

I have 750 Dreams

Has a new particle been discovered?
What else may lie above and beyond it?

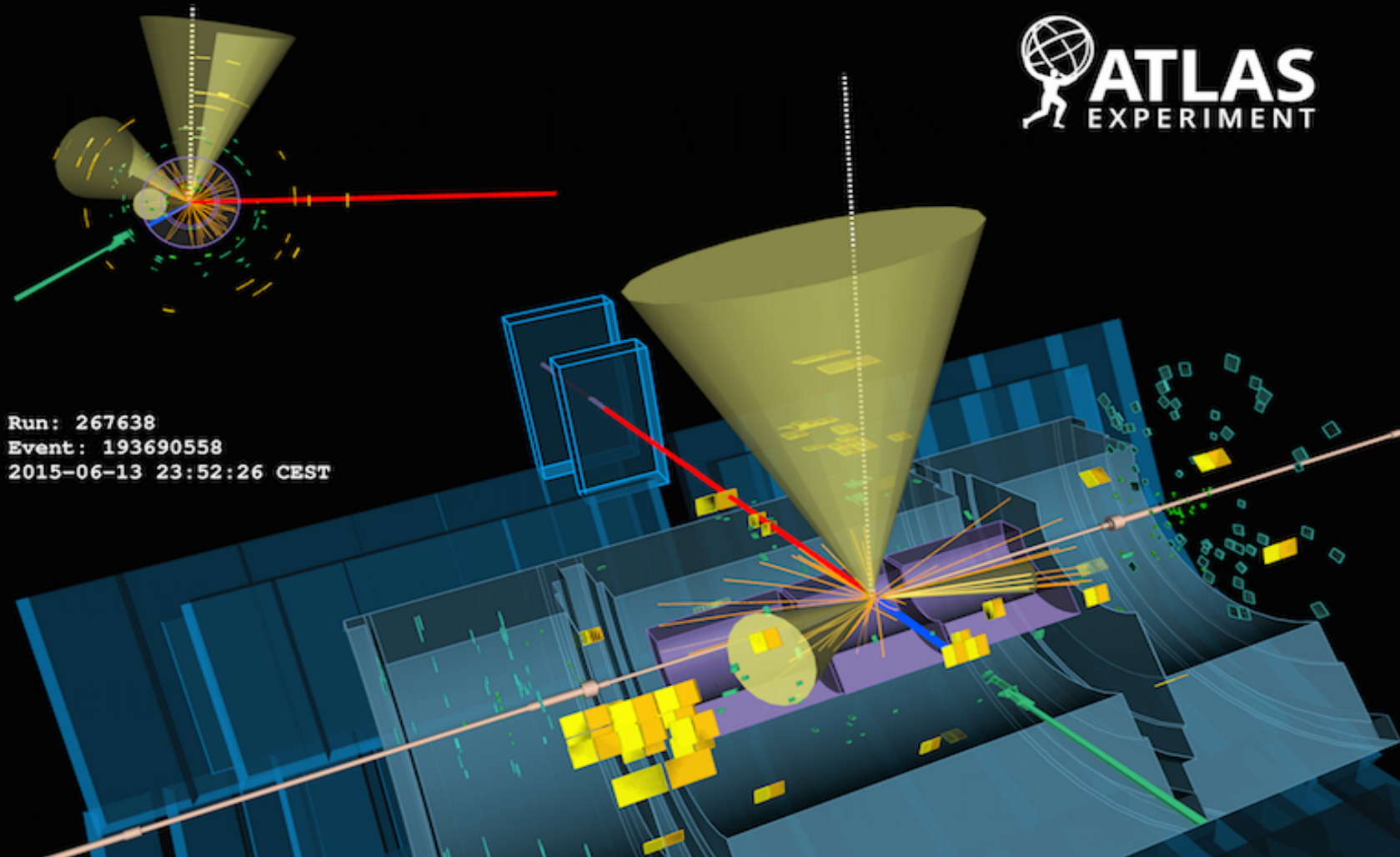
John Ellis

KING'S
College
LONDON

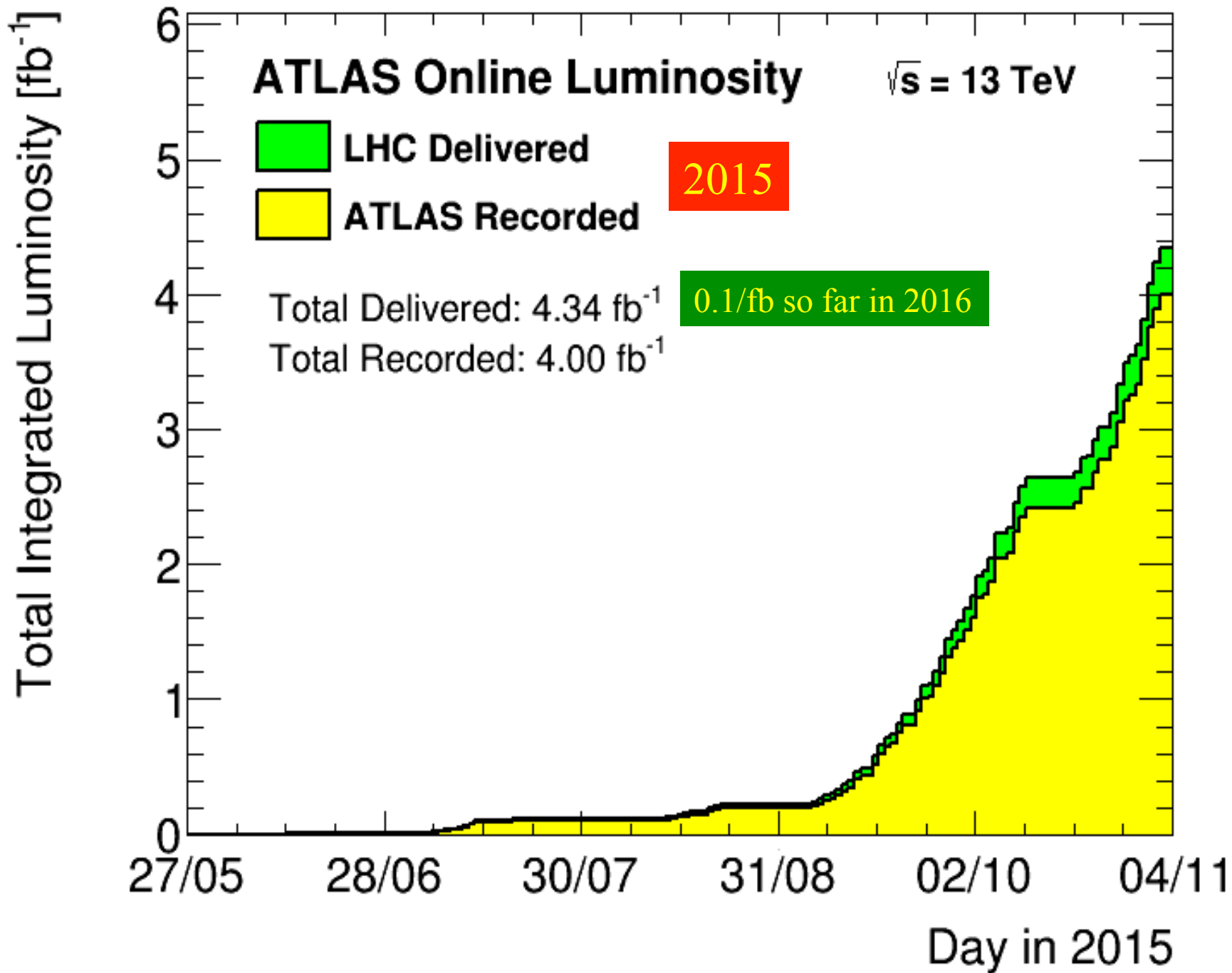
Papers with Fernando

- [Supersymmetry parameter analysis: SPA convention and project](#)
- [Juan Antonio Aguilar-Saavedra \(Lisbon, IST\) et al.. Nov 2005.](#)
- **Eur.Phys.J. C46 (2006) 43-60**
- e-Print: [hep-ph/0511344](#) | **PDF**
- [Cited by 324 records](#)

- [The Hunt for New Physics at the Large Hadron Collider](#)
- [Pran Nath \(Northeastern U.\) et al.. Jan 2010.](#)
- **Nucl.Phys.Proc.Suppl. 200-202 (2010) 185-417**
- e-Print: [arXiv:1001.2693 \[hep-ph\]](#) | **PDF**
- [Cited by 125 records](#)

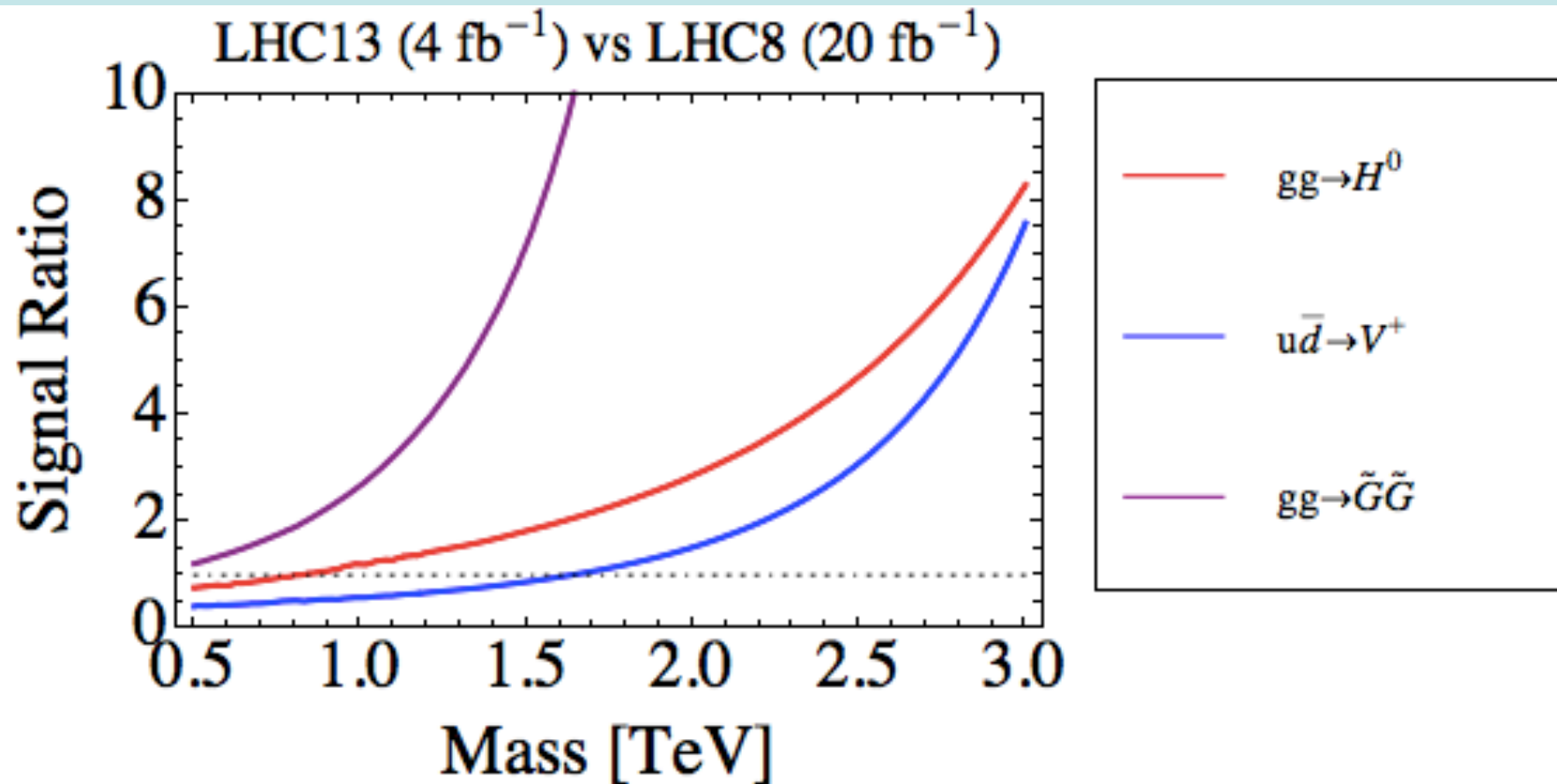


- Top production, mass, $H t \bar{t}$ production
- Possible connection to $X(750)$



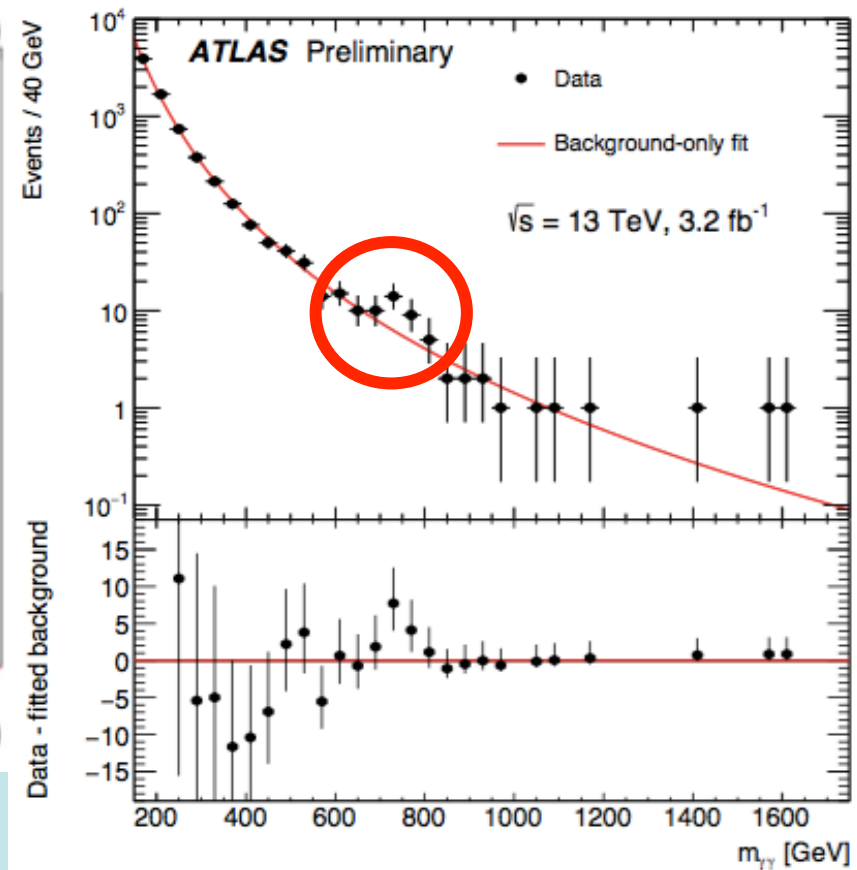
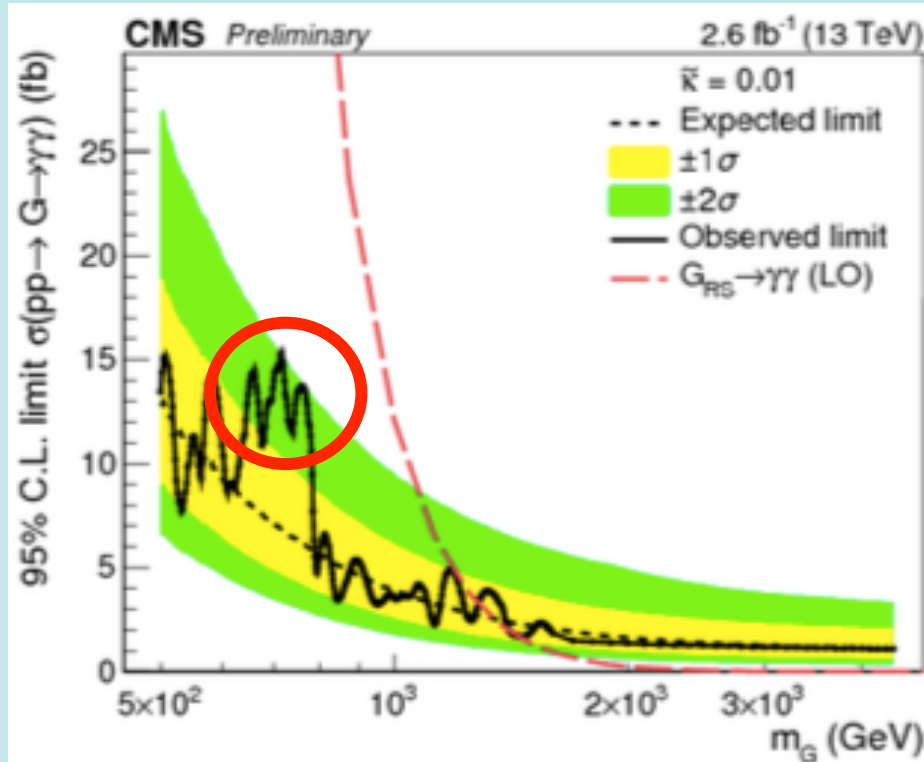
Why we are so excited by Run 2

- 2015 luminosity already explores new physics



Reported on Tuesday, Dec. 15

- Peaks in $\gamma\gamma$ invariant mass distributions



- Possible new particle X with mass $\sim 750 \text{ GeV}$ decaying into 2 photons



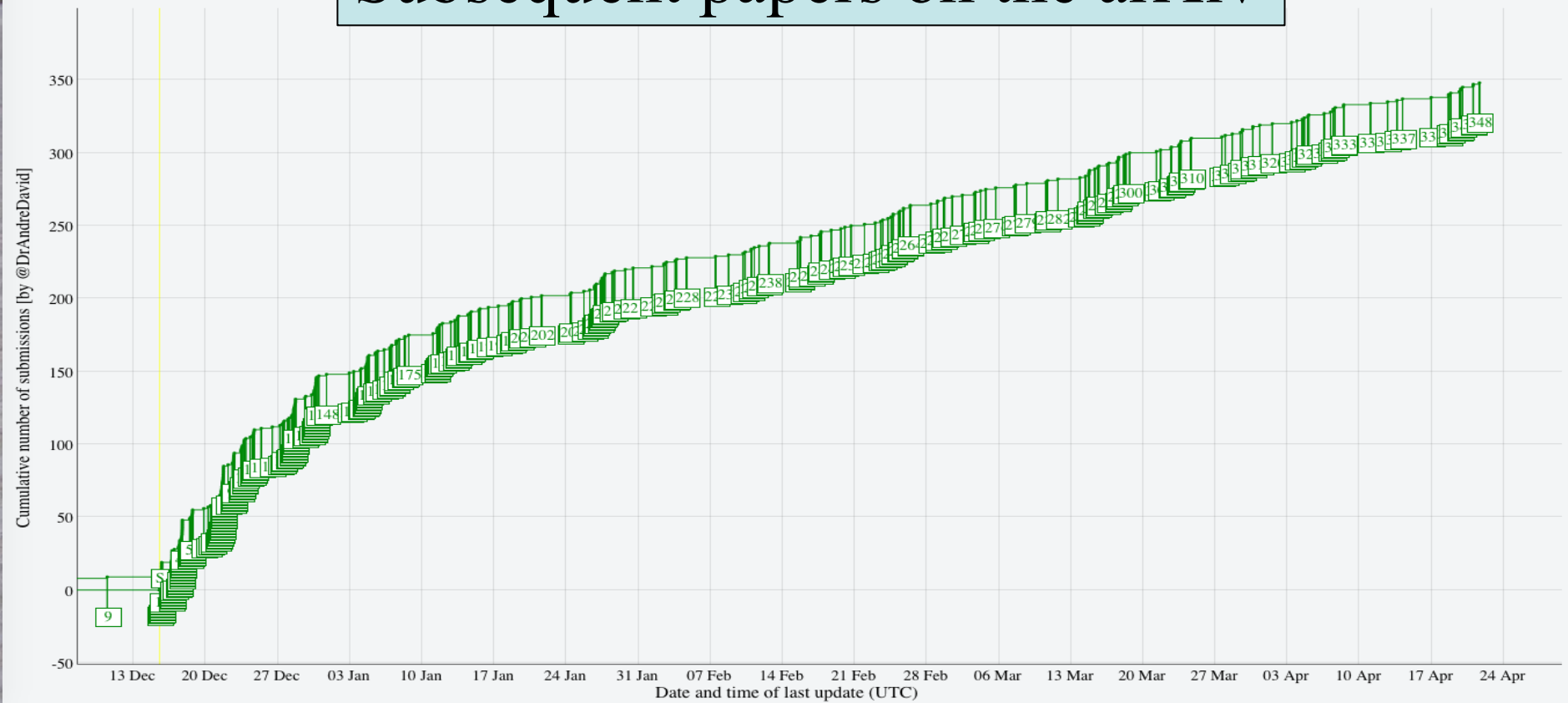
“Who ordered that”

I.I. Rabi

He was talking about the muon ...

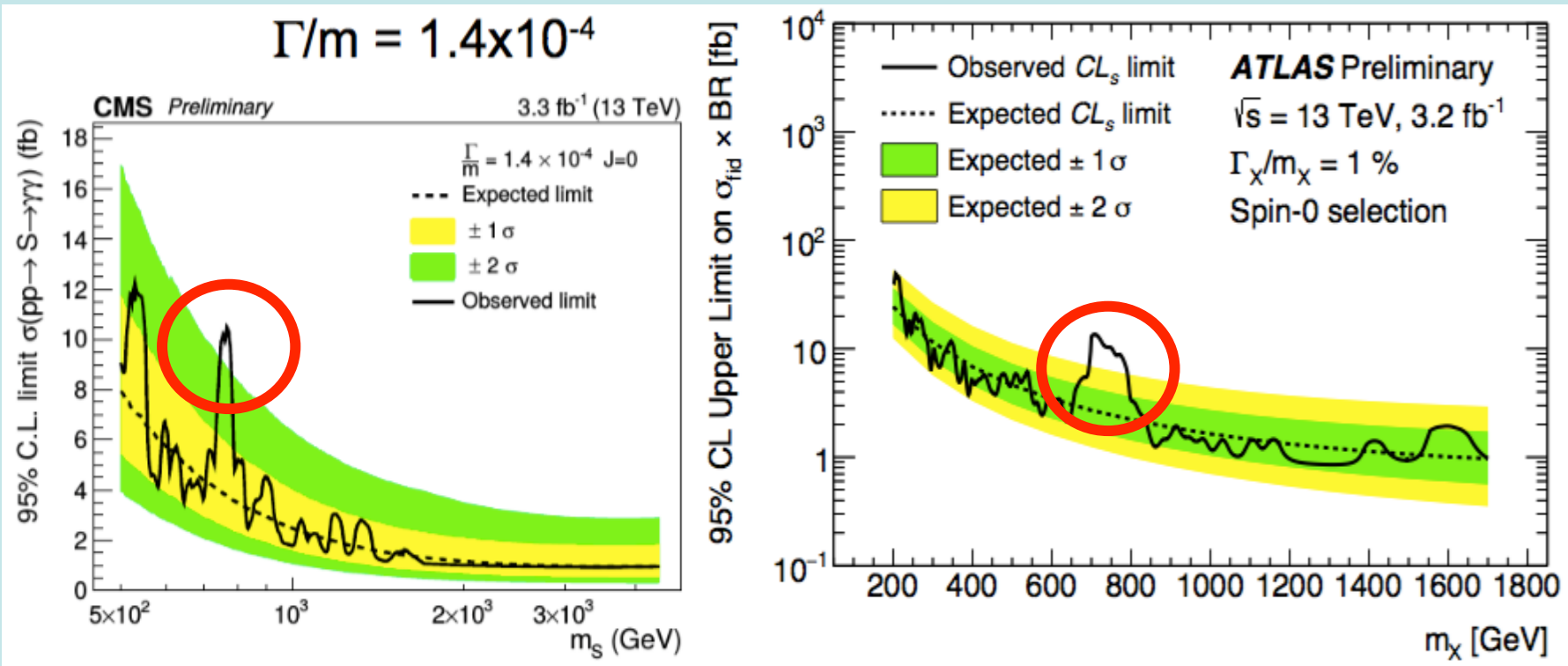
A Much-Chased Ambulance

Subsequent papers on the arXiv

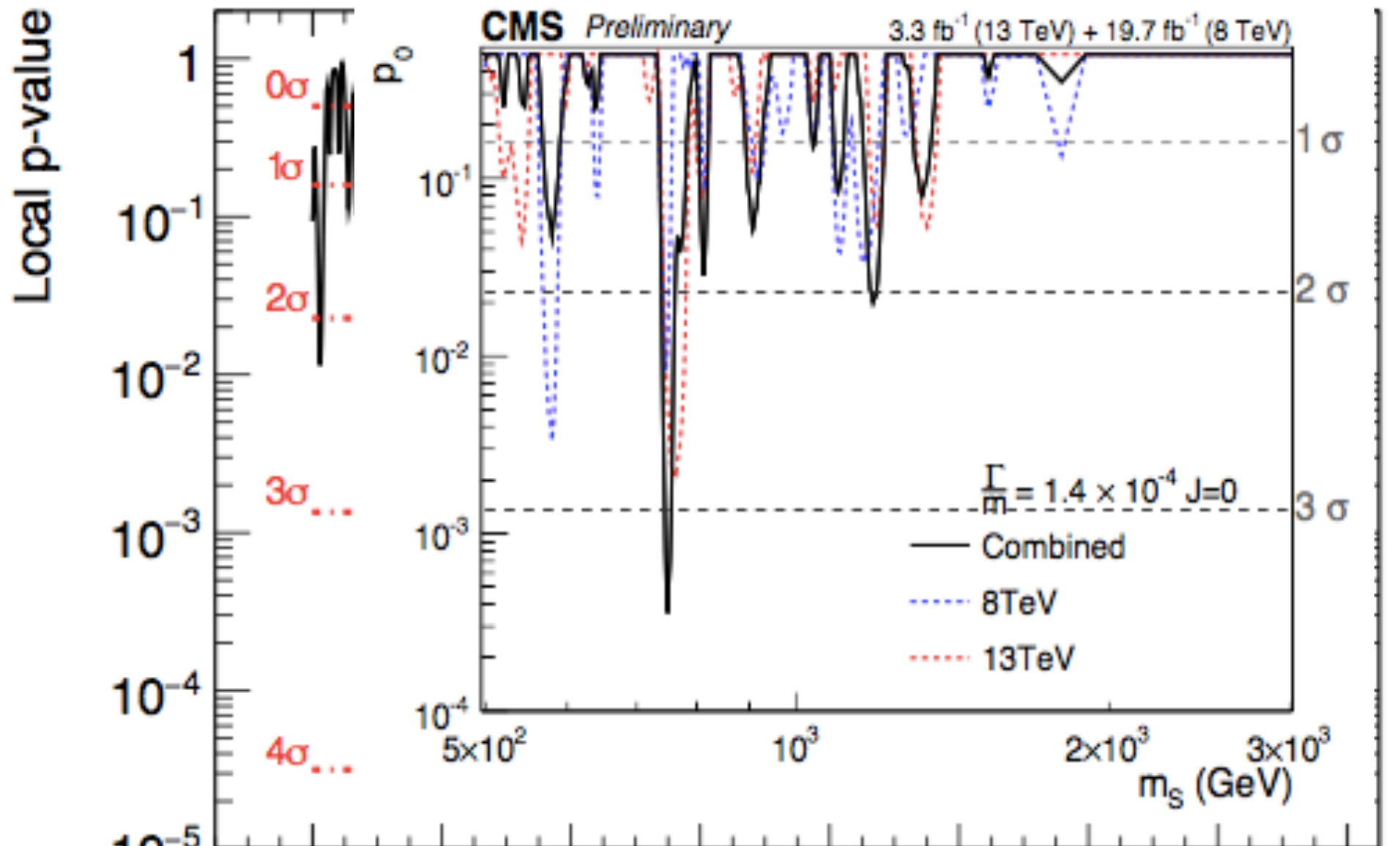


Update on Thursday, March 17

- **Peaks in $\gamma\gamma$ invariant mass distributions**



- Hint of new X(750) particle has not gone away
- **Wait and see!**



Combined local significance $\sim 5\sigma$

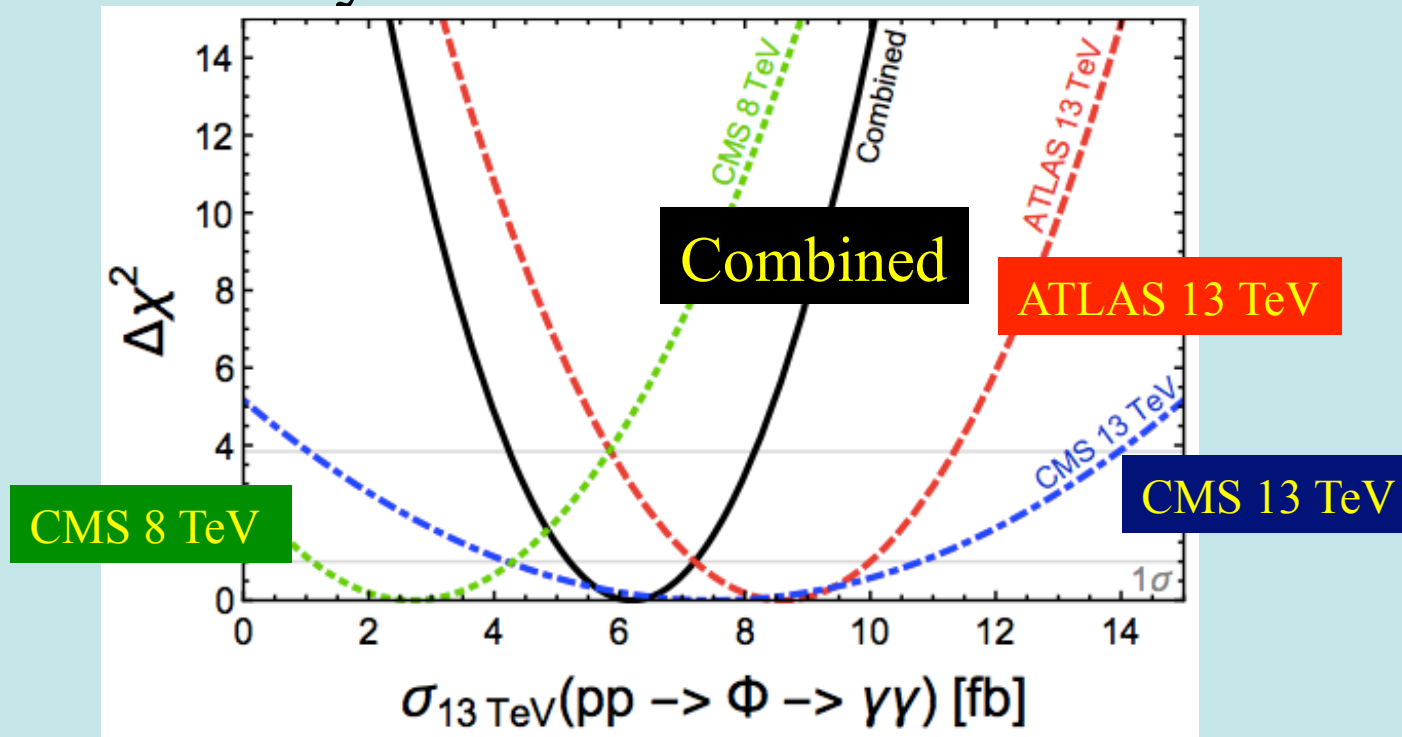
Combined global significance $\sim 4\sigma$

1600 1800

$m_X \text{ [GeV]}$

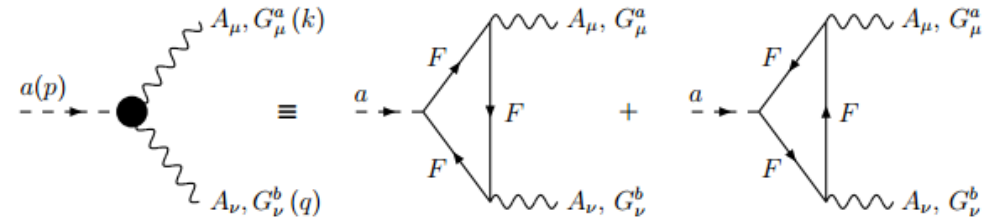
Global Analysis of X Signal

- Assume scalar/pseudoscalar (angular distribution?)
- Combined analysis of CMS and ATLAS data



- Some tension between data from Run 1 and Run 2?

X Decays?

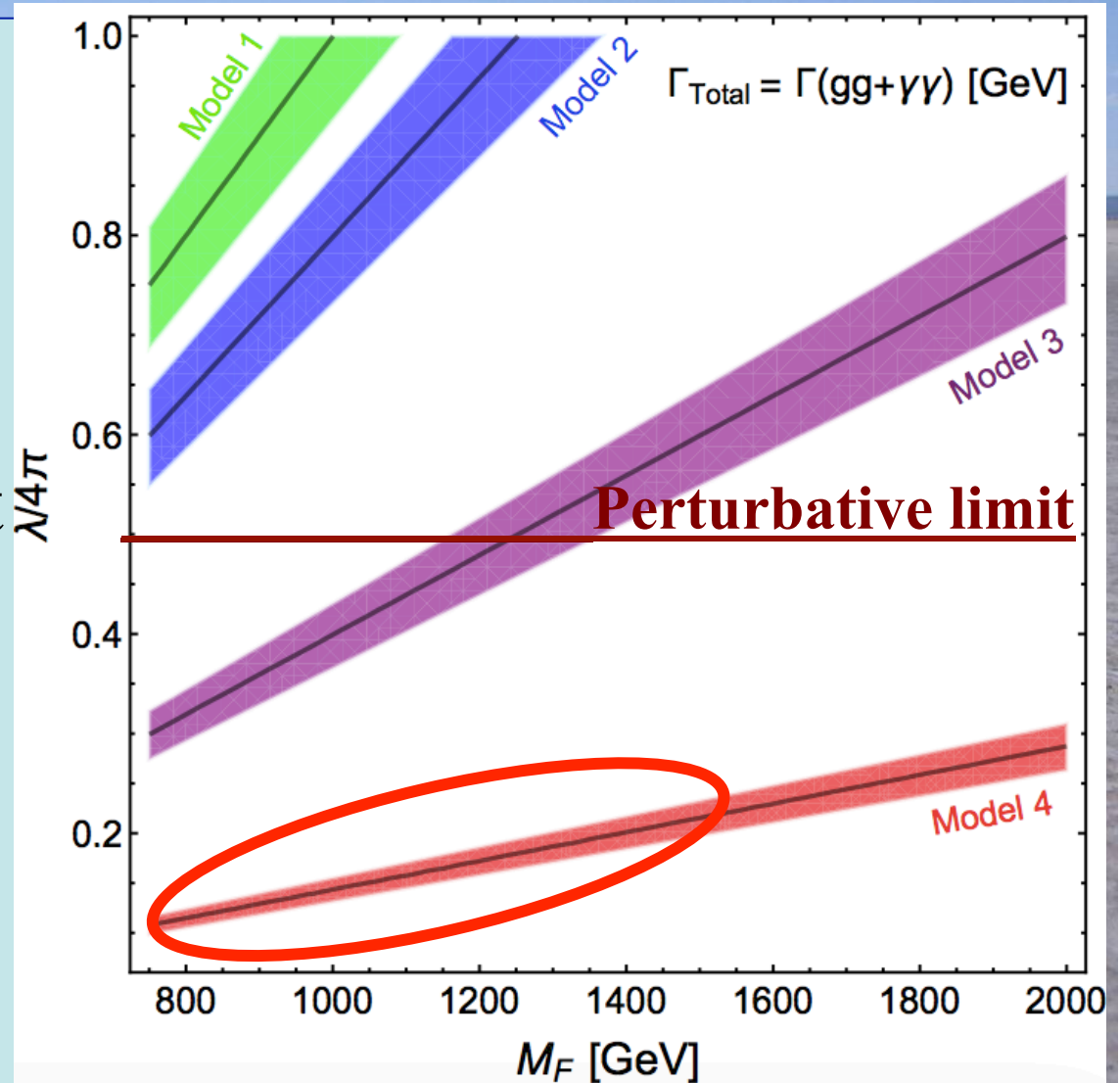


- Decay to $\gamma\gamma$ via anomalous triangle diagrams
- Probably also production via gluon fusion
- **Loops need heavy particles, $m > 350$ GeV**
- **Can't be 4th generation/minimal supersymmetry**
- Single vector-like quark enough, could be more
 - 1: Single VL quark, cf, t_R
 - 2: Doublet of VL quarks, cf, q_L
 - 3: Doublet + 2 singlets, cf, q_L, t_R, b_R
 - 4: Complete VL generation, including leptons
- **Assume gg decays dominant**

JE, S.Ellis, Quevillon, Sanz & You,
arXiv:1512.05327

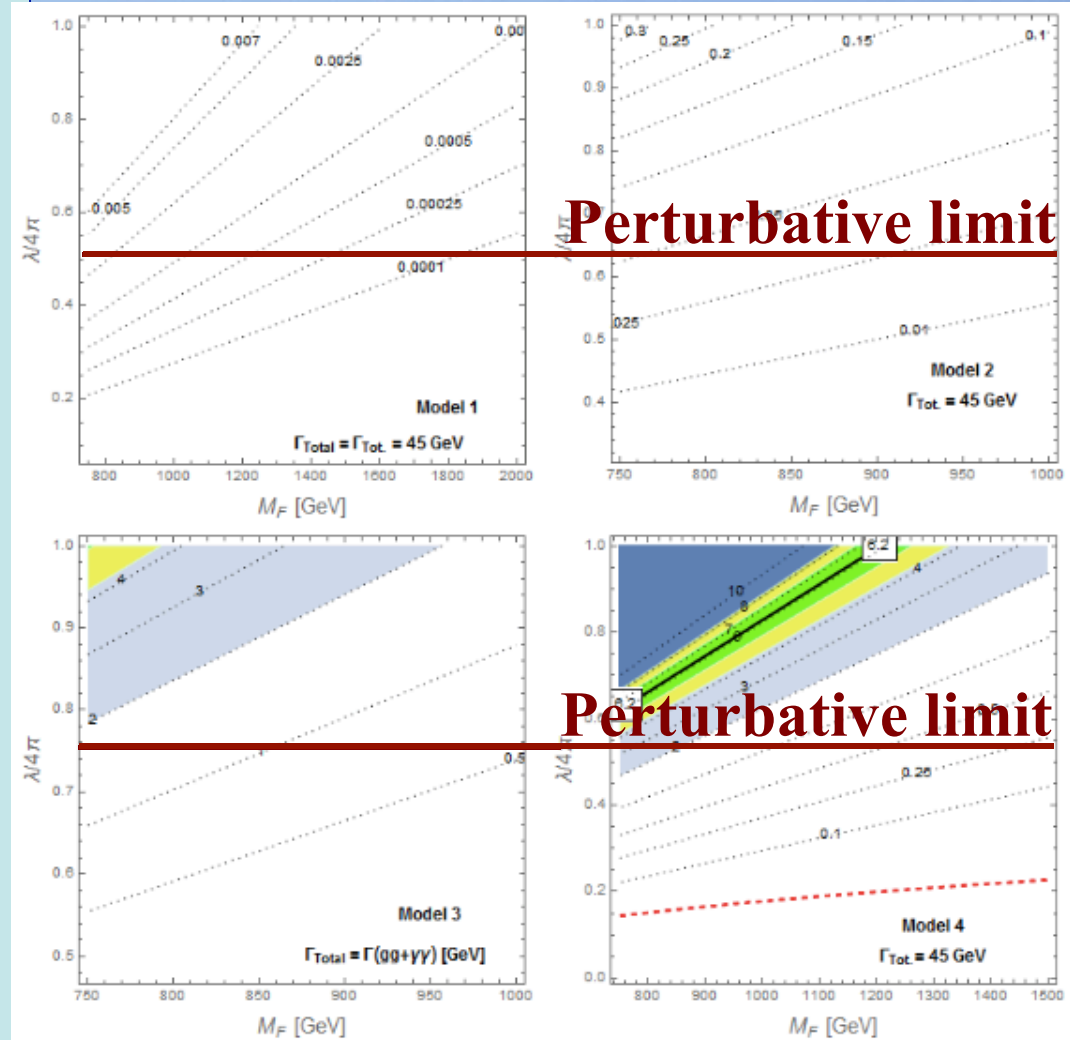
Scalar/Pseudoscalar Models for X

- Required X couplings λ to heavy fermions in different models
- Black line = best fit
- **Band = 1 σ**
- **Perturbative limit**
- **Neutral fermion could be dark matter**



Scalar/Pseudoscalar Models for X

- What if $\Gamma_X=45$ GeV?
- Required X couplings λ to heavy fermions in different models
- Black line = best fit
- **Green band = 1 σ**
- **Perturbative limit**
- **More fermions in loops?**



How to Probe Possible Models?

- Other possible decay modes

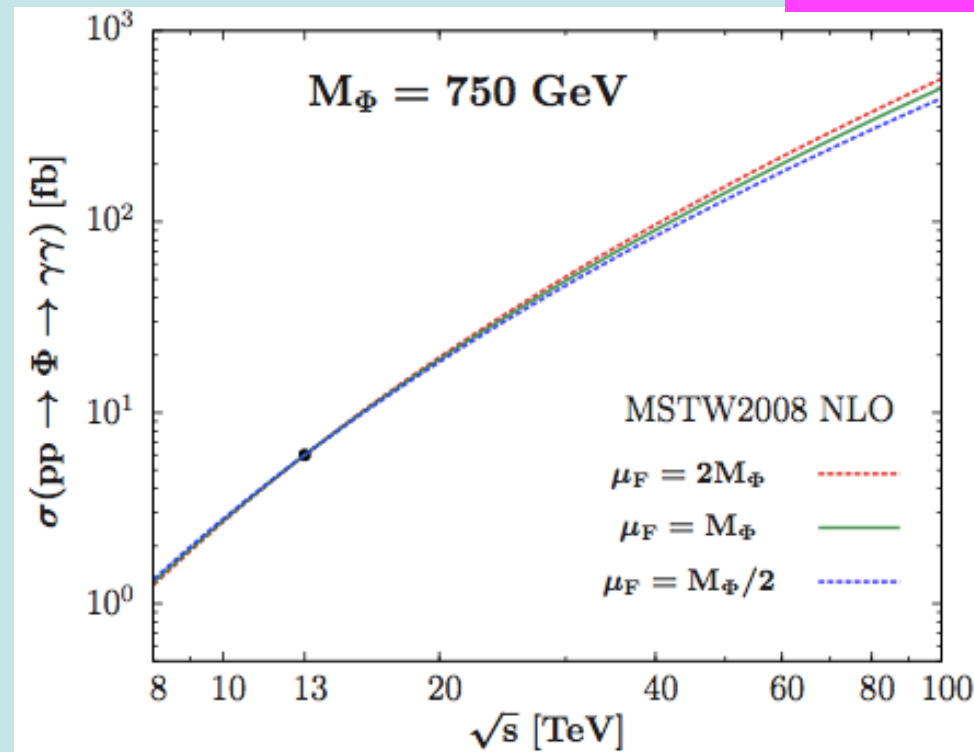
Model	$Tr[Y^2]$	$Tr[D(r)^2]$	$\frac{BR(X \rightarrow gg)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow Z\gamma)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow ZZ)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow W^\pm W^\mp)}{BR(X \rightarrow \gamma\gamma)}$
1	8/3	0	180	1.2	0.090	0
2	1/3	3	460	10	9.1	61
3	11/3	3	460	1.1	2.8	15
4	20/3	4	180	0.46	2.1	11
Current limit			$\sim 2 \times 10^4$	7	13	46

- Predictions \leq experimental limits
- Potentially accessible to experiment
- Also look for heavy fermions!
- **Work for a generation – if X particle exists!**
- **Will know in 2016**

Possible Future X Signal

- Assuming production by gluon-gluon fusion
- Normalized to $\sigma_{\text{B}}(\gamma\gamma) = 6 \text{ fb}$

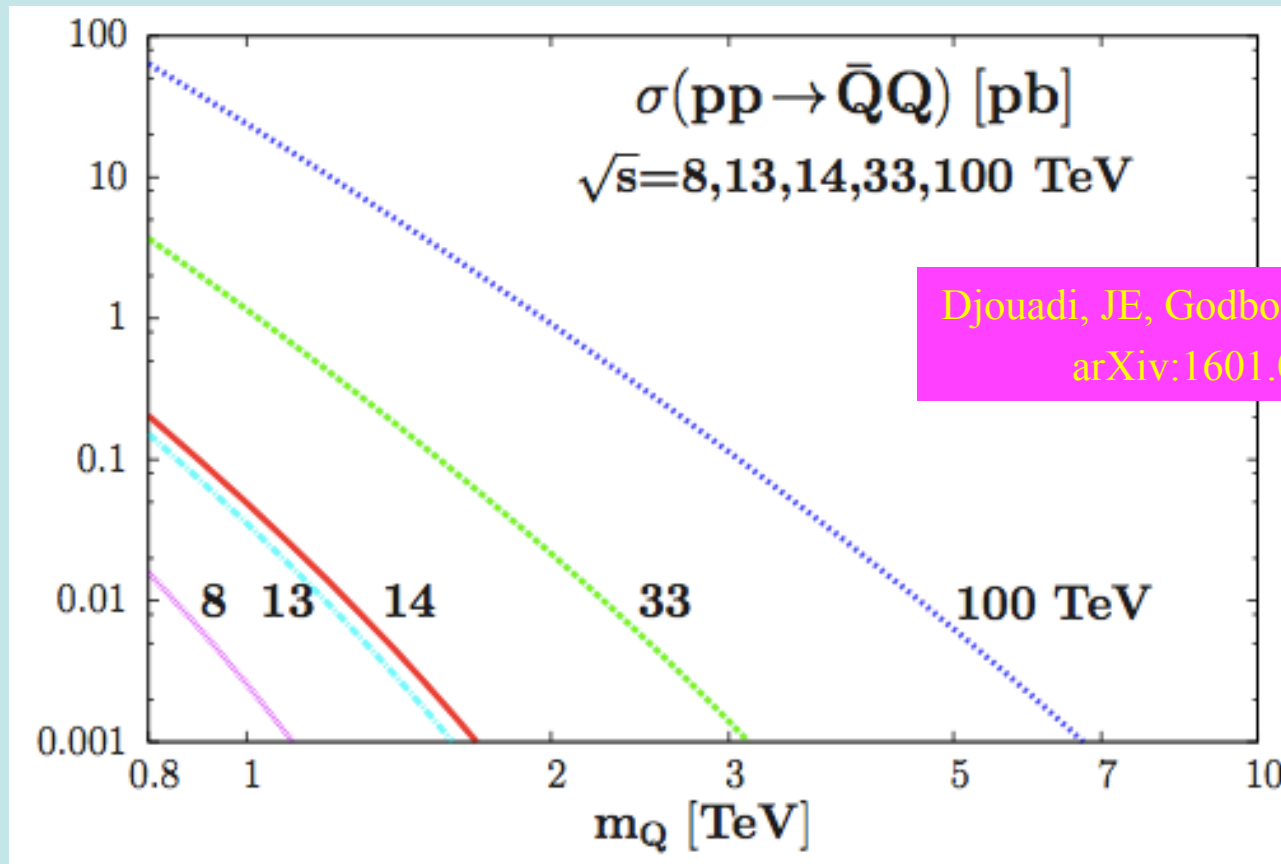
Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696



- PDF, ren'n scale uncertainties @ 100 TeV $\sim 30\%$

Cross Sections for Vector-Like Q

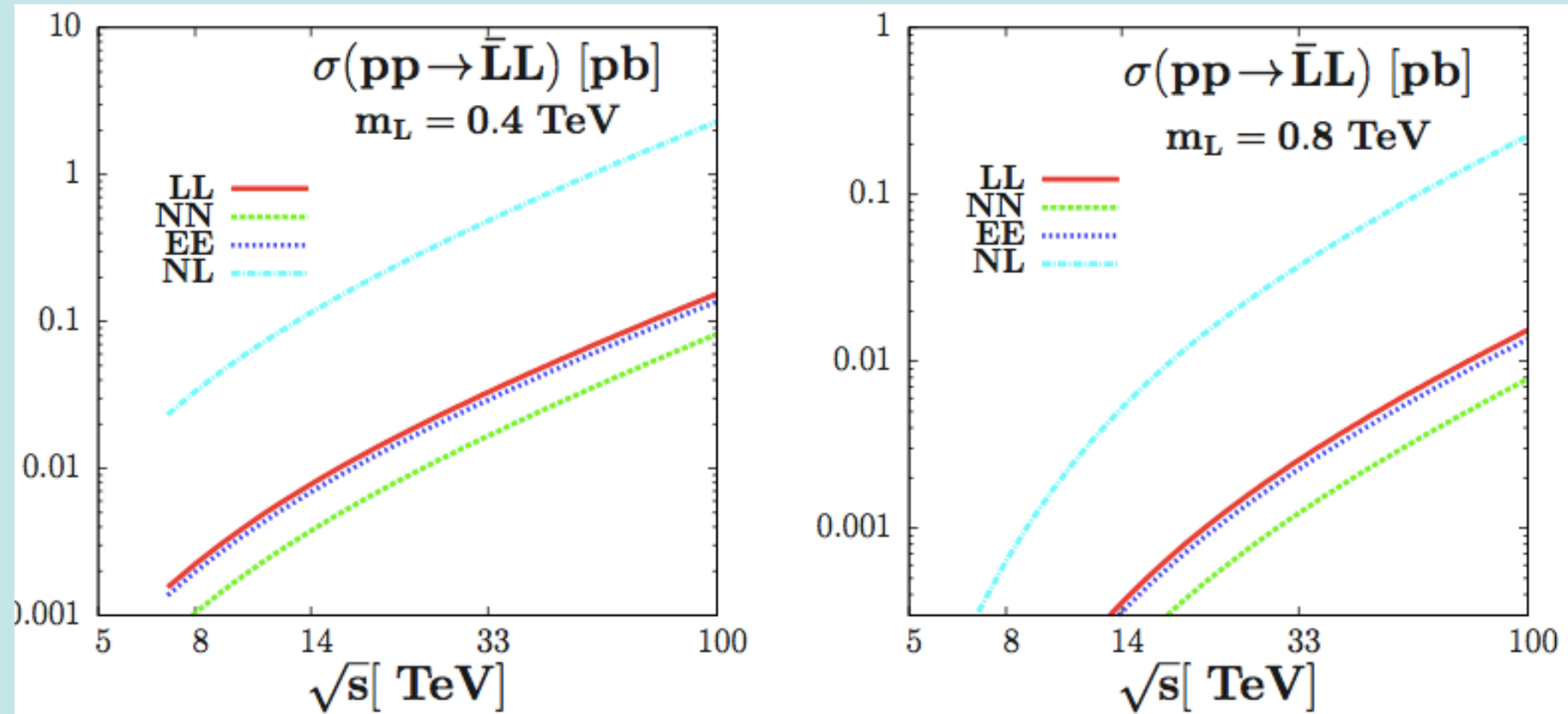
- Pair-production at LHC, future circular colliders



- Present lower mass limit ~ 800 GeV

Cross Sections for Vector-Like L

- Pair-production at LHC, future circular colliders



- Present mass limit < 400 GeV

Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

Sensitivity to Vector-Like Q, L

model	Vector-like quark mass sensitivity				Vector-like lepton mass sensitivity			
	100fb ⁻¹	300fb ⁻¹	300fb ⁻¹	20ab ⁻¹	100fb ⁻¹	300fb ⁻¹	300fb ⁻¹	20ab ⁻¹
	13 TeV	14 TeV	33 TeV	100 TeV	13 TeV	14 TeV	33 TeV	100 TeV
1	1.4	1.7	3.1	11.7				
2	1.5	1.8	3.4	12.7				
3	1.6	2.0	3.7	13.7				
4	1.6	2.0	3.7	13.7	0.56	0.73	1.7	5.3

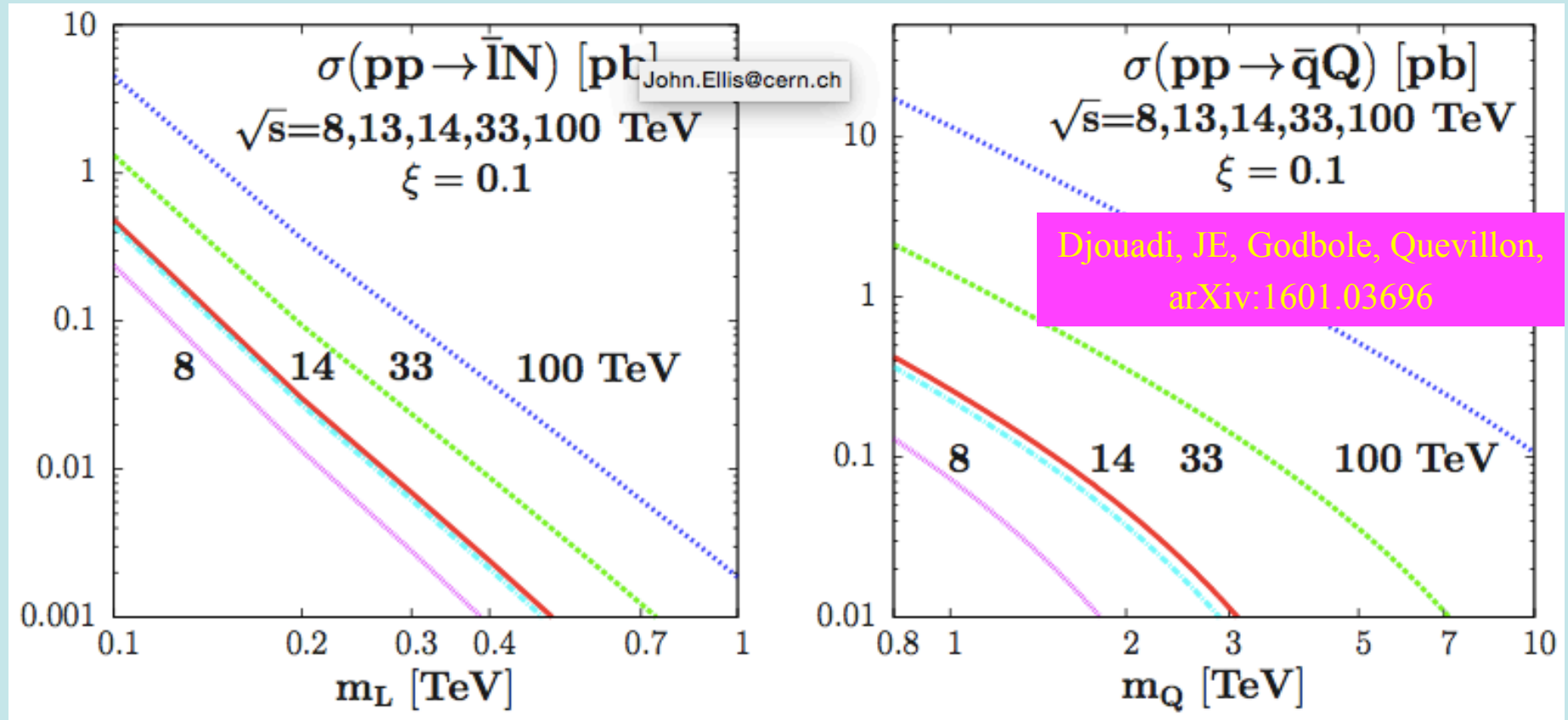
- Model 1: Single VL quark, cf, t_R
 - Non-perturbative coupling required
- Model 2: Doublet of VL quarks, cf, q_L
 - Non-perturbative coupling favoured
- Model 3: Doublet + 2 singlets, cf, q_L, t_R, b_R
 - Perturbative range covered by LHC
- Model 4: Complete VL generation, including leptons
 - Covering perturbative range needs higher energy

Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

How do they mix with conventional q, l ?

Single Vector-Like Q, L Production

- Single production at LHC, future circular colliders



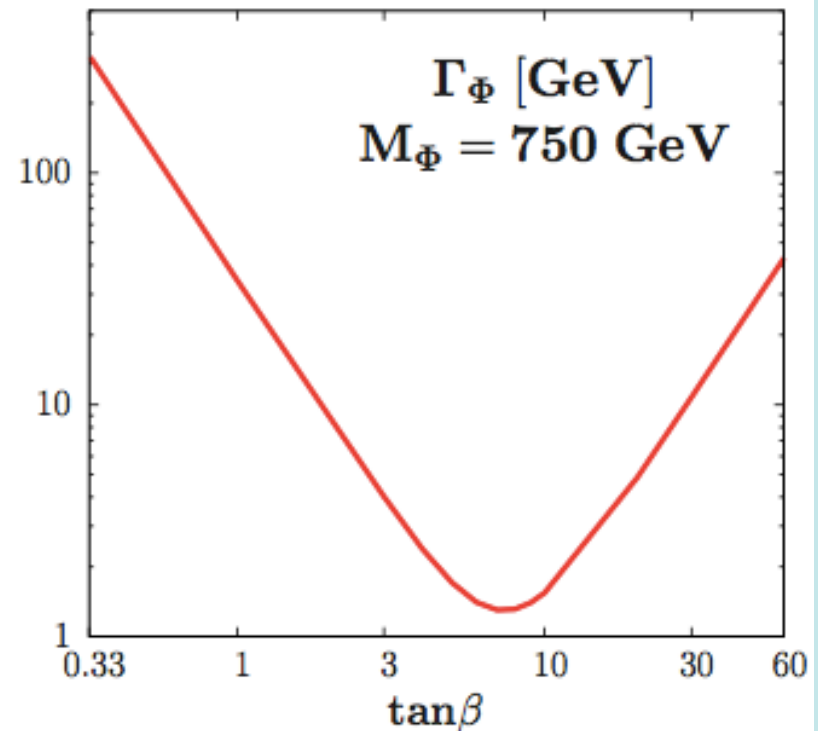
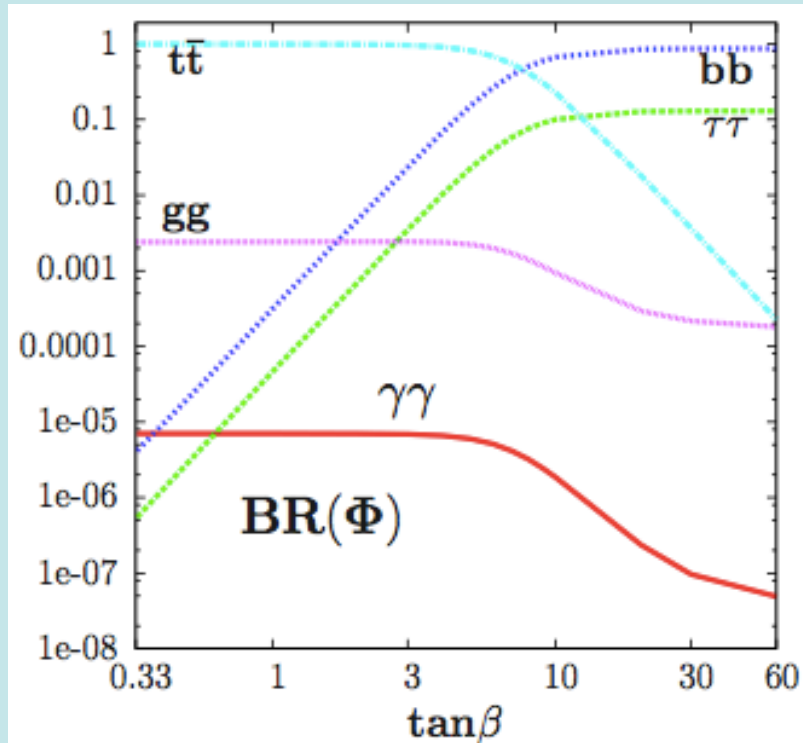
- Assuming mixing angle with light fermions $\xi = 0.1$

Alternative Higgs Doublet Scenario

- After singlet, doublet?
- Heavy Higgses in 2 Higgs doublet model: $\Phi = H, A$
- Nearly degenerate in many versions, e.g., SUSY
- Expect $t \bar{t}$ decays to dominate
- Can accommodate $\Gamma_{\Phi} \sim 45 \text{ GeV}$ (ATLAS)
- Need larger enhancement of loops compared to singlet model
- **Rich bosonic phenomenology**

$\Phi = H, A$ Decays in Doublet Model

- Dependences on $\tan \beta$ of branching ratios, Γ_Φ

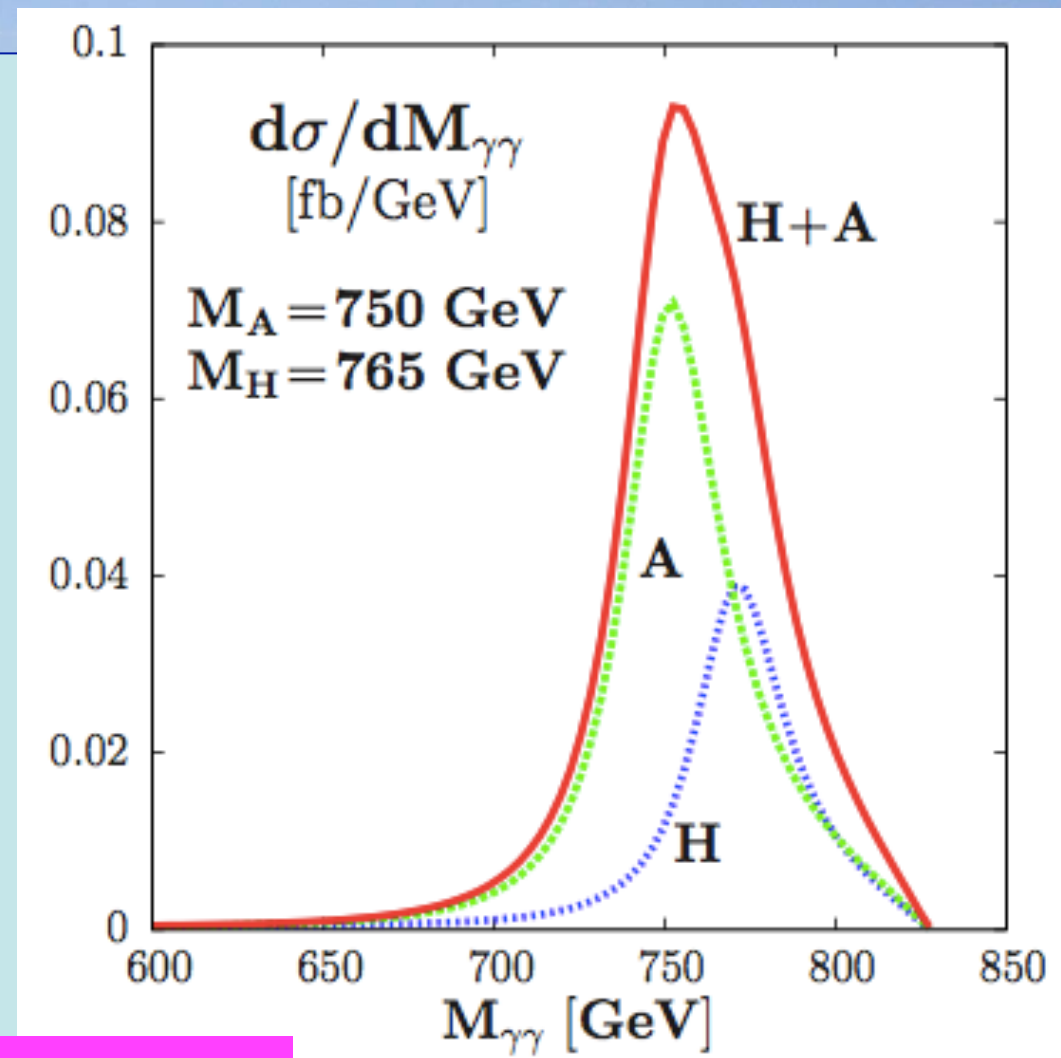


- Prefer $\tan \beta \sim 1$
- Dominant Φ decays to $t \bar{t}$

Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

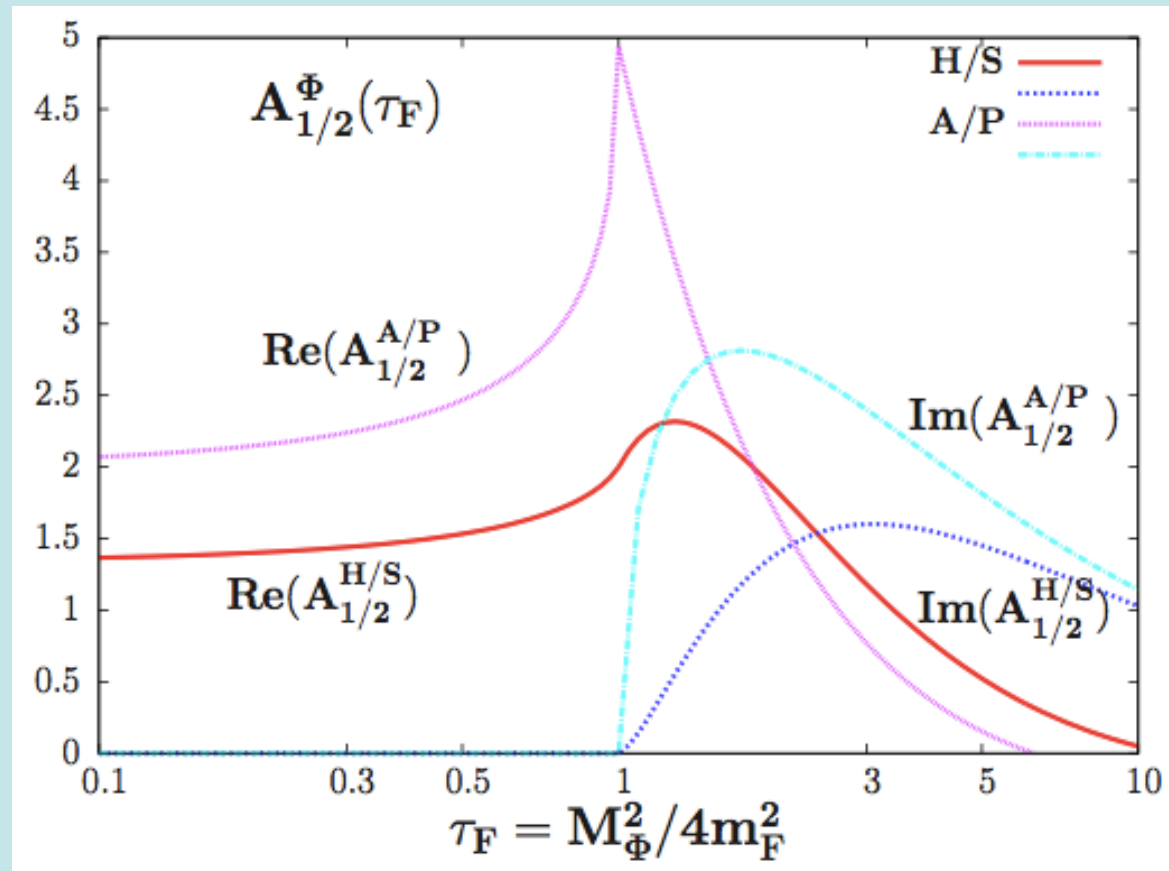
Lineshape in pp Collisions

- +MSSM: $\tan \beta = 1$
- $M_H - M_A \sim 15 \text{ GeV}$
- $\Gamma_H, \Gamma_A \sim 33, 36 \text{ GeV}$
- $\sigma B(A \rightarrow \gamma\gamma) = 2 \times \sigma B(H \rightarrow \gamma\gamma)$
- Asymmetric
‘Breit-Wigner’
- **Resolvable?**



Fermion Loop Form Factors

- Triangle diagrams suppressed for small M_F

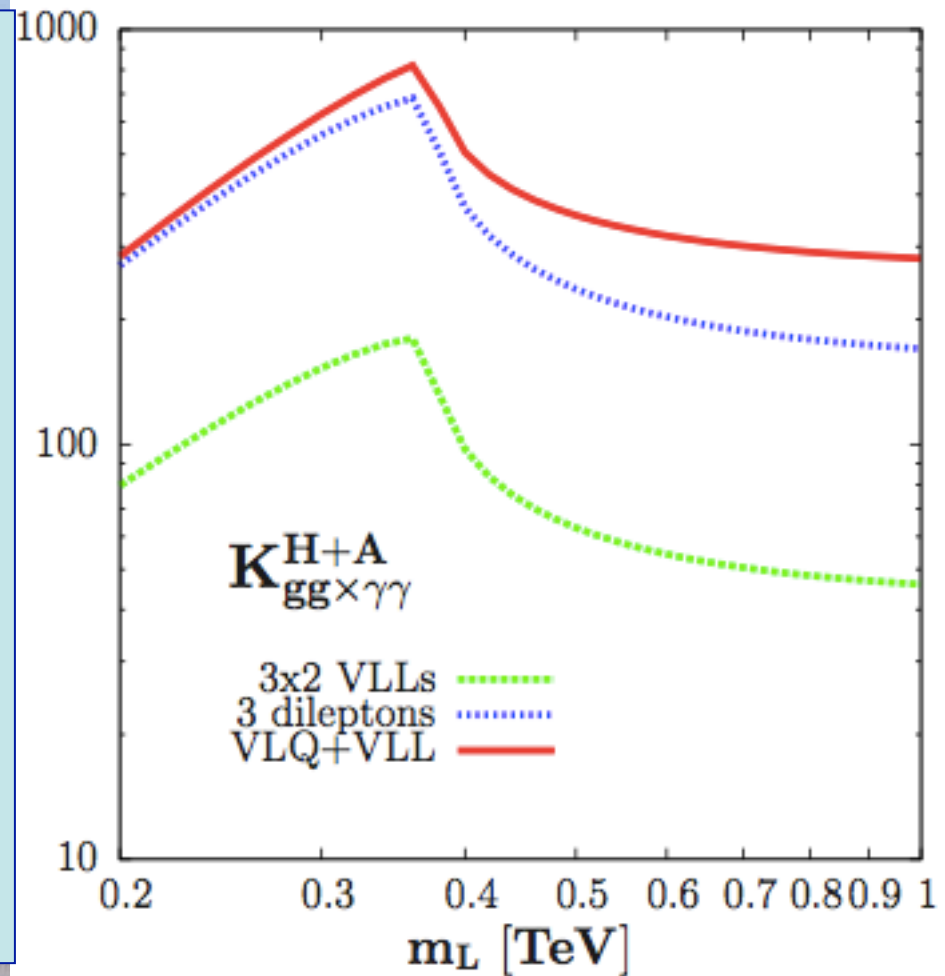


- Enhanced if $m_F \sim M_{\Phi}/2$

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

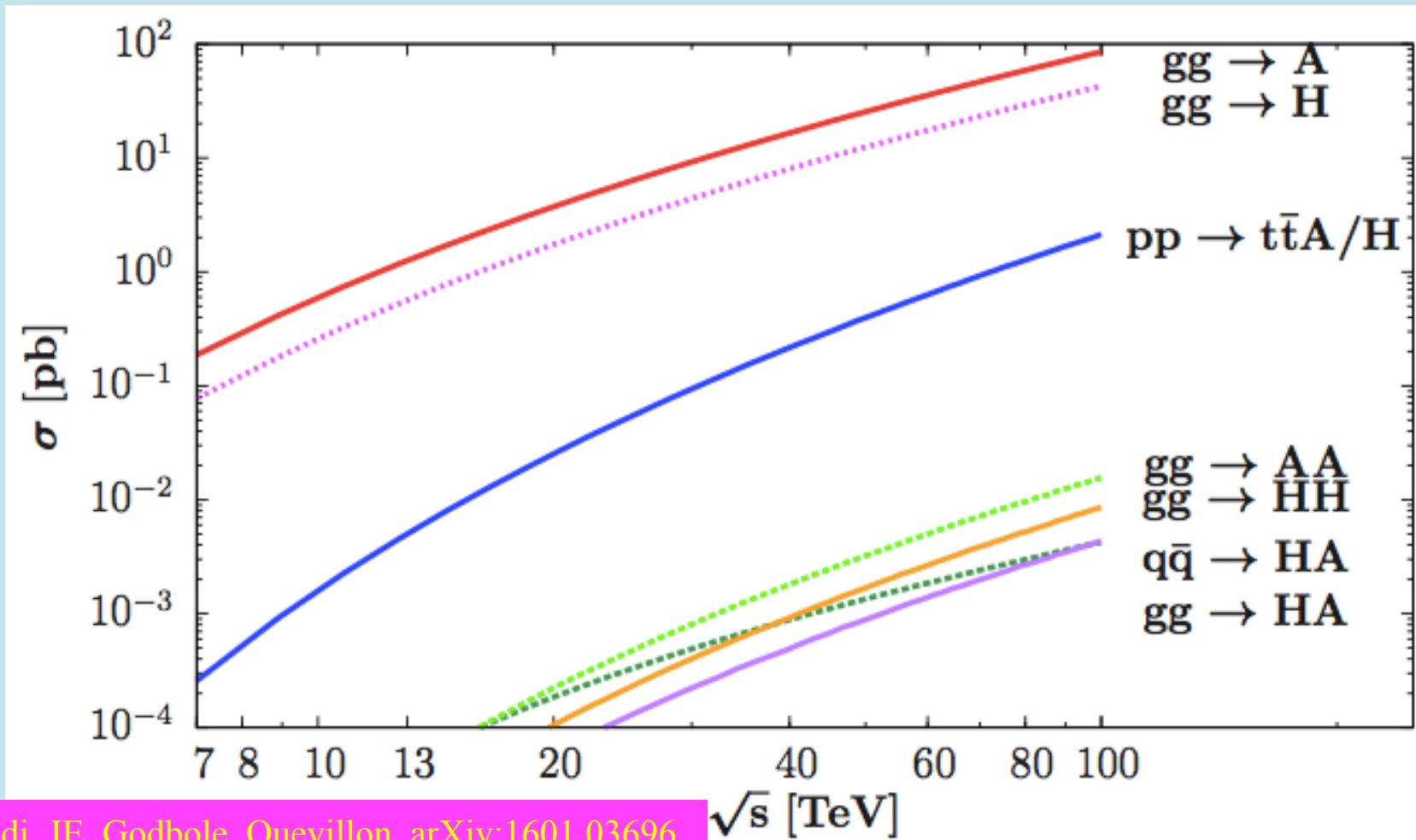
Obtaining Loop Enhancement

- Need loop enhancement
 ~ 500 if $\Gamma \sim 45$ GeV
- **Vector-like generation of quarks and leptons**
- **3 doubly-charged leptons**
- **3 pairs of vector-like leptons**



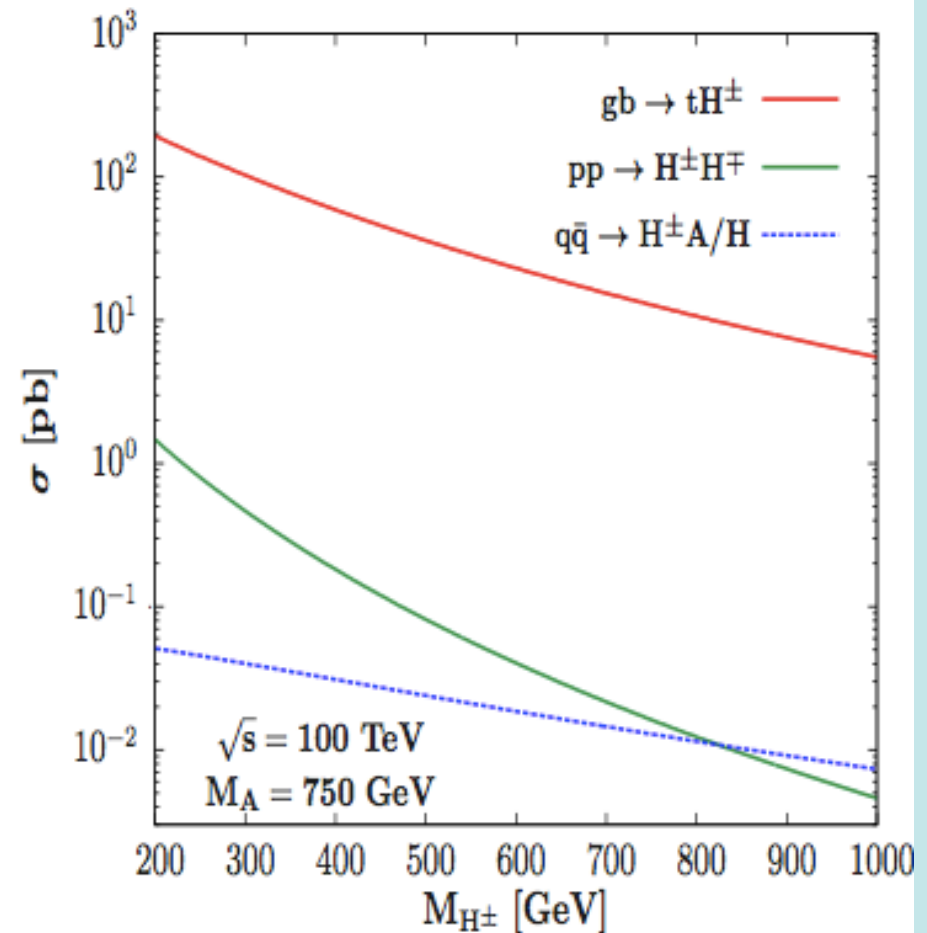
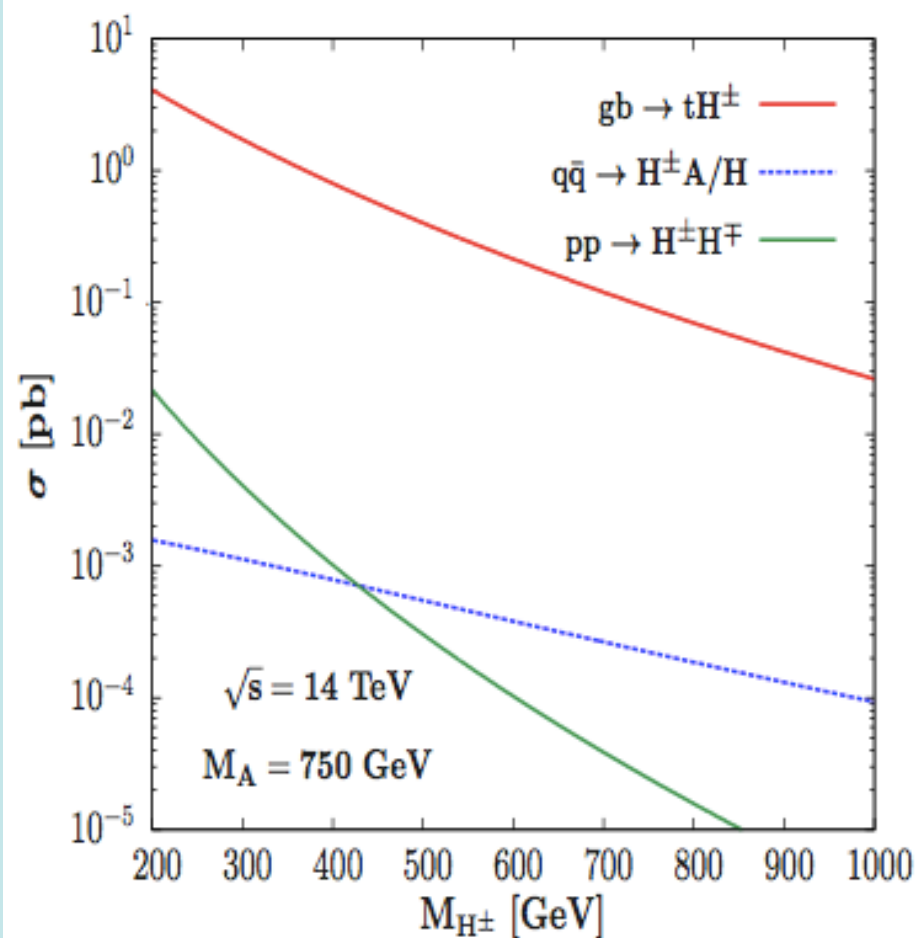
Possible $\Phi = H, A$ Signals

- Normalized to $\sigma_B(\gamma\gamma) = 6 \text{ fb @ } 13 \text{ TeV}$



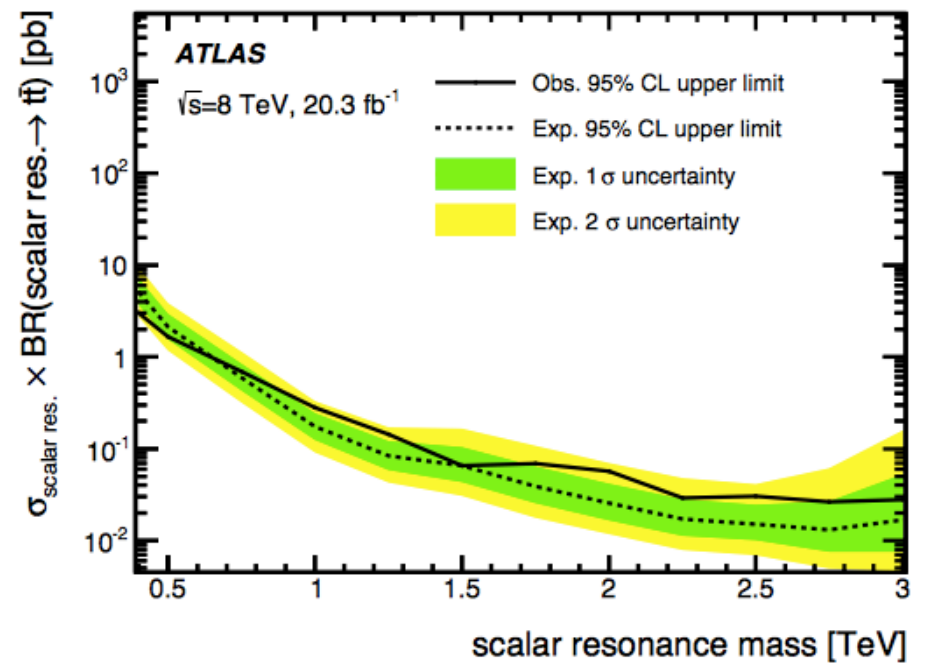
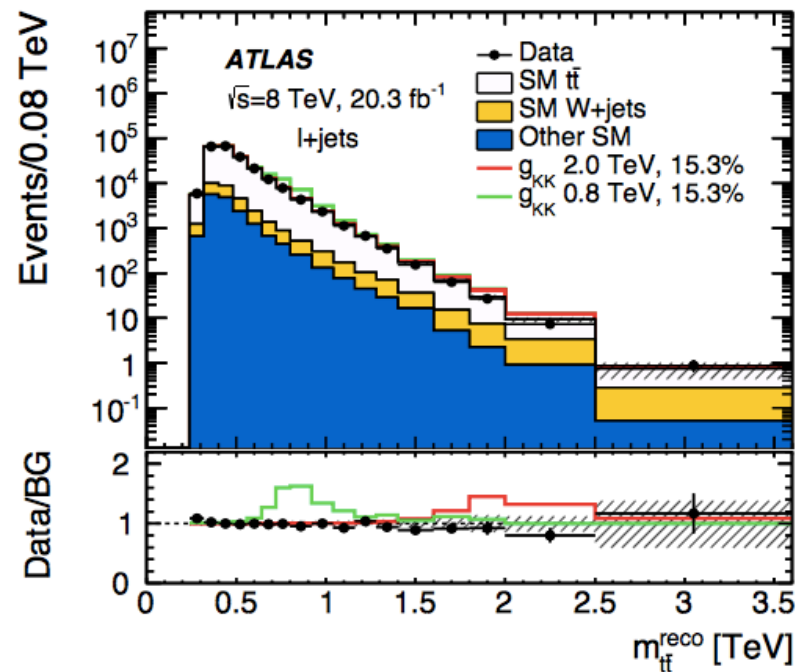
Possible H^\pm Signals

- @ 14, 100 TeV for varying $M_{H^\pm} \neq M_\Phi$ in general



ATLAS Search for Scalar $\rightarrow t \bar{t}$

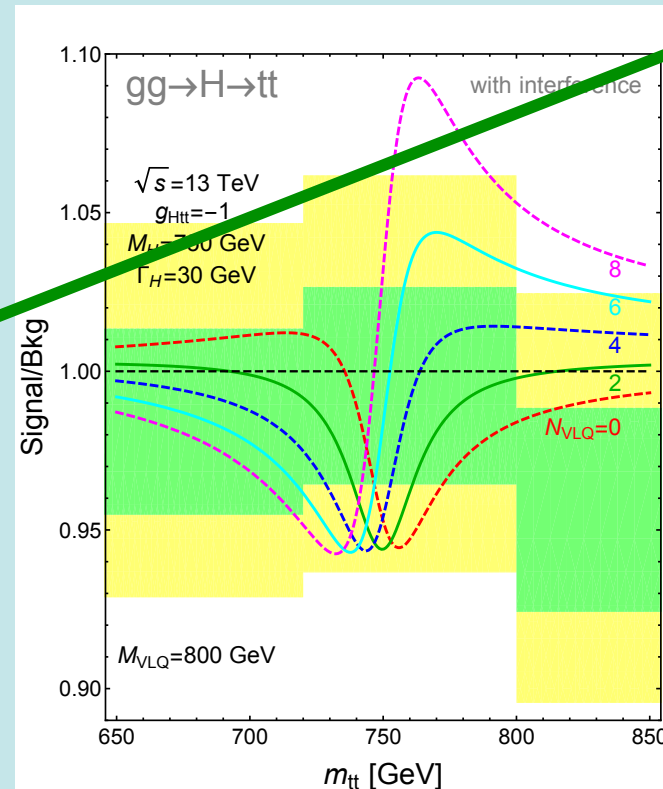
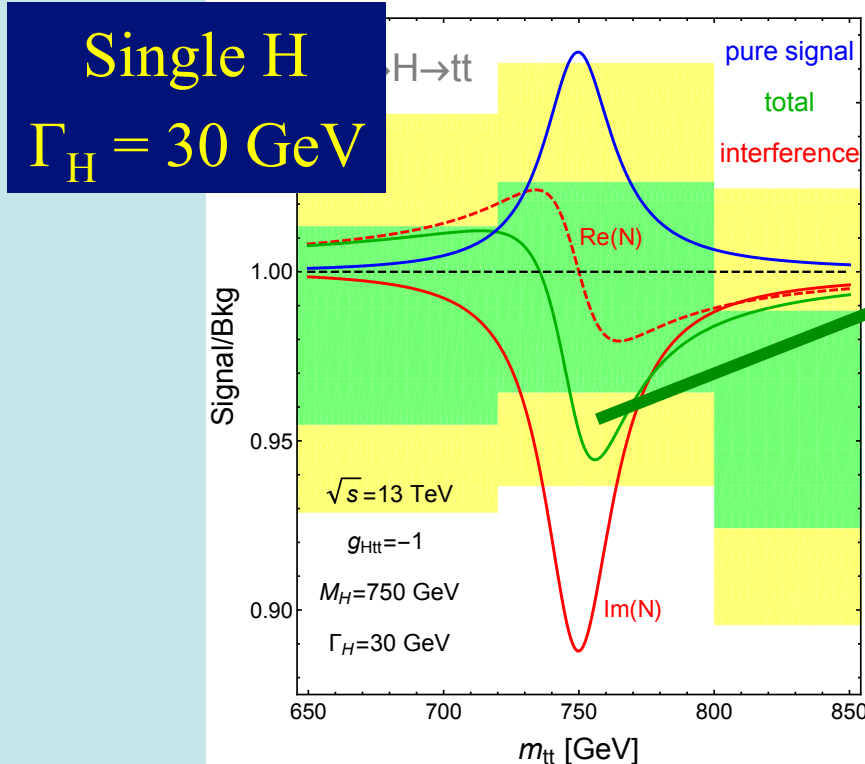
- No sign of any feature in the $t \bar{t}$ mass spectrum



- Absence of peak interpreted as upper limit on resonance production
- BUT interference effects could give a DIP!**

Interference Effects in Scalar $\rightarrow t \bar{t}$

- Interference with $gg \rightarrow t \bar{t}$ background can give **dip**



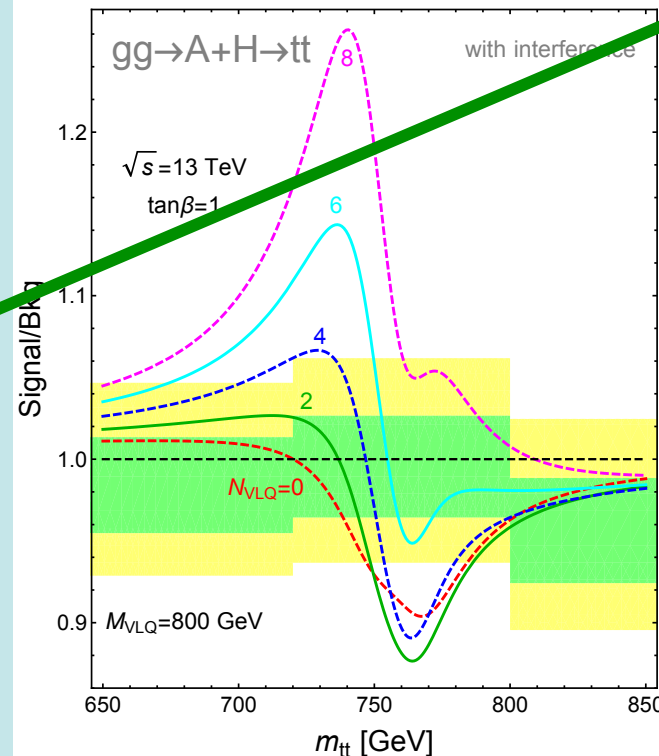
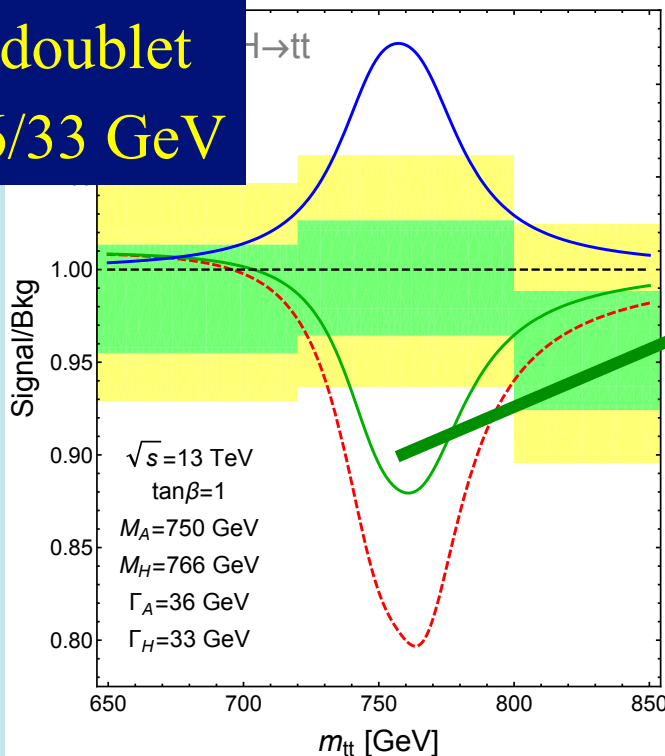
Top loop alone vs. + vector-like quarks

- Brazil bands from ATLAS 8 TeV data

Interference Effects in Doublet $\rightarrow t \bar{t}$


- Interference with $gg \rightarrow t \bar{t}$ background can give **dip**

A/H doublet
 $\Gamma = 36/33 \text{ GeV}$



Top loop alone vs. + vector-like quarks

- Brazil bands from ATLAS 8 TeV data



*“Plus un fait est extraordinaire,
plus il a besoin d’être appuyé de
fortes preuves”*

Laplace, 1812

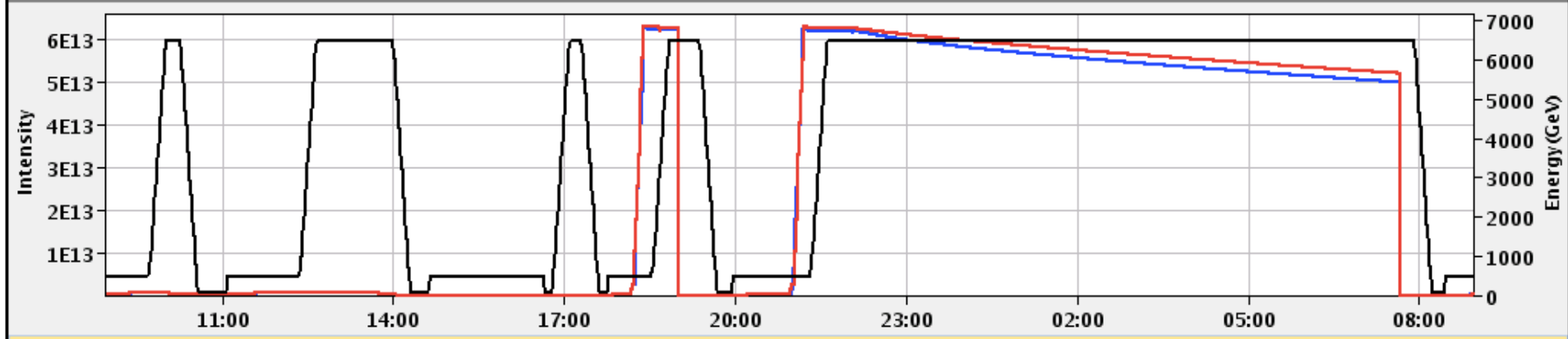
*“The more extraordinary a claim, the
stronger the proof required to support it.”*

12-May-2016 08:56:21 Fill #: 4916 Energy: 450 GeV I(B1): 7.77e+09 I(B2): 7.70e+09

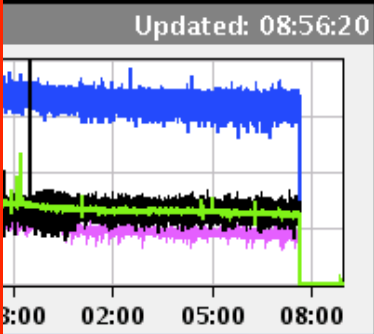
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi [(ub.s) ⁻¹]	0.000	0.000	0.000	0.000
BRAN Luminosity [(ub.s) ⁻¹]	0.0	0.0	0.0	0.0
Fill Luminosity (nb) ⁻¹	58867.137	0.000	0.000	3343.732
Beam 1 BKGD	0.000	0.000	0.000	0.000
Beam 2 BKGD	0.000	0.000	0.000	0.000

LHCb VELO Position **OUT** Gap: 58.0 mm INJECTION PROBE BEAM TOTEM: **STANDBY**

Performance over the last 24 Hrs Updated: 08:56:20

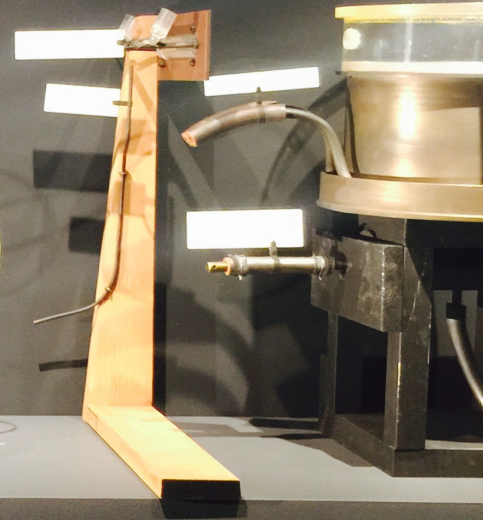
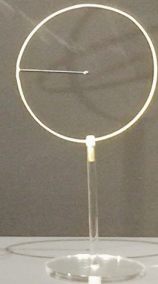


Collisions at 13 TeV
have started again!



— ATLAS — ALICE — CMS — LHCb — ATLAS — ALICE — CMS — LHCb

Higgs champagne in Singapore



The wall is over Champagne bottle, 2012

In 1964, Robert Brout, François Englert, Gerard 't Hooft, Carl Richard Hagen, Tom Kibble and Peter Higgs put forward a bold new idea to explain how fundamental particles acquire mass. Higgs suggested that if they were right, a new particle should exist.

On the evening of 3 July 2012, Higgs shared the bottle of champagne with his friends, theoretical physicist John Ellis and former CERN Director-General Chris Llewellyn Smith. The next day, CERN announced the discovery of the particle he had proposed almost five decades earlier, the Higgs boson.

Higgs, R. Brout, F. Englert, G. 't Hooft, C. R. Hagen, T. Kibble, J. Ellis, P. Higgs

2012年7月3日晚，Higgs 和他的朋友们——理论物理学家 John Ellis 和前任 CERN 主任克里斯蒂安·李维林·史密斯 (Chris Llewellyn Smith) 一起分享了一瓶香槟。第二天，CERN 宣布发现了 Higgs 粒子，这是 Higgs 在 50 年前提出的粒子。Higgs 粒子在 2012 年 7 月 4 日被发现。



Bohr's atom Rutherford – Bohr atomic models, 1920

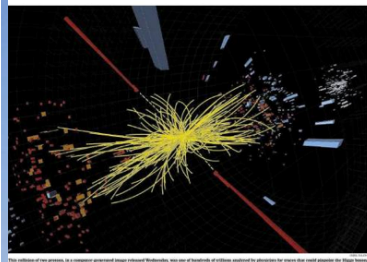
In the early 20th century, the electron was the only subatomic particle known. When Ernest Rutherford and his team at Manchester discovered that atoms had another particle at their centre – later named the 'proton' – a new theory was needed to describe the atom's inner structure.

20 世纪初，人们只知道一种亚原子粒子——电子。英国曼彻斯特大学的欧内斯特·卢瑟福 (Ernest Rutherford) 和他的团队发现原子中心还有另一种粒子——后来被称为“质子”。这就需要一种新的理论来描述原子的内部结构。

These models, showing steps of electrons orbiting a nucleus, depict the atomic theory proposed by Rutherford in 1911 and refined by Niels Bohr in 1913. This planetary structure became the visual image of the atom in popular culture.

这些模型展示了电子围绕原子核运动的步骤，描绘了 1911 年由卢瑟福提出的原子理论，并在 1913 年由尼尔斯·玻尔进行了完善。这种行星状结构成为大众文化中原子的视觉形象。





Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small... Physicists say the discovery of a subatomic particle that looks like the Higgs boson...

July 4th 2012
The discovery of a new particle

The Economist
A giant leap for science
Finding the Higgs boson

News article snippet with photo of a man in a suit, likely related to the Higgs boson discovery.

News article snippet in Japanese: '新素粒子検出 年内に結論'

Milhares de moradores de bairros sociais em risco de perderem RSI
A mudança está a passar despercebida, mas deve afectar milhares de beneficiários de RSI...

Science: la matière dévoilée
Le boson de Higgs, particule mystérieuse pour expliquer l'univers, vient d'être découvert...

MK
ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ
METRO СПУСКАЕТ НА ВОДУ

AD ALGEMEEN DAGBLAD
EINDELIJK BELIJK NA 48 JAAR
Zieke Kaj en zijn moeder toch samen in de VS

Frankfurter Allgemeine
Masse macht's
Große Mehrheit in...

Oil Backed Up, Iranians Put It On Idled Ships
Subsidies of Tankers as Embargo Tightens

Physicists Find Elusive Particle Seen as Key to Universe



Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

The Gazette
EL PAIS
EL PERIODICO GLOBAL EN ESPAÑOL

Science: la matière dévoilée
7.2 milliards de plus dès 2012

ALGÈRE L'INDÉPENDANCE
Une fête sans panache

fallada la partícula clave para a comprensión del universo
La Audencia Nacional imputa a toda la cúpula de Bankia

DANGEROUS MOVE
Freeing captured animals may lead to disasters

CHINA DAILY
MOVIE PLOT
Iron Man film company looks to China for screen success

THE TIMES OF INDIA
Big bang moment: Scientists may have found 'God particle'
Adarsh scam: Finally, CBI charges sheets 13

THE HINDU
Elusive particle found, looks like Higgs boson
CERN physicists had evidence of game-changing discovery of subatomic particle

CORRIERE DELLA SERA
La particella che può svelare i segreti dell'universo
Czaszkie Higgsa fizycy najpierw wymyślił, potem szukali 40 lat
BOSKA MASA

গাজেতা
বিশ্বজ্ঞানের 'ঈশ্বর' দর্শন
'পেয়েছি, যা খুঁজছিলাম'

July 4th 2016

The discovery of a
new particle?

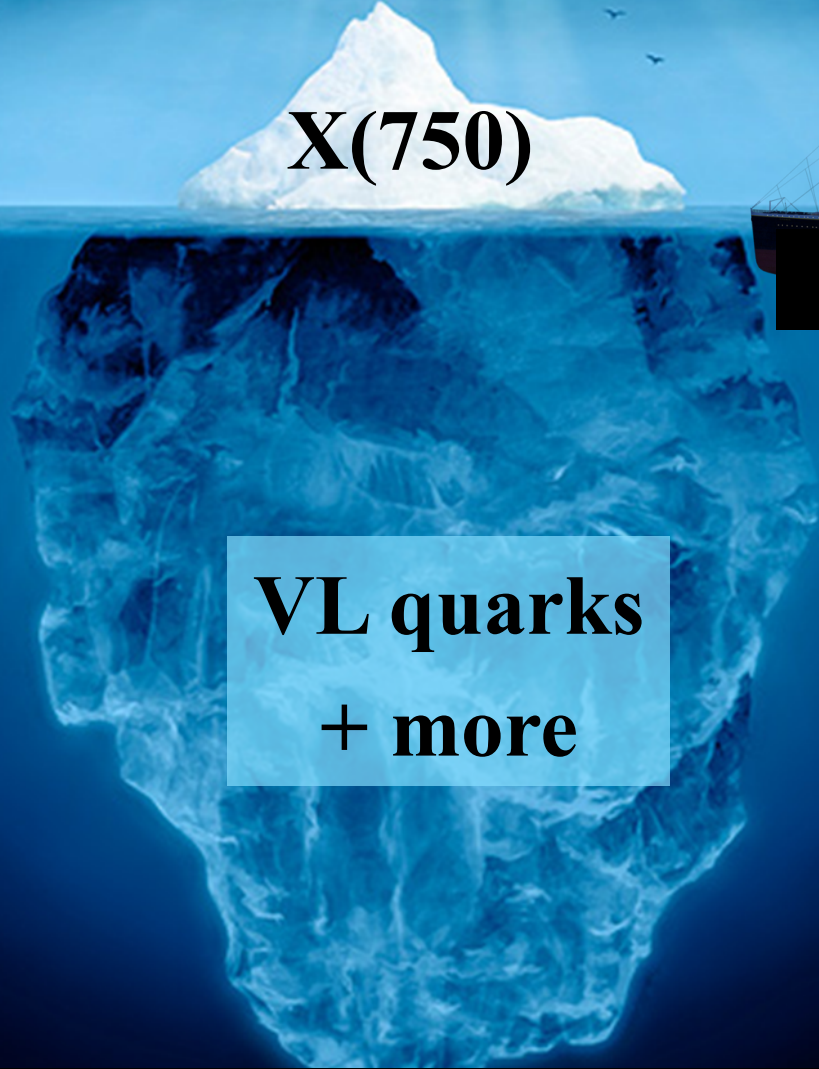


Summary

X(750)

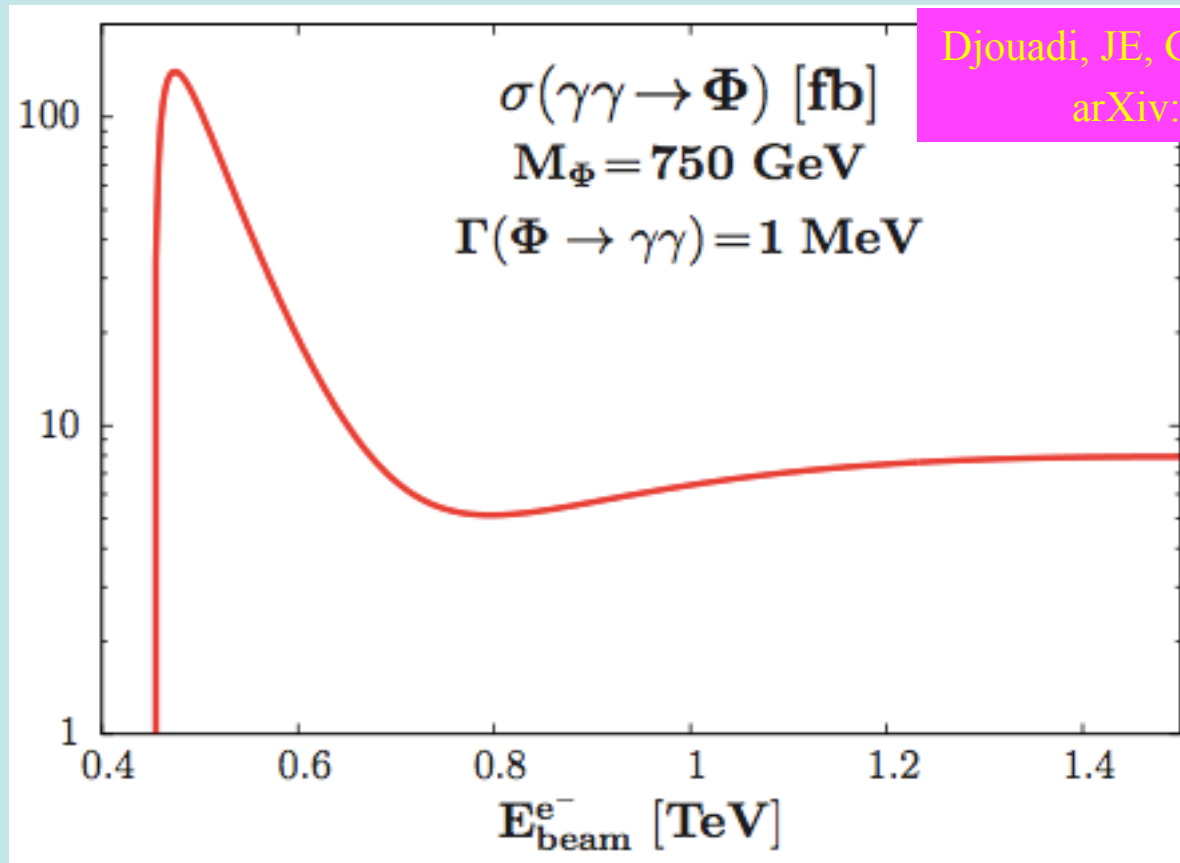
Standard Model

**VL quarks
+ more**



$\gamma\gamma \rightarrow X$ Signal at e^+e^- Collider

- For $\sigma_B(\gamma\gamma) = 6$ fb, assuming $X \rightarrow gg$ dominant



Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

- Centre-of-mass energy ~ 1 TeV preferred!

$\gamma\gamma \rightarrow \Phi$ Signal at e^+e^- Collider

- For $\sigma_B(\gamma\gamma) = 6$ fb, assuming $\Gamma(\Phi=H,A) = 45$ GeV
- e^+e^- centre-of-mass energy ~ 1 TeV

Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

