High luminosity opportunities for BSM

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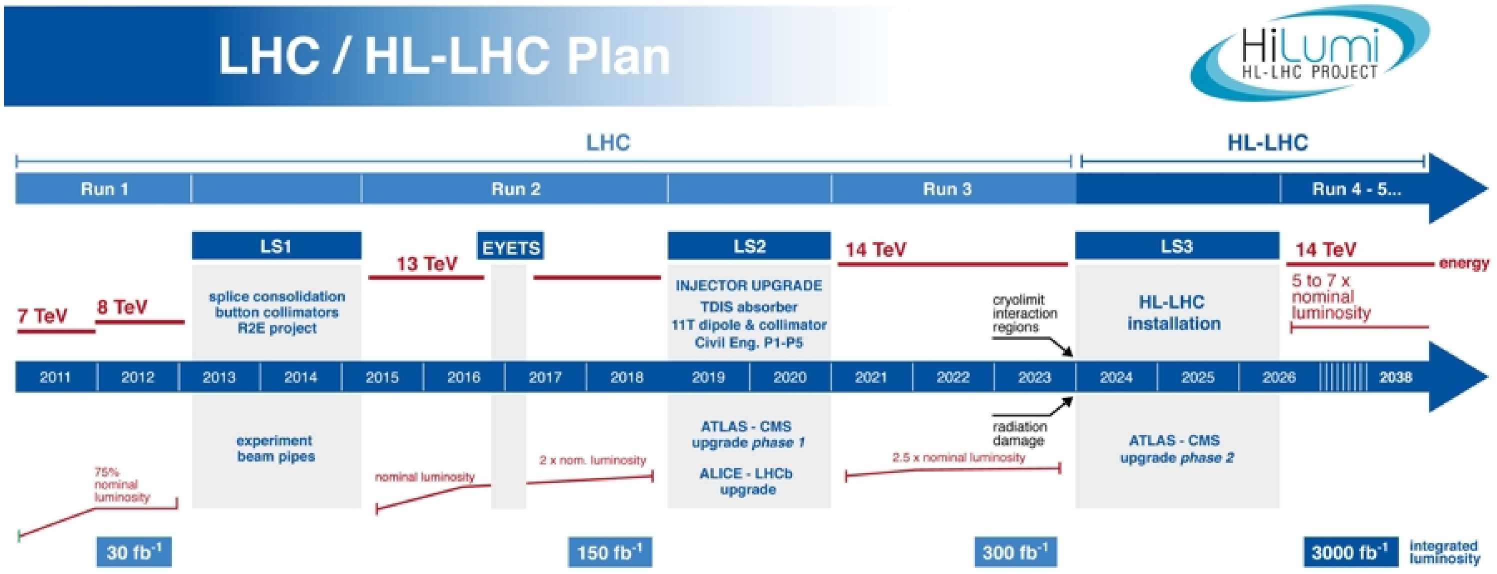
US ATLAS Workshop 2018

BSM	...and the LHC
Hierarchy problem	MET-based searches
Dark matter	Exotic fermions
Neutrino masses	Resonances
Baryogenesis	Mono-X
Strong CP	L-violating final states
Flavor	Higgs physics
Cosmological constant	Rare meson decays
...	SM precision

Outline—what can we probe at HL-LHC?



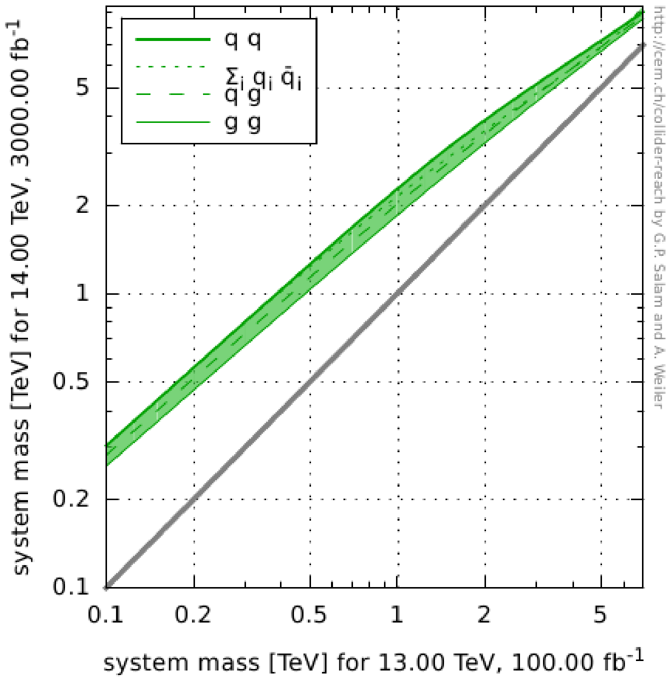
Emphasis on physics with most gains at high luminosity

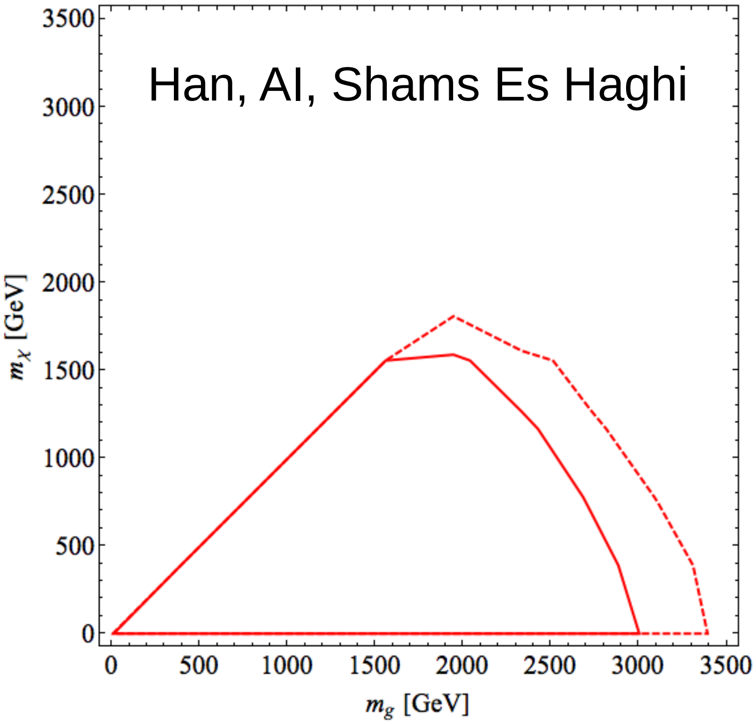
Direct BSM production
- states that hide under large backgrounds or have low statistics

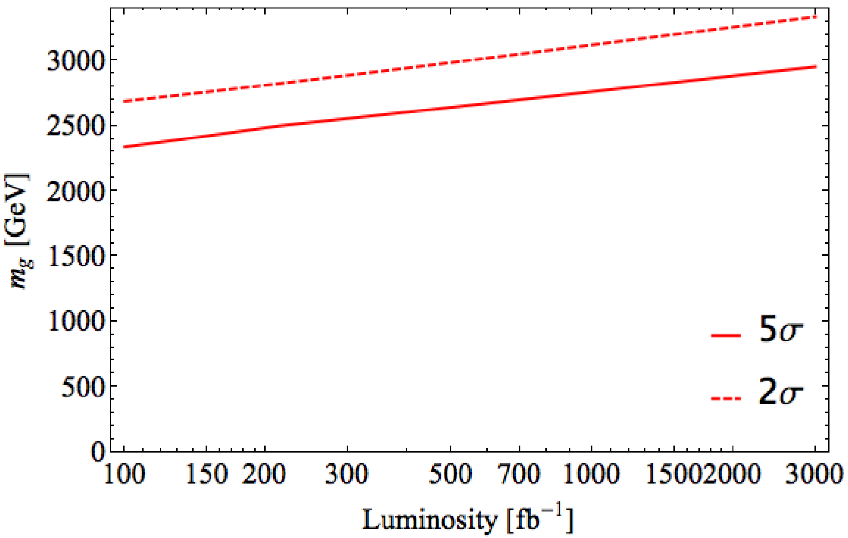
BSM from SM physics
- rare, exotic decays
- precision to extract indirect effects

Direct production of new states

Estimate from parton luminosity scaling: largest gains at low mass for current LHC → HL-LHC







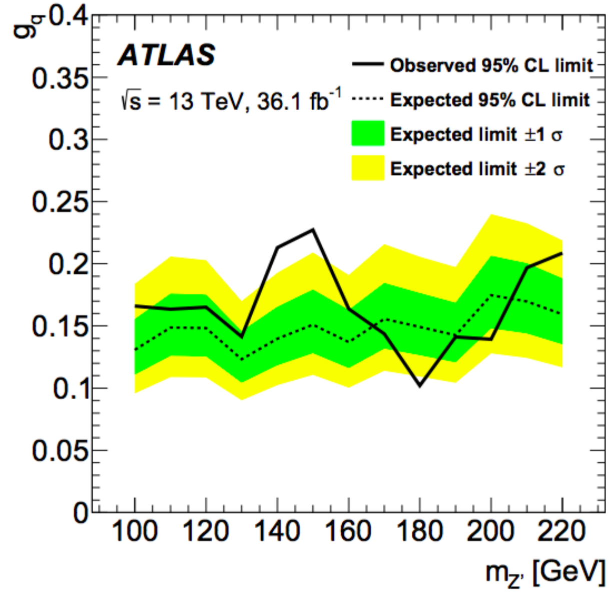
e.g. gluino reach doesn't gain significantly after a few hundred fb^{-1}

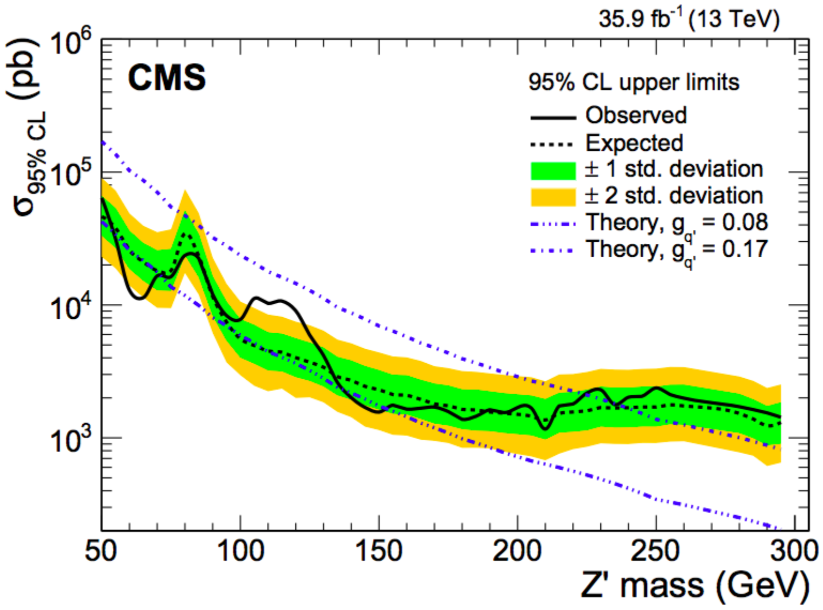
Improved analysis techniques

Jet substructure for low mass dijet resonances

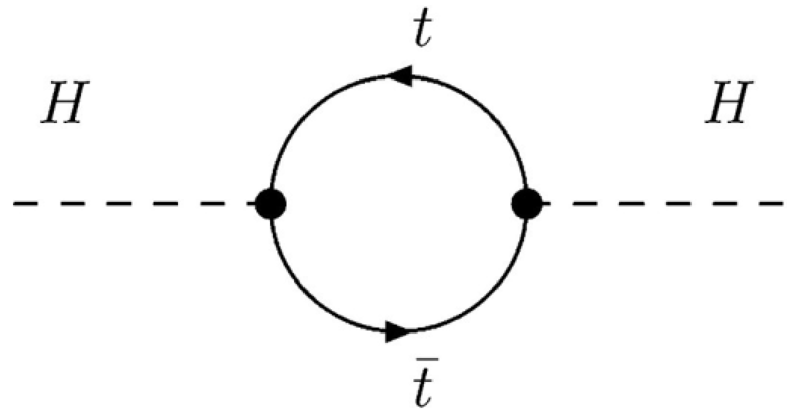
Limits now below 100 GeV

Already used for boosted Higgs → bb



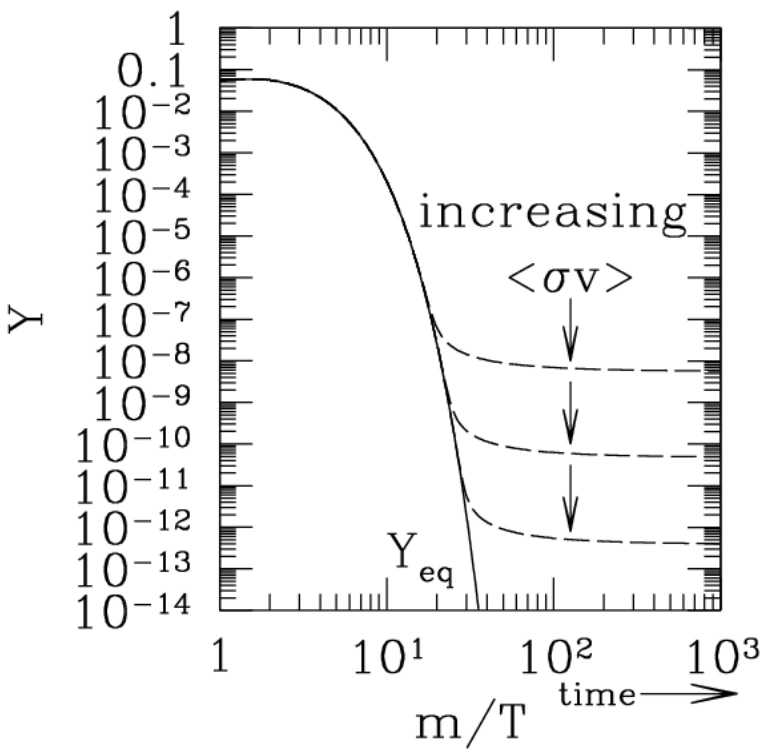


Electroweak searches for high luminosity



<u>Motivation 1, naturalness</u>

In SUSY Higgsino mass affects fine-tuning at tree level



<u>Motivation 1', naturalness</u>

top partners charged under *different* SU(3) from color, but still under EW group

folded SUSY Burdman, Chacko, Goh, Harnik hep-ph/0609152

quirky little Higgs Cai, Cheng, Terning 0812.0843

<u>Motivation 2, dark matter</u>

Simple example of WIMP paradigm for dark matter (thermal masses tricky at LHC)

New electroweak states and MET

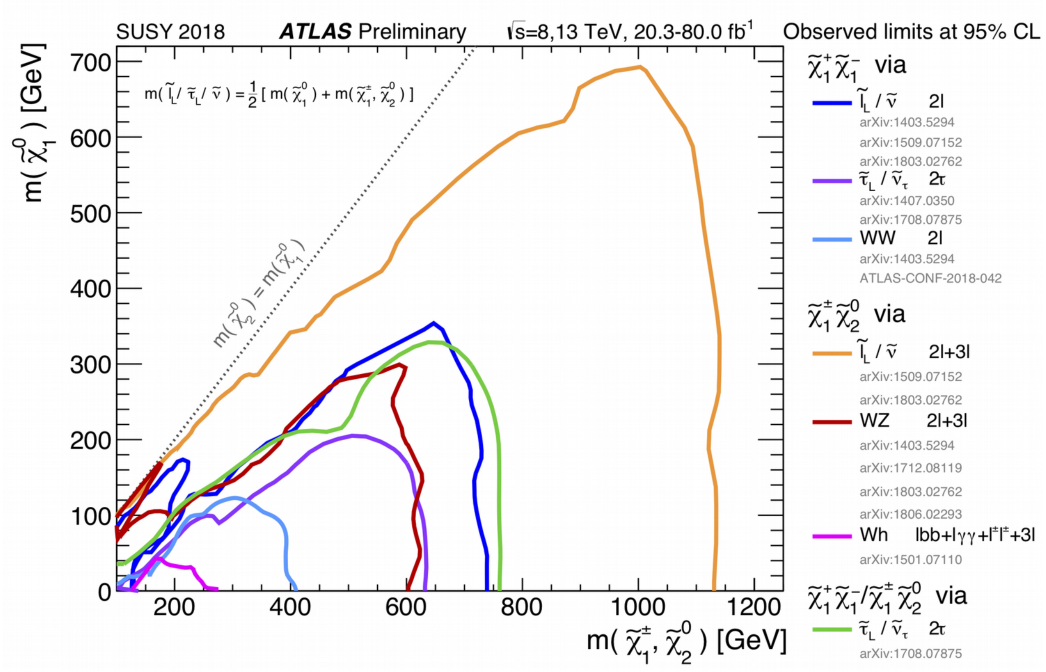
Assume:

EW multiplet odd under Z_2 symmetry, to avoid decays into SM particles that are covered by resonance searches

Q = 0 member of multiplet is lightest state, and hence invisible at colliders

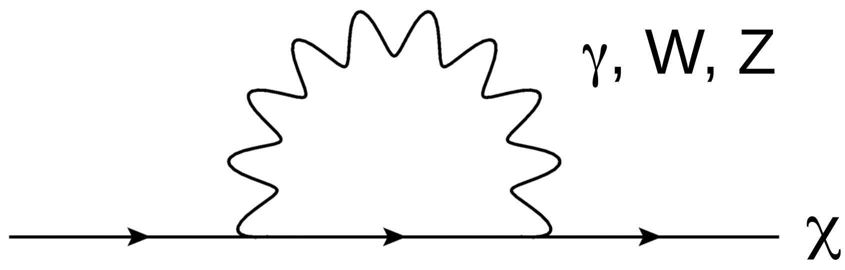
Any non-trivial $SU(2)_L$ multiplet χ contains at least one charged particle

Can produce charged particle and look for decay products plus MET



Mass splitting in EW multiplets

Small mass difference from radiative corrections



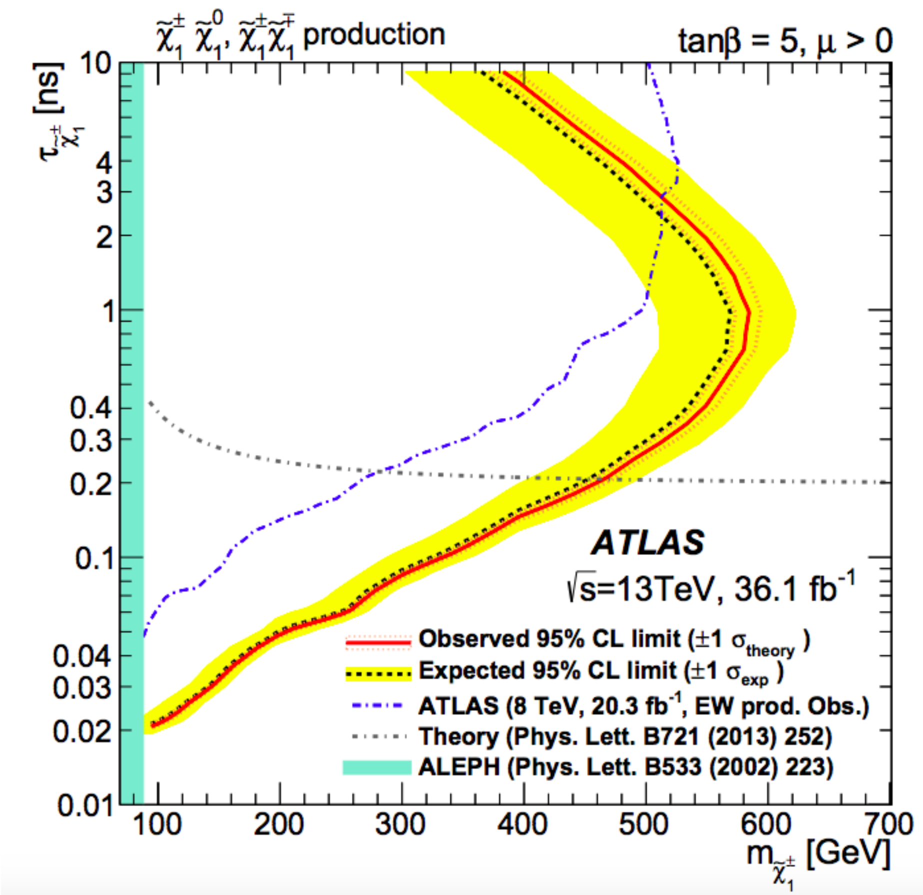
$$M(\chi^+) - M(\chi^0) = \left(1 + \frac{2Y}{c_w}\right)\frac{\alpha_2}{2} M_W \left(1 - c_w\right)$$
$$\approx 166 + 189(2Y)\ \mathrm{MeV}$$

Extra splitting possible from EWSB (scalar: dimension 4)

$$\mathcal{L} \supset \frac{i}{\Lambda}\left(\bar{\chi}\vec{\sigma}\chi\right)\left(H^\dagger\vec{\sigma}H\right) \to M(\chi^+) - M(\chi^0) \sim \frac{v^4}{\Lambda^2 m_\chi}$$

Signatures: small splitting

For mass difference well below GeV, $\chi^+ \to \chi^0 + \pi^+$ gives disappearing tracks



Insertable B-layer allows reconstruction of particles with significantly shorter lifetime, 12 cm rather than 30 cm

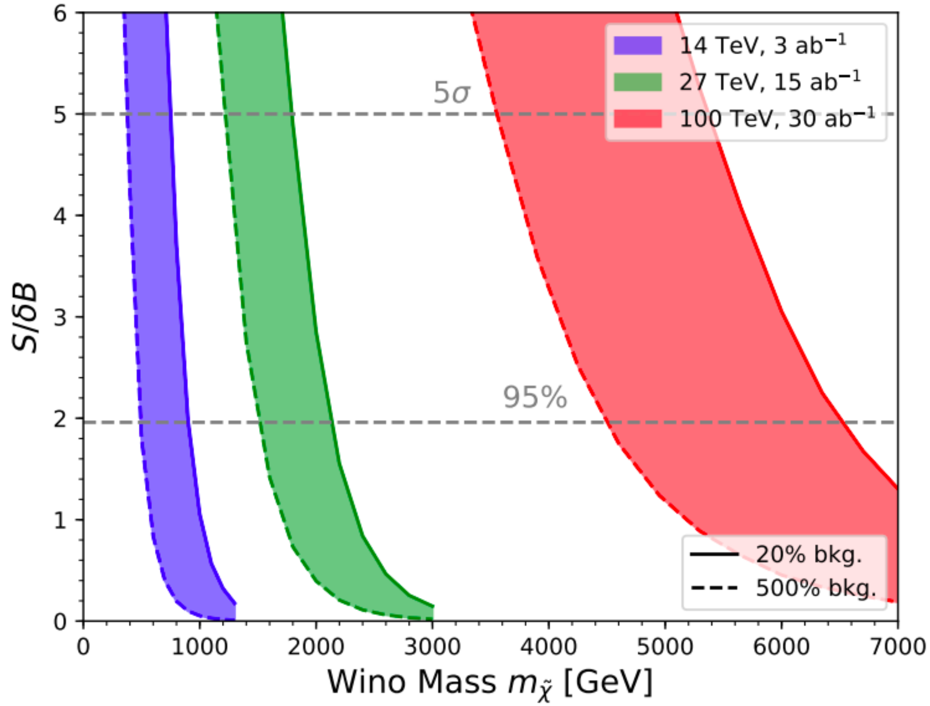
$$\Gamma \quad \propto \quad G_F^2 \Delta M^3 f_\pi^2 \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\to \tau \quad \approx \quad \frac{44 \text{ cm}}{n^2 - 1}$$

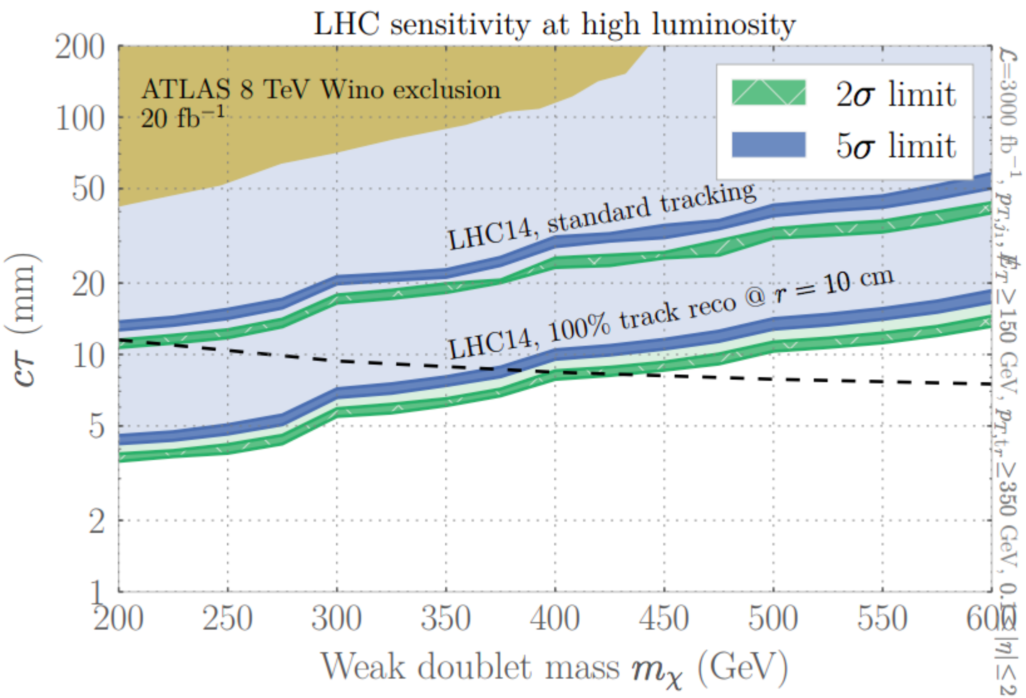
Y = 0 *n*-plet

The future of disappearing track searches

Prospects for triplet increase to 0.5-0.9 TeV with full luminosity, depending on background



Han, Mukhopadhyay, Wang 1805.00015



Getting closer to beam would improve reach further

Mahbubani, Schwaller, Zurita 1703.05327

Intermediate splittings?

For mass differences between ~0.5-5 GeV, leptons from χ^+ decay are too soft to see in detector

But decay is prompt enough to avoid disappearing tracks!

→ alternative: go back to mono-X searches

canonical example: EW doublets with Y = ½

<u>8 TeV monojet limits</u>

$$\text{ATLAS} : m_\chi > 103\,\text{GeV}\,(\text{SR4})$$

$$\text{CMS} : m_\chi > 73\,\text{GeV}\,(\text{SR5}),$$

Han et al., 1401.1235

Current limits comparable to LEP

Need to go beyond monojets

Future monojet sensitivity hindered by large V + jet backgrounds

Table 1: Summary of the statistical and systematic contributions to the total uncertainty on the $Z(\nu\nu)$ background.

E_T^{miss} (GeV) $\rightarrow$	>250	>300	>350	>400	>450	>500	>550
(1) $Z(\mu\mu)$+jets statistical unc.	1.7	2.7	4.0	5.6	7.8	11	16
(2) Background	1.4	1.7	2.1	2.4	2.7	3.2	3.9
(3) Acceptance	2.0	2.1	2.1	2.2	2.3	2.6	2.8
(4) Selection efficiency	2.1	2.2	2.2	2.4	2.7	3.1	3.7
(5) R_{BF}	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total uncertainty (%)	5.1	5.6	6.6	7.9	9.9	13	18

CMS, 1408.3583

Current background errors smaller, still above 2%

Exclusive Signal Region	EM2	EM4	EM6	EM8	EM9
Observed events (36.1 fb^{-1})	67475	27843	2975	512	223
SM prediction	67100 ± 1400	27640 ± 610	2825 ± 78	463 ± 19	213 ± 9

ATLAS, 1711.03301

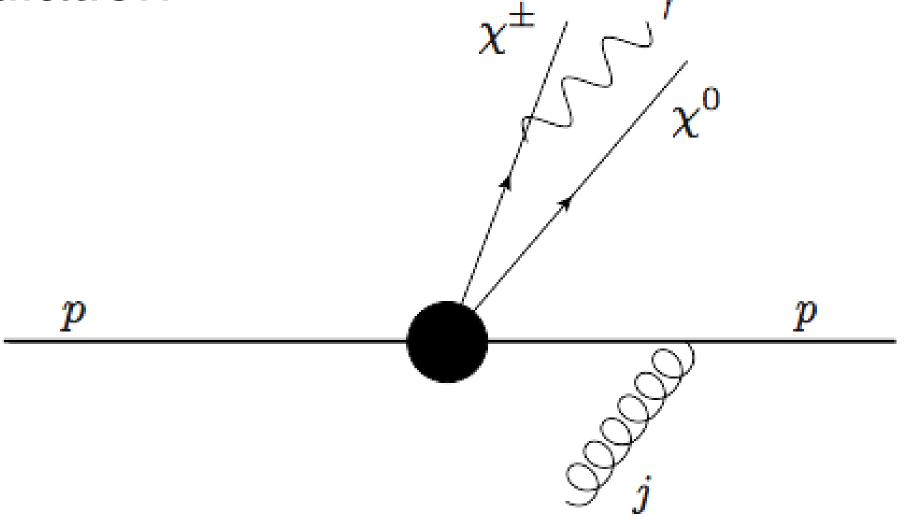
Multiple systematics: jet quality, pile-up, shower modelling, PDFs each near 1%

Photon final-state radiation

Even if χ^+ decays promptly and invisibly, it can still produce electroweak radiation

Take advantage of photon radiation by boosting

In monojet events with $p_T(j) > m_\chi$, jet recoils against missing energy + any radiation

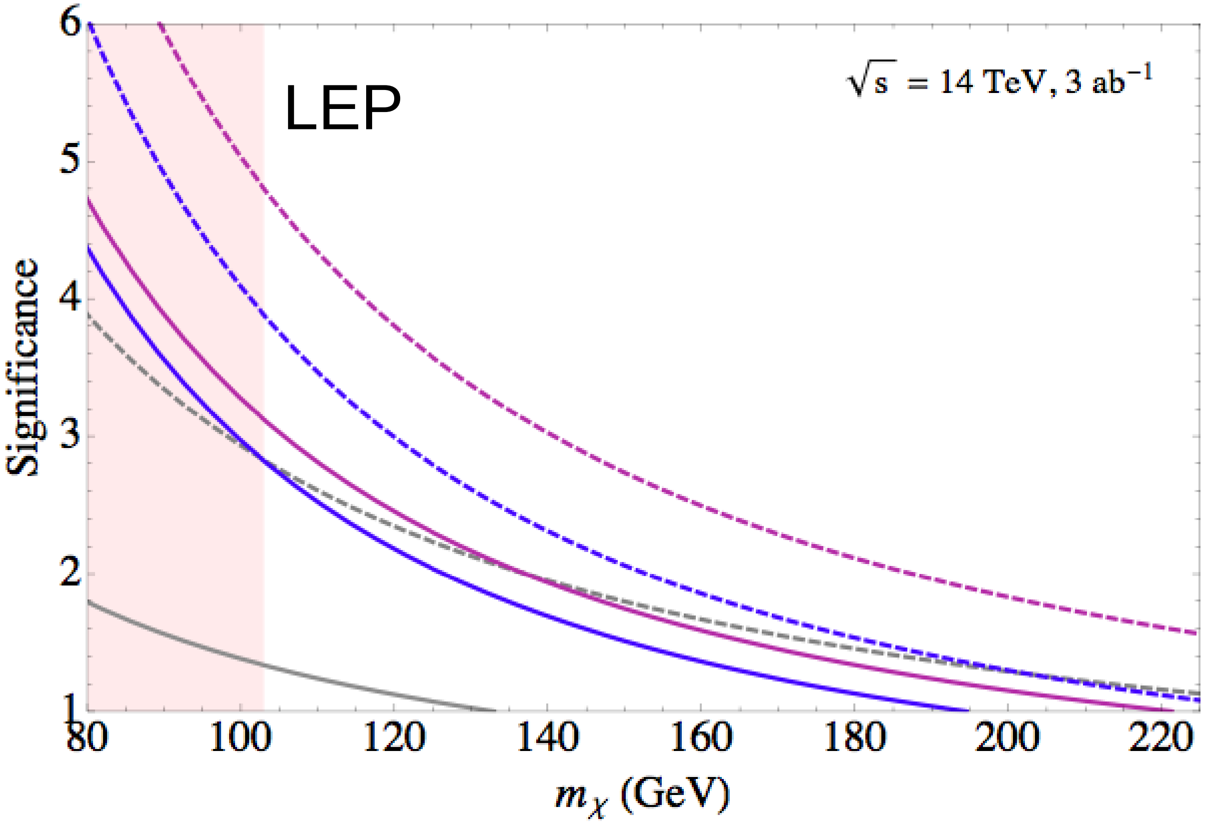


Al, Izaguirre, Shuve
1605.00658

Pay statistical price of α for radiation, but benefit from low backgrounds and extra kinematic handle in γ + j + MET

Limits – electroweak doublet

Adding photon to monojet final state helps, improving search that is independent of model-dependent mass splitting



Photon + jet + MET

Monojet

Combination

Solid: 5% systematics
Dashed: 2% systematics

Probing BSM with SM precision

Higgs measurements: see Dorival's talk

EW gauge boson production

Top physics

Z physics

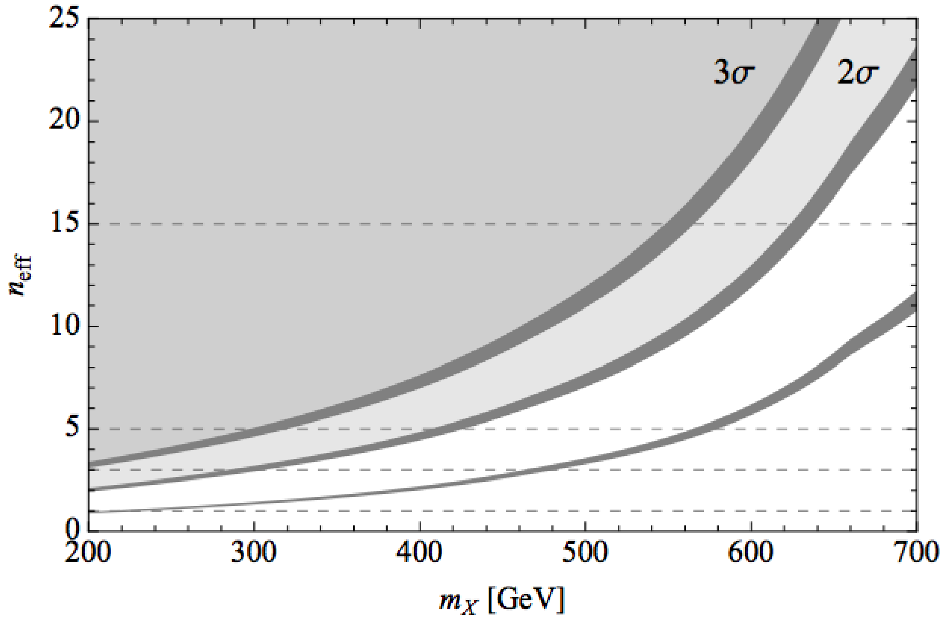
Jets

	"γ" $t \to Zu$	"σ" $t \to Zu$
Reference	$4.3 \cdot 10^{-5}$	$4.3 \cdot 10^{-5}$

Layout	Set	$t \to Hu$	$t \to Hc$	$t \to Hu+Hc$
Reference	A	$2.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
	B	$2.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$

ATL-PHYS-PUB-2016-019

Rare top decays



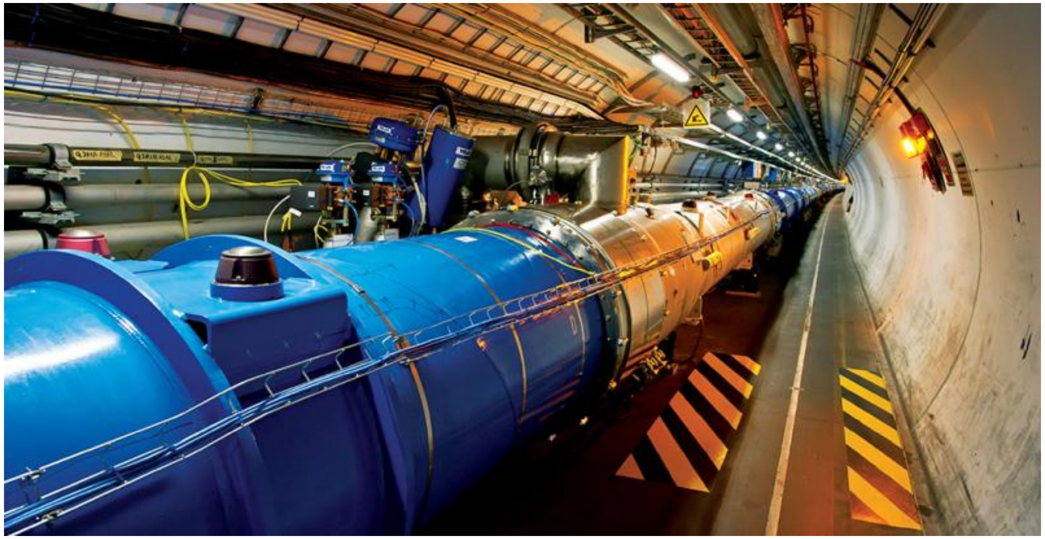
High energy measurements of α_s constrain running, probing new colored states

Becciolini et al. 1403.7411

Z bosons at high luminosity

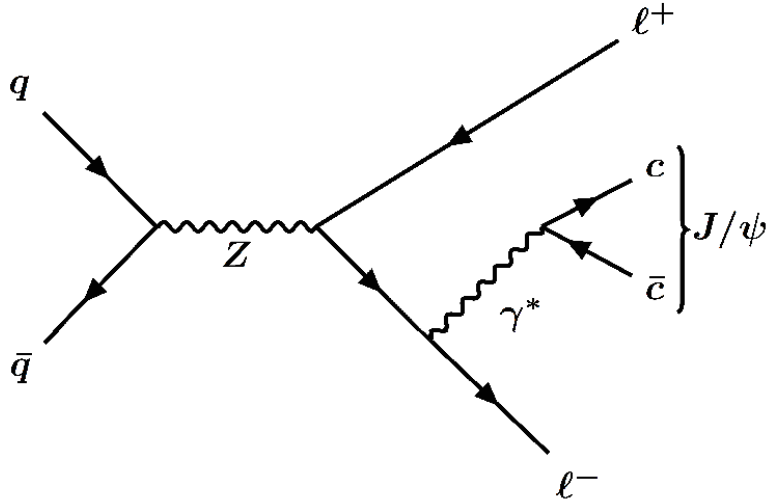
2×10^7 Z bosons recorded at LEP, all experiments and decays

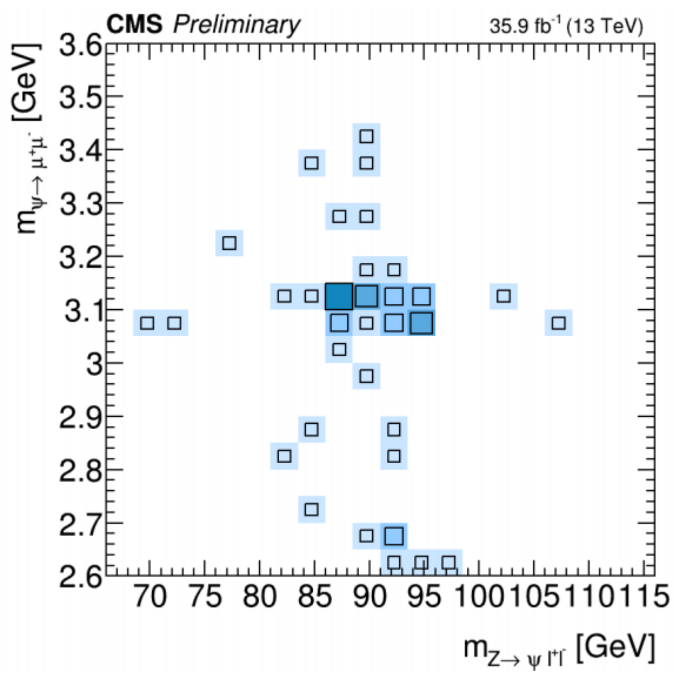
HL-LHC: 5×10^9 leptonic Z events per detector



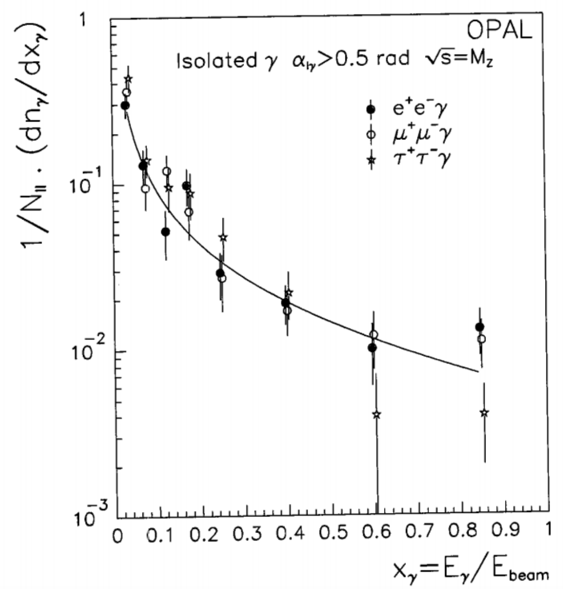
Opportunity to probe rare decays and subtle new physics effects

Rare Z decays





First observed with 13 TeV data
with BR ~ 10^{-6}



Still not seen: Z → $\ell^+ \ell^- \gamma$

OPAL BR bound < 5-6 × 10^{-4}

Future: radiative decay as background Al and Katz 1712.01840

More with SM processes: limiting general NP

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

B, L conservation, MFV → 59 independent dim. 6 operators

Higher dimension operators grow with energy

Look for interference with SM

LHC is already competitive see Chris's talk

Interference suppression

SM and BSM give different helicities for any 2 → 2 process involving a transverse V

Channel	SM	BSM_6
$++++$	ε_V^4	ε_V^0
$+++-$	ε_V^2	ε_V^0
$++--$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}++$	ε_V^2	ε_V^0
$+\frac{1}{2}-\frac{1}{2}+-$	ε_V^0	ε_V^2
$+\frac{1}{2}-\frac{1}{2}\,0+$	ε_V^1	ε_V^1
$+\frac{1}{2}-\frac{1}{2}\,0\,0$	ε_V^0	ε_V^0

Channel	SM	BSM_6
$0+++$	ε_V^3	ε_V^1
$0++-$	ε_V^1	ε_V^1
$0\,0++$	ε_V^2	ε_V^0
$0\,0+-$	ε_V^0	ε_V^2
$0\,0\,0+$	ε_V^1	ε_V^1
$0\,0\,0\,0$	ε_V^0	ε_V^0

$$\epsilon_V = m_V/\sqrt{s}$$

Azatov, Contino, Machado, Riva 1607.05236

$0 = V_L, \phi$

$+, - = V_T$

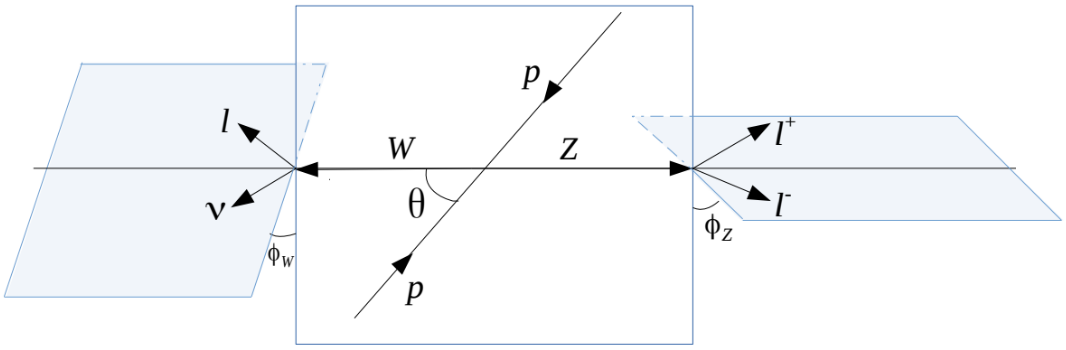
$+½, -½ = \psi$

e.g. in $W_T W_T$ and $W_T W_L$ production, interference between SM and EFT does not grow with E Baglio, Dawson, Lewis 1708.03332

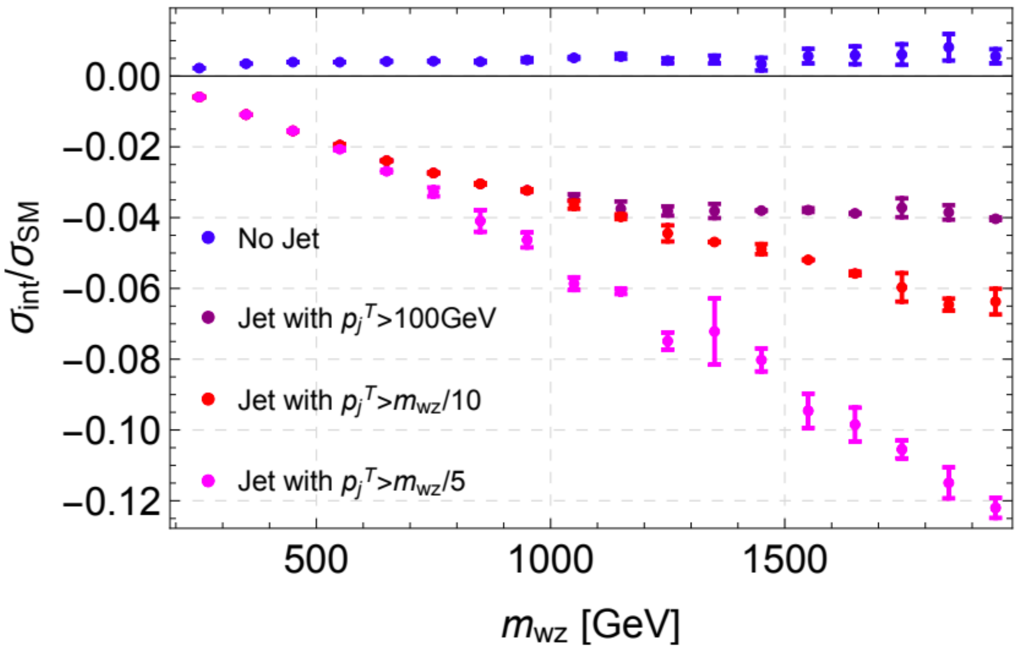
Restoring interference

Intermediate particles with different helicities interfere

Use azimuthal angles to disentangle full 2 → 4



Azatov, Elias-Miro, Reyimuaji, Venturini 1707.08060
Panico, Riva, Wulzer 1708.07823



Go beyond LO

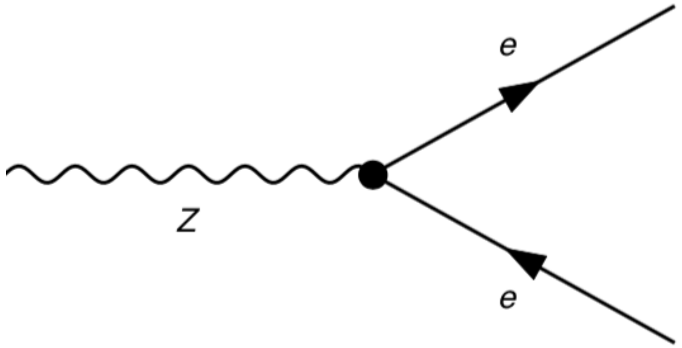
Originally used to probe G^3 operator in 3-jet events
Dixon and Shadmi
hep-ph/9312363

Example – W^3 in Z decay at NLO

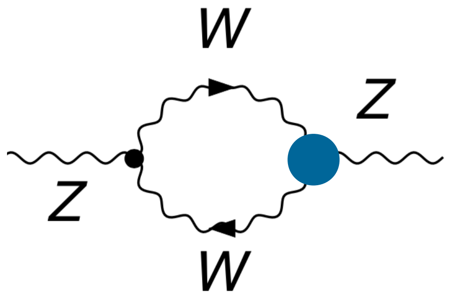
Suppressed interference in
q q → W W

$$\mathcal{O}_W = \epsilon_{abc} W_\mu^{\nu a} W_\nu^{\rho b} W_\rho^{\mu c}$$

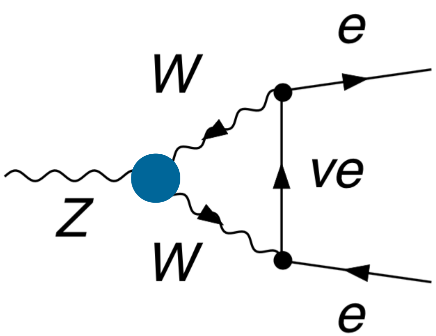
No tree level contribution,
but appears at one loop
Dawson and Al 1808.xxxxx



Z 2-point function



loop correction



also: Z-photon mixing

NLO Z decay in SMEFT

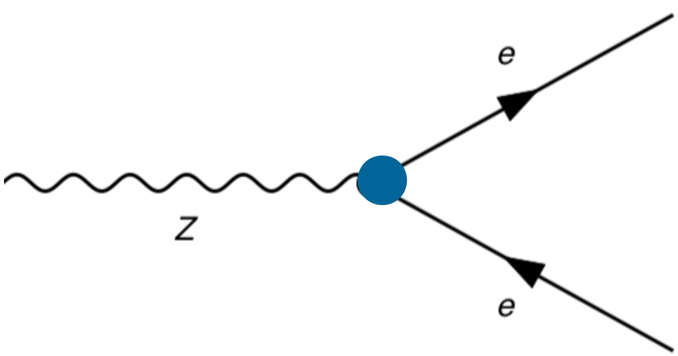
Keep only HWB and W^3 operators for simplicity

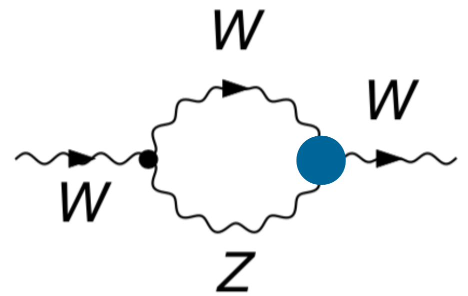
$$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_W = \epsilon_{abc} W_\mu^{\nu a} W_\nu^{\rho b} W_\rho^{\mu c}$$

Input parameters G_F, M_W, M_Z, M_H, M_t

W 2-point function



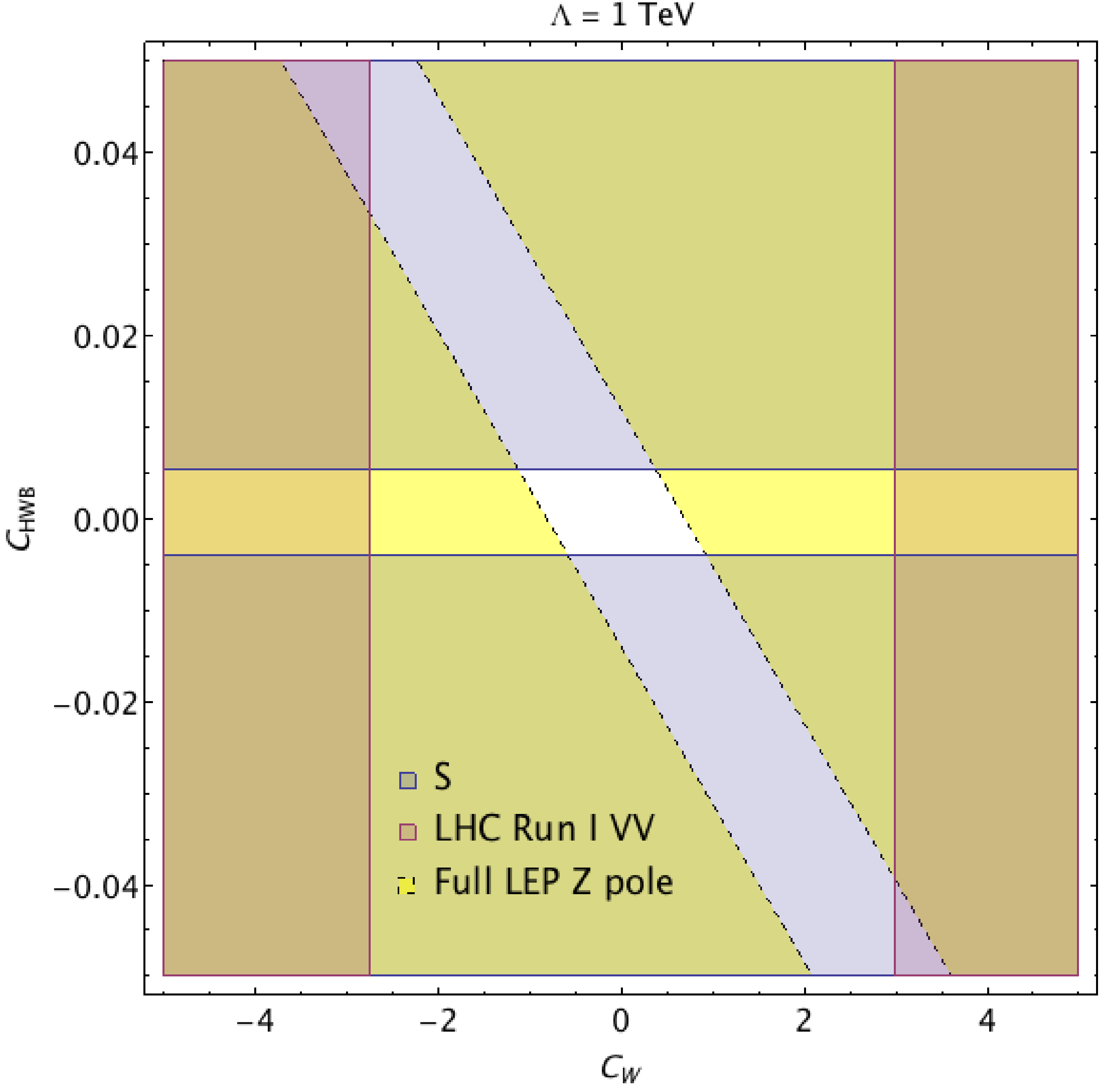


affects input parameter M_W

HWB operator gets contribution from W^3 operator at one loop

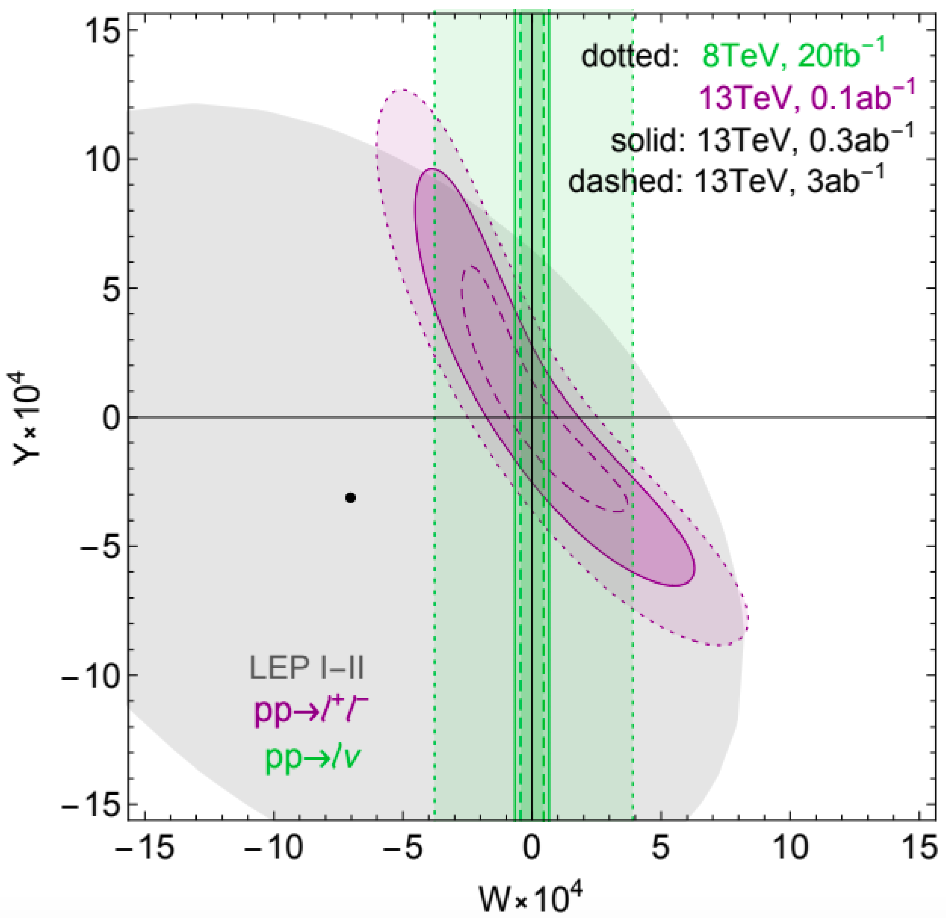
Renormalize with MS-bar scheme for EFT operators, on shell scheme for SM parameters

Z pole measurements improve on limits from WW production



NLO in Drell-Yan

Gauge boson operators at one loop also affect q q → ℓ ℓ, ℓ ν



Take advantage of interference increasing with energy

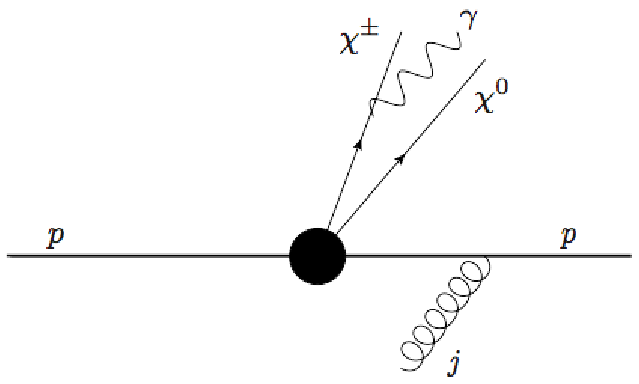
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{W}{4m_W^2}\left(D_\rho W^a_{\mu\nu}\right)^2 - \frac{Y}{4m_W^2}\left(\partial_\rho B_{\mu\nu}\right)^2$$

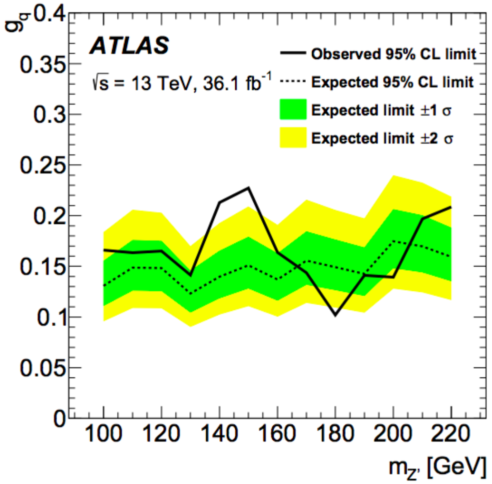
Farina et al., 1609.08157

Summary

High luminosity offers probes of new physics that is often *different* from what was tested in Runs 1 and 2

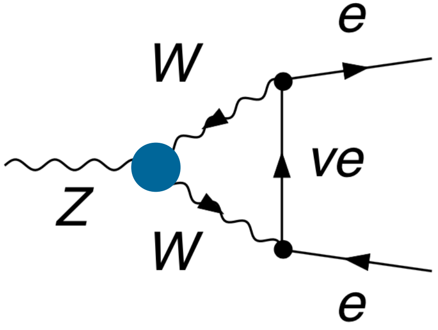
Analysis and detector improvements can increase reach more than expected





EW BSM: can probe genuinely new space using HL, depending on systematics

SM processes: lots of data gives possibilities to probe rare decays and do precision studies

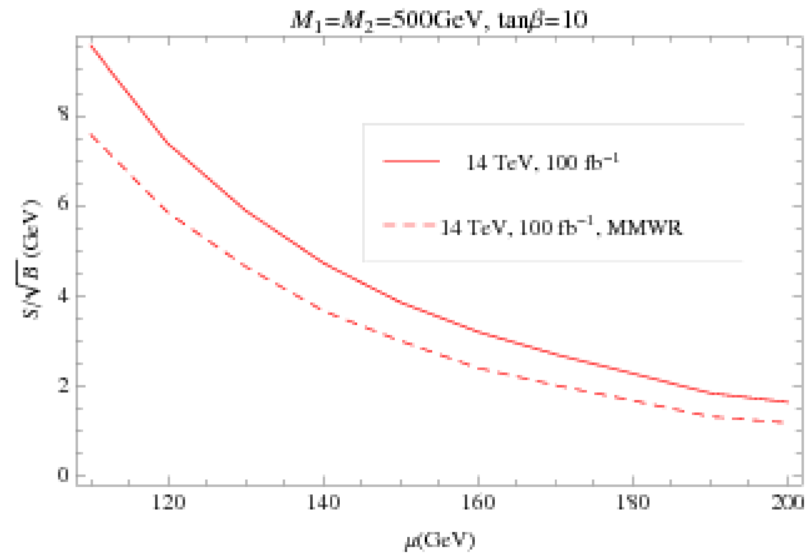


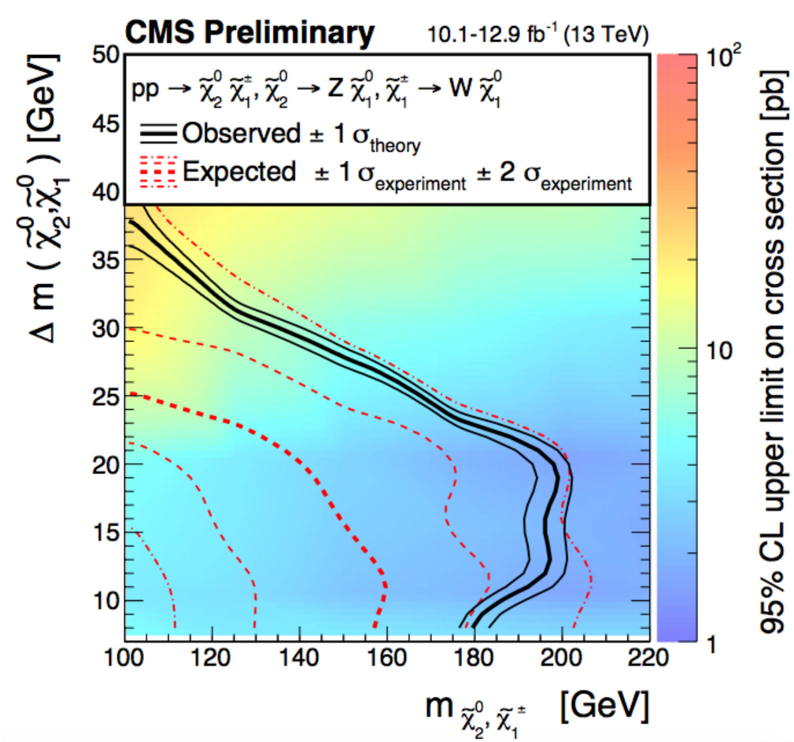
Backup

Signatures: large splitting

For several GeV mass splittings, can still use leptons from $\chi^+ \rightarrow \chi^0 + W^*$

Schwaller and Zurita, 1312.7350; Han et al., 1401.1235; Low and Wang, 1404.0682





Multiple states also give leptons from off-shell Z

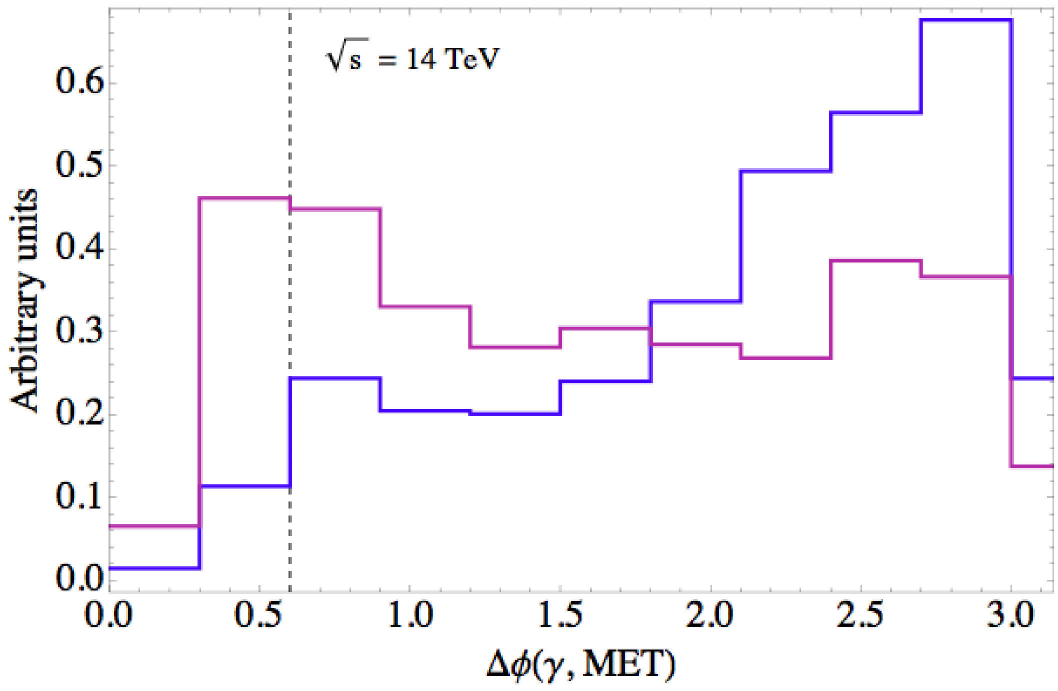
Standard example: gaugino sector of MSSM

Photon + jet + MET search

Trigger on hard jet and missing energy, then look for soft photon (15 GeV) with small angular separation from MET

Backgrounds: Z + γ + j, W + γ + j, tops, QCD fakes

Require photon $m_T > m_W$, $p_T(j_1)$ / MET > 0.5; optimize other cuts

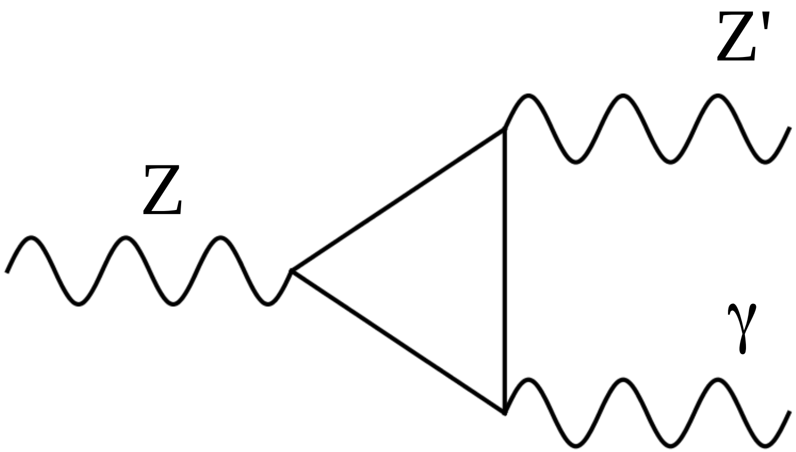


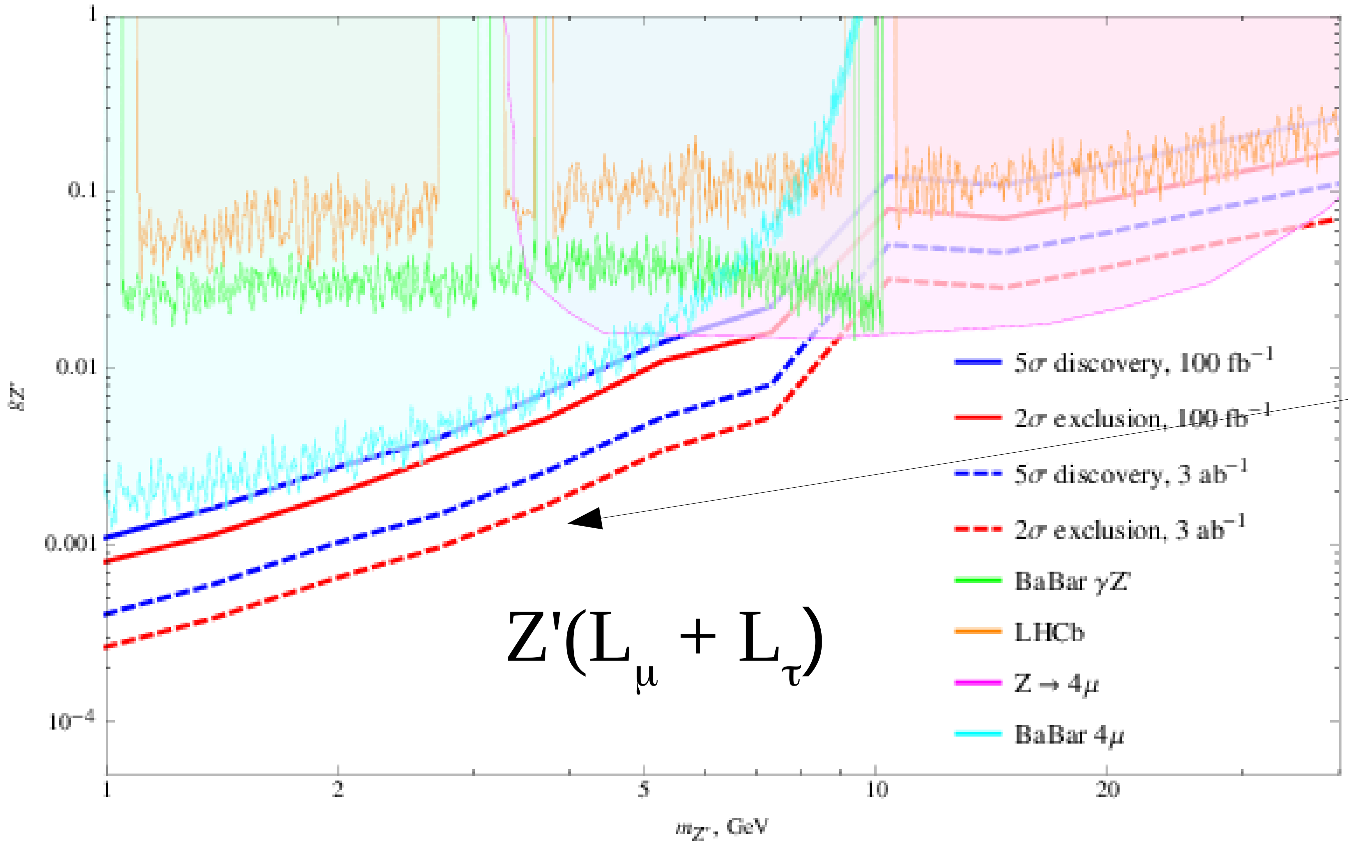
125 GeV Higgsino

Z, W backgrounds

Future: radiative decay as *background*

New GeV-scale U(1)'
with mixed anomaly
with SM



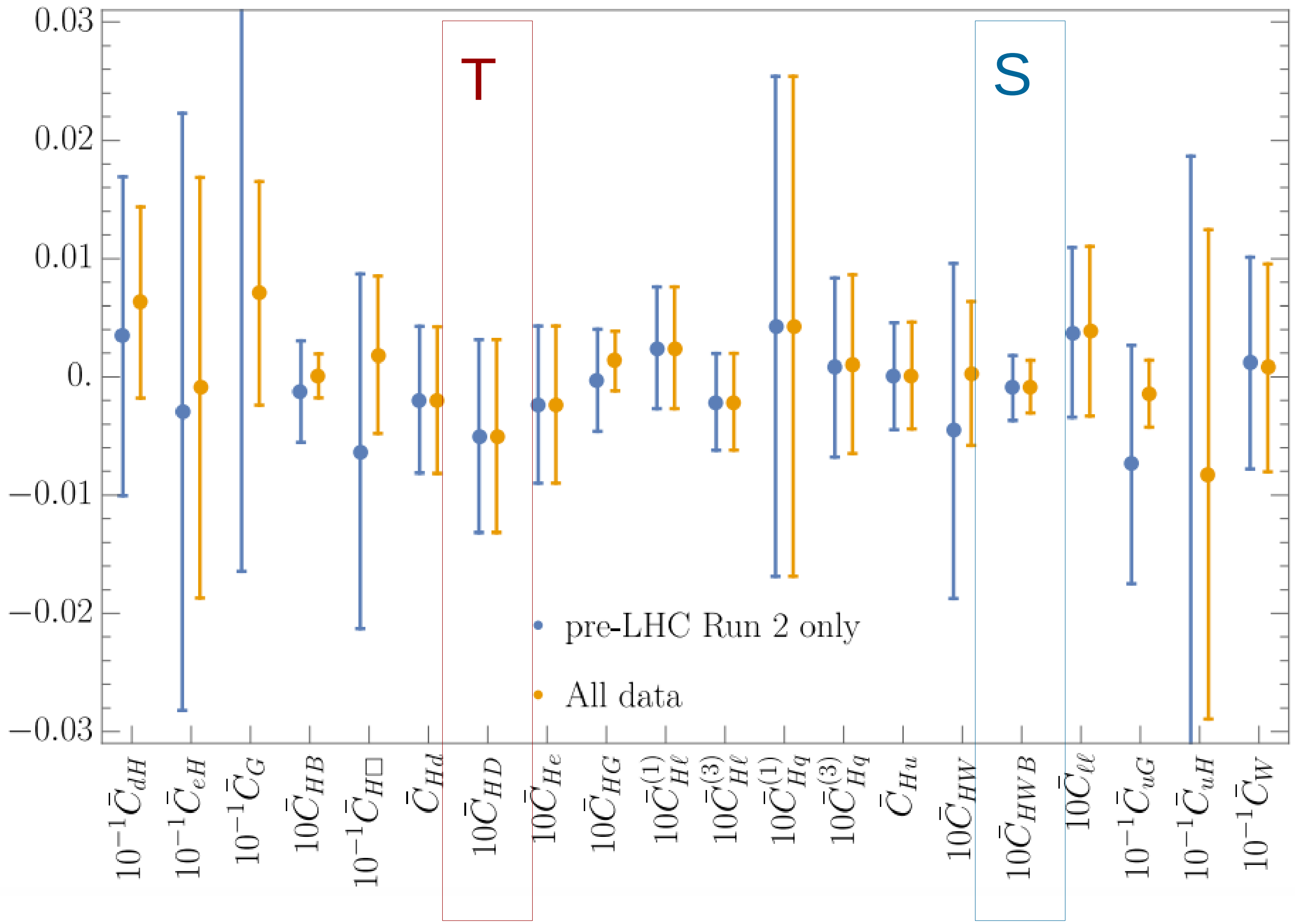


Lepton-jet search at low mass

Al and Katz 1712.01840

Constraining SMEFT operators

Fit to EWPO, LHC diboson and Higgs data shows where LHC bounds already compete with those from LEP



Ellis, Murphy, Sanz, You 1803.03252