Standard Model and open problems

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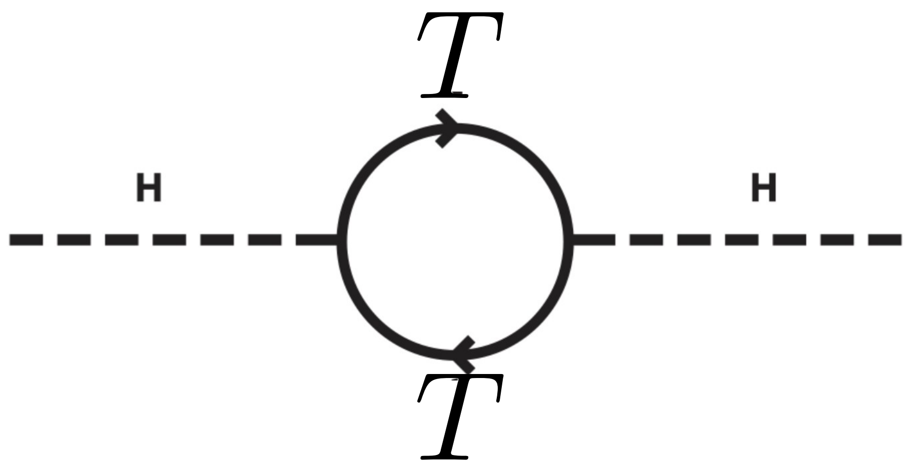
The hierarchy problem

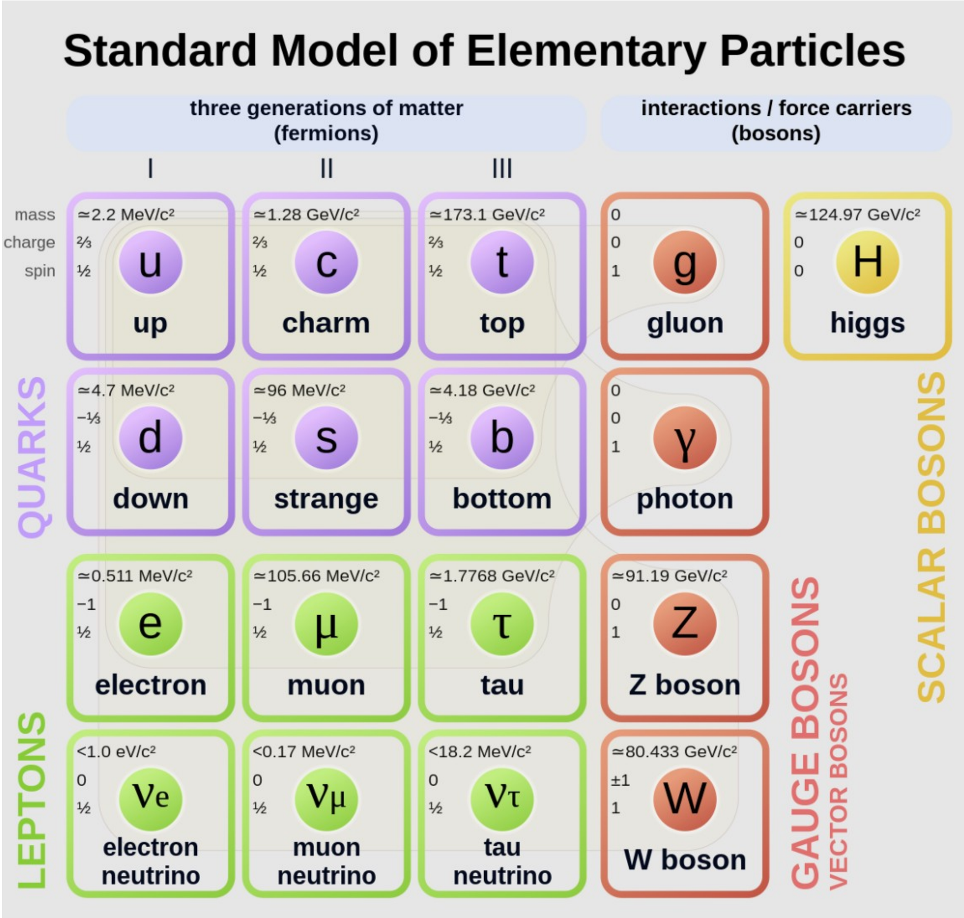


$$m_H^2 \sim m_{H^0}^2 - m_T^2$$

Supersymmetry: scalar linked with fermion (which doesn't suffer the problem)
Composite Higgs models: scalar composite of fermions (which don't suffer the problem)

Some more fundamental problem: **dark matter**

One interesting hypothesis: it is formed by **neutral weakly-interacting non-relativistic** particles



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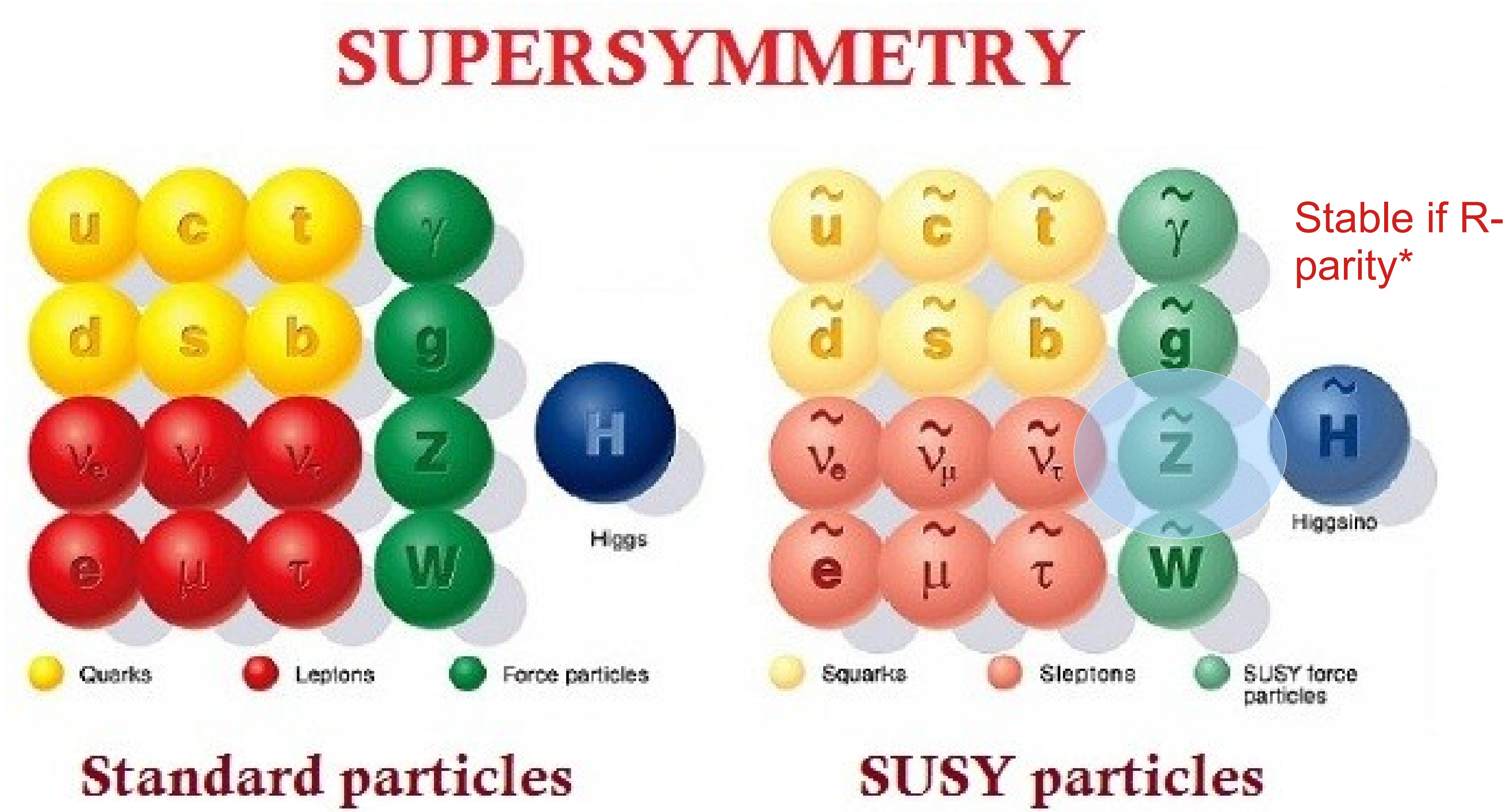


Composite Higgs models also work!

e.g. SO(6)$\rightarrow$ SO(5)

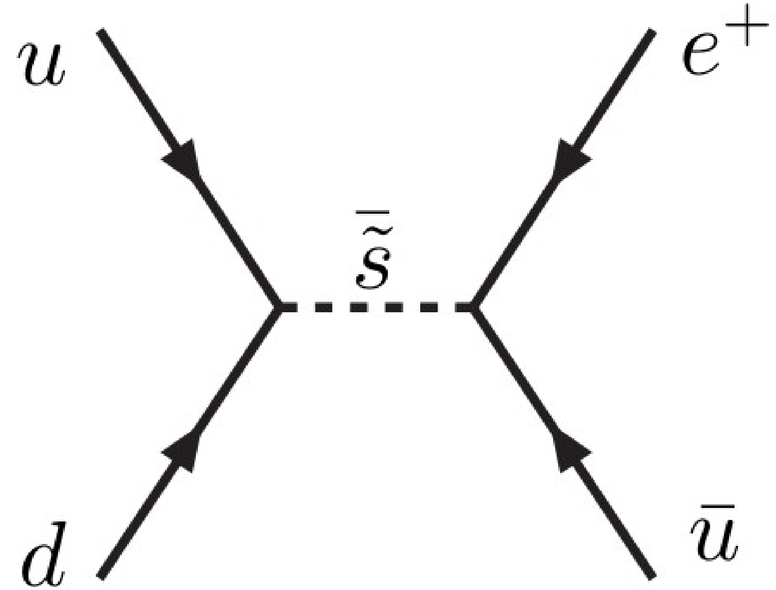
$$L = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu S)^2 - \left\{ \frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{3}\kappa S^3 + \frac{1}{4}\lambda_S S^4 + \frac{1}{3}\kappa_{hS} h^2 S + \frac{1}{4}\lambda_{hS} h^2 S^2 \right\}$$

A comparison with R-parity in SUSY

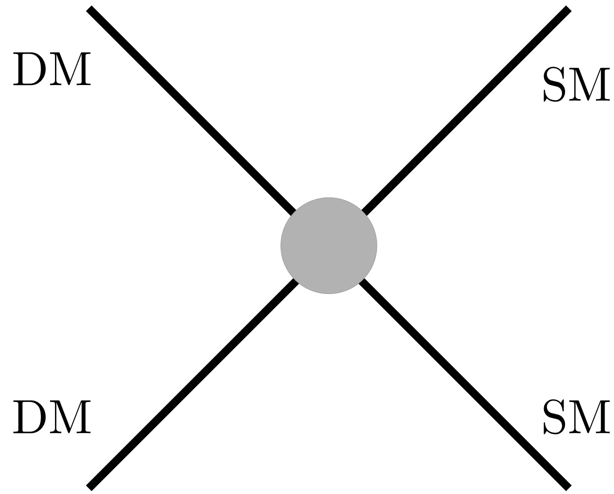
(motivation relies *also* on dark matter)

Avoiding proton decay

- Baryon parity
- Lepton parity
- Many others, see *e.g.* Smirnov and Visani, *9601387*. None preferred by GUT



The beauty of dark matter within composite Higgs models



$$L \sim (\partial_\mu S^2)(\partial^\mu |H|^2) \Rightarrow \mathcal{M} \sim p^2$$

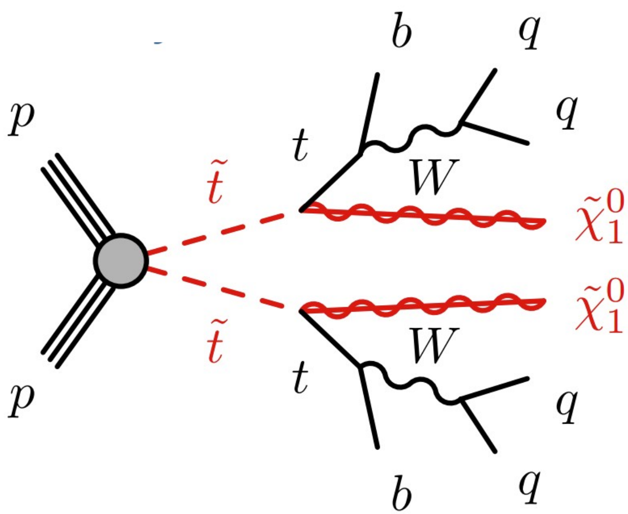
$$p^2 \sim m_S^2$$

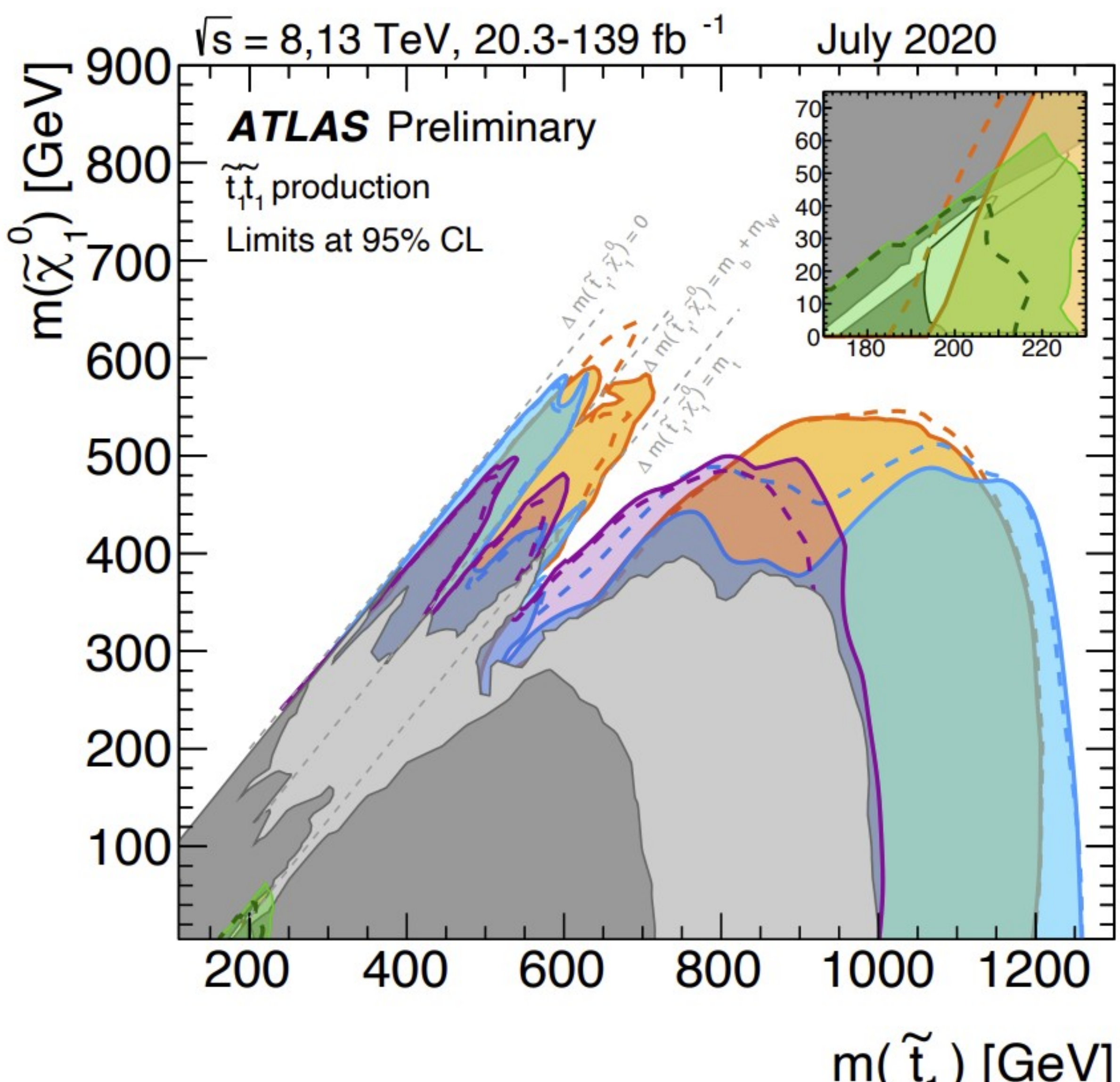
At annihilation scale

$$p^2 \sim p^2_{\text{transferred}} \sim v^2$$

At direct detection experiment scale

Signals and status of SUSY and CHMs:





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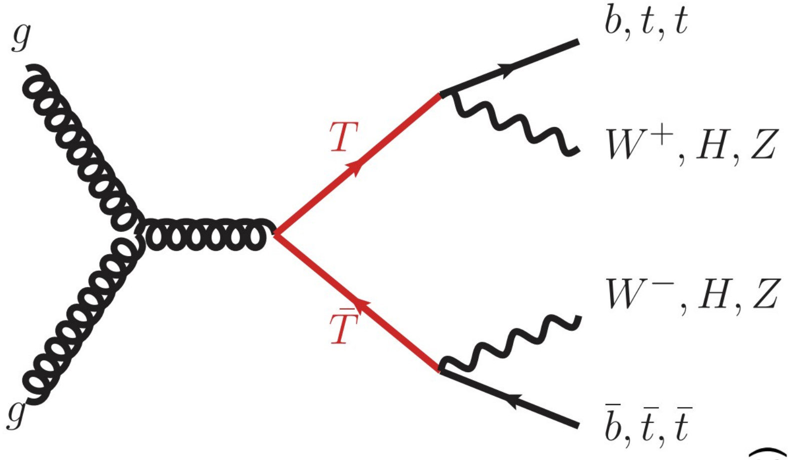
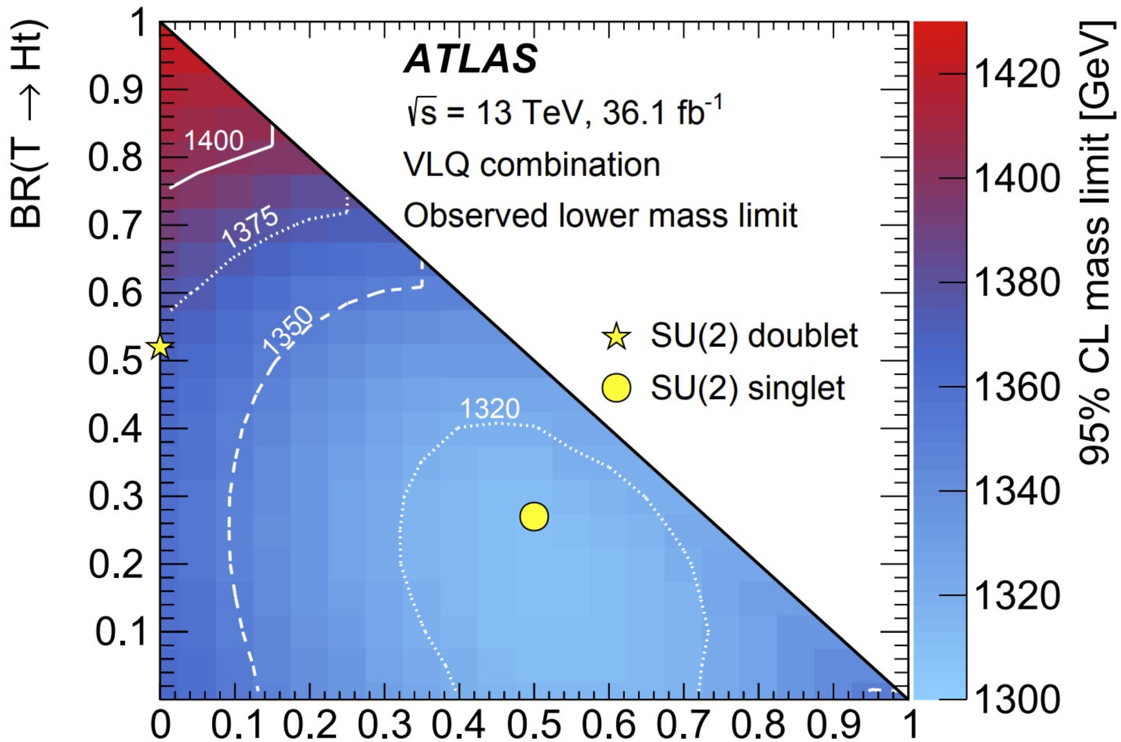
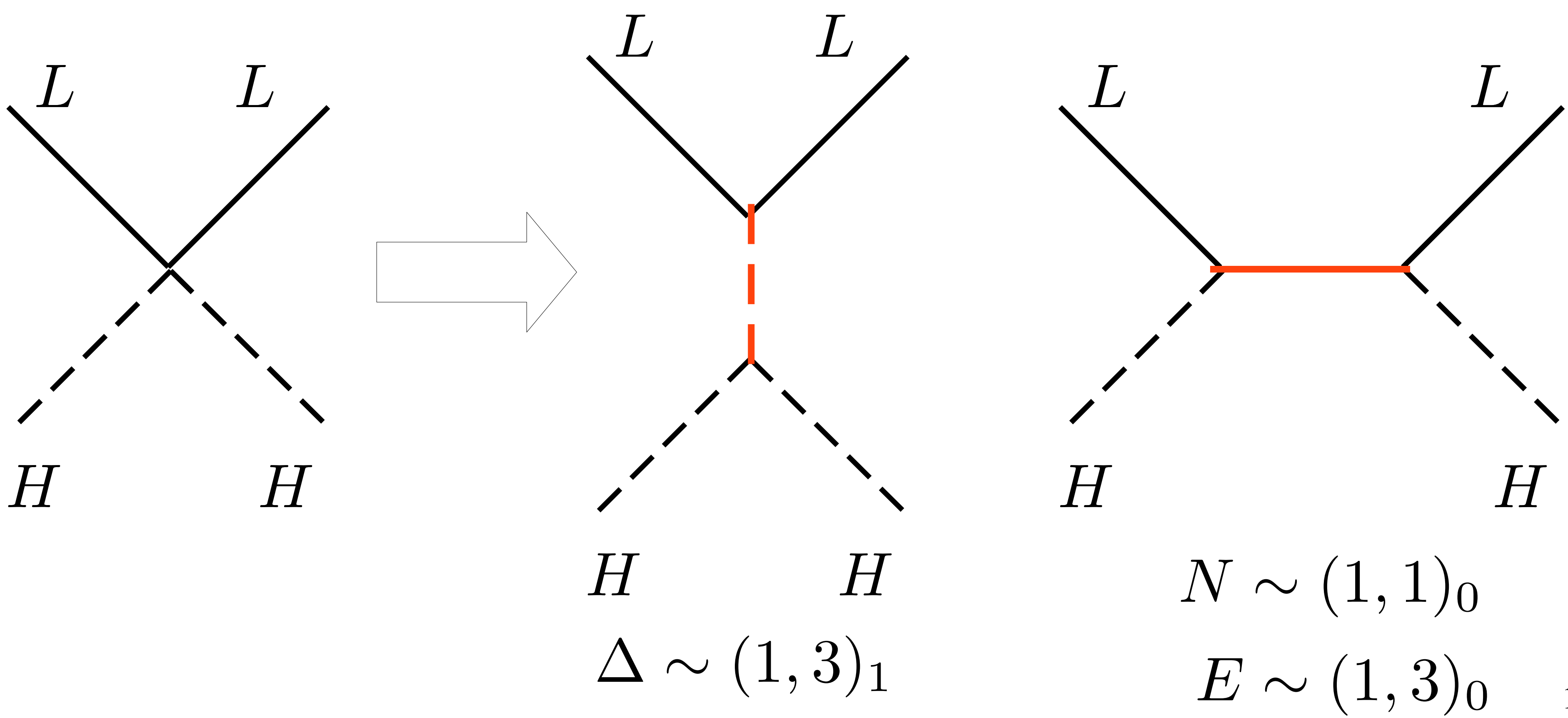




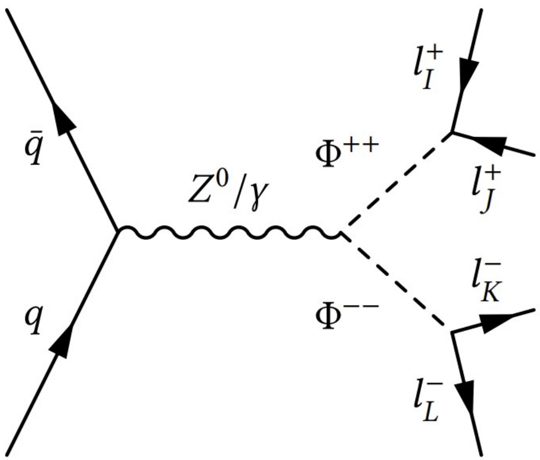
Neutrino masses

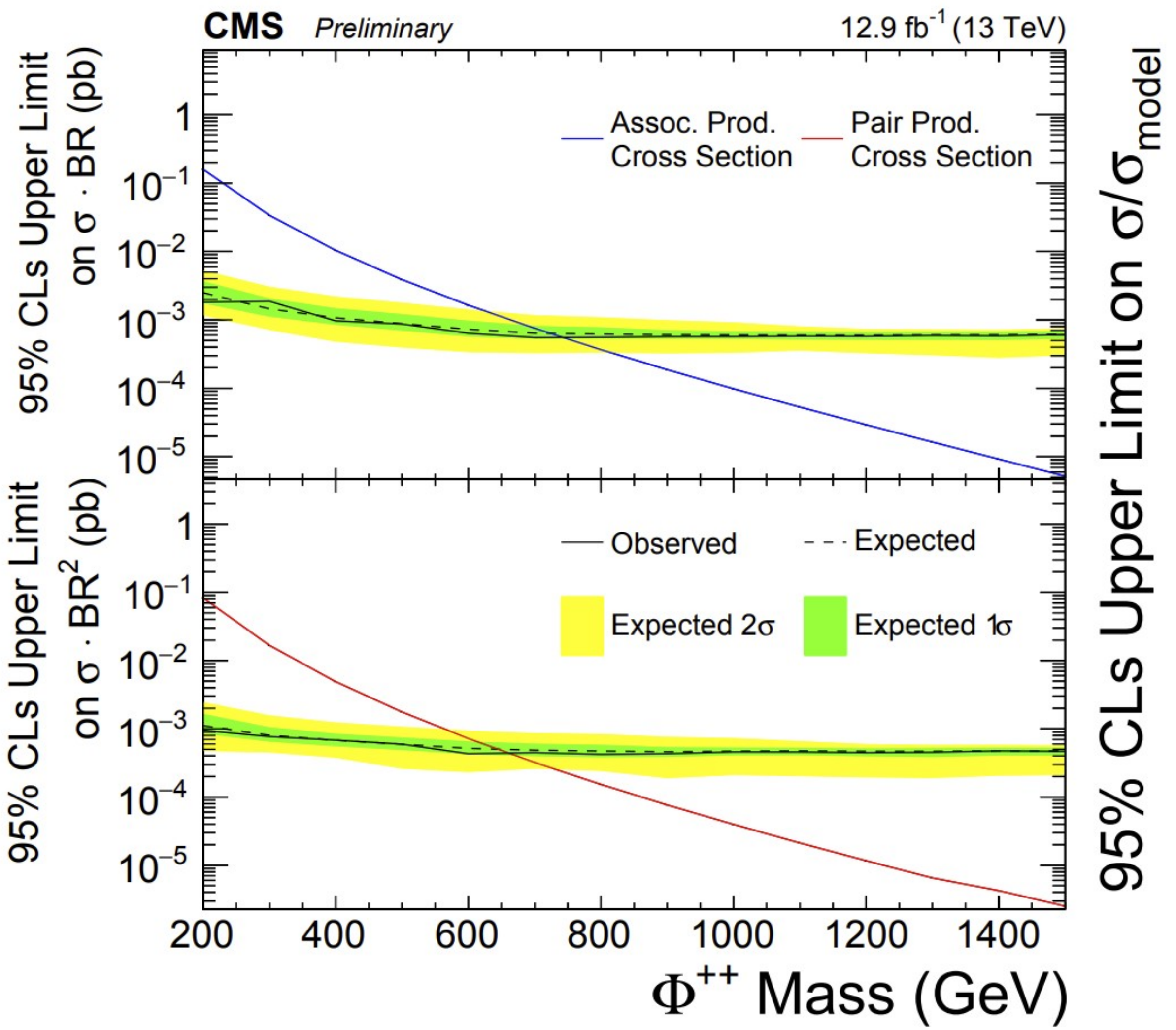
They can arise at dimension-5. How can this be completed in the UV? $\mathcal{O}^{(5)} = (\overline{L_L^c}\tilde{\phi}^*)(\tilde{\phi}^\dagger L_L)$ *



Neutrino masses

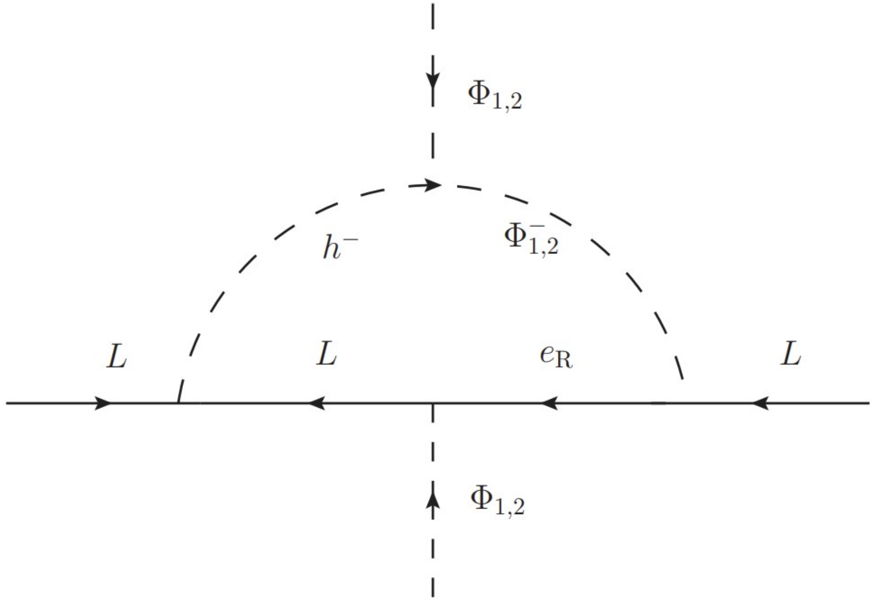
Searches at the LHC



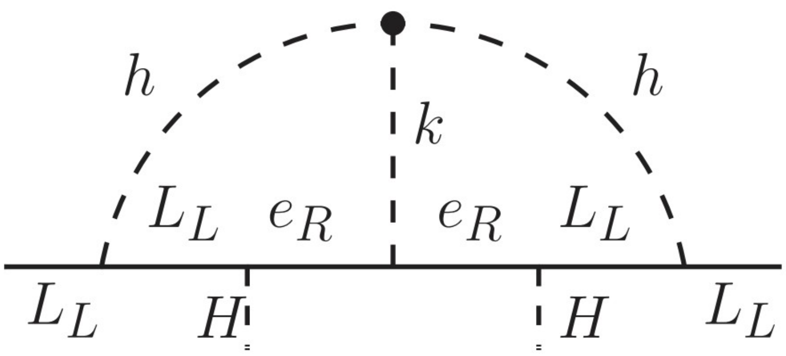


Neutrino masses

Low-mass models?



Zee model
[picture from
[1701.05345]



Zee-Babu model
[picture from
[1710.05885]

Other (potential) problems of the SM:

* g-2, flavour anomalies, ... *

* Why three generations?
* Why charge is quantised?

* How to make computations without using Lagrangians/fields? What do we learn from that?

Why should I care about not using Lagrangians/fields?

Much **easier** to learn than Lagrangian physics (not so powerful yet, though)

Make use only of **observable** quantities

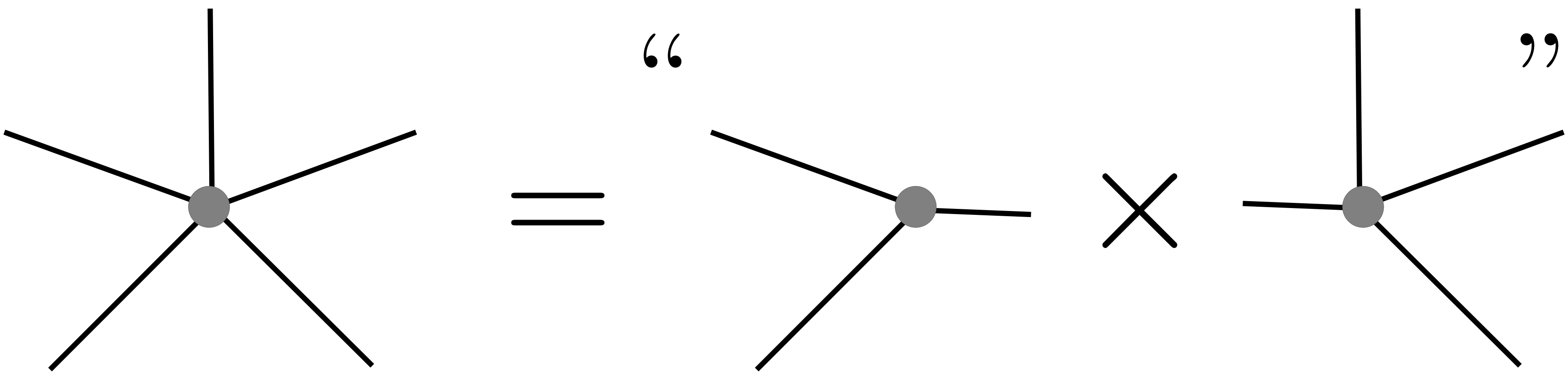
Much better **understanding** of what is fundamental and what is auxiliary

Infinitely easier to apply to high-spin particles: quantum **gravity**!

Sooner or later, the **standard** approach to particle physics

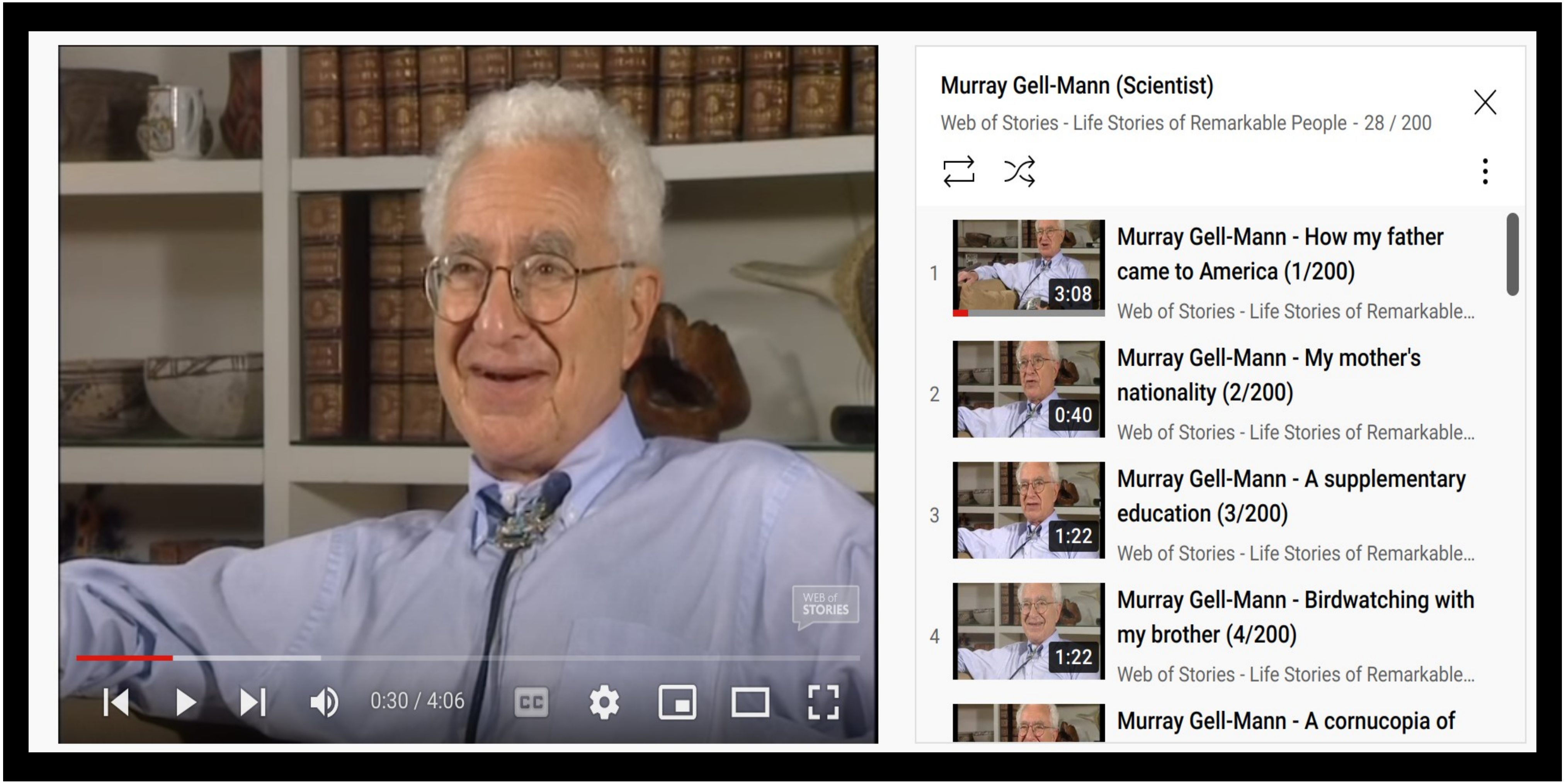
The goal: computing amplitudes without using fields/Lagrangians (for **massless** particles)

Strategy:



And 3-point amplitudes are completely determined by quantum mechanics and special relativity

Find the correct notation



Find the correct notation: spinor-helicity variables

$$p = (p^0, \vec{p}) \qquad P = p_\mu \sigma^\mu = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$$

$$\det P = 0 \Rightarrow P = \left(\quad \right) \left(\right)$$

$$p\rangle \qquad [p$$

*

$$\langle p_i p_j \rangle \equiv \langle ij \rangle = \left(\quad \right) \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \left(\right)$$

$$[p_i p_j] \equiv [ij] = \left(\quad \right) \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \left(\right)$$

Find the correct notation: spinor-helicity variables

$$p = (p^0, \vec{p}) \qquad P = p_\mu \sigma^\mu = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$$

$$\langle ij \rangle = -\langle ji \rangle$$

$$[ij] = -[ji]$$

$$[p_i p_j] \equiv [ij] = \left(\qquad \right) \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \left(\right)$$

Find the correct notation

The magic: all sensible quantities appearing in an amplitude can be written simply as products of **angles** and **brackets**, e.g.:

$$s_{ij} = (p_i + p_j)^2 = \langle ij \rangle [ij]$$

$$(\overline{u_1} \gamma^\mu P_R u_2)(\overline{u_3} \gamma_\mu P_R u_4) = 2\langle 13 \rangle [42]$$

Main result

An amplitude can be written simply as a linear combination of products of **angles** and **brackets**:

$$\mathcal{M}(1,2,\cdots,4) = \sum_i \langle 12\rangle^{a_i} \langle 13\rangle^{b_i} \cdots [34]^{c_i} \cdots$$

Little-group scaling:

$$\#[i] - \#\langle i\rangle = 2h_i$$

*

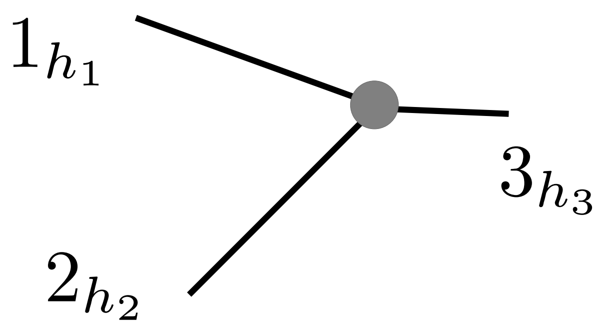
Locality + unitarity (only single poles!):

$$\text{residue}(M, \text{pole} = s, t, u) = \mathcal{M}' \times \mathcal{M}''$$

*

3-point amplitudes are fixed

3-point amplitudes are products of only brackets or only angles, e.g.:



$$\mathcal{M} = [12]^a [23]^b [31]^c$$

$$a = h_1 + h_2 - h_3$$

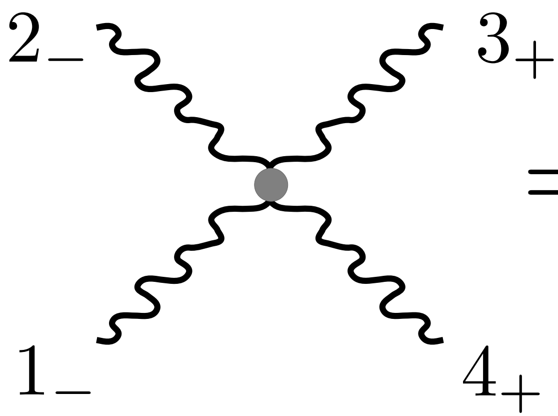
$$b = h_2 + h_3 - h_1$$

*

$$c = h_1 + h_3 - h_2$$

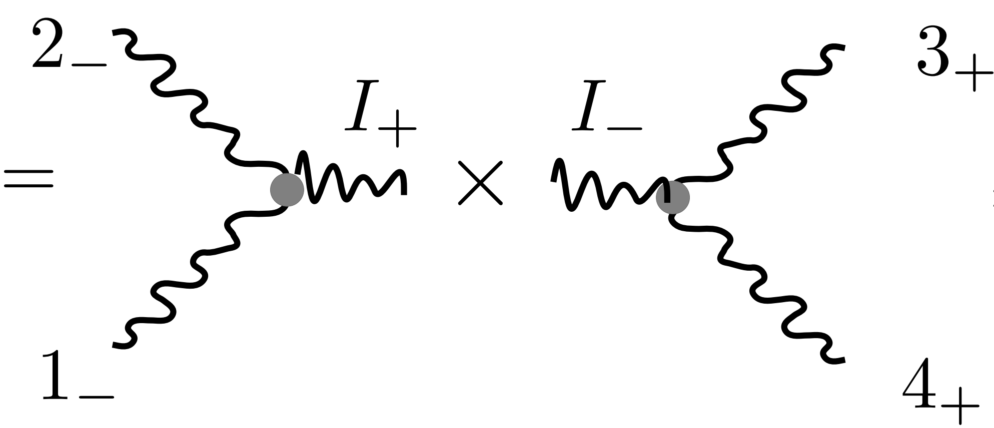
4-point amplitudes: factorisation

Let's focus on scattering of (isolated) spin-1 bosons



$$= \langle\ \rangle [\ ] \cdots \times \mathcal{F}(s, t, u)$$

$r_s =$



$$= g^2 \frac{\langle 12 \rangle^3}{\langle 2I \rangle \langle I1 \rangle} \frac{[34]^3}{[I3][4I]}$$ *

4-point amplitudes: factorisation

Let's focus on scattering of (isolated) spin-1 bosons

$$r_s = g^2 \frac{\langle 12 \rangle^2 [34]^2}{u}$$

$$r_t = g^2 \frac{\langle 12 \rangle^2 [34]^2}{s}$$

Notice little-group scaling

$$r_u = g^2 \frac{\langle 12 \rangle^2 [34]^2}{t}$$

4-point amplitudes: factorisation

Let's focus on scattering of (isolated) spin-1 bosons

$$r_s = \frac{\langle 12\rangle^2[34]^2}{u}$$

$$r_t = \frac{\langle 12\rangle^2[34]^2}{s}$$

$$r_u = \frac{\langle 12\rangle^2[34]^2}{t}$$

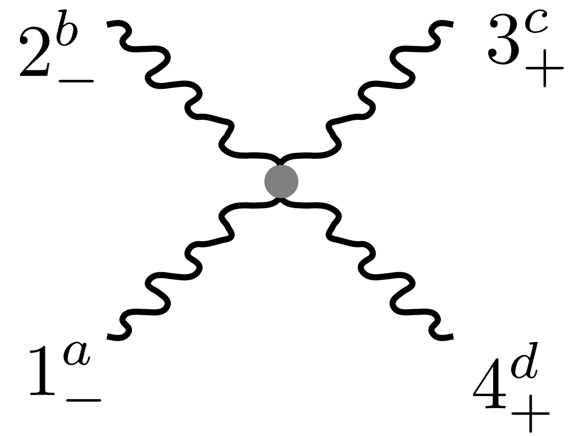
$$\mathcal{M} = \langle 12\rangle^2[34]^2\left(\frac{A}{s}+\frac{B}{t}+\frac{C}{u}\right)$$ X

$$\mathcal{M} = \langle 12\rangle^2[34]^2\frac{A}{stu}$$ X

$$\mathcal{M} = \langle 12\rangle^2[34]^2\left(\frac{A}{st}+\frac{B}{tu}+\frac{C}{su}\right)$$?

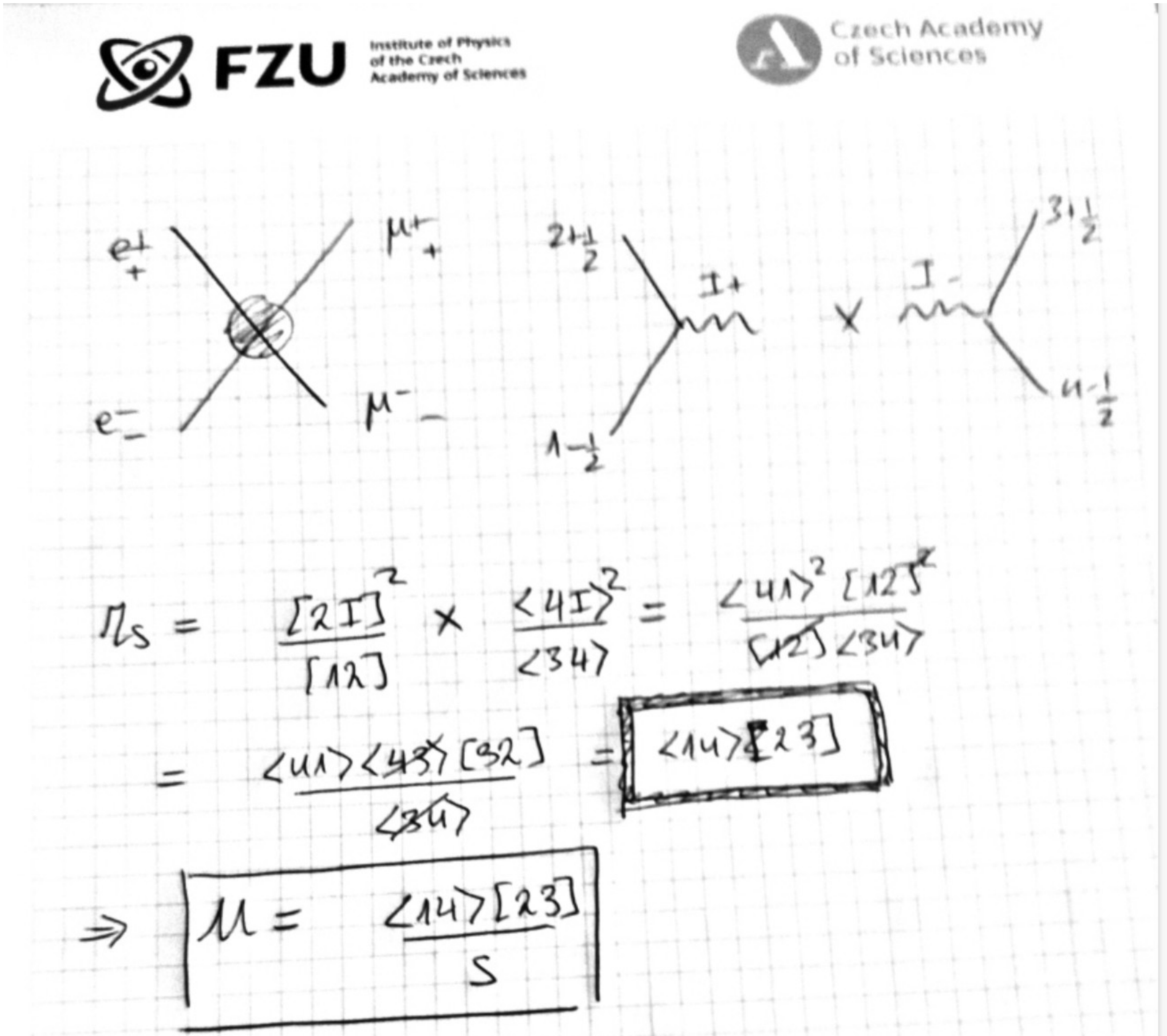
$$C - A = -1$$
$$A - B = -1$$
$$B - C = -1$$
X

What about family of spin-1 particles?



$$f_{abe}f_{ecd} + f_{ace}f_{bce} + f_{bde}f_{ace} = 0$$

e+ e- to mu+ mu-


FZU
Institute of Physics of the Czech Academy of Sciences
Czech Academy of Sciences
e^+_+
e^-_-
μ^+_+
μ^-_-
$2^{+\frac{1}{2}}$
$1^{-\frac{1}{2}}$
I^+
I^-
$3^{+\frac{1}{2}}$
$4^{-\frac{1}{2}}$
$M_s = \frac{[2I]^2}{[12]} \times \frac{\langle 4I \rangle^2}{\langle 34 \rangle} = \frac{\langle 41 \rangle^2 [12]^2}{[12] \langle 34 \rangle}$
$= \frac{\langle 41 \rangle \langle 43 \rangle [32]}{\langle 34 \rangle} = \langle 14 \rangle [23]$
$\Rightarrow \mathcal{M} = \frac{\langle 14 \rangle [23]}{s}$

Gravity

Let's focus on scattering of (isolated) spin-2 bosons

$$r_s = \frac{\langle 12\rangle^4[34]^4}{ut}$$

$$r_t = \cdots$$

$$r_u = \cdots$$

$$\mathcal{M} = \langle 12\rangle^4[34]^4\left(\frac{A}{s}+\frac{B}{t}+\frac{C}{u}\right)$$ X

$$\mathcal{M} = \langle 12\rangle^4[34]^4\left(\frac{A}{st}+\frac{B}{tu}+\frac{C}{su}\right)$$ X

$$\mathcal{M} = \langle 12\rangle^2[34]^2\frac{A}{stu}$$ V

Current knowledge based on this method

(Isolated) spin-1 particles must be non-interacting

Yang-Mills is the only consistent theory for gluons

Graviton couples universally to all particles

There can be only one type of graviton

Particles of spin larger than 2 must be non-interacting

If there exists at least one particle with spin $3/2$, then there is supersymmetry

Current knowledge based on this method

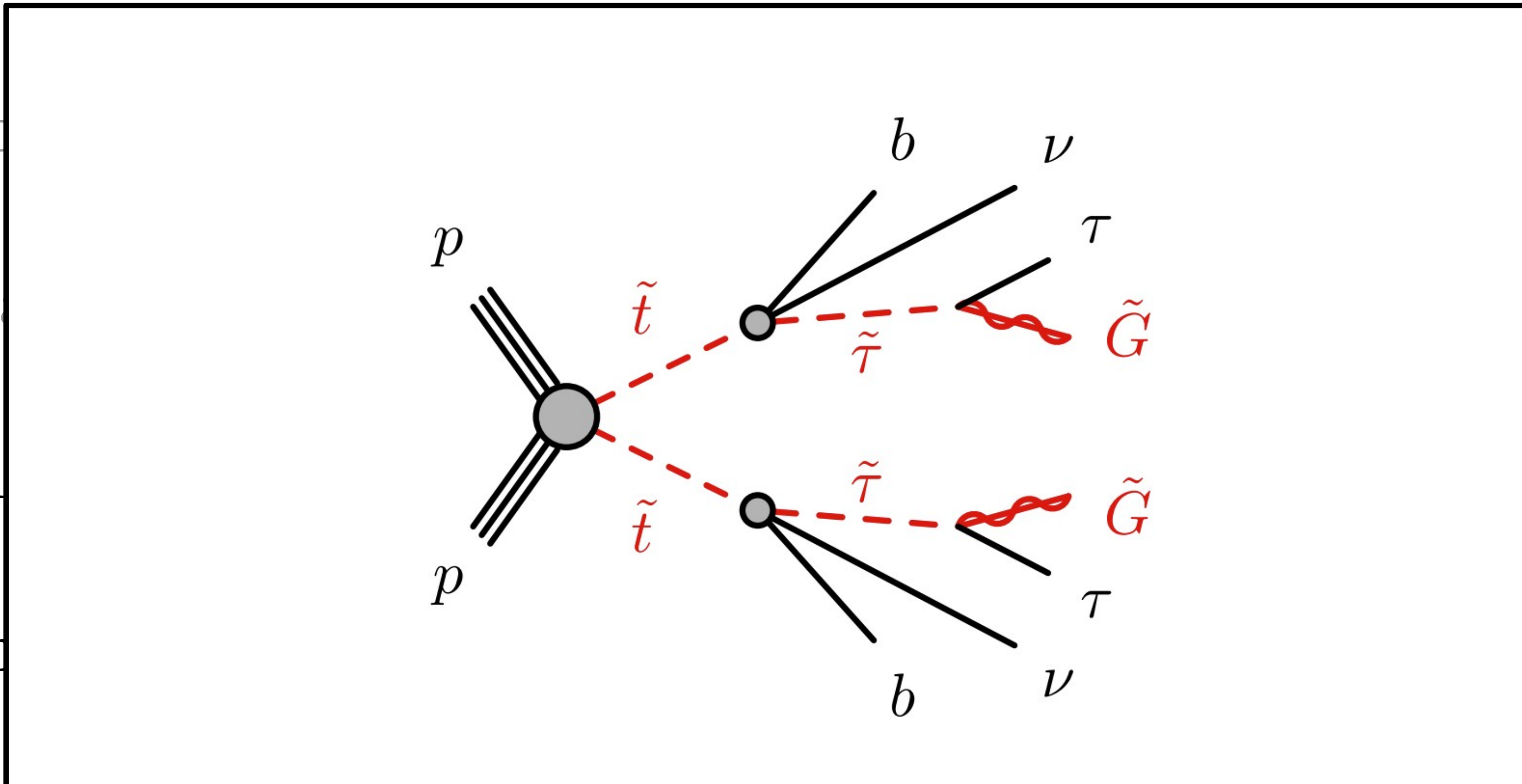
(Isolated) spin-1 particles must be non-interacting

Ya

Gr

Th

Pa ... ting



If there exists at least one particle with spin 3/2, then there is supersymmetry