University of Zurich[UZH]

Lepton-Quark Fusion at Hadron Colliders, precisely

IJS-FMF high-energy physics seminars
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Based on

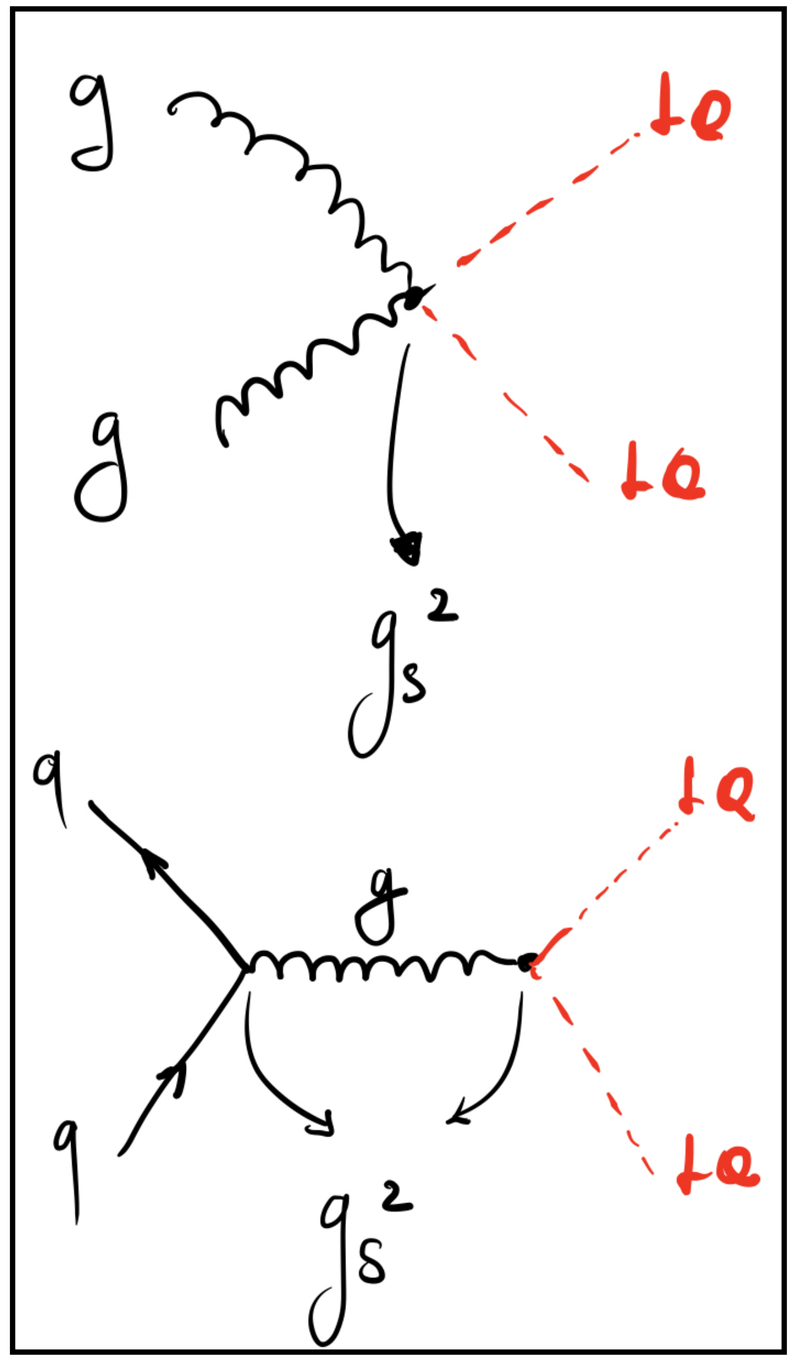
A. Greljo, N. Selimović: arXiv:2012.02092

OUTLINE

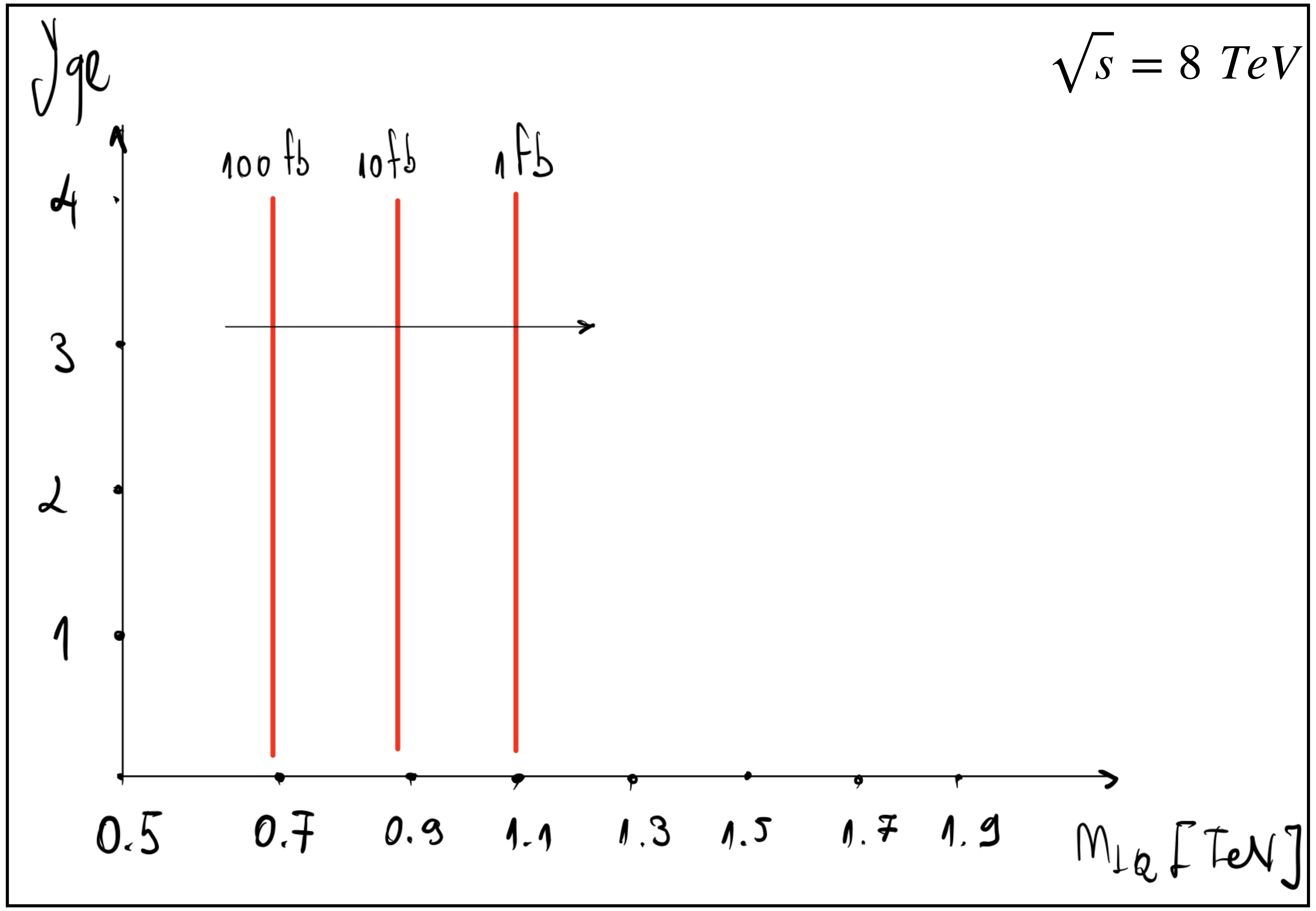
- Leptoquark production mechanisms
- LUX method & ***Lepton PDFs***
- Lepton-Quark fusion @ NLO:
    - ***QED***
    - ***QCD***
- Flavor @ high - p_T

PAIR PRODUCTION

Pure QCD

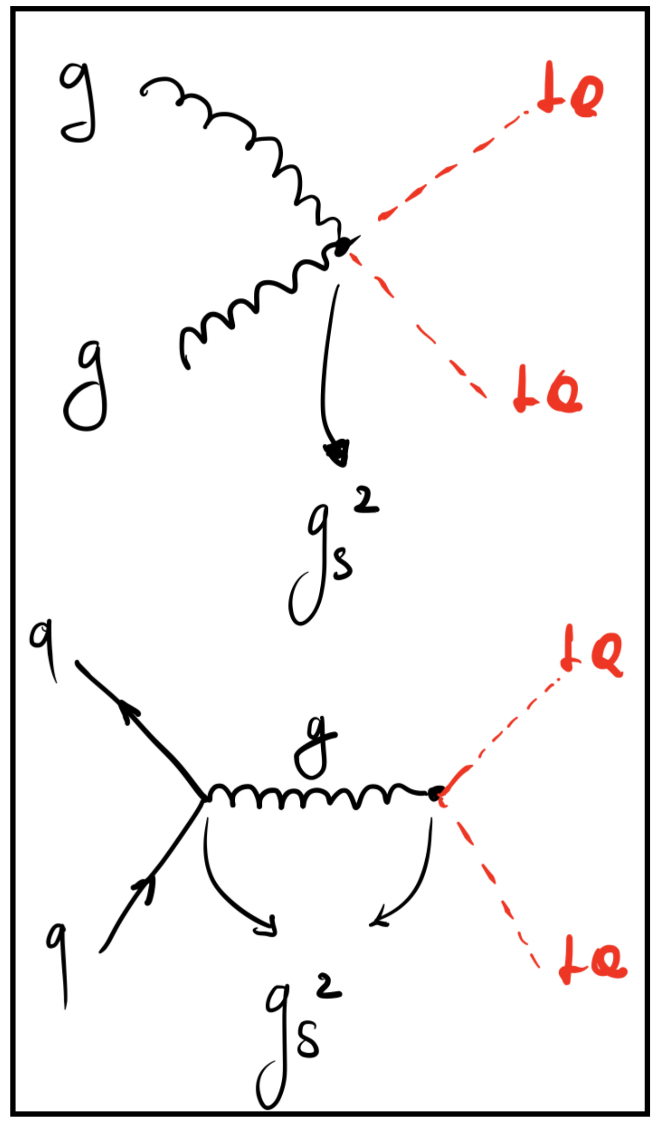


$$\mathscr{L} \supset -y_{q\ell}\, \bar{q}\, S_{LQ}\, \ell \;+\; h.c.$$

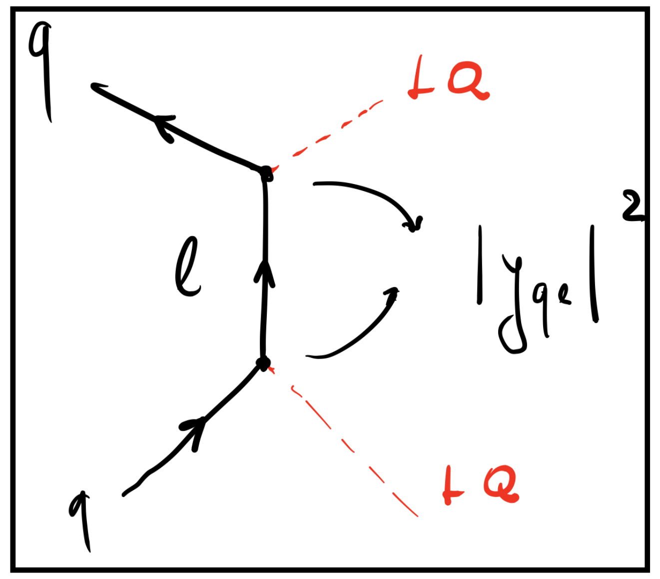


PAIR PRODUCTION

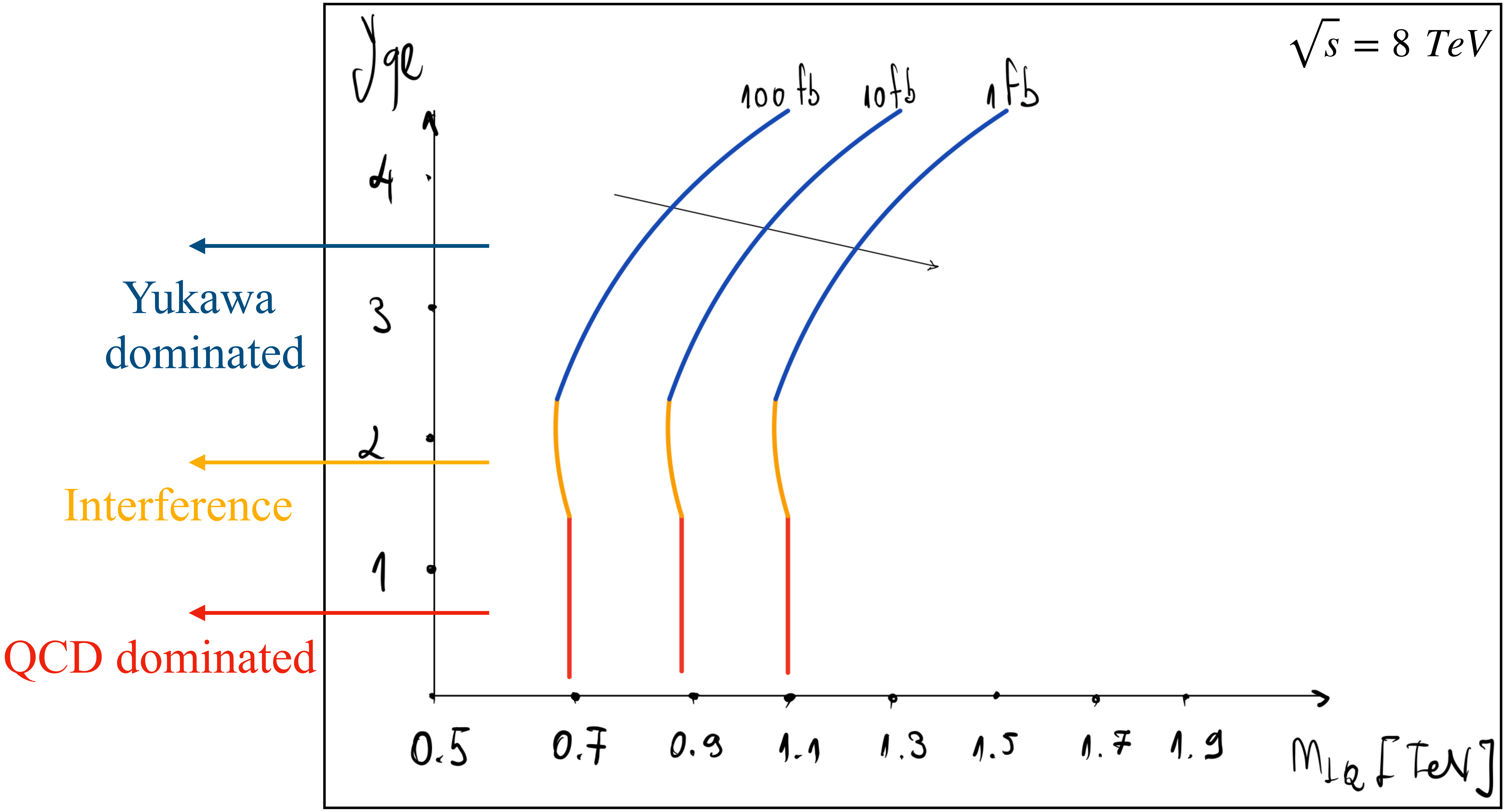
Pure QCD



+ lepton t-channel

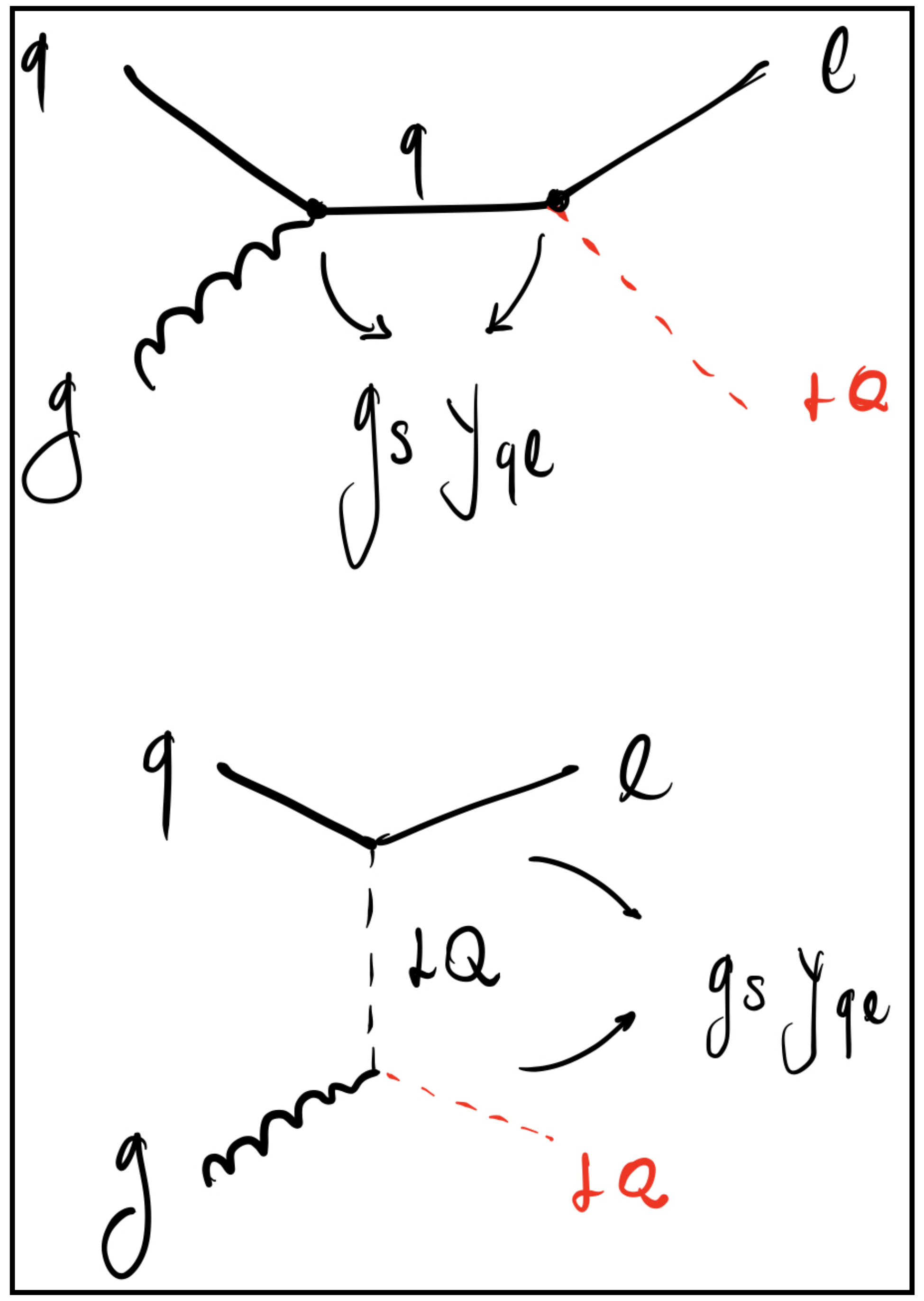


$$\sigma_{pair}(y_{q\ell}, m_{LQ}) = a_0(m_{LQ}) + a_2(m_{LQ})\,|\,y_{q\ell}\,|^2 + a_4(m_{LQ})\,|\,y_{q\ell}\,|^4$$

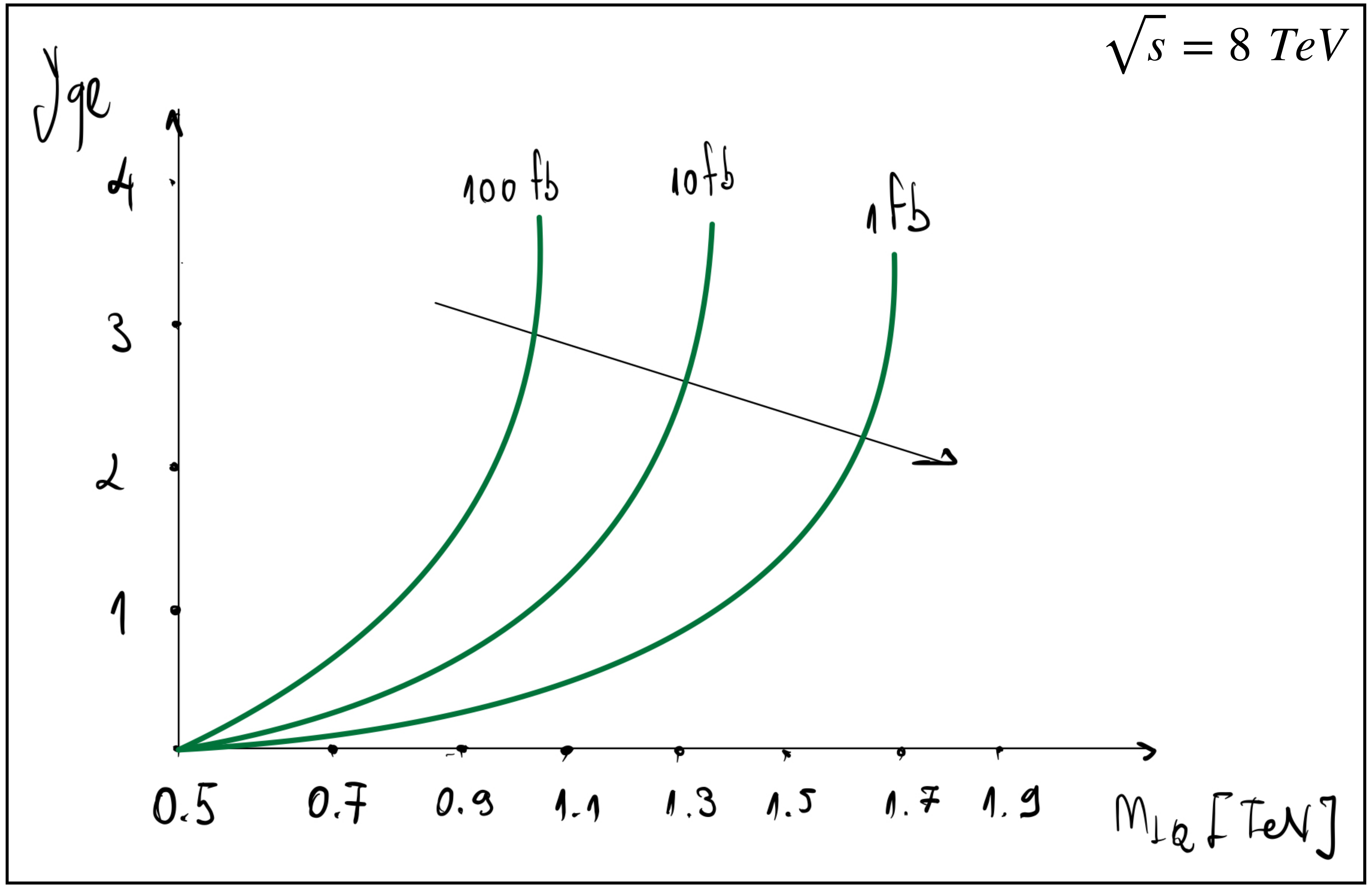


[I. Dorsner, S. Fajfer, and A. Greljo: Cornering Scalar Leptoquarks at LHC, arXiv:1406.4831]

SINGLE PRODUCTION (+ ℓ)

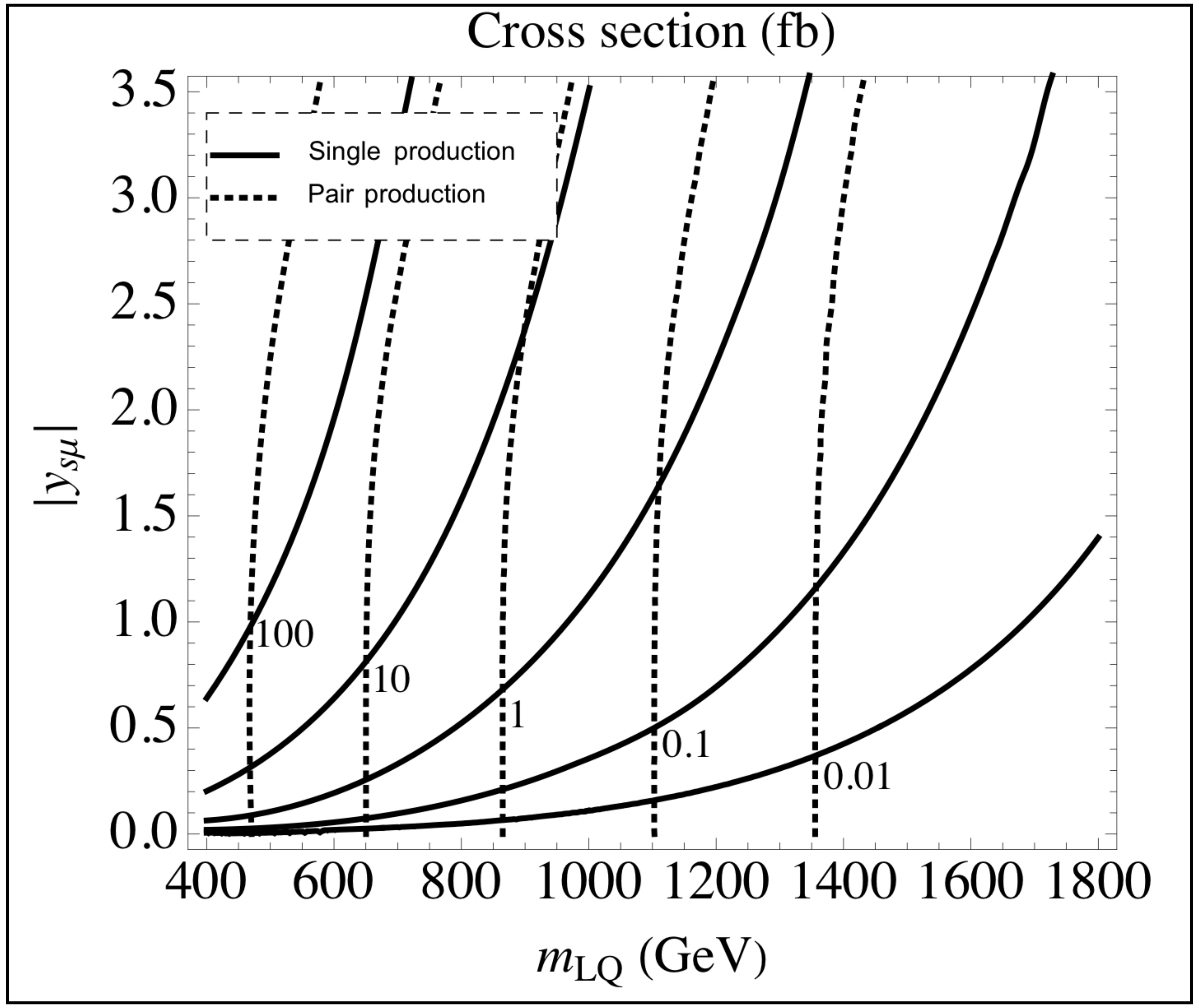


$$\sigma_{single}(y_{q\ell}, m_{LQ}) = a(m_{LQ})\,|\,y_{q\ell}\,|^2$$



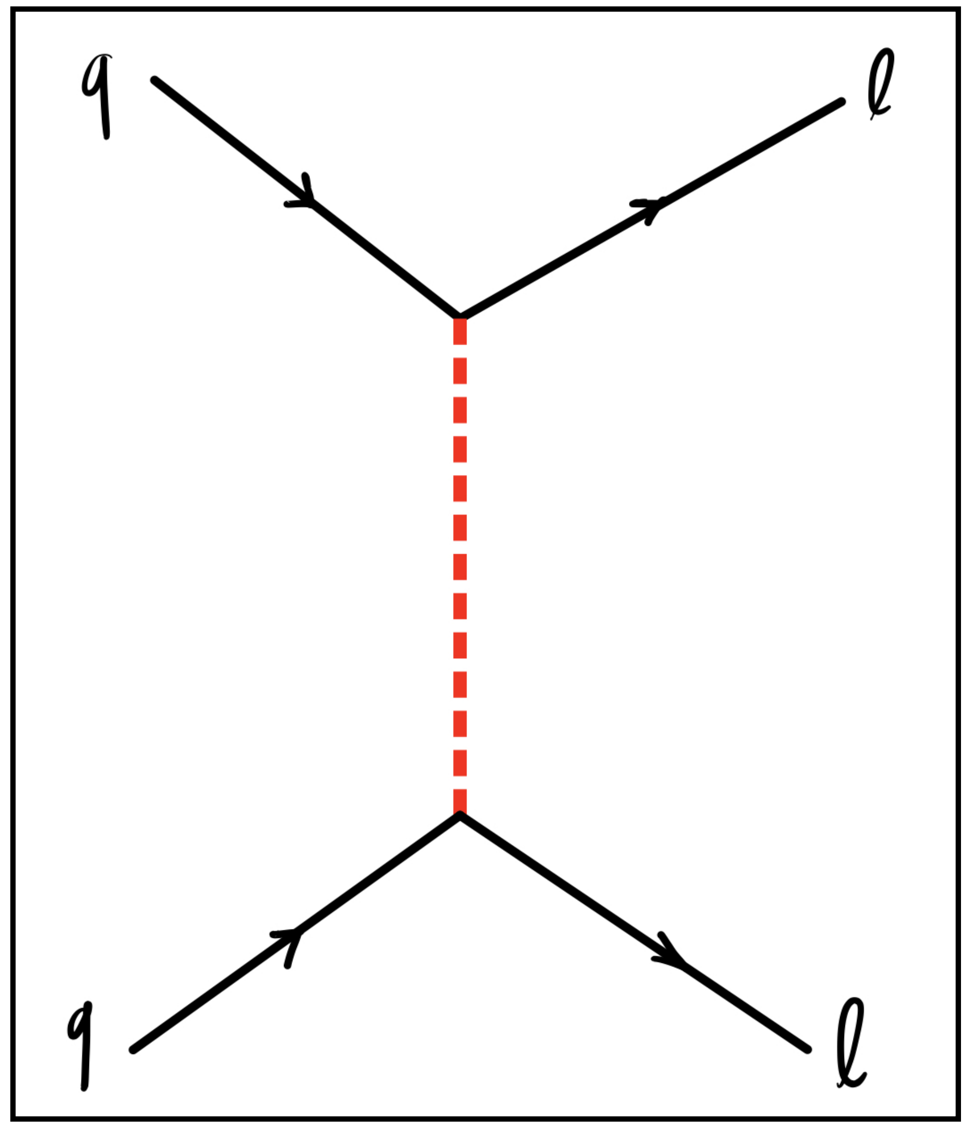
[I. Dorsner, S. Fajfer, and A. Greljo: Cornering Scalar Leptoquarks at LHC, arXiv:1406.4831]

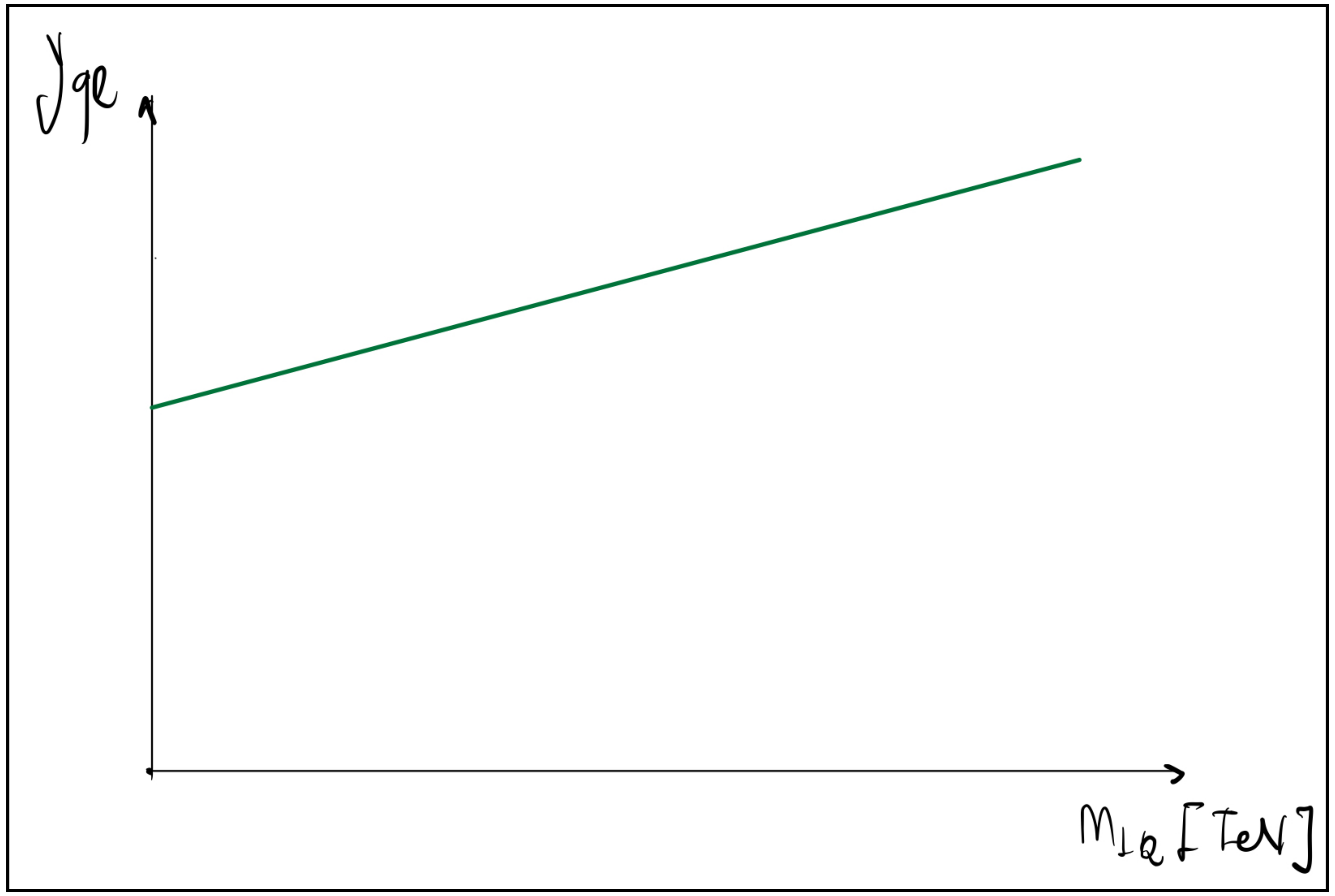
COMPARISON: Pair VS Single



[I. Dorsner, S. Fajfer, and A. Greljo: Cornering Scalar Leptoquarks at LHC, arXiv:1406.4831]

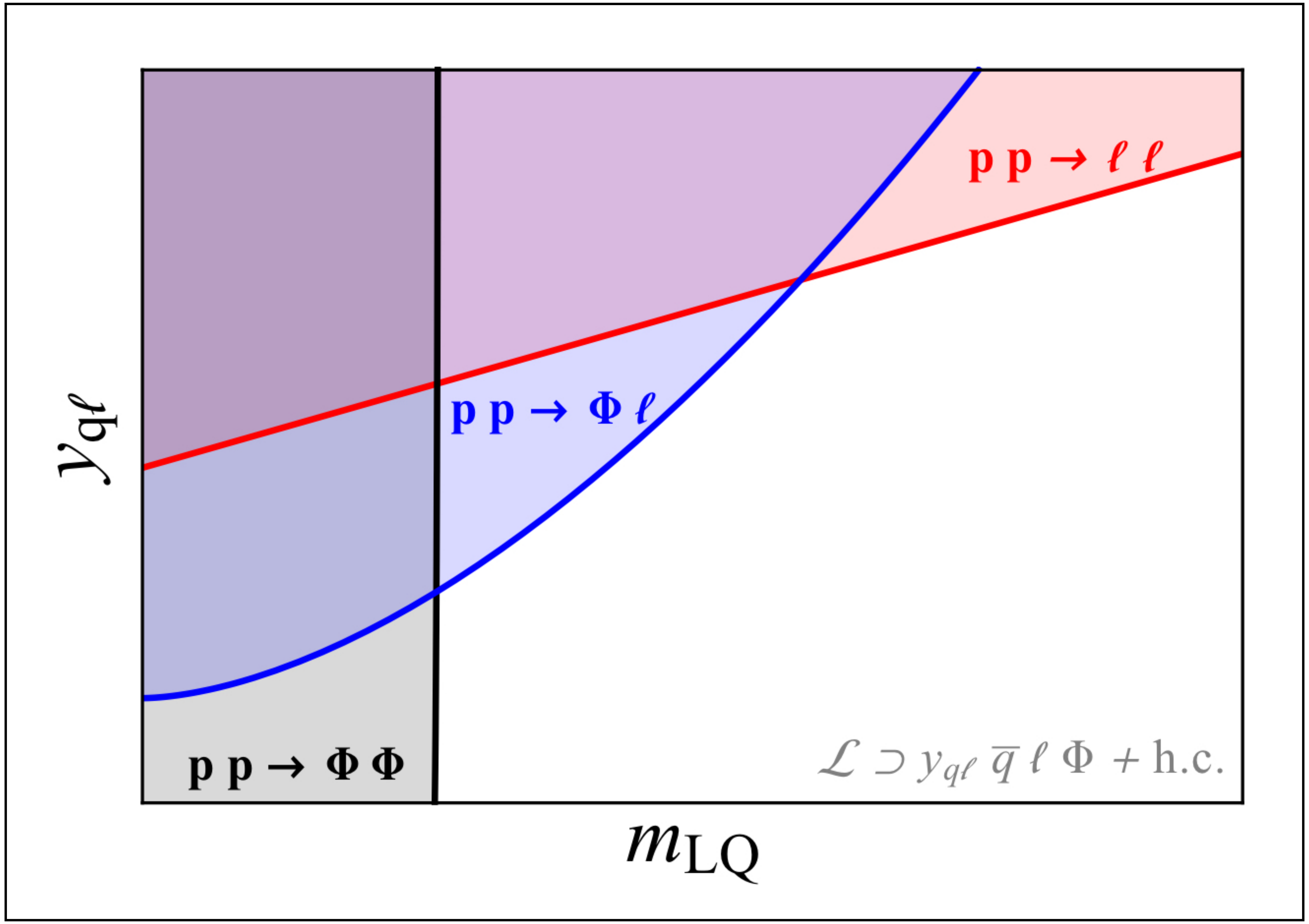
INDIRECT: Drell-Yan t-channel





[D. A. Faroughy, A. Greljo, and J. F. Kamenik: Confronting lepton flavor universality violation in B decays with high-pT tau lepton searches at LHC arXiv:1609.07138]

COMPARISON: Pair VS Single VS DY

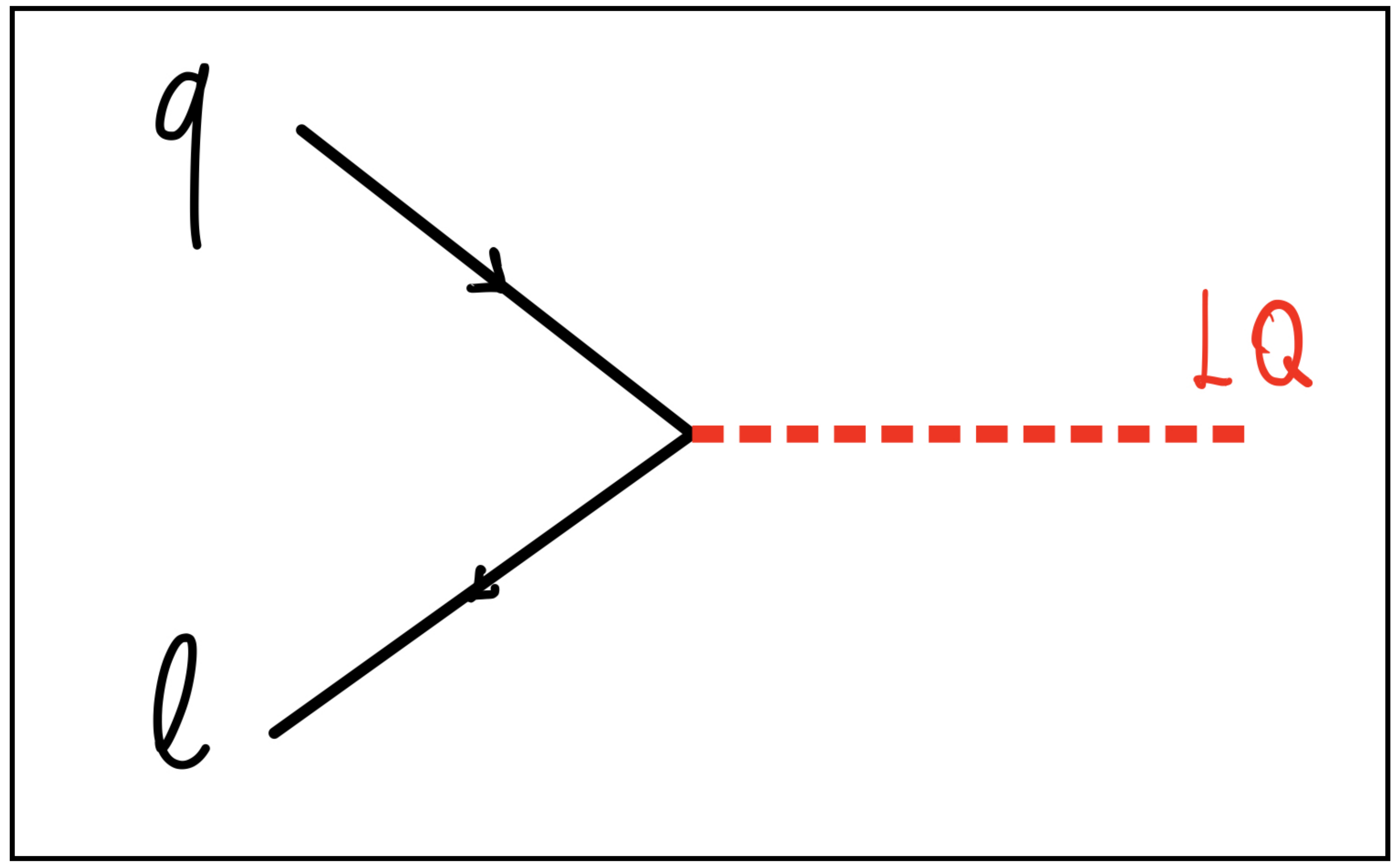


[I. Doršner and A. Greljo, Leptoquark toolbox for precision collider studies, arXiv:1801.07641]

RESONANT SINGLE PRODUCTION (RSP)

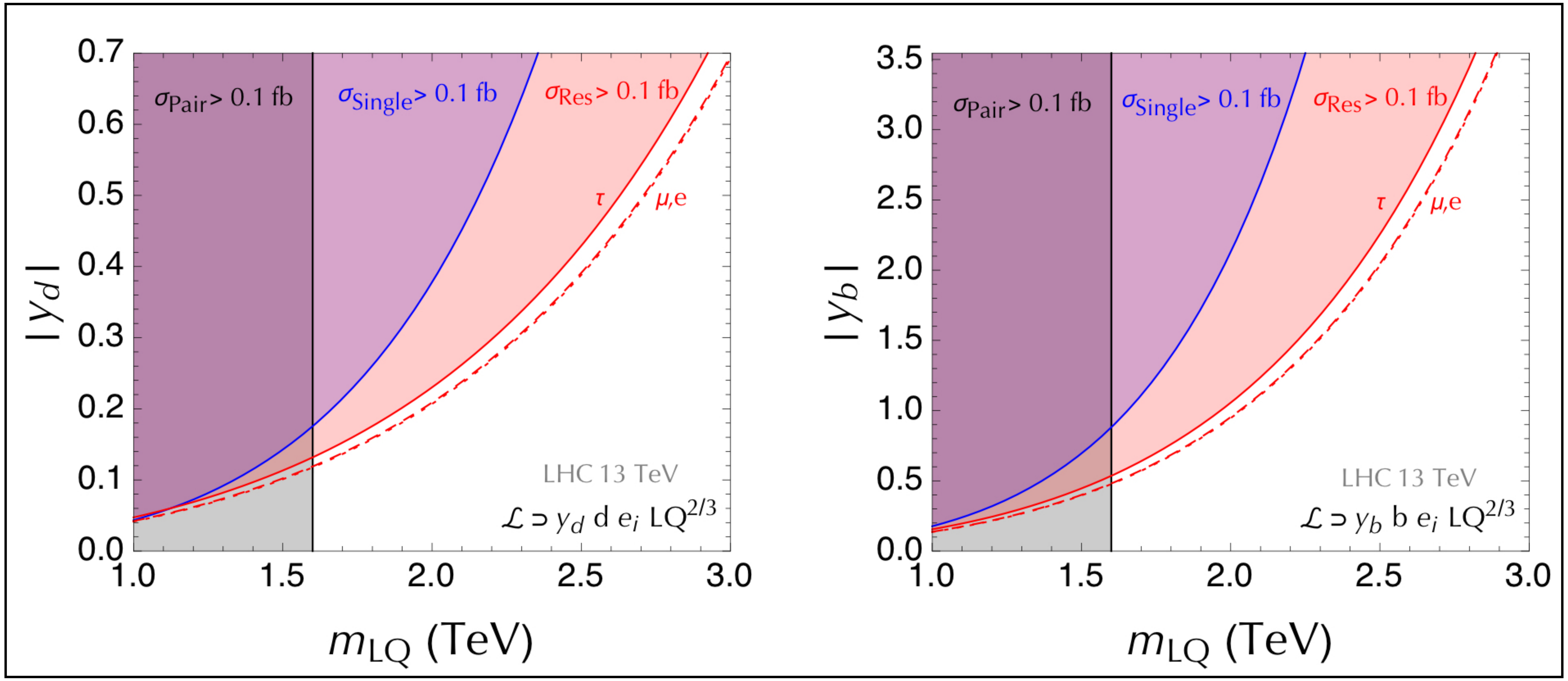
Originally:
[J. Ohnemus, S. Rudaz, T.F. Walsh, P.M. Zerwas, Single leptoquark production at hadron colliders, Physics Letters B, Volume 334, Issues 1–2, 1994]

[L. Buonocore, U. Haisch, P. Nason, F. Tramontano, and G. Zanderighi, Lepton-quark collisions at the Large Hadron Collider, arXiv:2005.06475]



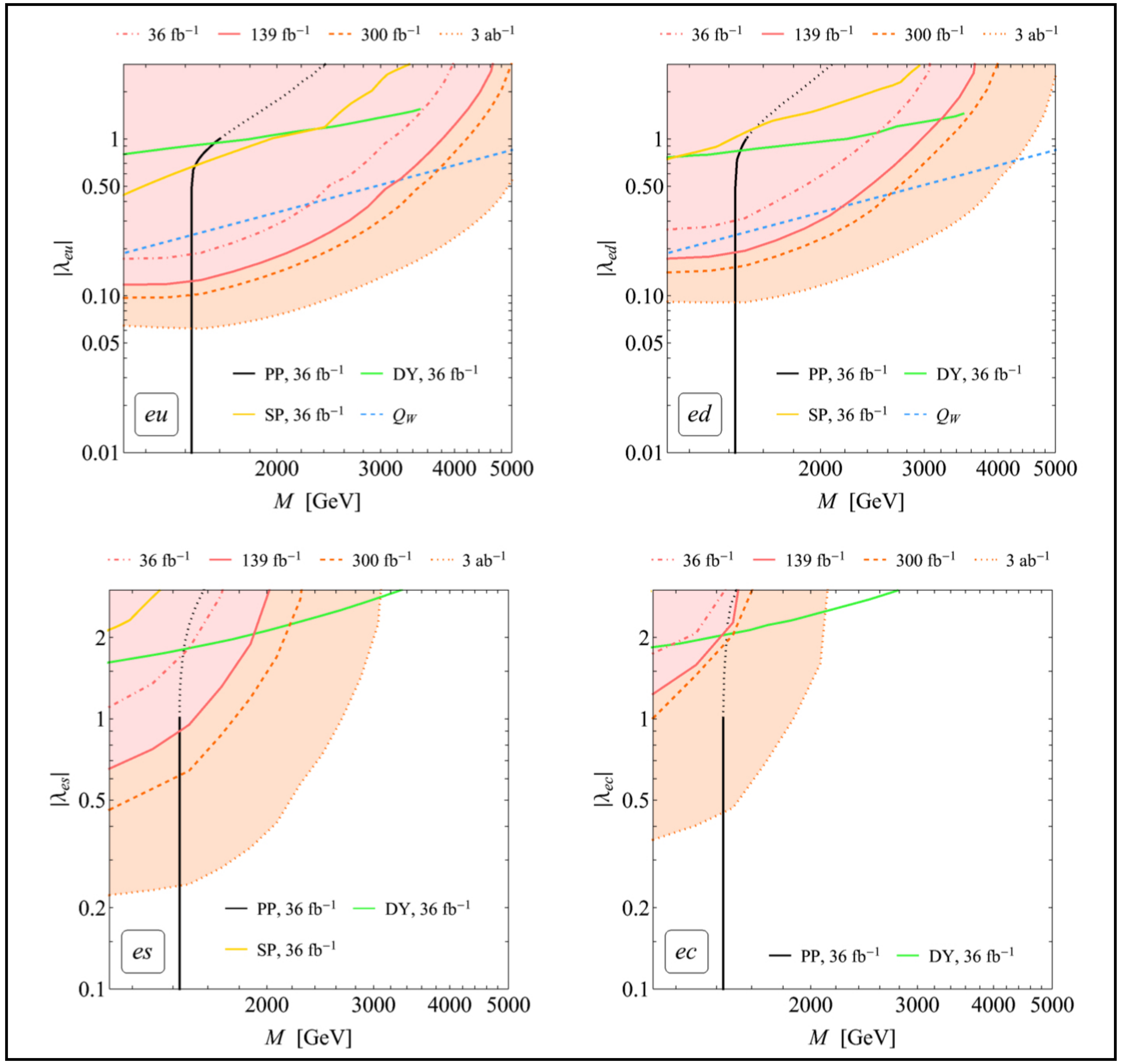
- $\sigma_R(y_{q\ell}, m_{LQ}) = a_R(m_{LQ})\,|y_{q\ell}|^2$
- *Phase-space enhancement*
- *Lepton PDF suppression*

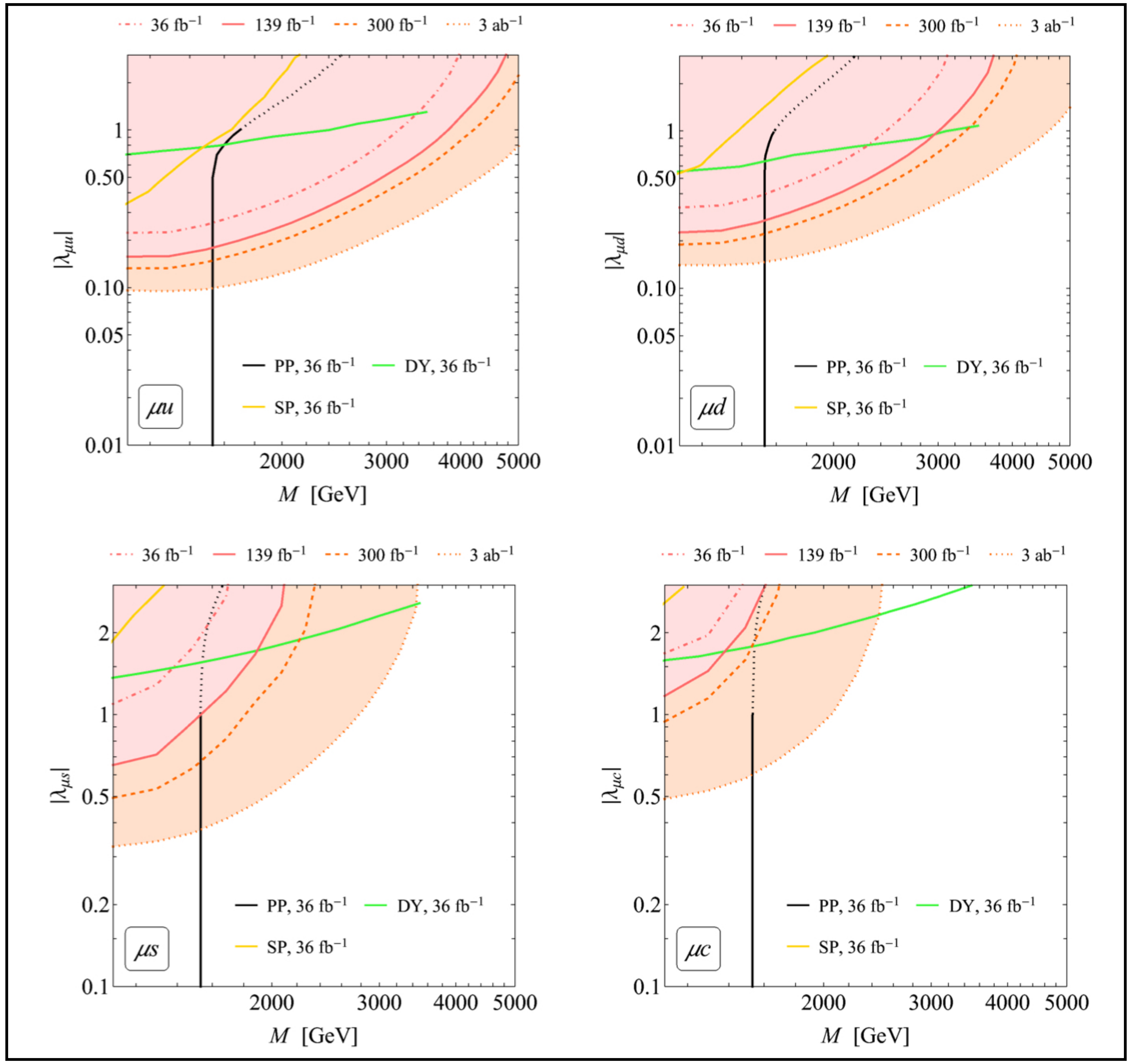
COMPARISON



- *PP*: $pp \to S^{\dagger}_{LQ} S_{LQ}$
- *SP*: $(pp \to S_{LQ}\,\ell) + c.c$
- *RSP*: $(pp \to S_{LQ}) + c.c$

RSP COLLIDER SIMULATION



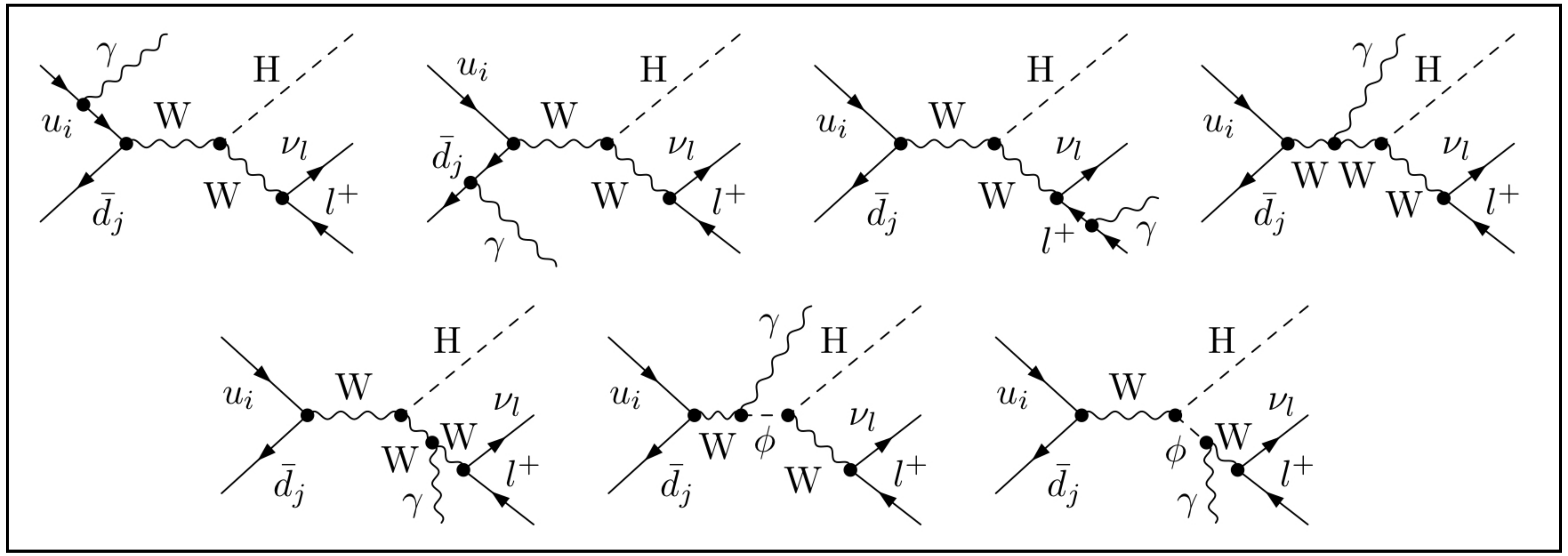


[L. Buonocore, U. Haisch, P. Nason, F. Tramontano, and G. Zanderighi, Lepton-quark collisions at the Large Hadron Collider, arXiv:2005.06475]

LUX METHOD

- *Motivation: γ - PDF limiting factor*
  - *Example: $HW^{\pm}$ production @ LHC*

[Manohar, P. Nason, G. P. Salam, and G. Zanderighi: How bright is the proton? A precise determination of the photon parton distribution function, arXiv:1607.04266].



[A. Denner, S. Dittmaier, S. Kallweit, and A. Muck, arXiv:1112.5142].

LUX METHOD

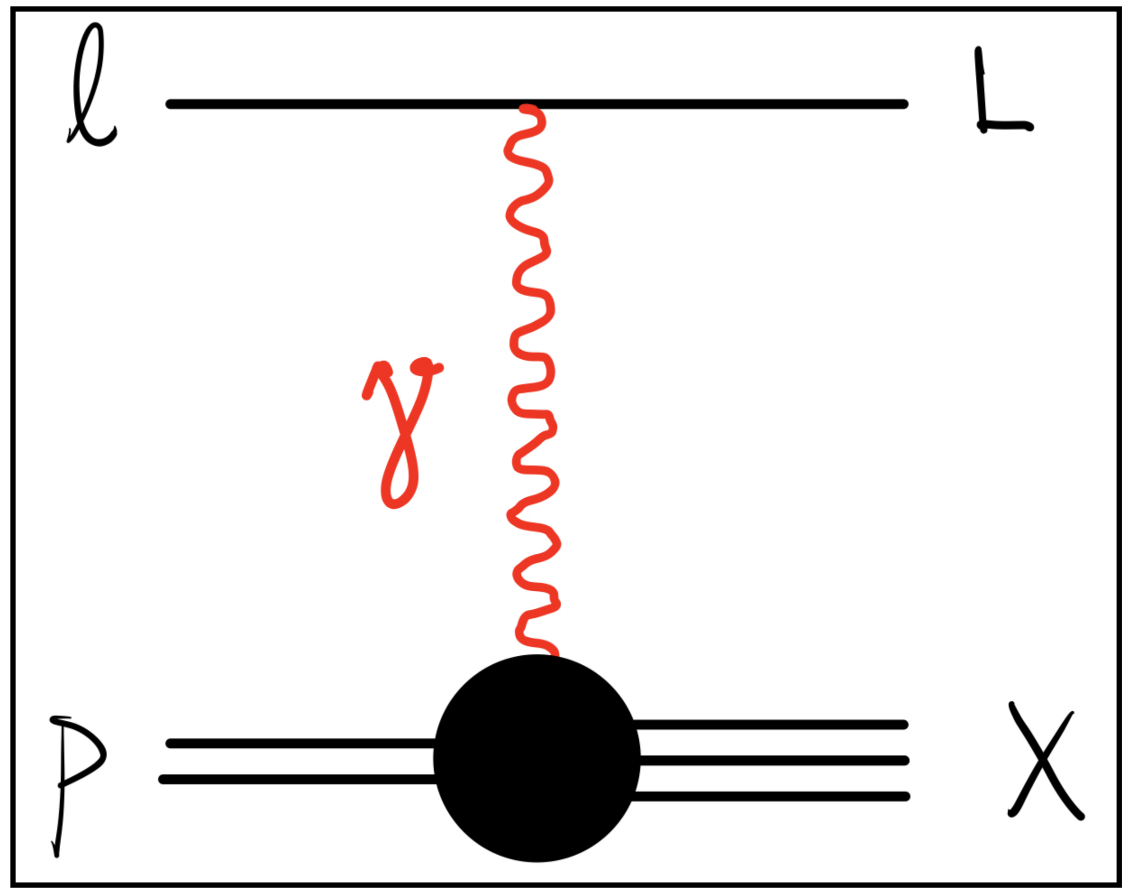
- *Idea: two different ways to think about the ep - scattering*

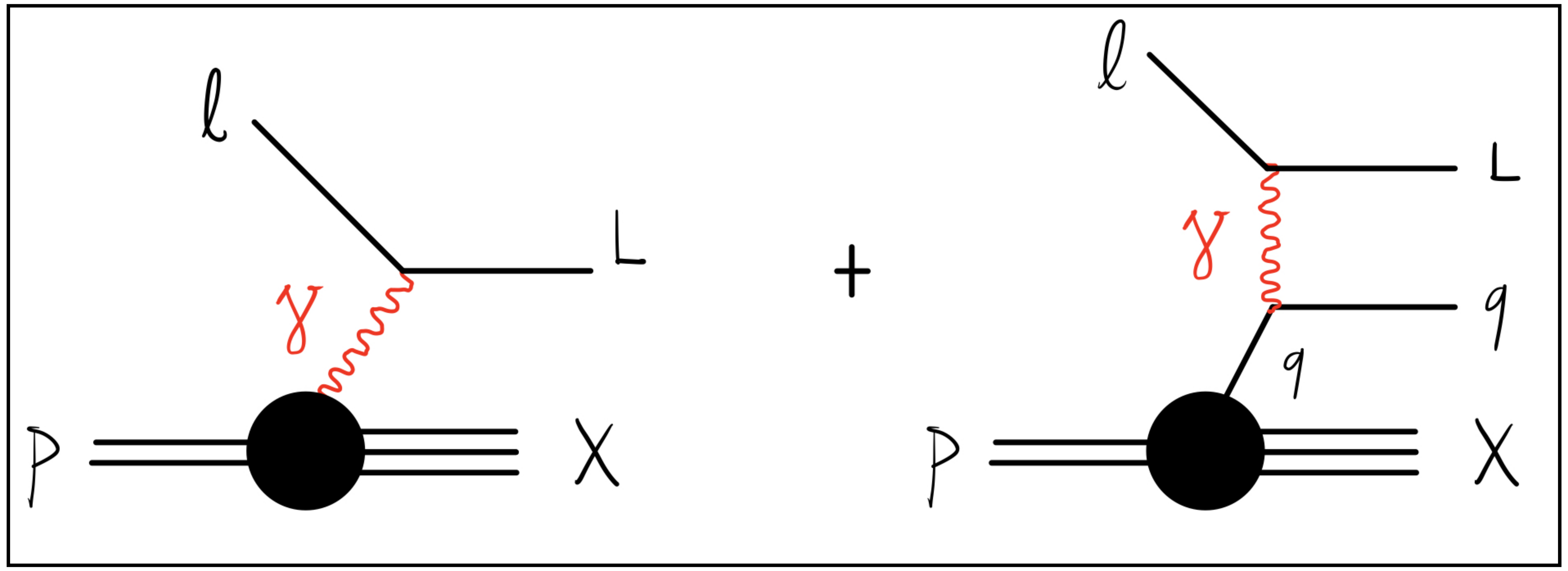
[Manohar, P. Nason, G. P. Salam, and G. Zanderighi: How bright is the proton? A precise determination of the photon parton distribution function, arXiv:1607.04266].

Deep Inelastic Scattering
(γ-emitted from e probes the proton structure)

Parton- model calculation
(e probing the photon field generated by the proton)

- *Simple fictitious process that connects the two:* $\mathscr{L}_{int} \supset \frac{e}{\Lambda}\,\bar{\ell}\,\sigma_{\mu\nu}\,F^{\mu\nu}\,L \implies \ell + p \to L + X$





~ structure functions $F_2(x, Q^2)$ & $F_L(x, Q^2)$

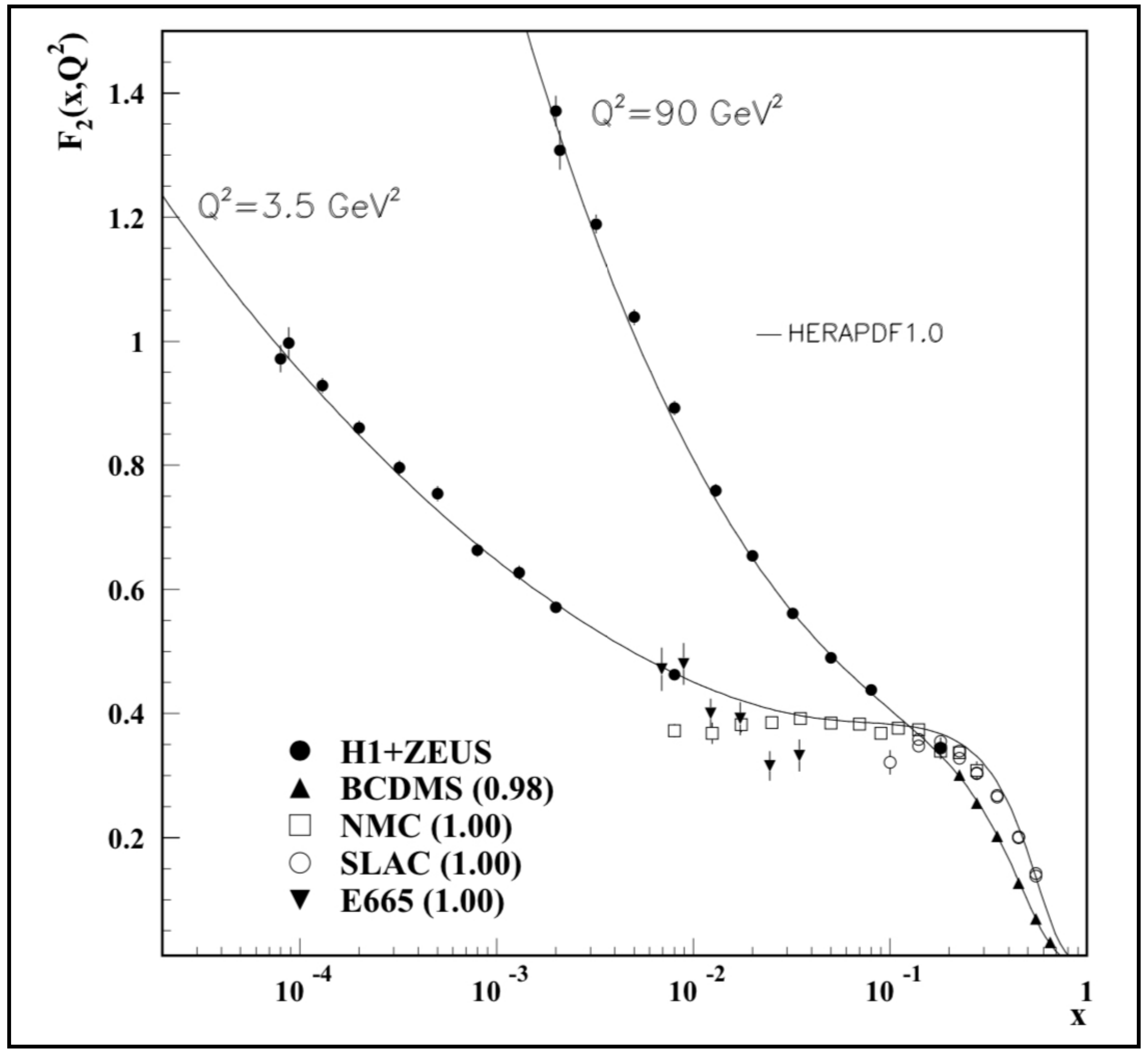
- ~ γ - *parton density distribution* f_γ

LUX METHOD

- *γ - PDF in terms of the structure functions $F_2(x, Q^2)$ & $F_L(x, Q^2)$*

$$x f_\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu)} \int_x^1 \frac{dz}{z} \left\{ \int_{Q^2_{\min}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2_{\rm ph}(-Q^2) \left[-z^2 F_L(x/z,Q^2) + \left(z p_{\gamma q}(z) + \frac{2x^2 m_{\rm p}^2}{Q^2} \right) F_2(x/z,Q^2) \right] - \alpha^2(\mu)\, z^2 F_2(x/z,\mu^2) \right\} + \mathcal{O}(\alpha\alpha_s, \alpha^2)$$

- *Long history of ep scattering experiments*



[PDG]

LUX METHOD

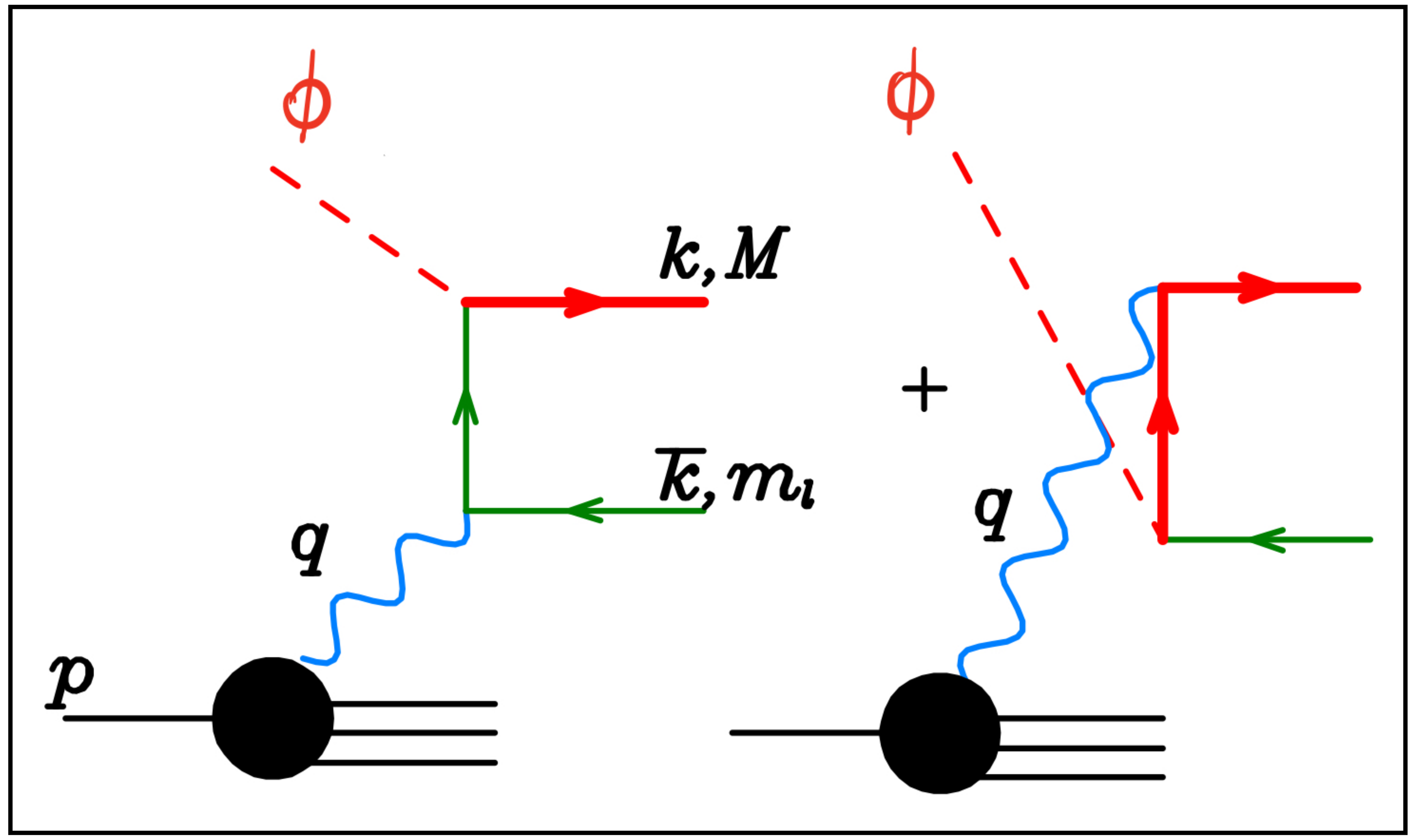
- *γ - PDF uncertainty* $< 3\,\%\ x \in [10^{-5}, 0.5]$, *better by* $\mathcal{O}(40)$
- *$\overline{MS}$ factorisation scheme*
- *Independent of the probe process*

[Manohar, A.V., Nason, P., Salam, G.P. et al. The photon content of the proton. J. High Energ. Phys. **2017,** 46]

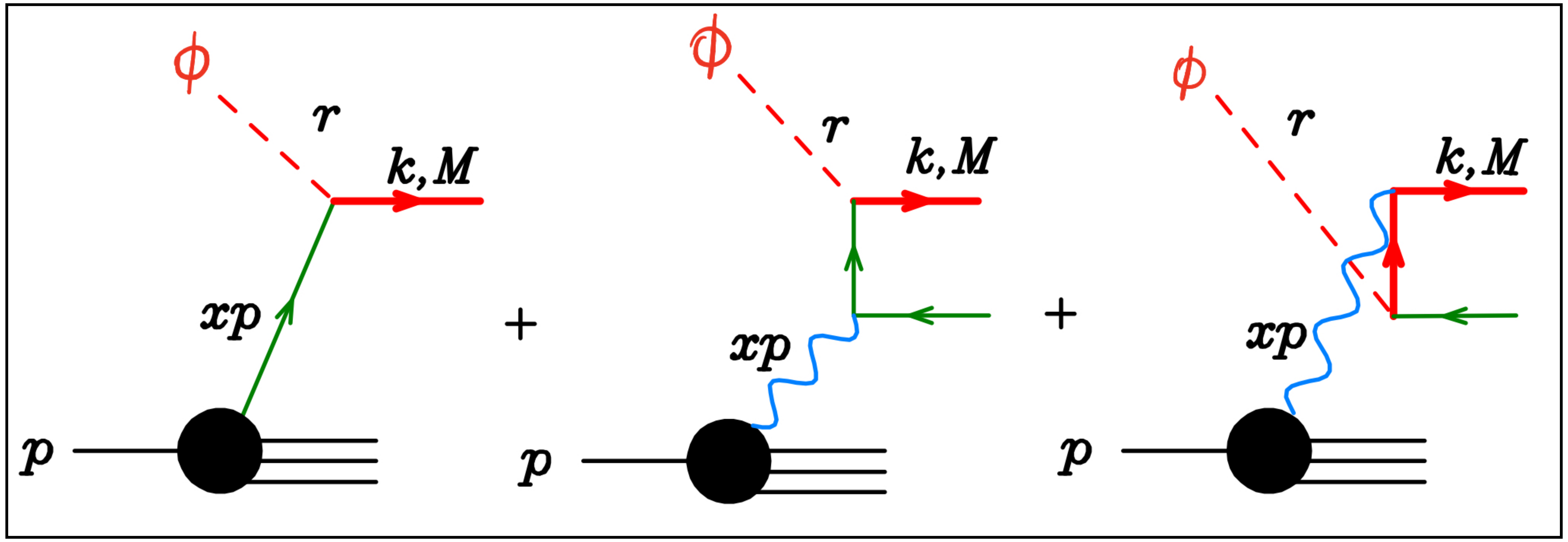
LEPTON PDFs

- *Fictitious collision determined by:* $\mathscr{L}_{int} \supset \bar{\psi}_h\, \psi\, \phi \implies \phi + p \to \psi + \psi_h$

DIS - like computation



Parton- model calculation



[L. Buonocore, P. Nason, F. Tramontano, and G. Zanderighi: Leptons in the proton, arXiv:2005.06477].

LEPTON PDFs

$$
\begin{aligned}
x_\ell f_\ell(x_\ell,\mu_F^2) &= M^2\int_0^1 \mathrm{d}x\, f_\ell(x,\mu_F^2)\,\delta(Sx-M^2)\\
&= -\frac{\alpha(\mu_F^2)}{2\pi}\int_{x_\ell}^1 \mathrm{d}x\, f_\gamma(x)\left\{z_\ell P_{\ell\gamma}(z_\ell)\left[\log\frac{M^2}{\mu_F^2}+\log\frac{(1-z_\ell)^2}{z_\ell^2}\right]+4z_\ell^2(1-z_\ell)\right\}\\
&+\left(\frac{1}{2\pi}\right)^2\int_{x_\ell}^1\frac{\mathrm{d}x}{x}z_\ell\int_x^1\frac{\mathrm{d}z}{z}\int_{\frac{m_\mathrm{p}^2x^2}{1-z}}^{\frac{E_\mathrm{cm}^2(1-z)}{z}}\frac{\mathrm{d}Q^2}{Q^2}\alpha^2(Q^2)\\
&\times\left\{P_{\ell\gamma}(z_\ell)\left[F_2\left(zP_{\gamma q}(z)+\frac{2m_\mathrm{p}^2x^2}{Q^2}\right)-F_Lz^2\right]\log\frac{M^2(1-z_\ell)}{z_\ell^3Q^2}\right.\\
&\left.+F_2\left[4(z-2)^2z_\ell(1-z_\ell)-zP_{\gamma q}(z)\right]+F_Lz^2P_{\ell\gamma}(z_\ell)-\frac{2m_\mathrm{p}^2x^2}{Q^2}F_2\right\}
\end{aligned}
$$

[L. Buonocore, P. Nason, F. Tramontano, and G. Zanderighi: Leptons in the proton, arXiv:2005.06477].

GENERALITIES

- *(SCALAR) LQs transform in the (anti)fundamental representation of* $SU(3)$
  - *Interaction with gluons completely specified* $\Longrightarrow$ *NLO QCD*
- *Various* $SU(2)_L \times U(1)_Y$ *multiplets possible*
  - *Interested only interaction with a photon after the EWSB*

$$|Q_{LQ}| = \{1/3,\ 2/3,\ 4/3,\ 5/3\}$$

$\Longrightarrow$ *NLO QED*

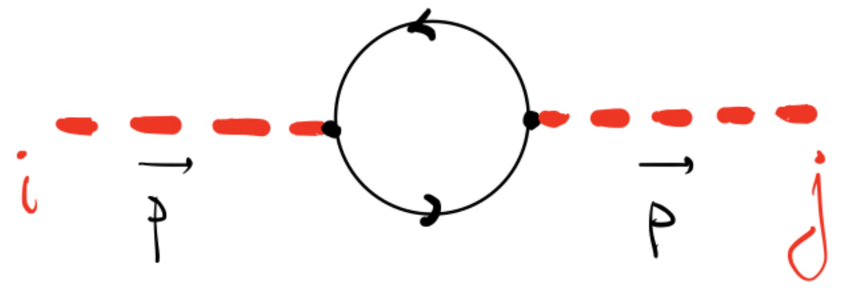
- *SM fermion content:*

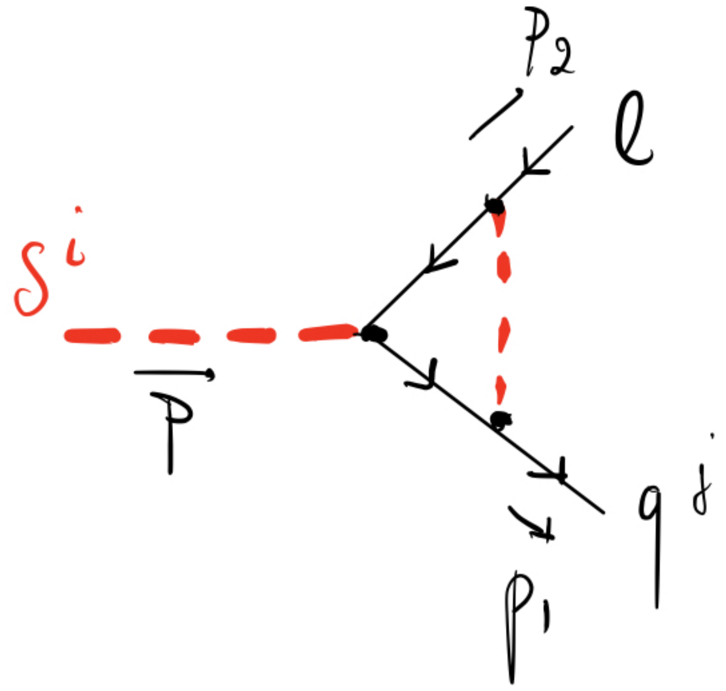
$$\mathcal{L} \supset -y^L_{q\ell}\, \bar{q} P_L \ell\, S_{Q_{\rm LQ}} - y^R_{q\ell}\, \bar{q} P_R \ell\, S_{Q_{\rm LQ}} + \text{ h.c.}$$

  - $q_{L,R}$, $\ell_{L,R}$ *charge and mass eigenstates*
  - *Access to* $u_{L,R}$, $d_{L,R}$, $s_{L,R}$, $c_{L,R}$, $b_{L,R}$, $e_{L,R}$, $\mu_{L,R}$, $\tau_{L,R}$

GENERALITIES

- $t_{L,R}$ - too heavy, ν - not created in photon splitting, higher order effect
- Massless fermions (corrections $\mathcal{O}(m_f/\sqrt{s})$ - negligible)
    - No $y^L_{q\ell}$ and $y^R_{q\ell}$ interference
    - All 1-loop corrections $\sim |y_{q\ell}|$ vanish





$$= -|Y^L_{q\ell}|^2 \delta^{ij} \int \frac{d^dk}{(2\pi)^d} \frac{P_L (\not{k}+\not{p}) P_L \not{k}}{k^2 (k+p)^2} = 0$$

$$= -|Y^L_{q\ell}|^2 \delta^{ij} \int \frac{d^dk}{(2\pi)^d} \frac{\bar{u}_q(p_1) P_L (\not{k}+\not{p}_1) P_L (\not{k}-\not{p}_2) P_L v_\ell(p_2)}{(k+p_1)^2 (k-p_2)^2 (k^2-m_{LQ}^2)} = 0$$

- RSP specified by 1 entry in the Yukawa matrix
- If several flavours contribute $\hat{\sigma} = \sum_{q,\ell} |y_{q\ell}|^2 \hat{\sigma}_{q\ell}$

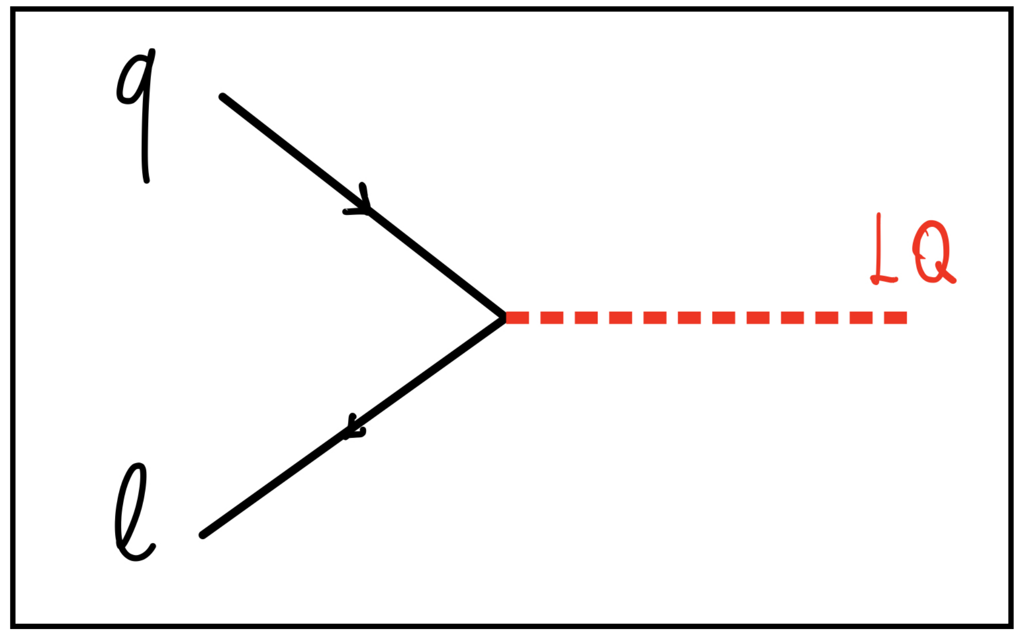
SIZE OF THE NLO CORRECTIONS

- *Hadronic cross-section:*

$$\sigma(s) = 2 \sum_{ij} \int_{\xi}^{1} dy\, f_i(y) \int_{\xi/y}^{1} dz\, \frac{\xi}{yz^2}\, f_j\left(\frac{\xi}{yz}\right)\, \hat{\sigma}_{ij}(z)$$

  - *Size set by* $f_{i,j}$ *and* $\hat{\sigma}_{ij}$
  - $\xi = m_{LQ}^2/s$, $z = m_{LQ}^2/\hat{s}$, y *- fraction of proton momentum by parton "i"*
  - $\{ij\} = \{q\ell,\, g\ell,\, q\gamma\}$

- *Leading order size:*



$$\sigma_{LO}(s) \sim \int \underbrace{(f_q \otimes f_\ell)}_{\mathcal{O}(?)} \overbrace{|y_{ql}|}^{\mathcal{O}(1)}{}^2$$

SIZE OF THE NLO CORRECTIONS

- *Power counting (in α_s):*

$$f_q \sim f_g \sim \mathcal{O}(\sum_n (\alpha_s L)^n) \sim \mathcal{O}(1)$$

$\alpha_s \sim 1/L$ $\quad L = \log(\mu_F^2/\Lambda^2)$ $\quad \mu_F$ *- factorisation scale* $\quad \Lambda$ *- hadronic scale*

- *QED coupling size: $\alpha \sim \alpha_s^2$*

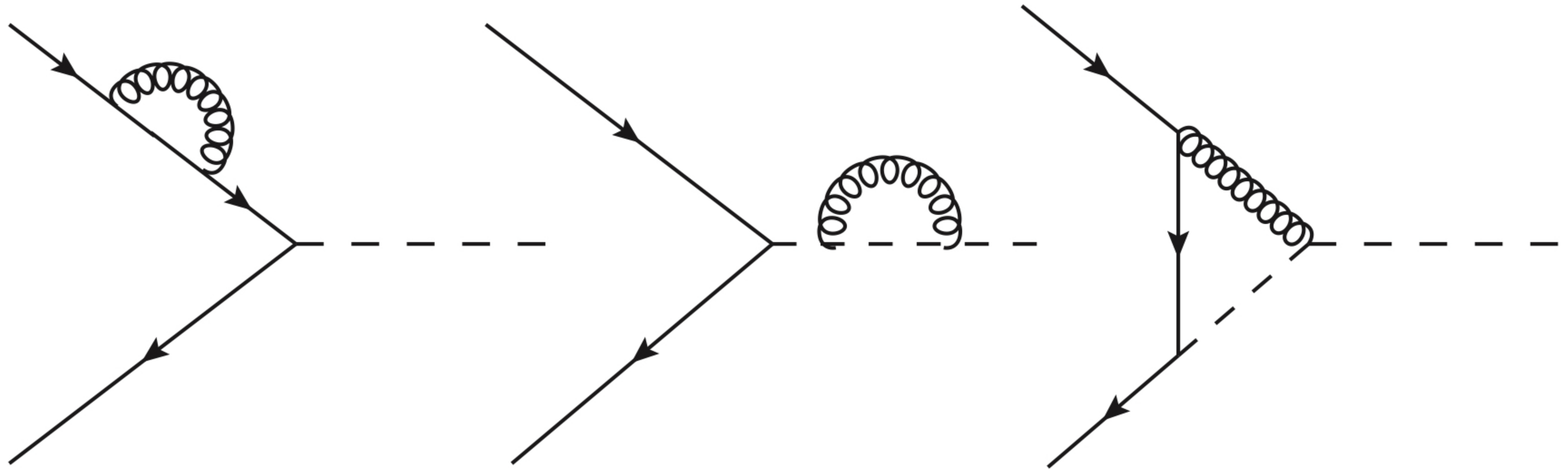
  - *γ - PDF, 1st order QED effect: $f_\gamma \sim \mathcal{O}(\alpha L) \sim \mathcal{O}(\alpha_s)$*
  - *ℓ - PDF, 2nd order QED effect: $f_\ell \sim \mathcal{O}((\alpha L)^2) \sim \mathcal{O}(\alpha_s^2)$*

- *Leading order size:* $\sigma_{LO}(s) \sim \int (f_q \otimes f_\ell) |y_{ql}|^2 \sim 1 \times \alpha_s^2 \times 1 \sim \alpha_s^2$

- *Typical NLO QCD correction:* $\sim \mathcal{O}(\alpha_s^3)$

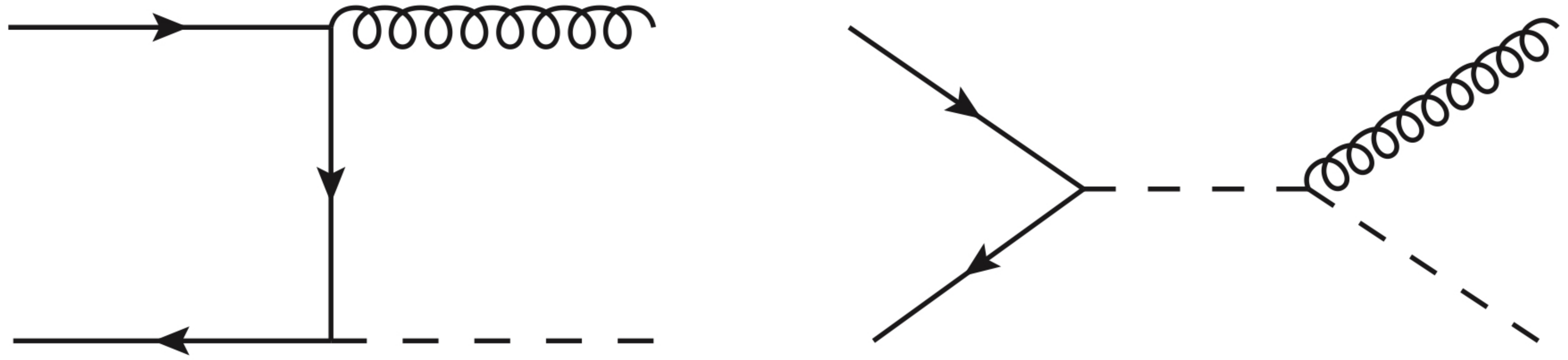
SIZE OF THE NLO QCD CORRECTIONS

Virtual corrections

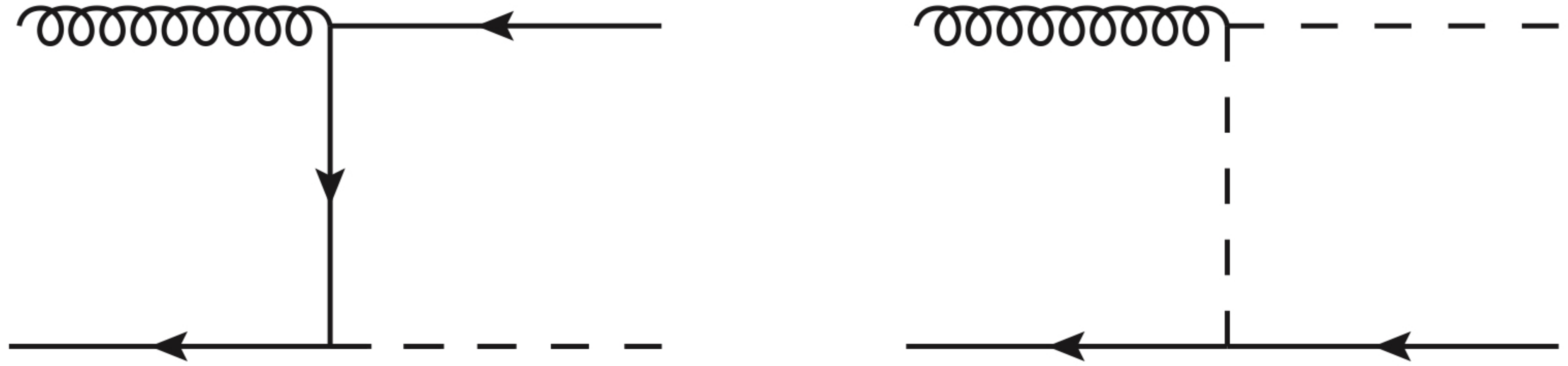


$q \ + \ \ell \rightarrow \ LQ$, *gluon dressed*

Real radiation

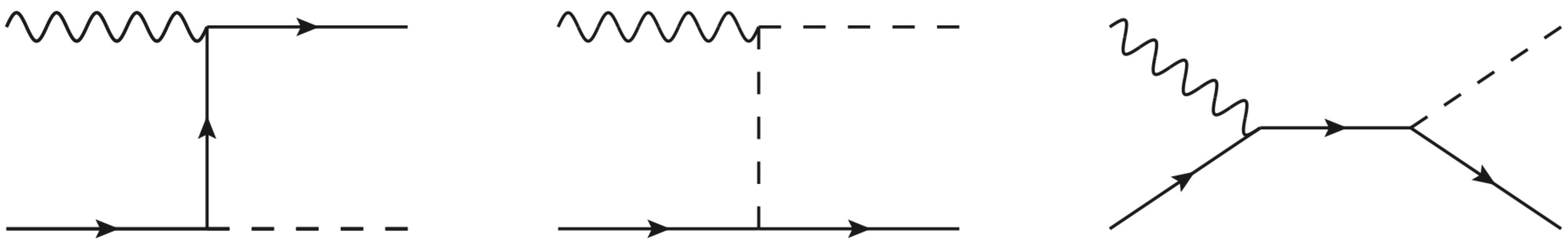


$q \ + \ \ell \rightarrow \ LQ$ + *soft gluon*



$g \ + \ \ell \ \rightarrow \ LQ$ + *soft quark*

SIZE OF THE NLO QED CORRECTIONS



$q \;+\; \gamma \rightarrow\;$ *LQ + soft lepton*

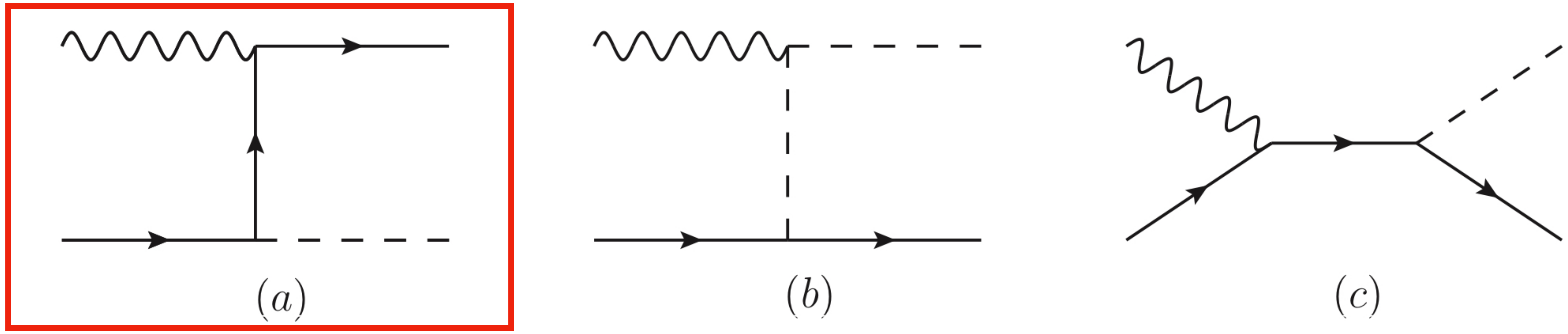
Size: $\sigma_{q\gamma}(s) \sim \int (f_q \otimes f_\gamma)\ \hat{\sigma}_{q\gamma} \sim 1 \times \alpha_s \times \alpha \sim \alpha_s^3$

NLO QED CALCULATION

- *LQ non-universal (depend on electric charge, in contrast to QCD corrections)*

$$\bar{u} + e^+ \longrightarrow S_{1/3}$$
$$d + e^+ \longrightarrow S_{2/3}$$
$$\bar{d} + e^+ \longrightarrow S_{4/3}$$
$$u + e^+ \longrightarrow S_{5/3}$$

Source of collinear divergence,
ℓ parallel to γ



$$q + \gamma \rightarrow LQ + \ell$$

$$i\mathcal{M} = -iy_{q\ell}\, e\, \bar{u}(k)\mathrm{P}_{L,R}\left[\boxed{\gamma^\mu \frac{(\not{p}_1 - \not{k})}{(p_1-k)^2}} + Q_{\mathrm{LQ}}\frac{(2q-p_1)^\mu}{(q-p_1)^2 - m^2} + Q_{\mathrm{q}}\frac{(\not{p}_1 + \not{p}_2)}{(p_1+p_2)^2}\gamma^\mu\right]\zeta(p_2)\epsilon_\mu(p_1)$$

NLO QED CALCULATION

- *Centre of mass frame kinematics:*

$q \qquad \ell$

$$p_1^\mu = \frac{\sqrt{\hat{s}}}{2}(1,0,0,1), \quad p_2^\mu = \frac{\sqrt{\hat{s}}}{2}(1,0,0,-1), \quad k = \frac{\sqrt{\hat{s}}}{2}(1-z)(1,0,\sin\theta,\cos\theta)$$

γ

$$z = m_{LQ}^2\,, \; \hat{s} = (p_1 + p_2)^2\,, \; \hat{t} = (p_1 - k)^2$$

- *Defining:* $w = (1-\cos\theta)/2 \quad \Longrightarrow \quad \hat{t} = -\,\hat{s}w(1-z)$
- *Collinear divergences regulated in Dimensional regularisation with* $d = 4 - 2\epsilon$
- *Averaged squared matrix element:*

$$|\overline{\mathcal{M}}|^2 = \frac{|y_{q\ell}|^2 e^2}{d-2}\left(\boxed{\mathcal{M}_{\text{div}}^2} + \mathcal{M}_{\text{fin}}^2\right)$$

Diagram (a) or its interference

NLO QED CALCULATION

$$\mathcal{M}^2_{\text{div}} = \frac{1}{w}\left[\frac{d-2}{2(1-z)} + 2Q_{\text{q}}z + Q_{\text{LQ}}\left(1 - \frac{1+2z}{1-w(1-z)}\right)\right],$$

$$\mathcal{M}^2_{\text{fin}} = \frac{(1-w)(1-z)}{1-w(1-z)}\left[Q^2_{\text{LQ}}\left(1 - \frac{2z}{1-w(1-z)}\right) - Q_{\text{q}}Q_{\text{LQ}}\left(1-2z\right)\right] + Q_{\text{q}}\left(d-2(1+z)\right) - Q_{\text{LQ}}\left(1-\frac{1+2z}{1-w(1-z)}\right) + \frac{d-2}{2}Q^2_{\text{q}}w(1-z)$$

- *Integrate over the phase-space:*

$$\frac{1}{16\pi\hat{s}}\left(\frac{4\pi\mu^2}{\hat{s}}\right)^{\frac{4-d}{2}}\int_0^1 |\overline{\mathcal{M}}|^2 \frac{\left[w(1-w)\right]^{\frac{d-4}{2}}(1-z)^{d-3}}{\Gamma(\frac{d-2}{2})}\,dw$$

- $\mathcal{M}^2_{fin}$ *safe for* $d = 4$*:*

$$\hat{\sigma}_{\text{fin}} = \frac{\pi|y_{q\ell}|^2}{4\hat{s}}\frac{\alpha}{2\pi}\left[Q_{\text{q}}Q_{\text{LQ}}(1-2z)(z - z\log z - 1) + Q^2_{\text{LQ}}(1+z-2z^2+3z\log z) + 2Q_{\text{q}}\left(1+\frac{Q_{\text{q}}}{4}\right)(1-z)^2 + Q_{\text{LQ}}(z-(1+2z)\log z - 1)\right]$$

NLO QED CALCULATION

- $\mathscr{M}^2_{\text{div}}$ *in* $d = 4 - 2\epsilon$*:*

$$\hat{\sigma}_{\text{div}} = \frac{\pi |y_{q\ell}|^2}{4\hat{s}} \frac{\alpha}{2\pi} \left(\frac{4\pi\mu^2}{\hat{s}}\right)^{\epsilon} \frac{1}{\Gamma(1-\epsilon)} \int w^{-1-\epsilon}(1-w)^{-\epsilon}(1-z)^{1-2\epsilon}\mathcal{F}(w,z)dw\,,$$

$$\mathcal{F}(w,z) = \frac{1}{1-z} + (1+\epsilon)\left[2Q_{\text{q}}z + Q_{\text{LQ}}\left(1 - \frac{1+2z}{1-w(1-z)}\right)\right].$$

- *Divergence explicit after:* $w^{-1-\epsilon} = -\frac{1}{\epsilon}\delta(w) + \frac{1}{w_+} + \mathcal{O}(\epsilon)$

Plus distribution: $\int_0^1 \frac{f(1-w)}{w_+} dw = \int_0^1 \frac{f(1-w) - f(1)}{w} dw$

$$\boxed{\begin{aligned}\hat{\sigma}_{\text{div}} = \frac{\pi |y_{q\ell}|^2}{4\hat{s}} \frac{\alpha}{2\pi} \left(\frac{4\pi\mu^2}{\hat{s}}\right)^{\epsilon} \frac{1}{\Gamma(1-\epsilon)} \Bigg[-\frac{1}{\epsilon}\left(\boxed{1 + 2(Q_{\text{q}} - Q_{\text{LQ}})z(1-z)}\right) + 2\log(1-z) \\ + Q_{\text{LQ}}(1-z)(1+2z)\log z - 2(Q_{\text{q}} - Q_{\text{LQ}})z(1-z)(1-2\log(1-z))\Bigg]\end{aligned}}$$

Divergence universal: $P_{\ell\leftarrow\gamma}(z) = z^2 + (1-z)^2$

PDF RENORMALISATION

- *Only hadronic cross-section $\sigma_{q\gamma}$ is physical (measurable)*
- *When convoluting with PDFs, absorb the collinear singularity into the "bare" PDFs*
  - *At factorisation scale μ_F*
  - *$\overline{MS}$ - factorisation scheme (no choice here)*

$$\hat{\sigma}^{CT} = \frac{\pi |y_{q\ell}|^2}{4\hat{s}} \frac{\alpha}{2\pi} (4\pi)^\epsilon \frac{1}{\epsilon \Gamma(1-\epsilon)} P_{\ell \leftarrow \gamma}(z)$$

Universal log

- *Finite result:* $\hat{\sigma}_{q\gamma} = \frac{\pi z |y_{q\ell}|^2}{4 m_{\mathrm{LQ}}^2} \frac{\alpha}{2\pi} \left(\boxed{-\log \left(\frac{z\, \mu_{\mathrm{F}}^2}{(1-z)^2 m_{\mathrm{LQ}}^2} \right) (z^2 + (1-z)^2)} + X_{Q_{\mathrm{LQ}}}(z) \right)$

$$X_{1/3}(z) = -\frac{2}{9}(1-z)(5-13z) + \frac{2}{9}(1-5z) z \log z$$

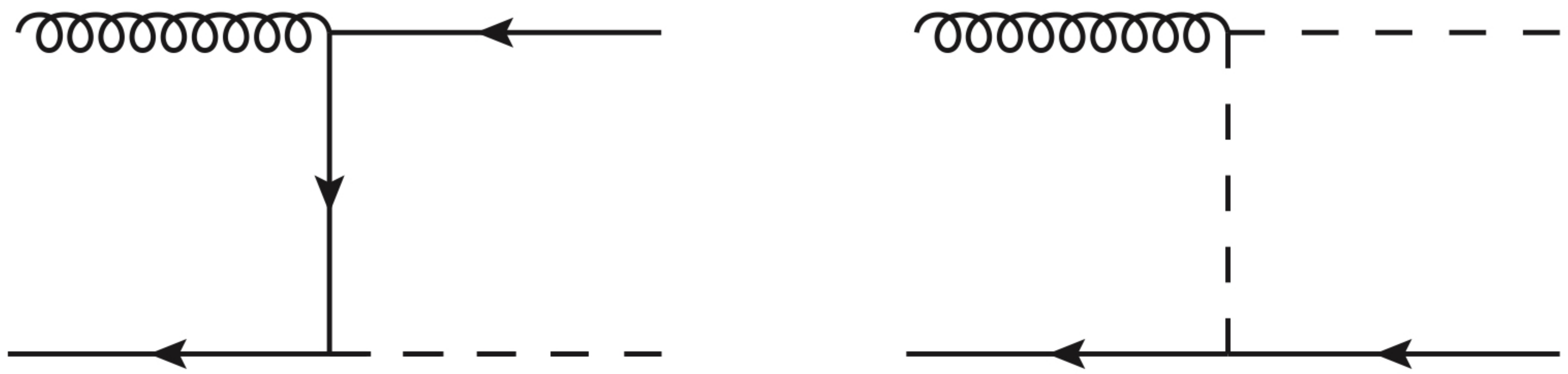
$$X_{2/3}(z) = -\frac{11}{18}(1-z)(1-5z) + \frac{8}{9}(1-2z) z \log z$$

$$X_{4/3}(z) = \frac{1}{18}(1-z)(13+103z) + \frac{16}{9}(2-z) z \log z$$

$$X_{5/3}(z) = \frac{2}{9}(1-z)(7+37z) + \frac{10}{9}(5-z) z \log z$$

NLO QCD CALCULATION

- *Completely analogous situation with gluon in the initial state (same structure of the correction)*



$g \;+\; \ell \;\rightarrow\; LQ \;+$ *soft quark*

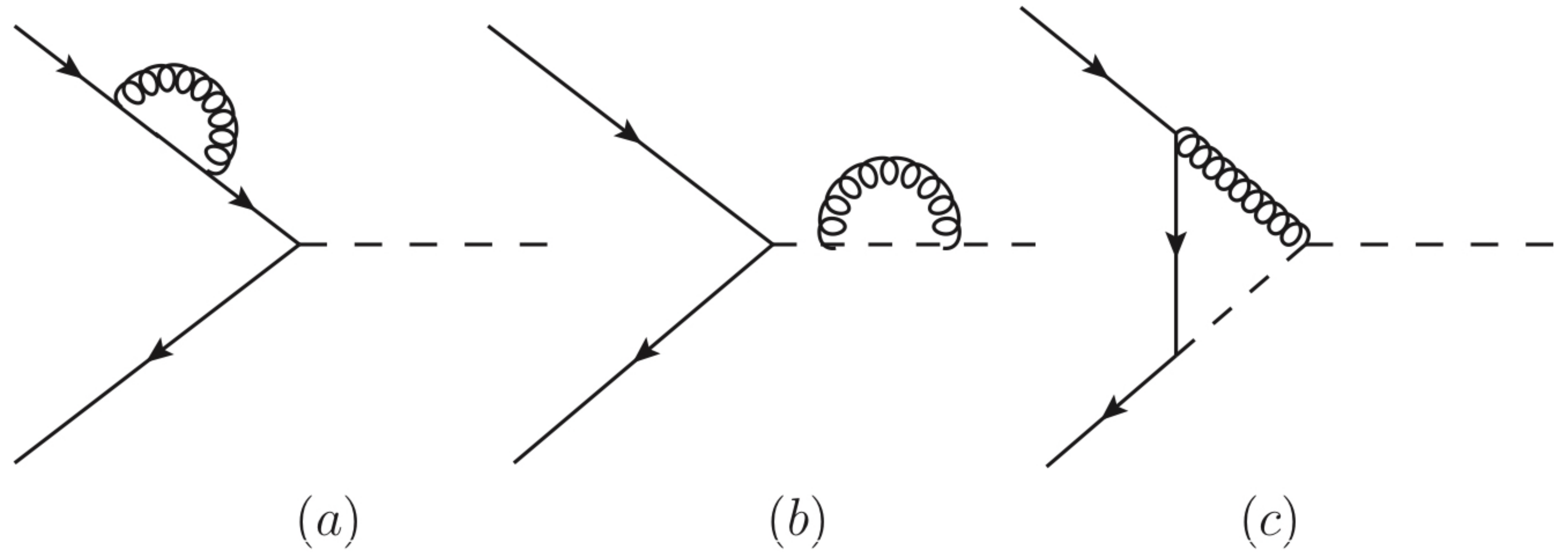
$$\hat{\sigma}_{g\ell}(z) = \frac{\pi z |y_{q\ell}|^2}{4 m_{\mathrm{LQ}}^2} \frac{\alpha_s}{2\pi} T_R \left[\boxed{ -\log\left(\frac{z \mu_{\mathrm{F}}^2}{(1-z)^2 m_{\mathrm{LQ}}^2} \right) (z^2 + (1-z)^2) } + 2z(1-z)(2 + \log z) \right]$$

The same log

- *New things appear in virtual corrections*

NLO QCD CALCULATION

- *Gluon loops: a) quark wave-function, b) LQ wave-function, c) $q - \ell - LQ$ vertex*



[J. Fuentes-Martín, G. Isidori, M. König, and N. Selimovic: Vector leptoquarks beyond tree level. II. O(as) corrections and radial modes, arXiv:2006.16250].

$$\mathcal{A}_{\rm NLO} = \mathcal{A}_{\rm tree}\left[1 + \frac{\alpha_s}{4\pi}\left(\frac{1}{2}\delta Z_{\rm q}(0) + \frac{1}{2}\delta Z_{\rm LQ}(m_{\rm LQ}^2) + \delta V_{\rm LQ}(m_{\rm LQ}^2)\right)\right]$$

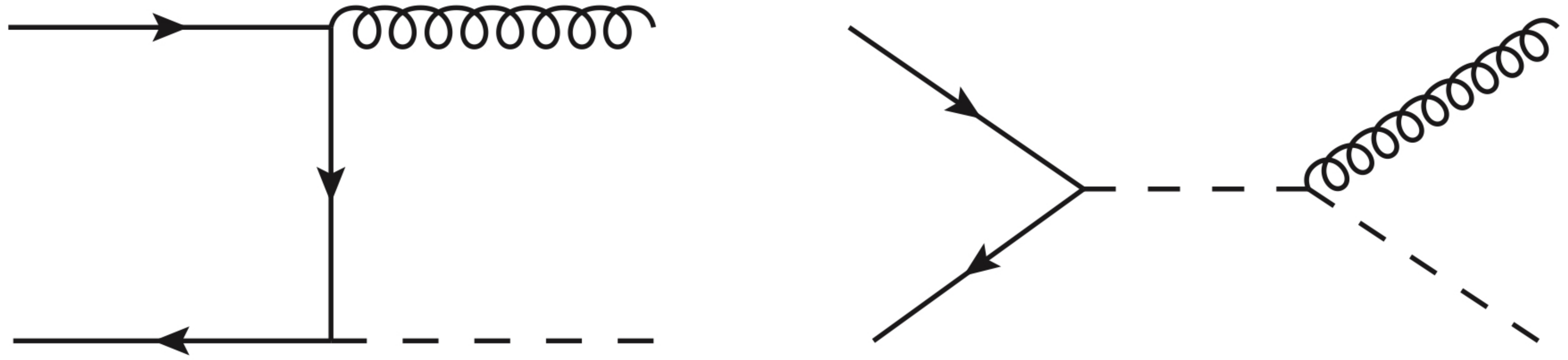
- *LQ mass renormalised on-shell*
- *Virtual correction:*

$$\boxed{L_\mu^{IR(UV)} = \log(\mu_{F(R)}/m_{LQ}^2)}$$

$$\hat{\sigma}^V(z) = \frac{\pi z |y_{q\ell}|^2}{4m_{\rm LQ}^2}\left\{1 + \frac{\alpha_s}{2\pi}C_F\left[\frac{3}{2}L_\mu^{\rm UV} - \underbrace{\frac{5}{2}\left(\frac{1}{\epsilon_{\rm IR}} + L_\mu^{\rm IR}\right)} - \frac{1}{\epsilon_{\rm IR}^2} - \underbrace{\frac{1}{\epsilon_{\rm IR}}L_\mu^{\rm IR} - \frac{1}{2}}\left(L_\mu^{\rm IR}\right)^2 - \frac{\pi^2}{12} - 2\right]\right\}\delta(1-z)$$

NLO QCD CALCULATION

- *IR divergences from virtual loops and real radiation cancel:*



$q + \ell \rightarrow$ LQ + soft gluon

$$\hat{\sigma}^R(z) = \frac{\pi z |y_{q\ell}|^2}{4m_{\mathrm{LQ}}^2}\frac{\alpha_s}{2\pi}C_F\left\{\delta(1-z)\left[-\frac{3}{2}L_\mu^{\mathrm{IR}} + \frac{5}{2}\underbrace{\left(\frac{1}{\epsilon_{\mathrm{IR}}} + L_\mu^{\mathrm{IR}}\right)} + \underbrace{\frac{1}{\epsilon_{\mathrm{IR}}^2} + \frac{1}{\epsilon_{\mathrm{IR}}}L_\mu^{\mathrm{IR}} + \frac{1}{2}\left(L_\mu^{\mathrm{IR}}\right)^2} - \frac{\pi^2}{4} + 2\right]\right.$$
$$\left. + 2(1+z^2)\left(\frac{\log(1-z)}{(1-z)}\right)_+ - \frac{2z}{(1-z)_+} - \frac{1+z^2}{(1-z)_+}\log\left(\frac{z\mu_{\mathrm{F}}^2}{m_{\mathrm{LQ}}^2}\right)\right\}.$$

- *Combination (virtual + real + quark PDF renormalised) is finite:*

$$\boxed{\hat{\sigma}_{q\ell}(z) = \frac{\pi z |y_{q\ell}|^2}{4m_{\mathrm{LQ}}^2}\left\{\left[1 + \frac{\alpha_s}{2\pi}C_F\left(\frac{3}{2}\log\left(\frac{\mu_{\mathrm{R}}^2}{\mu_{\mathrm{F}}^2}\right) - \frac{\pi^2}{3}\right)\right]\delta(1-z) - \frac{\alpha_s}{2\pi}C_F\left[\frac{2z}{(1-z)_+} - 2(1+z^2)\left(\frac{\log(1-z)}{(1-z)}\right)_+ + \frac{1+z^2}{(1-z)_+}\log\left(\frac{z\mu_{\mathrm{F}}^2}{m_{\mathrm{LQ}}^2}\right)\right]\right\}}$$

NUMERICS

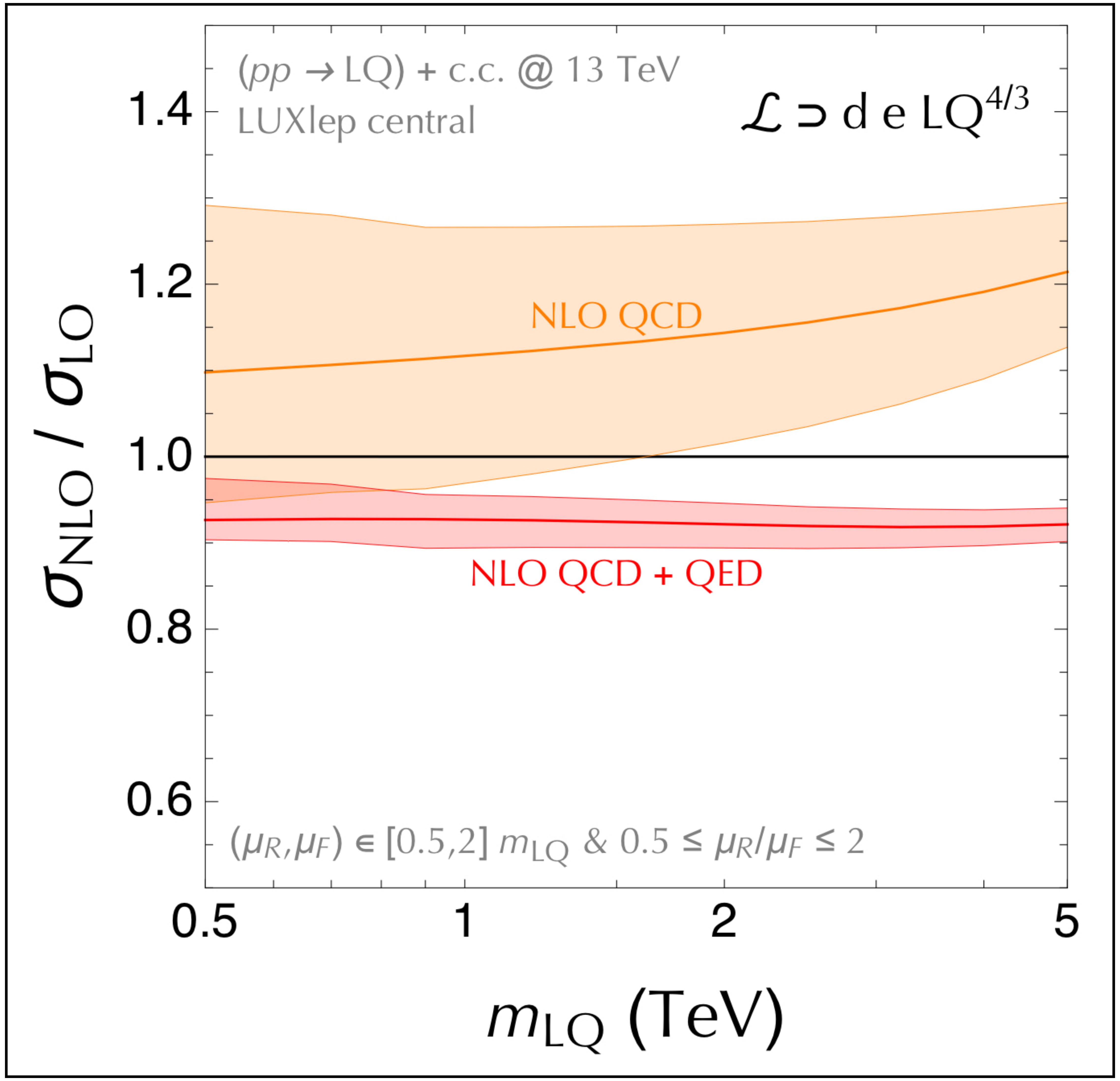
- *Partonic cross-sections convoluted with* `LUXlep-NNPDF31_nlo_as_0118_luxqed` (v2)
- *Large LQ mass window* $m_{LQ} = [500 \; - \; 5000]$ *GeV*
- *Lepton PDFs* Q^2 *- dependence up to* m_b^2
    - *Extrapolation by solving DGLAP equations using* `HOOPET`

[G. P. Salam and J. Rojo : A Higher Order Perturbative Parton Evolution Toolkit (HOPPET), arXiv:0804.3755]

- *Gauge couplings and the LQ coupling renormalisation running included*
    - *Central renormalisation and factorisation scales* $\mu_R = \mu_F = m_{LQ}$
    - *Higher-orders uncertainty* $\{\mu_R, \mu_F\} \in [0.5 \; - \; 2] \; m_{LQ}$ *with* $0.5 \leq \mu_R/\mu_F \leq 2$
- *PDF errors by the method of replicas*
    - *Error = standard deviation over 100 replicas*

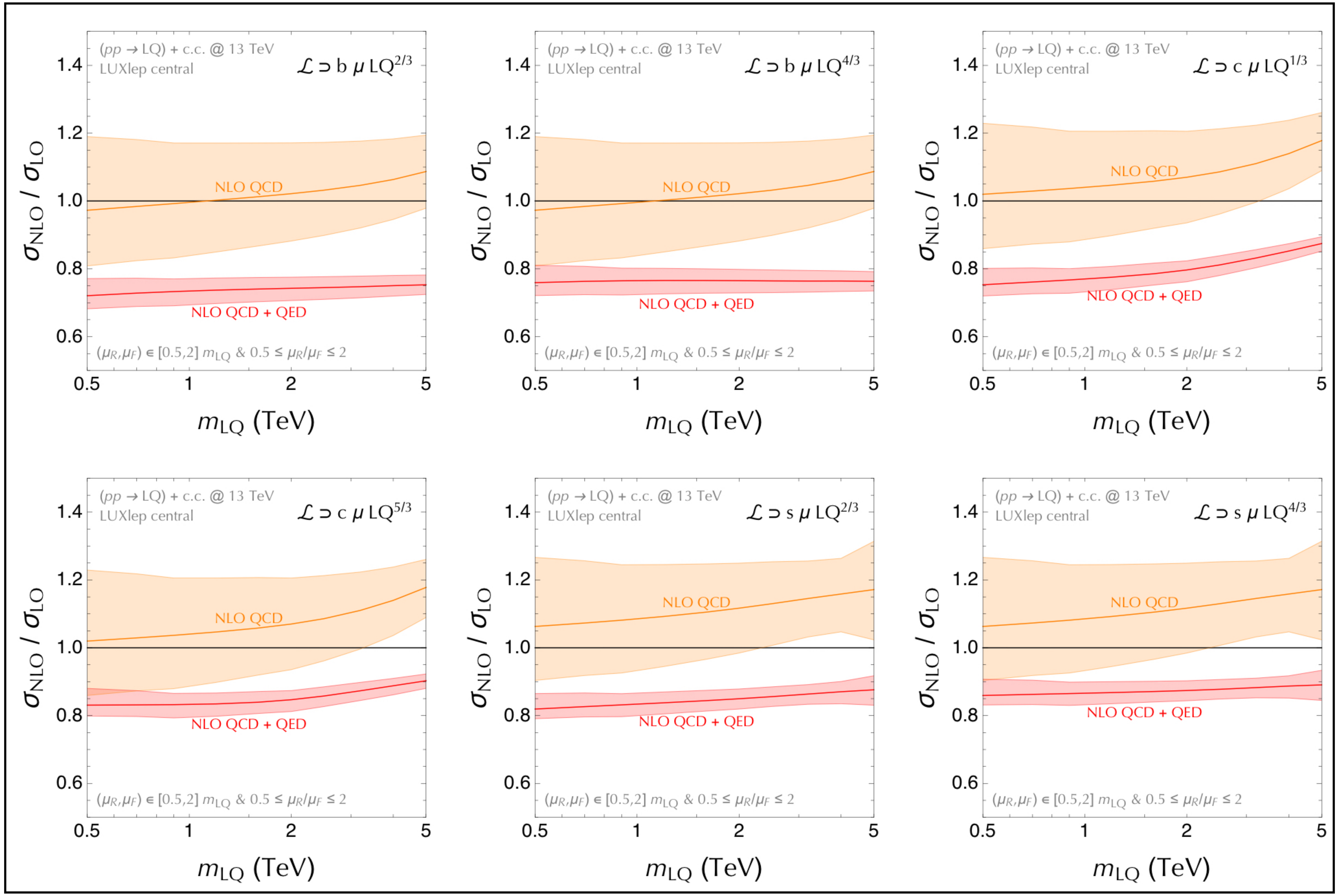
[NNPDF Collaboration, R. D. Ball et al.: Parton distributions from high-precision collider data, arXiv:1706.00428].

MAIN RESULTS



- *Report cross section for* $(pp \to LQ) + c.c$
- *Scale variation uncertainty* $<$ *few %* *(QED inclusion essential)*
- *NLO K-factors only slight dependence on* m_{LQ}, Q_{LQ}, *and lepton flavor*

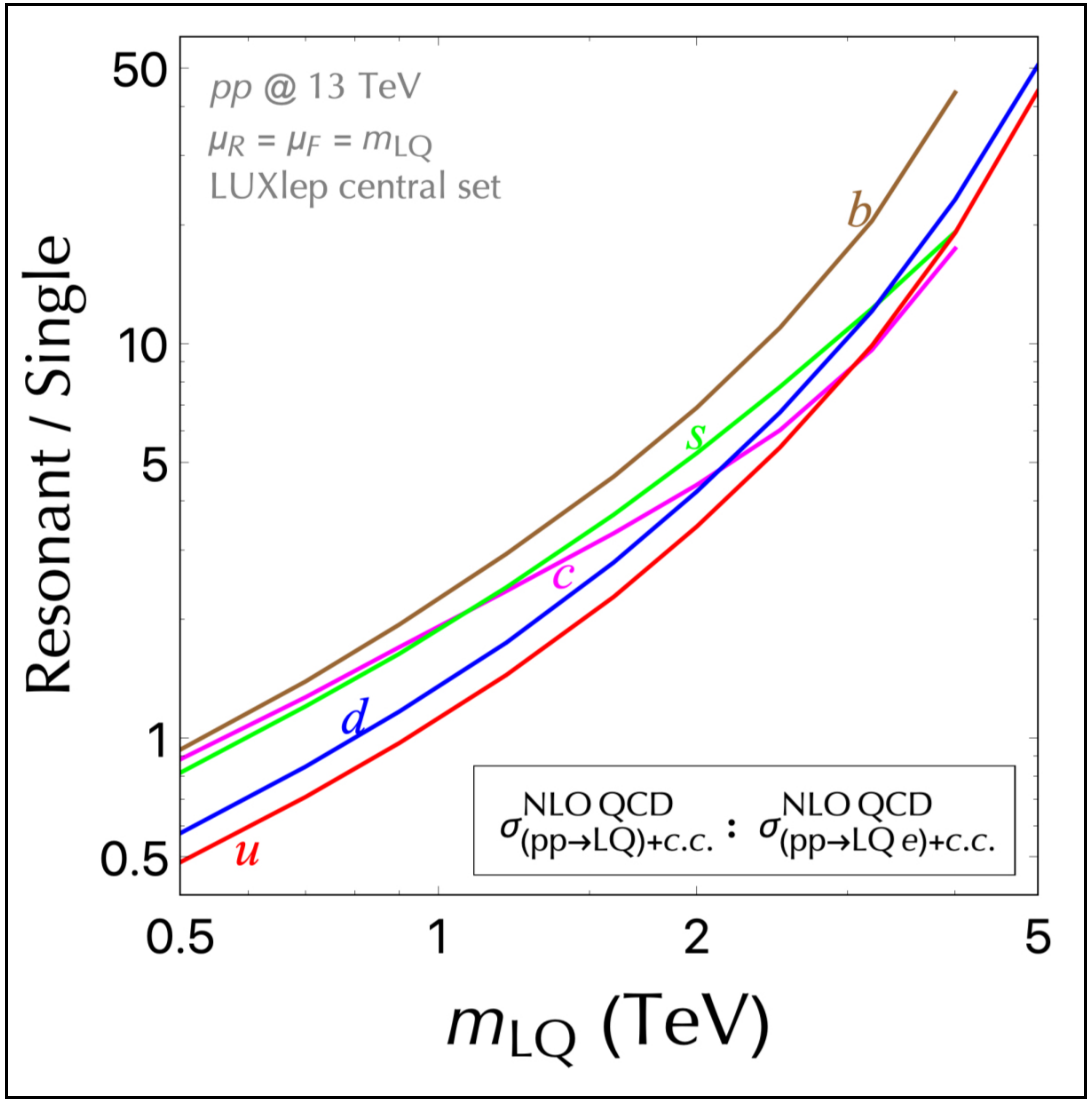
MAIN RESULTS



RESULTS

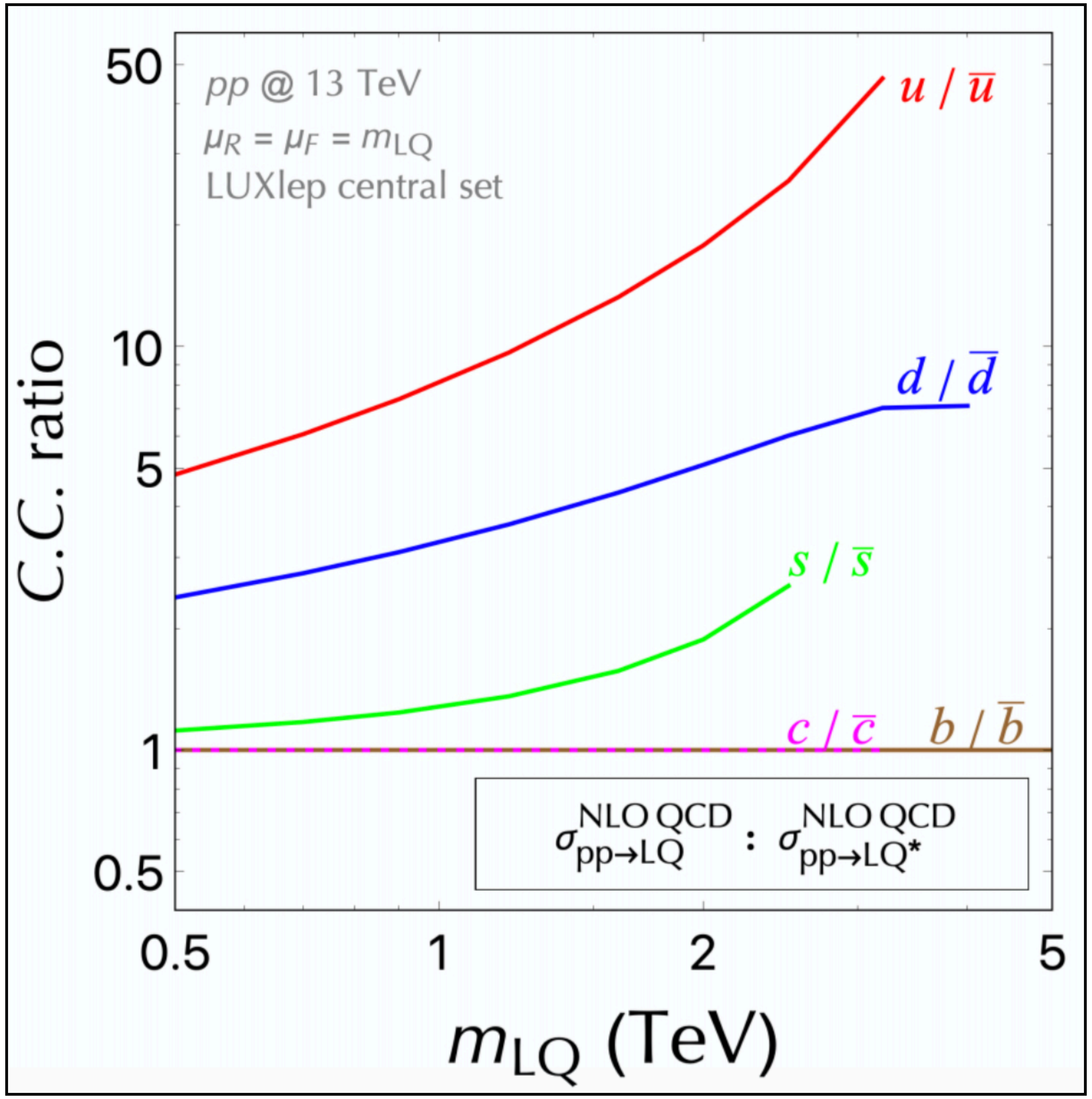
- *Dependence of NLO K-factors on the PDF uncertainties:*
    - *Calculate σ_{NLO}/σ_{LO} for each replica*
    - *1σ band around the central PDF prediction does not exceed scale variation band*
    - *PDF uncertainties cancel*
- *Lepton shower Monte Carlos in the near future* [P. Richardson and T. Sjostrand, work in progress]
    - *Applications in the future LHC RSP searches to correct the overall signal yield*

FLAVOR AT HIGH - P_T



- *RSP/SP does not depend on LQ Yukawa + sensitive to initial quark flavour*
  $\Longrightarrow$ flavour structure of the dominant LQ coupling in production

FLAVOR AT HIGH - P_T



- *C.C. ratio has flavour discriminating power*
- *Poor knowledge of sea quarks at large x significant limiting factor*

CONCLUSIONS

- *NLO QCD and QED corrections to resonant LQ production calculated*
- *Results applicable for a general scalar LQ model with arbitrary flavour couplings*
- *Estimation of theoretical uncertainties*
- *Leading source of error: limited knowledge of sea quark PDFs at large x*
- *(If LQ discovered) measurements of the resonant process, its charge-conjugate, and single process would help deducing the flavour structure of LQ interactions*

HVALA!