New Results from CMS

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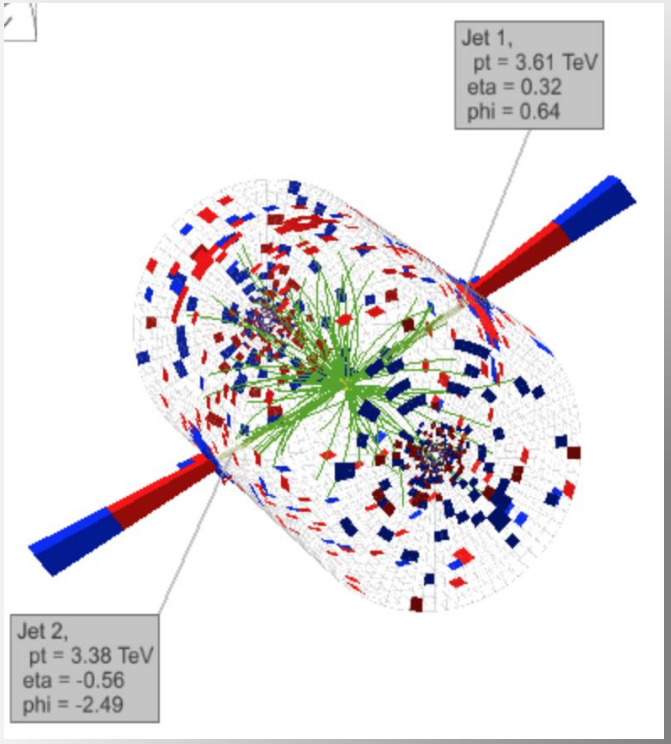
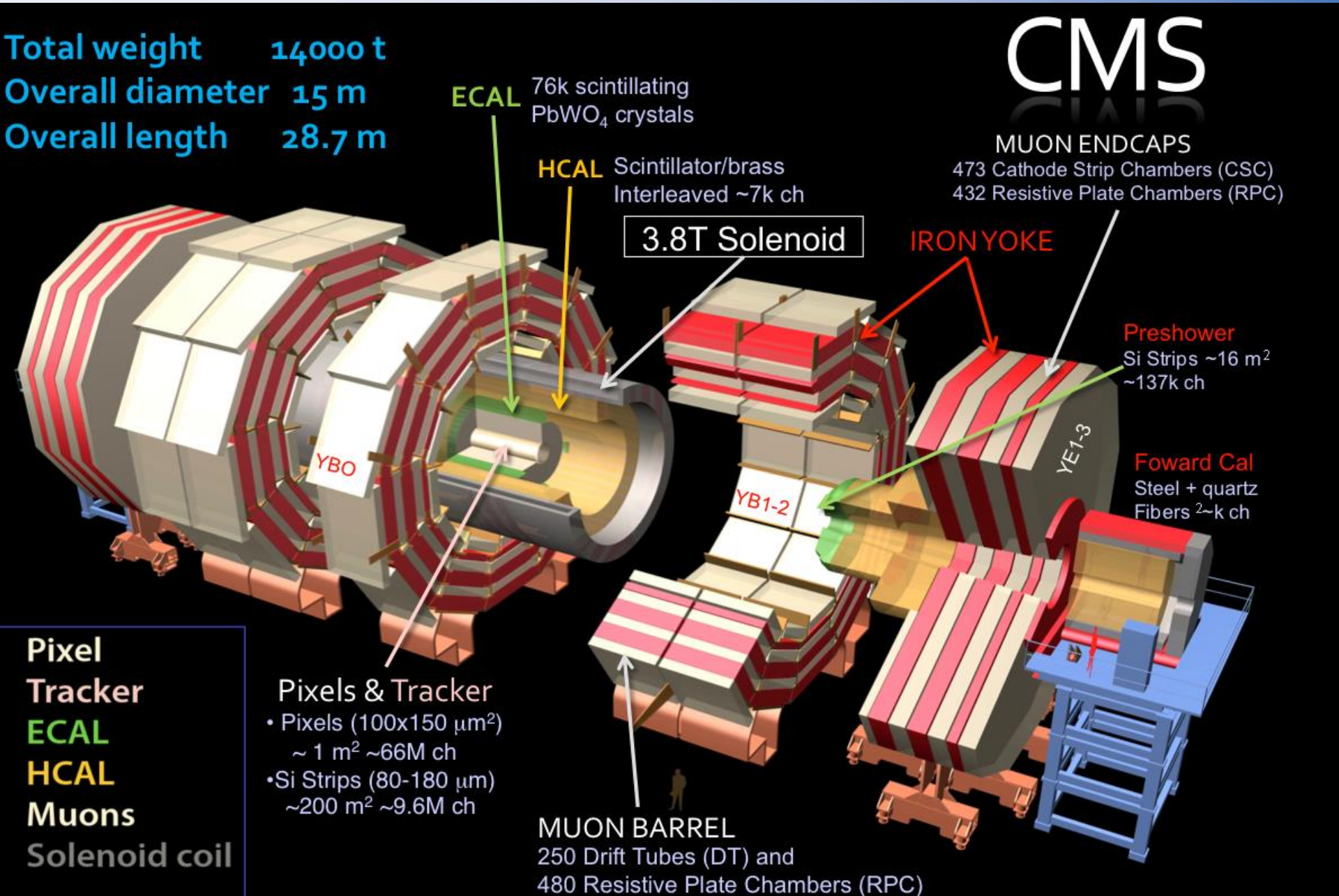
4th September 2017



Outline

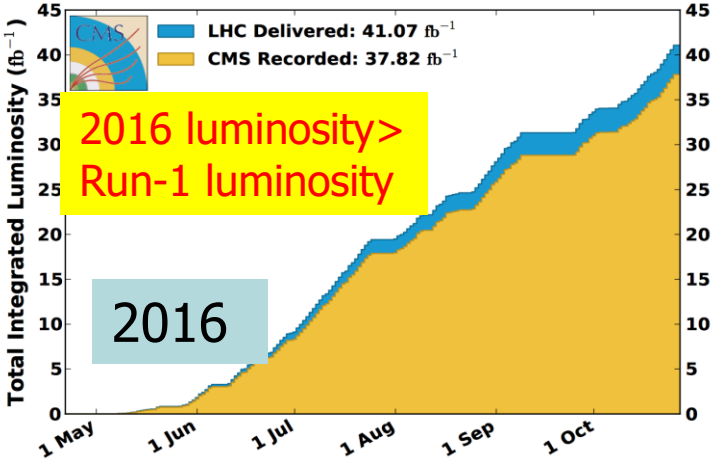
- Introduction
- Physics results
  - The Standard Model at 7, 8 and 13 TeV
  - The Higgs particle
  - Searches for New Physics & Dark Matter
  - Summary/Outlook

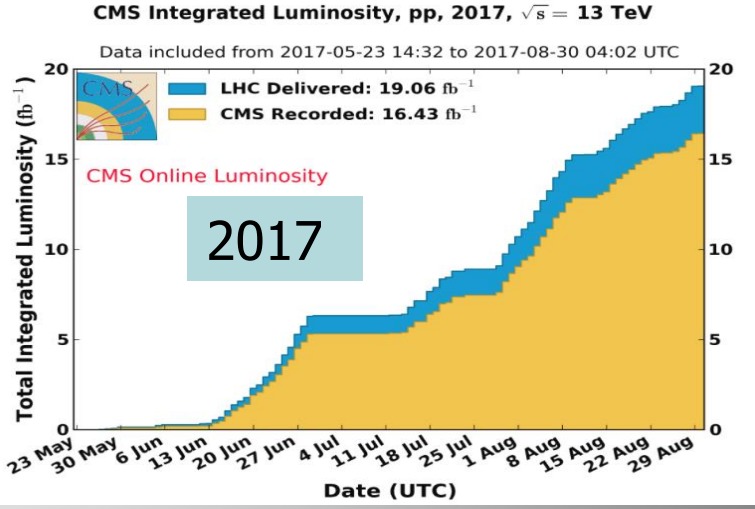
The CMS Detector



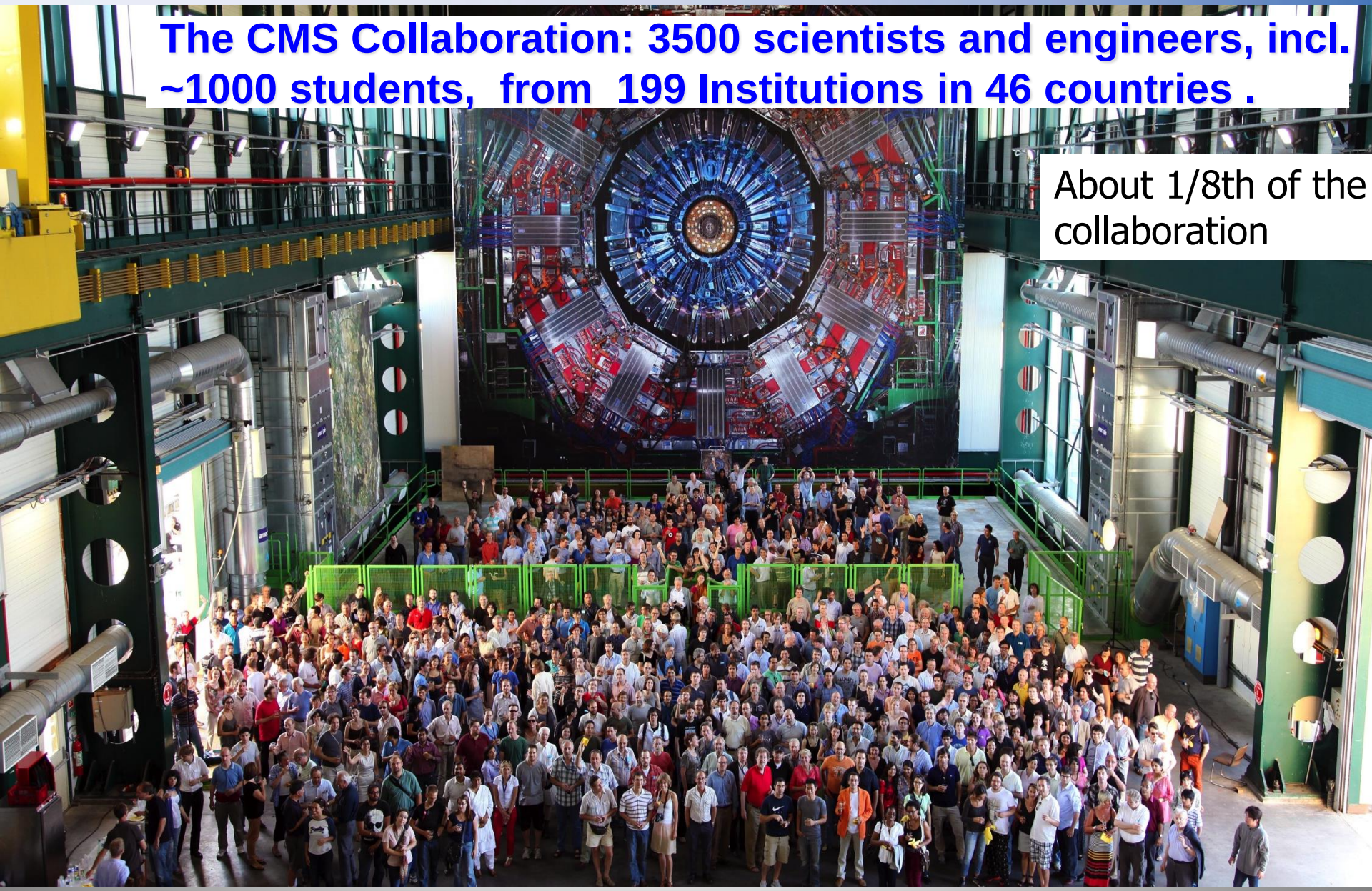
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts



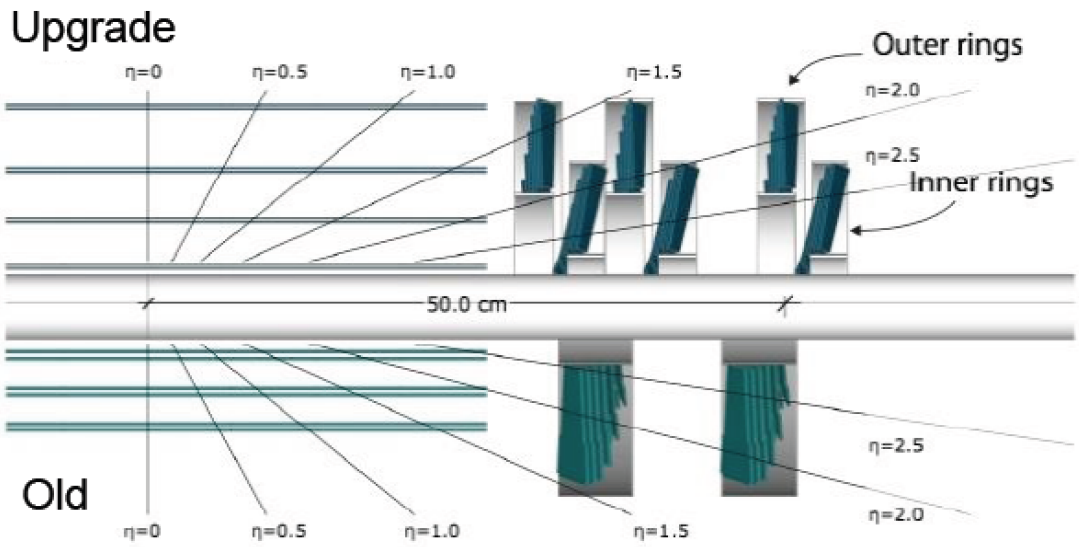


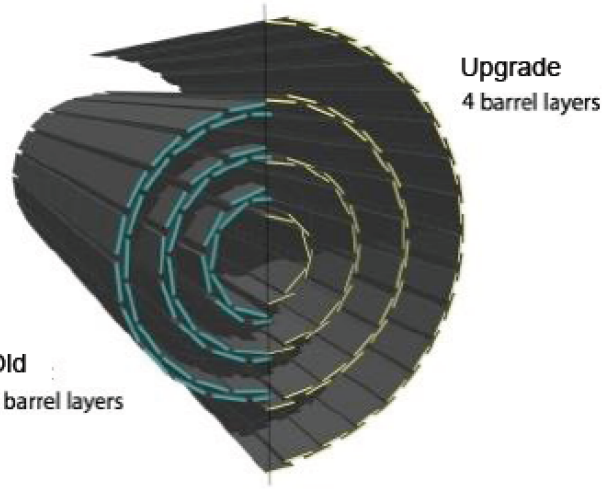
CMS Collaboration June 27, 2012



New for the 2017 Run

EYTS 2017: Pixel Detector Upgrade



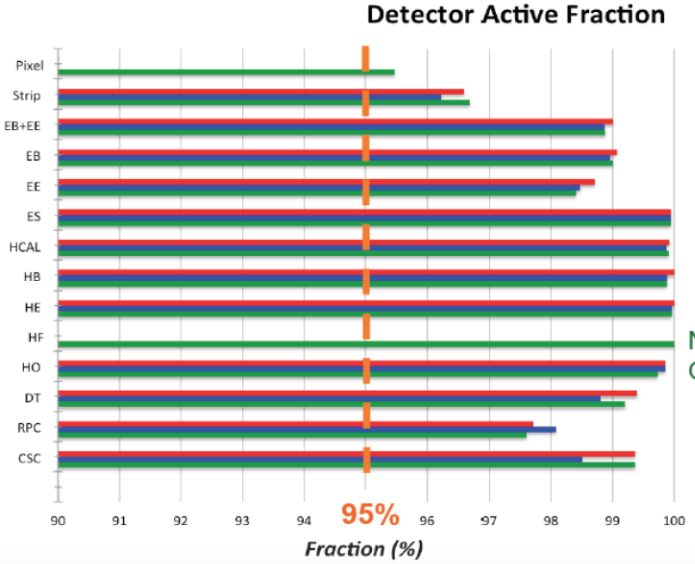


- 4 layers, 3 disks
  - smaller radius inner layer (3cm)
- New readout chip
  - higher efficiency at high rate & high pile-up (up to 100 PU)
- CO2 cooling and DC-DC powering
  - less material

Further:
HF readout upgrade,
GEM demonstrator
slice added..

CMS Performance @ 13 TeV

Some examples from the Run-2 data



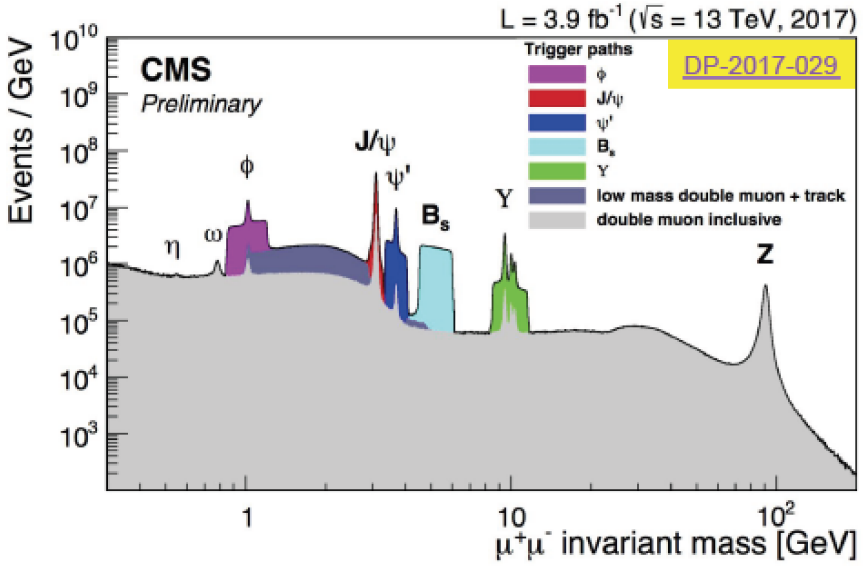
New Pixel detector
- Number of readout chips roughly doubled to 29696

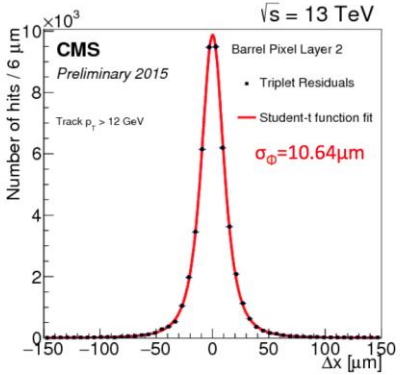
Beginning 2016 pp (Apr)

End of 2016 pp (Nov)

Beginning 2017 pp (mid June)

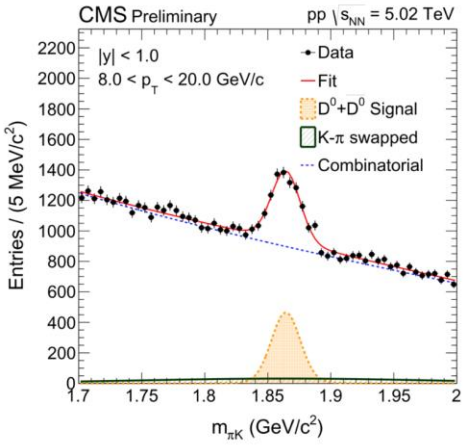
New Hadronic Forward Calorimeter



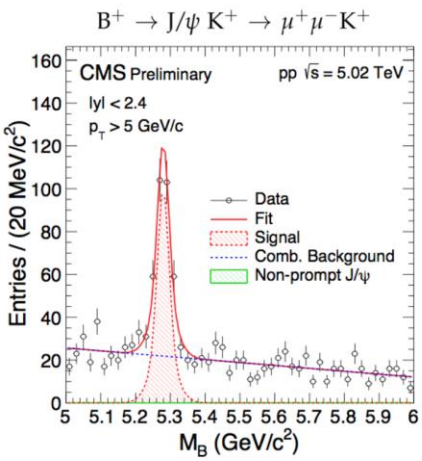


Pixel Detector Resolution:
- Transverse to the beam: σ_ϕ=10.64 μm
- Parallel to the beam: σ_z=29.09 μm

D^0 mesons peak from D^0 mesons online trigger

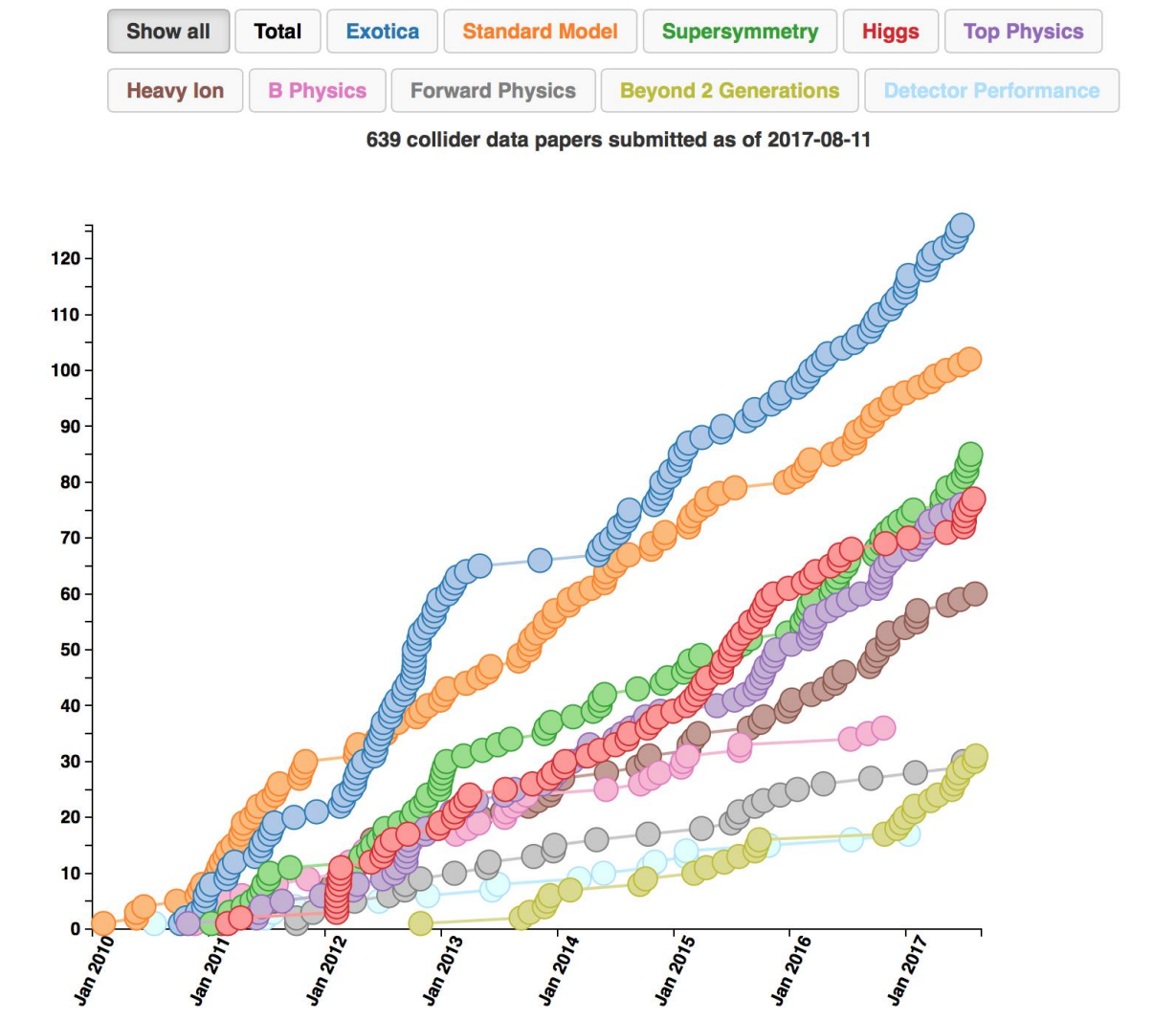


B^+ meson peak from dimuon triggered sample



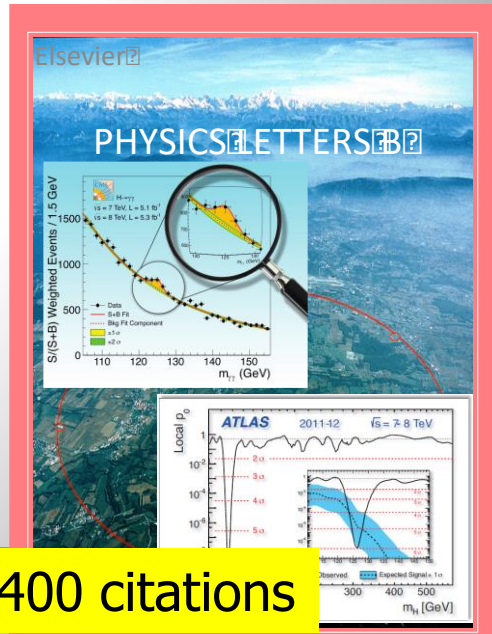
CMS continues to have an excellent performance

CMS Publications



> 650 publications on pp (and pPb/PbPb) physics since 1/2010

About 80 papers on Higgs studies!!
Paper 16 was the discovery paper!



>7400 citations

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

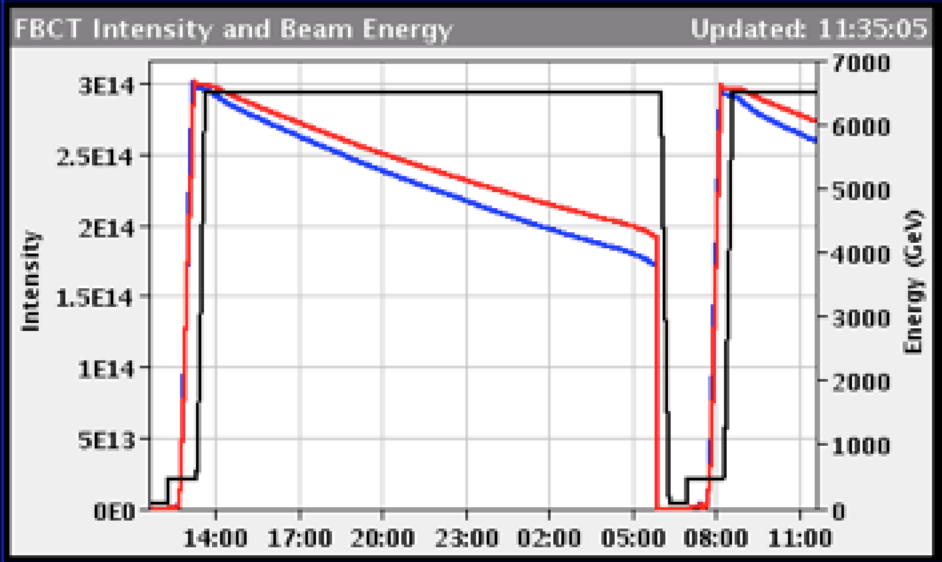
Running of the LHC in 2017

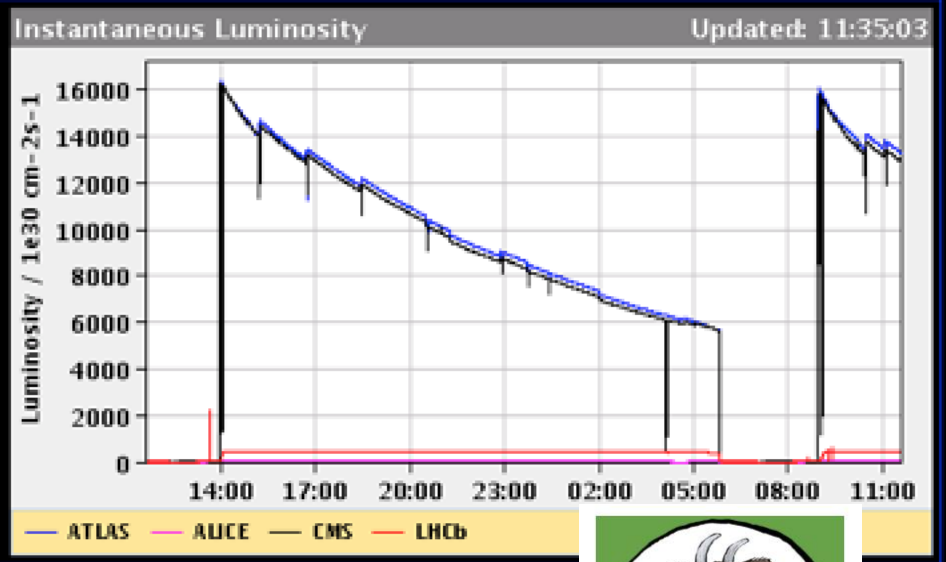
LHC Page1 | Fill: 6052 | E: 6499 GeV | t(SB): 02:34:18 | 06-08-17 11:35:04

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	2.59e+14	I(B2):	2.74e+14

Inst. Lumi [(ub.s)^-1] IP1: 13314.07 IP2: 2.49 IP5: 12939.28 IP8: 431.68





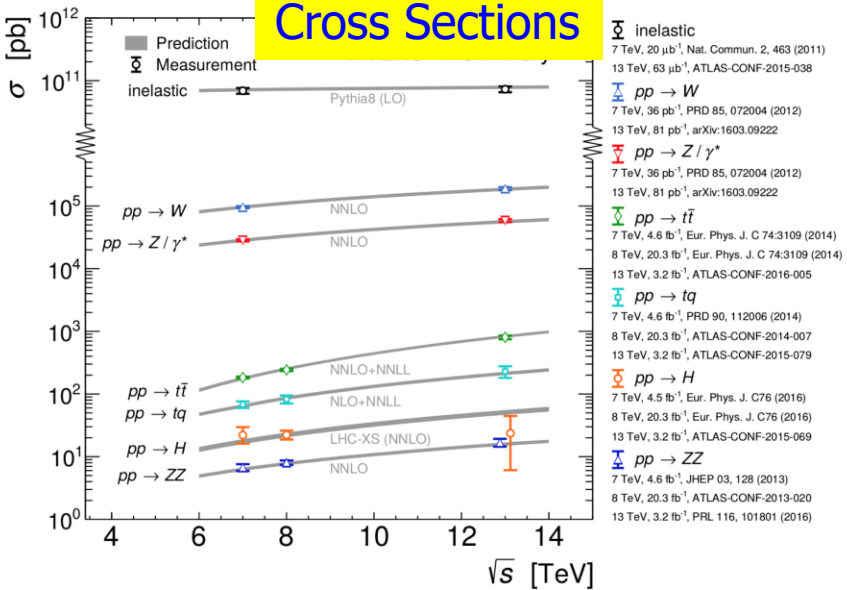
- Total collected so far in Run-2: ~60 fb^{-1}
- Running possible with >2000 bunches (but now Grufallo/16L2 limit!)

Standard Model Measurements

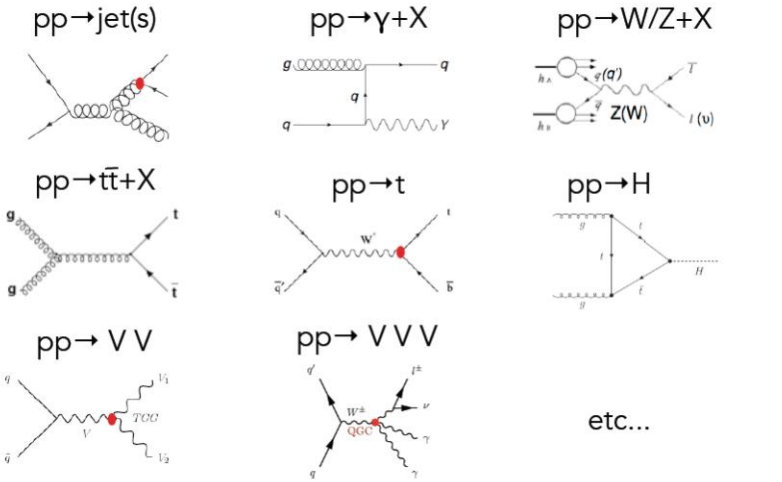
Standard Model Measurements

- Standard Model measurements form an integer part of the physics program of the LHC
- Precision measurements allow test for a wide range of SM predictions, and extract fundamental parameters (eg α_s)
  - Requires matching precision at theory prediction side
- Important to understand backgrounds for searches for new physics

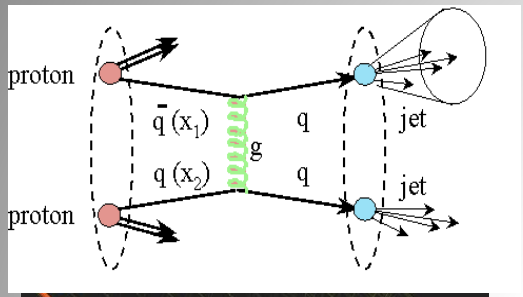
Cross Sections

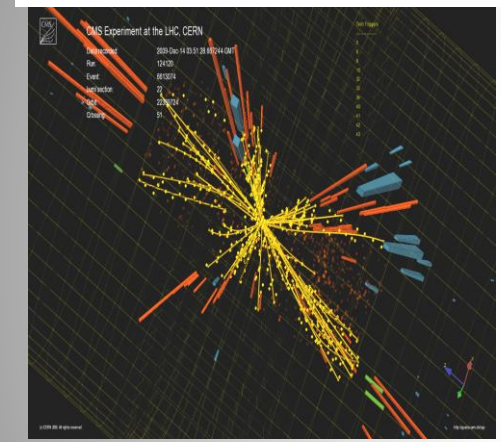


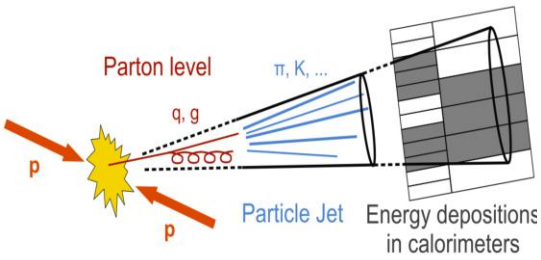
Many processes studied: Examples



Inclusive Jet Production (13 TeV)

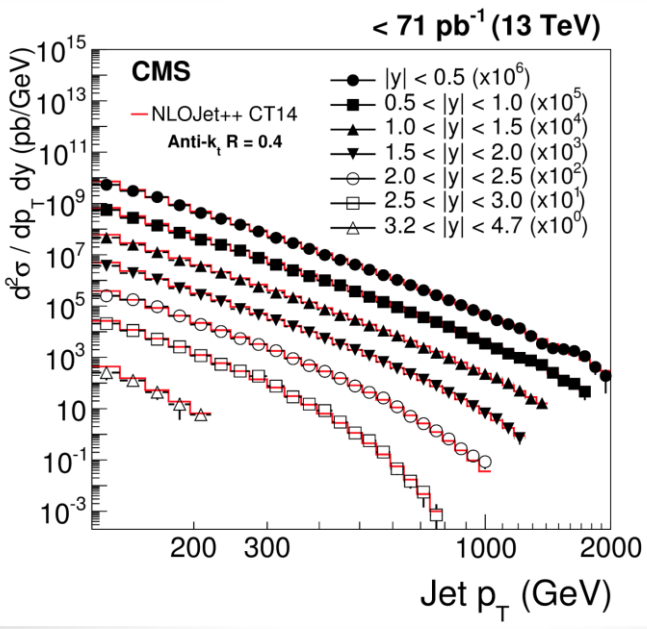


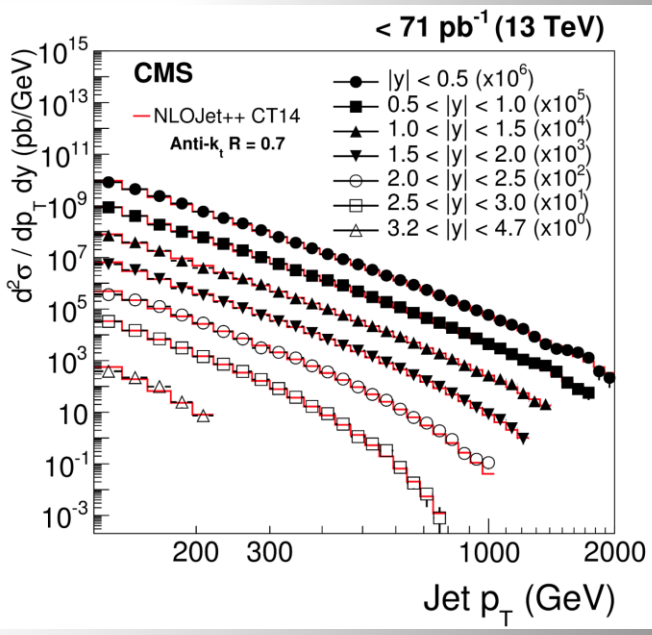




arXiv:1605.04436

Differential cross sections with R=0.7 and R=0.4
Jet p_T spectrum consistent with predictions from NLOJET++



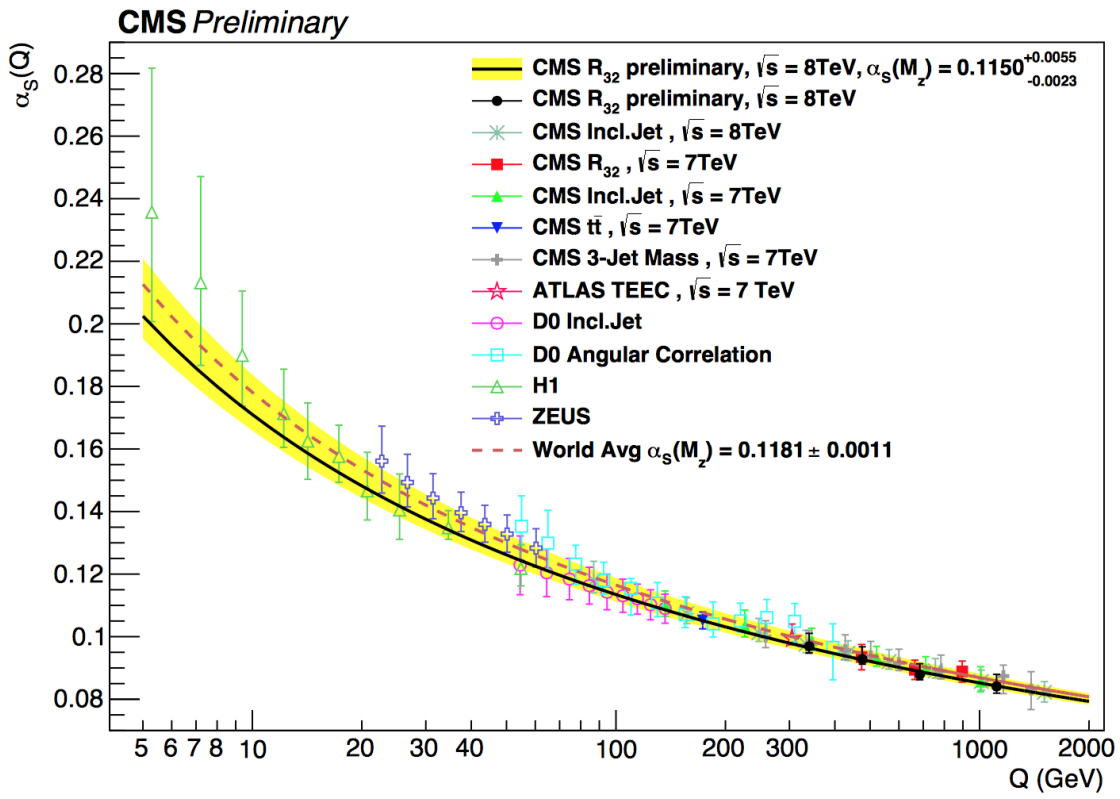


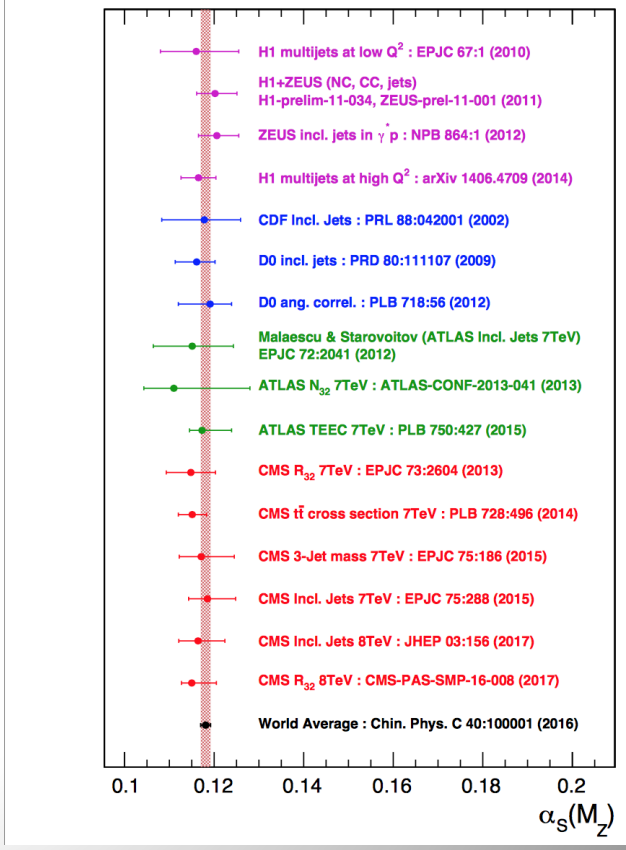
Agreement with NLO calculations over the full range, up to and beyond 2 TeV p_T jets… QCD predictions work well…

New Determination of α_s (8 TeV)

- Inclusive multi jet production
- α_s from the ratio of 3/2 jet events

CMS-PAS-SMP-16-008

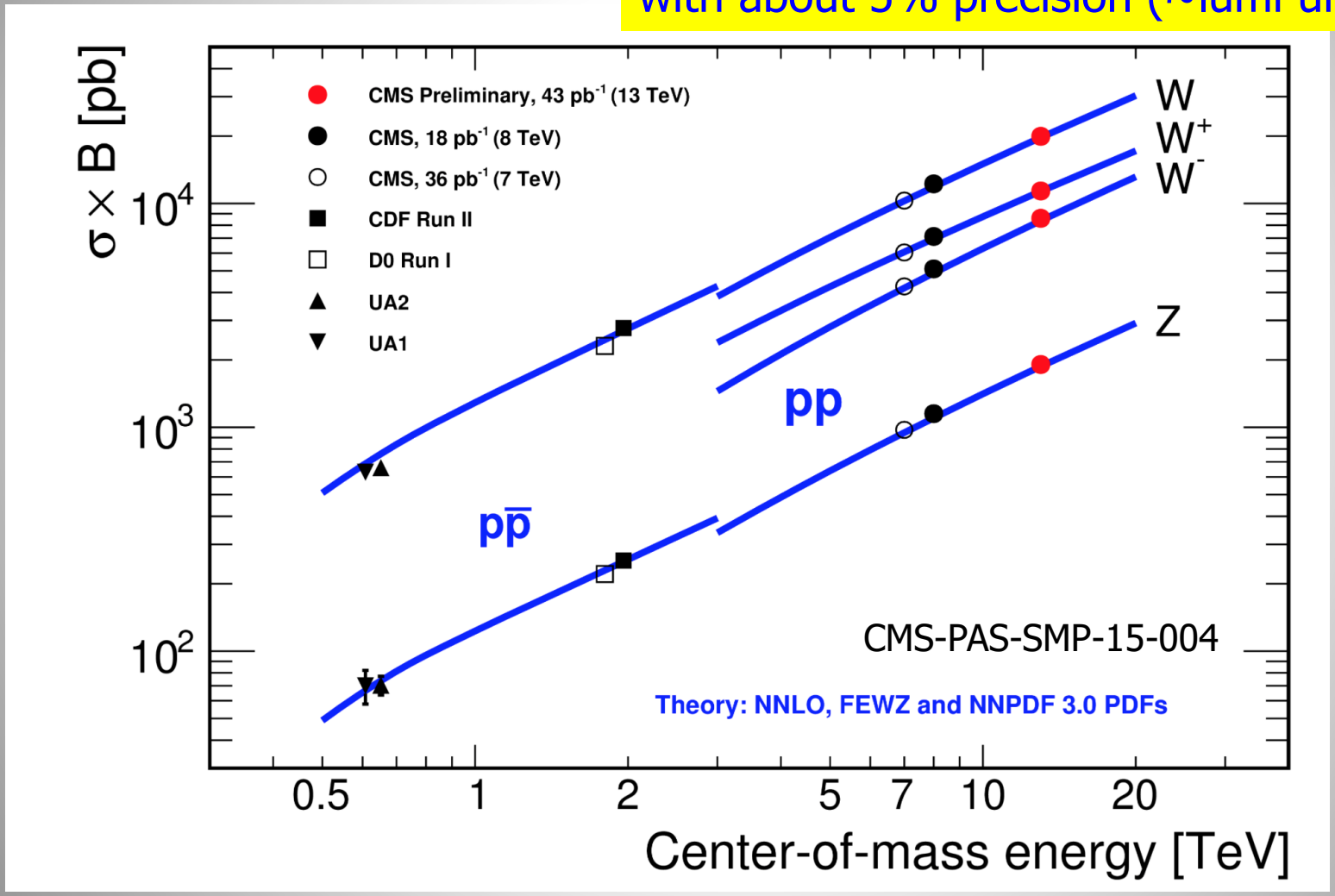




$$\alpha_s(M_Z) = 0.1150 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP}) \,^{+0.0050}_{-0.0000}\,(\text{scale})$$

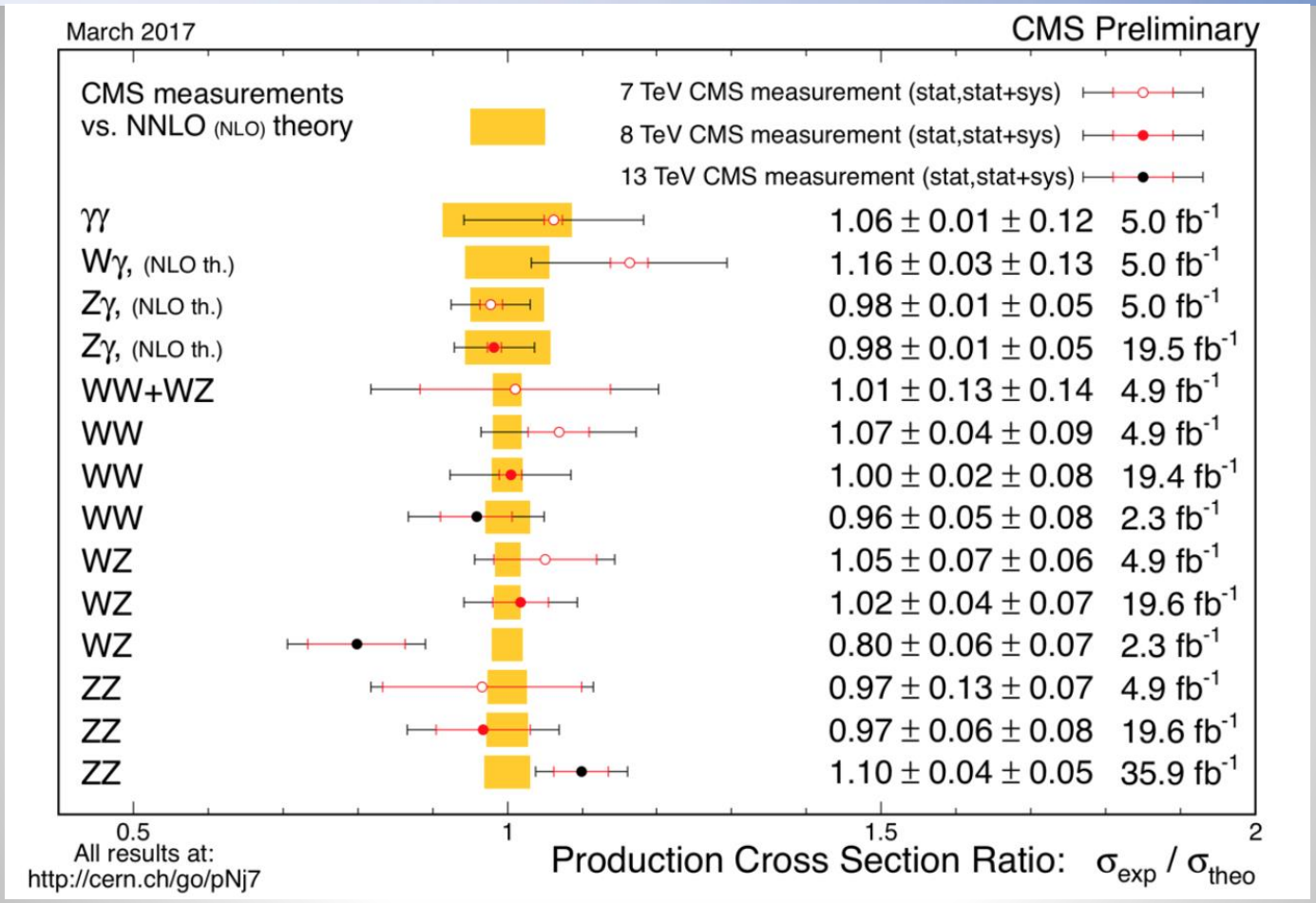
W and Z Boson Production

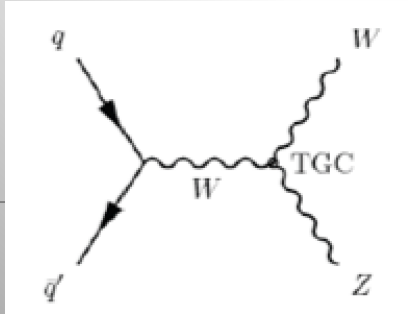
Contains a new measurements at 13 TeV!
with about 5% precision (~lumi uncert.)

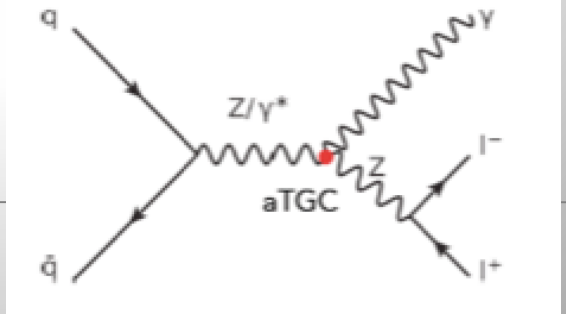


Many detailed EWK studies possible –and done-- with the large Z,W samples

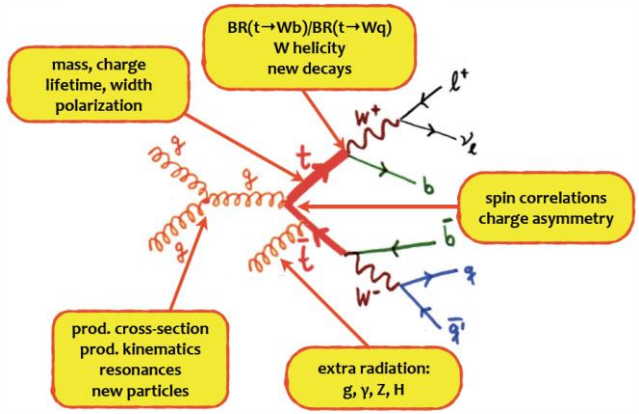
Multi-Boson Production







Top Production

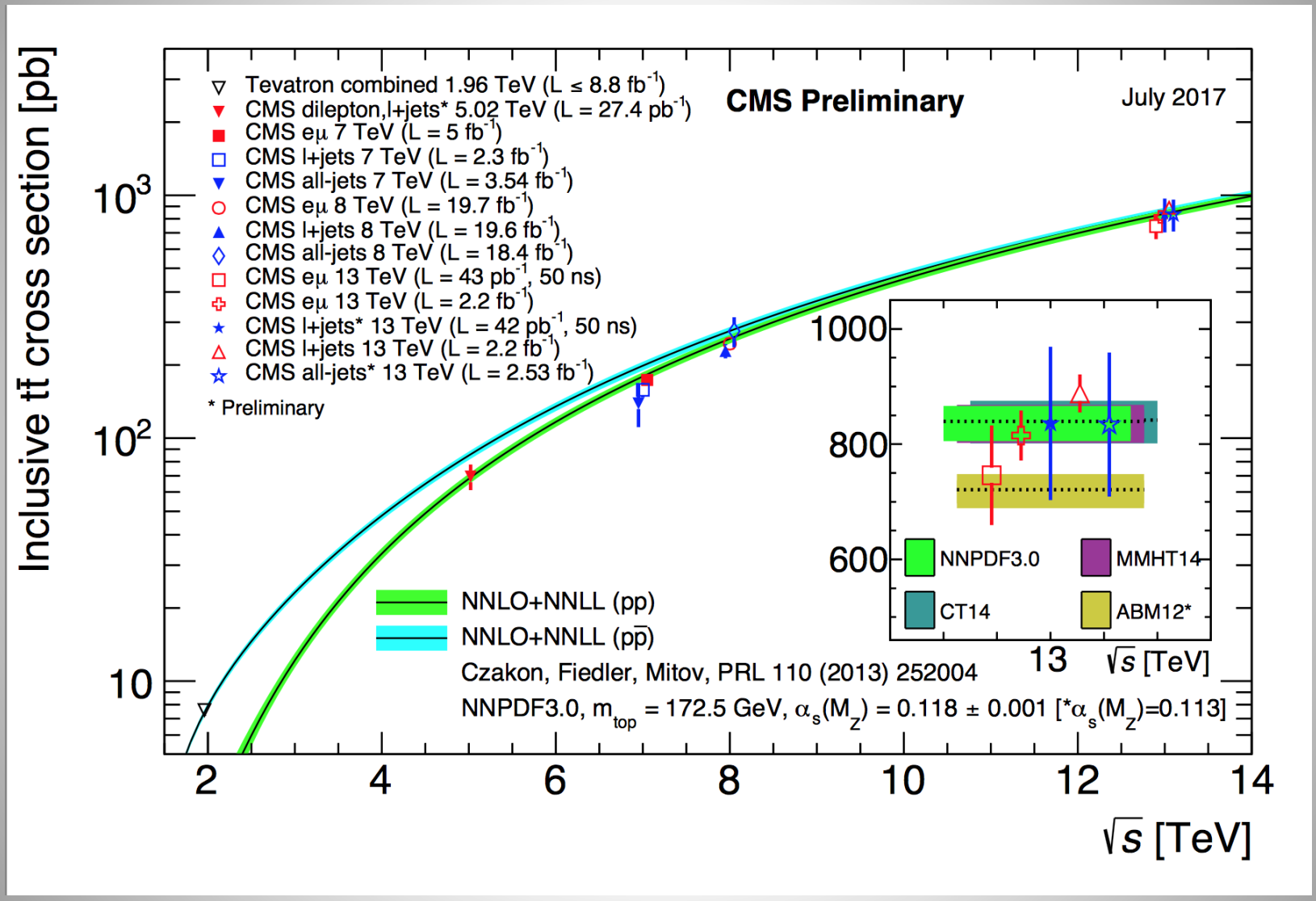


- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 → Special role in EWK symmetry breaking?

LHC is a top factory with ~5.10^6 produced tt-pairs (run-1)

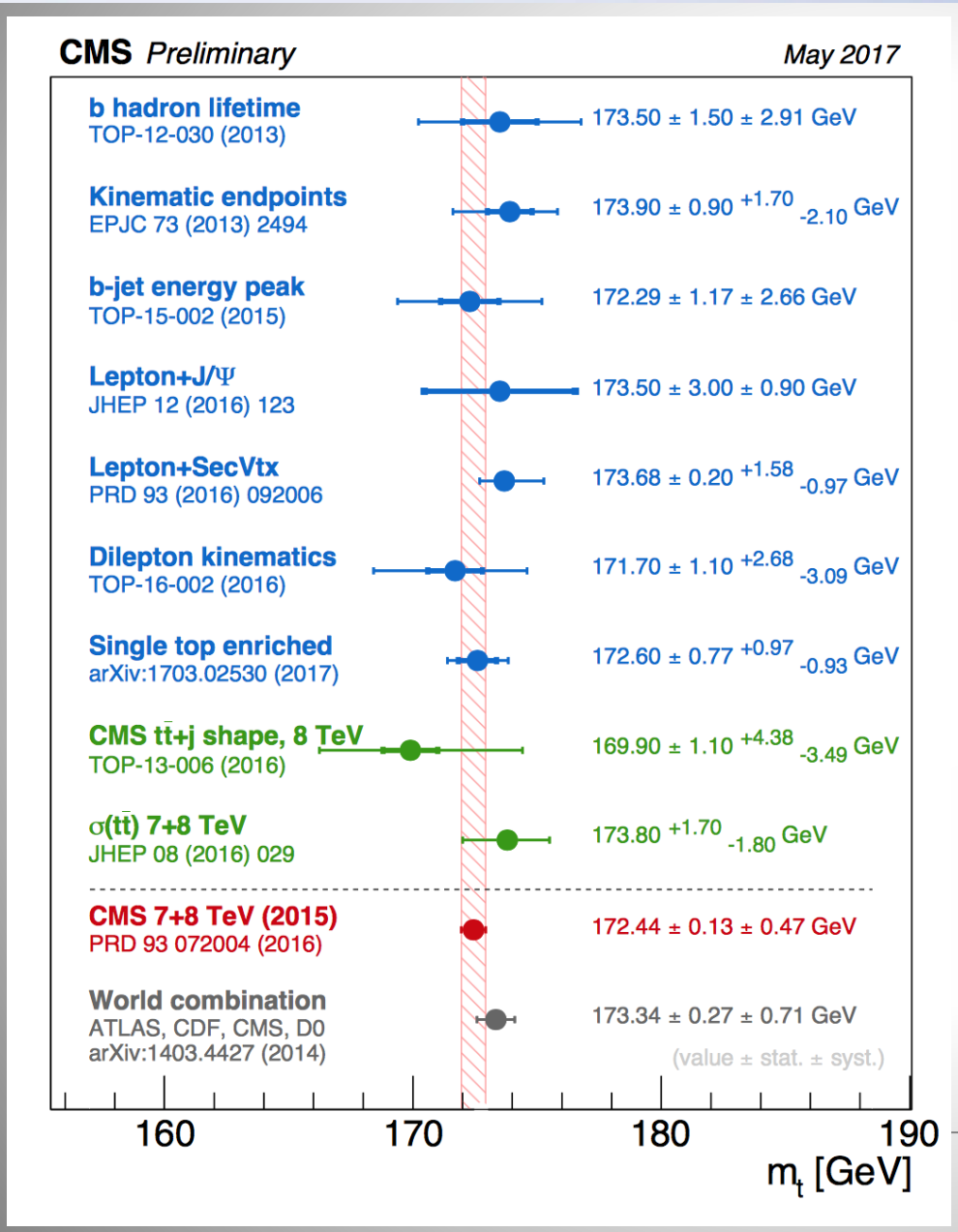
~3.10^7 produced tt-pairs (2016)

Top Quark Cross Sections



Good agreement with the SM predictions up to the new 13 TeV

Top Mass Determination



Steady improvements over the last years in run-1

Precision now is ~0.3%, similar to the theoretical uncertainty

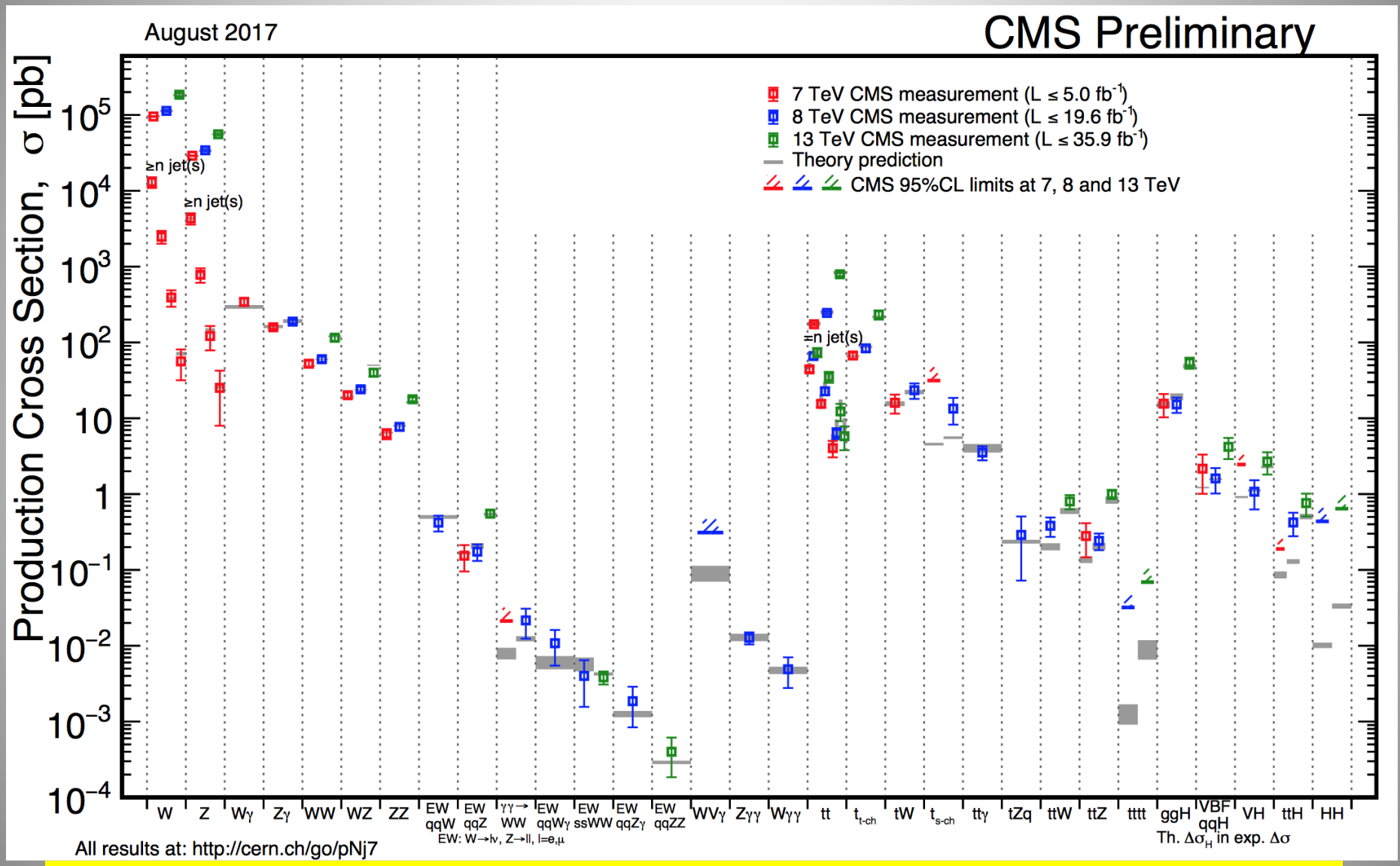
Hadronization model uncertainties one of the main limitations

Many alternative methods have been and are being explored using J/psi, secondary vertices,... This is not the last word yet

Experiment combination under way

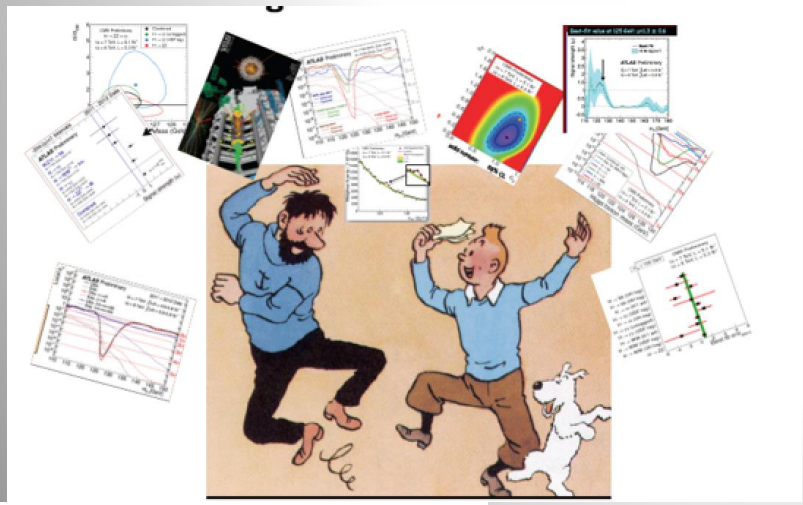
Note: the average value LHC somewhat lower than Tevatron one: 174.34 ± 0.64 GeV

Summary: Cross Sections at 7/8/13 TeV



Measurements in good agreement with the Standard Model predictions

Higgs

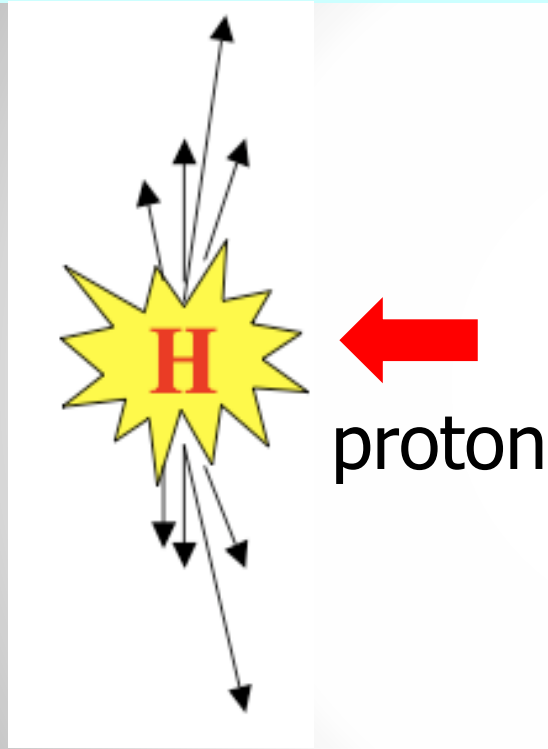


The party 5 years ago

What happened since?

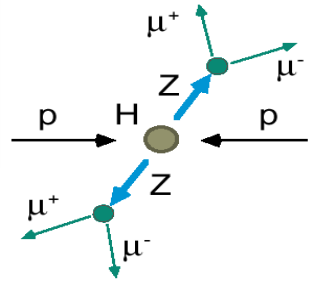
2012: A Milestone in Particle Physics

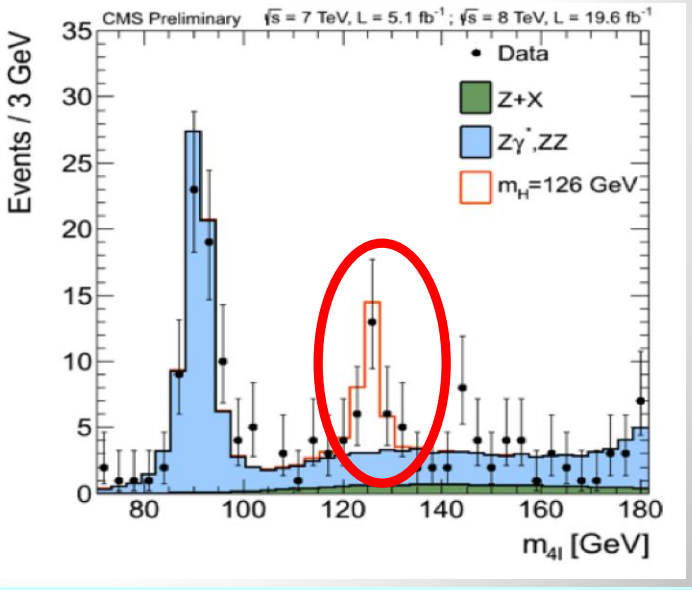
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

proton



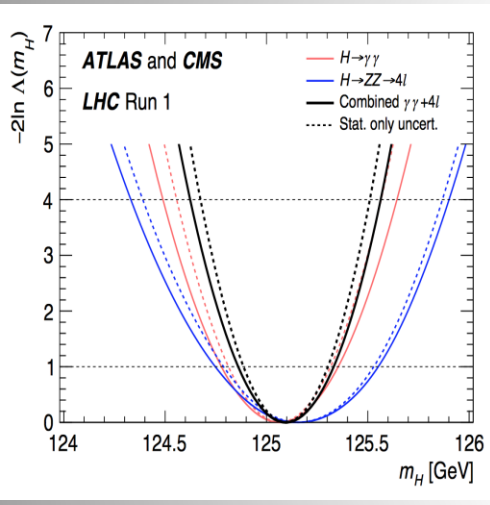


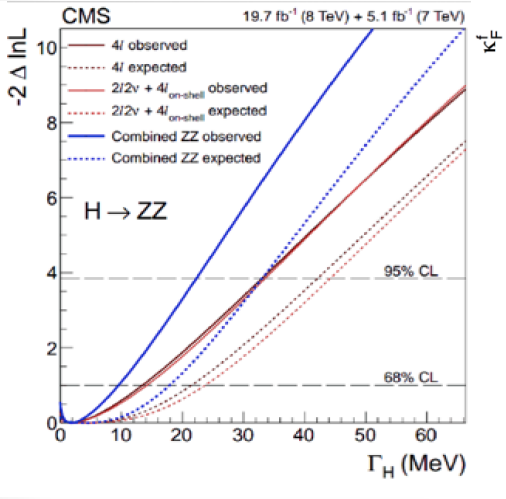
2013

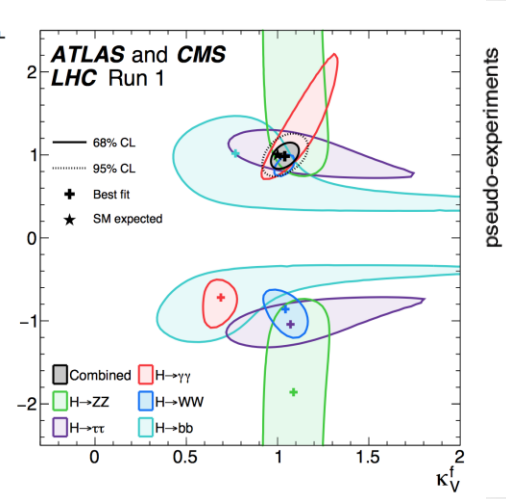
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

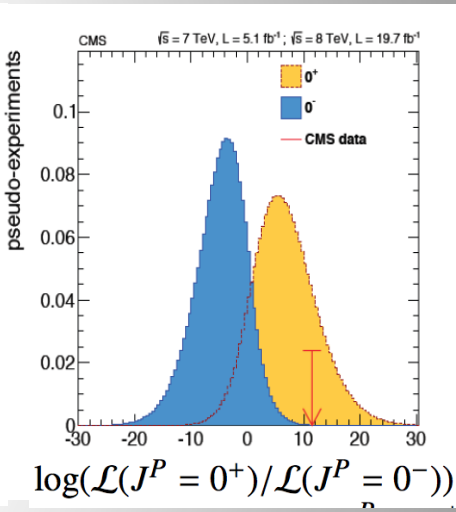
Brief Higgs Summary from Run-1

We know already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

Couplings are within ~20% of the SM values

Spin =
$0^{+(+)}$ preferred over 0^-,1,2

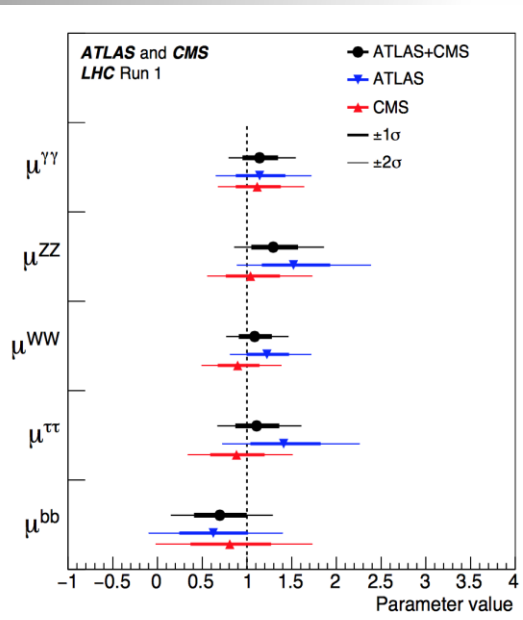
We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses…

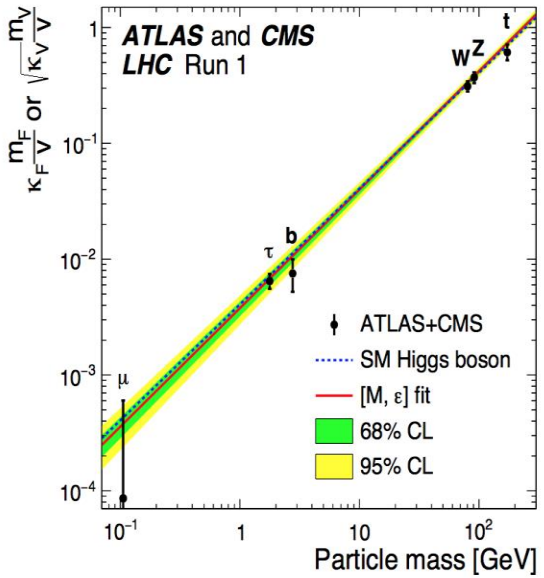
Higgs: ATLAS+CMS Combination

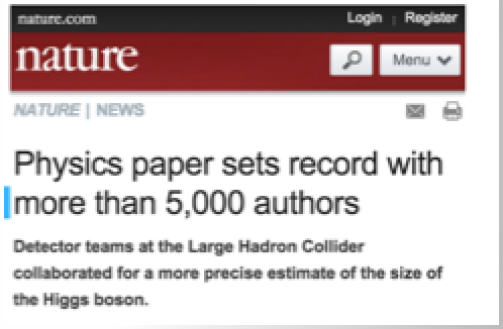
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

The Run-1 Higgs Legacy!

arXiv:1606.02266 /
JHEP 1608 (2016) 045
5153 authors!!





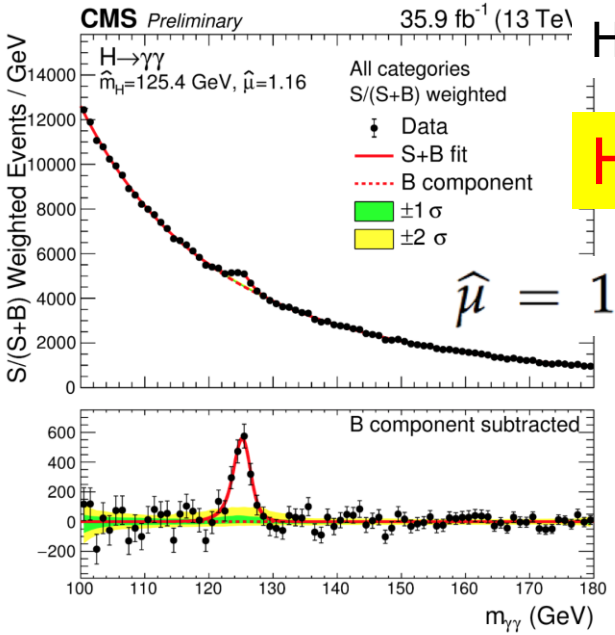


The newly found boson has properties as expected for a Standard Model Higgs

Signal strength/SM:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

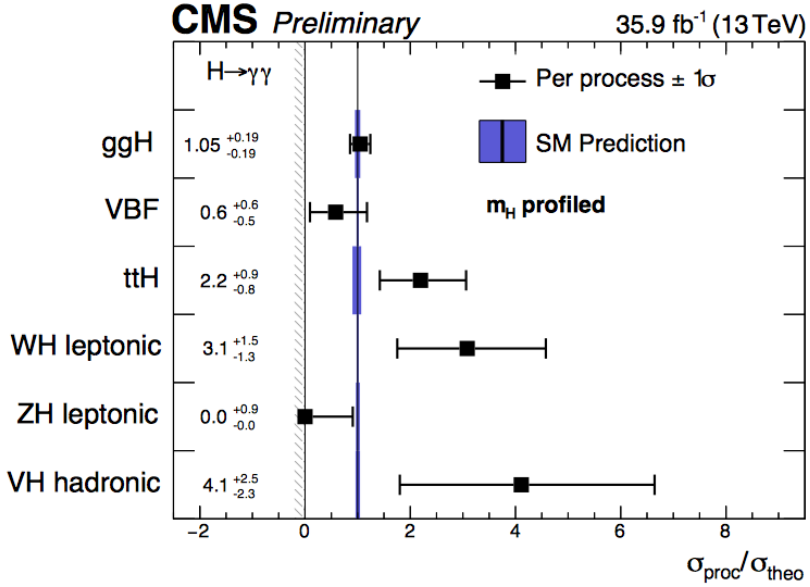
New 13 TeV Higgs Results

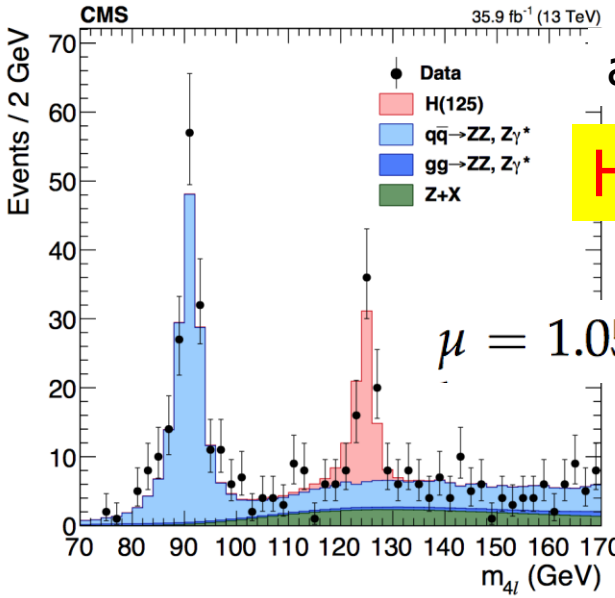


HIG-16-040

H→γγ

$$\hat{\mu} = 1.16^{+0.15}_{-0.14}$$





arXiv:1706.09936

H→ZZ→4 leptons

$$\mu = 1.05^{+0.19}_{-0.17}$$

2016 data:
Cross section ~ x 2
Luminosity ~ x 1.5

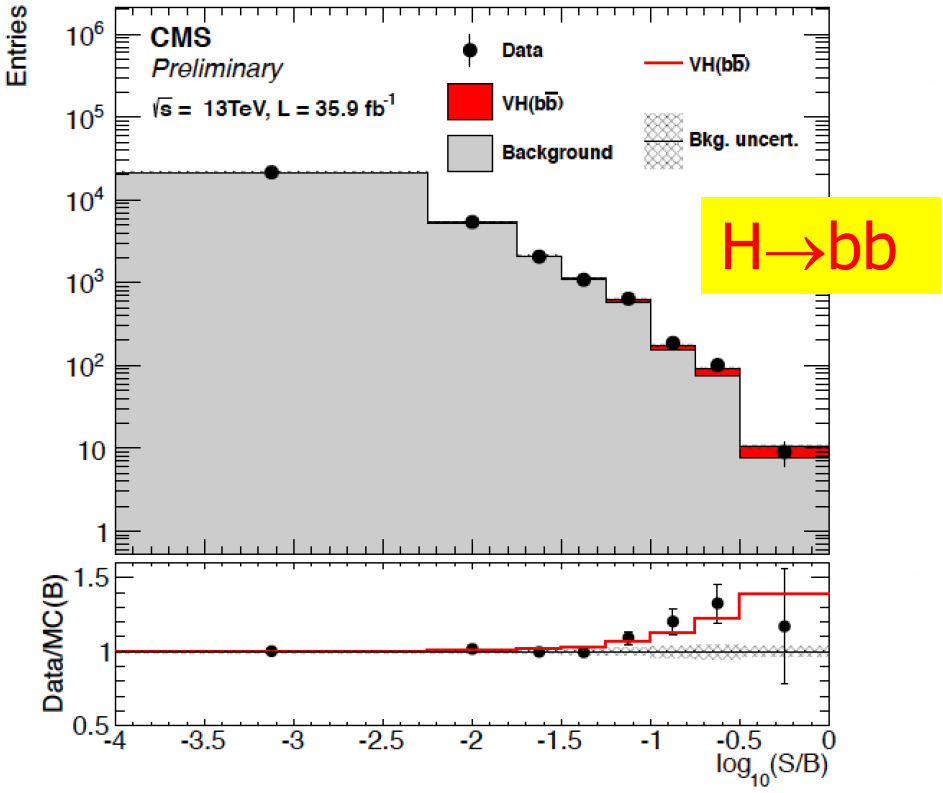
New mass determination from H-> 4leptons

$$125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})\ \text{GeV}$$

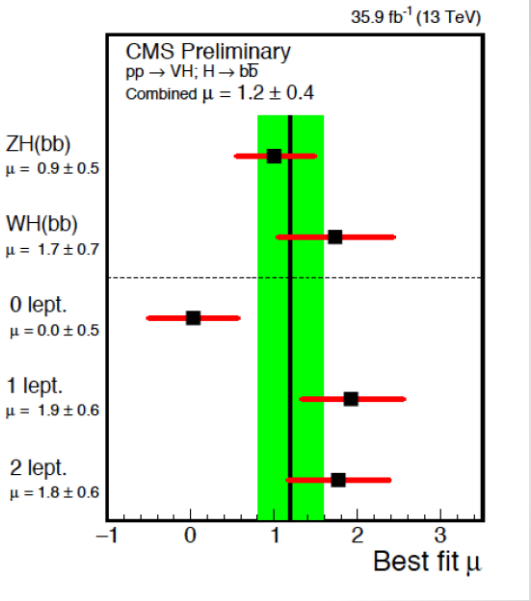
More precise than run-1 combined result

New 13 TeV Higgs Results

Higgs to bb using the associated channels WH and ZH, with W,Z→ leptons



H→bb



HIG-16-044

$m_H = 125$ GeV	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
All channels	2.8	3.3

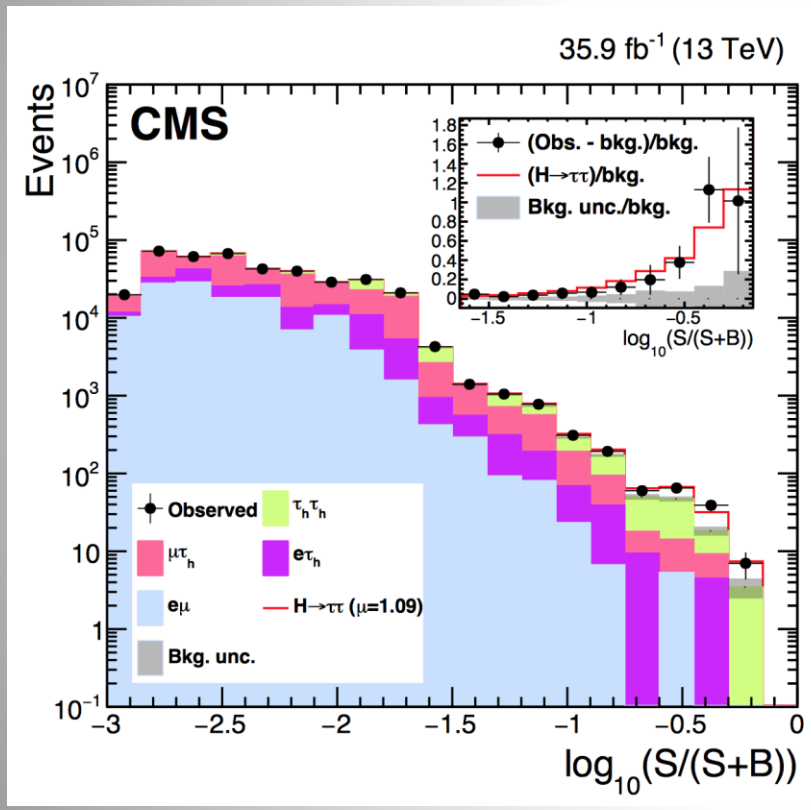
Direct evidence for H->bb in CMS!

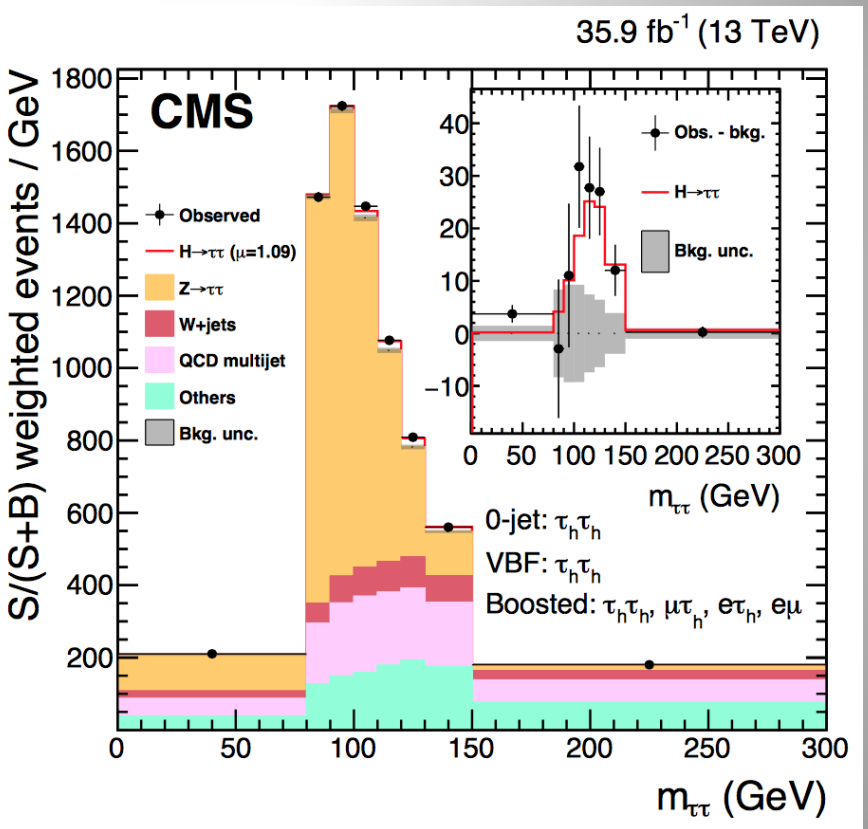
- Combination with CMS Run I (7 & 8TeV):
  3.8σ (**3.8σ** expected)
  $1.06^{+0.31}_{-0.29} \times \sigma_{SM}$

New 13 TeV Higgs Results

Higgs to ττ using 0-jet, VBF and boosted categories

arXiv:1708.00373





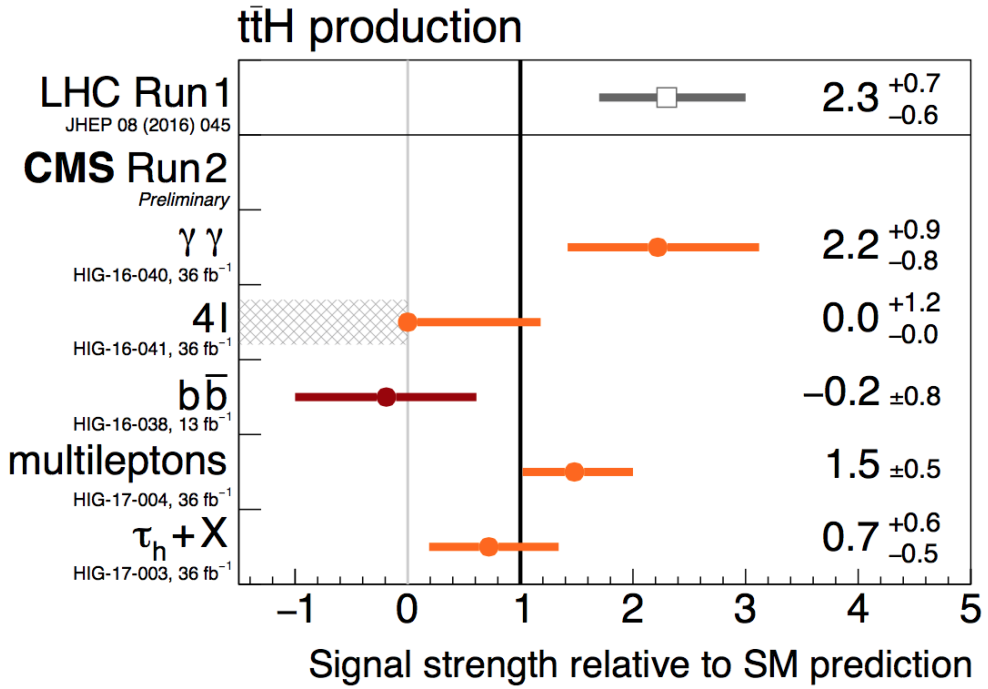
	Signal Strength	Obs. significance	Exp. significance
Run 2	$1.09^{+0.27}_{-0.26}$	4.9σ	4.7σ
Run 1 & 2	0.98±0.18	5.9σ	5.9σ

Observation for H →ττ in CMS!

New 13 TeV Higgs Results

ttH production with H to leptons, taus, photons, b-quarks

- Observation if the ttH channel gives direct evidence and measurement for the top-Higgs coupling
- Run-1 combined ATLAS and CMS significance was 2.3σ
- 2016 data : cross section x 4 and luminosity x 2
- The 2016 data are getting there.
  Including the 2017 data should lead to clear evidence for ttH!!

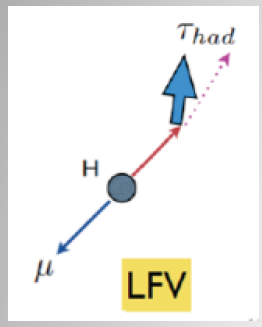


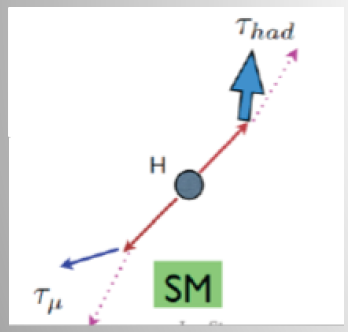
Andre David
April '17 CERN Courier

Search for LFV Decays: H →μτ

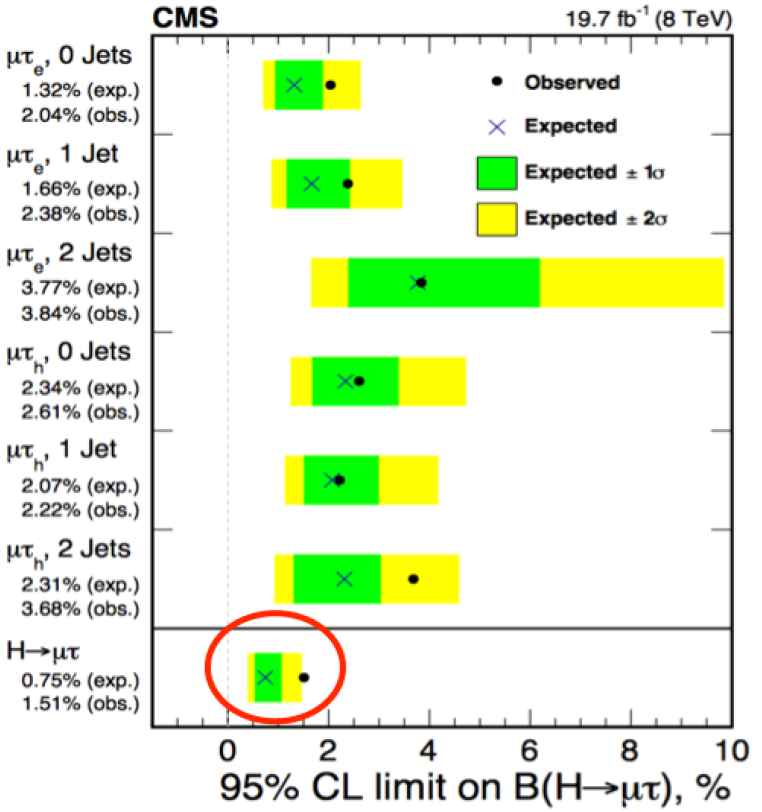
arXiv:1502.07400

Recall: Results from the 8 TeV





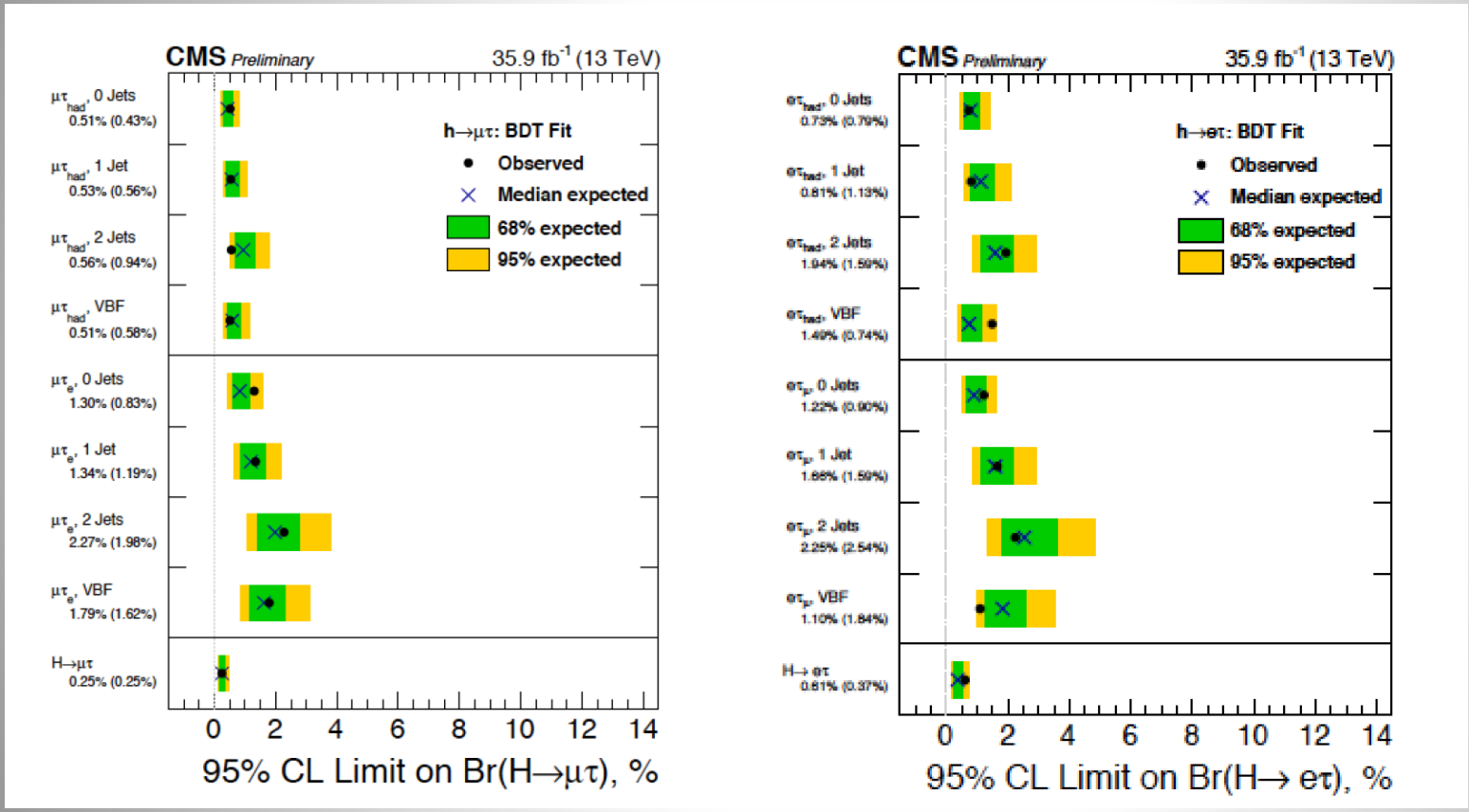
- Comparable sensitivity from all channels
- $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95%
- **Large improvement of previous limits**
- Background-only p-value of 0.010 (2.4 σ)
  - Best fit $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$.



Mild excess giving a 2.4σ effect in Run-1… What about 2016 data?

Search for LFV Decays: H →μτ, eτ

The 2016 data does NOT show an excess



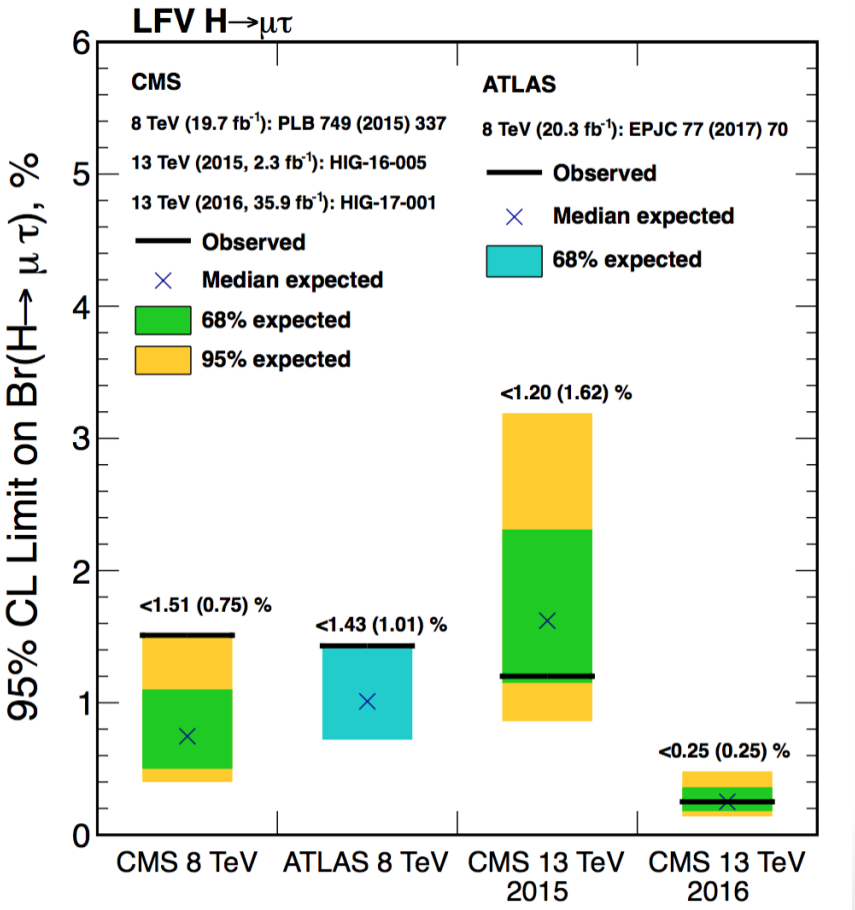
HIG-17-001

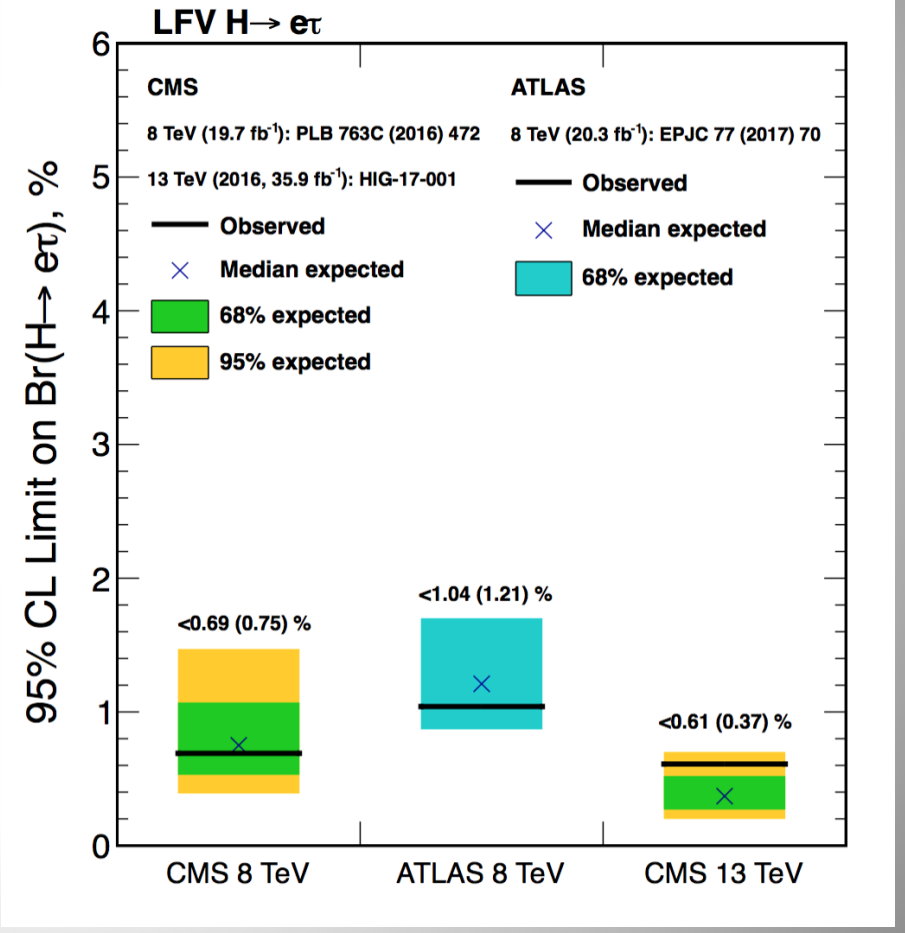
☹ It would Have been Nice…

	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	$0.02 \pm 0.20\%$	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

Search for LFV Decays: H →μτ, eτ

LHC measurements overview





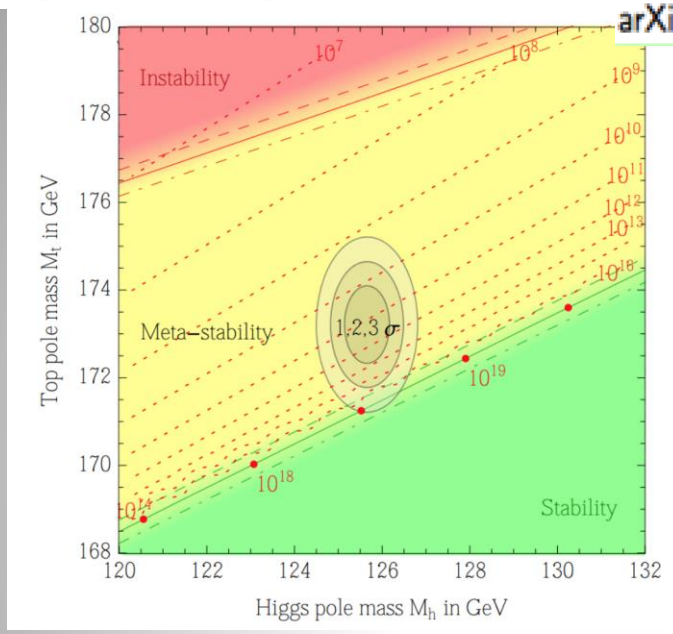
Higgs @ 13 TeV

- Higgs particle is still there ! ☺
- Precision on e.g. cross sections/sensitivy improves with factor ~2 wrt Run-1 results
- The mild deviations seen in Run-1 seem to be gone ☹
- Evidence for $H \rightarrow bb$ in the associated production channel
- Observation of $H \rightarrow \tau\tau$ in a single experiment
- ttH is getting close to be observable directly
- No deviations from Standard Model Higgs expectations yet!!

The Higgs Boson is still very much Standard Model-like!

Physics Beyond the Standard Model?

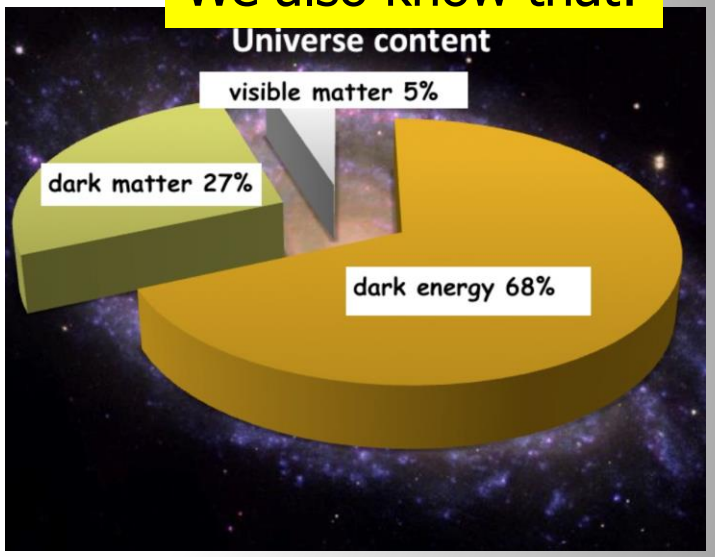
Important SM parameter → stability of EW vacuum



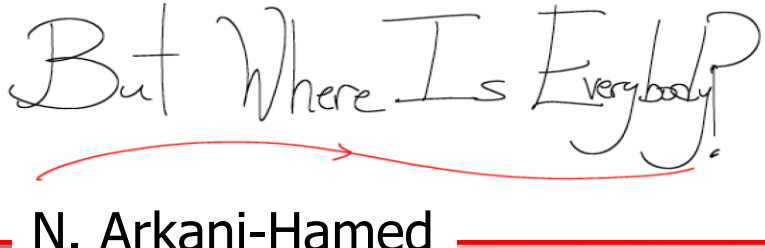
arXiv:1403.6535

A Higgs at 125 GeV
Precise measurements of the top quark and the Higgs mass

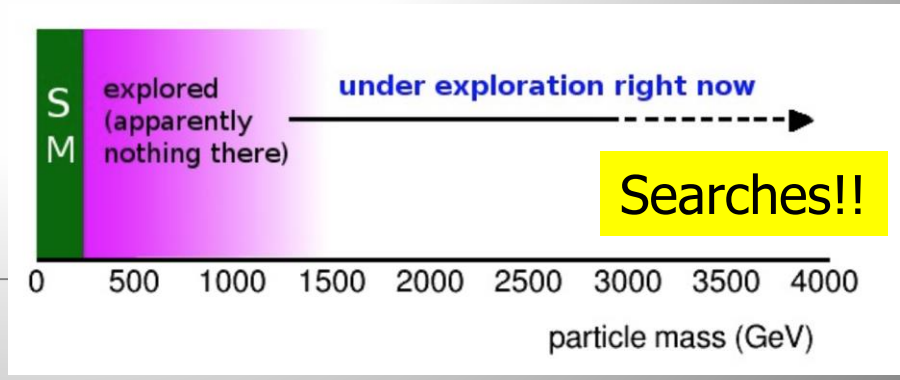
We also know that:



New Physics inevitable?
But at which scale/energy?

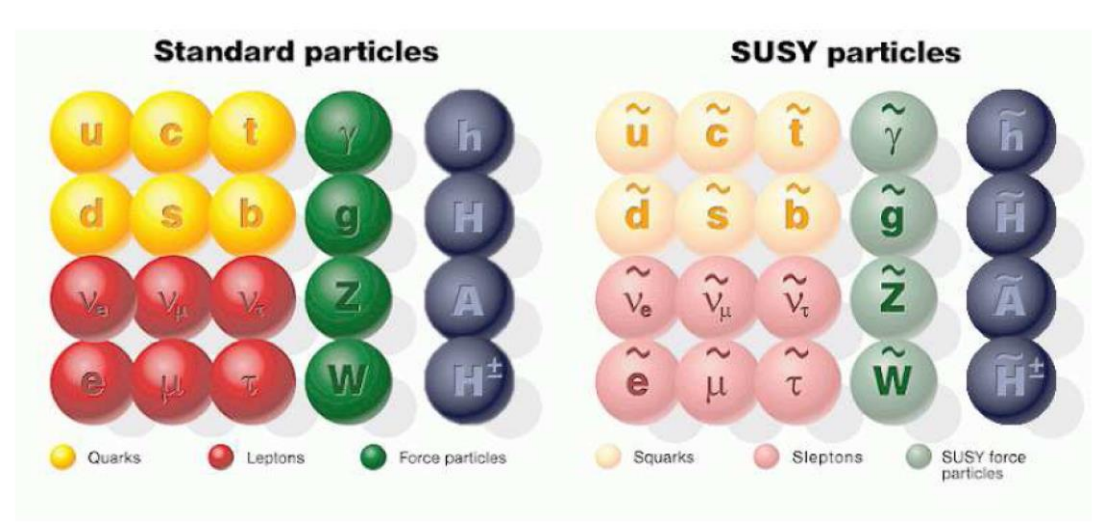


N. Arkani-Hamed

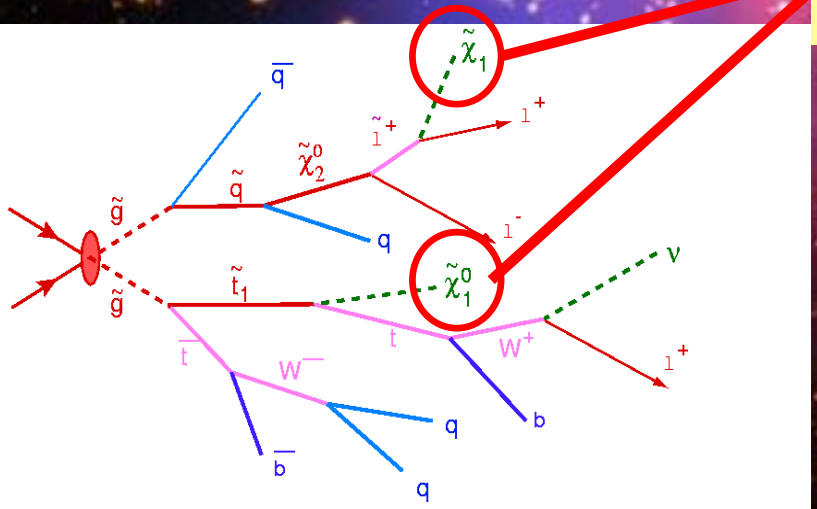


Searches for BSM Physics

Supersymmetry: a new symmetry in Nature?



Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

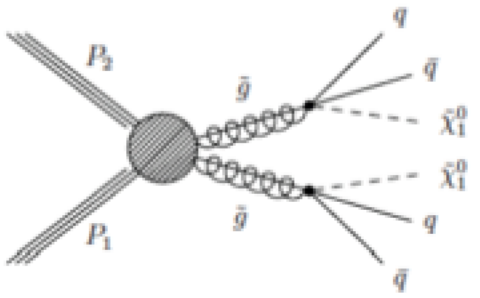


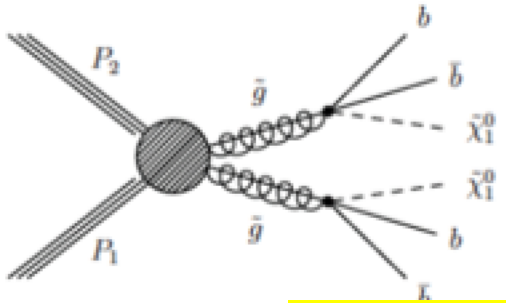
SUSY particle production at the LHC

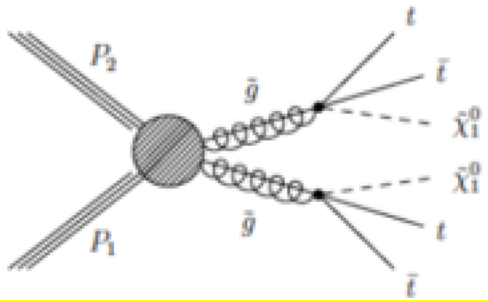
"One day all these trees will be SUSY phenomenology papers"

adac

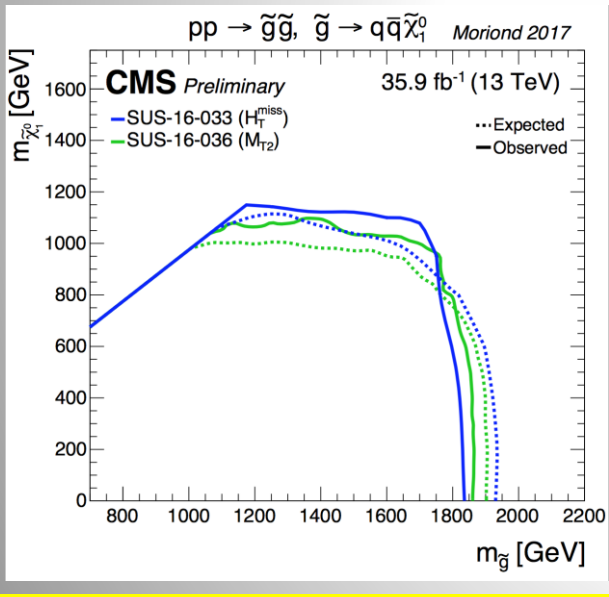
Supersymmetry: Gluinos

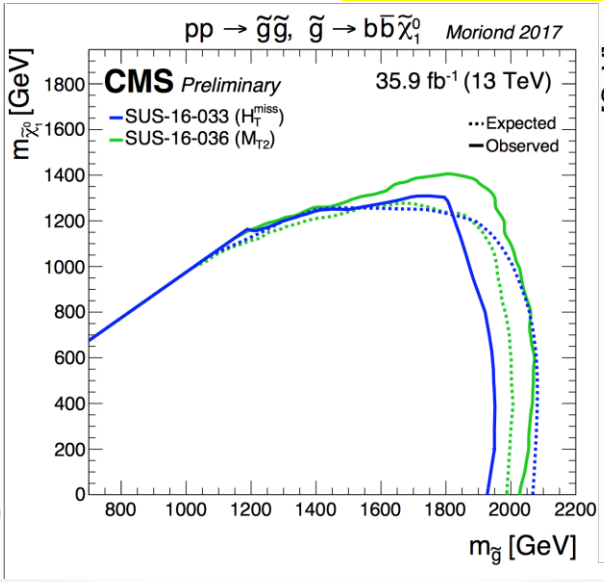


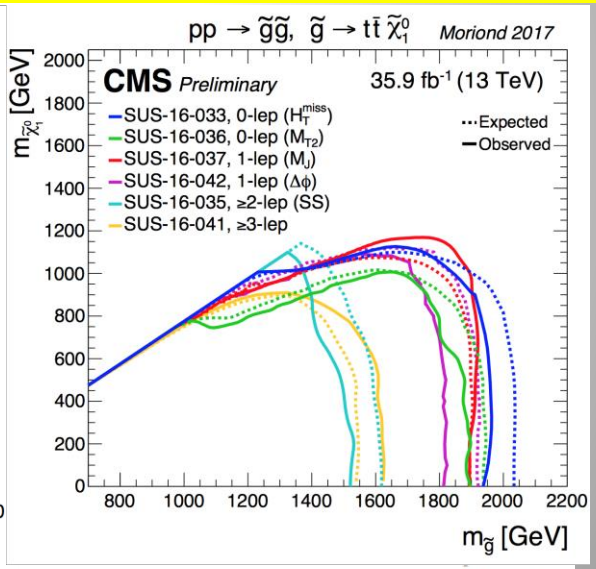




Interpretation in simplified models (SMS)







No significant signal to date

Within the context of the SMS:

Exclude with gluino masses ~ 2100 GeV for neutralino masses up to 800 GeV

What is really needed from SUSY?

End 2011: Revision!

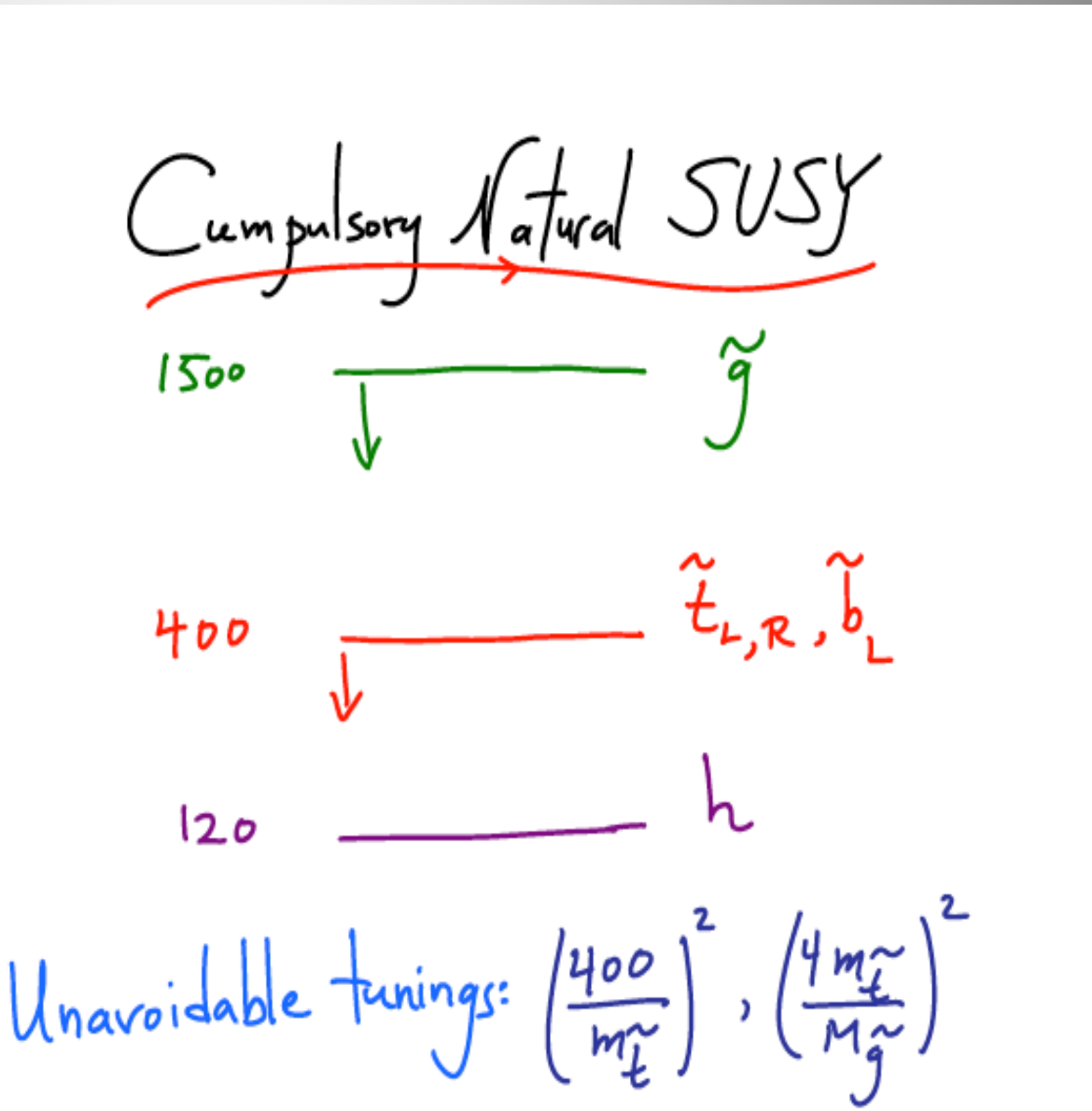
N. Arkani-Ahmed
CERN Nov 2011

and many many more ..

LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

Moving away from constrained SUSY models to 'natural' models

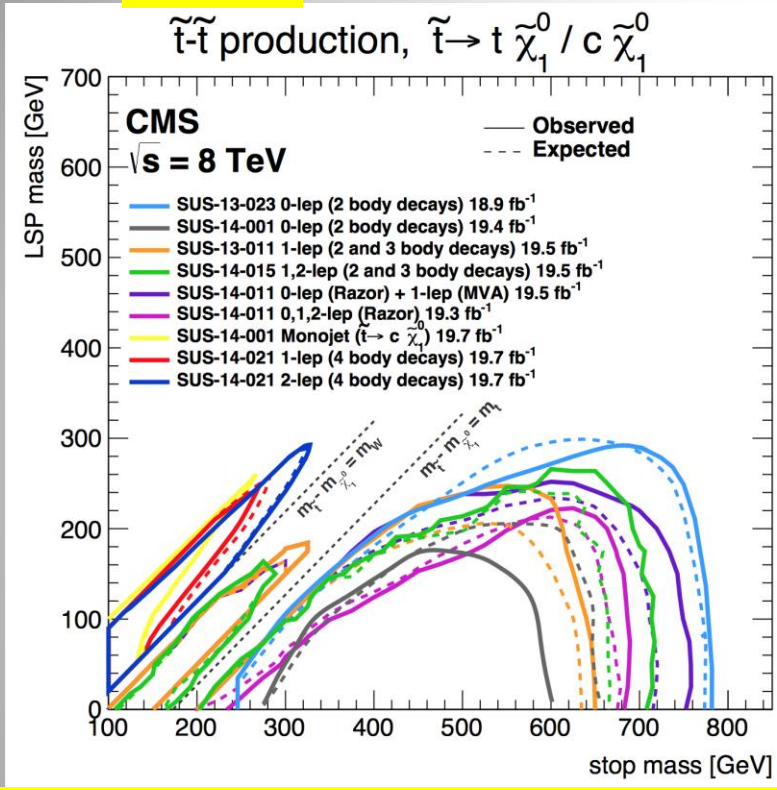
Natural SUSY survived LHC so far, but we are getting close to push it to its limits!



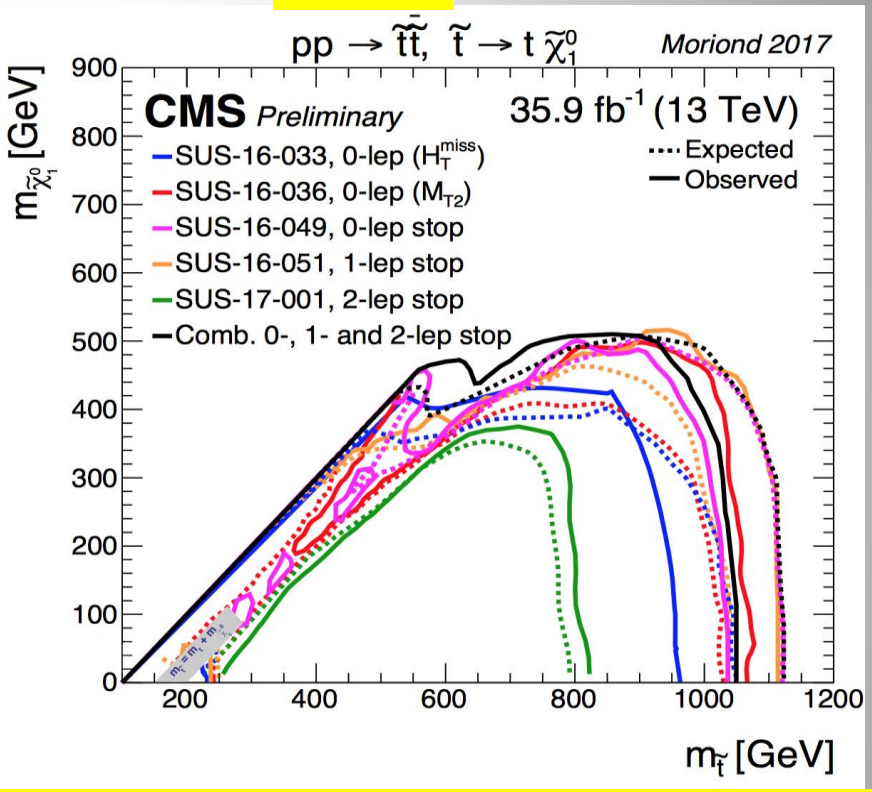
Also:Barbieri & Giudice (1988): Natural Models!

Top Squark Search Summaries

Run-1



Run-2



Within the context of the SMS:

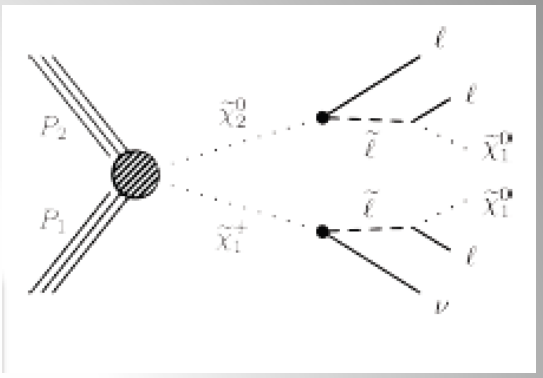
Exclude with masses up to 1000 GeV for neutralino masses up to 500 GeV

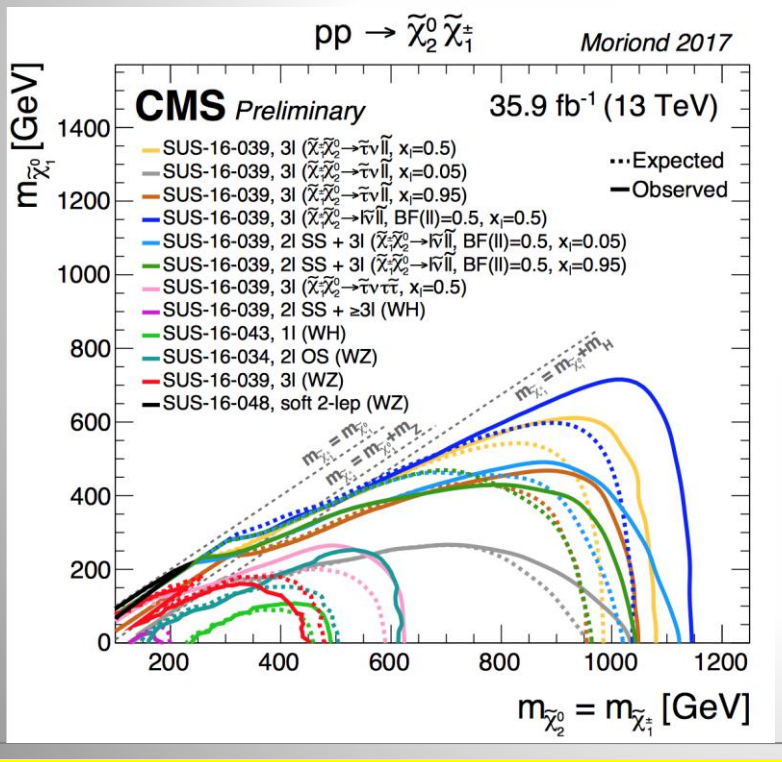
Sensitivity is ~ 200-400 GeV better than Run-1 reach & gaps being covered

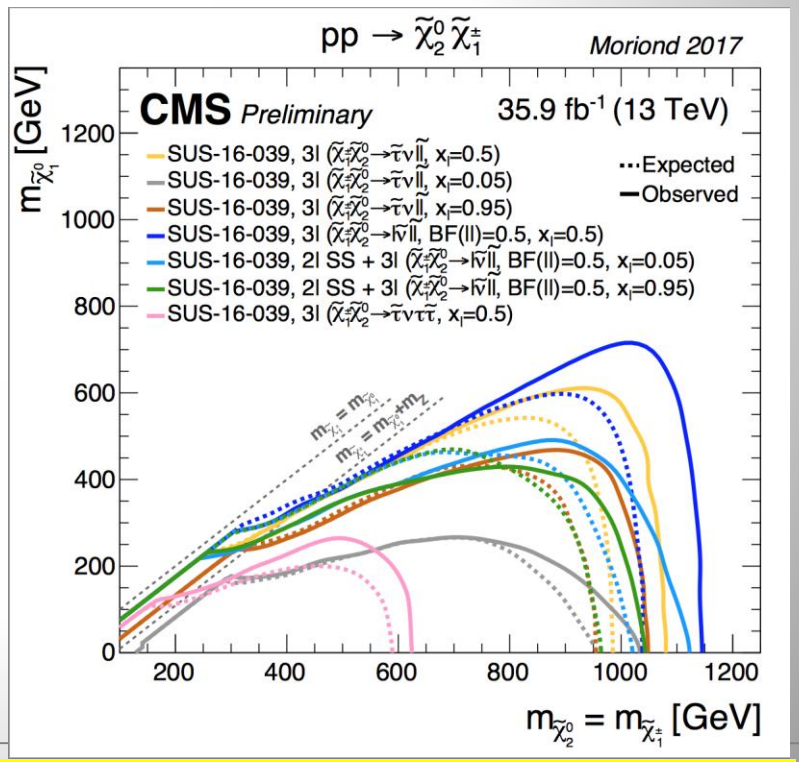
Is this getting critical for Natural Models??

Chargino and Neutralino Production

Direct production of "electroweakino pairs
- Decays via sleptons /sneutrinos
- Using benchmarks to illustrate different scenarios
- Multilepton searches (incl. taus)







Exclude masses up to 1100 GeV for neutralino masses up to 600 GeV

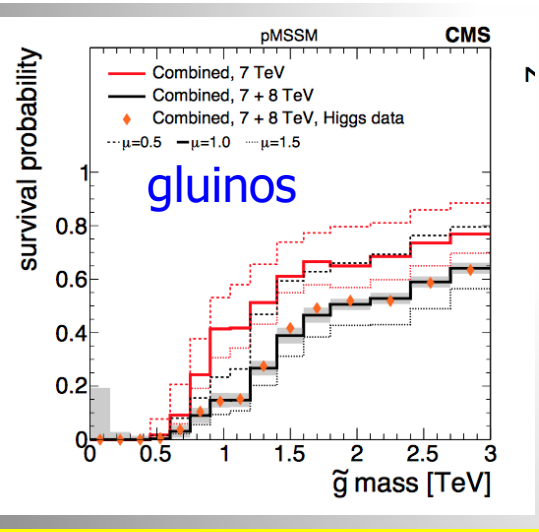
Phenomenological MSSM analysis

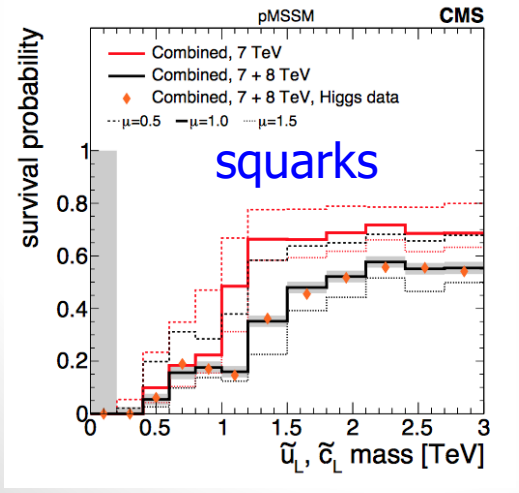
SMS don't always fully cover signatures…
-> the 19 parameter phenomenological MSSM (pMSSM) analyses

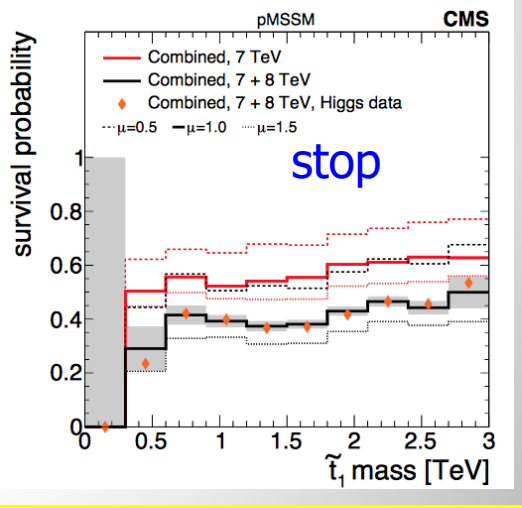
arXiv:1606.03577

- three independent gaugino mass parameters M_1, M_2, and M_3,
- the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$,
- the higgsino mass parameter μ and the pseudoscalar Higgs boson mass m_A,
- 10 independent sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (for the 2nd generation we take $m_{\tilde{Q}_2} \equiv m_{\tilde{Q}_1}, m_{\tilde{L}_2} \equiv m_{\tilde{L}_1}, m_{\tilde{U}_2} \equiv m_{\tilde{U}_1}, m_{\tilde{D}_2} \equiv m_{\tilde{D}_1}$, and $m_{\tilde{E}_2} \equiv m_{\tilde{E}_1}$; left-handed up- and down-type squarks are by construction mass degenerate), and
- the trilinear couplings A_t, A_b and A_τ.

$$
\begin{aligned}
-3 \le\ & M_1, M_2 \le 3\,\text{TeV},\\
0 \le\ & M_3 \le 3\,\text{TeV},\\
-3 \le\ & \mu \le 3\,\text{TeV},\\
0 \le\ & m_A \le 3\,\text{TeV},\\
2 \le\ & \tan\beta \le 60,\\
0 \le\ & m_{\tilde{Q}_{1,2}}, m_{\tilde{U}_{1,2}}, m_{\tilde{D}_{1,2}}, m_{\tilde{L}_{1,2}}, m_{\tilde{E}_{1,2}}, m_{\tilde{Q}_3}, m_{\tilde{U}_3}, m_{\tilde{D}_3}, m_{\tilde{L}_3}, m_{\tilde{E}_3} \le 3\,\text{TeV},\\
-7 \le\ & A_t, A_b, A_\tau \le 7\,\text{TeV},
\end{aligned}
$$



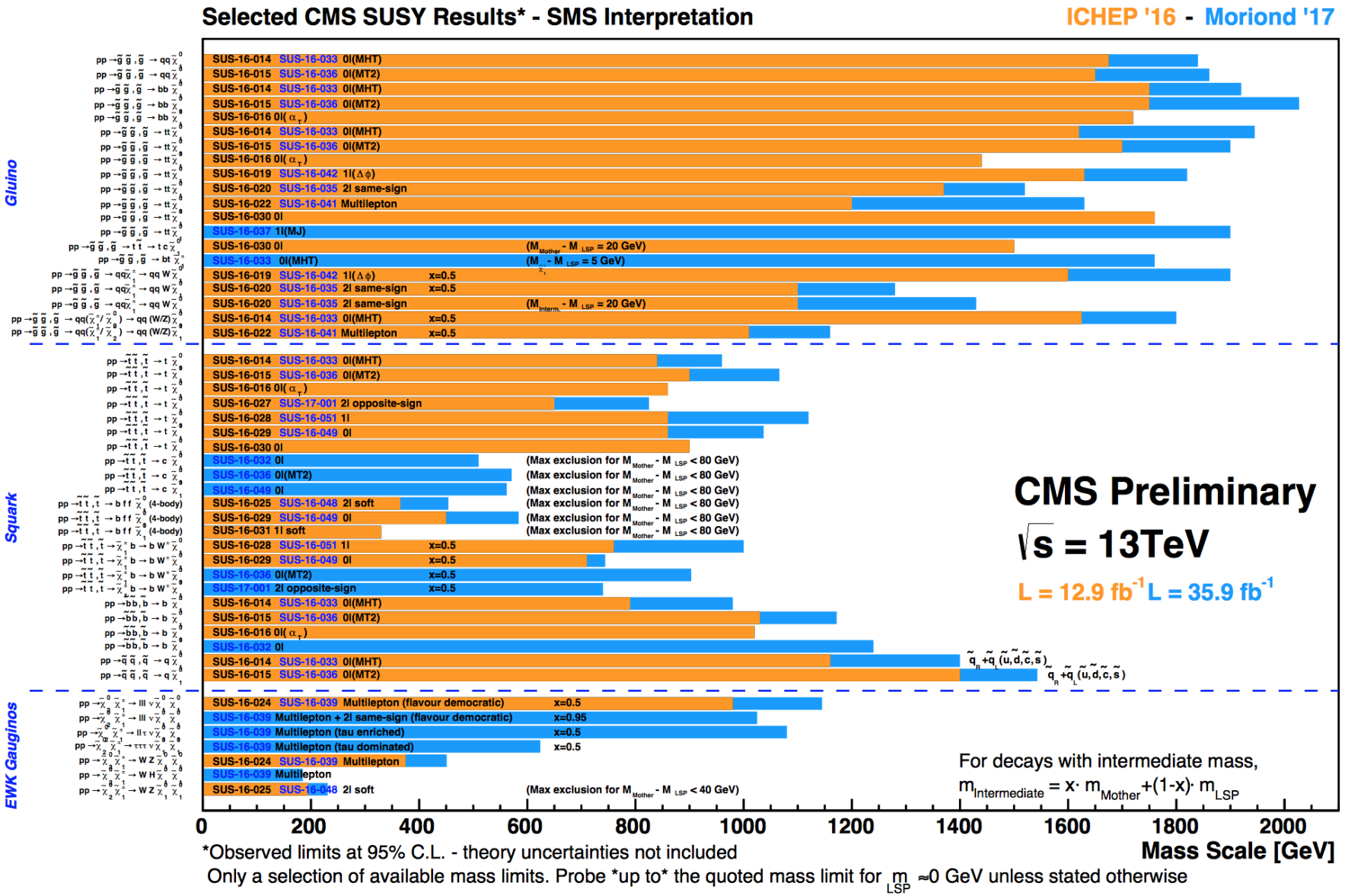




Based on 7/8 TeV limits

10^8 points sampled: Leads to softer limits on the sparticles masses
Gluinos > 500 GeV, stops > 250 GeV => there is still low mass phase space left!

The SUSY Chart So Far…



*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_{LSP} ≈0 GeV unless stated otherwise

SUSY (as seen outside HEP…)

November '16 ago on the web page of The Economist (!?!):

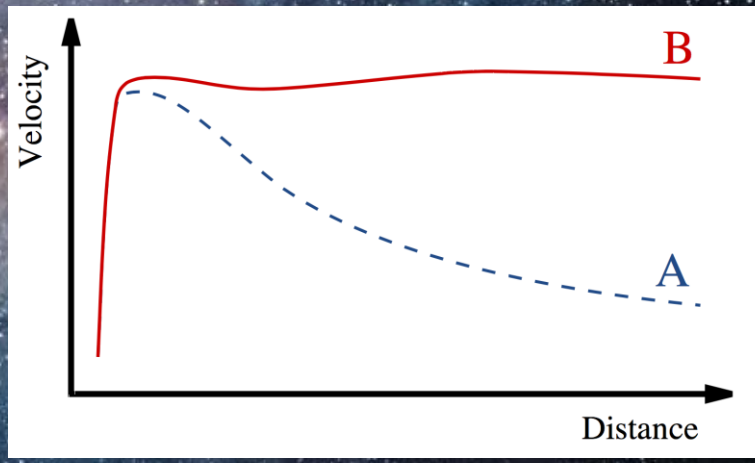
Supersymmetry is a beautiful idea. But no evidence supports it

But not giving up as yet!!!

http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

Dark Matter: The Next Challenge !?!

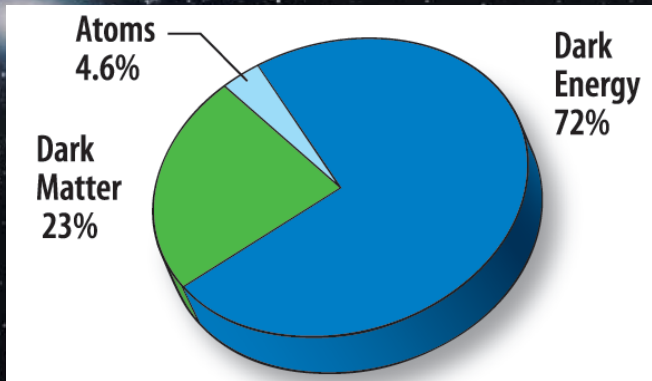
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



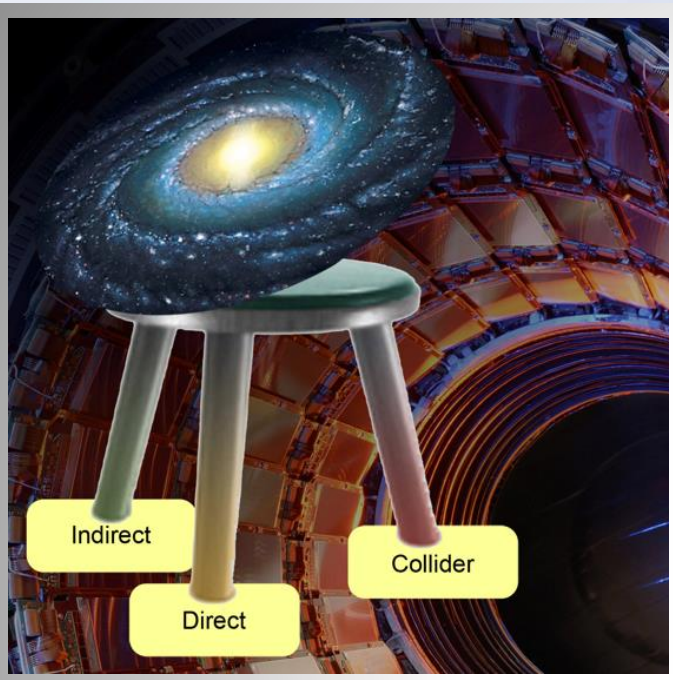
'Supersymmetric' particles ?

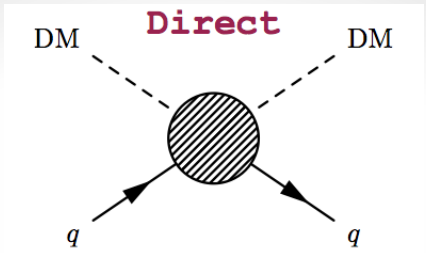

F. Zwicky 1898-1974

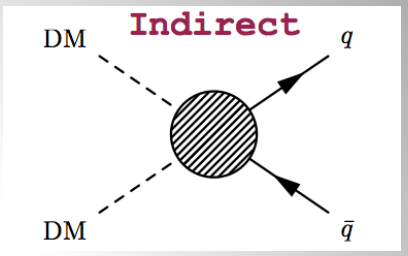

Vera Rubin ~ 1970

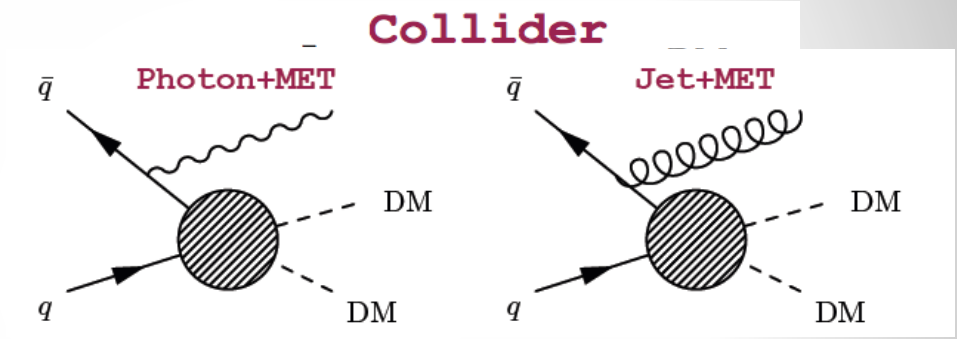


The Dark Matter Connection









Use effective theory or better simplified models to relate measurements to Dark Matter studies

arXiv:1407.8257
arXiv:1411.0535

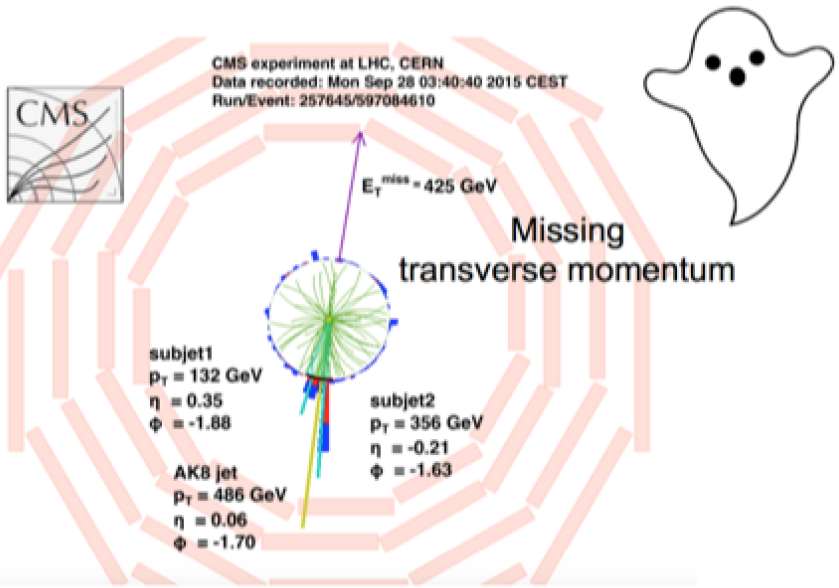
- Mono-jets: Generally very powerful
- Mono-photons: First used for dark matter searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals

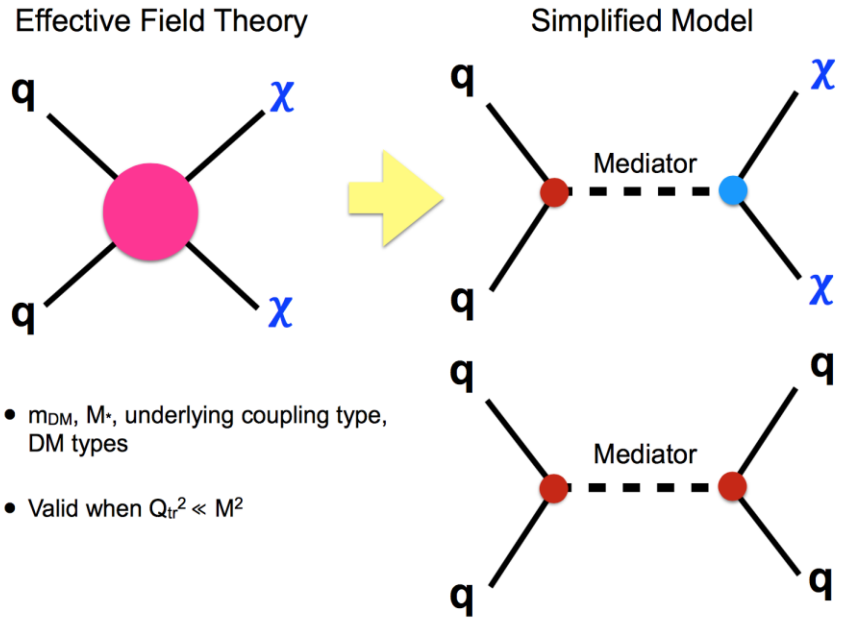
Missing Transverse Momentum

Are Dark Matter Particles WIMPs?

Neutral weakly-interacting massive and stable on detector distance scales

-> Dark Matter appears as Missing Transverse Momentum MET in Detectors





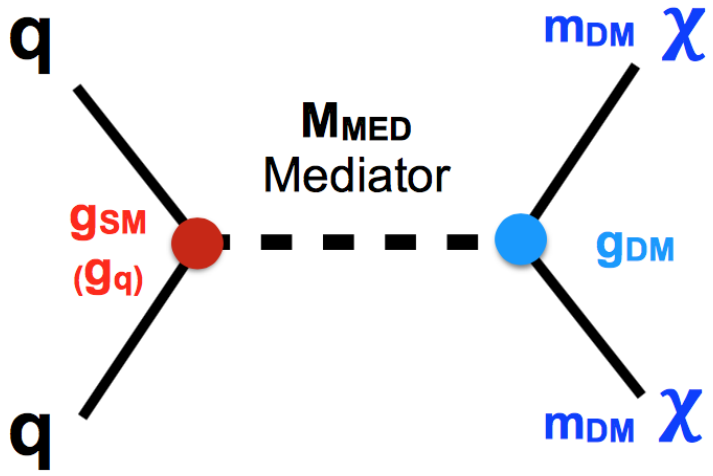
Simplified Models

Simplified models as used for SUSY analyses at the LHC

Features of Mediators

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

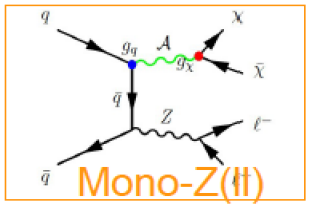
- Mediator has minimal decay width
- Minimal flavor violation
- Minimal set of parameters 4
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}

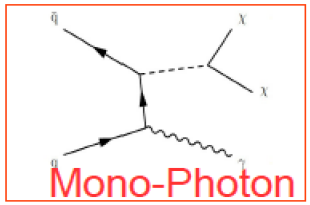


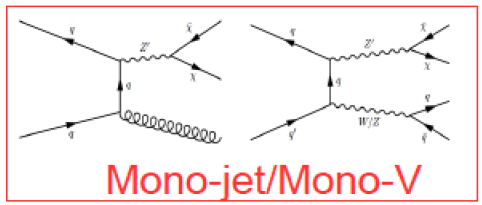
Tae Min Hong, LHCP 2017

Dark Matter Searches: Evolution

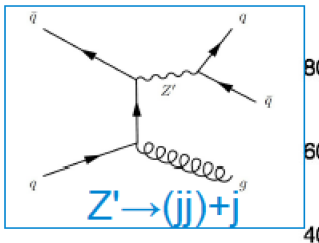
- Dark Matter hunt is one of the new main physics goals for the LHC!
- New developments with Simplified Models, allow including many more search channels such as dijets (aka "In Search for the Mediator")

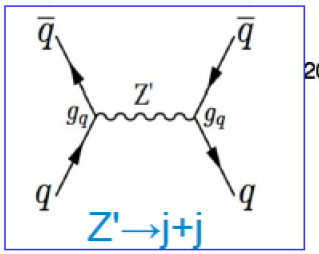


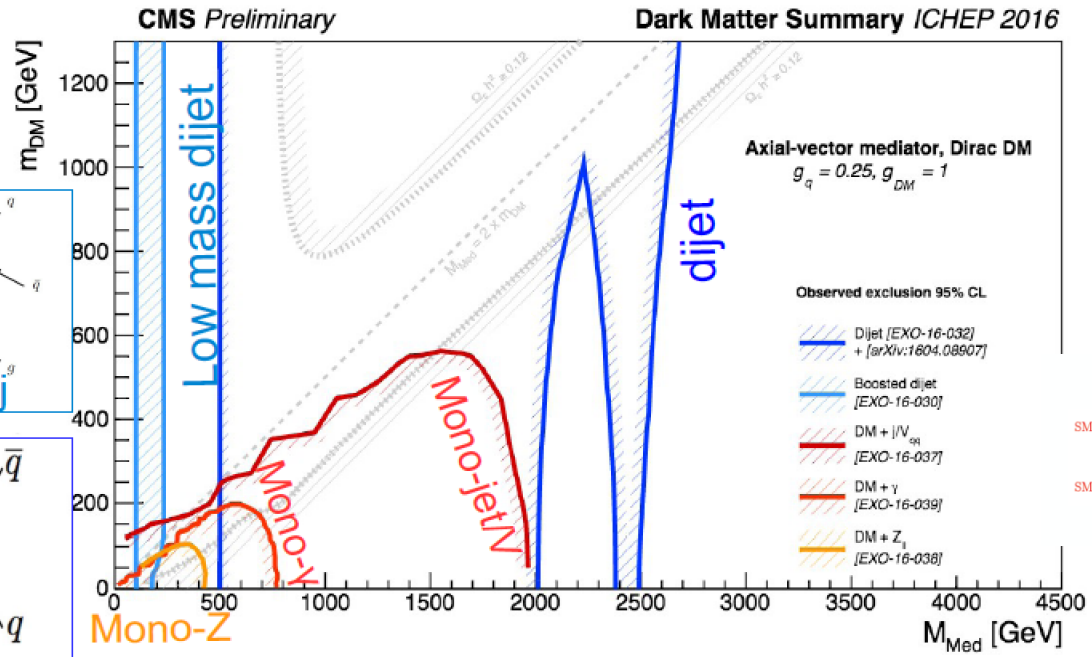


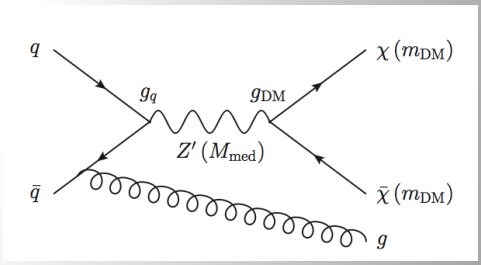


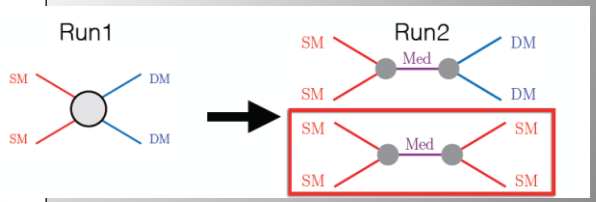
A strategy for future studies







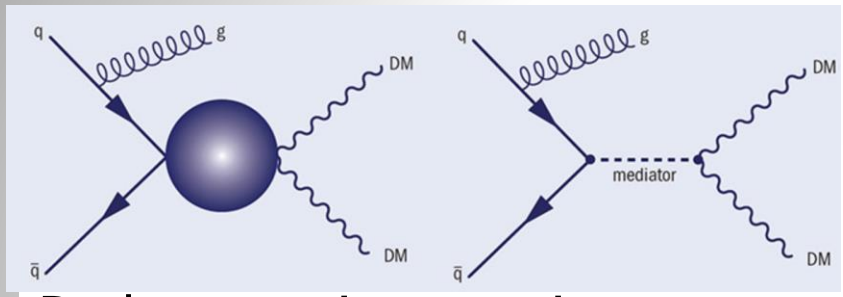




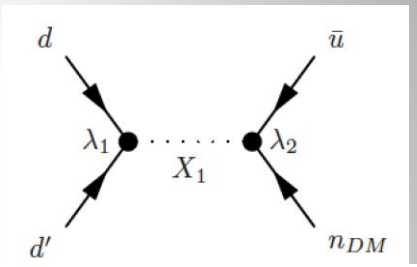
‘Mono-jets’ for ED and Dark Matter Searches

EXO-16-048

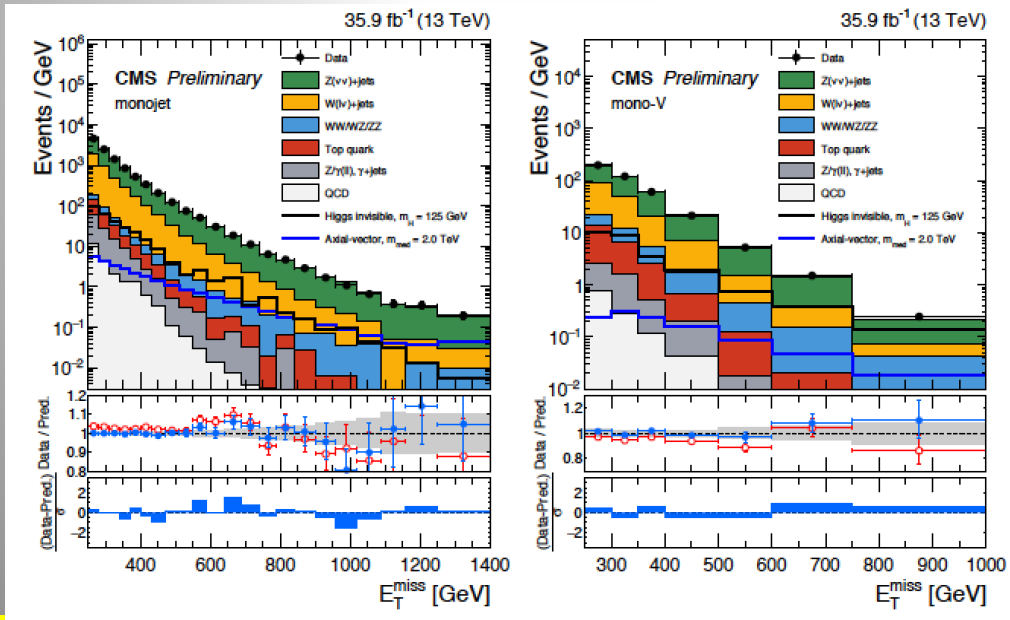
Search for new physics in final states with an energetic jet or boosted hadronically decaying vector bosons

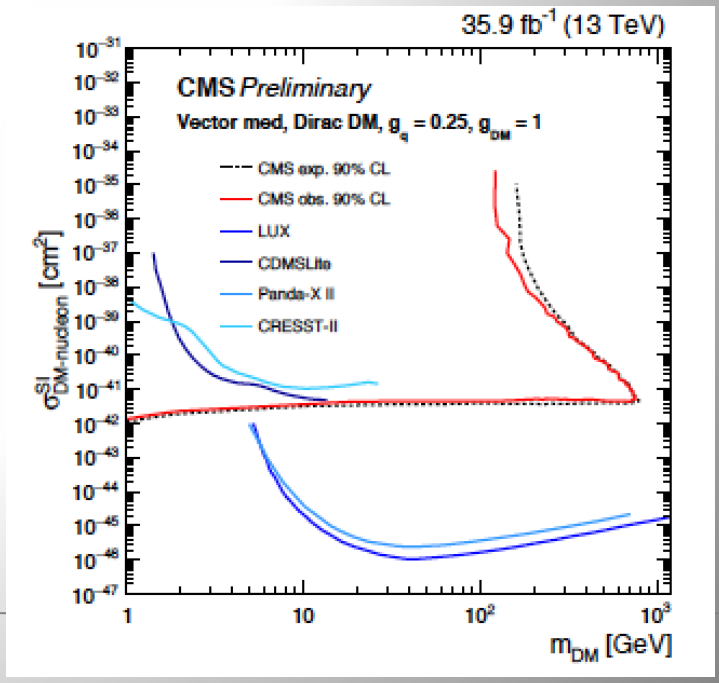


Dark matter in mono-jet events



Dark matter in non-thermal model





More DM limits given in the summary plots

Search for Large Extra Dimensions

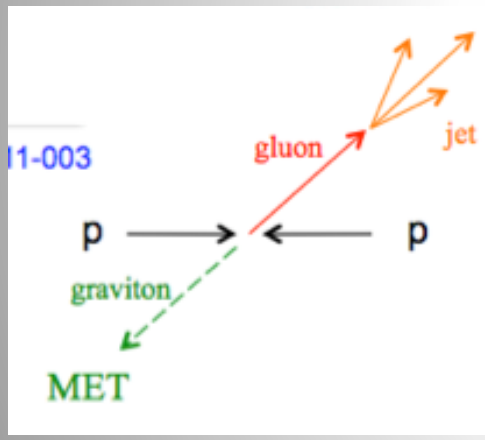
Mono-jet final state +Missing E_T (ADD)

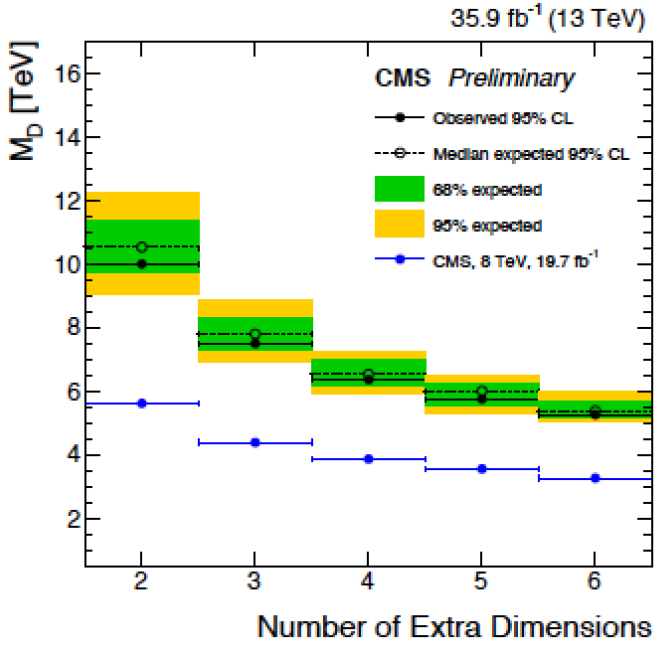
EXO-16-048

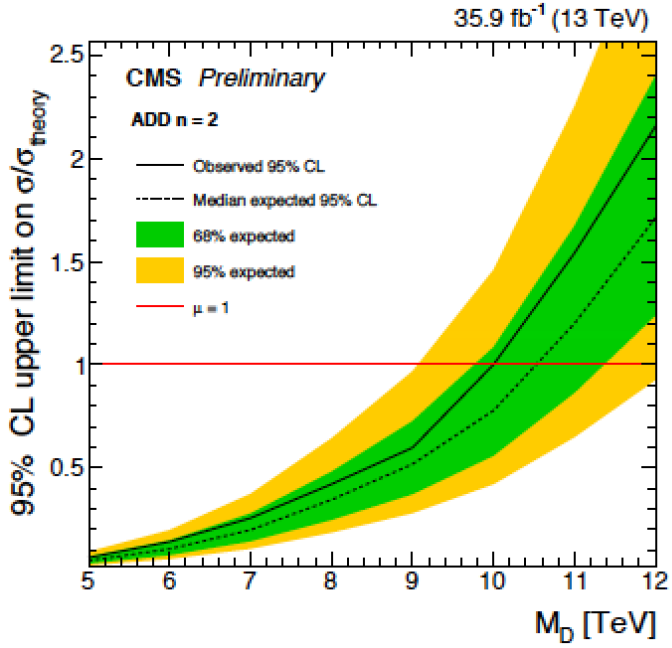
p_T jet > 100/250 GeV
MET > 250 GeV

Limits on M_D between 6 and 10 TeV

Lower limit on the Planck Scale versus number of extra dimensions





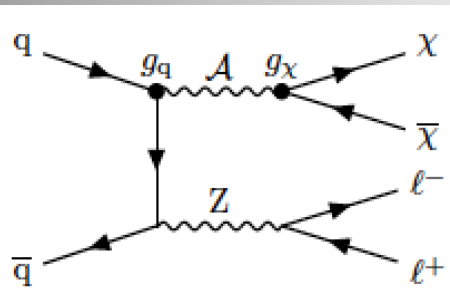


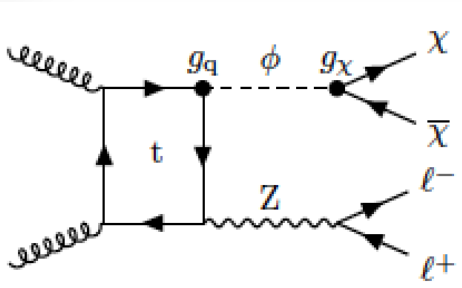
Monojets searches are typically the among the most sensitive ones

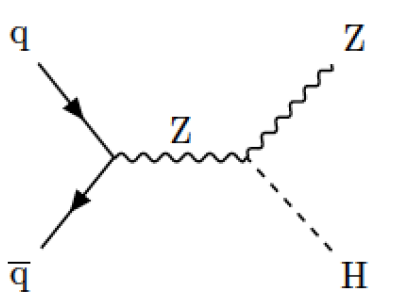
Search using Z + MET final states

EXO-16-052

Search for Dark Matter, Extra Dimensions, Invisible Higgs



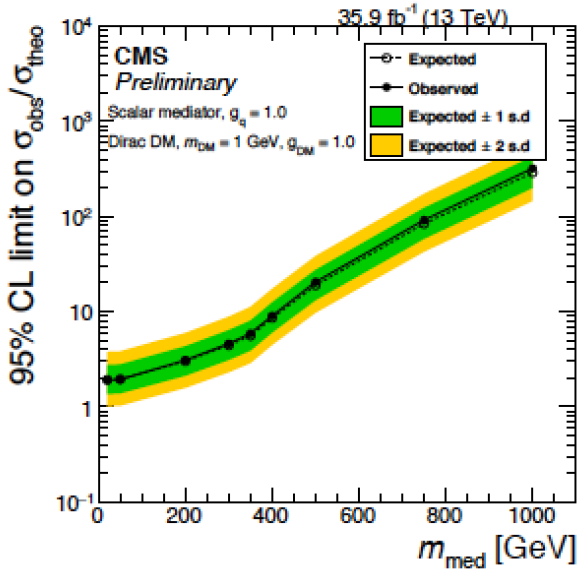


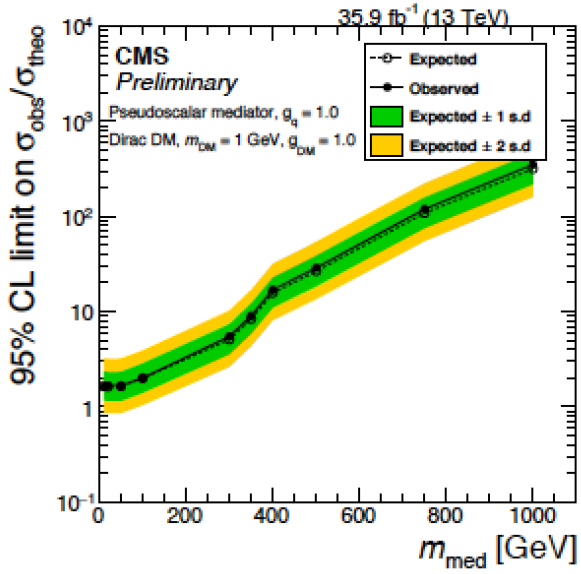


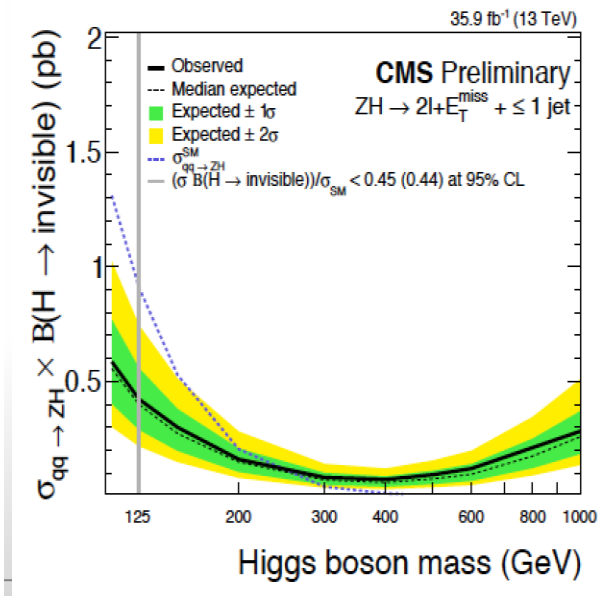
Dark Matter

Search: ETmiss > 100 GeV + Z boson

Invisible Higgs

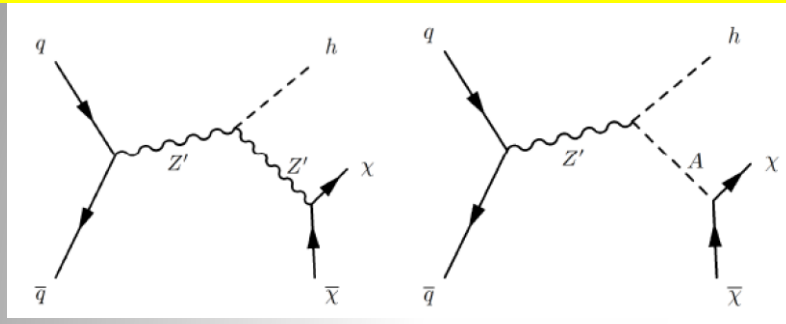




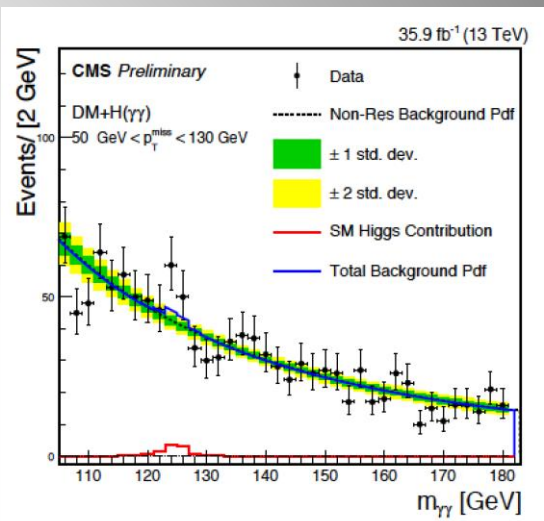


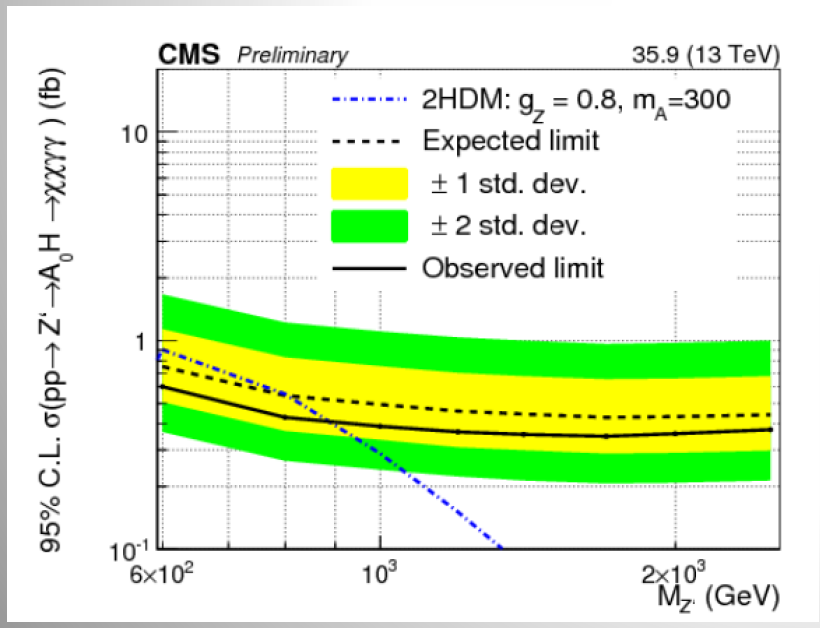
Search with MET + Higgs->γγ

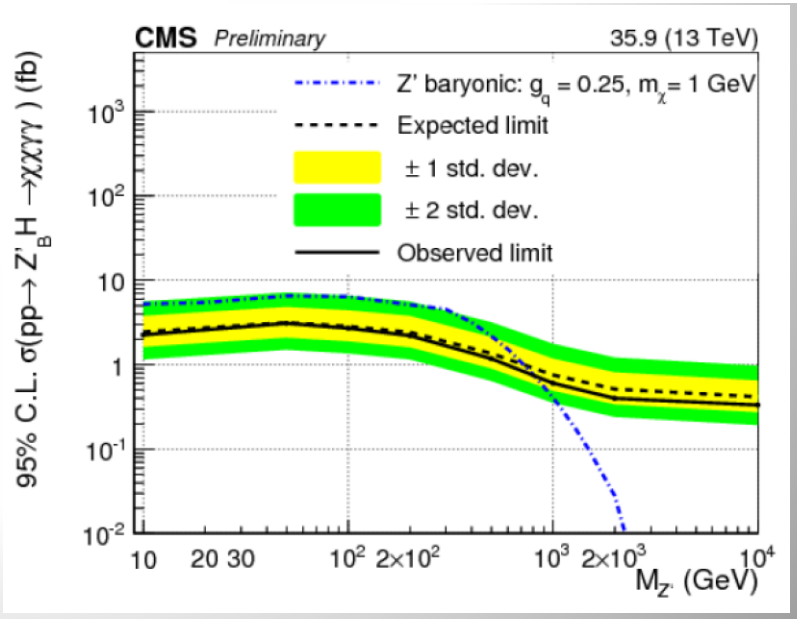
Search for dark matter produced in association with a Higgs boson decaying in two photons



EXO-16-054

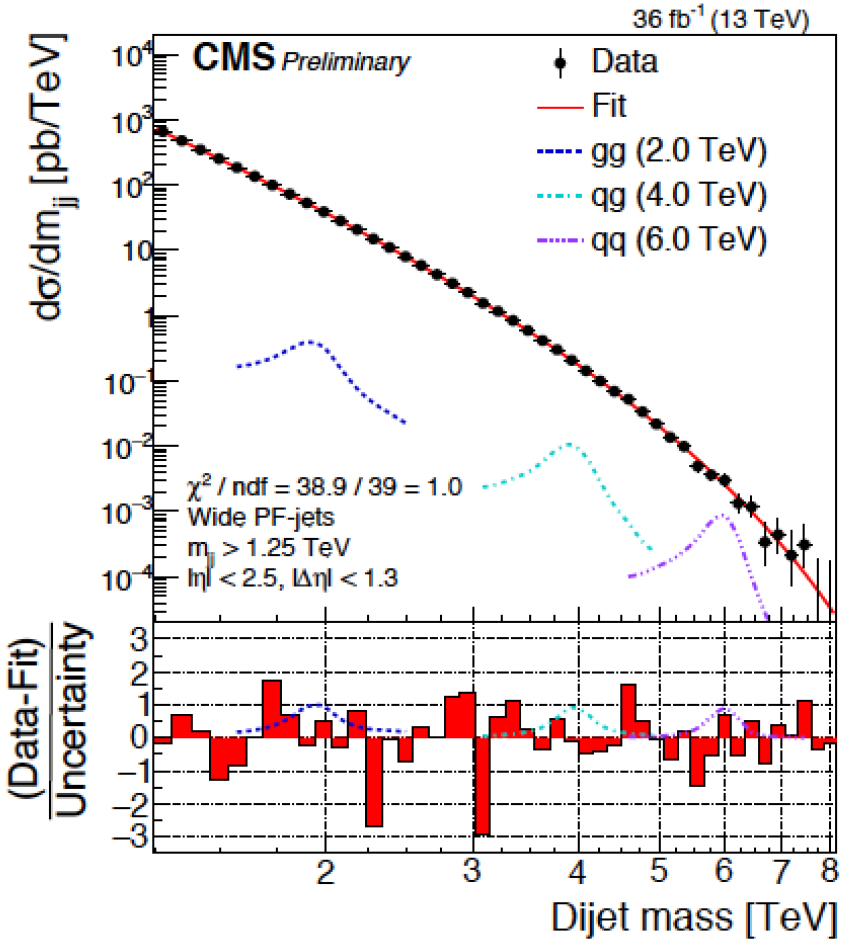






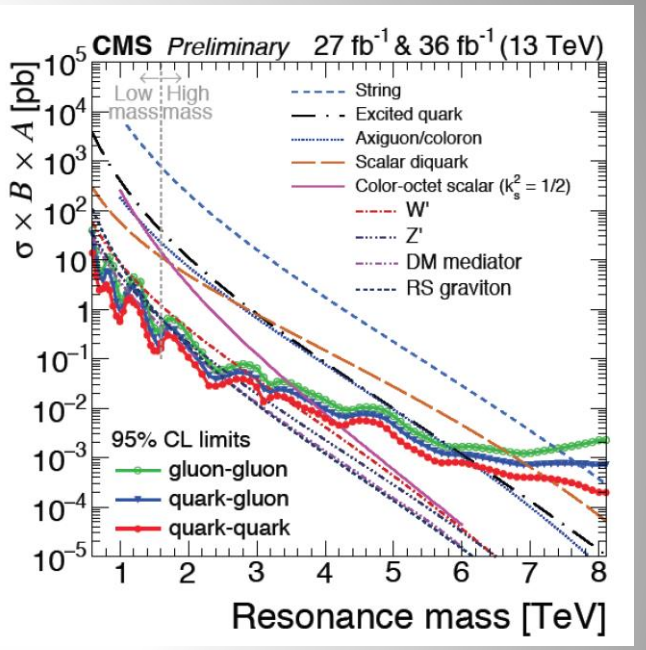
Limits on Two-Higgs Doublet Z' signals 900 GeV Baryonic Z' signals 800 GeV

Dijet Resonance Searches @13TeV



Background: QCD smooth shape fit

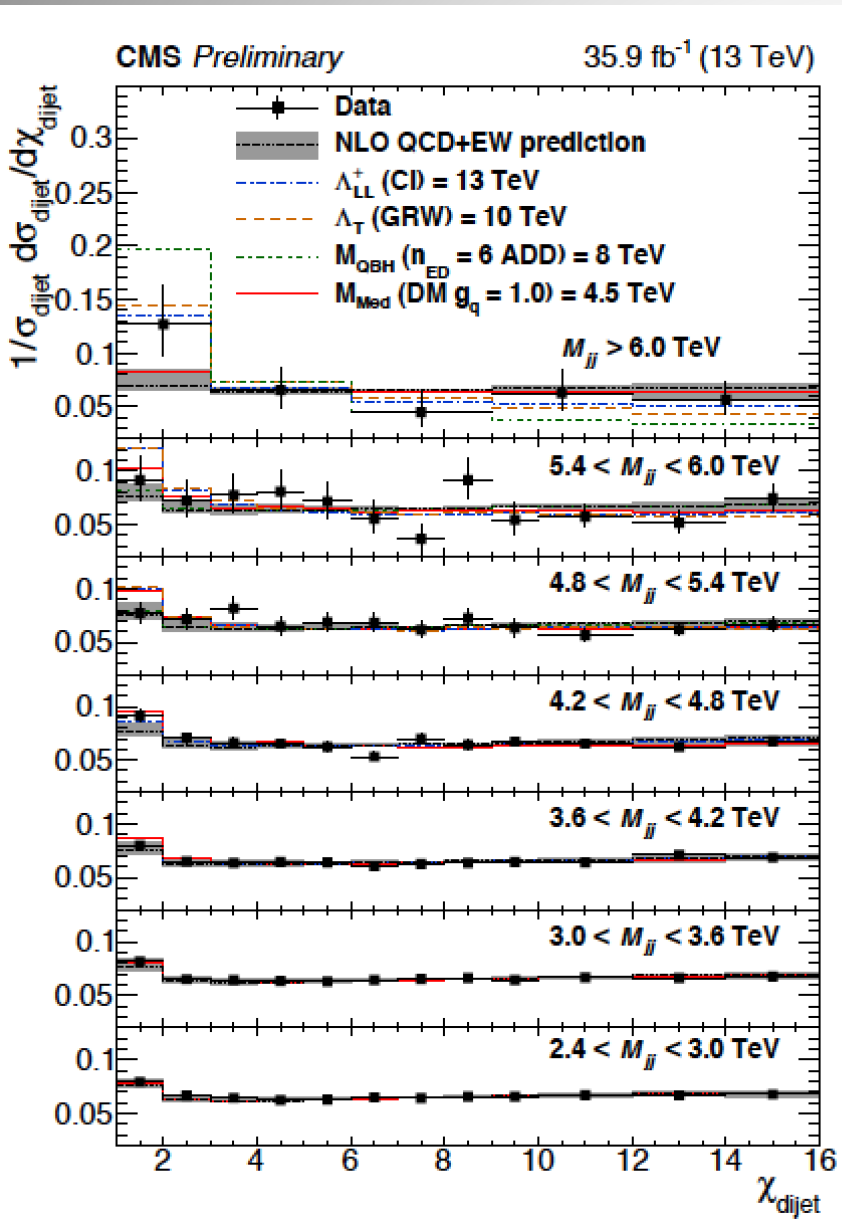
EXO-16-056



Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W′	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

36 fb^{-1} limits from 13 TeV between 1.7 and 7.7 TeV, dependent on model

Dijet Angular Correlations

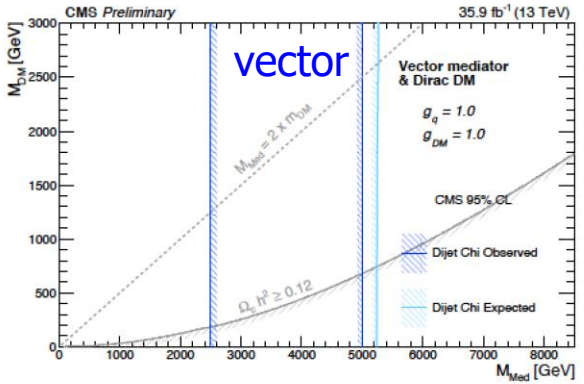


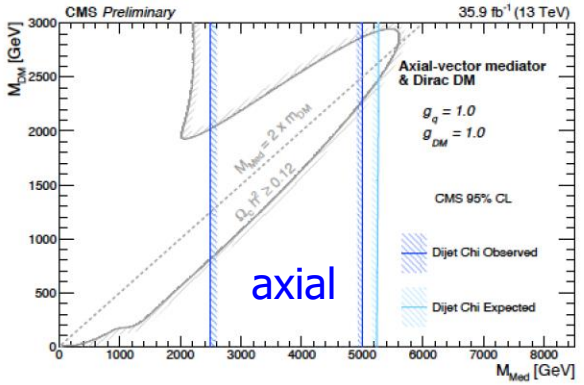
Contact interactions, EDs, BHs, dark matter searches...

CIs: Exclusion up to 13 TeV (dest. int) and 17 TeV (const. int.)

EXO-16-046

Exclusion in the DM plane



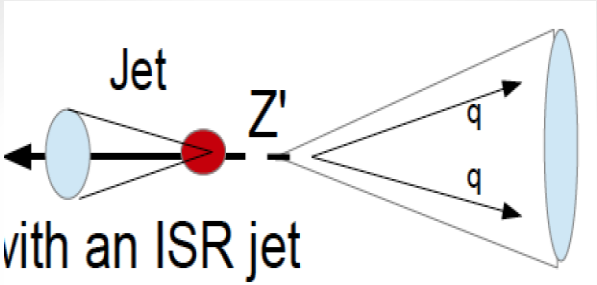


$$= e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

θ^*: jet angle to beam axis in dijet rest frame

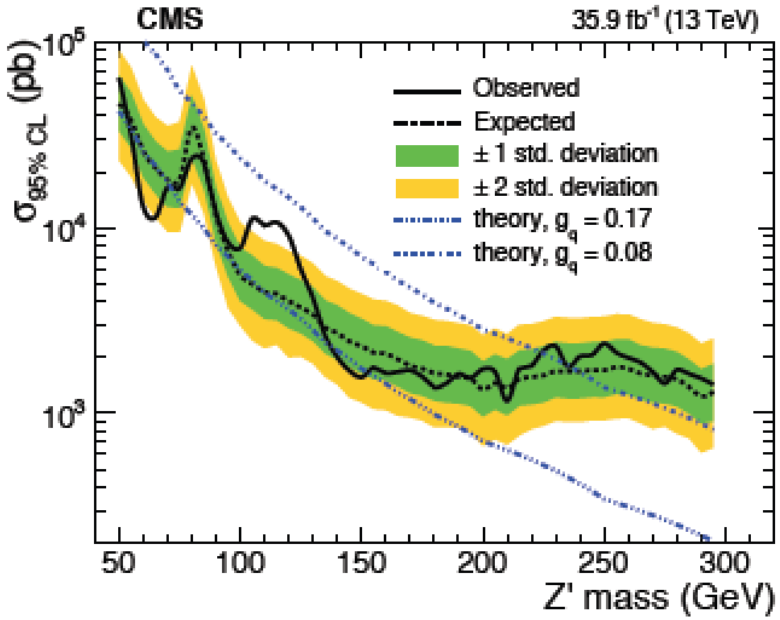
Search for Light Vector Resonances

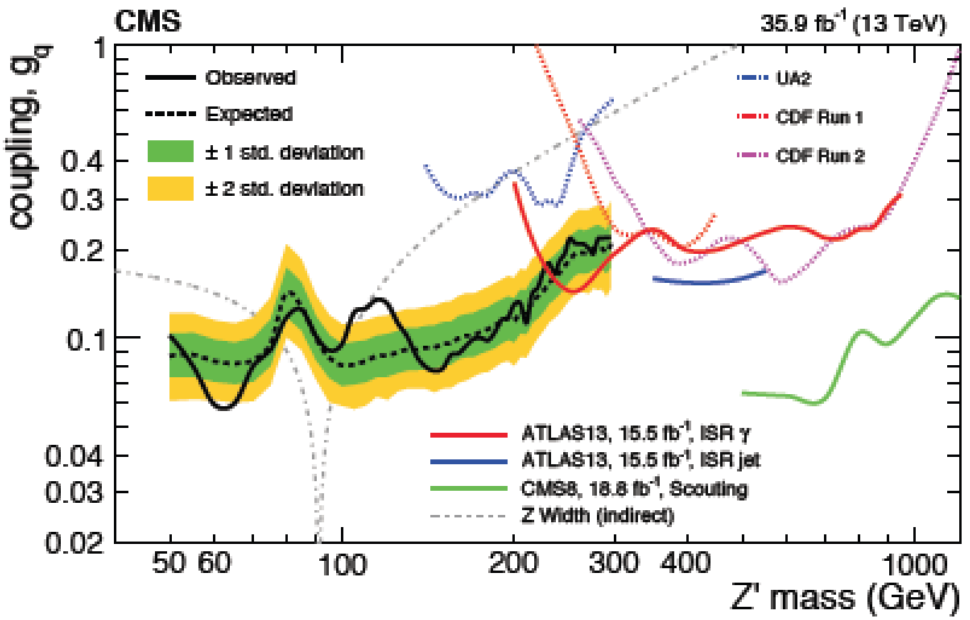
Bump hunting in dijets produced with an ISR jet or high p_T jet to give the trigger



EXO-17-001

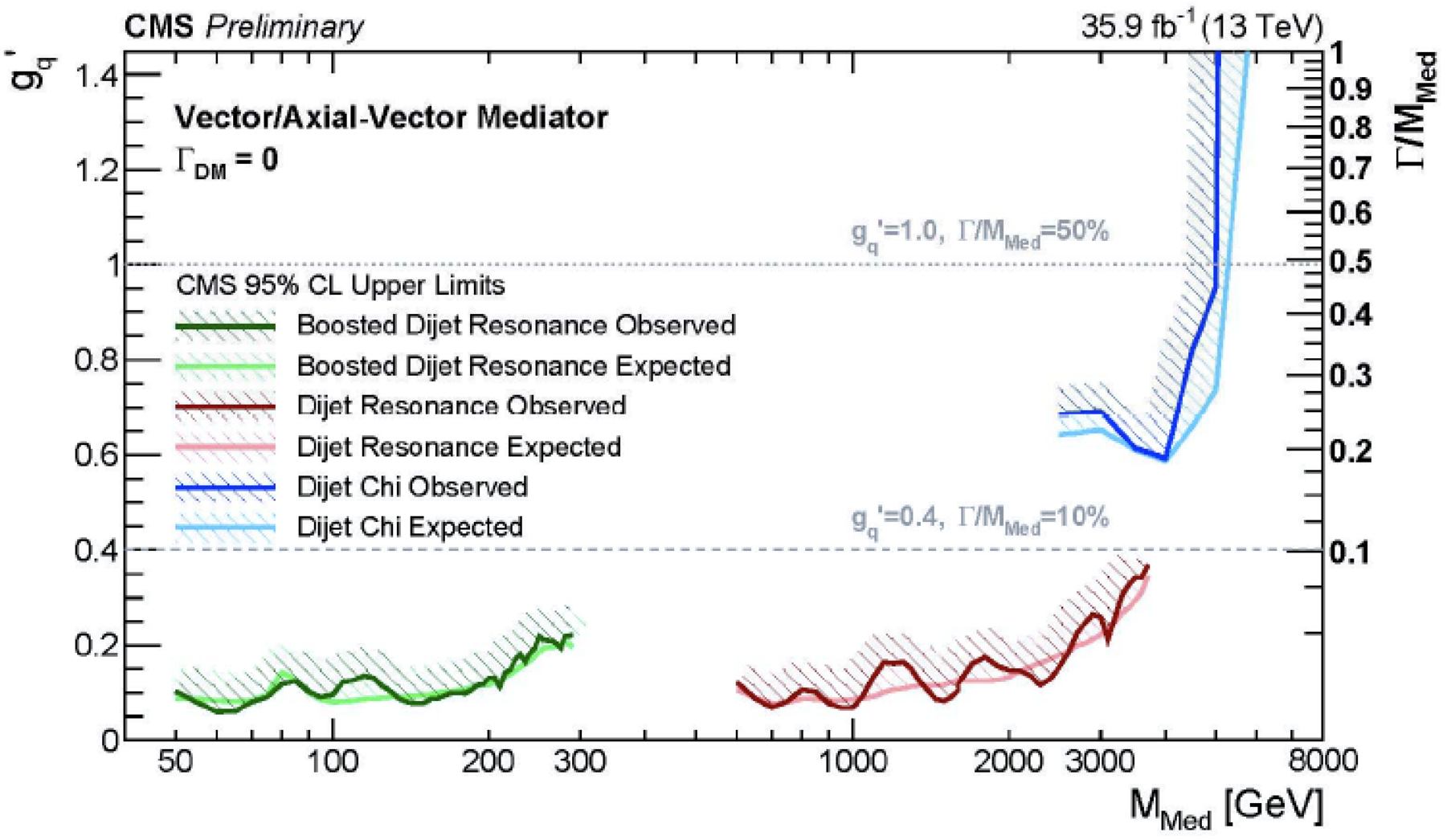
- AK8 jet: p_T>500 GeV
- Jet substructure



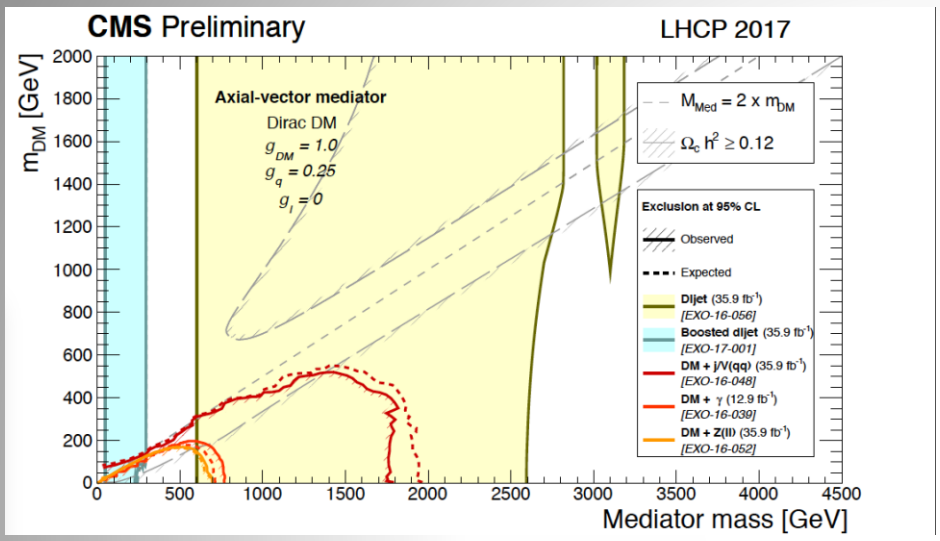


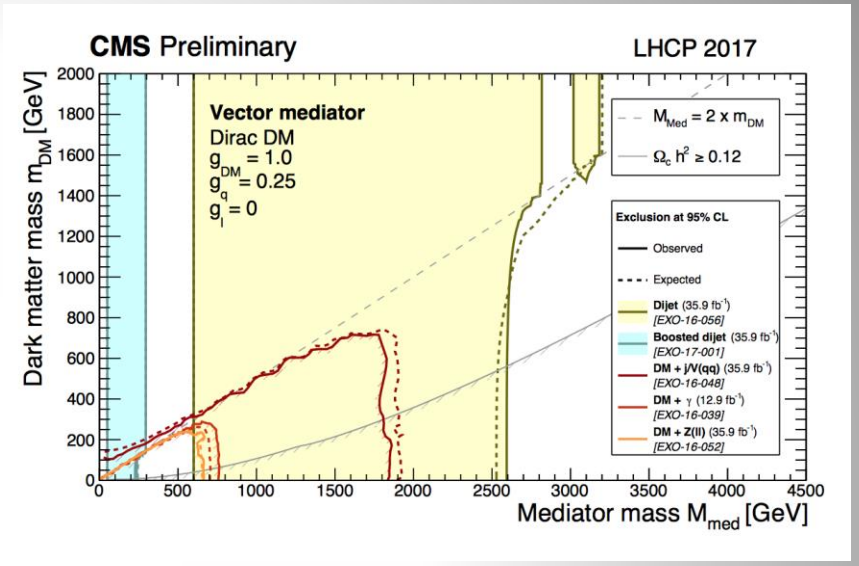
Sensitivity 'beats' the old UA2 result, going now well below 140 GeV
Mild excess around 115 GeV observed: 2.9σ (2.2σ) local (global) significance

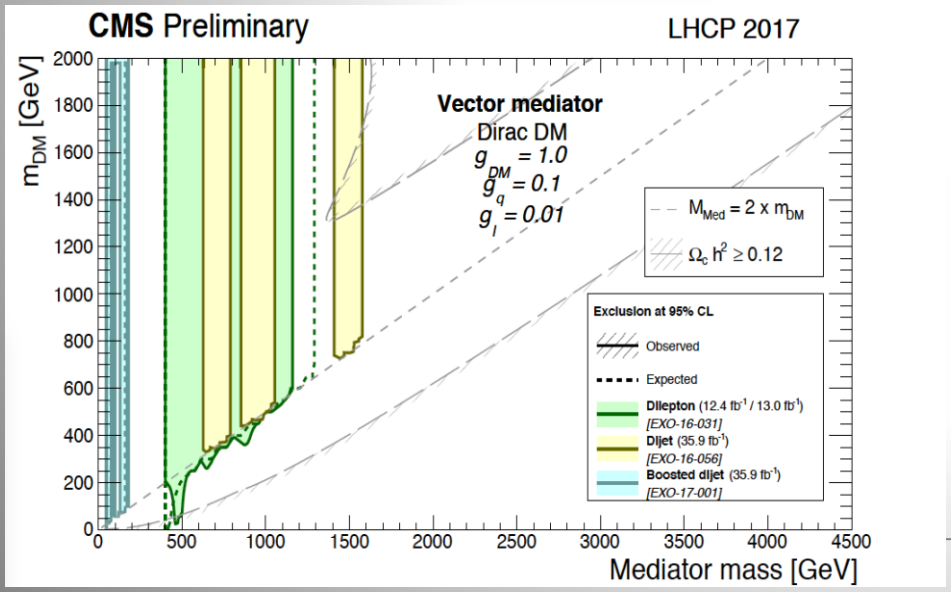
Combined Dijet on Dark Matter

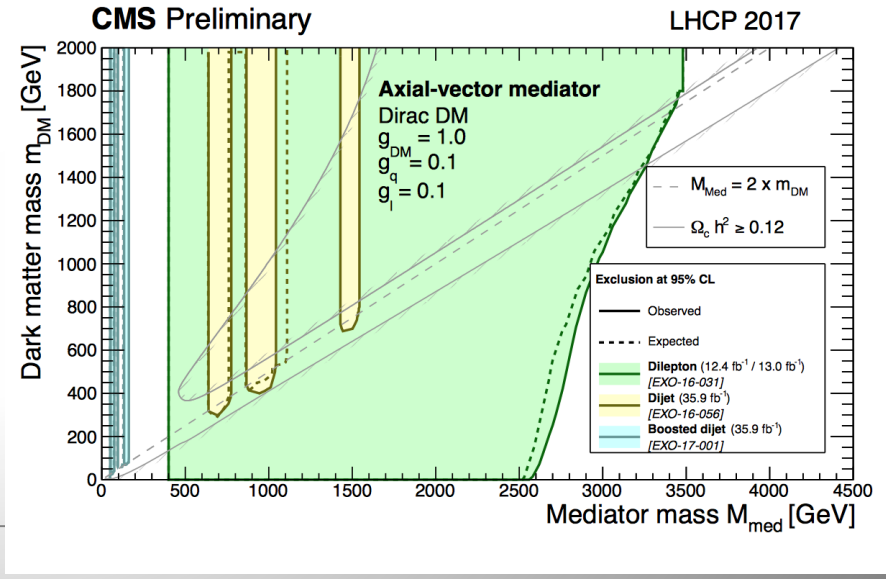


Dark Matter Search Summary Plots



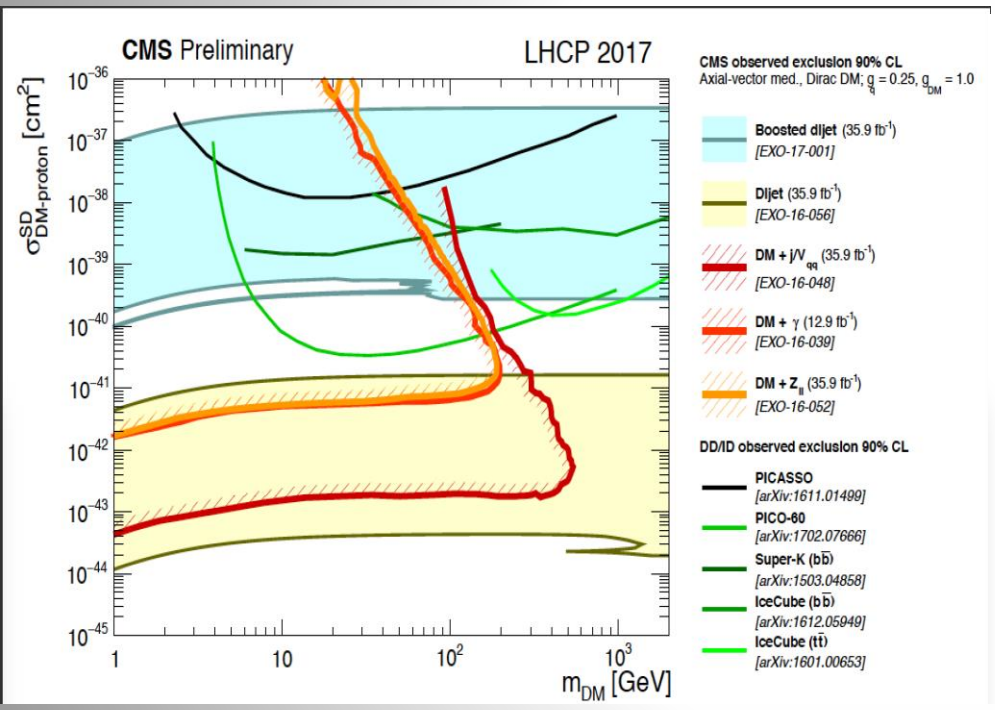




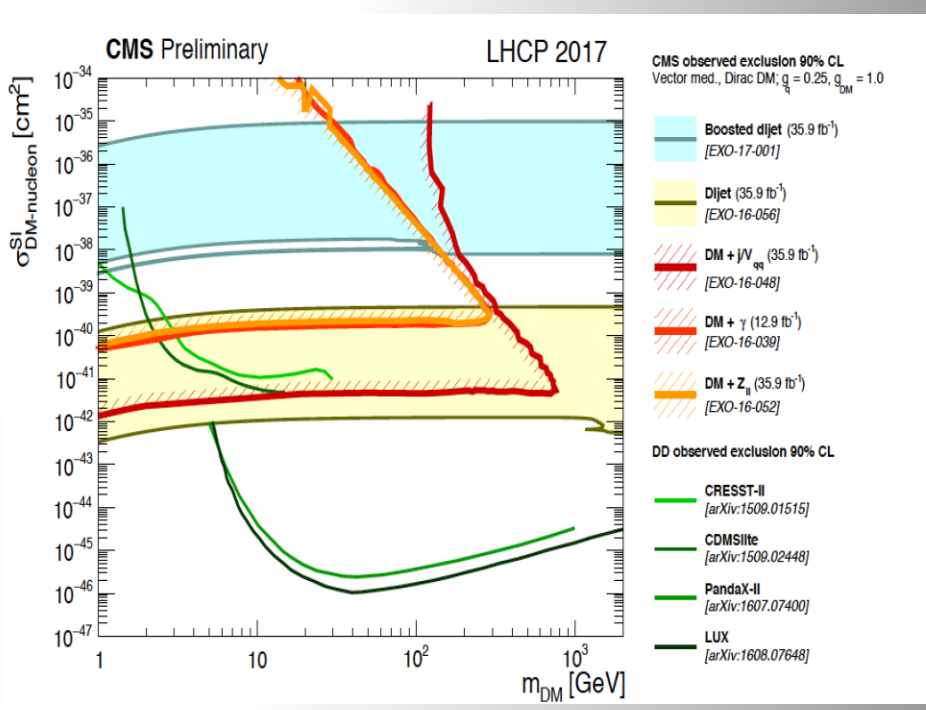


Comparison with Direct Detection

Axial-vector mediator and
Spin dependent direct limits



Vector mediator and
Spin independent direct limits

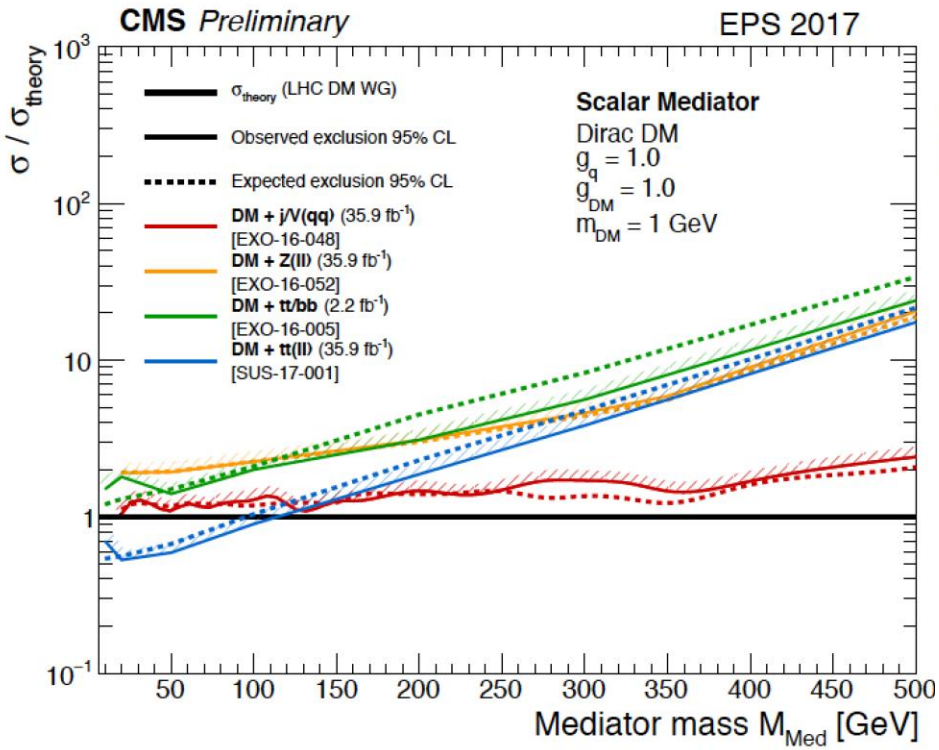


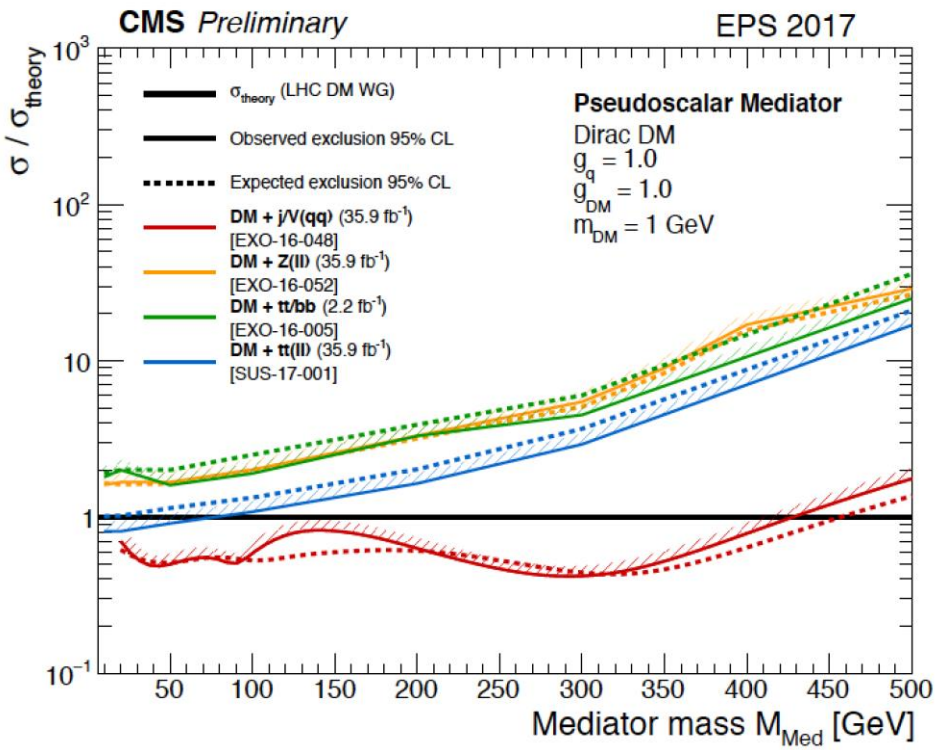
90% CL limits

More reliable comparisons with direct detection results now possible via the SMS method

Dark Matter Search Summary Plots

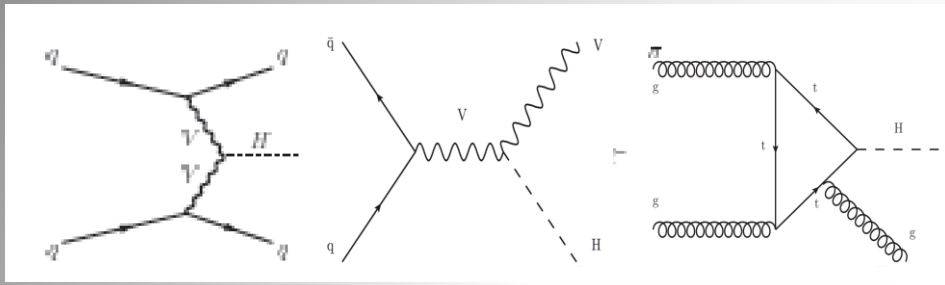
Collider results for scalar/pseudoscalar mediators





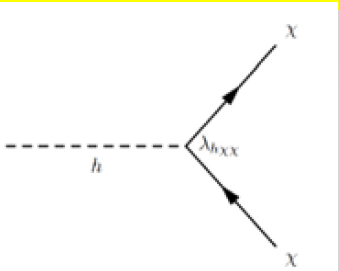
EPS 2017

Invisible Higgs Decay Channel

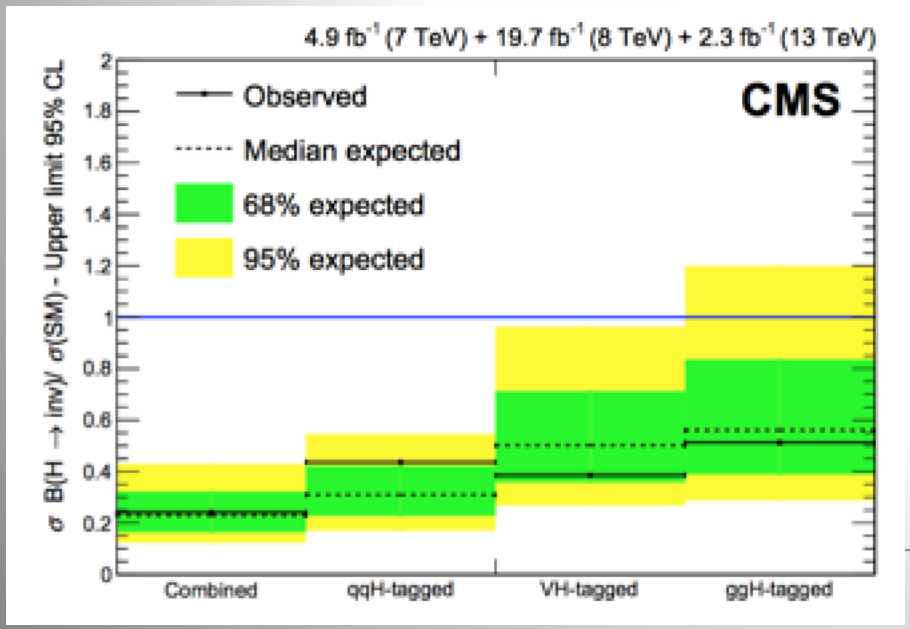


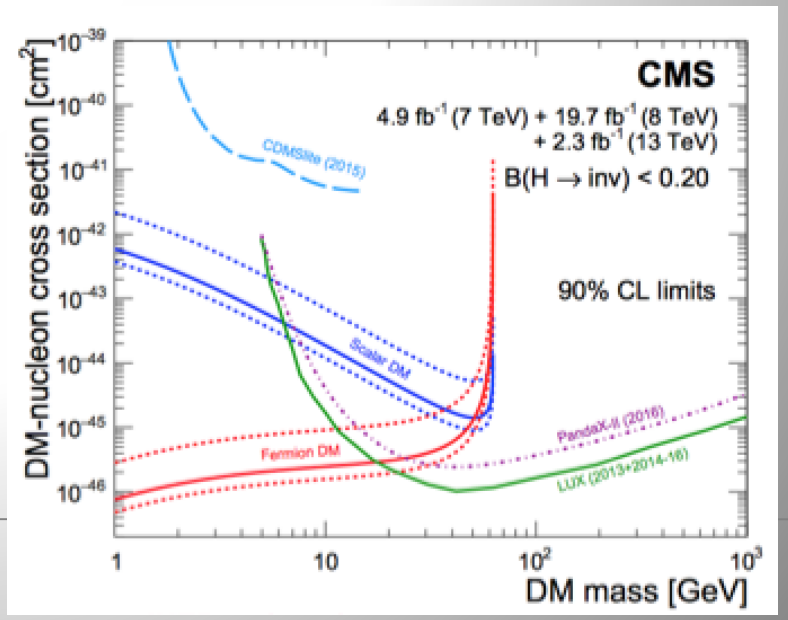
Search for invisible Higgs decays using
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles
(if $M<M_H/2$): Higgs Portal Models

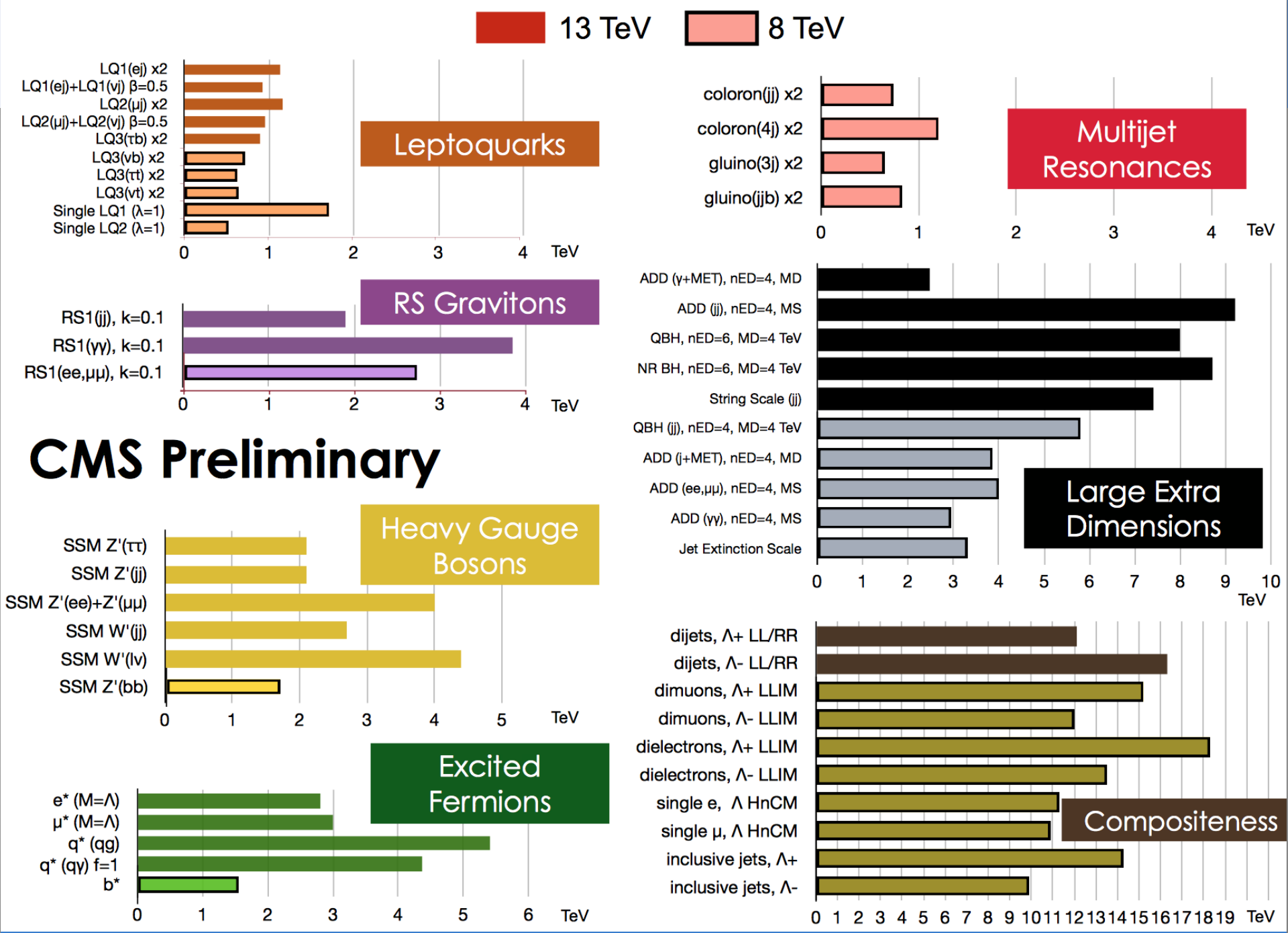
Combined result from the three channels
BR(H→invisible)<24%(23% exp) at 95% CL.
for a Higgs with a mass of 125 GeV



arXiv:1610.09218

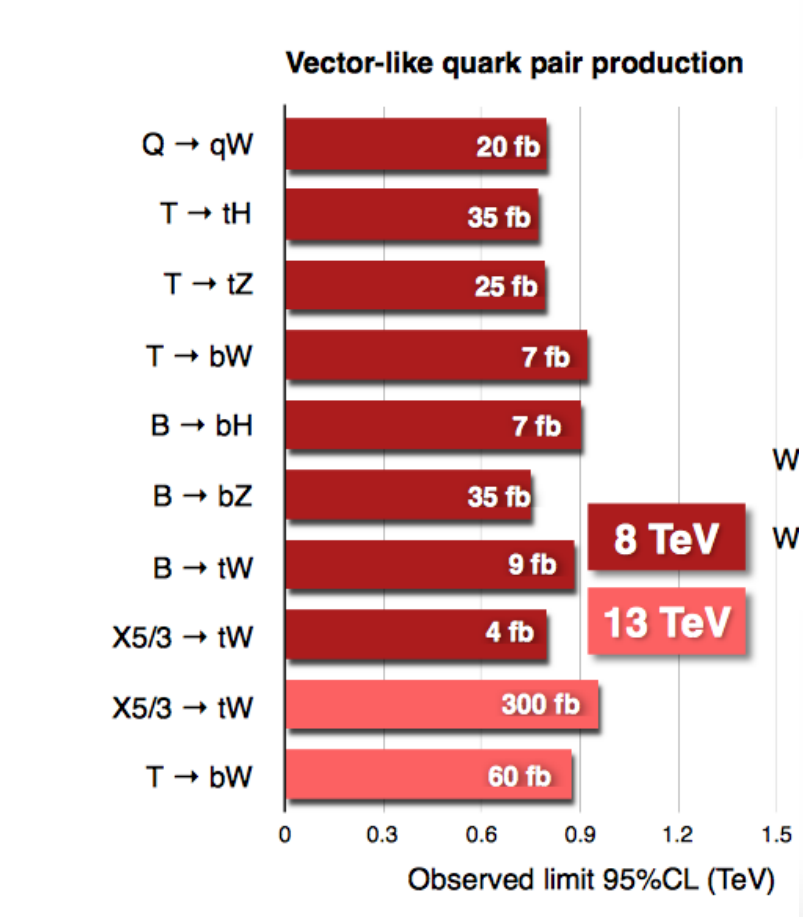


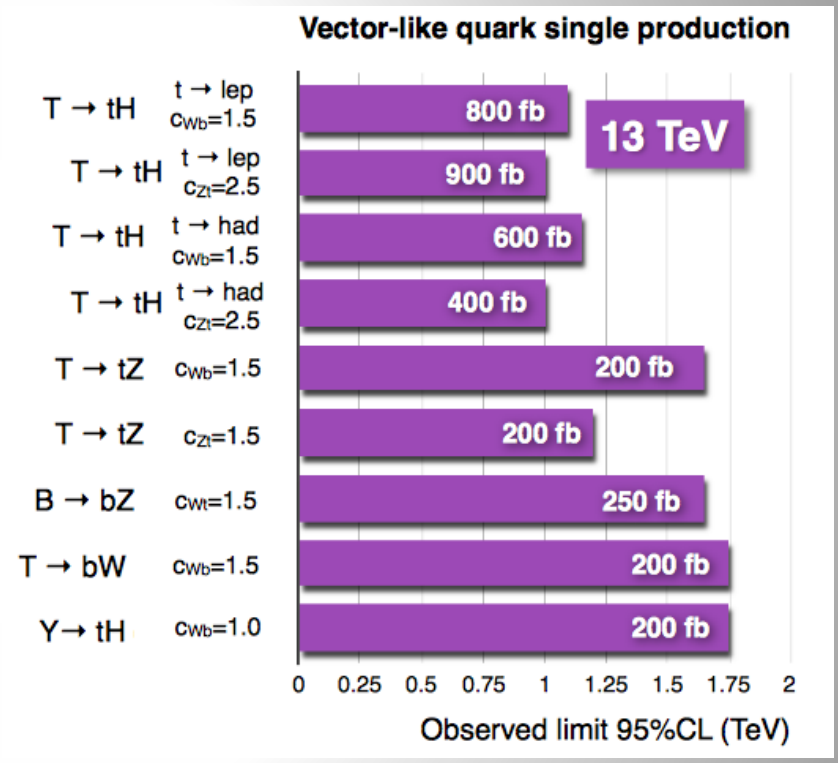



13 TeV
8 TeV
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS Gravitons
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Heavy Gauge Bosons
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Excited Fermions
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
TeV

Vector-like Quark Production Overview

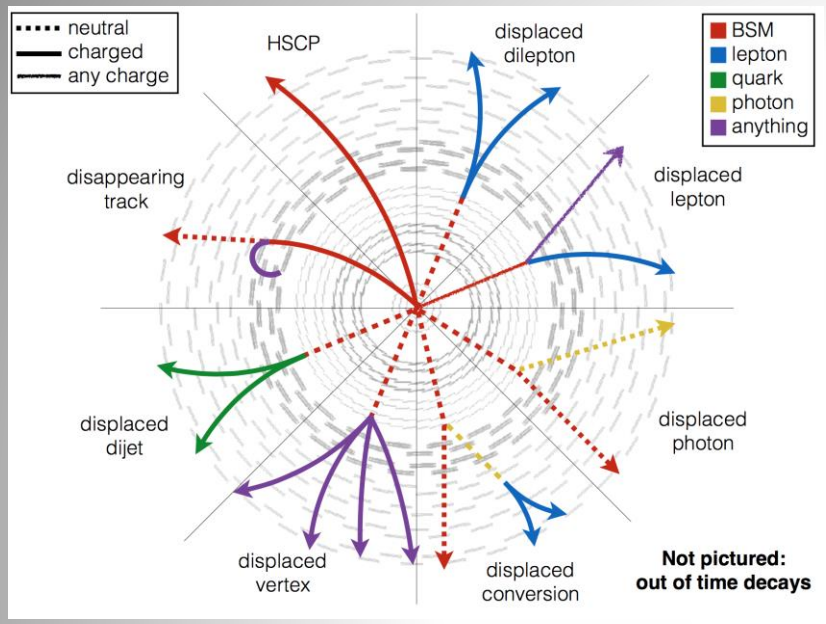
- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin





Exclusions up to masses of
800-950 GeV and up to 1.75 TeV
for singly produced VLQs (model dep.)

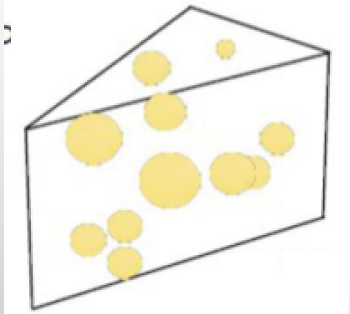
Searches for Long Lived Particles



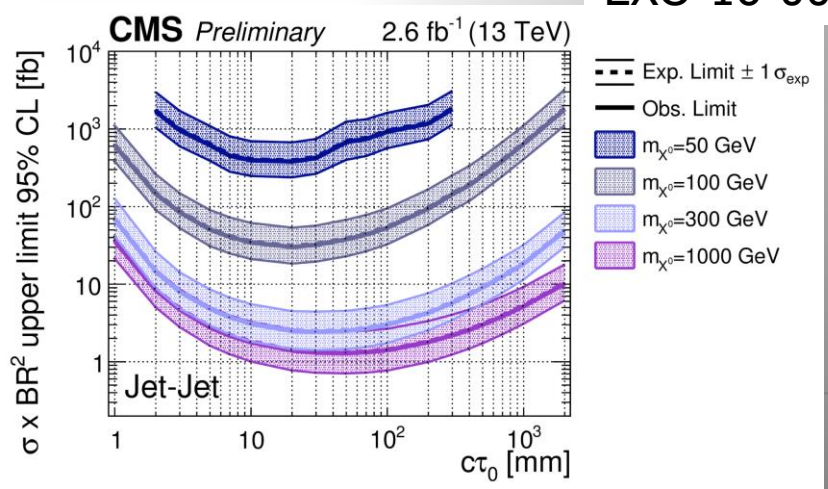
Increasing interest and effort: Look for unusual signals in the detector from long-lived particles

•Example displaced Jets: search for pair-produced long-lived decays to four jet final states.

Present coverage?

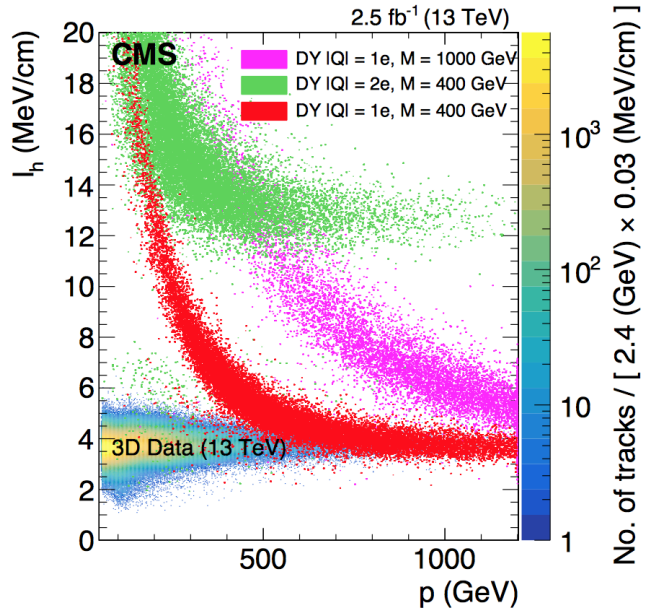


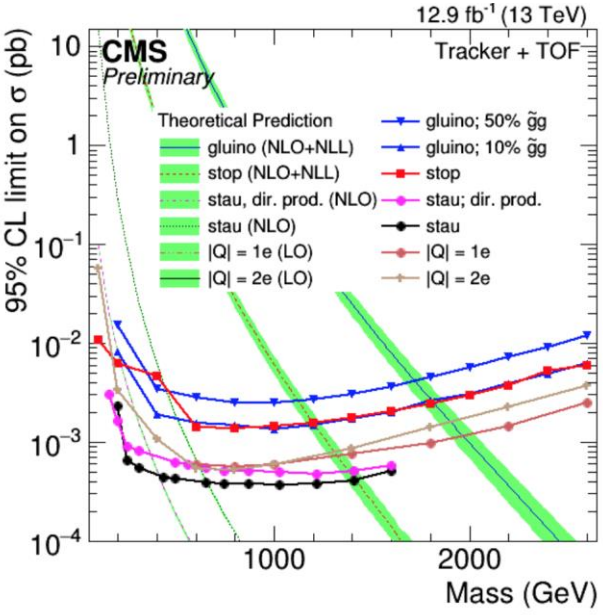
EXO-16-003



LHC-wide organized study ->
https://indico.cern.ch/e/LHC_LLP_October_2017

Heavy Stable Ionizing Particles





Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss (de/dx)
- Slower than speed of light (lowβ) via time of flight measurements with the muon system

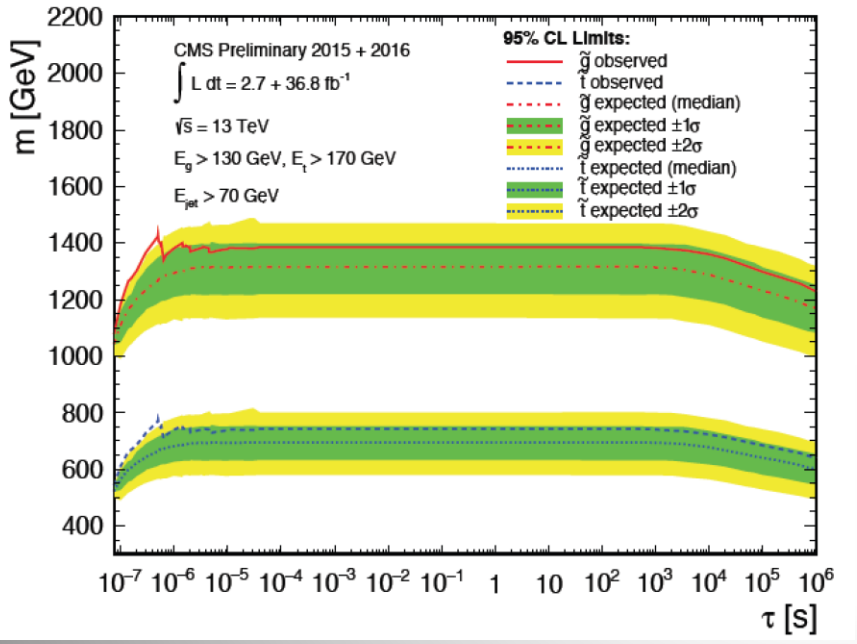
Time of flight $\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$ EXO-16-036

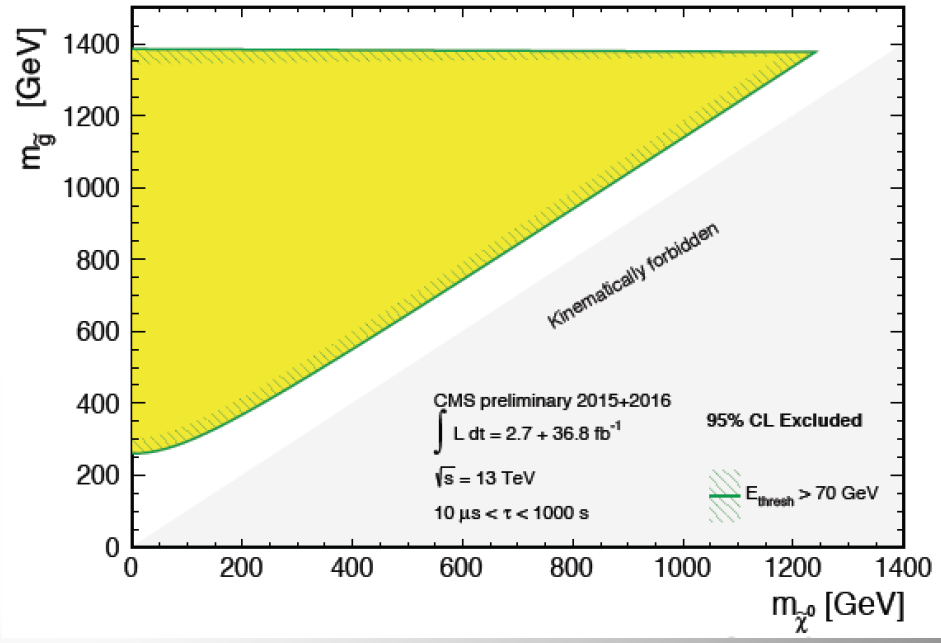
Model	Analysis	Mass Limits
Gluino $f = 0.1$	tracker-only	$M > 1850(1850)$ GeV
	tracker+TOF	$M > 1810(1810)$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1840(1840)$ GeV
Gluino $f = 0.5$	tracker-only	$M > 1760(1760)$ GeV
	tracker+TOF	$M > 1720(1720)$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1800(1800)$ GeV
Stop	tracker-only	$M > 1250(1250)$ GeV
	tracker+TOF	$M > 1200(1200)$ GeV
Stop CS	tracker-only	$M > 1220(1220)$ GeV
GMSB Stau	tracker-only	$M > 660(660)$ GeV
	tracker+TOF	$M > 660(660)$ GeV
Pair Prod. Stau	tracker-only	$M > 170(170)$ GeV
	tracker+TOF	$M > 360(360)$ GeV
DY $Q = 1e$	tracker-only	$M > 720(720)$ GeV
	tracker+TOF	$M > 730(730)$ GeV
DY $Q = 2e$	tracker-only	$M > 670(750)$ GeV
	tracker+TOF	$M > 890(890)$ GeV

Search for Stopped Long Lived Particles

EXO-16-004

- Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions
- 586 hours trigger lifetime in 2016 included in this search.
- Searches for long lived gluinos and stops (R-hadrons) with jets
- 13 events observed in 2016 -> consistent with background

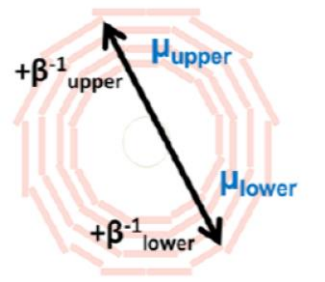




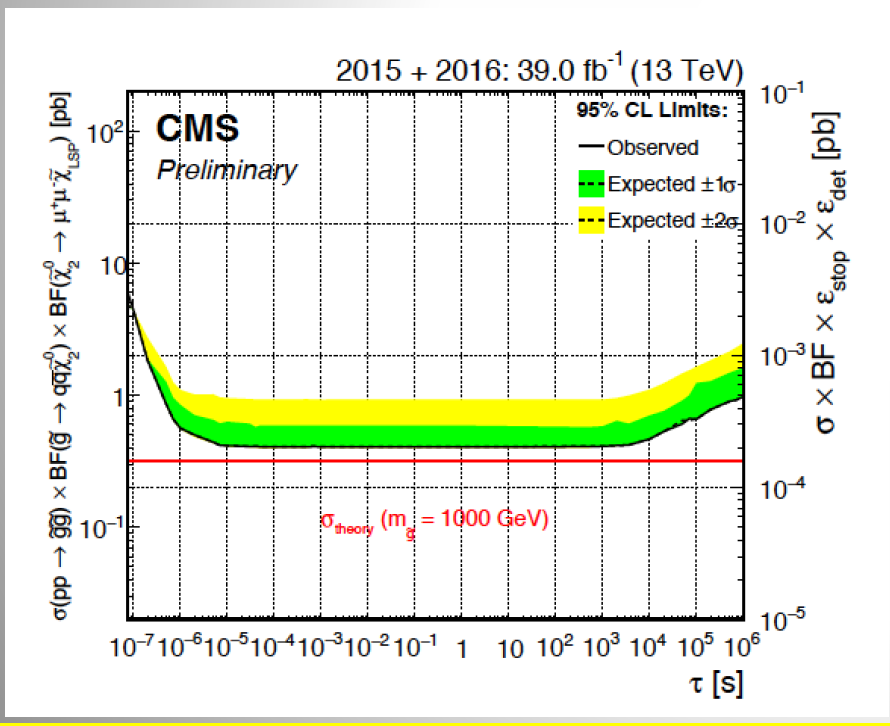
Limits on M_{stop} < 744 GeV and M_{gluino} <1385 GeV 95% CL for lifetimes from 10 μsec to 1000s

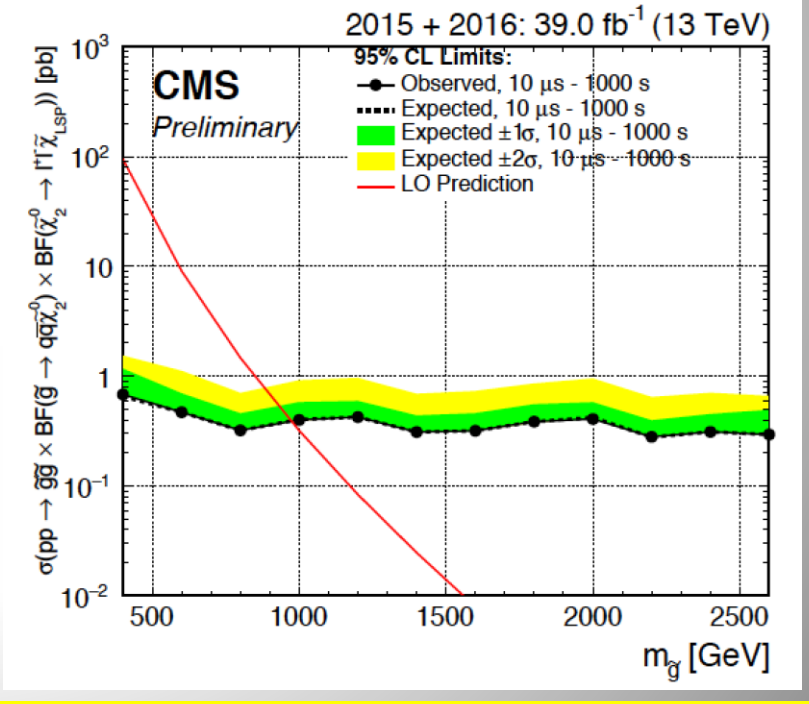
Search for Stopped Long Lived Particles

EXO-17-004



- Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions
- 744 hours trigger lifetime in 2015/16 included in this search.
- Searches for long lived gluinos with delayed muons
- No events observed in 2015/16.



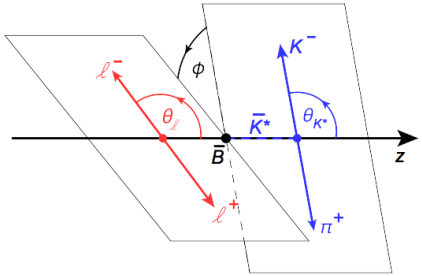


Limits on $400 < M_{gluino} < 970$ GeV 95%CL for lifetimes from 10 μsec to 1000s

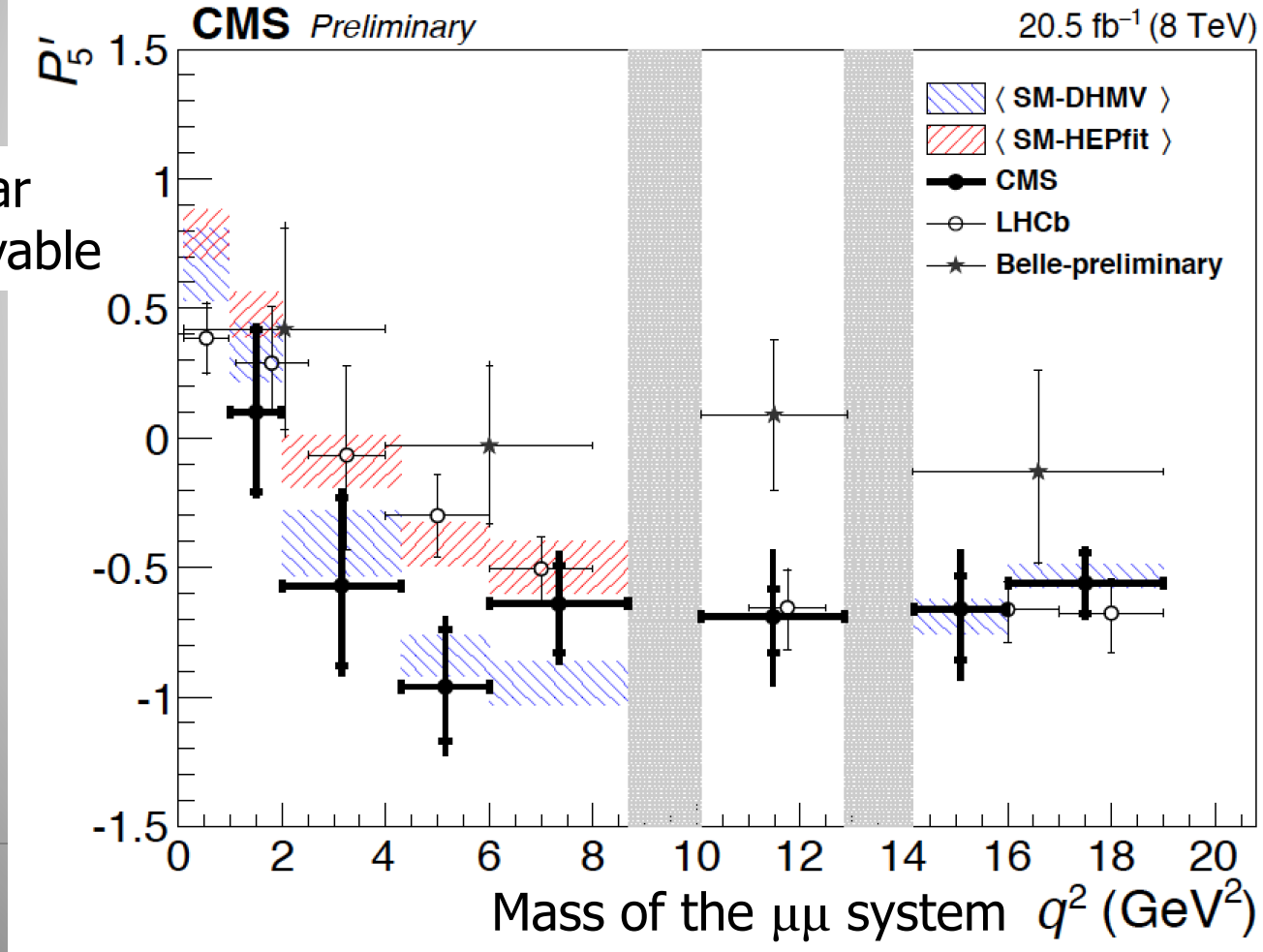
New Physics in Rare Decays?

Analysis of the B0→K*μ+μ- decay (LHCb)

LHCB: arXiv:1512.04442 CMS: BPH-15-008



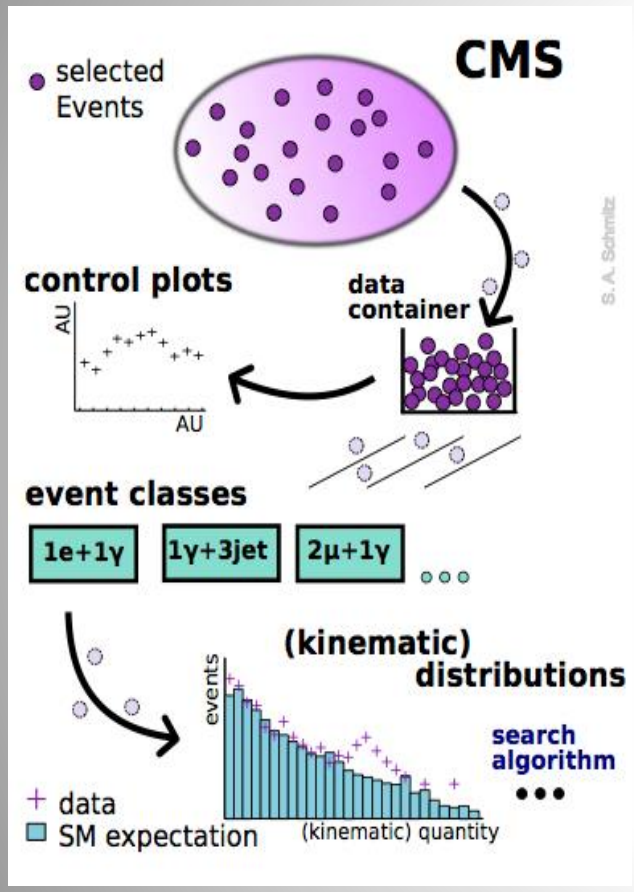
Angular observable



No obvious problem with the 'Standard Model'

A General Search View!

CMS-EXO-14-016



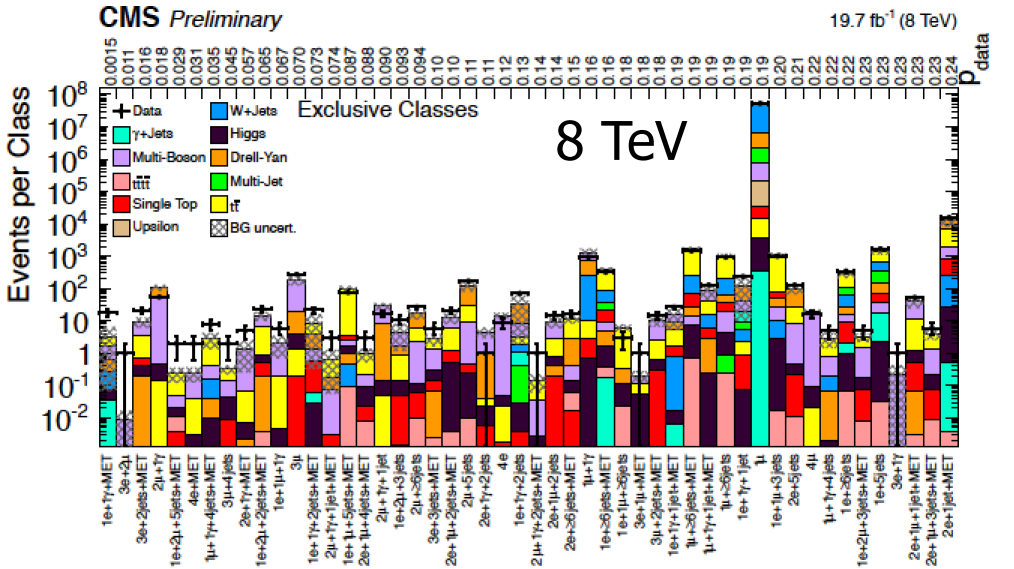
Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles

No outlying deviation found



Rates (exclusive classes) as expected for 19.7 fb^{-1} for CMS
→muons, electrons, photons, MET

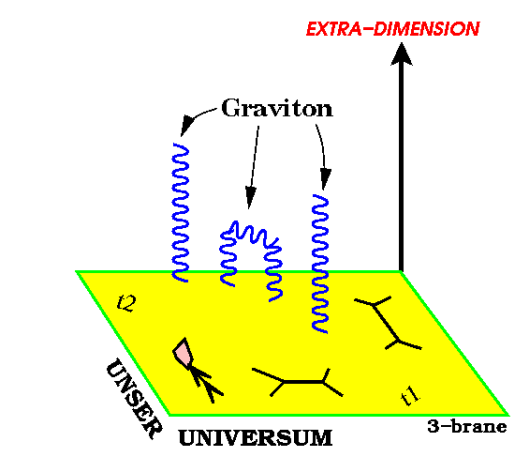
Analysis ongoing for 13 TeV

Summary

- Standard Model measurements @ 13 TeV show no surprise. E.g. W/Z and top cross sections according to expectations
- New Higgs measurements at 13 TeV. So far the Higgs is very consistent with Standard Model expectations.
- No sign of new physics in the first 13 TeV data… This starts to cut into the 'preferred regions' for a large number of models, like SUSY.
- Dark Matter and Long Lived Particle searches are being explored in a more systematic way
- The LHC is continuing to explore the Terascale. We have much data to look forward to: it takes on signific
  to show the way!! Collected >60 fb^{-1}@ 13 TeV s

And hopefully one day soon:

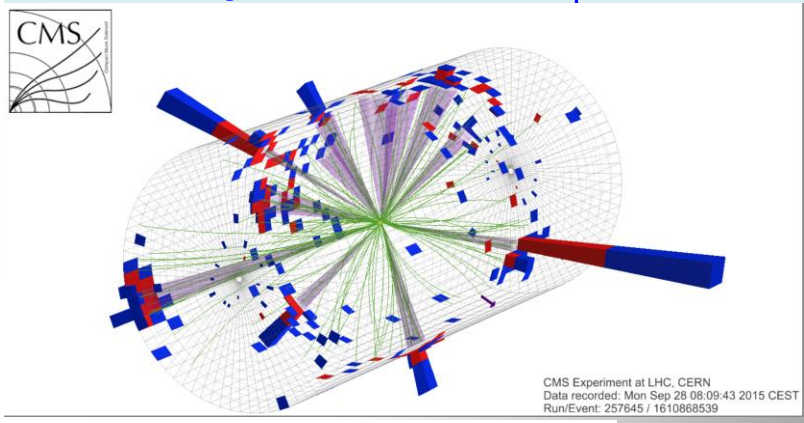
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

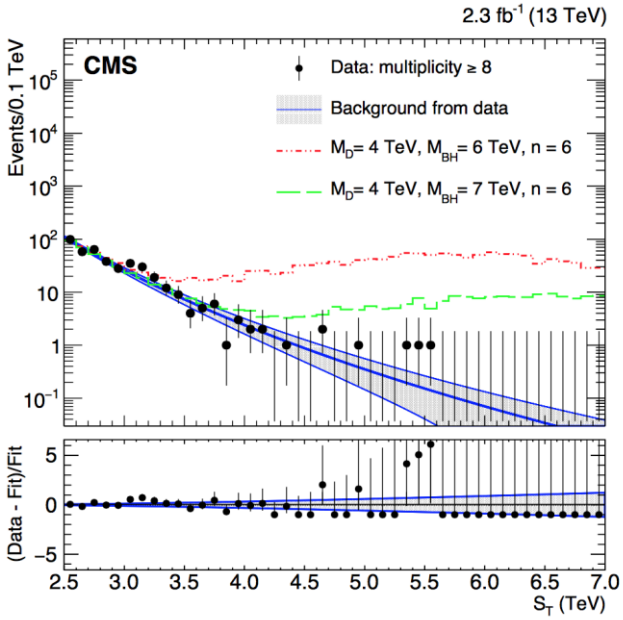
2015: 12 jet event with S_T=5.4 TeV

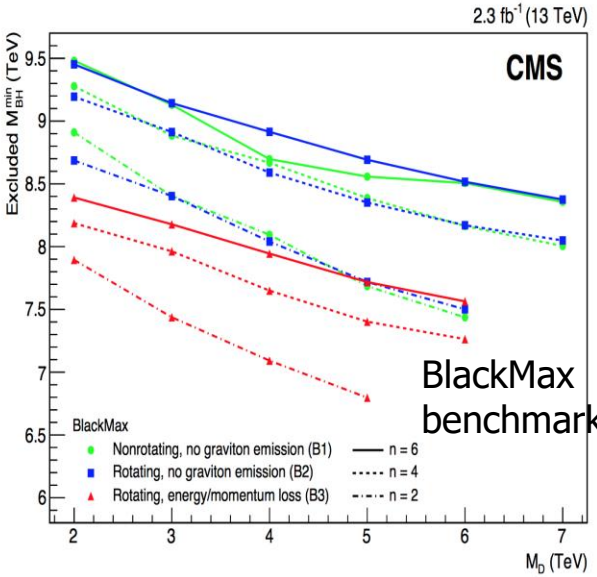


arXiv:1705.01403

Look for the decay producs of an evaporating black hole

- Define S_T to be the scalar sum of all high p_T objects found in the event
- Look for deviations at high S_T





BlackMax benchmarks

Black hole mass excluded in range below ~8-9 TeV depending on assumptions