News from the LHC

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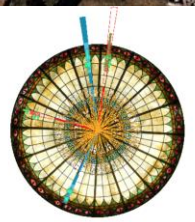
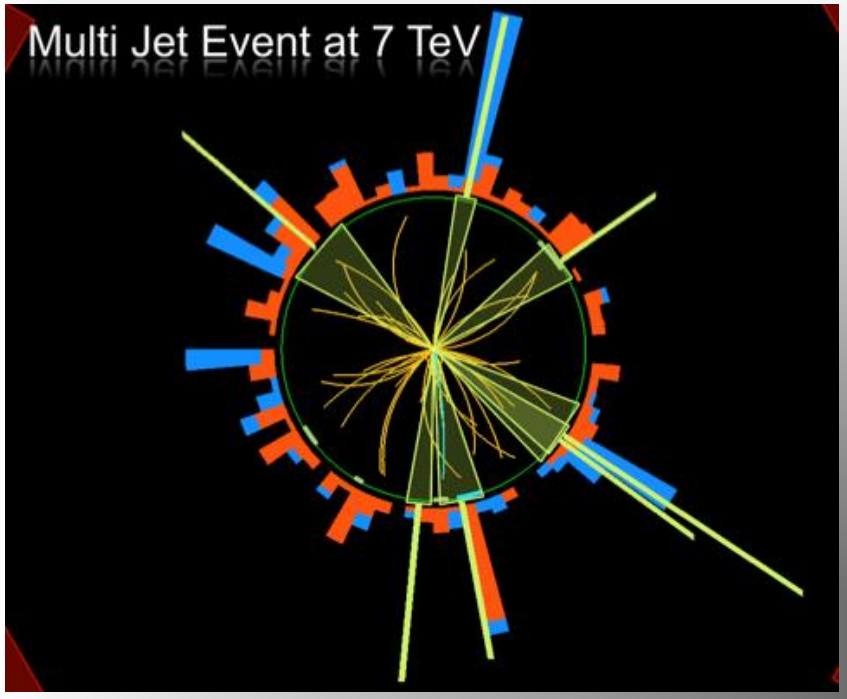
27th April 2015

DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
Dallas, Texas
April 27 – May 1, 2015



CERN



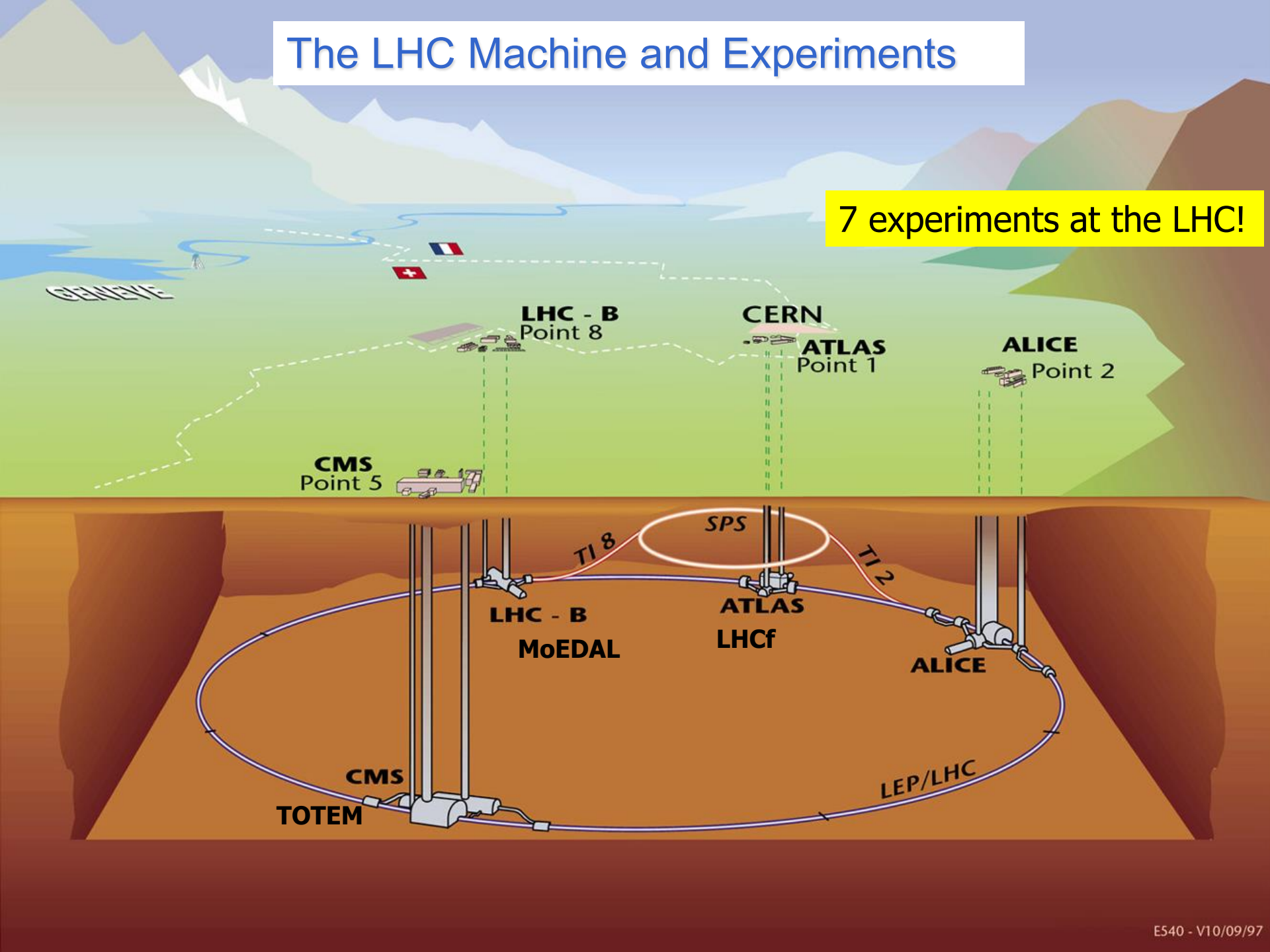
Outline

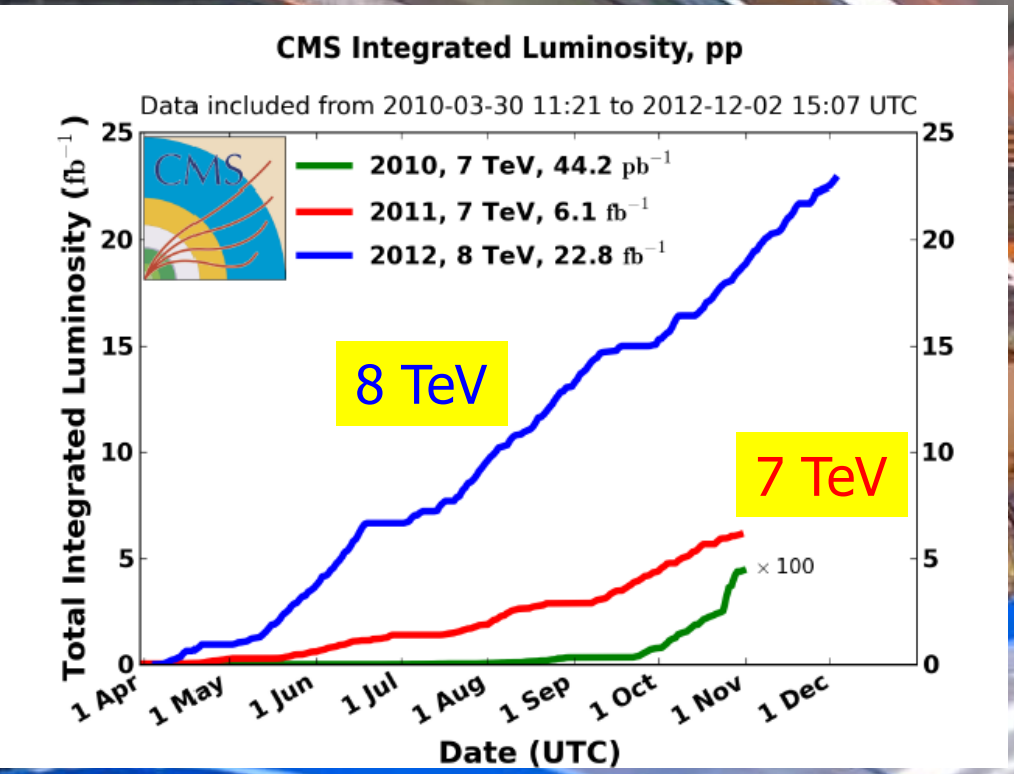
- The LHC today! Getting ready for Run-II
- QCD & PDFs at the LHC
- EWK & top Physics a the LHC
- The Higgs boson
- Searches Beyond the SM
- Prospects for Run-II
- Summary

A number of selected topics…

The LHC: Past and Future

The LHC Machine and Experiments





Run-I: LHC did very well in 2011/2012

2011: luminosity 3 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ 5 fb^{-1} collected in total

2012: luminosity 7.8 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ 20 fb^{-1} collected in total

LHC: Coming Back Alive!

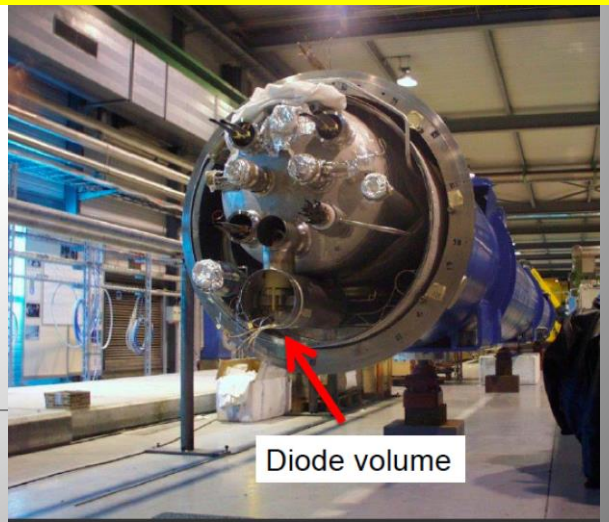
Circuit	Status	#M Firm 1	#M Firm 2	#M Firm 3	#MQ Firm 1	#MQ Firm 2	#MQ Firm 3	#MQ total	#CQ total
RB.A12	11080 A reached	50	95	9	2	1	4	7	7
RB.A23	11080 A reached	56	58	40	0	2	15	17	17
RB.A34	11080 A reached	44	81	29	1	7	8	16	16
RB.A45	11080 A reached	48	44	62	-	3	48	51	49
RB.A56	11080 A reached	28	42	84	0	0	18	18	17
RB.A67	11080 A reached	57	36	61	0	1	21	22	21
RB.A78	11080 A reached	53	40	61	2	10	7	19	19
RB.A81	11080 A reached	64	24	66	0	3	26	29	26

End of March:

Sector 3-4 showed a fault to ground in the last steps!!

The short could be burnt away in the week before Easter!! Oufff!!

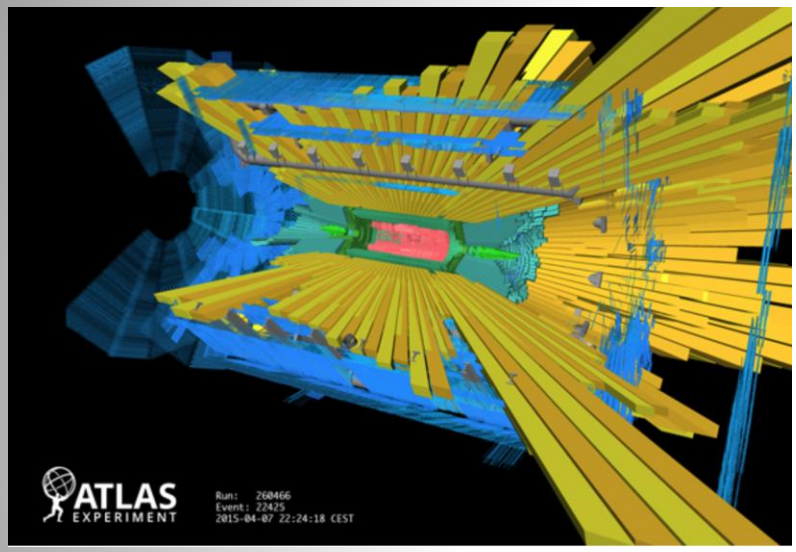
Delay~ 2 weeks

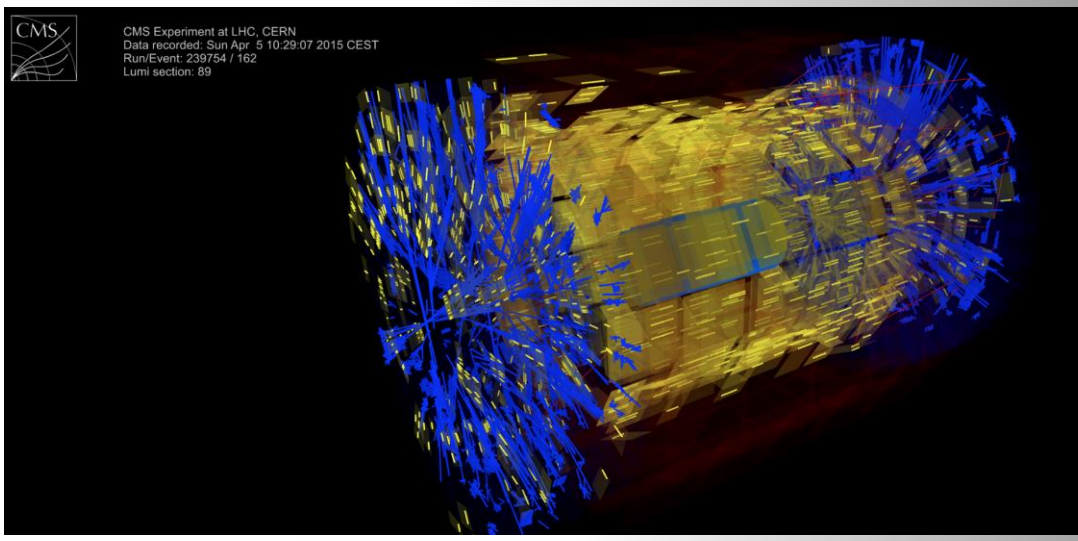


Still a lot of validation/commissioning to be done with beam during the next ~6 weeks…

LHC: First Splashes and Ramps to 6.5 TeV

The beam is back!!



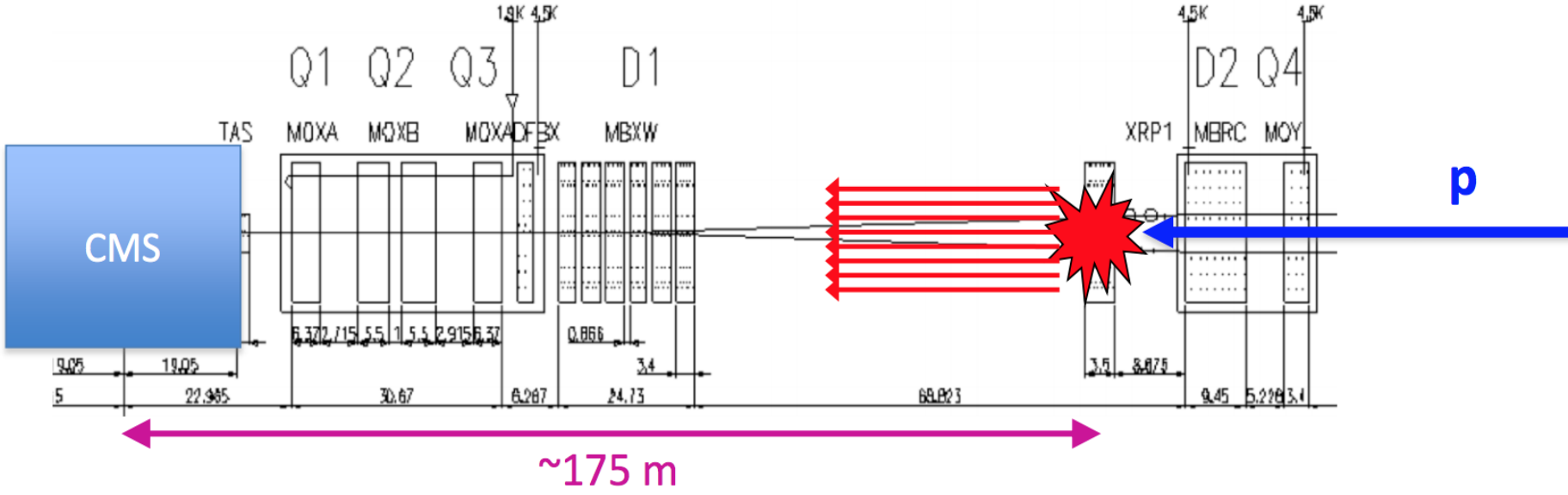


5th April (Easter Sunday, Christ resurrection day) splashes at injection energy of 450 GeV/beam, by beam dump just in front of the experiment

Two weeks ago: Ramp of both beams to an energy at 6.5 GeV
The machine works! (with low intensities so far)

“Beam Splash”

~3 – 4 x 10^9 protons at 450 GeV/c hit TCT collimators
~175m upstream of CMS

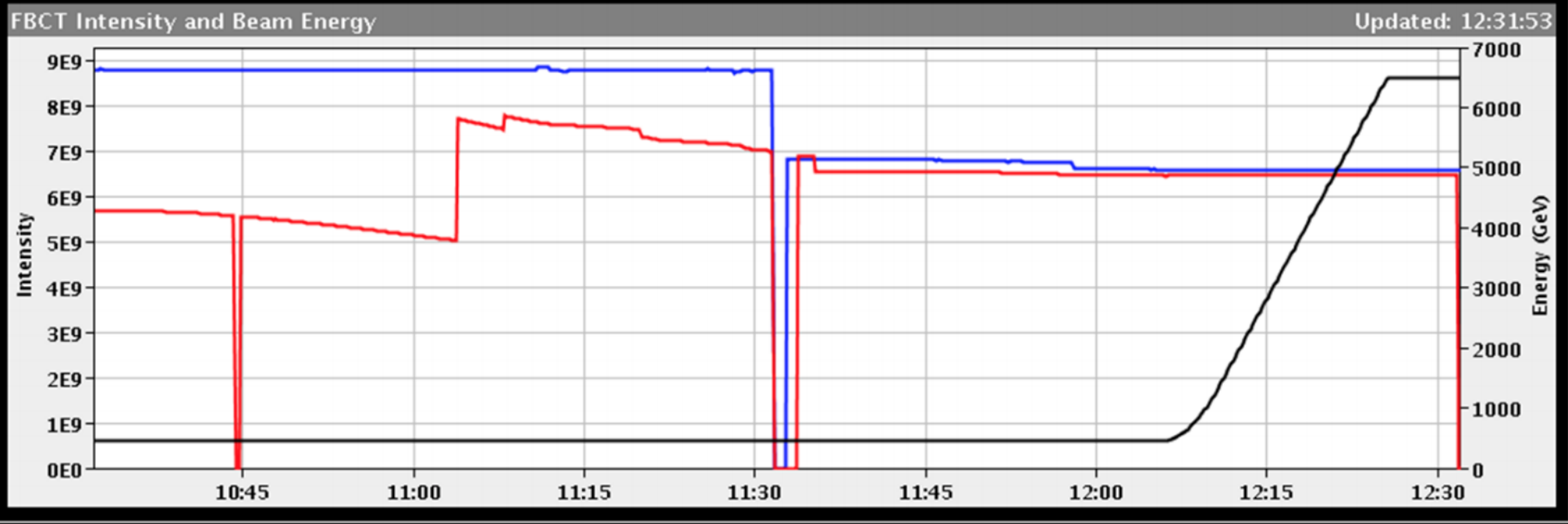


LHC Page1

LHC Page1 | Fill: 3609 | E: 6500 GeV | 11-04-15 12:31:53

BEAM SETUP: FLAT TOP

Energy:	6500 GeV	I(B1):	5.34e+09	I(B2):	7.64e+07



Comments (11-Apr-2015 12:29:40)

Both beams up at 6.5 TeV!!!

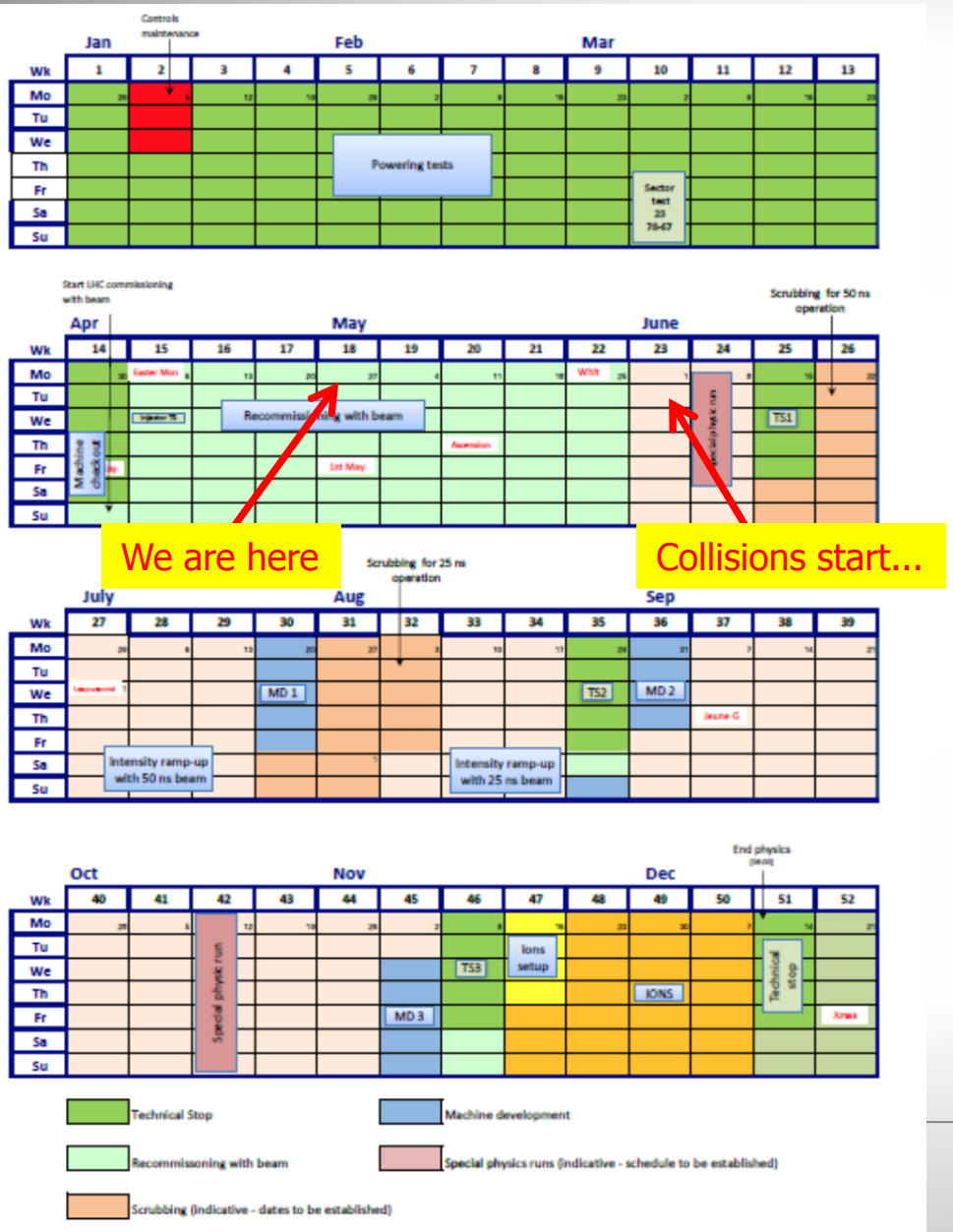
Accelerating beams to 6.5 TeV

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	false
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: alternating R1 R2 pilot

PM Status B1: ENABLED | PM Status B2: ENABLED

The 2015 Schedule



As we know it today. Still flexible…

The Plan

Includes the present delay of 2 weeks. Still intense commissioning ongoing

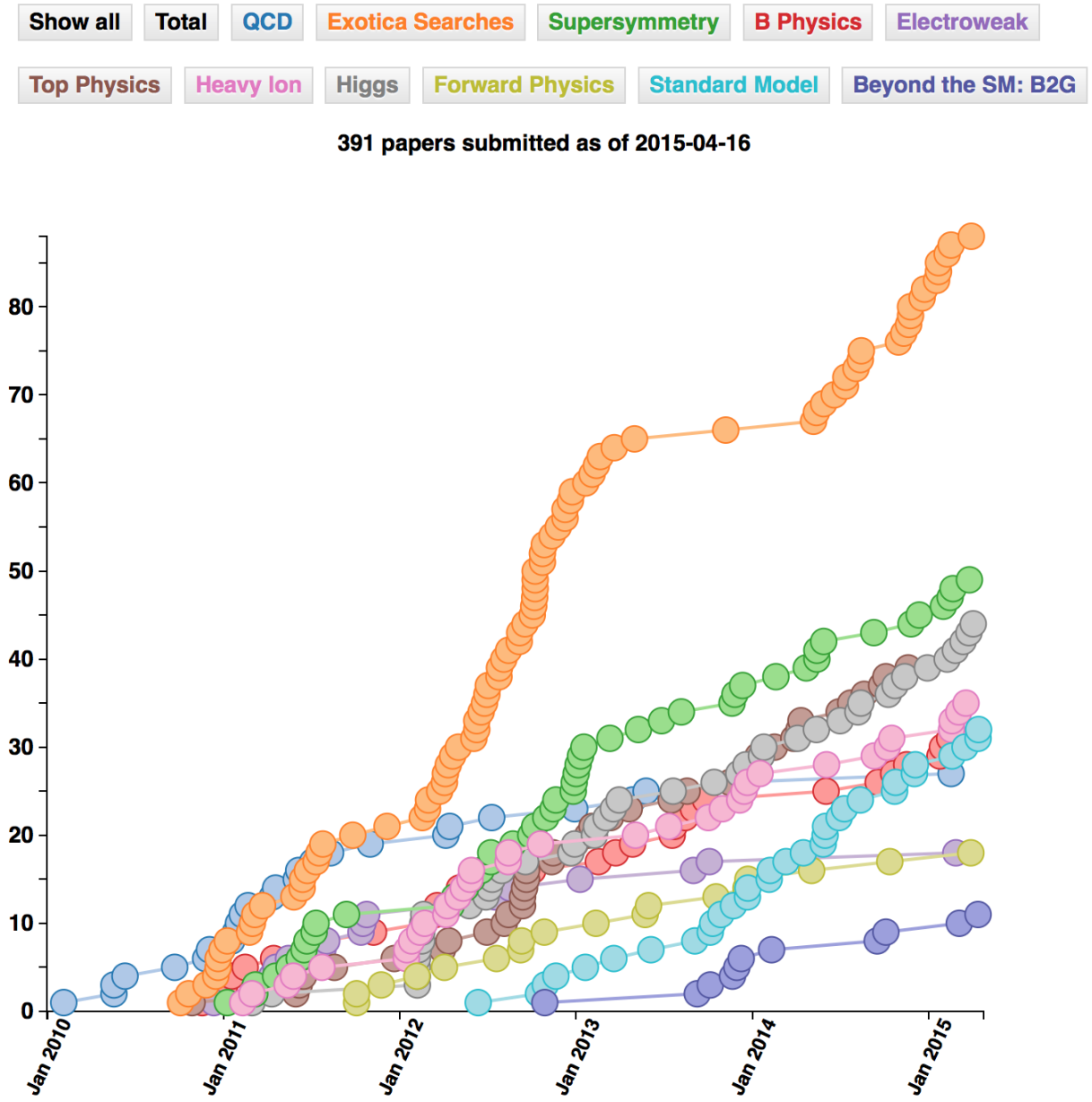
The beam energy will not be changed in 2015

Bunch spacing will be changed from 50ns to 25ns (less pile-up) in summer

Total integrated lumi for 2015: O(10) fb^{-1}

Physics is about to restart at 13 TeV!!

Publications: Example CMS



~400 publications on pp (and pPb/PbPb) physics since January 2010

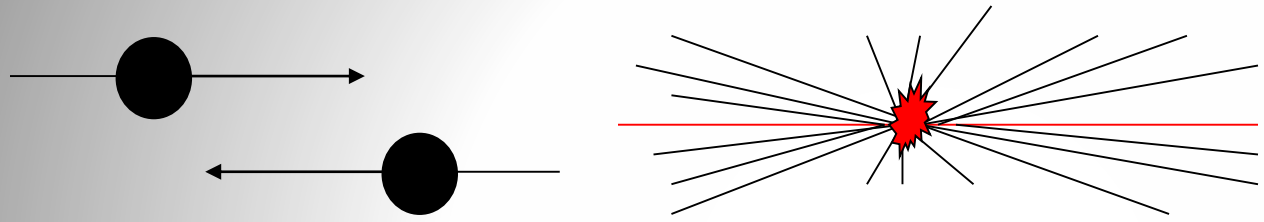
Many on Higgs, supersymmetry and exotica searches

About 150 papers on QCD, EWK, TOP, Forward Physics, B-physics, HI…
There are still papers Being completed

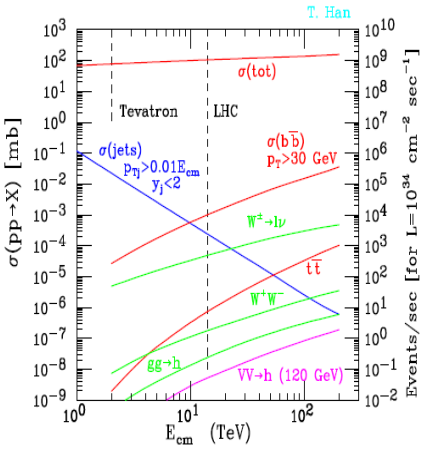
Similar for ATLAS

Understanding Soft Collisions

Most collisions at the LHC do not involve a hard scattering scale: these are so called soft collisions. They make up most of a "minimum bias" event sample

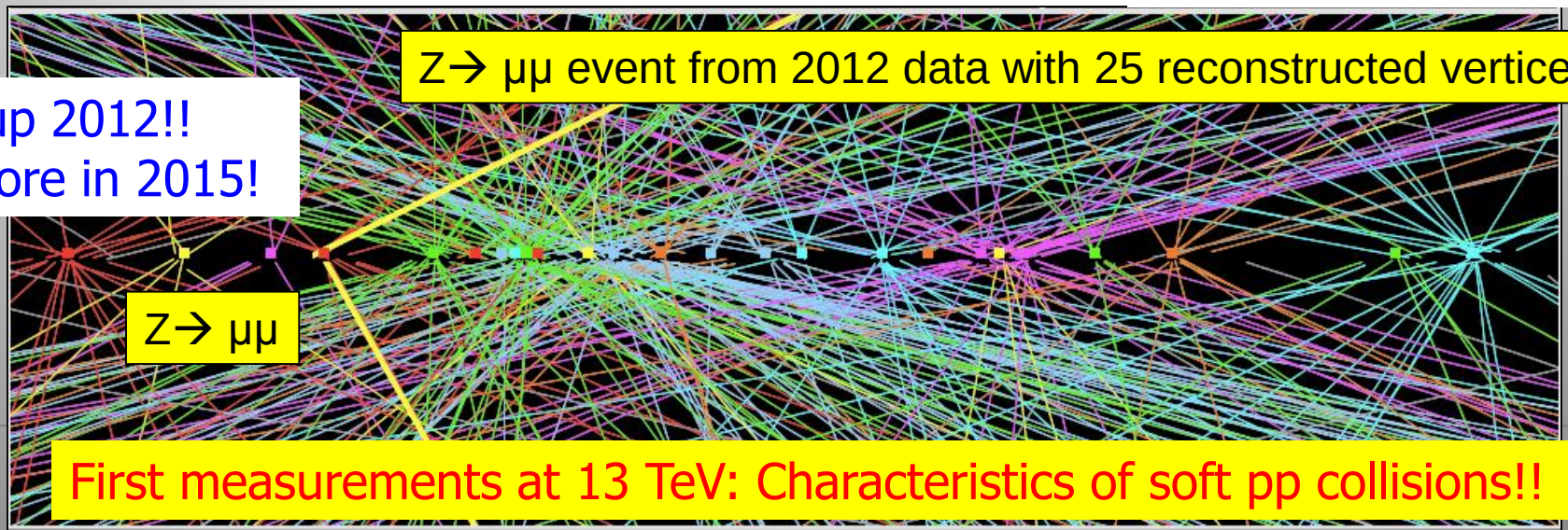


Scattering cross sections for various SM processes:



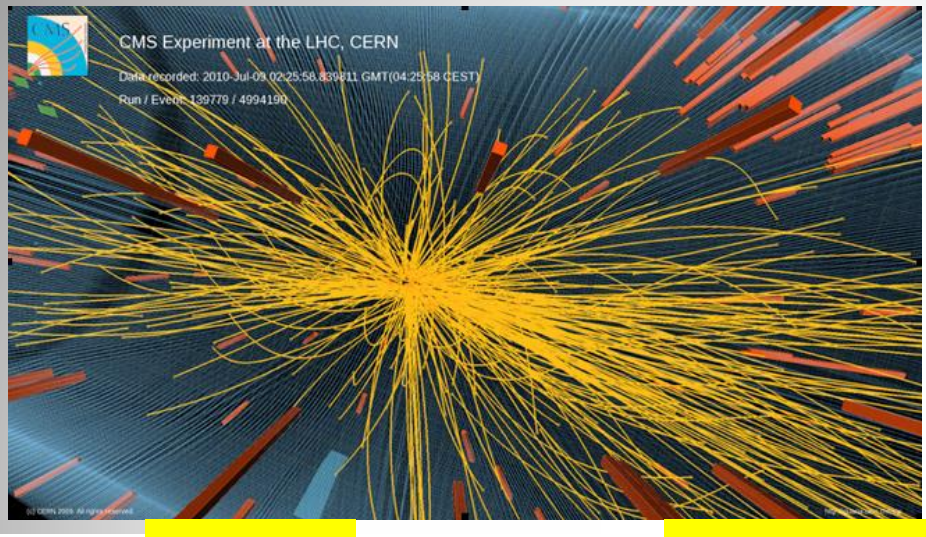
- Detailed studies of multi-particle production in pp
- Monte Carlos tunes, eg for describing the pile-up

Pile-up 2012!!
2x more in 2015!



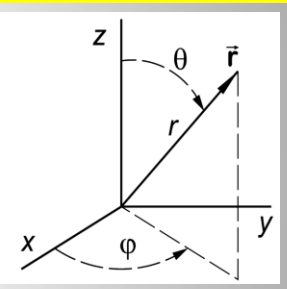
First measurements at 13 TeV: Characteristics of soft pp collisions!!

Correlations Between Produced Particles



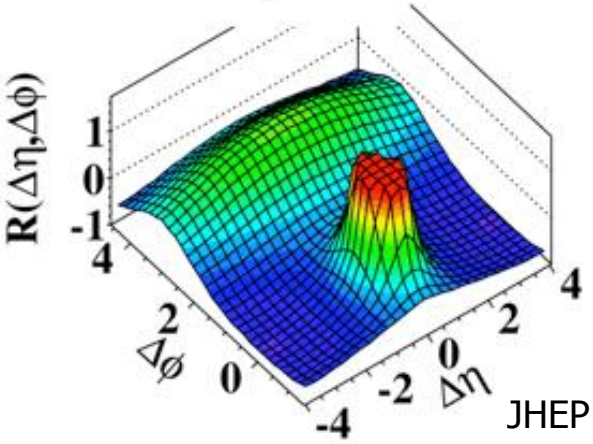
- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

$\eta = -\ln \tan\theta/2$



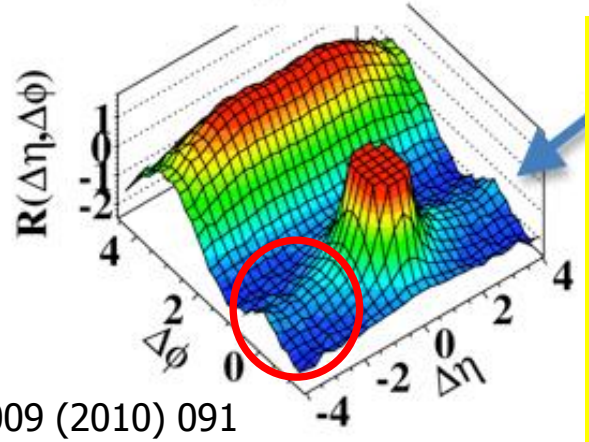
All events

MinBias, 1.0GeV/c<p_T<3.0GeV/c



High multiplicity events

N>110, 1.0GeV/c<p_T<3.0GeV/c



JHEP 1009 (2010) 091

A new phenomenon in the 'stronge force'?

- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

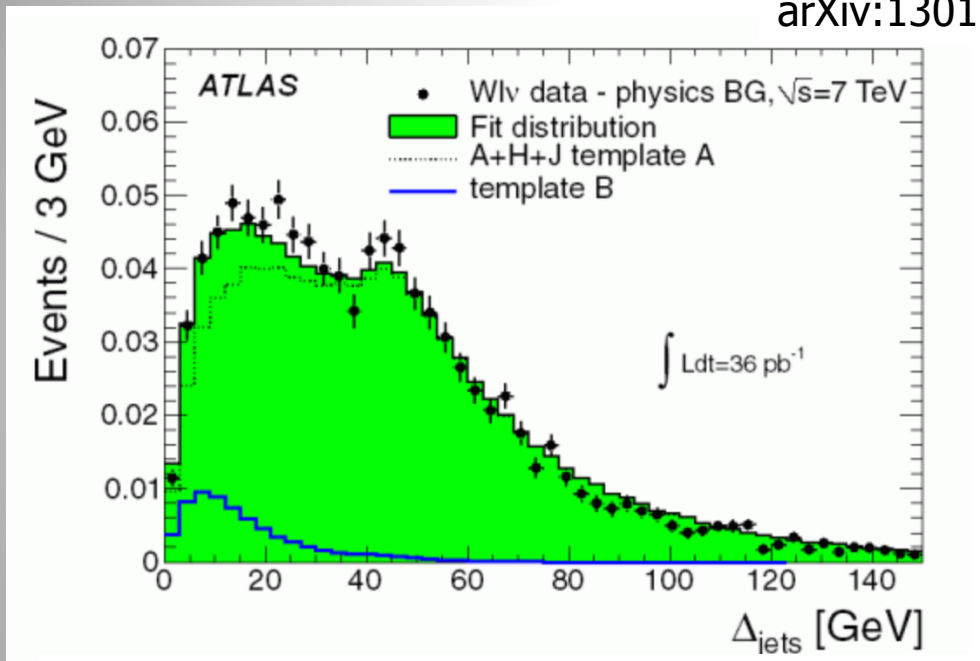
…

- Understanding the "Ridge" in pp collisions? New measurements at 13 TeV!
- Was first seen in AA, then pp (unexpected) and now also pA (~unexpected)

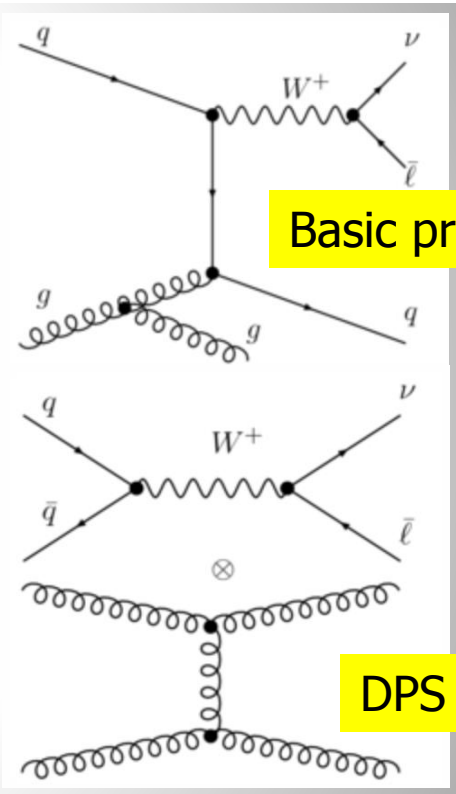
Double Parton Scattering

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.08 ± 0.01 (stat.) ± 0.02 (sys.)

arXiv:1301.6872



Difference between the transverse momenta of the two jets (p_T > 20 GeV)



Basic process

DPS

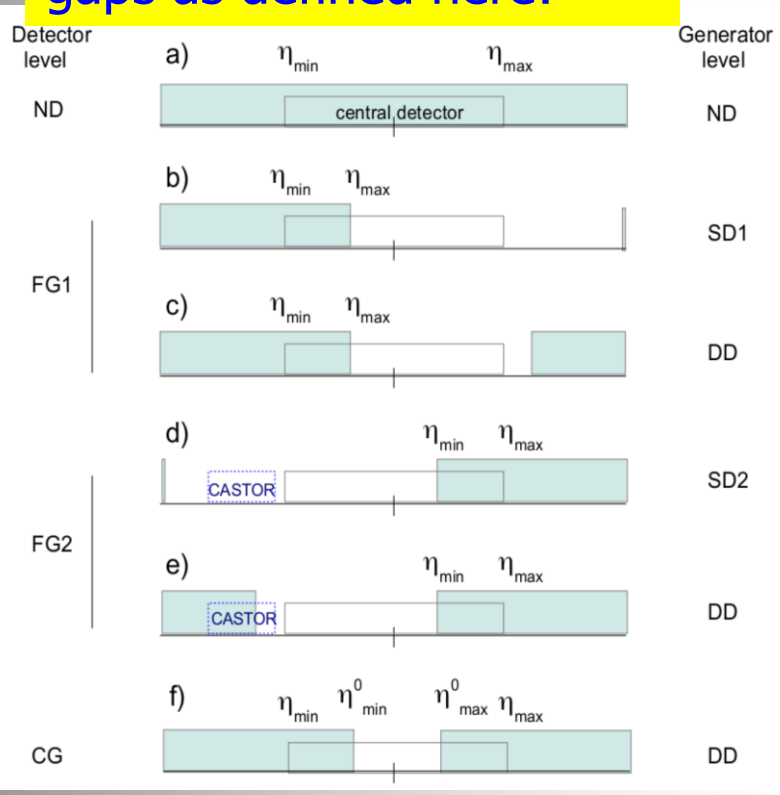
DPS can be important for searches where after cuts only a few events remain…

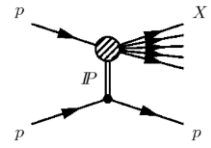
- How well do we control DPS at the LHC energies?
- Expect increase of DPS for pp collisions at 13 TeV

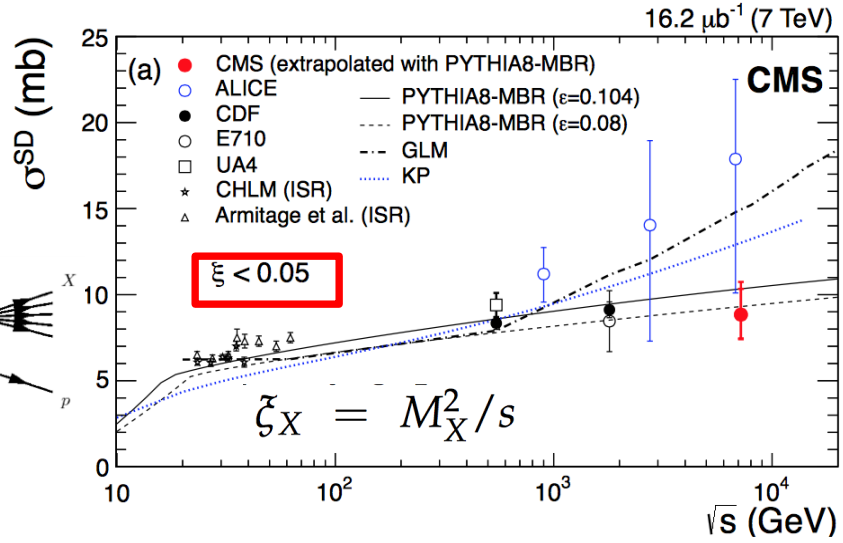
Diffraction at the LHC

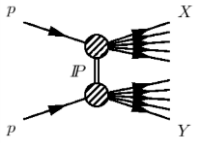
arXiv:1503.08689

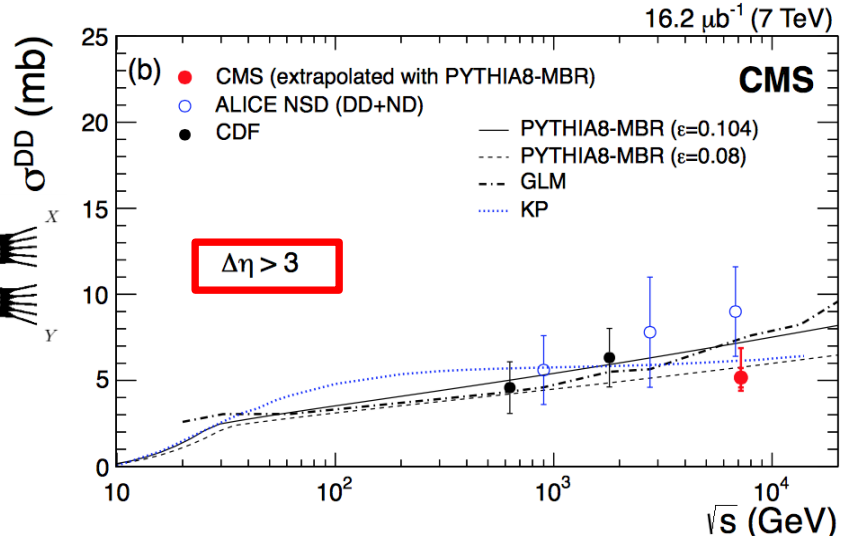
Analysis based on rapidity gaps as defined here:











Run-II+ detectors:
FSCs, TOTEM-CMS, ALFA, upgrades…
-> Many future opportunities…

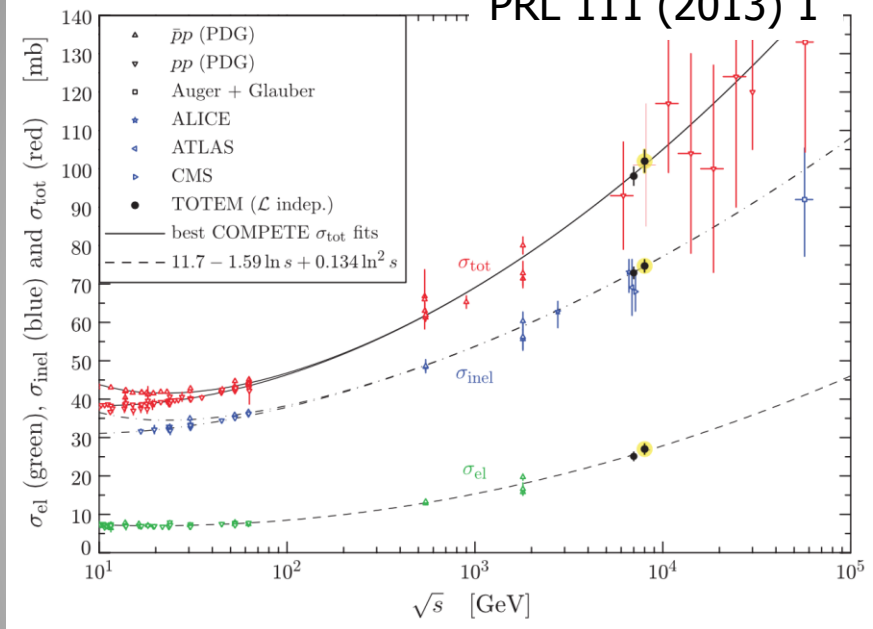
Low mass extrapolation?

Total pp Cross Section

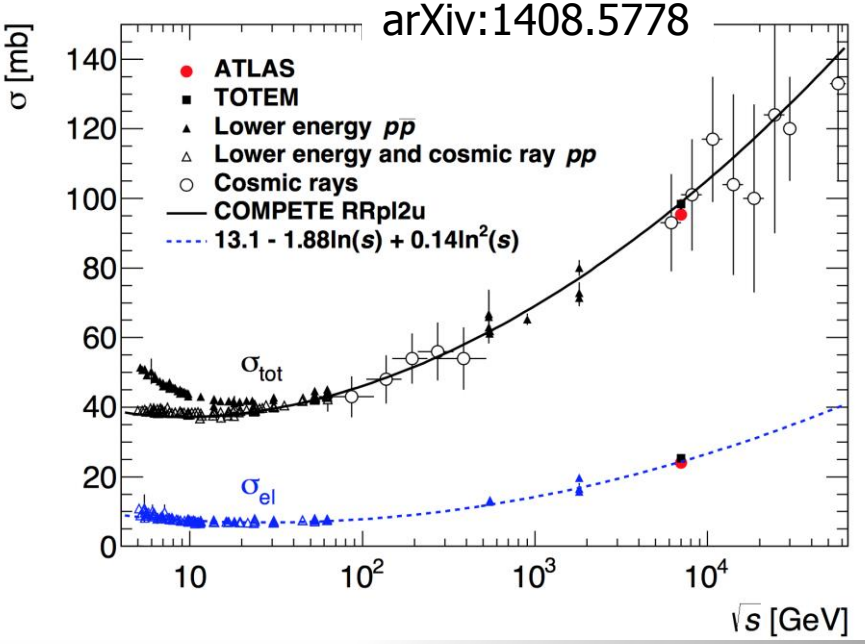
TOTEM Roman Pots + Forward Detectors
TOTEM uses the same IP as CMS (IP5)

ALFA Roman Pots from ATLAS

PRL 111 (2013) 1



arXiv:1408.5778



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\frac{dN_{el}/dt\big|_0}{N_{el}+N_{inel}}$$

$$\sigma_{tot} = (101.7 \pm 2.9)mb$$

$$\sigma_{inel} = (74.7 \pm 1.7)mb$$

$$\sigma_{el} = (27.1 \pm 1.4)mb$$

$$\sigma_{\mathrm{tot}} = 95.35 \pm 1.30 \text{ mb}$$

$\sigma_{\mathrm{inel}} = 71.34 \pm 0.36\ (\mathrm{stat.}) \pm 0.83\ (\mathrm{syst.})$ mb

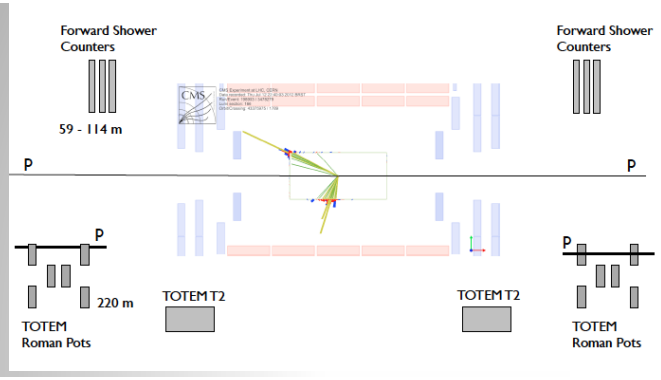
$\sigma_{\mathrm{el}} = 24.00 \pm 0.19\ (\mathrm{stat.}) \pm 0.57\ (\mathrm{syst.})$ mb

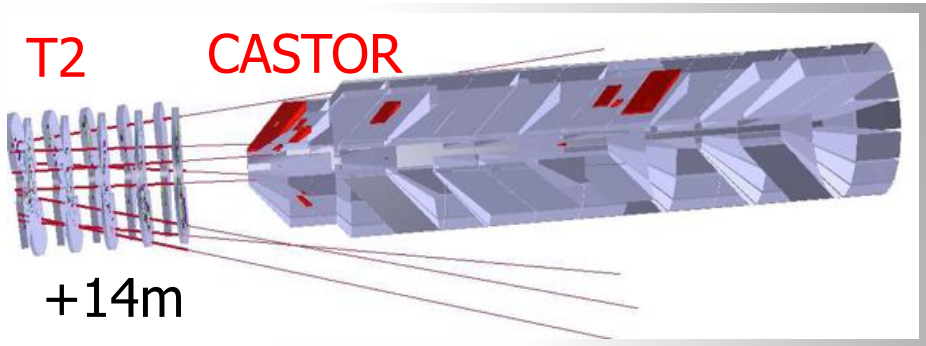
Agreement at the ~2σ level

CMS + TOTEM Combined Analyses

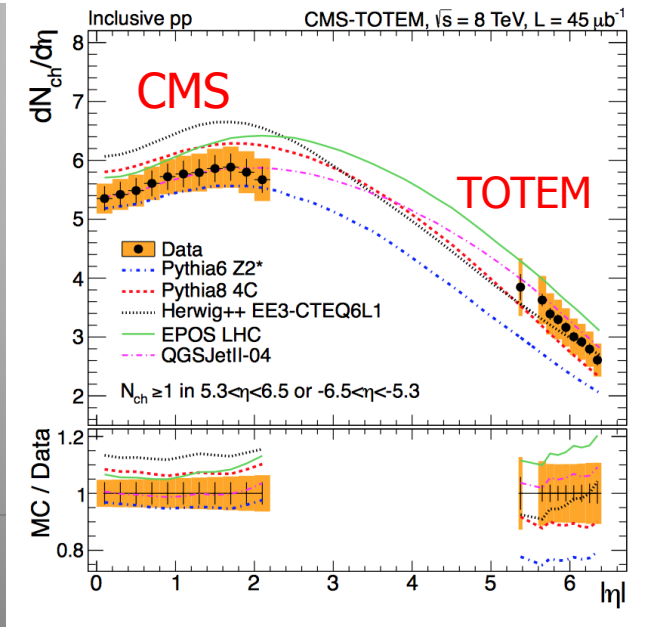
Since end of 2011: "Common data taking of CMS with TOTEM"

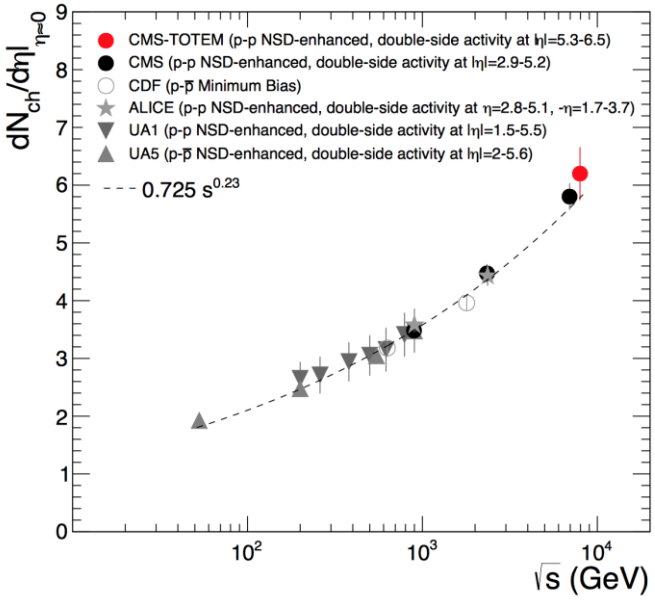
RP (TOTEM) + Central Di-jet (CMS) T2 (TOTEM) + CASTOR (CMS)





CMS central energy flow with TOTEM T2 minbias trigger





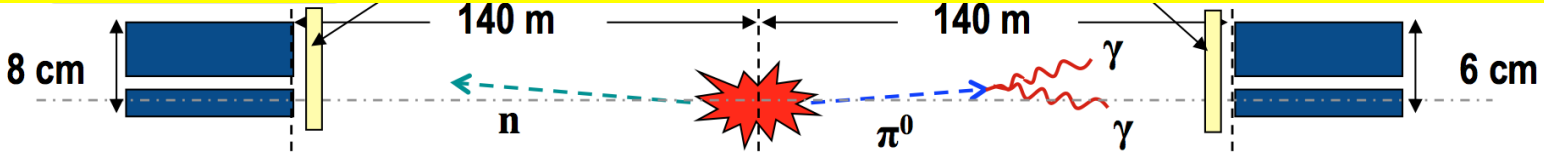
arXiv:1405.0722

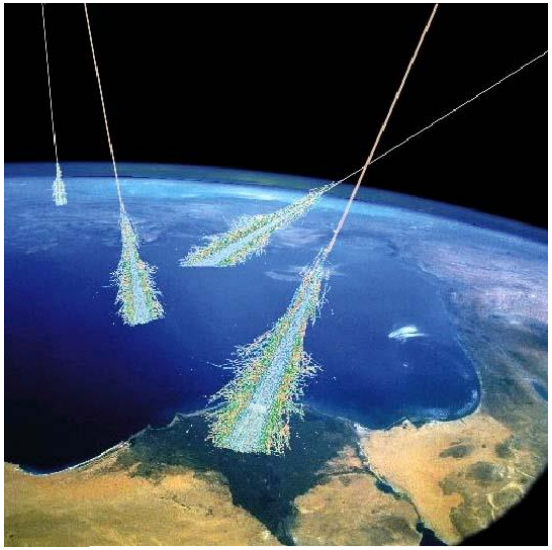
First common paper of CMS and TOTEM

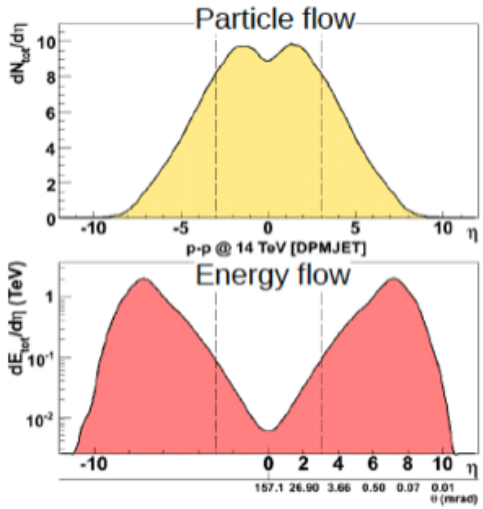
More analyses in the pipeline

Forward Particles Measurements

- LHCf uses the same Interaction Point as ATLAS (IP1)
- LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP): Measure the forward photons/pions for cosmic ray studies



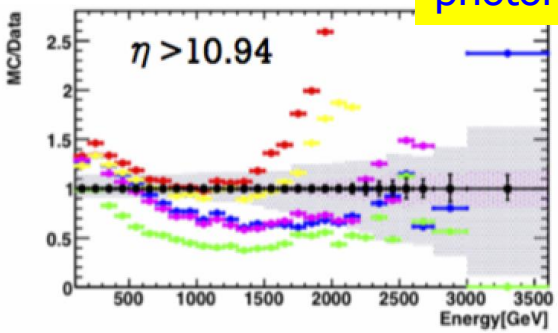




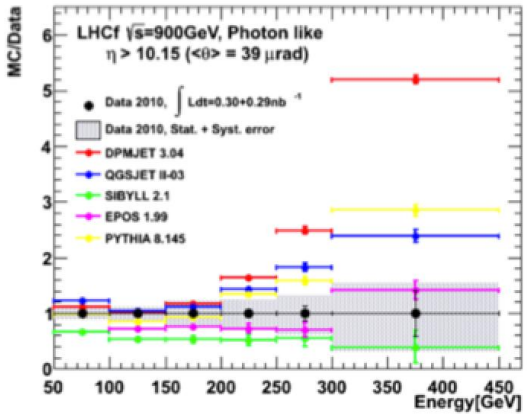
arXiv:1310.3731

photons

7TeV



900GeV

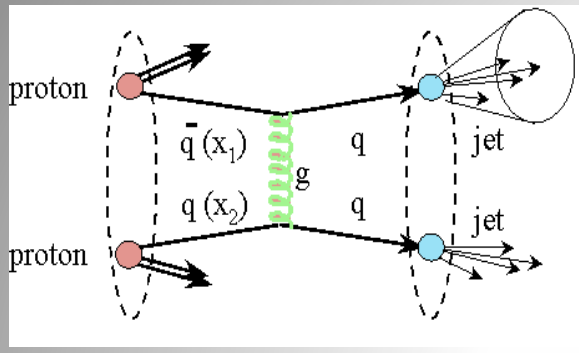


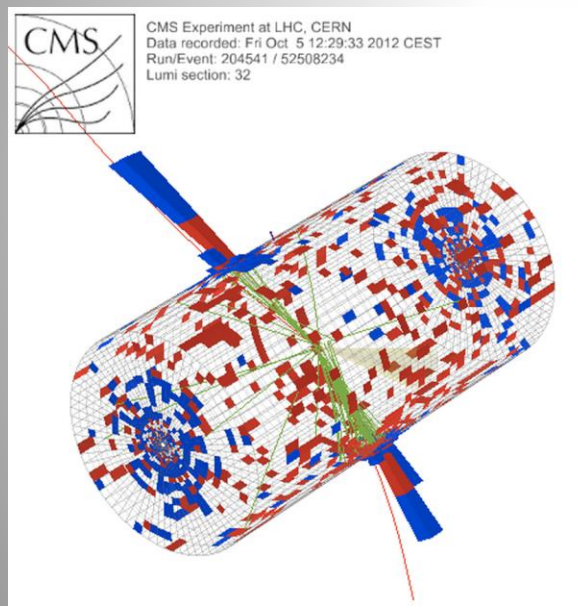
Forward gamma measurement compared to Monte Carlos for Cosmic Ray studies

No model reproduces the data well !!

LHC data connection with cosmic rays

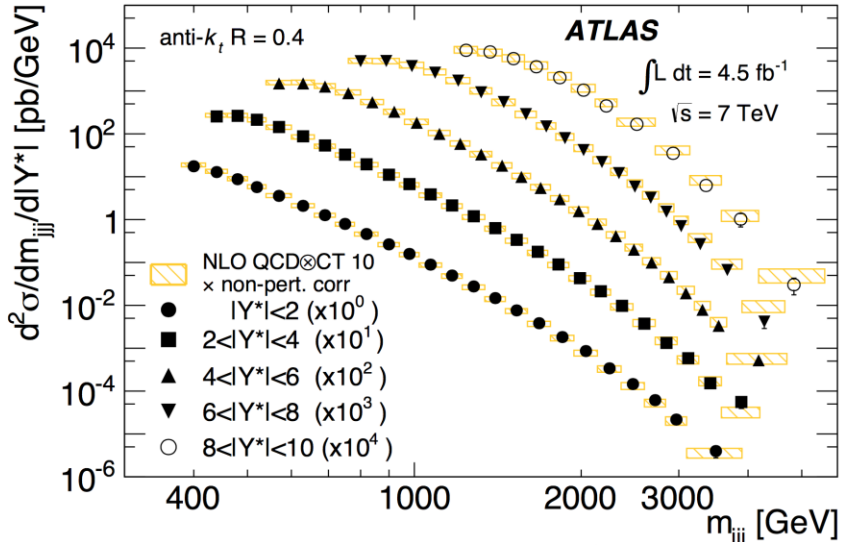
QCD: Jet Production





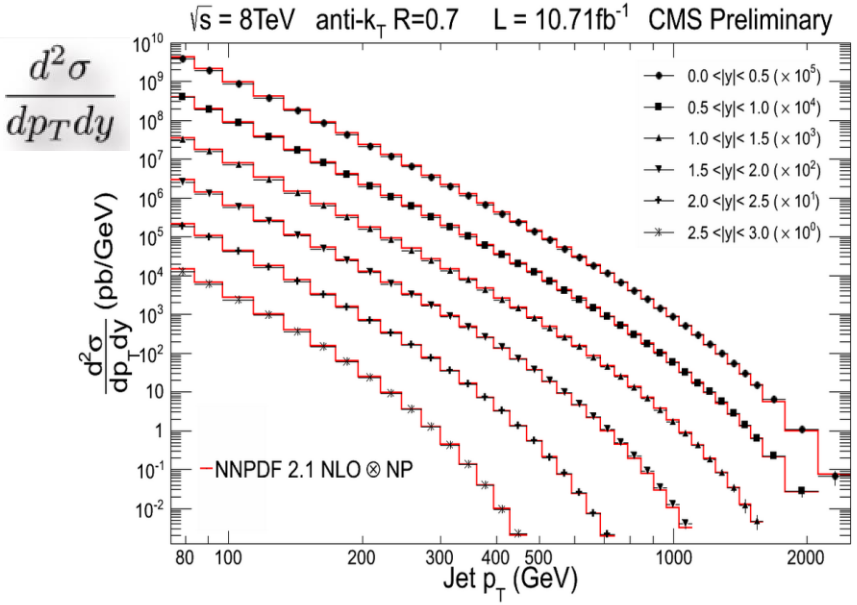
Di-jet invariant mass = 5.15 TeV (R=1.1 jets)
60% of the full pp √s

Study the strong force using jet production



3-jet studies

arXiv:1411.1855



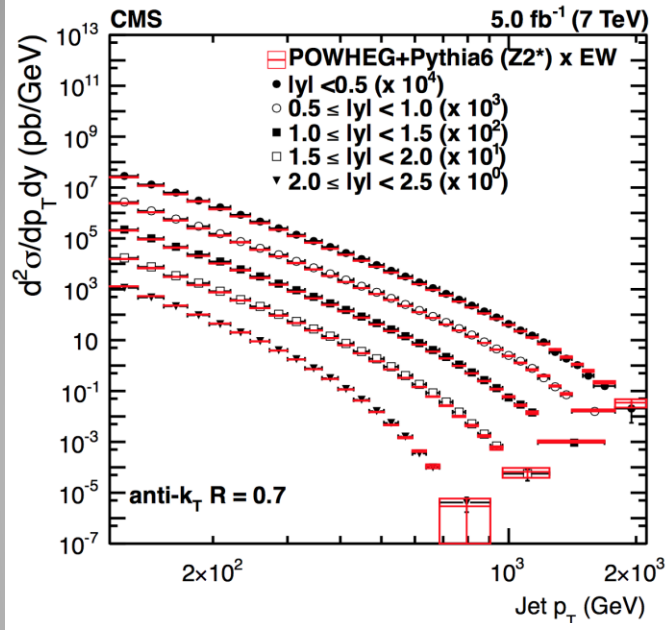
Inclusive jet studies @ 8 TeV

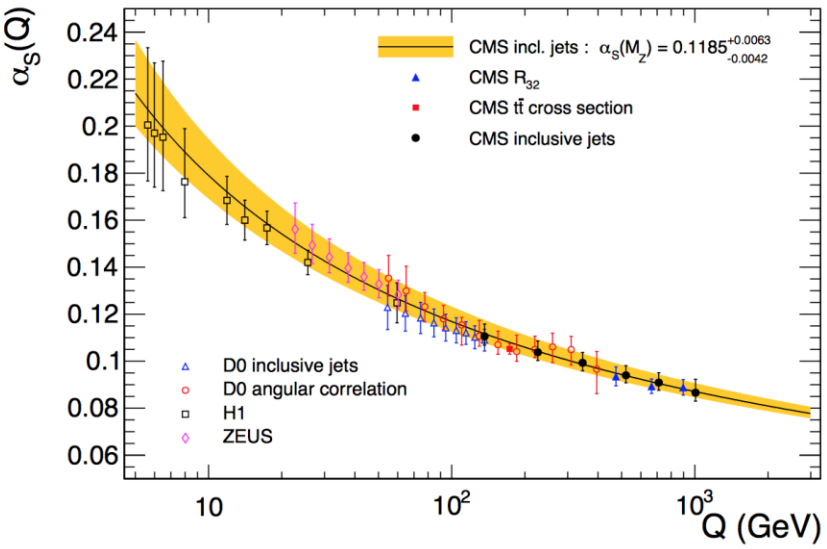
CMS-PAS-SMP-12-012

pQCD ⊗ non-perturbative corrections

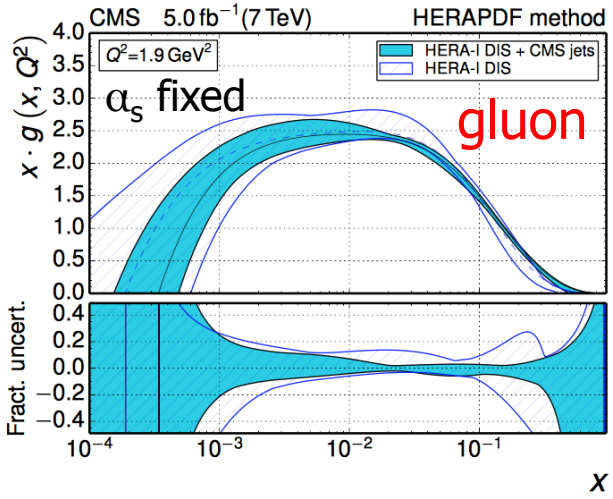
QCD Studies: Extracting α_s and PDFs

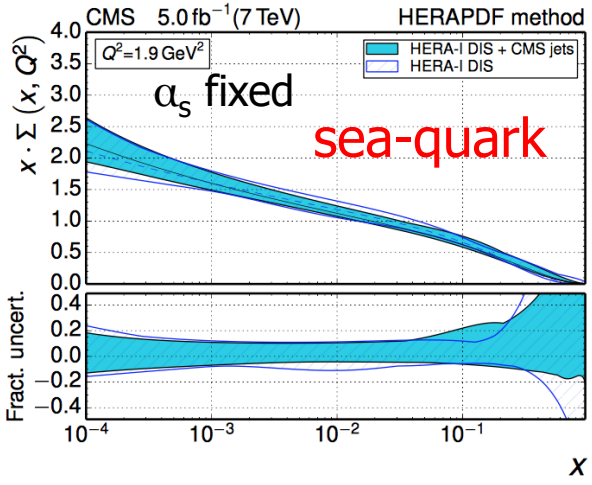
Extracting the strong coupling constant from inclusive jet cross sections





$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp})\,^{+0.0060}_{-0.0037}\,(\text{theo})$$





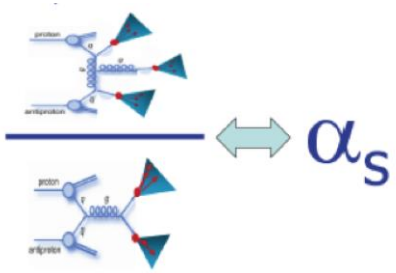
arXiv:1410.6765

Using HERAFitter

Constraints on PDFs

QCD Studies: Extracting α_s

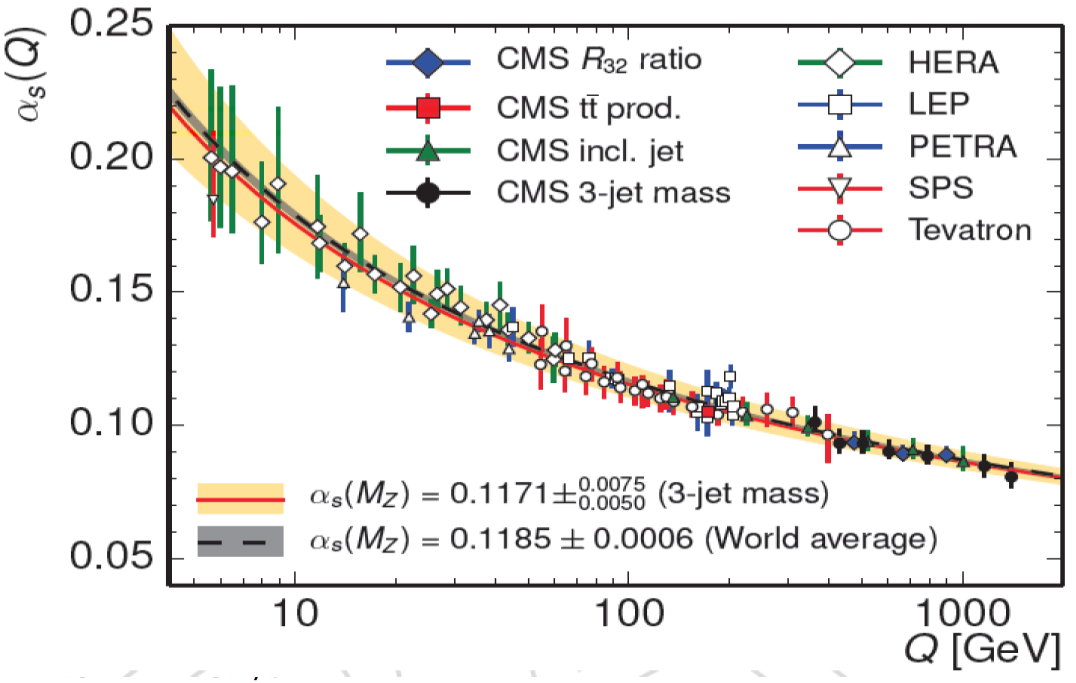
The ration of 3 to 2 jet events is sensitive to the fundamental QCD parameter α_s
Di-jets within the range of 420 - 1390 GeV, p_T of all jets larger than 150 GeV



$$R_{32} = \frac{d\sigma_{3+}/dp_T}{d\sigma_{2+}/dp_T} \propto \alpha_s(Q)$$

$$Q = \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$
420–600	474	$0.1147\,^{+0.0061}_{-0.0021}$	$0.0936\,^{+0.0040}_{-0.0014}$
600–800	664	$0.1132\,^{+0.0050}_{-0.0031}$	$0.0894\,^{+0.0031}_{-0.0019}$
800–1390	896	$0.1170\,^{+0.0058}_{-0.0032}$	$0.0889\,^{+0.0033}_{-0.0018}$



$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF})^{+0.0050}_{-0.0000}\,(\text{scale}) = 0.1148\,^{+0.0055}_{-0.0023}$$

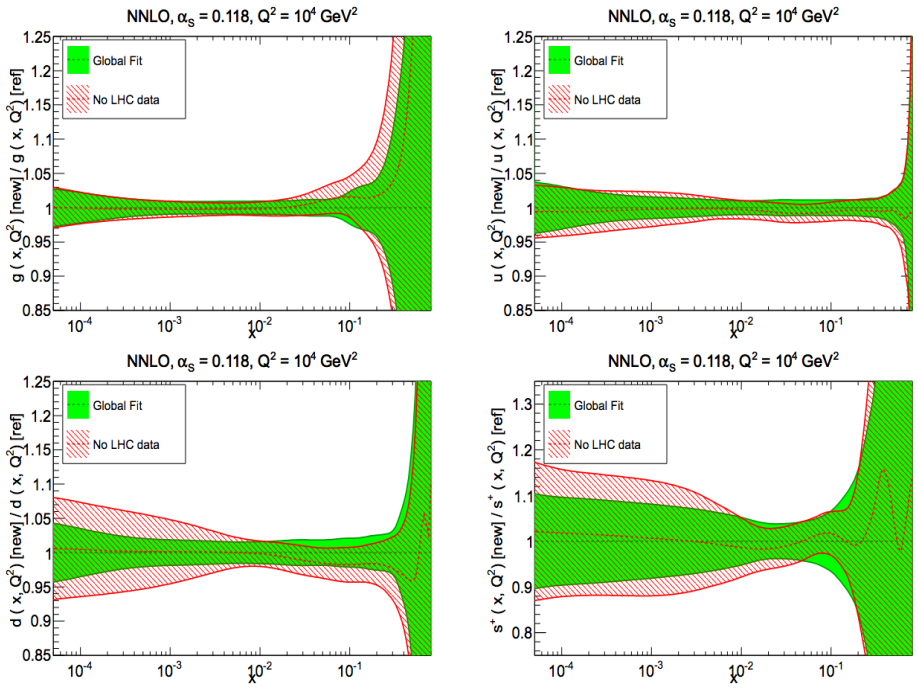
arXiv:1304.7498

ATLAS prelim: $\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\,^{+0.016}_{-0.003}(\text{theory})$. ATLAS-CONF-2013-041

Several new studies: 3-jet mass, top cross section… Many Opportunities!
Theory uncertainties are main precision delimiter!

PDFs: Impact of the LHC Data

arXiv:1410.8849: NNPDF Parton Distributions for the LHC Run-II



LHC data included

ATLAS							
	ATLAS W,Z 2010	[47]	M	full	i	30 (30/30)	
	ATLAS 7 TeV jets 2010	[50]	M	full	i,j	90 (90/9)	
	ATLAS 2.76 TeV jets	[63]	M	full	j	59 (59/3)	$20 \le p_T^{\rm jet} \le 200$ GeV $0 \le \lvert\eta^{\rm jet}\rvert \le 4.4$
	ATLAS high-mass DY	[56]	M	full		11 (5/5)	$116 \le M_{ll} \le 1500$ GeV
	ATLAS W p_T	[57]	M	full		11 (9/-)	$0 \le p_T^W \le 300$ GeV
CMS							
	CMS W electron asy	[48]	M	cov		11 (11/11)	
	CMS W muon asy	[58]	M	cov		11 (11/11)	$0 \le \lvert\eta_l\rvert \le 2.4$
	CMS jets 2011	[62]	M	full		133 (133/83)	$114 \le p_T^{\rm jet} \le 2116$ GeV $0 \le \lvert\eta^{\rm jet}\rvert \le 2.5$
	CMS $W+c$ total	[60]	M	cov		5 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$
	CMS $W+c$ ratio	[60]	M	cov		5 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$
	CMS 2D DY 2011	[59]	M	cov		124 (88/110)	$20 \le M_{ll} \le 1200$ GeV $0 \le \lvert\eta_{ll}\rvert \le 2.4$
LHCb							
	LHCb W rapidity	[49]	M	cov		10 (10/10)	
	LHCb Z rapidity	[61]	M	cov		9 (9/9)	$2.0 \le \eta_l \le 4.5$
$\sigma(t\bar{t})$							
	ATLAS $\sigma(t\bar{t})$	[65–67]	M	none		3 (3/3)	-
	CMS $\sigma(t\bar{t})$	[68–70]	M	none		3 (3/3)	-

Plan for a discussion forum among the experiments for PDF sensitive measurements

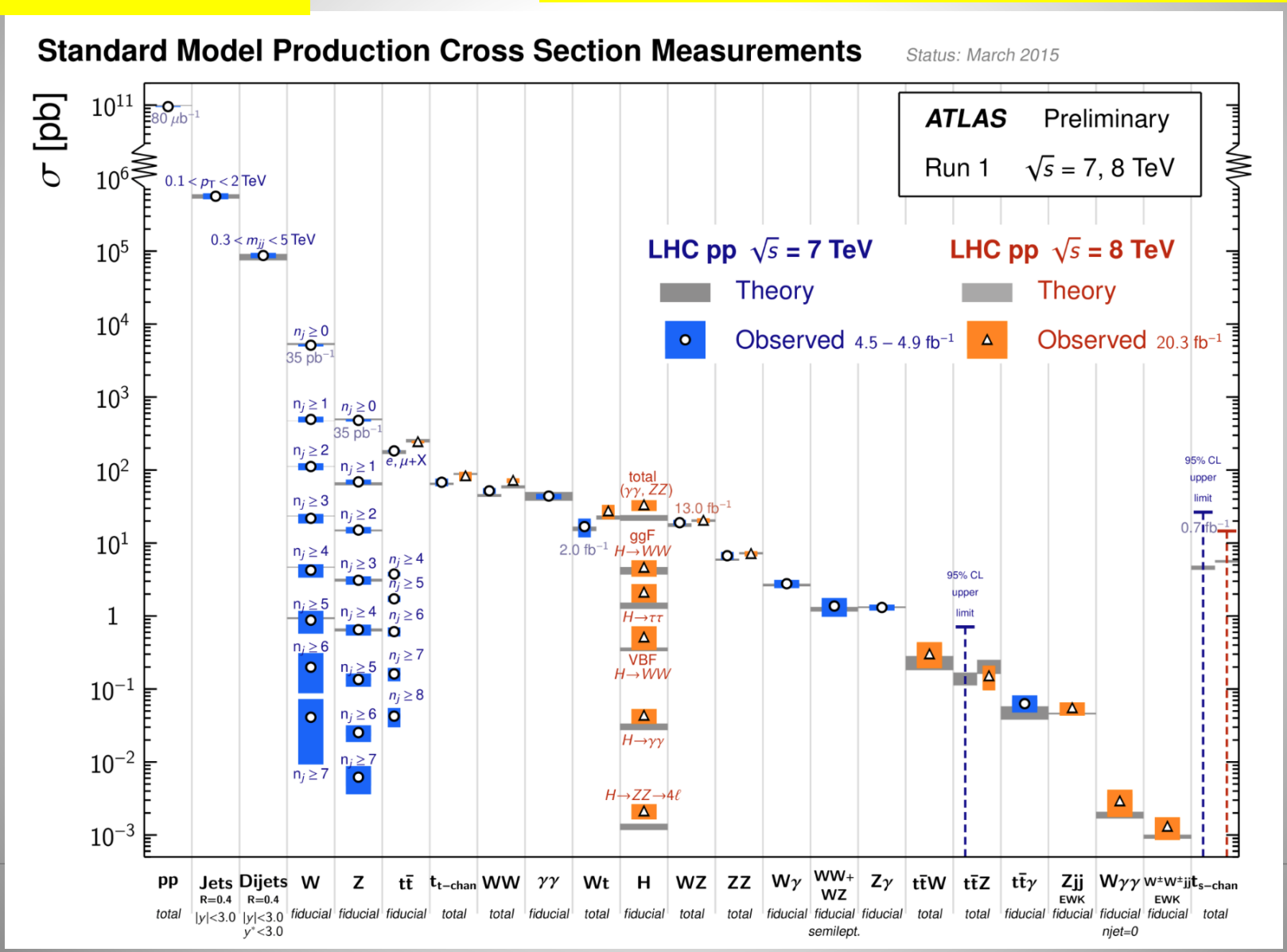
Also, in preparation:

The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II

EWK Studies at the LHC

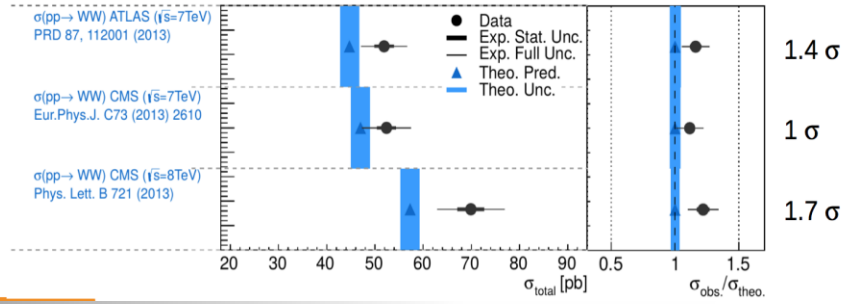
General overview

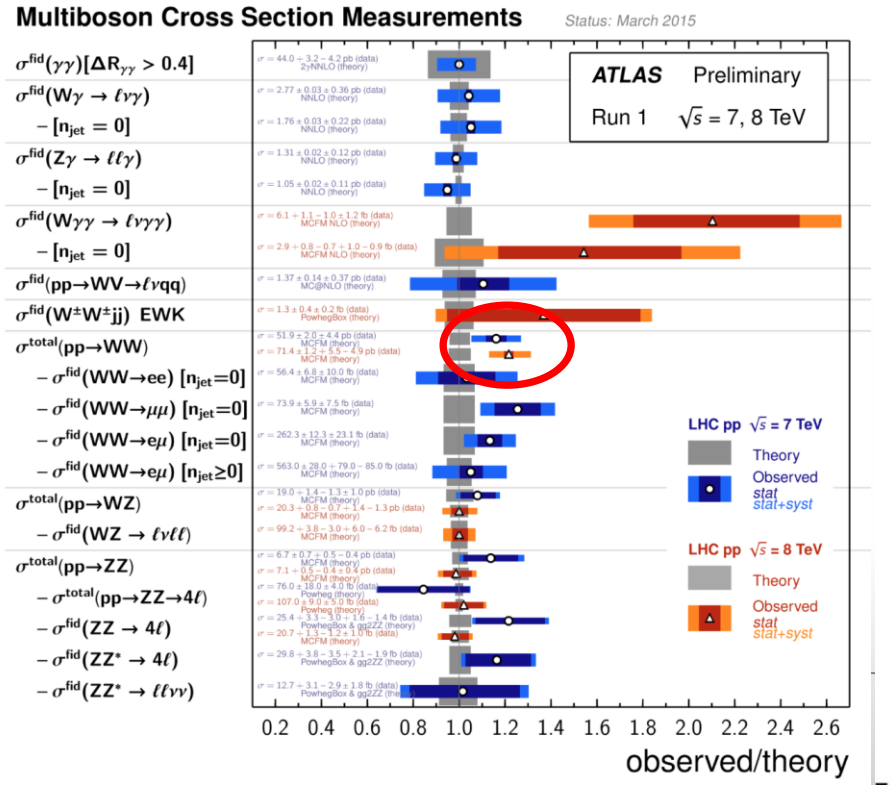
The Standard Model works fine at 7 & 8 TeV



WW Production?

Summer 2014: Is there a problem with WW production?
CMS and ATLAS measured ~ 1-2σ higher values comp. to NLO at 7 and 8 TeV





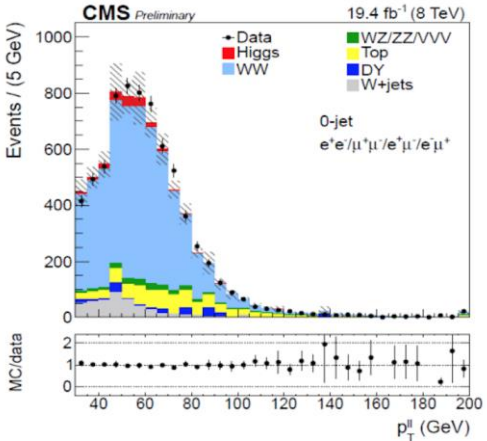
Developments: full NNLO calculations (arXiv:1408.5243), New CMS analysis

New features CMS-SMP-14-016

- Reweight pT(WW) of MC to an NNLL pT resummation calculation ==> **correlated with jet-veto**
- compare to latest NNLO cross-section

σ_{tot}=60.1±0.9(stat)±3.2(exp)±3.1(th)±1.6(lum) pb

Agrees with NNLO: $59.8^{+1.3}_{-1.1}$ pb



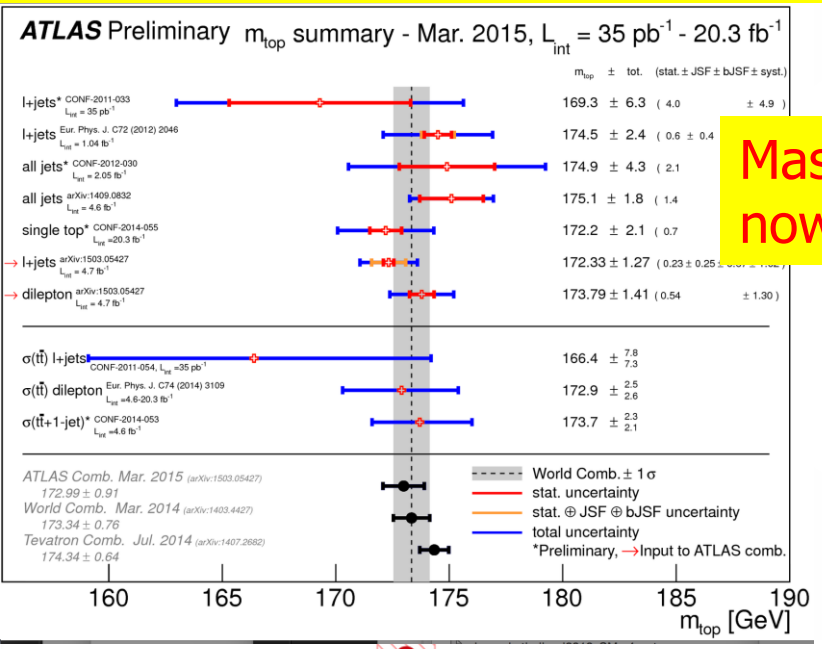
Discrepancy seems al but gone…??

Verify at 13 TeV…

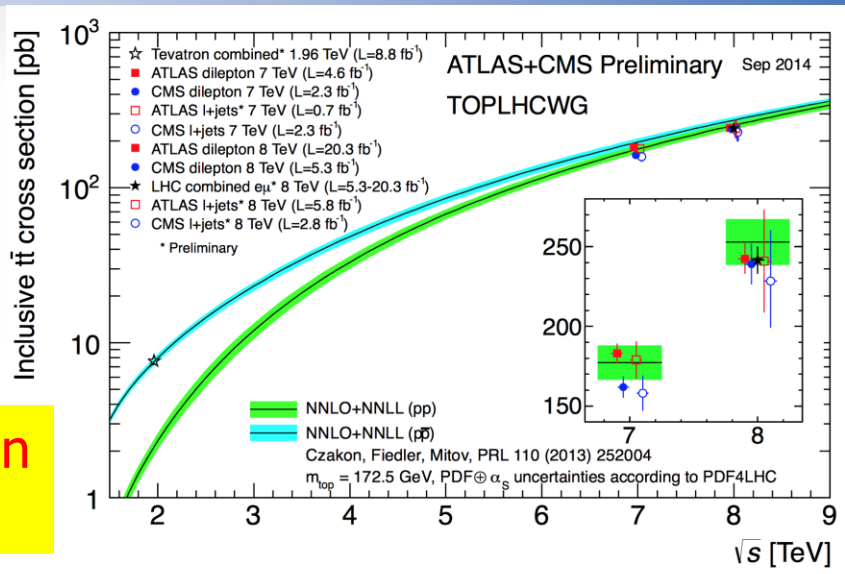
TOP @ LHC

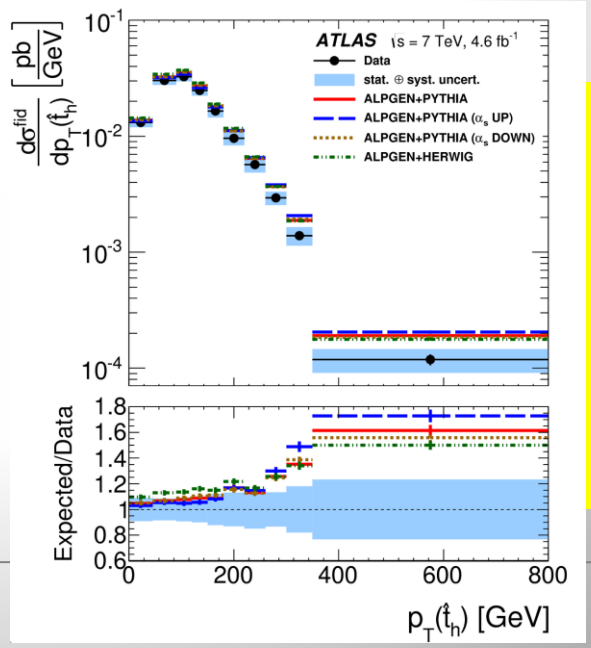
The LHC is a top factory:

- 5.10^6 ttbar pairs produced/experiment
- Lepton+jet channel: $\sim 10^5$ events/study
- Many detailed top property studies…



Mass precision now ~ 0.4%





The predicted top p_T distrib. does not agree with the measurements

Higher orders?

Extraction of α_s from ttbar cross section, fixing top mass, at NNLO

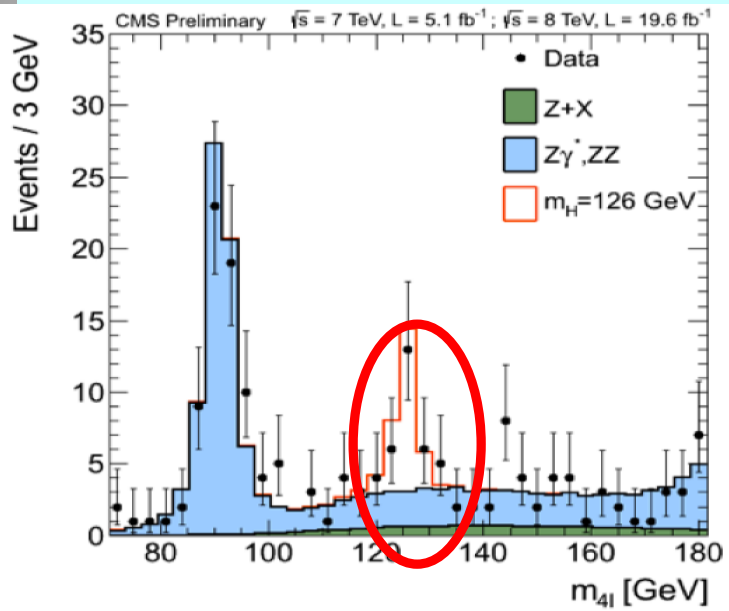
$$\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$$

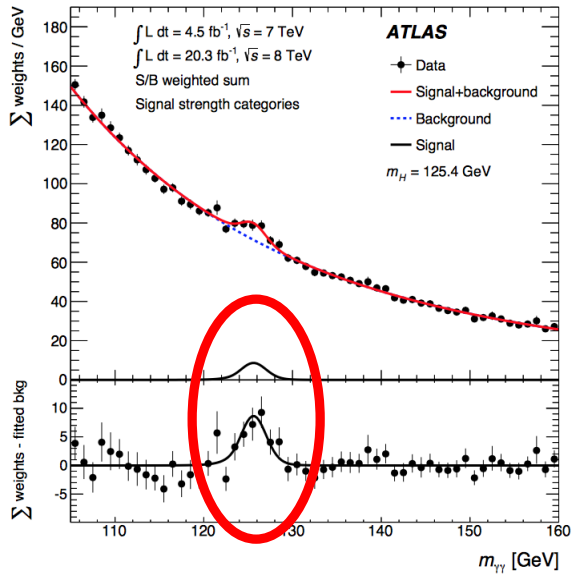
arXiv:1307.1907

2012: A Milestone in Particle Physics

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

2013





2015: Higgs Boson well established.

All accessible channels studied

	untagged	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible				

Results released

In progress

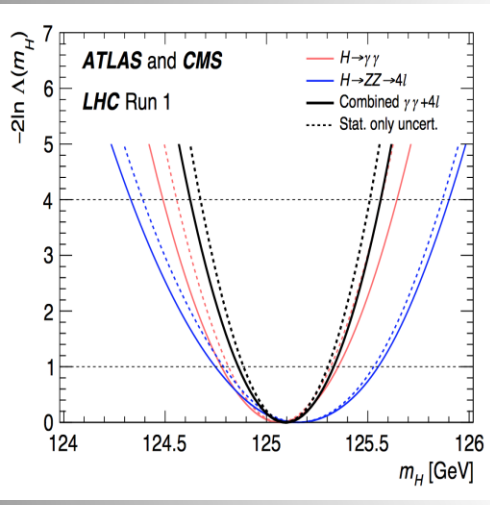
Results Summary @ 125 GeV

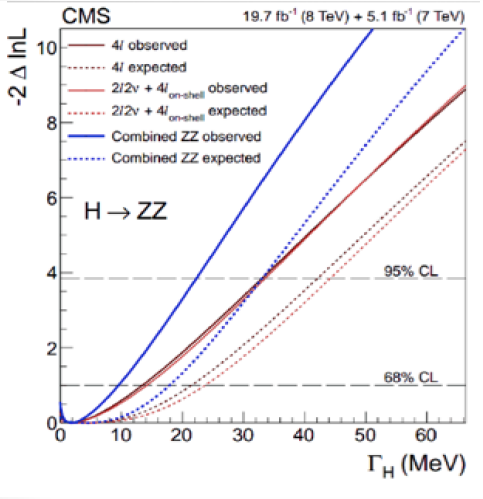
Run-I Legacy papers

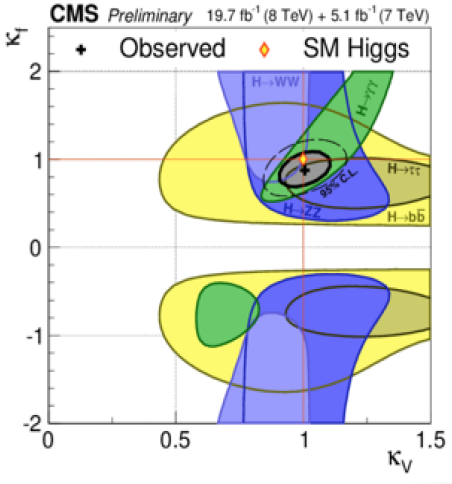
Channel	ATLAS Lumi [fb-1]	CMS Lumi [fb-1]	Specialty	σ Obs. (exp.)	Mass [GeV]	Signal strength μ	$J^P = 0^+$
H→γγ	4.8+20.7	5.1+19.6	mass, discovery, couplings	5.2 (4.6)	126.	1.17±0.27	✓
				5.7 (5.3)	124.7	1.14+ 0.26- 0.23	✓
H→ZZ→4l	4.6+20.7	5.1+19.7	mass, discovery, couplings	8.1 (6.0)	124.7	1.44 ± 0.4	✓
				6.8 (6.7)	125.6	0.93 +0.29- 0.25	✓
H→WW→2l2ν	4.6+20.7	4.9+19.4	cross section, couplings	6.1 (5.8)	Compatible with 125GeV	1.09 +023-0.21	✓
				4.3 (5.8)	125.5+3.6– 3.8 (μ = 1)	0.72 +0.20- 0.18	✓
H→bb	4.5+20.3	5.1+18.9	couplings to fermions	1.4 (2.6)	--	0.52 +0.40- 0.27	--
				2.1 (2.1)	Compatible with 125GeV	1.0 ± 0.5	--
H→ττ	20.3	4.9+19.4	couplings to fermions	4.5 (3.4)	Compatible with 125GeV	1.43 +0.43–0.37	--
				3.2 (3.7)	122 ±7 GeV	0.78 ± 0.27	--

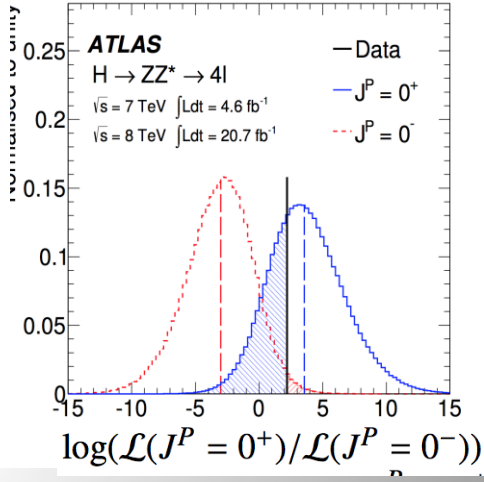
Brief Higgs Summary

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









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

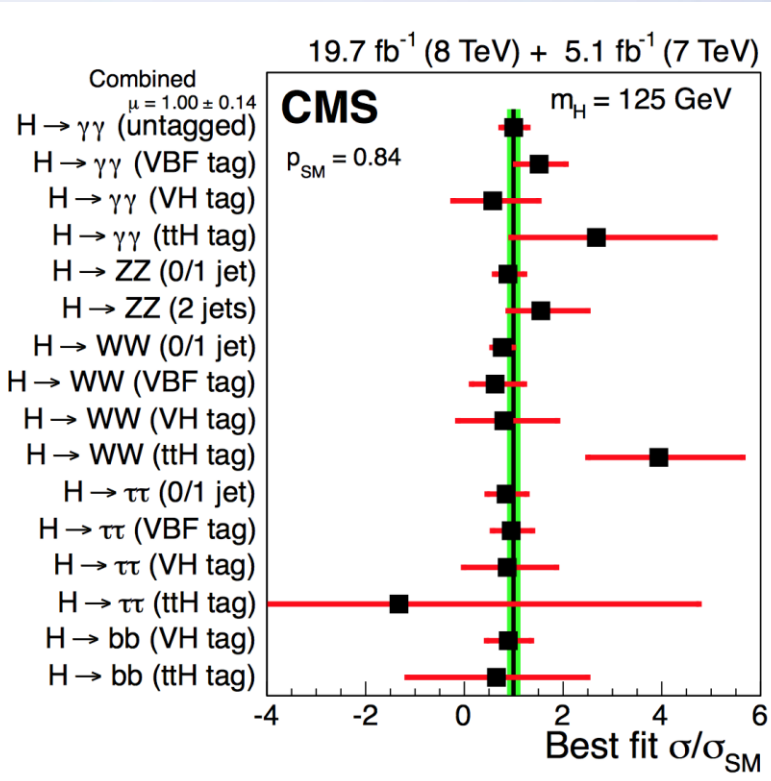
Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

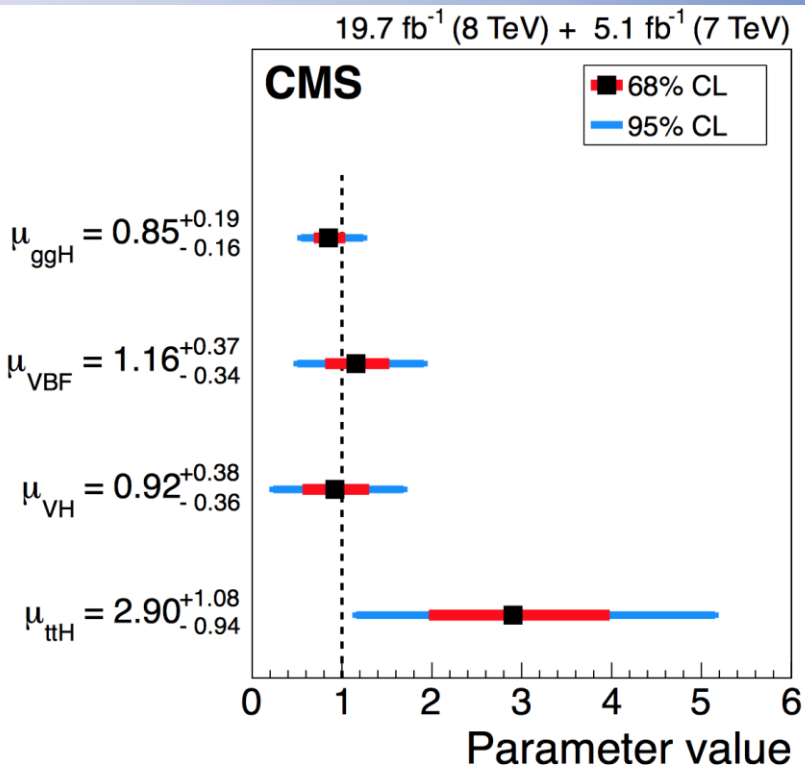
Couplings are within 20% of the SM values

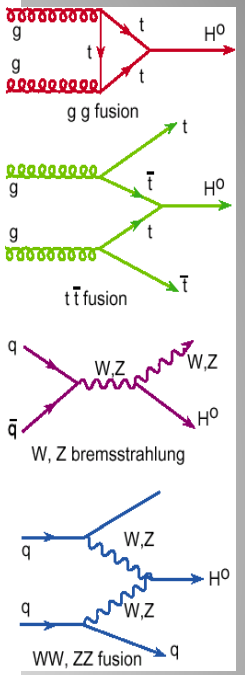
Spin =
$0^{+(+)}$ preferred over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

Combination of the Higgs Data







Overall consistency with the Standard Model

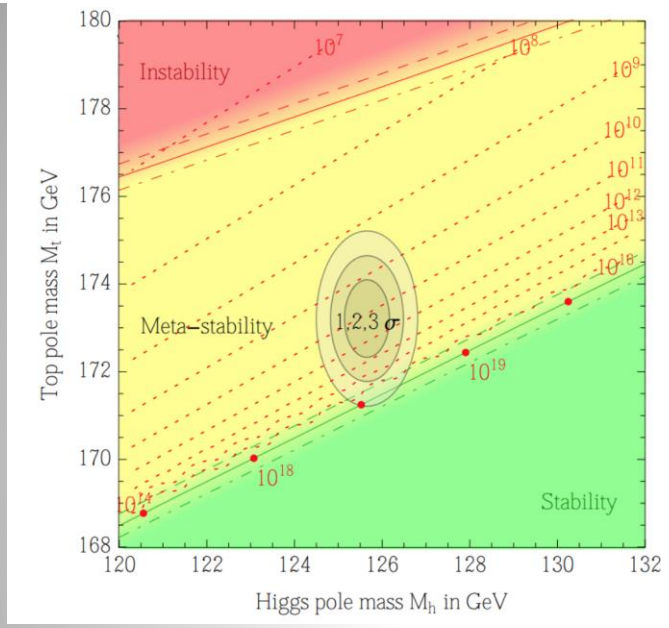
Simultaneous fit of the four production cross sections, normalized to the SM
The decay BR's are assumed to be the SM ones

$1.00 \pm 0.09\,(\text{stat})\,^{+0.08}_{-0.07}\,(\text{theo}) \pm 0.07$ CMS arXiv:1412.8662

$1.18 \pm 0.10 \pm 0.07^{+0.08}_{-0.07}$ ATLAS-CONF-2015-007

Searches for New Physics

Important SM parameter → stability of EW vacuum

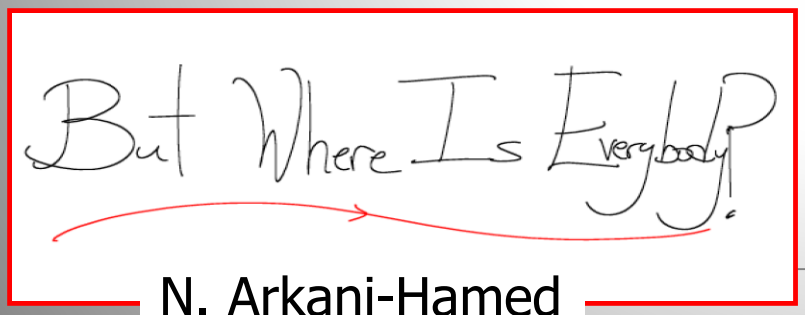


arXiv:1205.6497

arXiv:1403.6535

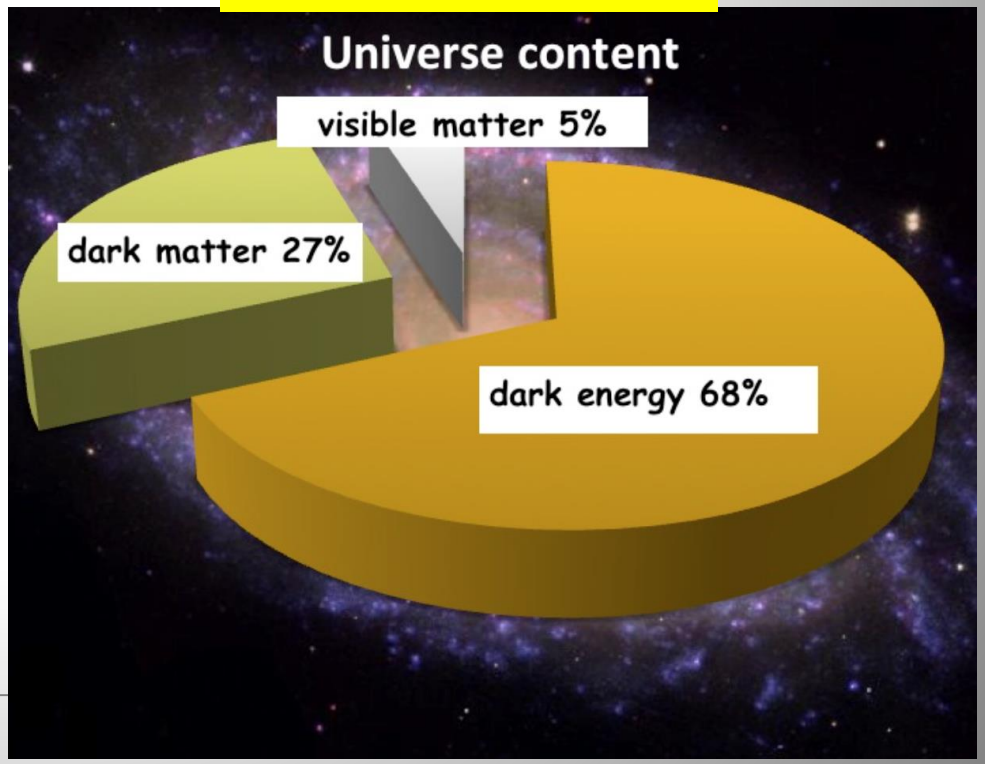
Precise measurements of the top quark and first measurements of the Higgs mass

New Physics inevitable?
But at which scale/energy?



N. Arkani-Hamed

We also know that:

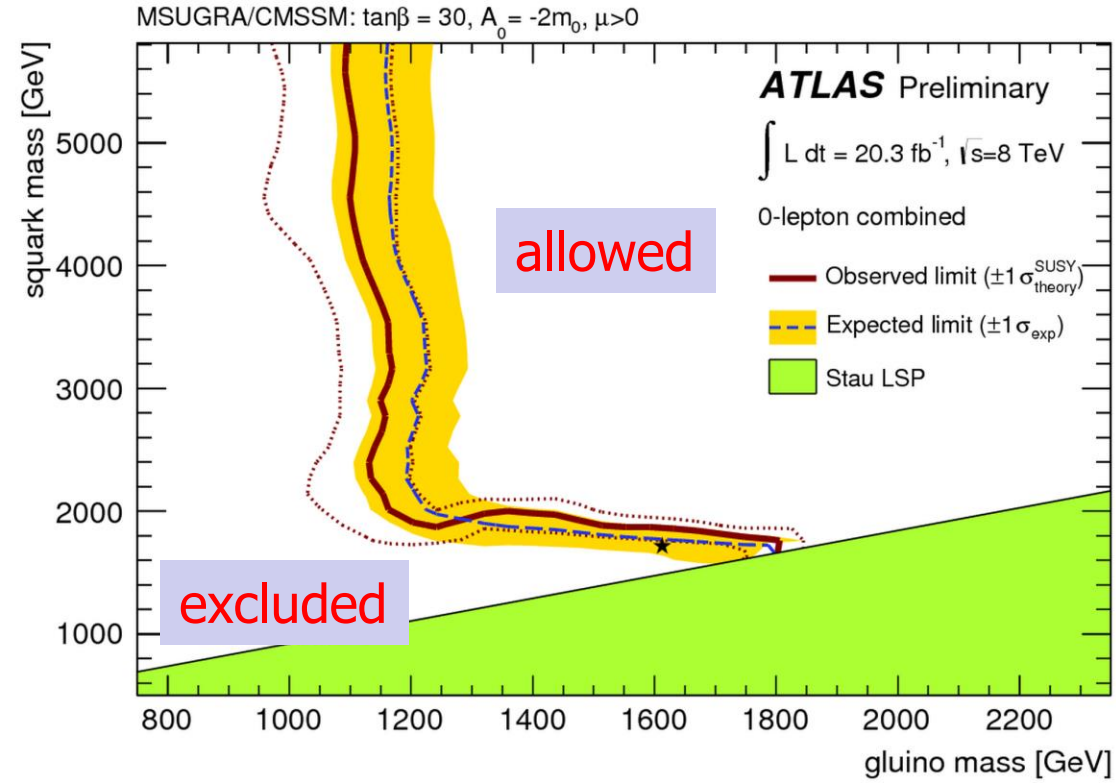


Searches for New Physics

- First Searches at the LHC (2010-2012)
  - Supersymmetry with MET plus jets, lepton(s), photons
  - Extra Dimensions and black holes, heavy resonances (in electrons, muons, taus, jets), leptoquarks, excited leptons and quarks, 4^{th} generation, a few very exotic signatures (R-hadrons)…
- Evolved Searches (2013-…)
  - Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes…
  - Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges…
  - More dedicated Dark Matter searches!
- We are now facing a restart of the machine at 13/14 TeV…

  Back to the basics or do we change paradigm?

SUSY Searches: No signal yet to date…



- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

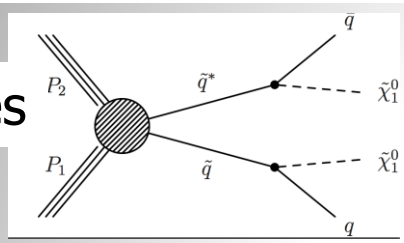
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

Also special searches for more contrived model regions

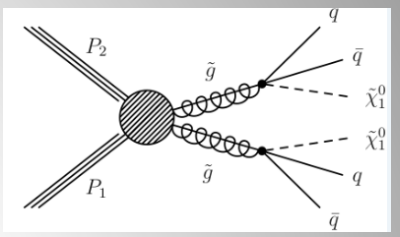
Limits on Squarks and Gluinos

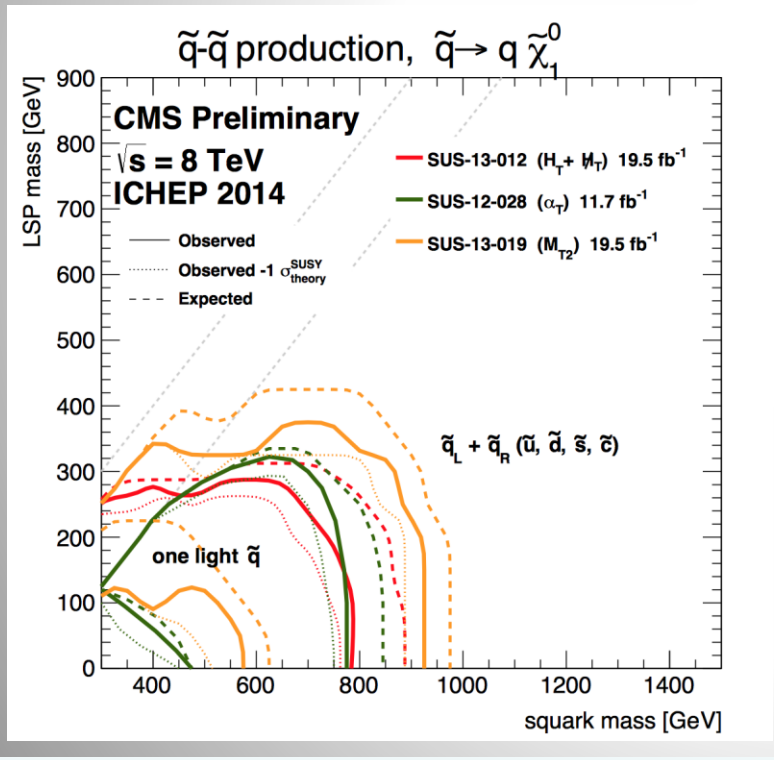
Results depend on the topologies studies, assumed mass of the LSP etc.

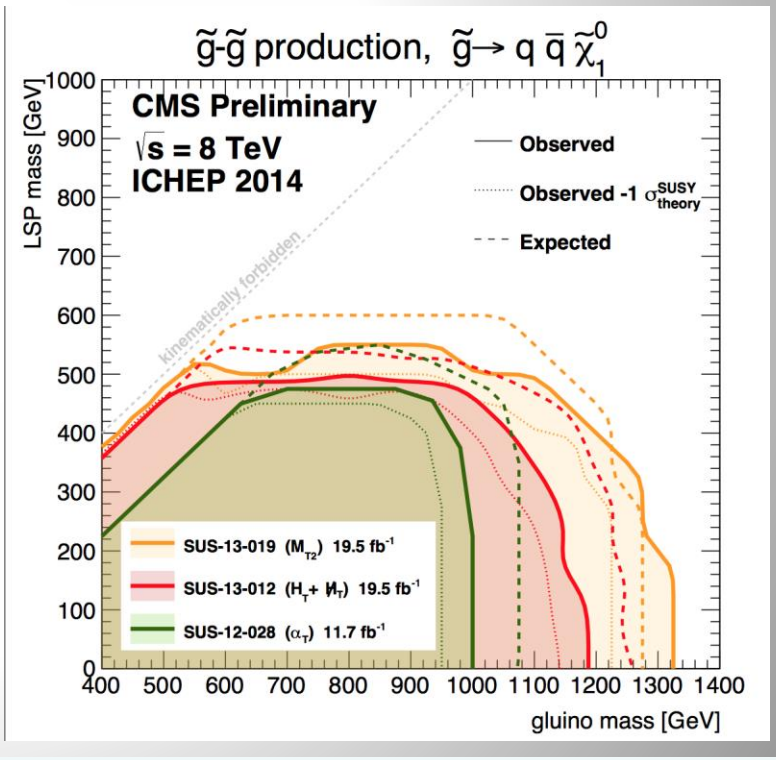
Examples



Popular presentation of data:
Simplified ModelS (SMS)

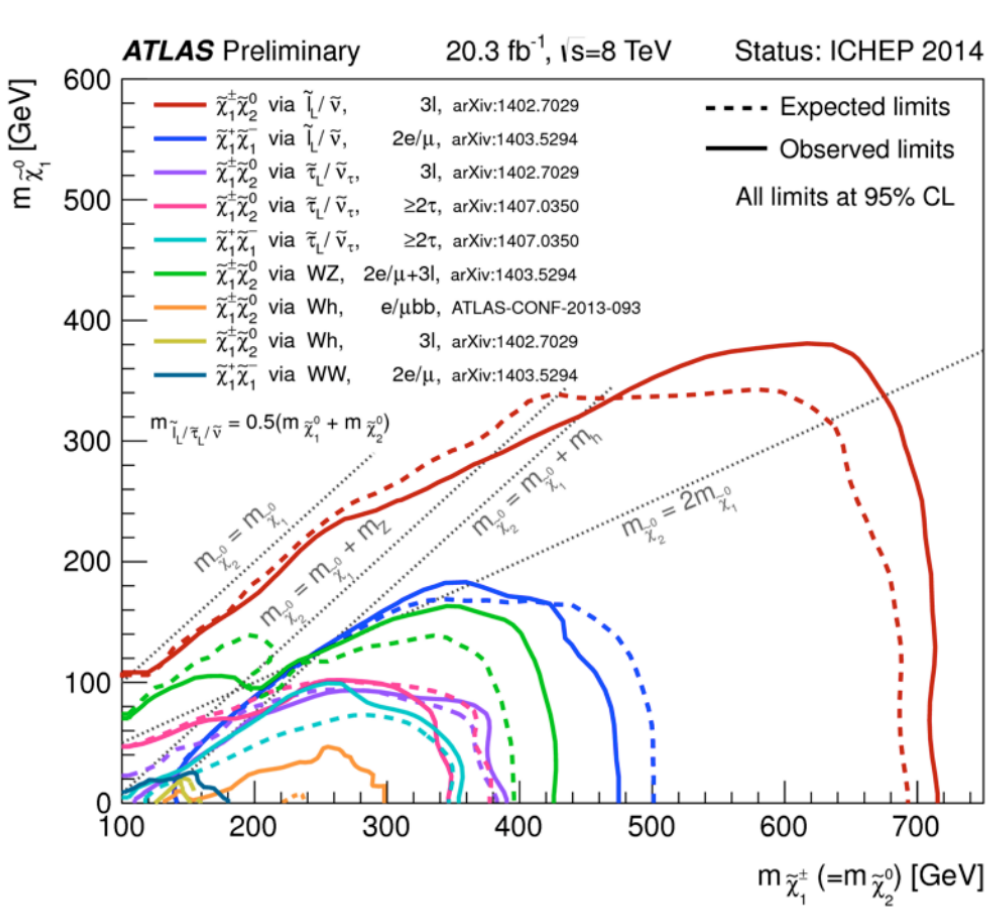


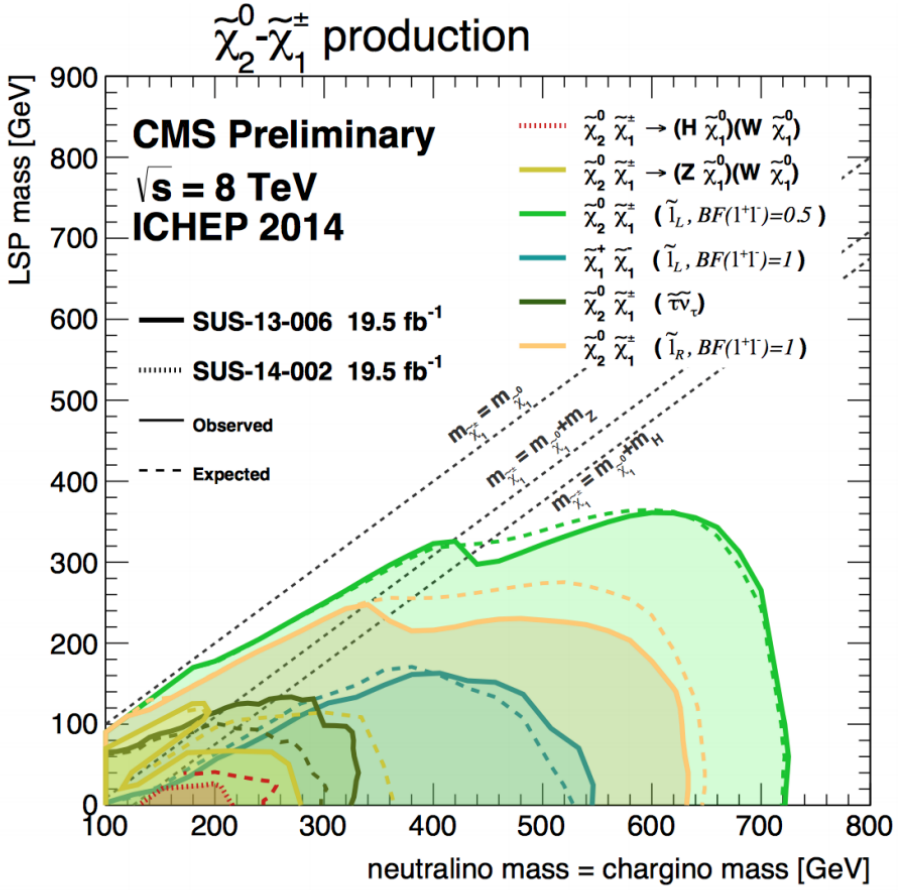




Combined limits typically > 1-1.3 TeV on sparticle masses

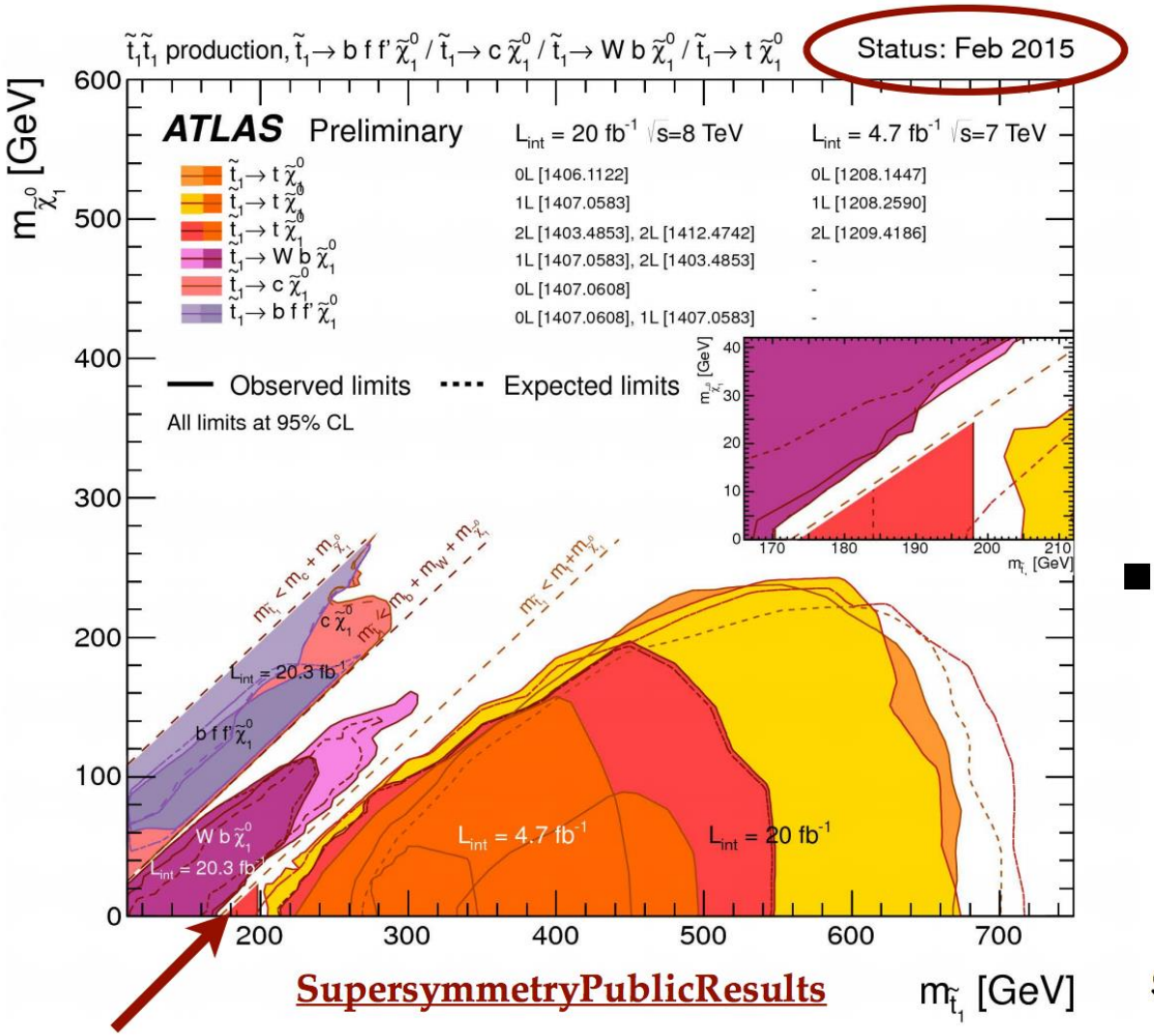
Electroweakino Searches

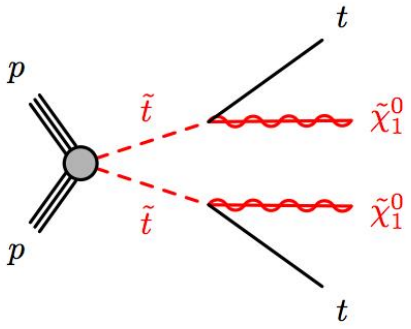




Natural SUSY?

Direct Stop Searches

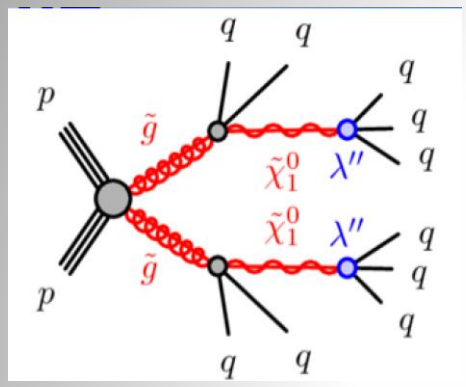


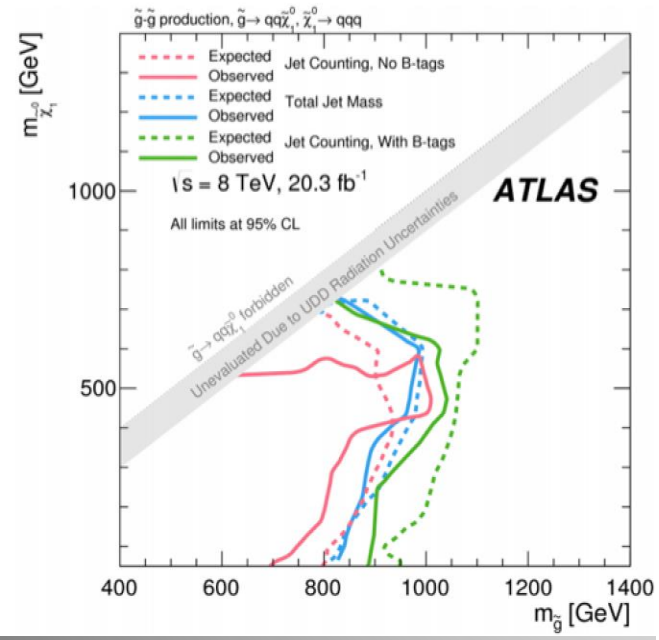


- Stealth stop region ($m_{\tilde{t}} \sim m_t$) nearly closed by precision $t\bar{t}$ measurements!

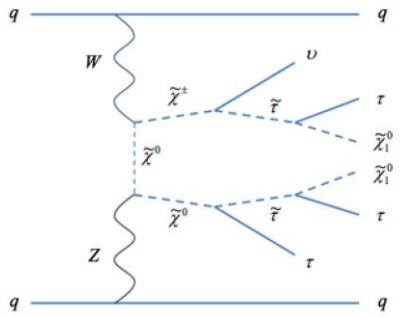
Recent New SUSY Search Results

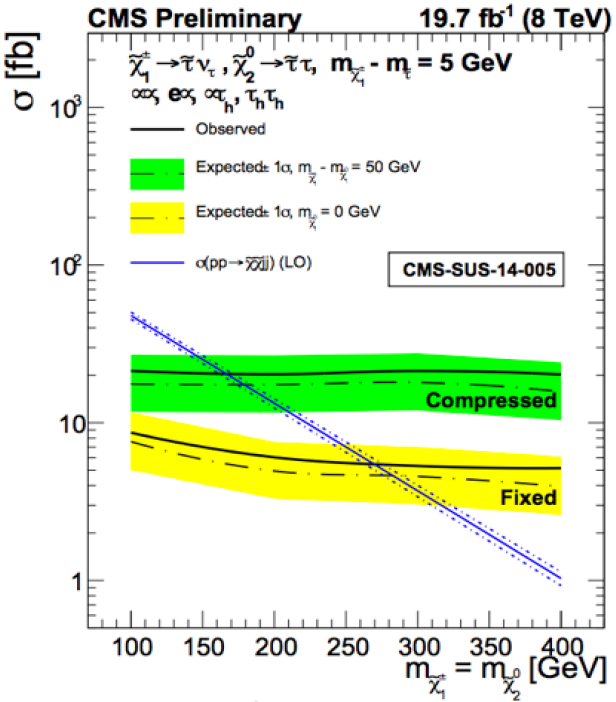
Multi-jet (≥6), no MET



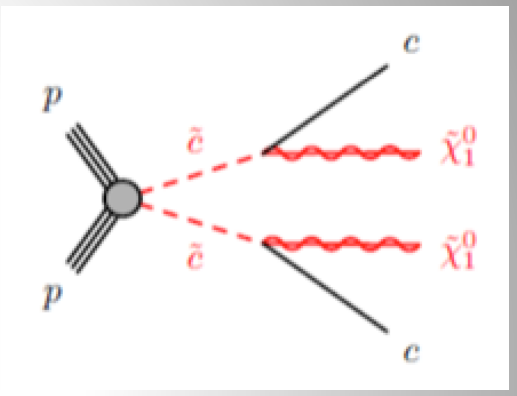


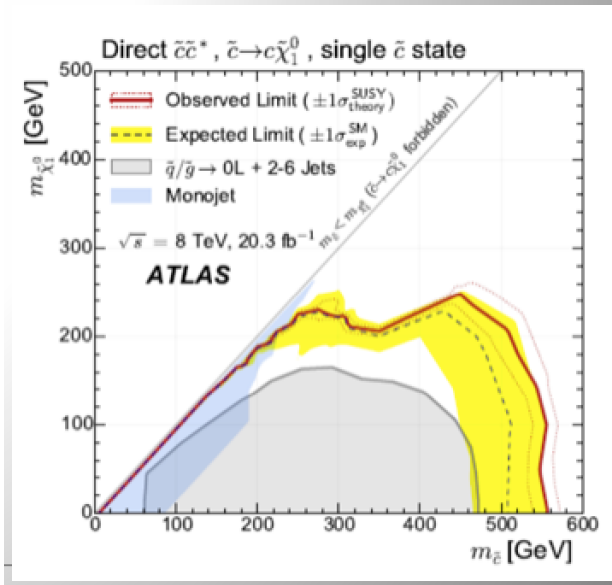
VBF EWKino production





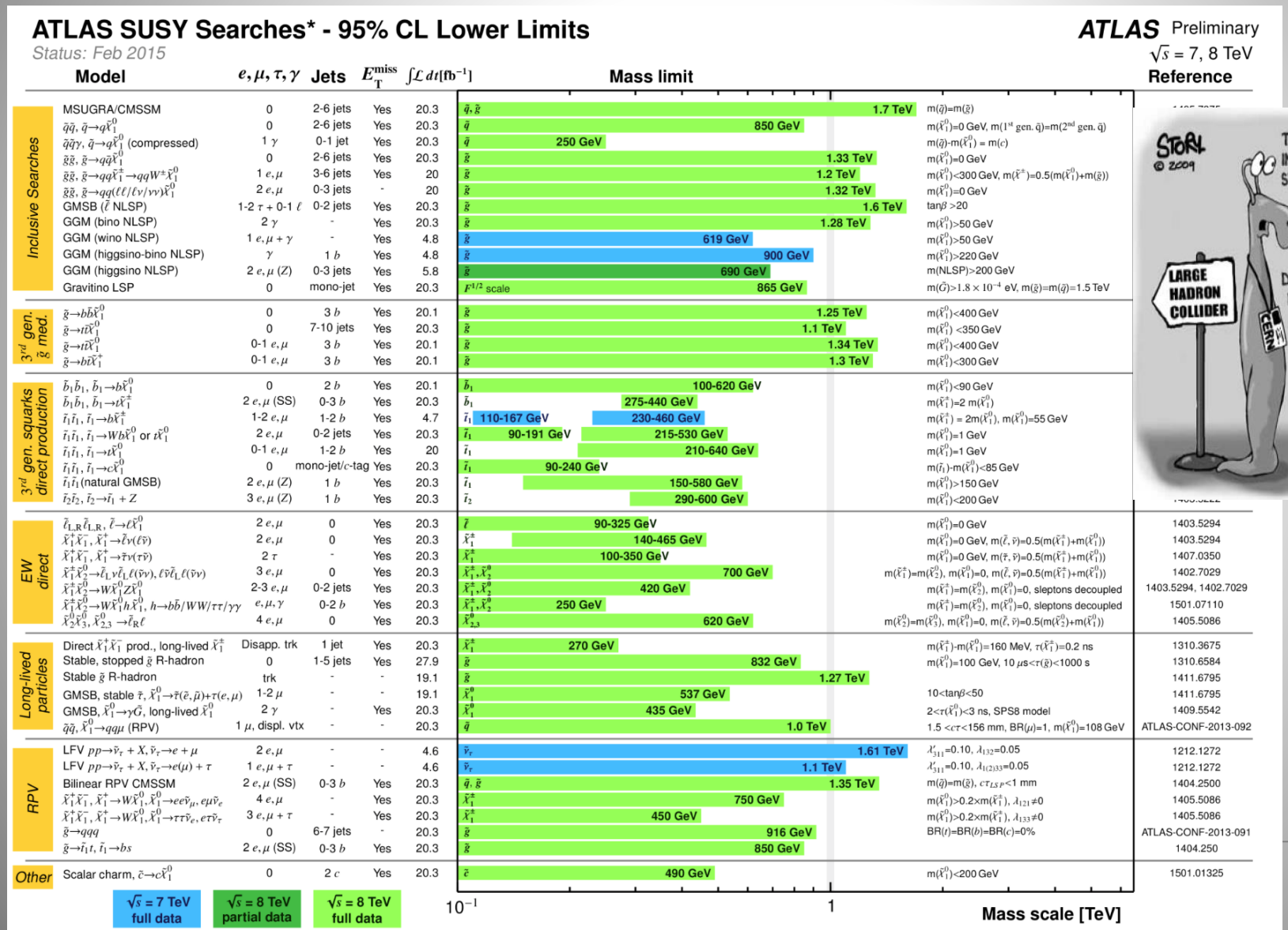
Scalar charm quark



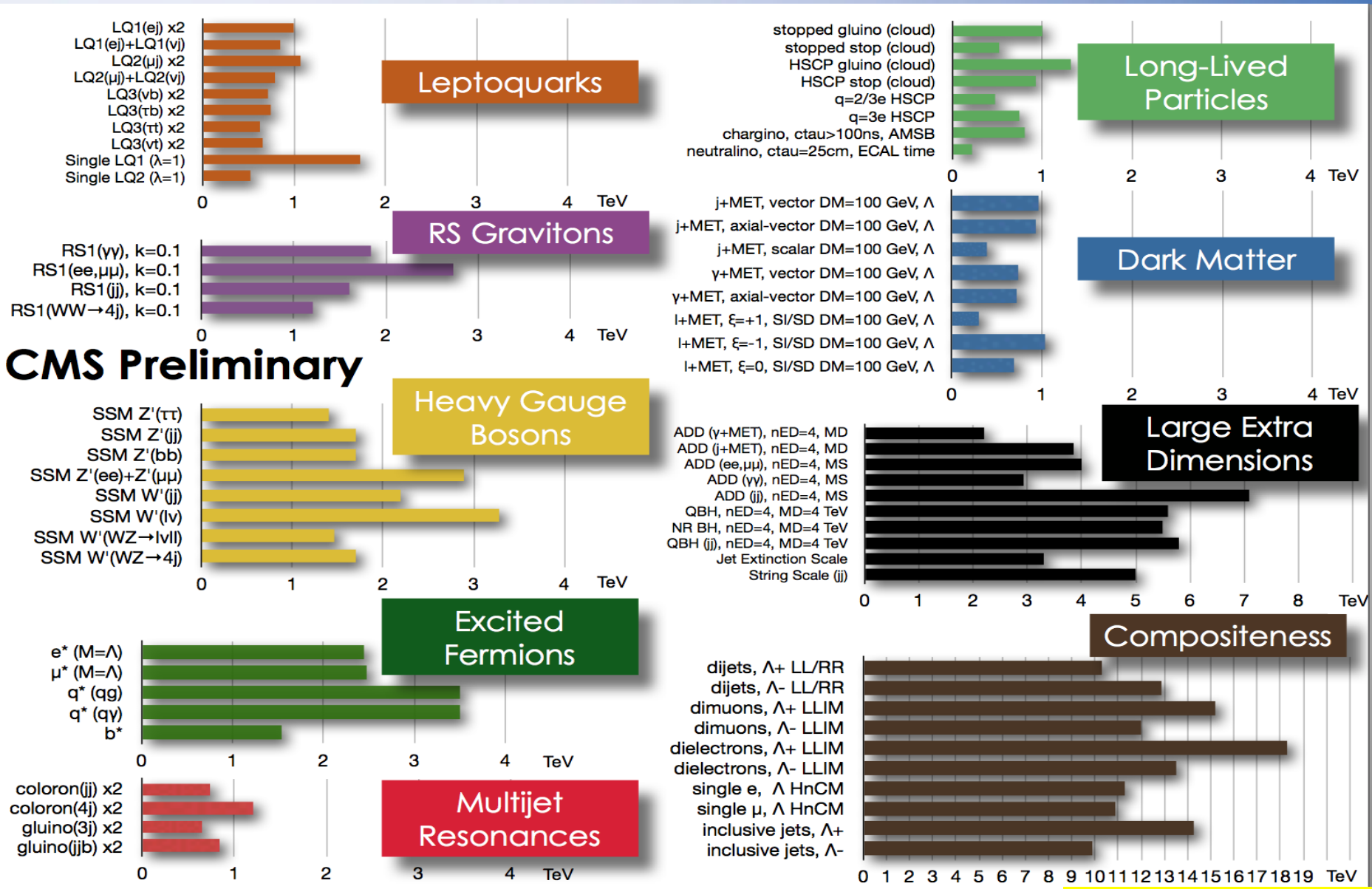


Summary of SUSY Searches

In short: no sign of SUSY with the data collected so far (similar for CMS)



Summary of Exotica Searches



CMS Exotica Physics Group Summary – Moriond, 2015

Similar for ATLAS

What Deviations did we Observe?

LHC Beyond-the-SM Anomalies (April 2015)

https://www.dropbox.com/s/2xrrcxns5wnc4ek/LHC_anomalies.pdf?dl=0

	Search	Dataset	Max Significance	Reference
Strong SUSY (jets+E_T^{miss}+X)	Z+jets+E_T^{miss}	ATLAS 8 TeV	3.0σ	arXiv:1503.03290 [hep-
	Dilepton mass edge	CMS 8 TeV	2.6σ	arXiv:1502.06031 [hep-
	Soft 2ℓ+E_T^{miss}	ATLAS 8 TeV	2.3σ	ATLAS-CONF-2013-06
	Same-sign ≥2ℓ+b+E_T^{miss}	ATLAS 8 TeV	2.5σ	arXiv:1504.04605 [hep-
EWK SUSY (leptons+E_T^{miss})	3ℓ+E_T^{miss} (WZ→3ℓ channel)	CMS 8 TeV	~2σ	EPJC 74 (2014) 3036
	4ℓ+E_T^{miss} (3ℓ+τ_{had} channel)	CMS 8 TeV	~3σ	PRD 90, 032006 (2014)
	3ℓ+E_T^{miss}	ATLAS 8 TeV	2.2σ	JHEP 04 (2014)169
Resonances	Dijet resonance search (M_{jj} ~ 1.8 TeV)	CMS 8 TeV	~2σ	PRD 91 (2015) 052009
	W(ℓν)H(bb) resonance (M_{WH} ~ 1.8 TeV)	CMS 8 TeV	2.2σ	CMS-PAS-EXO-14-010
	X→h(bb)h(γγ) (M_X ~ 300 GeV)	ATLAS 8 TeV	3.0σ	PRL 114 (2015) 081802
	1st gen. leptoquarks (eejj / evjj channels)	CMS 8 TeV	2.6σ / 2.4σ	CMS-PAS-EXO-12-041
	Heavy right-handed neutrinos	CMS 8 TeV	2.8σ	EPJC 74 (2014) 3149
Higgs	ttH (same-sign muon channel)	CMS 8 TeV	$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$	JHEP 09 (2014) 087
	Higgs→μτ (lepton flavor violation)	CMS 8 TeV	2.5σ	CMS-PAS-HIG-14-005
Flavor	B → Kℓℓ (Kμμ / Kee)	LHCb 8 TeV	2.6σ	PRL 113 (2014) 151601
	B → Kμμ (branching ratio)	LHCb 8 TeV	2.2σ	JHEP 06 (2014) 133
	B → Kμμ (P_5' angular distribution)	LHCB 8 TeV	3.7σ	LHCb-CONF-2015-00?
SM measurements	WW cross section*	CMS 7 TeV	1.0σ	EPJC 73 2610 (2013)
	WW cross section*	CMS 8 TeV	1.7σ	PLB 721 (2013)
	WW cross section*	ATLAS 7 TeV	1.4σ	PRD 87, 112001 (2013
	WW cross section*	ATLAS 8 TeV	2.0σ	ATLAS-CONF-2014-033

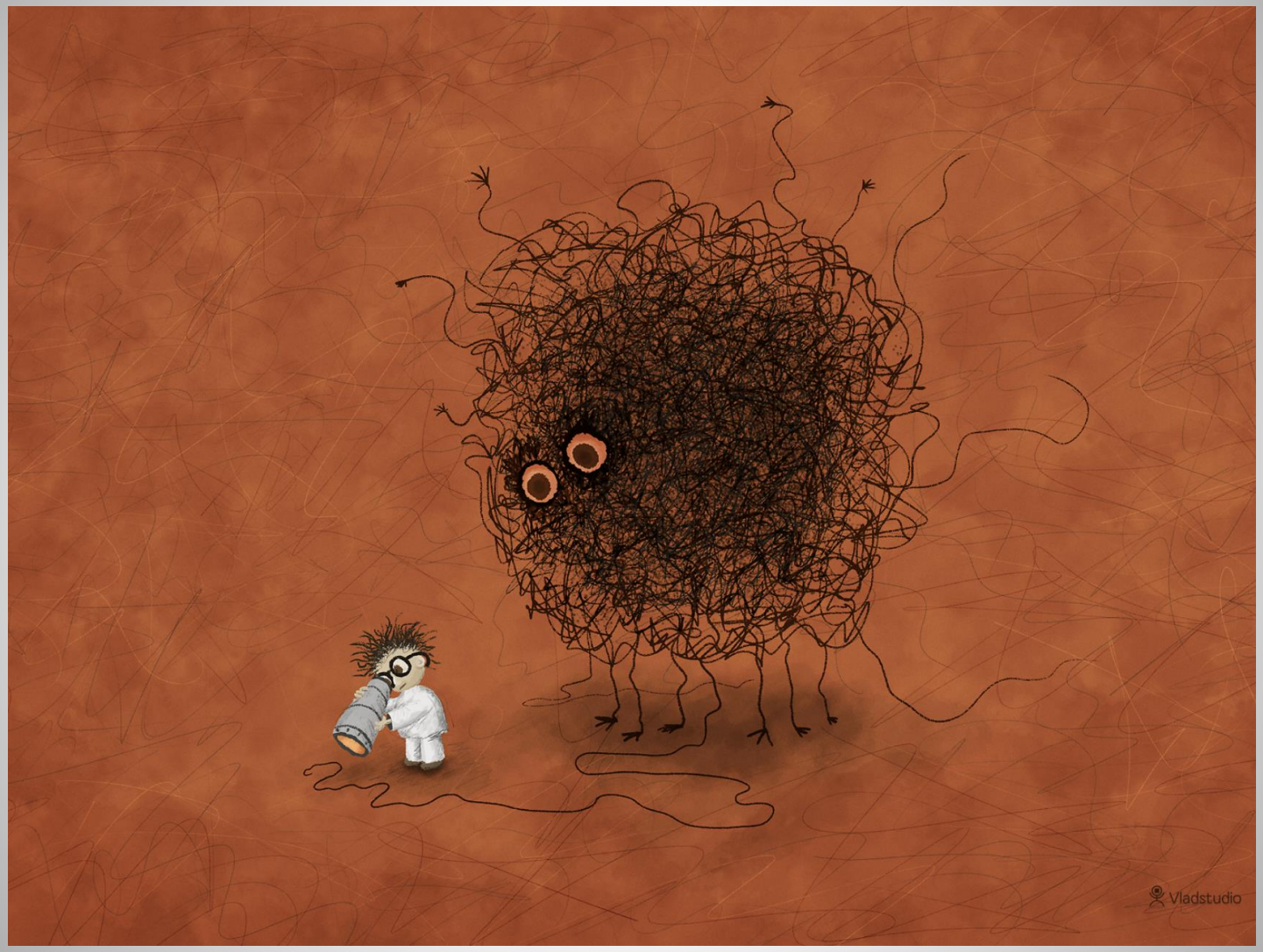
?

To be watched in Run-II !!

* See Jaiswal and Okui 2014 and Monni and Zanderighi 2014 for likely explanation

Send comments/updates to Ben Hooberman, benhoob@illinois.edu

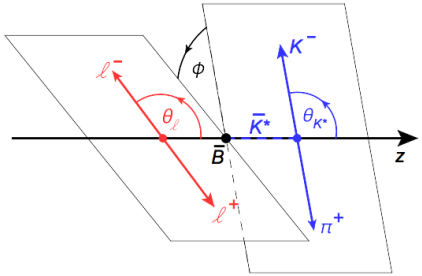
Are we looking at the right place??



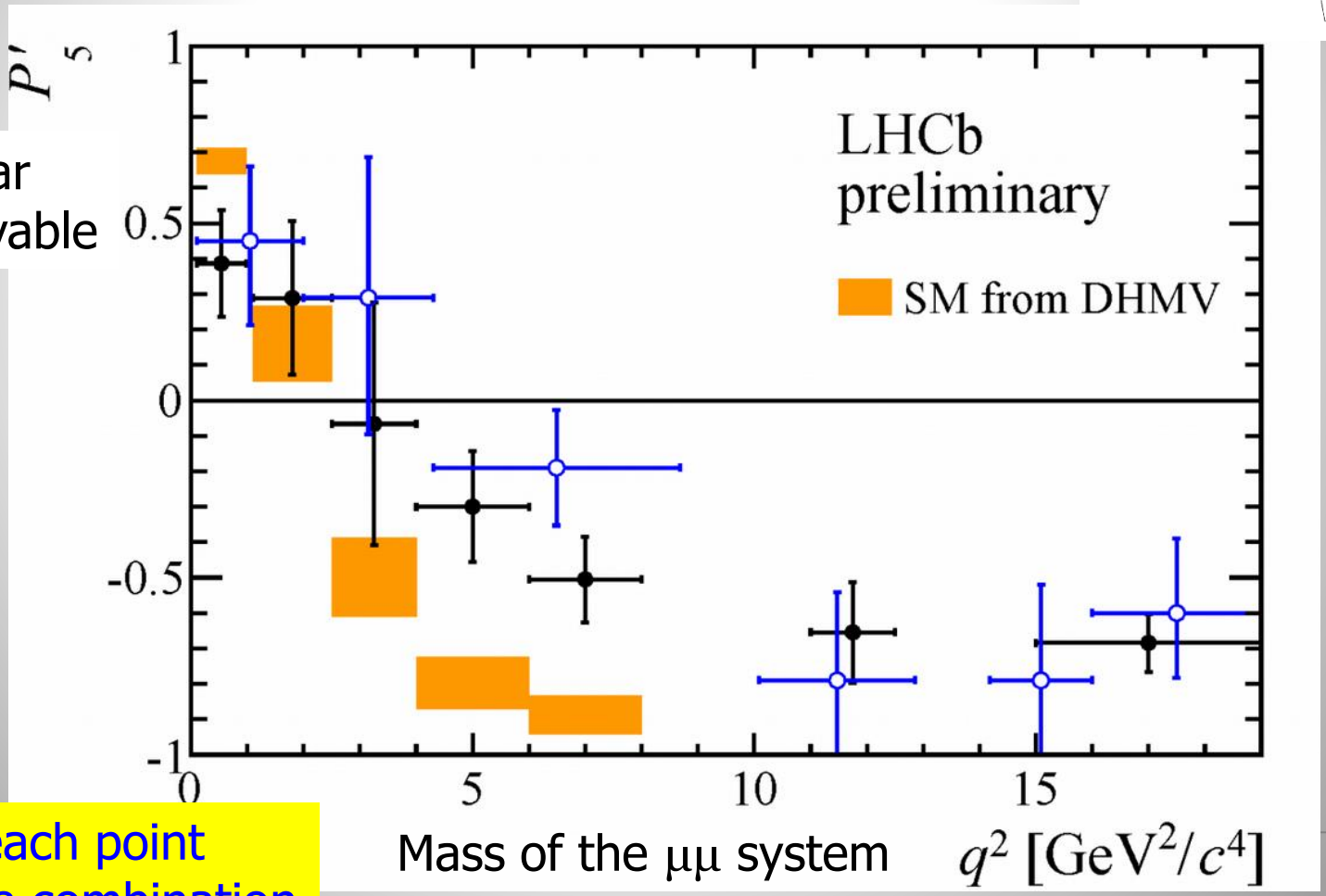
New Physics in Rare Decays?

Analysis of the B0→K*μ+μ- decay (full run-I data-set)

http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#P5p



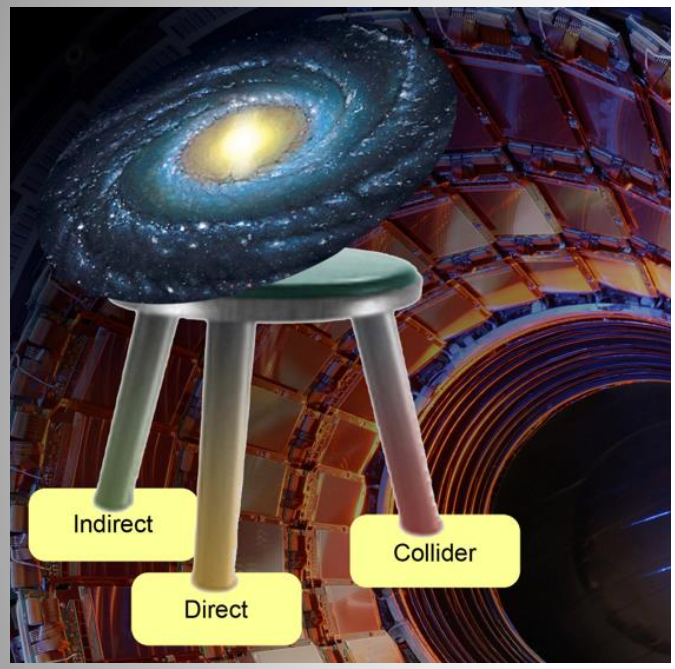
Angular observable

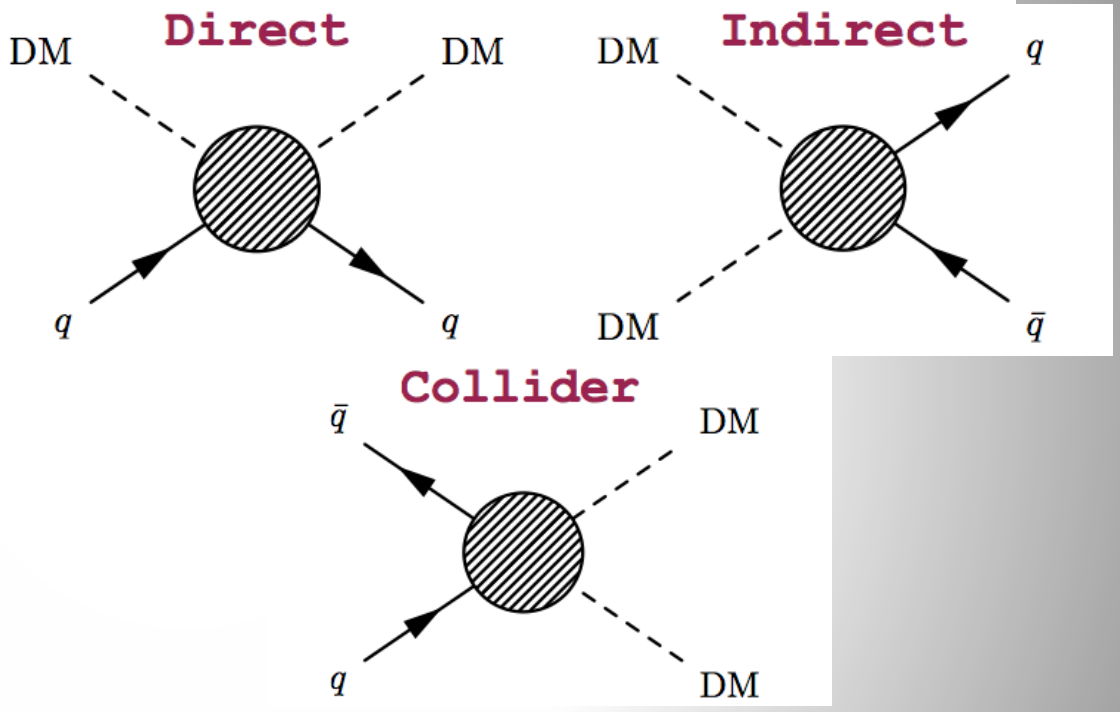


2.9σ for each point
3.7σ naive combination

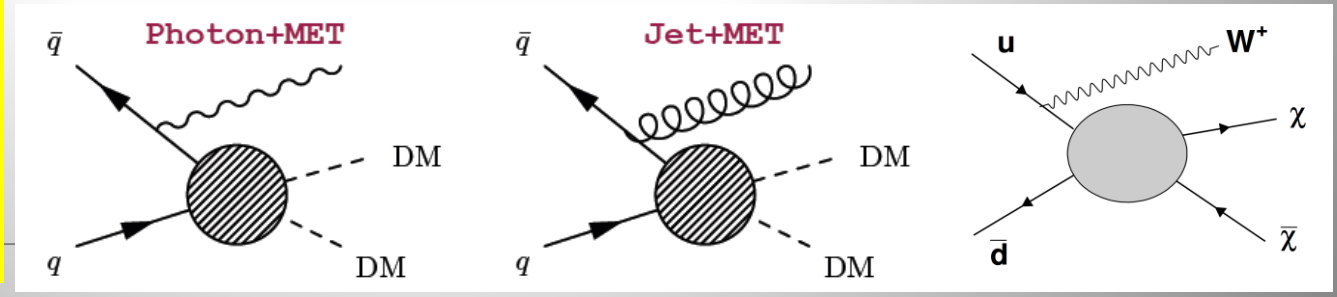
The Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)





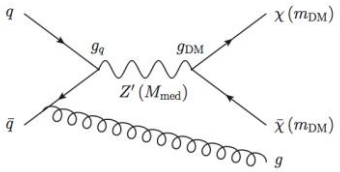
Use effective theory or better simplified models to relate measurements to Dark Matter studies



Mono-object Searches in CMS

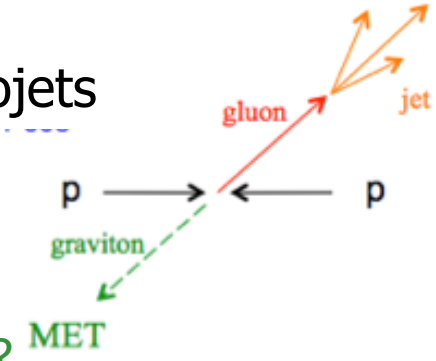
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed

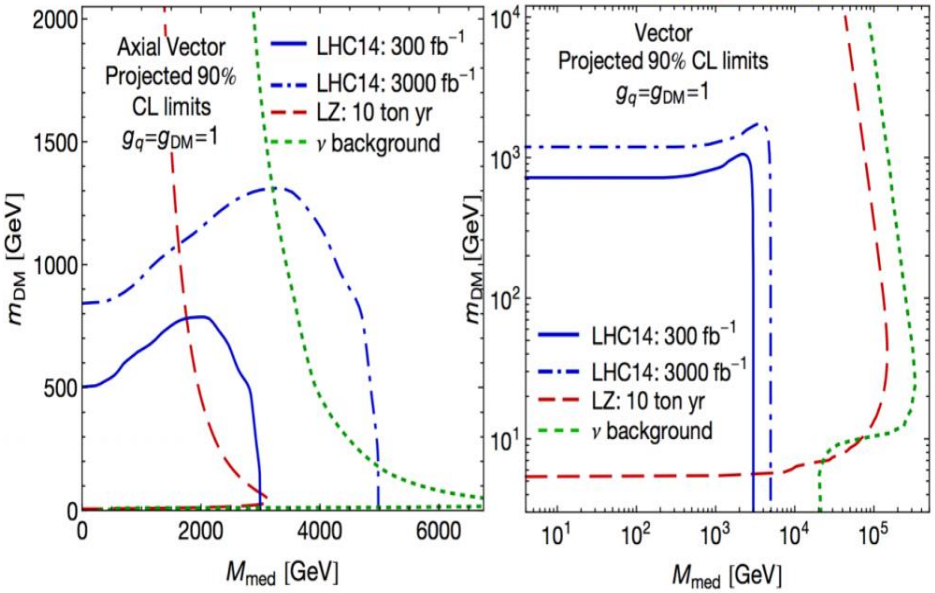


arXiv:1407.8257
arXiv:1411.0535

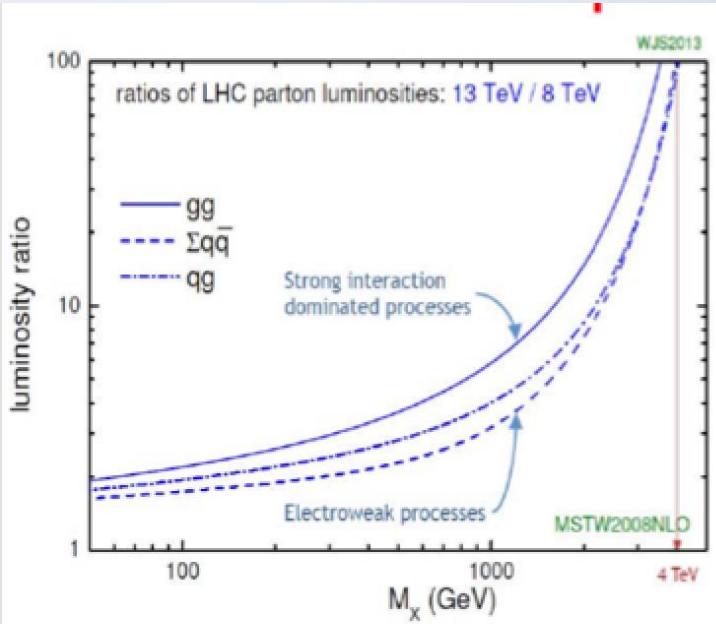
Example Monojets



Dark Matter?



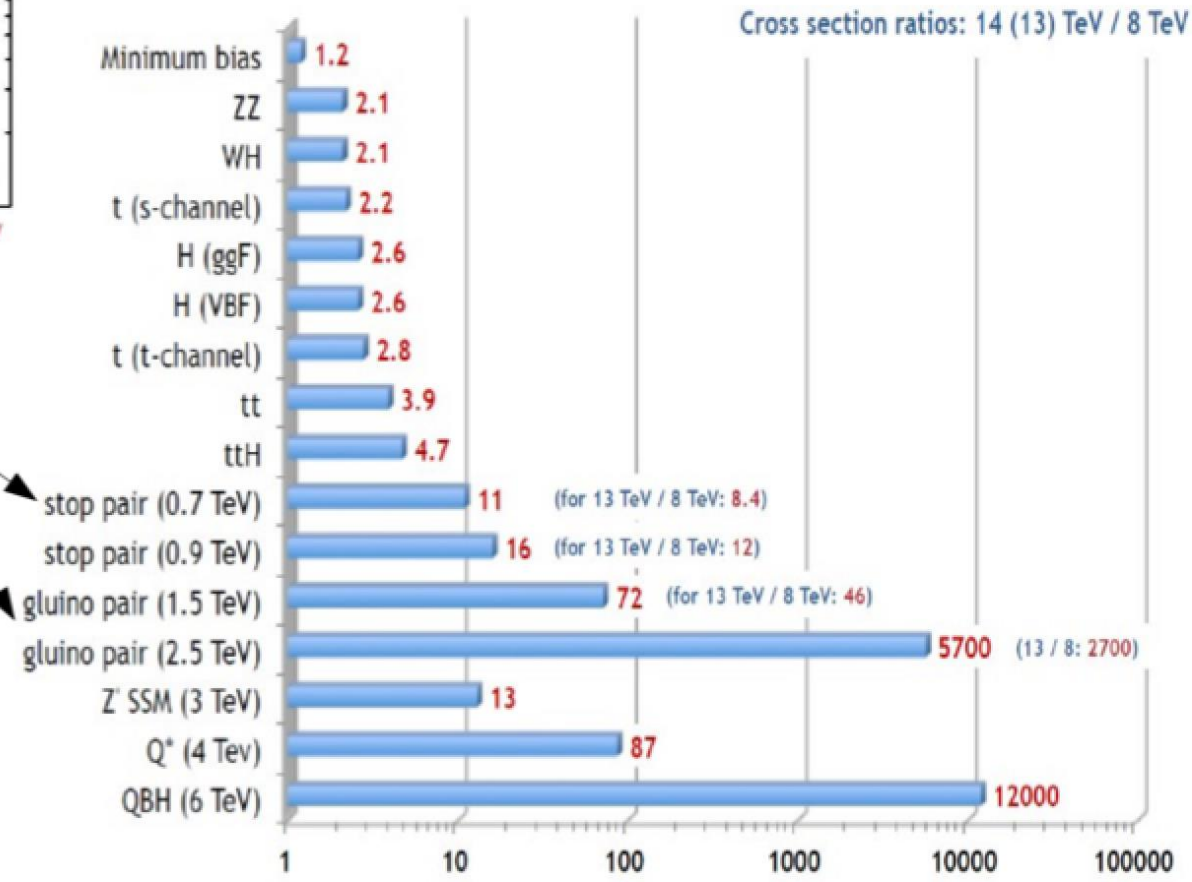
Prospects for Searches at 14 TeV



0.5-1 fb^{-1} would be enough for first analyses entering new territory
We should collect that during summer 2015

~Reach we had with 8 TeV 20 fb-1

With 1 fb-1 we will produce ~twice as many gluino pairs at 1.5 TeV as in full Run 1
With 5 fb-1 we will produce ~twice as many stop pairs at 0.7 TeV as in full Run 1



Summary: Looking Forward to Run-II

- The LHC is gearing up to start operation in 2015 at 13 TeV. The final commissioning is ongoing. First collisions in June
- LHC run-I has produced a lot of data relevant to this workshop series: QCD studies at high scales, PDF studies, diffraction, electroweak studies… These studies will be preformed next at the new collision energy. Higgs is a new laboratory for studies.
- In particular LHC data start playing a role in constraining the PDFs. Reversely, knowledge on PDFs will remain an important input for many LHC measurements (crucial e.g. in W-mass…)
- No significant sign of new physics yet in the 20 TeV. This cuts into the 'preferred regions' for a models, like SUSY. A number of 2-3 sigma effe
- It will take only ONE significant deviation to cha

So maybe one day soon: