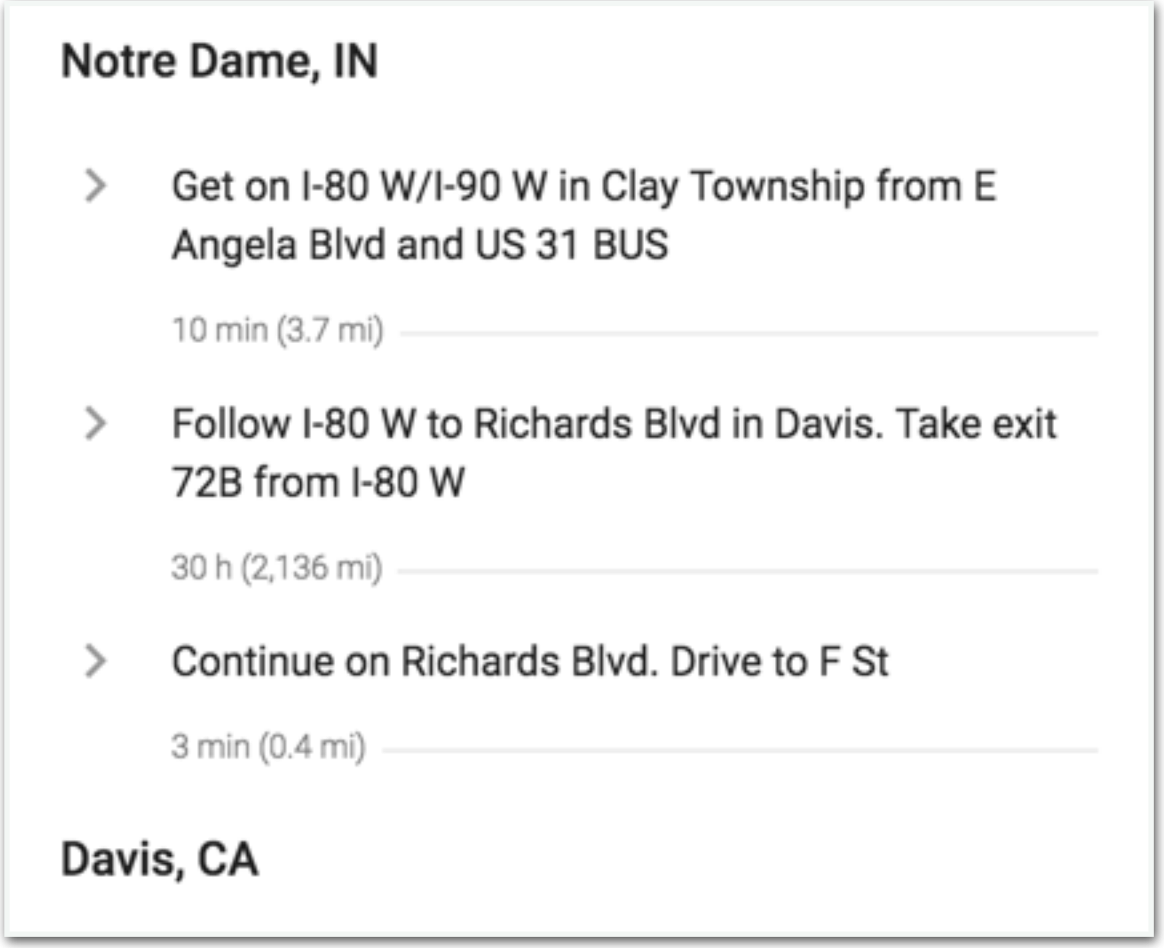
New Physics Anticipations in LHC Dilepton Angles

1610.03795

Nirmal Raj



Notre Dame, IN

- Get on I-80 W/I-90 W in Clay Township from E Angela Blvd and US 31 BUS

  10 min (3.7 mi)

- Follow I-80 W to Richards Blvd in Davis. Take exit 72B from I-80 W

  30 h (2,136 mi)

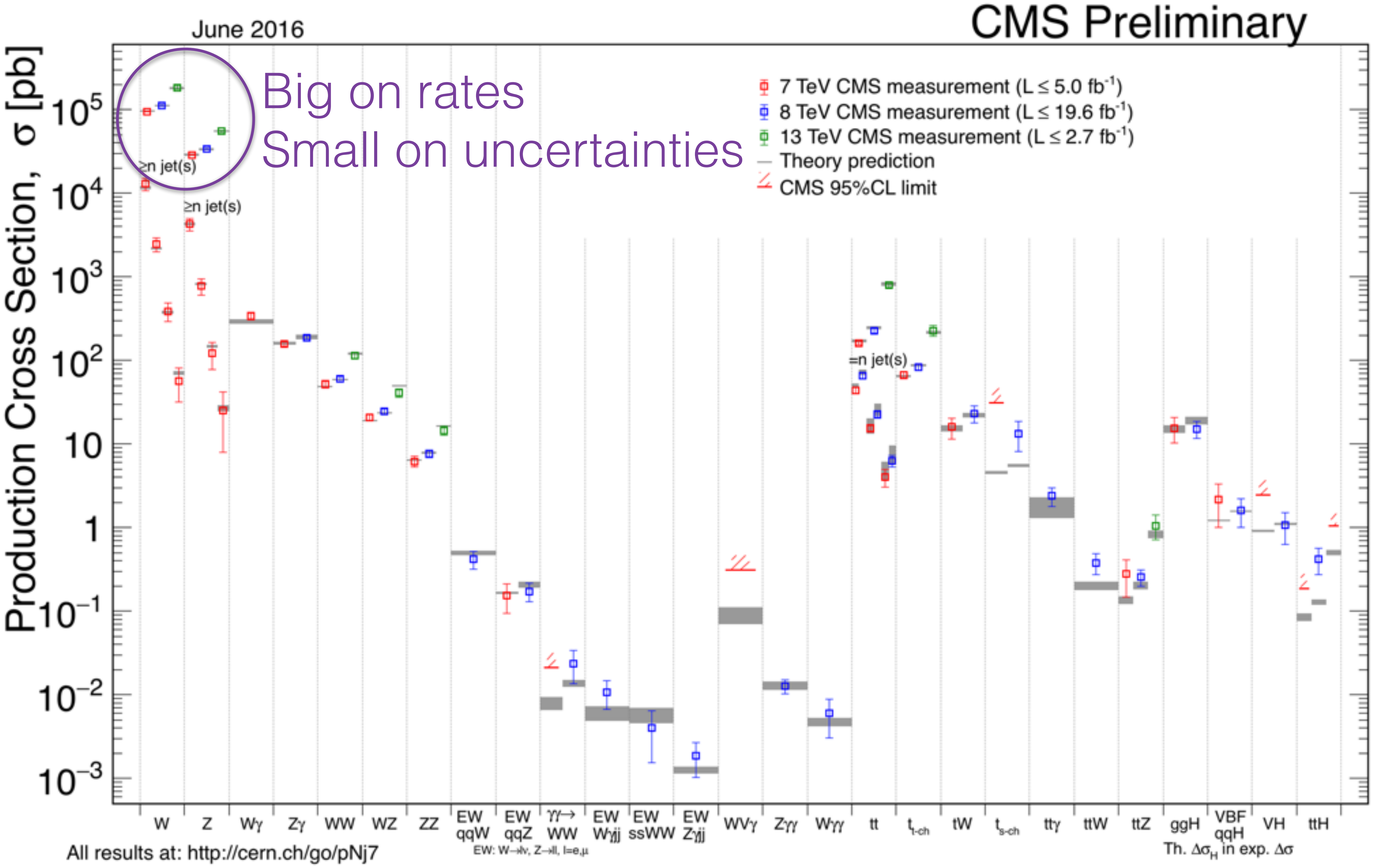
- Continue on Richards Blvd. Drive to F St

  3 min (0.4 mi)

Davis, CA

UC Davis
15 Nov 2016

Shape of the Energy Frontier

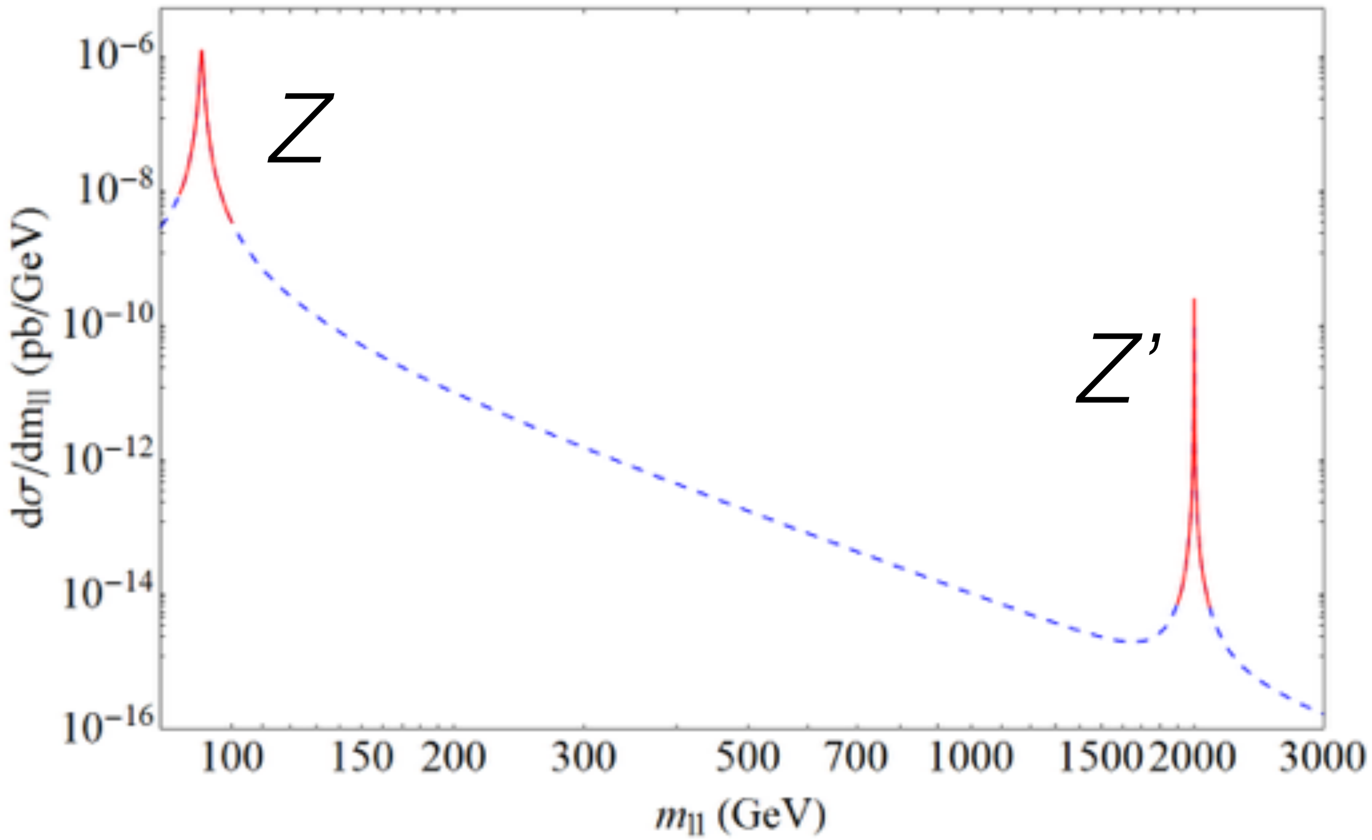


Big on rates

Small on uncertainties

At LHC Run 2, what new keys can we expect to find under the Drell-Yan lamppost?

(1) Resonances

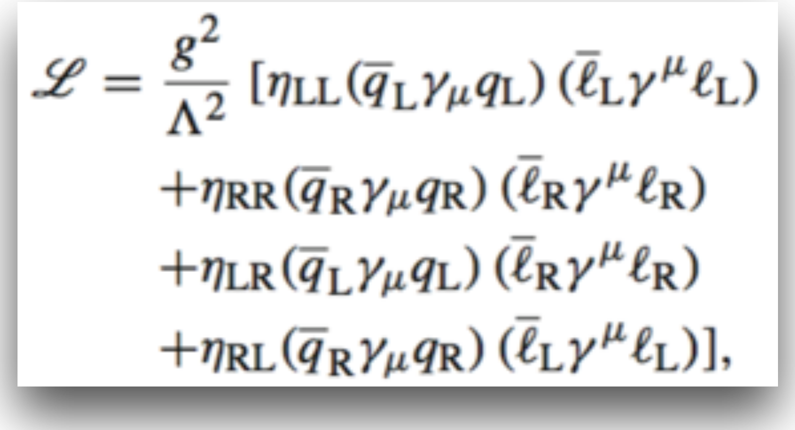


- Predicted by simple theory extensions of SM (e.g., U(1)')

- Particle mass is distinct

- Width extractable

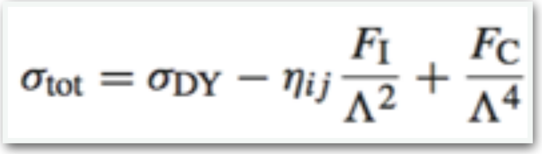
(2) Contact operators



$$\mathscr{L} = \frac{g^2}{\Lambda^2}\,[\eta_{\mathrm{LL}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})\,(\bar{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}}) + \eta_{\mathrm{RR}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})\,(\bar{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}}) + \eta_{\mathrm{LR}}(\overline{q}_{\mathrm{L}}\gamma_\mu q_{\mathrm{L}})\,(\bar{\ell}_{\mathrm{R}}\gamma^\mu \ell_{\mathrm{R}}) + \eta_{\mathrm{RL}}(\overline{q}_{\mathrm{R}}\gamma_\mu q_{\mathrm{R}})\,(\bar{\ell}_{\mathrm{L}}\gamma^\mu \ell_{\mathrm{L}})],$$

ATLAS 1407.2410

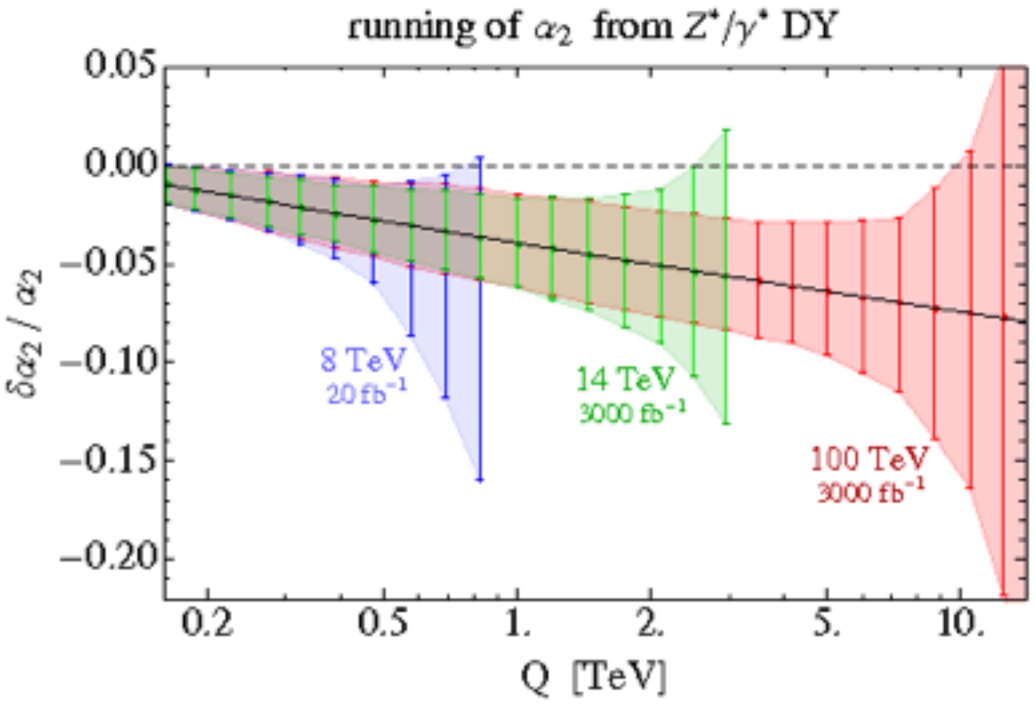
CMS 1412.6302



$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{DY}} - \eta_{ij}\frac{F_{\mathrm{I}}}{\Lambda^2} + \frac{F_{\mathrm{C}}}{\Lambda^4}$$

- Great for probing high scales.
- Doesn’t work when mass of d. o. f. compares with process momenta.
- Operator combinations => recasting unclear.

(3) Running



1410.6810,
Alves, Galloway, Ruderman, Walsh

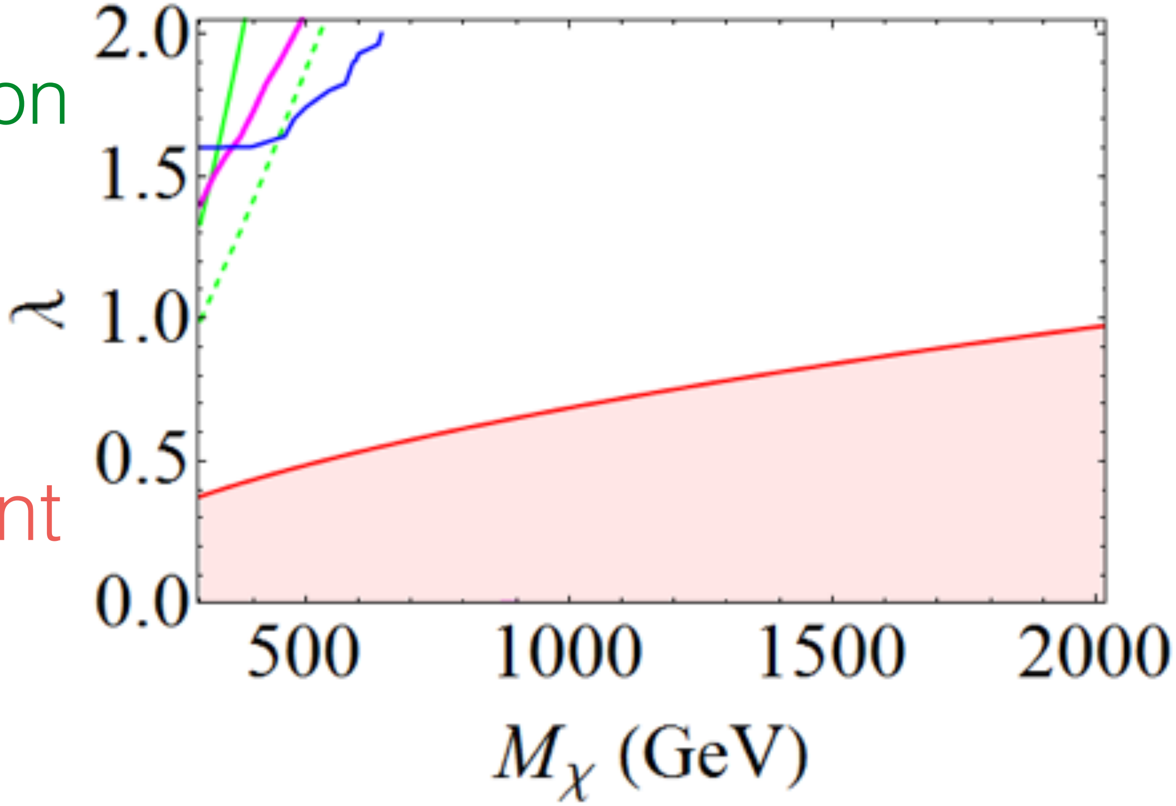
(4) Loopy features

Direct detection

Jets + MET

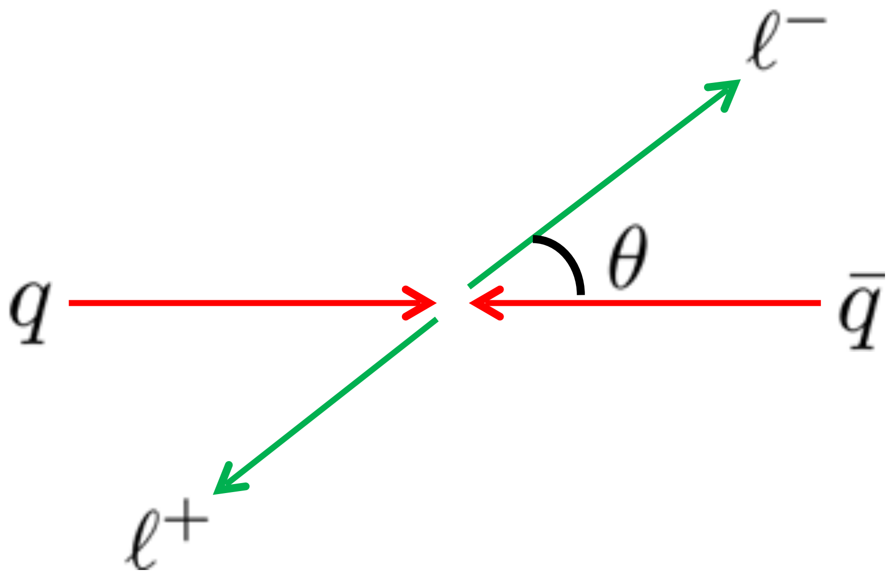
Dileptons

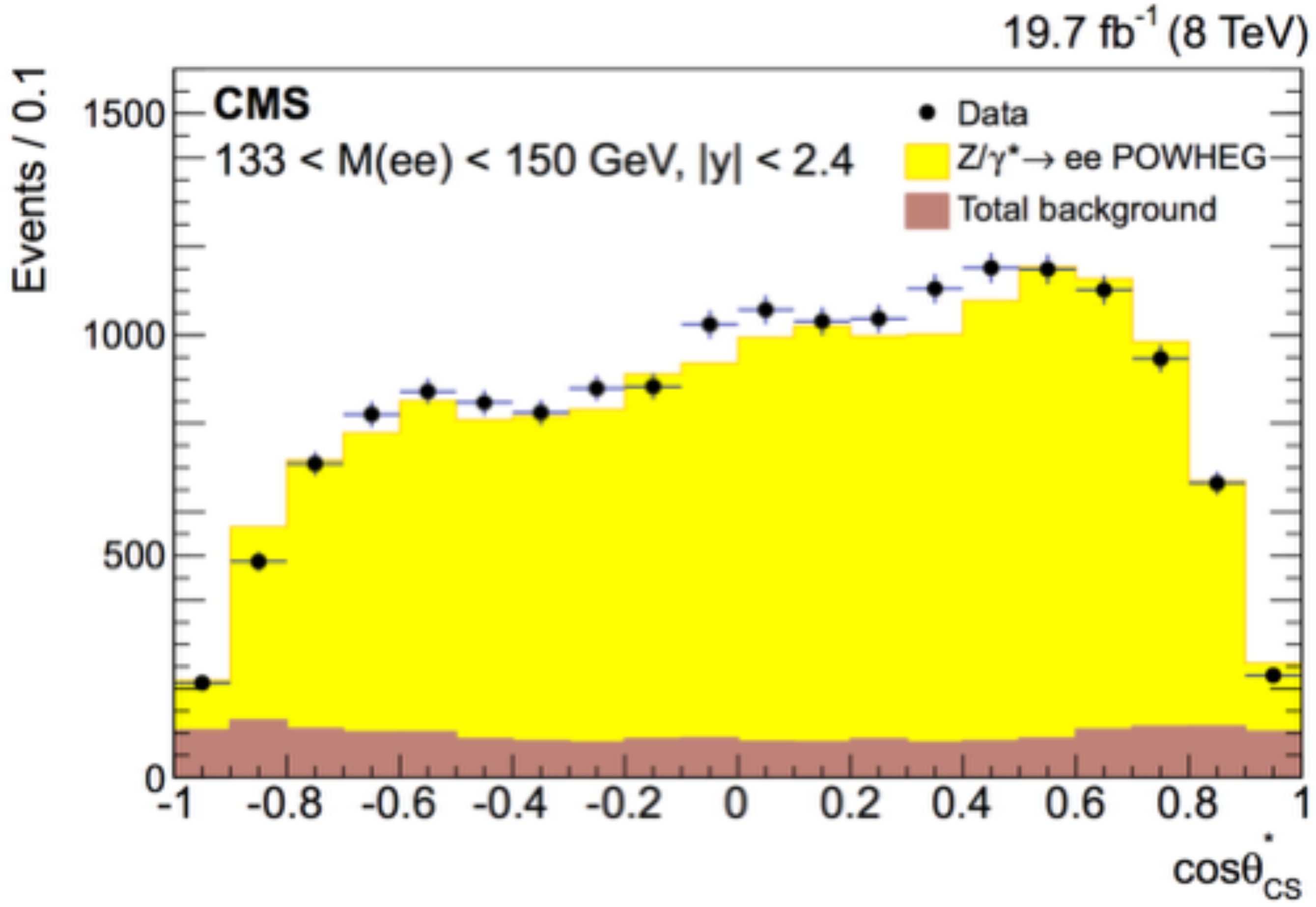
DM overabundant



"Dark Matter in Dileptons"
1411.6743
Altmanshoffer, Fox, Harnik,
Kribs, N.R.

(5) Angular spectra?





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Can New Physics debut here?

(5) Angular spectra?

Sequence of *Z* boson arrival

Late 1970s, early 80s

PETRA @ $\sqrt{s}$ = 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.

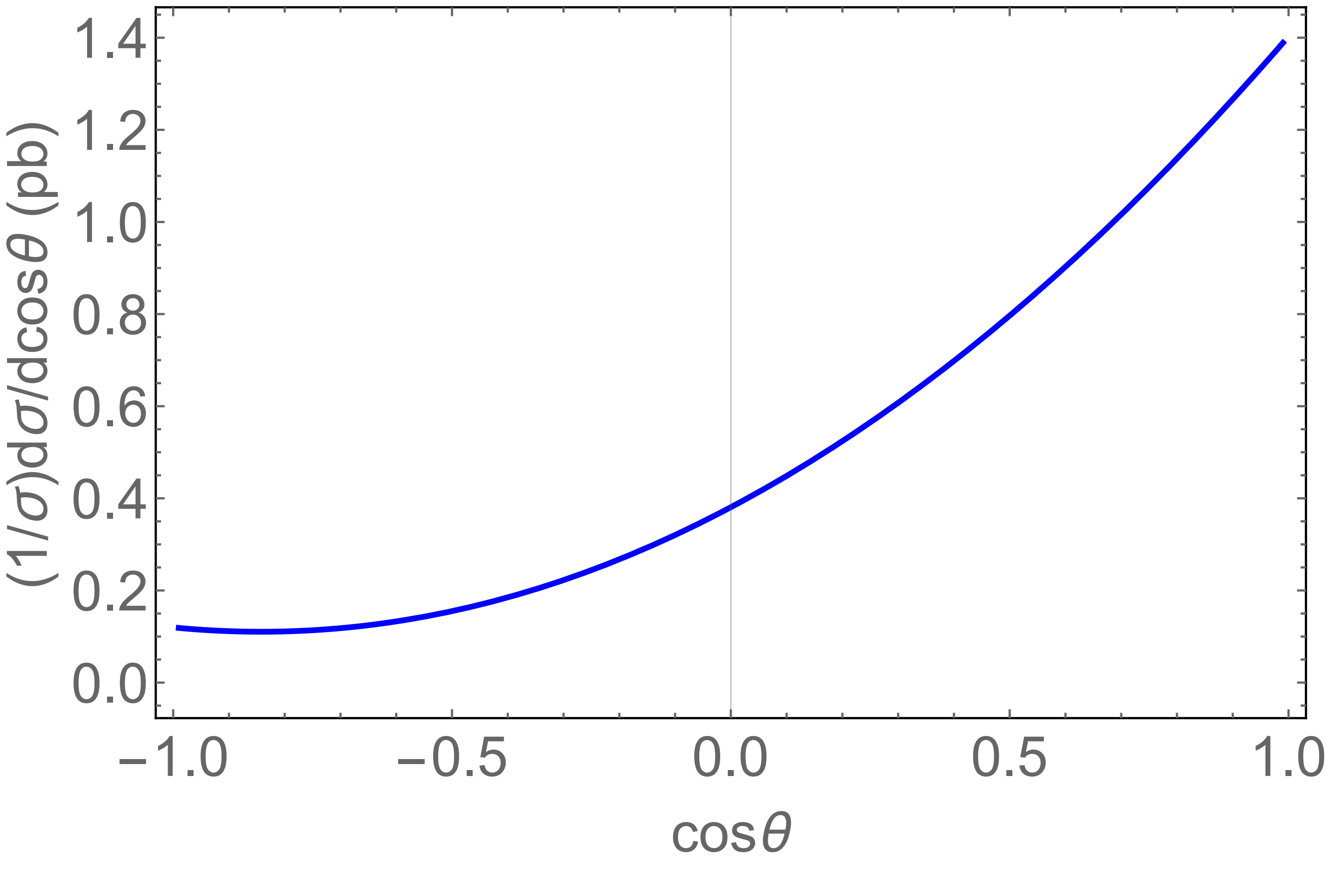
Later

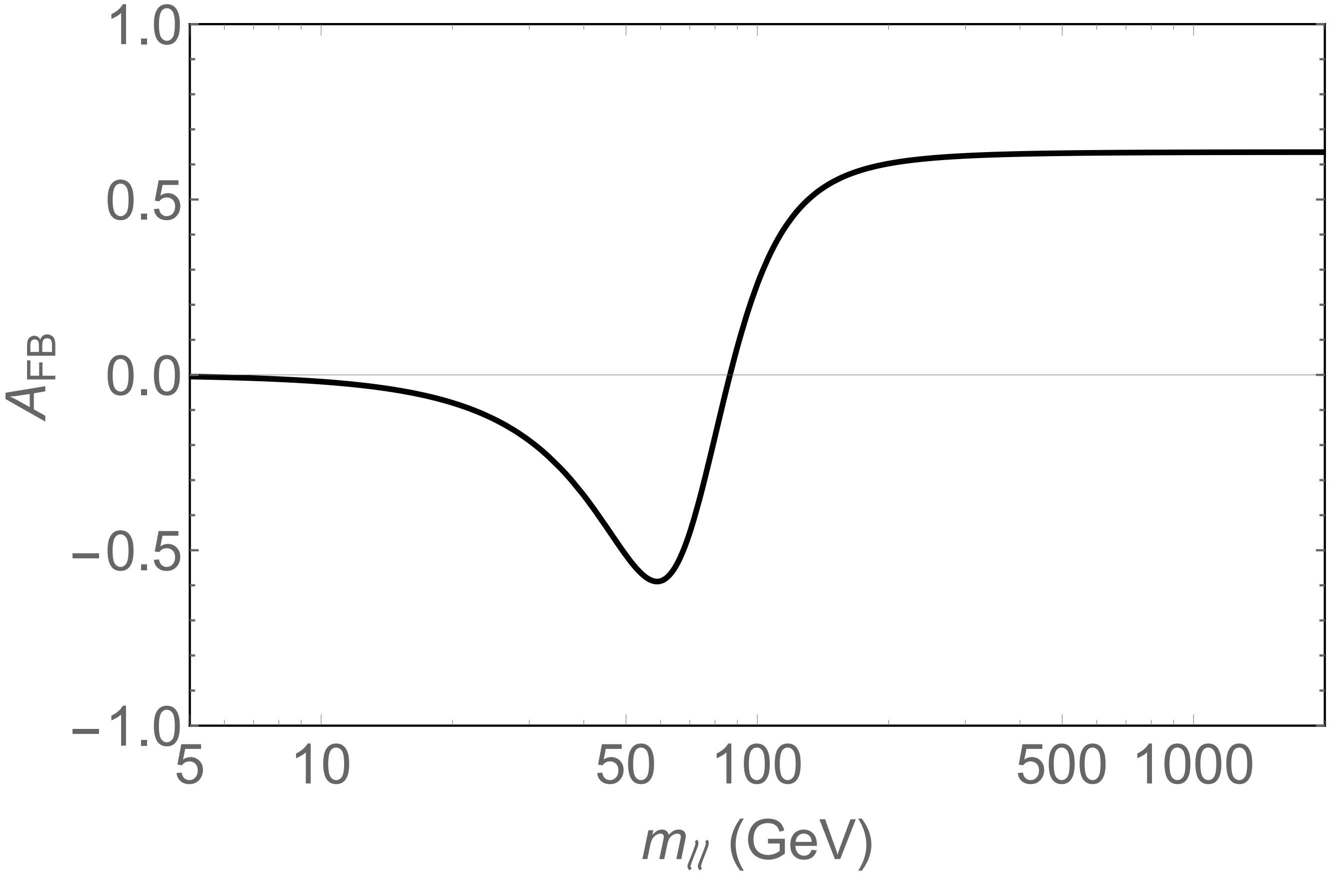
Angular spectra studied to pin down spin
and chiral couplings.

Forward-backward asymmetry

e+ e- —> l+ l-

$m_{ll} >> M_Z$





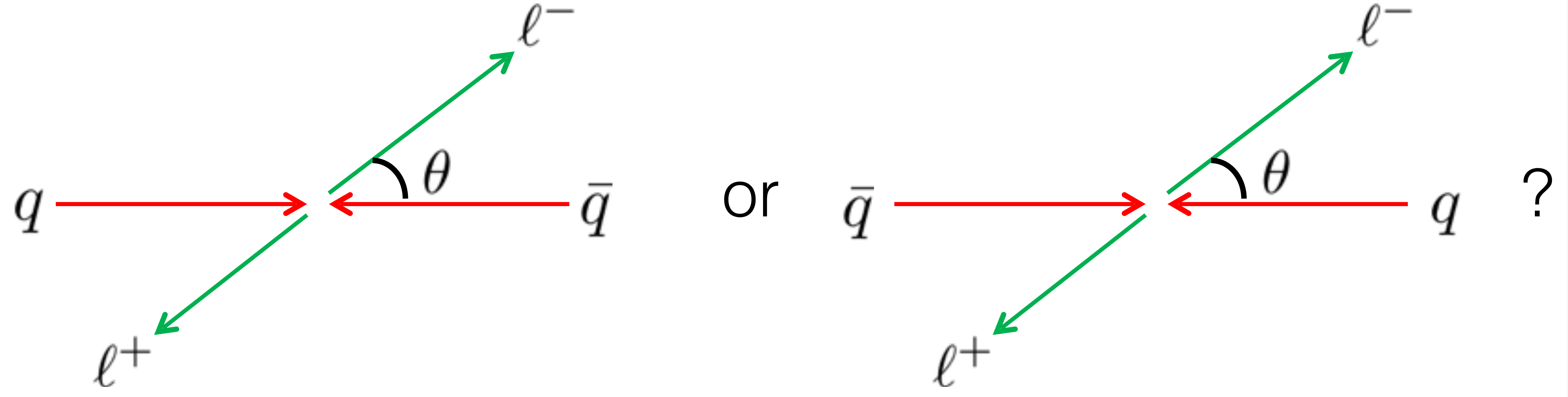
A_{FB} = area of right half minus left half
(normalized with total area)

Forward-backward asymmetry

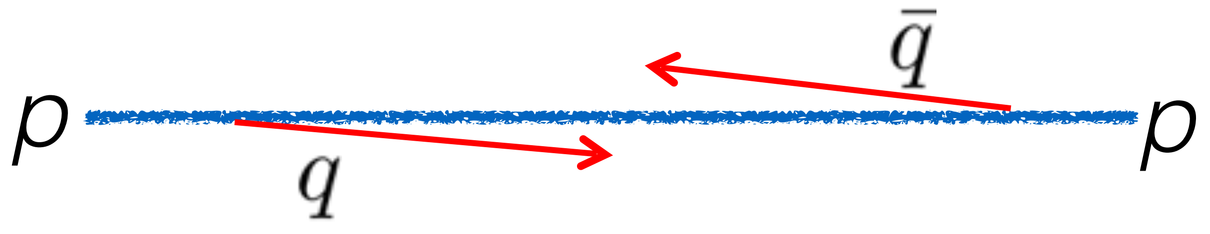
p p —> l+ l-

Four subtleties:

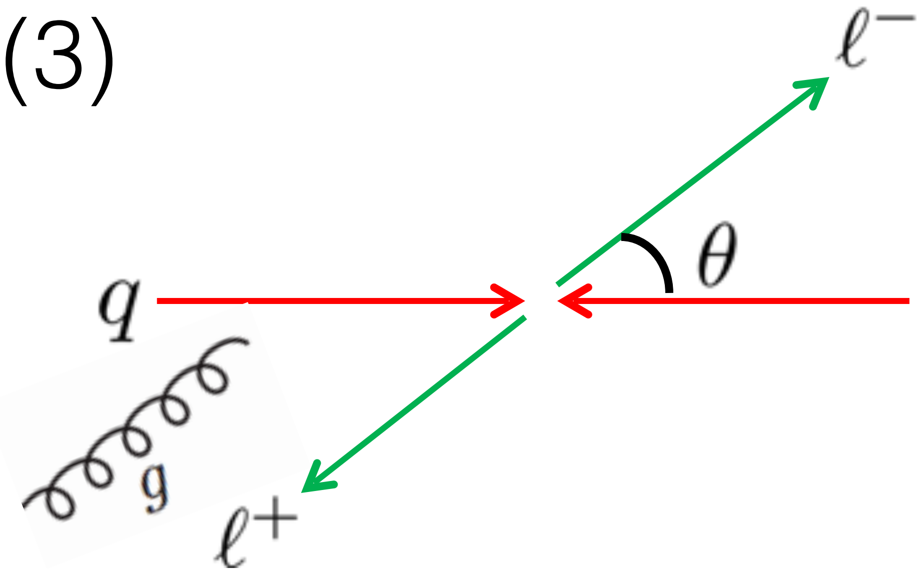
(1)



(2)



(3)

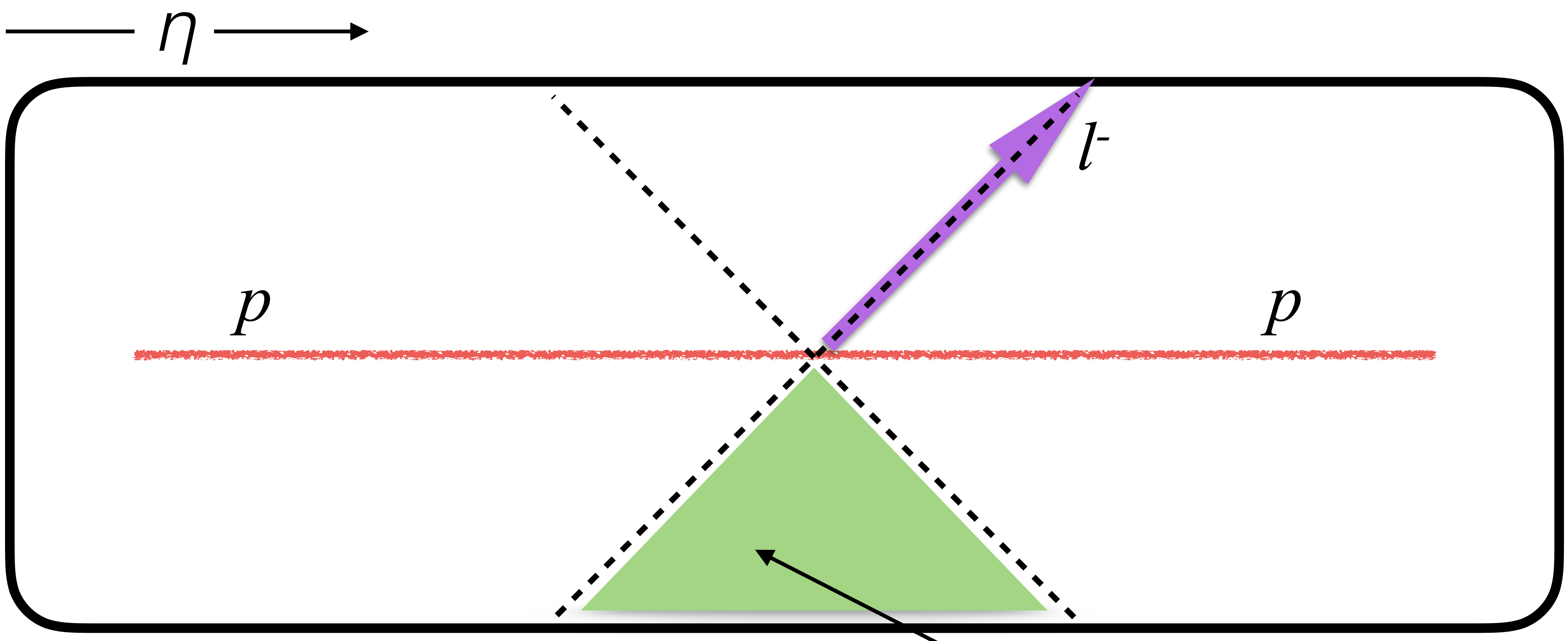


(4) Detector resolution of η

(2)-(4) negligible **at high m_{ll}** and with large enough bins

Forward-backward asymmetry

p p —> l+ l-



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

Identical to charge asymmetry:

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

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

Collins & Soper (1977):

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

Discovery sequence: expectation

Resonance

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

Disentangle spin
and couplings.

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

Recall Higgs sequence

m_{ll} spectra

angular
spectra
(A_{FB})

Non-resonance

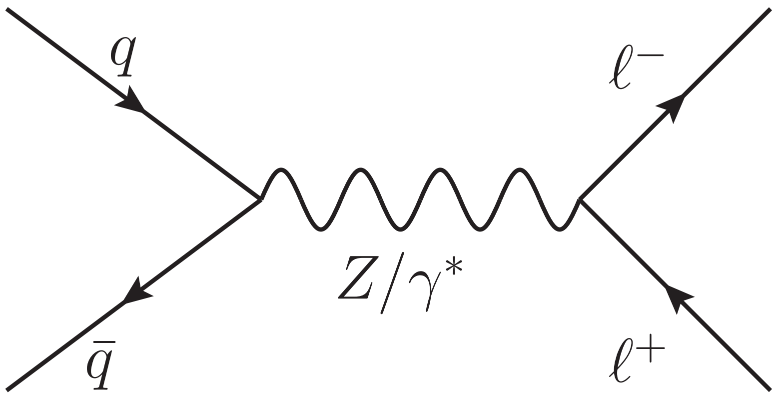
(t-channel, loops, etc.)

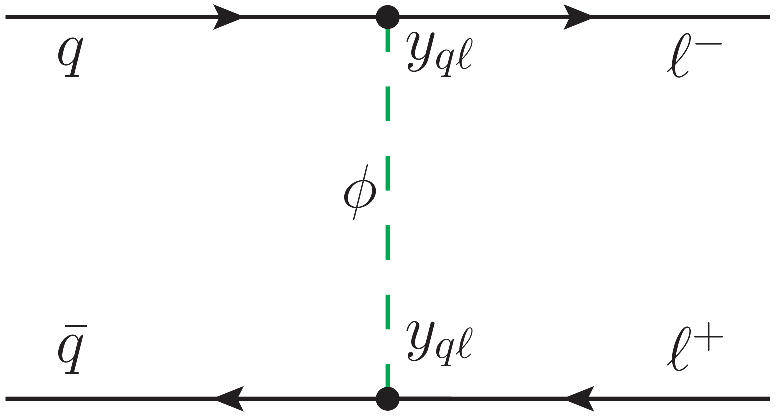
Use both for discovery:
all at once extract
mass, spin, couplings.

Non-resonance: simple example

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

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





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

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

Qualitatively different spectra…
Can LHC A_{FB} data kill the parameter space?

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

Leptoquark models

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

$$\begin{aligned}\mathcal{L} &= -y_{ij}\bar{u}_{R,i}R_2^a\epsilon^{ab}L^b_{L,j} + y'_{ij}\bar{e}_{R,i}R_2^{a*}Q^a_{L,j} + \text{h.c.}\\ &= (yV_{\text{PMNS}})_{ij}\bar{u}_{R,i}\nu_{L,j}R_2^{2/3} - y_{ij}\bar{u}_{R,i}e_{L,j}R_2^{5/3}\\ &\quad + y'_{ij}\bar{e}_{R,i}d_{L,j}R_2^{2/3*} + (y'V^{\dagger}_{\text{CKM}})_{ij}\bar{e}_{R,i}u_{L,j}R_2^{5/3*} + \text{h.c.}\end{aligned}$$

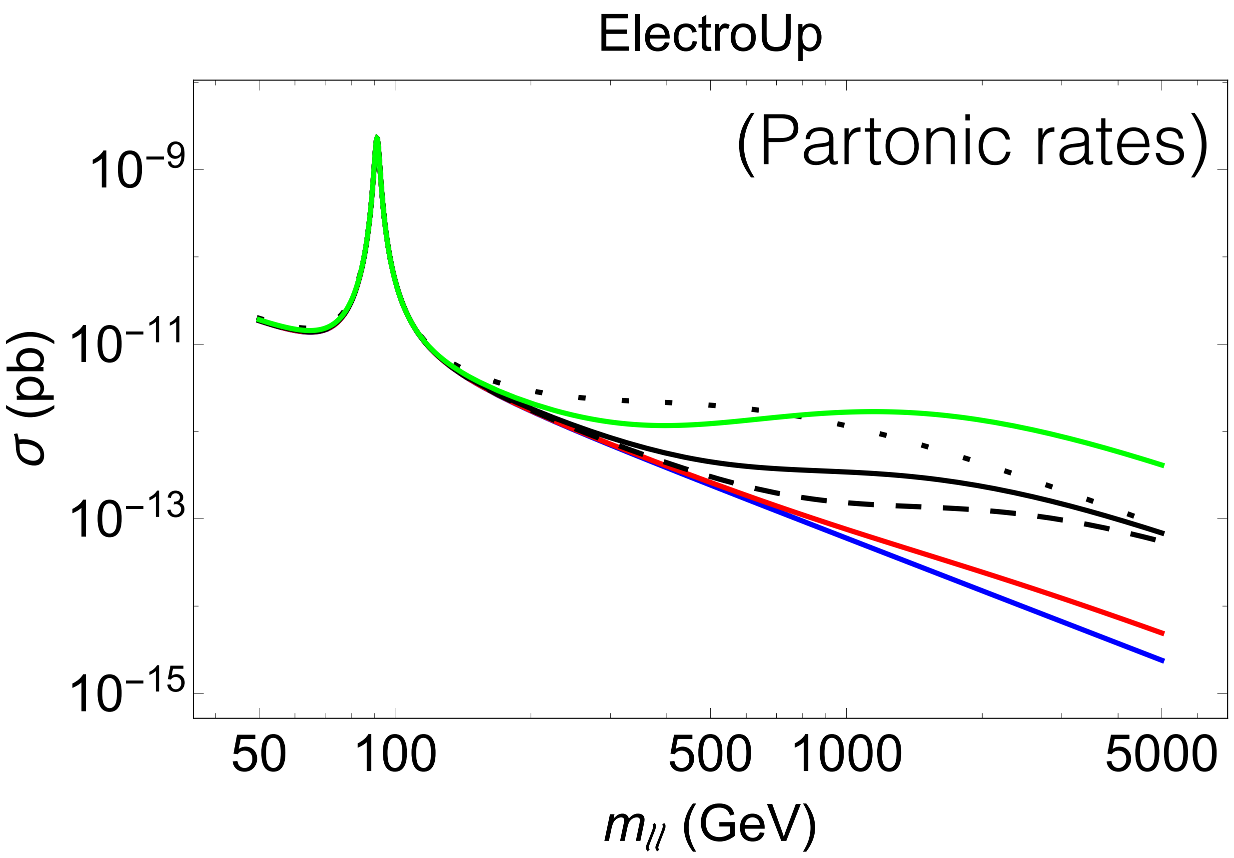
$y'_{ij} = 0,\ y_{ij} = y_{ue}\,\delta_{i1}\delta_{j1}$: ElectroUp
$y'_{ij} = 0,\ y_{ij} = y_{u\mu}\,\delta_{i1}\delta_{j2}$: MuoUp

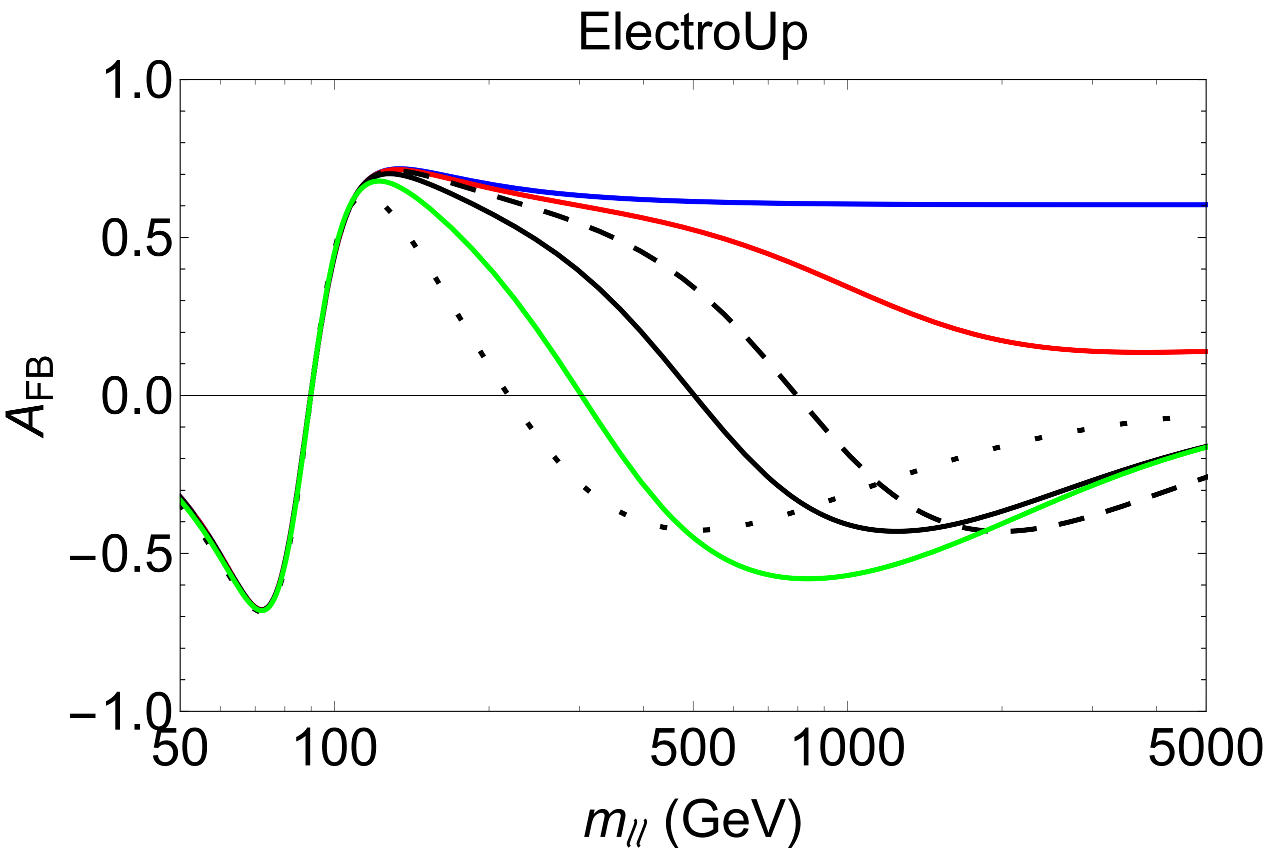
$\tilde{R}_2(\mathbf{3},\mathbf{2},1/6)$

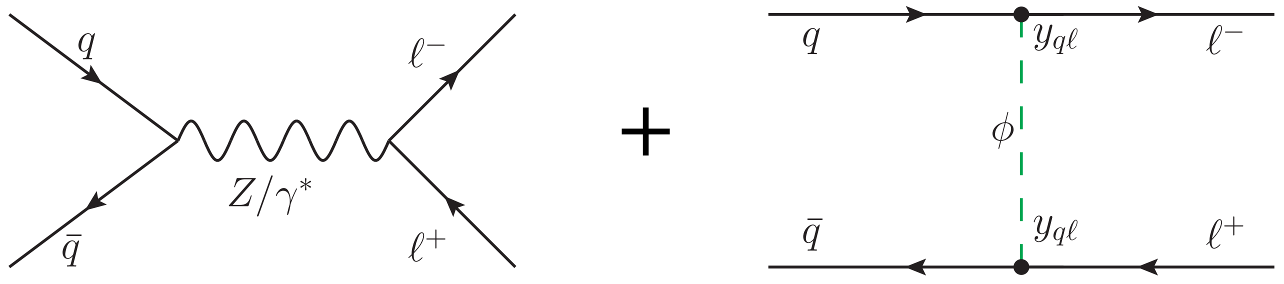
$$\begin{aligned}\mathcal{L} &= -y_{ij}\bar{d}_{R,i}\tilde{R}_2^a\epsilon^{ab}L^b_{L,j} + \text{h.c.}\\ &= -y_{ij}\bar{d}_{R,i}e_{L,j}\tilde{R}_2^{2/3} + (yV_{\text{PMNS}})_{ij}\bar{d}_{R,i}\nu_{L,j}\tilde{R}_2^{-1/3} + \text{h.c.}\end{aligned}$$

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

Dilepton probes







SM

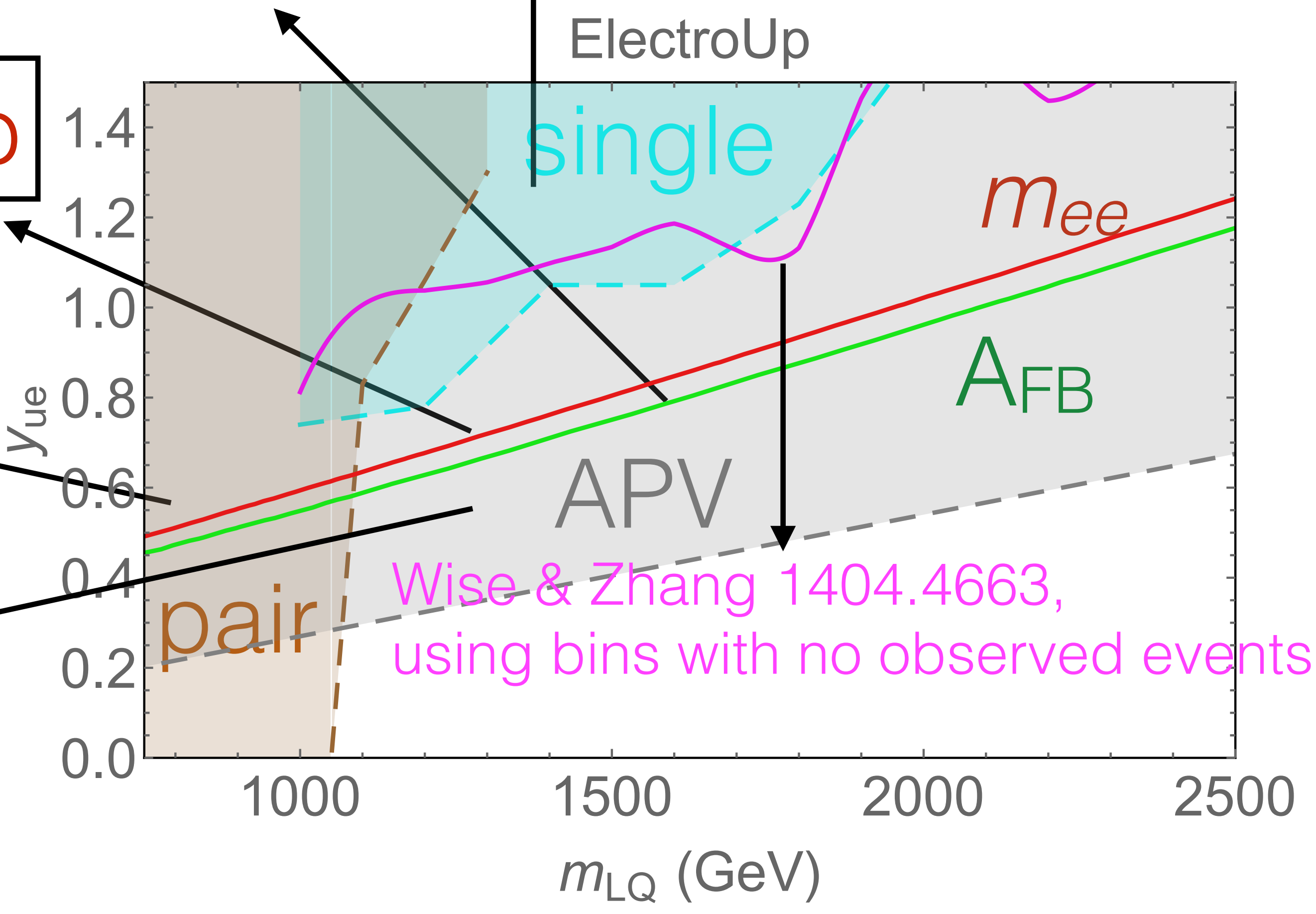
(m_{LQ} = 1 TeV,

y_{ue} = 0.4, 1.0, 1.6)

(y_{ue} = 1,

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

All constraints



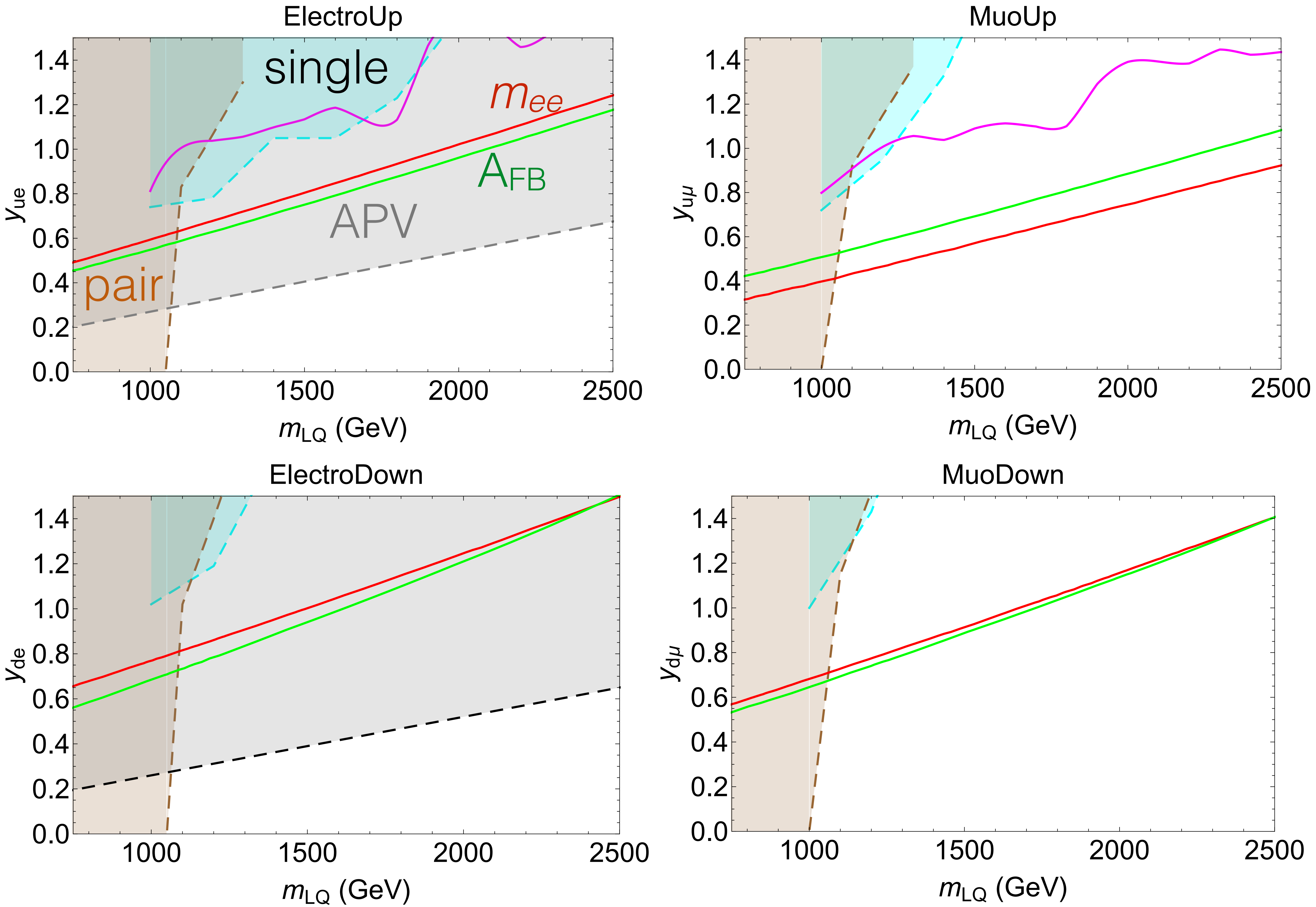
CMS 8 TeV, 20 ifb,
Signature: e+e-j

CMS 8 TeV, 20 ifb

ATLAS 8 TeV, 20 ifb

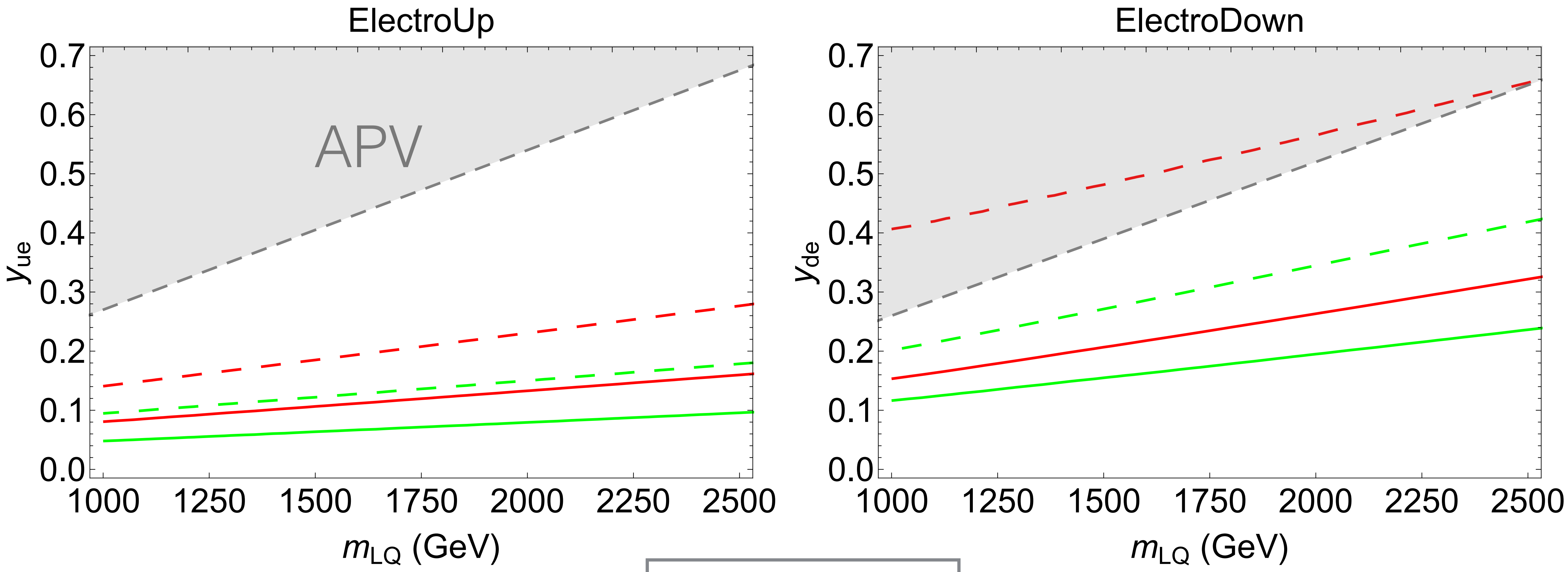
ATLAS 8 TeV, 20 ifb,
Signature: e+e-jj

Wood, et al (1997)
[atomic parity violation]


ElectroUp
single
pair
APV
m_{ee}
A_{FB}
y_{ue}
MuoUp
$y_{u\mu}$
ElectroDown
y_{de}
MuoDown
$y_{d\mu}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1000
1500
2000
2500
m_{LQ} (GeV)

Forecasts

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



m_{ll} spectra

A_{FB}

300 ifb

3000 ifb

Clarity

e+e- collider	**Hadron collider**
$A_{\rm FB}$ Lorentz-invariant	$A_{\rm FB}$ not Lorentz-invariant
$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = \frac{N_{\rm F} - N_{\rm B}}{N_{\rm tot}}$	$A_{\rm FB}^{\rm CS} = \frac{N(\Delta\|y\| > 0) - N(\Delta\|y\| < 0)}{N(\Delta\|y\| > 0) + N(\Delta\|y\| < 0)}$ $\Delta\|y\| \equiv \|y^{\ell^-}\| - \|y^{\ell^+}\|$
Photon $A_{\rm FB} = 0$, Z $A_{\rm FB} \neq 0$	SM $A_{\rm FB} \neq 0$

↓

Z physics conspicuous

Can we characterize dilepton angular distributions with a **Lorentz-invariant** quantity **vanishing in the SM**?

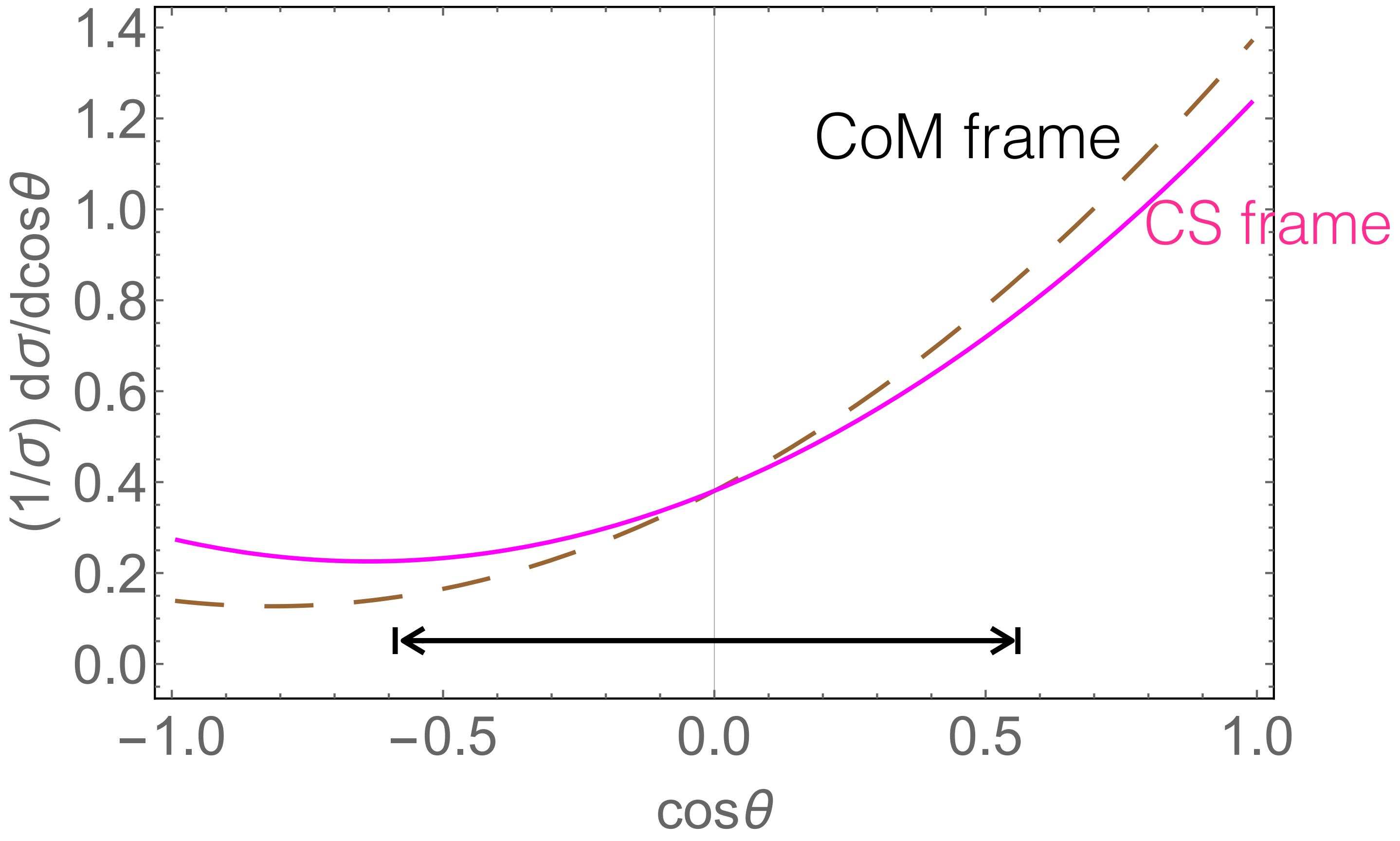
Clarity

Lorentz-invariant
+ vanishing in SM

$$\boxed{A_{\rm CE}(m_{\ell\ell}) \equiv \frac{\left[\int_0^{y_0} - \int_{y_0}^{\infty}\right] d|\Delta y| \left(\frac{d^2\sigma}{d|\Delta y|\, dm_{\ell\ell}}\right)}{\int_0^{\infty} d|\Delta y| \left(\frac{d^2\sigma}{d|\Delta y|\, dm_{\ell\ell}}\right)}}$$

See, e.g., R. Diener, S. Godfrey, T. Martin 0909.2022

Advantage to phenomenologist: $|\cos\theta| = \tanh(|\Delta y|/2)$



Area under curve in symmetric range is frame-independent

End remarks

LHC dilepton angular spectra

* largely ignored — can be a rich probing ground.

  - If new physics is non-resonant, can expect first hints here.
  - A_{FB} measurements (and l^+l^- kinematic spectra) give indirect limits on leptoquarks rivalling or bettering direct search limits. Demonstrates previous statement.

* to grab more limelight, need clearer interface between theory & experiment, like centre-edge asymmetry — Lorentz-invariant and vanishing in the SM.