Elementary Particle Physics: theory and experiments

LHC:

Searches for New Physics

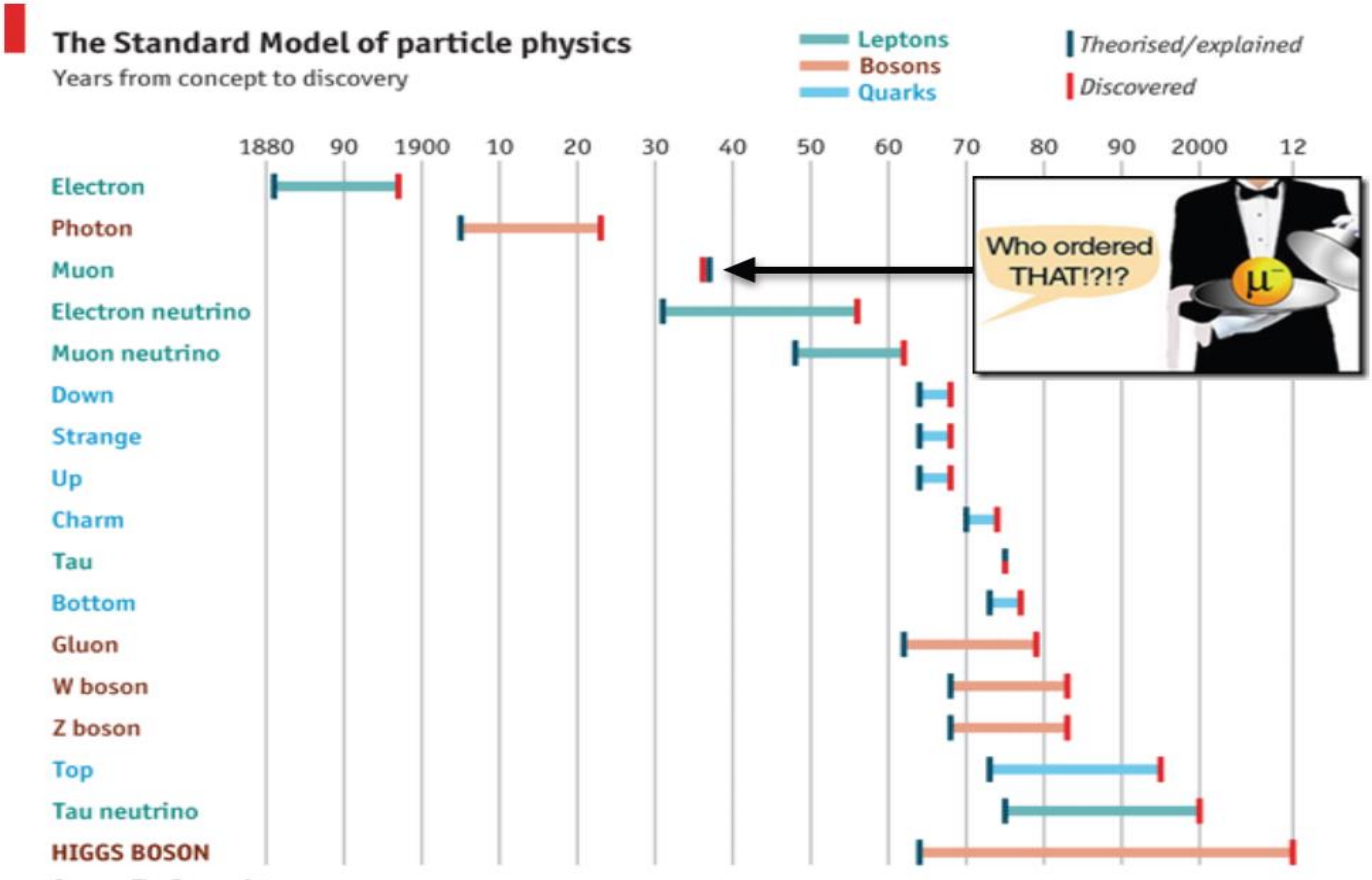
Selected new results at 13 TeV

LEP:

Few precision measurements

Based on seminar: M. Kado, CERN Council meeting, 15.12 2015

Uncharted discoveries?



Source: *The Economist*

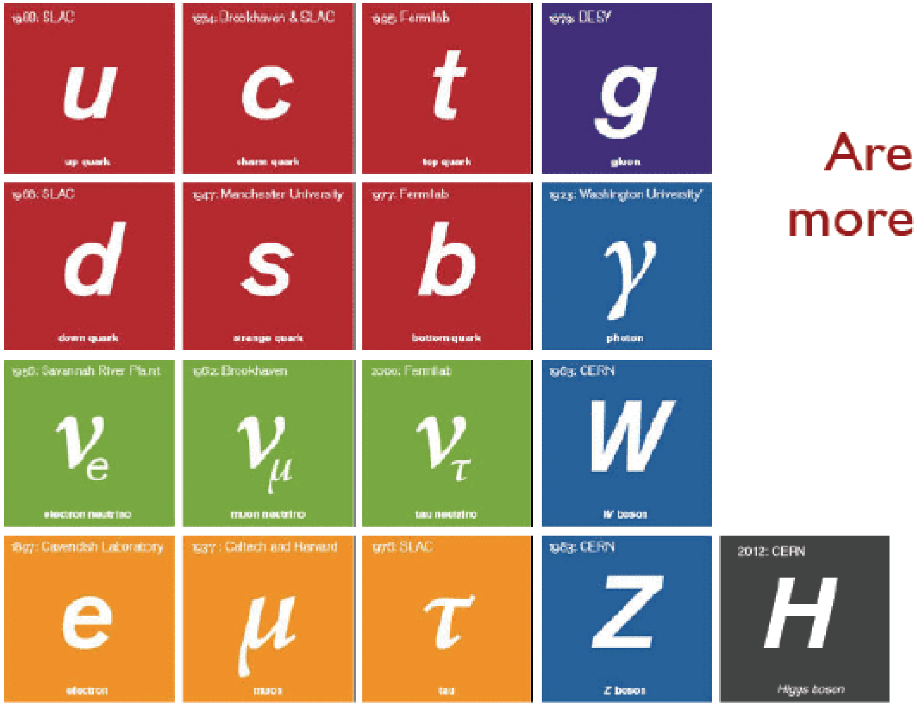
Many unanswered questions …

Why there are 3 families of particles? Are there more?

Why is the top quark so heavy?

Why there's more matter then anti-matter?

How do neutrinos get mass?



Are there more forces?

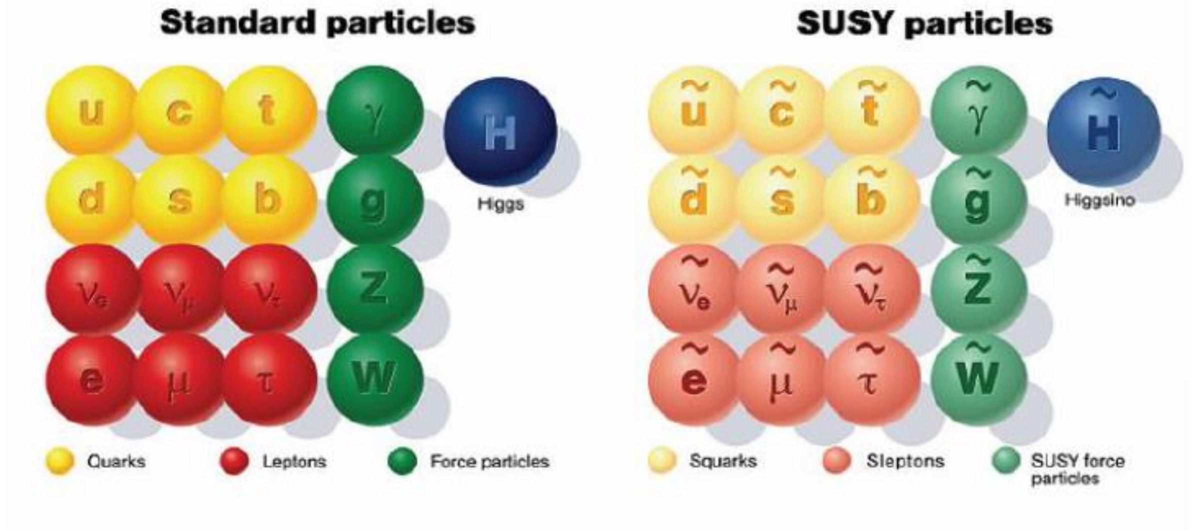
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



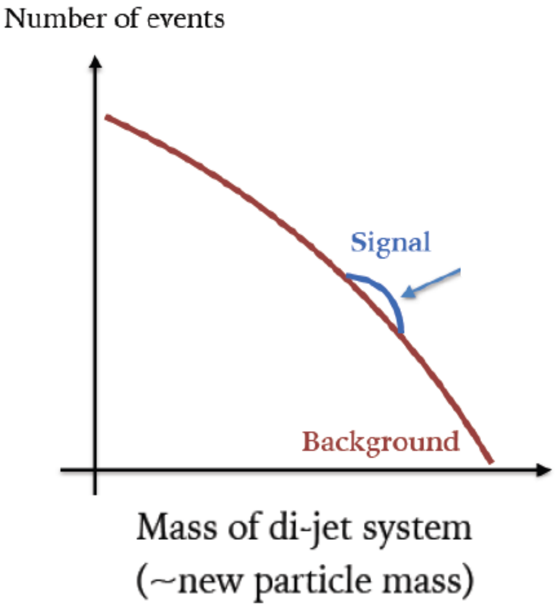
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest?

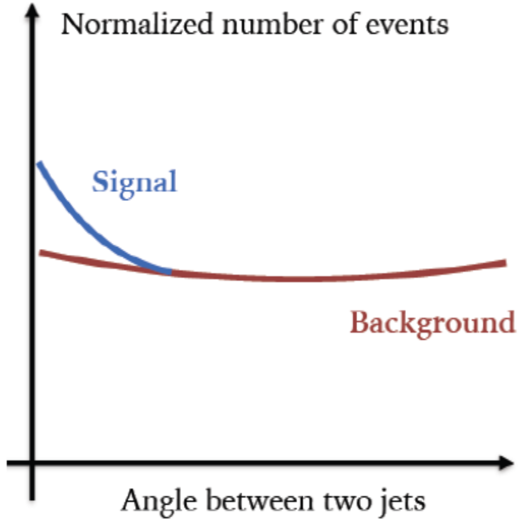
New particles:

resonant excess (bump) over Standard Model background



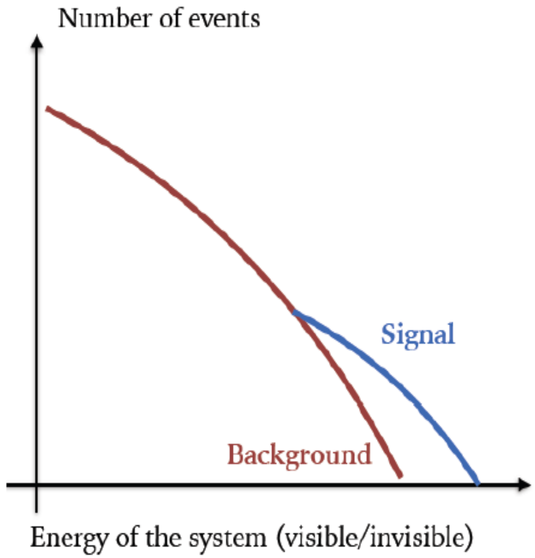
New interactions:

more central production (~Rutherford experiment)

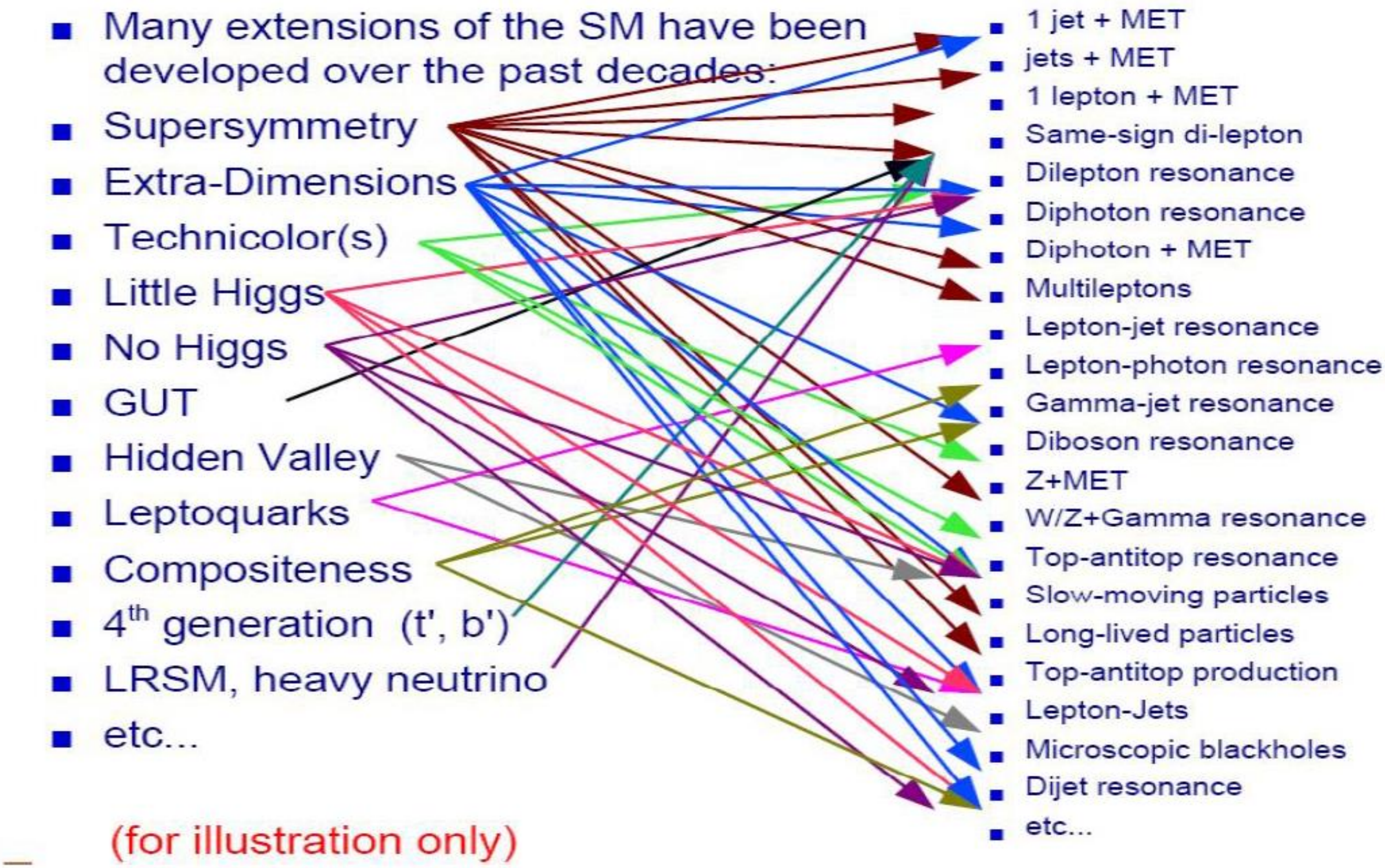


New particles and states:

larger multiplicity of objects at high masses



Long list of models and signatures

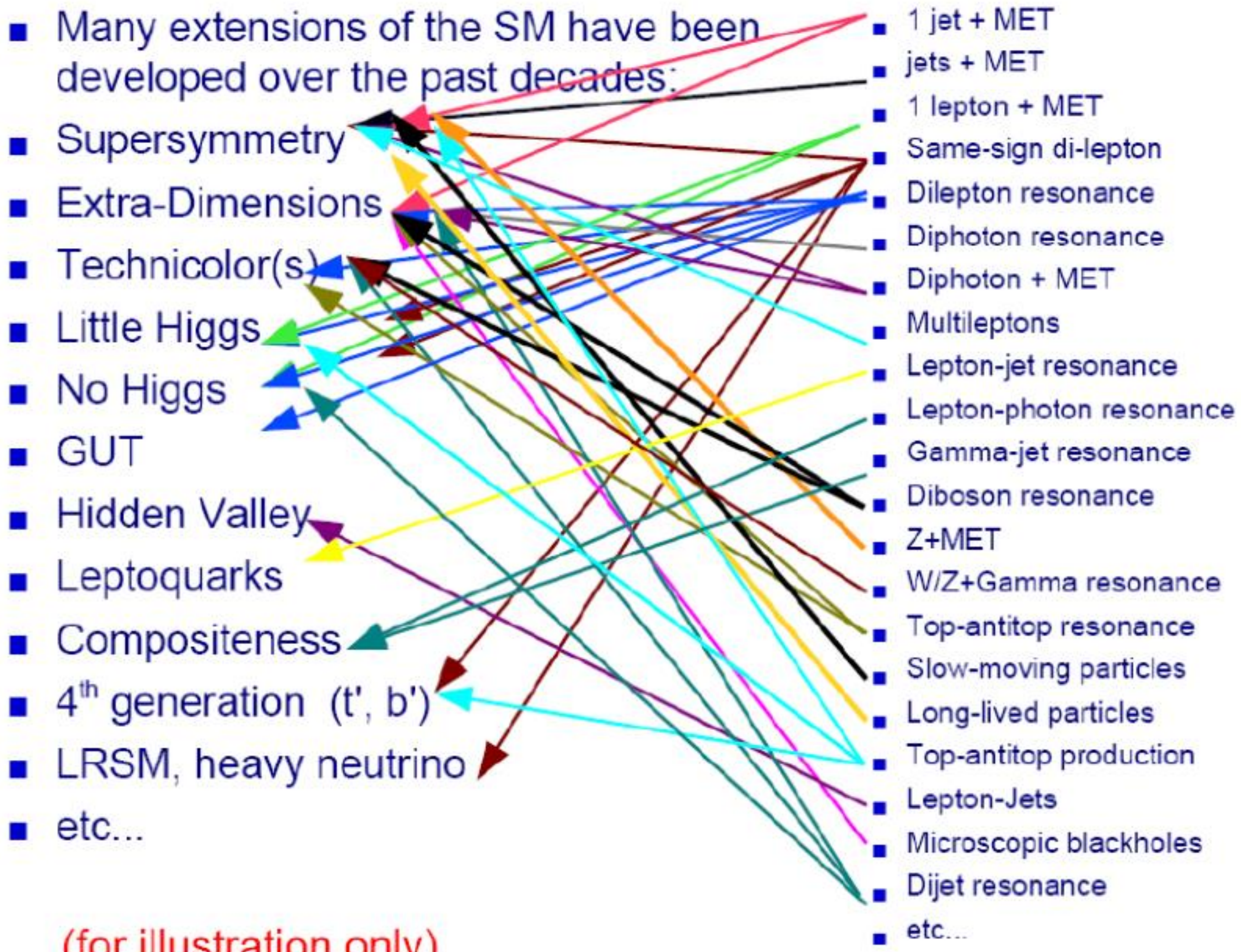


- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

Long list of models and signatures



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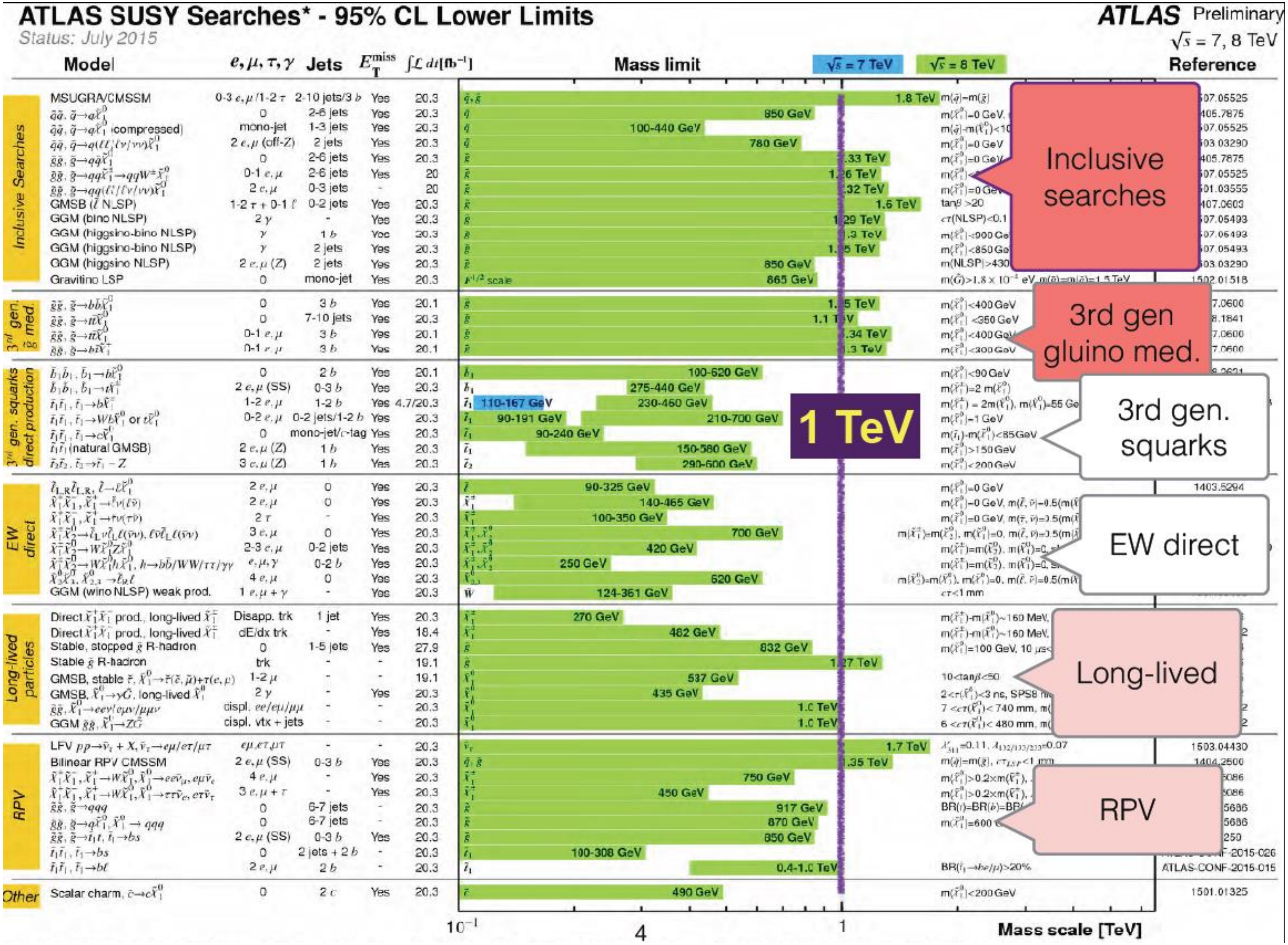
A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

→ Less model-dependent

→ Important to cover every possible signature



1 TeV

Inclusive searches

3rd gen gluino med.

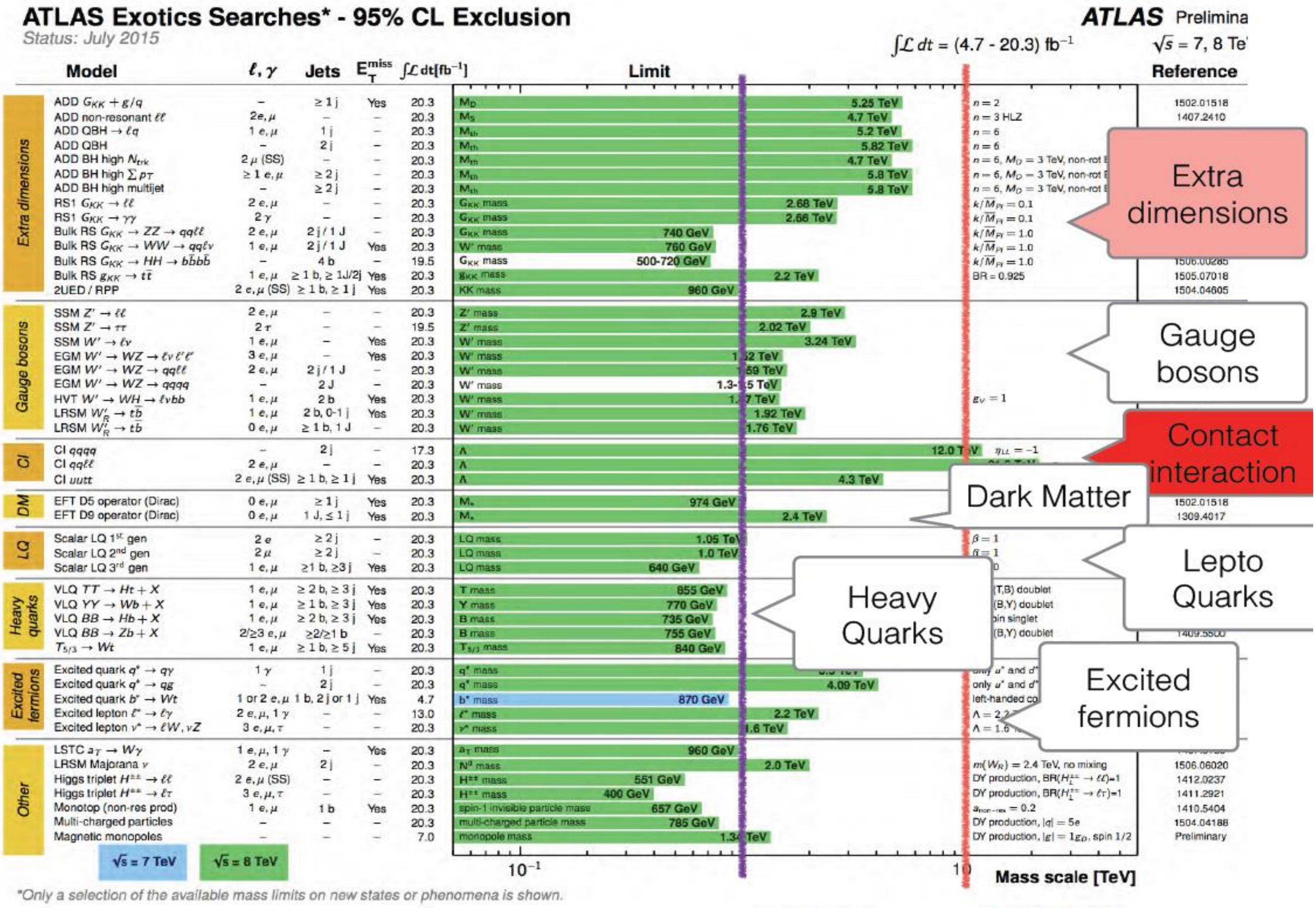
3rd gen. squarks

EW direct

Long-lived

RPV

4



ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Prelimina

$\int \mathcal{L}\,dt = (4.7 - 20.3)\ \text{fb}^{-1}$

$\sqrt{s} = 7, 8$ Te

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D	5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	M_S	4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH → ℓq	1 e, μ	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	
	ADD QBH	–	2 j	–	20.3	M_{th}	5.82 TeV	$n = 6$	
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th}	4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot	
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot	
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot	
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass	2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass	740 GeV	$k/\overline{M}_{Pl} = 1.0$	
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass	760 GeV	$k/\overline{M}_{Pl} = 1.0$	
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass	2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass	960 GeV		1504.04605
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass	2.9 TeV		
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass	2.02 TeV		
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass	3.24 TeV		
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass	1.[illegible]2 TeV		
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass	[illegible]59 TeV		
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass	1.3-[illegible]5 TeV		
	HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass	1.[illegible]7 TeV	$g_V = 1$	
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		
CI	CI $qqqq$	–	2 j	–	17.3	Λ	12.0 TeV	$\eta_{LL} = -1$	
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ			
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ	4.3 TeV		
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_*	974 GeV		1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_*	2.4 TeV		1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass	1.05 TeV	$\beta = 1$	
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass	1.0 TeV	$\beta = 1$	
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass	640 GeV	0	
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass	855 GeV	(T,B) doublet	
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass	770 GeV	(B,Y) doublet	
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass	735 GeV	in singlet	
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass	755 GeV	(B,Y) doublet	1409.5500
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass	840 GeV		
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q* mass		only u* and d*	
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q* mass	4.09 TeV	only u* and d*	
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass	870 GeV	left-handed co	
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ* mass	2.2 TeV	Λ = 2.2	
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν* mass	1.6 TeV	Λ = 1.6	
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass	960 GeV		
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass	551 GeV	DY production, $BR(H_L^{\pm\pm} \to \ell\ell)$=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $BR(H_L^{\pm\pm} \to \ell\tau)$=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	Preliminary

🟦 $\sqrt{s} = 7$ TeV 🟩 $\sqrt{s} = 8$ TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

Extra dimensions

Gauge bosons

Contact interaction

Dark Matter

Lepto Quarks

Heavy Quarks

Excited fermions

1 TeV

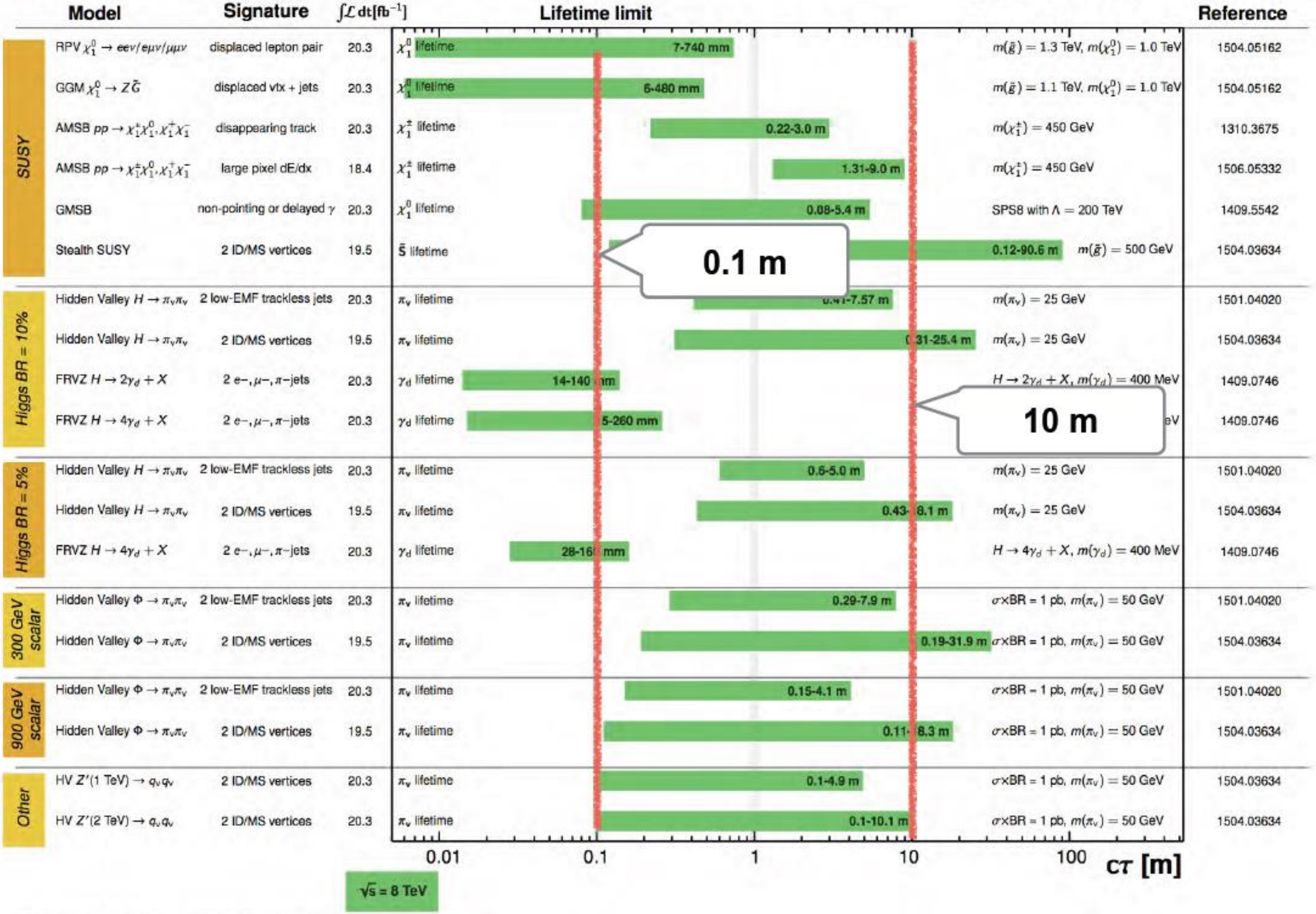
10 TeV

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\,dt = (18.4 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8$ TeV



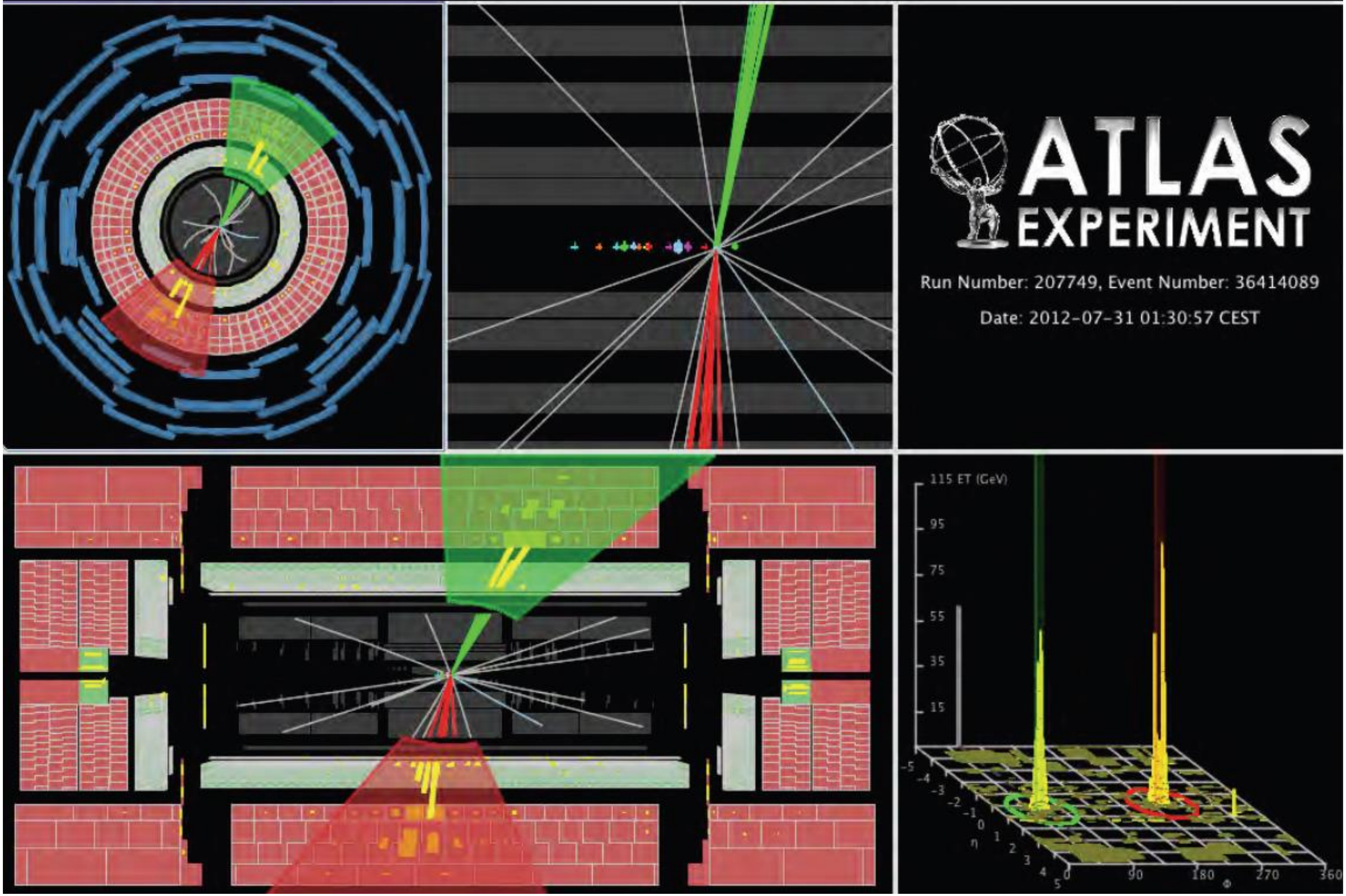
	Model	Signature	$\int \mathcal{L}\,dt\,[\mathrm{fb}^{-1}]$	Lifetime limit			Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	7-740 mm	$m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	6-480 mm	$m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^{\pm}$ lifetime	0.22-3.0 m	$m(\chi_1^{\pm}) = 450$ GeV	1310.3675
	AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^{\pm}$ lifetime	1.31-9.0 m	$m(\chi_1^{\pm}) = 450$ GeV	1506.05332
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with $\Lambda = 200$ TeV	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	0.12-90.6 m	$m(\tilde{g}) = 500$ GeV	1504.03634
Higgs BR = 10%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.41-7.57 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.31-25.4 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	14-140 mm	$H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	5-260 mm	eV	1409.0746
Higgs BR = 5%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.6-5.0 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.43-8.1 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	28-160 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
300 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.29-7.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.19-31.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
900 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.15-4.1 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.11-8.3 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime	0.1-4.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime	0.1-10.1 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634

0.1 m

10 m

*Only a selection of the available lifetime limits on new states is shown.

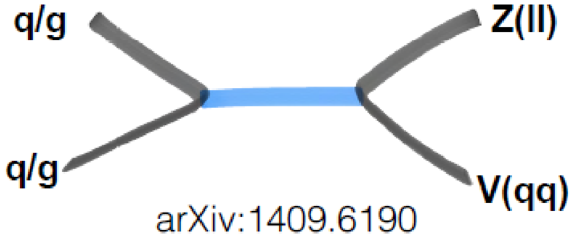
Exotics VV Resonance Searches



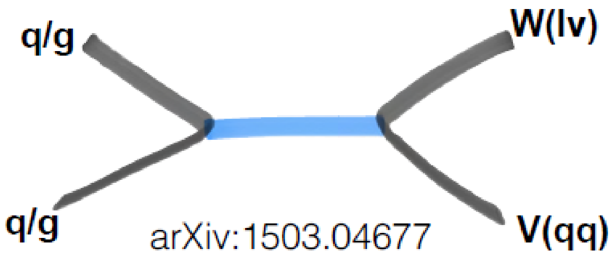
Run I VV resonances searches

- Narrow Resonance
    - Spin-2
    - Vector (neutral or charged)
    - Scalars for llqq, lvqq

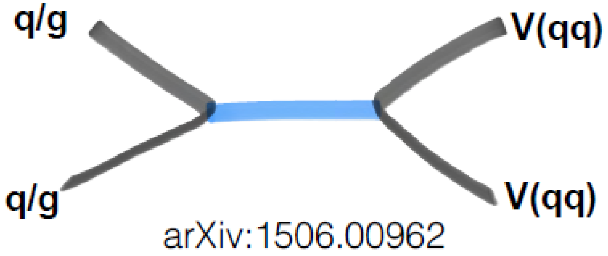
	W	Z
ll,lv	22%	7%
ττ, τν	11%	3%
νν		20%
qq	67%	70%



arXiv:1409.6190



arXiv:1503.04677



arXiv:1506.00962

Boson tagging techniques

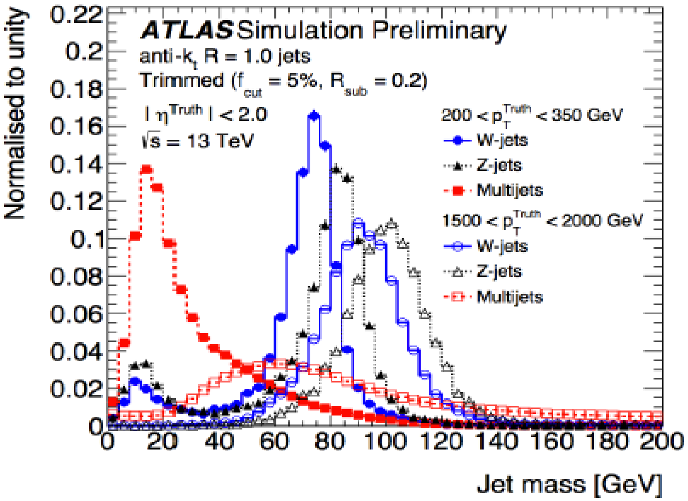
Searches for VV or VH resonances in several topologies involving boson (W, Z and H) tagging

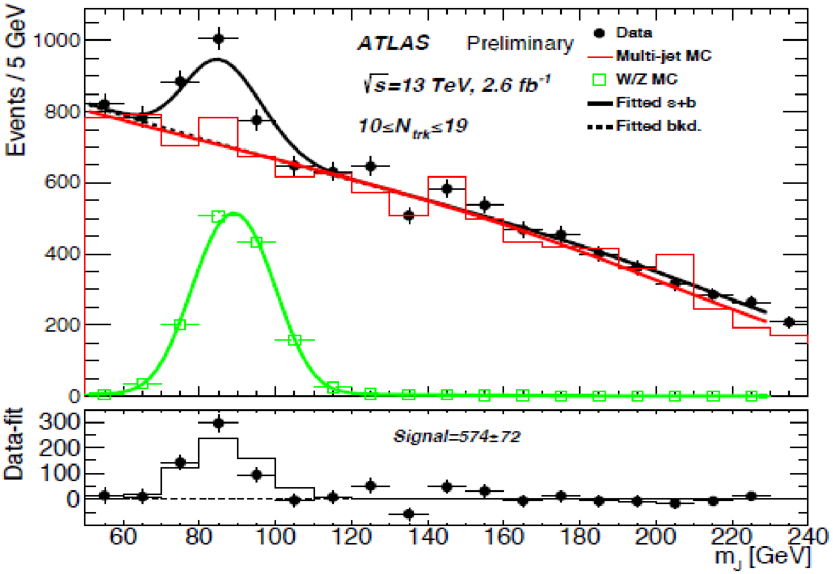
Nominal boson tagging algorithm

- Anti-kT R=1.0
- Trimming: fcut = 5% and Rsub = 0.2
- pT dependent (energy correlation ratio) D2 selections for W and Z separately (Multijet reduction by 40 – 70)

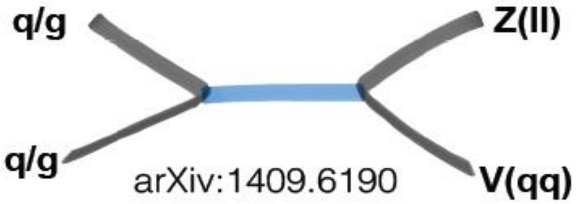
Boson tagging at work

W and Z peak in the data from dijet events applying the nominal boson tagging algorithm





Run I VV resonances searches



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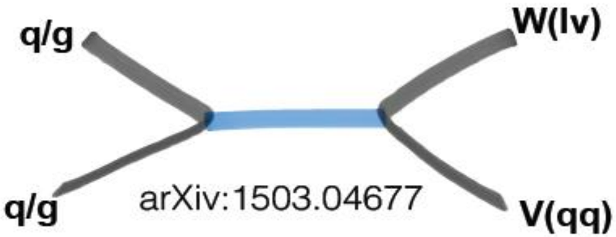
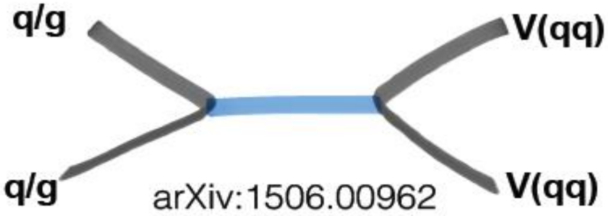


arXiv:1503.04677



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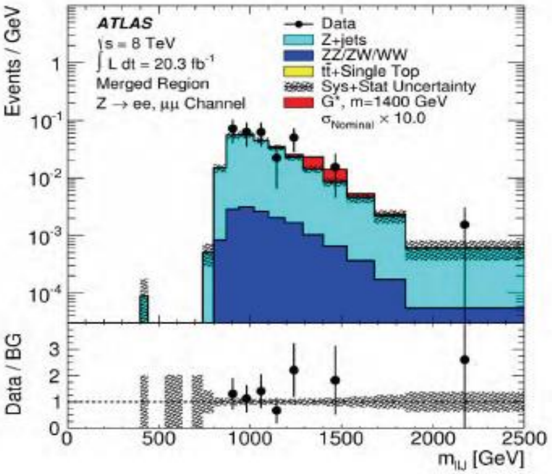

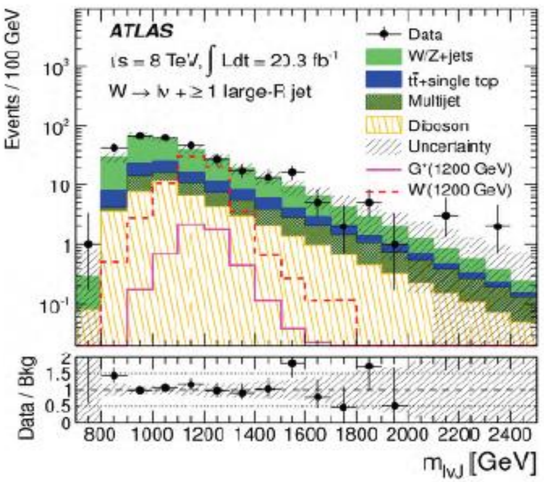

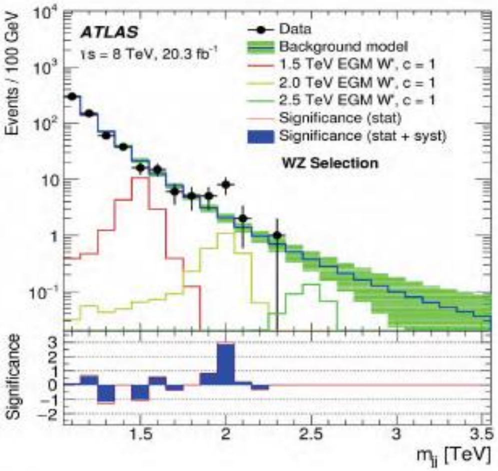

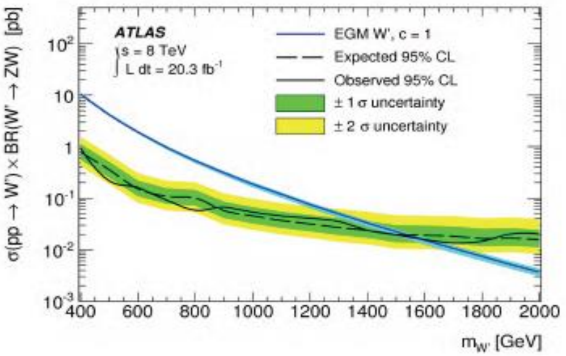

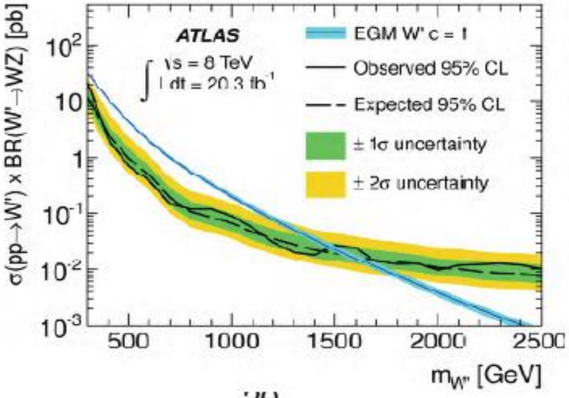

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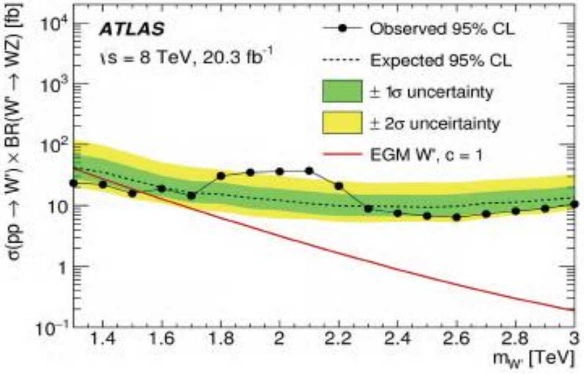
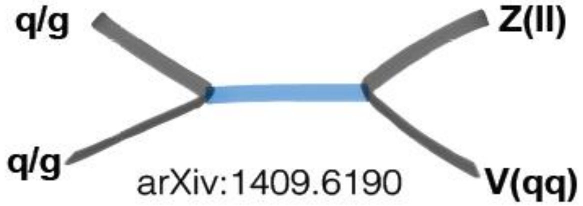
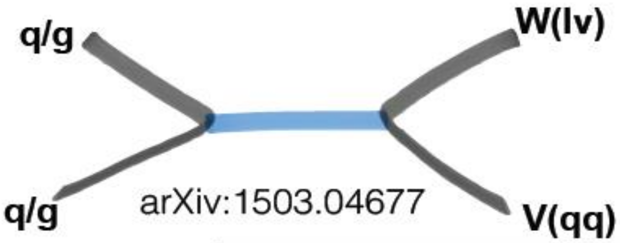


Run I VV resonances searches



arXiv:1409.6190



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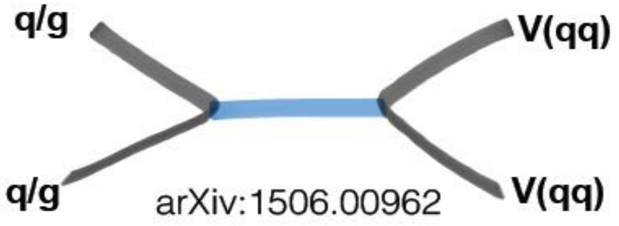

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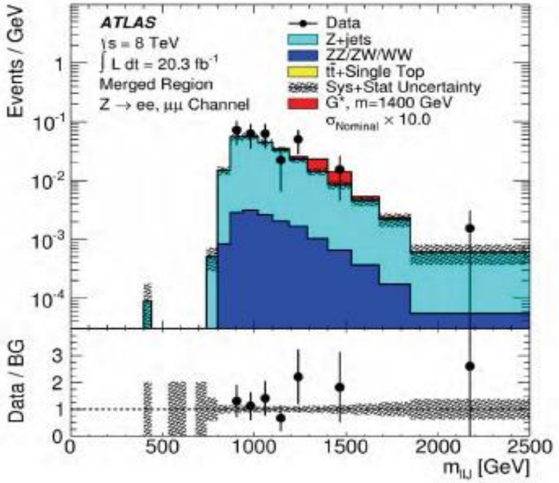
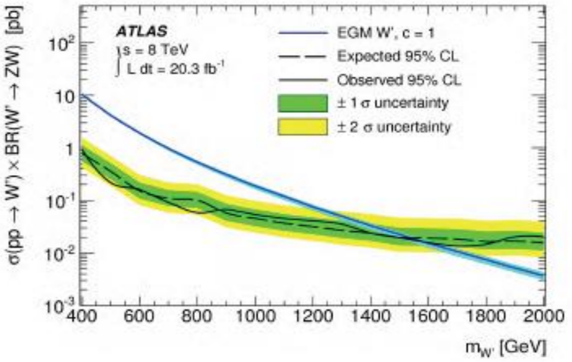
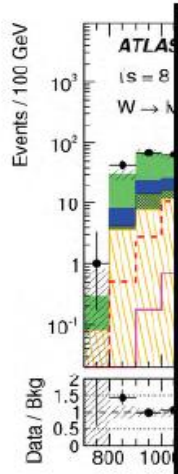
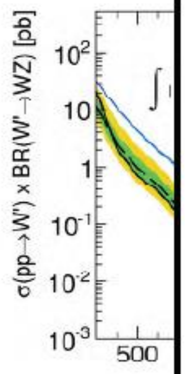
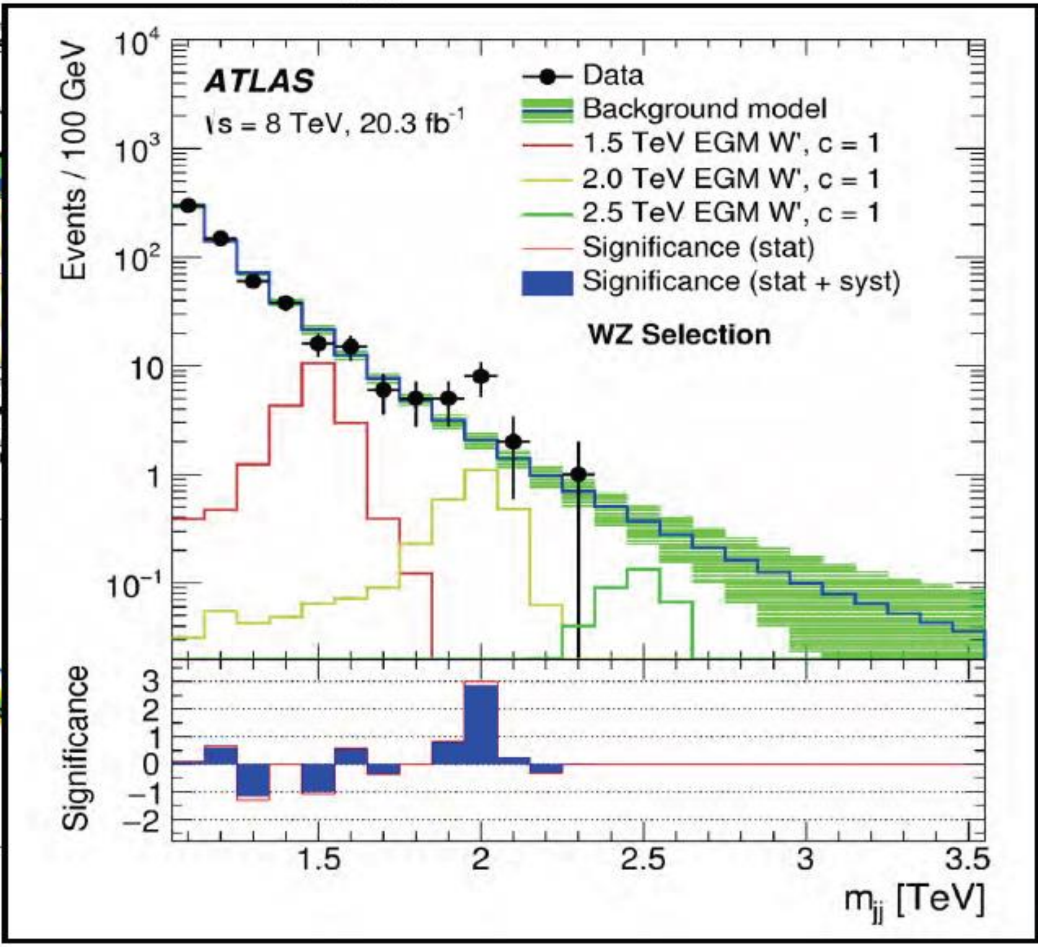


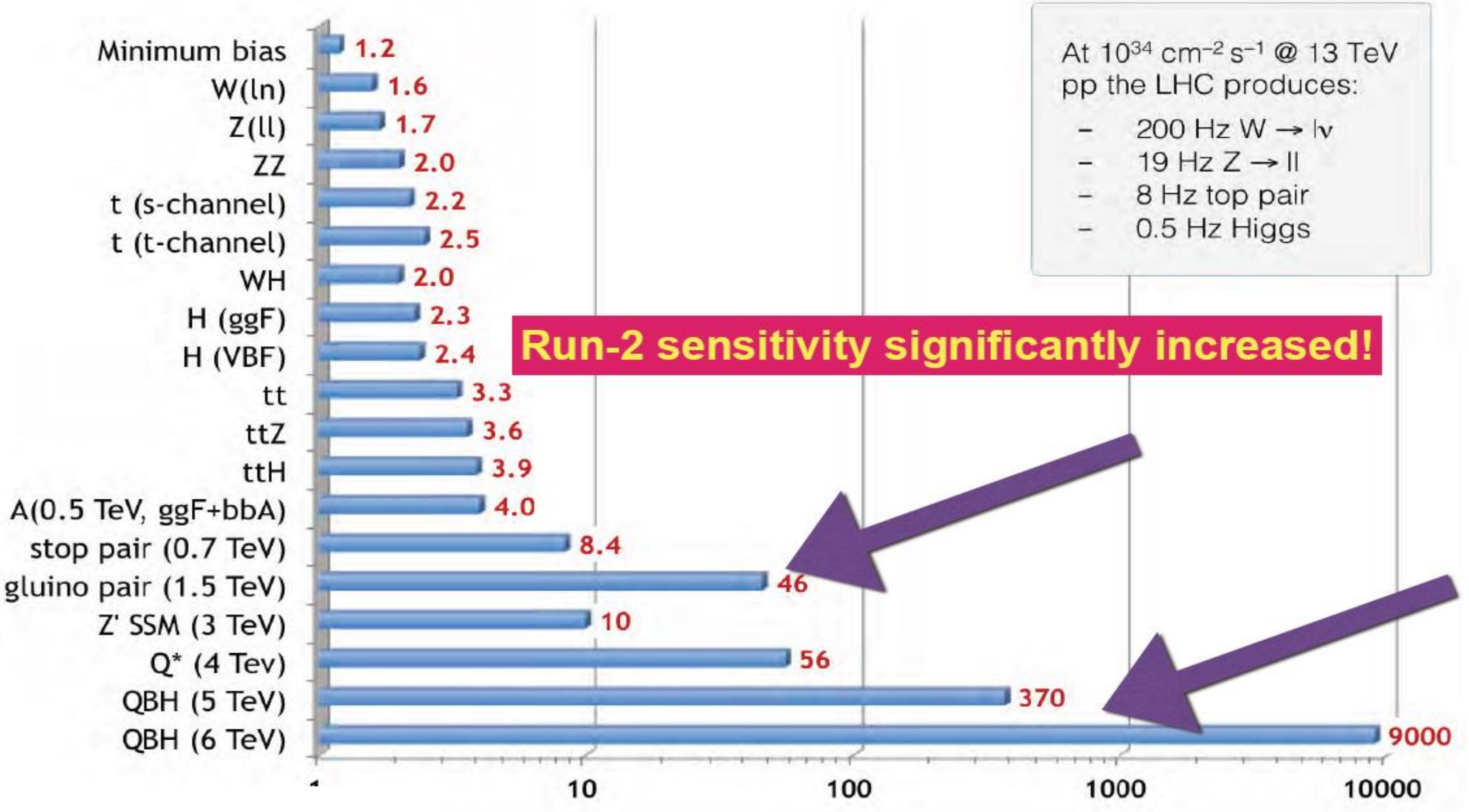








Run-2 prospects



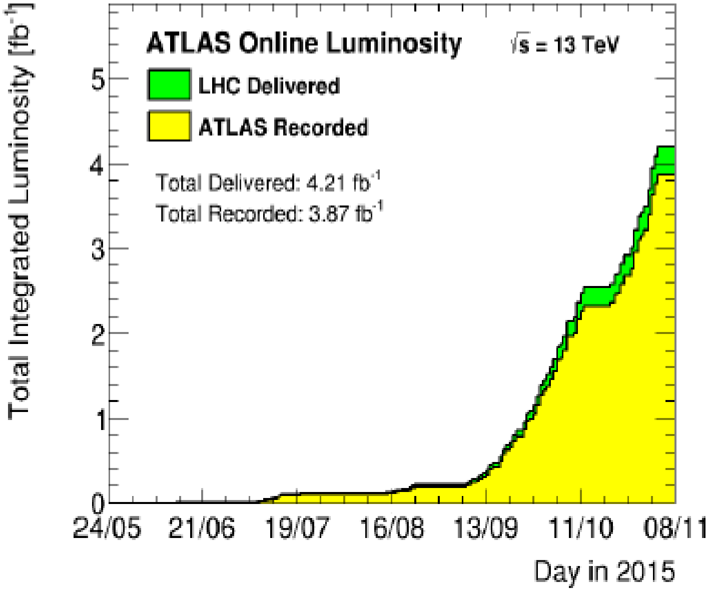
13 TeV / 8 TeV inclusive pp cross-section ratio

At 10^{34} cm^{-2} s^{-1} @ 13 TeV pp the LHC produces:

- 200 Hz W → lν
- 19 Hz Z → ll
- 8 Hz top pair
- 0.5 Hz Higgs

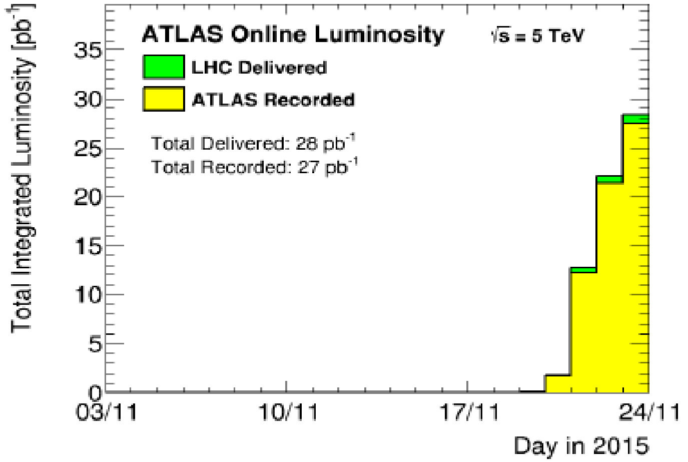
Run-2 sensitivity significantly increased!

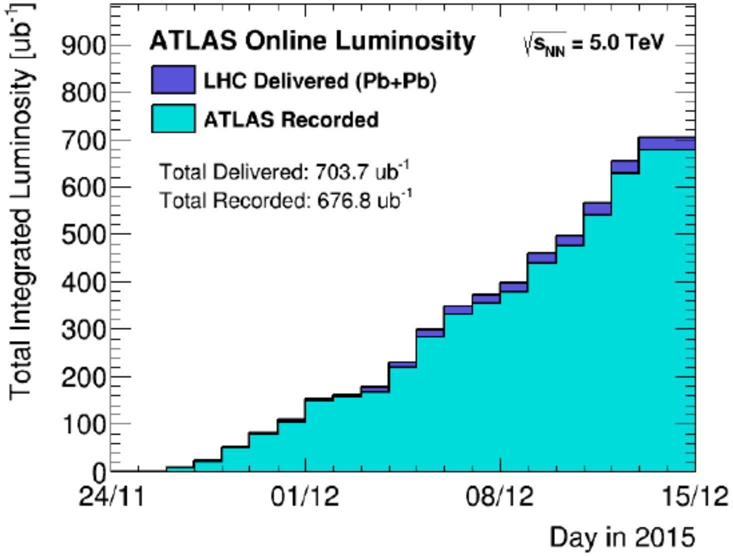
Summarizing 2015 for ATLAS



Heavy-ion data taking completed on Sunday → 0.68 nb^{-1}, compared to expectation of 0.3-0.5 nb^{-1}

ATLAS d.t. efficiency 96% for HI





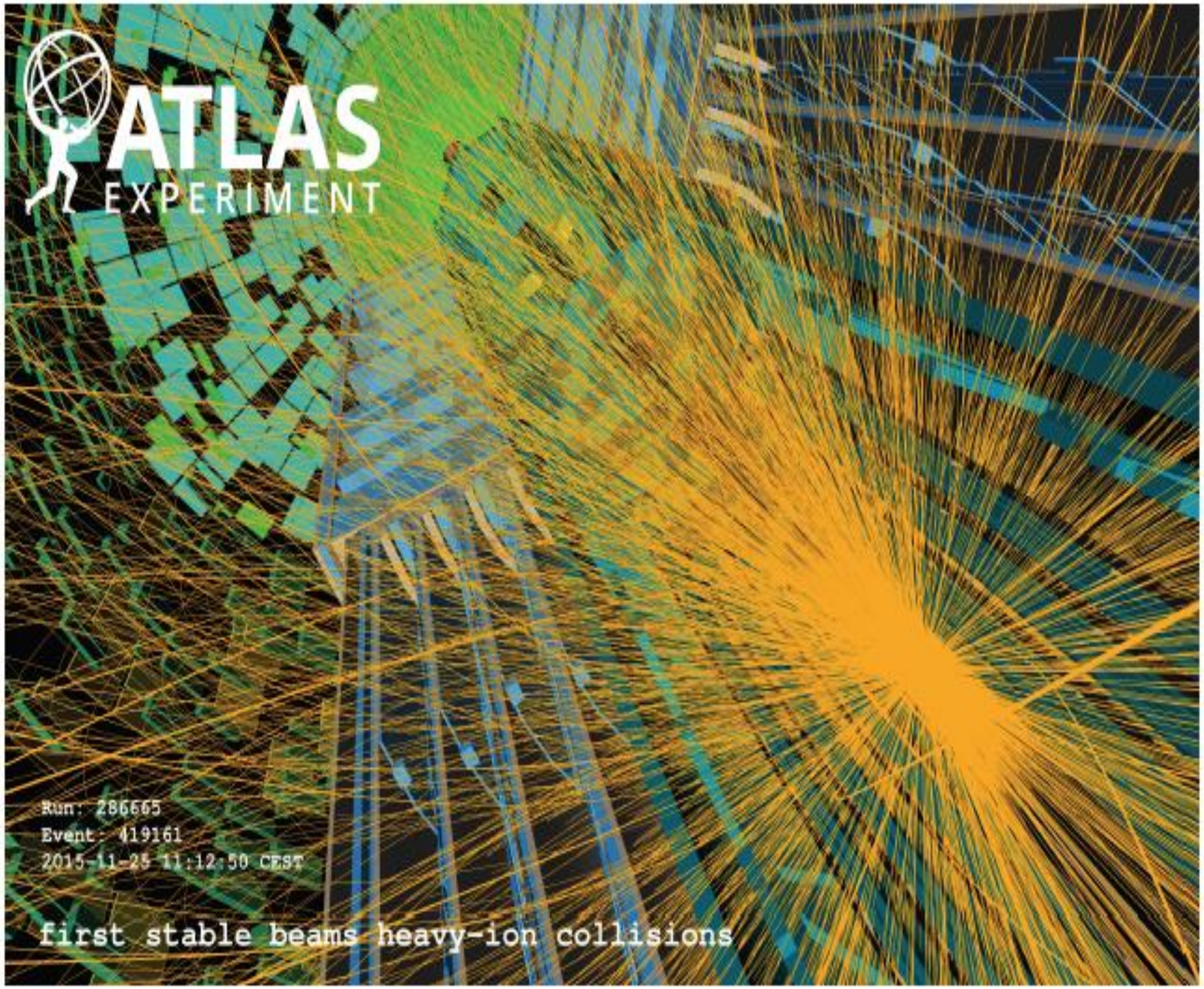
Heavy ion collisions

PbPb

Collision

at **1.1 PeV**

Events with charged track multiplicities of up to 10k tracks



End-of-The-Year (2015) Results

- important to understand background control regions
- but also essential to keep “eyes wide open” for possible signals

Glimpse at the Higgs in the discovery channels

Mass taken to be ATLAS-CMS Combined value ***(PRL 114, 191803)***: $m_H = 125.09 \pm 0.24\ GeV$

ATLAS-CONF-2015-060

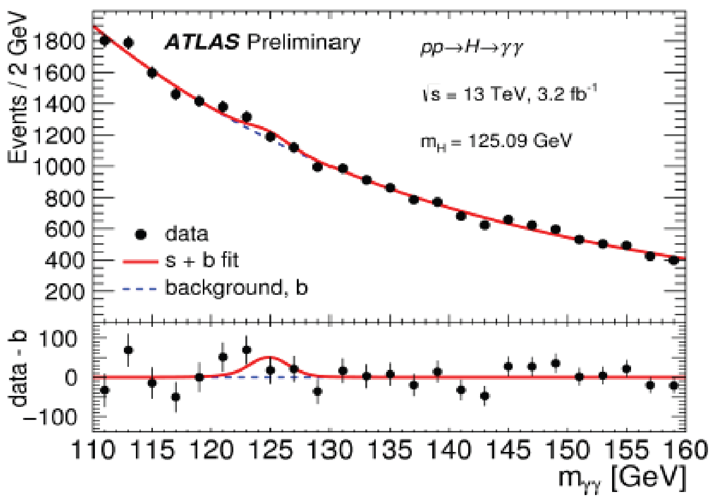
Diphoton Channel

Fully inclusive analysis

- Photon ET thresholds: 0.25 $m_{\gamma\gamma}$ and 0.35 $m_{\gamma\gamma}$
- Track and Calorimeter based isolation criteria
- Simple fit function for background estimate
- **Number of candidate events fitted:**

  113 ± 74 (stat) +43/-25 (syst)

Sensitivity to SM Higgs: **1.9σ** (Observed **1.5σ**)



Four lepton Channel

Fully Inclusive analysis

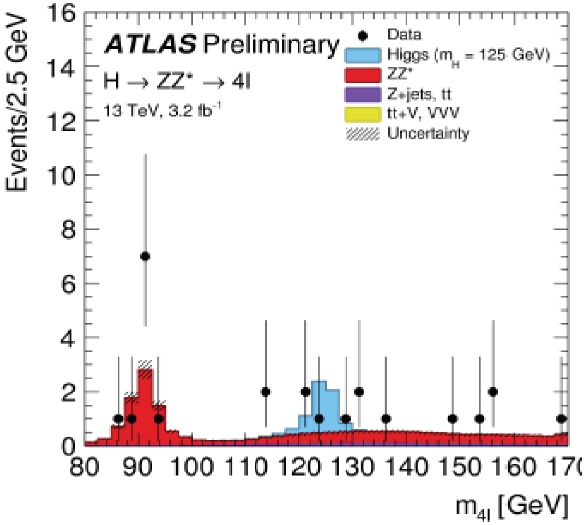
- Electron pT thresholds: 6, 10, 15, 20 GeV
- Muon pT thresholds: 7, 10, 15, 20 GeV
- Irreducible background (ZZ) from MC
- Reducible from CRs (from Isolation and IP)
- **Nb of candidates in [120,130] GeV**: **4**
- **From fit**:

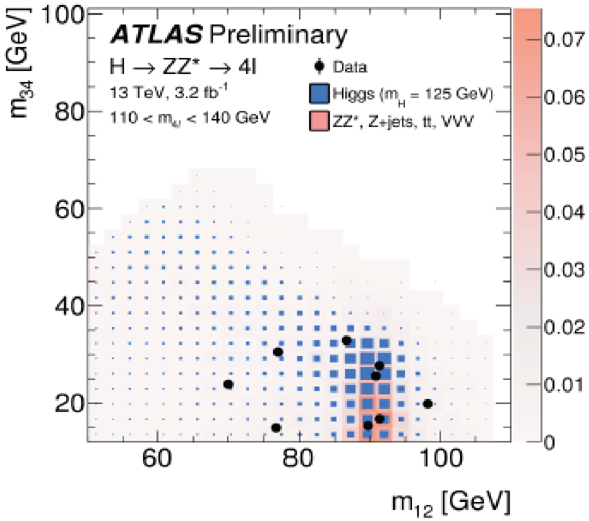
  1.0 +2.3/-1.5

Sensitivity to SM Higgs: **2.8σ**

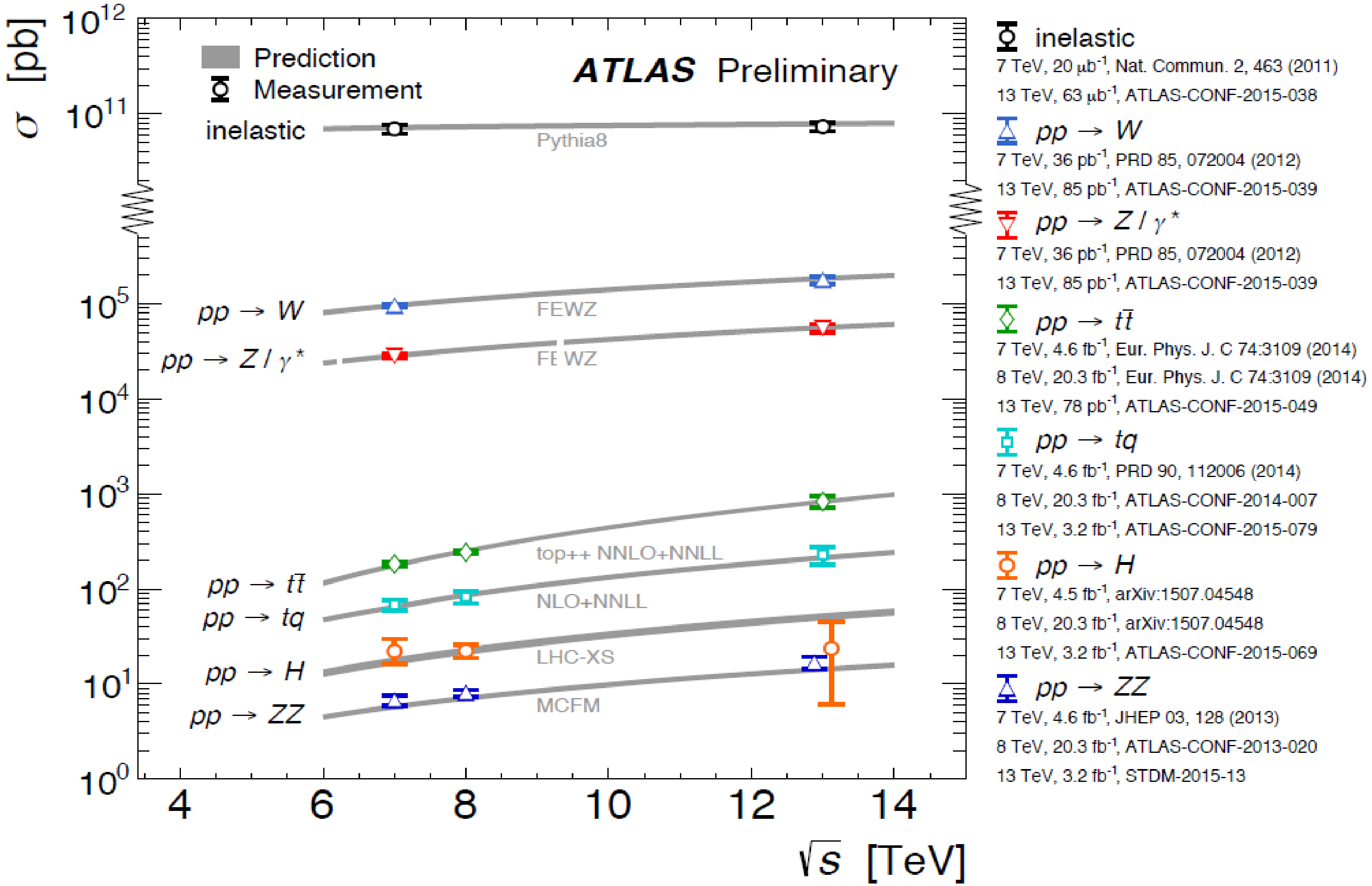
(Observed **0.7σ**)

ATLAS-CONF-2015-059





Summary of total cross-section measurements



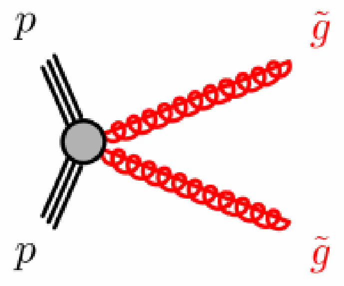
Early searches for SUSY

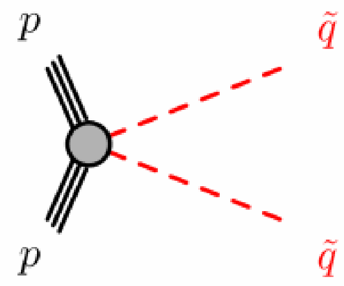
At this early stage of the Run-2 main focus of SUSY searches:
Strong production of Guinos and (to lesser extent) Squarks

Ratio of 13 TeV / 8 TeV Cross sections:

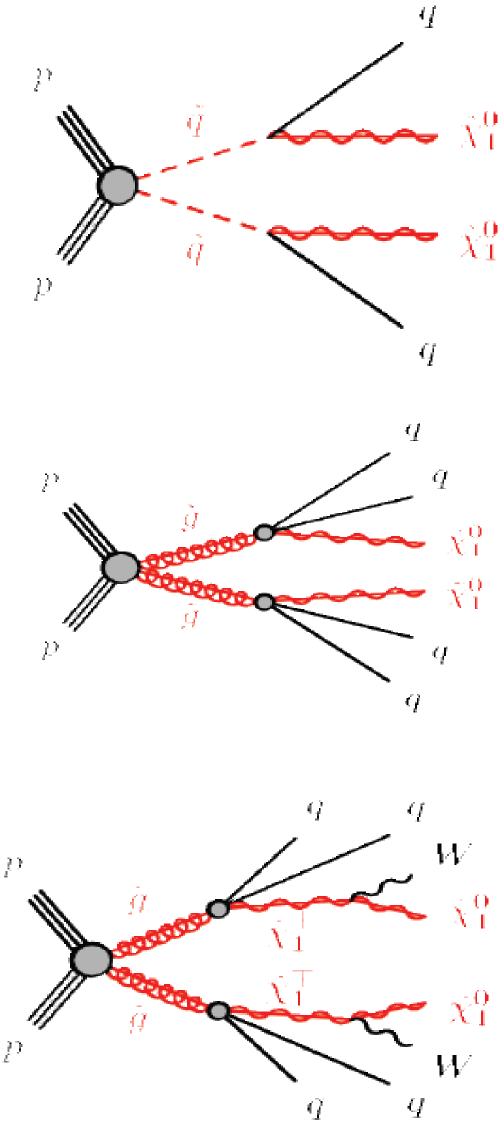
- Squarks and Gluinos 1.5 TeV: **35**
- Squarks and Gluinos 1 TeV: **15**

44 Signal regions to cover large number of decay chains (Jets, MET, Leptons, b-Jets)



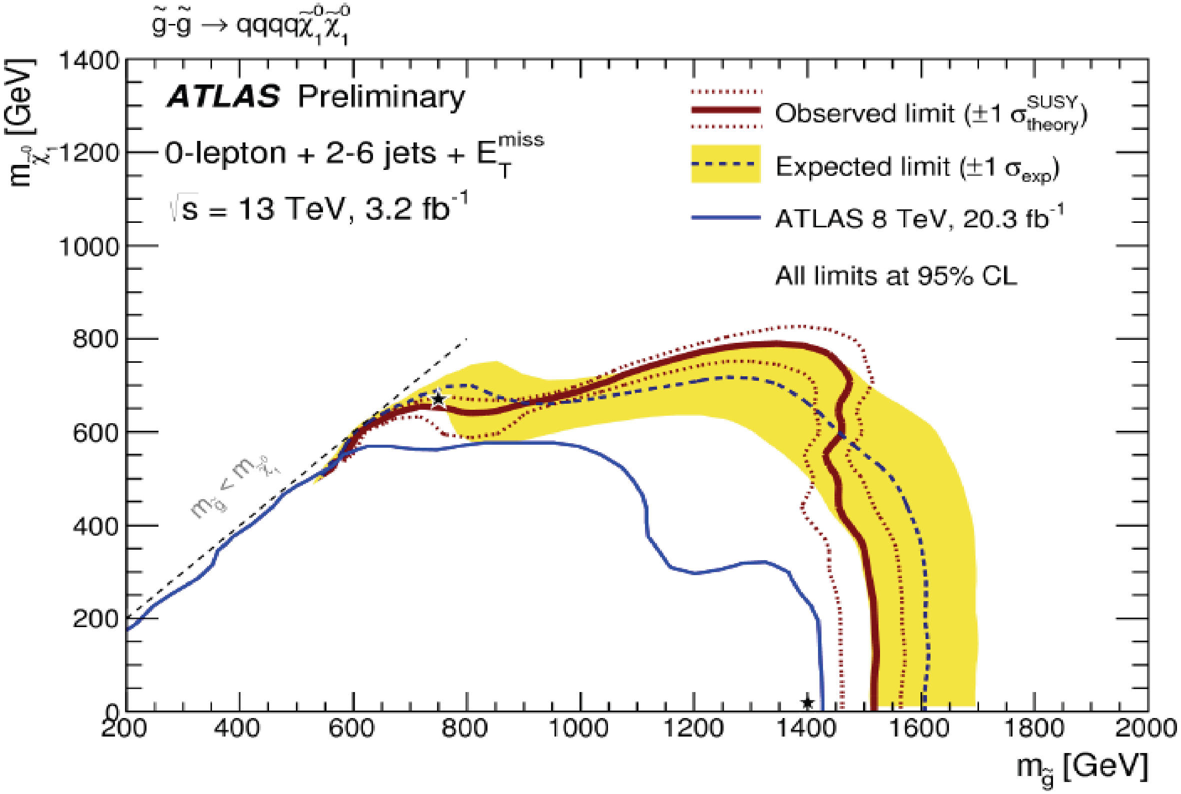


Strongly produced SUSY particles



2-6 Jets-MET Signatures

ATLAS-CONF-2015-062

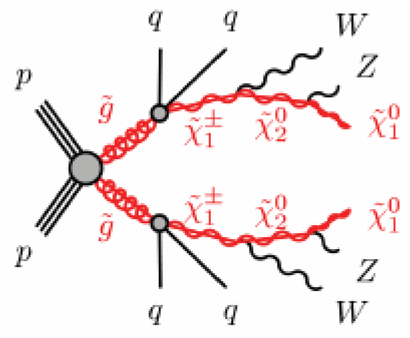


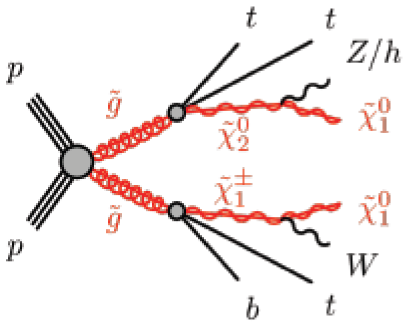
Limits on gluino mass reach 1.5 TeV

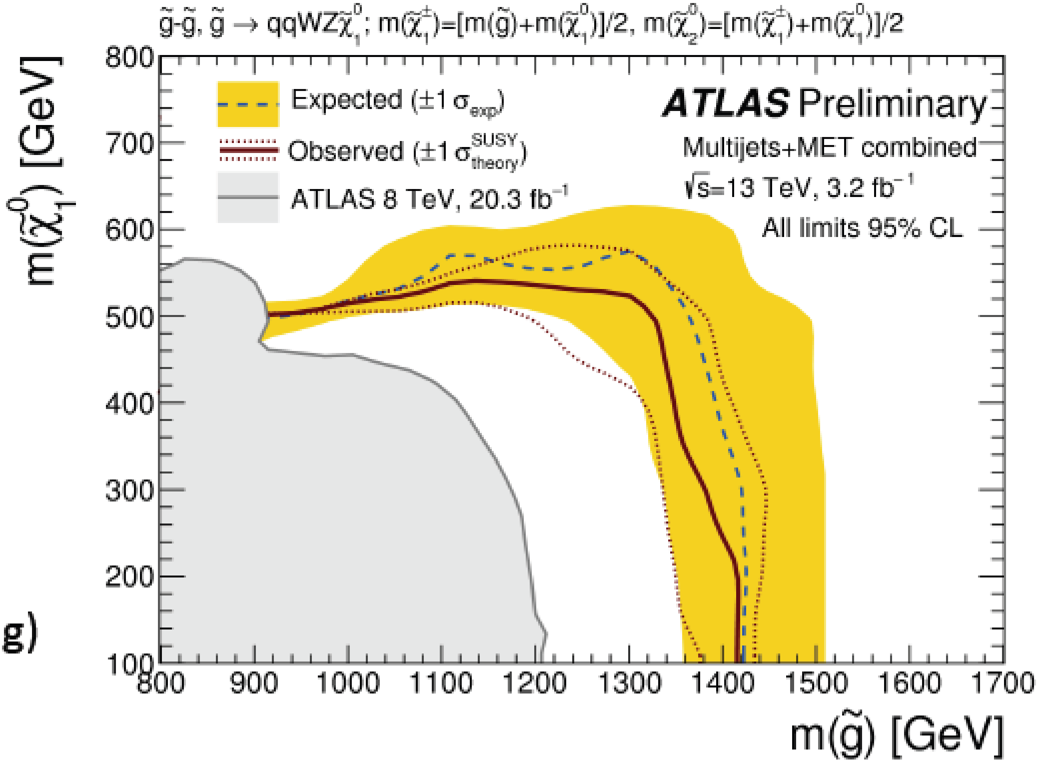
Strongly produced SUSY particles

7-10 Jets-MET Signatures

ATLAS-CONF-2015-077



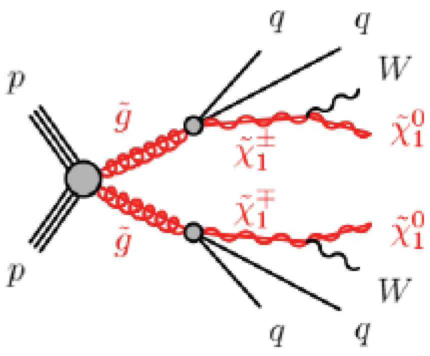




ıg)

Limits on Gluino mass reach 1.4 TeV

Strongly produced SUSY particles

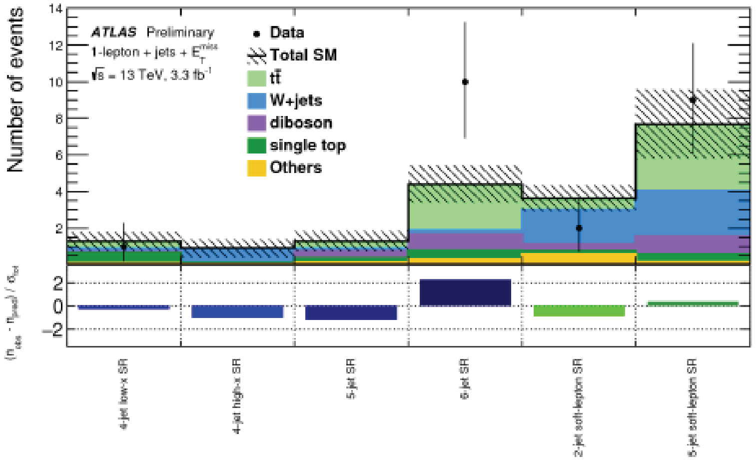


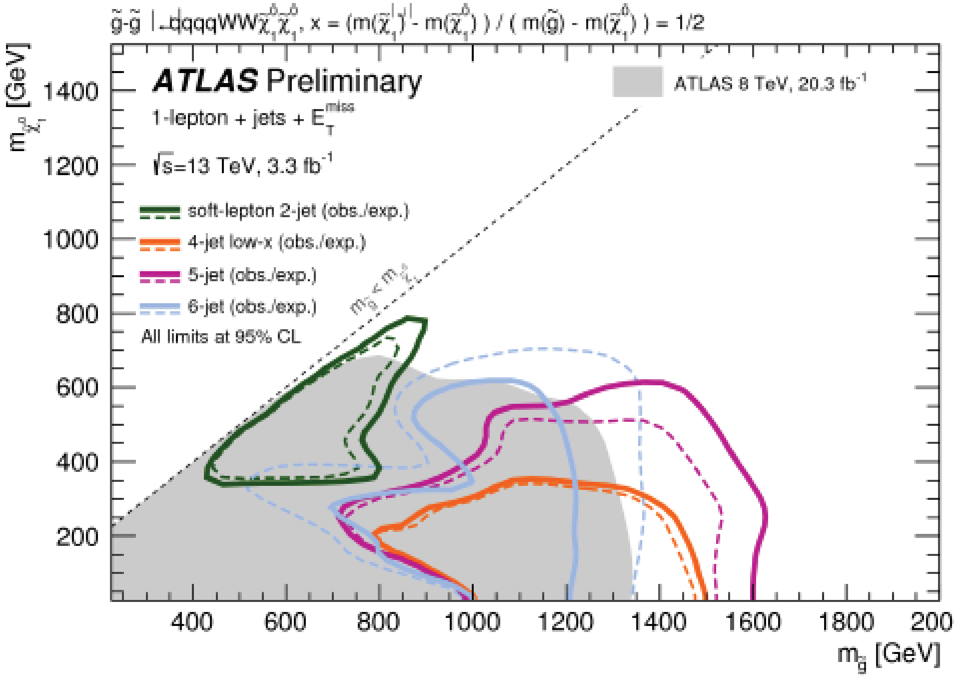
1 Lepton-Jets and MET Signatures

ATLAS-CONF-2015-076

s

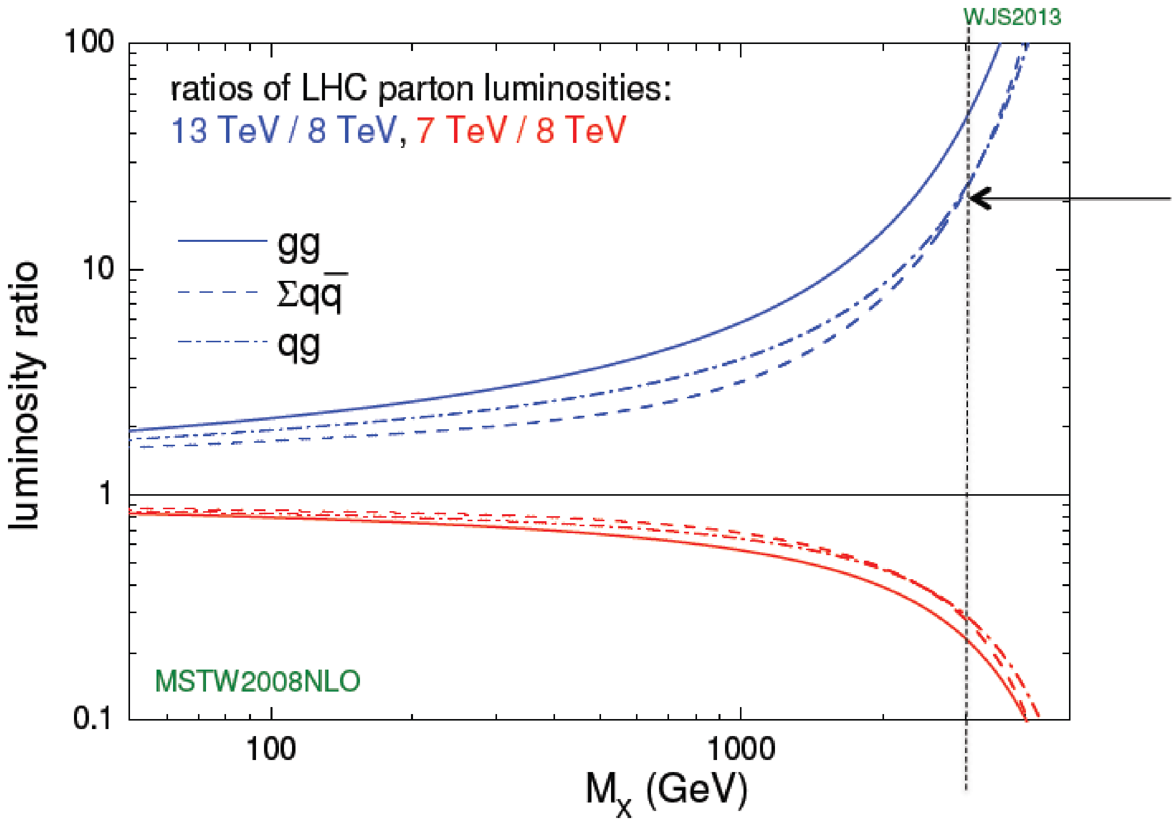
No significant excess found





Gluino exclusion up to 1.6 TeV

Early searches for New Phenomena



Ratio of 13 TeV / 8 TeV

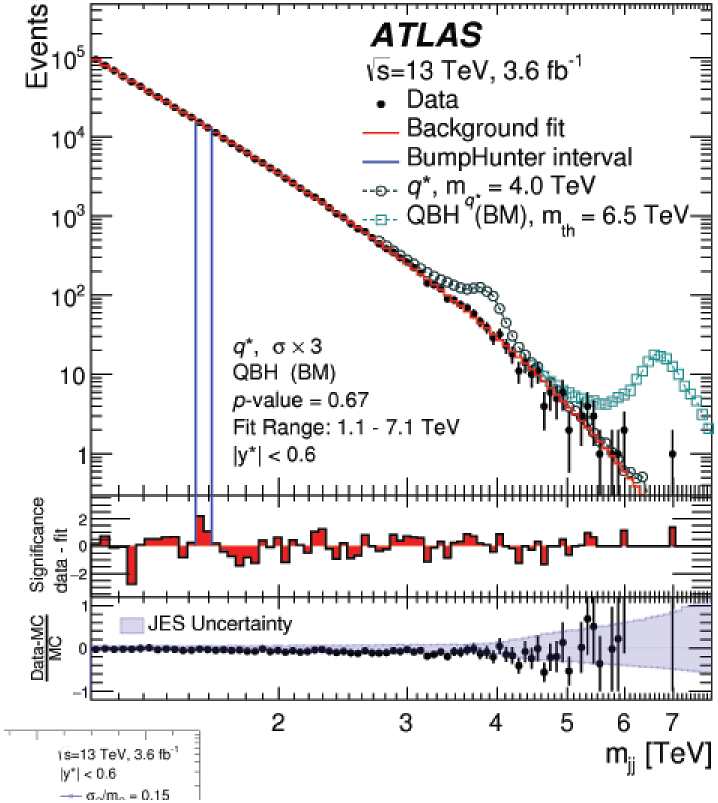
Cross sections:

-	Z’ at 3 TeV:	**20**
-	q* at 4 TeV:	**56**
-	QBH at 5 TeV:	**370**
-	QBH at 6 TeV:	**9000**

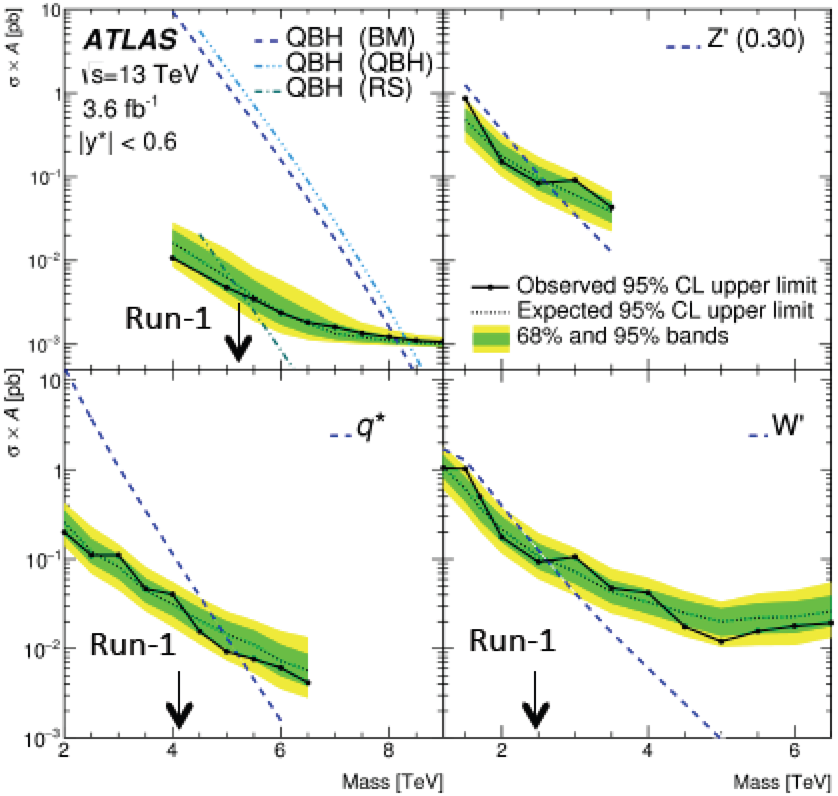
Dijet Resonant Searches

1512.01530

- Sensitive to Quantum Black Holes, Excited quarks, W’, Z’

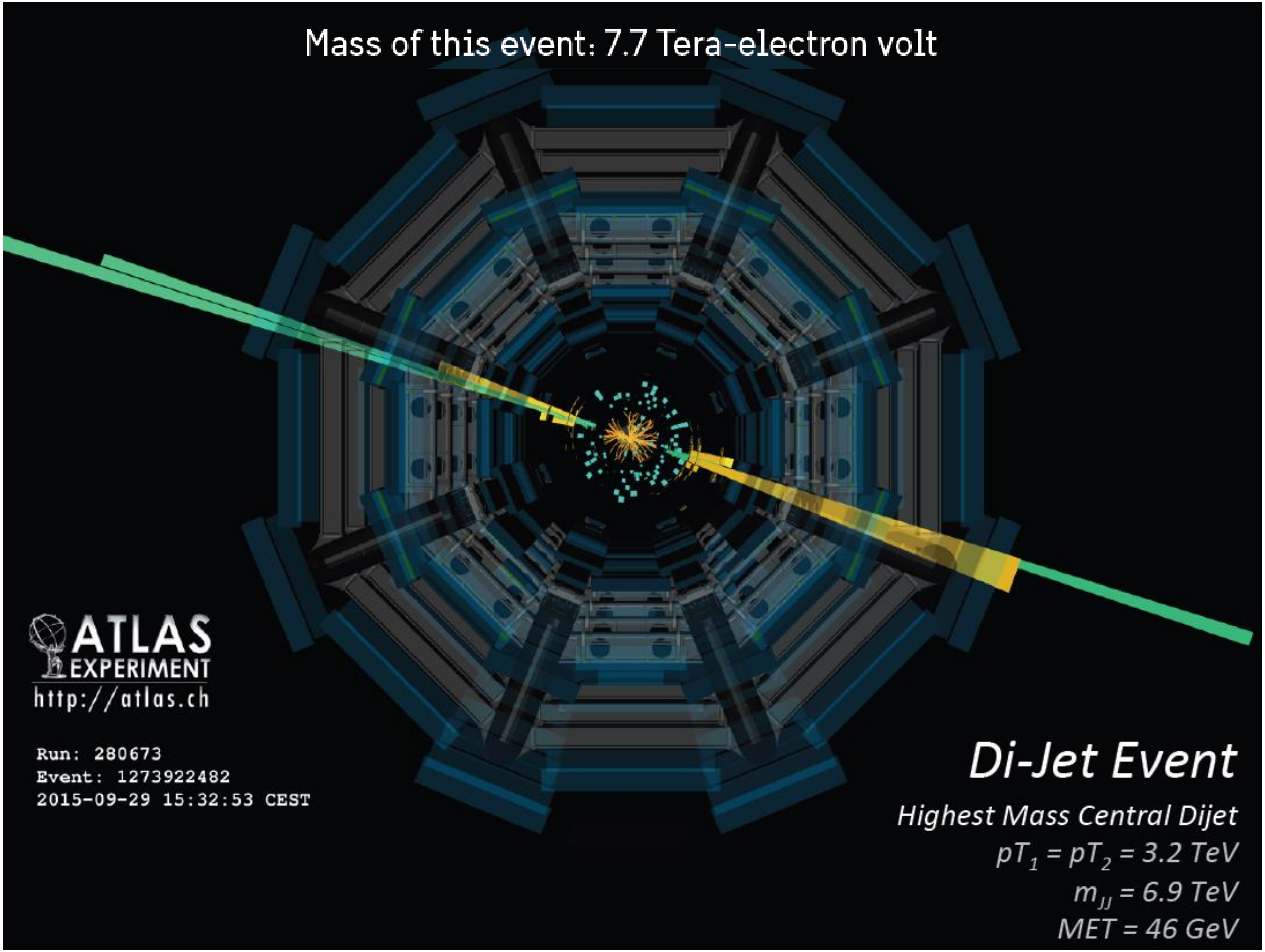


No significant excess found



Limits on QBH reaching 8 TeV

Mass of this event: 7.7 Tera-electron volt



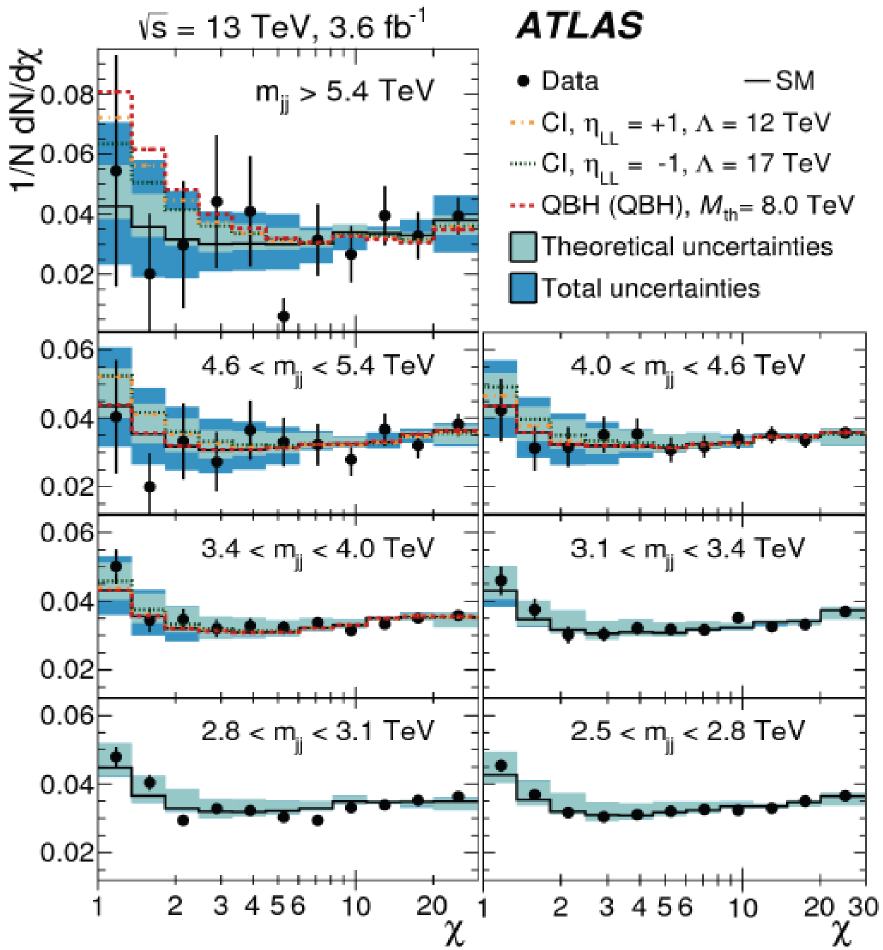
Dijet Angular Searches

Search in dijet mass bins using angular distribution

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

1512.01530

Search for distortions of the dijet angular distribution from Contact Interactions of particles at much higher masses O(Λ) with color-singlet left-handed chiral couplings (in 4-fermion effective field theory)



No deviations observed, limits set at 12 TeV on Λ (for $\eta_{LL} = 1$)

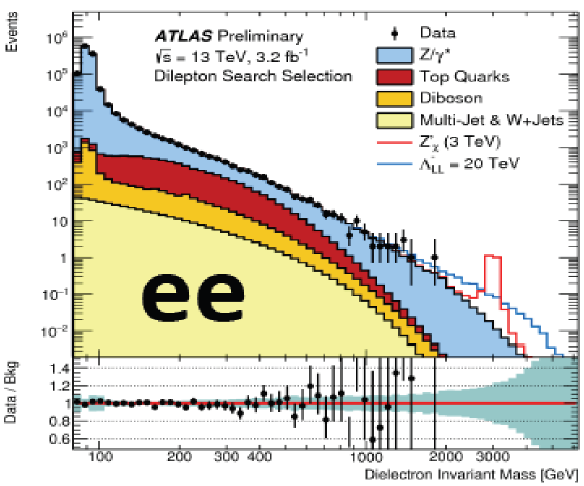
Dilepton Resonances (LFC and LFV)

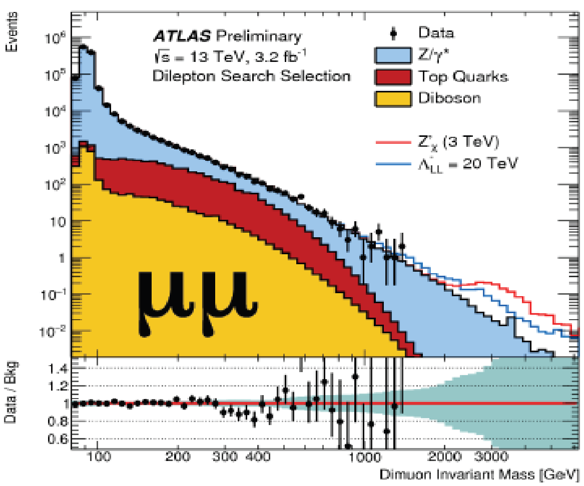
Search for Z’ in dilepton (LFC) and (LFV) *(in eμ decays)*

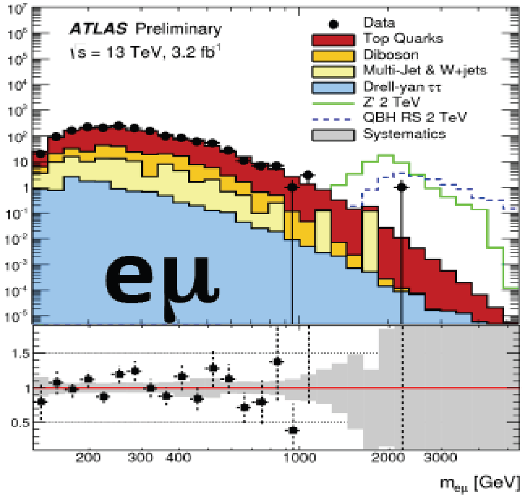
[ATLAS-CONF-2015-070](#)

[ATLAS-CONF-2015-072](#)

- Main background DY is taken from MC
- Top and diboson extrapolated at very high masses using a functional form
- Background from MC except for MJ in dielectron uses Matrix method (based on electron ID)







Highest di-electron mass event at 1.8 TeV

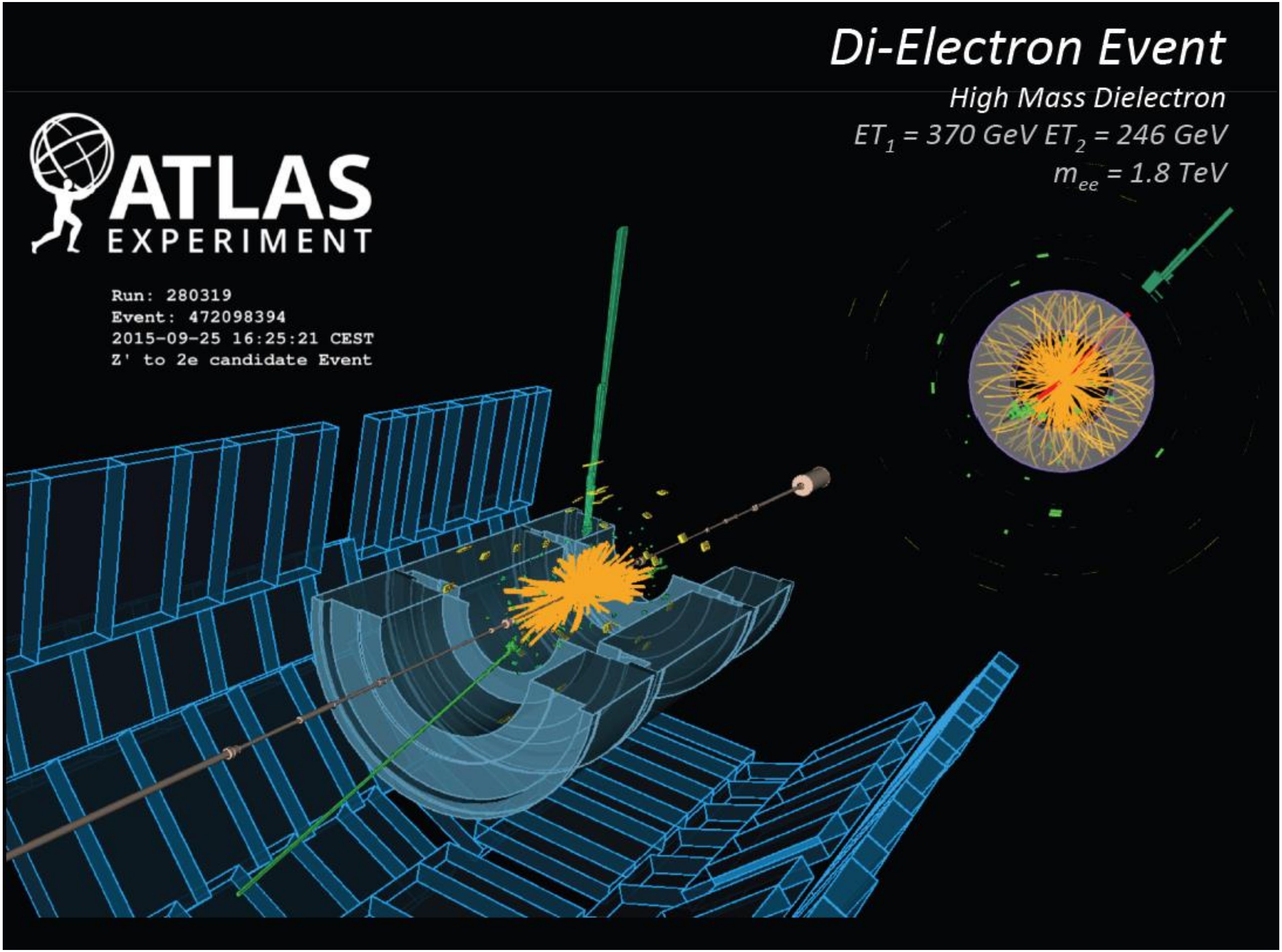
Highest di-muon mass event at 1.4 TeV

Highest eμ mass event at 2.1 TeV

No Excess found !

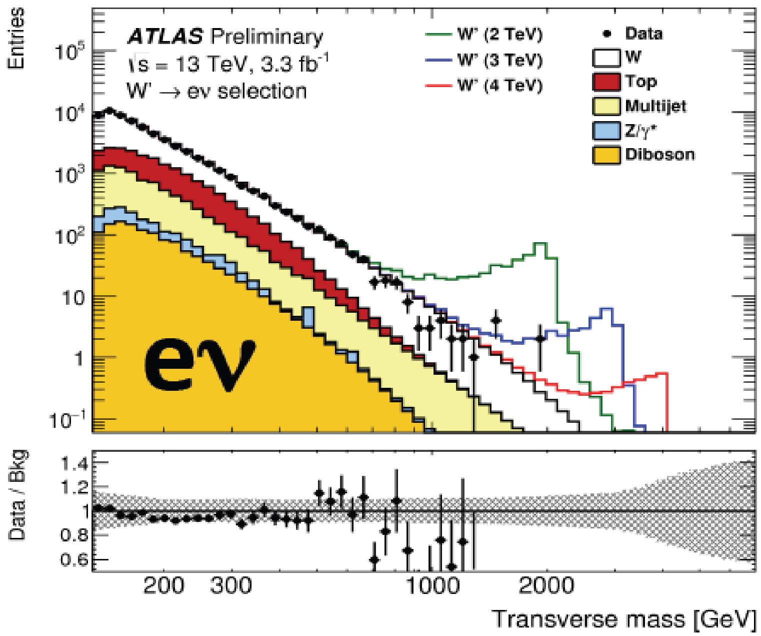
95% CL Limit on SSM Z’ at 3.4 TeV (2.9 TeV from Run-1)

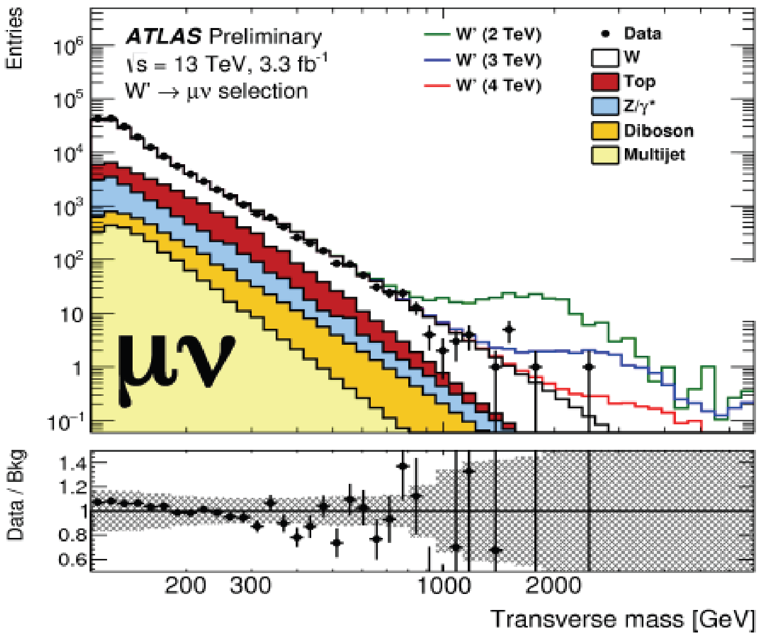
95% CL Limit on SSM LFV Z’ at 3.0 TeV (2.5 TeV from Run-1)


Di-Electron Event
High Mass Dielectron
ET_1 = 370 GeV ET_2 = 246 GeV
m_{ee} = 1.8 TeV
ATLAS
EXPERIMENT
Run: 280319
Event: 472098394
2015-09-25 16:25:21 CEST
Z' to 2e candidate Event

Search for Resonant Lepton-MET

- Search for W’ in lepton-MET final states ATLAS-CONF-2015-063





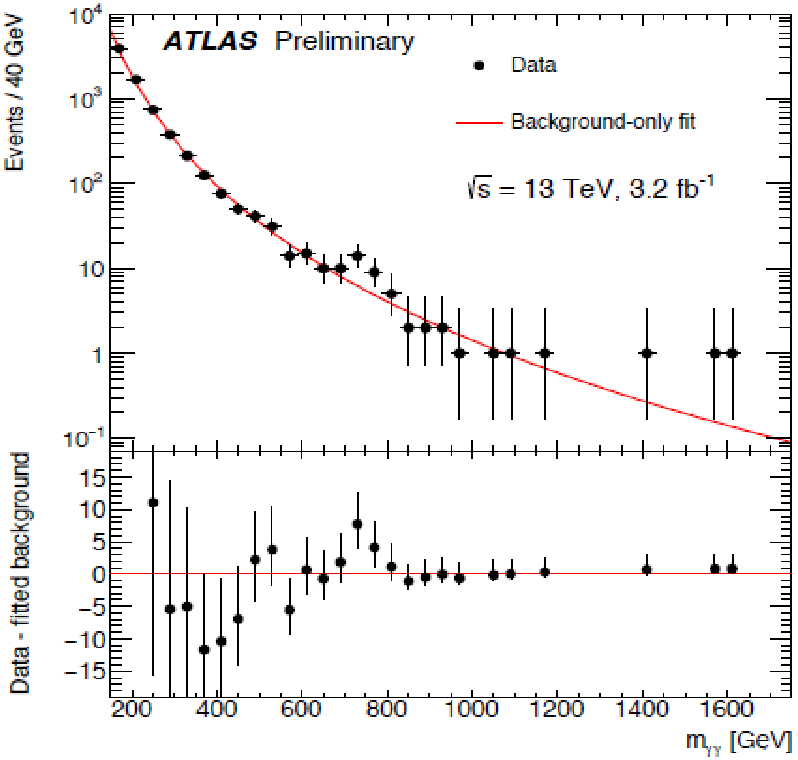
Highest electron-MET mass event at 1.95 TeV

Highest muon-MET mass event at 2.2 TeV

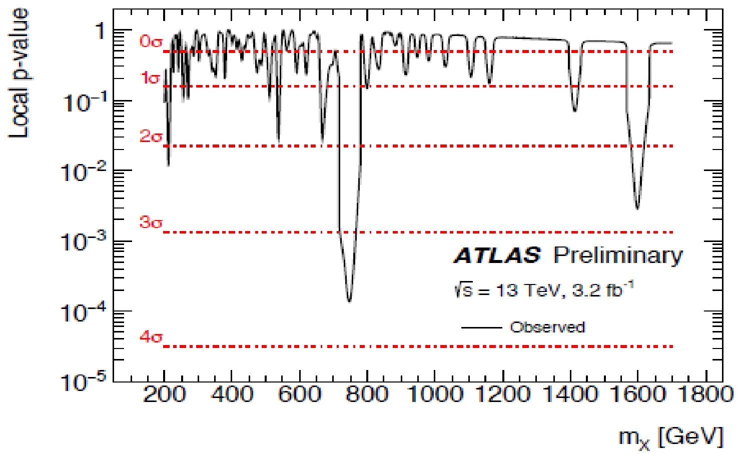
No Excess found !

95%CL Limit on SSM W’ at 4.1 TeV (3.2 TeV at Run-1)

Search for Two Photons Resonance



ATLAS-CONF-2015-081



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV

- Taking a LEE in a mass range (fixed before unblinding) **of 200 GeV to 2.0 TeV** the global significance of the excess is **2.0σ**

In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV (Approx. 6% of the best fit mass of approximately 750 GeV)

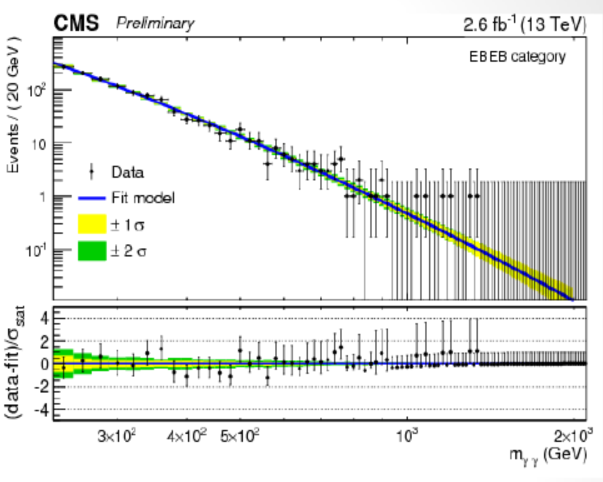
- As expected the local significance increases to **3.9σ**

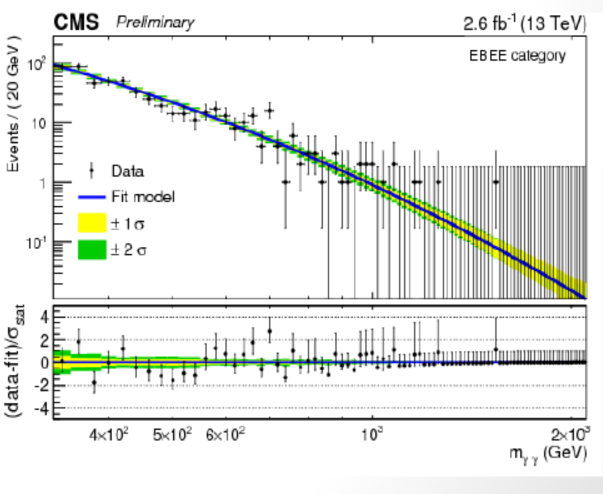
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

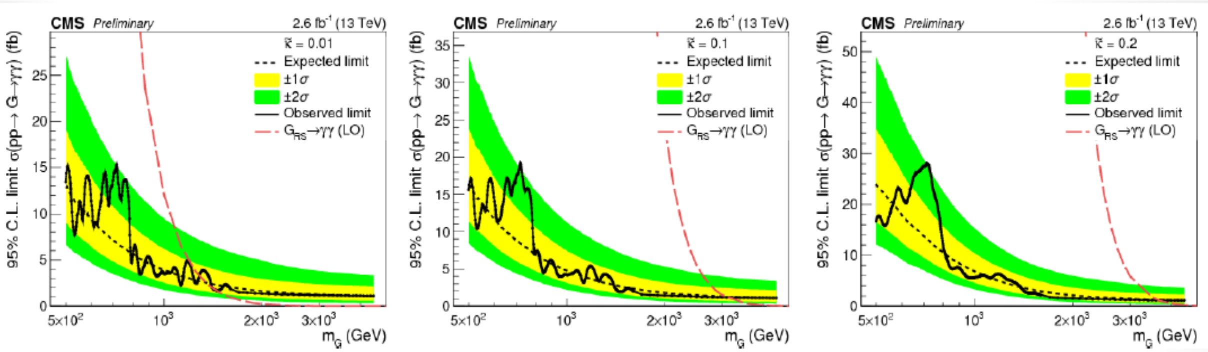
Search for Two Photons Resonance

And what about CMS?

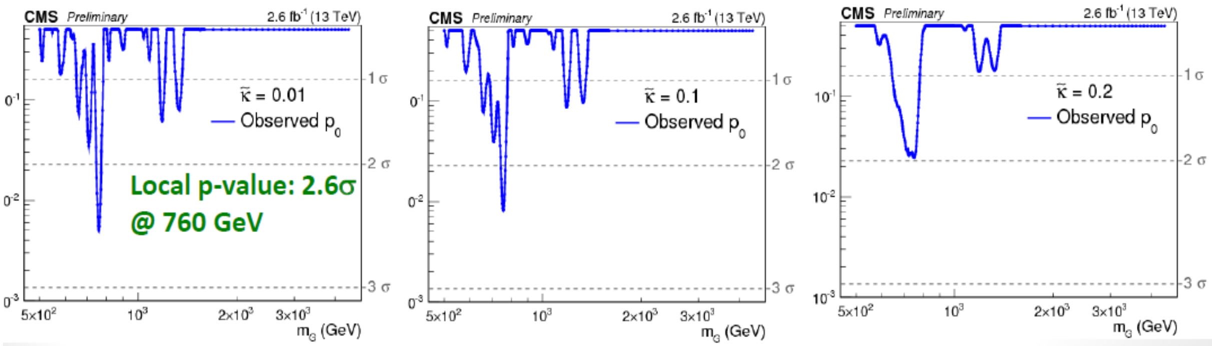
EXO-15-004







Narrow Width → **Wide (6%) Width**



Local p-value: 2.6σ @ 760 GeV

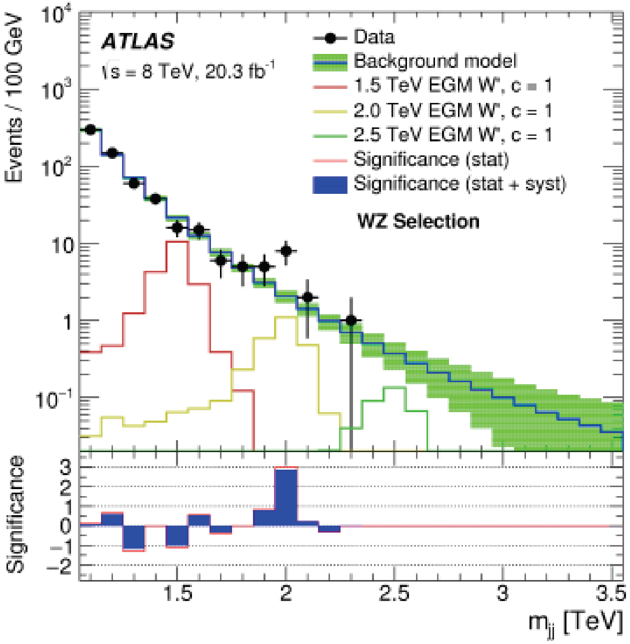
Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ

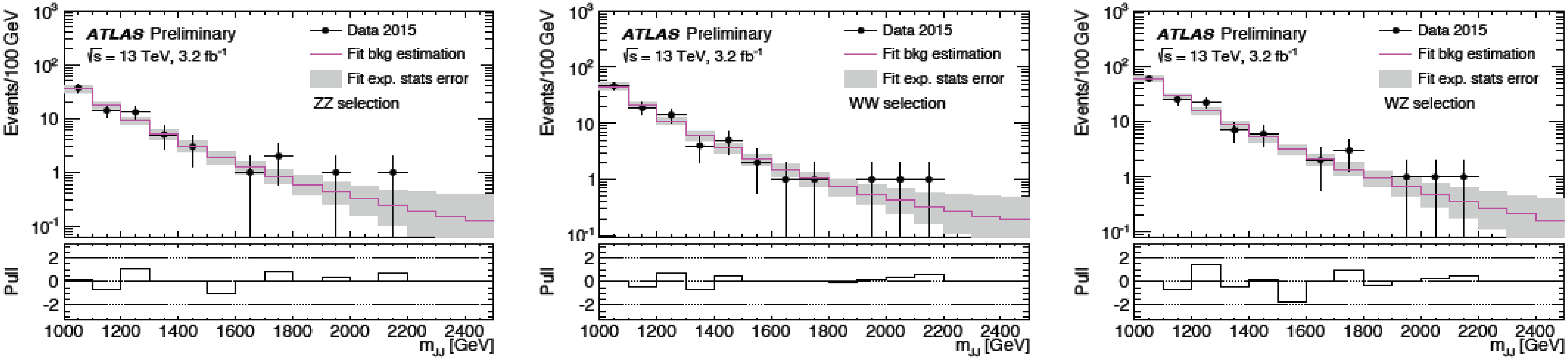
Fully hadronic JJ Diboson Searches

ATLAS-CONF-2015-073

Run-1

- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed** however sensitivity not high enough for conclusive probe of the Run 1 excess





Summary (from ATLAS Collaboration)

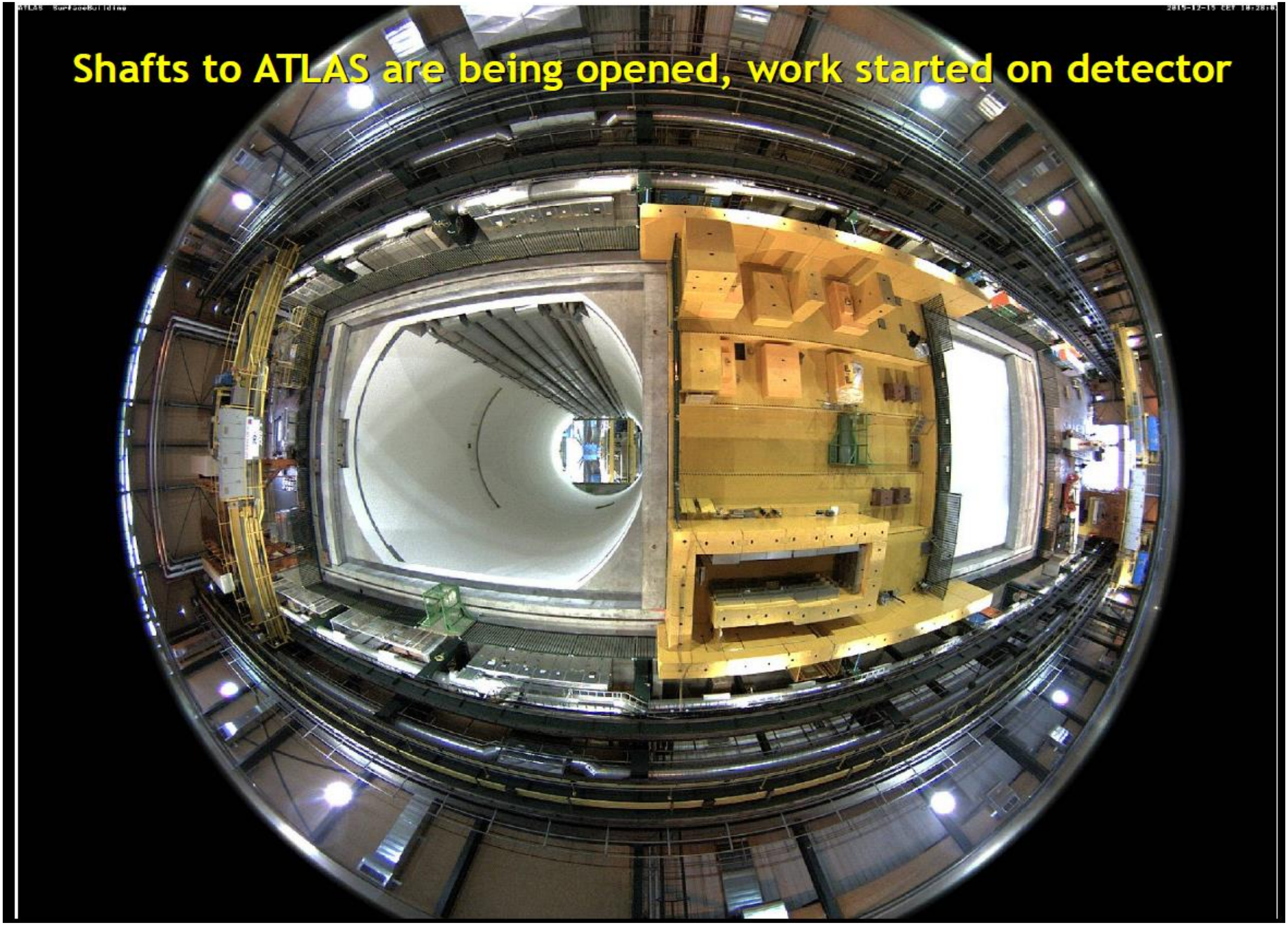
- The ATLAS Collaboration has released a host of new results with the full 2015 13 TeV dataset, *in **24 Conference Notes** and **4 Journal Papers***

  (Available at the following location: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV)

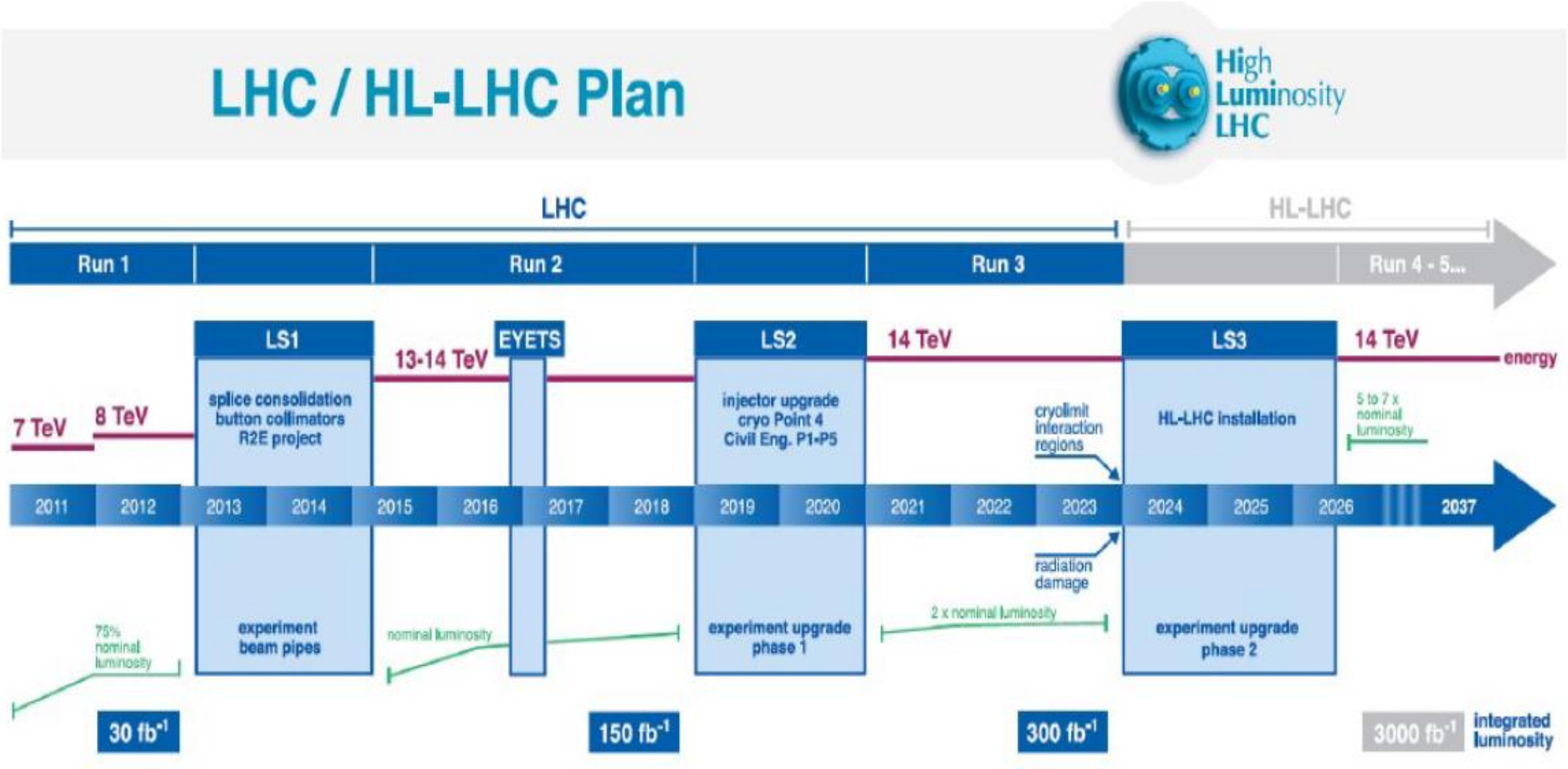
  - New measurements of single top and diboson cross sections
  - First look at H(125 GeV) production
  - Many searches for new physics with sensitivity exceeding the Run 1 reach, investigating a vast number of topologies and event characteristics
  - Modest excesses begging for more data

- Eagerly awaiting a much larger haul of data in 2016!

Shafts to ATLAS are being opened, work started on detector

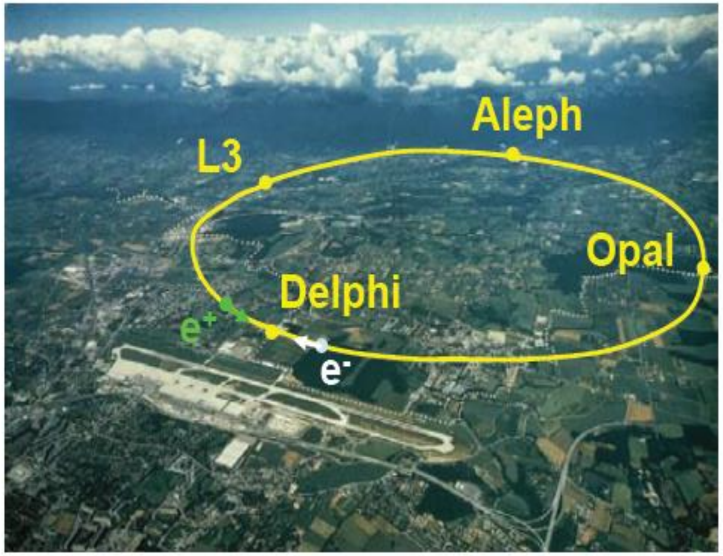


LHC Schedule



Electroweak measurements at LEP

★The **Large Electron Positron** (LEP) Collider at CERN **(1989-2000)** was designed to make precise measurements of the properties of the Z and W bosons.



- 26 km circumference accelerator straddling French/Swiss boarder
- Electrons and positrons collided at 4 interaction points
- 4 large detector collaborations (each with 300-400 physicists):
  - **ALEPH,**
  - **DELPHI,**
  - **L3,**
  - **OPAL**

Basically a large Z and W factory:

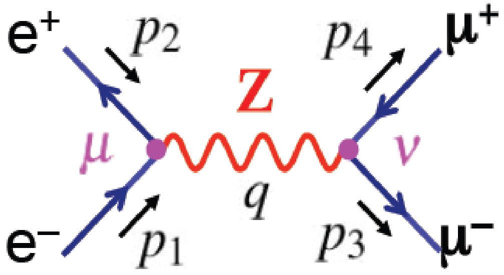
- ★ **1989-1995:** Electron-Positron collisions at $\sqrt{s}$ = **91.2 GeV**
  - 17 Million Z bosons detected
- ★ **1996-2000:** Electron-Positron collisions at $\sqrt{s}$ = **161-208 GeV**
  - 30000 W^+W^- events detected

from M. A. Thomson lectures at Cambridge University in 2011

The Z resonance

★ Want to calculate the cross-section for $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$

- Feynman rules for the diagram below give:



e⁺e⁻ vertex: $\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \frac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)$

Z propagator: $\dfrac{-ig_{\mu\nu}}{q^2 - m_Z^2}$

μ⁺μ⁻ vertex: $\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \frac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)$

➡
$$-iM_{fi} = [\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].\frac{-ig_{\mu\nu}}{q^2 - m_Z^2}.[\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]$$

➡
$$\boxed{M_{fi} = -\frac{g_Z^2}{q^2 - m_Z^2} g_{\mu\nu}[\overline{v}(p_2)\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].[\overline{u}(p_3)\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]}$$

★ Convenient to work in terms of helicity states by explicitly using the Z coupling to **LH** and **RH** chiral states (ultra-relativistic limit so helicity = chirality)

$$\tfrac{1}{2}(c_V - c_A\gamma^5) = c_L\tfrac{1}{2}(1-\gamma^5) + c_R\tfrac{1}{2}(1+\gamma^5)$$

LH and RH projections operators

from M. A. Thomson lectures at Cambridge University in 2011

The unpolarised cross-section

- Hence the complete expression for the unpolarized differential cross section is:

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{1}{64\pi^2 s}\langle|M_{fi}|^2\rangle \\ &= \frac{1}{64\pi^2}\cdot\frac{1}{4}\cdot\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\times \\ &\quad \left\{\tfrac{1}{4}[(c_V^e)^2+(c_A^e)^2][(c_V^\mu)^2+(c_A^\mu)^2](1+\cos^2\theta)+2c_V^e c_A^e c_V^\mu c_A^\mu\cos\theta\right\}\end{aligned}$$

- Integrating over solid angle $d\Omega = d\phi\, d(\cos\theta) = 2\pi\, d(\cos\theta)$

$\int_{-1}^{+1}(1+\cos^2\theta)d(\cos\theta) = \int_{-1}^{+1}(1+x^2)dx = \frac{8}{3}$ and $\int_{-1}^{+1}\cos\theta\, d(\cos\theta) = 0$

$$\boxed{\sigma_{e^+e^-\to Z\to\mu^+\mu^-} = \frac{1}{192\pi}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\left[(c_V^e)^2+(c_A^e)^2\right]\left[(c_V^\mu)^2+(c_A^\mu)^2\right]}$$

- Note: the total cross section is proportional to the sums of the squares of the vector- and axial-vector couplings of the initial and final state fermions

$$(c_V^f)^2+(c_A^f)^2$$

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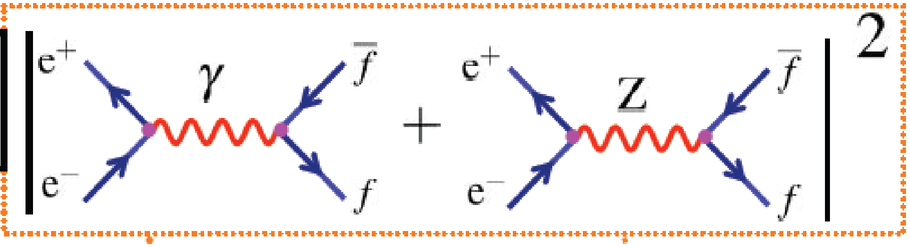
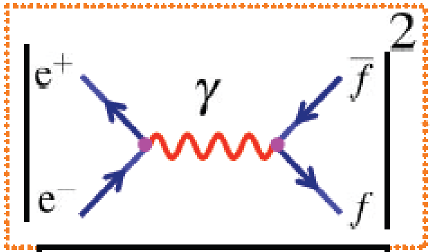
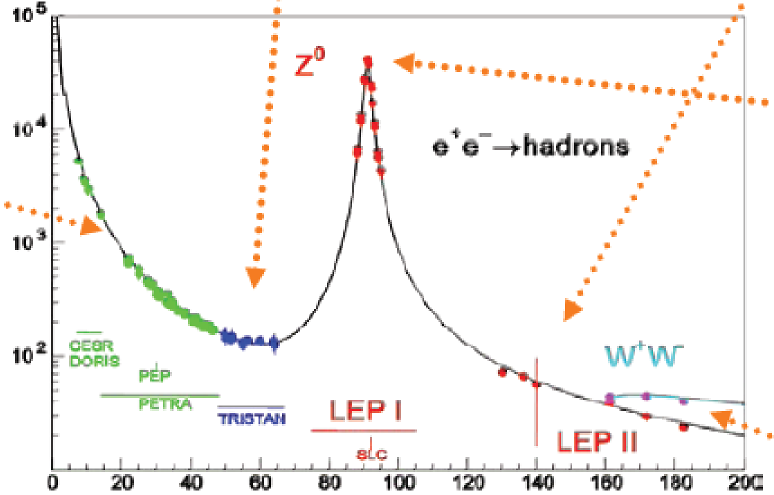
e^+e^- annihilation in Feynman Diagrams

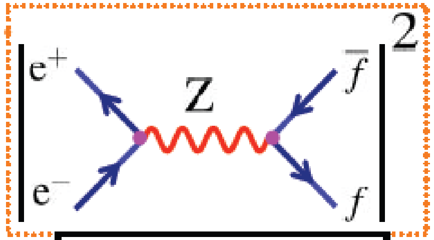
In general e^+e^- annihilation involves both photon and Z exchange : + interference





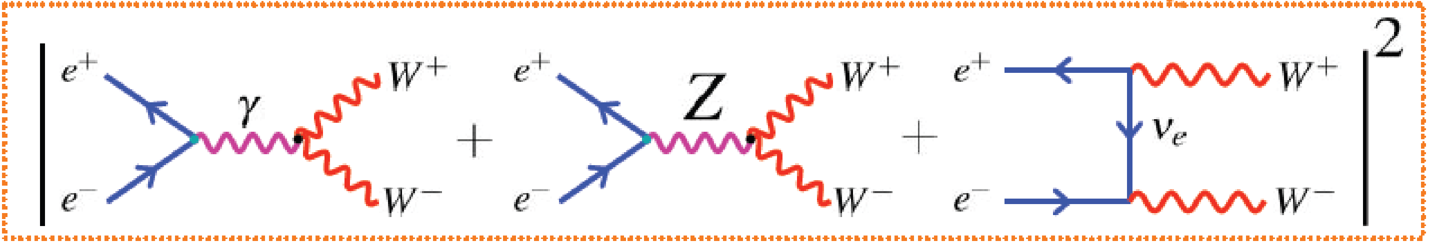
Well below Z: photon exchange dominant





At Z resonance: Z exchange dominant

High energies: WW production



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Cross-section measurements

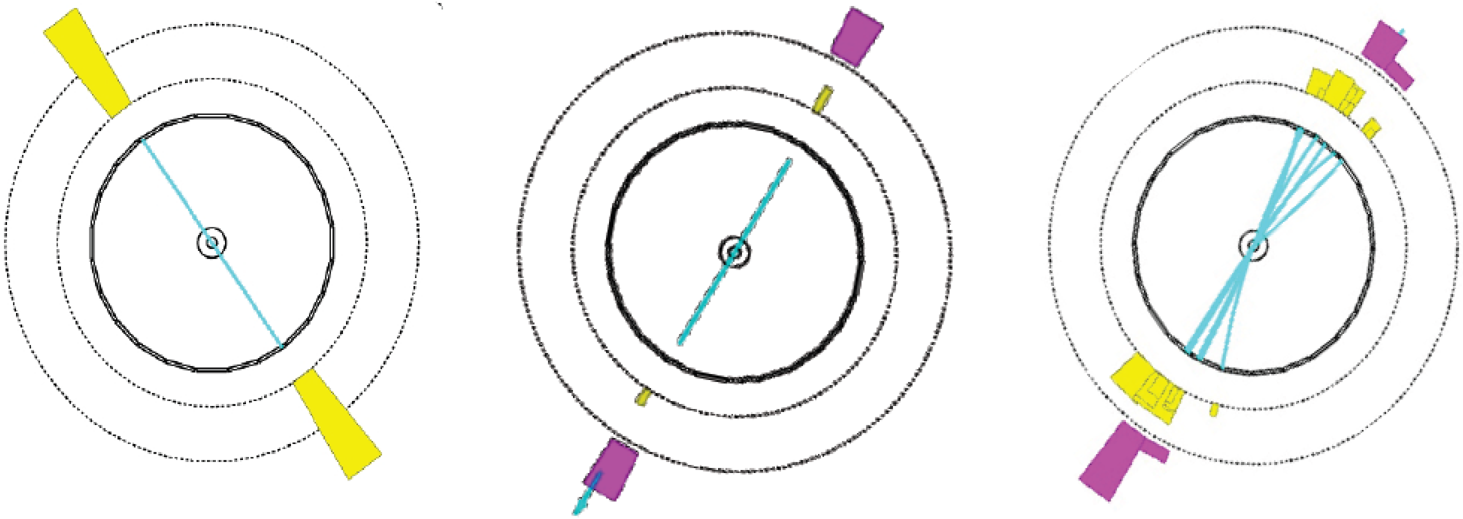
- ★ At Z resonance mainly observe four types of event:

$$e^+e^- \to Z \to e^+e^- \qquad e^+e^- \to Z \to \mu^+\mu^- \qquad e^+e^- \to Z \to \tau^+\tau^-$$

$$e^+e^- \to Z \to q\bar{q} \to \mathrm{hadrons}$$

- ★ Each has a distinct topology in the detectors, e.g.

$$e^+e^- \to Z \to e^+e^- \qquad e^+e^- \to Z \to \mu^+\mu^- \qquad e^+e^- \to Z \to \mathrm{hadrons}$$



- ★ To work out cross sections, first count events of each type
- ★ Then need to know "integrated luminosity" of colliding beams, i.e. the relation between cross-section and expected number of interactions

$$N_{\mathrm{events}} = \mathcal{L}\sigma$$

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Measurements of the Z-line shape

- ★ Measurements of the Z resonance lineshape determine:
  - m_Z : peak of the resonance
  - Γ_Z : FWHM of resonance
  - Γ_f : Partial decay widths
  - N_ν : Number of light neutrino generations
- ★ Measure cross sections to different final states versus C.o.M. energy $\sqrt{s}$

- ★ Starting from

$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\Gamma_{ee}\Gamma_{ff} \qquad (3)$$

maximum cross section occurs at $\sqrt{s} = m_Z$ with peak cross section equal to

$$\boxed{\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}}$$

- ★ Cross section falls to half peak value at $\sqrt{s} \approx m_z \pm \frac{\Gamma_Z}{2}$ which can be seen immediately from eqn. (3)
- ★ Hence $\Gamma_Z = \frac{\hbar}{\tau_Z} = \text{FWHM of resonance}$

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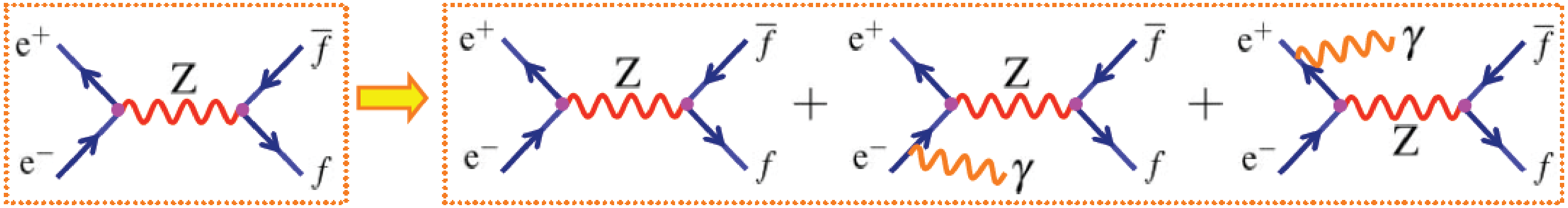
Measurements of the Z-line shape

- ★ In practise, it is not that simple, QED corrections distort the measured line-shape
- ★ One particularly important correction: initial state radiation (**ISR**)



- ★ Initial state radiation reduces the centre-of-mass energy of the e^+e^- collision

$$e^+ \xrightarrow{E} \quad \xleftarrow{E} e^- \qquad \sqrt{s} = 2E$$

becomes

$$\xrightarrow{E} \quad \xleftarrow{E-E_\gamma} \qquad \sqrt{s'} \approx 2E\left(1 - \frac{E_\gamma}{2E}\right)$$

- ★ Measured cross section can be written:

$$\sigma_{\text{meas}}(E) = \int \sigma(E')f(E',E)\,\mathrm{d}E'$$

Probability of e+e- colliding with C.o.M. energy **E'** when C.o.M energy before radiation is **E**

- ★ Fortunately can calculate $f(E',E)$ very precisely, just QED, and can then obtain Z line-shape from measured cross section

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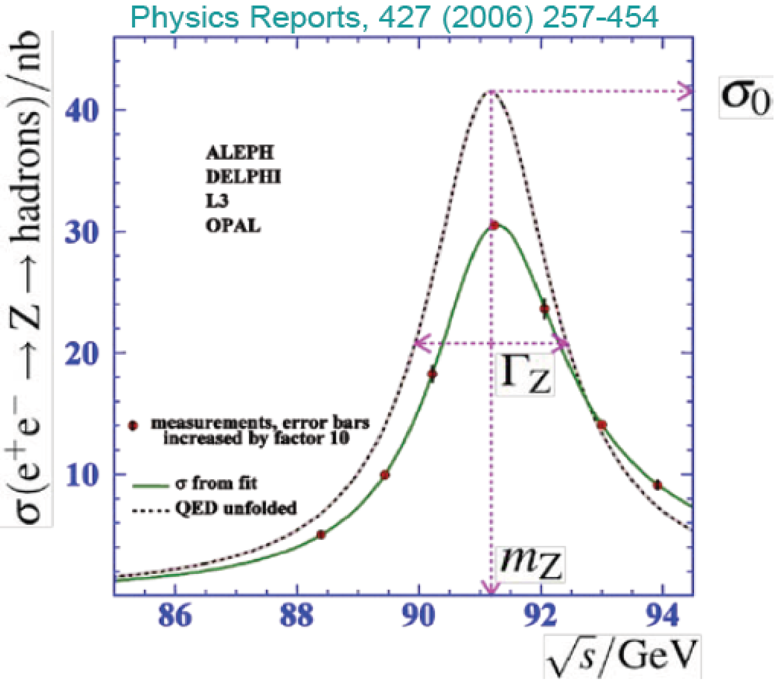

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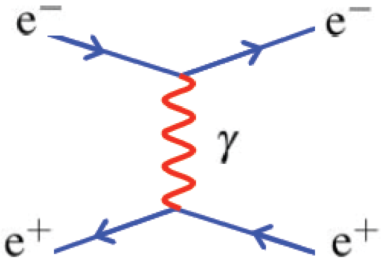
Measurements of the Z-line shape

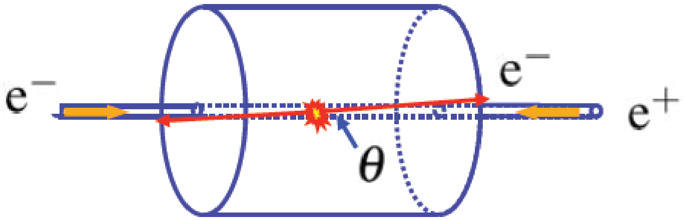
- ★ To calculate the integrated luminosity need to know numbers of electrons and positrons in the colliding beams and the exact beam profile

  - very difficult to achieve with precision of better than 10%

- ★ Instead "normalise" using another type of event:



- ♦ Use the QED Bhabha scattering process
- ♦ QED, so cross section can be calculated very precisely
- ♦ Very large cross section – small statistical errors
- ♦ Reaction is very forward peaked – i.e. the electron tends not to get deflected much



$$\frac{d\sigma}{d\Omega} \propto \frac{1}{q^4} \propto \frac{1}{\sin^4\theta/2} \Rightarrow \boxed{\frac{d\sigma}{d\theta} \propto \frac{1}{\theta^3}}$$

Photon propagator

- ♦ Count events where the electron is scattered in the very forward direction

$$N_{\text{Bhabha}} = \mathscr{L}\,\sigma_{\text{Bhabha}} \Rightarrow \mathscr{L}$$

σ_{Bhabha} known from QED calc.

- ★ Hence all other cross sections can be expressed as

$$\boxed{\sigma_i = \frac{N_i}{N_{\text{Bhabha}}}\sigma_{\text{Bhabha}}} \Rightarrow$$

Cross section measurements
Involve just event counting !

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Measurements of the Z-line shape

- In principle the measurement of m_Z and Γ_Z is rather simple: run accelerator at different energies, measure cross sections, account for ISR, then find peak and FWHM

$$\boxed{m_Z = 91.1875 \pm 0.0021\,\text{GeV}} \qquad \boxed{\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}}$$

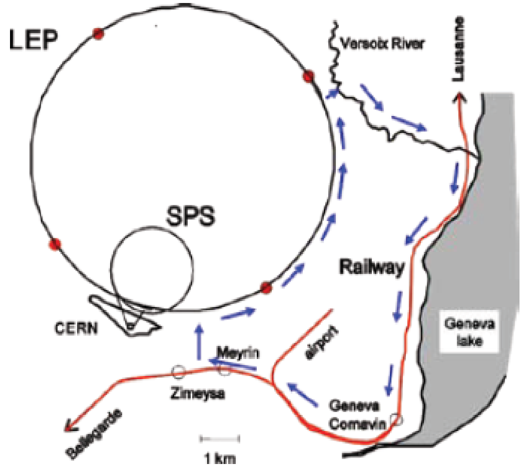
- 0.002 % measurement of m_Z !
- To achieve this level of precision – need to know energy of the colliding beams to better than 0.002 % : sensitive to unusual systematic effects…

Moon:

- As the moon orbits the Earth it distorts the rock in the Geneva area very slightly !
- The nominal radius of the accelerator of **4.3 km** varies by **±0.15 mm**
- Changes beam energy by **~10 MeV** : need to correct for tidal effects !

Trains:

- Leakage currents from the TGV railway line return to Earth following the path of least resistance.
- Travelling via the Versoix river and using the LEP ring as a conductor.
- Each time a TGV train passed by, a small current circulated LEP slightly changing the magnetic field in the accelerator
- LEP beam energy changes by ~10 MeV



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Number of generations

- ★ Total decay width measured from Z line-shape: $\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$
- ★ If there were an additional 4th generation would expect $Z \rightarrow \nu_4 \overline{\nu}_4$ decays even if the charged leptons and fermions were too heavy (i.e. > $m_Z/2$)
- ★ Total decay width is the sum of the partial widths:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

- ★ Although don't observe neutrinos, $Z \rightarrow \nu\overline{\nu}$ decays affect the Z resonance shape for all final states
- ★ For all other final states can determine partial decay widths from peak cross sections:

$$\sigma^0_{f\overline{f}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

- ★ Assuming lepton universality:

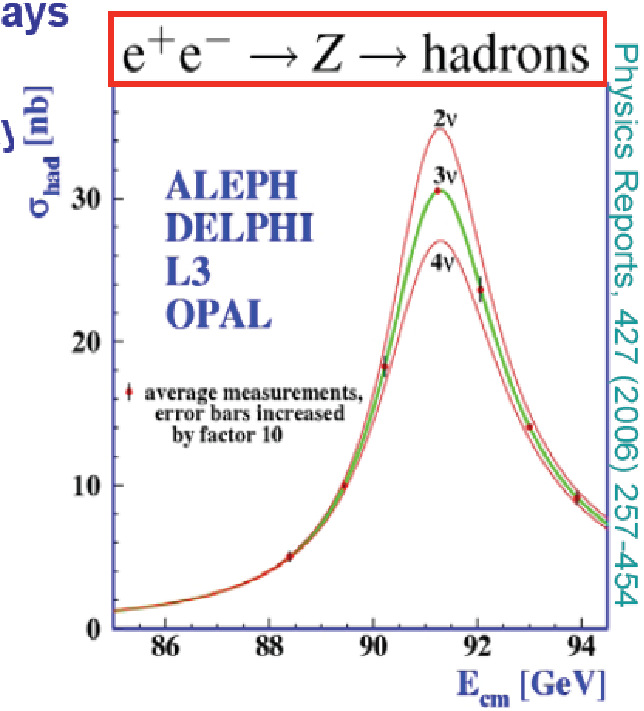
$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{\text{hadrons}} + \boxed{N_\nu}\Gamma_{\nu\nu}$$

measured from Z lineshape

measured from peak cross sections

calculated. e.g.

⇨ $\boxed{N_\nu = 2.9840 \pm 0.0082}$



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- ★ **ONLY 3 GENERATIONS** (unless a new 4th generation neutrino has very large mass)

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Forward-Backward Asymmetry

★ The expression for the differential cross section:

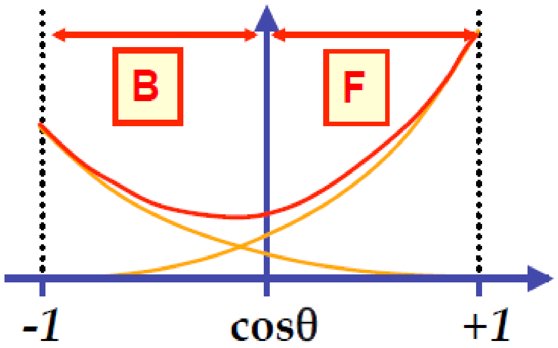
$$\langle|M_{fi}|\rangle^2 \propto [(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2](1+\cos^2\theta)+[(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2]\cos\theta$$

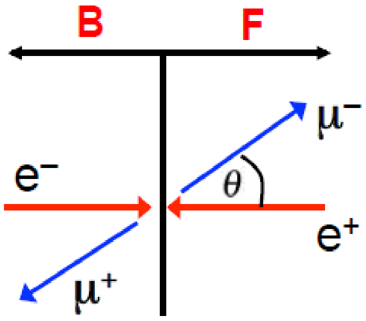
★ The differential cross sections is therefore of the form:

$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta)+B\cos\theta] \quad \begin{cases} A = [(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2] \\ B = [(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2] \end{cases}$$

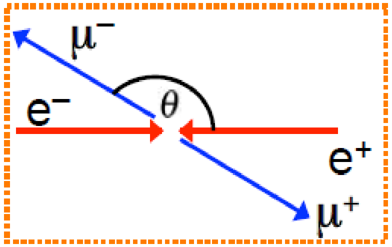
★ Define the **FORWARD** and **BACKWARD** cross sections in terms of angle incoming electron and out-going particle

$$\boxed{\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta} \qquad \boxed{\sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}$$





e.g. "backward hemisphere"



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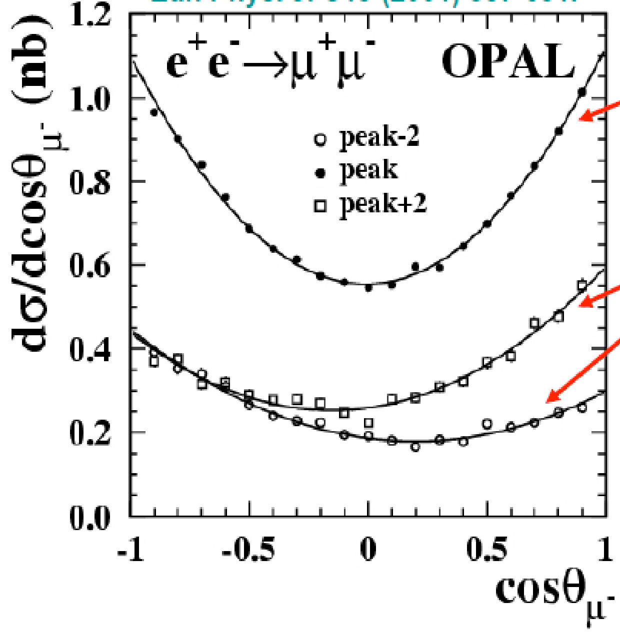
Measured Forward-Backward Asymmetry

- ★ Forward-backward asymmetries can only be measured for final states where the charge of the fermion can be determined, e.g. $e^+e^- \to Z \to \mu^+\mu^-$

OPAL Collaboration,
Eur. Phys. J. C19 (2001) 587-651.



Because $\sin^2\theta_W \approx 0.25$, the value of A_{FB} for leptons is almost zero

For data above and below the peak of the Z resonance interference with $e^+e^- \to \gamma \to \mu^+\mu^-$ leads to a larger asymmetry

★ LEP data combined:

$$A_{FB}^{0,e} = 0.0145 \pm 0.0025$$

$$A_{FB}^{0,\mu} = 0.0169 \pm 0.0013$$

$$A_{FB}^{0,\tau} = 0.0188 \pm 0.0017$$

- ★ To relate these measurements to the couplings uses $A_{\mathrm{FB}} = \frac{3}{4} A_e A_\mu$
- ★ In all cases asymmetries depend on A_e
- ★ To obtain A_e could use $A_{FB}^{0,e} = \frac{3}{4} A_e^2$

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Determination of the Weak Mixing Angle

$$\left.\begin{array}{ll}\bigstar\ \textbf{From LEP :} & A_{FB}^{0,f} = \frac{3}{4}A_e A_f \\ \bigstar\ \textbf{From SLC :} & A_{LR} = A_e\end{array}\right\} \quad A_e, A_\mu, A_\tau, \ldots$$

Putting everything together ⇨

$$\boxed{\begin{aligned} A_e &= 0.1514 \pm 0.0019 \\ A_\mu &= 0.1456 \pm 0.0091 \\ A_\tau &= 0.1449 \pm 0.0040 \end{aligned}}$$

includes results from other measurements

with $$A_f \equiv \frac{2c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} = 2\frac{c_V/c_A}{1 + (c_V/c_A)^2}$$

- ★ **Measured asymmetries give ratio of vector to axial-vector Z coupings.**
- ★ **In SM these are related to the weak mixing angle**

$$\frac{c_V}{c_A} = \frac{I_W^3 - 2Q\sin^2\theta_W}{I_W^3} = 1 - \frac{2Q}{I_3}\sin^2\theta_W = 1 - 4|Q|\sin^2\theta_W$$

- ★ **Asymmetry measurements give precise determination of** $\sin^2\theta_W$

$$\boxed{\sin^2\theta_W = 0.23154 \pm 0.00016}$$

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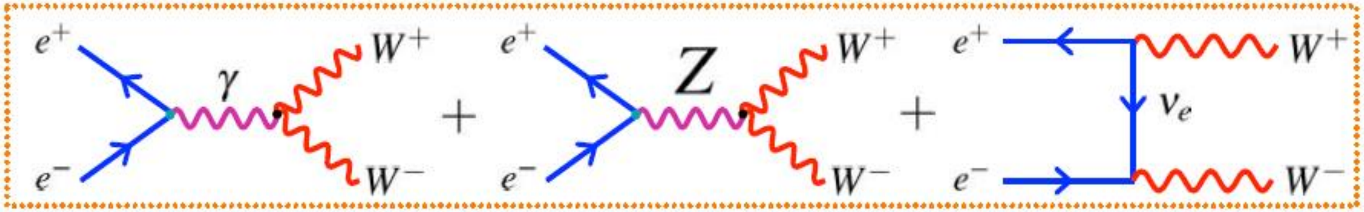
W^+W^- production

- From 1995-2000 LEP operated above the threshold for W-pair production
- Three diagrams “CC03” are involved

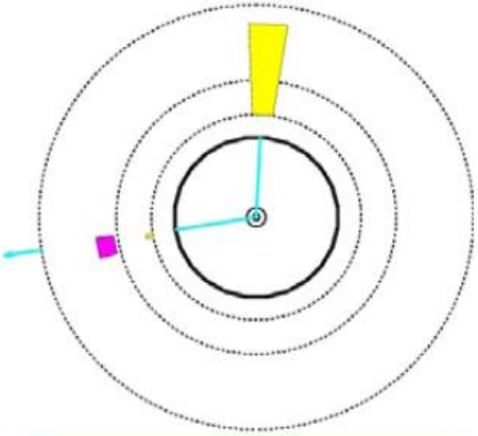


- W bosons decay (p.459) either to leptons or hadrons with branching fractions:

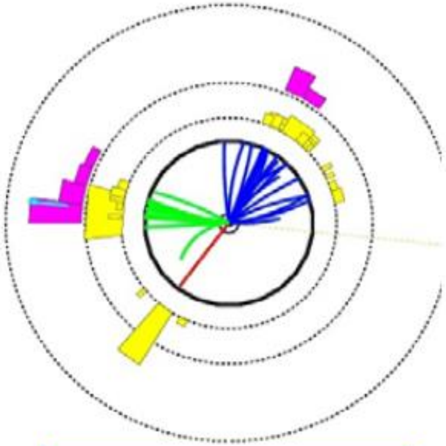
$$Br(W^- \rightarrow \text{hadrons}) \approx 0.67 \qquad Br(W^- \rightarrow \mathrm{e}^-\overline{\nu}_\mathrm{e}) \approx 0.11$$

$$Br(W^- \rightarrow \mu^-\overline{\nu}_\mu) \approx 0.11 \qquad Br(W^- \rightarrow \tau^-\overline{\nu}_\tau) \approx 0.11$$

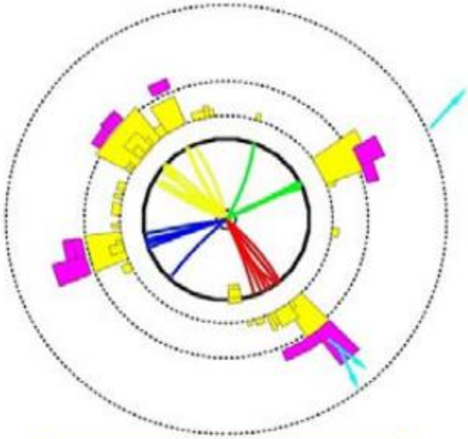
- Gives rise to three distinct topologies



$W^+W^- \rightarrow \ell^+\nu\ell^-\overline{\nu}$



$W^+W^- \rightarrow q\overline{q}\ell\nu$



$W^+W^- \rightarrow q\overline{q}q\overline{q}$

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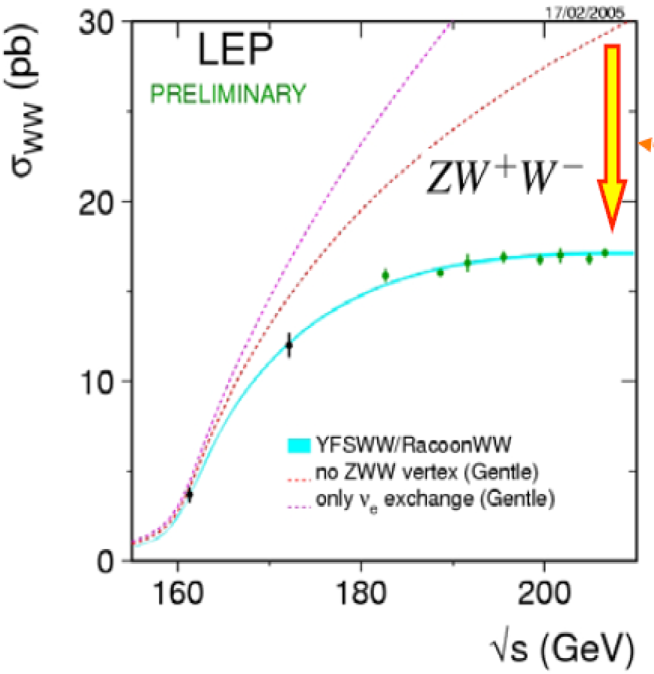
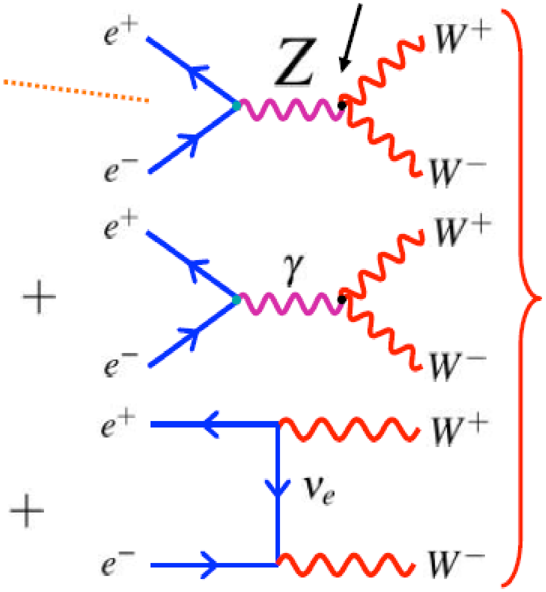
e^+e^- -> W^+W^- cross-section

- Measure cross sections by **counting events** and normalising to low angle Bhabha scattering events



- Data consistent with SM expectation
- Provides a direct test of ZW^+W^- vertex



- Recall that without the Z diagram the cross section violates unitarity
- Presence of Z fixes this problem

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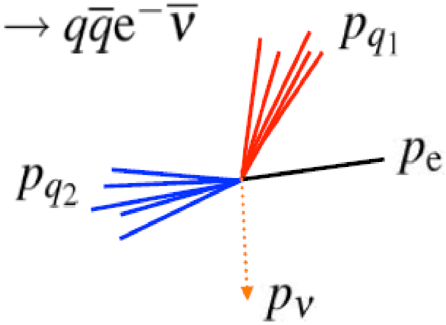
W-mass and W-width

★ Unlike $e^+e^- \to Z$, the process $e^+e^- \to W^+W^-$ is not a resonant process

⇨ Different method to measure W-boson Mass

•Measure energy and momenta of particles produced in the W boson decays, e.g.

$W^+W^- \to q\bar{q}e^-\bar{\nu}$

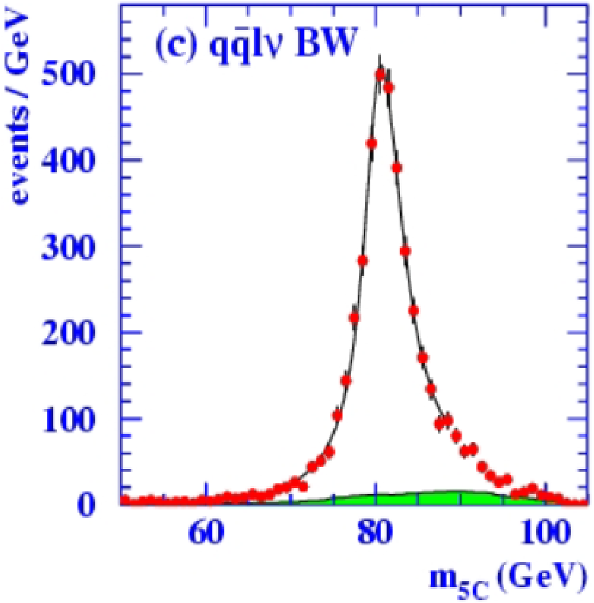


- Neutrino four-momentum from energy-momentum conservation !

$$p_{q_1} + p_{q_2} + p_e + p_\nu = (\sqrt{s}, 0)$$

- Reconstruct masses of two W bosons

$$M_+^2 = E^2 - \vec{p}^2 = (p_{q_1} + p_{q_2})^2$$
$$M_-^2 = E^2 - \vec{p}^2 = (p_e + p_\nu)^2$$



$$\approx \frac{1}{2}(M_+ + M_-)$$

★ Peak of reconstructed mass distribution gives

$$\boxed{m_W = 80.376 \pm 0.033\,\text{GeV}}$$

★ Width of reconstructed mass distribution gives:

$$\boxed{\Gamma_W = 2.196 \pm 0.083\,\text{GeV}}$$

Does not include measurements from Tevatron at Fermilab

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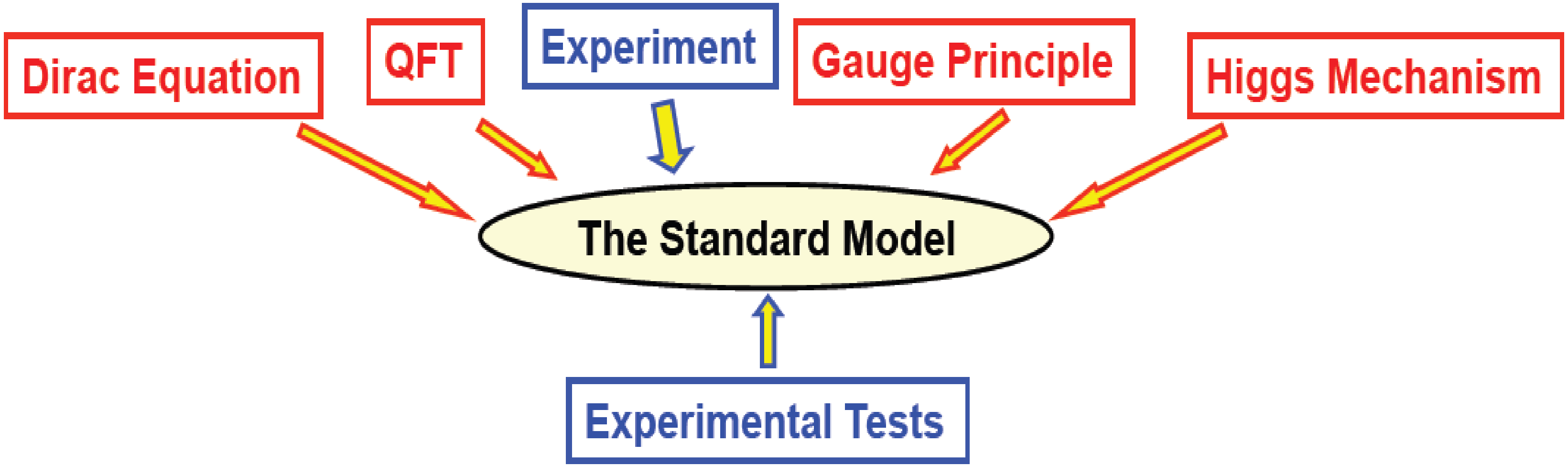
Concluding remarks

- The Standard Model of Particle Physics is one of the great scientific triumphs of the late 20th century
- Developed through close interplay of experiment and theory



Dirac Equation

QFT

Experiment

Gauge Principle

Higgs Mechanism

The Standard Model

Experimental Tests

- Modern experimental particle physics provides many precise measurements. and the Standard Model successfully describes all current data !
- Despite its great success, we should not forget that it is just a model; a collection of beautiful theoretical ideas cobbled together to fit with experimental data.
- There are many issues / open questions…

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