image: CucombreLibre@flickr

Theory Vision

*Gavin P. Salam, CERN**

*on leave from CNRS and University of Oxford/Royal Society

LHCP Bologna 2018

A theory view today

*Gavin P. Salam, CERN**

image: CucombreLibre@flickr

* on leave from CNRS and University of Oxford/Royal Society

A typical "Vision" talk addresses the "big unanswered questions"

Nature of dark matter (& dark energy)

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

Matter-antimatter asymmetry of the universe

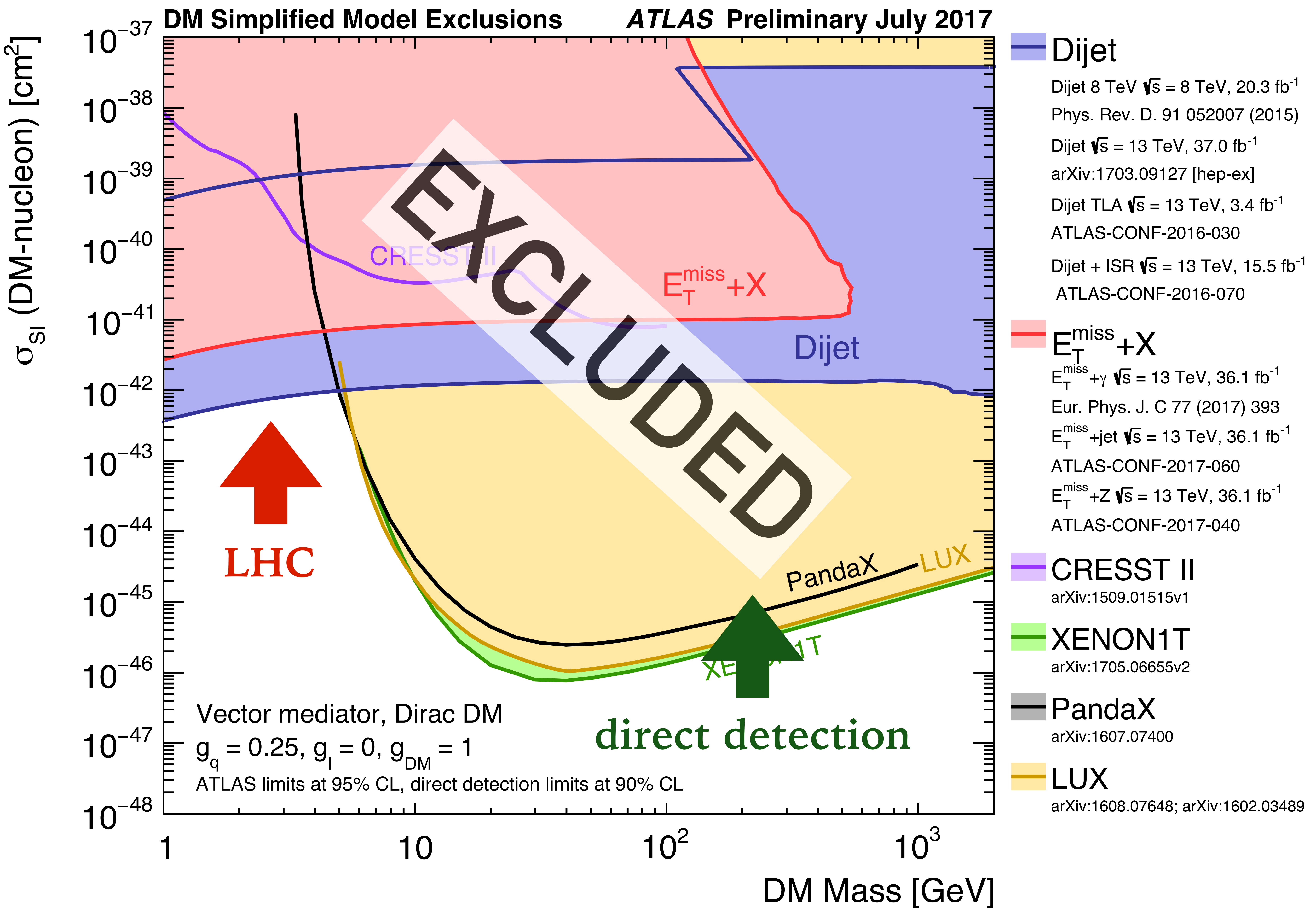
[...]

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

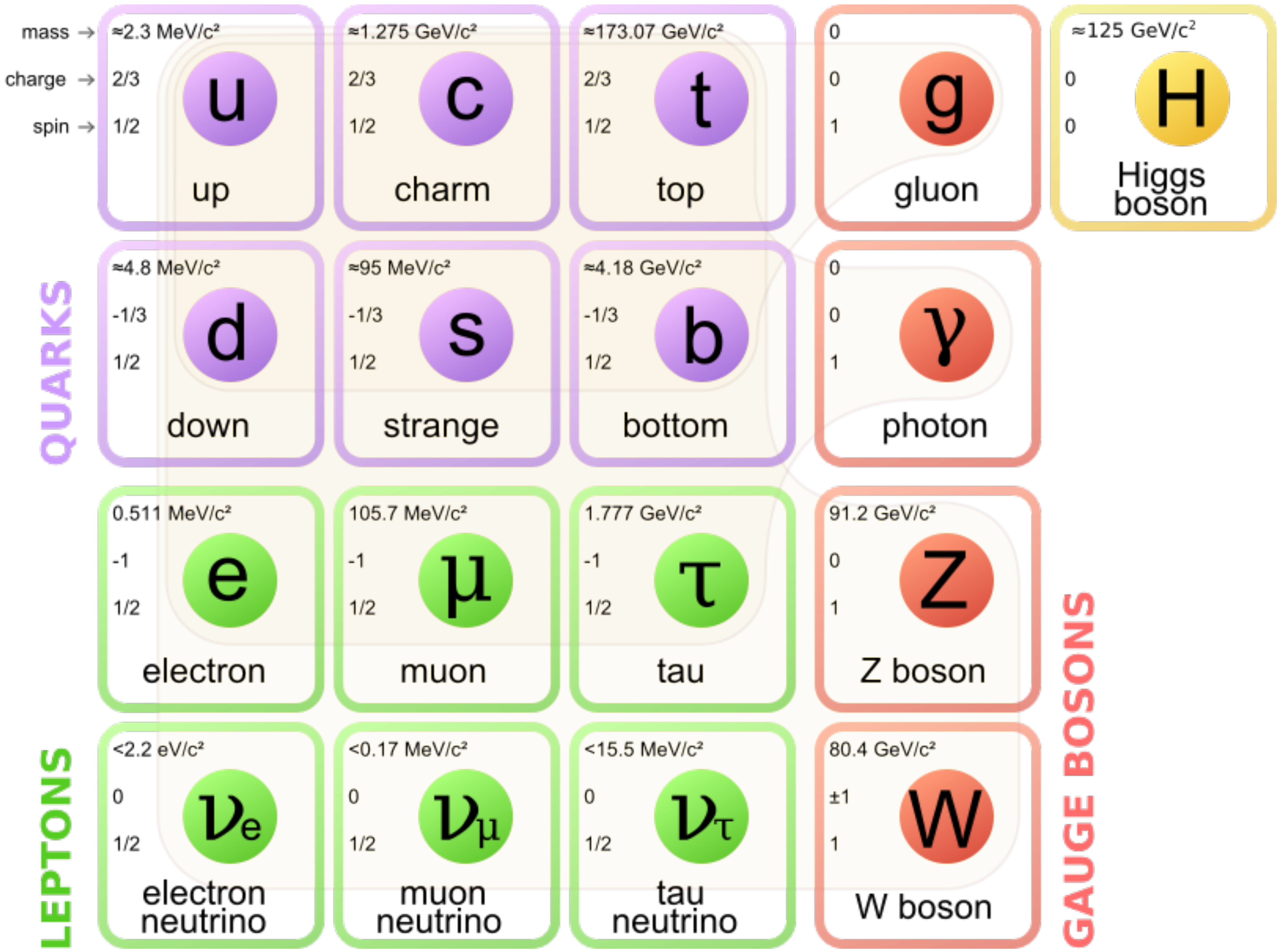
Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

Masses ~ GeV upwards

(search interpretations strongly model dependent)



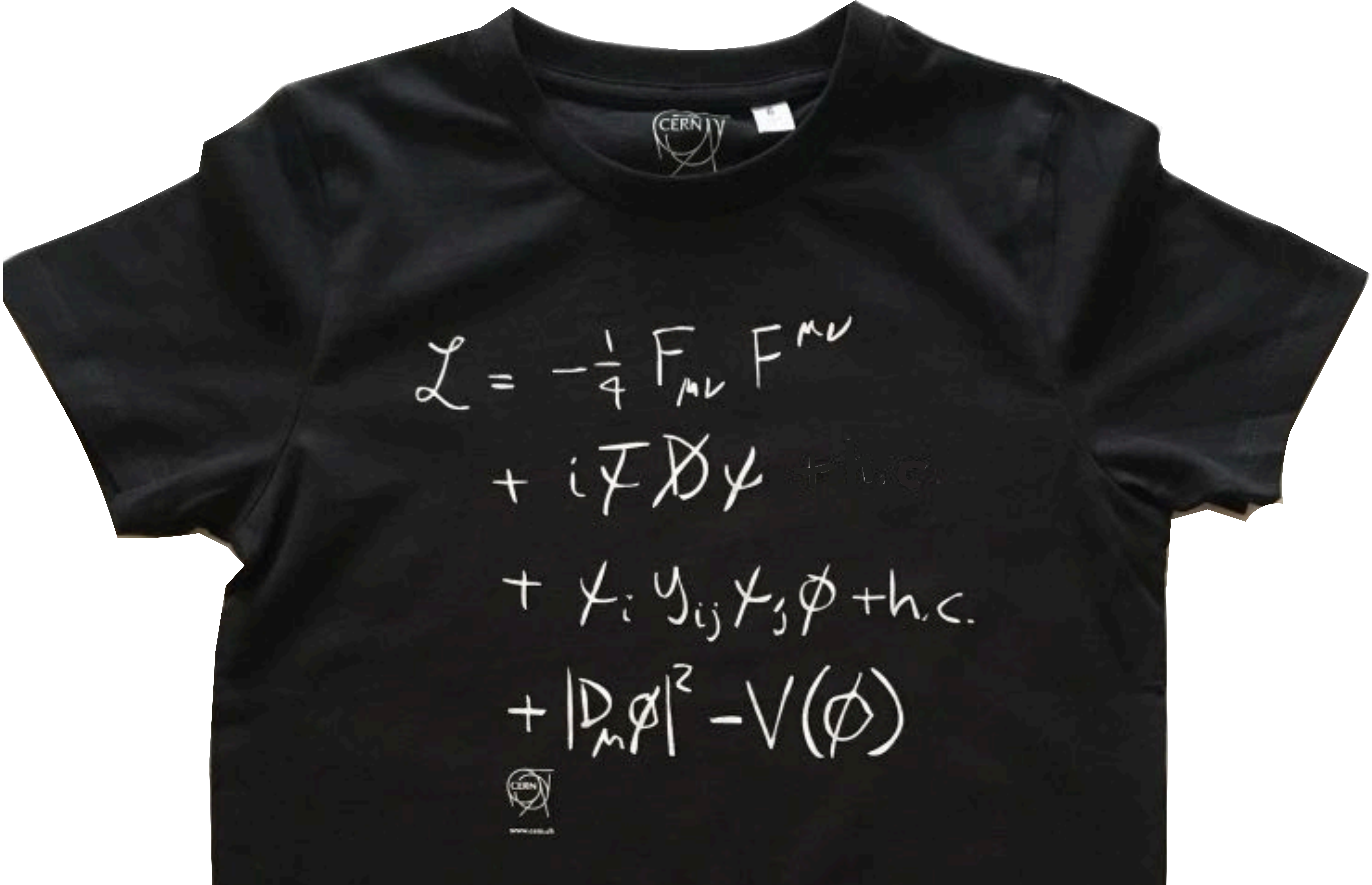
and much less about the standard model (SM)...



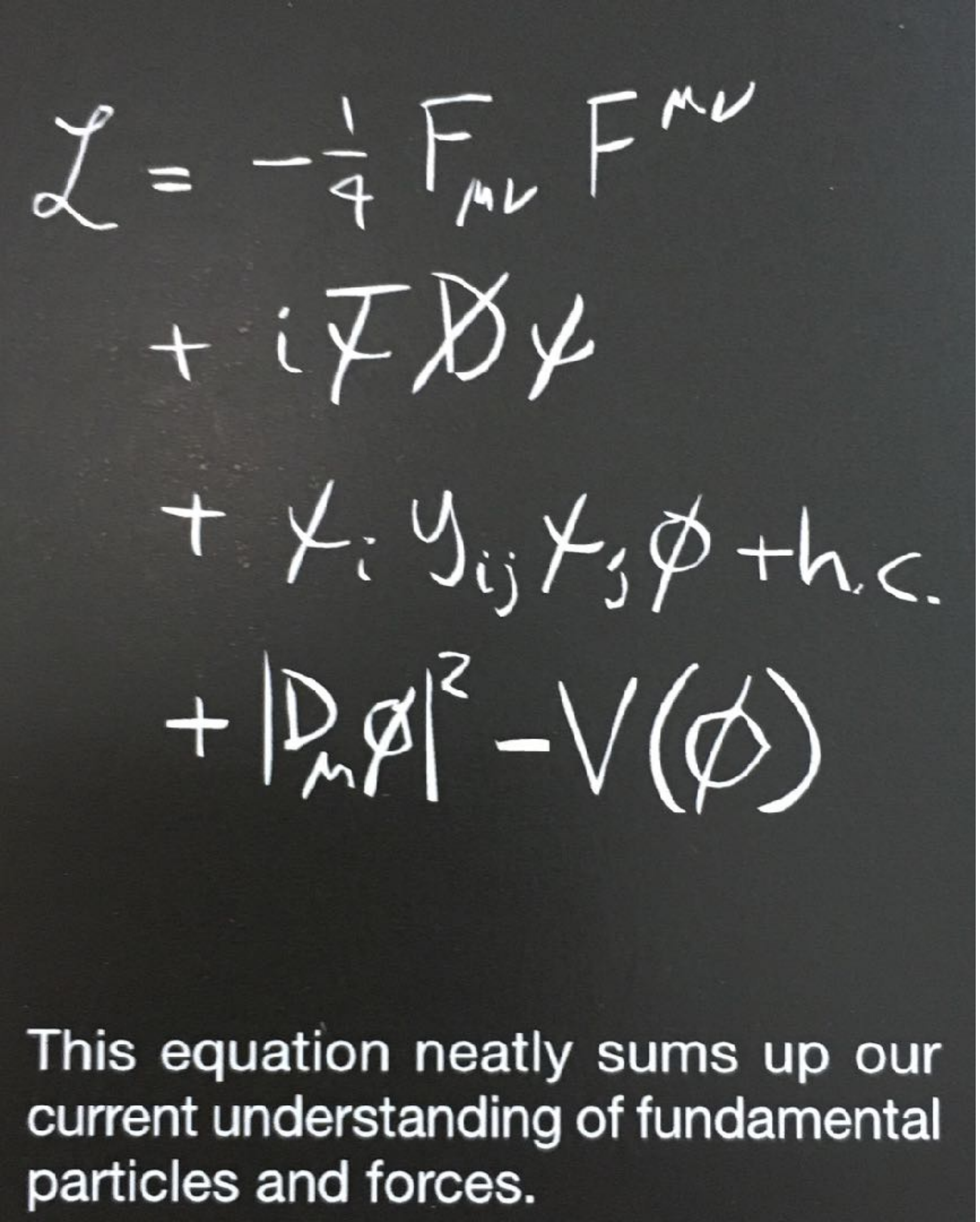
since experiments have already found all its particles...

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

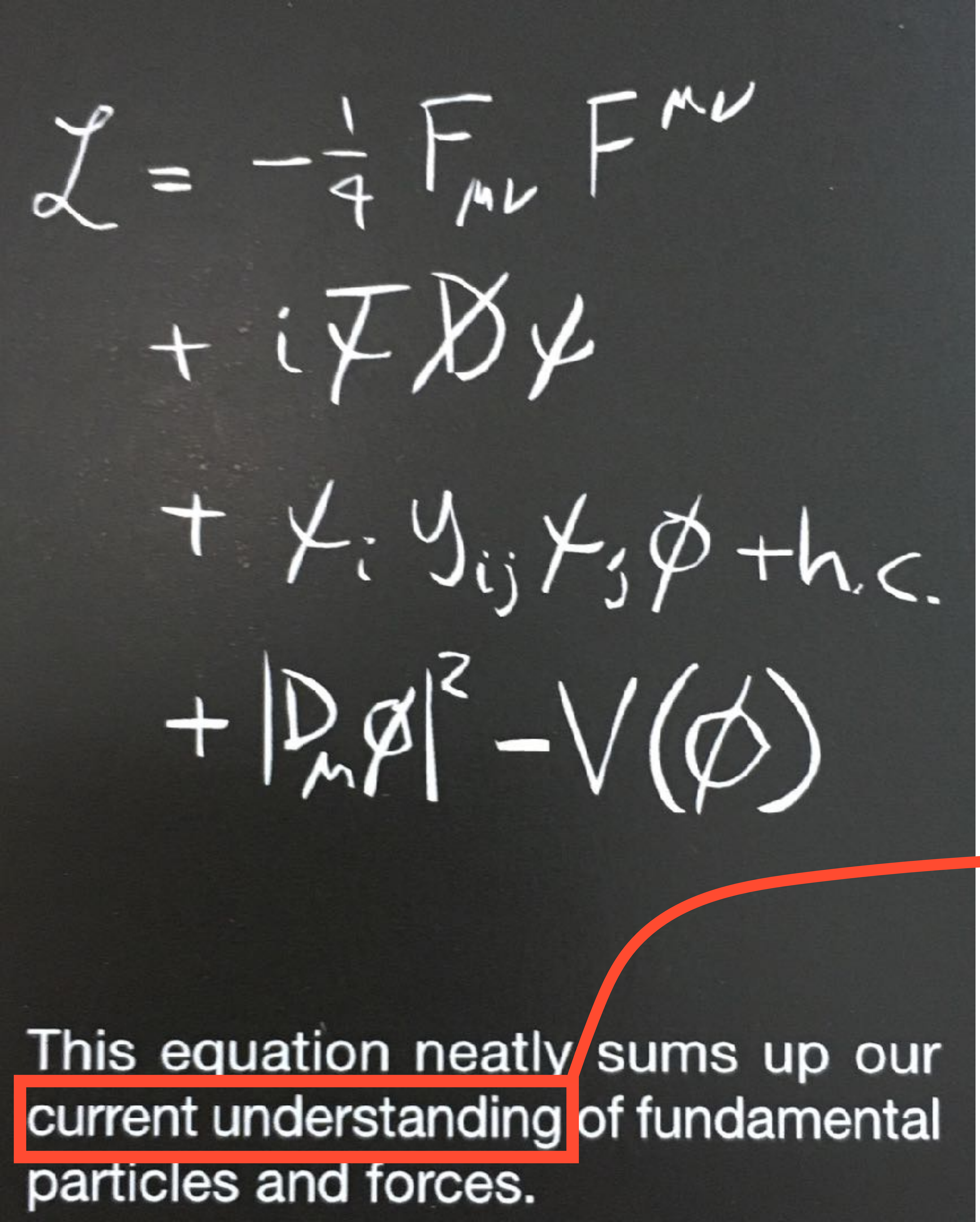


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
CERN



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

STANDARD MODEL — KNOWABLE UNKNOWNS



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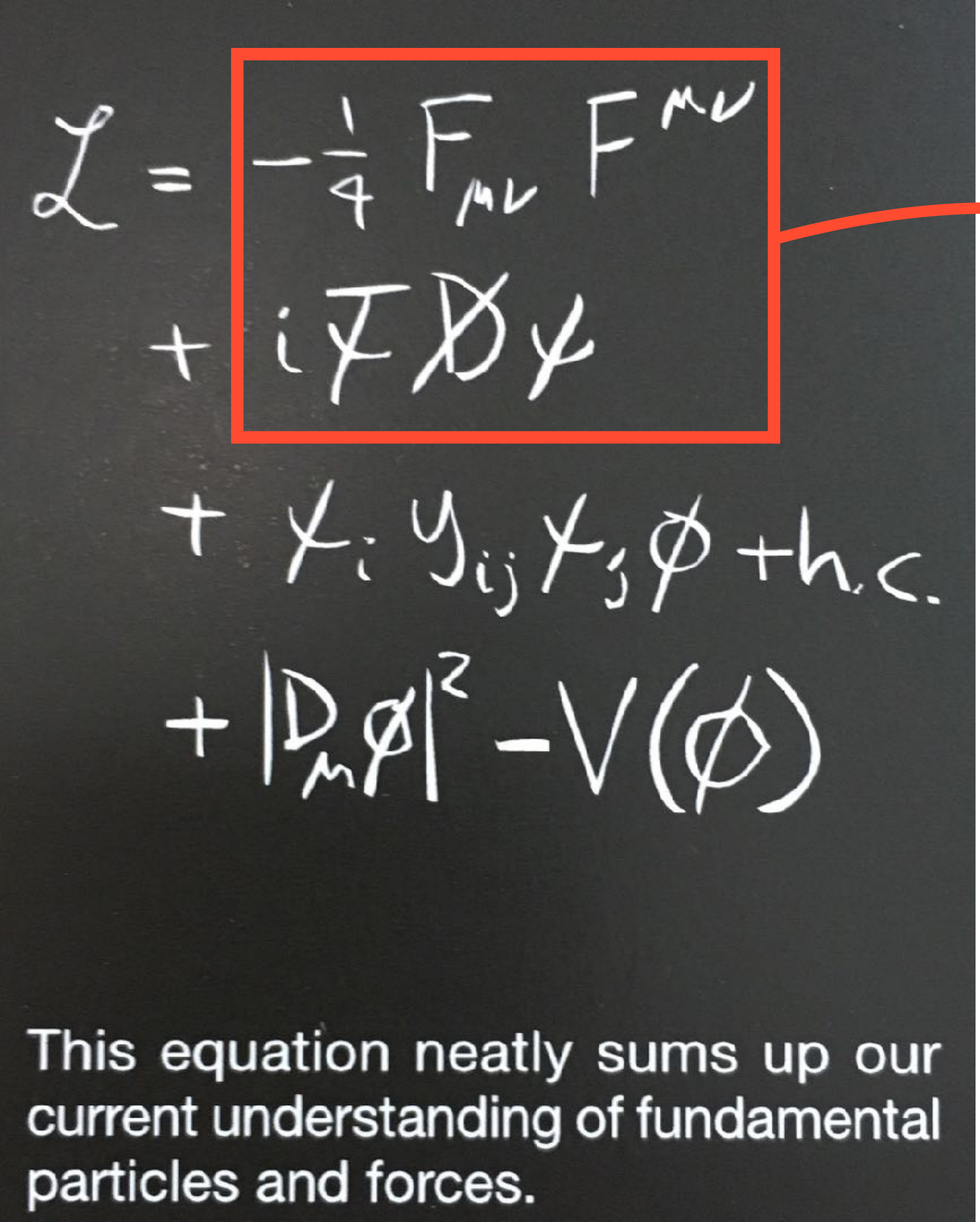
“understanding” = knowledge ?

“understanding” = assumption ?

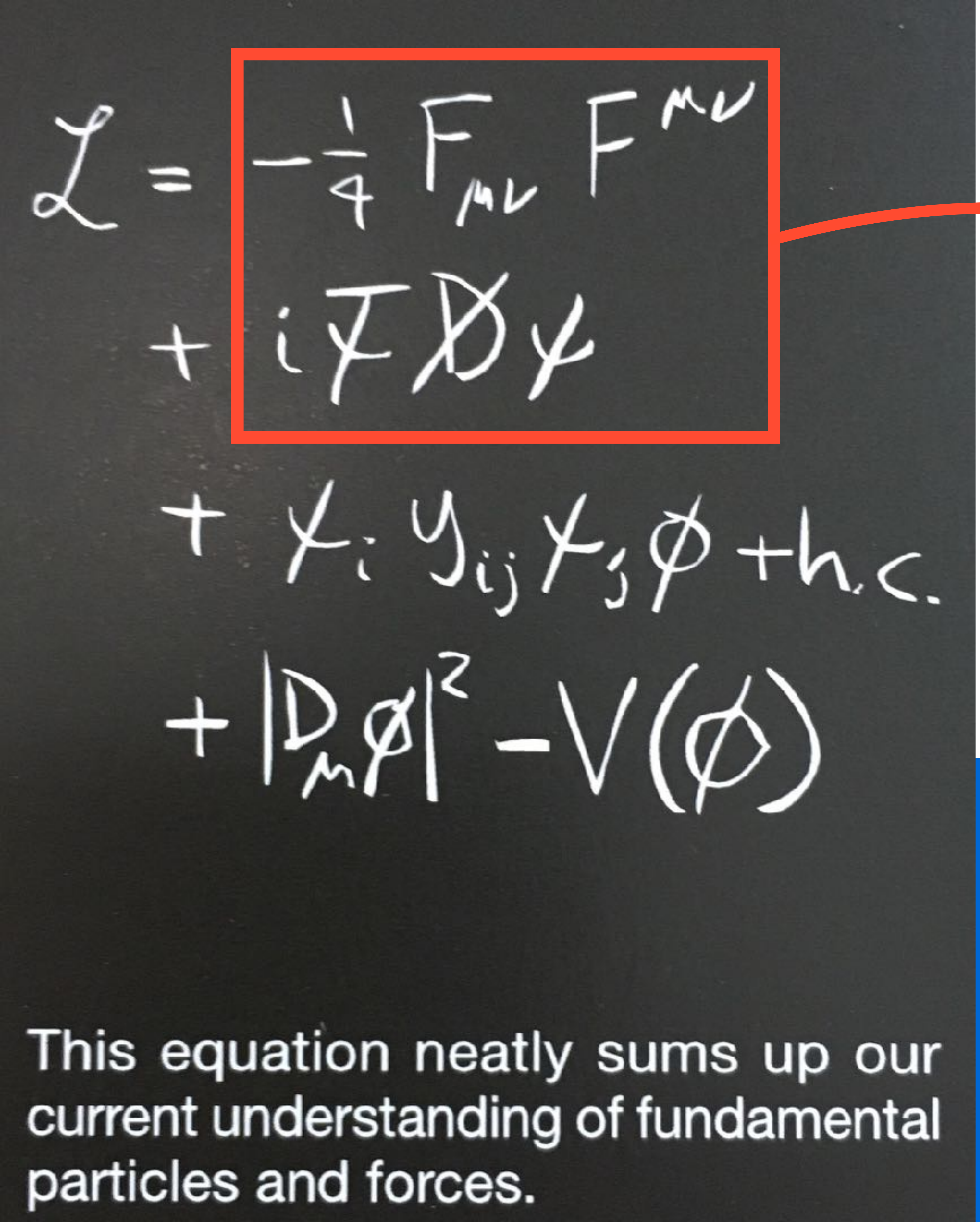


Gauge part

e.g. qqγ, qqZ, qqg, eνW, ggg, 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.)



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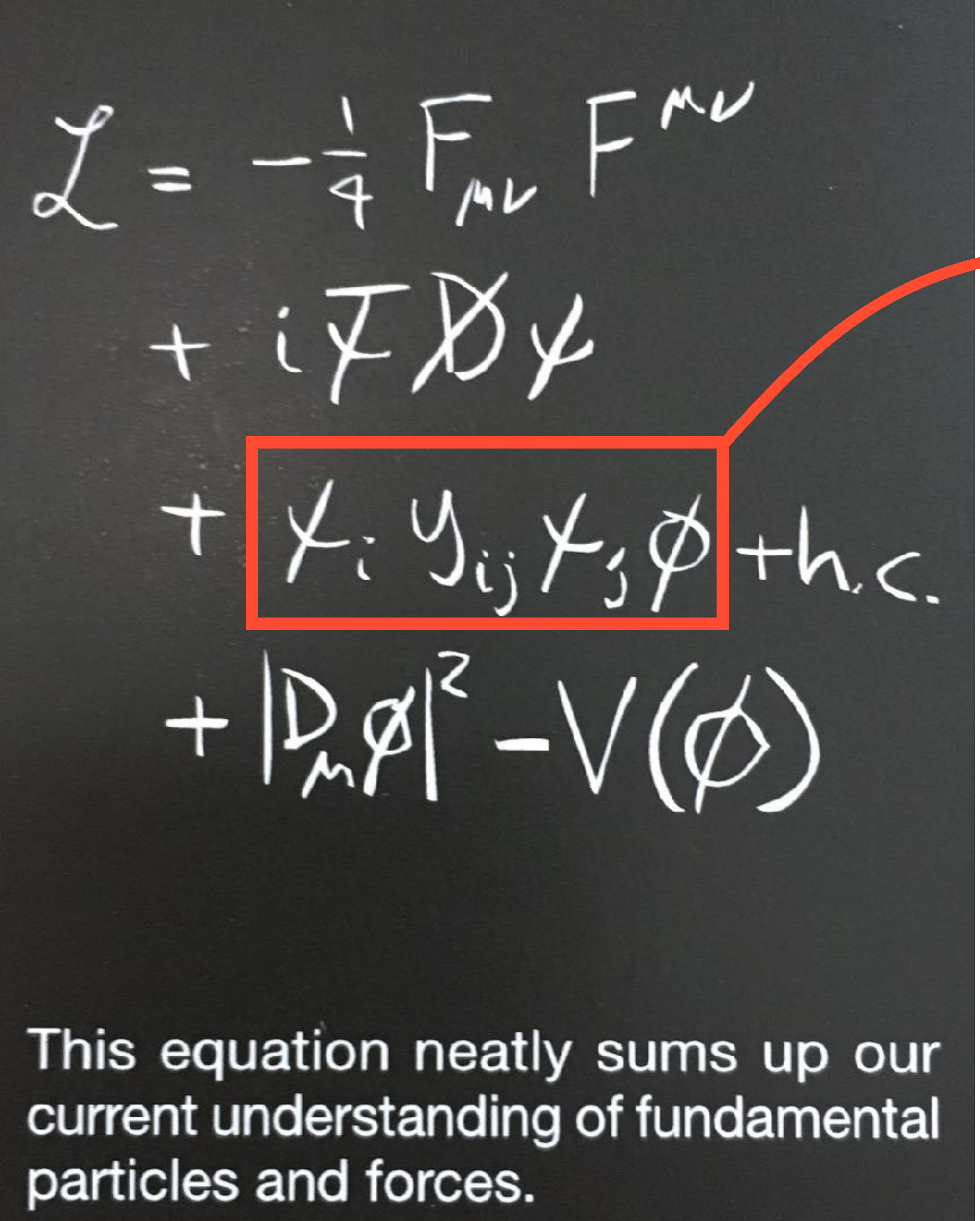
(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)

Many SM studies probe this part.

In some respects dates back to 1860’s, i.e. **Maxwell’s equations.**

If you test another corner of this (as one should), don’t be surprised if it works

Yukawa couplings

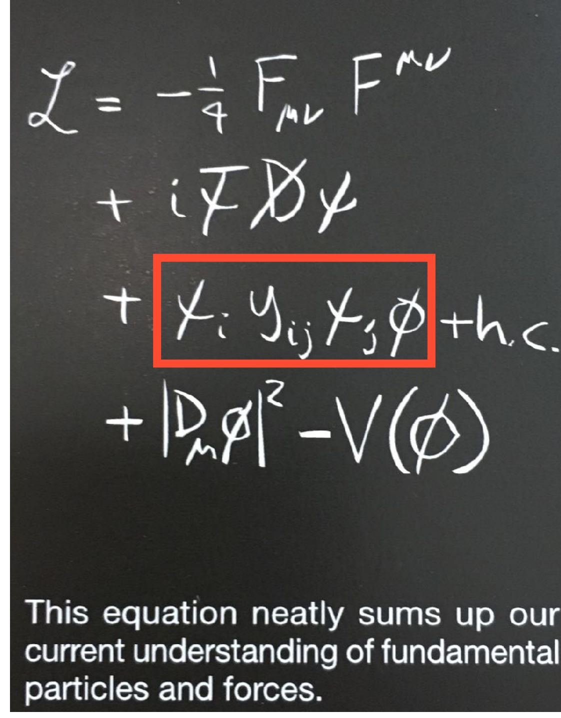


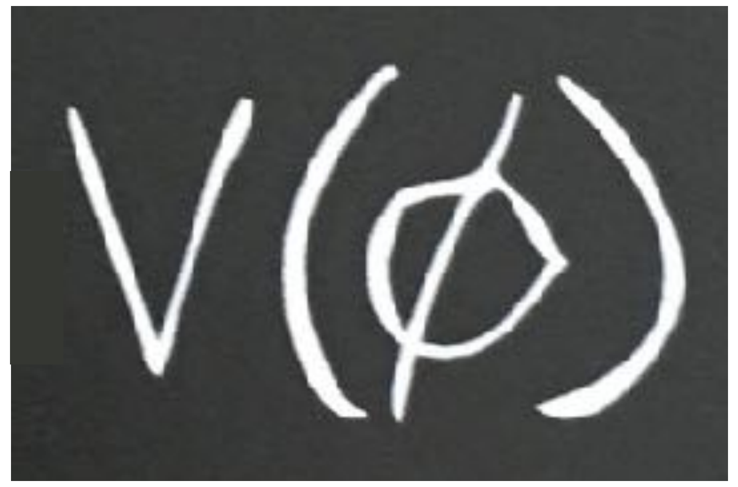
until 6 years ago this was essentially conjecture

no such term had ever been seen in nature

hadn't even been probed in electroweak precision tests

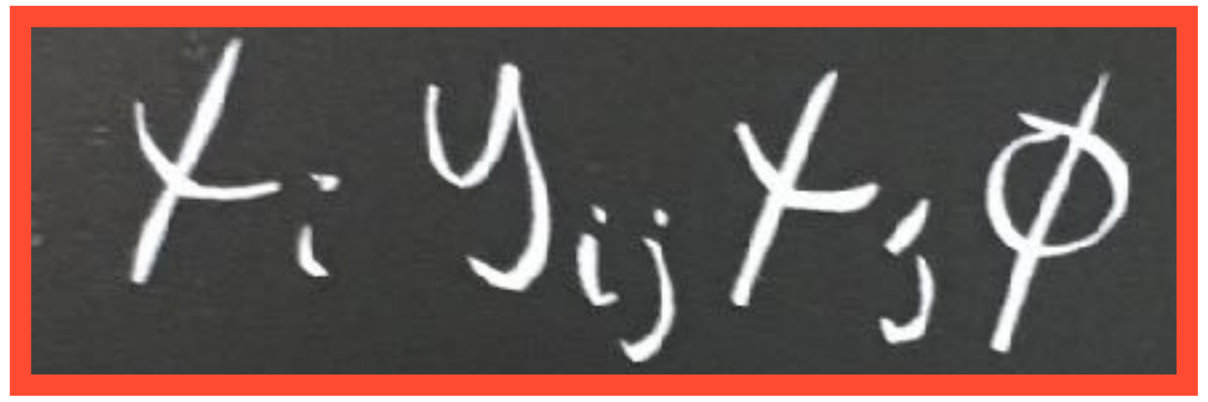
Why do Yukawa couplings matter?
(1) A part of the Higgs sector that's unlike any other experimentally-probed interaction





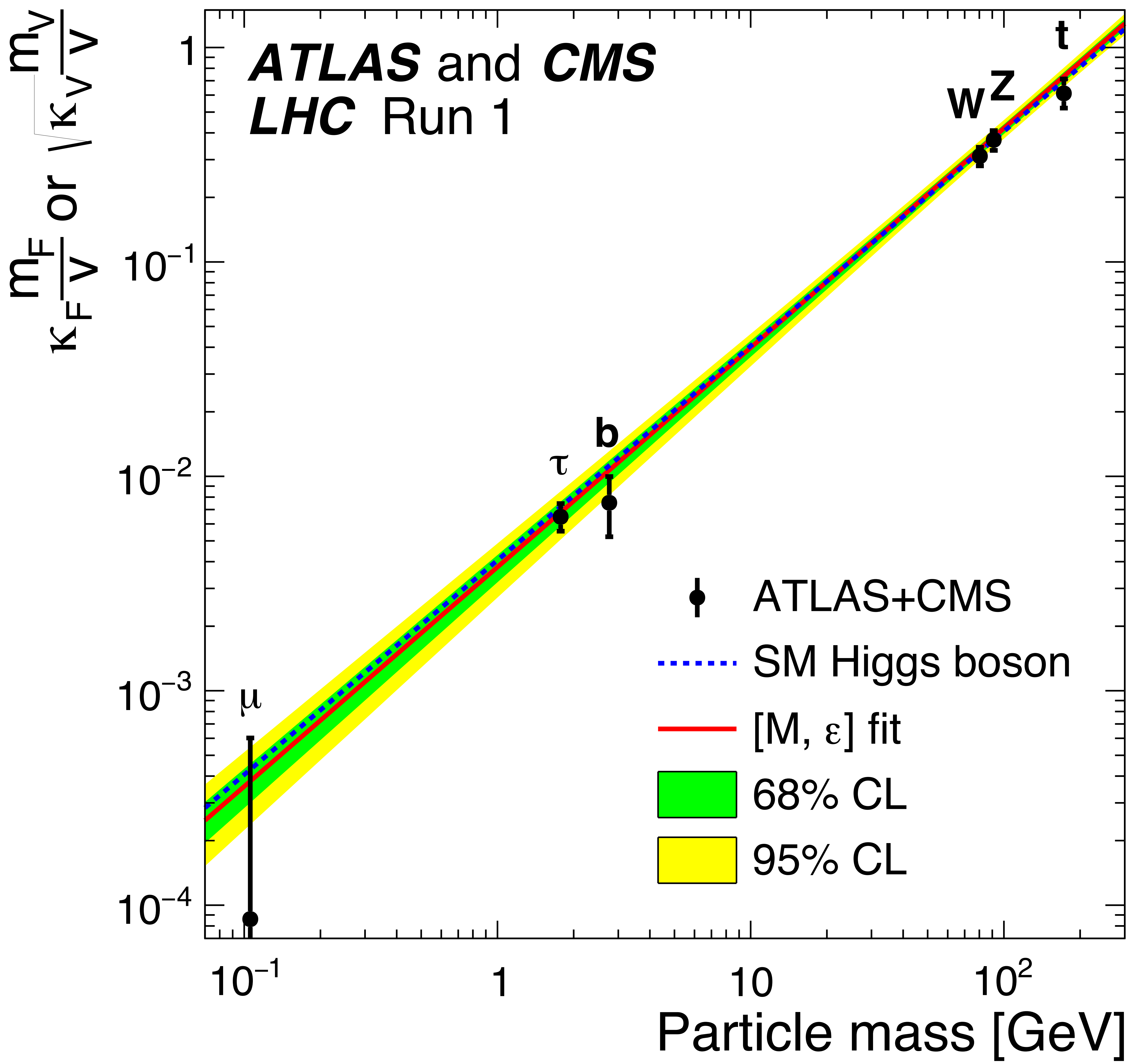
($-\mu^2\varphi^2 + \lambda\varphi^4$, HHH) the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like what we've seen before



(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we've probed before

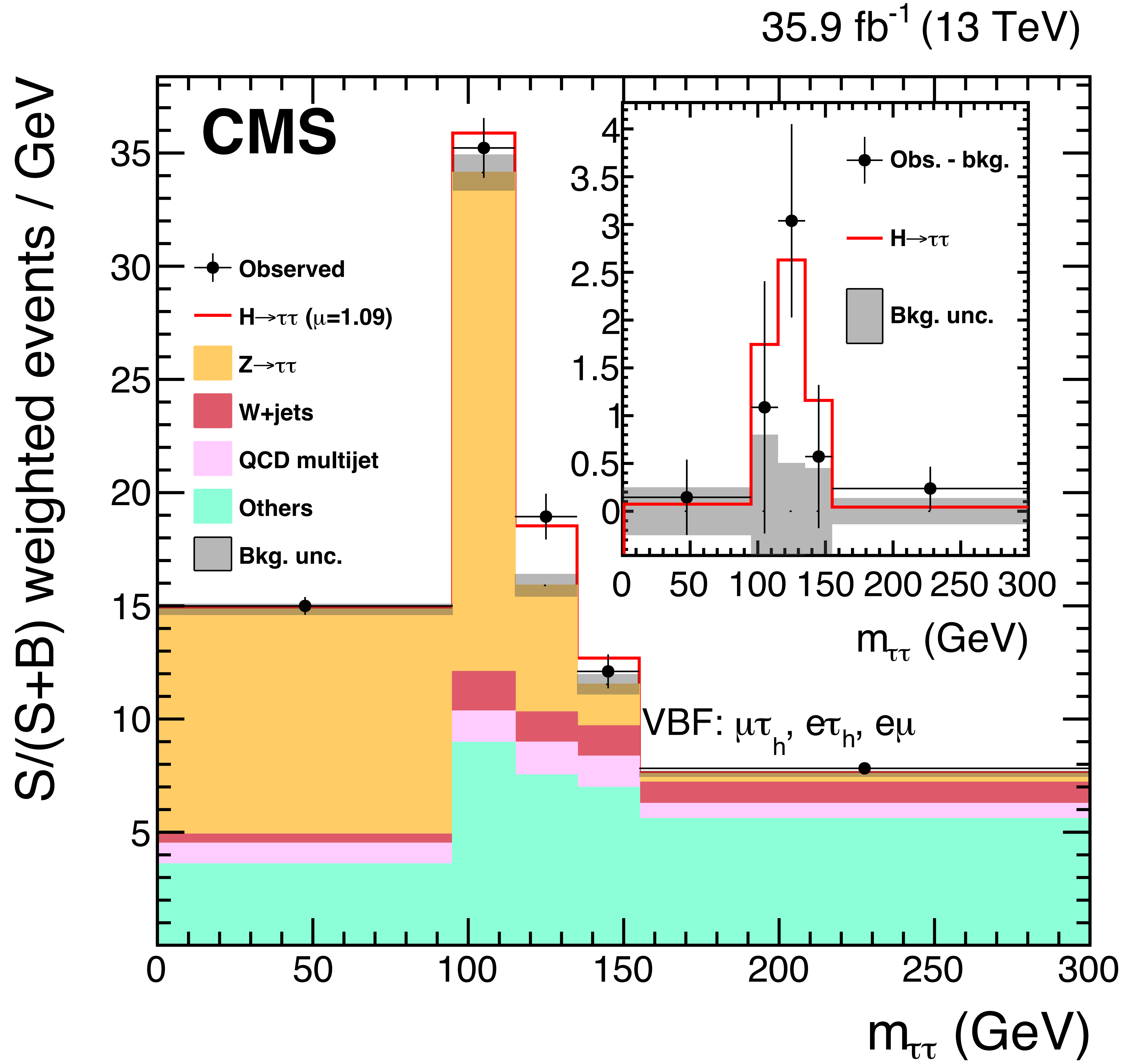
the status two years ago



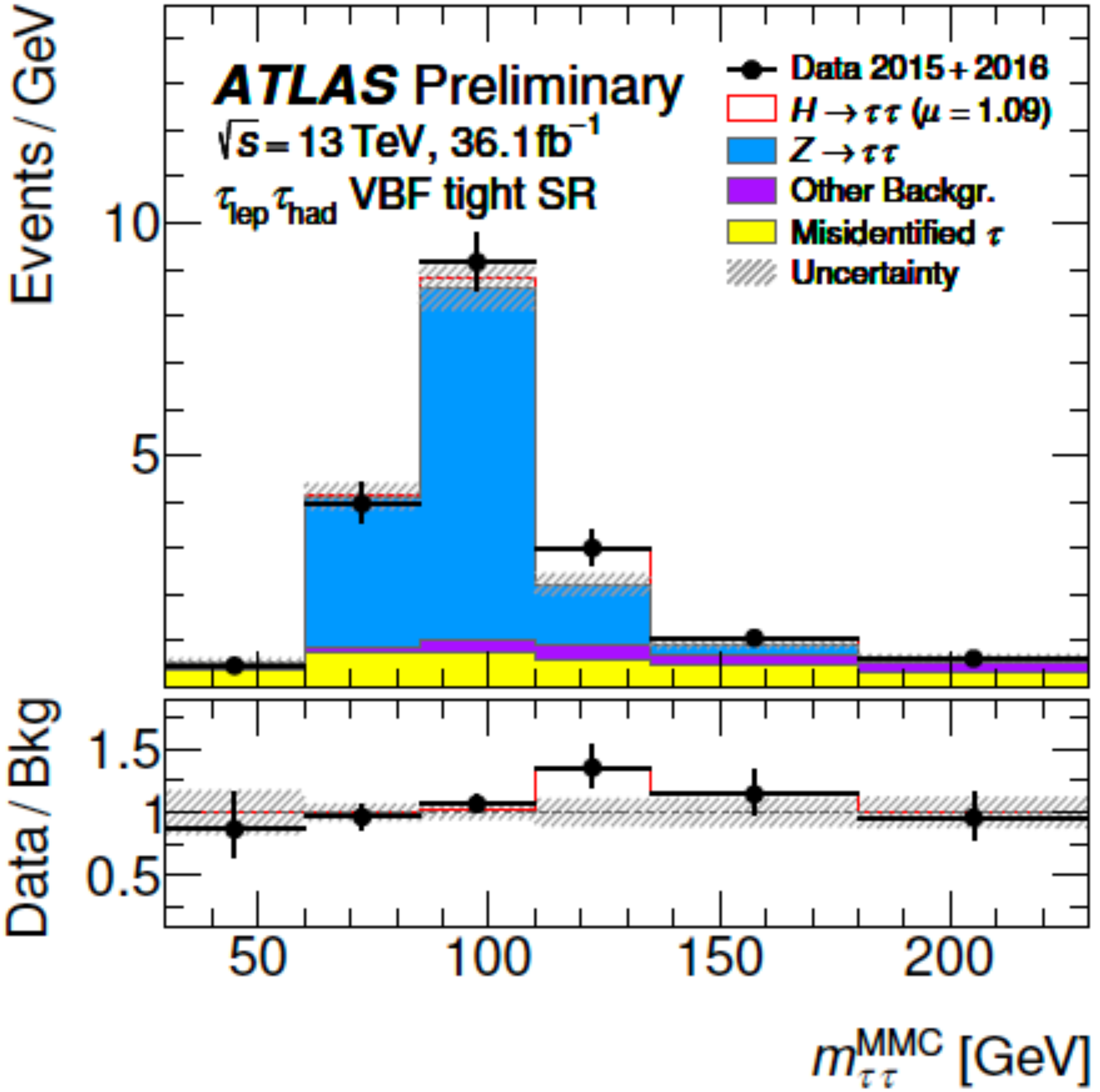
- A beautiful plot, appears to show SM working perfectly
- But it mixes two very different kinds of interaction: gauge for W,Z, Yukawa for fermions
- would not look anything like as convincing without underlying fit assumptions
  - no new particles in loops
  - no BSM decays

the news of the past 12 months

A year ago:
CMS >5-sigma H → τ τ

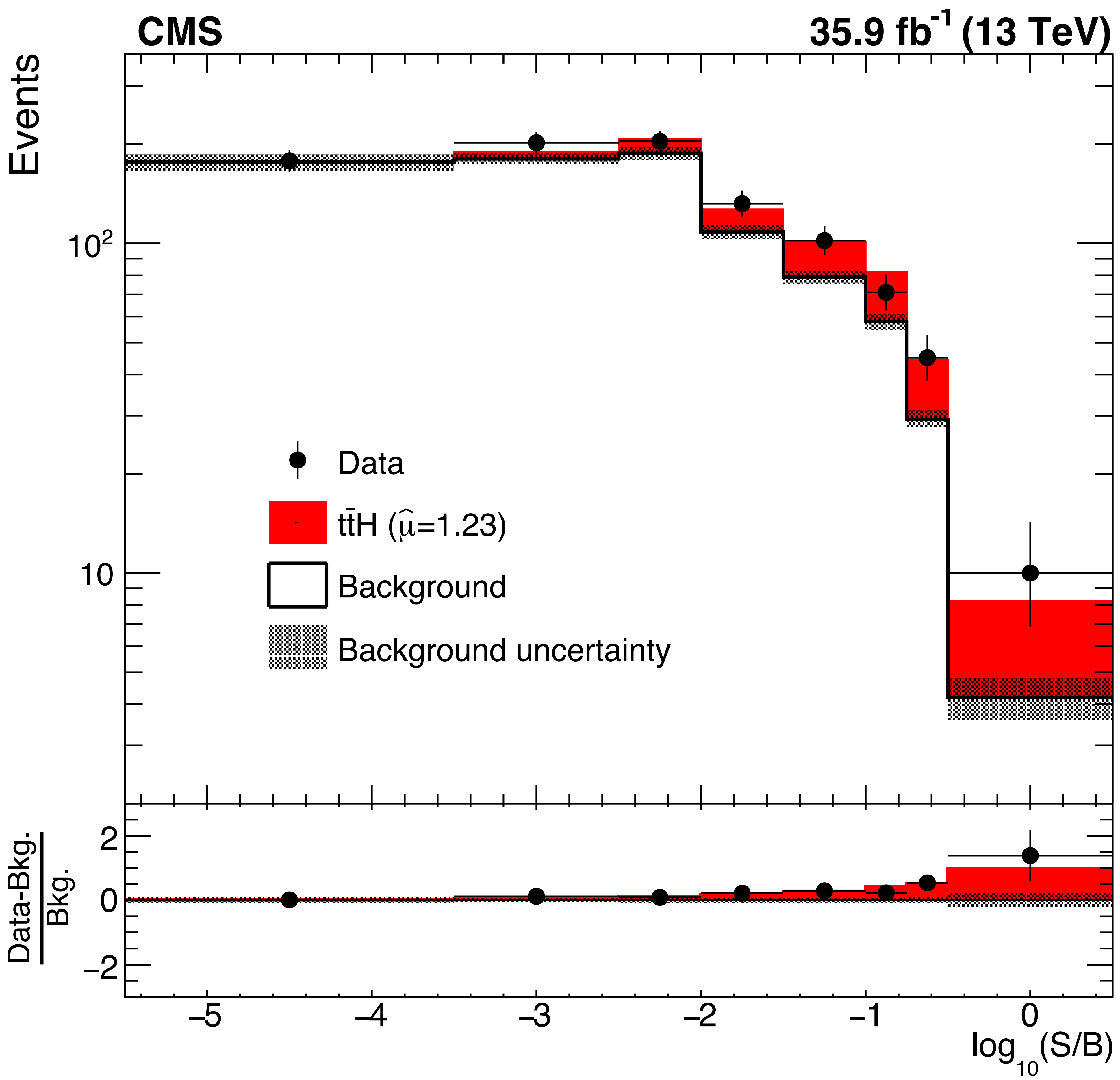


This week:
ATLAS >5-sigma H → τ τ



the news of the past 12 months

A few weeks ago:
CMS >5-sigma ttH



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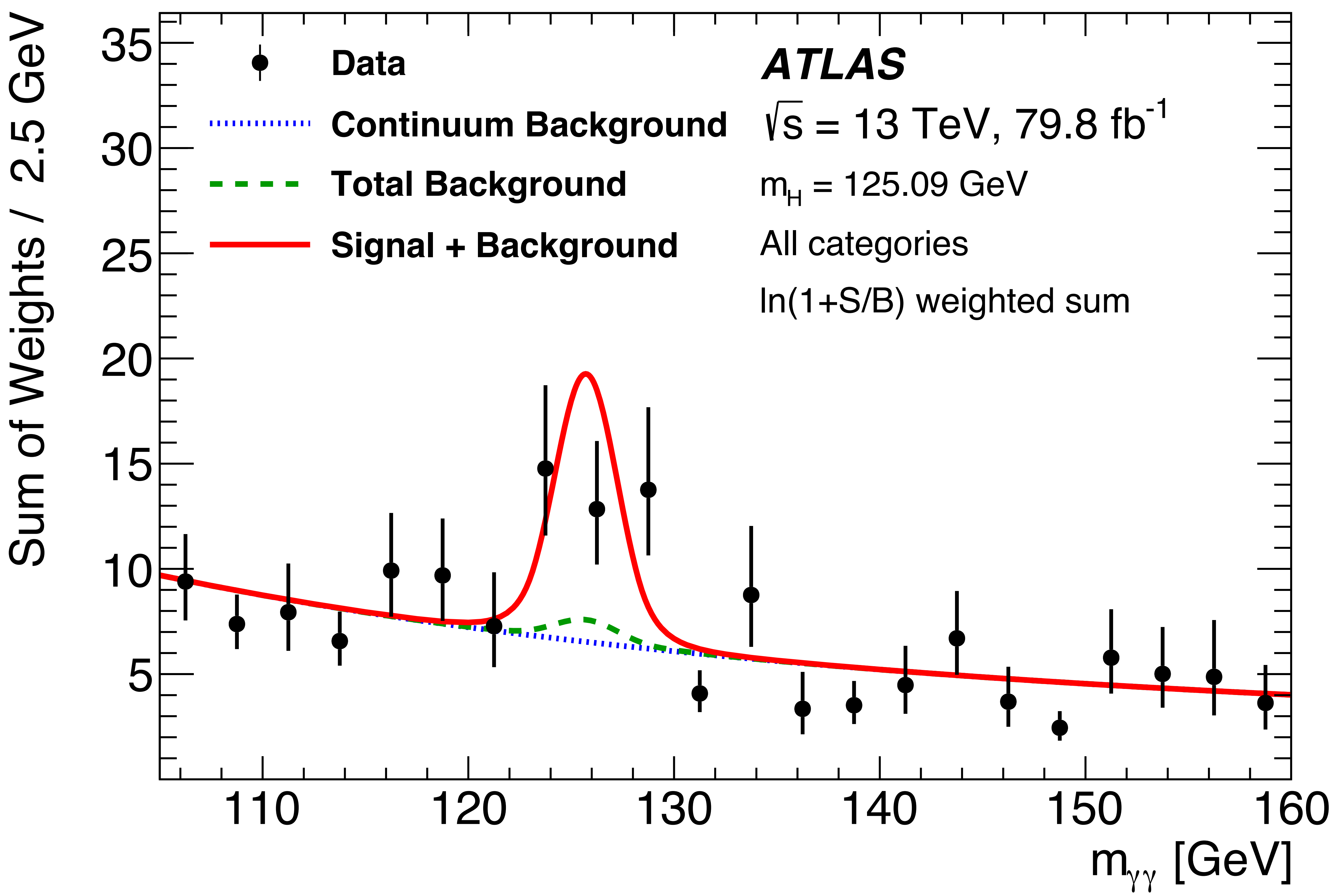
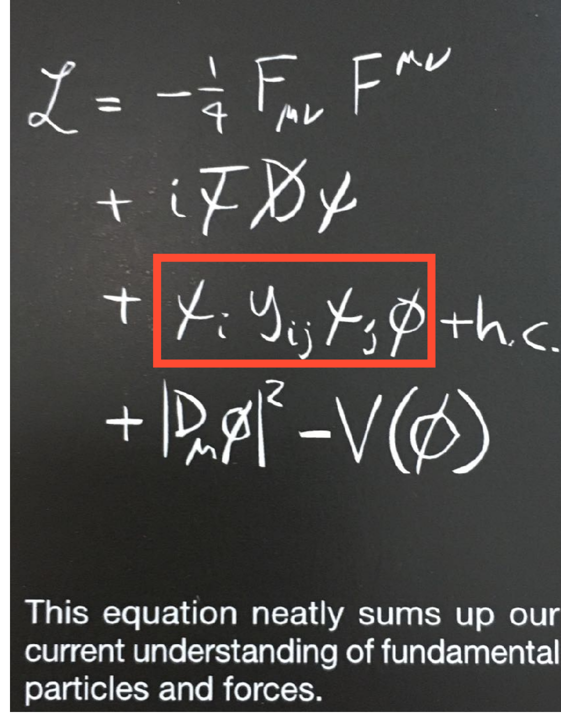


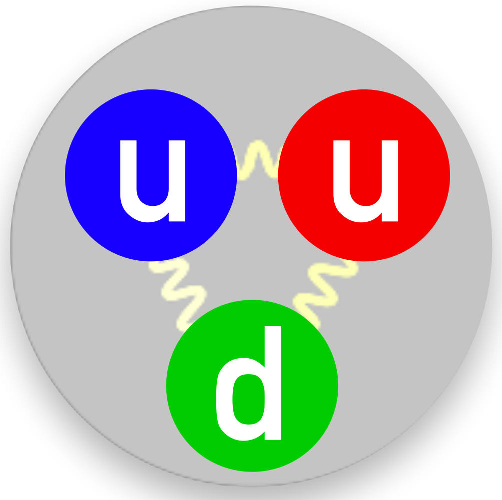
Why do Yukawa couplings matter?
(2) Because, within SM **conjecture**, they're what give masses to all **quarks**



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

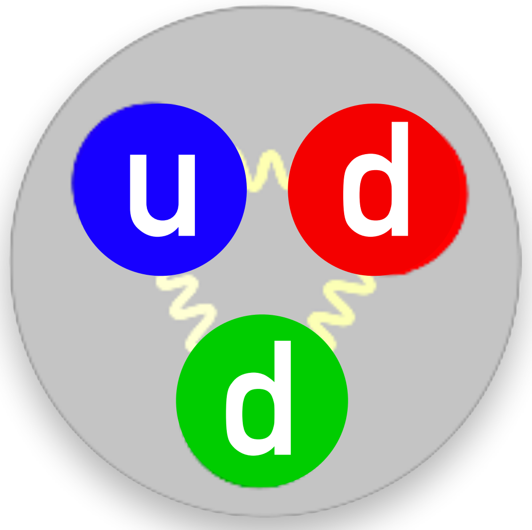
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton
mass = 938.3MeV



proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

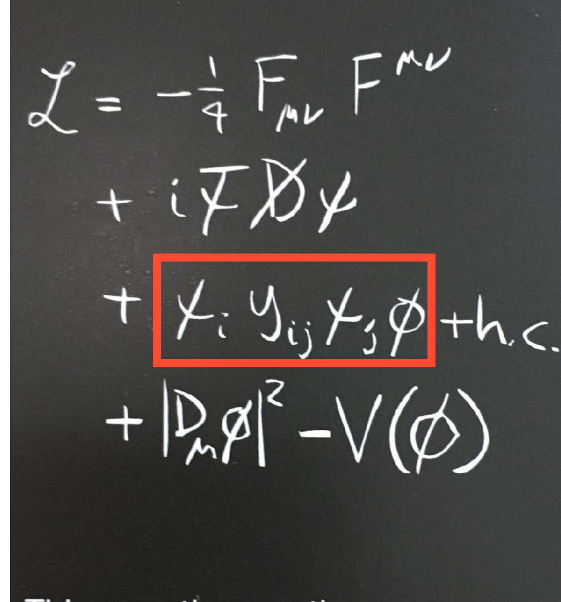
neutron
mass = 939.6MeV



So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

Why do Yukawa couplings matter?
(3) Because, within SM **conjecture**, they're what give masses to all **leptons**


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

Bohr radius

$$a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

electron mass determines size of all atoms

it sets energy levels of all chemical reactions

what should we be saying about it?

The $>5\sigma$ observations of ttH and $H \to \tau\tau$, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction**, Yukawa interactions.

Yukawa interactions are important not merely because they had never before been directly observed, but also because they are **hypothesized to be responsible for the stability of hydrogen,** and for determining the size of atoms and the energy scales of chemical reactions.

what should we be saying about it?

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Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

I disagree.

Because the non-gauge part of the standard model is far from being fullly explored.

2 Yukawas out of 9

We know nothing about the self coupling

“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

Bottom-Yukawa coupling

How?

- Look for Higgs decays into t
- Huge background from jet e additional objects to tag: VB
- Complex final states ⟹ mul jets to objects and to disting

Greatest challenges

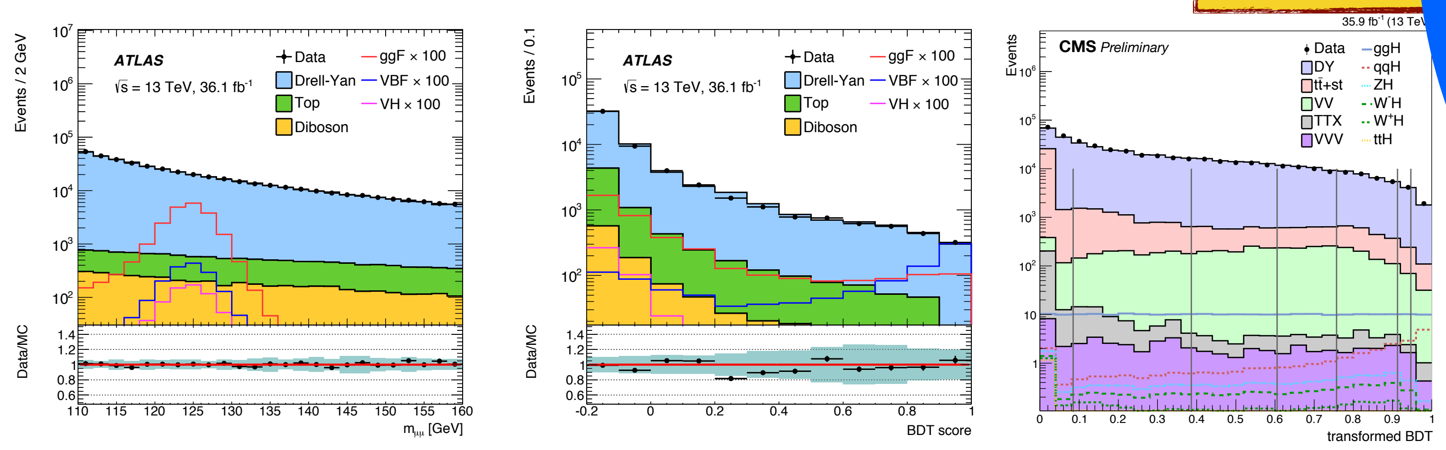
- Good **flavour tagging** perfo
- Large backgrounds from *tt* a

Grefe — C. Grefe - Higgs

Search for $H\to\mu\mu$

Phys. Rev. Lett. 119 (2017) 0518

CMS-PAS-HIG-17-0



- Loose event selection **requiring two isolated OS muons** and veto *b*-jets
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions; fit to di-muon mass distribution in all signal regions

ATLAS:
- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)
- All other events categorised in 6 *ggF* categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_\mu|$

CMS:
- Separate signal from background using BDT ($p_T^{\mu\mu}$, $\eta_{\mu\mu}$, m_{jj}, $|\Delta\eta_{jj}|$, $N_{b\text{-jets}}$ etc.)
- De sc

Grefe — C. Grefe - Higgs couplings to ferm

so much more to do with the Higgs sector

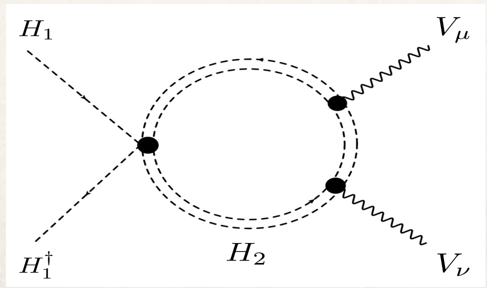
EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \ldots$$

dimension-6 — dimension-8; BSM effects — SM particles

example: 2HDM



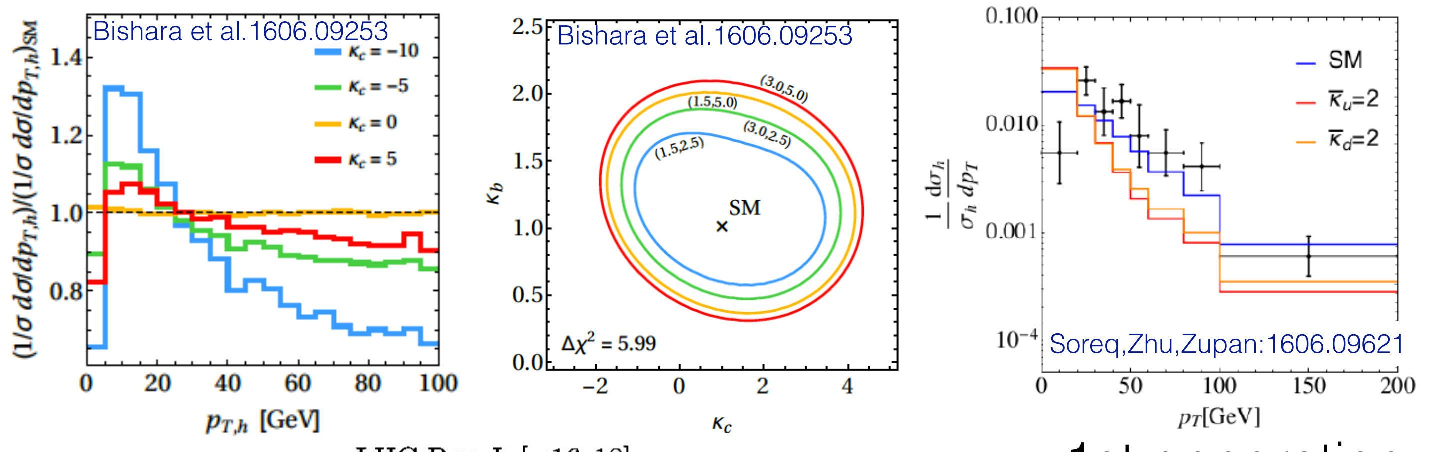
$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

where $\bar{c}_W = \dfrac{m_W^2\,(2\tilde\lambda_3+\tilde\lambda_4)}{192\,\pi^2\,\tilde\mu_2^2}$

Sanz

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT



κ_c — LHC Run I: $[-16, 18]$; LHC Run II: $[-1.4, 3.8]$; HL-LHC: $[-0.6, 3.0]$

1st generation
To be fully explored

Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging)
(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)
$ZH(H\to c\bar{c})$ gives a limit of 110 x SM expectation (ATLAS-CONF-2017-078)

Vryonidou — LHCP2018 — 13

The Higgs potential

Higgs potential: $V(H) = \frac{1}{2}M_H^2H^2 + \lambda_{HHH}vH^3 + \frac{1}{4}\lambda_{HHHH}H^4$

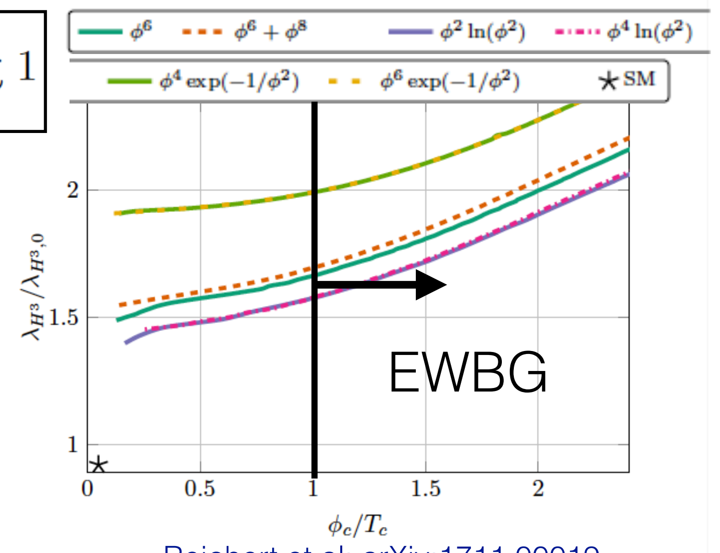
Fixed values in the SM: $\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

Electroweak baryogenesis requires a first order strong EWPT ⟶ $\frac{\phi_c}{T_c} \gtrsim 1$

$\lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1$
EW baryogenesis is disfavoured
$\lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1$
EW baryogenesis is favoured



Reichert et al: arXiv:1711.00019

Vryonidou — LHCP2018 — 20

A cosmological Higgs

HIGGS

Dark Matter — Higgs portal, Higgs DM mediator

UV sensitivity — Naturalness, heavy new physics, Relaxation

Inflation — Higgs inflation, Inflaton vs Higgs

Phase transitions — Baryogenesis, gravitational waves

Fate of the Universe — Stability

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

Sanz

EFT (expressive formulation of constraints) or not?

- If you've observed a given channel, and it agrees roughly (±30%) with SM, then go to EFT
- if you've not observed it, e.g. charm Yukawa, Higgs self coupling, then use of EFT is more debatable

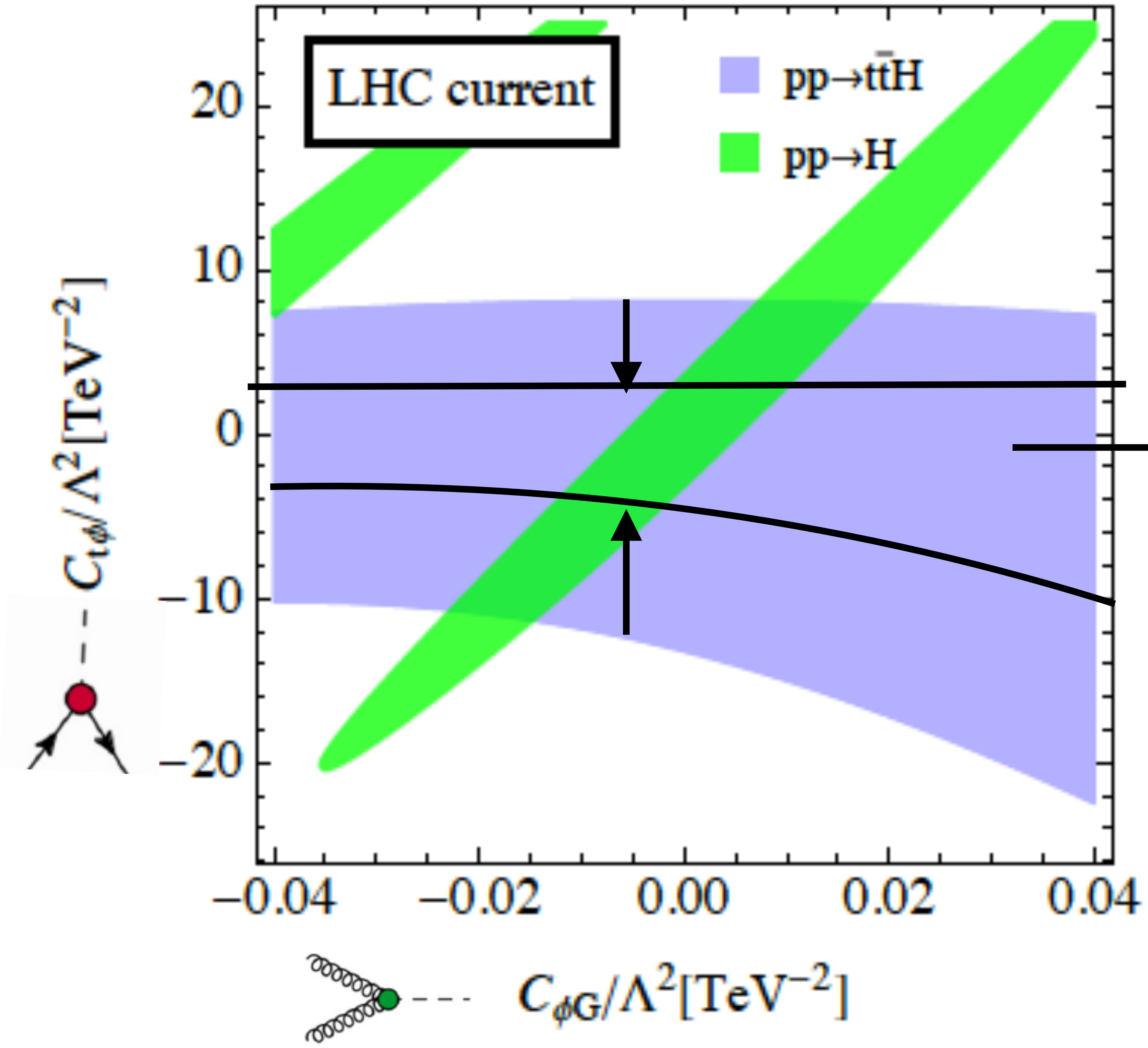
establish SM first

then use (lack of) any deviations to (constrain) characterise new physics

dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles



impact of recent ttH observation

Current limits using LHC measurements

Vryonidou

2nd & 1st generation Yukawas

- the hierarchy of masses between generations remains a mystery (even if it's one that some people consign to the "hopeless" category)
- Does not necessarily come from hierarchy of dimensionless Yukawa coefficients
- E.g. the Giudice-Lebedev mechanism (and follow-up work)

0804.1753

$$-\mathcal{L}_Y = Y_{ij}(\phi)\bar{\psi}_i \psi_j \phi + \text{h.c.} \qquad\qquad Y_{ij}(\phi) = c_{ij}\left(\frac{\phi^\dagger \phi}{M^2}\right)^{n_{ij}}$$

- smallness of certain masses is consequence of vev^2/M^2 suppression, not small c_{ij}
- measured Hqq interaction larger by factor $(2n_{ij} + 1)$
- cf. also various more recent discussions, e.g. by Bauer, Carena, Carmona

1801.00363

dark matter & other searches

"

Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider's second run

-a large LHC experiment's spokesperson [2015]

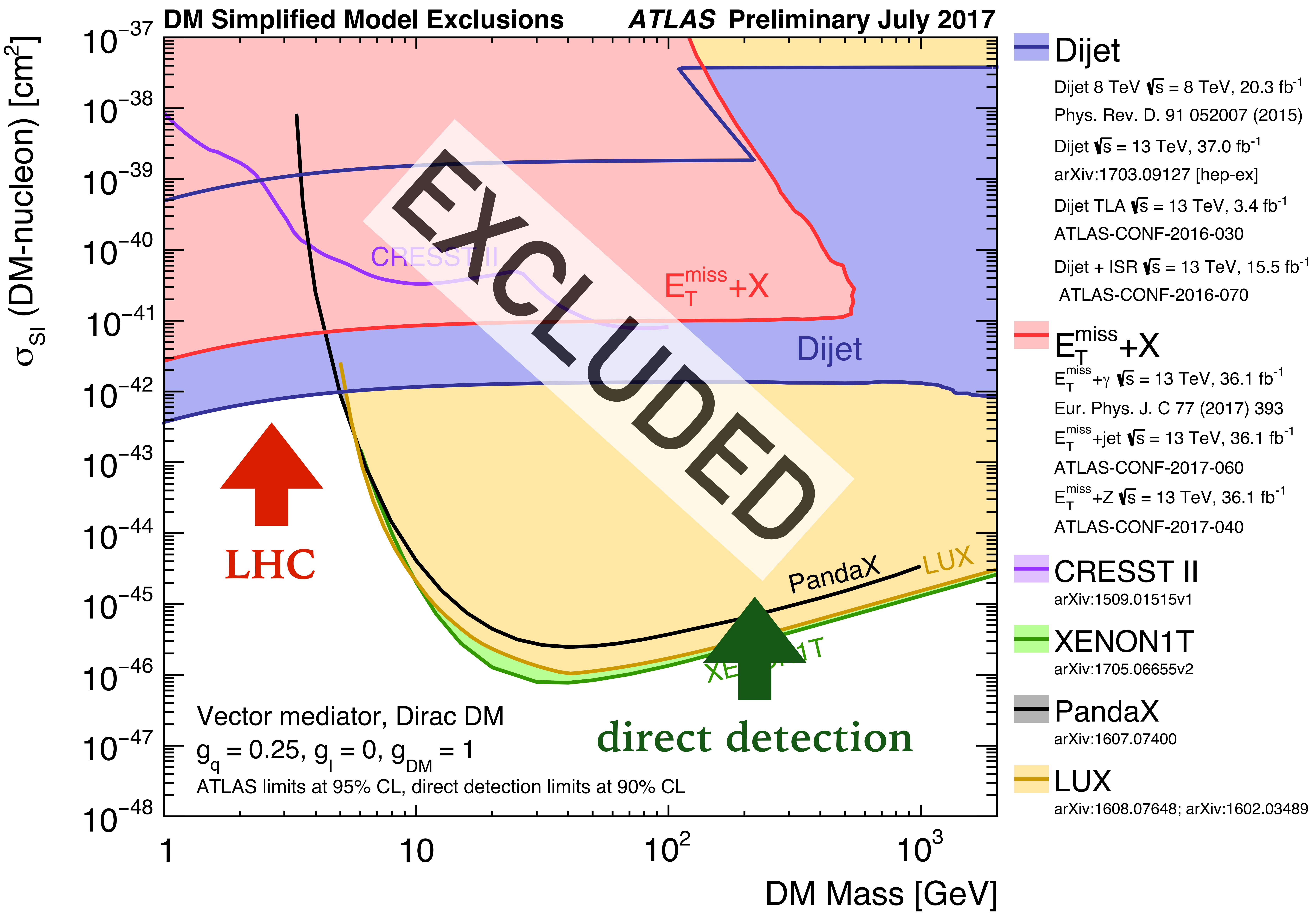
https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

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)



musn't be (too) disappointed at lack of dark matter signal at LHC

Evidence for dark matter exists since the 1930s.

Today we know that

- **there are many possible models**
- **the range of parameters they span is large**

We must deploy full ingenuity in searching for dark matter, including at LHC.

But must also recognise that it has remained elusive for 80–90 years, and chances of finding it in any given year are small!

Snowmass non-WIMP dark matter report, 1310.8642

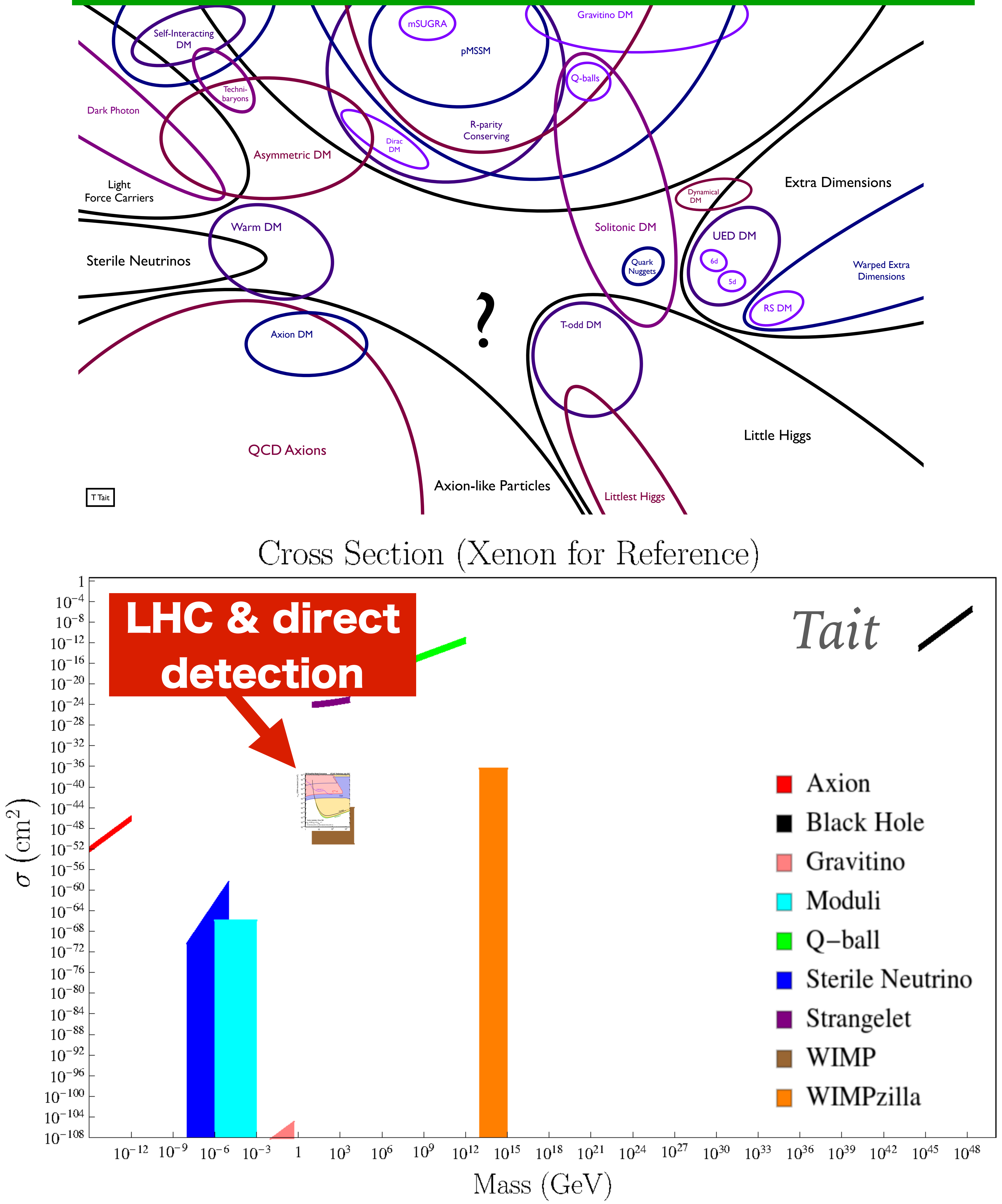
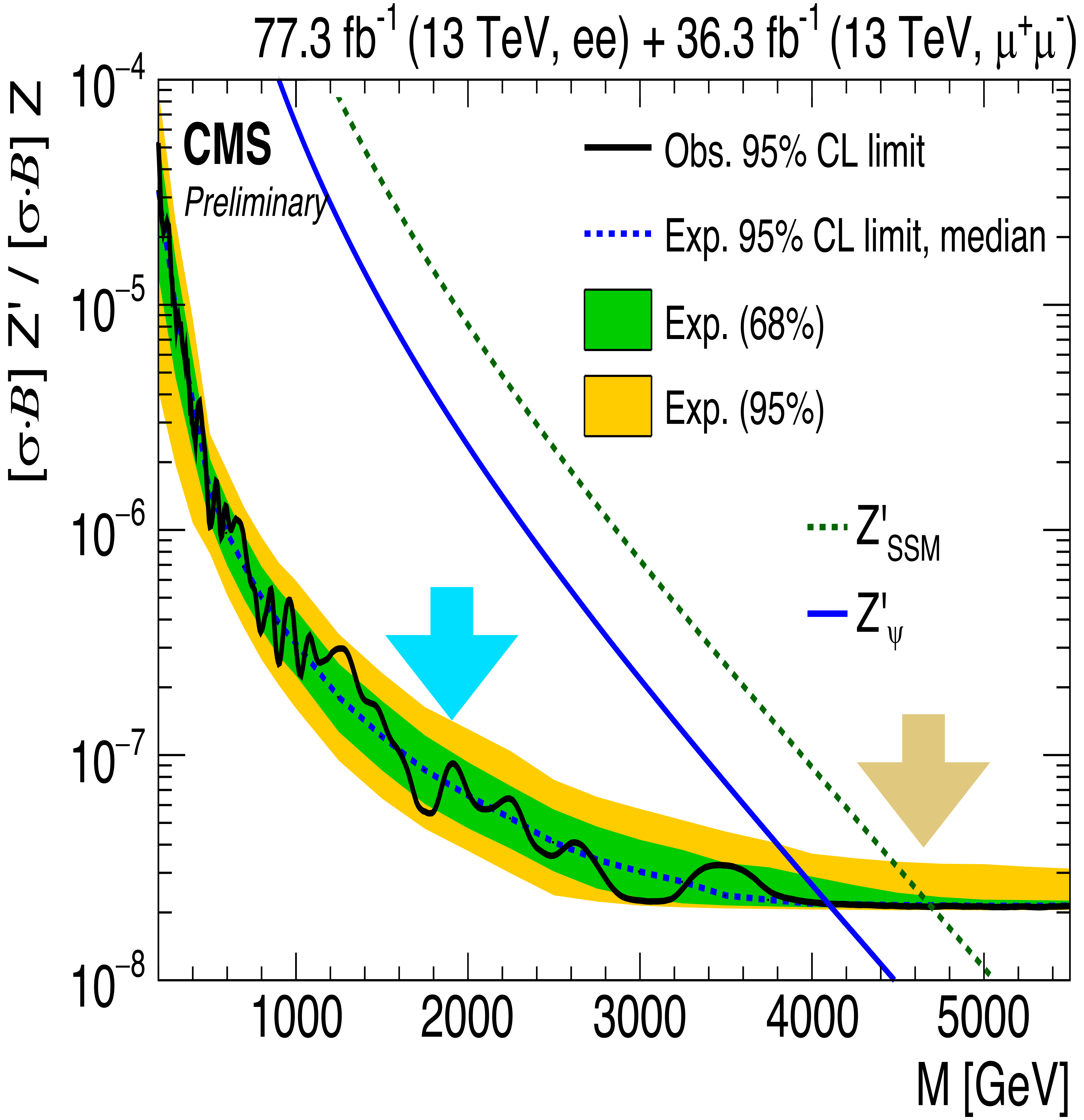


Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of masses and interaction cross sections.*

don't underestimate the value of luminosity

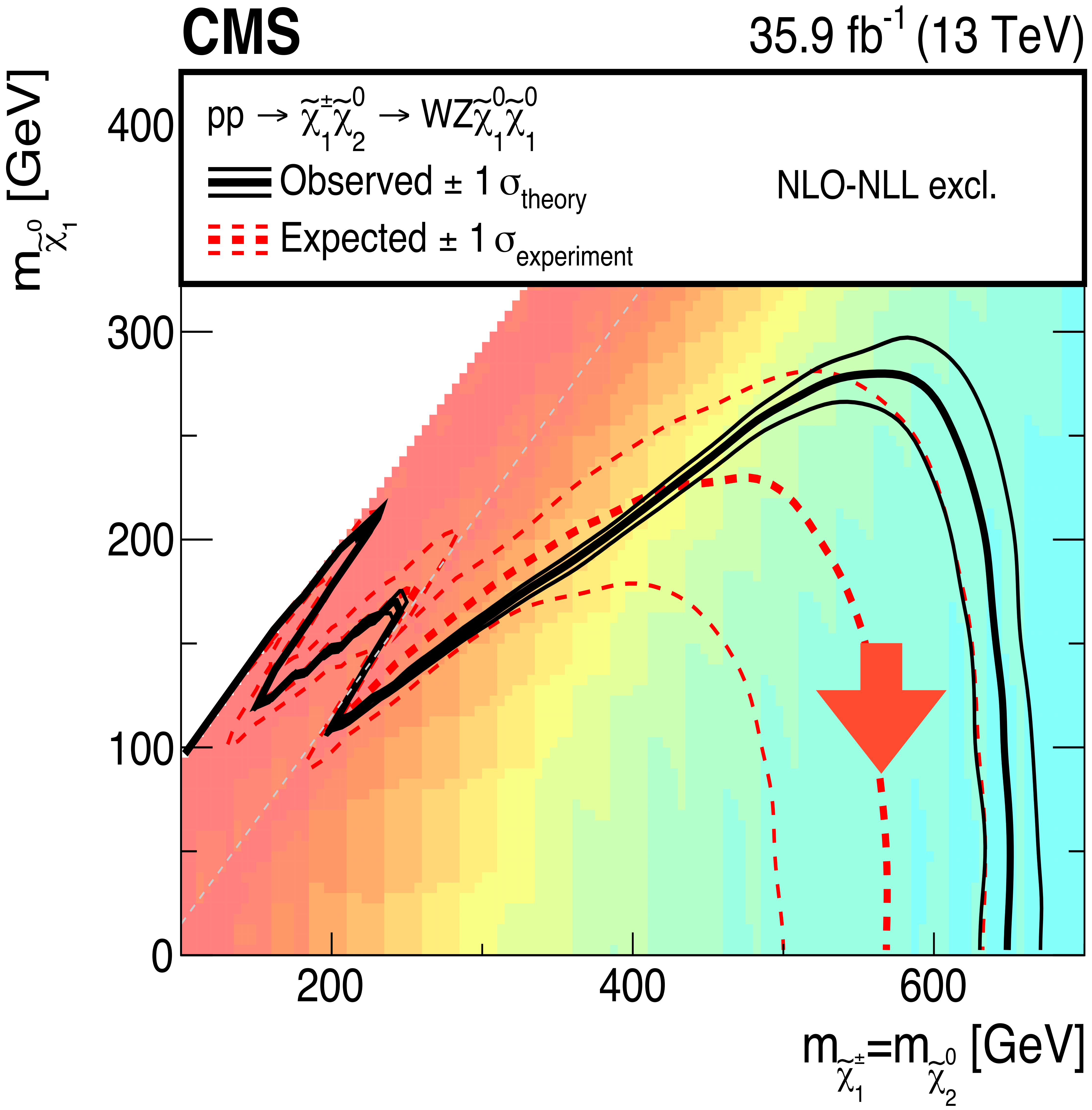


- Suppose we had a choice between
  - HL-LHC (14 TeV, $3ab^{-1}$)
  - or going to higher c.o.m. energy but limited to $80fb^{-1}$.
- How much energy would we need to equal the HL-LHC?

today's reach (13 TeV, $80fb^{-1}$)	HL-LHC reach (14 TeV $3ab^{-1}$)	energy needed for same reach with $80fb^{-1}$
4.7 TeV SSM Z'	6.7 TeV	20 TeV
2 TeV weakly coupled Z'	3.7 TeV	37 TeV

estimated with http://collider-reach.cern.ch , Weiler & GPS

don't underestimate the value of luminosity



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4.7 TeV SSM Z'	6.7 TeV	20 TeV
2 TeV weakly coupled Z'	3.7 TeV	37 TeV
680 GeV chargino	1.4 TeV	54 TeV

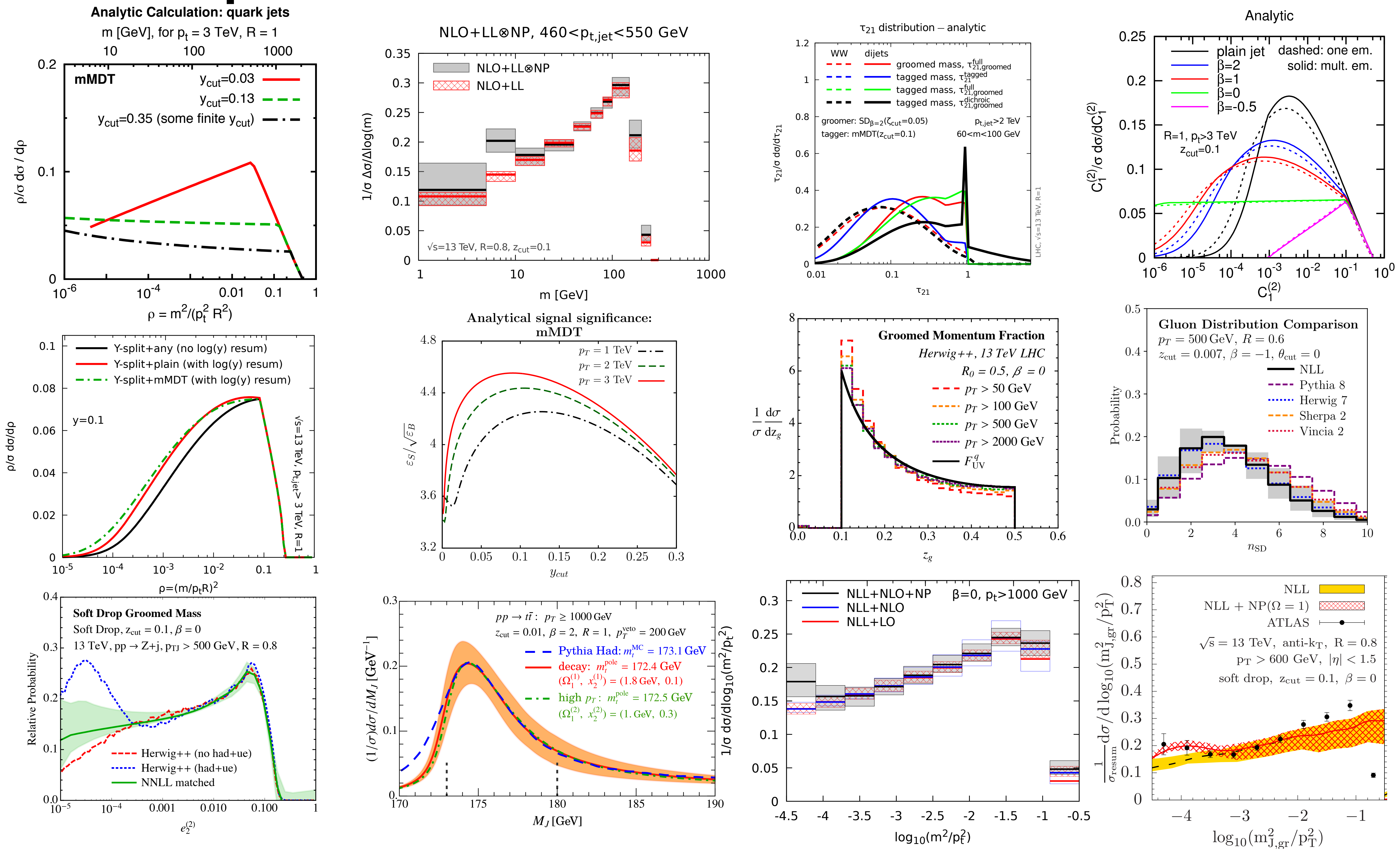
Facini

Cover All Signatures

- We don't know the description of nature so we really don't know what new physics will look like in our detector

- Personal opinion: If we cannot prove that an existing measurements or search forbids new physics in a given final state/topology, **we have to look!**

Explosion of Jet Substructure Calculations!



arXiv:1307.0007, 1402.2657, 1502.01719, 1503.01088, 1603.09338, 1609.07149, 1612.03917, 1704.02210, 1704.06266, 1708.02586, 1712.05105, 1803.03645, 1803.04719

Larkoski

flavour anomalies

the current place where there are hints of something happening

charged current

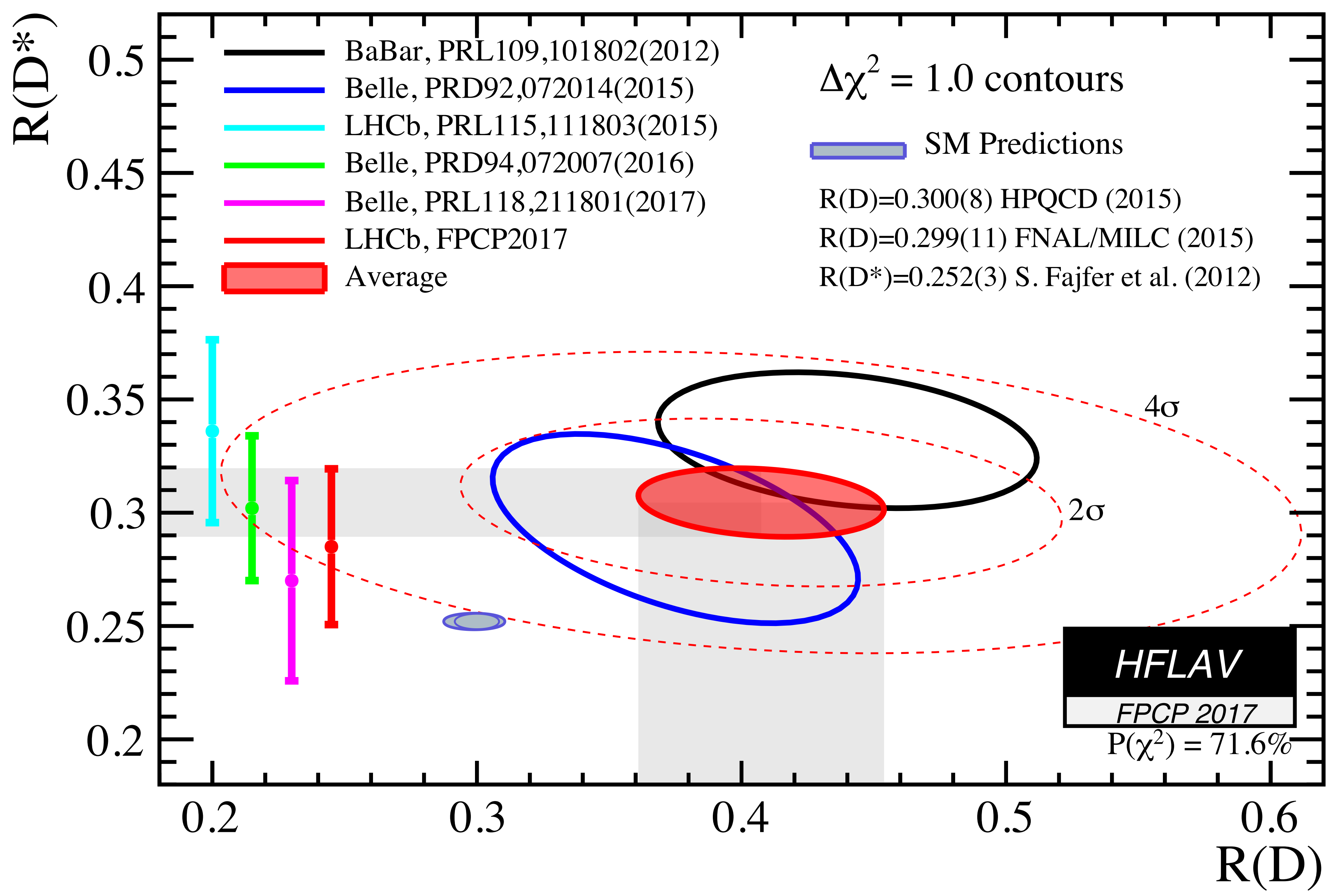
neutral current

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

$R(D^*)$ and $R(D)$ combination

Combine LHCb's $R(D^*)$ results with results from B factories:

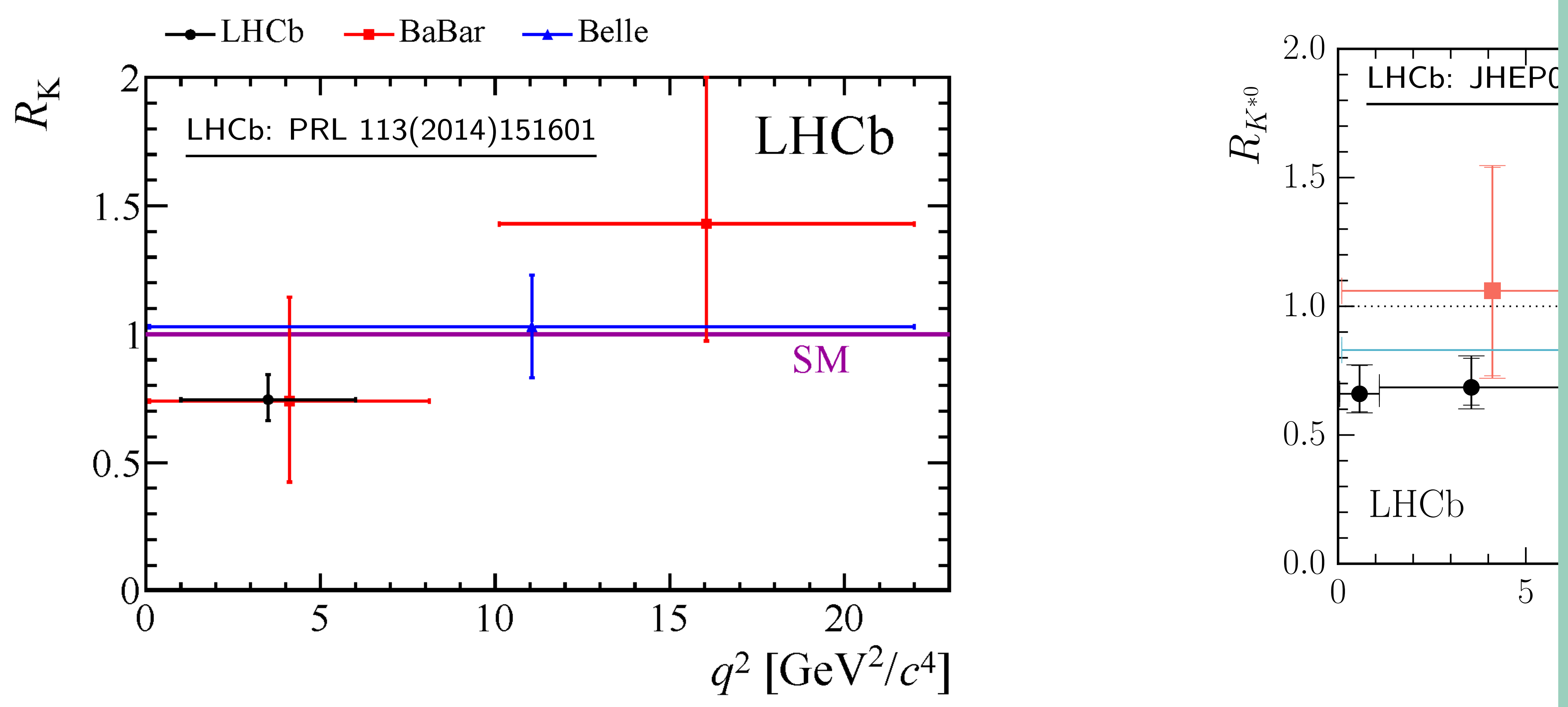


⇒ $R(D^*)$ and $R(D)$ average $\sim 4\ \sigma$ from SM
(latest SM computation: JHEP 11 (2017) 061)

$R(K)$ and $R(K^*)$ results

(See Andrea Mogini's talk on Monda

BaBar: PRD 86(2012)032012   Belle: PRL 103 (2009) 171801



- All LHCb results below SM expectations:
  - $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central q^2, $\sim 2.6\,\sigma$ from SM;
  - $R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low q^2, $\sim 2.2\,\sigma$ from SM;
  - $R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central q^2, $\sim 2.4\,\sigma$ from SM;
- B factories have less precise but compatible results.

Humair

flavor	generic	minimal
$R_{K^{(*)}}$ tree	30 TeV	6 TeV
$R_{K^{(*)}}$ loop	few TeV	0.5 TeV
$R_{D^{(*)}}$ tree	$\sim$ a TeV	0.3 TeV

Hiller

Linking the anomalies is intriuging however not straightforward, lower deviation in $R_{D^{(*)}}$, in particular R_{D^*} more ”natural”.

- In general the main observable generating tensions is $R(D^{(*)})$, with EW precision tests and B_s-mixing.

- Still work has to be done to find a completely satisfying NP model for the B-anomalies.

Marzocca

standard model theory

Summary & Outlook

Huss

- **precision Drell–Yan predictions:**
  - ↪ fixed order: NNLO QCD, NLO EW, mixed QCD–EW (pole approx.)
  - ↪ $\mathcal{O}(\alpha_s\alpha)$ mass shift: $\Delta M_W^{\alpha_s\alpha} \sim -14\,\text{MeV}$
  - ↪ compatible with NLO(QCD+EW)⊗PS(QCD+QED): $\Delta M_W^{\alpha_s\alpha} \sim -16 \pm 3\,\text{MeV}$
- **the inclusive p_T^V spectrum:**
  - ↪ N^3LL+NNLO: excellent agreement vs. data & residual uncertainties ~few %
  - ↪ bottom-quark effects: $\sim \pm 0.5\%$ $(\Delta M_W < 5\,\text{MeV})$
  - ↪ $(\text{NLL+NLO})_{\text{QED}}$: $\sim \pm 0.5\%$
- **$V + \text{jet}$ production**
  - ↪ NNLO QCD available $\forall$ $V = W^\pm, Z/\gamma^*, \gamma$
  - ↪ NLO EW important in tails of distributions
  - ↪ first steps towards multi-jet merging including EW corrections
- **Di-boson production**
  - ↪ NNLO QCD available $\forall$ $VV' \in \{W^\pm, Z/\gamma^*, \gamma\}$
  - ↪ NNLO⊗PS: NNLO accuracy in inclusive quantities & captures soft-g effects
  - ↪ NLO EW: prediction for *off-shell* processes

Summary & Outlook

Huss

- **precision Drell–Yan predictions:**
  - ↪ fixed order: NNLO QCD, NLO EW, mixed QCD–EW (po
  - ↪ $\mathcal{O}(\alpha_s\alpha)$ mass shift: $\Delta M_W^{\alpha_s\alpha} \sim -14\,\text{MeV}$
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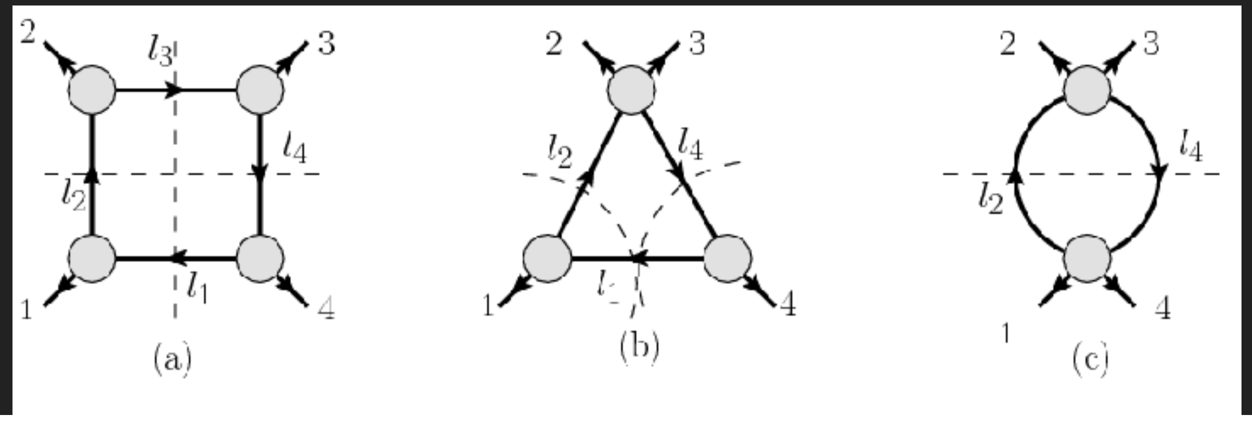
Melnikov on analytical approaches

VIRTUAL CORRECTIONS: REDUCTIONS

Generalized unitarity provides a different approach to the reduction to master integrals; reduction coefficients are reconstructed from cuts of scattering amplitudes. Very successful method at one-loop; attempts to generalise to two- loops.

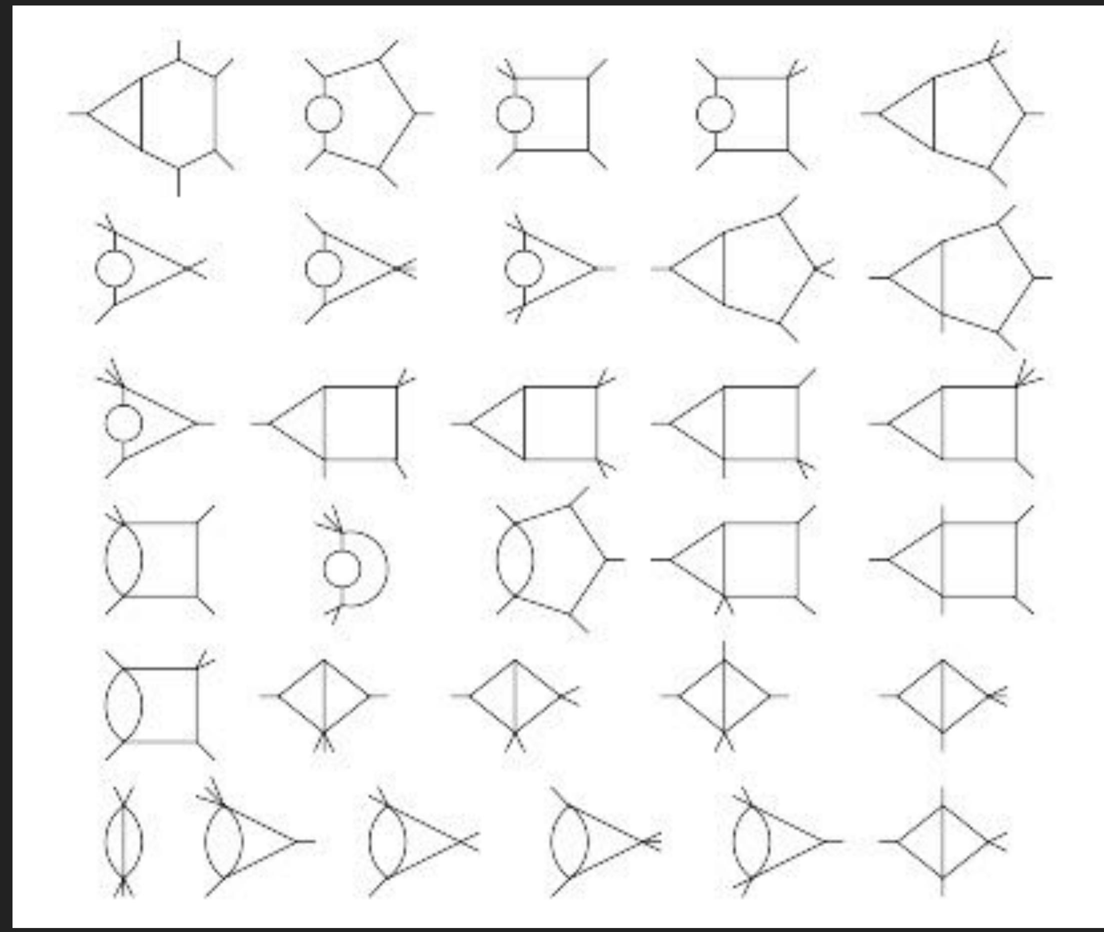
Recent progress with the evaluation of planar (large N$_c$) contribution to five-gluon two-loop amplitude.

An impressive proof of concept that unitarity works at two-loops but still far from a real computation of the full scattering amplitude and e.g. the phenomenology of the three-jet NNLO cross sections.



	ϵ^{-4}	ϵ^{-3}	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
$\widehat{A}^{(2),[0]}_{--+++}$	12.5	27.7526	-23.773	-168.117	-175.207±0.004
$P^{(2),[0]}_{--+++}$	12.5	27.7526	-23.773	-168.116	—
$\widehat{A}^{(2),[0]}_{-+-++}$	12.5	27.7526	2.5029	-35.8094	69.661±0.009
$P^{(2),[0]}_{-+-++}$	12.5	27.7526	2.5028	-35.8086	—

Badger, Bronnum-Hansen, Hartano, Peraro



Similar results in Abreu, Cordero, Ita, Page, Zeng

Summary & Outlook

Huss

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  - ↪ (NLL+NLO)$_Q$
- **V + jet produ**
  - ↪ NNLO QCD a
  - ↪ NLO EW imp
  - ↪ first steps to
- **Di-boson prod**
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  - ↪ NNLO⊗PS: N
  - ↪ NLO EW: pre

VIRTUAL CORRECTIONS: REDUCTIONS

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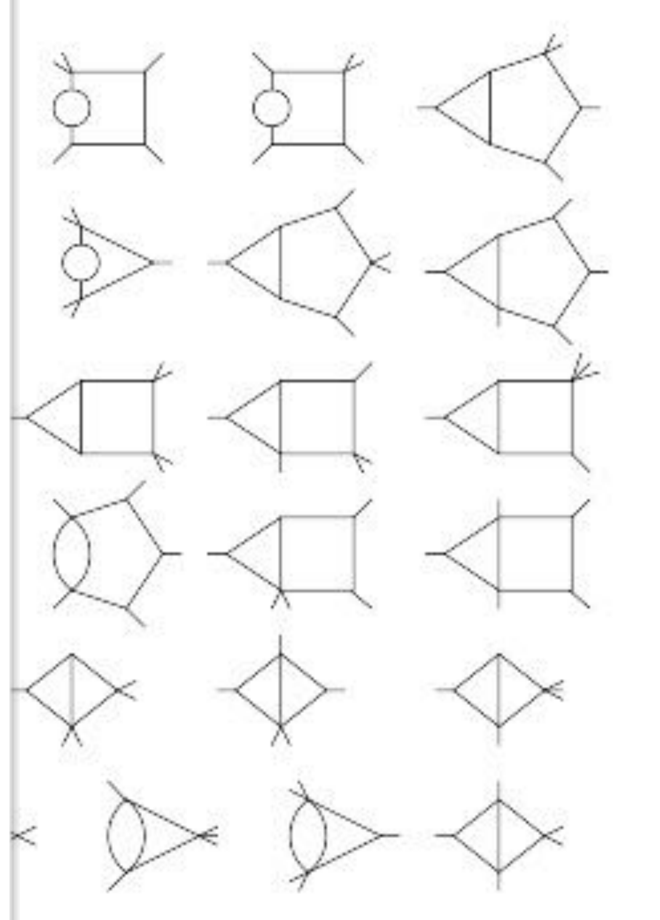
...on of the full scattering



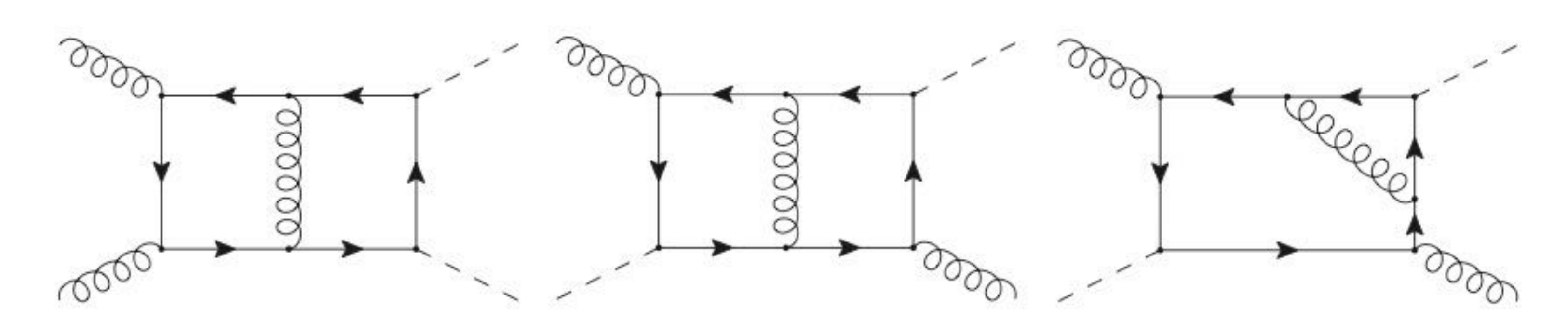
...breu, Cordero, Ita, Page, Zeng

VIRTUAL CORRECTIONS: INTEGRALS

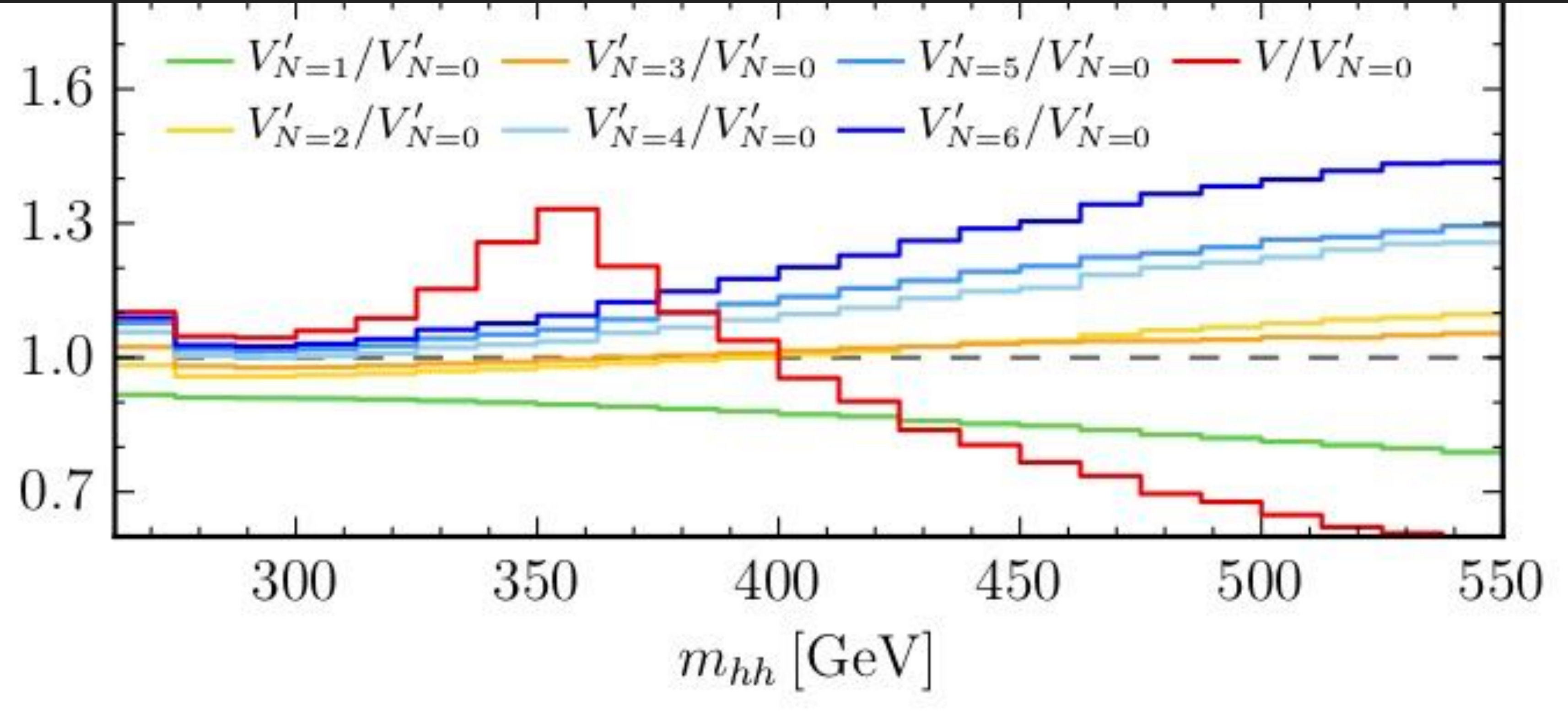
Melnikov on numerical approaches

Master integrals can also be computed upon numerical integration over Feynman parameters (SecDec). This method has been successfully applied to double Higgs and Higgs + jet production at the LHC with full top mass dependence.

$$\vec{I} = \int_0^1 ... \int_0^1 \mathrm{d}x_1 ....\mathrm{d}x_n \, \frac{\vec{N}(x_1, x_2, ..., x_n)}{D(x_1, x_2, ...x_n)}$$

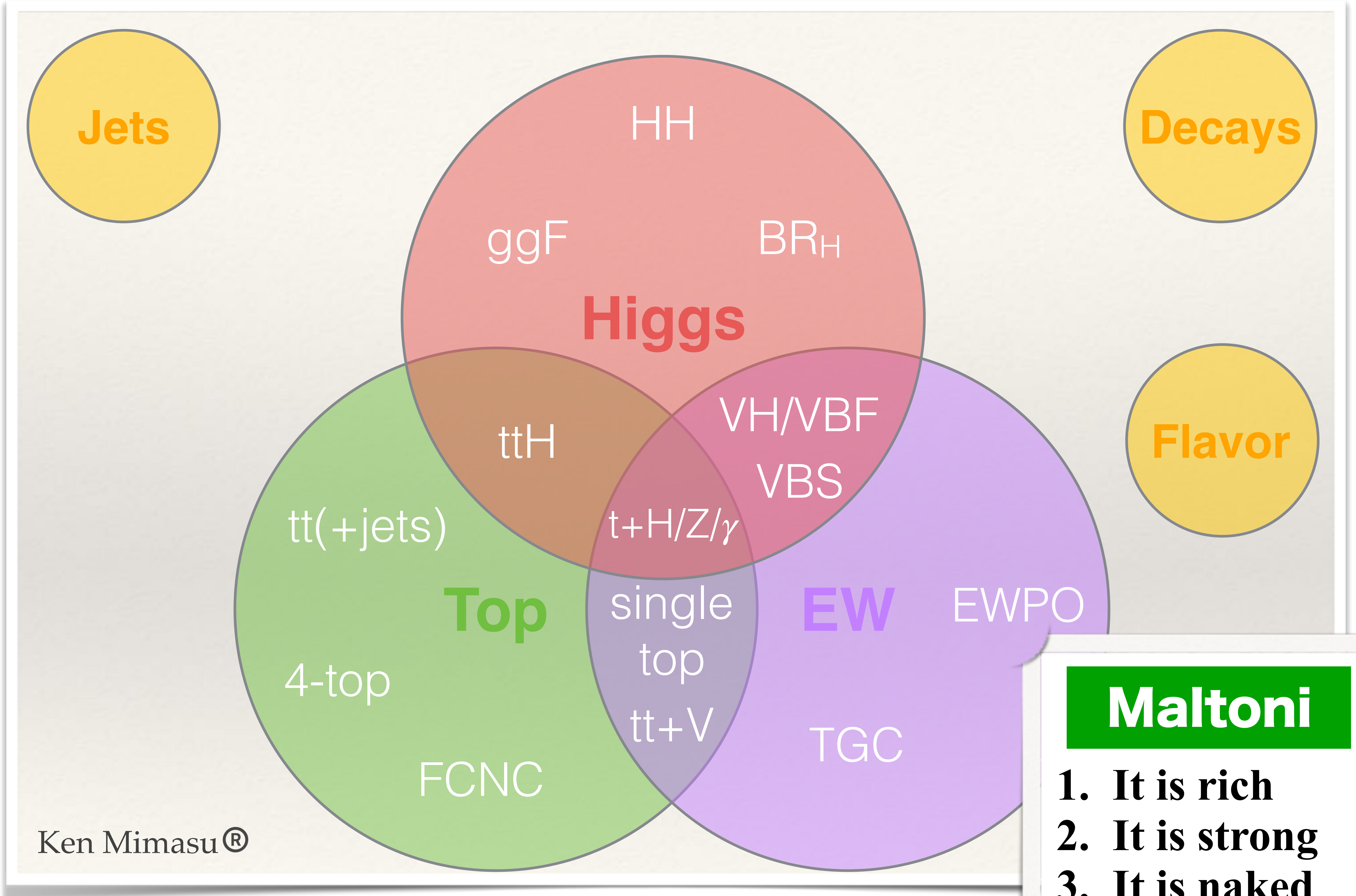


Double-Higgs production $gg \to HH$



Borowka, Greiner, Heinrich, Kerner, Jones, Schenk, Zirke

top



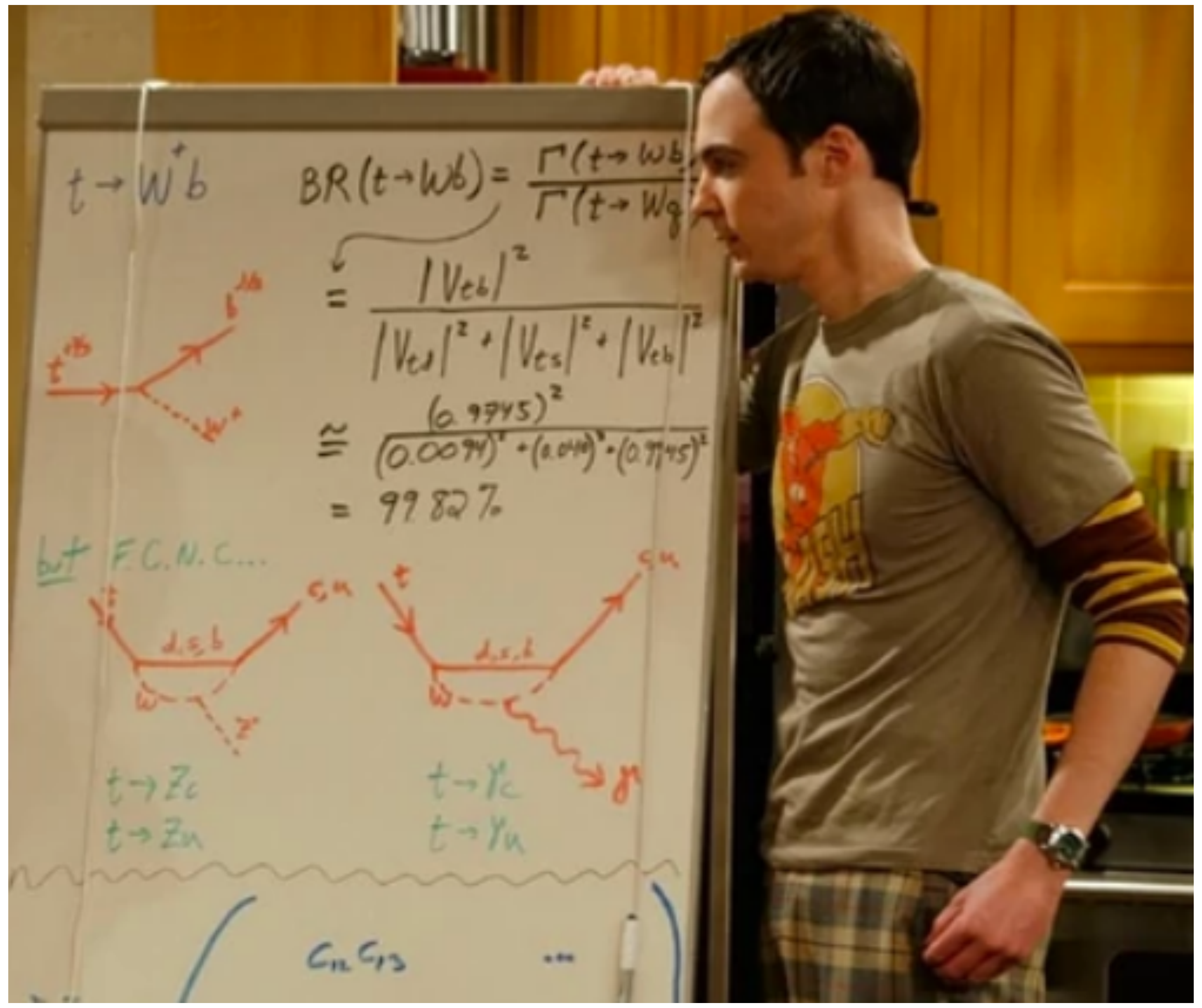
Maltoni

1. **It is rich**
2. **It is strong**
3. **It is naked**
4. **It is popular**
5. **It goes beyond**

The top quark is the Ronaldo of elementary particles

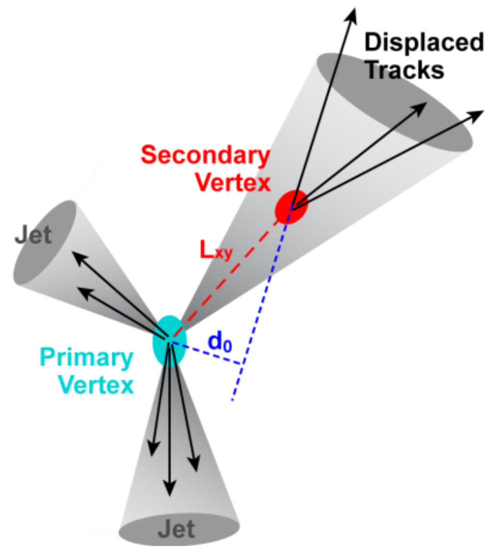
Top quarks are key to almost everything!

Search for new physics

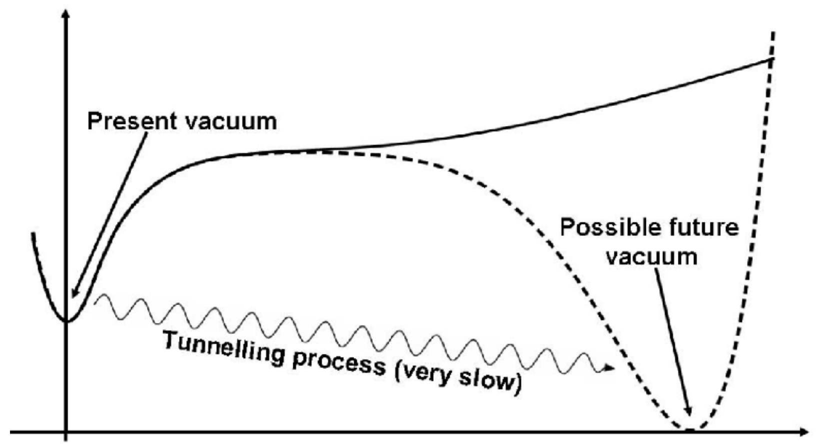


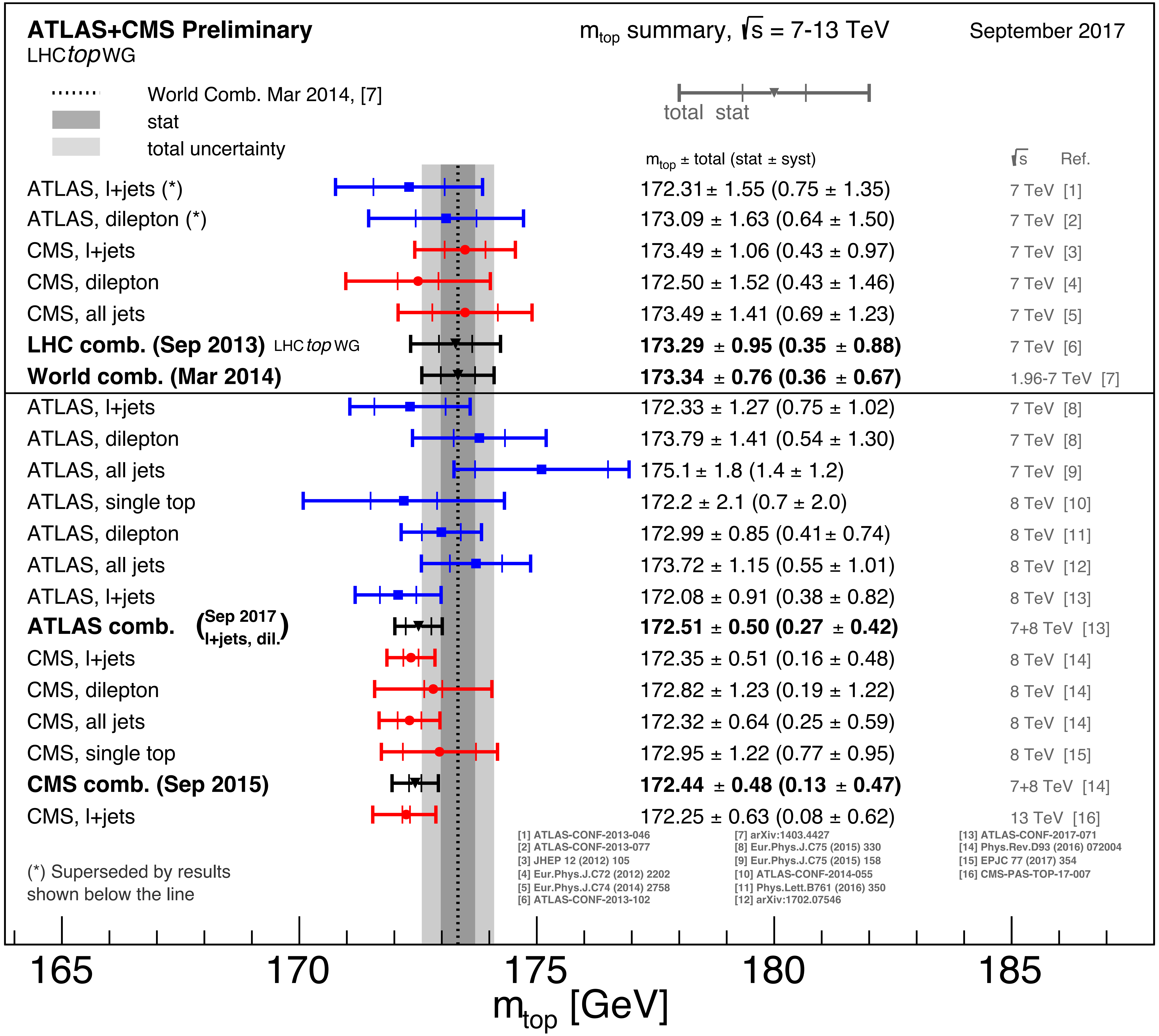
Search for rare processes

b-tagging calibration



Stability of the Universe





top-quark mass

Controversies [in top mass]

Nason

We remind that

1. Some authors implicitly claim that the Pole Mass and the Monte Carlo mass parameter (or "Monte Carlo Mass") in direct measurements differ by terms of order $\alpha_s(m_t)$.
2. Other authors, also advocating the "Monte Carlo Mass" concept, claim differences relative to the Pole Mass of order of a hadronic scale (Hoang,Stuart 2008).

Our view is in clear contrast with (1), but is not in substantial contradiction with (2): we prefer to say that direct measurements measure the Pole Mass up to corrections of the order of a hadronic scale, rather than saying that they measure a "Monte Carlo Mass".

Ravasio, Jezo, Oleari, Nason, 1801.03944

Pythia8, hvq, tt_dec,bb41 comparison

	No smearing		15 GeV smearing
	MEC	MEC − no MEC	MEC
$b\bar{b}4\ell$	172.793 ± 0.004 GeV	-12 ± 6 MeV	172.717 ± 0.002 GeV
$t\bar{t}dec$	172.814 ± 0.003 GeV	-4 ± 5 MeV	172.857 ± 0.001 GeV
hvq	172.803 ± 0.003 GeV	$+61 \pm 5$ MeV	172.570 ± 0.001 GeV

stability (to within 300 MeV) of top-mass peak in different MC formulations (Pythia8 + X)

POWHEG-bb41, Herwig7 - Pythia8 comparison

	No smearing		15 GeV smearing	
	Hw7.1	Py8.2 − Hw7.1	Hw7.1	Py8.2 − Hw7.1
$b\bar{b}4\ell$	172.727 ± 0.005 GeV	$+66 \pm 7$ MeV	171.626 ± 0.002 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 ± 0.004 GeV	$+39 \pm 5$ MeV	171.678 ± 0.001 GeV	$+1179 \pm 2$ MeV
hvq	173.038 ± 0.004 GeV	-235 ± 5 MeV	172.319 ± 0.001 GeV	$+251 \pm 2$ MeV

Pythia v. Herwig comparison shows up to ***1 GeV*** *differences*

Pythia8, hvq, $t\bar{t}$_dec, $b\bar{b}4l$ comparison

Ravasio, Jezo, Oleari, Nason, 1801.03944

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$b\bar{b}4\ell$	172.793 ± 0.004 GeV	−12 ± 6 MeV	172.717 ± 0.002 GeV
$t\bar{t}dec$	172		GeV
hvq	172		GeV

stability (to within 300 MeV) of top-mass peak in different MC formulations (Pythia8 + X)

POWHE

There can be two sources of difference:

1) the parton shower (and its interface with NLO)

2) non-perturbative effects

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*Pythia v. Herwig comparison shows up to **1 GeV** differences*

Prestel

Recent developments in Monte Carlo Event Generators

- Improving the fixed-order **perturbative precision** of event generators:
  Many color-singlet processes described at NNLO+PS with MINLO
  Inclusion of NLO EW effects in full swing in AMC@NLO and SHERPA
- Interesting developments in defining **shower at higher order**:
  Treatment of subleading color relevant, even for leading-color PS
  Can systematically correct PS through fully differential NLO calculation in exponent.
- Continuous improvements of **non-perturbative physics**:
  Improved models of complete cross section and photoproduction.
  More sophisticated color reconnection models.
  Exciting new ideas in modelling of collectivity (in pp and heavy-ion)

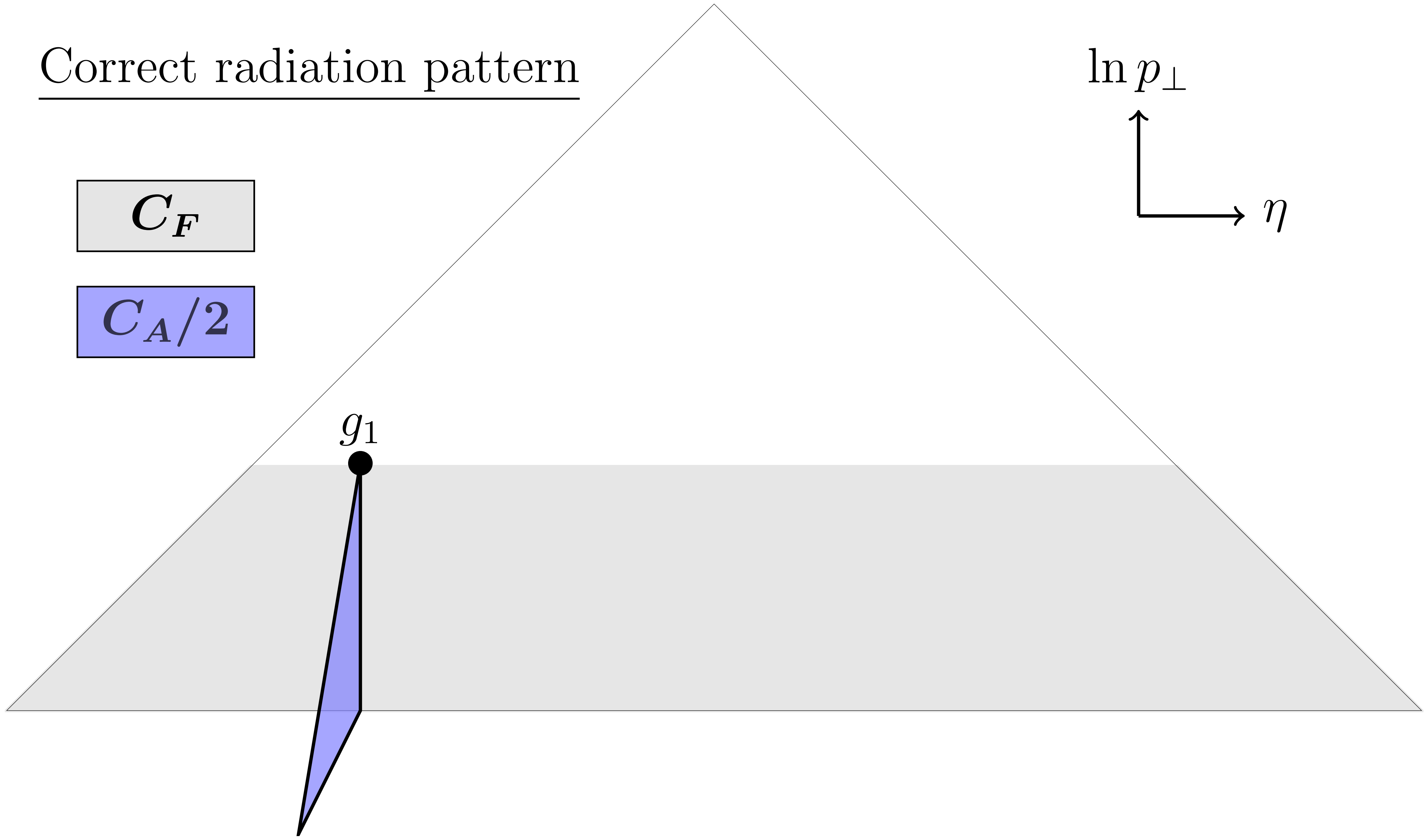
understanding relation between parton showers, resummation & all-order matrix elements

➤ important if we want to take parton showers to the next level of accuracy

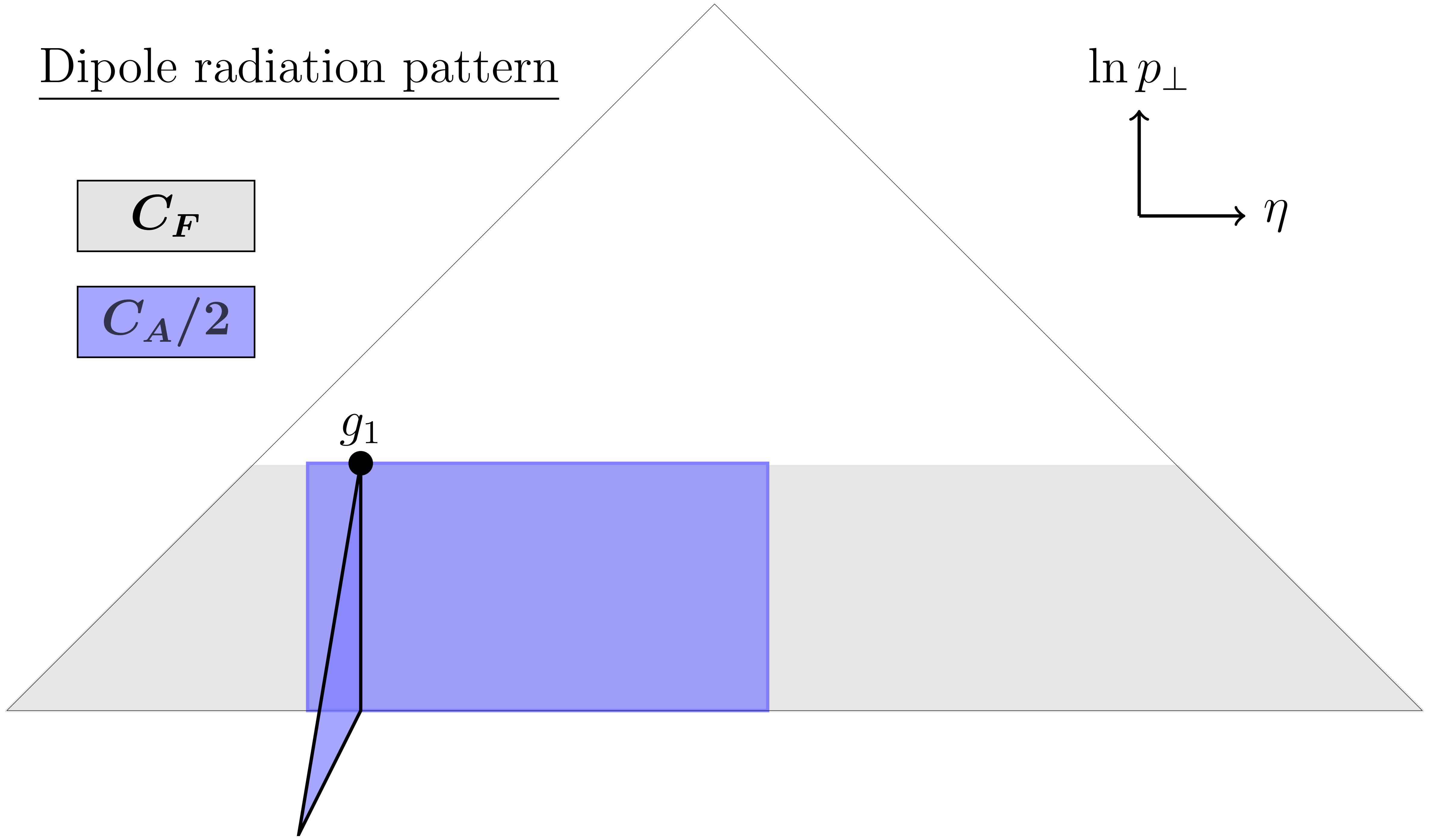
Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

phase-space diagrams for emission density (with implications for log accuracy)

QCD matrix elements



k_t-ordered dipole parton showers

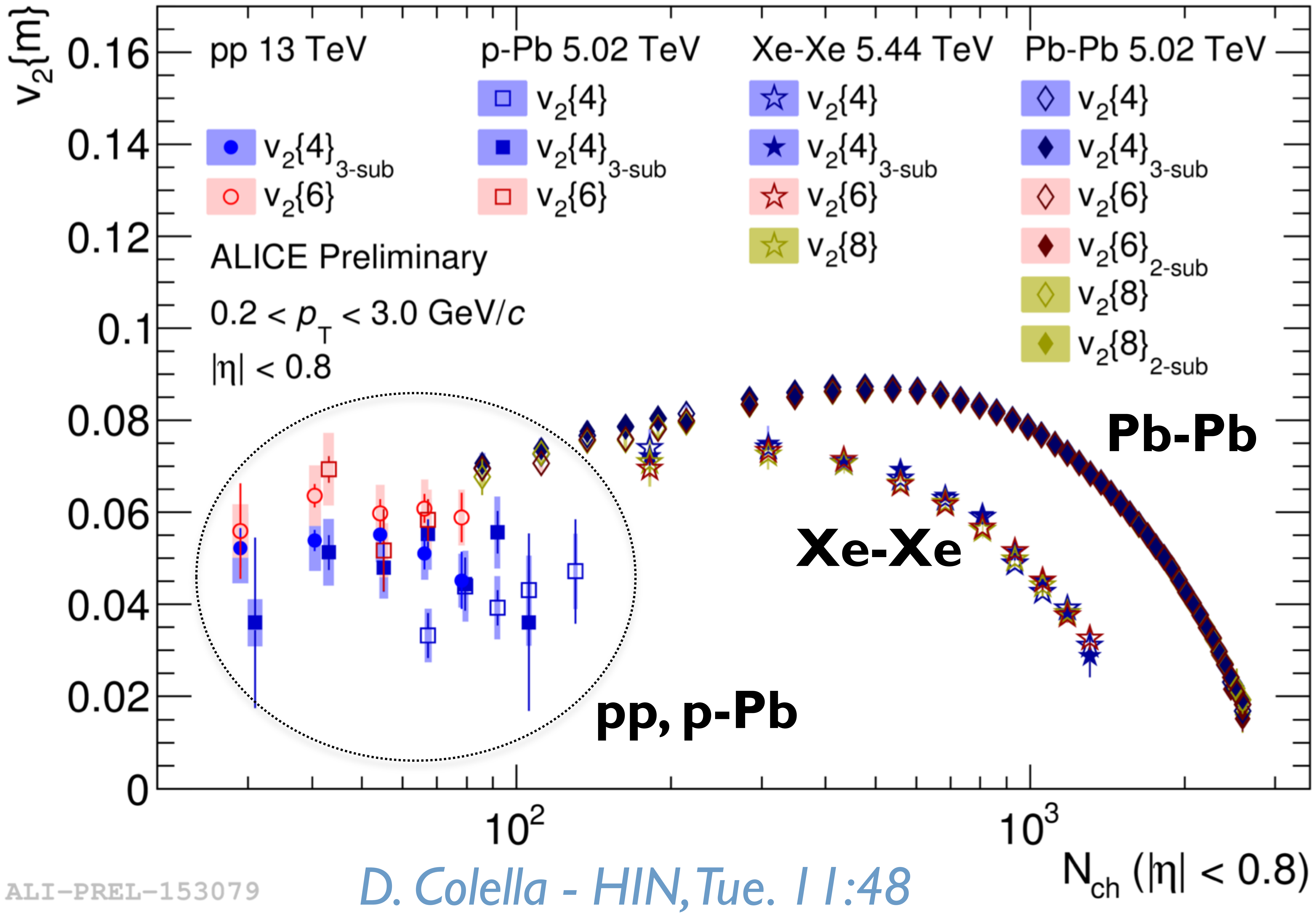


heavy-ion collisions

and hints of a continuum between pp and PbPb

Florchinger: "Little bangs in the laboratory"

True collectivity in small systems!



D. Colella - HIN, Tue. 11:48

via Bellini

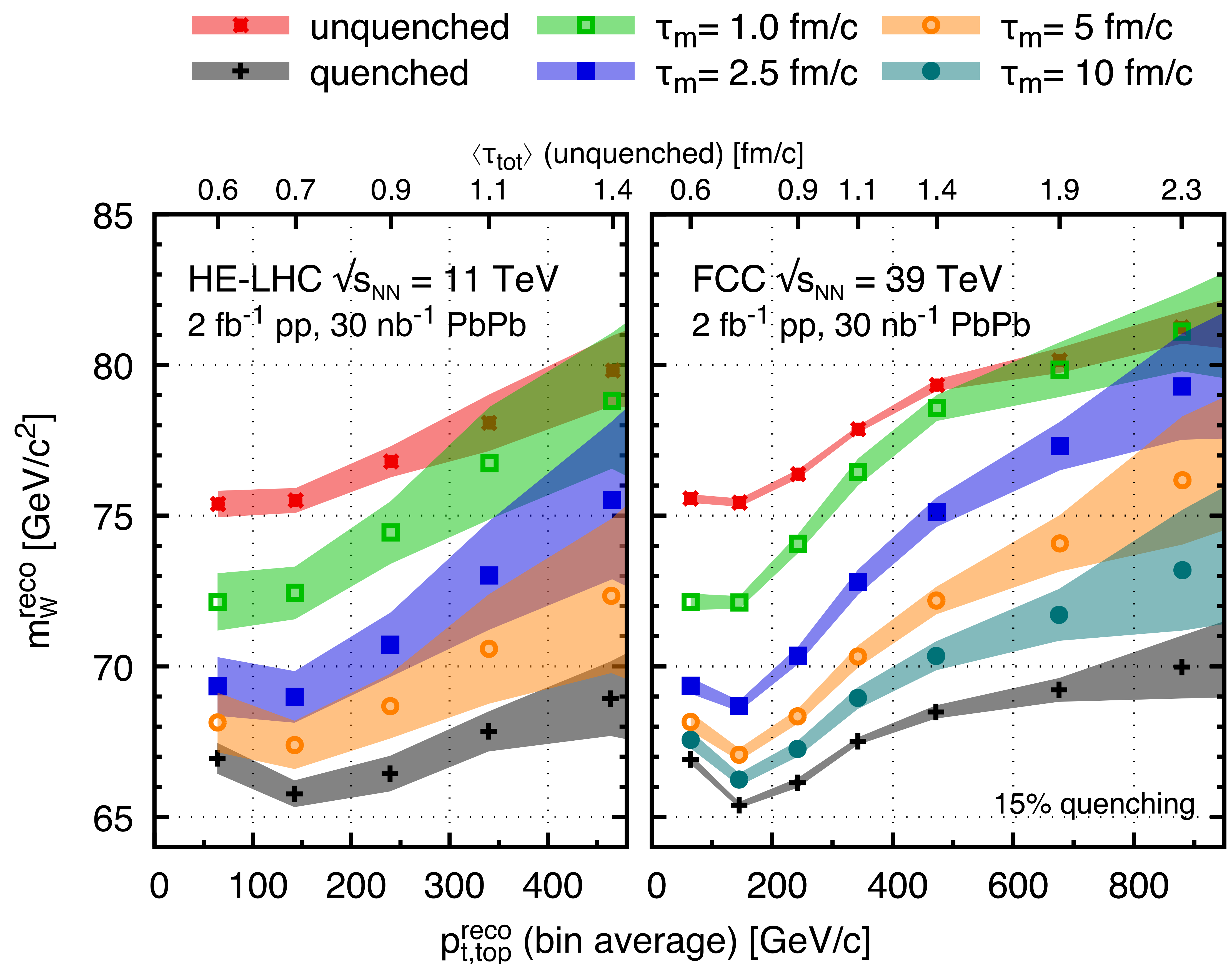
on one hand, discovering that heavy-ion observables and methods reveal ***surprises to understand about basic pp physics***

interplay between heavy-ion physics and top physics

Probing the time structure of the quark-gluon plasma with top quarks

Liliana Apolinário,[1,2] José Guilherme Milhano,[1,2,3] Gavin P. Salam,[3,*] and Carlos A. Salgado[4]

arXiv:1711.03105v3



finite top lifetime

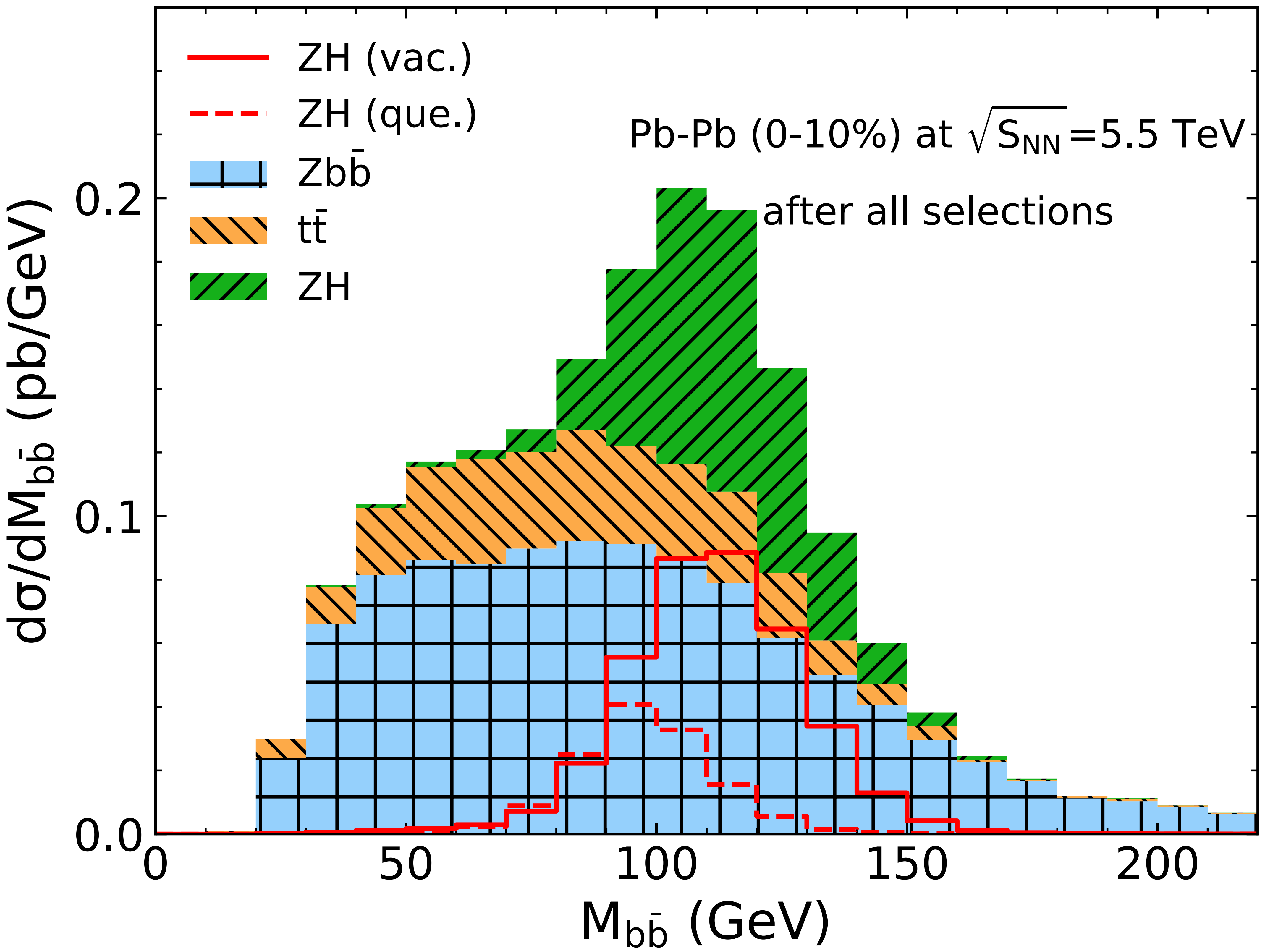
reconstructed top mass tells you something about time structure of the medium

interplay between heavy-ion physics and Higgs physics

Higgs properties revealed through jet quenching in heavy ion collisions

Edmond L. Berger,[1,*] Jun Gao,[2,†] Adil Jueid,[2,‡] and Hao Zhang[3,4]

arXiv:1804.06858v2



long Higgs lifetime

no jet b-jet quenching, so enhancement of H→bb signal relative to pp collisions

interplay between heavy-ion physics and Higgs physics

Higgs properties revealed through jet quenching in heavy ion collisions

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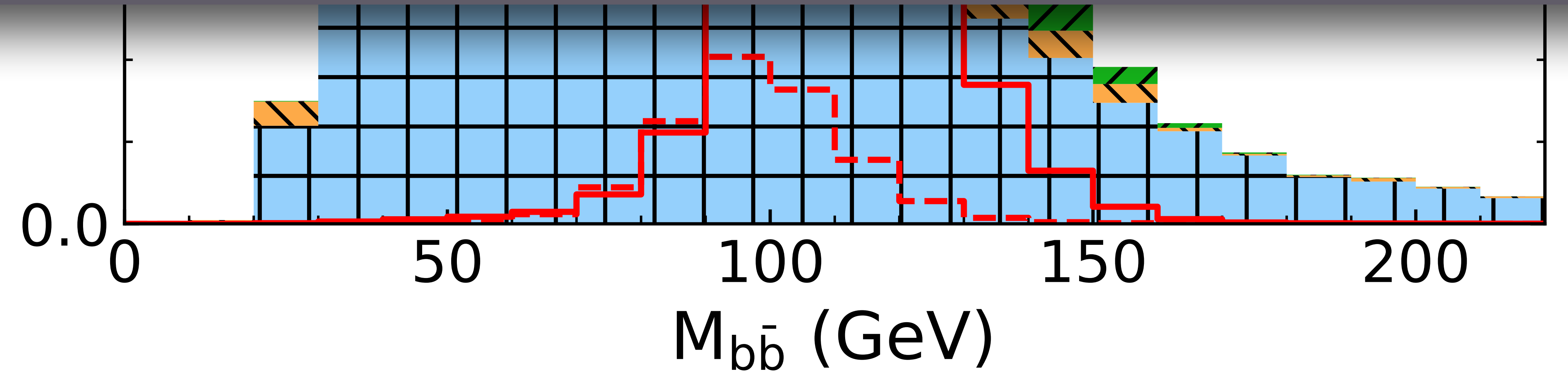
arXiv:1804.06858v2

open question of how much luminosity is needed (both for Higgs and top) and whether lumi is achievable.

But for now, these are fun questions to think about

long Higgs lifetime

o jet b-jet quenching, enhancement of H→bb signal relative to pp collisions



conclusions

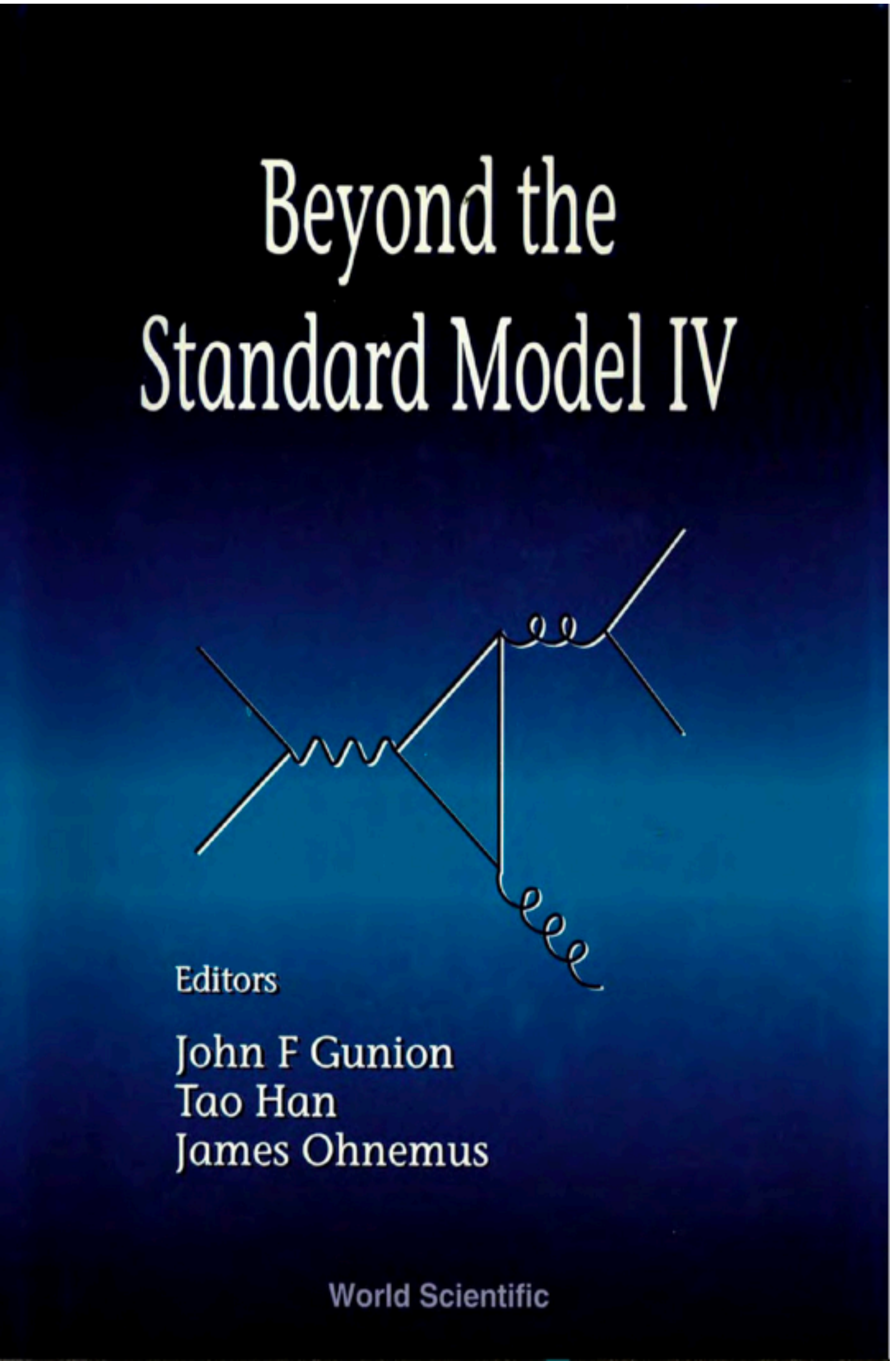
“

I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]

http://cerncourier.com/cws/article/cern/35456

it would be so much more exciting if we'd discovered new physics, right?



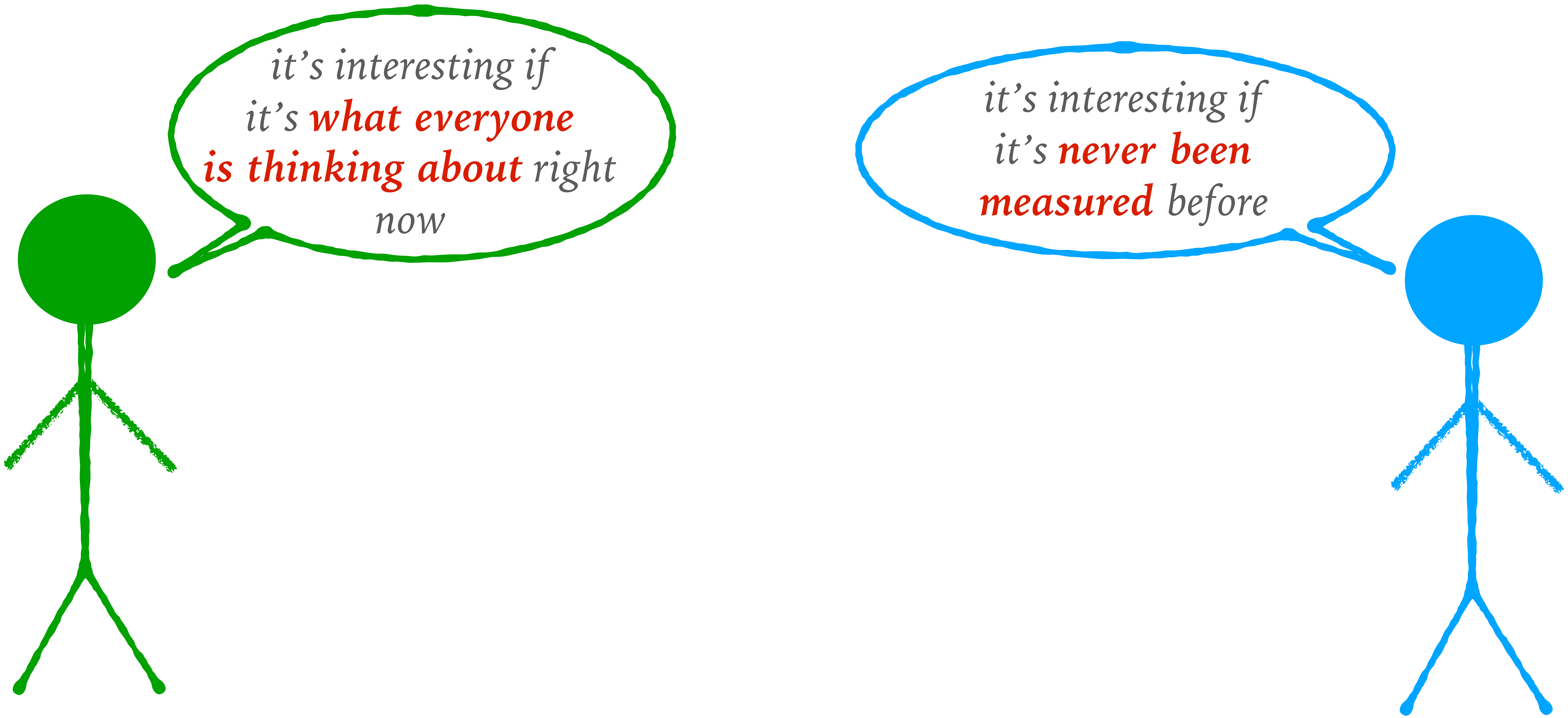
not everyone would agree

Back in 1995:

1. The Desert. A fun aspect of supersymmetry is that it allows us to obtain exact results about strongly interacting gauge theories. However in the MSSM we have nothing but boring perturbative physics to explore below the Planck scale and the interesting dynamics of supersymmetry breaking is hidden.

some theorists

experimenter



both have a point
(don’t let one side dampen the other side’s interest)

we must not underestimate our ignorance about the Higgs sector

we must not undersell the value of exploring and establishing it

e.g. accessing the triple-Higgs coupling, keystone of SM

“

I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

-Carlo Rubbia [2008]

http://cerncourier.com/cws/article/cern/35456


image: pixabay, AnnRoss