Higgs Hunting 2025

Results and prospects in the electroweak symmetry breaking sector

Theory Concluding Talk

Gavin Salam

Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

Almost every problem of the Standard Model originates from Higgs interactions

$$\mathscr{L} = y\,H\,\psi\,\bar{\psi} + \mu^2\,|H|^2 - \lambda\,|H|^4 - V_0$$

flavour

naturalness

stability

cosmological constant

Even if the SM seems to be right at the moment, there are still important issues that it cannot address, at least not in a straightforward way. Several of them are related to the physics of Higgs field.

Melnikov
Theory Conclusion,
HH2024

- unification of interactions
- nature of EW symmetry breaking
- origin of quark/lepton families
- masses and Yukawa couplings
- matter anti-matter asymmetry

} H

- nature of dark matter
- connection to gravity

} H

Talk by Bibhushan Shakya

The Standard Model

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi + \underbrace{(D_\mu\phi)^\dagger(D_\mu\phi) + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 + \left(\lambda^{ij}\bar{\psi}^i_L\phi\psi^j_R + \text{h.c.}\right)}_{\mathscr{L}_{\text{SB}}}$$

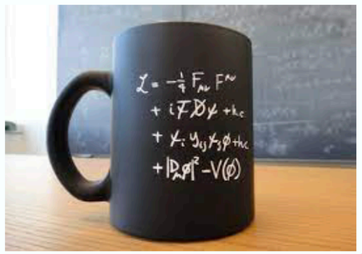
$\Delta\mu^2 \sim \Delta m_H^2 \sim \Lambda^2$

vacuum (meta)stability

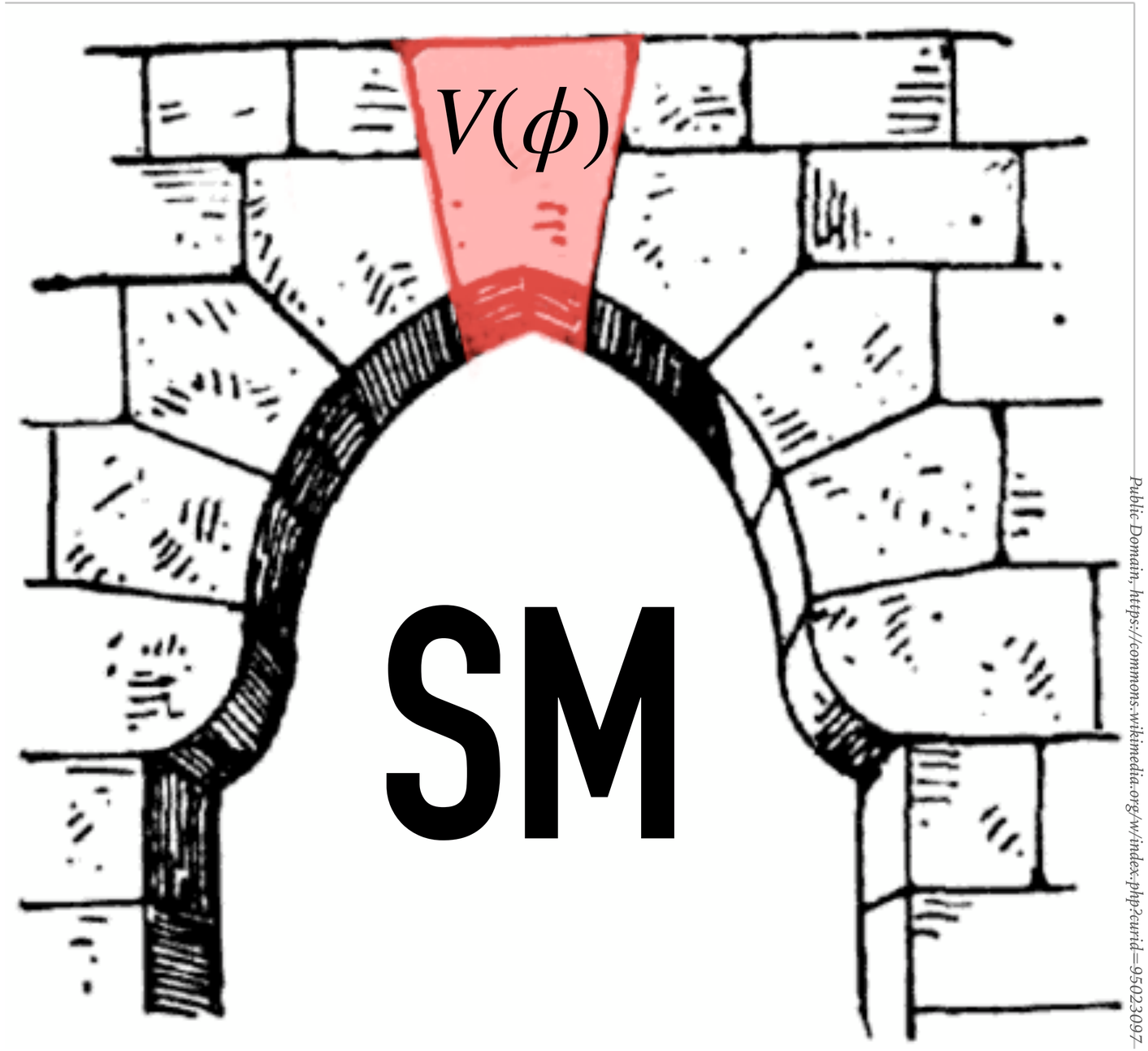
Flavour problem

source of most of the SM problems but at the time the simplest solution providing the necessary ingredients to break the EW symmetry

Grazzini
Theory Conclusion,
HH2023



di-Higgs



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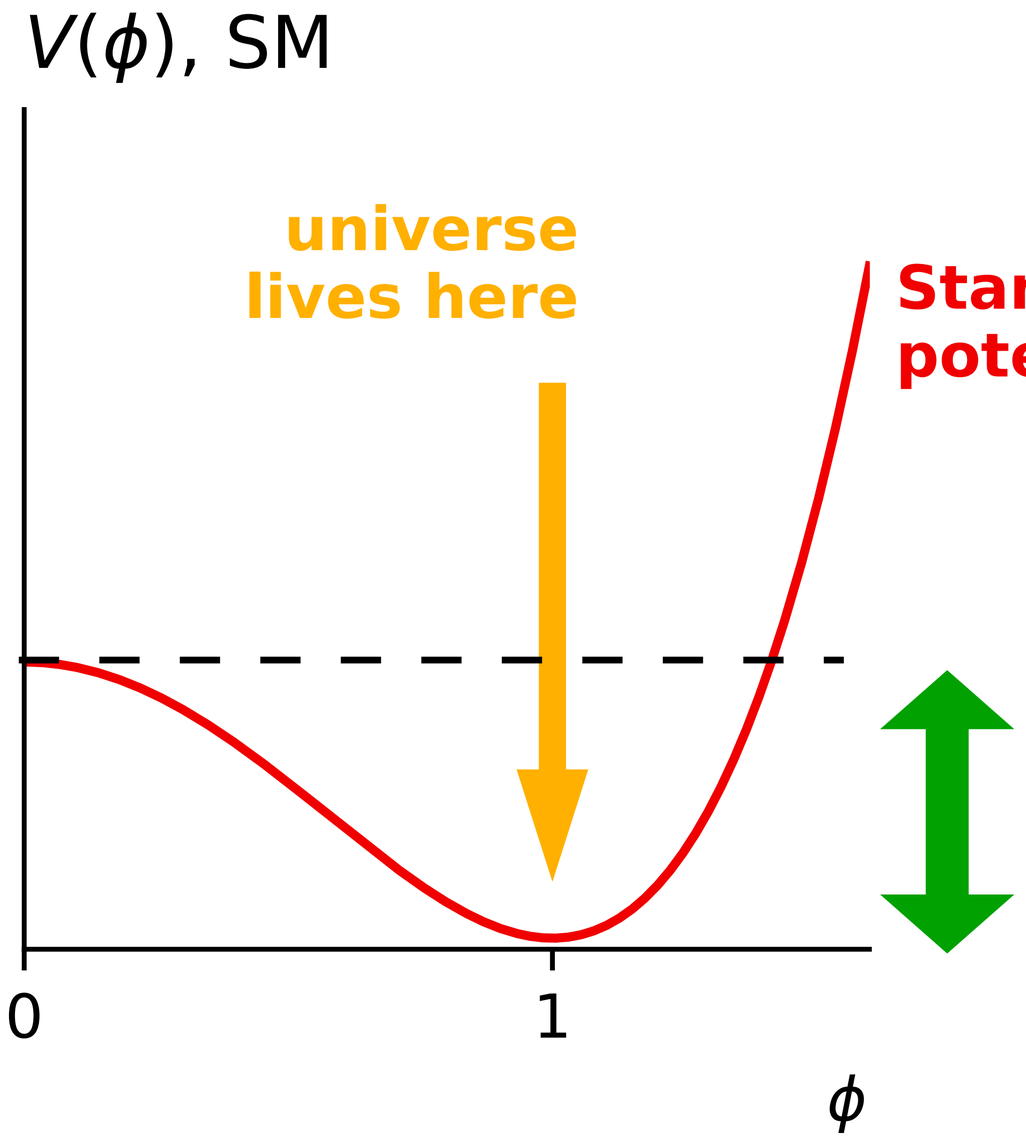
unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

Higgs potential – remember: it's an energy density



Corresponds to an energy density of
$1.5 \times 10^{10}\,\mathrm{GeV/fm^3}$

$E = mc^2 \rightarrow$ Mass density of $2.6 \times 10^{28}\,\mathrm{kg/m^3}$
i.e. **>40 billion times nuclear density**

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https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg

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Earth at neutron star density

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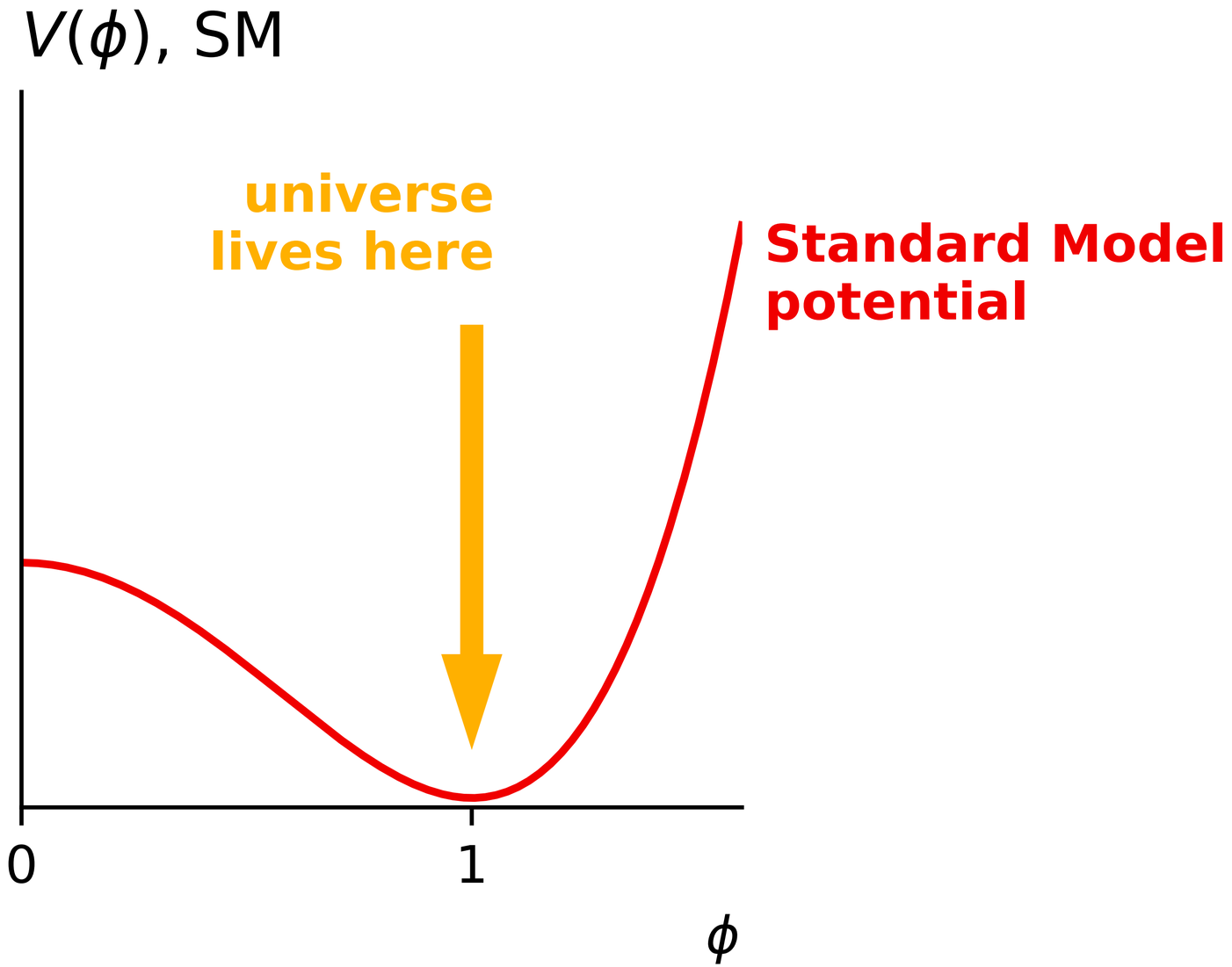
Earth at neutron star density

Earth at Higgs potential density

Higgs potential

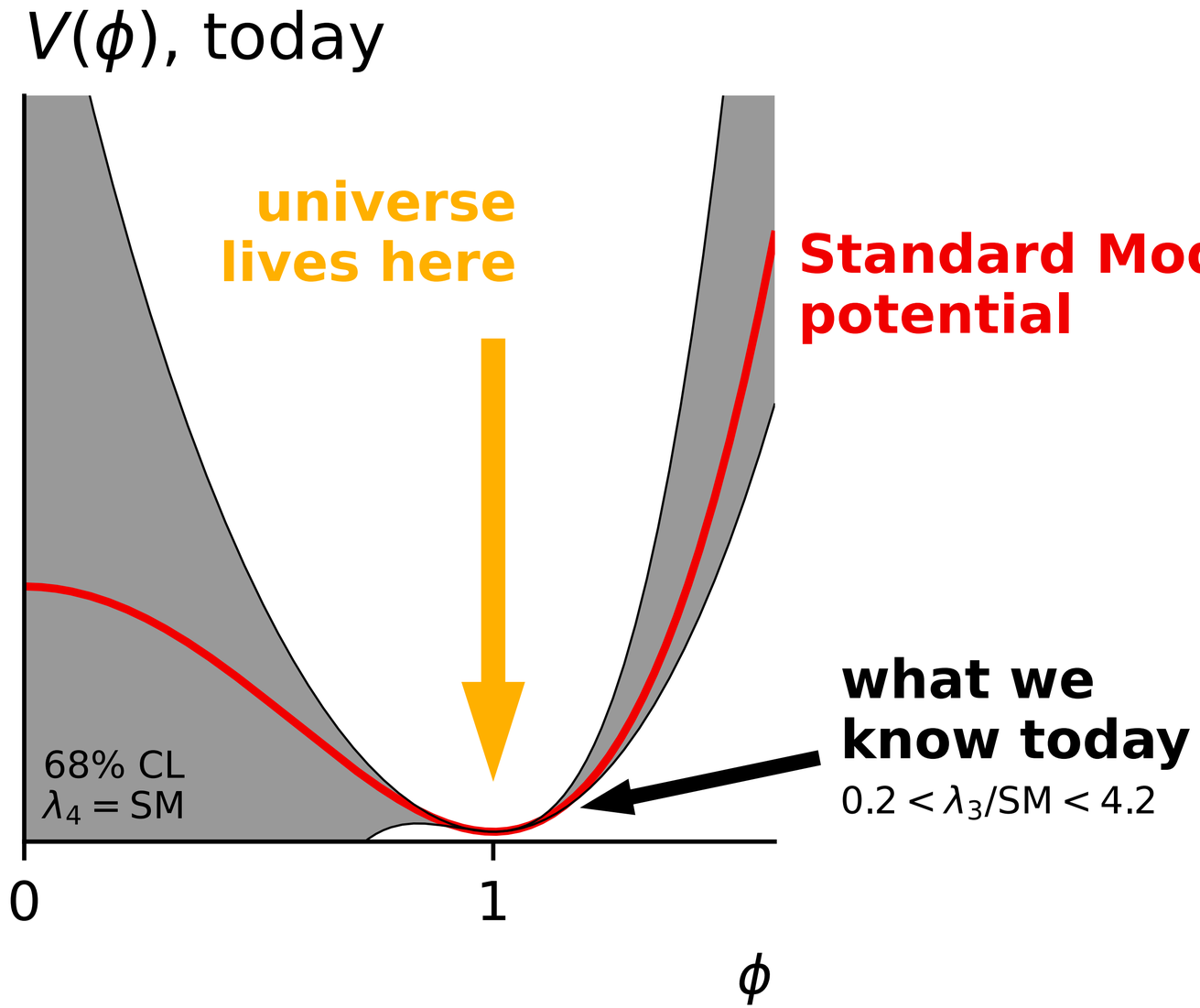


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



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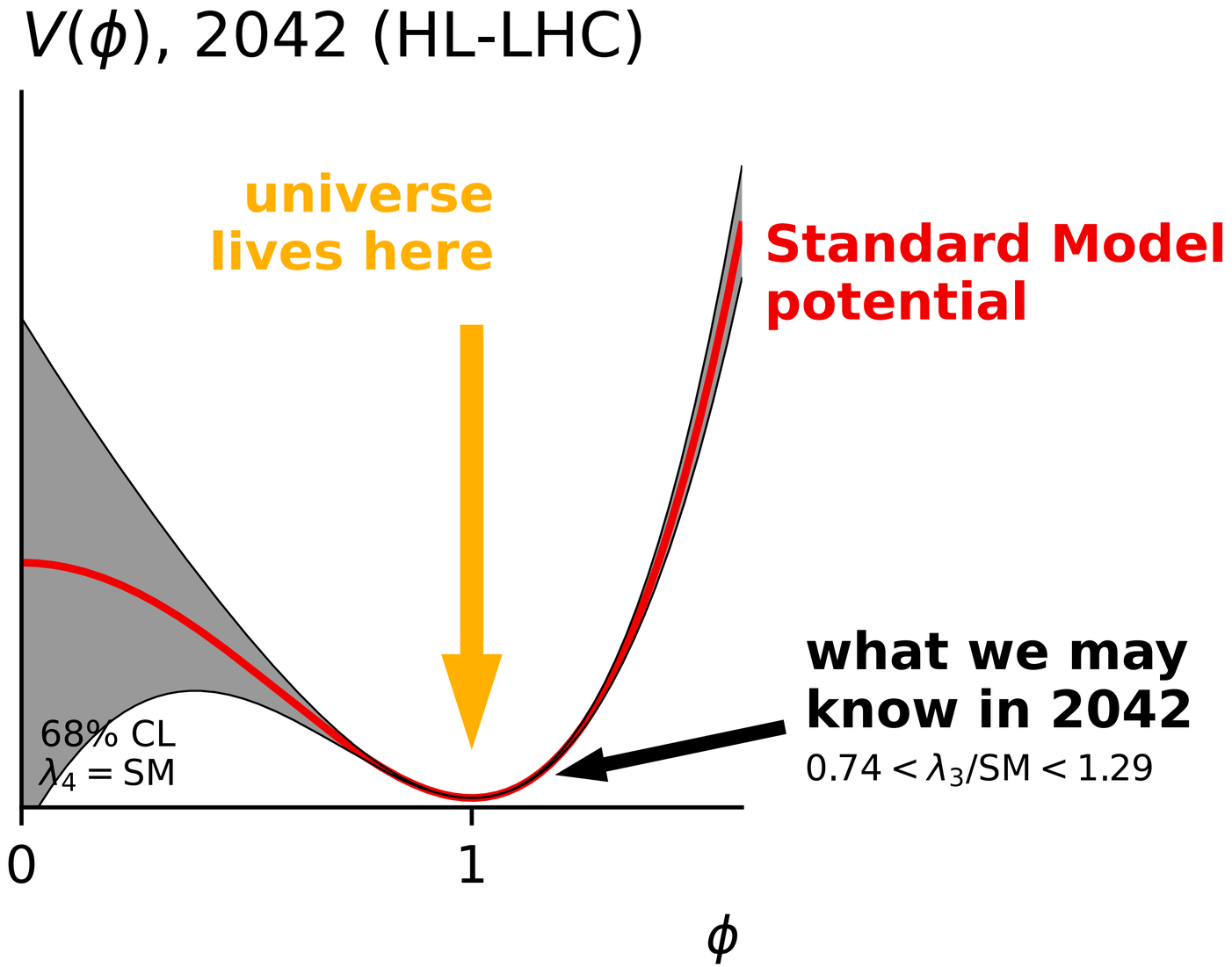

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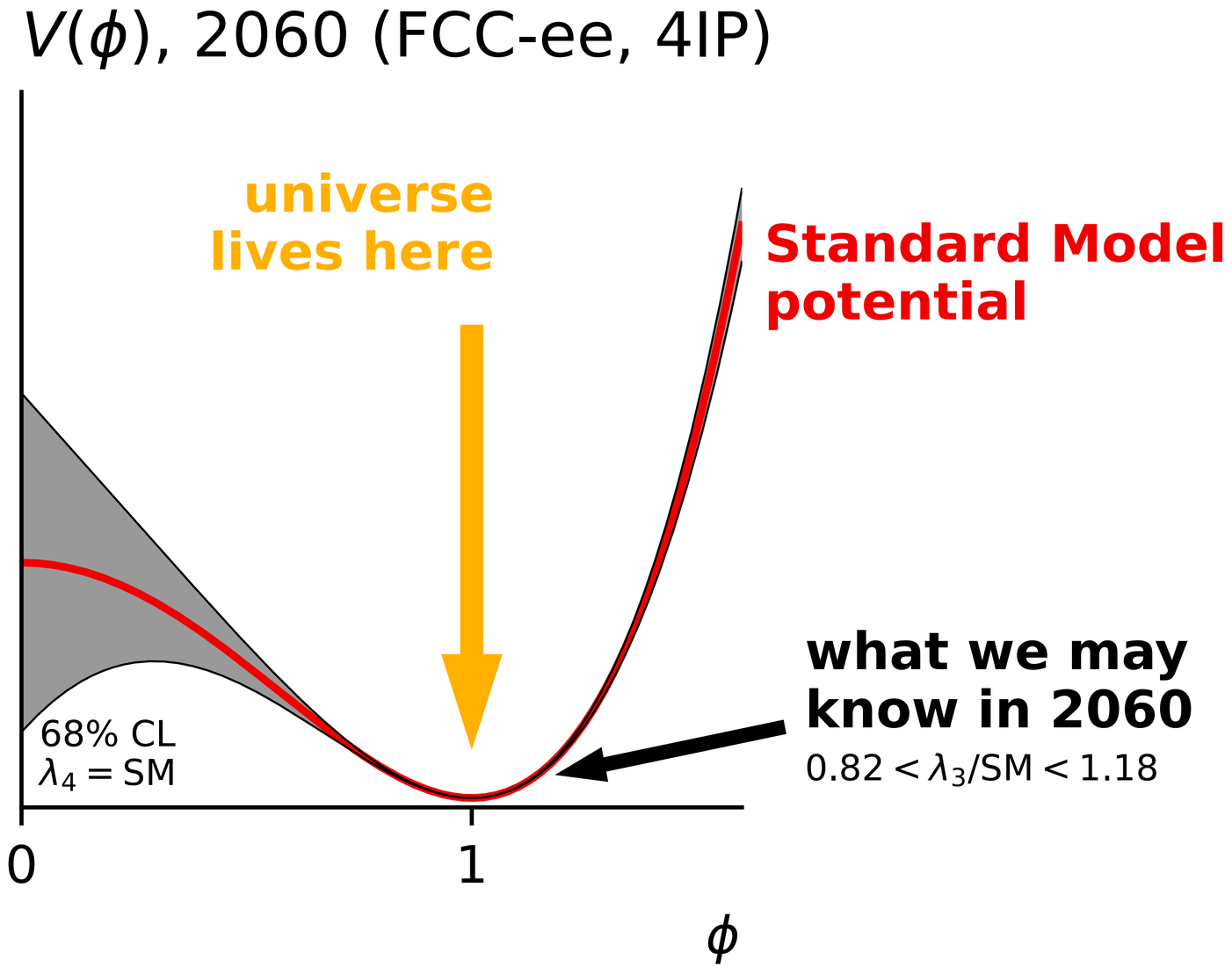

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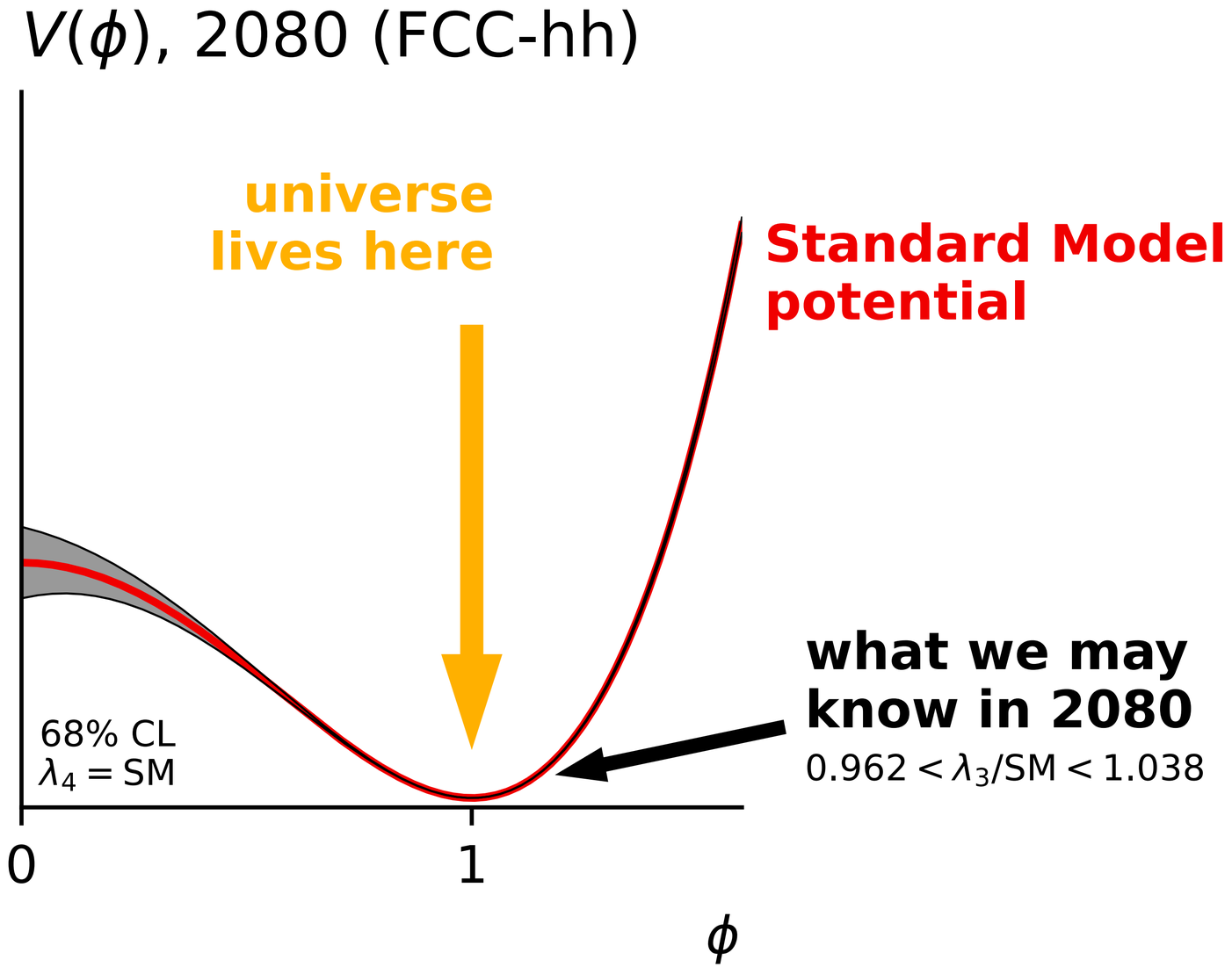

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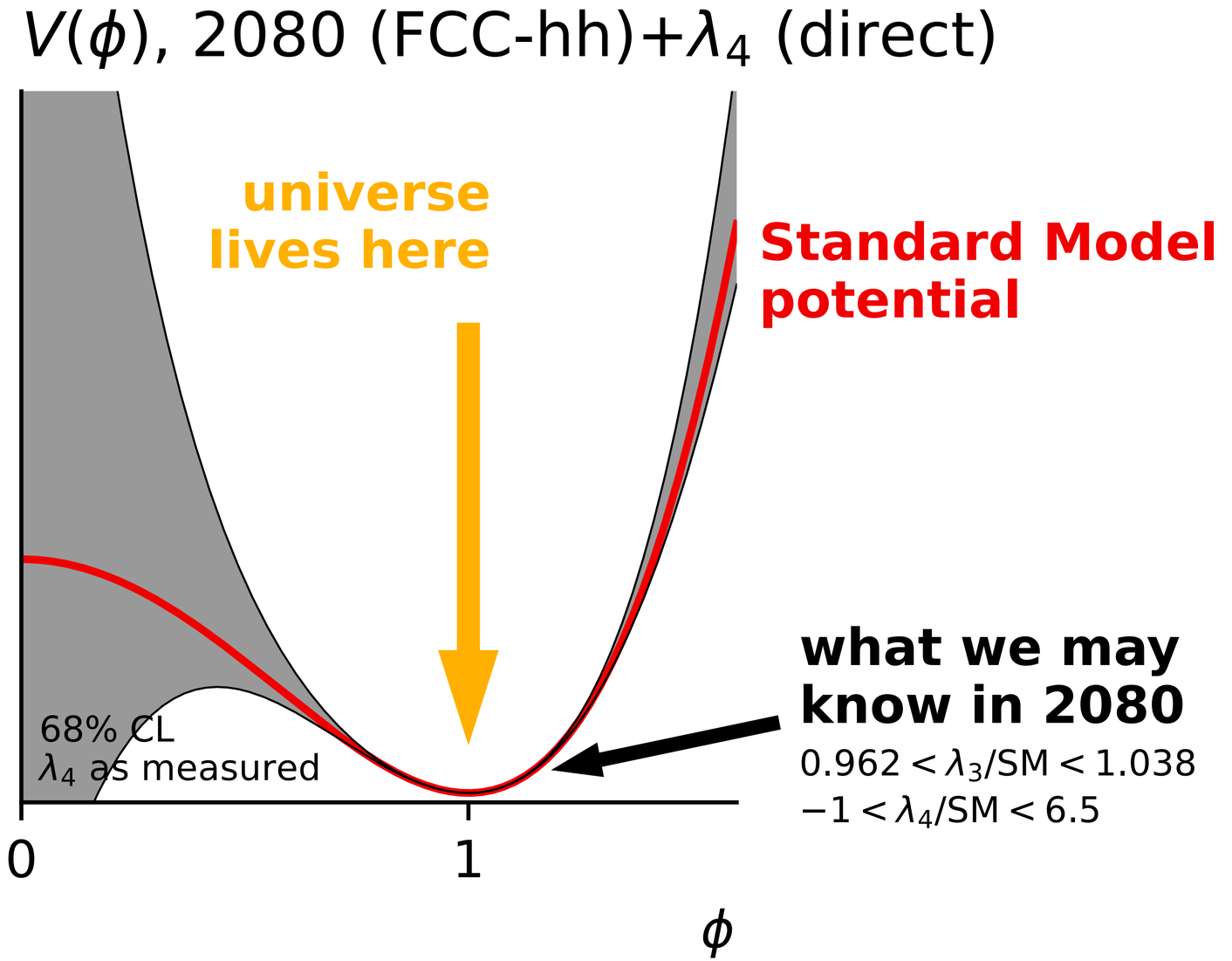

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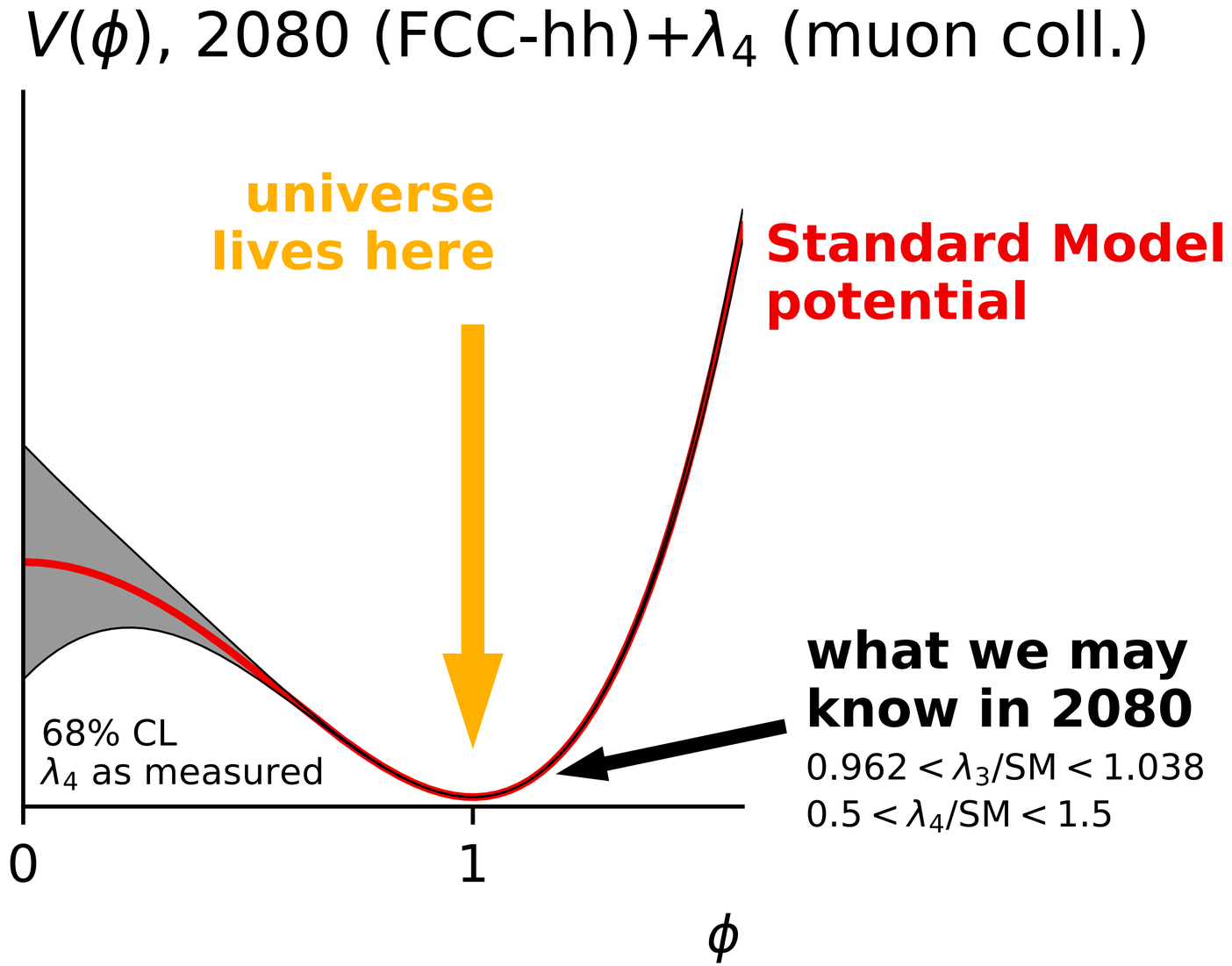

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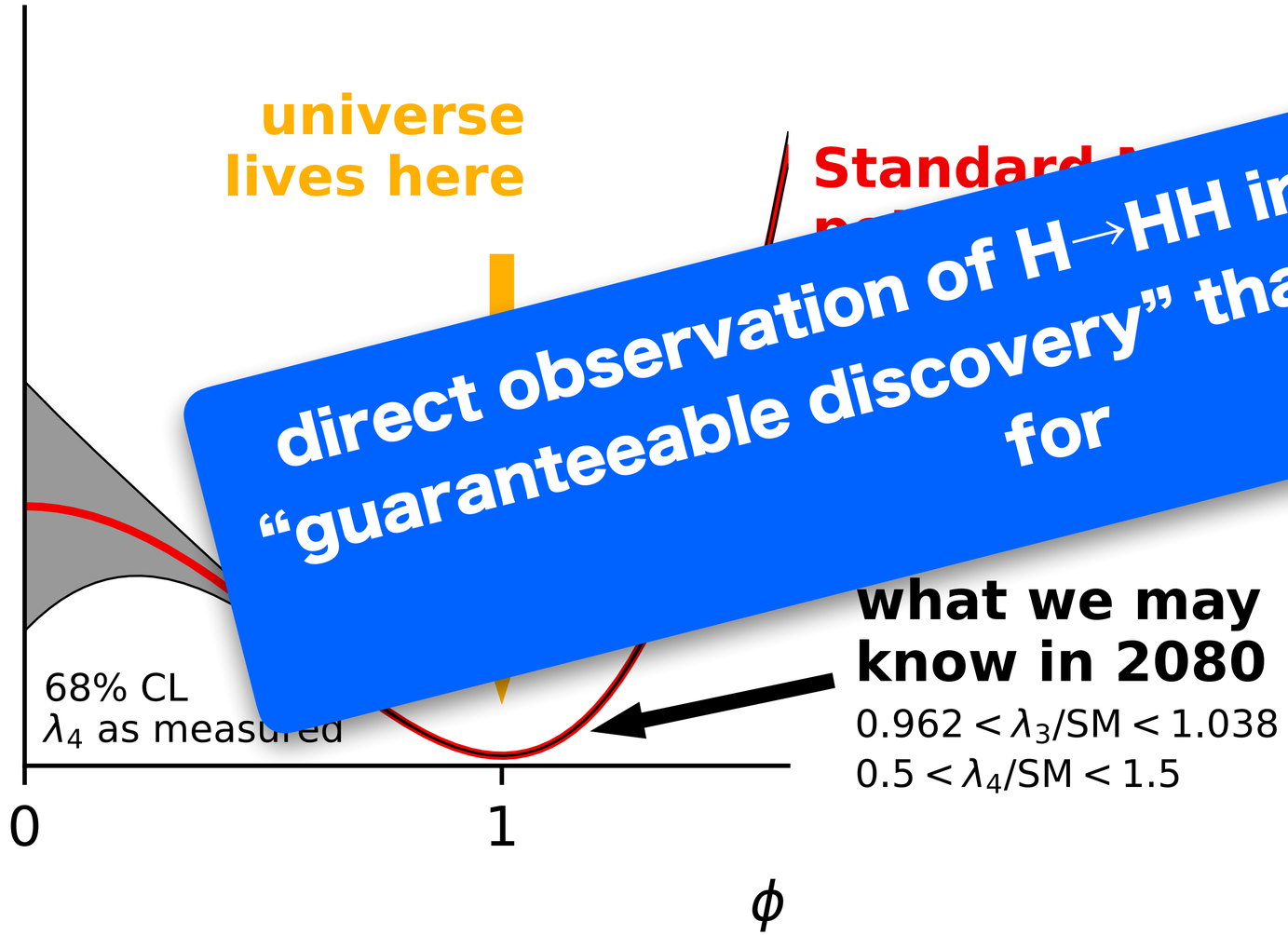
Higgs potential

$V(\phi)$, 2080 (FCC-hh)+λ_4 (muon coll.)



what we may know in 2080

$0.962 < \lambda_3/\mathrm{SM} < 1.038$

$0.5 < \lambda_4/\mathrm{SM} < 1.5$

direct observation of H→HH interaction is a "guaranteeable discovery" that HEP is aiming for

Studying H→HH probes
spe… …tical property
…'s shape:

…ive (λ_3),
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at the minimum

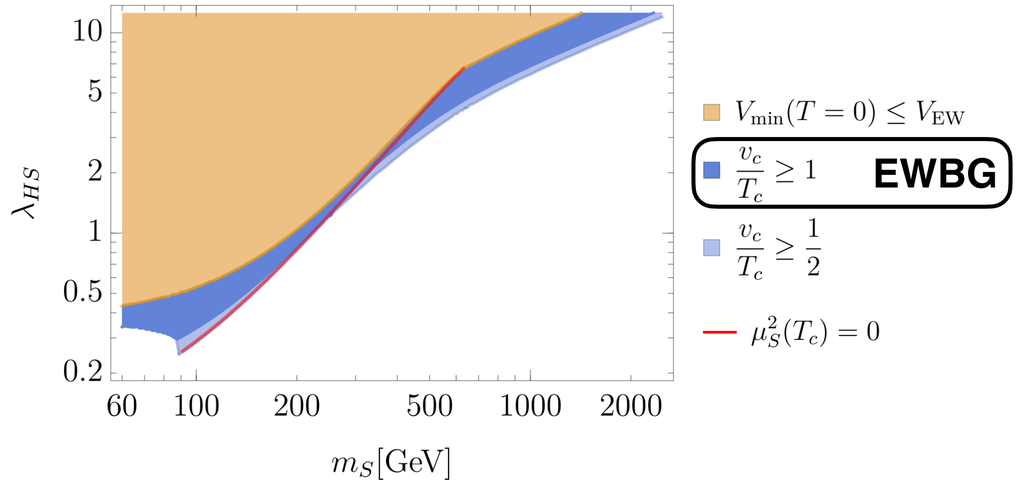
[reconstruction in plot assumes higher derivatives as in SM]

CAVEATS ABOUT THESE PLOTS

- How many derivatives should we constrain?
  → not really the right question…
- Realistic models tend to have more complex structures
- Value is that of a cartoon — illustrates our progress, but not to be taken too seriously

SM + Singlet

$$V_{\rm tree}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \underbrace{\frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4}_{\textbf{new}}$$



Matsedonskyi

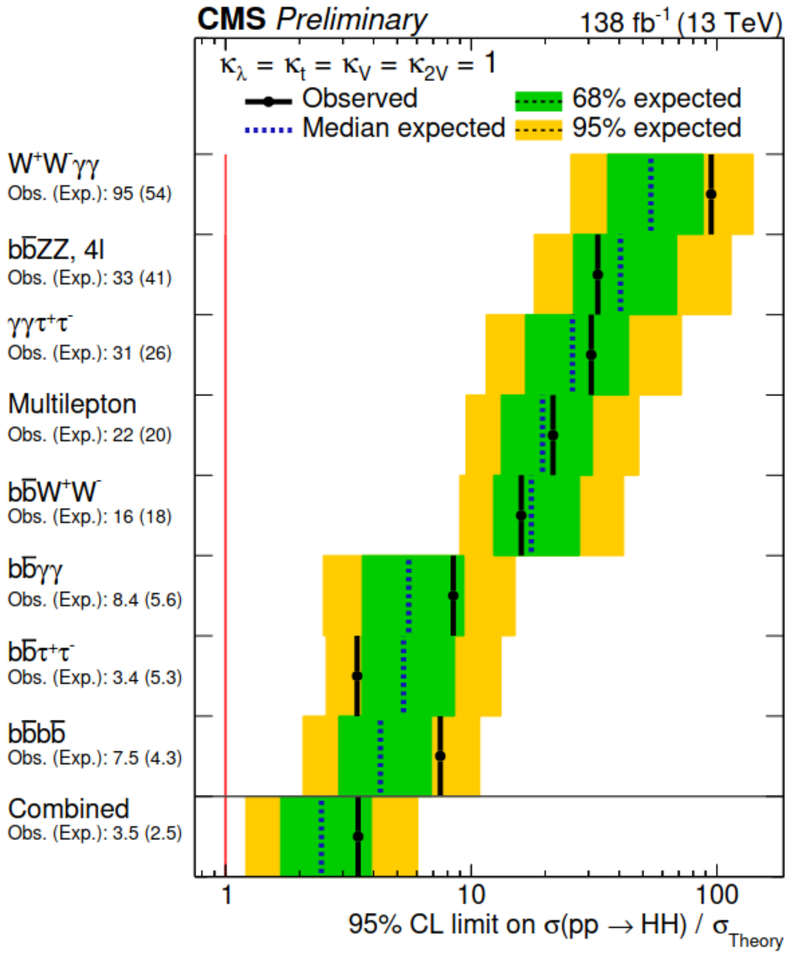
A.Benival et al, 1702.06124

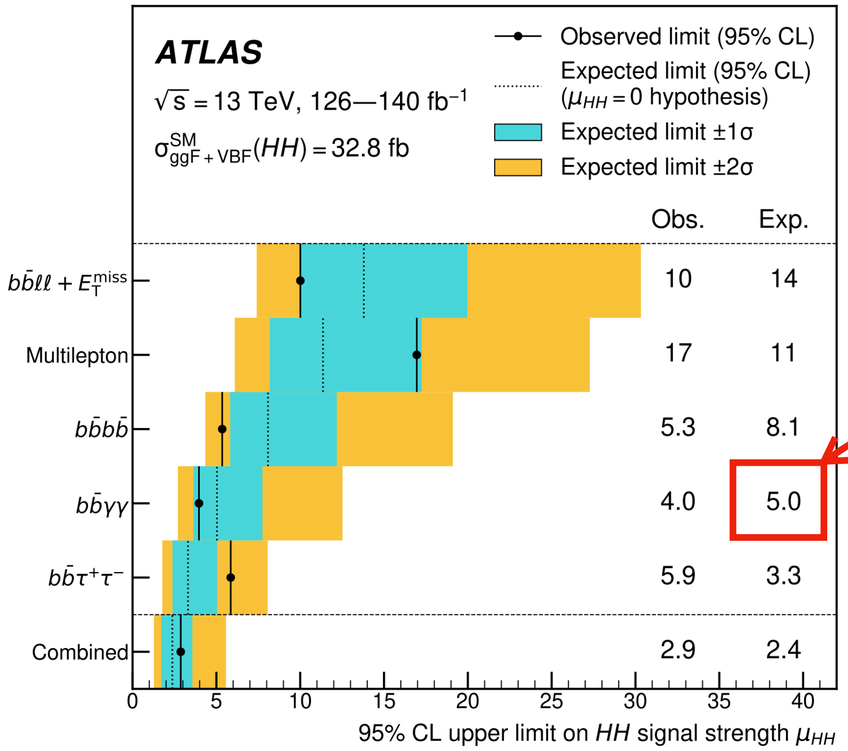
21

Run2

Similar sensitivity from ATLAS and CMS but different hierarchy across channels

Results are limited by stat. uncertainties



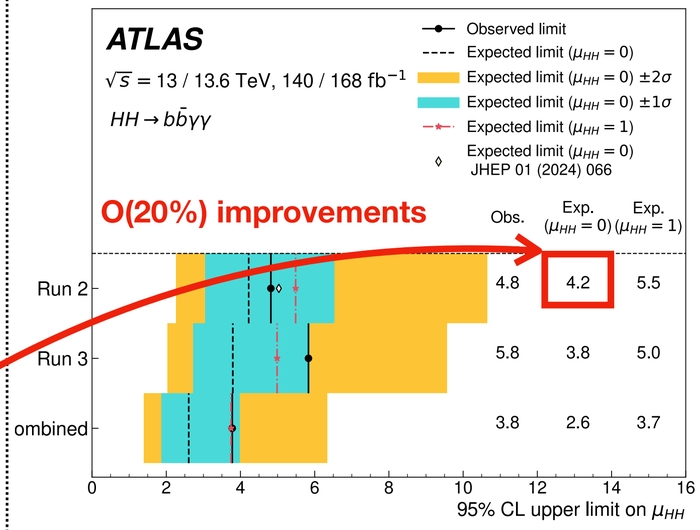


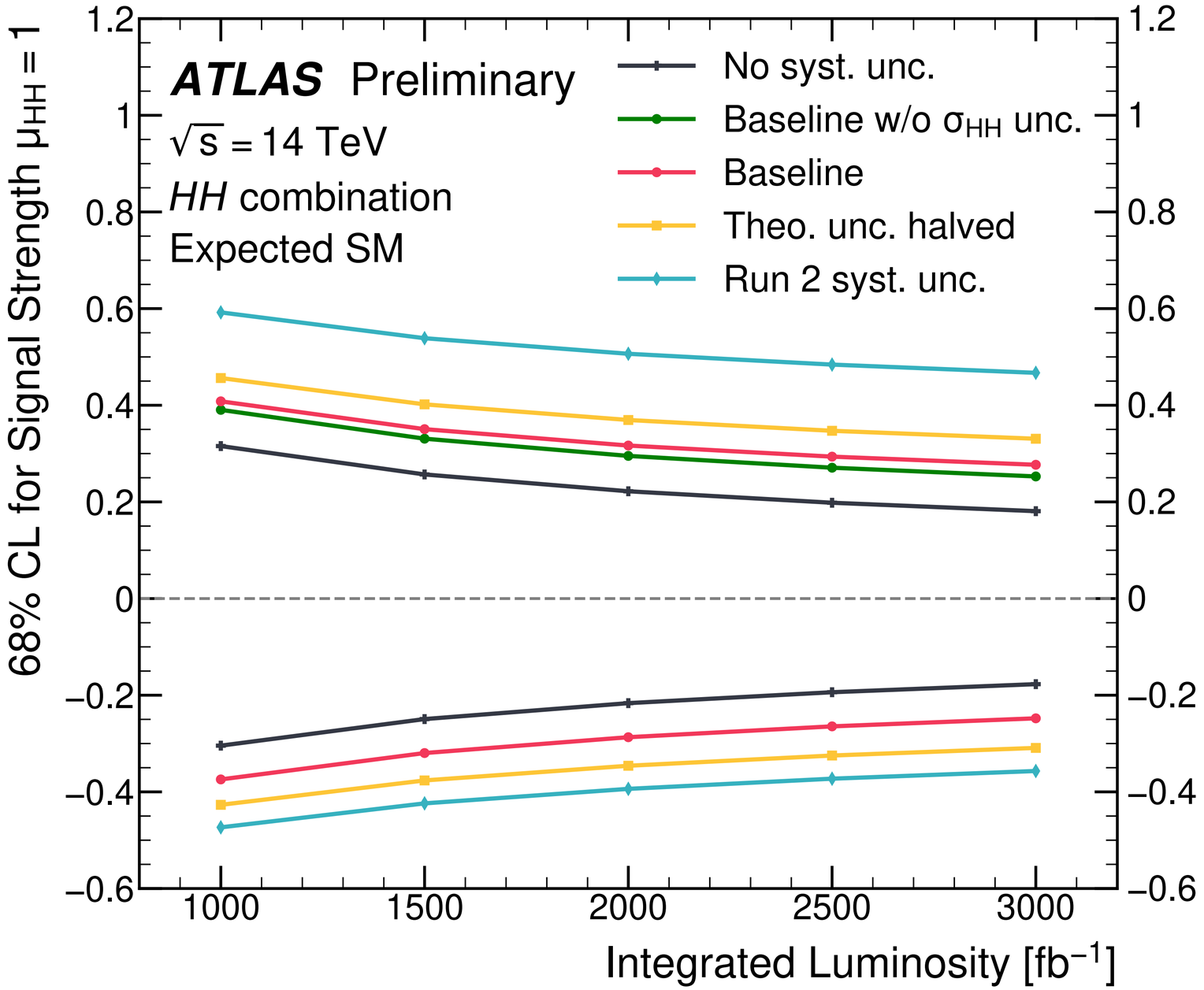
ATLAS - CMS combination (on-going) of Run2 analysis could be <1.7

We can expect it to reach ~1 with new improvements, given 500/fb (Run1+Run2+Run3)

Run3 getting in the game

Opportunity to maximise the analysis sensitivity (data streams, triggers, object reconstruction, analysis techniques)

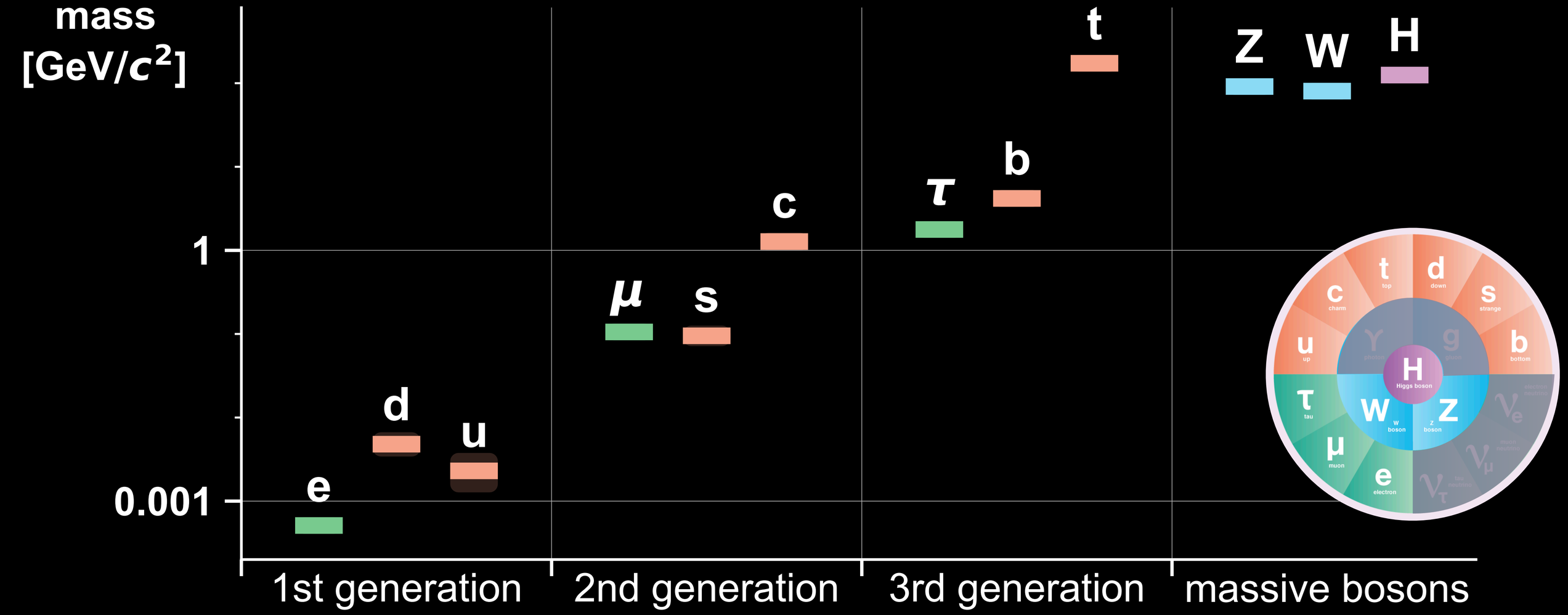




ATL-PHYS-PUB-2025-006

Yukawas

Standard Model massive particles (except ν)



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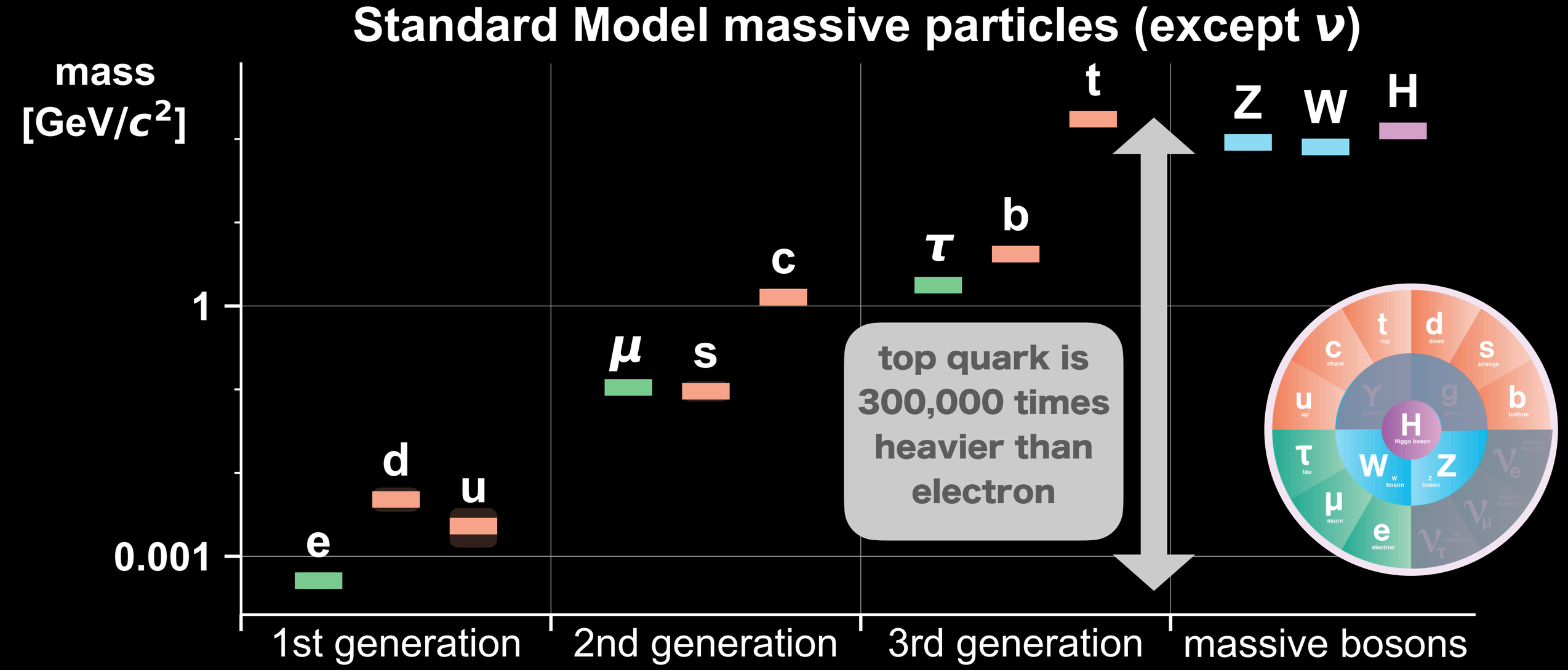
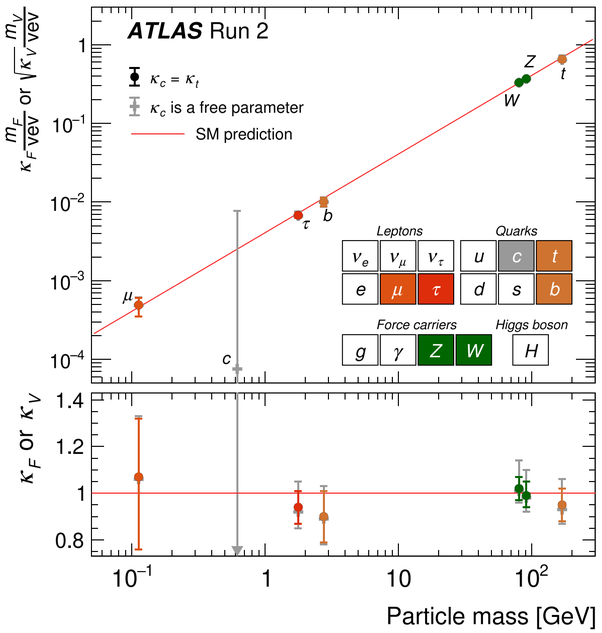
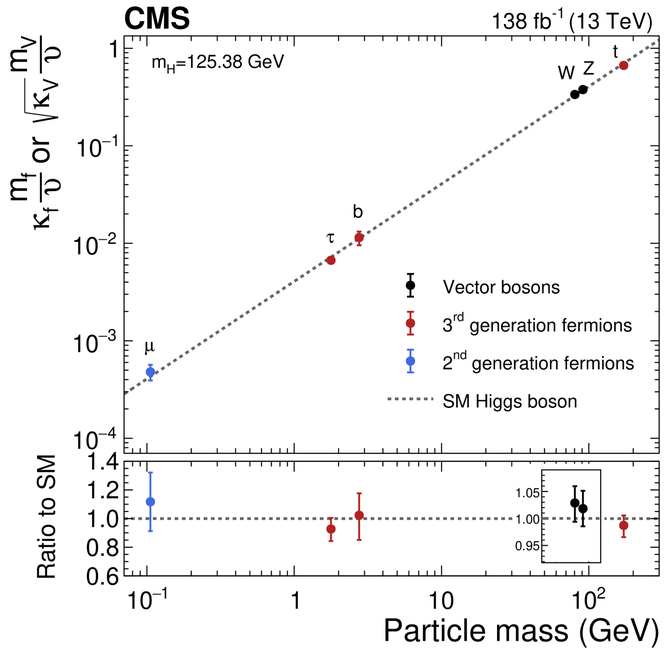


Particle masses

The Higgs mechanism in the Standard Model predicts $m_i = g_i v$

- In impressive agreement with experiment





Eric Laenen
ESPP Symposium

- After Newton and Einstein, we have established a new concept of “mass”!

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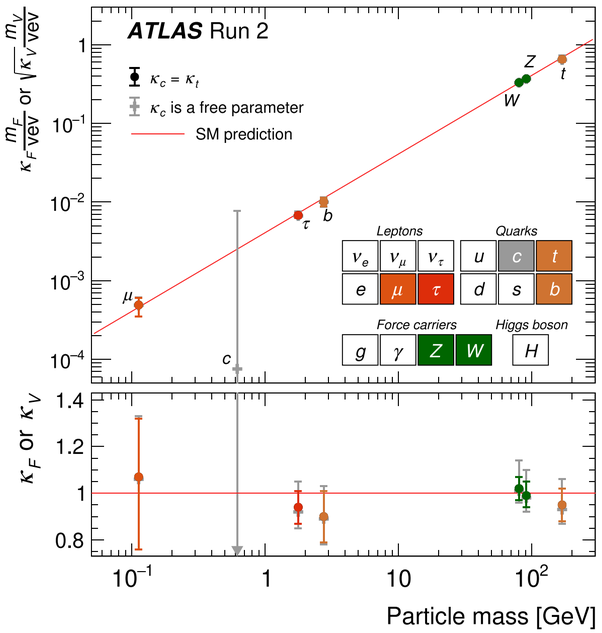
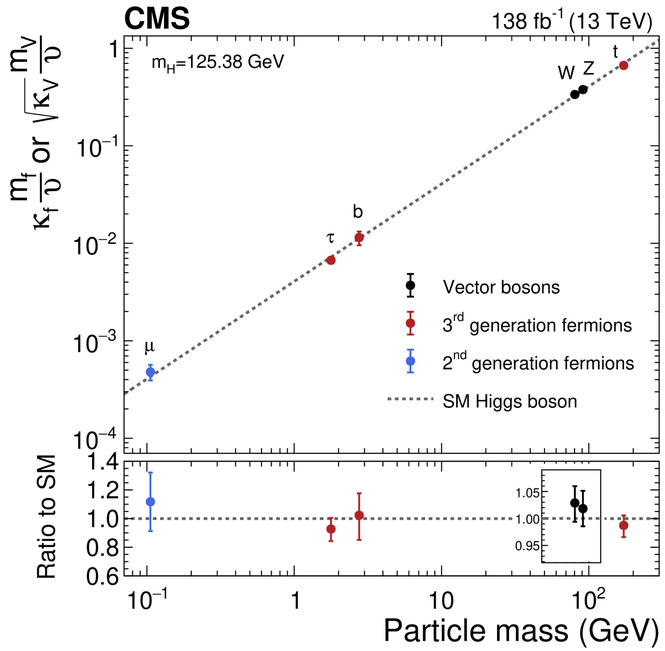




Eric Laenen
ESPP Symposium

- After Newton and Einstein, we ~~have established~~ a new concept of "mass"!

→ are establishing ?

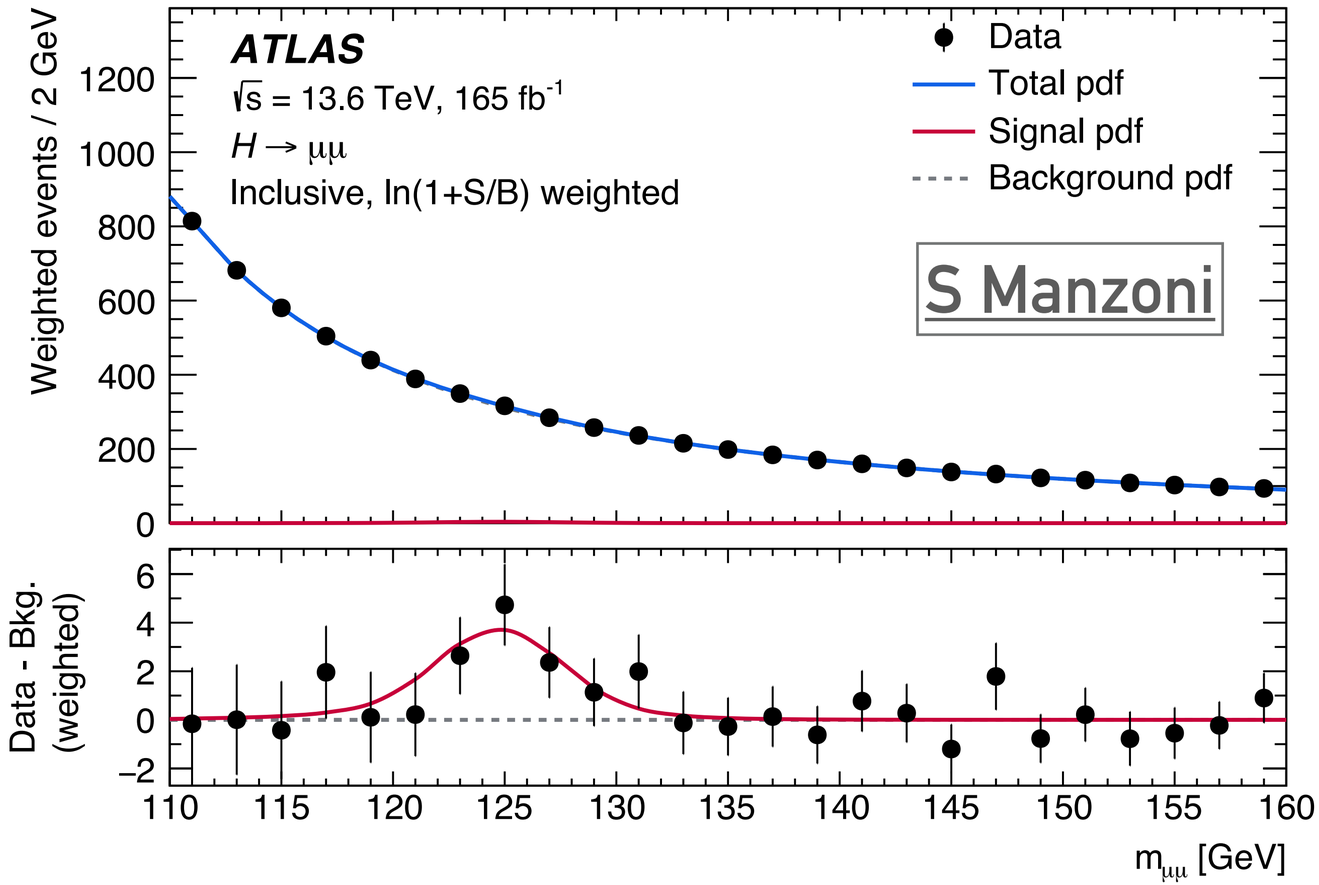
Do we need 5σ ?

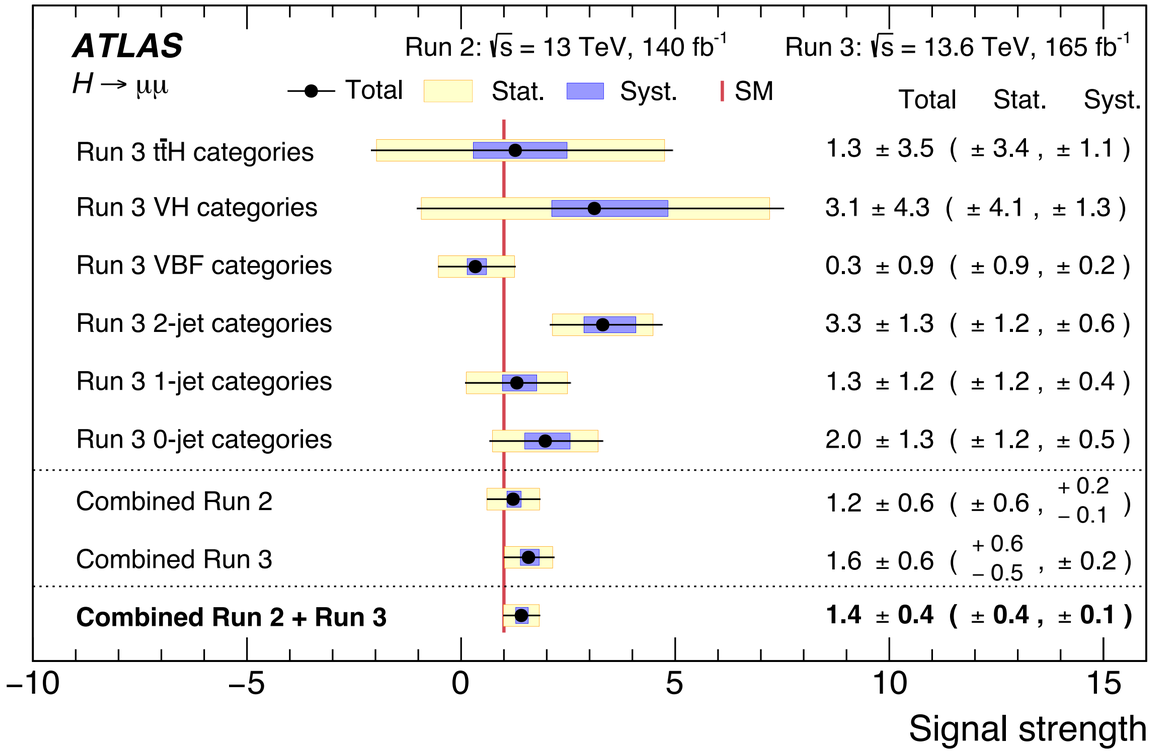
We've seen many >3σ anomalies come and go. Sometimes even simultaneously in more than one experiment [cf. 750 GeV γγ in ATLAS & CMS → ~ 500 theory articles]

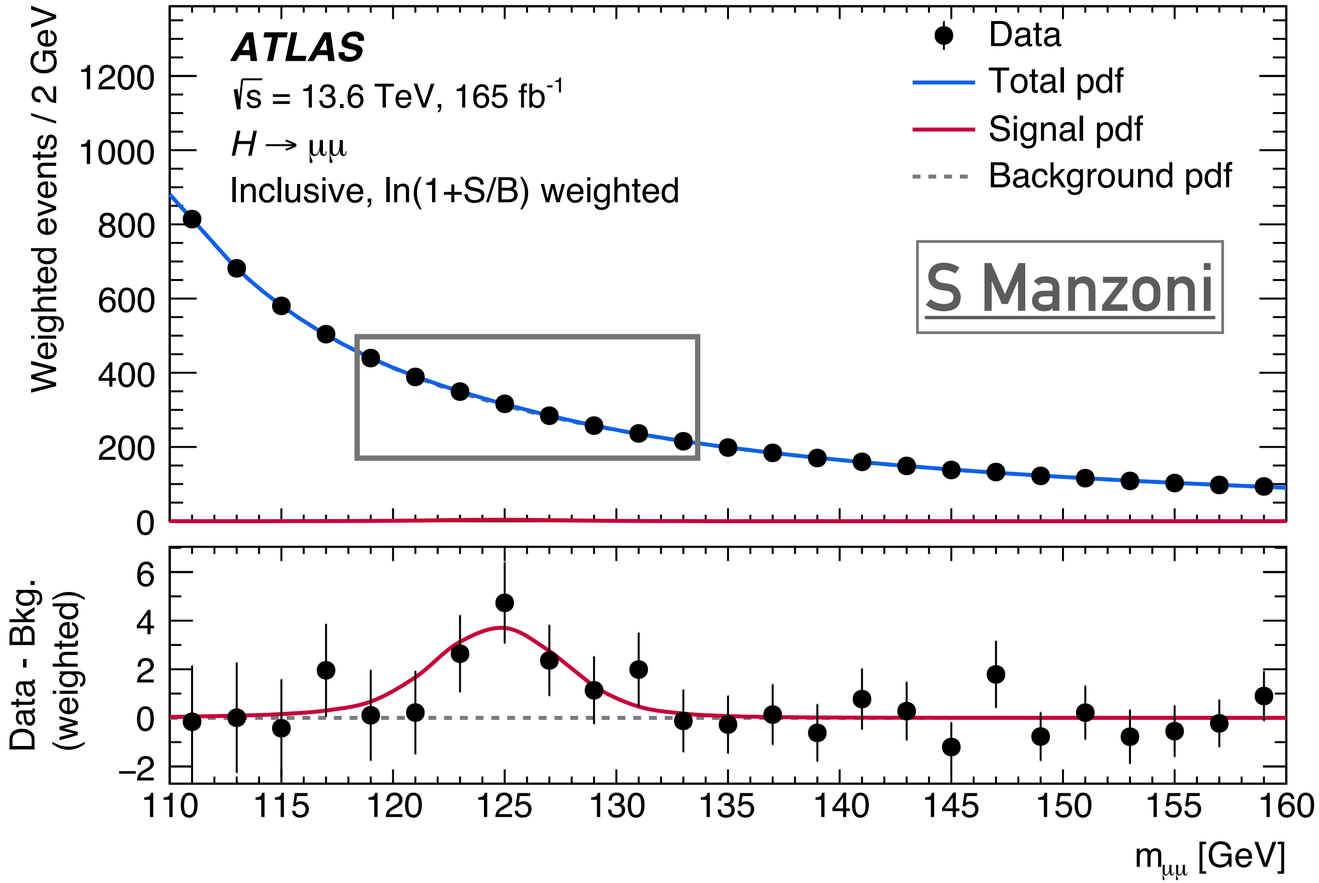
What about when we "expect" something to be there?

[E.g. wrt $H \to \mu\mu$ on Yukawa plot]

- **Bayesian view**: if we expect it to be true, we need less evidence
- **Psychology-driven view**: if we expect it to be true, it's easy to be biased by that expectation, so be extra careful.
- We're exploring a big problem — the origin of the hierarchy of fermion masses
- With $H \to \mu\mu$ and $H \to c\bar{c}$, for the first time we're touching on the second generation for – an important problem, and a major step towards the particles we're made of


ATLAS
√s = 13.6 TeV, 165 fb-1
H → μμ
Inclusive, ln(1+S/B) weighted
Data
Total pdf
Signal pdf
Background pdf
S Manzoni
Weighted events / 2 GeV
Data - Bkg. (weighted)
mμμ [GeV]


ATLAS
H → μμ
Run 2: √s = 13 TeV, 140 fb-1
Run 3: √s = 13.6 TeV, 165 fb-1
Total
Stat.
Syst.
SM
Total Stat. Syst.
Run 3 tt̄H categories 1.3 ± 3.5 (± 3.4 , ± 1.1)
Run 3 VH categories 3.1 ± 4.3 (± 4.1 , ± 1.3)
Run 3 VBF categories 0.3 ± 0.9 (± 0.9 , ± 0.2)
Run 3 2-jet categories 3.3 ± 1.3 (± 1.2 , ± 0.6)
Run 3 1-jet categories 1.3 ± 1.2 (± 1.2 , ± 0.4)
Run 3 0-jet categories 2.0 ± 1.3 (± 1.2 , ± 0.5)
Combined Run 2 1.2 ± 0.6 (± 0.6 , +0.2 −0.1)
Combined Run 3 1.6 ± 0.6 (+0.6 −0.5 , ± 0.2)
Combined Run 2 + Run 3 1.4 ± 0.4 (± 0.4 , ± 0.1)
Signal strength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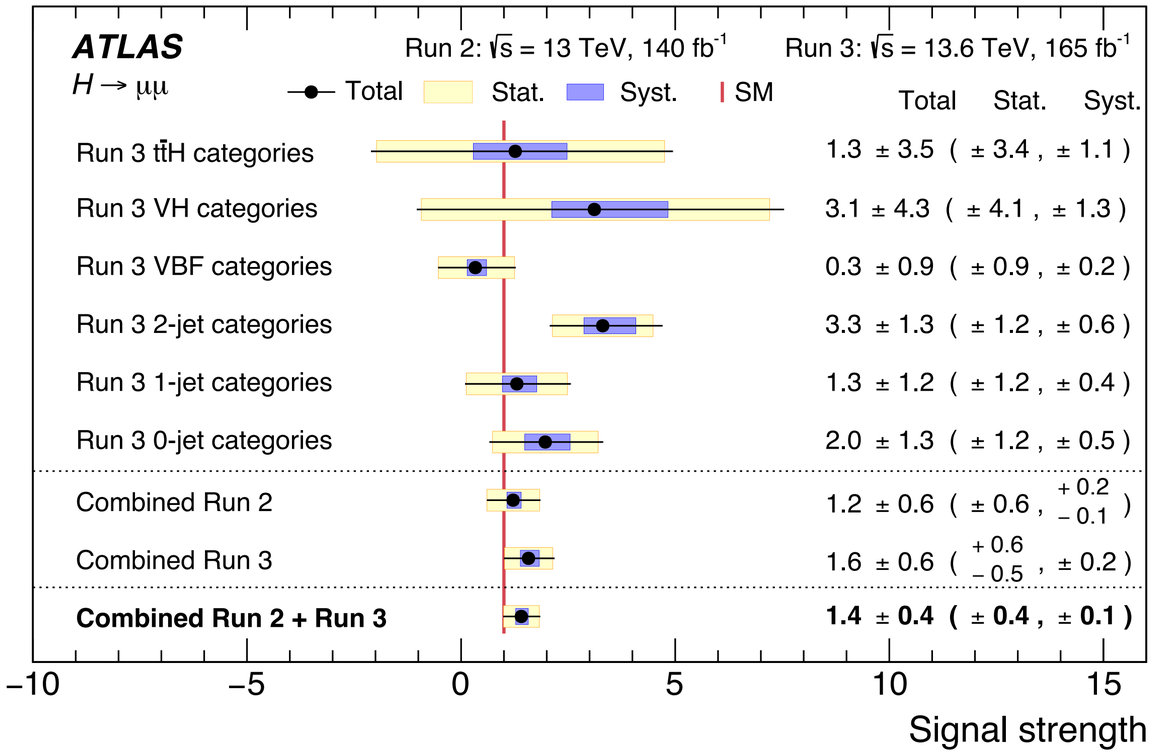
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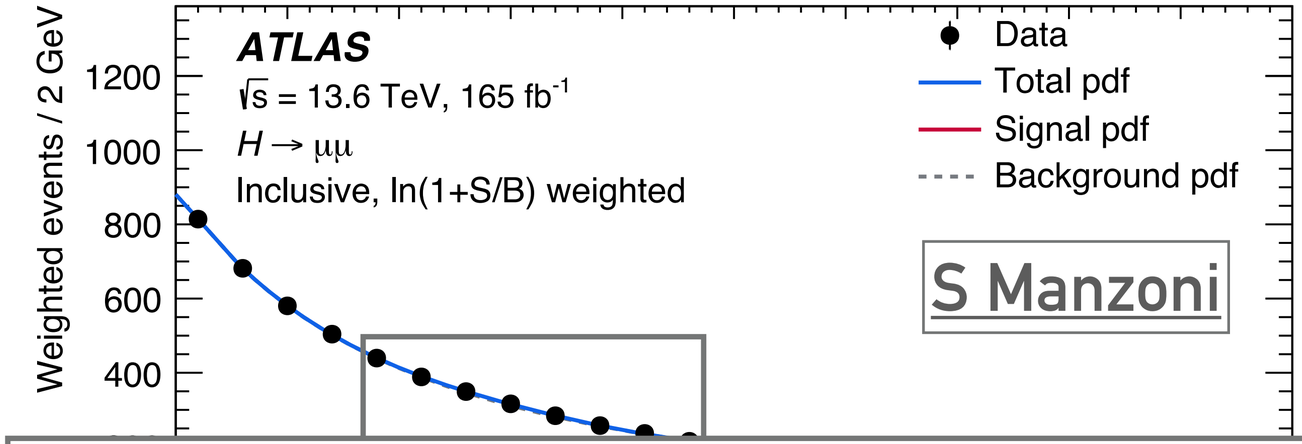
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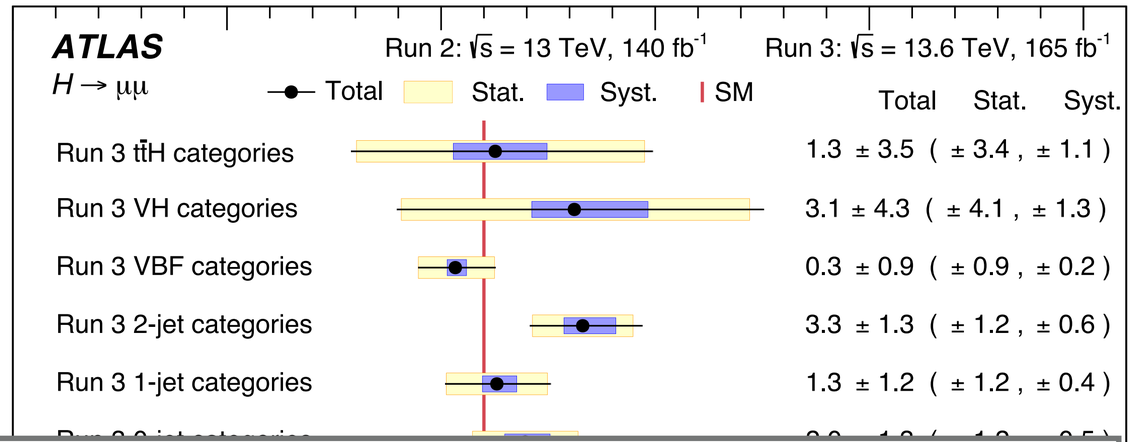
Weighted events / 2 GeV
1200
1000
800
600
400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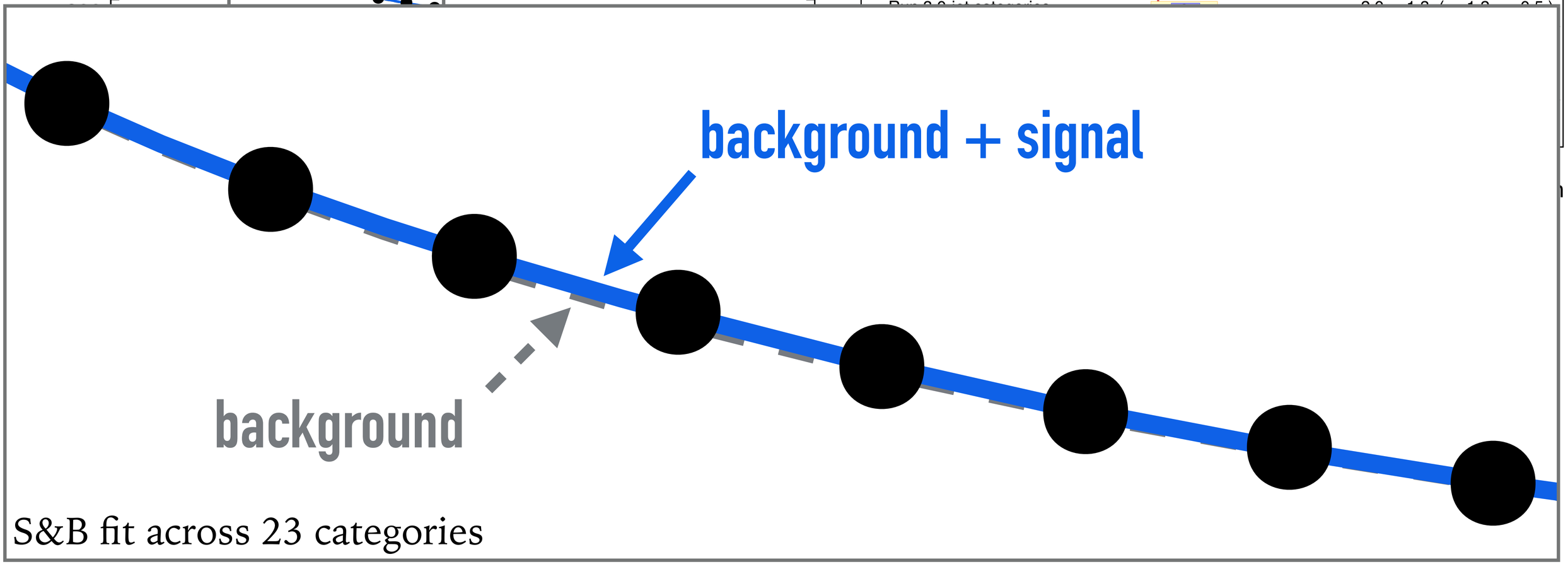
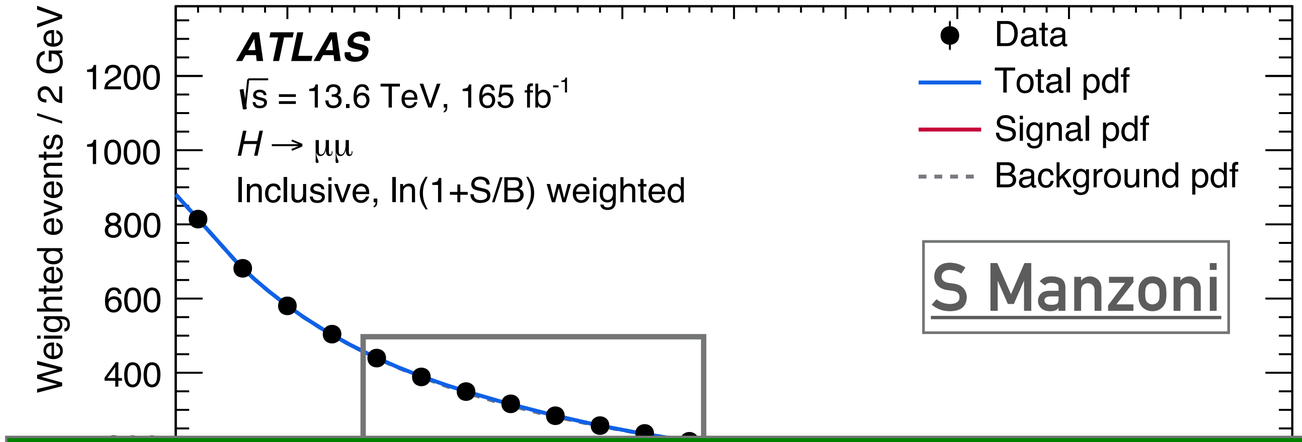
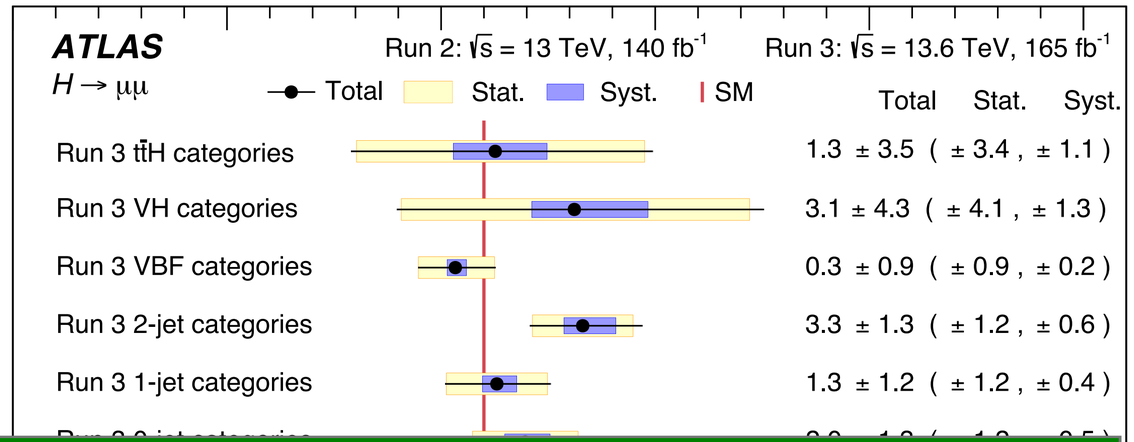

background + signal
background
S&B fit across 23 categories





My view: we should definitely wait for 5σ (per experiment) before we say we make strong public claims

If and when ATLAS & CMS reach 5σ on $H\to\mu\mu$, i.e. first observation of origin of mass for 2nd generation, it deserves a big announcement

searches / CP-structure / EFT

looking for anything that is absent in the SM

Tentativo di una Teoria dei Raggi β

Ramond

Nota di ENRICO FERMI

"La Ricerca Scientifica", 4, (1933),491-495 1933

Based on the earlier "Nota preliminare in "La Ricerca Scientifica", 2, fasc, 1933",

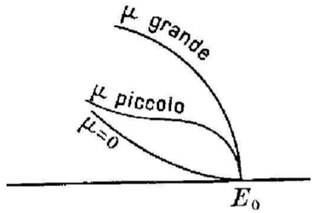
Fermi proposes a theory of beta decay, where electrons and neutrinos are described in the language that describes the emission of a light quantum from an excited atom.

No light particles in nuclei, and Heisenberg's two states of a heavy particle

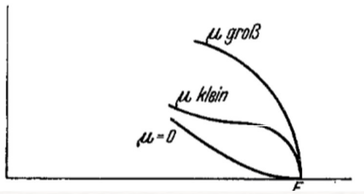
Hamiltonian is such that each transition from neutron to proton is associated with the creation of an electron and neutrino

"non può farsi altro che col criterio della massima semplicità"

("criterion of simplicity"/ "Einfacheitskriterion")

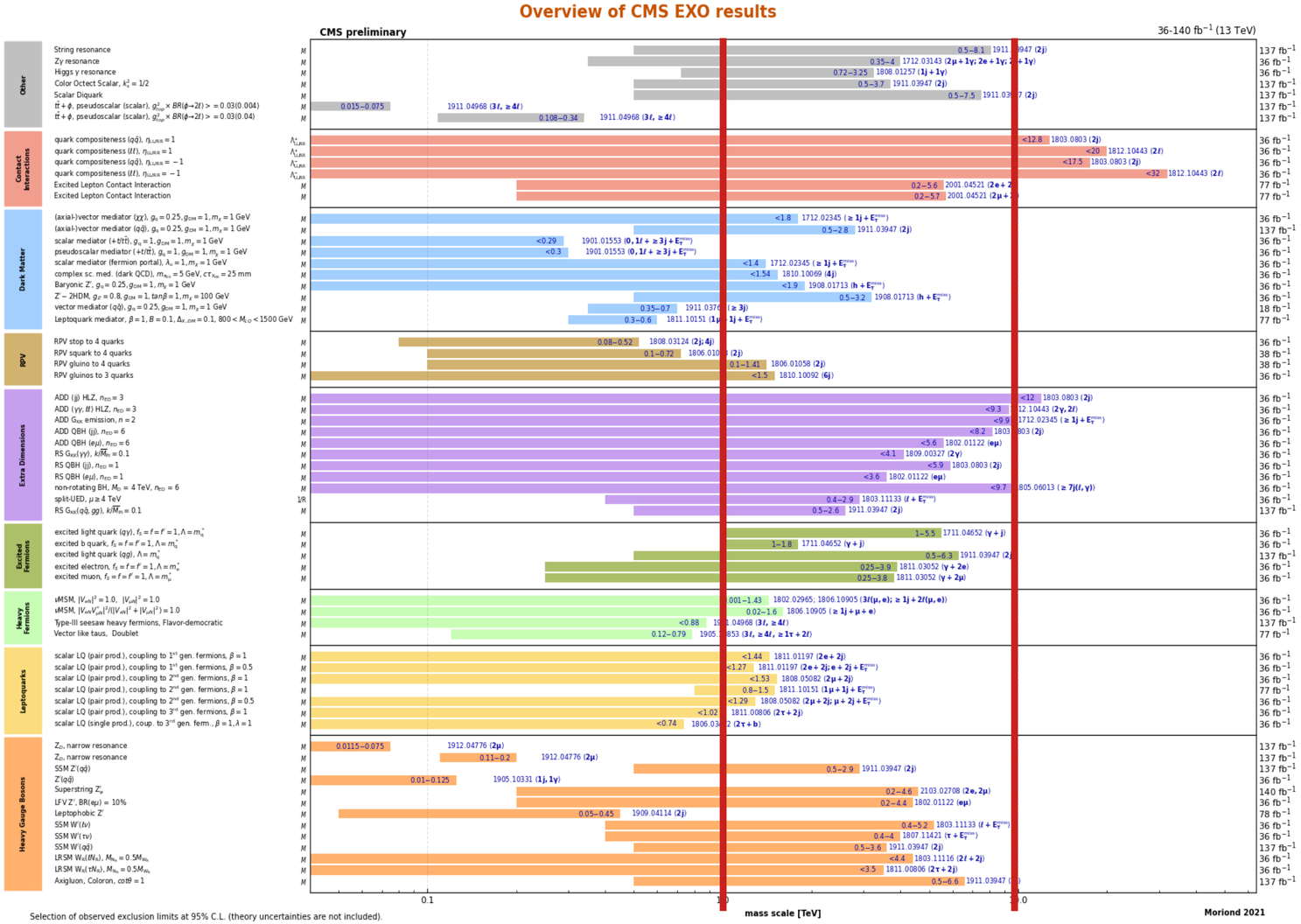


mass determination
From extreme kinematics



What is experiment telling us?

Jose Santiago



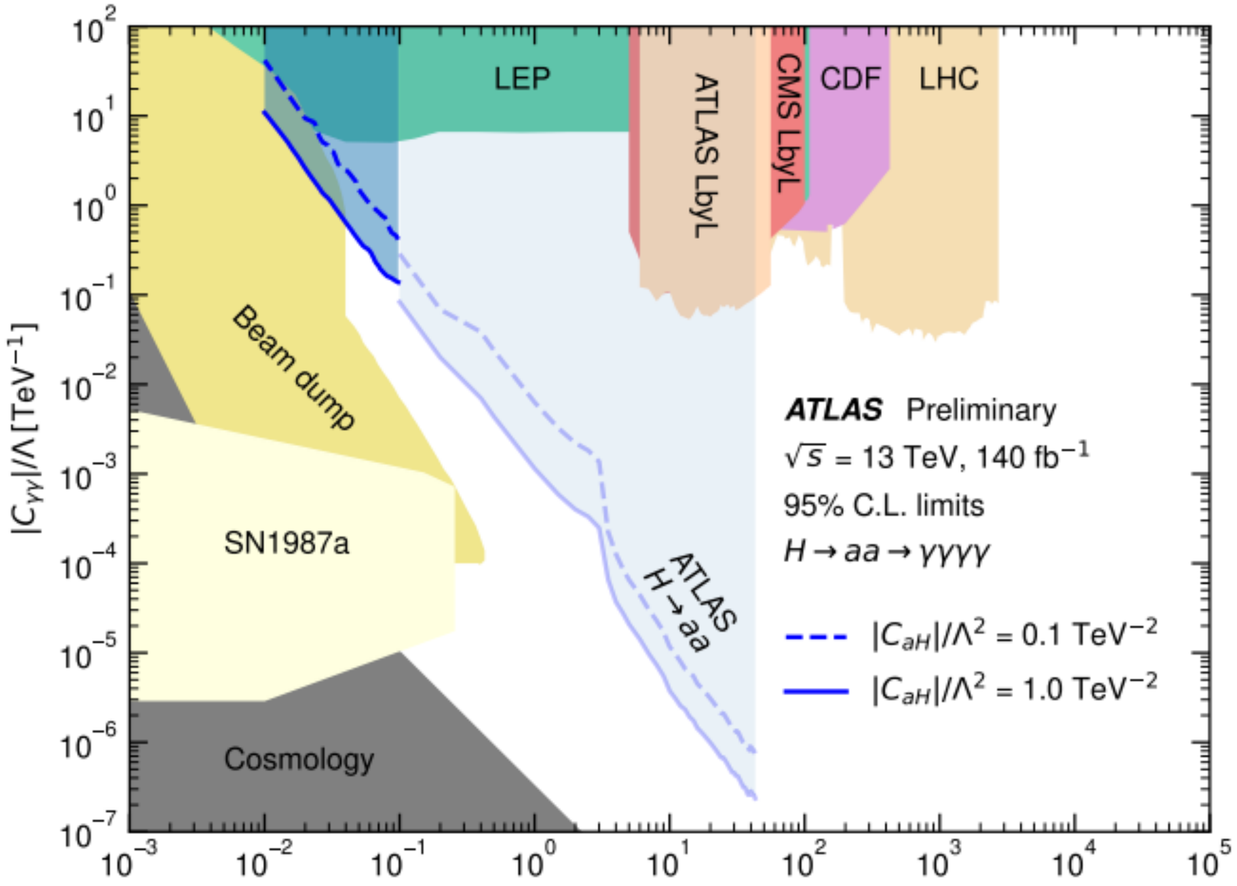
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

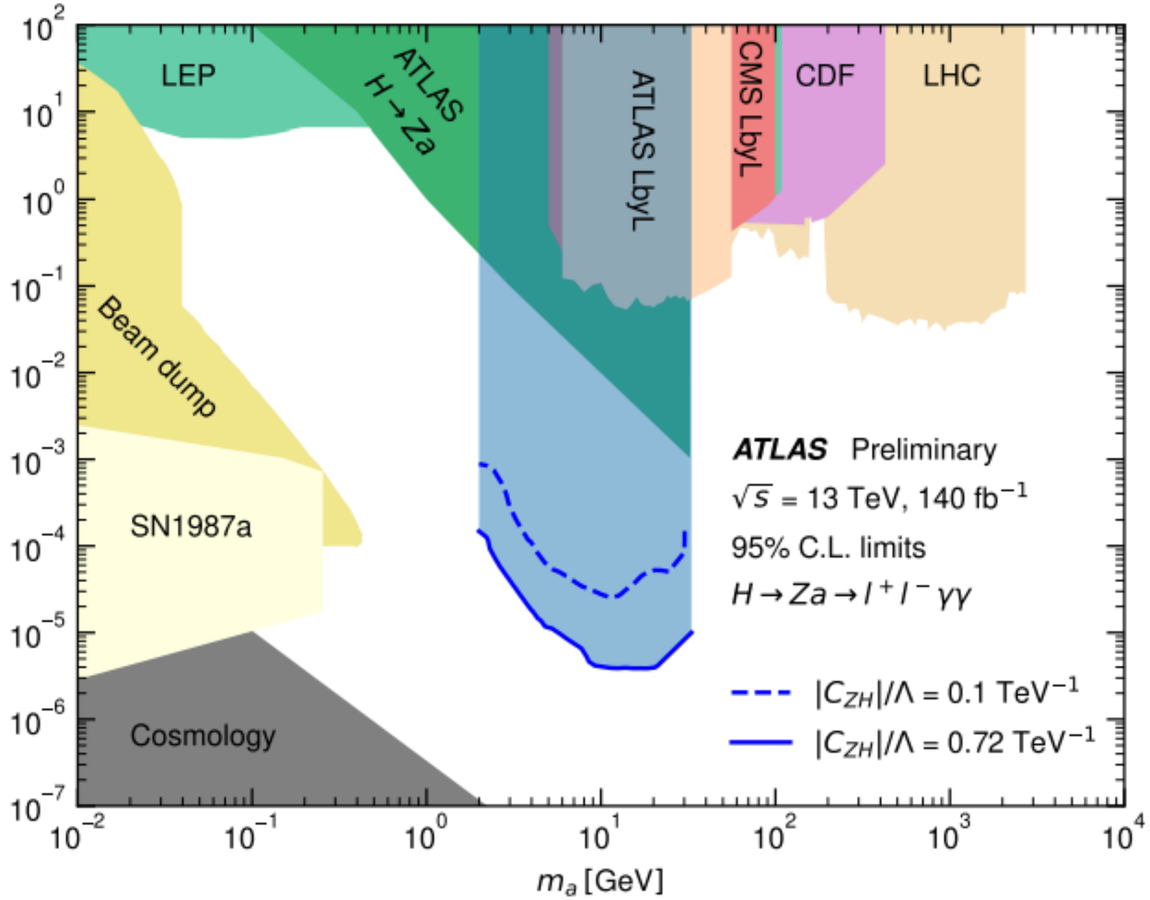
1 TeV 10 TeV

Turning all the stones! NP seems to be relatively heavy.

H→ Za → llγγ and H → aa → 4γ

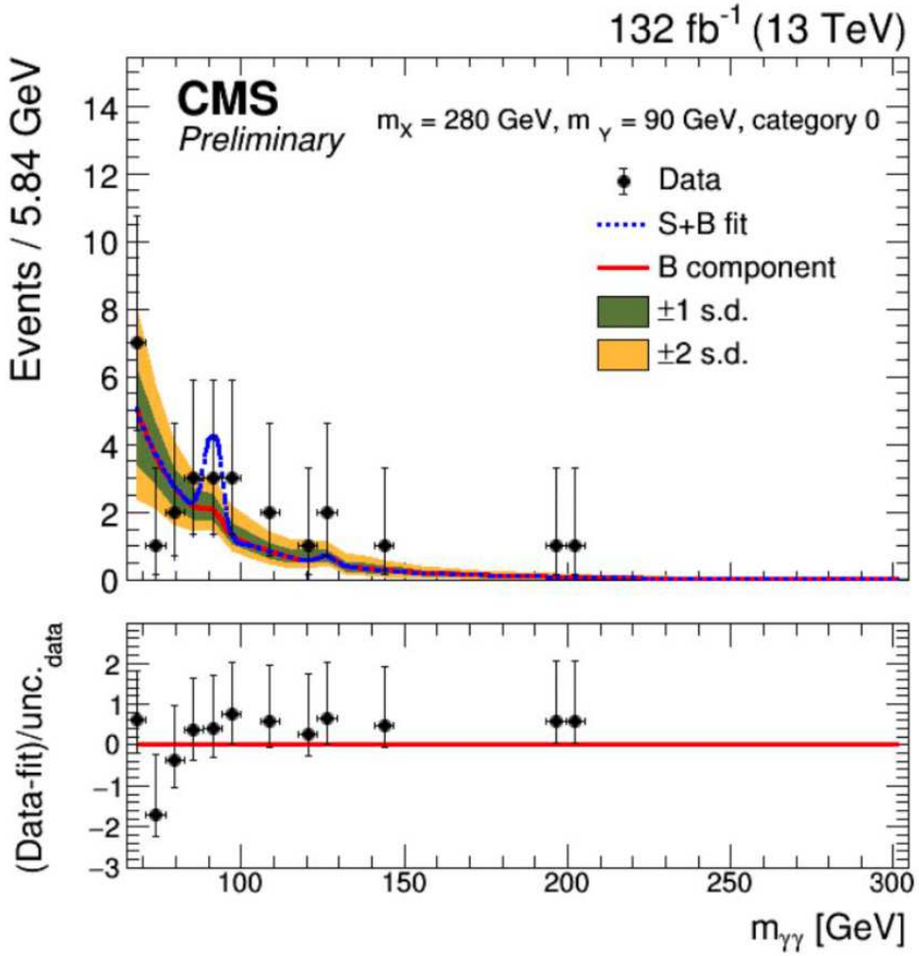
ATL-PHYS_PUB-2025-007





Extended the H → aa → 4γ to lower mass points, and H→ Za by including long-lived particles

Finally (unintendedly?) some news on the h_{95}:



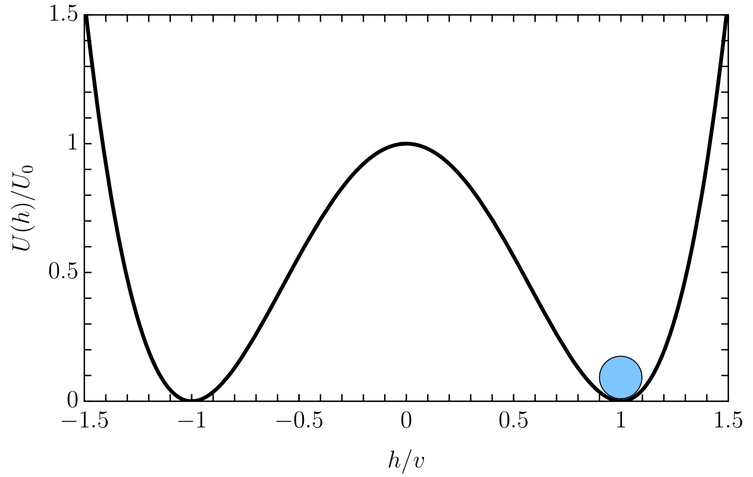
⇒ several other excesses around ∼ 95 GeV showed up

⇒ never a combined analysis/interpretation ⇒ common systematic effect?

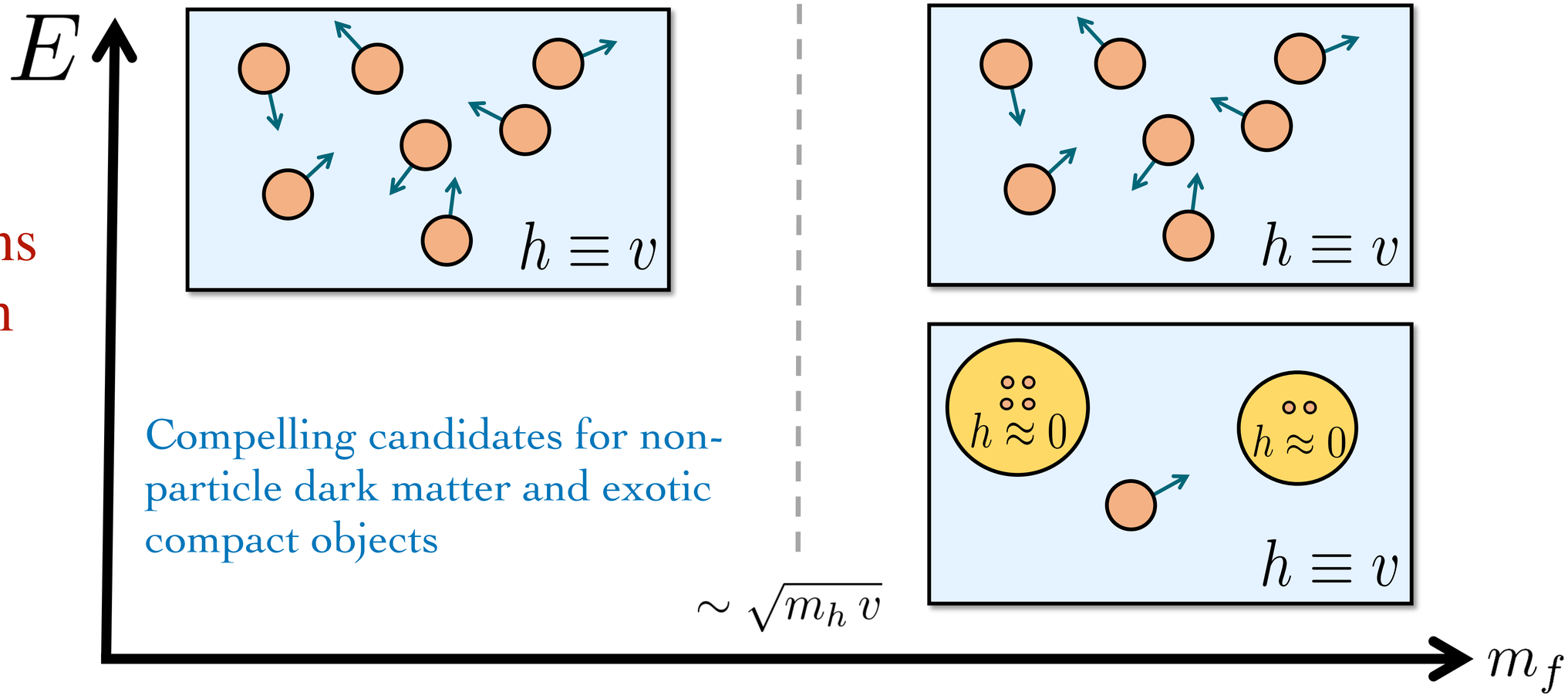
Del Grosso, Pani, Urbano [arXiv:2401.06716]

Sub-solar mass fermion-boson stars?

$$M_c \approx M_\odot \left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2, \quad R_c \approx 5.5\,\mathrm{km}\left(\frac{0.34\,\mathrm{GeV}}{q}\right)^2$$



It becomes energetically convenient to confine fermions in false vacuum pockets



Compelling candidates for non-particle dark matter and exotic compact objects

Urbano

Precision

$Total\ \mu$

$ATLAS: 1.023 \pm 0.054$

$CMS: 1.014 \pm 0.054$

$of\ which\ theory = 0.039$

$H \to Z\gamma$

$H \to c\bar{c}$

HH

$width$

$etc.$

$H \to \mu\mu$

$ggH,\ VH,\ VBF,\ ttH$

$H \to 3rd\ gen$

$H \to VV$

$CP\ structure$

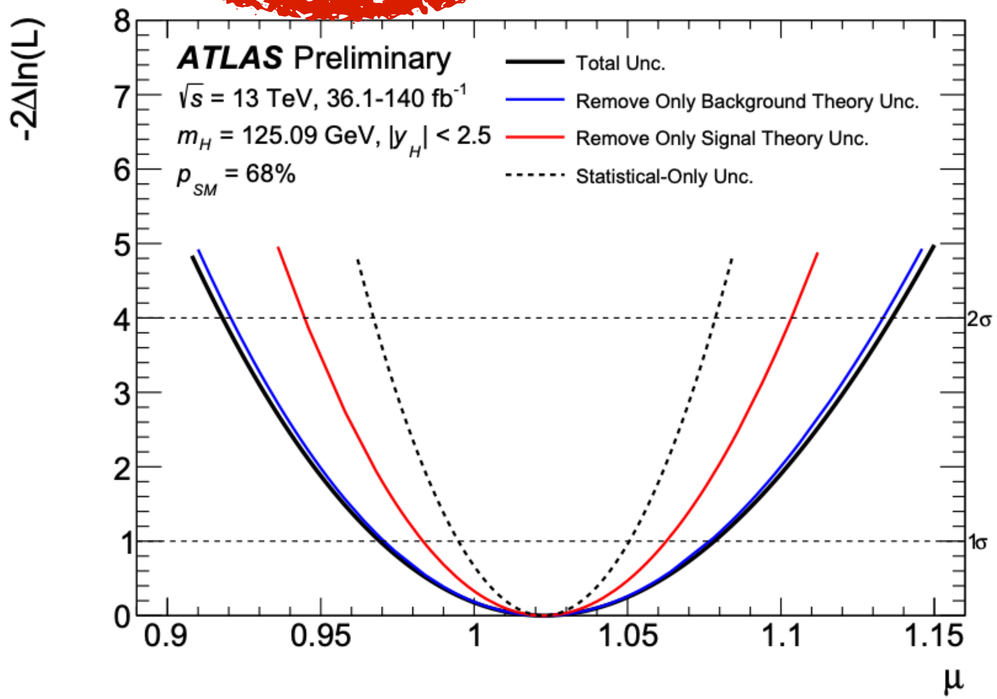
$etc.$

$mass$

Global Signal strength (μ)

- Rate of Higgs boson production and decay processes:
  - $\mu_{if} = \dfrac{(\sigma_i \times B_f)}{(\sigma_i^{SM} \times B_f^{SM})} = 1.023 \pm 0.028\ (\text{stat.})\ ^{+0.026}_{-0.025}\ (\text{exp.})\ ^{+0.039}_{-0.036}\ (\text{sig. theo.})\ \pm 0.012\ (\text{bkg. theo.})$

1.5% @ 500fb^{-1}



- Around 10% reduction in the total uncertainty with respect to Nature result (1.05 ± 0.06)
- Measurement in good agreement with respect to SM:
  - P-value compatibility at 68%

Alves

Charting the Higgs Sector

Ultimate Precision at 13 TeV

HIG-21-018

Combination of 16 CMS published analyses incorporating

7 decay channels
(γγ, ZZ, WW, bb, ττ, μμ, Zγ)

6 production channels
(ggH, VBF, WH, ZH, ttH, tH)

Searches for H to invisible

H off-shell production

A wide array of the interpretations is provided

Signal strengths
inclusive/production/decay/production×decay

Signal strengths with $\sigma \times \mathcal{B}$

Cross sections
STXS stage 0/STXS stage 1.2

Coupling modifiers
resolved/effective/off-shell/ratio

Higgs self-couplings

SMEFT

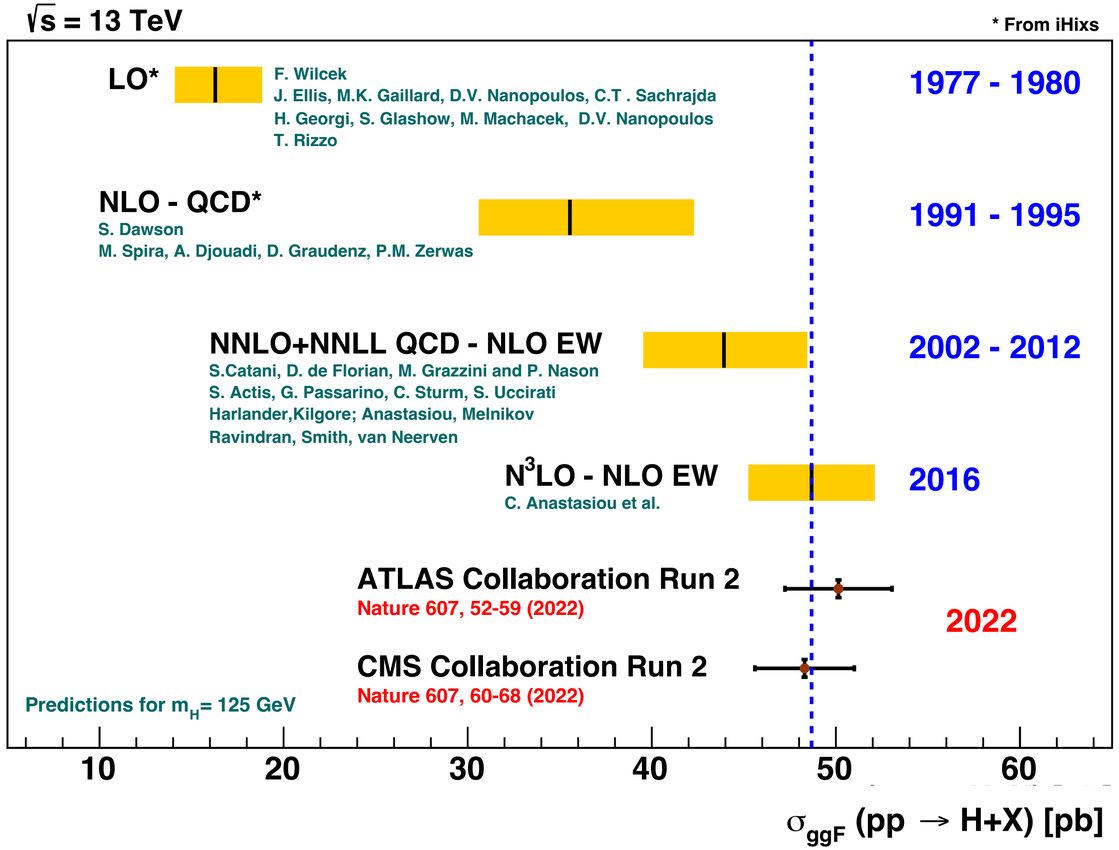
Recent Highlights

Signal strength inclusive

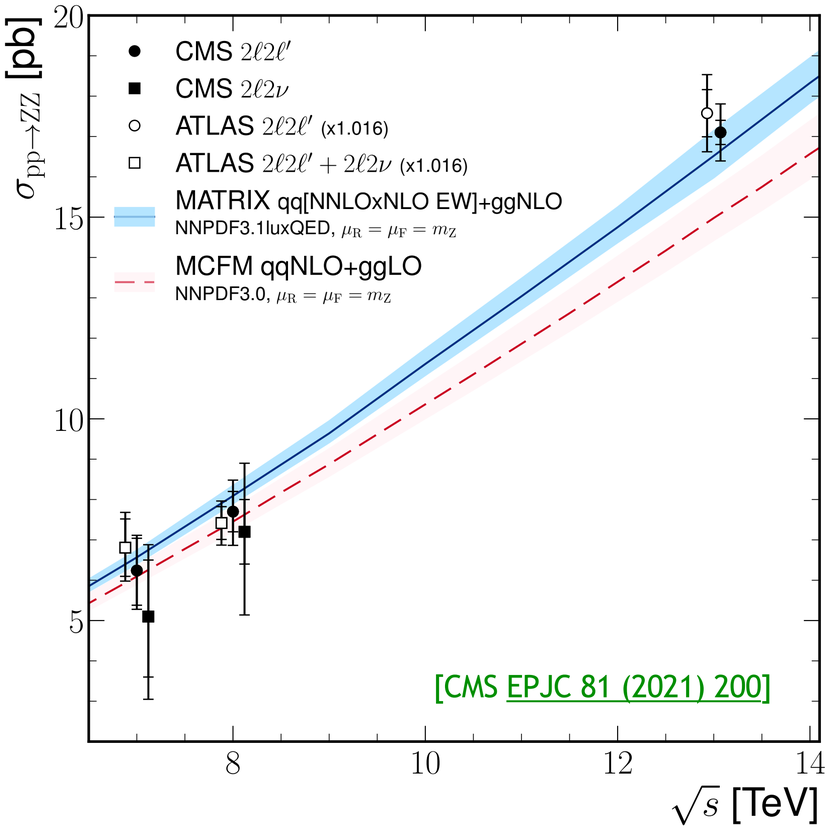
$$\sigma/\sigma_{\mathrm{SM}} = 1.014\,^{+0.055}_{-0.053}(\text{total}) = 1.014 \pm 0.028\ (\text{stat.})\,^{+0.025}_{-0.024}(\text{exp.})\,^{+0.040}_{-0.039}(\text{theo.})$$

5.4% *2.7%* *2.5%* *3.9%*

Theory predictions better be under control



Higgs-boson production

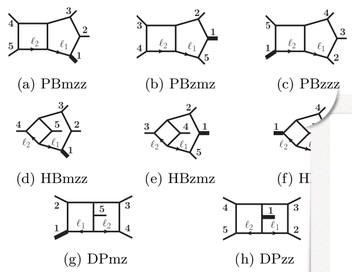


di-boson production

Buccioni

Computer algebra for multi-loop amplitudes

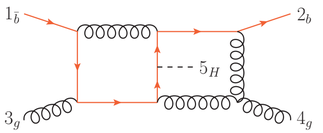
- Innovations in integral reduction
  - reconstruct coefficients from numerical samples over finite prime number field
    (FinRed: A.von Manteuffel, R.Schabinger; FiniteFlow: T.Peraro)
  - trimming of linear systems (Kira: F.Lange, J.Usovitsch, Z.Wu; Blade: X.Guan, X.Liu, Y.Q.Ma, W.H.Wu)
  - optimization of integral basis for reconstruction (G.De Laurentis, H.Ita, B.Page, V.Sotnikov)
- Innovations in integral computation
  - numerical computation from series expansion
    (AMFlow: X.Liu, Y.Q.Ma)
  - optimized analytical function basis
    - two-loop pentagon functions
      (S.Abreu, D.Chicherin, H.Ita, B.Page, V.Sotnikov, W.Tschernow, S.Zoia)
    - three-loop graded transcendental functions
      (J.Henn, P.Jakubcik, J.Lim, C.Mella, N.Syrrakos, L.Tancredi, W.Torres Bobadilla, TG)

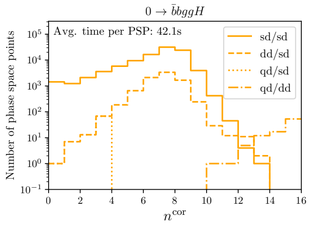


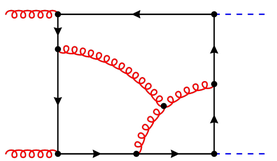
T Gehrmann

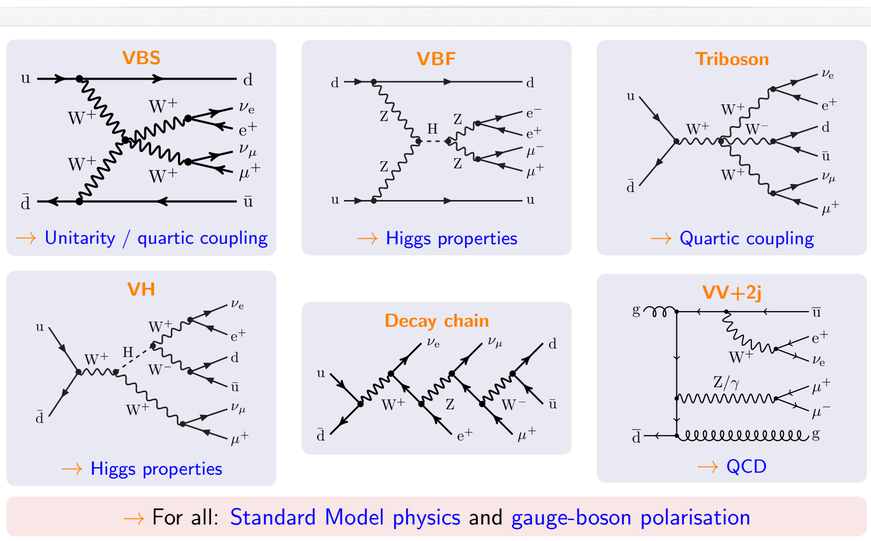
Multi-loop amplitude results

- Two-loop amplitudes for qqH production
  - closed fermion loop contributions to qq⟶ttH
    (B.Agarwal, G.Heinrich, S.Jones, M.Kerner, S.Klein, J.Lang, V.Magerya, A.Olsson; F.Febres Cordero, G.Figueiredo, M.Kraus, B.Page, L.Reina)
  - full amplitudes for qq⟶bbH and gg⟶bbH (m_b=0)
    (S.Badger, H.Bayu Hartanto, R.Poncelet, Z.Wu, Y.Zhang, S.Zoia)
  - test-case for ML surrogate approximations
    (V.Breso, G.Heinrich, V.Mageyra, A.Olsson)
- Three-loop amplitudes for H+jet production
  - leading colour amplitudes for gg ⟶Hg and gq ⟶Hq
    (X.Chen, X.Guan, B.Mistlberger)
- Three-loop amplitudes for HH production
  - expansion in masses or transverse momenta for gg⟶HH
    (J.Davies, K.Schönwald, M.Steinhauser)



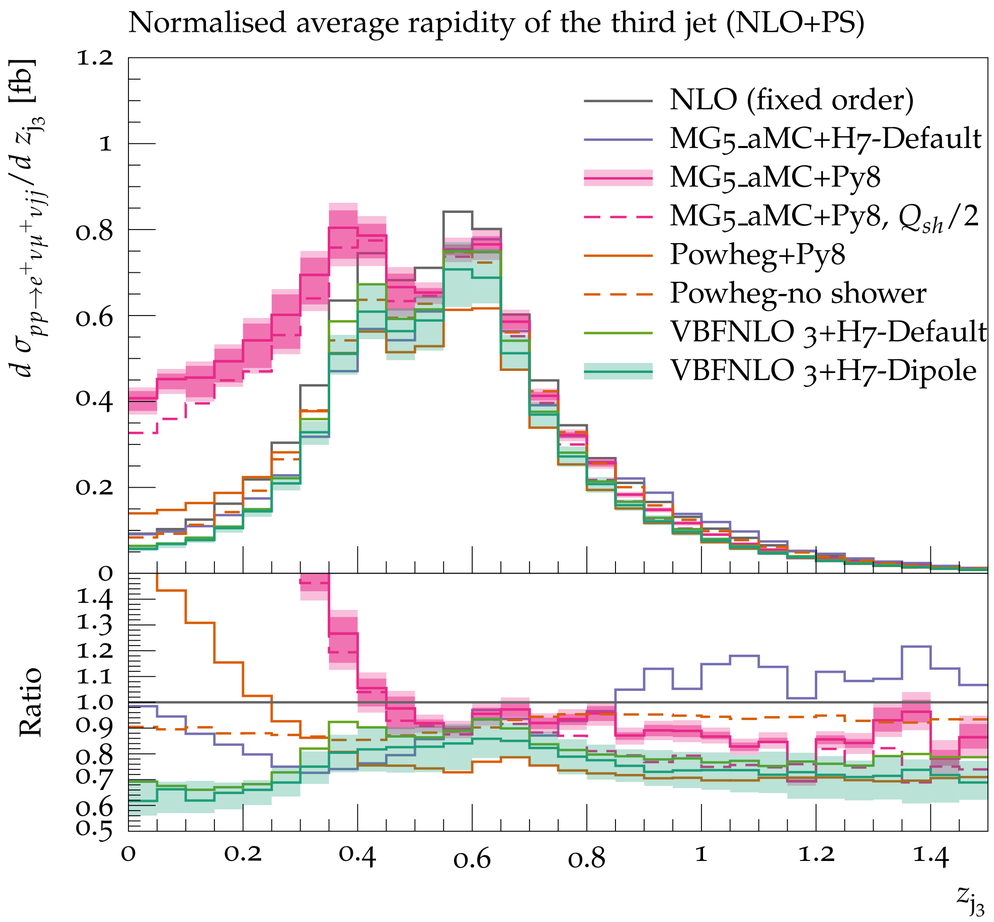


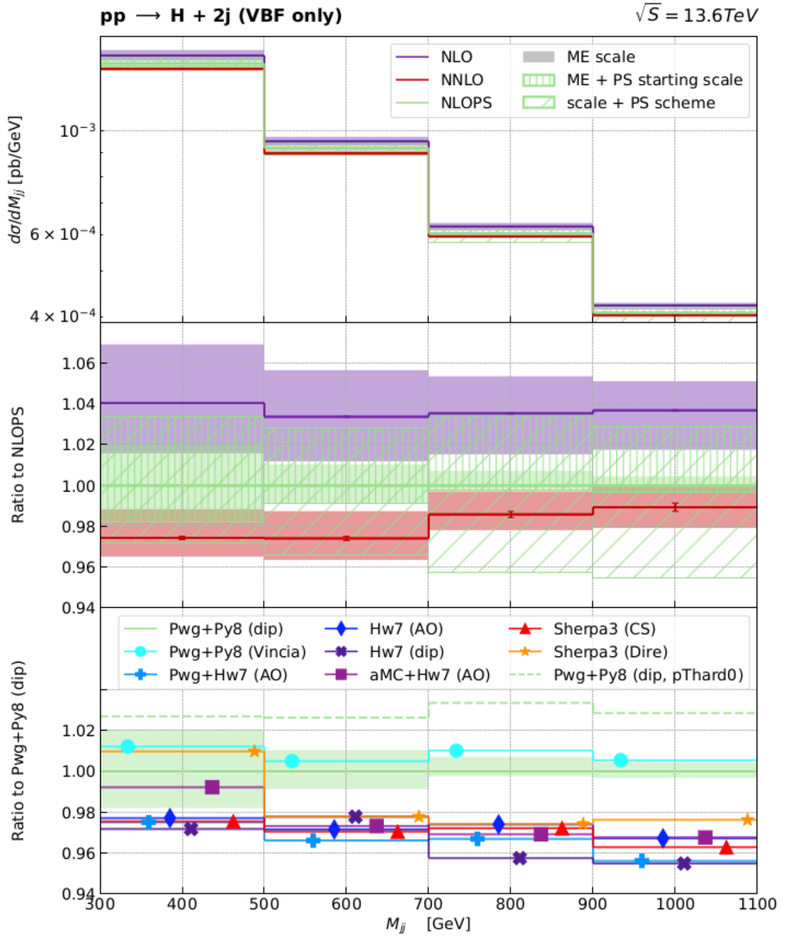




M Pellen

NLO+PS for VBS → → → → NLO+PS for VBF





M Pellen

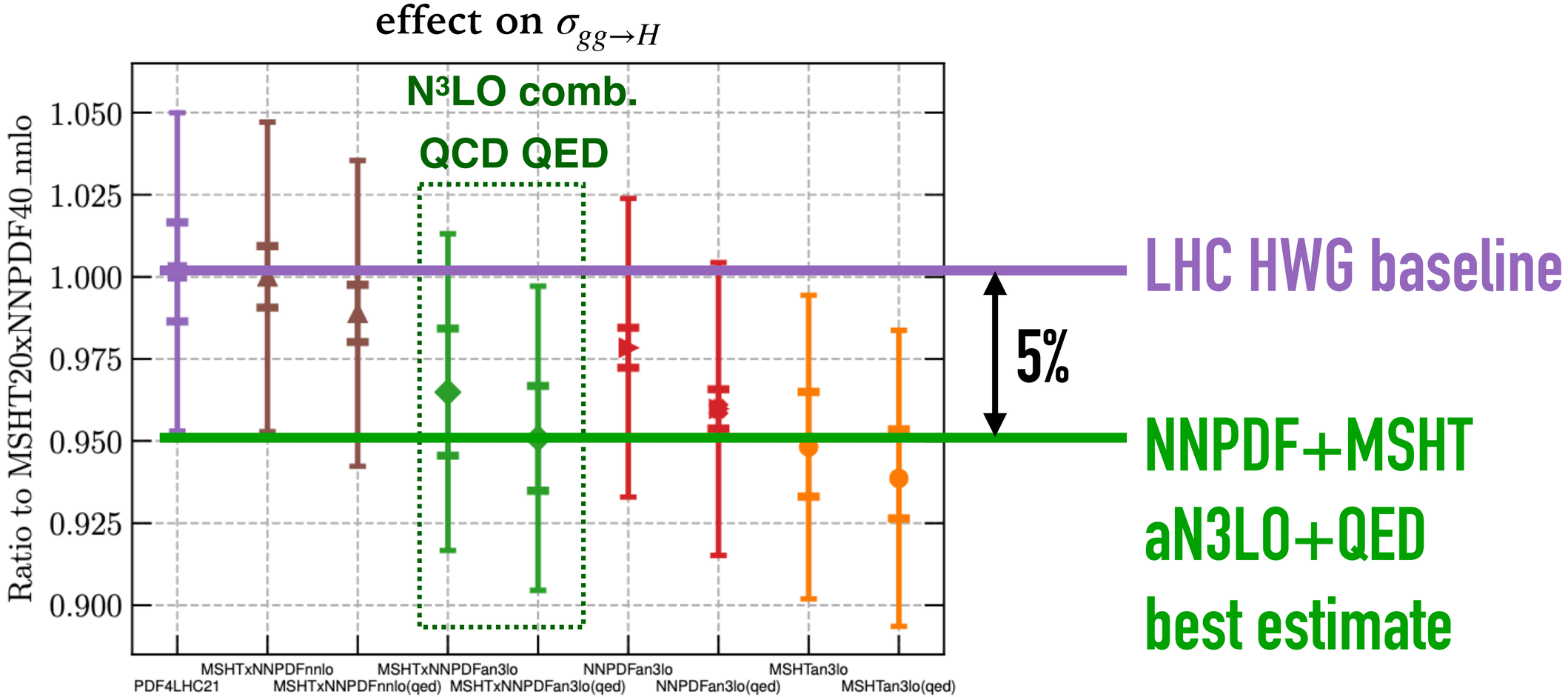
[Ballestrero, MP, et al.; 1803.07943] → → → → [Barone, MP, et al.; 2507.XXXX]

`https://cds.cern.ch/record/2936976`

In between:

[Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435], [Buckley et al.; 2105.11399], [Höche, Mrenna, Payne, Preuss, Skands; 2106.10987]

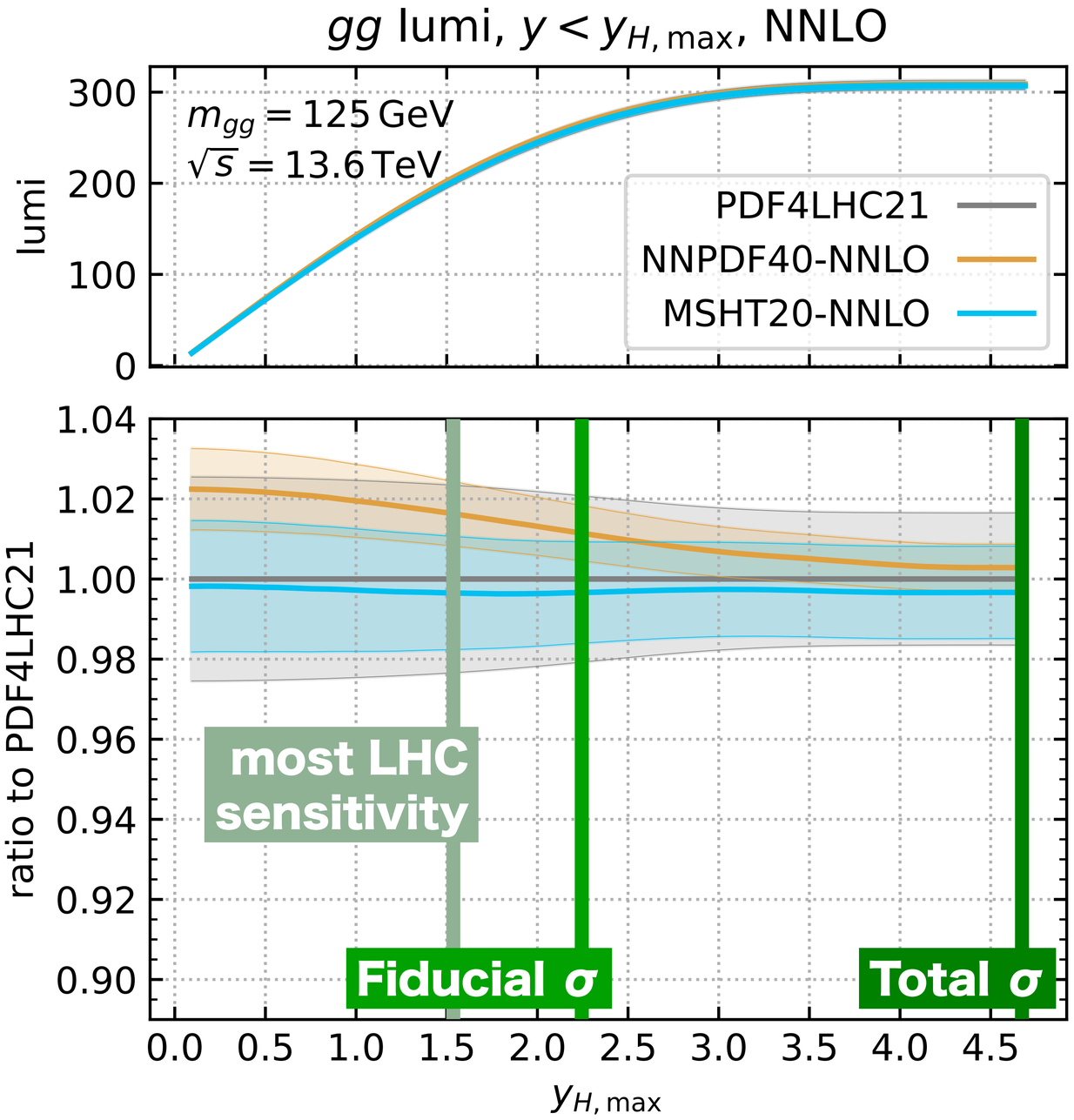
aN3LO PDFs



aN³LO (+QED) PDF corrections: **-3.5% (-5%)**

PDF4LHC21 close to **NNLO combination**

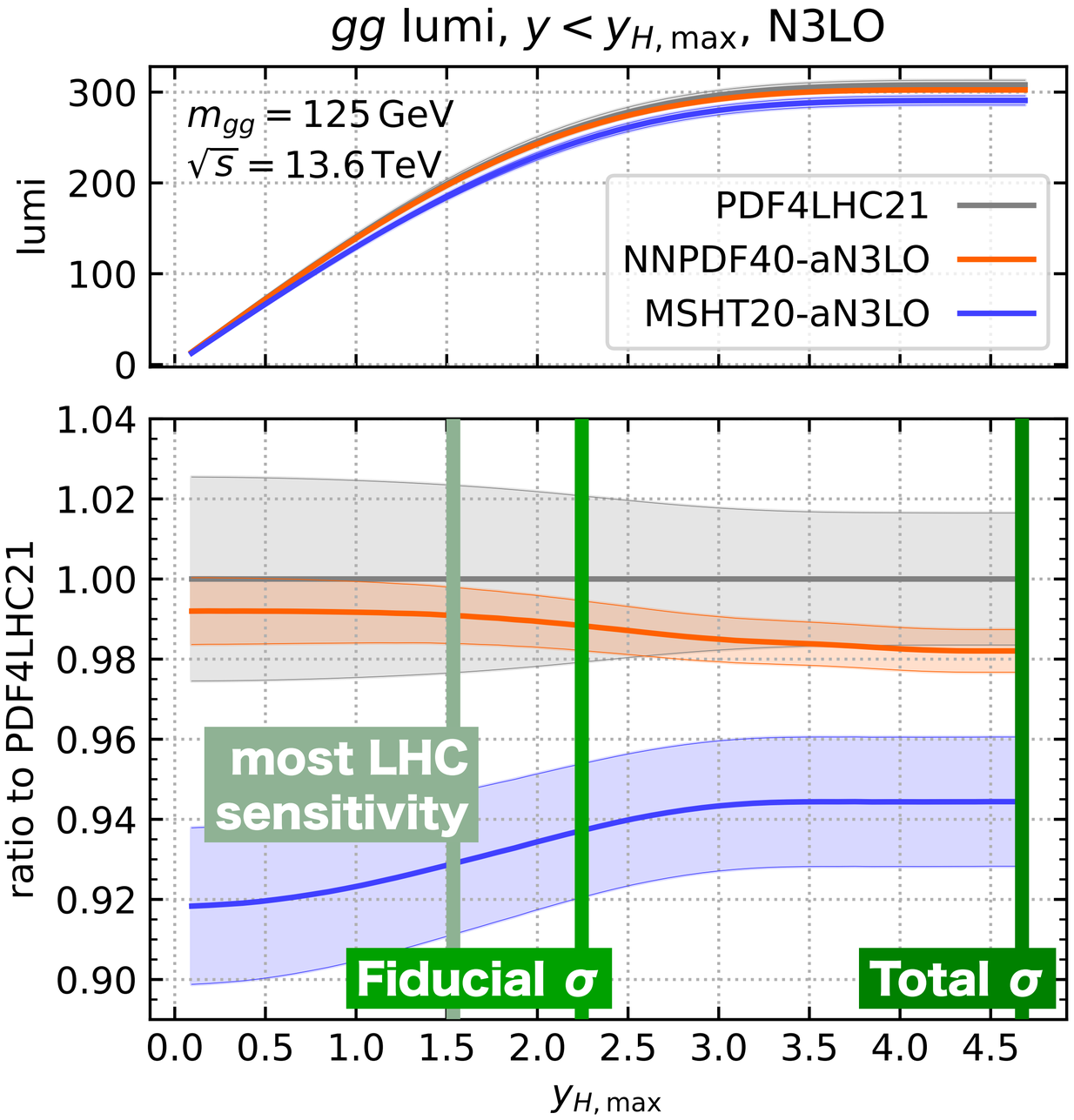
Juan Rojo [annotated]



number of gg collisions @m_H, limited rap

At NNLO, 1-2% differences between PDF4LHC

Conclusions can differ for total cross section and central rapidities

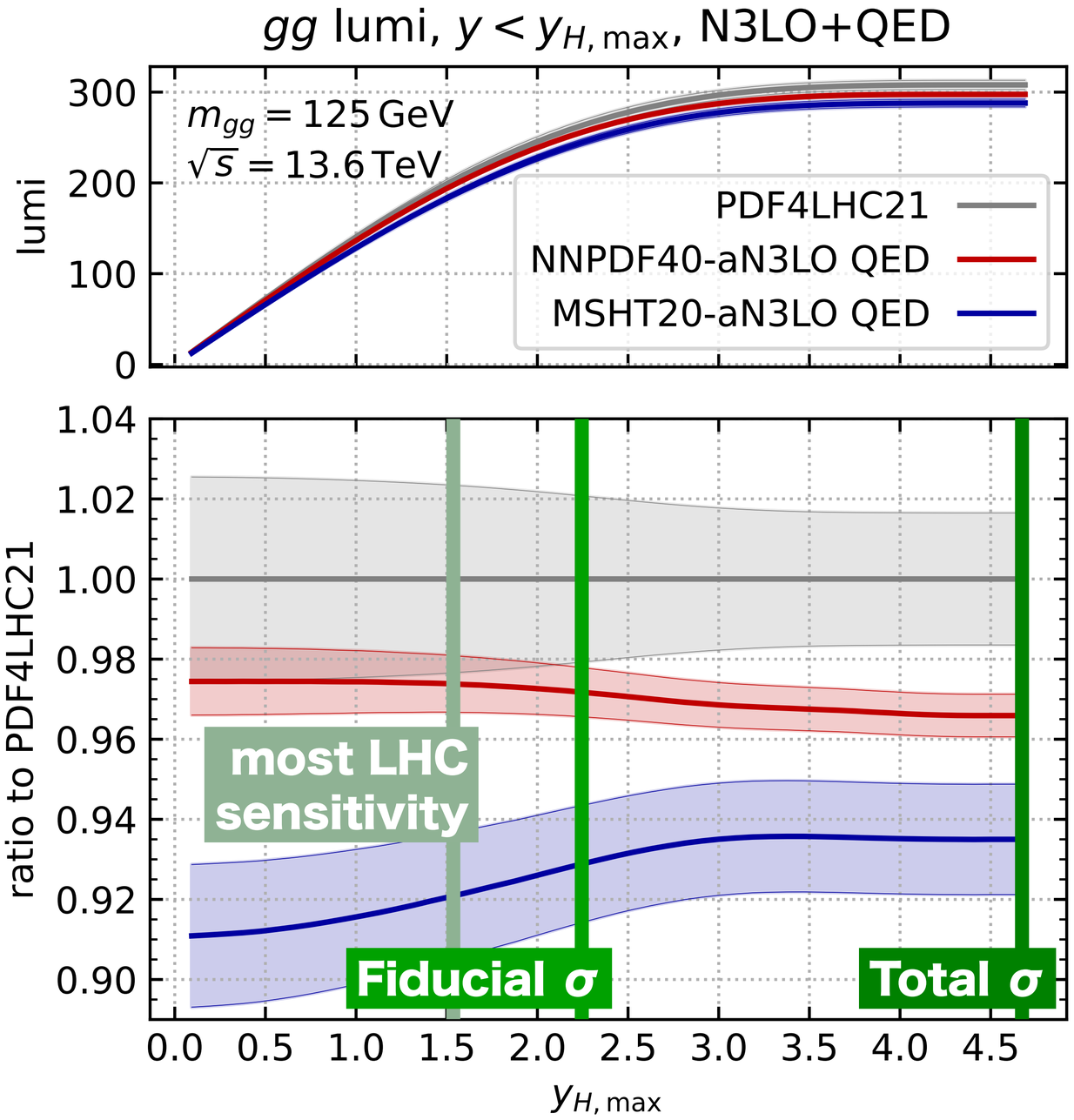


number of gg collisions @m_H, limited rap

At NNLO, 1-2% differences between PDF4LHC

Conclusions can differ for total cross section and central rapidities

At aN3LO, differences between sets much larger, especially at central rapidities (~6%). Methodological differences still to be resolved?



number of gg collisions @m_H, limited rap

At NNLO, 1-2% differences between PDF4LHC

Conclusions can differ for total cross section and central rapidities

At aN3LO, differences between sets much larger, especially at central rapidities (~6%). Methodological differences still to be resolved?

QED no longer optional at today's 1-2% precision

Strong coupling – new lattice determination [Dalla Brida et al, 2501.06633]

$$\alpha_s(M_Z) = 0.11873 \pm 0.00056$$

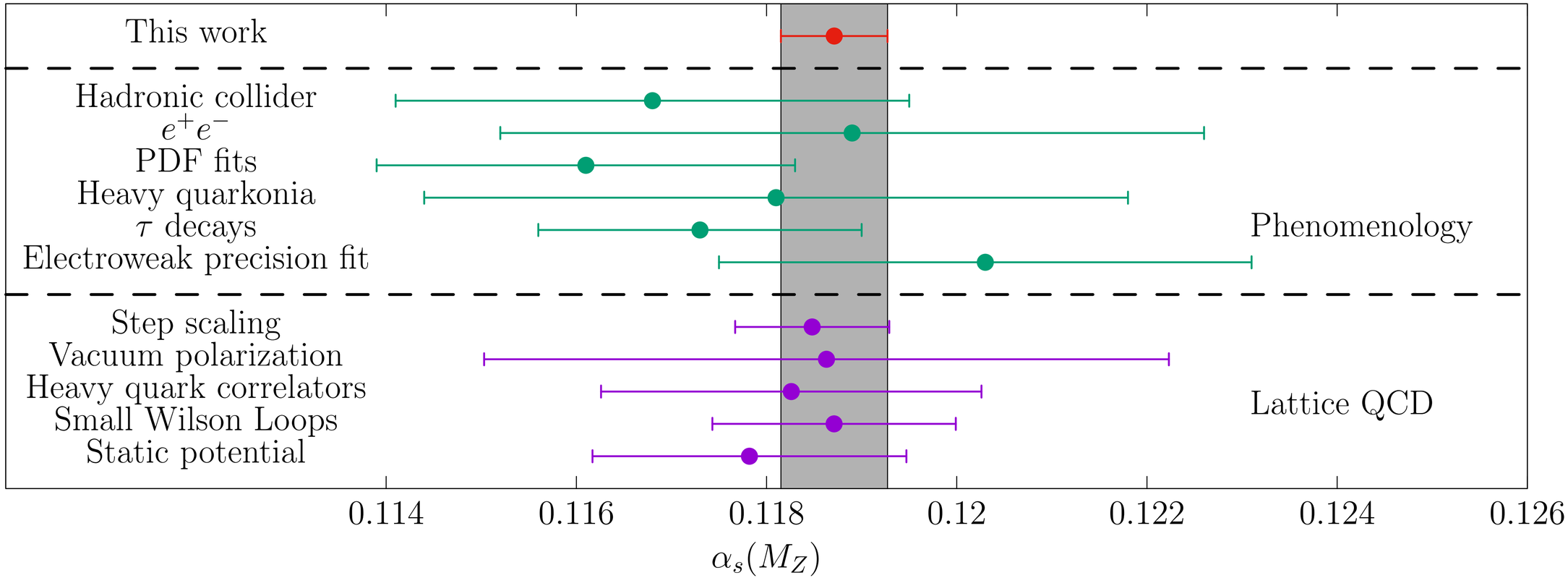


Fig. 3: Our result for $\alpha_s(m_Z)$ compared with other results from the literature (cf. text).

Non-perturbative corrections, hadronisation

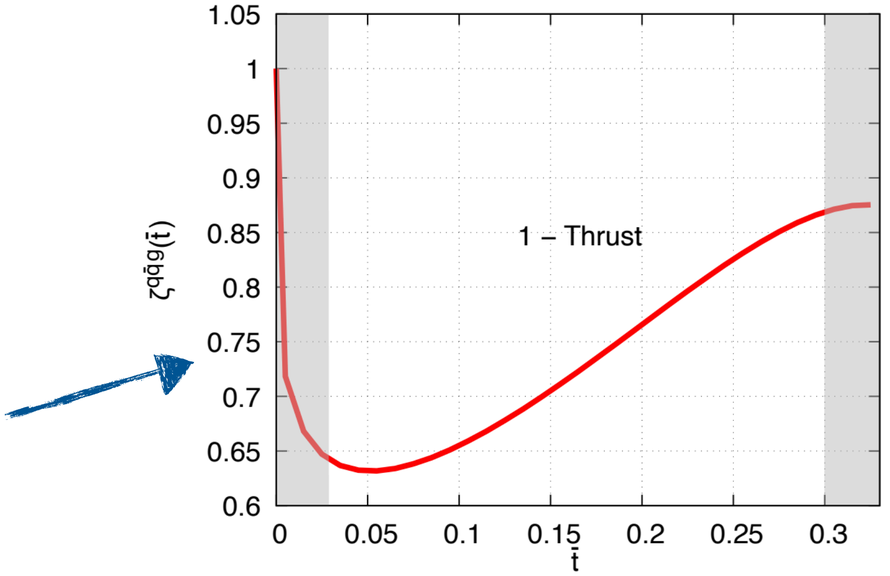
Elephant in the room in precision jet physics

Mismodeling of non-**perturbative/hadronisation effects** potential **serious limitation**

- interplay with Monte Carlo generators: tuning of hadronisation models
- analytic results typically derived in simple scenarios (then extrapolated)

Ways forward and challenges (possibly a breakthrough):

- examples of **first analytical studies**:
  I. **(linear)** power corrections in shape observables [Luisoni et al 2012.00622] [Caola et al 2204.02247]
  II. soft anomalous dimension for $1/Q$ power corrections [Dasgupta et al 2411.16867]



- **analytic approaches in their infancy (relation to full QCD not yet robust)**

  refined analytic methods highly desirable

- devise **observables with reduced sensitivity**

Thanks to accuracy at e^+e^- colliders, we have a **unique opportunity!**

profound investigation of (arguably) the least understood regime of QCD

Buccioni

It's not just calculations, PDFs, α_s: what you measure also matters

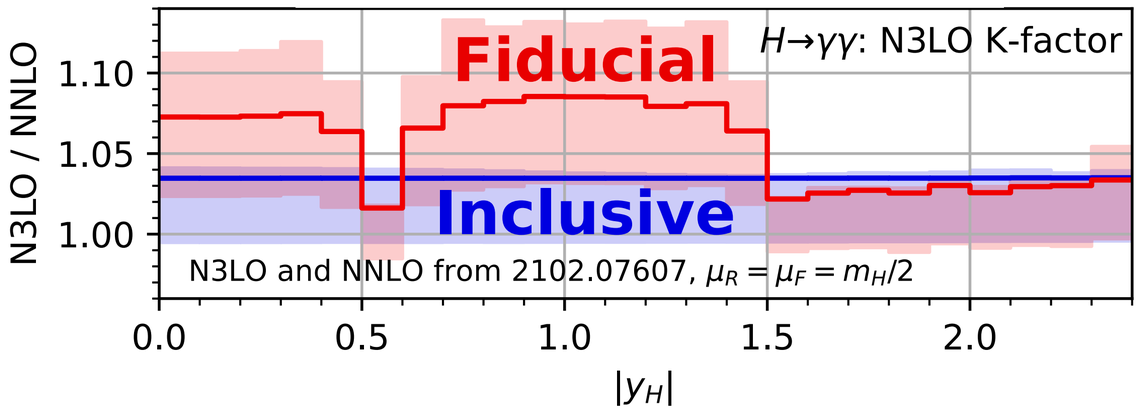
standard cuts

$$p_{t1} > 0.35 m_{\gamma\gamma},\ p_{t2} > 0.25 m_{\gamma\gamma}$$

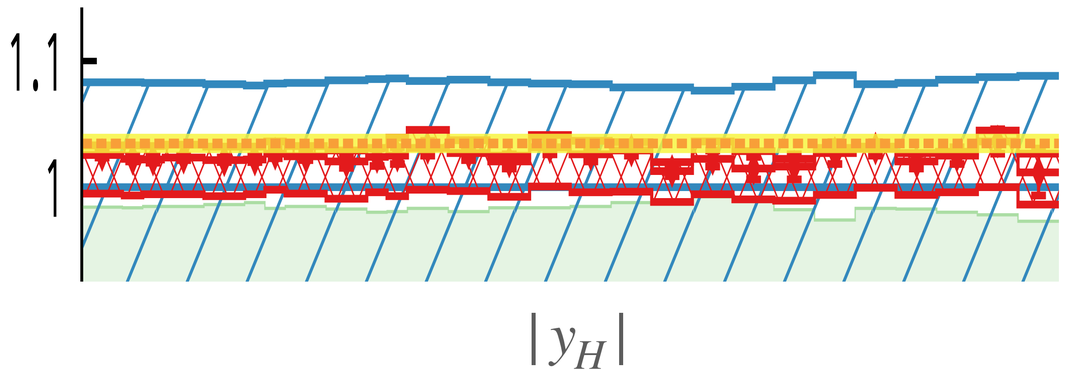
product cuts

$$\sqrt{p_{t1} p_{t2}} > 0.35 m_{\gamma\gamma},\ p_{t2} > 0.25 m_{\gamma\gamma}$$

Higgs N3LO/NNLO v. rapidity



Higgs N3LO/NNLO v. rapidity



Huss et al preliminary @ Higgs 2021

new techniques

Unified Particle Transformer (UParT)

A unified approach for jet tagging in Run 3 (CMS-DP-2024-066)

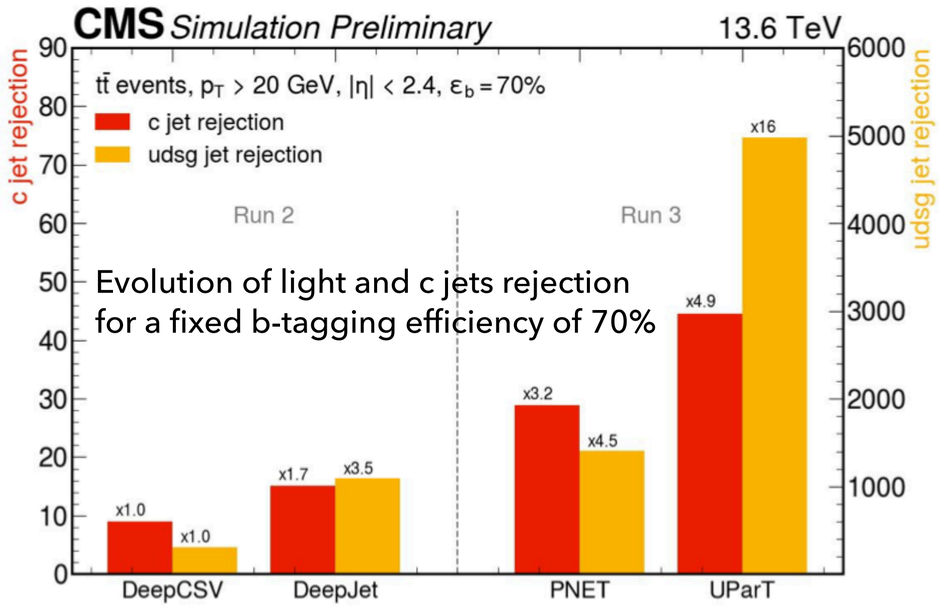
AK4 Jet heavy flavor tagging

~~A modified ParticleTransformer, with the inclusion of~~ Adversarial Training to enhance robustness against MC mismodeling.

- Perform a distortion of the input features, allowing the model to learn to classify the jet flavor in a region around the jet input features

Additional outputs and augmented loss function:

- τ_h + first time identification of jets originating from s-quarks in CMS.
- Regression tasks for flavor-aware jet energy regression and resolution estimation



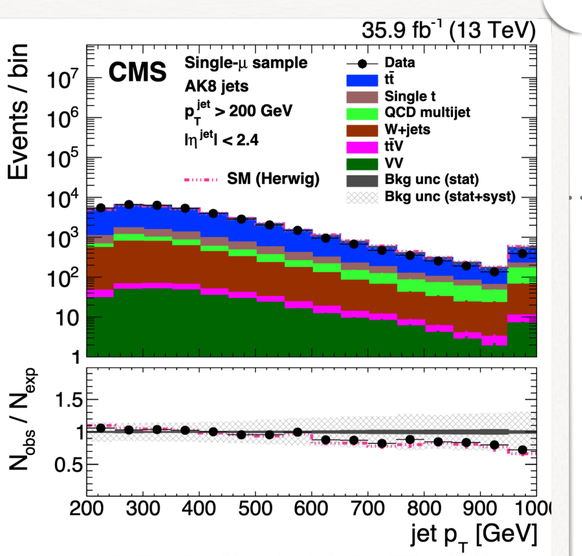
UParT shows state-of-the-art heavy flavor jet tagging performance

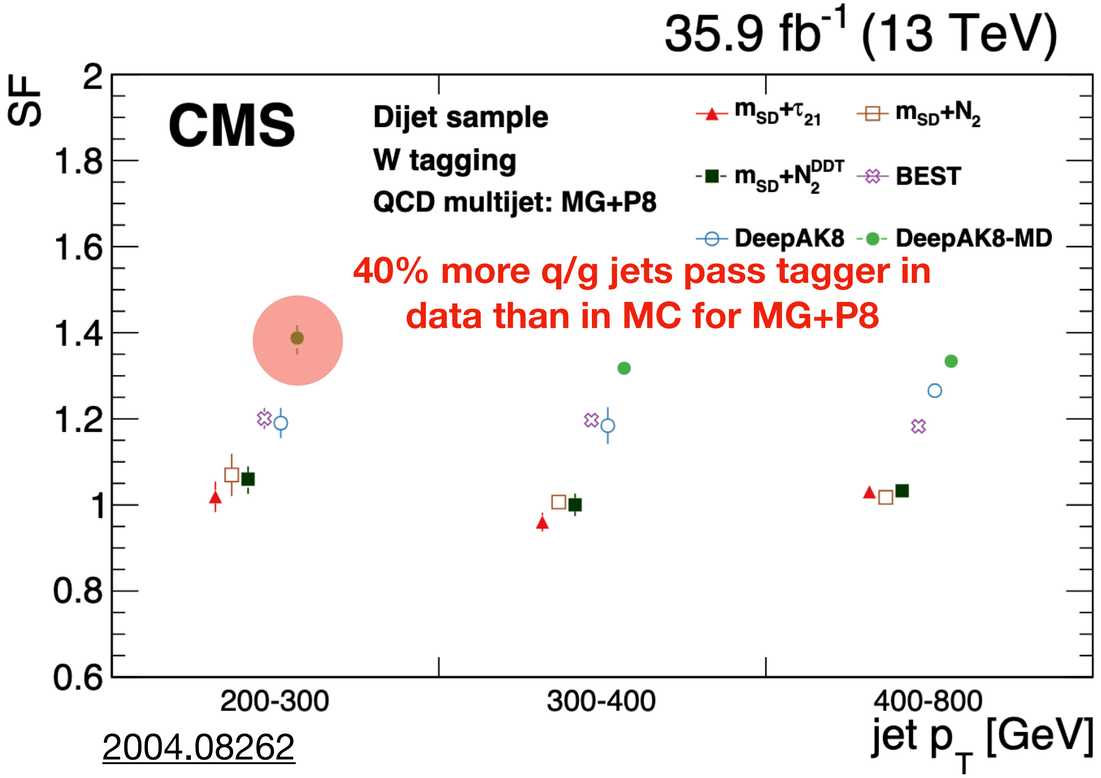
$$L = \underbrace{CatEntropy(x, x_{truth})}_{\textit{Classification}} + \underbrace{\gamma_{regr} \cdot log(cosh(y - y_{truth}))}_{\textit{Regression}} + \underbrace{\gamma_{quantile} \cdot [p_{0.16}(z - z_{truth}) + p_{0.84}(z - z_{truth})]}_{\textit{Quantile regression (resolution estimation)}}$$

tagging: a diversion

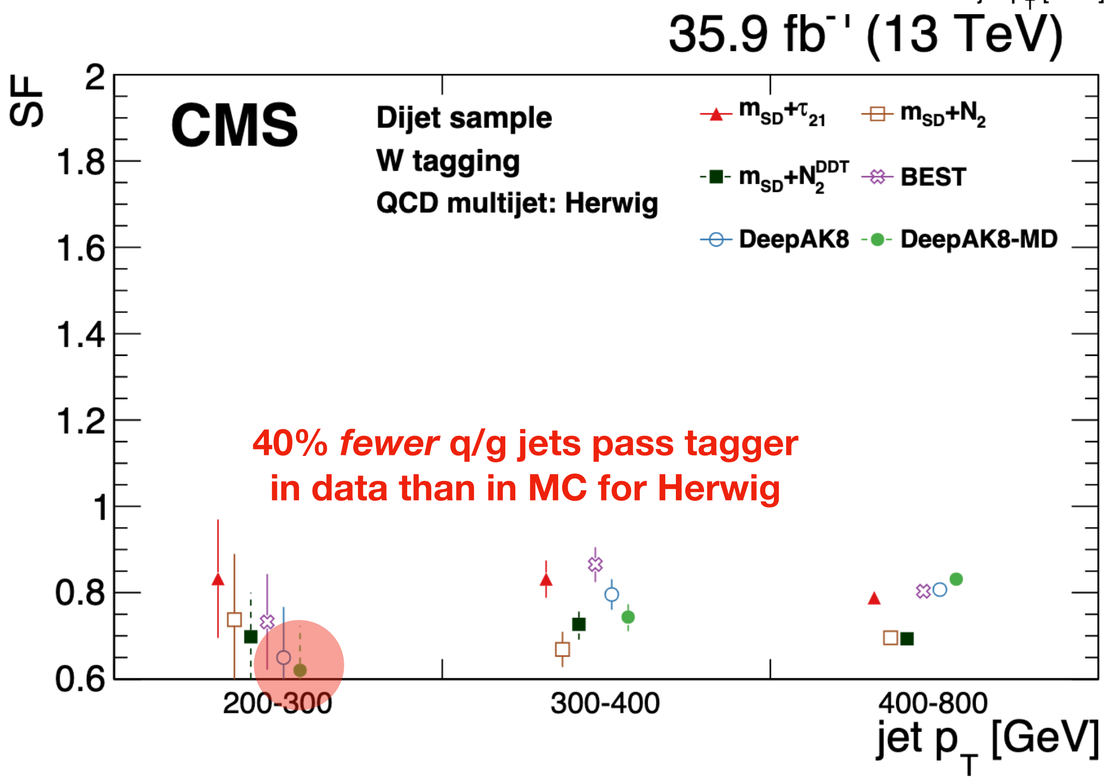
Jennifer Roloff, PSR25

- Taggers typically trained on MC — also need to determine the efficiency in data (***scale factors***)
- Scale factors (SF) can depend on the specific MC generator that is used
  - Can be large scale factors *and* large differences across MC predictions
- ML is learning features that don't exist on data — better MC would *reduce modeling uncertainties* and potentially *improve tagger performance*





2004.08262



Talks on higher accuracy with parton showers at PSR 2025

Conceptual and technical challenges in the matching of parton showers to higher-order calculations

Speaker: Peter Skands (Monash University (AU))

25-PSR-Matching.pdf

LHC phenomenology with KrkNLO matching

Speaker: Andrzej Konrad Siodmok (Jagiellonian University (PL))

PSR2025_KrkNLO_...

Current status of NNLOPS simulations at LHC

Speaker: Luca Rottoli (Universita & INFN, Milano-Bicocca (IT))

rottoli_PSR_2025.pdf

Logarithmically-accurate and positive-definite NLO shower matching with ESME

Speaker: Alexander Karlberg (CERN)

14072025PSR.pdf

NNLO matching in VINCIA

Speaker: Basem El-Menoufi

PSR2025_ElMenoufi...

Final-state NLO matching in Alaric

Speaker: Peter Meinzinger (Zürich University)

PSR_2025_Meinzin...

The Alaric project

Speaker: Stefan Hoeche (Fermilab)

Alaric_PSR25.pdf

PanScales efforts towards NNLL showers

Speaker: Gregory Soyez (IPhT, CEA Saclay)

panscales-nnll.pdf

Status of NLL-Accurate Parton Showers in Herwig

Speaker: Siddharth Sule (The University of Manchester (GB))

s-sule-herwig-nll-v2....

Recent progress in subleading-colour effects and amplitude-level evolution

Speaker: Simon Platzer (University of Graz (AT))

slides-small.pdf

Hadronization models with NLL-accurate showers in Herwig

Speaker: Andre Hoang (Austrian Academy of Sciences (AT))

Hoang-Hadronizatio...

negative weights

Jennifer Roloff, PSR25

- Negative weights are becoming more problematic for MC statistical uncertainties
- Often feed MC predictions into training for MC algorithms for both taggers and event selection
  - Most ML models are also not set up to handle negative weights — need some sort of workaround
- Increasingly difficult as the total integrated luminosity increases
  - *Need MC to scale with data!*

VVZ production 2412.15123

Since XGBoost cannot handle negative-weight events, the absolute value of each event weight is used.

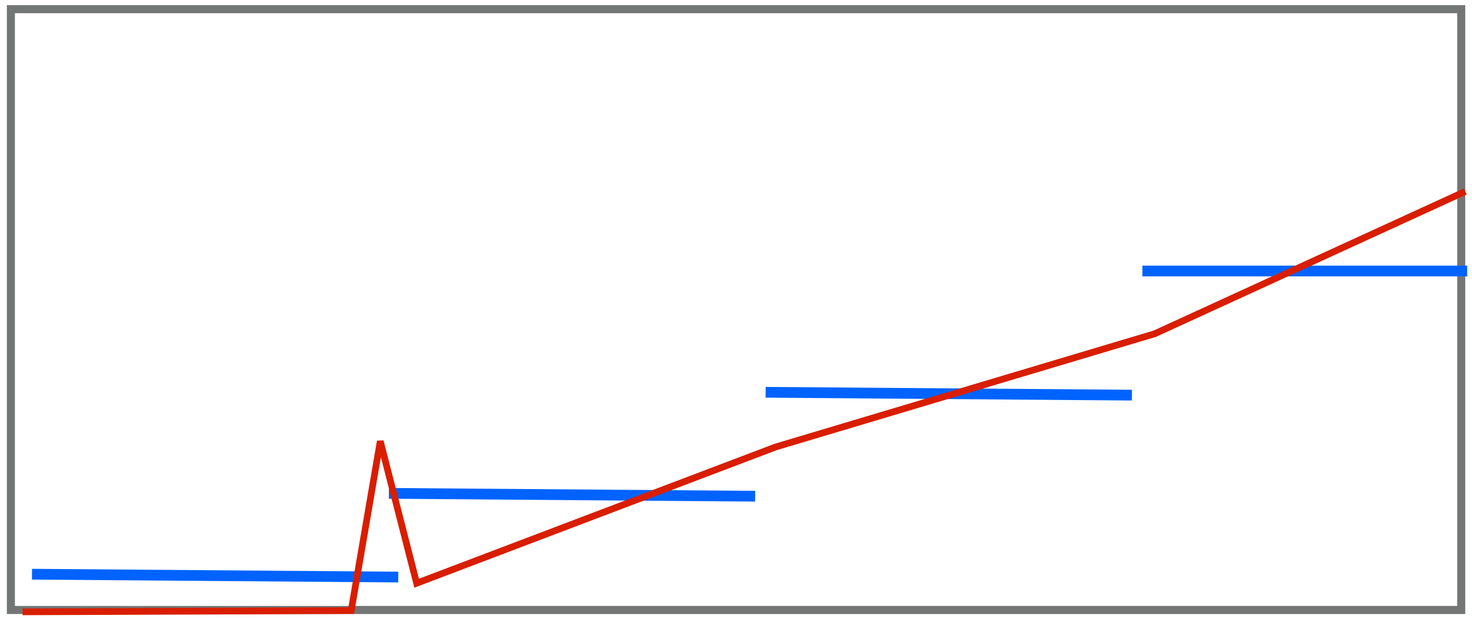
4-tops 2211.01136

spin correlations. To avoid the use of negative weights present in the nominal NLO sample in the training of the multivariate discriminant used to separate SM $t\bar{t}t\bar{t}$ events from background (see Section 5.2), a sample was produced with similar generator settings, but at LO. An additional $t\bar{t}t\bar{t}$ sample was produced with the

$H \to c\bar{c}$ 2205.05550

background normalizations. The main experimental systematic uncertainties are associated with limited simulation sample sizes, particularly due to large fractions of negatively weighted events in the NLO V+jets samples, and the c jet identification efficiencies, representing ≈37 and ≈23% of the total, respectively. Theoretical uncertainties in the cross sections, p_T spectra, PDFs, renormalization and factorization scales, represent ≈22% of the total uncertainty in μ.

toponium



Is **data in wide bins** really evidence for **narrow toponium**?

Nason, Re, Rottoli, 2505.00096
see also Beneke & Ruiz-Femenia, 1606.02434

plane of complex max

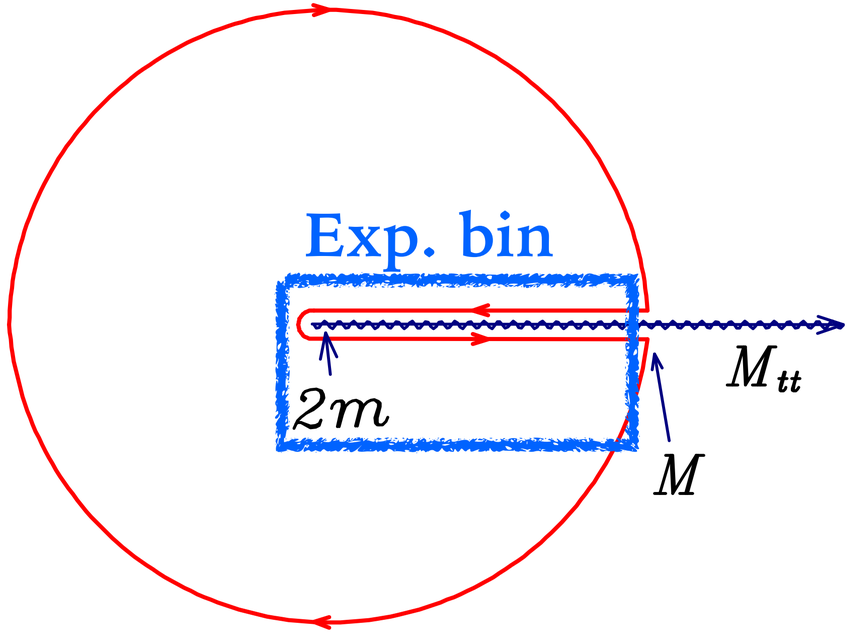


Figure 1: Illustration of the cross section integrated in the invariant mass of the $t\bar{t}$ pair up to a given cut $M_{t\bar{t}}^{(\mathrm{cut})}$ in terms of a contour integral of the forward amplitude for complex energies.

Nason, Re, Rottoli, 2505.00096
see also Beneke & Ruiz-Femenia, 1606.02434

plane of complex max

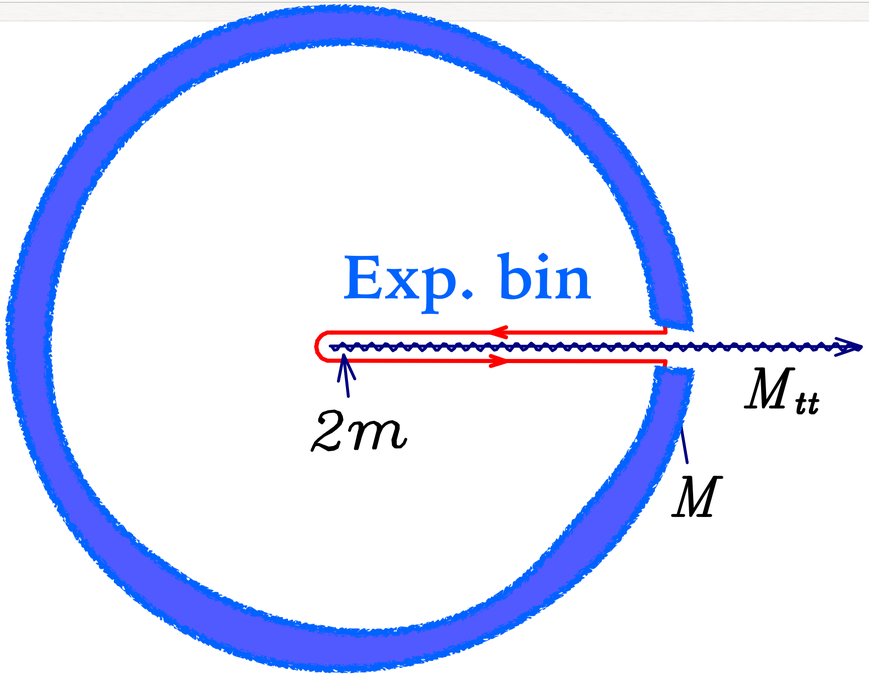
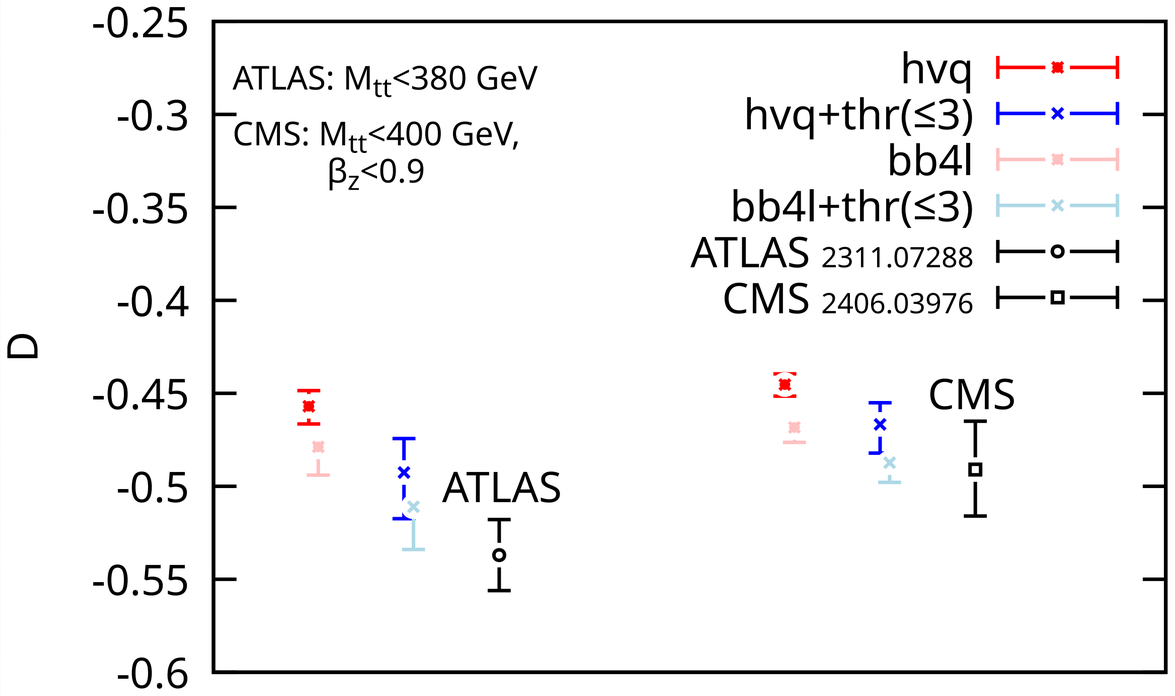
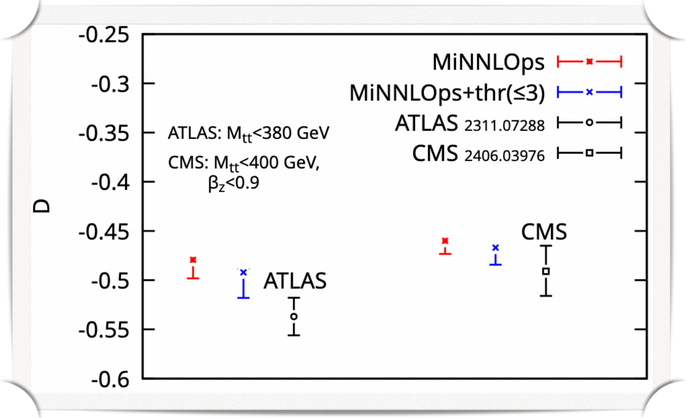


Figure 1: Illustration of the cross section integrated in the invariant mass of the $t\bar{t}$ pair up to a given cut $M_{t\bar{t}}^{(\mathrm{cut})}$ in terms of a contour integral of the forward amplitude for complex energies.



Generator choice impact quite relevant. Needs work.

Tension with data (especially ATLAS) gone away.



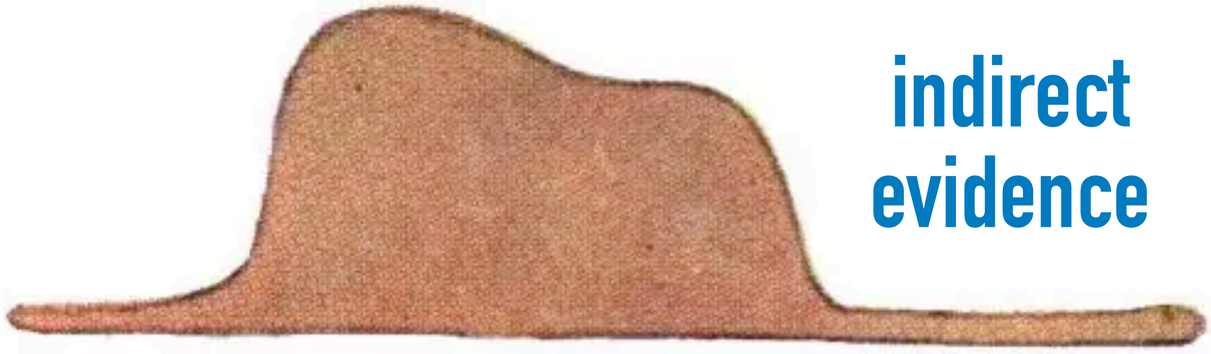
Nason @ CERN-TH

Conclusions

- Radiative effects in spin correlations in $t\bar{t}$ production and decay can be classified in standard perturbation theory, provided the coefficients of the perturbative expansion of the partonic cross sections are correctly interpreted (as distributions).
- NNNLO corrections (that include bound state effects) are quite small, it is unlikely that their effect can be established by data.
- NLO and NNLO effects seem to give the most important contributions, and seem to be required by data.
- MC modeling has an important impact, and it is not easy to interpret. A better understanding of the effect of decay modeling is also very important in the NNLO implementation of $t\bar{t}$ production where at the moment the same (MadSpin style) implementation of correlation in decays used in hvq is at work.
- In general, we have seen a nice example of the interplay between perturbative and non-perturbative corrections, in a framework where the latter arise from a geometric (rather than factorial) divergence of the perturbative expansion. This leaves us wondering if other geometric singularities are at work in QCD, and are relevant for bound state formation.

43

Mon dessin numéro 1



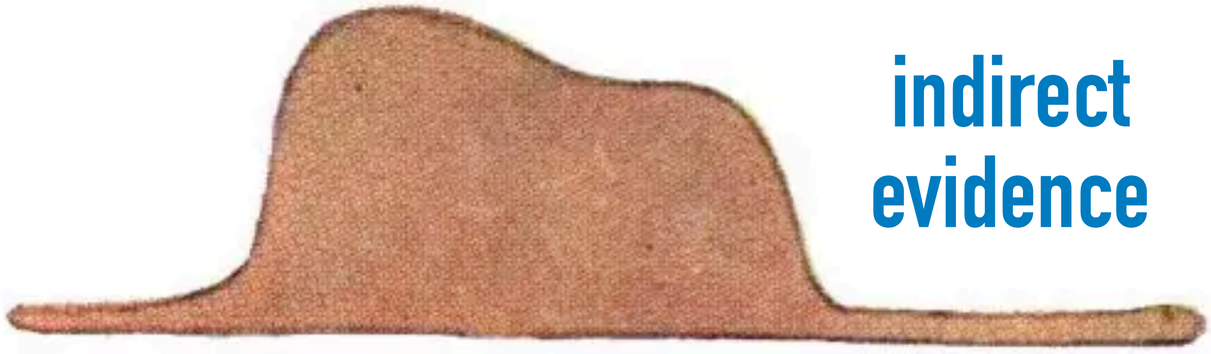
indirect evidence

« Pourquoi un chapeau ferait-il peur ? »

“Why should any one be frightened by a hat?”

Le Petit Prince, Antoine de Saint-Exupéry

Mon dessin numéro 1



indirect evidence

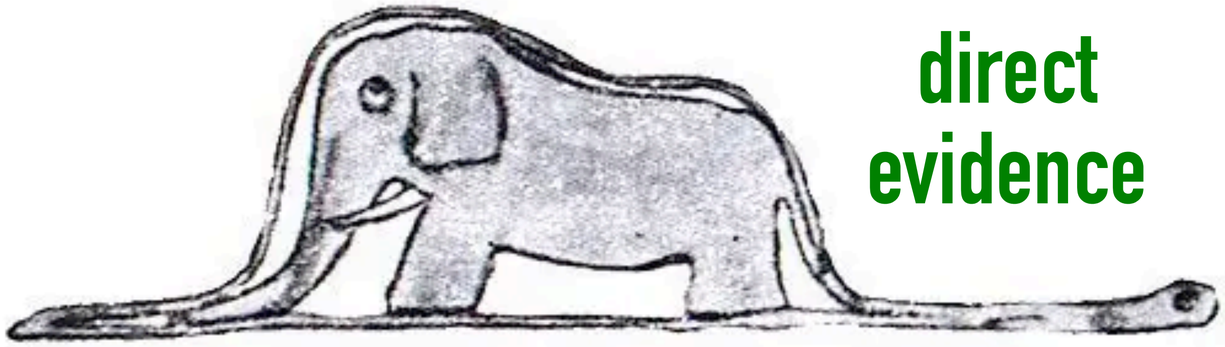
« Pourquoi un chapeau ferait-il peur ? »

"Why should any one be frightened by a hat?"

Le Petit Prince, Antoine de Saint-Exupéry

« Mon dessin ne représentait pas un chapeau. Il représentait un serpent boa qui digérait un éléphant. »

"My drawing was not a picture of a hat. It was a picture of a boa constrictor digesting an elephant."



direct evidence

Mon dessin numéro 2

over to Maria for her conclusions on what you actually measure