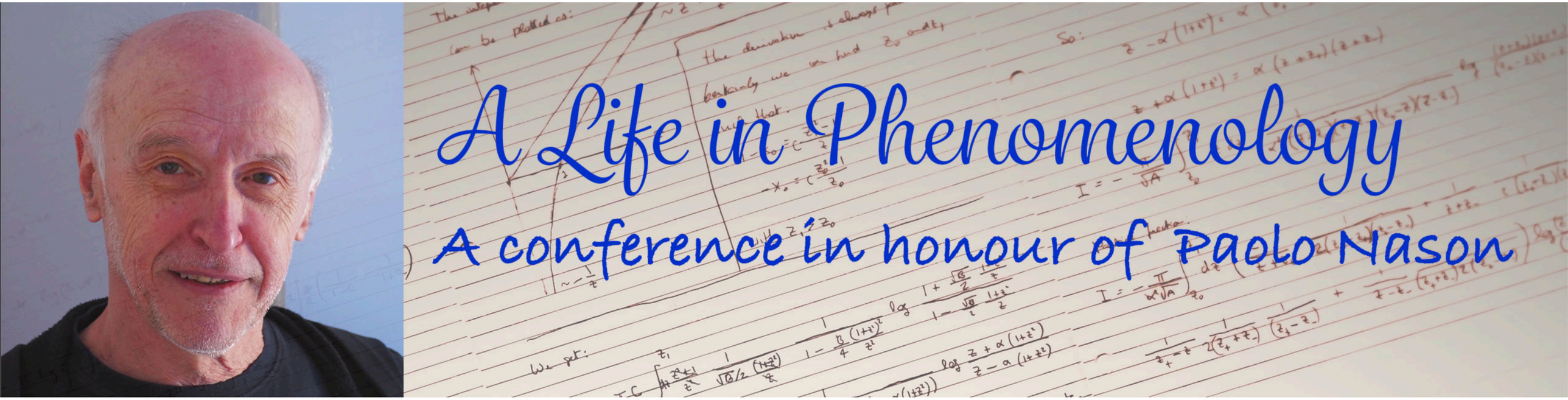
LIGHT (AND LEPTONS) IN THE PROTON



Milano Bicocca, September 2022

Gavin Salam
Rudolf Peierls Centre for Theoretical Physics & All Souls College, University of Oxford

European Research Council
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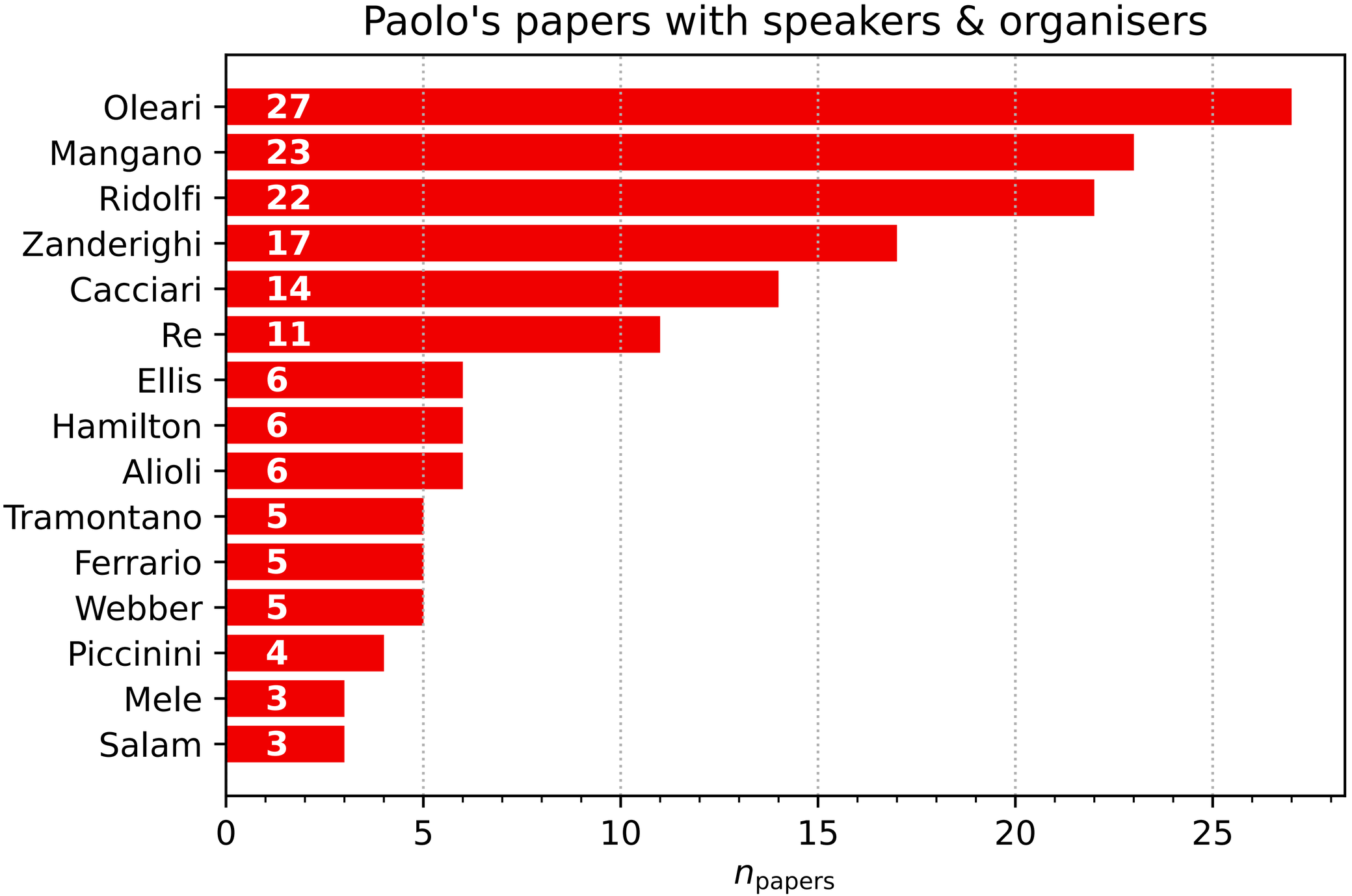
THE ROYAL SOCIETY
Science and Technology Facilities Council
UNIVERSITY OF OXFORD


Paolo's papers with speakers & organisers
Oleari
Mangano
Ridolfi
Zanderighi
Cacciari
Re
Ellis
Hamilton
Alioli
Tramontano
Ferrario
Webber
Piccinini
Mele
Salam
27
23
22
17
14
11
6
6
6
5
5
5
4
3
3
0
5
10
15
20
25
n_{papers}

Three papers in common with Paolo

Multiplicative-accumulative matching of NLO calculations with parton showers #1

Paolo Nason (INFN, Milan Bicocca and Milan Bicocca U.), Gavin P. Salam (Oxford U., Theor. Phys. and Oxford U.) (Nov 5, 2021)

Published in: *JHEP* 01 (2022) 067 • e-Print: 2111.03553 [hep-ph]

pdf DOI cite 2 citations

The Photon Content of the Proton #2

Aneesh V. Manohar (UC, San Diego), Paolo Nason (INFN, Milan Bicocca and Milan Bicocca U.), Gavin P. Salam (CERN), Giulia Zanderighi (CERN and Oxford U., Theor. Phys.) (Aug 3, 2017)

Published in: *JHEP* 12 (2017) 046 • e-Print: 1708.01256 [hep-ph]

pdf DOI cite 180 citations

How bright is the proton? A precise determination of the photon parton distribution function #3

Aneesh Manohar (CERN and UC, San Diego), Paolo Nason (INFN, Milan Bicocca), Gavin P. Salam (CERN), Giulia Zanderighi (CERN and Oxford U., Theor. Phys.) (Jul 14, 2016)

Published in: *Phys.Rev.Lett.* 117 (2016) 24, 242002 • e-Print: 1607.04266 [hep-ph]

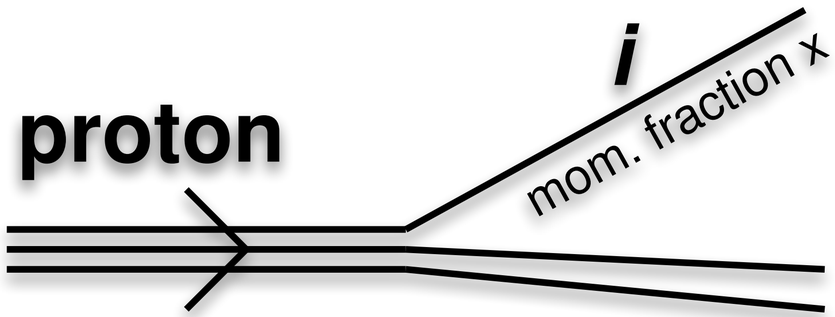
pdf DOI cite 272 citations

Paolo's papers with ≥ 250 citations

		ncit	/yr	jrn	nAu	title
1.	0709.2092	4059	271	jhp	3	Matching NLO QCD computations with Parton Shower simulations: the POWHEG method
2.	1002.2581	3776	300	jhp	4	A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX
3.	0409146hp	3448	192	jhp	1	A New method for combining NLO QCD with shower Monte Carlo algorithms
4.	87-12	1644	47	npb	3	The Total Cross-Section for the Production of Heavy Quarks in Hadronic Collisions
5.	89-04	1204	36	npb	3	The One Particle Inclusive Differential Cross-Section for Heavy Quark Production in Hadronic Collisions
6.	0707.3088	1149	76	jhp	3	A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction
7.	0305252hp	1127	58	jhp	3	Matching NLO QCD and parton showers in heavy flavor production
8.	91-09-24	985	32	npb	3	Heavy quark correlations in hadron collisions at next-to-leading order
9.	9803400hp	936	38	jhp	3	The P(T) spectrum in heavy flavor hadroproduction
10.	1111.5869	886	82	plb	5	Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation
11.	0907.4076	860	65	jhp	4	NLO single-top production matched with shower in POWHEG: s- and t-channel contributions
12.	0306211hp	806	42	jhp	4	Soft gluon resummation for Higgs boson production at hadron colliders
13.	9801375hp	686	28	npb	4	NLL resummation of the heavy quark hadroproduction cross-section
14.	1205.6344	610	59	jhp	6	Theoretical predictions for charm and bottom production at the LHC
15.	0911.5299	601	47	jhp	2	NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG
16.	0303085hp	590	30	jhp	5	The t anti-t cross-section at 1.8-TeV and 1.96-TeV: A Study of the systematics due to parton densities and scale dependence
17.	0805.4802	589	41	jhp	4	NLO vector-boson production matched with shower in POWHEG
18.	0812.0578	581	42	jhp	4	NLO Higgs boson production via gluon fusion matched with shower in POWHEG
19.	0502203hp	509	29	prl	3	QCD predictions for charm and bottom production at RHIC
20.	9604351hp	507	19	npb	4	The Resummation of soft gluons in hadronic collisions
21.	88-02	468	14	npb	4	Total Cross-Sections for Heavy Flavor Production in Hadronic Collisions and QCD
22.	1107.5051	466	42	jhp	4	W+W-, WZ and ZZ production in the POWHEG BOX
23.	0102134hp	458	21	jhp	3	The p(T) spectrum in heavy flavor photoproduction
24.	1206.3572	370	36	jhp	3	MINLO: Multi-Scale Improved NLO
25.	0804.2800	370	26	jhp	5	Updated predictions for the total production cross sections of top and of heavier quark pairs at the Tevatron and at the LHC
26.	1012.3380	327	28	jhp	5	Jet pair production in POWHEG
27.	9702287hp	321	13	p	4	Heavy quark production
28.	1309.0017	321	35	jhp	4	NNLOPS simulation of Higgs boson production
29.	1306.2542	301	33	jhp	4	$HW^{\pm}$/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO
30.	88-06	283	8	npb	2	QCD Radiative Corrections to the Photoproduction of Heavy Quarks
31.	9602208hp	283	11	plb	4	The Top cross-section in hadronic collisions
32.	90-12	277	9	npb	2	The Fragmentation function for heavy quarks in QCD
33.	1607.04266	272	44	prl	4	How bright is the proton? A precise determination of the photon parton distribution function
34.	9310350hp	269	9	plb	4	Improving the Weizsacker-Williams approximation in electron - proton collisions
35.	0312132hp	265	14	jhp	5	QCD analysis of first b cross-section data at 1.96-TeV
36.	1001.2312	262	21	npb	4	Heavy quarks in deep-inelastic scattering

status 2015

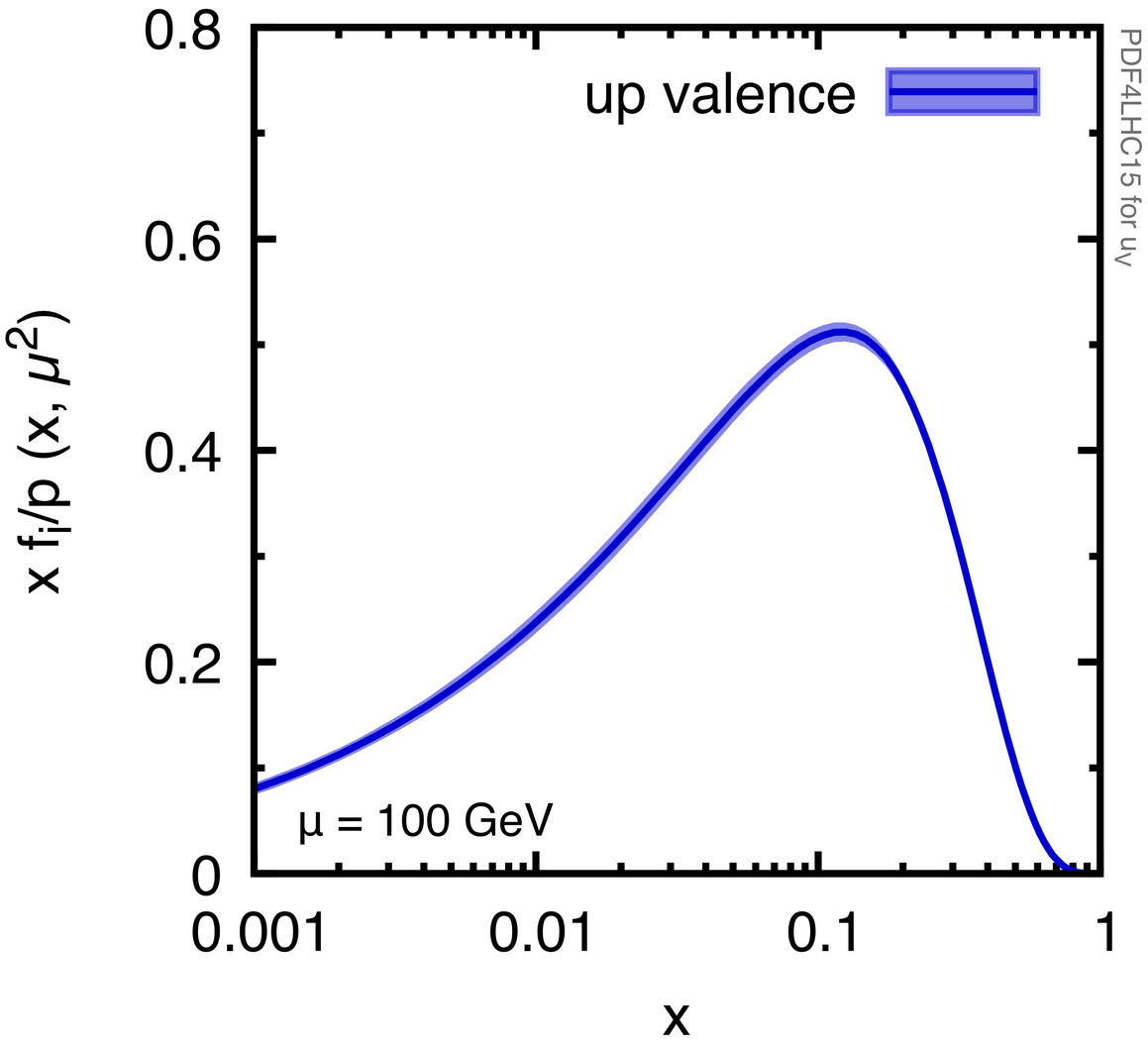
parton distribution functions (PDFs)



LHC physics
needs PDFs in region
$\sim 10^{-3} - 0.5$

Typically known with good
precision ~1–3%

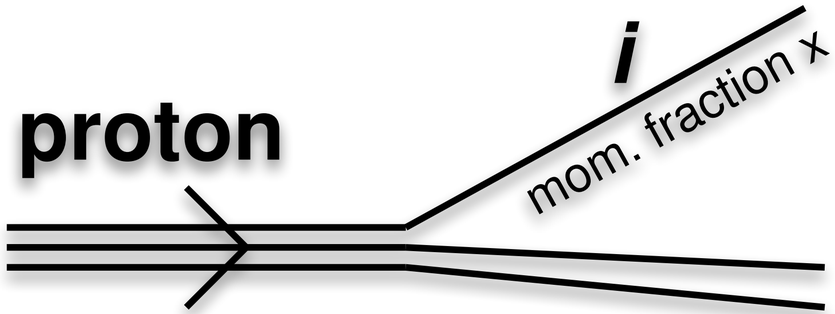
$f_{u/p}(x, \mu^2)$



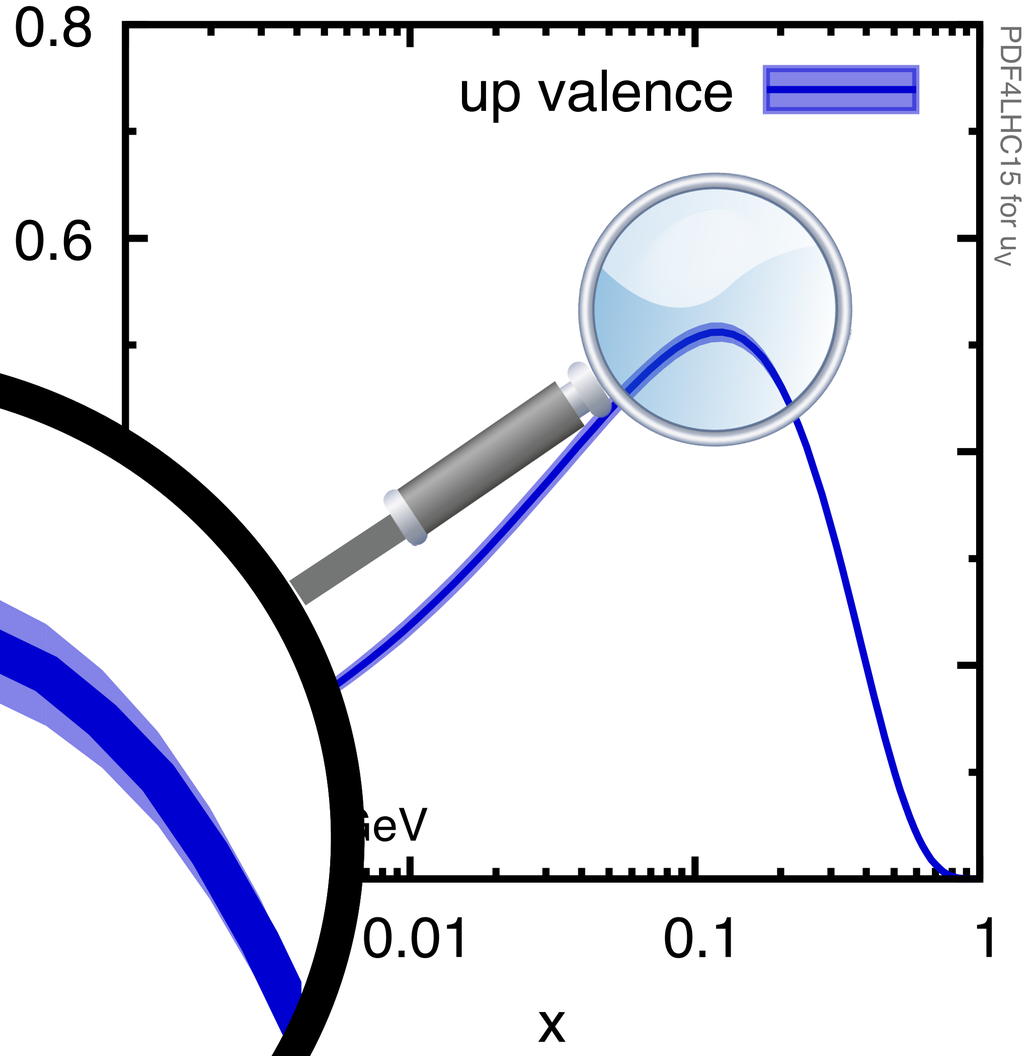
E.g. NNPDF, MMHT, CT & PDF4LHC working group (+ also HERAPDF, ABM, …)

parton distribution functions (PDFs)

status 2015

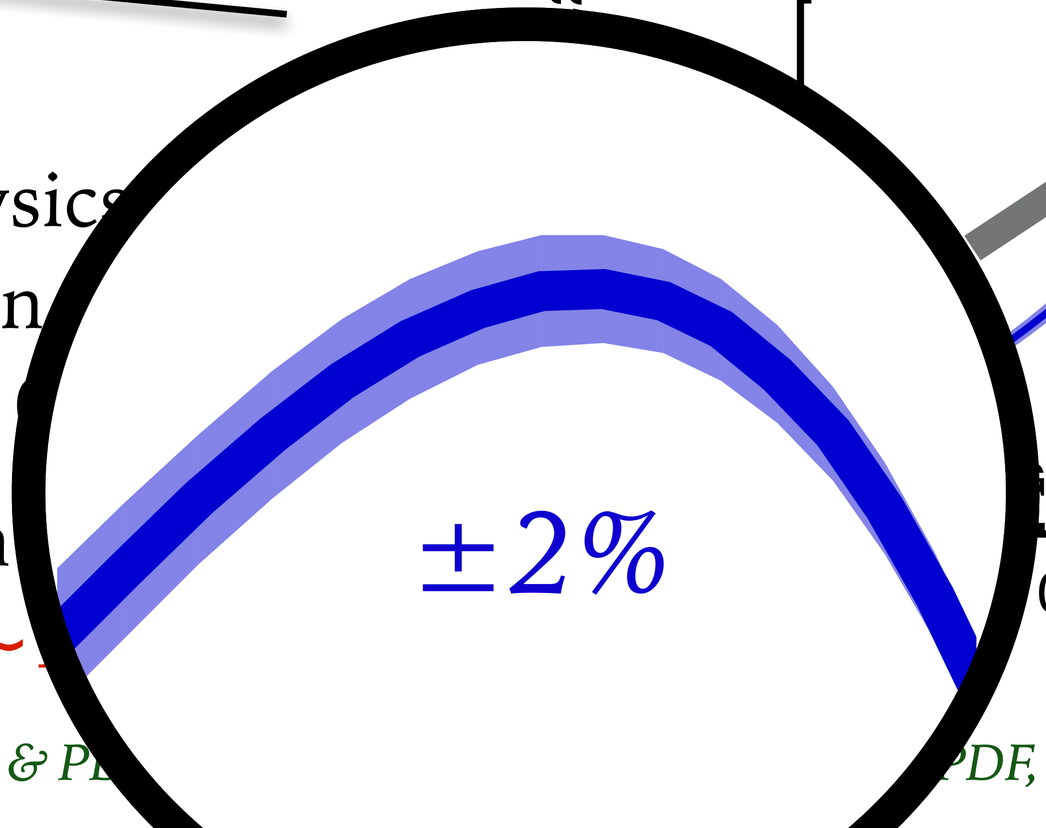


$f_{u/p}(x, \mu^2)$



LHC physics
needs PDFs in
~ 10^{-3} –

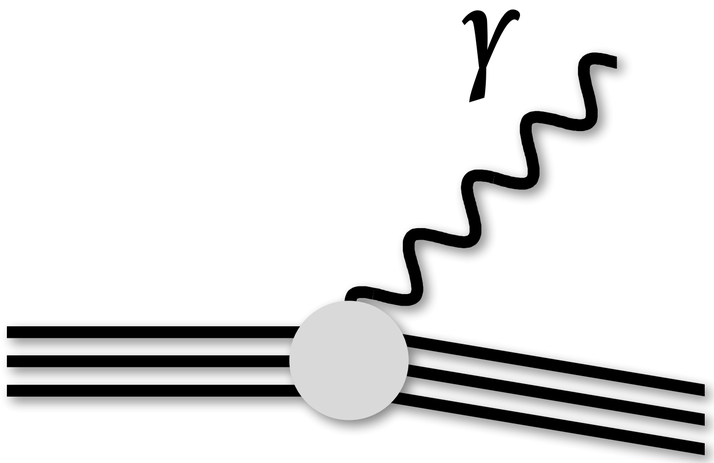
Typically known
precision ~



E.g. NNPDF, MMHT, CT & PD *PDF, ABM, …)*

status 2015

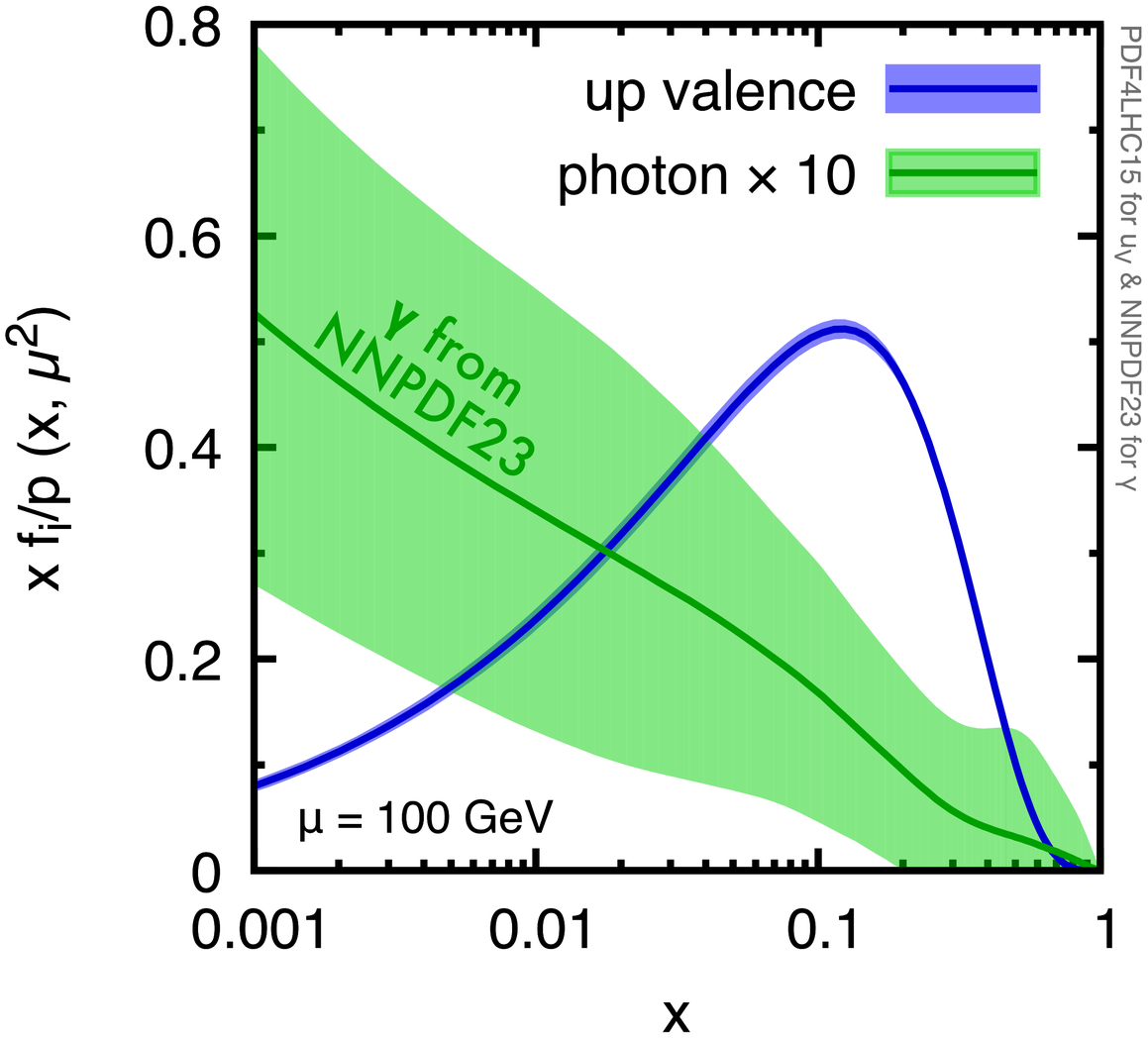
parton distribution functions (PDFs)



One exception:

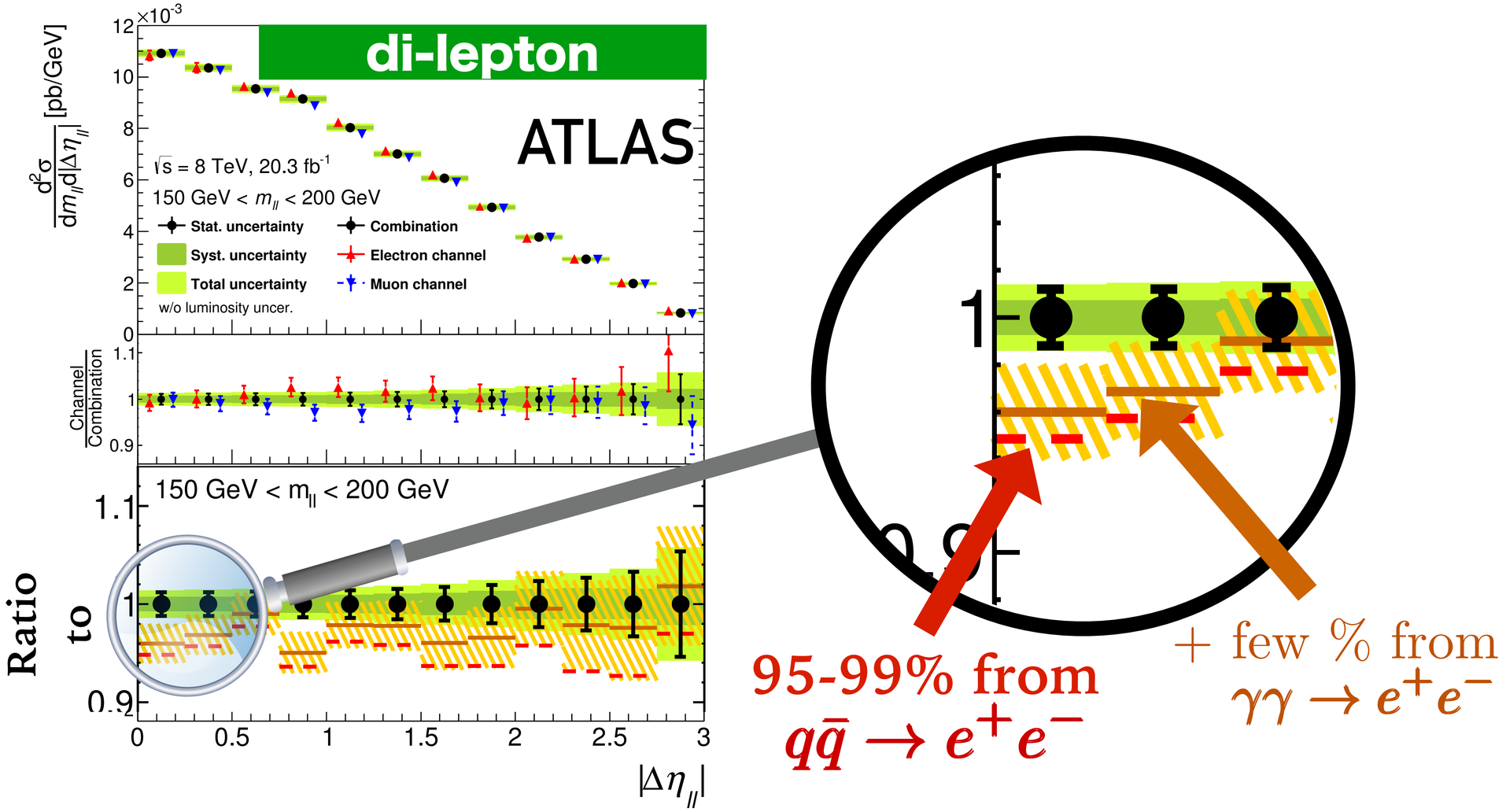
the photon distribution inside the proton
(had up to 100% uncertainty)

$f_{i/p}(x, \mu^2)$



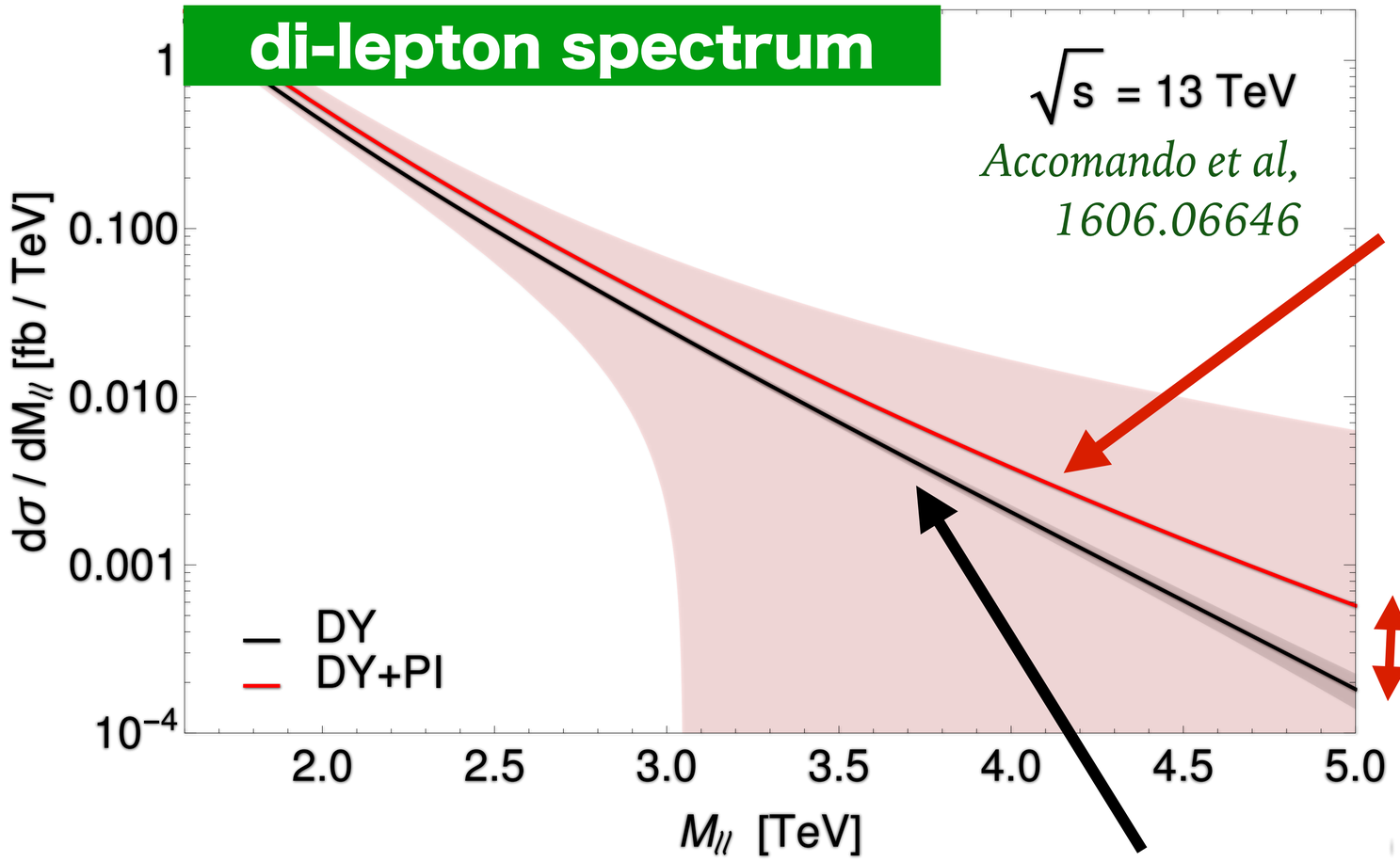
model-independent γ PDF fit (c. 2013)

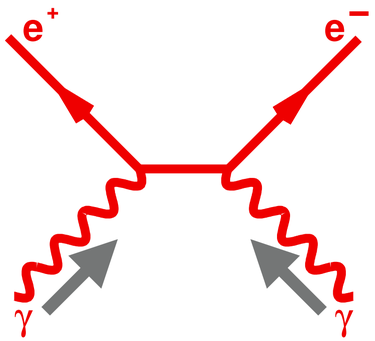
status 2015



it mattered for di-lepton, di-boson, ttbar, EW higgs, etc.

status 2015

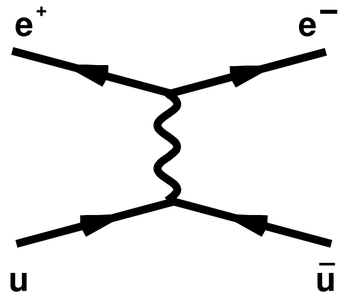




photon-induced contribution & uncertainty dominate [NNPDF23]

~100%

"normal" qqbar→ e^+e^- contribution



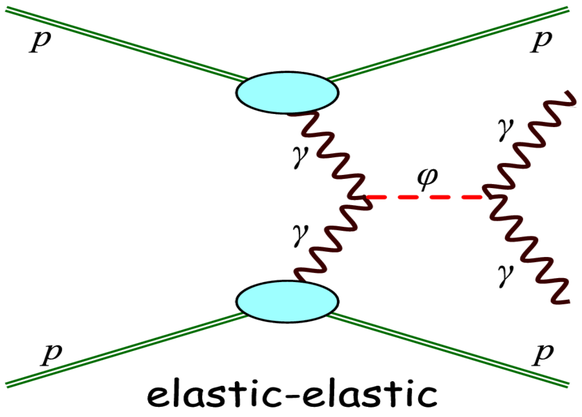
status 2015/16

Photon fusion

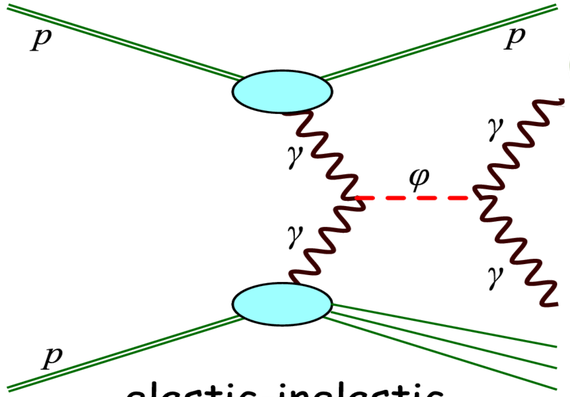
The 750 GeV excess from photon-photon and quark-quark processes

Tanumoy Mandal

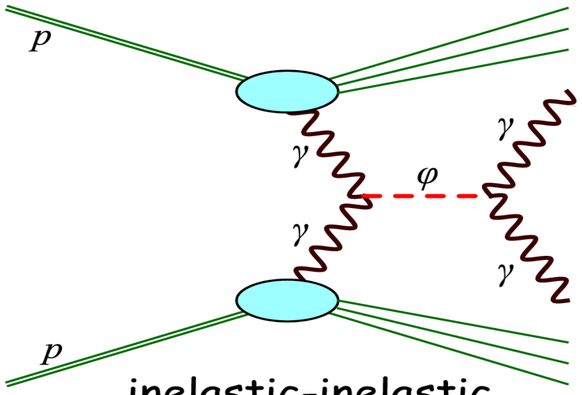
(Moriond QCD, March 20, 2016)



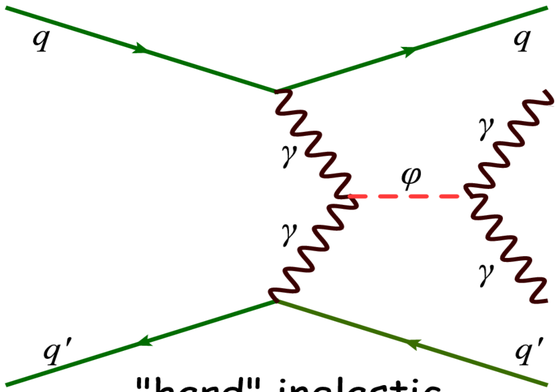
elastic-elastic



elastic-inelastic



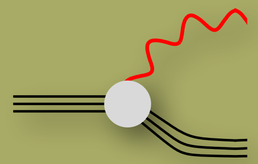
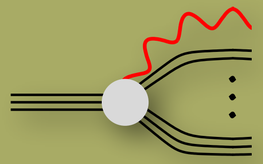
inelastic-inelastic



"hard" inelastic

1512.05751;1512.05776;1512.08502;1601.00386;1601.00638;1601.01144;1601.01571;1601.01712;
1601.03772;1601.07167;1601.07187;1602.02380;1602.07574;1601.07774;1603.00287 ... more

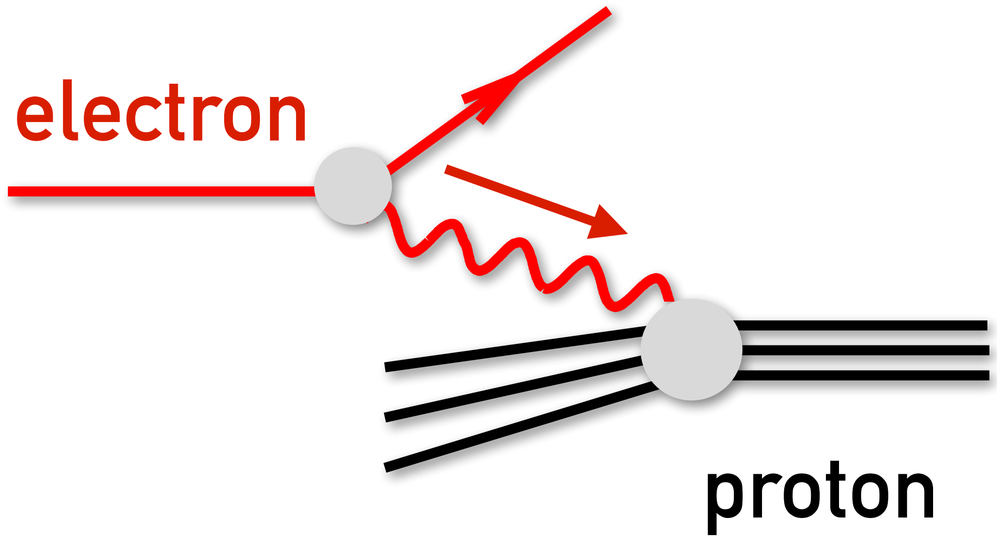
Widely discussed photon-PDF estimates

	 elastic	 inelastic	LHAPDF public computer-readable form?
Gluck Pisano Reya 2002	dipole	model	✘
MRST2004qed	✘	model	✓
CT14qed_inc	dipole	model (data-constrained)	✓
Martin Ryskin 2014	dipole (only electric part)	model	✘
Harland-Lang, Khoze Ryskin 2016	dipole	model	✘
NNPDF23qed (& NNPDF30qed)	no separation; fit to data		

elastic part long known: Budnev, Ginzburg, Meledin & Serbo, Phys.Rept. 1974

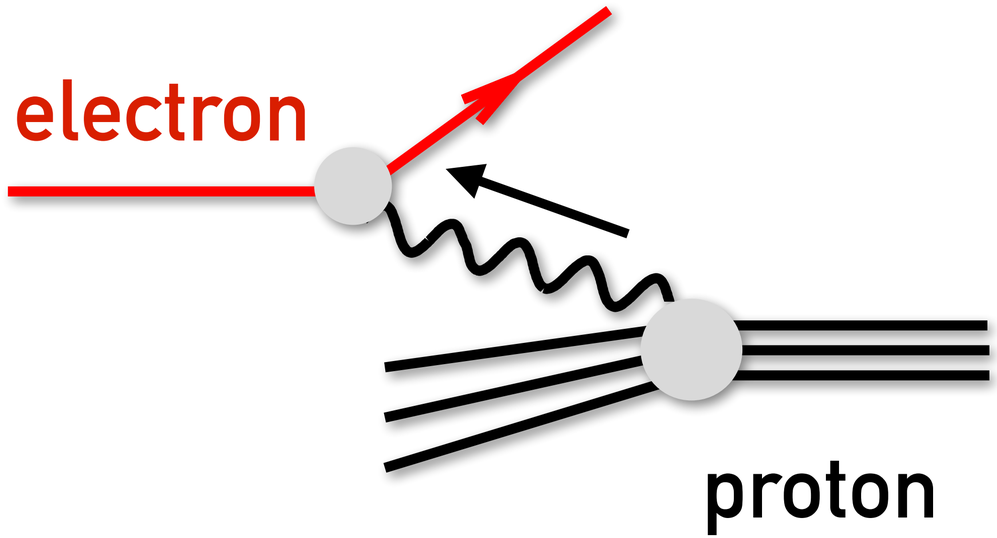
How do you do better? → Use electron–proton scattering

- Experiments have been going on for decades
- Usually seen as photons from electron probing proton structure



How do you do better? → Use electron–proton scattering

- Experiments have been going on for decades
- Usually seen as photons from electron probing proton structure
- But **can be viewed as electron probing proton's photonic field**



- Everything about unpolarized EM electron–proton interaction encoded in two "structure functions" $F_2(x,Q^2)$ & $F_L(x,Q^2)$

$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(\left(1-y+\frac{y^2}{2}\left(1+2x^2\frac{m_p^2}{Q^2}\right)\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right)$$

February 2016

Gian Giudice
Congratulations, Paolo!

Import-3 19 February 2016 at 21:32

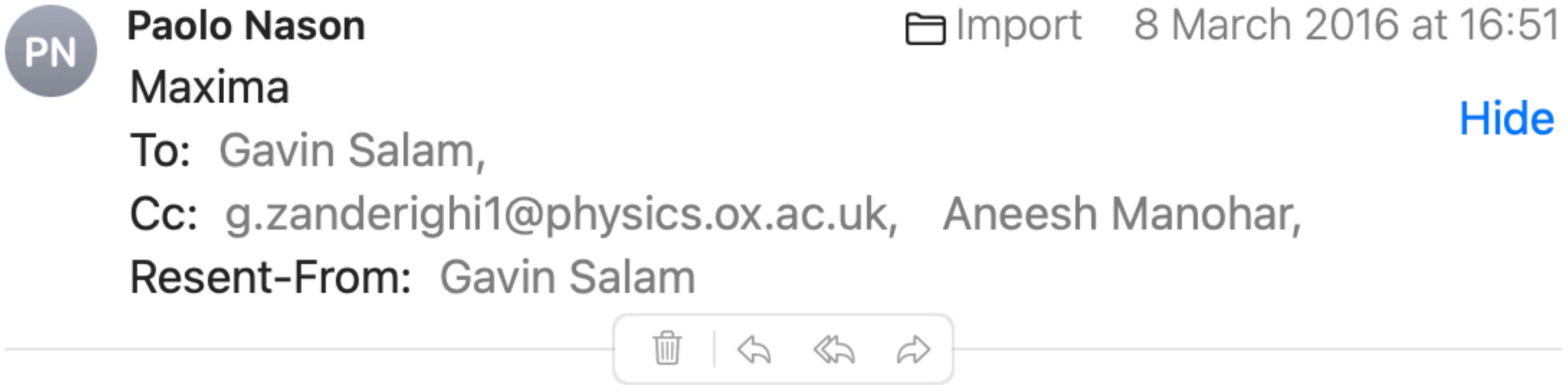
Hide

On behalf of the CERN Theory Department, I wish to congratulate our colleague and former TH staff member, Paolo Nason, on his appointment to the Accademia Nazionale dei Lincei. Paolo joins in this prestigious academy our Director General, Fabiola Gianotti, and three other former TH staff members, Luciano Maiani, Guido Martinelli, and Gabriele Veneziano.

--

Gian Francesco Giudice
Theoretical Physics Department, CERN
CH 1211 Geneva 23, Switzerland
Tel. +41 22 767 3203

Most of the world uses Mathematica…



Part A: getting the core formula

- expect photon distribution to be an integral over standard DIS structure functions, F_2 and F_L

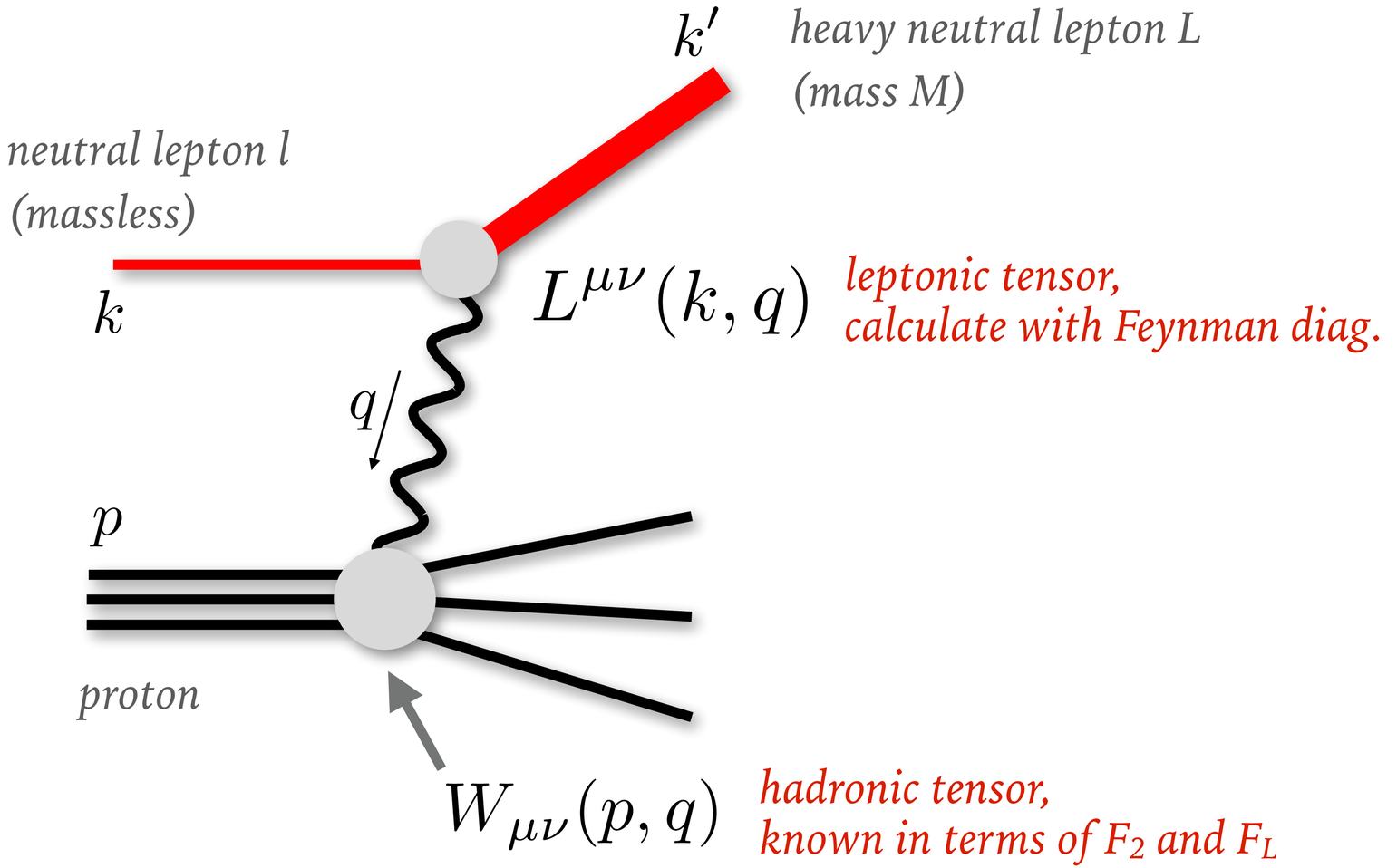
$$f_{\gamma/p}(x,\mu^2) = \int dx' \int dQ^2 \left[c_2(\ldots)F_2(x',Q^2) + c_L(\ldots)F_L(x',Q^2)\right]$$

- **Our task: figure out the coefficients $c_2(\ldots)$ and $c_L(\ldots)$ multiplying F_2 and F_L**

Manohar, Nason, GPS & Zanderighi, arXiv:1607.04266
(use of BSM inspired by Drees & Zeppenfeld, PRD39(1989)2536)

Heavy-lepton cross section in terms of structure functions

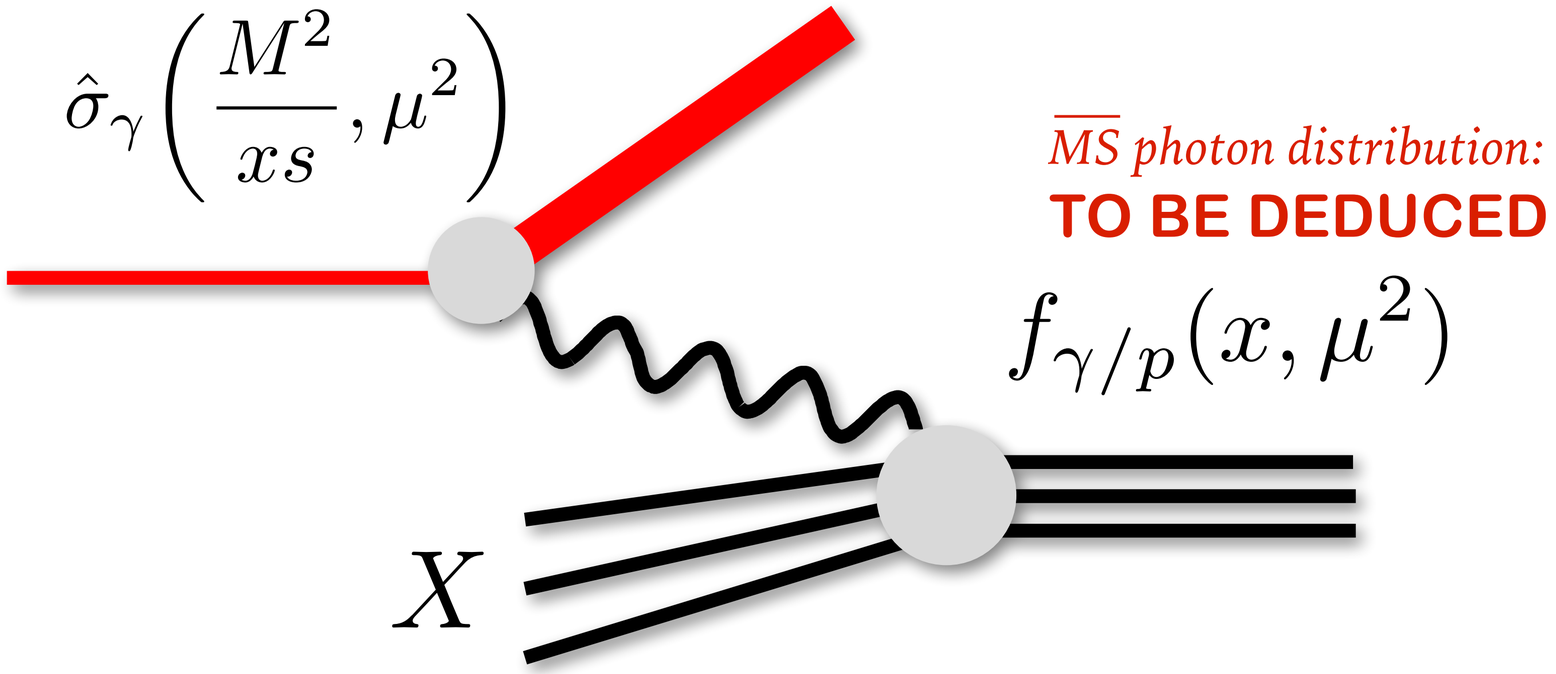
(use of BSM inspired by Drees & Zeppenfeld, PRD39(1989)2536)



$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4} e^2_{\rm ph}(q^2)\,[4\pi W_{\mu\nu}\,L^{\mu\nu}(k,q)] \times 2\pi\delta((k-q)^2 - M^2)$$

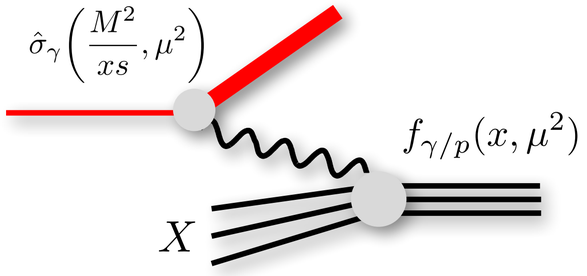
Cross section in terms of structure functions

hard-scattering cross section
calculate in collinear factorisation



$$\sigma = c_0 \sum_a \int \frac{dx}{x}\, \hat{\sigma}_a \left(\frac{M^2}{xs}, \mu^2\right)\, x f_{a/p}\left(x, \mu^2\right)$$

Cross section in terms of structure functions



Hard cross section driven by the photon distribution at LO

$$\hat{\sigma}_a(z,\mu^2) = \alpha(\mu^2)\delta(1-z)\delta_{a\gamma} + \frac{\alpha^2(\mu^2)}{2\pi}\left[-2+3z+zp_{\gamma q}(z)\ln\frac{M^2(1-z)^2}{z\mu^2}\right]\sum_{i\in\{q,\bar{q}\}} e_i^2\delta_{ai} + \cdots,$$

Quarks and gluons come in at higher orders

Photon PDF in terms of F_2 and F_L — the LUXqed approach

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\right.$$
$$\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$
$$\left. - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}$$

This includes terms

$\alpha\, L\, (\alpha_s\, L)^n$

$\alpha\, (\alpha_s\, L)^n$

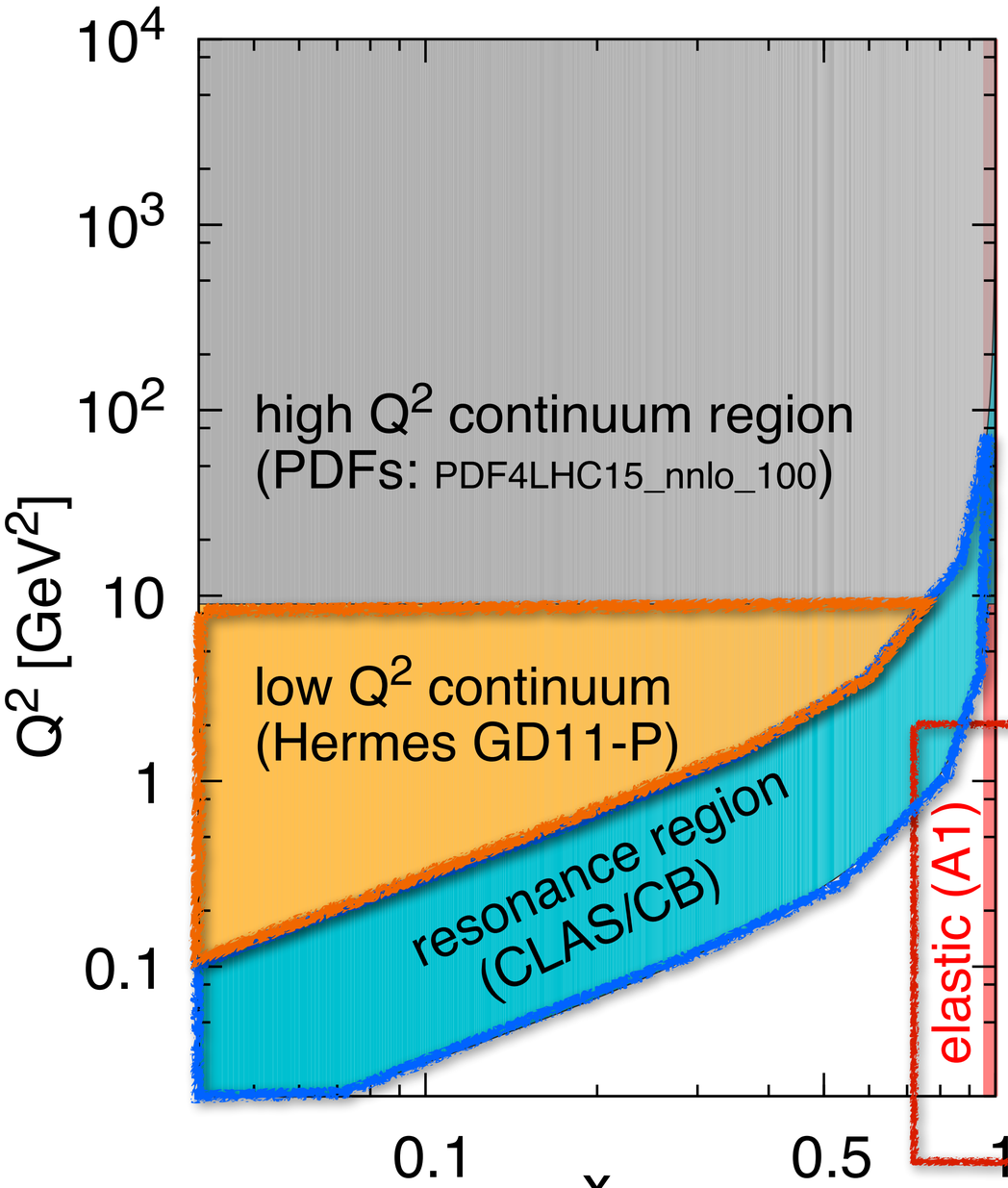
$\alpha^2\, L^2\, (\alpha_s\, L)^n$

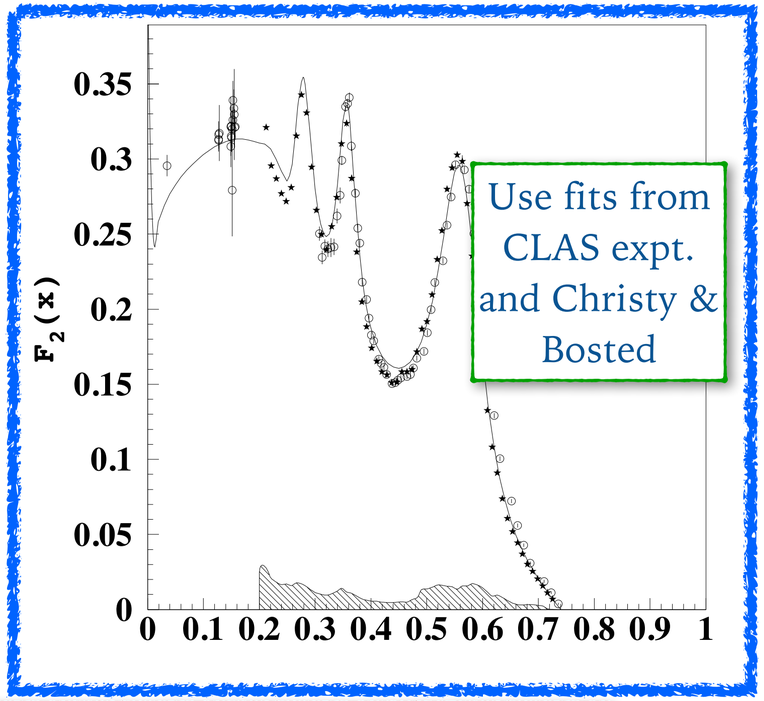
($L = \ln \mu^2/\Lambda^2$)

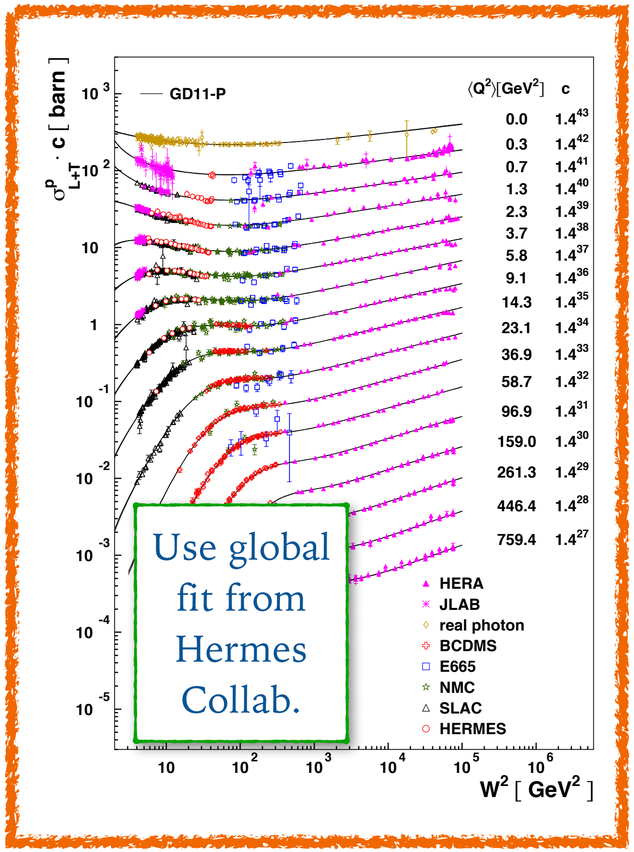
our 2017 work went one order higher (e.g. extra power of α_s)

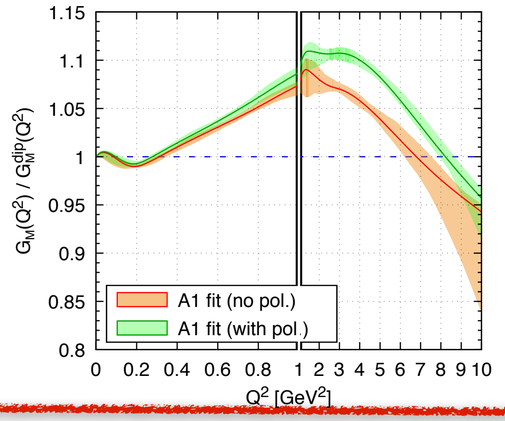
It subsequently emerged that two "forgotten" papers, Anlauf et. al, CPC70(1992)97 Mukherjee & Pisano, hep-ph/0306275, had the correct integrand (but not the limits)

Part B: finding F_2 and F_L data to put into the formula









$$F_2^{\rm el} = \frac{[G_E(Q^2)]^2 + [G_M(Q^2)]^2\tau}{1+\tau}\delta(1-x)\,,$$

$$F_L^{\rm el} = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,,$$

July 2016: Finishing the paper

PN **Paolo Nason** Import-2 14 July 2016 at 07:23

WRONG TITLE !!!!

Hide

To: g.zanderighi1@physics.ox.ac.uk, Gavin Salam, Aneesh Manohar,

Resent-From: Gavin Salam

Ha! the title is wrong!

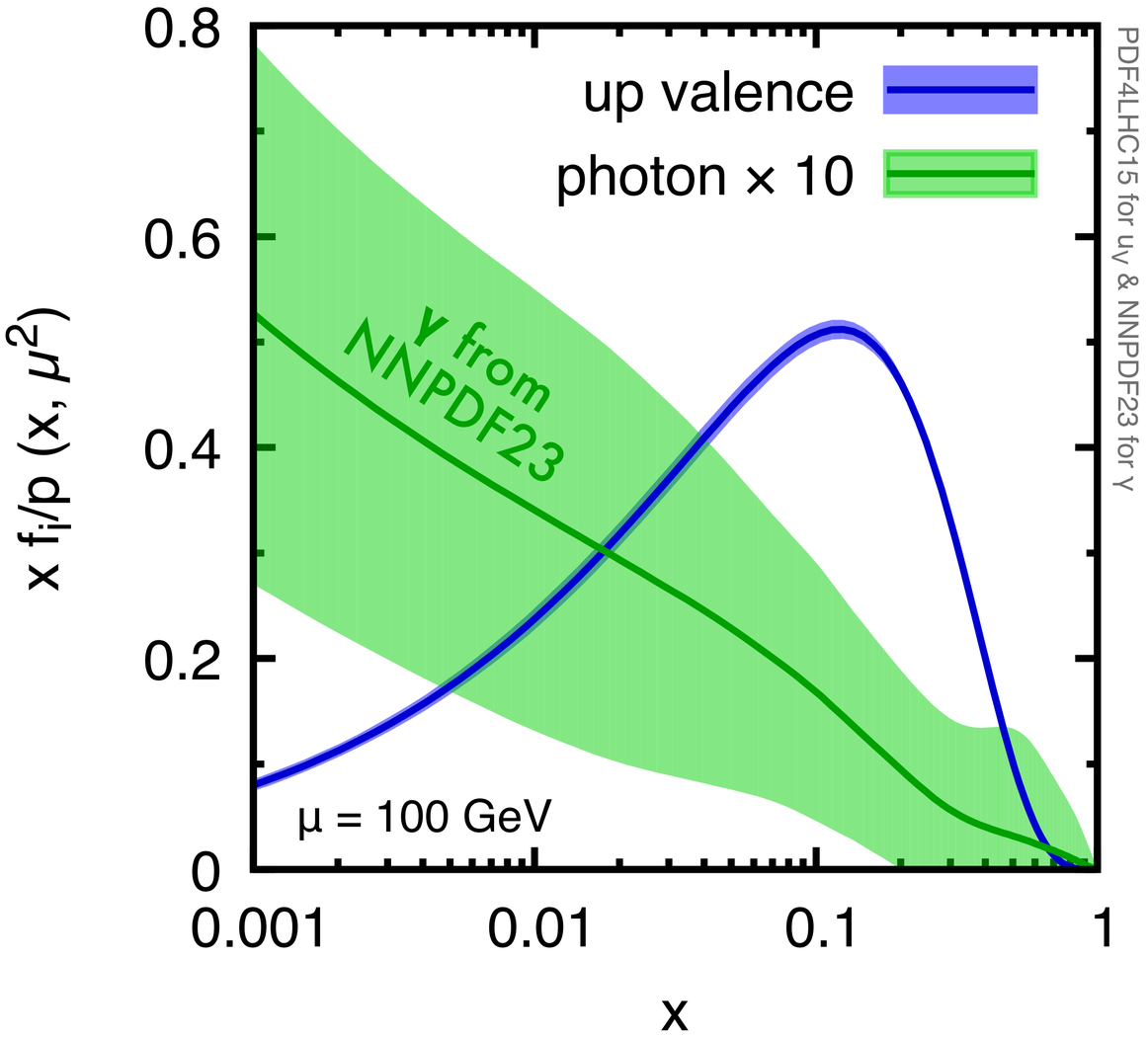
It says how bright is the photon!

How could we miss this?

P.

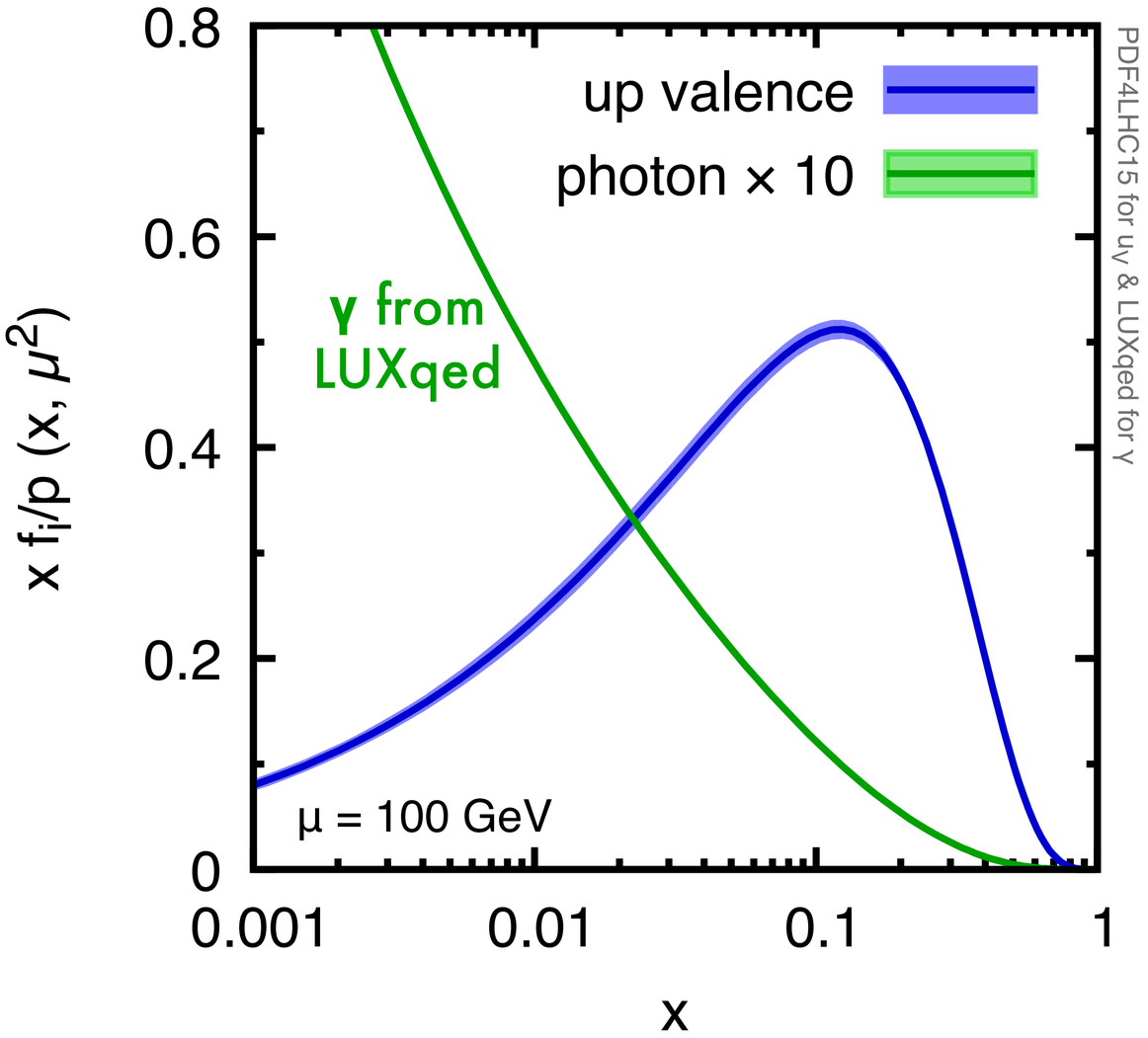
photon PDF results

- Model-independent uncertainty (NNPDF) was 50–100%

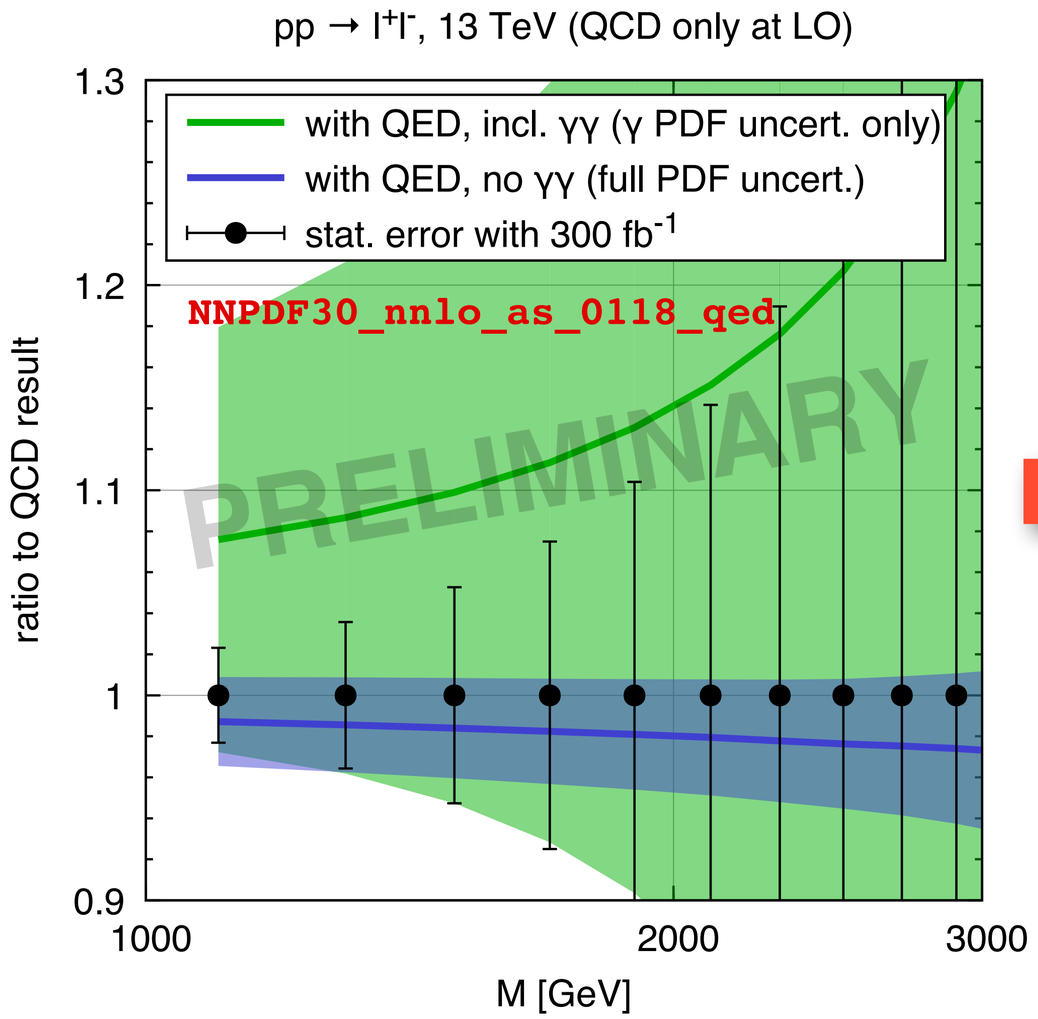


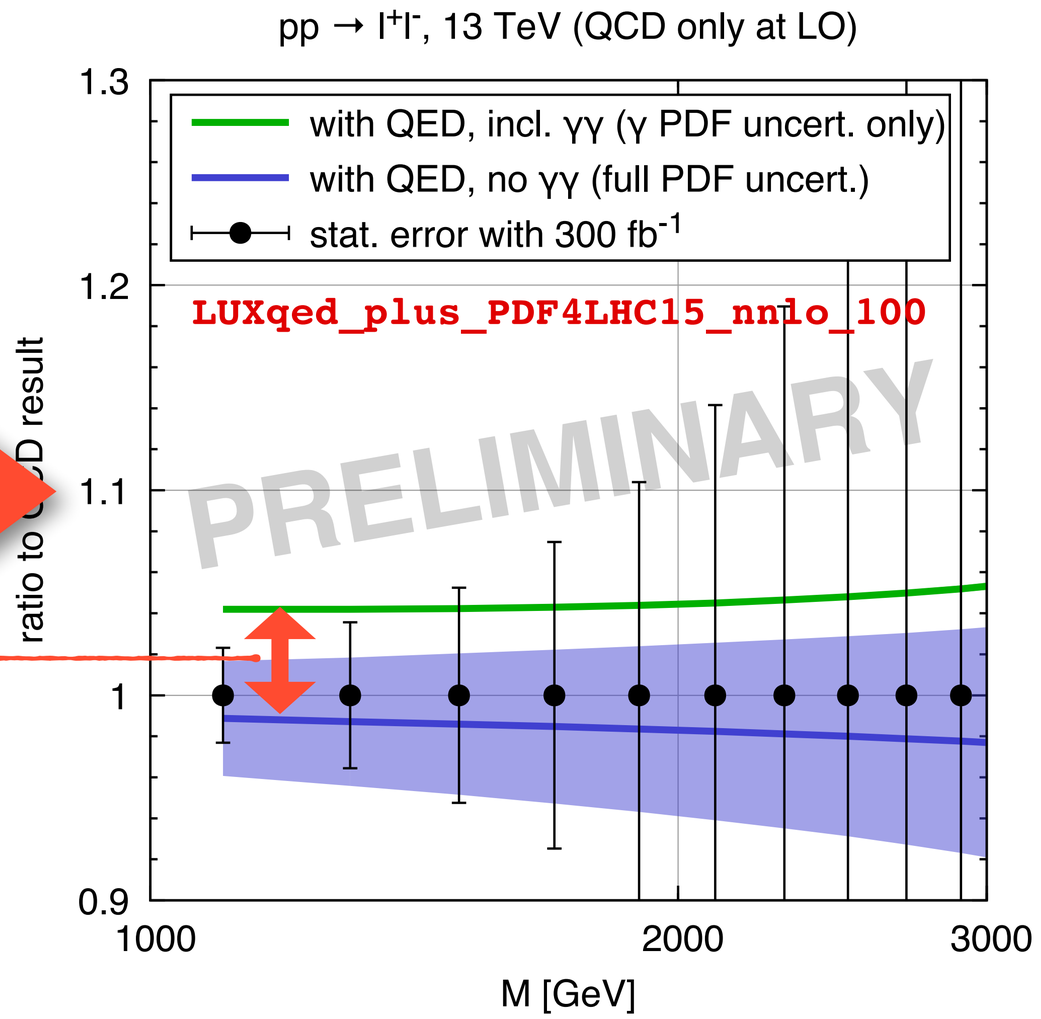
photon PDF results

- Model-independent uncertainty (NNPDF) was 50–100%
- Goes down to O(1%) with LUXqed determination



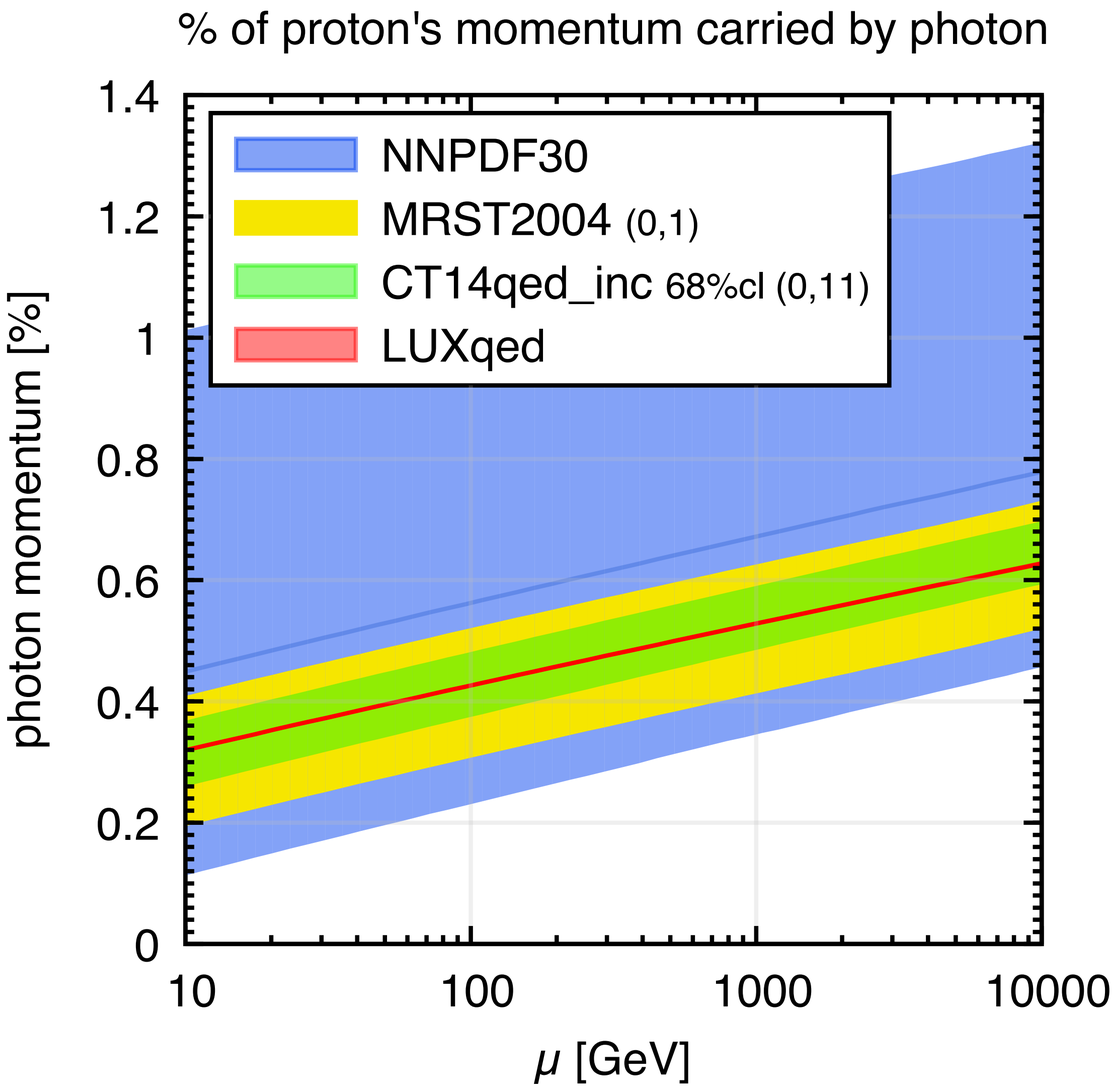
di-lepton spectrum





γγ component has few-% effect on Drell-Yan spectrum; negligible uncertainty

How bright is the proton? [γ momentum fraction]



momentum (μ = 100 GeV)	
gluon	46.8 ± 0.4%
up valence	18.2 ± 0.3%
down valence	7.5 ± 0.2%
light sea quarks	20.7 ± 0.4%
charm	4.0 ± 0.1%
bottom	2.5 ± 0.1%
photon	0.426 ± 0.003%

`LUXqed_plus_PDF4LHC15_nnlo_100`

(1+107 members, symmhessian, errors handled by LHAPDF out of the box, valid for μ > 10 GeV)

Where do we submit? → PRL

Referee A

[…]
This work is interesting but it does not meet the criteria of innovation and impact expected for publication in Physical Review Letters.

[…]

Luckily, referees B & C were more positive; paper eventually accepted…

Where do we submit? → PRL

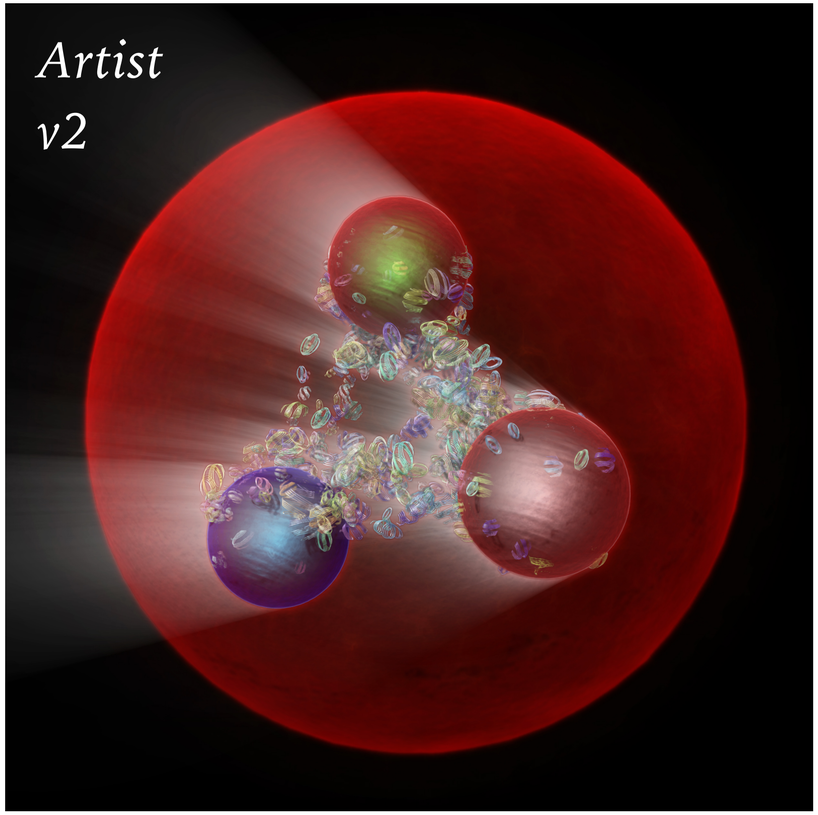
Subject: To_author LU16377 Manohar PRL Editors' Suggestion
Date: Wed, 26 Oct 2016 16:01:04 -0400
From: prl@aps.org
Reply-To: prl@aps.org
To: g.zanderighi1@physics.ox.ac.uk

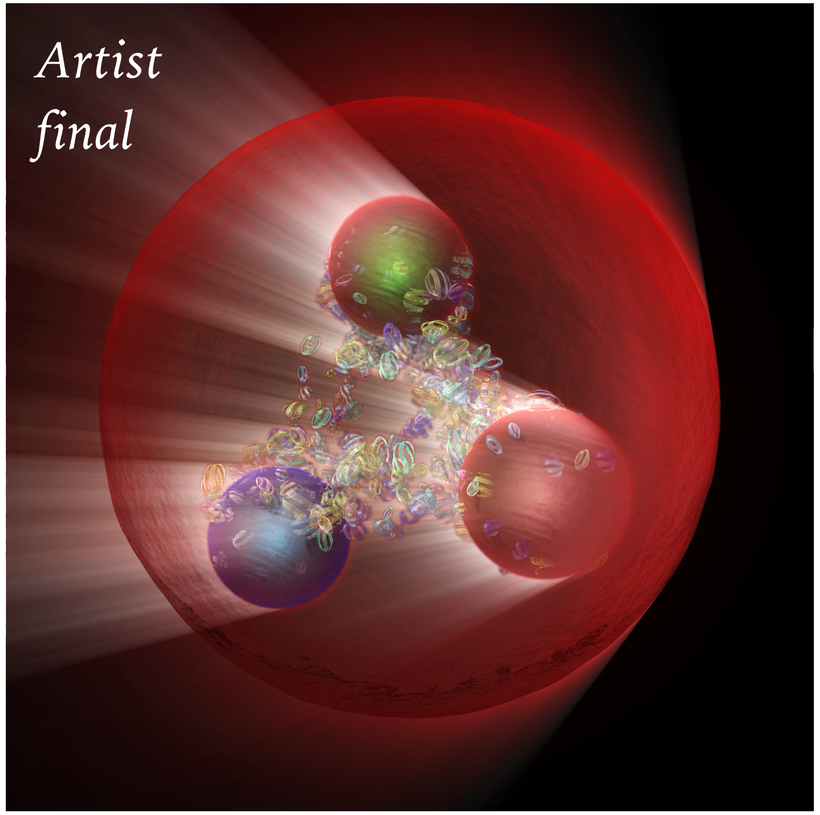
Dear Dr. Zanderighi,

We are pleased to inform you that we have selected your recently accepted manuscript to be a PRL Editors' Suggestion. [...]

Please reply to this email with an image that meets the criteria appended below.

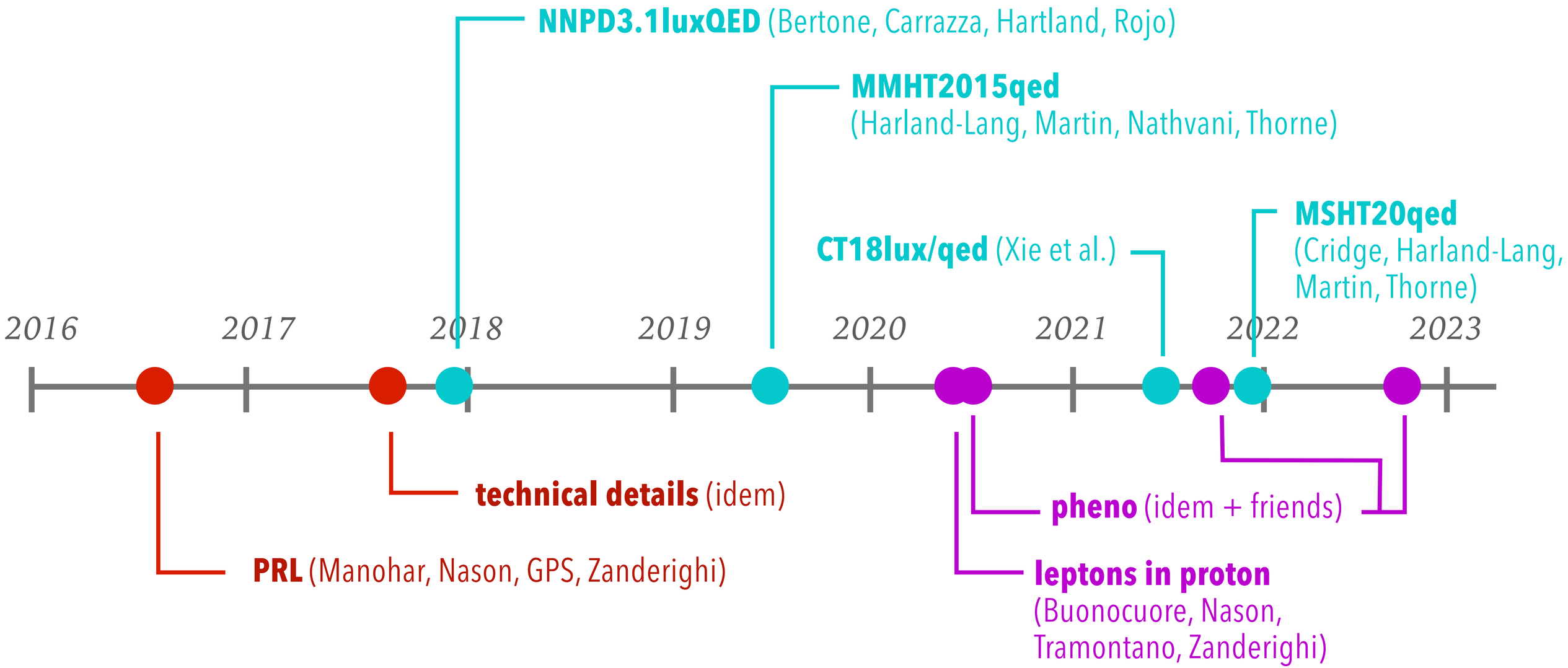
October 2016 — Getting CERN's help for an image





with thanks to CERN artist Daniel Dominguez for his patience with us!

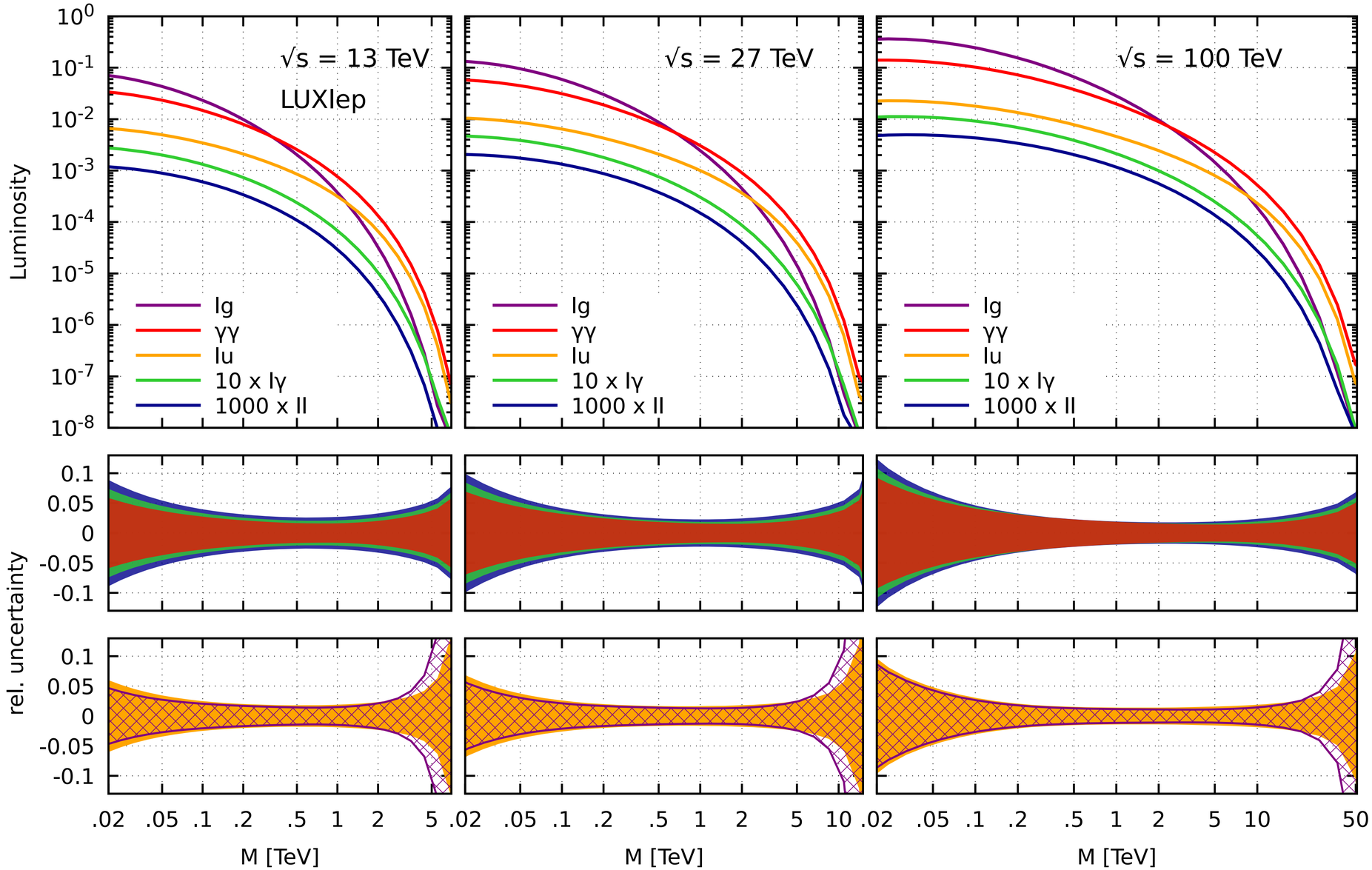
Key subsequent developments



Leptons in the proton: 2005.06477 (Buonocore, Nason, Tramontano, Zanderighi)

$$
\begin{aligned}
x_\ell f_\ell(x_\ell,\mu_F^2) = & \left(\frac{1}{2\pi}\right)^2 \int_{x_\ell}^1 \frac{\mathrm{d}x}{x} z_\ell \int_x^1 \frac{\mathrm{d}z}{z} \int_{\frac{m_\mathrm{p}^2 x^2}{1-z}}^{\frac{\mu_F^2}{1-z}} \frac{\mathrm{d}Q^2}{Q^2} \alpha^2(Q^2) \\
& \left\{ P_{\ell\gamma}(z_\ell) \log \frac{\mu_\mathrm{F}^2}{(1-z_\ell) z_\ell \left(Q^2 + \frac{m_\ell^2}{z_\ell(1-z_\ell)}\right)} \left[F_2 \left(z P_{\gamma q}(z) + \frac{2m_\mathrm{p}^2 x^2}{Q^2} \right) - F_L z^2 \right] \right. \\
& + F_2 \left[4(z-2)^2 z_\ell (1-z_\ell) - (1 + 4 z_\ell (1-z_\ell))\, z P_{\gamma q}(z) \right] \\
& + F_L z^2 P_{\ell\gamma}(z_\ell) - \frac{2m_\mathrm{p}^2 x^2}{Q^2} F_2 - \left(F_2 \frac{2m_\mathrm{p}^2 x^2}{Q^2} - z^2 F_L \right) 4 z_\ell (1-z_\ell) \\
& + \frac{m_\ell^2 F_2}{m_\ell^2 + Q^2 z_\ell (1-z_\ell)} \left[z P_{\gamma q}(z) - 8 z_\ell (1-z_\ell) \left(1 - z - \frac{m_\mathrm{p}^2 x^2}{Q^2} \right) + \frac{2m_\mathrm{p}^2 x^2}{Q^2} \right] \\
& \left. - \frac{m_\ell^2 F_L z^2}{m_\ell^2 + Q^2 z_\ell (1-z_\ell)} \left[2 - P_{\ell\gamma}(z_\ell) \right] \right\}. \qquad (2.25)
\end{aligned}
$$

Leptons in the proton: 2005.06477 (Buonocore, Nason, Tramontano, Zanderighi)



partonic luminosities with leptons and photons

Conclusions

As usual, when Paolo touches something,
chances are it will come out fundamentally changed

(And then he takes it through to the end)

I look forward to many more such fundamental advances from you, Paolo!