LUND UNIVERSITY

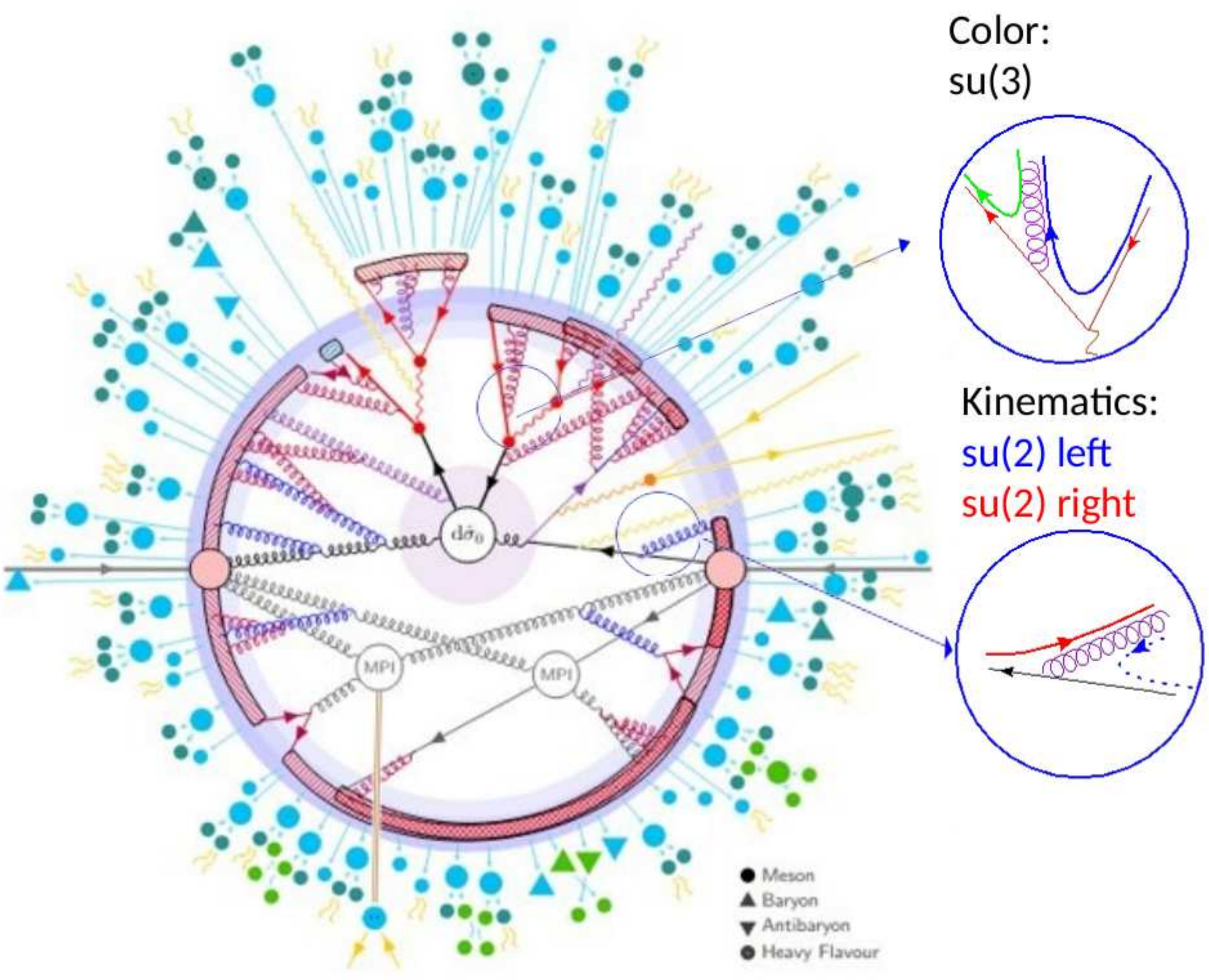
Chirality flow

Thanks to my collaborators:
Joakim Alnefjord, Emil Boman, Andrew Lifson, Christian Reuschle, Simon Plätzer, Adam Warnerbring, Zenny Wettersten

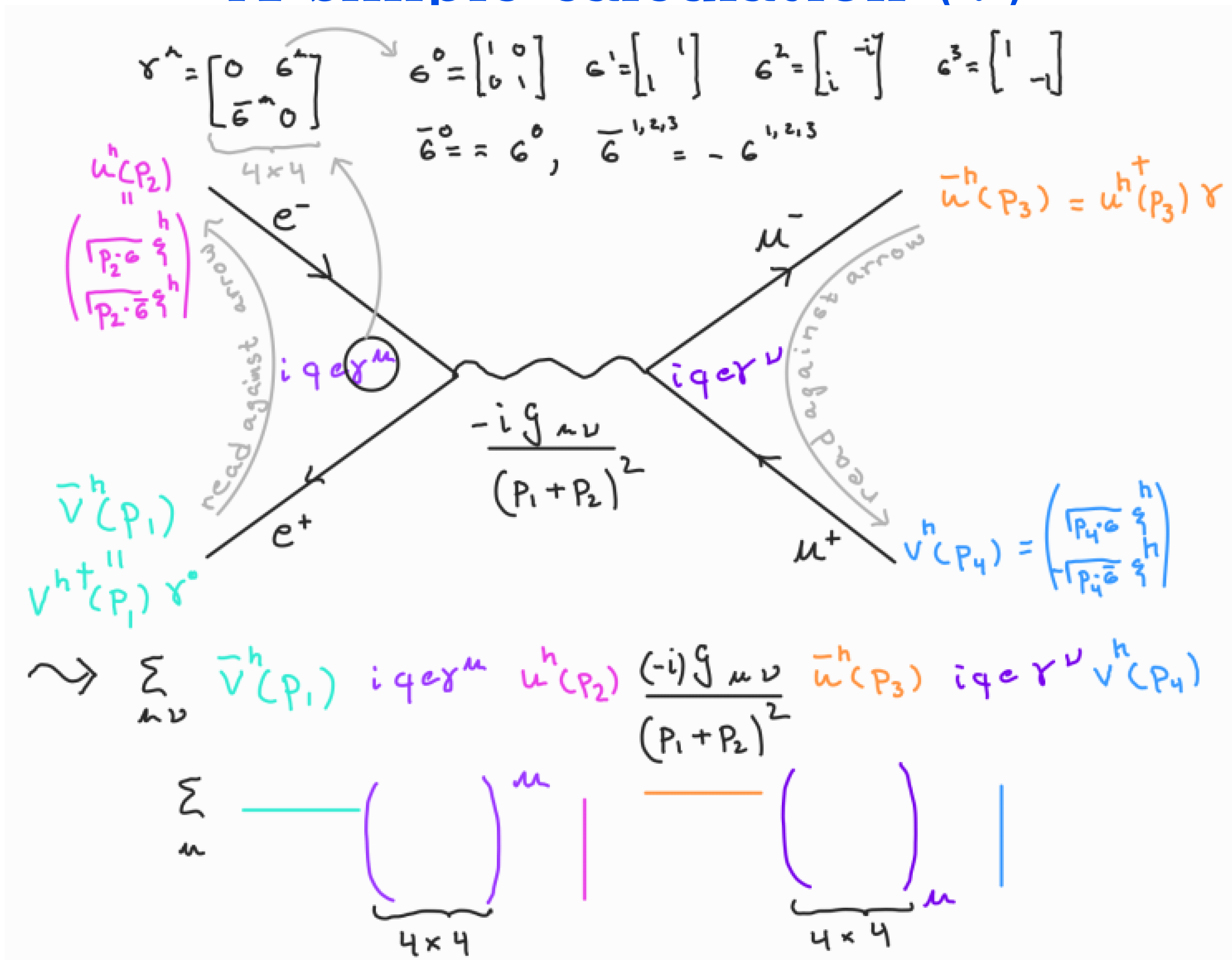
- Inspiration from QCD color
- Dissection of spacetime
- Simplification of Feynman rules, examples
- Conclusion and outlook

Saint-Jacut-de-la-Mer
June 2024
Malin Sjödahl

The bigger picture

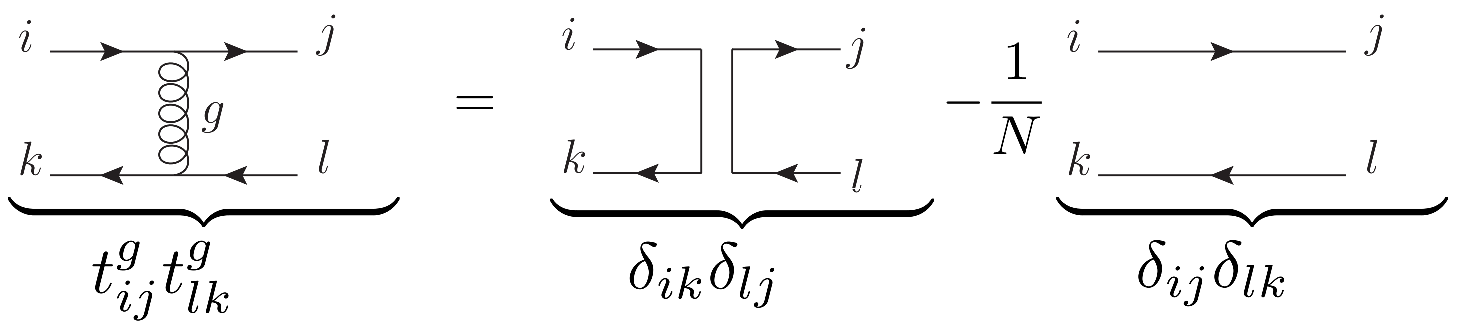


A simple calculation (?)



In QCD we translate color to flows

- For the strong force (QCD) we have color as well: For each quark-gluon vertex a factor t^a_{ij}, a generator of SU(3), i.e., a matrix giving an infinitesimal rotation of a complex three-component vector
- Fierz identity (here $T_R = 1$)



SU($N = 3$) remove gluon indices

- The Dirac spinor structure transforms under the direct sum representation $\underbrace{(\frac{1}{2},0)}_{\text{left}}\oplus\underbrace{(0,\frac{1}{2})}_{\text{right}}$ in the chiral/Weyl basis

$$\begin{pmatrix} u_L \\ u_R \end{pmatrix} \to \begin{pmatrix} e^{-i\bar{\theta}\cdot\frac{\bar{\sigma}}{2}+\bar{\eta}\cdot\frac{\bar{\sigma}}{2}} & 0 \\ 0 & e^{-i\bar{\theta}\cdot\frac{\bar{\sigma}}{2}-\bar{\eta}\cdot\frac{\bar{\sigma}}{2}} \end{pmatrix} \begin{pmatrix} u_L \\ u_R \end{pmatrix}$$

  i.e. actually two copies of **SL(2,$\mathbb{C}$)**, infinitesimally two su(2)
- Consider the matrix

$$p^{\dot{\alpha}\beta} = (p_\mu \sigma^\mu)^{\dot{\alpha}\beta} = \begin{pmatrix} p_0+p_3 & p_1-ip_2 \\ p_1+ip_2 & p_0-p_3 \end{pmatrix}^{\dot{\alpha}\beta}$$

  If we transform this as indicated by the indices $\Lambda^{\dot{\alpha}}{}_{\dot{\beta}}\Lambda^{\alpha}{}_{\beta}p^{\dot{\beta}\beta}$, we recover the transformation of a four-vector!

- Lorentz group $\sim$ two copies of su(2), $so(3,1) \cong su(2) \oplus su(2)$
- Can we do something similar for the Lorentz structure?

- Consider massless particles: chirality $\sim$ helicity
- Spinors (in notation from the spinor-helicity formalism)

$$u^+(p) = v^-(p) = \begin{pmatrix} 0 \\ |p\rangle \end{pmatrix} \qquad u^-(p) = v^+(p) = \begin{pmatrix} |p] \\ 0 \end{pmatrix}$$

$$\bar{u}^+(p) = \bar{v}^-(p) = \begin{pmatrix} [p| , & 0 \end{pmatrix} \qquad \bar{u}^-(p) = \bar{v}^+(p) = \begin{pmatrix} 0 , & \langle p| \end{pmatrix}$$

Note that incoming particles and antiparticles have bracket type corresponding to their helicity, but outgoing have the opposite

- Amplitudes have to be Lorentz invariant
- Lorentz inner products formed using **the only SL(2,$\mathbb{C}$) invariant object** $\epsilon^{\alpha\beta}$, $\epsilon^{12} = -\epsilon^{21} = \epsilon_{21} = -\epsilon_{12}$

$$\underbrace{\epsilon^{\alpha\beta}|i\rangle_\beta}_{\equiv\langle i|^\alpha}|j\rangle_\alpha = \langle i|^\alpha|j\rangle_\alpha = \langle ij\rangle, \quad \underbrace{\epsilon_{\dot\alpha\dot\beta}|i]^{\dot\beta}}_{\equiv[i|_{\dot\alpha}}|j]^{\dot\alpha} = [i|_{\dot\alpha}|j]^{\dot\alpha} = [ij]\ ,$$

where $|j]^{\dot\alpha} = |p_j]^{\dot\alpha}$ etc.

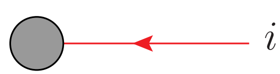
- $\implies$ Amplitudes are built up of contractions of form $\langle ij\rangle, [ij] \sim \sqrt{s_{ij}}$
- If we manage to create a flow picture, the "flow" must contract dotted and undotted indices separately

- First step: Notation for spinor inner products (only possible Lorentz invariants)

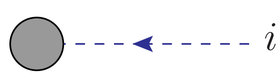
$$\langle i|^{\alpha}|j\rangle_{\alpha} \equiv \langle ij\rangle = -\langle ji\rangle =$$ 

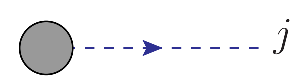
$$[i|_{\dot\beta}|j]^{\dot\beta} \equiv [ij] = -[ji] =$$ 

- Spinors and Kronecker deltas

$$\langle i|^{\alpha} =$$ 

, $$|j\rangle_{\alpha} =$$ 

$$[i|_{\dot\beta} =$$ 

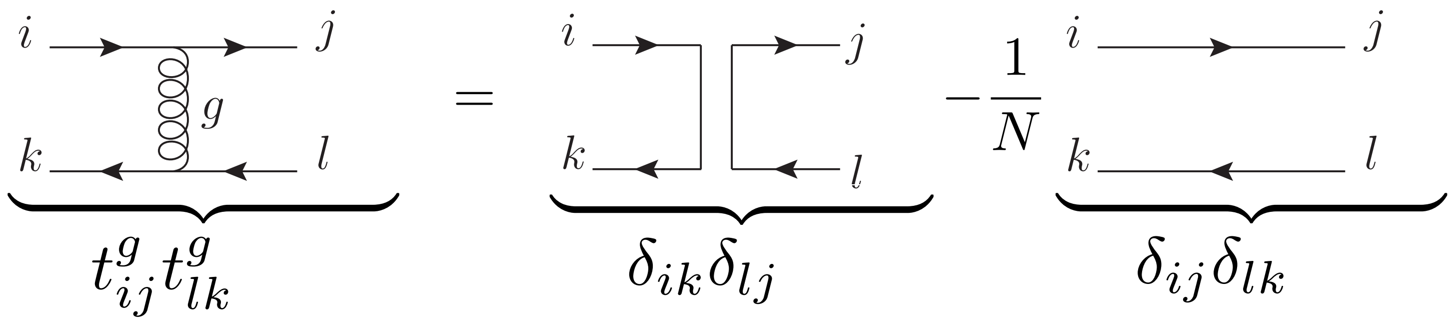
, $$|j]^{\dot\beta} =$$ 

$$\delta_{\alpha}^{\ \beta} \equiv \mathbb{1}_{\alpha}^{\ \beta} =$$ 

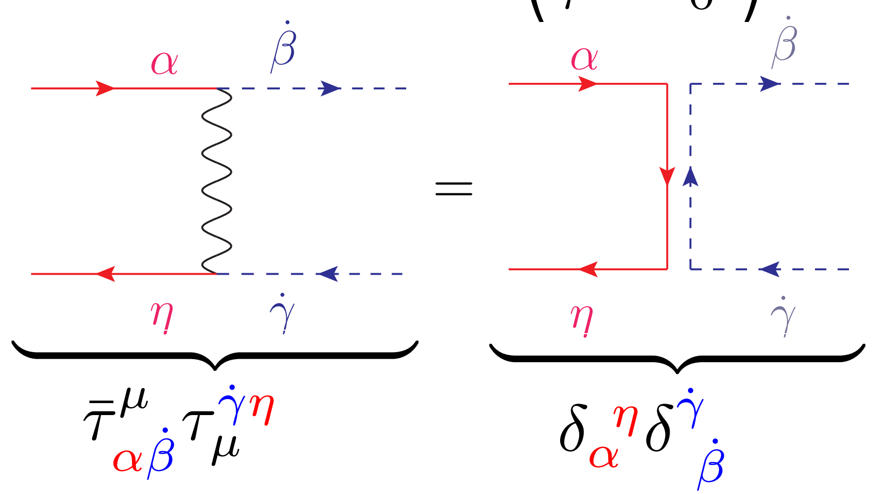
, $$\delta^{\dot\beta}_{\ \dot\alpha} \equiv \mathbb{1}^{\dot\beta}_{\ \dot\alpha} =$$ 

Towards chirality flow: Photon exchange

- Recall color, a single $SU(N)$: generators $t^a \to \delta$'s

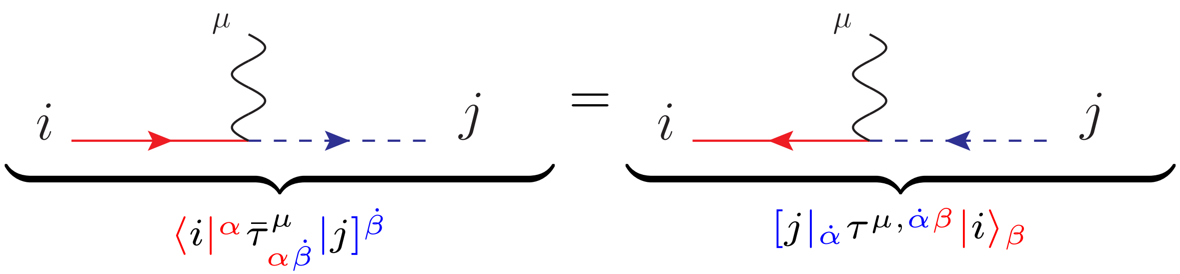


- For the Lorentz structure $\gamma^\mu = \sqrt{2}\begin{pmatrix} 0 & \tau^\mu \\ \bar{\tau}^\mu & 0 \end{pmatrix}$ in vertices

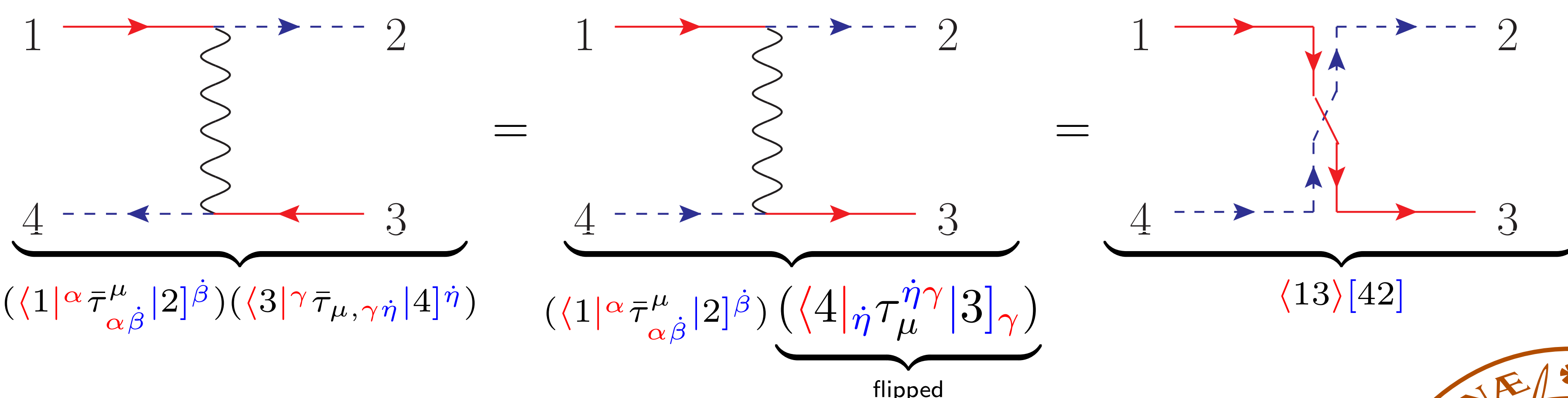


Non-matching arrows?

Arrows opposed? Flip them (when contracted between external spinors) First use charge conjugation

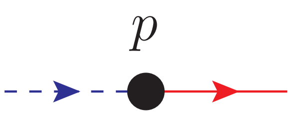


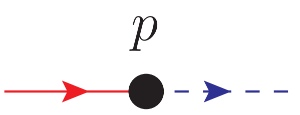
Then use Fierz identity $\bar{\tau}^{\mu}_{\alpha\dot{\beta}}\tau_{\mu}^{\dot{\gamma}\eta} = \delta_{\alpha}^{\ \eta}\delta^{\dot{\gamma}}_{\ \dot{\beta}}$ to remove vector index



Fermion propagators

- We split $\not{p}_{4d} \equiv p_\mu \gamma^\mu = p_\mu \sqrt{2} \begin{pmatrix} 0 & \tau^\mu \\ \bar{\tau}^\mu & 0 \end{pmatrix}$ into two terms

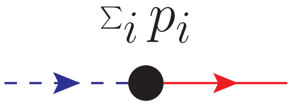
$\not{p} \equiv \sqrt{2} p^\mu \tau_\mu^{\dot{\alpha}\beta} =$ 

$\bar{\not{p}} \equiv \sqrt{2} p_\mu \bar{\tau}^\mu_{\alpha\dot{\beta}} =$ 

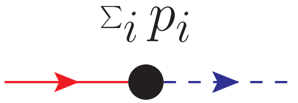
- For massless momenta we have

$$\sqrt{2} p^\mu \tau_\mu \equiv \not{p} = |p]\langle p| \;, \quad \sqrt{2} p^\mu \bar{\tau}_\mu \equiv \bar{\not{p}} = |p\rangle [p|$$

- In a propagator, we have $p^\mu = \sum p_i^\mu \;,\; p_i^2 = 0$

$\not{p} =$ 

$= \sum_i |i]^{\dot{\alpha}} \langle i|^{\beta}$ for $p_i^2 = 0$

$\bar{\not{p}} =$ 

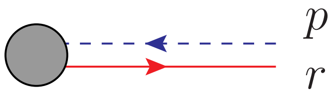
$= \sum_i |i\rangle_\alpha [i|_{\dot{\beta}}$ for $p_i^2 = 0$

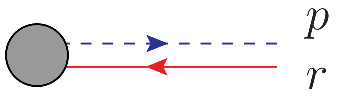
External gauge bosons

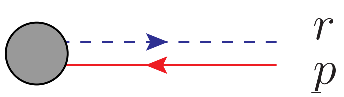
- In the spinor-helicity formalism

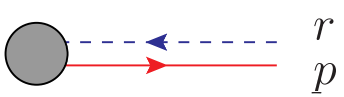
$$\epsilon_L{}^{\mu}(p,r) \to \frac{|r\rangle [p|}{\langle rp \rangle} \text{ or } \frac{|p]\langle r|}{\langle rp\rangle}, \qquad \epsilon_R{}^{\mu}(p,r) \to \frac{|r]\langle p|}{[pr]} \text{ or } \frac{|p\rangle [r|}{[pr]}$$

- $\Longrightarrow$ easy to translate to chirality flow

$$\epsilon_L{}^{\mu}(p,r) \to \frac{1}{\langle rp \rangle}$$ 

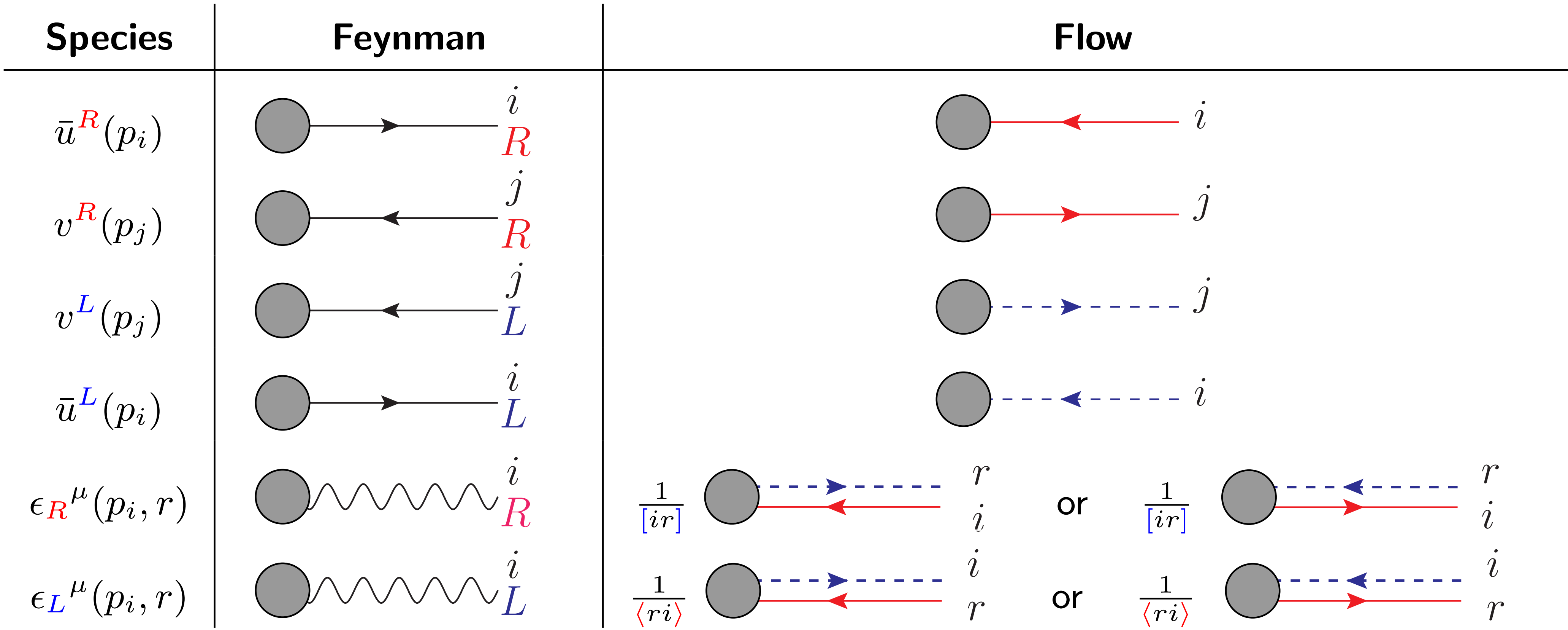
, or
$$\epsilon_L{}^{\mu}(p,r) \to \frac{1}{\langle rp \rangle}$$ 

$$\epsilon_R{}^{\mu}(p,r) \to \frac{1}{[pr]}$$ 

, or
$$\epsilon_R{}^{\mu}(p,r) \to \frac{1}{[pr]}$$ 

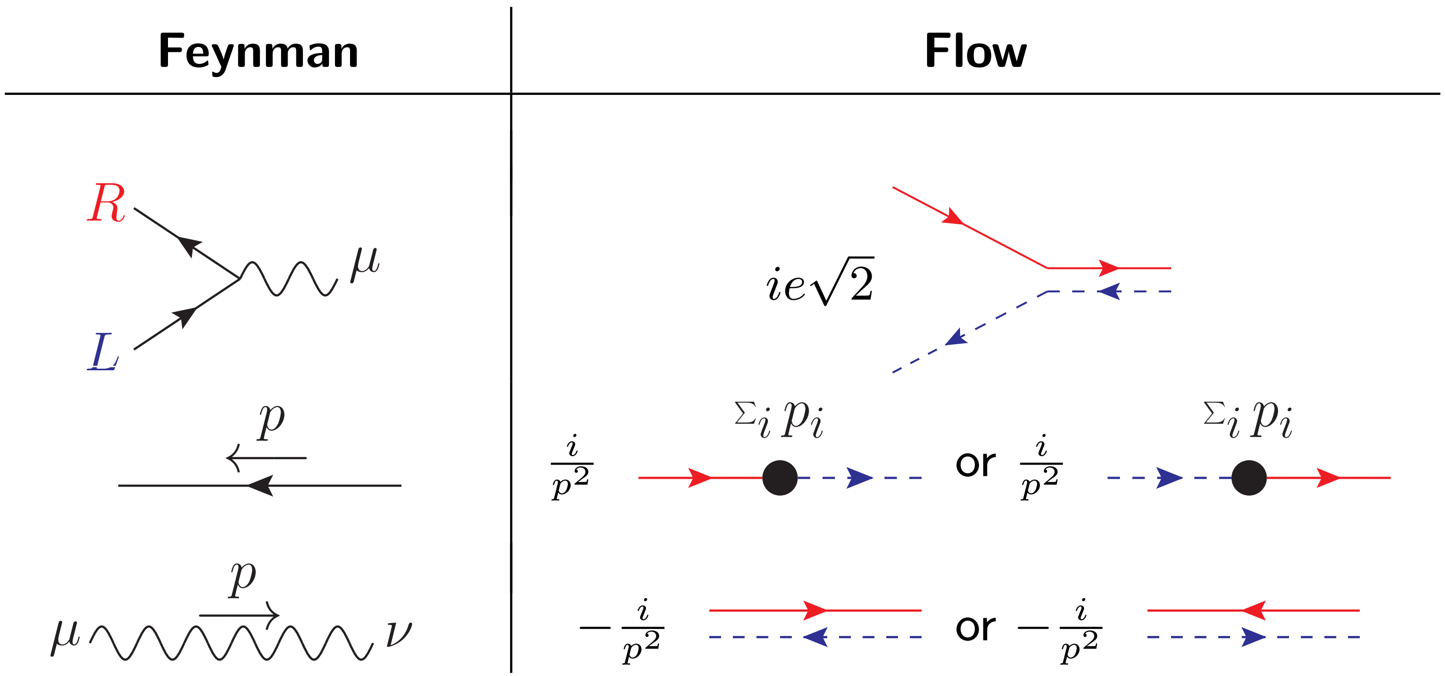
- In a Feynman diagram choose arrow directions which give aligned arrows through momentum dots, and opposing arrows for the two spinors of a gauge boson. (After careful consideration one can prove that this flow picture always works.)

The QED flow rules: massless particles



Use left and right chiral spinors $\underbrace{su(2)}_{\text{dotted}}$, $\underbrace{su(2)}_{\text{undotted}}$ and R/L for outgoing $-/+$ helicity (A. Lifson, C. Reuschle and MS, 2003.05877 (EPJC))

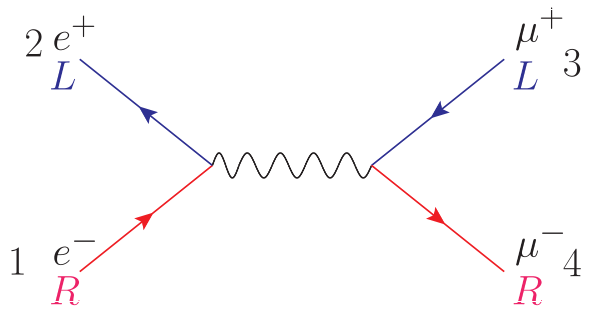
The QED flow rules: vertices and propagators



Stitch together such that arrow directions match

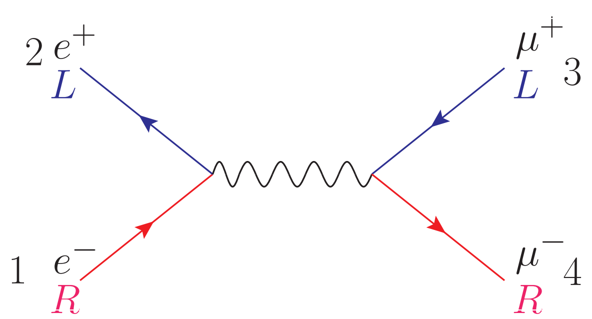
Simplest QED example

- Ordinary Feynman diagrams



$$= \frac{ie^2}{s_{e^+e^-}} \bar{v}^+(p_2)\gamma^\mu u^-(p_1)\bar{u}^+(p_4)\gamma_\mu v^-(p_3) = \ldots$$

- Regular spinor-helicity, easy

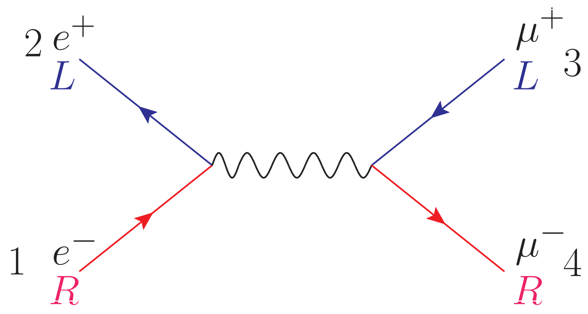


$$= \frac{2ie^2}{s_{e^+e^-}}\left([2|_{\dot\alpha}\tau_\mu^{\dot\alpha\beta}|1\rangle_\beta\right)\left(\langle 4|^\alpha \bar\tau^\mu_{\alpha\dot\beta}|3]^{\dot\beta}\right)$$

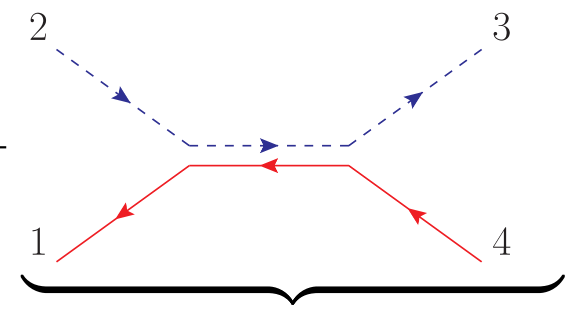
$$= \frac{2ie^2}{s_{e^+e^-}}[2|_{\dot\alpha}|3]^{\dot\alpha}\langle 4|^\beta|1\rangle_\beta \equiv \frac{2ie^2}{s_{e^+e^-}}[2\,3]\langle 4\,1\rangle$$

Simplest QED example

- Chirality flow, super easy and intuitive



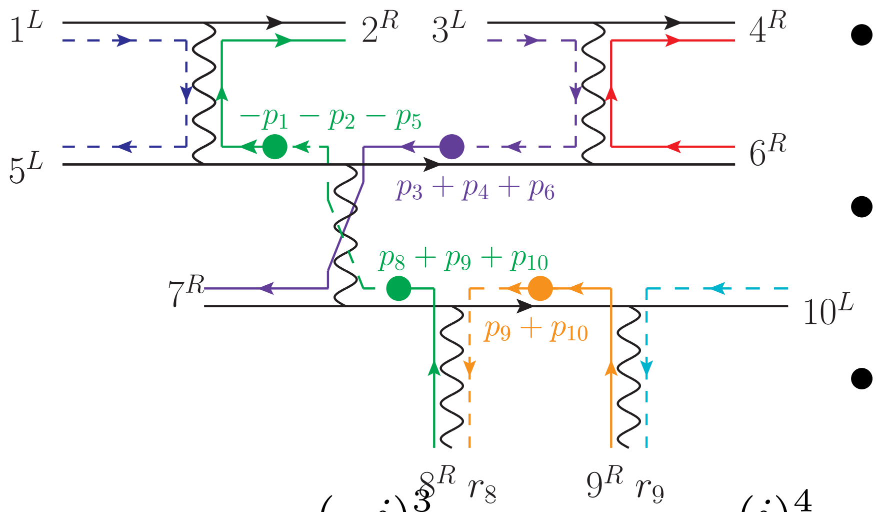
$$= \frac{2ie^2}{s_{e^+e^-}}$$



$[2\,3]\langle 4\,1\rangle$

- TODO: A slightly more complicated example on the board

A complicated QED example



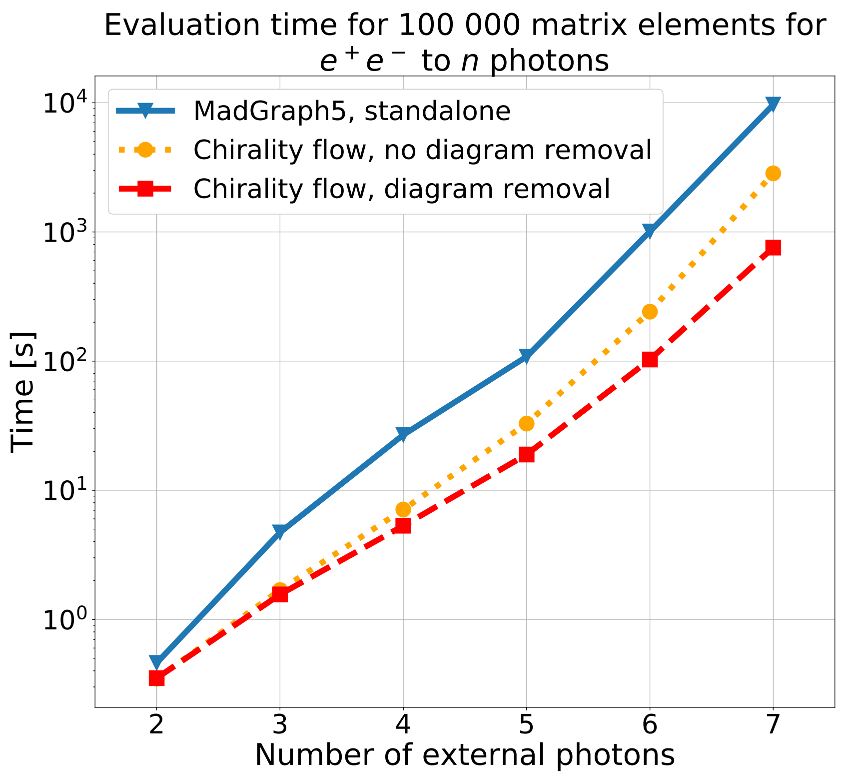
- Pick any consistent arrow direction
- Compare to standard QFT: 12 γ^μ matrices
- Here all particles crossed to outgoing

$$= \underbrace{(\sqrt{2}ei)^8}_{\text{vertices}} \underbrace{\frac{(-i)^3}{s_{1\,2}\ s_{3\,4}\ s_{8\,9\,10}}}_{\text{photon propagators}} \underbrace{\frac{(i)^4}{s_{1\,2\,5}\ s_{3\,4\,6}\ s_{8\,9\,10}\ s_{9\,10}}}_{\text{fermion propagators}} \underbrace{\frac{1}{[8r_8][9r_9]}}_{\text{polarization vectors}} [15]\langle 64\rangle[10\ r_9]$$

$$\times \left(\underbrace{\langle 9\,9\rangle}_{0}[9r_8] + \langle 910\rangle[10r_8] \right) \left(\underbrace{[33]}_{0}\langle 37\rangle + [34]\langle 47\rangle + [36]\langle 67\rangle \right)$$

$$\times \left(-\langle 89\rangle[91]\langle 12\rangle - \langle 89\rangle[95]\langle 52\rangle - \langle 8\,10\rangle[10\ 1]\langle 12\rangle - \langle 8\,10\rangle[10\ 5]\langle 52\rangle \right)$$

Implementation



Evaluation time in MadGraph5_aMC@NLO, $e^+e^- \to n$ photons

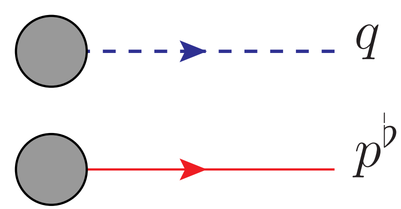
(A. Lifson, M. Sjodahl and Z. Wettersten 2203.13618 (EPJC))

Massive momenta and spinors

- Decompose massive momentum p as sum of massless
  $p^\mu = p^{\flat,\mu} + \alpha q^\mu \;, \quad (p^\flat)^2 = q^2 = 0 \;, \quad \alpha = \frac{p^2}{2p\cdot q} = \frac{m^2}{2p\cdot q}$
  $\not{p} \equiv \sqrt{2} p^\mu \tau_\mu = |p^\flat]\langle p^\flat| + \alpha |q]\langle q|$

- Massive spinors and polarization vectors written in terms of massless Weyl spinors of momentum $p^\flat, q$,

$$u^+(p) = \left(-\frac{m}{[qp^\flat]} \right), \text{ etc.}$$



(All spinors in 2011.10075 eq. 3.11-3.16)

- q is arbitrary but physical, as it defines the spin direction s^μ

$$s^\mu = \frac{1}{m}(p^\mu - 2\alpha q^\mu) = \frac{1}{m}\left(p^\mu - \frac{m^2}{p\cdot q} q^\mu\right)$$

- Can also measure spin along the direction of motion

$$p^\mu = p_f^\mu + p_b^\mu$$

$$\begin{aligned} \alpha &\rightarrow 1, \\ p^\flat &\rightarrow p_f = \frac{p^0 + |\vec{p}|}{2}(1, \hat{p}) \\ q &\rightarrow p_b = \frac{p^0 - |\vec{p}|}{2}(1, -\hat{p}) \end{aligned}$$

Spin measured along $s^\mu = \frac{1}{m}(p_f^\mu - p_b^\mu) = \frac{1}{m}(|\vec{p}|, p^0 \hat{p})$, spatial components along the direction of motion

(Full Standard Model in J. Alnefjord, A.Lifson, C.Reuschle and M. Sjodahl 2011.10075 (EPJC))

What is spin?

- Spin operator Σ^μ and Pauli-Lubanski operator W^μ

$$\frac{1}{2}\Sigma^\mu = -\frac{1}{4m}\epsilon^{\mu\nu\lambda\omega}P_\nu\sigma_{\lambda\omega} = \frac{1}{m}W^\mu$$

- Here $W^2 = -m^2 J(J+1)$, is the 2nd quadratic Casimir operators of the Poincaré algebra, along $P^2 = m^2$, $(P_\nu = i\partial/\partial x^\nu)$, and $\sigma^{\mu\nu}$ (giving the Lorentz generators for the $(1/2, 1/2)$-representation) is defined as $\sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$.
- The spin projected onto s^μ is given by the operator

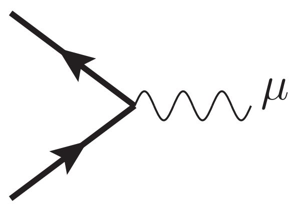
$$\mathcal{O}_s = -\frac{\Sigma^\mu s_\mu}{2} = \frac{1}{4m}\epsilon^{\mu\nu\lambda\omega}s_\mu P_\nu\sigma_{\lambda\omega} \ ,$$

such that the spin direction, in this sense, is only defined up to a four-momentum proportional to p.

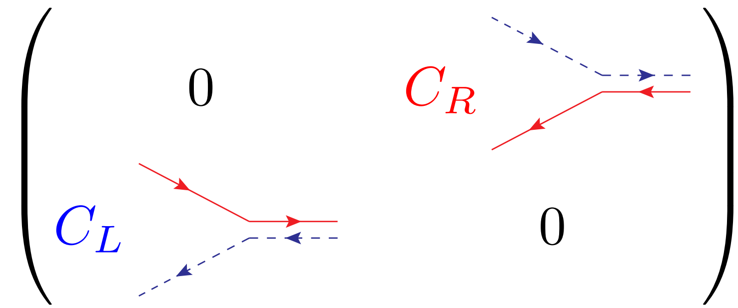
- Adding any linear combination of p to $s = (1/m)\,(p - 2\alpha q)$ leaves $\mathcal{O}_s$ invariant
- Therefore, we could equally well have used $s' = -2\alpha q/m = -mq/(p \cdot q)$ for the spin direction, when expressed as above. When rewritten as $\mathcal{O}_s = \frac{1}{2}\gamma^5 s^\mu \gamma_\mu$ the spin vector must be taken to be s.
- Thus q plays the role of defining the *other* four-vector (aside from p) which determines the operator $\mathcal{O}_s$, and thereby what we mean with positive and negative spin.
- In the non-relativistic limit $p = (m, 0, 0, 0)$ and $s = (0, \hat{s})$. Clearly, adding any linear combination of p to s or q will leave $\mathcal{O}_s$ invariant.

Fermion vertices

- Fermion-vector vertex



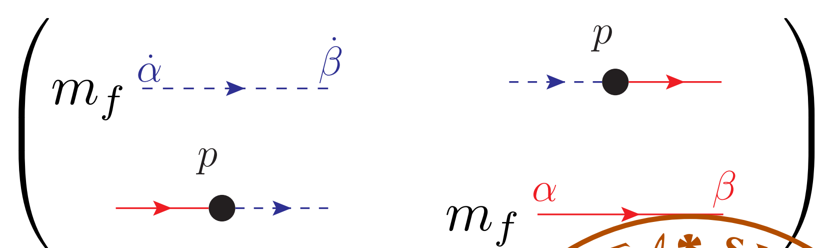
$$= ie(P_L C_L + P_R C_R)\gamma^\mu = ie\sqrt{2}$$



Left and right chiral couplings may differ, in particular $C_R = 0$ for $W^\pm \Rightarrow$ **electroweak sector nice** in chirality flow

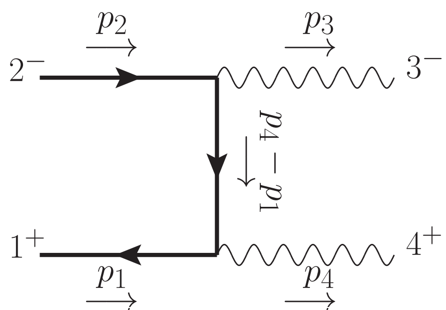
- Fermion propagator

$$\frac{i}{p^2 - m_f^2}\begin{pmatrix} m_f \delta^{\dot{\alpha}}{}_{\dot{\beta}} & \sqrt{2} p^{\dot{\alpha}\beta} \\ \sqrt{2}\bar{p}_{\alpha\dot{\beta}} & m_f \delta_\alpha{}^\beta \end{pmatrix} = \frac{i}{p^2 - m_f^2}$$



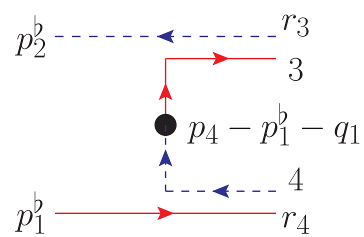
A massive example

Consider the diagram of $e^+_{1+} e^-_{2-} \to \gamma_3^{-=R} \gamma_4^{+=L}$ and include the mass m_e

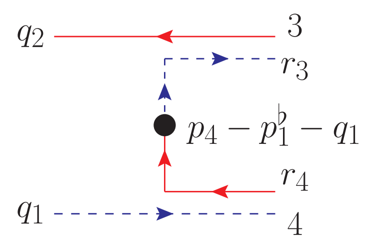


- Obtain 3 new terms
- Simplify with choices of q_1, q_2, r_3, r_4
  $q_2 = p_3, r_3 = p_2^\flat$ ...

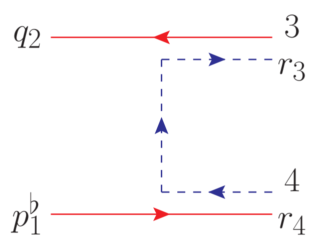
$$= \frac{-2ie^2}{((p_4 - p_1)^2 - m_e^2)[3r_3]\langle 4r_4\rangle} \Bigg\{$$



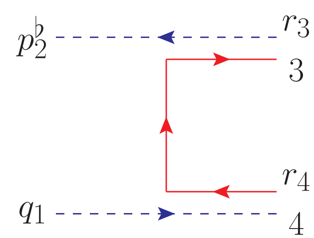
$$- \frac{m_e}{[q_1 p_1^\flat]} \frac{m_e}{\langle p_2^\flat q_2\rangle}$$



$$+ m_e \Bigg(\frac{m_e}{\langle p_2^\flat q_2\rangle}$$

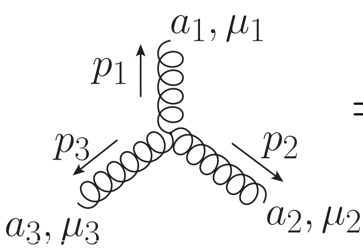


$$- \frac{m_e}{[q_1 p_1^\flat]}$$



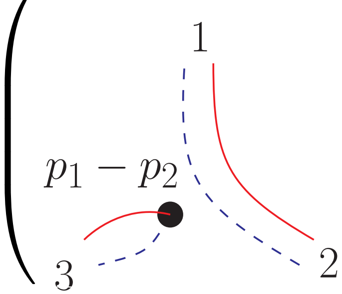
$$\Bigg) \Bigg\}$$

The non-abelian QCD vertices

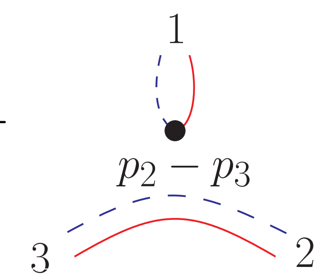


$$= i\frac{g_s}{\sqrt{2}} i f^{a_1 a_2 a_3}\left(g^{\mu_1\mu_2}(p_1-p_2)^{\mu_3} + g^{\mu_2\mu_3}(p_2-p_3)^{\mu_1} + g^{\mu_3\mu_1}(p_3-p_1)^{\mu_2}\right)$$

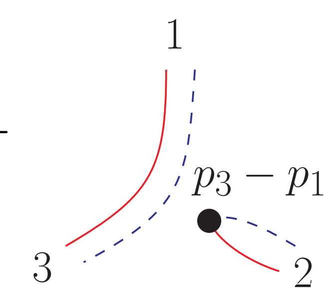
$$\to i\frac{g_s}{\sqrt{2}} i f^{a_1 a_2 a_3}\frac{1}{\sqrt{2}}\Bigg($$



$$+$$

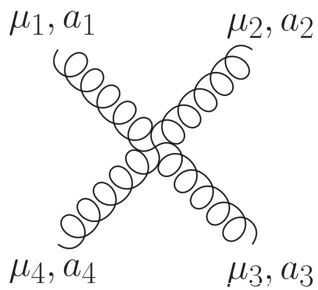


$$+$$



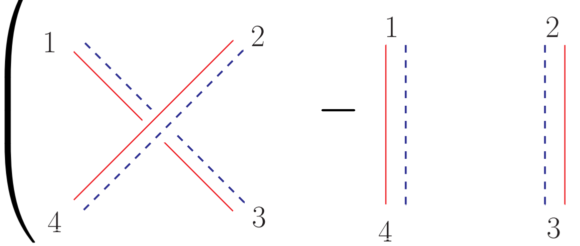
$$\Bigg),$$

Here f^{abc} is the color factor in the vertex, the SU(3) structure constants (A.Lifson, C.Reuschle and M. Sjodahl 2011.10075 (EPJC))



$$= i\left(\frac{g_s}{\sqrt{2}}\right)^2 \sum_{Z(2,3,4)} i f^{a_1 a_2 b} i f^{b a_3 a_4} \left(g^{\mu_1\mu_3} g^{\mu_2\mu_4} - g^{\mu_1\mu_4} g^{\mu_2\mu_3}\right)$$

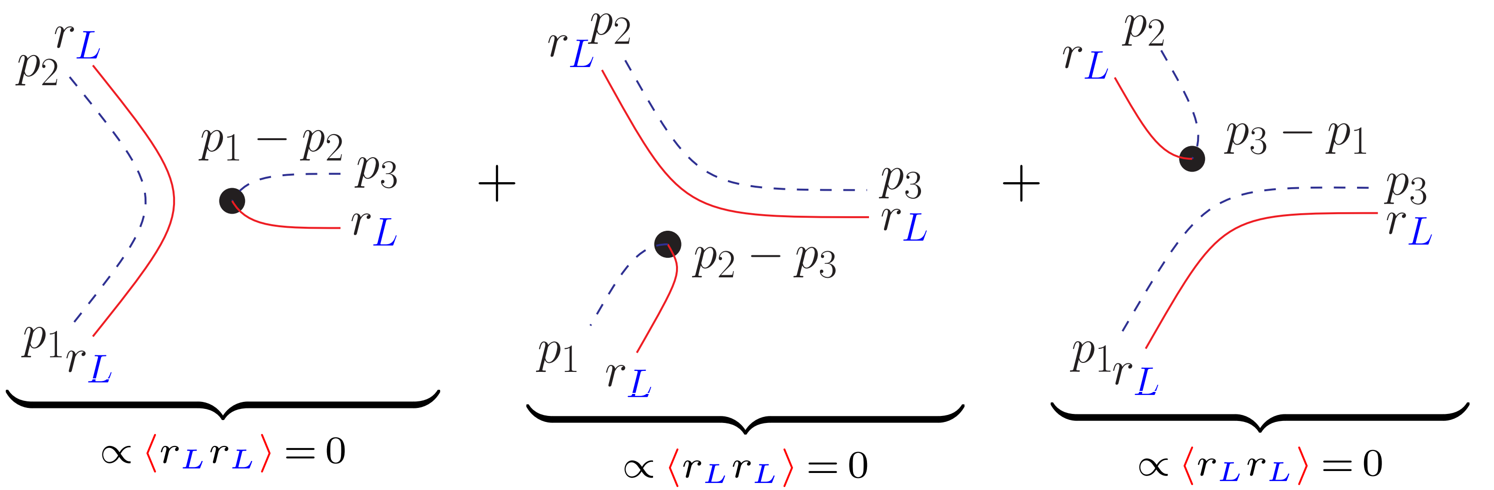
$$\to i\left(\frac{g_s}{\sqrt{2}}\right)^2 \sum_{Z(2,3,4)} i f^{a_1 a_2 b} i f^{b a_3 a_4} \left(\quad - \quad \right)$$



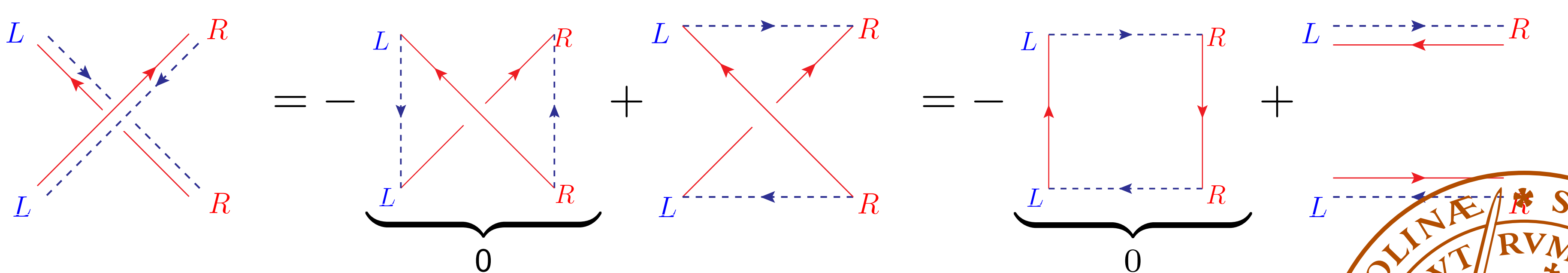
where $Z(2,3,4)$ denotes the set of cyclic permutations of the integers $2, 3,$ and 4

TODO: A QCD example on the board...

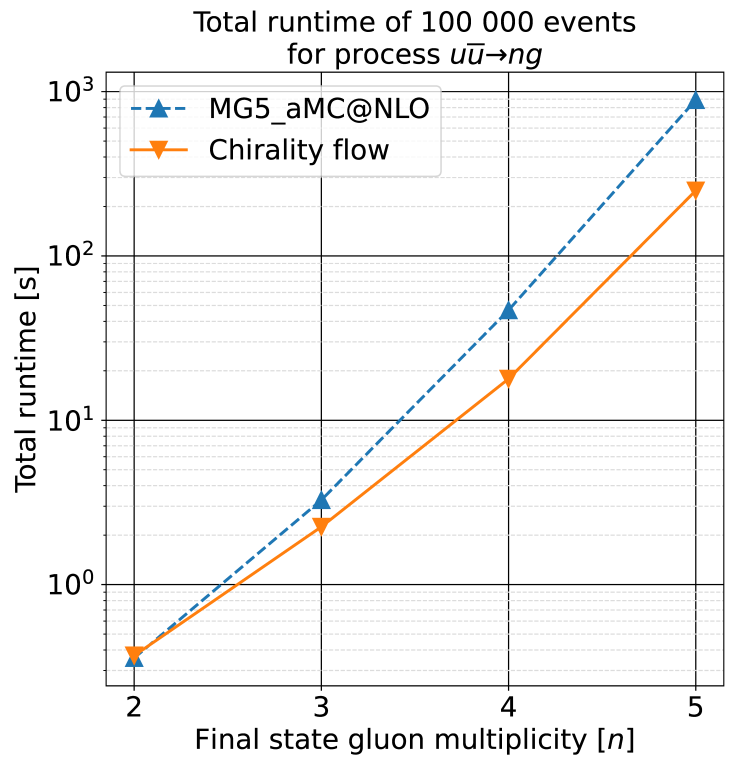
The gluon vertices can be simplifed due to a nice gauge choice, for example, we can not have three left gluons



The four-gluon vertex simplifies further due to the Schouten identity

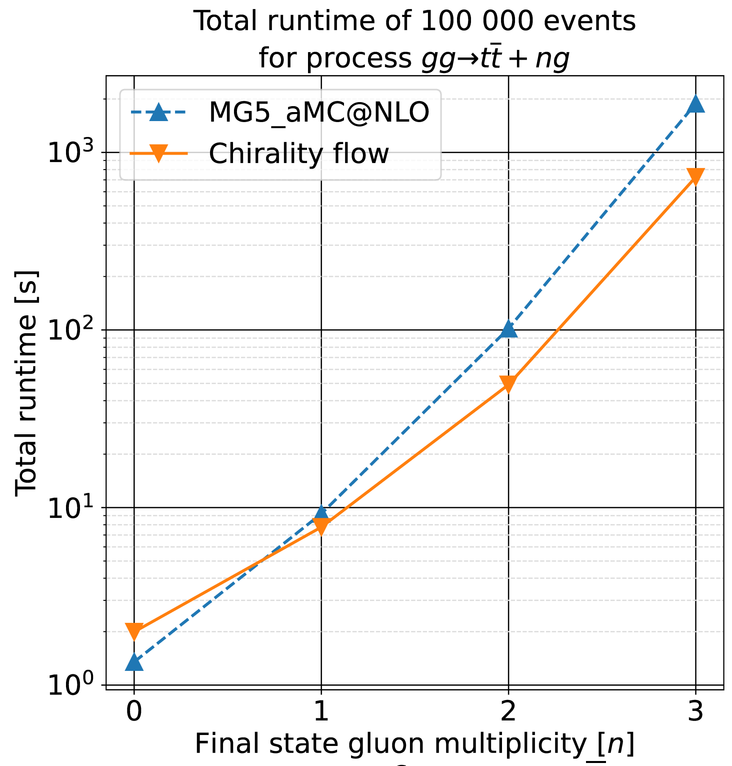


Implementation



Runtime for the Lorentz structure of $u\bar{u} \rightarrow ng$ for the standalone version of `MadGraph5_aMC@NLO` and for the chirality-flow branch. (E. Boman, A. Lifson, M. Sjodahl, A. Warnerbring, Z. Wettersten, 2312.07447 (JHEP))

Implementation



Runtime for the Lorentz structure of $gg \to t\bar{t} + ng$, for the standalone version of `MadGraph5_aMC@NLO` and for the chirality-flow branch. (E. Boman, A. Lifson, M. Sjodahl, A. Warnerbring, Z. Wettersten, 2312.07447 (JHEP))

Electroweak physics

- This sector is chiral $\rightarrow$ largest amount of simplification expected
- In particular the $W^{\pm}$ vertex is simple
- TODO: Consider W exchange

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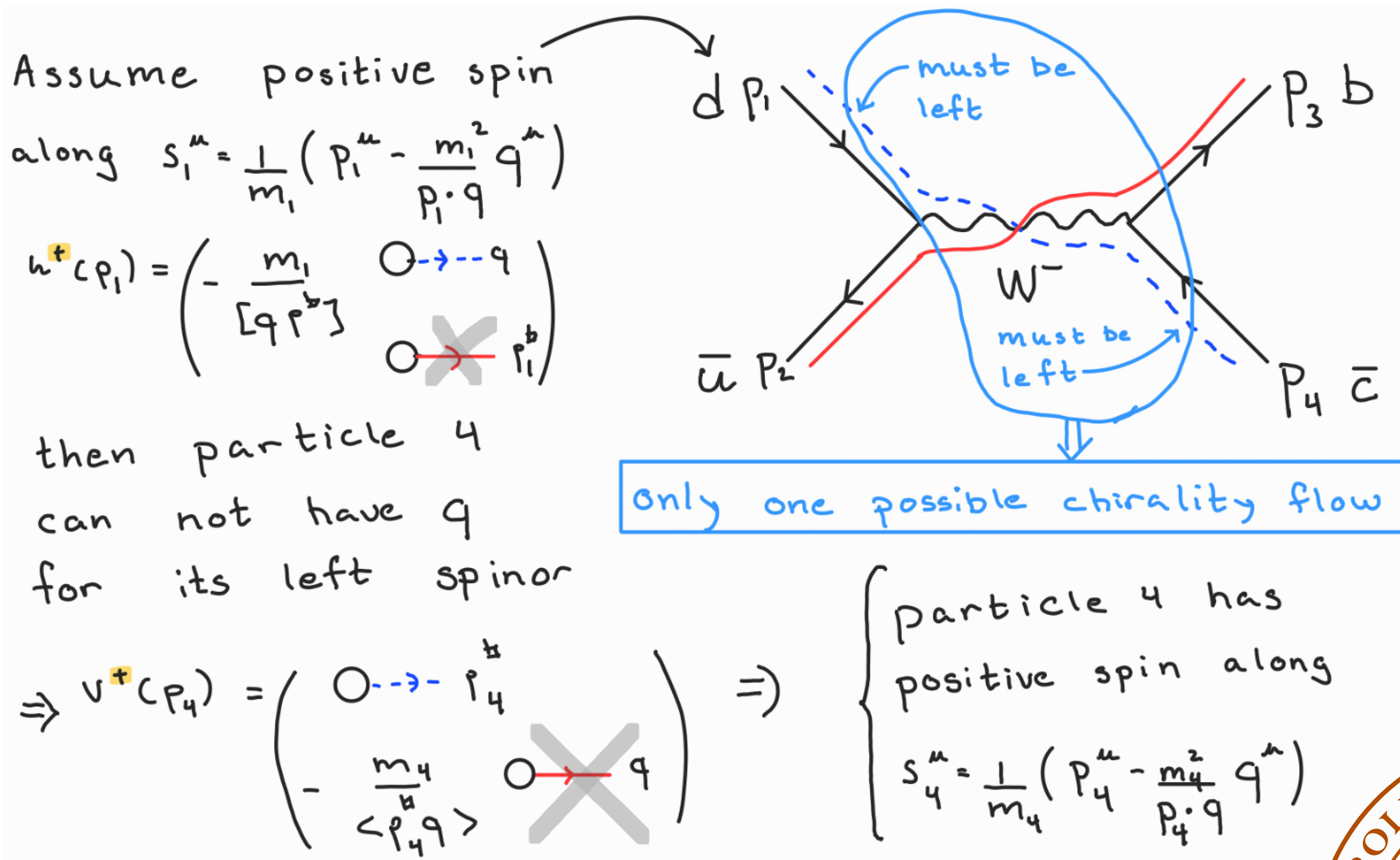


Conclusion and outlook

- Splitting Lorentz structure into su(2), su(2), we are able to recast all standard model Feynman rules to chirality-flow rules
- This gives a transparent and intuitive way of writing down values of Feynman diagrams, simplifying pen-and paper calculations to the extent that they are often trivial
- Vertices can be simplified by good gauge choices, and the four-gluon vertex further by the Schouten identity
- Significant speed-up for event generation

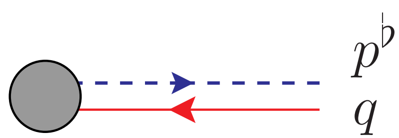
Backup: Massive polarization vectors

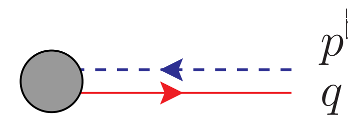
External gauge bosons, for helicity states $p^\flat \to p_f$, $\alpha \to 1$, $q \to p_b$

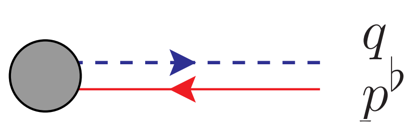
$$\epsilon_L{}^\mu(p) \to \frac{|p^\flat]\langle q|}{\langle q p^\flat\rangle} \quad \text{or} \quad \frac{|q\rangle[p^\flat|}{\langle q p^\flat\rangle} \qquad \epsilon_R{}^\mu(p) \to \frac{|q]\langle p^\flat|}{[p^\flat q]} \quad \text{or} \quad \frac{|p^\flat\rangle[q|}{[p^\flat q]}$$

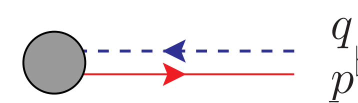
$$\epsilon_0^\mu(p) = s^\mu = \frac{1}{m}(p^{\flat,\mu} - \alpha q^\mu)$$

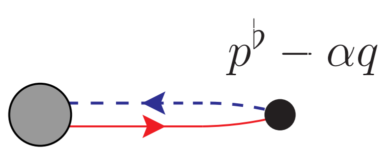
for incoming (outgoing) bosons, use L/R for $-/+$ $(-/+)$ spin along s^μ-axis. Translate to chirality flow

$\epsilon_L{}^\mu(p) \to \frac{1}{\langle q p^\flat\rangle}$ 

, or $\epsilon_L{}^\mu(p) \to \frac{1}{\langle q p^\flat\rangle}$ 

$\epsilon_R{}^\mu(p) \to \frac{1}{[p^\flat q]}$ 

, or $\epsilon_R{}^\mu(p) \to \frac{1}{[p^\flat q]}$ 

$\epsilon_0^\mu(p) \to \frac{1}{m\sqrt{2}}$ 

, or $\epsilon_0^\mu(p) \to \frac{1}{m\sqrt{2}}$