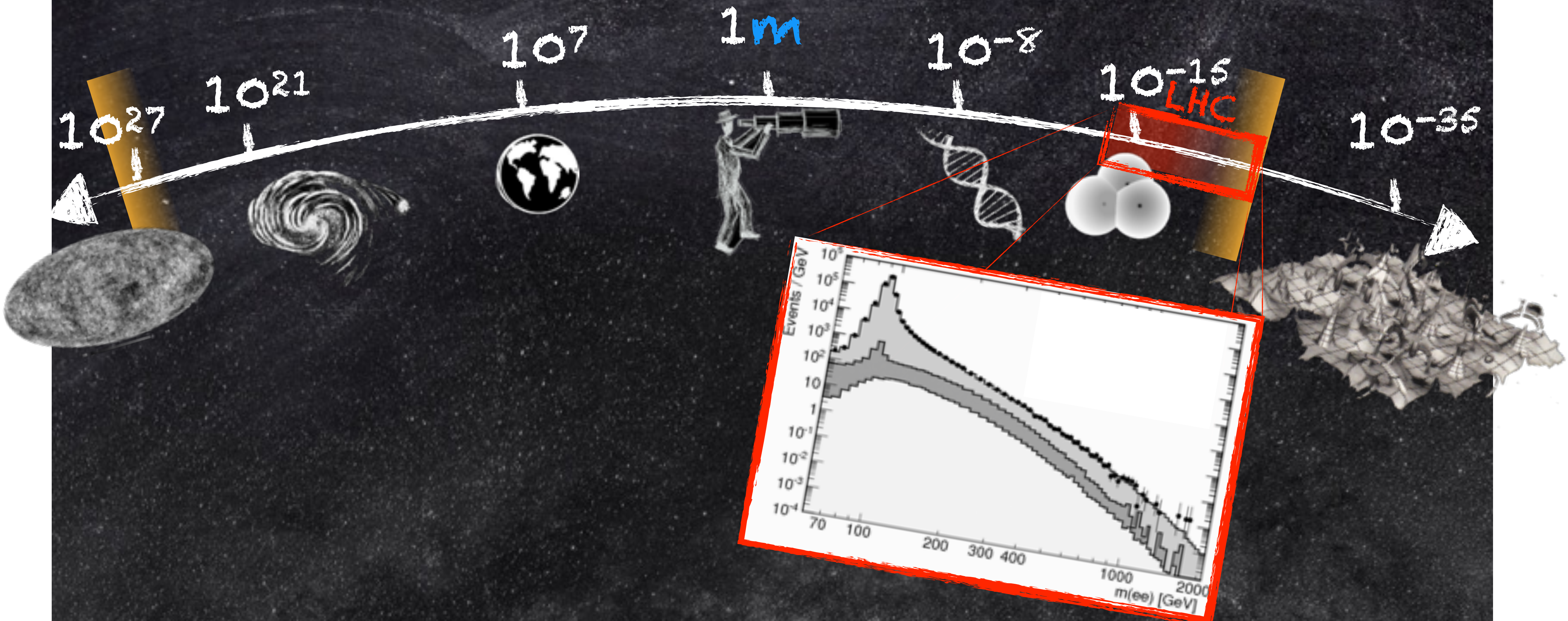
Standard Model Precision Tests: What are we searching for?

Francesco Riva
(CERN)

In collaboration with
Liu, Pomarol, Rattazzi 1603.03064,
Azatov, Contino, Machado 1607.05236
Bellazzini, Serra, Sgarlata, to appear

Standard Model Precision Tests: What are we searching for?



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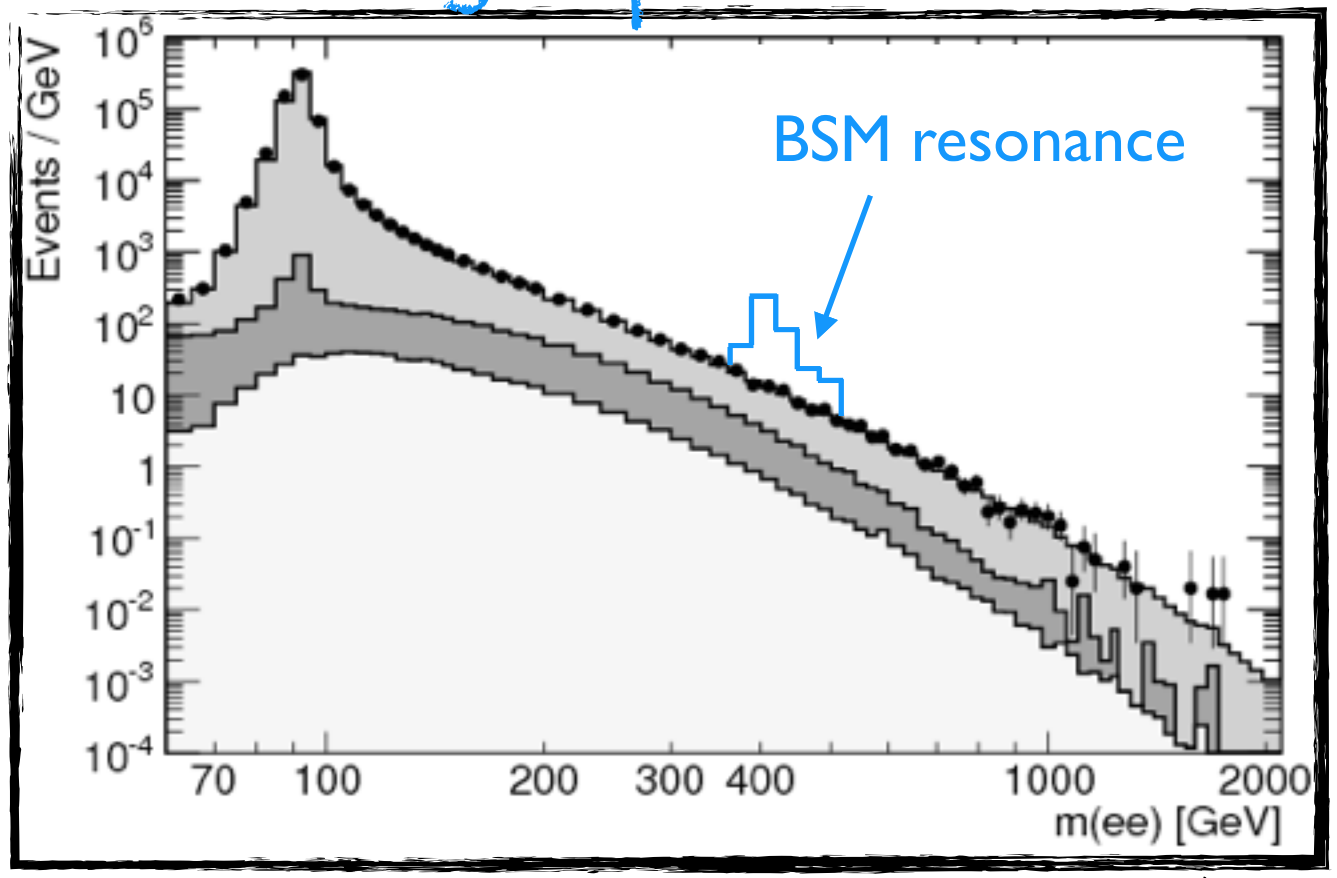
LHC Exploration
(so far 2009-2015)

Focus: Search for new light particles



Energy frontier (13 TeV)

- Experimentally: First accessible signal/Easy to study
- Theoretically: Present in many (weakly coupled) models

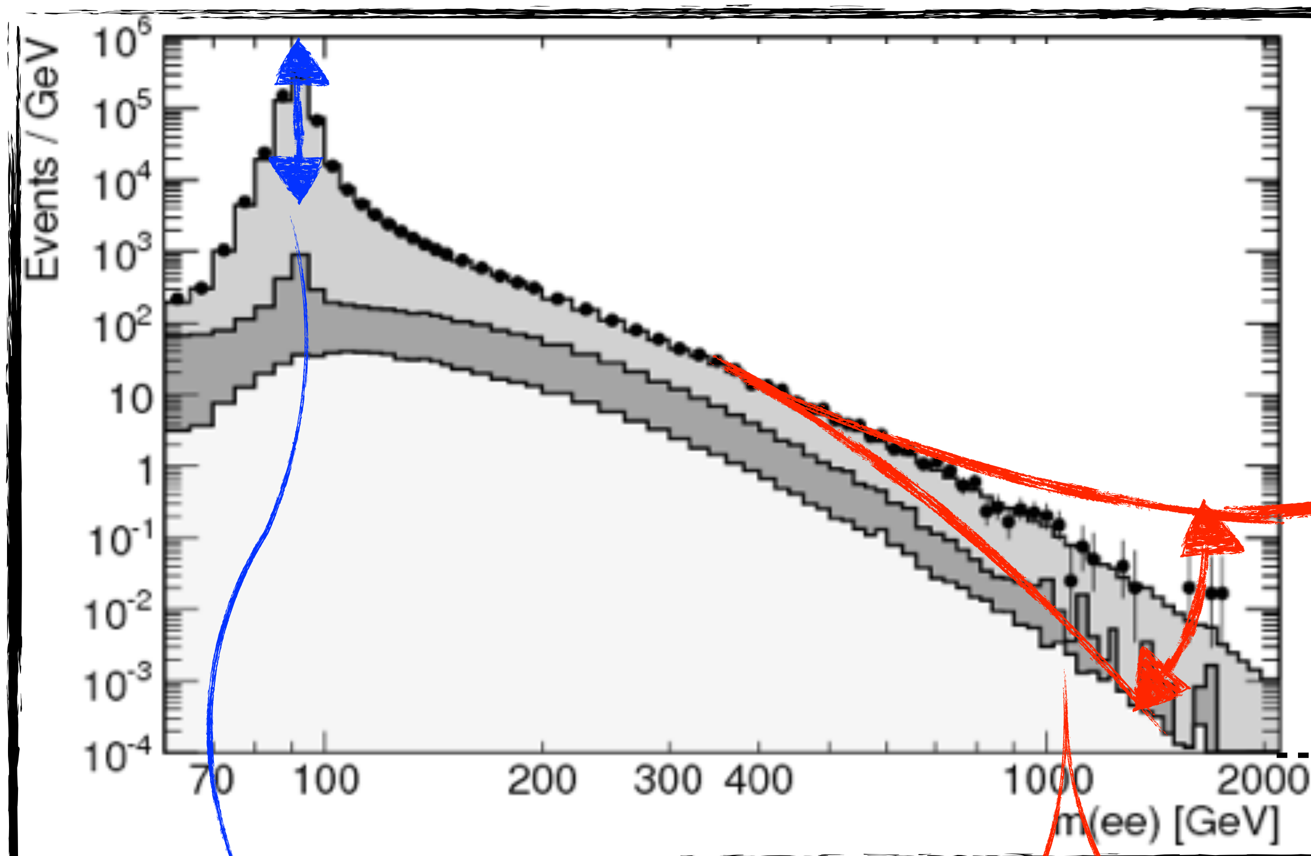
LHC Exploration
(now -> 2030's)

Focus: Standard Model Precision Tests

(2035: 3000 fb^{-1})

intensity frontier

(2016: 40 fb^{-1})



?

10-100 TeV

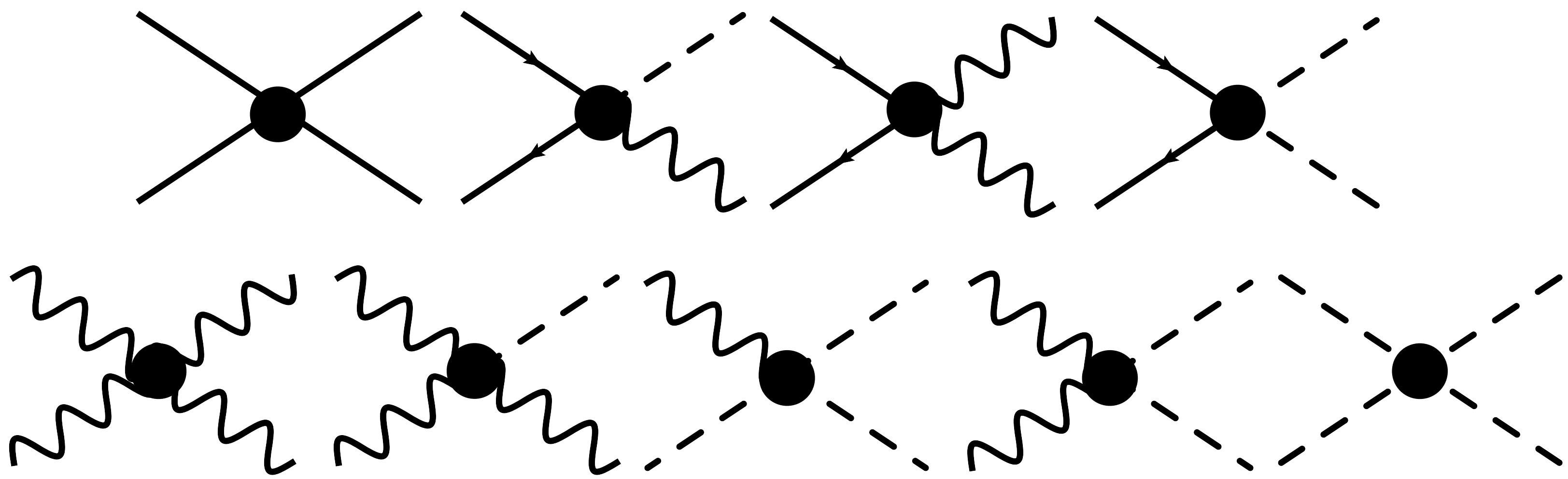
M

$$\sigma \propto \sum |Amp|^2 \simeq SM^2 (1 + c_i \frac{E^2}{M^2} + c_i^2 \frac{E^4}{M^4})$$

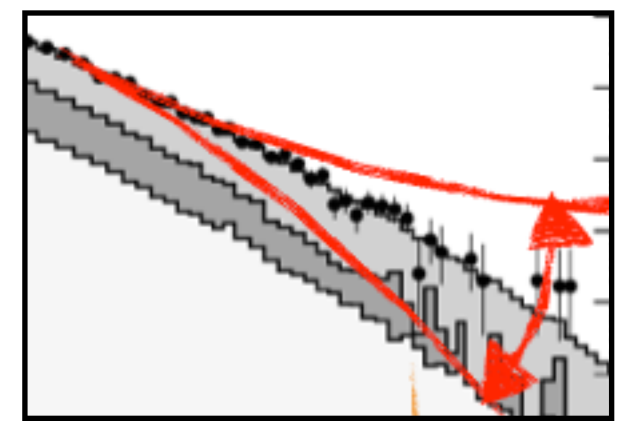
Effective Field Theory

- **Experimentally/Theoretically:** very challenging (See Caola)
- **Theoretically:** Present in many strongly coupled models

Precision Tests at High-Energy



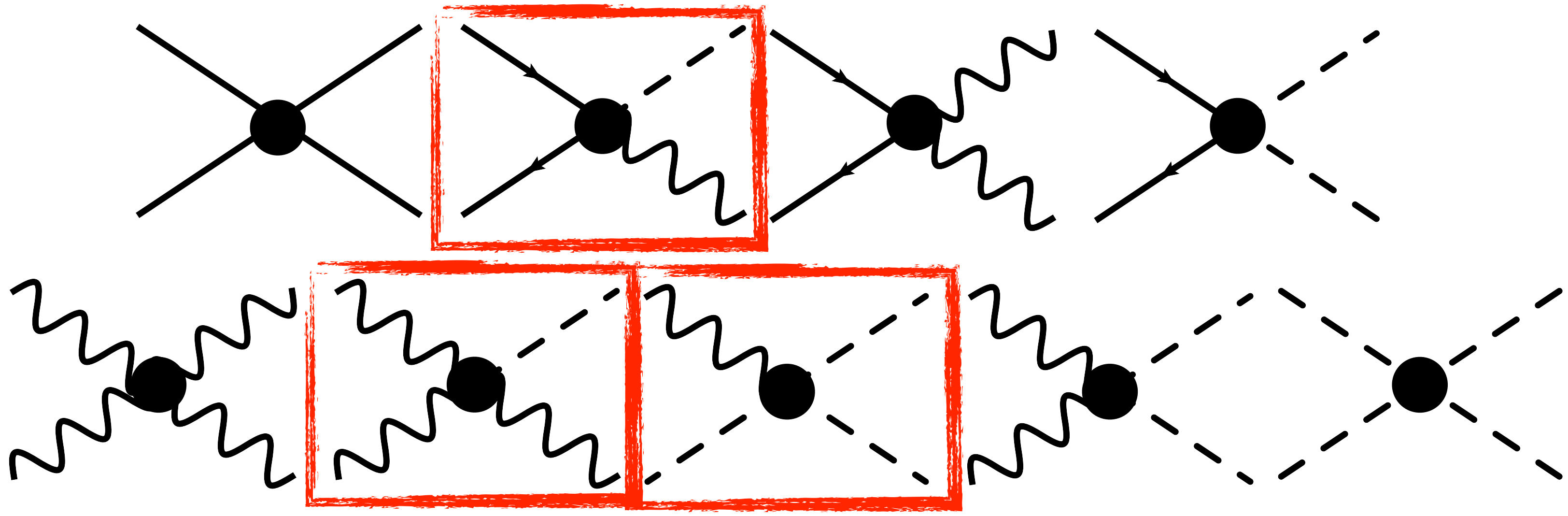
- 2>2 Processes exploit LHC High-E reach



- Each process represents an independent probe of independent New Physics...

- ...yet some are potentially better than others

Obstacles to Precision 1



The SM and D=6 Lagrangians are invariant under

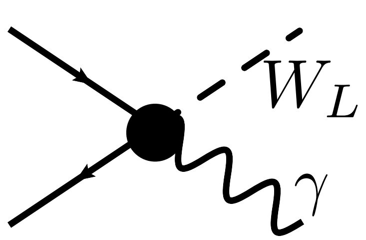
$\phi \to -\phi,$ (broken by Yukawas in SM)

- Amplitudes with an odd number of scalars suppressed by

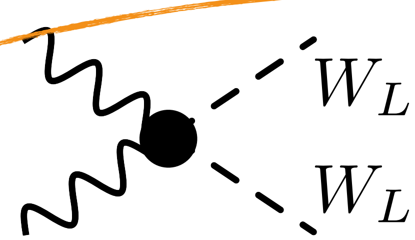
$$\frac{g_{SM}\langle\phi\rangle}{E} = \frac{m_{SM}}{E}$$ (≈0.1 for a W@800GeV)

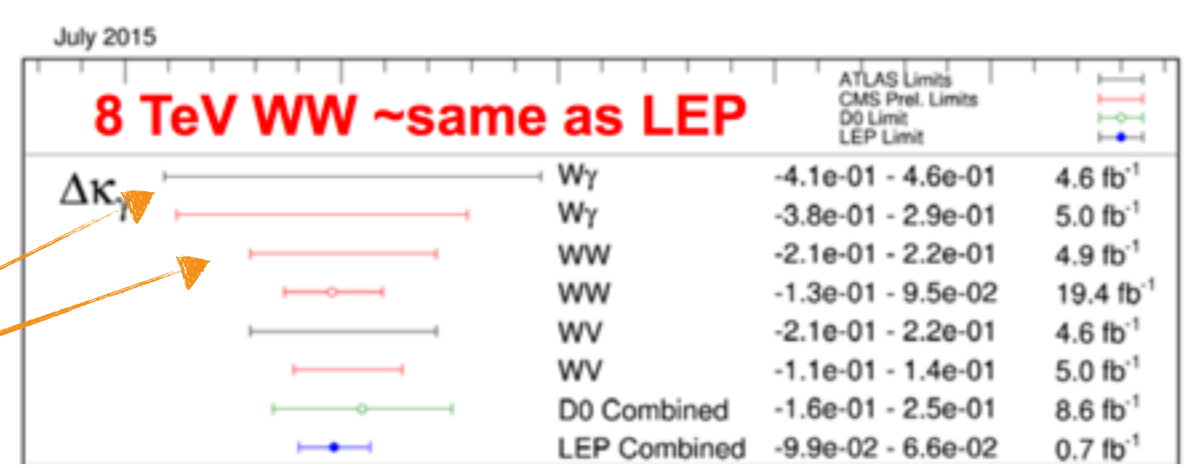
Exemple:

Anomalous TGC κ_γ modifies

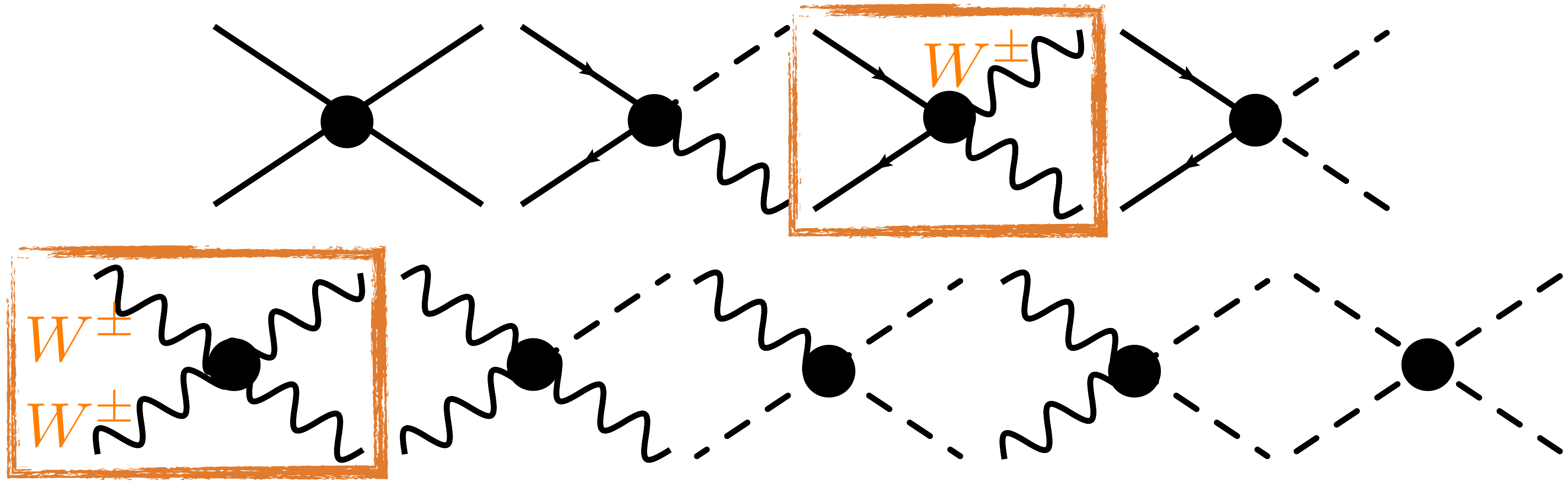


and

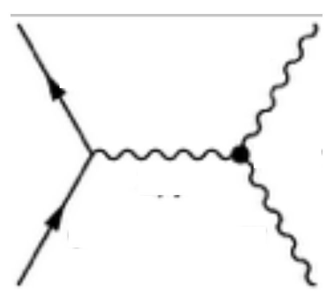


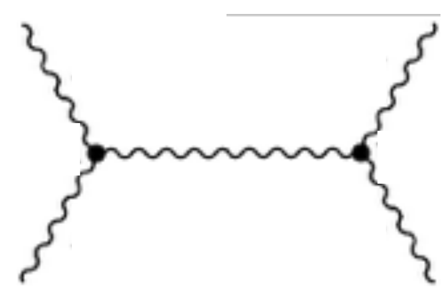


Obstacles to Precision 2



Selection rules: at dim-6 some processes not modified



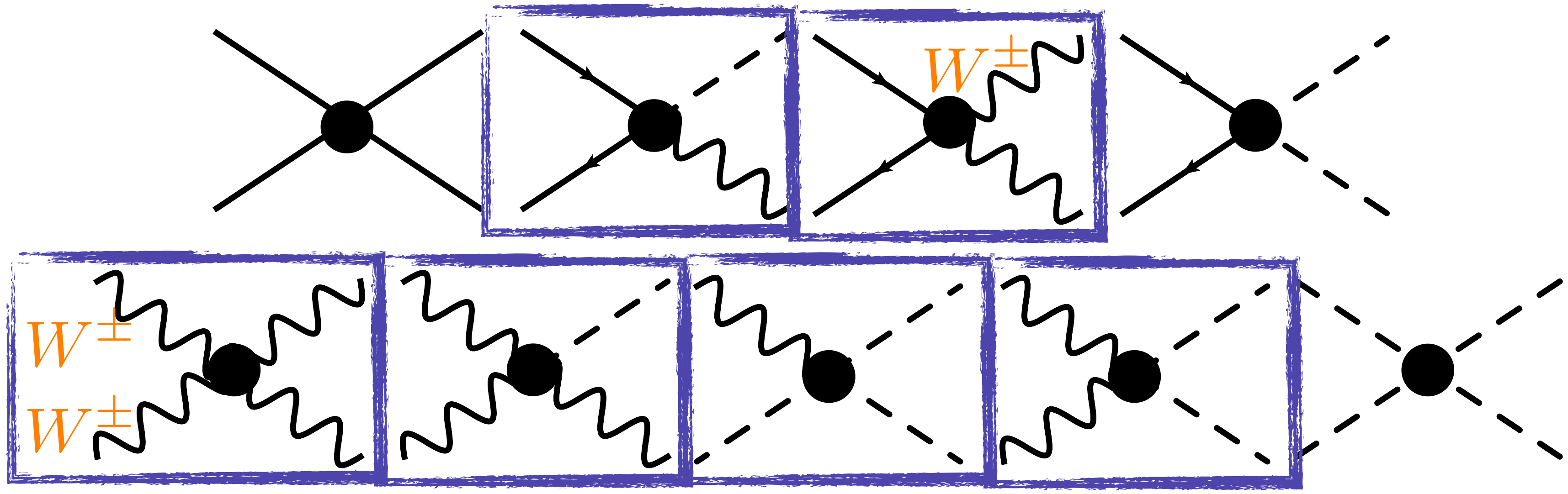


- $\psi\psi ZZ$
- $\psi\psi\gamma\gamma$
- $ZZZZ$
- $\gamma\gamma\gamma\gamma$

only at dim-8

(unfortunate: Z leptonic decays could make for precision observables)

Obstacles to Precision 3



No-Interference: At LHC, E/mW > O(10) , states have well defined helicity h

Any BSM dim-6 operator

A_4	$\lvert h(A_4^{SM})\rvert$	$\lvert h(A_4^{BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR'16

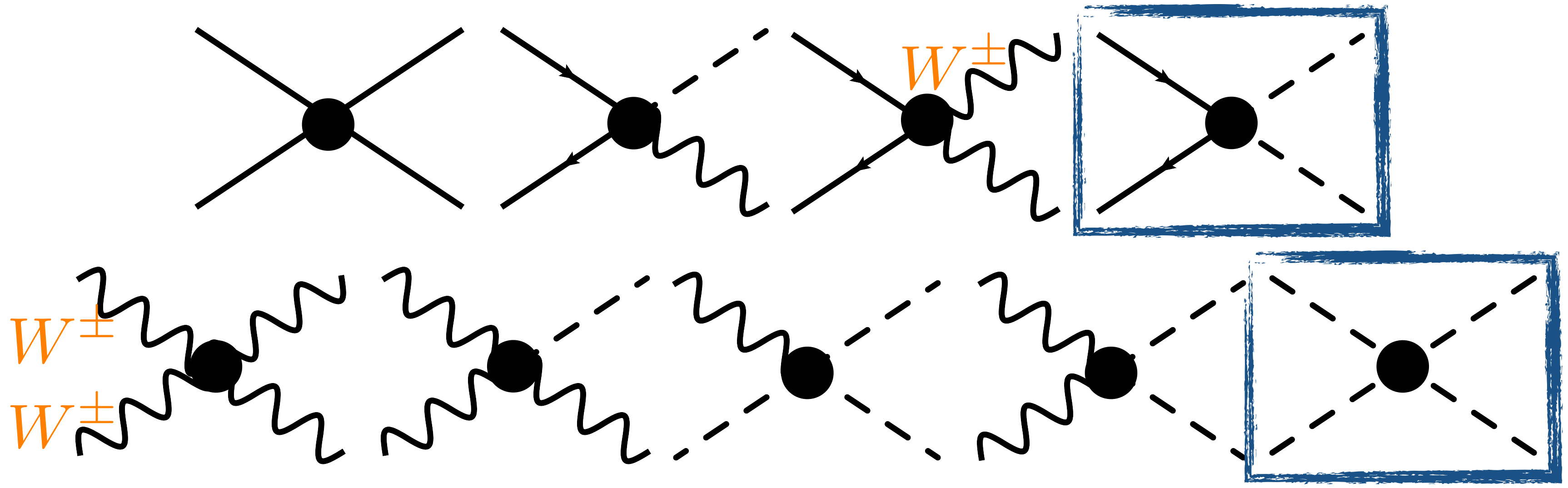
Massless limit + tree level + at least one transverse vector

- SM and BSM₆ contribute to different helicity amplitudes
- No interference

$$\sigma \propto \sum |Amp|^2 \simeq SM^2(1 + c_i \frac{E^2}{M^2} + c_i^2 \frac{E^4}{M^4})$$

- Small effects, even smaller!

Obstacles to Precision 4



Suppression in total cross-section for longitudinal component

$W_L W_L \to W_L W_L$

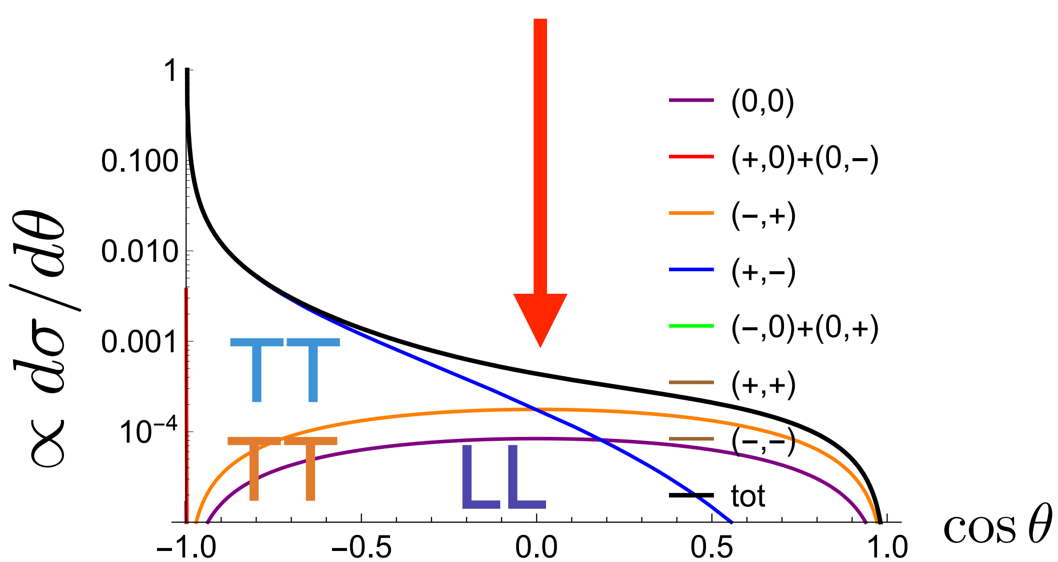
$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} = \frac{(1-a^2)^2}{2304}\frac{s^2}{M_W^4} \qquad \text{for } a \neq 1\,,$$

Contino,Grojean,Moretti,Piccinini,Rattazzi'10

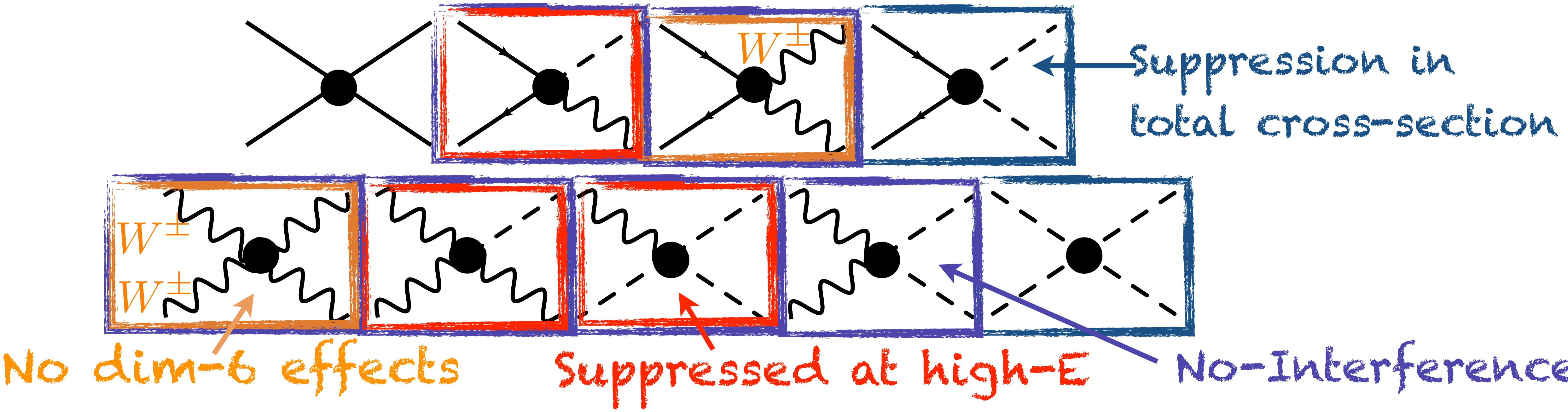
$\bar{\psi}\psi \to W_L W_L$

$$\frac{d\sigma_{LL}/d\cos\theta}{d\sigma_{TT}/d\cos\theta} = \frac{1}{72}\left(29 s_W^4 - 30 s_W^2 + 9\right) \approx 5\%$$

Franceschini,Panico,Pomarol,Rattazzi,FR,Wulzer 'soon



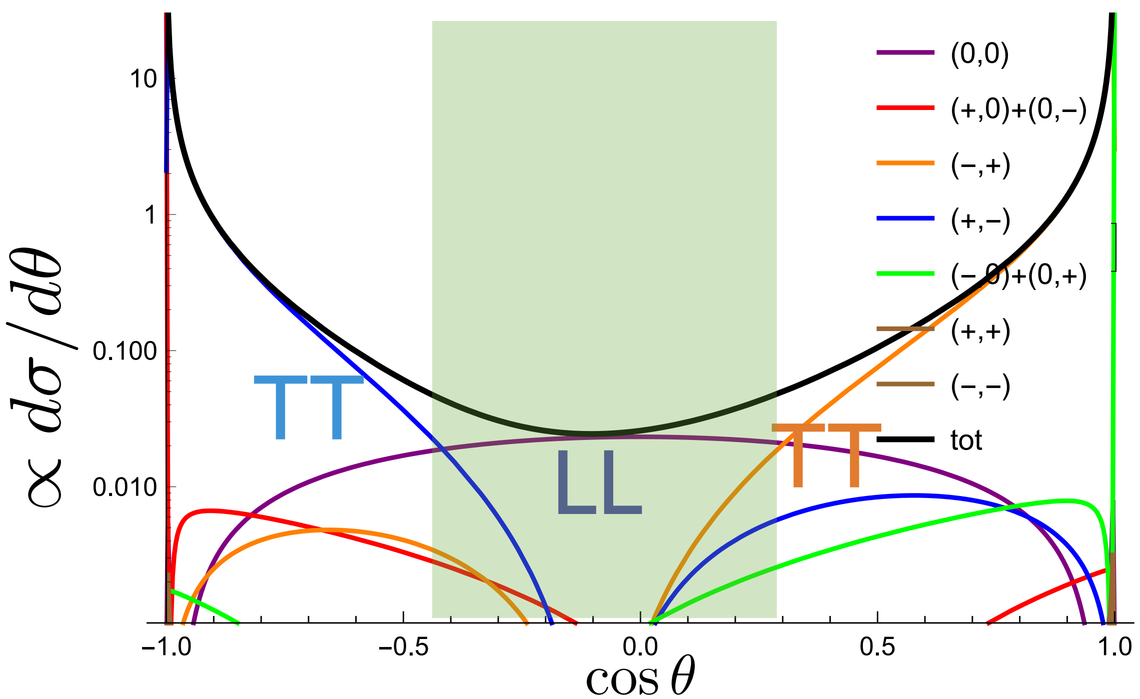
Obstacles to Precision



Ways Around?

1) Same physics (operators) in similar unsuppressed amps

- $W_L W_L \to hh$ Contino,Grojean,Moretti,Piccinini,Rattazzi'10
- $\bar{\psi}\psi \to Wh$ ...but Boosted Higgs>bb!?
- $\bar{\psi}\psi \to WZ$



$$A^{+-}(\bar{d}u \to WZ) \propto \cos\theta - \frac{\tan\theta_W}{3}$$

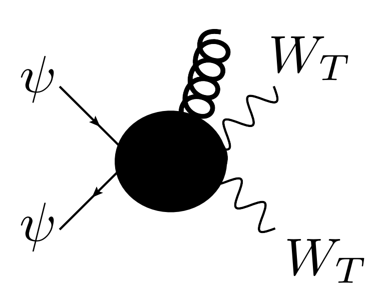
Baur,Han,Ohnemus'95

→ in central region LL dominates... but not at NLO!

Franceschini,Panico,Pomarol,Rattazzi,FR,Wulzer 'soon

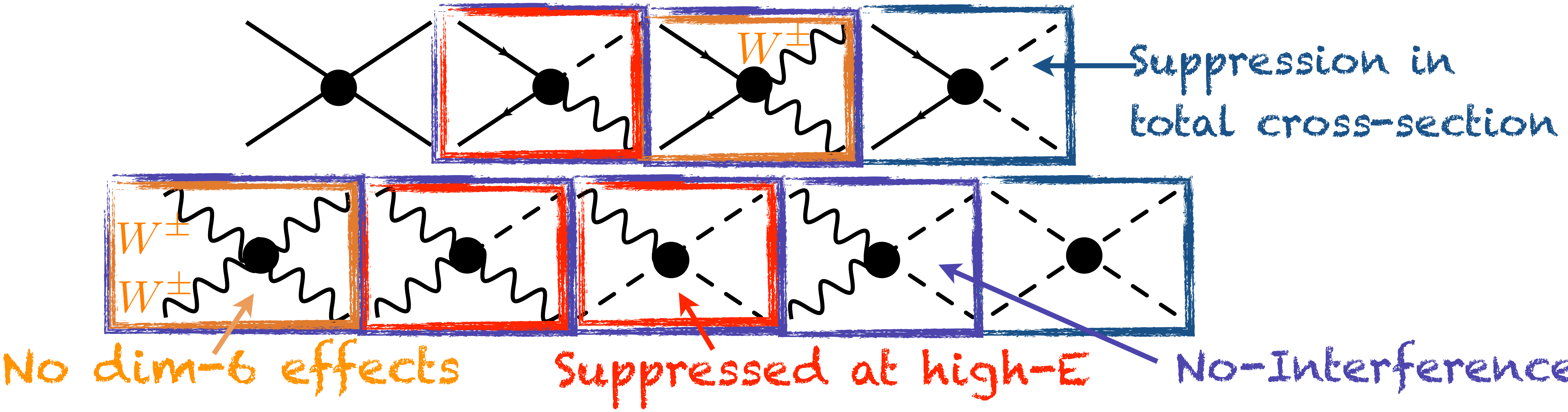
- polarization measurements?

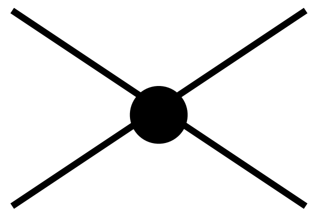
2) NLO effects do interfere



for gluons see Dixon,Shadmi'93;

Obstacles to Precision





◀ Focus on the most promising

What can we learn?

What do we WANT to learn? Power-counting

captures broad BSM hypotheses in the EFT language

▶ simplest: BSM has one scale M, one coupling g_*, symmetries

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{M^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{M^4}\mathcal{O}_j^{(8)} + \cdots$$

$$c_i^{(D)} \sim (\text{coupling})^{n_i-2}$$

n_i=number of fields in $\mathcal{O}_i^{(D)}$

operators allowed by symmetries

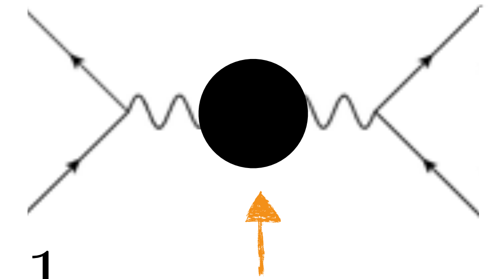
Manohar,Georgi'84; Cohen,Kaplan,Nelson'97; Luty'97; Giudice,Grojean,Pomarol,Rattazzi,'07

BSM hypothesis 1: Vectors

New physics couples to transverse vectors only

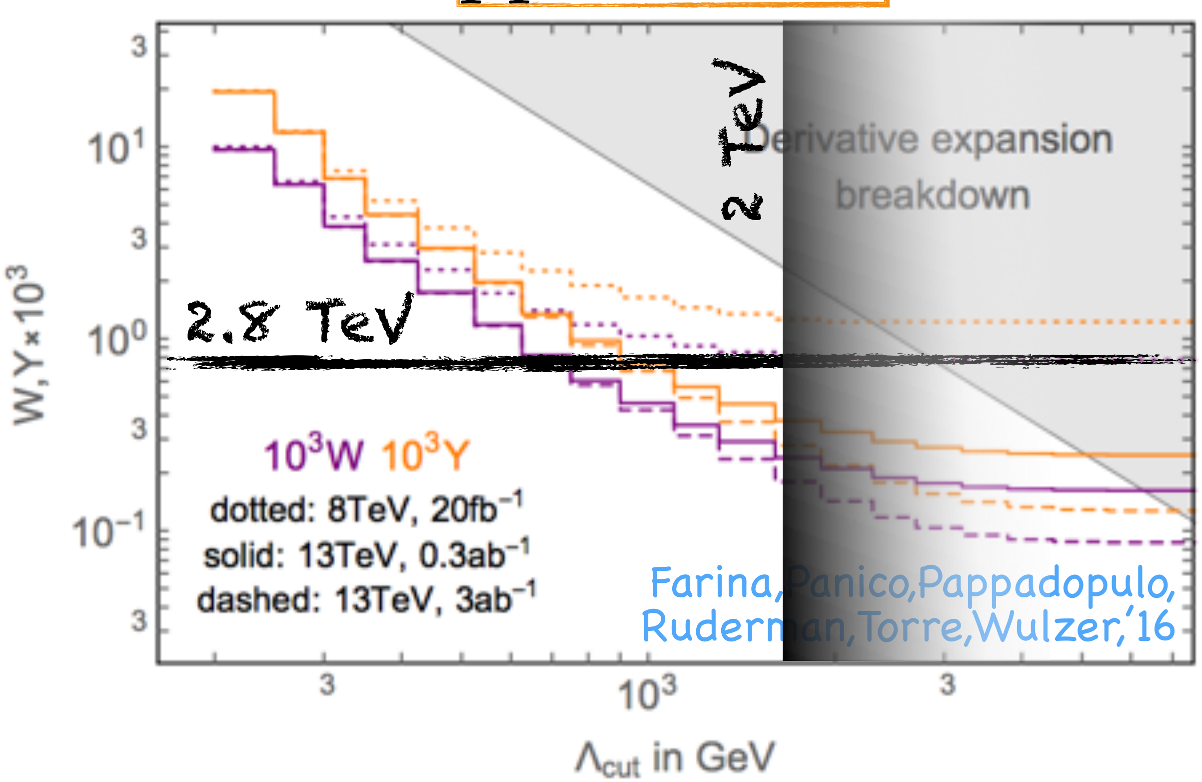
(e.g universal theories, "composite" vectors,...)

Liu,Pomarol,Rattazzi,FR'16



$$\frac{1}{M^2}(D_\rho W^{a,\nu}_\mu)^2$$

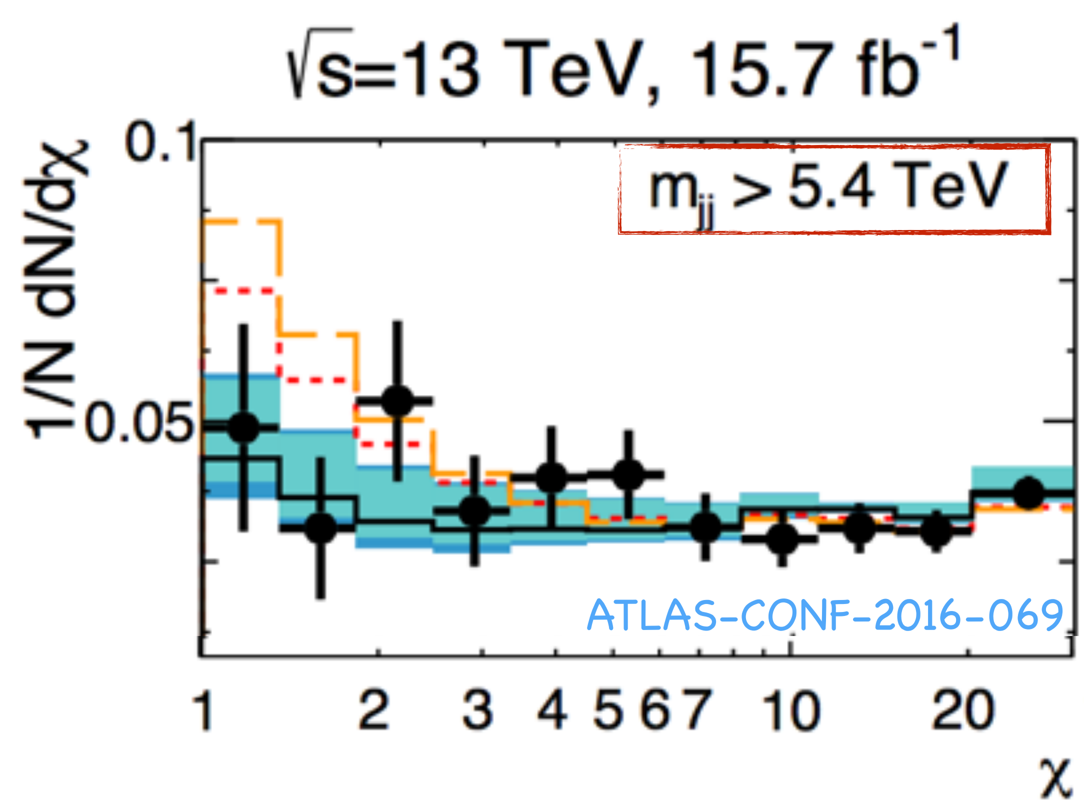
$pp \to l^+l^-$



$M \gtrsim 2.8\,\mathrm{TeV}$

Consistent with EFT

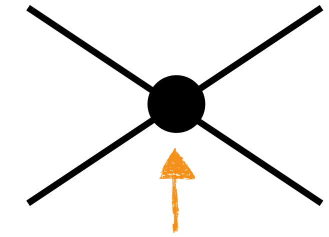
$pp \to jj$

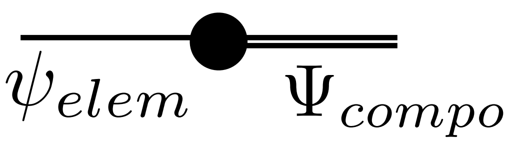


$M \gtrsim 6\,\mathrm{TeV}$

BSM hypothesis 2: Composite Fermions

New physics couples to a fermion only (e.g d_R)
(e.g fermion partial compositeness in RS)





Enhanced if BSM strongly coupled → $\frac{g_*^2}{M^2}(\bar{\psi}\gamma_\mu\psi)^2$

$g_* \lesssim 4\pi$

$pp \to jj$ $\qquad M \gtrsim 40\,\mathrm{TeV} \qquad (g_* = 4\pi)$

Beyond reach of any future direct collider...

Bellazzini,FR,Serra,Sgarlata' to appear

BSM hypothesis 3: Quarks as Pseudogoldstinos

Spontaneously broken supersymmetry: massless goldstino ψ

Shift symmetry $\delta\psi = \xi + i\frac{g_*^2}{2M^4}\partial_\mu\psi(\bar{\psi}\gamma^\mu\xi - \bar{\xi}\gamma^\mu\psi)$

(like goldstone bosons)

$$\mathcal{L}_{eff} = i\bar{\psi}^a\gamma^\mu\partial_\mu\psi^a + \frac{g_*^2}{8M^4}(\partial_\mu\bar{\psi}^a\gamma^\mu\psi^a)^2 + \cdots + \text{~~SUSY~~}$$

dimension-6 forbidden by symmetry

First interaction at dimension-8

Can the SM fermions be approximate goldstini?

- dim-4 (=SM gauge and Yukawas) ~~SUSY~~ : small, protected
- dim-6 small
- BSM first at dim-8, can be associated with large $g_* \simeq 4\pi$

$M \gtrsim 9\,\text{TeV}$ if only dR pseudogoldstino

$M \gtrsim 19\,\text{TeV}$ if all quarks pseudogoldstini

Bellazzini,FR,Serra,Sgarlata' to appear

BSM hypothesis 3: Quarks as Pseudogoldstinos

Why interesting?

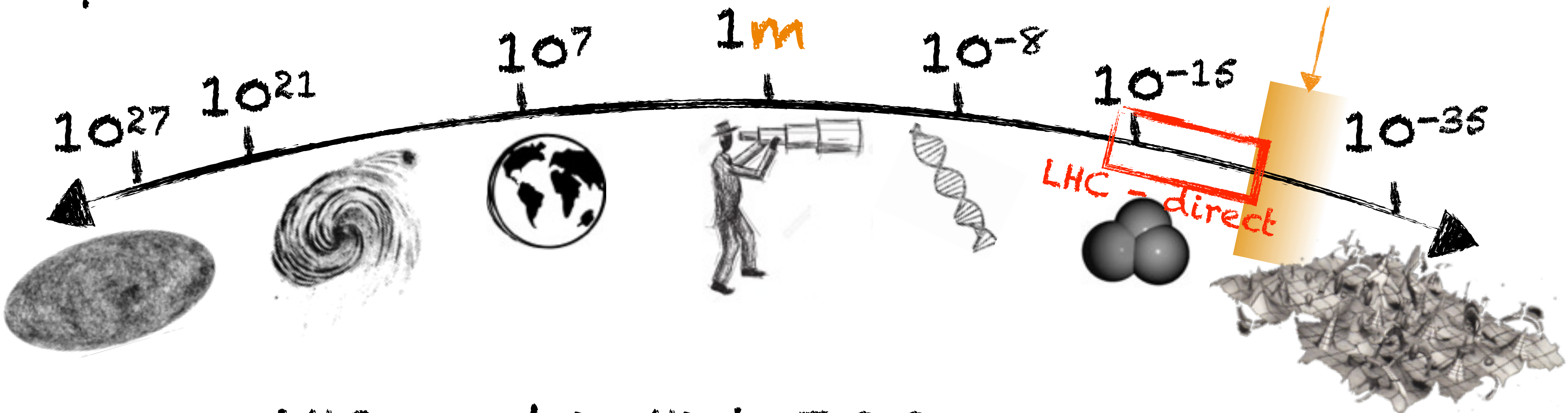
- We are used to BSM $\sim \dfrac{E^2}{M^2}$
- This is a structured scenario with "softer" interactions $\sim \dfrac{E^4}{M^4}$
- Are even softer behaviors $\sim \dfrac{E^6}{M^6}$ possible?

NO! Positivity constraints from analyticity,unitarity:
Symmetries that protect dim-10 (or higher) are never exact

Adams,Arkani-hamed,Dubovsky,Nicolis,Rattazzi'06;
Bellazzini'16;...
Bellazzini,FR,Serra,Sgarlata' to appear

Message

SM precision tests will define the new distance frontier

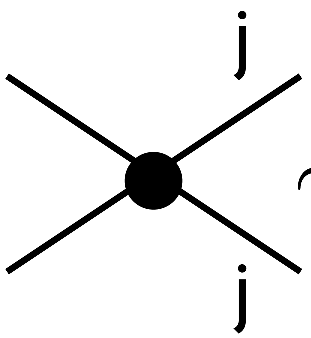


- LHC good in High-E 2>2 processes

Many challenges: non-interference, suppression in σ_{tot} ,...

- Only 4-fermion amplitudes sinn-free

Message



$\sim$

g_{SM}^2 Standard Model

$g_{SM}^2 \dfrac{E^2}{M^2}$ New physics in vectors $M \gtrsim 6\,\mathrm{TeV}$

$g_*^2 \dfrac{E^2}{M^2}$ New physics in fermions (strongly coupled/composite) $M \gtrsim 40\,\mathrm{TeV}$ $(g_* = 4\pi)$

$g_*^2 \dfrac{E^4}{M^4}$ New physics: SM fermions as pseudo-goldstini $M \gtrsim 9\,\mathrm{TeV}$ $(g_* = 4\pi)$

BSM perspective (with well-defined hypotheses) quantifies our knowledge of small distances (and of the SM)