New Physics Anticipations in LHC Dilepton Angles

1610.03795

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> 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)

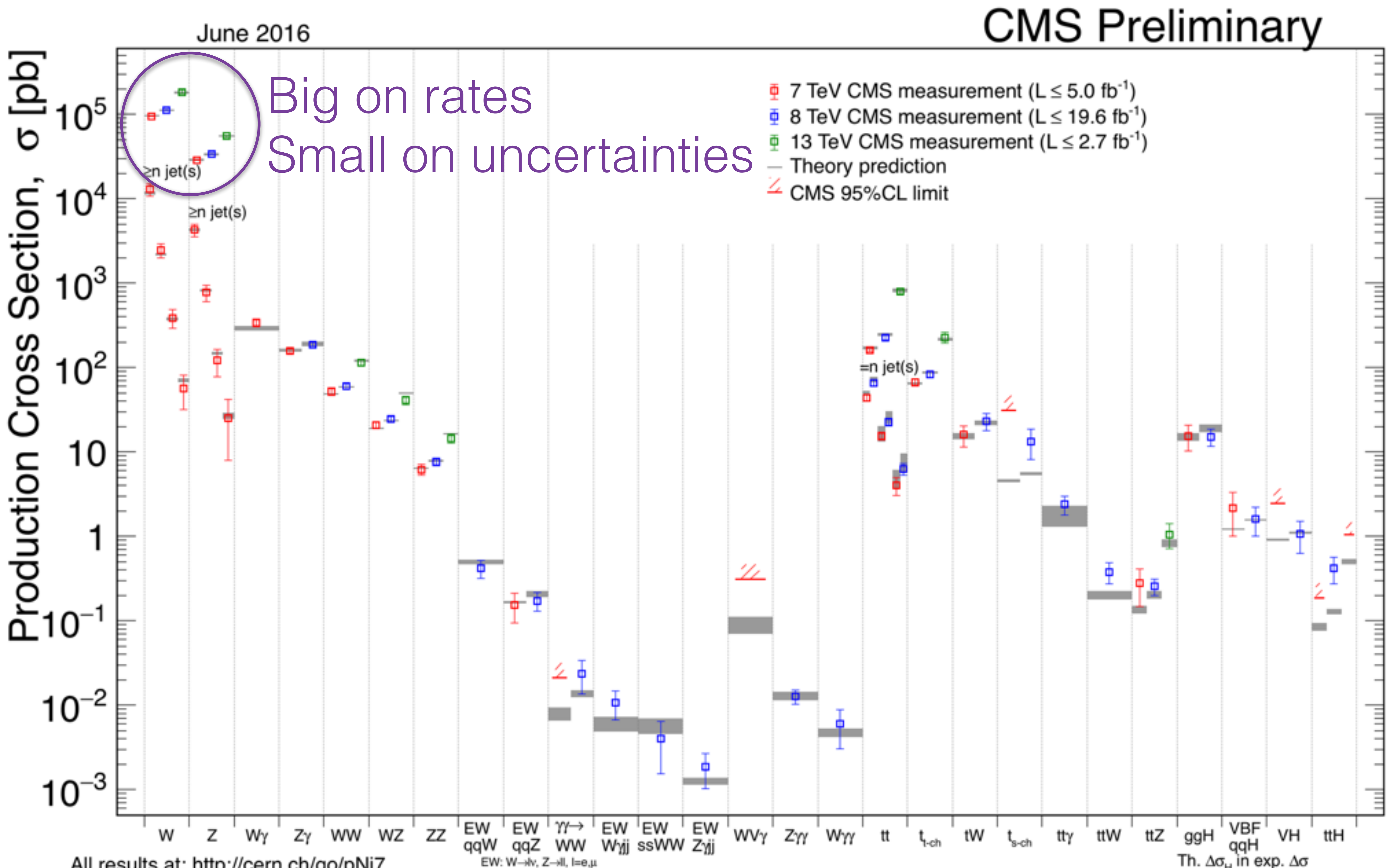
> Continue on Richards Blvd. Drive to F St

3 min (0.4 mi)

Davis, CA

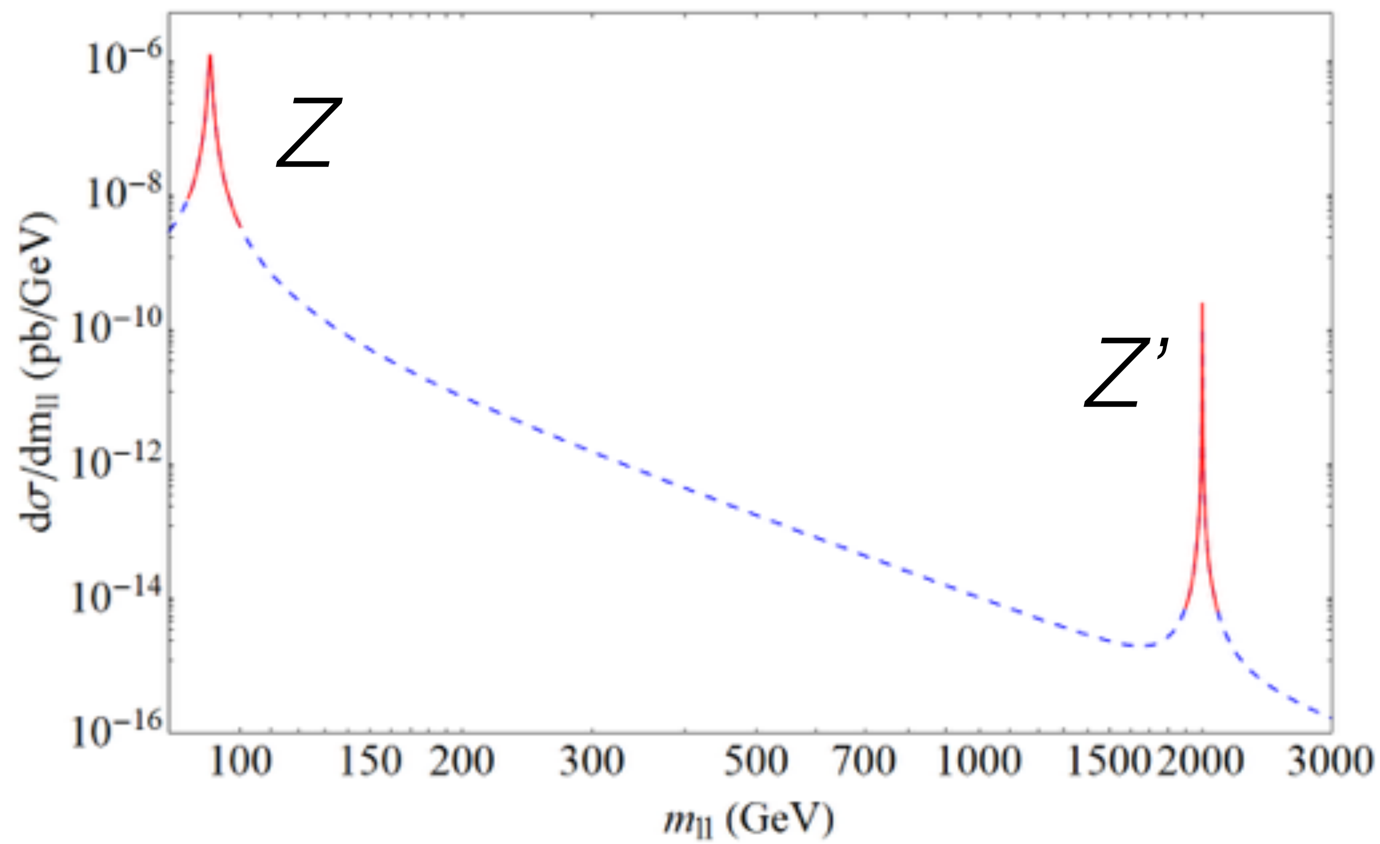
UC Davis
15 Nov 2016

Shape of the Energy Frontier



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

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

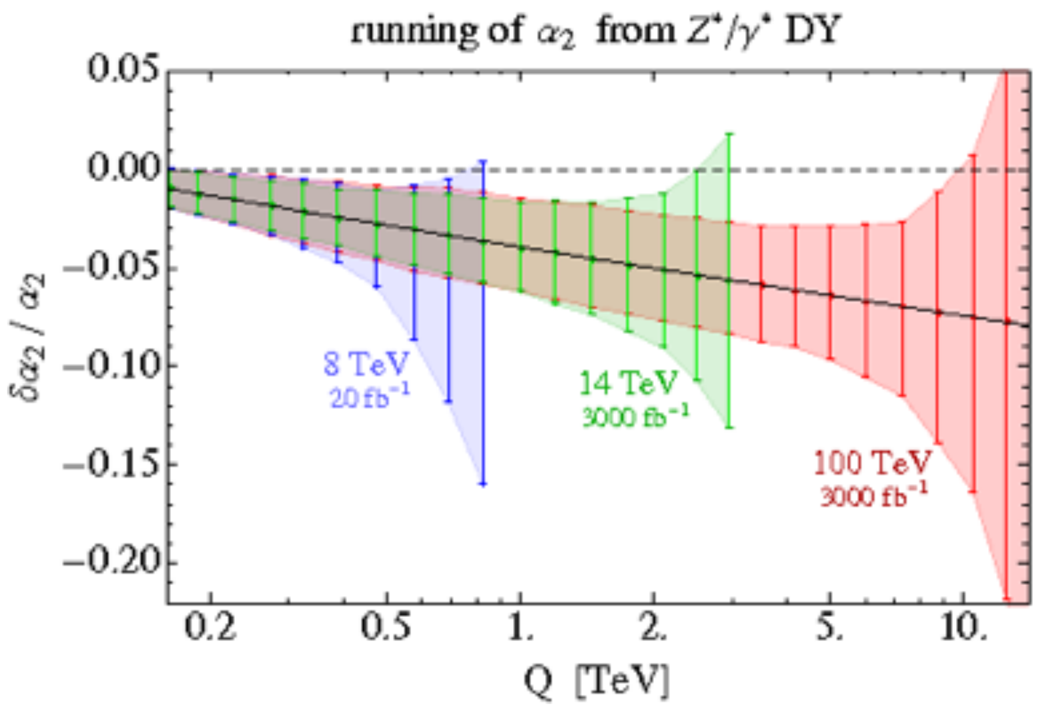
ATLAS 1407.2410

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

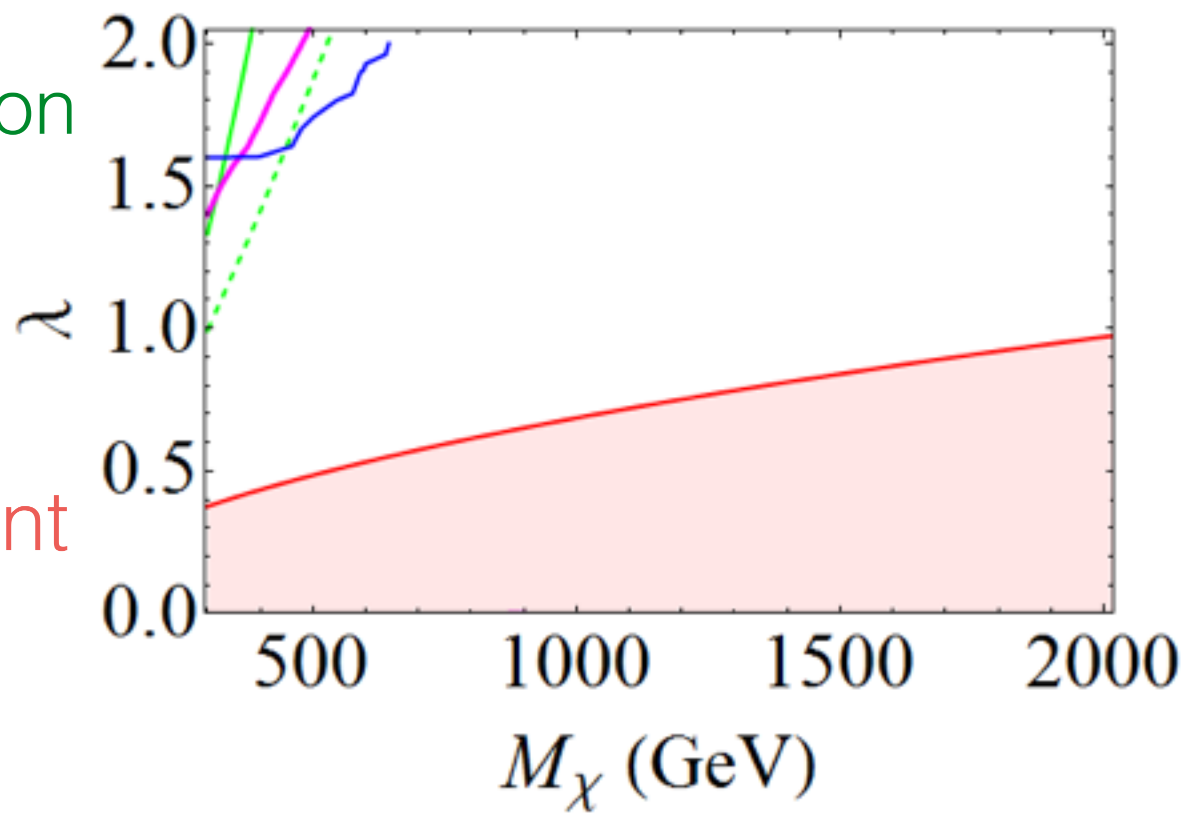


1410.6810,
Alves, Galloway, Ruderman, Walsh

(4) Loopy features

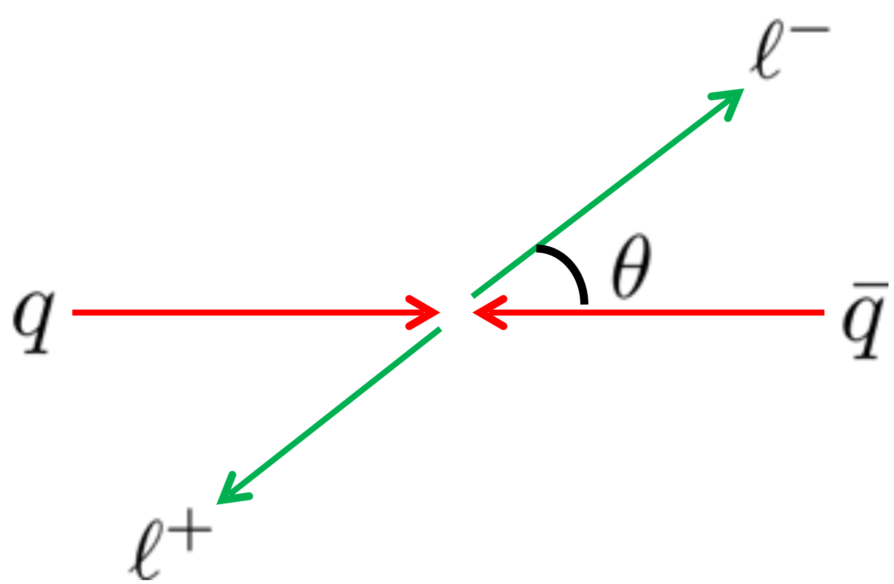
Direct detection
Jets + MET
Dileptons

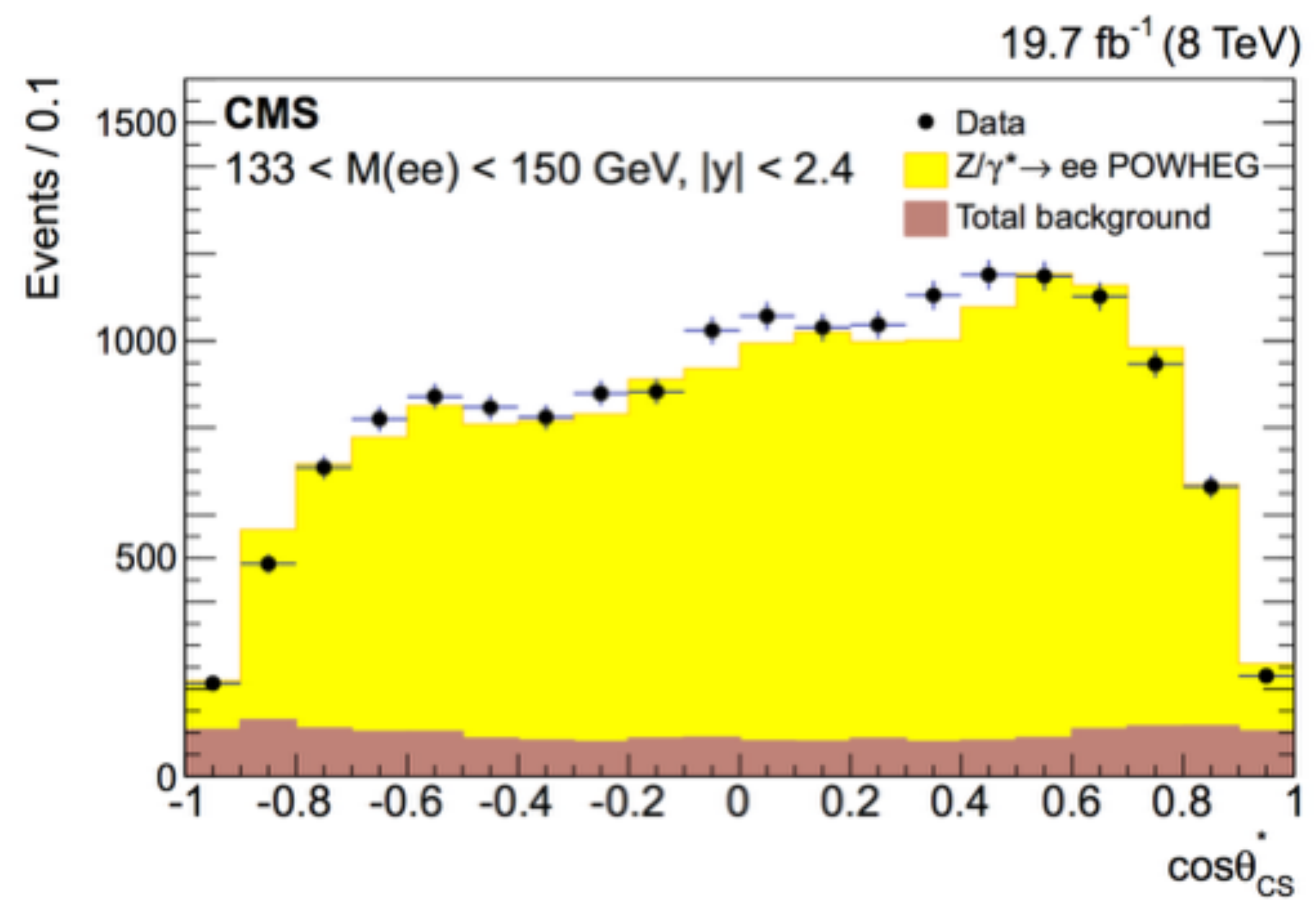
DM overabundant



"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 @ √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.

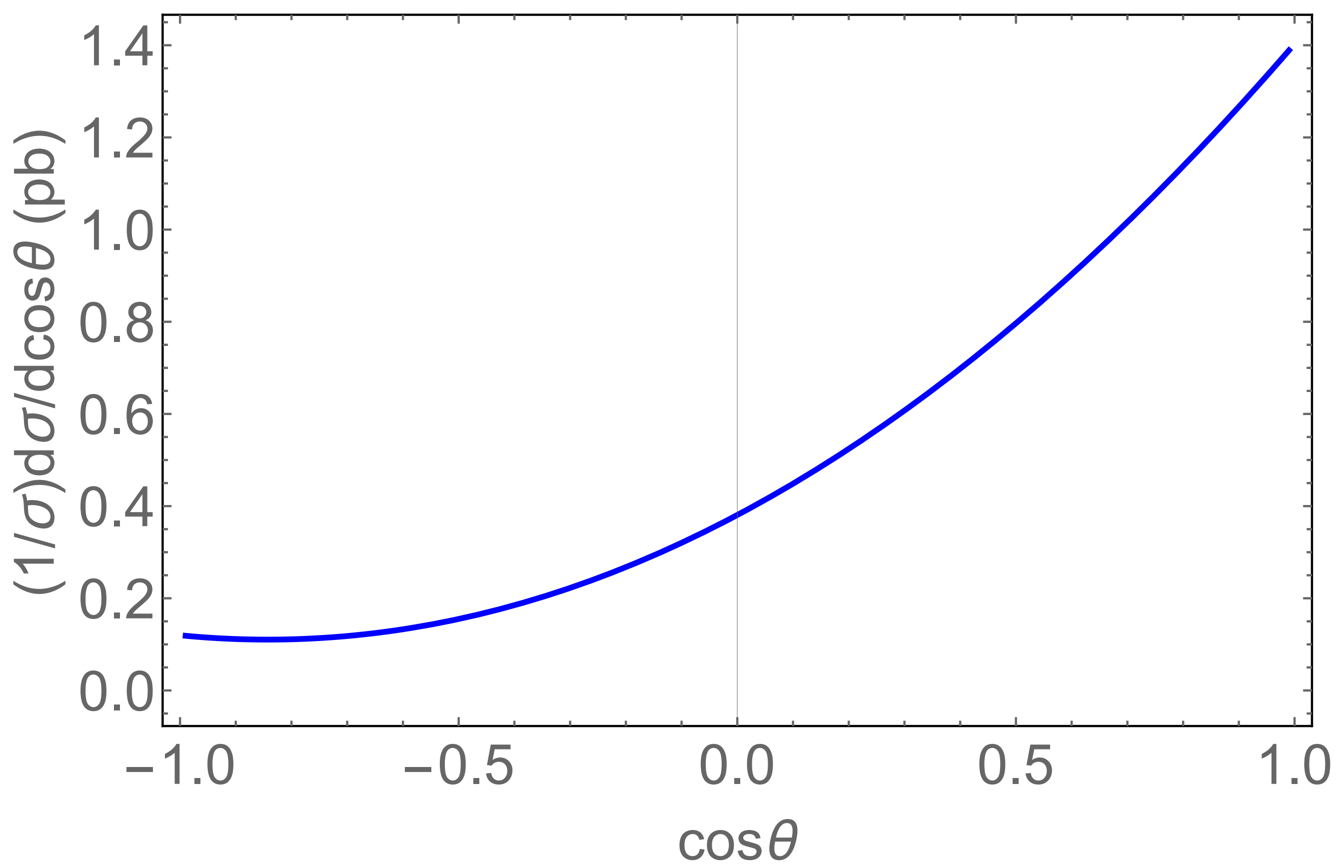
Later

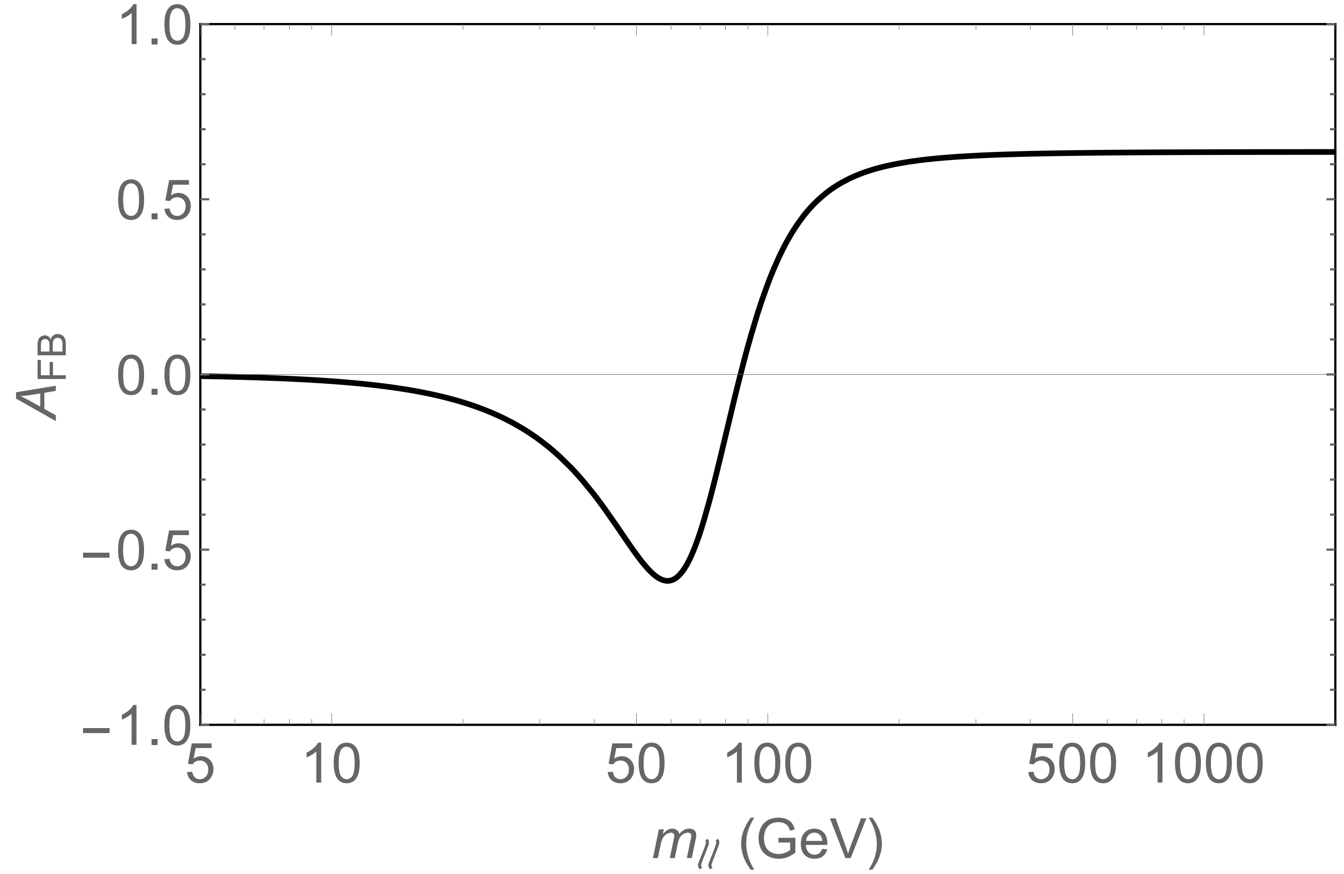
Angular spectra studied to pin down spin
and chiral couplings.

Forward-backward asymmetry

$e^+ e^- \longrightarrow l^+ l^-$

$m_{ll} >> M_Z$



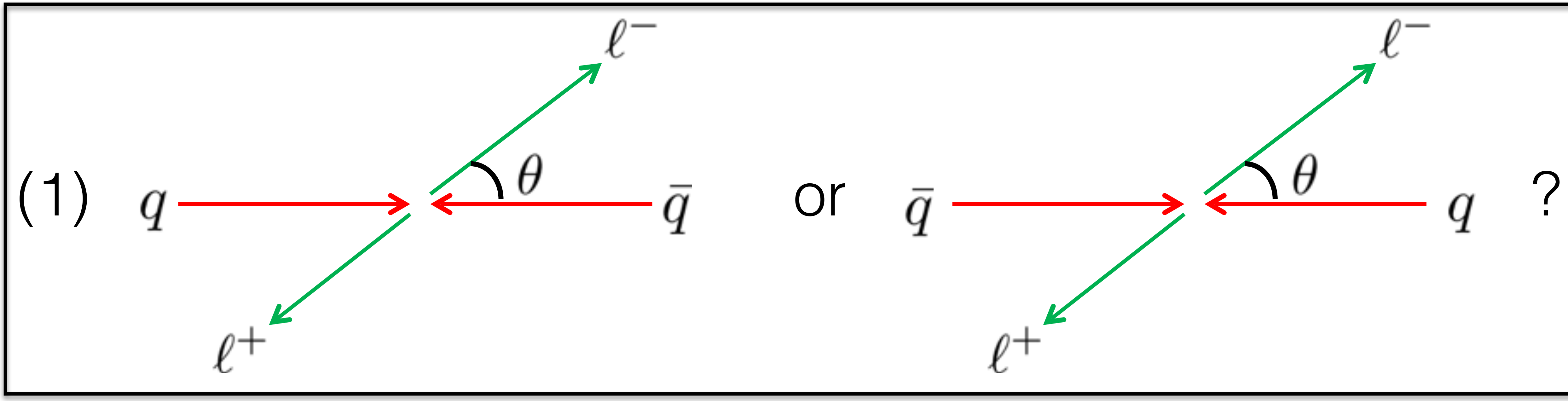


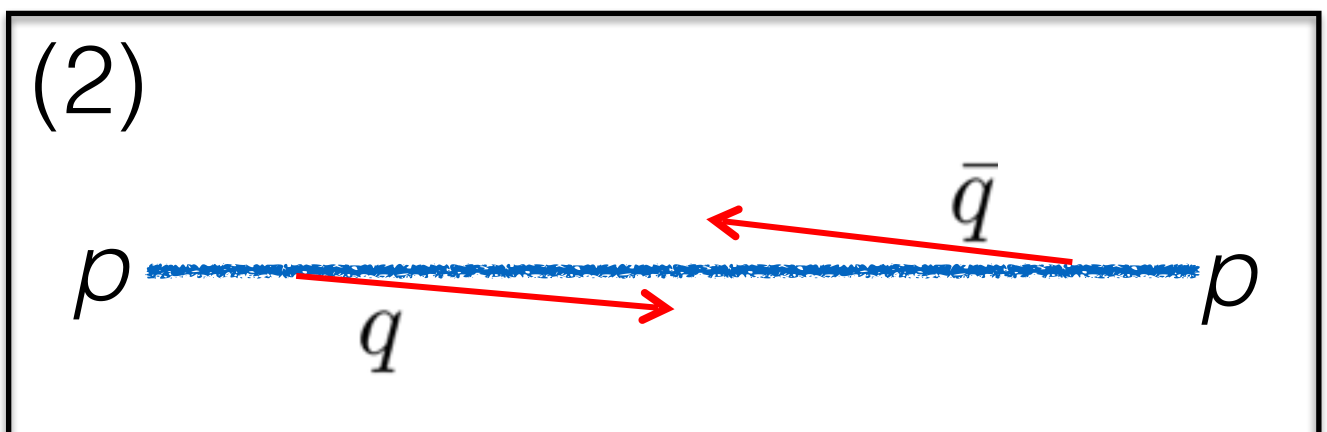
A_{FB} = area of right half minus left half
(normalized with total area)

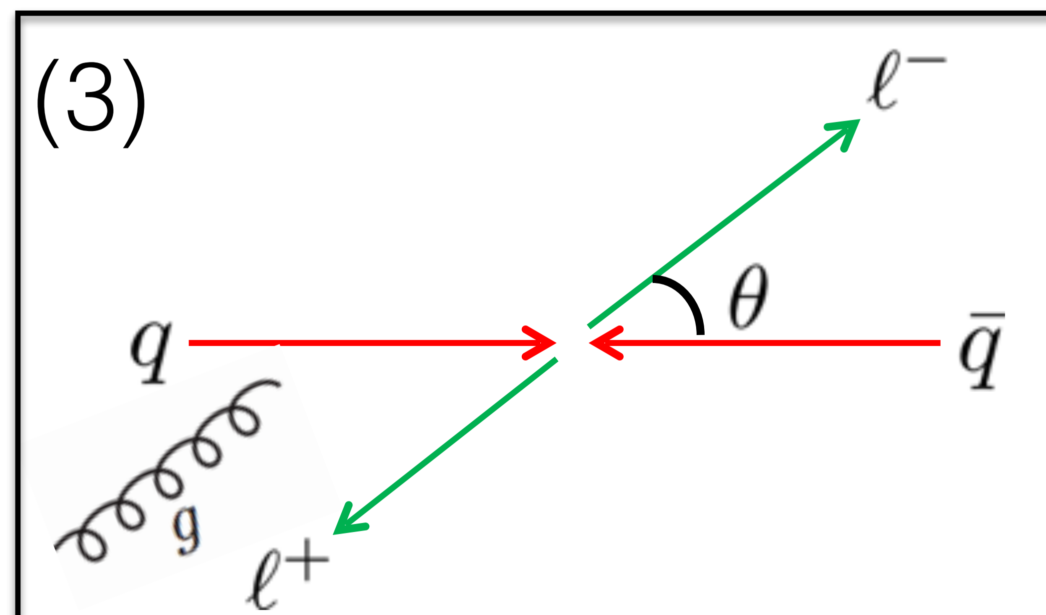
Forward-backward asymmetry

p p —> l+ l-

Four subtleties:





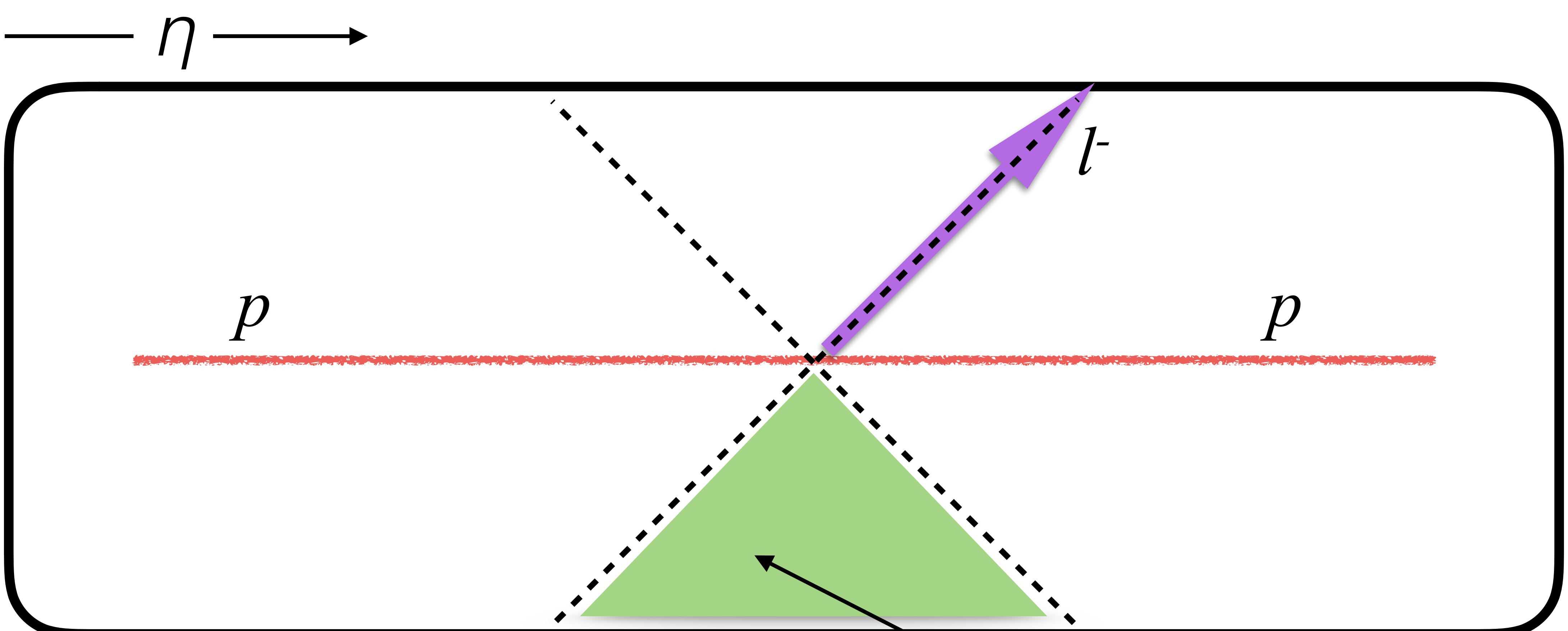


(4) Detector resolution of η

(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:

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

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

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.

m_{ll} spectra

angular spectra (A_{FB})

Non-resonance

(t-channel, loops, etc.)

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

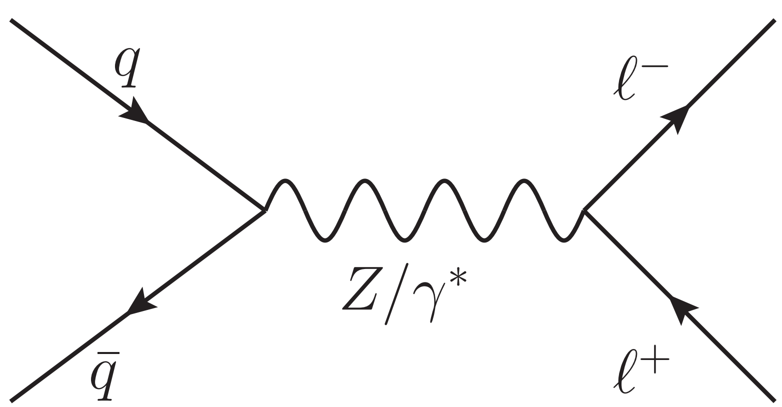
See Z' papers
F Petriello, et al (2008)
T Han, et al (2011)
V Barger, et al (2013)

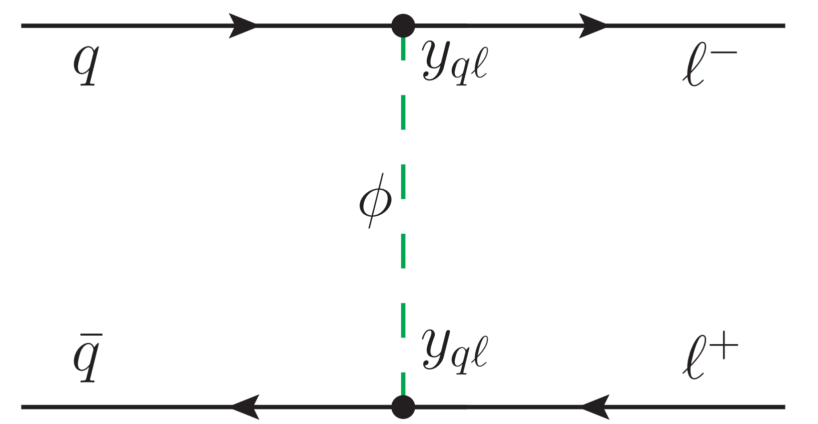
Recall Higgs sequence

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…
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

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

$$\mathcal{L} = -y_{ij}\bar{u}_{R,i}R_2^a\epsilon^{ab}L_{L,j}^b + y'_{ij}\bar{e}_{R,i}R_2^{a*}Q_{L,j}^a + \text{h.c.}$$

$$= (yV_{\text{PMNS}})_{ij}\bar{u}_{R,i}\nu_{L,j}R_2^{2/3} - y_{ij}\bar{u}_{R,i}e_{L,j}R_2^{5/3}$$

$$+ y'_{ij}\bar{e}_{R,i}d_{L,j}R_2^{2/3*} + (y'V_{\text{CKM}}^\dagger)_{ij}\bar{e}_{R,i}u_{L,j}R_2^{5/3*} + \text{h.c.}$$

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

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

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

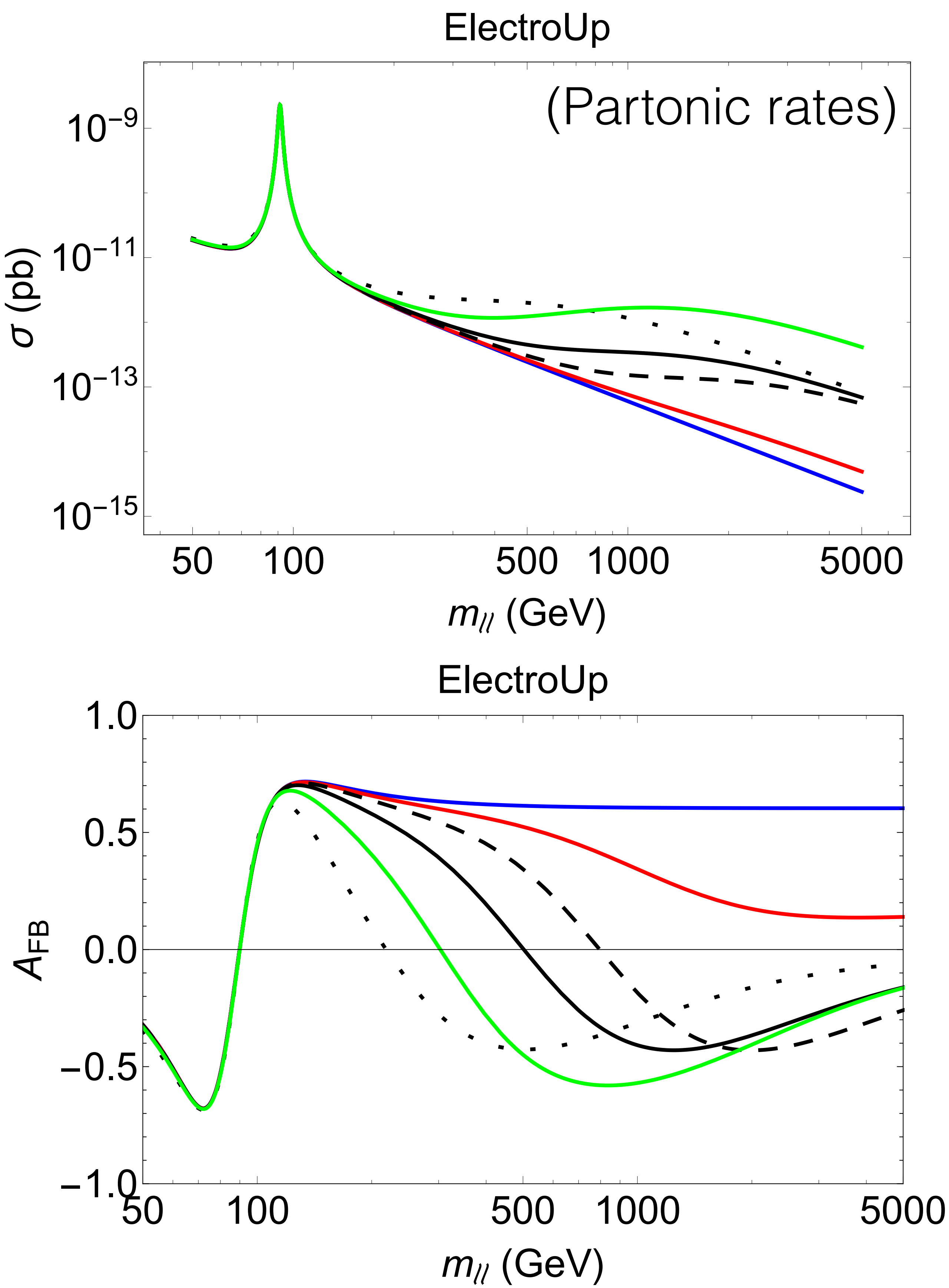
$$\mathcal{L} = -y_{ij}\bar{d}_{R,i}\tilde{R}_2^a\epsilon^{ab}L_{L,j}^b + \text{h.c.}$$

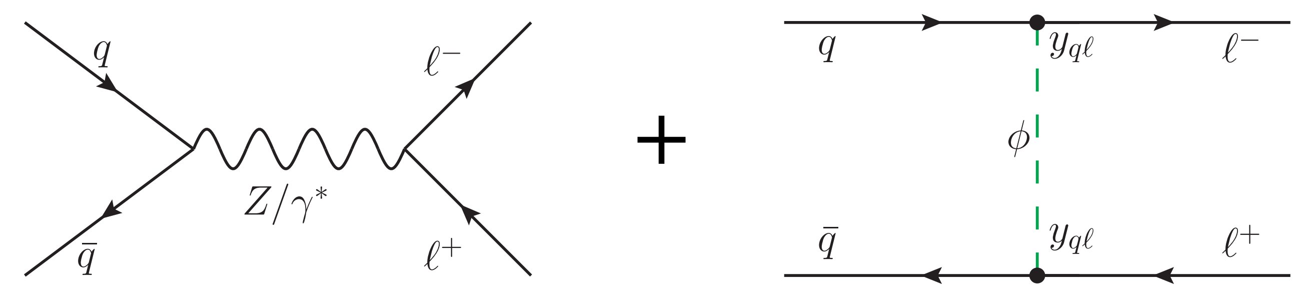
$$= -y_{ij}\bar{d}_{R,i}e_{L,j}\tilde{R}_2^{2/3} + (yV_{\text{PMNS}})_{ij}\bar{d}_{R,i}\nu_{L,j}\tilde{R}_2^{-1/3} + \text{h.c.}$$

$y_{ij} = y_{de}\,\delta_{i1}\delta_{j1}$: ElectroDown

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

Probes: Dileptons





SM

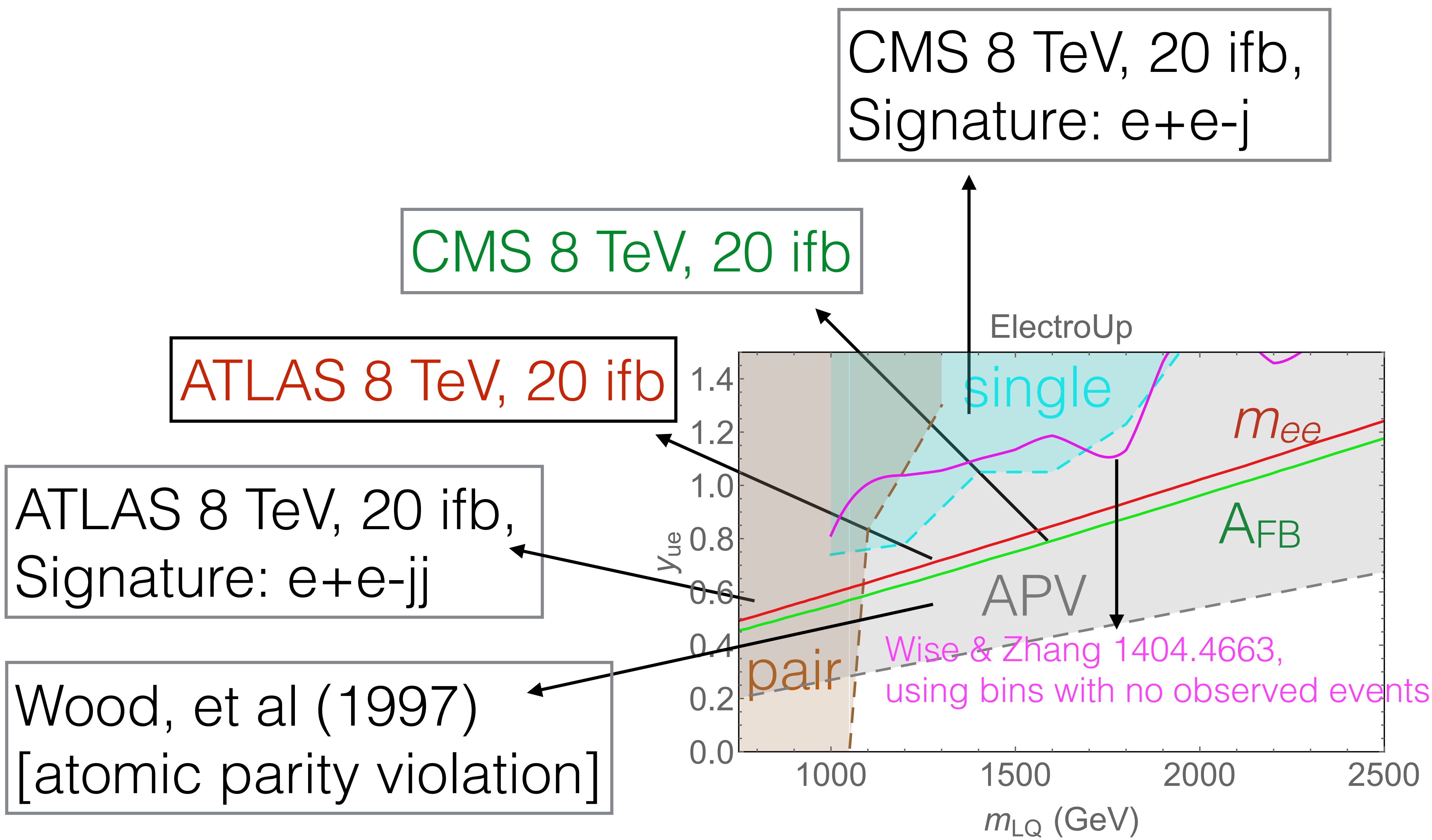
(m_{LQ} = 1 TeV,

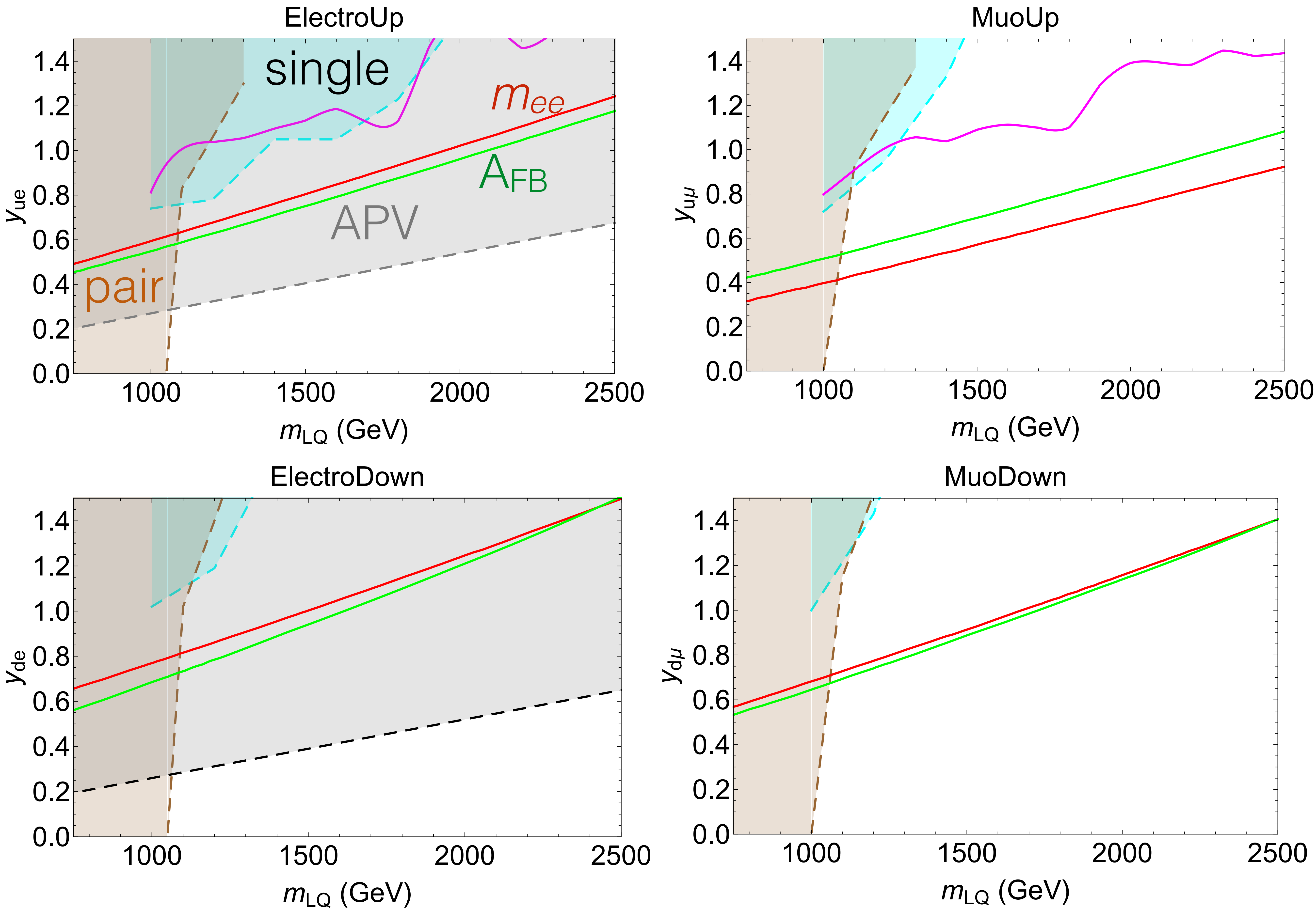
y_{ue} = 0.4, 1.0, 1.6)

(y_{ue} = 1,

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

All constraints

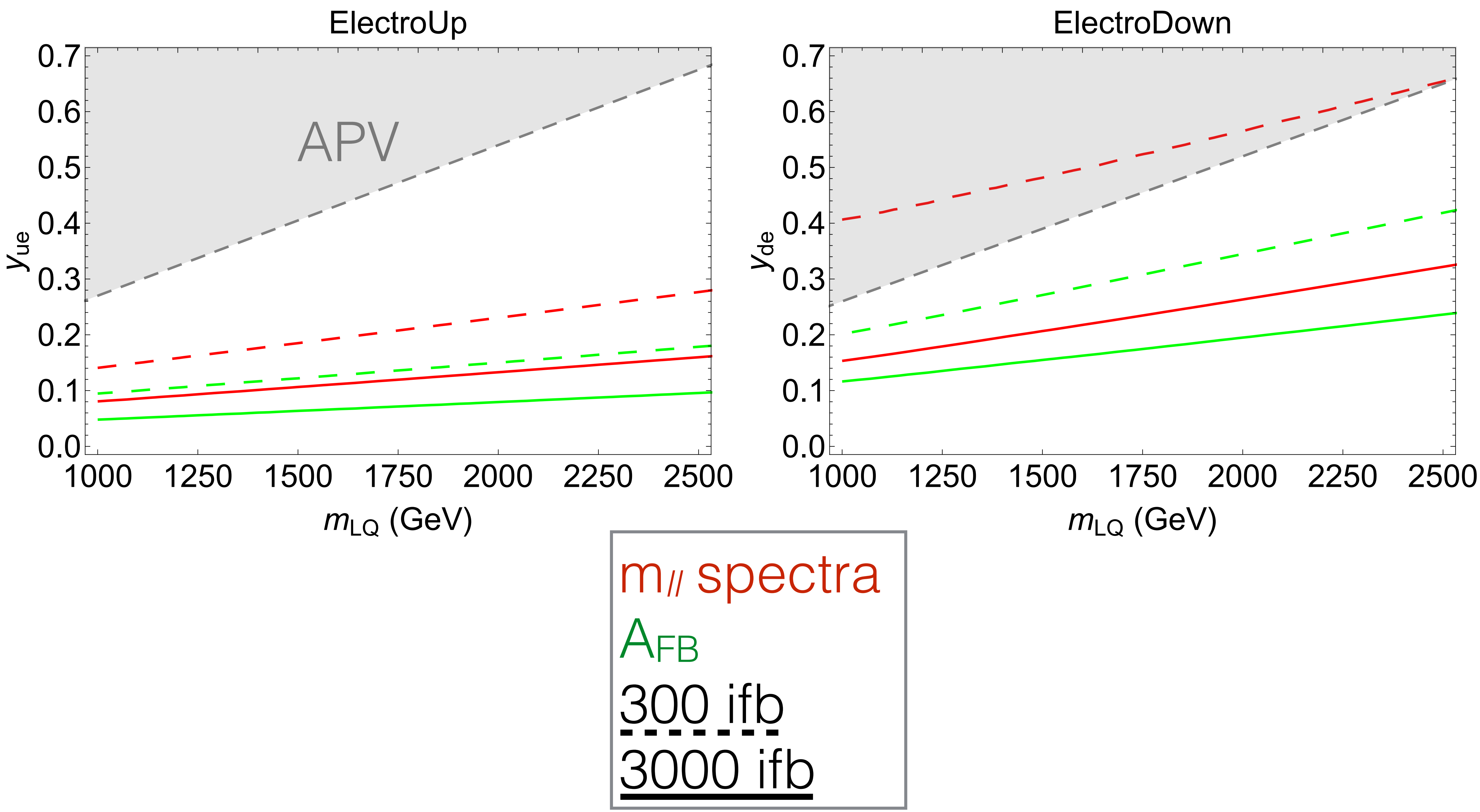




ElectroUp
single
m_{ee}
A_{FB}
APV
pair
y_{ue}
m_{LQ} (GeV)
MuoUp
$y_{u\mu}$
m_{LQ} (GeV)
ElectroDown
y_{de}
m_{LQ} (GeV)
MuoDown
$y_{d\mu}$
m_{LQ} (GeV)

Forecasts

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



Clarity

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

↓ Z physics conspicuous

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

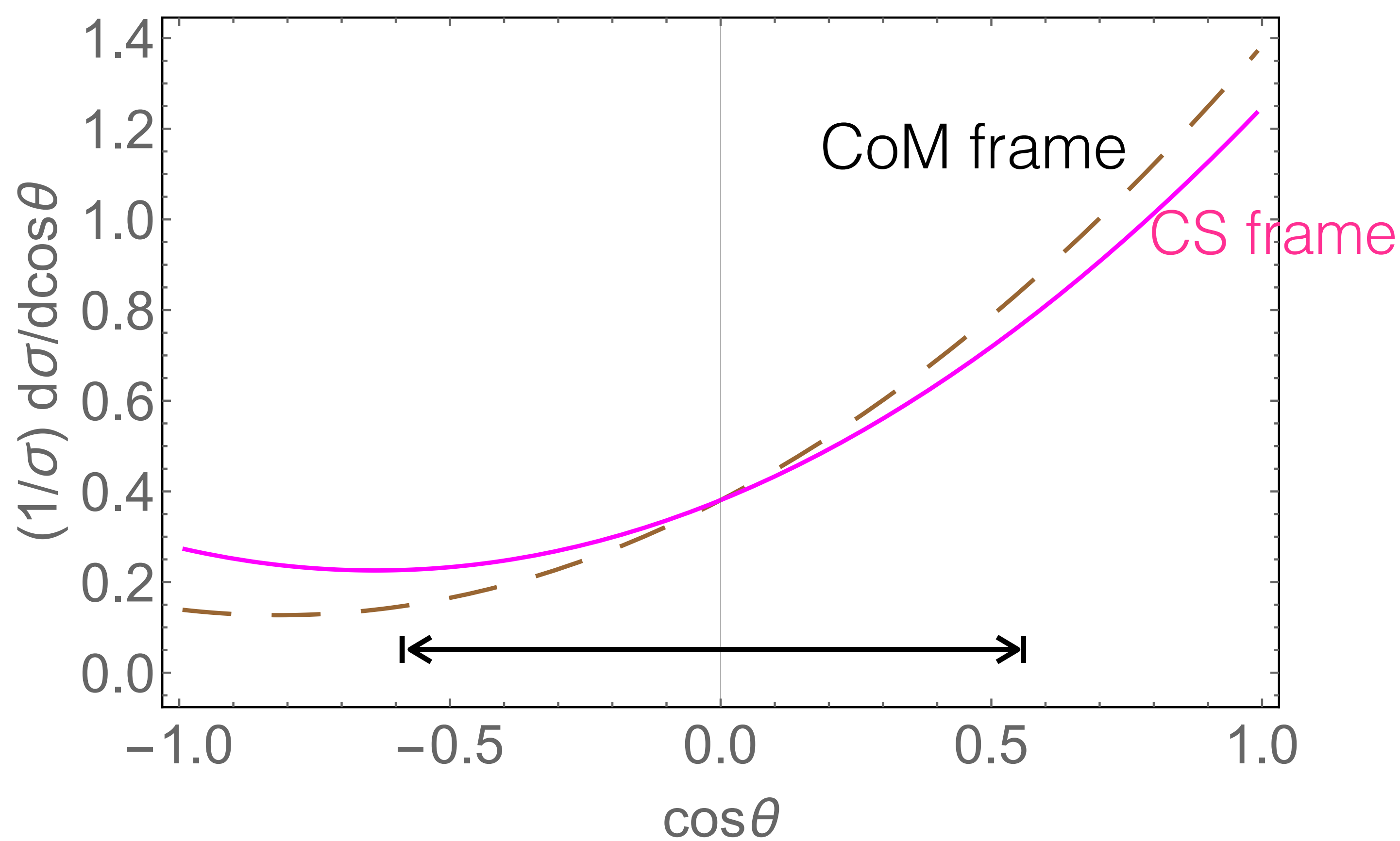
Clarity

Lorentz-invariant
+ vanishing in SM

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

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.