LHC results:
Highlights and Perspectives

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A QUICK NOTE

This is a pretty big topic to cover in ~1 hour

Matt Nguyen has graciously agreed to cover the latest Heavy Ion results for me.

Thanks Matt!

Introduction

Hard to cover all the very nice LHC results in ~1 hour

The LHC program is vast!
Driven by **deep, fundamental questions** about our universe

My goal is to give you a taste of some of the recent exciting results from the LHC

- My examples will try to address a wide range fundamental questions we'd like to understand
- Then I'd like to wrap up with some encourage thoughts for the future

(apologies if your favorite analysis is not discussed)

Outline

Precision SM tests and the stability of the universe

The Higgs lamppost and the Higgs portal

Classic searches with weaker couplings

Indirect probes and being ready for the unexpected

Connecting with the cosmos

Outline

Where we are

QCD / Electroweak
W mass measurement

Precision SM tests and the stability of the universe

Higgs
VHbb, ggH, extend Higgs sectors

The Higgs lamppost and the Higgs portal

Searches
- SUSY, Exotics, Long-lived
  - Electrweakinos, long-lived
- Flavor and flavor anomalies
  - Anomalies at tree level, Anomalies in penguins, Leptoquarks
- Dark matter and dark sectors
  - LHCb, Mono-X, and pushing lower (jet substructure)

Classic searches with weaker couplings

Indirect probes and being ready for the unexpected

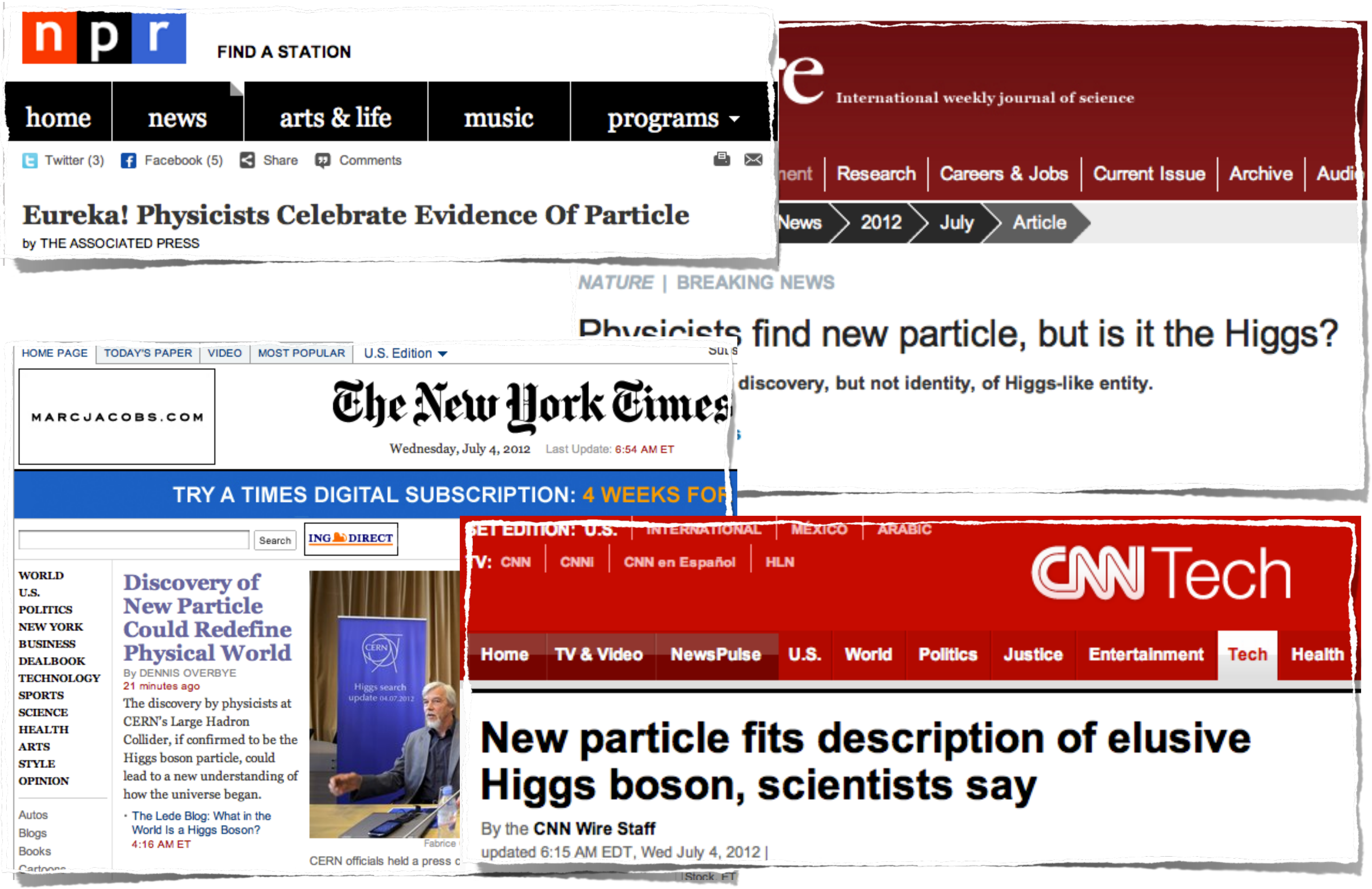
Connecting with the cosmos

Where we're going!

Higher Luminosity, Detector upgrades, and Beyond!

Where we are

July 4, 2012



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Eureka! Physicists Celebrate Evidence Of Particle

by THE ASSOCIATED PRESS

International weekly journal of science

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NATURE | BREAKING NEWS

Physicists find new particle, but is it the Higgs?

discovery, but not identity, of Higgs-like entity.

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The New York Times

Wednesday, July 4, 2012 Last Update: 6:54 AM ET

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Discovery of New Particle Could Redefine Physical World

By DENNIS OVERBYE
21 minutes ago

The discovery by physicists at CERN's Large Hadron Collider, if confirmed to be the Higgs boson particle, could lead to a new understanding of how the universe began.

- The Lede Blog: What in the World Is a Higgs Boson? 4:16 AM ET

CERN Higgs search update 04.07.2012

Fabrice

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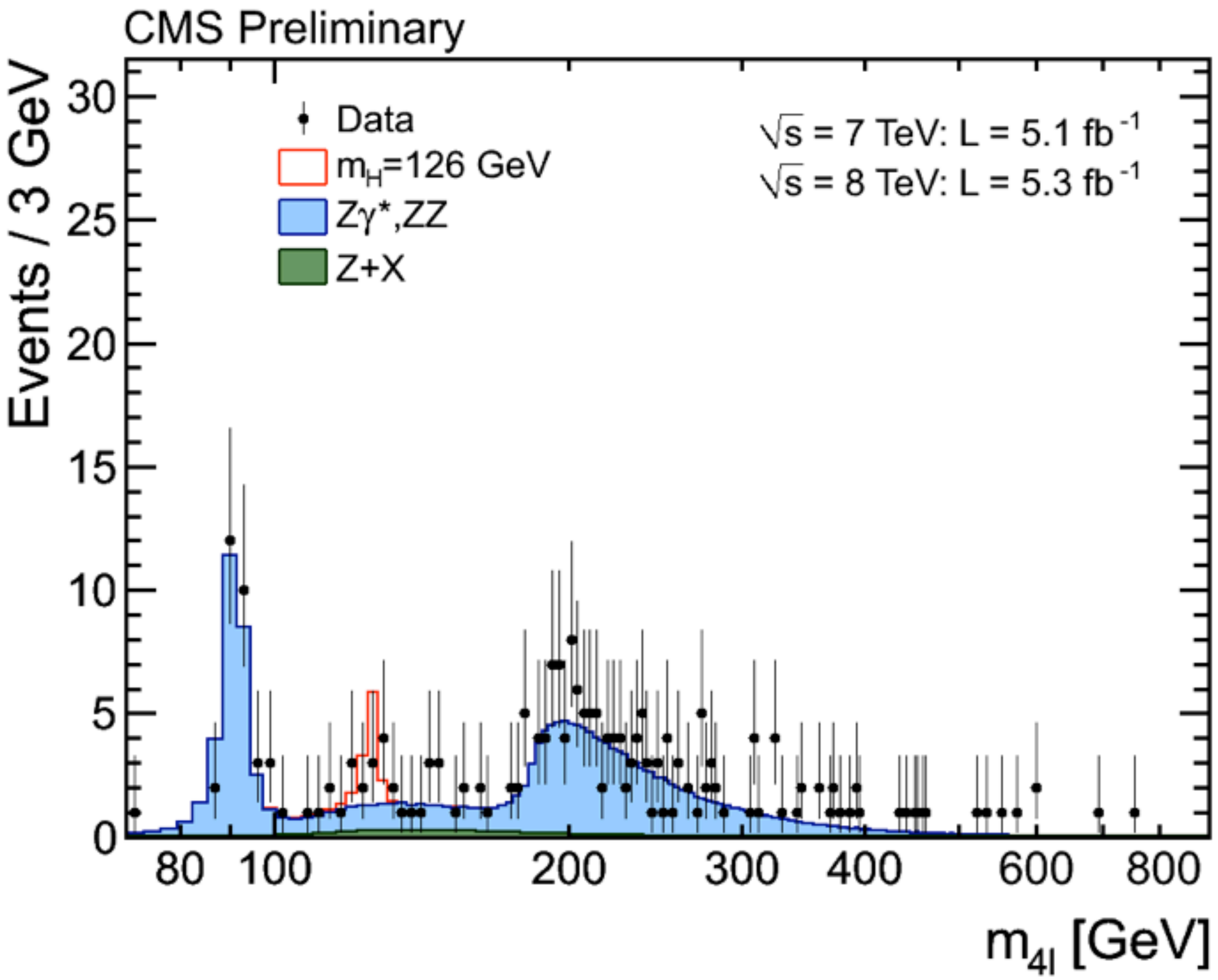
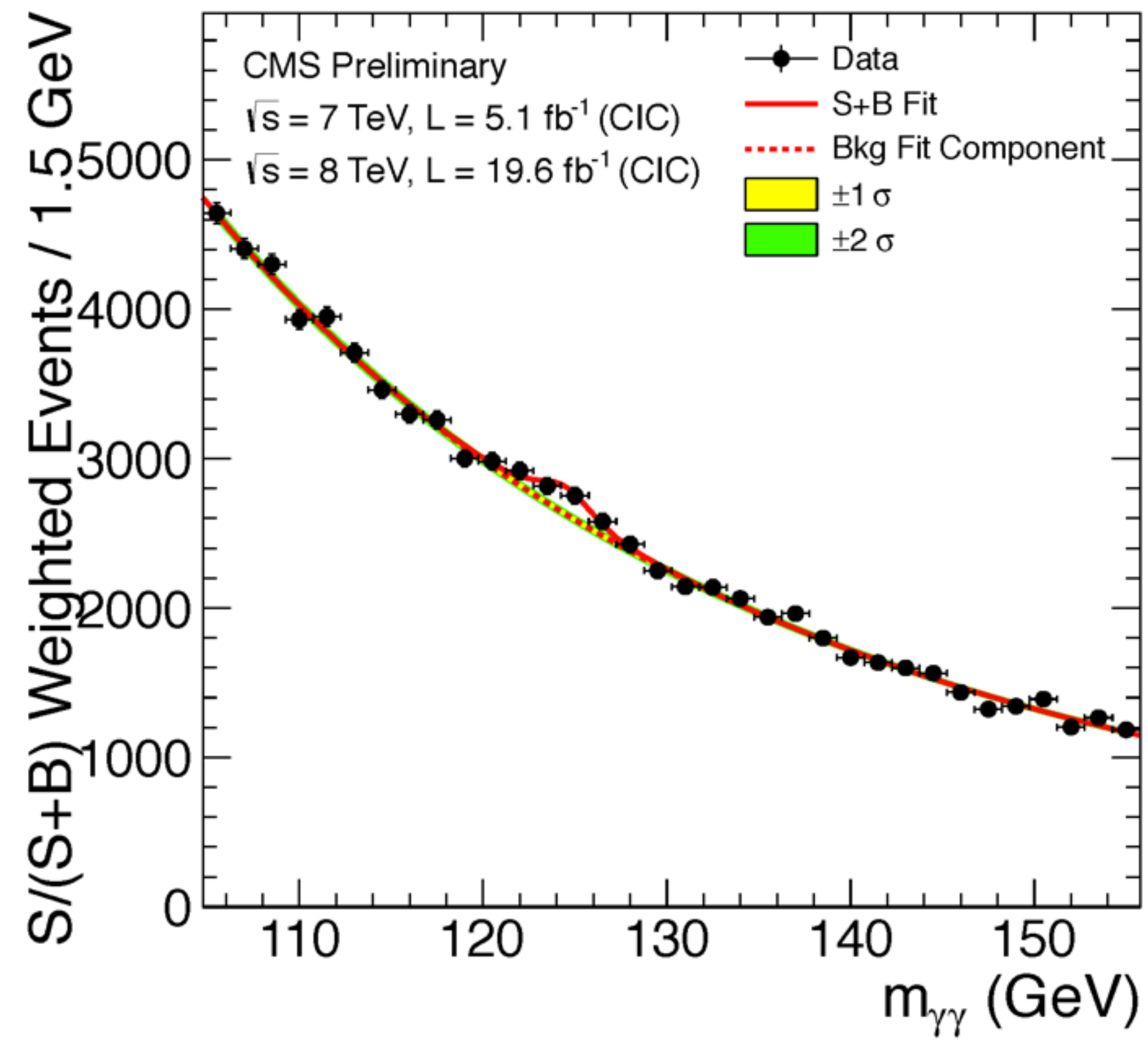
New particle fits description of elusive Higgs boson, scientists say

By the CNN Wire Staff
updated 6:15 AM EDT, Wed July 4, 2012 |

Higgs discovery

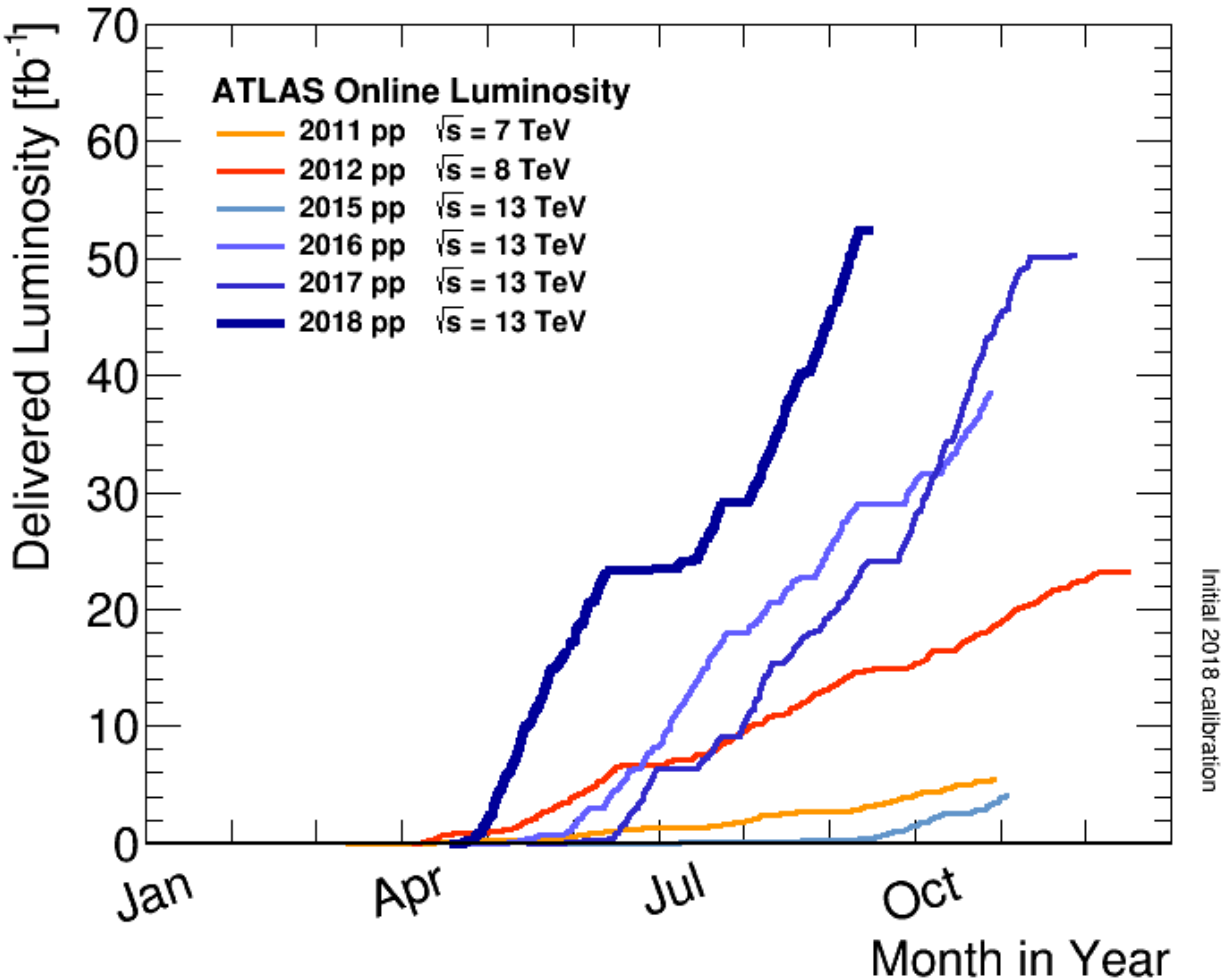




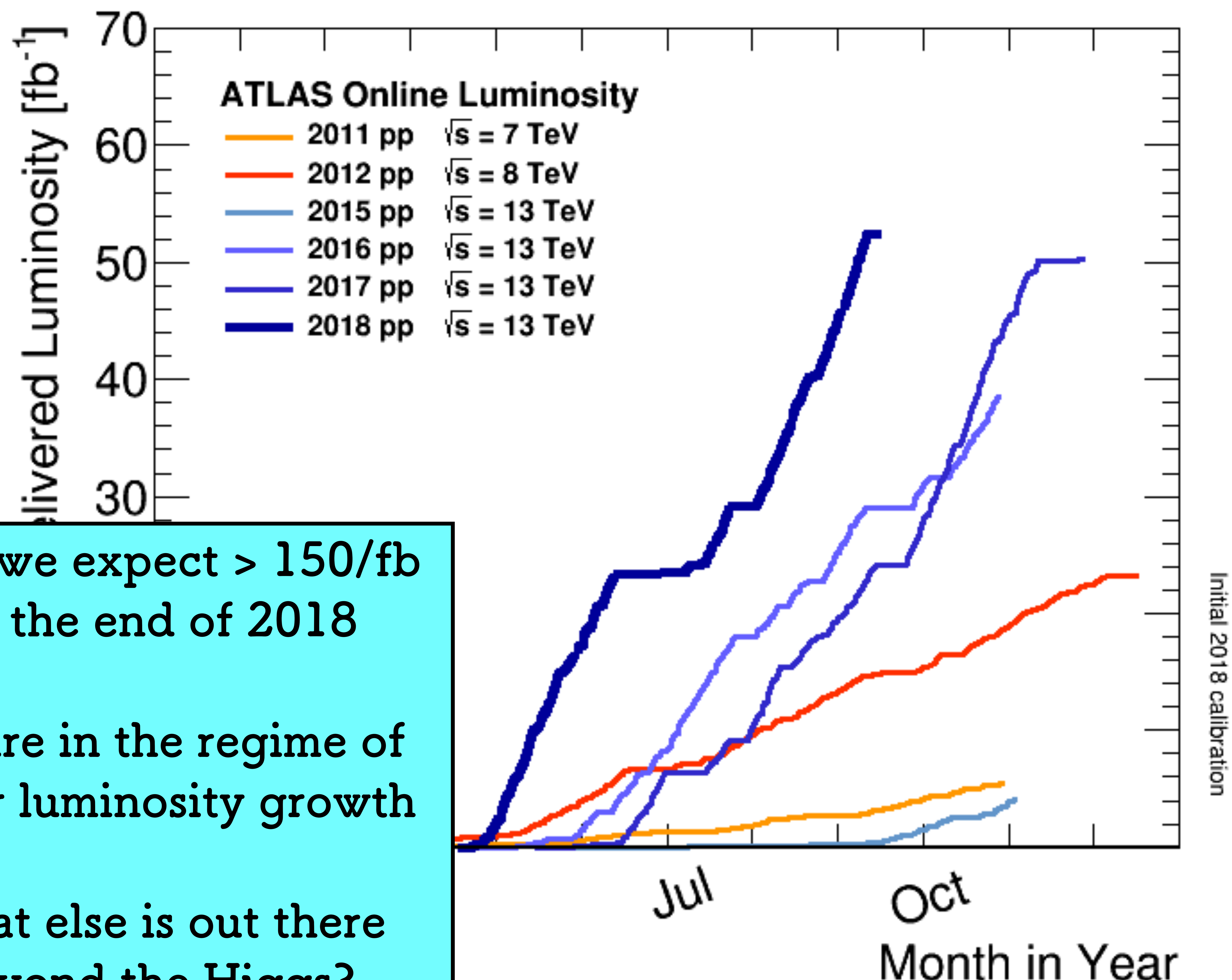
The Higgs discovery was a major milestone in our understanding of the Standard Model!

A major achievement by the experiments and accelerator

FAST FORWARD - 2018



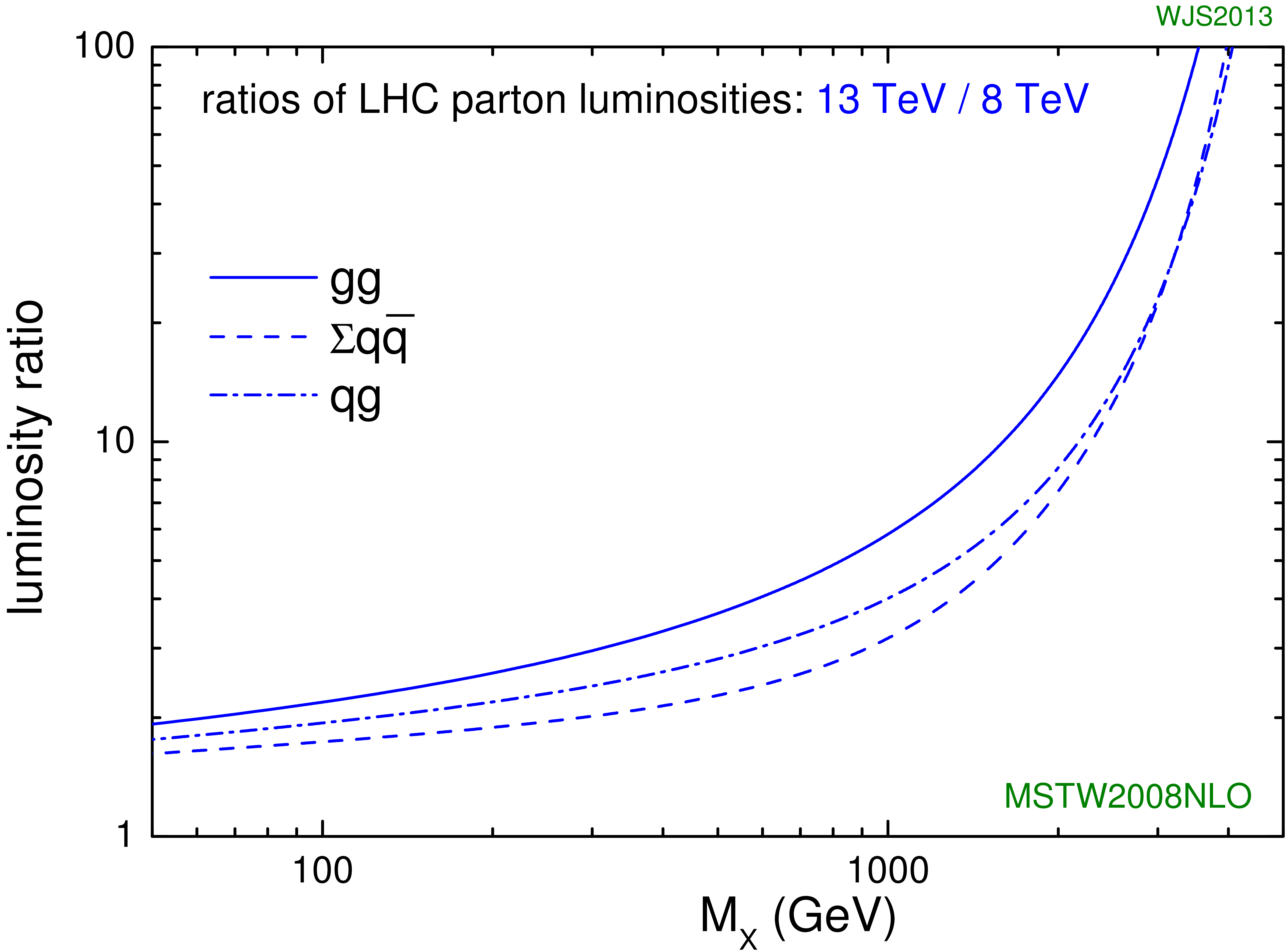
FAST FORWARD - 2018



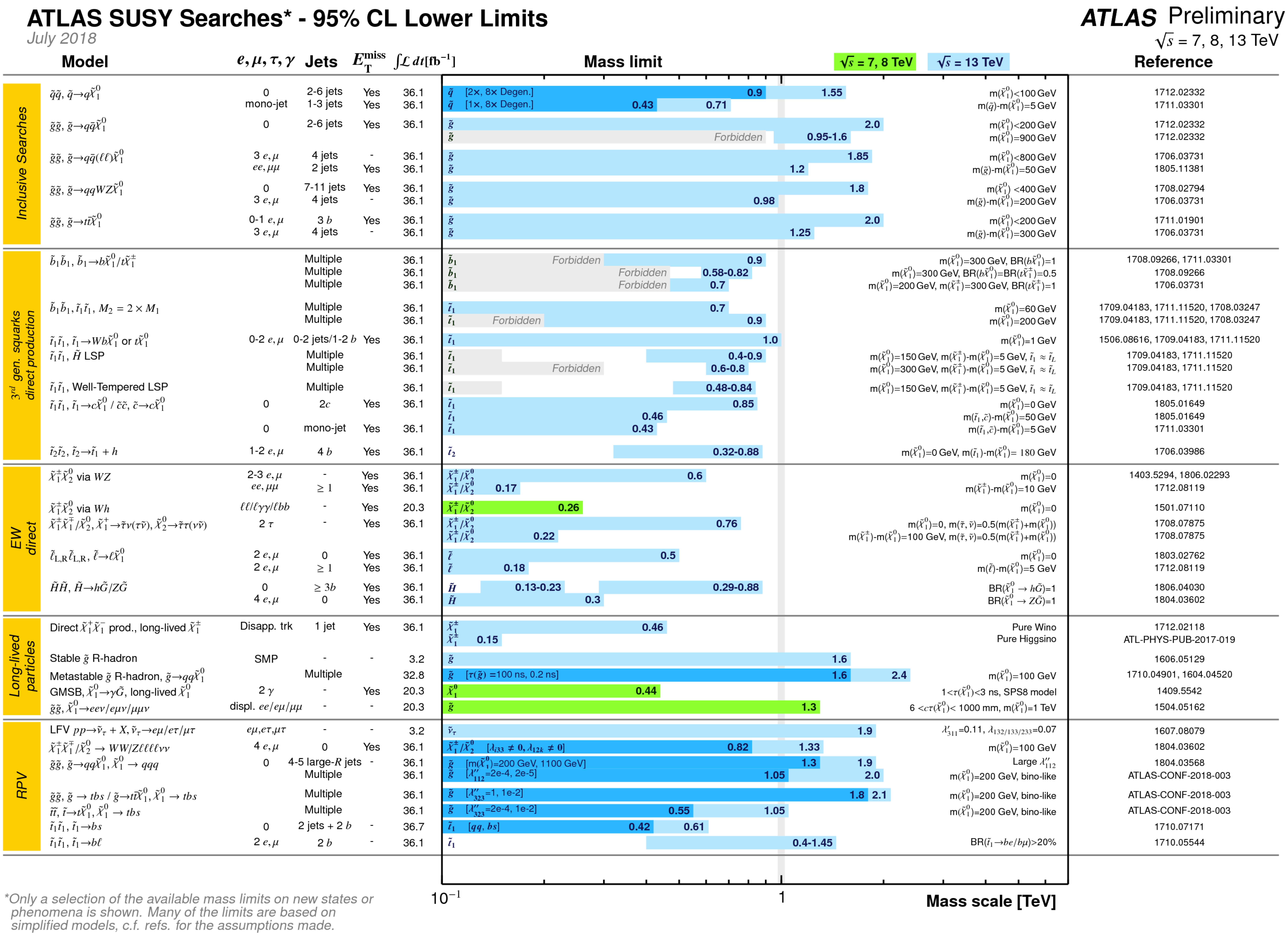
Now we expect > 150/fb by the end of 2018

We are in the regime of linear luminosity growth

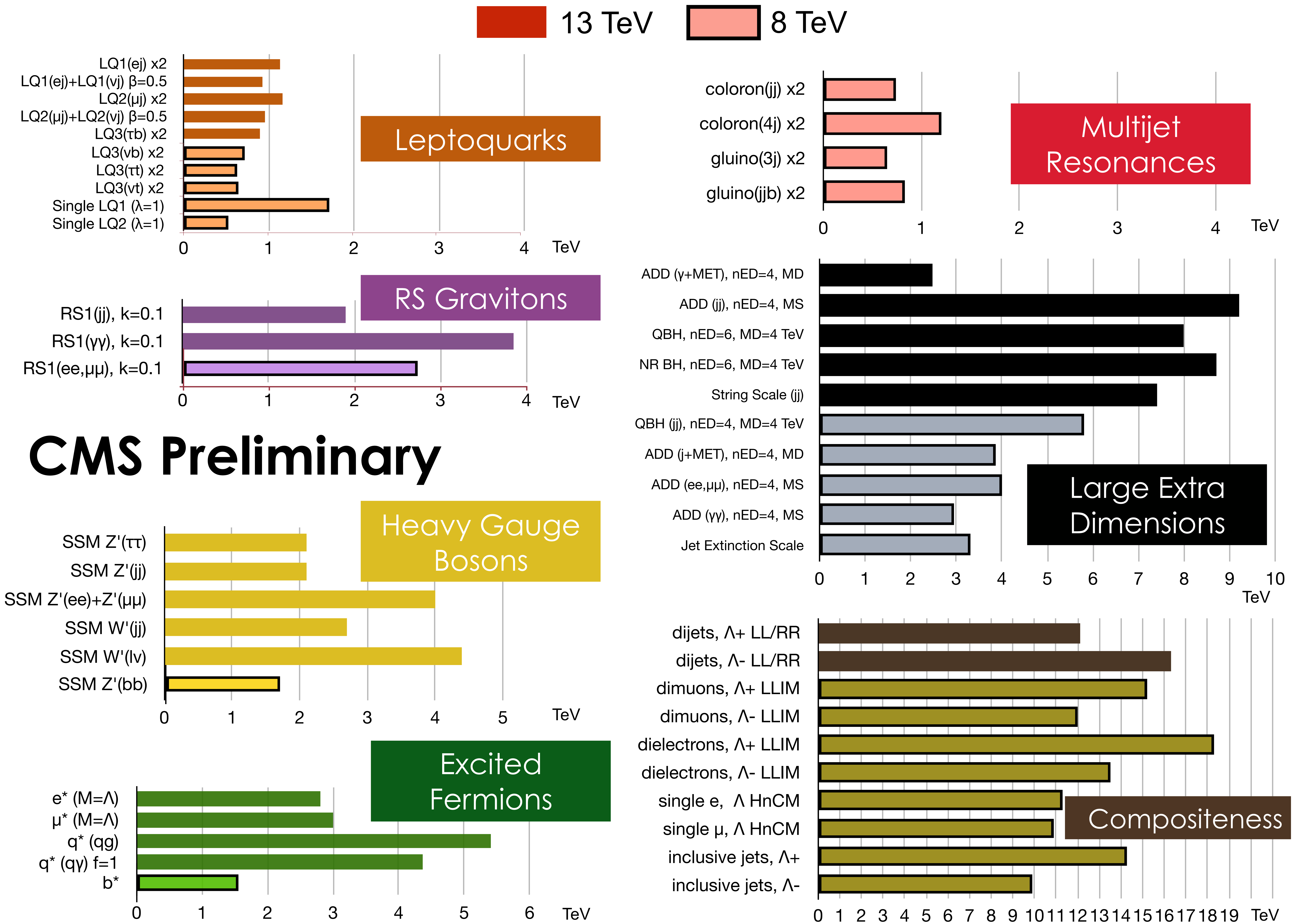
What else is out there beyond the Higgs?


WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
$\Sigma q\bar{q}$
qg
MSTW2008NLO
luminosity ratio
M_X (GeV)
100
10
1
100
1000

SUSY SEARCH SUMMARY



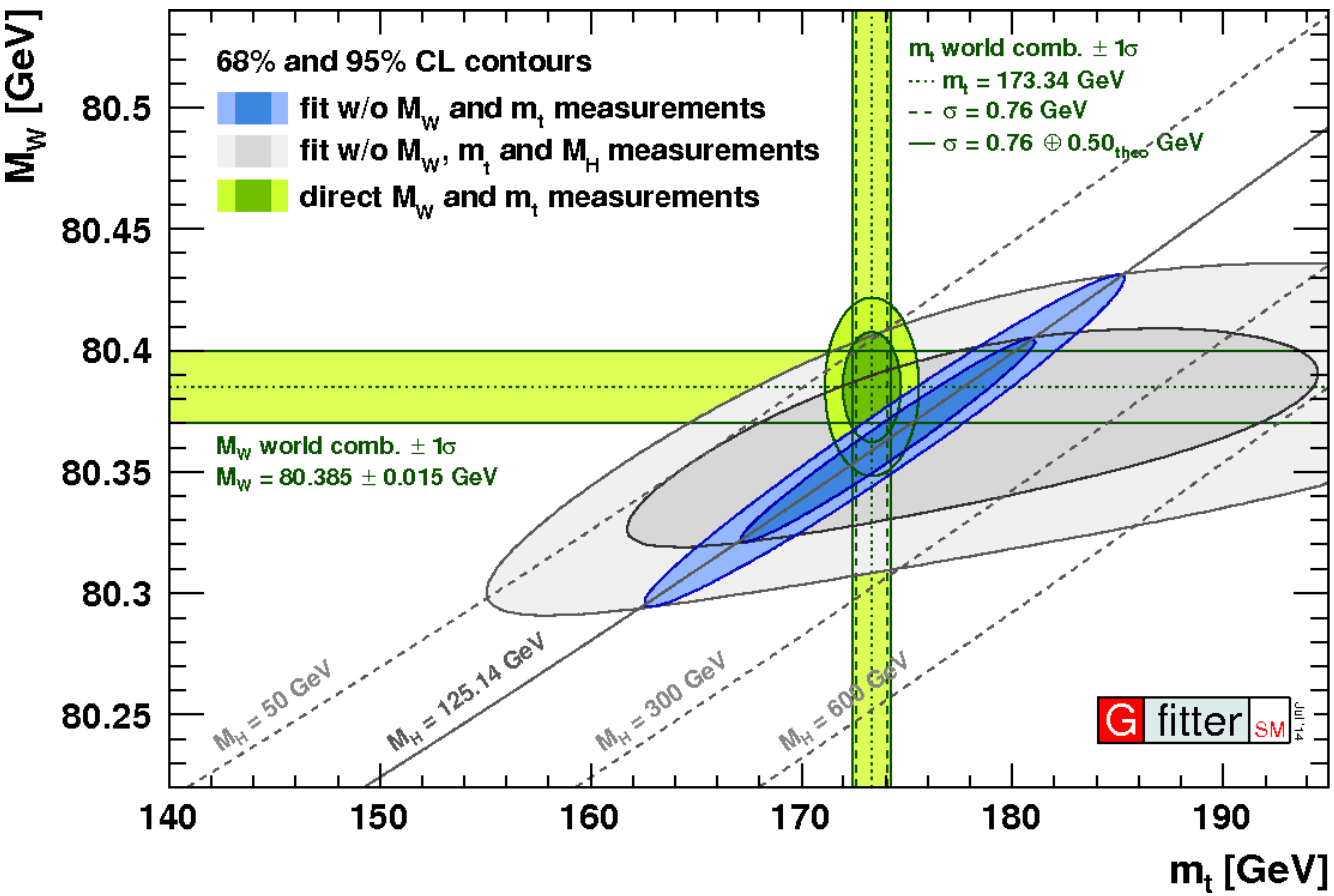
CMS EXOTICS SUMMARY

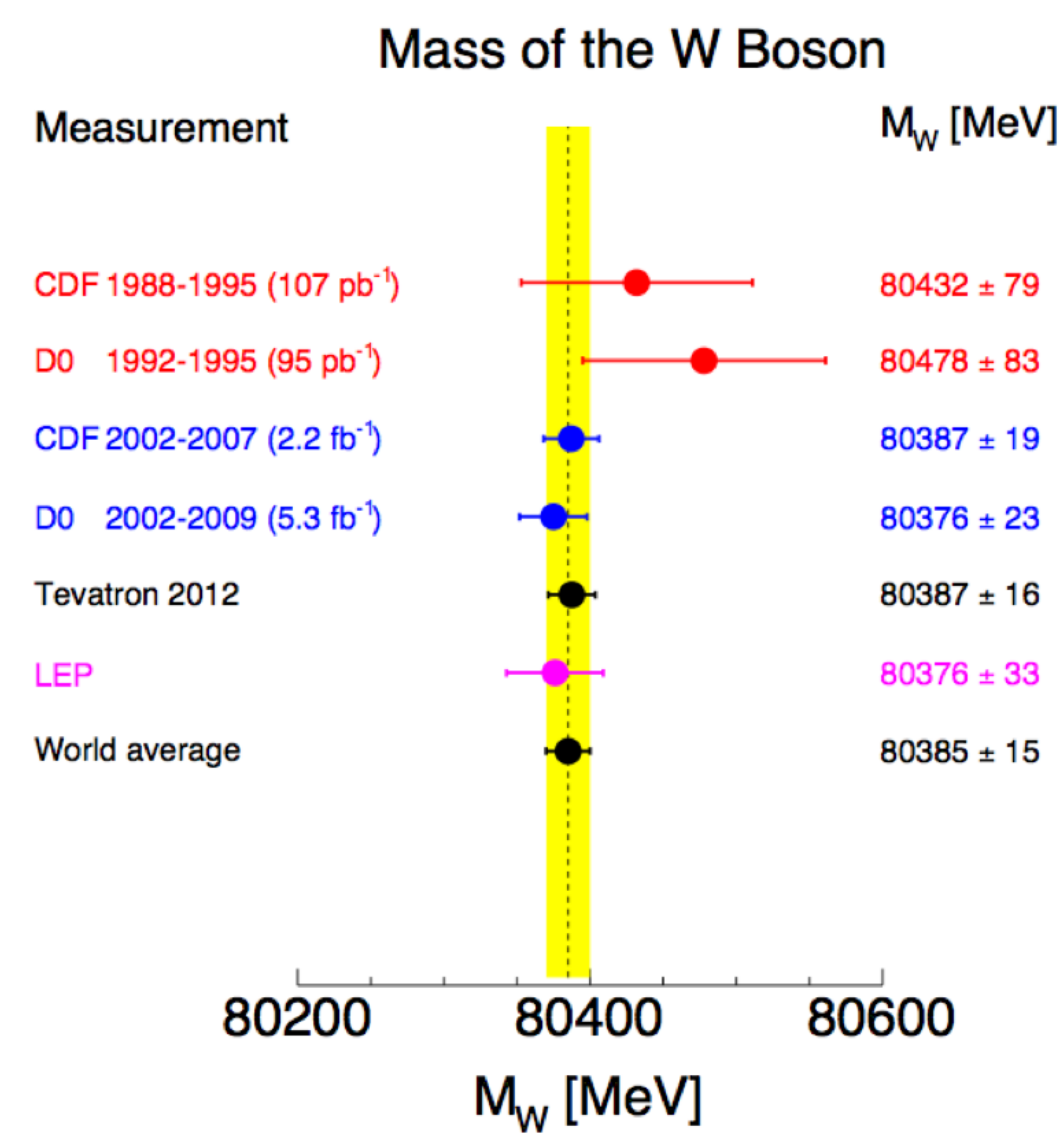


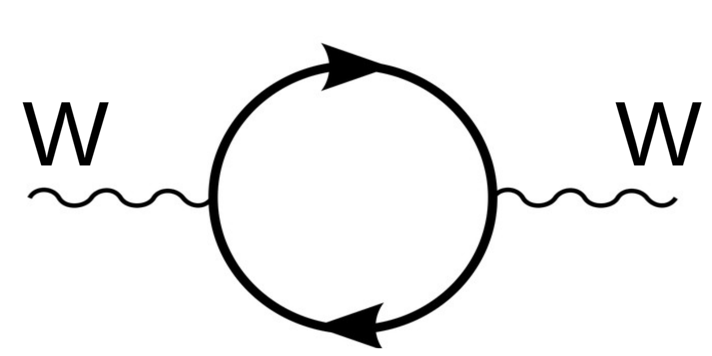
QCD / Electroweak measurements

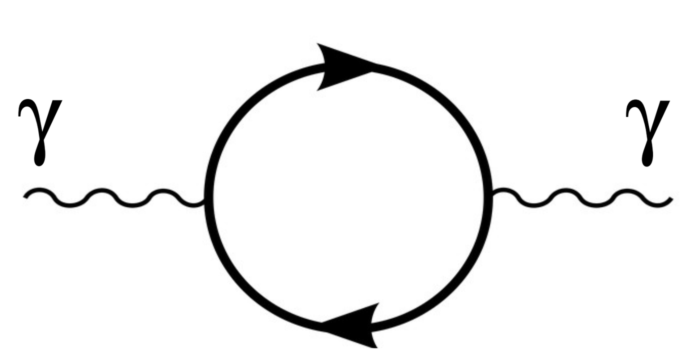
STANDARD MODEL CONSISTENCY

Relationship of m_W, m_t, m_H provide stringent test of SM
and is sensitive to BSM physics



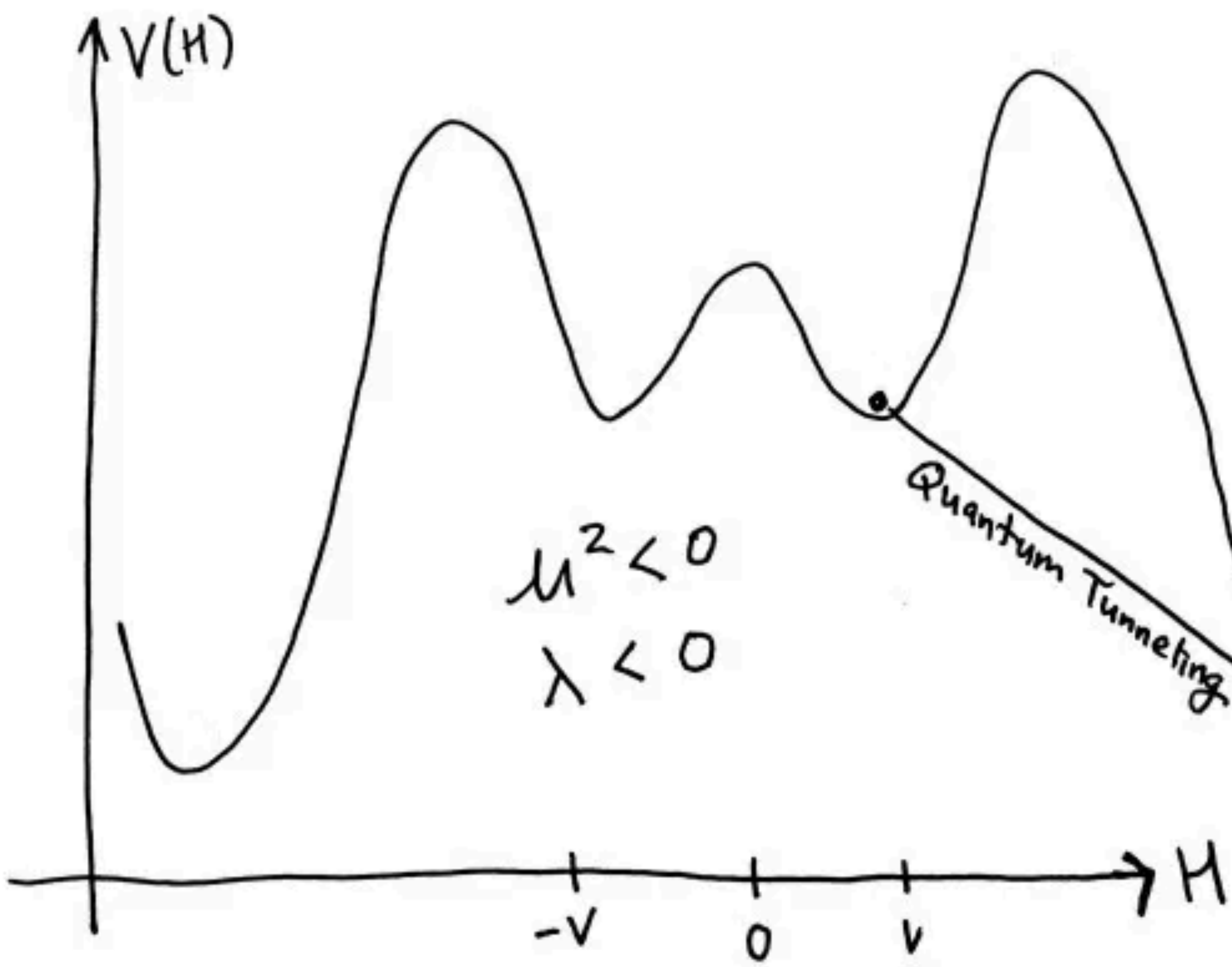


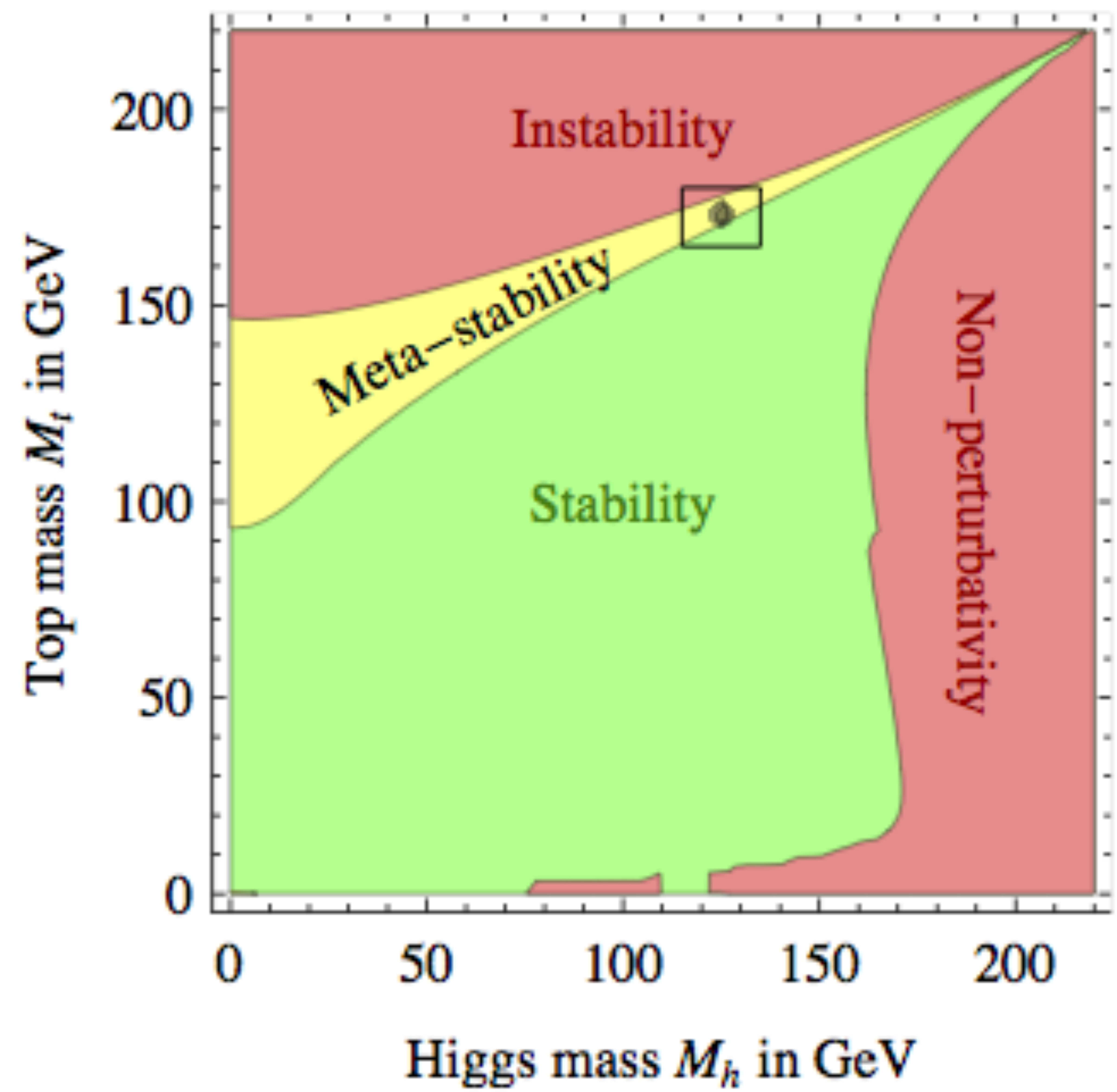




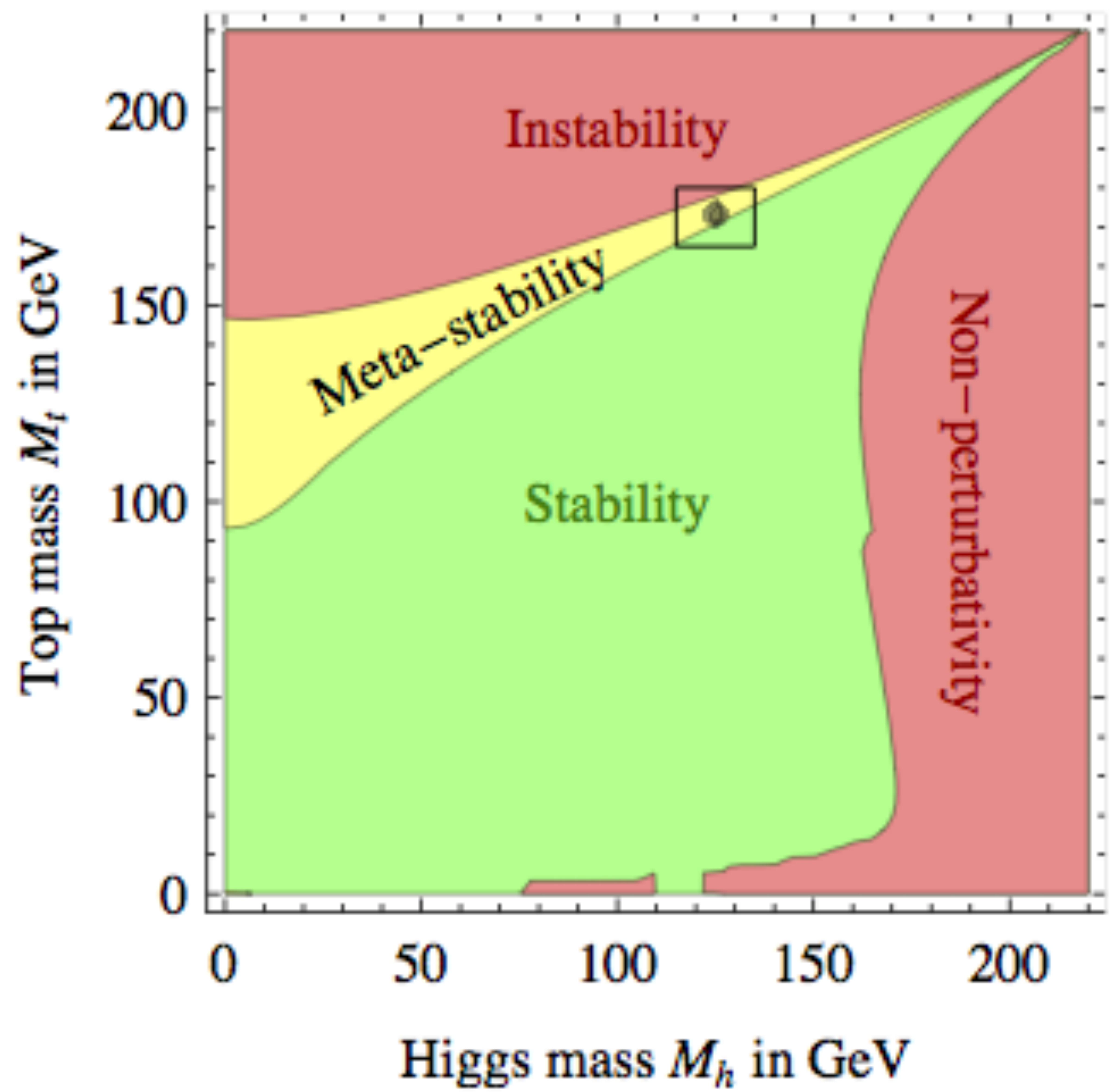
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$

VACUUM STABILITY

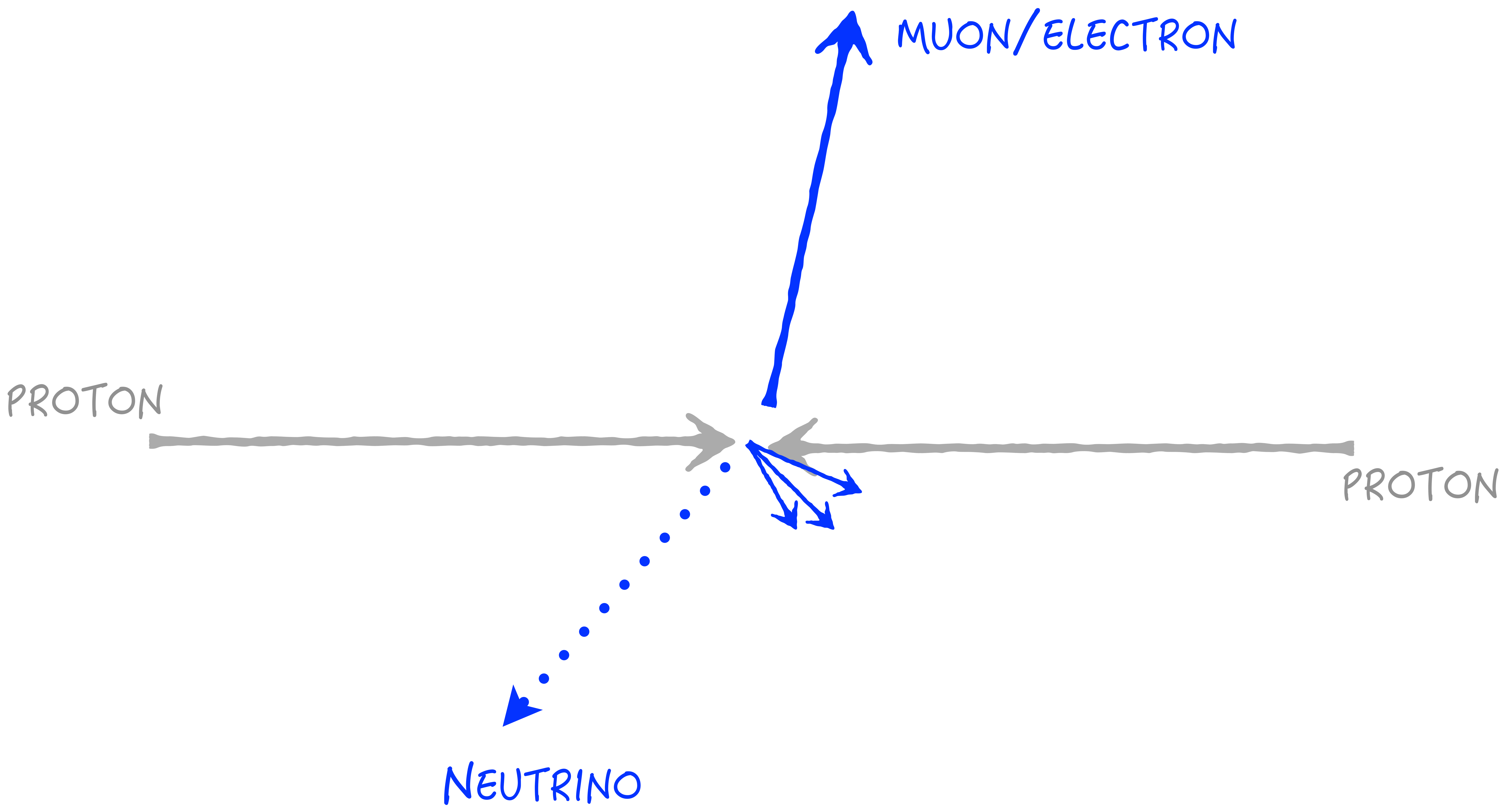




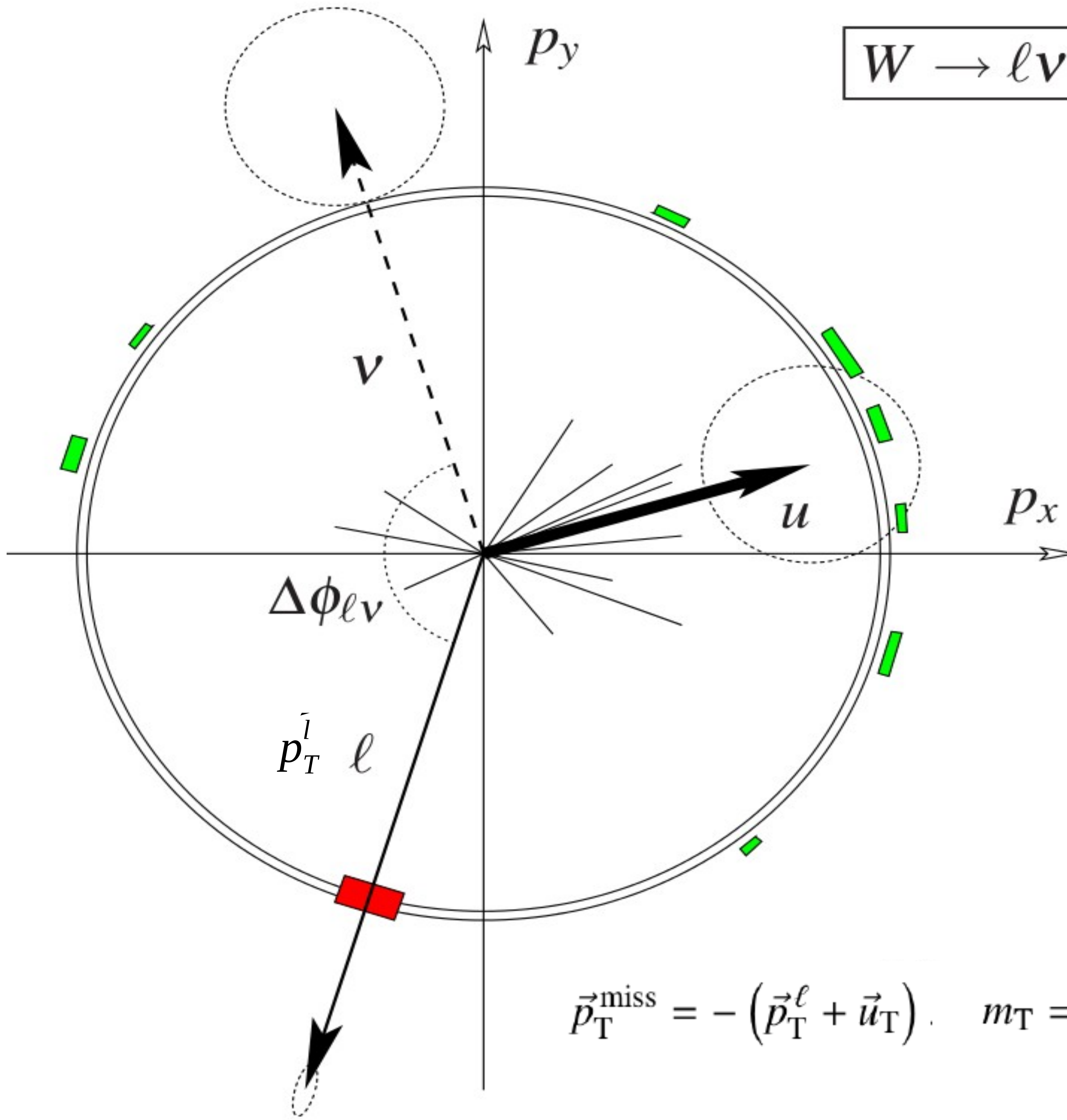
Vacuum stability



W mass measurement



Measurement strategy



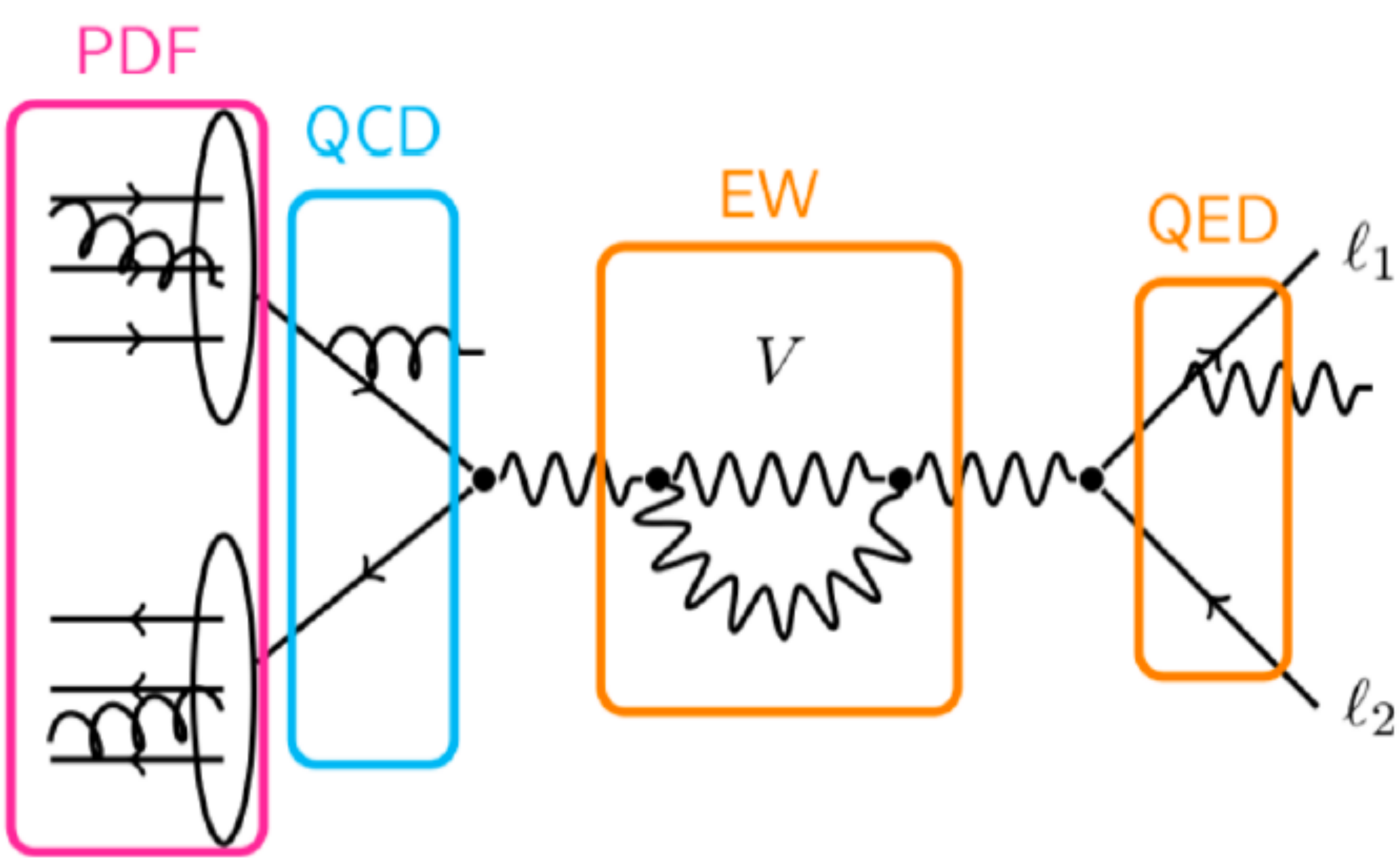
$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right) \quad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

Challenges at a hadron collider

To have an extremely precise measurement of the W mass, there are a number of core challenges:

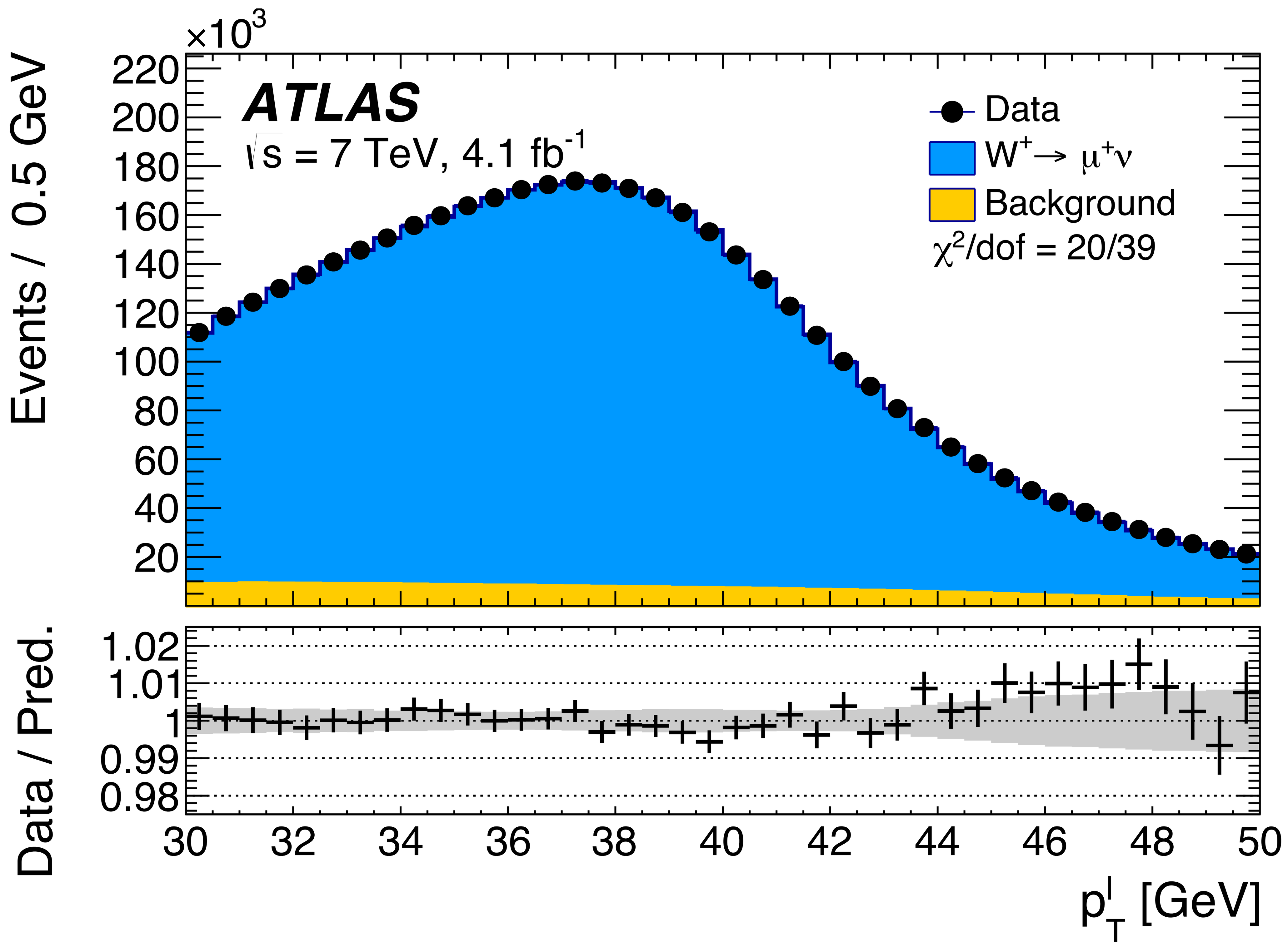
- Electron and muon energy scale
- Recoil measurement
- Expectation of the pT and rapidity distribution of the W bosons

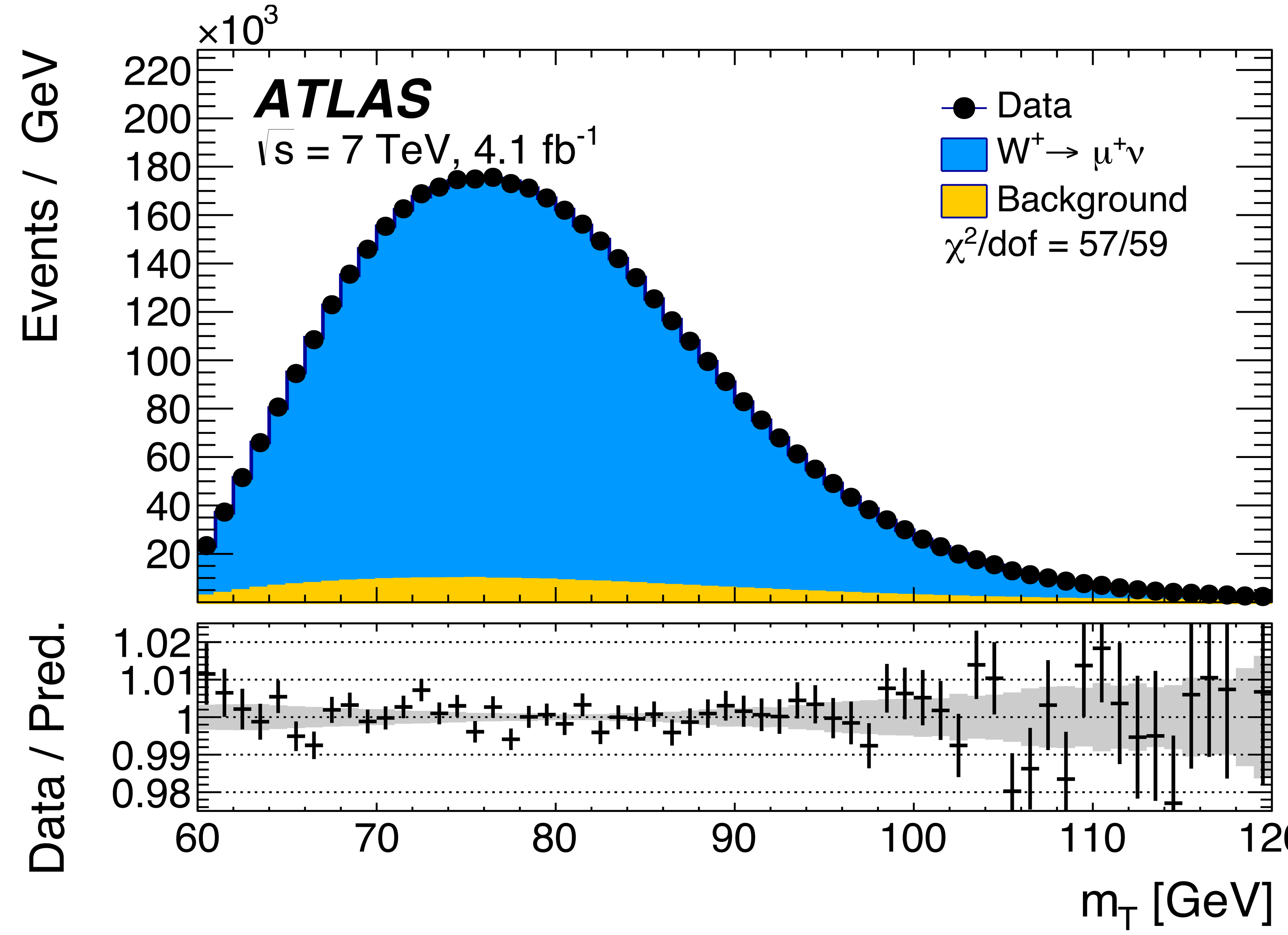
Use the precise Z boson properties to constrain uncertainties



No single generator can model all these effects

Final distributions

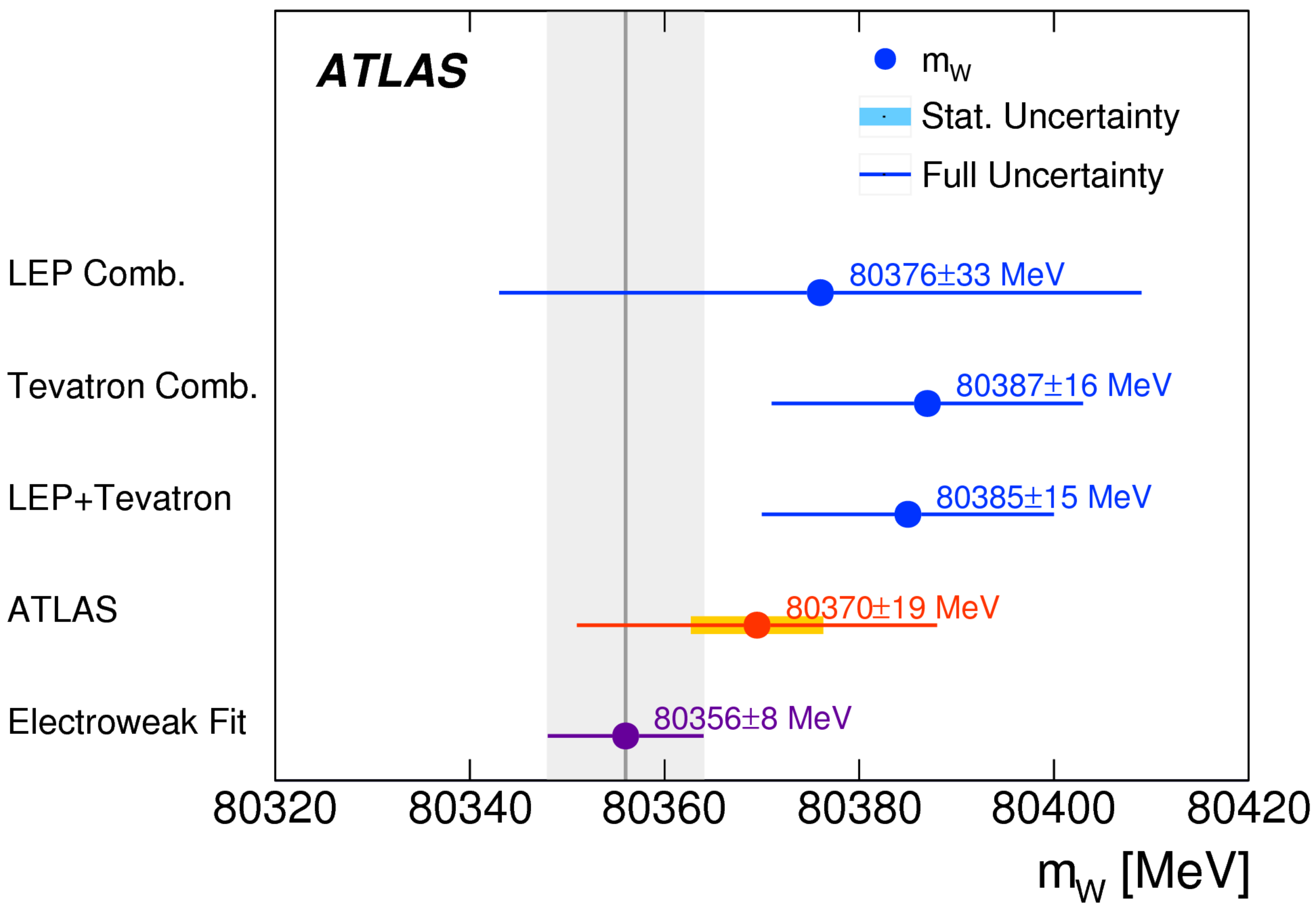


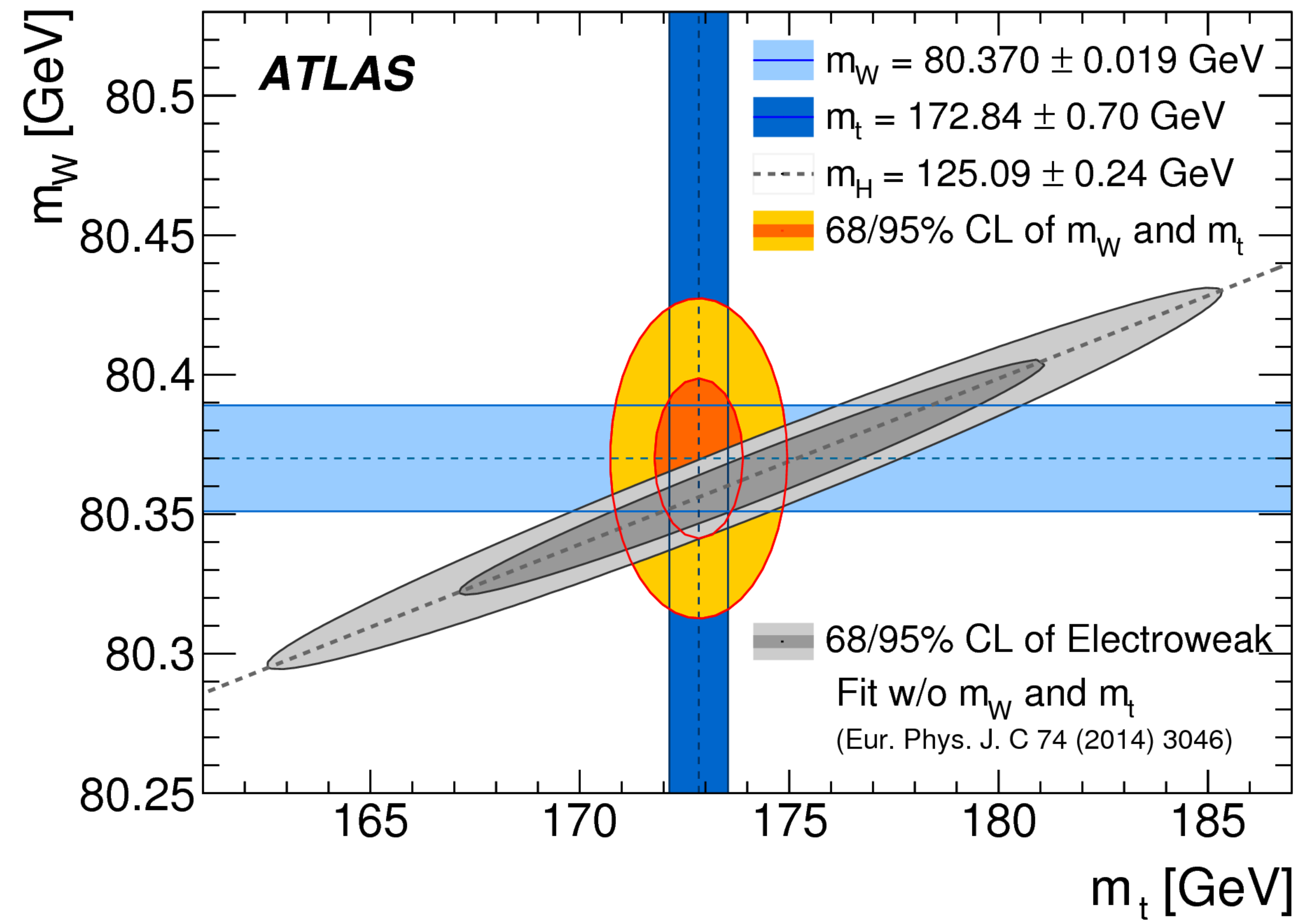


Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

LHC W mass versus other measurements



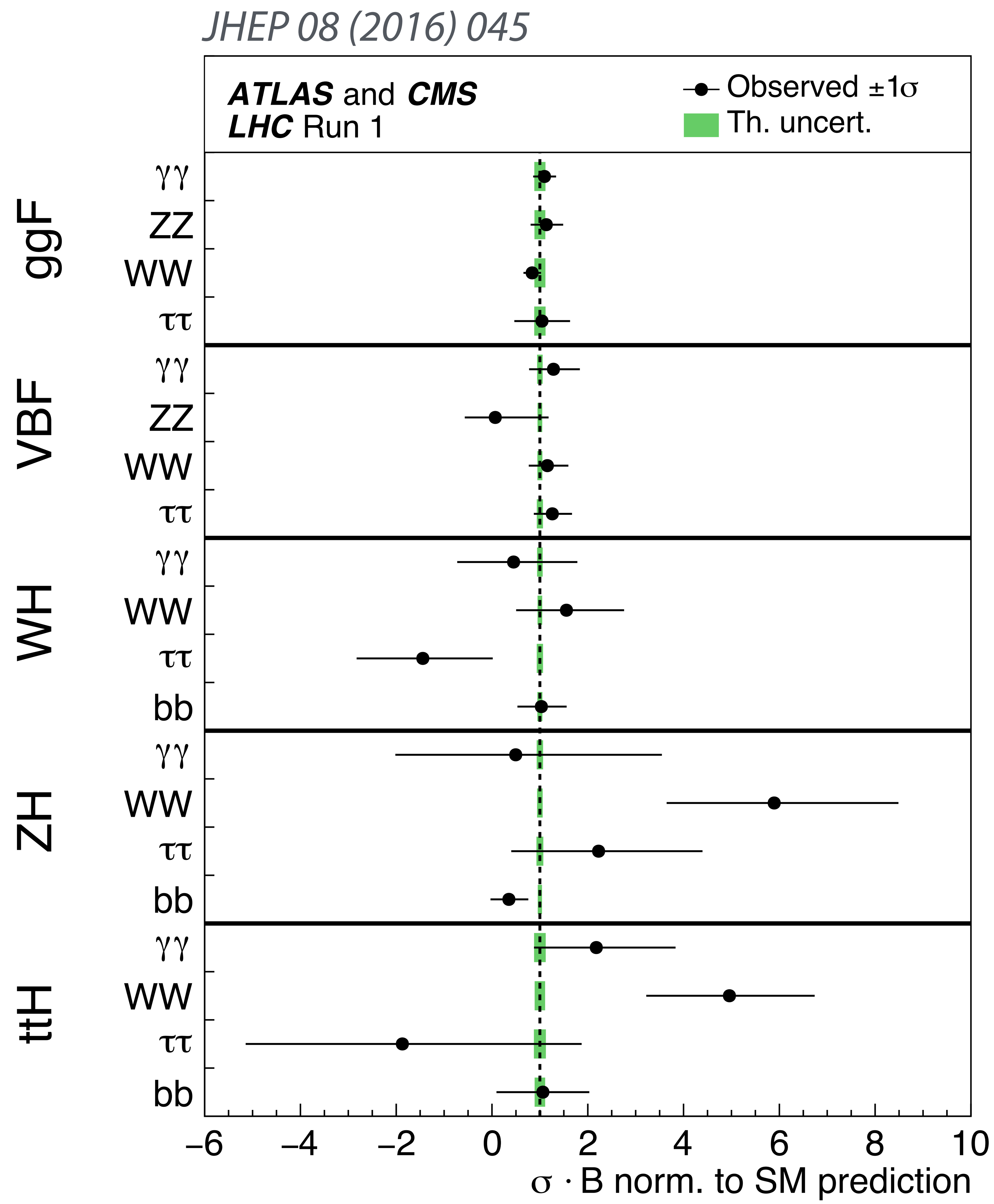


Measurement competitive with world best single measurement from Tevatron!

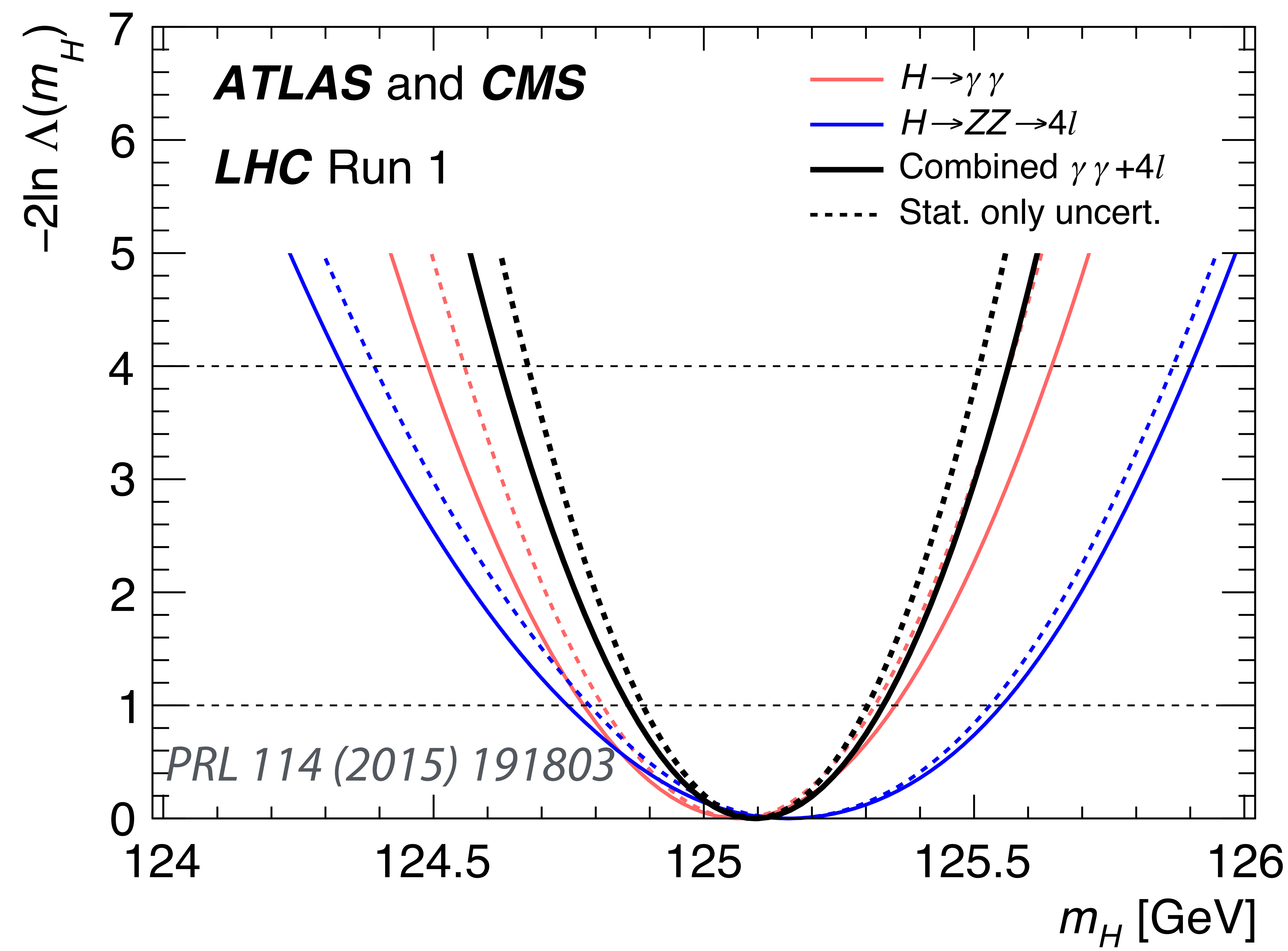
Consistent with SM expectation

Higgs measurements

Higgs run 1 legacy



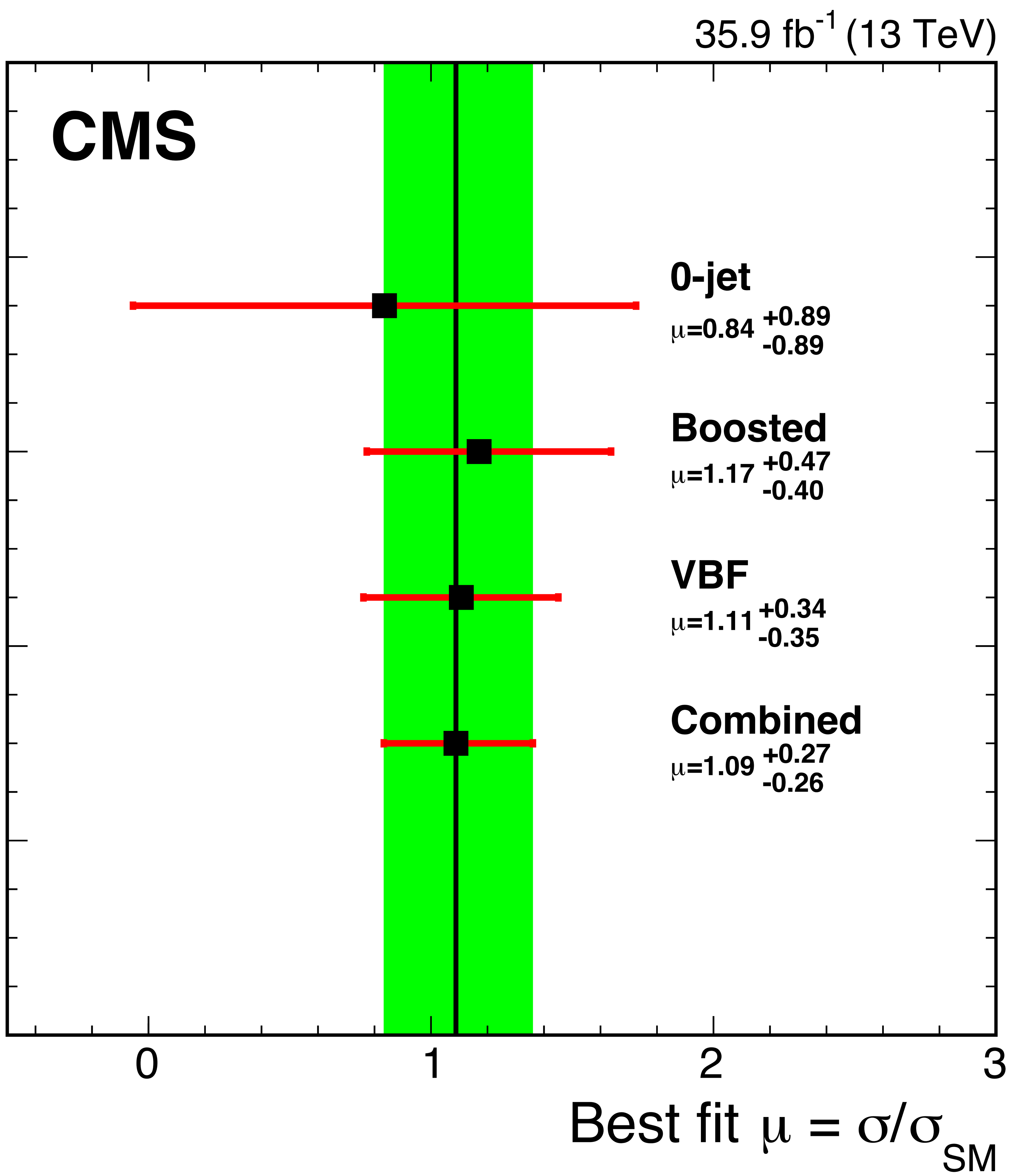
$m_H = 125.09 \pm 0.24$ GeV $= \pm 0.21$ (stat.) ± 0.11 (syst) GeV



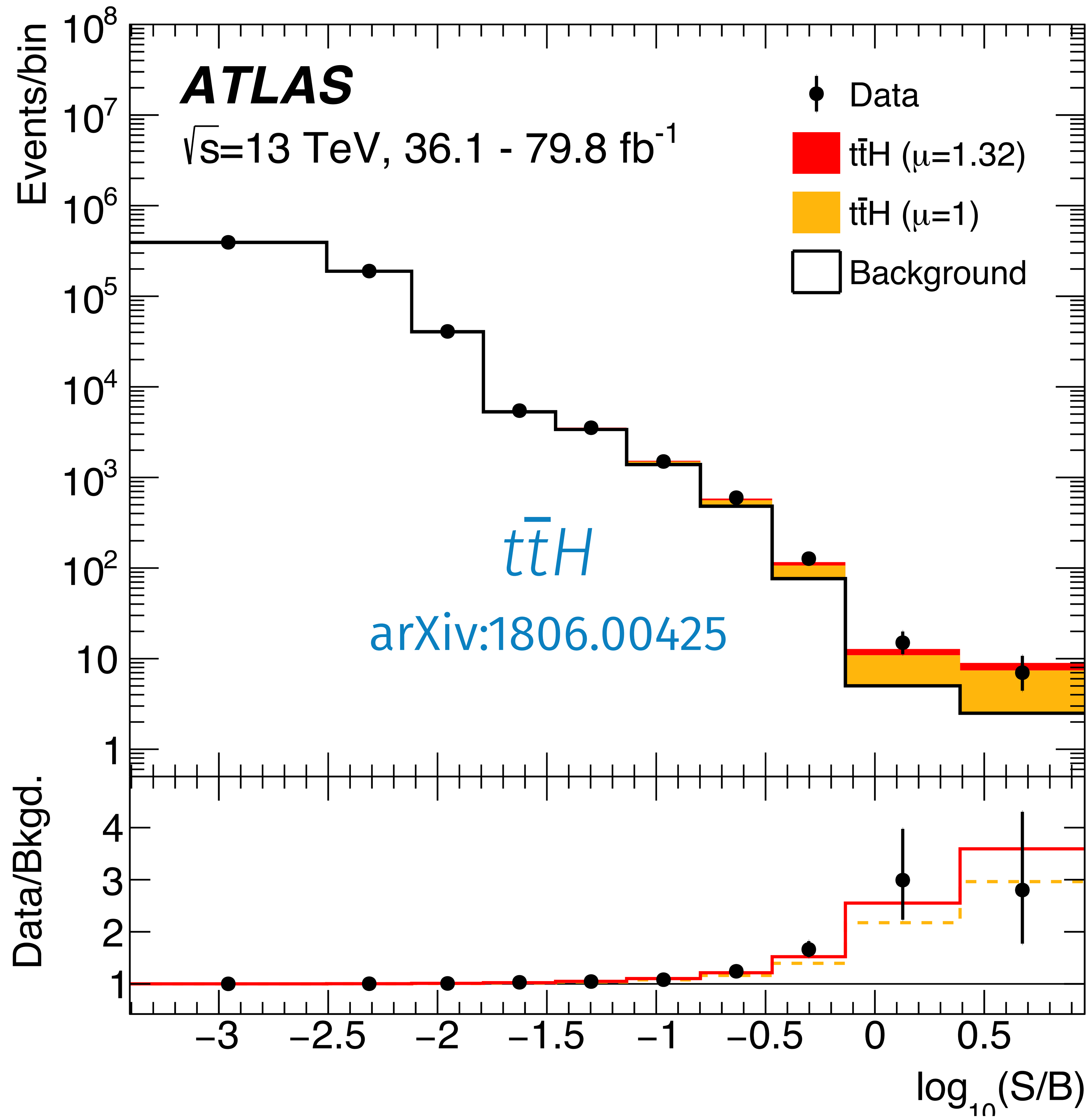
No direct observation of Higgs couplings to fermions

One of the focuses of Run 2 (H to ττ, tt, bb)

Run 2 Highlights (not covered)

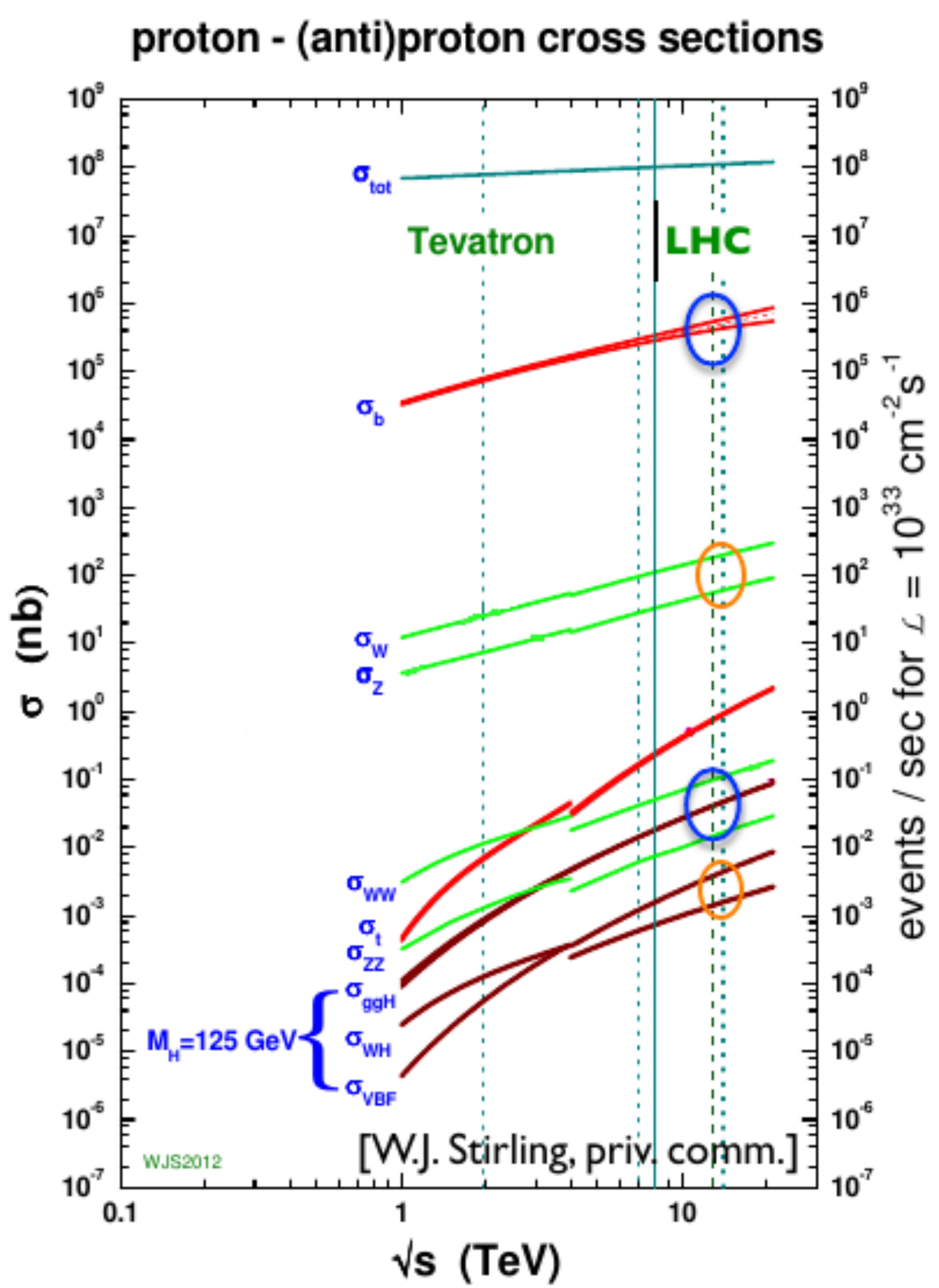


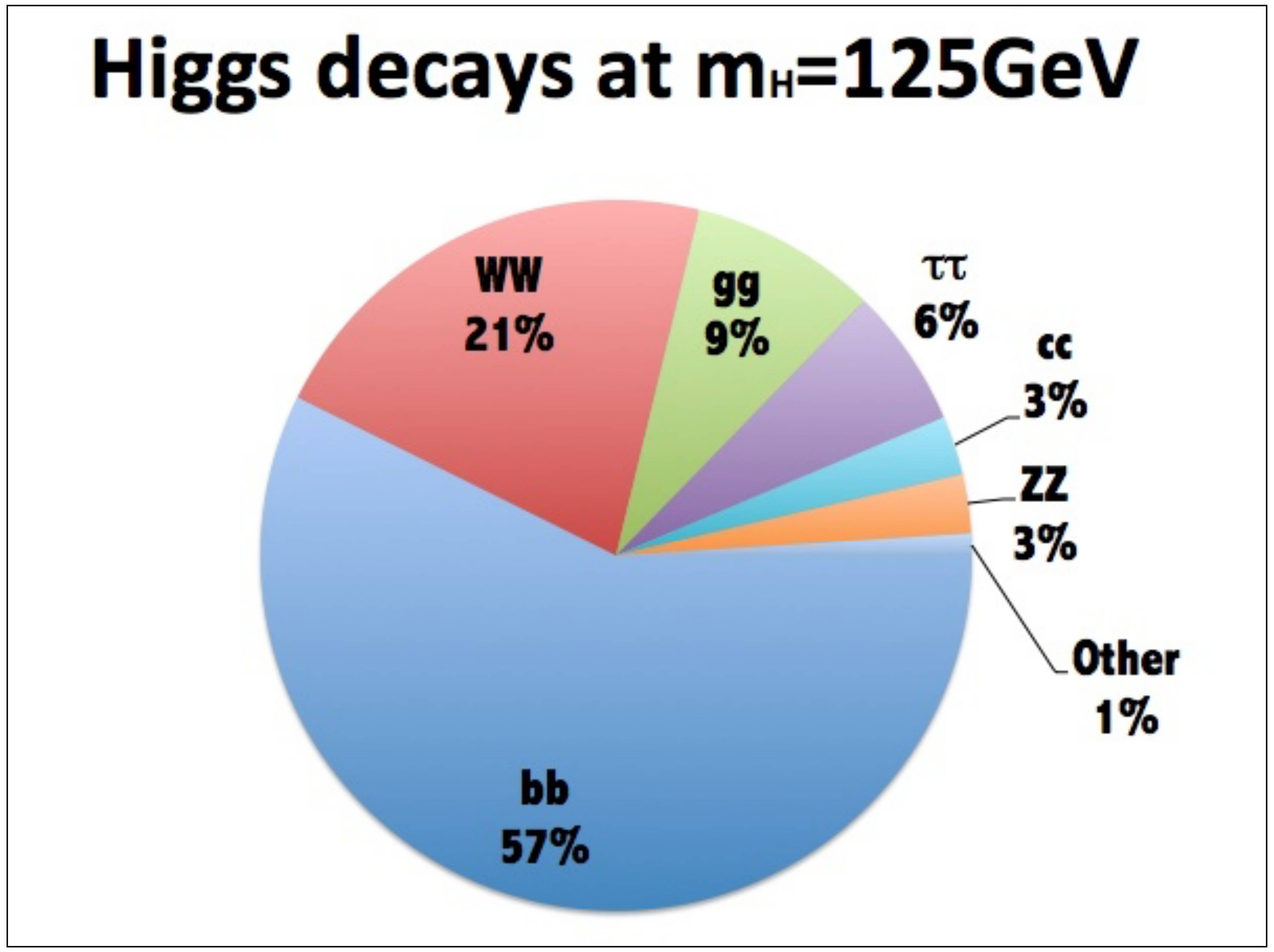
H to ττ



ttH

Hot take! Hbb

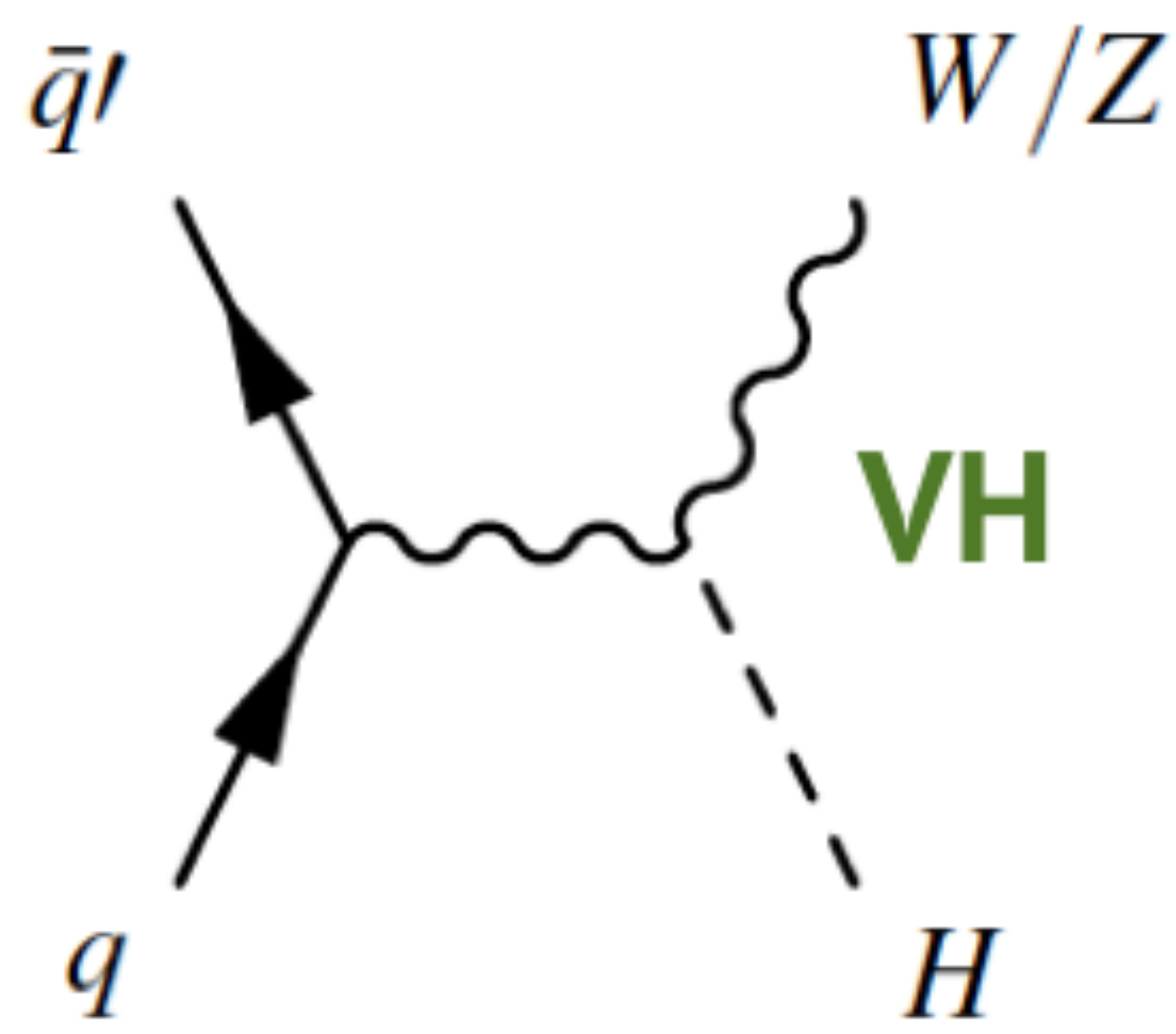


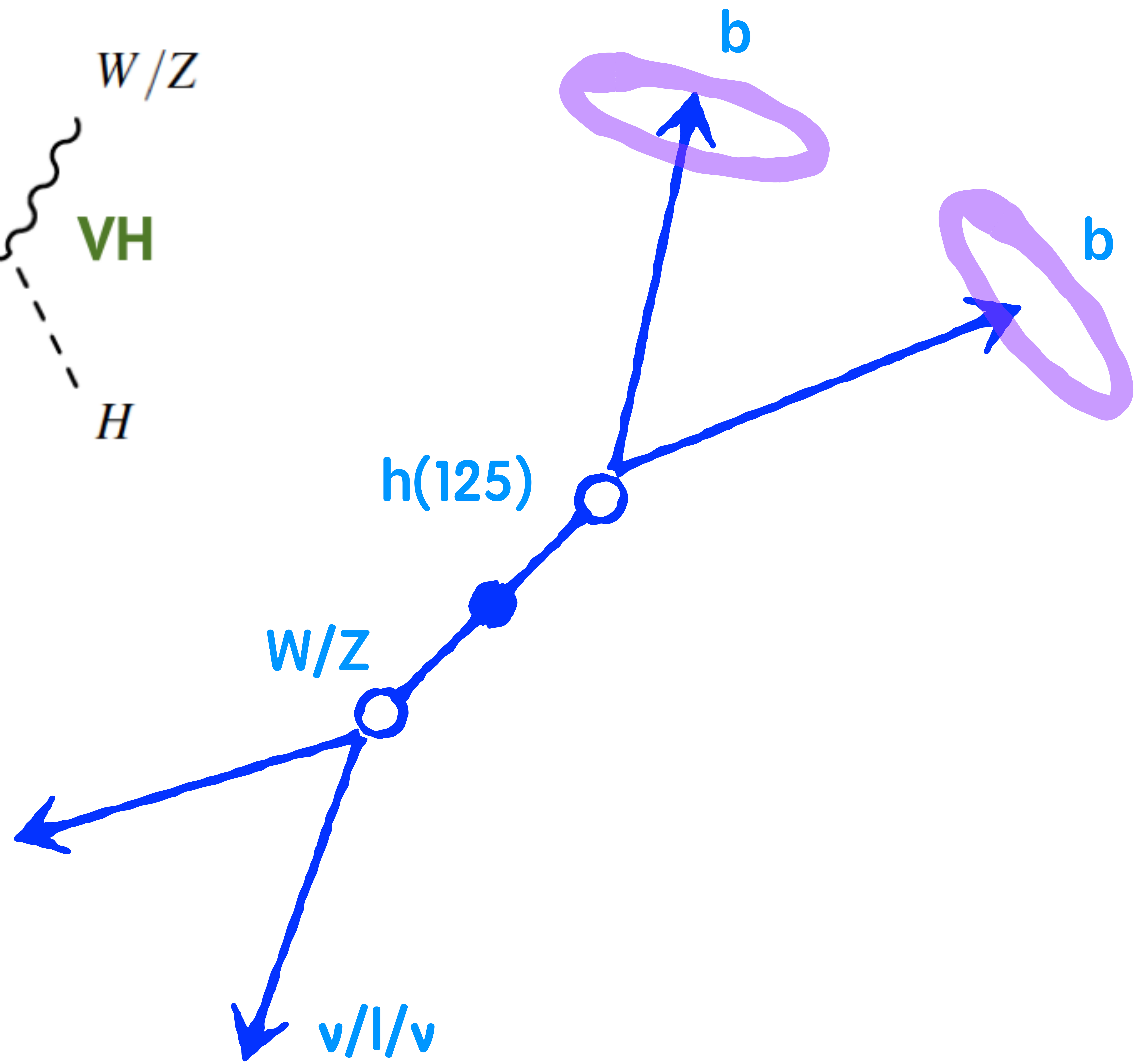


Important to observe Hbb

A majority of the total width of the Higgs

VH(→BB)





VH(→BB) KEY ANALYSIS ELEMENTS

Main backgrounds

V + jets: reducible background from V + bb is challenging to model because of g > bb simulation

ttbar: large cross-sections with natural heavy flavor

VZ: a nice validation process

1. Very high performance b-tagging

   Critical performance of CMS/ATLAS tracking pixel detectors

2. Mass resolution of bb jet invariant mass

   Includes mass regression and kinematic fits for the whole VH system

3. "boosted" regime: requiring high pT V or H reduces SM backgrounds and increases S/B

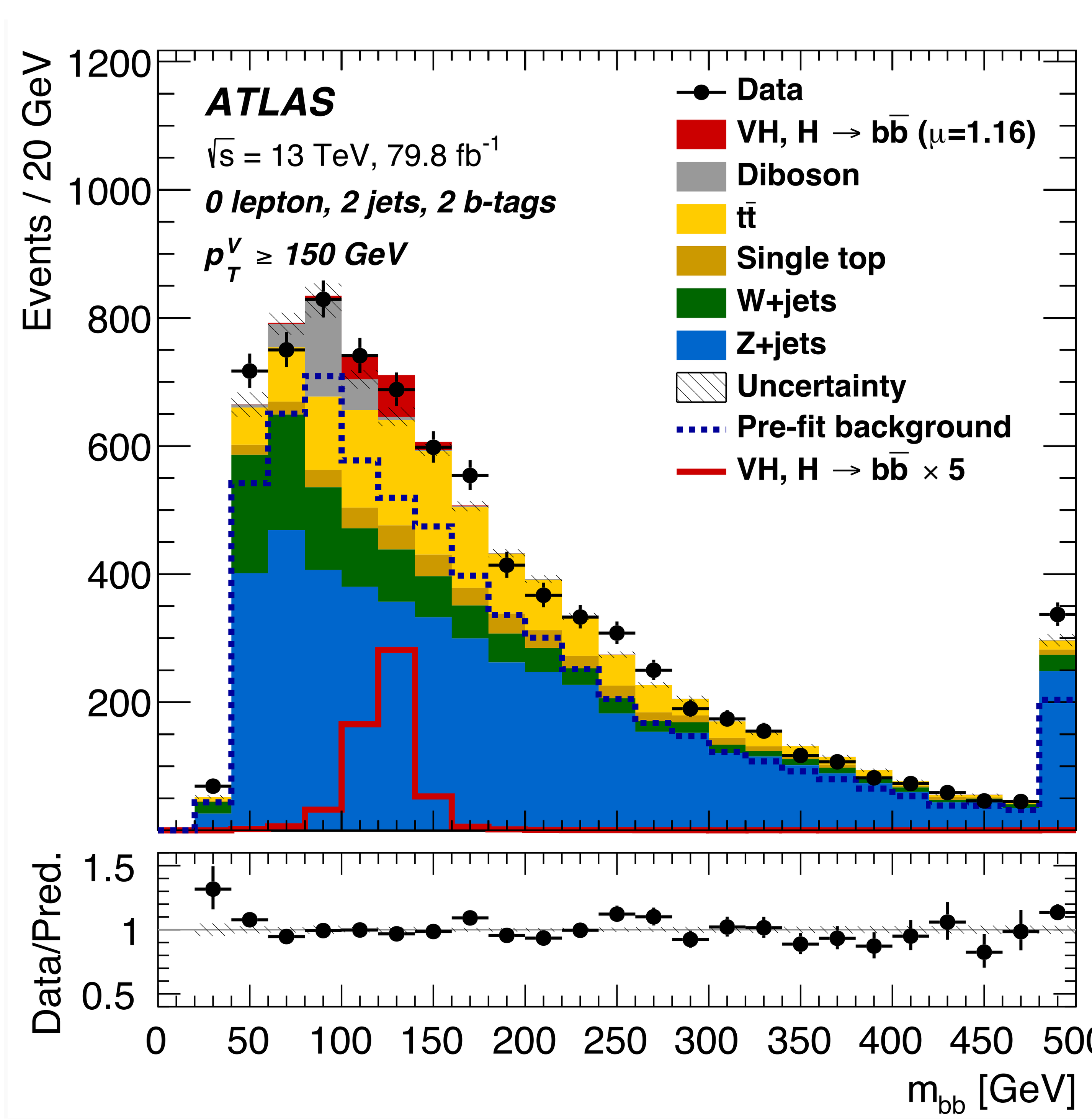
MBB DISTRIBUTIONS

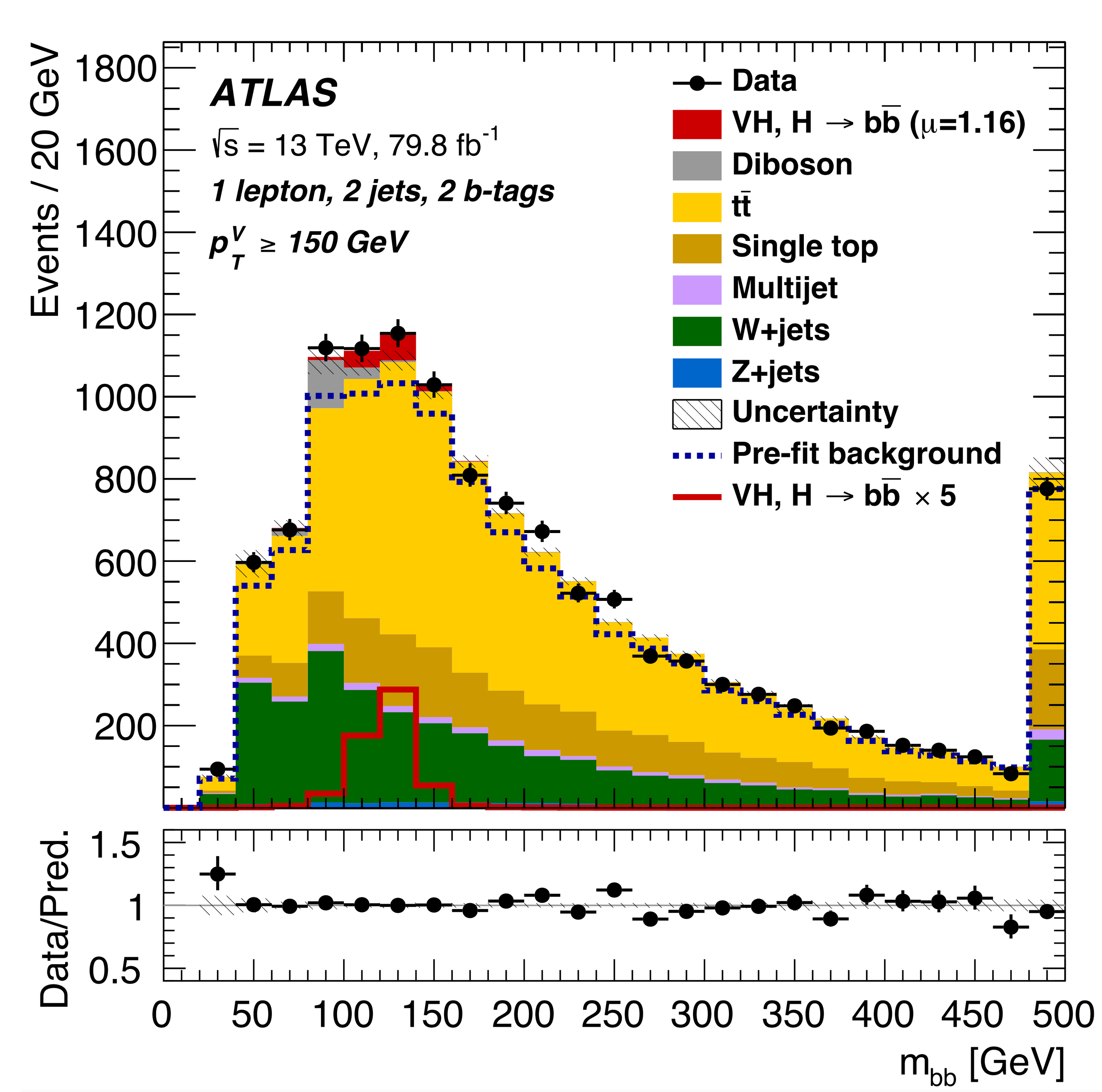
A number of kinematic variables are included in a multivariate discriminant

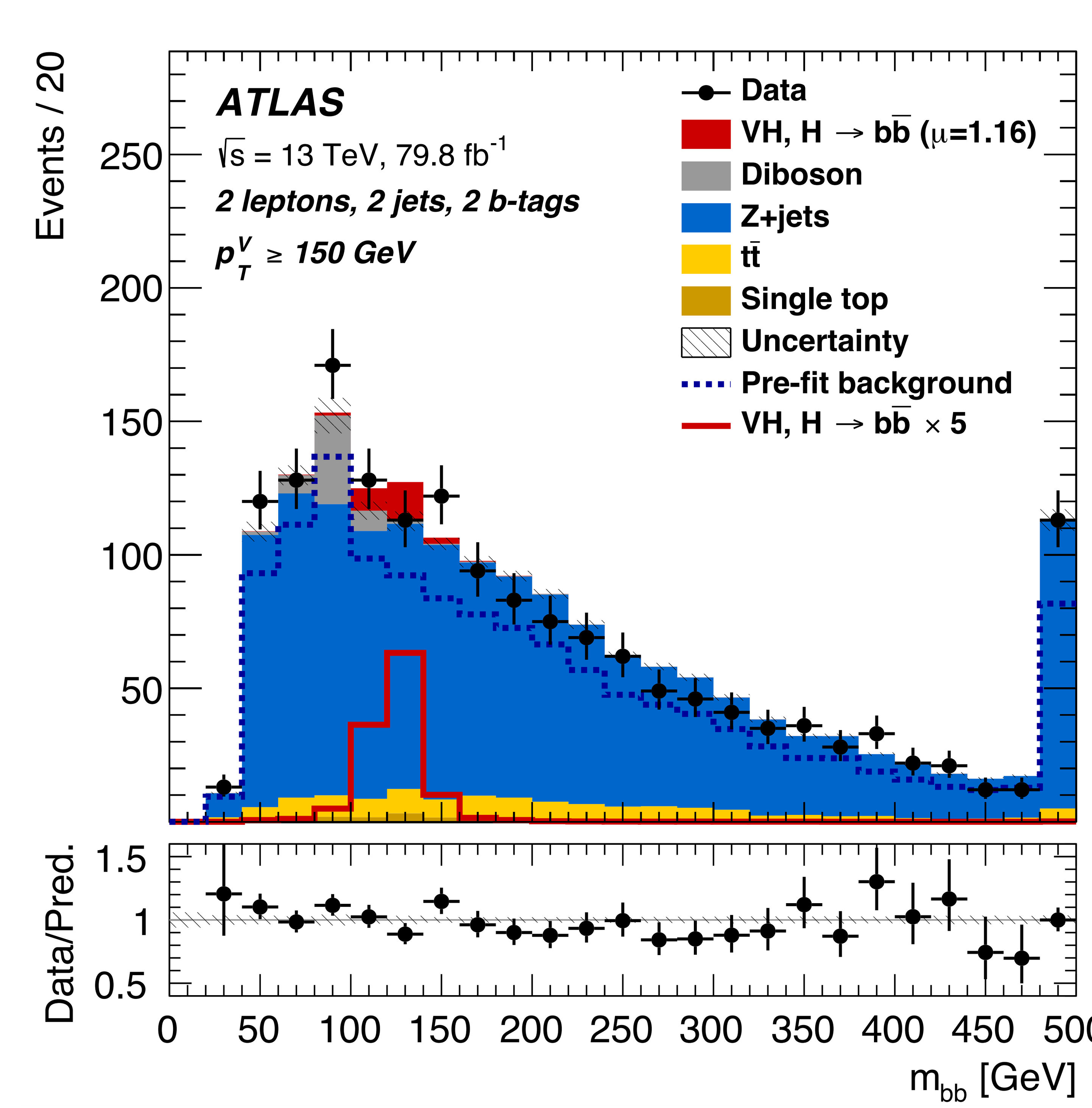
- Most important: m_{bb}, ΔR_{bb}, pT(V) most important

Control regions are fit simultaneously to control backgrounds from V+jets and ttbar (fit in the BDT discriminant)

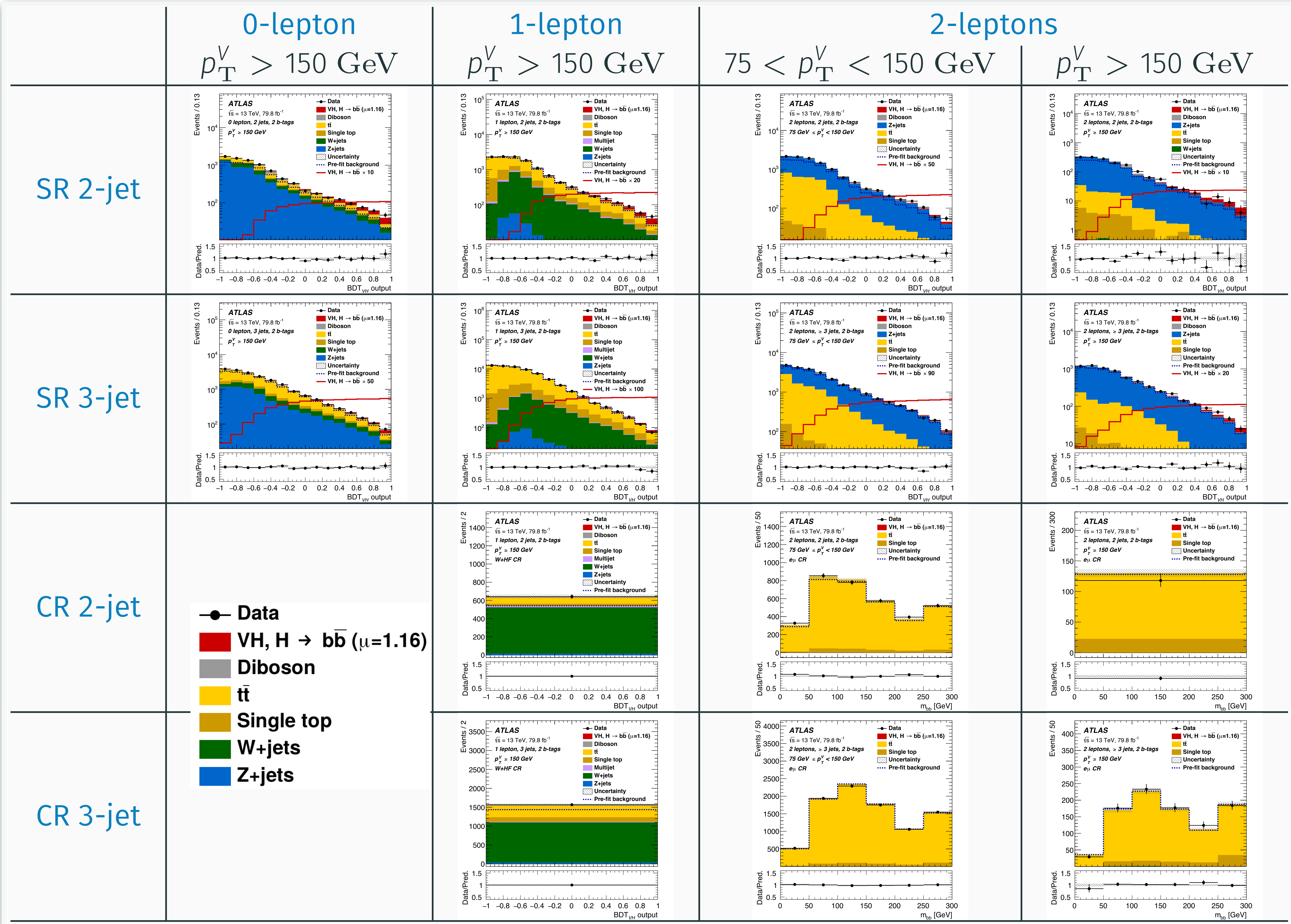
Diboson fit can be used to validate methodology







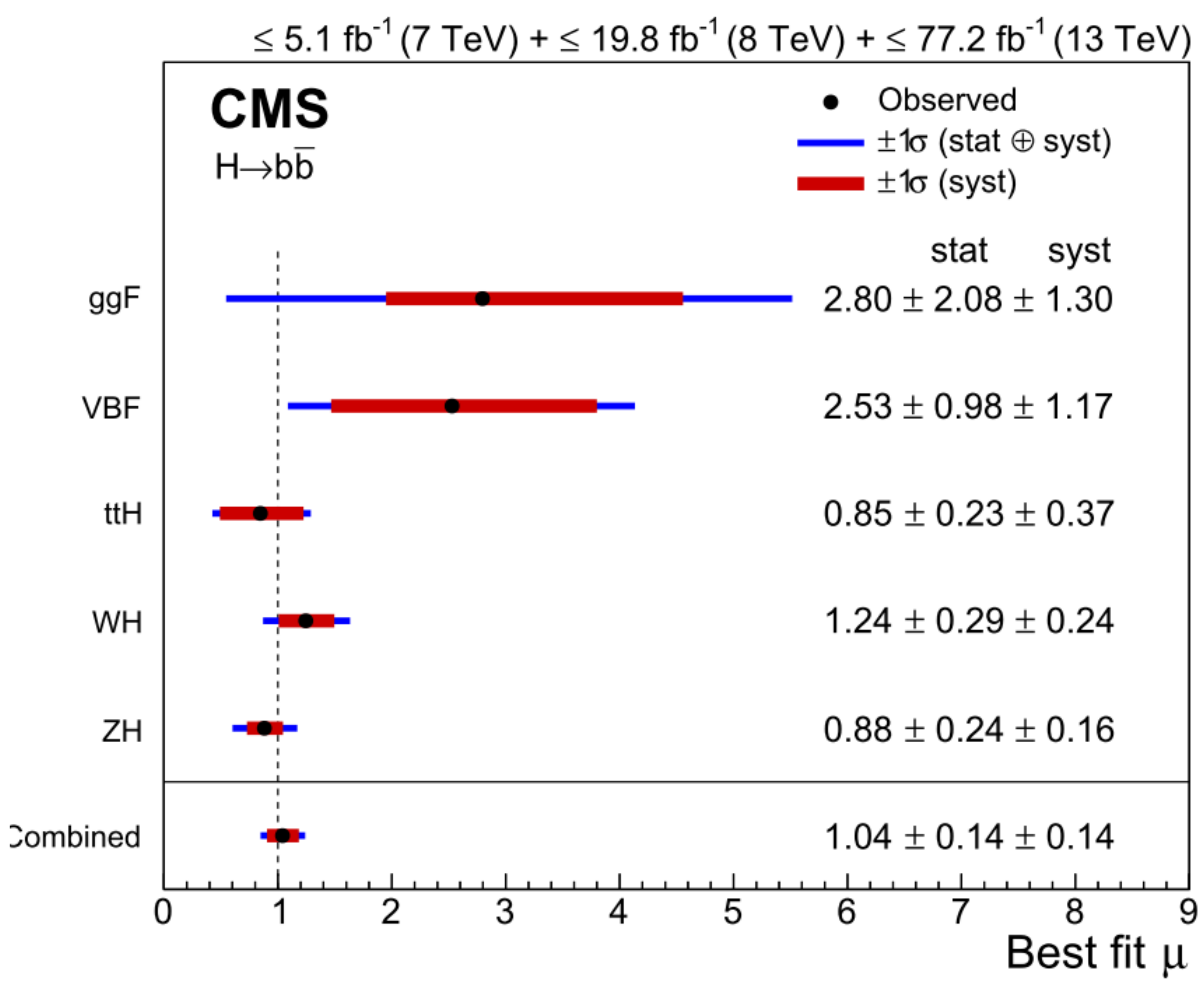
Combined multi-category fit

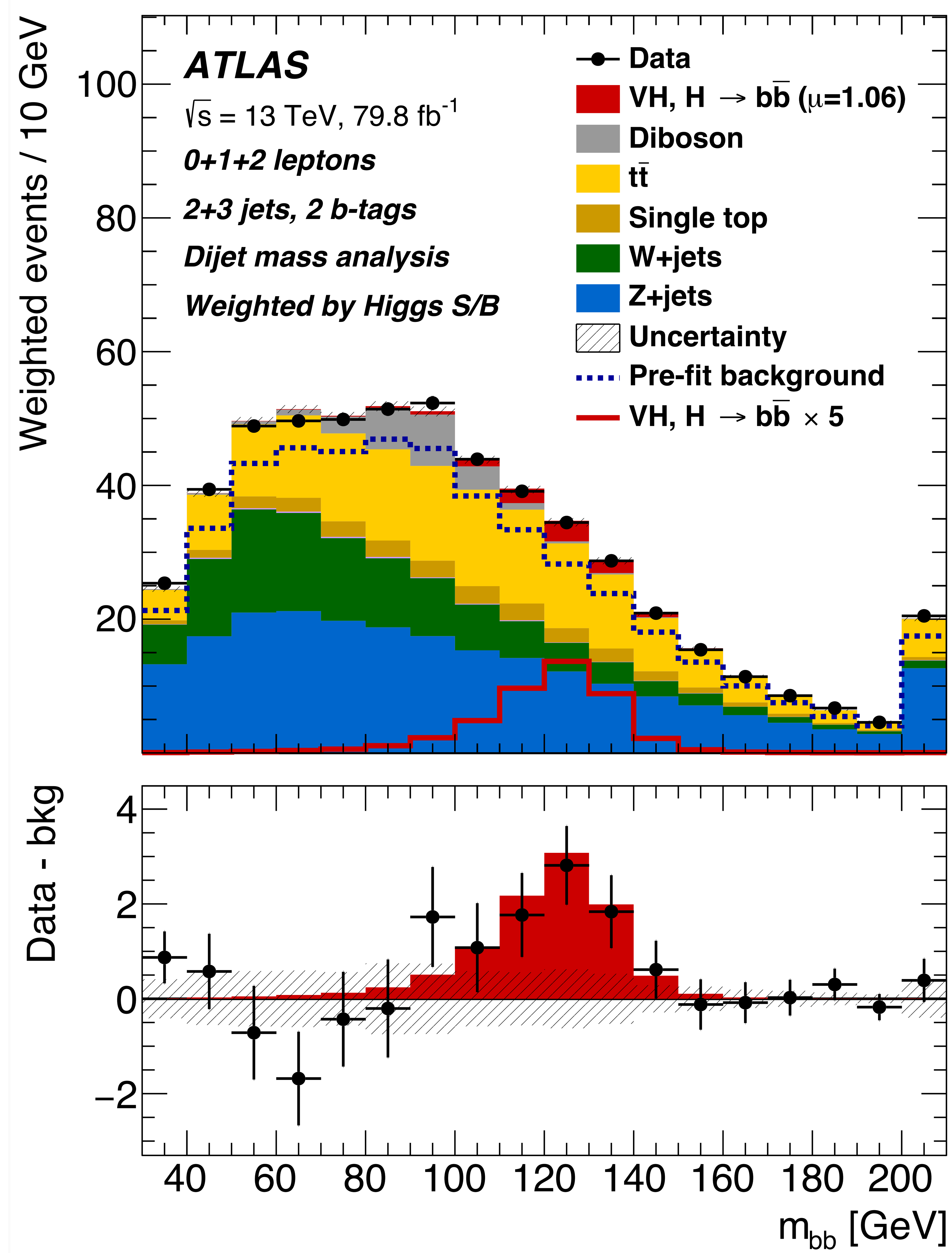


VHBB OBSERVATION!

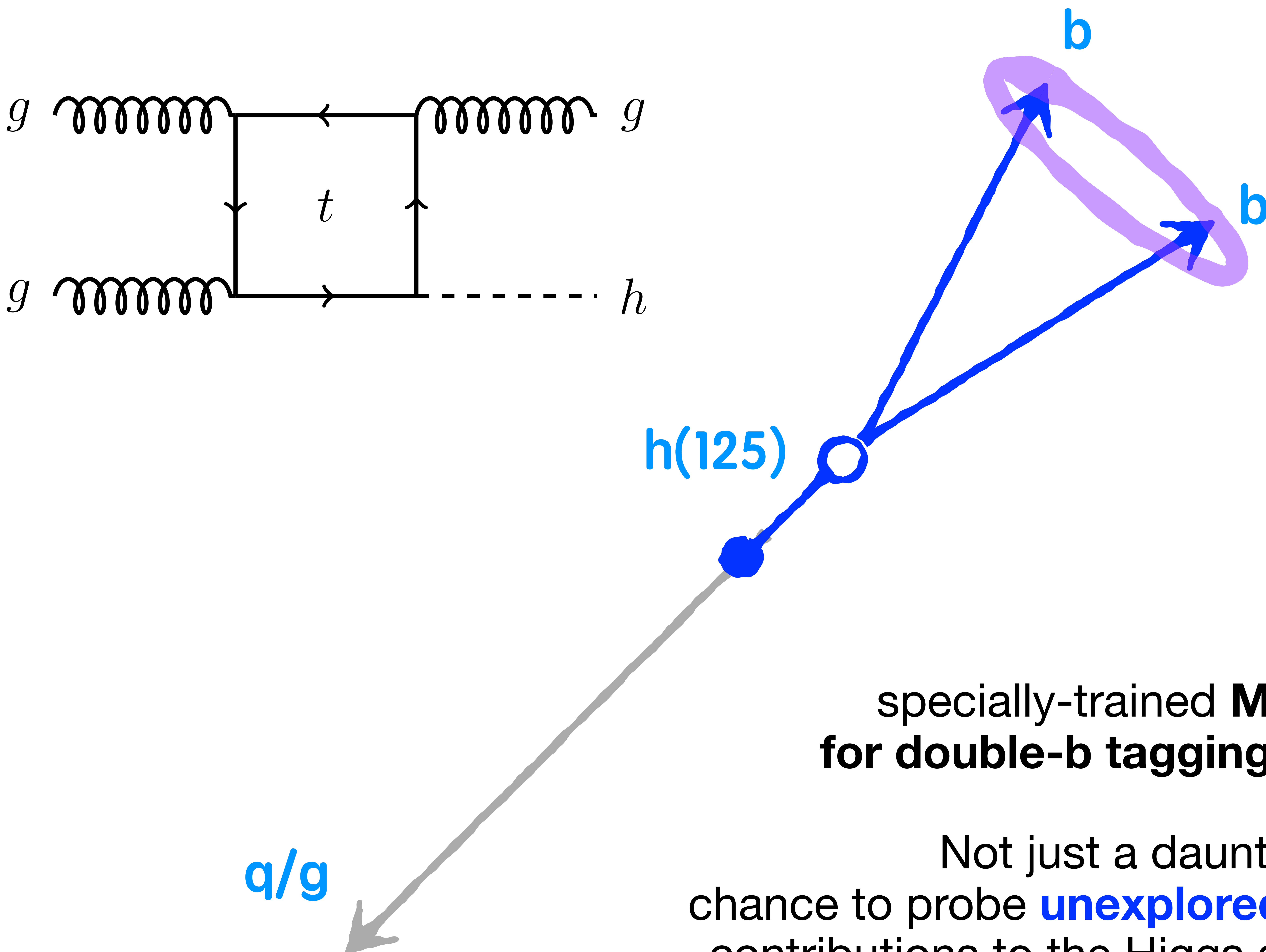
Combining with Run 1 result, final VH(bb) result:
4.9 σ (obs), 5.1 σ (exp)
Combining with other production modes (VBF, ttH):
5.4 σ (obs), 5.5 σ (exp)

CMS also reported a similar result:
5.6 σ (obs), 5.5 σ (exp)



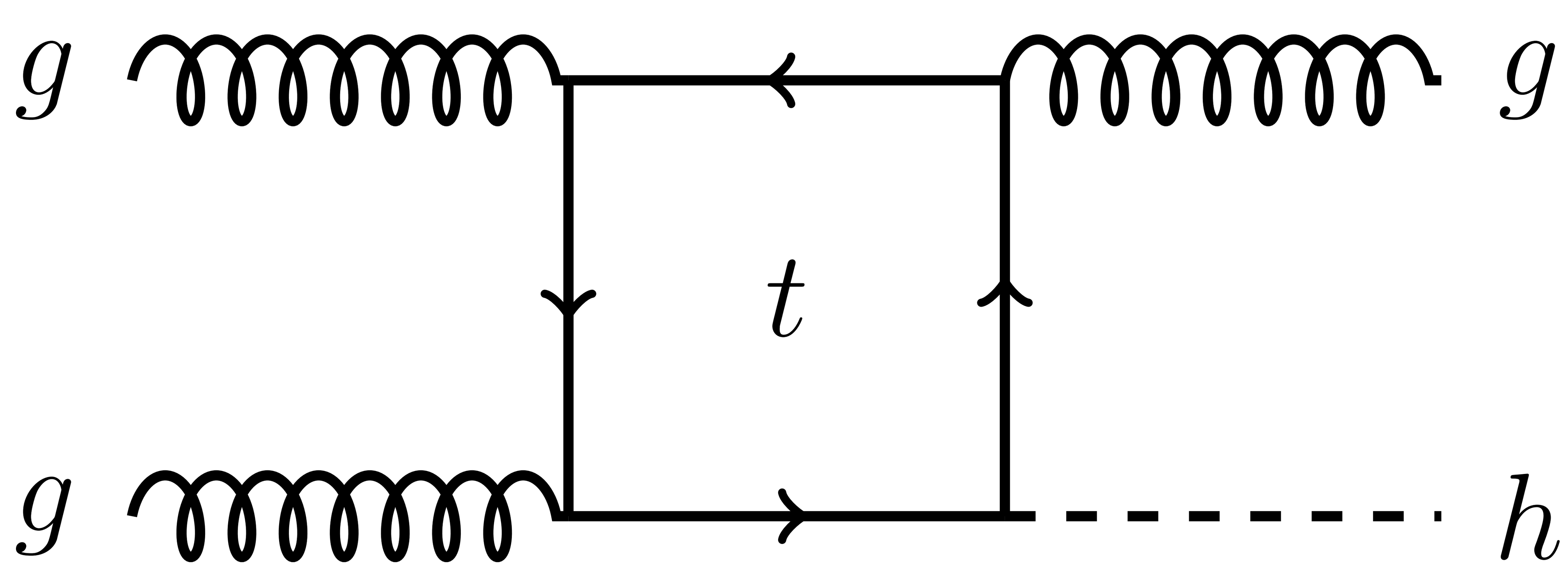


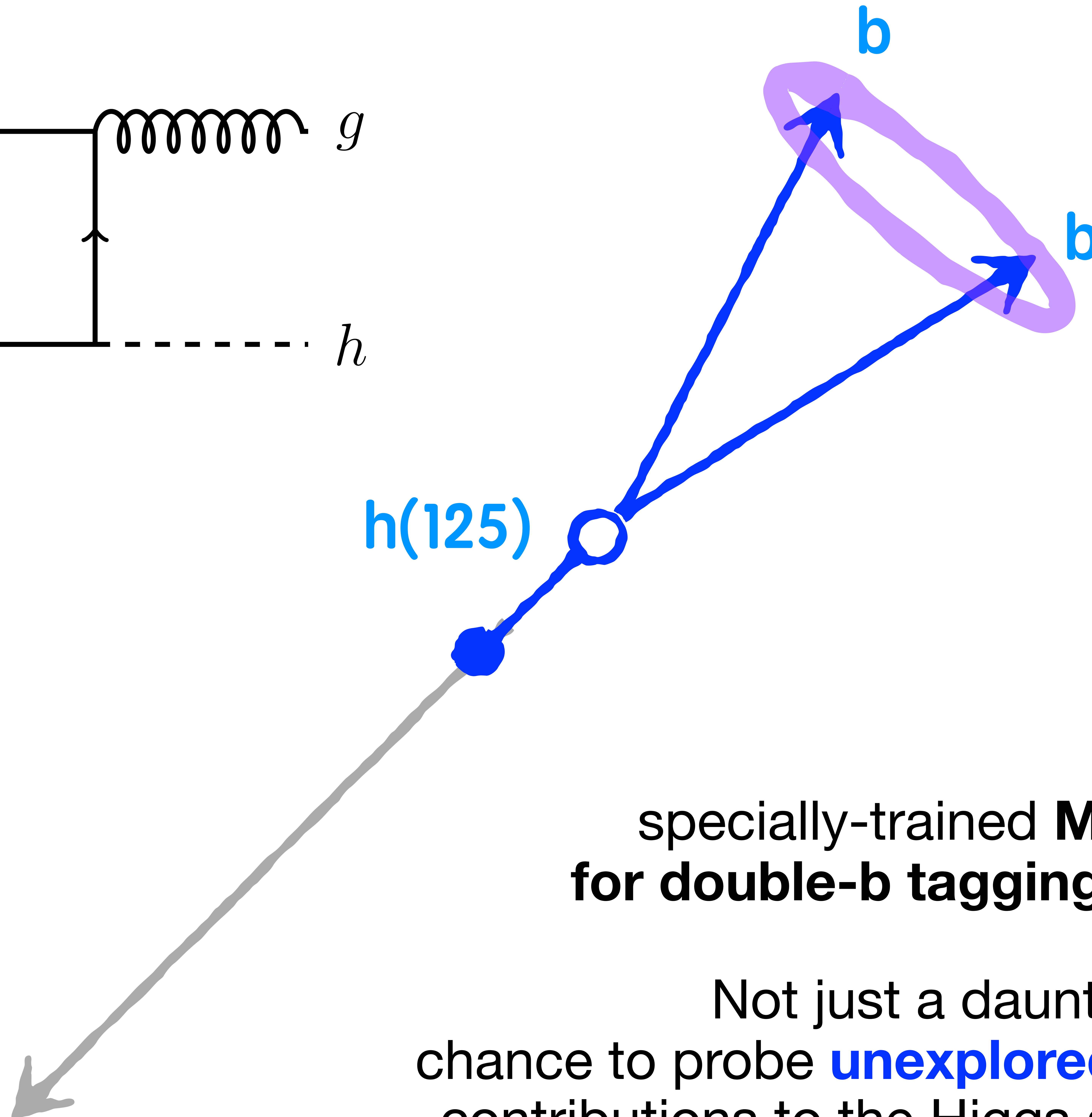
GG→H→BB



specially-trained **ML techniques for double-b tagging** in a single jet

Not just a daunting challenge, chance to probe **unexplored** new physics contributions to the Higgs at very high p_T

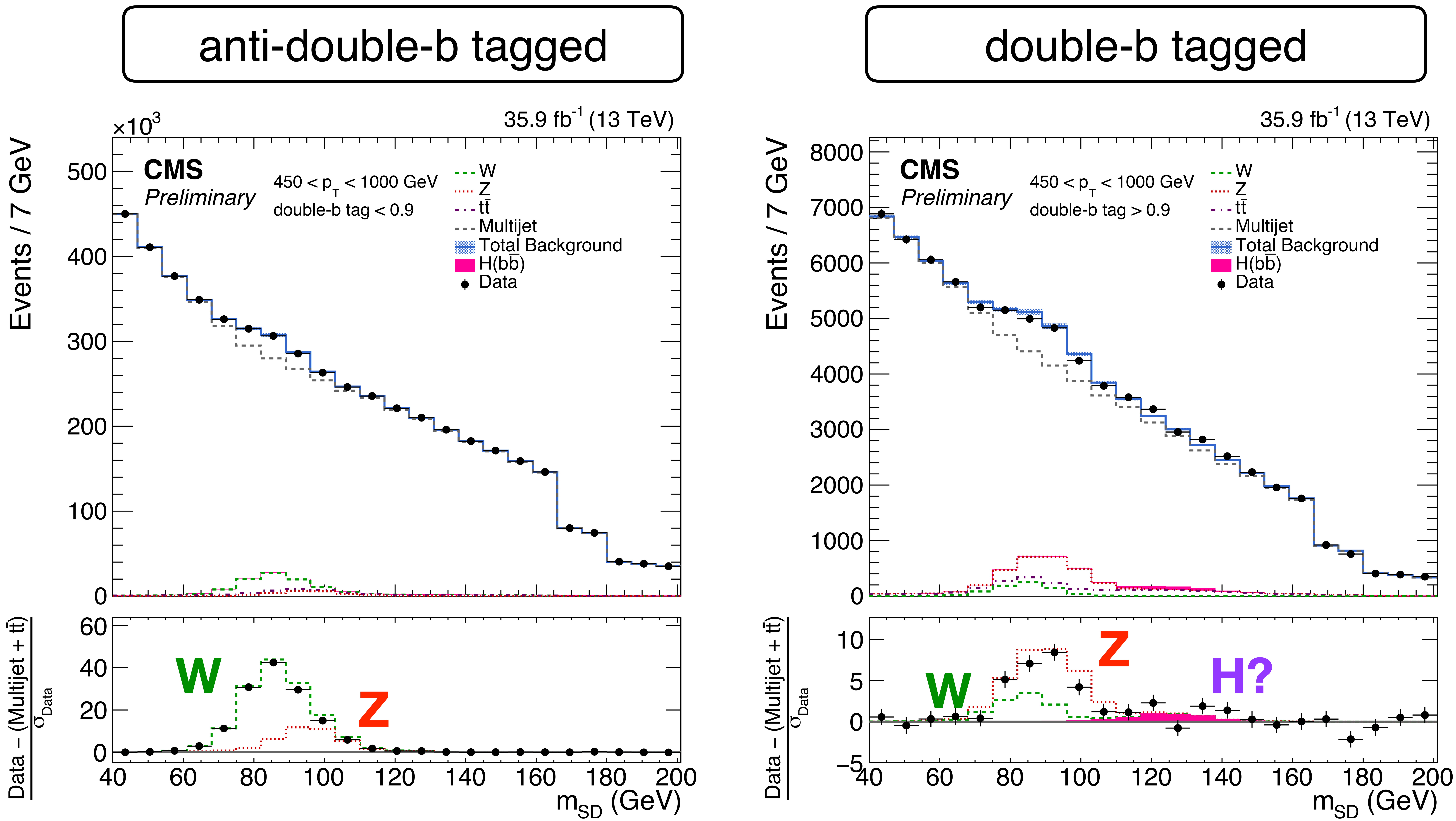




specially-trained **ML techniques for double-b tagging** in a single jet

Not just a daunting challenge, chance to probe **unexplored** new physics contributions to the Higgs at very high p_T

n.b. this is a very hard SM Higgs calculation at very high pT!

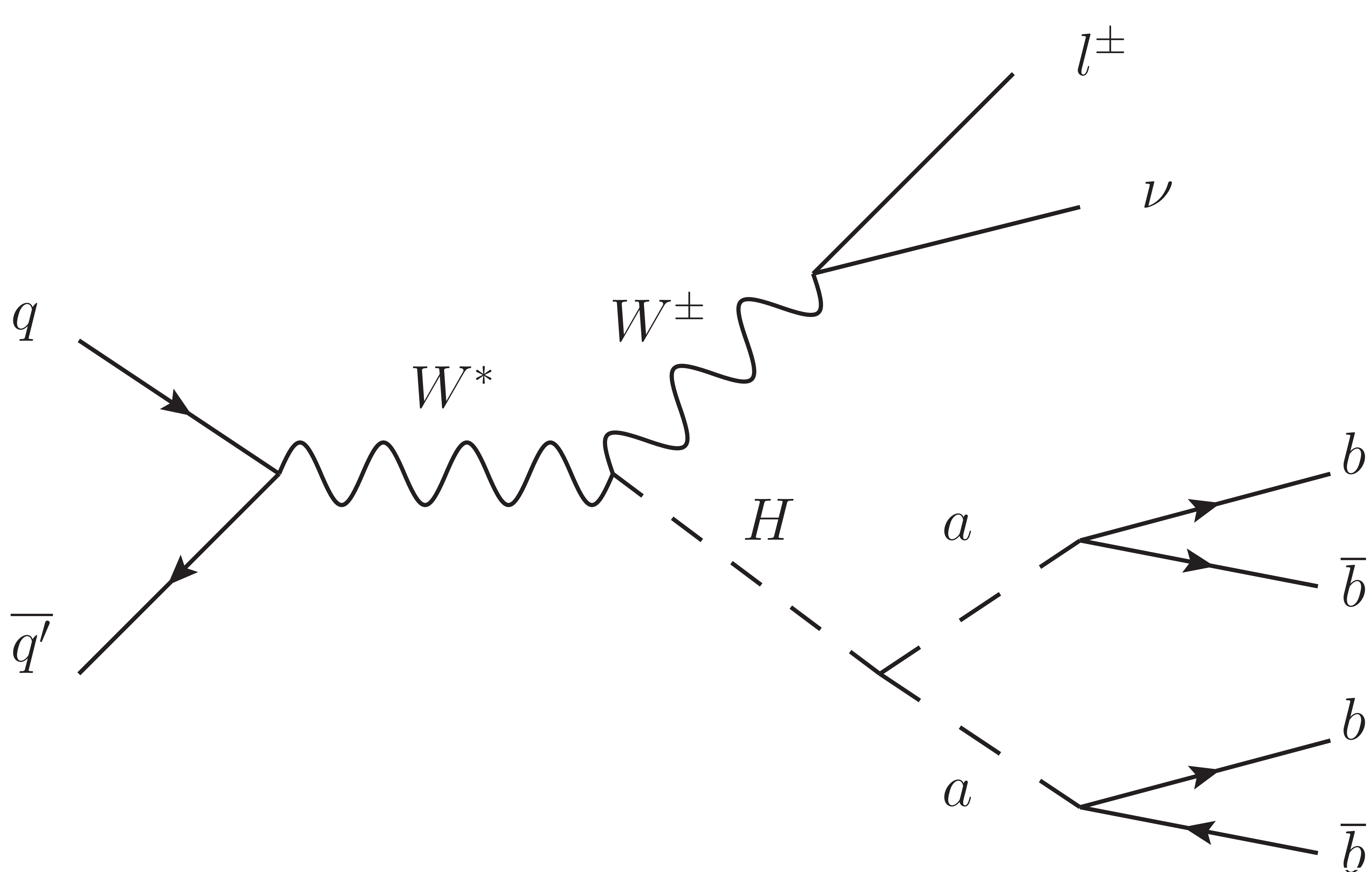

anti-double-b tagged
double-b tagged
CMS
Preliminary
35.9 fb-1 (13 TeV)
450 < pT < 1000 GeV
double-b tag < 0.9
double-b tag > 0.9
W
Z
tt̄
Multijet
Total Background
H(bb̄)
Data
Events / 7 GeV
Data − (Multijet + tt̄) / σData
mSD (GeV)
W
Z
H?

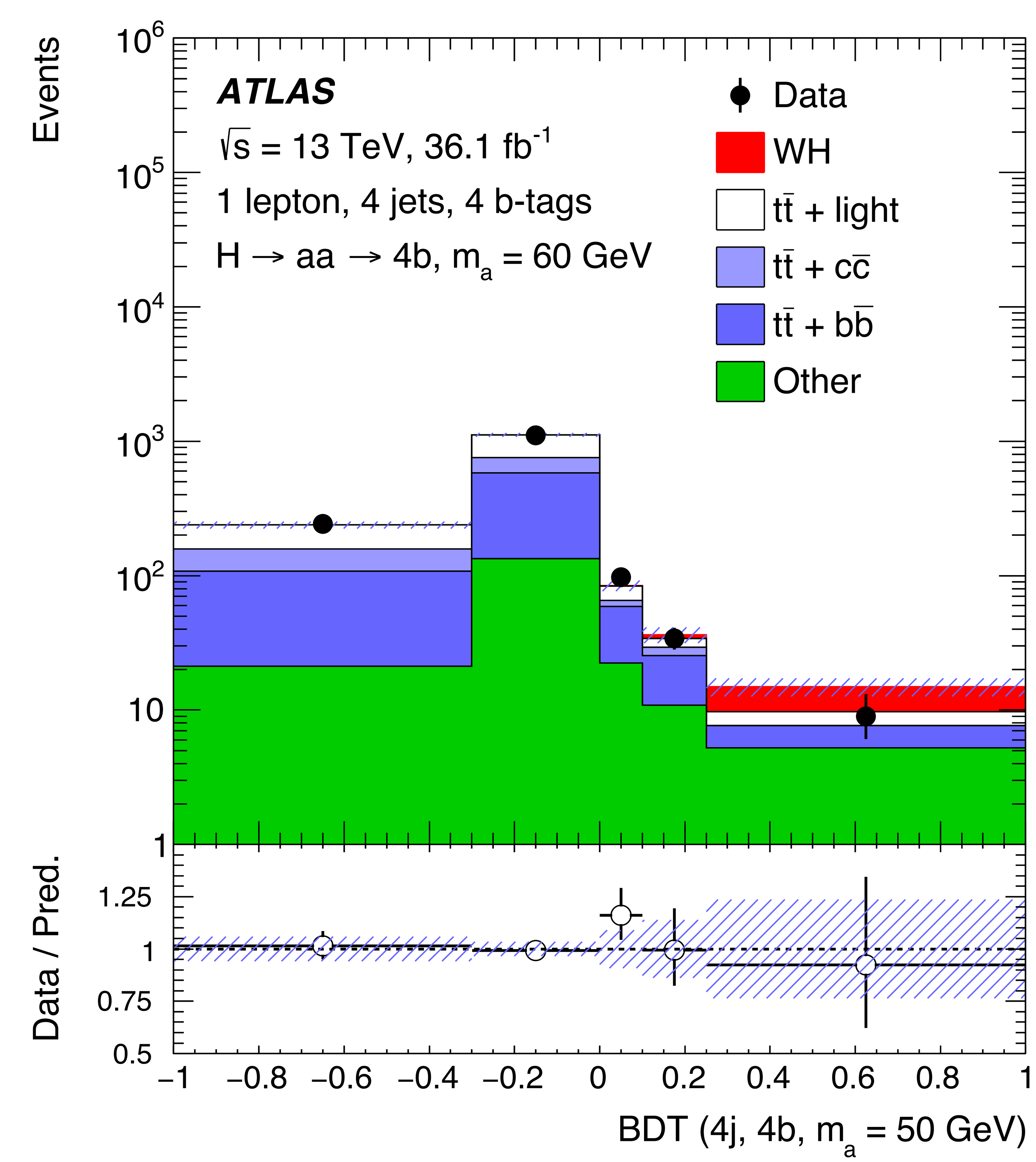
Higgs portal

We have just begun to scratch the surface on the exploration of the Higgs boson

- A wide array of searches looking for exotic decays of the Higgs and Higgs partners in extended Higgs sectors (e.g. in MSSM)

A fun example with a twist on traditional VH search:





The evolution of searches

Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy ◁

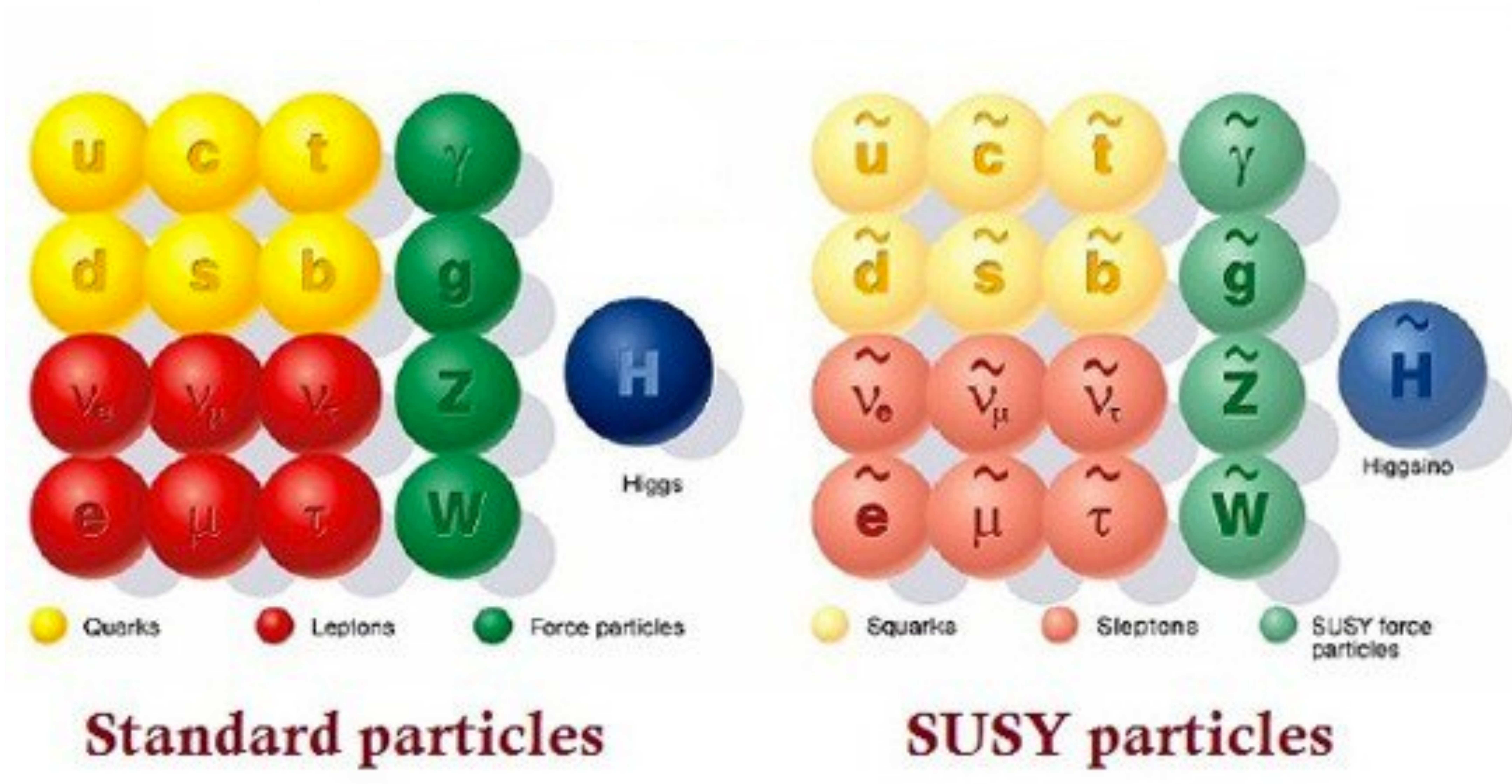
Neutral naturalness (twin Higgs, folded susy) ◁

Relaxion ◁

Christophe Grojean

SUSY, Exotics, Long-lived

SUSY is a popular BSM scenario to explore
(a very broad framework to explore BSM final states)
Solution the hierarchy problem and coupling unification
Natural DM candidate

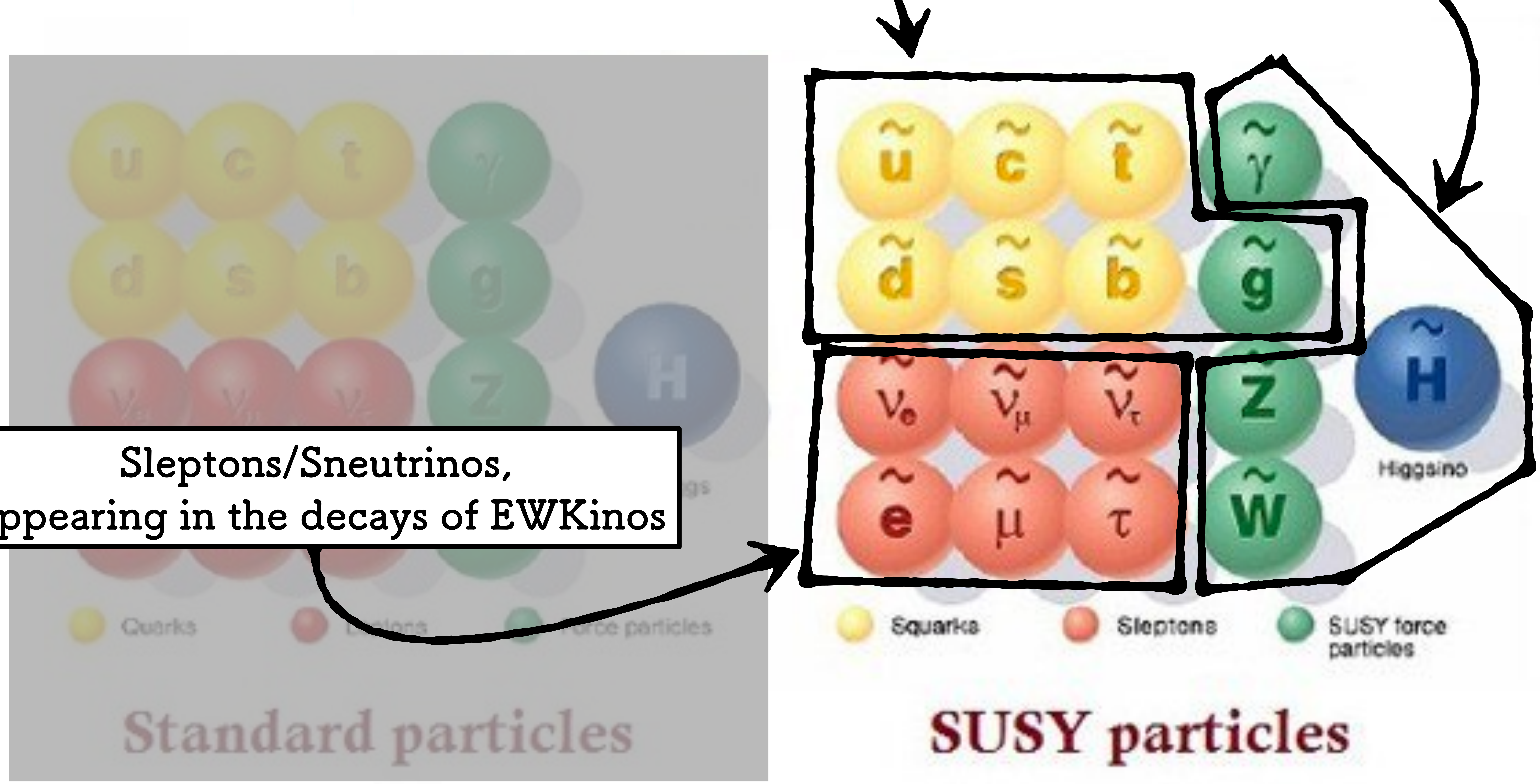


Supersymmetry

Strong SUSY dominated searches early
High cross-sections, high mass final states
Striking signatures (MET tails)

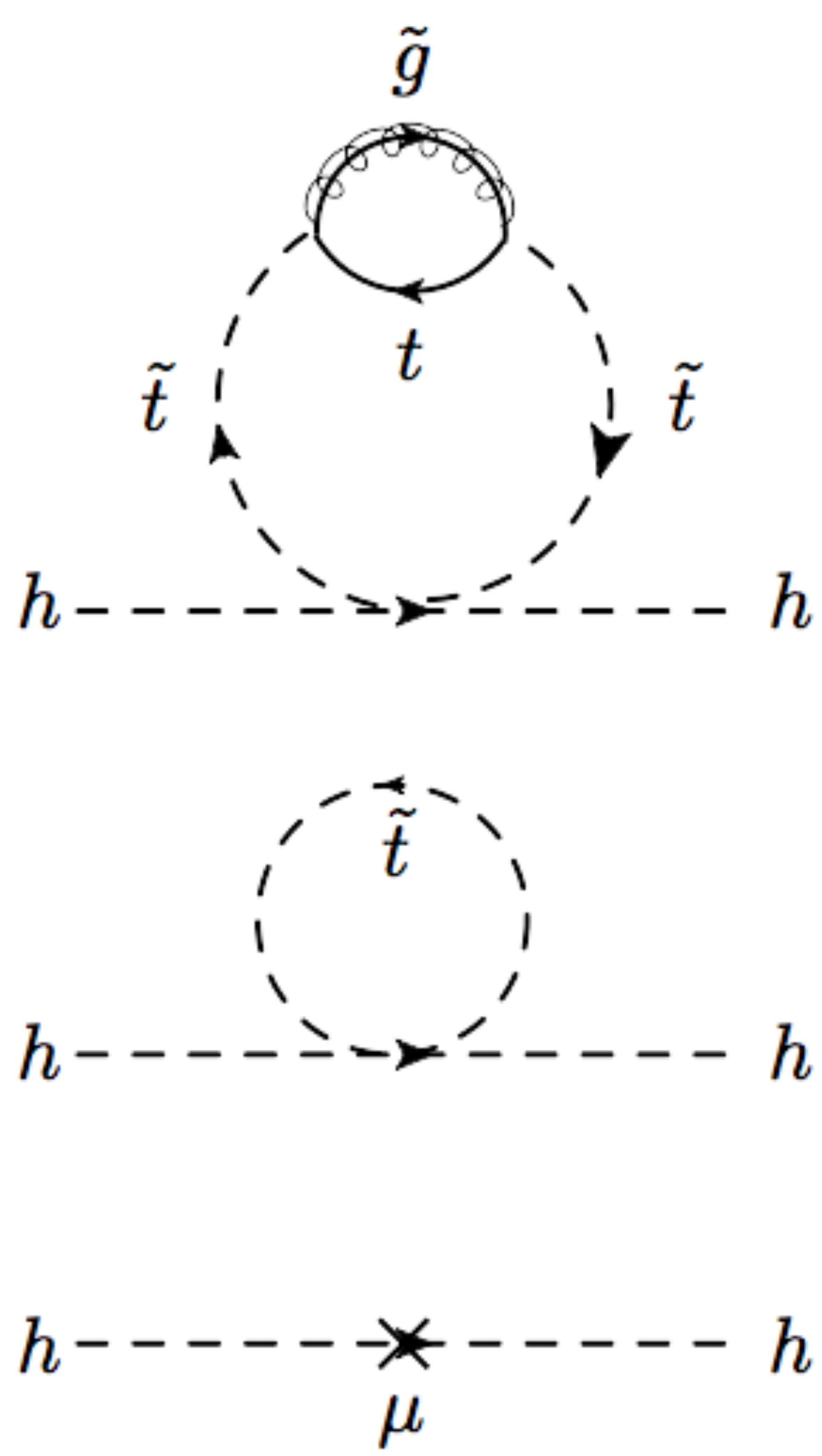
EWKinos (Wino/Bino):
Neutralinos: χ_1^0 χ_2^0 χ_3^0 χ_4^0
Chargino: $\chi_1^\pm$ $\chi_2^\pm$

Sleptons/Sneutrinos,
Appearing in the decays of EWKinos



NATURAL SUSY

Christophe Grojean



$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$

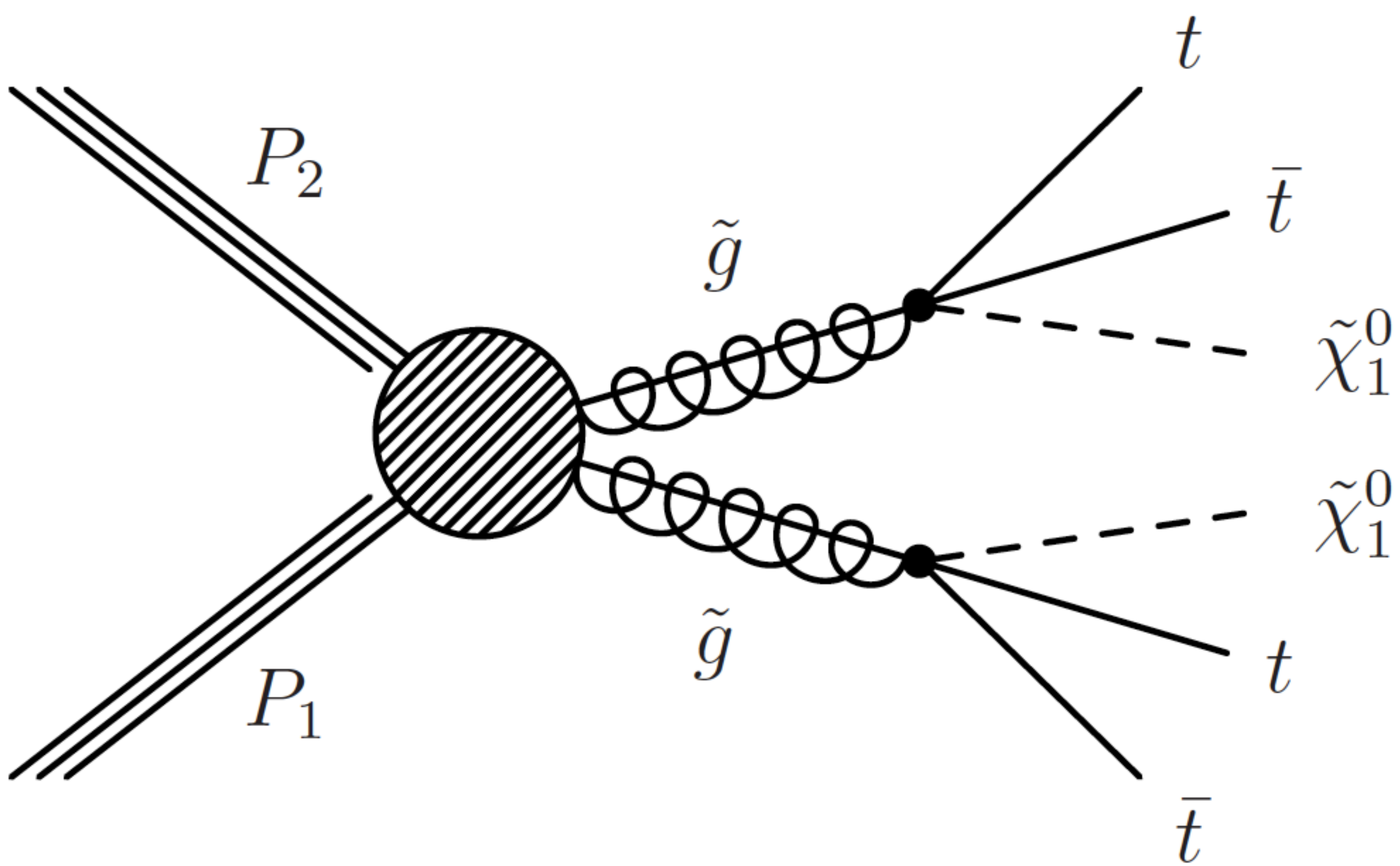
$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log\frac{\Lambda}{m_{stop}}$$

} **light stops, light gluinos!**
well tested @ LHC
but most questionable predictions
(RG effects)

$$\delta m_H^2 \sim |\mu|^2$$

} light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

Canonical SUSY - Stops



SAMPLE EWK SUSY SPECTRUM

In principle, any bino/wino/higgsino mass hierarchy is allowed

$\tilde{\chi}_3^0\ \tilde{\chi}_4^0\ \tilde{\chi}_2^{\pm}$ — $\tilde{H}$ (higgsino)

Δm ~ few – tens of GeV

$\tilde{\chi}_2^0\ \tilde{\chi}_1^{\pm}$ — $\tilde{W}$ (wino)

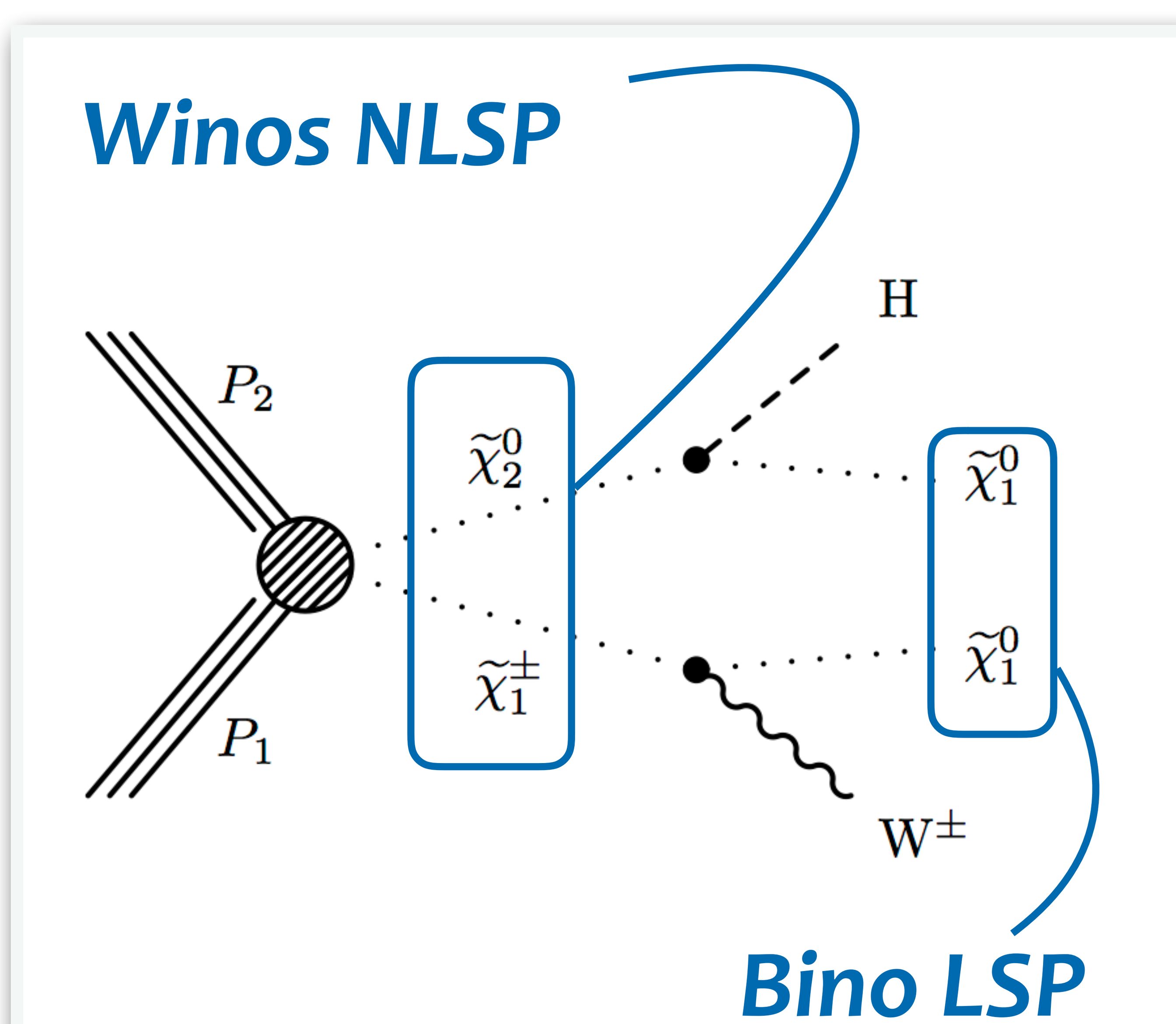
Δm ~ few hundreds MeV
(assuming heavy sfermions and higgsinos)

$\tilde{\chi}_1^0$ — $\tilde{B}$ (bino)

— $\tilde{G}$ (gravitino)

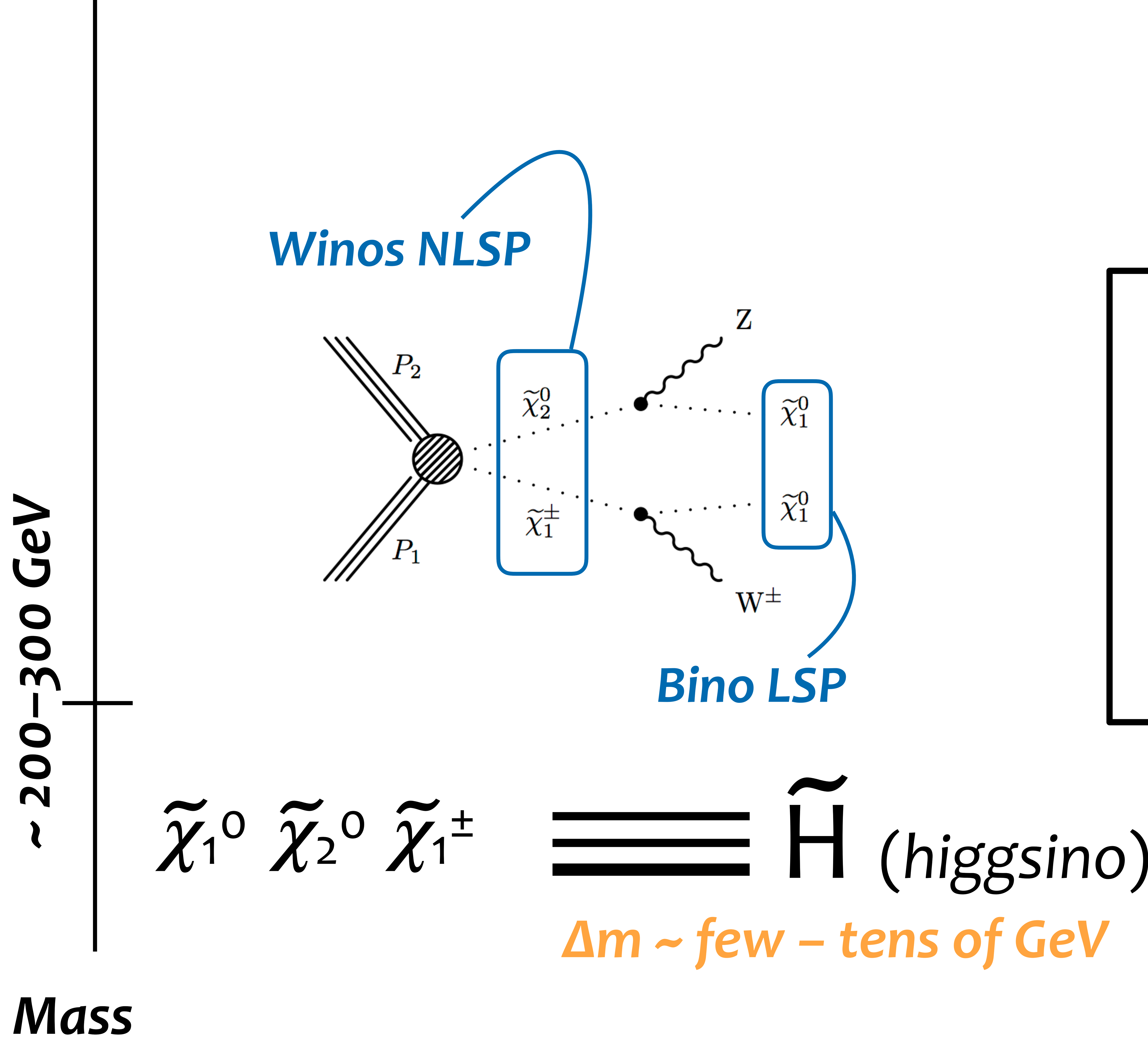
Appears in GMSB/GGM models, mass ~keV

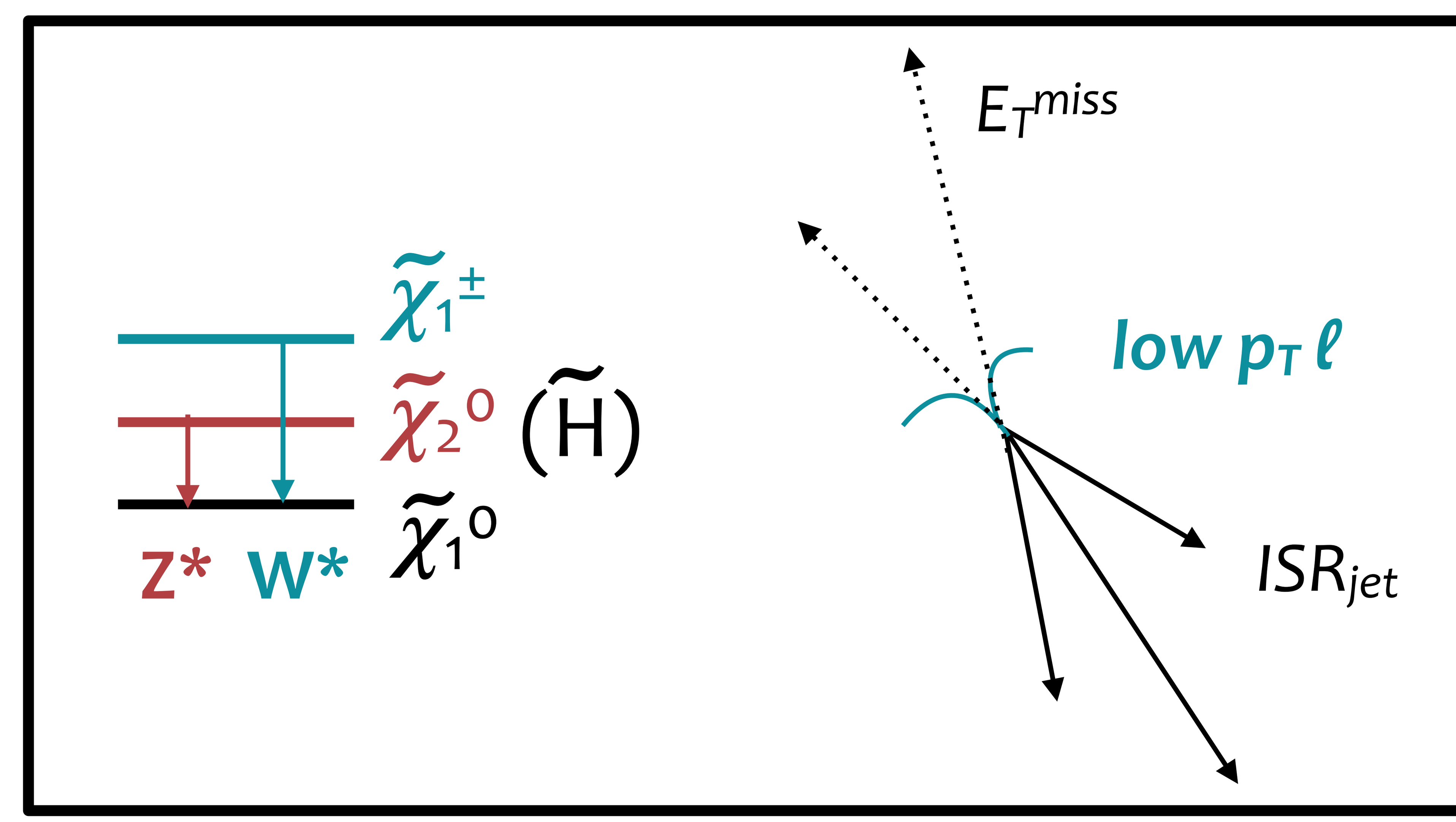
Mass



Strong SUSY constants are pushed by going to the energy limit, while EWK SUSY signatures have weaker couplings are require large datasets

Compressed spectrum are common in SUSY spectra where the Higgsino is the lightest stable particle





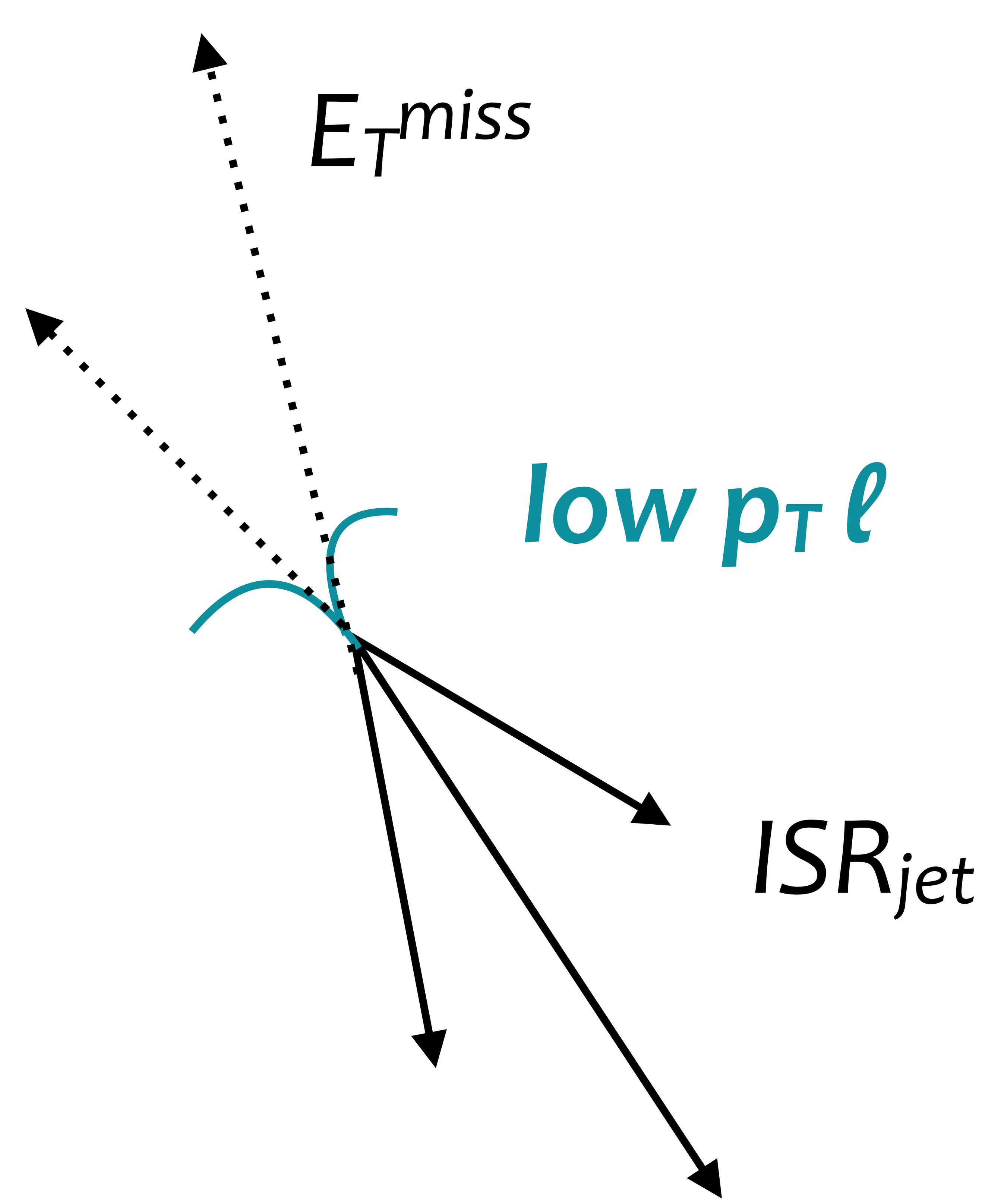
Search strategy

Look for soft Z* → μμ/ee

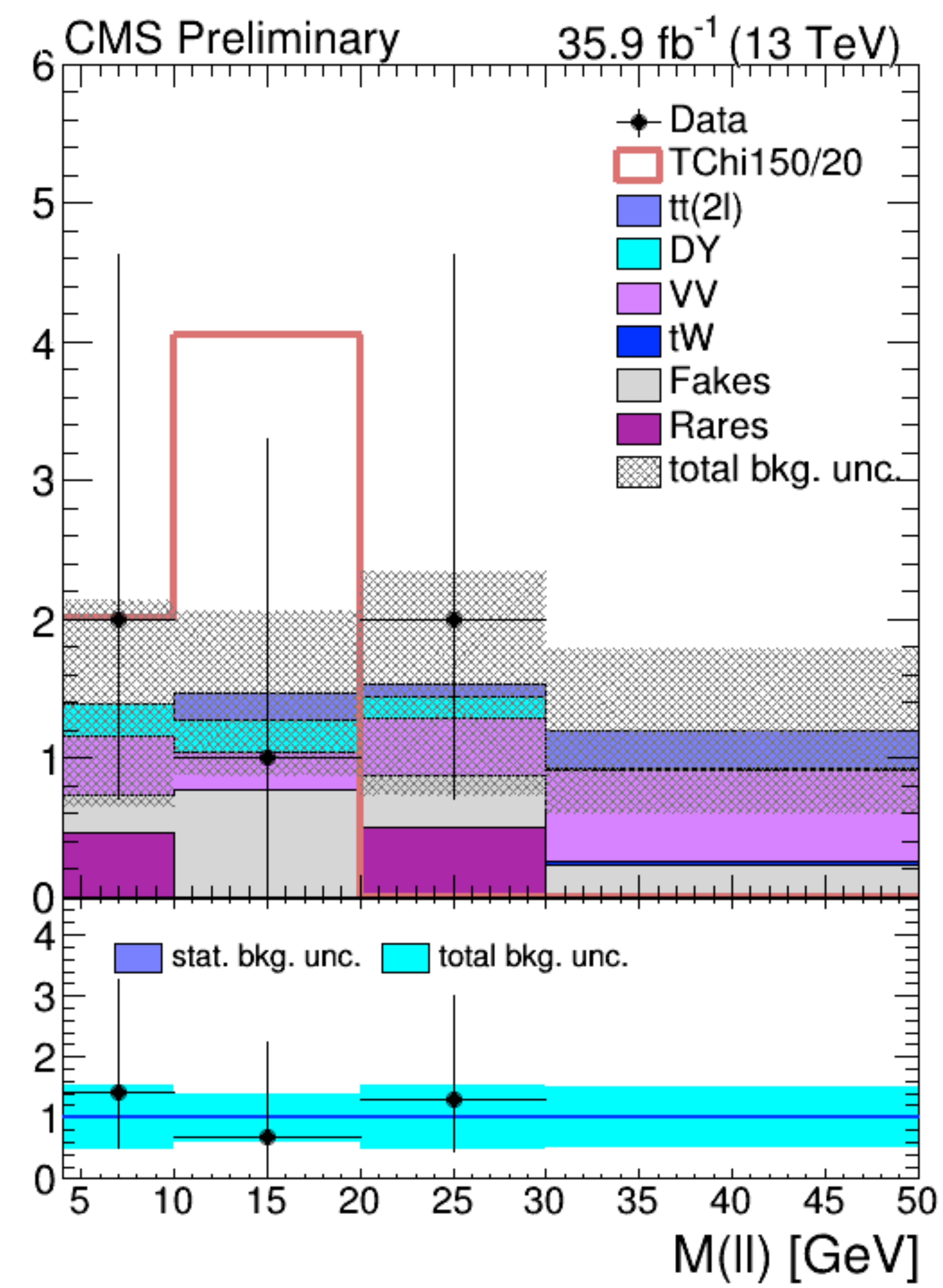
- Special trigger requirements to get down to low MET (μμ/ee + MET)

Require presence of high pT ISR jet

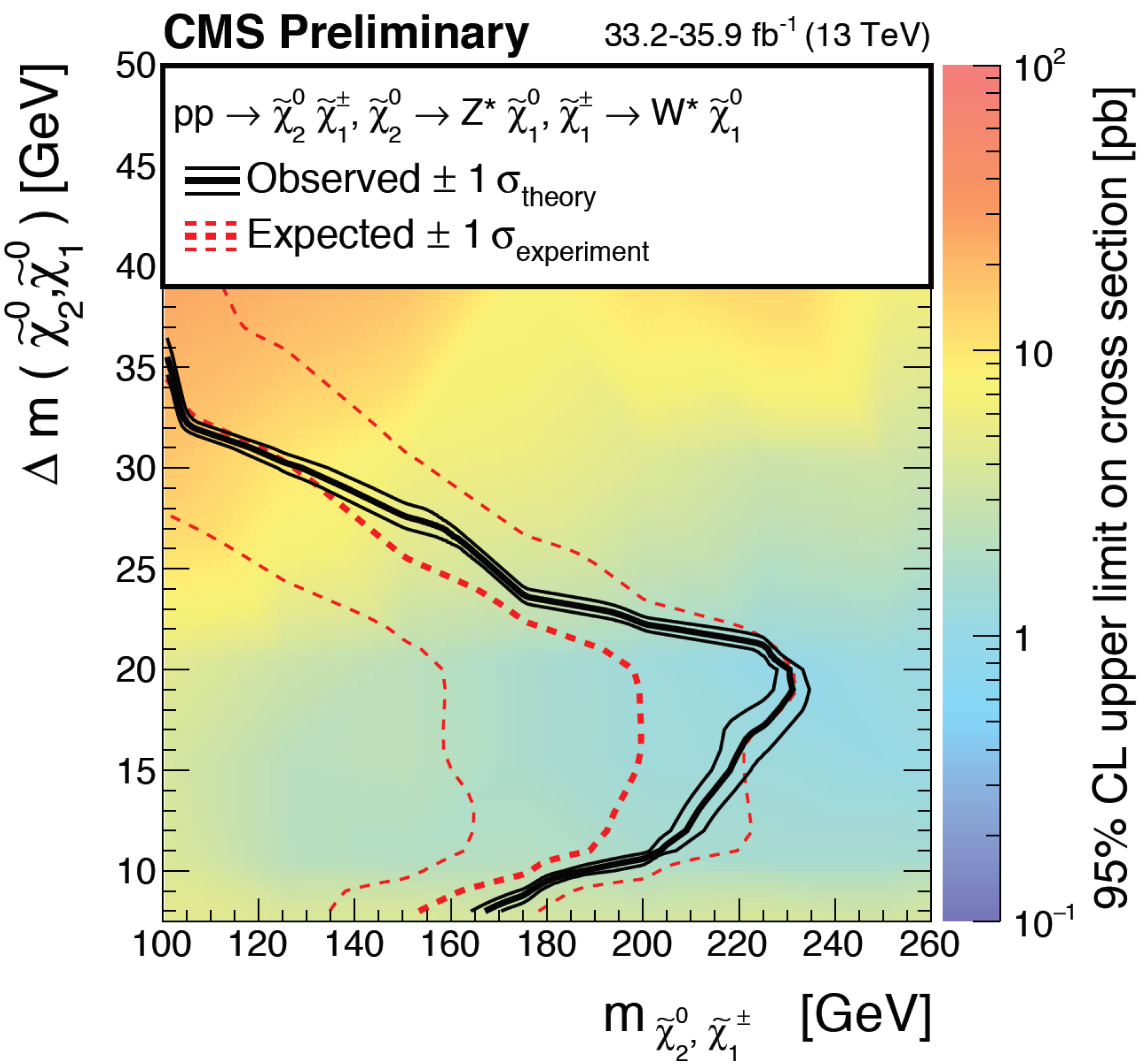
Backgrounds from DY to taus with soft leptons and non-prompt leptons from b-jets in ttbar



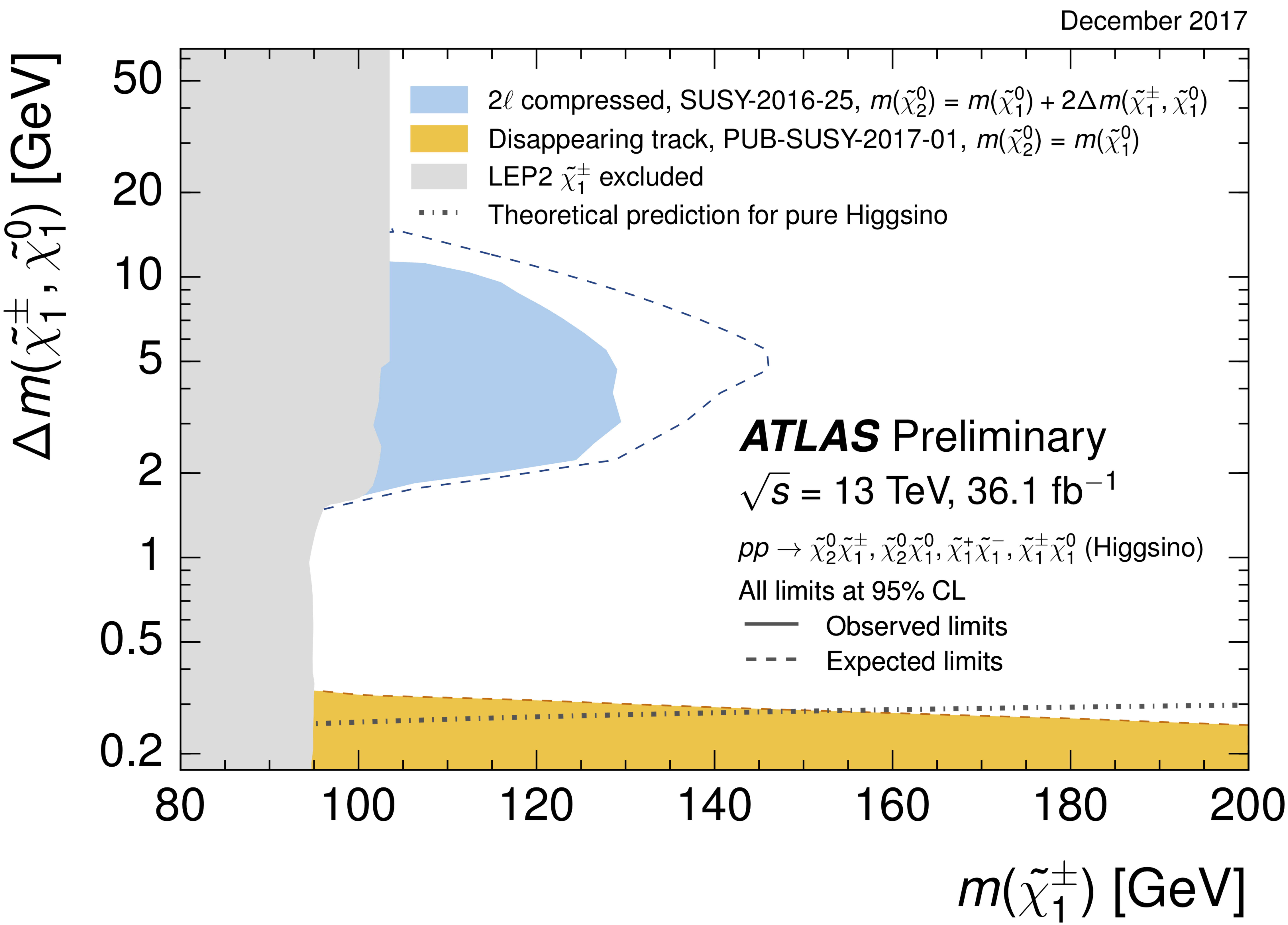
$E_T^{miss} > 250$



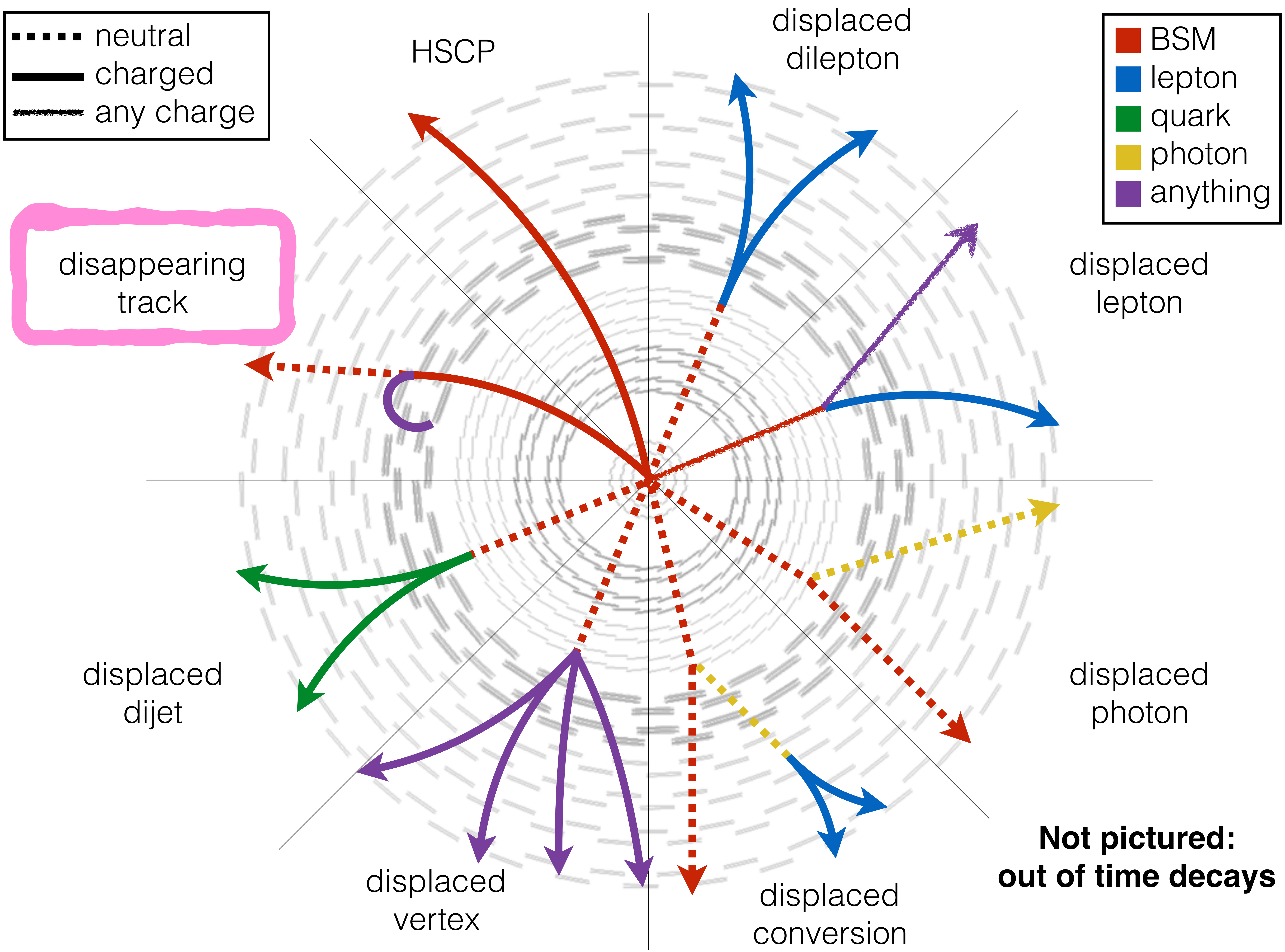
Compressed Higgsino Limits



Going even more compressed!



LONG-LIVED SIGNATURES



Not pictured:
out of time decays

INDIRECT PROBES, FLAVOR, AND THE UNEXPECTED

INDIRECT PROBES

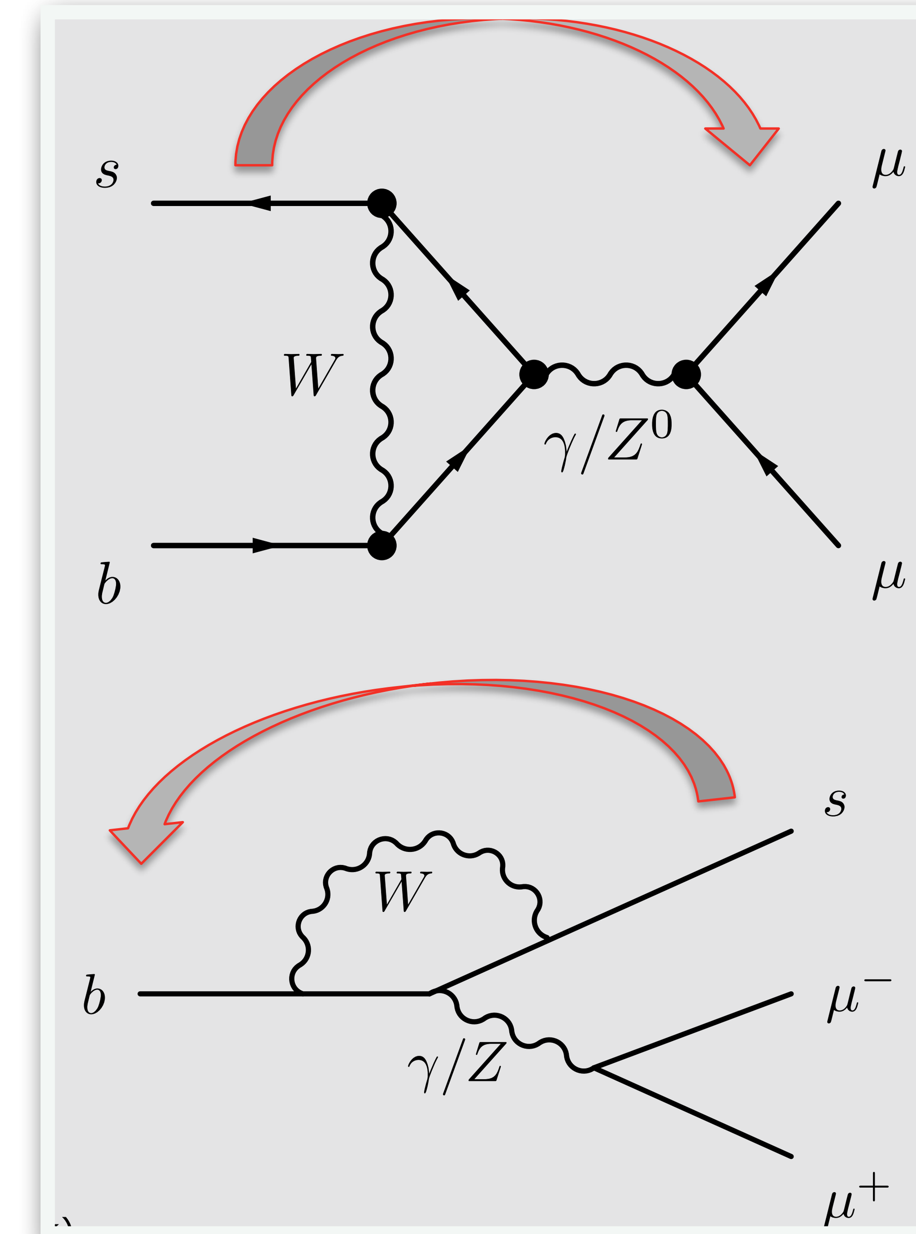
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \rightarrow e\nu$	UA1, UA2	1983
c	$K^0 \rightarrow \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \rightarrow \pi\pi$	CKM, 3rd gen	1964/	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \rightarrow e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \rightarrow Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \rightarrow 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?

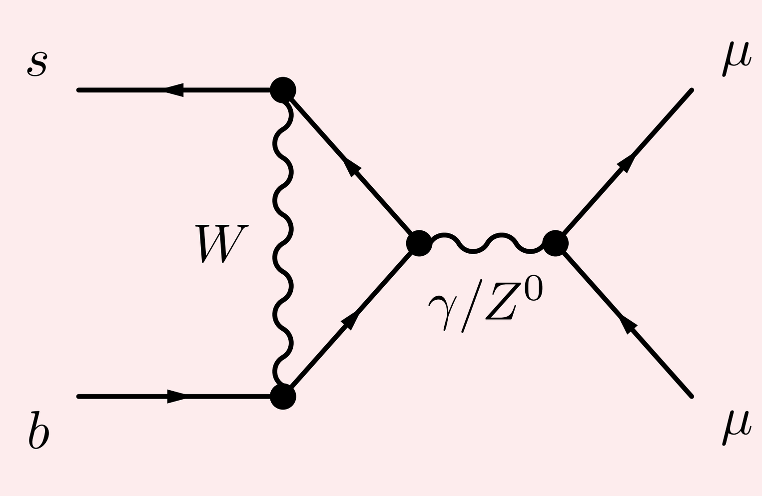
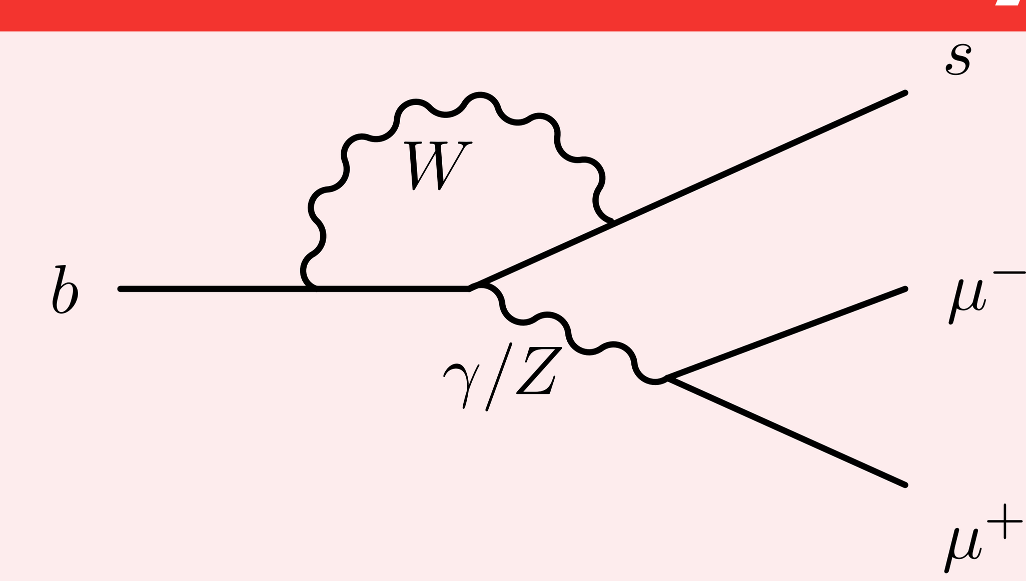
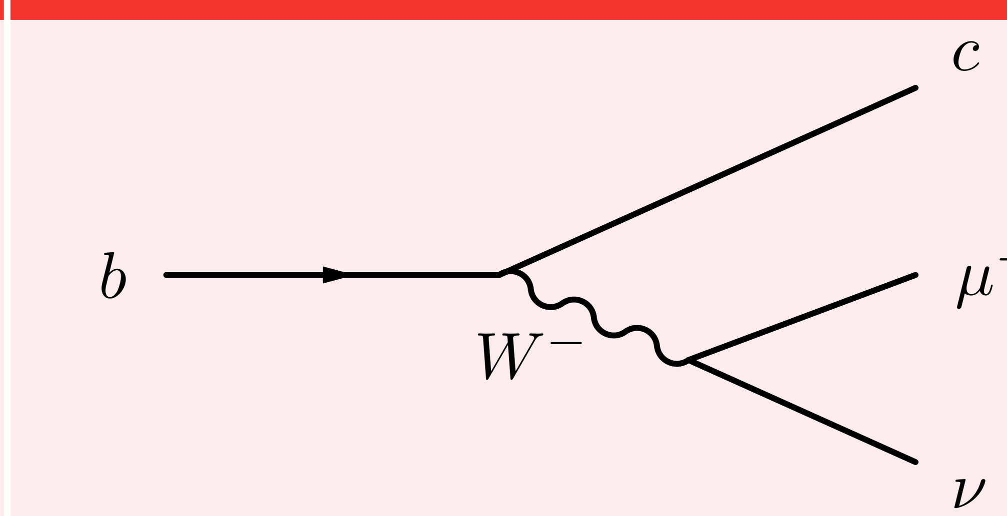
Indirect (lower energy) hints for new physics are often a precursor for direct new physics discoveries

Complementary approaches to probing the standard model!

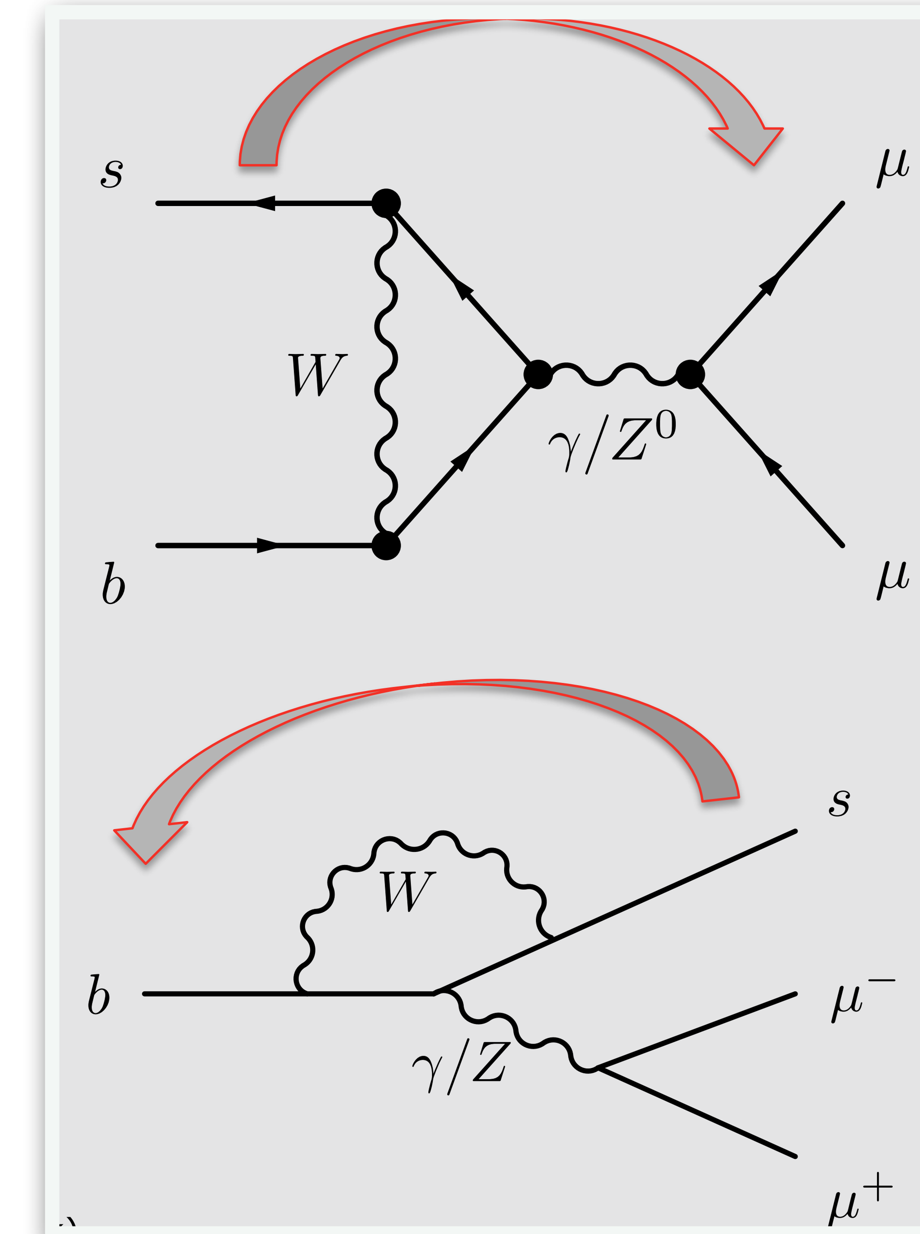
LHCb RARE DECAY RESULTS

A wealth of sensitive probes in rare processes suppressed in the SM and can be enhanced by new physics effects



	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+\nu\nu$ $K^0 \to \pi^0\nu\nu$	$\Sigma^+ \to p\mu^+\mu^-$	
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h^+h^-\mu^+\mu^-$ $J/\psi \to D^0 e^+e^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	
Beauty	$B^0_{(s)} \to \mu^+\mu^-$ $B^0_{(s)} \to \tau^+\tau^-$ $B^0_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0_s \to \varphi\mu^+\mu^-$ $B^0_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\,\mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu\,/\,\tau^+\nu$ $B_c^+ \to J/\psi\mu^+\nu\,/\,\tau^+\nu$

LHCB RARE DECAY RESULTS



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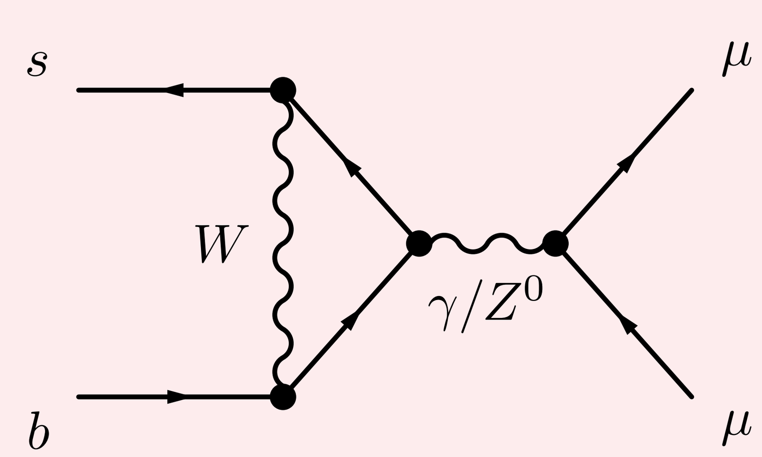
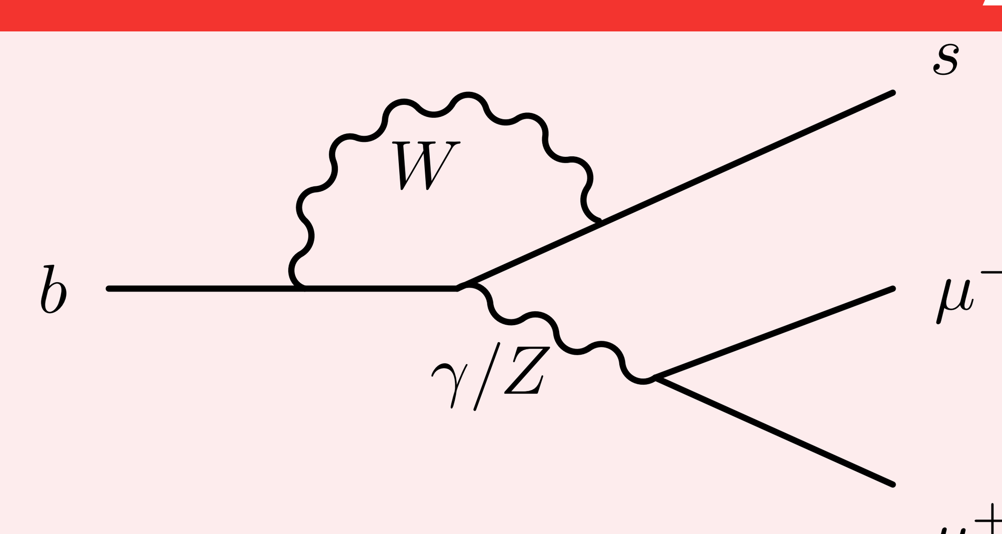
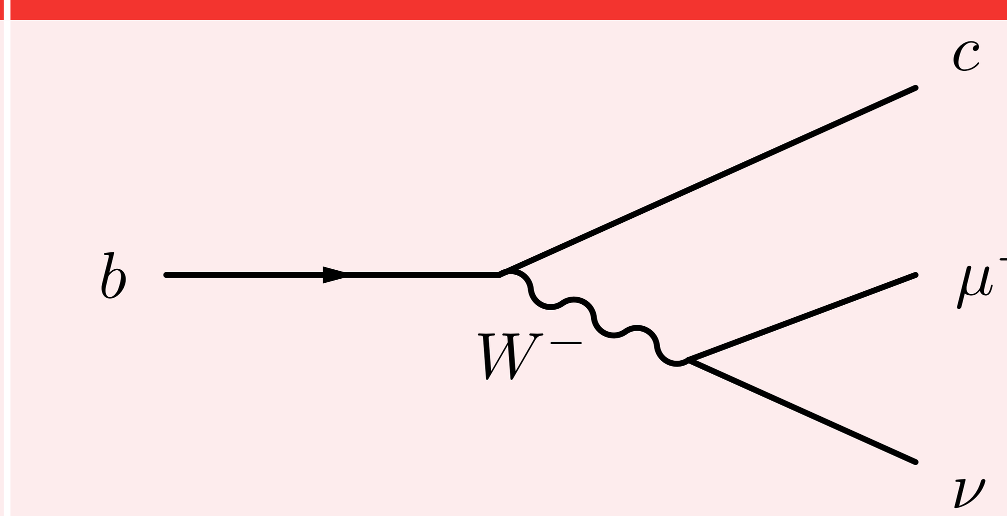
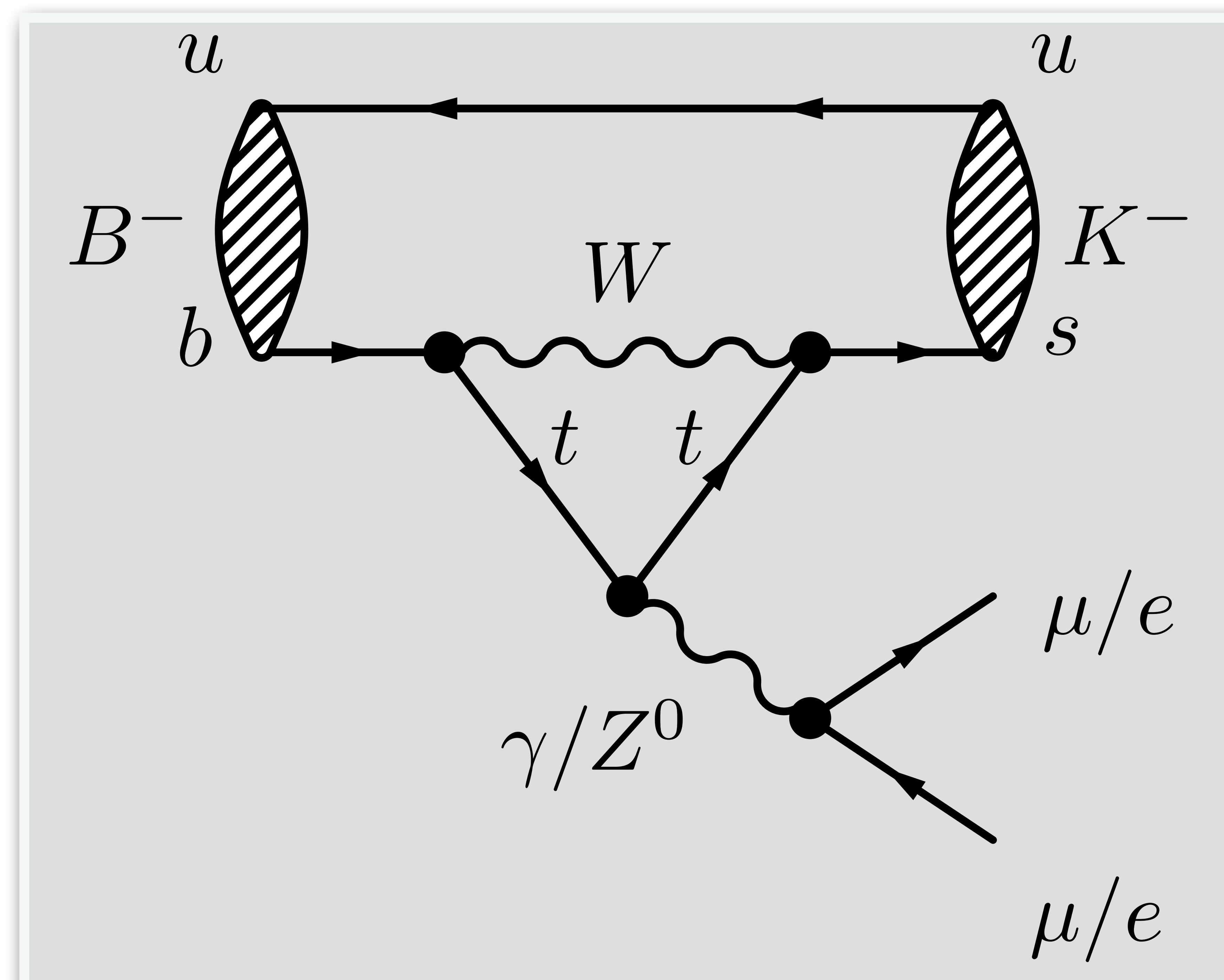
				
Strange	$K_S{}^0 \to \mu^+\mu^-$	$K^+ \to \pi$ $K^0 \to \pi$		
Charm	$D^0 \to \mu^+\mu^-$ $D^0 \to e^+\mu^-$	$D^0 \to h$ $J/\psi \to D^0 e^+e^-$		
Beauty	$B^0{}_{(s)} \to \mu^+\mu^-$ $B^0{}_{(s)} \to \tau^+\tau^-$ $B^0{}_{(s)} \to e^+\mu^-$	$B^0 \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^+ \to K^{(*)}\mu^+\mu^-/e^+e^-$ $B^0{}_s \to \varphi\mu^+\mu^-$ $B^0{}_s \to K^*\mu^+\mu^-$	$\Lambda_b \to \Lambda\, \mu^+\mu^-$	$B^0 \to D^{(*)}\mu^+\nu\, /\, \tau^+\nu$ $B_c{}^+ \to J/\psi\mu^+\nu\, /\, \tau^+\nu$

Many interesting results!
Will focus on recent anomalies in lepton flavor non-universality

B→Kμμ/B→Kee

Studying ratios of processes in different lepton flavor final states probes new physics scenarios which violate lepton flavor universality

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$



SM expectation: R_K = 1

Similar expectations for both the charged and neutral final states

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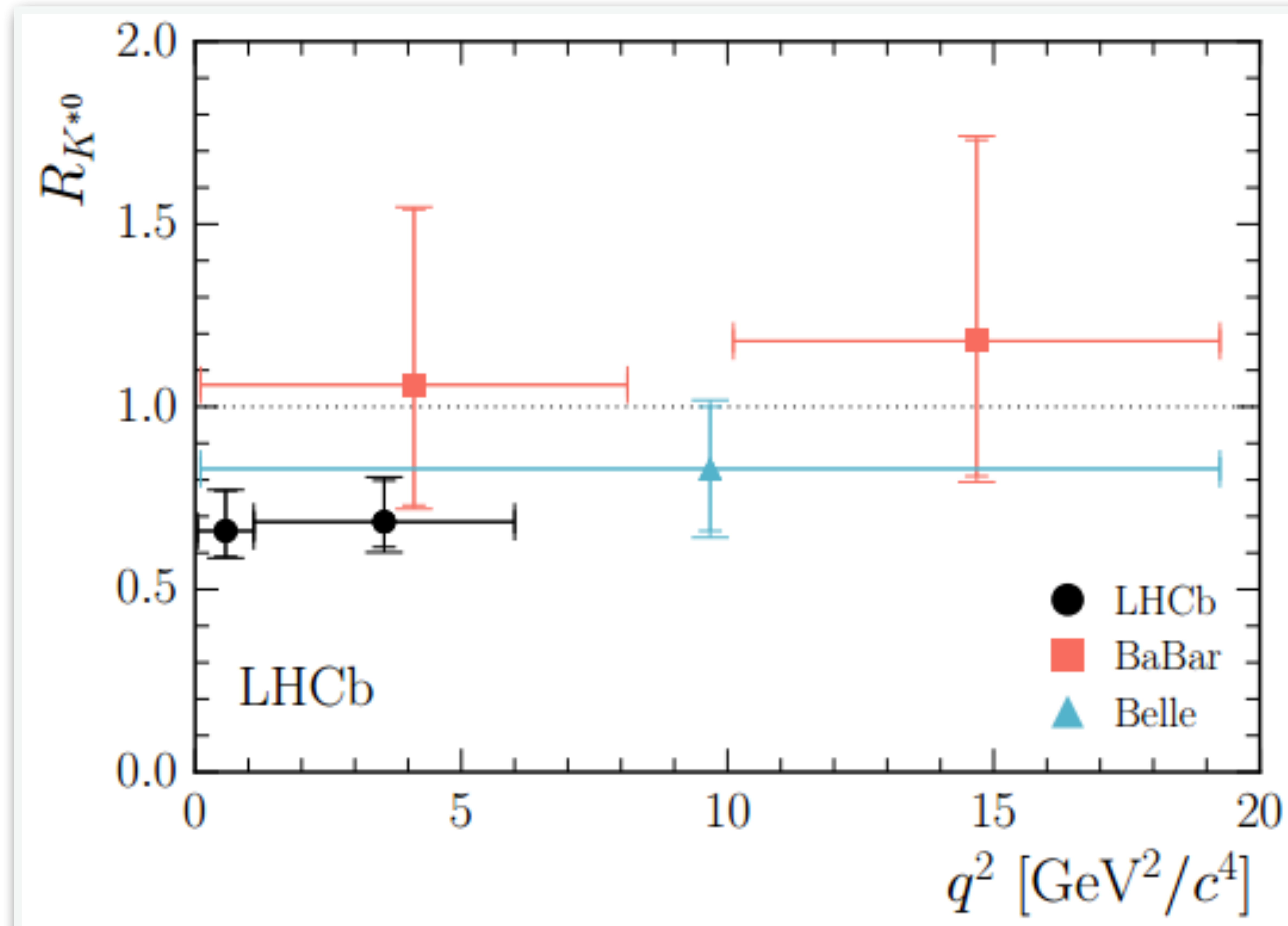
Deviations at the 2.5 σ level



$$R_{K^{*0}} = \begin{cases} 0.66 \, {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \text{GeV}^2/c^4 \\ 0.69 \, {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \text{GeV}^2/c^4 \end{cases}$$

$B \to K\mu\mu / B \to Kee$

Studying ratios of processes in different lepton flavor final states probes new physics scenarios which violate lepton flavor universality

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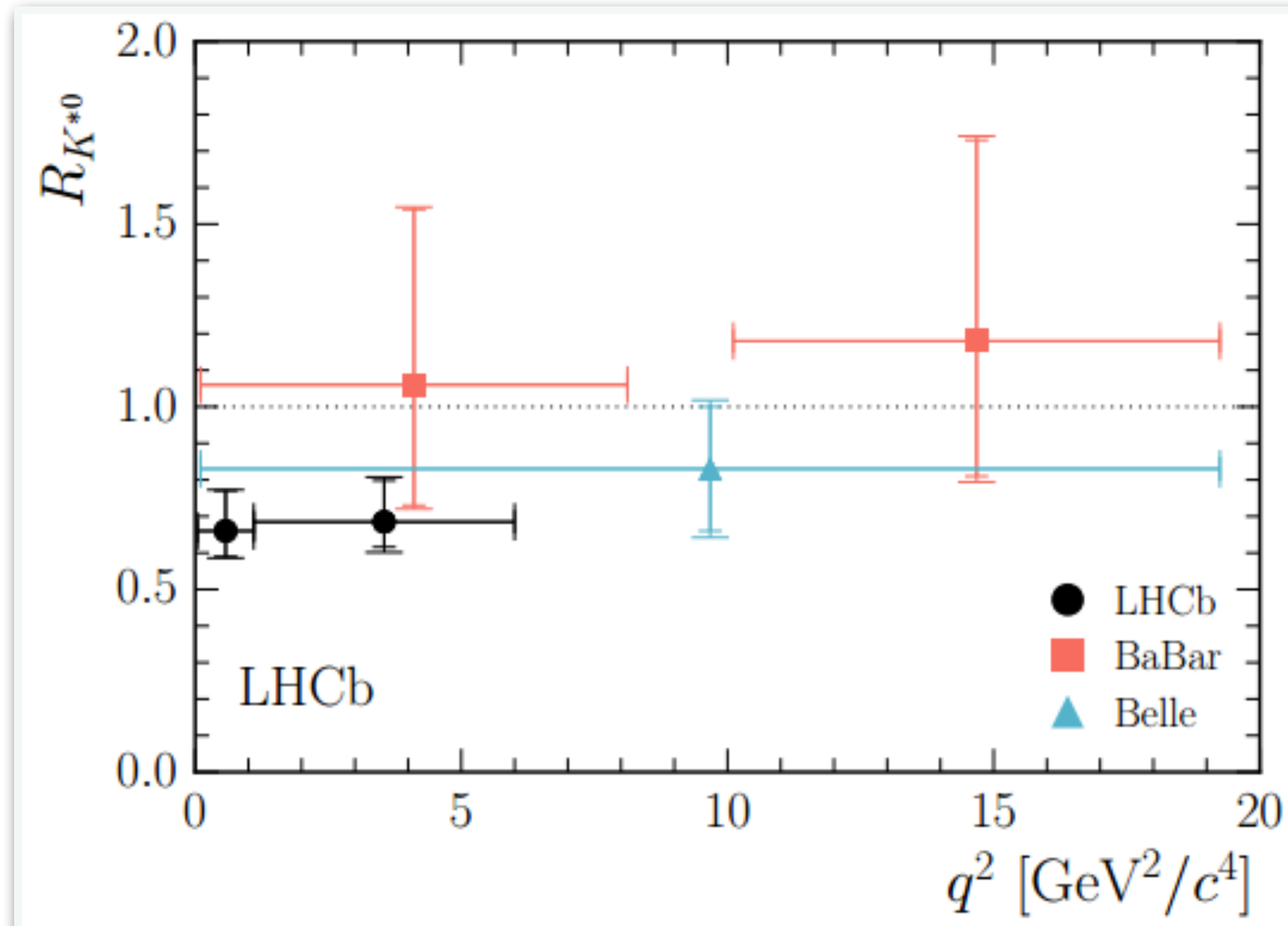


Additional deviations in:

$B^0 \to K^{*0}\mu\mu$: angular analysis (3.4σ deviation, arXiv: 1412.04442)

$B^0 \to \phi\mu\mu$: differential branching fraction (3σ deviation, arXiv: 1506.08777)

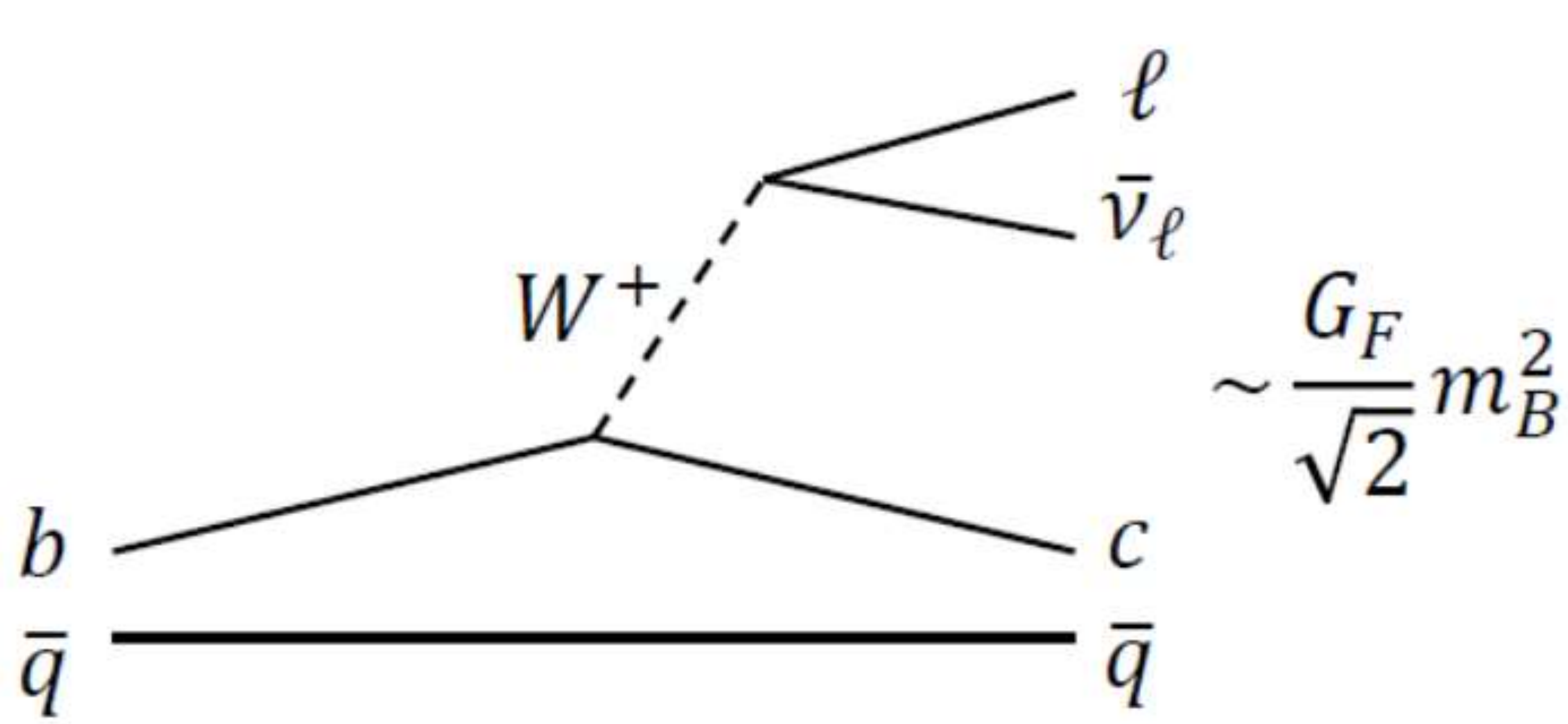
SEMILEPTONIC B DECAYS

Common b decay through semi-leptonic "beta decay" (b → clν)

- $B^0 \to D^{*-} l^+ \nu$, $D^{*-} \to D^0 \pi^-$, $D^0 \to K^+ \pi^-$ is a popular final state because of simple 3 charged hadron final state

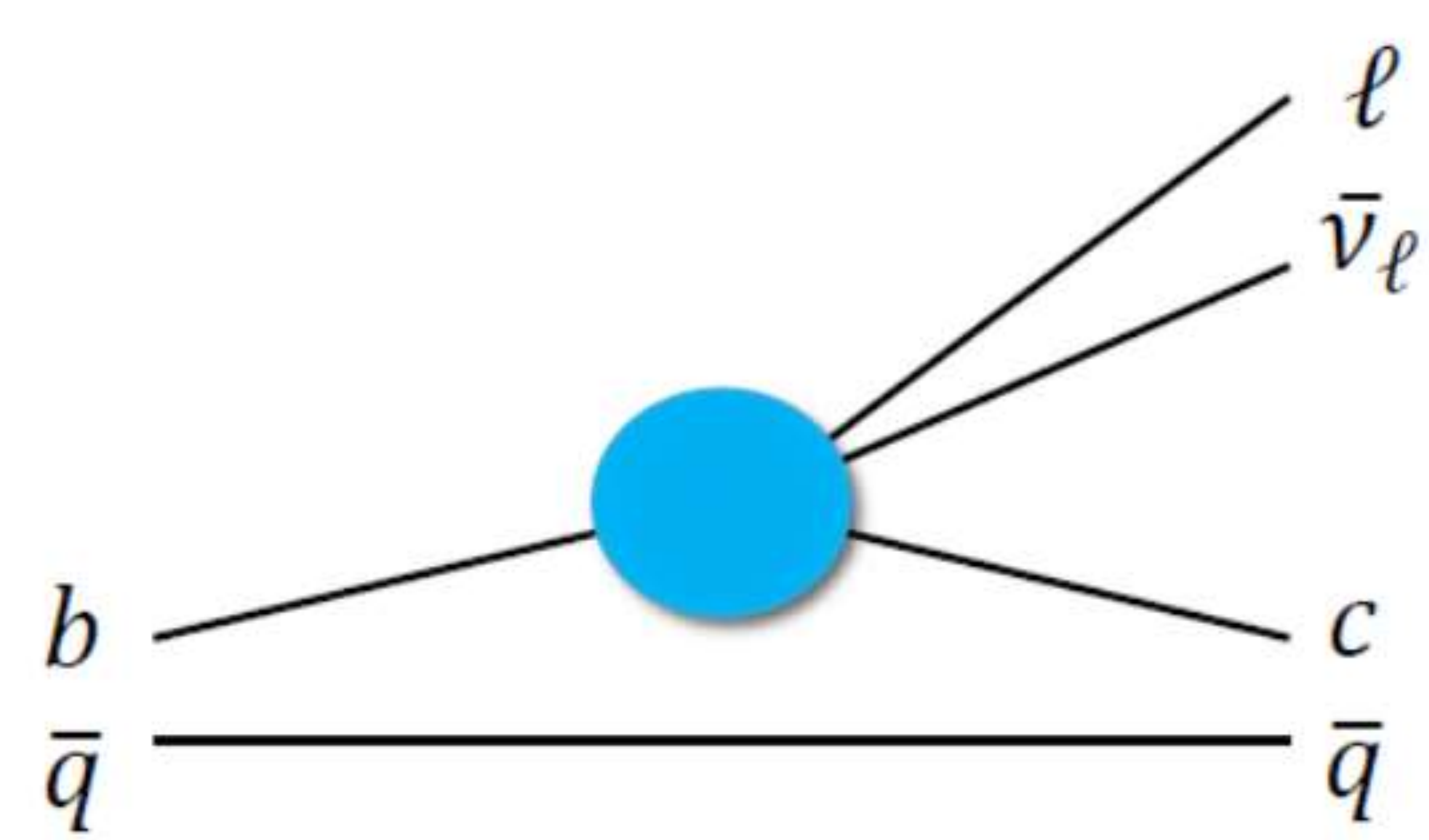
Light leptons (muon, electrons) are studied well, but tau decays have not been experimentally accessible until recently

SM canonical decay



Effective operator with NP

(charged higgs, leptoquark, etc.)



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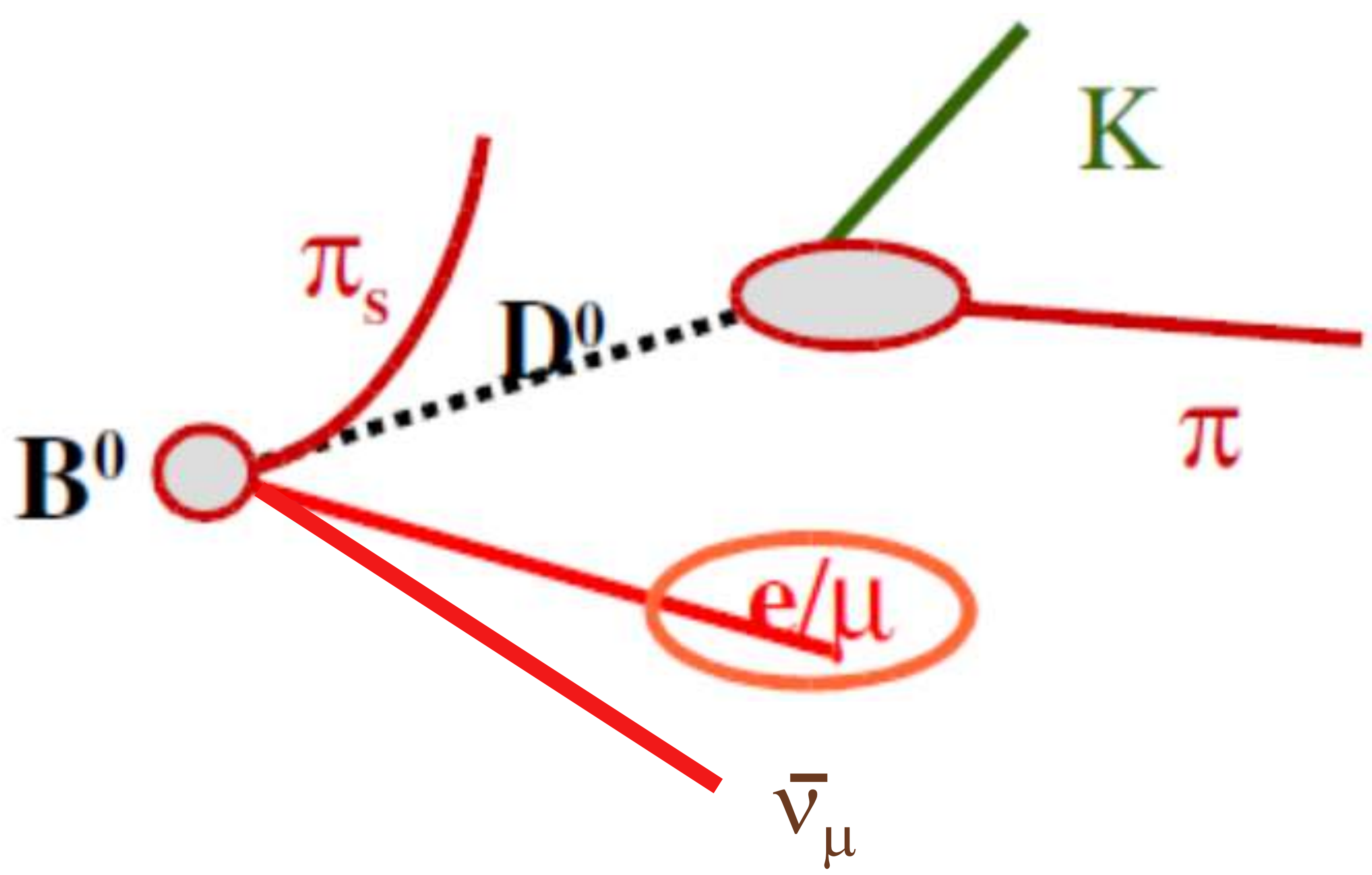
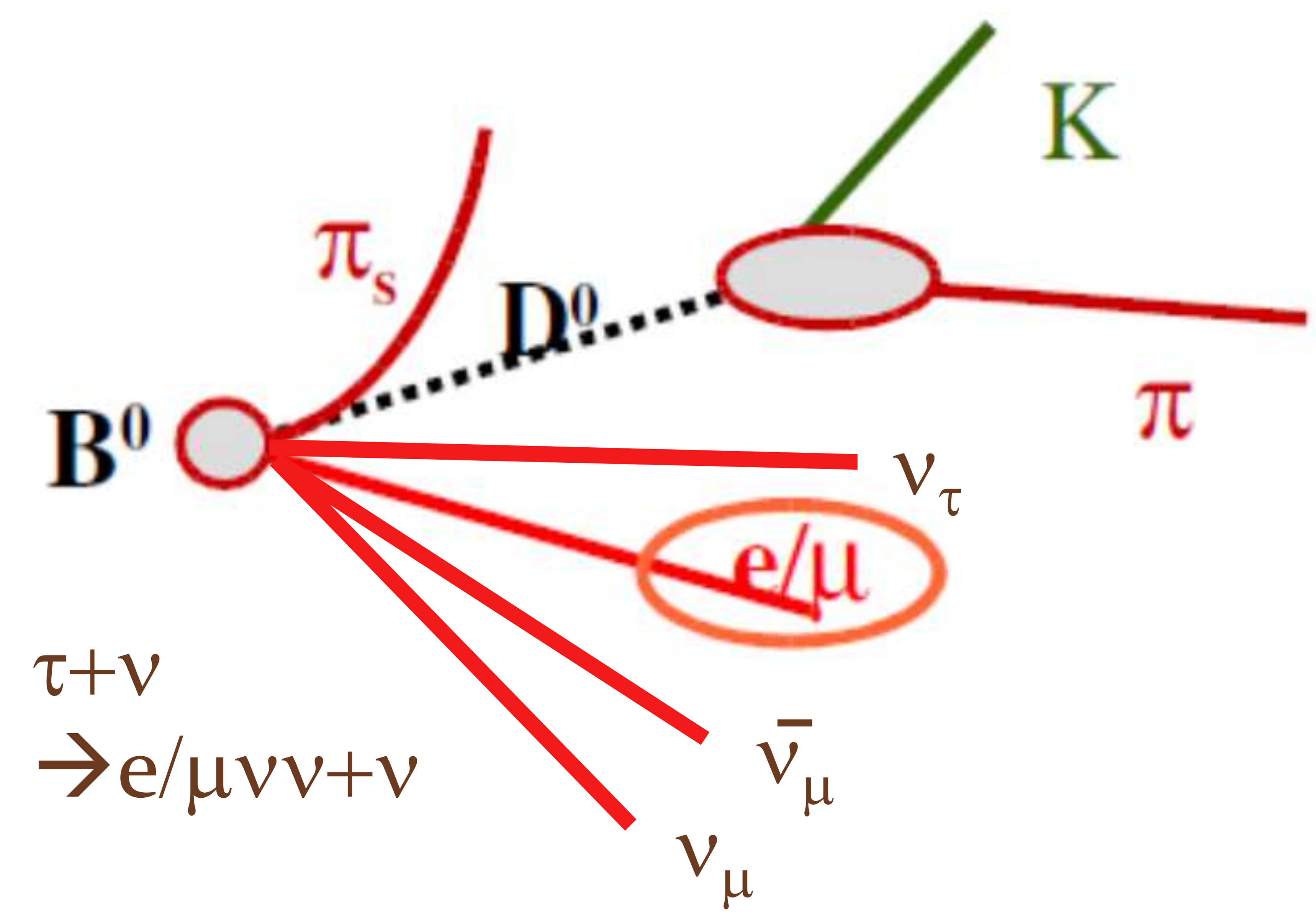
electron/muon final state

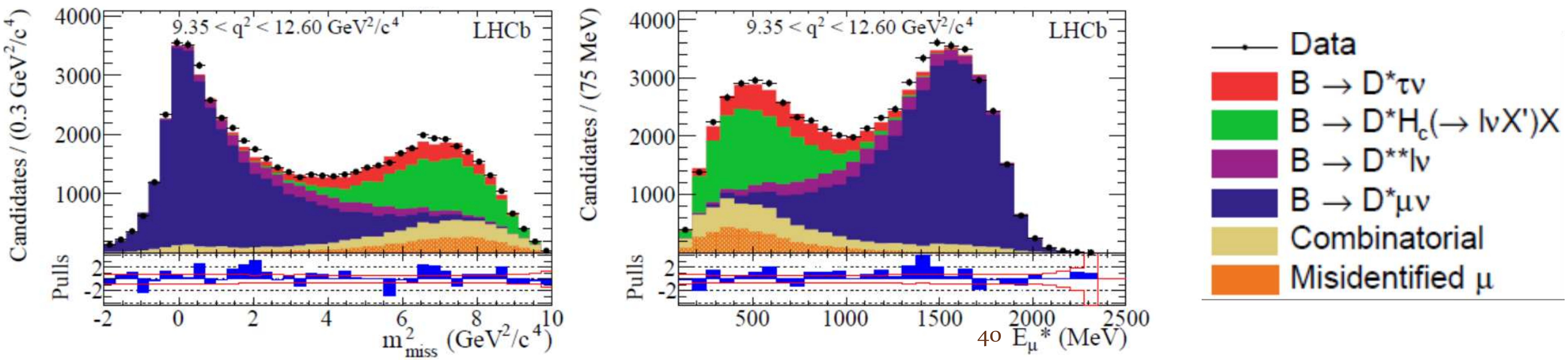


tau final state



$$\mathcal{R}(D^*) = \mathcal{B}(\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu)$$

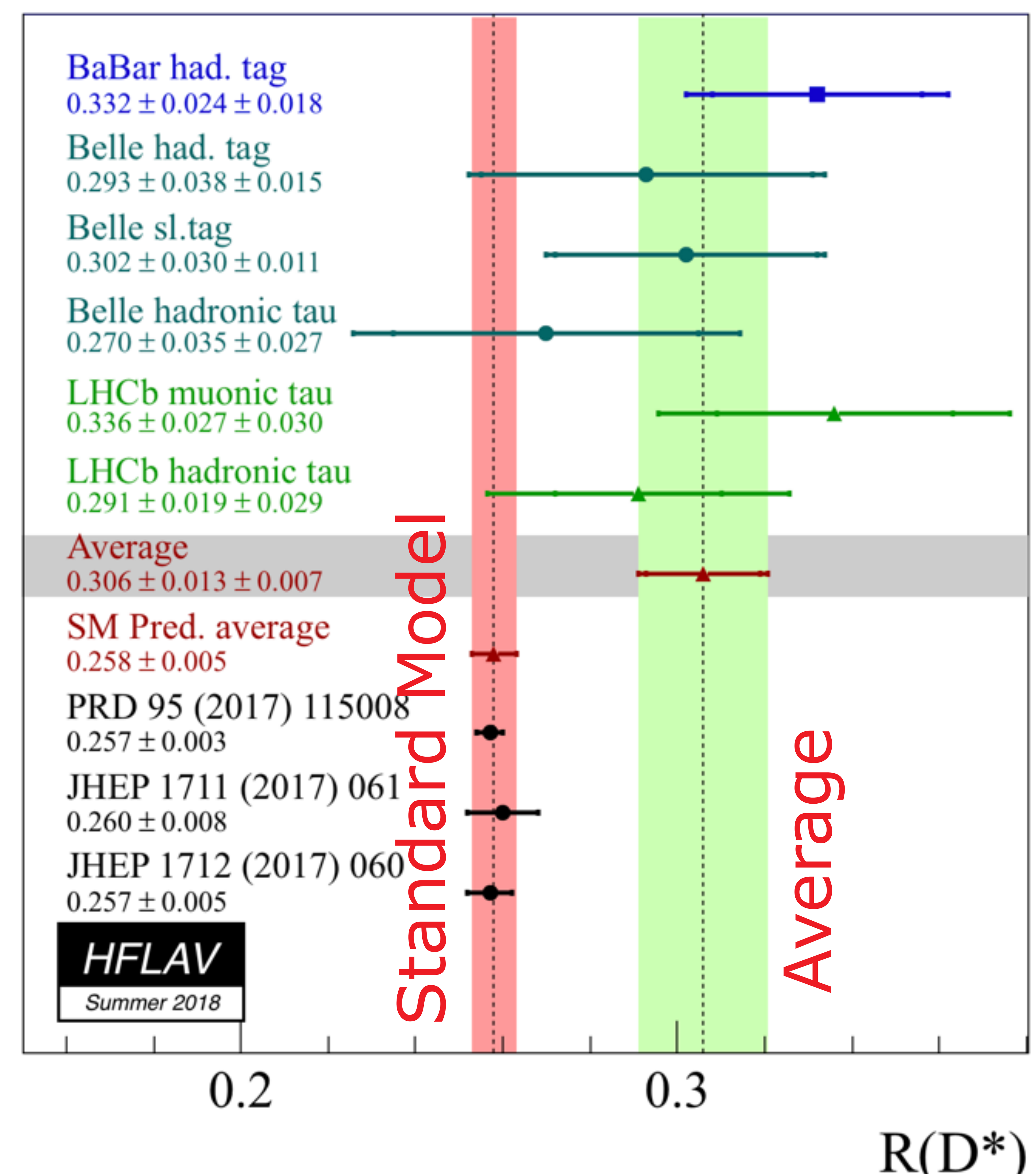
R(D*) RESULTS



A global tau anomaly?

R(D*) has a combined 4 σ deviation

Seen across multiple experiments, multiple c modes (D,D*,J/Ψ), and multiple tau final states (μ , 1-prong, 3-prong)



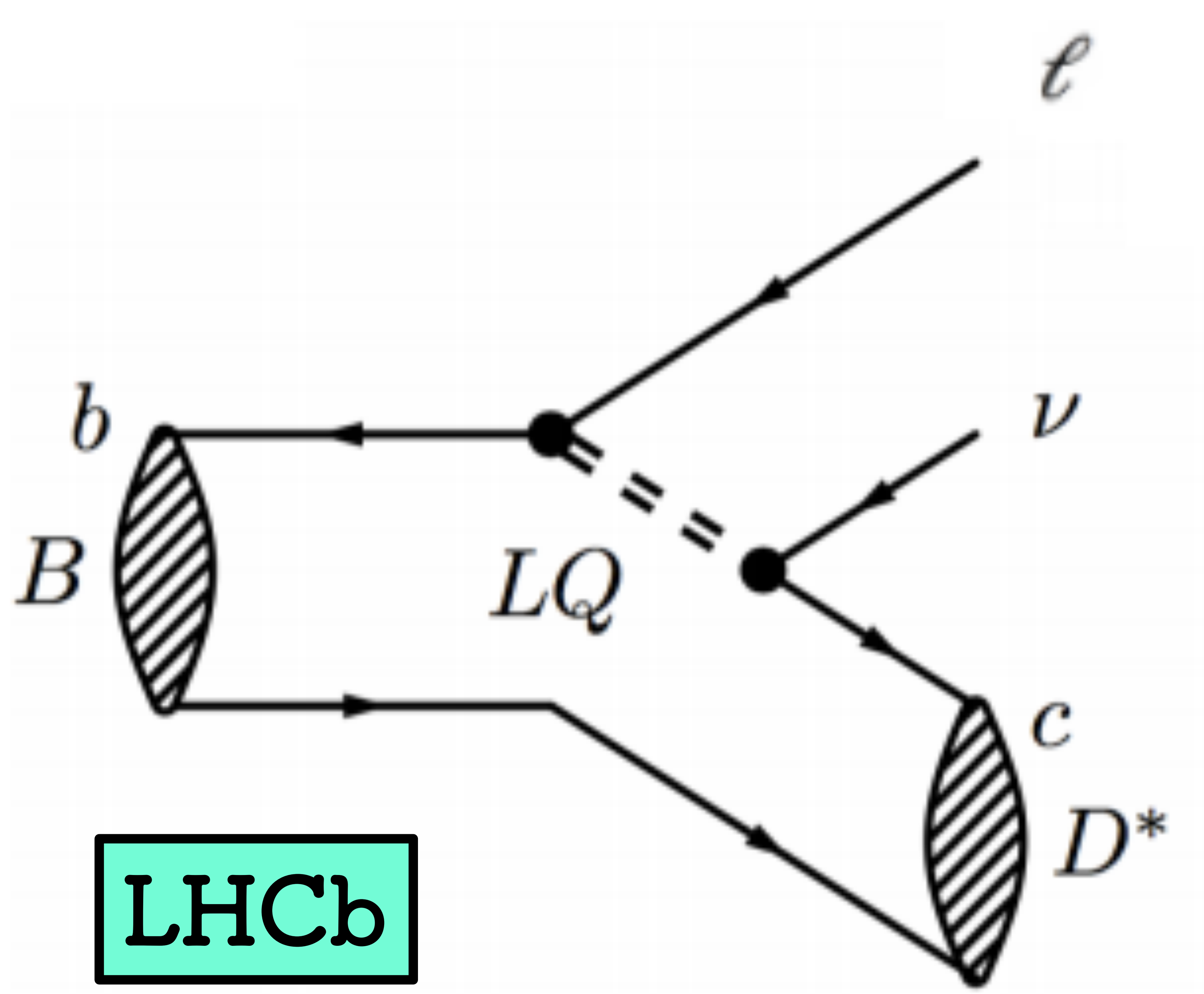
Connection to high energy seaches!

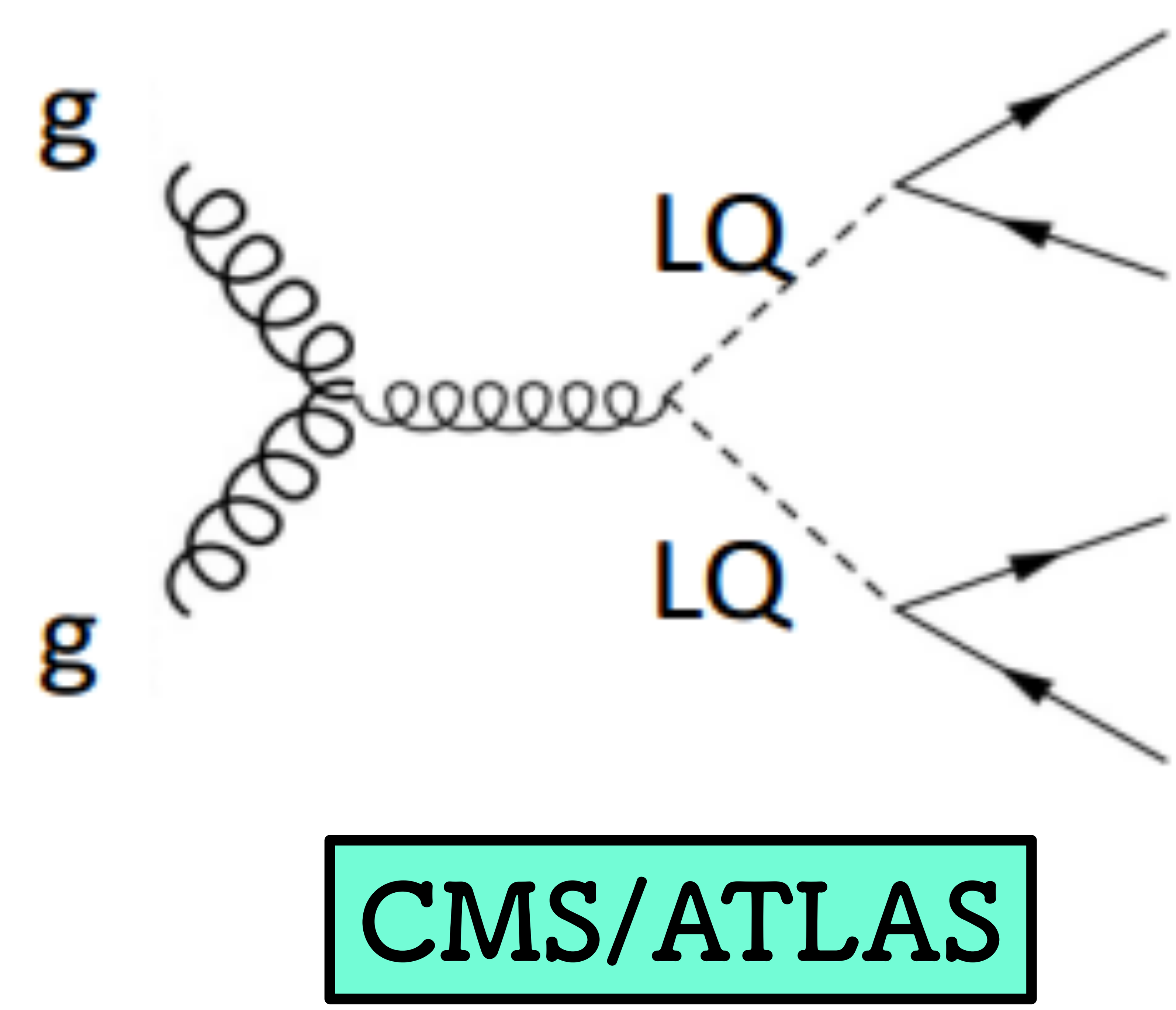
Leptoquarks provide an explanation for the B anomalies

A new boson that carries both lepton and baryon number

Can show up in GUTs, Composite models and SUSY

Mass scales may be accessible at CMS/ATLAS (~1 TeV)





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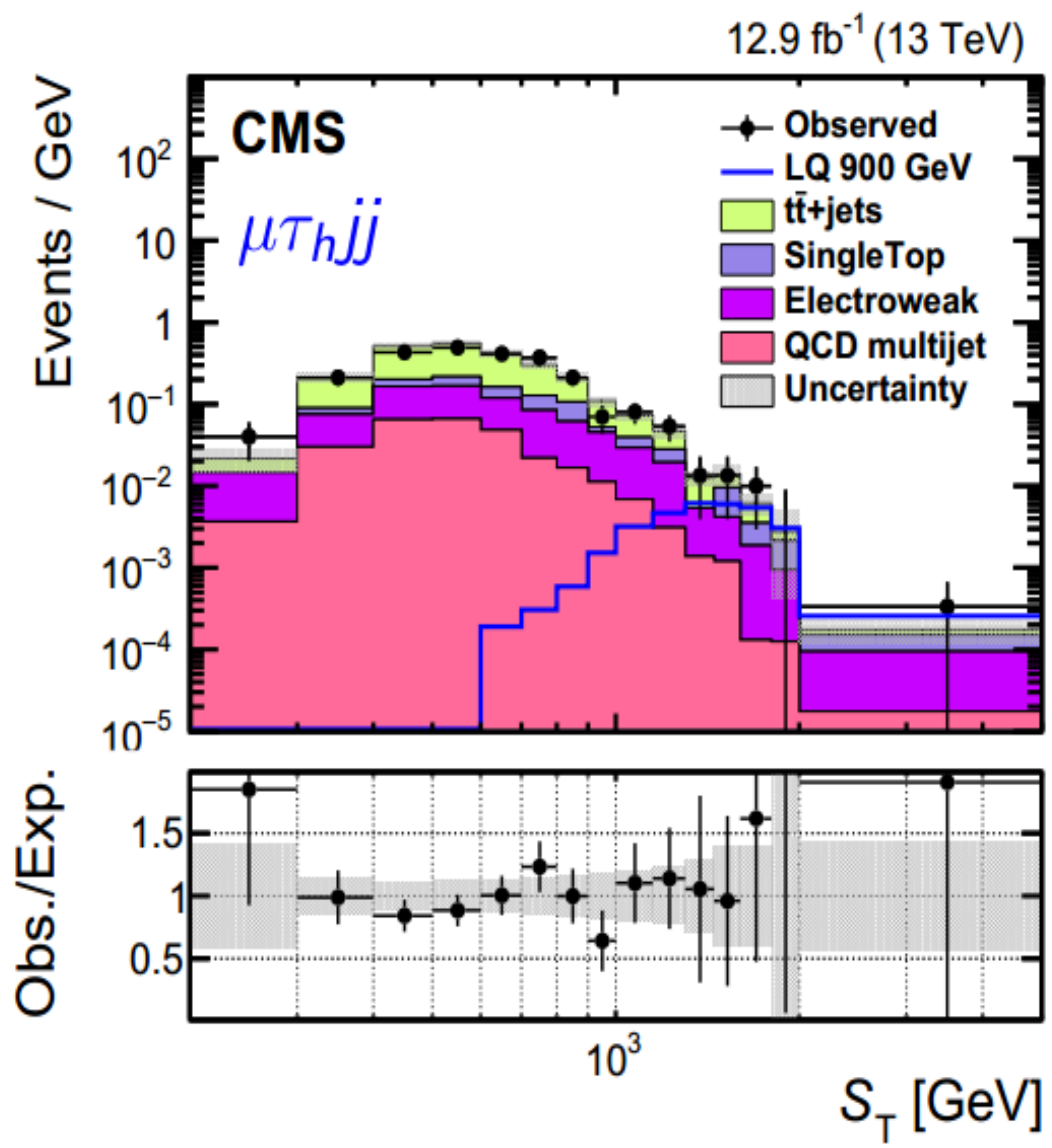
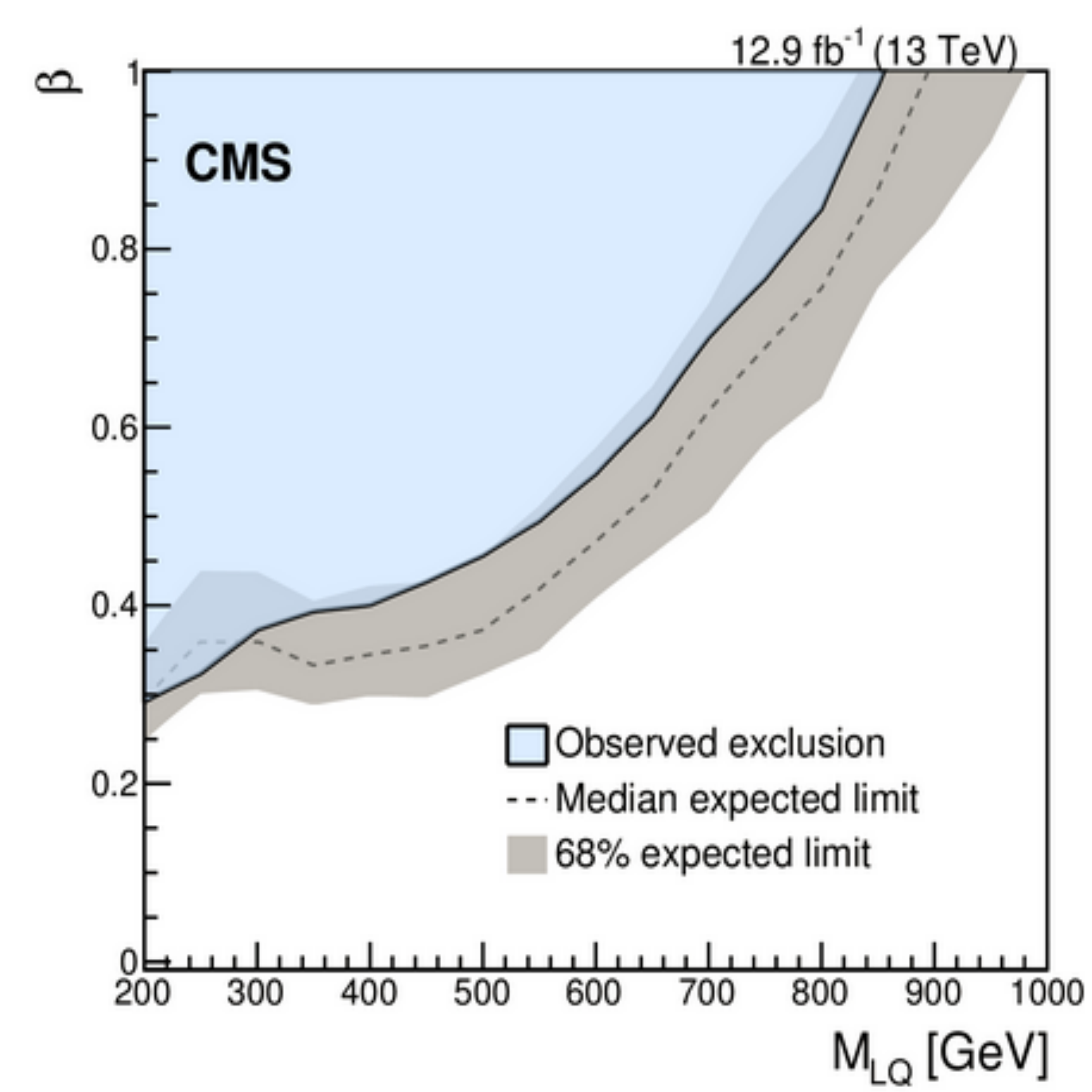


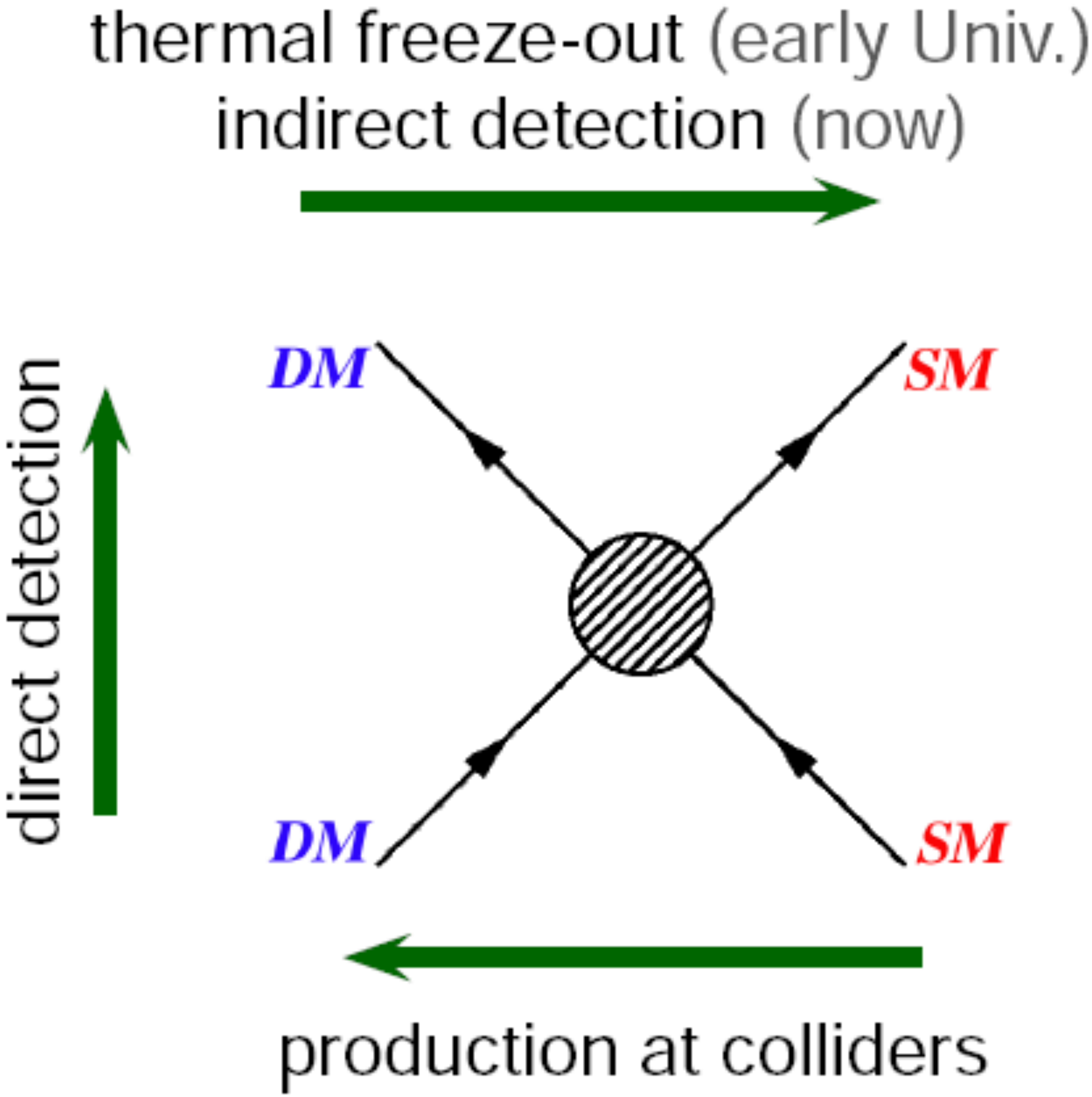
Unfortunately no signs yet!

LQ+LQ → τ b τ b final state

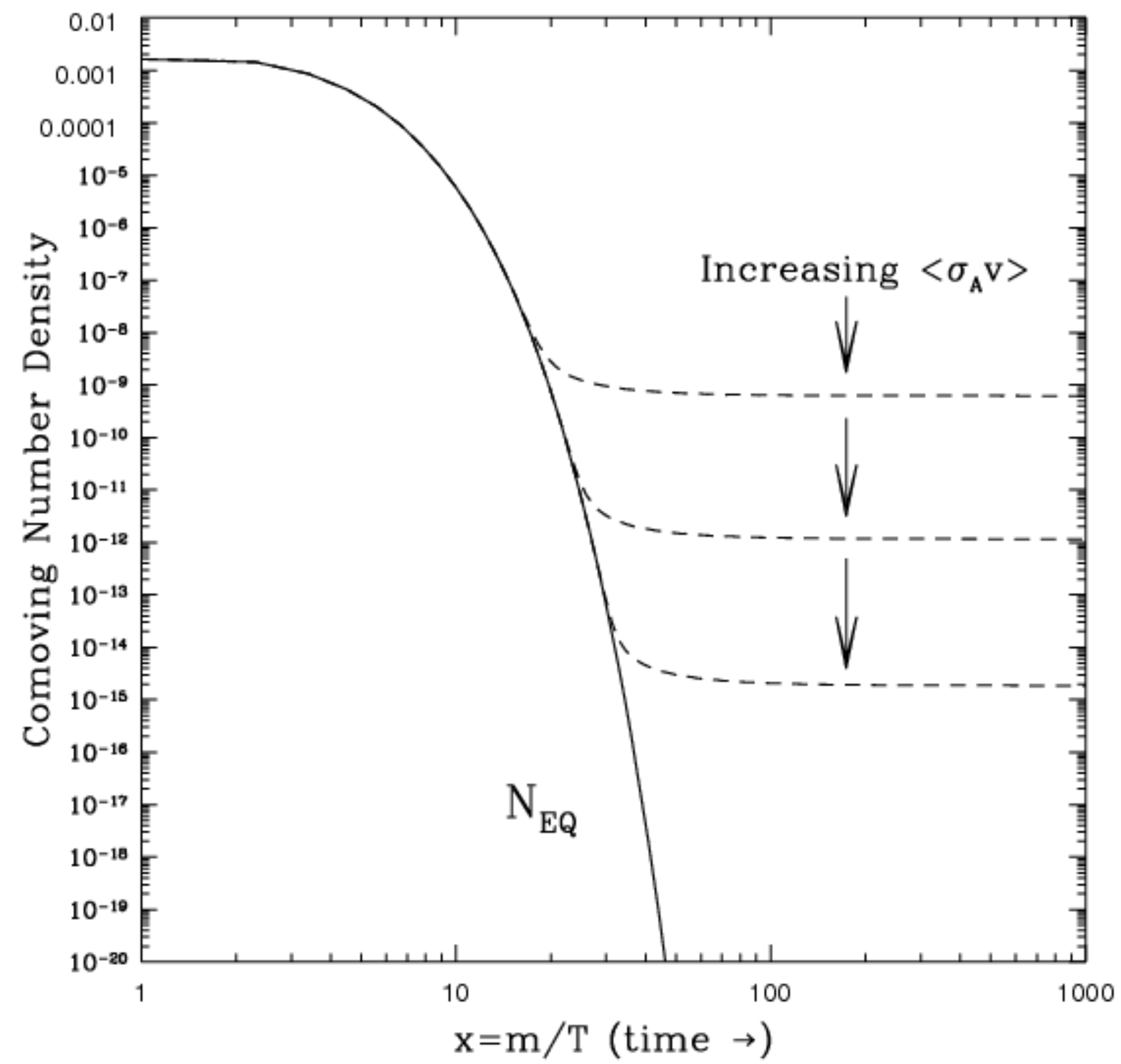


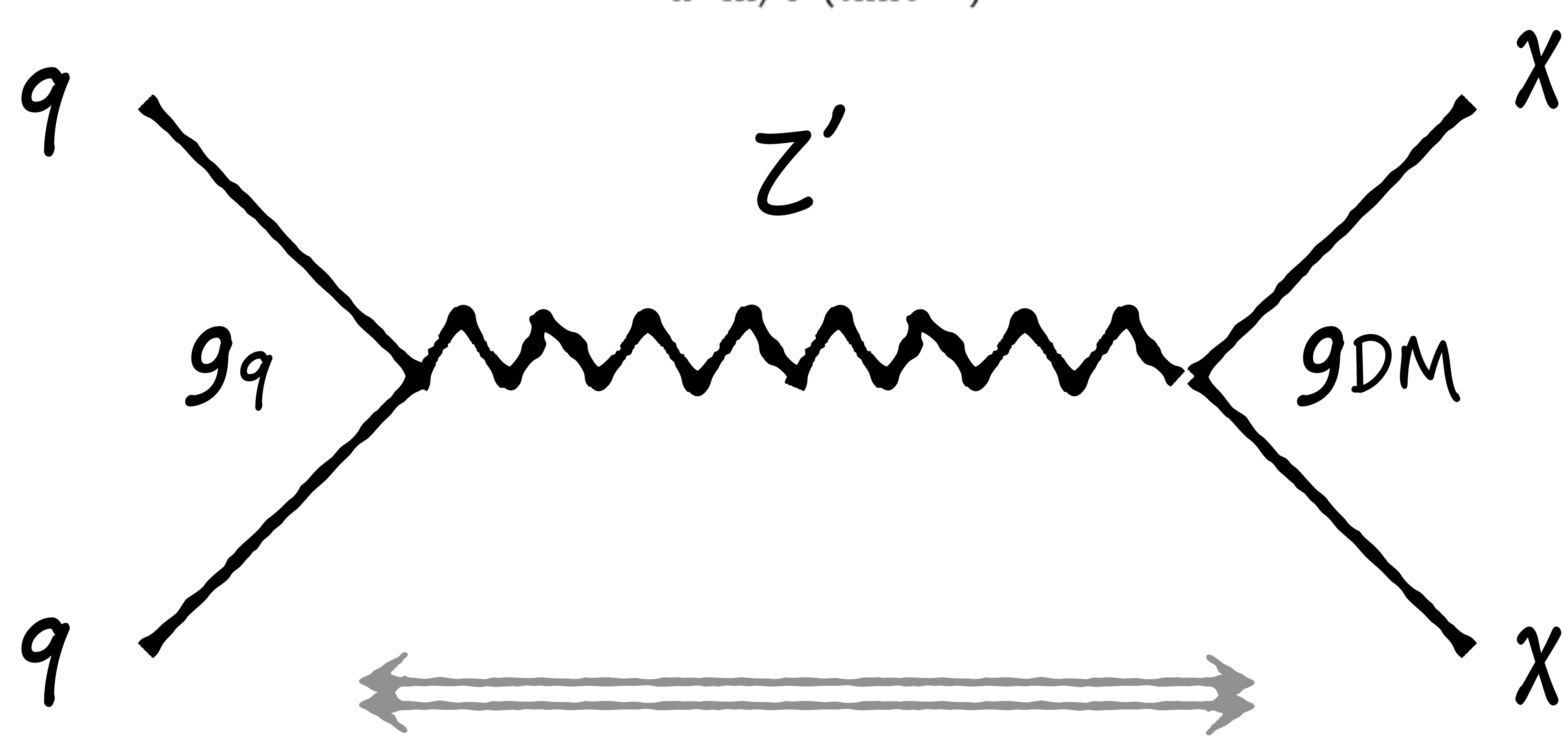
Connection with the cosmos

Dark Matter @ LHC



Dark matter complementarity

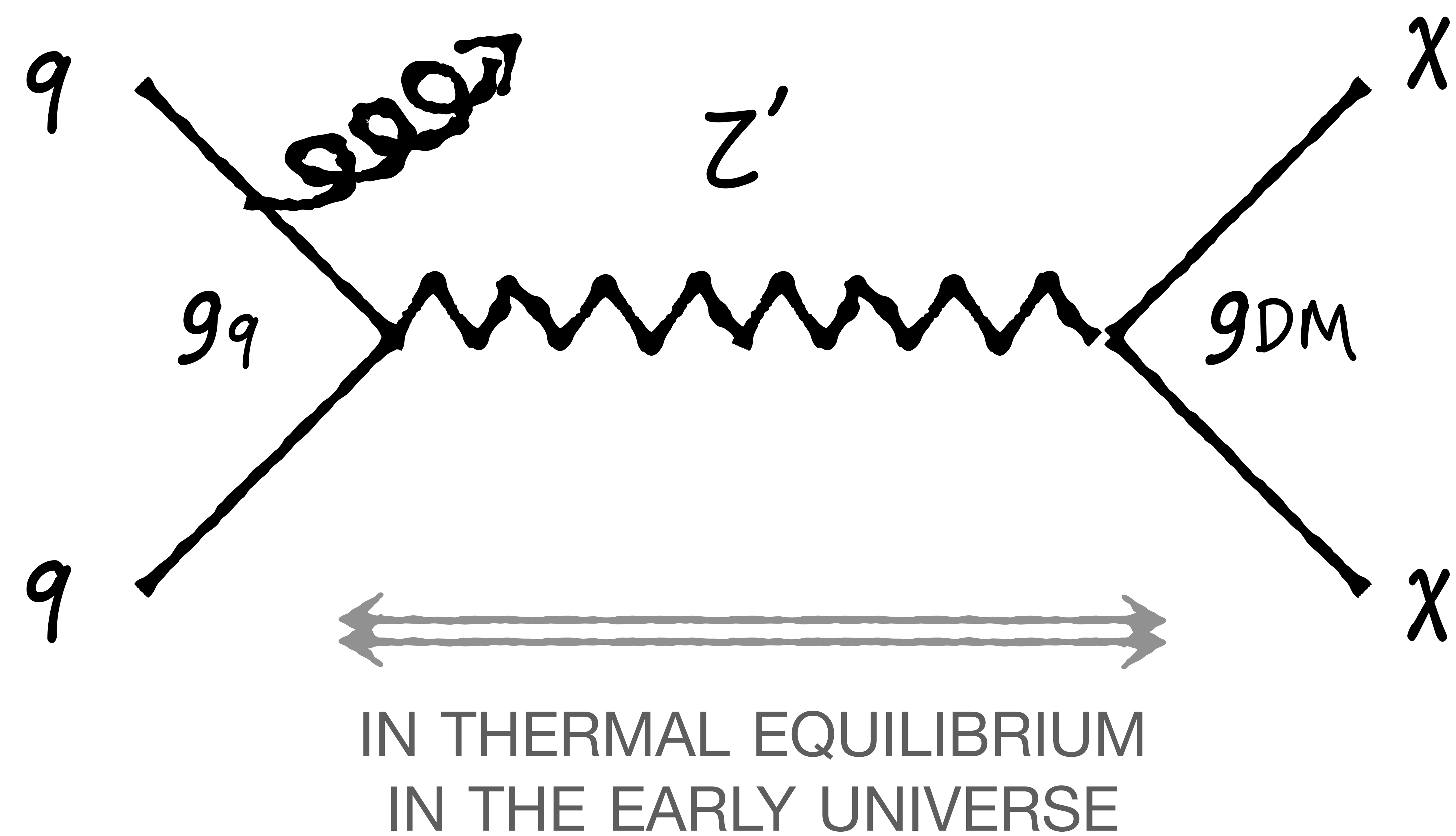




IN THERMAL EQUILIBRIUM
IN THE EARLY UNIVERSE

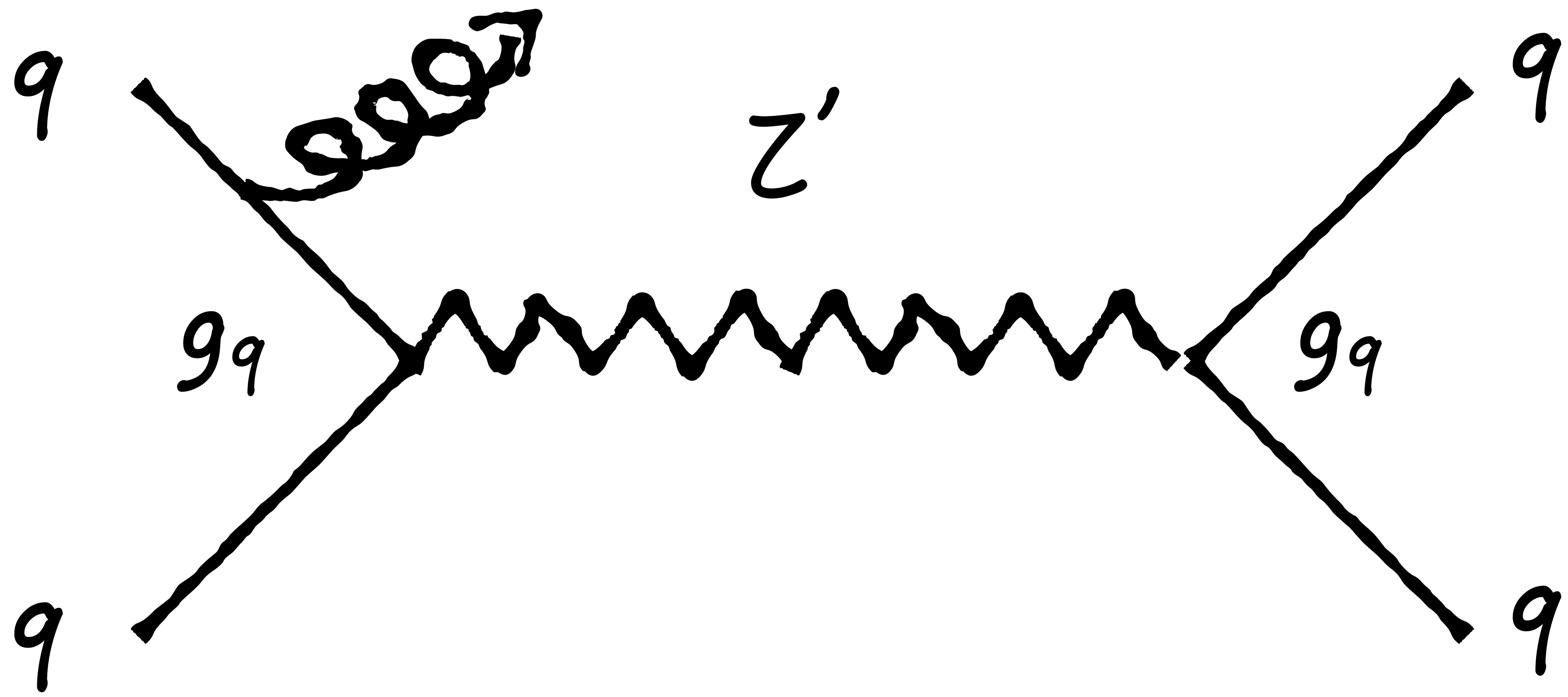
Dark matter complementarity

Mono-jet



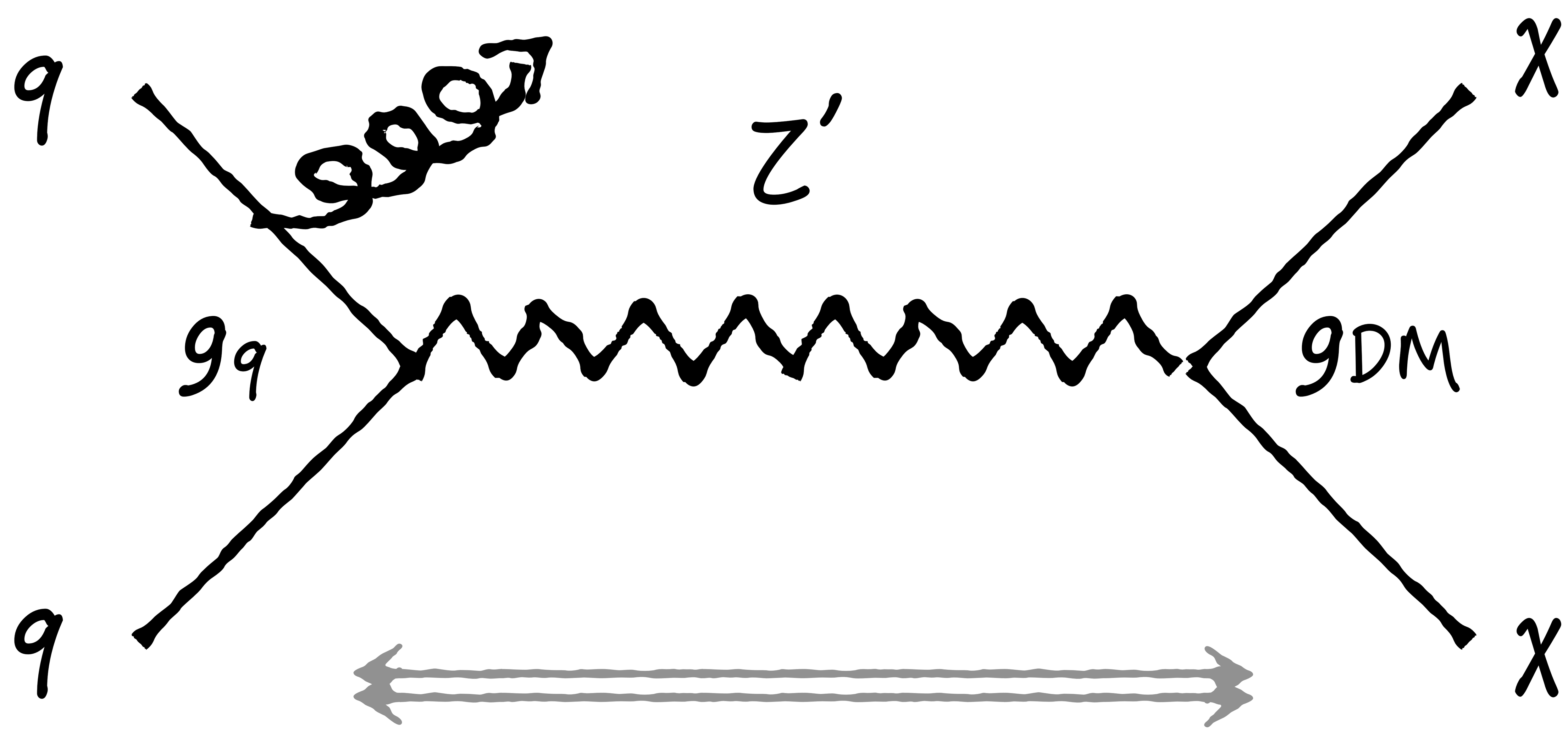
important when
$\mathbf{m_{Z'} > 2 \times m_{\chi}}$

DIJETS



dominant when
$m_{Z'} < 2 \times m_\chi$

MONO-JET



important when
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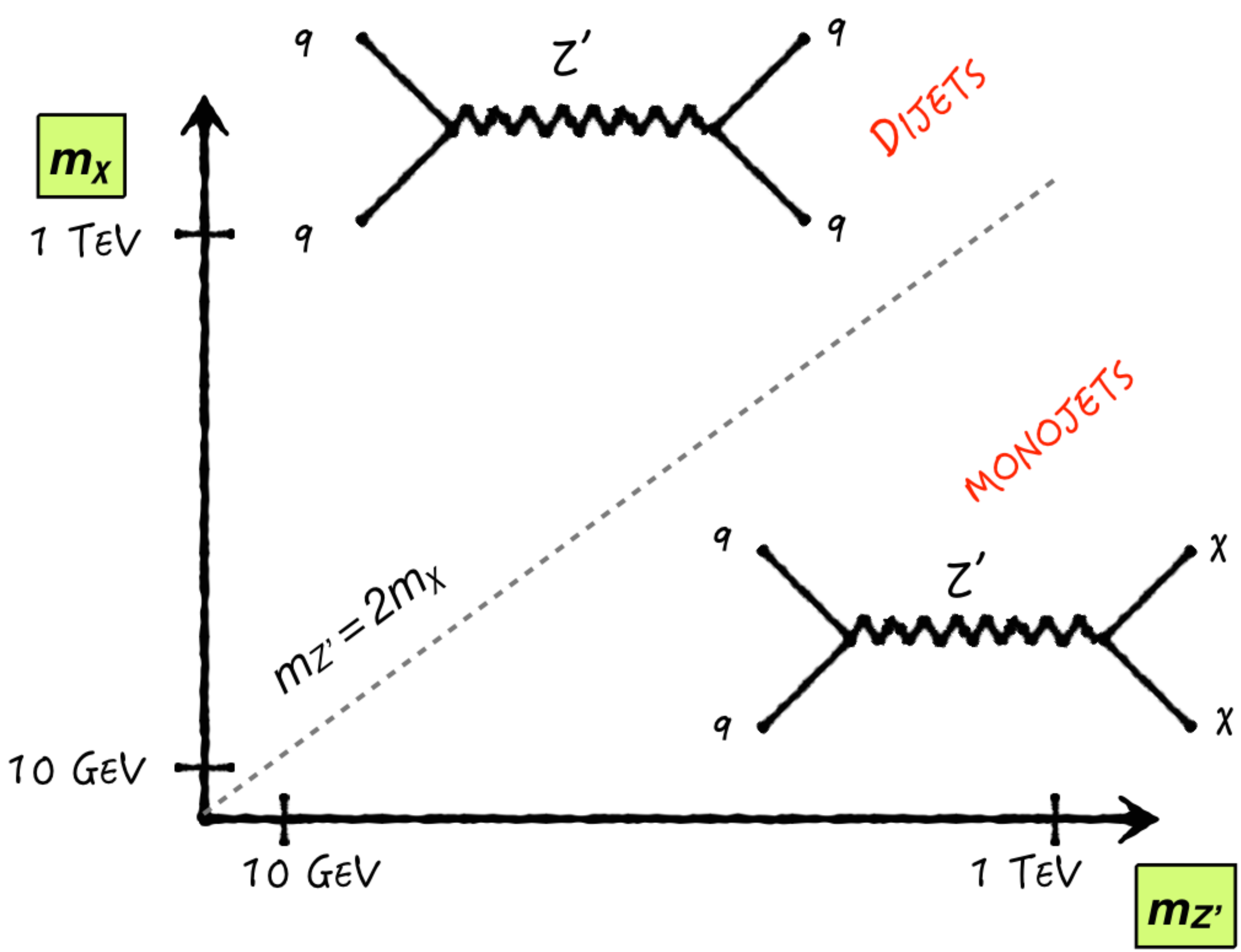
IN THERMAL EQUILIBRIUM
IN THE EARLY UNIVERSE

DARK MATTER COMPLEMENTARITY



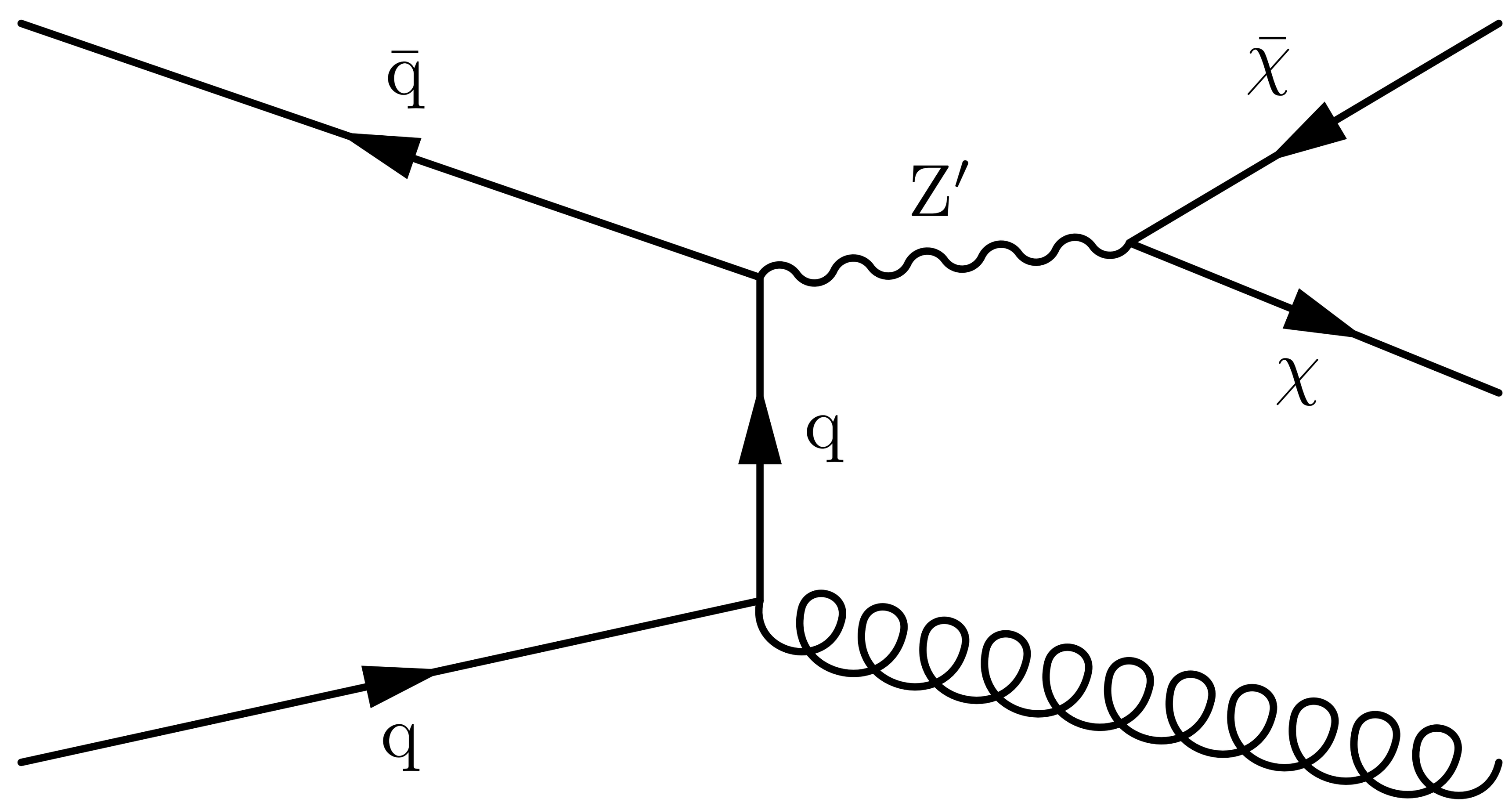
Dark matter simplified models

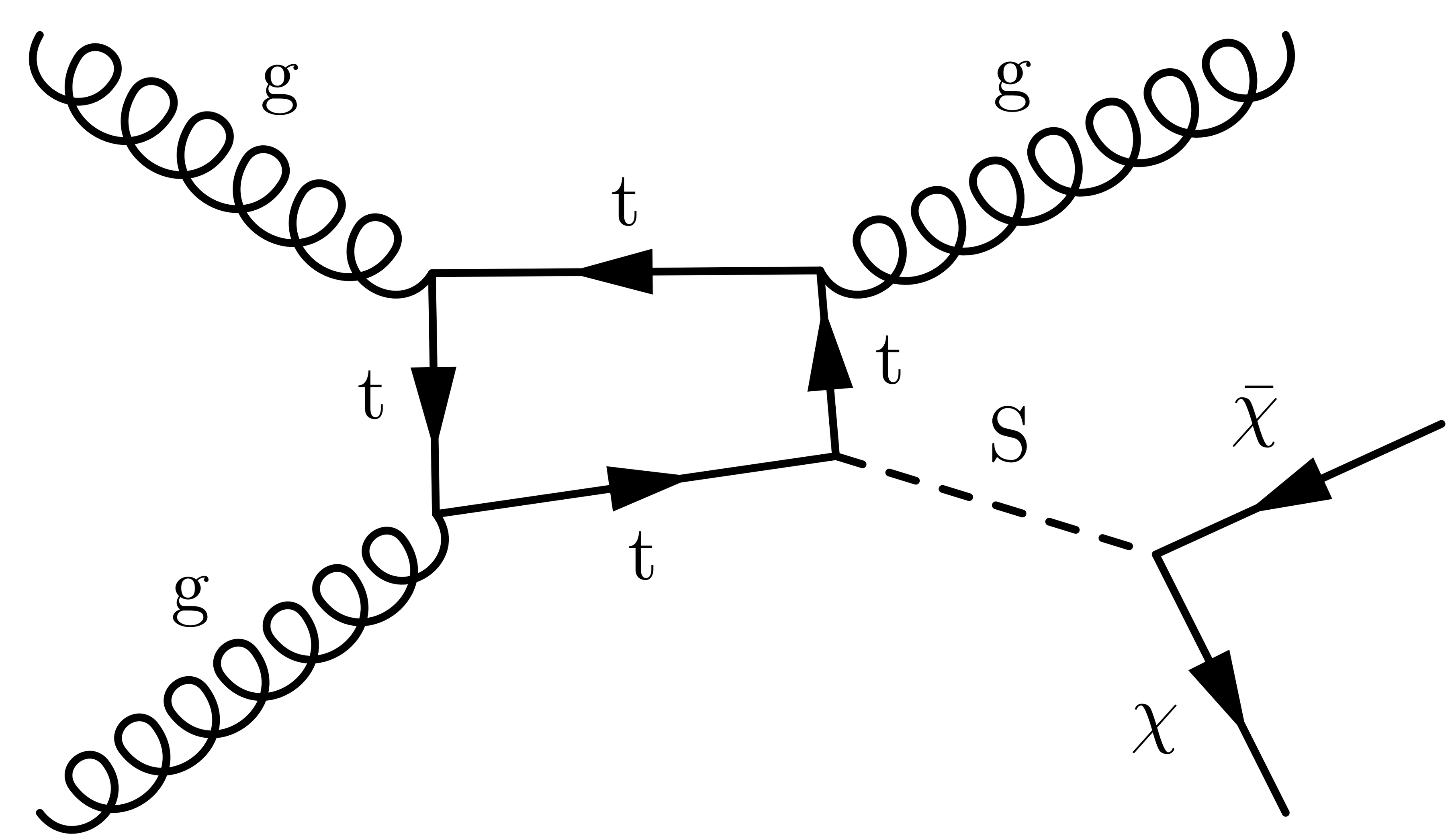
Dark matter search phase space is described by 4 parameters

- M_{Med}, M_{DM}, g_{DM}, $g_{q(SM)}$

Interpretations are typically now presented in the simplified model framework:

- vector, axial-vector, scalar, pseudoscalar





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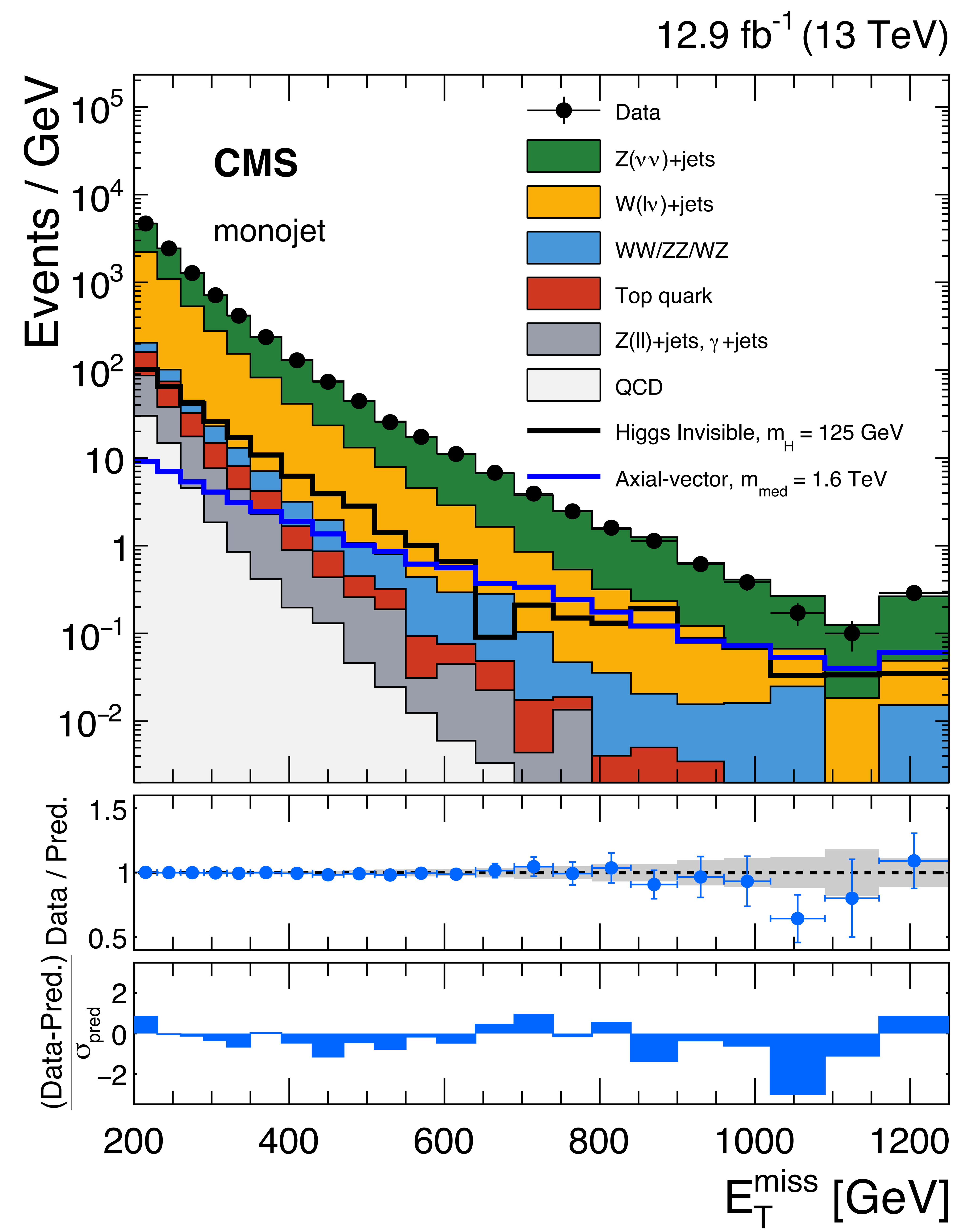
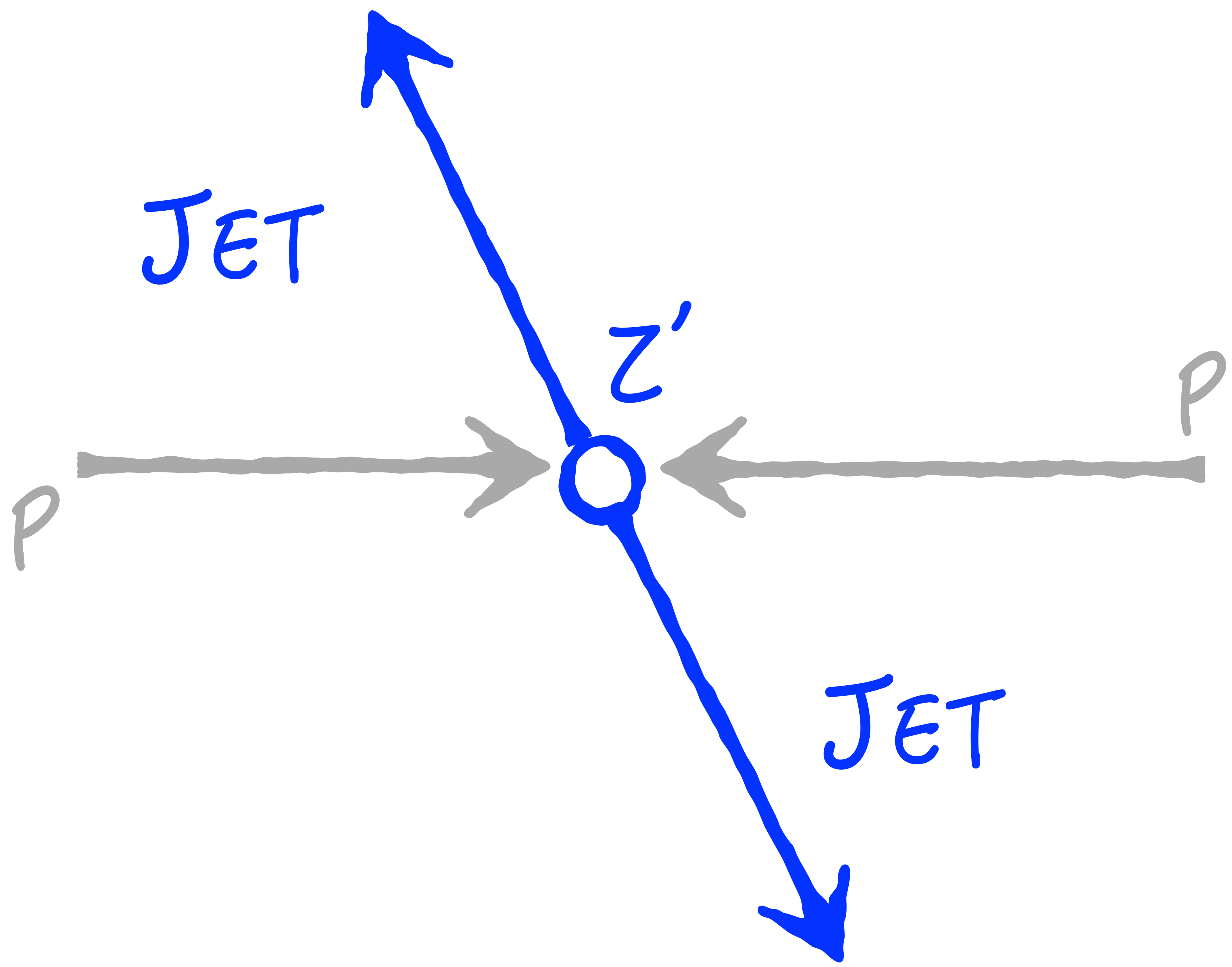
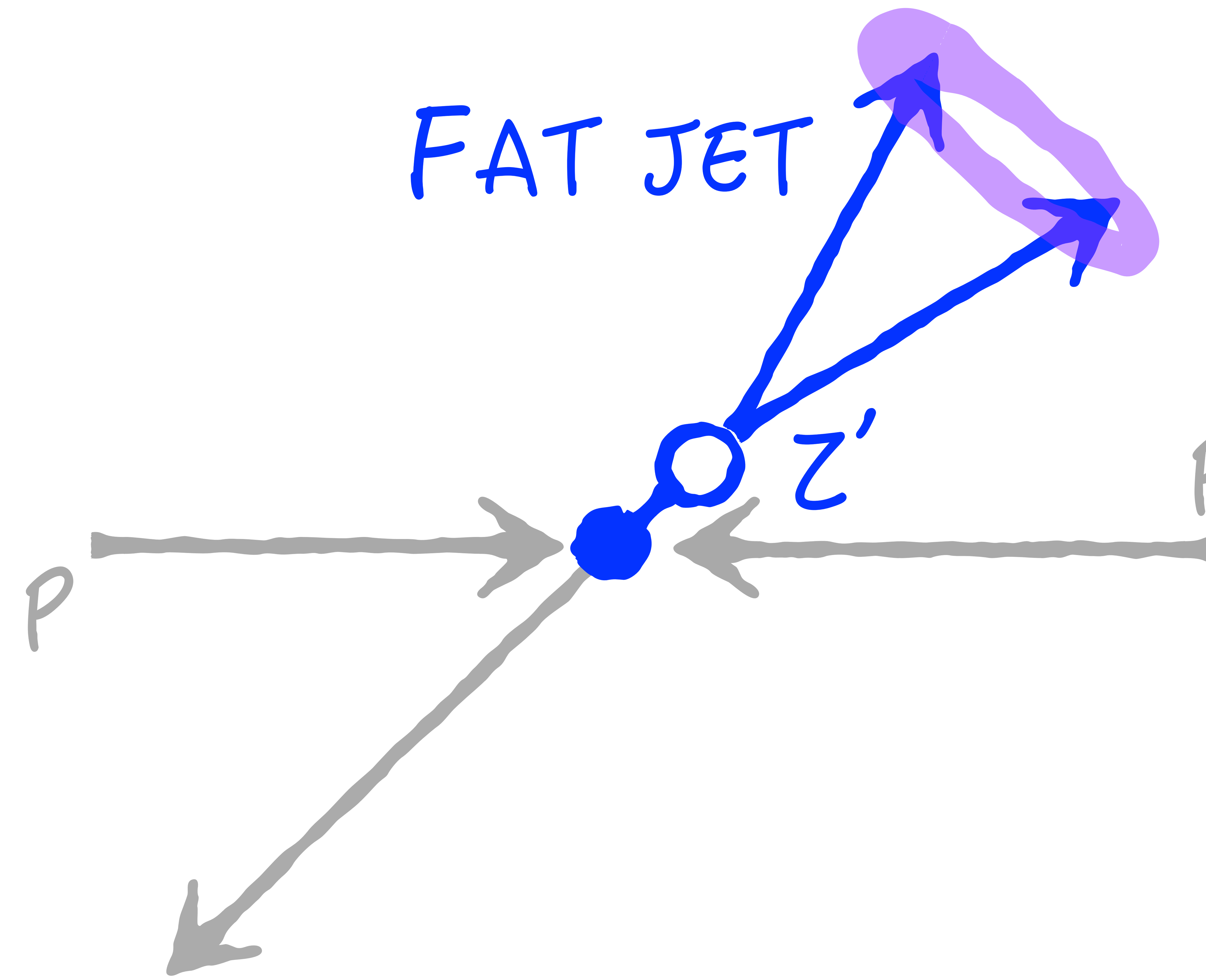
Canonical search looks in the MET tails in mono-jet

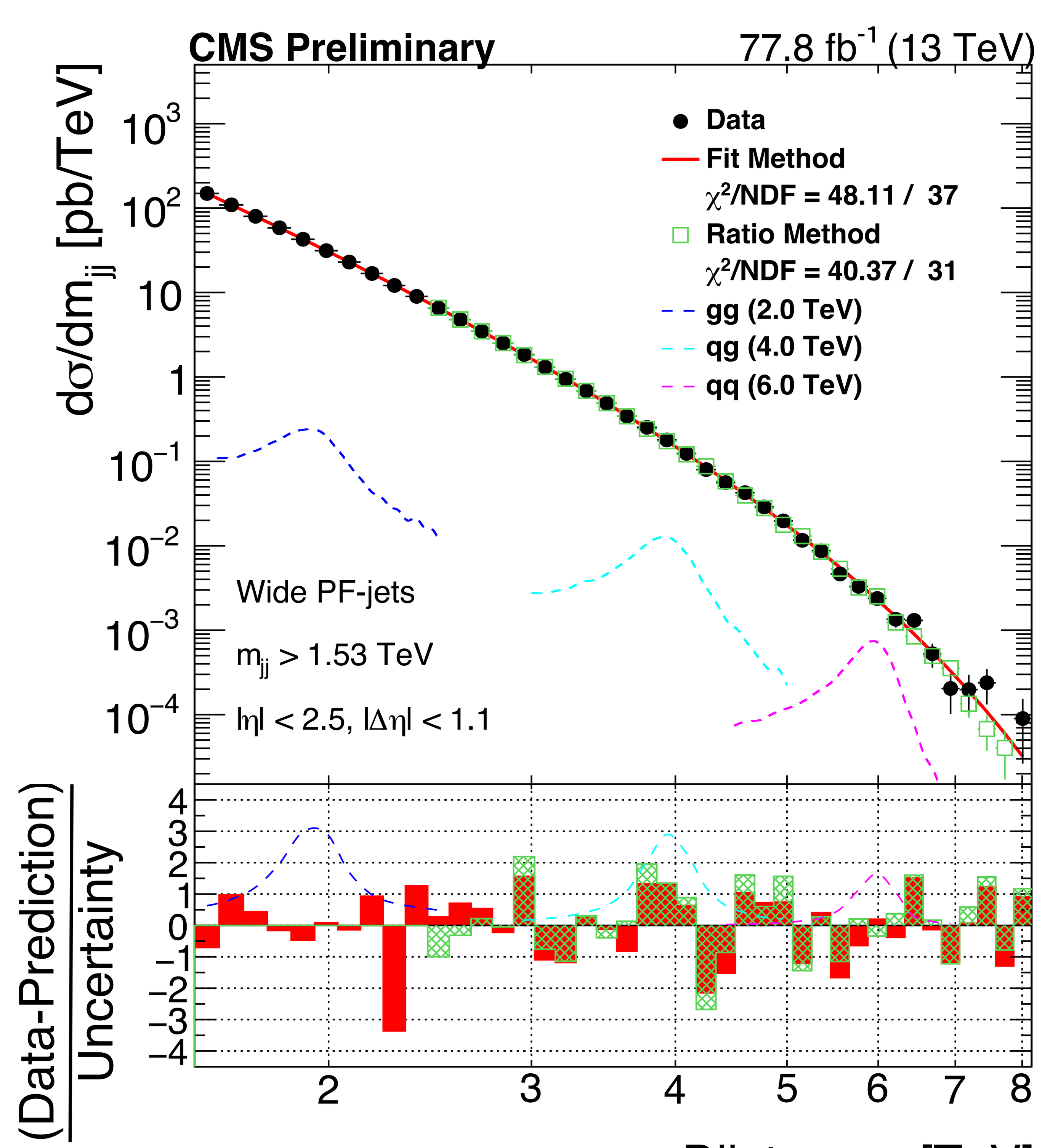
- A wide suite of "mono-X" results! (mono-V, mono-top, mono-di-b,…)

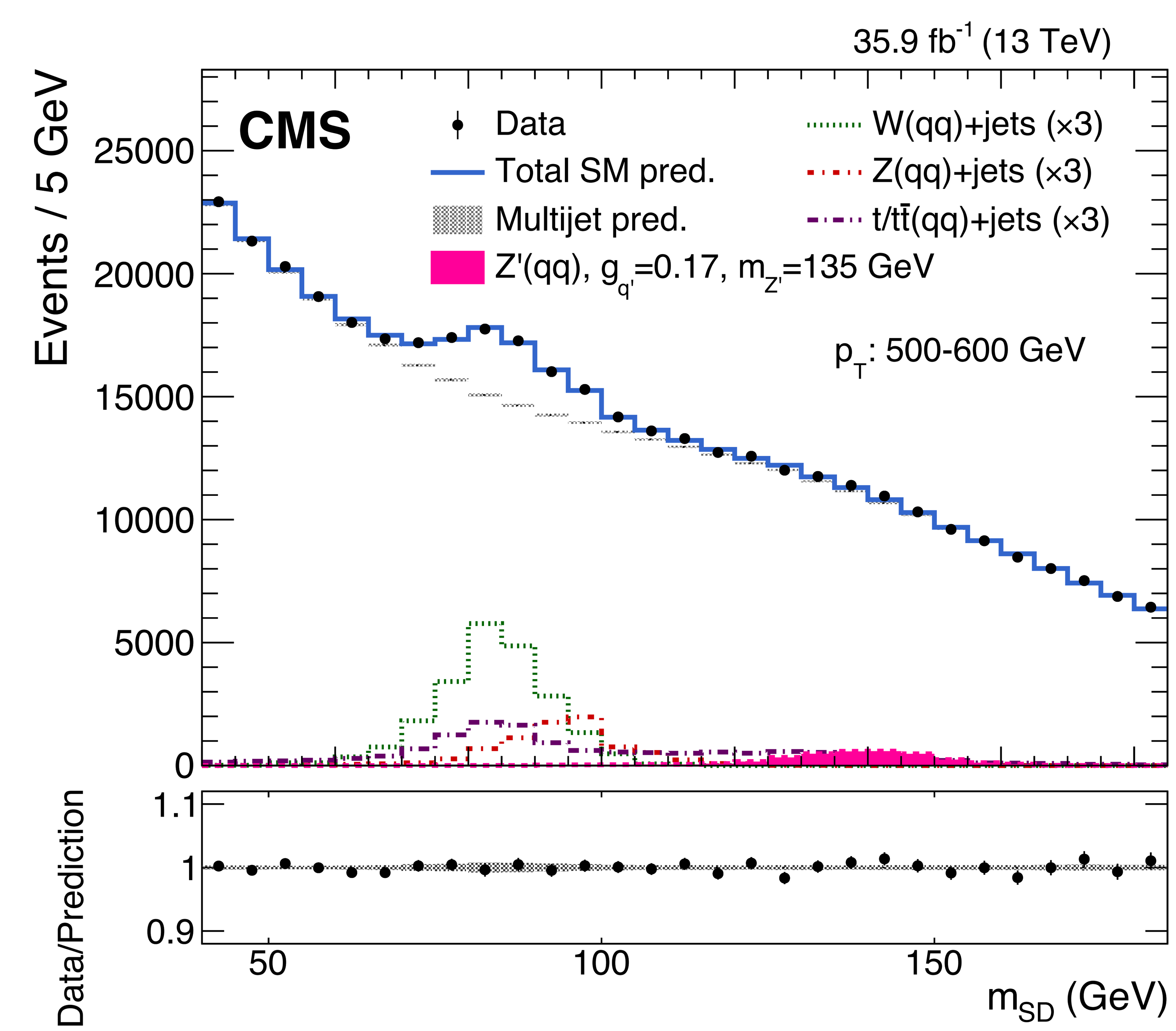


VISIBLE MEDIATOR SEARCHES

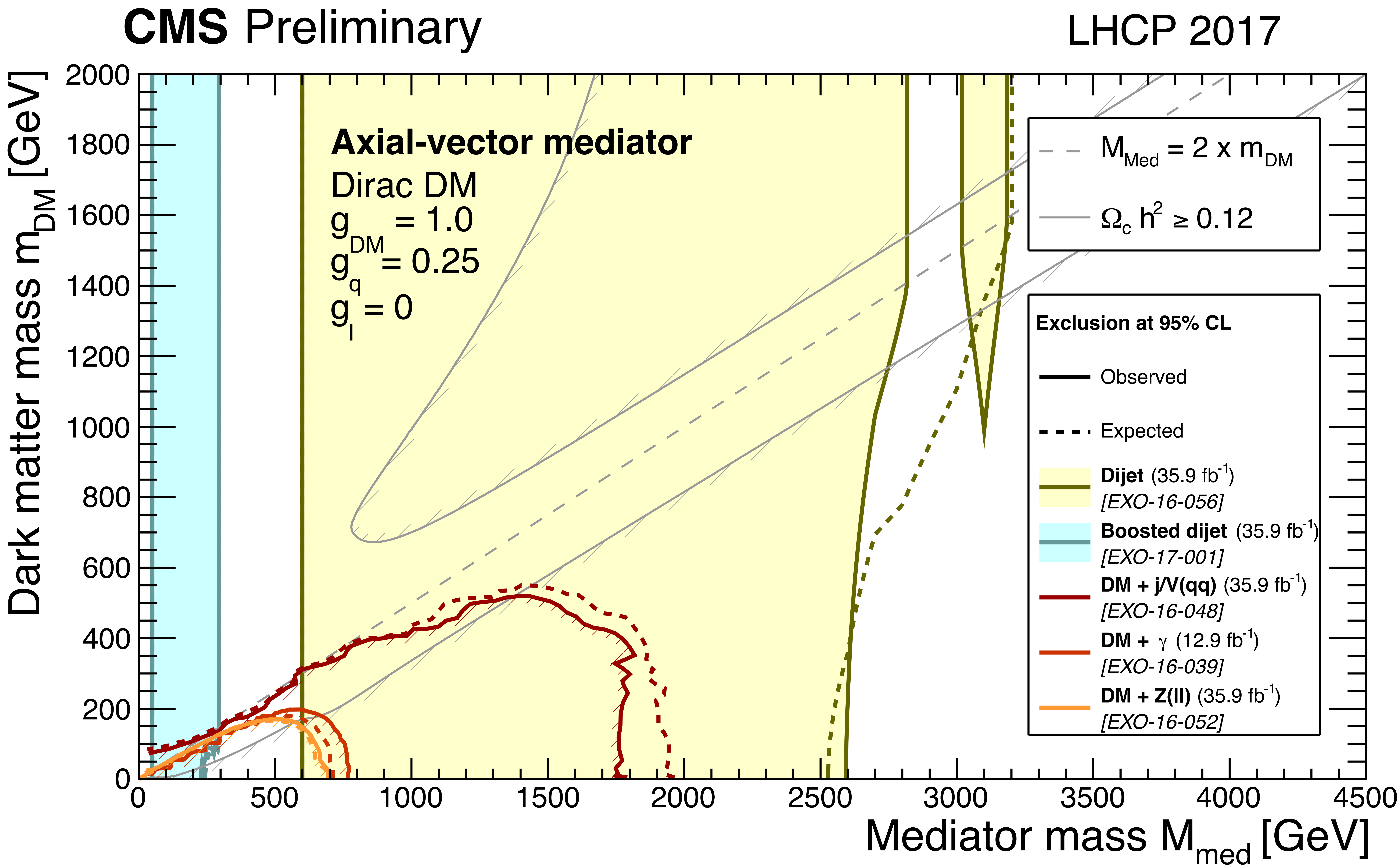




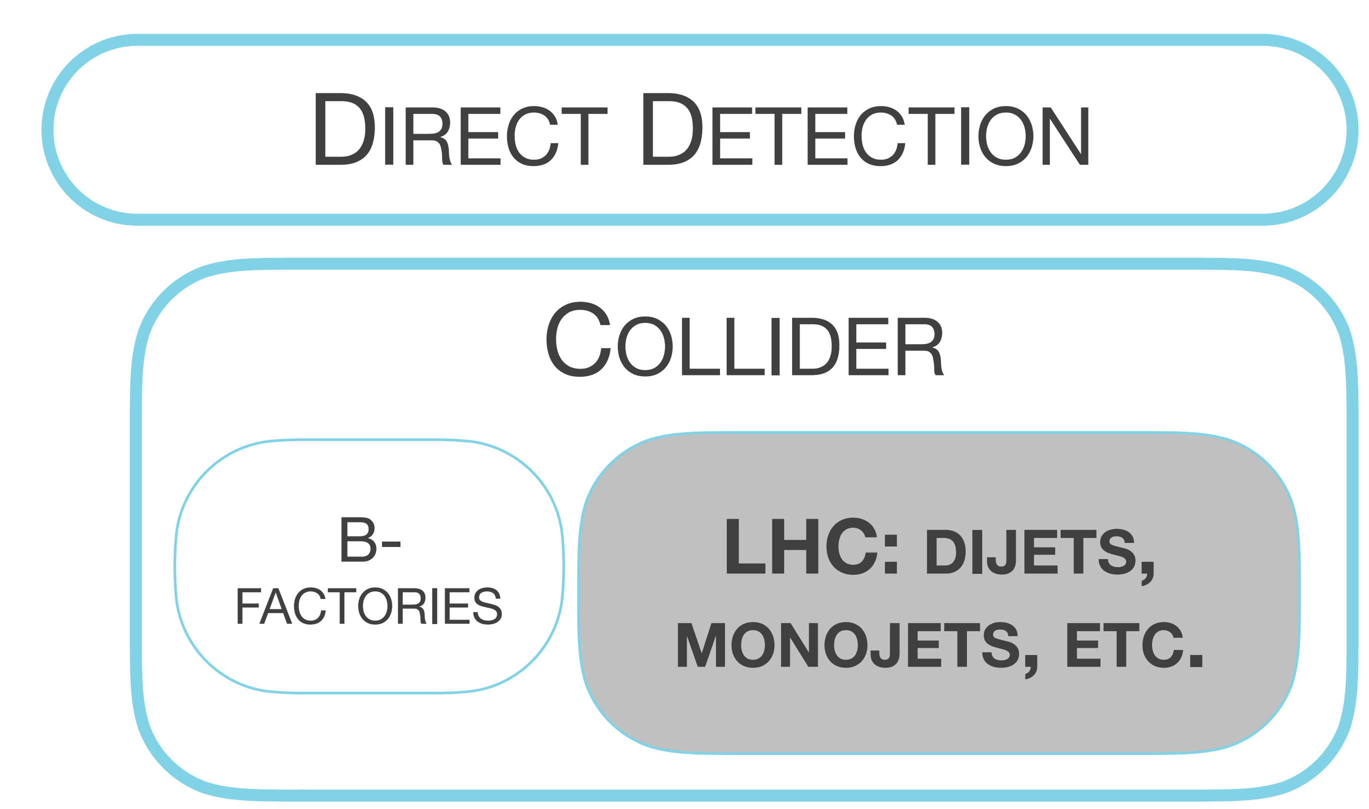




DARK MATTER SUMMARY



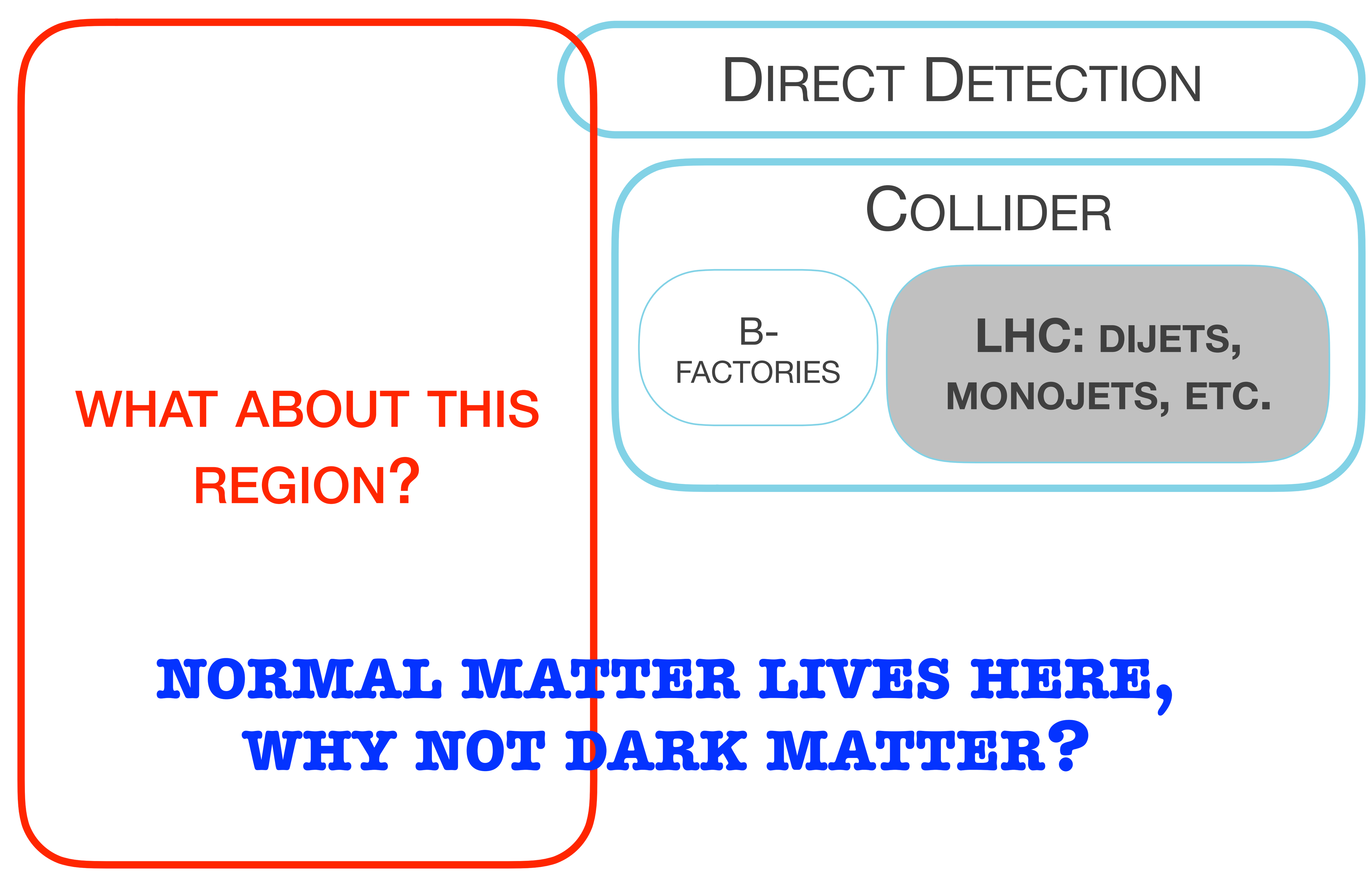
ZOOMING OUT ON DARK MATTER



THERMAL ORIGIN OF DARK MATTER
REMAINS THE SIMPLEST EXPLANATION

ZOOMING OUT ON DARK MATTER

THERMAL ORIGIN OF DARK MATTER REMAINS THE SIMPLEST EXPLANATION



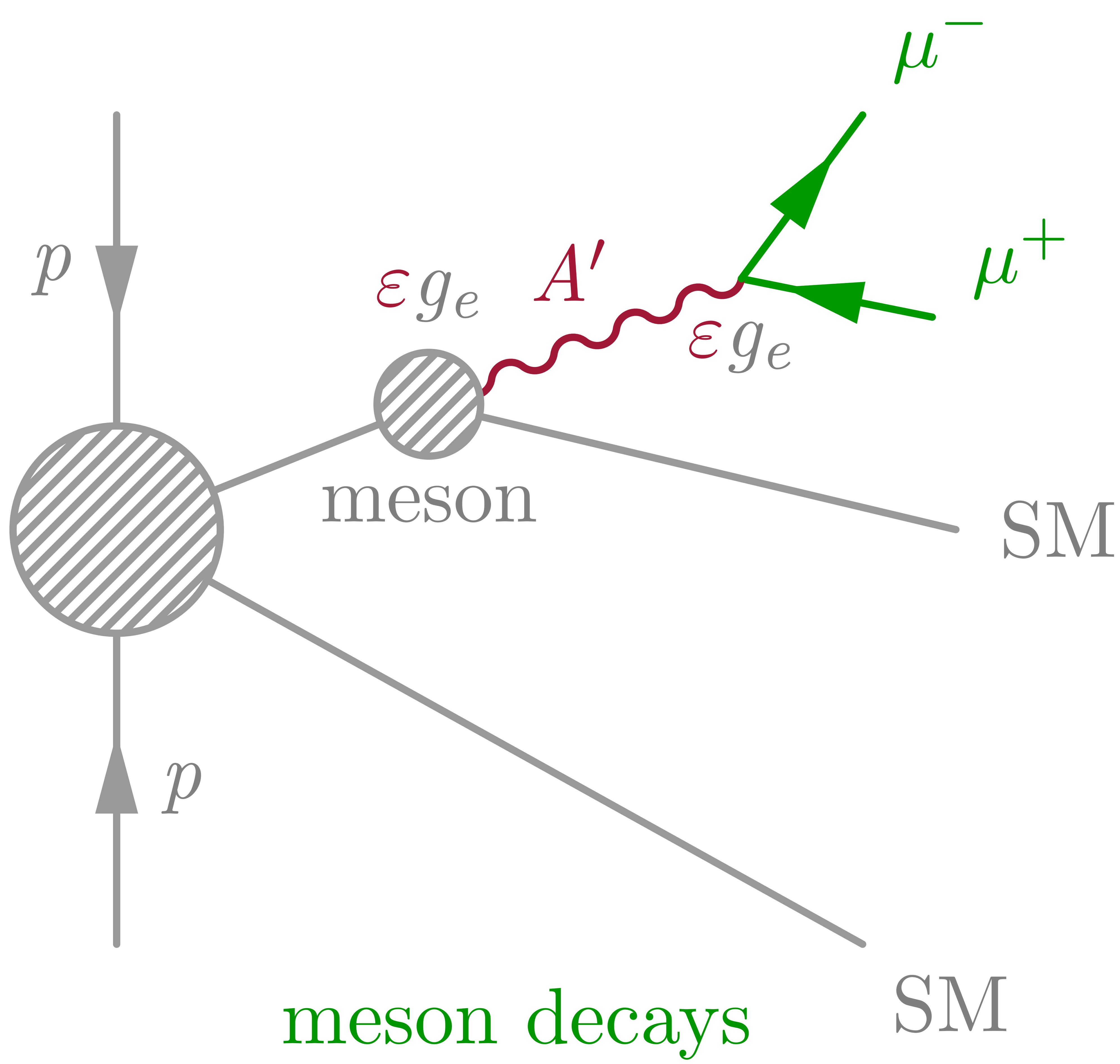
LIGHT DARK MATTER IS EQUALLY INTERESTING, BUT OUT OF THE REACH OF CONVENTIONAL DARK MATTER SEARCHES

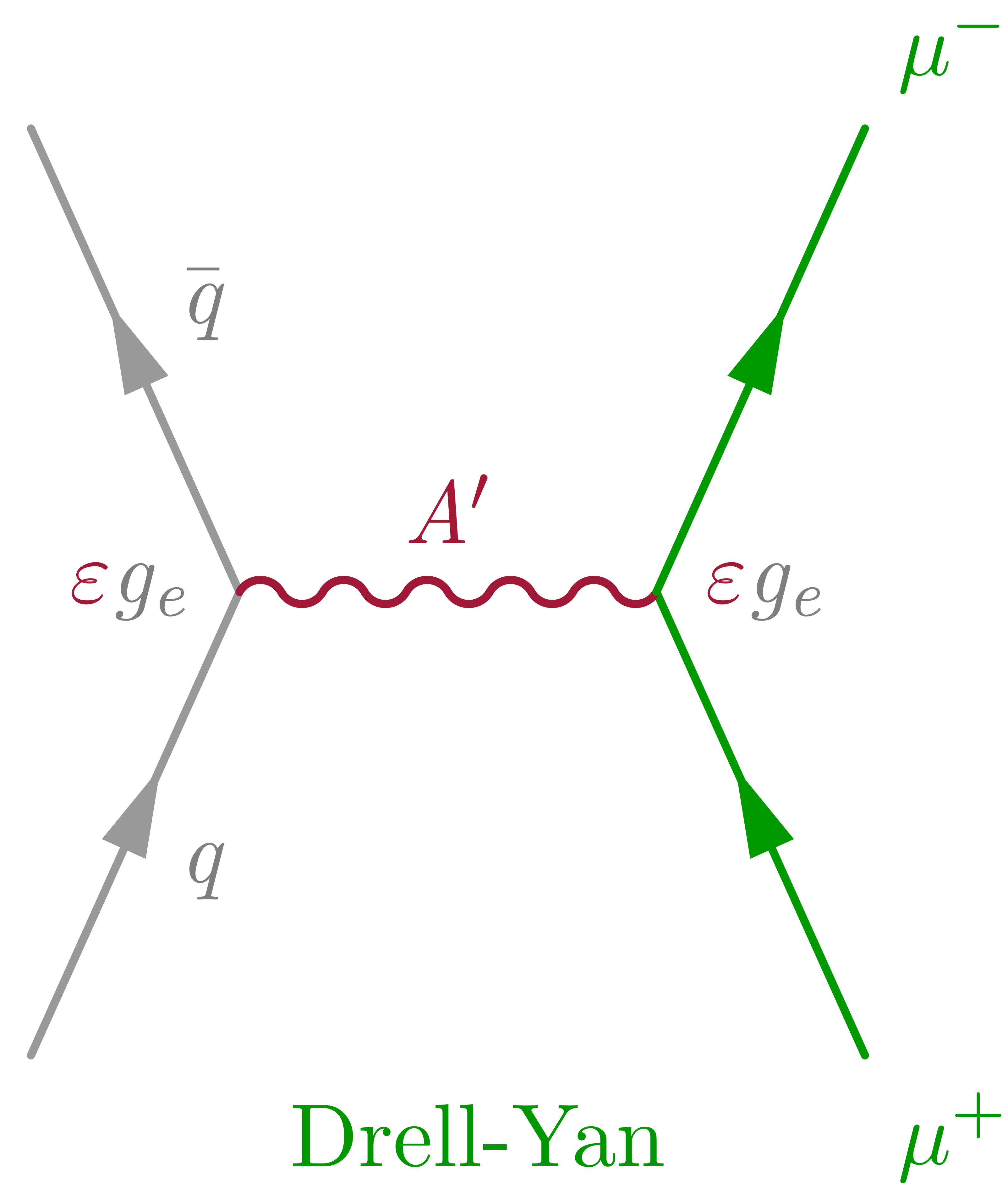
Light mediators and dark sectors

Future projections - but I wanted to highlight the LHCb capabilities!

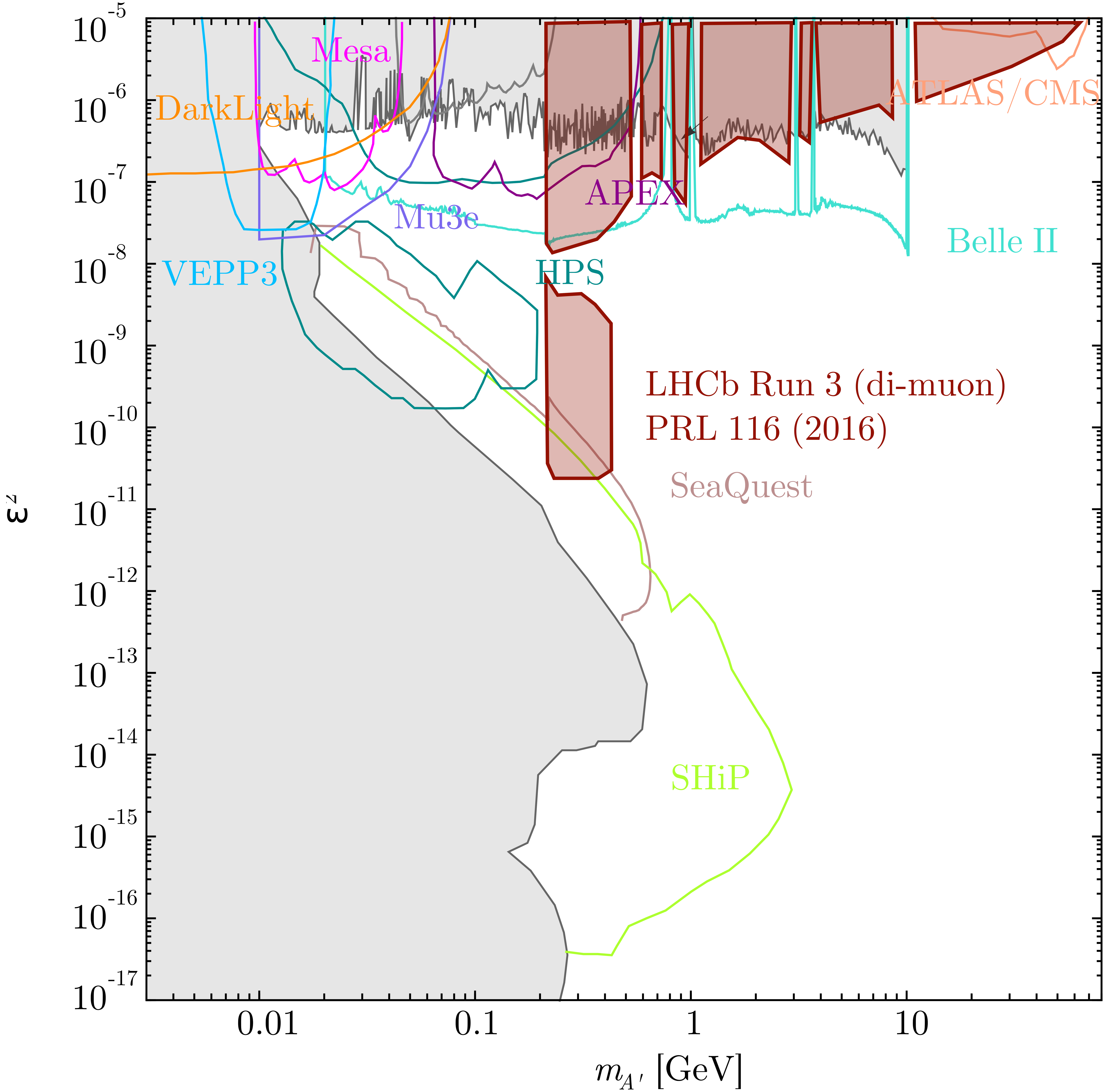
Lighter dark sector mediators can be probed very well by LHCb in both prompt and displaced signals

A large open area in the dark sector program!



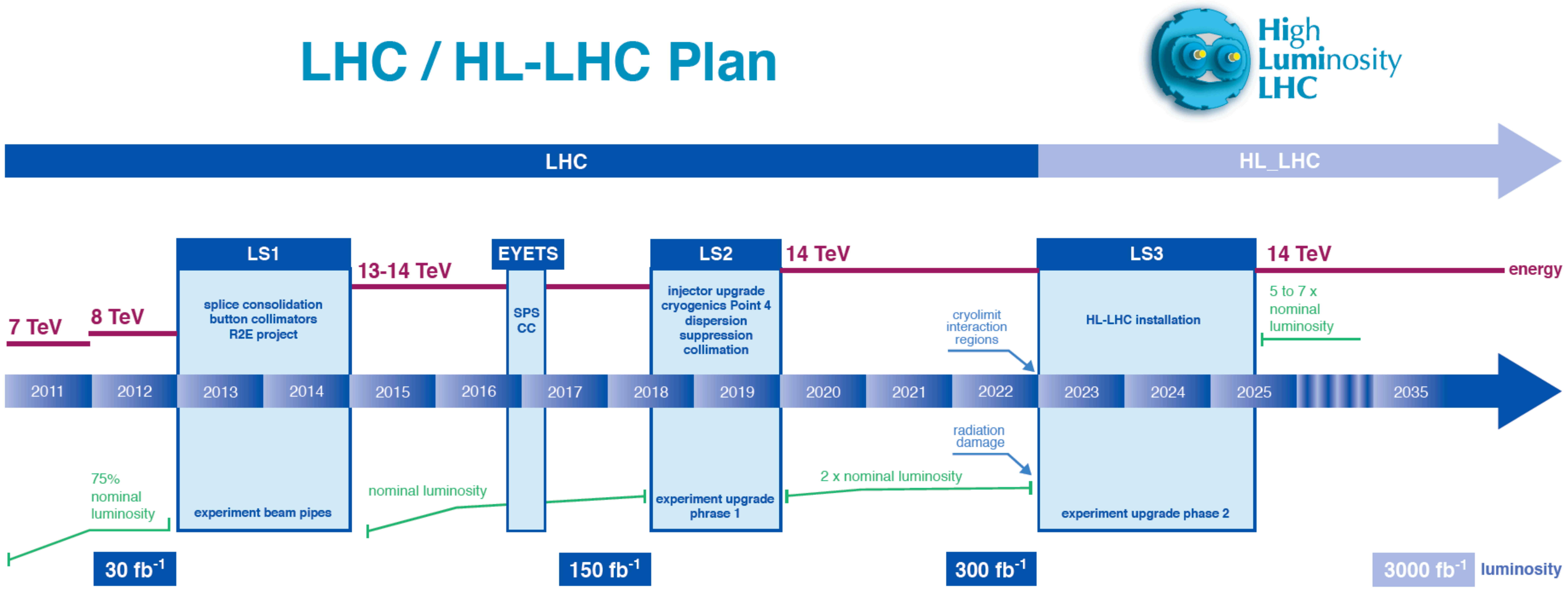


Projected reach



Where we are going

LHC / HL-LHC Plan



More luminosity = pileup

Pileup is the greatest experimental challenge going forward, it affects everything.

detector design, object performance and physics sensitivity

radiation damage to detectors, degrades energy/position measurements, lost untriggered events forever

Detector Upgrades...

CMS example

Trigger/HLT/DAQ

- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region 1.5<h<2.4
- Muon tagging 2.4<h<3

New Endcap Calorimeters

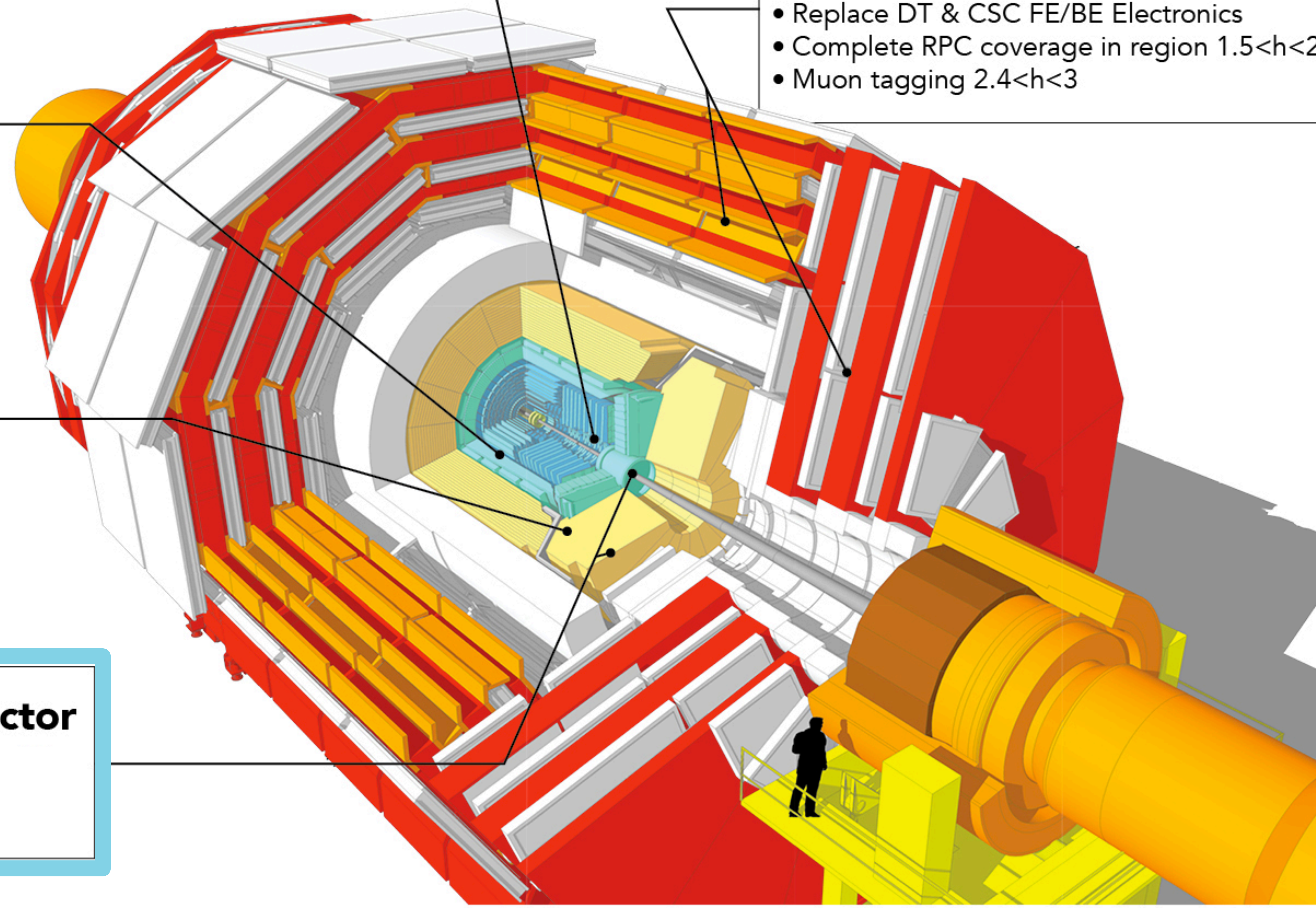
- Rad. tolerant – high granularity
- 3D capable

New Tracker

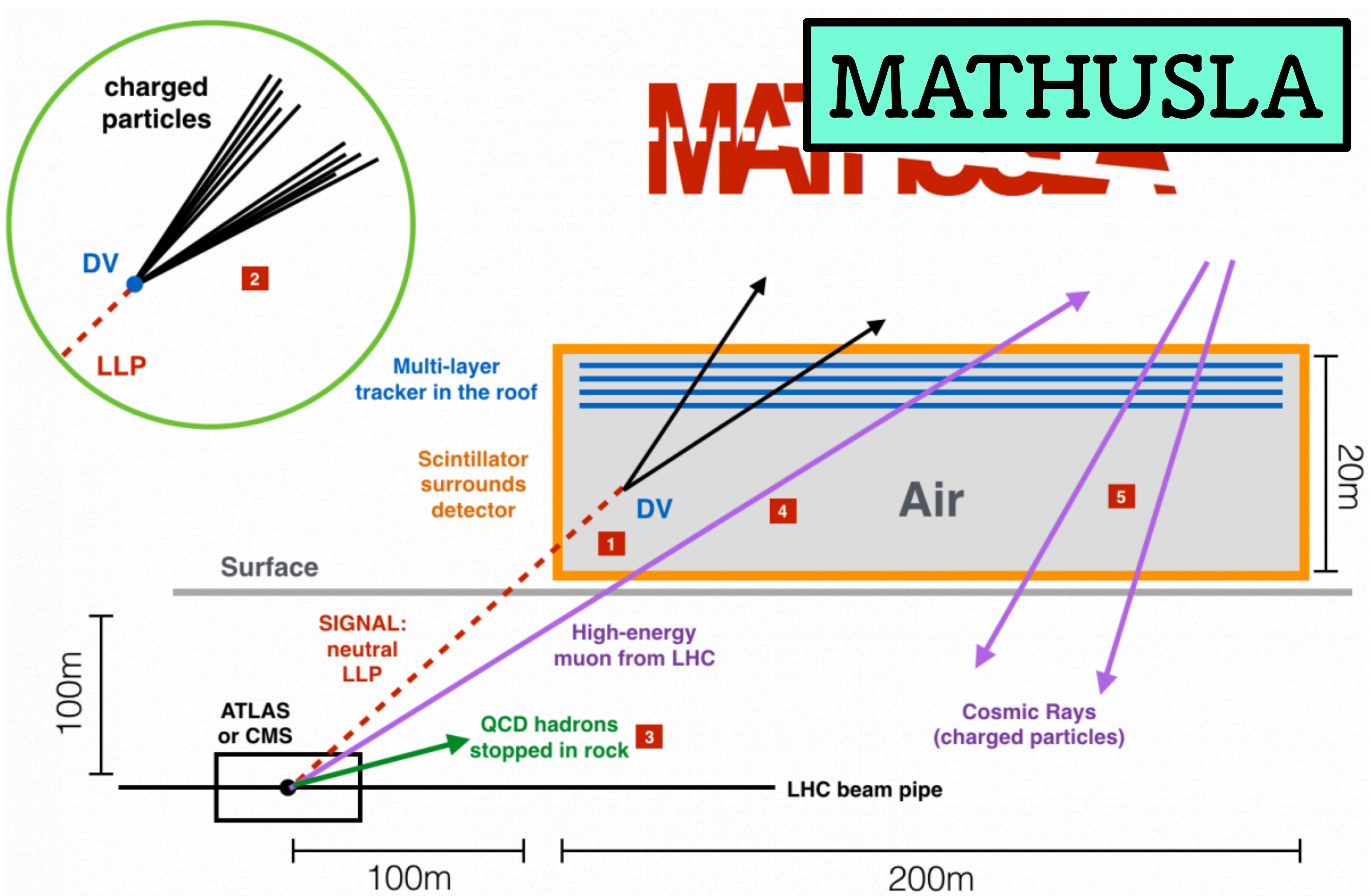
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to h=4

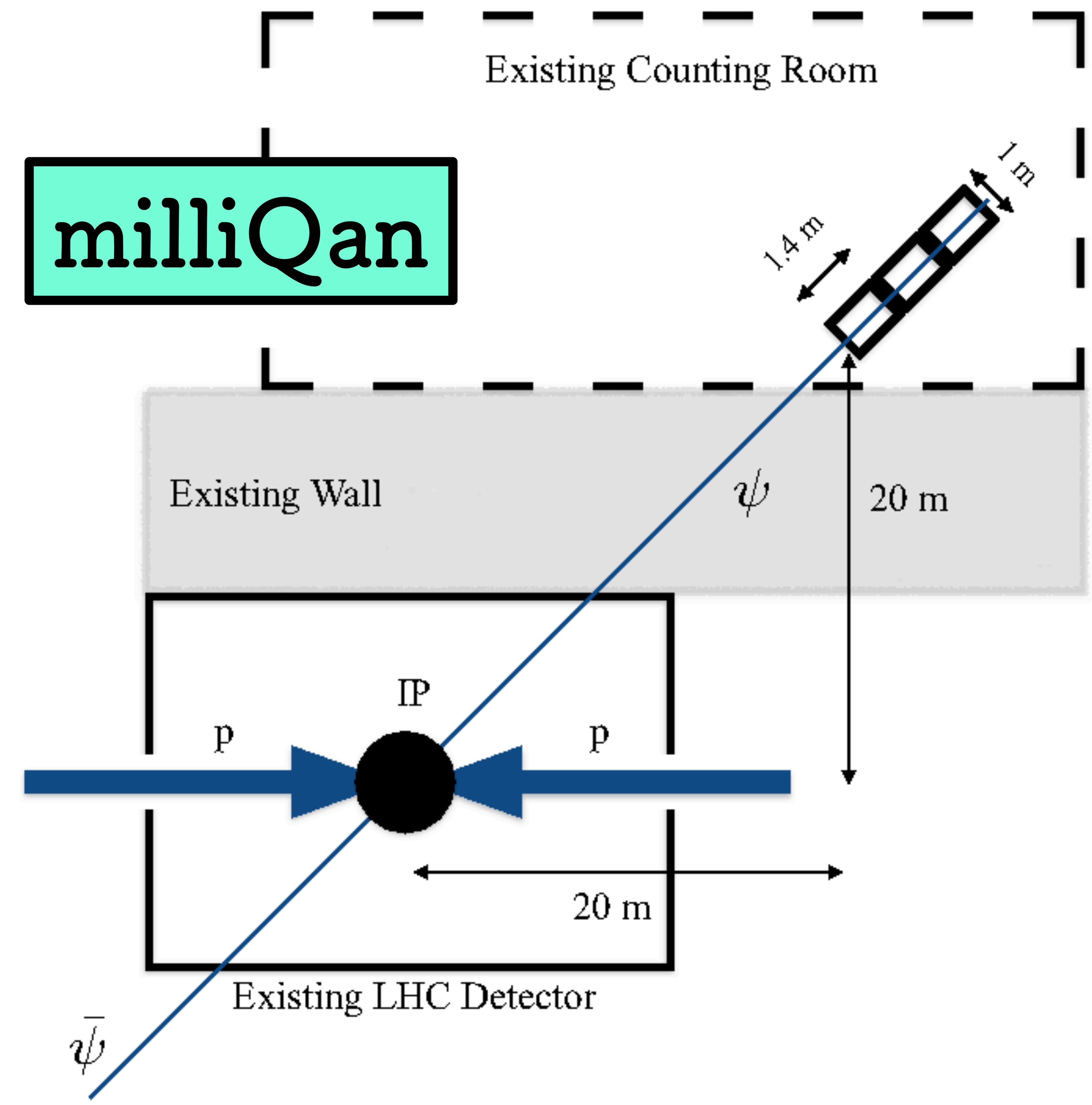
MIP Precision Timing Detector

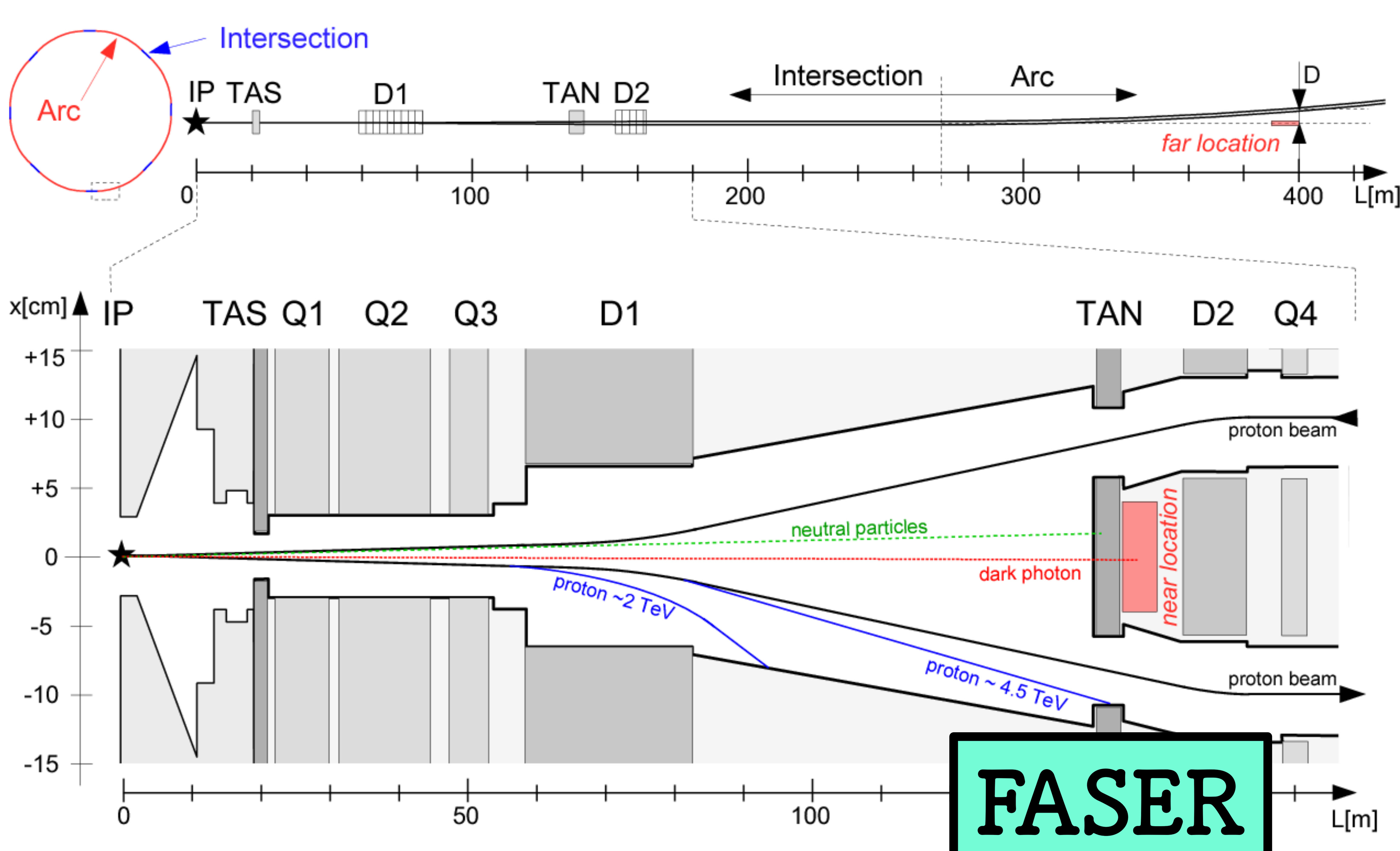
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

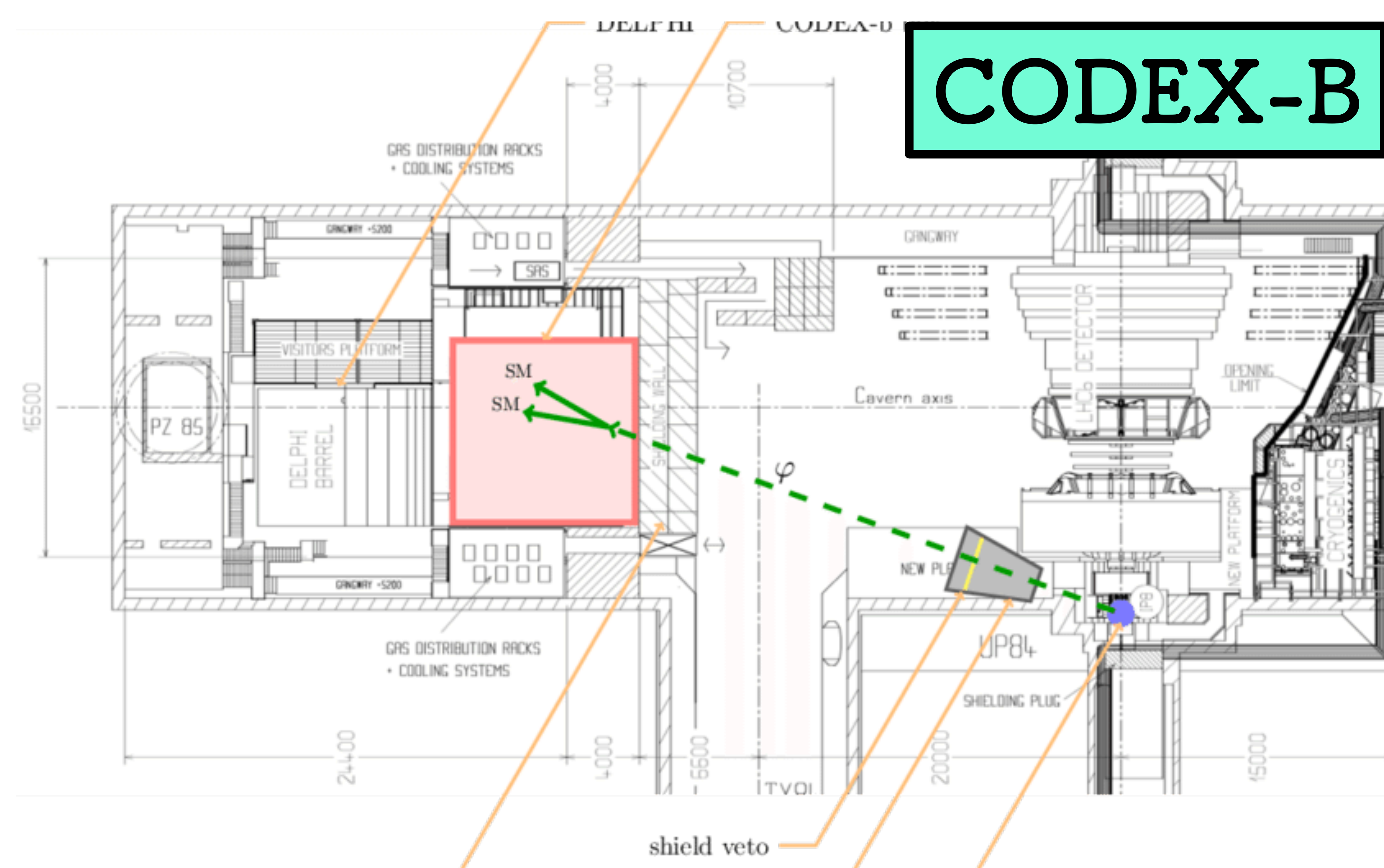


AND PROPOSALS!







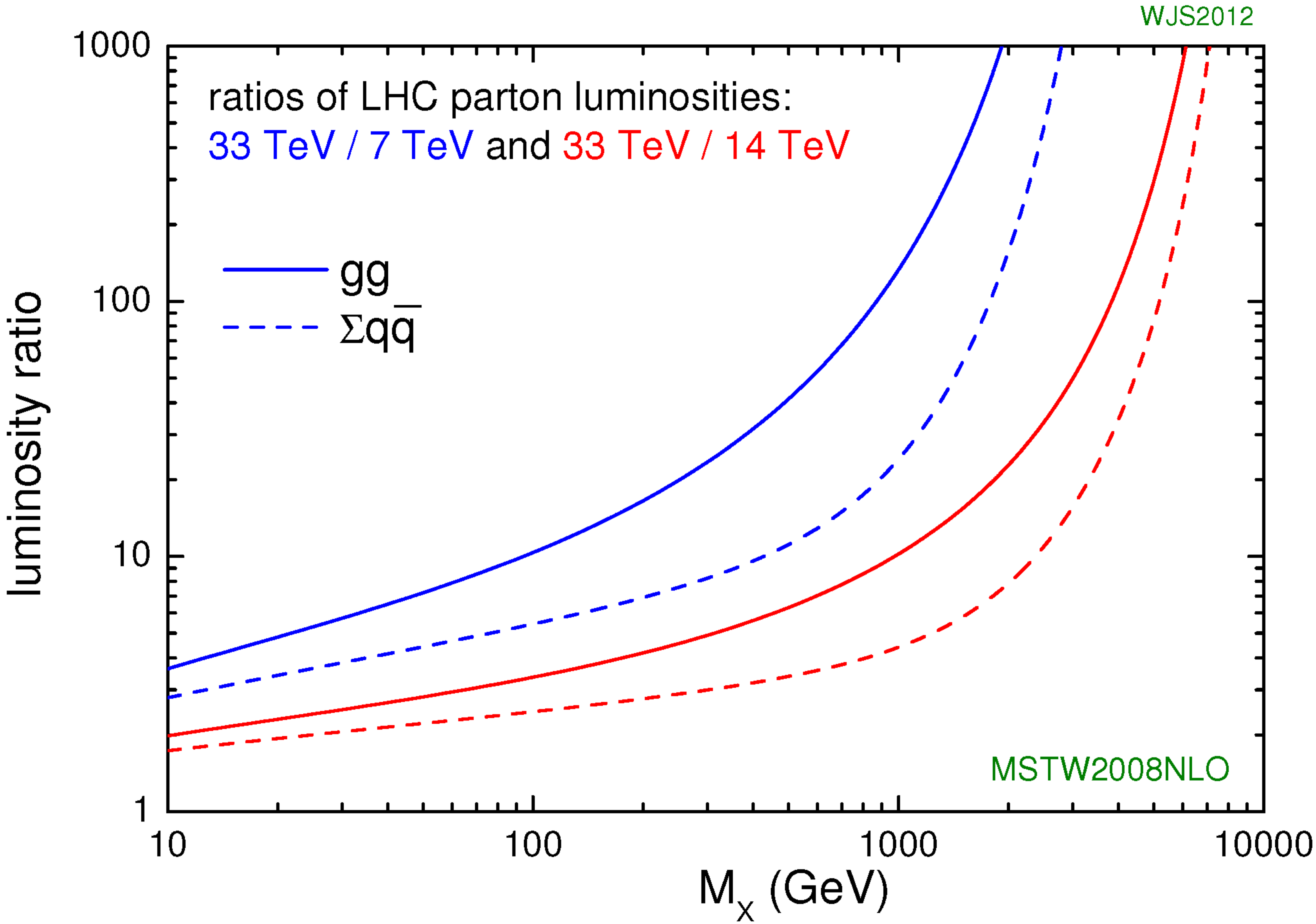


Future hadron colliders

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997

Many options are being discussed for future hadron colliders
Also lepton collider machines are being discussed

You will be an important part of driving our future!


WJS2012
ratios of LHC parton luminosities:
33 TeV / 7 TeV and 33 TeV / 14 TeV
gg
Σqq̄
MSTW2008NLO
luminosity ratio
1
10
100
1000
10
100
1000
10000
M_X (GeV)

Summary

Summary

The LHC has an amazing and broad physics program!
I've only scratched the surface...

The Higgs lamppost
and the Higgs portal

Precision SM tests and the
stability of the universe

Indirect probes and being
ready for the unexpected

Classic searches with weaker couplings

Studying the quark-gluon
plasma

Connecting with the cosmos

...and so on...

We've only collected a small fraction of the total LHC luminosity

With a little patience, hard work, ingenuity and luck, there remains an amazing amount of physics ahead of us