LEPTONS IN THE PROTON & IMPLICATIONS TO LHC PHENOMENOLOGY

Luca Buonocore

University of Zurich, INFN-sezione di Napoli

L. Buonocore, P. Nason, F. Tramontano and G. Zanderighi [JHEP 08 (2020) 08, 019]

L. Buonocore, U. Haisch, P. Nason, F. Tramontano and G. Zanderighi [2005.06475]

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University of Zurich UZH

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI NAPOLI Gruppo Collegato di Salerno

INTRODUCTION

- Hadrons are usually viewed as "broad band beams" of **coloured** particles (quarks and gluons). Hard processes described by factorisation formulae in terms of convolutions with partonic PDFs

$$\sigma(h_1 + h_2 \to V + X) = \sum_{ab} \int dx_1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \hat{\sigma}_{ab \to V+X}(\hat{s}, \mu_R) + \dots$$

- Indeed hadrons are made of **constituent/valence quark**s and (soft and collinear) QCD radiation is copiously produced (**sea** of gluons and quarks)

- Order of quark and gluon PDFs

$$(\alpha_s L)^k \qquad \alpha_s(\alpha_s L)^k \qquad L \equiv \ln \frac{Q^2}{\Lambda^2}$$

  - Λ is a characteristic **hadronic scale**.
  - Since $L \sim 1/\alpha_s$, all the contributions becomes relevant!

INTRODUCTION: MOTIVATIONS

- QCD radiation is certainly the dominant effect. When **electromagnetism** is taken into account, **photons and eventually leptons can be radiated** starting from quarks.

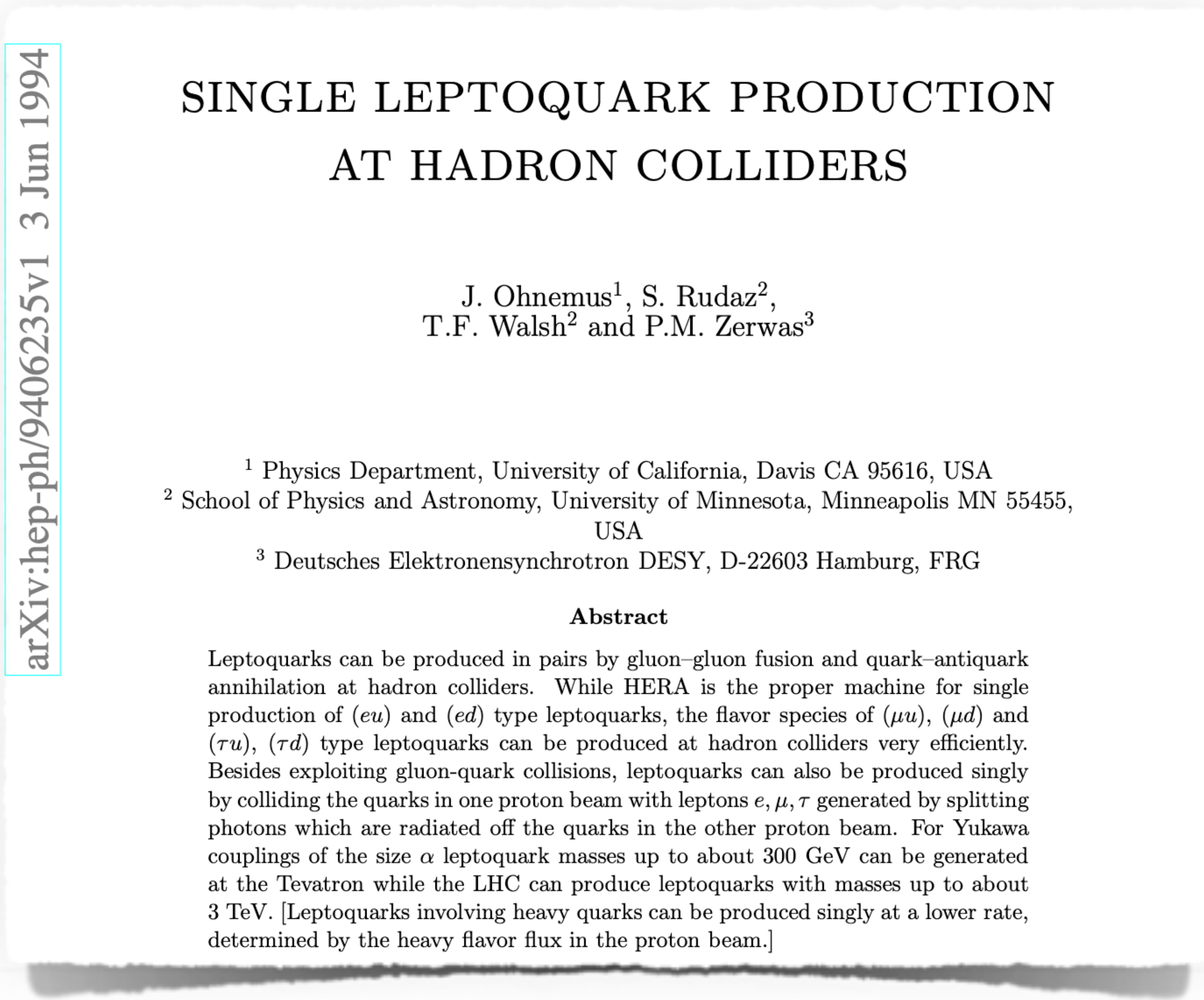
- Being down by **two powers** of electromagnetic α (naive estimate), leptonic luminosities are indeed <u>very small</u> compared to the ones of the other partons inside the proton.

- It might be interesting to look at lepton initiated processes in hadronic colliders
  - in principle, all lepton-lepton combinations are available (and in a broad energy spectrum): potential to measure **exotic SM processes**
  - potential to look at exotic **BSM physics**

- LHC will take data for the next 15-20 years: **explore all of its possibilities!**

INTRODUCTION: MOTIVATIONS

- A crucial aspect which prevented so far to fully explore the phenomenology offered by lepton initiated processes is **the lack of a precise determination of the lepton densities**



arXiv:hep-ph/9406235v1 3 Jun 1994

SINGLE LEPTOQUARK PRODUCTION AT HADRON COLLIDERS

J. Ohnemus[1], S. Rudaz[2], T.F. Walsh[2] and P.M. Zerwas[3]

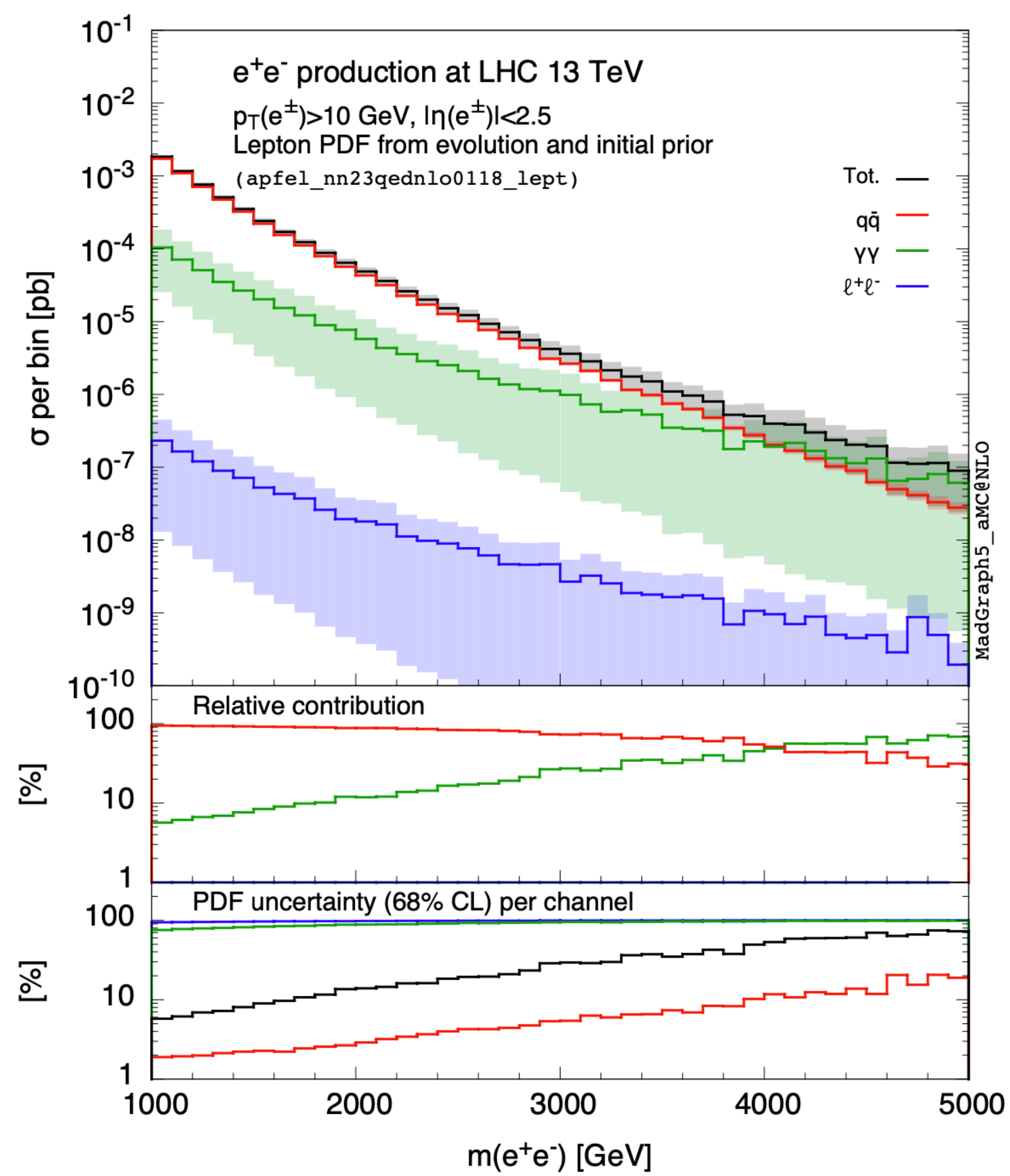
[1] Physics Department, University of California, Davis CA 95616, USA
[2] School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA
[3] Deutsches Elektronensynchrotron DESY, D-22603 Hamburg, FRG

Abstract

Leptoquarks can be produced in pairs by gluon–gluon fusion and quark–antiquark annihilation at hadron colliders. While HERA is the proper machine for single production of (eu) and (ed) type leptoquarks, the flavor species of (μu), (μd) and (τu), (τd) type leptoquarks can be produced at hadron colliders very efficiently. Besides exploiting gluon-quark collisions, leptoquarks can also be produced singly by colliding the quarks in one proton beam with leptons e, μ, τ generated by splitting photons which are radiated off the quarks in the other proton beam. For Yukawa couplings of the size α leptoquark masses up to about 300 GeV can be generated at the Tevatron while the LHC can produce leptoquarks with masses up to about 3 TeV. [Leptoquarks involving heavy quarks can be produced singly at a lower rate, determined by the heavy flavor flux in the proton beam.]

1994 paper: very interesting, but almost forgotten...

[Bertone,Carrazza,Pagani,Zaro, *JHEP* 11 (2015) 194]



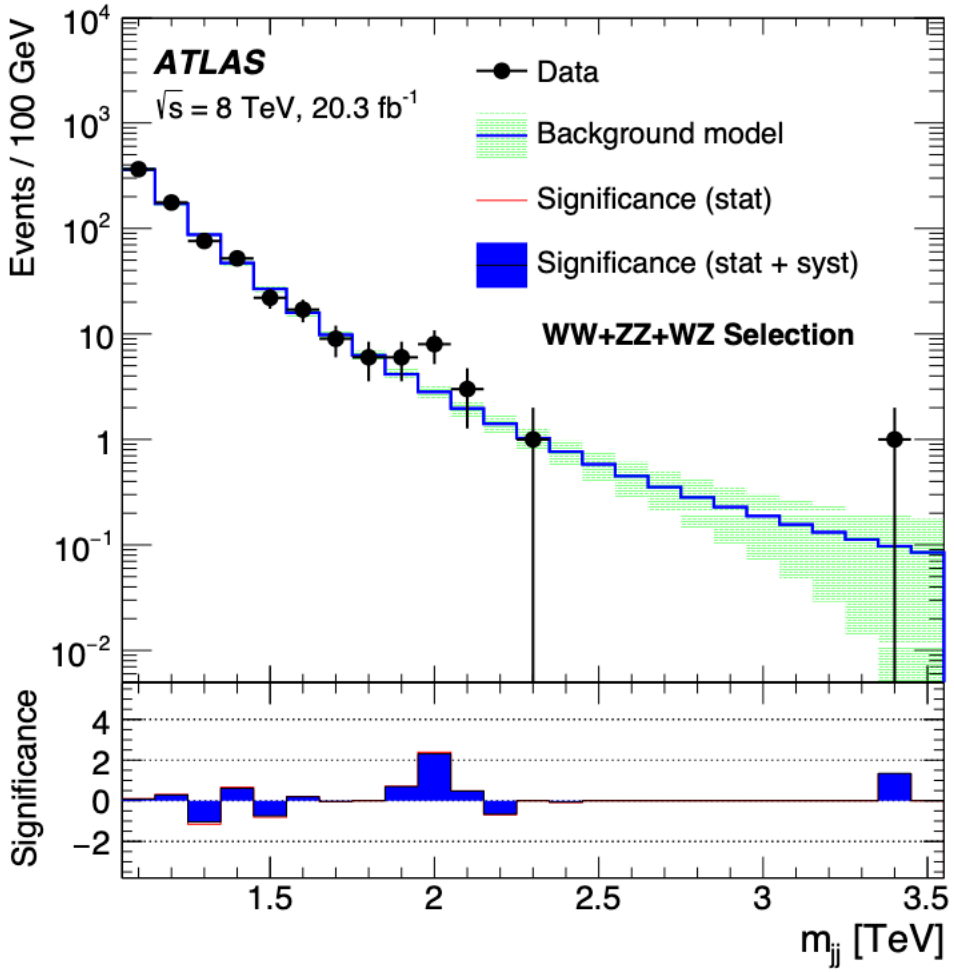
OUTLINE

- Lepton PDF formula and the LUXlep set
- LHC Phenomenology
- New limits on minimal scalar LeptoQuarks models
- Conclusions

LEPTON PDF FORMULA and THE LUXlep SET

The “LUX” APPROACH for the PHOTON PDF

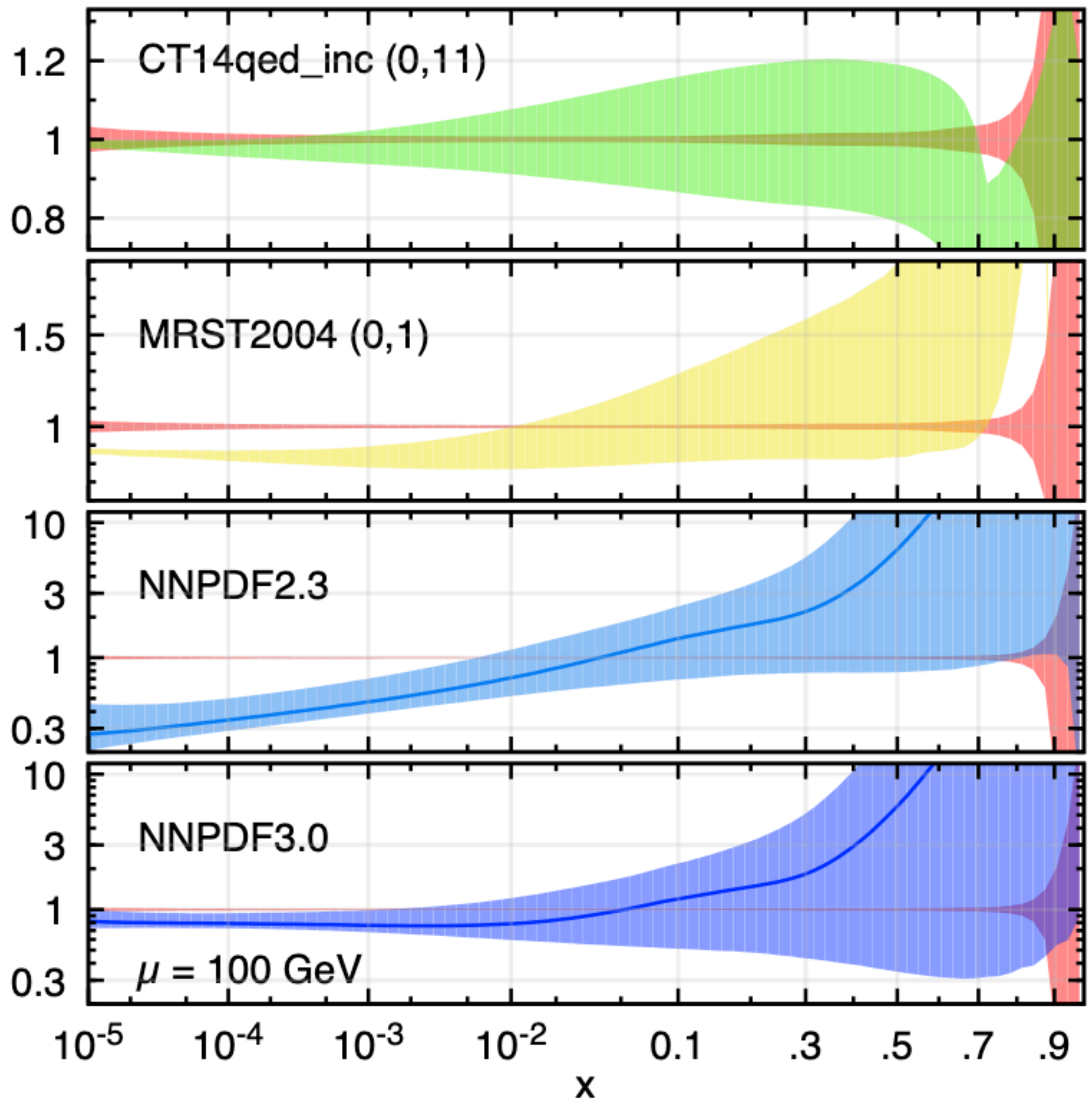
- **LUX breakthrough** in 2016-2017
  [Manohar, Nason, Salam, Zanderighi, *Phys.Rev.Lett*. 117 (2016) 24, 242002]
  [Manohar, Nason, Salam, Zanderighi, *JHEP* 12 (2017) 046]
  - determination of the photon density within **~5% uncertainty**
  - **different motivations**: uncertainty on the photon induced processes started to dominate the production of **high mass objects**

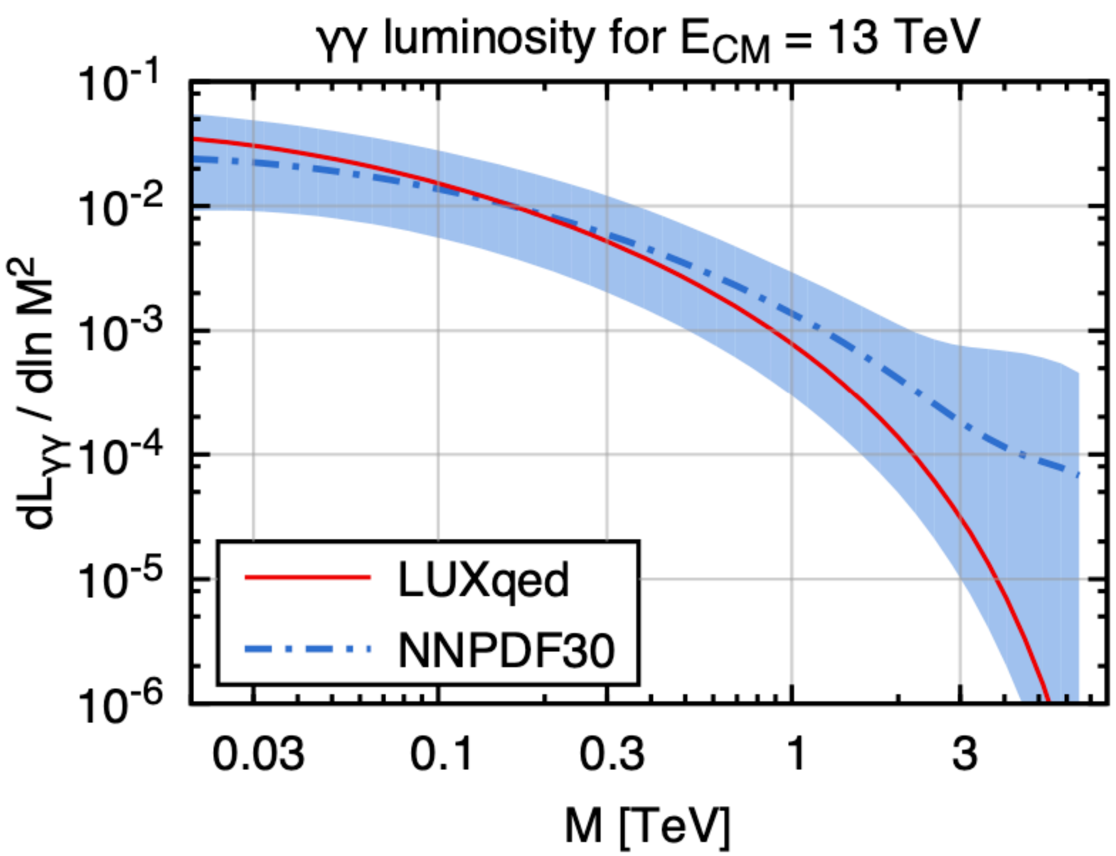


ATLAT boosted jets analysis (2015):

- 2 TeV excess in boson pair production
- Not confirmed in 13 TeV run
- The worry was that at very high scales gluon and quarks soften due to AP evolution.
- **Photons mostly stay the same**: importance of elastic contribution at low-Q^2

Before the "LUX" and after ...





- Order of magnitude improvements in the knowledge of the photon content of proton (paradigmatic case: comparison with the "agnostic" photon of NNPDF30
- <u>LUX approach can be used also for leptons (at order α^2)</u>!

THE LUX APPROACH in a NUTSHELL

- Relate the photon PDF to the electro-production structure functions and form factors for electron-proton scattering
  - physical ground: photon equivalent approximation and **virtual quanta** method, **collinear factorisation**
  - the computation **can be systematically improved** including higher order corrections to reach the desired accuracy goal

- Make use of the good quality data **(already) available**
  - electro-production structure functions measured in a **wide range of energies**
  - allow to **constrain** the photon PDF from **low- to high-Q^2**

- In general, no need to perform a global fit analysis
  - a new set which includes the photon can be produced starting from an existing one (which does not include it).

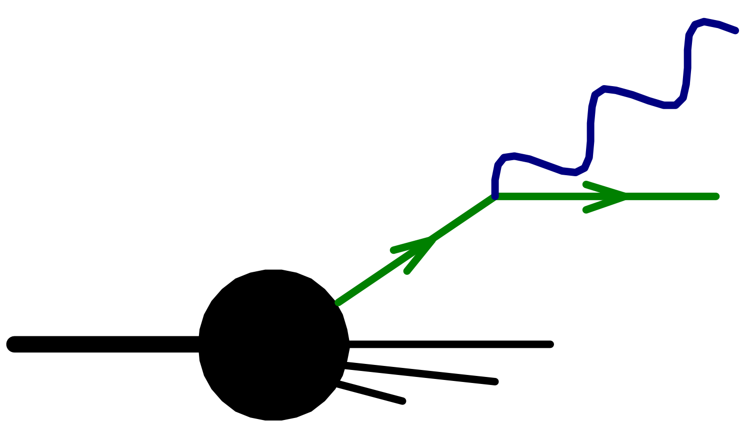
(PHYSICAL) COUNTING SCHEME for photons

- Let's start from quark and gluon again …

$$(\alpha_s L)^k \qquad \alpha_s(\alpha_s L)^k \qquad L \equiv \ln \frac{Q^2}{\Lambda^2}$$

- The photon PDF is **down by a factor** αL relatively to the quark density (the powers of $(\alpha_s L)^k \sim 1$ are always understood in the following)

- αL is not of order one! This complicates the relative importance of the couplings



αL (collinear-enhanced term)

LO contribution

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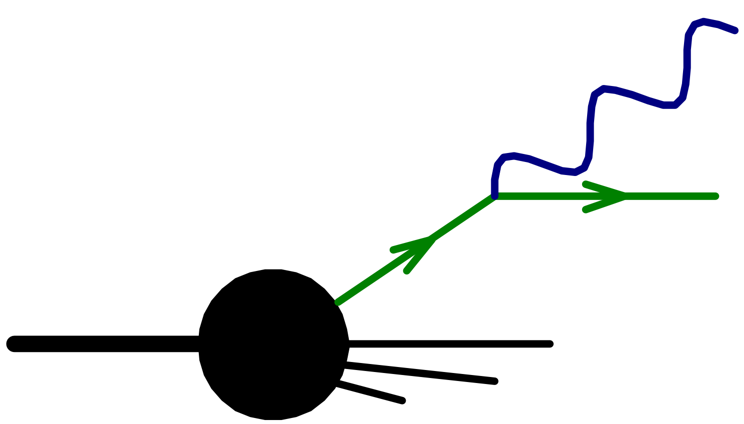

α (non-collinear-enhanced term)

down by $1/L \sim \alpha_s$ wrt LO

NLO contribution

(PHYSICAL) COUNTING SCHEME for photons

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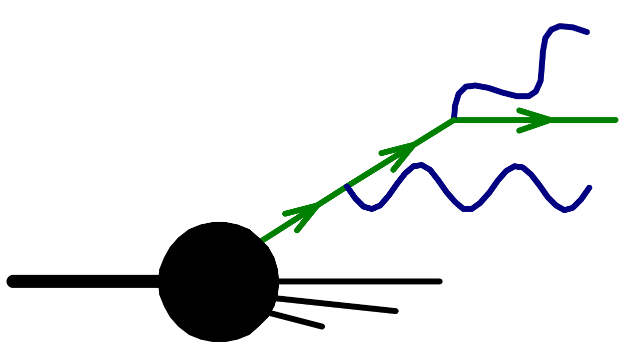
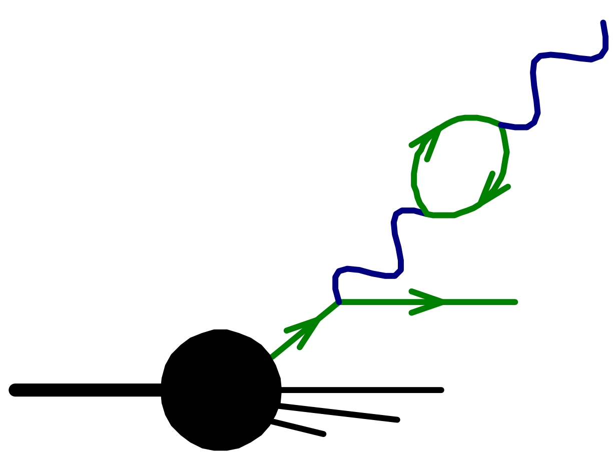


$\alpha^2 L^2$



$\alpha^2 L^2$

Assuming $\alpha \sim \alpha_s^2$

down by $\alpha L \sim \alpha_s$ wrt LO

NLO contributions

(PHYSICAL) COUNTING SCHEME for leptons

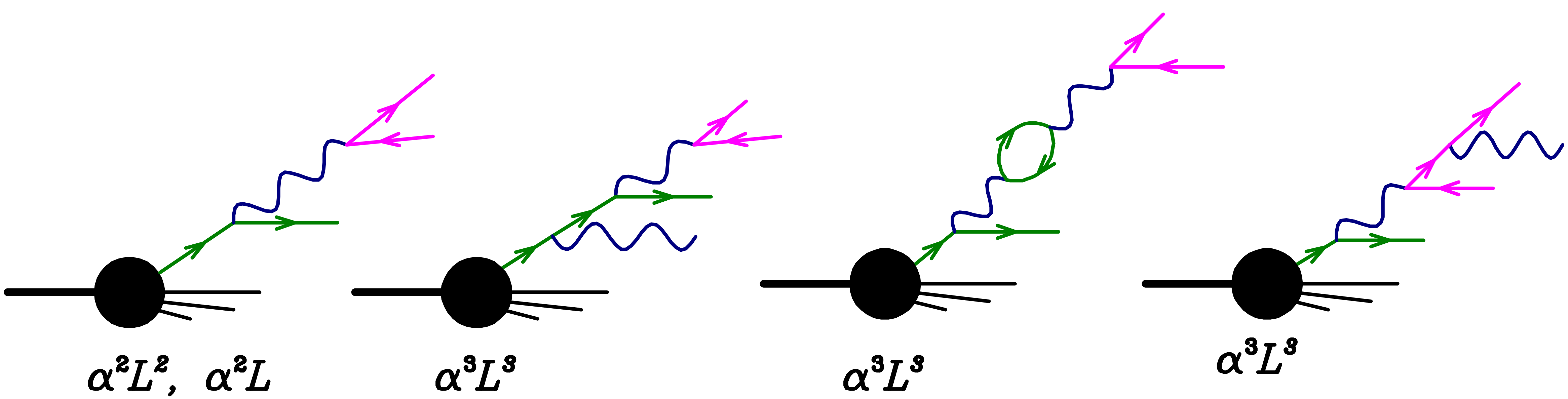
- Photon PDF

$$\begin{array}{lcccc} & \text{LO} & & \text{NLO} & \\ f_\gamma: & \alpha L & \alpha & \alpha^2 L^2 & \dots \end{array}$$

- Terms down by α with respect to LO are neglected (NNLO in our counting)

- Similarly for lepton PDFs

$$\begin{array}{lcccc} & \text{LO} & \text{NLO} & & \\ f_\ell: & \alpha^2 L^2 & \alpha^2 L & \alpha^3 L^3 & \dots \end{array}$$

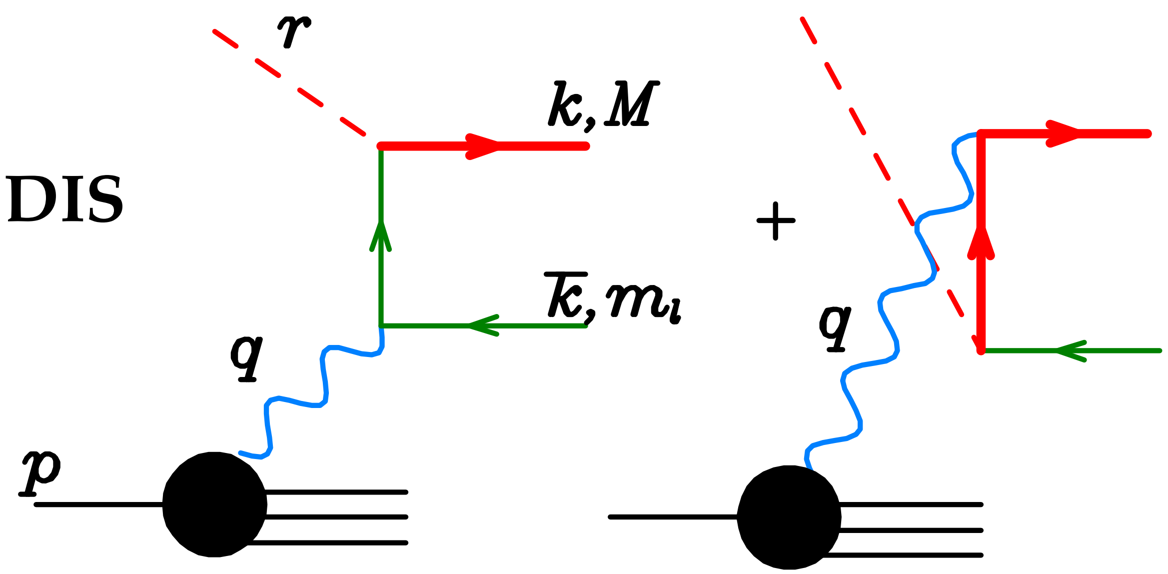


APPLICATION TO THE LEPTON PDF CASE

- Consider a fictitious BSM scalar probe that couples only to leptons and allow a flavour changing transitions to a BSM heavy lepton L of mass M

$$\mathscr{L} \sim \phi_0 \bar{L} l + \mathrm{h.c.}$$

1. The cross section can be computed as in **DIS**



$$\sigma = \frac{1}{4p\cdot r}\int \frac{d^4q}{(2\pi)^4}\frac{1}{Q^4} L^{\mu\nu}(r,q)(4\pi)W_{\mu\nu}(p,q)$$

Leptonic Tensor

$$W_{\mu\nu}(p,q) = F_1\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) + \frac{F_2}{p\cdot q}\left(p_\mu - \frac{p\cdot q\ q_\mu}{q^2}\right)\left(p_\nu - \frac{p\cdot q\ q_\nu}{q^2}\right)$$

Hadronic Tensor (scattering of virtual photon)

$$Q^2 = -q^2 > 0, x_{\rm bj} = \frac{Q^2}{2p\cdot q}$$

$F_1(x_{\rm bj}, Q^2), F_2(x_{\rm bj}, Q^2)$ **are the proton structure functions**

DIS-like COMPUTATION

- Integration domain

$$\int \frac{dE^2_{cm}}{2\pi} \frac{1}{4p\cdot r} \frac{1}{16\pi^2 E^2_{cm}} \int_x^{1-\frac{2xm_\mathrm{P}}{E_{cm}}} dz \int_{\frac{m^2_\mathrm{P}x^2}{1-z}}^{\frac{E^2_{cm}(1-z)}{z}} \frac{dQ^2}{Q^2}\alpha^2 \qquad E^2_{cm} = (r-q)^2$$

logarithmic integral

dominated at low Q^2

- Sketch of the structure of the integral function

$$F_i \times P(Q^2, m^2_\mathrm{P}, m^2_\ell, \ldots) \log\frac{M^2}{Q^2} + F_i \times R(Q^2, m^2_\mathrm{P}, m^2_\ell, \ldots)$$

explicit logarithm of Q^2

- P and R do not include logarithmic enhanced terms in Q^2

DIS-like COMPUTATION

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$$\int \frac{dE^2_{cm}}{2\pi}\frac{1}{4p\cdot r}\frac{1}{16\pi^2 E^2_{cm}}\int_x^{1-\frac{2xm_P}{E_{cm}}} dz \int_{\frac{m_P^2 x^2}{1-z}}^{\frac{E^2_{cm}(1-z)}{z}} \frac{dQ^2}{Q^2}\alpha^2 \qquad E^2_{cm} = (r-q)^2$$

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	P	R
$\frac{m_P^2}{Q^2}, \frac{m_\ell^2}{Q^2}$	L	no log
$\mathcal{O}(1)$	L^2	L
$\mathcal{O}(Q^2)$	~~no log~~	~~no log~~

formally of order α^2 (NNLO)

no log $\equiv$ no log-enhanced

DIS-like COMPUTATION

- Integration domain

$$\int \frac{dE_{\rm cm}^2}{2\pi}\frac{1}{4p\cdot r}\frac{1}{16\pi^2 E_{\rm cm}^2}\int_x^{1-\frac{2xm_{\rm P}}{E_{\rm cm}}} dz \int_{\frac{m_{\rm P}^2 x^2}{1-z}}^{\frac{E_{\rm cm}^2(1-z)}{z}} \frac{dQ^2}{Q^2}\alpha^2 \qquad E_{\rm cm}^2 = (r-q)^2$$

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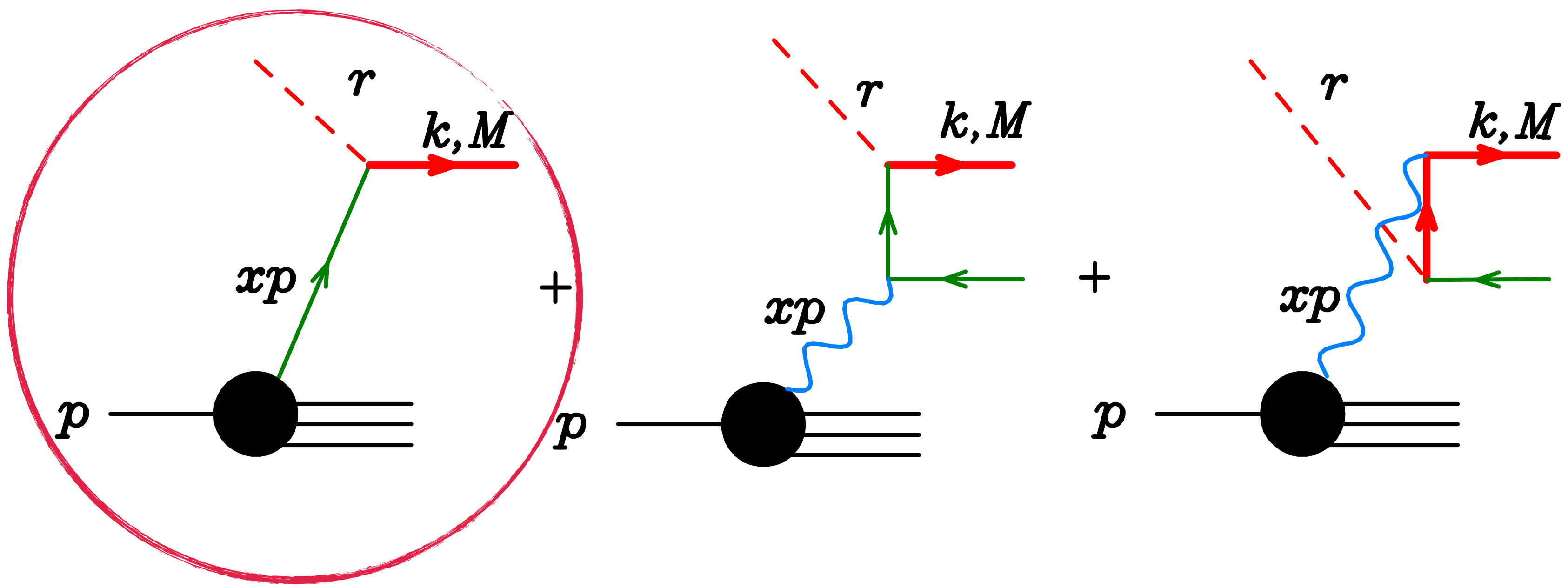
Terms proportional to $\frac{m_{\rm P}^2}{Q^2}, \frac{m_\ell^2}{Q^2}$ are the **only exception** to our counting rule: Keep them!

- they are formally NNLO, but are **dominated by small Q^2 values**
- being insensitive to the high scale $M \approx \mu_F$, **scale variation does not capture** the uncertainty associated to those contributions
- they are **universal**. No new terms of this kind can be generated at higher orders

PARTON MODEL CALCULATION

2. The cross section can be computed applying the collinear factorisation



$$\frac{\sigma}{\sigma_B} = \int dx f_\ell(x, \mu_F^2) \delta(Sx - M^2)$$

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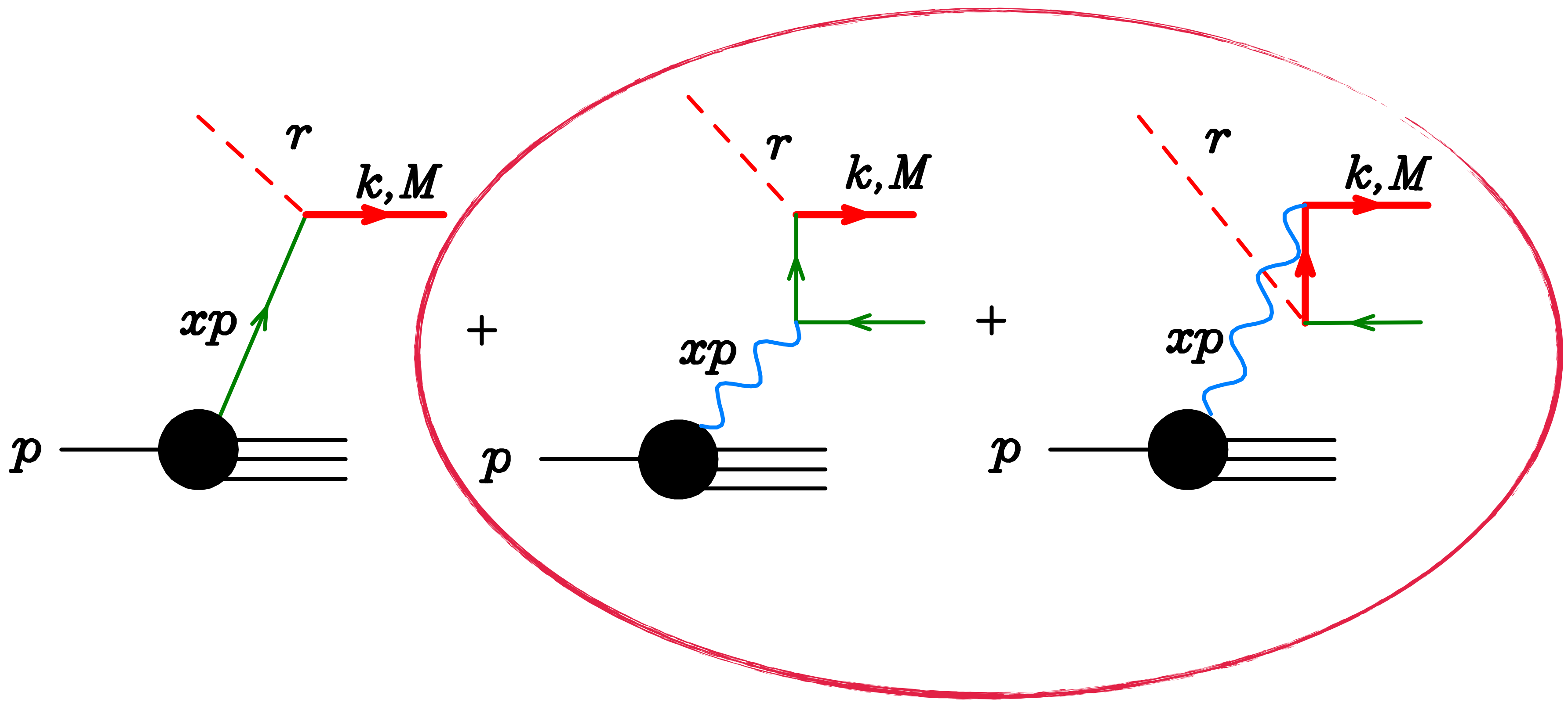

$$\frac{\sigma}{\sigma_B} = \int dx f_\ell(x, \mu_F^2) \delta(Sx - M^2) \qquad z_\ell = \frac{M^2}{xS}$$

$$+ \frac{\alpha}{2\pi} \frac{1}{M^2} \int_{\frac{M^2}{S}}^{1} dx f_\gamma(x, \mu_F^2) \left\{ z_\ell P_{l\gamma}(z_\ell) \left[\log \frac{M^2}{\mu_F^2} + \log \frac{(1 - z_\ell)^2}{z_\ell^2} \right] + 4 z_\ell^2 (1 - z_\ell) \right\}$$

LEPTON PDF FORMULA

- **Compare** the two cross sections for the probe process & **Retain** only terms that contribute within our accuracy
- $\alpha^3 L^3$ contributions **not included** here

matching
neglecting $\mathcal{O}(E_{\rm cm}^2/\mu_F^2)$

$$x_\ell f_\ell(x_\ell,\mu_F^2) = \left(\frac{1}{2\pi}\right)^2 \int_{x_\ell}^1 \frac{\mathrm{d}x}{x} z_\ell \int_x^1 \frac{\mathrm{d}z}{z} \int_{\frac{m_{\rm p}^2 x^2}{1-z}}^{\frac{\mu_F^2}{1-z}} \frac{\mathrm{d}Q^2}{Q^2} \alpha^2(Q^2)$$

L^2-enhanced terms

$$\Bigg\{ P_{\ell\gamma}(z_\ell) \log \frac{\mu_F^2}{(1-z_\ell) z_\ell \left(Q^2 + \frac{m_\ell^2}{z_\ell(1-z_\ell)}\right)} \left[F_2 \left(z P_{\gamma q}(z) + \frac{2 m_{\rm p}^2 x^2}{Q^2} \right) - F_L z^2 \right]$$

$$+ F_2 \left[4(z-2)^2 z_\ell (1-z_\ell) - (1 + 4 z_\ell (1-z_\ell))\, z P_{\gamma q}(z) \right]$$

L-enhanced terms

sub-leading terms

$$+ F_L z^2 P_{\ell\gamma}(z_\ell) - \frac{2 m_{\rm p}^2 x^2}{Q^2} F_2 - \left(F_2 \frac{2 m_{\rm p}^2 x^2}{Q^2} - z^2 F_L \right) 4 z_\ell (1-z_\ell)$$

$$+ \frac{m_\ell^2 F_2}{m_\ell^2 + Q^2 z_\ell (1-z_\ell)} \left[z P_{\gamma q}(z) - 8 z_\ell (1-z_\ell) \left(1 - z - \frac{m_{\rm p}^2 x^2}{Q^2} \right) + \frac{2 m_{\rm p}^2 x^2}{Q^2} \right]$$

$$- \frac{m_\ell^2 F_L z^2}{m_\ell^2 + Q^2 z_\ell (1-z_\ell)} \left[2 - P_{\ell\gamma}(z_\ell) \right] \Bigg\}$$

AP EQUATION

- By construction, the Lepton PDF formula is expected to satisfy a suitable Altarelli-Parisi equation.

- Taking the derivative with respect to the factorisation scale, we get

$$\frac{d}{d\ln\mu_F^2} f_\ell = \frac{\alpha(\mu_F^2)}{2\pi} P_{\ell\gamma} \otimes f_\gamma + \left(\frac{\alpha(\mu_F^2)}{2\pi}\right)^2 \sum_q P_{\ell q} \otimes f_q$$

$\alpha \times \alpha L = \alpha^2 L$ leading term

$\alpha^2 \times \mathcal{O}(1) = \alpha^2$ NLO correction

- Formally the second terms is a **NNLO QED** evolution kernel. Be aware, it should be included in DGLAP equations for the lepton pdf if NLO accuracy is required!

As a byproduct of our computation, we get an expression for the NNLO QED splitting kernel $P_{\ell q}$ in agreement with [De Florian,Sborlini,Rodrigo, JHEP 10 (2016) 056]

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$$\alpha \times \alpha L = \alpha^2 L \qquad \alpha^2 \times \mathcal{O}(1) = \alpha^2$$

- Since we did not include $\alpha^3 L^3$ terms, we miss the NLO contribution

$$\frac{\alpha(\mu_F^2)}{2\pi} P_{\ell\ell} \otimes f_\ell$$

$$\alpha \times \alpha^2 L^2 = \alpha^3 L^2 \sim \alpha^2$$

- We can restore its dominant contribution by solving suitable AP equations!

CONSTRUCTION OF A FULL PDF WITH LEPTONS

- The lepton PDF formula
  - can be computed numerically with high accuracy
  - requires experimental input for structure functions and form factors of the proton (fit + **uncertainties**) in both low- and high-Q^2 (from pdfs fit) regime (same data as for photon PDF)
  - allows the determination of the lepton densities at a given (almost) arbitrary scale. Sensitive to higher twist at low scales!

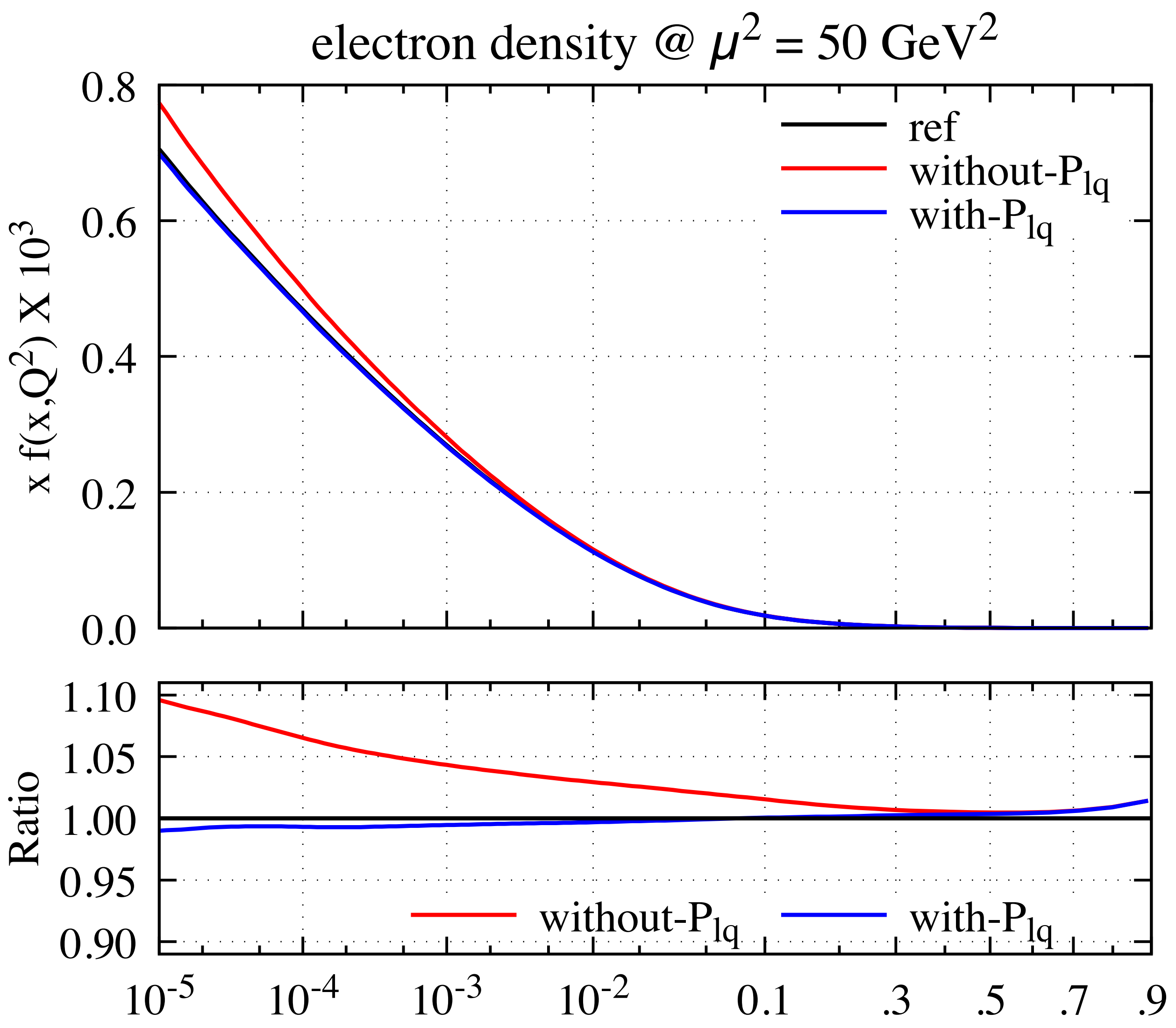
- To build a full grid, **use DGLAP** evolution (more efficient) starting from an already available pdf set! We use a input **NNPDF31_nlo_as_0118 luxqed**
  - use the lepton PDF formula to extract an initial condition for the lepton densities at a suitable reference scale (our choice $\mu_{\text{ref}} = 20\,\text{GeV}$)
  - solve the integro-differential DGLAP equations including all the relevant splitting kernels which contribute to the desired target accuracy:

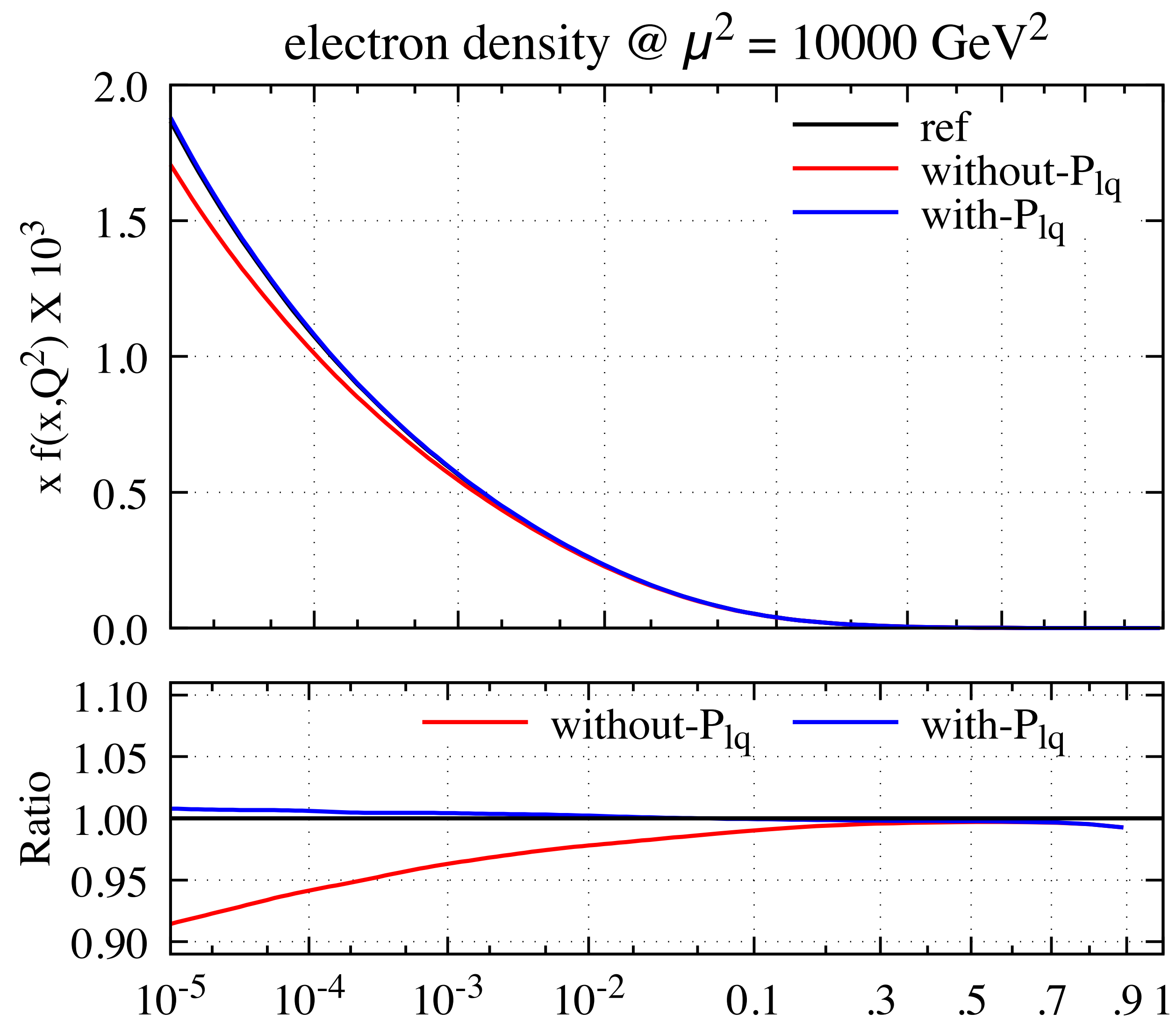
$$\alpha_s, \quad \alpha_s\alpha, \quad \alpha^2 \; (P_{\ell q} \text{ must be included!})$$

  - make available the grid in a standard format (aka LHAPDF)

IMPORTANCE of the $\mathcal{O}(\alpha^2)\ P_{\ell q}$-SPLITTING in DGLAP

- If not included, it leads to $\mathcal{O}(10\%)$ differences in the small-x region, where its contribution is logarithmic enhanced





UNCERTAINTIES on LEPTON DENSITIES

We consider

- 6 variations on the fits used as input data for the proton structure functions and form factor (as in the photon PDF papers)
- a scale variation prescription to estimate the uncertainty due to missing higher orders
- replicas to take into account PDF uncertainties

Procedure: for each replica member m in the original NNPDF set

1. we apply our method to add leptons
2. we compute the correction

$$\Delta_i^{(m)}(x,\mu_F) = \sum_{j=1}^{7} \frac{f_{i,(j)}^{(0)}(x,\mu_F) - f_i^{(0)}(x,\mu_F)}{f_i^{(0)}(x,\mu_F)} f_i^{(m)}(x,\mu_F) \times R(m,j)$$

7 variations of the central set

Gaussian distributed random number with unit variance

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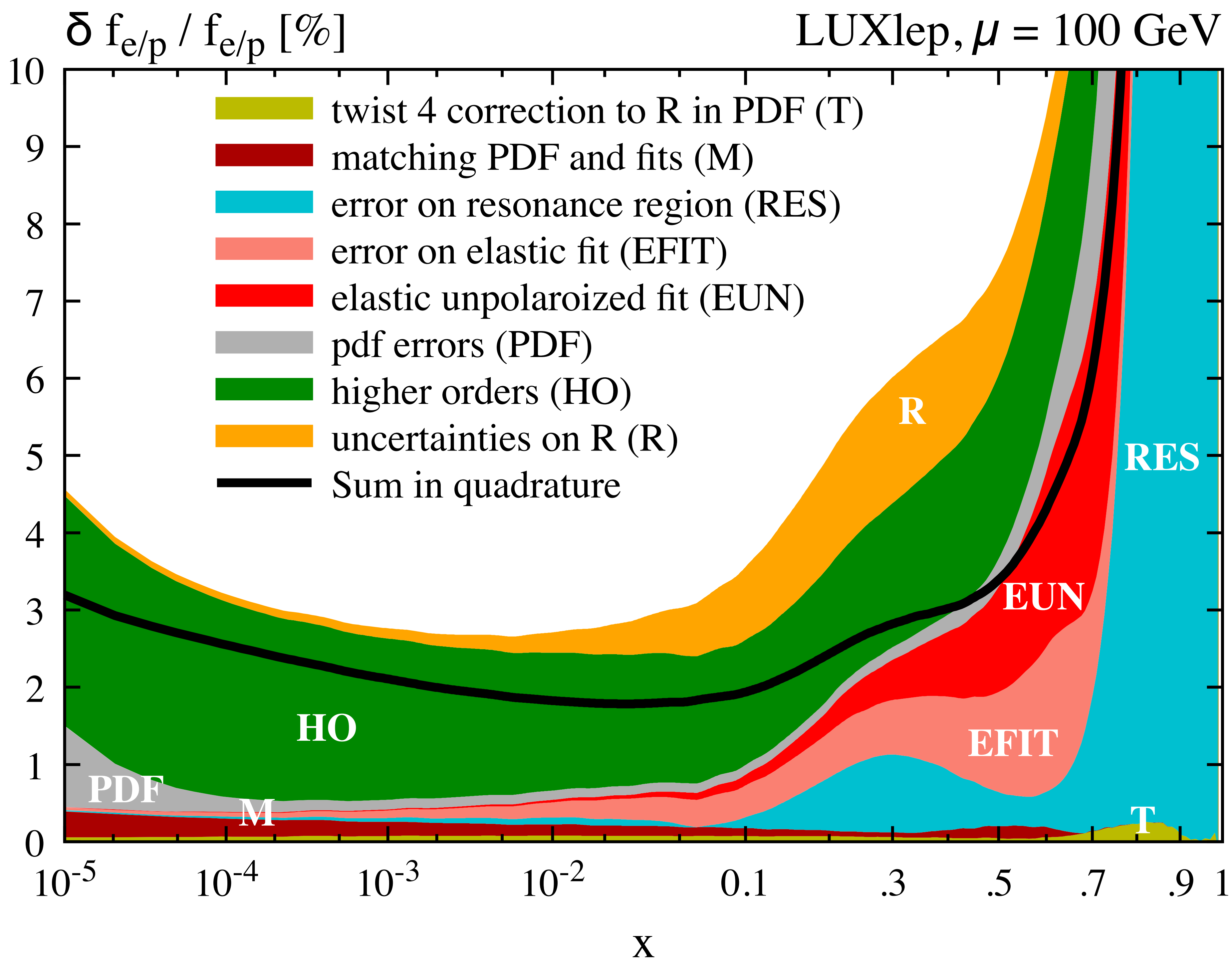
Procedure: for each replica member m in the original NNPDF set

1. we apply our method to add leptons
2. we compute the correction
3. we correct the replicas as

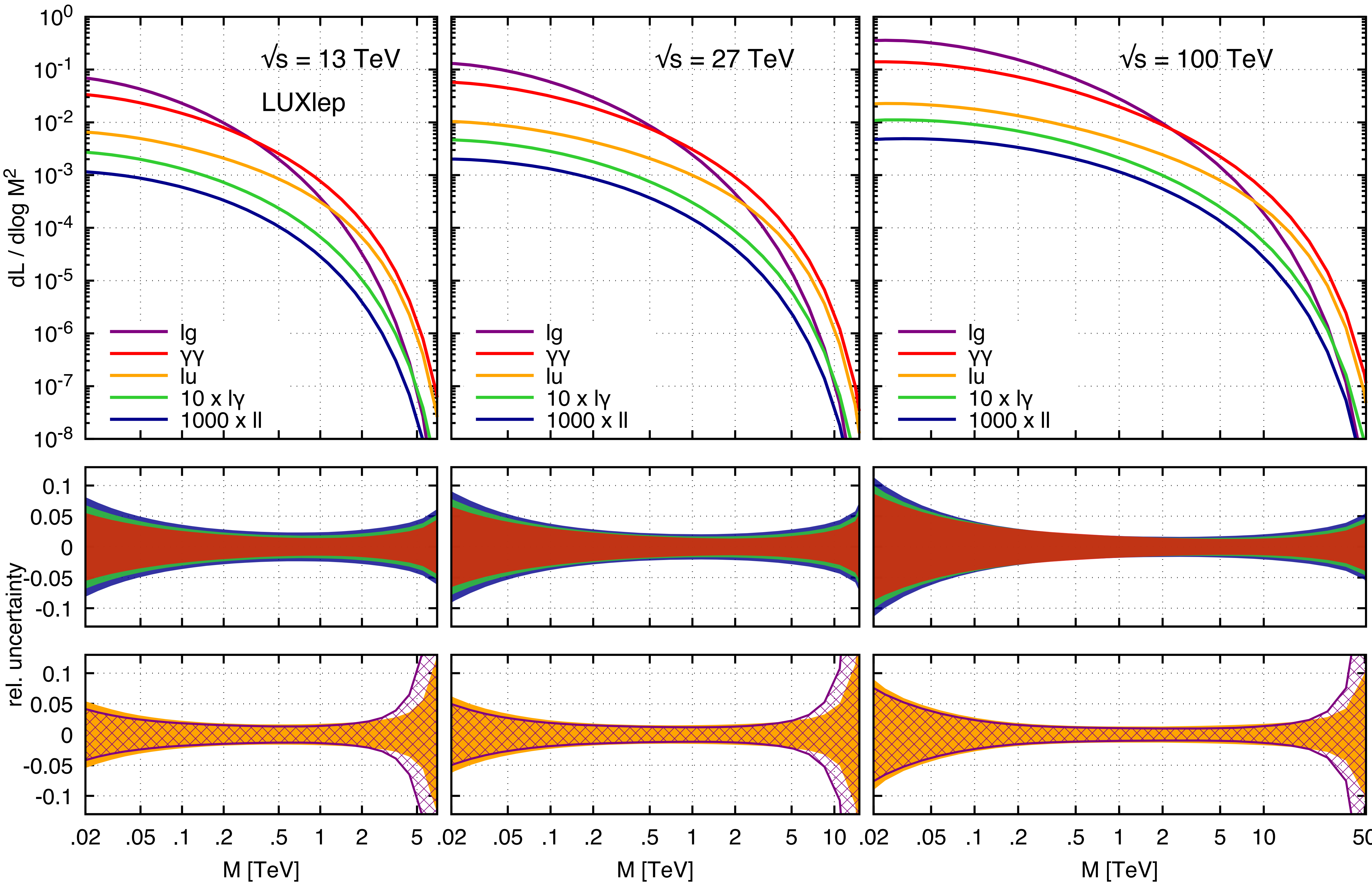
$$f_i^{(m)}(x, \mu_F) \to f_i^{(m)}(x, \mu_F) + \Delta_i^{(m)}(x, \mu_F) - \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \Delta_k^{(m)}(x, \mu_F)$$

so that the average of all replicas is not shifted.

UNCERTAINTIES on LEPTON DENSITIES



LUMINOSITIES



LHC PHENOMENOLOGY

SM LEPTON-LEPTON SCATTERING

- Lepton densities are **very small**, but lepton-lepton processes might be observed. Consider different flavours/same sign combination

$$p_{T,\ell} > 20\,\text{GeV}, \quad |\eta| < 2.4$$

	$e^+\mu^-$	$e^+\tau^-$	$\mu^+\tau^-$	e^+e^+	$\mu^+\mu^+$	$\tau^+\tau^+$
$\sigma_{13\text{TeV}}$ [fb]	$0.29^{+0.13}_{-0.10}$	$0.18^{+0.11}_{-0.08}$	$0.16^{+0.10}_{-0.07}$	$0.24^{+0.10}_{-0.08}$	$0.19^{+0.09}_{-0.07}$	$0.08^{+0.06}_{-0.04}$
$\sigma_{27\text{TeV}}$ [fb]	$0.53^{+0.25}_{-0.18}$	$0.34^{+0.21}_{-0.15}$	$0.30^{+0.19}_{-0.14}$	$0.440^{+0.19}_{-0.14}$	$0.34^{+0.16}_{-0.12}$	$0.14^{+0.12}_{-0.07}$

- We considered only WW background and we found it is negligible after requiring suitable **signal-like cuts**. Heavy flavour production background might be relevant

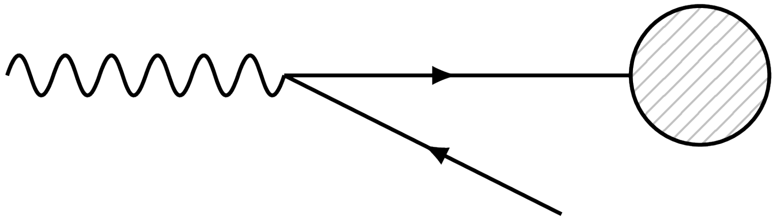
REMARKS

1. A dedicated analysis **requires Shower Monte Carlo programs** for lepton initiated processes
2. Theoretical uncertainty dominated by factorisation scale variation. “NLO” corrections should be included

SM LEPTON-LEPTON SCATTERING

1. **Parton Shower**
   - Hardest radiation accompanying an initial state lepton **is another lepton**
   - **Reduced hadronic activity** in the event
   - So far, no Parton Shower program handle (backward) initial state shower originated by leptons
   - Peter Richardson provided us a patch for Herwig. Analysis are on going

2. **"NLO" corrections**
   - What do we mean by "NLO"? There are not any coloured particles
   - To match the NLO accuracy of the LeptonPDF computation, photon induced corrections must be added



$$\Longrightarrow \frac{[f_\gamma]\times\alpha}{[f_\ell]} = \frac{\alpha^2 L}{\alpha^2 L^2} = \frac{1}{L} \approx \alpha_s$$

SM LEPTON-LEPTON SCATTERING

1. **Parton Shower**
   - Hardest radiation accompanying an initial state lepton **is another lepton**
   - **Reduced hadronic activity** in the event
   - So far, no Parton Shower program handle (backward) initial state shower originated by leptons
   - Peter Richardson provided us a patch for Herwig. Analysis are on going

2. **"NLO" corrections**
   - What do we mean by "NLO"? There are not any coloured particles
   - To match the NLO accuracy of the LeptonPDF computation, photon induced corrections must be added

→ NLO+PS within the reach!

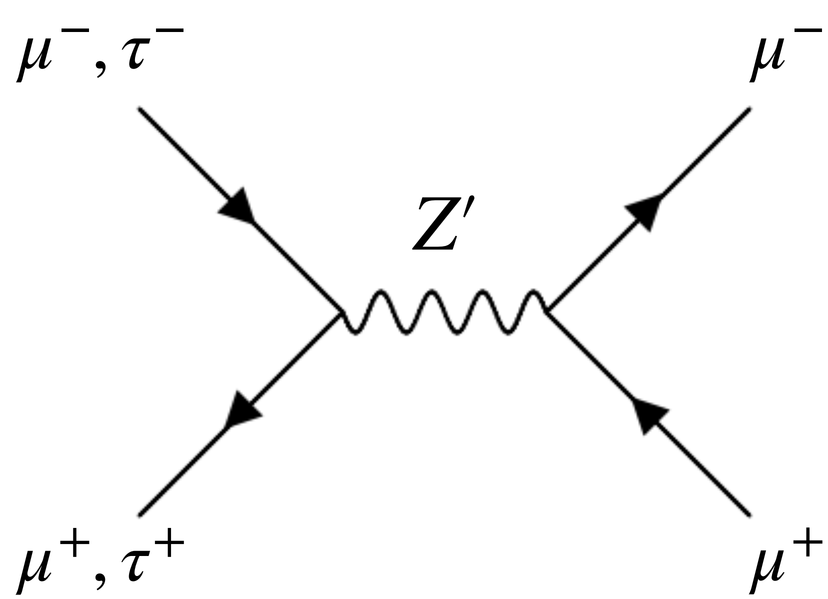
BSM searches: $L_\mu - L_\tau$ Z' boson

- One of the simplest idea is to look for new **"hadro-phobic" gauge forces**
- A minimal extension of the SM is provided by gauging **anomaly-free** combinations of family leptons numbers [*He, Joshi, Lew, Volkas, PRD 44 (1991 2118)*]:

$L_e - L_\mu$ $\qquad$ $L_e - L_\tau$ $\qquad$ $L_\mu - L_\tau$

Least constrained

lepton-lepton resonant s-channel production



- **Analysis**: bump search in the di-muon invariant mass spectrum

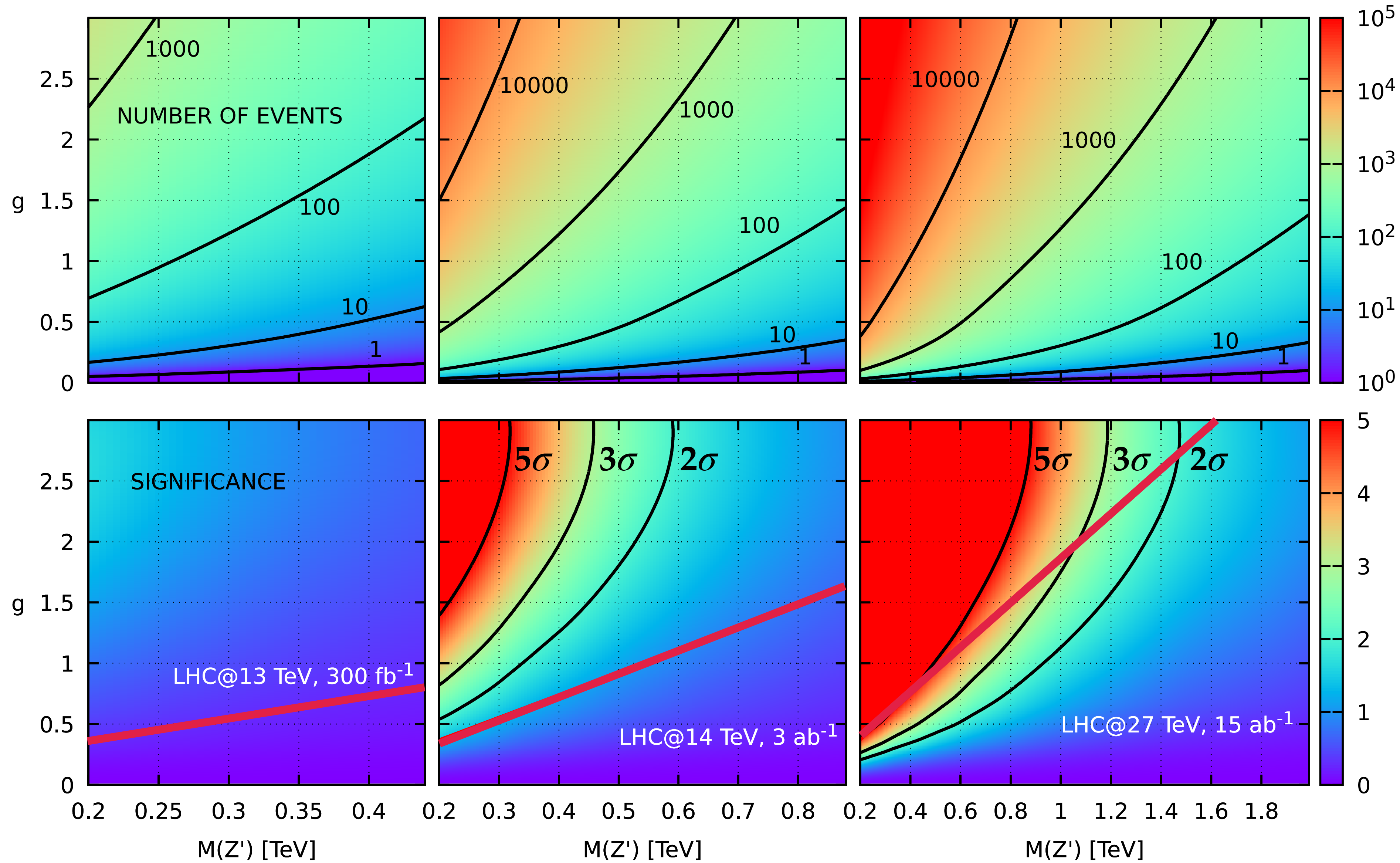
$$b_w = \sqrt{\Gamma_{Z'}^2 + r^2 M_{Z'}^2}, \qquad \Gamma_{Z'} = \frac{g}{4\pi} M_{Z'}$$

reconstruction efficiency from [1812.10529]
r: μ energy resolution from [1804.04528]

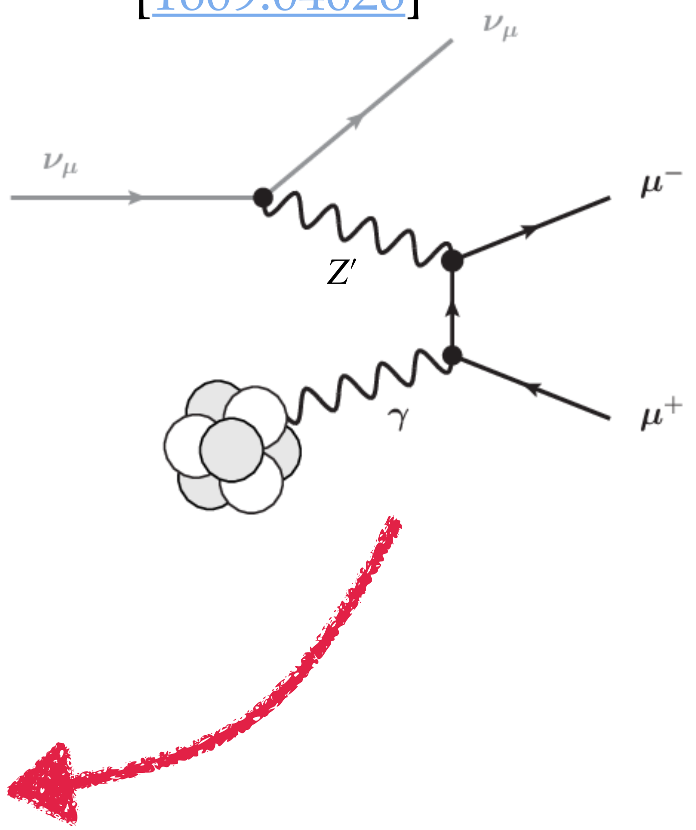
- **Background**: di-muon Drell-Yan production

BSM searches: $L_\mu - L_\tau\ Z'$ boson

- Direct LHC limits **weaker** than indirect constraints from **neutrino trident** (low energy physics constraint). Need HE-LHC upgrade to make them comparable in strength
- **Hadronic activity** may play a role to reduce the Drell-Yan background



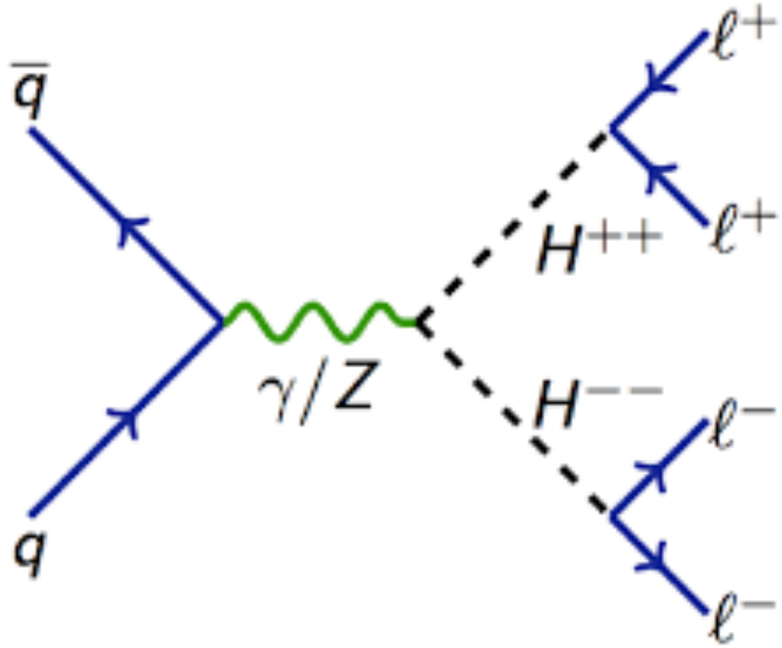
[1609.04026]



BSM searches: doubly charged Higgs $H^{\pm\pm}$

- Look for BSM processes with (almost) **background free**
- Example: **doubly charged Higgs** (mainly occurring in extensions of the SM which aim to accommodate neutrino masses)
- $H^{\pm\pm}$ couples to leptons and W bosons. We assume a typical scenario in which the <u>coupling to W bosons is negligible</u>

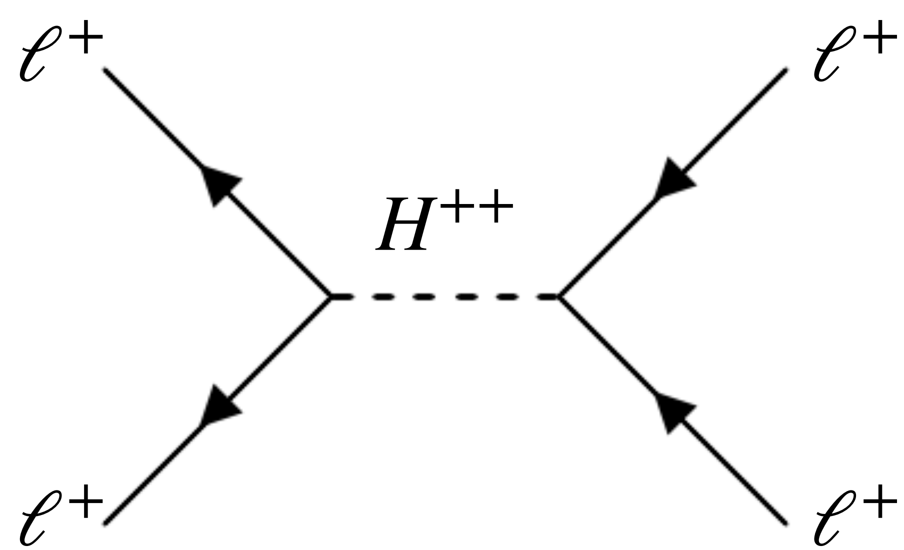
Pair Production



ATLAS [1710.09748]

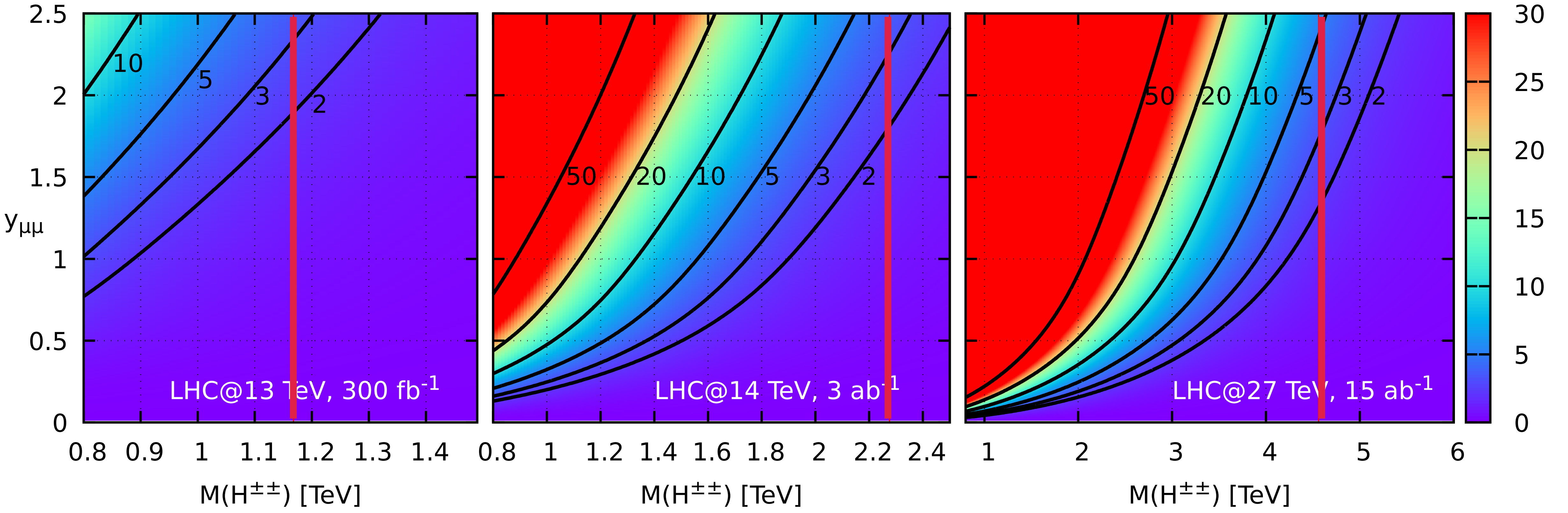
CMS [1902.04773]

Single resonant production



BSM searches: doubly charged Higgs $H^{\pm\pm}$

- We assumed **background free** and minimal coupling to one lepton species
- For sufficiently **large** Yukawa $y_{\mu\mu}$ coupling s-channel production for a doubly charged Higgs **may have a mass reach comparable** to analyses relying upon pair production



Pair Production projection taken from *de Melo et al* [1909.07429]

REMARKS – "take home message"

Proton can be seen as broad band beams of leptons

- this gives access to **single resonant production** of new states which **preferably** couple to leptons
- sensitivity to coupling (complementarity to pair production)

Lepton densities are in fact small but handful events can be produced. Ideal situations:

- **large** enough **couplings**
- rare SM events/signatures to be (almost) **background free**

So far we consider lepton-lepton processes

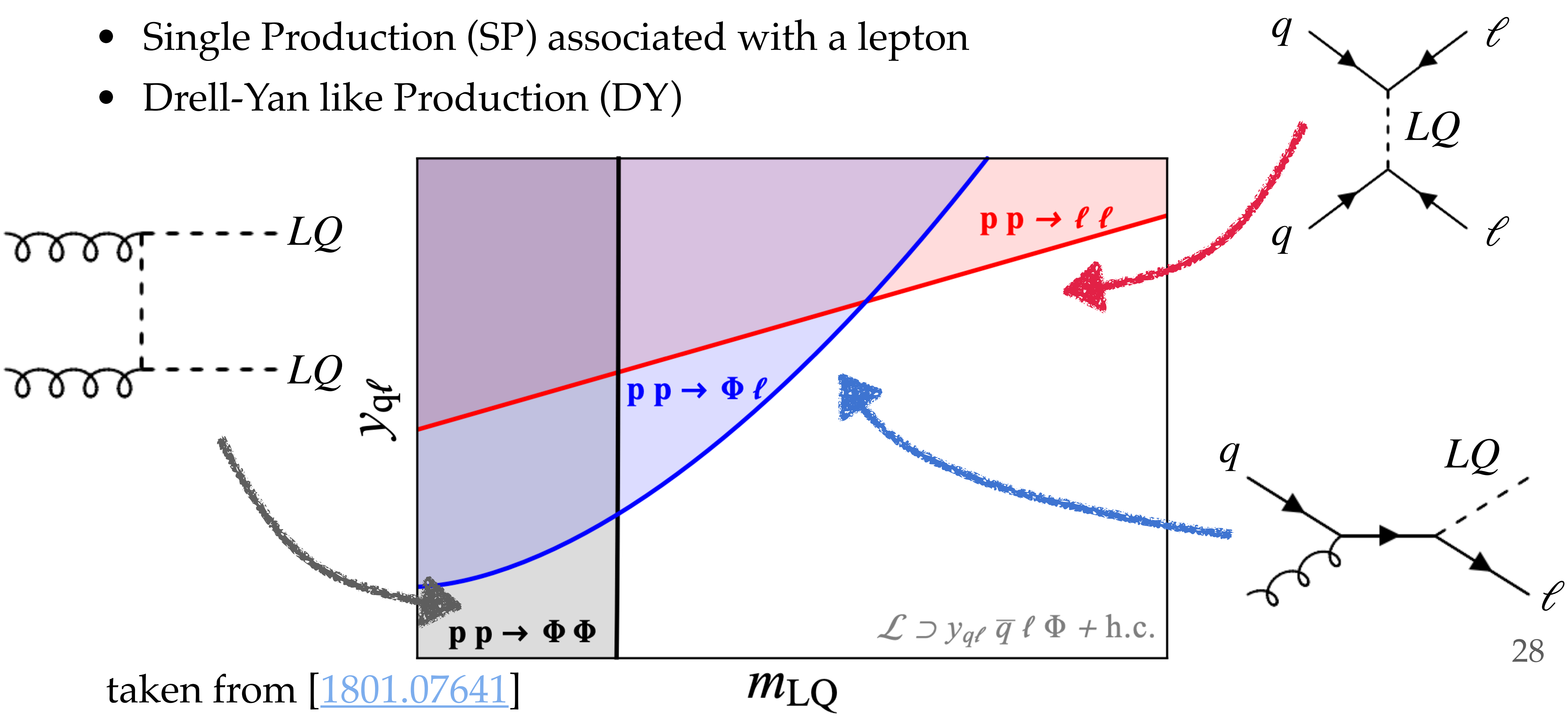
- in lepton-quark collisions only one lepton PDF suppression!
- ideal BSM candidate: **LeptoQuark** searches in single resonant channel

LeptoQuarks Searches at LHC: INTRO

LeptoQuark appear in several extensions of the Standard Model, and are advocated as a possible explanation of the flavour anomalies
(for a recent review *Dorsner et al* [1603.04993])

At LHC, the searches focus on three production mechanisms

- Pair Production (PP)
- Single Production (SP) associated with a lepton
- Drell-Yan like Production (DY)



taken from [1801.07641]

LeptoQuarks Searches at LHC: STATUS

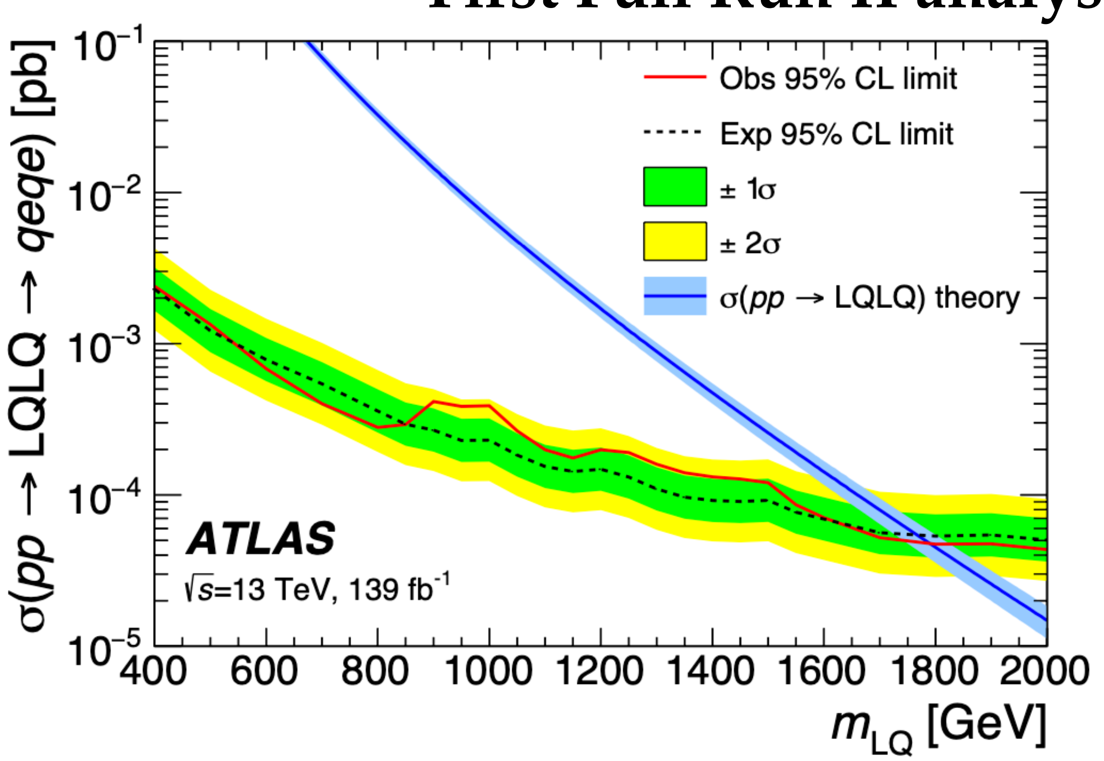
LQ			
	Scalar LQ 1st gen	LQ mass 1.4 TeV	1902.00377
	Scalar LQ 2nd gen	LQ mass 1.56 TeV	1902.00377
	Scalar LQ 3rd gen	LQ_3^u mass 1.03 TeV	1902.08103
	Scalar LQ 3rd gen	LQ_3^d mass 970 GeV	1902.08103

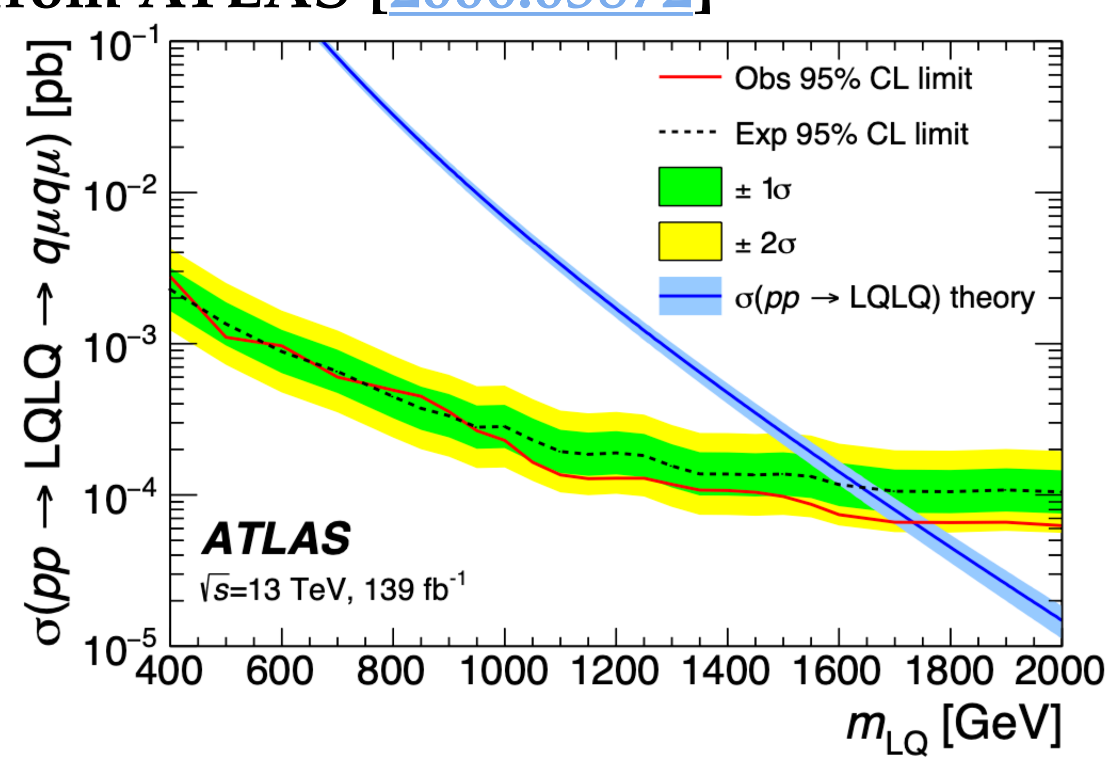
ATLAS Exotics Searches

Leptoquarks				
	scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 1$	<1.44	1811.01197 (**2e + 2j**)	36 fb^{-1}
	scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 0.5$	<1.27	1811.01197 (**2e + 2j; e + 2j + E_T^{miss}**)	36 fb^{-1}
	scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$	<1.53	1808.05082 (**2μ + 2j**)	36 fb^{-1}
	scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$	0.8−1.5	1811.10151 (**1μ + 1j + E_T^{miss}**)	77 fb^{-1}
	scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 0.5$	<1.29	1808.05082 (**2μ + 2j; μ + 2j + E_T^{miss}**)	36 fb^{-1}
	scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$	<1.02	1811.00806 (**2τ + 2j**)	36 fb^{-1}
	scalar LQ (single prod.), coup. to 3rd gen. ferm., $\beta = 1, \lambda = 1$	<0.74	1806.03472 (**2τ + b**)	36 fb^{-1}

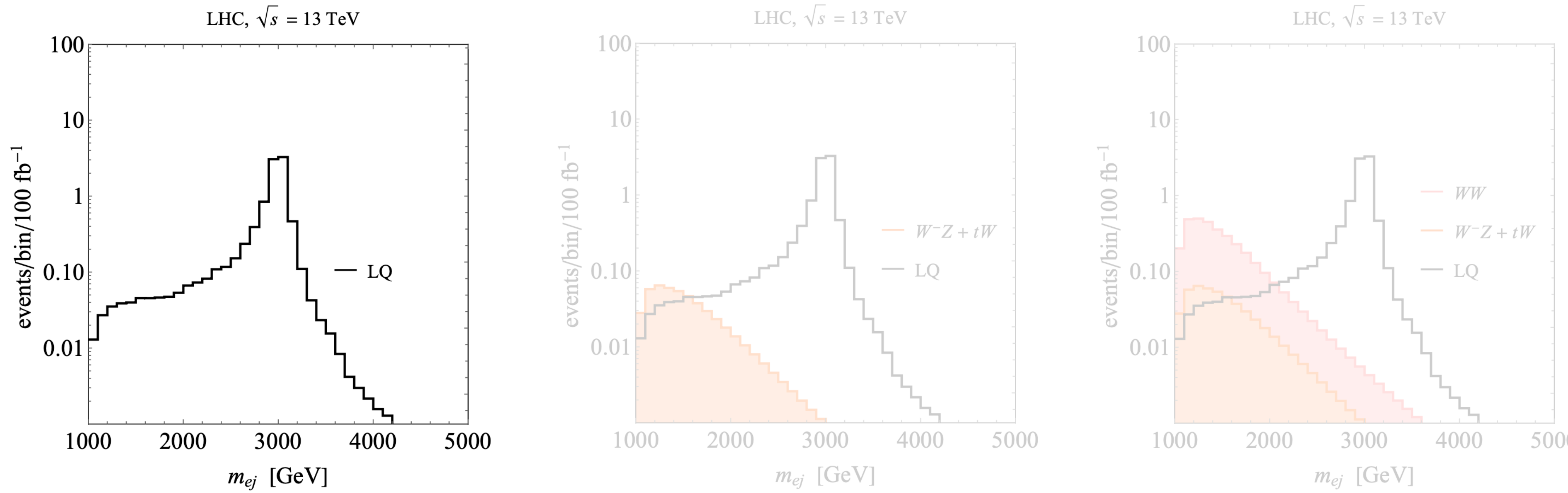
CMS EXO results

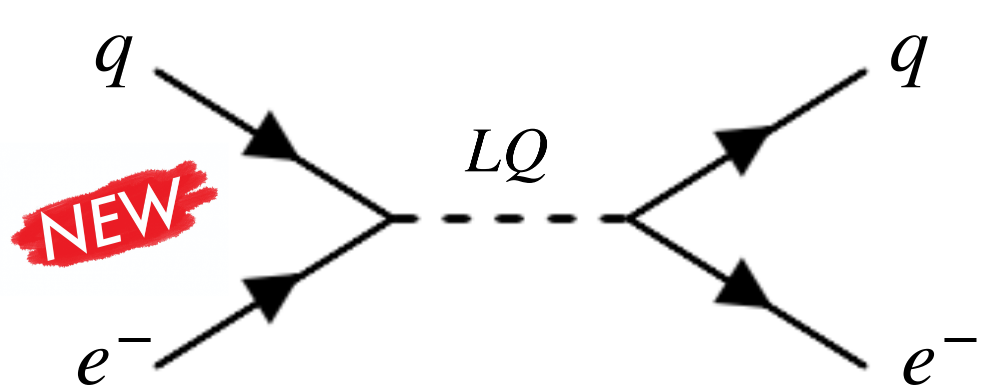
First Full Run II analysis from ATLAS [2006.05872]





LeptoQuarks Searches at LHC: s-channel production





Minimal scalar LeptoQuark which couples to e^- and u quark

Benchmark point: $M_{LQ} = 3\,\text{TeV}, \quad \lambda_{eu} = 1$

Simulated at LO+PS

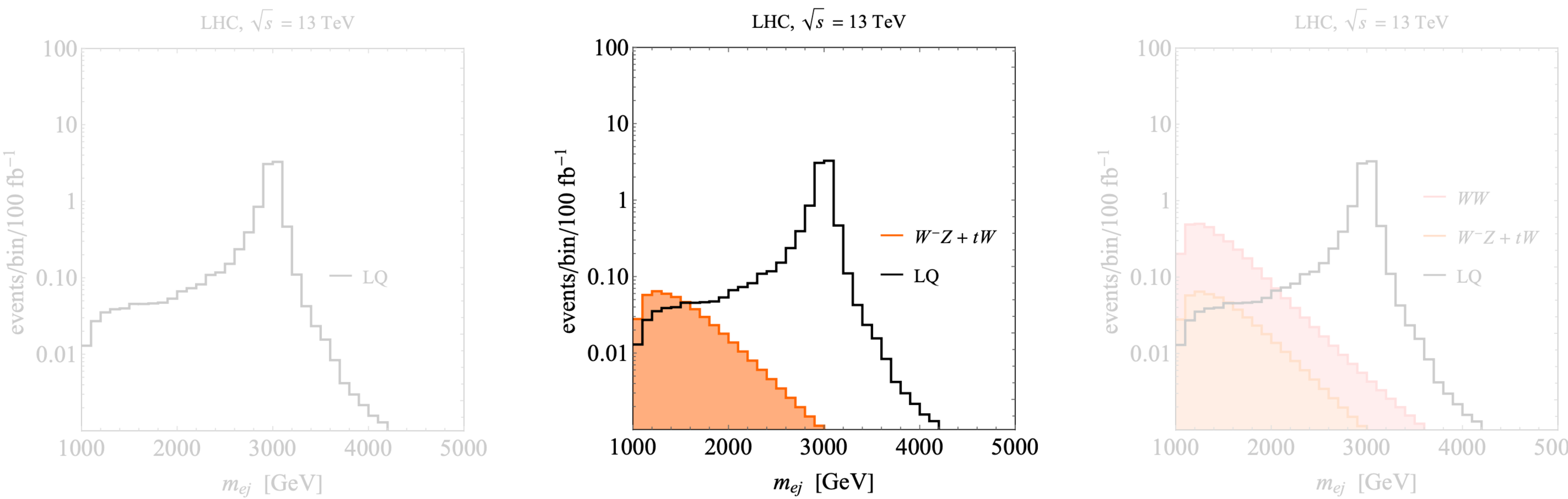
To target signal

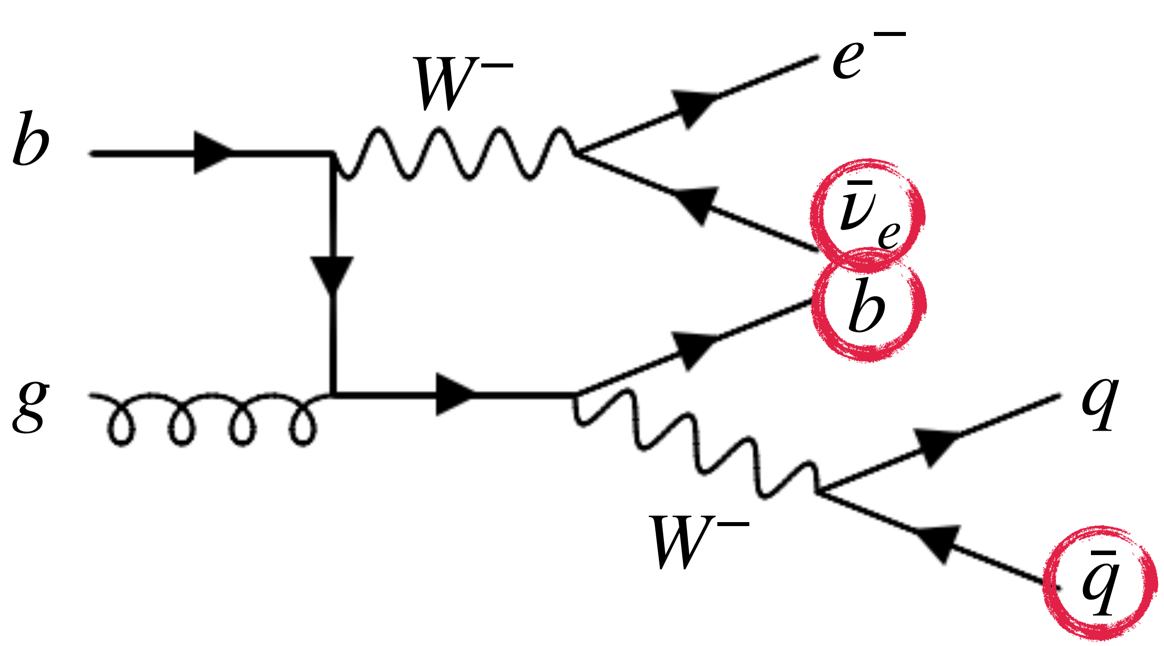
$$|\eta_{\ell_1}| < 2.5, \qquad p_{T,\ell_1} > 500\,\text{GeV}, \qquad |\eta_{j_1}| < 2.5, \qquad p_{T,j_1} > 500\,\text{GeV}$$

Suppress background: cut on missing energy, veto on extra leptons and jets

$$E_{T,\text{miss}} < 50\,\text{GeV}, \qquad |\eta_{\ell_2}| < 2.5 \quad p_{T,\ell_2} > 7\,\text{GeV}, \qquad |\eta_{j_2}| < 2.5, \qquad p_{T,j_1} > 30\,\text{GeV}$$

LeptoQuarks Searches at LHC: s-channel production

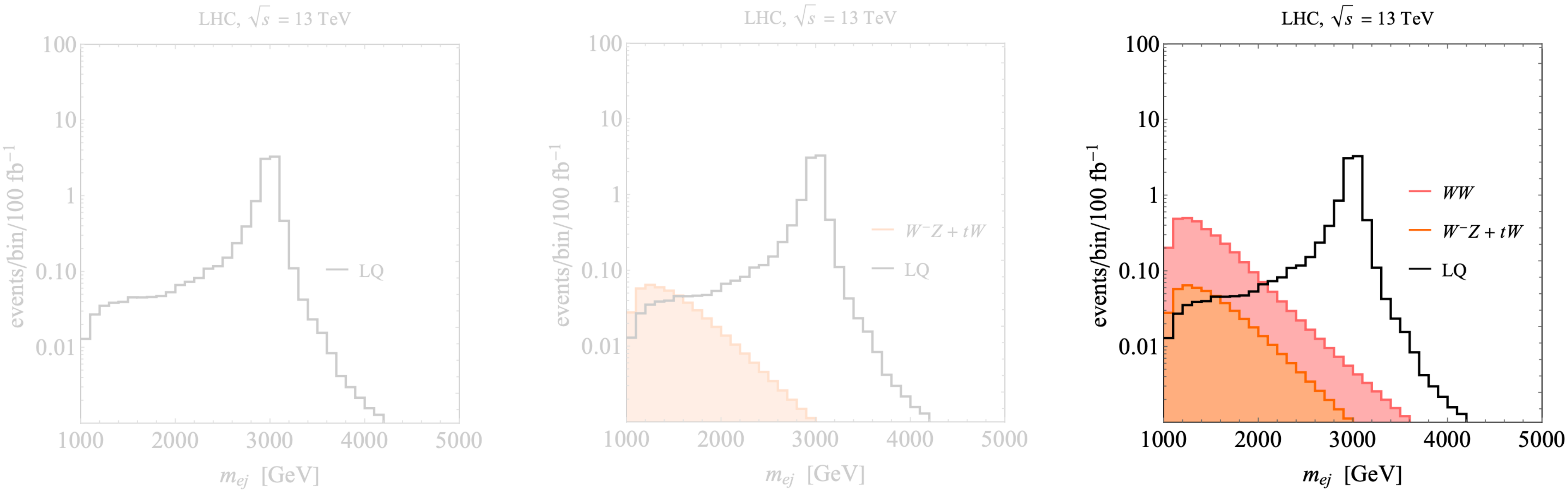


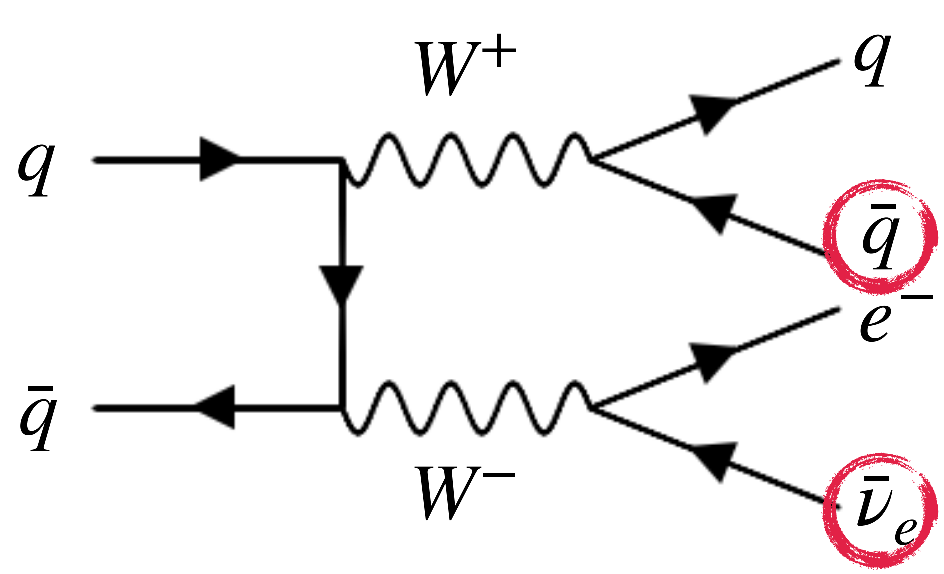


Simulated at LO+PS and normalised to the NLO QCD result

Suppressed by E_T miss & jet veto requirements

LeptoQuarks Searches at LHC: s-channel production





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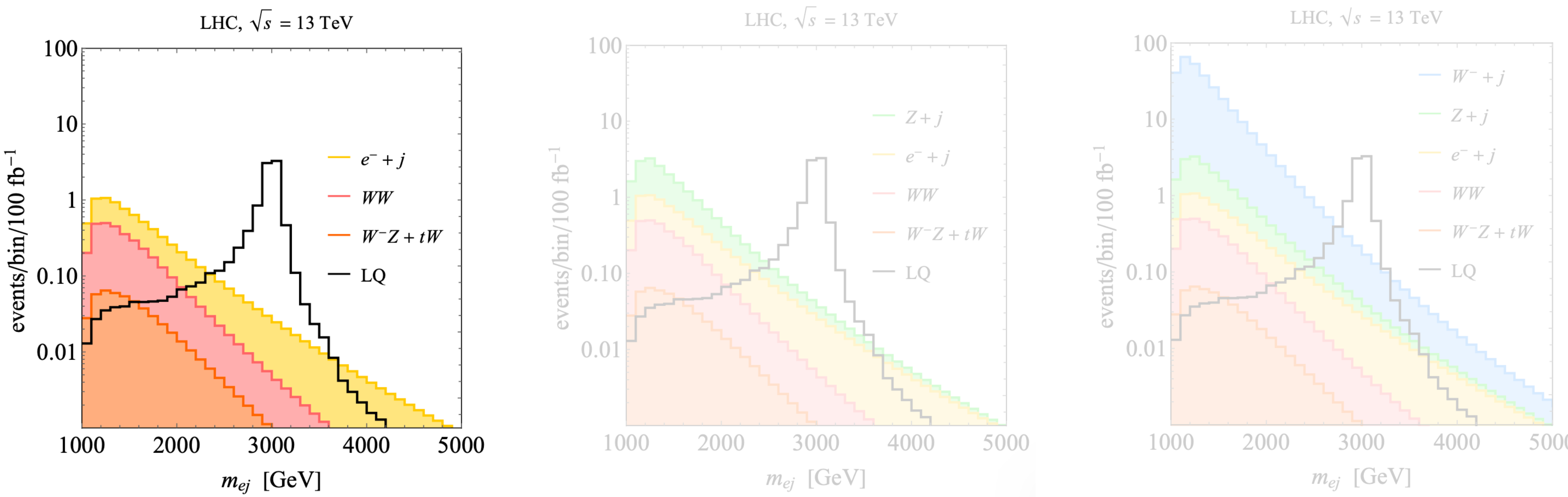
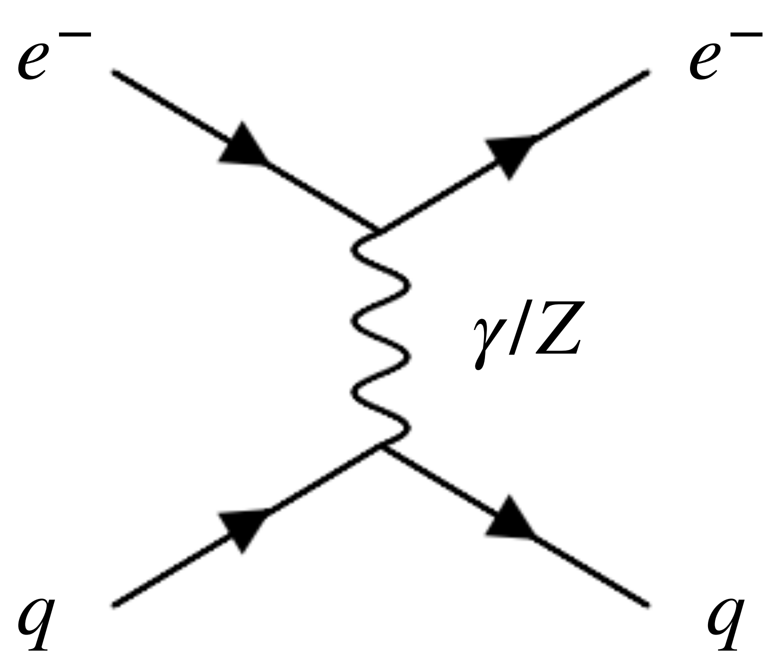
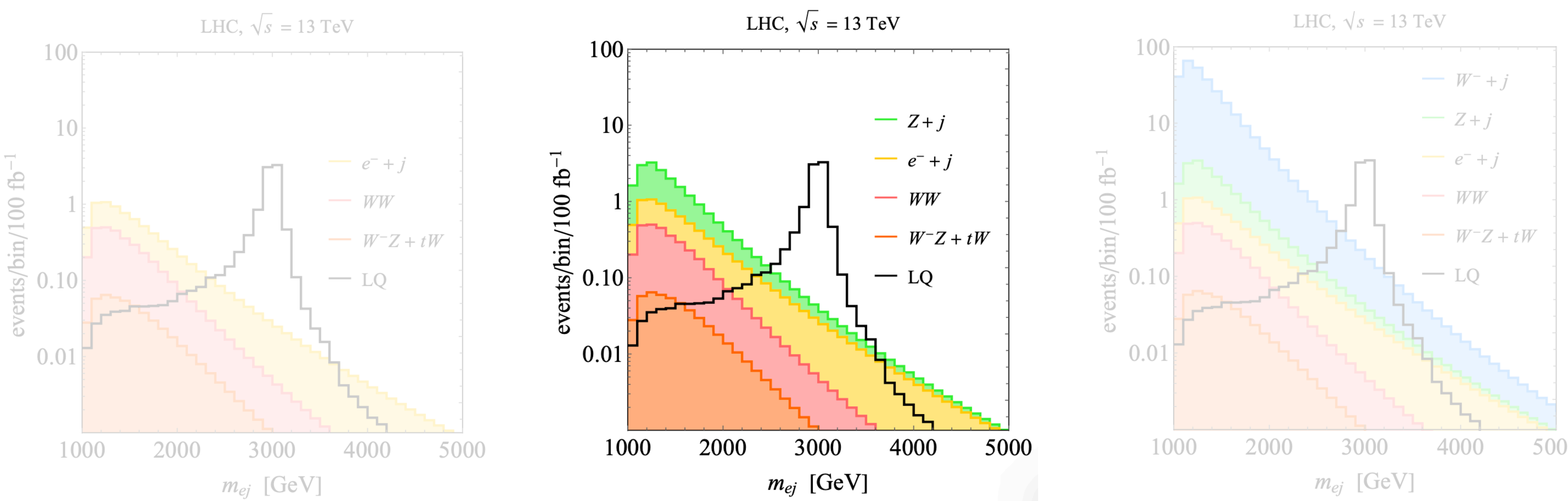


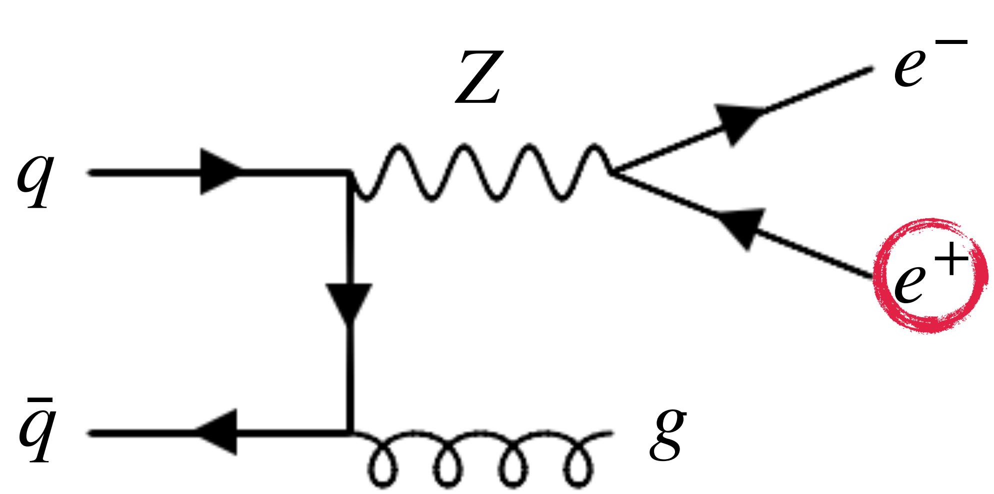


Irreducible background.
Simulated at LO+PS

Relevant at high-invariant lepton-jet mass

LeptoQuarks Searches at LHC: s-channel production

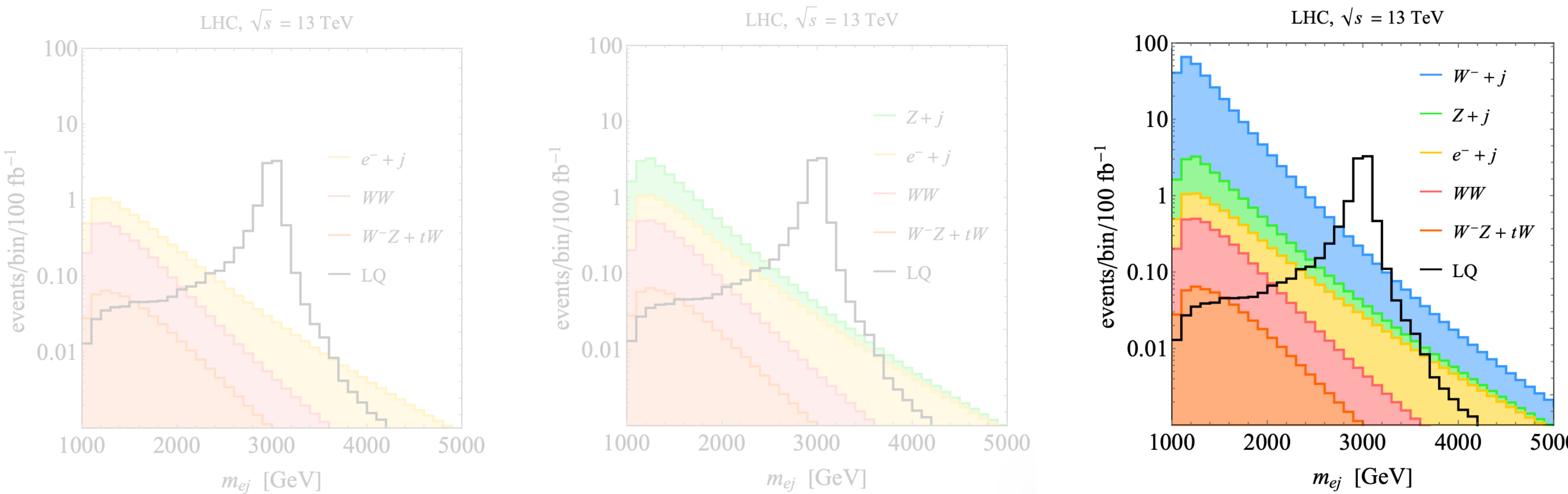


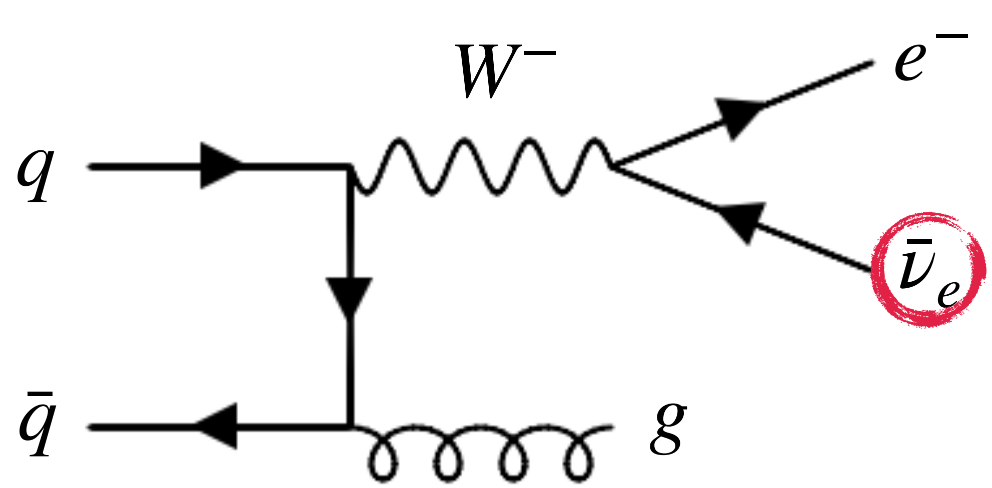


Simulated at LO+PS and normalised to the NLO QCD result

Suppressed by lepton veto requirement

LeptoQuarks Searches at LHC: s-channel production

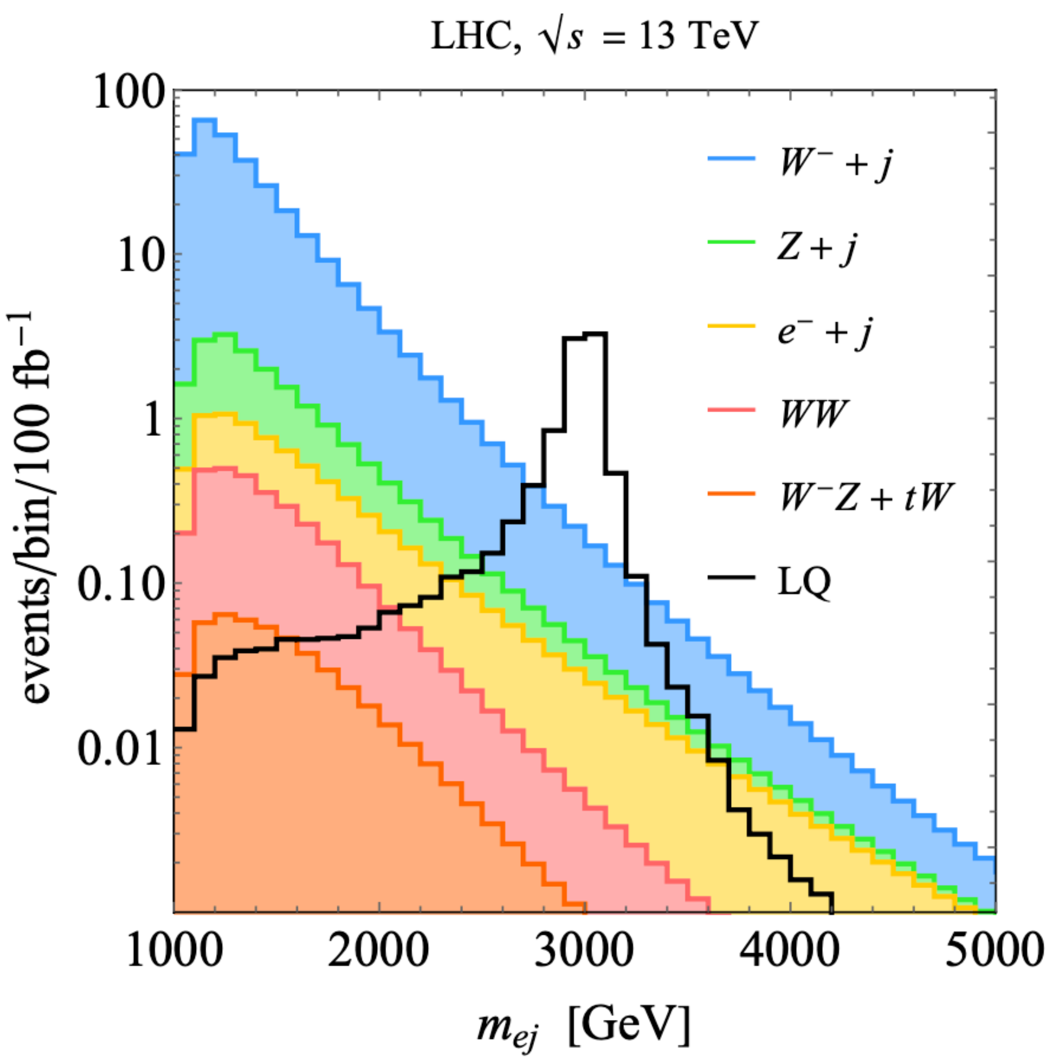




Main background. Simulated at NLO(QCD)+PS (NNLO QCD + NLO EW should effectively reduce the cross section in the region of interest *J.M. Lindert et al* [1705.04664])

Suppressed by E_T miss requirement

LeptoQuarks Searches at LHC: s-channel production



LQ signal exhibits a **mass peak** over a steeply falling background

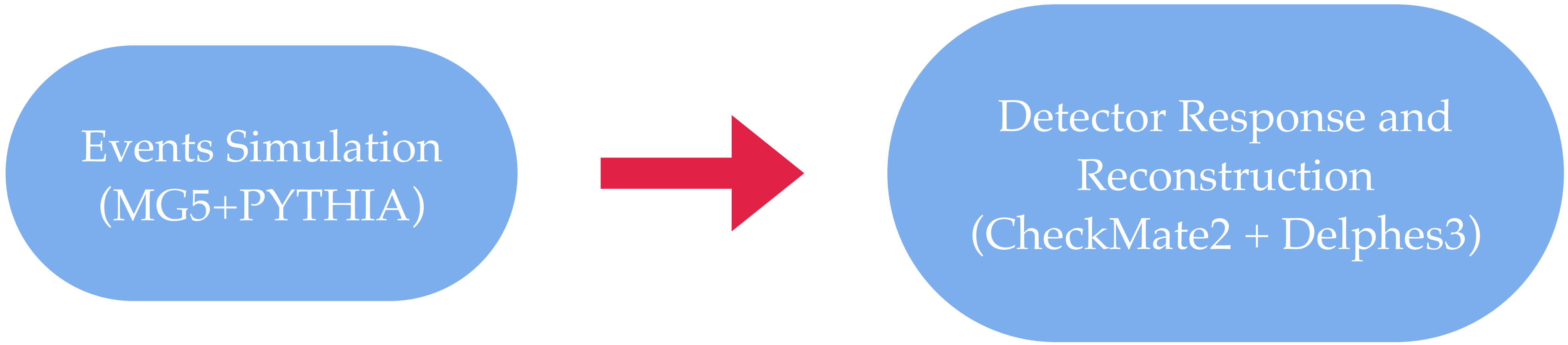
Fake leptons due to multi-jets misidentification and **mass resolution effects** must be included

REMARKS

- PYTHIA does not handle lepton initiated processes. For the signal, we **trade leptons with photons** before showering. This leads to a **higher hadron activity** and hence a larger rejection (**conservative estimate**).

- We estimate the uncertainty to be of $\mathcal{O}(10\%)$ by studying the process $\gamma q \to e^- e^+ q$ and therefore the mis-modelling only mildly affects our analysis

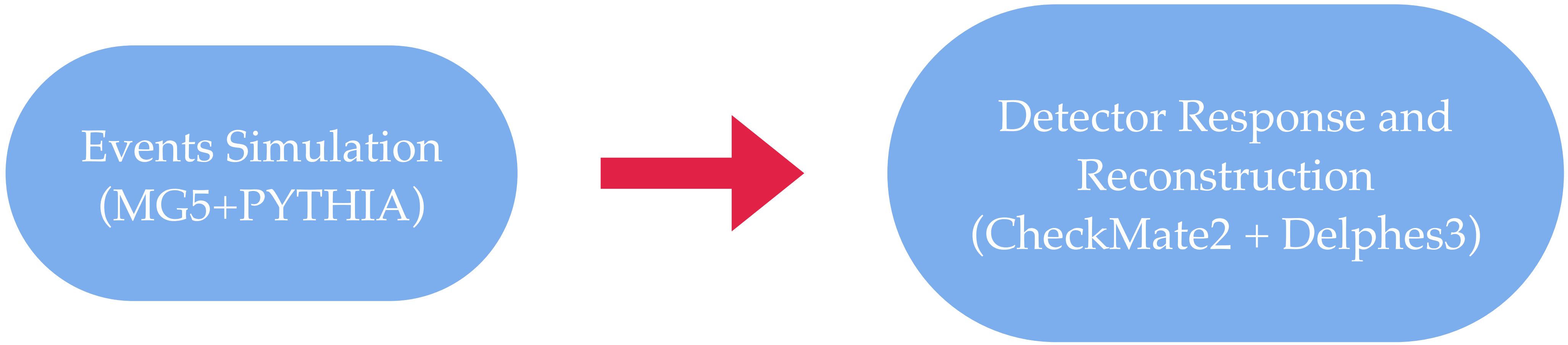
LeptoQuarks Searches at LHC: analysis details & follow-up



- **Multijet backgrounds**: incorporated as a systematic uncertainty taken from the ATLAS $\ell + E_{T,\mathrm{miss}}$ search [1906.05609] and doubling the quoted error.
- **Lepton-jet mass resolution**: estimated by combining the information on the dilepton & dijet mass resolutions given in [1903.06248] & [1910.08447].

- **Multijet backgrounds refinement**: background estimate and systematic uncertainty extrapolated from the ATLAS $\ell + j$ search [1311.2006].
- Added PDF uncertainties on the main background
- Better estimate of lepton-jet mass resolution and of the broadening of the reconstructed LQ peak

LeptoQuarks Searches at LHC: analysis details & follow-up



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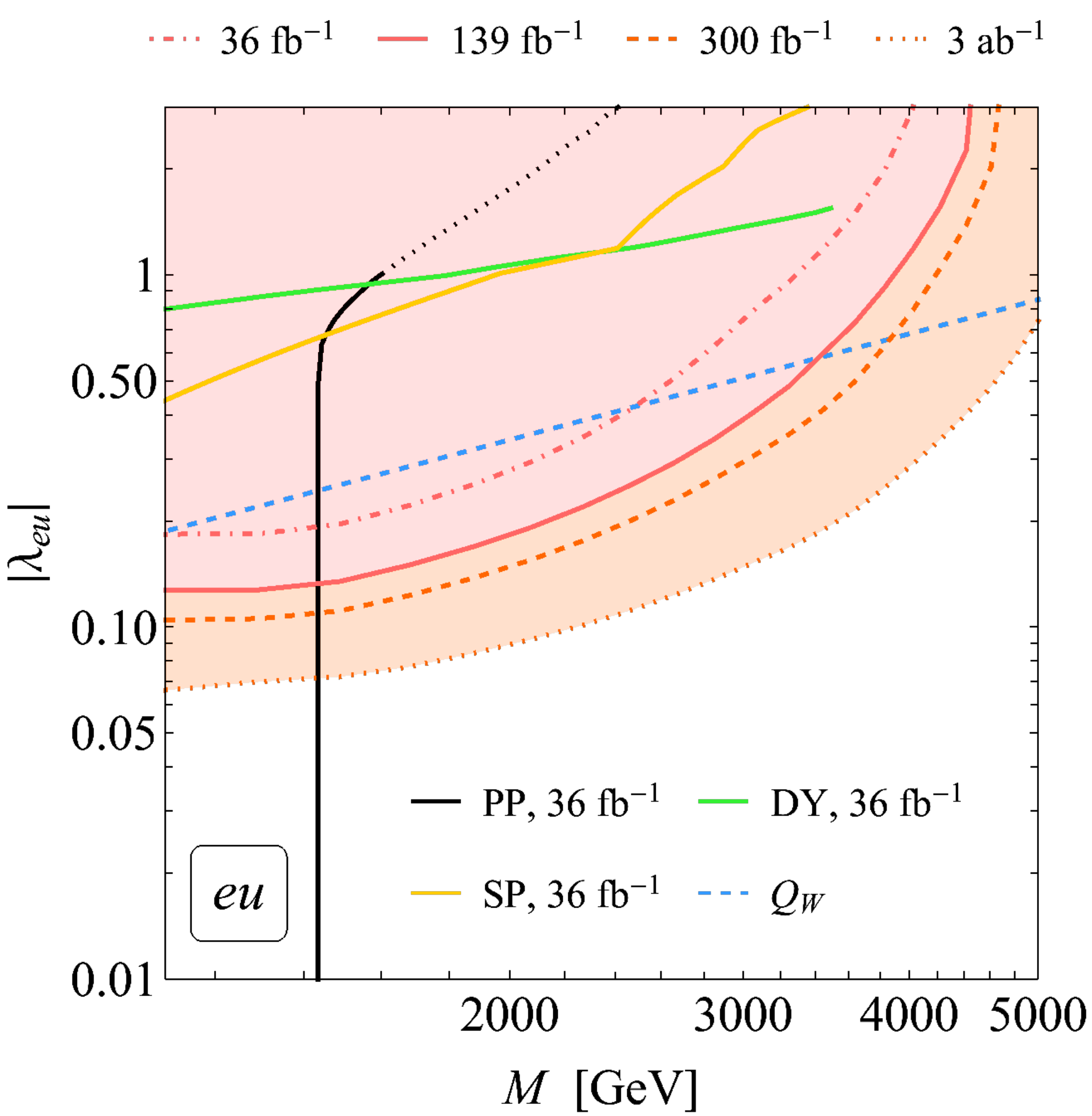
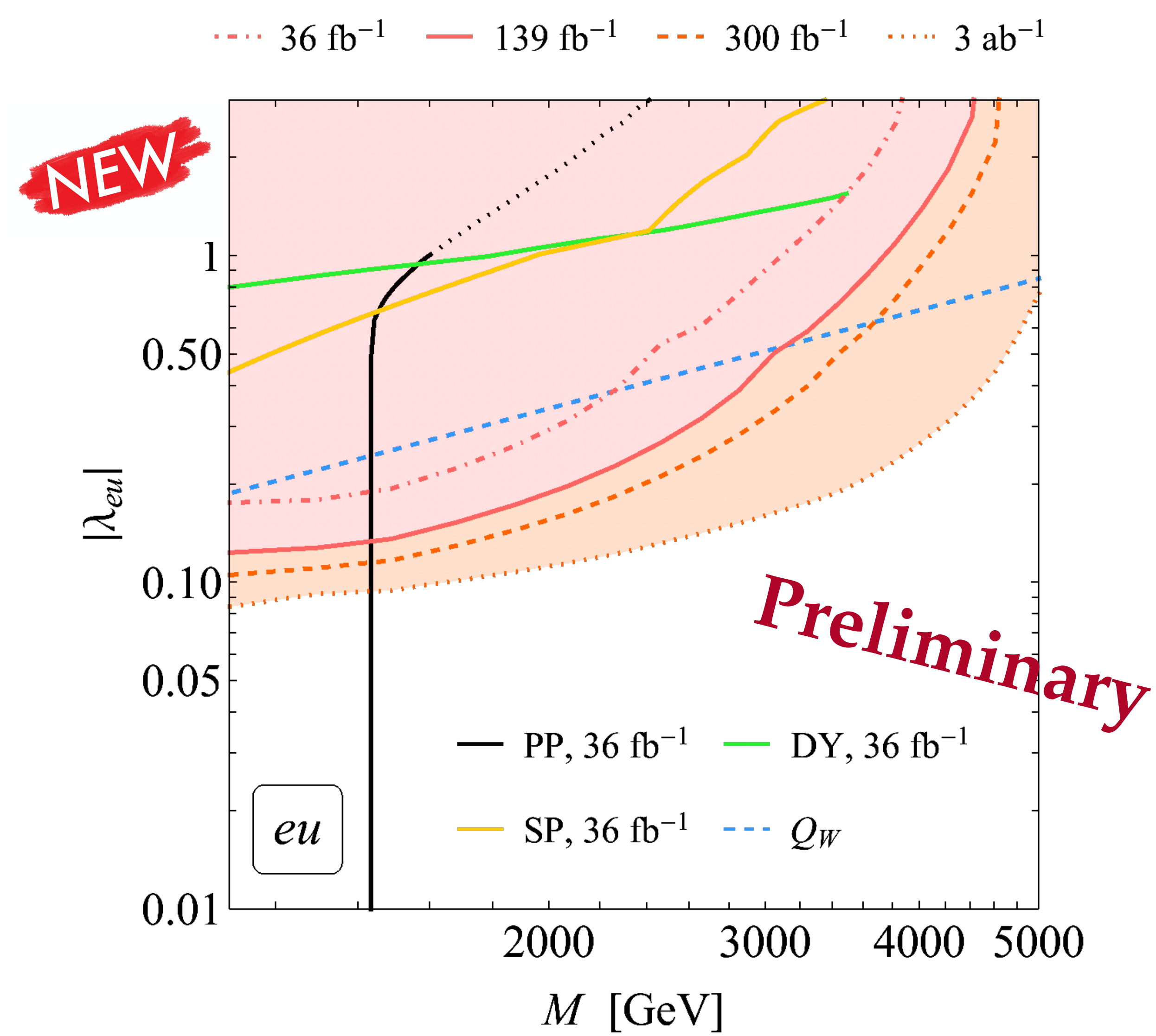
- **Lepton-jet mass resolution**: estimated by combining the information on the dilepton & dijet mass resolutions given in [1903.06248] & [1910.08447].

tot syst	1 TeV	2 TeV	3 TeV
e+j	7.6%	37%	143%
μ+j	9.4%	20%	65%

mass res	1 TeV	2 TeV	3 TeV
e+j	2.3%	1.7%	1.6%
μ+j	6.7%	12%	17%

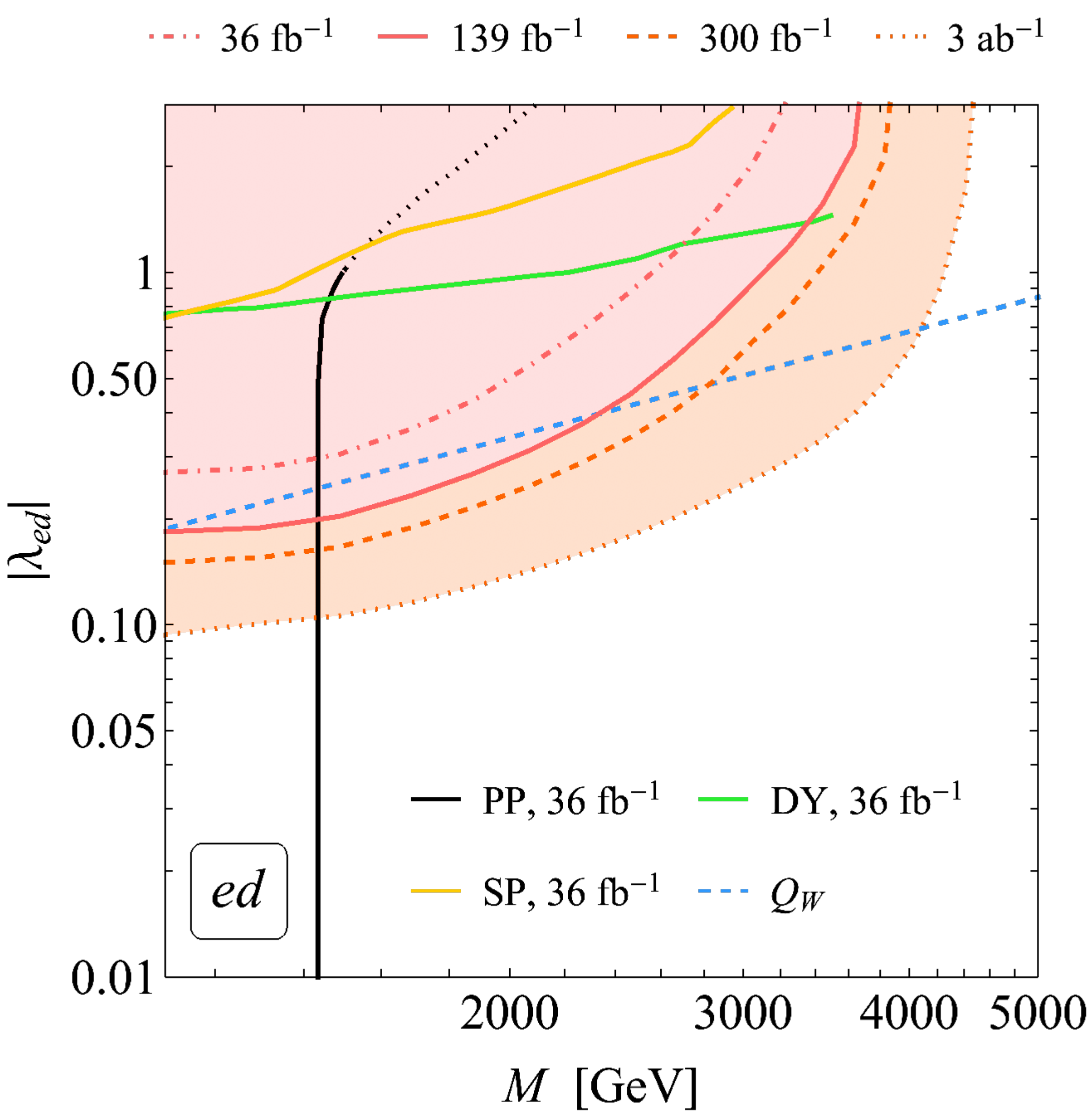
LeptoQuarks Searches at LHC: eu 95% CL limits

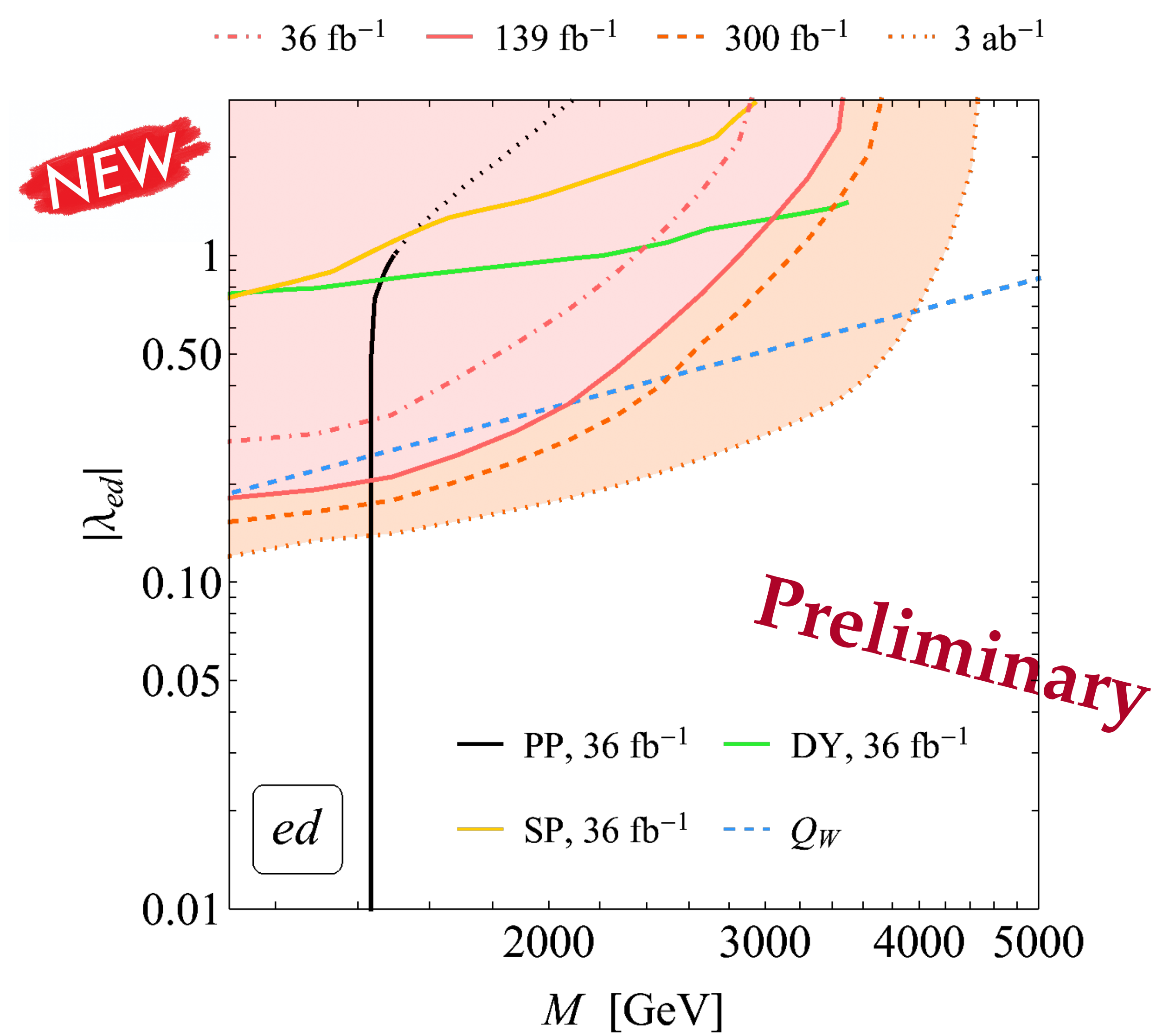




- Existing limits taken from [1810.10017]
- **Overall results are not spoiled** after the refinement of the analysis
- We get **stronger limits** than the ones arising from **atomic parity violation** and **parity-violating electron scattering experiments** for LQ masses up to 3 TeV (5 TeV) with the full Run II (HL-LHC).

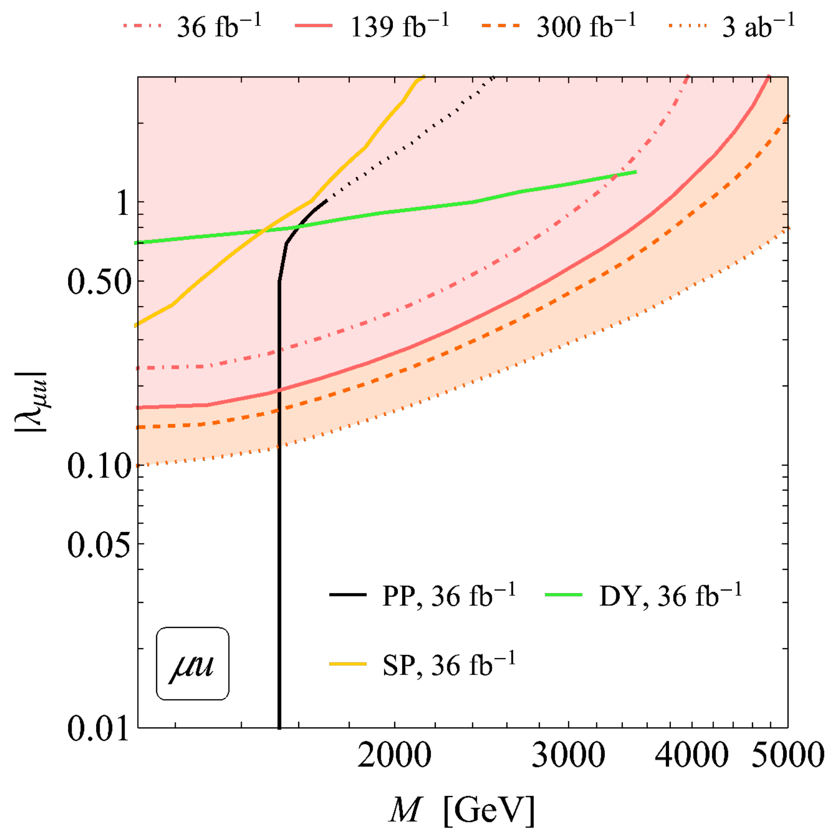
LeptoQuarks Searches at LHC: *ed* 95% CL limits

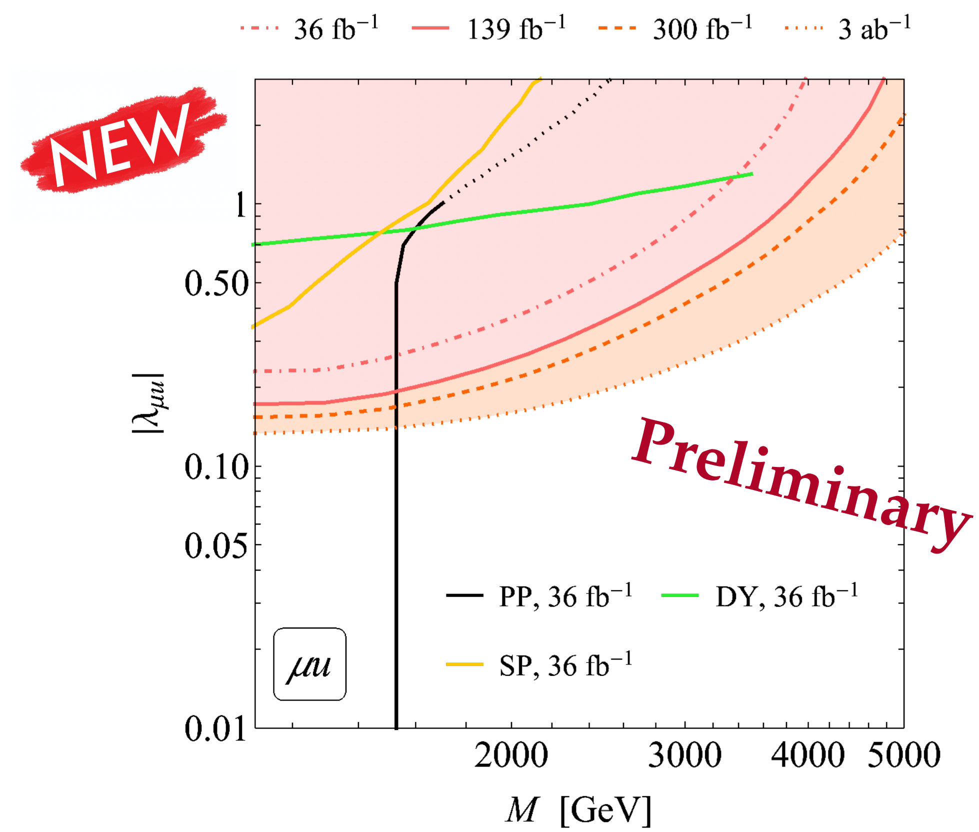


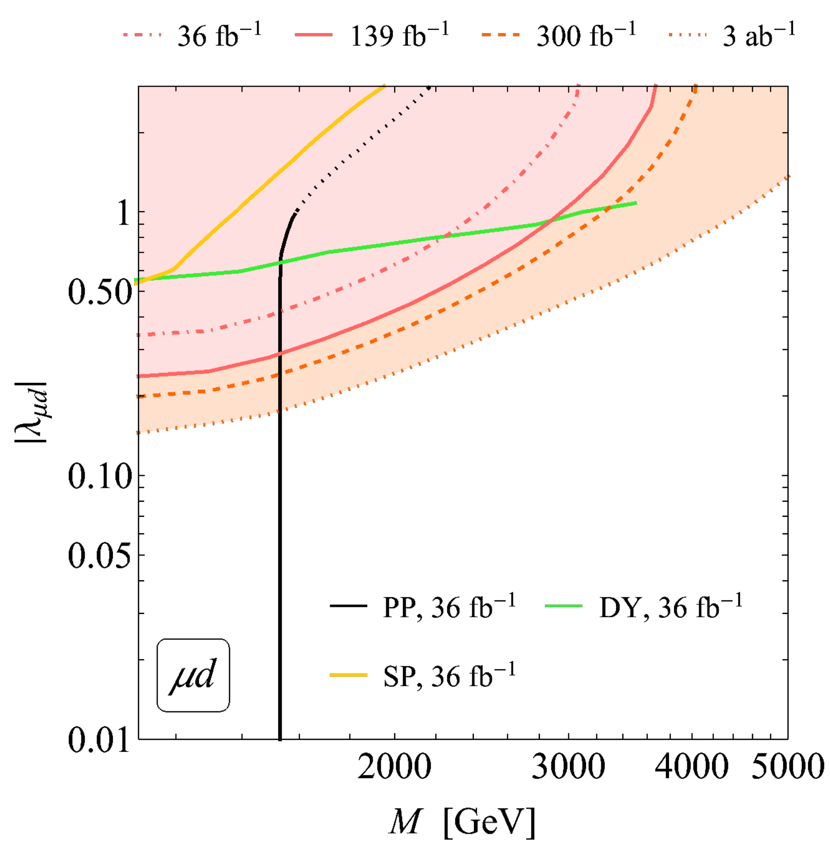


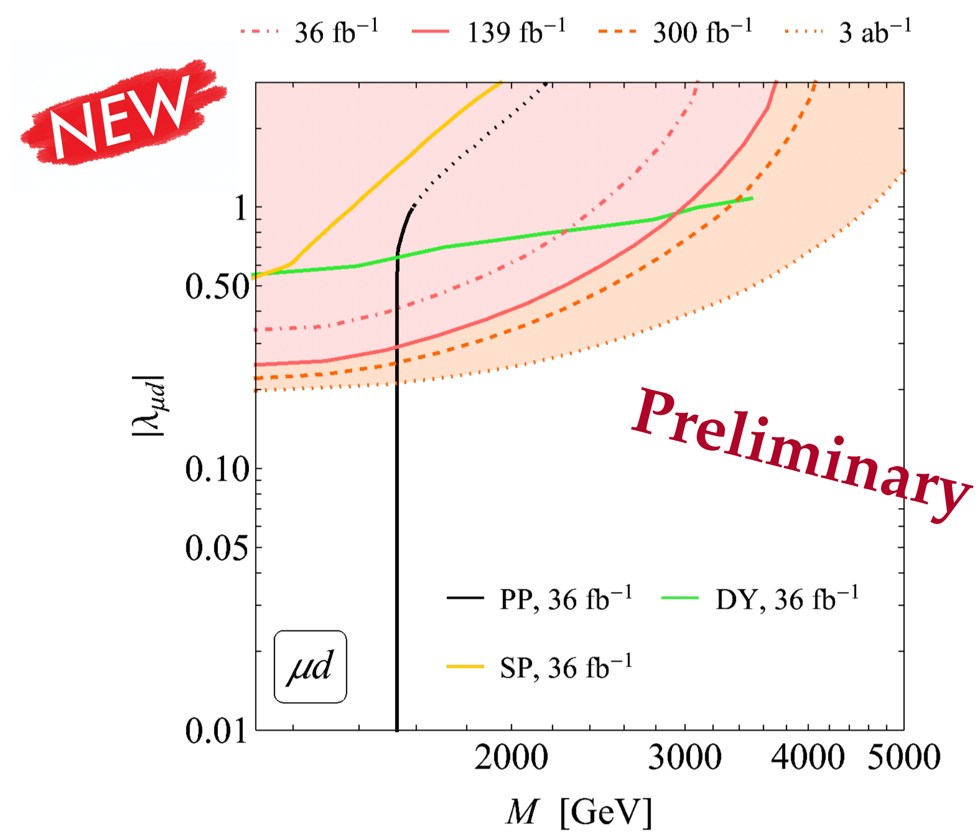
- Analogous results for the limits on the λ_{ed} coupling. The limits are slightly weaker due to smaller *d* luminosity.
- We get **stronger limits** than the ones arising from **atomic parity violation** and **parity-violating electron scattering experiments** for LQ masses up to 2 TeV (4 TeV) with the full Run II (HL-LHC).

LeptoQuarks Searches at LHC: μq 95% CL limits









CONCLUSIONs

- Lepton densities in the proton can be modelled with high precision using the LUX approach

- Using NLO lepton PDFs, lepton initiated processes are pushed to a level of accuracy comparable to the ones involving coloured partons

- NLO+PS implementations are within the reach. They are desirable to fully exploit the small hadron activity for background rejection

- A comment upon NLO corrections to lepton initiated processes: $\mathcal{O}(\alpha)$-photon induced processes must be included as NLO QCD. In essence, this is due to the relative importance of photon and lepton densities.

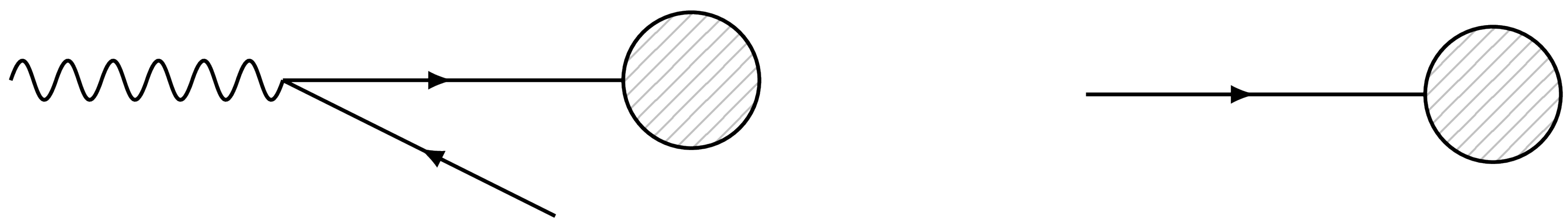
CONCLUSIONs

- Despite the small cross sections
    - ✦ handful of SM lepton-lepton scattering events already produced with the full Run II luminosity and **might be measurable**
    - ✦ lepton initiated processes has **the potential to enlarge New Physics sensitivity in hadron collisions**
- General ideas for BSM searches
    - ✦ **simple resonant searches** for new interactions which **preferably** couple to leptons
    - ✦ enough **large couplings**, **exotic SM signatures** (to reduce background)
- We provide the first concrete example of a general search strategy for **resonant LQ production** induced by lepton PDFs
    - ✦ sensitive direct probe of 1st & 2nd-generation scalar LQs at the LHC
    - ✦ in view of its **simplicity** and **discovery reach**, ATLAS&CMS should performed dedicated resonance searches in lepton-jet final states

BACKUP

INTRODUCTION: MOTIVATIONS

In general, lepton PDFs do not open new production mechanisms



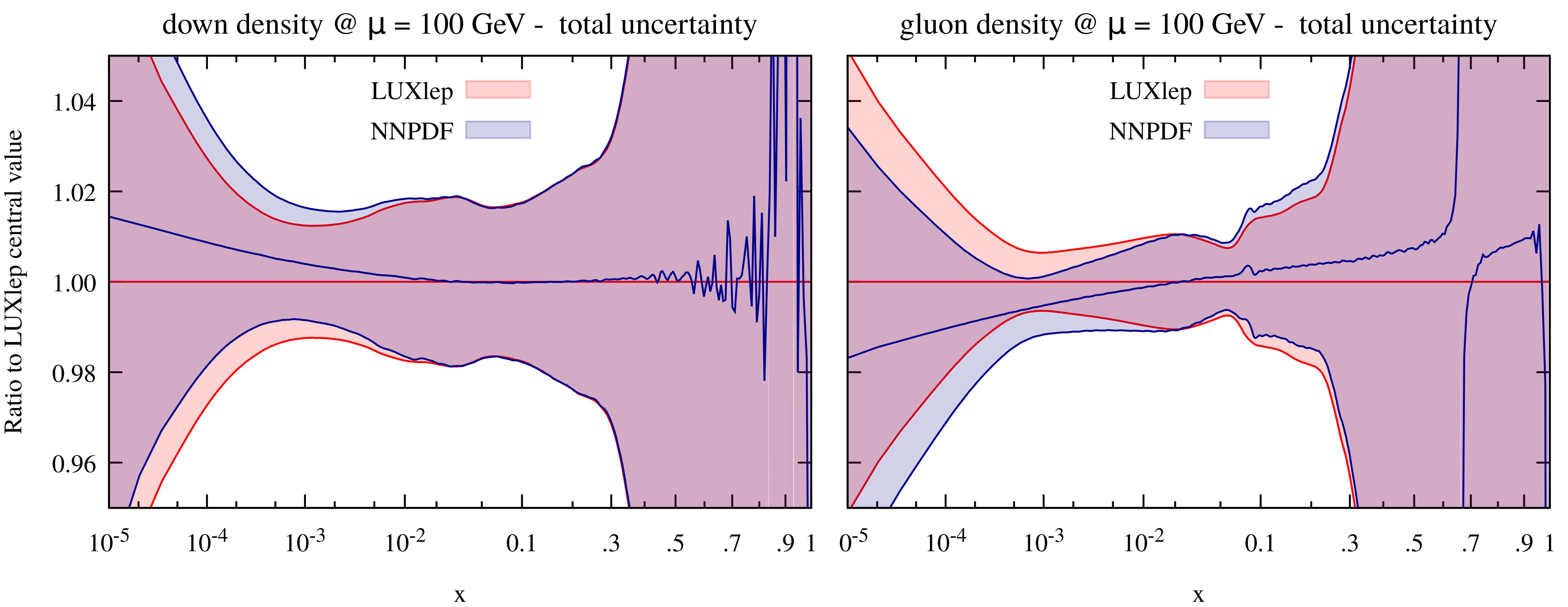
4F vs 5F!

PROs

- Lepton masses very small (numerical instabilities). Potential large collinear $\alpha \log \frac{Q}{m_\ell}$ effectively taken into account (and resummed in DGLAP)
- Smaller final state multiplicities
- Reduced hadronic activity (PS programs for lepton initiated processes required!)

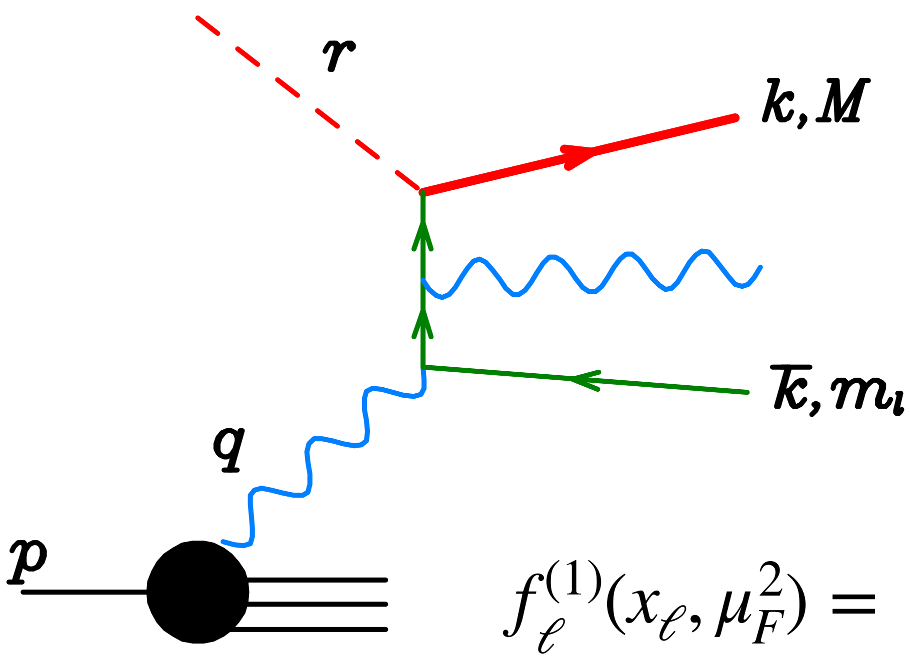
COMPARISON among QUARK/GLUON PFDs

- Slightly differences (especially for gluons), within uncertainties
  - mainly due to the use of a different evolution framework (HOPPET)
  - effects of lepton PDF negligible on quark/gluon densities and momentum sum rule (sub per mille effect)



$\mathcal{O}(\alpha^3 L^3)$ corrections

- We need to add only diagrams with photon emission off leptons
- The dominant contribution can be computed in the collinear approximations

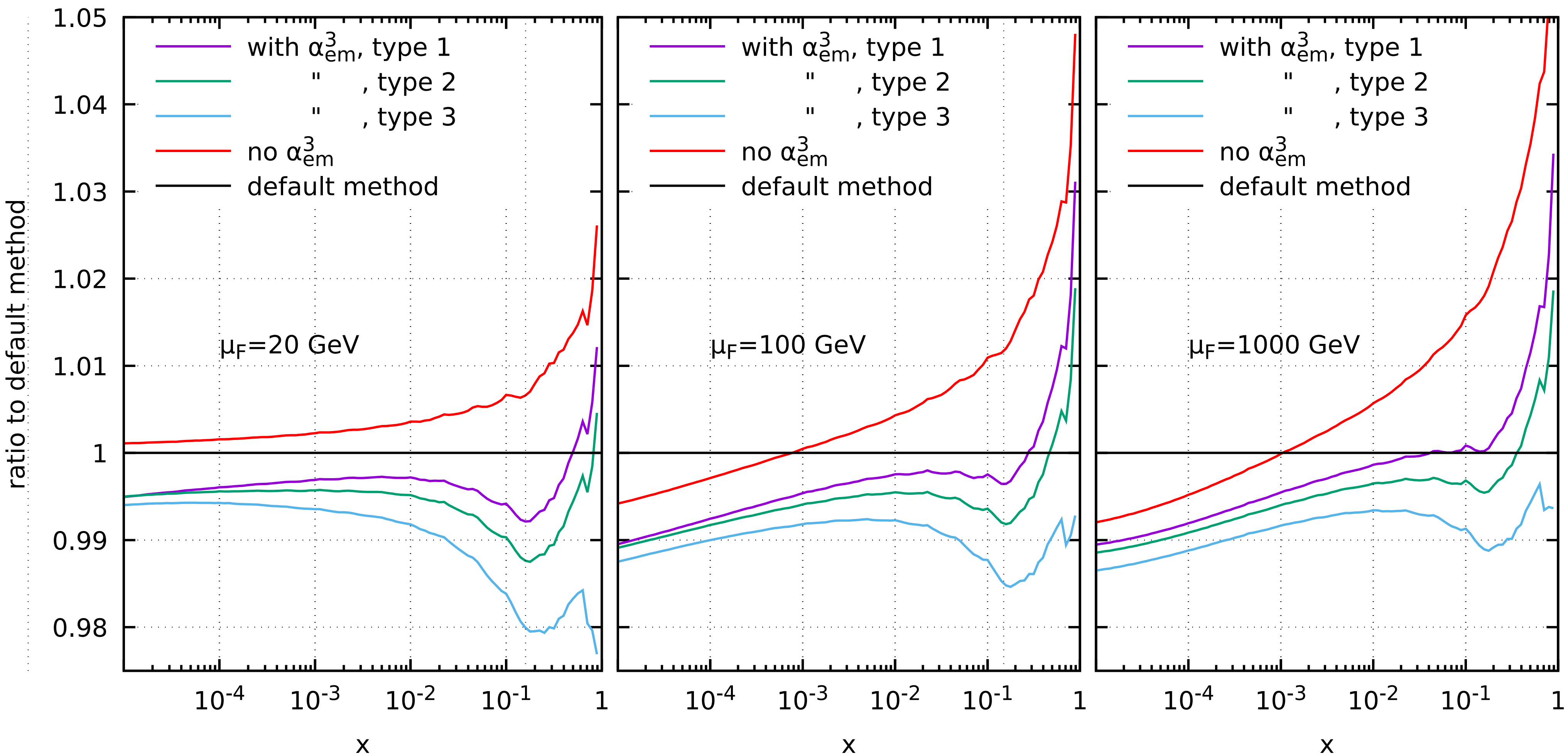


$$f_\ell^{(1)}(x_\ell, \mu_F^2) = \left(\frac{\alpha}{2\pi}\right)^3 \int_0^1 dx_{\rm bj} \int_0^1 dz P_{\gamma q}(z) \int_0^1 dz_\ell P_{\ell\gamma}^{(2)}(z_\ell)$$

$$\delta(x_{\rm bj} z z_\ell - x_\ell) \int_{m_{\rm P}^2}^{\mu_F^2} \frac{dQ^2}{Q^2} \sum_i f_i(x_{\rm bj}, Q^2) c_i^2 \frac{1}{2} \log^2 \frac{M^2}{Q^2}$$

two explicit logs and one from Q^2 integration. Here $P_{\ell\gamma}^{(2)} = P_{\ell\ell} \otimes P_{\ell\gamma}$

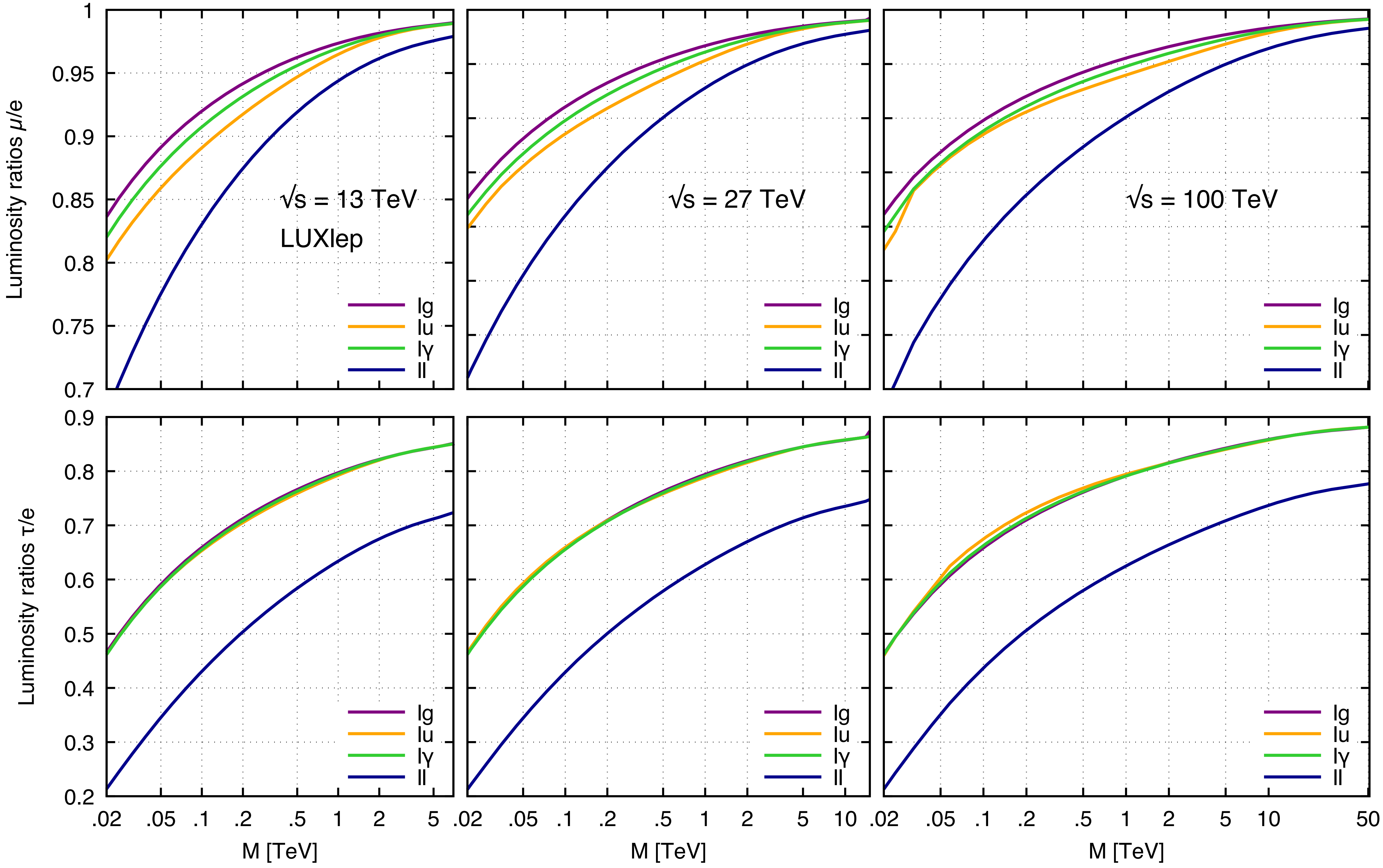
$\mathcal{O}(\alpha^3 L^3)$ corrections - comparison with DGLAP



Our default method compared with three variants of the direct calculation of the $\alpha^3 L^3$ terms. We conclude that

- The effect of the $\alpha^3 L^3$ term is quite modest.
- There are large differences among the different method for its inclusion. This seems to indicate that sub-leading α^3 terms are not much smaller than the leading one.

Luminosities for different leptons species



CONSTRUCTION OF A FULL PDF WITH LEPTONS

- In practice, it's a bit more involved
  - we use a input NNPDF31_nlo_as_0118 luxqed
  - we rely on HOPPET as DGLAP solver (different evolution framework, it does not include the $P_{\ell q}$ splitting)
  - we add missing $\alpha^3 L^3$ contributions through evolution

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  - we add missing $\alpha^3 L^3$ contributions through evolution

1. Choose a reference scale where the Lepton (and Photon) PDF are extracted with our formula

Remarks: $\mu_{\rm ref}$ cannot be arbitrarily small, otherwise too sensitive to power suppression terms in Q^2 (higher twist)

CONSTRUCTION OF A FULL PDF WITH LEPTONS

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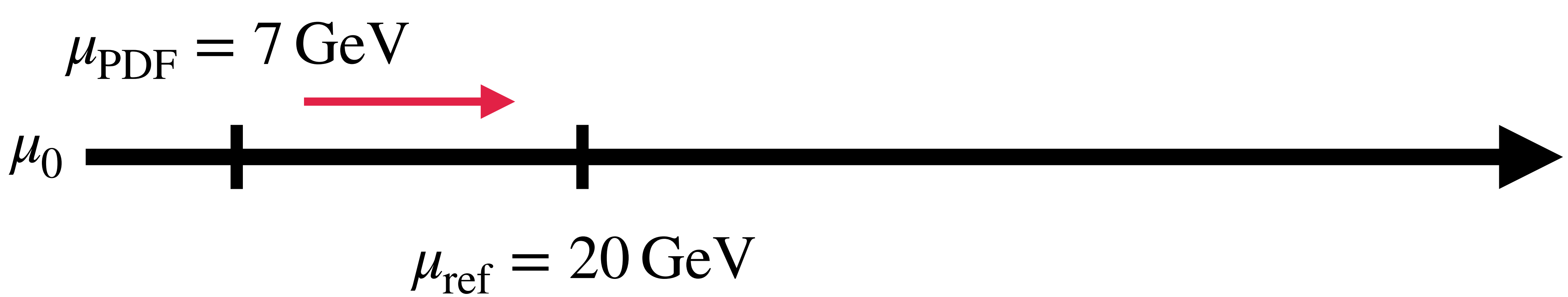
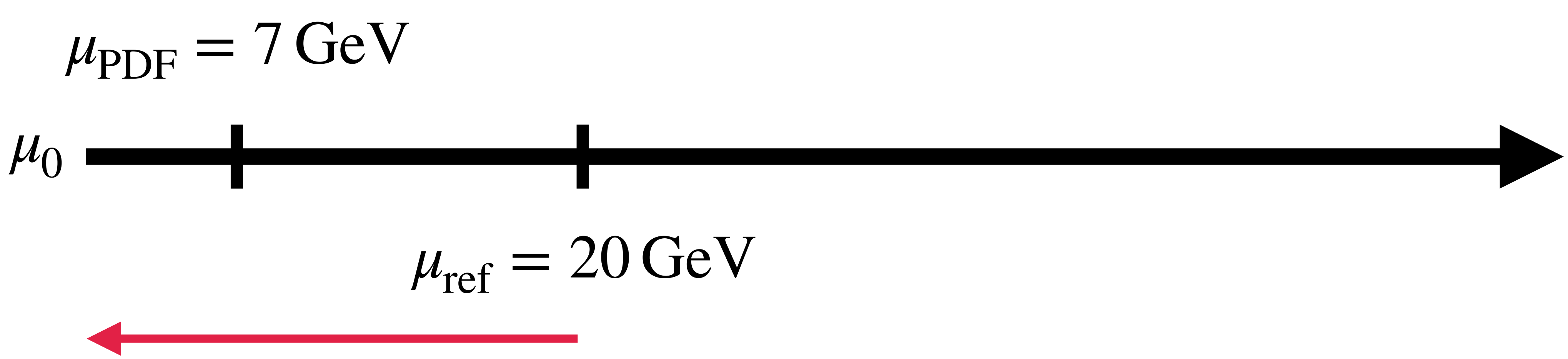


2. Choose a second scale $\mu_{\rm PDF}$ at which the original partons in NNPDF are loaded
3. Evolve from $\mu_{\rm PDF}$ to $\mu_{\rm ref}$ with all splitting turned on but the ones into leptons

Remarks: this is to avoid numerical instabilities due to the use of a different evolution program

CONSTRUCTION OF A FULL PDF WITH LEPTONS

- In practice, it's a bit more involved
  - we use a input NNPDF31_nlo_as_0118 luxqed
  - we rely on HOPPET as DGLAP solver (different evolution framework, it does not include the $P_{\ell q}$ splitting)
  - we add missing $\alpha^3 L^3$ contributions through evolution



5. Add (replace) the lepton (photon) densities at $\mu_{\rm ref}$
6. Evolve down from $\mu_{\rm ref}$ to μ_0 with all splitting turned on but the $P_{\ell\ell}$ which is responsible for the transition $\ell \to \ell + \gamma$

Remarks: this matches our calculation of the lepton PDF

CONSTRUCTION OF A FULL PDF WITH LEPTONS

- In practice, it's a bit more involved
  - we use a input NNPDF31_nlo_as_0118 luxqed
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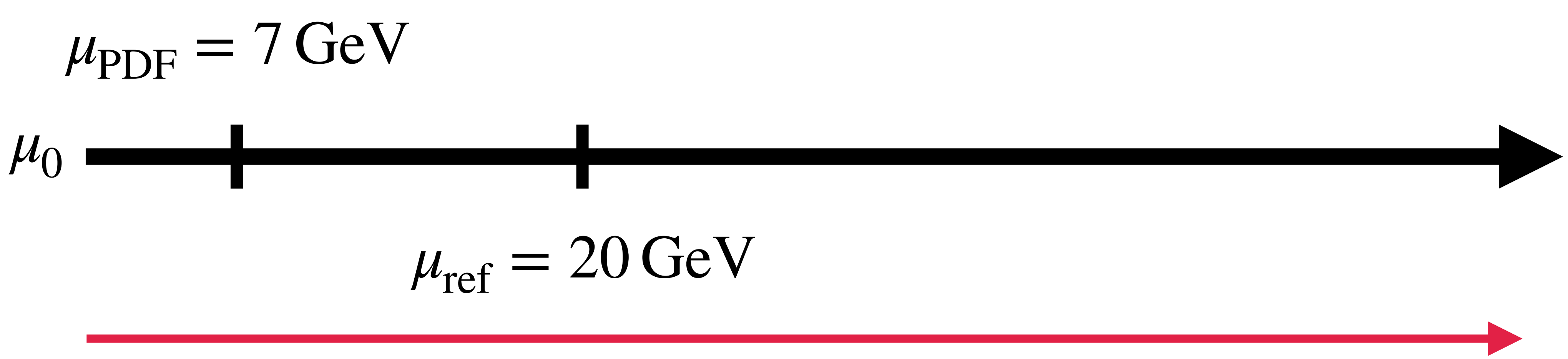

7. Finally, evolve from μ_0 to all scales with the full set of splitting, including $P_{\ell\ell}$

Remarks: in this way, we effectively take into account $\alpha^3 L^3$ contributions