University of Zurich[UZH]

Leptons in the proton

Luca Buonocore
University of Zurich

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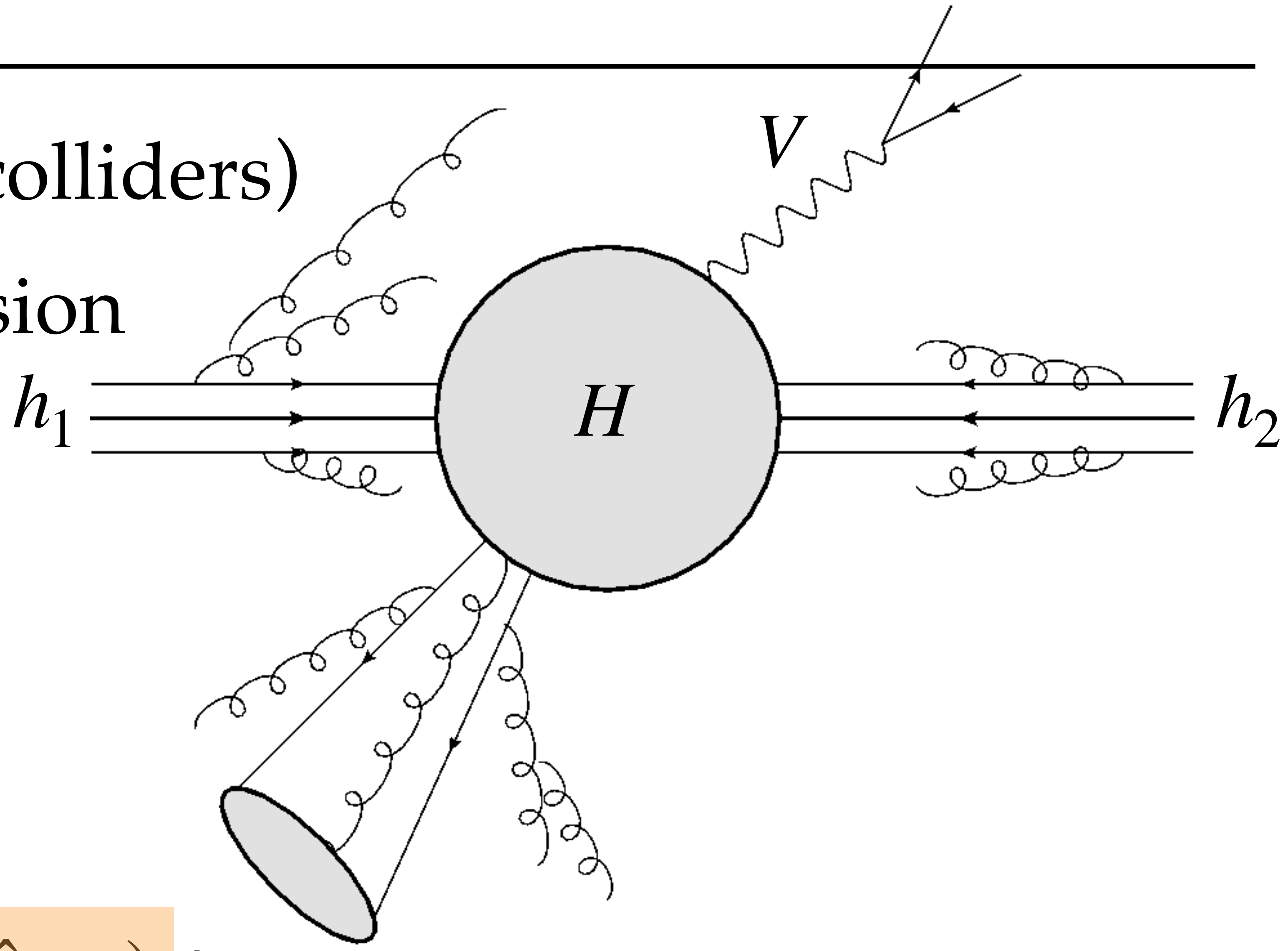
Introduction

- Rich program of precision measurements at LHC and HL-LHC (and future colliders)
- Requires theoretical predictions of SM observables at a similar level of precision
- From SM to physical predictions for collider observables is not a easy path
  still a lot to learn



Energy

Hard scale

Collinear factorisation

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

see talks by A. Huss, J. Mazzitelli

parton branching evolution

RESUMMATION/PARTON SHOWER

perturbative QFT

transition to hadrons

Hadronic scale
$\Lambda \lesssim 1$ GeV

Hadronization

Multiparticle interactions

Underlying event

non-perturbative QFT

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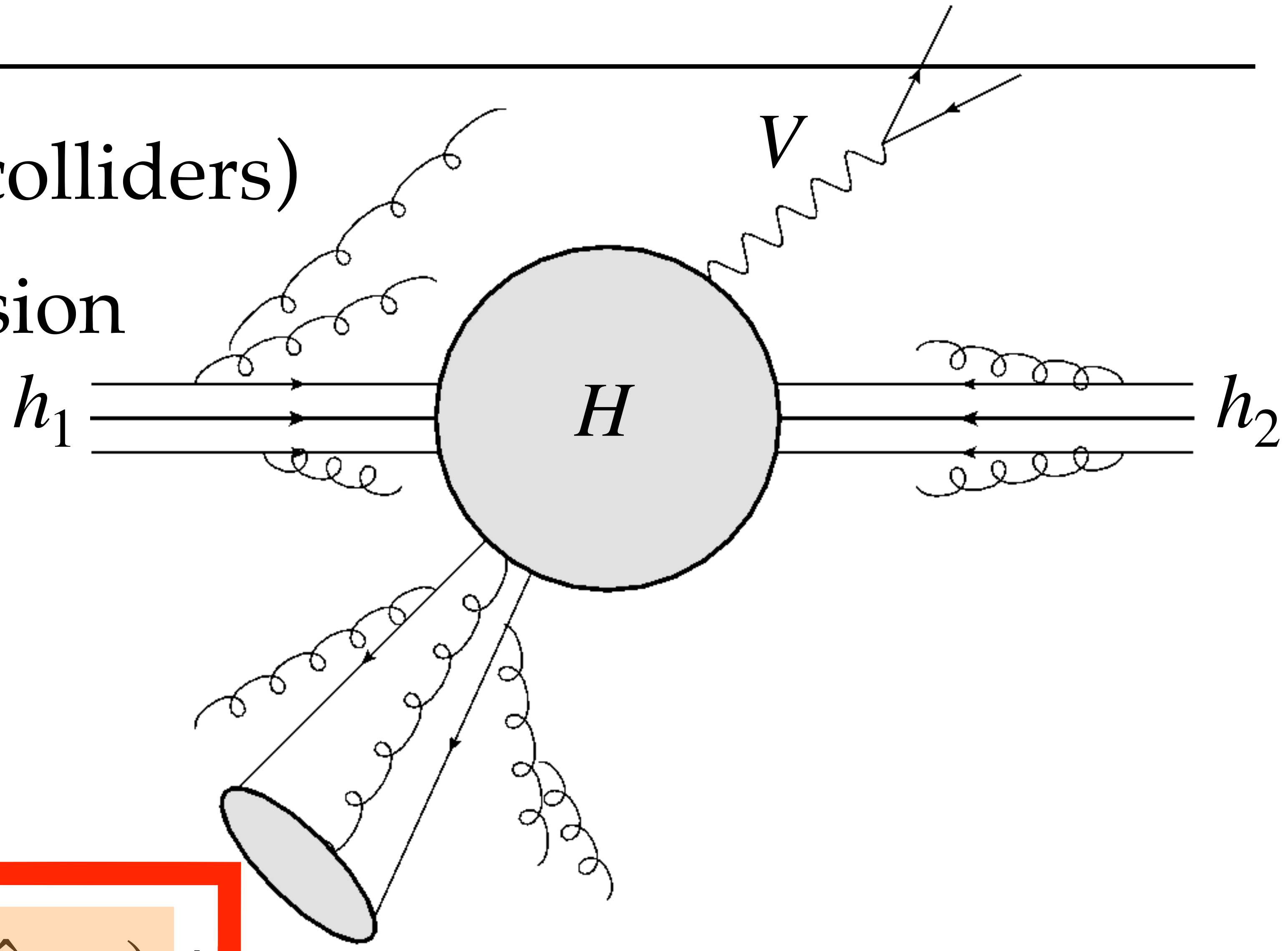

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Hadronic scale
$\Lambda \lesssim 1$ GeV

FOCUS on PDFs

- **parton densities** parametrise our understanding of the structure of proton in term of its constituents
- dependence on the collinear factorisation scale μ_F dictated by DGLAP (**perturbative**)
- dependence on the momentum fraction x extracted by data (**non perturbative**)

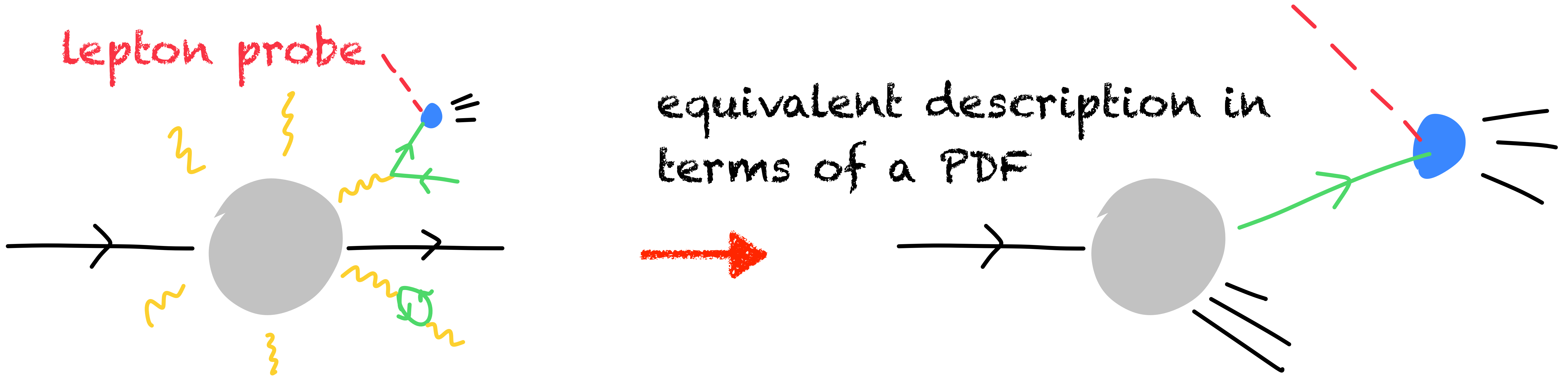
Lepton PDF: not so "Unorthodox" QCD …

- In a **pure QCD model,** protons are made of constituent/valence **quarks** 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!

- Protons (and quarks) **carry also an electric charge**: photon and leptons can be radiated!



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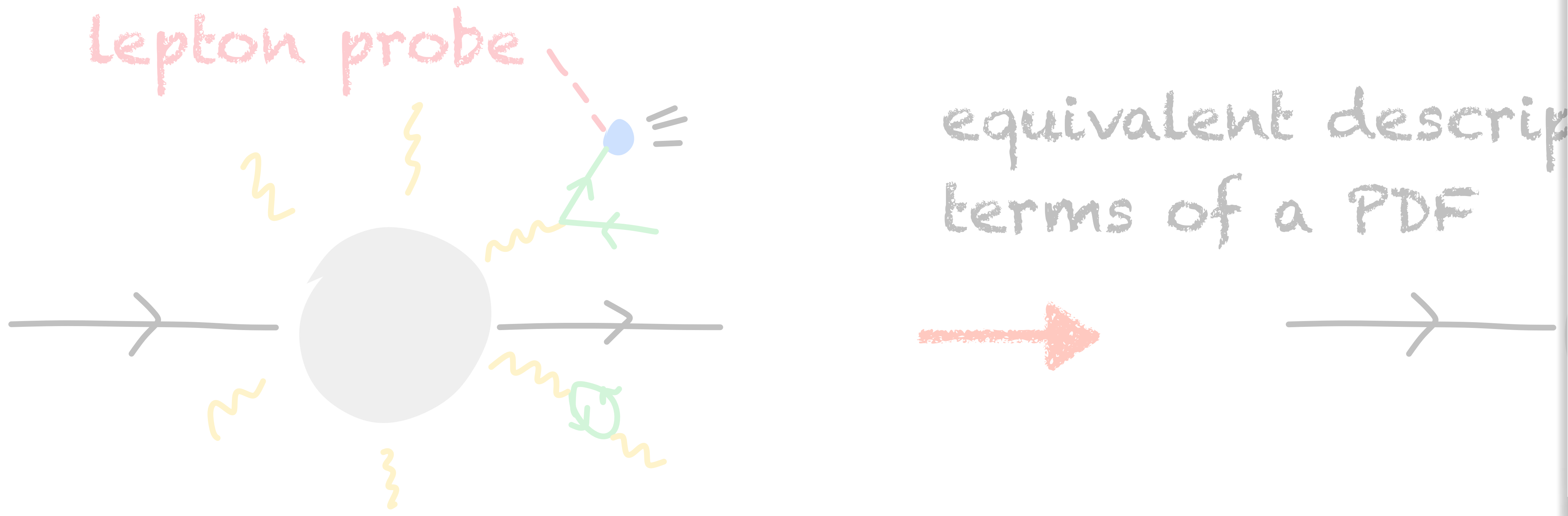


$$f_\ell \sim \alpha^2 f_q$$

Lepton density **very small** (by naive power counting)

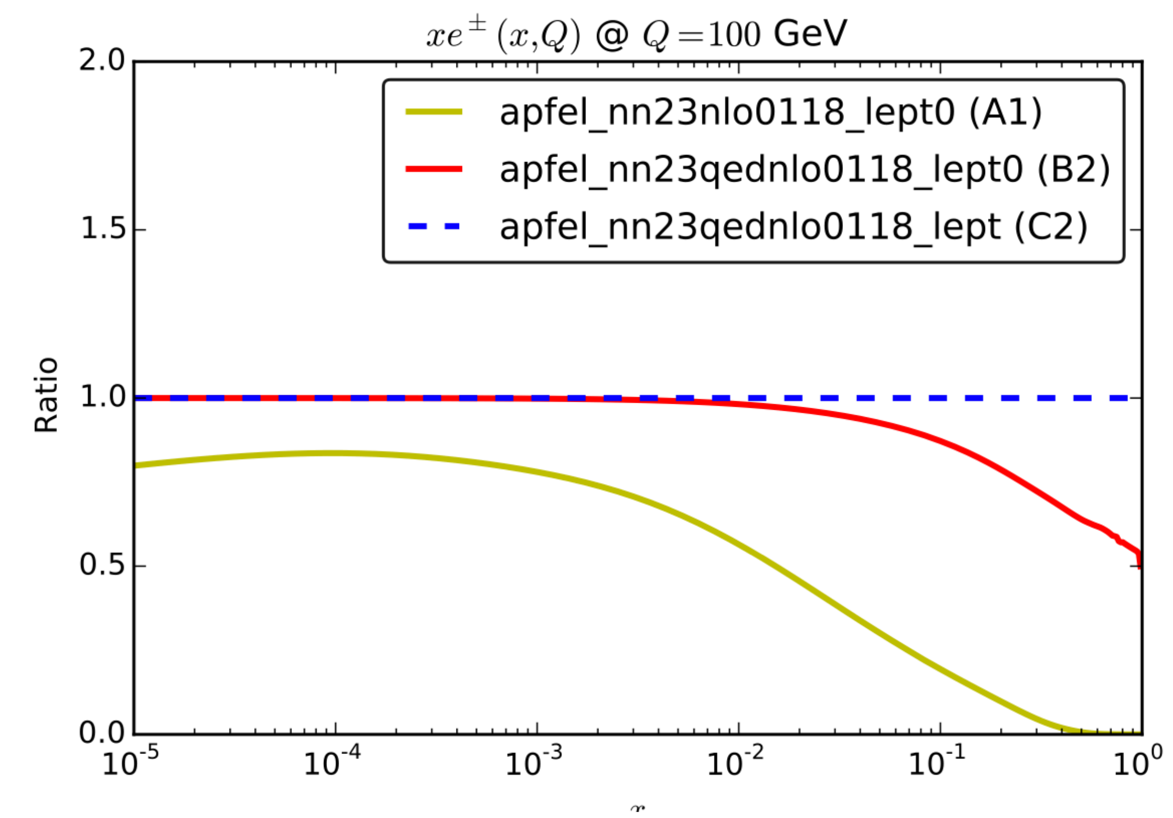
Are lepton-initiated processes relevant for LHC phenomenology?

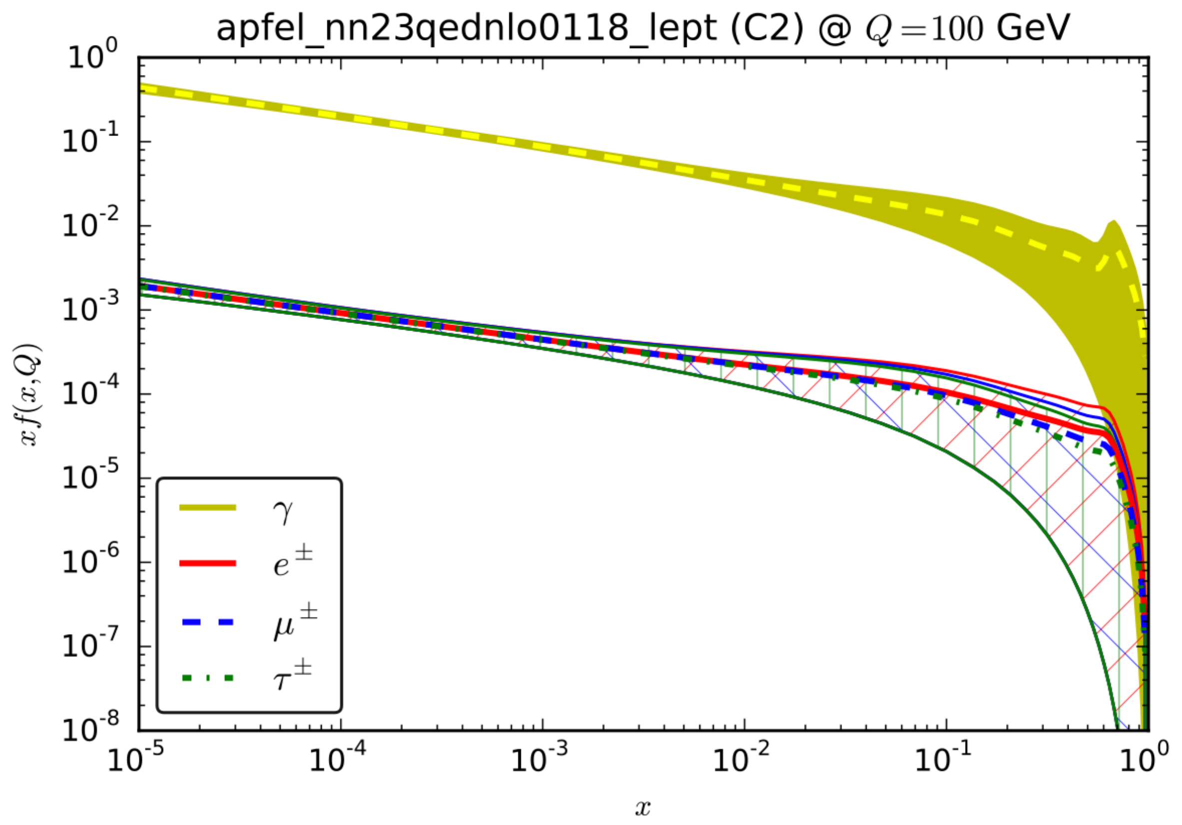
- in principle, all lepton-lepton combinations are available (and in a broad energy spectrum): potential to measure **rare SM processes**
- potential to look for **exotic BSM physics**

Leptons PDF: quest for precision (pre-LUX)

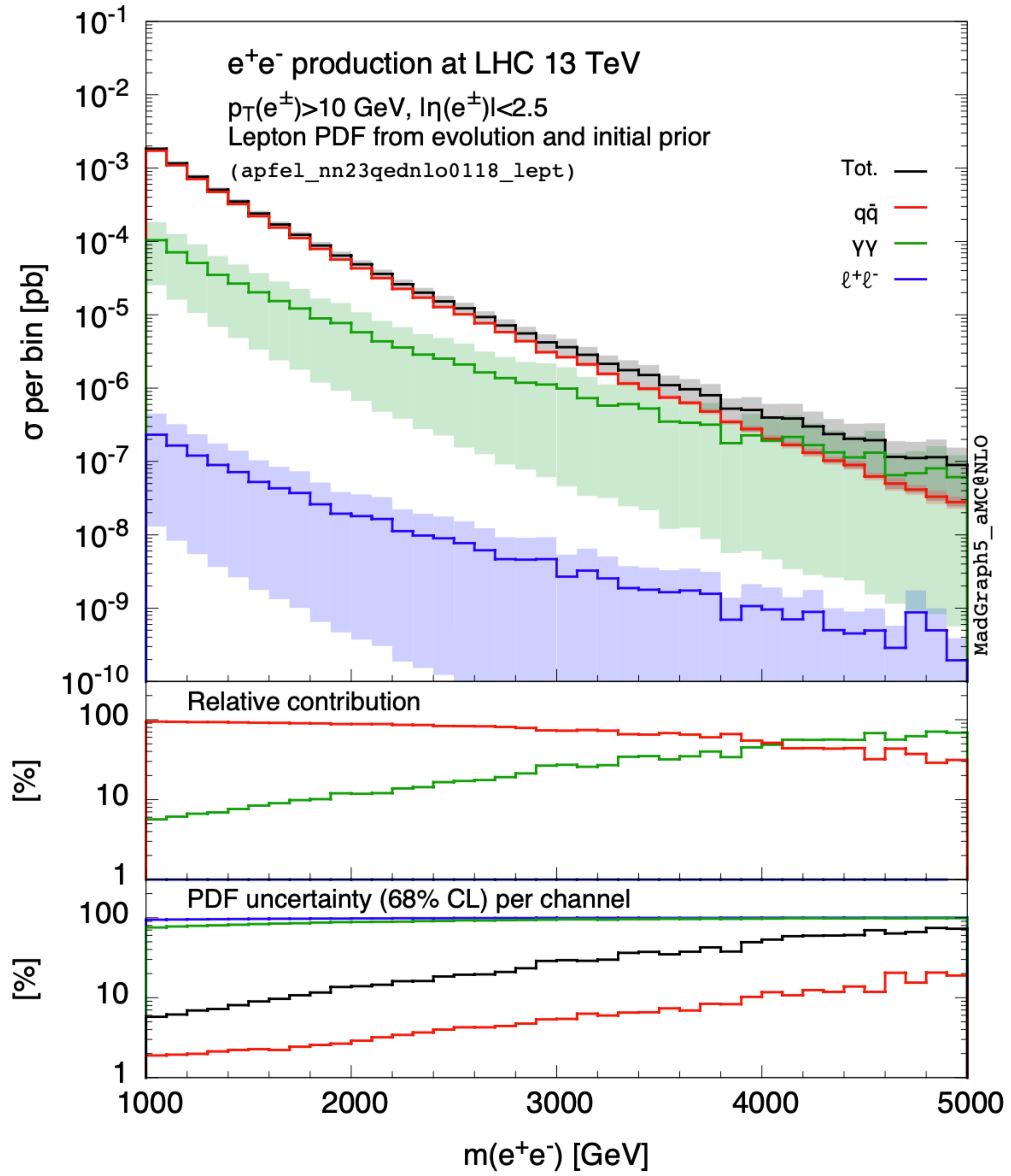
A crucial aspect which prevented to fully explore the phenomenology offered by lepton initiated processes is **the lack of a precise determination lepton densities**

[Bertone,Carrazza,Pagani,Zaro, 2015]





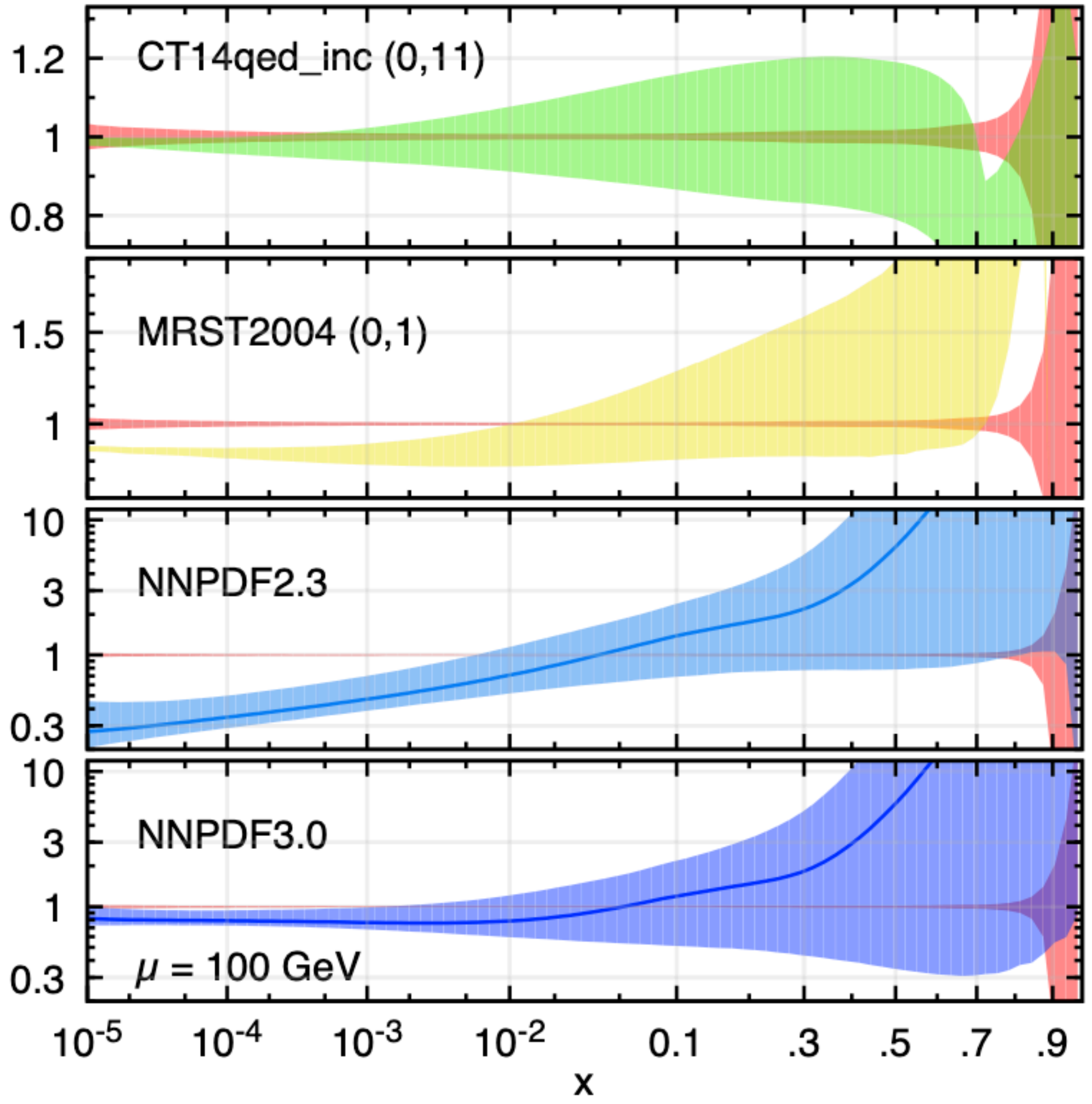
- Photon PDF affected by large errors (PRE-LUX)
- Large sensitivity to initial conditions
- LO determination affected by large uncertainty bands



Leptons PDF: quest for precision (pre-LUX)

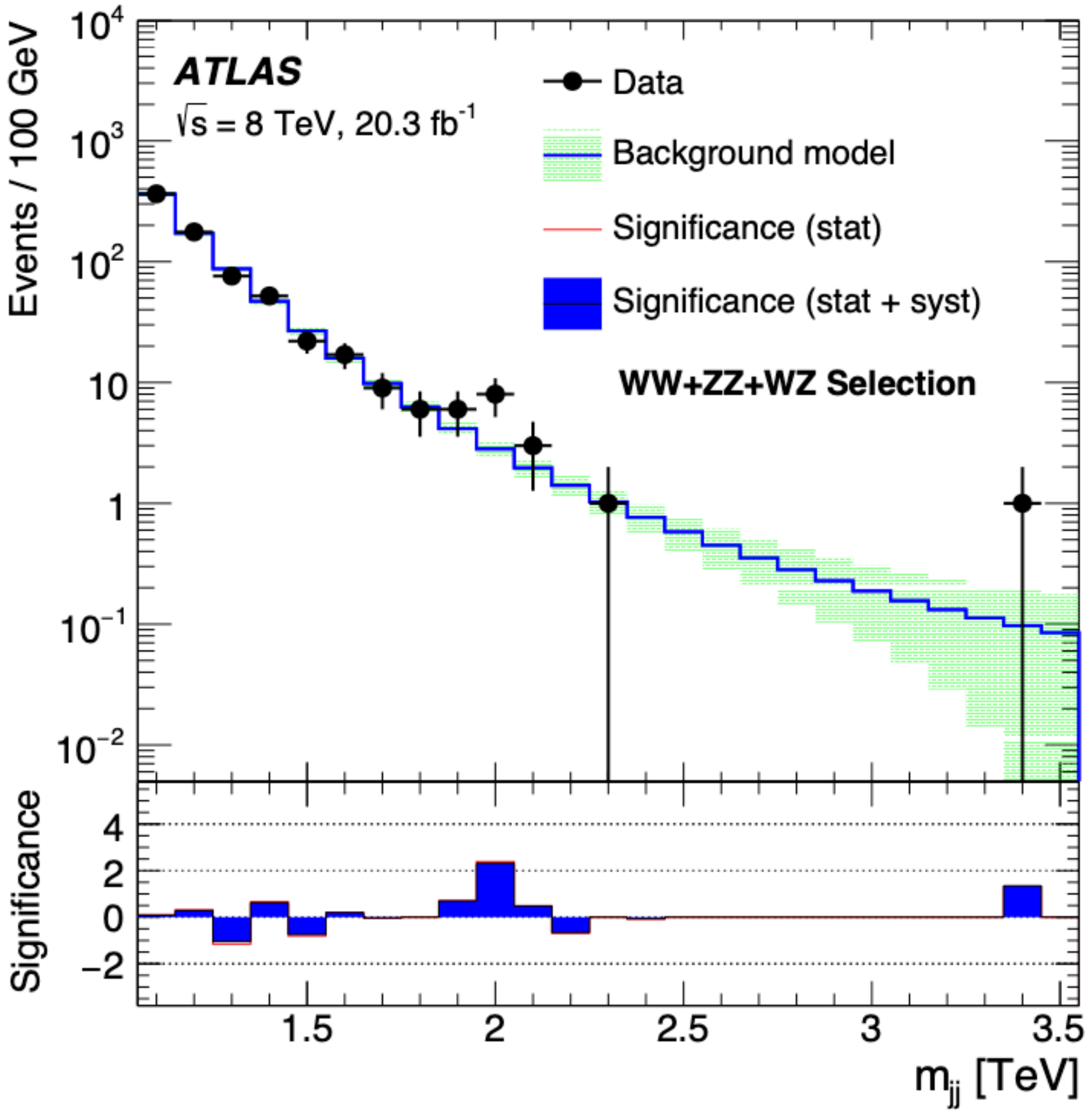
LUX breakthrough in 2016-2017: new approach to **precisely** determine the **photon** content of the proton

Main motivation: uncertainty on the photon induced processes started to dominate the production of **high mass objects;** sensitivity to photon initiated processes already at Run II-III



ATLAS boosted jets analysis (2015):

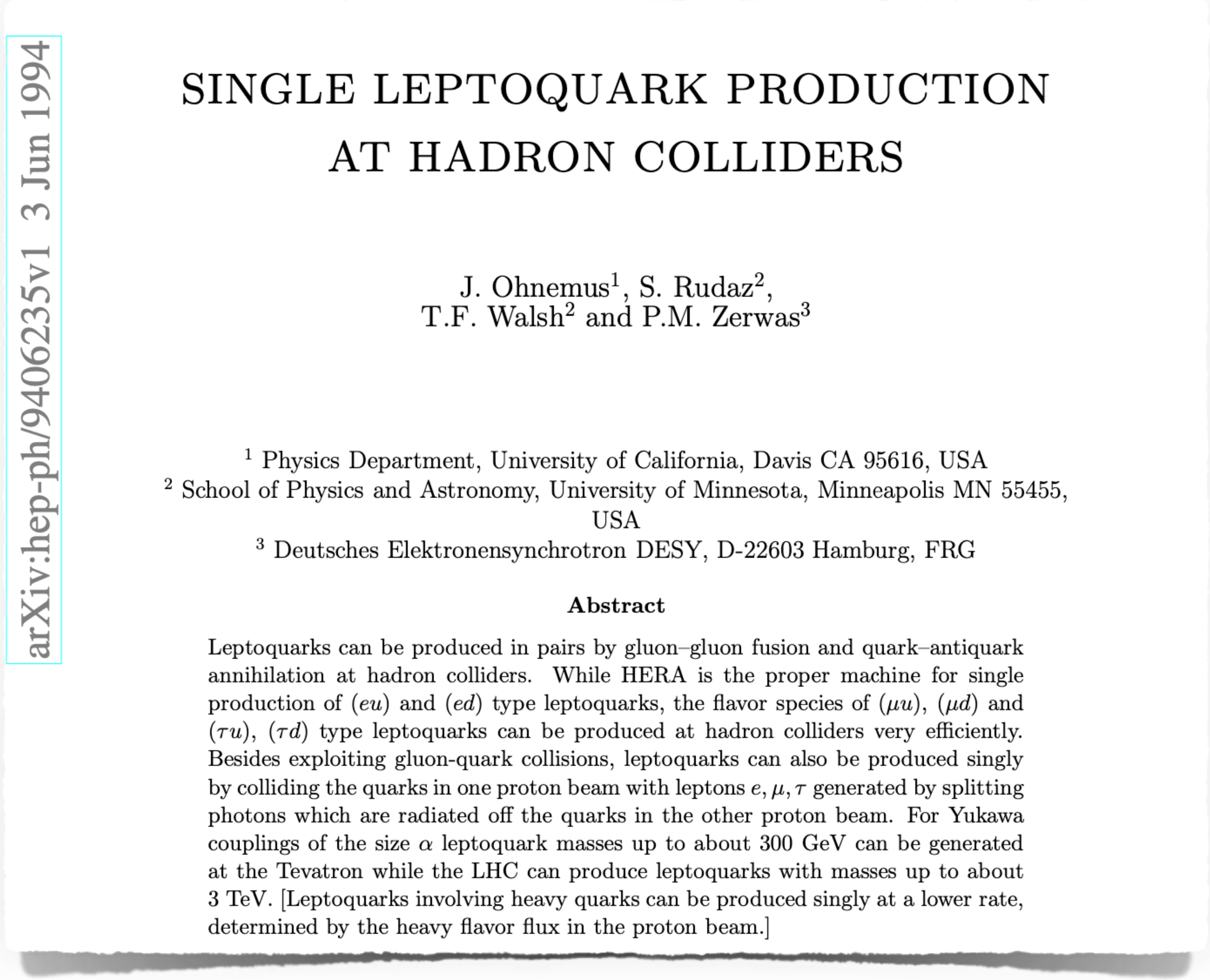
- 2 TeV excess in boson pair production
- Not confirmed in 13 TeV run
- The worry was that at very high scales gluon and quarks soften due to AP evolution.
- **Photons mostly stay the same**: importance of elastic contribution at low-Q^2



Leptons PDF: quest for precision (pre-LUX)

Lepton densities smaller than the one of the photon

Different motivations: look for rare and exotic processes! But **also in this case, a precise determination of the lepton densities is required to make reliable estimates at the LHC**


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]

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[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…

Based on a simplified leading logarithmic formula for the lepton densities

$$f_\ell \sim \alpha^2 \ln \frac{Q^2}{m_\ell^2} \ln \frac{Q^2}{\Lambda^2}$$

which is **not correct** in the limit $m_\ell < \Lambda$ due to screening effects of the proton finite size

Outline

- Extraction of the lepton densities
- Application I: lepton-lepton scattering at LHC
- Application II: hunting LeptoQuarks
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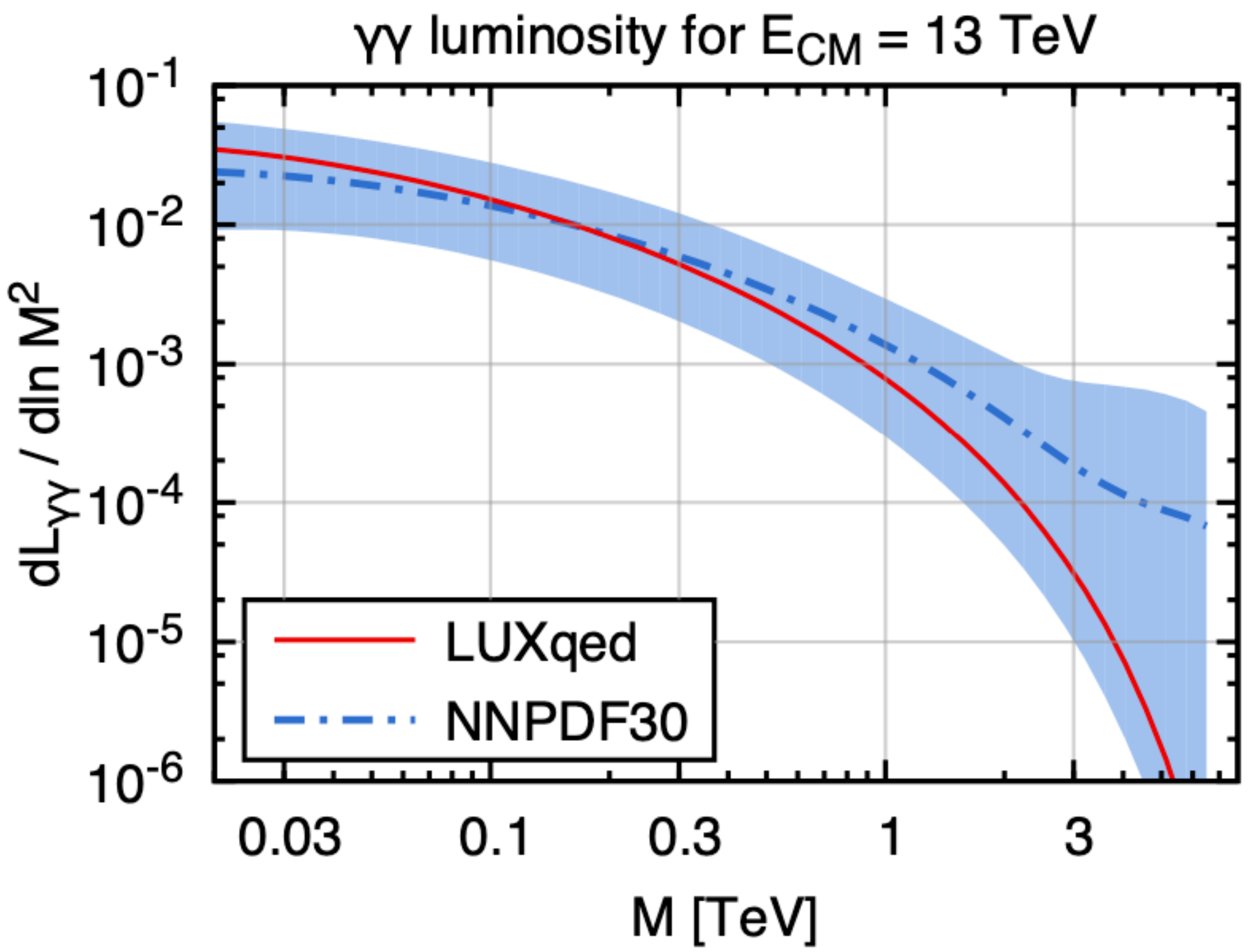
The LUX method for the photon PDF

- Relate the photon PDF to the **electro-production structure functions and form factors** for electron-proton scattering

- 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**



LUX breakthrough in 2016-2017

- determination of the photon density within **~5% uncertainty**

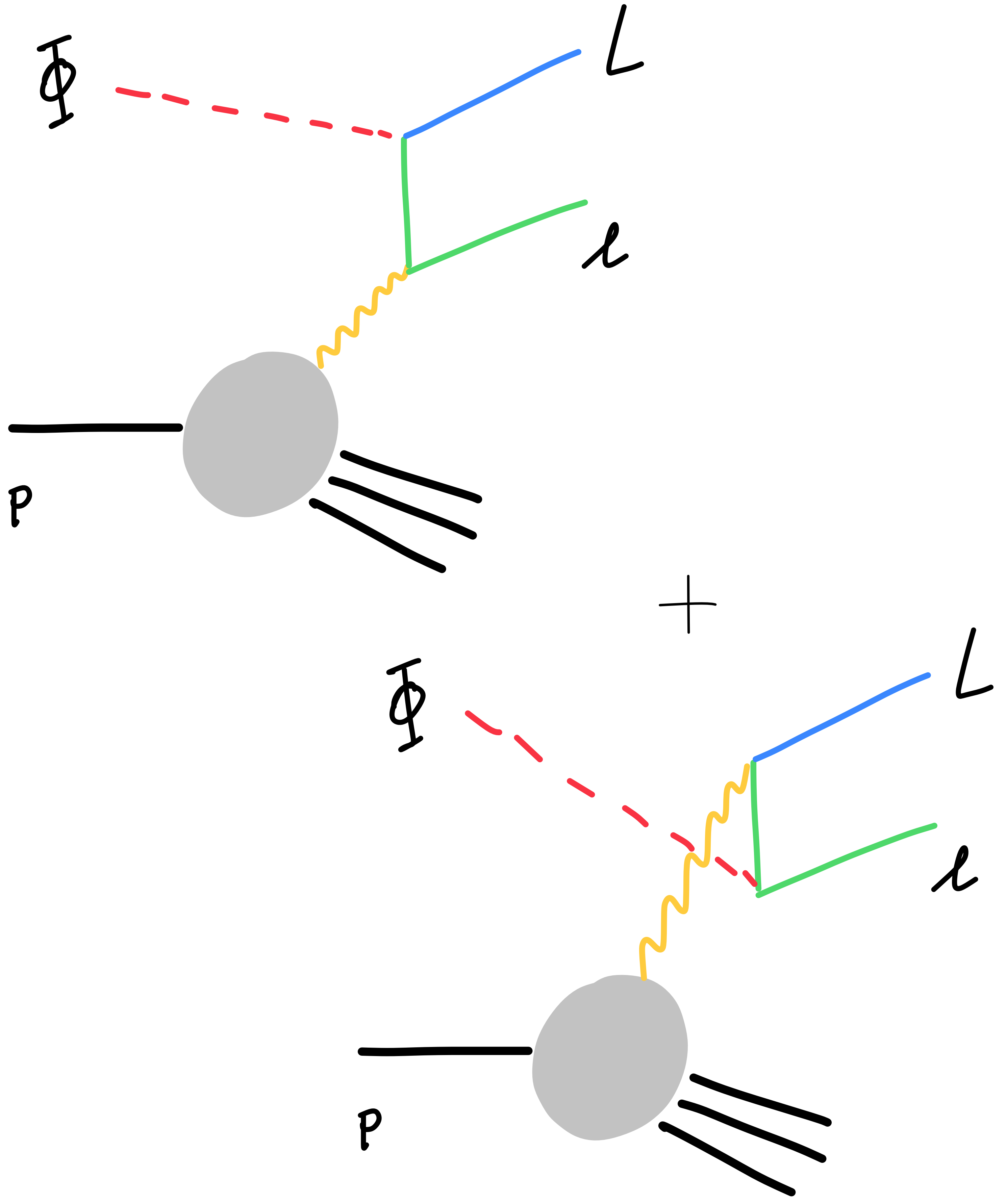
[Manohar, Nason, Salam, Zanderighi, *Phys.Rev.Lett.* 117 (2016) 24, 242002]
[Manohar, Nason, Salam, Zanderighi, *JHEP* 12 (2017) 046]

Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

BSM leptophilic probe

$$\mathcal{L} \sim \Phi \bar{L} \ell + hc$$



1. Hadronic tensor calculation in terms of electron-production structure functions F_2, F_L

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

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

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

Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

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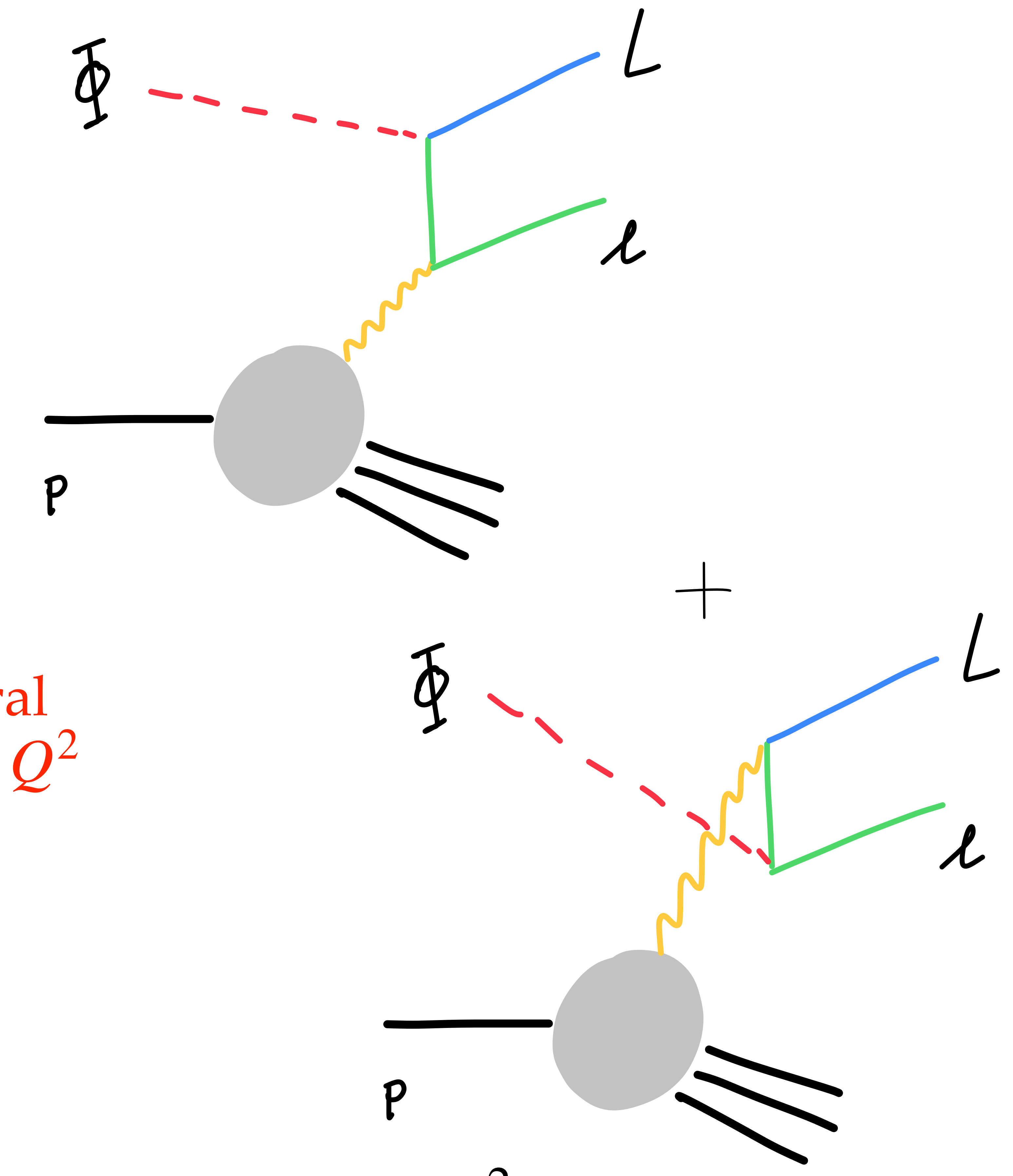


1. Hadronic tensor calculation in terms of electron-production structure functions F_2, F_L

$$\sigma = \int \frac{dE_{cm}^2}{2\pi} \frac{1}{4\, p \cdot r} \frac{1}{16\pi^2 E_{cm}} \int_x^{1-\frac{2xm_P}{E_{cm}}} dz \int_{\frac{m_P^2 x^2}{1-z}}^{\frac{E_{cm}^2(1-z)}{z}} \frac{dQ^2}{Q^2} \alpha^2 \mathcal{J}$$

logarithmic integral dominated at low Q^2

- Sketch of the structure of the integral function

$$F_i \times P(Q^2, m_p^2, m_\ell^2, \ldots) \ln \frac{M}{Q^2} + F_i \times R(Q^2, m_p^2, m_\ell^2, \ldots)$$

explicit logarithm of Q^2

- P and R complicated rational function but do not include logarithmic enhanced terms in Q^2

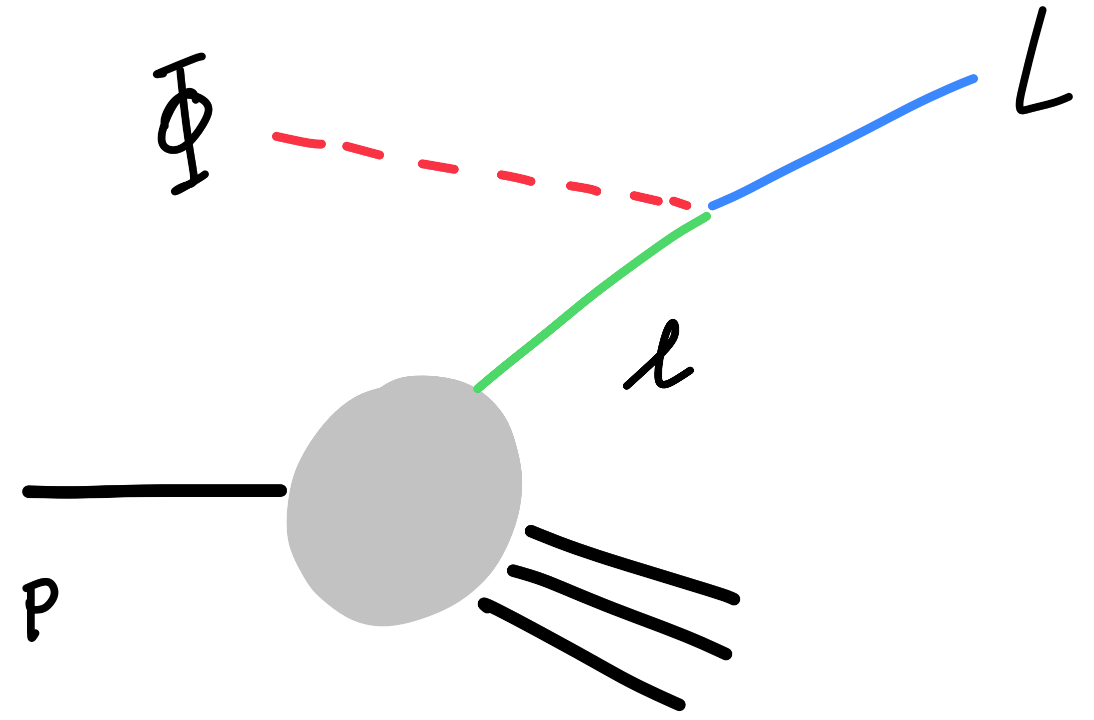
Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

BSM leptophilic probe

$$\mathcal{L} \sim \Phi \bar{L} \ell + h.c.$$

2. Collinear factorisation approach in terms of the lepton pdf



LO

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

Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

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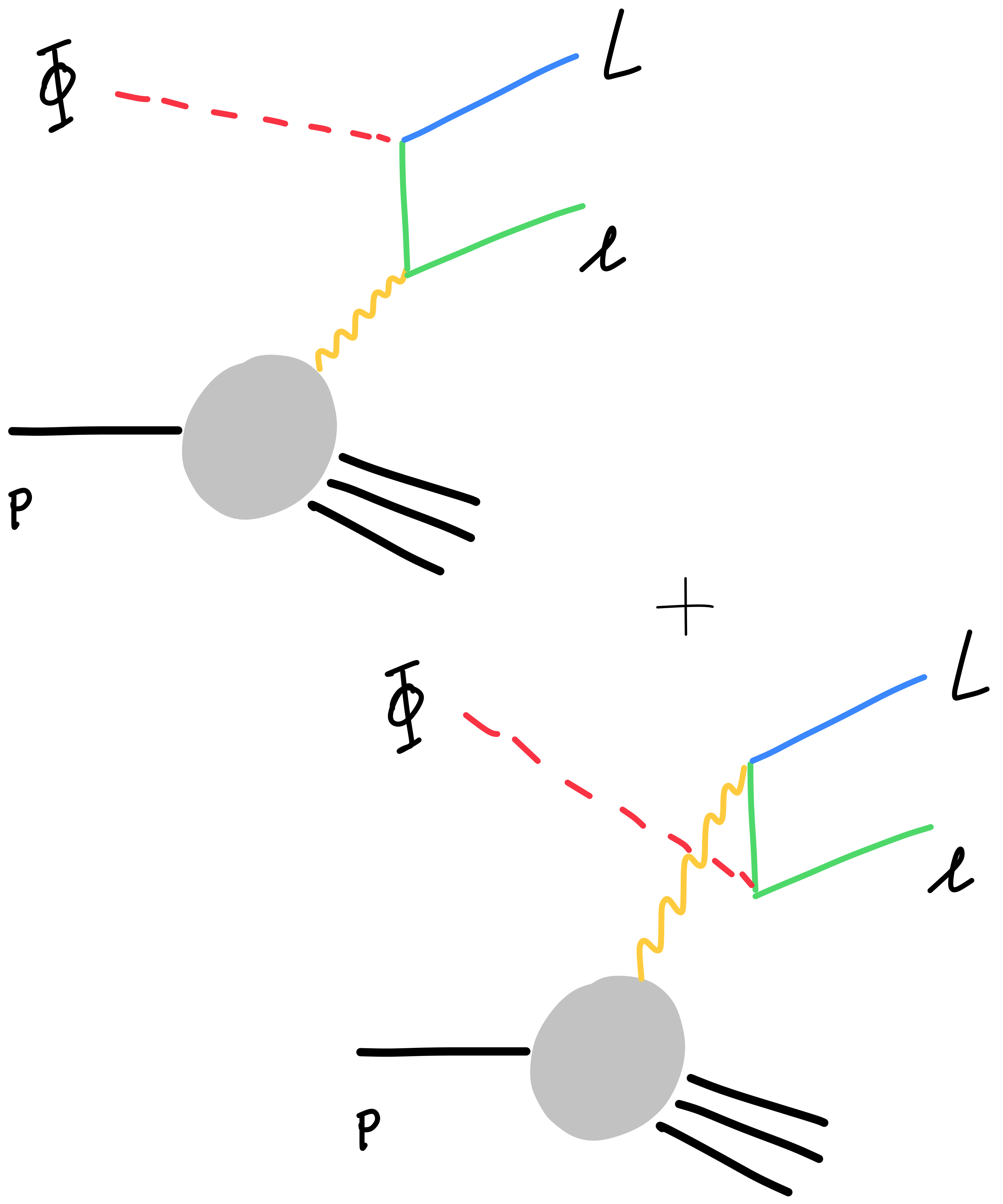

2. Collinear factorisation approach in terms of the lepton pdf

LO

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

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

NLO

$$z_\ell = \frac{M^2}{xS}$$

Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

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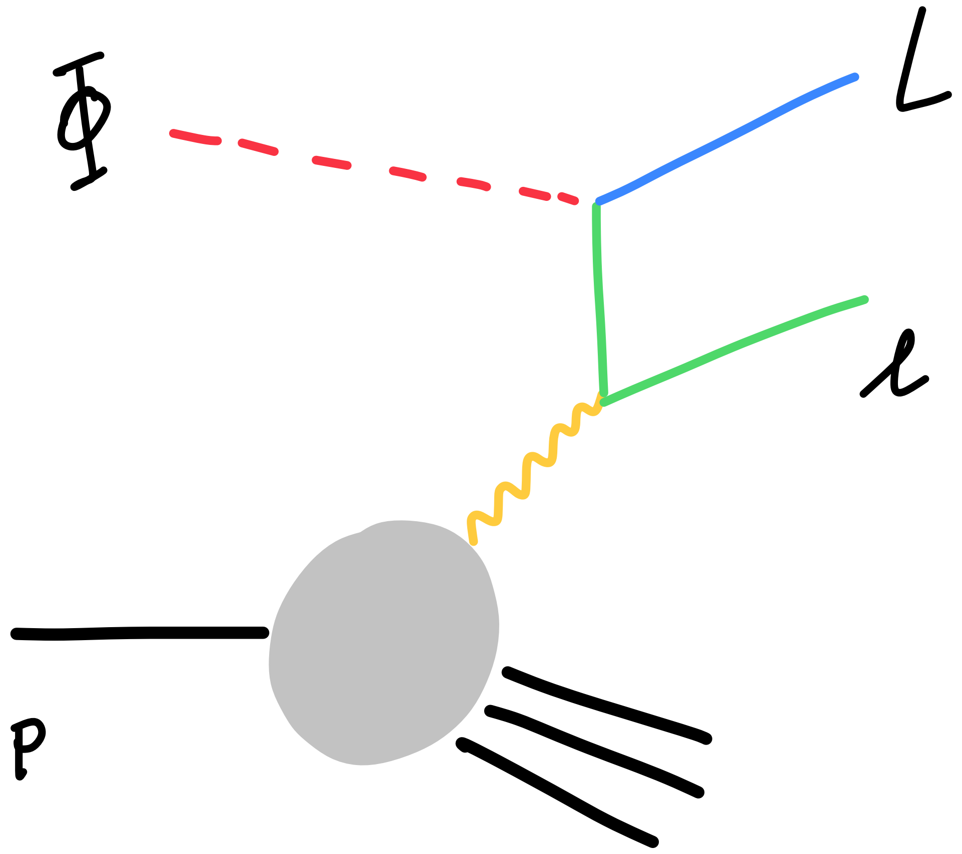

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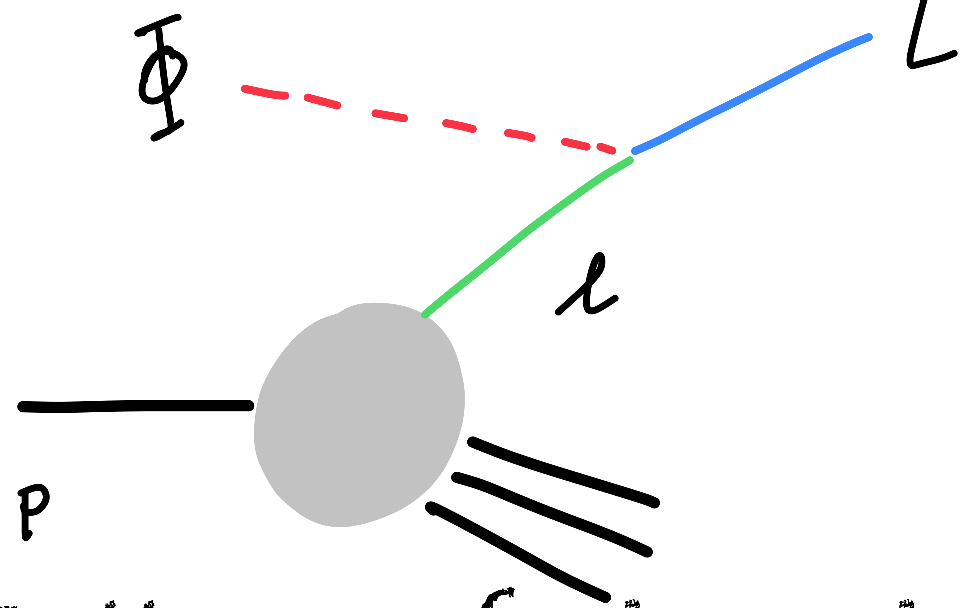


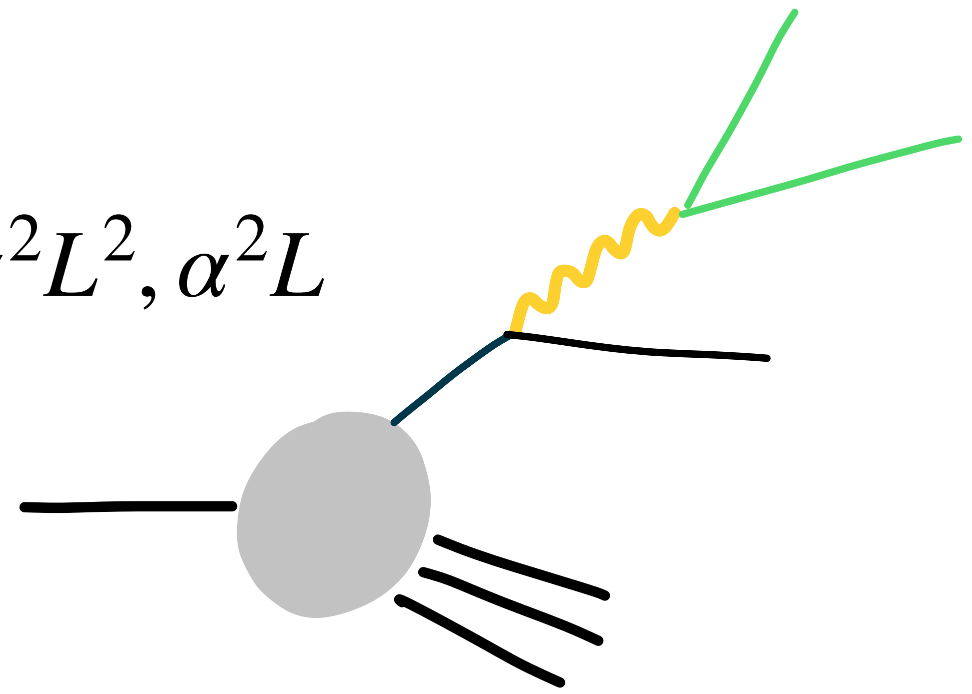
2. Collinear factorisation approach in terms of the lepton pdf

Power counting

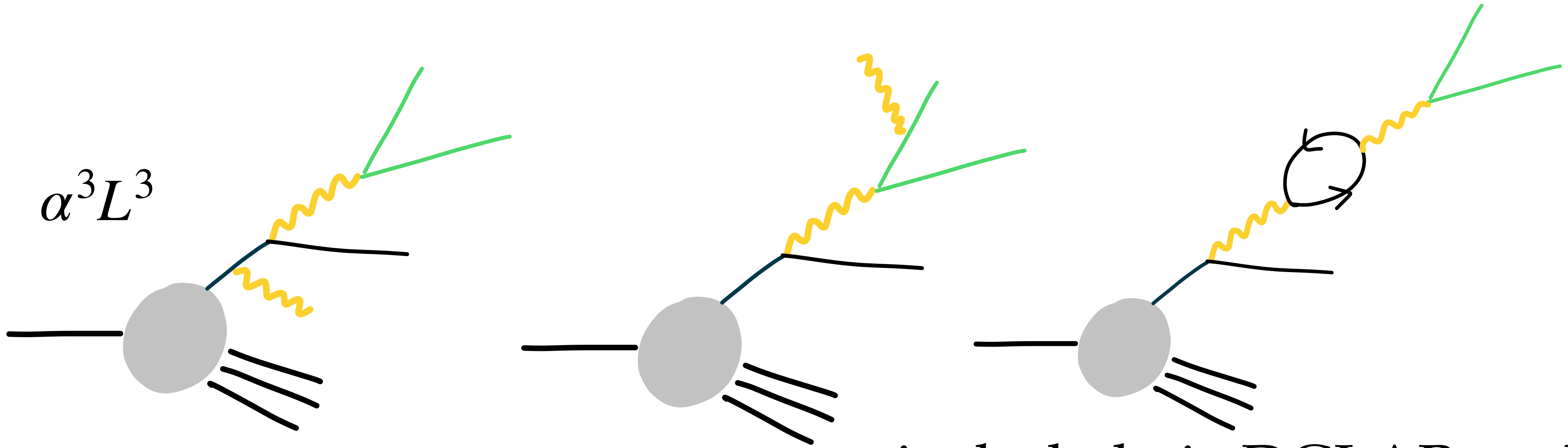
- large collinear logarithm $L = \log(Q^2/\Lambda^2_{\text{had}}) \sim 1/\alpha_s$
- $\alpha \approx \alpha_s^2$

	LO		NLO	
f_ℓ :	$\alpha^2 L^2$	$\alpha^2 L$	$\alpha^3 L^3$	…

$\alpha^2 L^2, \alpha^2 L$



$\alpha^3 L^3$



included via DGLAP evolution

Extraction of lepton PDFs

[LB, Nason, Tramontano, Zanderighi, 2020]

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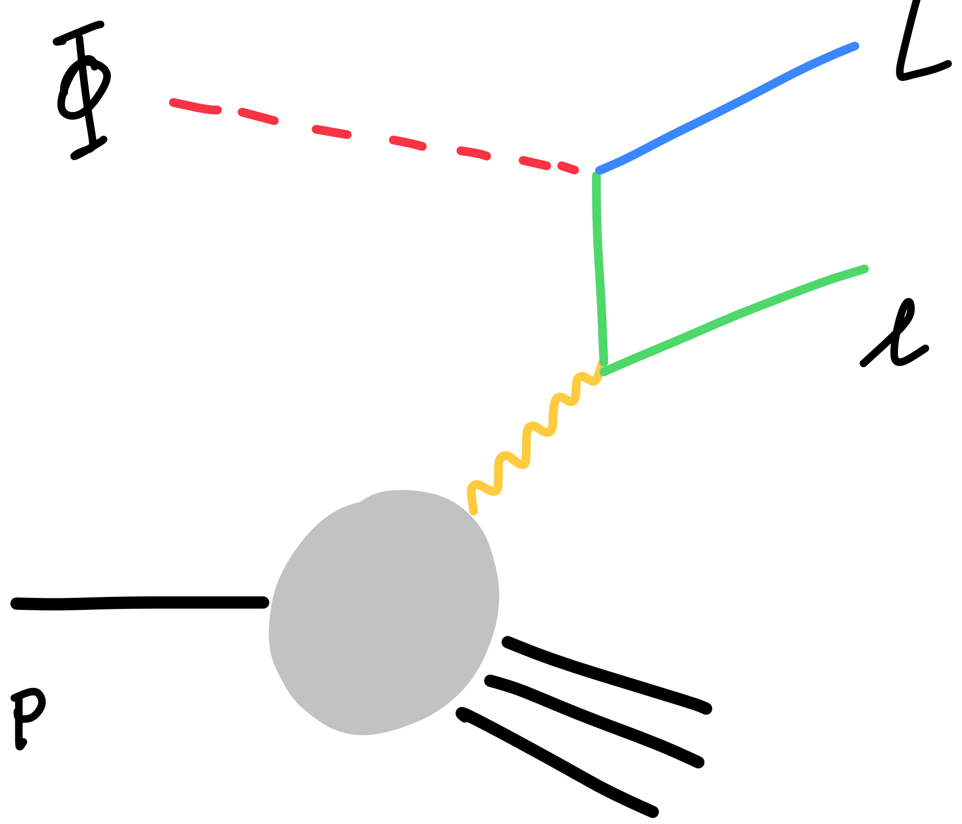
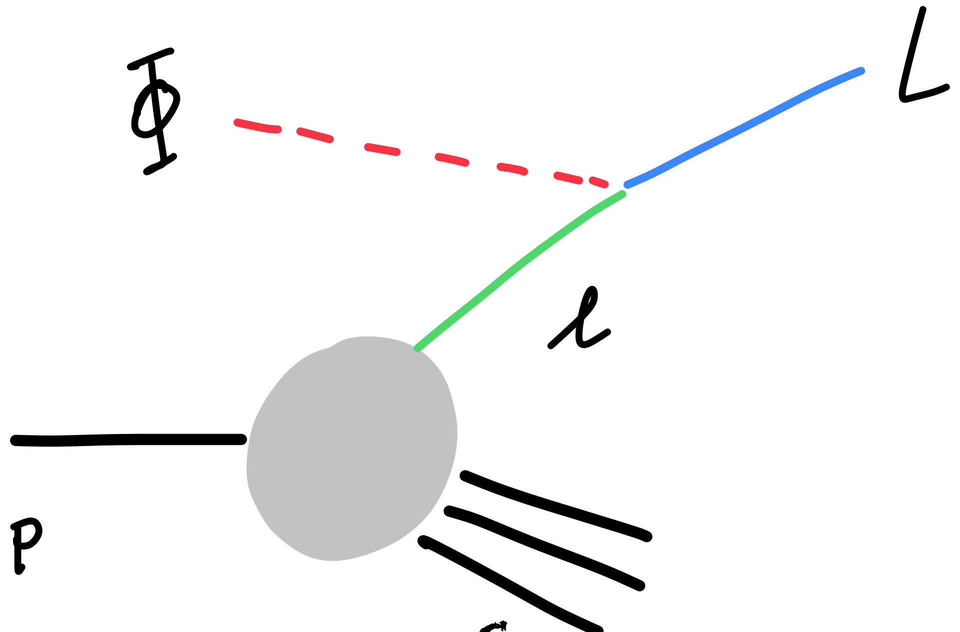




1. Hadronic tensor calculation in terms of electron-production structure functions F_2, F_L

2. Collinear factorisation approach in terms of the lepton pdf

Counting scheme

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

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

formally NNLO

no log ≡ no log-enhanced

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

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

L^2-enhanced terms:

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

L-enhanced terms:

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

sub-leading terms:

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

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

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

PDF set with leptons

[LB, Nason, Tramontano, Zanderighi, 2020]

- Lepton PDF formula provides the lepton **densities at a given factorisation scale**
  - can be computed numerically with high accuracy
  - **experimental input**: structure functions and form factors of the proton (fit + **uncertainties**) in both low- and high-Q^2 (from pdfs fit) regime. Recycle the same data as for photon PDF
  - be aware of **power corrections** (higher-twist) at low scales

- Inclusion of lepton densities has a negligible impact on proton momentum

- Non need for a new global fit to build a full grid: **use DGLAP** evolution starting from an already available pdf set. We start from **NNPDF31_nlo_as_0118 luxqed** and
  - use the lepton PDF formula to extract an **initial condition** for the lepton densities at a suitable reference scale (our choice $\mu_{\rm ref} = 20\,\mathrm{GeV}$)
  - solve the integro-differential DGLAP equations including all the relevant splitting kernels which contribute to the desired target accuracy:

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

Uncertainties

[LB, Nason, Tramontano, Zanderighi, 2020]

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 (theory uncertainties)**
- **replicas** to take into account PDF uncertainties

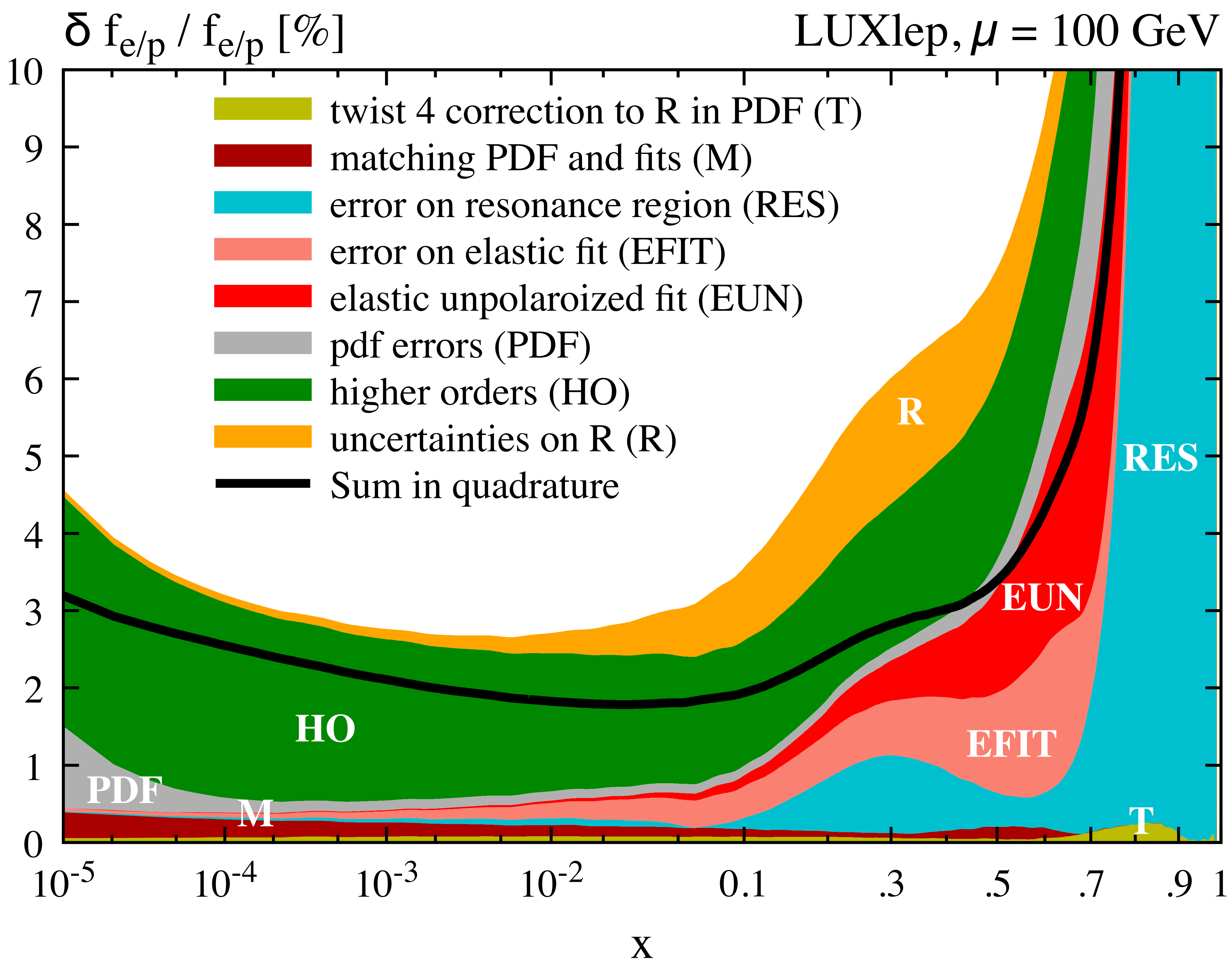
Procedure: for each replica member *m* in the original NNPDF set

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

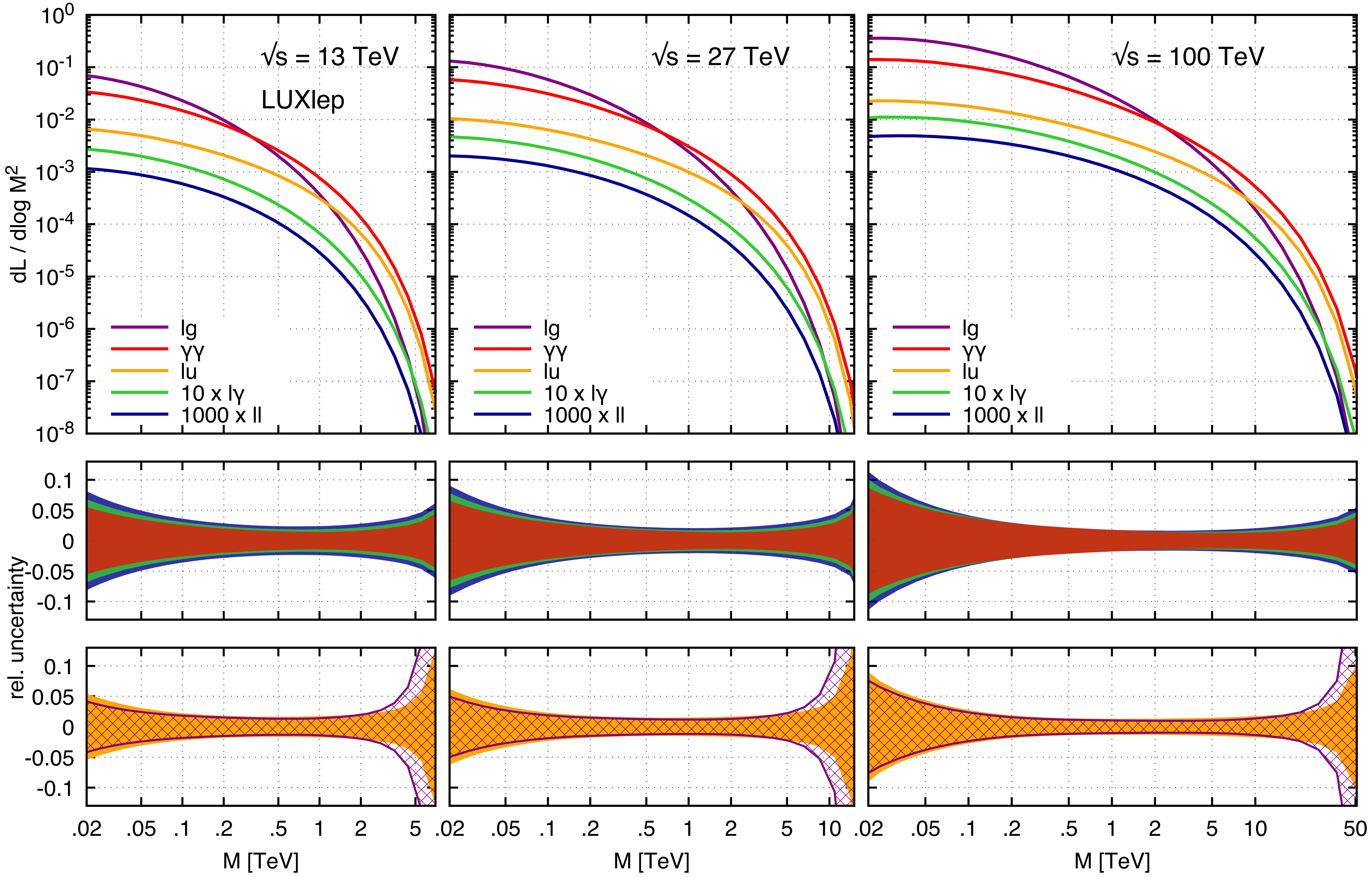
Gaussian distributed random number with unit variance



Lepton Luminosities

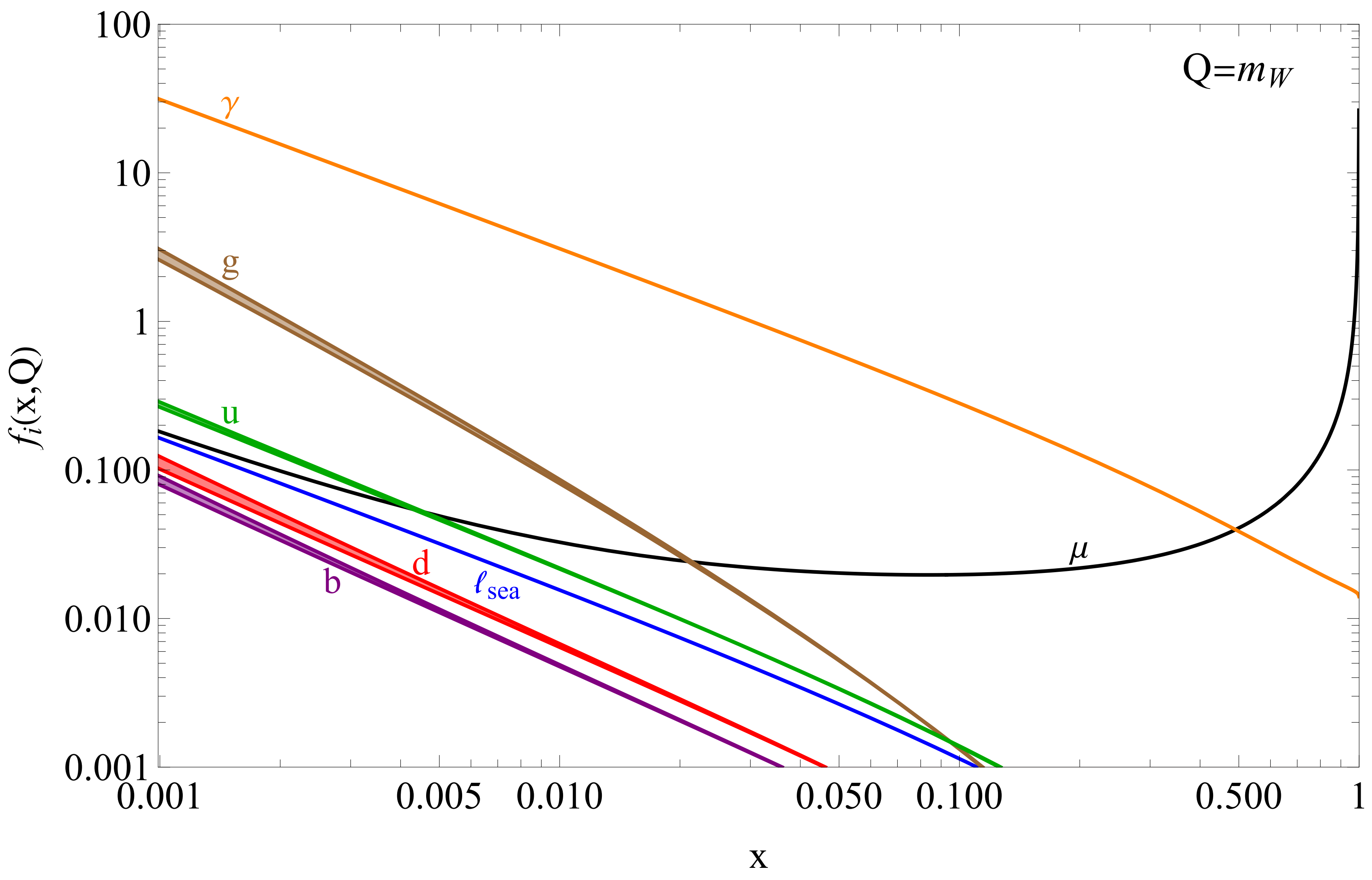
- PDF uncertainty reduced to the $\mathcal{O}(5-10\%)$ level
- PDF with lepton available for download as LHAPDF pdf

82400	LUXlep-NNPDF31_nlo_as_0118_luxqed	(tarball)	(info file)



Lepton PDFs very small but ...

More PDFs!



High-energy

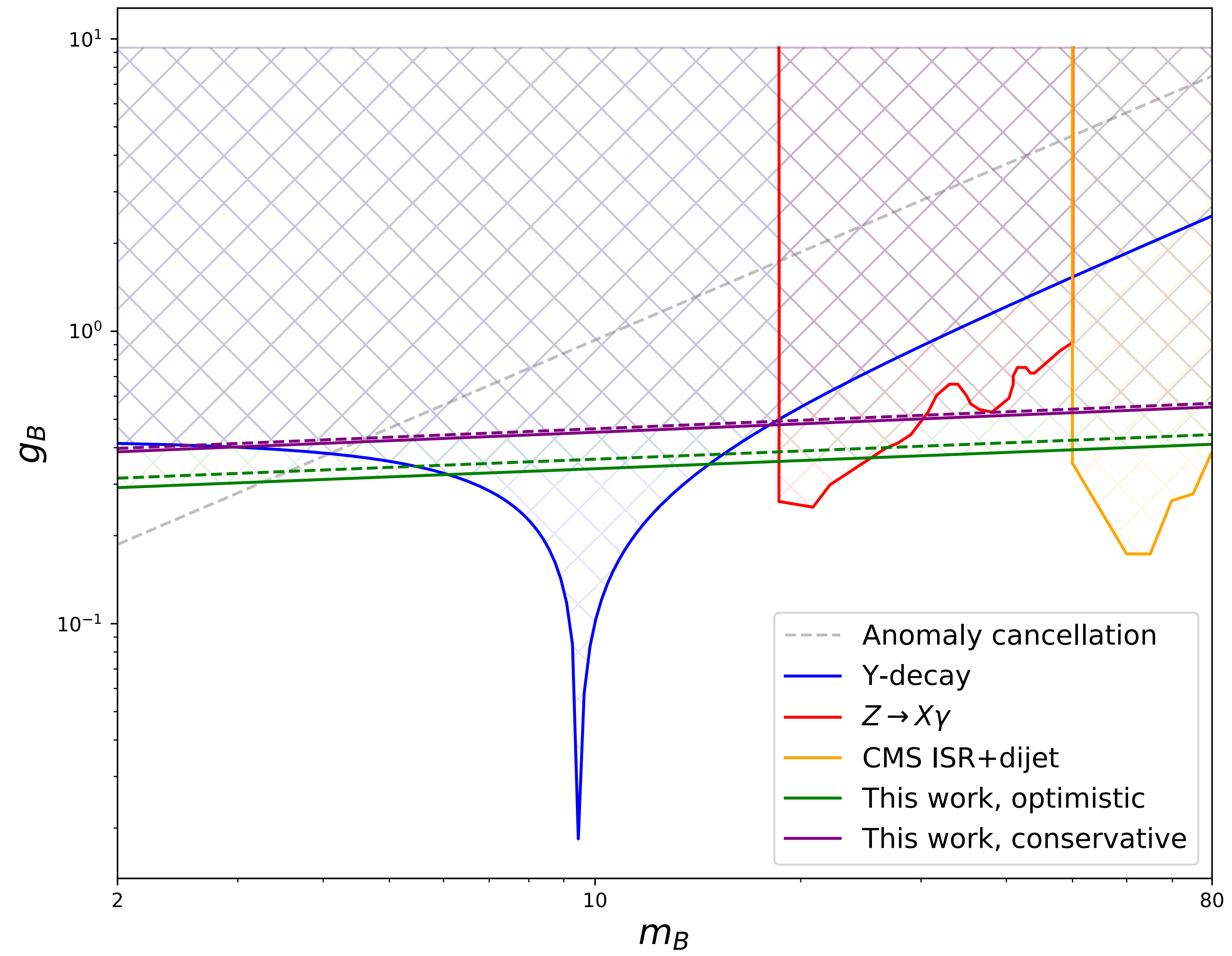
- EW bosons, polarized PDF
  [Fornal, Manohar, Waalewijn, 2018] [Bauer, Webber, 2018]

Applications to lepton colliders

- Muon PDFs for future **muon colliders**
  [Garosi, Marzocca, Trifinopoulos, 2023]
- Precise electron PDFs for future e^+e^- **machines**
  [Bertone, Cacciari, Frixione, Stagnitto, (Zaro) 2019 (2022)]

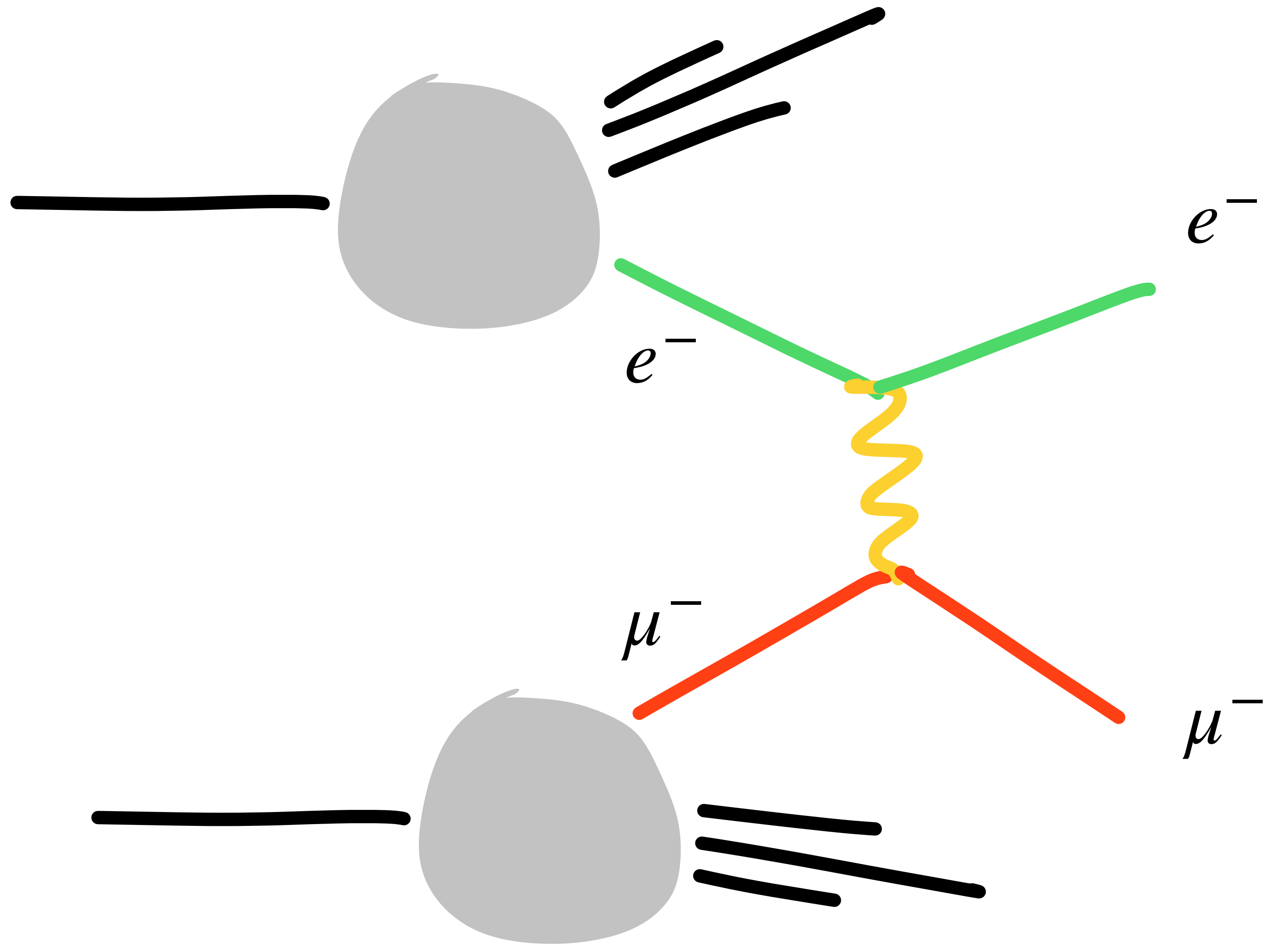
Dark Side of the proton! **[McCullough, Moore, Ubiali 2022]**

- Content of **Dark Photon** inside the proton
- Competitive projected limits in the range ~[2-50] GeV



Outline

- Extraction of the lepton densities
- Application I: lepton-lepton scattering at LHC
- Application II: hunting LeptoQuarks
- Summary



Lepton scattering

[LB, Nason, Tramontano, Zanderighi, 2021]

Lepton scattering processes as a **laboratory framework**

- **direct measurement** of lepton induced processes
- consider rare SM signatures at hadron colliders: **back-to-back same sign and/or different flavour**
- study selection cuts to increase signal-background ratio
- **NLO corrections**
- **full event simulation** via parton shower (so far only available with **Herwig**)

provided by P. Richardson

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

	$e^+\mu^-$	$e^+\tau^-$	$\mu^+\tau^-$	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]	$0.53^{+0.25}_{-0.18}$	$0.34^{+0.21}_{-0.15}$	$0.30^{+0.19}_{-0.14}$	$0.440^{+0.19}_{-0.14}$	$0.34^{+0.16}_{-0.12}$	$0.14^{+0.12}_{-0.07}$

1. Handful of events attainable already with the **current** integrated luminosity. The feasibility to measure them requires a dedicated and careful analysis of the signal and backgrounds
2. Theoretical uncertainty dominated by factorisation scale variation

Lepton scattering @NLO+PS

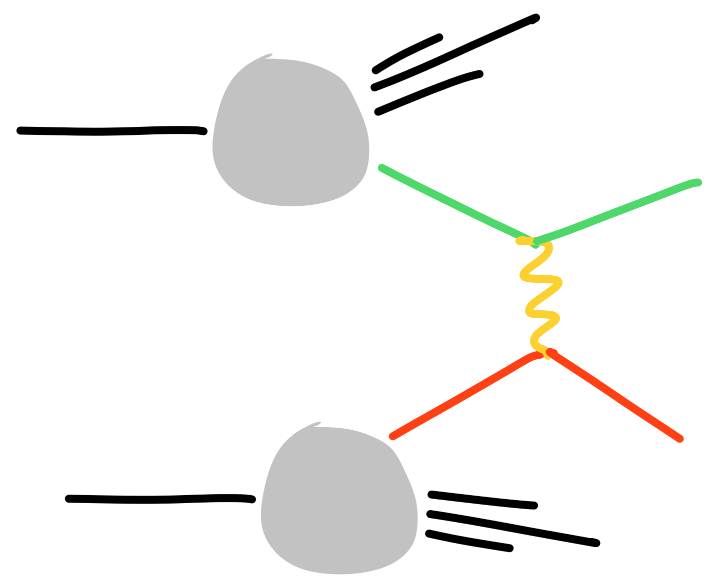
[LB, Nason, Tramontano, Zanderighi, 2021]

Lepton scattering processes as a **laboratory framework**

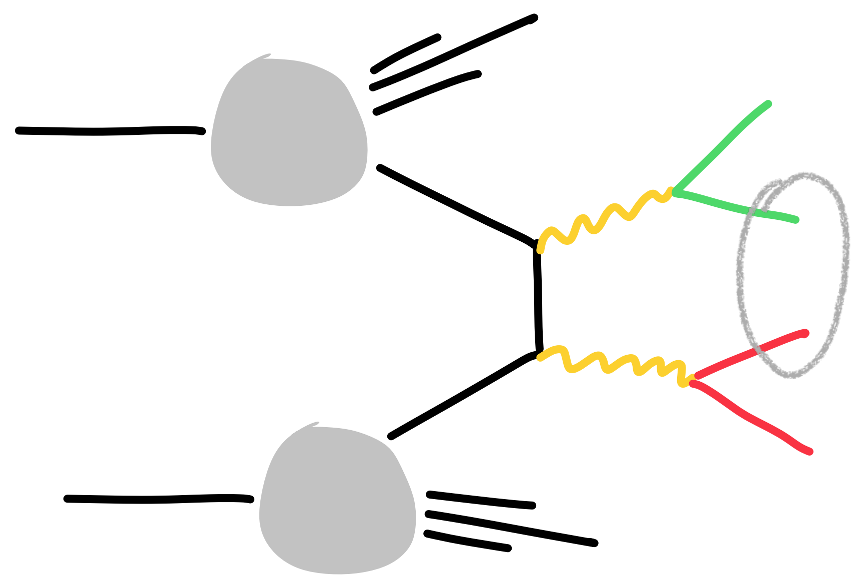
- **direct measurement** of lepton induced processes
- consider rare SM signatures at hadron colliders: **back-to-back same sign and/or different flavour**
- study selection cuts to increase signal-background ratio
- **NLO corrections**
- **full event simulation** via parton shower (so far only available with **Herwig**) provided by P. Richardson

The **NLO+PS** computation can be compared and validated against the **hadronic tensor (HT)** computation which does not receive QCD corrections

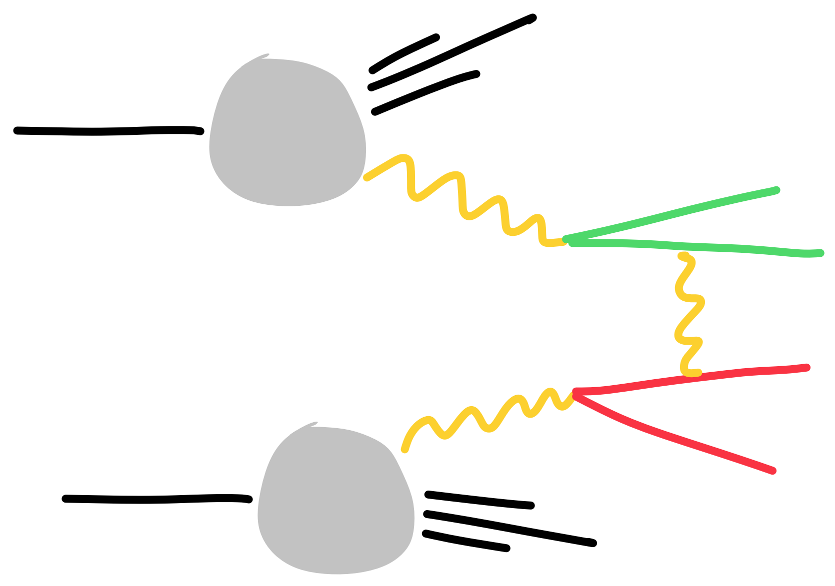
Lepton pdf approach
LO process



Main background
Double Drell-Yan (DDY)



Hadronic tensor approach
sample diagram



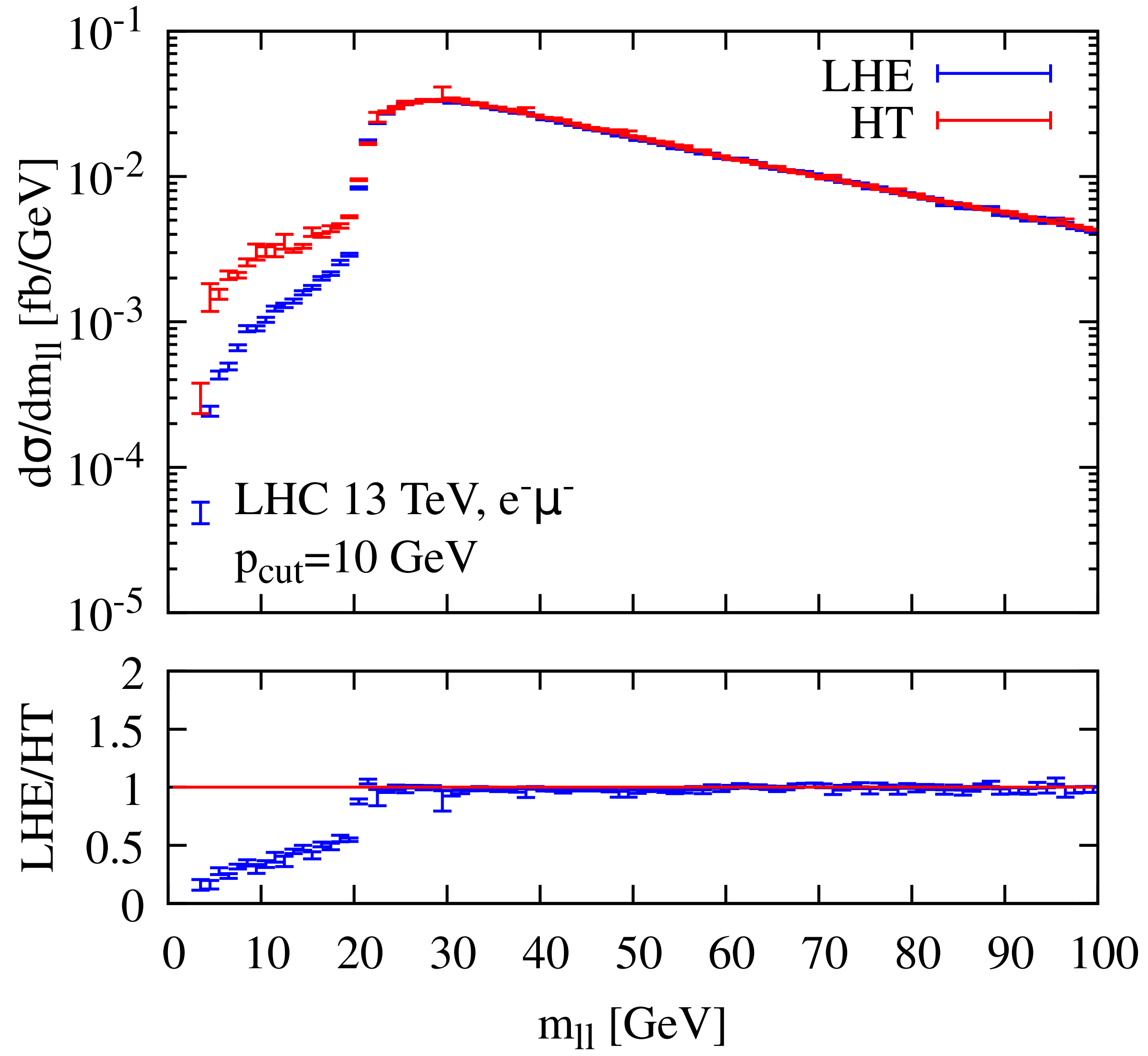
Lepton scattering @NLO+PS

[LB, Nason, Tramontano, Zanderighi, 2021]

Minimal requirements (T) $p_T > p_{\rm cut}, \quad p_{\rm cut} = 5, 10, 20$ GeV $\quad |\eta_l| < 2.4$

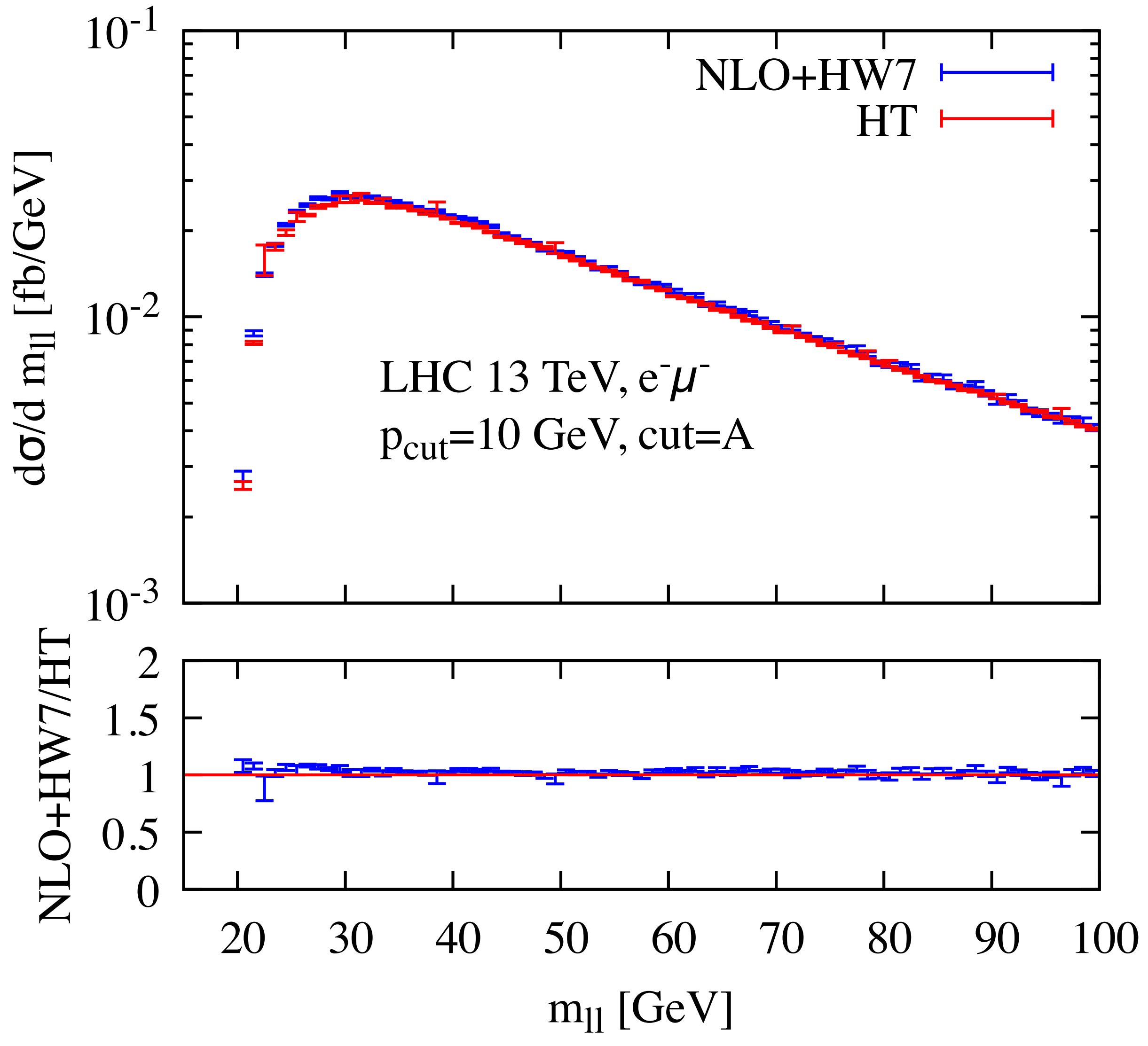
isolation : $\Delta_r > 0.3$ for leptons $p_T > 0.9$ GeV

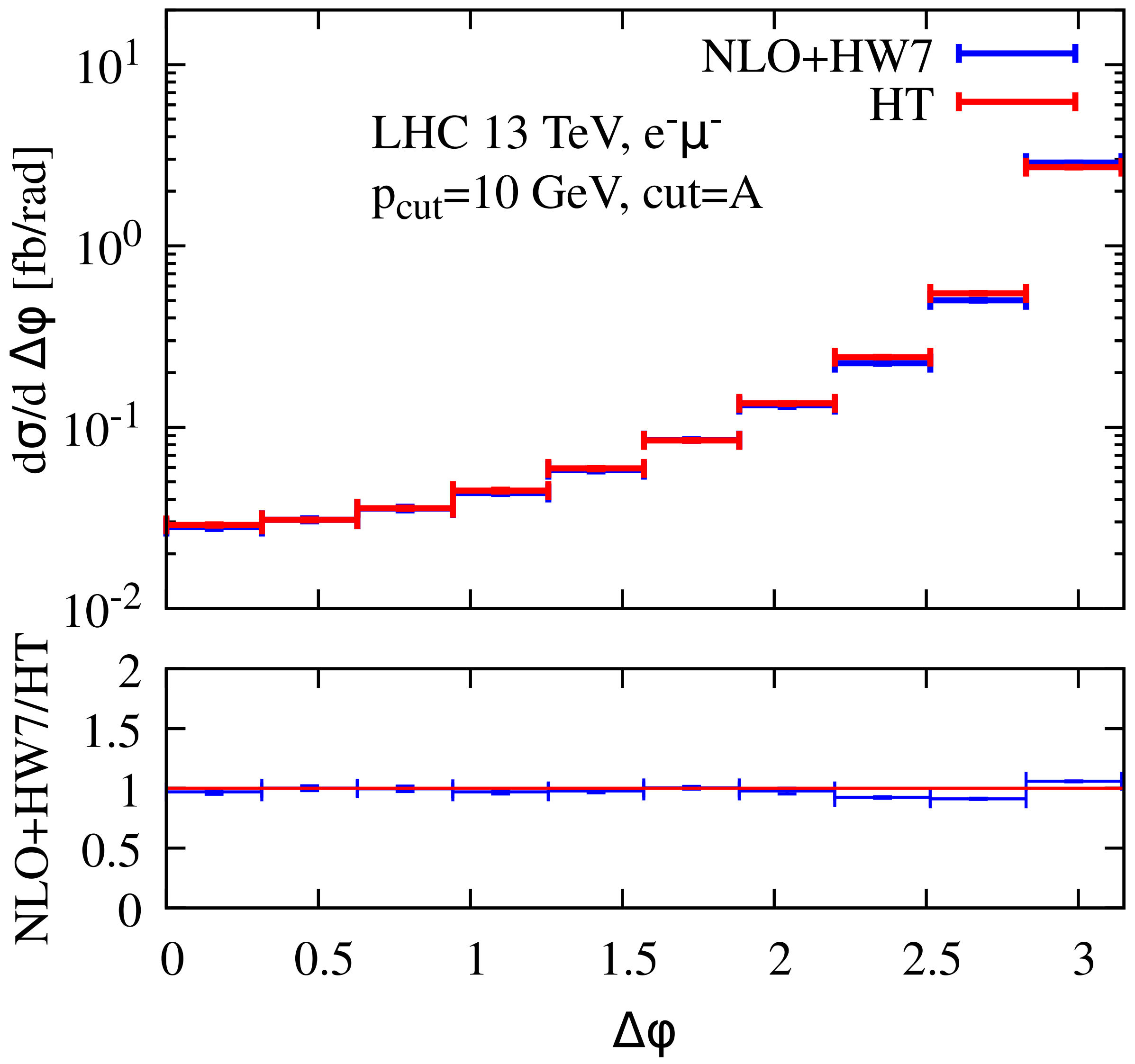
LHE vs HT

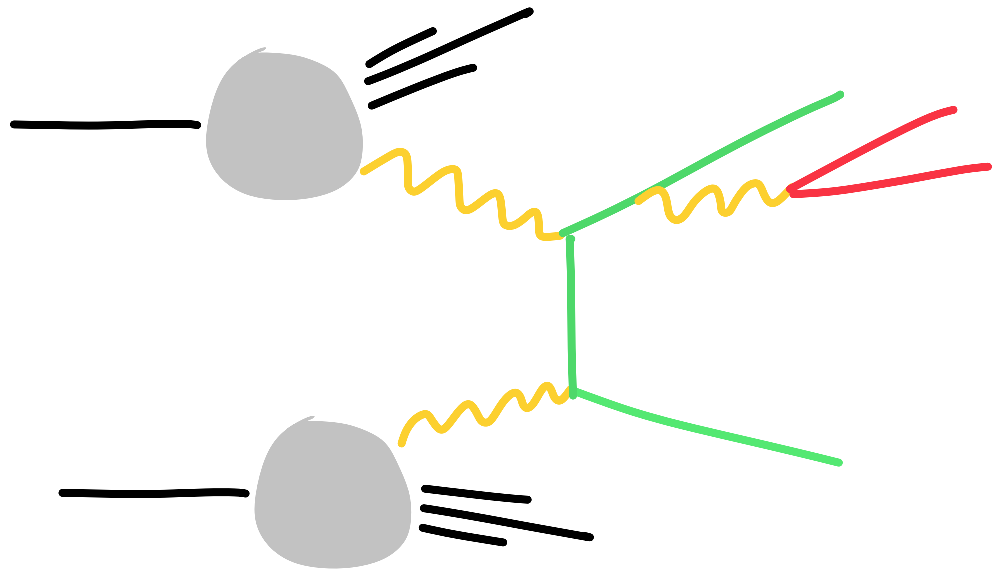


$m_{l\ell} > |p_T^{(l)}| + |p_T^{(\ell)}|$

NLO+PS vs HT







- Excellent agreement after cut on invariant mass
- Tuning of Herwig (intrinsic $k_T = 2.2$ GeV to all initial state particles, global recoil)

HT can be used as a reference for MCs tuning as it receives no strong corrections

Lepton scattering @NLO+PS

[LB, Nason, Tramontano, Zanderighi, 2021]

Additional requirements $m_{l\ell} > |p_T^{(l)}| + |p_T^{(\ell)}|$ cut A

factorisation scale

$\mu_F = p_{T,l}$

$$\frac{|p_T^{l\ell}|}{|p_T^{(l)}| + |p_T^{(\ell)}|} < 0.2$$ cut B

$$\frac{|p_T^{l\ell}|}{|p_T^{(l)}| + |p_T^{(\ell)}|} < 0.1$$ cut C

veto events with extra leptons in acceptance with $p_T > 3$ GeV cut D

$e^-\mu^-$	T	TA	TAB	TABD	TAC	TACD
σ (fb), $p_{\rm cut} = 10$ GeV						
LO	$1.432^{+0.734}_{-0.520}$	$1.432^{+0.734}_{-0.520}$	$1.432^{+0.734}_{-0.520}$	$1.432^{+0.734}_{-0.520}$	$1.432^{+0.734}_{-0.520}$	$1.432^{+0.734}_{-0.520}$
NLO	$1.28_{-0.14}$	$1.03^{+0.02}_{-0.24}$	$0.56^{+0.15}_{-0.40}$	$0.31^{+0.23}_{-0.49}$	$0.2^{+0.3}_{-0.5}$	$0.1^{+0.3}_{-0.6}$
LHE	$1.469_{-0.128}$	$1.281_{-0.093}$	$0.920_{-0.129}$	$0.752_{-0.145}$	$0.687_{-0.119}$	$0.652_{-0.121}$
NLO+HW7	1.488	1.262	0.847	0.664	0.563	0.496
HT	1.53	1.234	0.80	0.63	0.55	0.50
DDY	51.7	17.	3.02	0.47	0.95	0.2

- Fixed order results less reliable when **increasing the complexity** of the applied cuts

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- Fixed order results less reliable when increasing the complexity of the applied cuts
- Very **good agreement** between NLO+PS and HT

Lepton scattering @NLO+PS

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- Fixed order results less reliable when increasing the complexity of the applied cuts
- Very good agreement between NLO+PS and HT
- Very large DDY background. The **additional cuts are effective to suppress it**

Outline

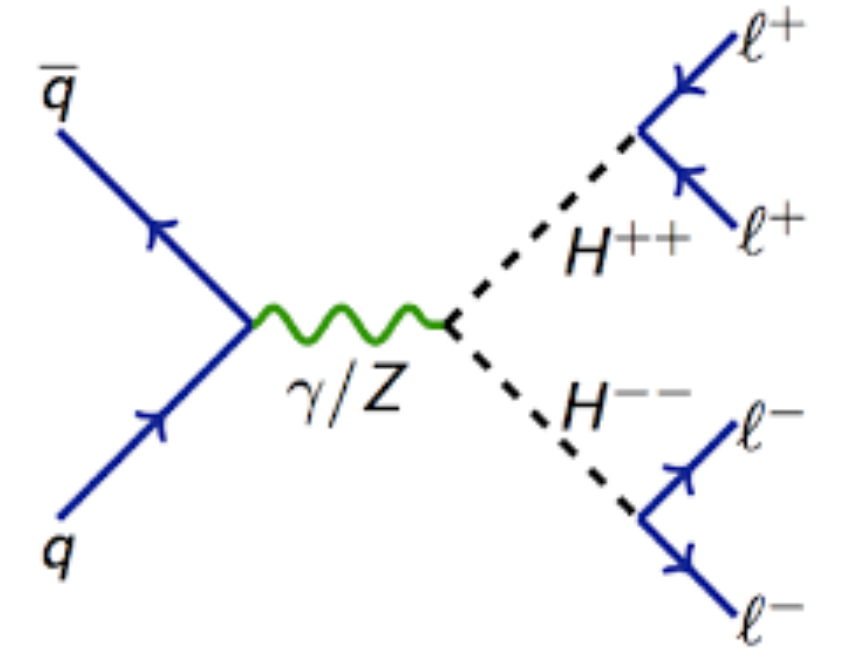
- Extraction of the lepton densities
- Application I: lepton-lepton scattering at LHC
- Application II: hunting LeptoQuarks
- Summary

Looking for Exotic Particles: general remarks

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
- provides **sensitivity to the couplings to leptons** (complementarity to **pair production**)

Pair Production

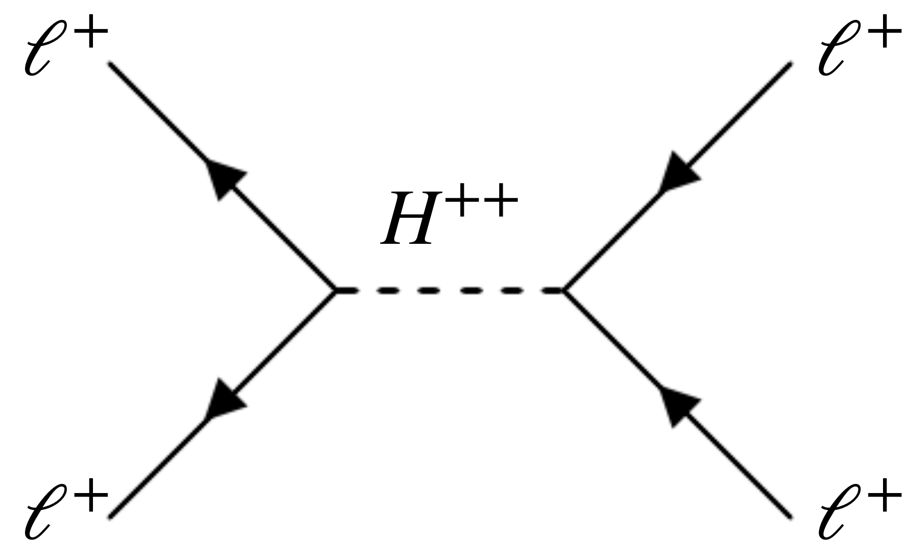


Lepton densities are in fact small but handful events can be produced. Ideal situations:

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

Example:
Doubly charged
Higgs states

Single resonant production



Compared to lepton-lepton processes

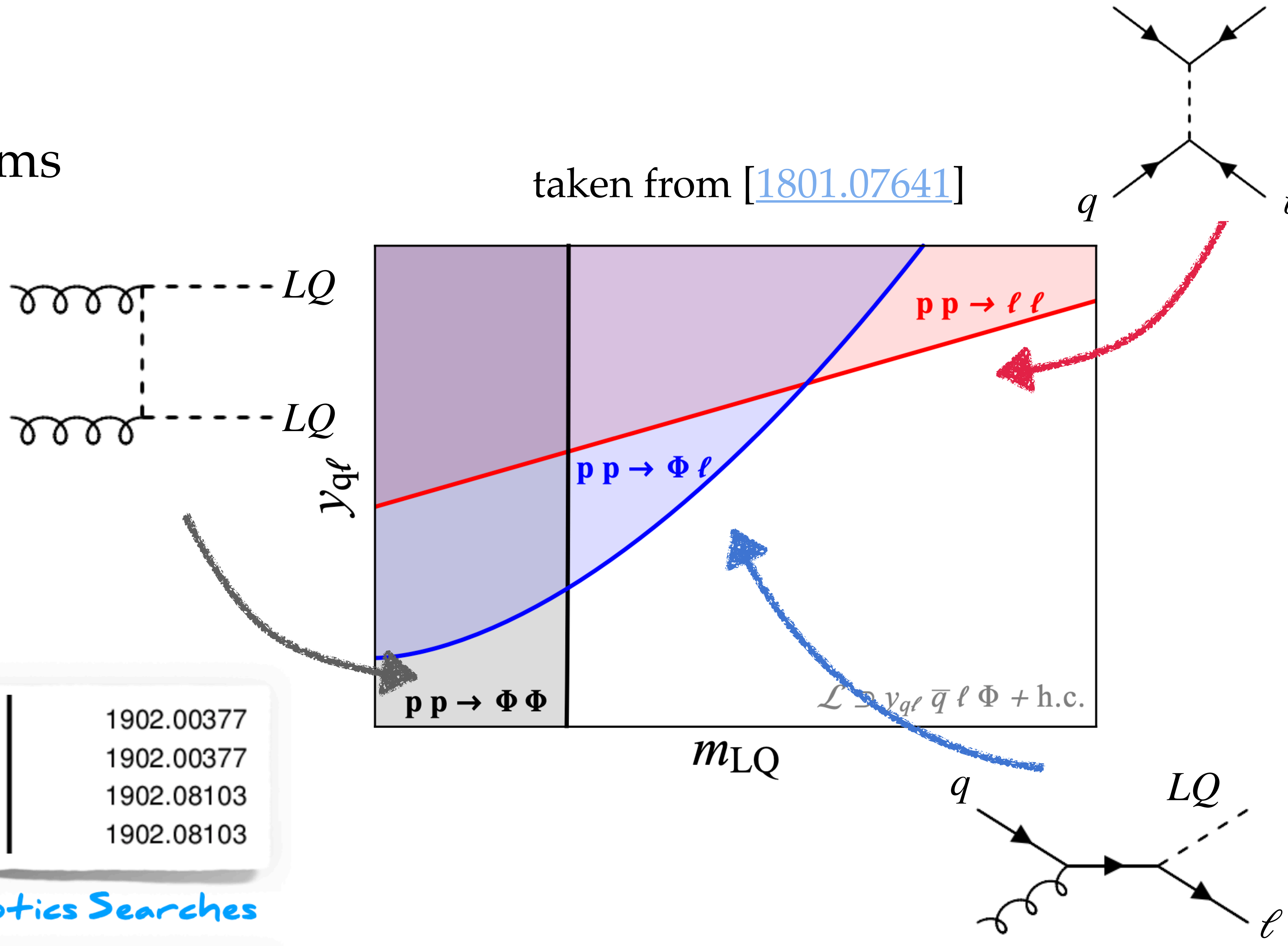
- in lepton-quark collisions only one lepton PDF suppression!
- ideal BSM candidate: **LeptoQuark** searches in single resonant channel

Leptoquarks searches at the LHC

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]



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

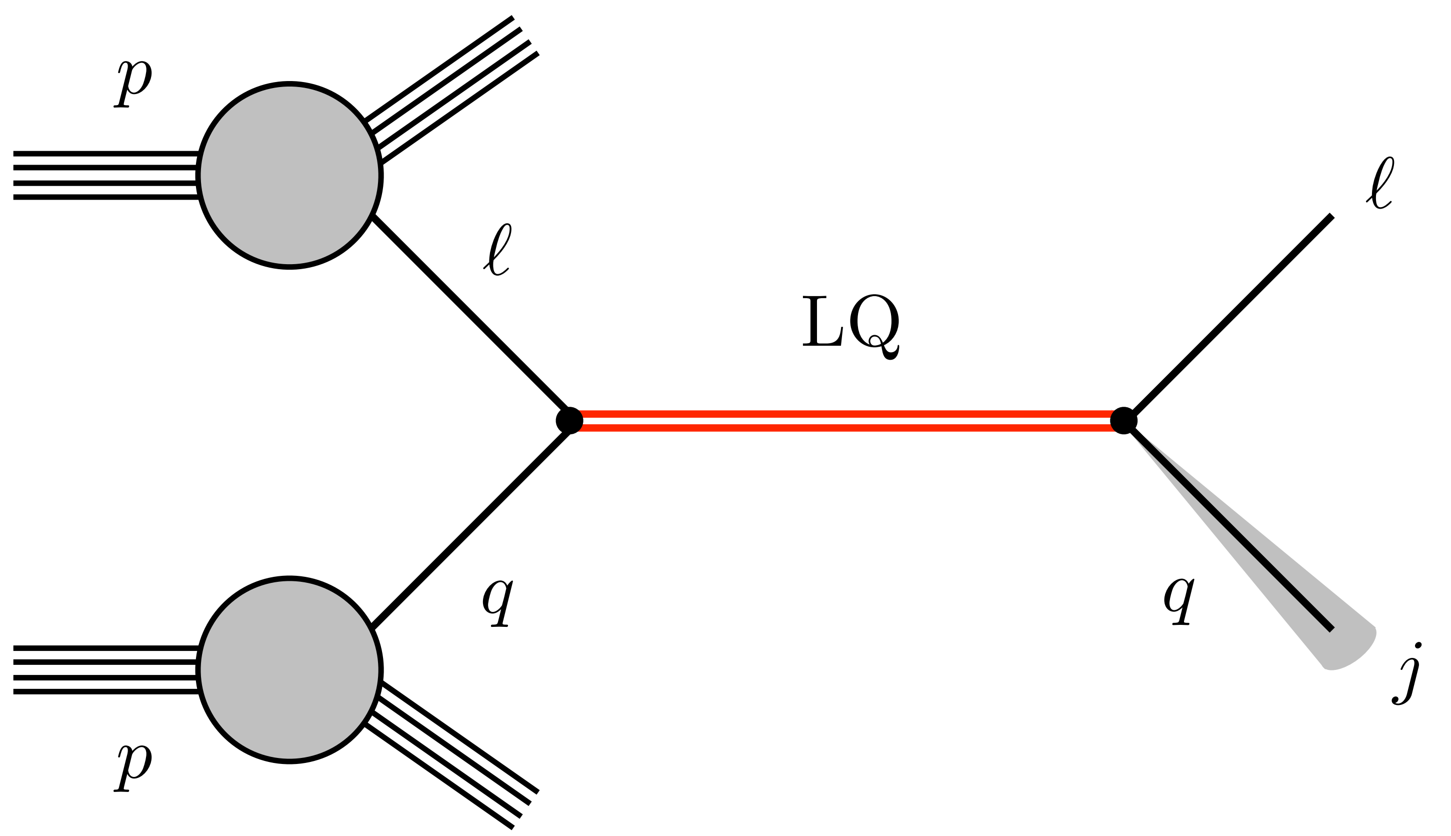
CMS EXO results

Leptoquarks searches at the LHC [LB, Haisch, Nason, Tramontano, Zanderighi, 2020]

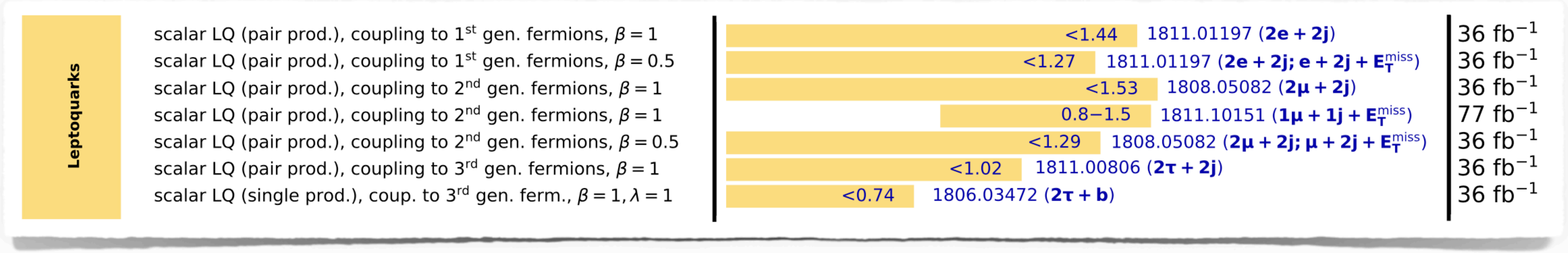
At LHC, the searches focus on three production mechanisms

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

quark-lepton scattering: NEW
Single Resonant production



ATLAS Exotics Searches



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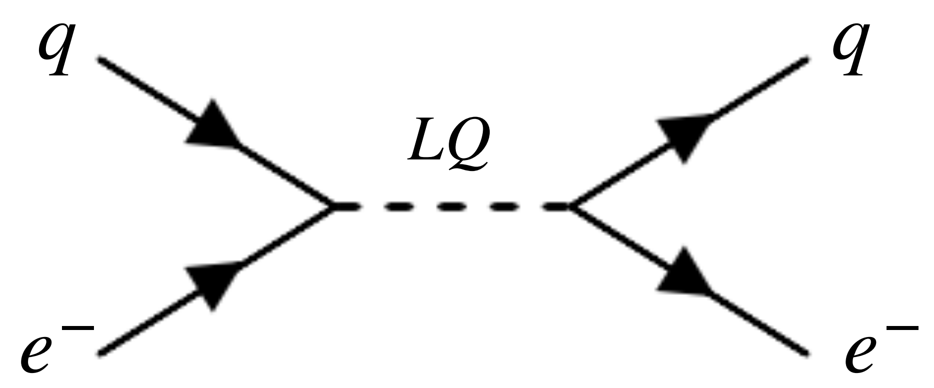
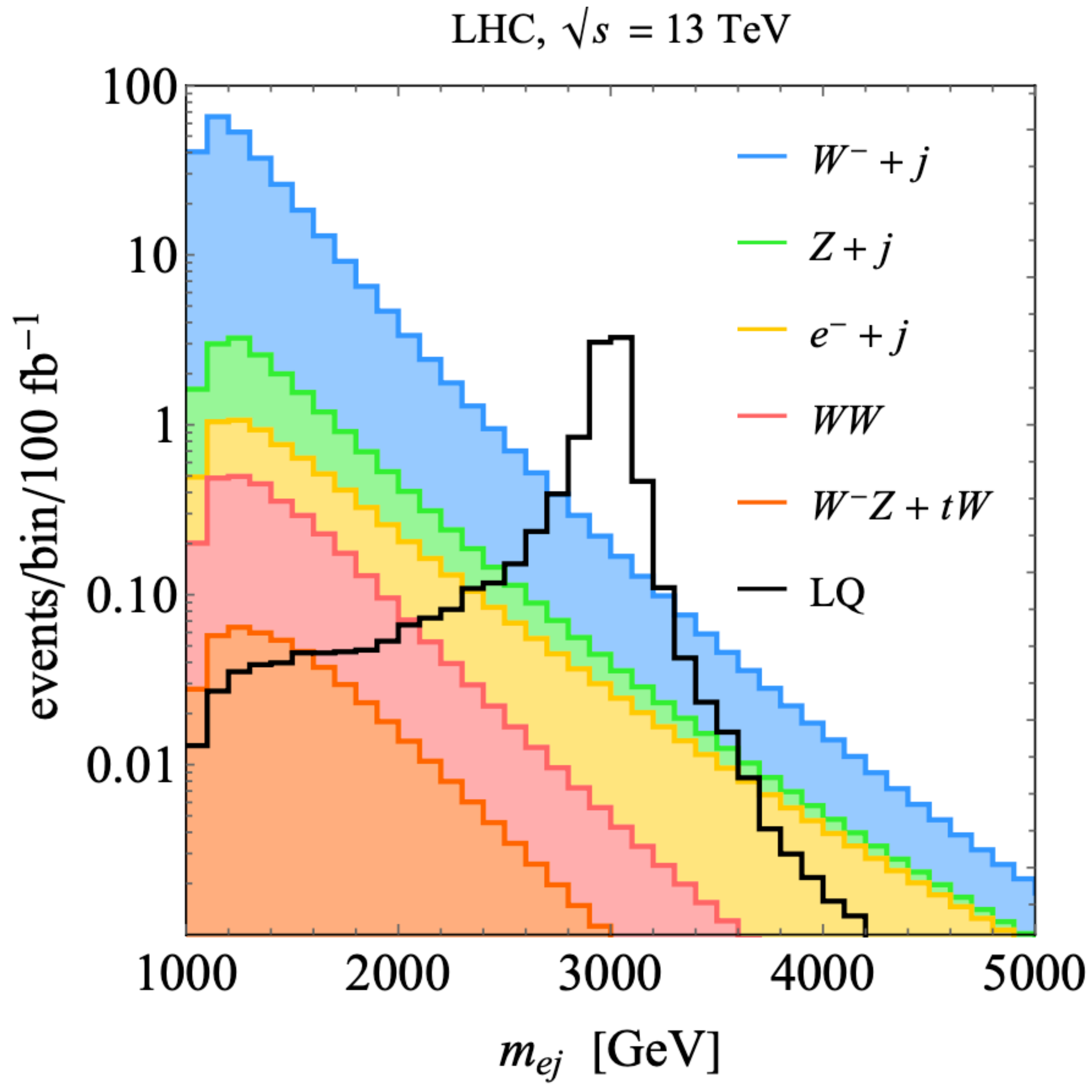




Minimal scalar LeptoQuark which couples to e^- and u quark
Benchmark point: $M_{LQ} = 3\,\text{TeV}, \quad \lambda_{eu} = 1$
Simulated at LO+PS

To target signal: **hard cuts** on the leading lemon and jet

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

To suppress the backgrounds: cut on missing energy, veto on extra leptons and jets

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

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

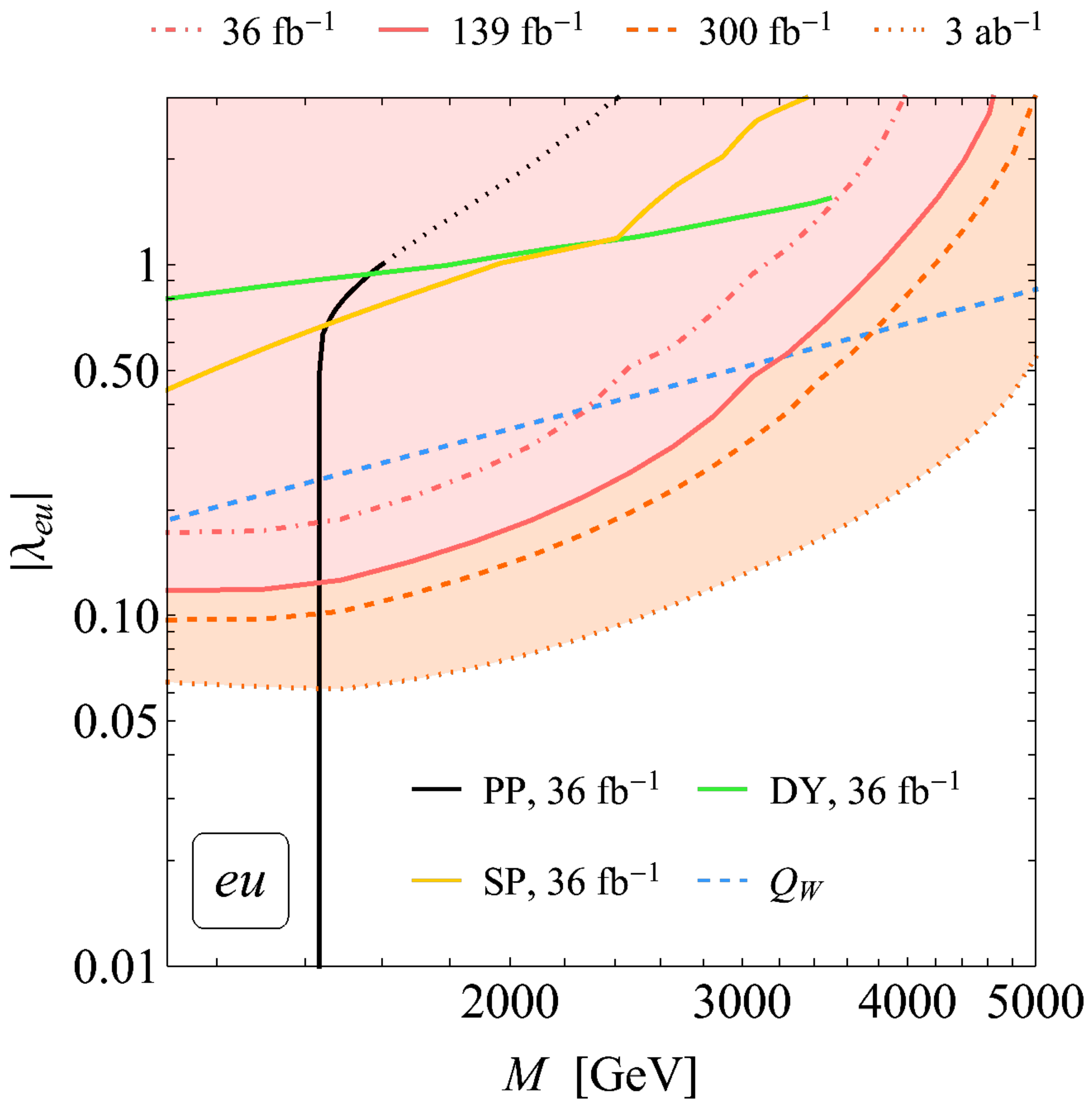
Leptoquarks searches at the LHC [LB, Haisch, Nason, Tramontano, Zanderighi, 2020]

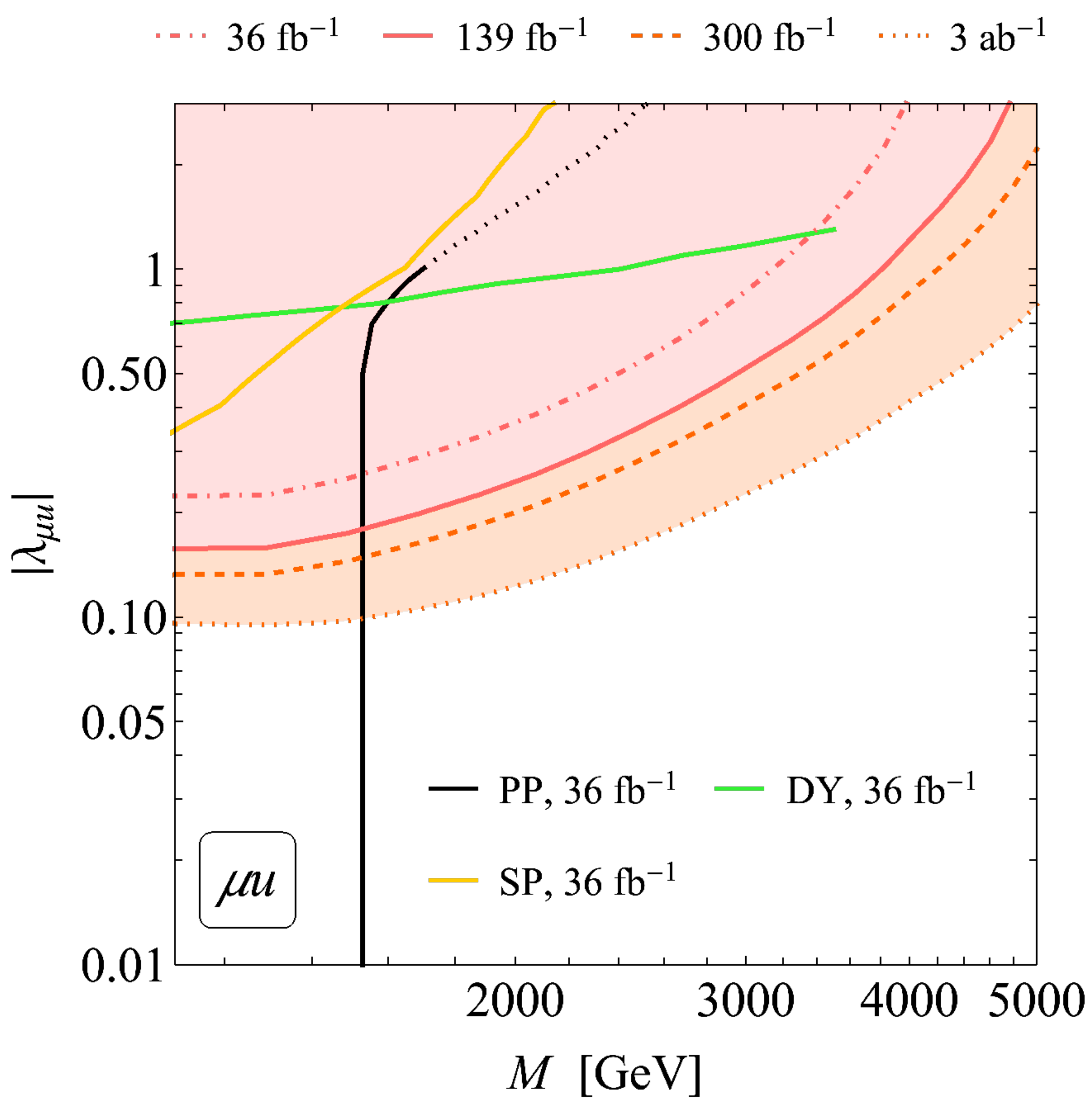
Inclusion of some experimental systematics

- **Multijet backgrounds**: background estimate extrapolated from the ATLAS $\ell + j$ search [1311.2006].
- **Lepton-jet mass resolution**: estimated by combining the information on the dilepton & dijet mass resolutions given in [1903.06248] & [1910.08447]
- Inclusion of PDF uncertainties for the main background

tot bkg syst	1 TeV	3 TeV	5 TeV
ℓ+j	4.3%	13%	70%

mass res	1 TeV	3 TeV	5 TeV
e+j	2.3%	1.7%	1.6%
μ+j	6.7%	12%	17%





Predicted Exclusion Limits

- **Most stringent** limits for 1&2 second generation LQ thanks to valence quarks
- For the electron case, **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 the LHC

[LB, Greljo, Krack, Nason, Selimovic, Tramontano, Zanderighi, 2022]

Remarks: signal events simulated with LO + PYTHIA8

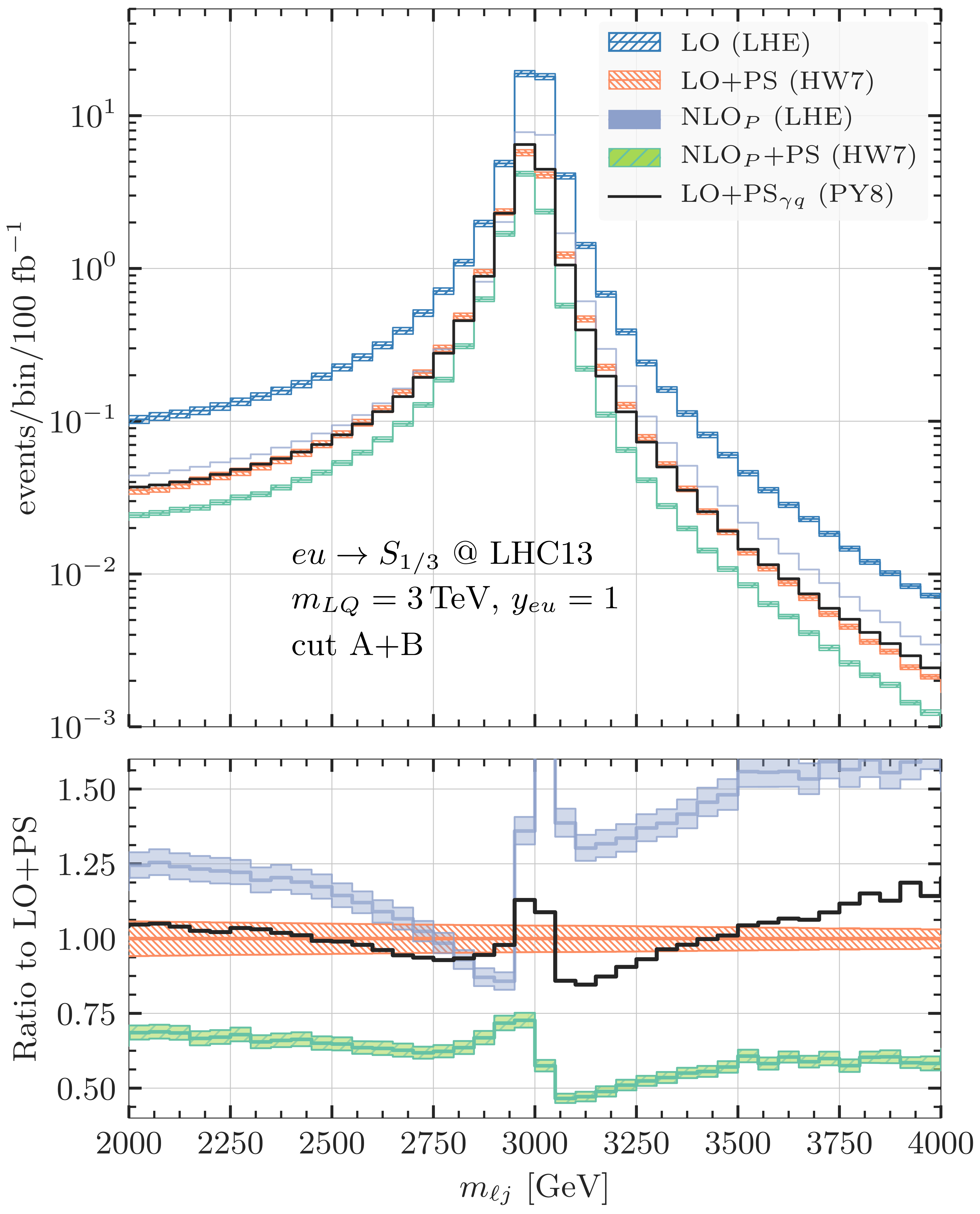
- PYTHIA does not handle lepton initiated processes. For the signal, we **trade leptons with photons** before showering.
- Estimate of the mismodelling $\mathcal{O}(10\%)$

NLO+PS implementation matched to HERWIG

available on https://powhegbox.mib.infn.it/#NLOps

Main results

- Only mild differences at LO+PS accuracy if one use a parton shower that handles leptons (HERWIG) compared to PYTHIA
- NLO (production) corrections lead to a further reduction of the acceptance of about 30% which translates into a relaxation of 15% on the exclusion limits



Summary

- **Precise determination** of lepton PDFs allows to explore the phenomenology of **"exotic" lepton initiated processes** and to **qualitatively assess their relevance**
- NLO+PS accuracy for lepton initiated processes
- Possibility to measure lepton-lepton scattering at LHC (HL-LHC)
- **Stringent limits** on minimal Leptoquark models already at Run II-III

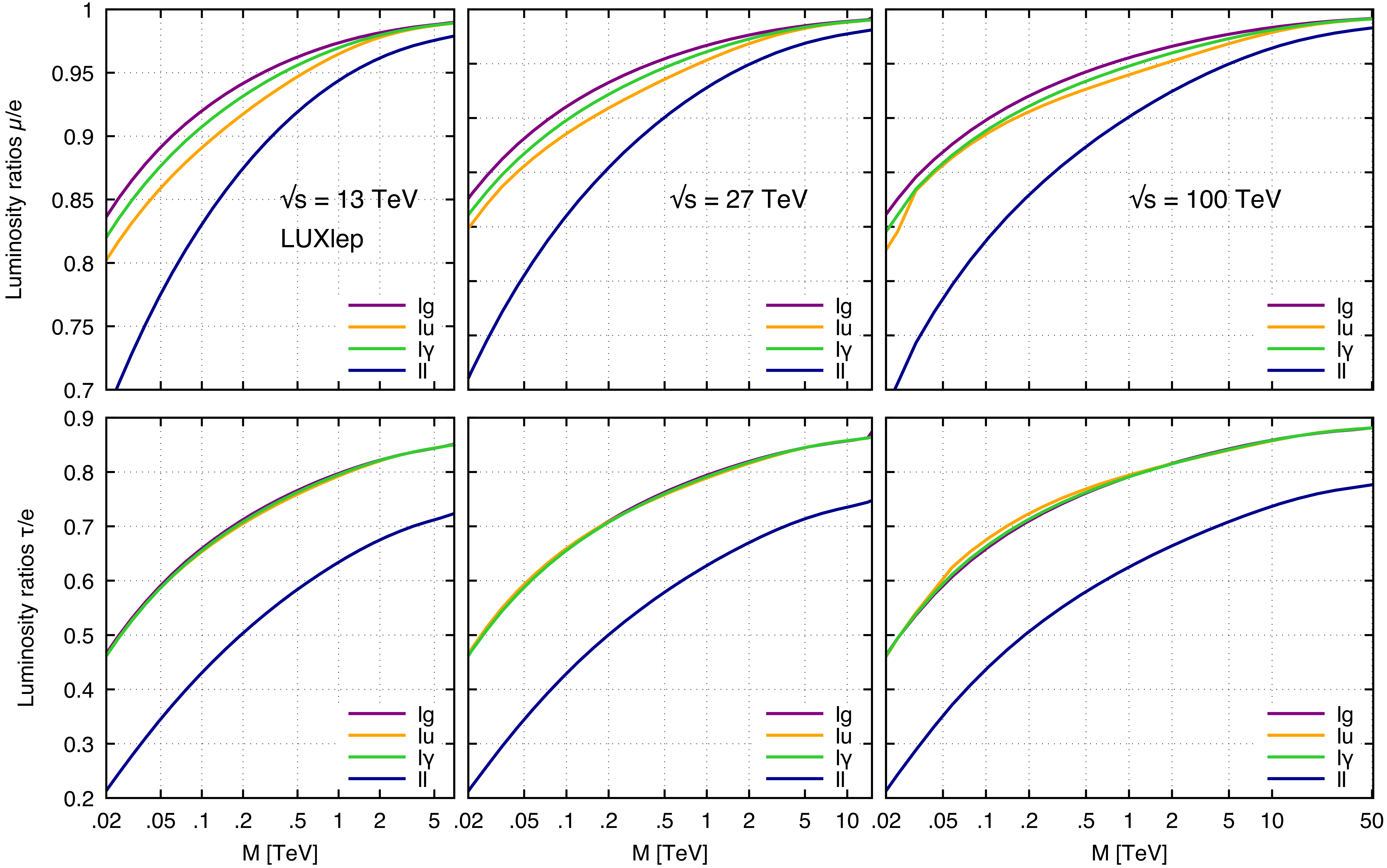
Prospects

The LHC is a photon/lepton collider too; have fun with it!

- Exploit reduced hadronic activity see talk by K. Krizka
- Compton scattering? Quark-lepton scattering (muon/tau DIS)?

Backup

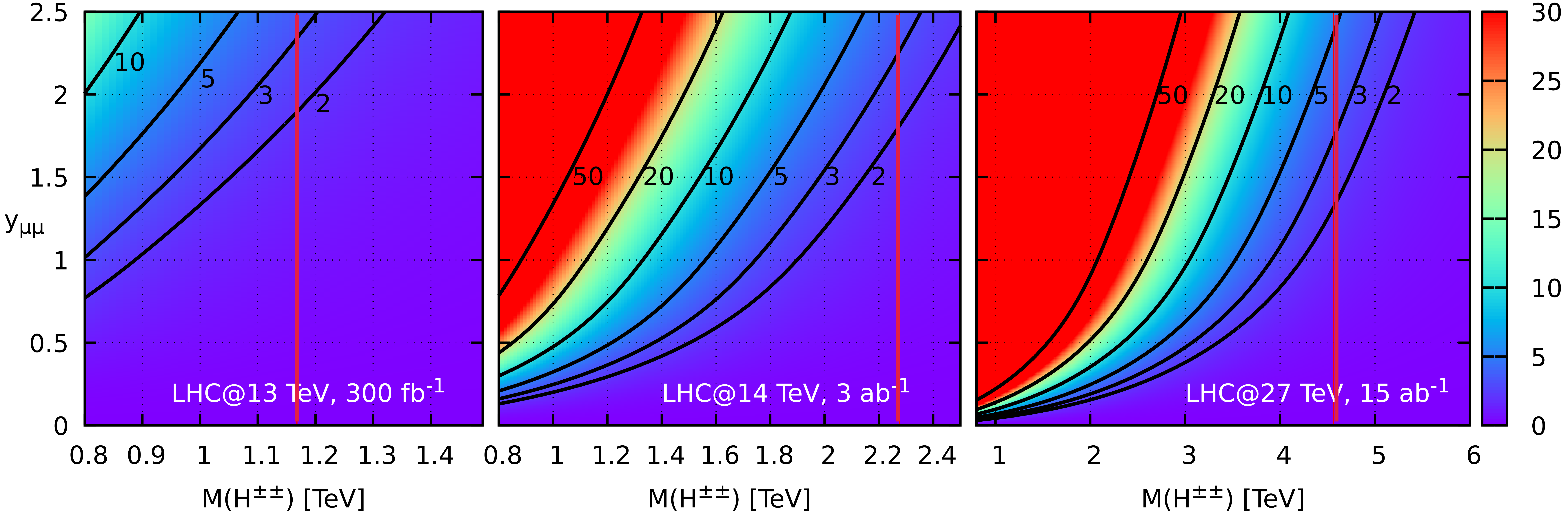
Luminosities for different leptons species



BSM searches: doubly charged Higgs

- We performed a simple bump search analysis, assuming **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

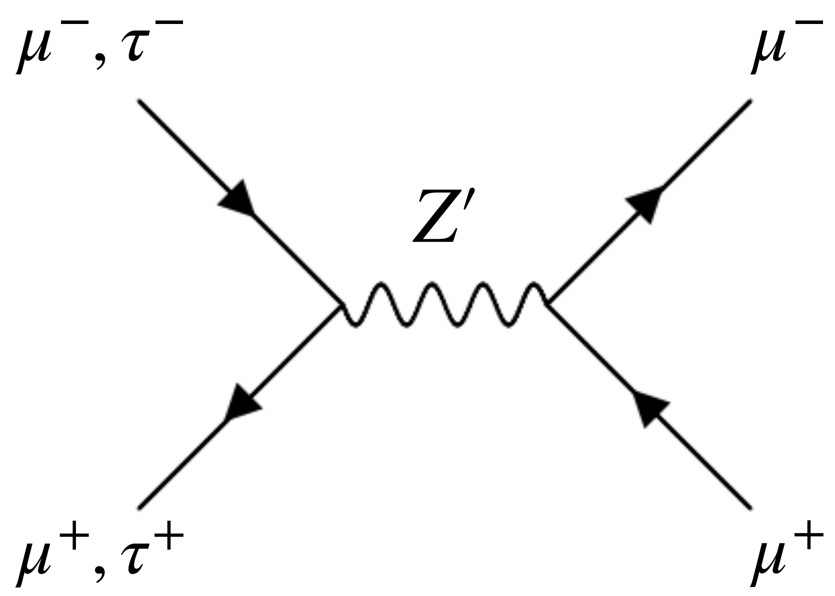
Pair Production projection taken from *de Melo et al* [1909.07429]



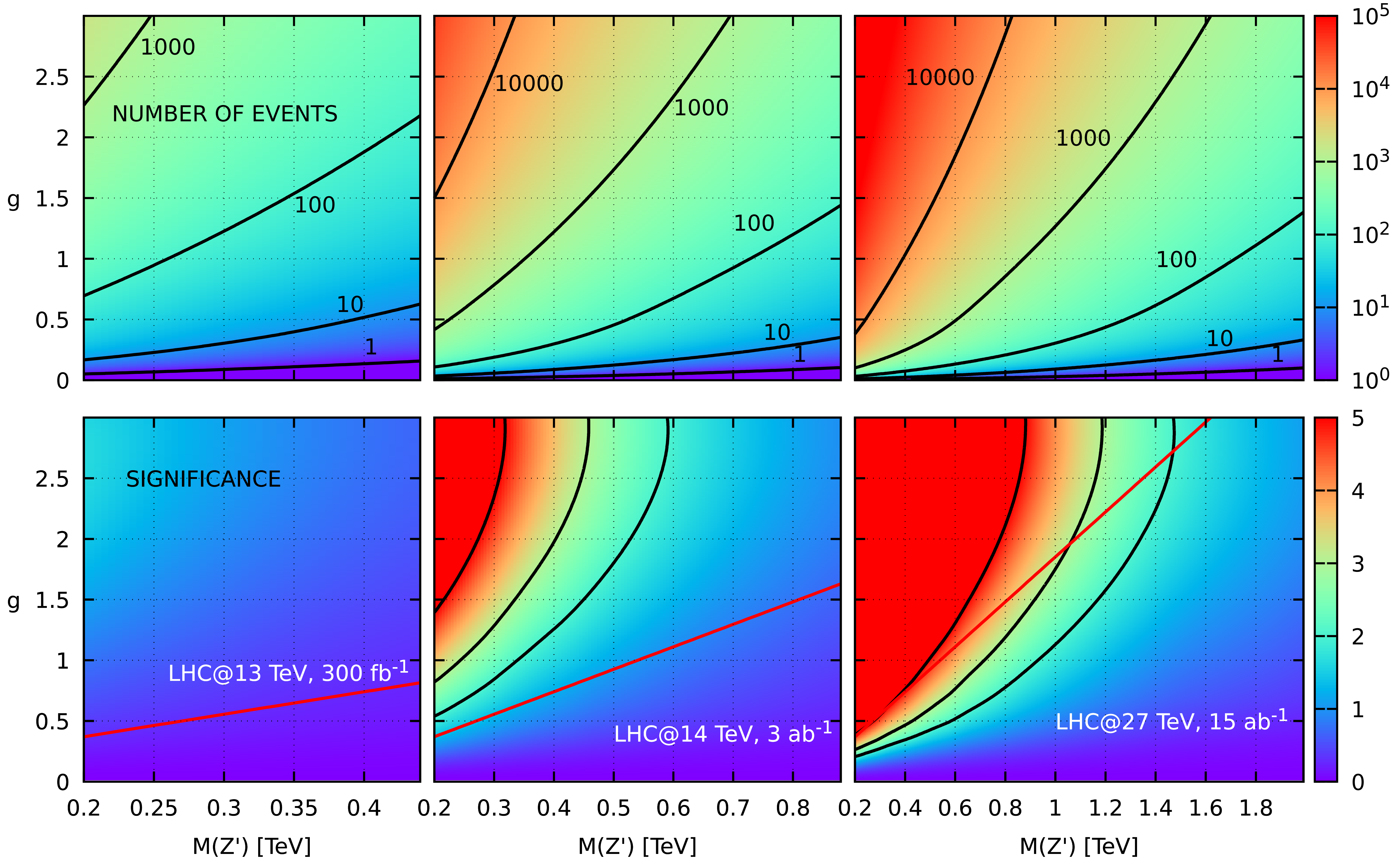
BSM searches: $L_\mu - L_\tau$ Z' boson

- 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)*]:

$L_e - L_\mu$ $\quad$ $L_e - L_\tau$ $\quad$ $L_\mu - L_\tau$



lepton-lepton resonant s-channel production



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

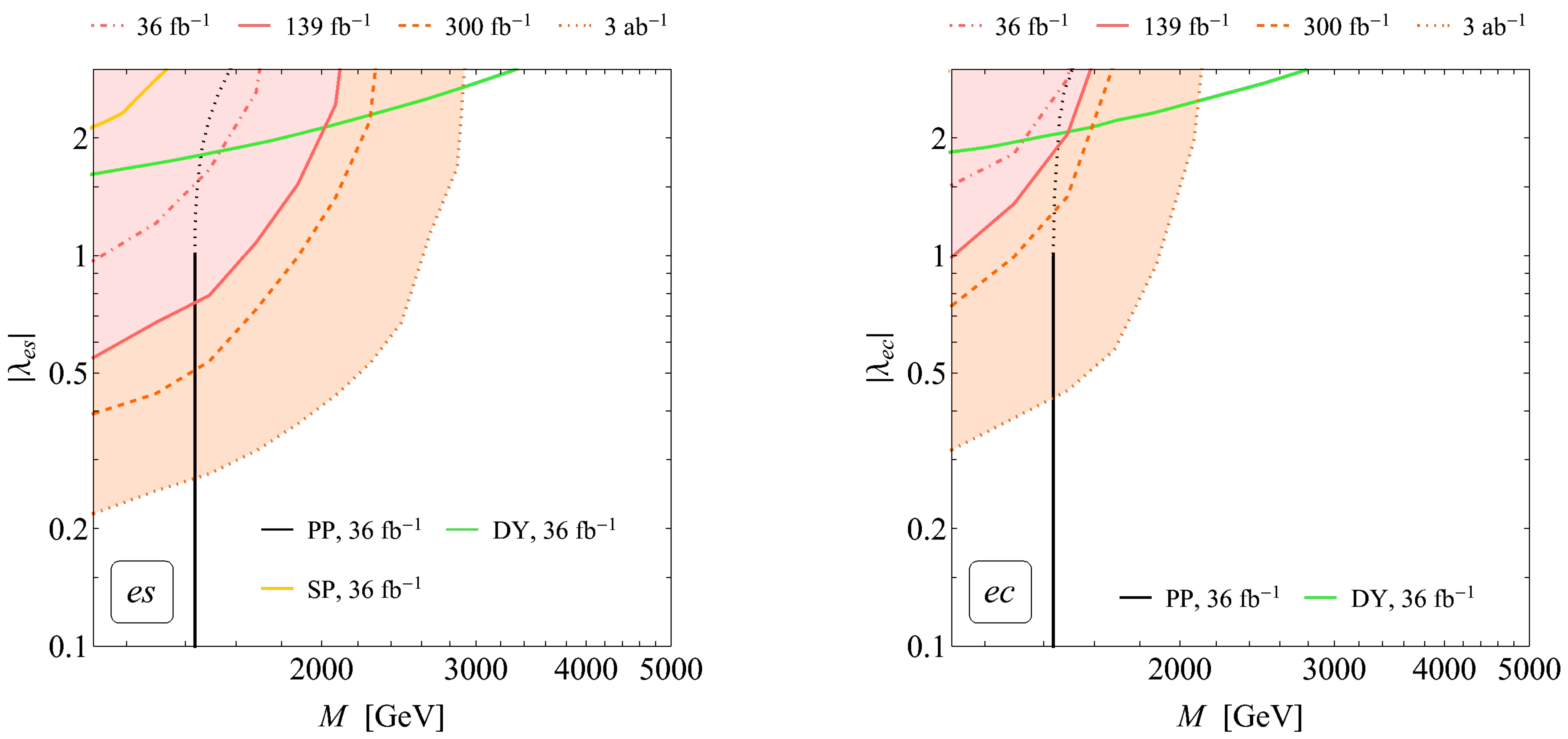
$$b_w = \sqrt{\Gamma_{Z'}^2 + r^2 M_{Z'}^2}, \qquad \Gamma_{Z'} = \frac{g}{4\pi} M_{Z'}$$

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

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

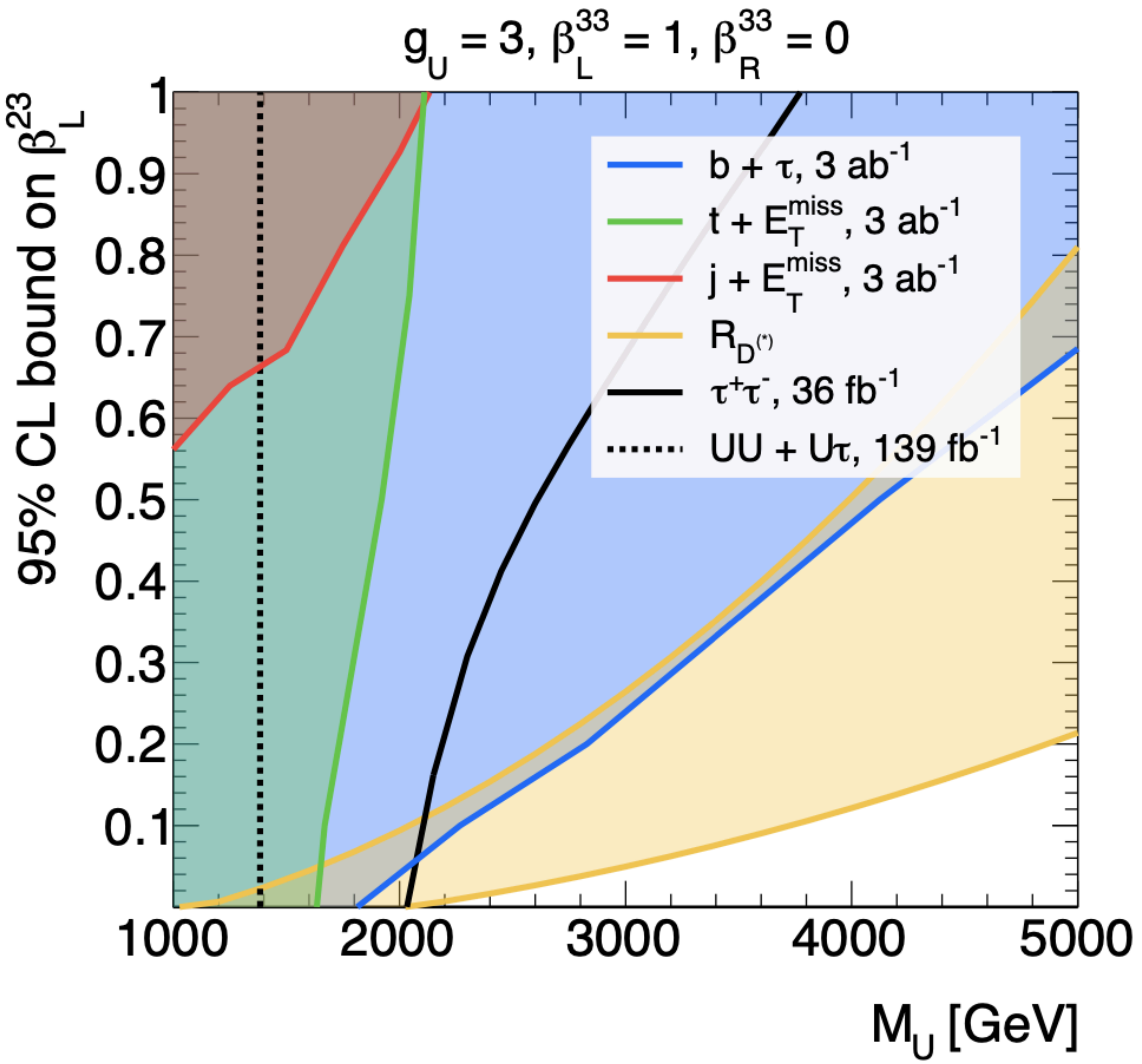
- Direct LHC limits **weaker** than indirect constraints from **neutrino trident** (low energy physics constraint). Need HE-LHC upgrade to make them comparable in strength
- **Hadronic activity** may play a role to reduce the Drell-Yan background

Leptoquarks limits



Third generation Leptoquarks

[Haisch, Polesello, 2021]



[LB, Greljo, Krack, Nason, Selimovic, Tramontano, Zanderighi, 2022]