Perspectives on SM, Higgs and beyond

Gavin P. Salam (CERN)

based in part on talks at Aix-les-Bains (HL-LHC) and KITP Santa Barbara

CMS week, CERN
3 February 2017

Bettmergrat, Wallis, Switerland, photo G. Salam

In discussing LHC physics we often mention “BIG” motivations

Dark matter

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

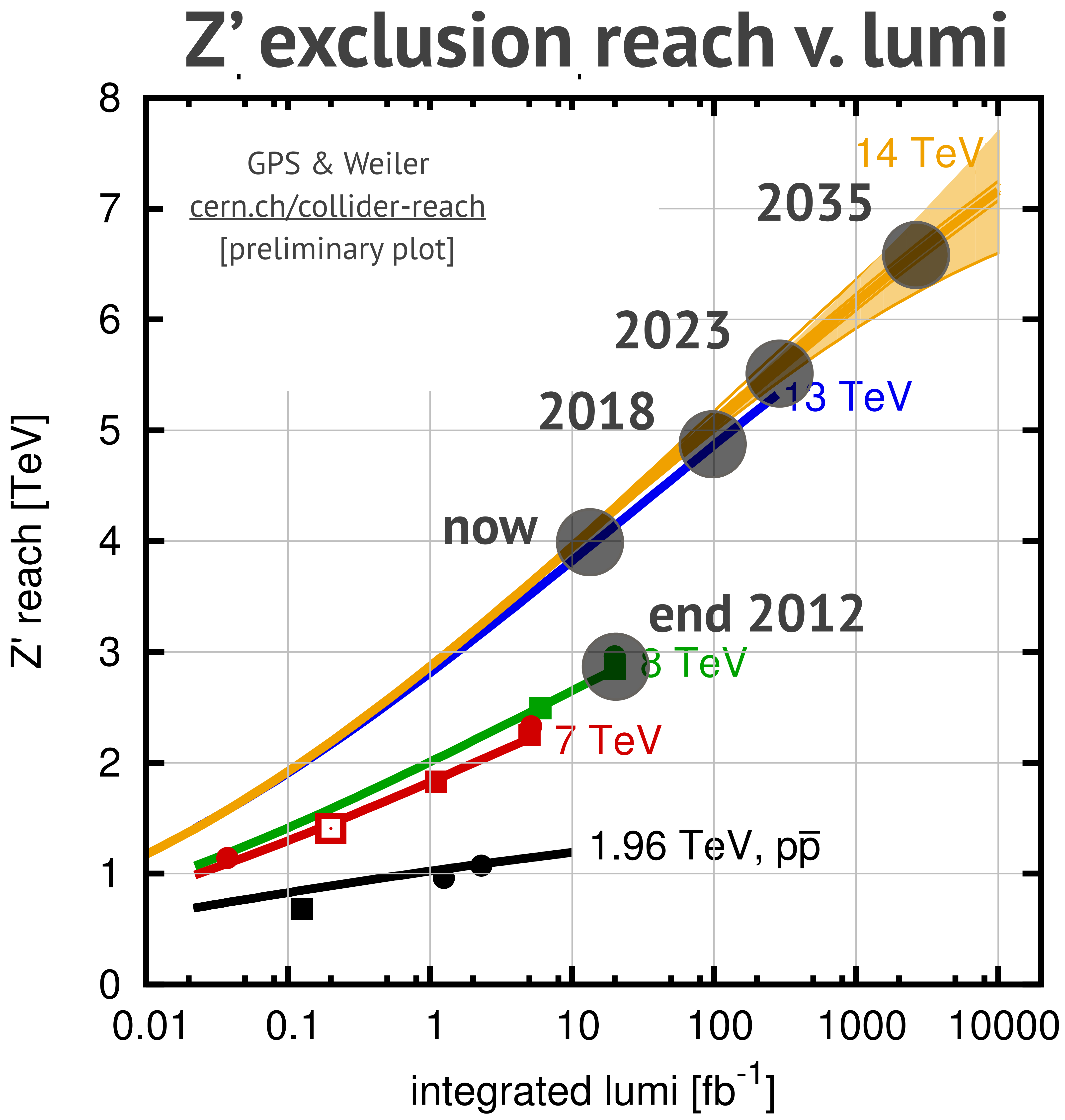
Flavour-asymmetry of the universe

[…]

The field has made enormous progress in excluding parameter space
(and finding reliable ways of communicating what has been excluded)

But if we ask “will the LHC solve these problems?”
there’s no way we can guarantee a positive answer

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



Today

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

Future

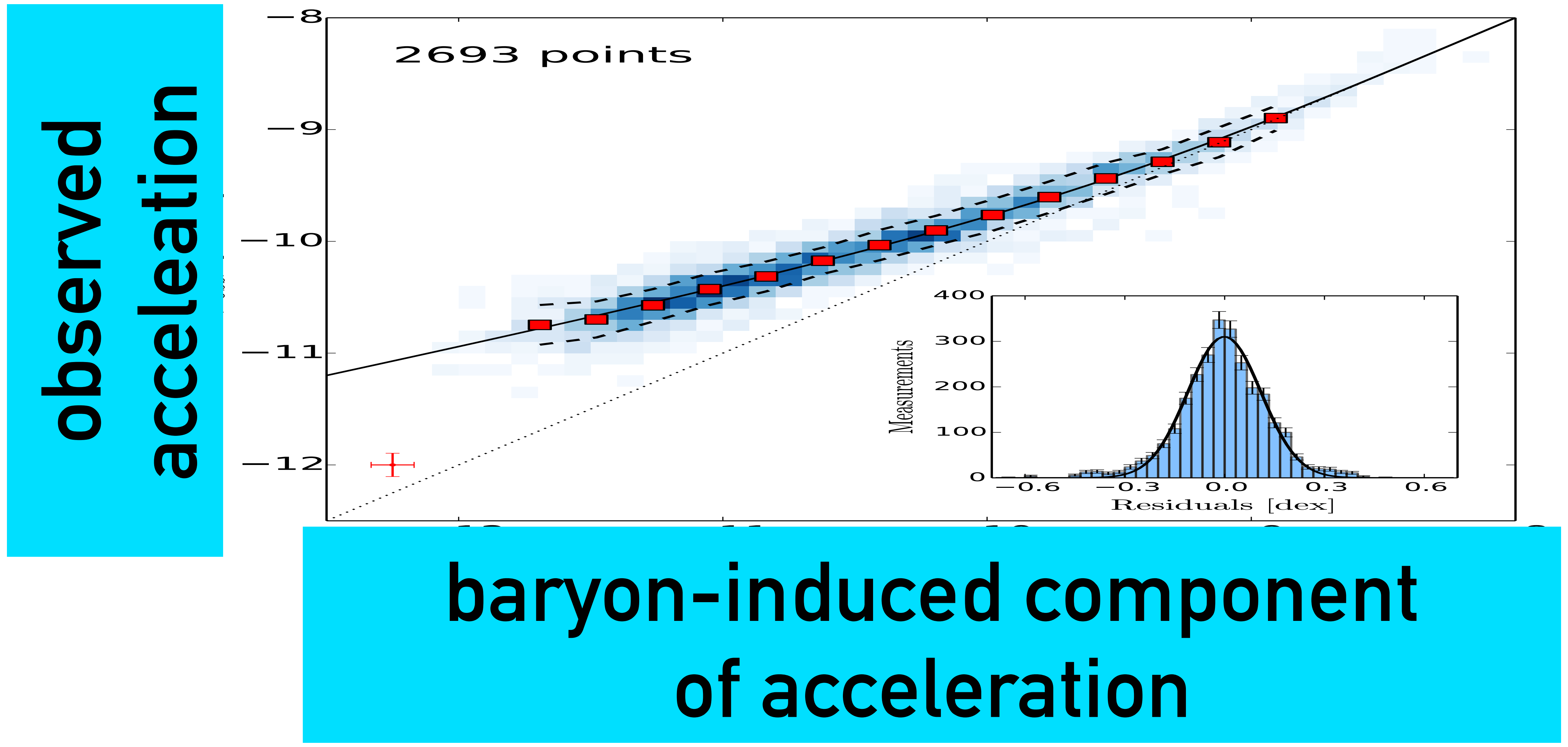
- 2018: 100 fb^{-1} @ 13 TeV
- 2023: 300 fb^{-1} @ 1? TeV
- 2035: 3000 fb^{-1} @ 14 TeV

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

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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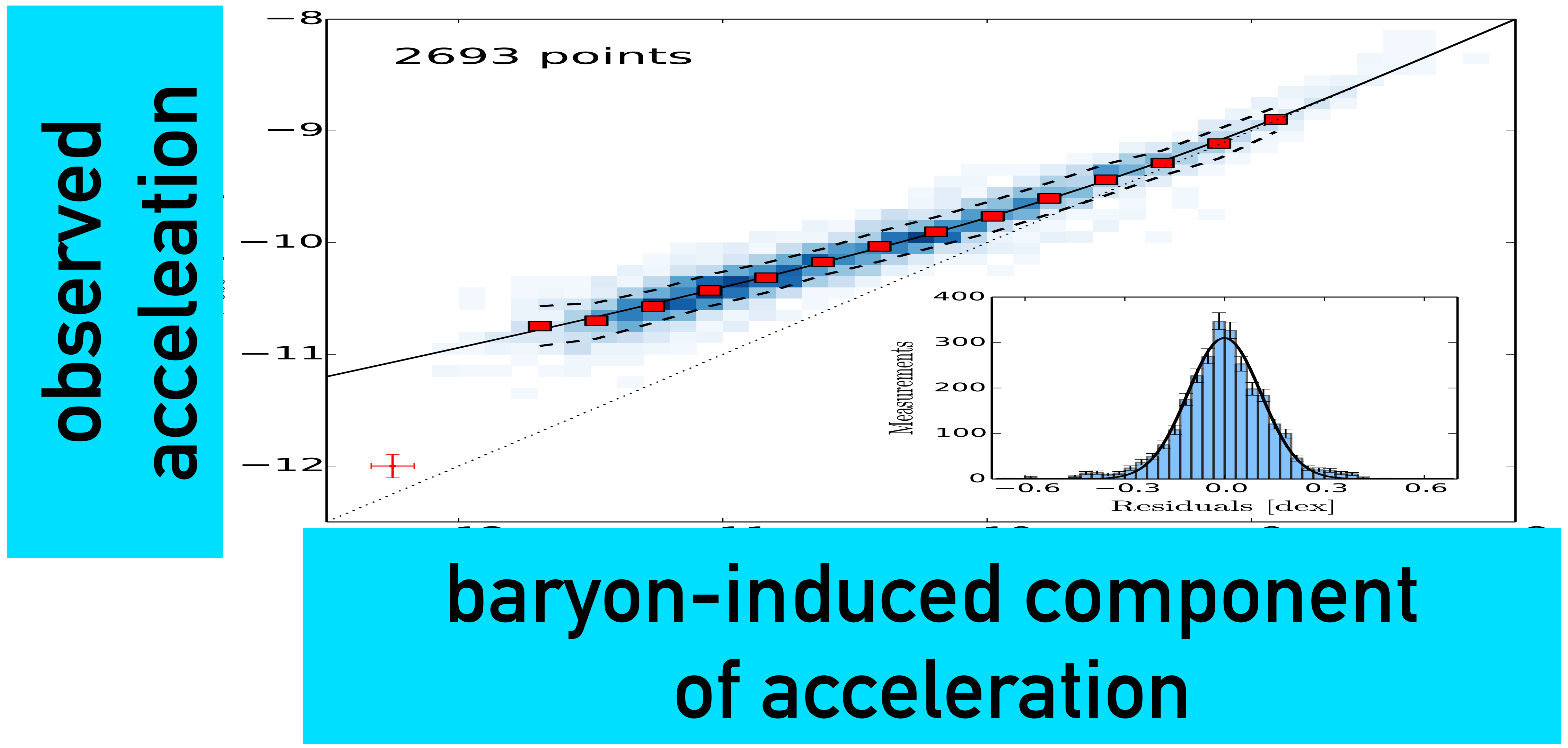
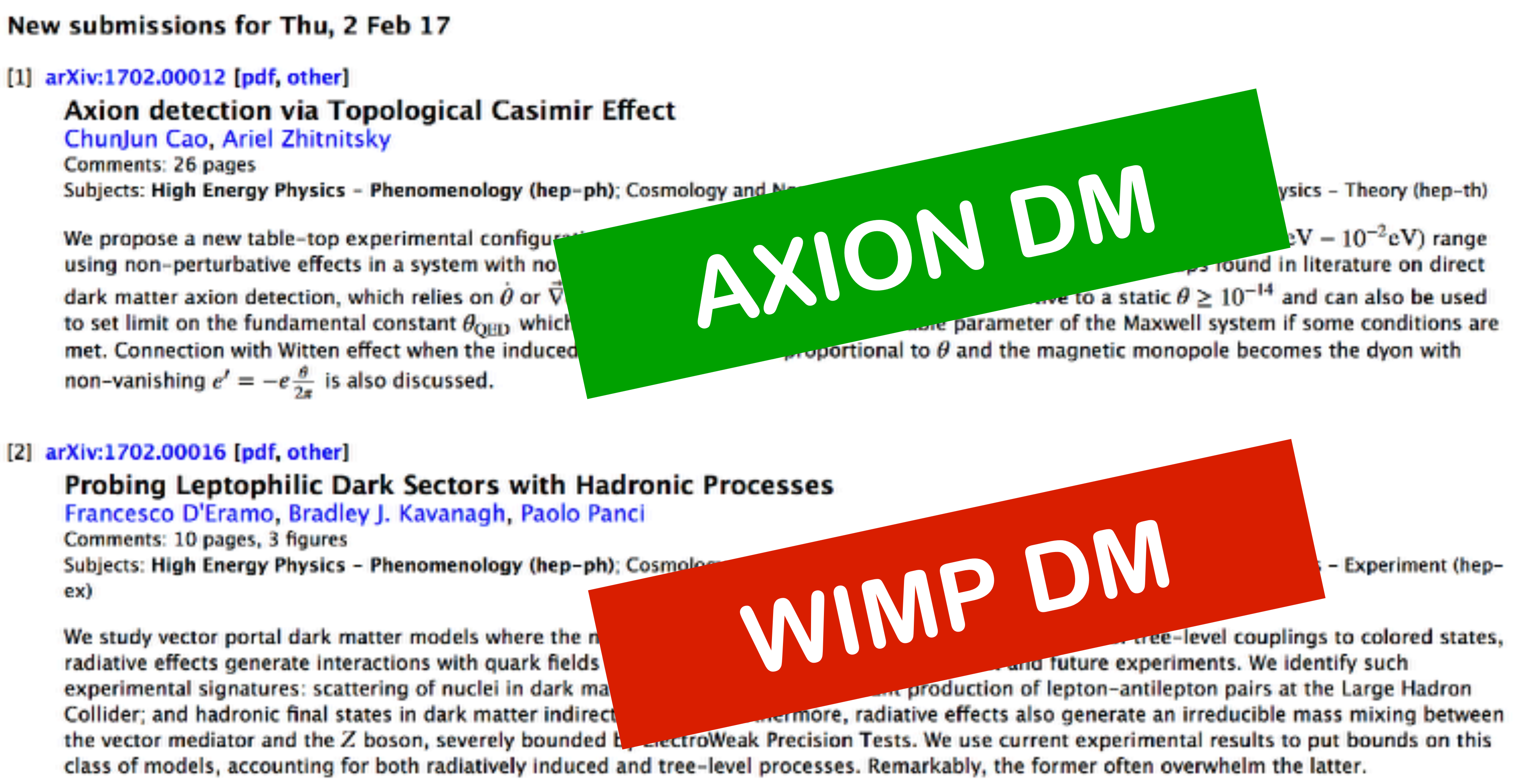




New submissions for Thu, 2 Feb 17

[1] arXiv:1702.00012 [pdf, other]
Axion detection via Topological Casimir Effect
ChunJun Cao, Ariel Zhitnitsky
Comments: 26 pages
Subjects: High Energy Physics - Phenomenology (hep-ph); Cosmology and N… …ysics - Theory (hep-th)

We propose a new table-top experimental configu… …$eV - 10^{-2}eV$) range using non-perturbative effects in a system with no… …found in literature on direct dark matter axion detection, which relies on $\dot{\theta}$ or $\vec{\nabla}$… …ve to a static $\theta \geq 10^{-14}$ and can also be used to set limit on the fundamental constant θ_{QED} which… …ble parameter of the Maxwell system if some conditions are met. Connection with Witten effect when the induced… …proportional to θ and the magnetic monopole becomes the dyon with non-vanishing $e' = -e\frac{\theta}{2\pi}$ is also discussed.

[2] arXiv:1702.00016 [pdf, other]
Probing Leptophilic Dark Sectors with Hadronic Processes
Francesco D'Eramo, Bradley J. Kavanagh, Paolo Panci
Comments: 10 pages, 3 figures
Subjects: High Energy Physics - Phenomenology (hep-ph); Cosmolo… …s - Experiment (hep-ex)

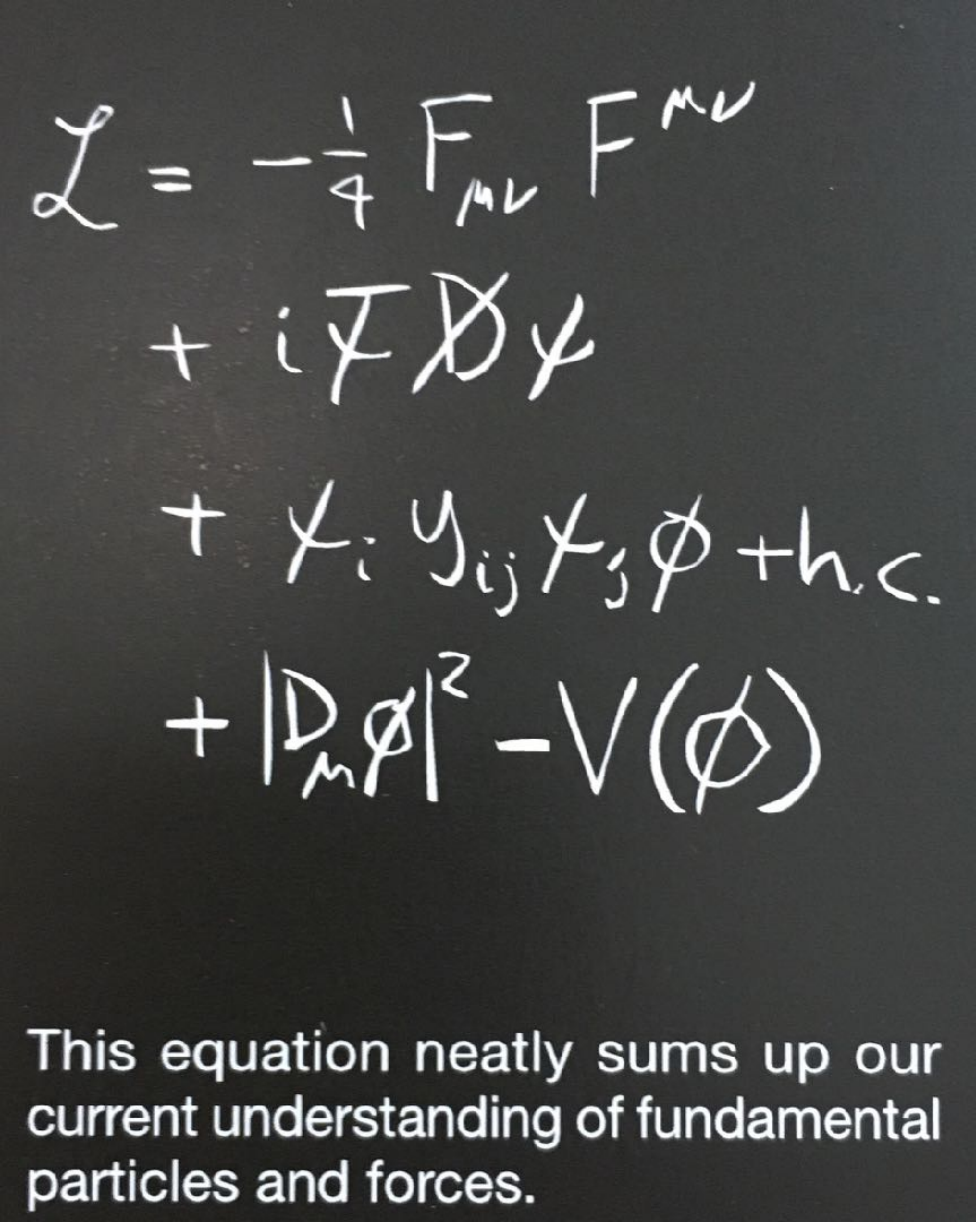
We study vector portal dark matter models where the m… …tree-level couplings to colored states, radiative effects generate interactions with quark fields… …and future experiments. We identify such experimental signatures: scattering of nuclei in dark ma… …production of lepton-antilepton pairs at the Large Hadron Collider; and hadronic final states in dark matter indirect… …ermore, radiative effects also generate an irreducible mass mixing between the vector mediator and the Z boson, severely bounded b… …ElectroWeak Precision Tests. We use current experimental results to put bounds on this class of models, accounting for both radiatively induced and tree-level processes. Remarkably, the former often overwhelm the latter.

THIS TALK?

What important questions can LHC answer?

Precision, as a requirement needed in order to address some of them.

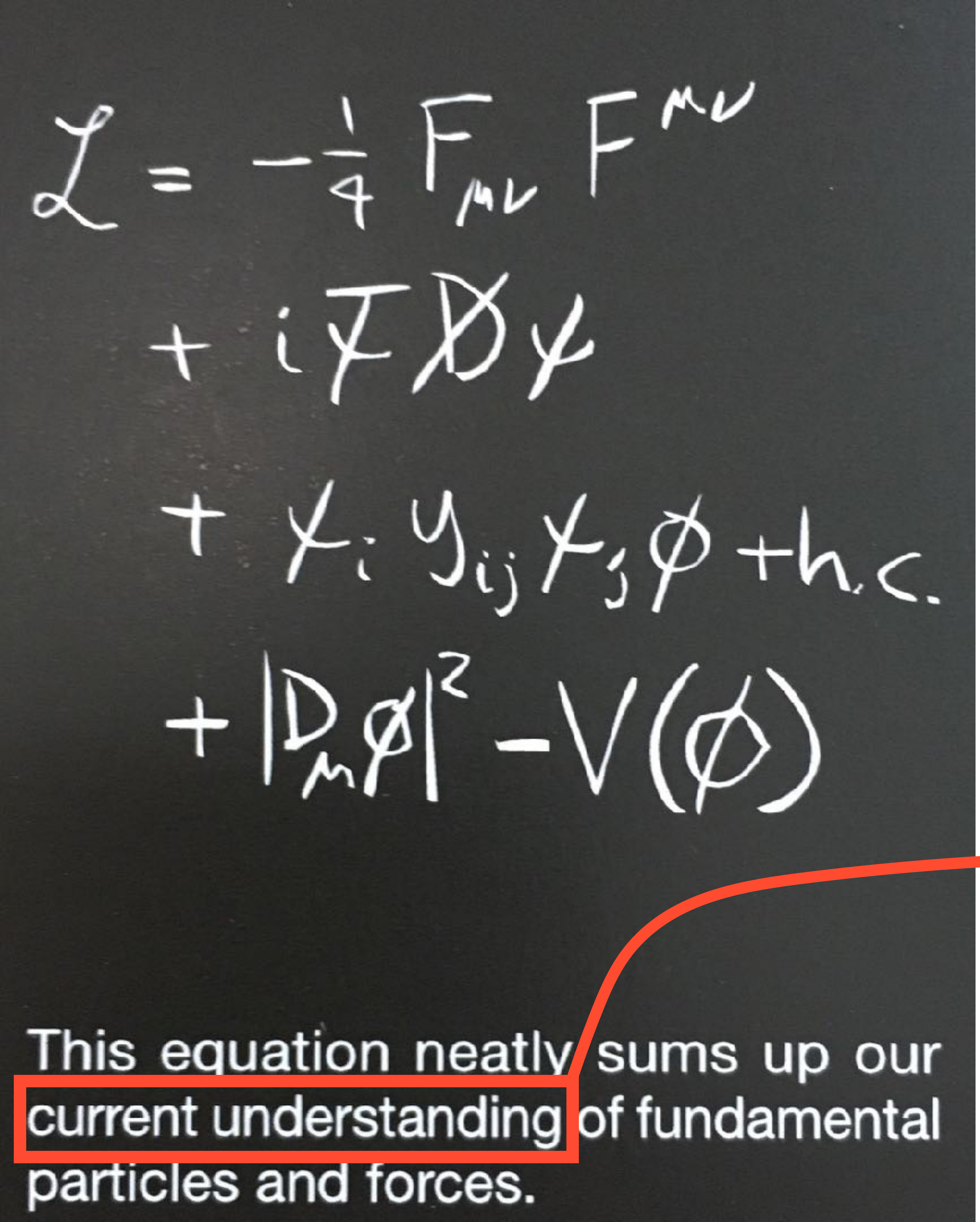
[& at the end a few remarks on searches]



Standard Model — knowable unknowns

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

STANDARD MODEL — KNOWABLE UNKNOWNS



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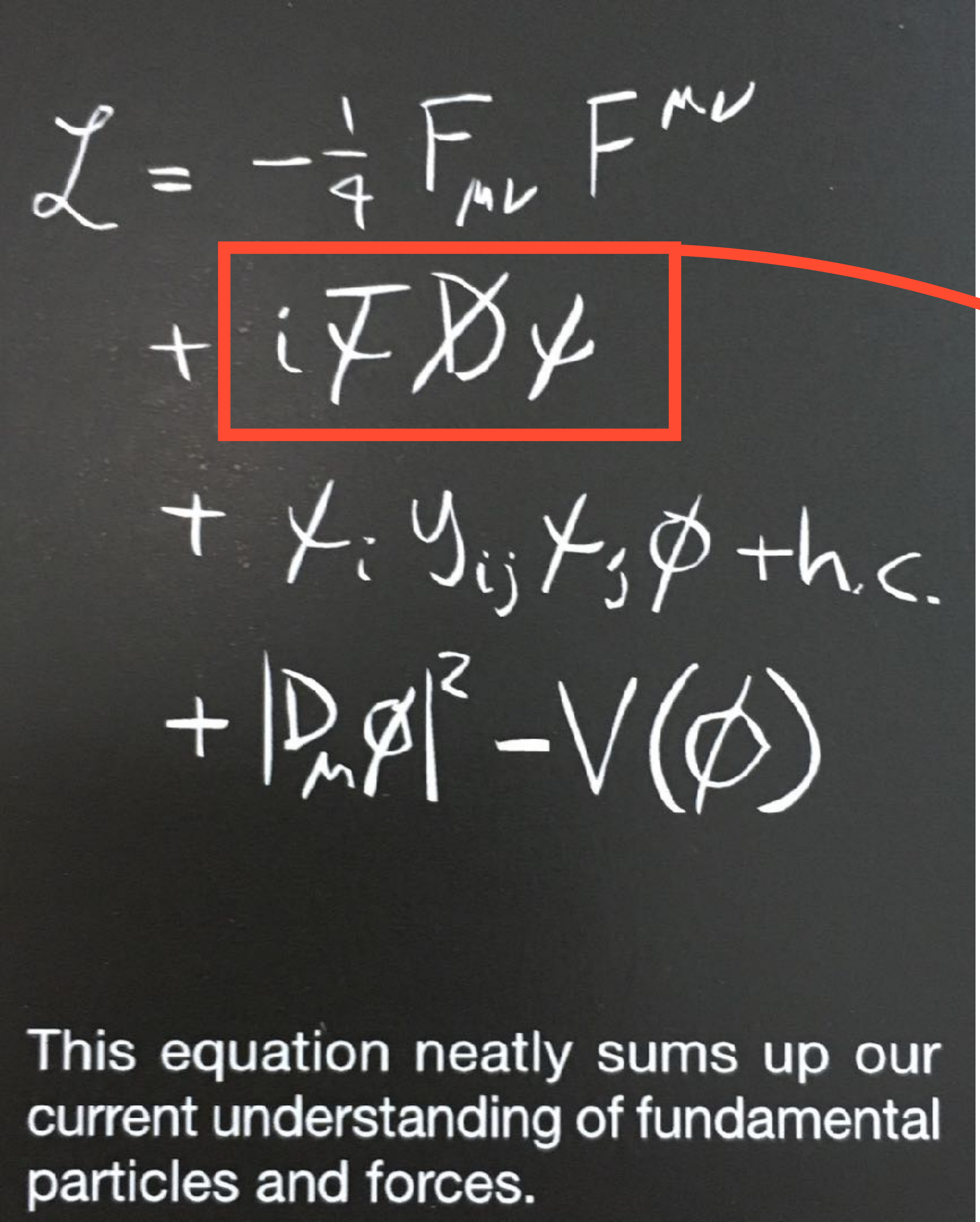
"understanding" = knowledge ?

"understanding" = assumption ?

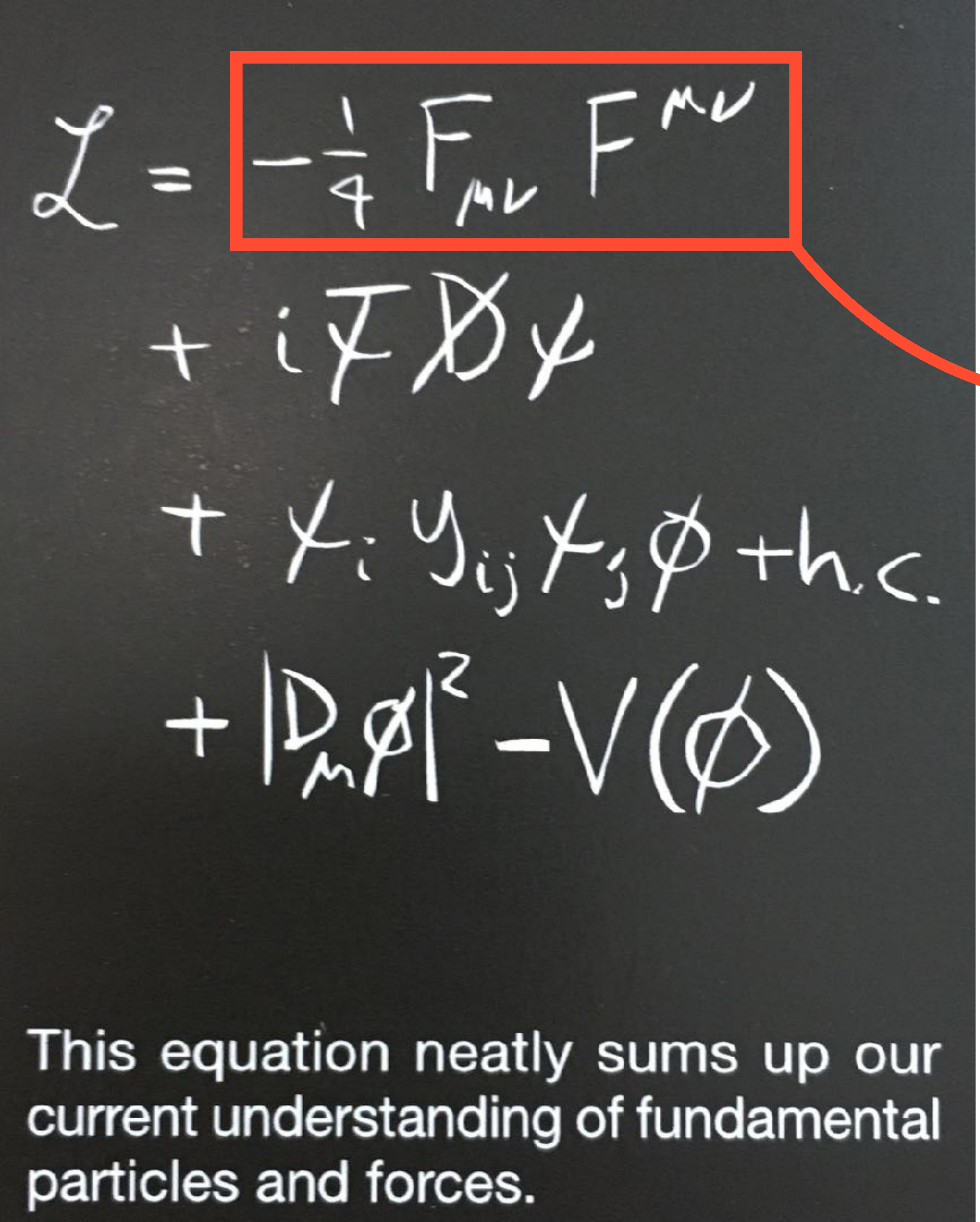


Gauge–Matter part

e.g. Zqq, qqg interactions — well established in DIS, e^+e^-, pp

≡ KNOWLEDGE

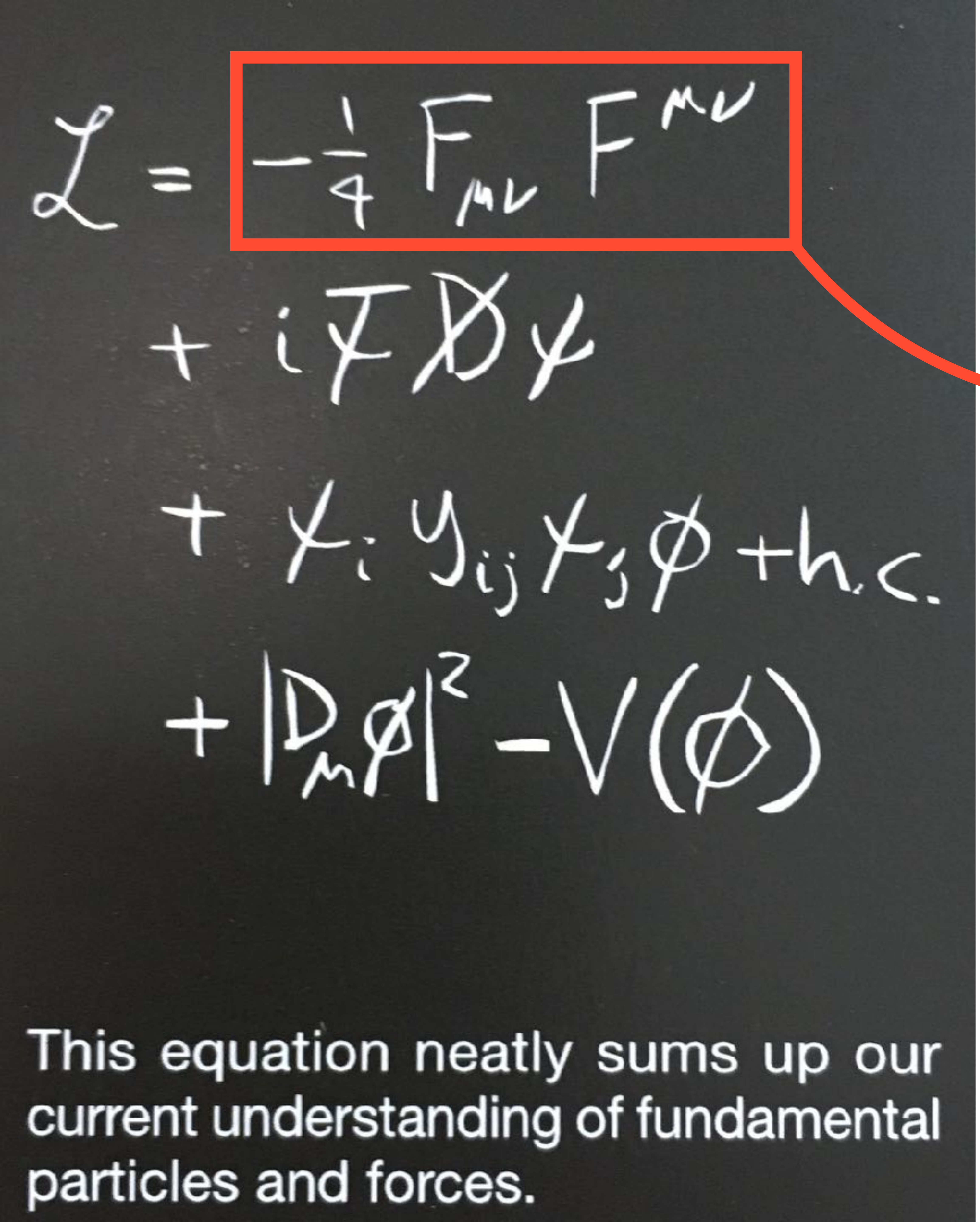
(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)



Pure Gauge

e.g. ZWW, 3-gluon interactions — well established at LEP ≡ KNOWLEDGE

& also being studied at LHC: TGCs



PURE GAUGE

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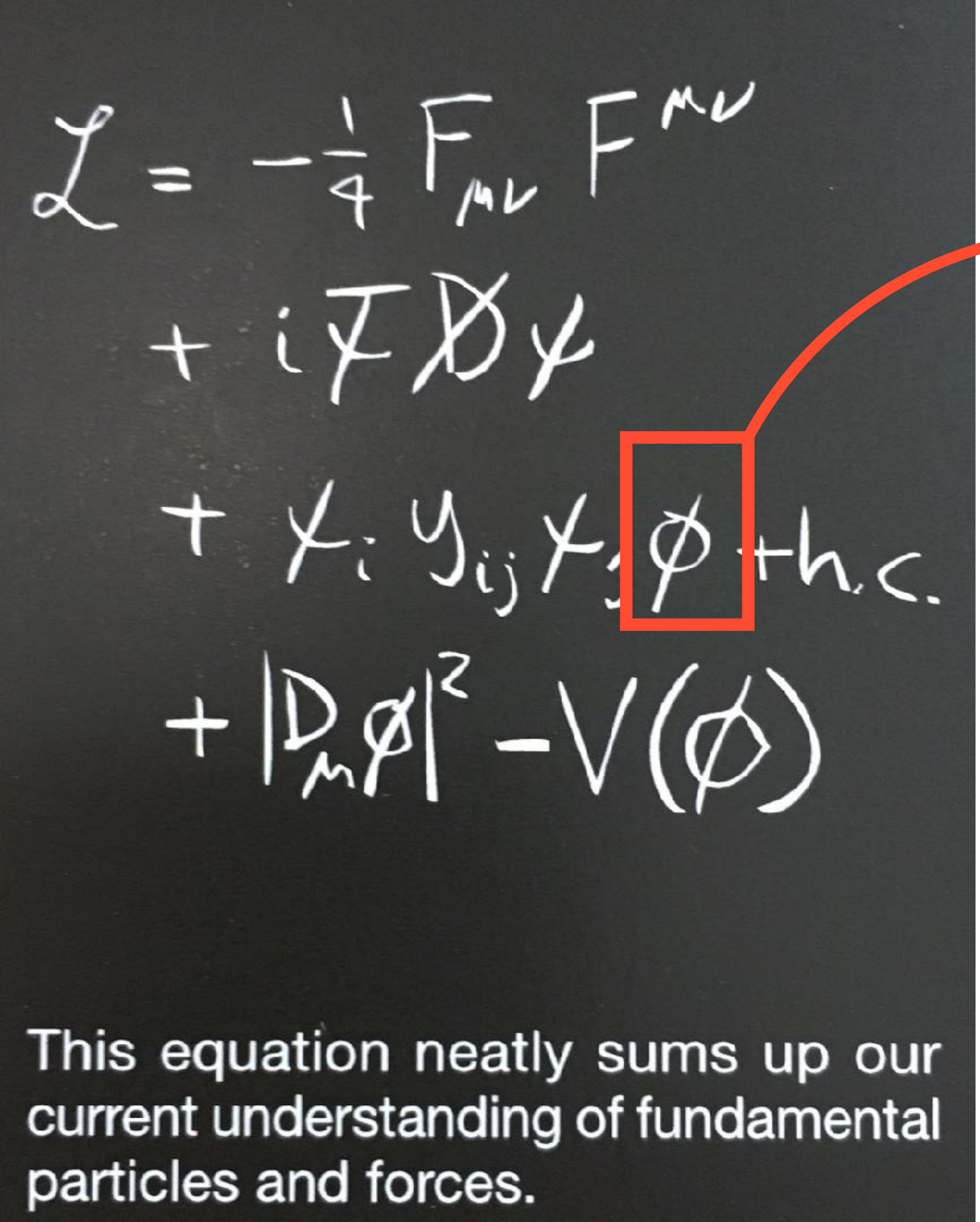
We've seen gauge sectors work over and over again
→ gives us the illusion there's nothing left to do in SM physics

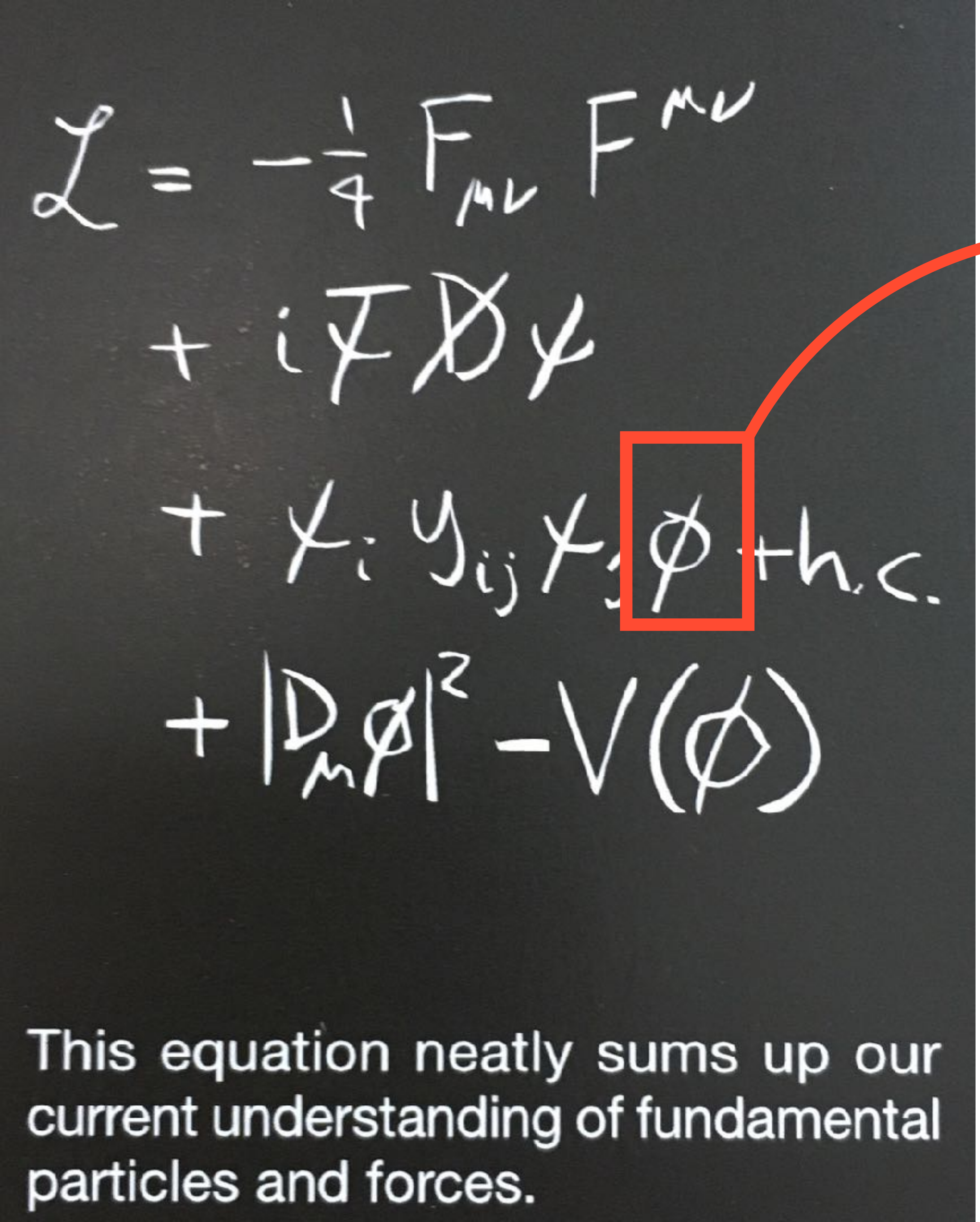


Higgs Boson

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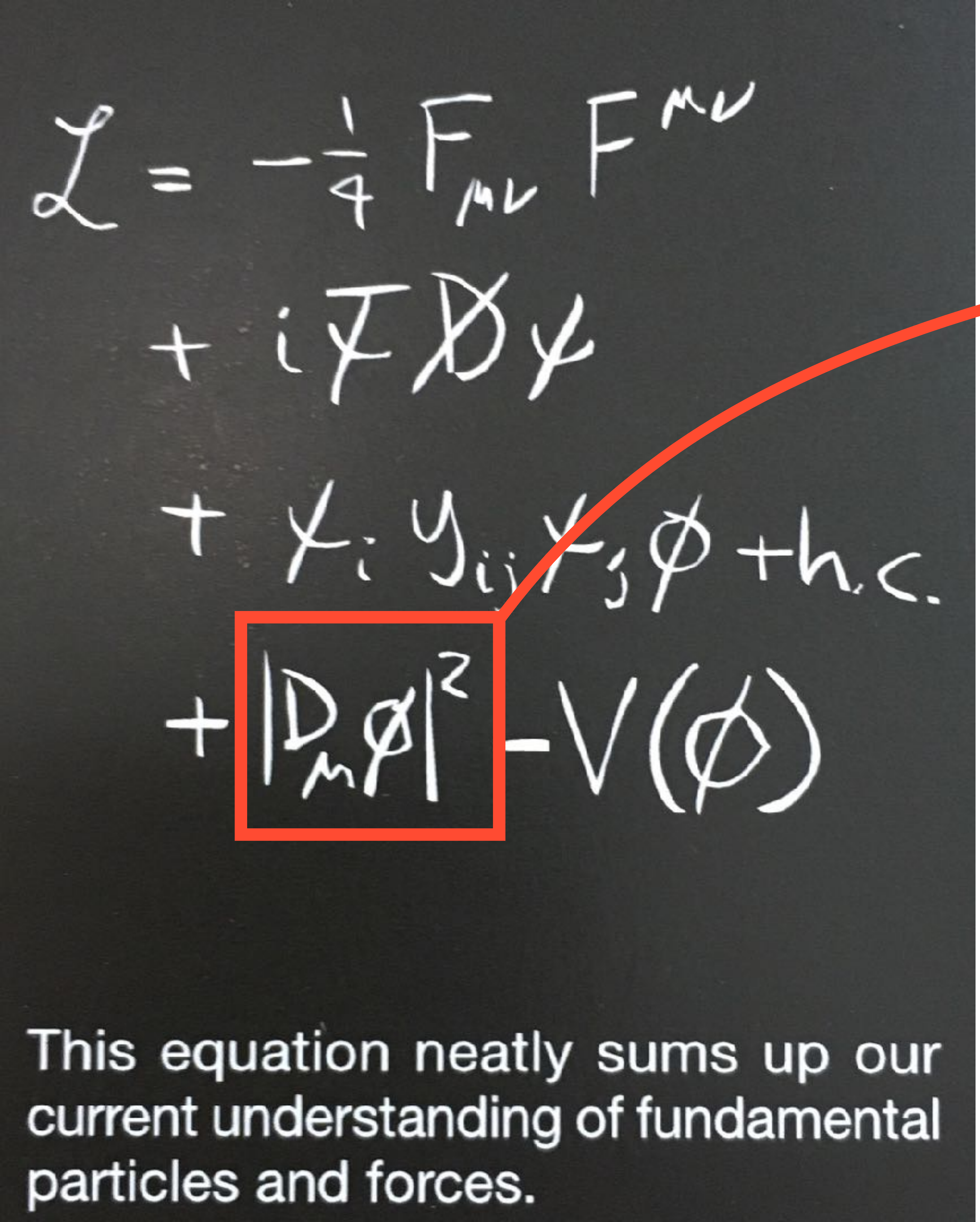
Novelty? If fundamental, very
(the only fundamental scalar we know of)



Gauge–Higgs interactions

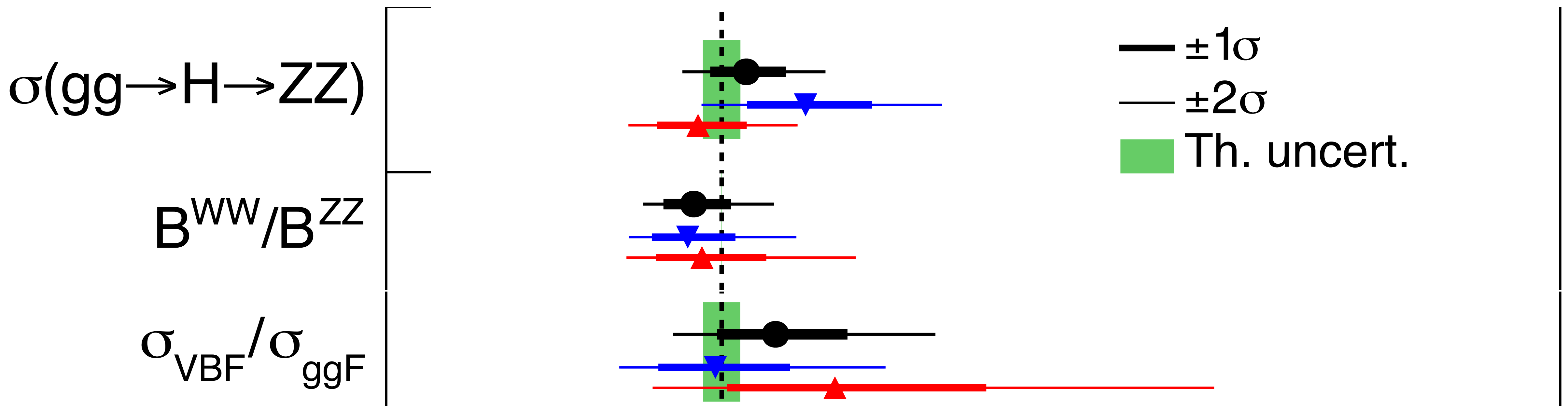
Definitely non-zero.

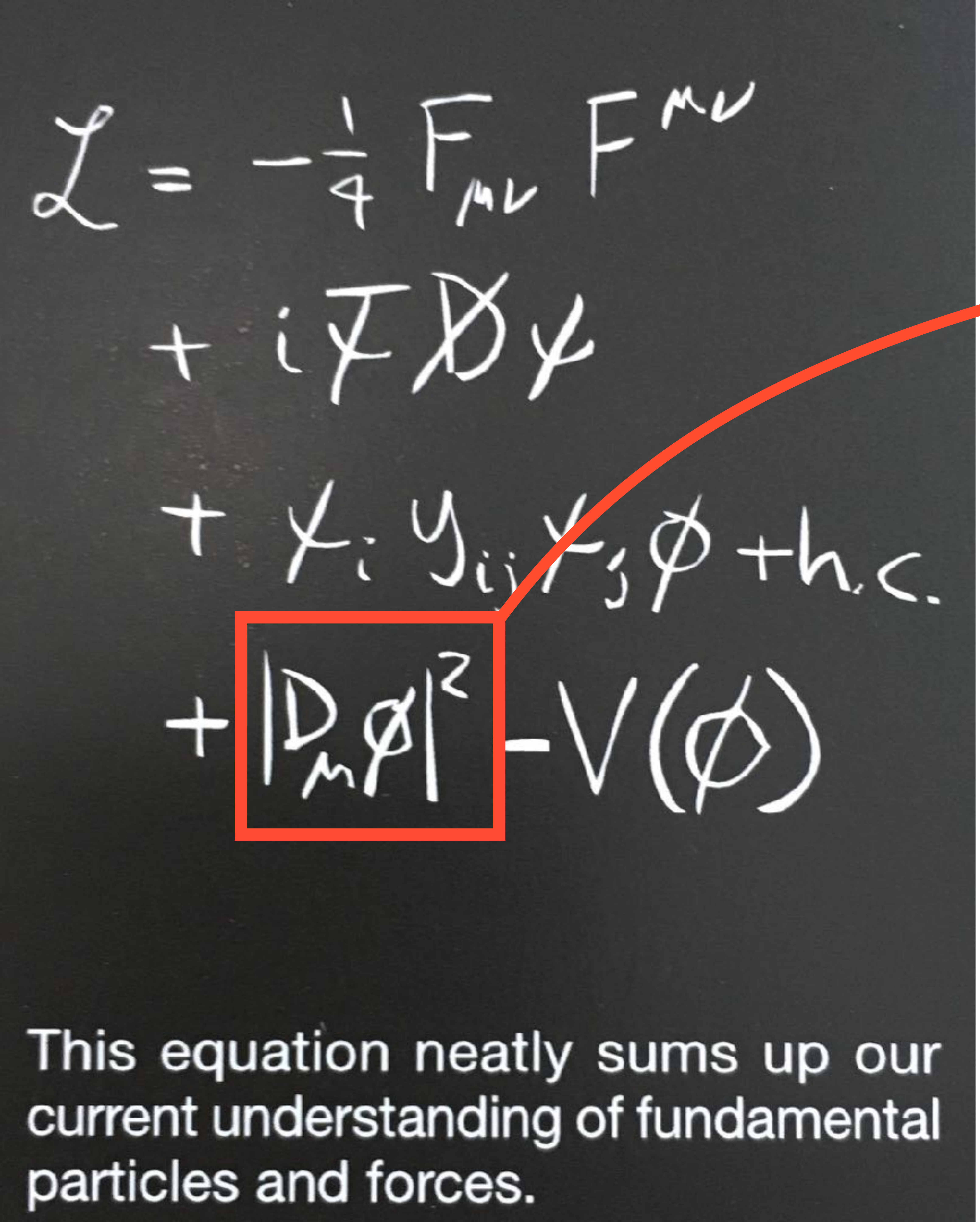
H→ZZ, H→WW, VBF

(would require "conspiracy" of couplings

in order to be substantially different)

≡ PROBABLY TRUE





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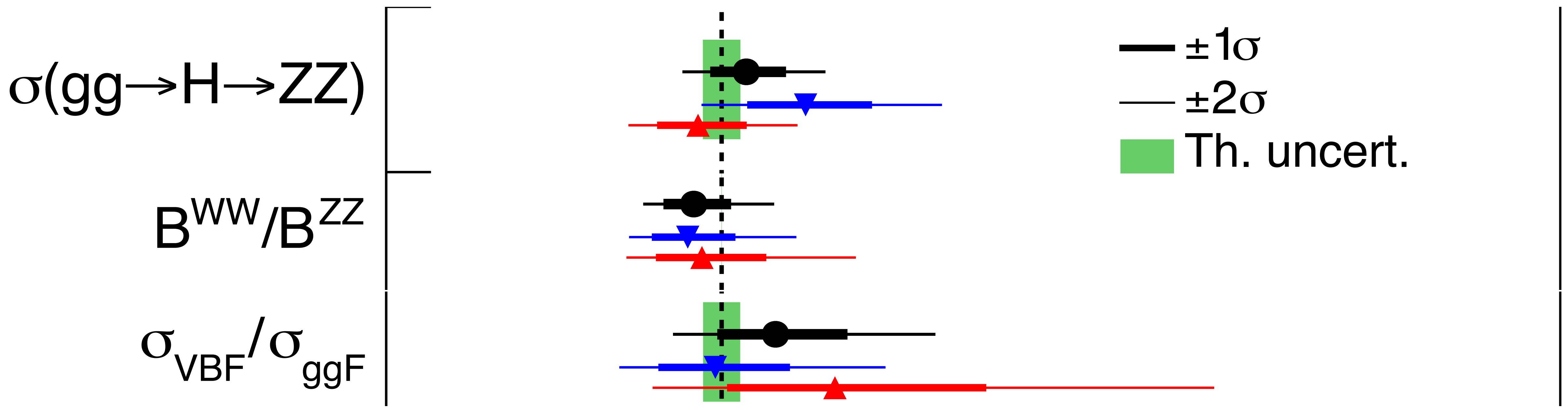
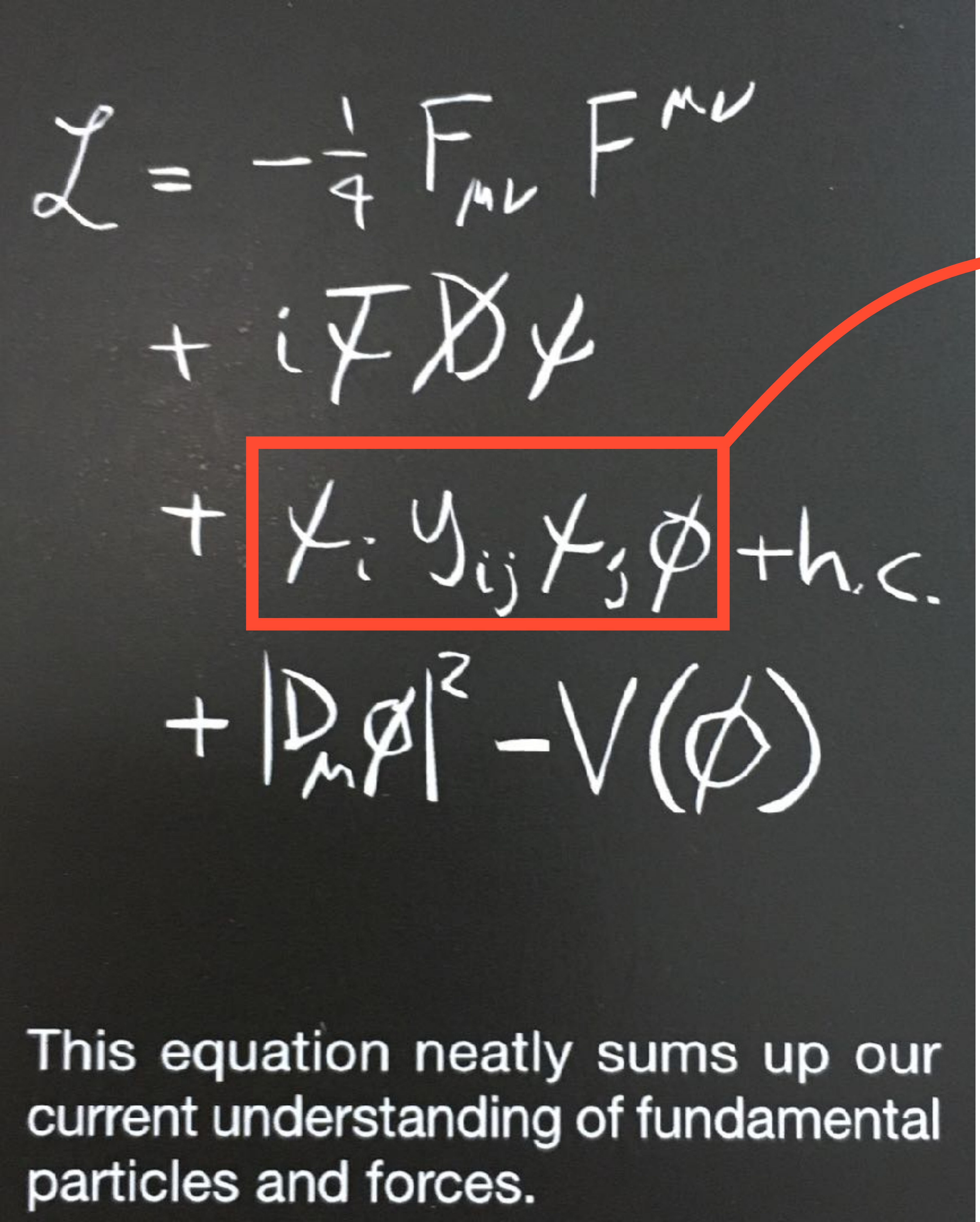


Novelty? Covariant derivative D is widespread, but first time we see it with a scalar



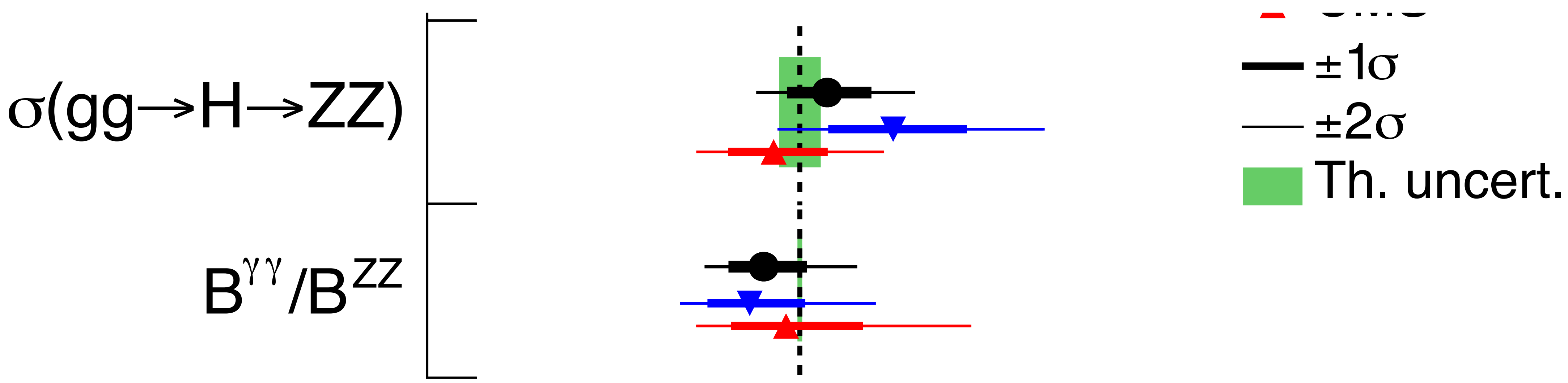
Yukawa Couplings

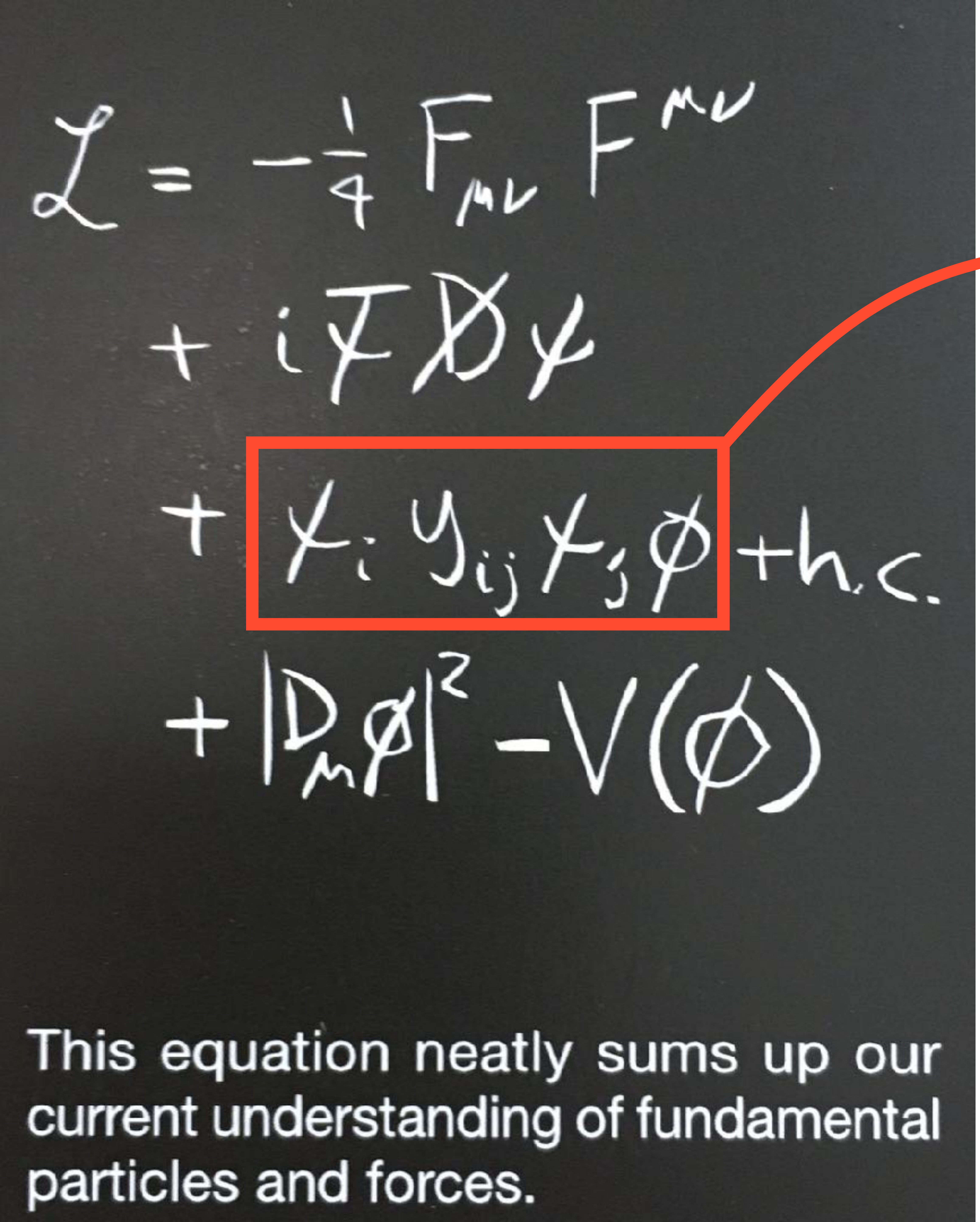
top? gg→H, H→ γγ ≡ INDIRECT

bottom? H branching ratios ≡ INDIRECT

tau? ~ observed ≡ ~ KNOWLEDGE

1st & 2nd gen? ≡ IGNORANCE





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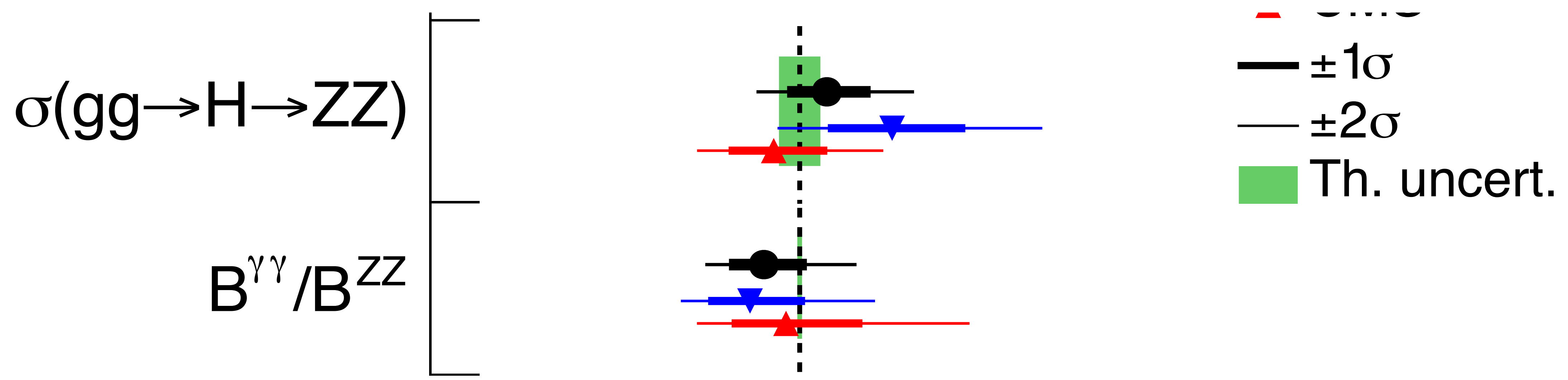
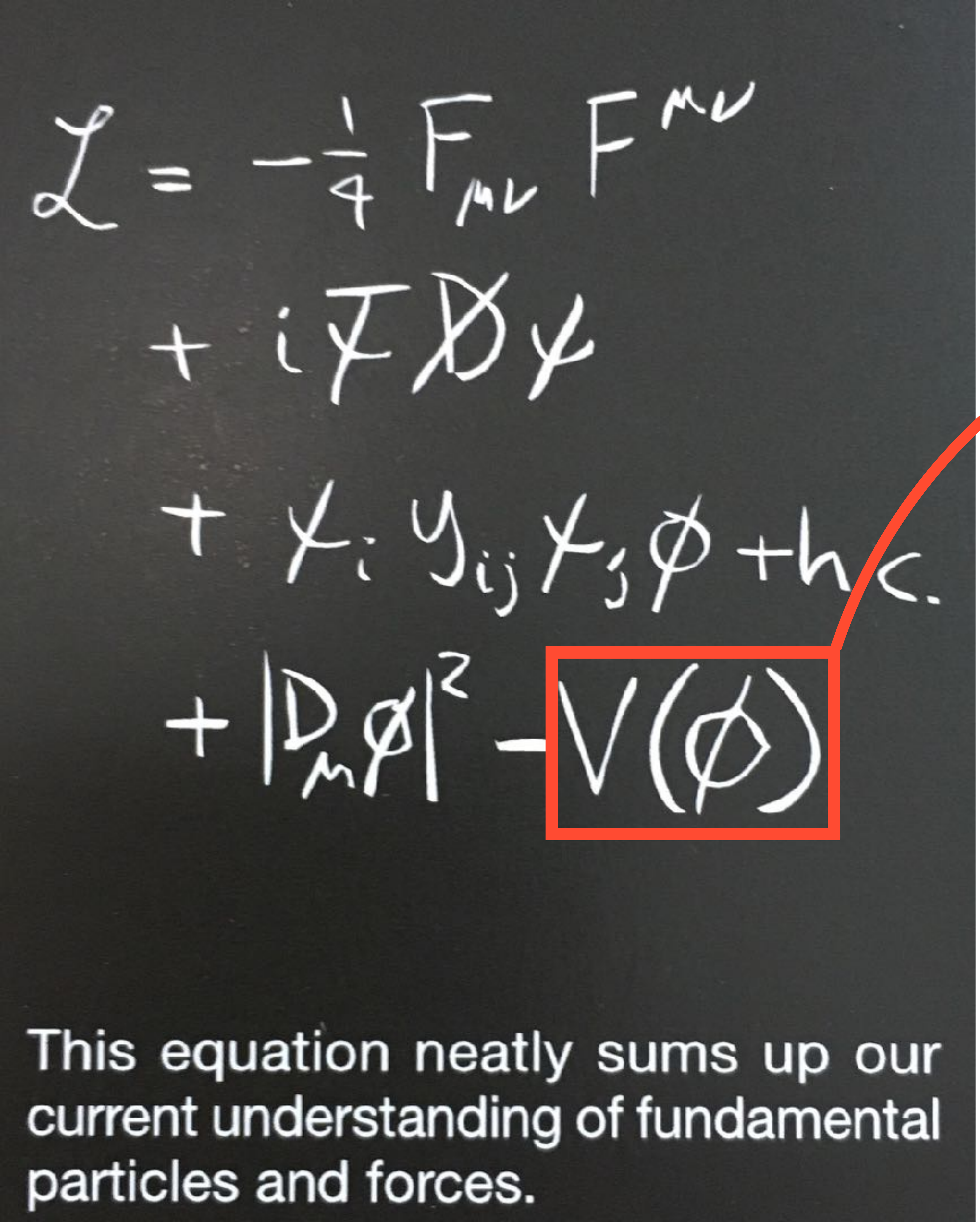
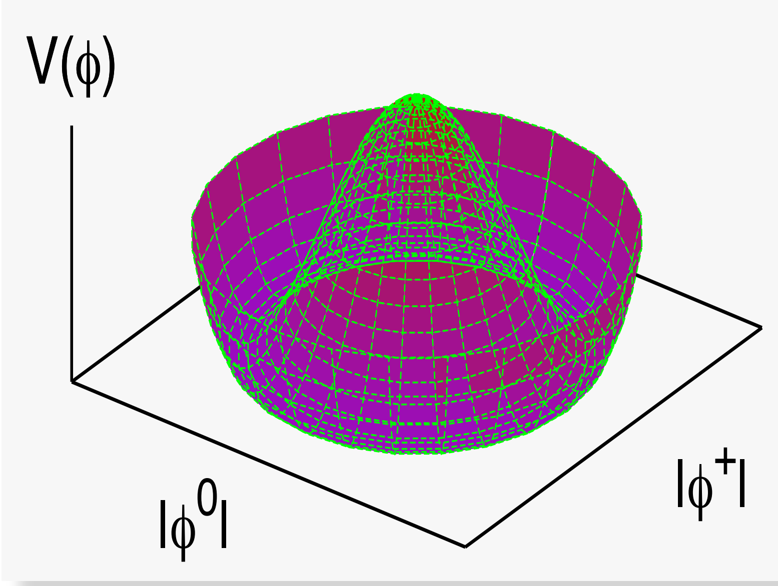


Novelty? We've never seen anything like it → mystery of 5 orders of magnitude in mass between electron & top, CKM



Higgs Potential



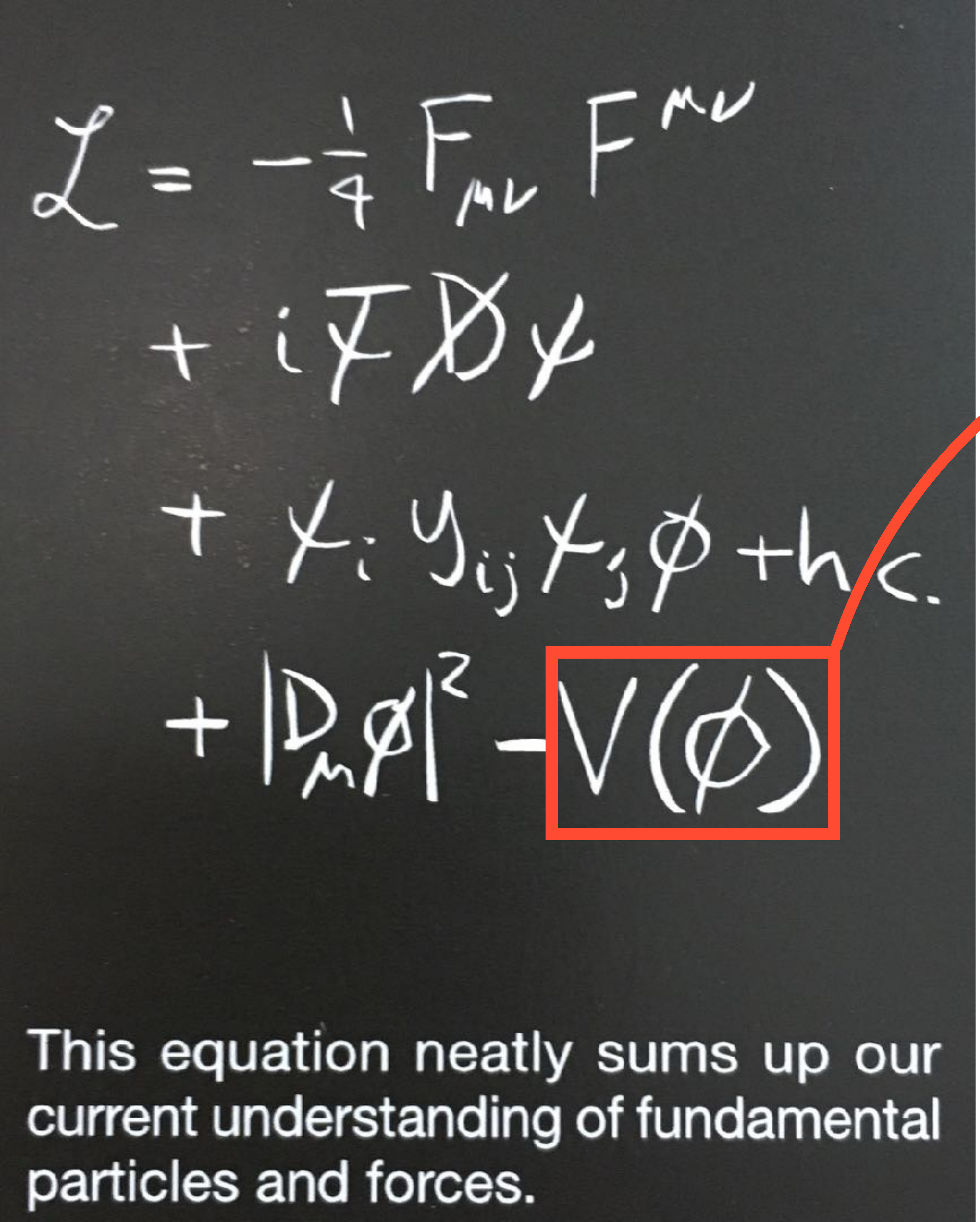
VEV? ≡ KNOWLEDGE

2nd derivative ($\sim m_H$)?

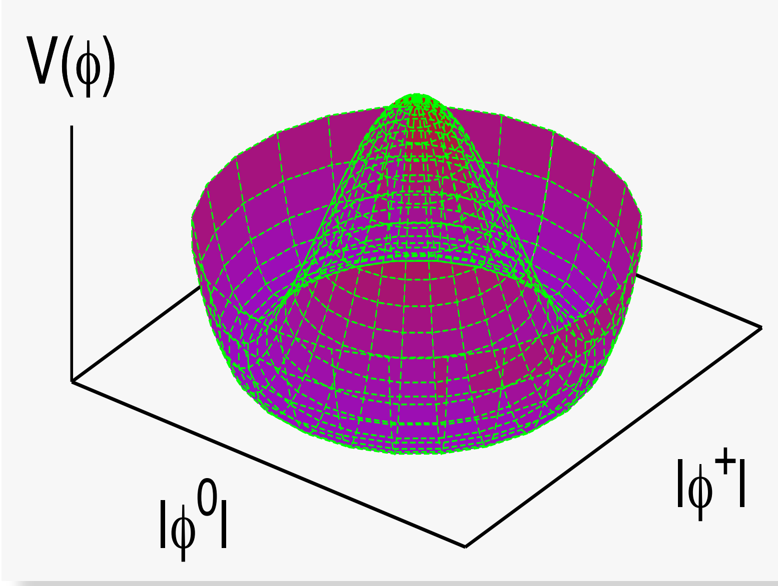
[not a prediction of the theory & any realistic theory must have a minimum & 2nd derivative]

≡ KNOWLEDGE

$\varphi^2 + \varphi^4$? ≡ ASSUMPTION



Higgs Potential



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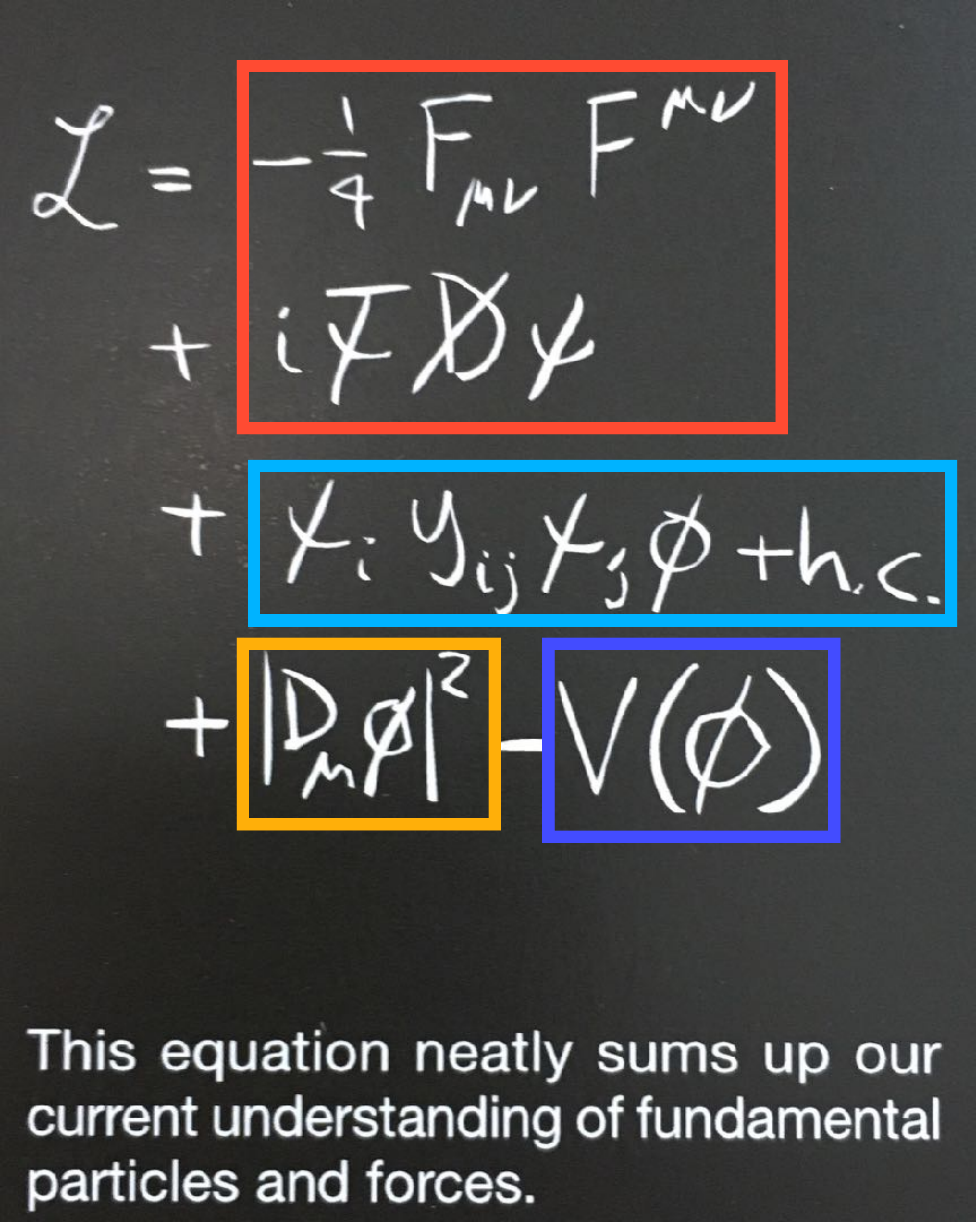
Novelty? Theorists' toy model, never seen in nature (as fundamental); Connects with stability of universe



Overall today?

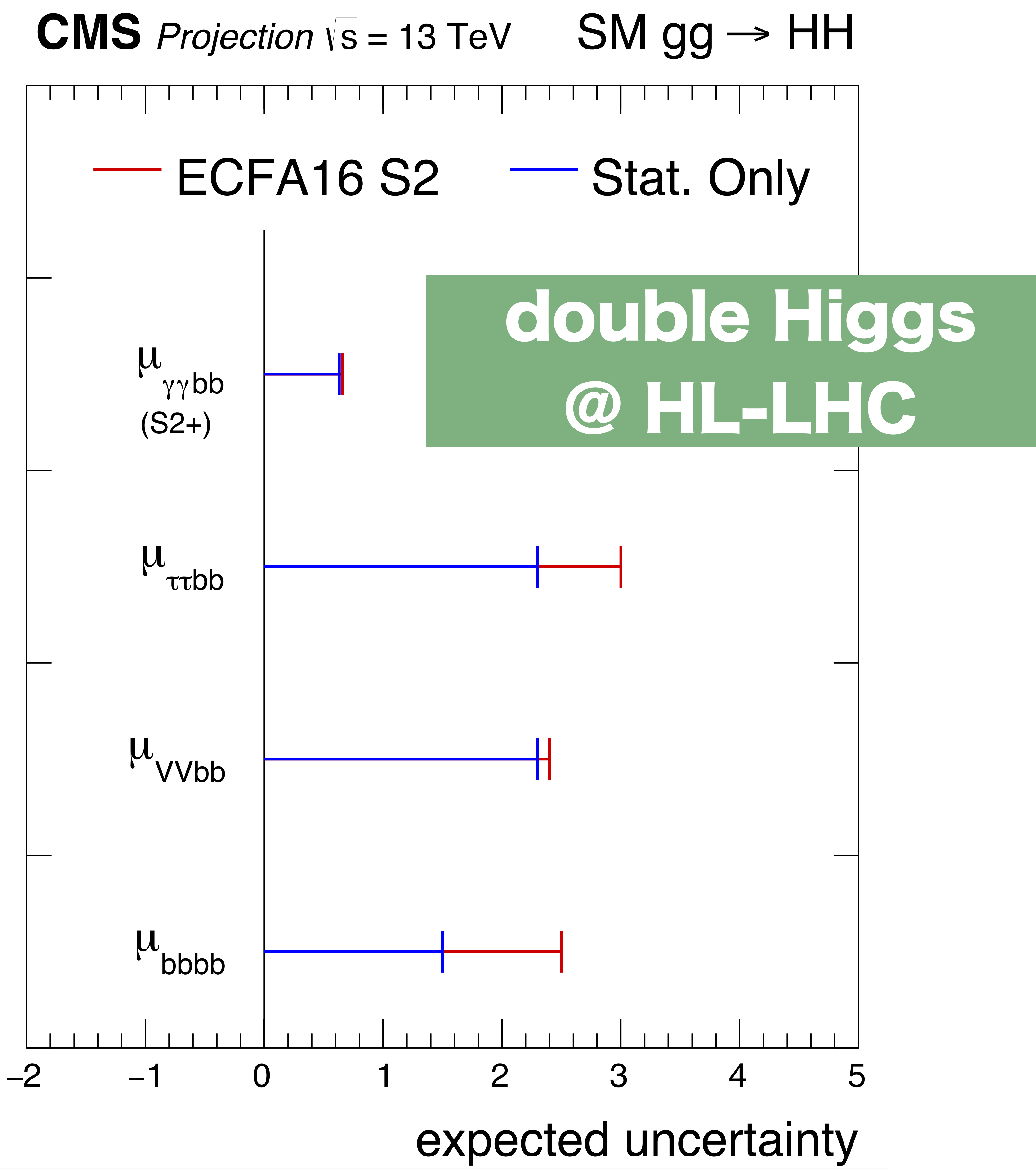
There remains a lot to establish in the Higgs sector

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)

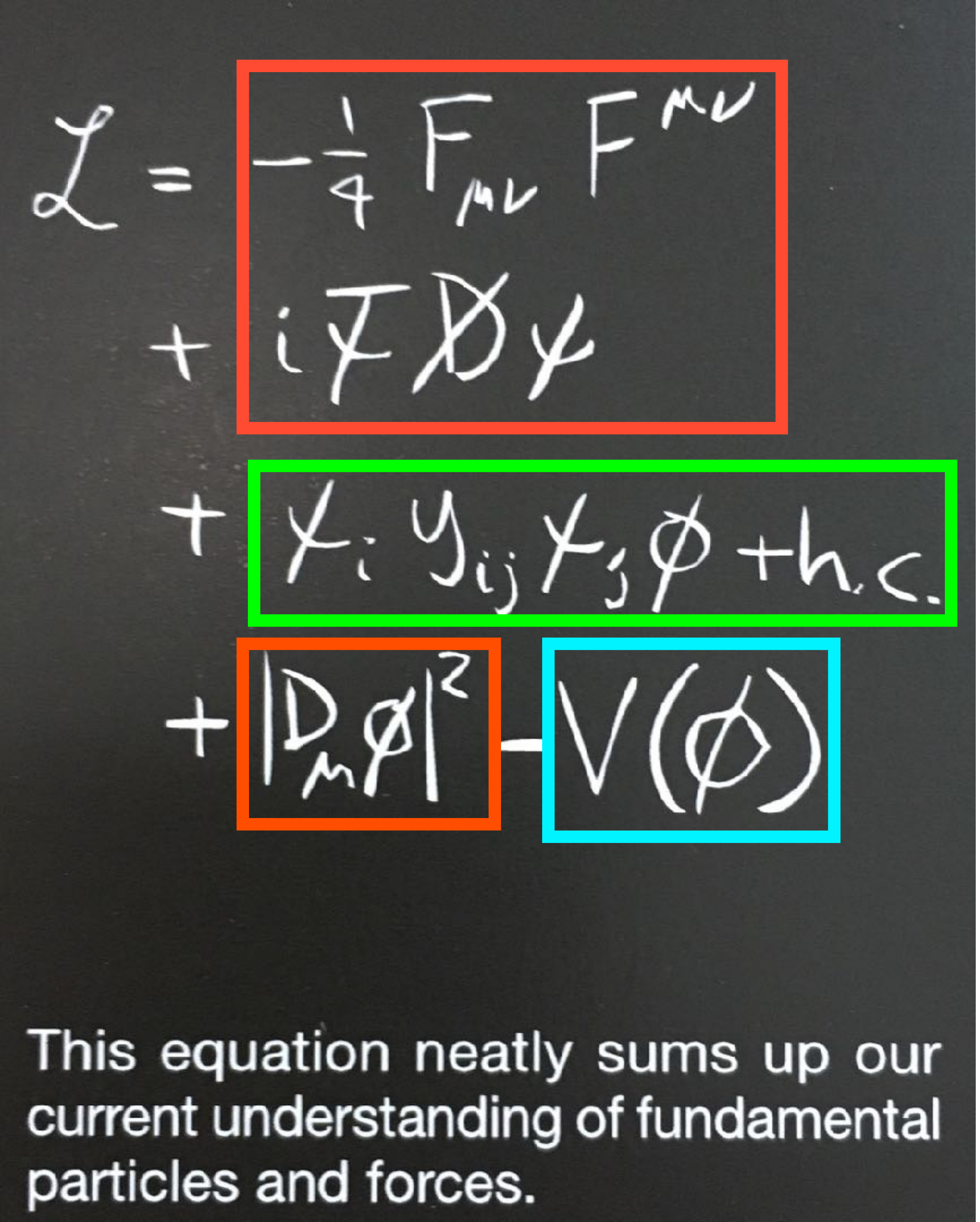
- HL-LHC: $gg \to HH$? (Higgs potential)
- HL-LHC: Hcc coupling? (2nd gen Yukawa)



cf. talks at HL-LHC workshop

What will the LHC bring? (continued)

- $\times 300$ sensitivity to rare decays involving new physics
- map out couplings to W/Z/3rd gen. with **precision** and across **broad kinematics,** which could reveal signs of
  - new particles in loops (too heavy to produce, or hard to observe)
  - non-fundamental nature of Higgs
  - or simply confirm, in detail, a highly non-trivial part of the standard model



BY END OF HL-LHC?

ASSUMPTION

KNOWLEDGE

or falsification

What's needed beyond luminosity?

- in some cases it's entirely an experimental question, e.g. H → μμ
- in many cases, mapping out full structure needs **precise theory and experiment**
- e.g. indirect constraints on Hcc Yukawa and triple Higgs

u, d, s, c quarks

Yotam Soreq, Hua Xing Zhu, and Jure Zupan, arXiv:1606.09621

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

HHH, sensitive to $\varphi^2+\varphi^4$ structure of potential

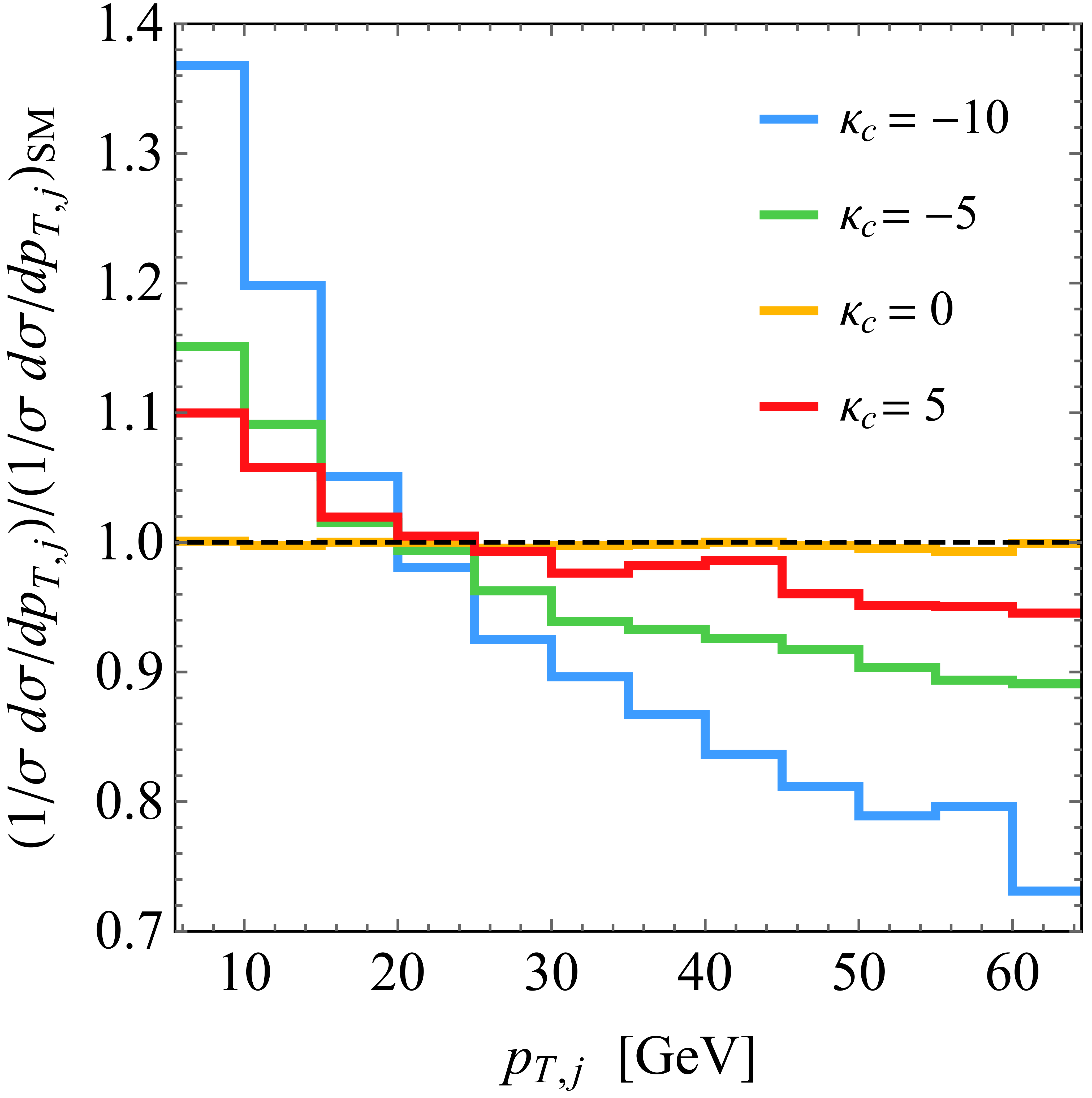
Wojciech Bizoń, Martin Gorbahn, Ulrich Haisch and Giulia Zanderighi, arXiv:1610.05771

G. Degrassia, P.P. Giardinob, F. Maltonic, D. Pagani, arXiv:1607.04251

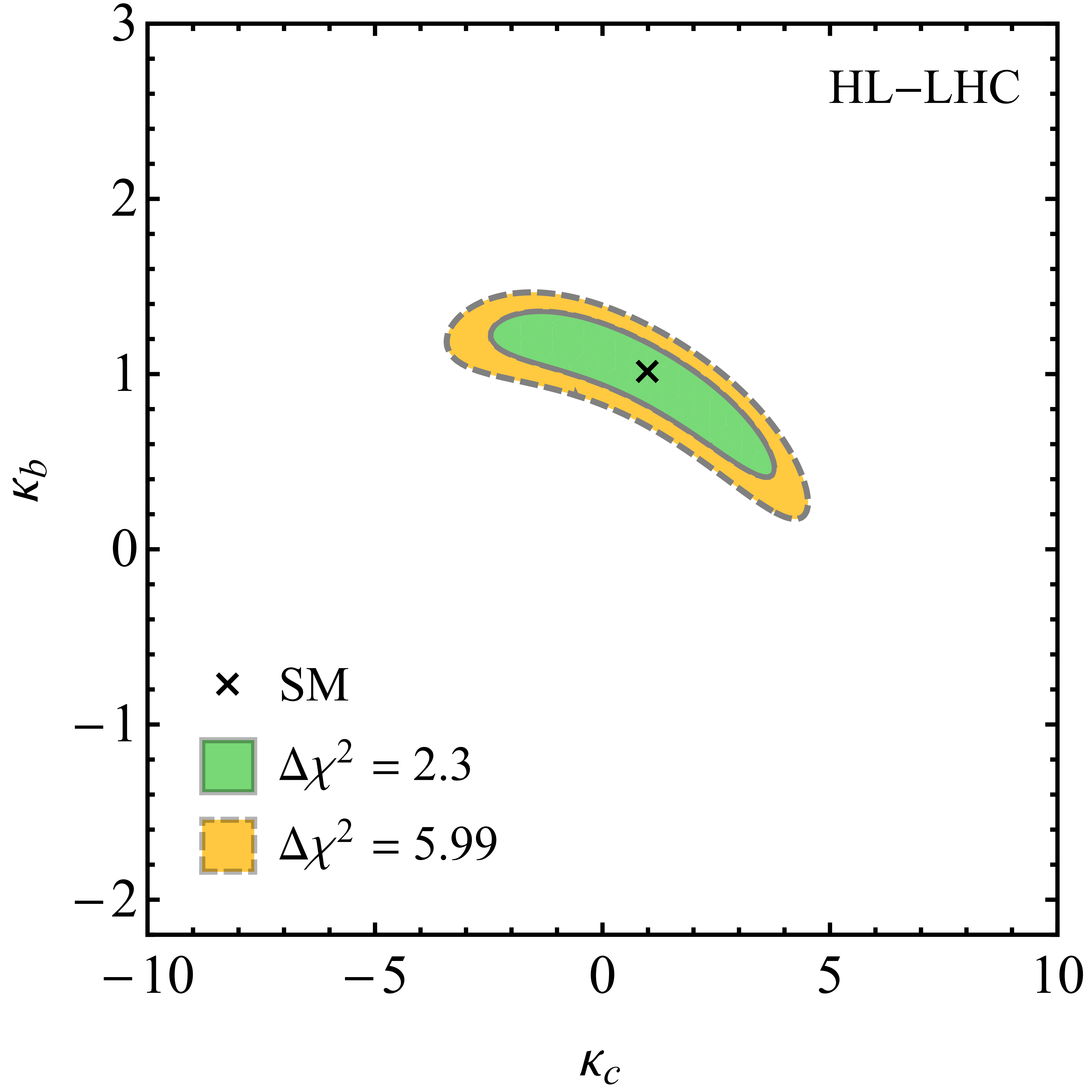
Martin Gorbahn and Ulrich Haisch, arXiv:1607.03773

indirect constraints on Hcc

impact of modified Hcc coupling on Higgs+jet p_T dist



joint limits on κ_c & κ_b @ HL-LHC



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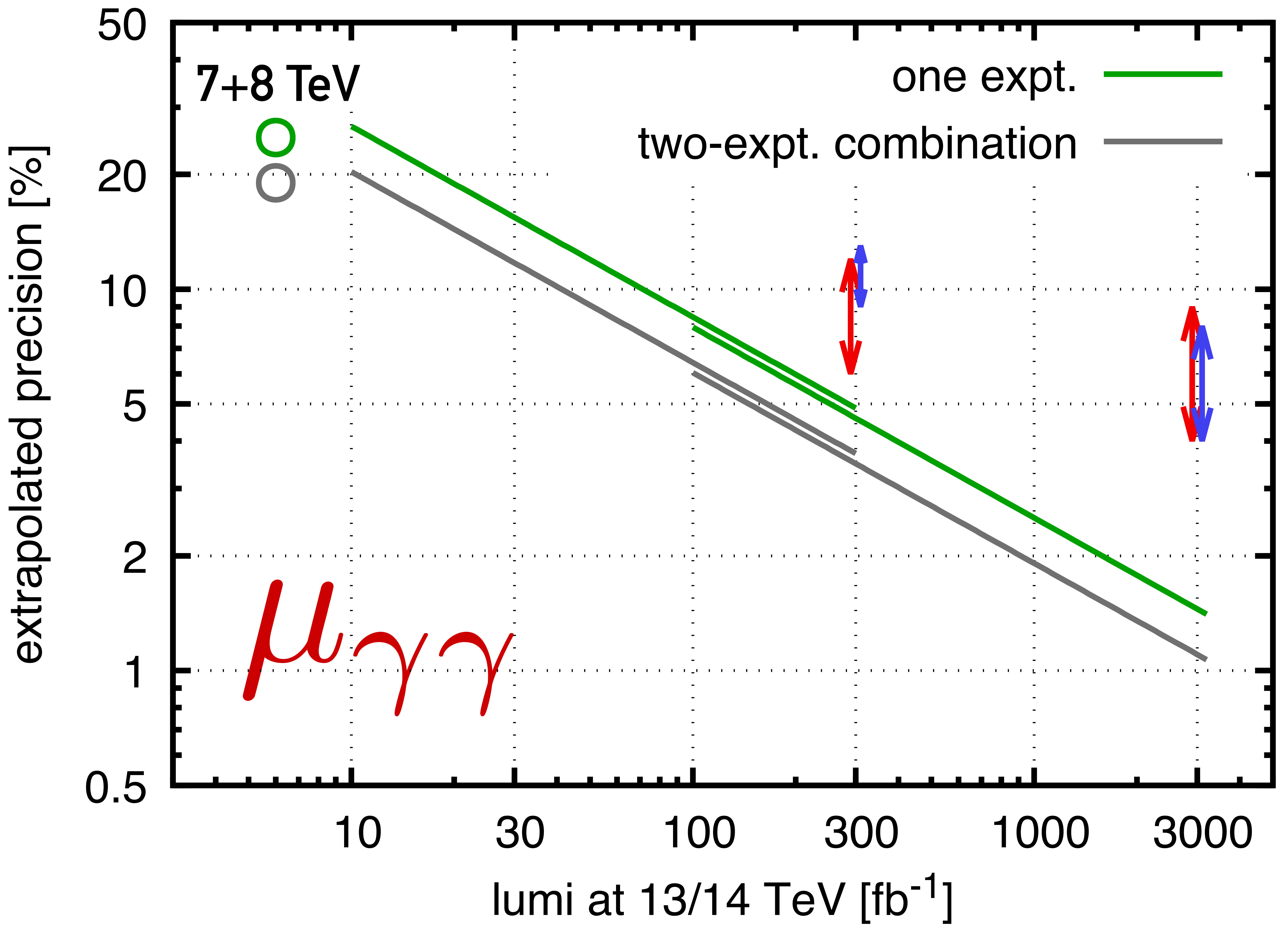
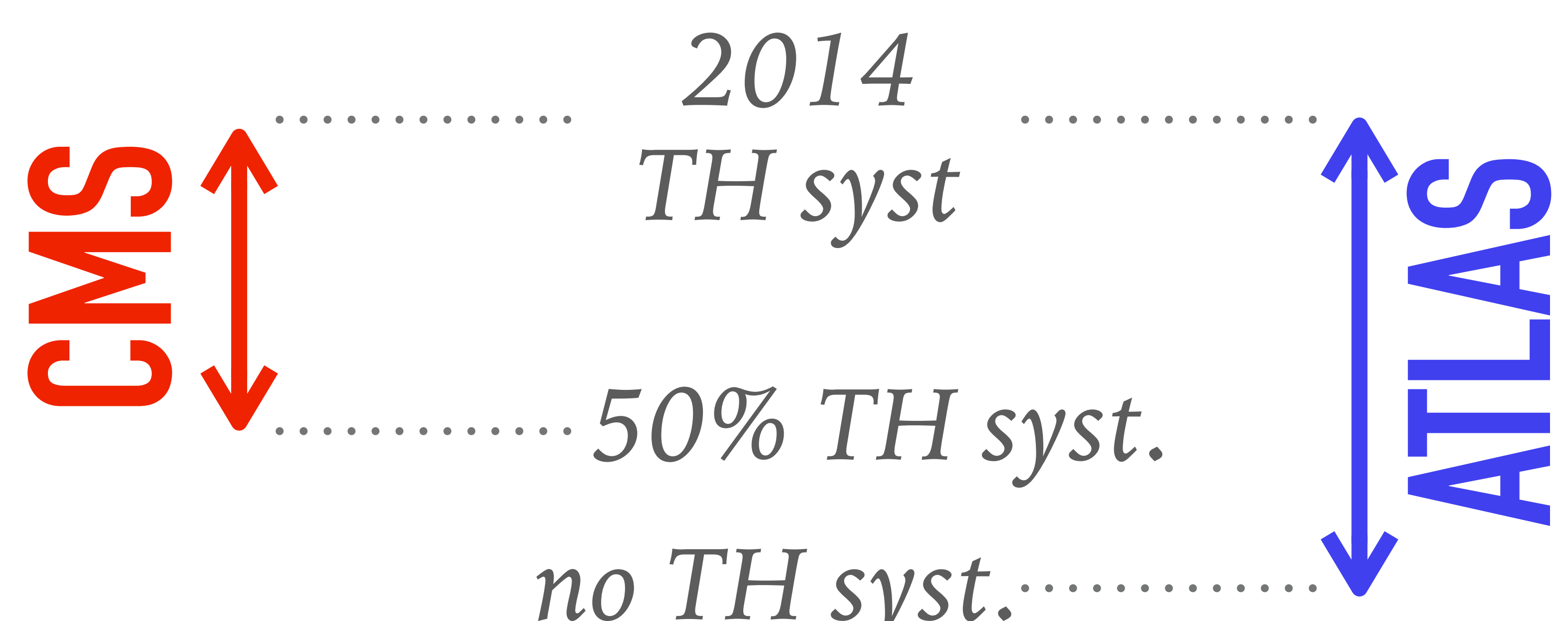
precision Higgs

NAIVELY EXTRAPOLATE 7+8 TEV RESULTS (based on lumi and σ)





Extrapolation suggests that we get "precision" value from full lumi only if we aim for O(1%) or better precision

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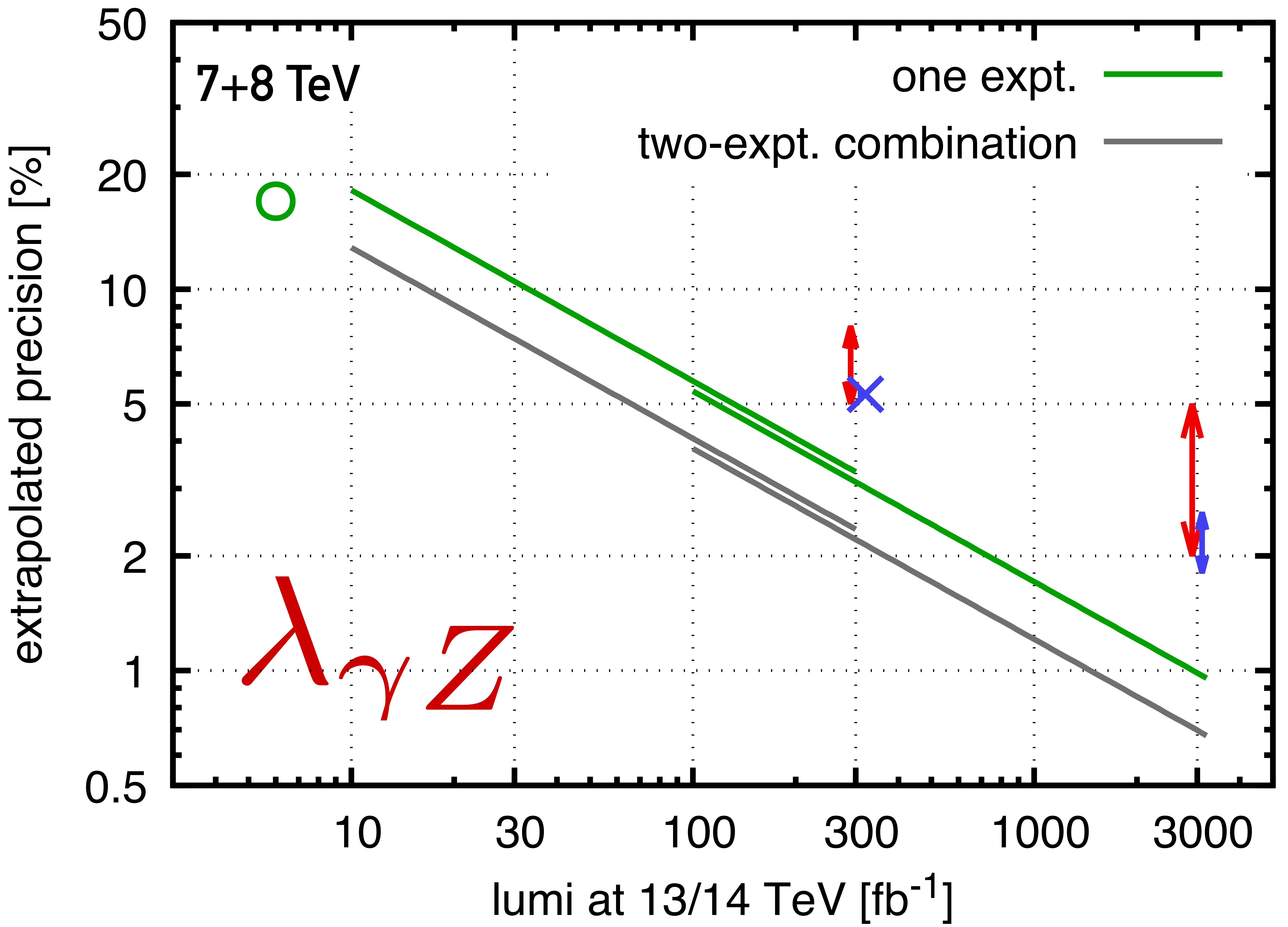

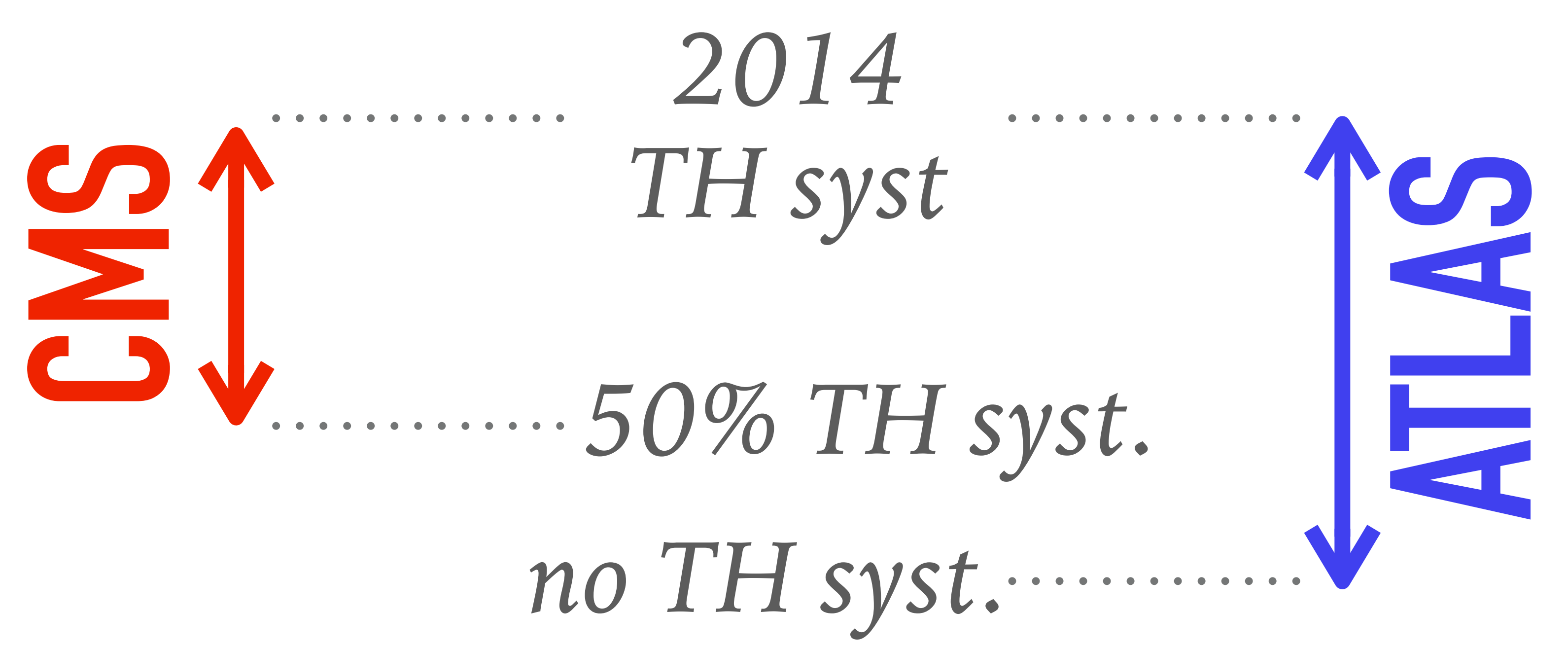

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recent higgs theory progress

take gluon fusion as main example

consider theory calculations & inputs
as well as pathway for progress

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

$$48.58\,\mathrm{pb} \pm 1.89\,\mathrm{pb}(3.9\%)\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

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+11% from scale choice, PDFs, N3LO, …

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CMS 2014 scenario 2 (reduction by 50%) already achieved!

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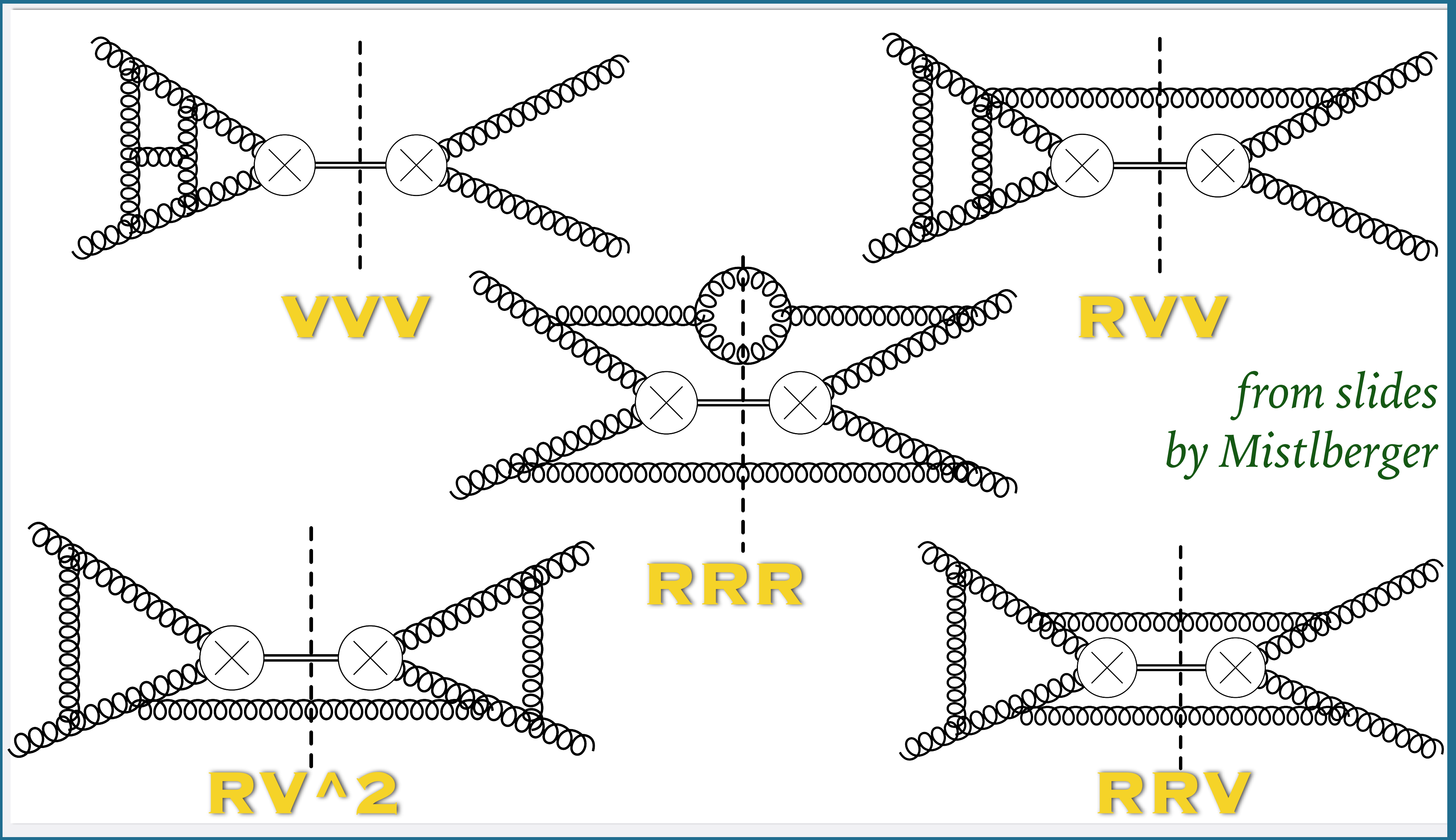
GLUON-FUSION (13 TEV)

N3LO Higgs production

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ’15-16

100,000 diagrams



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Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

GLUON-FUSION (13 TEV) — theory uncertainty

Anastasiou et al., (1602.00695, N3LO)

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t, b, c)$	$\delta(1/m_t)$
$^{+0.10\ \text{pb}}_{-1.15\ \text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

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added linearly $^{+4.6\%}_{-6.7\%}$

added in quadrature $^{+2.1\%}_{-3.1\%}$

HXSWG Gaussian ±3.9%

vs. ±7.5% in YR4

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improvement needs N4LO (or new insight) i.e. unlikely to get better in next decade

progress requires N3LO PDF fits (may be possible in next years?)

likely to improve with new calculations in next years?

added linearly $^{+4.6\%}_{-6.7\%}$

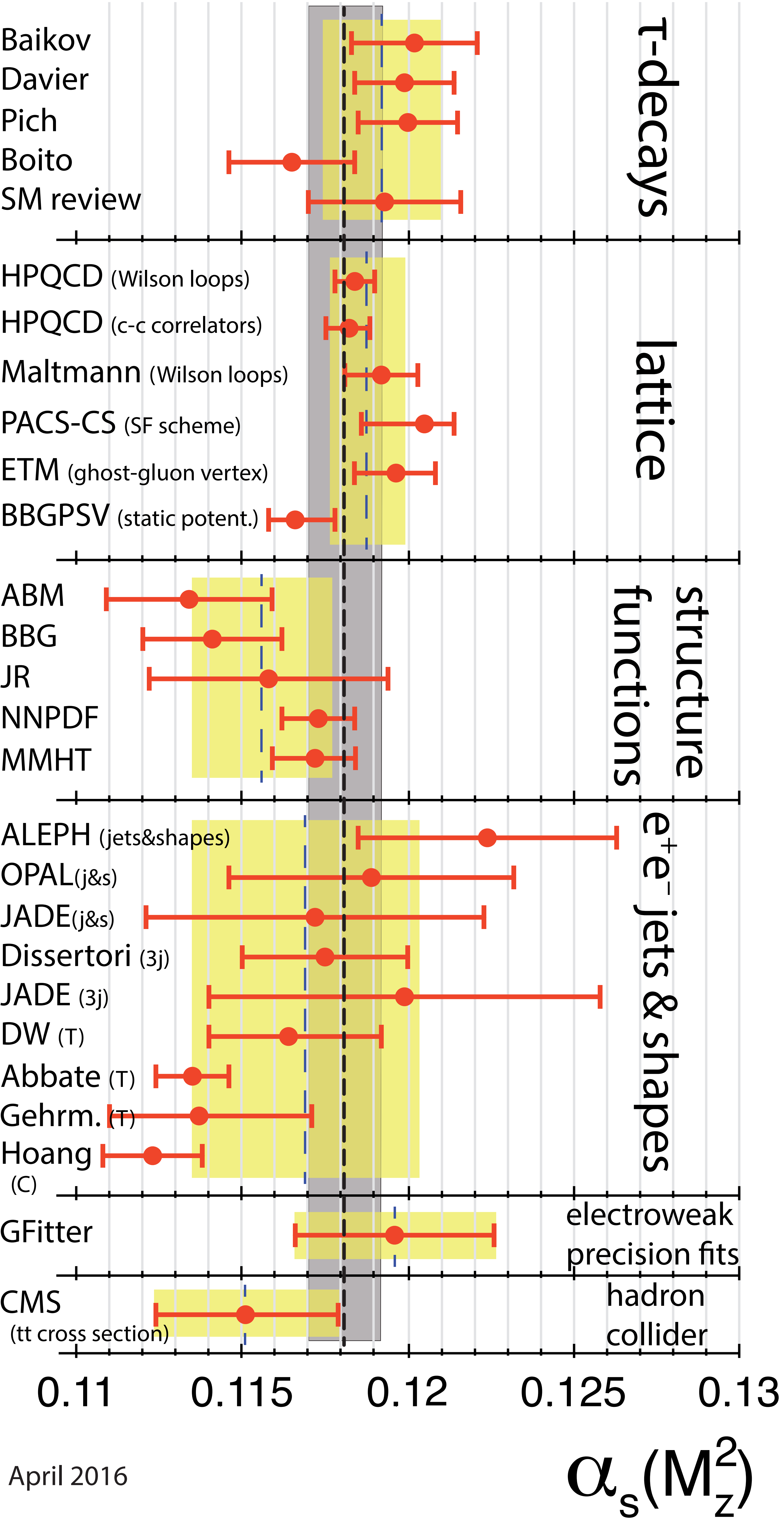
added in quadrature $^{+2.1\%}_{-3.1\%}$

HXSWG Gaussian ±3.9%

vs. $\pm 7.5\%$ *in YR4*

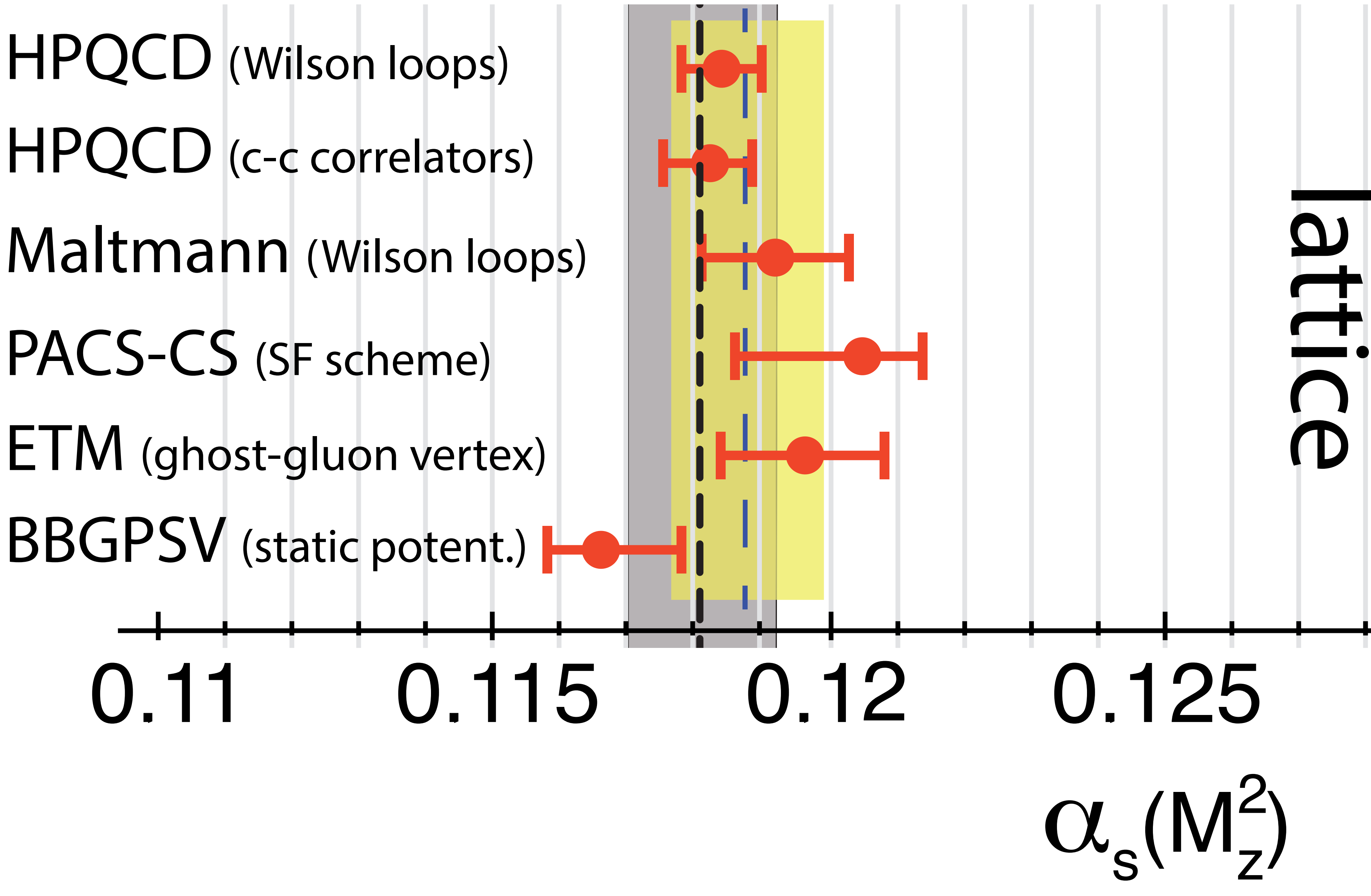
the inputs

strong coupling (e.g. $\pm 2.6\%$ on ggF)
PDFs (e.g. $\pm 1.9\%$ on ggF)



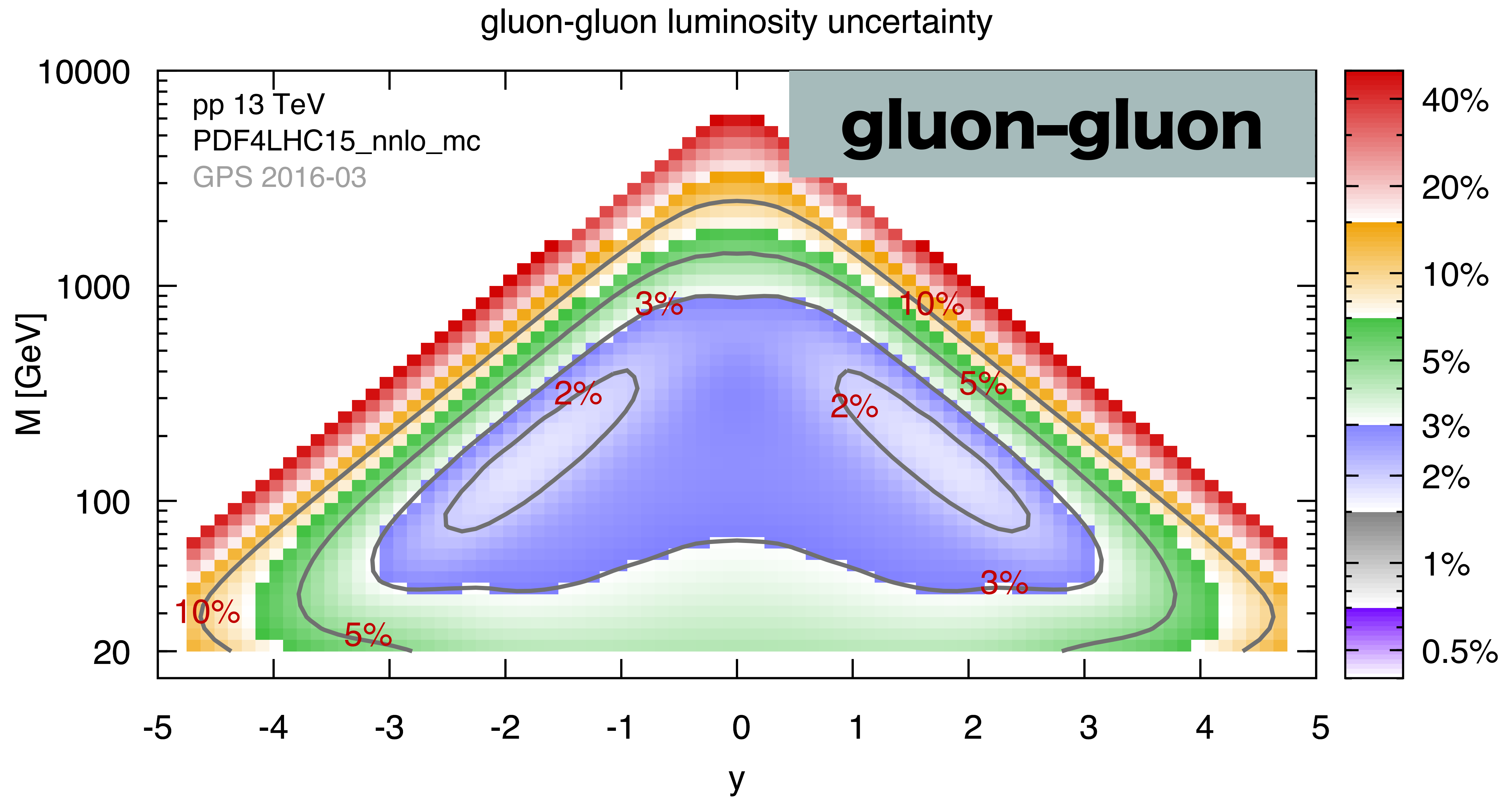
PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%). WHAT WAY FORWARD?

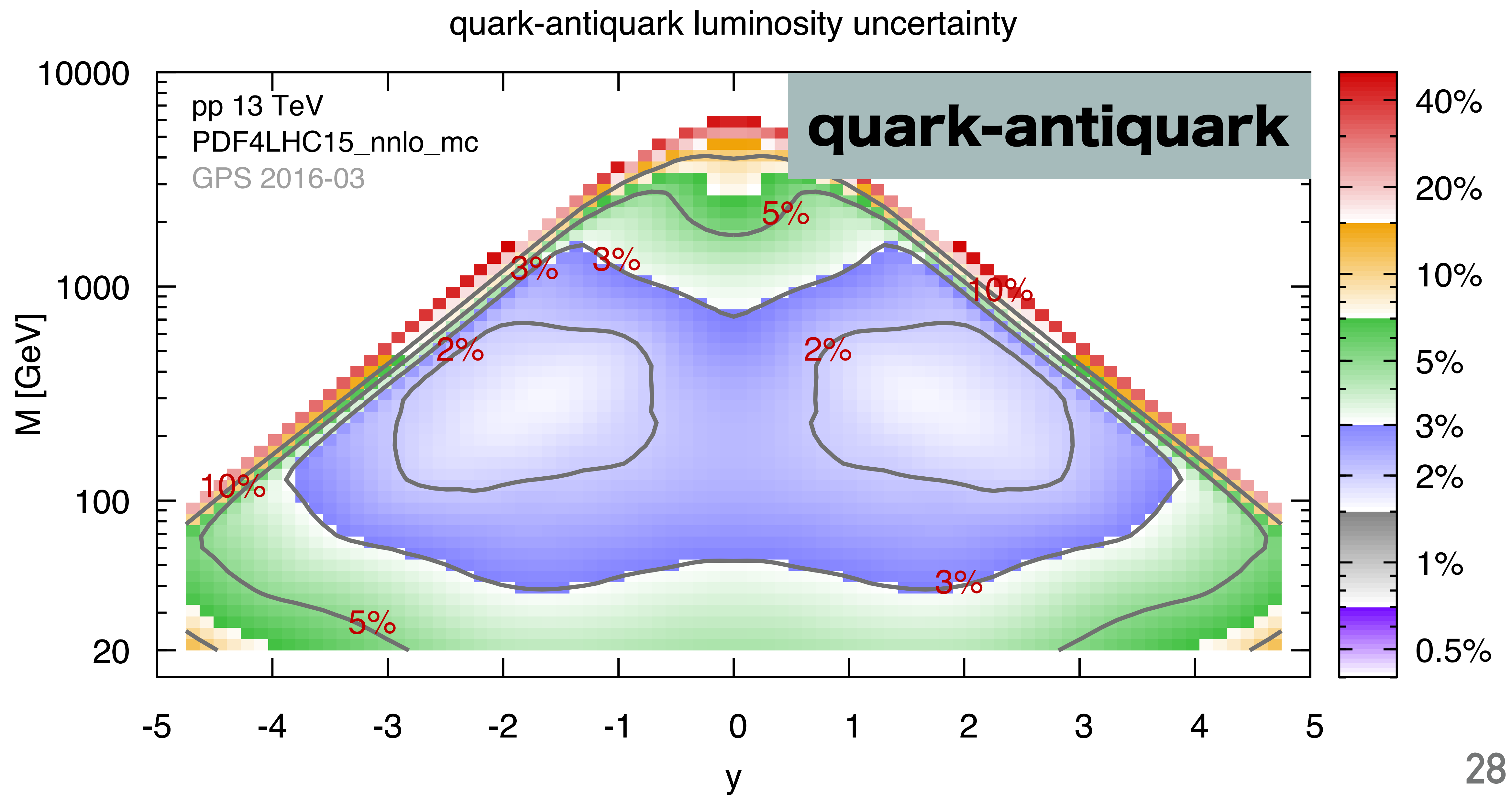
- For gluon-fusion & ttH, this comes in squared. It also correlates with the PDFs and affects backgrounds.
- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations



PDFs: WHAT ROUTE FOR PROGRESS?

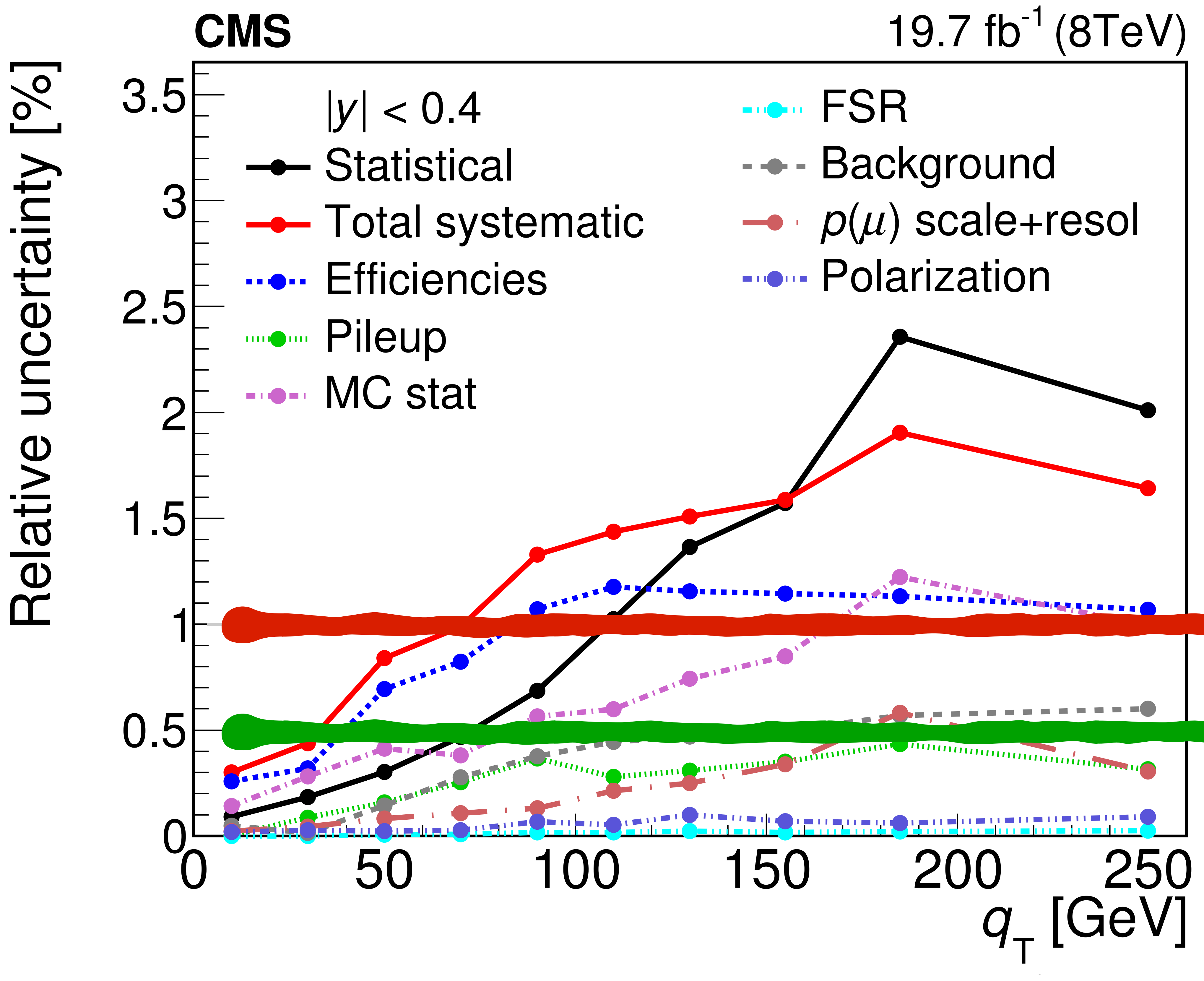
- Current status is 2–3% for core "precision" region
- Path to ~1% is not clear — e.g. Z p_T's strongest constraint is on qg lumi, which is already best known (why?)
- It'll be interesting to revisit the question once ttbar, incl. jets, Z p_T, etc. have all been incorporated at NNLO
- **Can we get measurements and theory to 1% accuracy?**

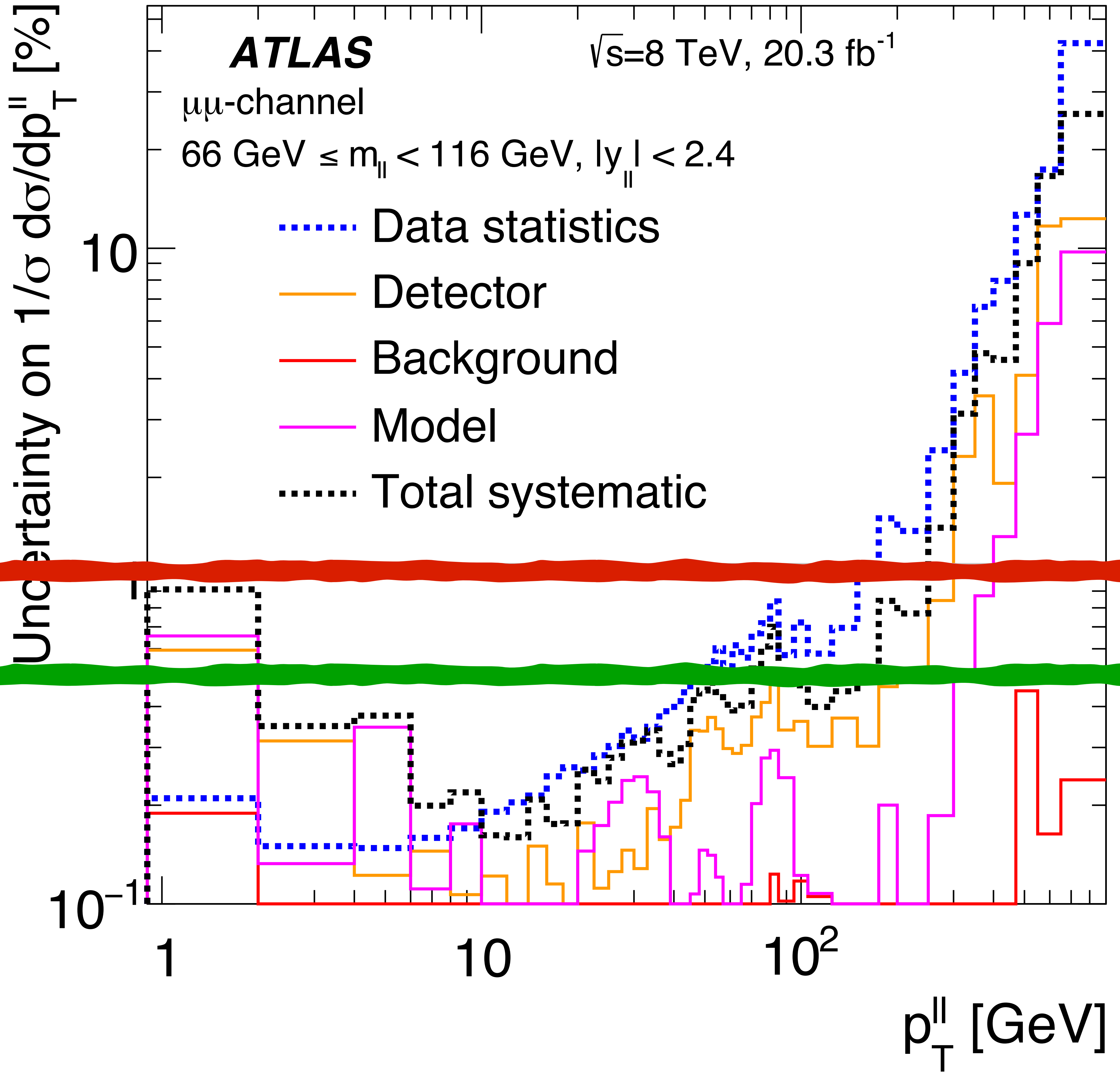




is 1% possible at a hadron collider?

Z p_T distribution: 0.5–1% precision!



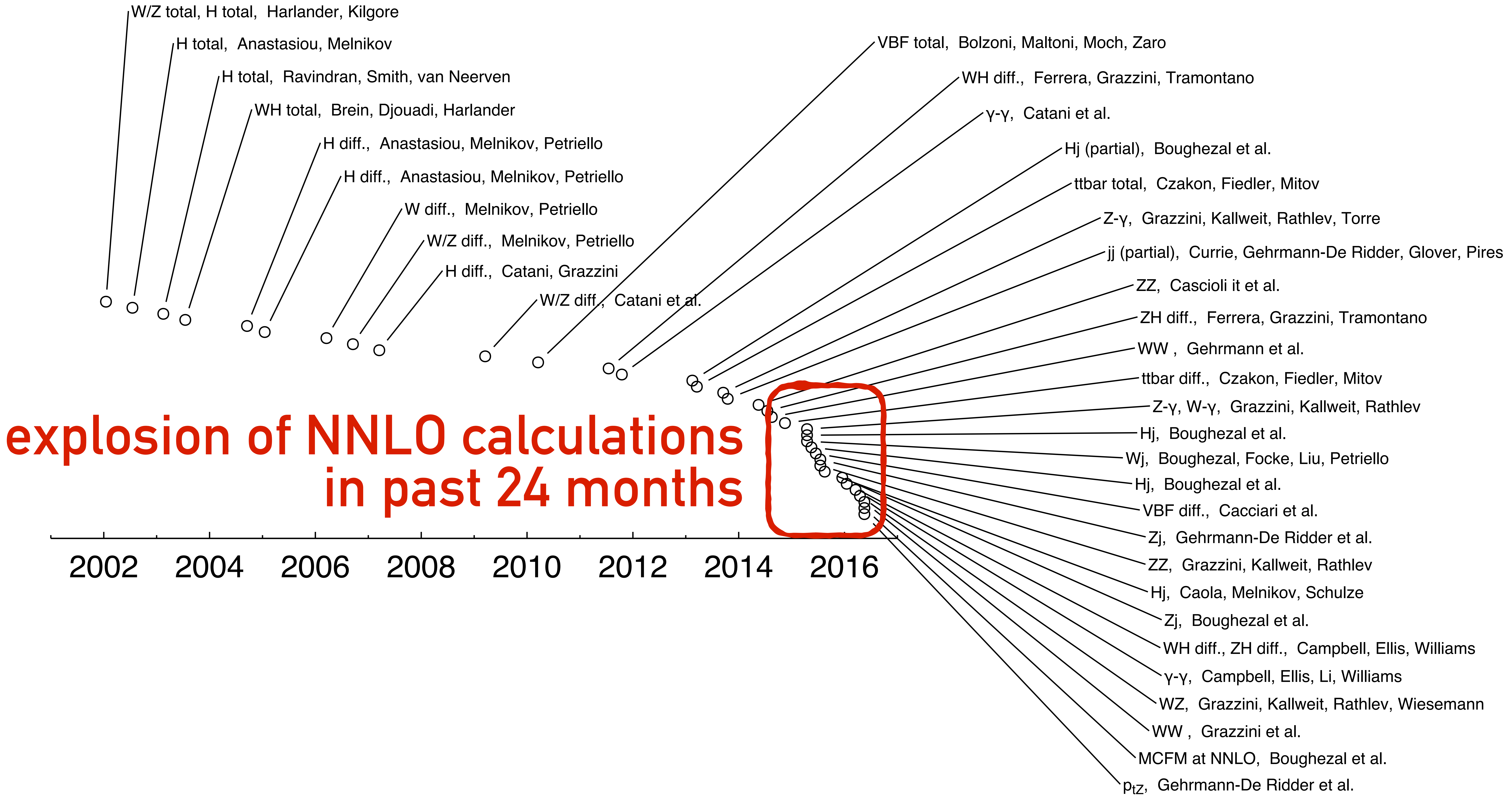


1%

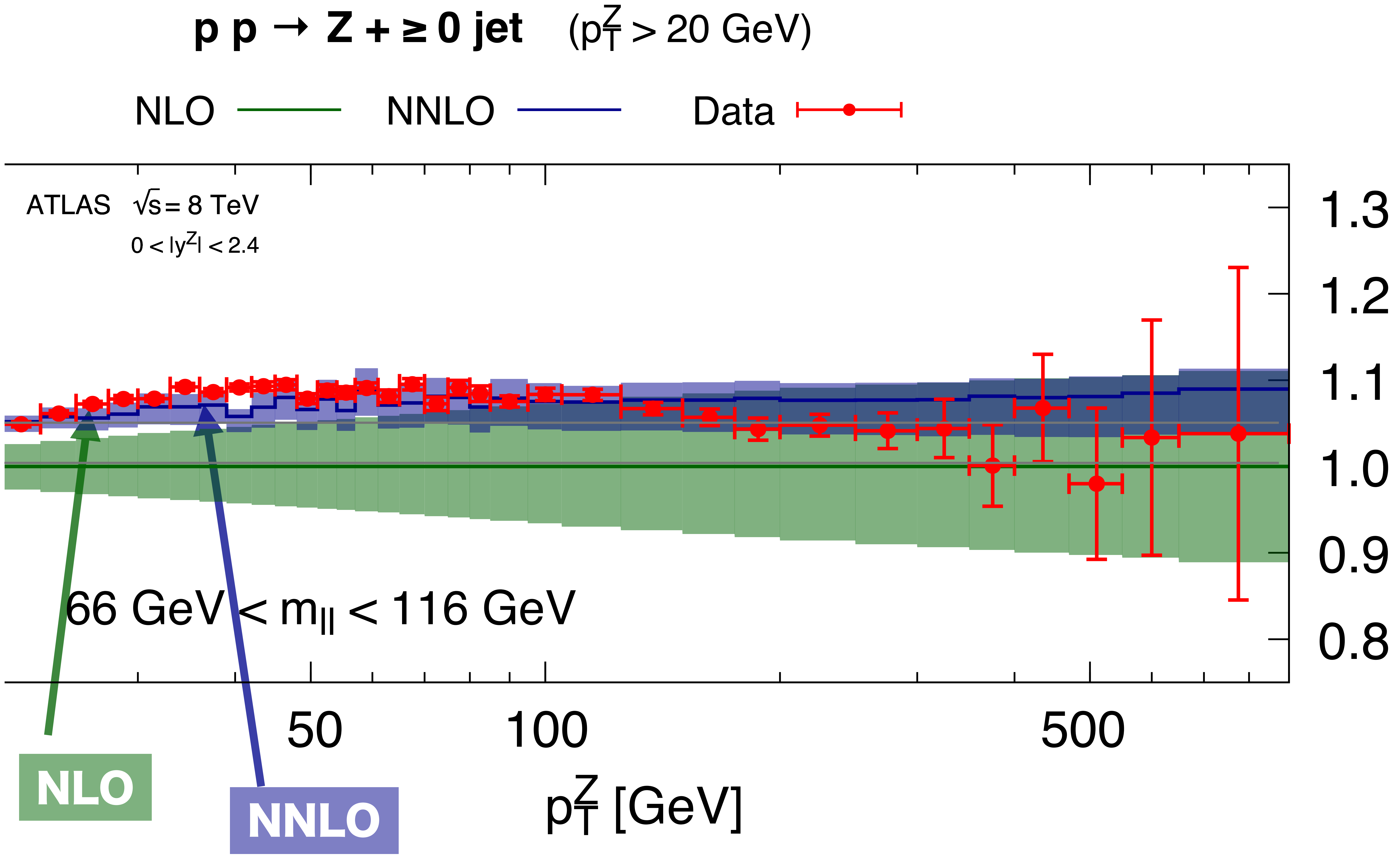
0.5%

NNLO hadron-collider calculations v. time

as of mid June 2016



Z p_T: Data v. theory calculation

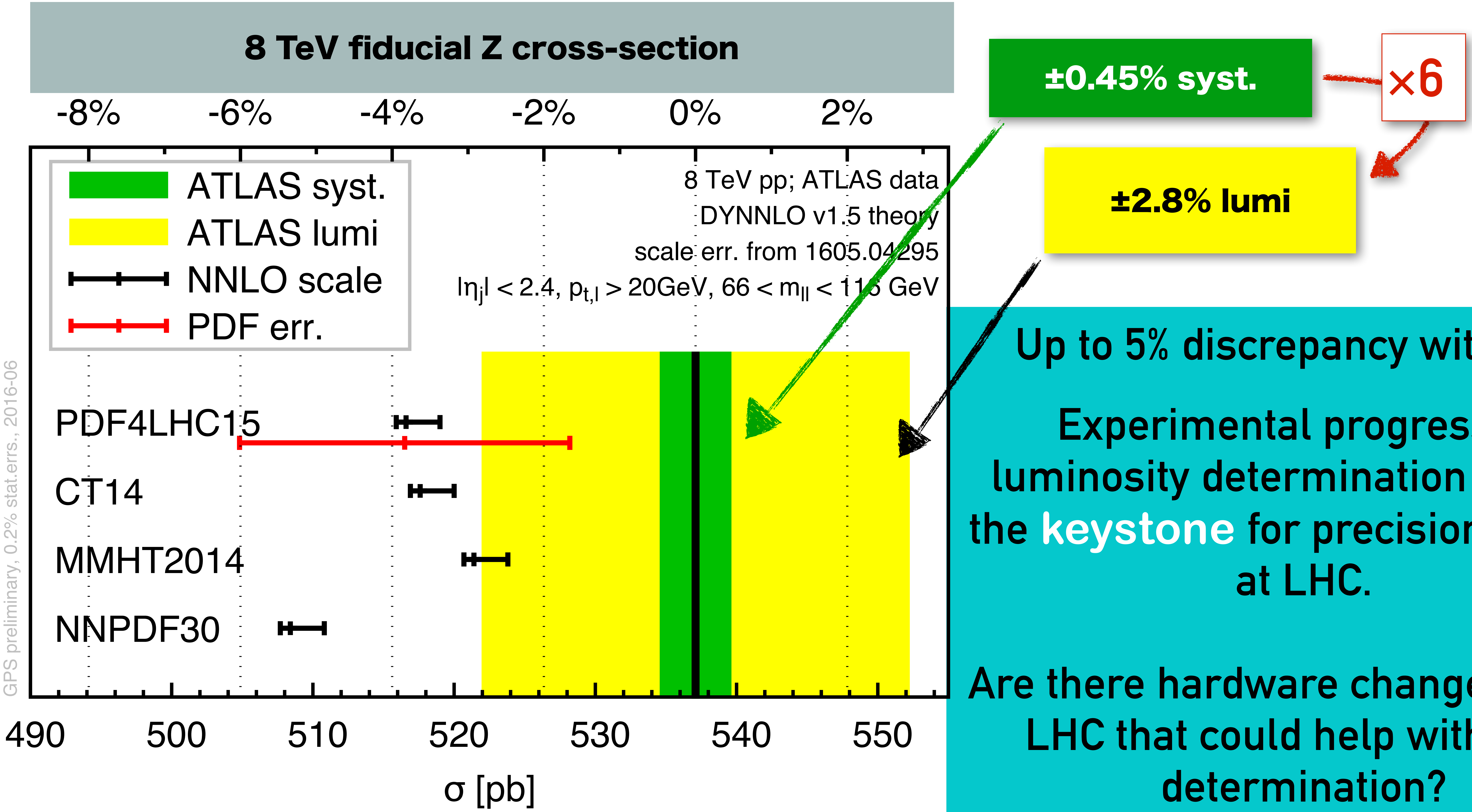


Gehrmann-de Ridder, Gehrmann Glover, Huss & Morgan

arXiv:1605.04295

NNLO ~ ±1.5 %

There are, however, issues. Notably in Z production



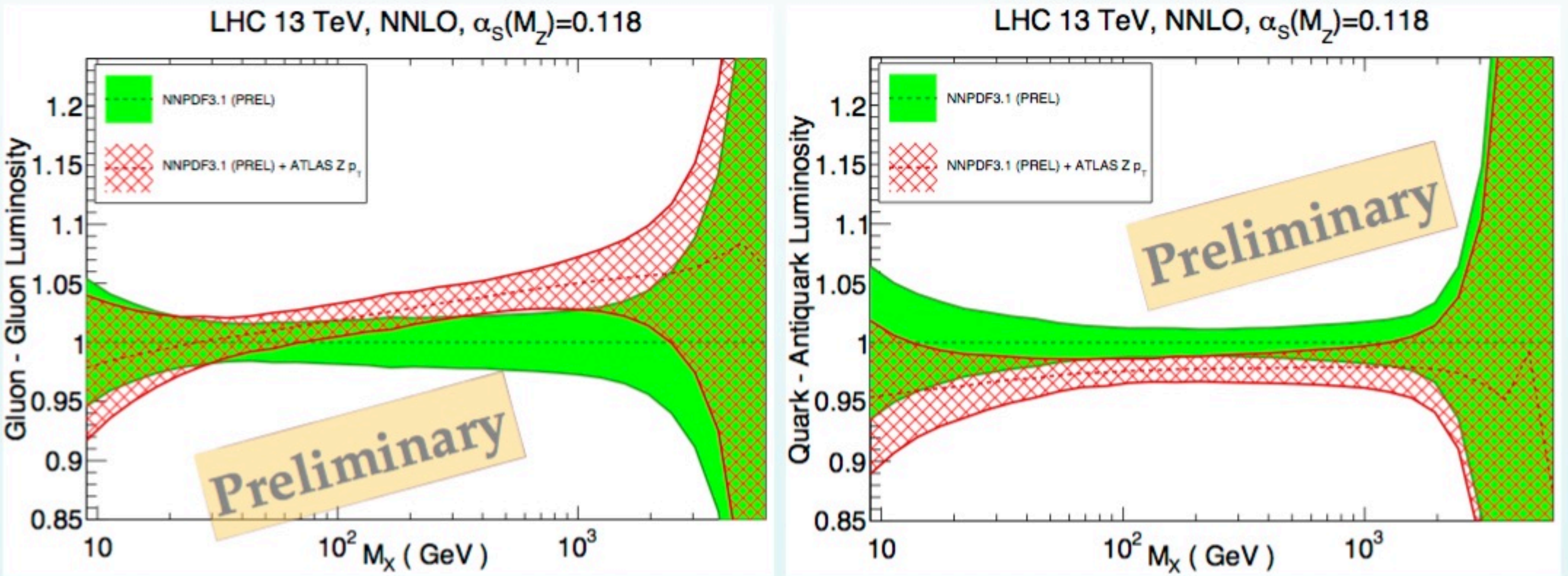
Up to 5% discrepancy with data

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?

Impact of Z p_T spectrum on PDF fits

Preliminary NNPDF3.1 NNLO fits suggest a **sizeable impact** of the **LHC Z p_T data** on the PDFs



Including the LHC Z p_T data could be a **game-changer** in global NNLO PDF fits ……

data-driven workarounds?

theory may have a hard limit
e.g. non-perturbative effects for cuts on jets

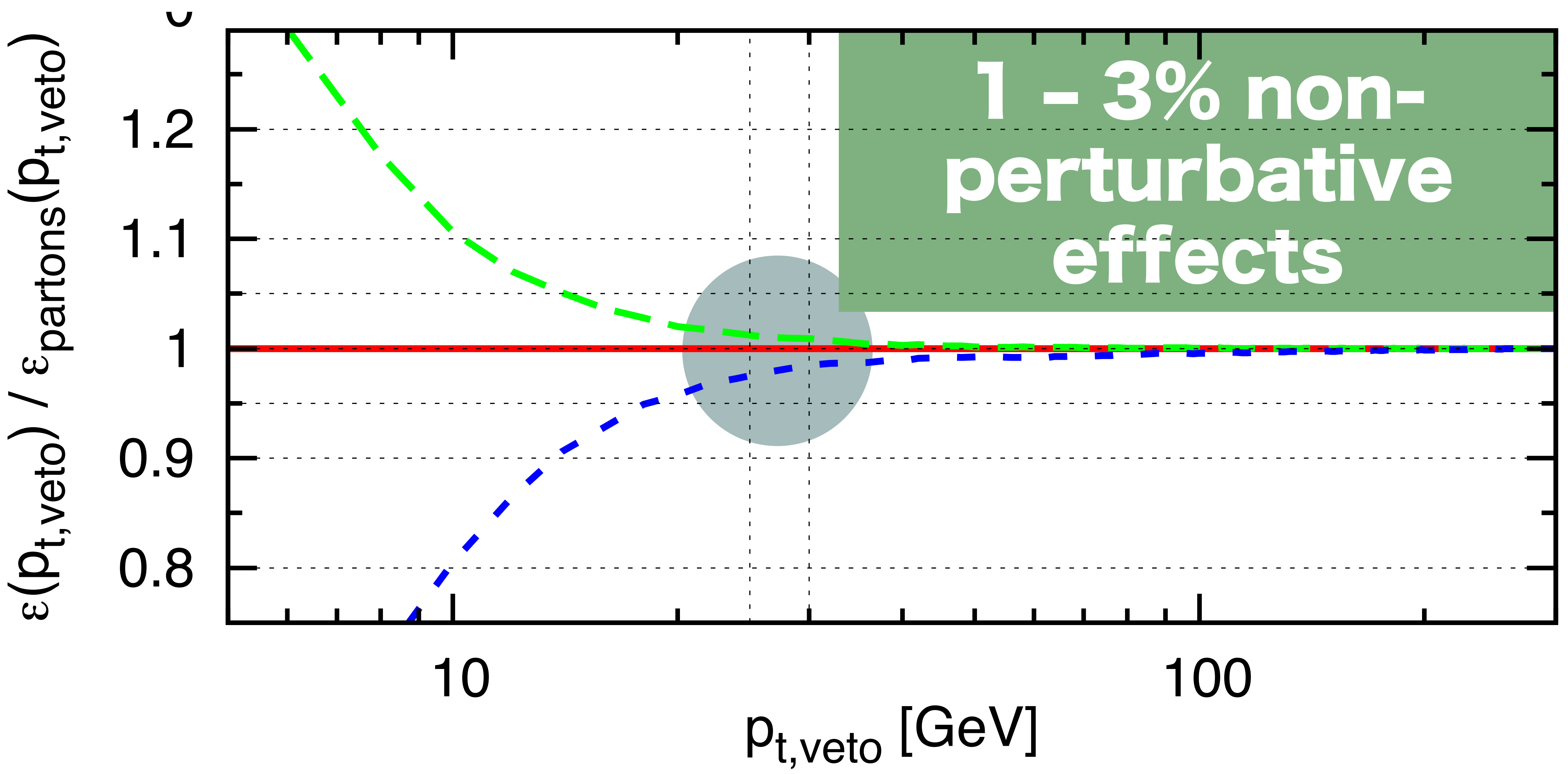
& are there issues in data-driven workarounds?

E.g. jet veto efficiency for $H \to WW^*$

LHC 13 TeV	$\epsilon^{N^3LO+NNLL+LL_R}$
$p_{t,veto} = 25\,\text{GeV}$	$0.539^{+0.017}_{-0.008}$
$p_{t,veto} = 30\,\text{GeV}$	$0.608^{+0.016}_{-0.007}$

perturbative uncert: 1.5-3%

Anastasiou, Duhr, Dulat, Herzog & Mistlberger 1503.06056
Boughezal, Caola, Melnikov, Petriello & Schulze 1504.07922
Banfi, Caola, Dreyer, Monni, GPS, Zanderighi & Dulat 1511.02886



Banfi, GPS, Zanderighi 1203.5773

Measurements of $H \to ZZ^*$ and $\gamma\gamma$ can constrain this directly.

Run I: ~ 40 evts. equiv.

HL-LHC: ~ 15k events equiv.

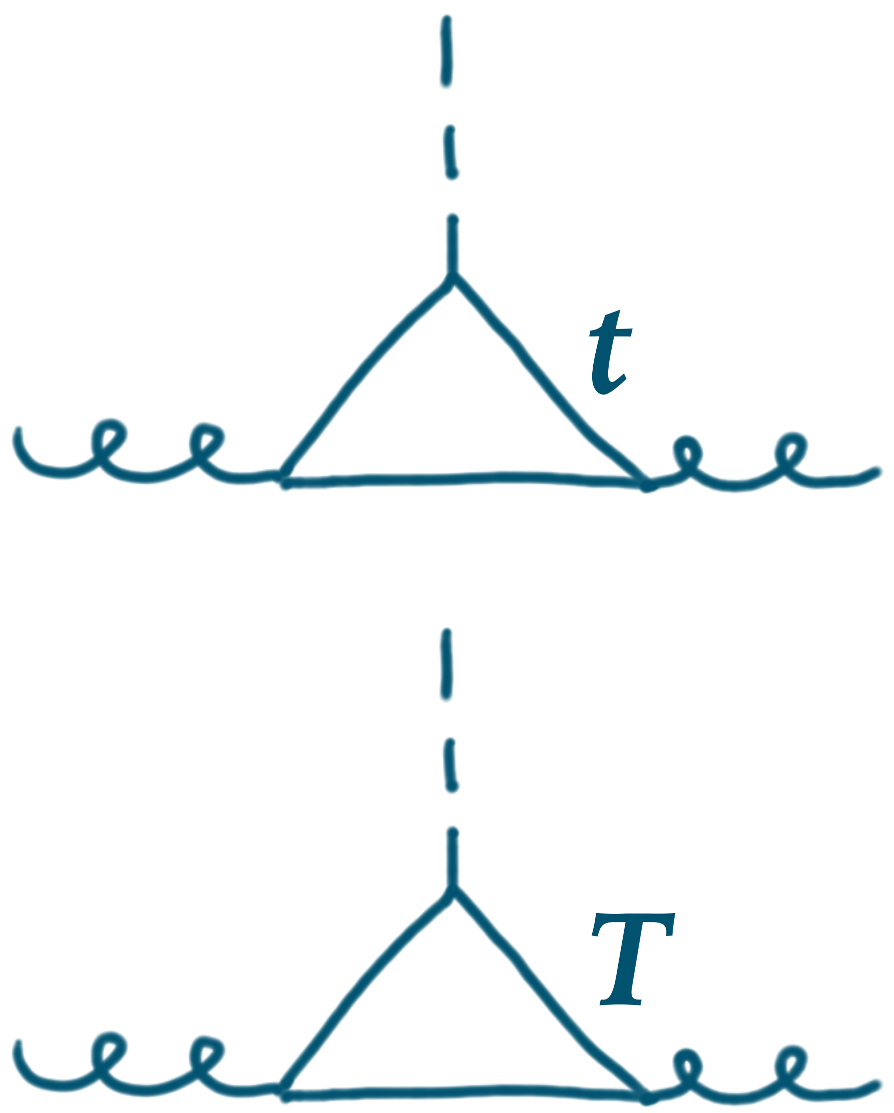
→ 1% uncertainties?

advocated notably by MLM

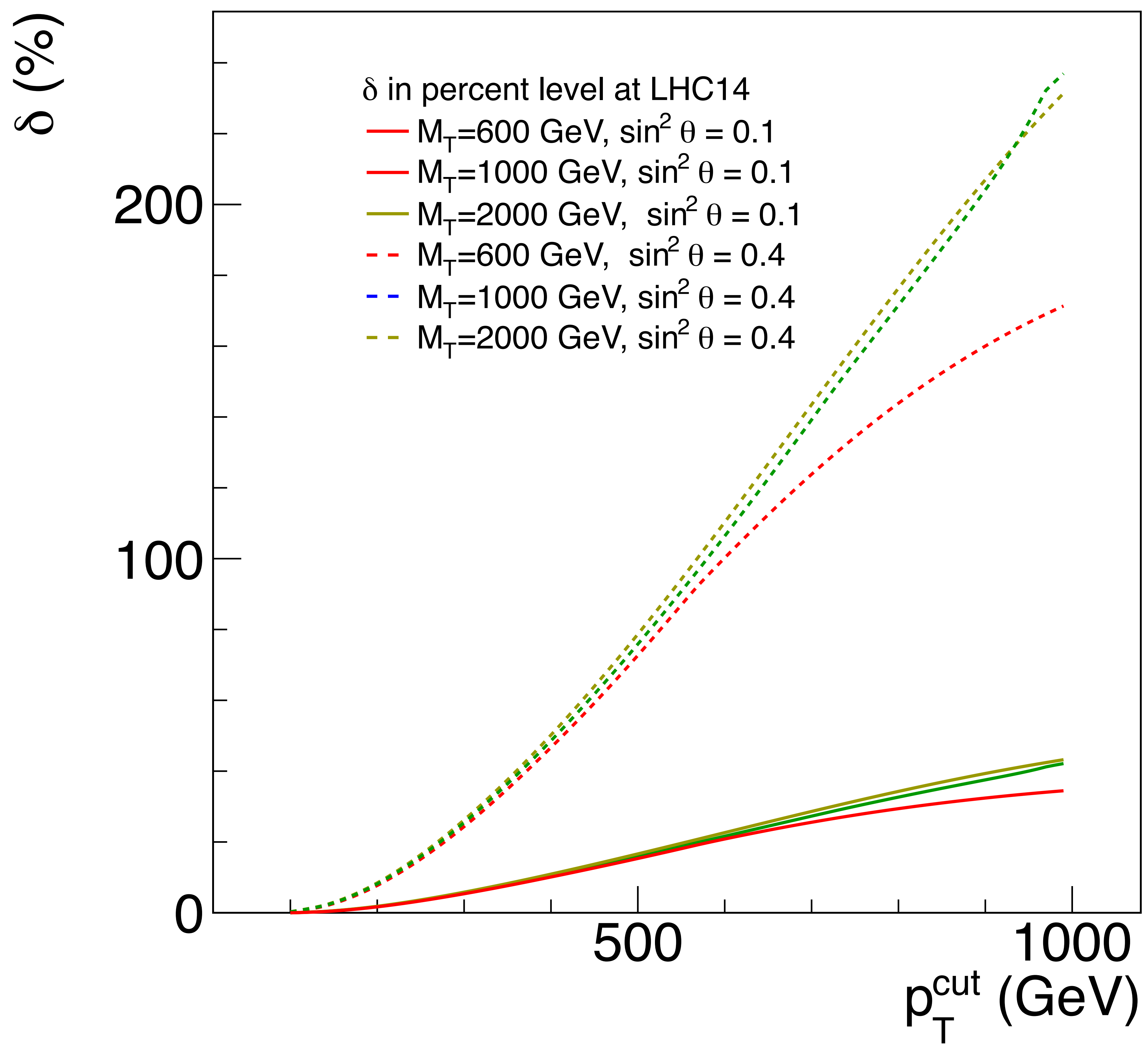
high-p_T Higgs

equally interesting:
off-shell Higgs

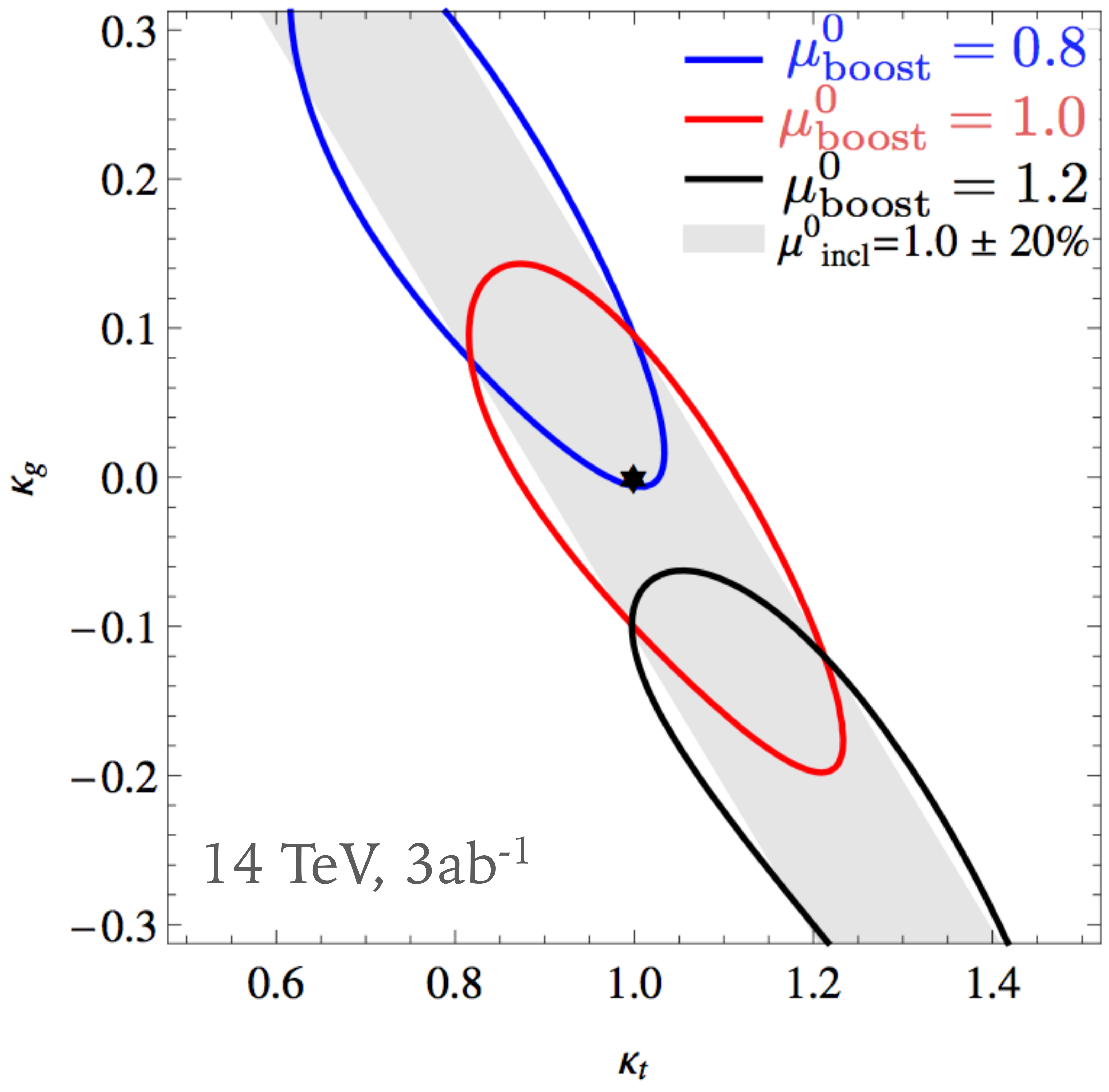
High-pt Higgs (e.g. to distinguish κ_g and κ_t)



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?

VH PRODUCTION AT LARGE M(VH)

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

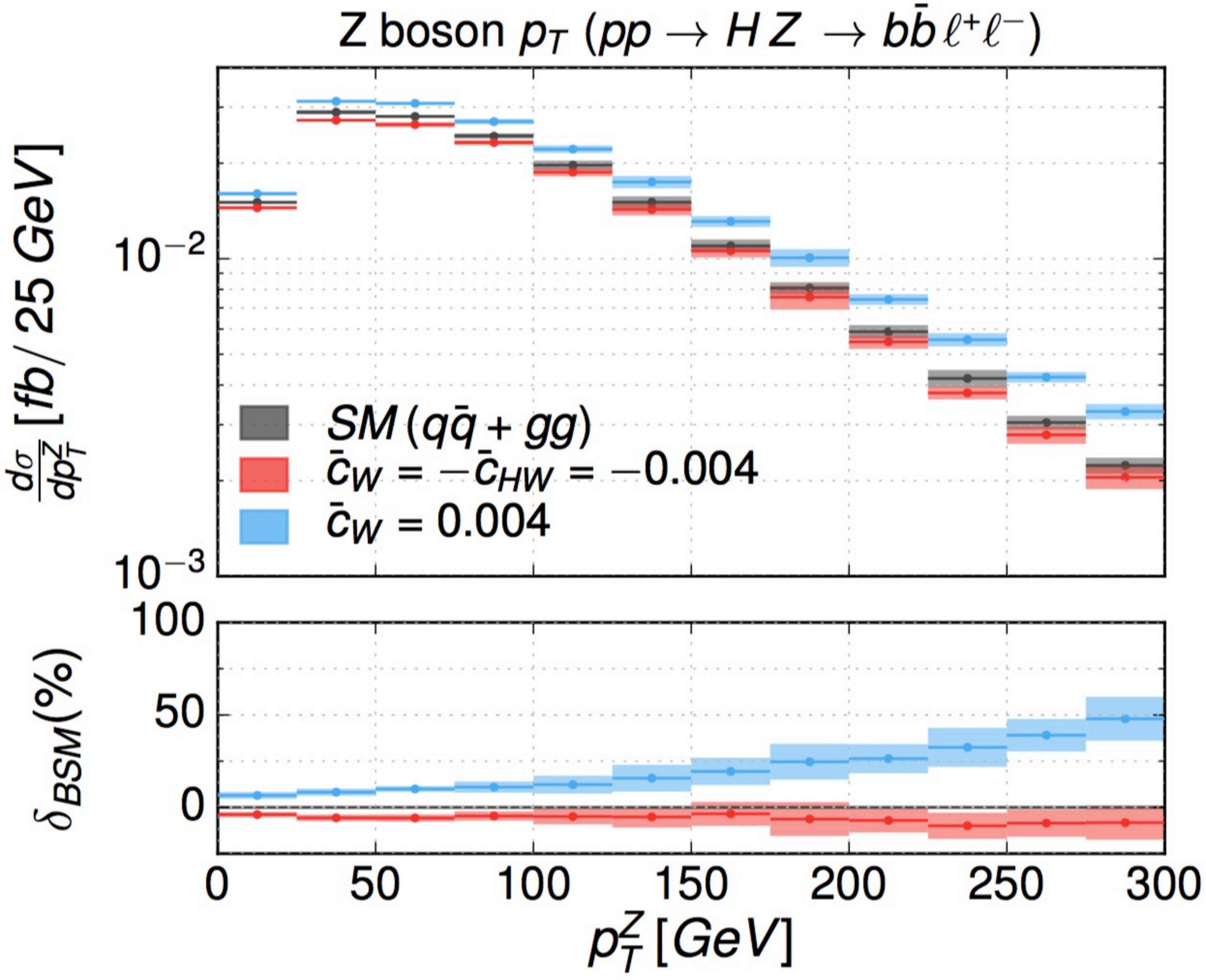
- Higher-dimension operators cause deviations that grow as, e.g.

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

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

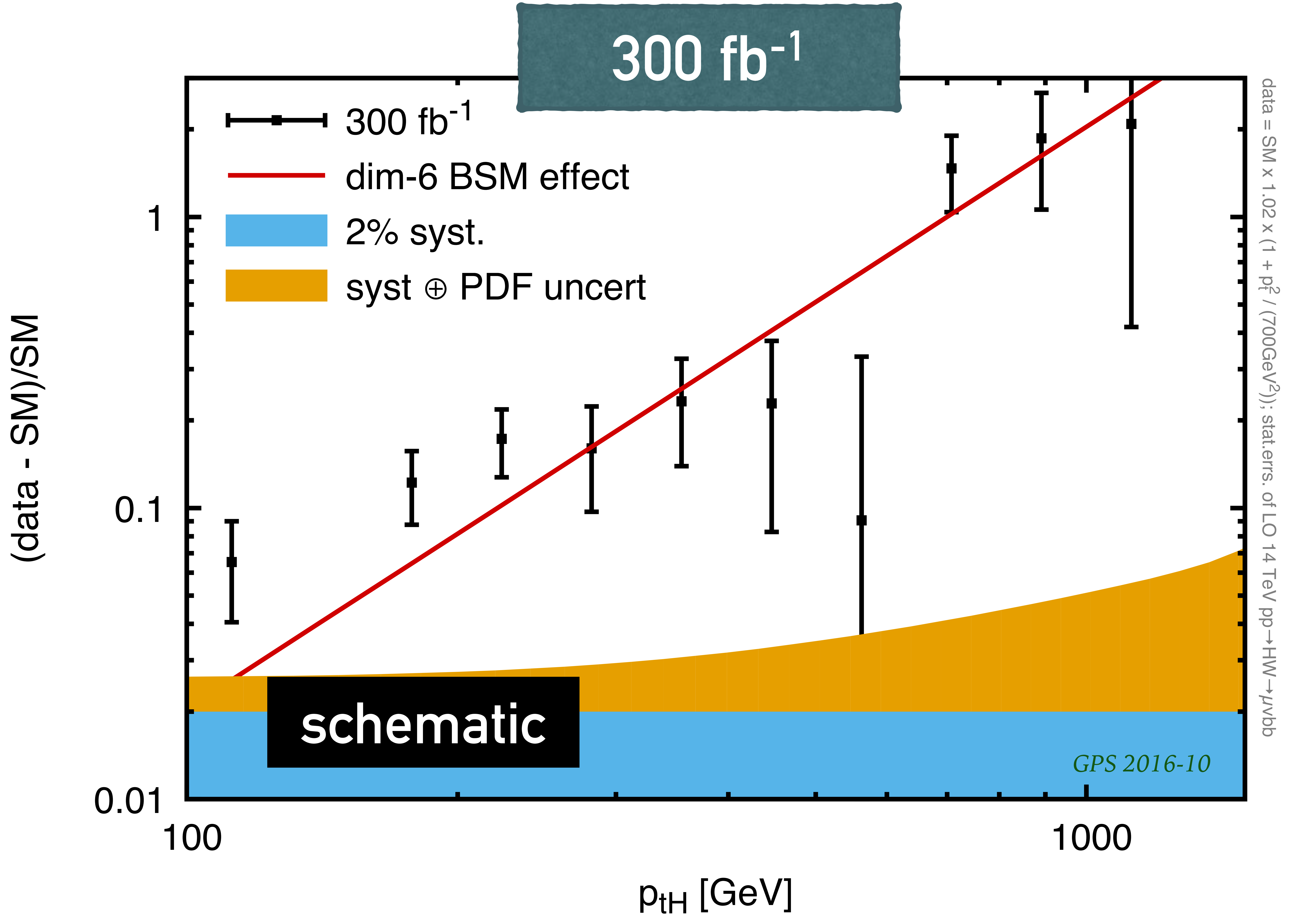
$$\Lambda \sim (\text{Lumi})^{1/4}$$

- 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



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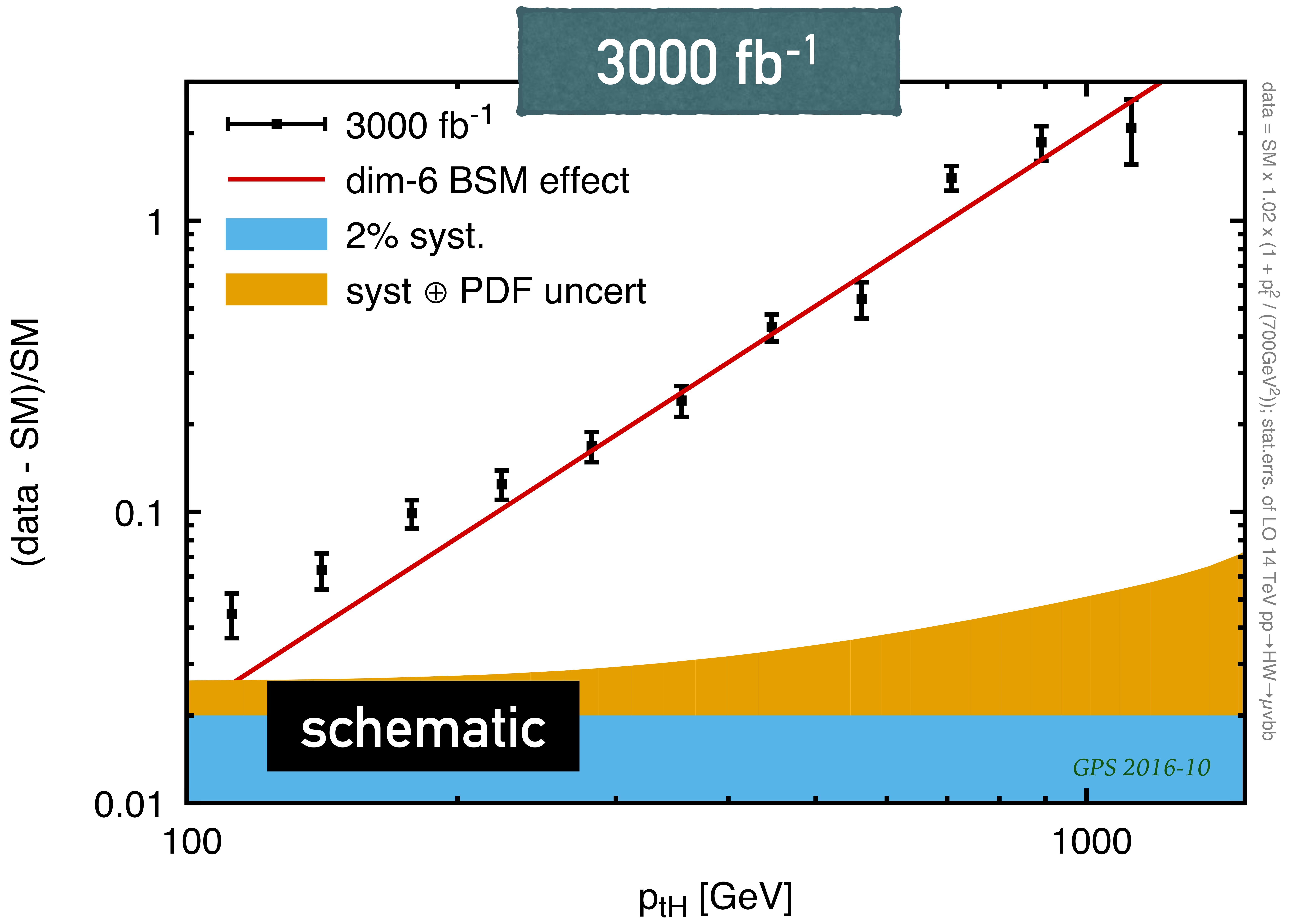
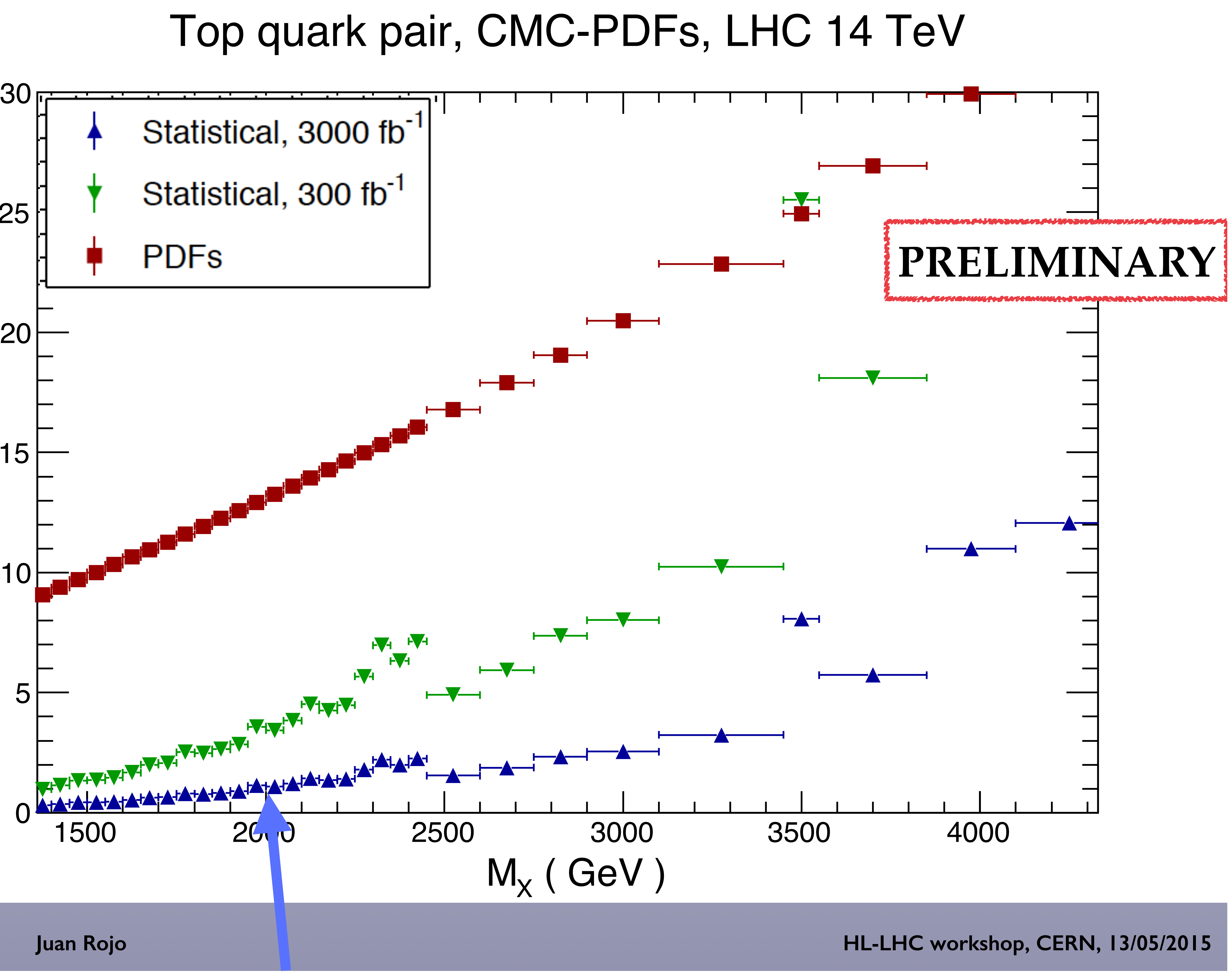


new physics isn't just a single number that's wrong (think g-2)

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



At HL-LHC, Statistical errors on ttbar production will be < 1% up to Mtt ~ 2 TeV

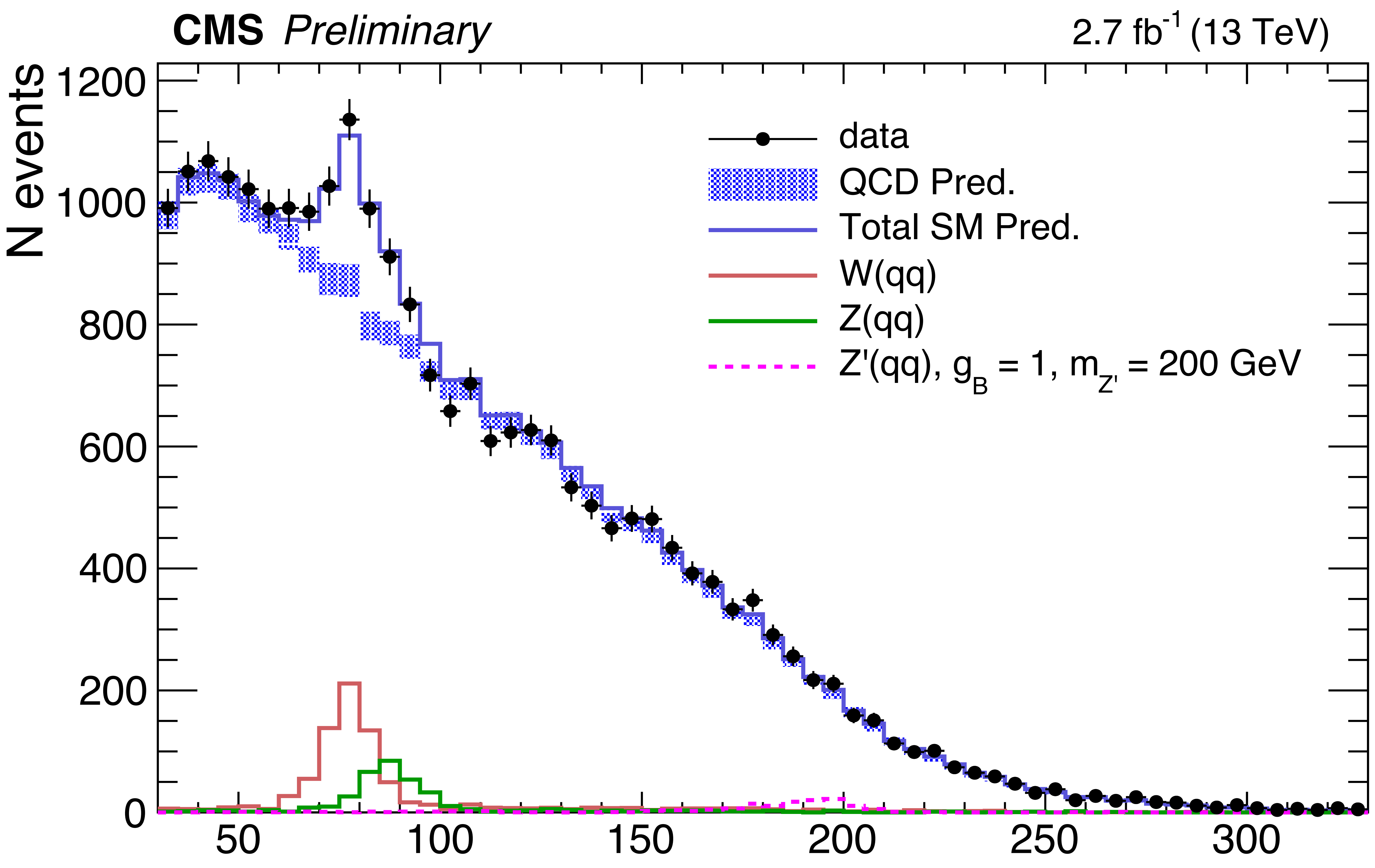
IN THE FUTURE?

- high-pt W, Z
- high-mass Drell-Yan
- high-mass ttbar

Will all be at ~1% statistical level up to and even beyond the TeV scale.

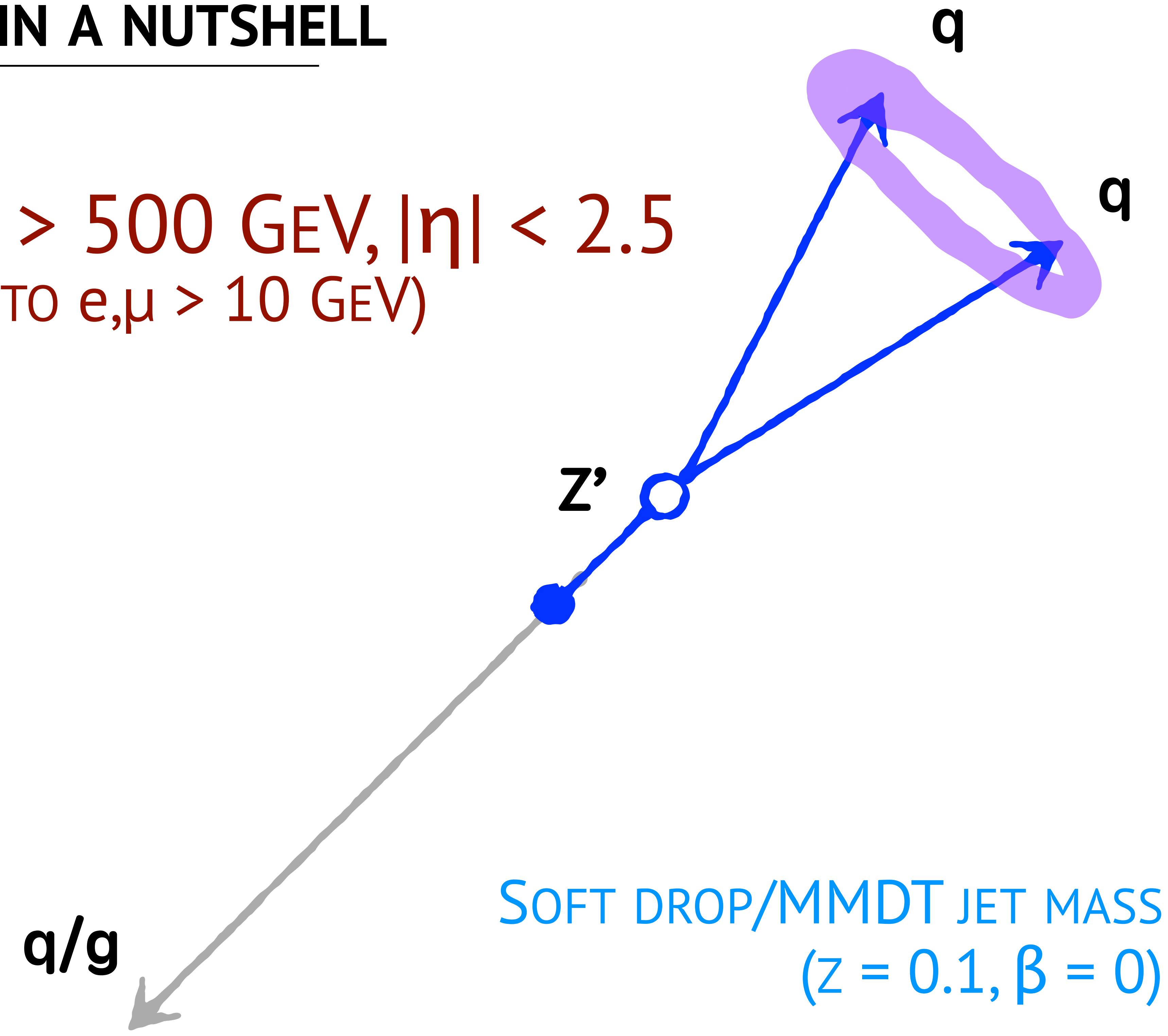
With leptonic final states, there's a chance systematic errors may also be < 1%.

The potential of jet substructure — hadronic W & Z peaks



IN A NUTSHELL

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



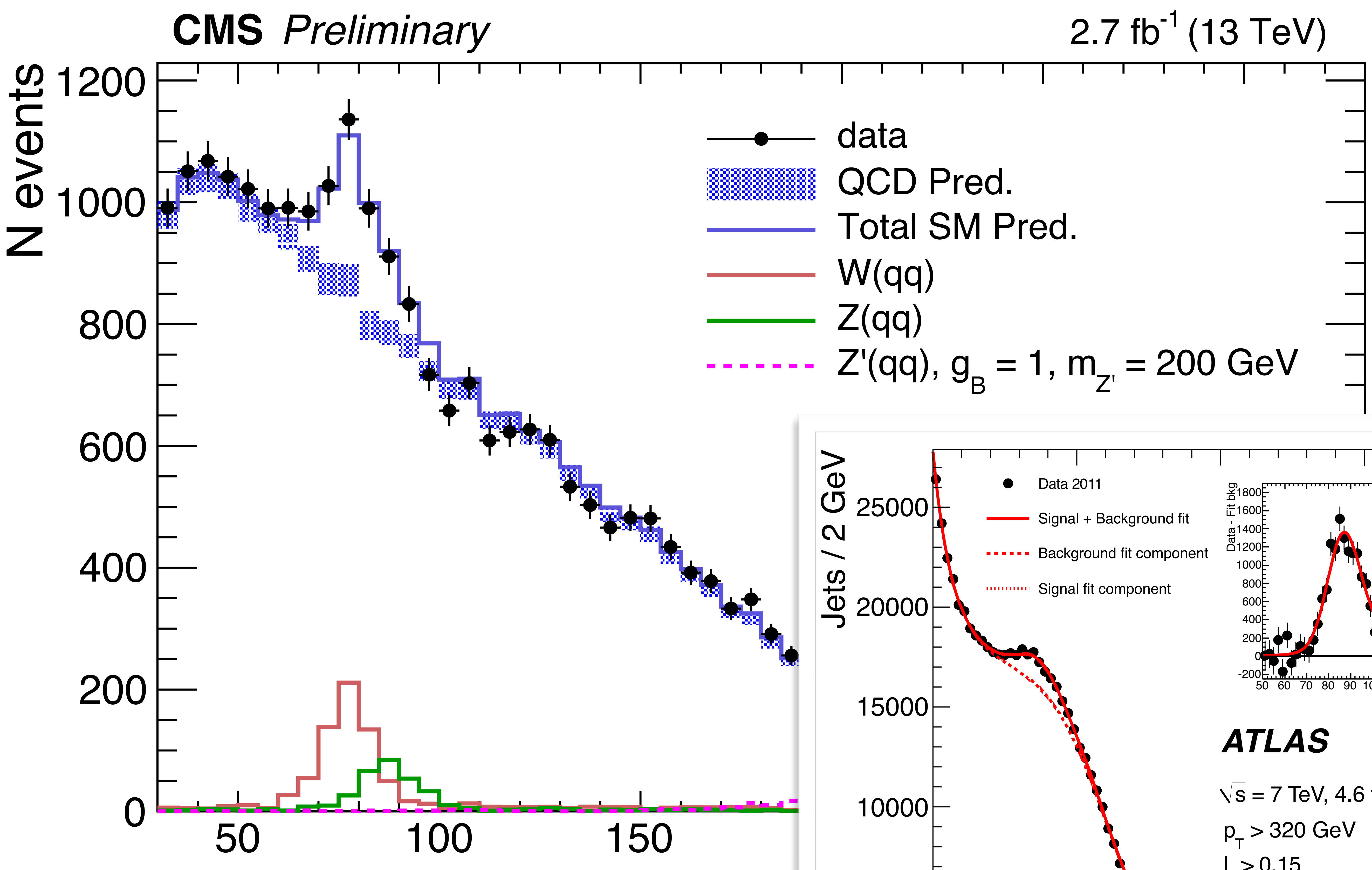
Soft drop/MMDT jet mass
(z = 0.1, β = 0)

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

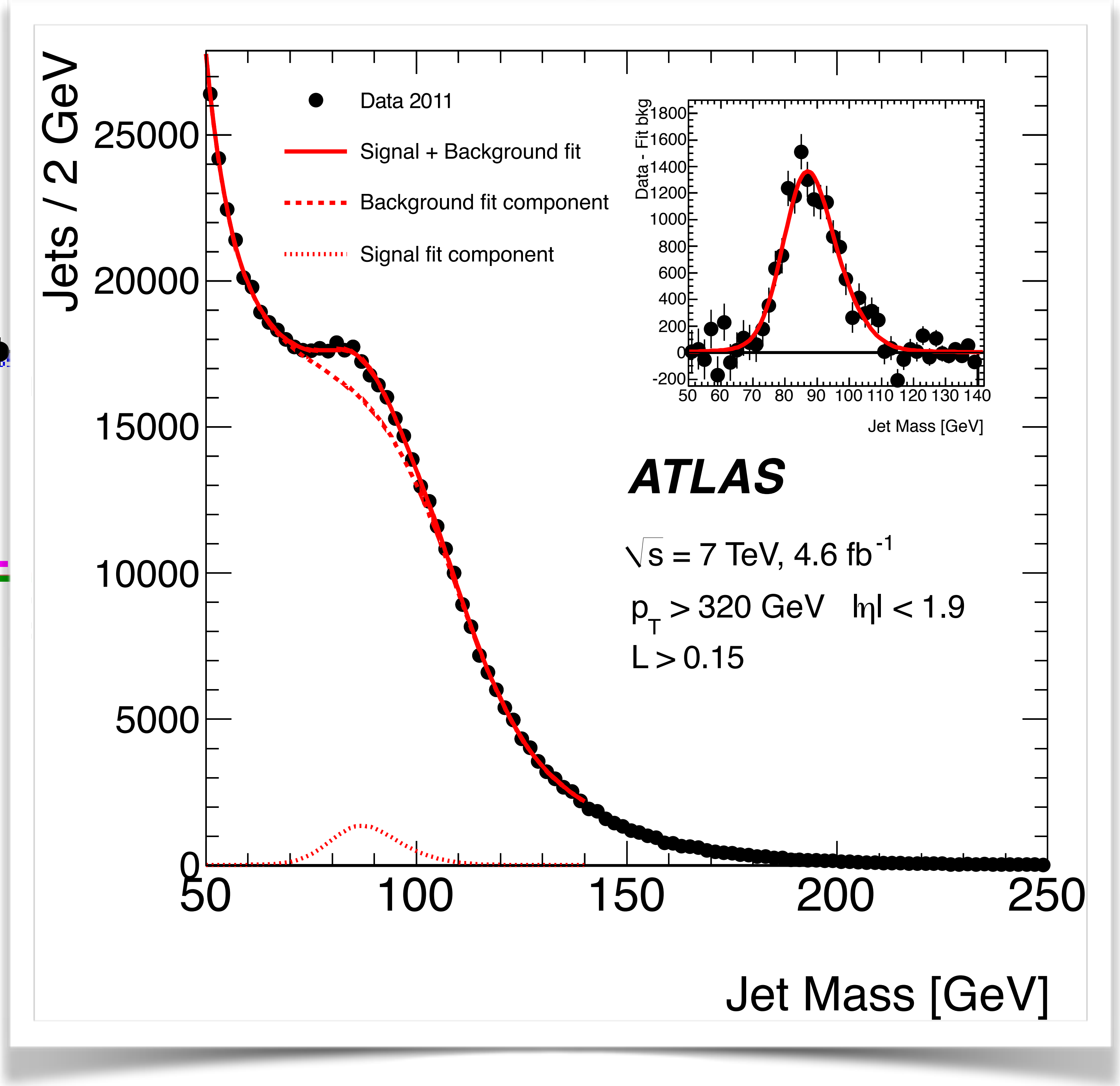
[PUPPI'ed inputs]

Nhan Tran @ Boost 2016

The potential of jet substructure — hadronic W & Z peaks



Nhan Tran @ Boost 2016



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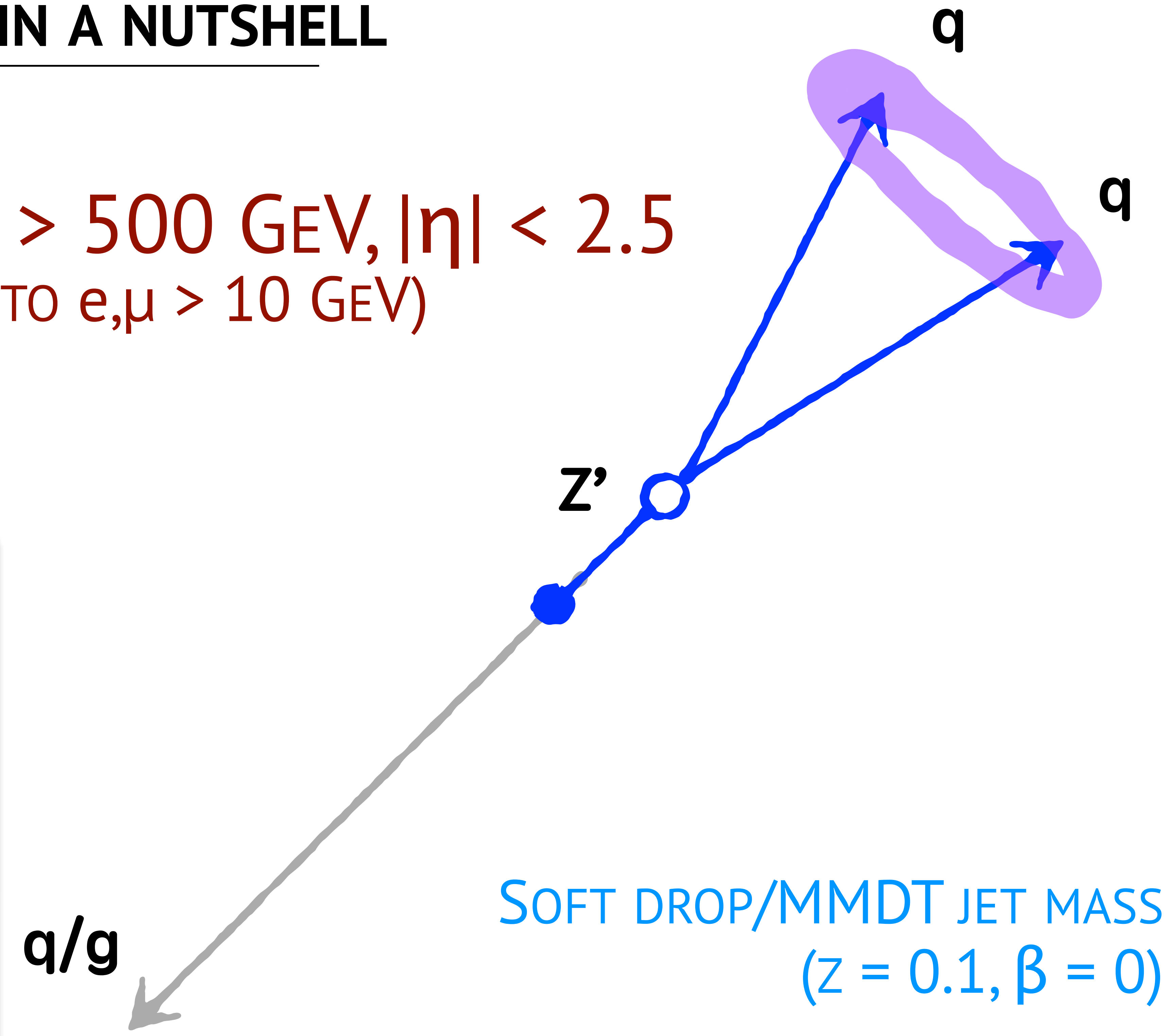

SOFT DROP/MMDT JET MASS
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[PUPPI'ED INPUTS]

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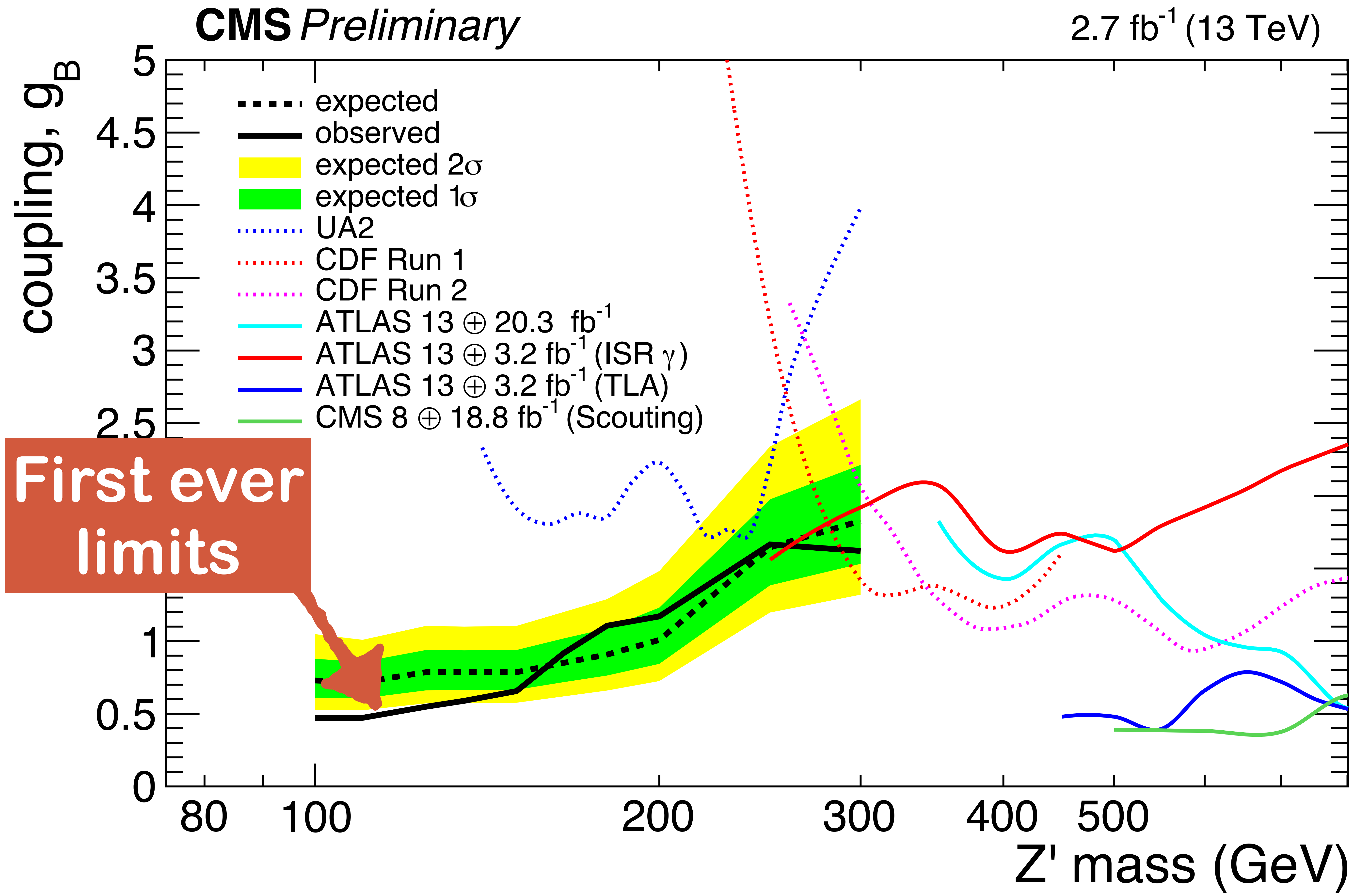

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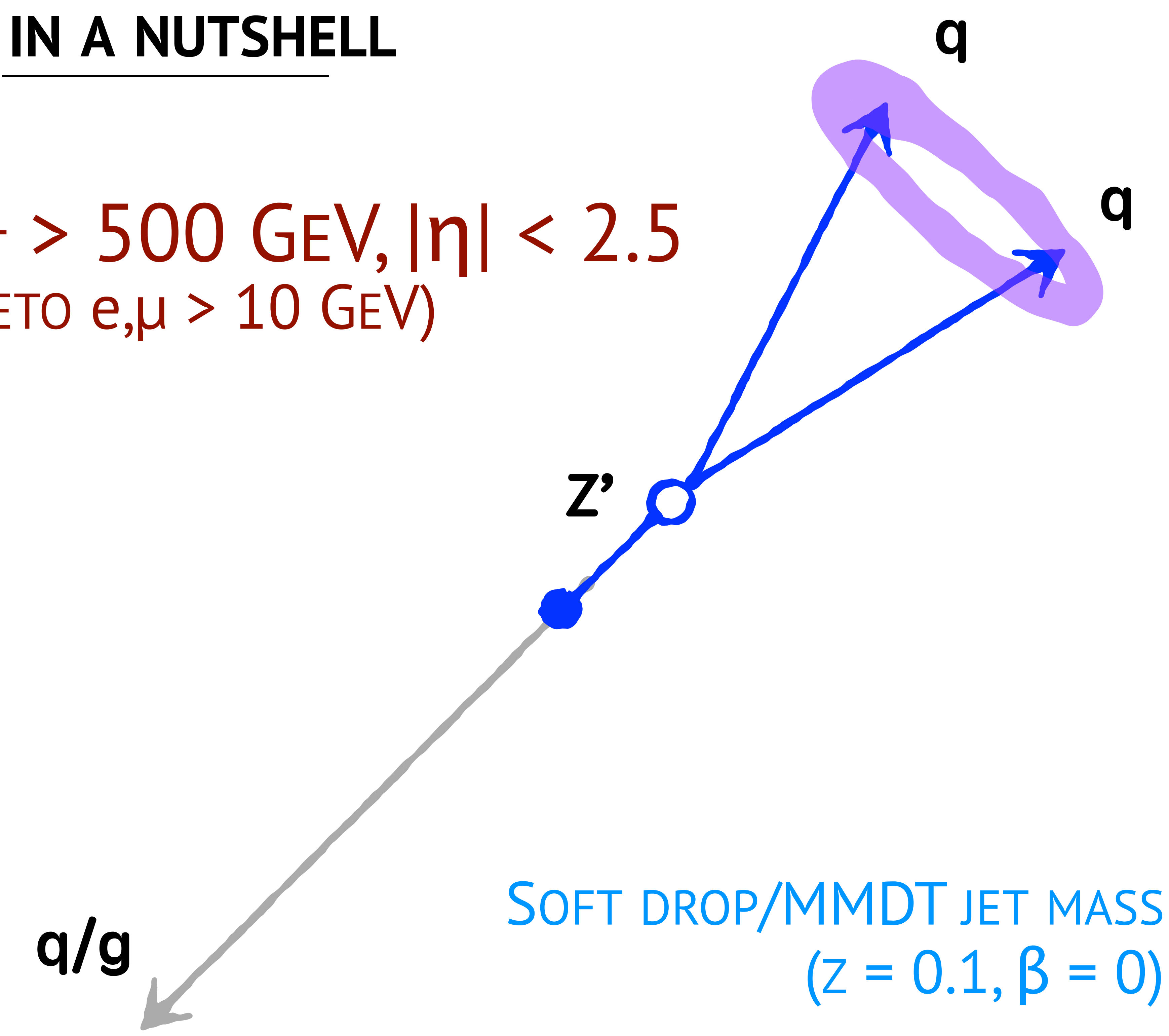

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[PUPPI'ed inputs]

outlook

MESSAGES

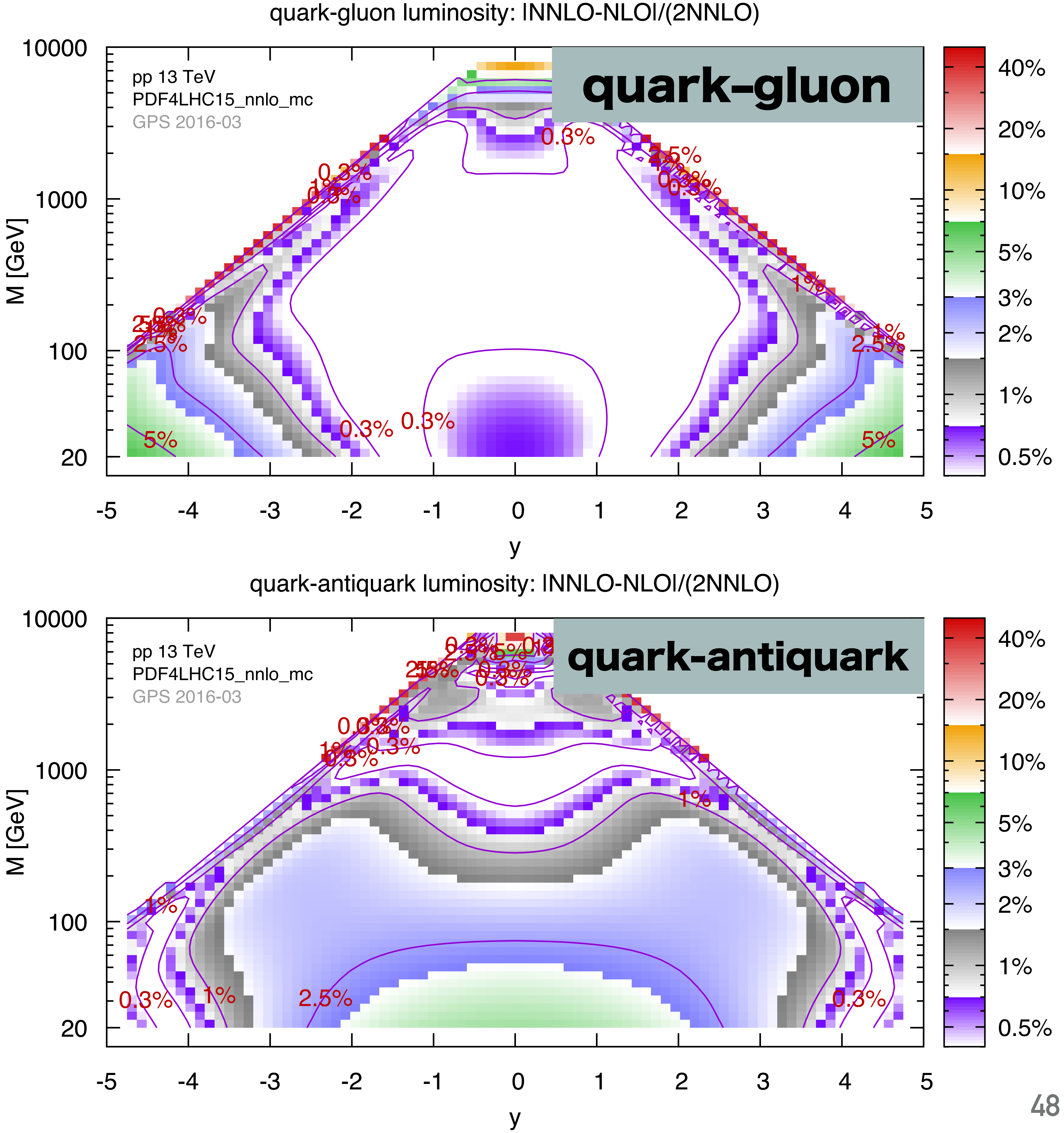
- Higgs sector is unlike any other that we've accessed experimentally
- Establishing its structure is a key part of our job as physicists

- One element involved is **precision**
  - Theory is already making big steps towards the HL-LHC precision goals
  - Ultimate goal might be O(1%) — challenging, but now is time to start thinking about how we get there (PDF fits, exp. lumi determination, etc.)
- Other element is **distributions, e.g. high-p_T**
  - BSM effects from high scales (Λ) grow ~ p_T^2 / Λ^2
  - Pattern of deviation over range of p_T's provides clear signature of new physics

EXTRA SLIDES

PDF THEORY UNCERTAINTIES

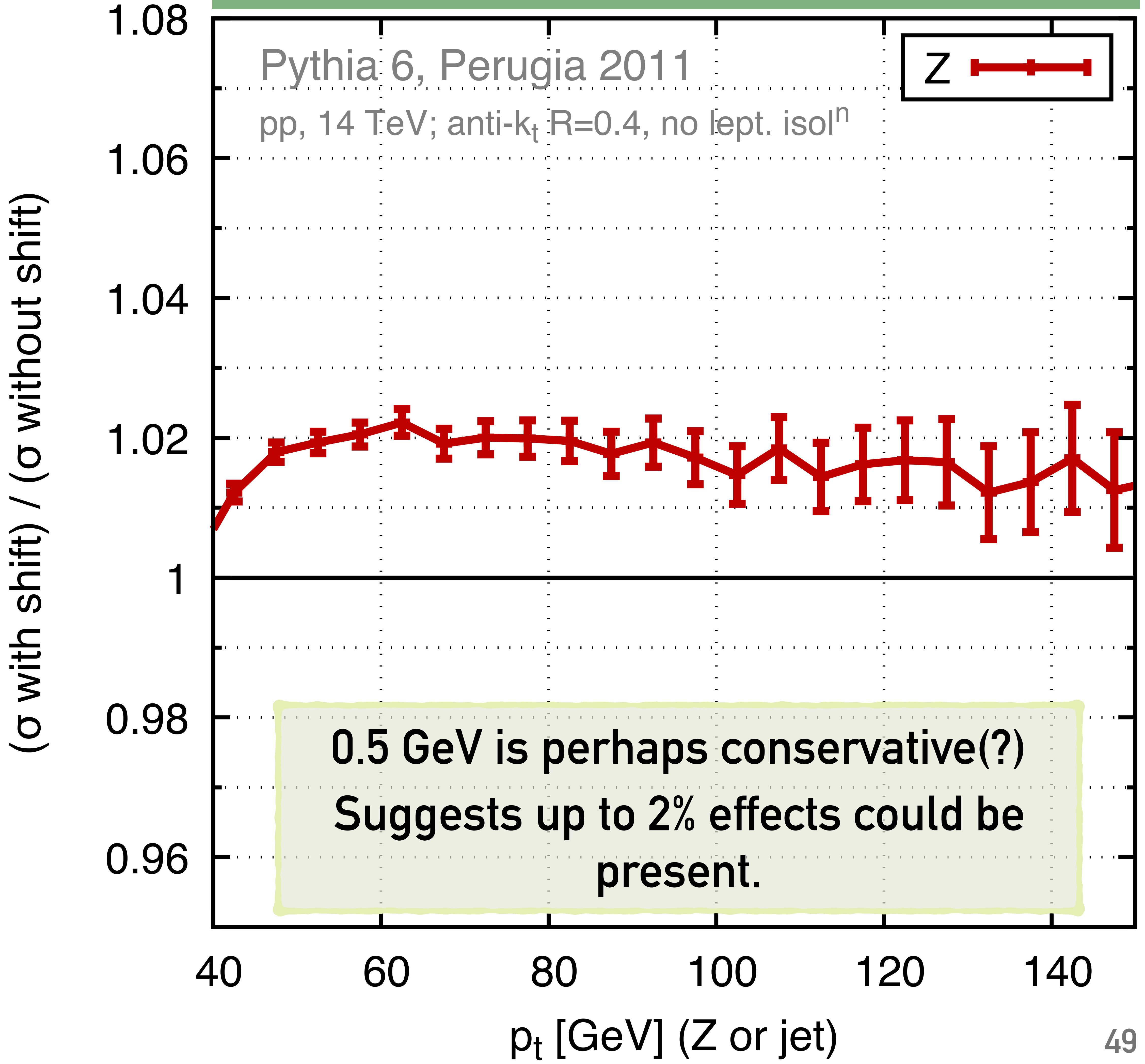
Theory Uncertainties



Non-perturbative effects in Z (& H?) p_T

- Inclusive Z & H cross sections should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z (&H) p_T **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off
  [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

impact of 0.5 GeV shift of Z p_T



PRECISION LHC PHYSICS NEEDS PRECISION THEORY

Progress on calculations has been stunning in the past years

- N3LO Higgs
- Many processes at NNLO
- NLO + PS automation
- First NNLO + PS
- NNLL Resummations
- EW + QCD, etc.

This progress is essential for LHC precision physics, but also only part of the story.

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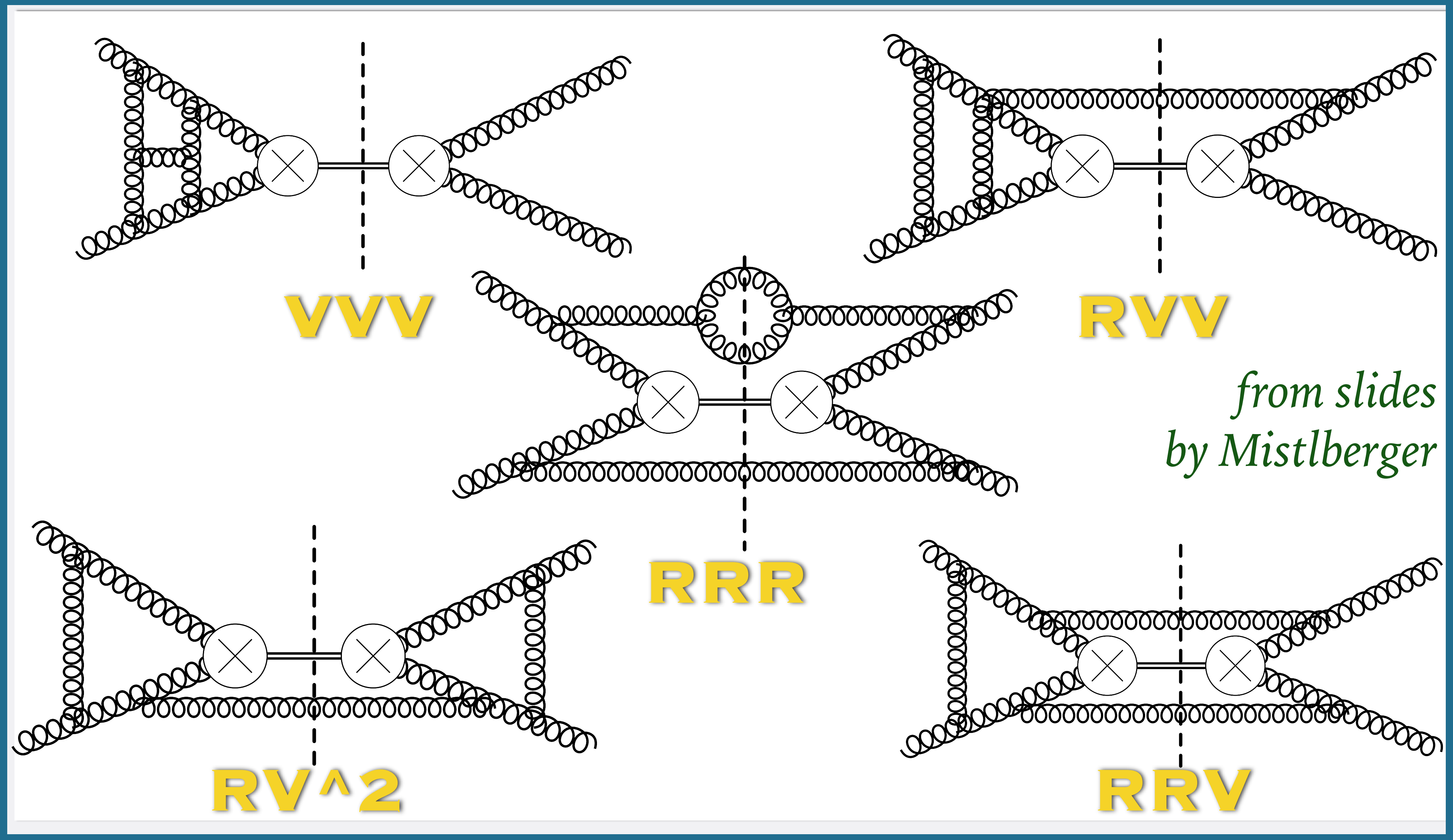
N3LO Higgs production

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ’15-16

100,000 diagrams



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This progress is essential for LHC precision physics, but also only part of the story.

The intention with this talk?

Start asking questions about what precision goals we might set ourselves, what obstacles we will meet, what techniques and measurements might help us progress

REFS

- ATLAS projections ATL-PHYS-PUB-2014-016
- CMS projections (snowmass): 1307.7135

- Current status — ATLAS/CMS combination note

- YR4 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt14TeV
- YR3 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014#s_14_0_TeV
- new ggF https://arxiv.org/abs/1602.00695
- ATLAS differential 1504.05833, CMS differential: ZZ 1512.08377 & gg 1508.07819

HIGGS TODAY & TOMORROW

Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

ATLAS-CMS Run I combination

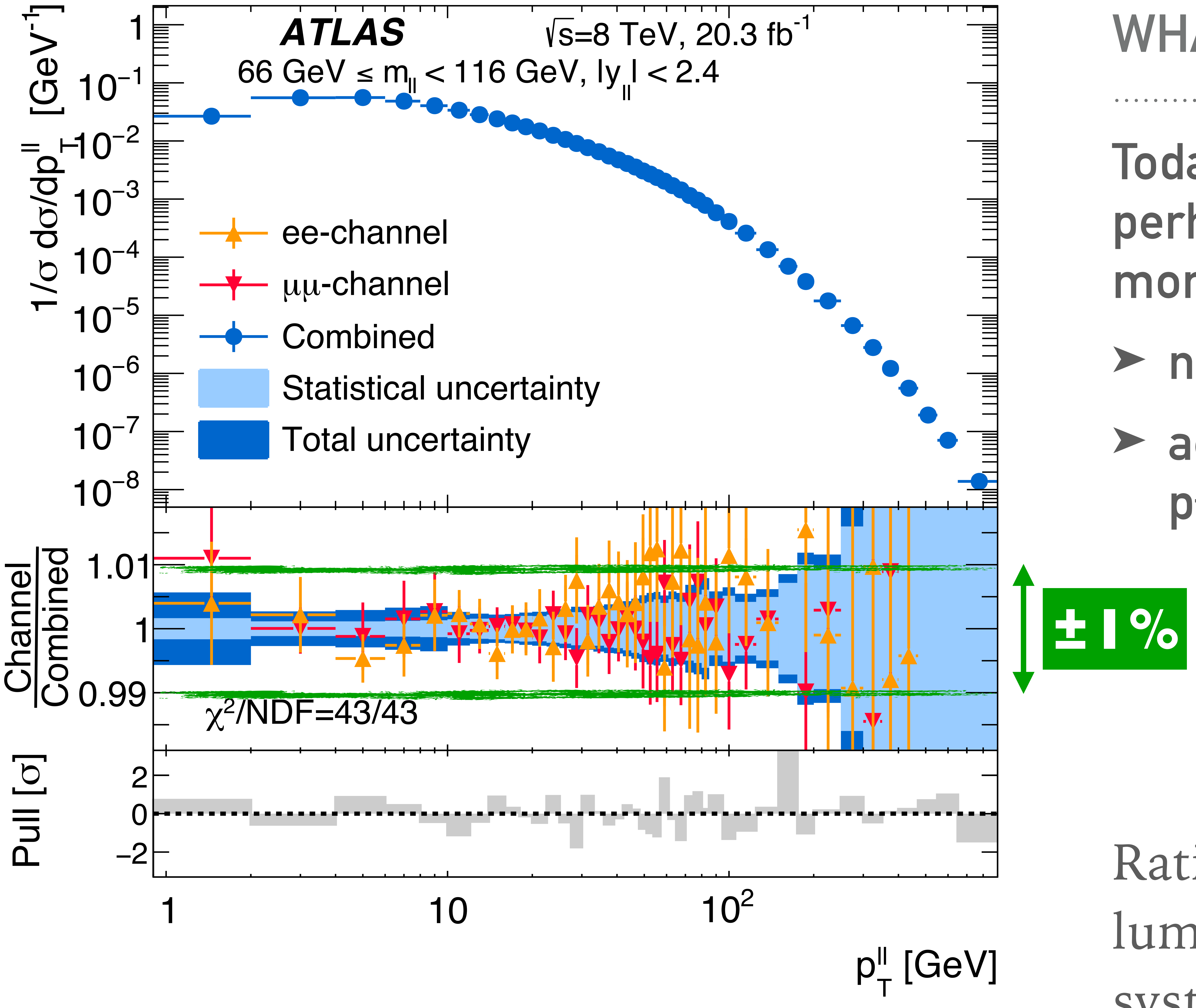
In most cases, stat. errors are largest single source

Best channels $\sim\pm 20\%$

HL-LHC prospects?

x2.5 in cross section
x150 in luminosity (→ 3000 fb^{-1})
~ 400 times more events

⇒ stat. errors in 1-2% range



WHAT'S POSSIBLE EXPERIMENTALLY?

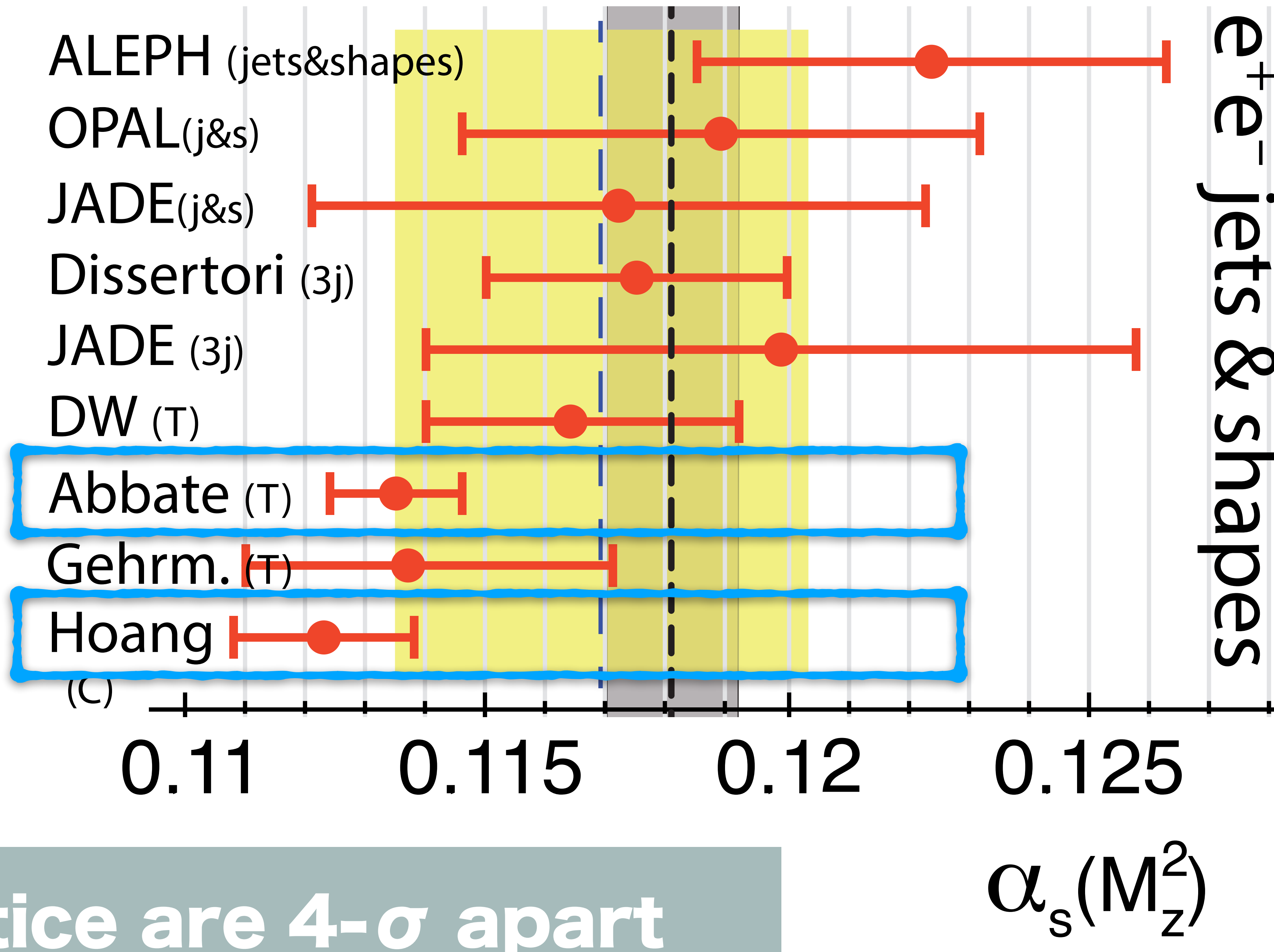
Today's most precise results are perhaps for the Z transverse momentum

- normalised to Z fiducal σ
- achieves <1%, from p_T = 1 to 200 GeV

Ratio to total cross section cancels lumi & some lepton-efficiency systematics.

E+E- EVENT SHAPES AND JET RATES

➤ Two "best" determinations are from same group (Hoang et al, 1006.3080,1501.04111)
$\alpha_s(M_Z) = 0.1135 \pm 0.0010$ (0.9%) [thrust]
$\alpha_s(M_Z) = 0.1123 \pm 0.0015$ (1.3%) [C-parameter]



thrust & "best" lattice are 4-σ apart

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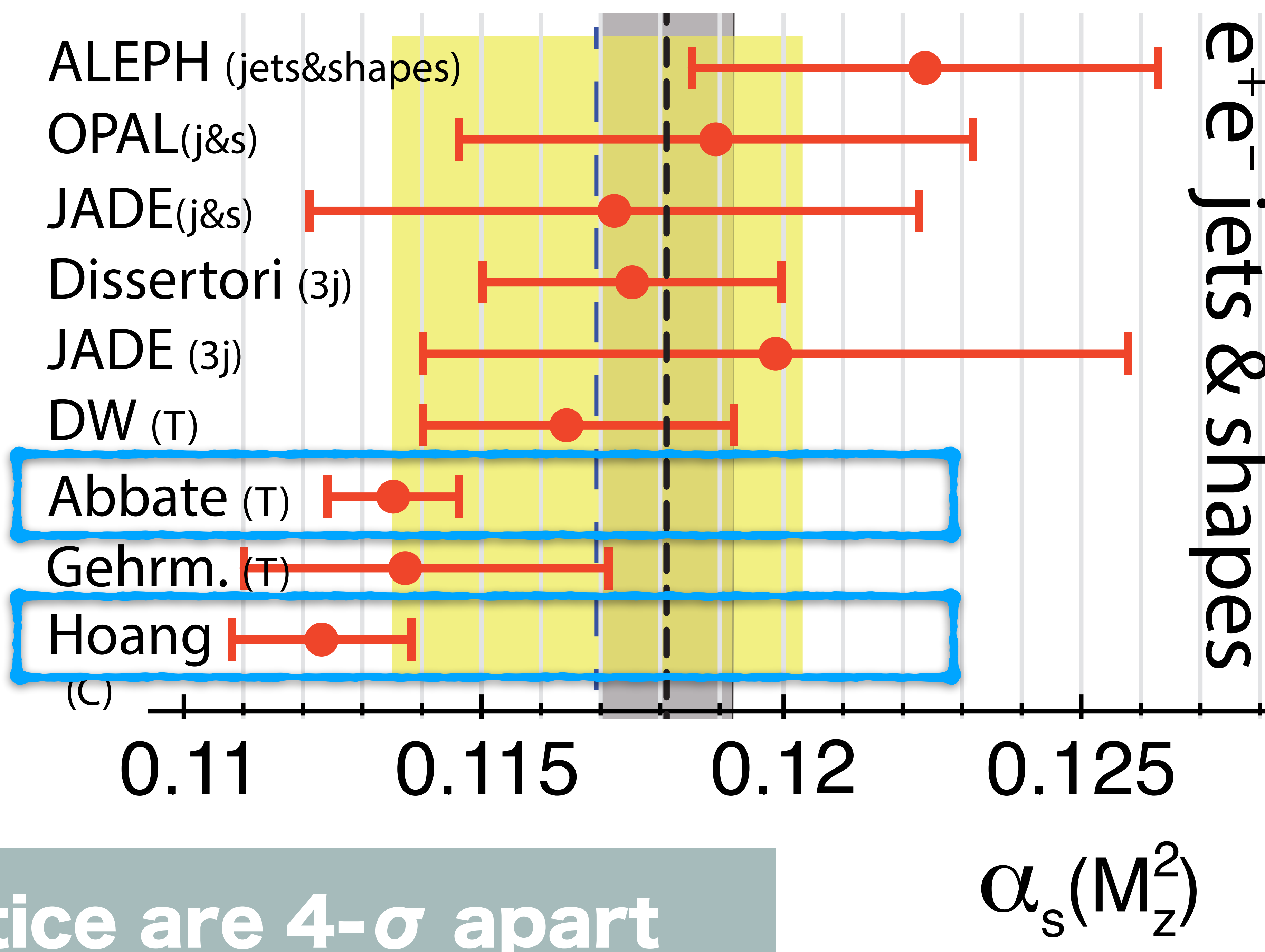
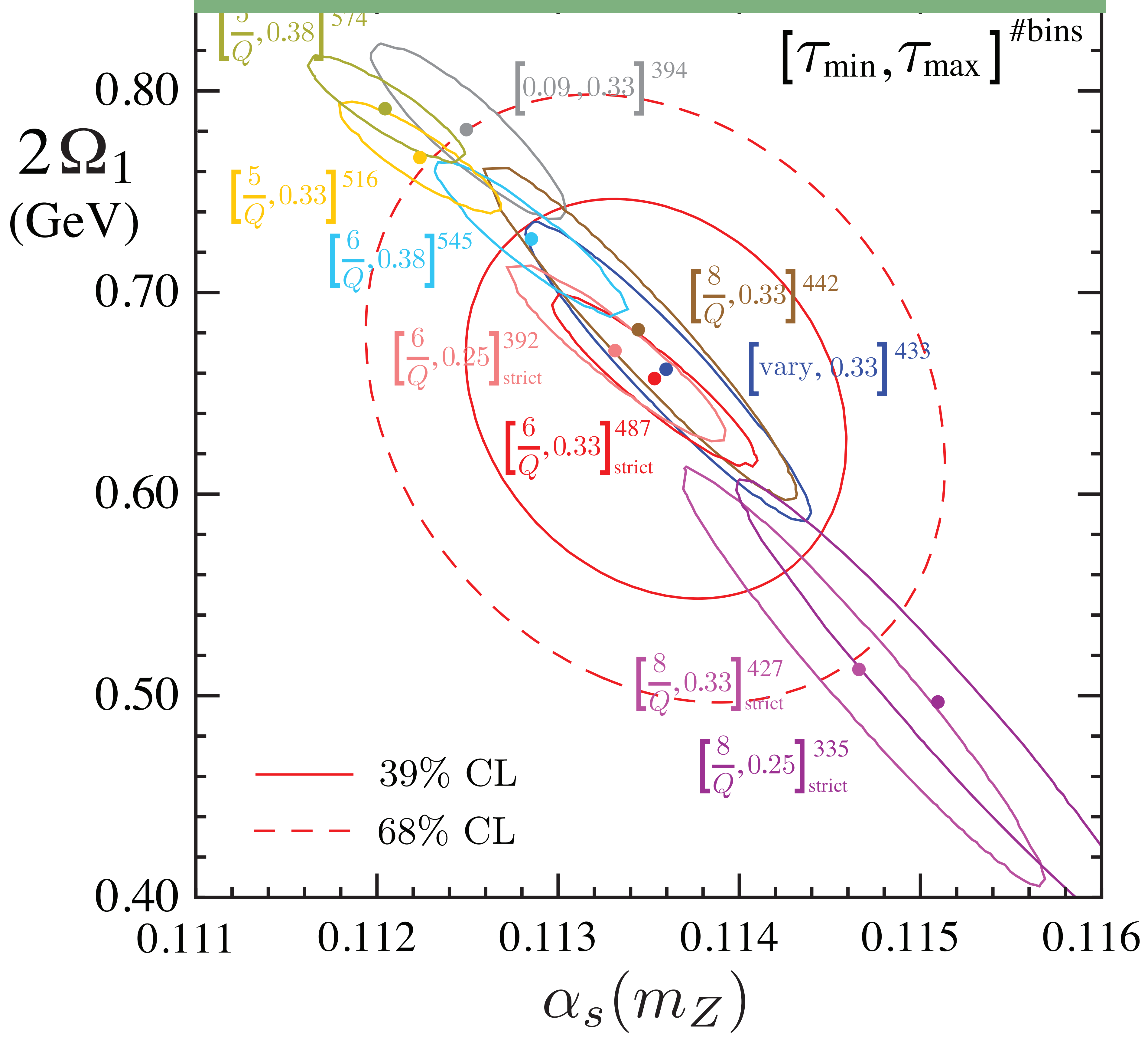


dependence on fit range



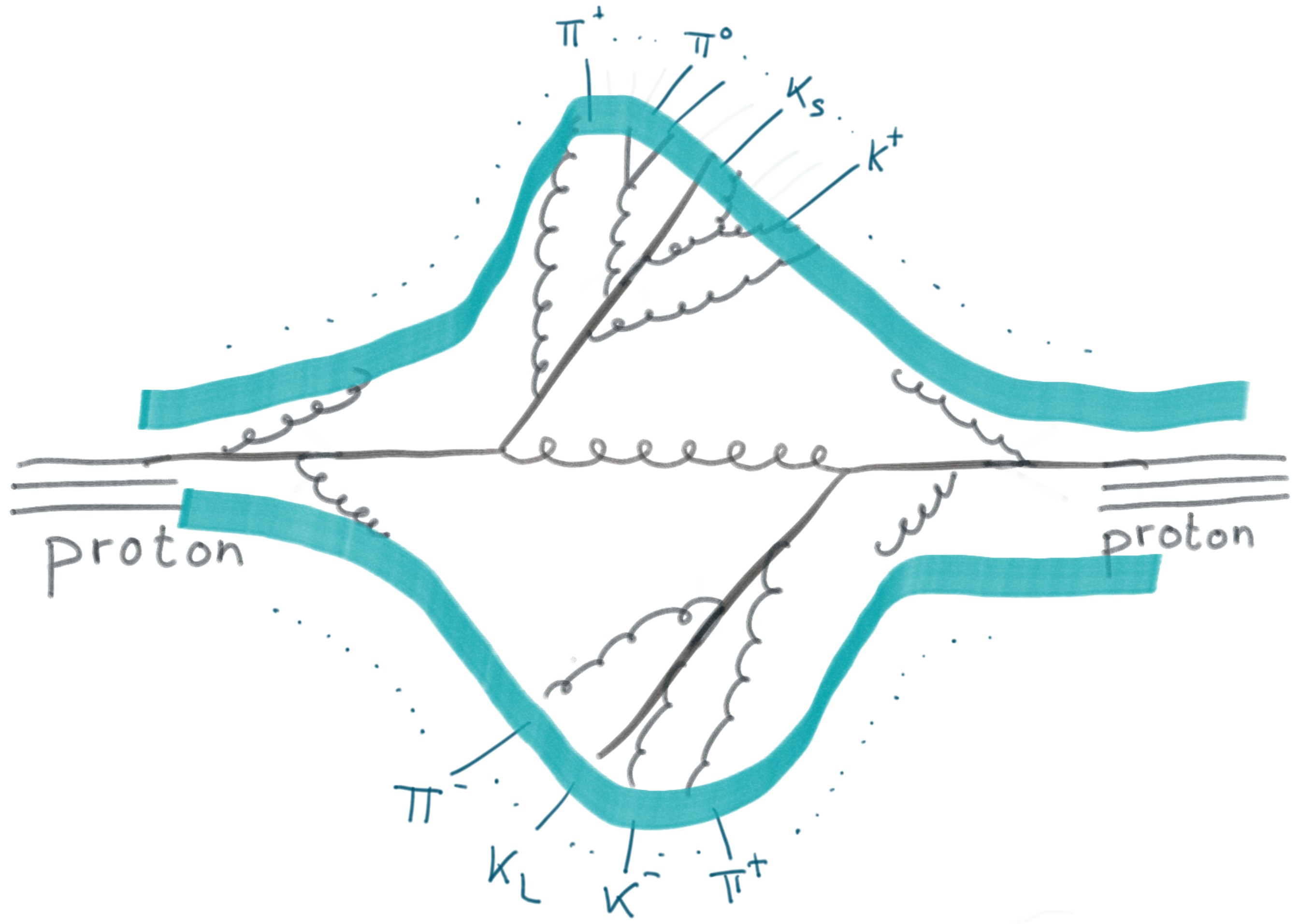
thrust & “best” lattice are 4-σ apart

Comments:

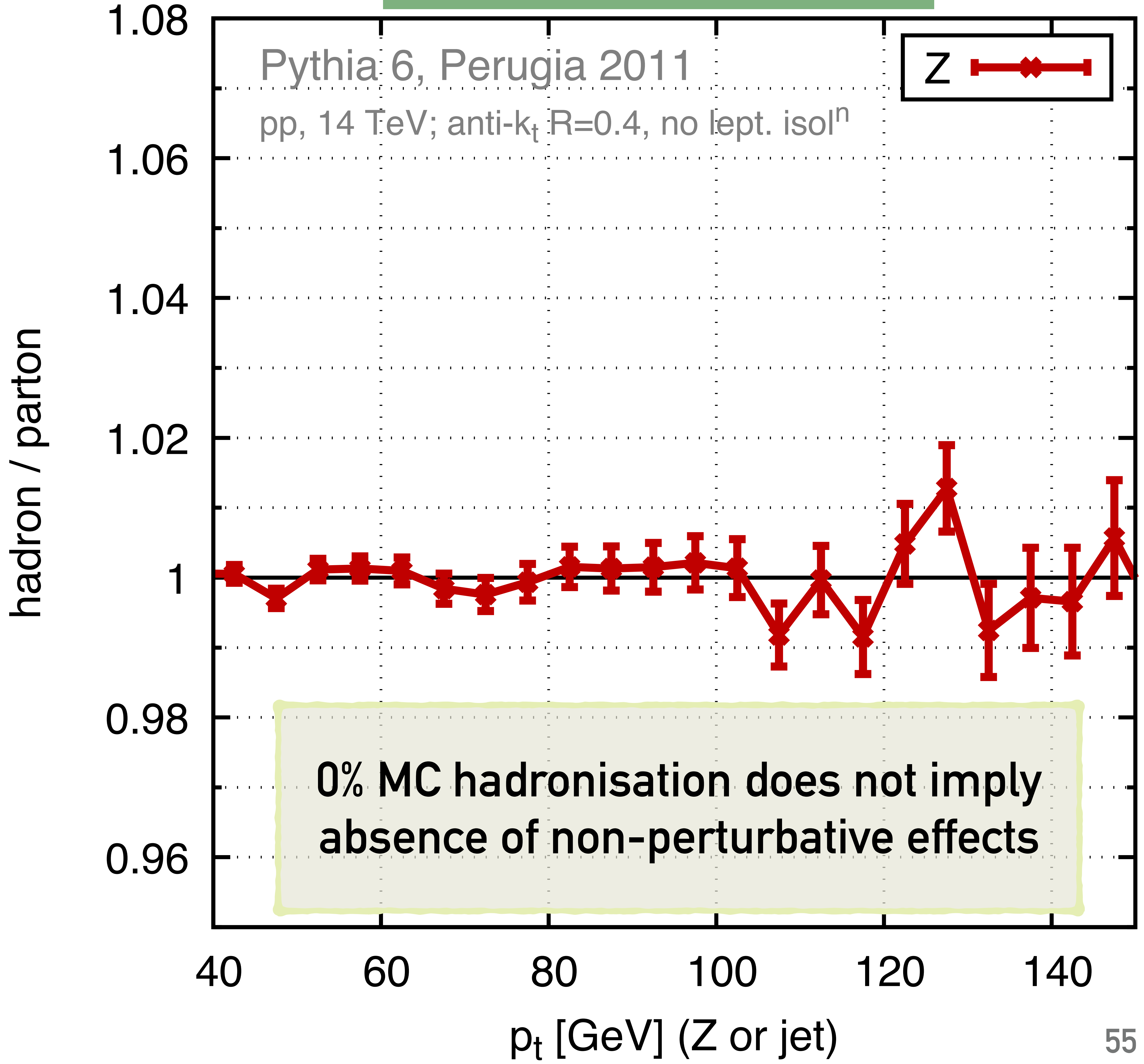
- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)

Non-perturbative effects in Z p_T

- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- It seems size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]



MC hadronisation



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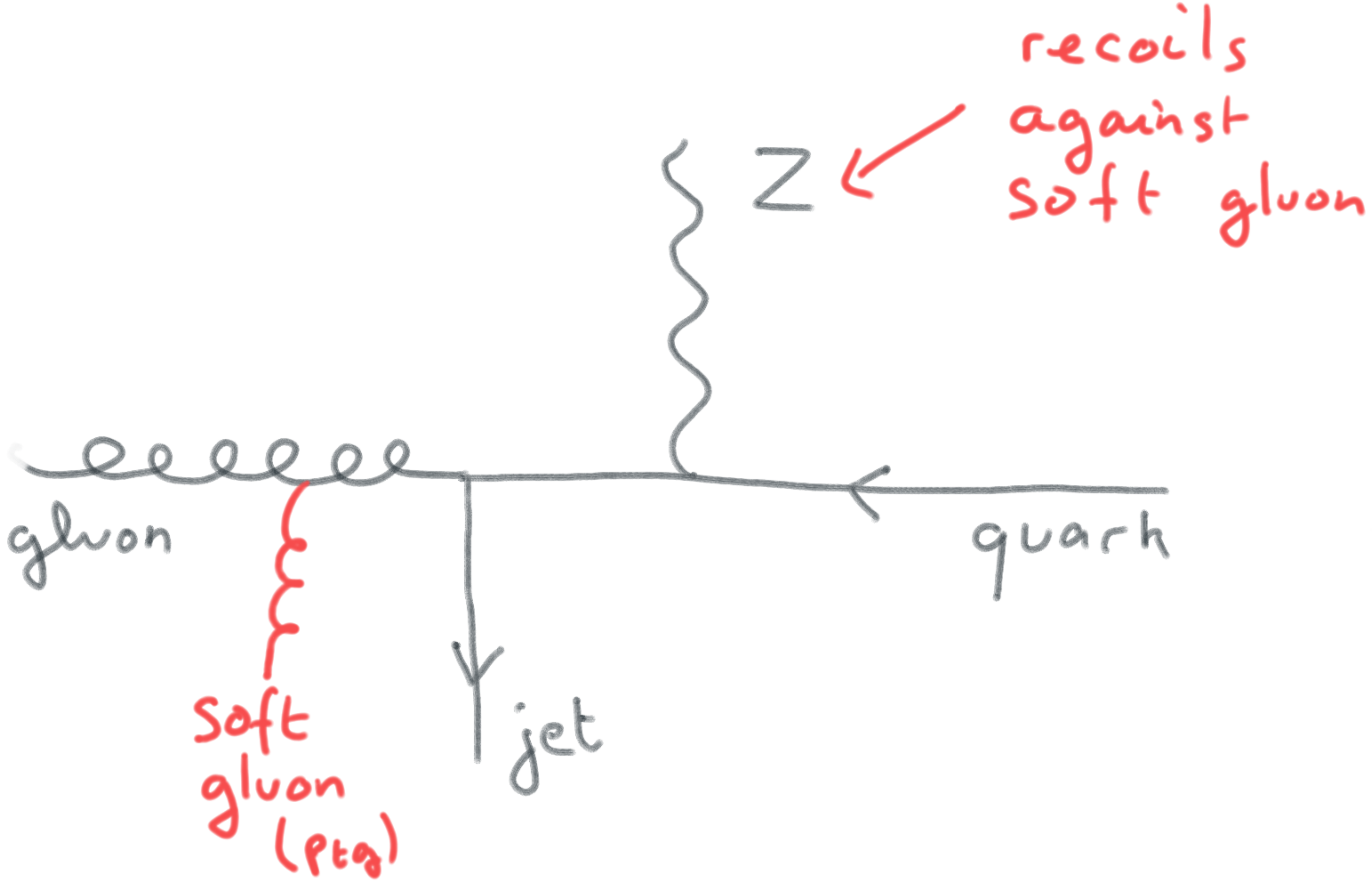

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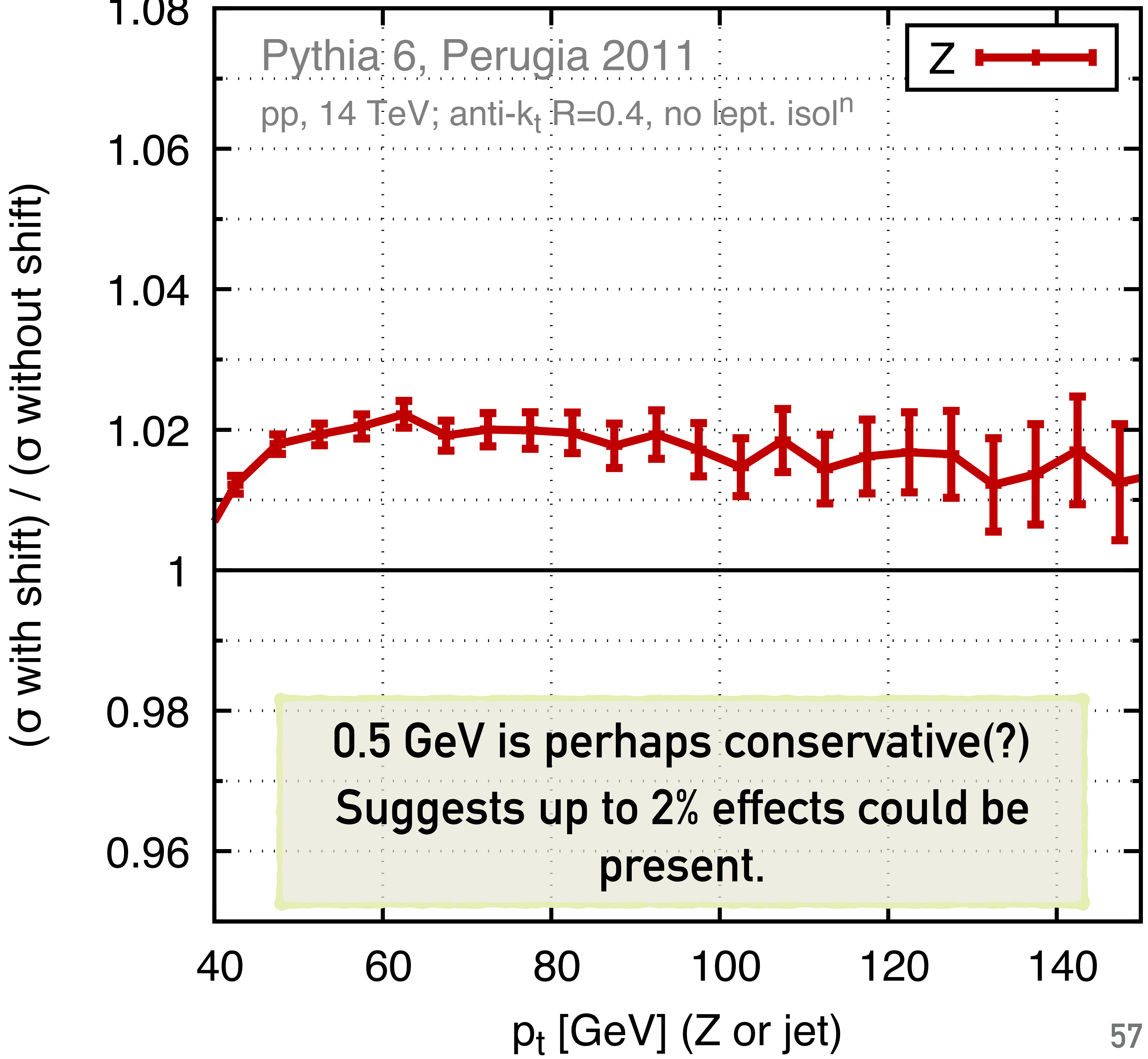
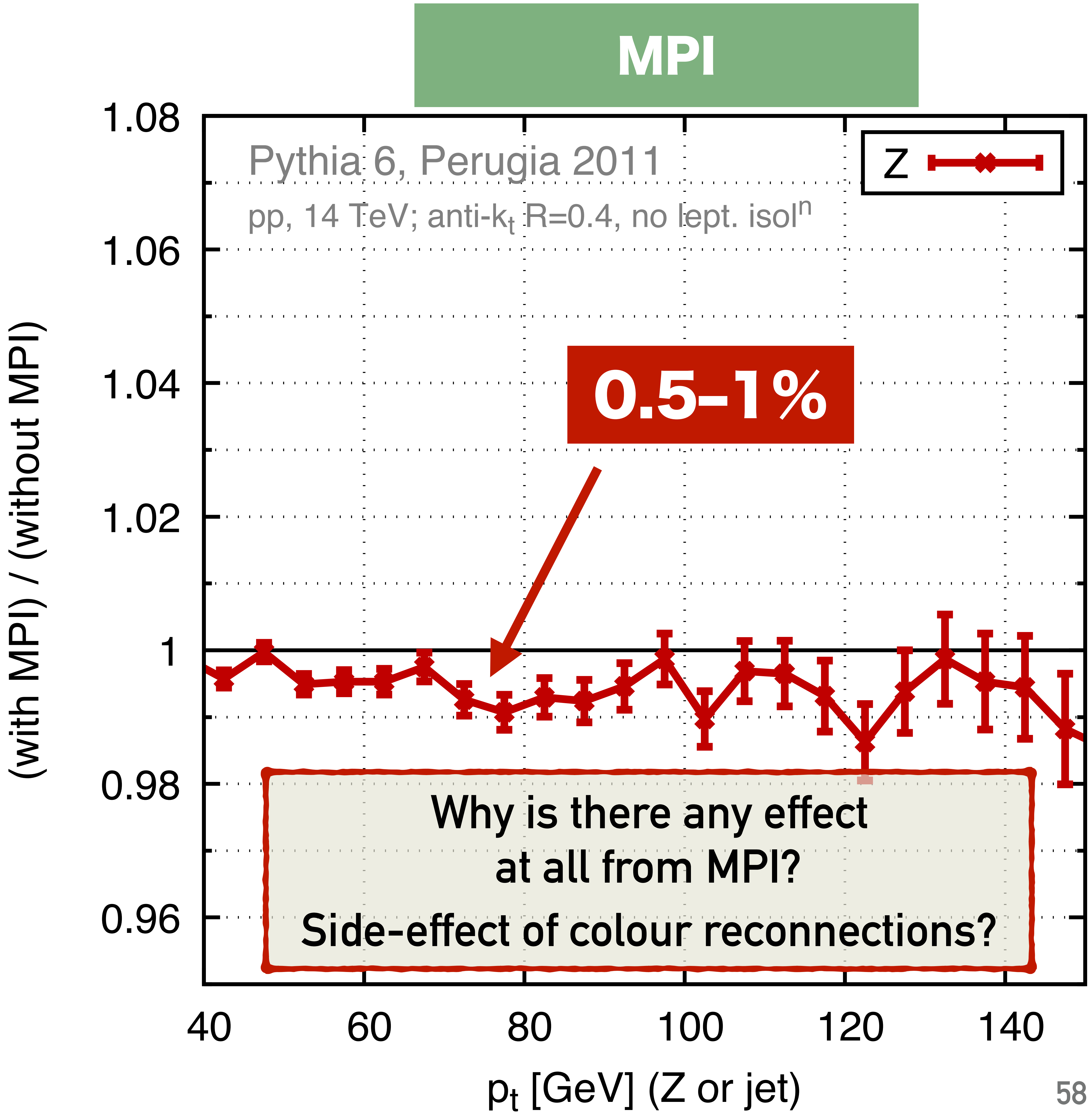


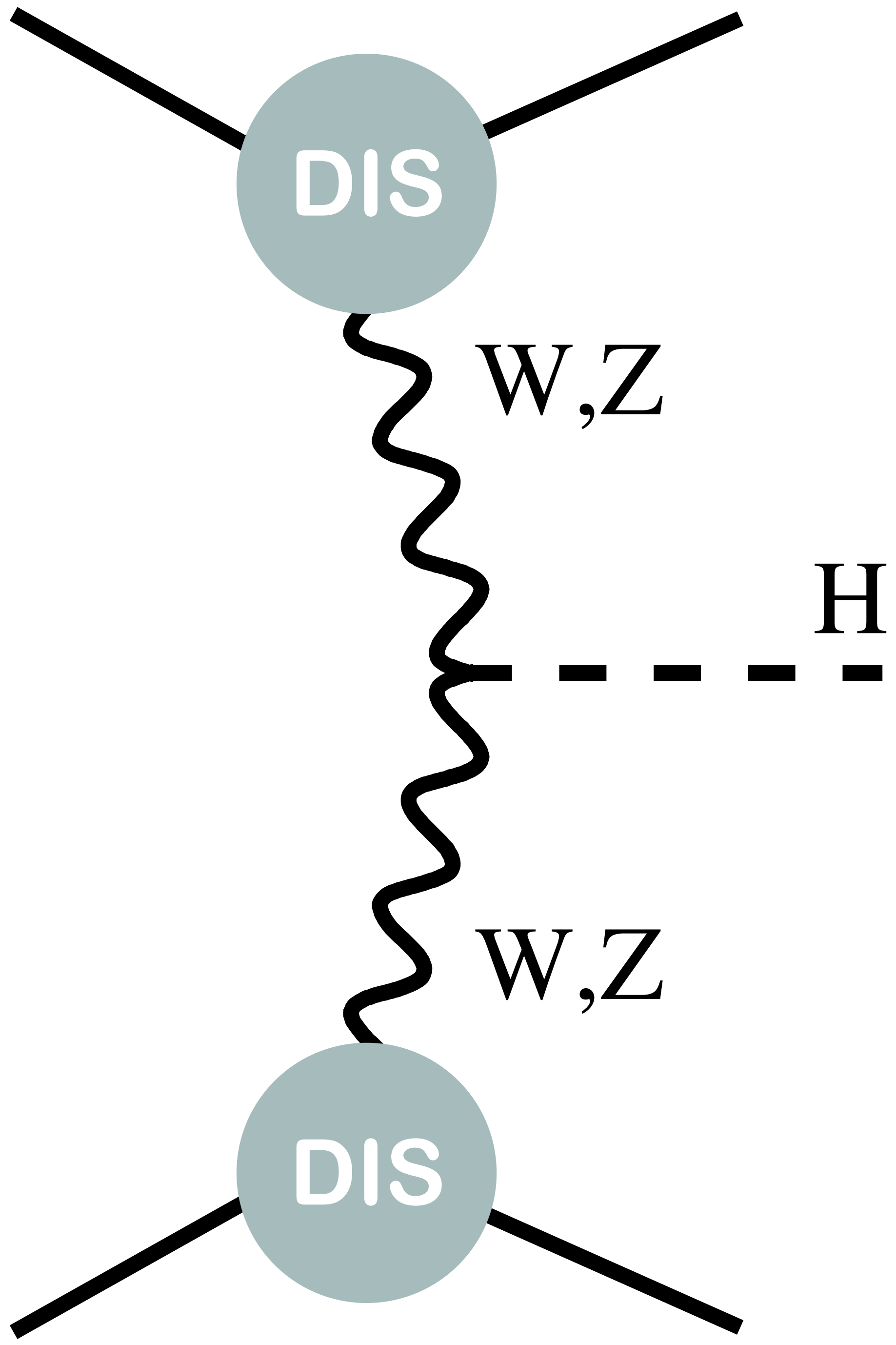
Multi-Parton Interactions?

➤ Naively, you'd expect these are not correlated with Z p_T — but in at least one MC (Pythia 6) switching them on/off changes distribution by O(1%)



VECTOR-BOSON FUSION → HIGGS

- double DIS approximation is powerful tool for VBF, using structure functions for the W/Z production (Han, Valencia & Willenbrock 1992, NNLO by Bolzoni et al 1003.4451)



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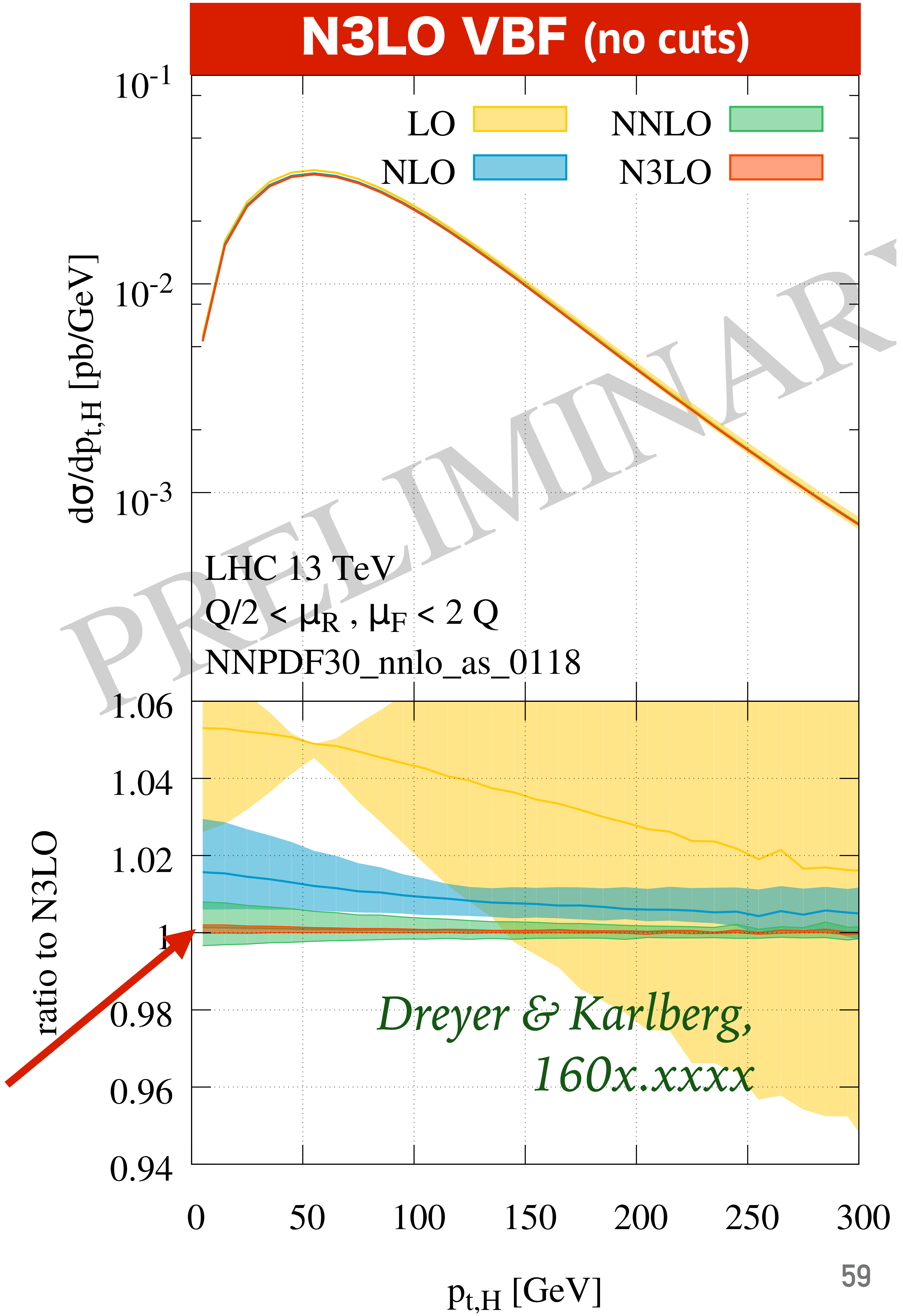
- good stability from NNLO to N3LO

N3LO



N3LO VBF (no cuts)

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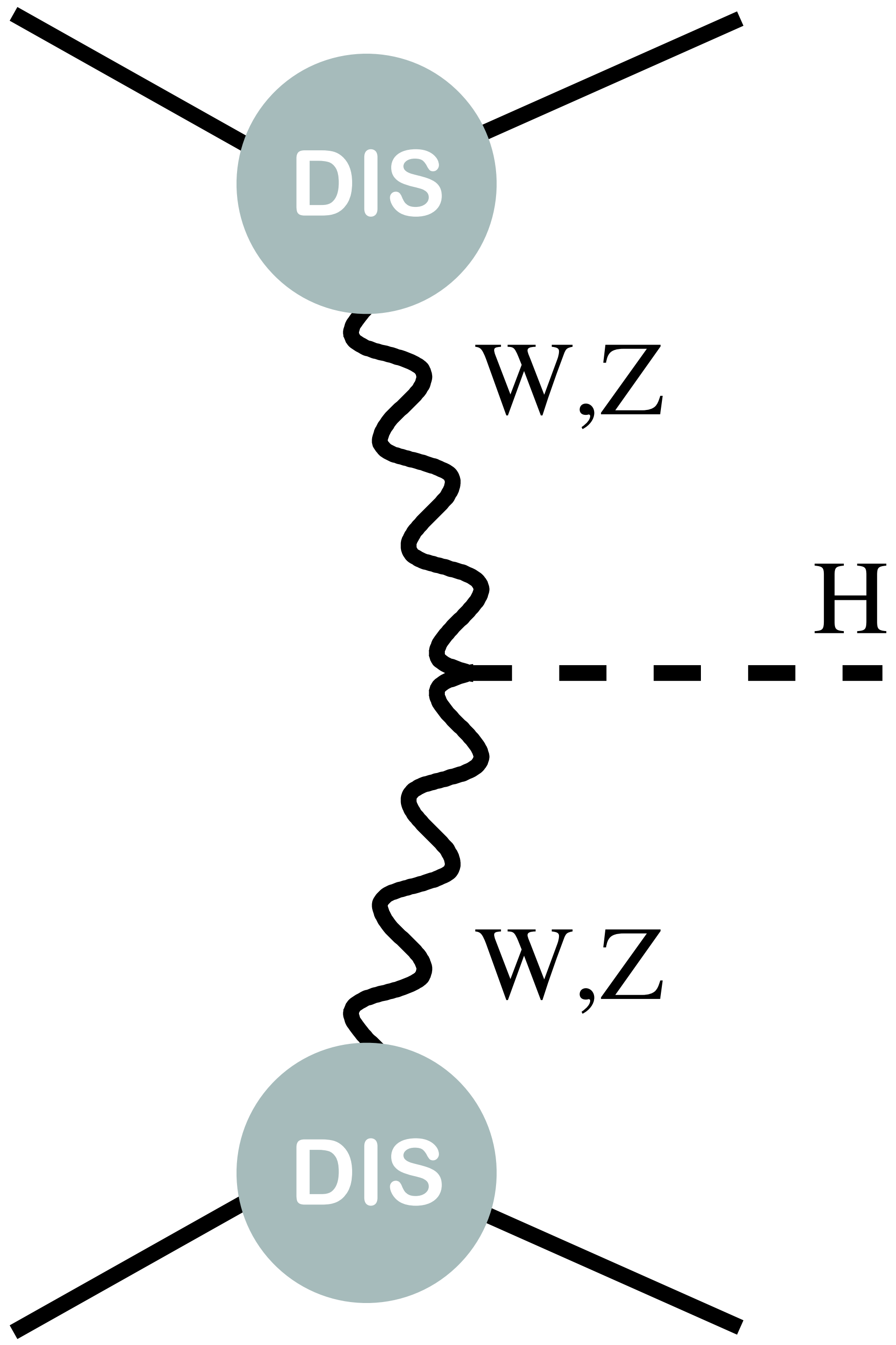

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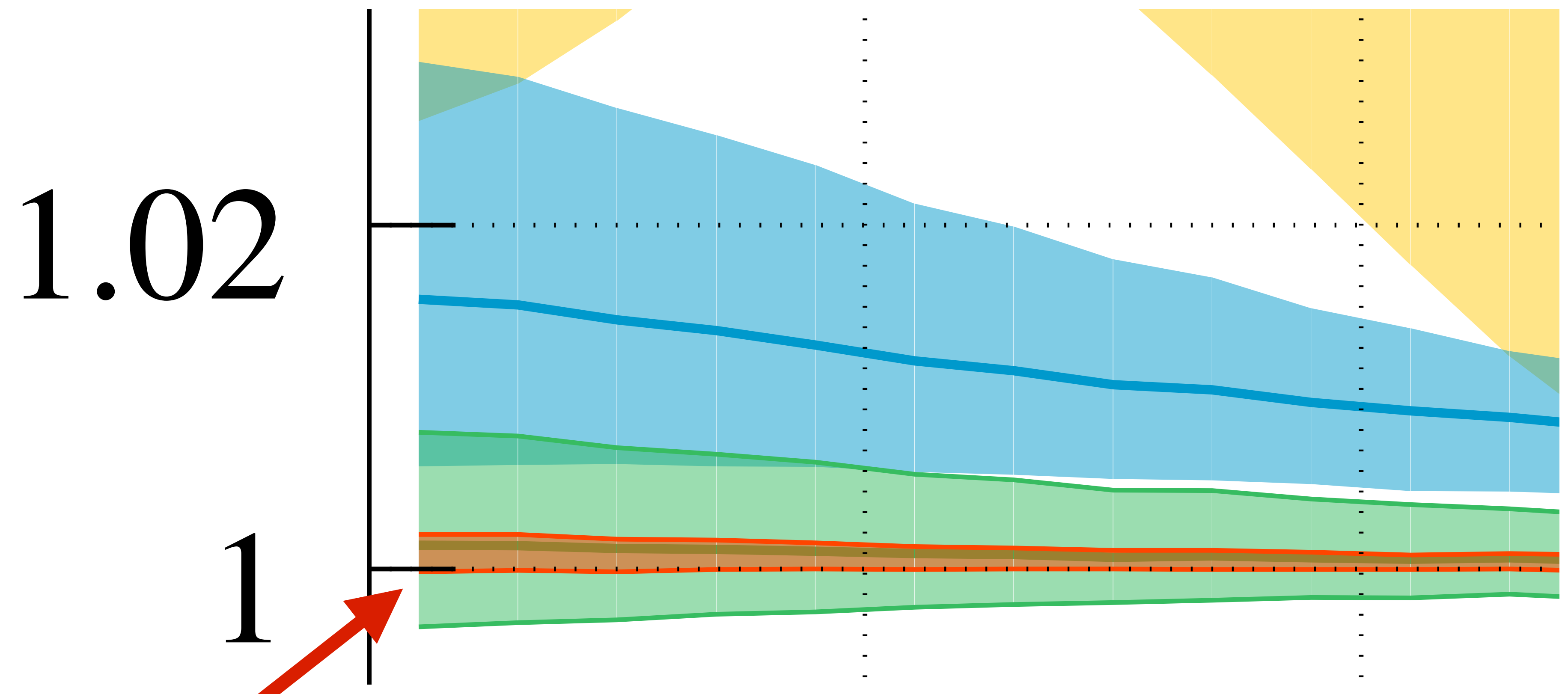


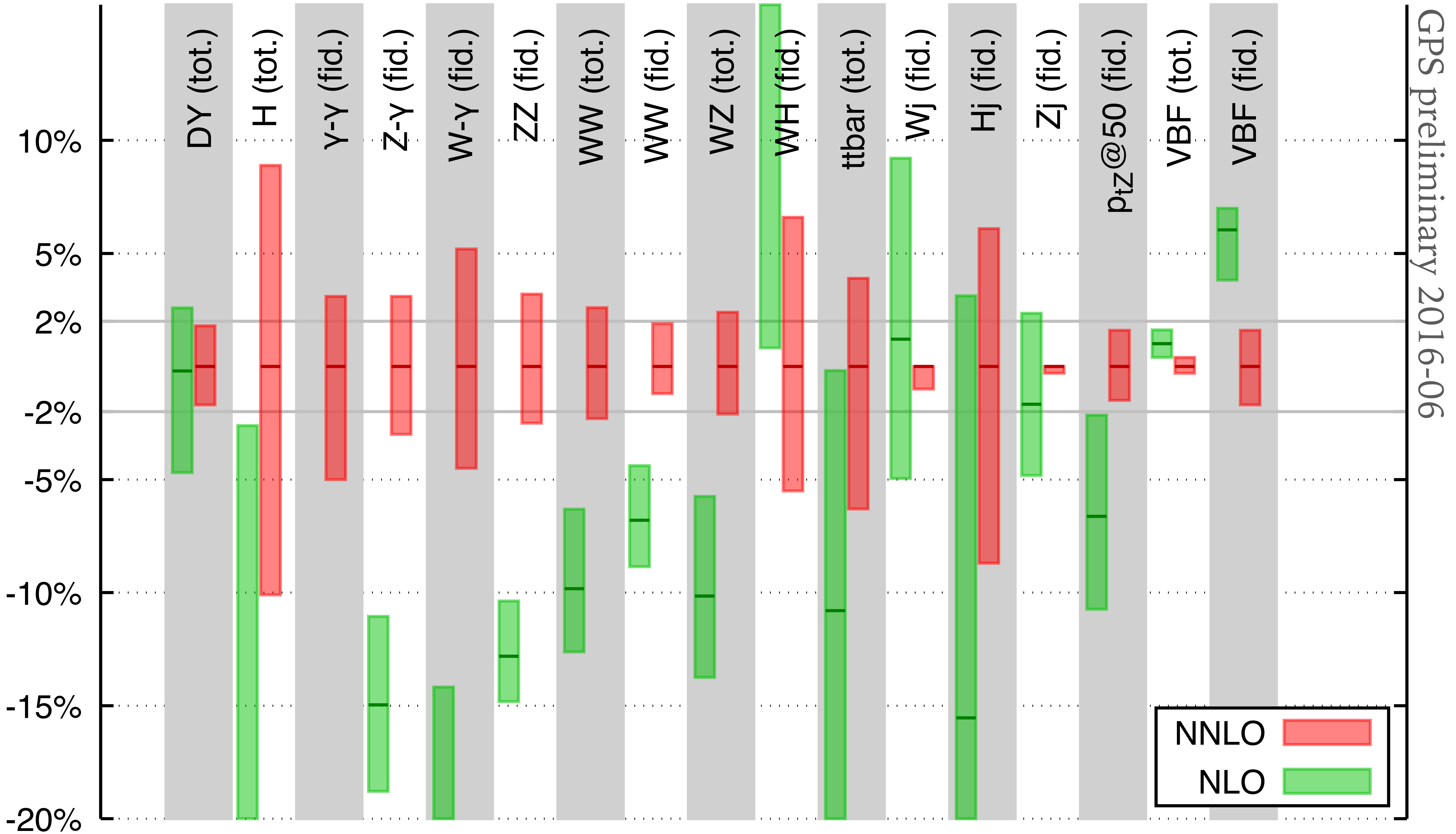
Dreyer & Karlberg, 160x.xxxx

N3LO

Exact in "$QCD_1 \otimes QCD_2$"

Non-trivial real-world corrections believed < 1%

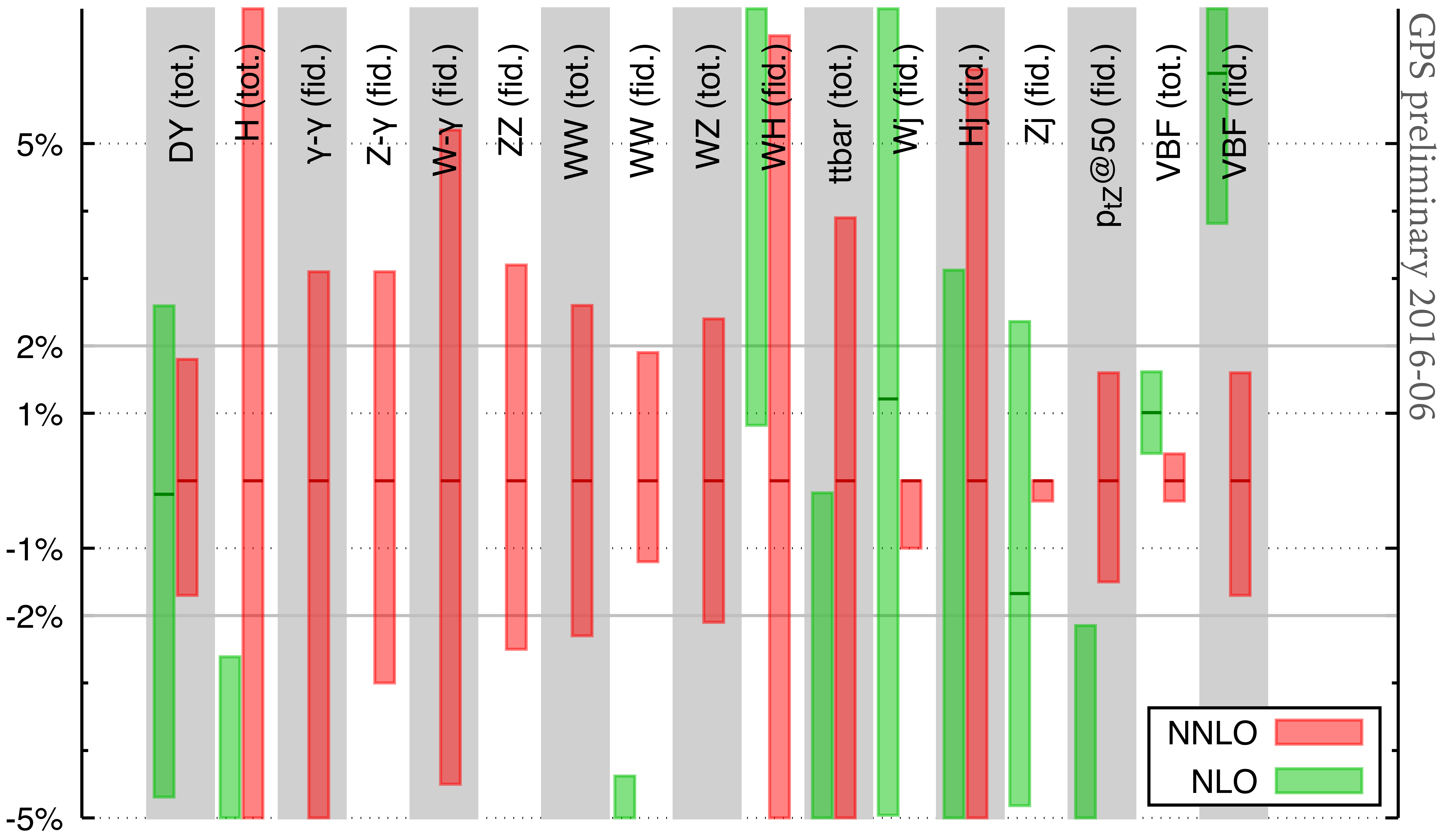
WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

Though only in 3/17 cases is NNLO (central) within NLO scale band…

WHAT PRECISION AT NNLO?



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Though only in 3/17 cases is NNLO (central) within NLO scale band…

ABSOLUTE CROSS-SECTIONS MEASURED TO ~ 1%?

Beam Imaging and Luminosity Calibration

arXiv:1603.03566v1 [hep-ex]

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We discuss a method to reconstruct two-dimensional proton bunch densities using vertex distributions accumulated during LHC beam-beam scans. The x-y correlations in the beam shapes are studied and an alternative luminosity calibration technique is introduced. We demonstrate the method on simulated beam-beam scans and estimate the uncertainty on the luminosity calibration associated to the beam-shape reconstruction to be below 1%.