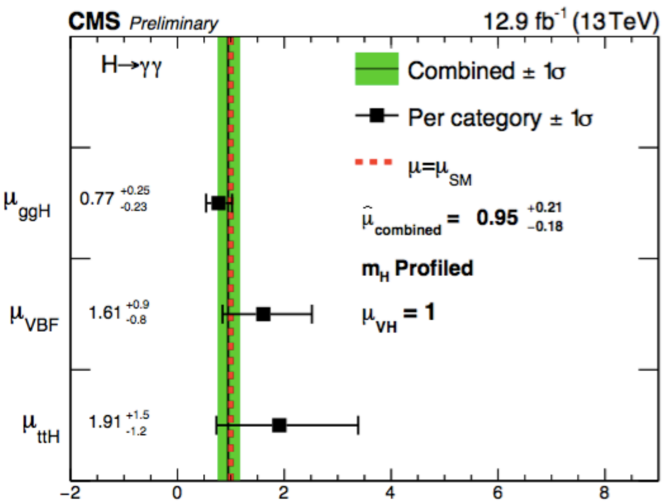
Differential X-section

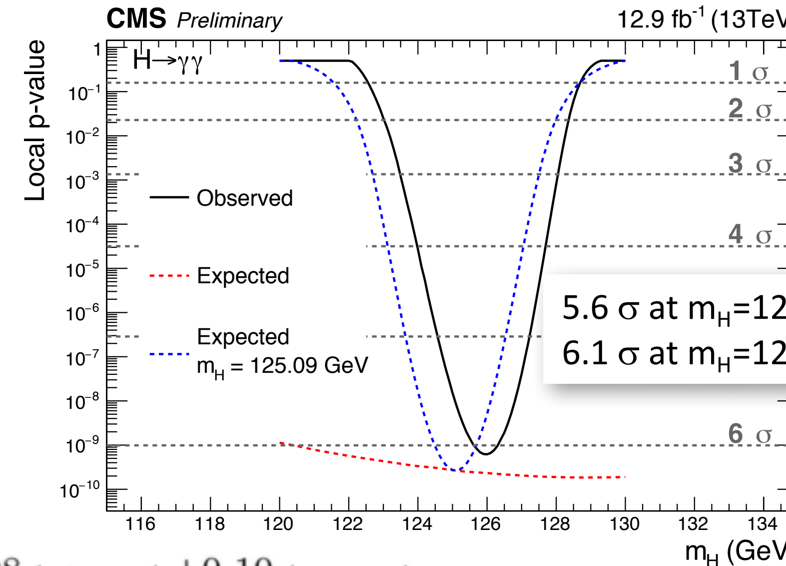


Higgs rediscovery: H→ γγ

HIG-16-020

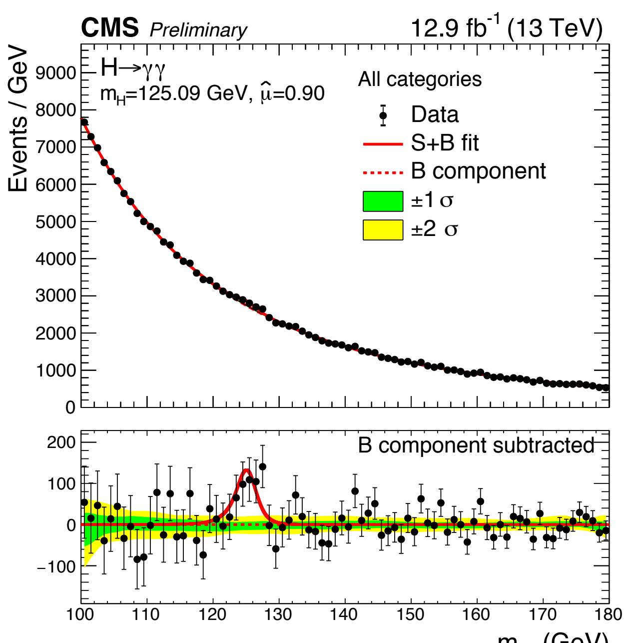
4 untagged categories
2 VBF categories
2TTH categories

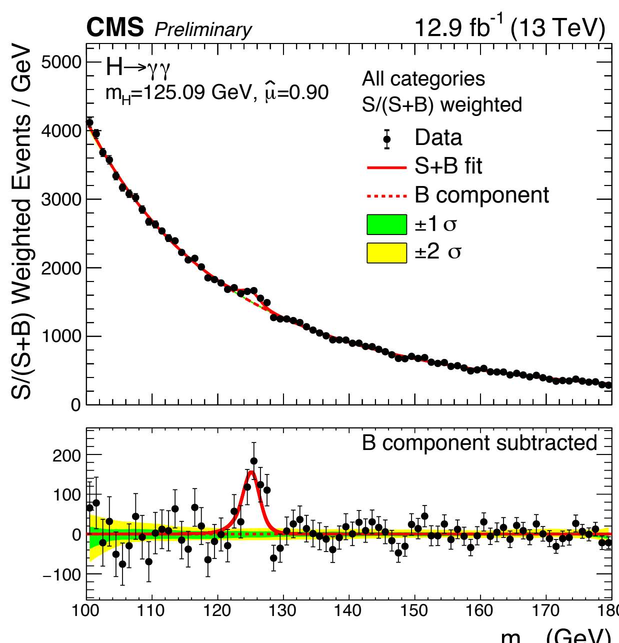


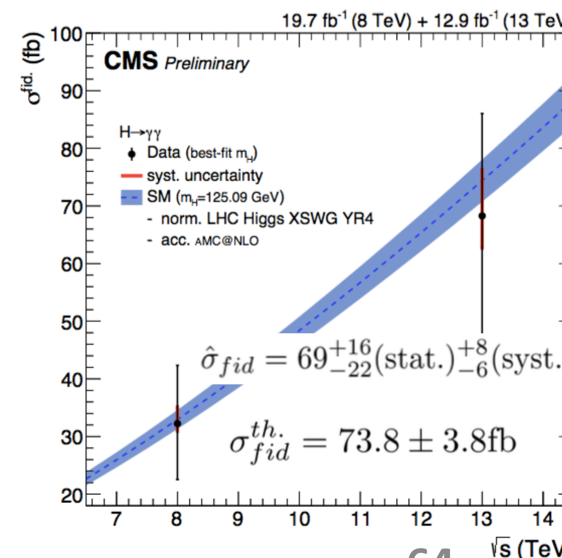


5.6 σ at m_H=125.09 GeV
6.1 σ at m_H=126 GeV

$$\hat{\sigma}/\sigma_{SM} = 0.95^{+0.21}_{-0.19} = 0.95 \pm 0.17(stat.)^{+0.08}_{-0.05}(theo.)^{+0.10}_{-0.07}(syst.)$$







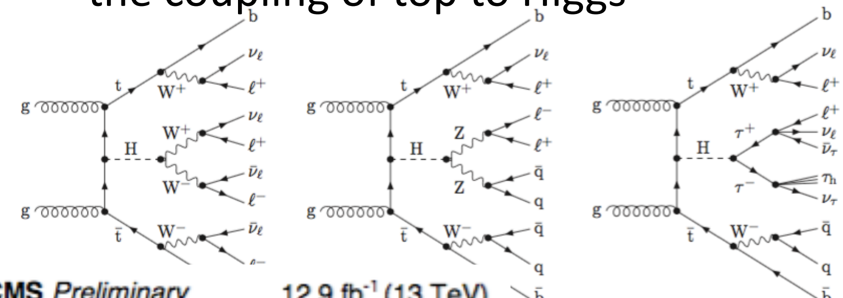
$$\hat{\sigma}_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

$$\sigma^{th.}_{fid} = 73.8 \pm 3.8\text{fb}$$

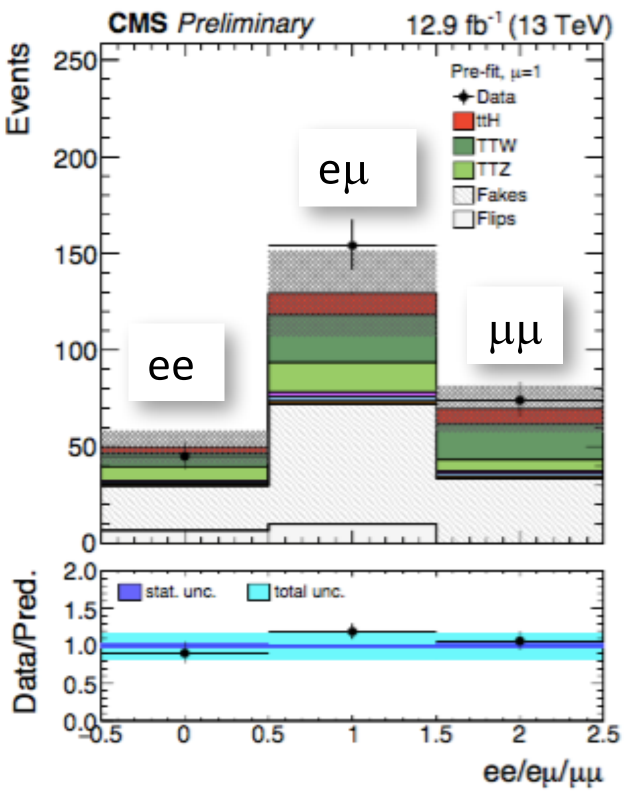
ttH production

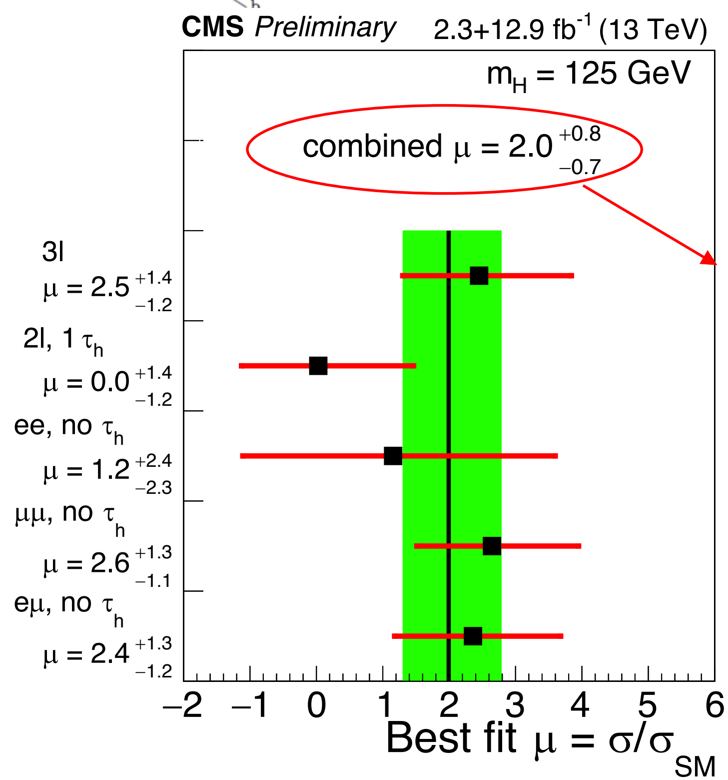
HIG-16-022

Important to study directly
the coupling of top to Higgs



Looking for final states with H decay to ZZ,WW and $\tau\tau$ (yielding events with 2-3 leptons).

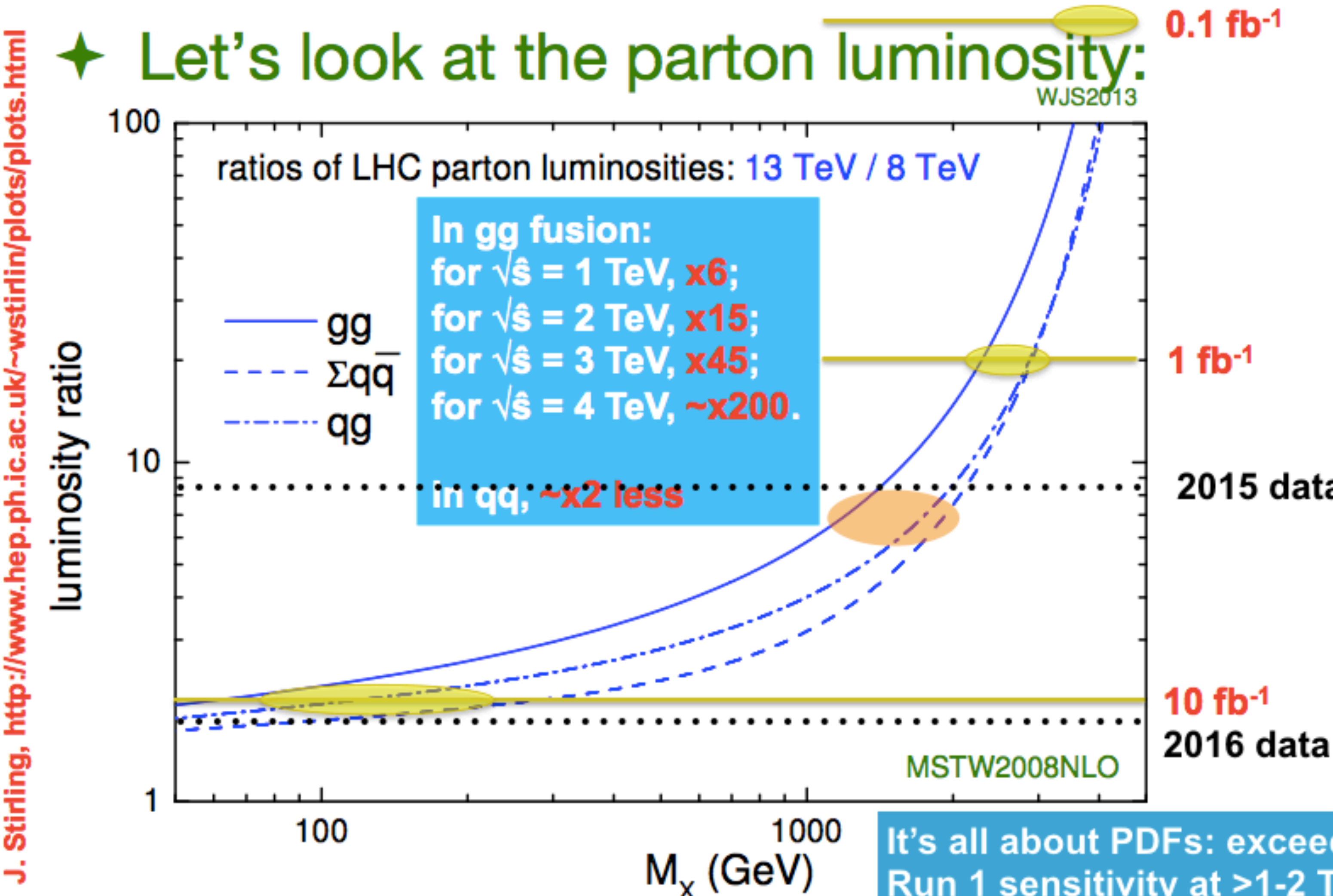




$\mu=2.0^{+0.8}_{-0.7}$ within statistics, compatible with SM

Searches

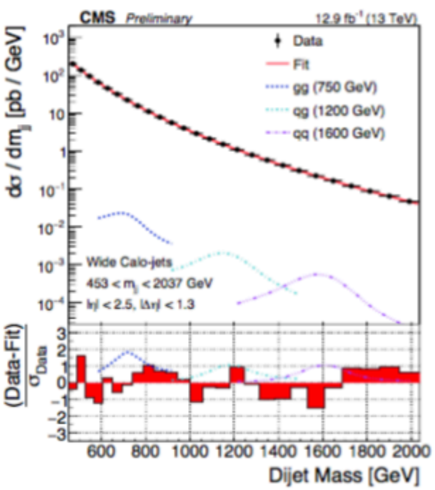
✦ Let's look at the parton luminosity:



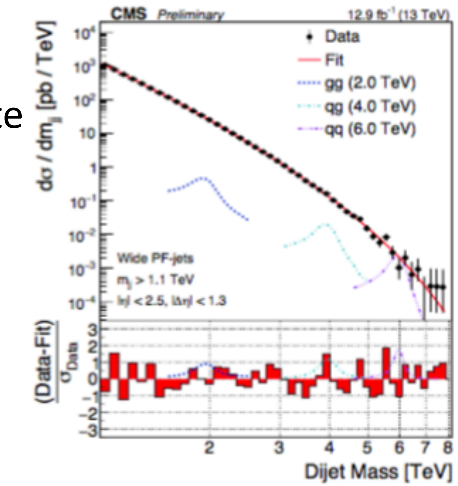
It's all about PDFs: exceed Run 1 sensitivity at >1-2 TeV

Search for di-jets resonances

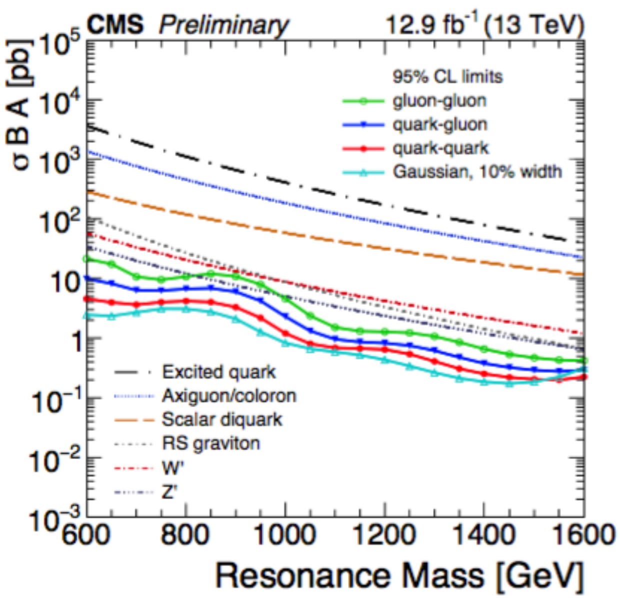
CMS PAS EXO-16-032

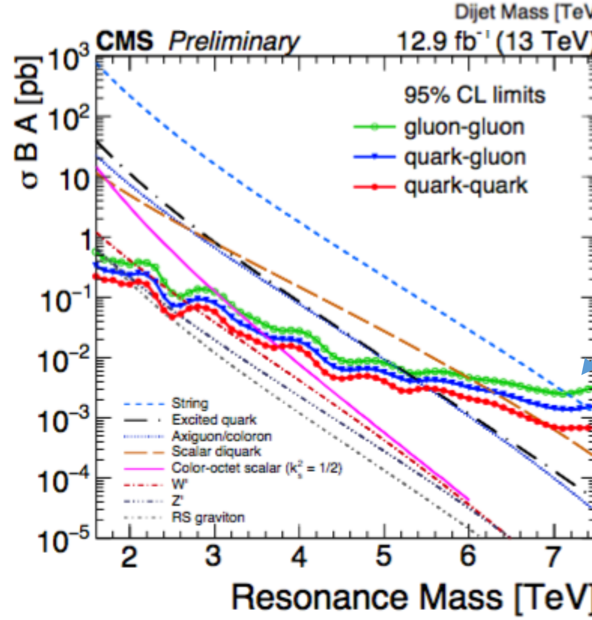


Low mass search: HLT ‘scouting’ pioneered by CMS in RUN1: Jets HLT information is directly saved allowing high logging rate



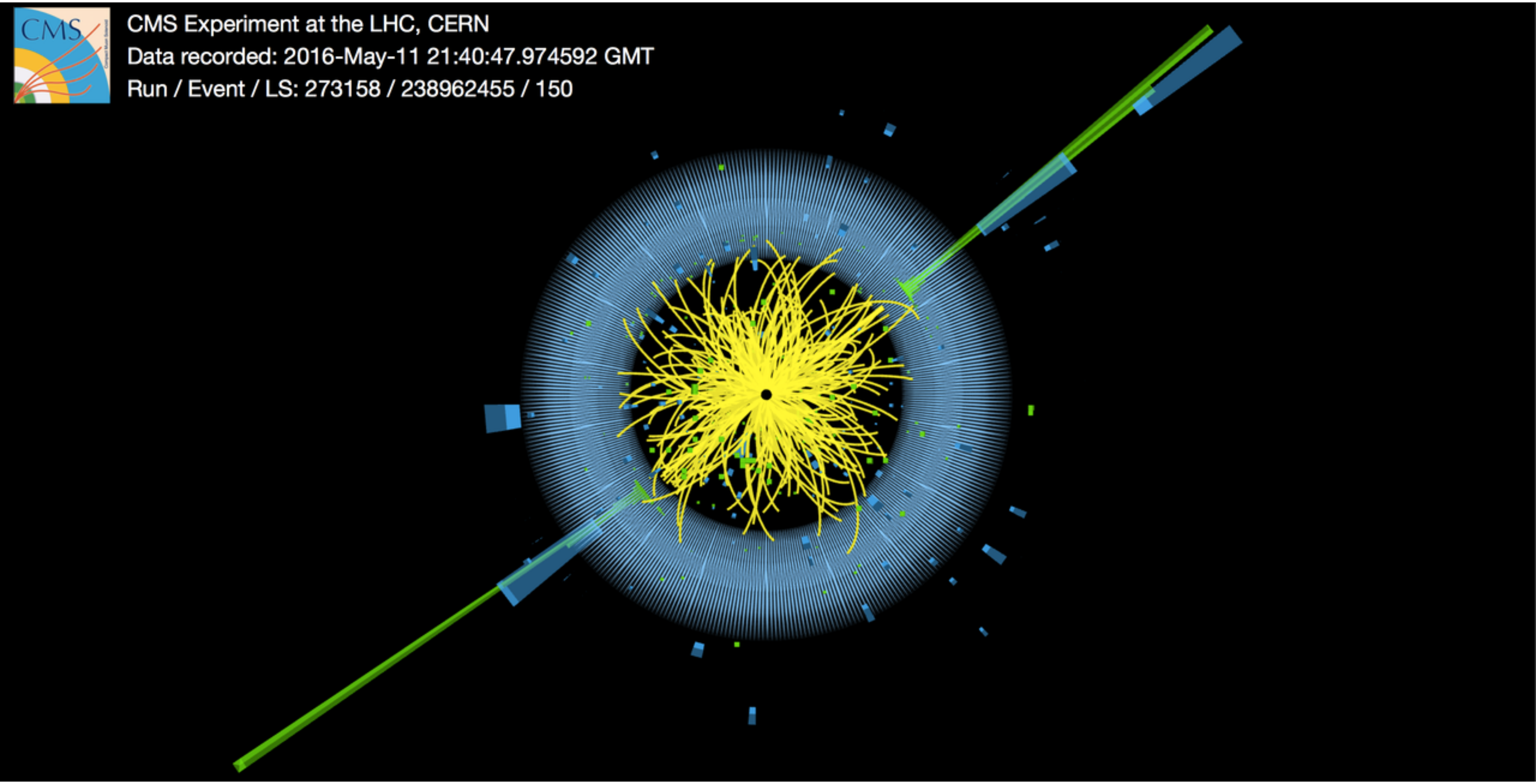
High mass search: fully efficient for $H_T > 800$ GeV and $m_{jj} > 1060$ GeV





Strongest limit: STRING resonances excluded up to 7.4 TeV

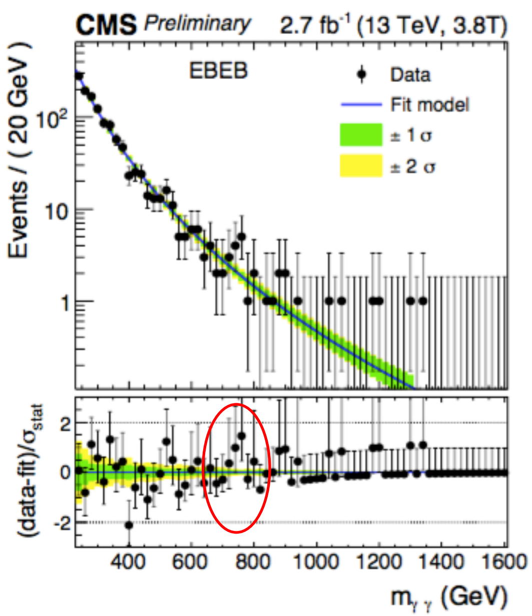
Highest mass di-jet event: 7.7 TeV



Search for di-photon resonances

2015 data

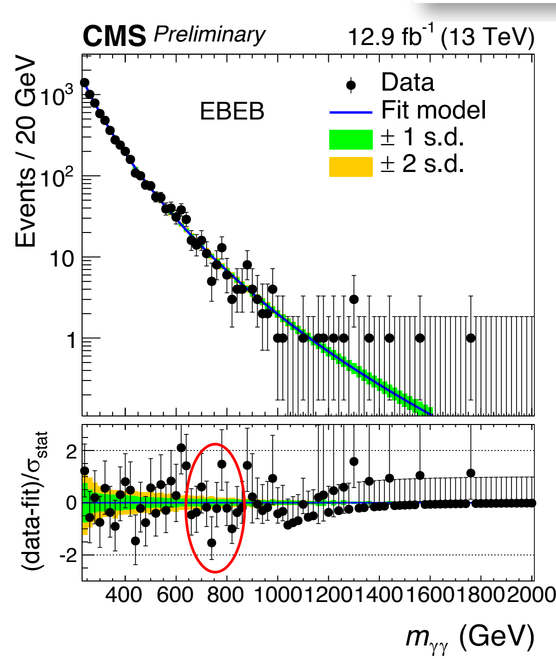
Phys. Rev. Lett. **117**

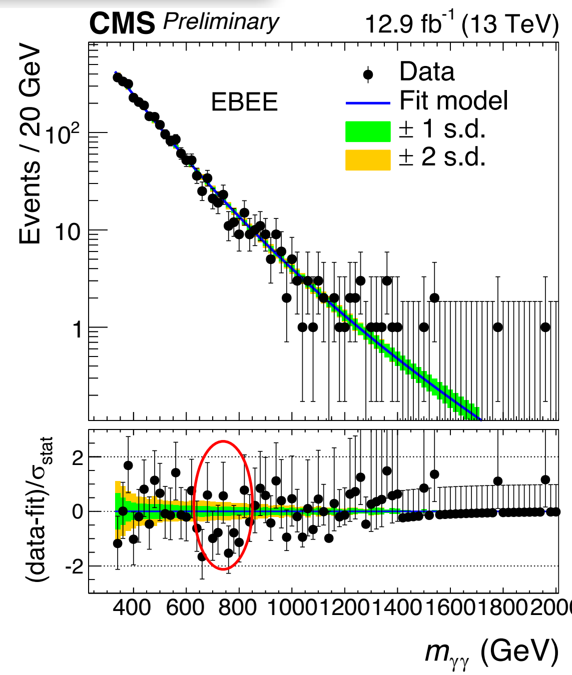


Clarification: the small excess at 750 GeV remained there after reprocessing and final calibration (CMS choice to reprocess prior to publishing).

2016 analysis: straight reload of 2015 analysis

CMS PAS EXO-16-027

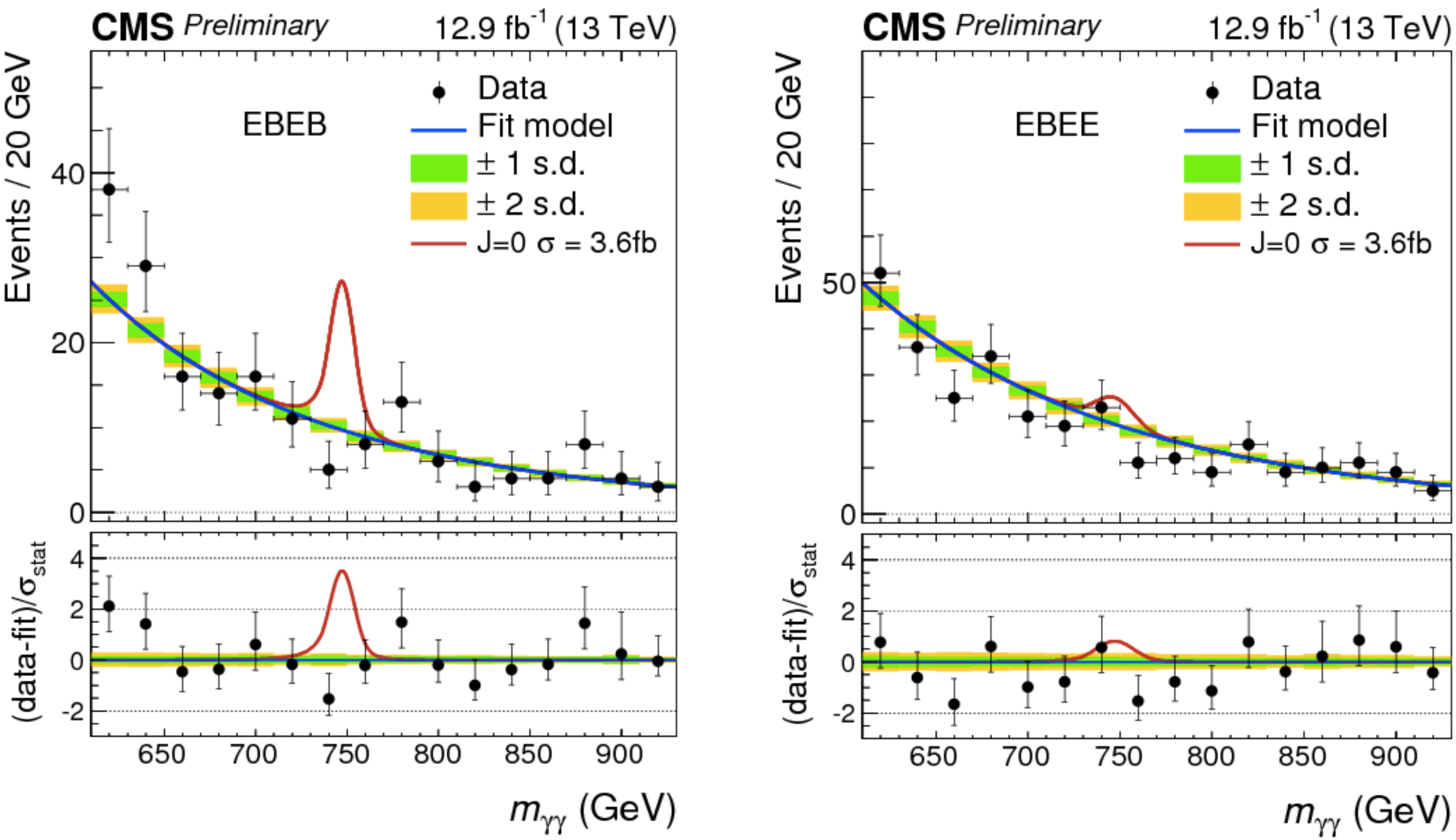




2016 data: no evidence of strengthening of this bump

750 GeV? What we would have seen

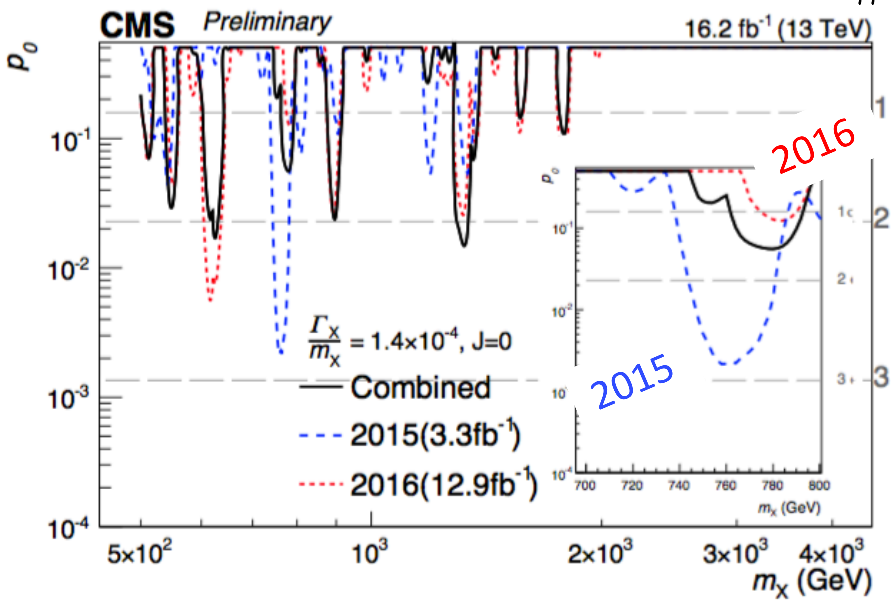
Recall that global significance of CMS 13 TeV(2015)+8 TeV was 1.6 σ

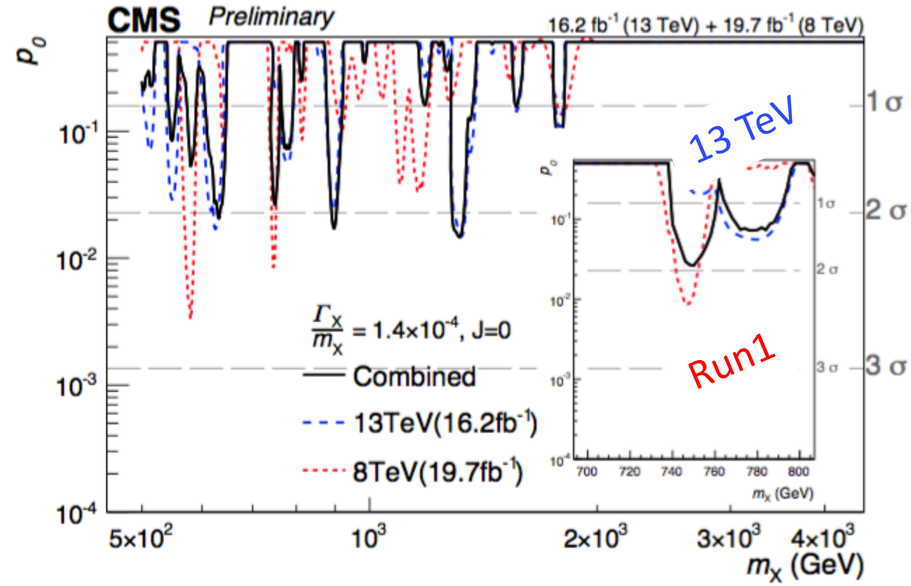


…not really ! Searched also in Zγ

P-values and limits

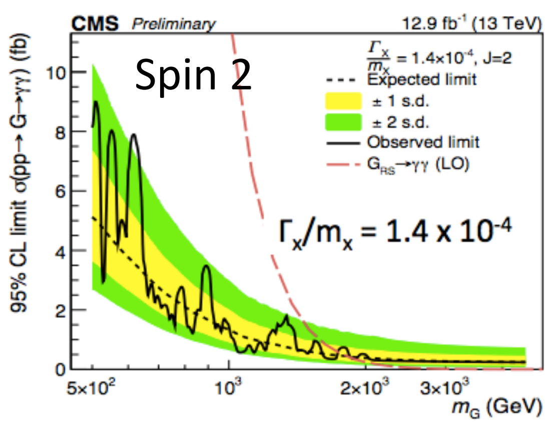
The 2016 data (based on 12.9 fb^{-1} of integrated luminosity) do not confirm the fluctuations observed earlier in the $m_{\gamma\gamma}$ spectrum in 2015 and Run1 at 8 TeV

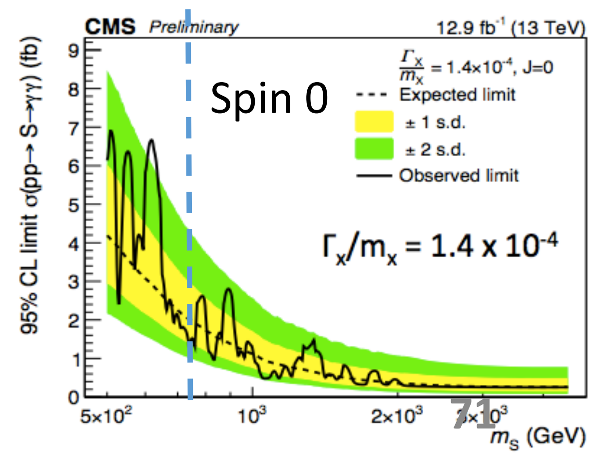




Limits on a RS graviton mass

Coupling	Exclusion
0.01	$m_G < 1.75$ TeV
0.1	$m_G < 3.75$ TeV
0.2	$m_G < 4.35$ TeV

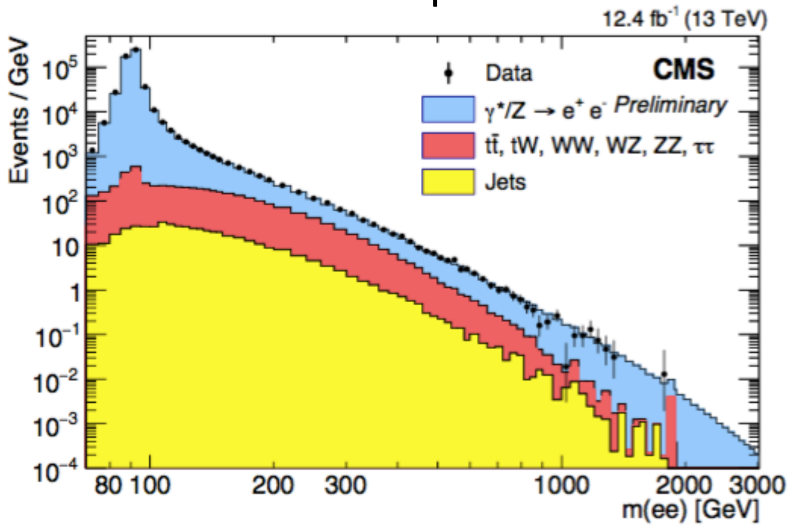


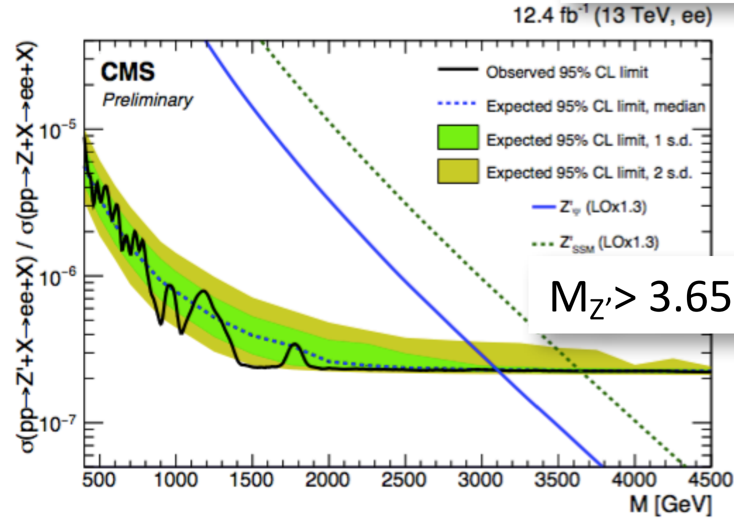


Search for dilepton resonance with 2016 data

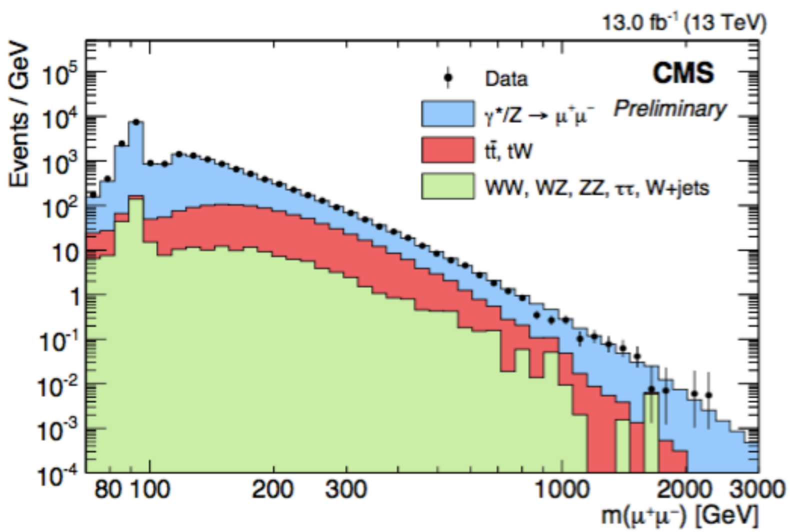
The M_{ee}=2.9 TeV detected early last year is still the highest mass dilepton observed at 13 TeV

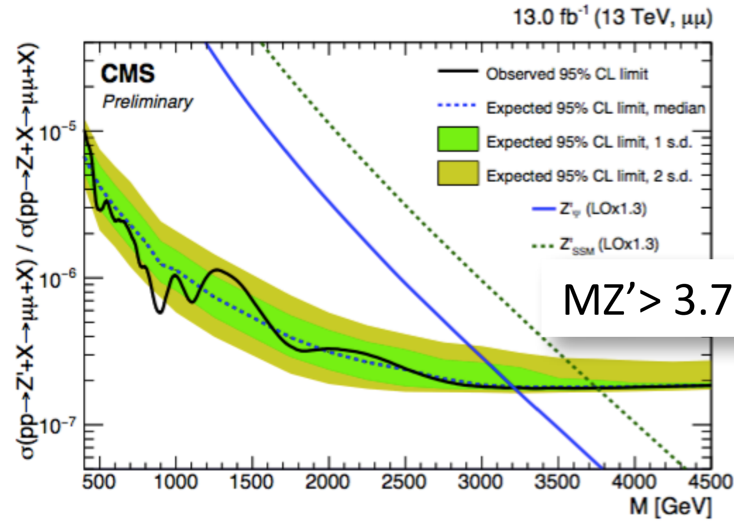
EXO-16-031





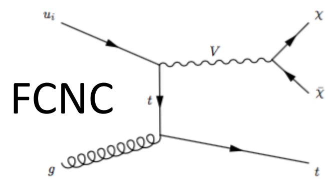
$M_{Z'}$> 3.65 TeV

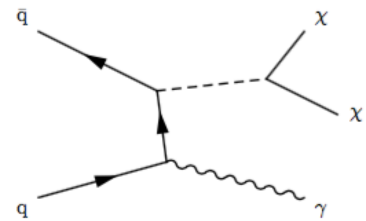


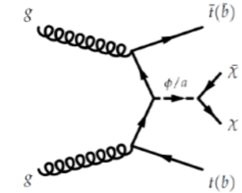


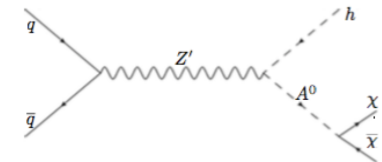
MZ'> 3.75 TeV

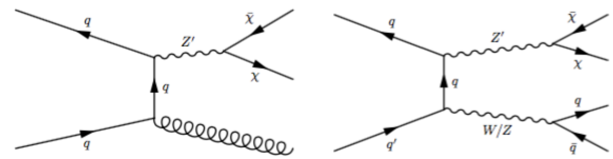
Dark Matter search



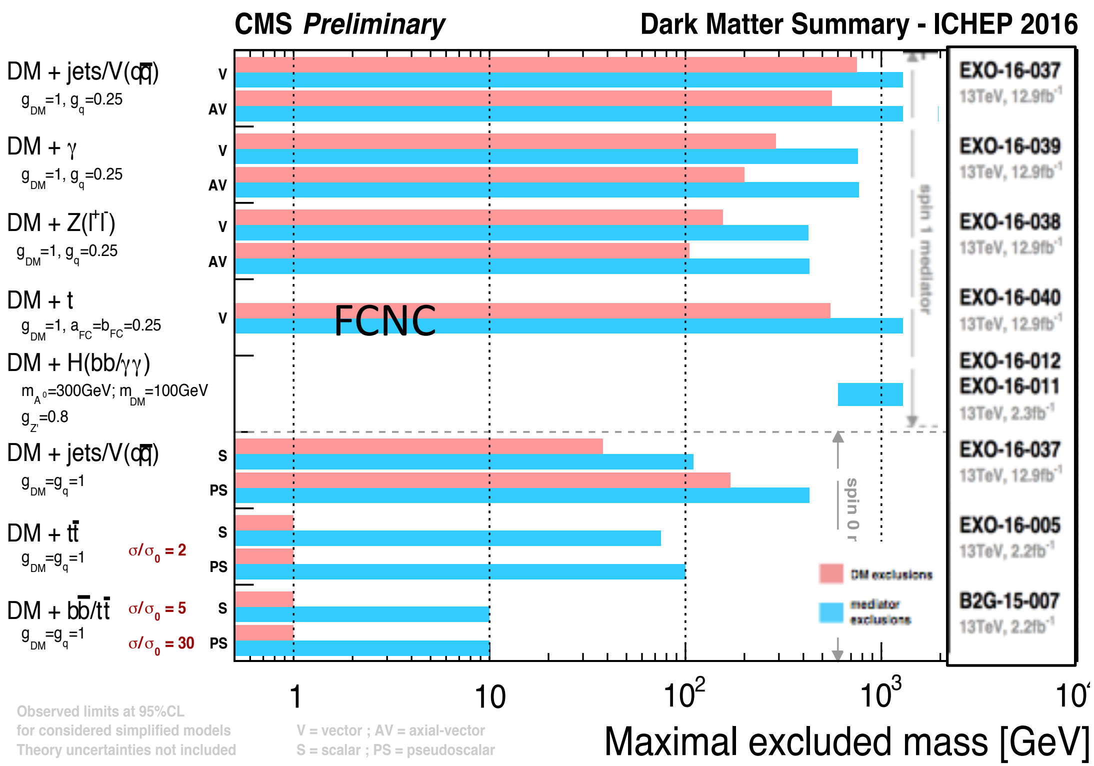


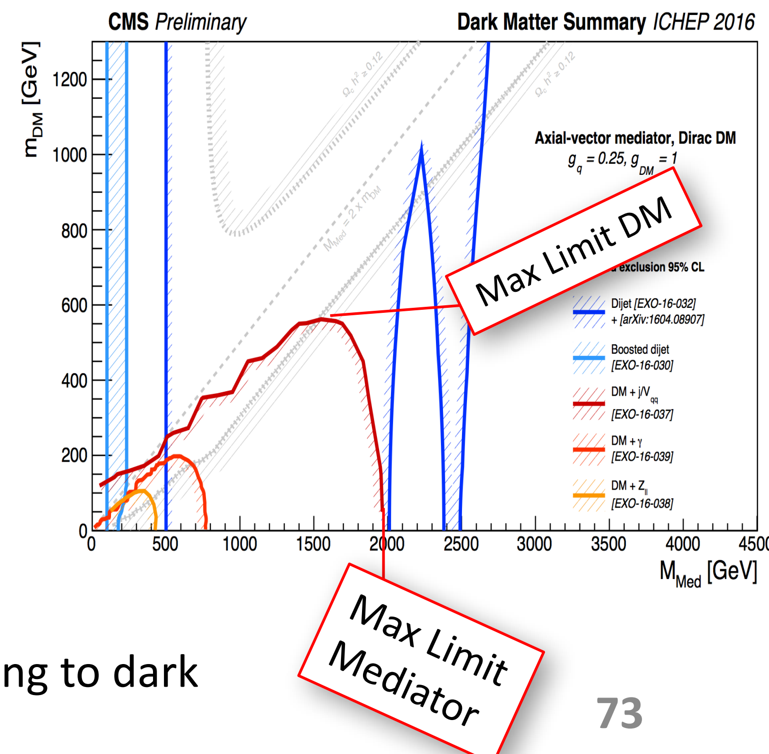






Basic idea: search of mono-object recoiling against MET





Summary of all Dark Matter Searches in Run II
Max and Min Limits on mediator search (blue) decaying to dark matter (red)

SUPERSYMMETRY SEARCHES

Search widely for both Strong and Electroweak production,

covering High Pt final states as well as degenerate states

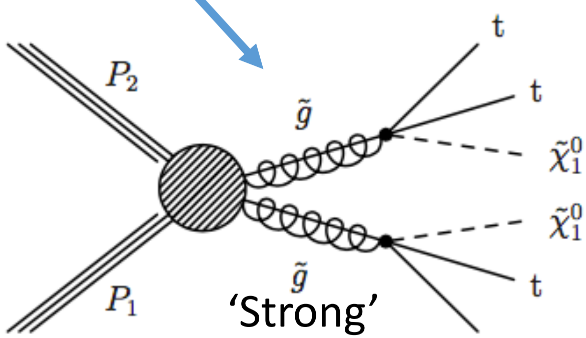
SUSY searches: multileptons

CMS PAS SUS-16-022

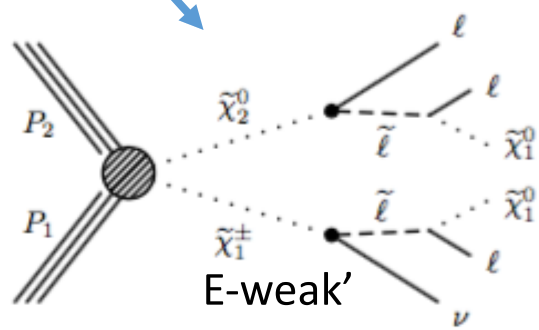
CMS PAS SUS-16-024

Clean signature for complex final states: selecting on the jet activity we can be sensitive to ‘strong’ SUSY productions or Electroweak SUSY production

Example of two SUSY production



‘Strong’ (T1tttt)



E-weak’

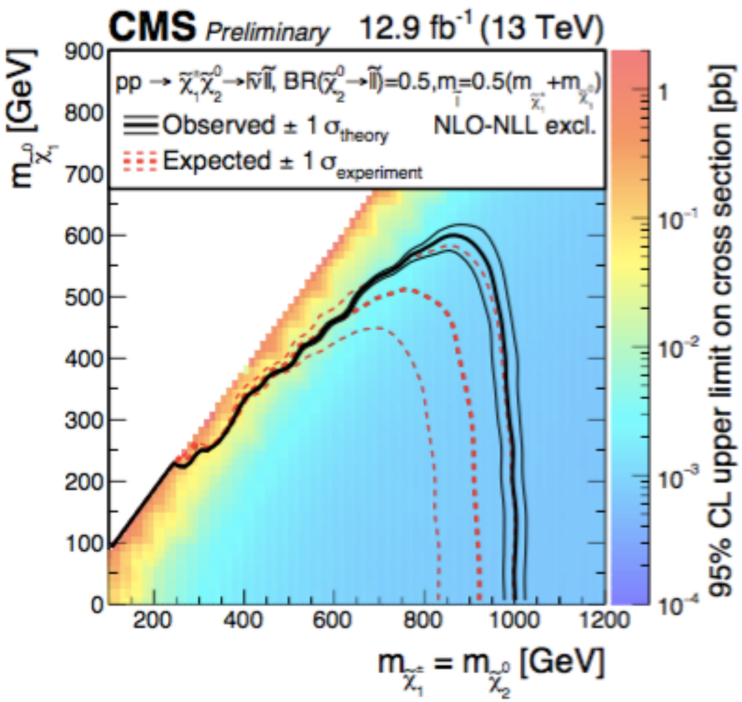
Analyses characterized by large number of Search Regions.

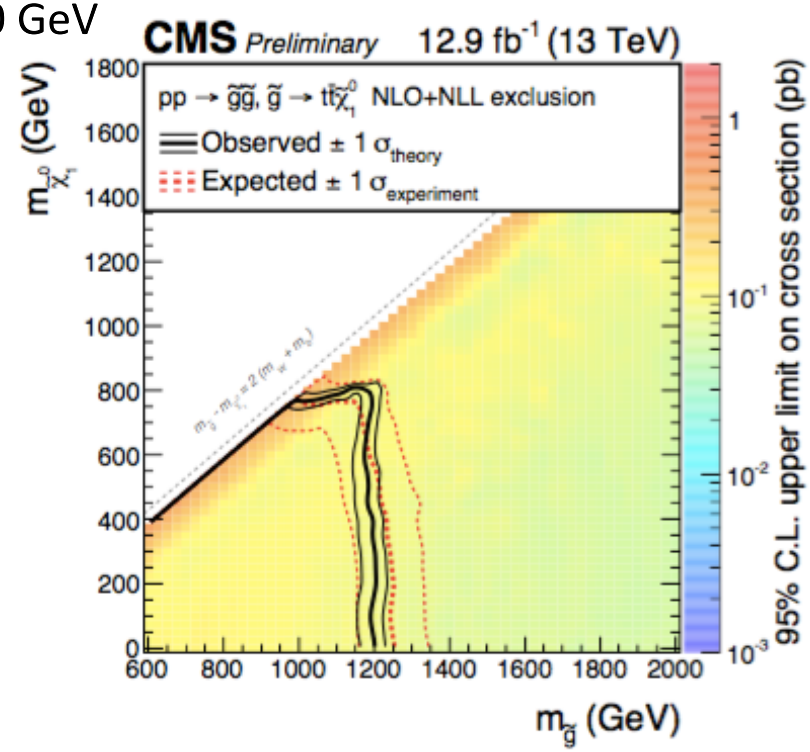
EWK searches: 118 different search regions (dependent on N_jets, N_btag, N_Leptons, flavour, charge…

Strong searches: 32 search regions (nature of jets, $E_T$miss, ΣE_T, di-leptons consistent/not consistent with Z decay.

SUSY Multileptons: some results

None of the search regions has shown significant deviations from the expected SM background : largest deviation 2.5 σ for same sign di-leptons, $N_{jet}=1, M_T<100$GeV, $E_t^{miss}>150$ GeV and pt(ll) ≥50 GeV





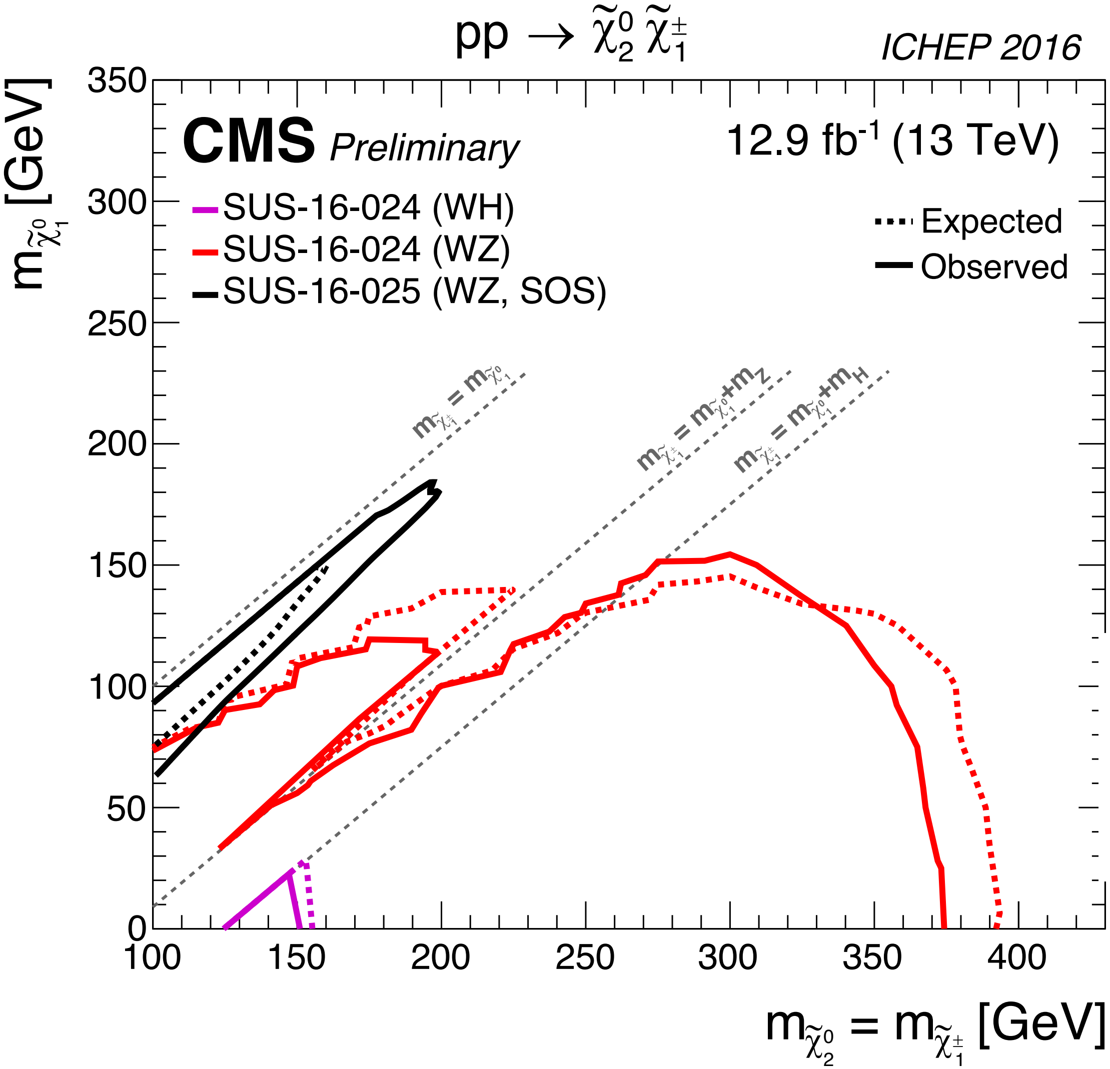
Electroweak production: In flavor democratic scenario we exclude Chargino masses up to 1 TeV (previous Run1 limit was 750 GeV)

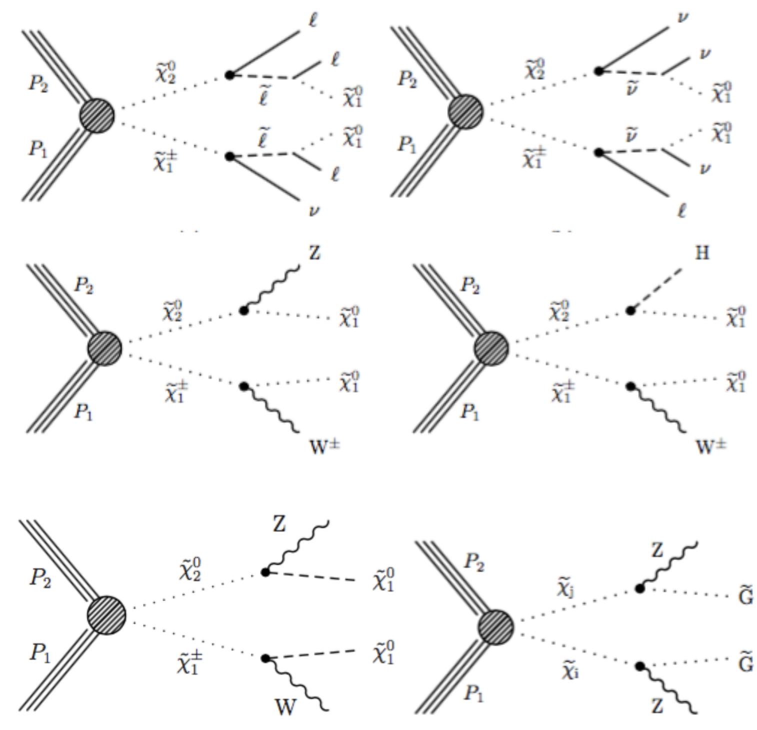
CMS PAS SUS-16-022

CMS PAS SUS-16-024

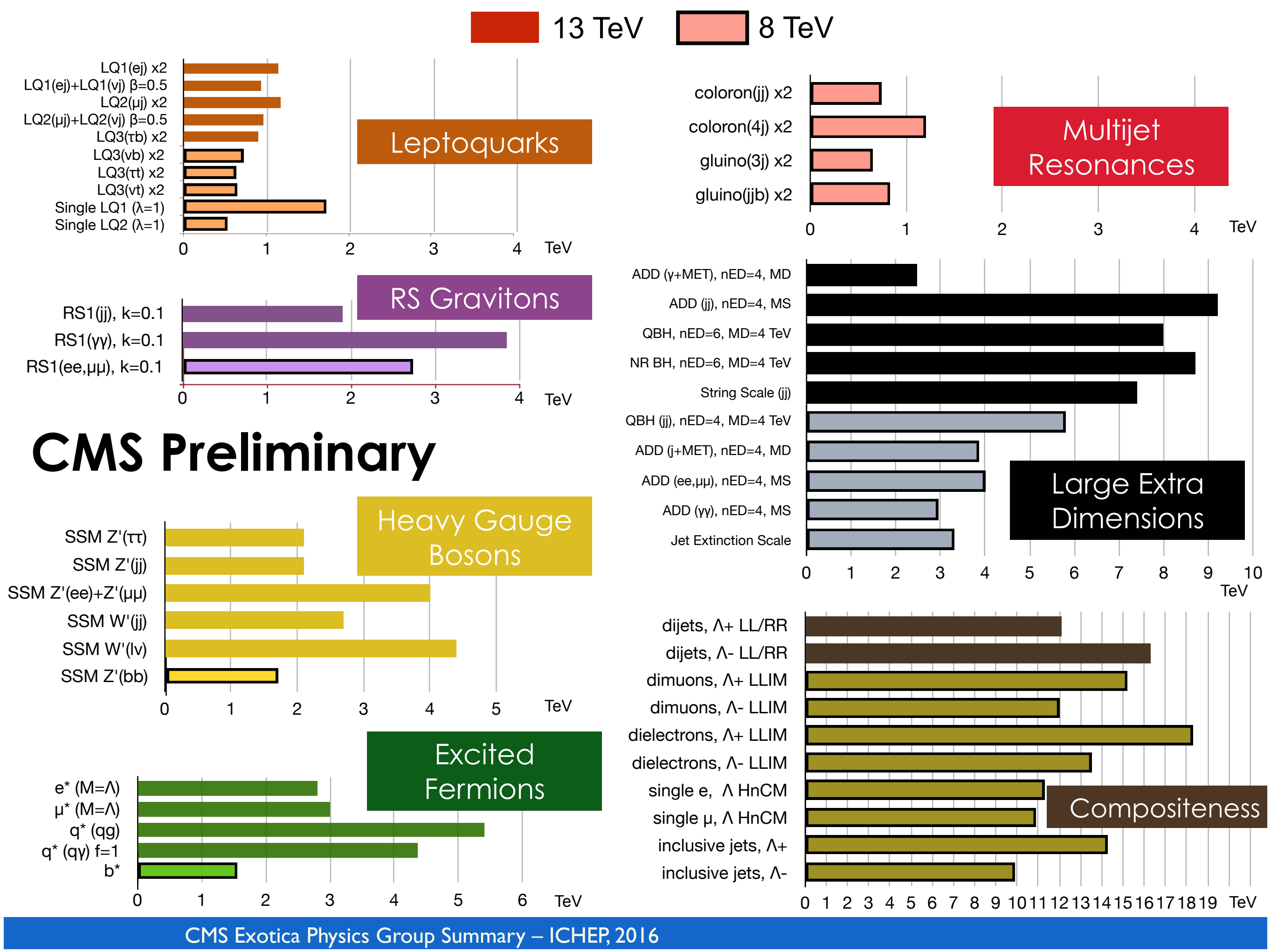
Strong production: we exclude gluino masses up to 1250 GeV and LSP masses up to 750 GeV for simplified model of T1tttt

SUSY compressed mass spectra; example from EWKino production

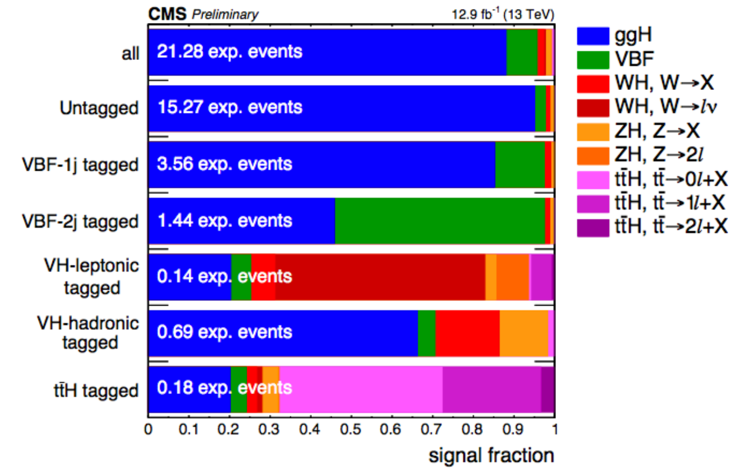


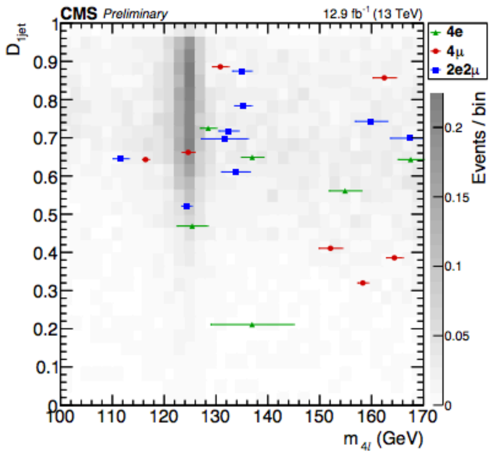


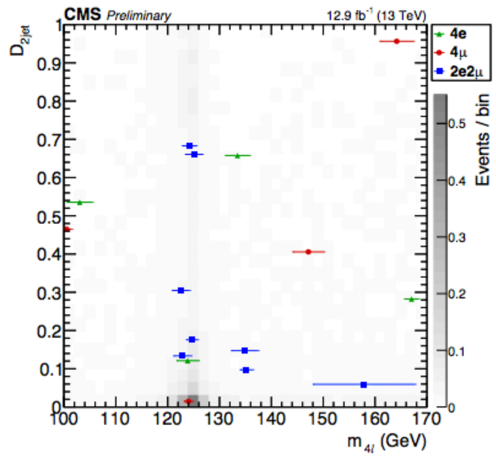
Summary of Exotica searches

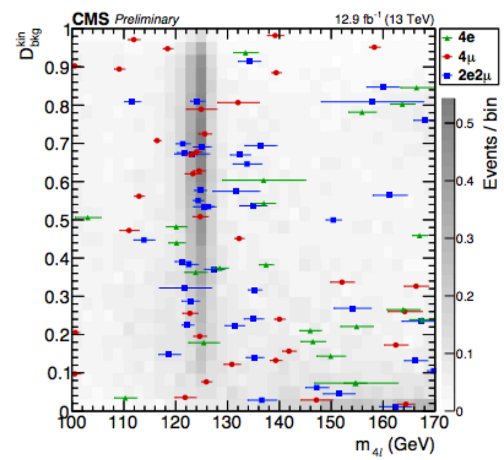


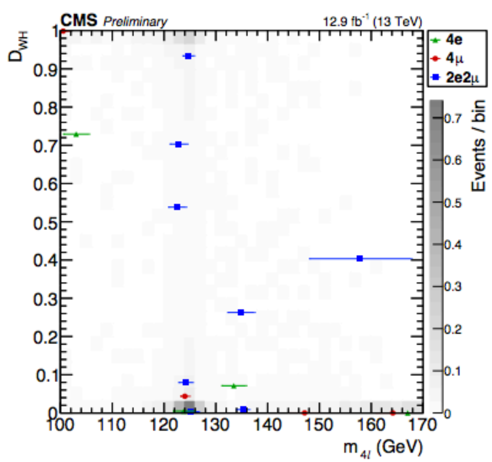
Kinematic distributions HZZ

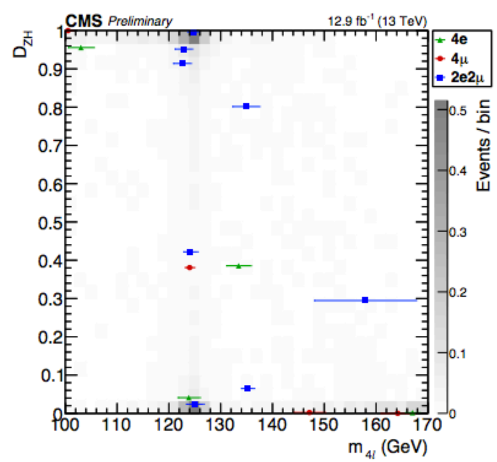












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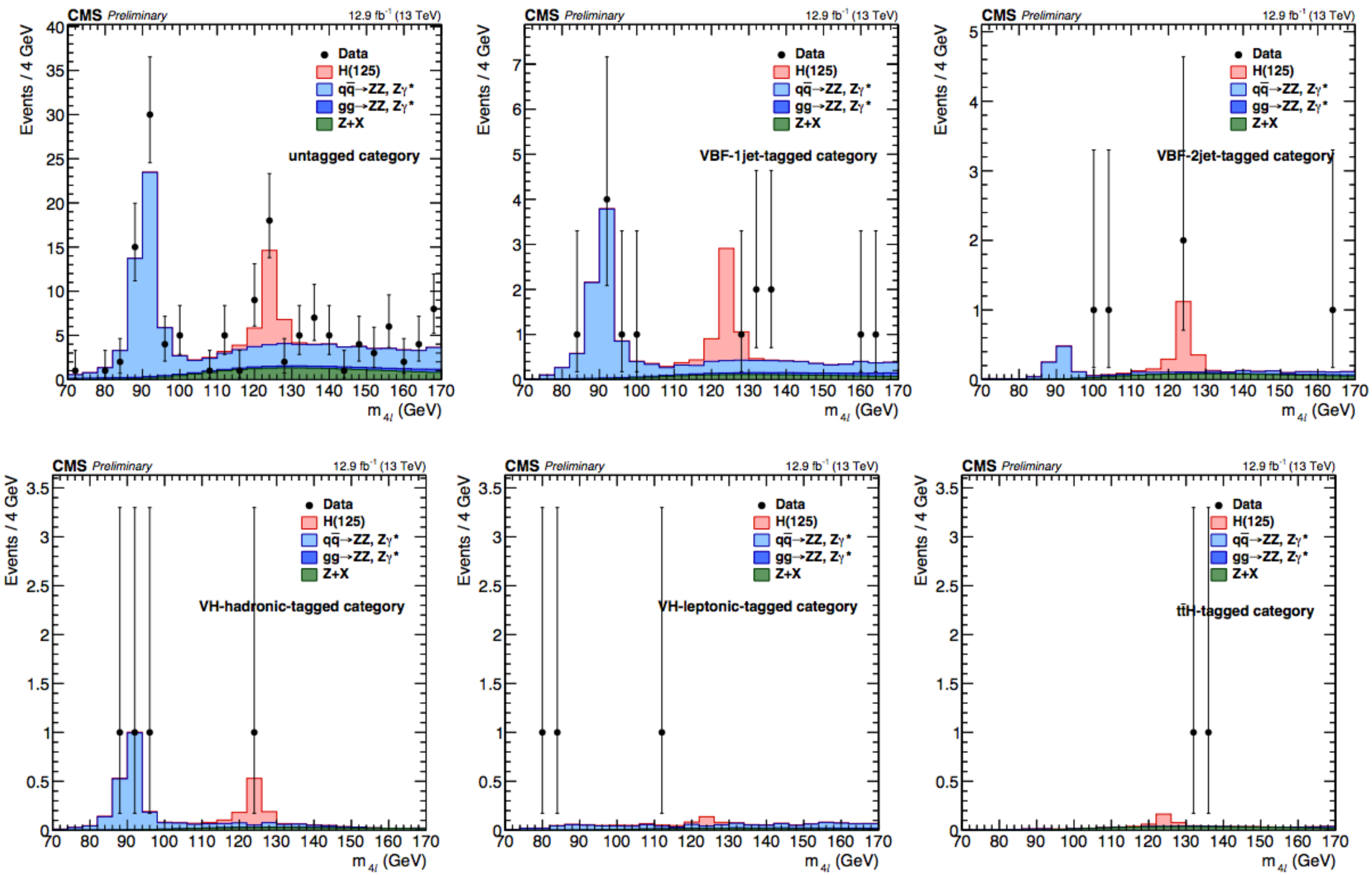
Kinematic distributions HZZ



Systematic uncertainties H → 4l

Table 5: Summary of the systematic uncertainties in the $H \to 4\ell$ measurements.

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	6.2 %
Lepton identification/reconstruction efficiencies	6 – 11 %
Background related uncertainties	
QCD scale ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 10 %
PDF set ($q\bar{q} \to ZZ$, $gg \to ZZ$)	3 – 5 %
Electroweak corrections ($q\bar{q} \to ZZ$)	1 – 15 %
$gg \to ZZ$ K factor	10 %
Reducible background (Z+X)	40 – 55 %
Event categorization (experimental)	2 – 18 %
Event categorization (theoretical)	3 – 20 %
Signal related uncertainties	
QCD scale ($q\bar{q} \to$ VBF/VH, $gg \to H/t\bar{t}H$)	3 – 10 %
PDF set ($q\bar{q} \to$ VBF/VH, $gg \to H/t\bar{t}H$)	3 – 4 %
BR($H \to ZZ \to 4\ell$)	2 %
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %
Event categorization (experimental)	2 – 15 %
Event categorization (theoretical)	8 – 20 %

Fiducial X-section HZZ

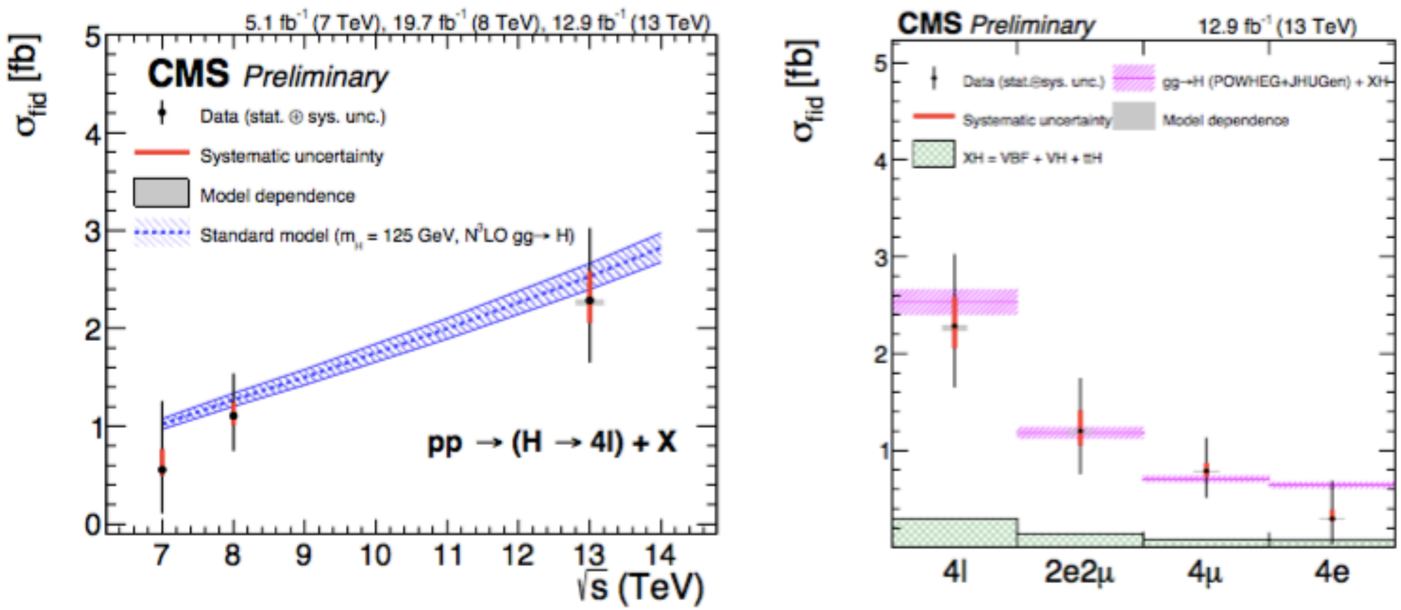
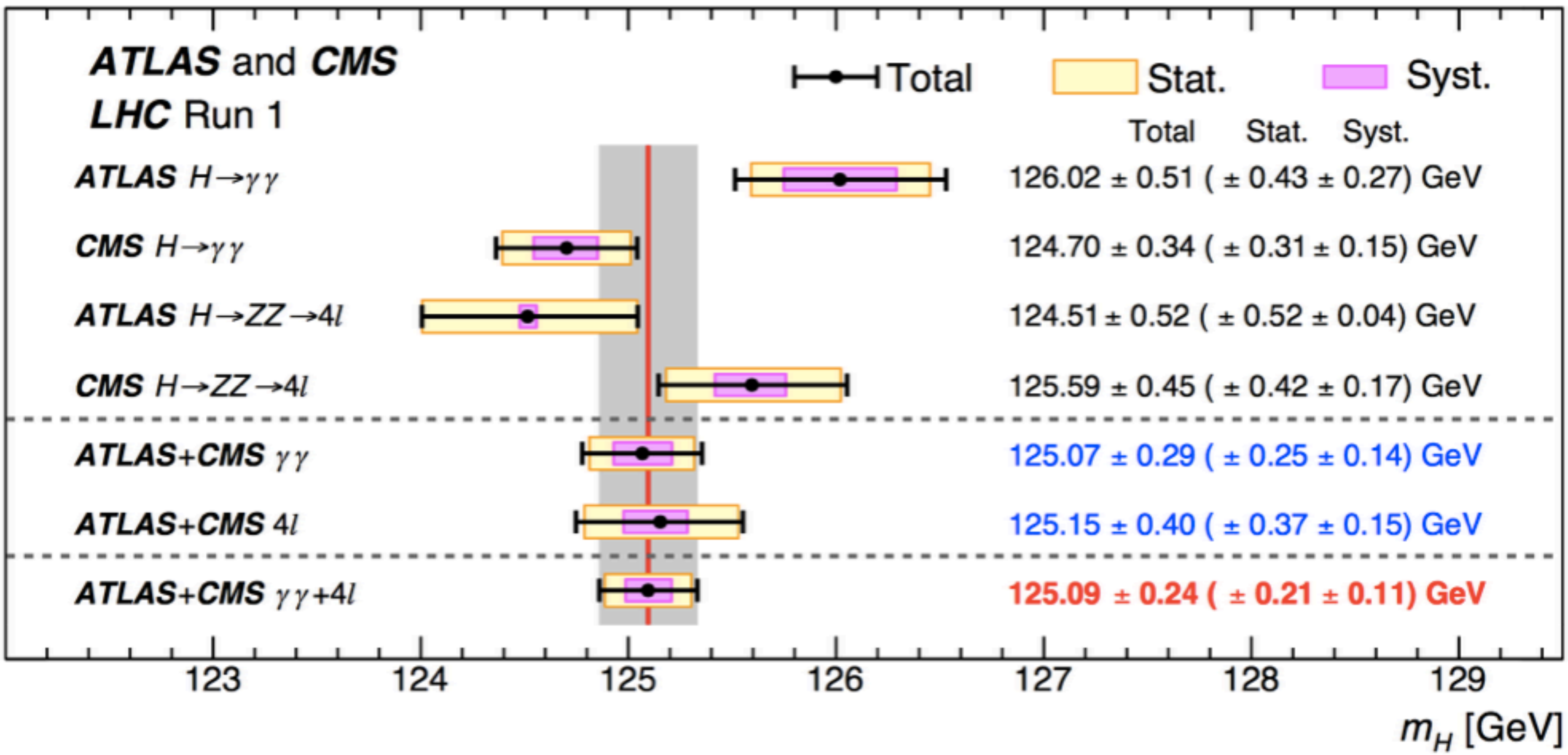


Figure 9: Left: The measured fiducial cross section as a function of $\sqrt{s}$. The acceptance is calculated using POWHEG at $\sqrt{s}$=13 TeV and HRES [50, 52] at $\sqrt{s}$=7 and 8 TeV and the theoretical uncertainty on the gluon fusion contribution is taken from Ref. [25]. The model dependence uses experimental constraints on the relative fraction of the various production modes, as described in the text, and is much less than 1% for the $\sqrt{s}$=7 and 8 TeV measurements. Right: measured fiducial cross section in each final state. The sub-dominant component of the the signal (VBF + VH + $t\bar{t}$H) is denoted as XH.

Hgg systematic uncertainties

- **Theory uncertainties** (PDFs, α_S, QCD scale, underlying event and parton shower, $H\rightarrow\gamma\gamma$ branching fraction)
- **ggH contamination** in VBF and ttH tagged categories
- **Trigger** efficiency, **integrated luminosity**, **vertex** efficiency, **preselection**
- Non-unformity of light collection, non-linearity, detector simulation, modeling of the material budget, shower shape corrections
- Photon energy **scale and resolution**
- **$BDT_{\gamma\ ID}$** and per-photon **energy resolution**
- **Jet** energy scale and smearings
- **b-tagging** efficiency, **gluon-splitting** fraction, **parton shower**, ID efficiency for **e and μ**

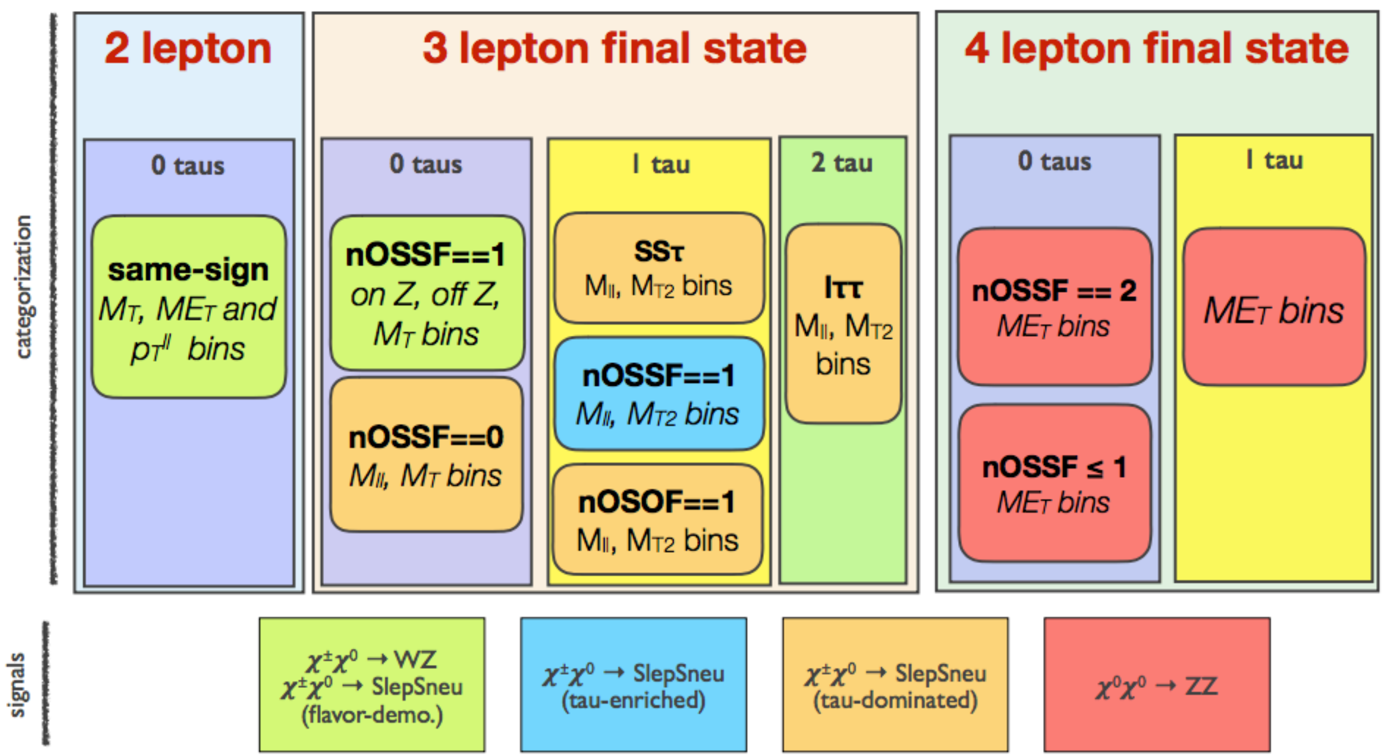
RUN1 Higgs combo



SUSY EWEAK multileptons

CMS PAS SUS-16-024

Categorization

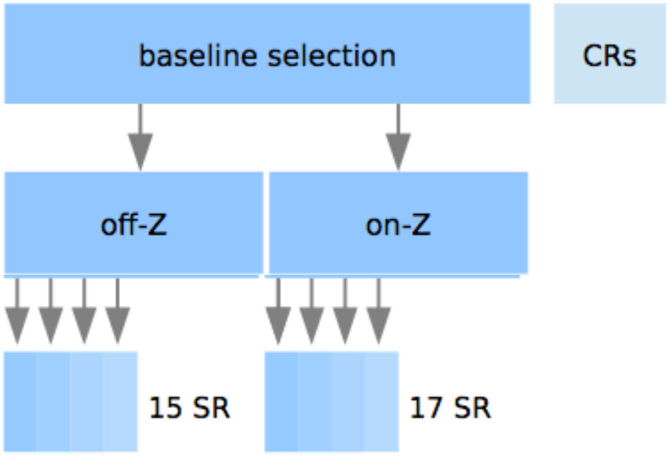


nOSSF = number of OSSF pairs (ee, μμ, ττ)
nOSOF = number of OS different flavour pairs (ee, μμ, eμ)

SUSY 'Strong' Multileptons

- Baseline selection similar to previous search but with improved DY rejection in on-Z regions 1 and 5
  - ≥3 well identified (tight) leptons, passing offline p_T thresholds
  - $m_{ll}^{ossf} > 12$ GeV — reject low mass DY
  - $N_{jets} \geq 2$ — reject DY, WZ
  - $E_T^{miss} > 50$ (70*) GeV — reject DY

    (*70 GeV in SR 1 and 5 on-Z)



- Categorize according to mass of opposite-sign same-flavor (ossf) pair
  - $|m_{ll}^{ossf} - m_Z| < 15$ GeV → on-Z, else: off-Z
- Different background compositions
  - Off-Z: largest contribution from non-prompt leptons
  - On-Z: less fakes, more WZ, DY largely suppressed by E_T^{miss} cut

Dijet resonance width

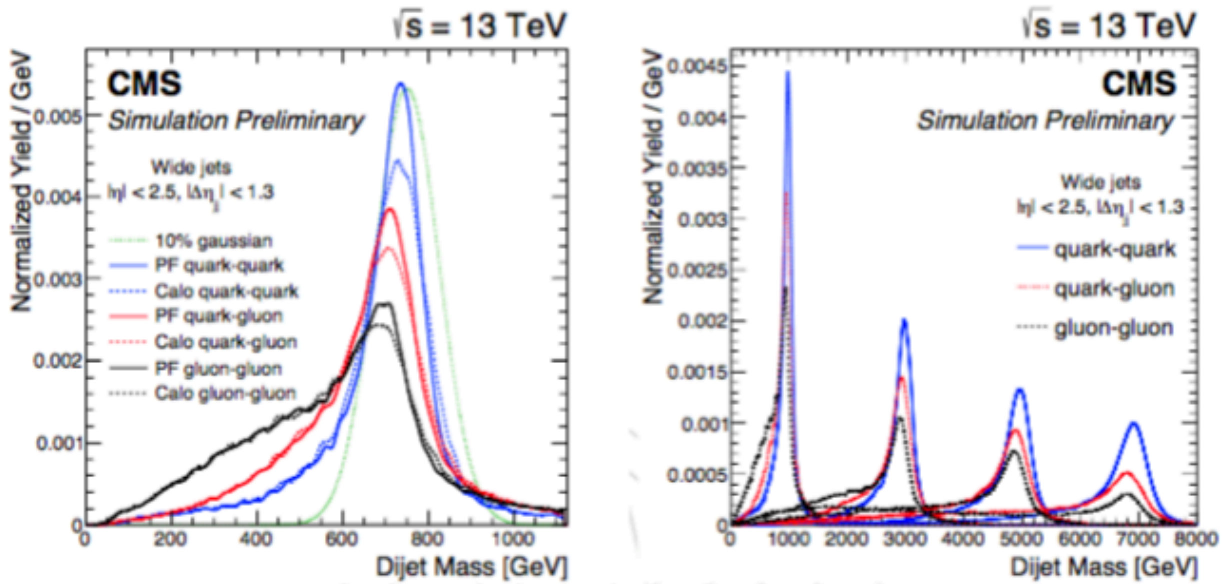
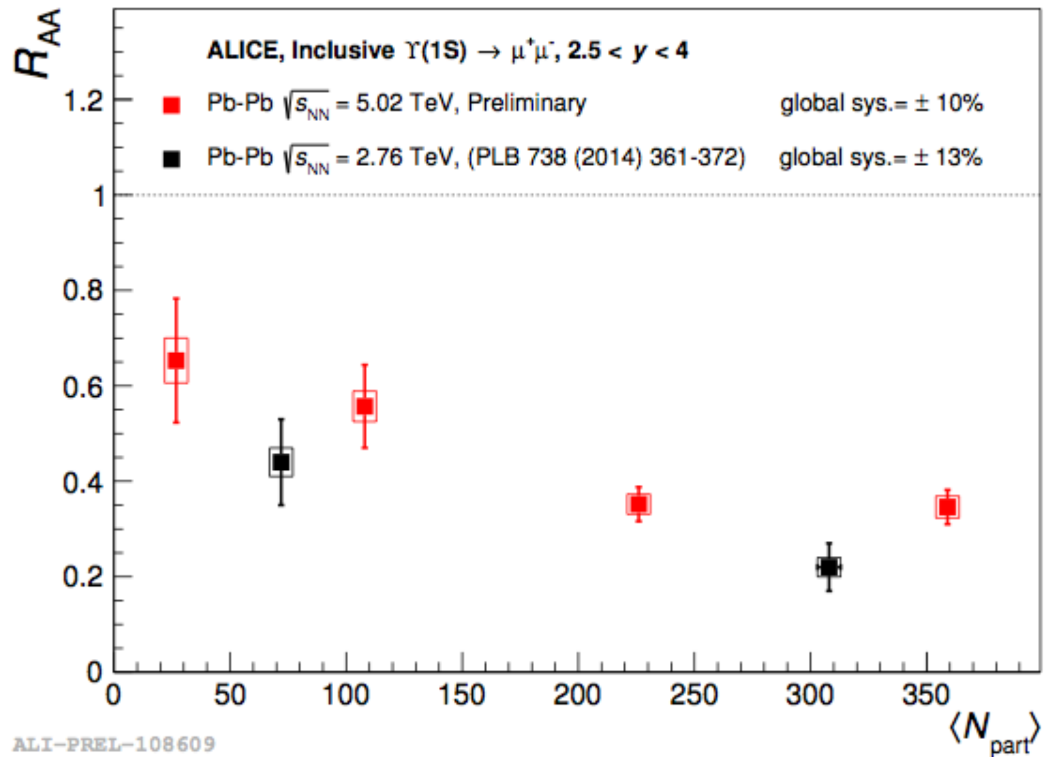
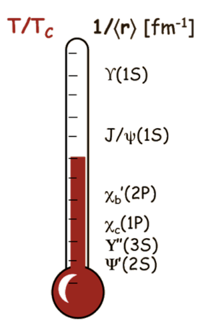


Figure 3: The reconstructed resonance mass spectrum predicted by the PYTHIA 8 MC event generator including simulation of the detector. Resonances from quark-quark processes modeled by $q\bar{q} \rightarrow G \rightarrow q\bar{q}$ (blue), quark-gluon processes modeled by $qg \rightarrow q^* \rightarrow qg$ (red), and gluon-gluon processes modeled by $gg \rightarrow G \rightarrow gg$ (black), where G is an RS graviton and q^* is an excited quark. (left) Resonances generated with a mass of 750 GeV are shown for wide jets from PF-jet reconstruction (solid) and calo-jet reconstruction (dashed). Also shown is a hypothetical Gaussian shape (dotted green) with a mean mass of 750 GeV and an RMS width equal to 10% of the mean mass. (right) Resonances generated with a mass of 1, 3, 5 and 7 TeV are shown for wide jets from PF-jet reconstruction.

Quarkonia: Υ suppression

Run 2: 5.02 TeV Pb-Pb





Υ suppression at 5.02 TeV similar to 2.76 TeV

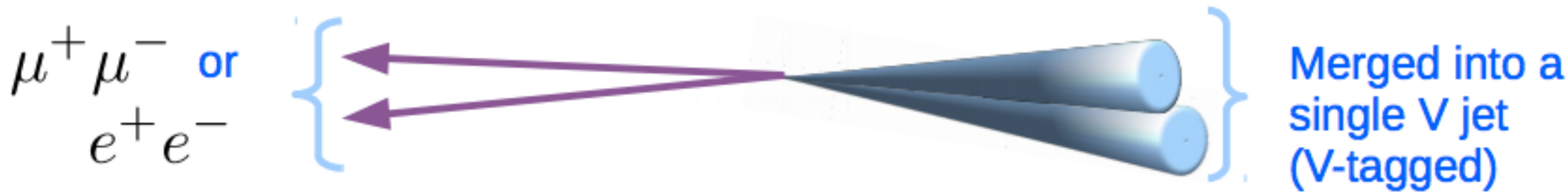
Does regeneration play a role for bottomonia, too?

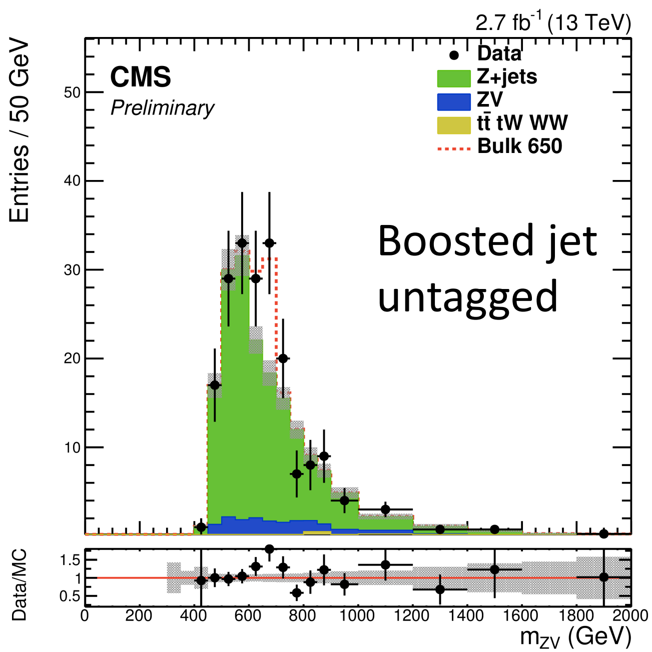
Search for di-bosons in llqq channel

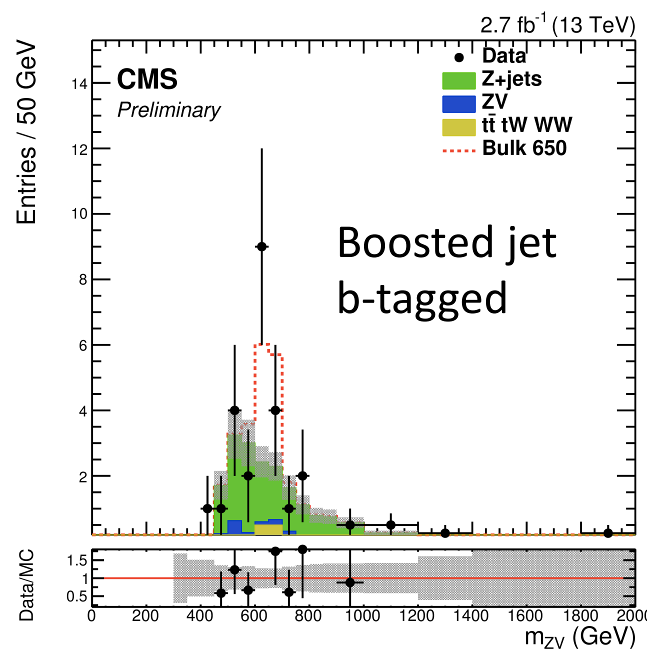
CMS PAS B2G-16-010

Analysis form 2015 dataset: reload with 2016 lumi not ready yet

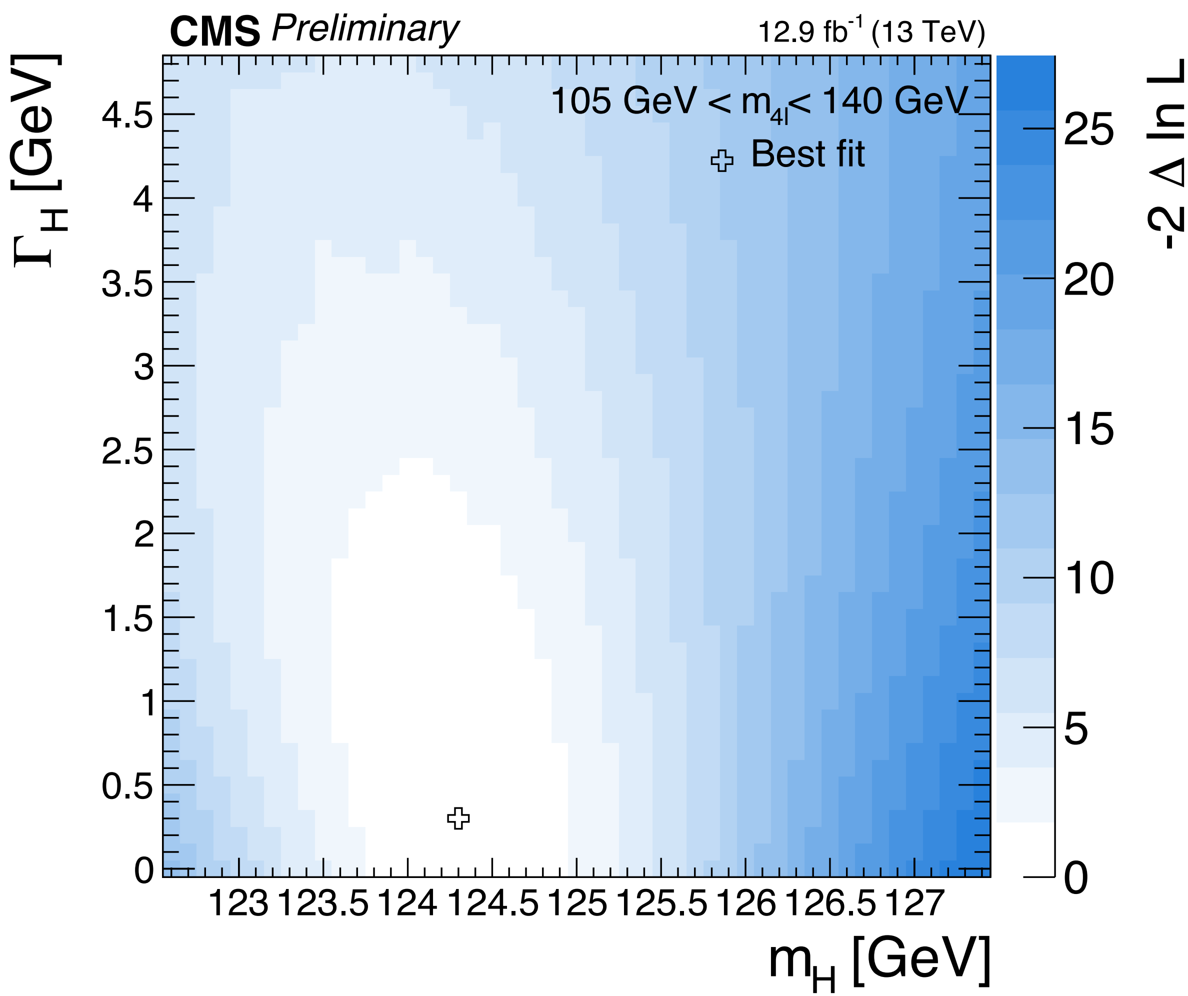
Excess at 650 : local P-value 3.4(3.9)σ for RS (Bulk) graviton interpretation (2.9-3.4σ including LEE)







H width from ZZ decay



Same sign dilepton E-weak SuSY search

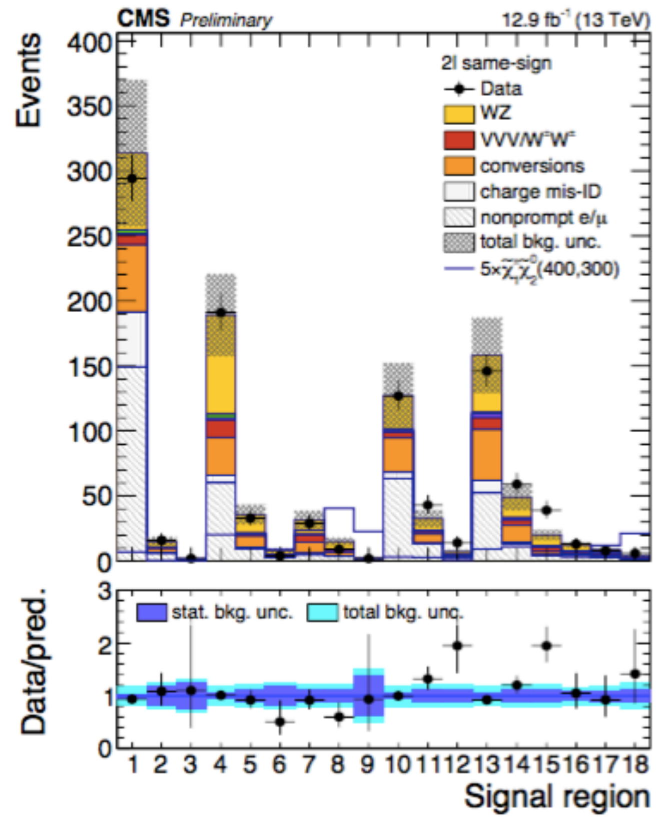
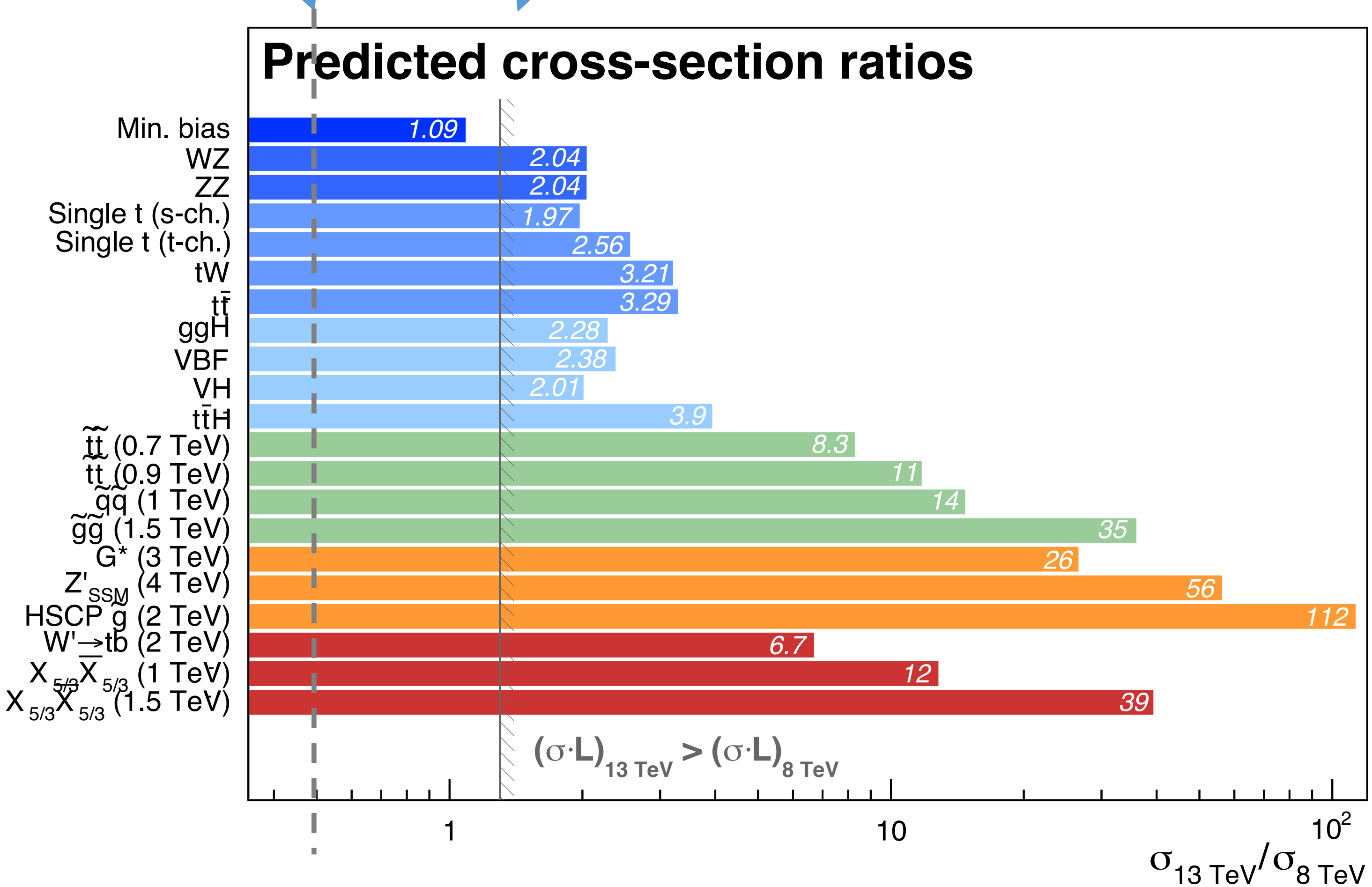


Figure 6: Expected yields and observed counts for the search regions defined in the same-sign dilepton category. The blue line represents the yield in the flavor-democratic scenario of $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$ production with $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 400\,\text{GeV}$, $m_{\tilde{\chi}^0_1} = 300\,\text{GeV}$, and $x_{\tilde{\ell}} = 0.05$, scaled up by a factor of 5. The lower panel shows the ratio between the observed and expected yields in all signal regions, with the dark blue band indicating the statistical background uncertainty, and the light blue band corresponding to the total background uncertainty propagated to the ratio.

Physics reach

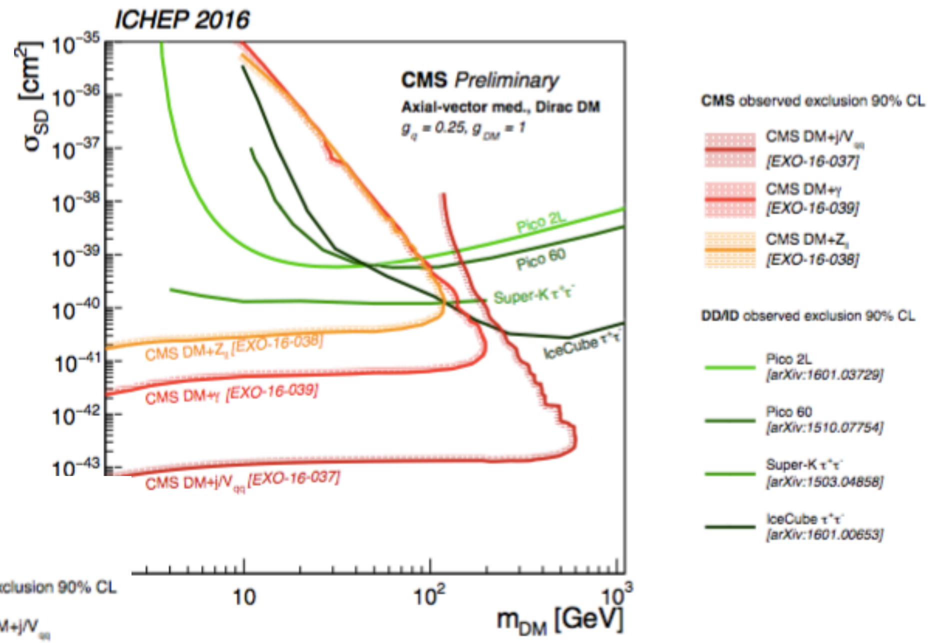
End 2016 ?

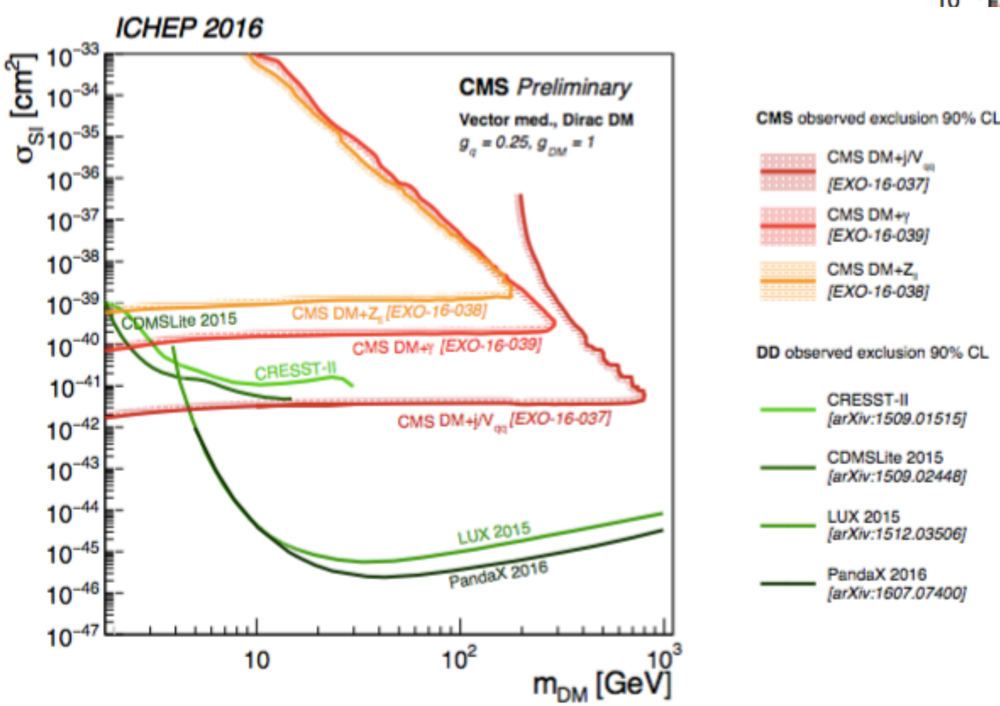
At ICHEP



Dark matter limits

Spin Dependent X-sections Vs m_{DM}

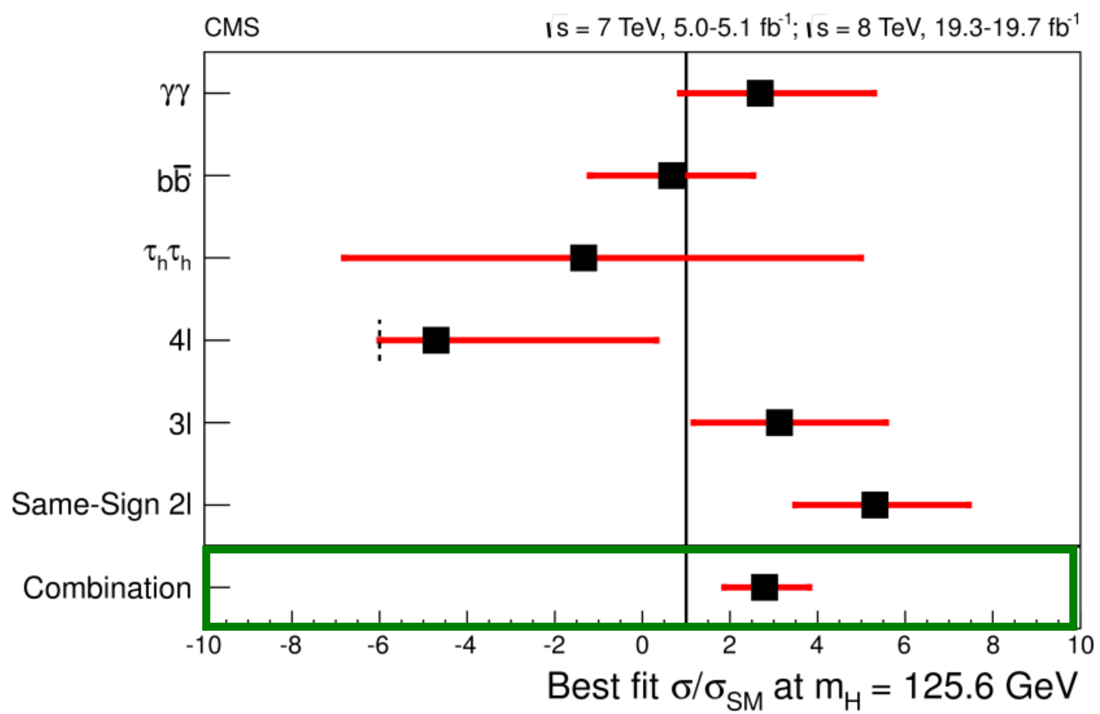




Spin Independent X-sections Vs m_{DM}

ttH: Run1

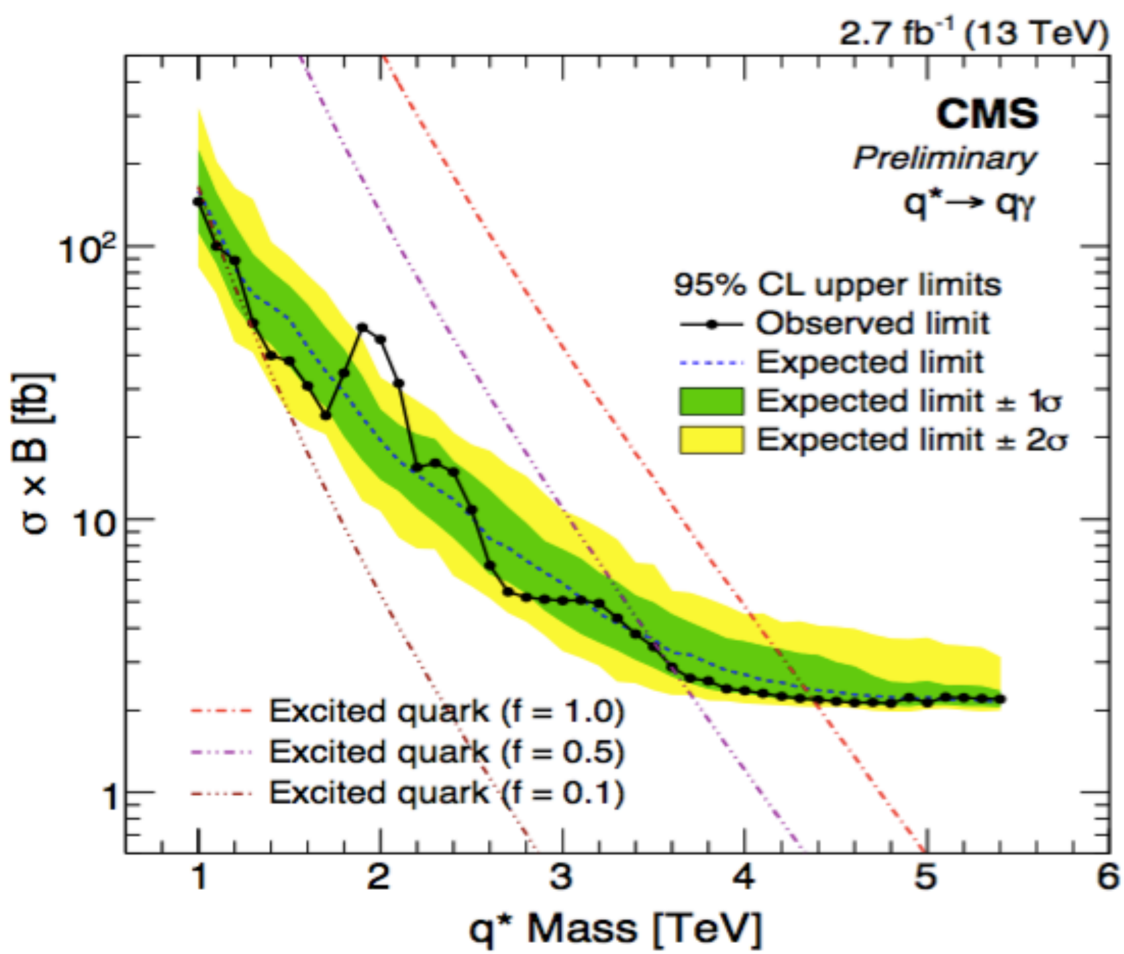
>2σ discrepancy with respect to the Standard model: driven by same sign di-muons



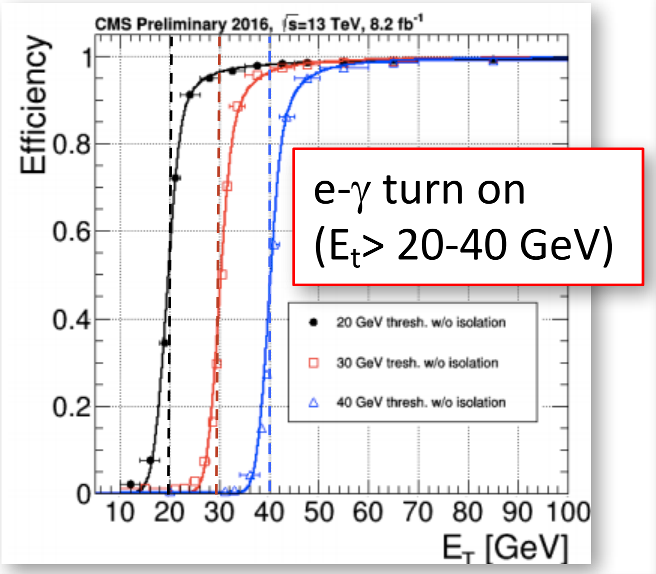
Search for excited quarks: q→γ+ jets

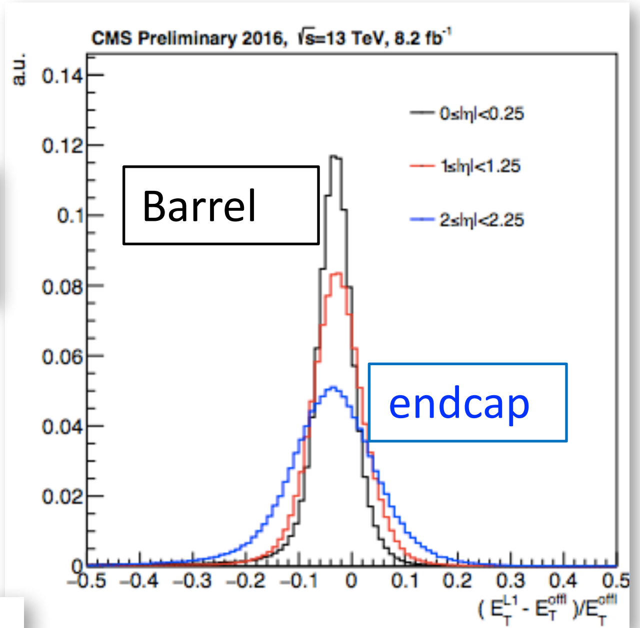
CMS PAS EXO-16-015

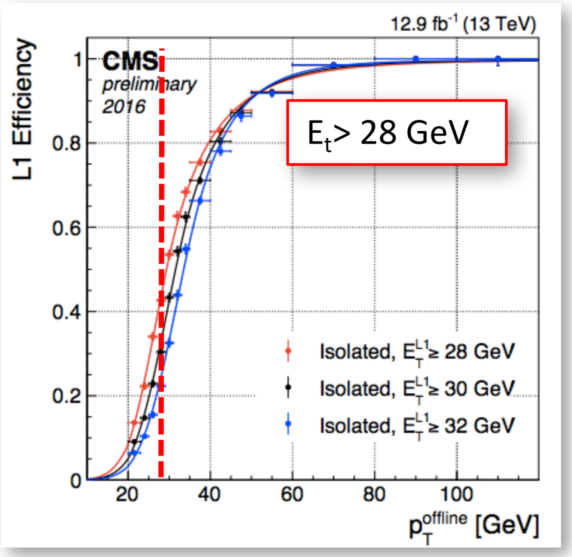
2015 data: analysis on 2016 ongoing

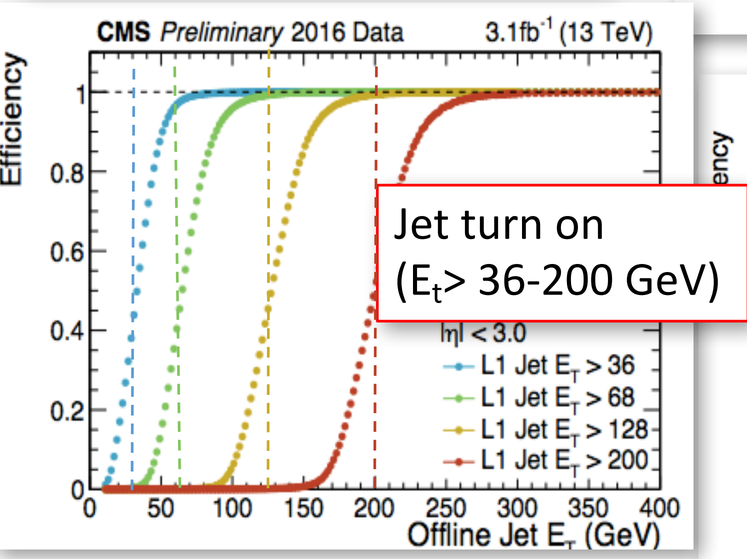


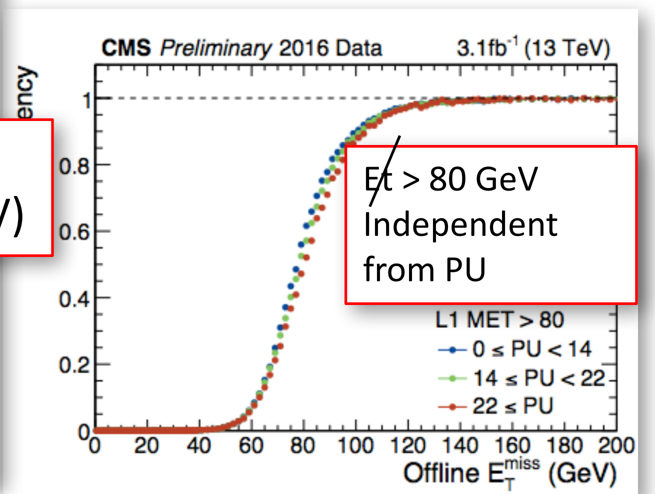
Trigger upgrade Performance

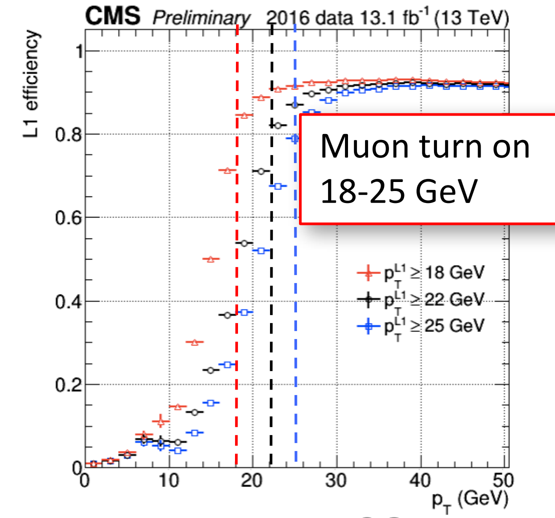






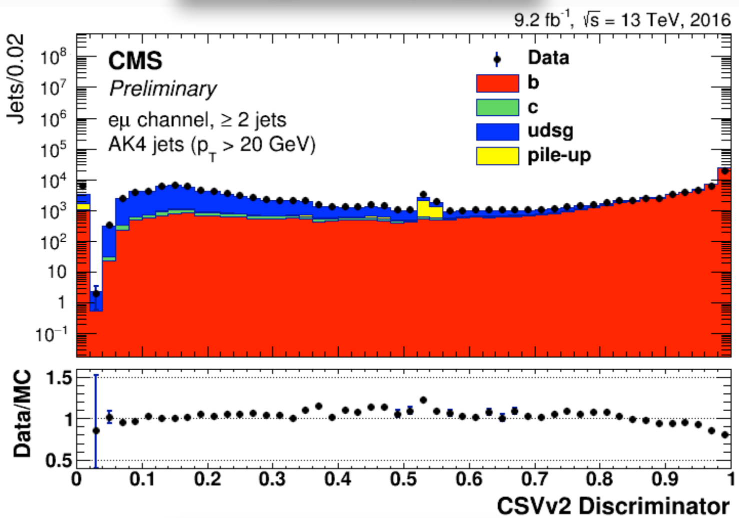




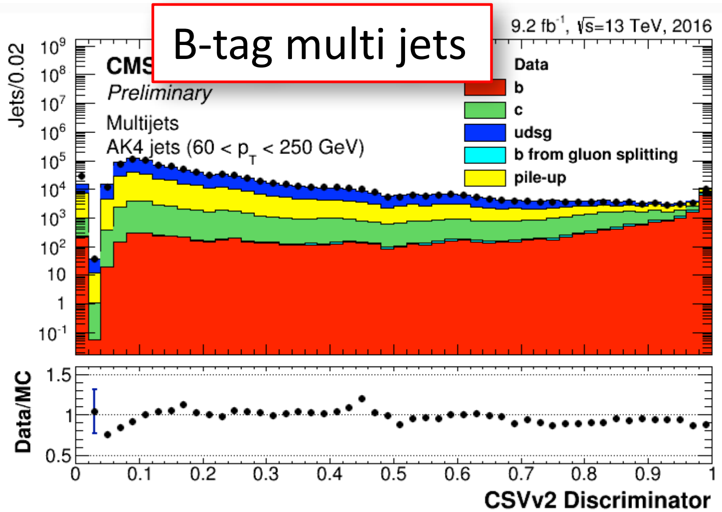


Physics Object performance

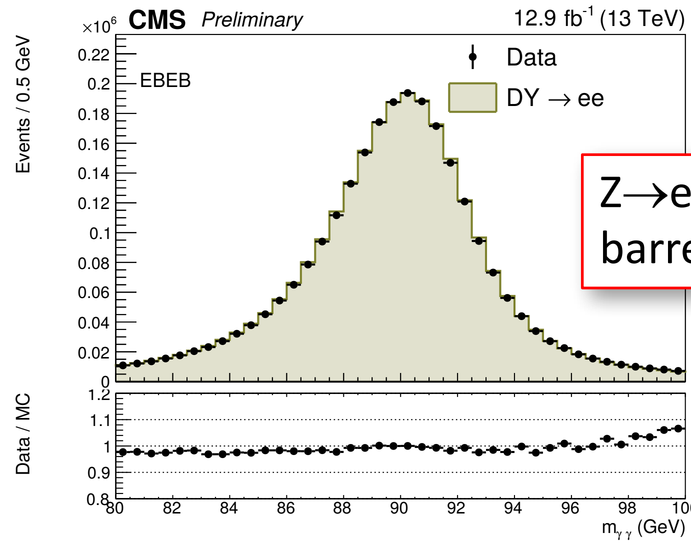
B-tag ttbar(e-μ)



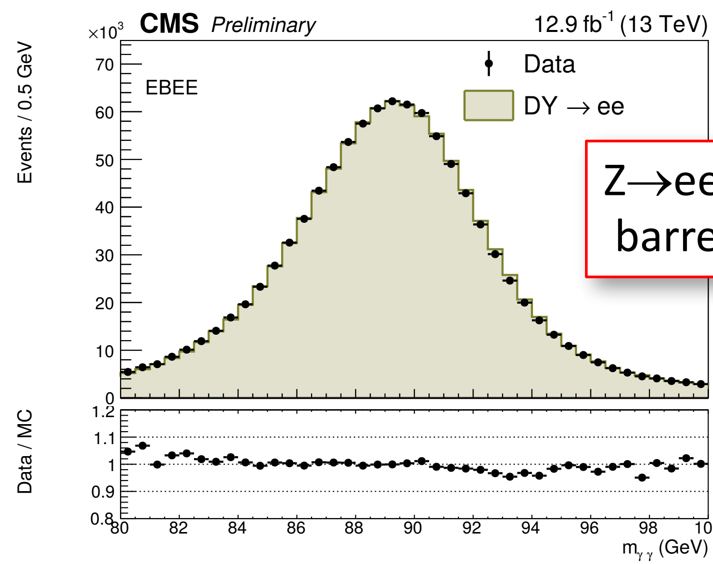
B-tag multi jets



CMS-DP-2016-042



Z→ee barrel

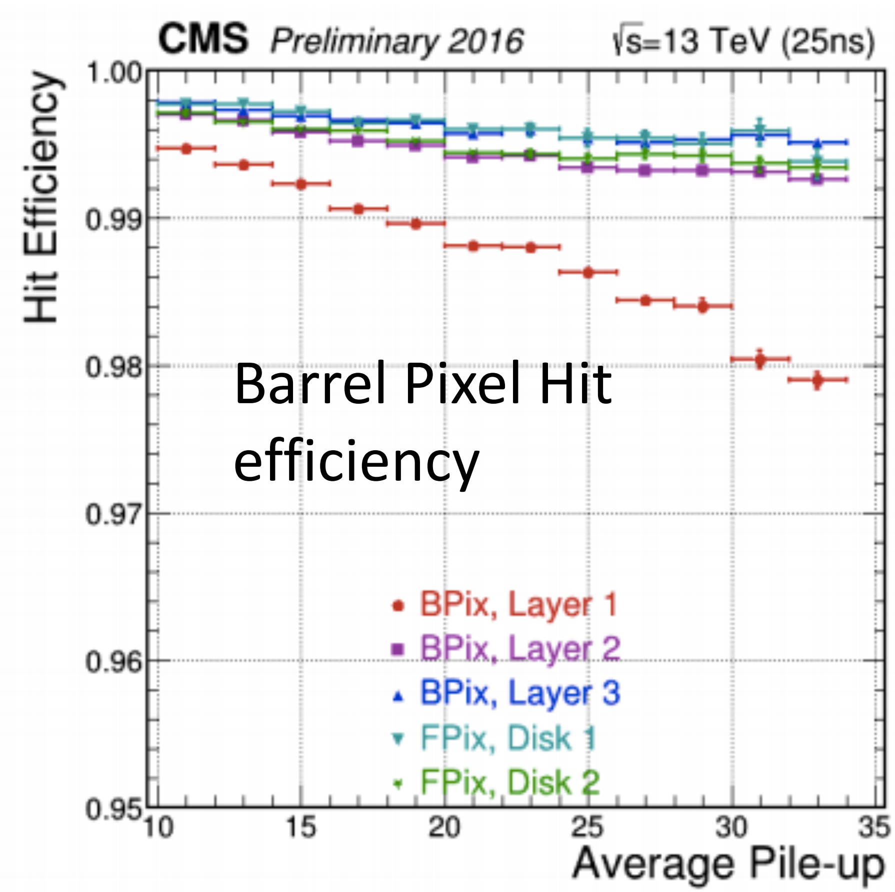


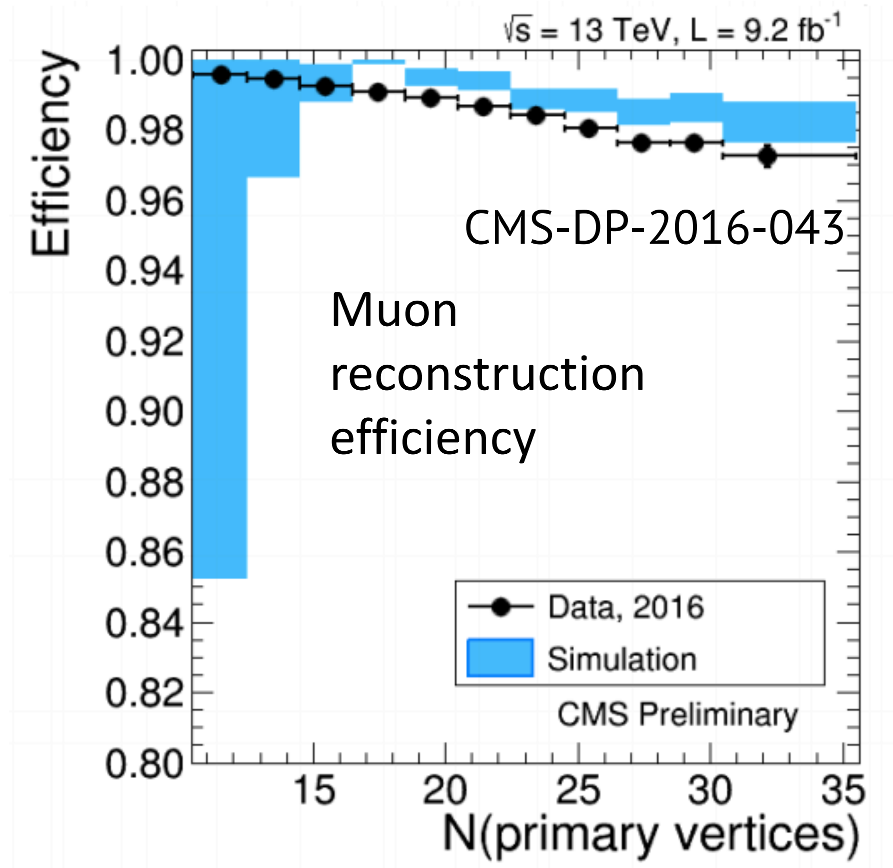
Z→ee barrel-endcap

CMS-DP-2016-049

High lumi→ High Pileup

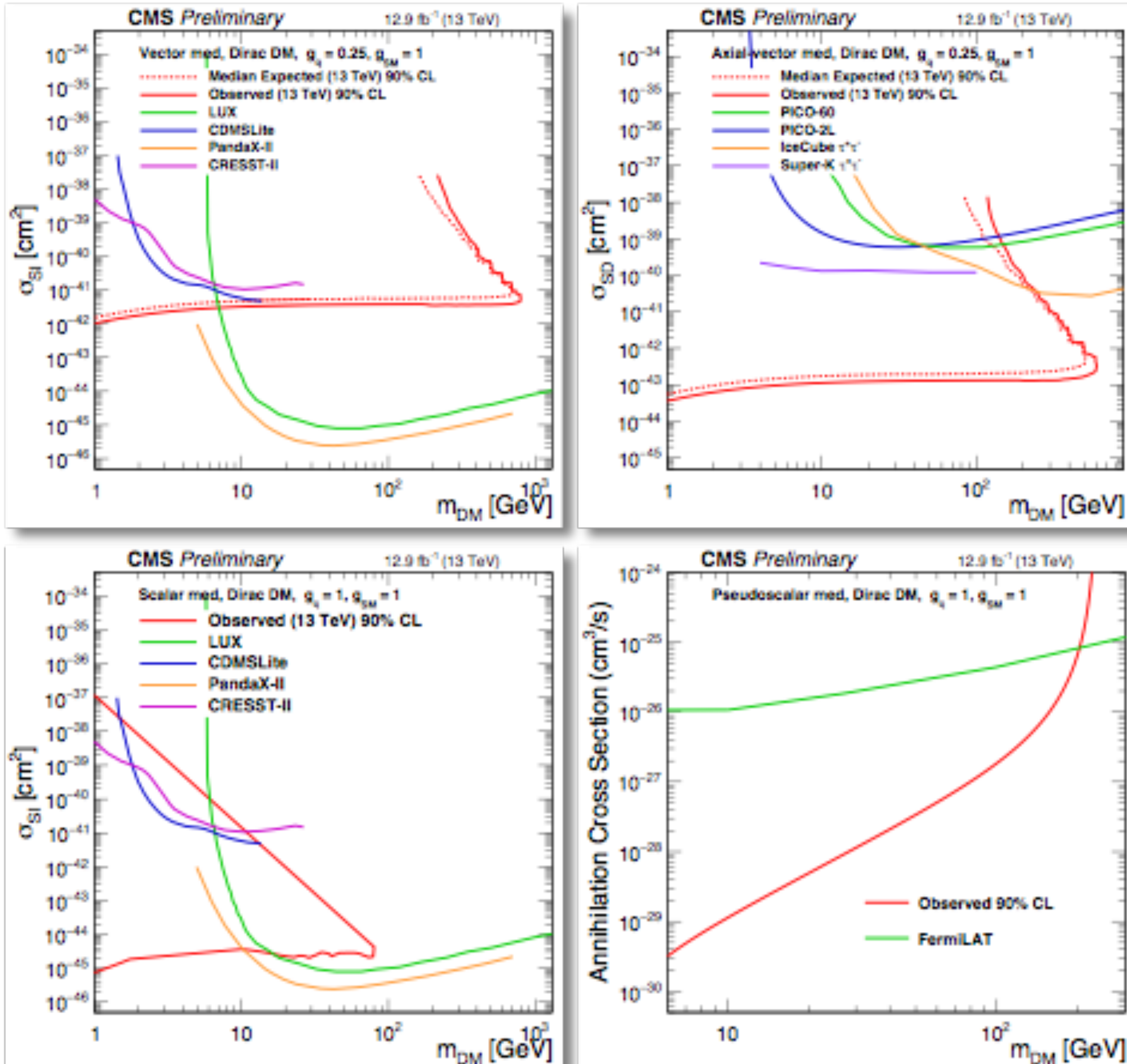
Dealing with Pileup close or above 40 is a challenge!





Dark Mattter: comparison with Indirect searched

CMS PAS EXO-16-037



Giudice & Lebedev (08); see also Bauer, et al. (15).
Ghosh, Gupta & GP; see also: Altmannshofer, et al. (15).