Title: Discovering New Physics in Scattering Angles at the LHC

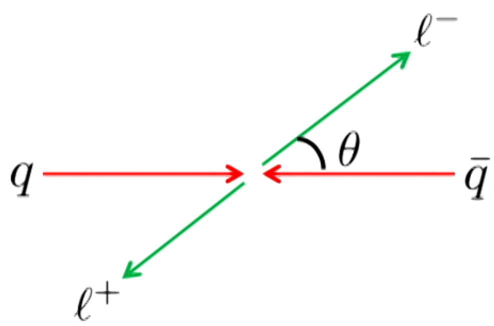
Date: Apr 18, 2017 01:00 PM

URL: http://pirsa.org/17040071

Abstract: <p>Since the Higgs, the LHC has offered no discoveries despite a sweeping hunt for new resonances. However, many well-motivated new physics models would not turn up in resonance searches, but could instead be uncovered in existing and forthcoming LHC data, by searching for novel angular distributions of Standard Model particles. I will show that in the upcoming years at the LHC, (1) through radiative corrections, dark matter can turn up in dilepton scattering angles in the parametric regions where it would elude conventional missing energy-based searches; the scattering patterns can reveal dark matter's mass, self-conjugation property, spin, and chirality of interactions, (2) through tree level interference, leptoquarks may emerge in dilepton scattering angles long before they would in dedicated direct searches; these angular measurements would also overtake the excellent sensitivities of low-energy precision measurements of atomic parity violation, and (3) Higgs Yukawa couplings to light quarks of the size of the bottom Yukawa could be measured using the Higgsstrahlung scattering angle.</p>

New Physics in Scattering Angles

Nirmal Raj
U of Notre Dame

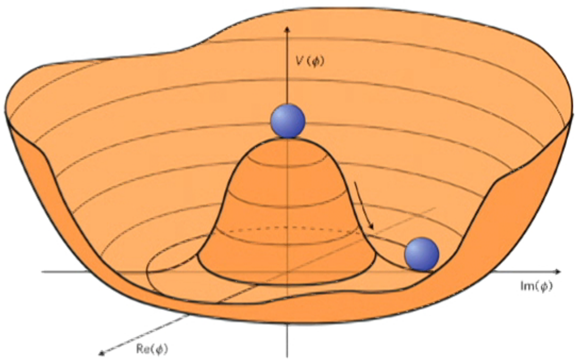


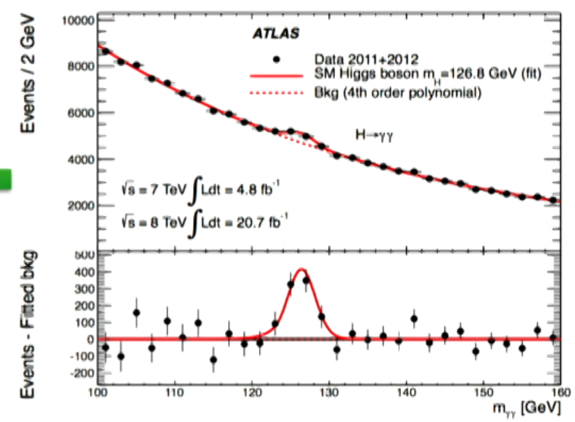
Based on

N.R.	1610.03795
W. Altmannshofer, P. Fox, R. Harnik, G. Kribs, *N.R.*	1411.6743
R. Capdevilla, A. Delgado, A. Martin, *N.R.*	1705.xxxxx
A. Delgado, A. Martin, *N.R.*	170?.xxxxx

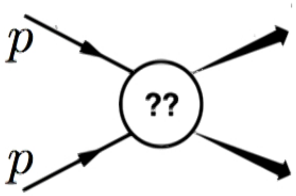
Perimeter Institute
17 Apr 2017

First triumph @ LHC





Beyond Standard

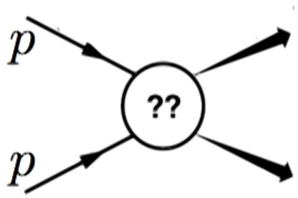


Preliminary Results - 2016 Run

Analysis	Approved Plots	CDS Entry	Luminosity
Searches for dijet resonances NEW	EXO16056	PAS EXO-16-056	36 fb^{-1}
Search for evidence of Type-III seesaw mechanism in multilepton final states NEW	EXO17006	PAS EXO-17-006	36 fb^{-1}
Search for high-mass resonances in dilepton final states	EXO16031	PAS EXO-16-031	13 fb^{-1}
Search for high-mass resonances in Z(ll)γ final state	EXO16034	PAS EXO-16-034	13 fb^{-1}
Search for high-mass resonances in Z(qq)γ final state	EXO16035	PAS EXO-16-035	13 fb^{-1}
Search for heavy stable charged particles	EXO16036	PAS EXO-16-036	13 fb^{-1}
Search for dark matter in Z(ll)+MET final state	EXO16038	PAS EXO-16-038	13 fb^{-1}
Search for dark matter and extra dimensions in photon+MET final state	EXO16039	PAS EXO-16-039	13 fb^{-1}
Search for dark matter in top(had)+MET final state	EXO16040	PAS EXO-16-040	13 fb^{-1}

Search for new high-mass phenomena in the dilepton final state using proton-proton collisions $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2017-027	36.1/fb	Apr 2017
Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2017-028	36.1/fb	Apr 2017
Search for Heavy Resonances Decaying to a W or Z Boson and a Higgs Boson in the $q\bar{q}^{(\prime)}b\bar{b}$ Final State in pp Collisions at $\sqrt{s}$=13 TeV with the ATLAS Detector	ATLAS-CONF-2017-018	36.1/fb	Mar 2017
Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in 36/fb of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS experiment	ATLAS-CONF-2017-016	36.1/fb	Mar 2017
Search for pair production of vector-like top quarks in events with one lepton and an invisibly decaying Z boson in $\sqrt{s}$=13 TeV pp collisions at the ATLAS detector	ATLAS-CONF-2017-015	36.1/fb	Mar 2017
Search for new phenomena in $t\bar{t}$ final states with additional heavy-flavour jets in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2016-104	13.3/fb	Sep 2016
Search for pair production of heavy vector-like quarks decaying to high-p_t W bosons and b quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2016-102	13.3/fb	Sep 2016
Search for pair production of vector-like top partners in events with exactly one lepton and large missing transverse momentum in $\sqrt{s}$=13 TeV pp collisions with the ATLAS detector	ATLAS-CONF-2016-101	13.3/fb	Sep 2016
Search for Dark Matter production associated with bottom quarks in 13.3 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector at the LHC	ATLAS-CONF-2016-086	13.3/fb	Aug 2016
A search for pair-produced resonances in four jets final states at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2016-084	15.4/fb	Aug 2016
A Search for Resonances Decaying to a W or Z Boson and a Higgs Boson in the $q\bar{q}b\bar{b}$ Final State	ATLAS-CONF-2016-083	13.3/fb	Aug 2016
Searches for heavy ZZ and ZW resonances in the llqq and vvqq final states in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2016-082	13.2/fb	Aug 2016
Search for new light resonances decaying to jet pairs and produced in association with a photon or a jet in proton-proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	ATLAS-CONF-2016-070	15.5/fb	Aug 2016

Beyond Standard



A sweeping hunt!

Preliminary Results - 2016 Run

Analys[illegible]	[illegible]ots	CDS Entry	Luminosity
Search [illegible]	[illegible]	PAS EXO-16-056	36 fb^{-1}
Search [illegible]	[illegible]	PAS EXO-17-006	36 fb^{-1}
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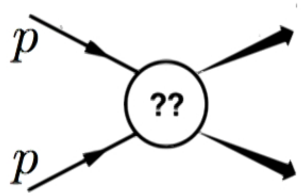


Preliminary Results - 2016 Run

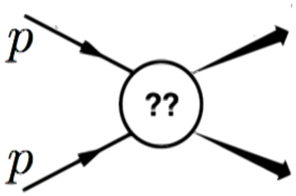
A sweeping hunt!

	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ	$(\mathbf{1},2)^*$	$[\mathbf{1},1]^*$	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamond\heartsuit}$	$[\mathbf{8},1]^*$	$(\bar{\mathbf{3}},{}^4/_3)^{\diamond\heartsuit}$	$(\bar{\mathbf{3}},{}^1/_3)^{\diamond\heartsuit}$	$[\mathbf{1},0]^*$	$[\mathbf{1},1]^*$	$[\mathbf{1},1]^*$
$\bar{\ell}$	$(\mathbf{1},0)$	$[\mathbf{1},-1]^*$	$(\bar{\mathbf{3}},-{}^{2(5^*)}/_3)^{\diamond\heartsuit}$	$[\mathbf{8},-1]^*$	$(\bar{\mathbf{3}},-{}^2/_3)^{\diamond\heartsuit}$	$(\bar{\mathbf{3}},-{}^5/_3)^*$	$[\mathbf{1},-2]^*$	$[\mathbf{1},-1]^*$	$[\mathbf{1},-1]^*$
γ	$[\mathbf{1},1]^*$	$(\mathbf{1},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{1},-1)$	$(\mathbf{1},0)$	$(\mathbf{1},0)$
q	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamond\heartsuit}$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$(\mathbf{3},{}^{-1(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{-2(-5^*)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$
$\bar{q}$	$(\mathbf{3},{}^{2(5^*)}/_3)^{\diamond\heartsuit}$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(-4^*)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$
g	$[\mathbf{8},1]^*$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{8},-1)$	$(\mathbf{8},0)$	$(\mathbf{8},0)$
b		$[\bar{\mathbf{3}},{}^1/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$[\bar{\mathbf{3}},{}^1/_3]$	$(\mathbf{3},{}^2/_3)$	$(\mathbf{3},-{}^1/_3)$	$[\bar{\mathbf{3}},-{}^2/_3]$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},{}^1/_3]$
$\bar{b}$			$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},-{}^1/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$(\mathbf{1}(\mathbf{8}),-1)$	$[\mathbf{3},-{}^4/_3]^*$	$[\mathbf{3},-{}^1/_3]$	$[\mathbf{3},-{}^1/_3]$
t				$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{3},-{}^1/_3)$	$(\mathbf{3},-{}^4/_3)$	$[\bar{\mathbf{3}},-{}^5/_3]^*$	$[\bar{\mathbf{3}},-{}^2/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$
$\bar{t}$					$(\mathbf{1}(\mathbf{8}),1)$	$(\mathbf{1}(\mathbf{8}),0)$	$[\mathbf{3},-{}^1/_3]$	$[\mathbf{3},{}^2/_3]$	$[\mathbf{3},{}^2/_3]$
W^+						$[\bar{\mathbf{3}},-{}^5/_3]^*$	$(\mathbf{1},-2)^*$	$(\mathbf{1},-1)$	$(\mathbf{1},-1)$
W^-							$(\mathbf{1},0)$	$(\mathbf{1},1)$	$(\mathbf{1},1)$
Z								$(\mathbf{1},0)$	$(\mathbf{1},0)$
h									$(\mathbf{1},0)$

"The unexplored landscape of two-body resonances"

N. Craig, P. Draper, K. C. Kong, Y. Ng, D. Whiteson 1610.09392

Beyond Standard



Preliminary Results - 2016 Run

A sweeping hunt!

	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ	$(\mathbf{1},2)^*$	$[\mathbf{1},1]^*$	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamond\heartsuit}$	$[\mathbf{8},1]^*$	$(\bar{\mathbf{3}},{}^{4}/_3)^{\diamond\heartsuit}$	$(\bar{\mathbf{3}},{}^{1}/_3)^{\diamond\heartsuit}$	$[\mathbf{1},0]^*$	$[\mathbf{1},1]^*$	$[\mathbf{1},1]^*$
$\bar{\ell}$	$(\mathbf{1},0)$	$[\mathbf{1},-1]^*$	$(\bar{\mathbf{3}},-{}^{2(5^*)}/_3)^{\diamond\heartsuit}$	$[\mathbf{8},-1]^*$	$(\bar{\mathbf{3}},-{}^{2}/_3)^{\diamond\heartsuit}$	$(\bar{\mathbf{3}},-{}^{5}/_3)^*$	$[\mathbf{1},-2]^*$	$[\mathbf{1},-1]^*$	$[\mathbf{1},-1]^*$
γ	$[\mathbf{1},1]^*$	$(\mathbf{1},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{1},-1)$	$(\mathbf{1},0)$	$(\mathbf{1},0)$
q	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamond\heartsuit}$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$(\mathbf{3},{}^{-1(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{-2(-5^*)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$
$\bar{q}$	$(\mathbf{3},{}^{2(5^*)}/_3)^{\diamond\heartsuit}$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(-4^*)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$
g	$[\mathbf{8},1]^*$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{8},-1)$	$(\mathbf{8},0)$	$(\mathbf{8},0)$
b		$[\bar{\mathbf{3}},{}^{1}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$(\mathbf{3},{}^{2}/_3)$	$(\mathbf{3},-{}^{1}/_3)$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$[\bar{\mathbf{3}},{}^{1}/_3]$	$[\bar{\mathbf{3}},{}^{1}/_3]$
$\bar{b}$			$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},-{}^{1}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$(\mathbf{1}(\mathbf{8}),-1)$	$[\mathbf{3},-{}^{4}/_3]^*$	$[\mathbf{3},-{}^{1}/_3]$	$[\mathbf{3},-{}^{1}/_3]$
t				$[\bar{\mathbf{3}},-{}^{2}/_3]$	$(\mathbf{3},-{}^{1}/_3)$	$(\mathbf{3},-{}^{4}/_3)$	$[\bar{\mathbf{3}},-{}^{5}/_3]^*$	$[\bar{\mathbf{3}},-{}^{2}/_3]$	$[\bar{\mathbf{3}},-{}^{2}/_3]$
$\bar{t}$					$(\mathbf{1}(\mathbf{8}),1)$	$(\mathbf{1}(\mathbf{8}),0)$	$[\mathbf{3},-{}^{1}/_3]$	$[\mathbf{3},{}^{2}/_3]$	$[\mathbf{3},{}^{2}/_3]$
W^+						$[\bar{\mathbf{3}},-{}^{5}/_3]^*$	$(\mathbf{1},-2)^*$	$(\mathbf{1},-1)$	$(\mathbf{1},-1)$
W^-							$(\mathbf{1},0)$	$(\mathbf{1},1)$	$(\mathbf{1},1)$
Z								$(\mathbf{1},0)$	$(\mathbf{1},0)$
h									$(\mathbf{1},0)$

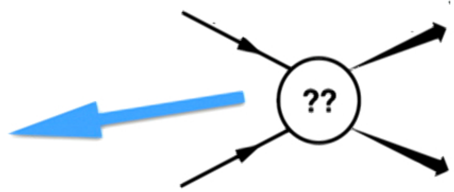
"The unexplored landscape of two-body resonances"

N. Craig, P. Draper, K. C. Kong, Y. Ng, D. Whiteson 1610.09392

By and large, searches look to <u>make</u> particles.

Discovery sequence: expectation

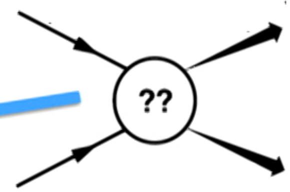
Resonance



Discover here:
"direct search".
Get mass
(and width).

invariant mass

Discovery sequence: expectation



Resonance

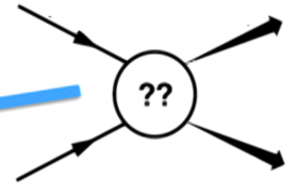
invariant mass

Discover here:
"direct search".
Get mass
(and width).

Disentangle spin
and couplings.

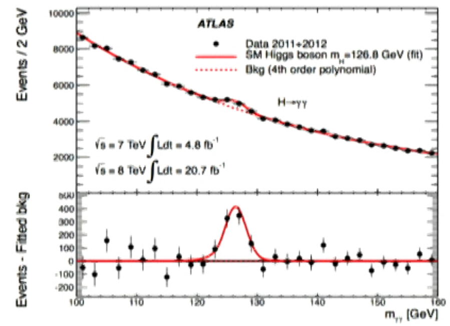
angular spectrum (A_{FB}, etc.)

Discovery sequence: expectation



Resonance

invariant mass



Discover here:
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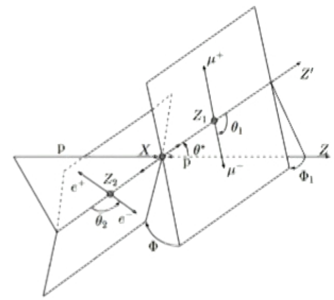
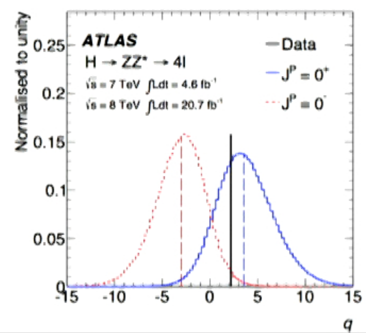


Disentangle spin and couplings.

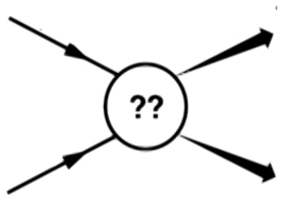
angular spectrum (A_{FB}, etc.)



Z' papers
F Petriello, et al (2008)
T Han, et al (2011)
V Barger, et al (2013)

Is the reverse sequence motivated?

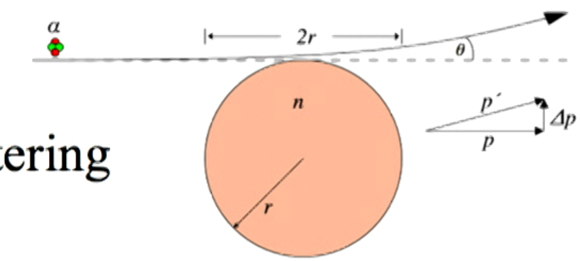
angular spectrum (A_{FB}, etc.)



invariant mass

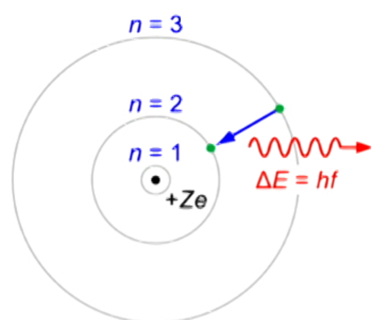
“New physics” in angular spectra - I

Rutherford scattering



$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \csc^4\left(\frac{\Theta}{2}\right).$$

Bohr model



(Explained
Rydberg formulae
for spectral emissions)

“New physics” in angular spectra - II

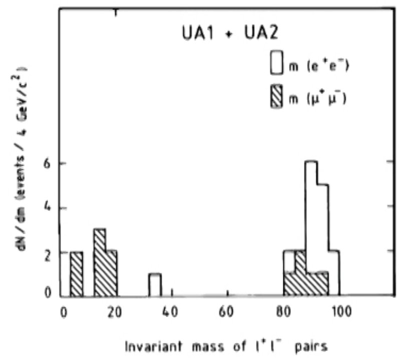
<u>Sequence of *Z* boson arrival</u>

Late 1970s, early 80s

PETRA @ √s = 30 - 40 GeV in e-e+ —> μ+ μ- saw a non-zero forward-backward asymmetry; derived a bound: **M_Z < 100 GeV**.

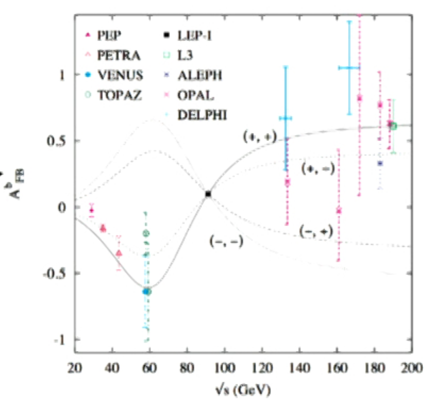
1983

SPS in p pbar —> e-e+ found resonance @ **95.5+/-2.5 GeV**.

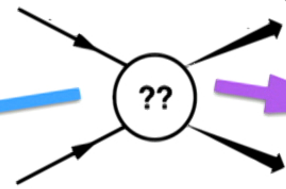


Later

Angular spectra studied to pin down spin and chiral couplings.



New physics in angular spectra - III



Resonance

Non-resonance

Discover here:
"direct search".
Get mass
(and width).

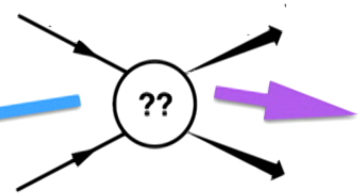
Disentangle spin
and couplings.

invariant mass

angular spectrum (A_{FB}, etc.)

?

"New physics" in angular spectra - III



Resonance

Non-resonance

Discover here: "direct search". Get mass (and width).

Disentangle spin and couplings.

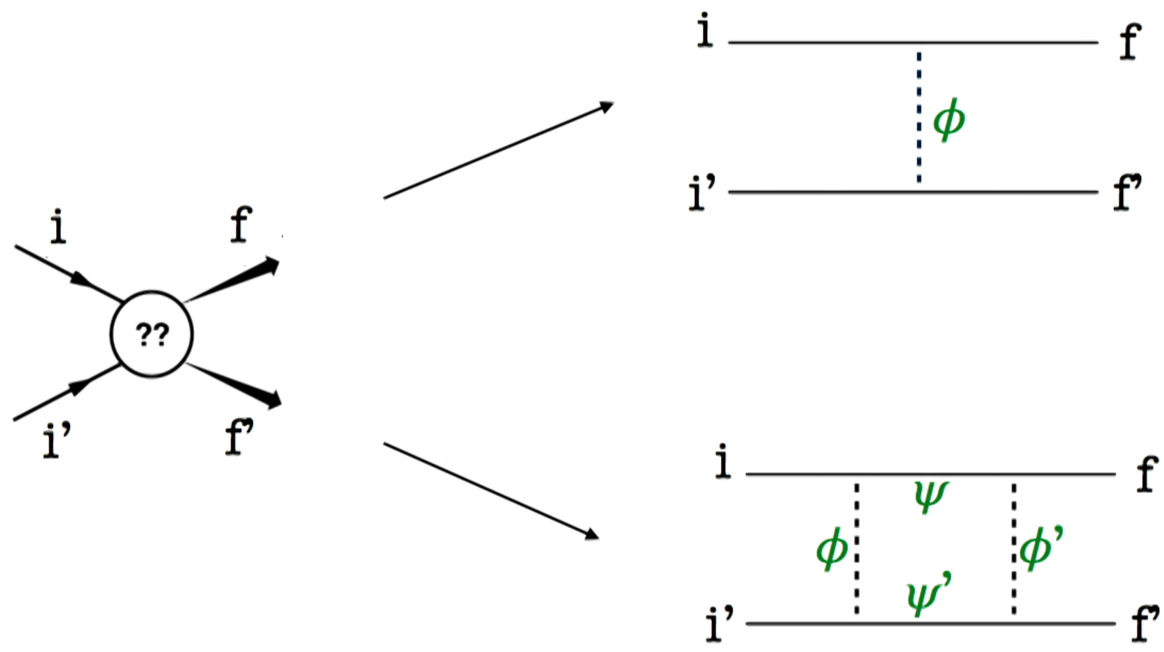
invariant mass

angular spectrum (A_{FB}, etc.)

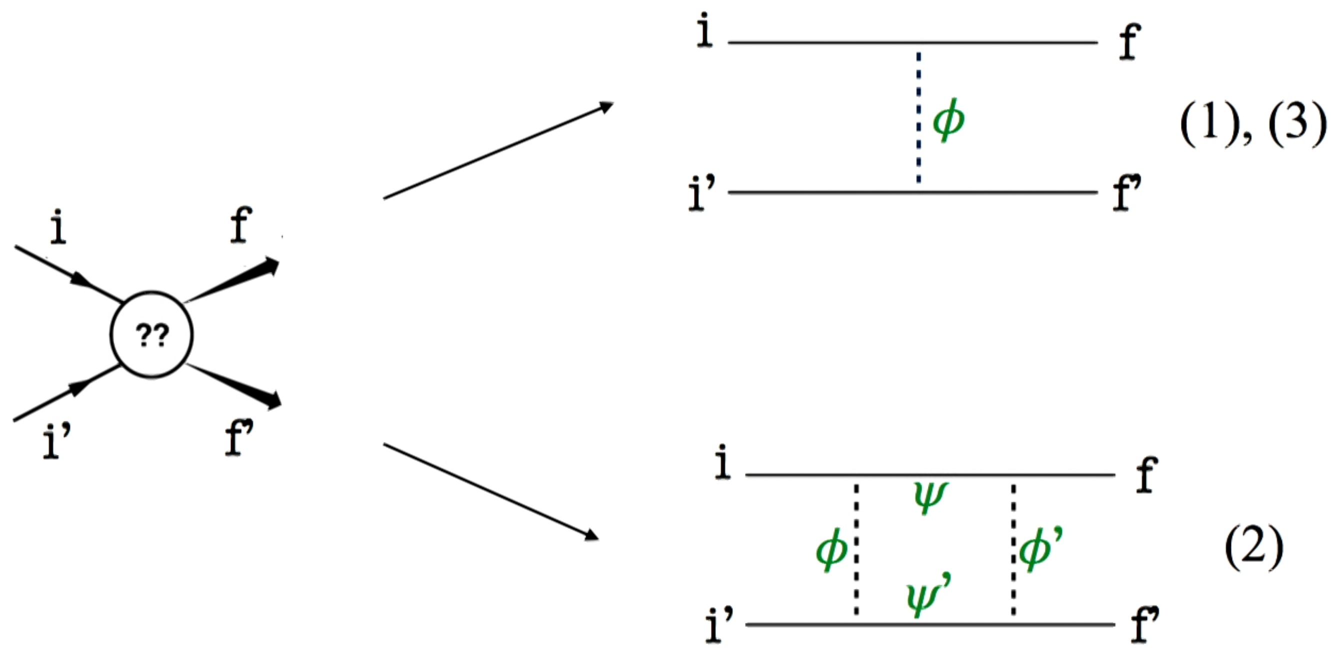
Use both for discovery: all at once extract mass, spin, couplings.

Signals can debut here!

Non-resonant new physics



This talk

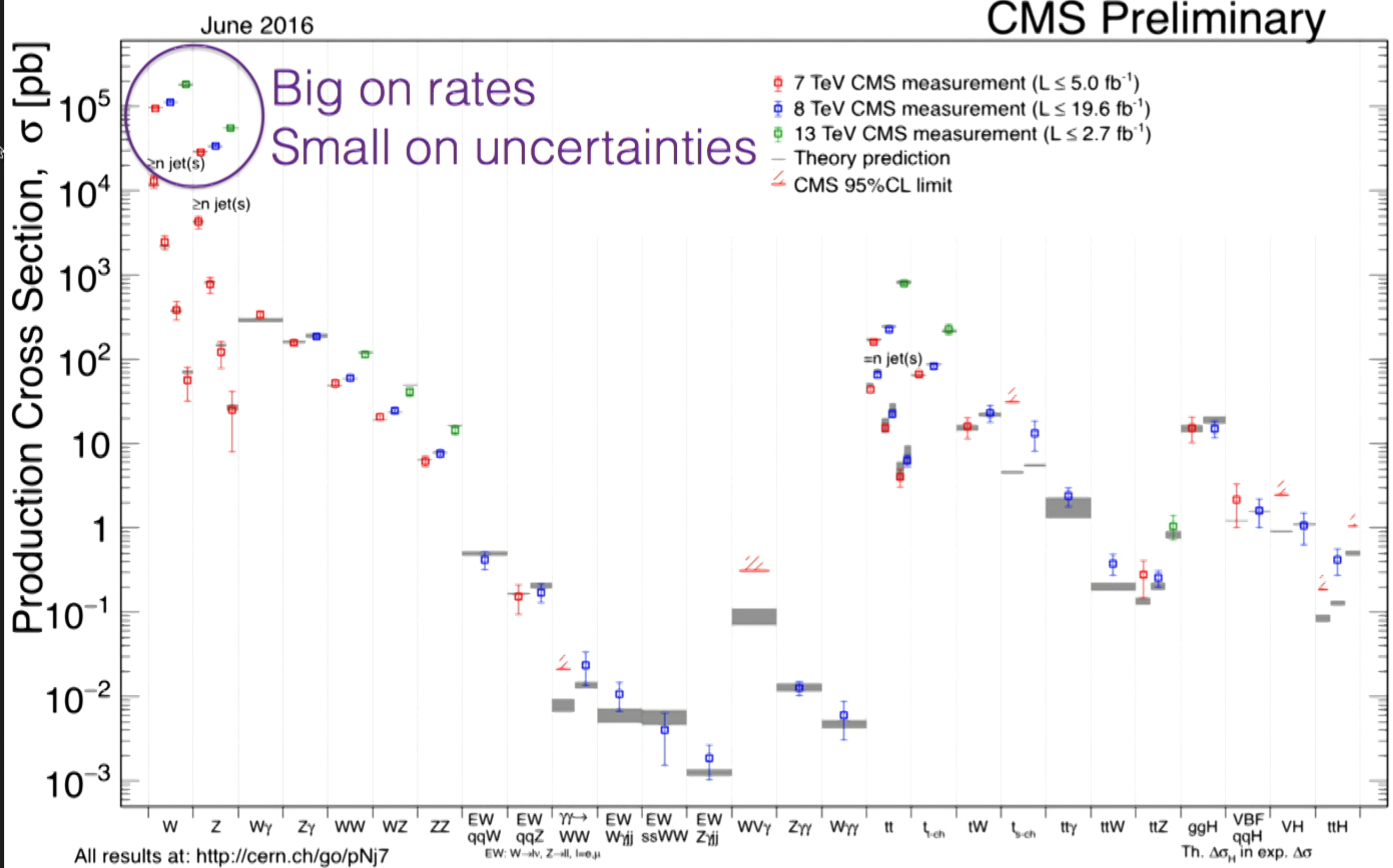


(1) Leptoquarks

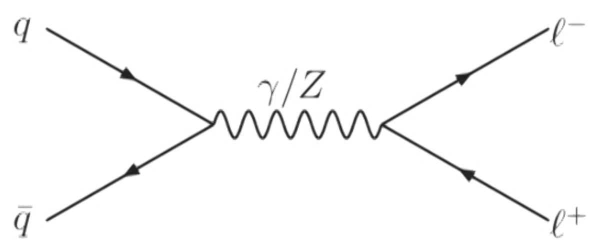
(2) Dark matter

(3) Light quark Yukawas

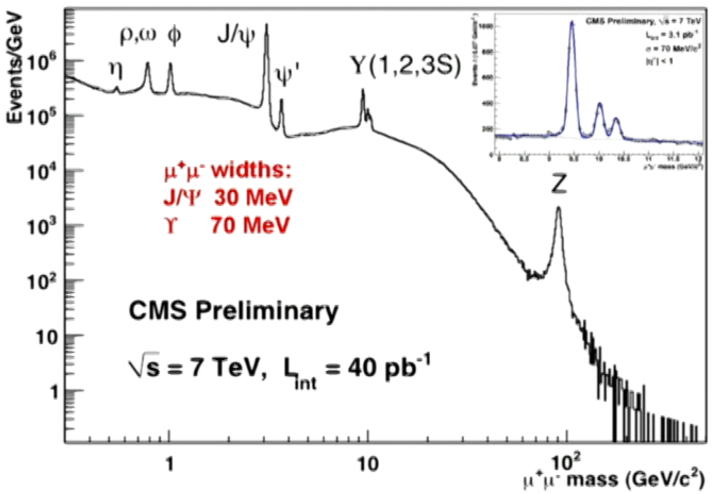
Shape of the Energy Frontier



Good old Drell-Yan



U Oregon. Photo: Kyle Cranmer

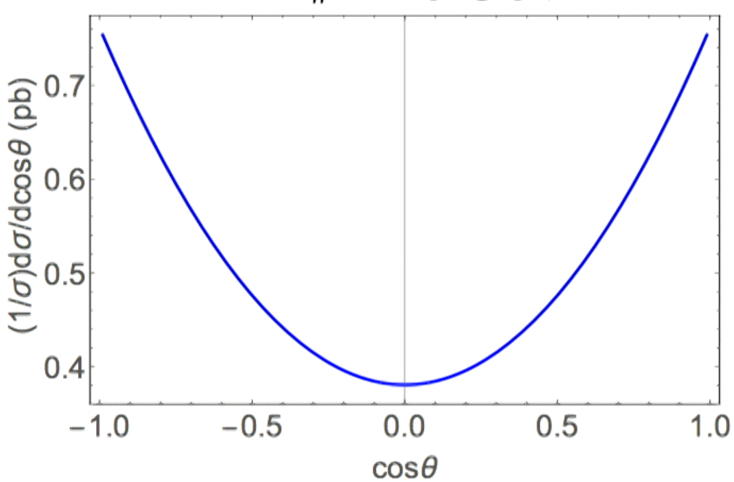


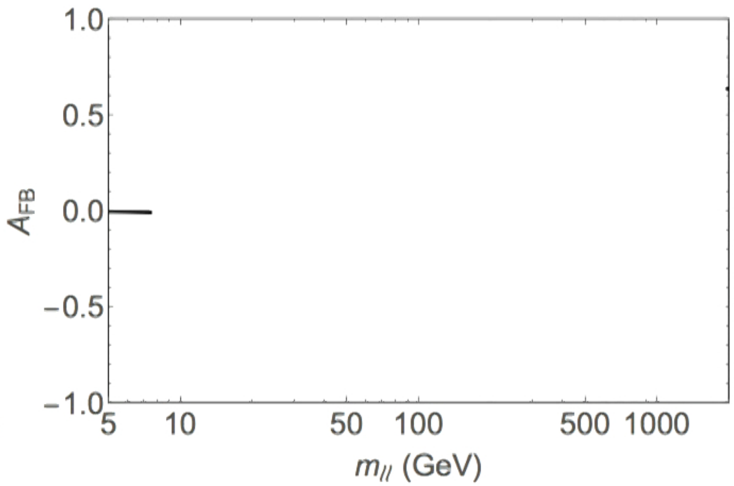
High rates,
clean backgrounds =>
great discovery mode.

Forward-backward asymmetry

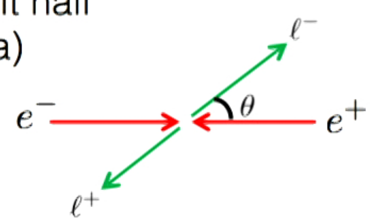
e+ e- —> l+ l-

m_{ll} ~ 10 GeV



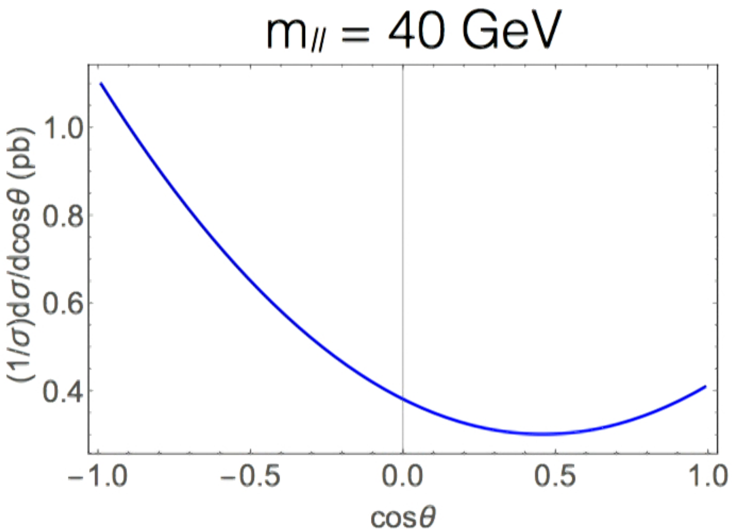


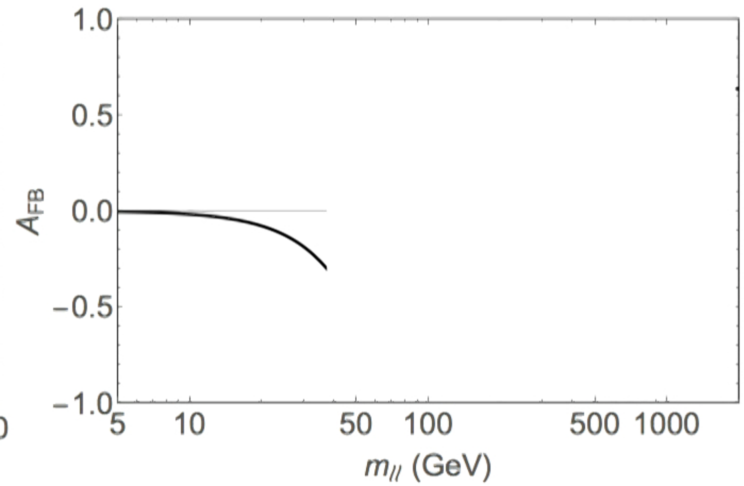
A_{FB} = area of right half minus left half
(normalized with total area)



Forward-backward asymmetry

e+ e- —> l+ l-





A_{FB} = area of right half minus left half
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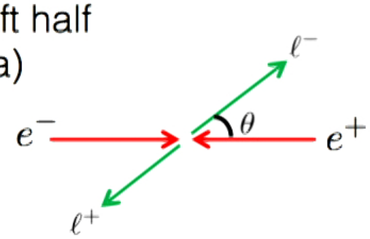
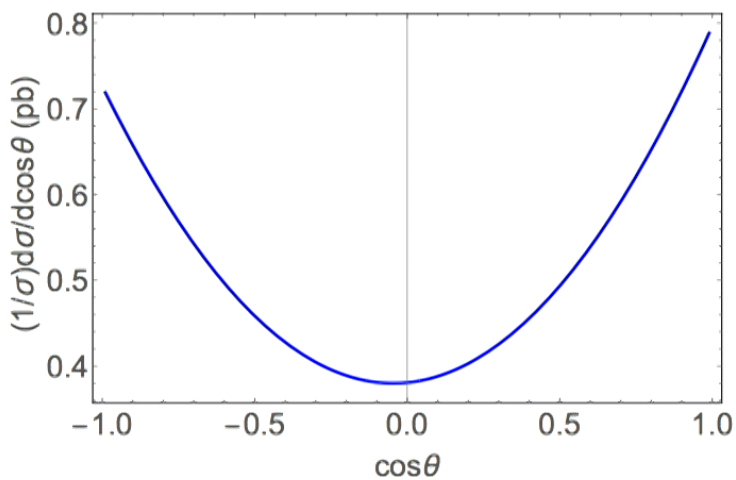
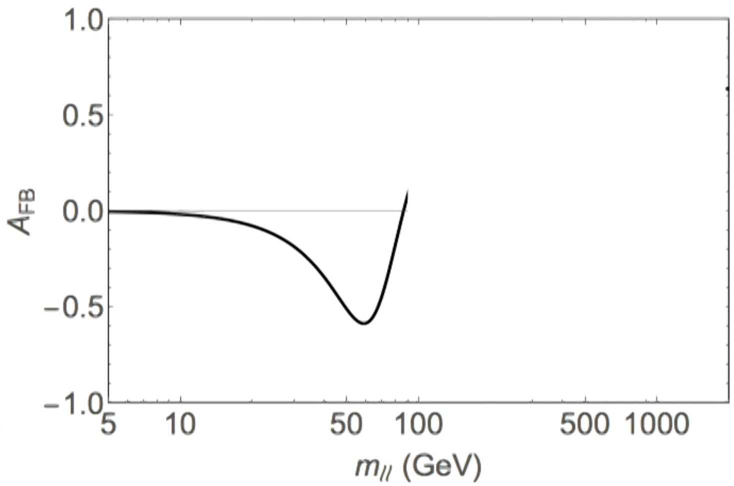


Forward-backward asymmetry

e+ e- —> l+ l-

m_{ll} = 88 GeV





A_{FB} = area of right half minus left half
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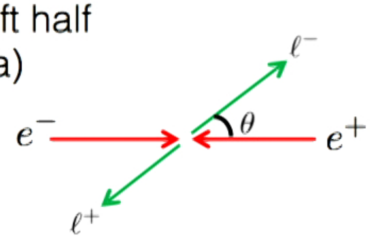
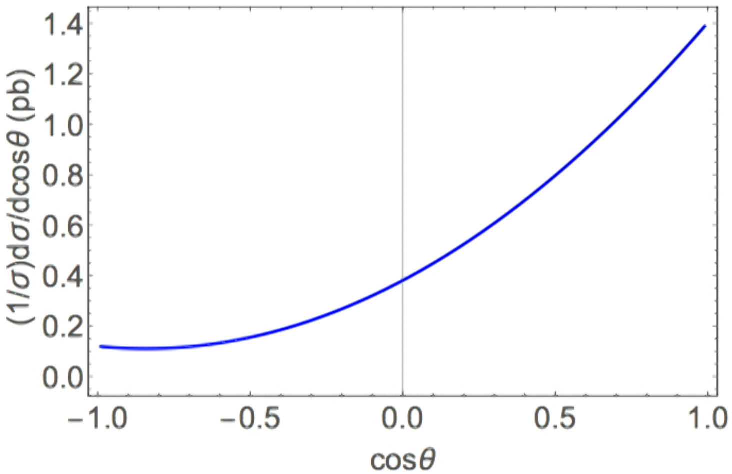
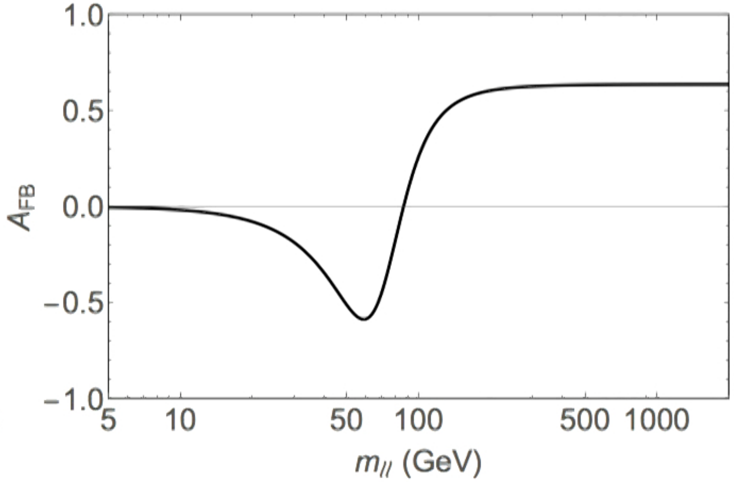


Forward-backward asymmetry

e+ e- —> l+ l-

$m_{ll} >> M_Z$





A_{FB} = area of right half minus left half
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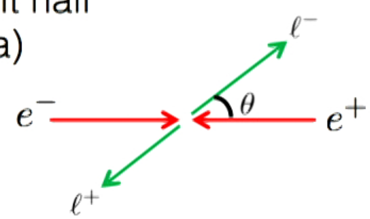
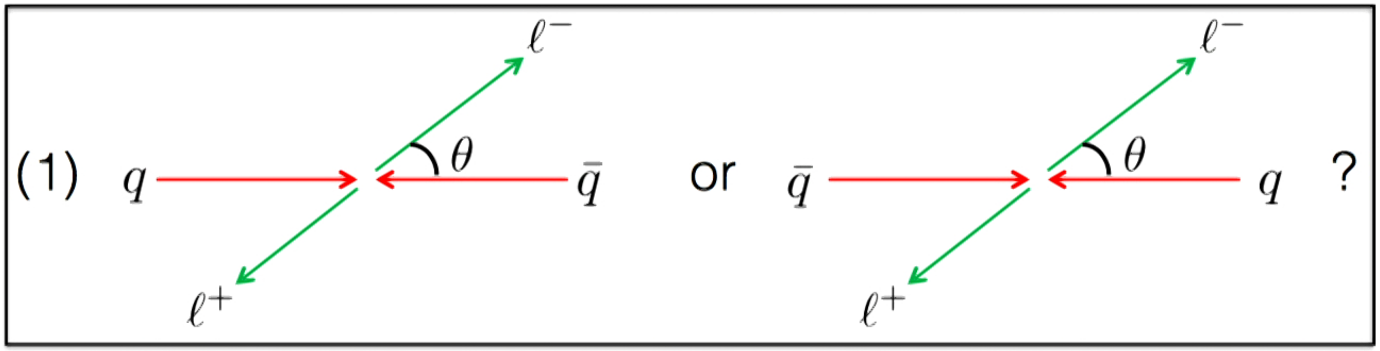
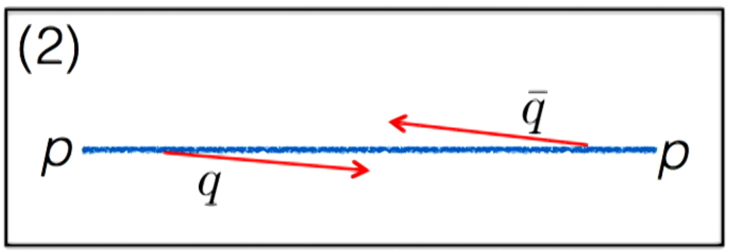


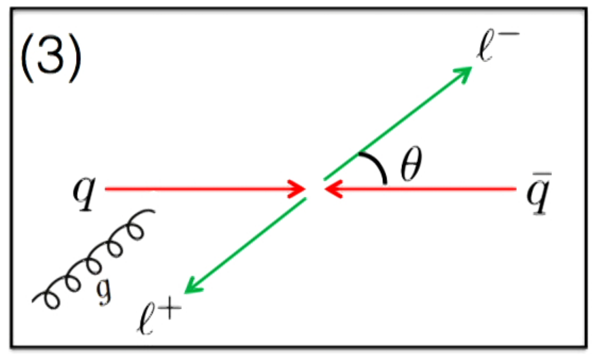
Forward-backward asymmetry

p p —> l+ l-

Four subtleties:





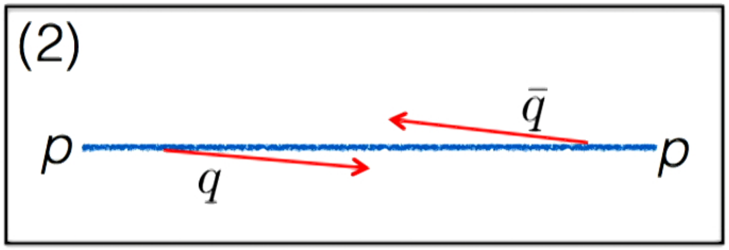


(4) Detector resolution of η

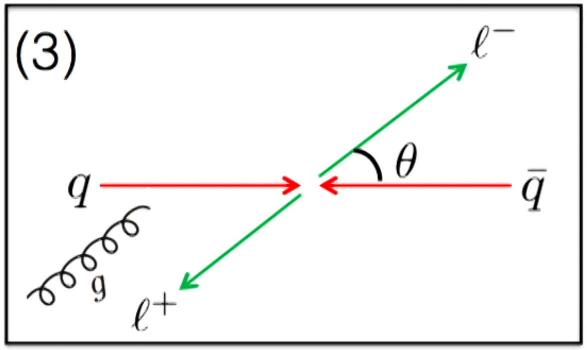
Forward-backward asymmetry

p p —> l+ l-

These three effects negligible **at high m_{ll}** and with large enough bins

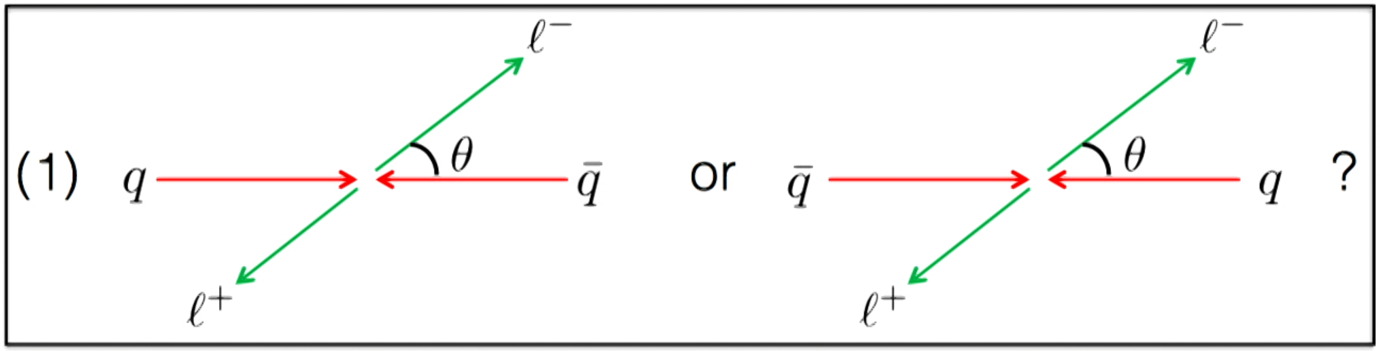


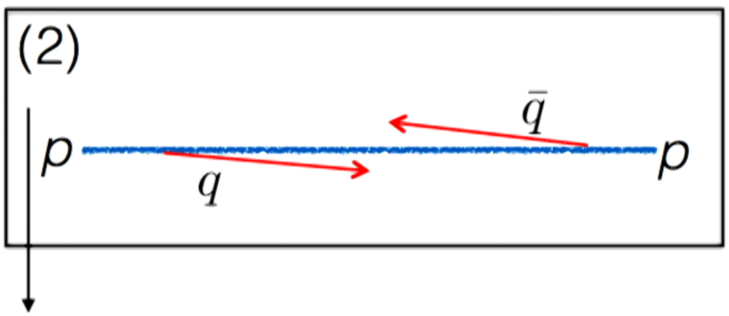
(4) Detector resolution of η



Forward-backward asymmetry

p p —> l+ l-





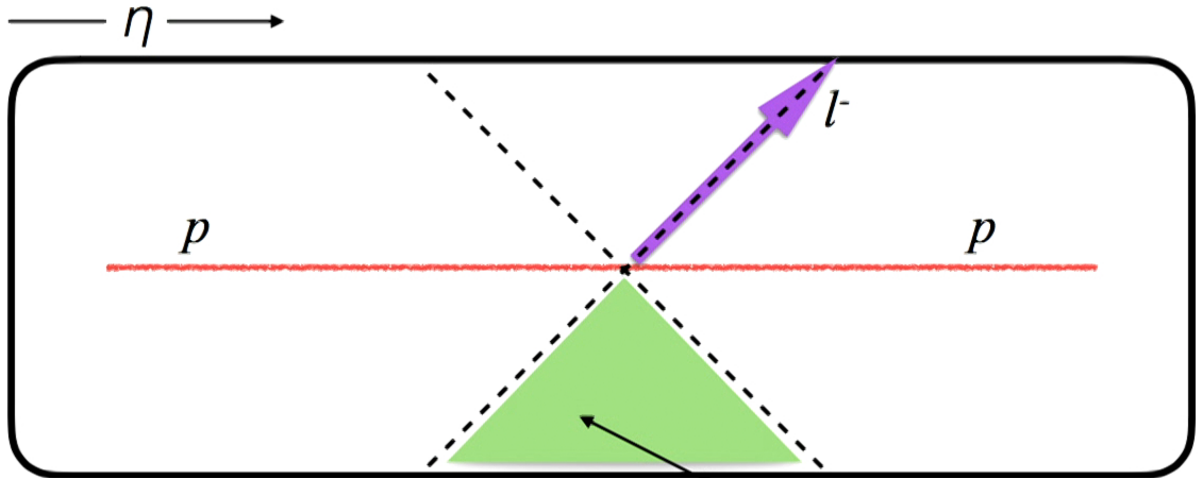
negligible @ high m_{ll}

Collins & Soper (1977):

$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

Forward-backward asymmetry

p p —> l+ l-



If l^+ falls here, “forward”.
Else, “backward”.

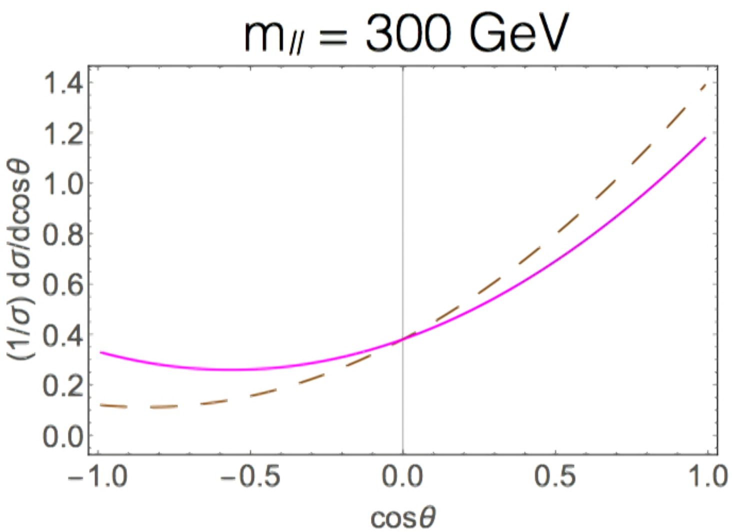
Identical to charge asymmetry:

$$A_{\rm FB}^{\rm CS} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)},$$

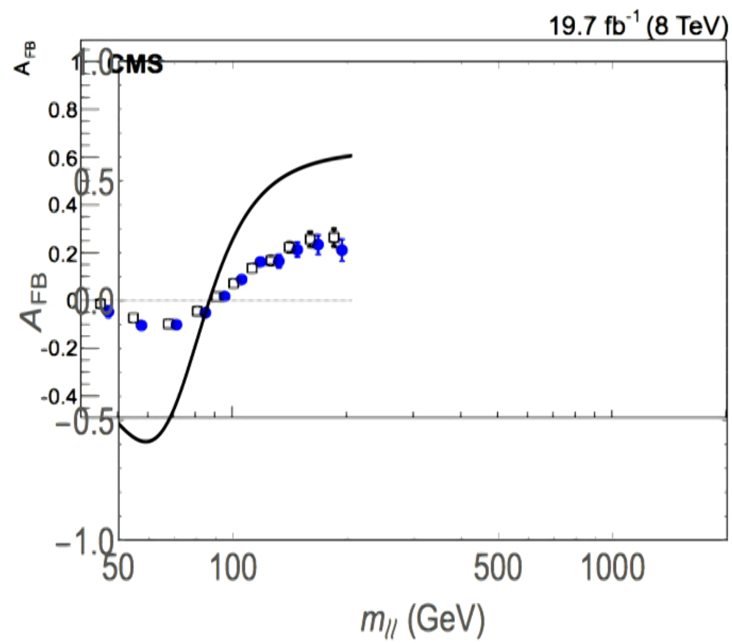
where $\Delta|\eta| \equiv |\eta^-| - |\eta^+|$.

Forward-backward asymmetry

p p —> l+ l-

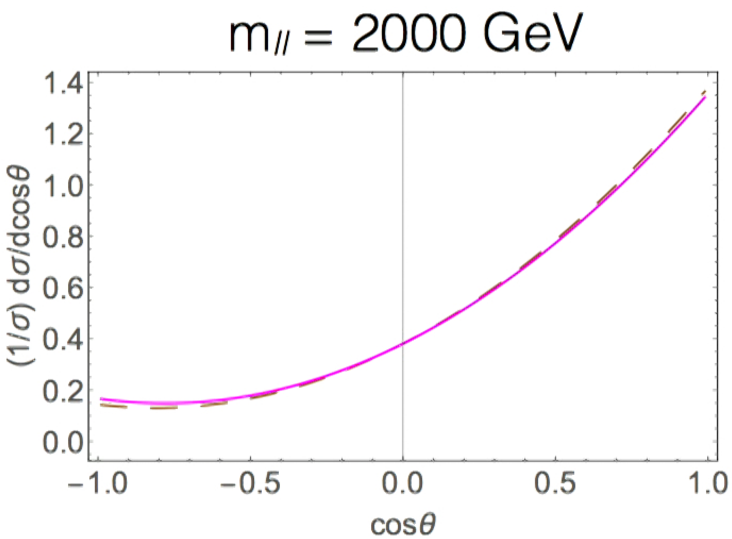


A_{FB} = area of right half minus left half (normalized with total area)



Forward-backward asymmetry

p p —> l+ l-



A_{FB} = area of right half minus left half
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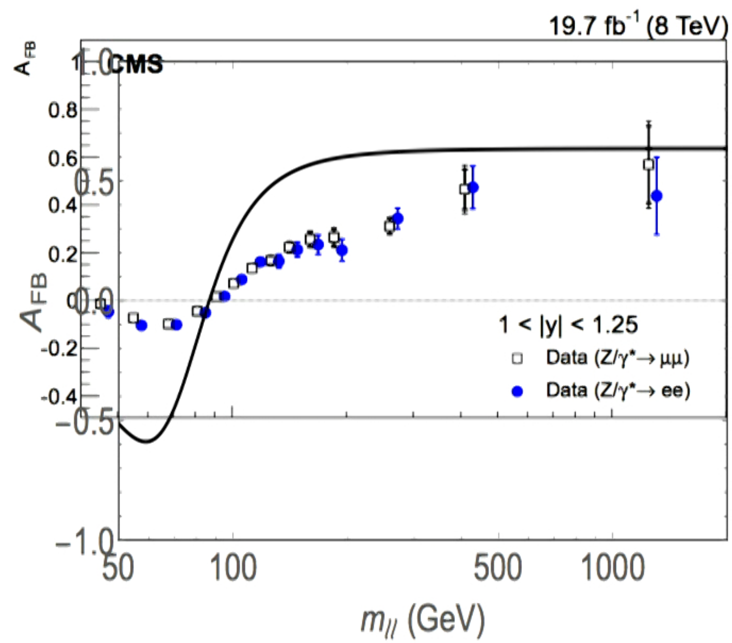
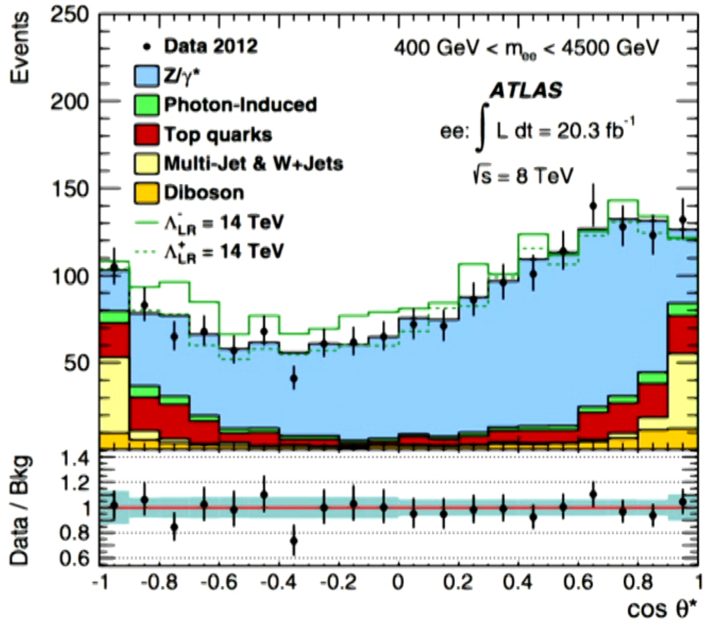
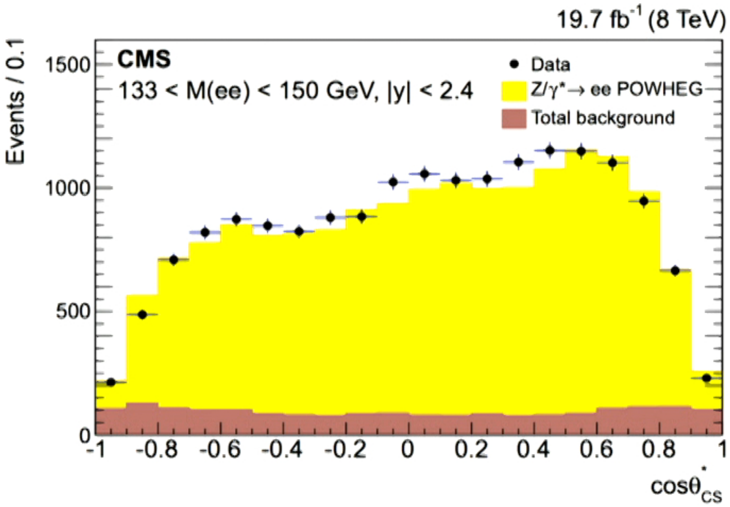


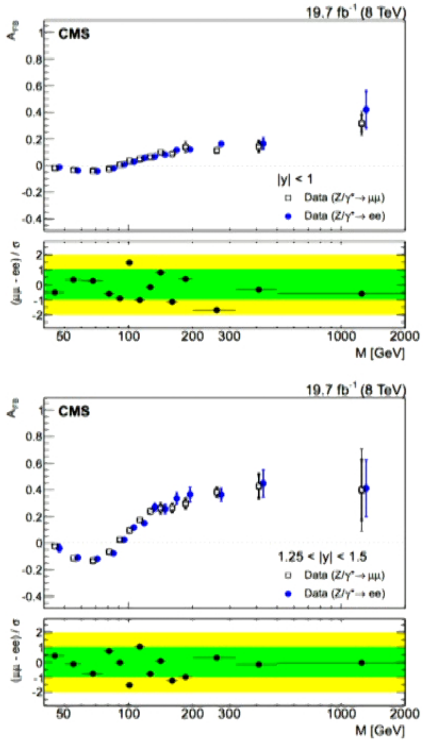
Dilepton angular spectra



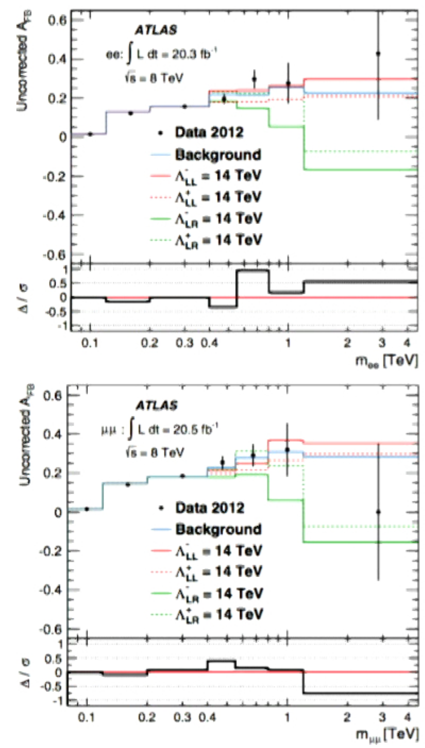


A_{FB} @ the LHC

1601.04768

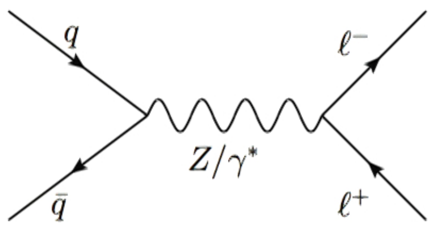


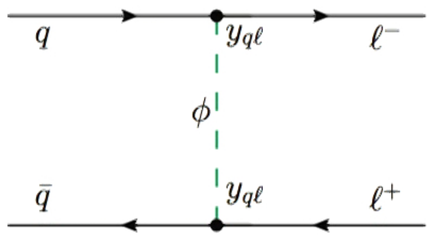
1407.2410



Do these constrain non-resonant entities?

Non-resonance: simple example





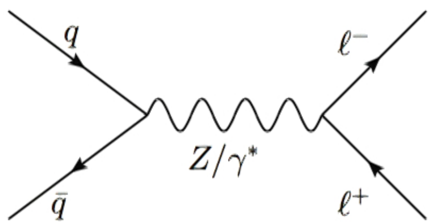
$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + a\cos\theta$$

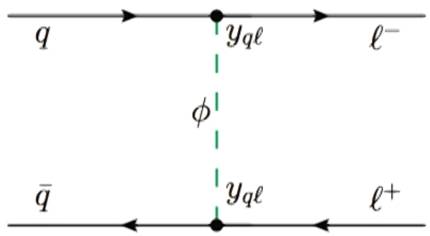
$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^4(\theta/2)}{(s\sin^2(\theta/2)+\bar{m}_t^2)^2}$$

Non-resonance: simple example

t-channel exchange of **leptoquark (LQ)**

$$\mathcal{L} \supset (\text{lepton})(\text{LQ})(\text{quark})$$





$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + a\cos\theta$$

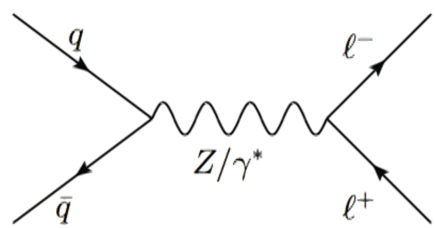
$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^4(\theta/2)}{(s\sin^2(\theta/2)+\bar{m}_t^2)^2}$$

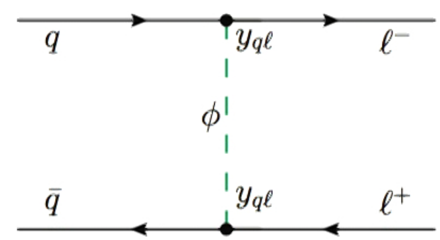
Qualitatively different spectra…
How well does existing LHC A_{FB} data already probe this?

Non-resonance: simple example

t-channel exchange of **leptoquark (LQ)**

$$\mathcal{L} \supset \text{(lepton)(LQ)(quark)}$$





$$\frac{d\sigma}{d\Omega} \propto (1 + \cos^2\theta) + a\cos\theta \qquad \frac{d\sigma}{d\Omega} \propto \frac{\sin^4(\theta/2)}{(s\sin^2(\theta/2) + \bar{m}_t^2)^2}$$

Qualitatively different spectra…
How well does existing LH[illegible] data already probe this?

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The leptoquark

Neglected child of particle physics
since it gives no easy solution to topical problems.

Usual motivations:

(1) Low-energy relics of GUTs.
(2) Technicolor/composite appearances.
(3) RPV SUSY.
(4) DM-SM mediator candidates.
(5) Ubiquitous explainers of flavor anomalies.

Useful motivation:

(6) Renormalizable interactions with SM fermions, and discoverable @ TeV scale.

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Leptoquark Models

$R_2(\mathbf{3}, \mathbf{2}, 7/6)$

$$\mathcal{L} = -y_{ij}\bar{u}_{R,i}R_2^a\epsilon^{ab}L_{L,j}^b + y'_{ij}\bar{e}_{R,i}R_2^{a*}Q_{L,j}^a + \text{h.c.}$$
$$= (yV_{\text{PMNS}})_{ij}\bar{u}_{R,i}\nu_{L,j}R_2^{2/3} - y_{ij}\bar{u}_{R,i}e_{L,j}R_2^{5/3}$$
$$+ y'_{ij}\bar{e}_{R,i}d_{L,j}R_2^{2/3*} + (y'V_{\text{CKM}}^\dagger)_{ij}\bar{e}_{R,i}u_{L,j}R_2^{5/3*} + \text{h.c.}$$

$y'_{ij} = 0$, $y_{ij} = y_{ue}\,\delta_{i1}\delta_{j1}$: ElectroUp
$y'_{ij} = 0$, $y_{ij} = y_{u\mu}\,\delta_{i1}\delta_{j2}$: MuoUp

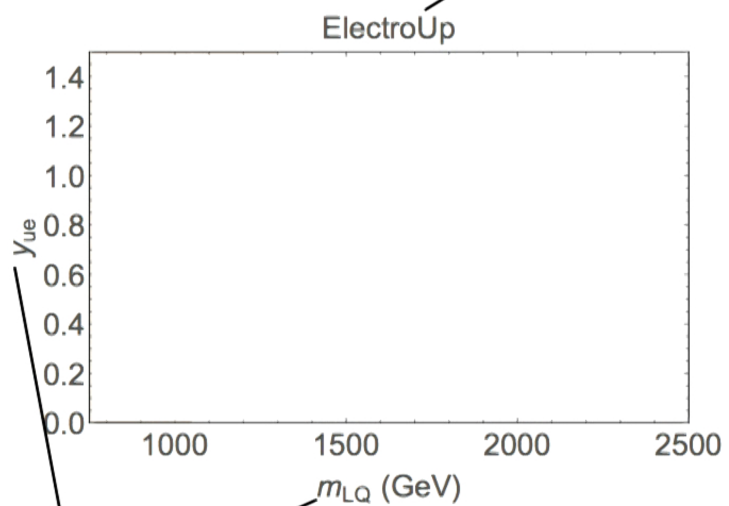
$\tilde{R}_2(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L} = -y_{ij}\bar{d}_{R,i}\tilde{R}_2^a\epsilon^{ab}L_{L,j}^b + \text{h.c.}$$
$$= -y_{ij}\bar{d}_{R,i}e_{L,j}\tilde{R}_2^{2/3} + (yV_{\text{PMNS}})_{ij}\bar{d}_{R,i}\nu_{L,j}\tilde{R}_2^{-1/3} + \text{h.c.}$$

$y_{ij} = y_{de}\,\delta_{i1}\delta_{j1}$: ElectroDown
$y_{ij} = y_{d\mu}\,\delta_{i1}\delta_{j2}$: MuoDown

Probing

Illustrative choice

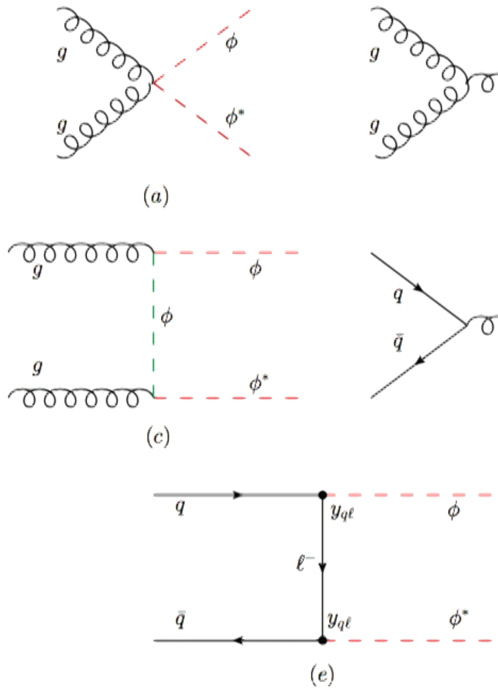


Free parameters

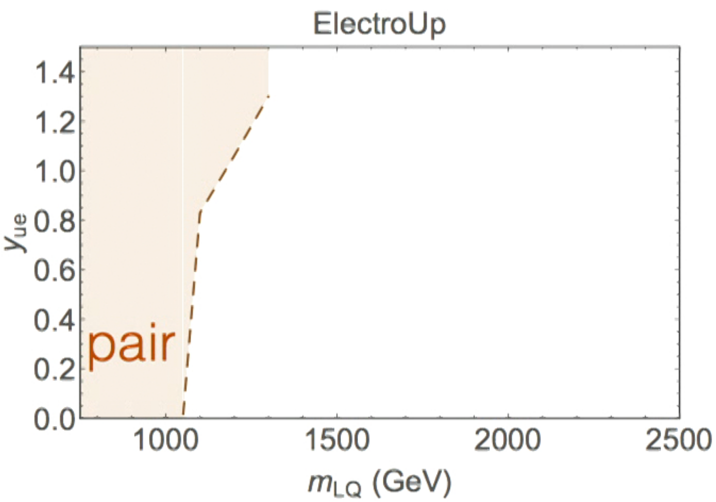
N.R. 1610.03795

Probes: (i) pair production

"direct search"



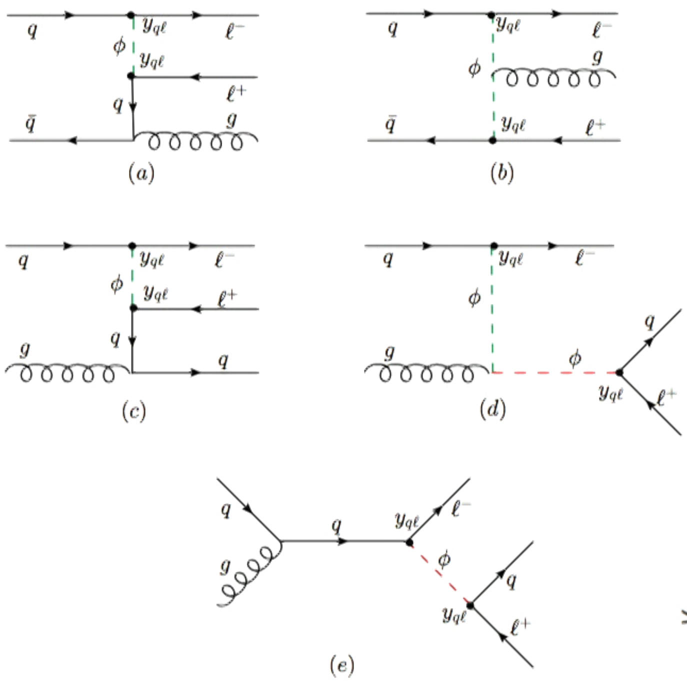
ATLAS 8 TeV, 20 ifb,
Signature: e+e-jj



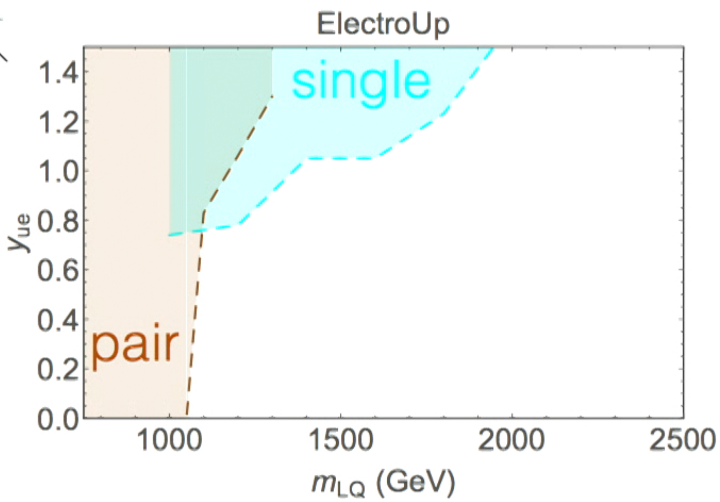
N.R. 1610.03795

Probes: (ii) single production

"direct search"

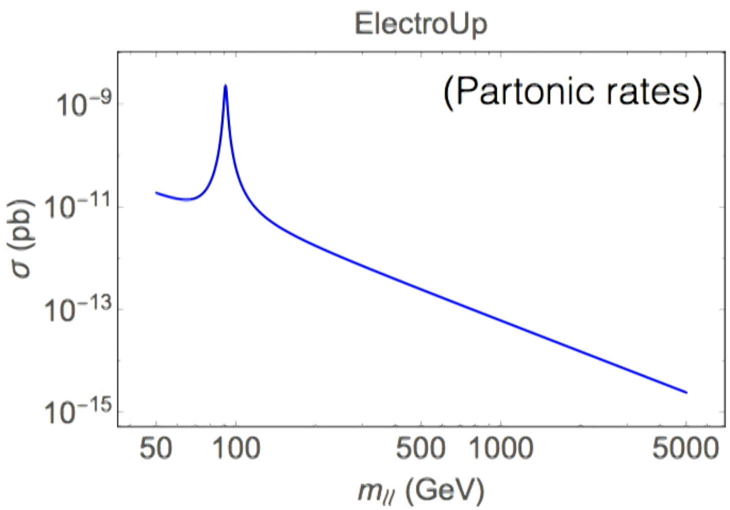


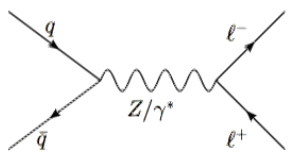
CMS 8 TeV, 20 ifb,
Signature: e+e-j



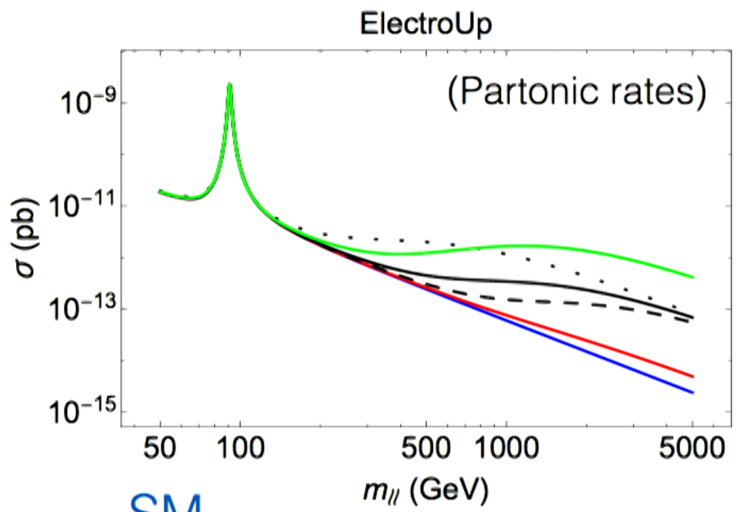
N.R. 1610.03795

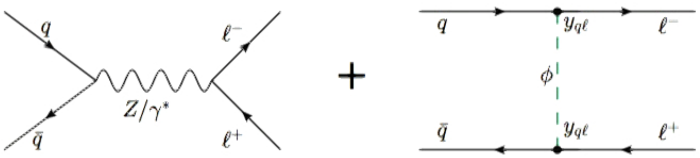
Probes: (iii) m_{ll} spectrum





Probes: (iii) m_{ll} spectrum





SM

(m_{LQ} = 1 TeV,

y_{ue} = 0.4, 1.0, 1.6)

(y_{ue} = 1,

m_{LQ}/TeV = 0.4, 1.0, 1.6)

Probes: (iii) m_{ll} spectrum

Recast

(i) Analytic cross-sections (ren scale = fac scale = m_{ll}),

(ii) Rescale events from ATLAS 8 TeV, 20 ifb by

$$d\sigma_{\rm total}/d\sigma_{\rm SM}$$

(iii) Shape analysis:

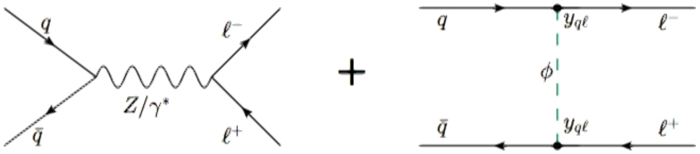
$$\chi^2_{\rm NP} = \sum_{i=1}^{N_{\rm bins}} \frac{(N^i_{\rm obs} - N^i_{\rm NP})^2}{N^i_{\rm NP} + \sigma^2_{\rm NP}},$$

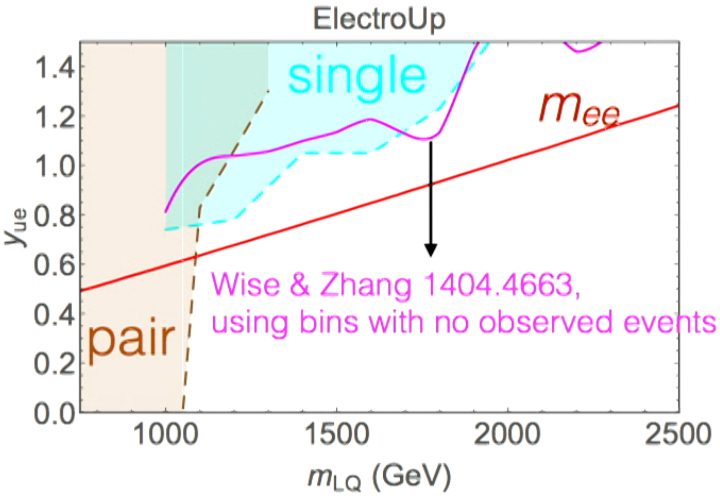
$$\chi^2_{\rm SM} = \sum_{i=1}^{N_{\rm bins}} \frac{(N^i_{\rm obs} - N^i_{\rm SM})^2}{N^i_{\rm SM} + \sigma^2_{\rm SM}}$$

95% C.L. limit:

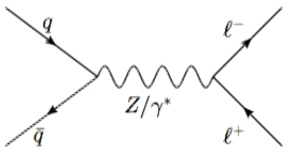
$$\Delta\chi^2 = \chi^2_{\rm NP} - \chi^2_{\rm SM} = 5.99$$

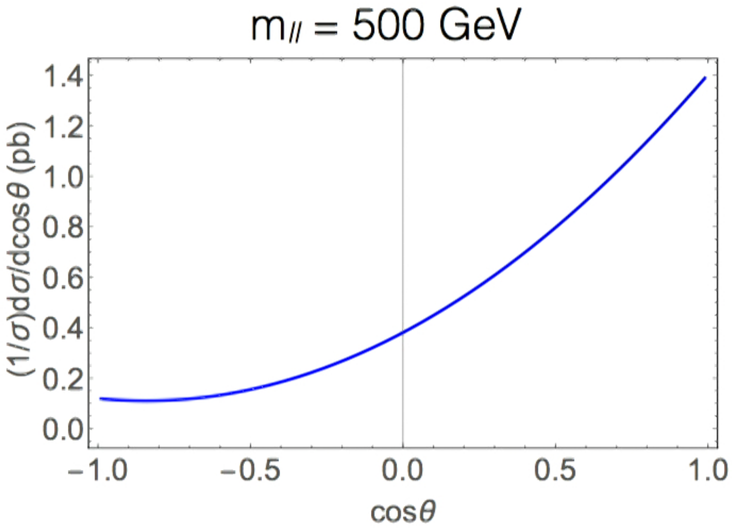
N.R. 1610.03795





Probes: (iv) A_{FB}





Probes: (iv) A_{FB}

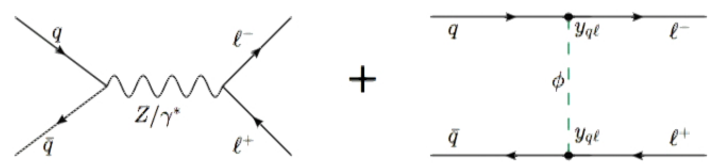
SM

(m_{LQ} = 1 TeV,

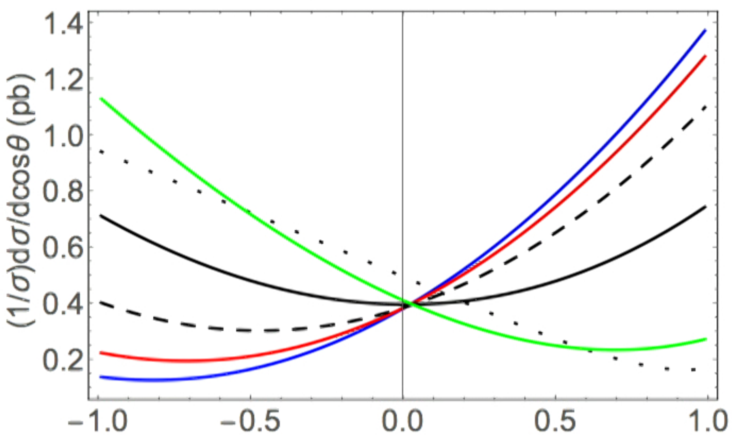
y_{ue} = 0.4, 1.0, 1.6)

(y_{ue} = 1,

m_{LQ}/TeV = 0.4, 1.0, 1.6)



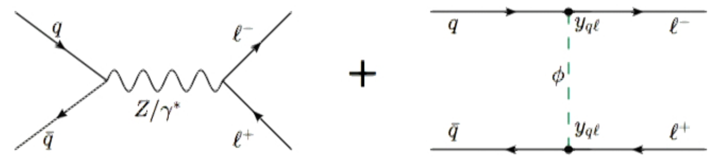
ElectroUp, m_{ll} = 500 GeV

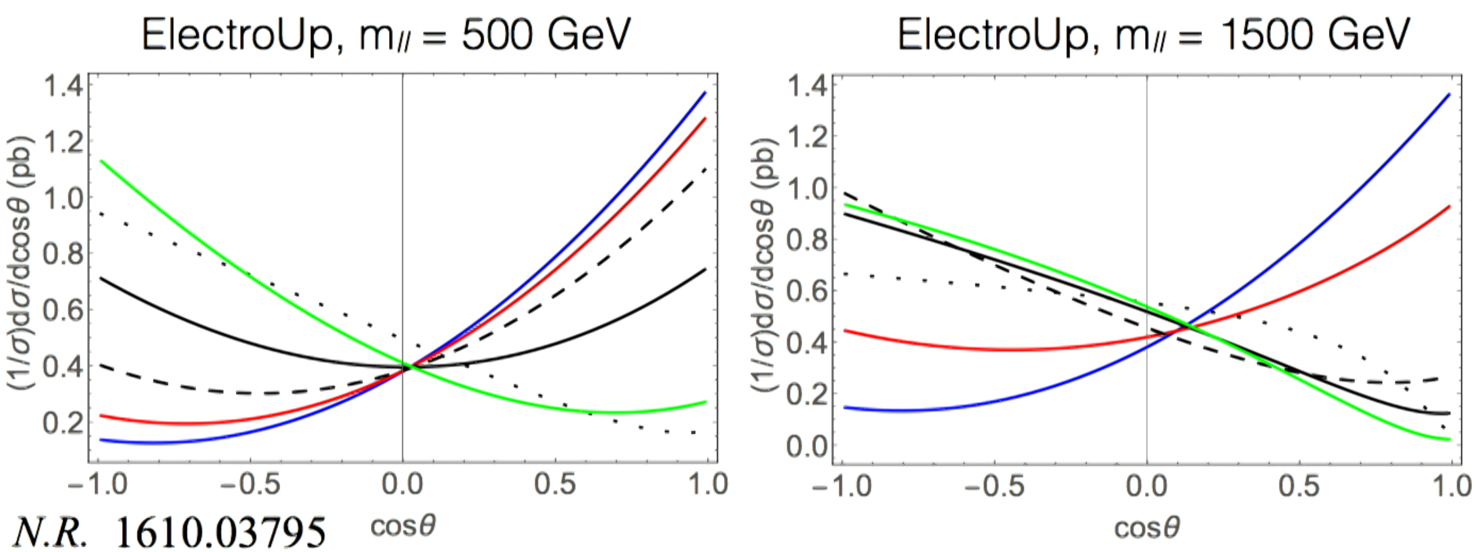


N.R. 1610.03795

Probes: (iv) A_{FB}

SM
(m_{LQ} = 1 TeV,
y_{ue} = 0.4, 1.0, 1.6)
(y_{ue} = 1,
m_{LQ}/TeV = 0.4, 1.0, 1.6)





N.R. 1610.03795

Probes: (iv) A_{FB}

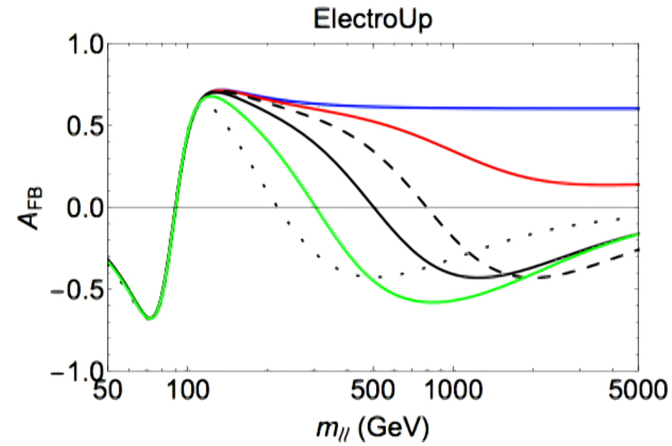
SM

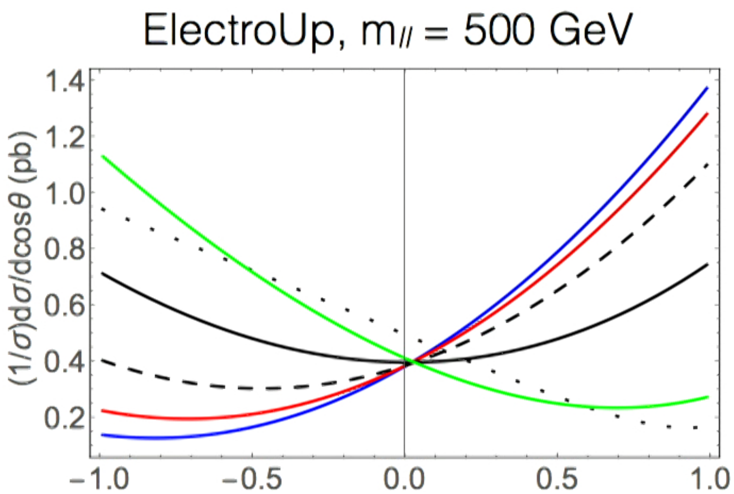
(m_{LQ} = 1 TeV,

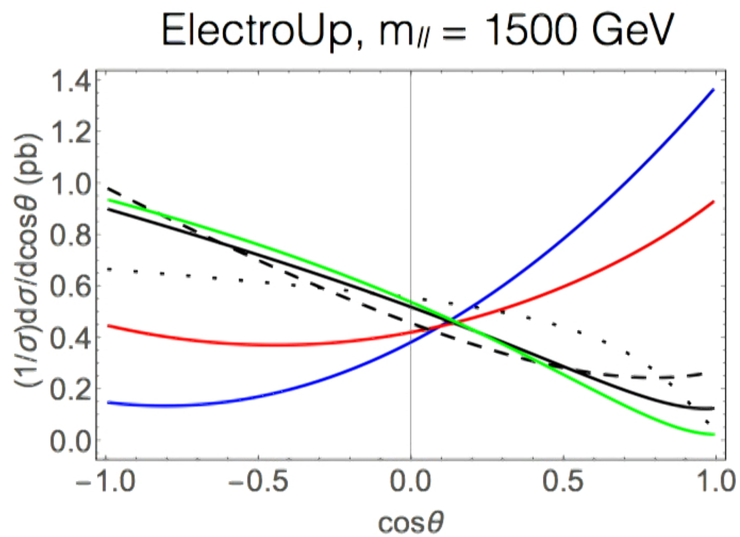
y_{ue} = 0.4, 1.0, 1.6)

(y_{ue} = 1,

m_{LQ}/TeV = 0.4, 1.0, 1.6)







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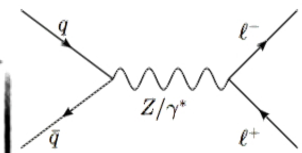
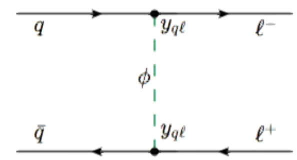
Probes: (iv) A_{FB}





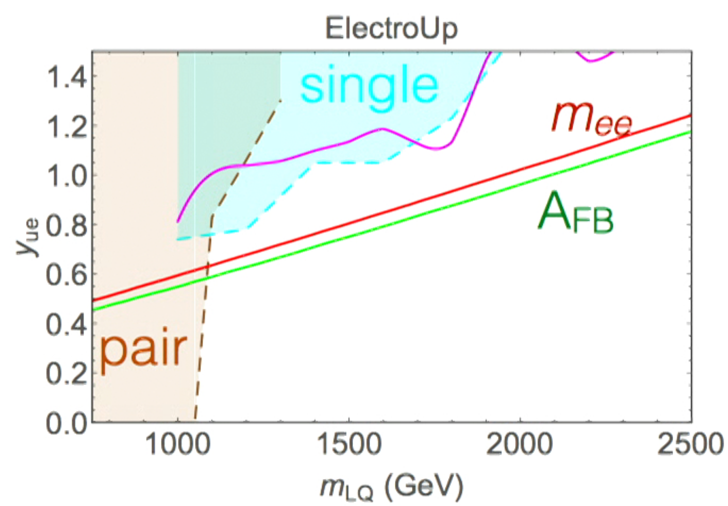
Recast
(i) MadGraph5 events with CMS criteria,
(ii) find SM perfectly aligned with CMS backgrounds for $500 < m_{ll}/\text{GeV} < 2000$,
(iii) shape analysis:

$$\chi^2_{\rm NP} = \sum_{\rm bins} \frac{(A^{\rm obs}_{\rm FB} - A^{\rm NP}_{\rm FB})^2}{\delta^2_{\rm NP}}$$

$$\chi^2_{\rm SM} = \sum_{\rm bins} \frac{(A^{\rm obs}_{\rm FB} - A^{\rm SM}_{\rm FB})^2}{\delta^2_{\rm SM}}$$

95% C.L. limit:

$$\Delta\chi^2 = \chi^2_{\rm NP} - \chi^2_{\rm SM} = 5.99$$



N.R. 1610.03795

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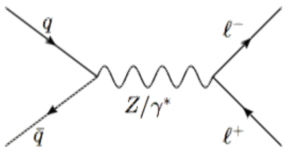
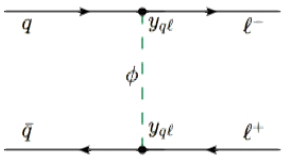
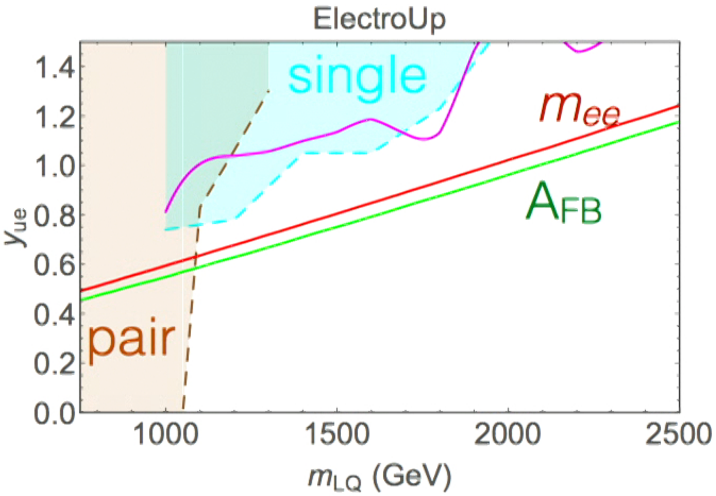
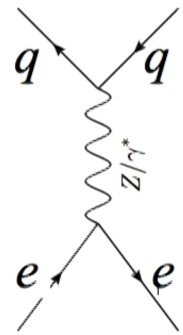


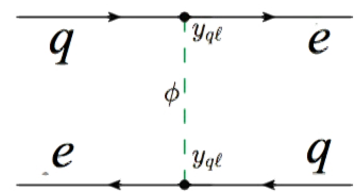




N.R. 1610.03795

Probes: (v) atomic parity violation





Wood, et al (1997)

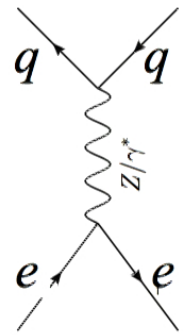
$$Q_W^{\text{expt}}(\text{Cs}) = -72.58 \pm 0.43,$$
$$Q_W^{\text{SM}}(\text{Cs}) = -73.23 \pm 0.20,$$

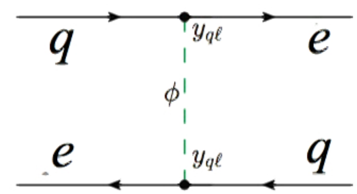
$$\mathcal{L}_{\text{APV}} = \frac{G_F}{\sqrt{2}} \bar{e}\gamma^\mu\gamma^5 e[C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d]$$

$$\delta Q_W(Z,N) = -2[(2Z+N)\delta C_{1u} + (Z+2N)\delta C_{1d}]$$

$$\delta C_{1(u/d)} = \frac{\sqrt{2}}{G_F}\frac{|y_{(u/d)e}|^2}{8m_{\text{LQ}}^2}$$

Probes: (v) atomic parity violation



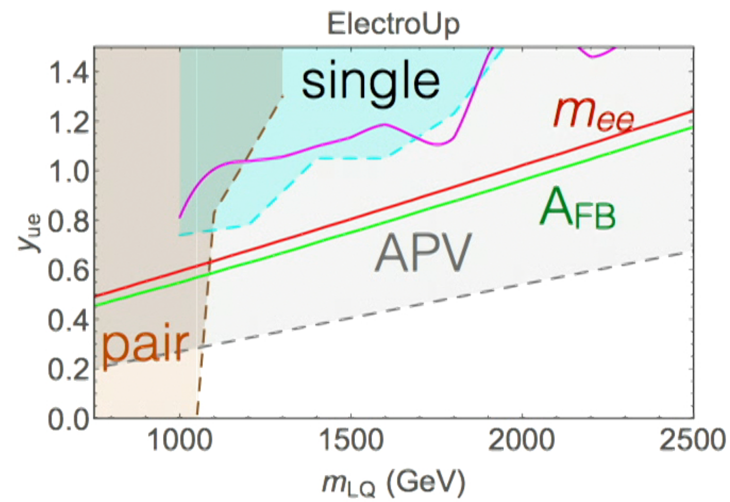


Recast

2 sigma limit:

$$|y_{ue}| \leq 0.27\left(\frac{m_{\rm LQ}}{1{\rm TeV}}\right) ,$$

$$|y_{de}| \leq 0.26\left(\frac{m_{\rm LQ}}{1{\rm TeV}}\right) .$$



$$\delta C_{1(u/d)} = \frac{\sqrt{2}}{G_F}\frac{|y_{(u/d)e}|^2}{8m_{\rm LQ}^2}$$

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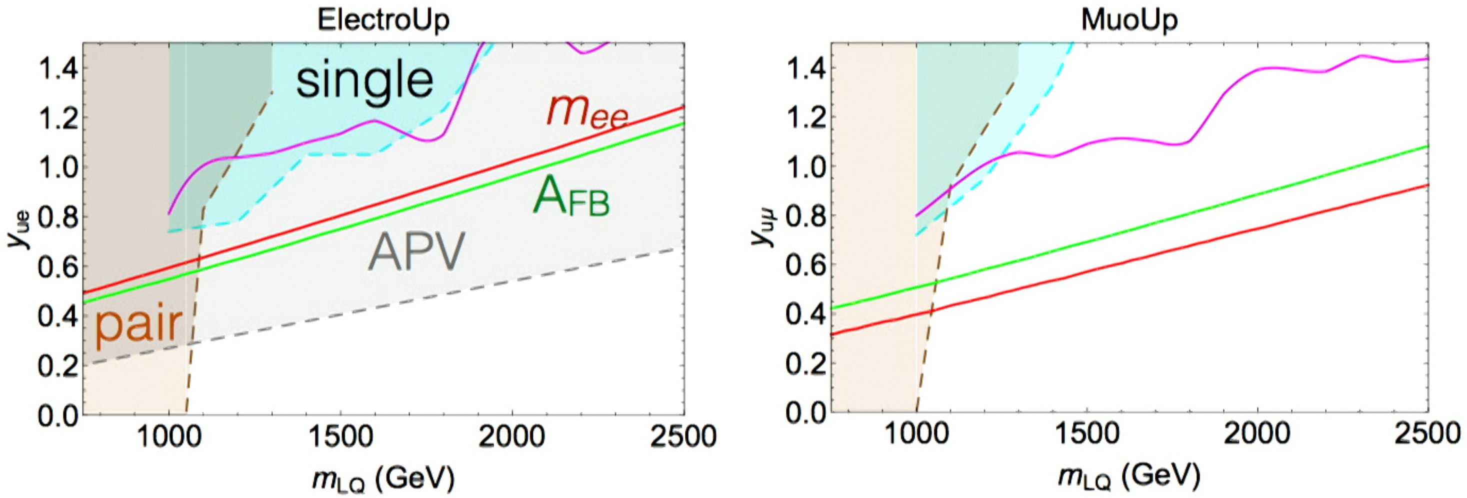
ElectroQuark v MuoQuark



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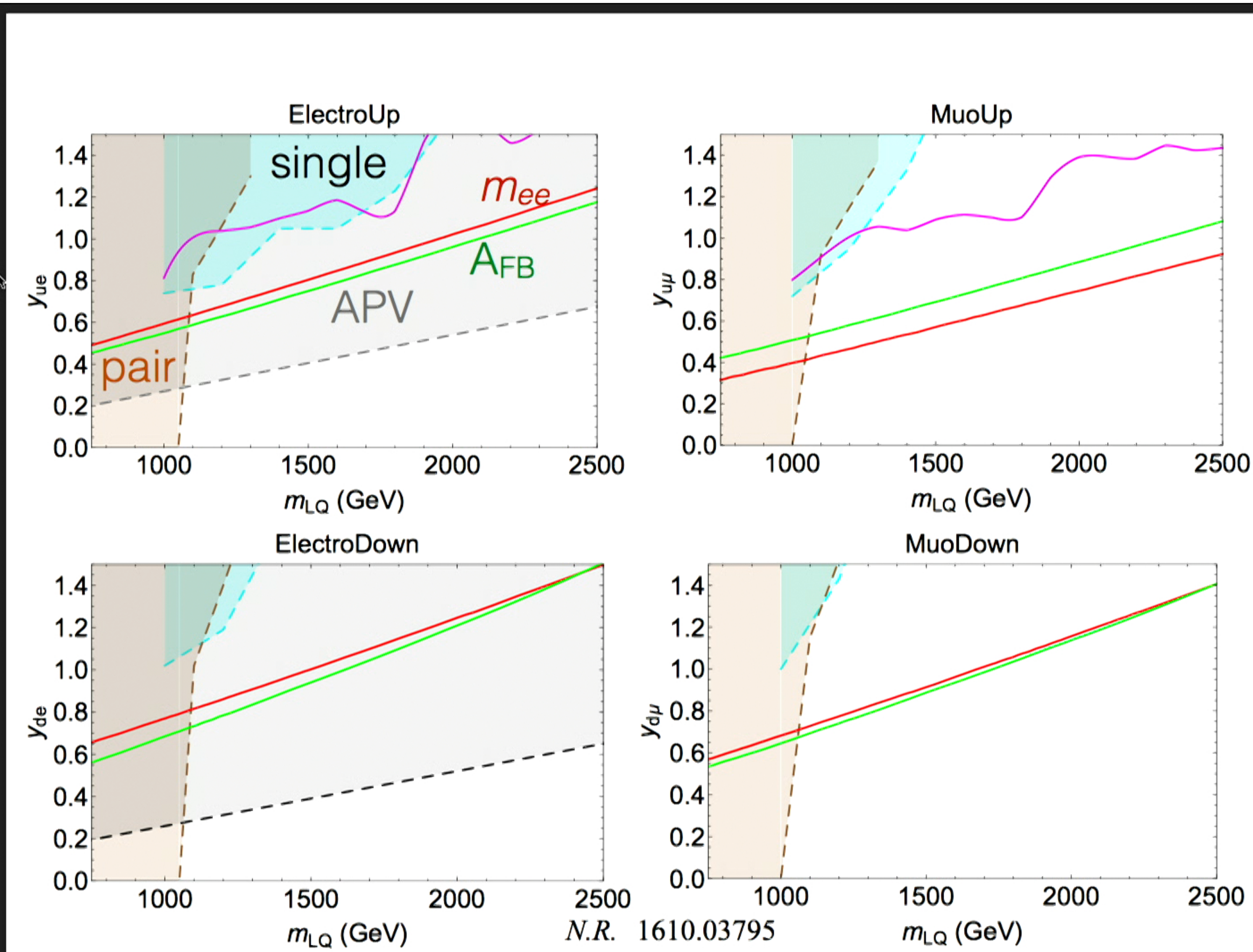
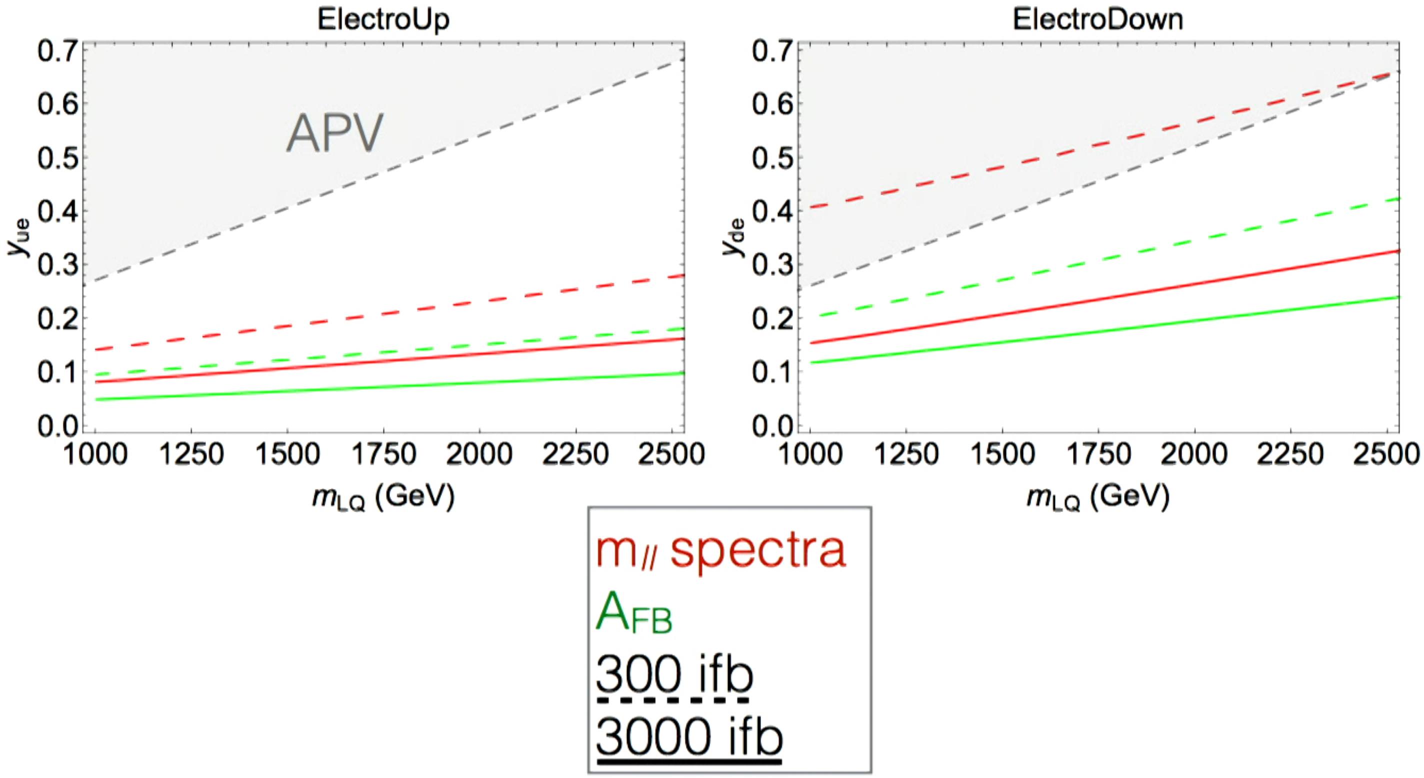

ElectroUp
single
m_{ee}
A_{FB}
APV
pair
y_{ue}
m_{LQ} (GeV)
MuoUp
$y_{u\mu}$
m_{LQ} (GeV)
ElectroDown
y_{de}
m_{LQ} (GeV)
MuoDown
$y_{d\mu}$
m_{LQ} (GeV)
N.R. 1610.03795

Forecast

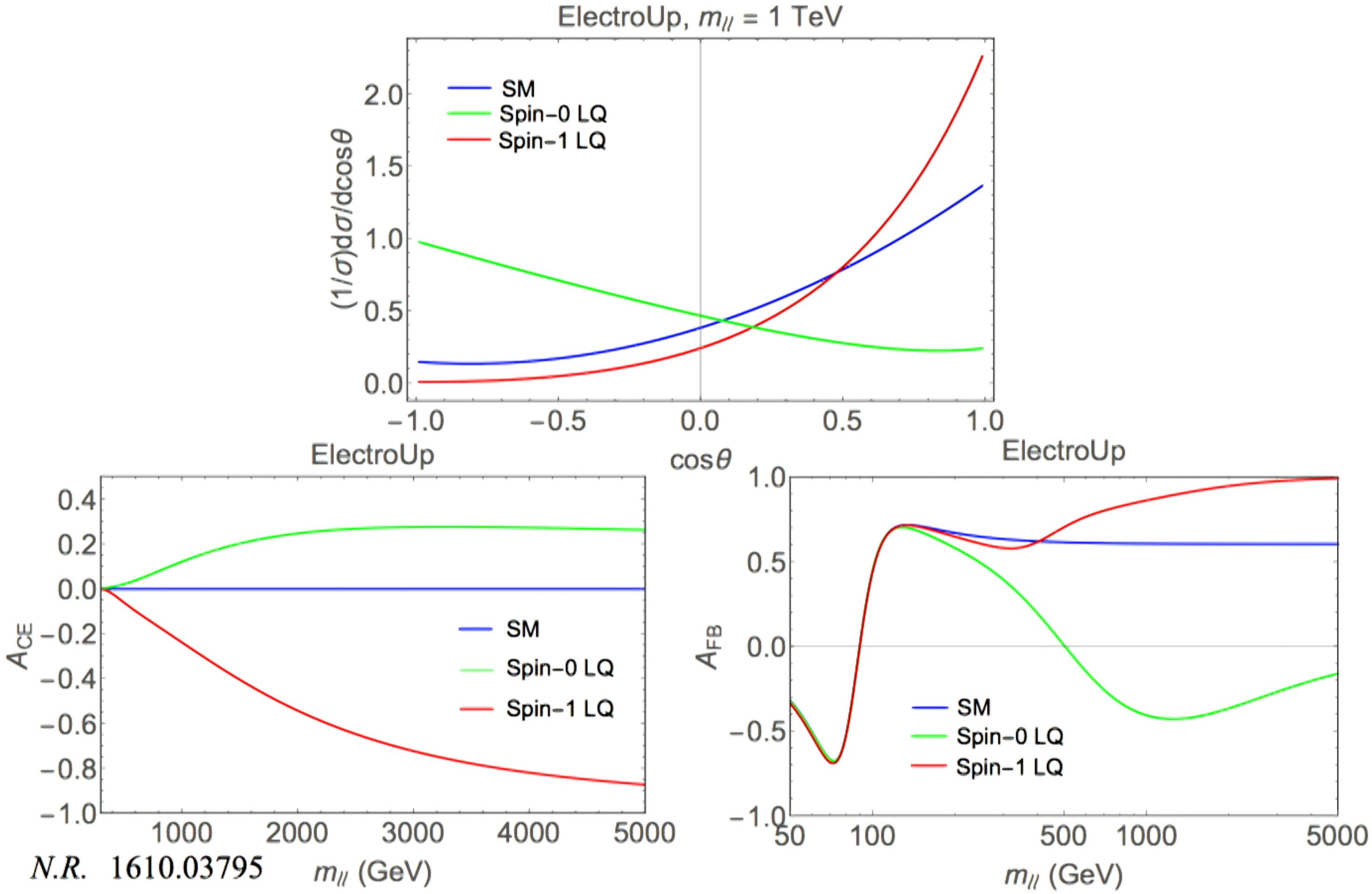
Can a **hadron** collider's dileptons
ever achieve more precision than
low-energy measurements of atomic parity violation?

Forecast



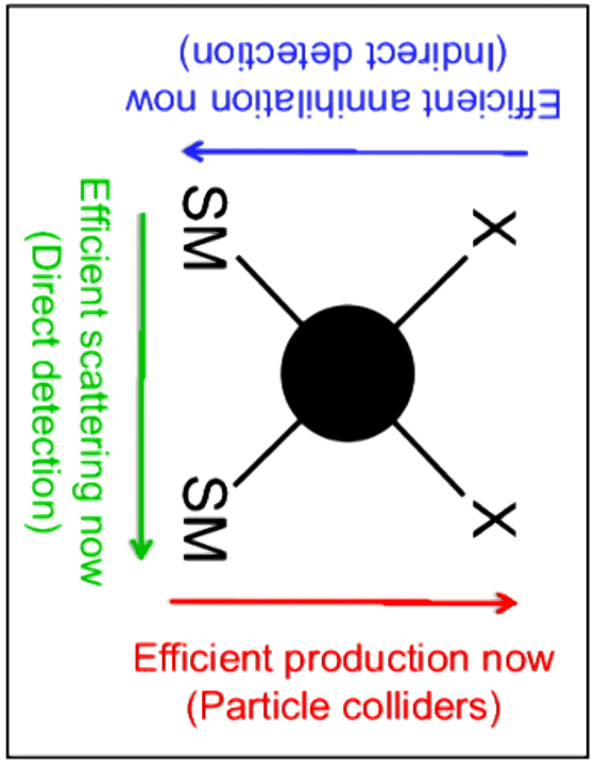
N.R. 1610.03795

Telling leptoquark spin

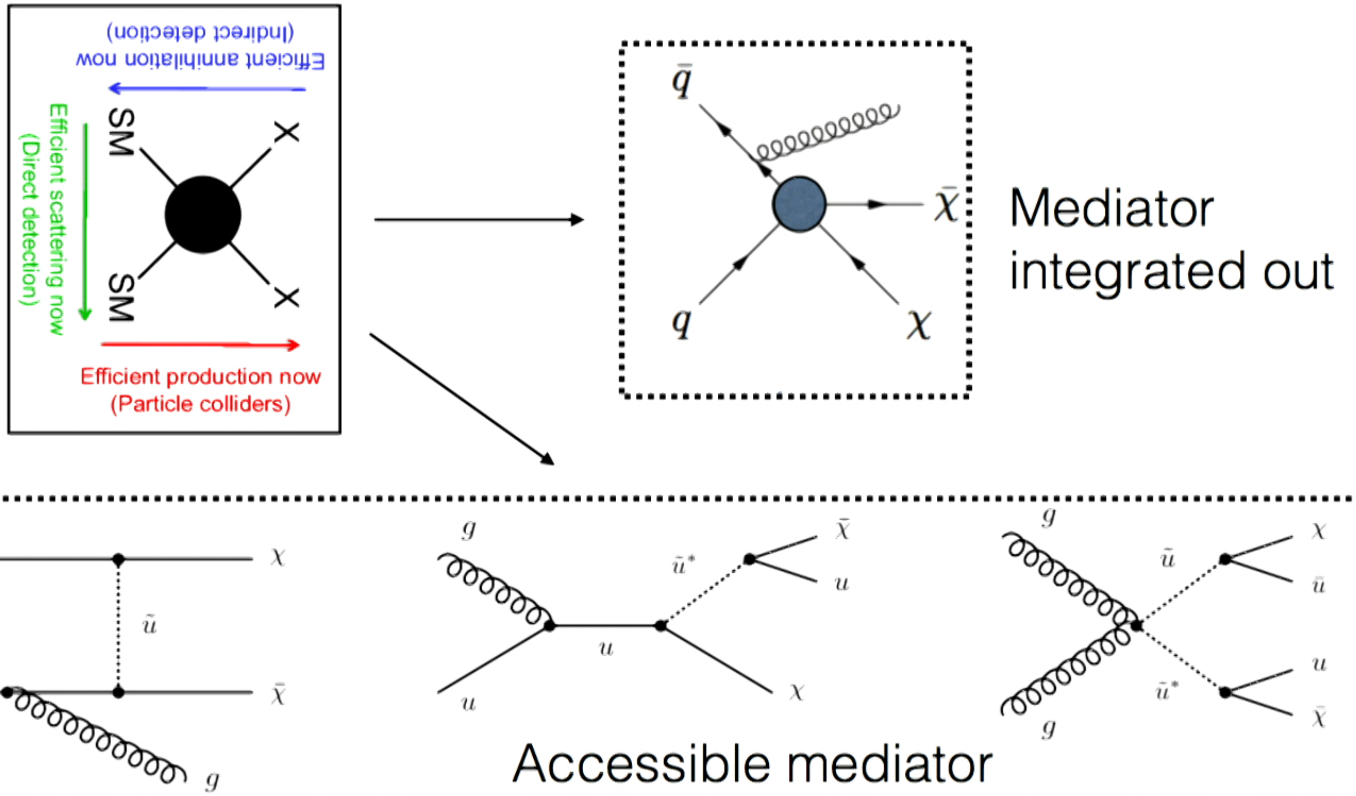


N.R. 1610.03795

Collider dark matter



Collider dark matter = missing energy?

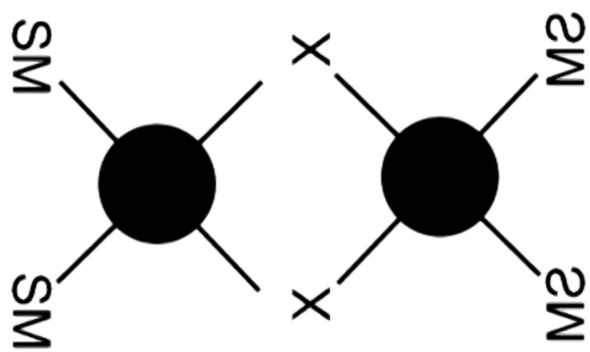


(Remember story of Z?)

Late 1970s
PETRA @ $\sqrt{s}$ = **30 - 40 GeV** in e-e+ —> μ+ μ- saw non-zero forward-backward asymmetry, derived **M_Z< 100 GeV**.

1983
SPS in p pbar —> e-e+ found resonance @ **95.5+/-2.5 GeV**

Always interference effects!



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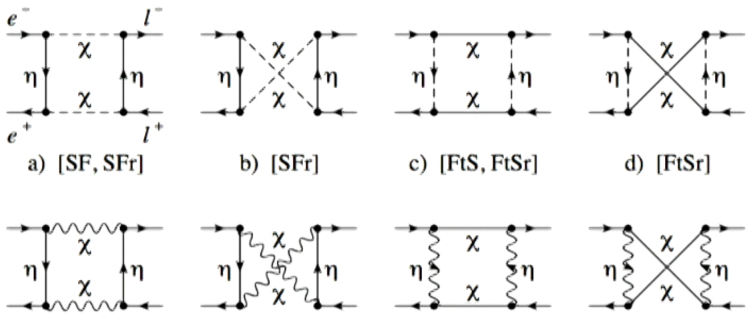


a) [SF, SFr] b) [SFr] c) [FtS, FtSr] d) [FtSr]

e) [VF, VFr] f) [VFr] g) [FtV, FtVr] h) [FtVr]

Leptophillic DM

↓

four-fermion contact operators

$(\bar{e}\gamma_\mu P_L e)(\bar{\ell}\gamma^\mu P_L \ell)$, $(\bar{e}\gamma_\mu P_R e)(\bar{\ell}\gamma^\mu P_R \ell)$

↓

LEP $\ell^+\ell^-$ production bounds

rival/ outdo

LEP mono-photon searches

Freitas, Westhoff 1408.1959

So at the LHC, can interference signals

(1) complement MET signals?

(2) tell us the character of dark matter?

Simplified model

$$\mathcal{L} = i\chi_A^\dagger \bar{\sigma}^\mu \partial_\mu \chi_A + i\chi_B^\dagger \bar{\sigma}^\mu \partial_\mu \chi_B + \mathcal{L}_{\text{DM mass}}$$
$$- \sum_{q=u,d} |D_\mu \tilde{q}|^2 - M_{\tilde{q}}^2 \tilde{q}\tilde{q}^* - (\sqrt{2}\, \lambda_{\tilde{q}} \tilde{q}^* \chi_B^\dagger q_R^\dagger + \text{h.c.})$$
$$- \sum_{\ell=e,\mu} |D_\mu \tilde{\ell}|^2 - M_{\tilde{\ell}}^2 \tilde{\ell}\tilde{\ell}^* - (\sqrt{2}\, \lambda_{\tilde{\ell}} \tilde{\ell}^* \chi_B^\dagger \ell_R^\dagger + \text{h.c.})\,,$$

Field	Spin	$SU(3)_c \otimes SU(2)_W \otimes U(1)_Y$	Z_2
χ_A, χ_B	$\mathbf{1/2}$	$(\mathbf{1}, \mathbf{1}, \mathbf{0})$	$-\mathbf{1}$
$\tilde{u}$	$\mathbf{0}$	$(\mathbf{3}, \mathbf{1}, \frac{\mathbf{2}}{\mathbf{3}})$	$-\mathbf{1}$
$\tilde{d}$	$\mathbf{0}$	$(\mathbf{3}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{3}})$	$-\mathbf{1}$
$\tilde{\ell} = \tilde{e}, \tilde{\mu}$	$\mathbf{0}$	$(\mathbf{1}, \mathbf{1}, -\mathbf{1})$	$-\mathbf{1}$

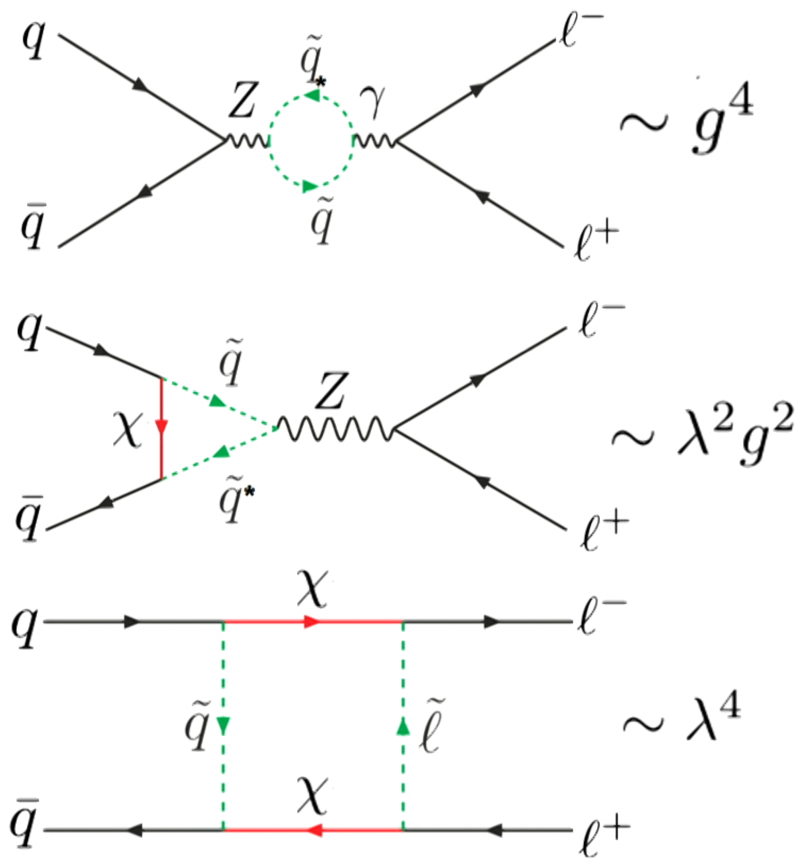
<u>This talk</u>

Model	Couplings	Mediator masses
U	$\lambda \equiv \lambda_{\tilde{\ell}} = \lambda_{\tilde{u}}$, $\lambda_{\tilde{d}} = 0$	$M_\phi \equiv M_{\tilde{\ell}} = M_{\tilde{u}}$

Loops

g: electroweak coupling

λ: matter-mediator-DM coupling



Boxes dominate for

$$\lambda \gtrsim 1$$

feature of simplified DM models
with successful freezeout +
LHC-detectability

Luty, et al 1307.8120; Bai, Berger, 1308.0612; DiFranzo, et al 1308.2679

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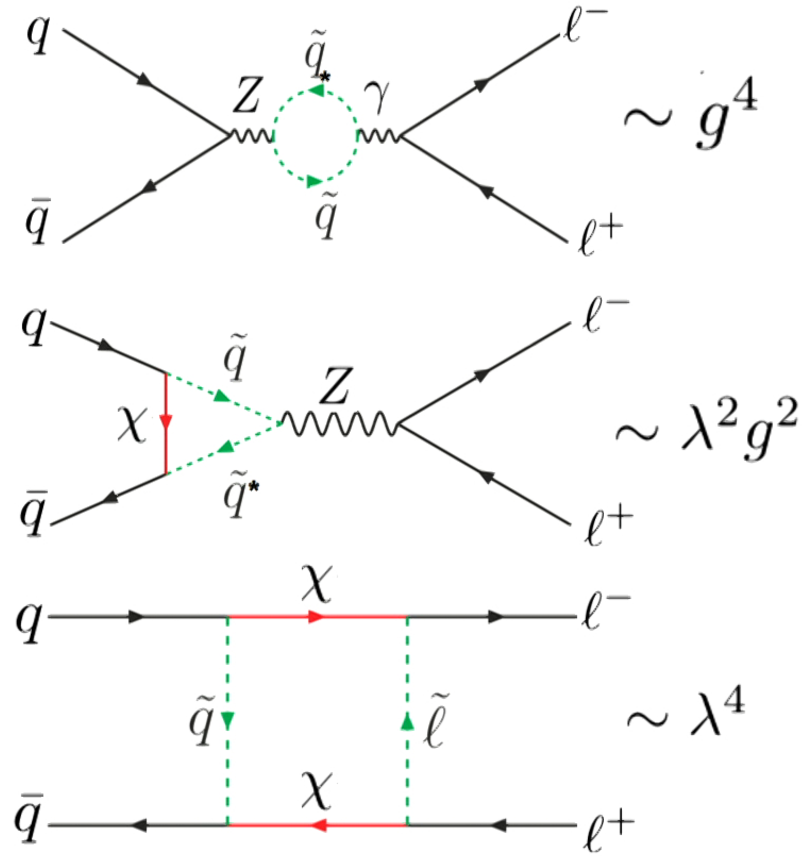
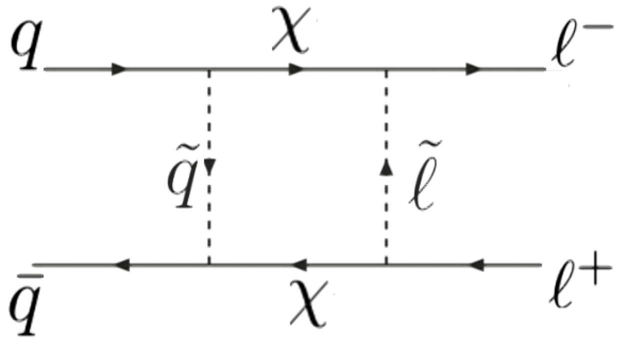


Luty, et al 1307.8120; Bai, Berger, 1308.0612; DiFranzo, et al 1308.2679

What do boxes do?

Altmannshofer, Fox, Harnik, Kribs, *N.R.* 1411.6743



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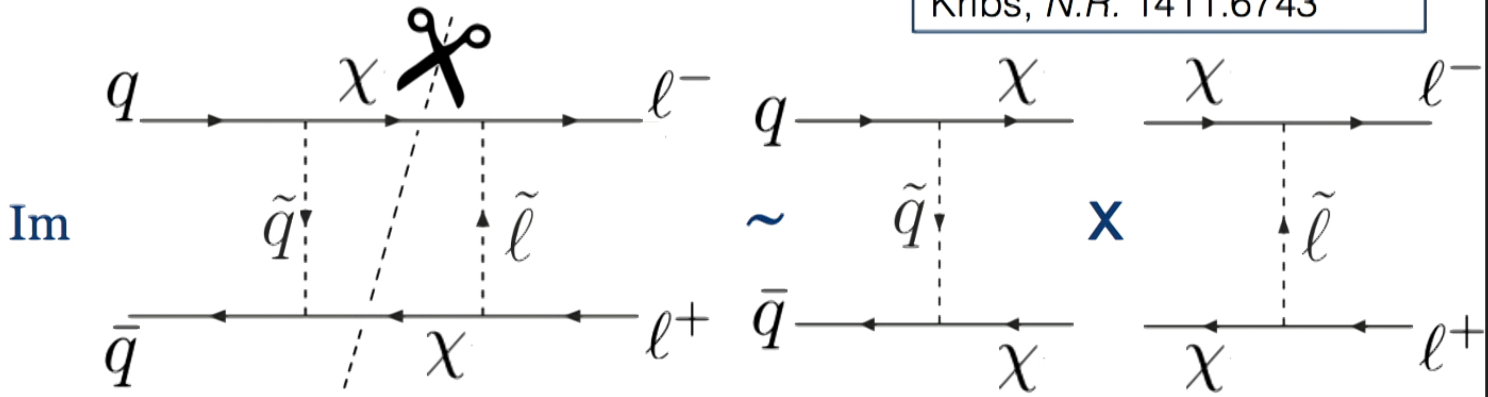

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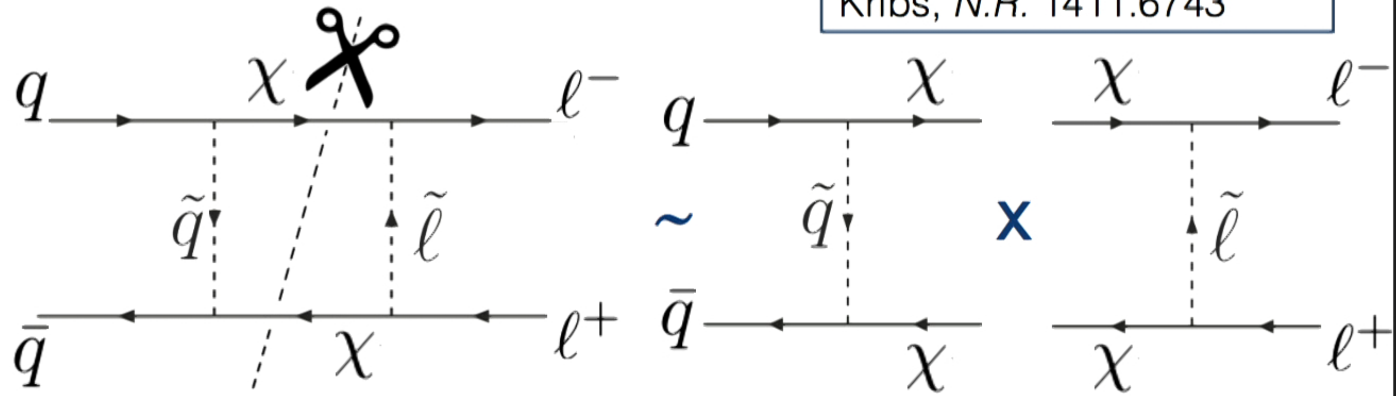
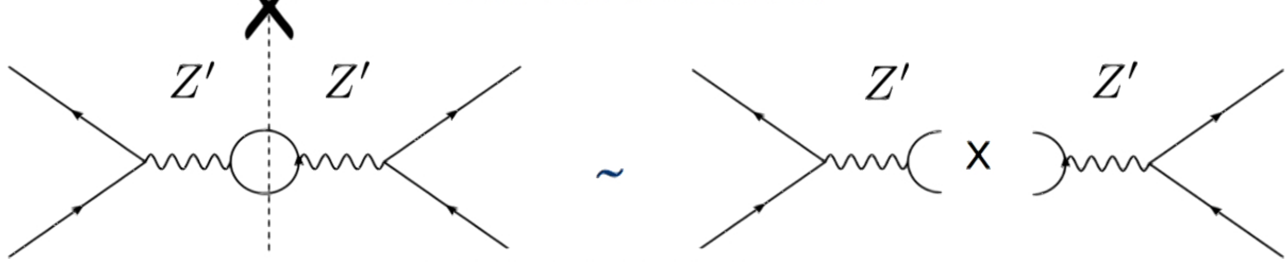
Altmannshofer, Fox, Harnik, Kribs, *N.R.* 1411.6743

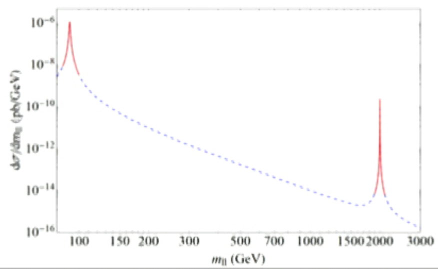
Im



a la resonances:

Im





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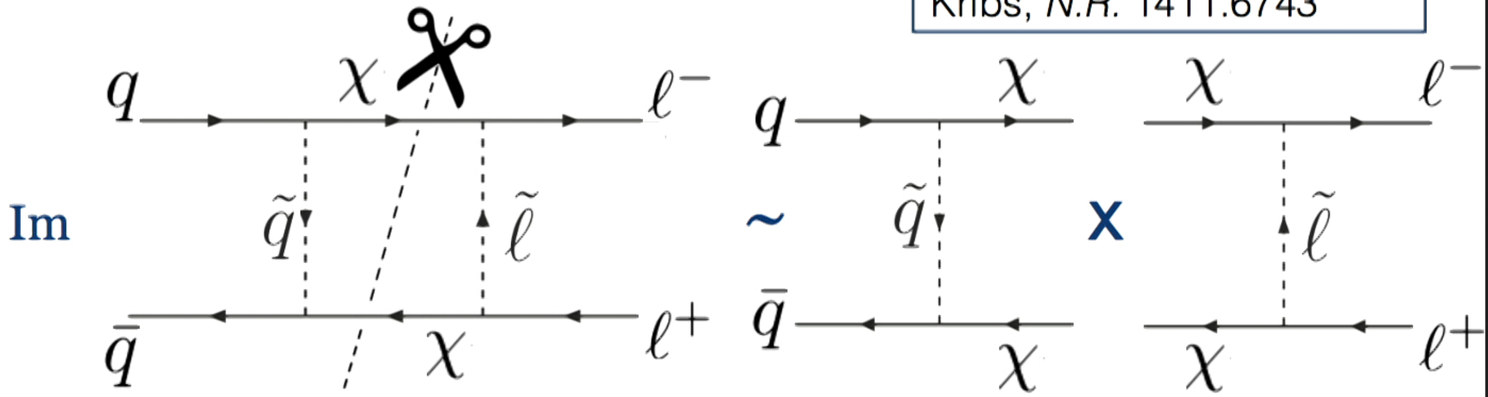
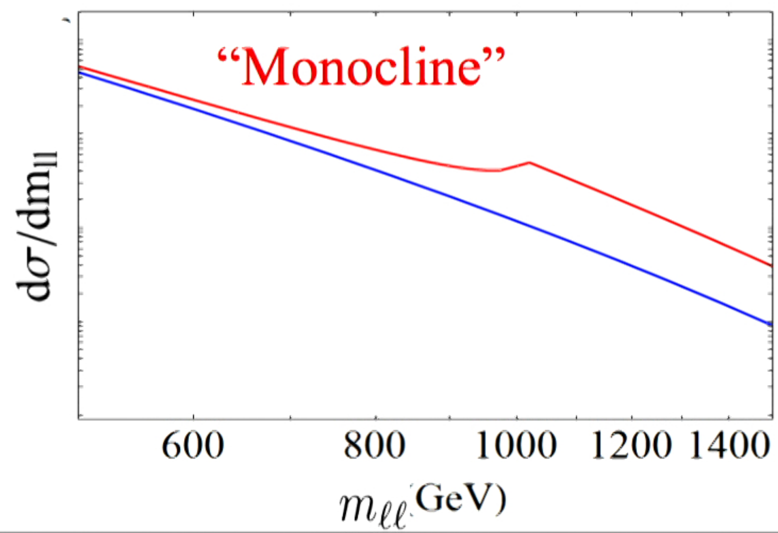




N.B. This happens even if hidden sector isn't "dark"

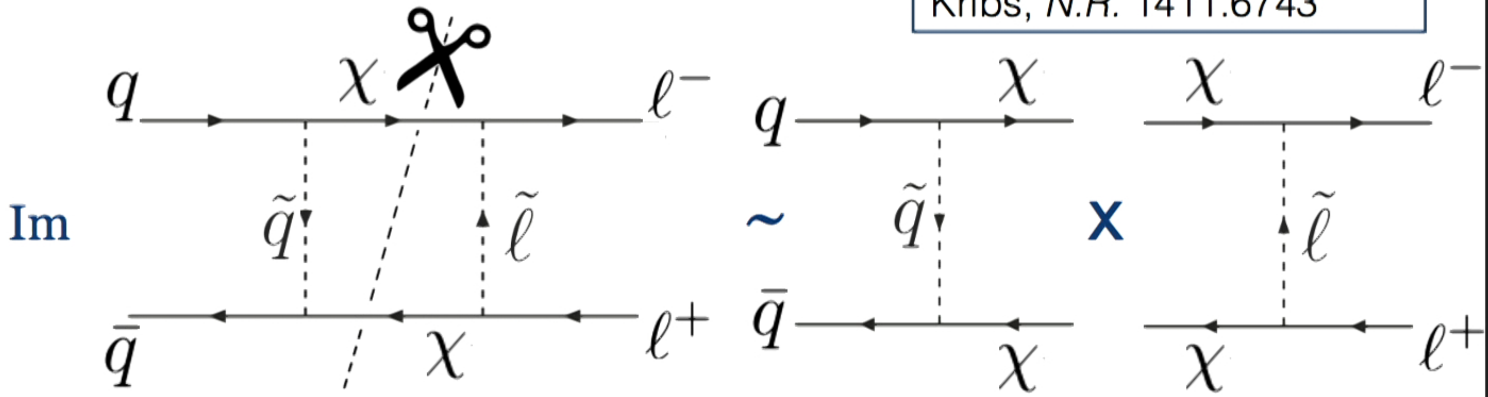
Blue $\lambda = 0$ (SM)

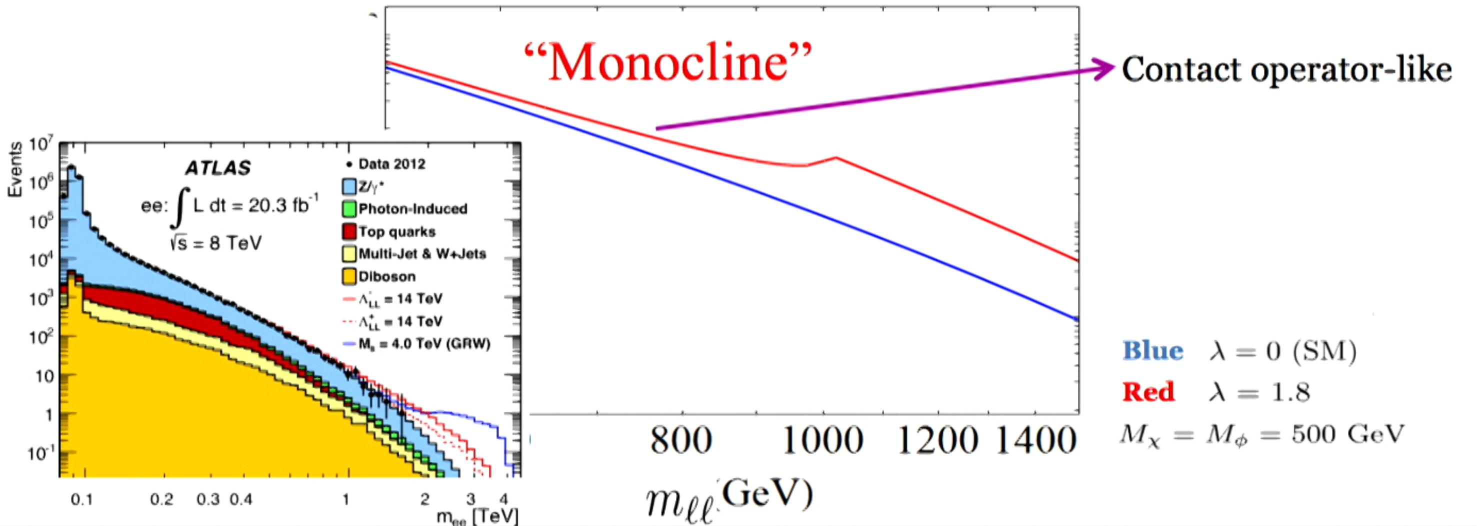
Red $\lambda = 1.8$

$M_\chi = M_\phi = 500$ GeV

What do boxes do?

Altmannshofer, Fox, Harnik, Kribs, *N.R.* 1411.6743





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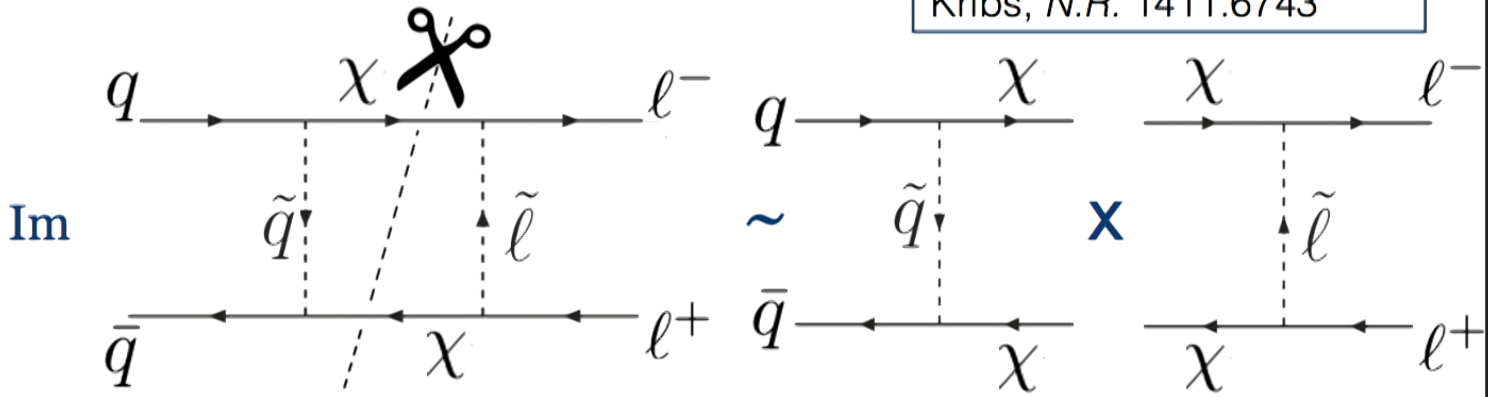
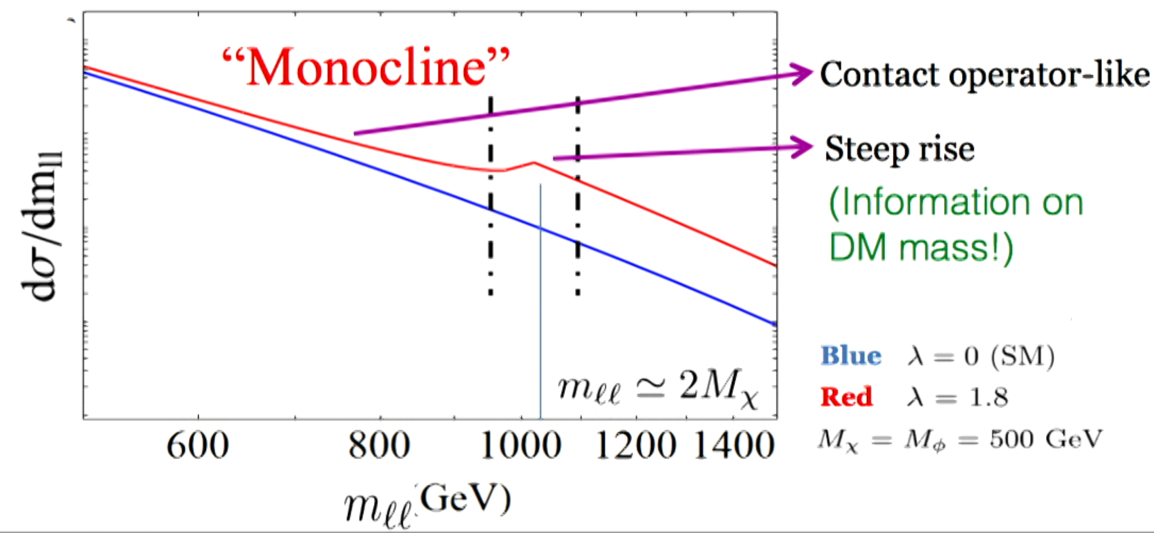
Altmannshofer, Fox, Harnik, Kribs, *N.R.* 1411.6743





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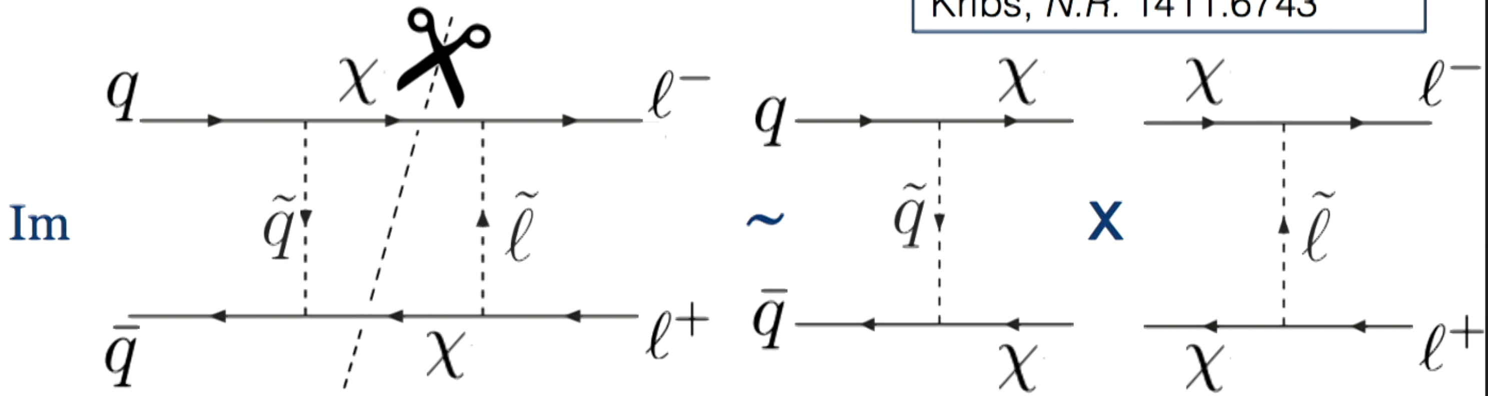
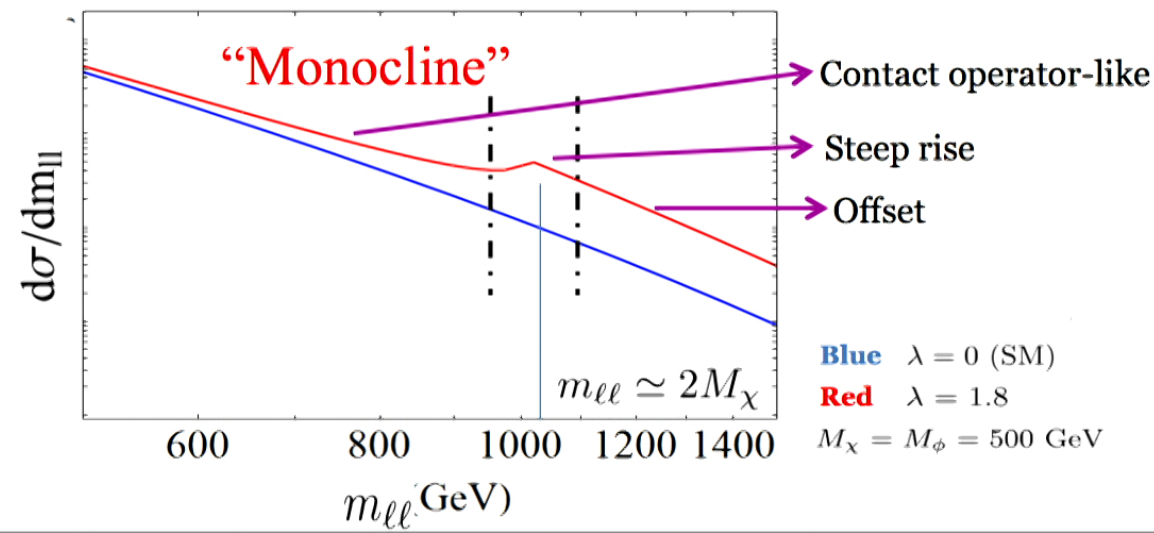
Altmannshofer, Fox, Harnik, Kribs, *N.R.* 1411.6743





Example constraints (8 TeV)

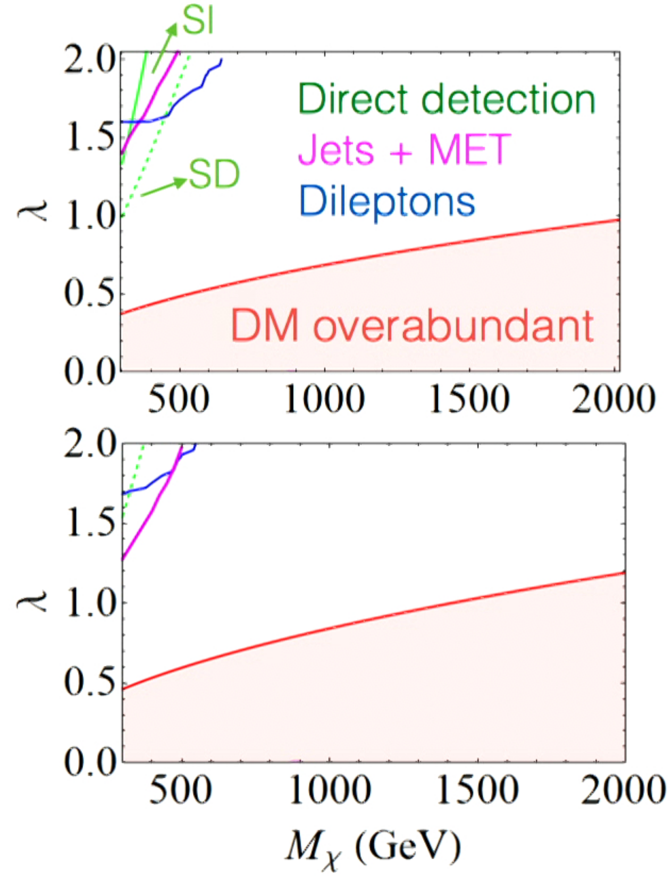
Couple to only up quarks

$M_\phi = 1.5\ M_\chi$ - - - - - -

M_χ ———

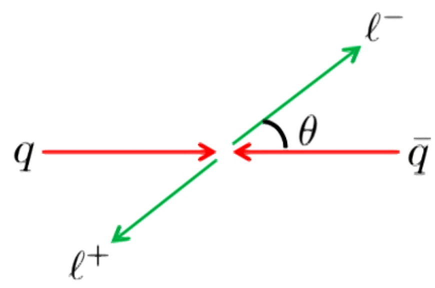
$M_\phi = 2\ M_\chi$ - - - - - -

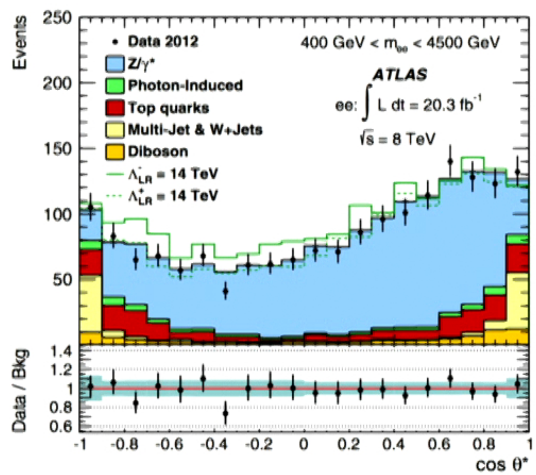
M_χ ———



W. Altmannshofer, P. Fox, R. Harnik, G. Kribs, *N.R.* 1411.6743

Angular spectra





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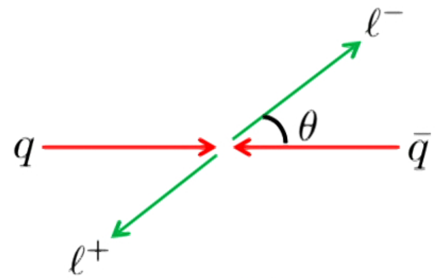
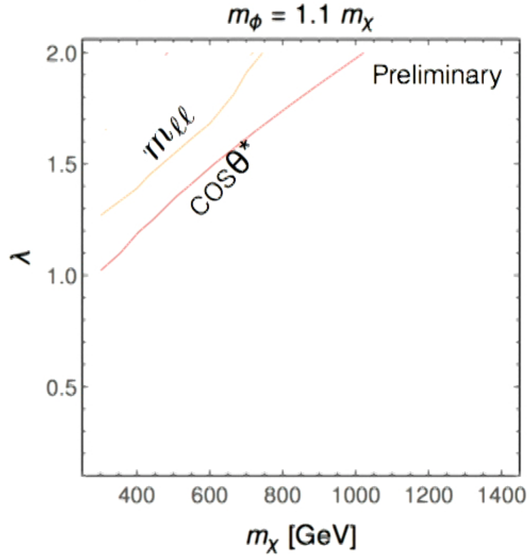
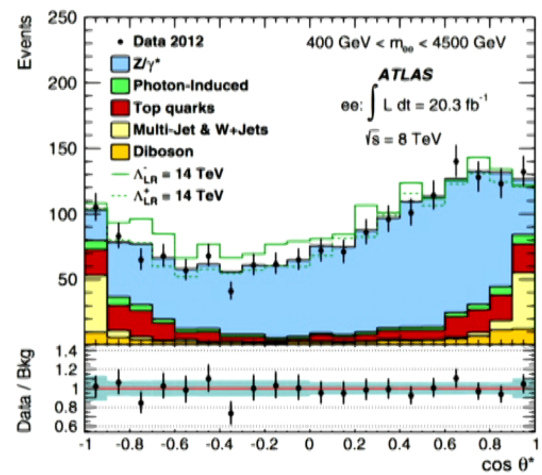
Angular spectra







Rival $m_{\ell\ell}$ spectra

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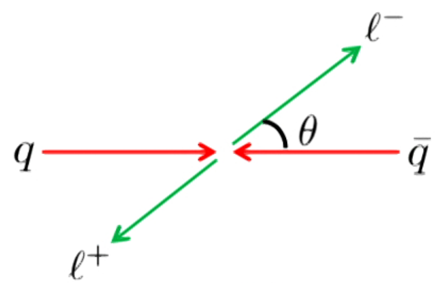
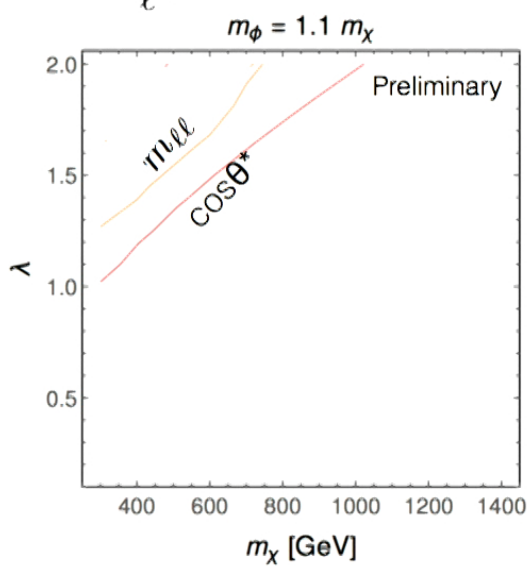
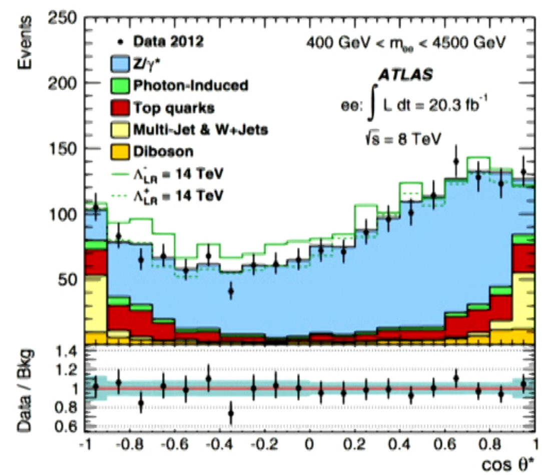
Angular spectra







Rival $m_{\ell\ell}$ spectra

Use features of both spectra to **characterize** DM — spin, self-conjugation, chirality of interactions.

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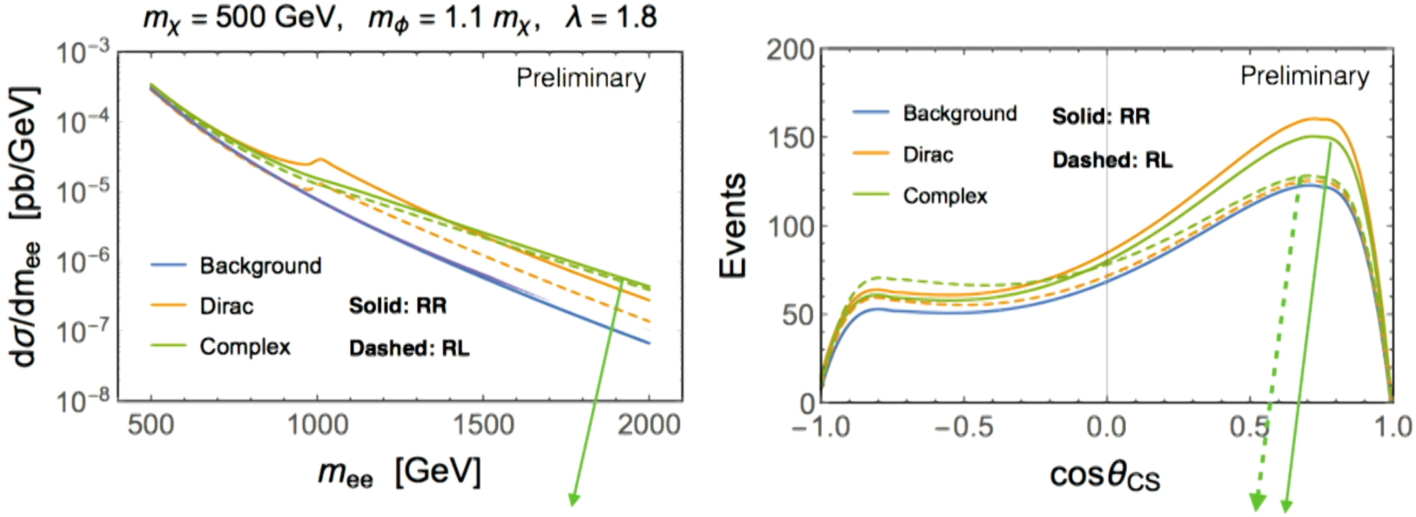
Example: chirality



can't tell between chirality combinations vs clear difference

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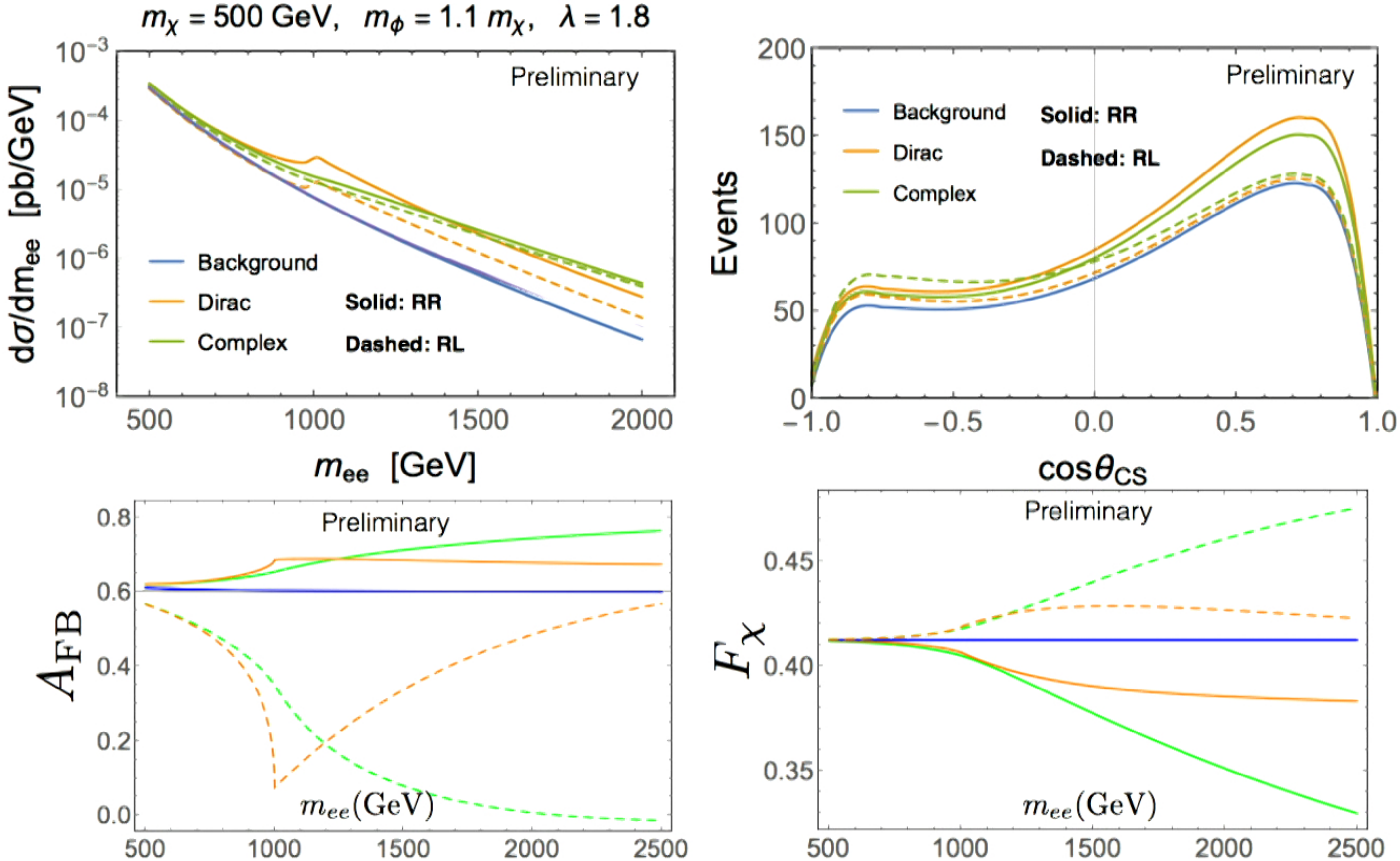
Example: chirality



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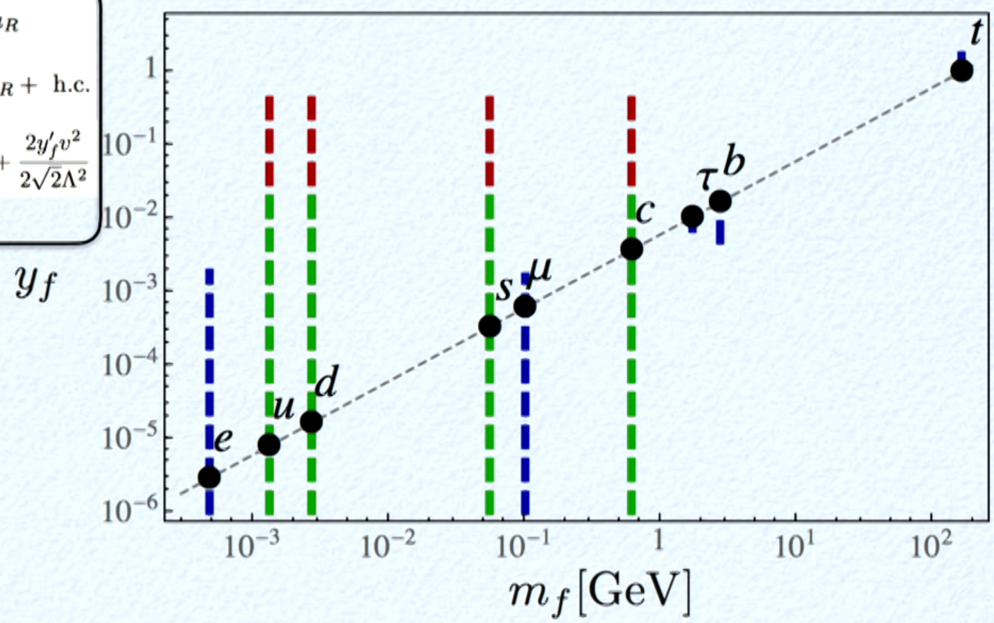
Higgs-fermion couplings

$$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.}$$

$$y_{f,\,\text{eff}}/\sqrt{2} = \frac{y_f}{\sqrt{2}} + \frac{3 y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2 y'_f v^2}{2\sqrt{2}\Lambda^2}$$

F. Yu 1609.06592



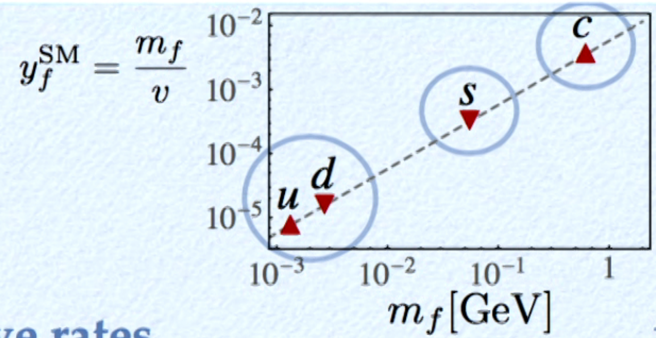
direct searches (ATLAS+CMS)

Γ_h<1.7 GeV (CMS)

global analysis

(Yotam Soreq, SLAC, Nov 08 2016)

The hunt



inclusive rates

Delaunay, Golling, Perez, YS, 1310.7029
Perez, YS, Stamou, Tobioka, 1505.06689, 1503.00290
Brivio, Goertz, Isidori, 1507.02916
ATLAS, 1407.0608
ATLAS, 1501.01325
ATL-PHYS-PUB-2015-001

Higgs kinematics

Bishara, Haisch, Monni, Re 1606.09253
YS, Zhu, Zupan 1606.09621

exclusive rates ($h \to \gamma V$)

Bodwin, Petriello, Stoynev, Velasco, 1306.5770
Kagan, Perez, Petriello, YS, Stoynev, Zupan, 1406.1722
Bodwin, Chung, Ee, Lee, Petriello 1407.6695
Perez, YS, Stamou, Tobioka 1503.00290
Koing, Neubert, 1505.03870
ATLAS, 1501.03276, 1607.03400
CMS, 1507.03031

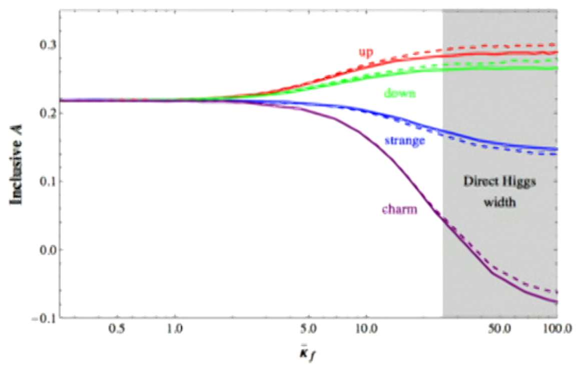
Higgs production

Zhou, 1505.06369
Yu 1609.06592

6

(Yotam Soreq, SLAC, Nov 08 2016)

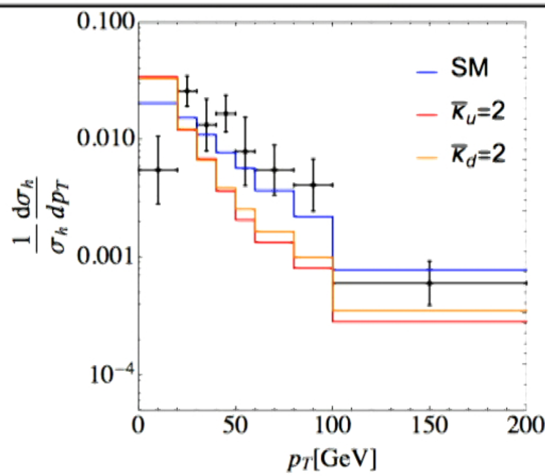
Sensitivities

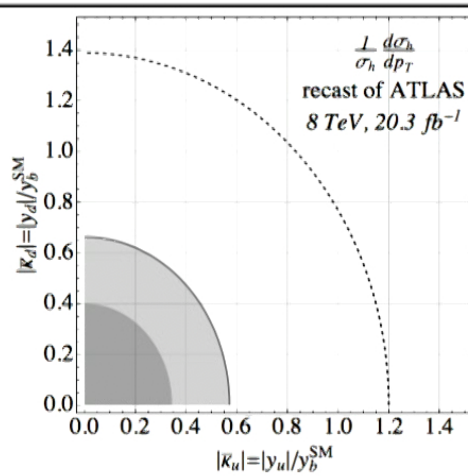


Wh charge asymmetry

Sensitivity to sub-percent deviations @ 3000 ifb

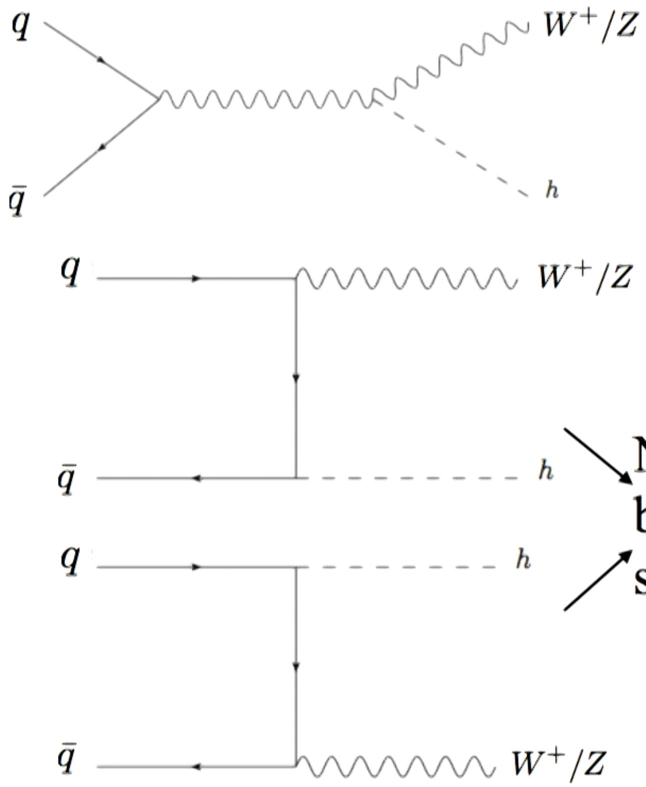
F. Yu 1609.06592





Soreq, Zhu, Zupan 1606.09621

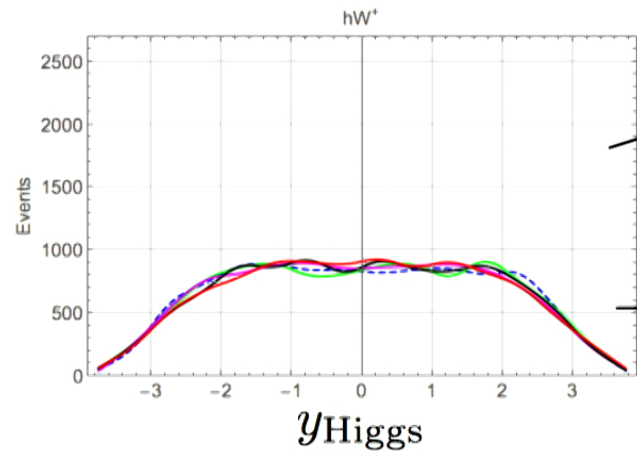
Higgstrahlung



Negligible in the SM,
but if Yukawa cranked up,
scattering is more forward!

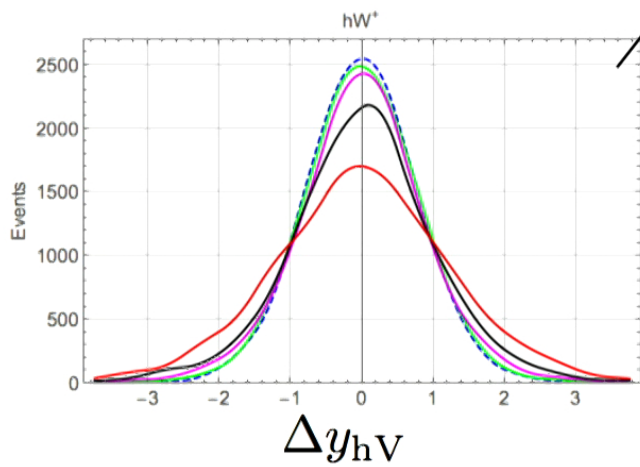
A. Delgado, A. Martin, *N.R.* 170?.xxxxx

Spectral variation with Yukawa



(Same behavior for $y_{\rm W}$)

(Very similar distributions for hZ, hW-)



SM

$\bar{\kappa}_u = 1$

$\bar{\kappa}_u = 2$

$\bar{\kappa}_u = 3$

$\bar{\kappa}_u = 10$

t-channel makes central events!

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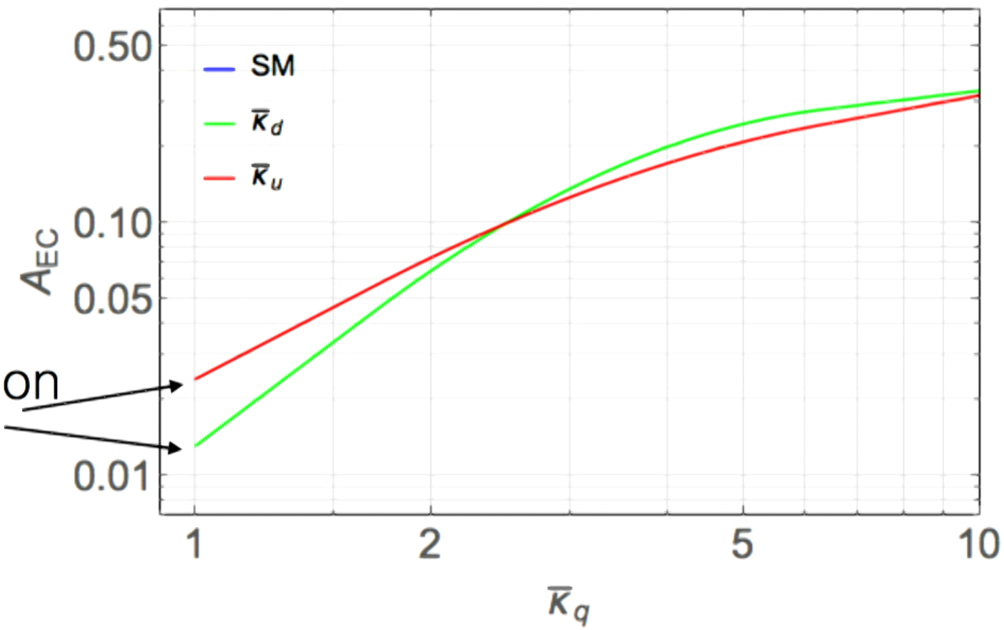
Edge-centre asymmetry



~1-2 % deviation
@ κ-bar = 1

\# events = 1000 fb x 300 fb^{-1} x 0.55 x 0.1
= 1.6 x 10^4

0.55 → $\mathrm{BR}(h \to b\bar{b})$; 0.1 → $\mathrm{BR}(W \to \ell\nu)$

Stat sensitivity ~ 1%

Doable!

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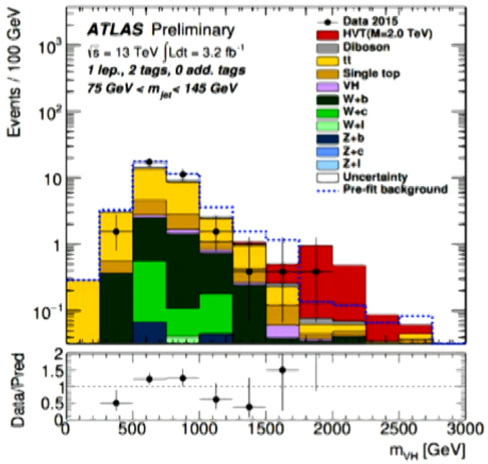
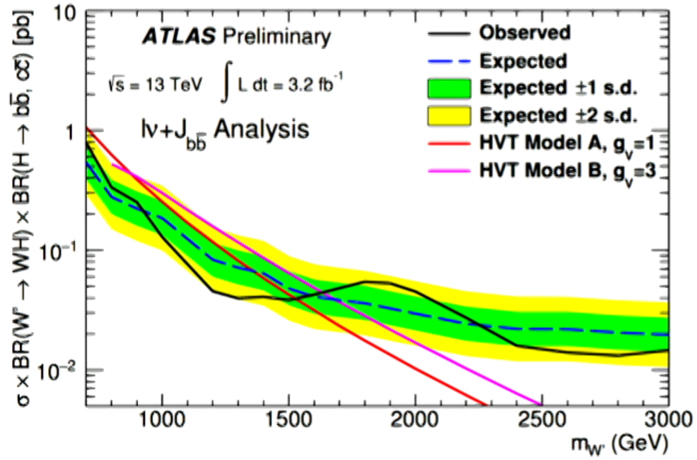
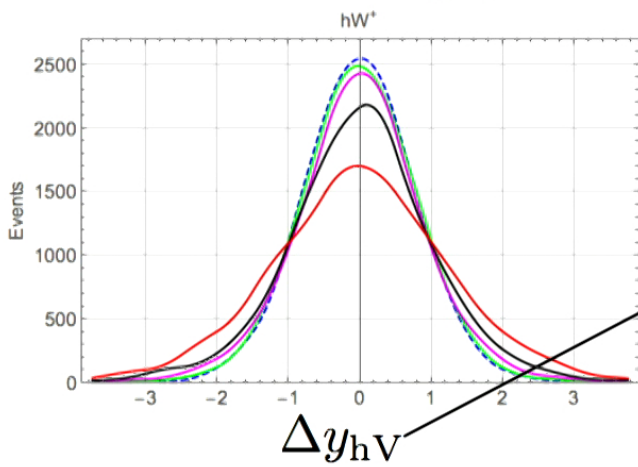
(VH measurements)







Not measured at the LHC!

A. Delgado, A. Martin, *N.R.* 1706.xxxxx

Takeaways - I

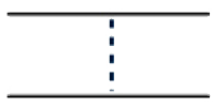
For phenomenologists

LHC 2 —> 2 scattering angles largely ignored —
but a **rich probing ground**.

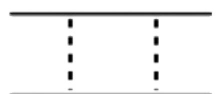
If new physics is not resonant, can expect first hints here.

Motivated scenario: a resonance (in a given search channel)
that is kinematically inaccessible
or giving lousy signal acceptance can still
modify matrix element of other channels.

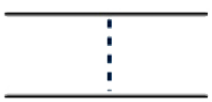
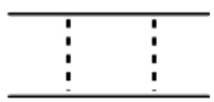
Takeaways - II

$\mathcal{L}_{\rm NP}$	$\mathcal{L} \supset m_\phi^2 \vert\phi\vert^2 + y_{ff'}\phi\bar{f}f'$
$\mathcal{M}_{\rm NP}$	Add t-channel 
Case in point	leptoquarks rival and *outdo* dedicated searches

Takeaways - II

$\mathcal{L}_{\rm NP}$	$\mathcal{L} \supset m_\phi^2 \lvert\phi\rvert^2 + y_{ff'}\phi\bar{f}f'$	$\mathcal{L} \supset \frac{m_\chi}{2}\chi\chi + m_\phi^2\lvert\tilde{\phi}\rvert^2 + \lambda_f\tilde{\phi}\bar{f}\chi$
$\mathcal{M}_{\rm NP}$	Add t-channel 	Add loops (=> threshold effects) 
Case in point	leptoquarks rival and *outdo* dedicated searches	dark matter and mediators discover with interference effects where MET signals weak distinguish quantum properties

Takeaways - II

$\mathcal{L}_{\rm NP}$	$\mathcal{L} \supset m_\phi^2 \vert\phi\vert^2 + y_{ff'}\phi\bar{f}f'$	$\mathcal{L} \supset \frac{m_\chi}{2}\chi\chi + m_\phi^2\vert\tilde{\phi}\vert^2 + \lambda_f \tilde{\phi}\bar{f}\chi$	$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y_u' \frac{H^\dagger H}{\Lambda^2}\bar{Q}\tilde{H}u_R + y_d \bar{Q}_L H d_R + y_d' \frac{H^\dagger H}{\Lambda^2}\bar{Q}Hd_R + \text{ h.c.}$
$\mathcal{M}_{\rm NP}$	Add t-channel 	Add loops (=> threshold effects) 	Strengthen existing t-channel 
Case in point	leptoquarks rival and *outdo* dedicated searches	dark matter and mediators discover with interference effects where MET signals weak distinguish quantum properties	Higgs - light quark couplings establish with q q —> V h scattering angle

(AND SO ON…)

Takeaways - III

For experimentalists

Always measure the scattering angles, regardless of whether or not a kinematic bump is discovered.

Interpret angular spectra in more ways than resonances and contact operators.

Thank you!