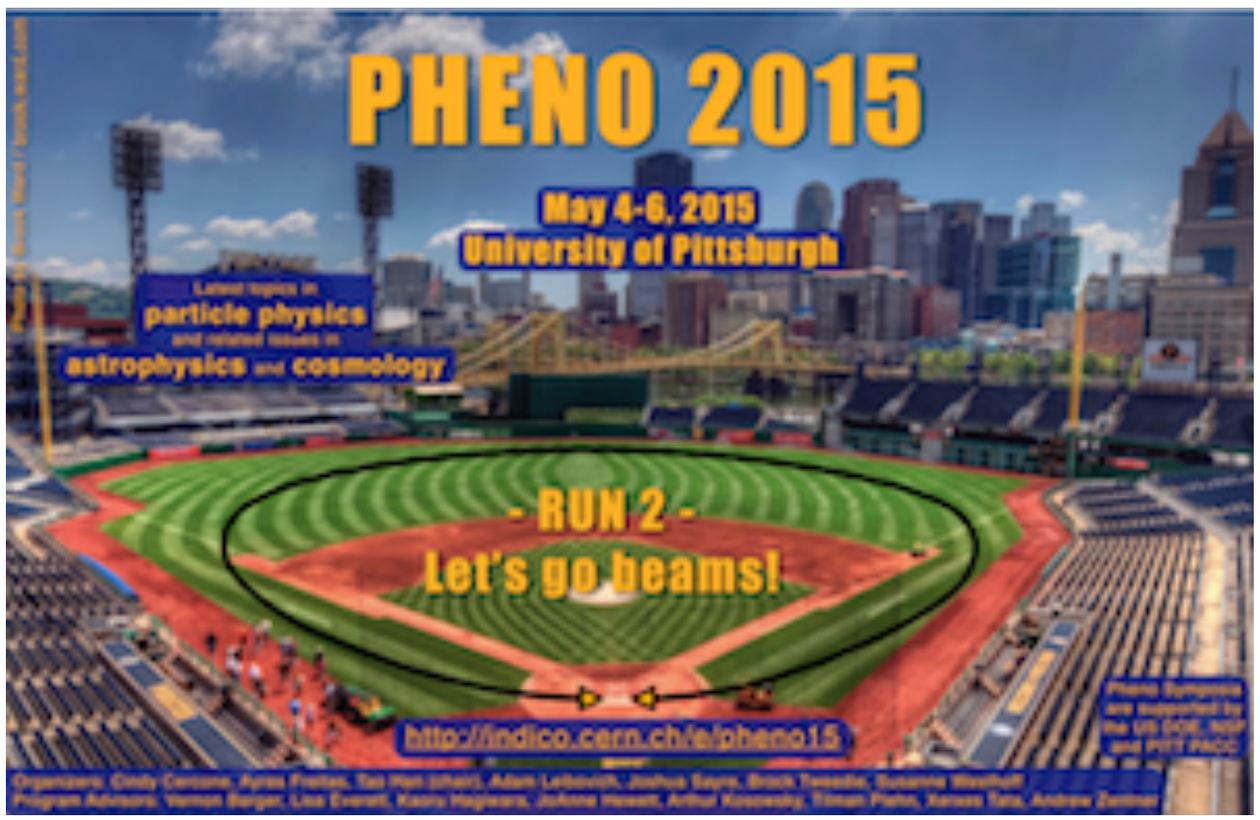
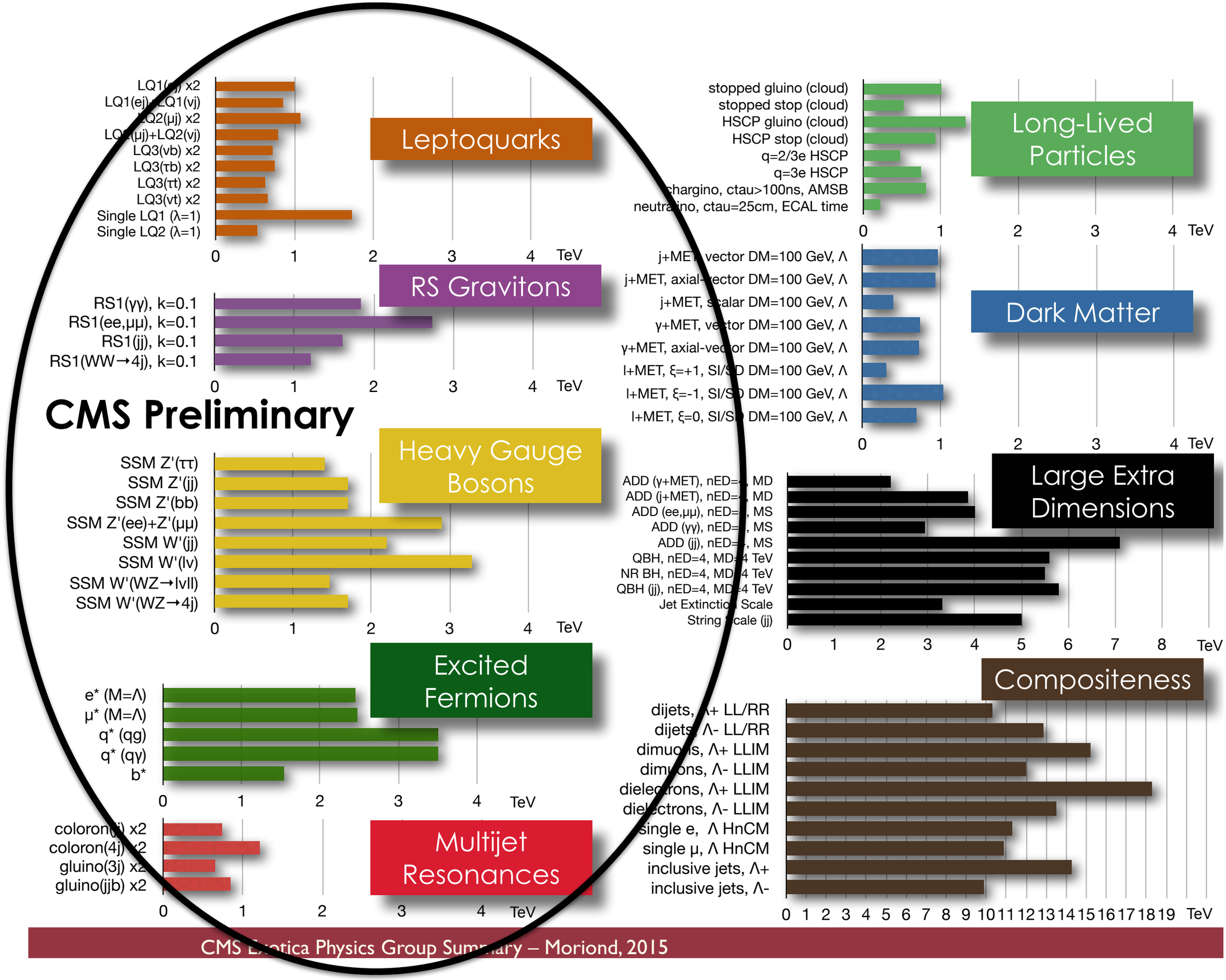
New Resonances: Theory and Experiment

R. Sekhar Chivukula

Pheno 2015

May 4, 2015





CMS Exotica Physics Group Summary – Moriond, 2015

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8\ \text{TeV}$

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass 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 $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	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 BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \rightarrow t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV		Preliminary
	CI $qq\ell\ell$	2 e, μ			20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.35 TeV	$\lvert C_{LL}\rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 $e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \rightarrow Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \rightarrow Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \rightarrow Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \rightarrow Wt + X$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		Preliminary
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	2 $e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 $e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=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, $\lvert q\rvert = 5e$	Preliminary
	Magnetic monopoles	–		–	2.0	monopole mass 862 GeV	DY production, $\lvert g\rvert = 1g_D$	1207.6411

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

10^{-1} 1 10

Mass scale [TeV]

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

New Resonances:
Theory and Experiment

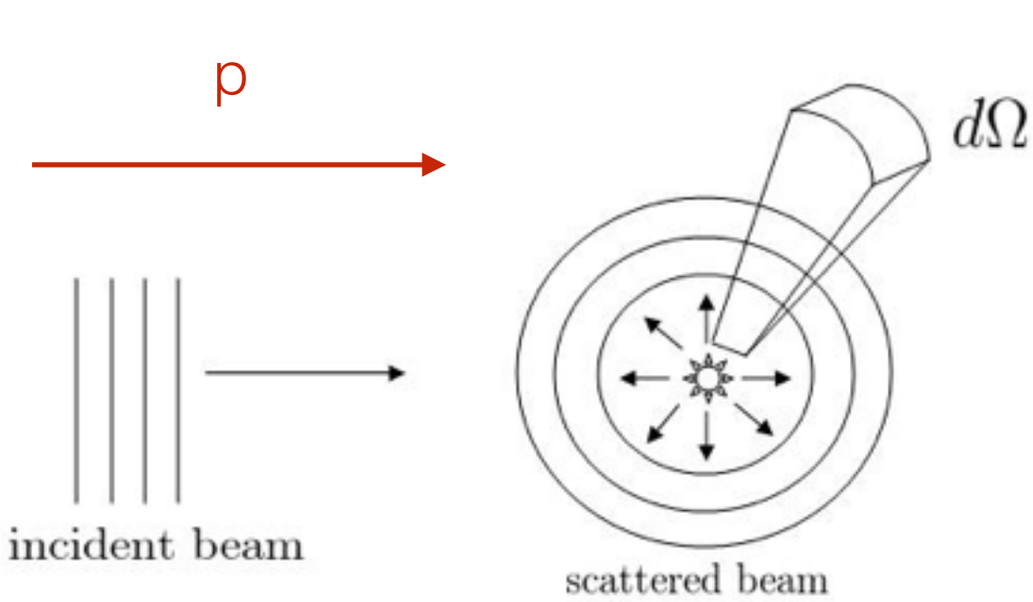
- What are Resonances?
- “s-channel” Resonances
- Pair-Produced Resonances
- Upcoming Talks

What are Resonances?

Resonances: in QM

Analytic Continuation

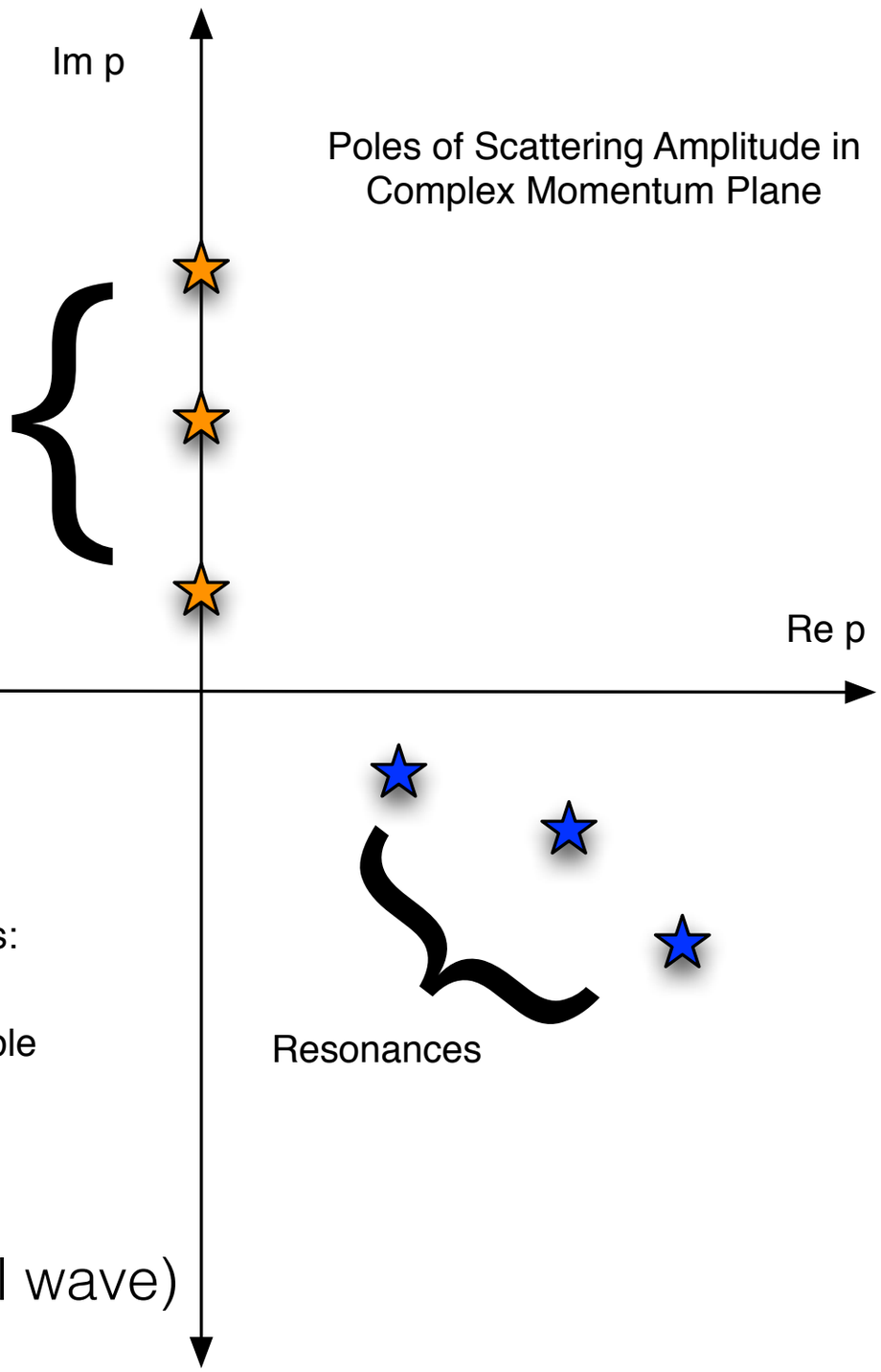
$$\psi(\vec{r}) = e^{ipz} + f(p, \cos\theta)\frac{e^{ipr}}{r}$$



Physical States:
Im p > 0
e^{ipr} normalizable

Bound States

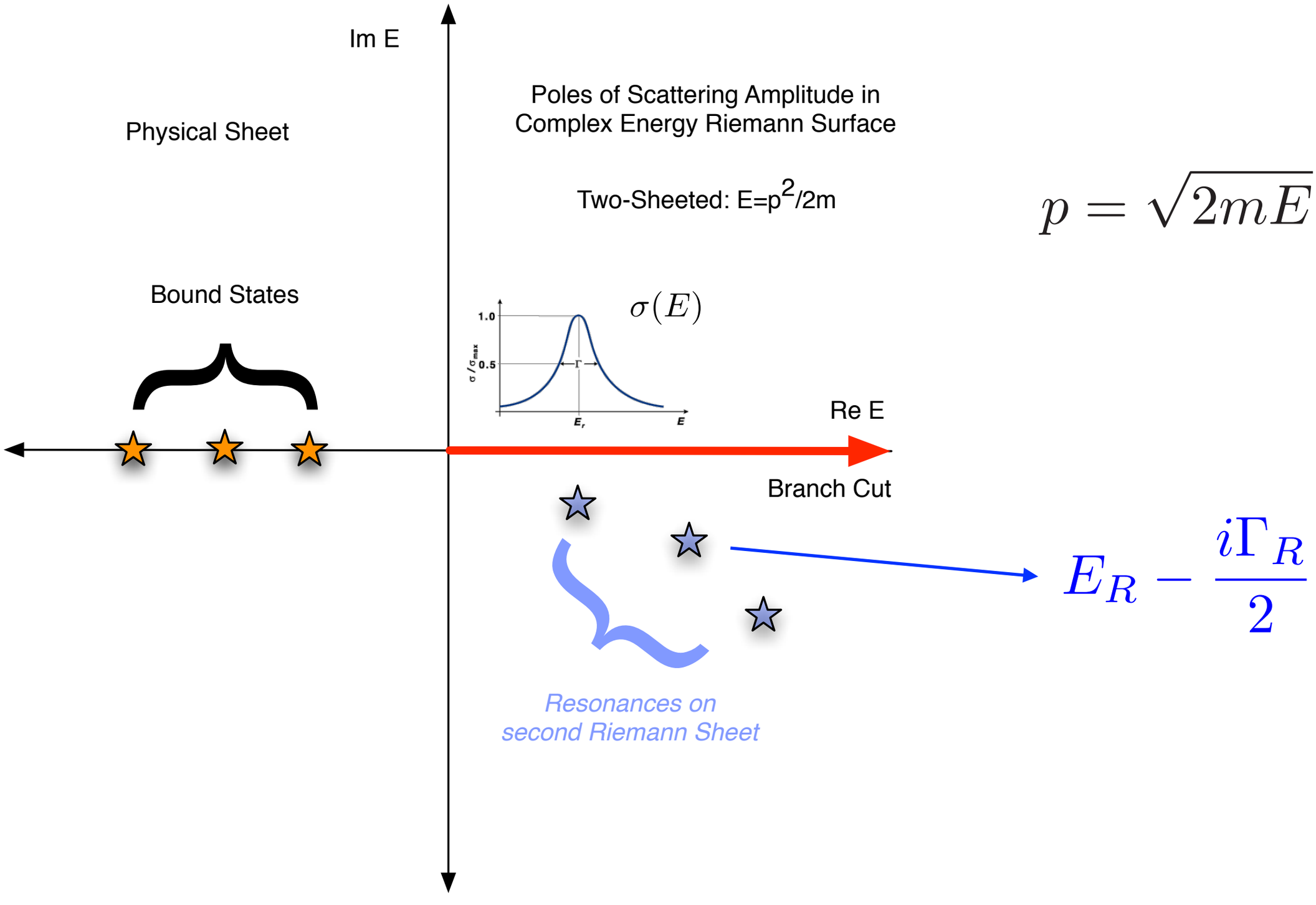
Unphysical States:
Im p < 0
e^{ipr} not normalizable



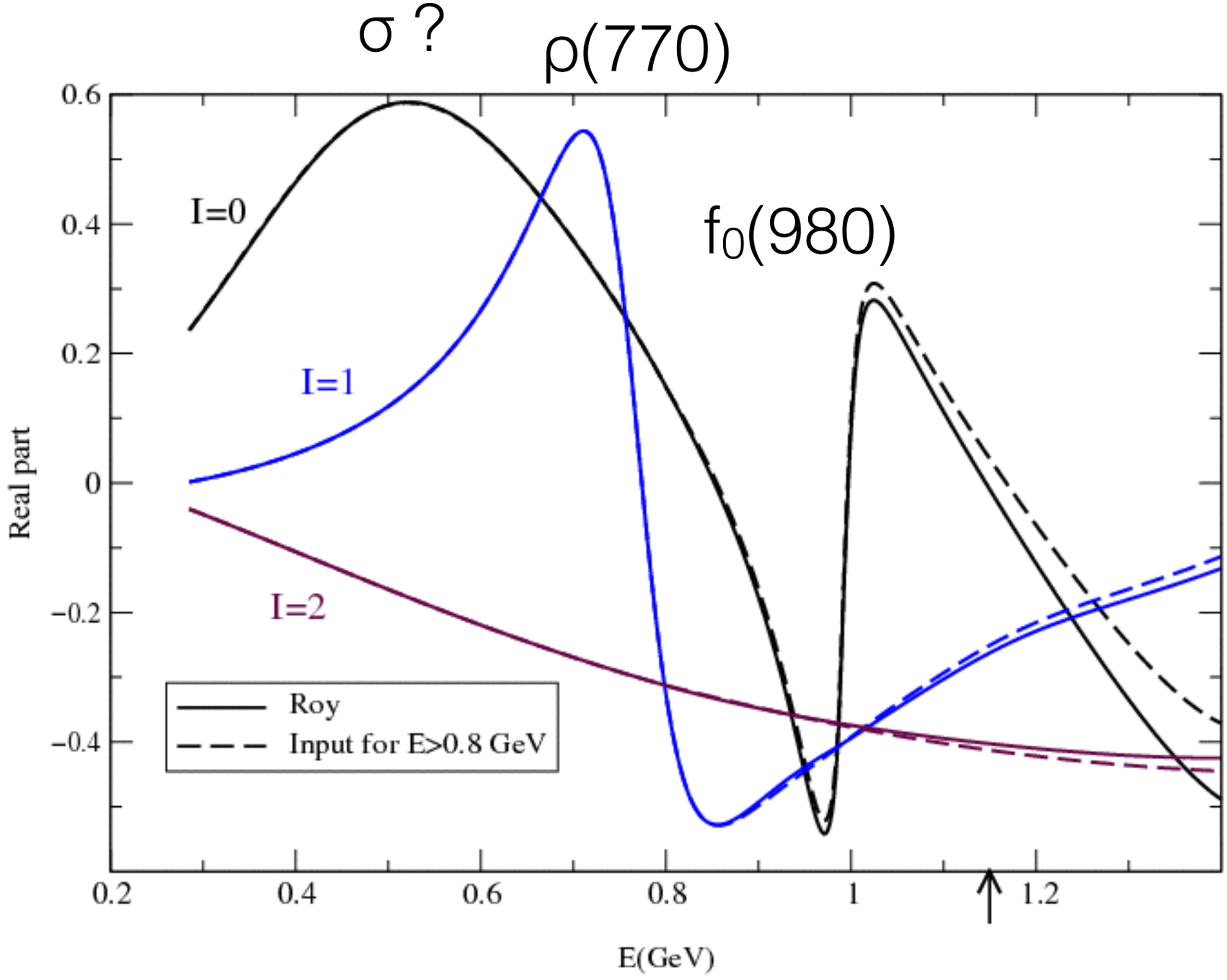
Poles of Scattering Amplitude in Complex Momentum Plane

(fixed angle or partial wave)

Resonances in E Plane



A Cautionary Tale: ππ Scattering



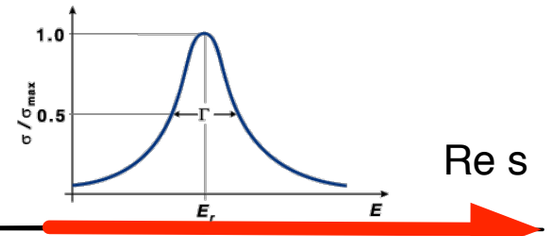
B. Ananthanarayan, et. al., hep-ph/0005297

I=0 ππ Scattering

Im s

Physical Sheet

Poles of ππ Scattering Amplitude in
Complex s Riemann Surface, at fixed t



Re s

Branch Cut

$4m_\pi^2$

$f_0(980)$

σ

Resonances on second Riemann Sheet

$m_\sigma \approx \Gamma_\sigma$

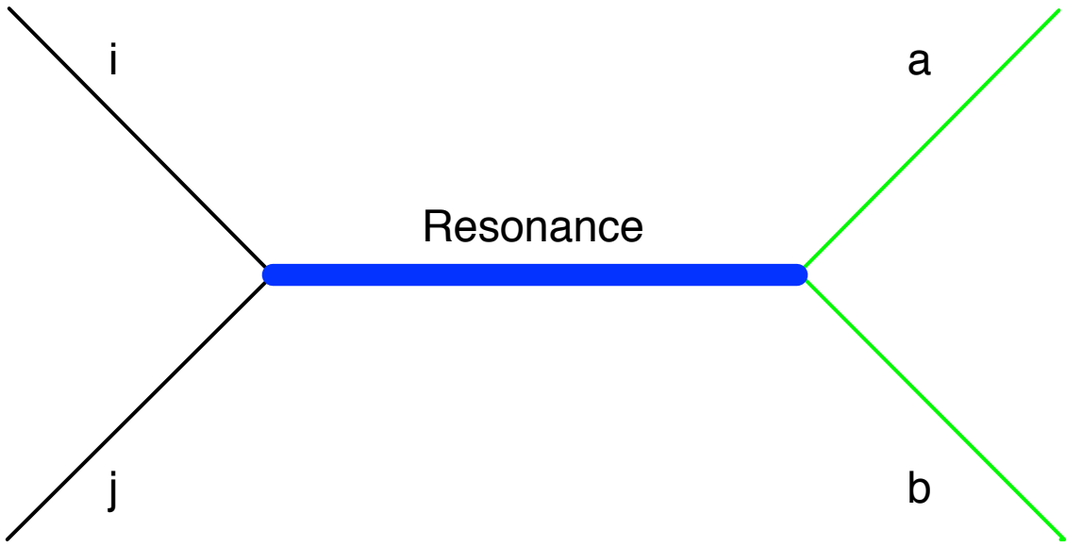
Is the σ resonance usefully considered a particle?

$$\sqrt{s_\sigma} = (400 - 550) - i(200 - 350)\,\mathrm{MeV}$$

PDG, 2014

“s-channel” Resonances

s-channel Resonance Production



i,j = u,d,g,γ,W,Z

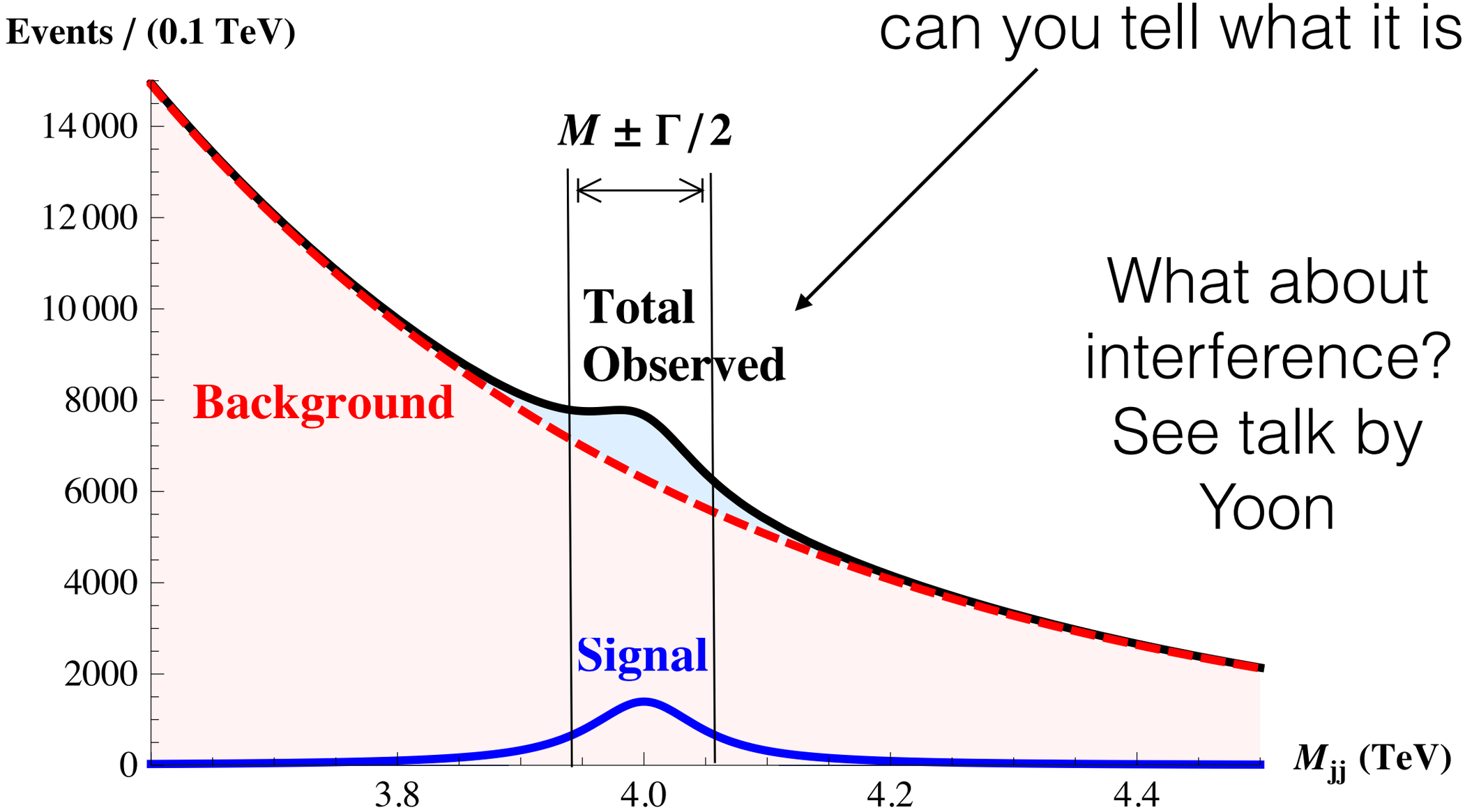
a,b = j,t,b,g,γ,W,Z,h

Characteristics vs. Observables

- i,j: event characteristics
- Couplings: BR: σ * BR
- Mass and width: $d\sigma/dm_{ab}$
- Spin: $d\sigma/d\cos\theta_{ab}$
- a,b: in each decay channel
  - flavor tagging
  - jet substructure

NB: If a,b can be light quarks,
t-channel process may be relevant

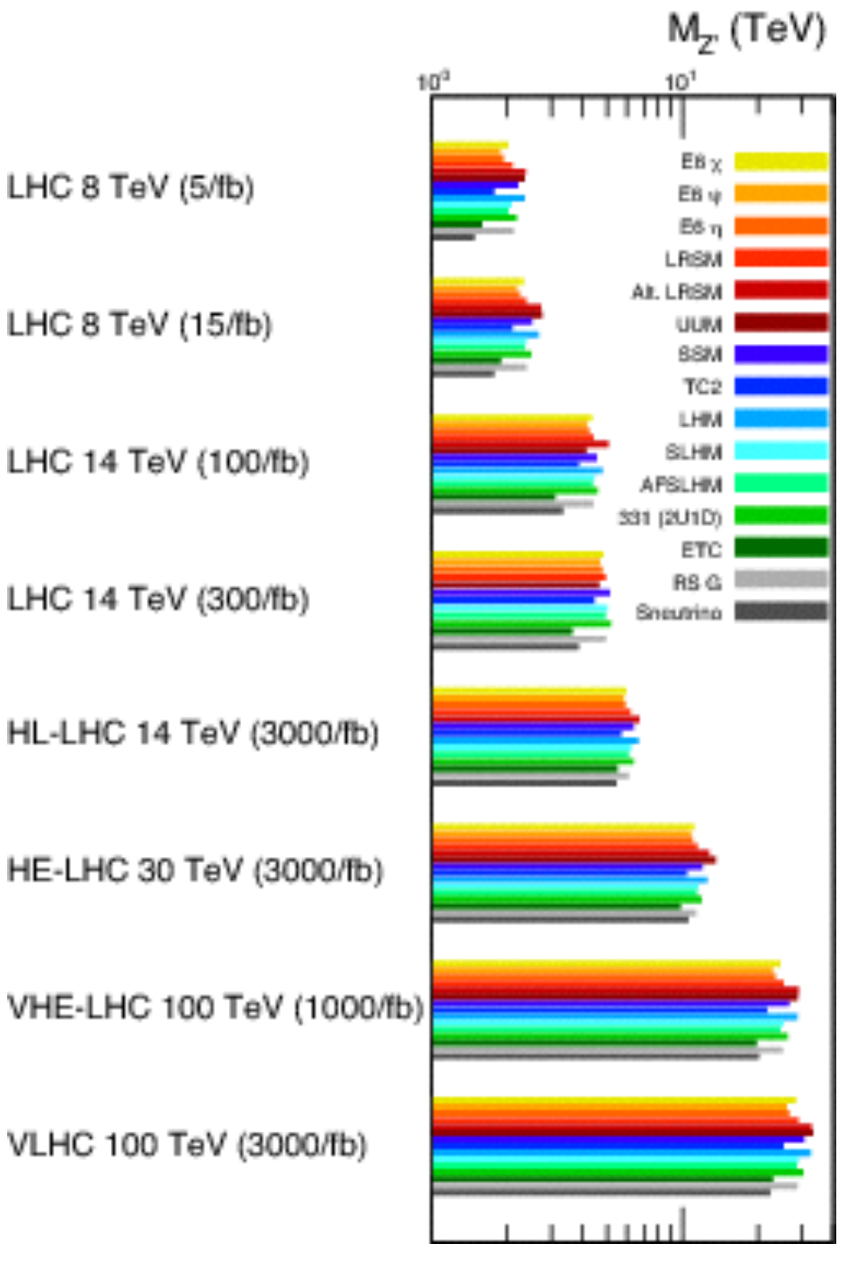
Observation



If you can see it,
can you tell what it is?

What about
interference?
See talk by
Yoon

New Gauge Bosons



GUTS, DEWSB, Extra-d,…

Color Octet Vector Resonances

Gauge bosons from extended color groups:

Classic Axigluon: P.H. Frampton and S.L. Glashow, Phys. Lett. B 190, 157 (1987).

Topgluon: C.T. Hill, Phys. Lett. B 266, 419 (1991).

Flavor-universal Coloron: R.S. Chivukula, A.G. Cohen, & E.H. Simmons, Phys. Lett. B 380, 92 (1996).

Chiral Color with $g_L \neq g_R$: M.V. Martynov and A.D. Smirnov, Mod. Phys. Lett. A 24, 1897 (2009).

New Axigluon: P.H. Frampton, J. Shu, and K. Wang, Phys. Lett. B 683, 294 (2010).

Similar color-octet states:

KK gluon: H. Davoudiasl, J.L. Hewett, and T.G. Rizzo, Phys. Rev. D63, 075004 (2001)
B. Lillie, L. Randall, and L.-T. Wang, JHEP 0709, 074 (2007).

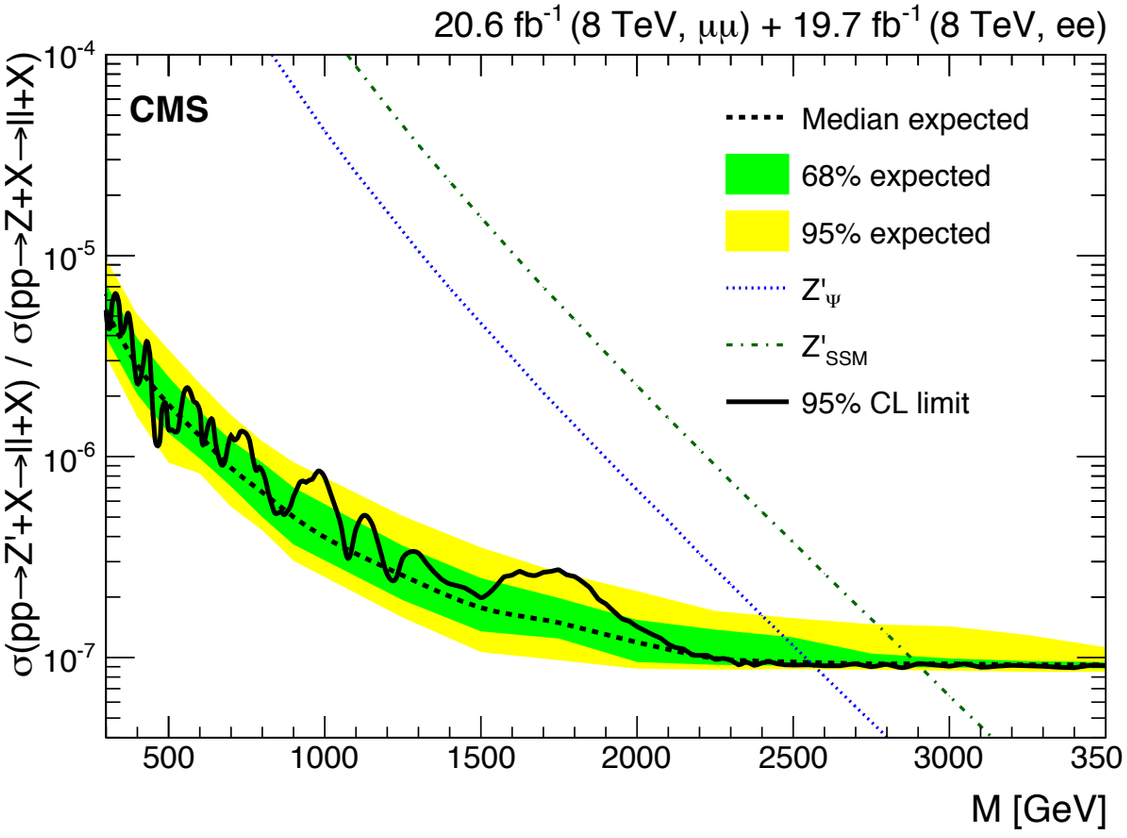
Techni-rho: E. Farhi and L. Susskind, Physics Reports 74, 277 (1981).

More exotic colored states:

Color sextets, colored scalars, low-scale scale string resonances...
T. Han, I. Lewis, Z. Liu, JHEP 1012, 085 (2010).

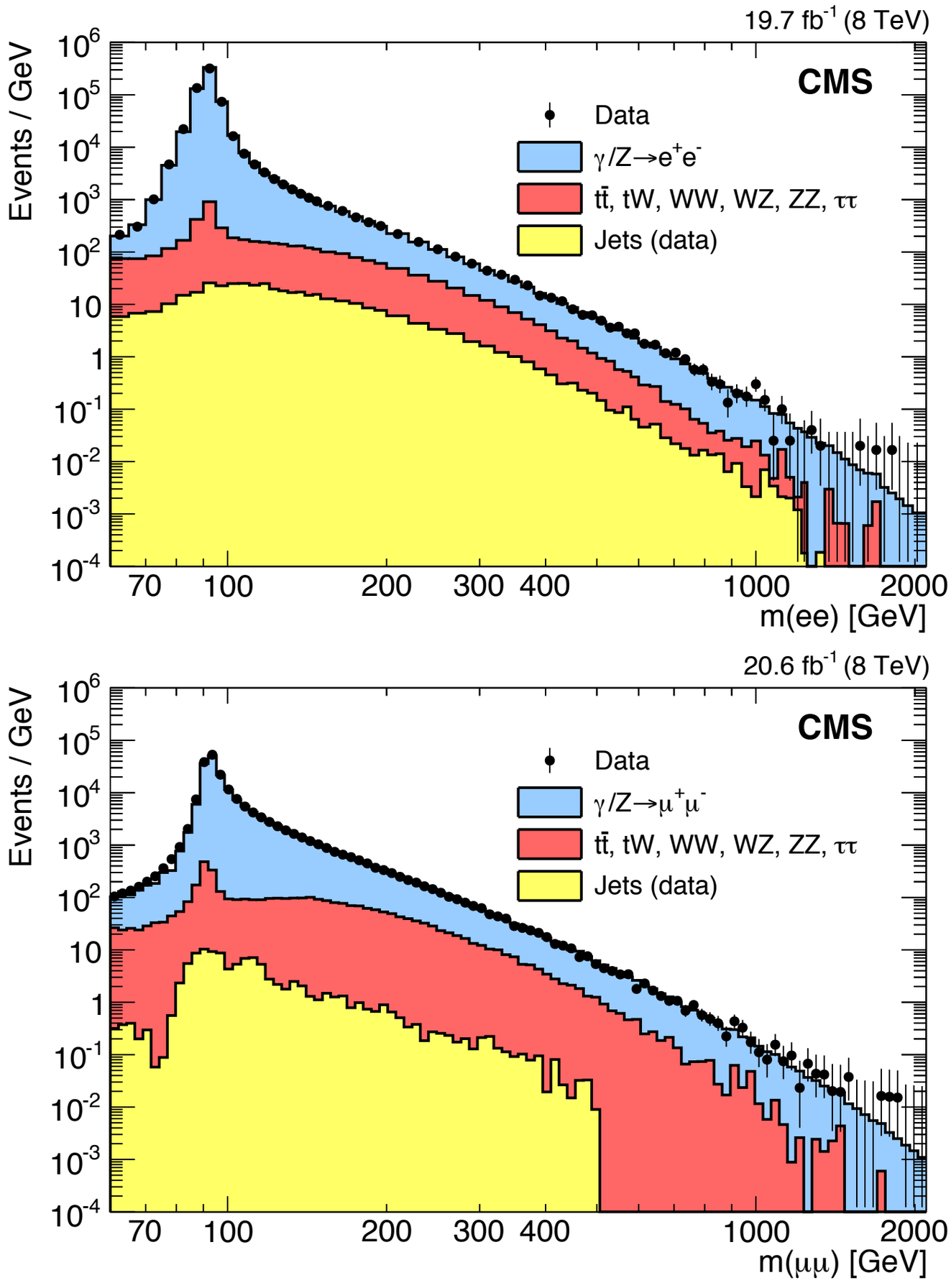
Dilepton Resonances

Flavor-independent Z'

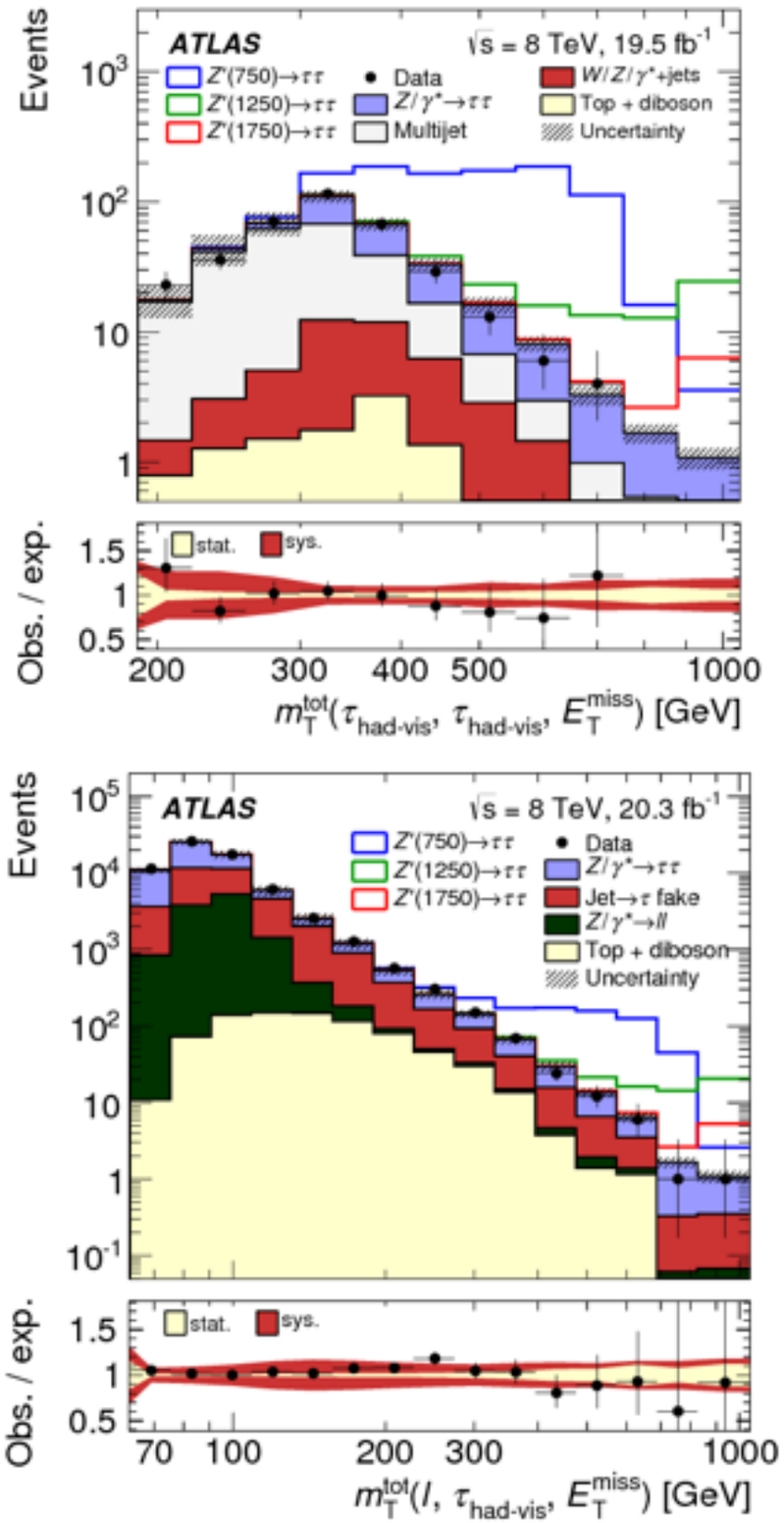


Limits: 2.5-3 TeV

CMS EXO-12-061

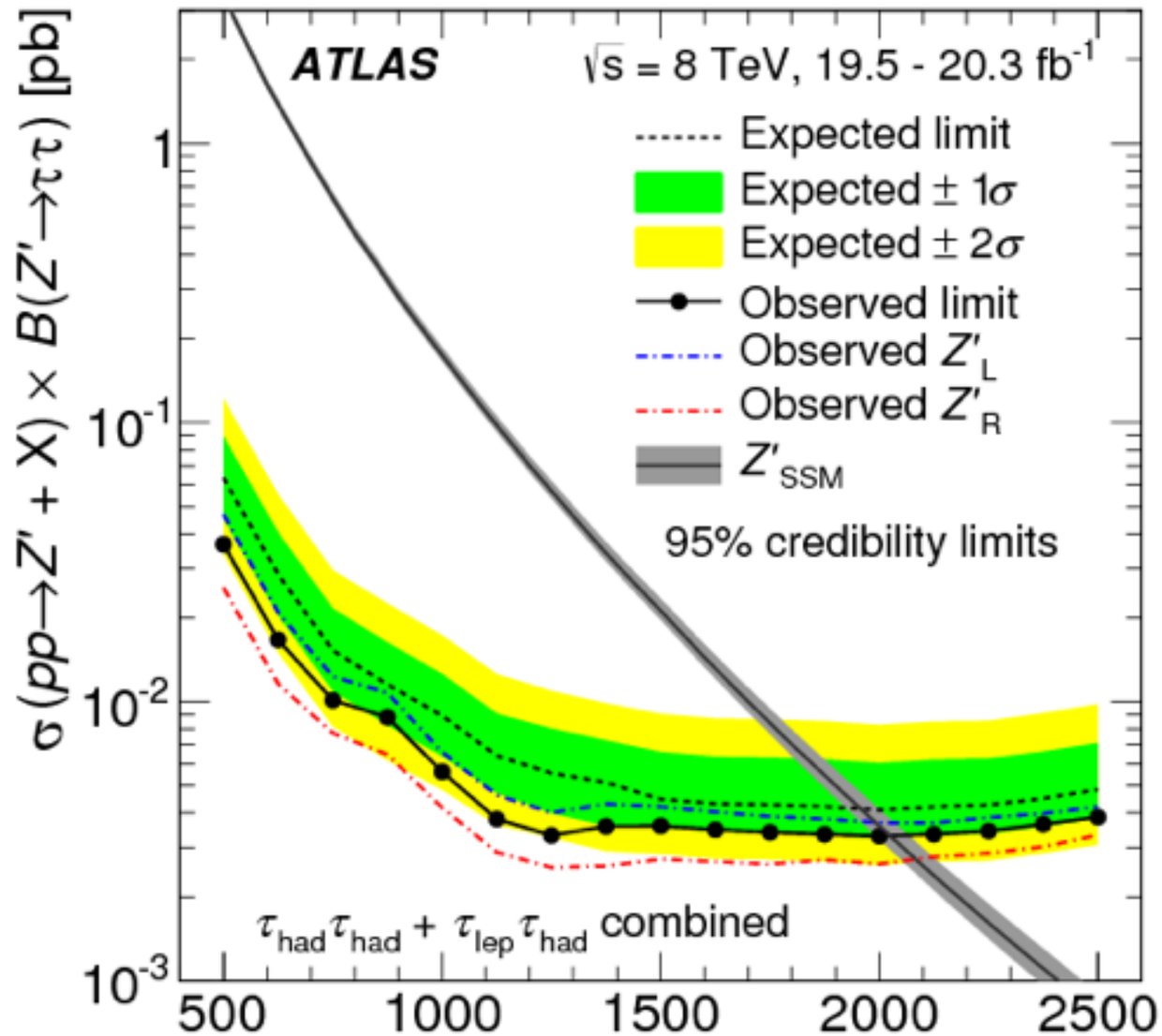


Third Generation Dilepton Resonances



Z'→τ+τ-→hadrons, leptons + E_T^{miss}

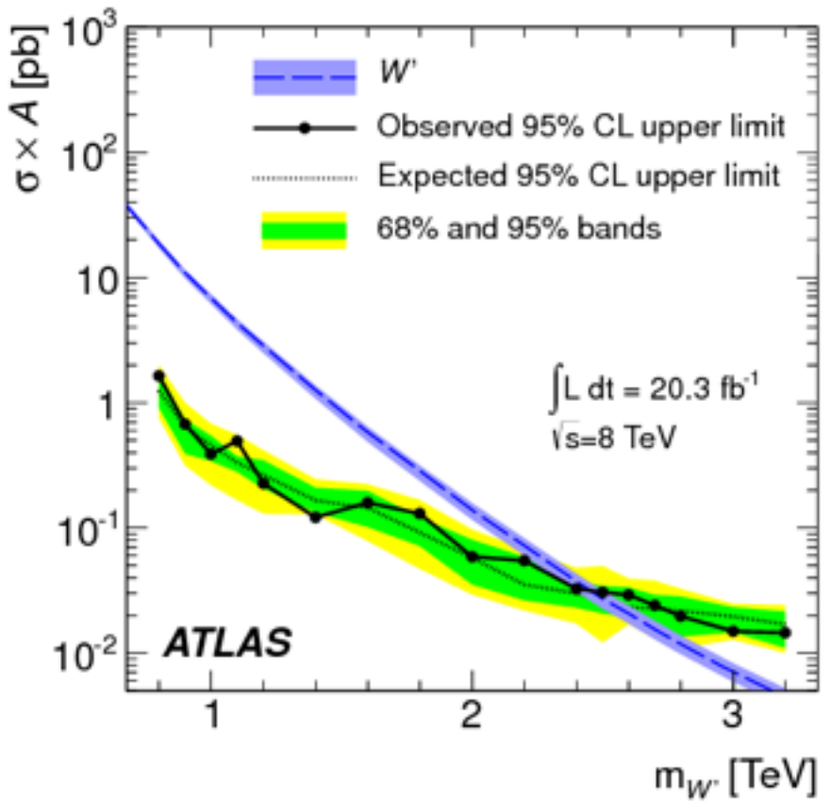
Limits: > 2 TeV

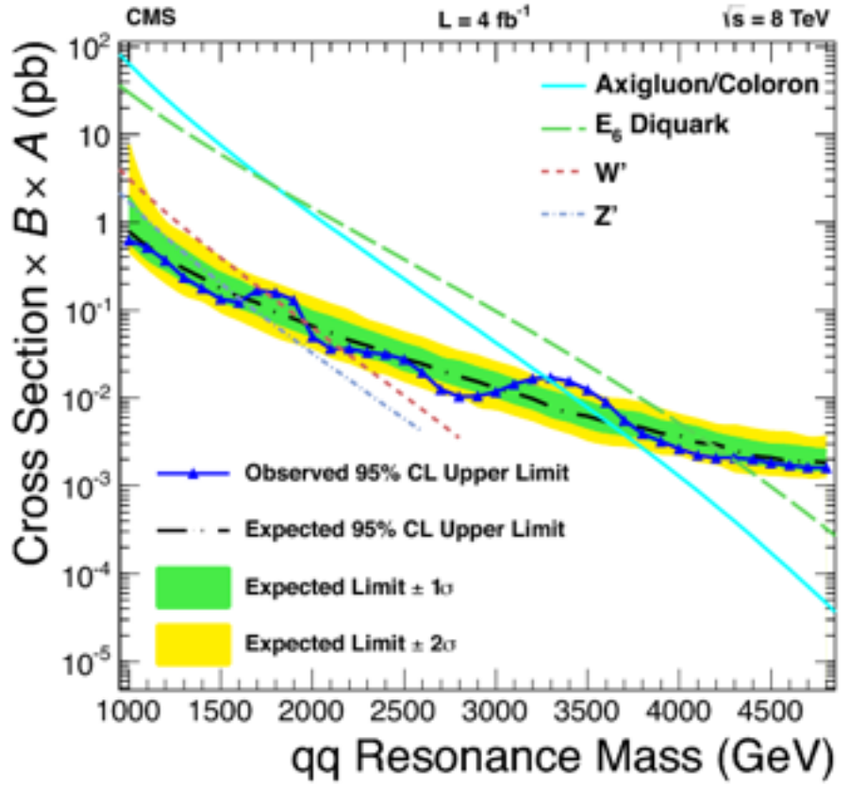


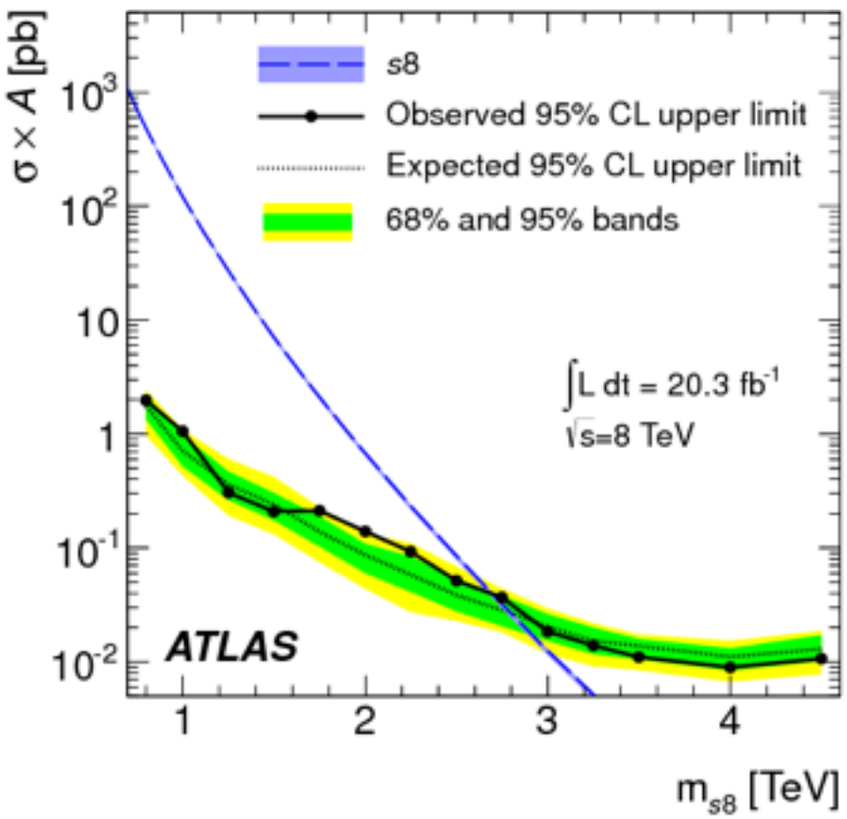
ATLAS CERN-PH-EP-2015-018

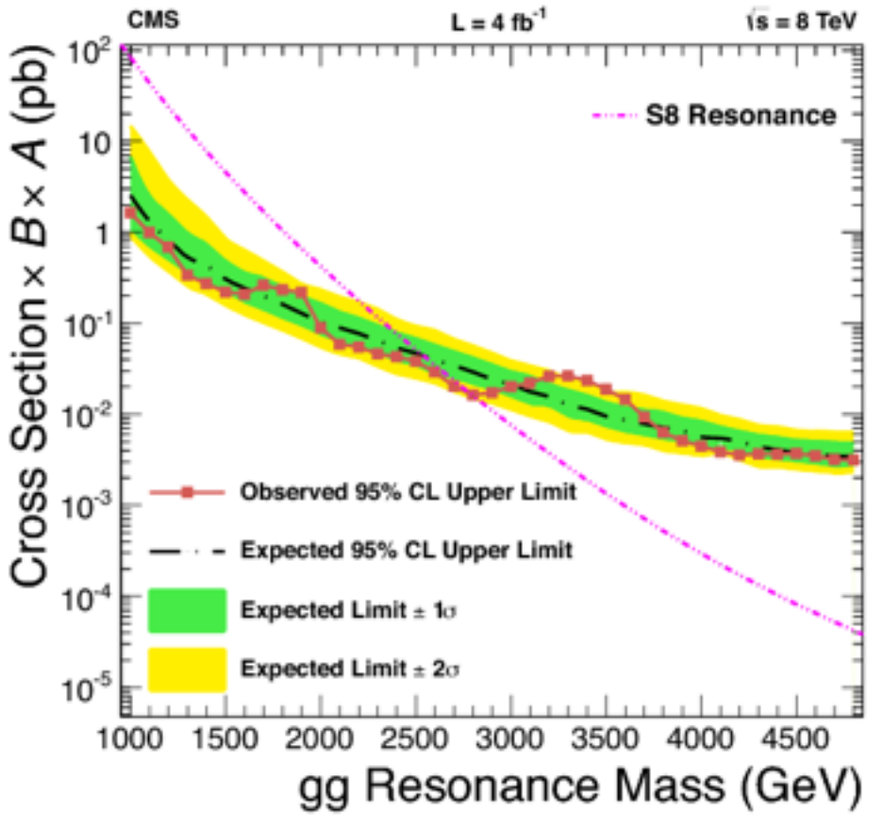
Dijet Resonances

ATLAS CERN-PH-EP-2014-147
CMS EXO-12-016







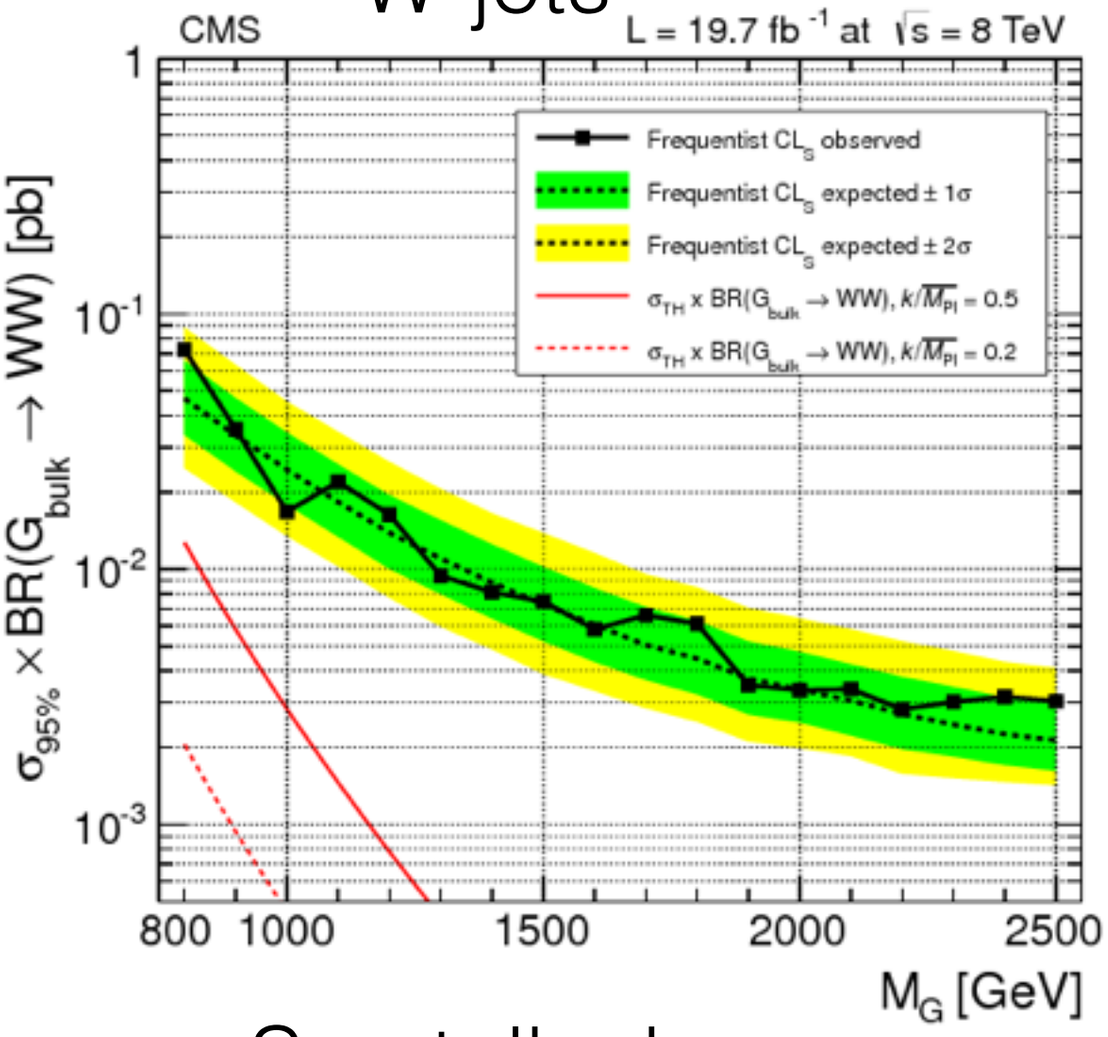


See talks by Vignaroli, Simmons, Ittisamai

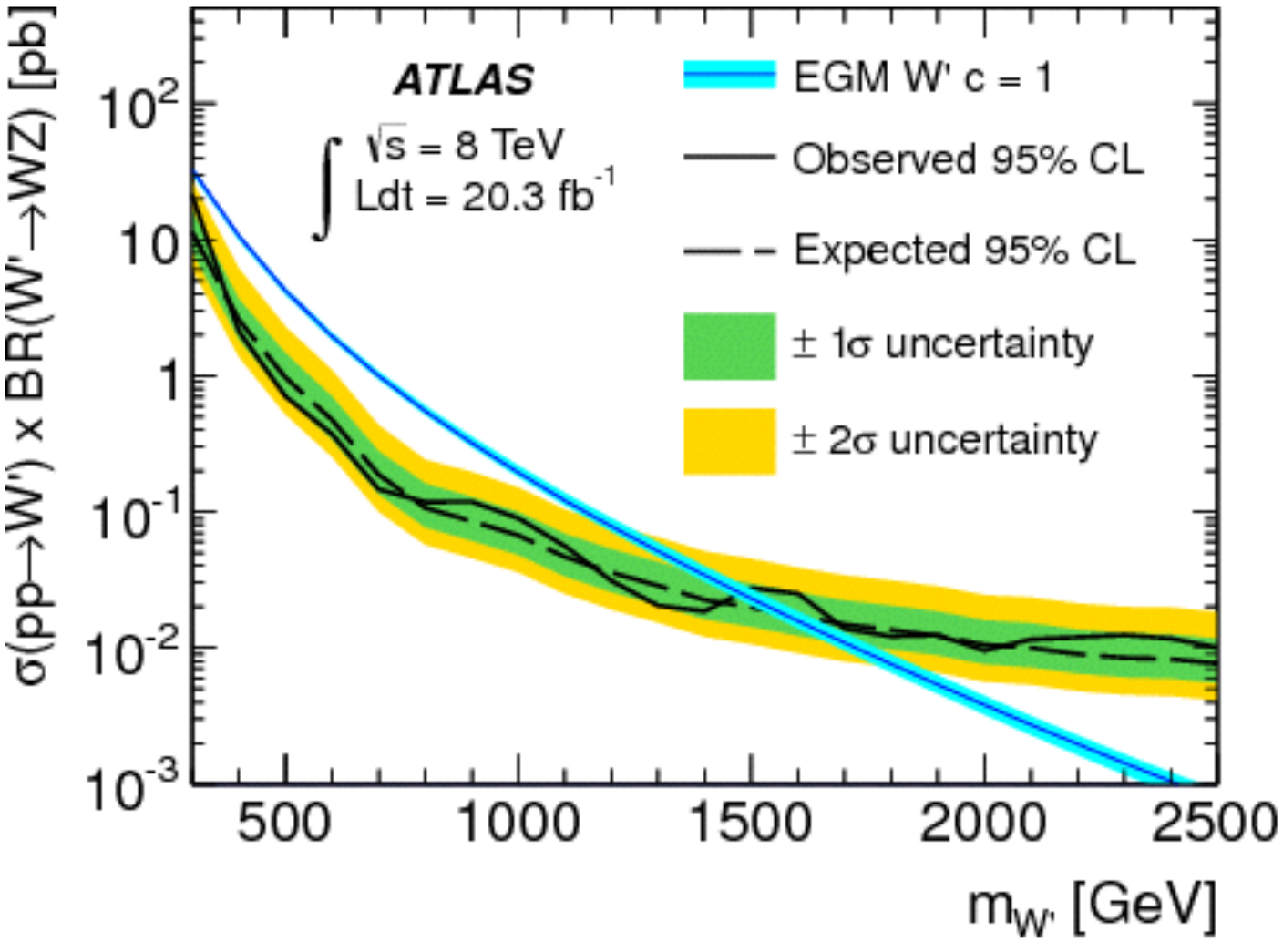
Diboson Resonances

pp → Resonance → WW/WZ → "jj" or lv "j"

Two highly-boosted "W-jets"



One highly-boosted "W-jet" for large $m_{W'}$

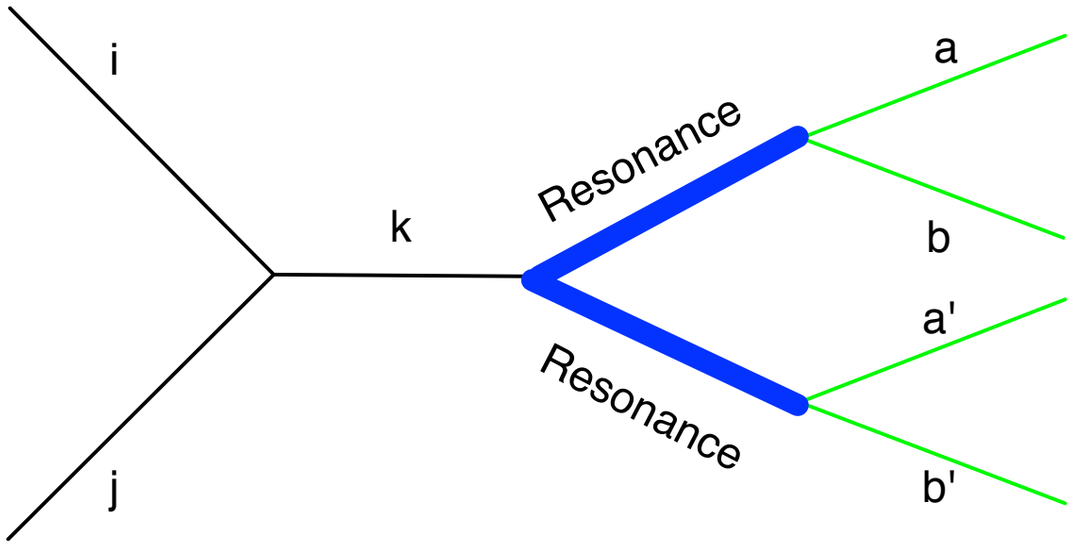


See talks by Ngadiuba and Angel!

CMS EXO-12-024 ATLAS CERN-PH-EP-2015-044

Pair Produced Resonances

Pair Production of Resonances



i,j,k = u,d,g,γ,W,Z

a,b = j,t,b,g,γ,W,Z,h

Characteristics vs. Observables

- i,j: event characteristics
- Couplings: BR: σ * BRs
- Mass: m_{ab} vs. $m_{a'b'}$
- Spin: $d\sigma/d\cos\theta_{ab,a'b'}$
- a,b: in each decay channel
  - flavor tagging
  - jet substructure

Note combinatorial issues!

Ancient History

Nuclear Physics B363 (1991) 83--96
North-Holland

MULTI-JET PHYSICS AT HADRON COLLIDERS

R. Sekhar CHIVUKULA[a], Mitchell GOLDEN[a] and Elizabeth H. SIMMONS[b]

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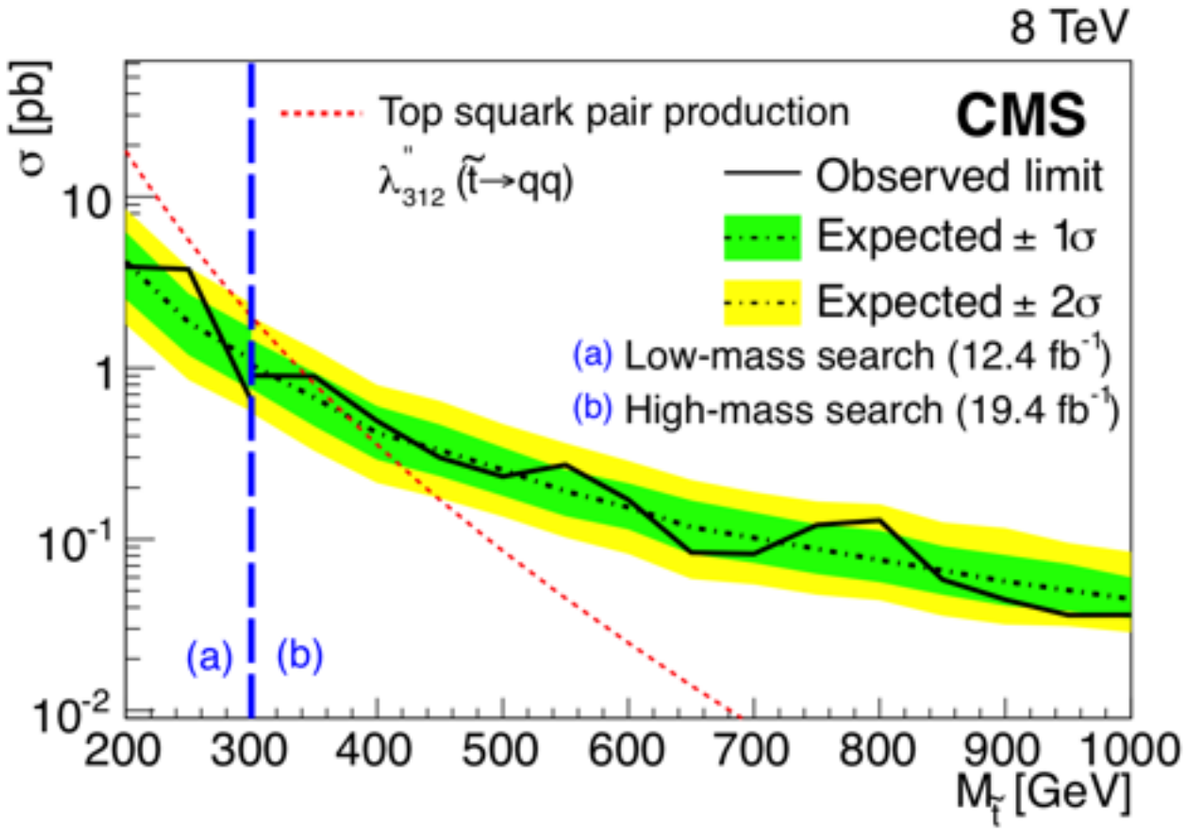
[b] *Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA*

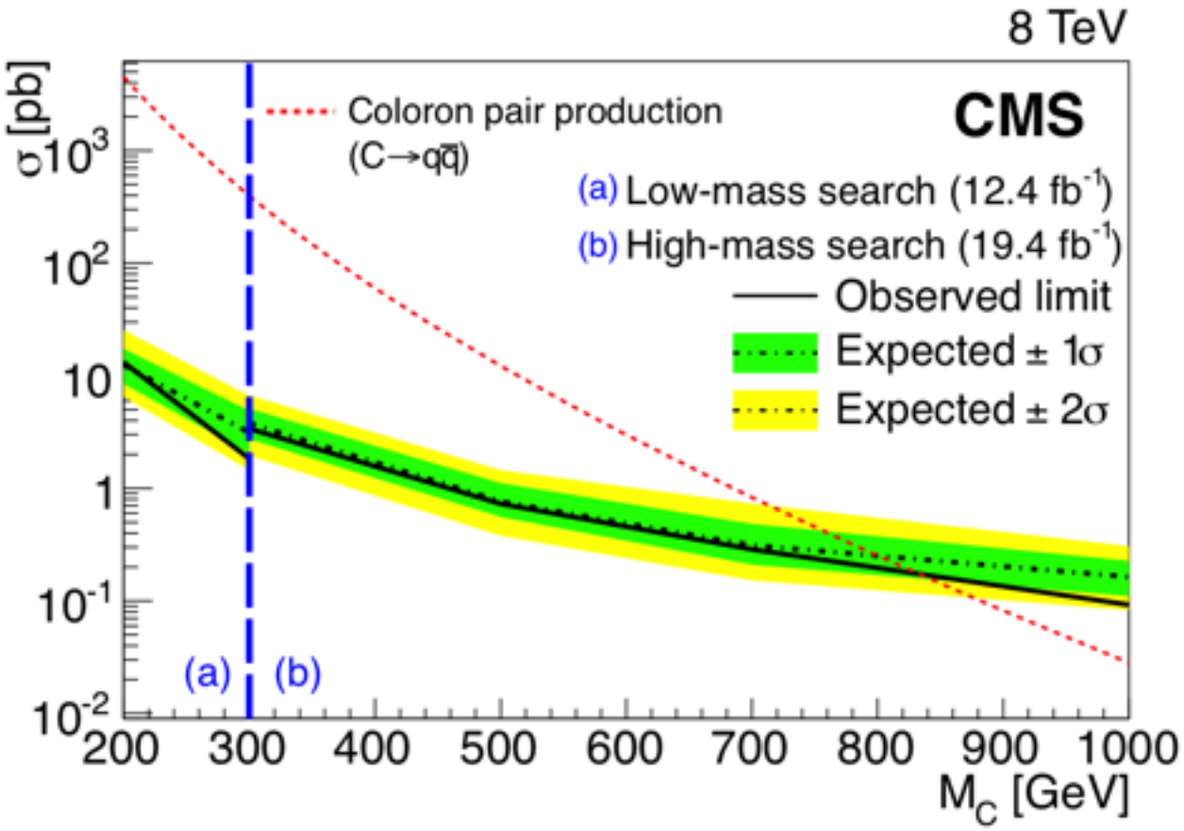
Received 18 March 1991
(Revised 30 April 1991)

We discuss four-jet and six-jet events at the SSC, LHC and Tevatron. First, the QCD backgrounds to non-standard physics are presented. Then we investigate multi-jet signals for hadronically-decaying color-octet pseudoscalars and color-sextet or octet fermions. Finally, the discovery potential of each collider is estimated.

Modern Implementation: Four-Jets



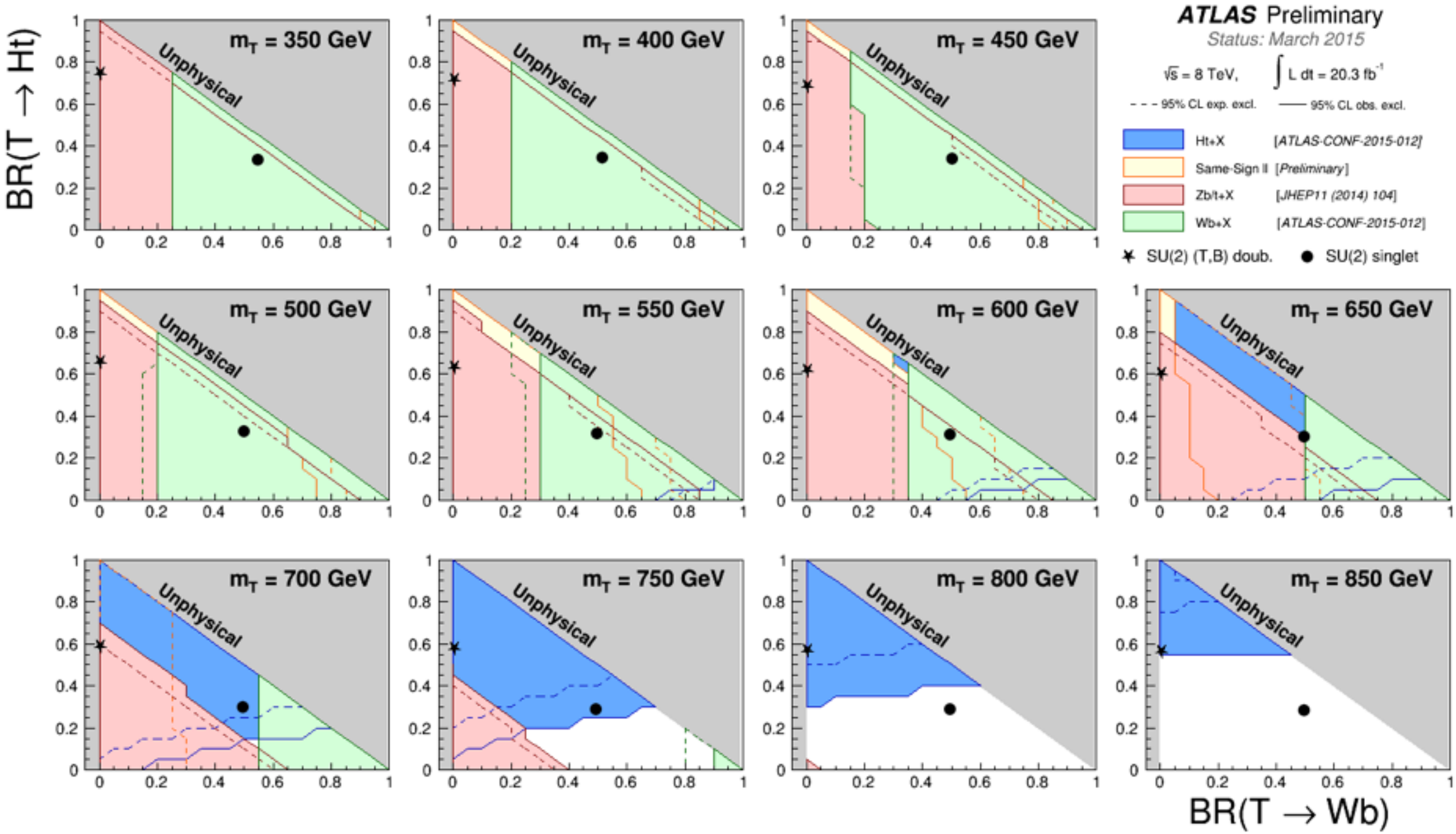
R-parity violating SUSY



Color-Octet Vector

CMS EXO-12-052

Vector Top Partners



ATLAS-CONF-2015-012

Upcoming Talks

Mon 04/05

16:00	**Mini-Review: New Resonances - Theory and Searches** *University of Pittsburgh*	*R. Sekhar CHIVUKULA* 16:30 - 17:00
17:00	**Distinguishing dijet resonances at the LHC using jet energy profiles** *University of Pittsburgh*	*Natascia VIGNAROLI* 17:00 - 17:15
	Separating Dijet Resonances using the Coloron Discriminant Variable at LHC *University of Pittsburgh*	*Prof. Elizabeth SIMMONS* 17:15 - 17:30
	Color Discriminant Variable to Seperate Coloron and Leptophobic Z' at the LHC *University of Pittsburgh*	*Pawin ITTISAMAI* 17:30 - 17:45
	Search for heavy resonances in diboson final states with the CMS detector at LHC *University of Pittsburgh*	*Jennifer NGADIUBA* 17:45 - 18:00
18:00	**Searches for new physics in diboson resonances and other signatures with the ATLAS detector at the LHC**	*Mr. Campoverde ANGEL*
	A pure resonance dip signal due to the imaginary interference in heavy resonance search	*Yeo Woong YOON*