Perspectives on SM, Higgs and beyond at LHC

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Theoretical Physics Colloquium
University of Oxford
17 February 2017

Bettmergrat, Wallis, Switerland

A typical introduction to a particle physics colloquium often starts with "big unanswered questions"

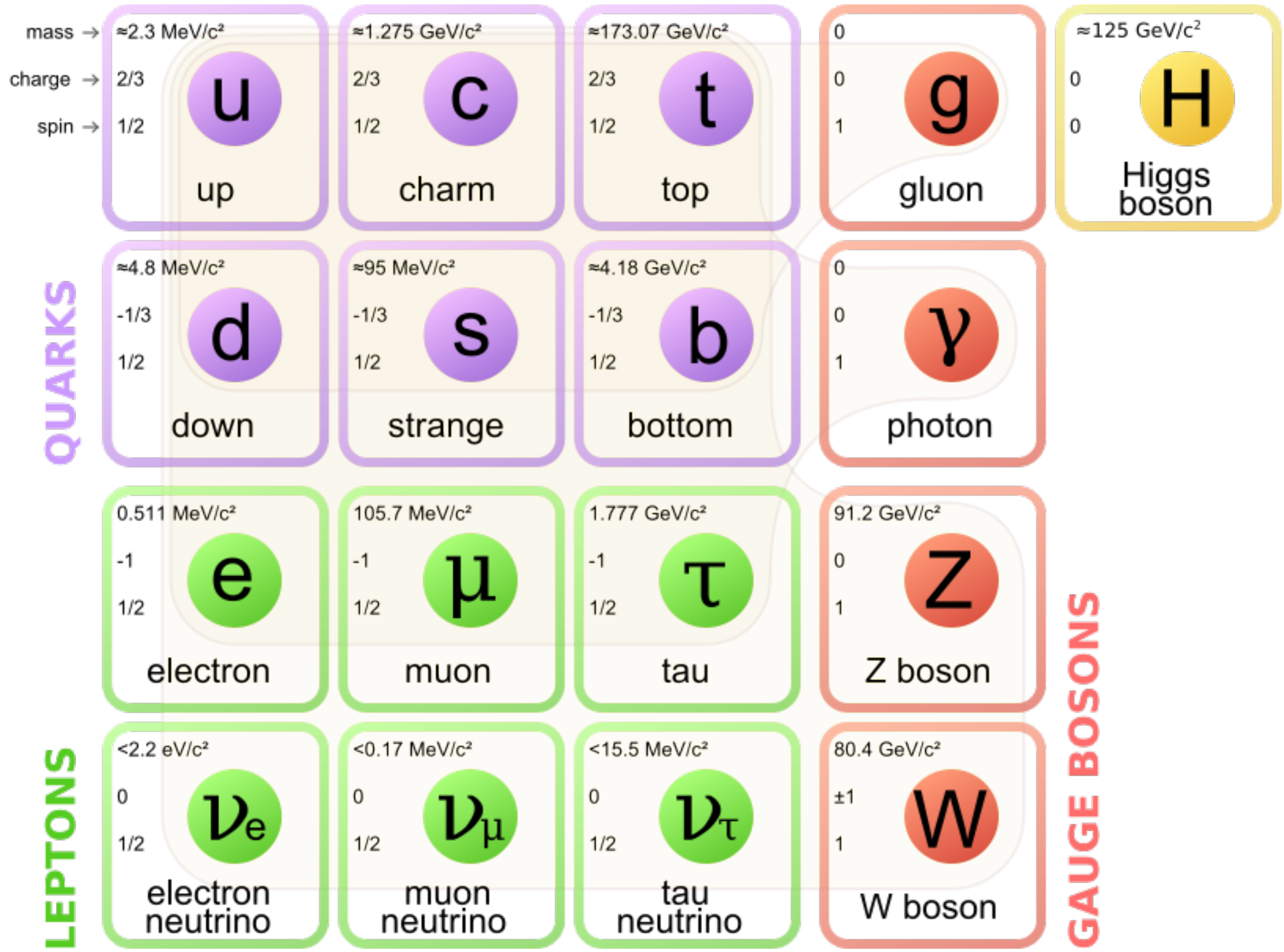
Nature of dark matter (& dark energy)

Fine-tuning (e.g. supersymmetry and similar)

Flavour-asymmetry of the universe

[…]

and less about the standard model (SM)...



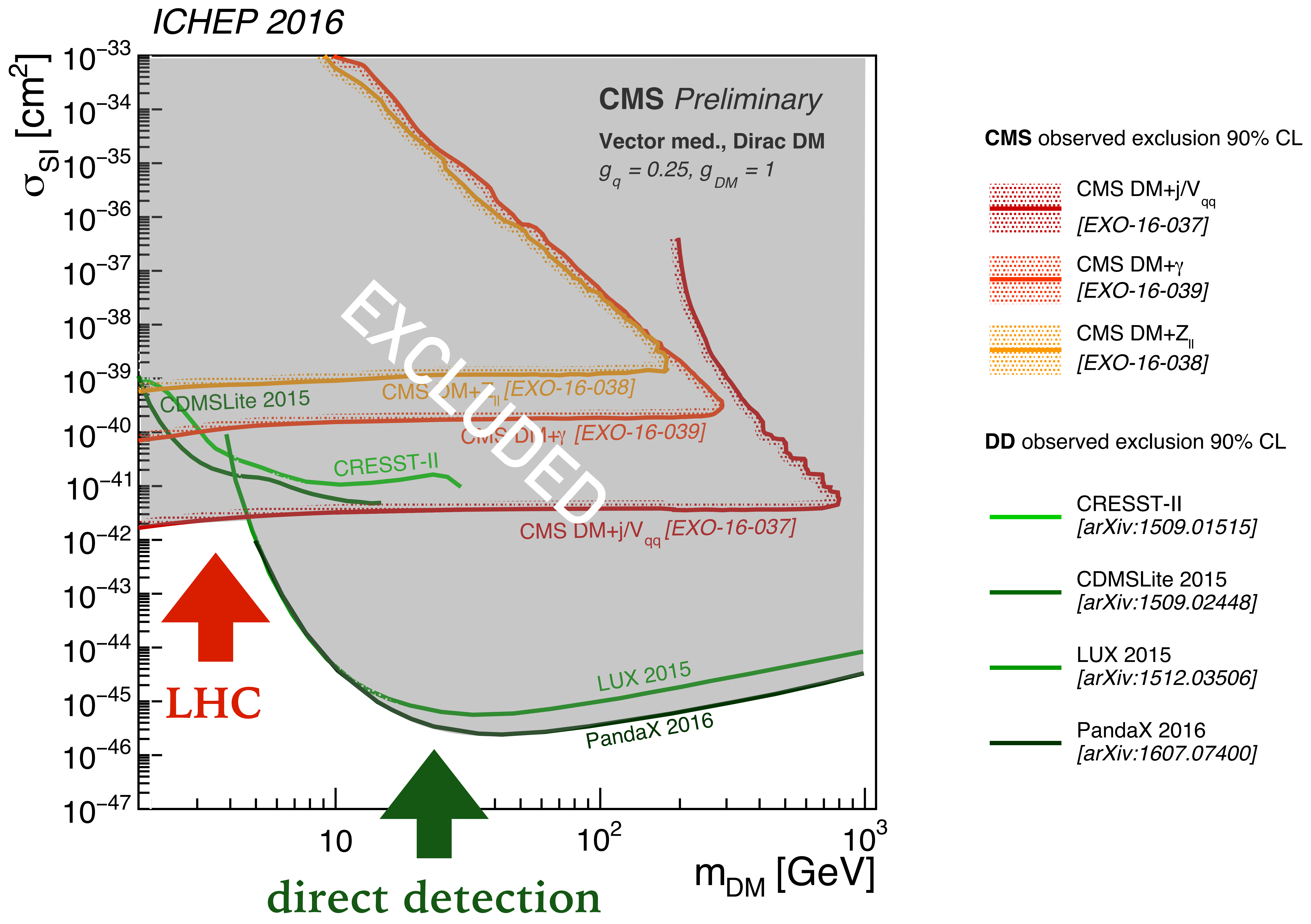
since experiments have already found all its particles...

Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

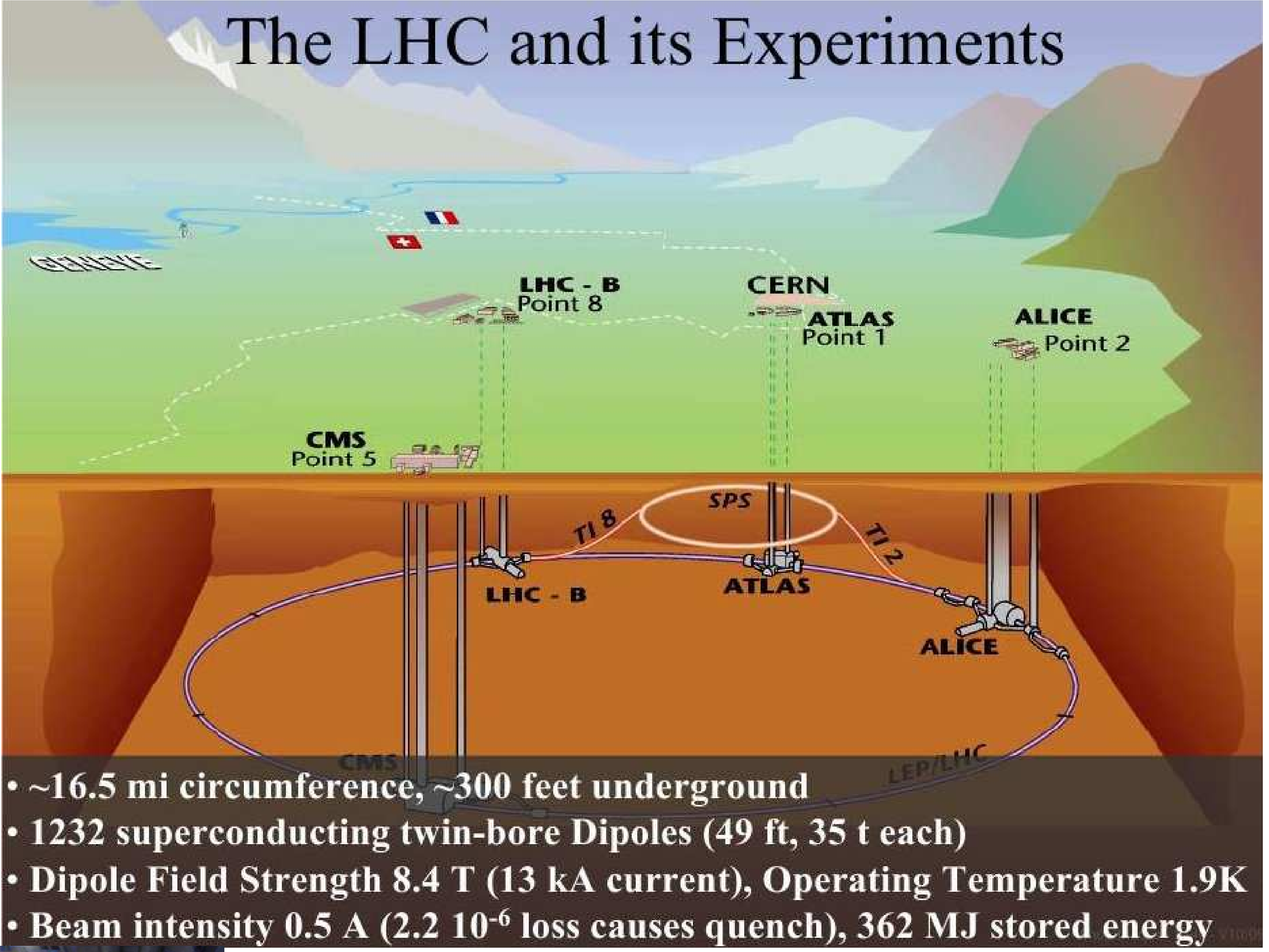
Masses ~ GeV upwards

(search interpretations strongly model dependent)

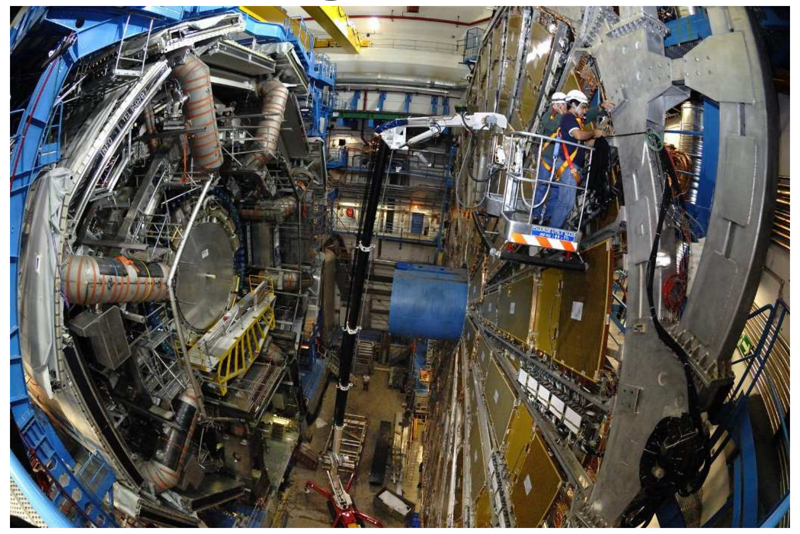


Searching for answers to the
"big unanswered questions" is vitally important,
(even if there's no way of knowing if it will pay off)

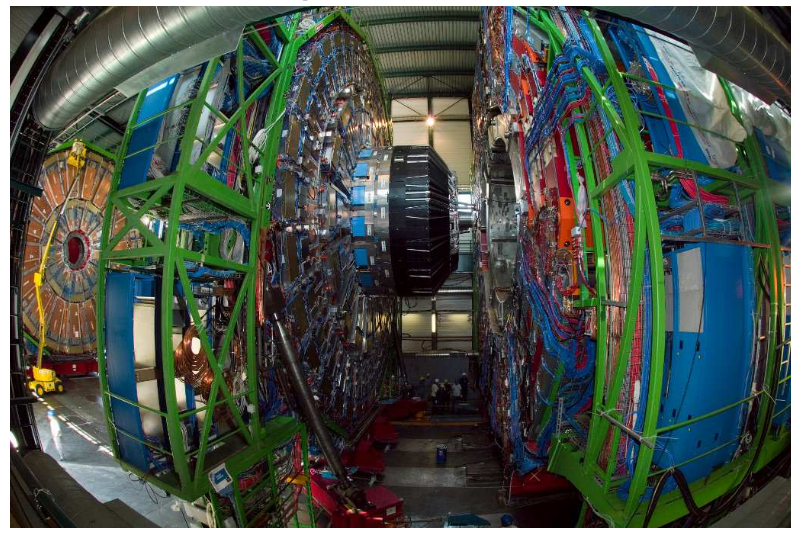
But we also shouldn't forget the importance of
"big answerable questions"
and the issue of how we go about answering them



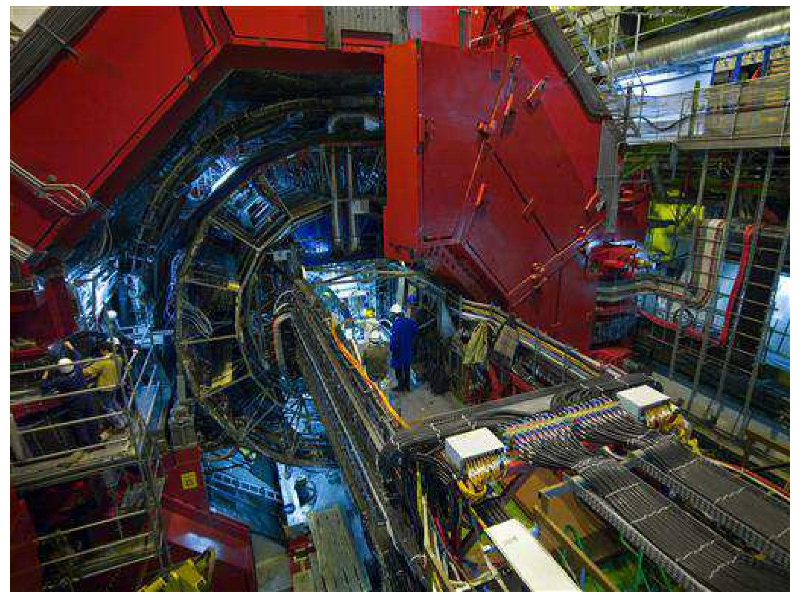
ATLAS: general purpose



CMS: general purpose



ALICE: heavy-ion physics



LHCb: B-physics

+ TOTEM, LHCf

perspective in context of LHC

Today

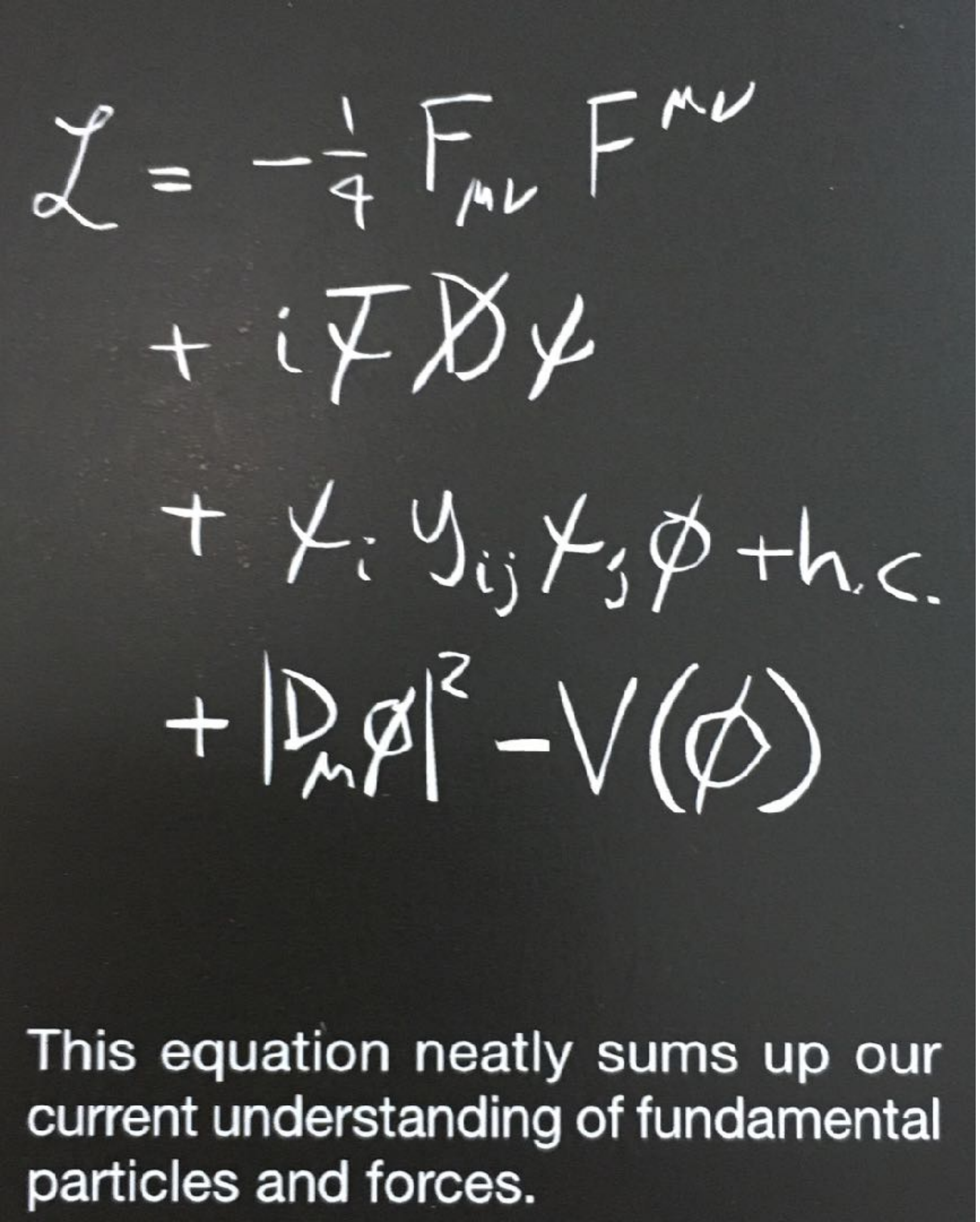
- $20\ fb^{-1}$ @ 8 TeV
- $13\ fb^{-1}$ @ 13 TeV (analysed)

Future

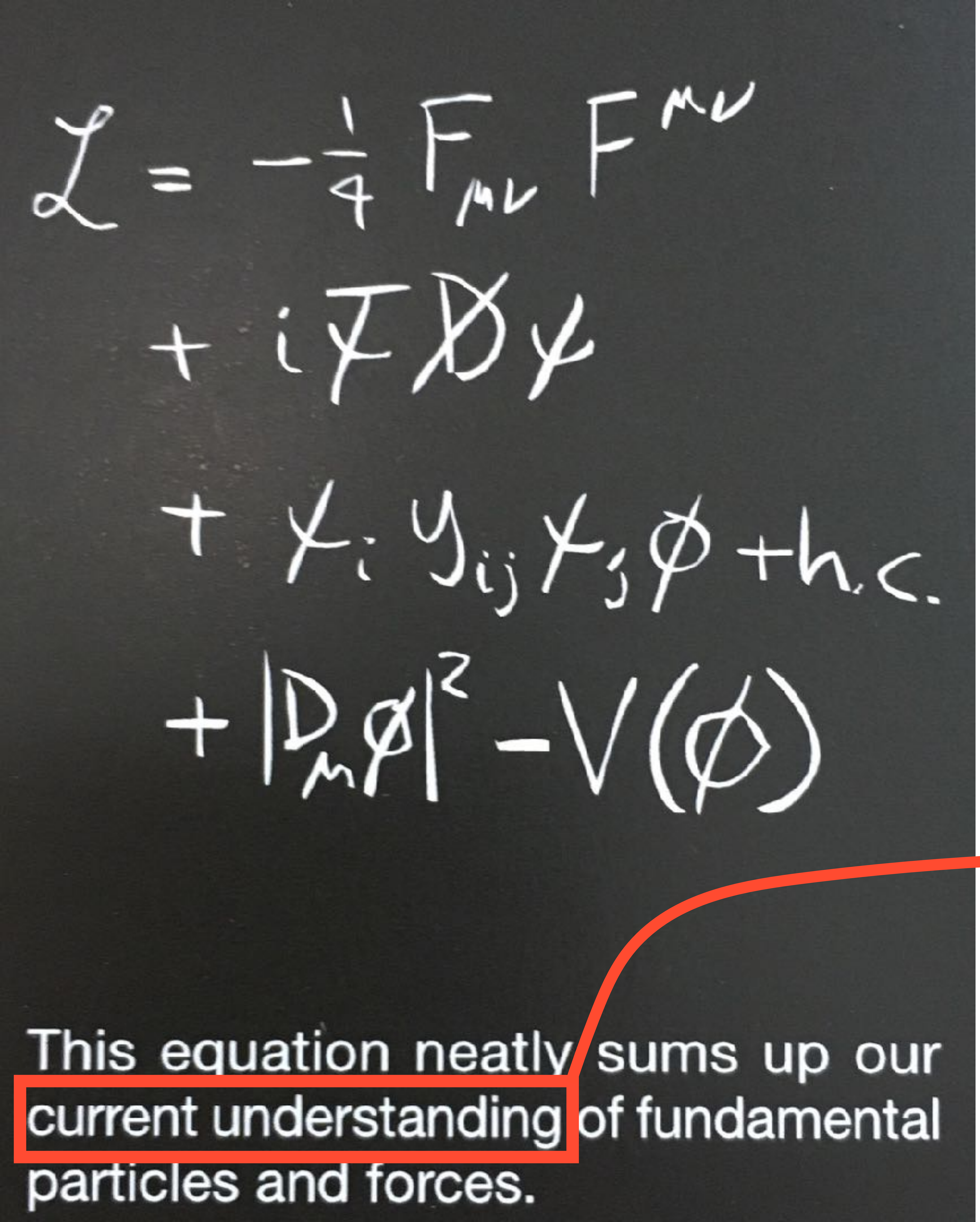
- 2018: $100\ fb^{-1}$ @ 13 TeV
- 2023: $300\ fb^{-1}$ @ 1? TeV
- 2035: $3000\ fb^{-1}$ @ 14 TeV

$1\ fb^{-1} = 10^{14}$ collisions

Current analyses based on < 1% of the ultimate dataset



This is what you get when you buy one of those famous CERN T-shirts



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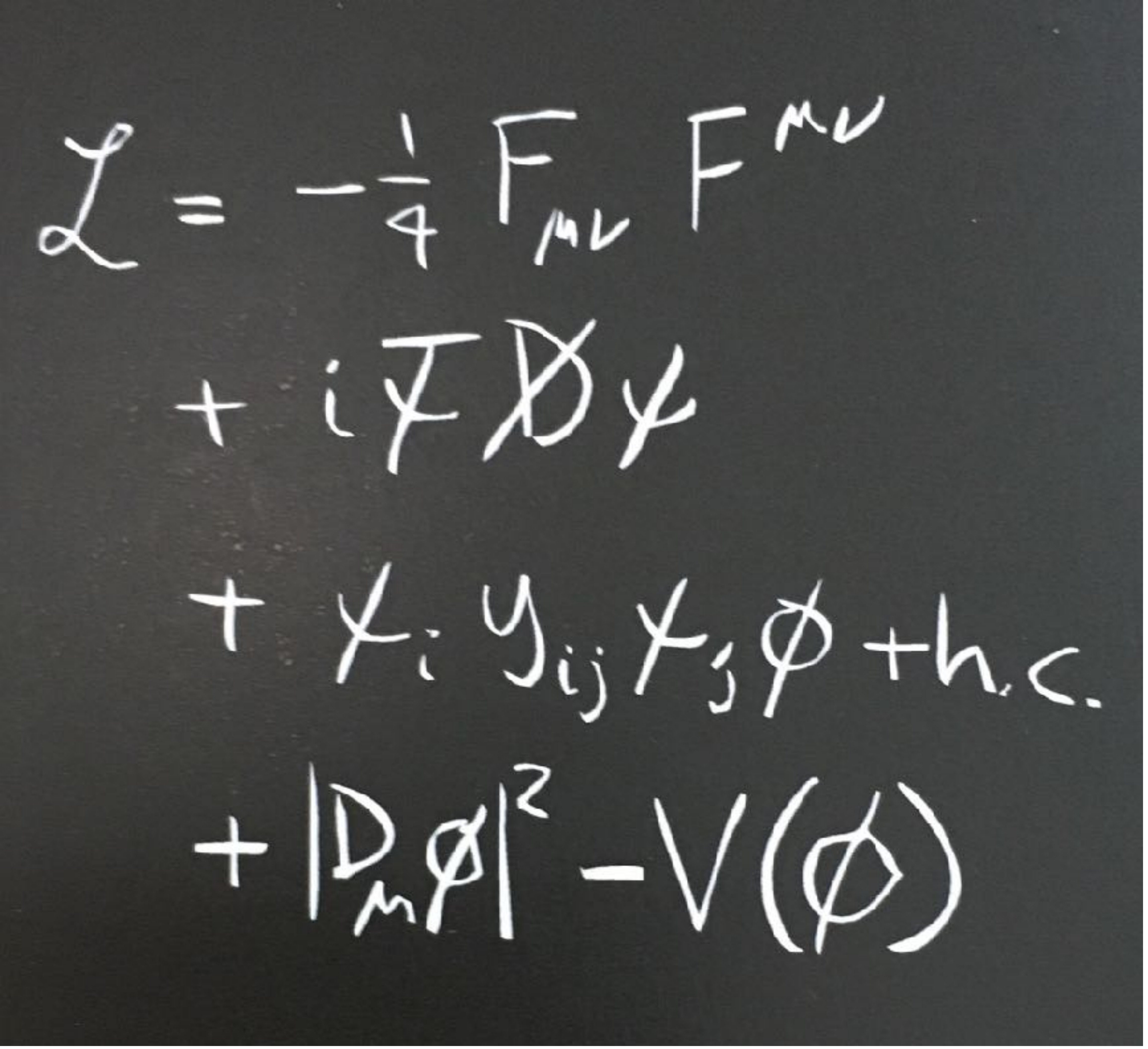
"understanding" = knowledge ?

"understanding" = assumption ?



Notation

$$A_\mu : \text{gauge field}$$

$$\psi : \text{fermion field}$$

$$\phi : \text{Higgs field}$$

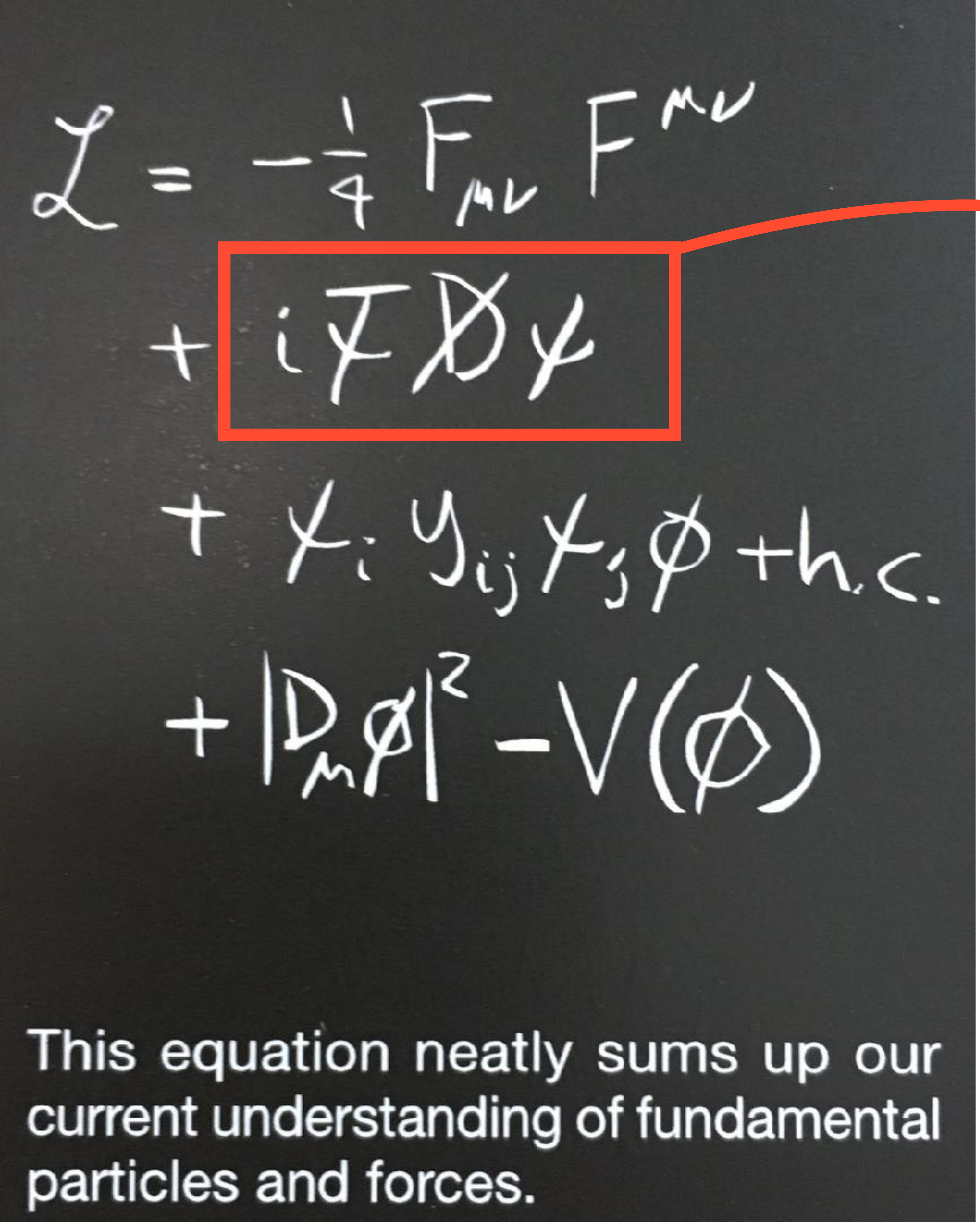
$$= \phi_0(\text{VEV}) + H(\text{Higgs})$$

$$D_\mu = \partial_\mu + ieA_\mu \text{ etc.}$$

$$F_{\mu\nu} \sim [D_\mu, D_\nu]$$

e.g. $\bar{\psi} D \psi \rightarrow \psi A_\mu \psi \rightarrow$ fermion-fermion-gauge vertex

i.e. terms of $\mathcal{L}$ map to particle interactions



GAUGE–MATTER PART

e.g. qqγ, qqZ, qqg, eνW interactions — well established in ep, e^+e^-, pp collisions, etc.

≡ KNOWLEDGE

(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)

GAUGE–MATTER PART

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

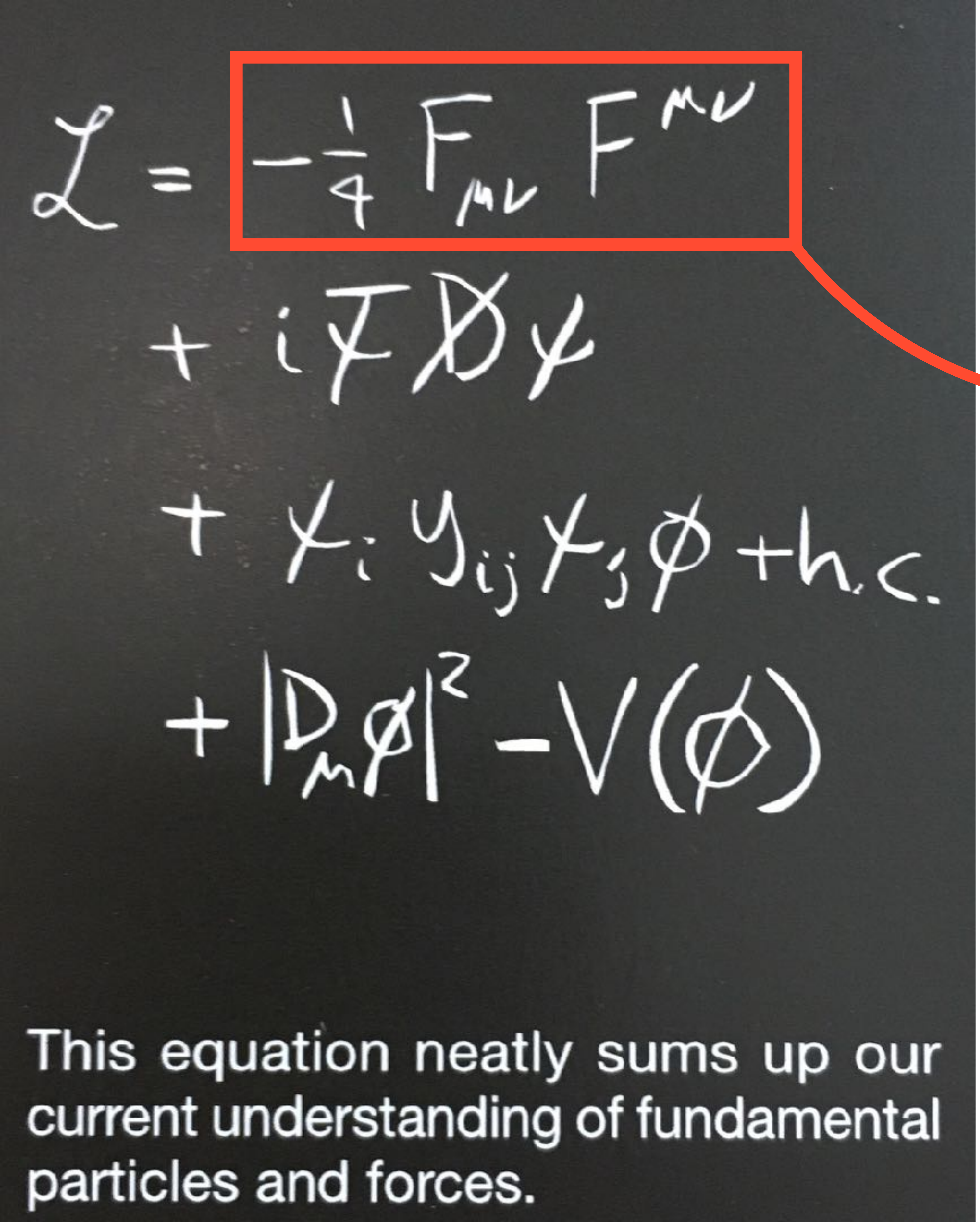
This equation neatly sums up our current understanding of fundamental particles and forces.

e.g. qqγ, qqZ, qqg, eνW interactions — well established in ep, e^+e^-, pp collisions, etc.

≡ **KNOWLEDGE**

(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)

Do we "know" everything about this part? E.g. direct emission of photon from top quarks is, today, at edge of observability. But it's so much like any other gauge-matter interaction that we almost take it for granted



Pure Gauge

e.g. ZWW, 3-gluon interactions — well established at LEP (e.g. $e^+e^- \rightarrow W^+W^-$)

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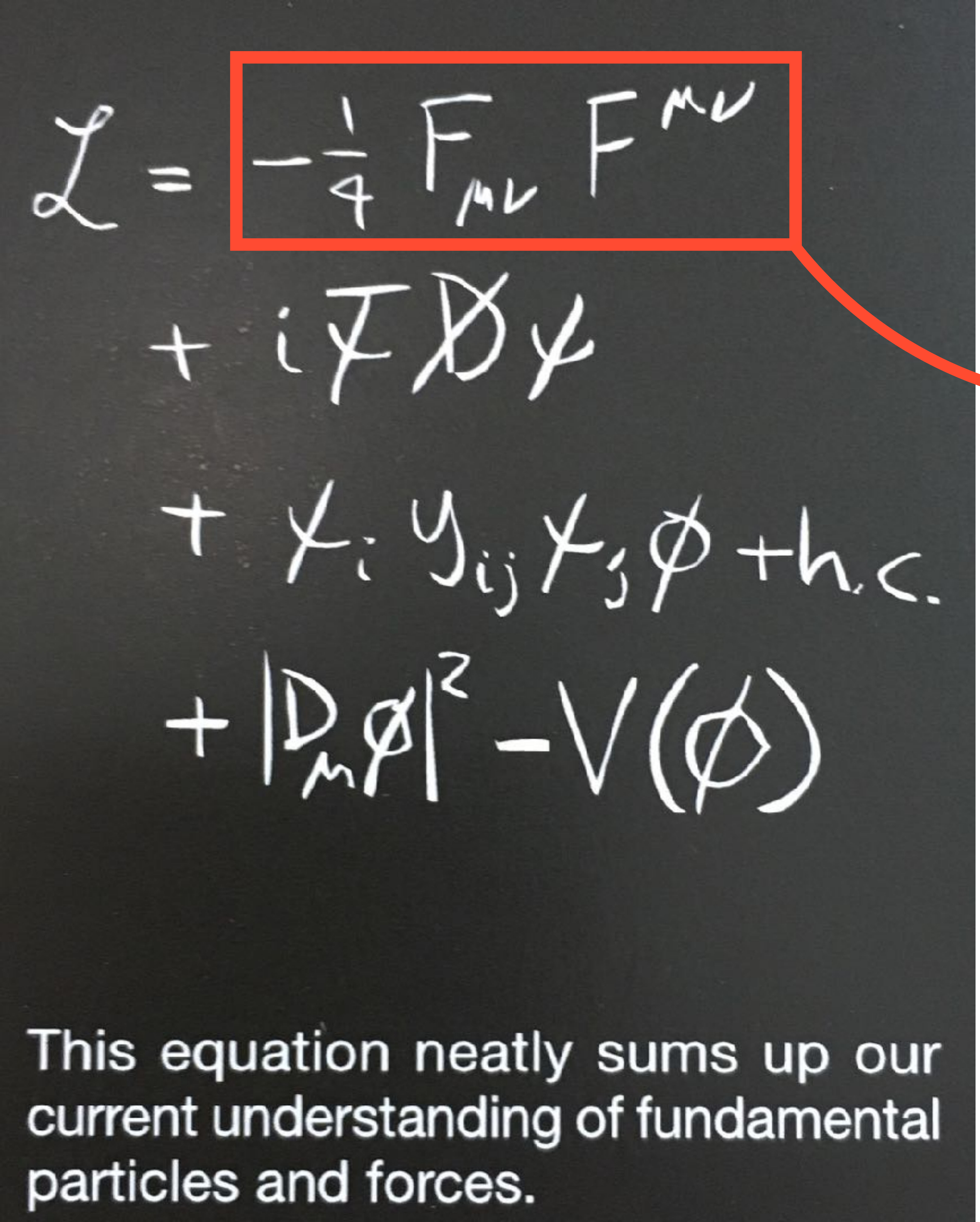

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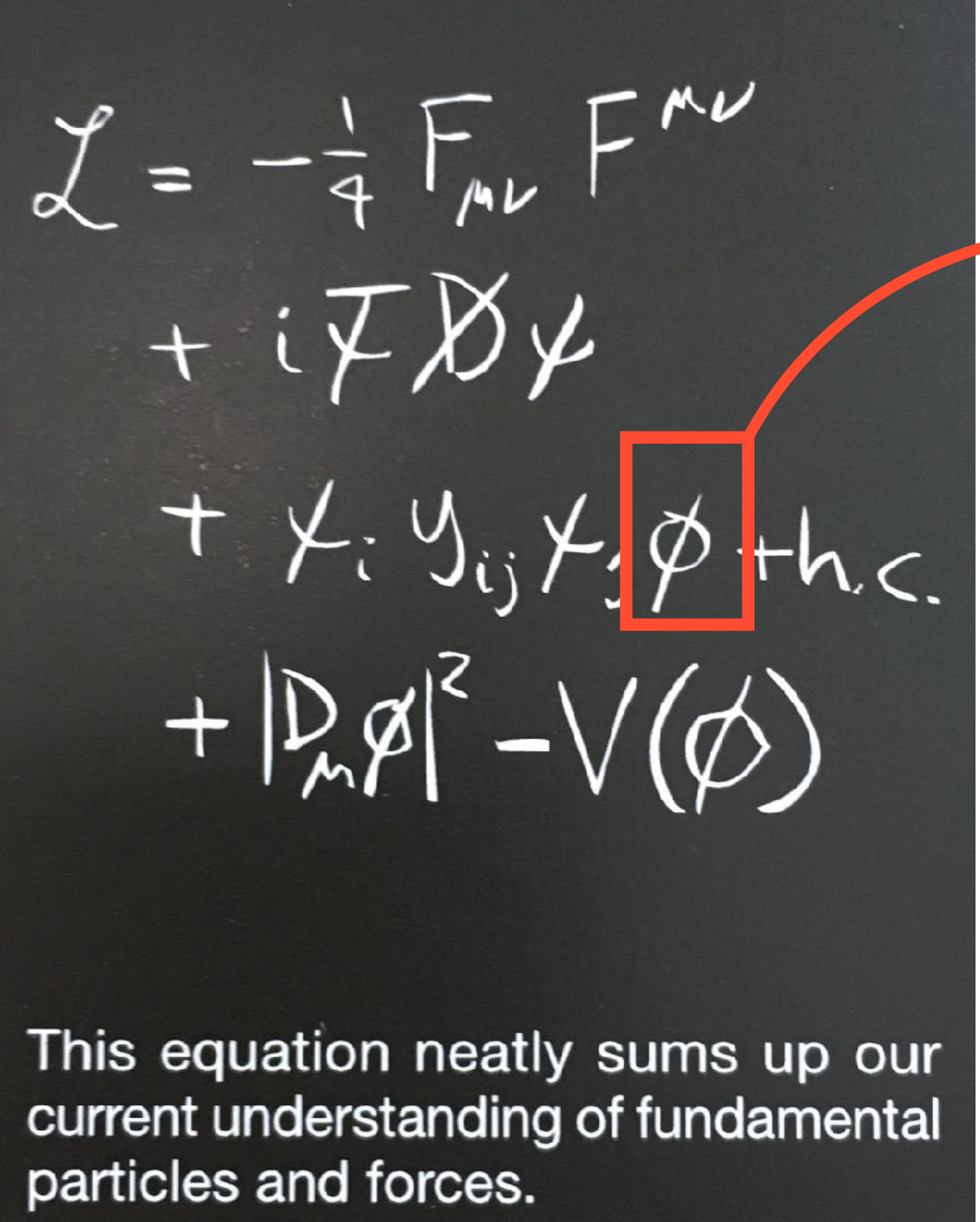
We've seen gauge sectors work over and over again
→ gives us the illusion that the SM is established

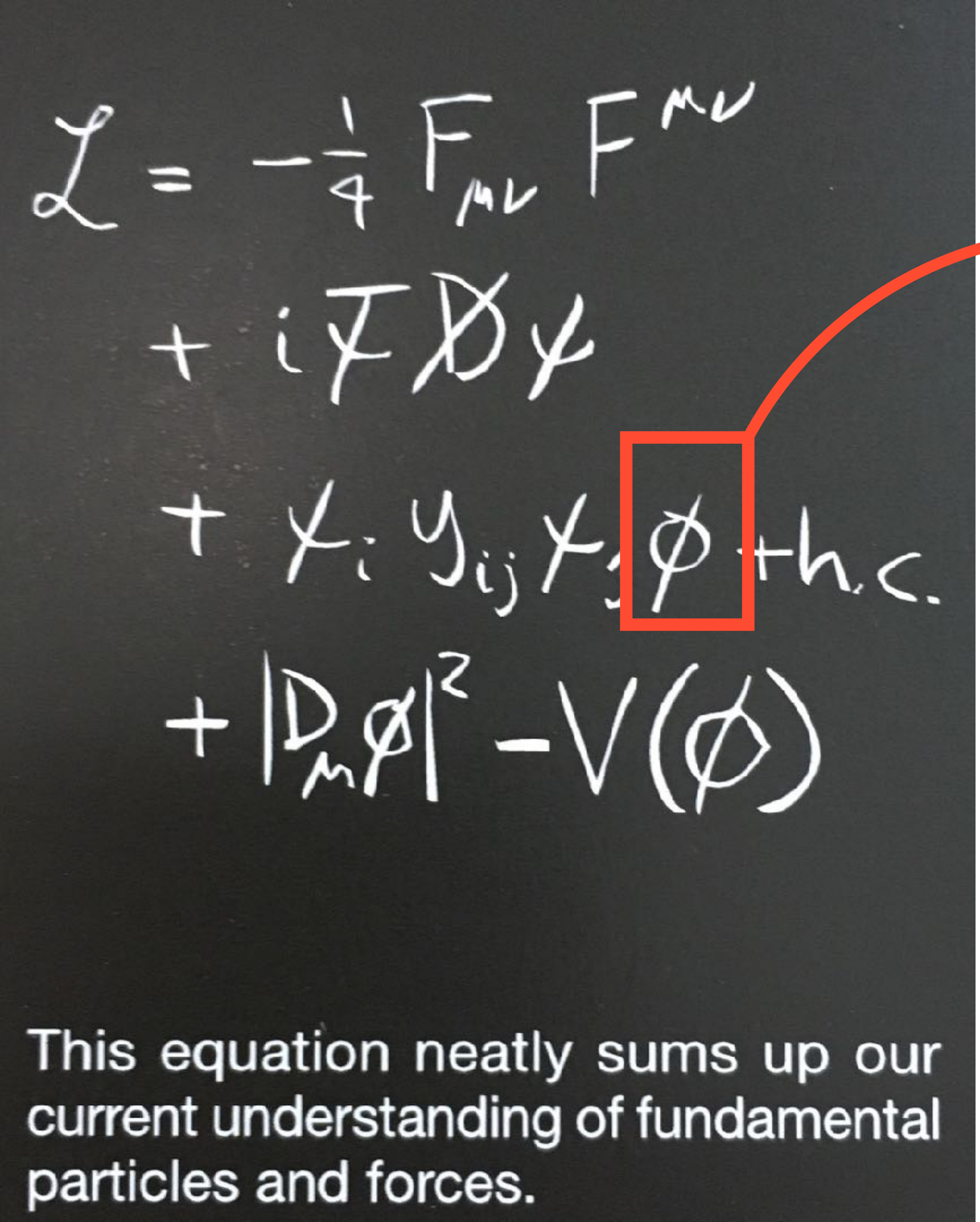


Higgs Boson

LEP precision made it compelling,
LHC discovered it
≡ KNOWLEDGE

it behaves in every way like a scalar
≡ KNOWLEDGE

is it fundamental/pointlike?
to find out need
~ high-p_T/offshell Higgses
→ **data barely sensitive…**



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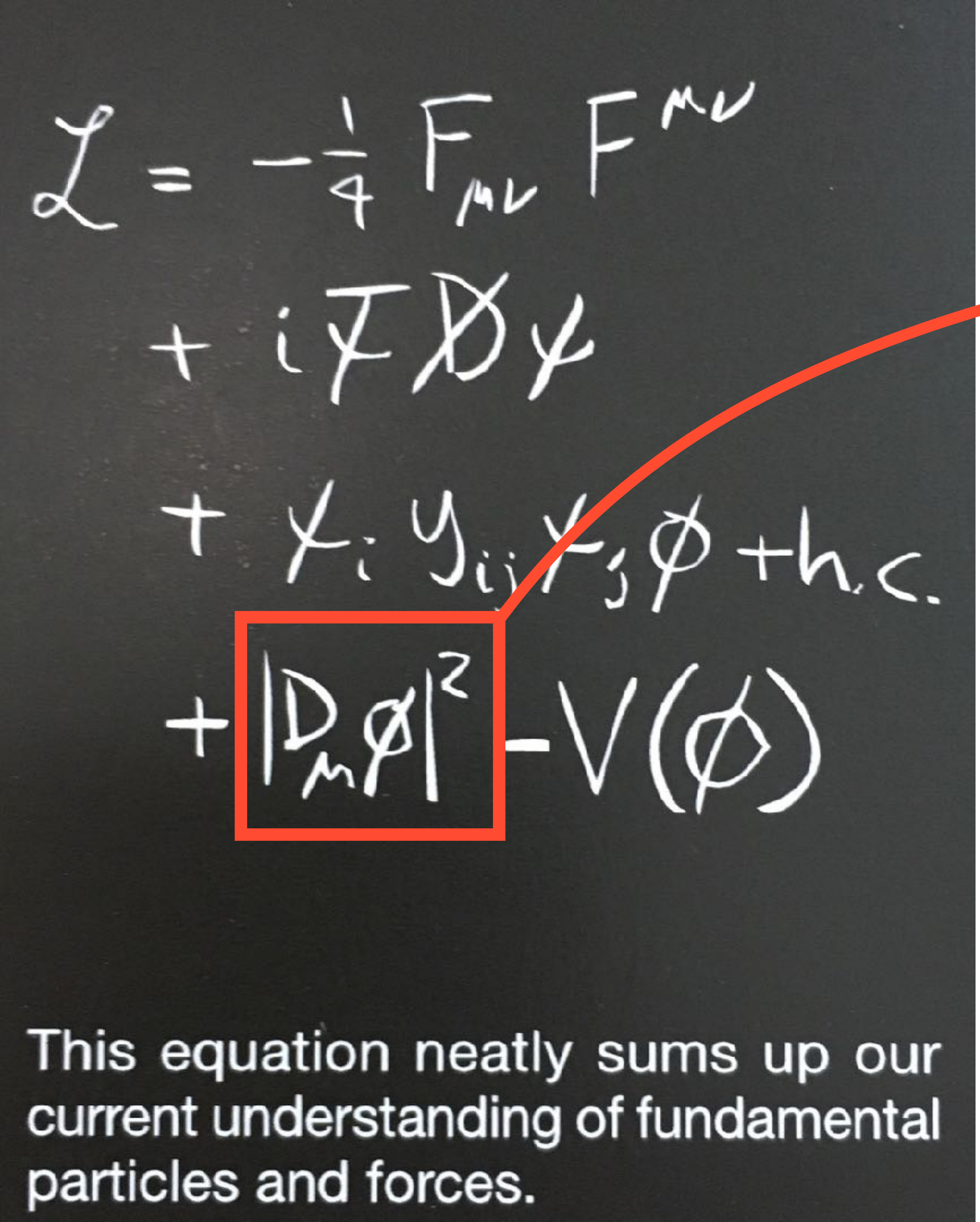
→ data barely sensitive…

Novelty? If fundamental, very (the only fundamental scalar we know of)



Gauge–Higgs interactions

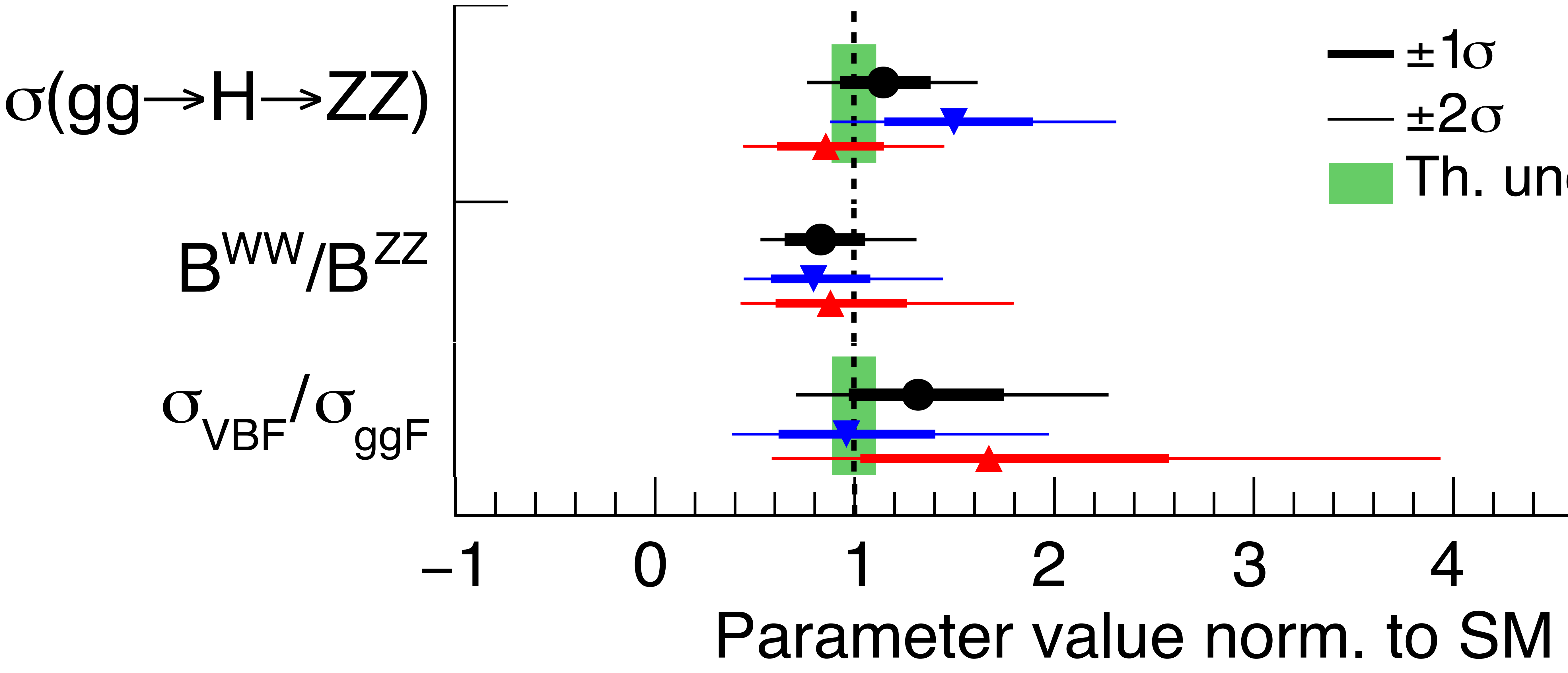
Definitely non-zero.

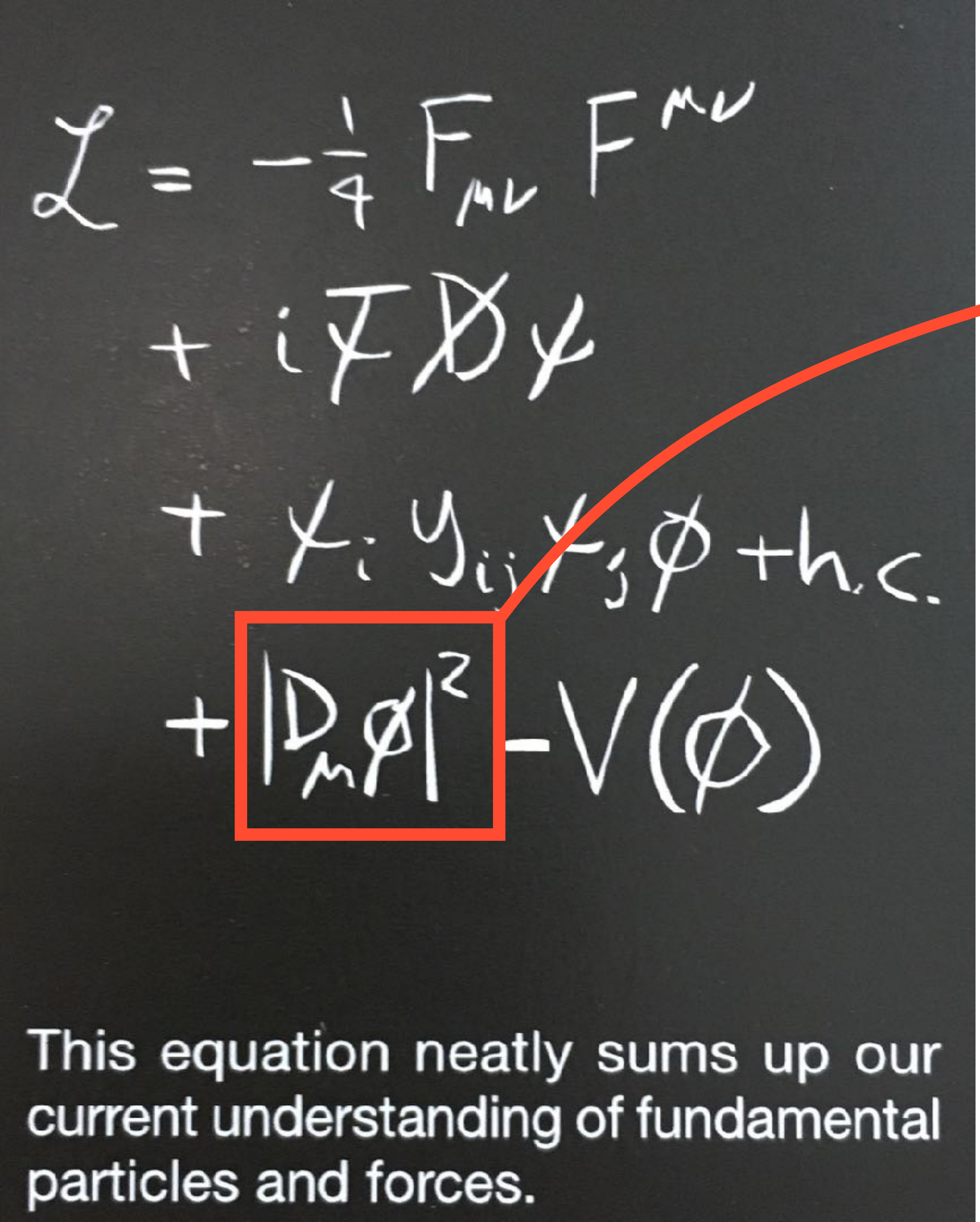
H→ZZ, H→WW, VBF

(would require "conspiracy" of couplings

in order to be substantially different)

≡ PROBABLY TRUE





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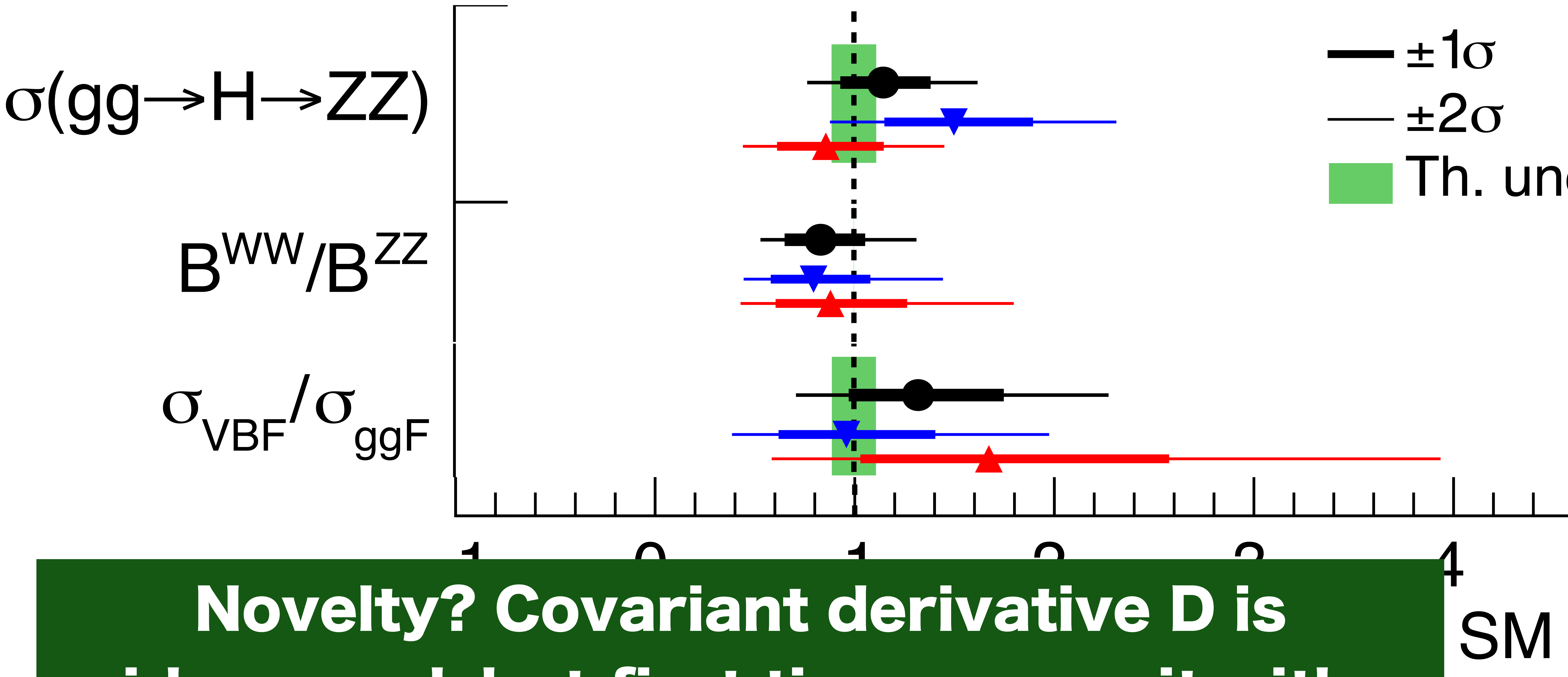
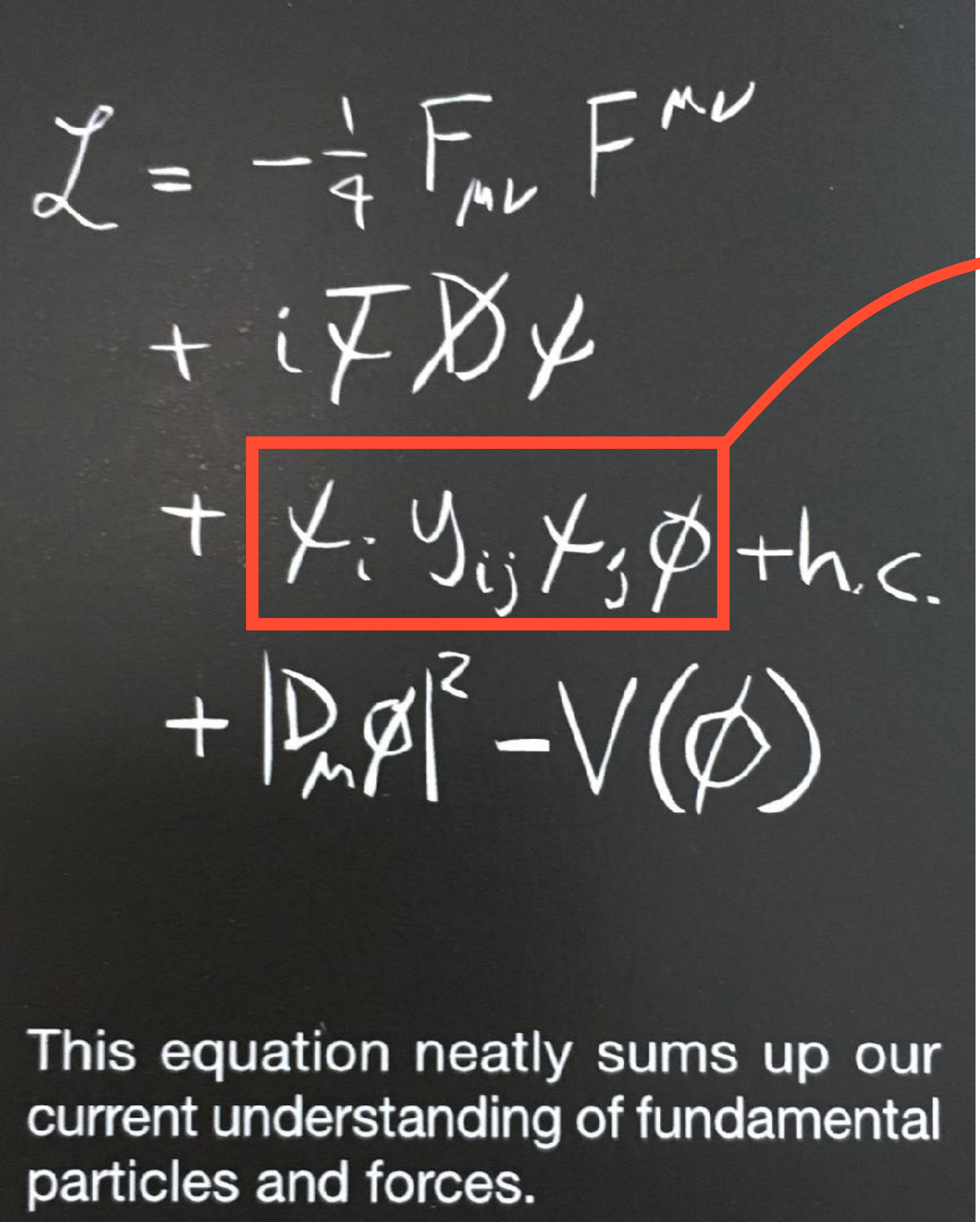


Novelty? Covariant derivative D is widespread, but first time we see it with a scalar



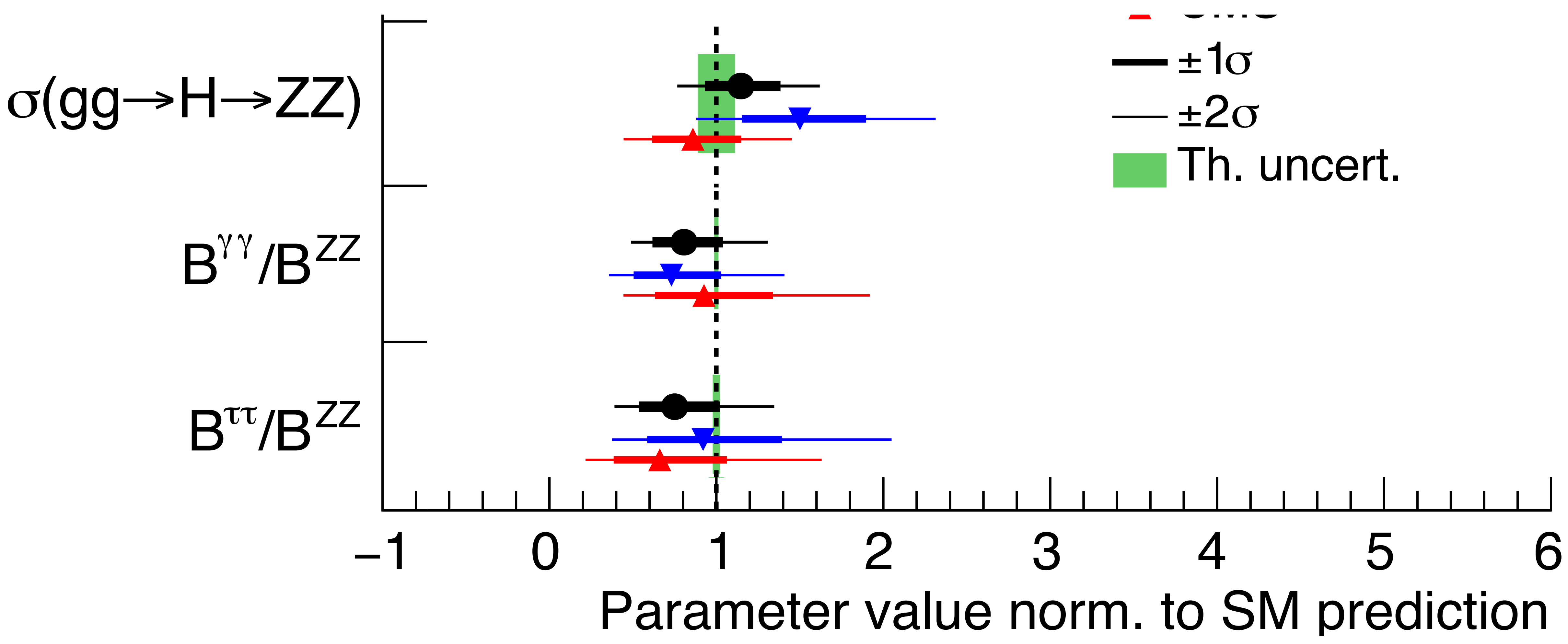
YUKAWA COUPLINGS

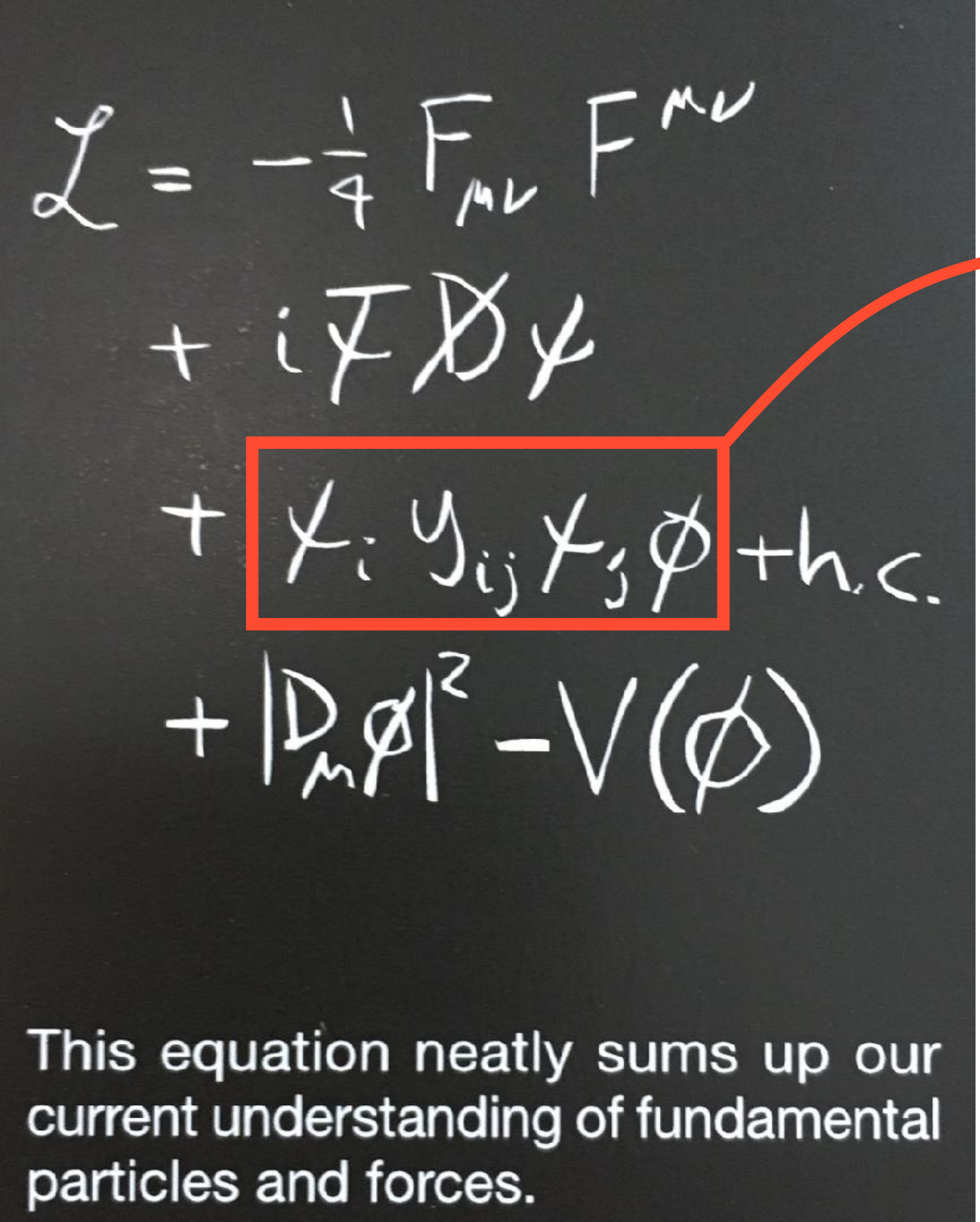
top? $gg \to H$, $H \to \gamma\gamma$ ≡ INDIRECT

bottom? H branching ratios ≡ INDIRECT

tau? ~ observed ≡ ~ KNOWLEDGE

1st & 2nd gen? ≡ IGNORANCE





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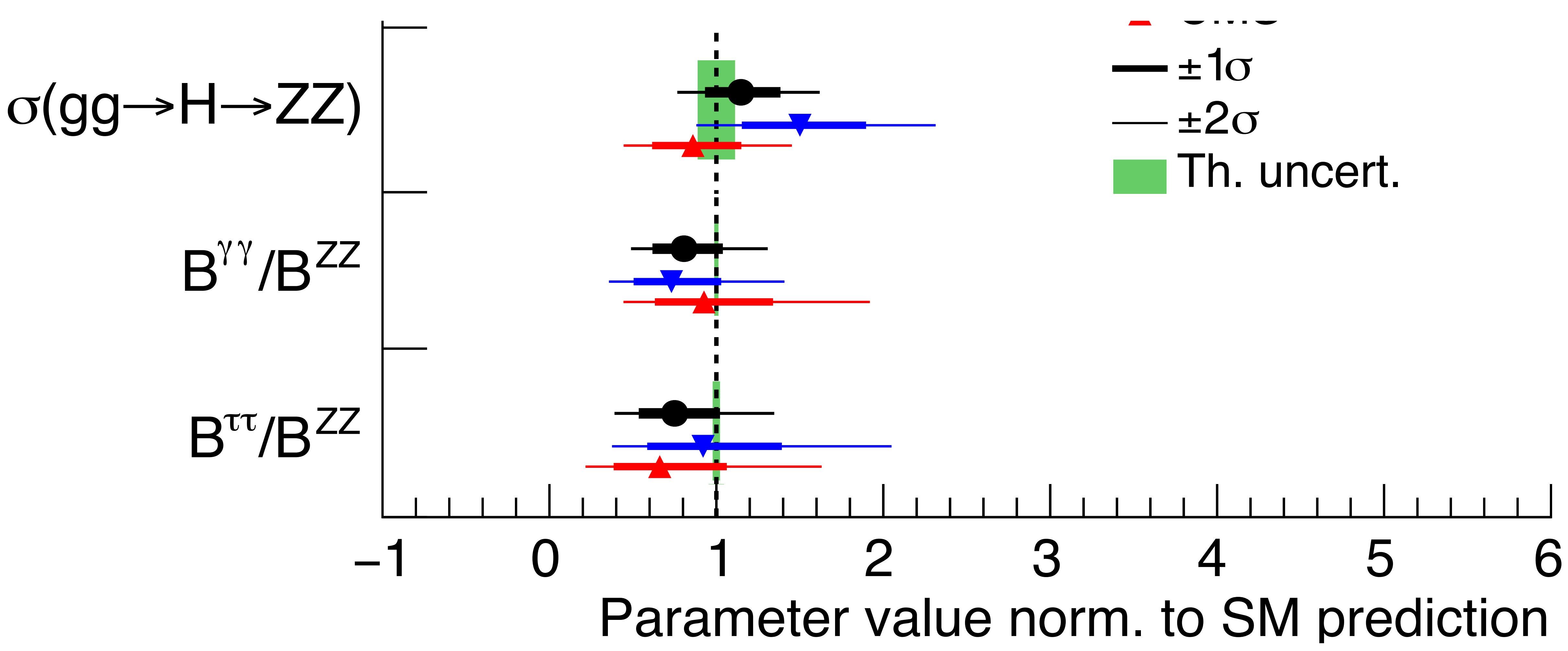
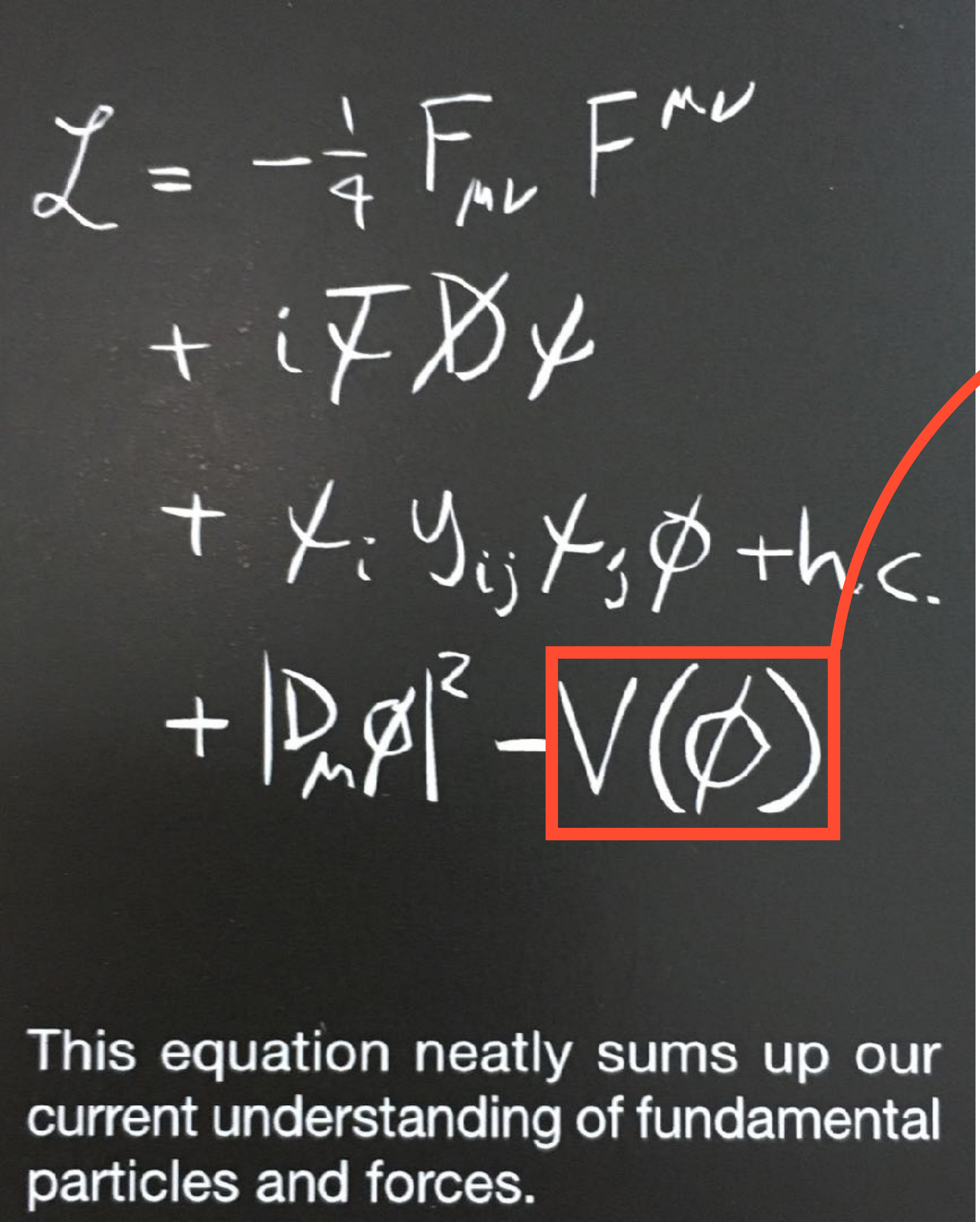
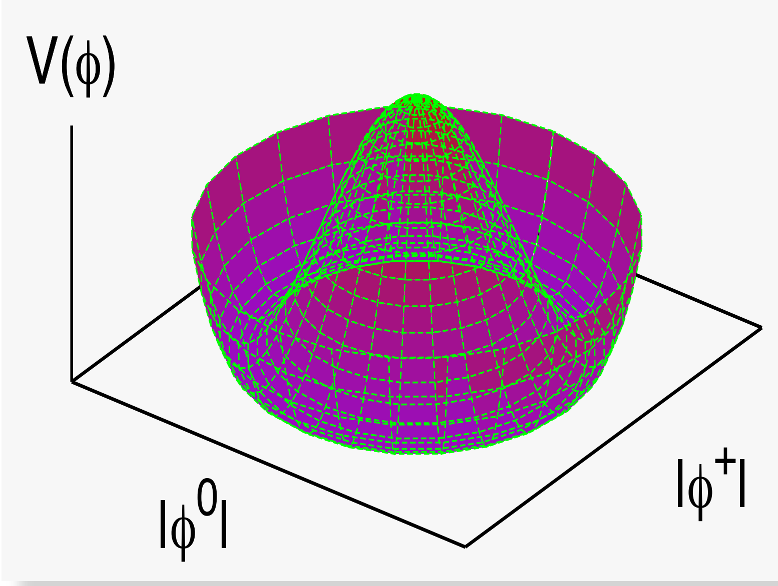


Novelty? We've never seen anything like it → mystery of 5 orders of magnitude in mass between electron & top, CKM



Higgs Potential



Vacuum Expectation Value (VEV)?

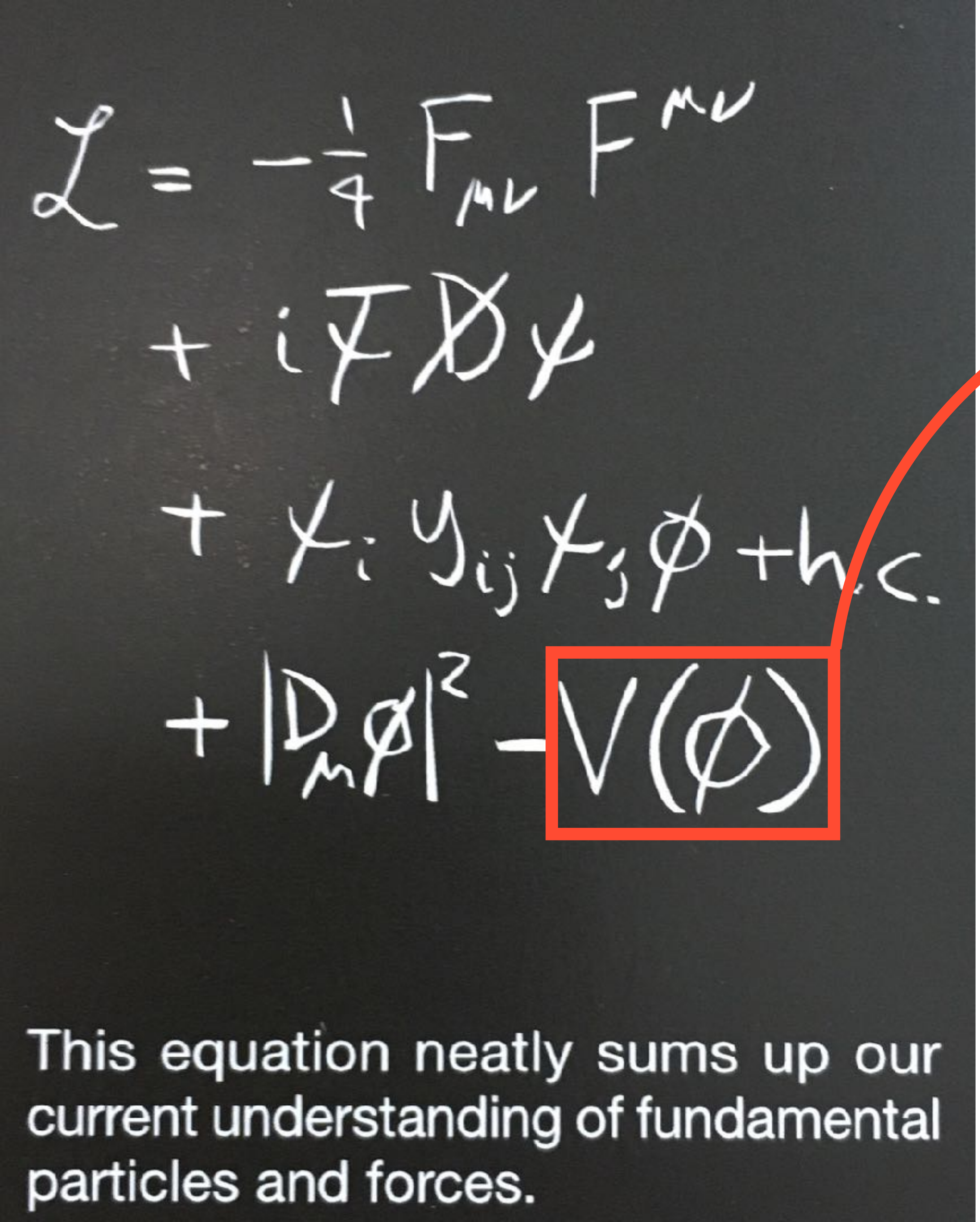
≡ KNOWLEDGE

2nd derivative ($\sim m_H$)?

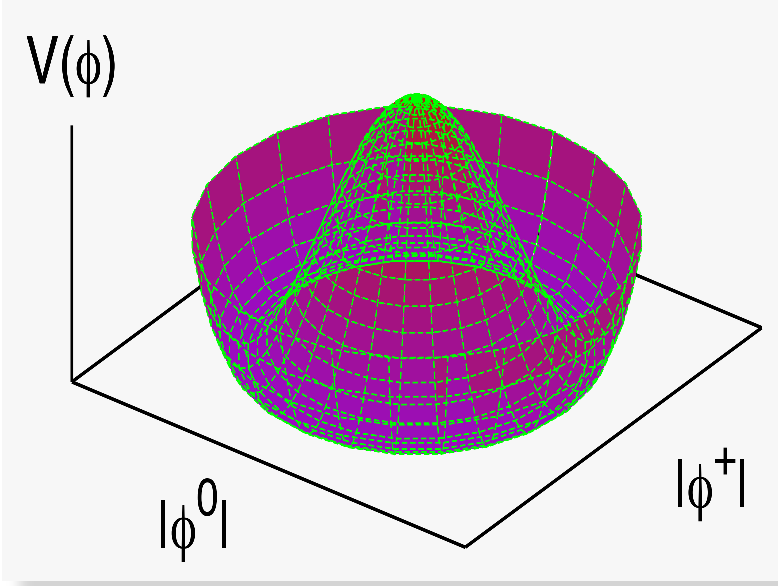
[not a prediction of the theory & any realistic theory must have a minimum & 2nd derivative]

≡ KNOWLEDGE

$\varphi^2 + \varphi^4$? ≡ ASSUMPTION



HIGGS POTENTIAL



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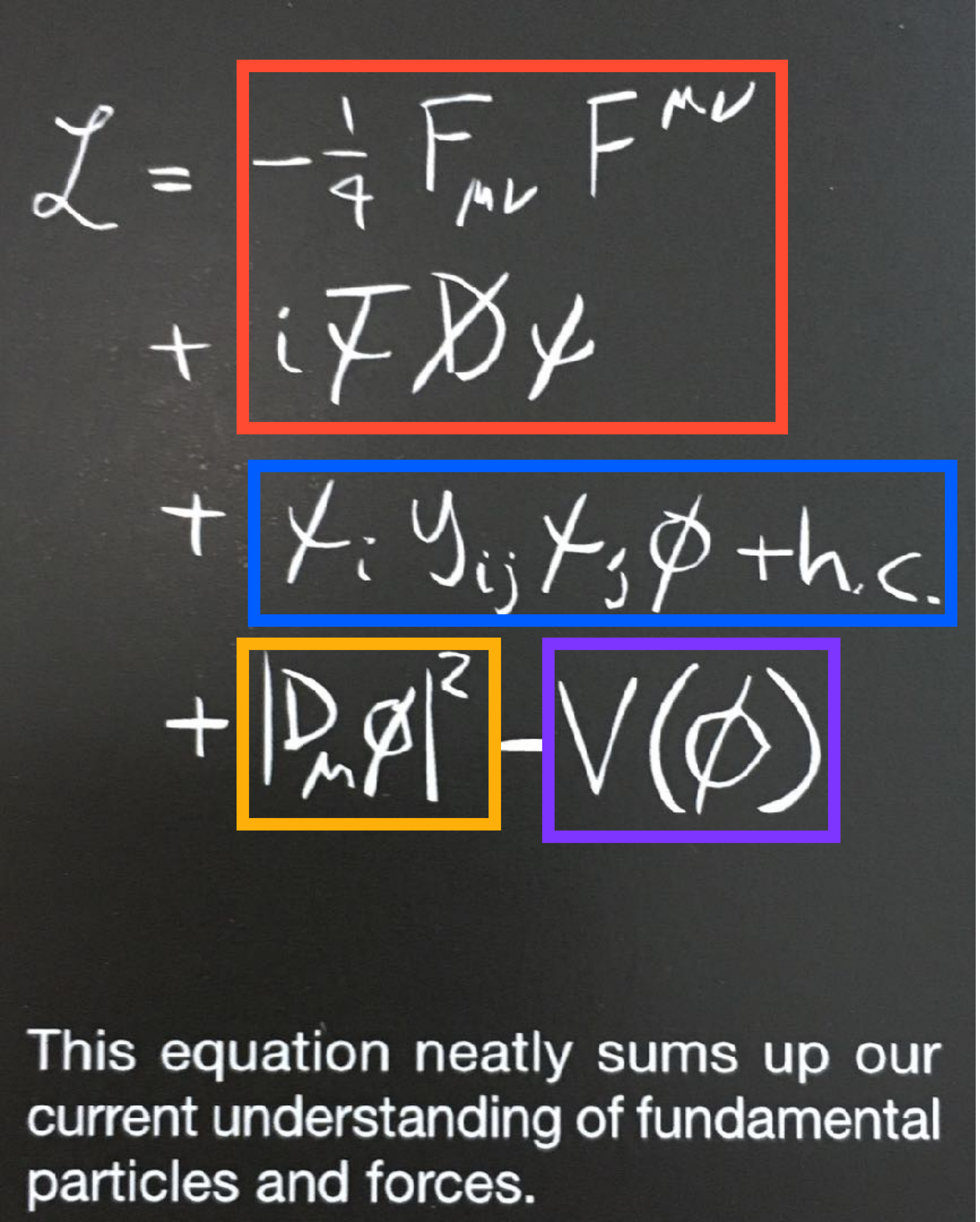
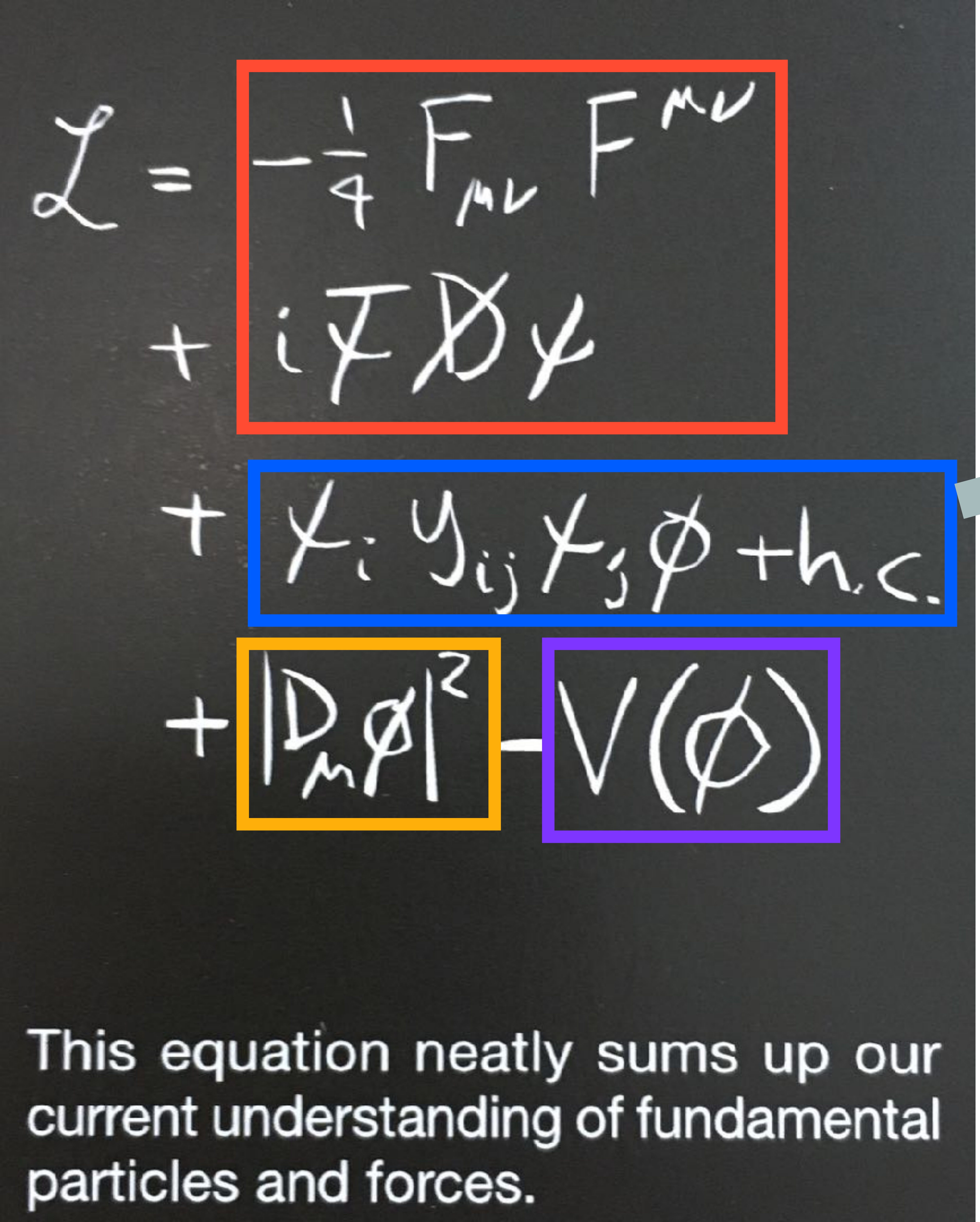
Novelty? Theorists' toy model, never seen in nature (as fundamental); Connects with stability of universe



Overall today

There remains a lot to establish in the Higgs sector



Overall today

t	b	τ
c	s	μ
u	s	e

ASSUMPTION KNOWLEDGE

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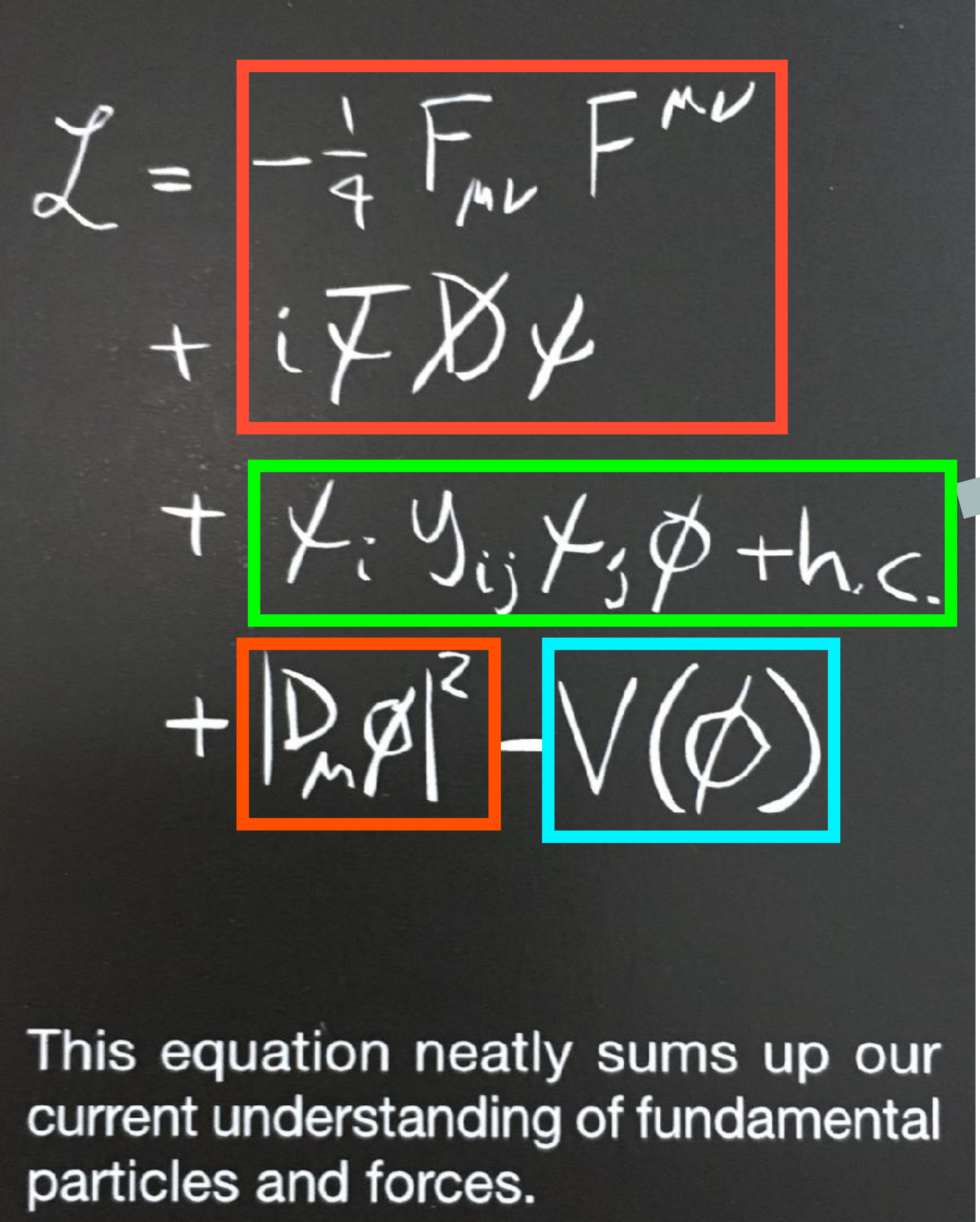


BY END OF THE LHC PROGRAMME (~2035)?

t	b	τ
c	s	μ
u	s	e

ASSUMPTION

KNOWLEDGE

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

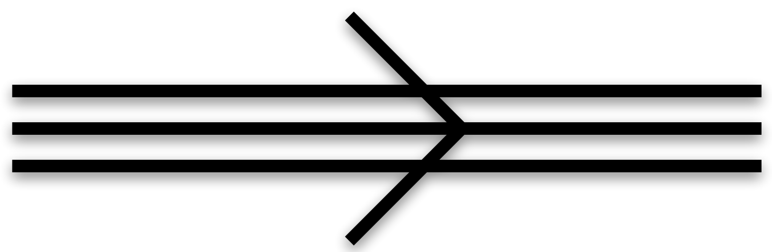
This equation neatly sums up our current understanding of fundamental particles and forces.

BY END OF THE LHC PROGRAMME (~2035)?

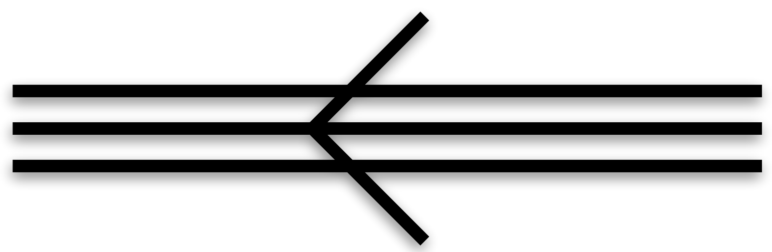
t	b	τ
c	s	μ
u	s	e

or falsification

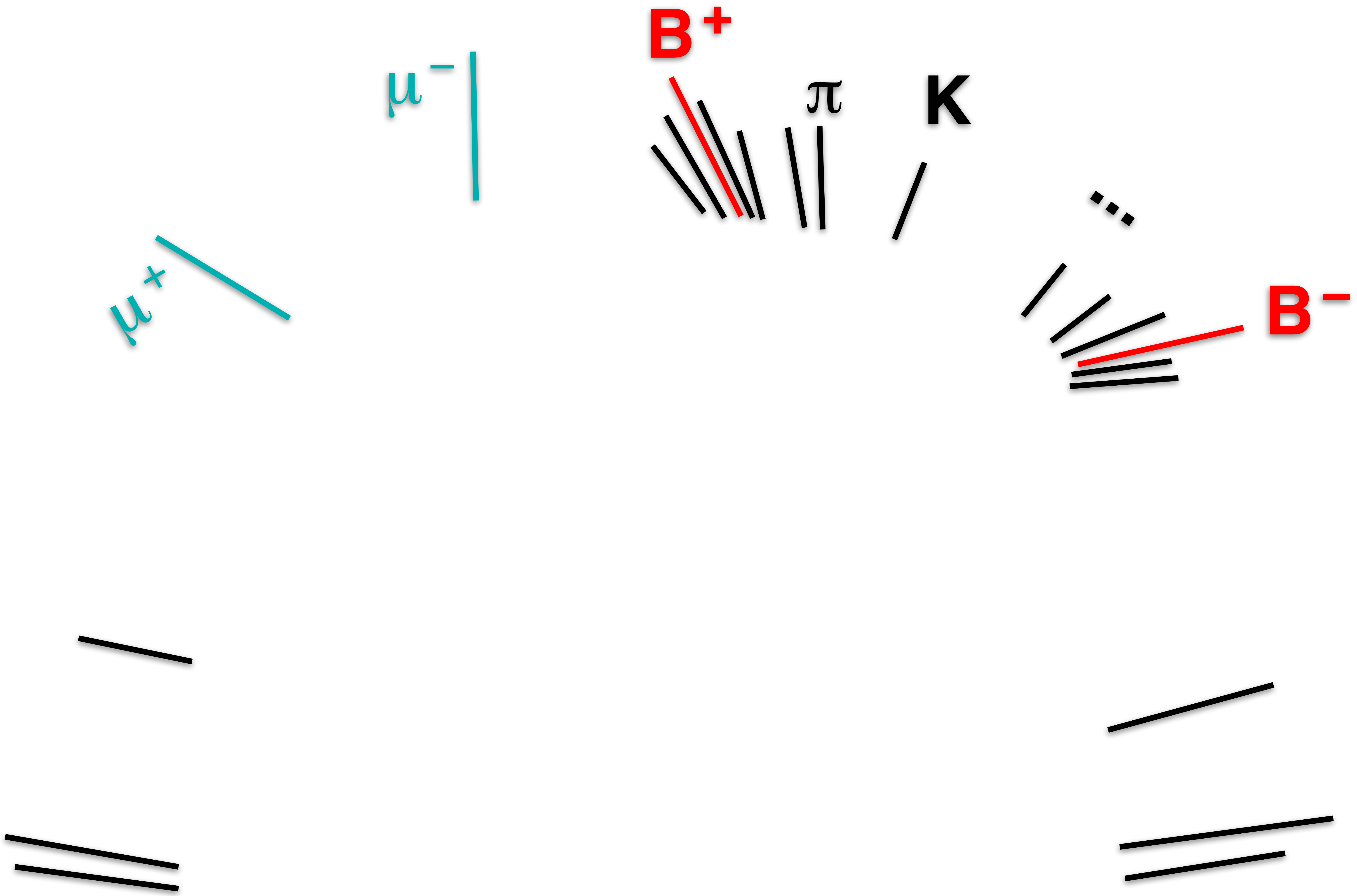
HOW?



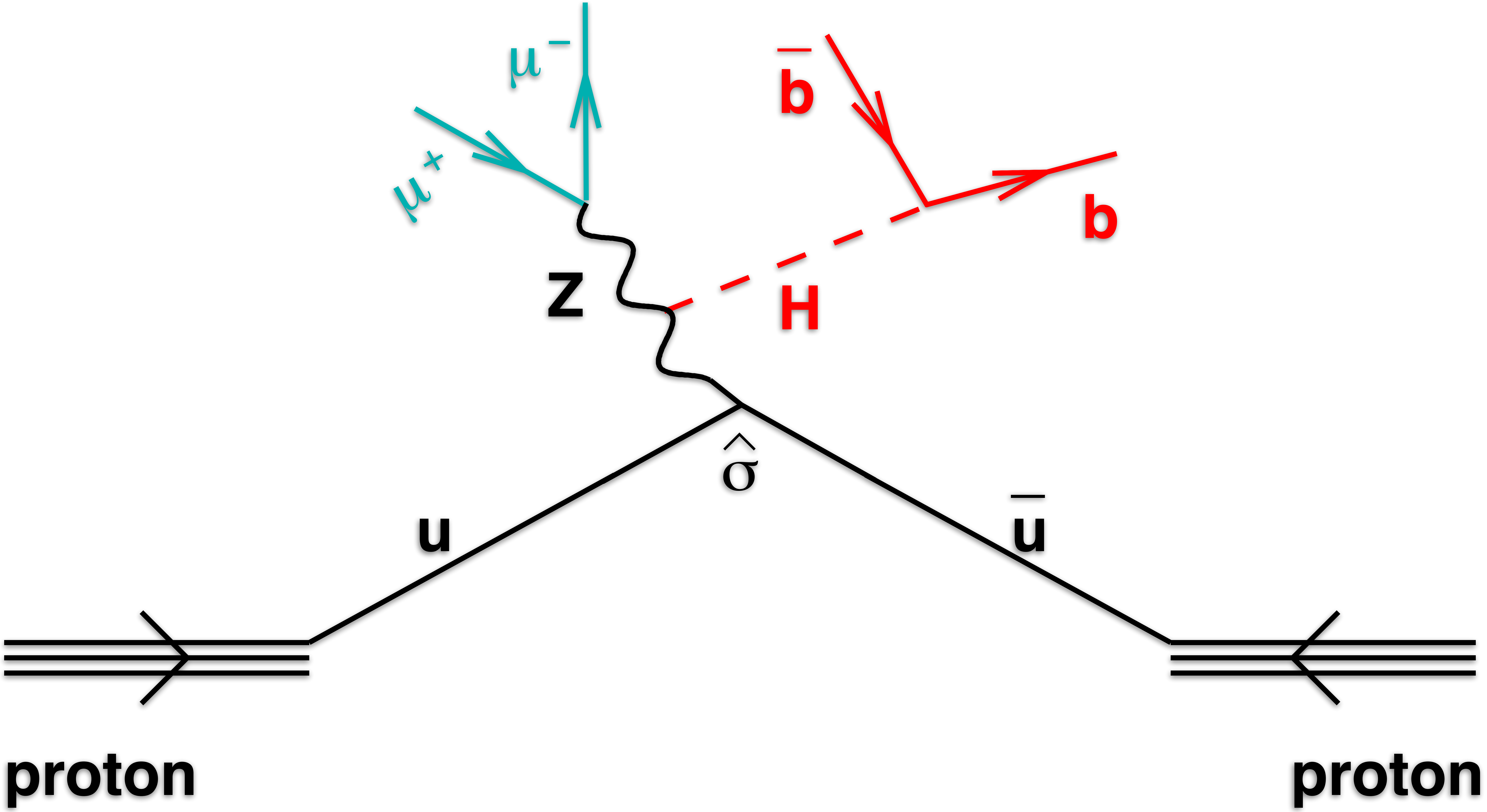
proton



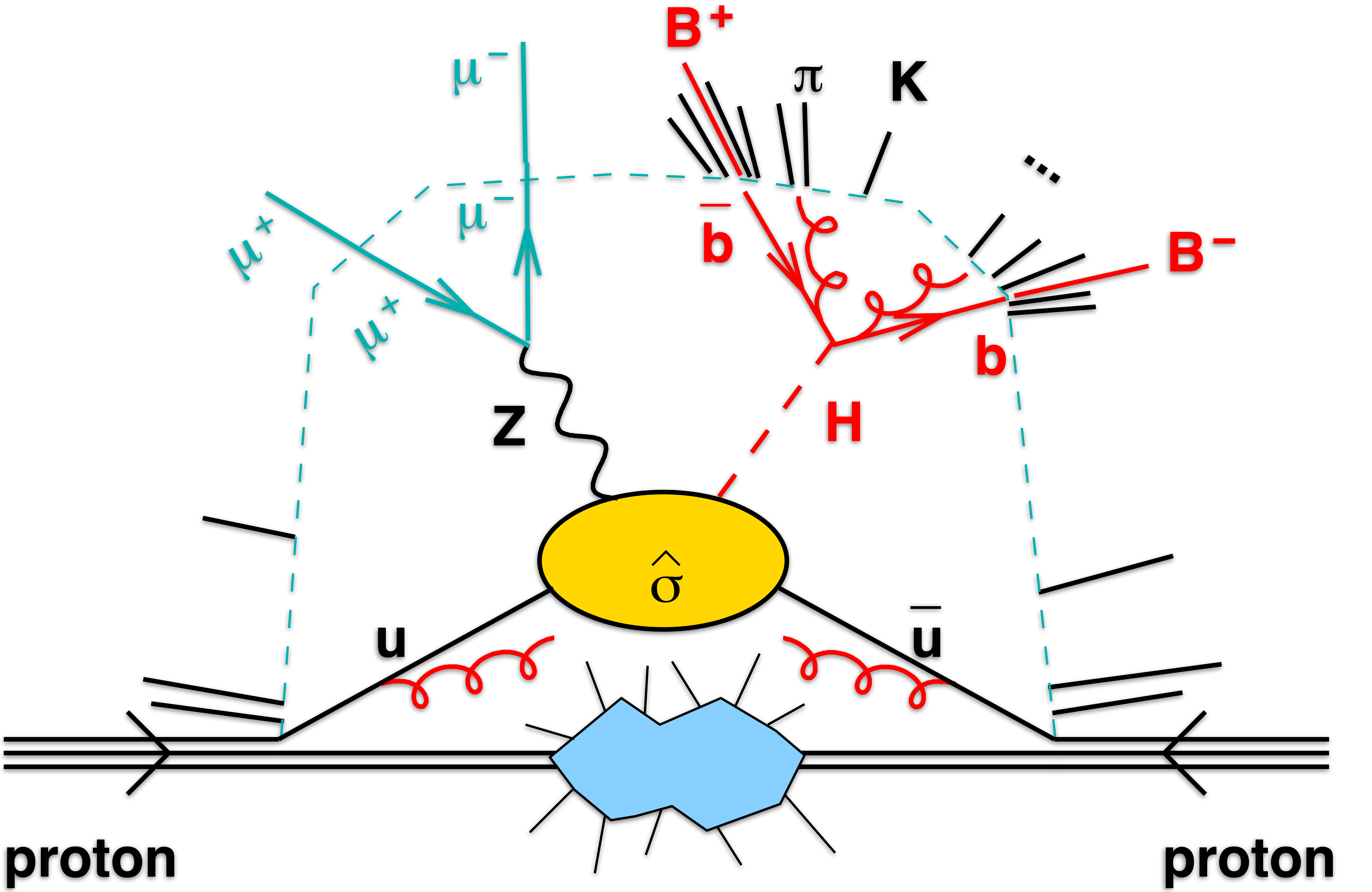
proton


B⁺
π
K
μ⁻
μ⁺
...
B⁻


ATLAS
EXPERIMENT

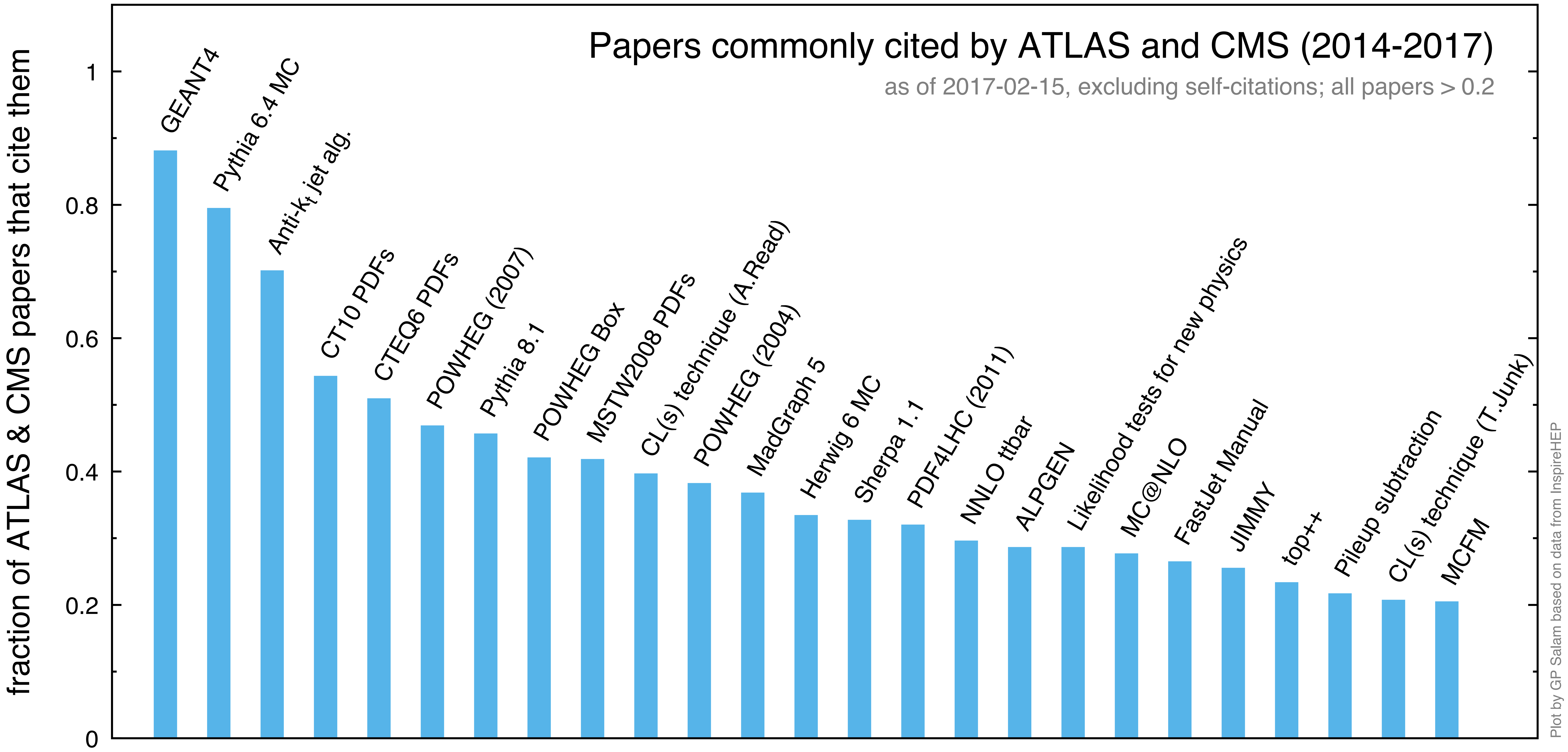


μ^-
μ^+
$\bar{b}$
b
Z
H
$\hat{\sigma}$
u
$\bar{u}$
proton
proton

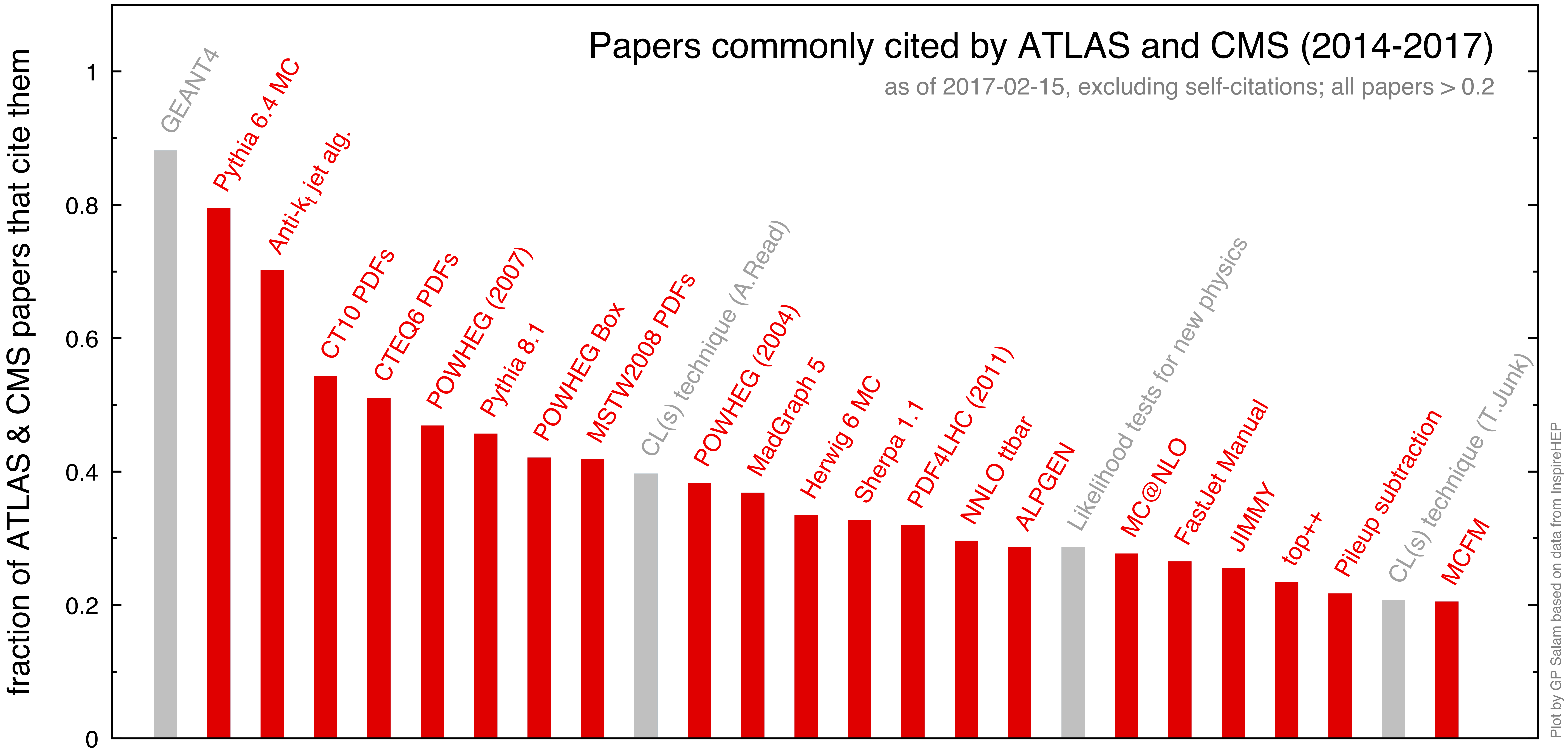


B^+
μ^-
π
K
μ^+
μ^-
$\bar{b}$
B^-
μ^+
b
Z
H
$\hat{\sigma}$
u
$\bar{u}$
proton
proton

What do ATLAS & CMS use to make sense of this?



In very large part: theoretical work



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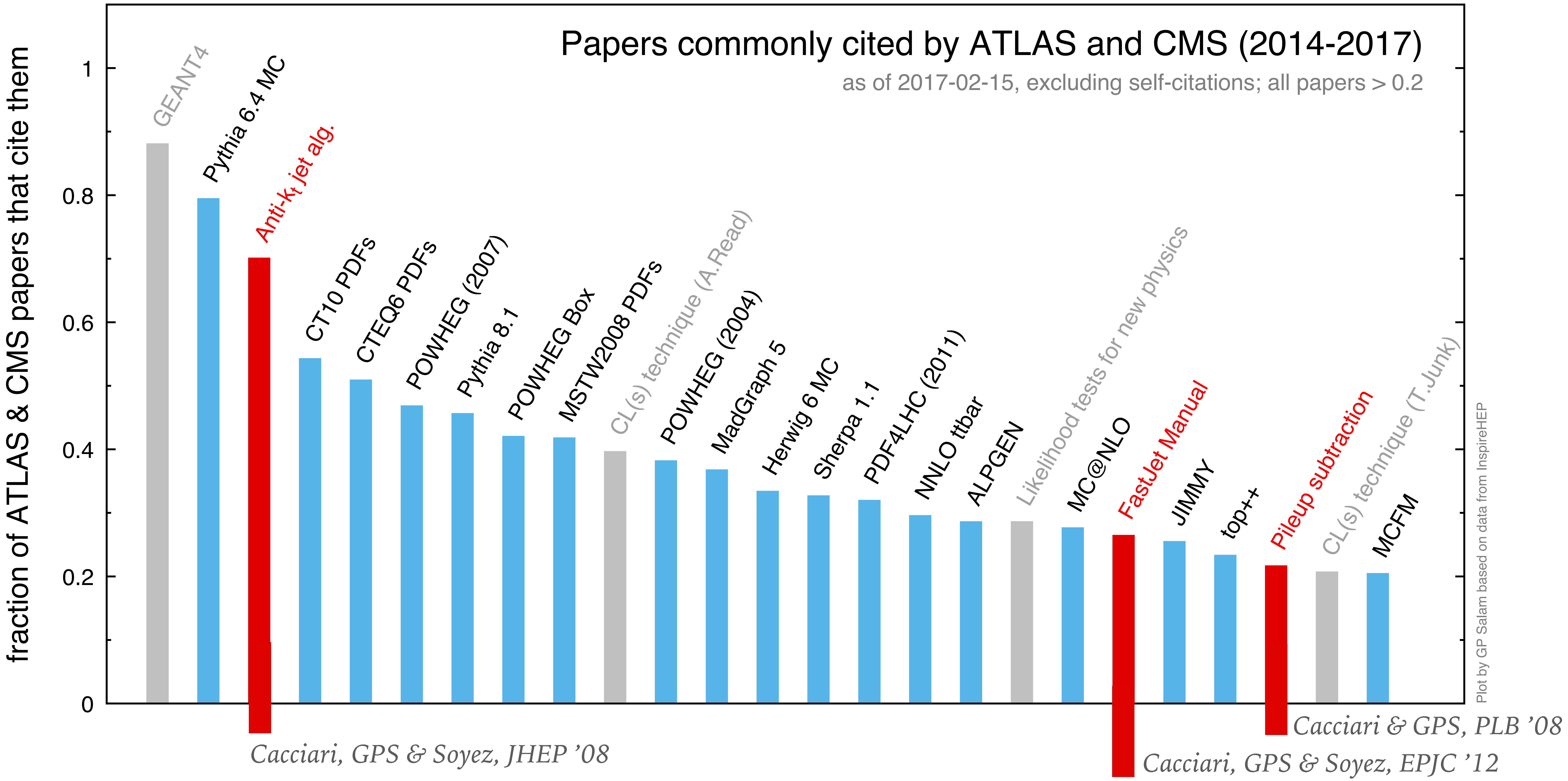
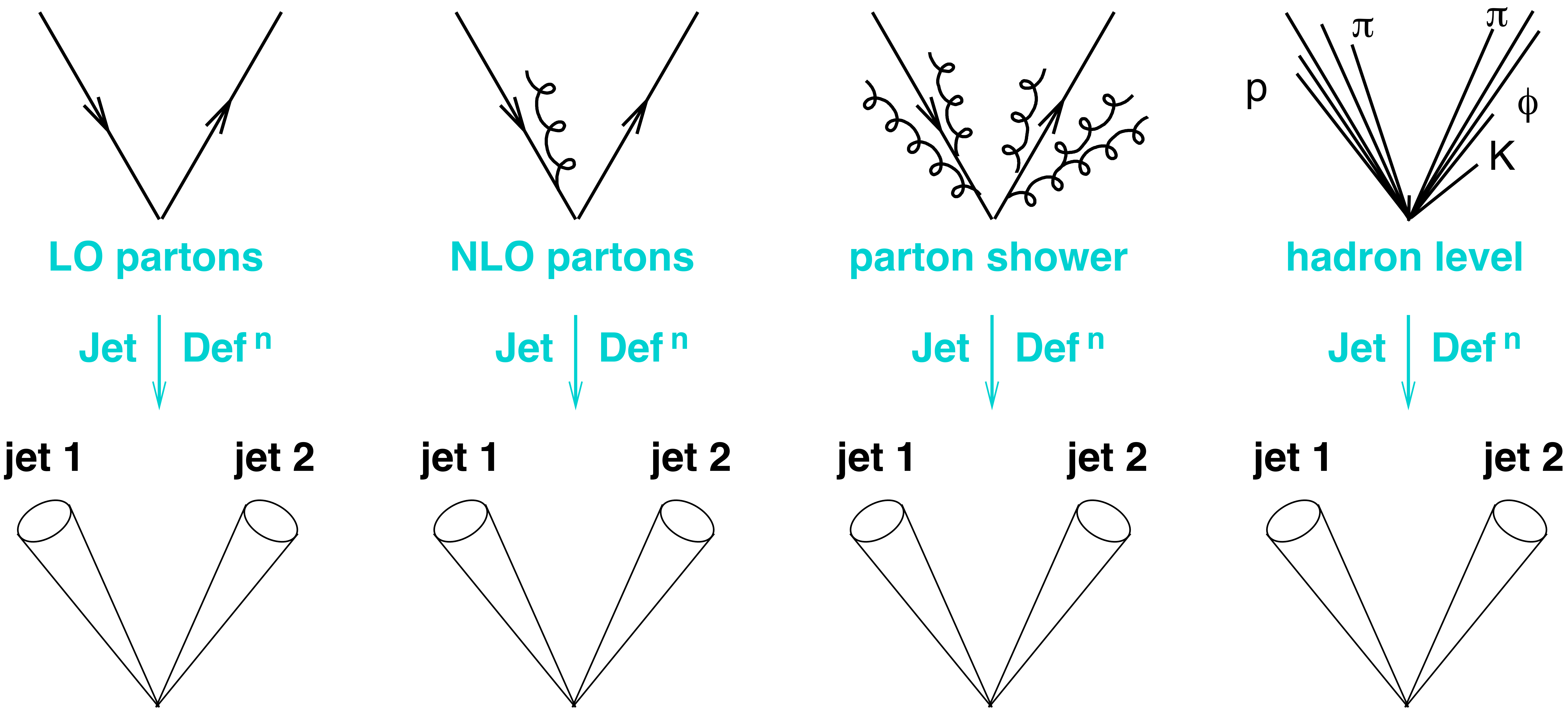
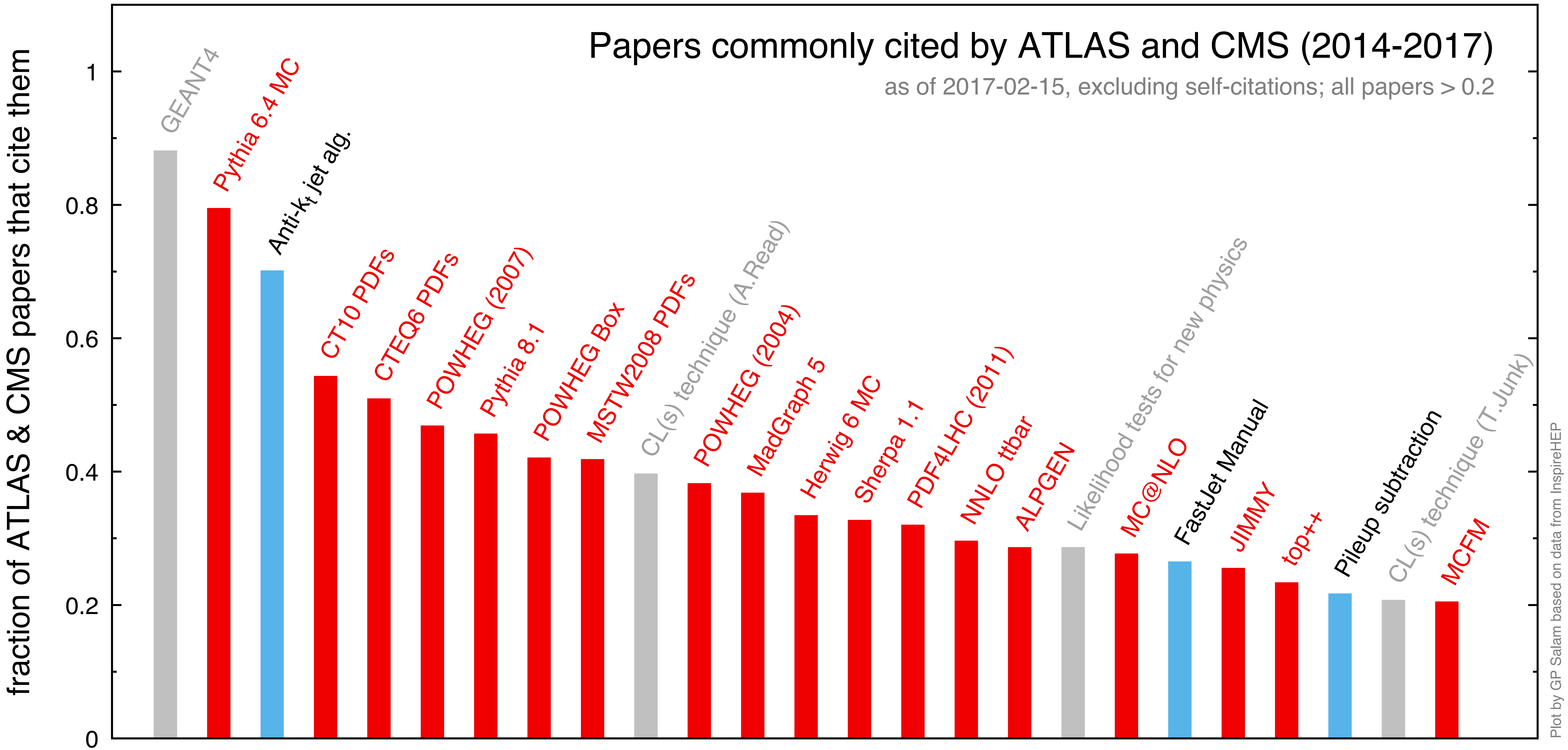


Jet definitions

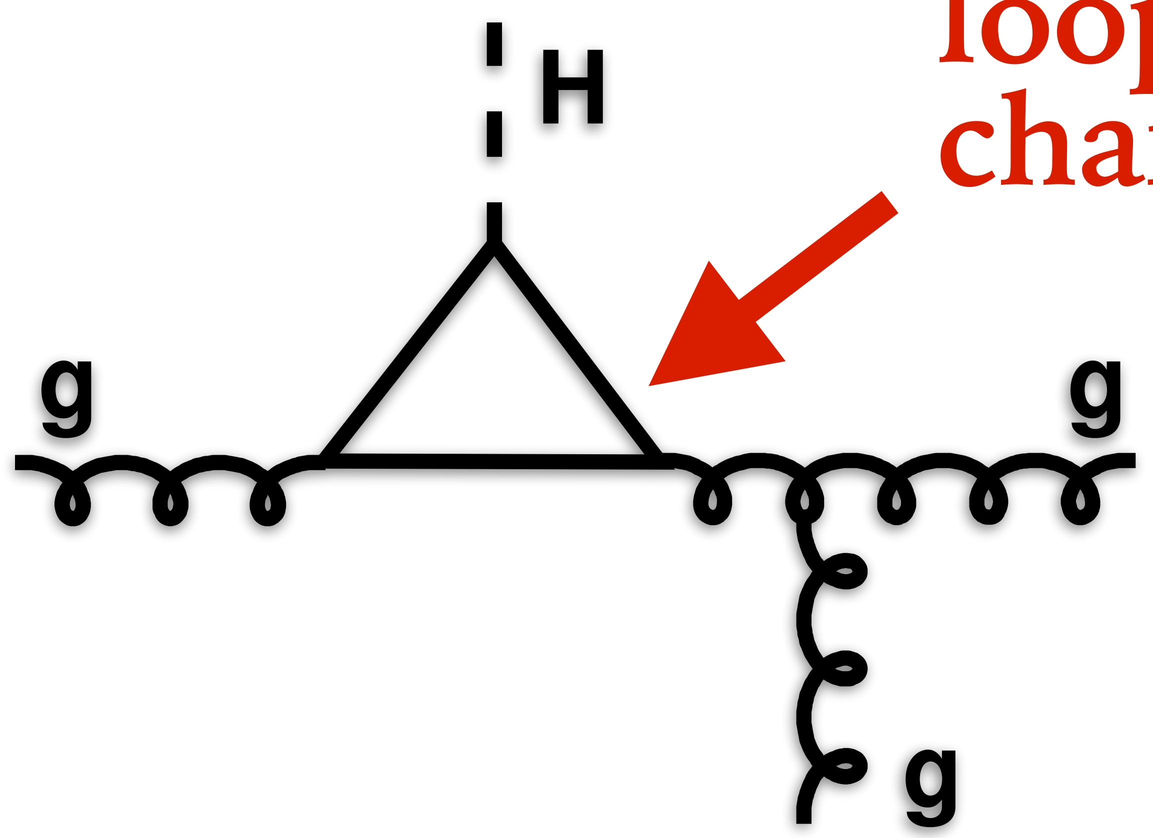


projection to jets gives simplified view of the essence of an event

Most of the rest: predicting what happens in hadron collisions



Key question today: **precision** of predictions. Here's an example why



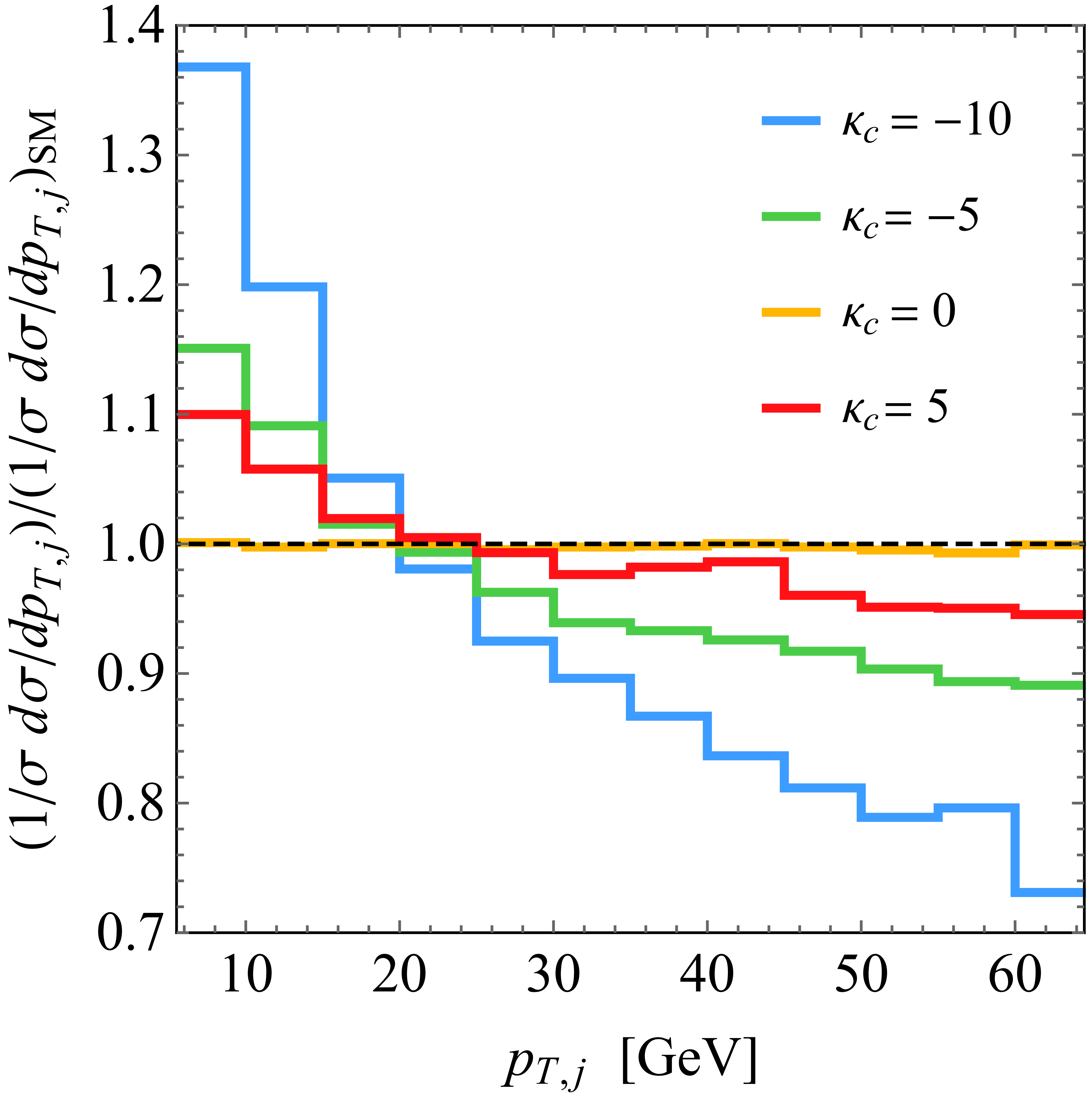
loop can have top, bottom charm (etc.) quarks

- quark mass affects momentum distribution of Higgs
- full distribution affected by relative contributions of top, bottom and charm

→ **sensitivity to Hcc Yukawa coupling**

Bishara, Haisch, Monni & Re, arXiv:1606.09253
(cf. also Soreq, Zhu, Zupan, arXiv:1606.09621)

impact of modified Hcc coupling on Higgs+jet pT dist



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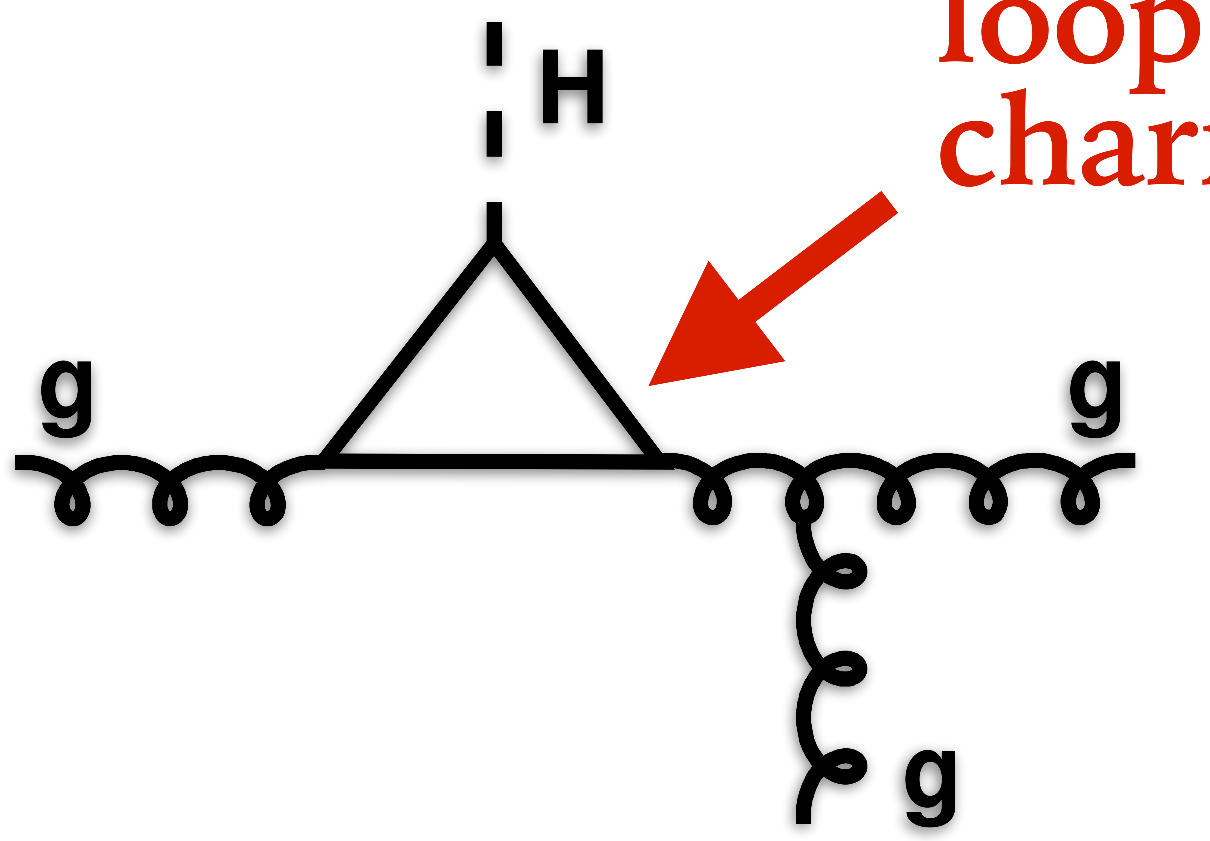
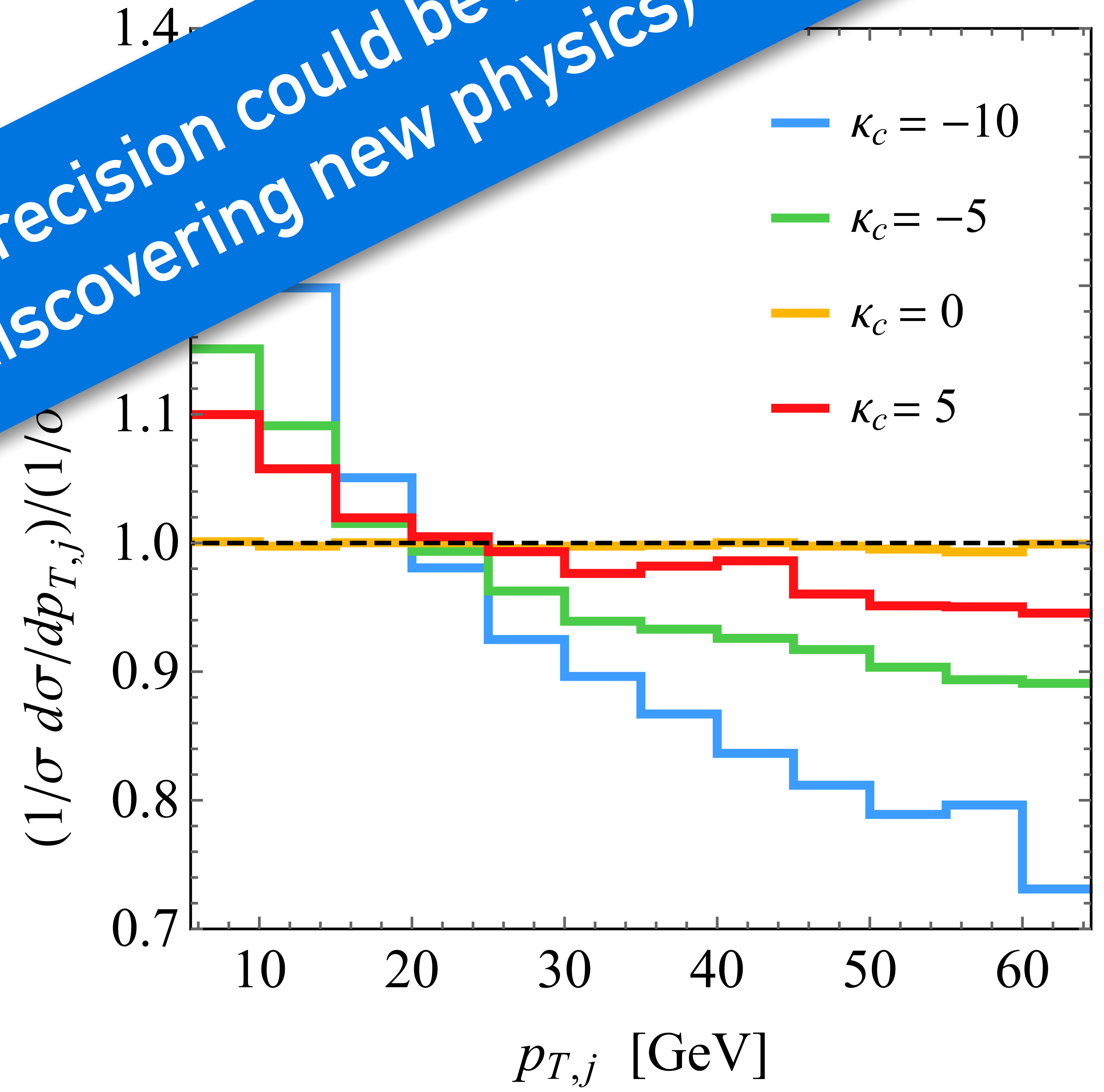


loop can have top, bottom
charm (etc.) quarks

impact ... coupling ... dist

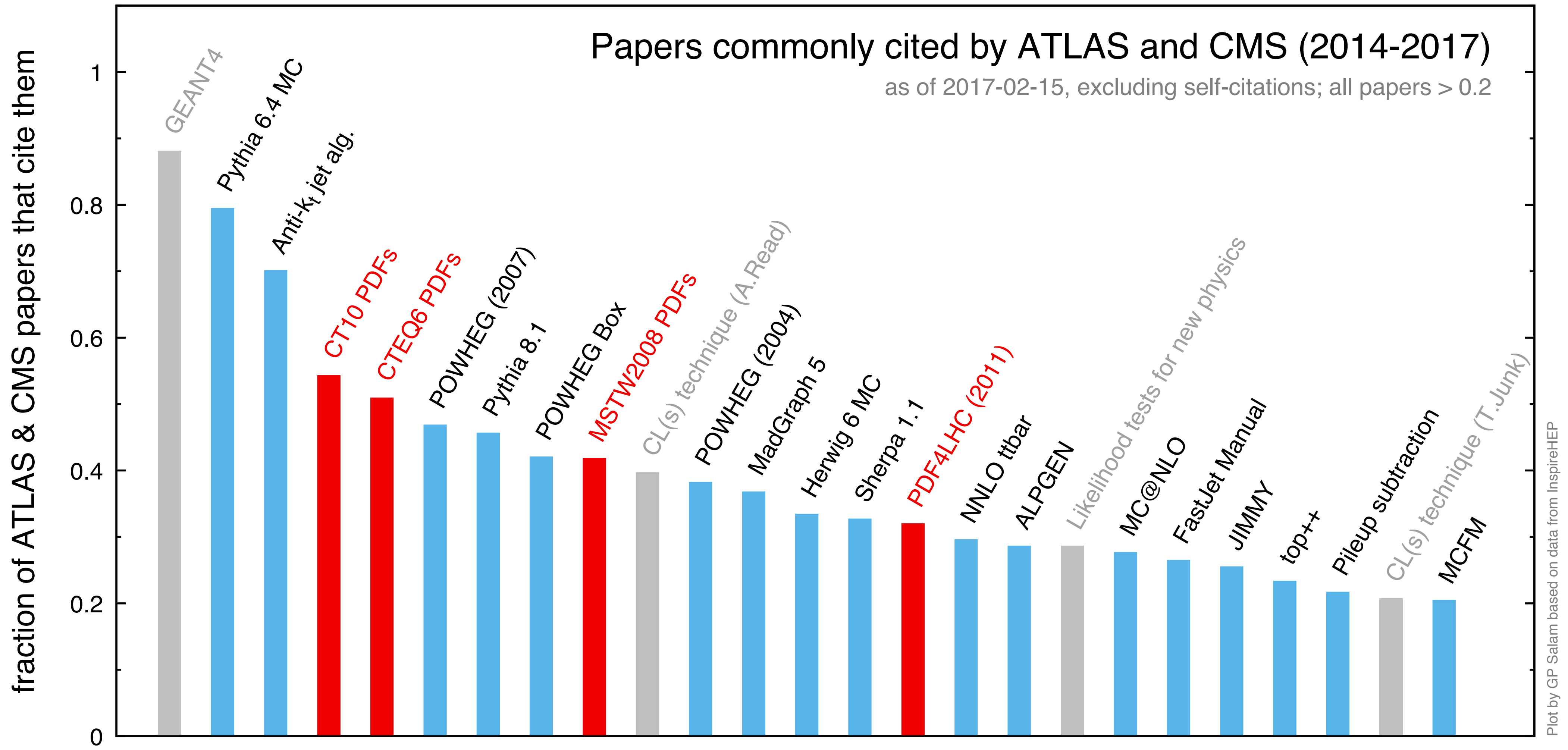


One of countless examples where precision could be key to establishing Standard Model (or discovering new physics)

- quark mass affects momen... of Higgs
- full distribu... ...ive contri... ...m and charm
- ...c Yukawa coupling

Bis... ...n, Monni & Re, arXiv:1606.09253
(cf. a... Soreq, Zhu, Zupan, arXiv:1606.09621)

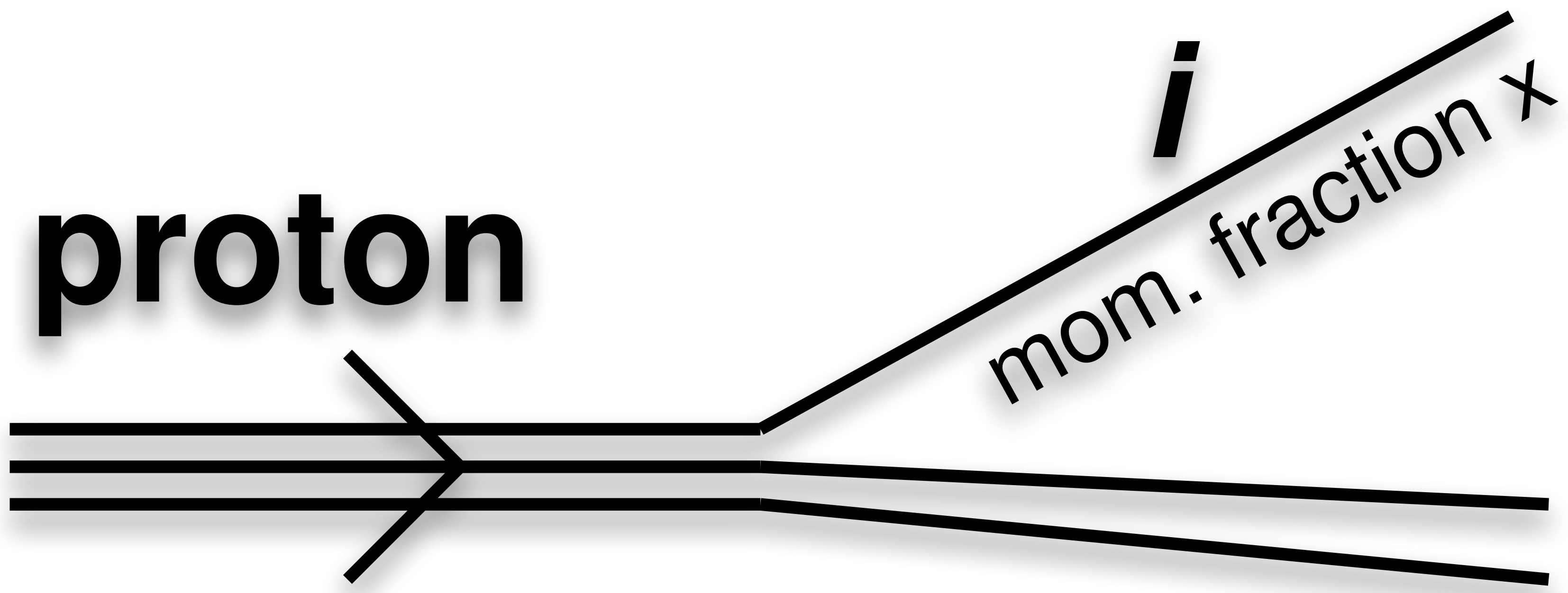
parton distribution functions (PDFs)



Protons are composite objects (uud + gluons + …)

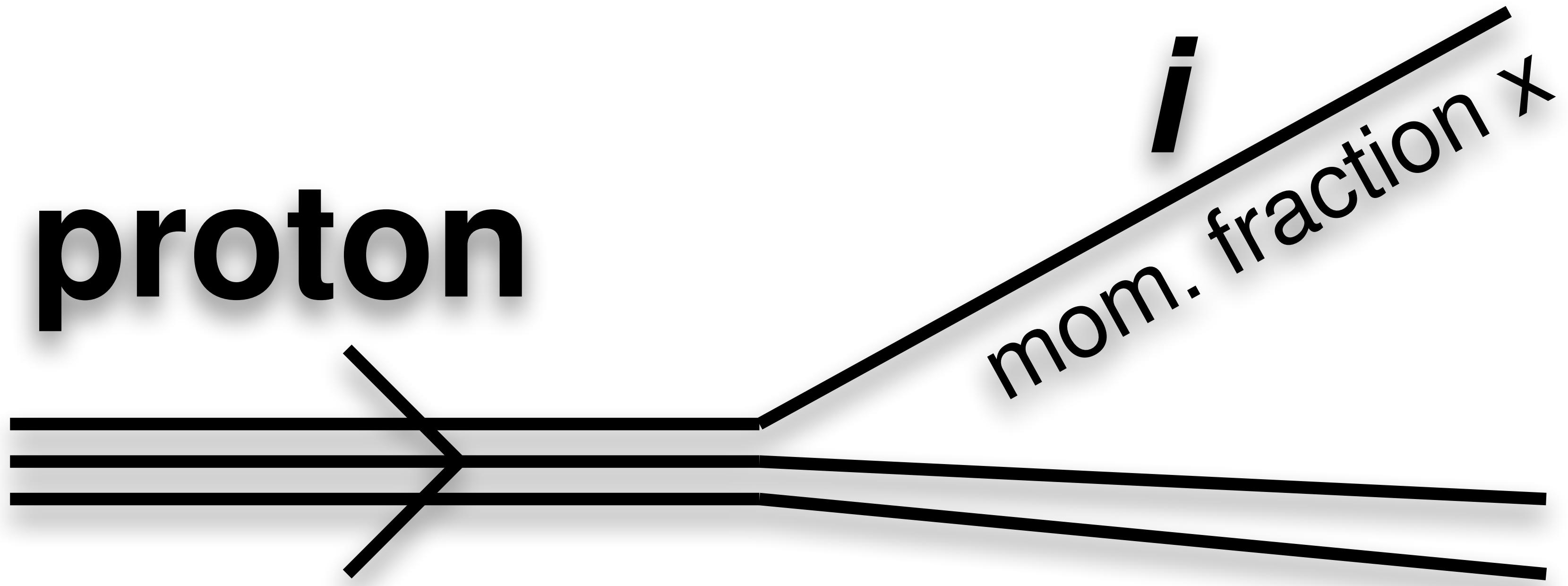
Quantitative LHC physics requires knowledge of PDFs:

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



- number of partons of flavour ***i*** [=u, d, g, …]
- inside a fast-moving proton ***p***
- carrying a fraction ***x*** of the proton's momentum
- when viewed with resolution momentum scale ***μ*** [~ 1/wavelength of probe]

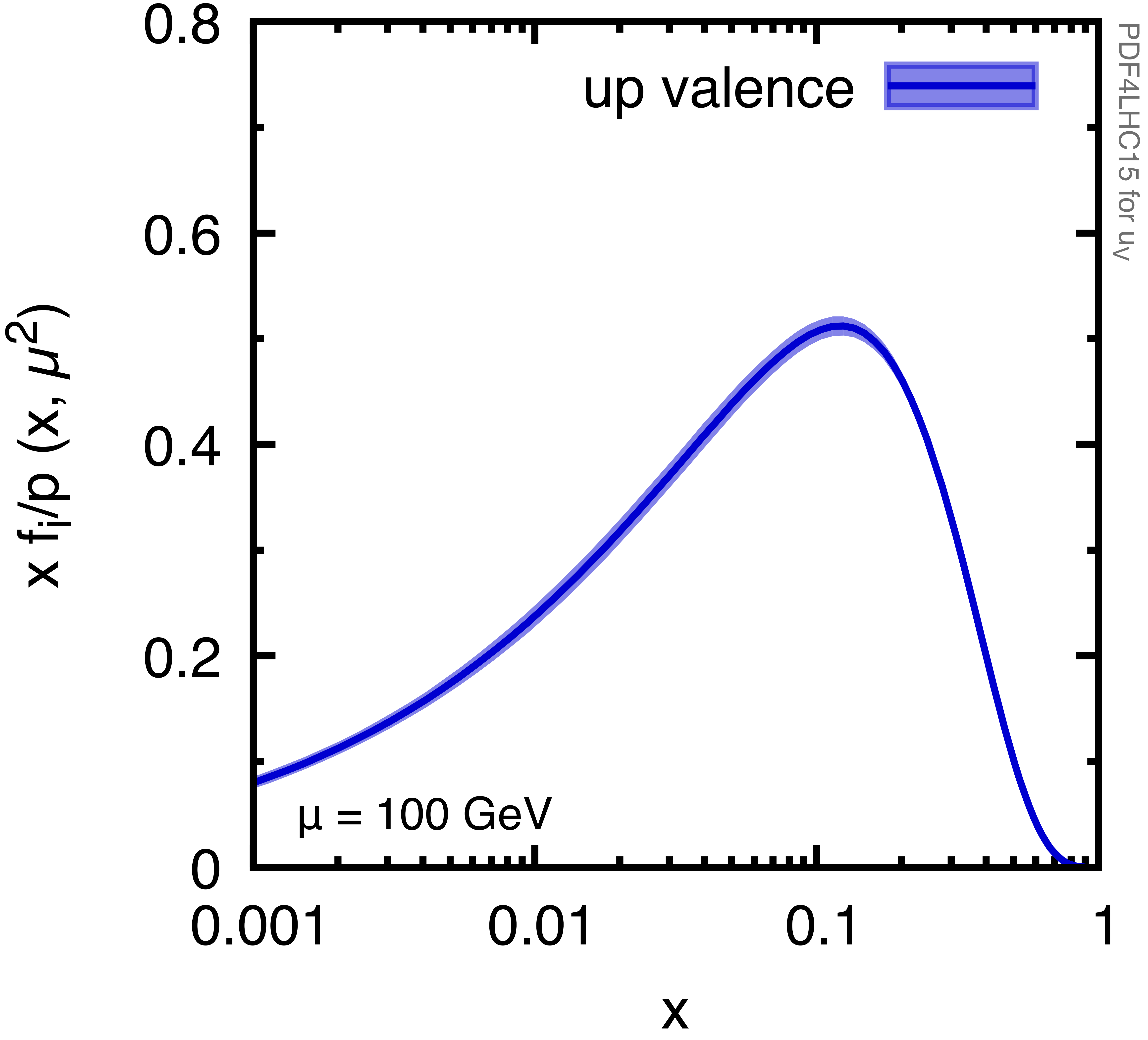
parton distribution functions (PDFs)



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

Typically known with good
precision ~1–3%

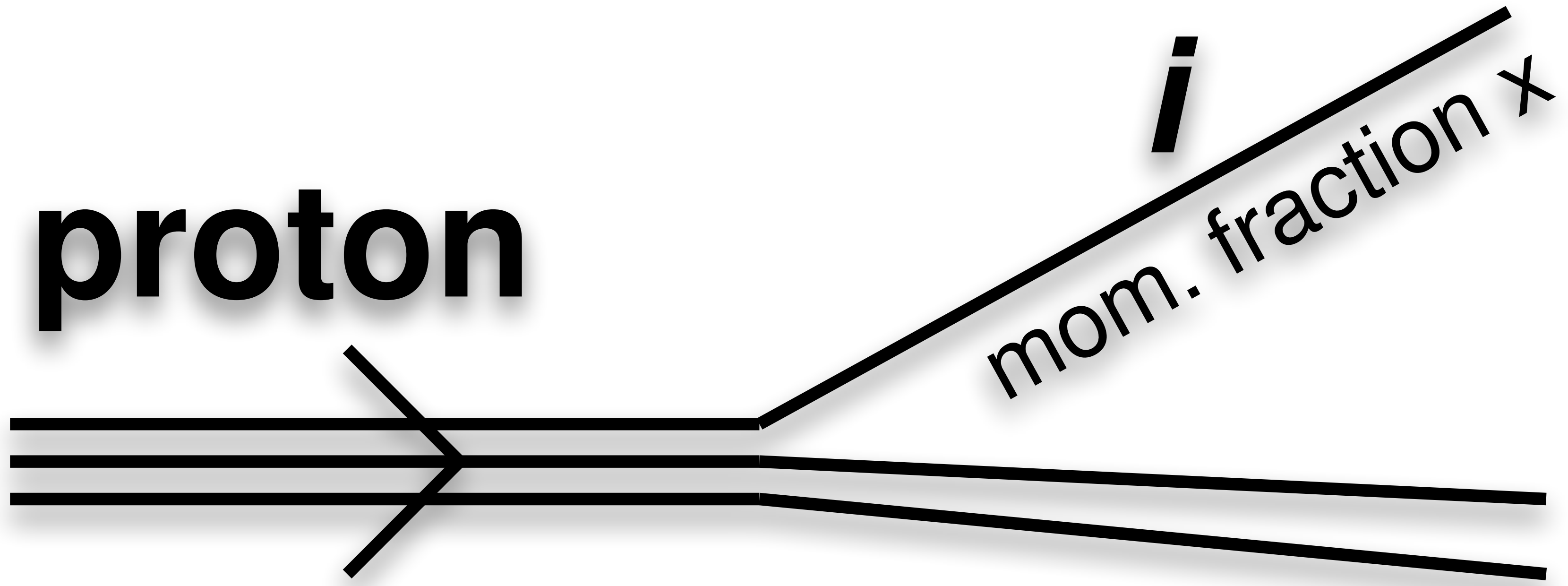
$$f_{i/p}(x, \mu^2)$$

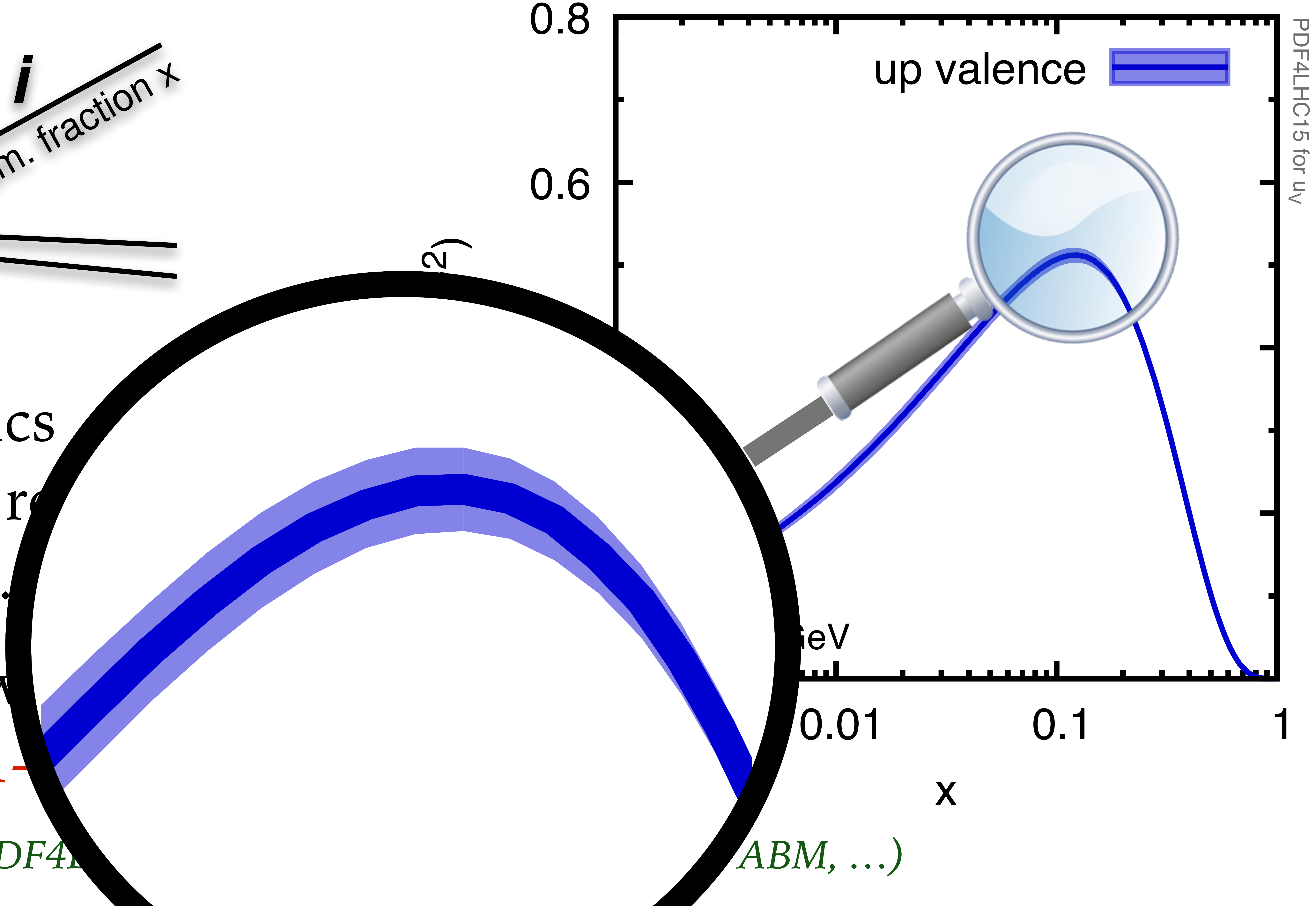


E.g. NNPDF, MMHT, CT & PDF4LHC working group (+ also HERAPDF, ABM, …)

parton distribution functions (PDFs)

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





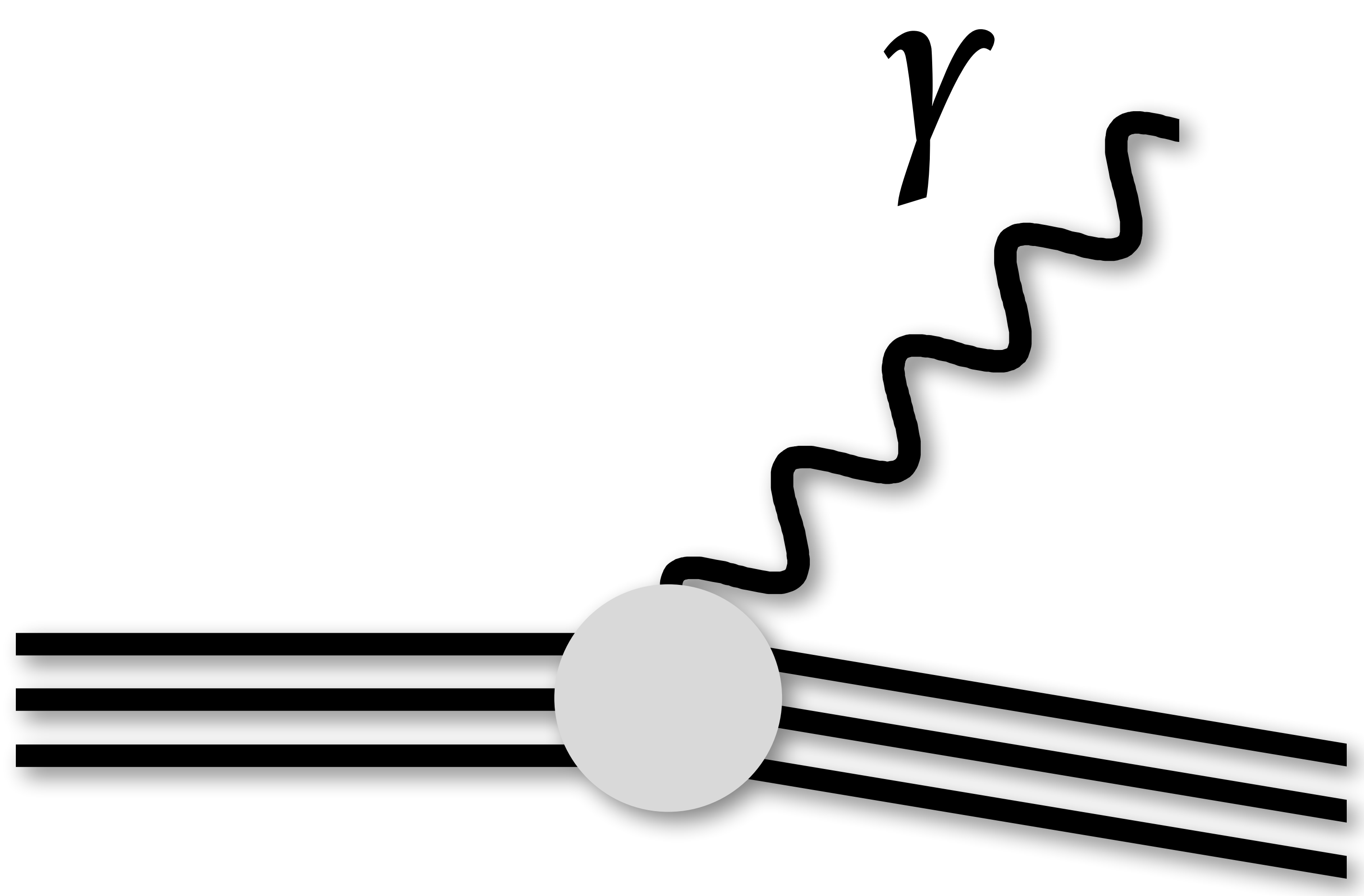
LHC physics
needs PDFs in r
~ 10^{-3} – 0.

Typically known w
precision ~1-

E.g. NNPDF, MMHT, CT & PDF4L ABM, …)

parton distribution functions (PDFs)

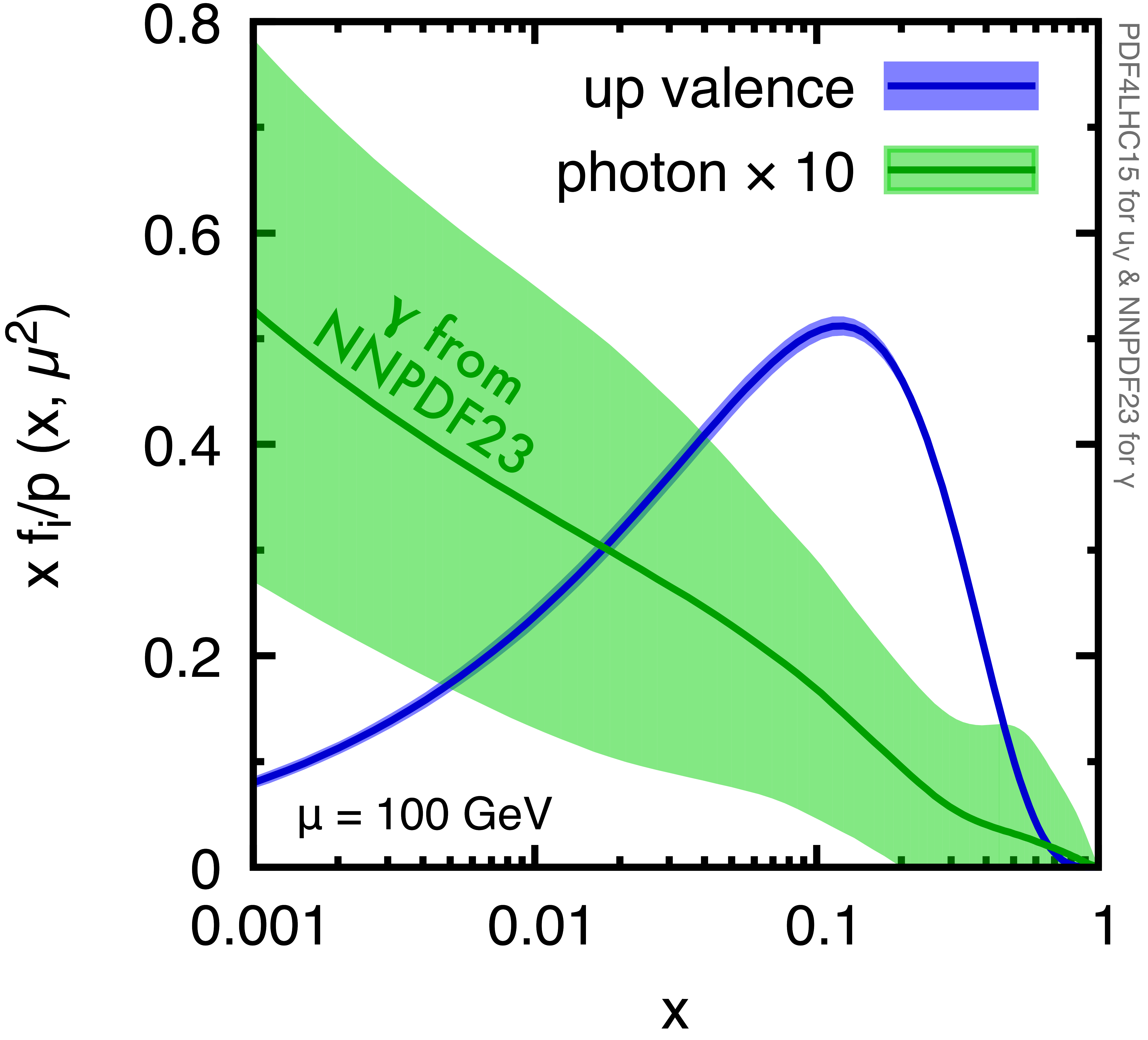
$$f_{i/p}(x, \mu^2)$$



One exception:

the photon distribution inside the proton

(had up to 100% uncertainty)



the photon distribution inside the proton

or "how much light accompanies a fast-moving proton?"

based on Manohar, Nason, GPS & Zanderighi
PRL '16 (Editors' Suggestion)
+ work in progress

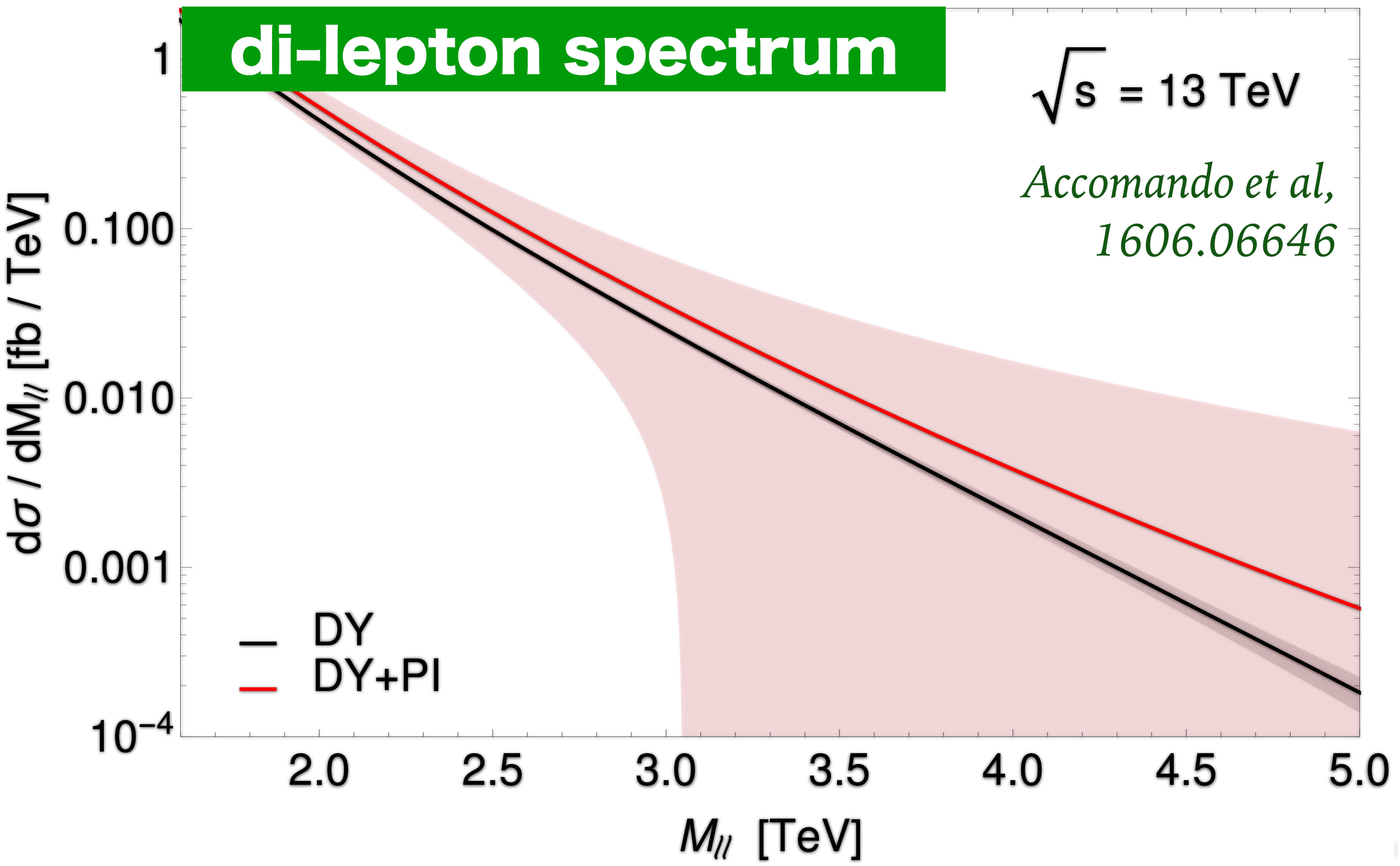
photon induced contribution to HW production

$pp \to H W^+ (\to l^+ \nu) + X$ at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0\ ^{+4.4}_{-2.9}$ fb

non-photon numbers from LHCHXSWG (YR4) including PDF uncertainties

← photon contribution brings the largest overall uncertainty

it matters in new-physics searches



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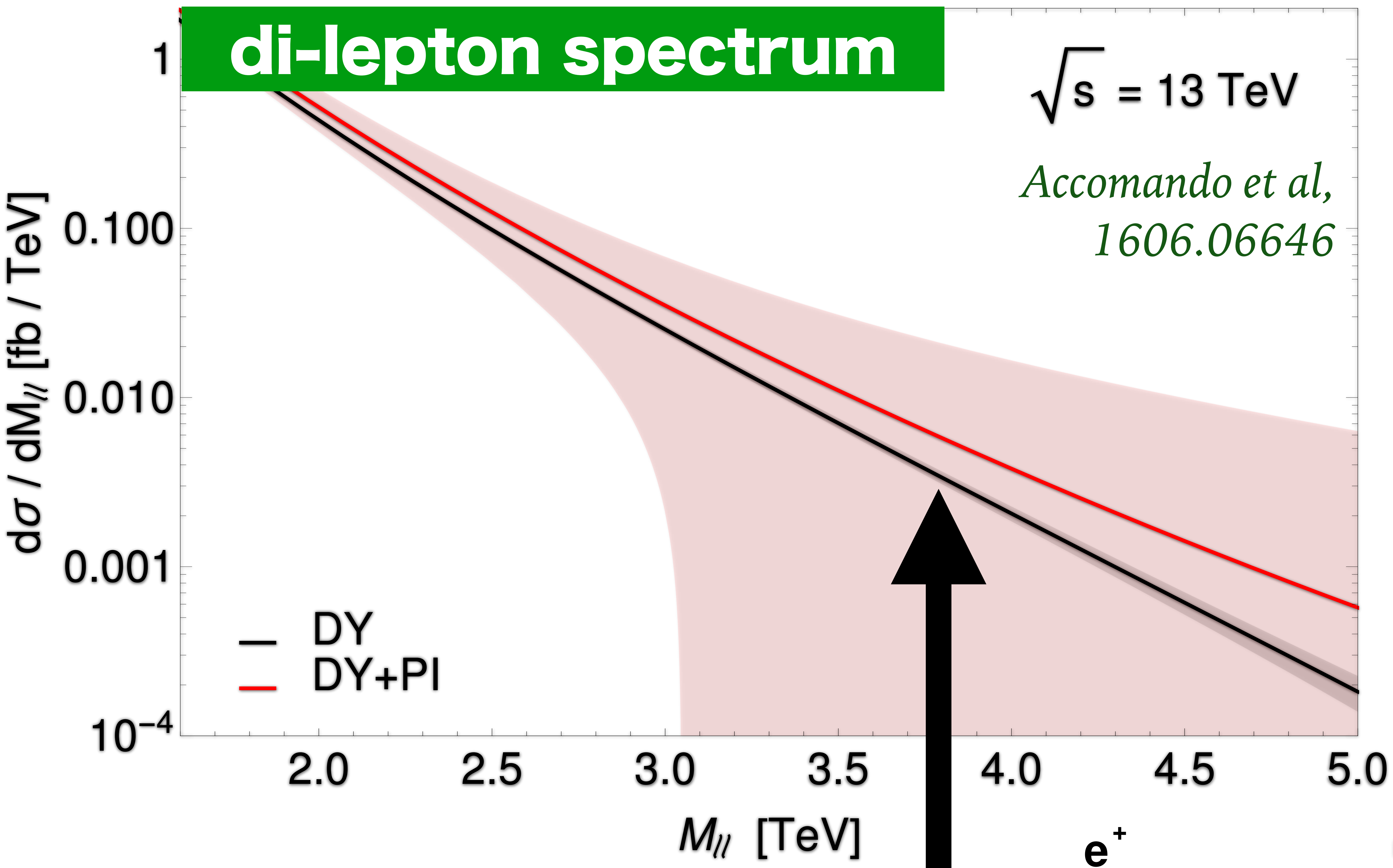
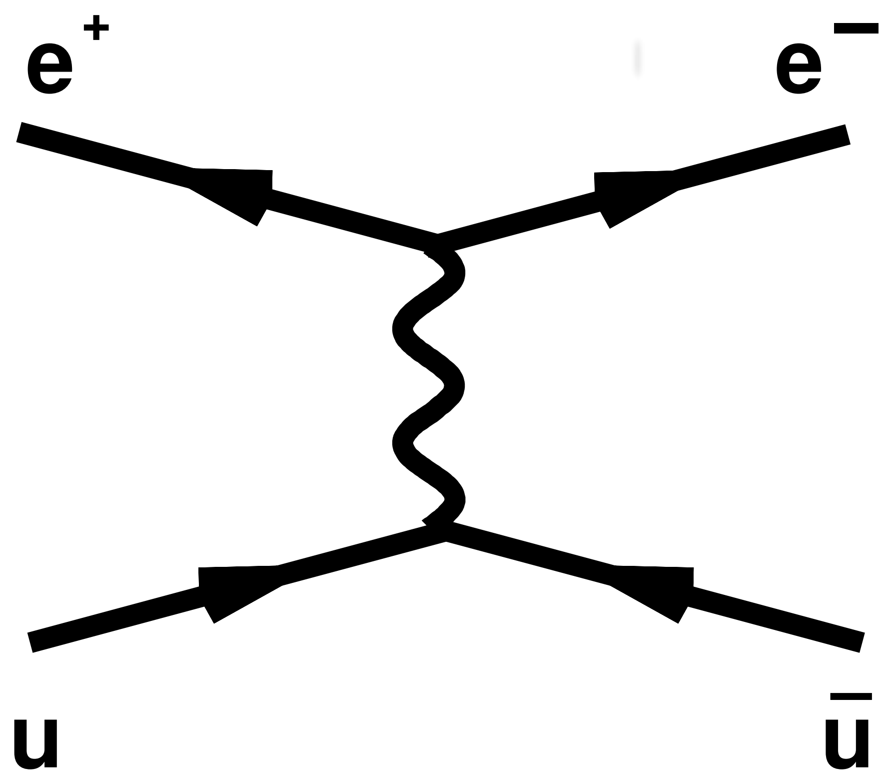


"normal" qqbar→ e^+e^- contribution



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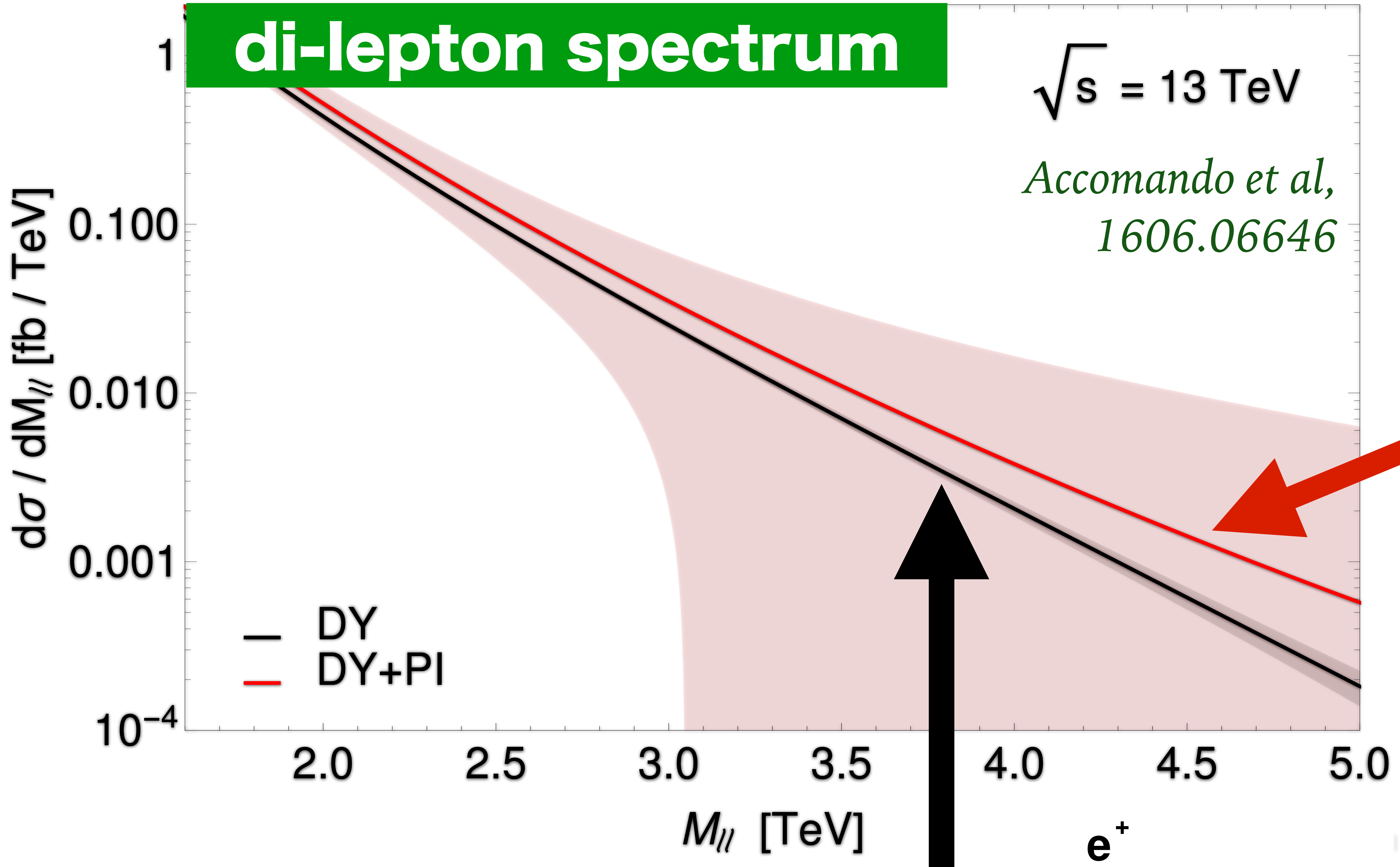
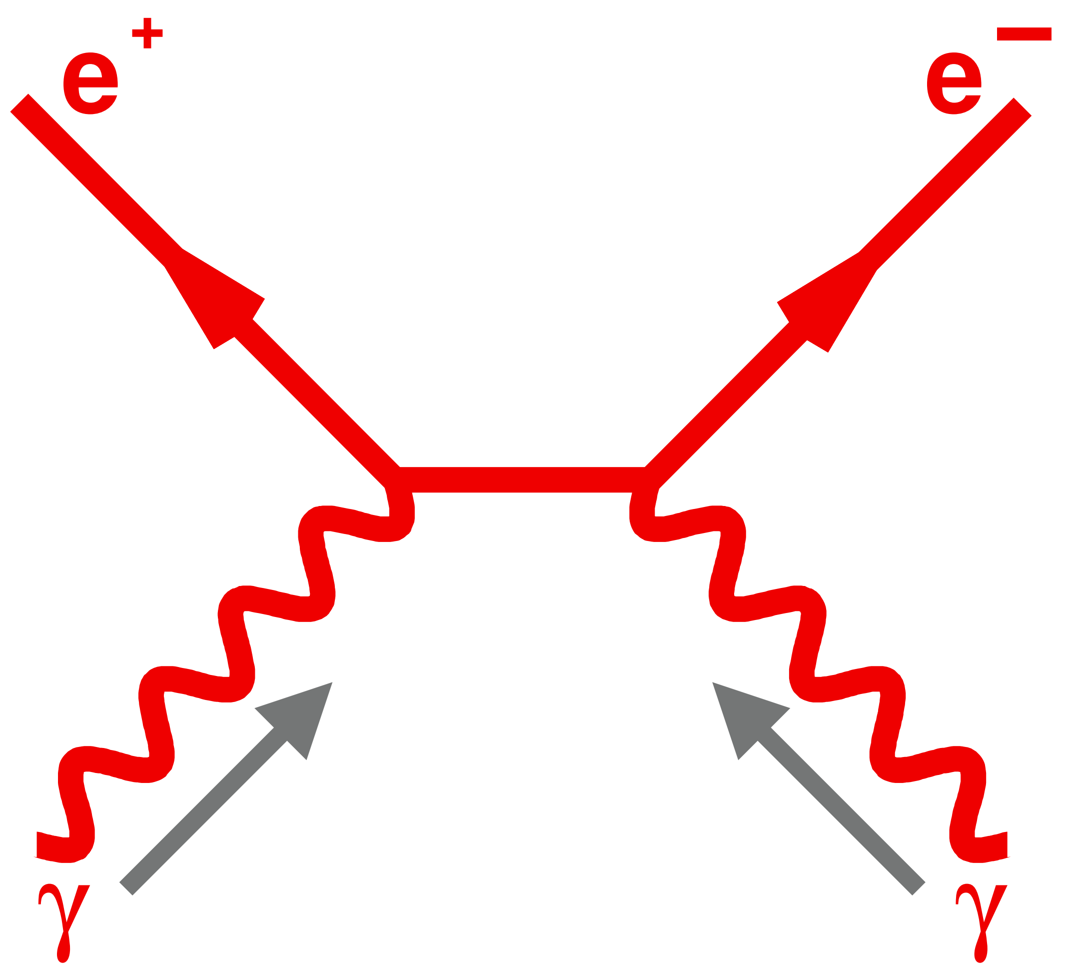
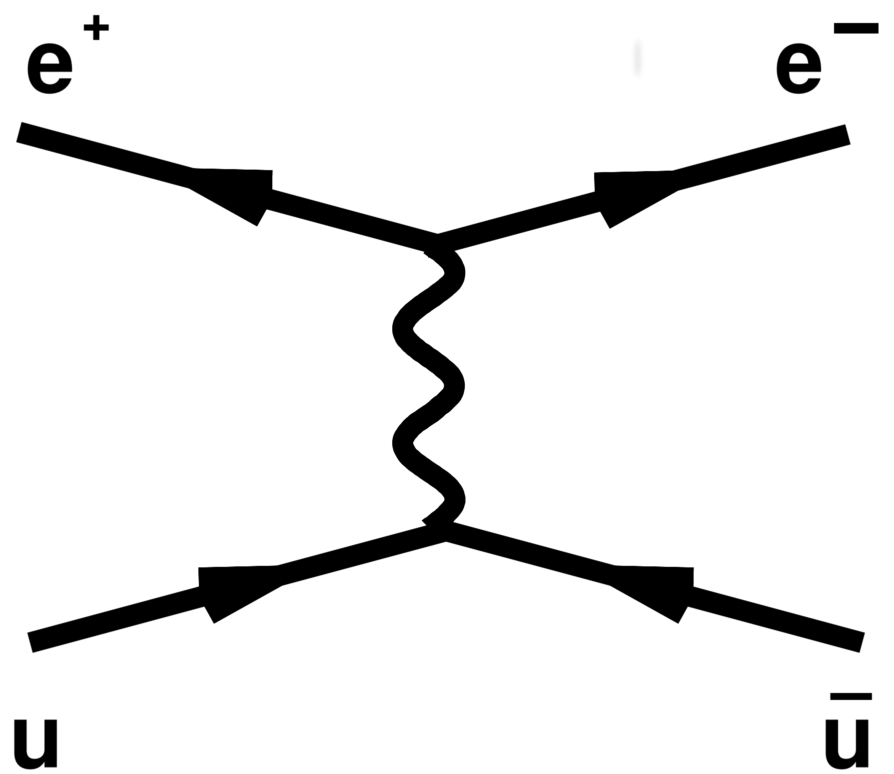


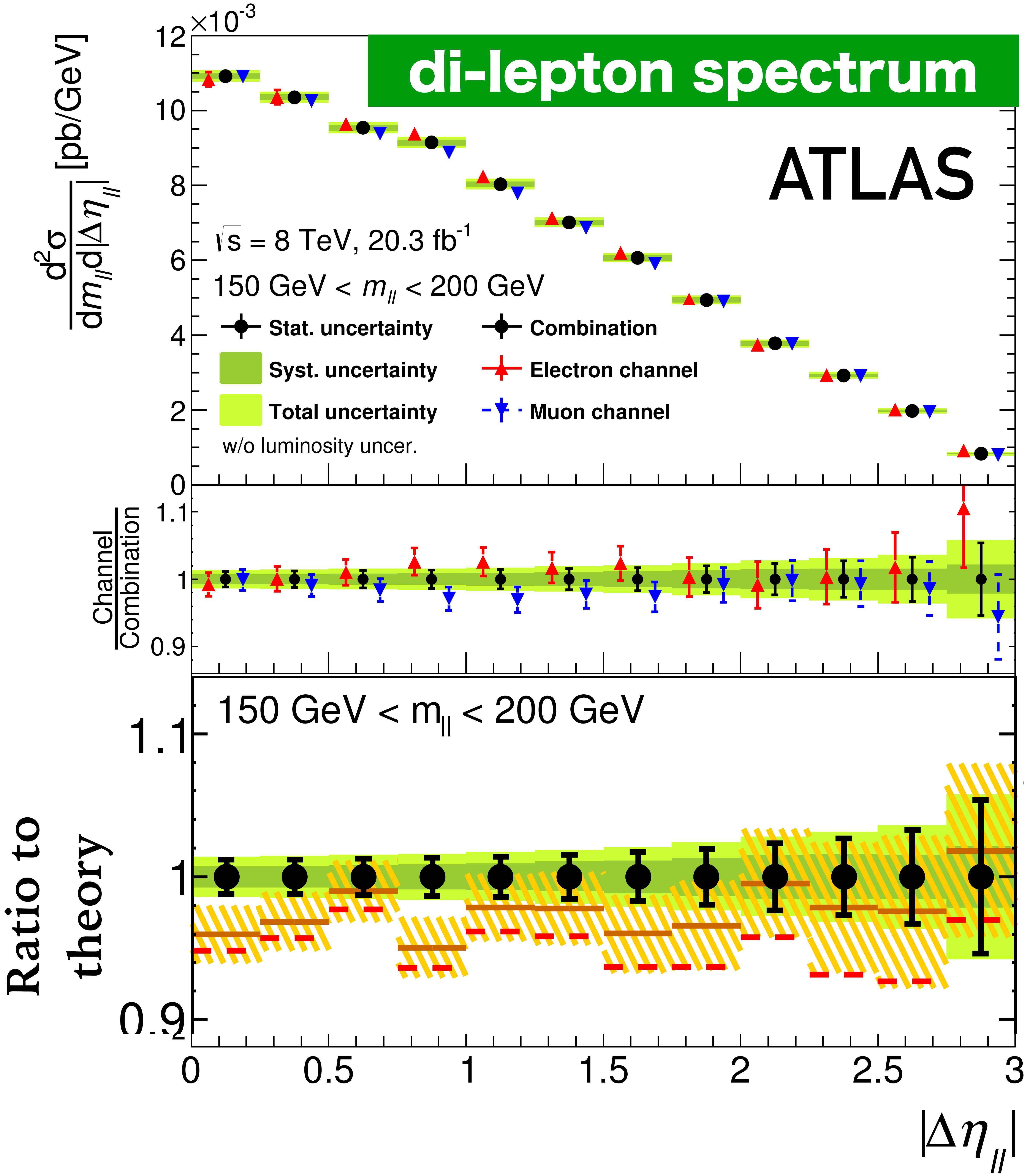


photon-induced contribution & uncertainty dominate [NNPDF23]

“normal” qqbar→ e^+e^- contribution



model-independent γ PDF fit (c. 2013)



model-independent γ PDF fit (c. 2013)

is there another way of doing this?

photon distribution from fast-moving charged particle

Point-like particle, e.g. electrons

➤ Fermi, Z. Phys. 1924 ; von Weizsäcker, Z. Phys 1924; Williams, Phys.Rev. 1934

$$f_{\gamma/e}(x,\mu^2) = \frac{\alpha}{2\pi}\left[\frac{1+(1-x)^2}{x}\log\left(\frac{1-x}{x^2}\frac{\mu^2}{m_e^2}\right) - 2\frac{1-x-x^2\frac{m_e^2}{\mu^2}}{x}\right]$$

photon distribution from fast-moving charged particle

Point-like particle, e.g. electrons

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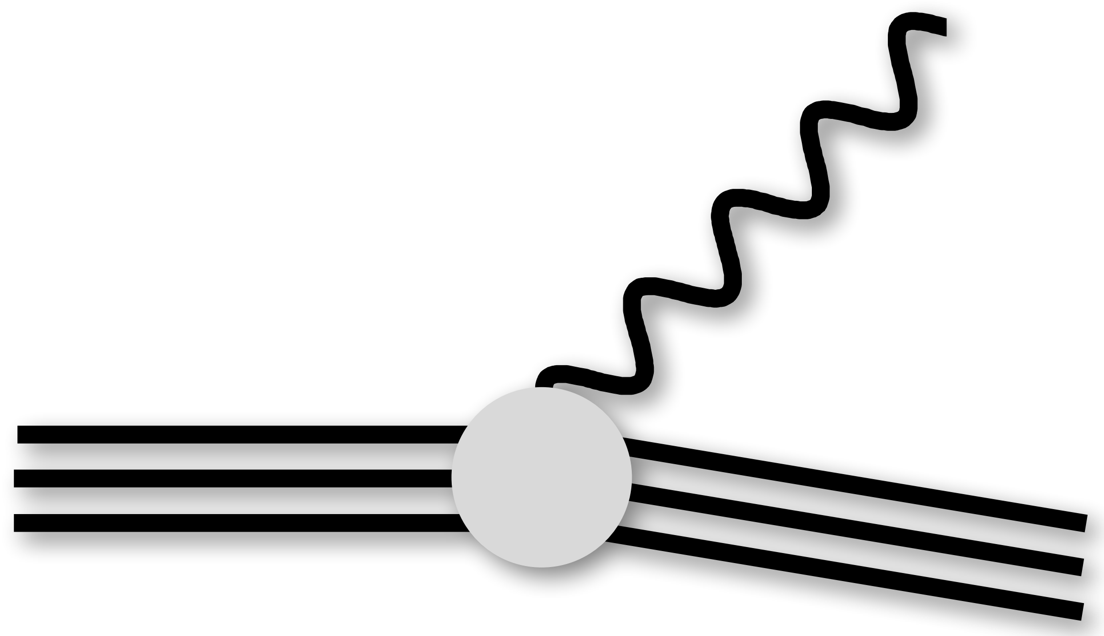
But protons are not point-like…

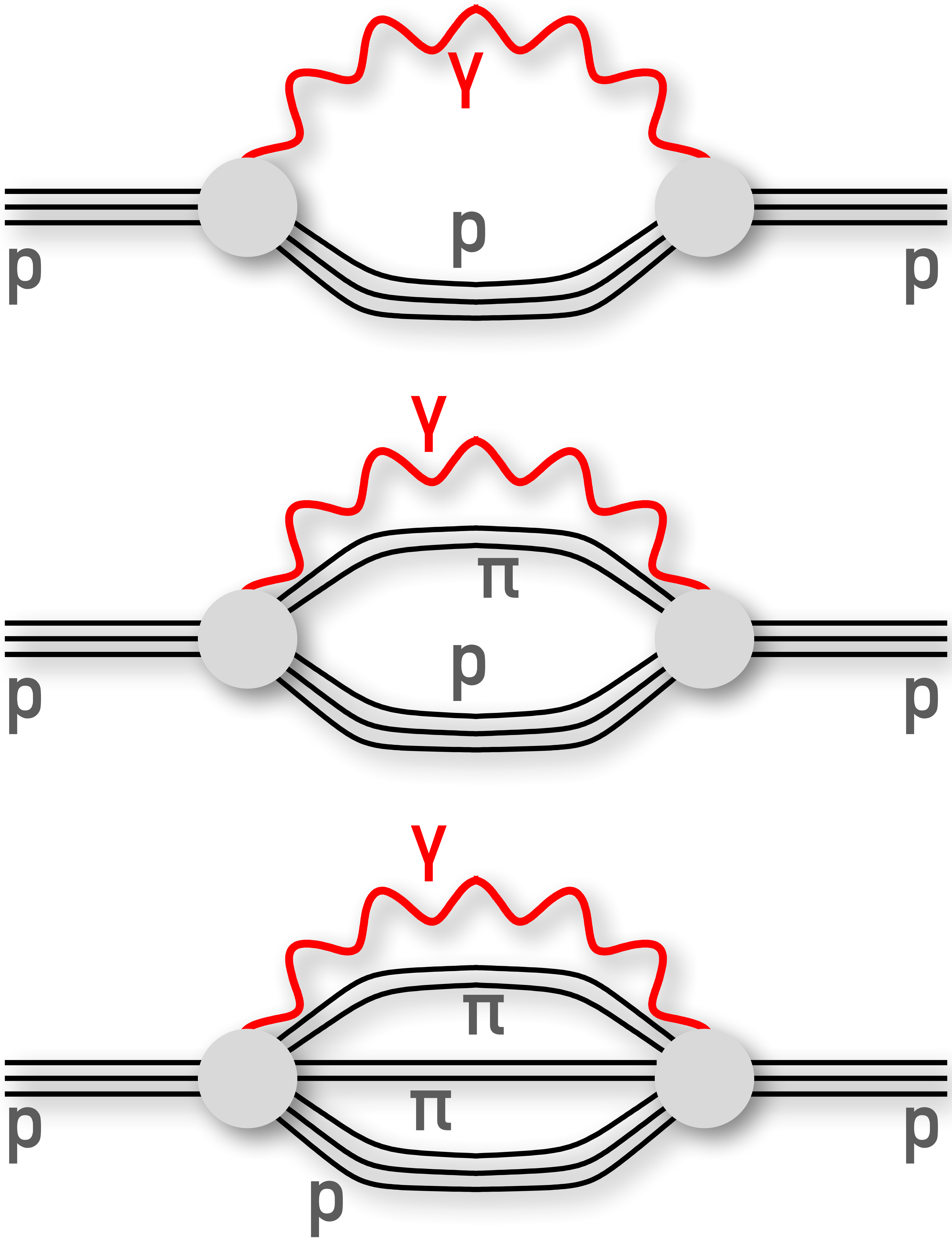
- Budnev, Ginzburg, Meledin & Serbo, Phys.Rept. 1974
  $\rightarrow$ an answer for the case where the proton remains intact after photon emission



given in terms of "proton form factors" (measurable from elastic ep scattering)

“number of photons” inside a proton?

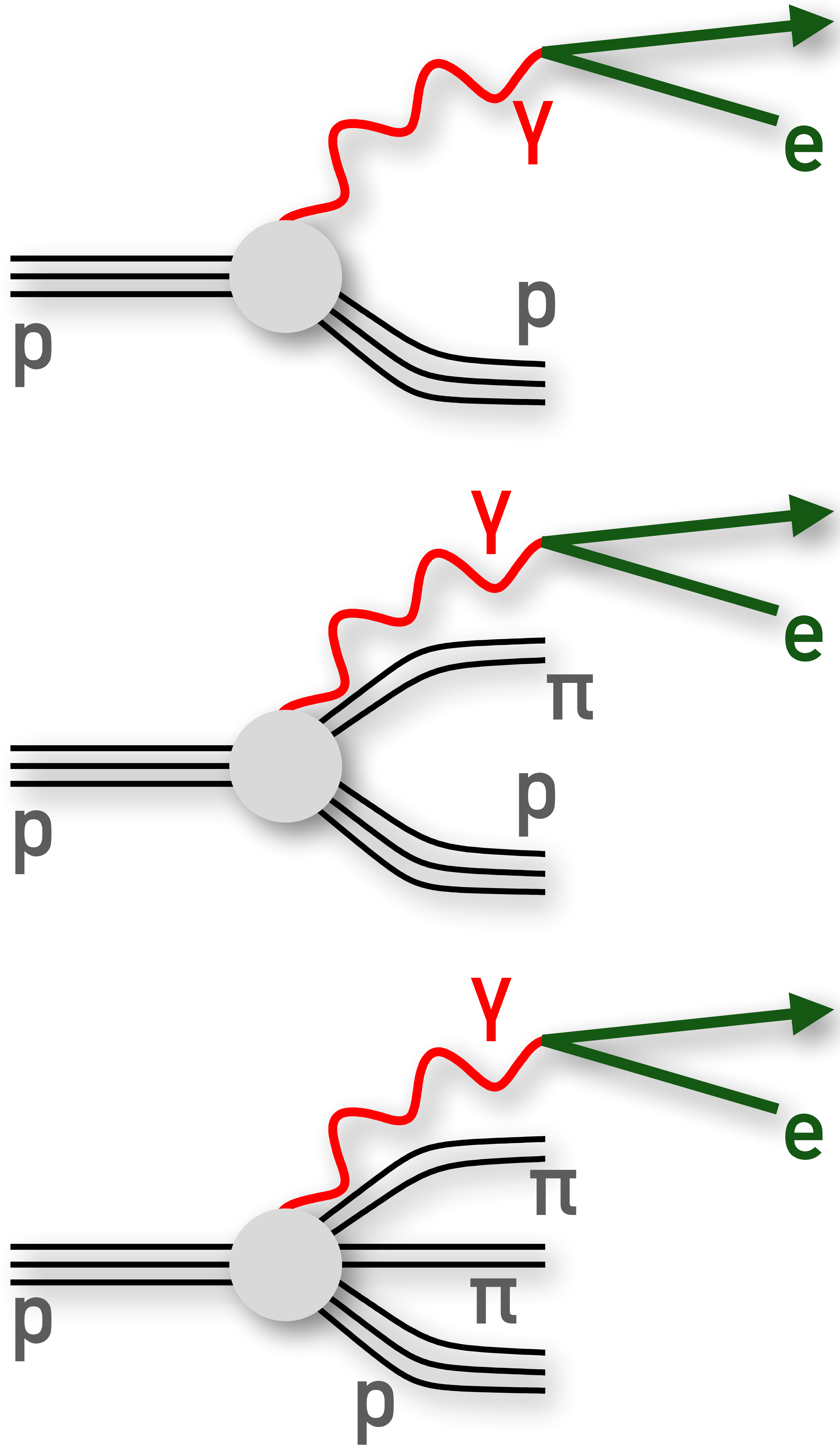
Proton constantly fluctuates in & out of different Fock states, some of which have a photon.



“number of photons” inside a proton?

Proton constantly fluctuates in & out of different Fock states, some of which have a photon.

If you absorb the γ, proton breaks up.



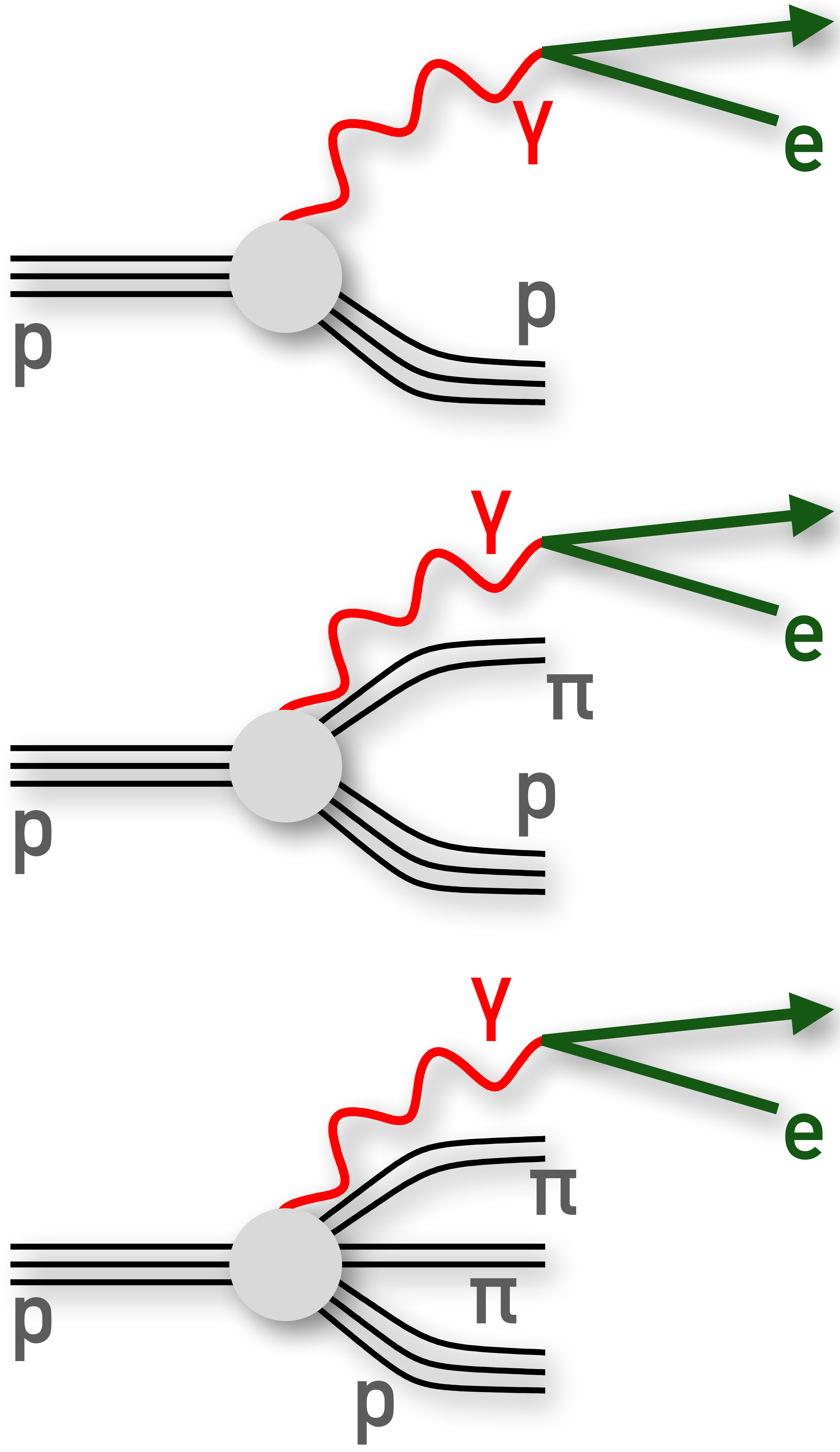
“number of photons” inside a proton?

Proton constantly fluctuates in & out of different Fock states, some of which have a photon.

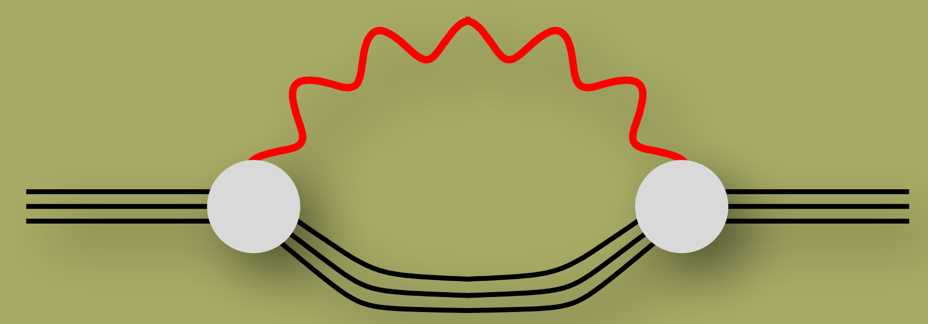
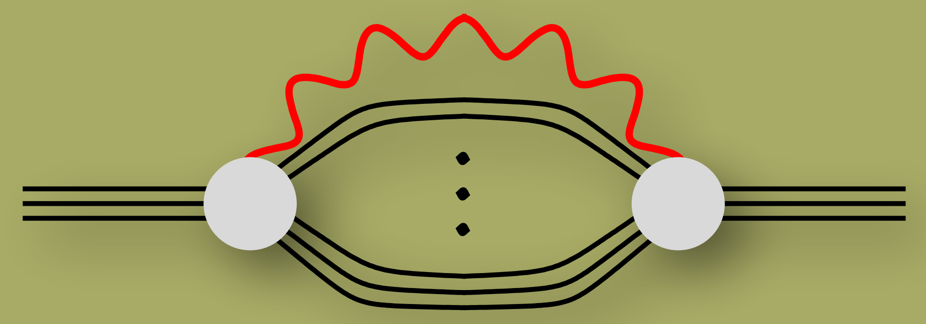
If you absorb the γ, proton breaks up.

Understanding this from first principles is a strong-coupling non-perturbative problem (beyond ability of lattice QCD)

Main approach in widely used γ determinations: **models.**

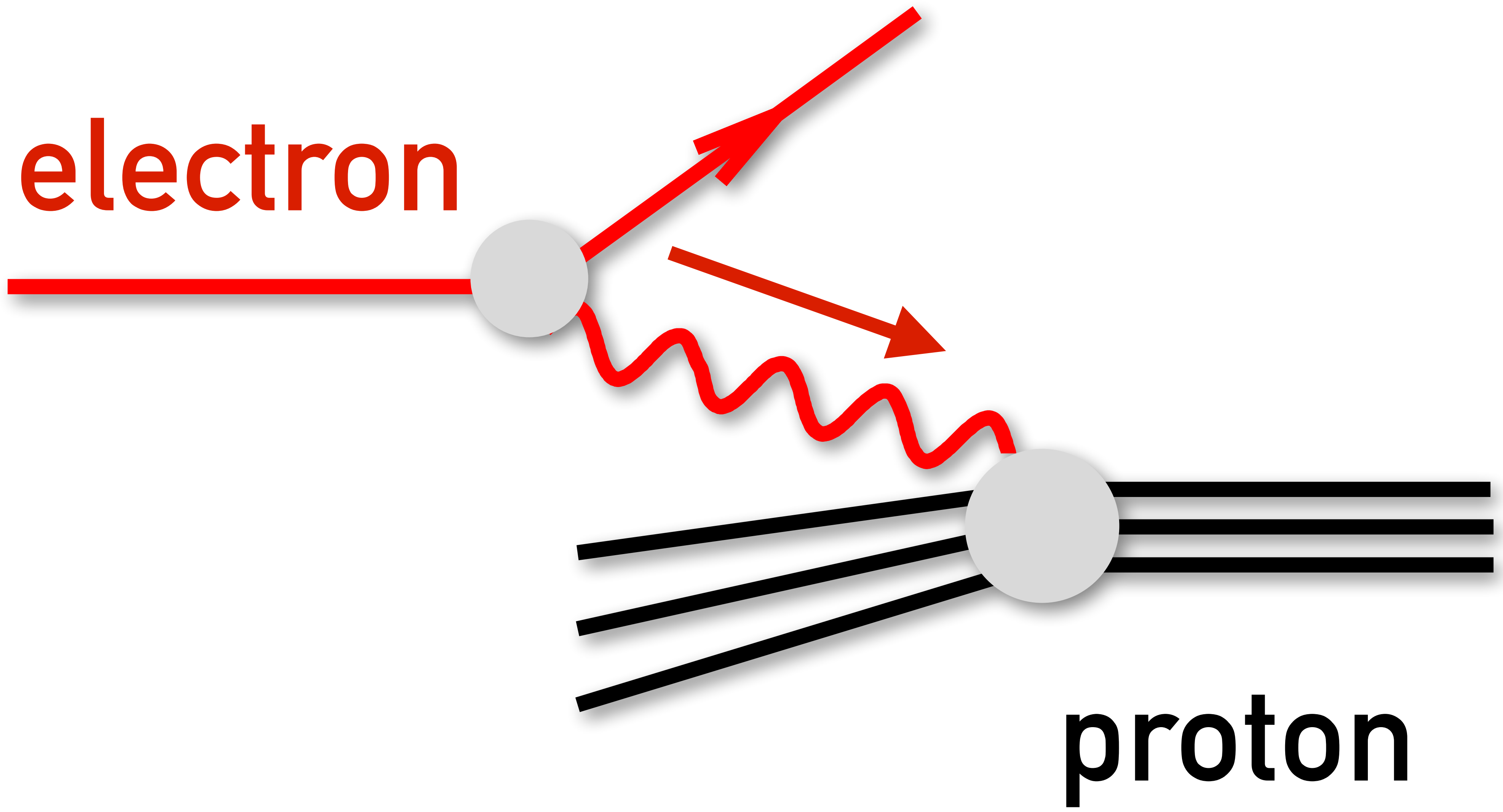


Widely discussed photon-PDF estimates

	 elastic	 inelastic	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	no separation; fit to data		✓

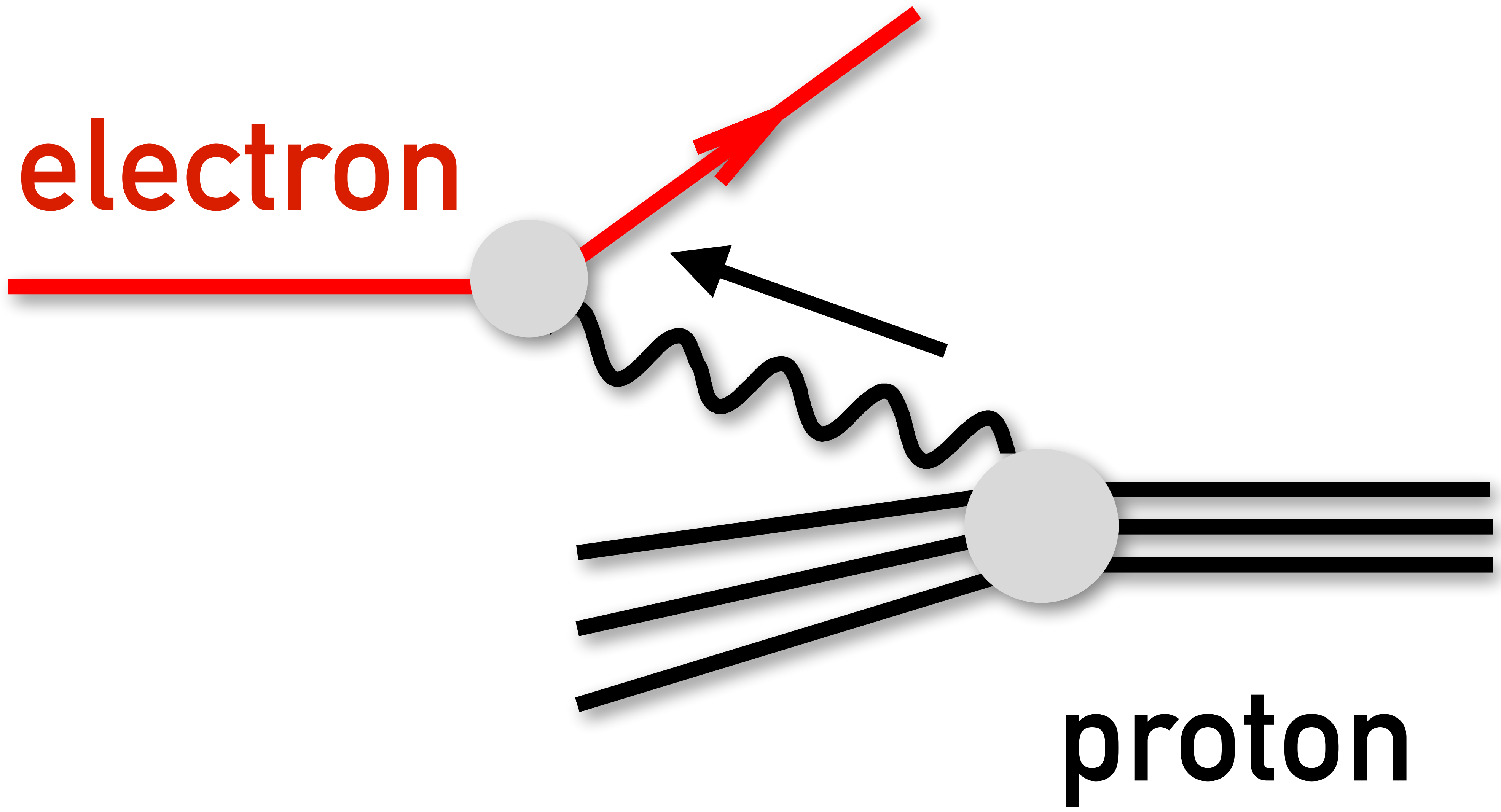
electron–proton scattering

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



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**



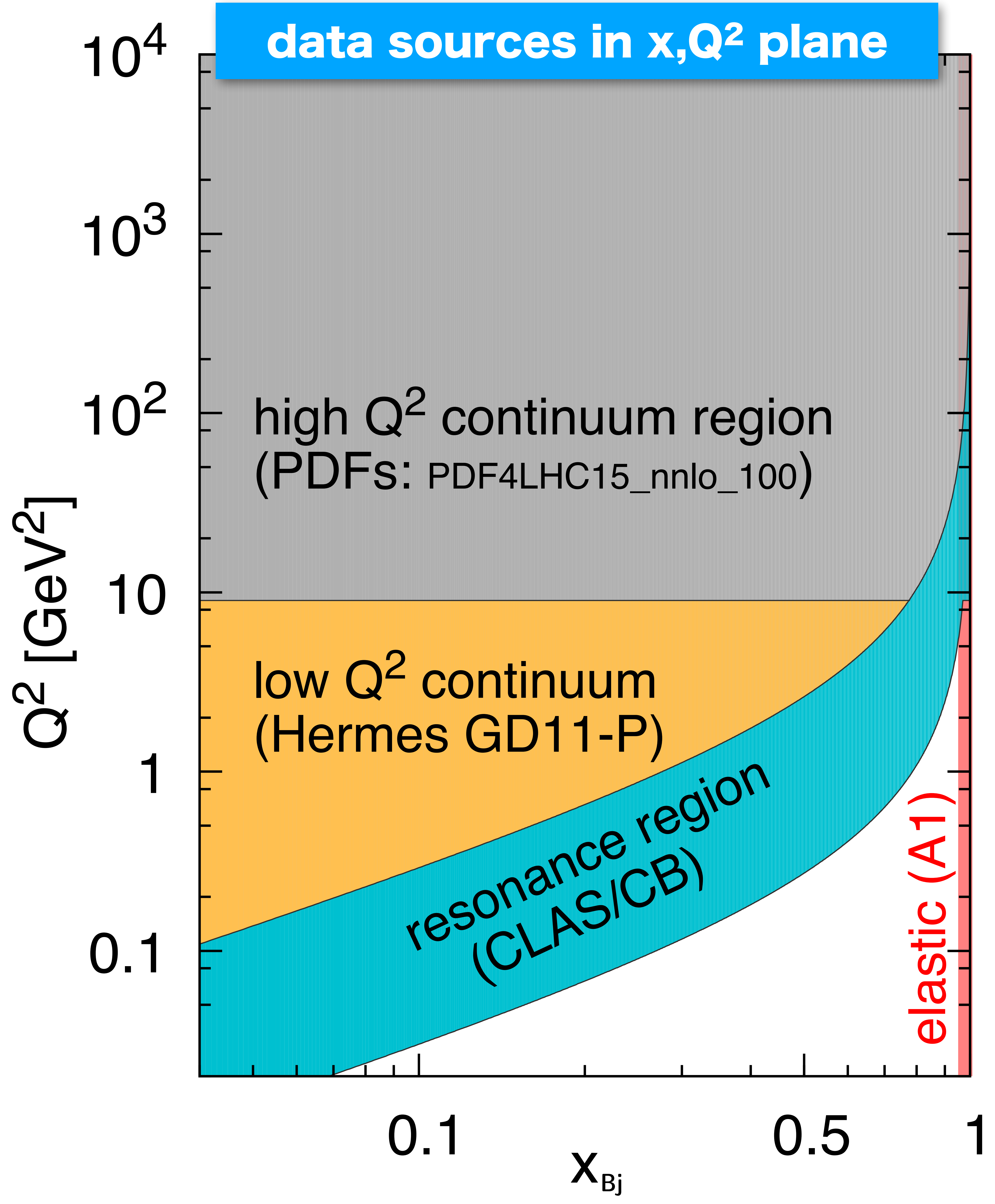
- Eveything about electron–proton interaction encoded in two "structure functions" $F_2(x,Q^2)$ & $F_L(x,Q^2)$

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

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

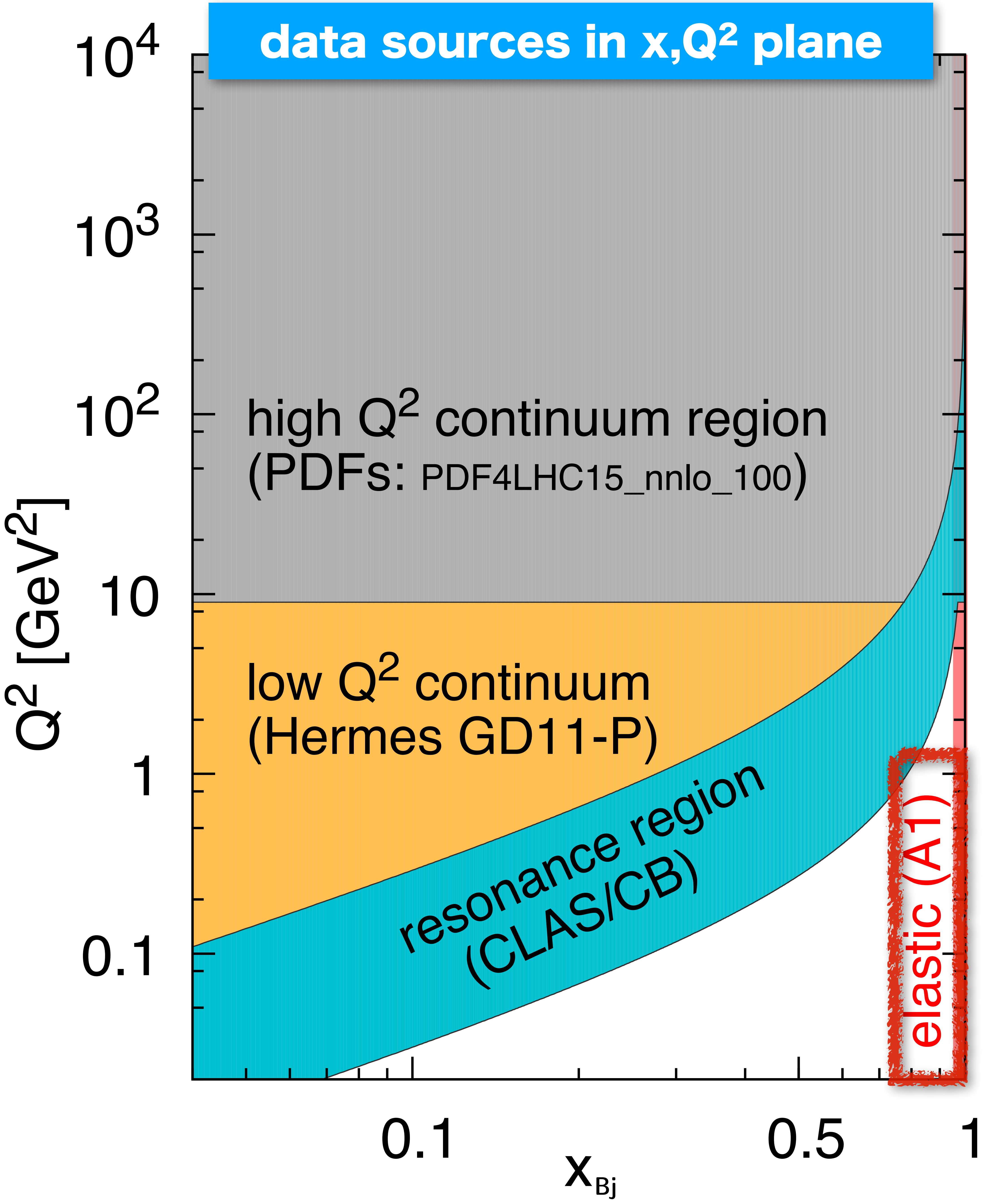
$$
xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}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

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)



DATA

- x, Q^2 plane naturally breaks up into regions with different physical behaviours and data sources
- We don't use F_2 and F_L data directly, but rather various fits to data



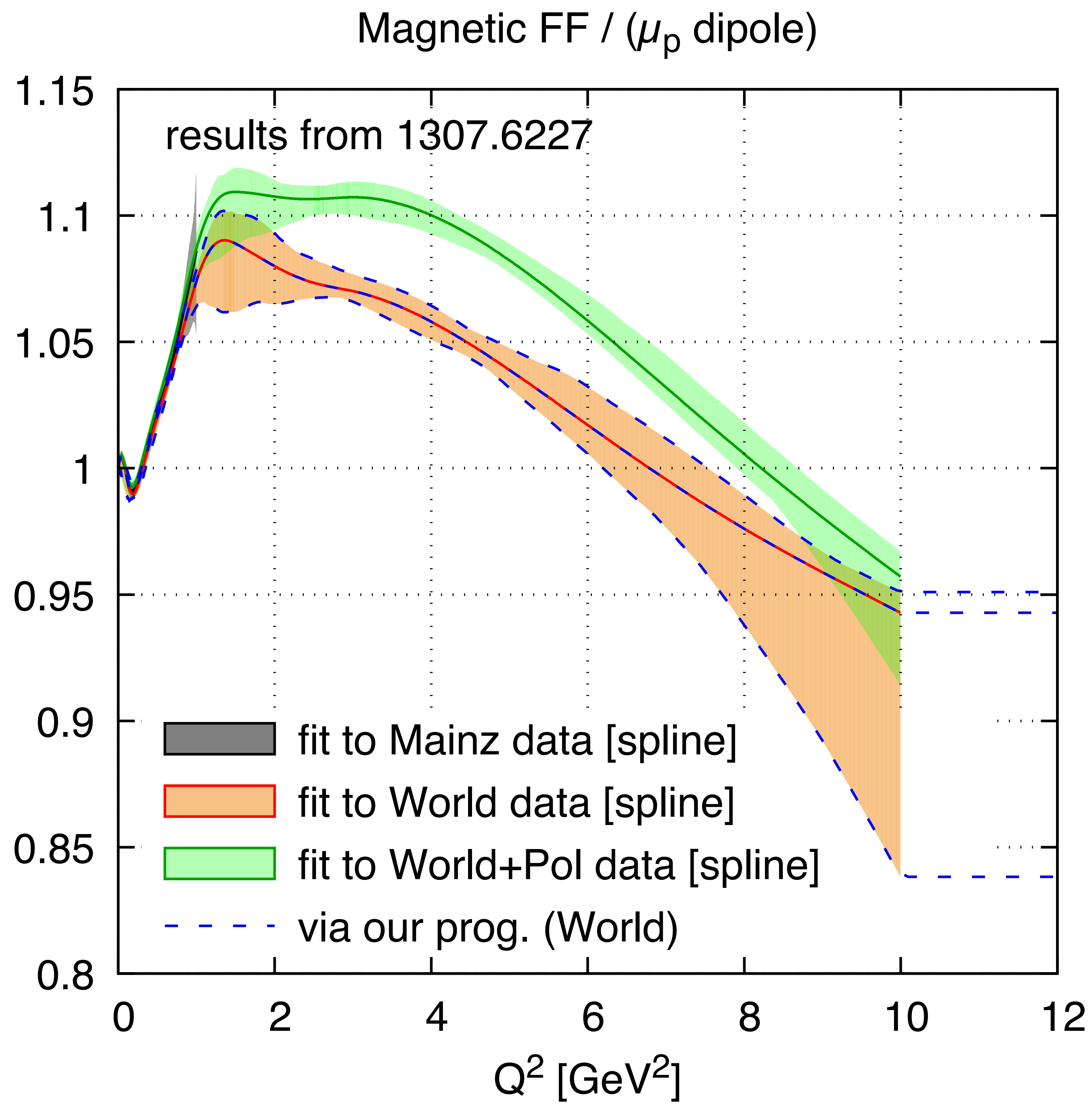
ELASTIC COMPONENT

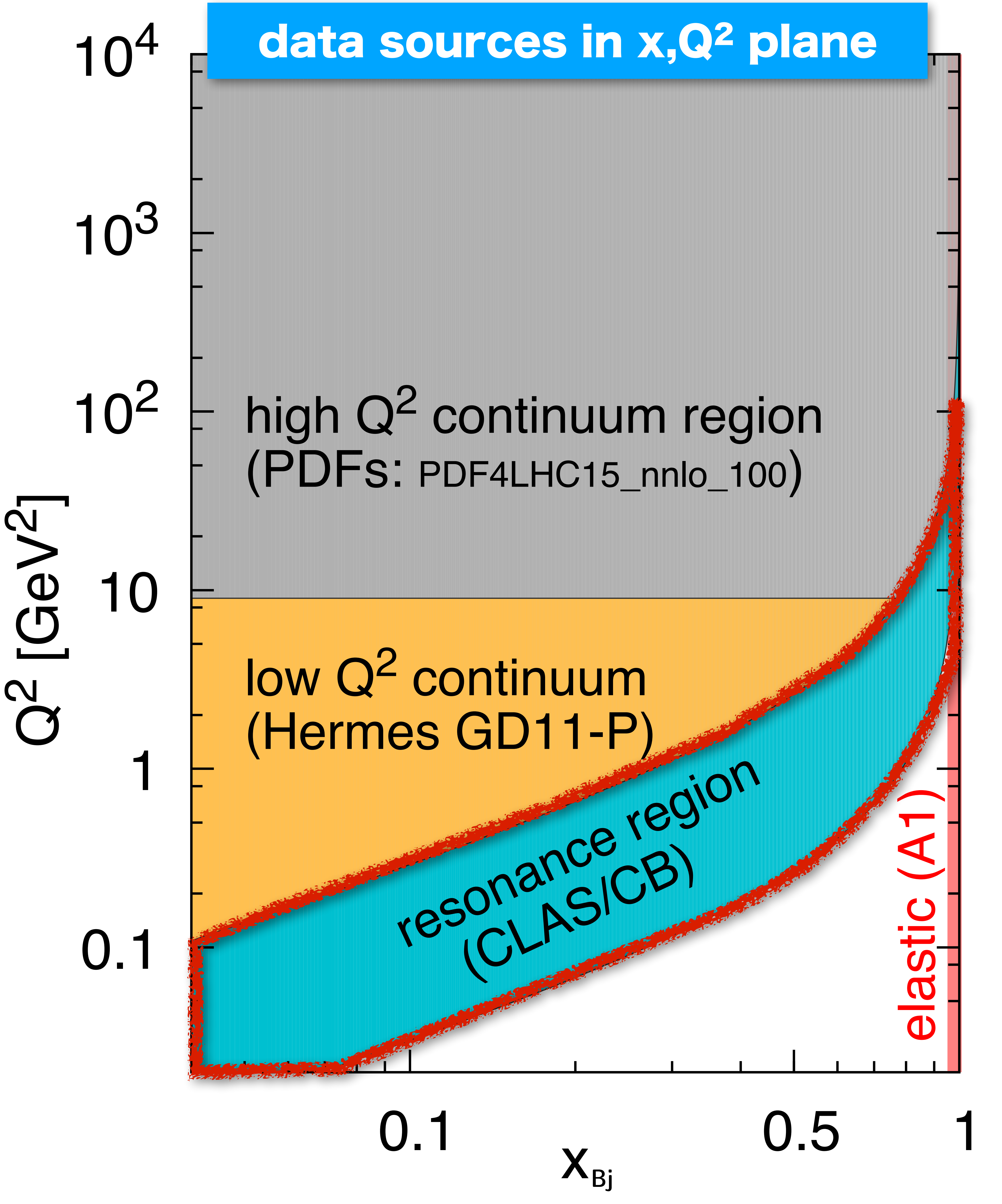
- Elastic component of $F_{2/L}$ lives at $x = 1$
- Express in terms of Sachs Form factors

$$\tau = Q^2/(4m_p^2)$$

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

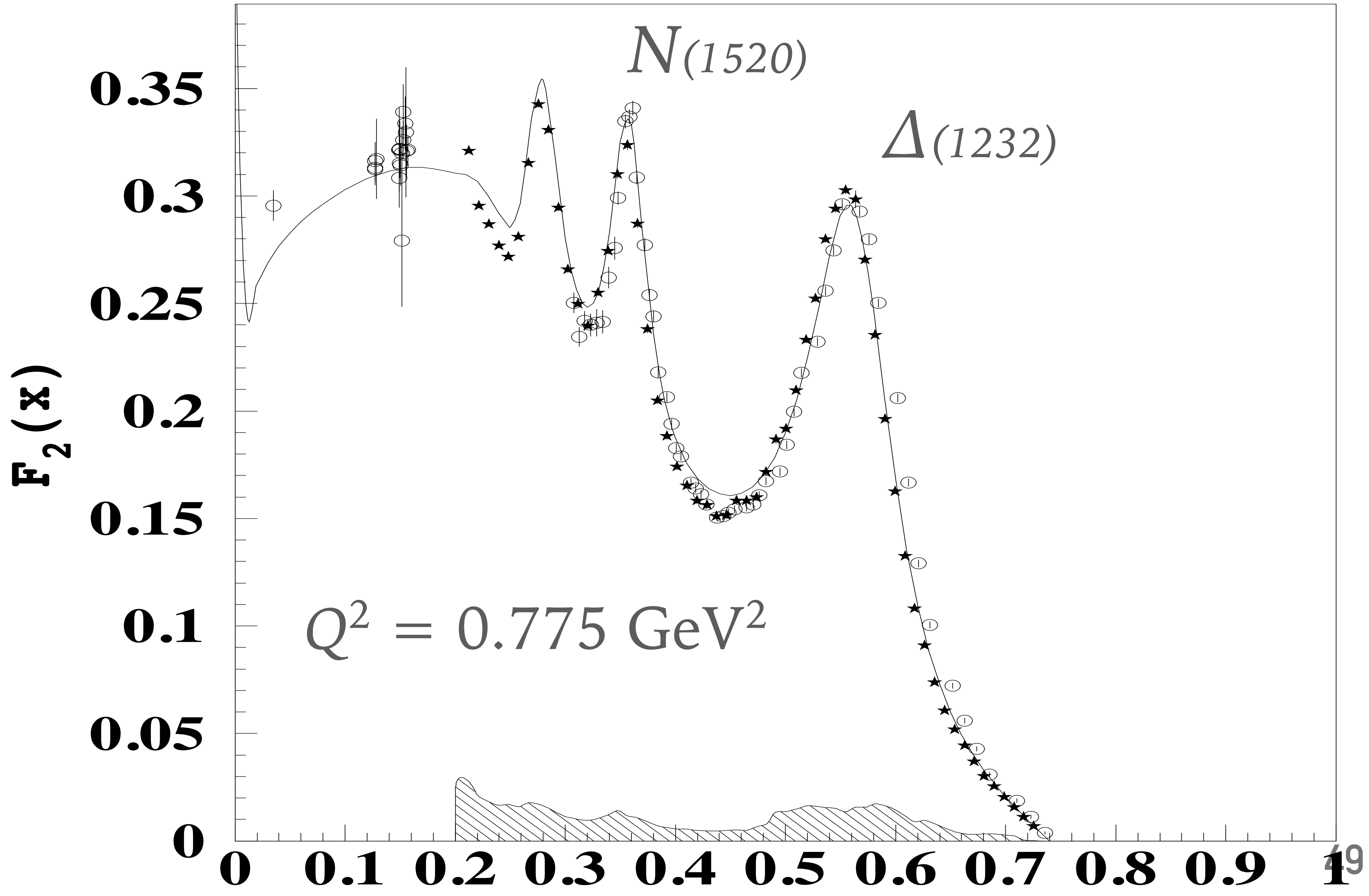
$$F_L^{\rm el} = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,,$$

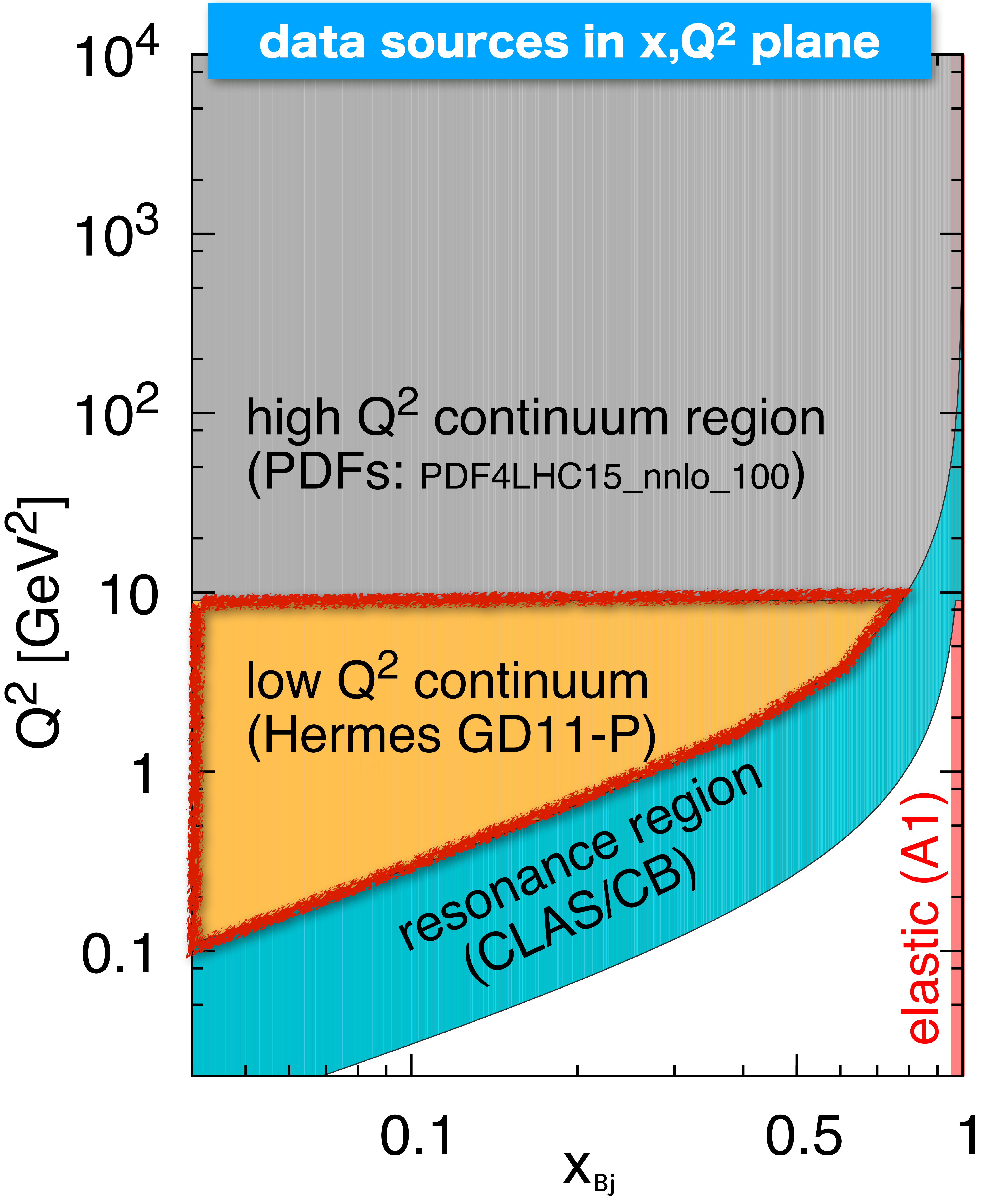




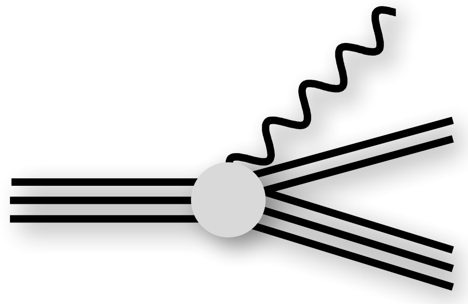
RESONANCE COMPONENT

- proton gets excited, e.g. to $\Delta \rightarrow p\pi$ and higher resonances
- relevant for $(m_p+m_\pi)^2 < W^2 < 3.5\,\text{GeV}^2$

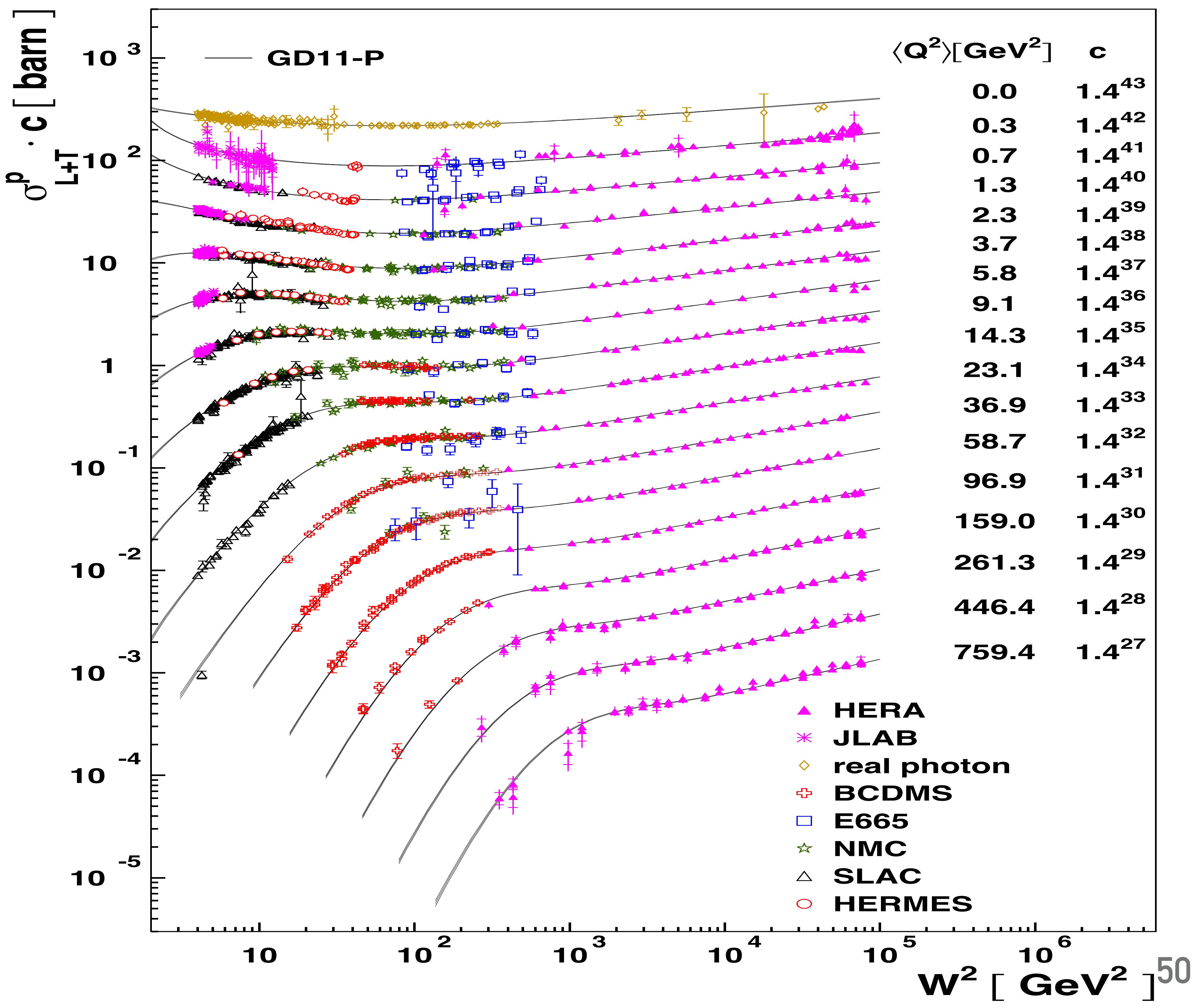


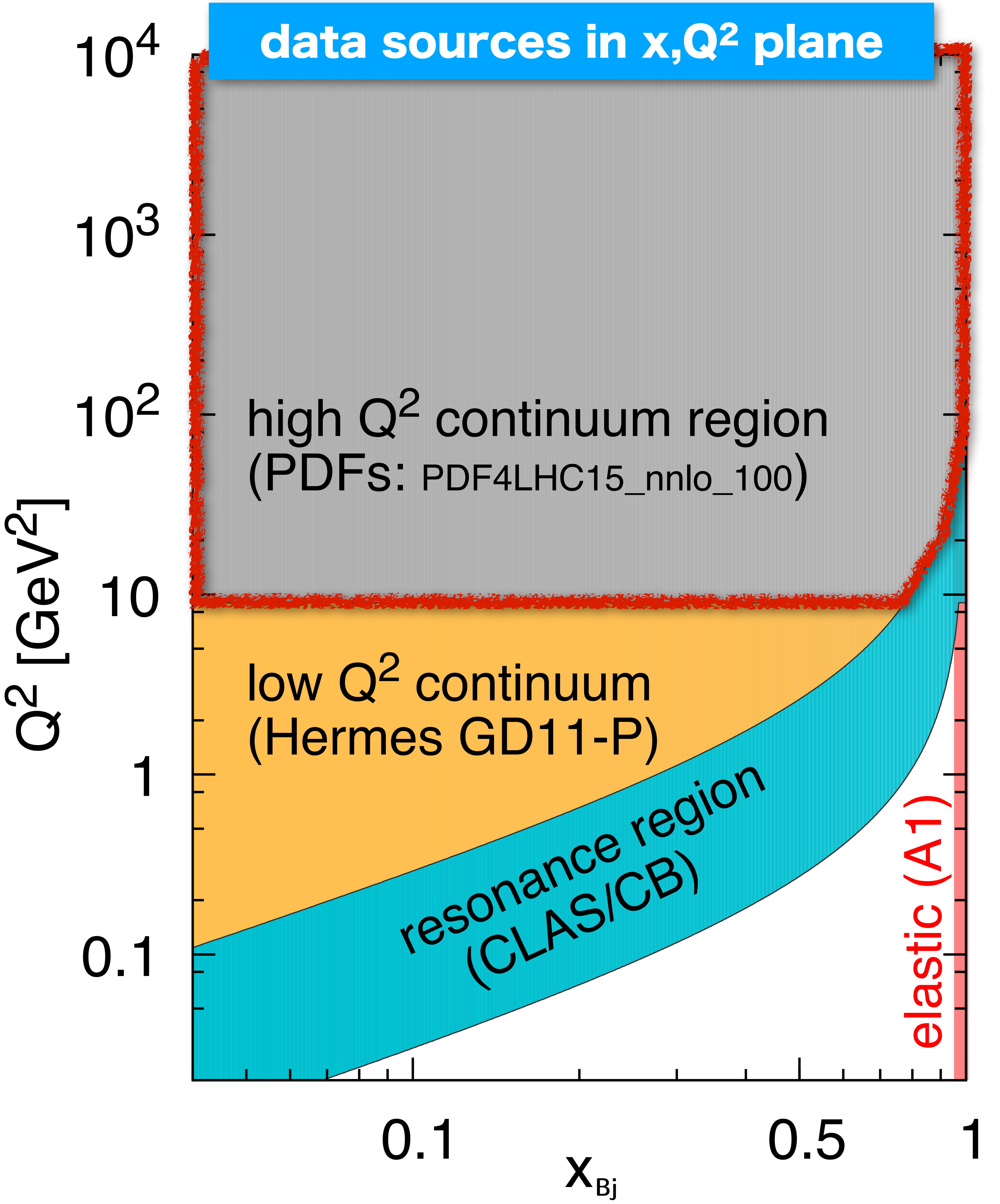


CONTINUUM COMPONENT



- Much data
- For $Q^2 \to 0$, $\sigma_{\gamma p}$ indep. of Q^2 at fixed W^2



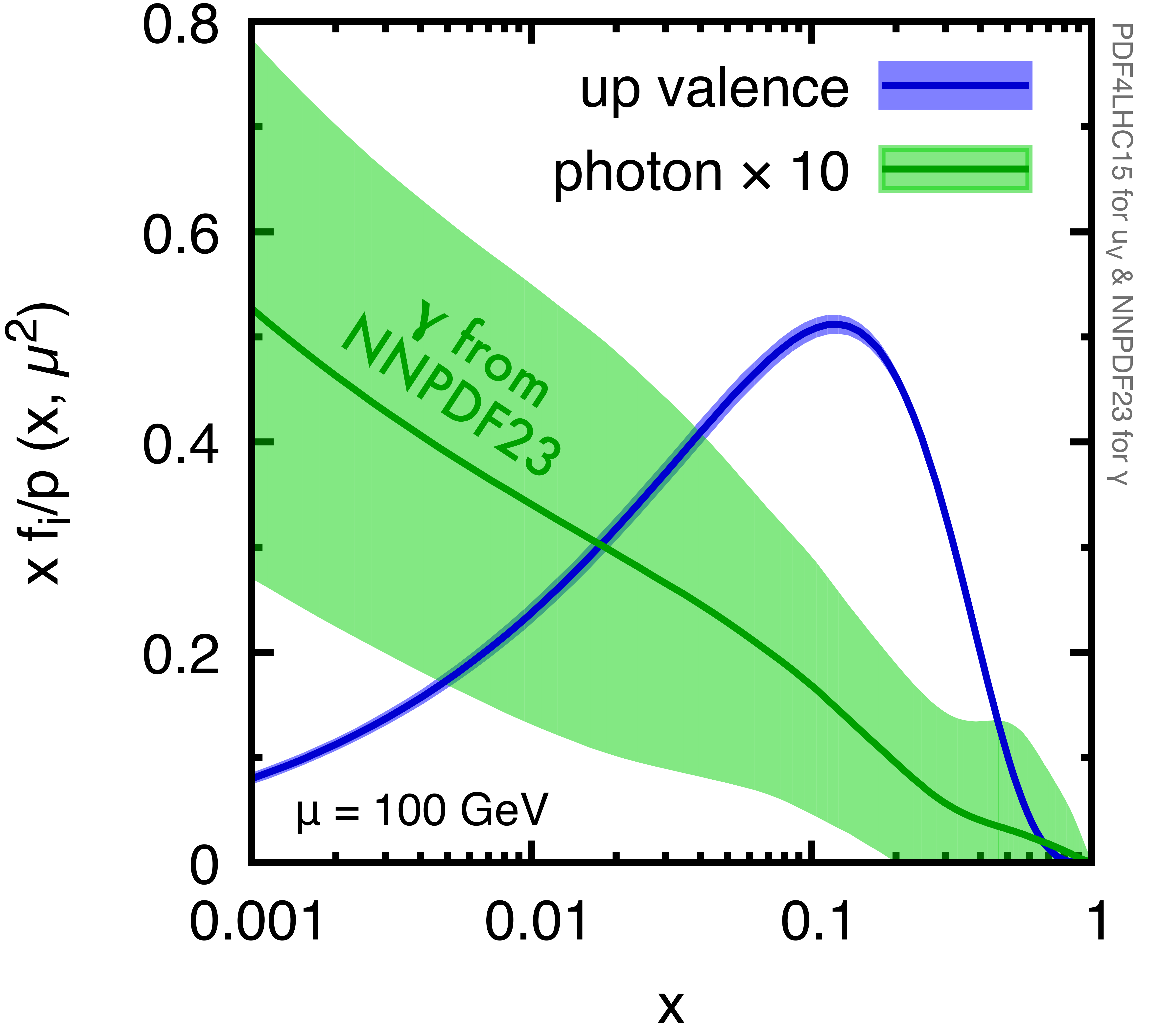


CONTINUUM COMPONENT

- Less direct data for F_2 and F_L at high Q^2
- But we can reliably use PDFs and coefficient functions (up to NNLO) to calculate them
- Our default choice is PDF4LHC15_nnlo_100 (and zero-mass variable flavour-number scheme)

photon PDF results

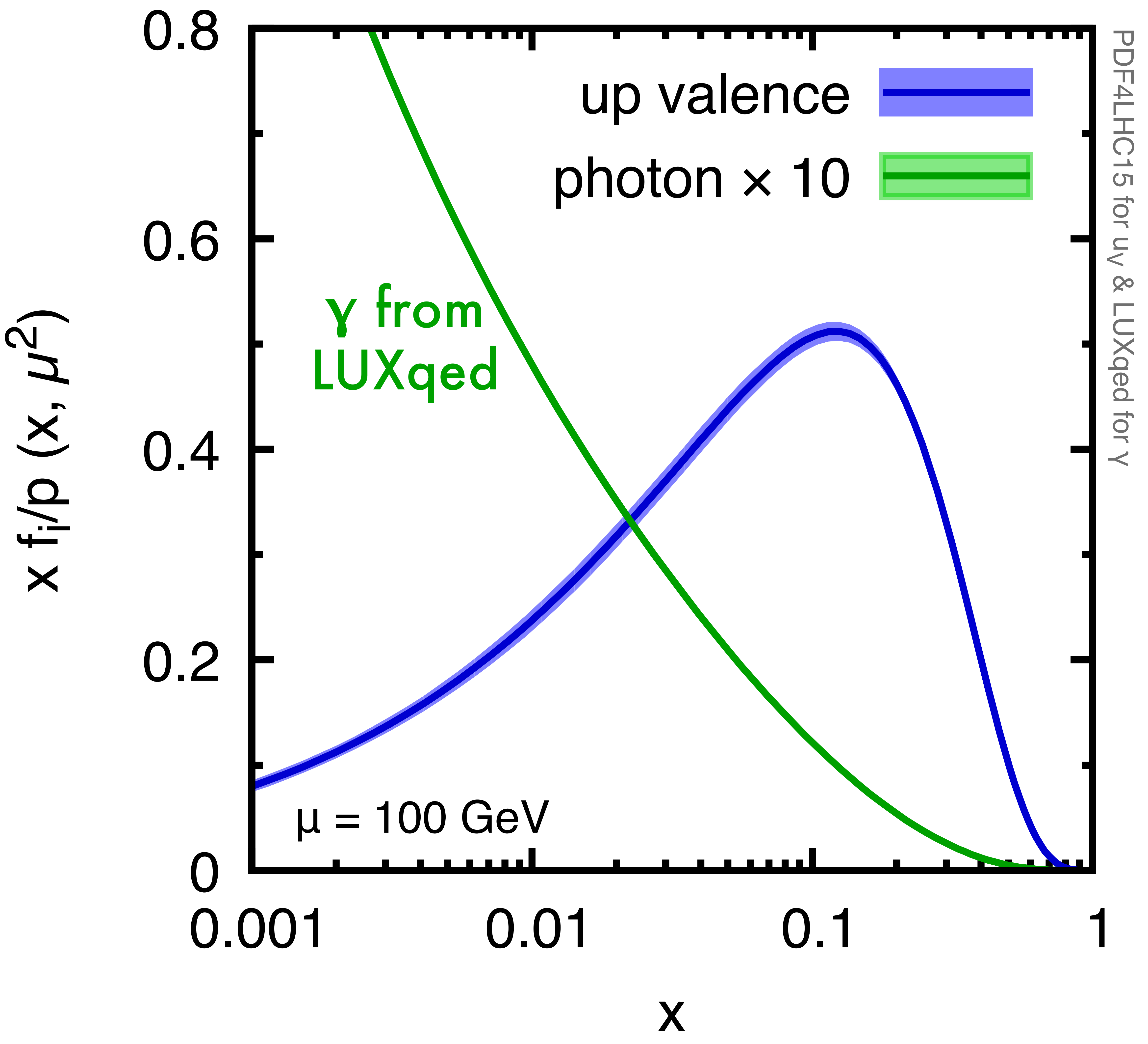
➤ Model-independent uncertainty (NNPDF) was 50–100%



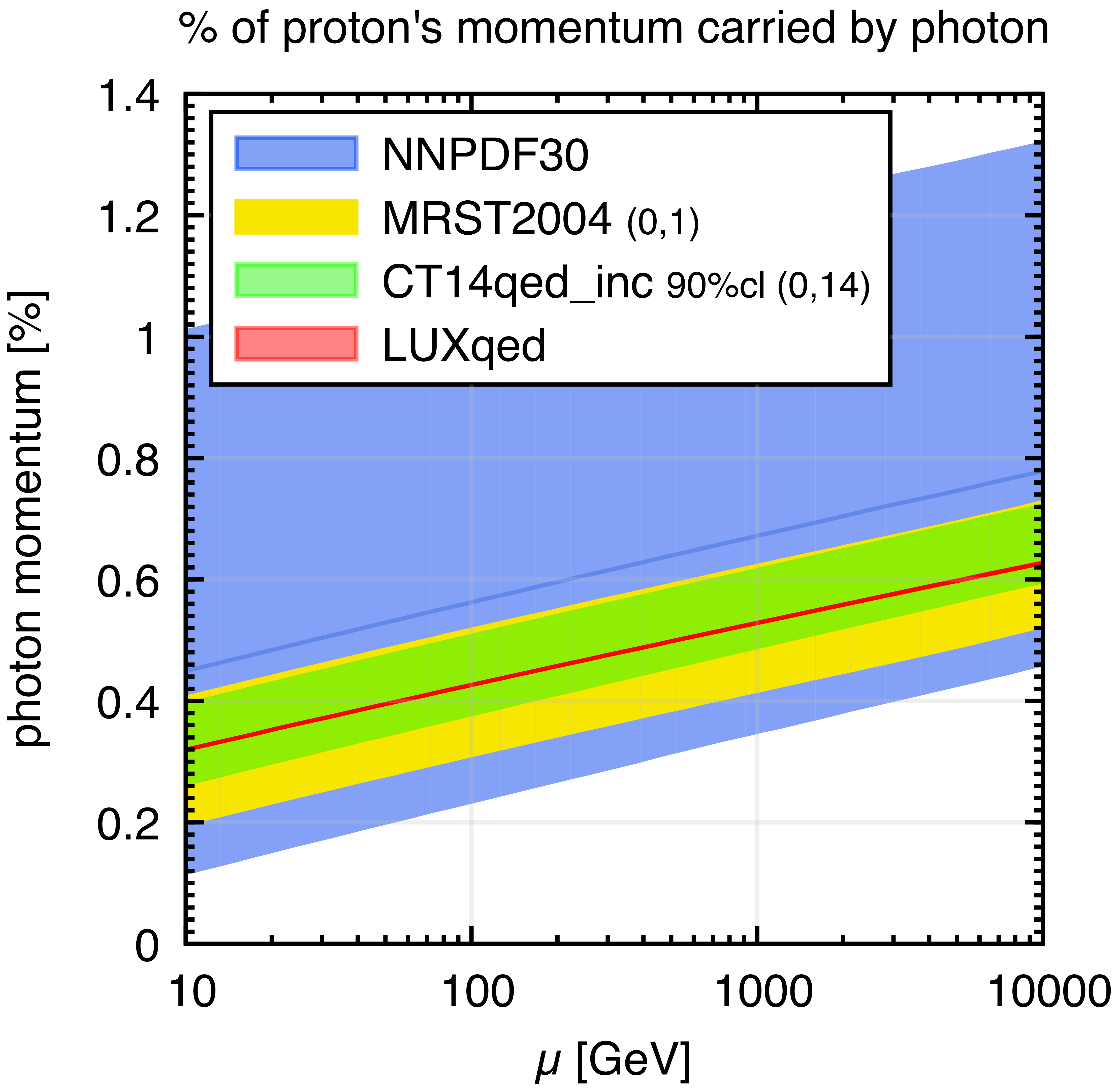
photon PDF results

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

pp → H W^+ (→ $l^+\nu$) + X at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0\,^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb



How much light is there in the proton? [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)

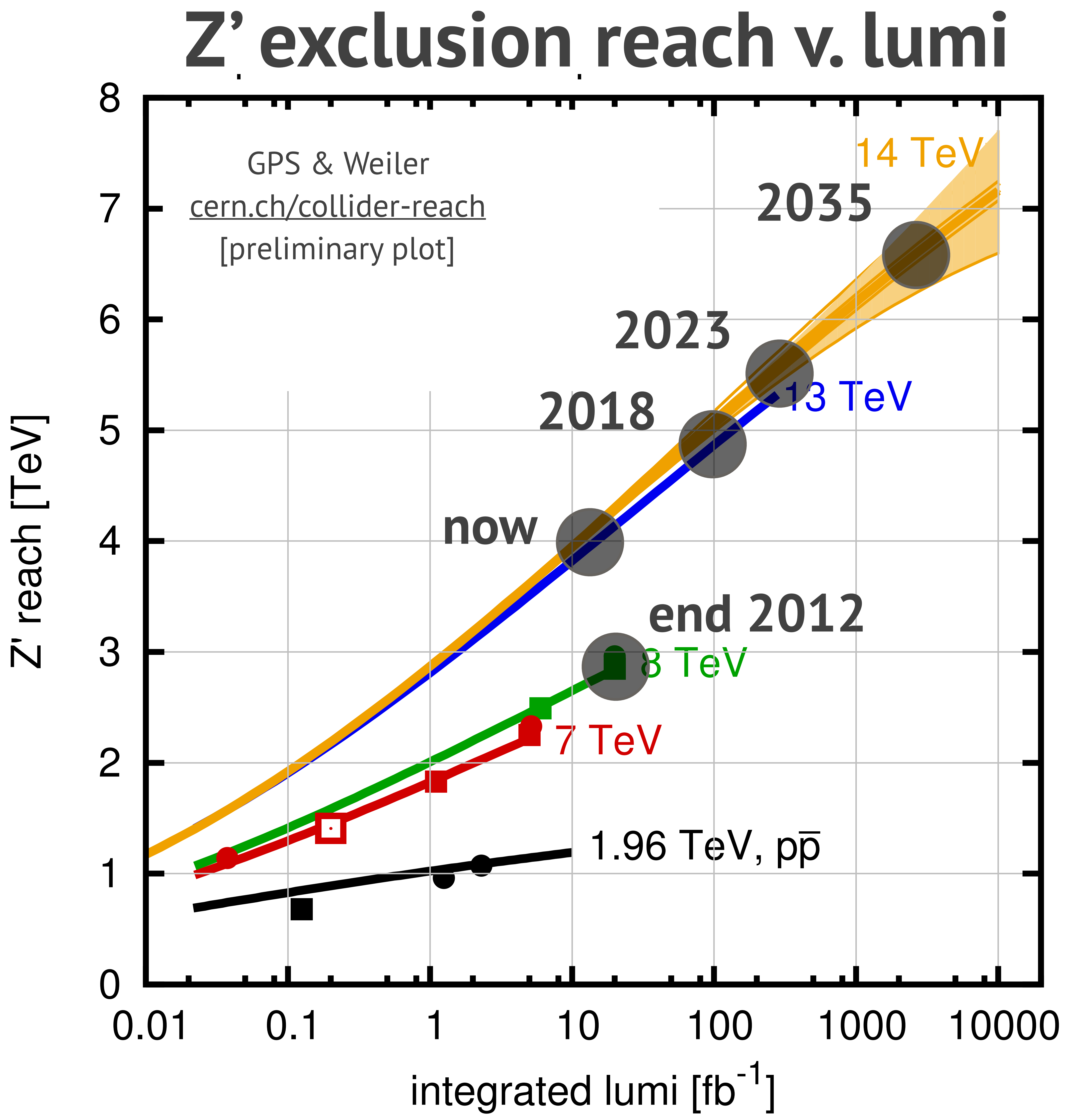
CONCLUSIONS

Summary

- The LHC has a rich programme in the years ahead to **establish** large parts of the **Higgs sector** of the Standard Model
- Extracting **qualitatively new information**, depends on **quantitative precision** in understanding proton–proton collisions
- New ways of thinking about precision LHC physics can bring big payoffs (and solve long-standing basic physics problems, e.g. γ PDF)
- Search for New Physics (BSM) continues, aided by the progress

EXTRA SLIDES

Discovery potential: (now → HL-LHC) > (run I → now)



Today

- 20 fb^{-1} @ 8 TeV
- 13 fb^{-1} @ 13 TeV (results)

Future

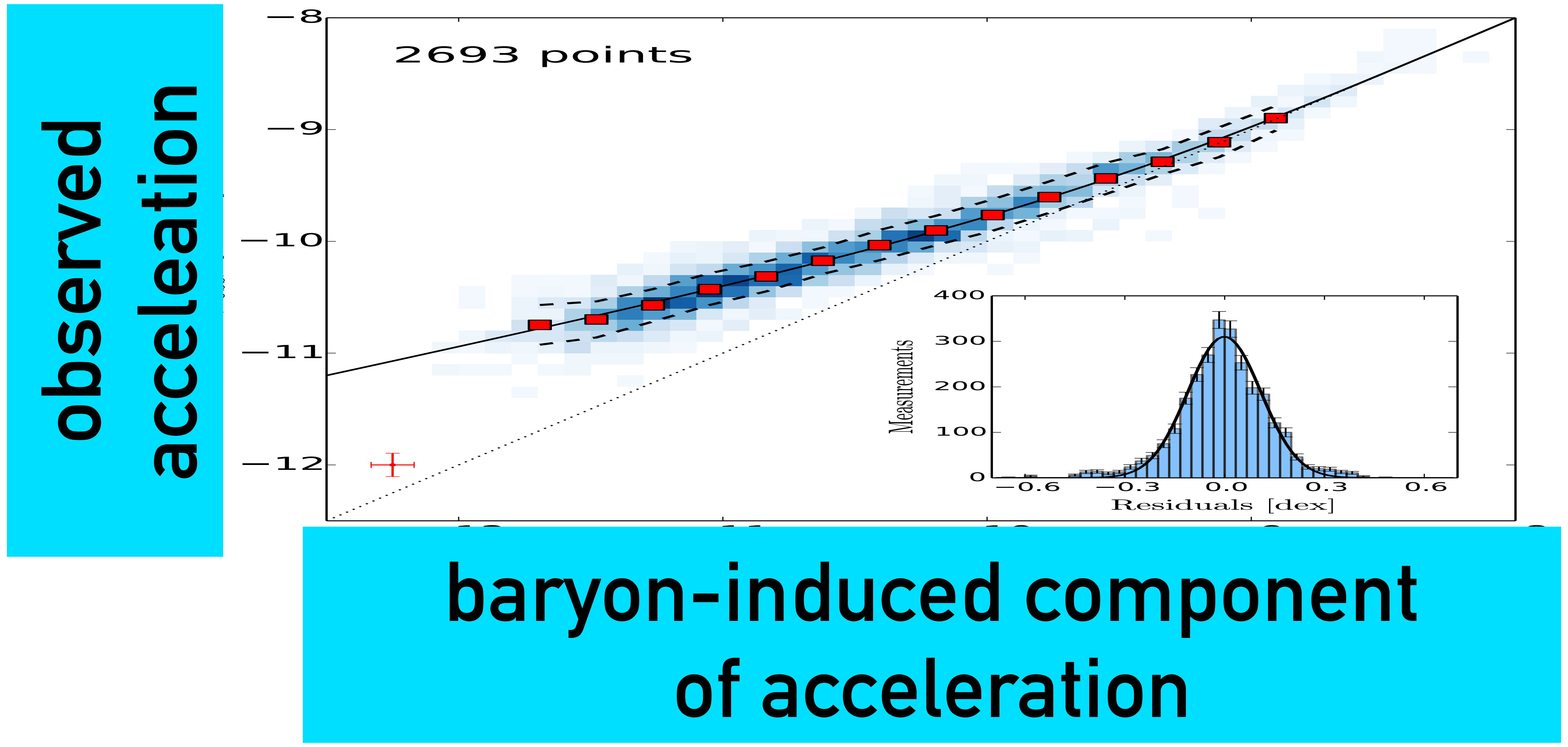
- 2018: 100 fb^{-1} @ 13 TeV
- 2023: 300 fb^{-1} @ 1? TeV
- 2035: 3000 fb^{-1} @ 14 TeV

1 fb^{-1} = 10^{14} collisions

But not clear that dark matter is “standard” WIMP-like

[…] **Standard cosmological […** simulations with] **dark matter halos […] do not naturally lead to realistic galaxies [44, 46].** Complicated […] “feedback” must be invoked […] Whether such processes can satisfactorily explain the radial acceleration relation and its small scatter remains to be demonstrated [47, 48].

PRL117, 201101 (2016)



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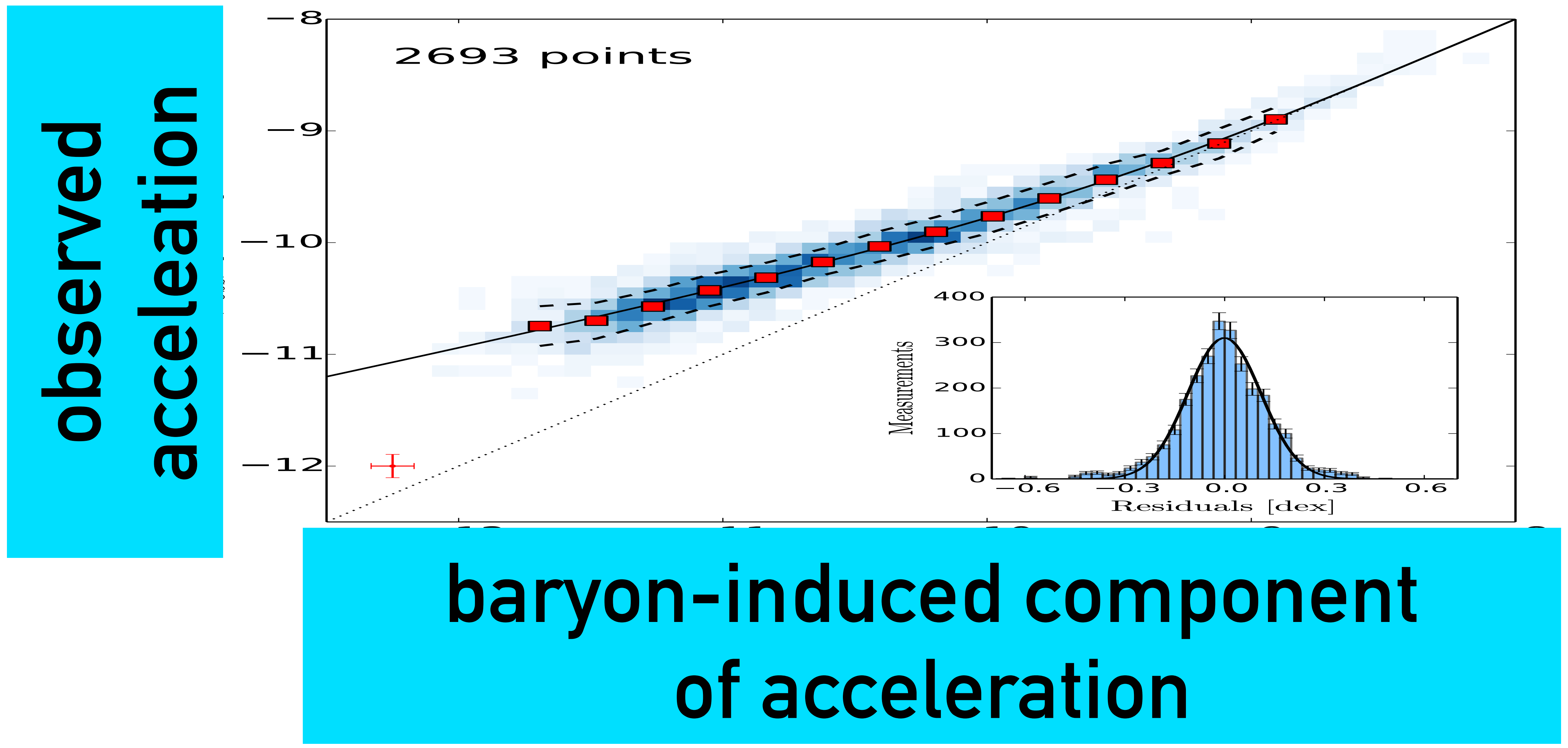
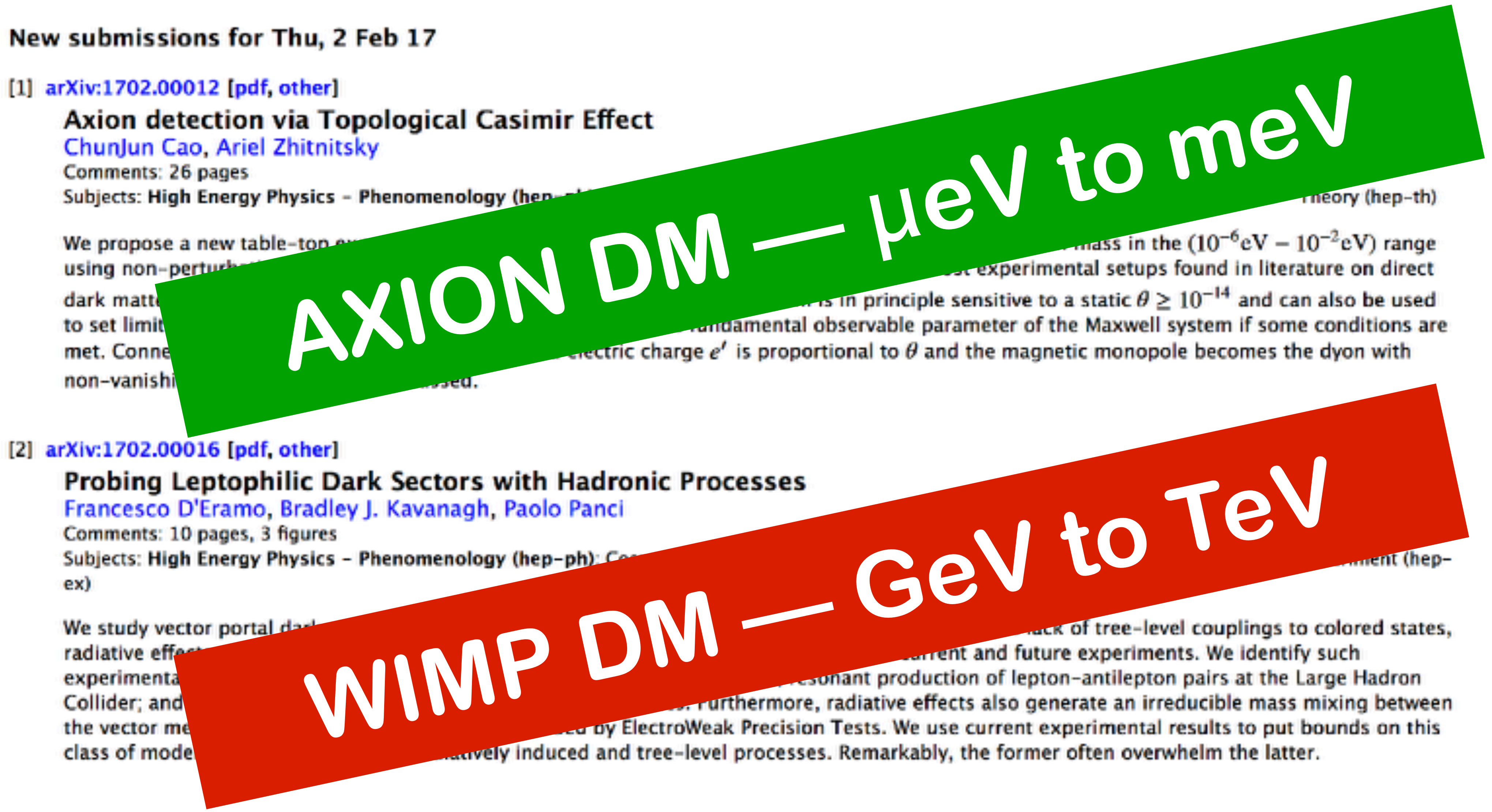
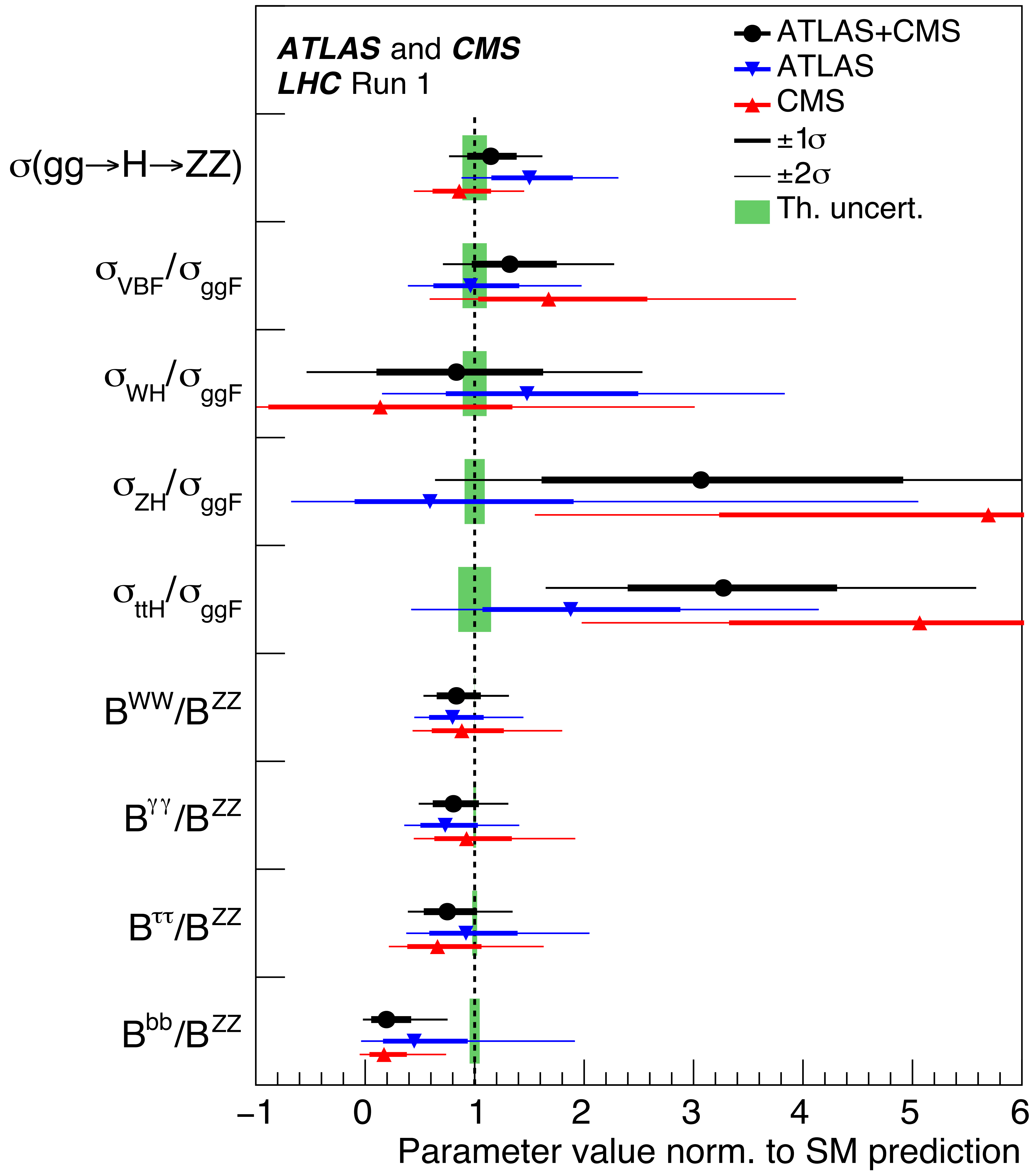




HIGGS
now & future

What do we know today? Broad picture looks standard-model like



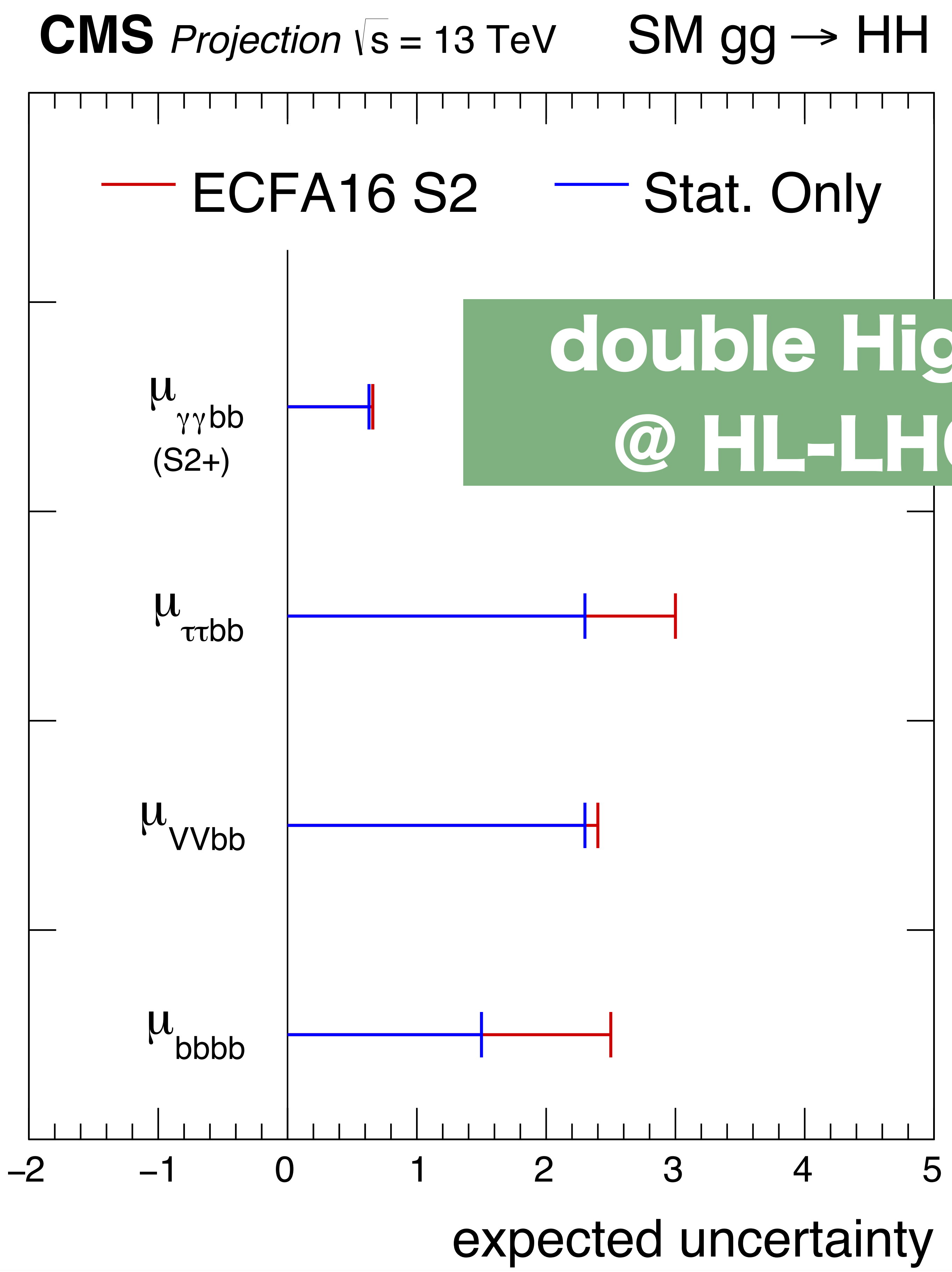
Coupling to electroweak and 3rd generation looks standard

- we see expected rate of decays to ZZ and WW (and some evidence of VBF/VH)
- observation consistent with σ(gluon fusion) means top-coupling is probably standard
- fact that all cross sections look right also means b-coupling is probably standard (because it dominates in denominator of branching ratios)
- reasonable evidence that coupling to tau is standard (direct observation)

To see the data, as is, with very non-standard (t,b,τ,W,Z) couplings would require some degree of conspiracy.

What will the LHC bring?

- Run 2: observation of $H \to bb$ (Yukawa)
- Run 2/3: observation of ttH (Yukawa)
- HL-LHC: observation of $H \to \mu\mu$ (2nd gen Yukawa)
- HL-LHC: Higgs width → SM \pm 50% (BSM constraint)
- HL-LHC: $H \to$ invisible < 10% (BSM constraint)
- HL-LHC: $gg \to HH$? (Higgs potential)
- HL-LHC: Hcc coupling? (2nd gen Yukawa)

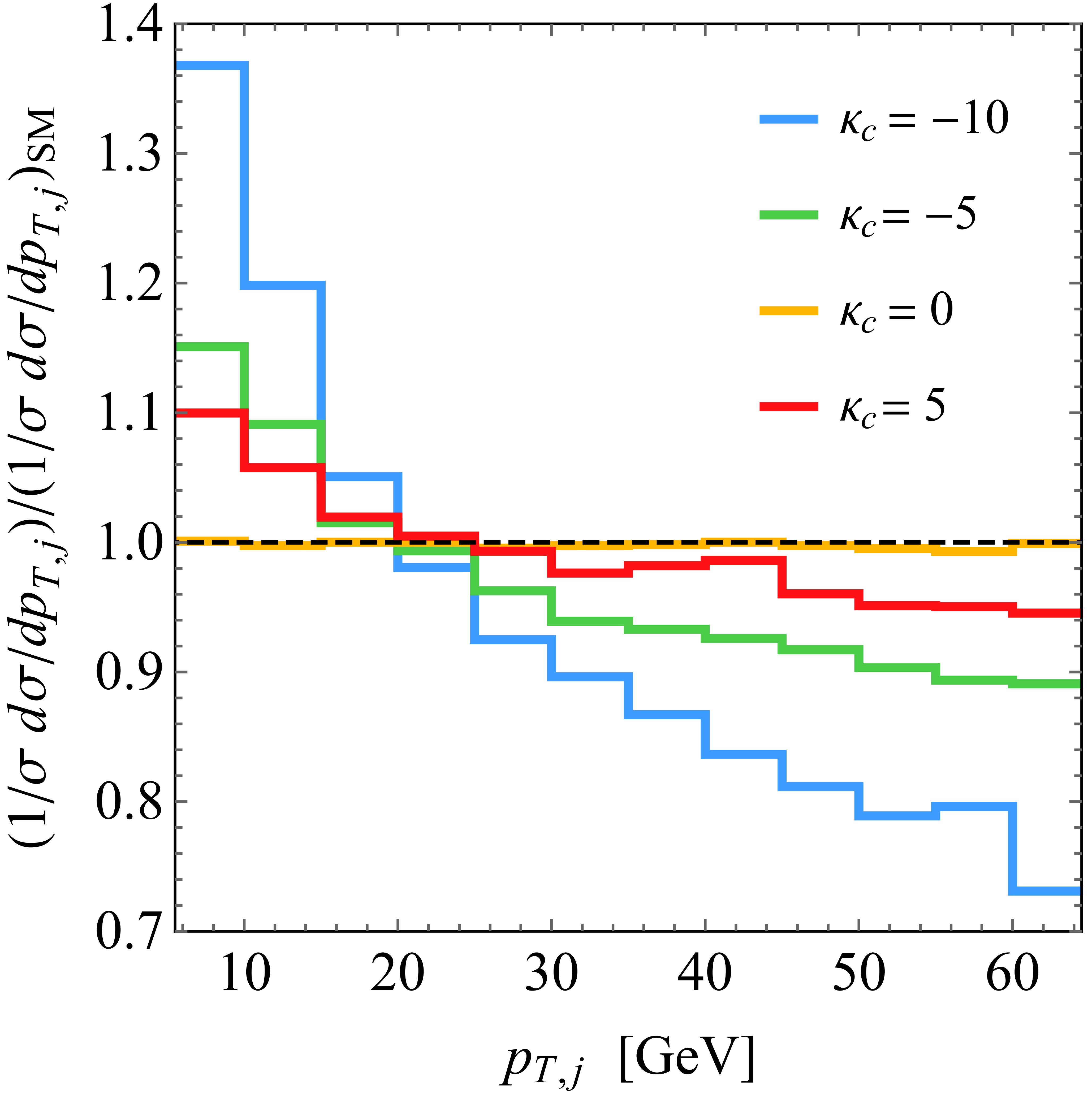


double Higgs @ HL-LHC

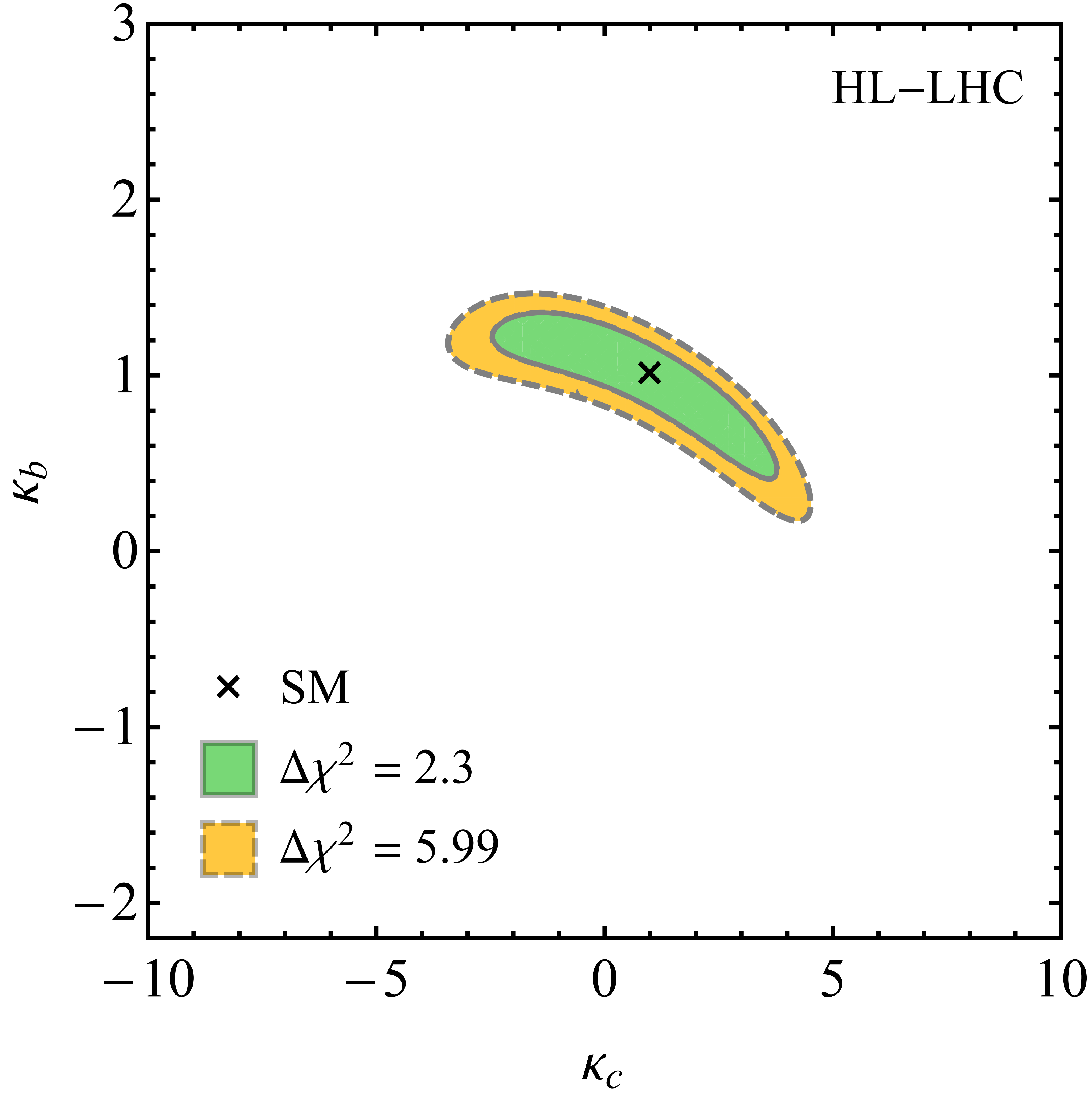
cf. talks at HL-LHC workshop

indirect constraints on Hcc

impact of modified Hcc coupling on Higgs+jet pT dist



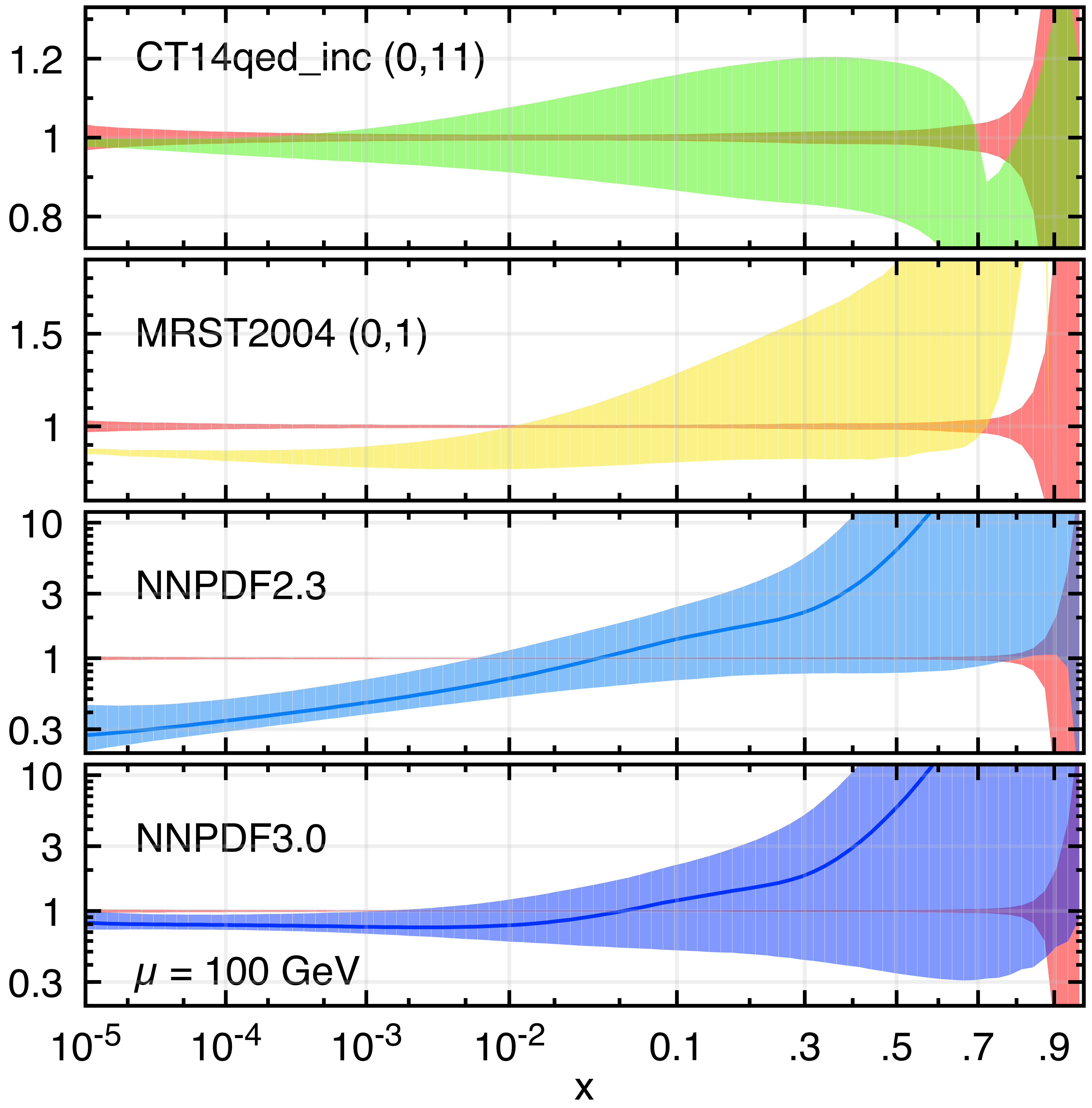
joint limits on κc & κb @ HL-LHC



Fady Bishara, Ulrich Haisch, Pier Francesco Monni and Emanuele Re, arXiv:1606.09253

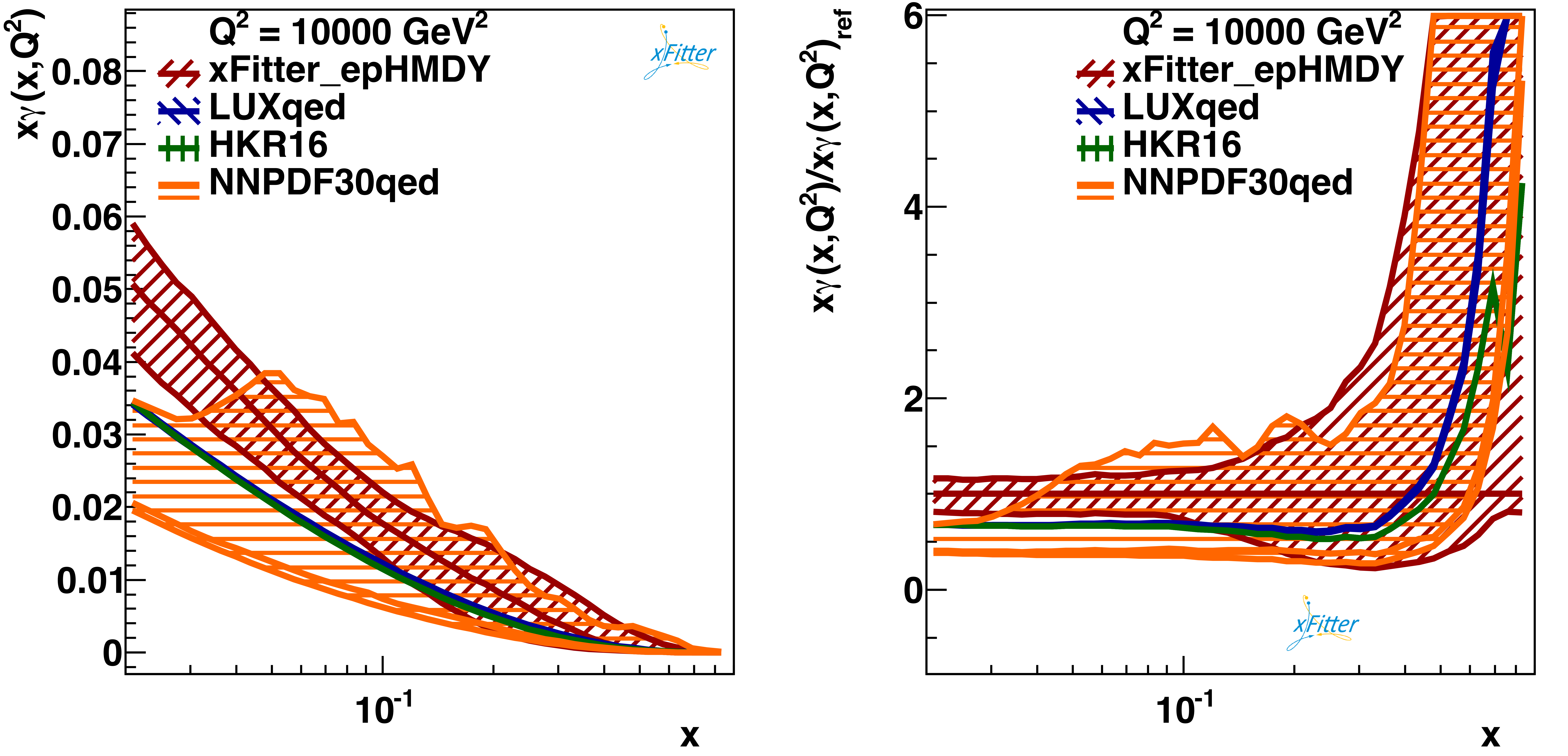
photon PDF

LUXqed v. other photon PDFs

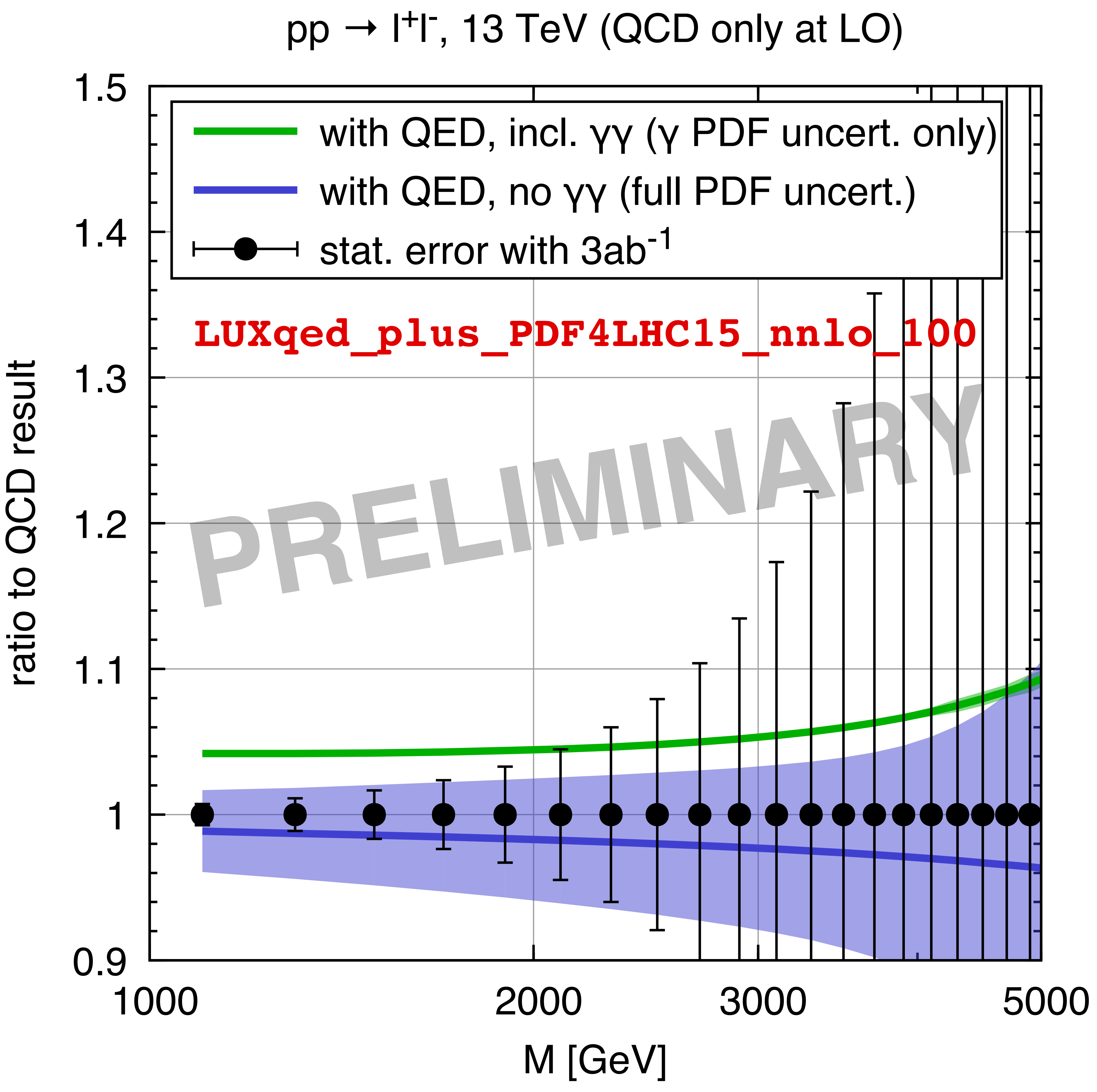


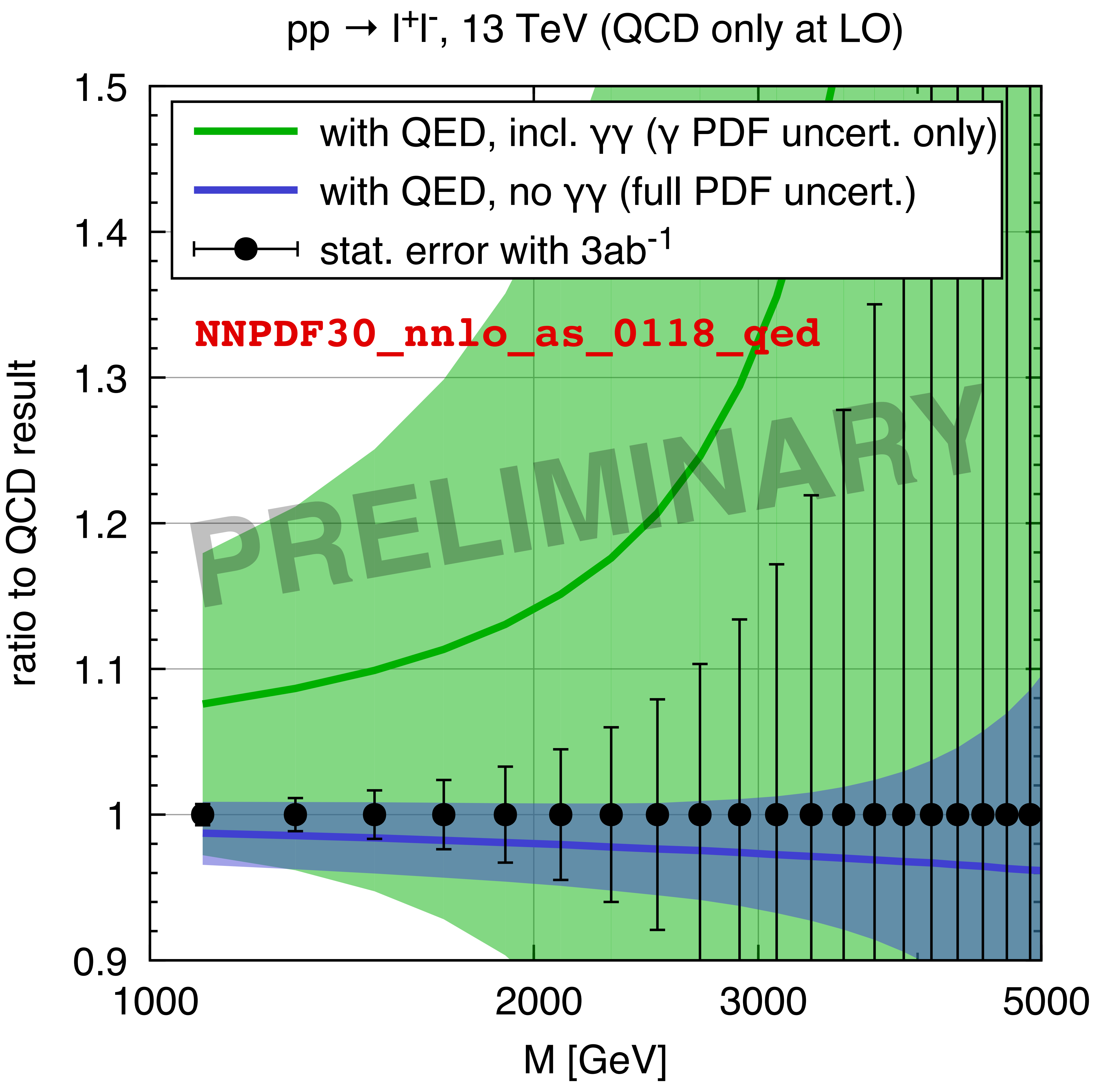
LUXqed v. a recent fit to Drell-Yan data

F. Giuli et al, 1701.08553



di-lepton spectrum with 3ab^{-1}

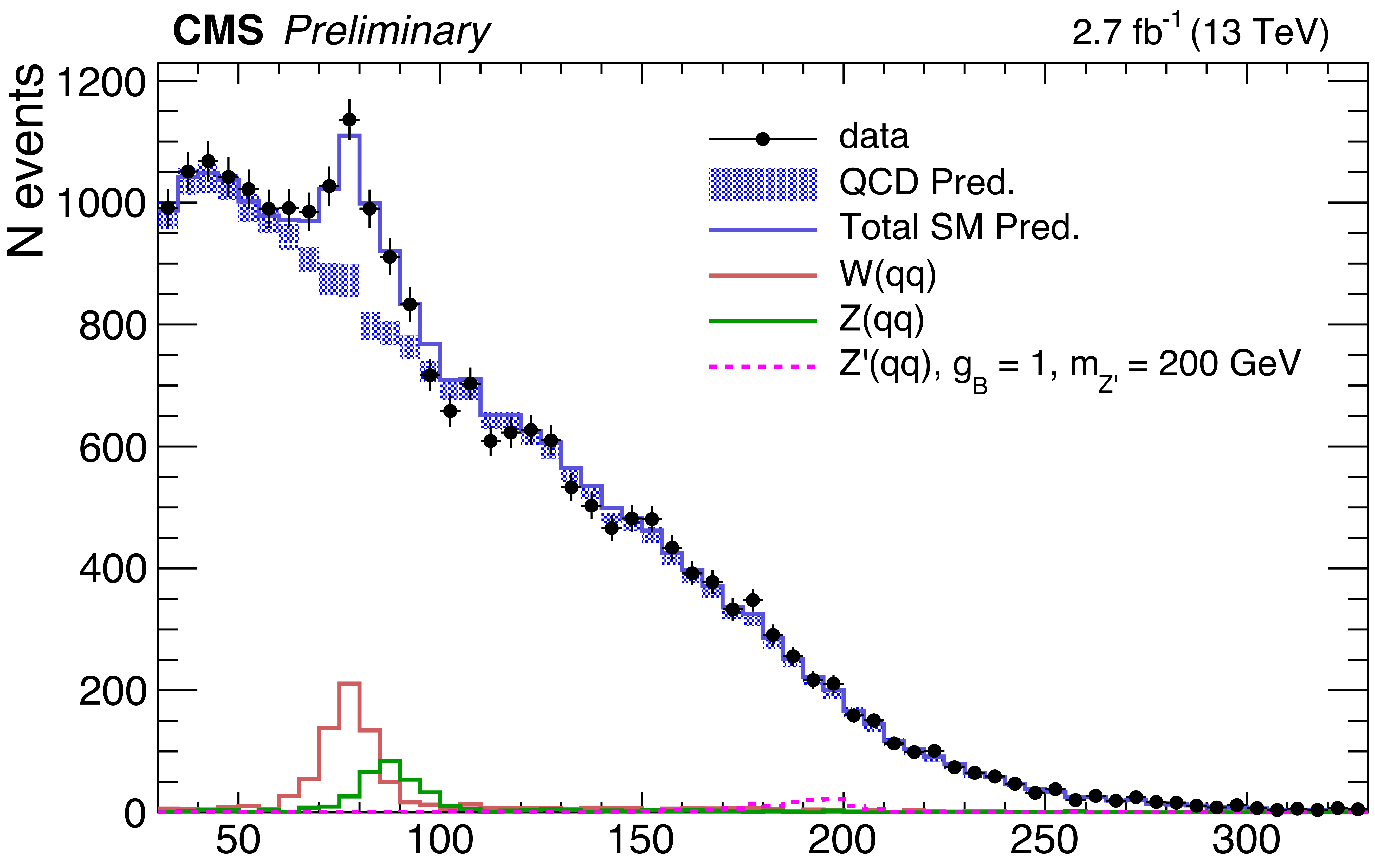




LUXQED photon has few % effect on di-lepton spectrum and negligible uncertainties

boosted hadronic decays

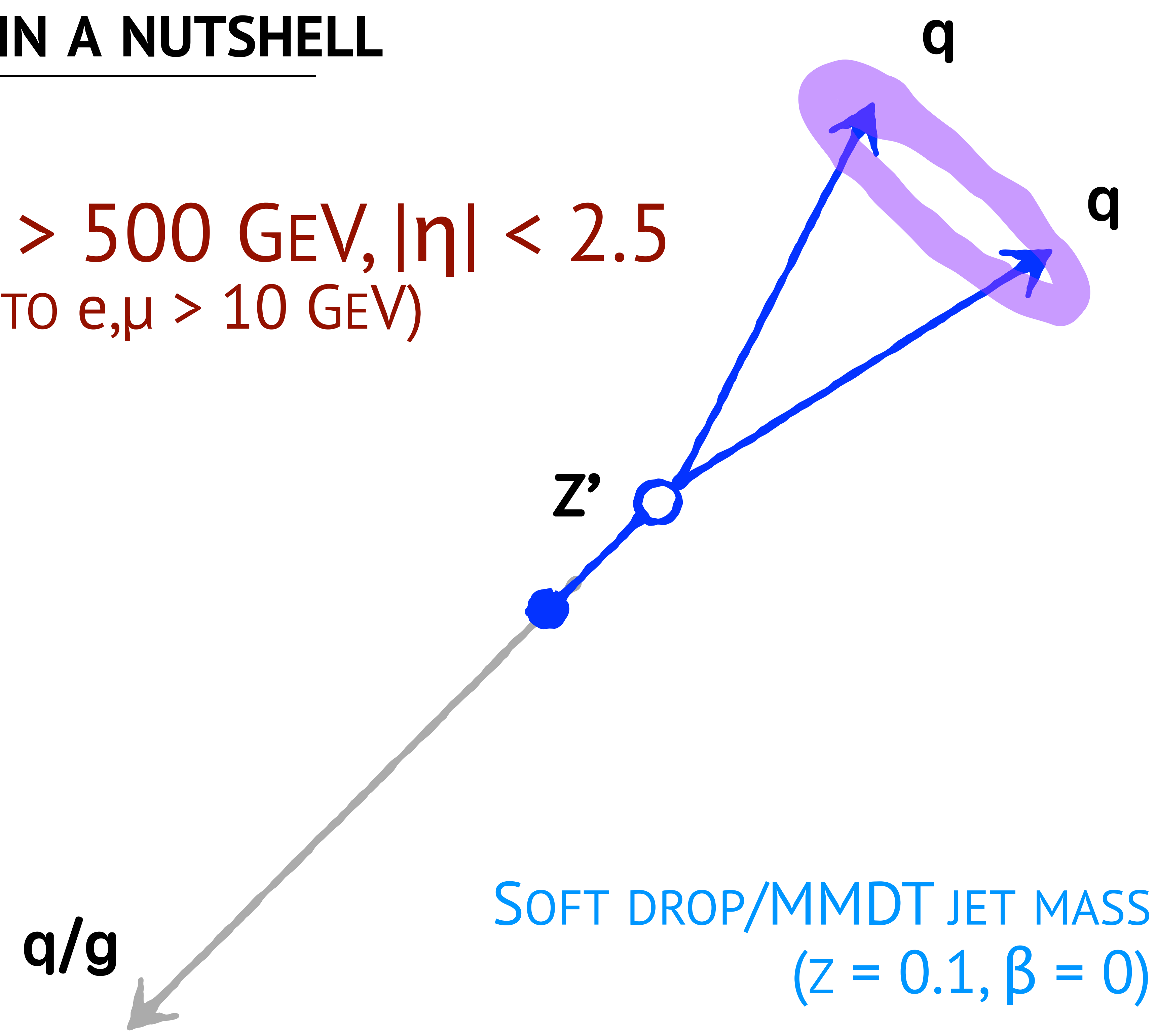
The potential of jet substructure — hadronic W & Z peaks



Nhan Tran @ Boost 2016

IN A NUTSHELL

$p_T > 500$ GeV, $|\eta| < 2.5$
(veto e,μ > 10 GeV)

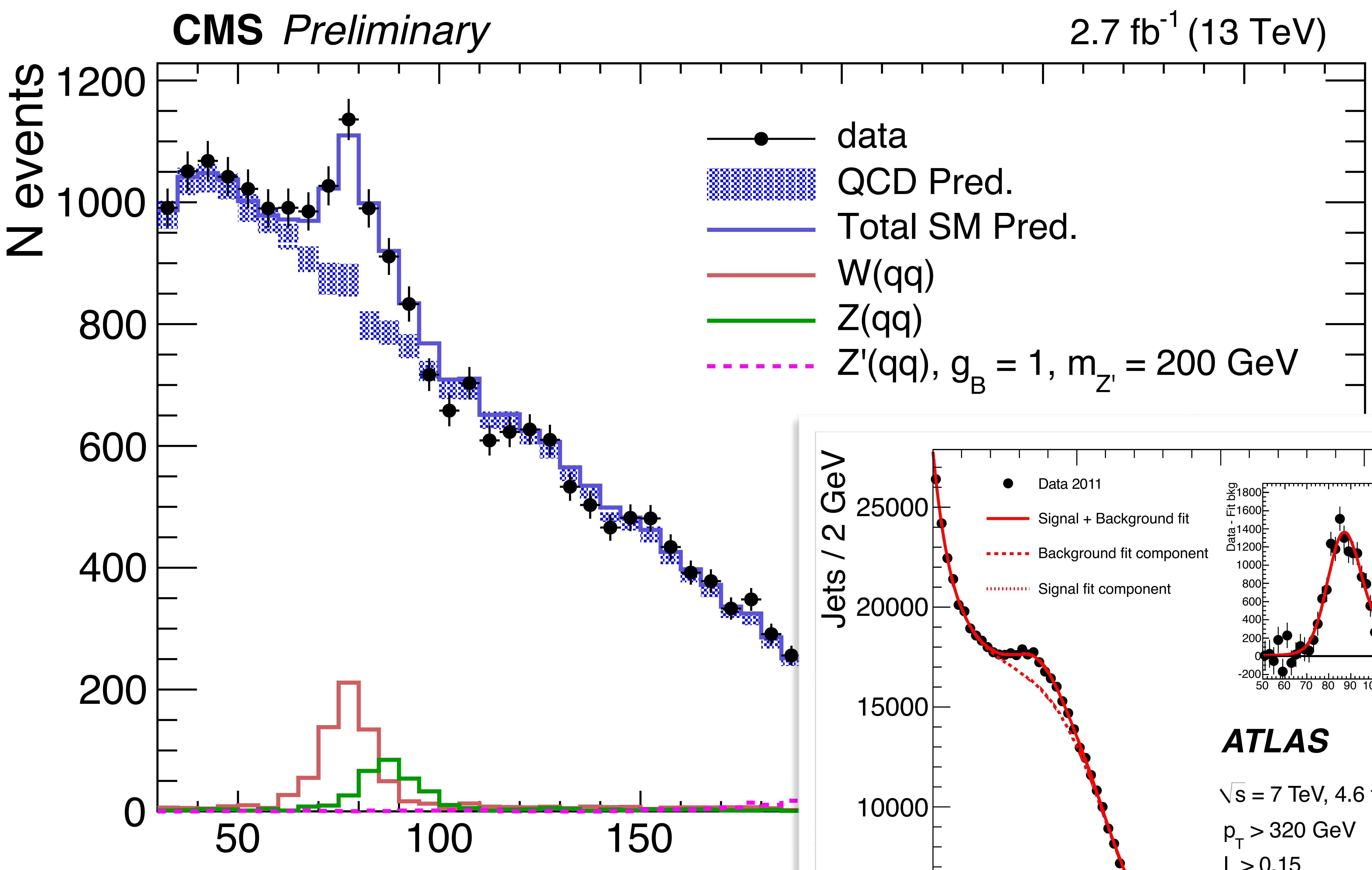


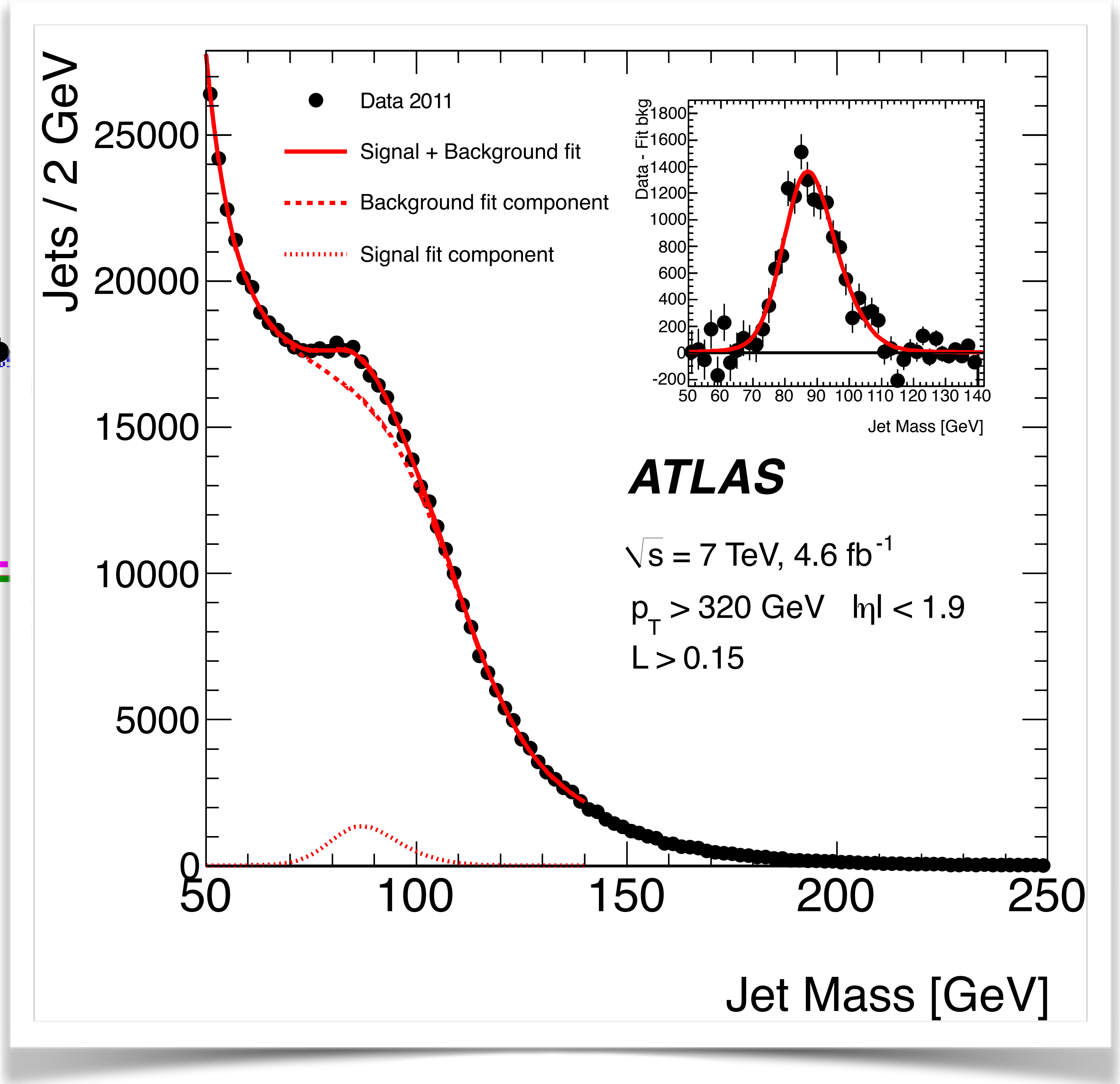
Soft drop/MMDT jet mass
($z = 0.1, \beta = 0$)

$\tau_{21}^{DDT} < 0.38$

[PUPPI'ed inputs]

The potential of jet substructure — hadronic W & Z peaks

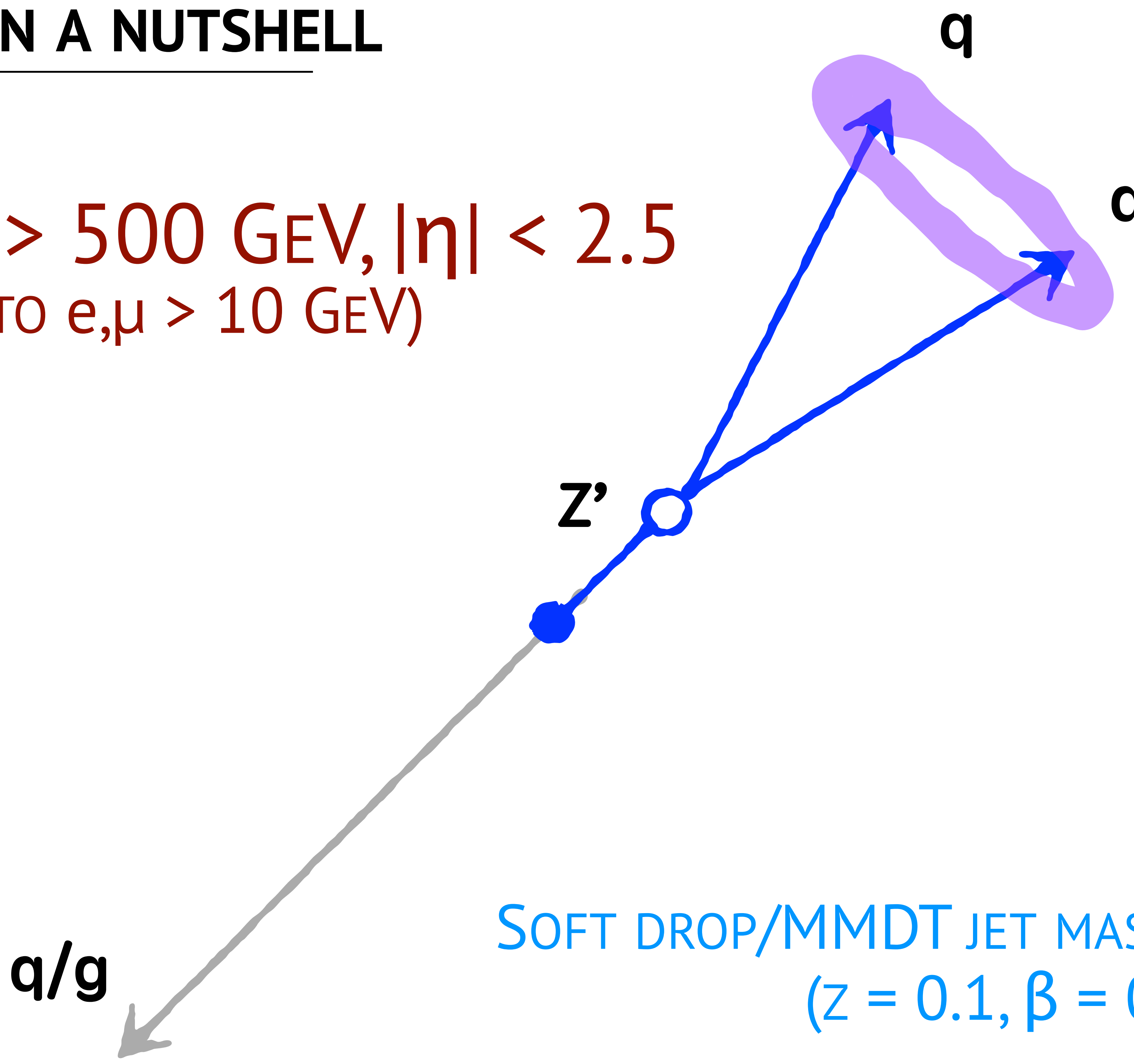




Nhan Tran @ Boost 2016

IN A NUTSHELL

P_T > 500 GeV, $|\eta| < 2.5$
(VETO e,μ > 10 GeV)



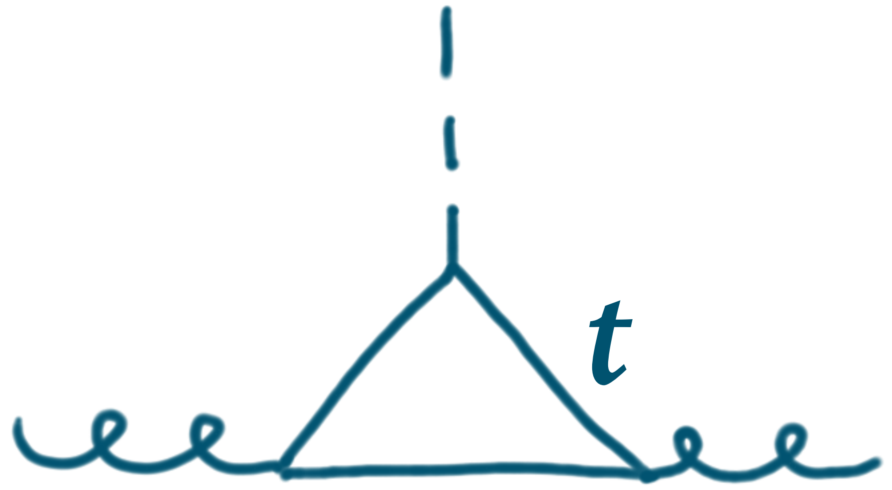
SOFT DROP/MMDT JET MASS
($z = 0.1$, $\beta = 0$)

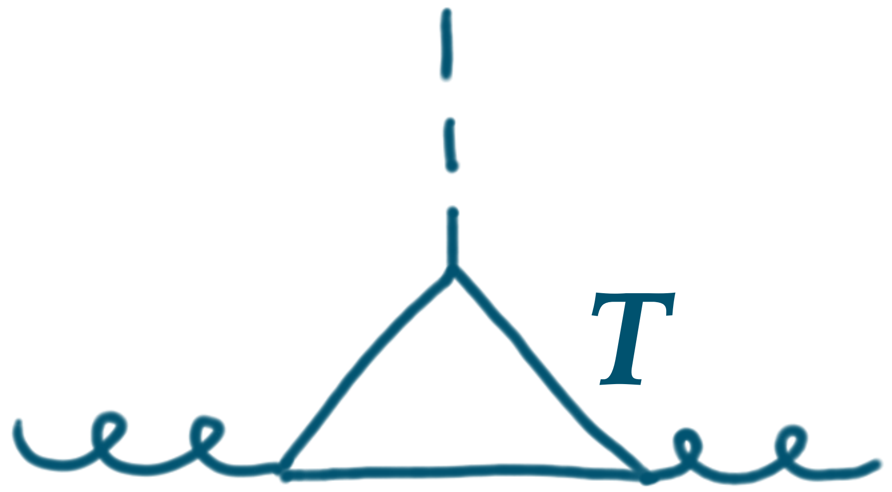
$\tau_{21}^{DDT} < 0.38$

[PUPPI'ED INPUTS]

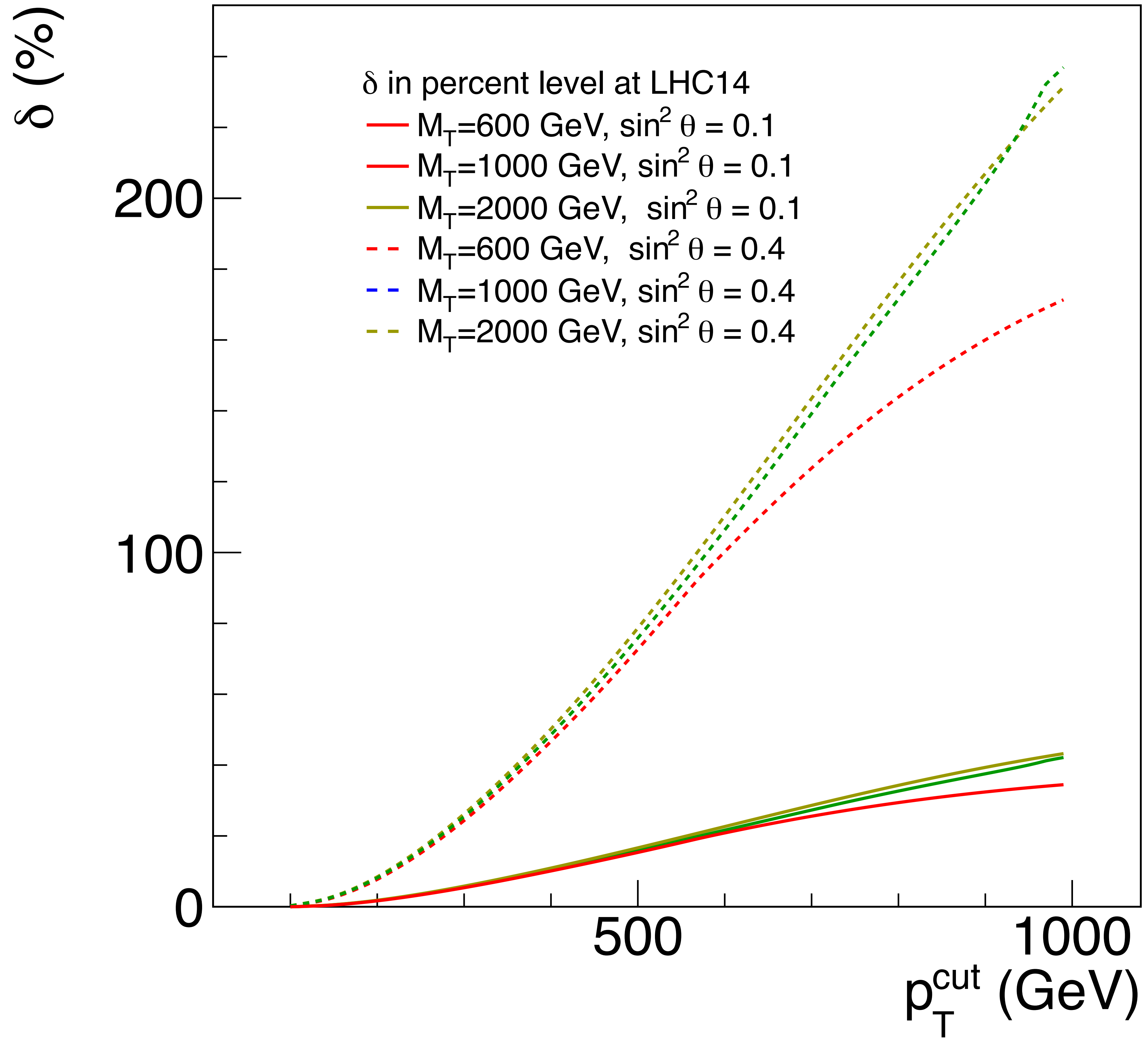
low v. high pT

High-pt Higgs (e.g. to distinguish κ_g and κ_t)

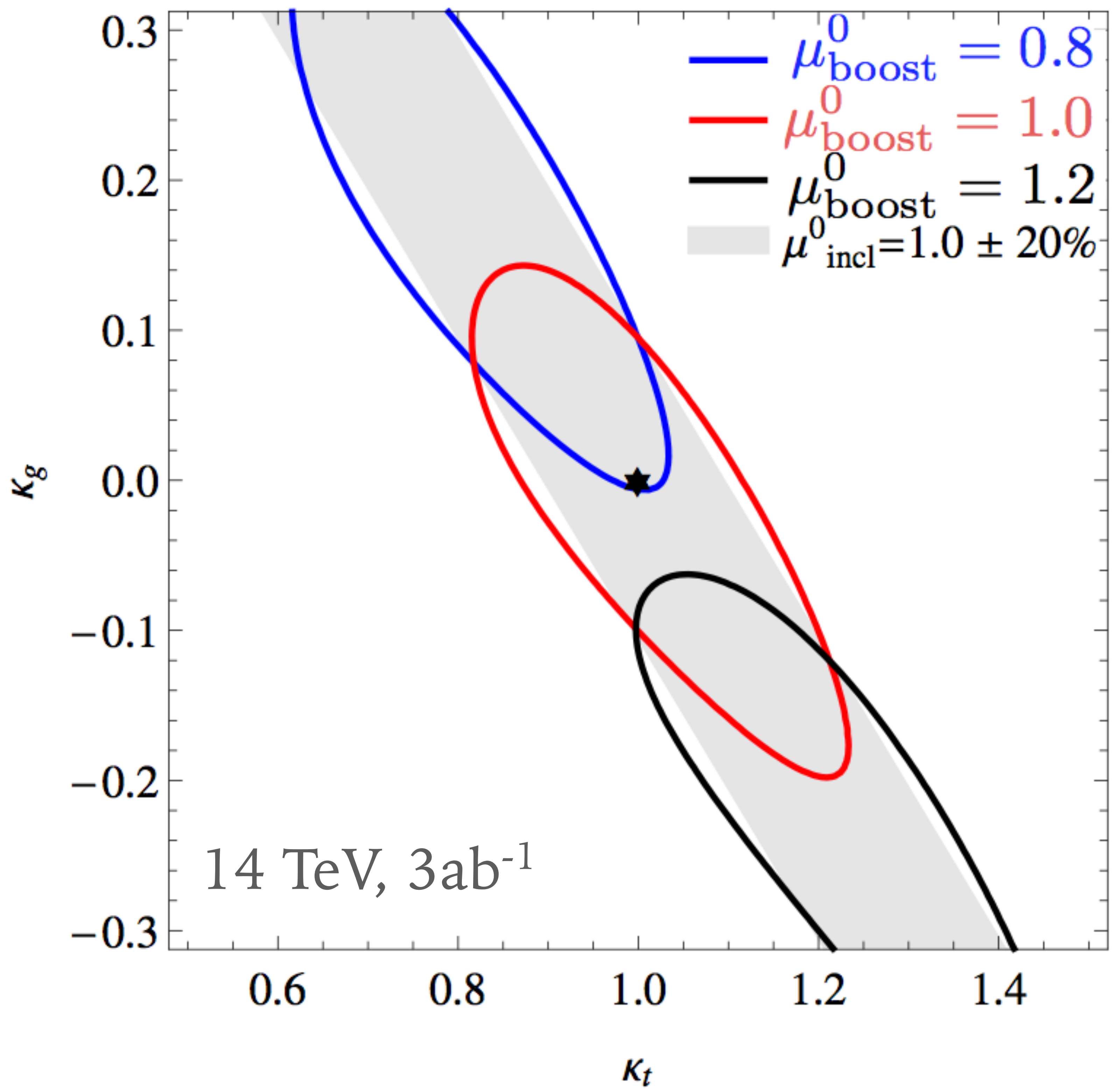




Structure of loops is best probed by going to high p_T



A.Banfi, A.Martin, V.Sanz (2013)



C.Grojean et al. (2013)

see also Azatov, Paul (2013)
S.Dawson, I.Lewis, M.Zeng (2014)

what are experimental prospects?
are there any theory-issues to be solved?

See also e.g.
Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320

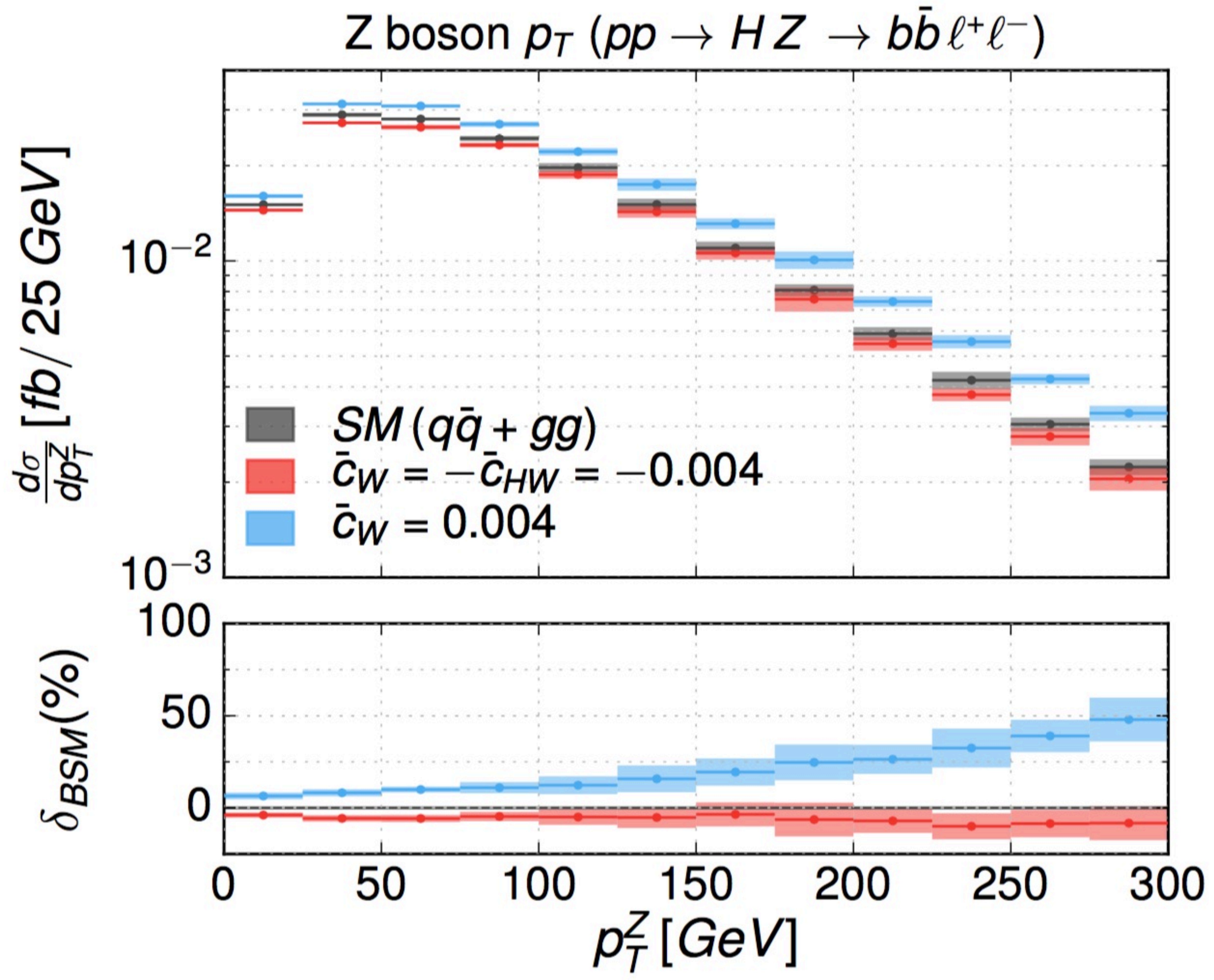
- Higher-dimension operators cause deviations that grow as, e.g.

$$\frac{\delta\sigma_{\text{dim-6}}}{\sigma} \sim \frac{p_T^2}{\Lambda^2}$$

- In some relevant range of p_T, Λ value to which you're sensitive grows as

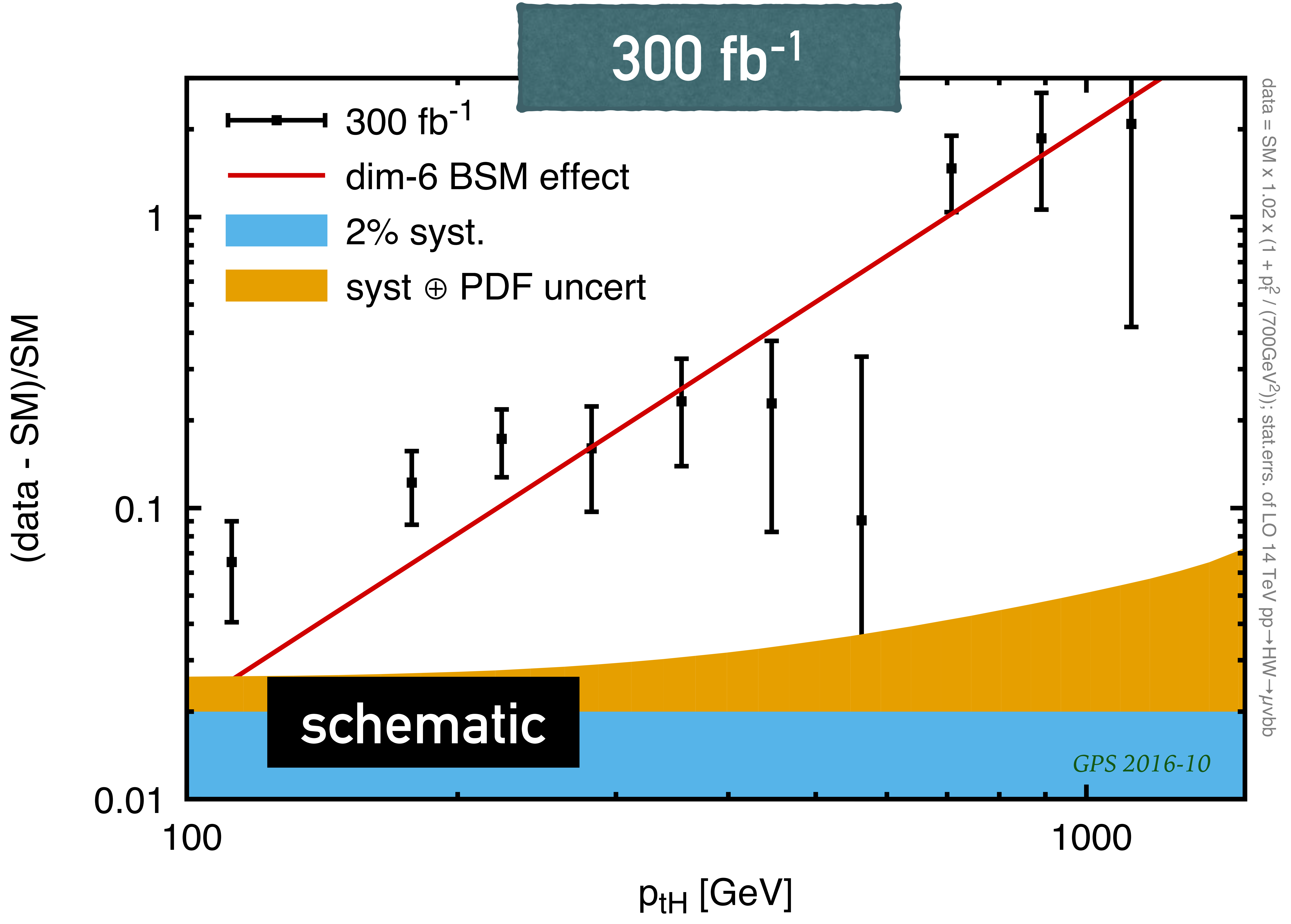
$$\Lambda \sim (\text{Lumi})^{1/4}$$

- that's faster than most direct searches (x100 in lumi → x1.5 in reach for Z')

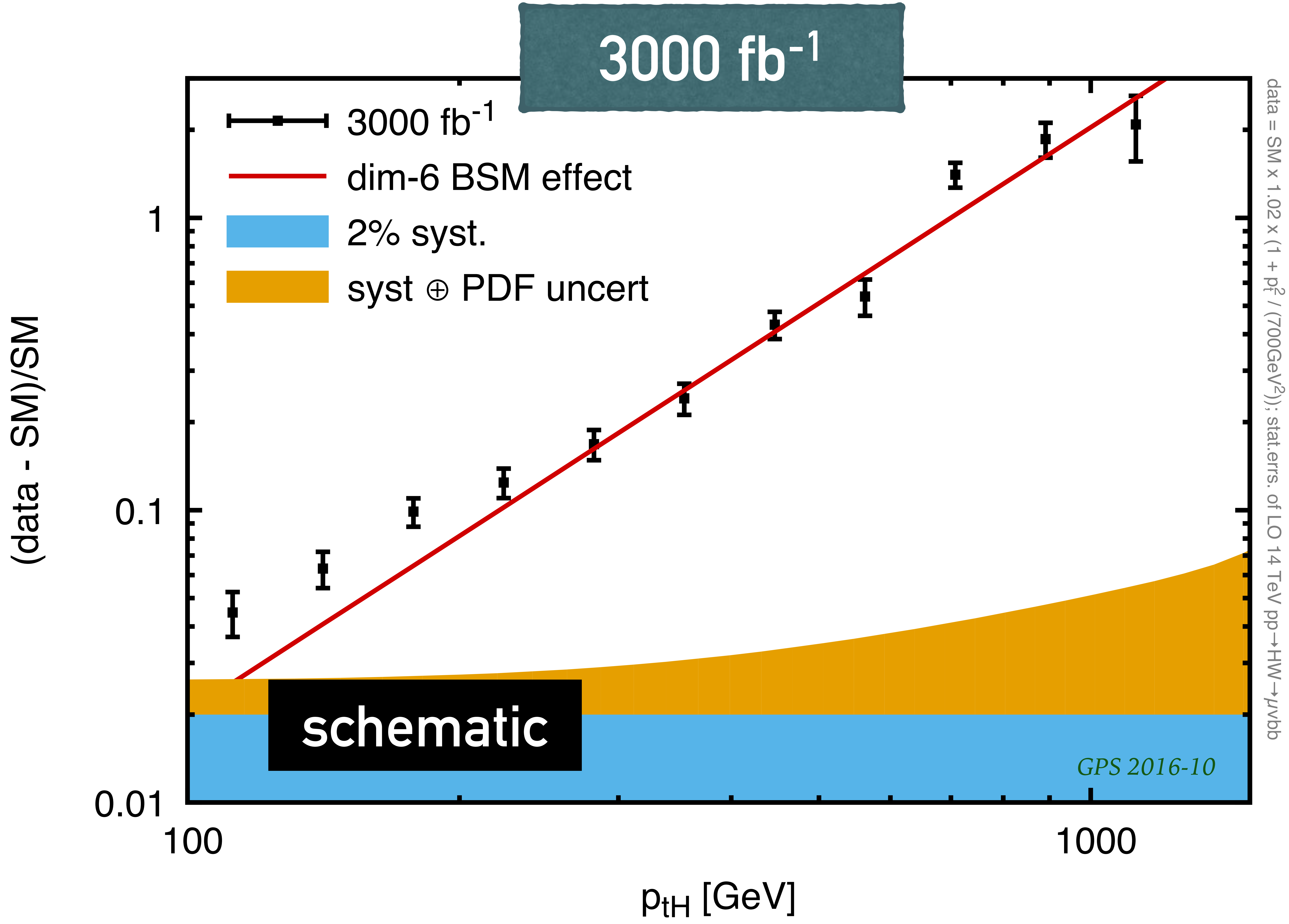


Mimasu, Sanz, Williams, arXiv:1512.02572v

WH at large Q^2 with dim-6 BSM effect



WH at large Q^2 with dim-6 BSM effect

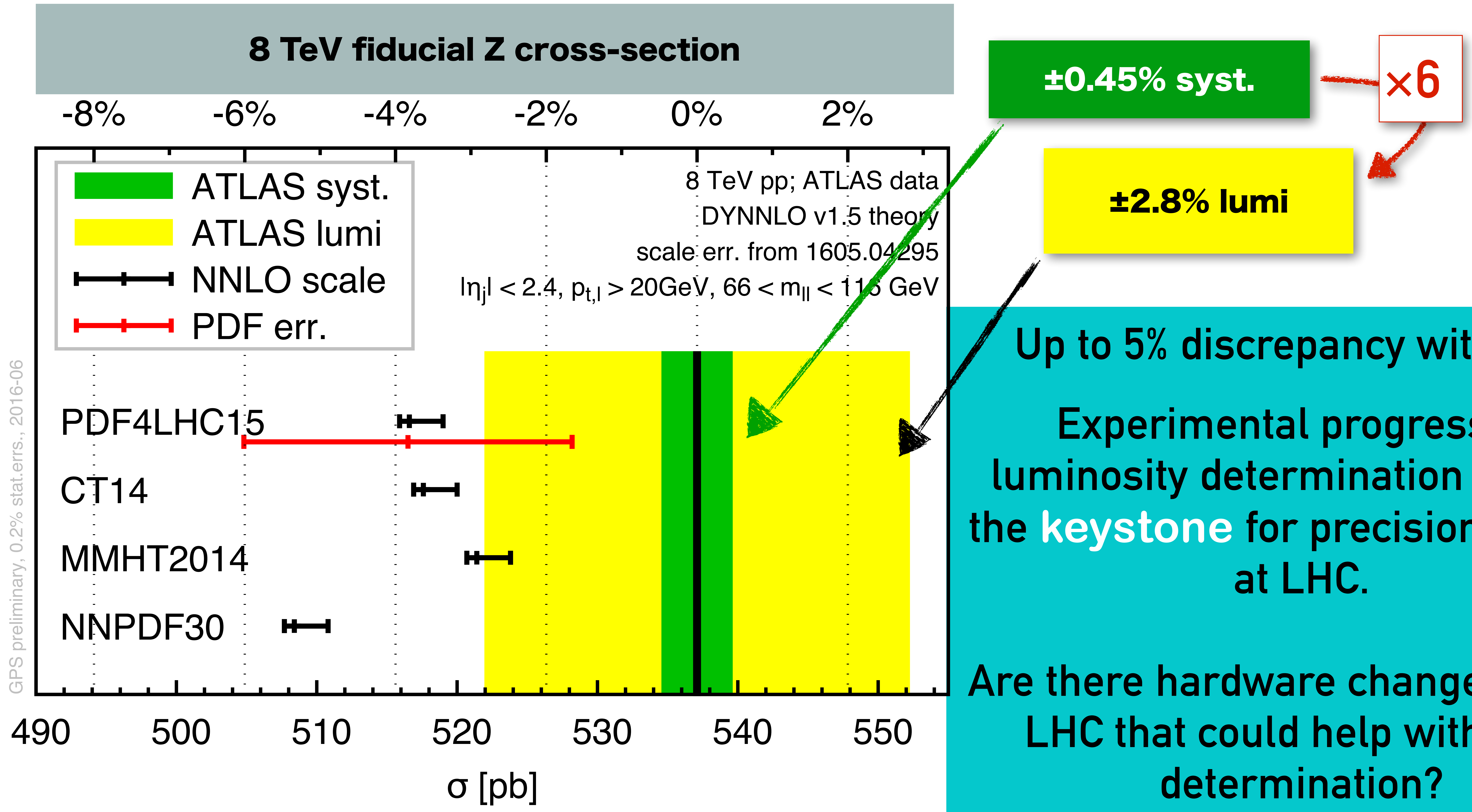


new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation ($\sim p_T^2$)

moderate and high p_T's have similar statistical significance — so it's useful to understand whole p_T range

There are, however, issues. Notably in Z production



Up to 5% discrepancy with data

Experimental progress on luminosity determination may be the **keystone** for precision physics at LHC.

Are there hardware changes to HL-LHC that could help with lumi determination?