LHC and beyond

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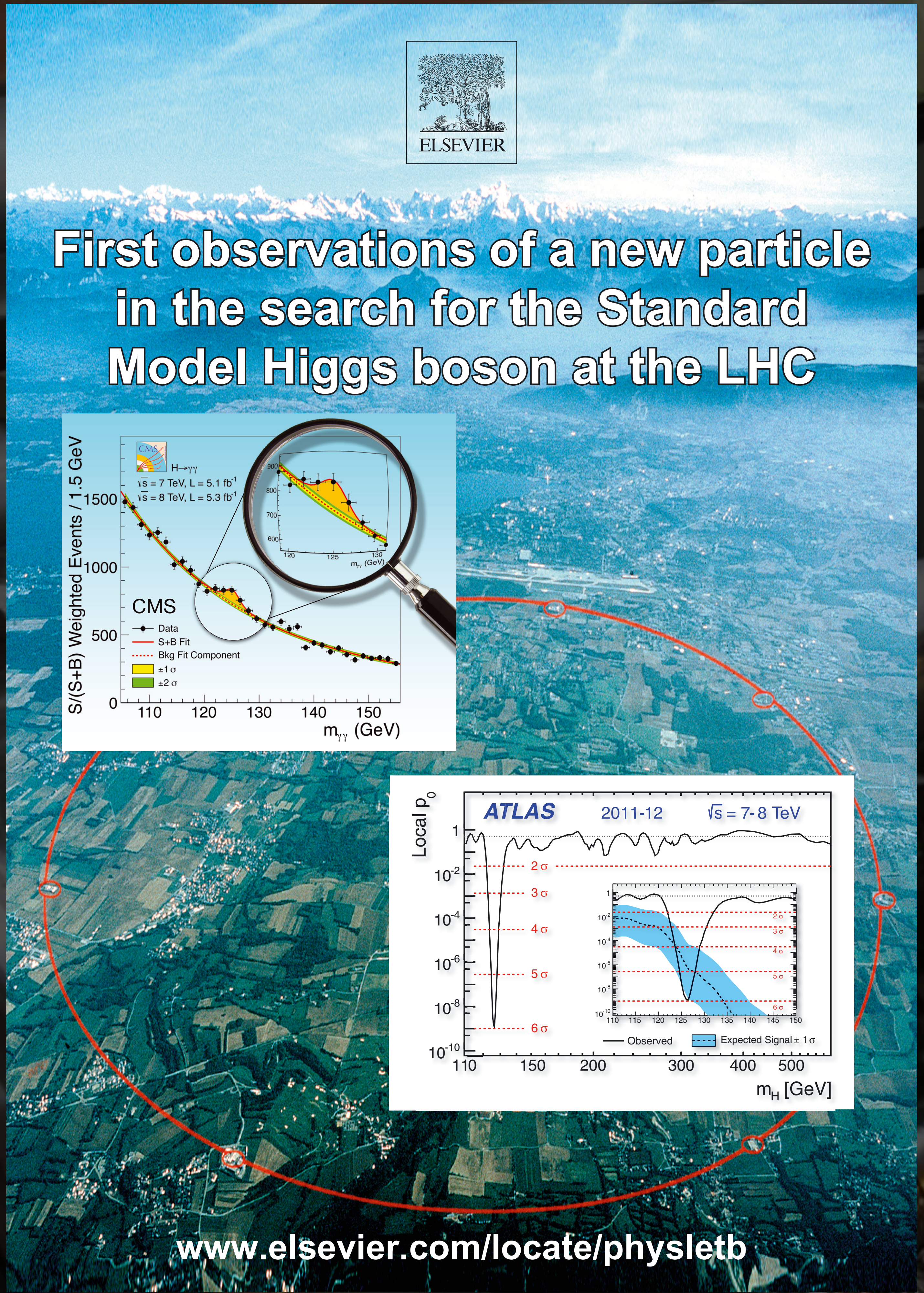
The Higgs Boson Discovery at LHC

Predicted in 1964, discovered in 2012! 48 year hunting!

ATLAS & CMS Observation



2013 Nobel Prize

François Englert and Peter Higgs

An effort by thousands of scientists and engineers from all over the world

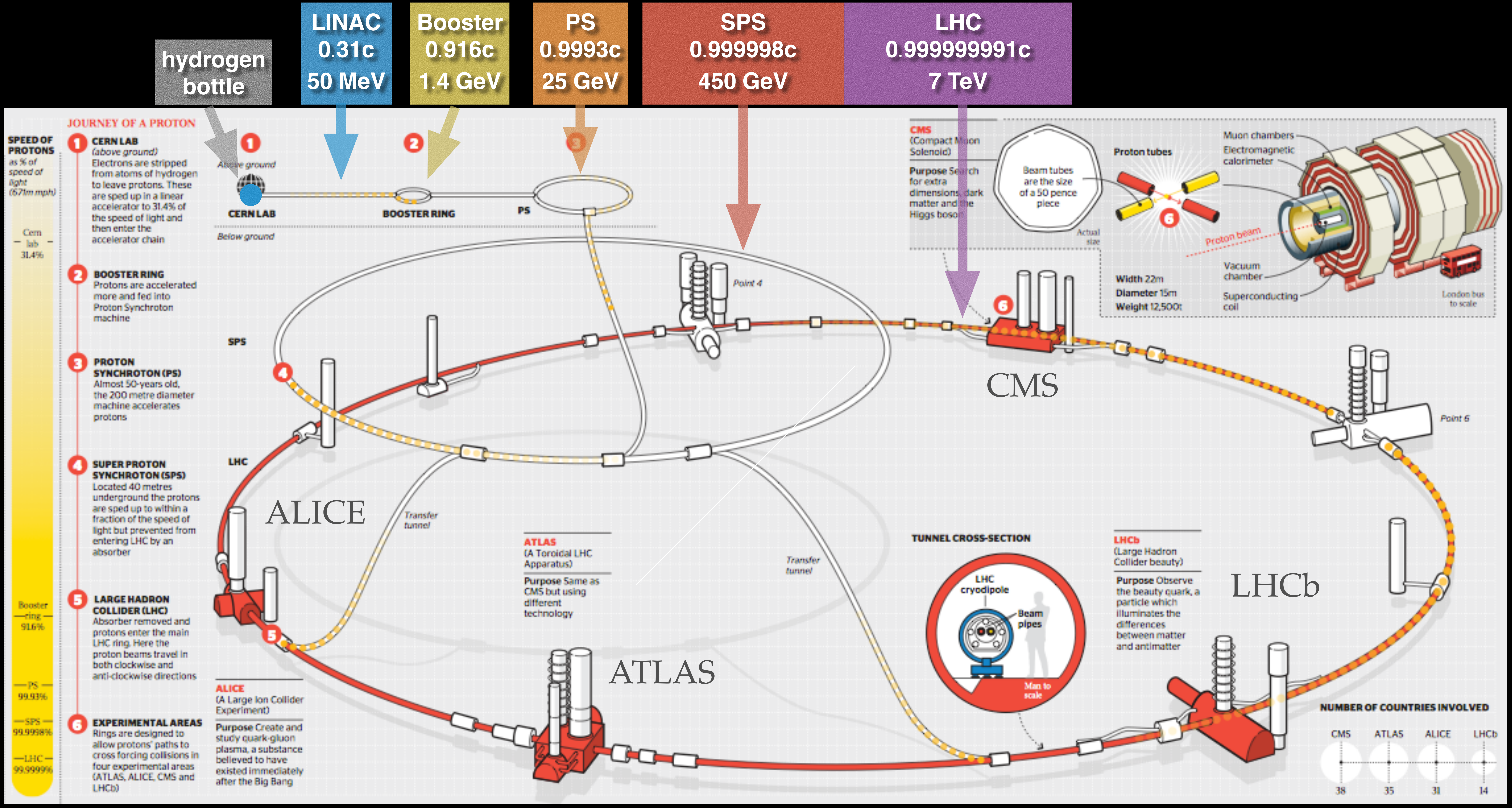
Huge impact to humanity

Technology
Cultural
International Collaboration

How did we get there and what are we doing now?


Large Hadron Collider
proton-proton collisions
Center of mass energy: 7-8-14 TeV
Lake Geneva
CMS
General Purpose
LHC ring:
27 km circumference
LHCb
B-physics
SPS ring
Airport
ALICE
Heavy ion physics
ATLAS
General Purpose
CERN

The LHC accelerator complex



Depth ~ 50-175 m

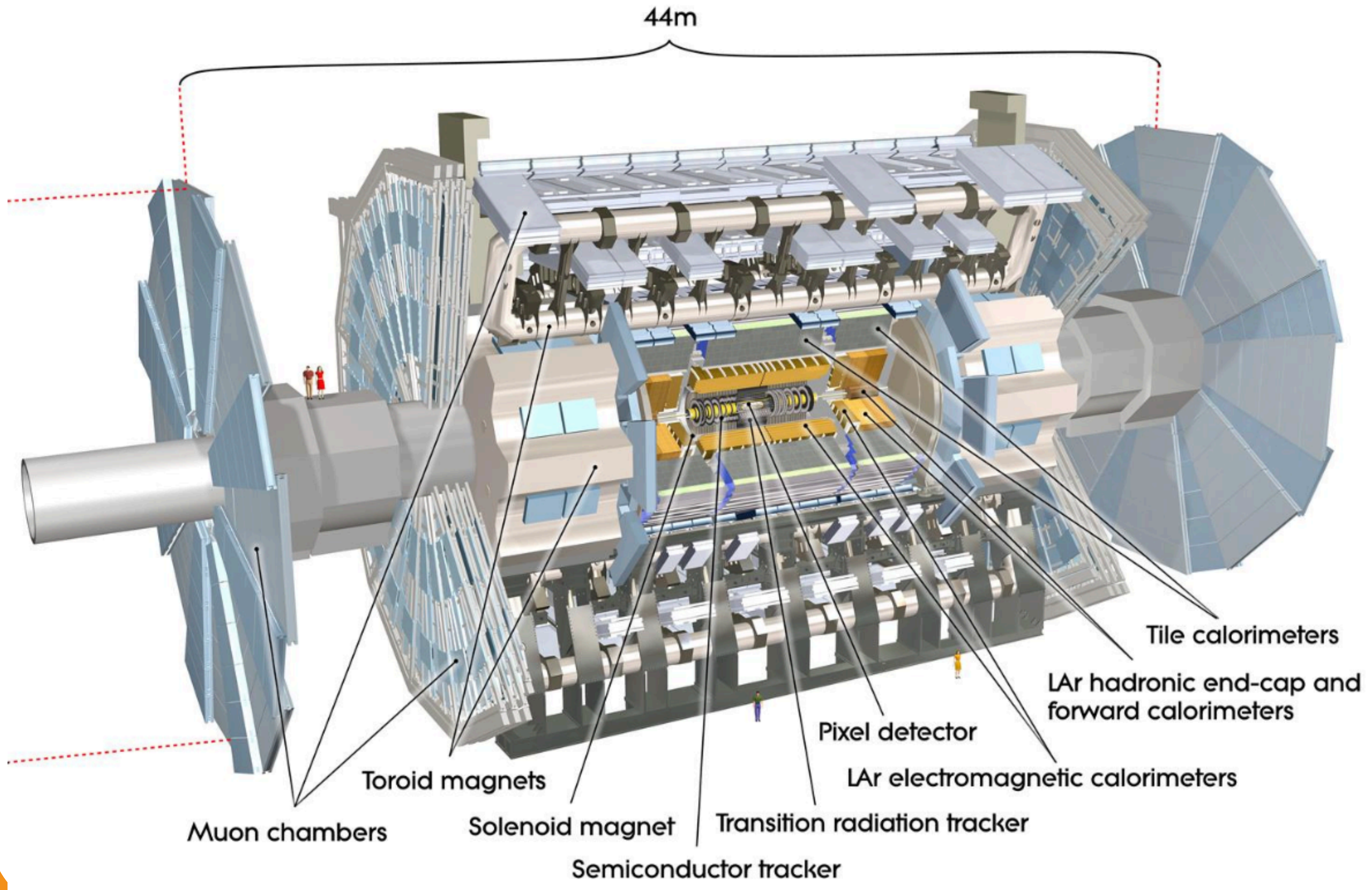
LHC Experiments: General Purpose Detectors

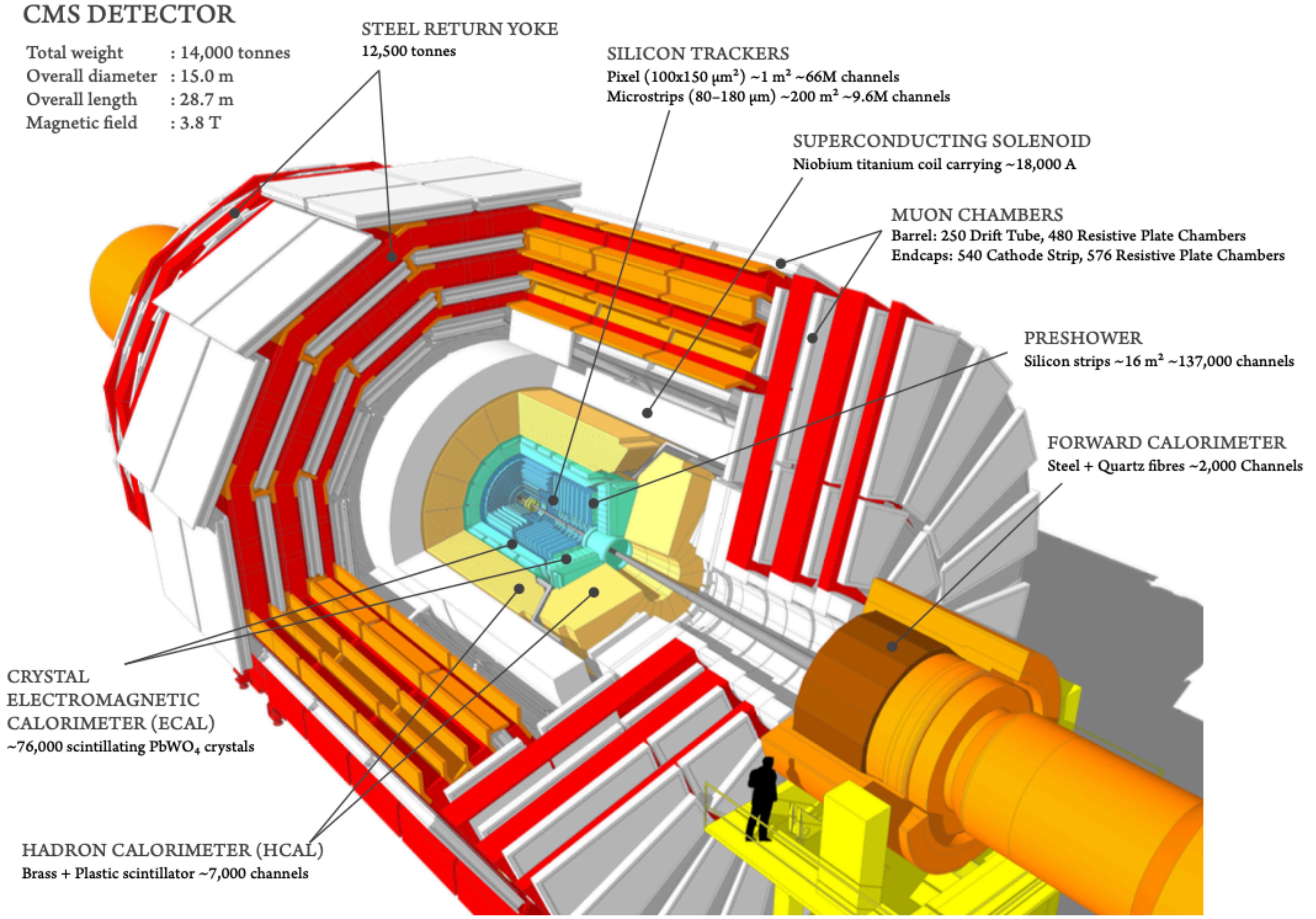
ATLAS

- 25 m diameter and 44 m length
- Over 7000 tons
- O(100) million readout channels

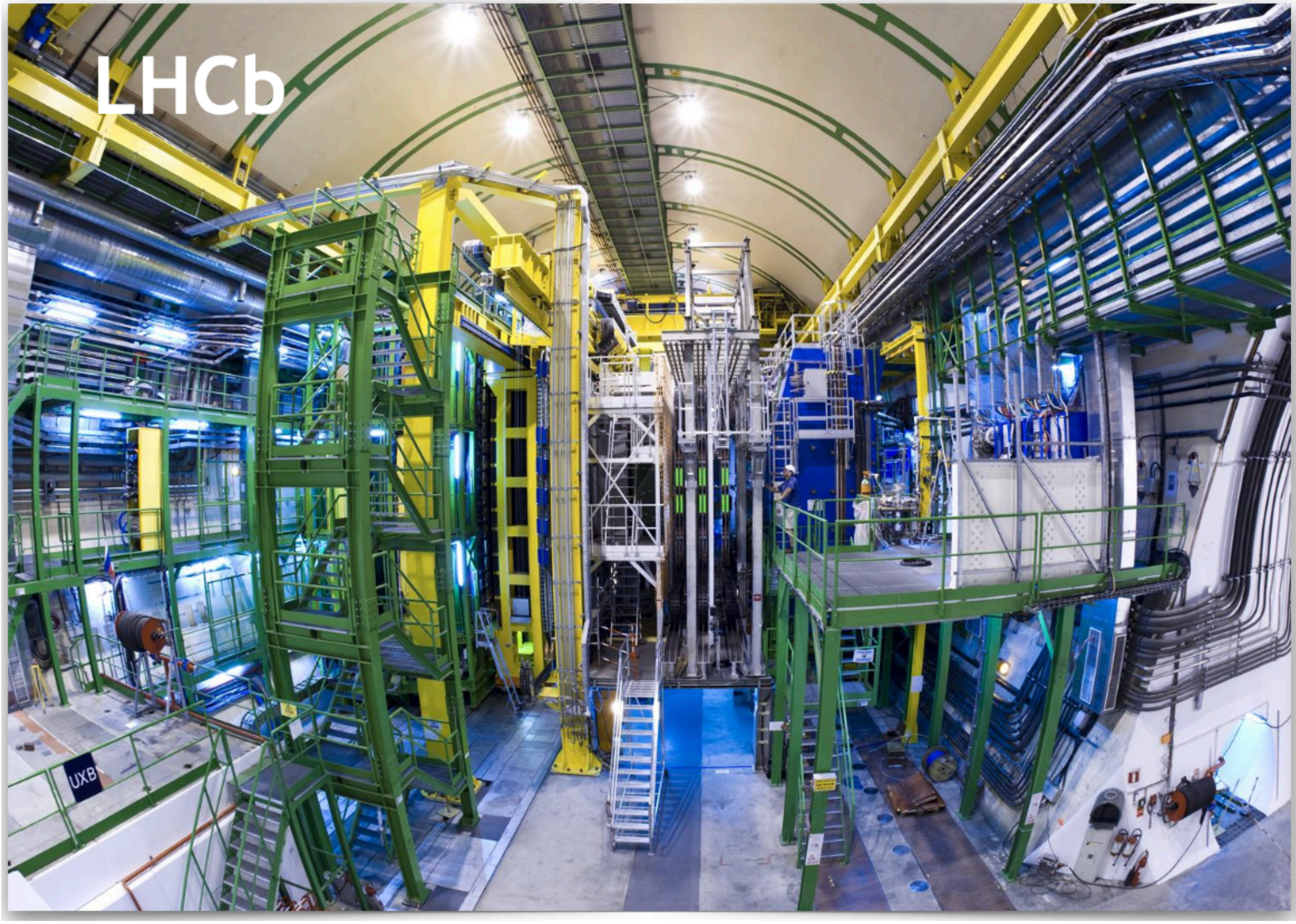
CMS

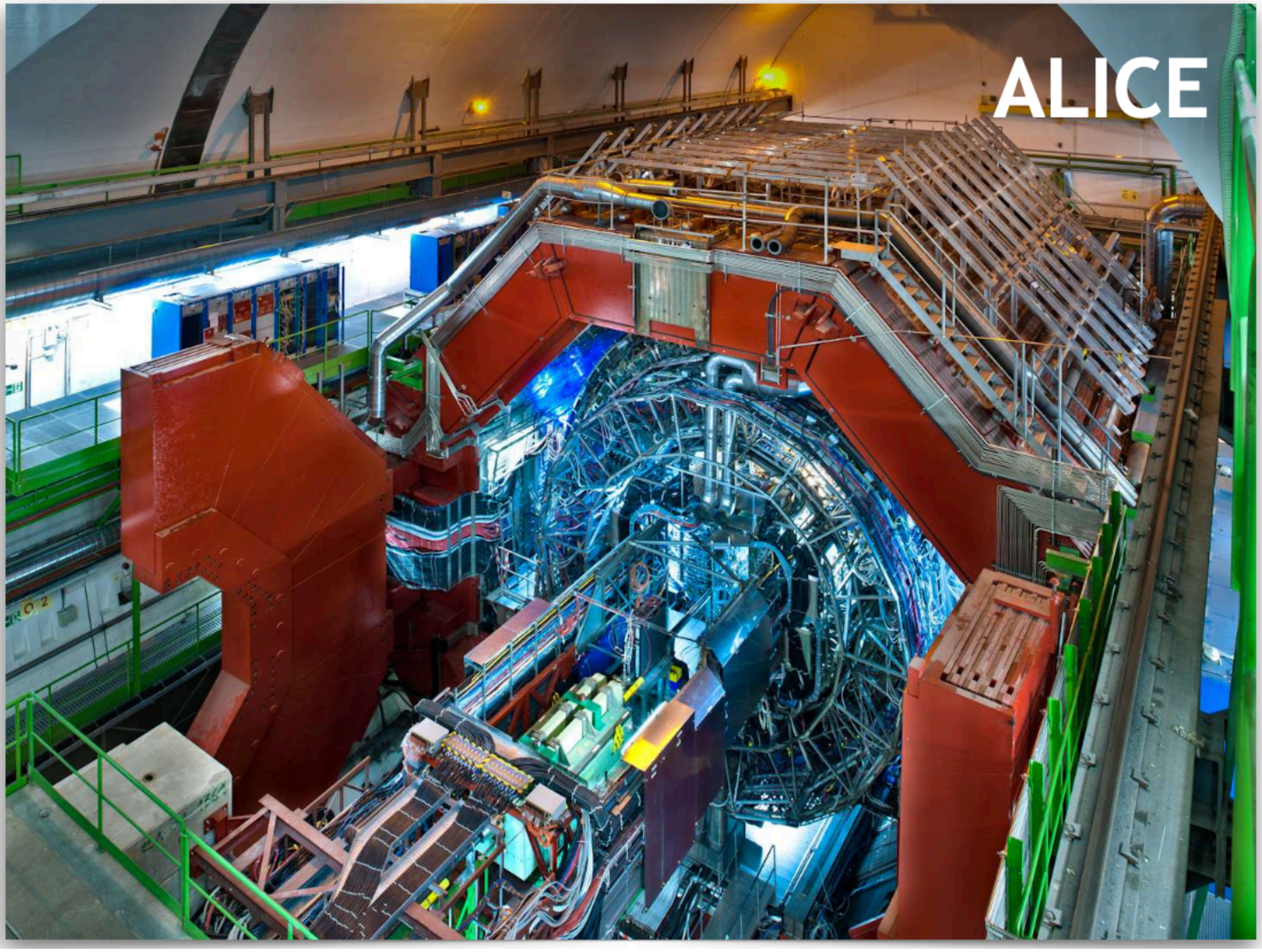
- 15 m diameter and 21 m length
- 14000 tons
- O(75) million readout channels



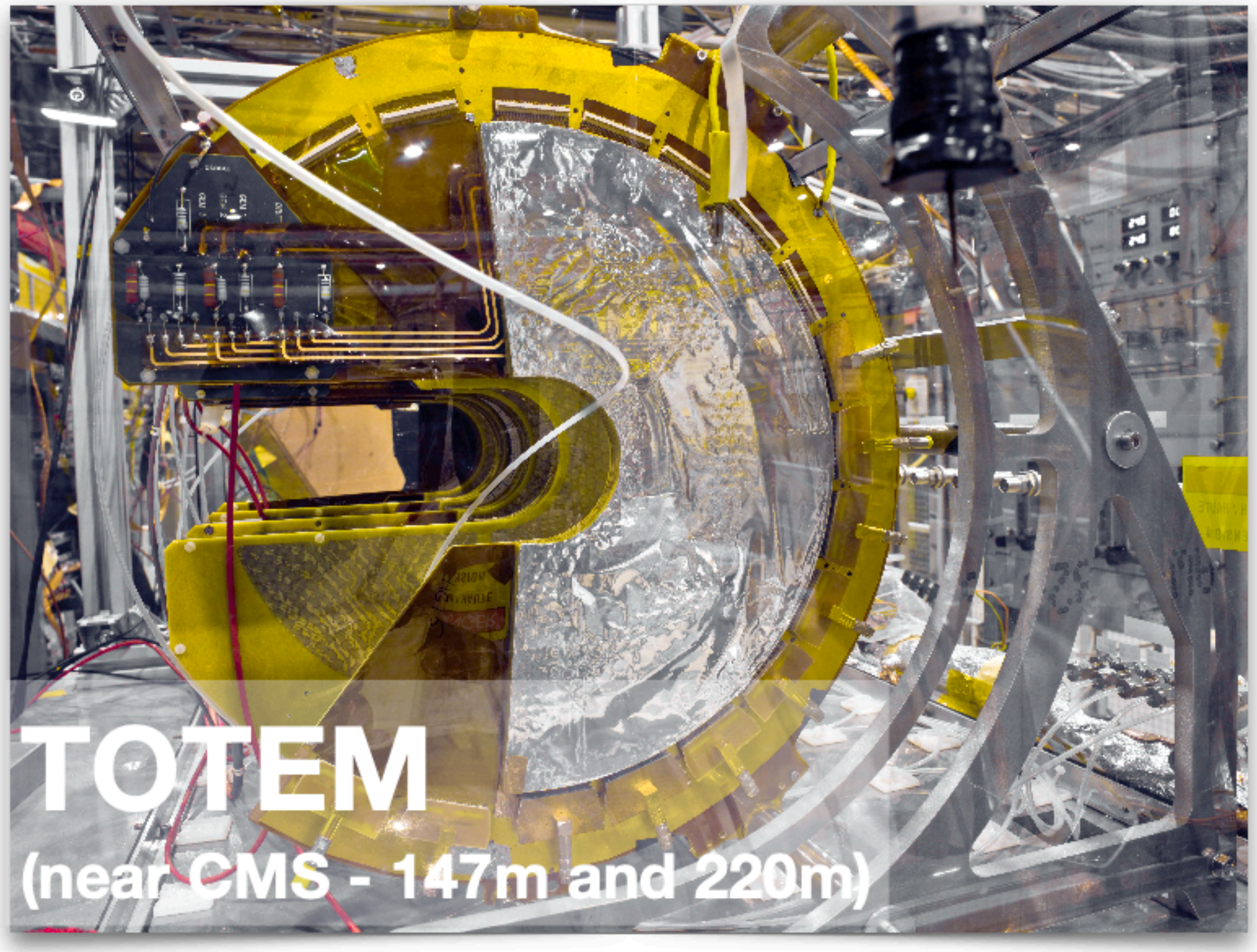


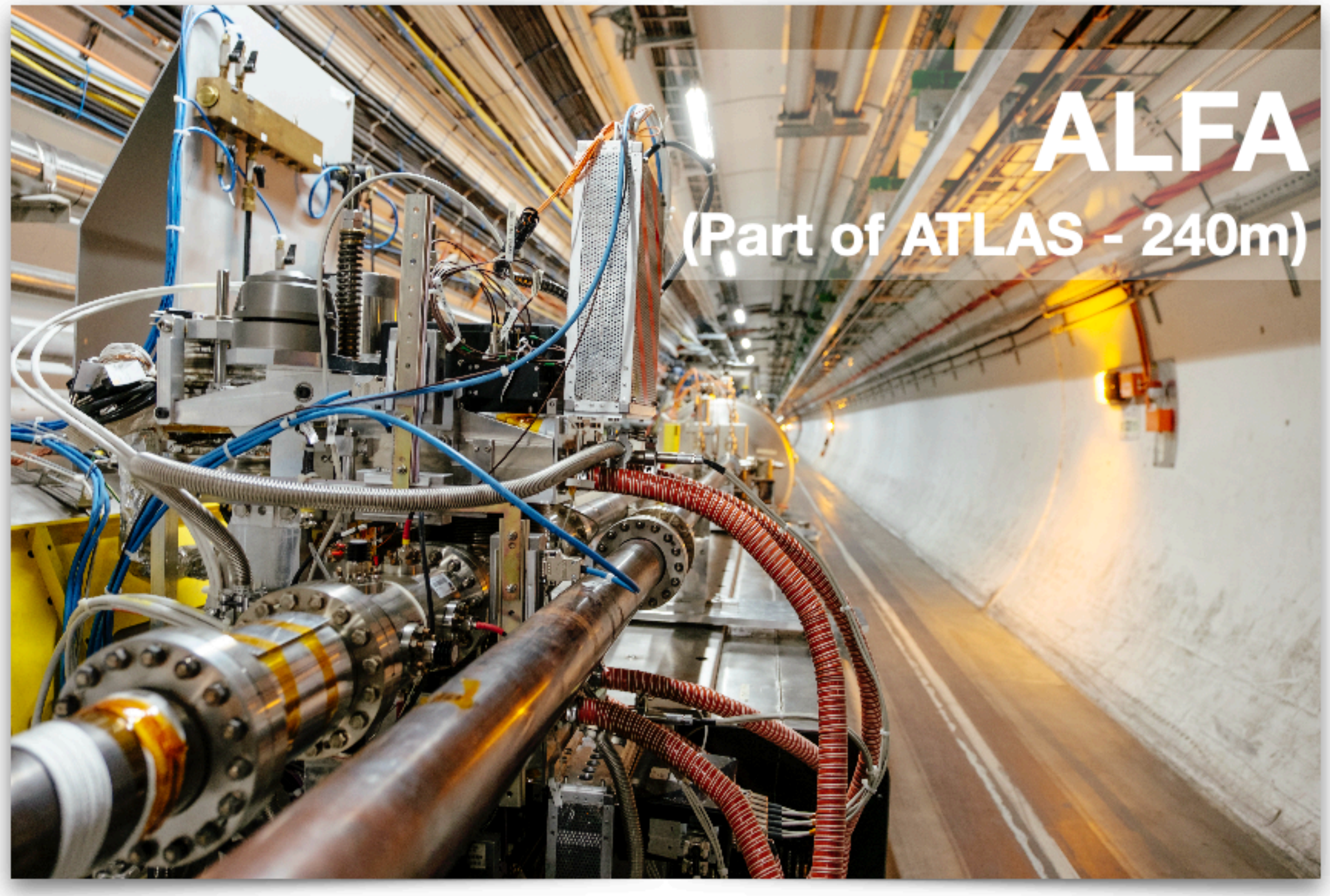
LHC Experiments: Specialized Detectors

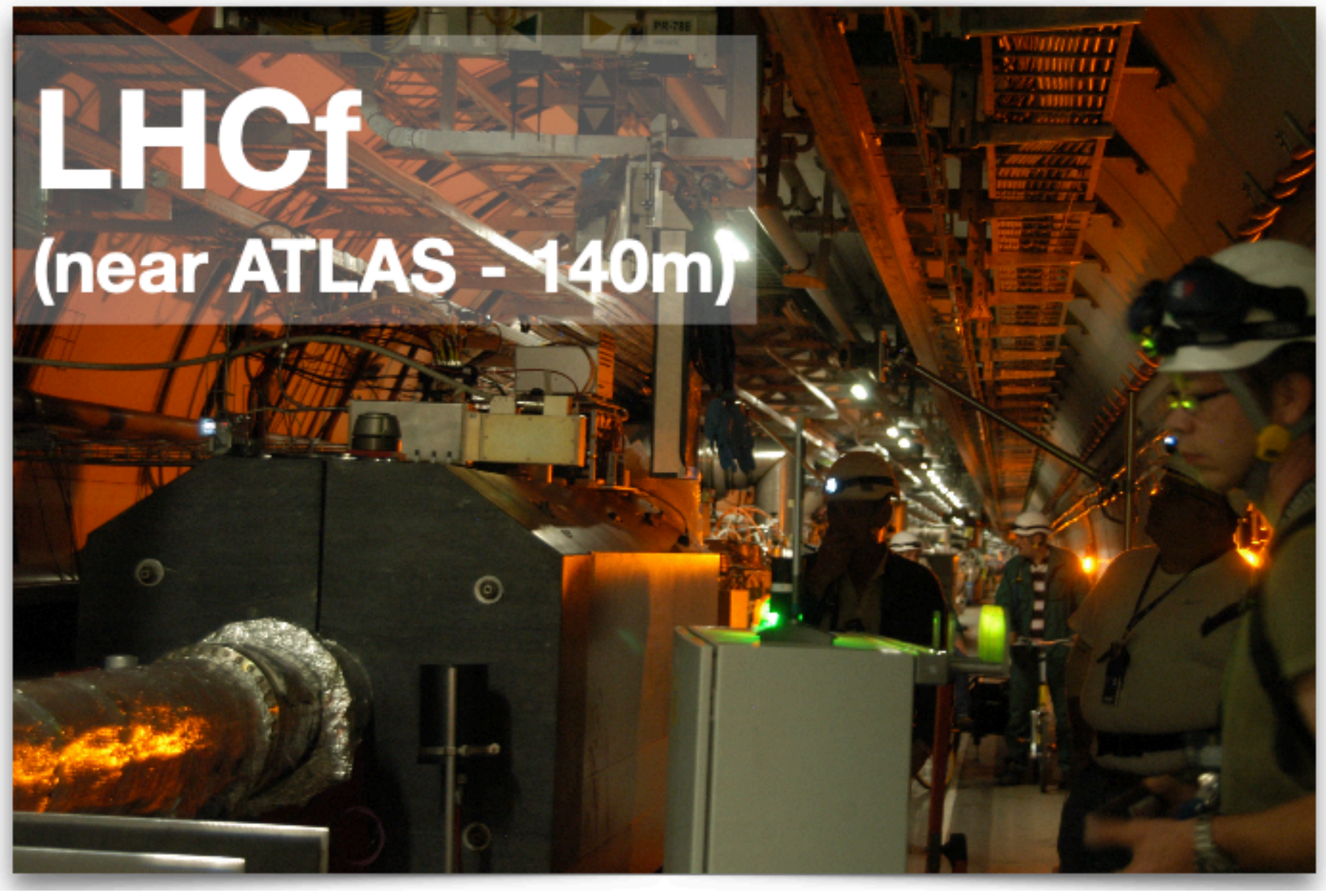


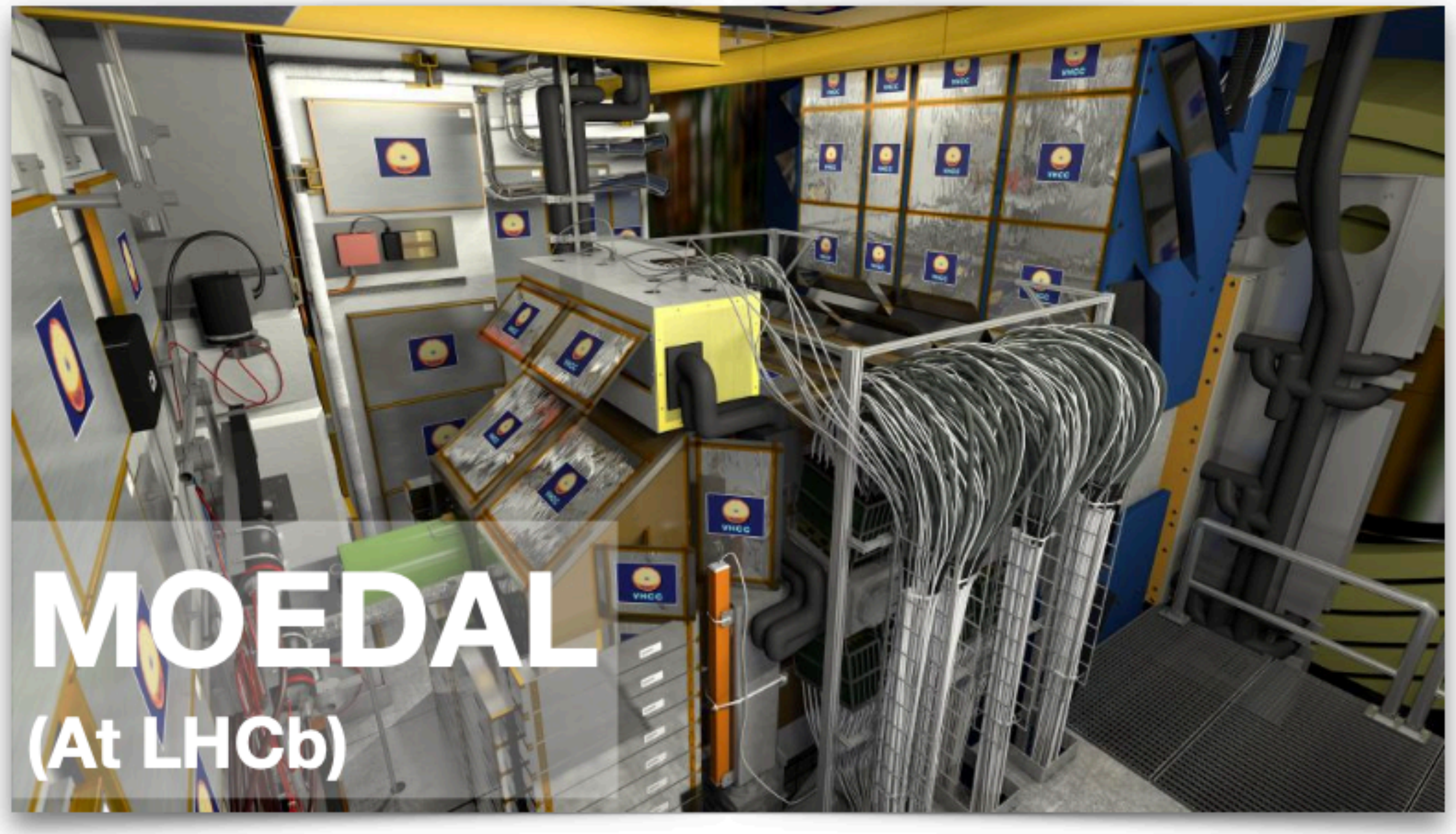


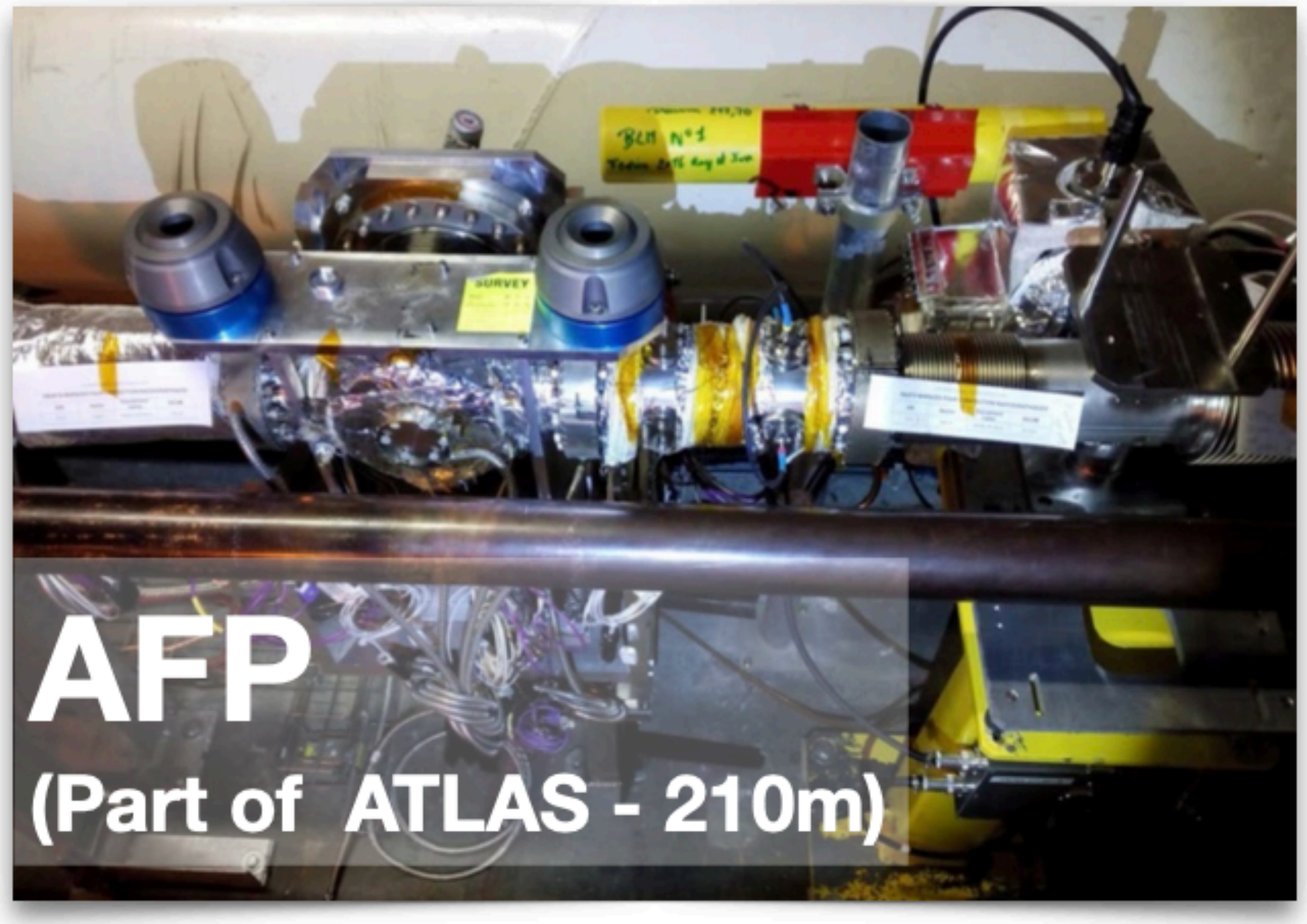
Other even more specialized experiments



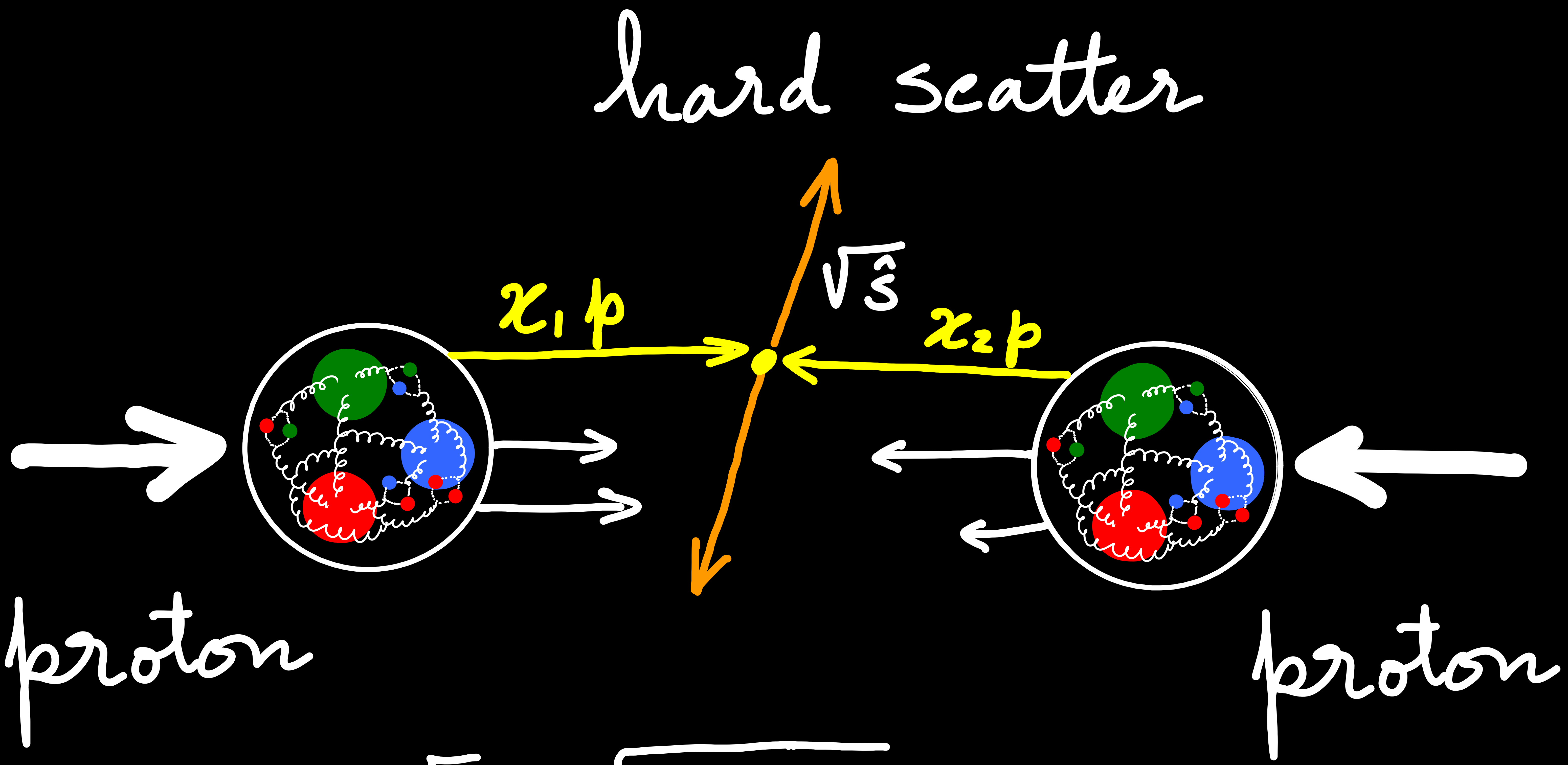




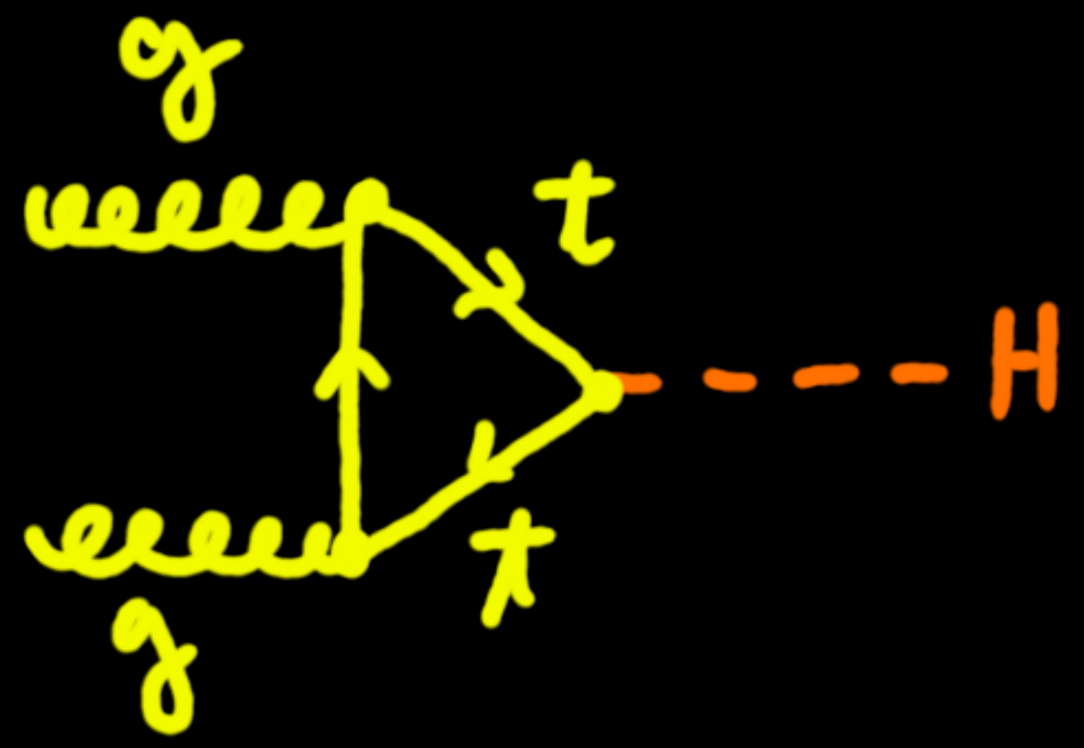




Look into the pp collisions...

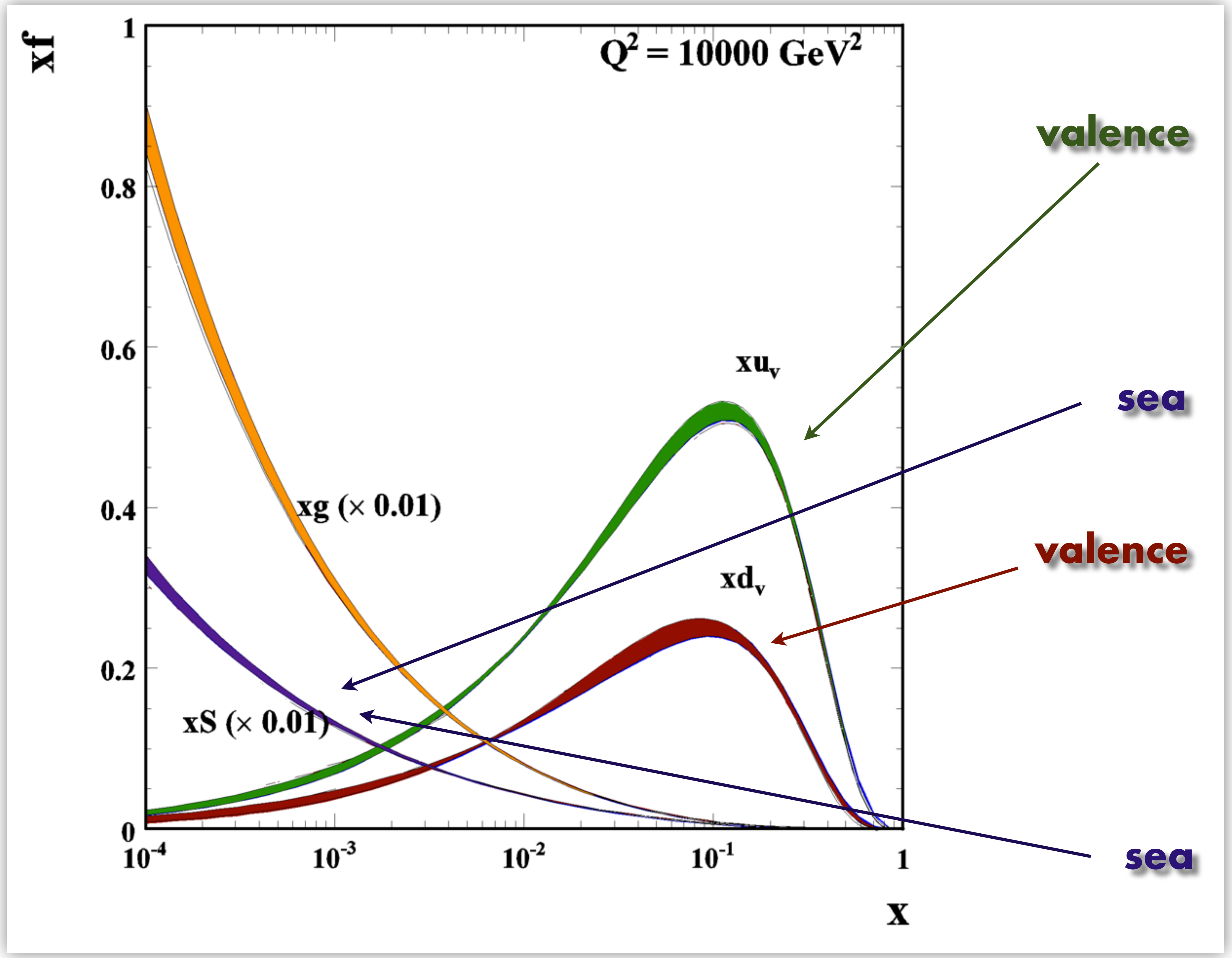


$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$$



Parton Distribution Functions (PDF)

- PDFs give the probability to find a parton with a momentum fraction of x
- PDFs are not calculable, but measured in experiments



PDFs Sum rules

Momentum sum rule

$$\sum_i \int_0^1 dx\, x f_i(x, Q^2) = 1$$

Flavour conservation sum rules

$$\int_0^1 (f_u(x, Q^2) - f_{\overline{u}}(x, Q^2))dx = 2$$

$$\int_0^1 (f_d(x, Q^2) - f_{\overline{d}}(x, Q^2))dx = 1$$

$$\int_0^1 (f_s(x, Q^2) - f_{\overline{s}}(x, Q^2))dx = 0$$

- In a proton, quarks heavier than u,v are only available in the sea

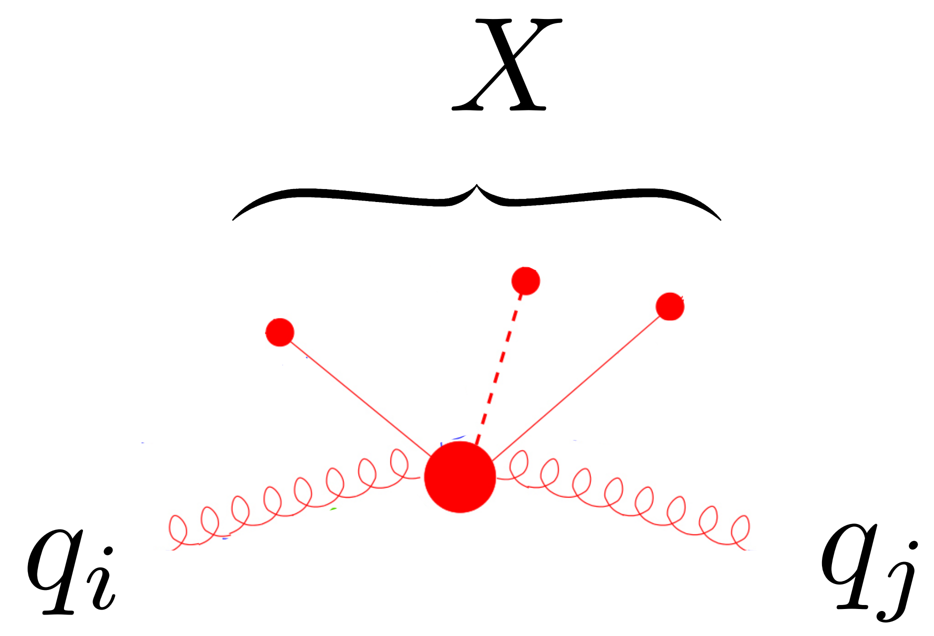
Hadronic Collisions Phenomenology

Truth-level event

$$a(q_i q_j \to X) = a_0 \times (1 + \alpha_S a_1 + \alpha_s^2 a_2 + \alpha_s^3 a_3 + \cdots)$$

$$\alpha_S \sim 0.1$$

α_s - strong coupling



Hard scattering

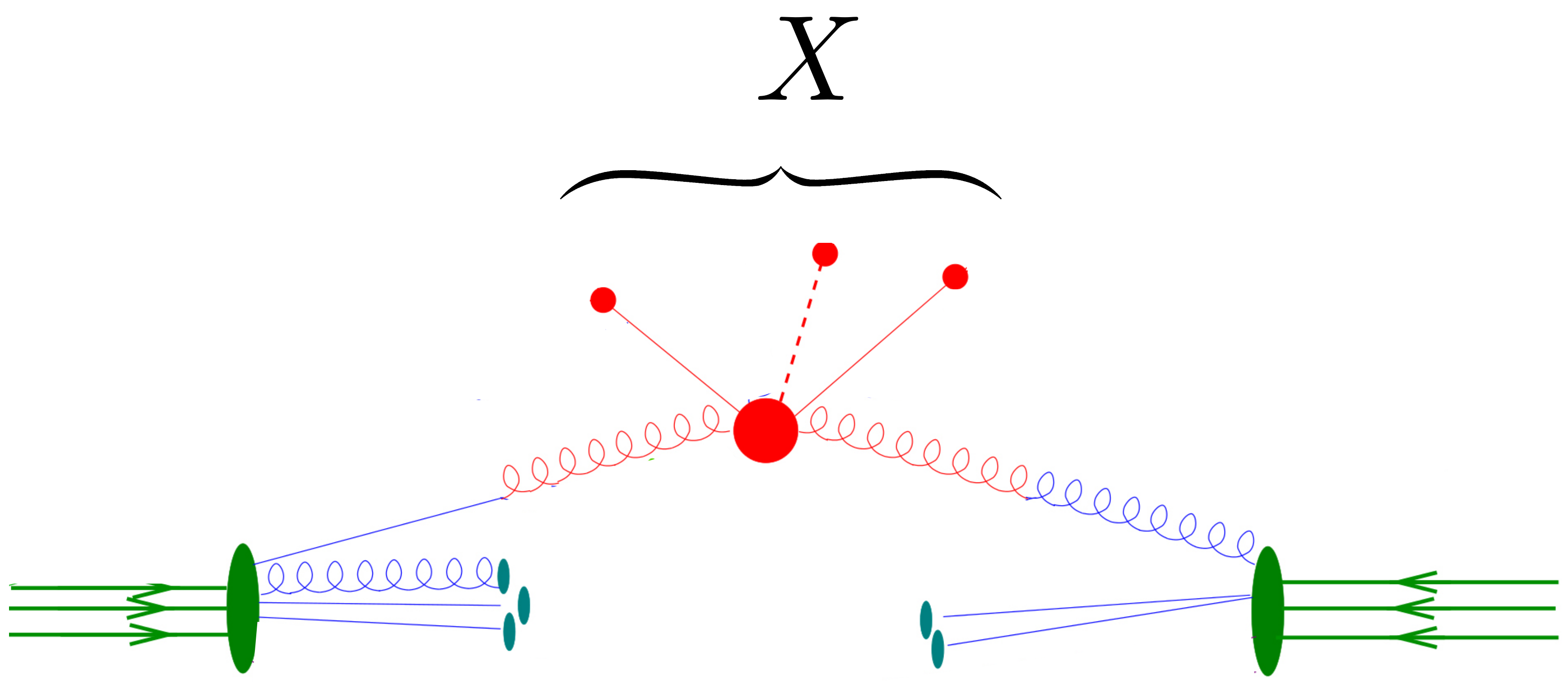
Perturbative regime (with large QCD corrections):
- NLO (now mostly automated)
- NNLO (state-of-the-art that has become standard)
- N3LO possible (with large impact on Higgs results)

Hadronic Collisions Phenomenology

Truth-level event

$$\sigma_W = \Sigma_q \int dx_1 dx_2 f_q(x_1) f_{\bar{q}}(x_2) \times \hat{\sigma}_{q\bar{q}}$$

total x-sec **parton distribution functions** **parton x-sec**



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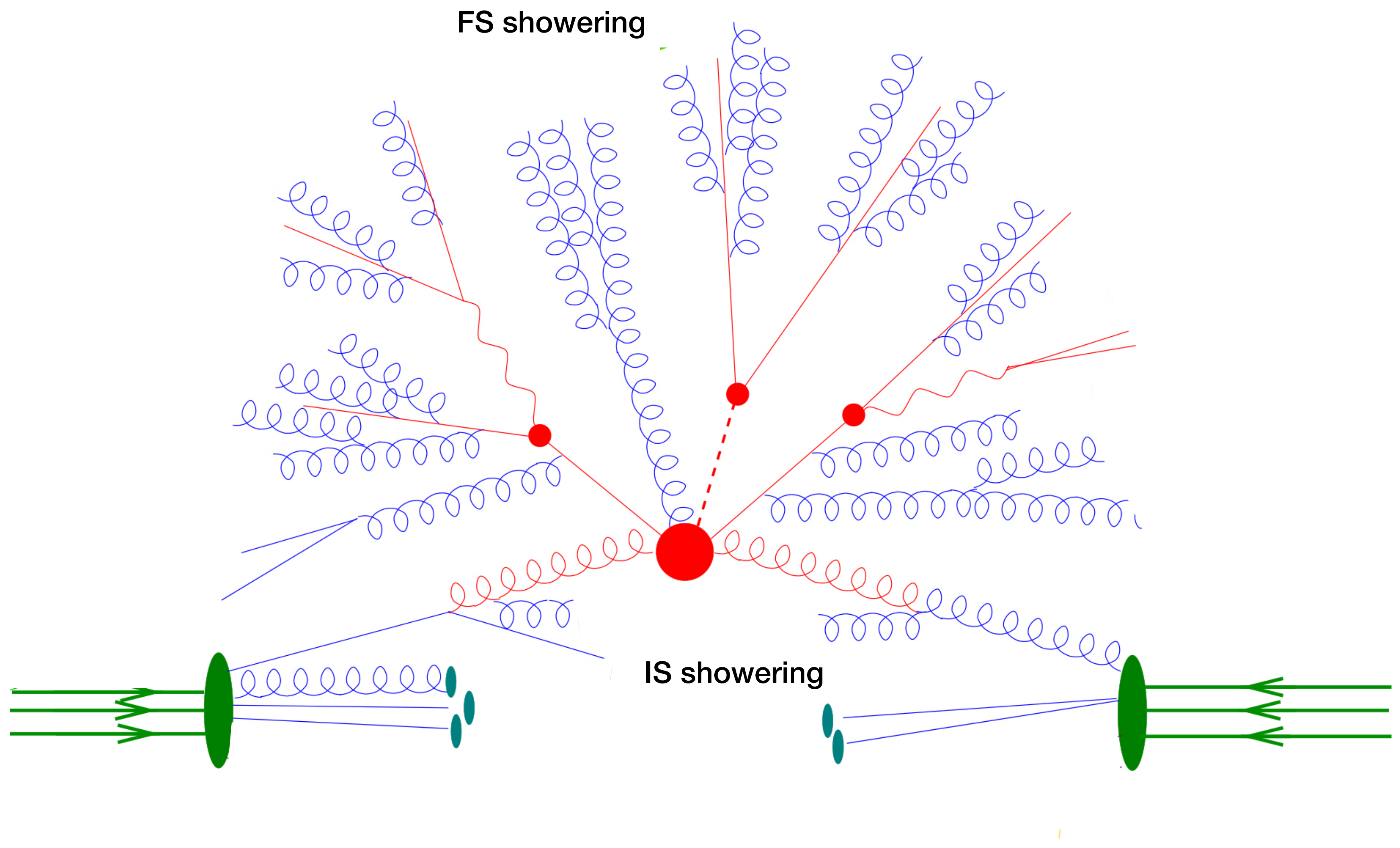

Parton shower
QCD radiation showers not calculable exactly - Approximated in the soft and collinear regime — Pythia/Herwig MC

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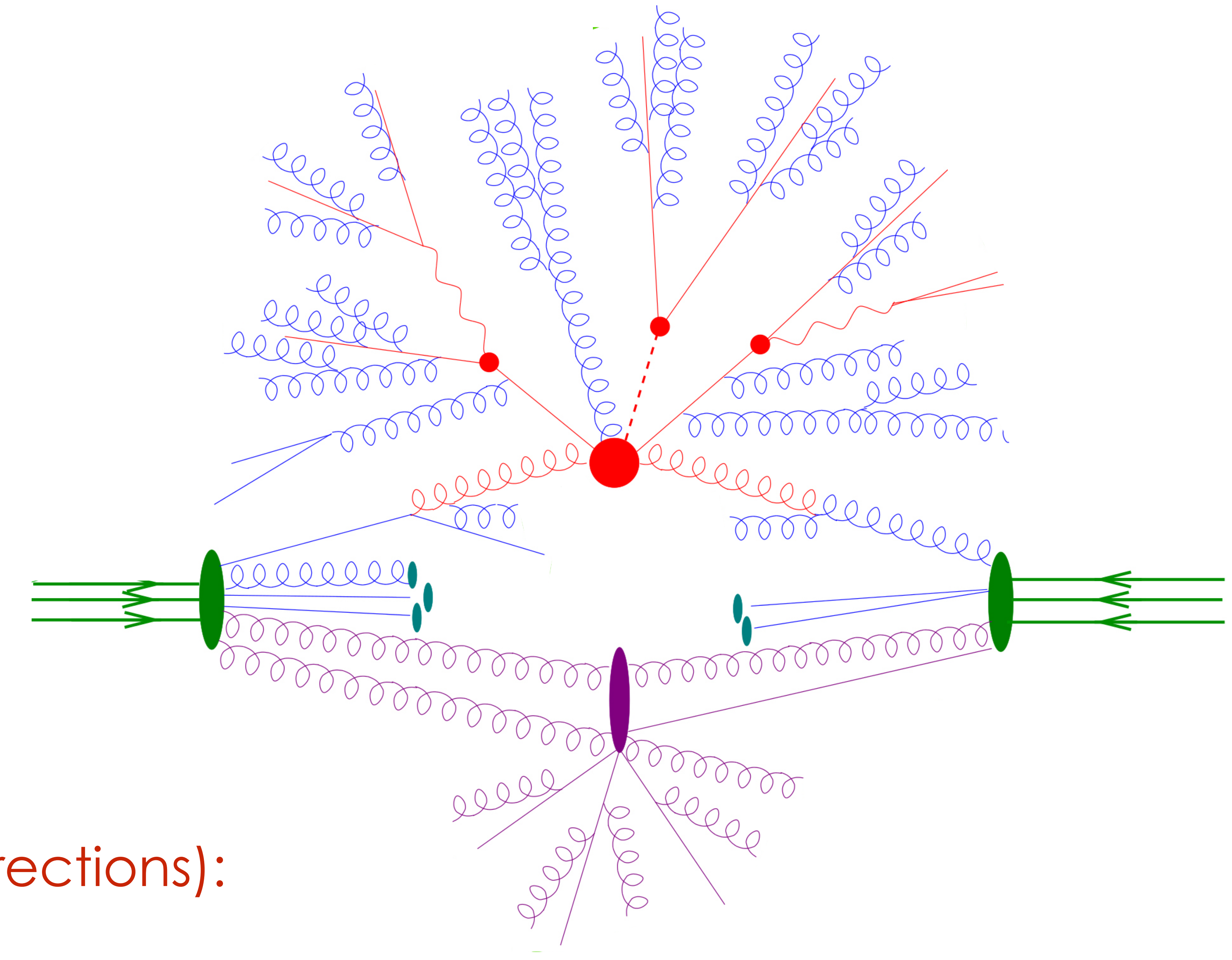

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Multiple parton interactions
Additional interactions between partons of the same protons

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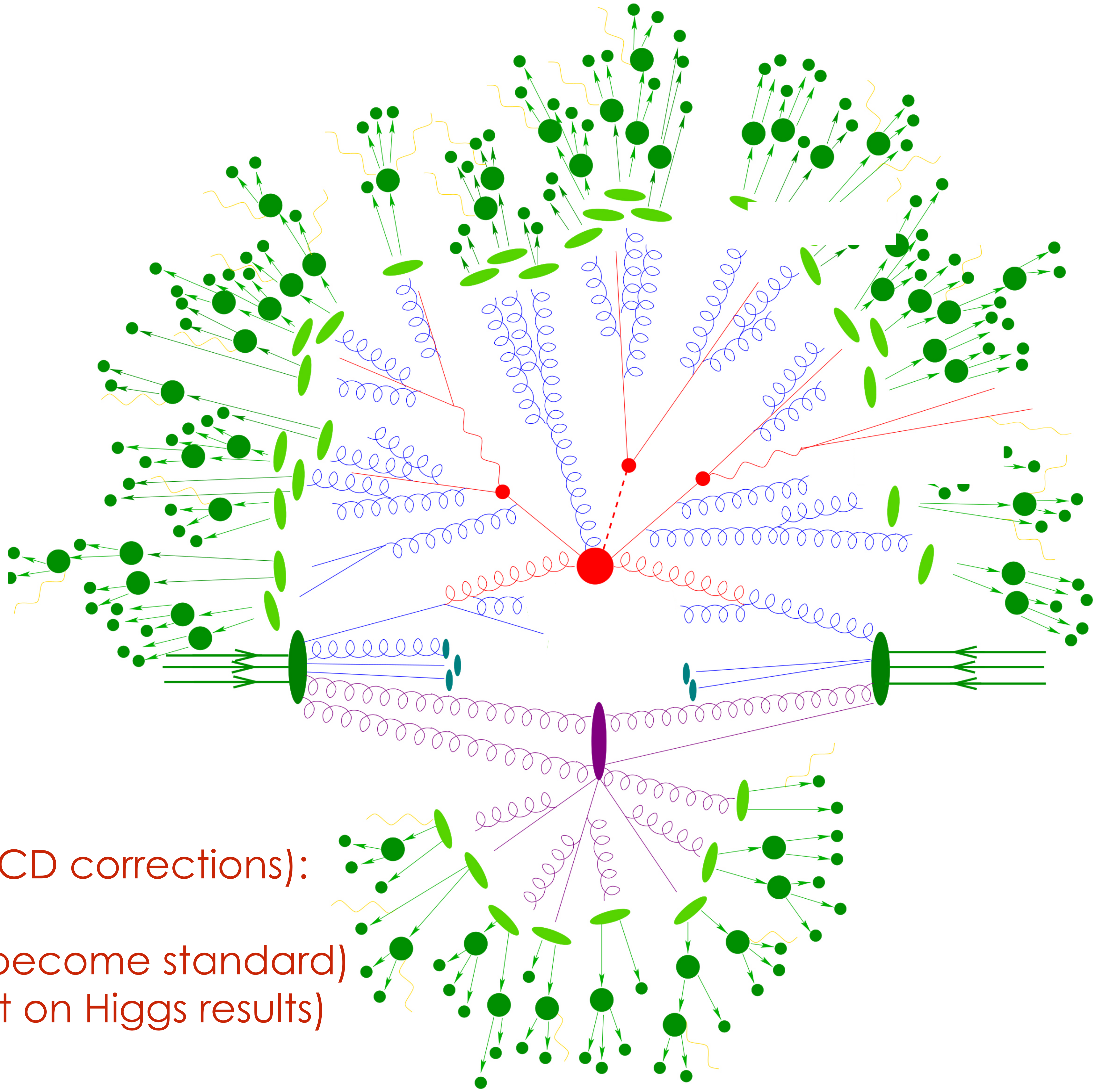
Truth-level event



Picture by Frank Krauss

Hadronization
Pythia, Herwig, Sherpa MC

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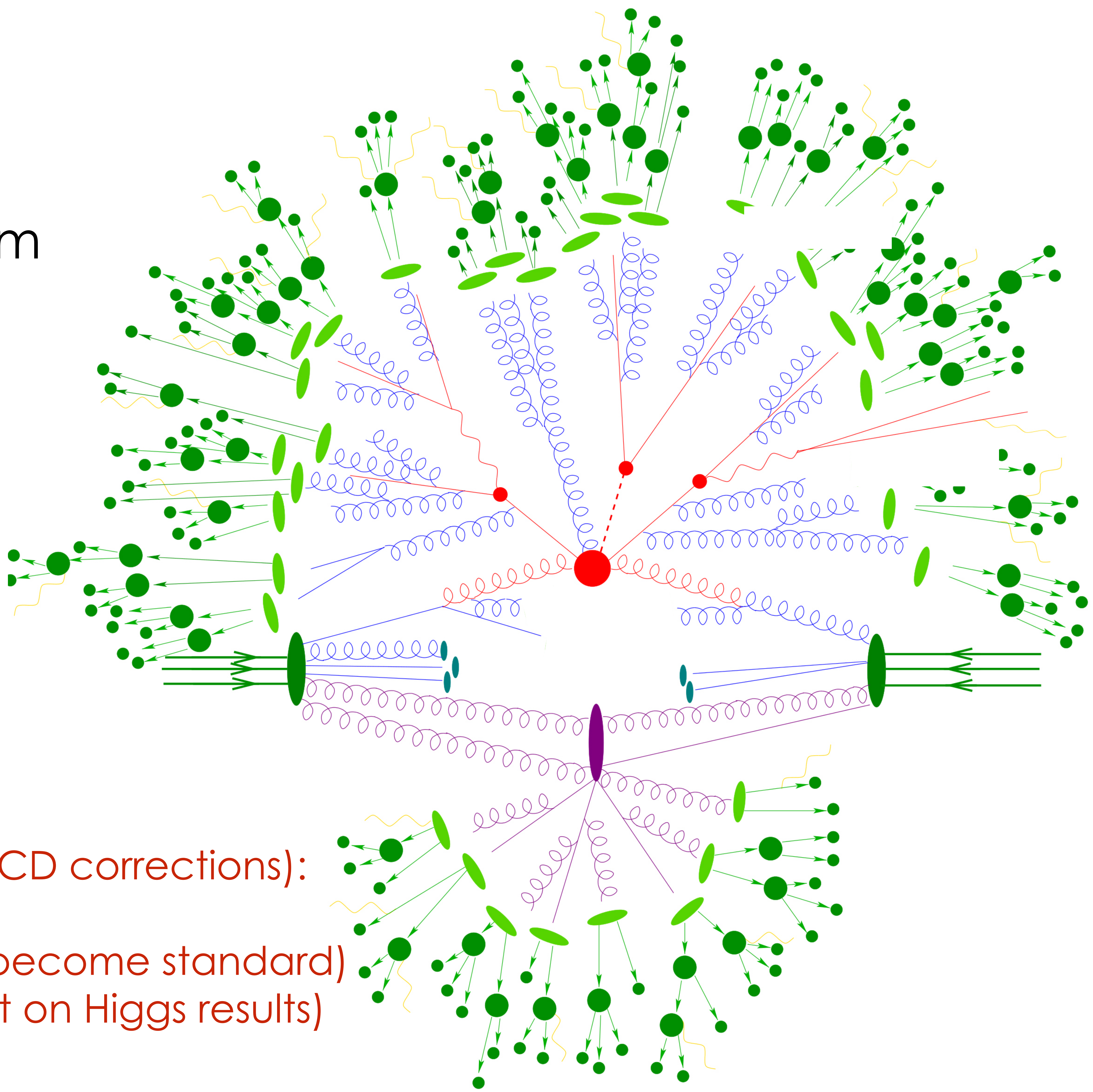
Hadronic Collisions Phenomenology

Truth-level event

Next
- Hadron decays
- Additional collisions from other protons (pile-up)

Reconstruction



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Picture by Frank Krauss

Luminosity

Number of collisions that can be produced in a detector **per cm² and per second**

Number of protons per bunch
1.2×10^{11}

Number of bunches
1400

Number of turns per second
11245

$$\mathcal{L}_p = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y}$$

Beam size at interaction point (IP)
~20-25 µm radius

$$N_{ev} = \int \mathcal{L}_p \, dt \times \sigma(pp \to X)$$

High-Luminosity LHC Plan

HL-LHC goal is deliver 3000 fb^{-1} in 10 years

- **Implies integrated luminosity of 250-300 fb^{-1} per year**
- **Requires peak luminosities of 5-7x10^{34} cm^{-2}s^{-1} while using luminosity leveling (3-5 hours at peak luminosity)**

Design for "ultimate" performance 7.5x10^{34} cm^{-2}s^{-1} and 4000 fb^{-1}

Hadron collisions - Luminosity

$$\mathcal{L} = \frac{N_p^2 f}{4\pi\sigma_x\sigma_y} \rightarrow \frac{N_p^2 f k_b}{4\pi\sigma_x\sigma_y} \rightarrow \frac{N_p^2 f k_b \gamma}{4\pi\beta^*\varepsilon_N} \rightarrow \frac{N_p^2 f k_b \gamma}{4\pi\beta^*\varepsilon_N} F$$

Luminosity for several bunches kb in trains

Beam size expressed in beam parameters, dependence in beam energy!

Correction due to geometrical effects (e.g. beam crossing angle)

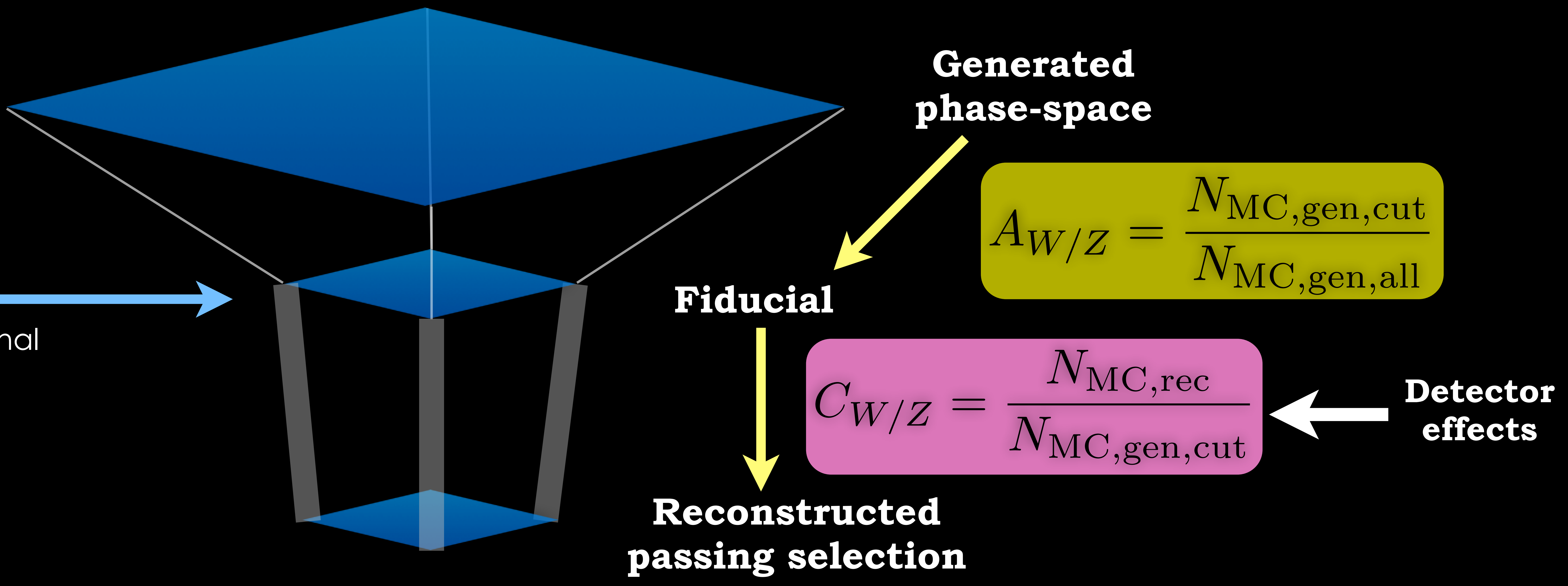
Luminosity grows with energy!

Emittance (fixed at injection)

Beta* Focussing

Parameter	2010	2011	2012	2016	2017	2018	Nominal	HL-LHC
CoM Energy	7 TeV	7 TeV	8 TeV	13 TeV	13 TeV	13 TeV	14 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.2 10^{11}	1.2 10^{11}	1.2 10^{11}	1.15 10^{11}	2.2 10^{11}
Bunches k	368	1380	1380	2300	2450	2500	2808	2760
Spacing	150 ns	50 ns	50 ns	25 ns	25 ns	25 ns	25 ns	25ns
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	2.3	2.6	3.75	2.5
β* (m)	3.5	1.5-1	0.6	0.4	0.3-0.4	0.4	0.55	0.15
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	~7×10^{33}	1.5×10^{33}	2.0×10^{34}	2×10^{34}	10^{34}	8×10^{34}
PU	~2	~10	~30	~30	~50	~50	~25	~130

Fiducial volume and acceptance



$$A_{W/Z} = \frac{N_{\mathrm{MC,gen,cut}}}{N_{\mathrm{MC,gen,all}}}$$

$$C_{W/Z} = \frac{N_{\mathrm{MC,rec}}}{N_{\mathrm{MC,gen,cut}}}$$

Fiducial volume:
phase space in which a given final state is measured (can include other than geometrical cuts)

Fiducial cross section

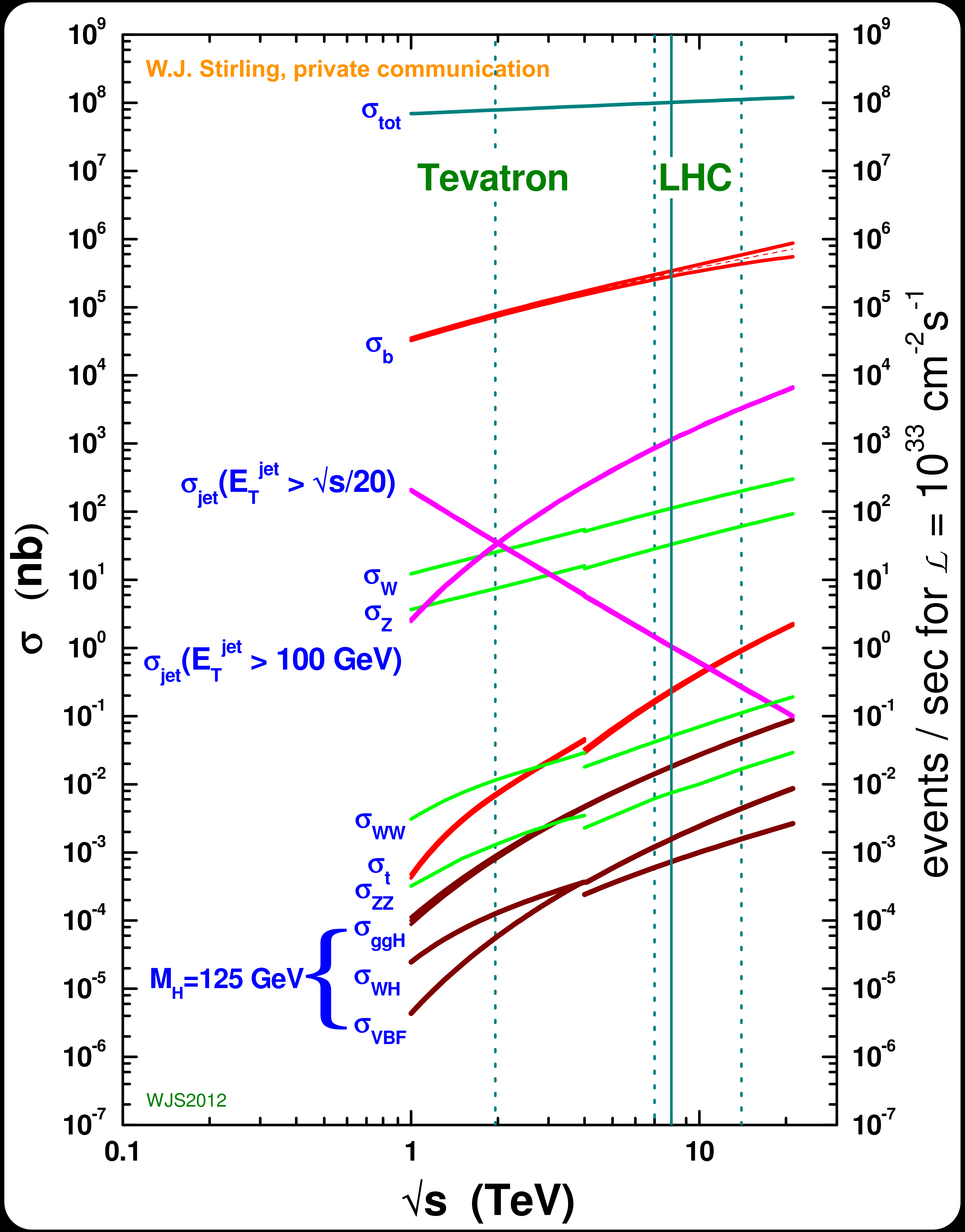
$$\sigma_{\mathrm{fid}} = \frac{N - B}{C_{W/Z} \cdot L_{\mathrm{int}}}$$

No theoretical uncertainty from extrapolation outside experimental acceptance

Total cross section

$$\sigma_{\mathrm{tot}} = \sigma_{W/Z} \times BR(W/Z \to \ell\nu/\ell\ell) = \frac{\sigma_{\mathrm{fid}}}{A_{W/Z}}$$

The total cross section at hadron collider



Total cross section: 100 mb

Nominal LHC Luminosity

$2 \times 10^{34}\ cm^{-2}\ s^{-1}$

Number of events produced:

σ x L =

$100 \times 10^{-27}\ (cm^2) \times 2 \times 10^{34}\ cm^{-2}\ s^{-1}$

~ 2×10^9 events/sec

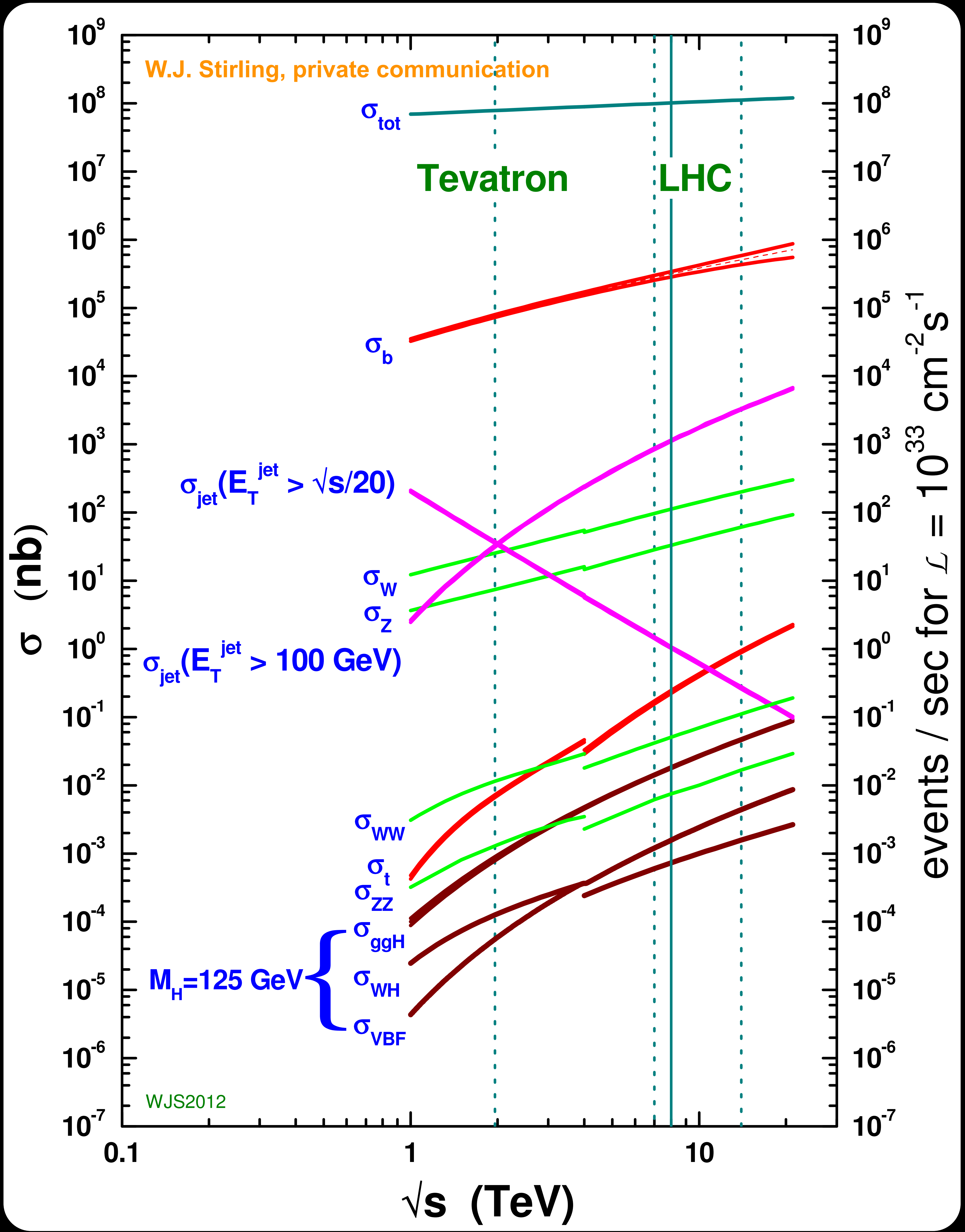
Production rates at Hadron Colliders

Tevatron timeline

(*) **W**: 1988
Z: 1988

Top: 1994
WW: 2005
WZ: 2007
ZZ: 2008

(*) Discovered at CERN in 1983 by UA1 and UA2



LHC timeline

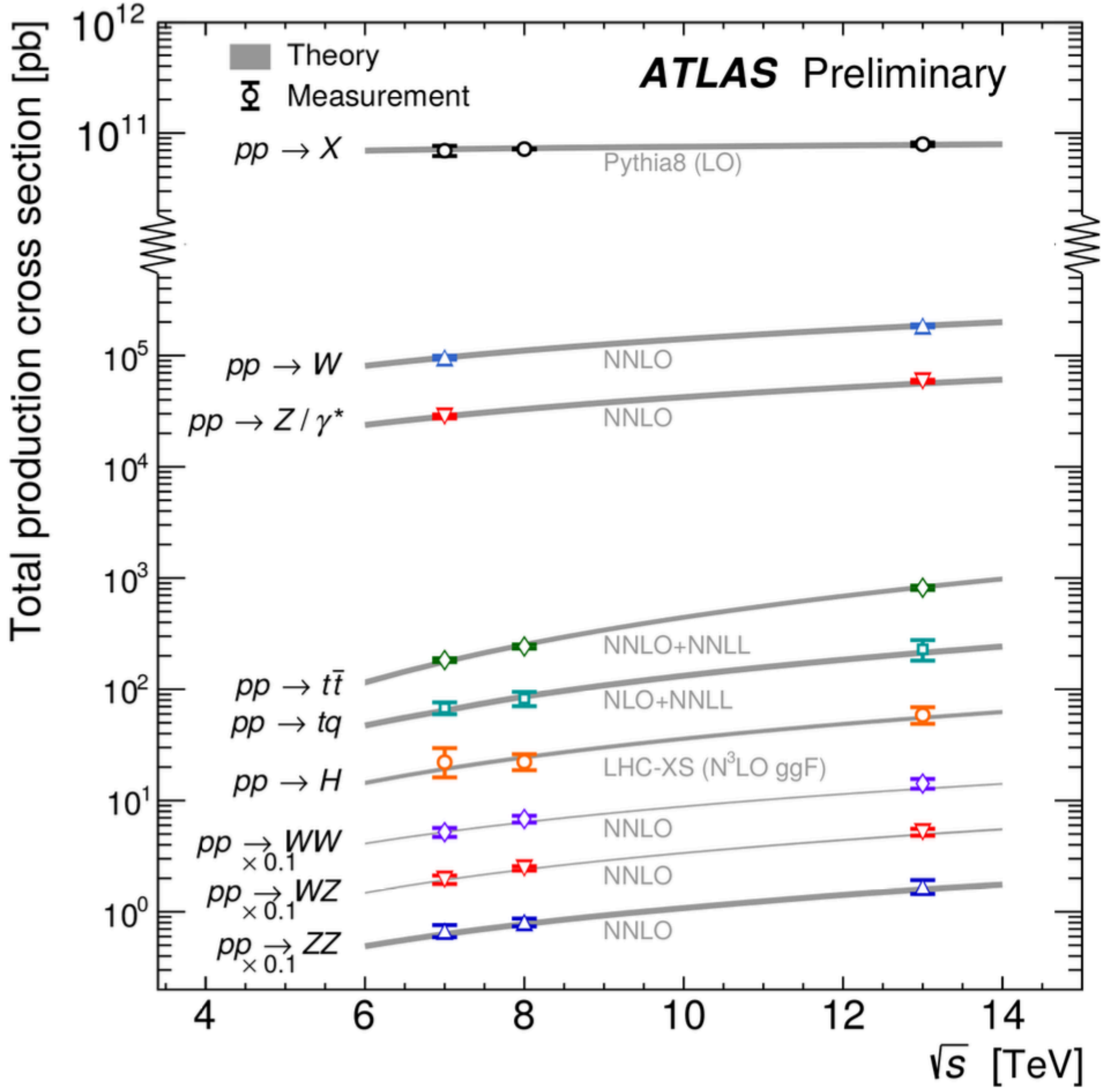
W: May 2010
Z: Jun 2010

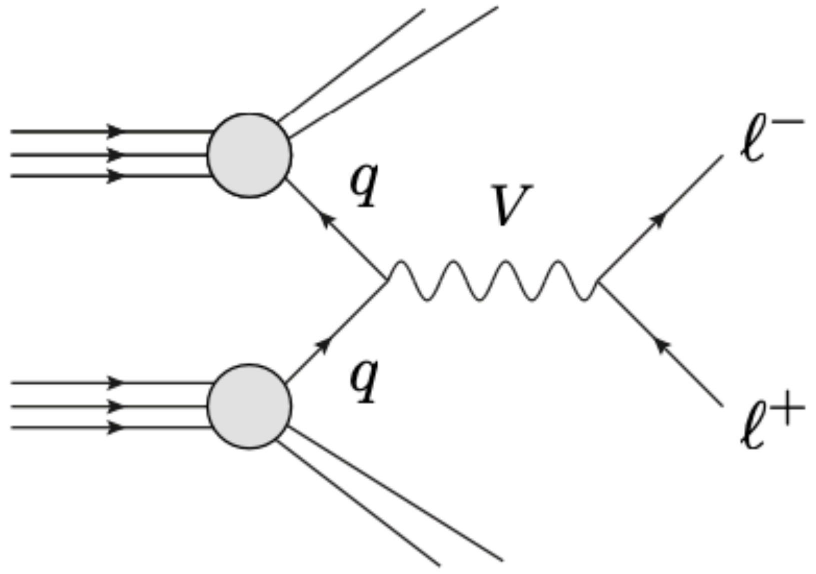
Top: Jul 2010

WW: Dec 2010
WZ: Mar 2011
ZZ: Jul 2011

H: July 4, 2012

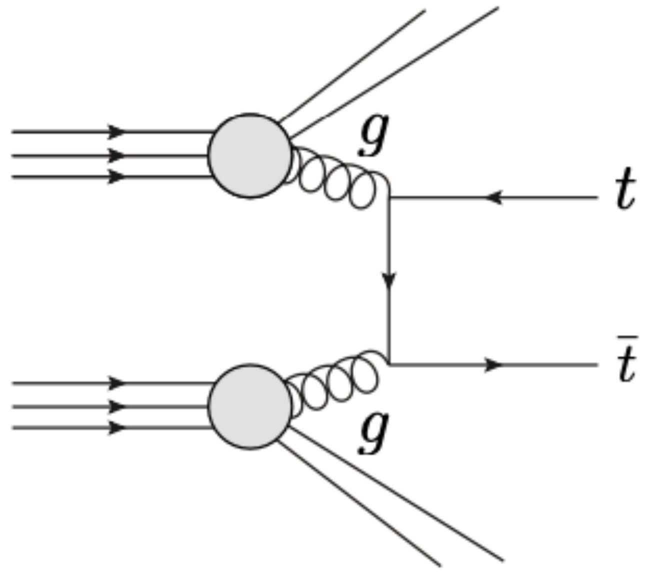
Total cross sections at LHC





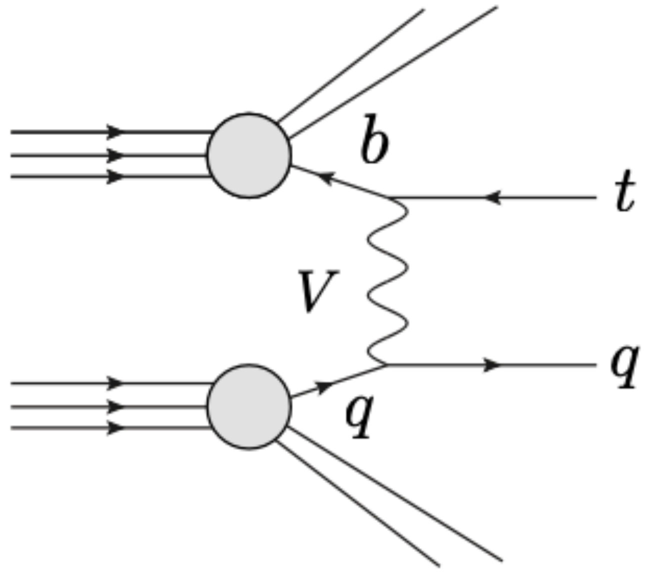
Vector boson production (often referred to as Drell Yan).

LEP ~4 M Z per experiment
LHC ~100 M (leptonic) / exp.
(for 100 fb^{-1})



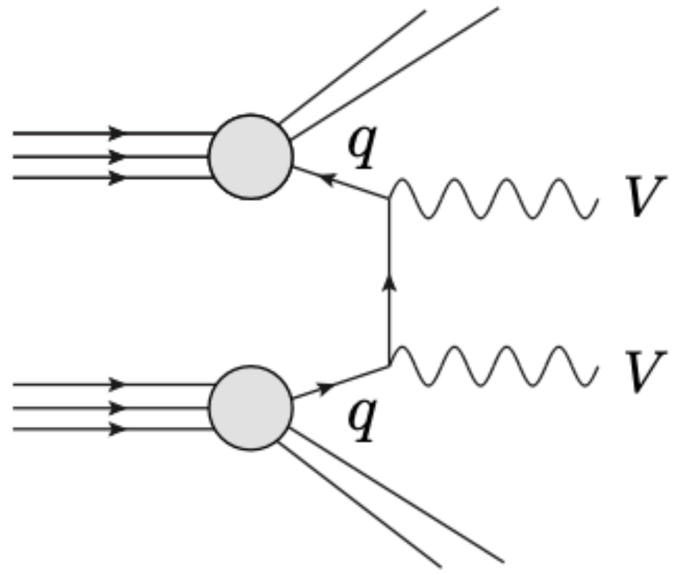
Top pair production

$t\bar{t} \sim 1\,\mathrm{nb}$



Single top production

$tq \sim 200\,\mathrm{pb}$

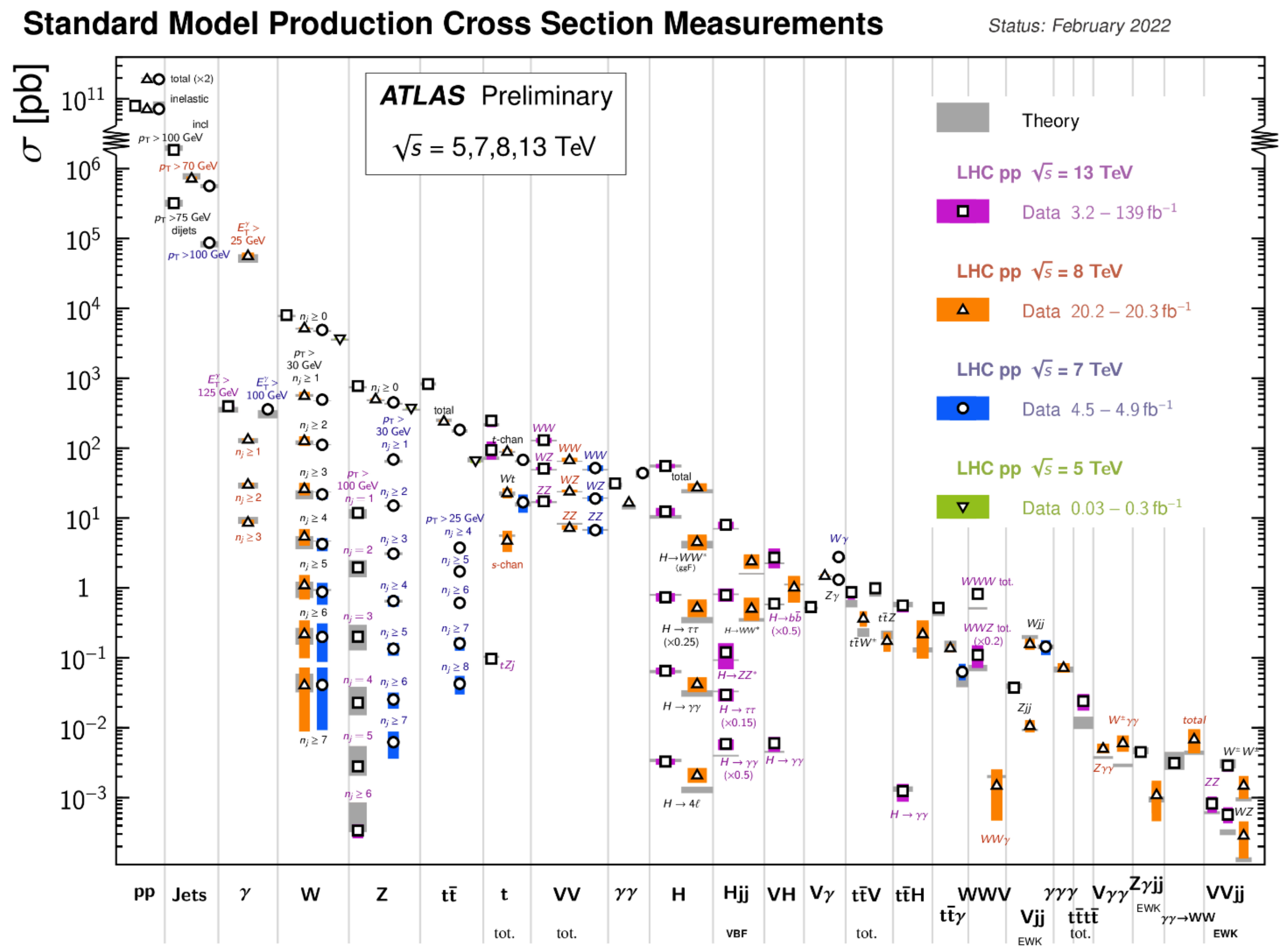


Diboson production

$WW \sim 100\,\mathrm{pb}$

$ZZ \sim 20\,\mathrm{pb}$

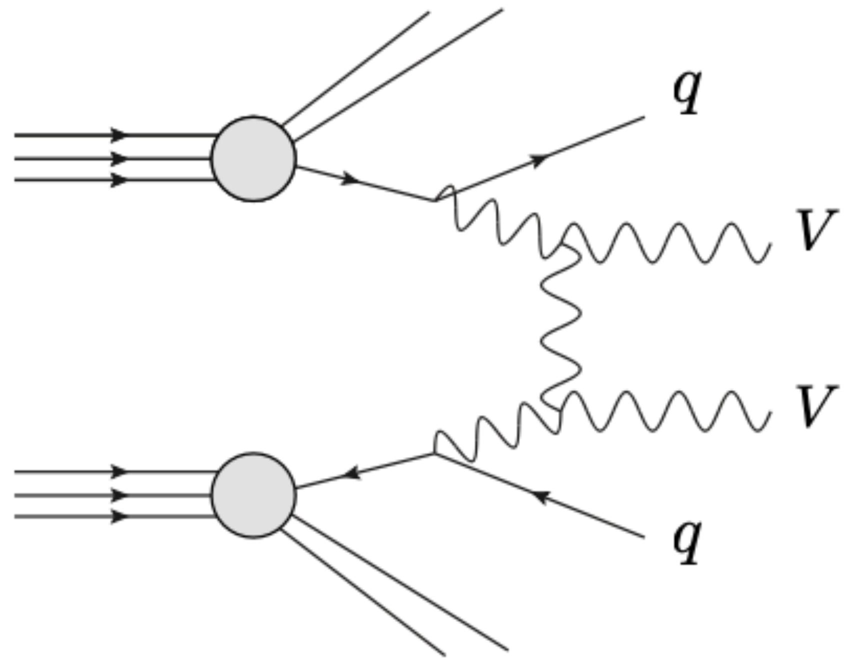
Fiducial cross sections at LHC



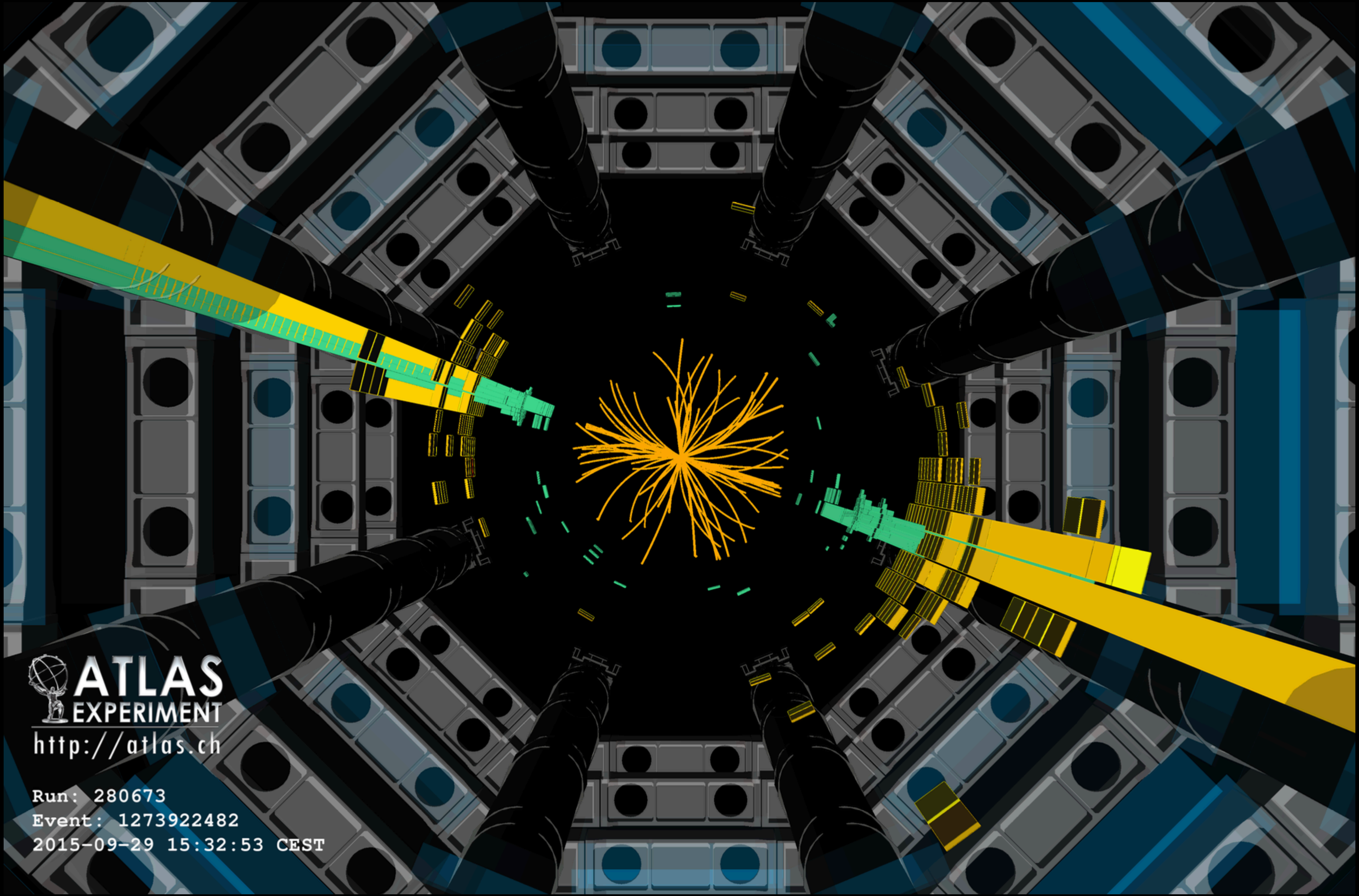
Very large number of fiducial cross section measurement made at the LHC

Down to processes as rare as three boson production

Now measured VBS diboson production (VVjj)

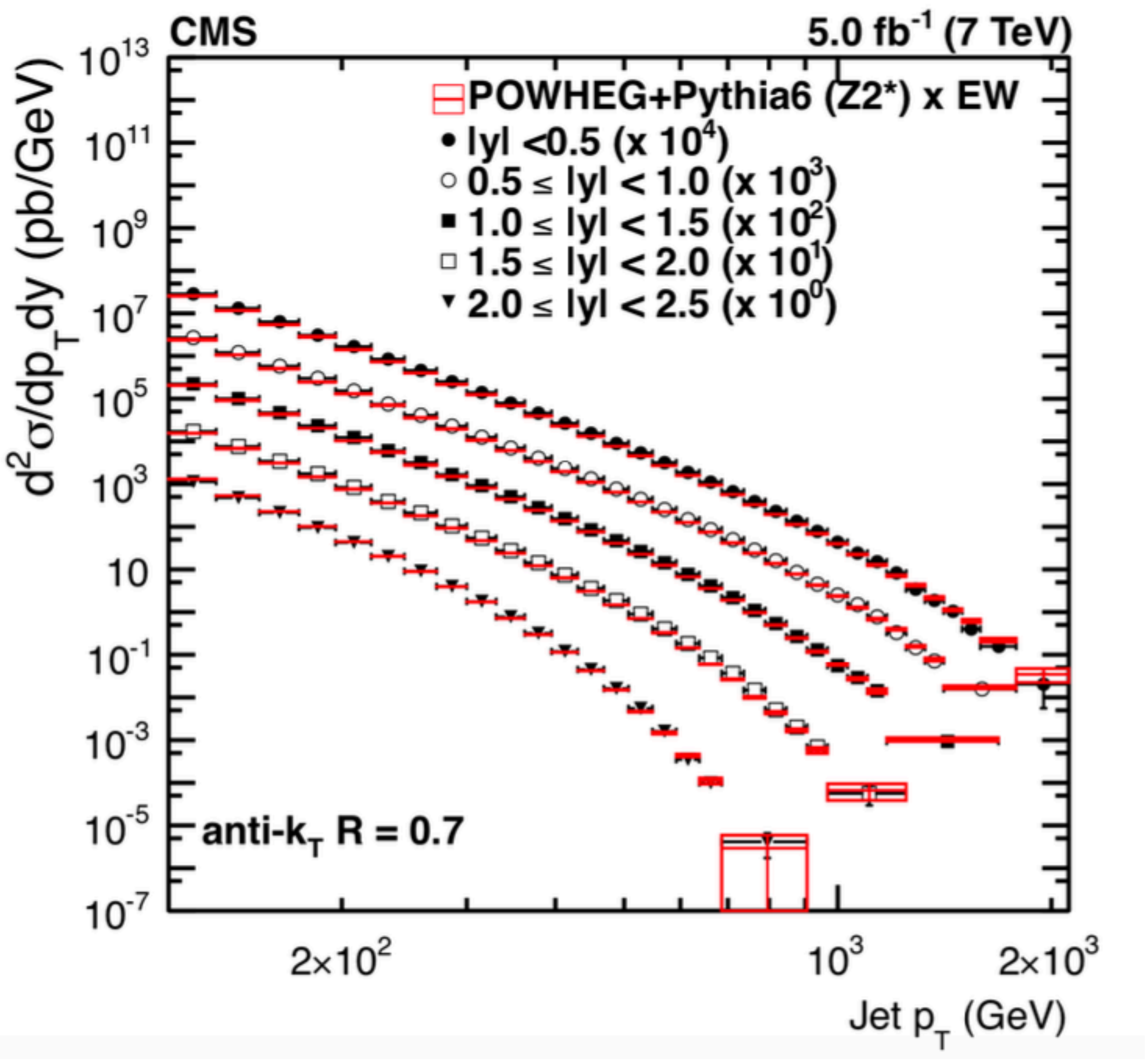


Jet cross sections



Differential jet production cross sections

Example: Double differential jet cross section measurement



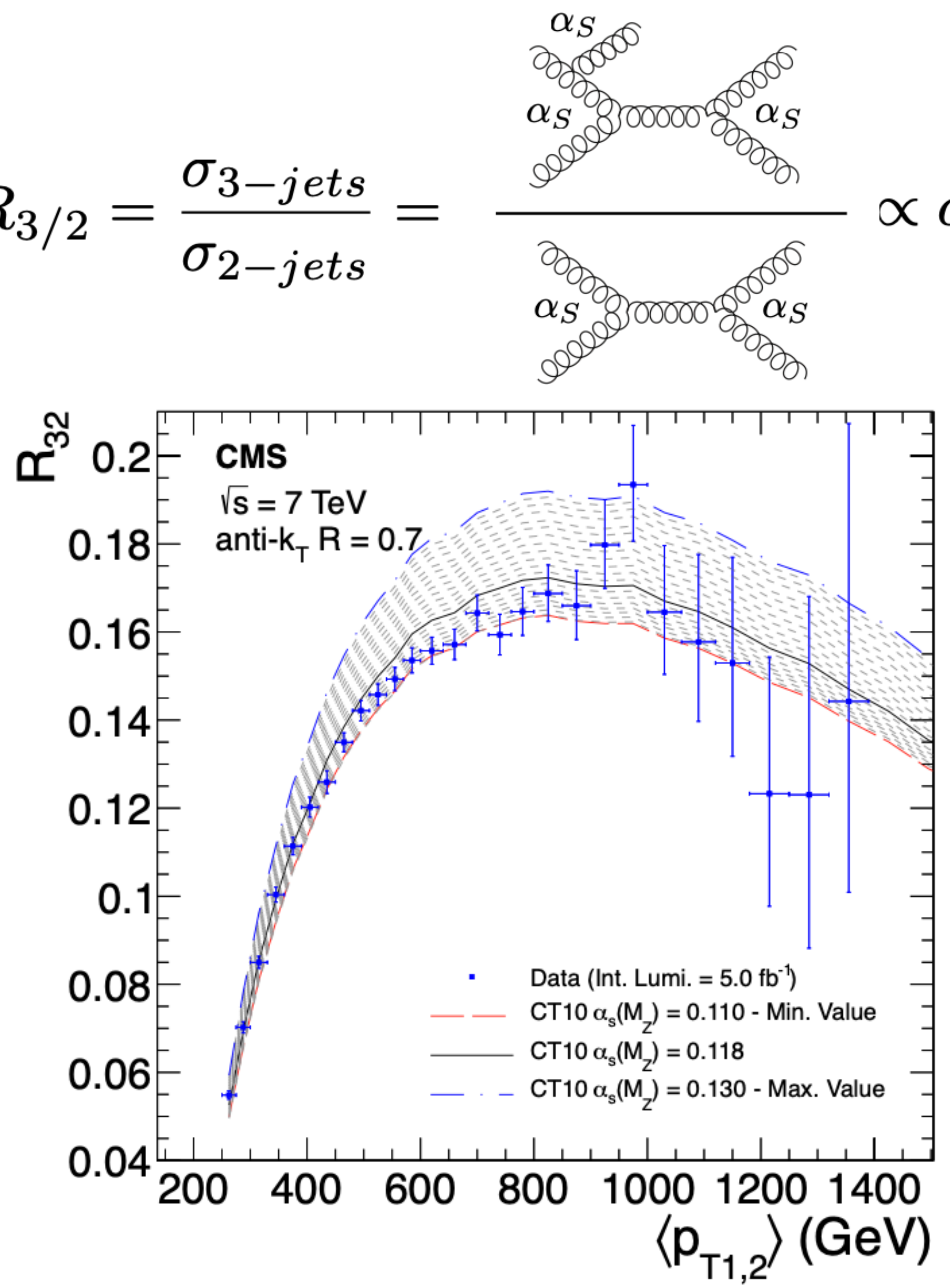
Count number of events in reconstructed bins of $(\Delta p_T, \Delta y)$

Unfold to truth particle jet quantities taking into account reconstruction and trigger efficiencies and unfolding resolution matrix

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\varepsilon \mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$$

Ratios of differential jet production cross sections

$$R_{3/2} = \frac{\sigma_{3-jets}}{\sigma_{2-jets}} = \frac{\text{[diagram]}}{\text{[diagram]}} \propto \alpha_S$$



Measurement of the ratio of cross sections

- **R3/2** is the ratio of inclusive 3-jet to inclusive 2-jet cross sections as a function of the average pT of the two leading jets:

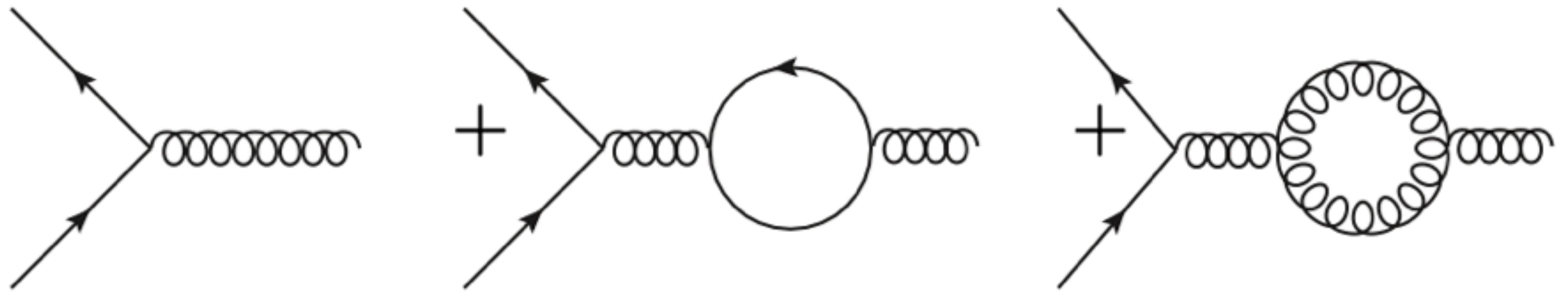
$$< p_{T_{1,2}} >$$

Using ratios can improve precision by cancelling systematic uncertainties.

- Again interesting dependence in strong coupling constant.
- Main experimental uncertainty partly canceled but still dominant.
- With the transverse momenta of all the jets can infer the energy scale of the process.

Measurement of the Strong Coupling Constant α_s

Crucial dependence of the strong coupling constant with the energy scale predicted (1973):



$$\alpha_S^{-1}(Q^2) = \alpha_S^{-1}(Q_0^2)\left[1 + \frac{33-2n_f}{12\pi}\alpha_S(Q_0^2)\ln\left(\frac{Q^2}{Q_0^2}\right)\right]$$

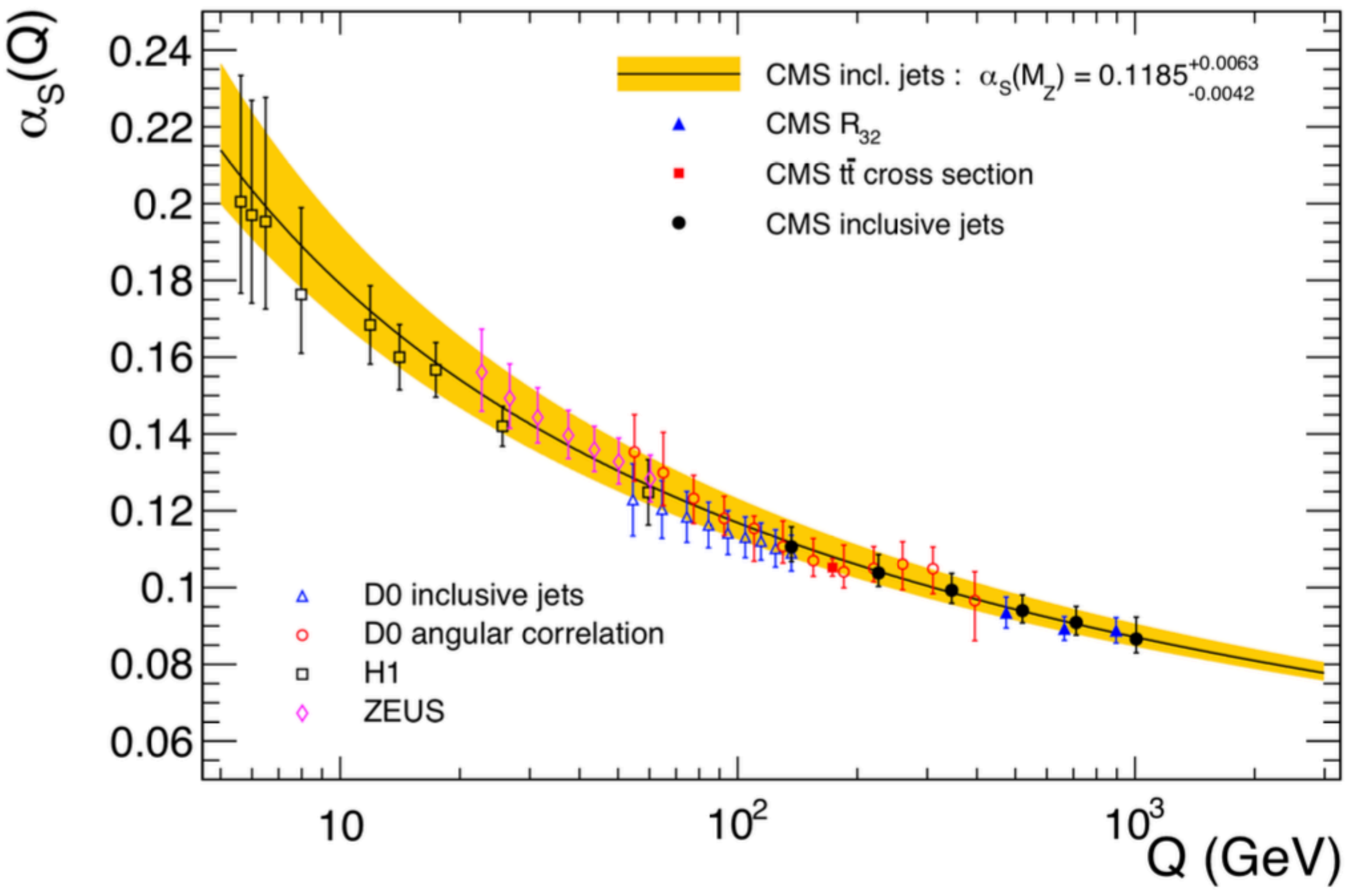
Asymptotic freedom: QCD is perturbative at high energies

2004

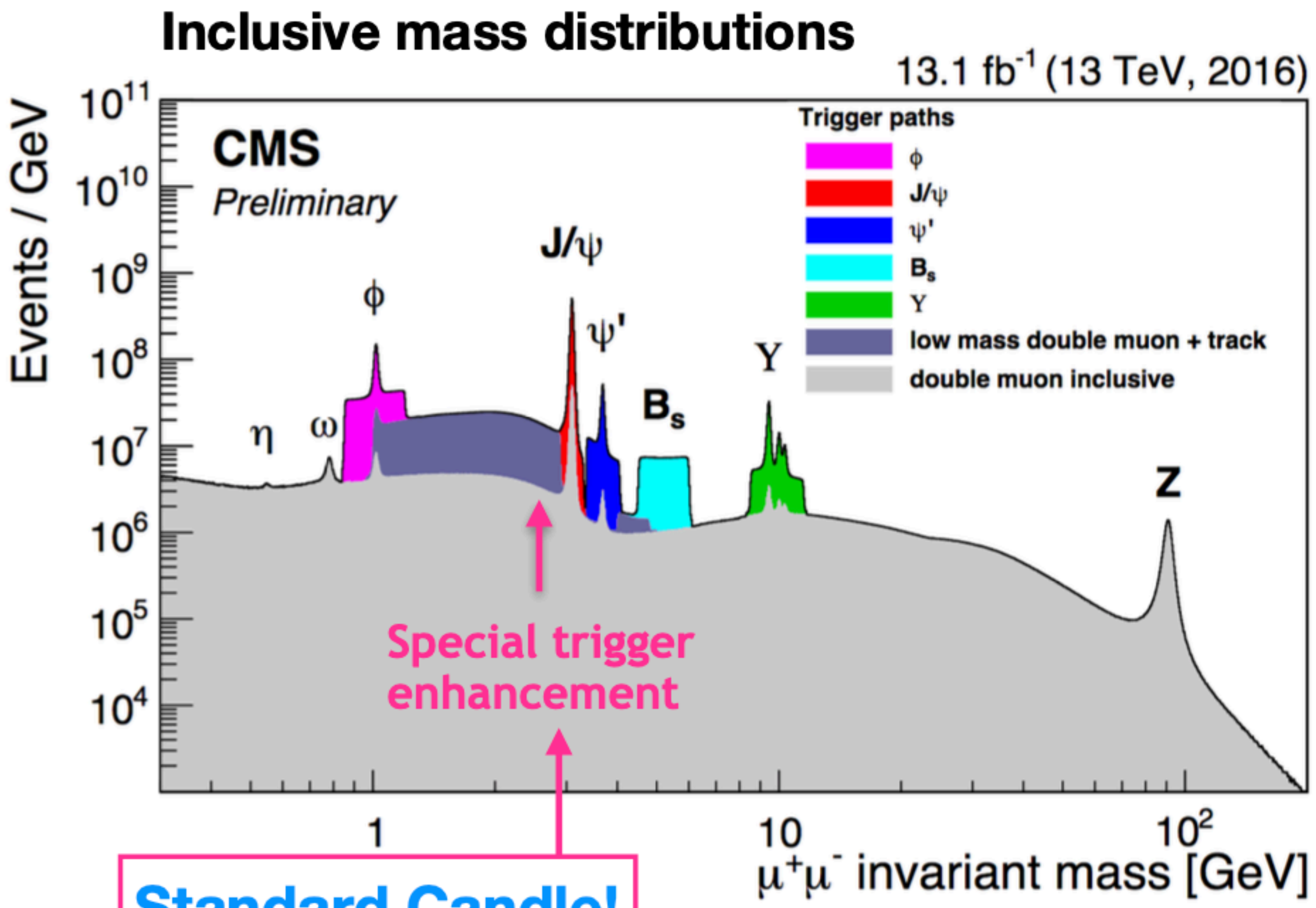
Asymptotic freedom and QCD

David Gross, David Politzer, Frank Wilczek

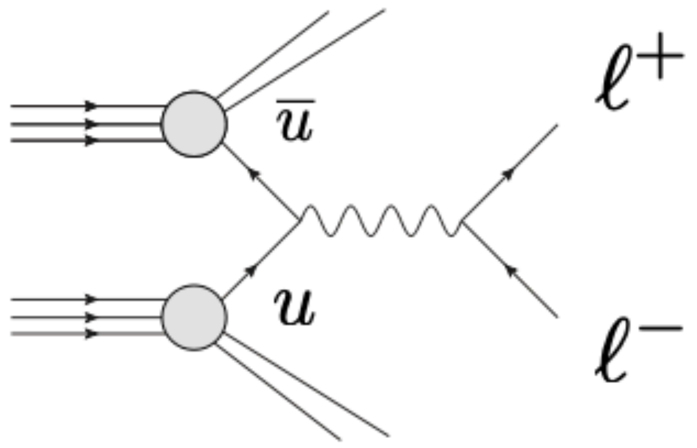
From the measurements of jet cross sections and their ratios, the strong coupling constant can be measured at the highest energy scales!



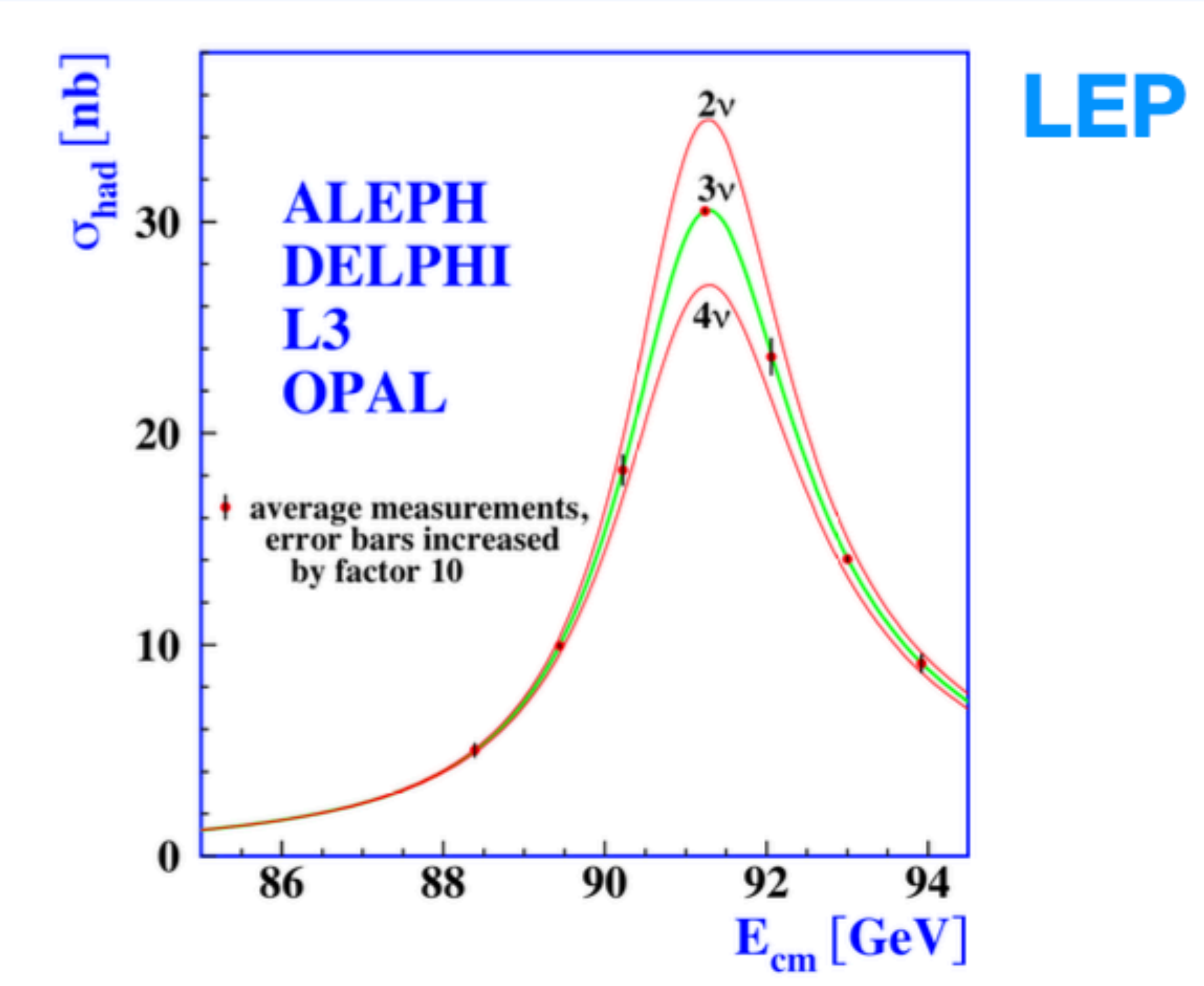
The di-lepton mass spectrum at LHC



Standard Candle!



Z, J/Psi and Upsilon in electrons and muons are extremely important standard candles for calibration.



$$m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$

$$\rho = 1.0050 \pm 0.0010$$

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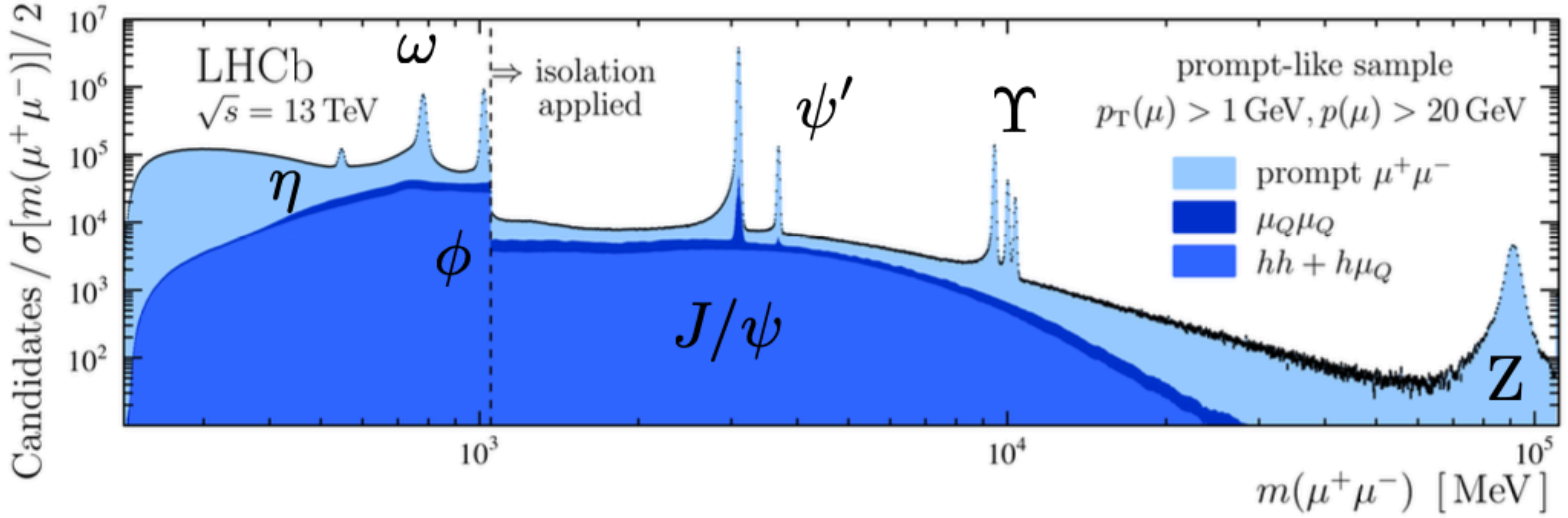
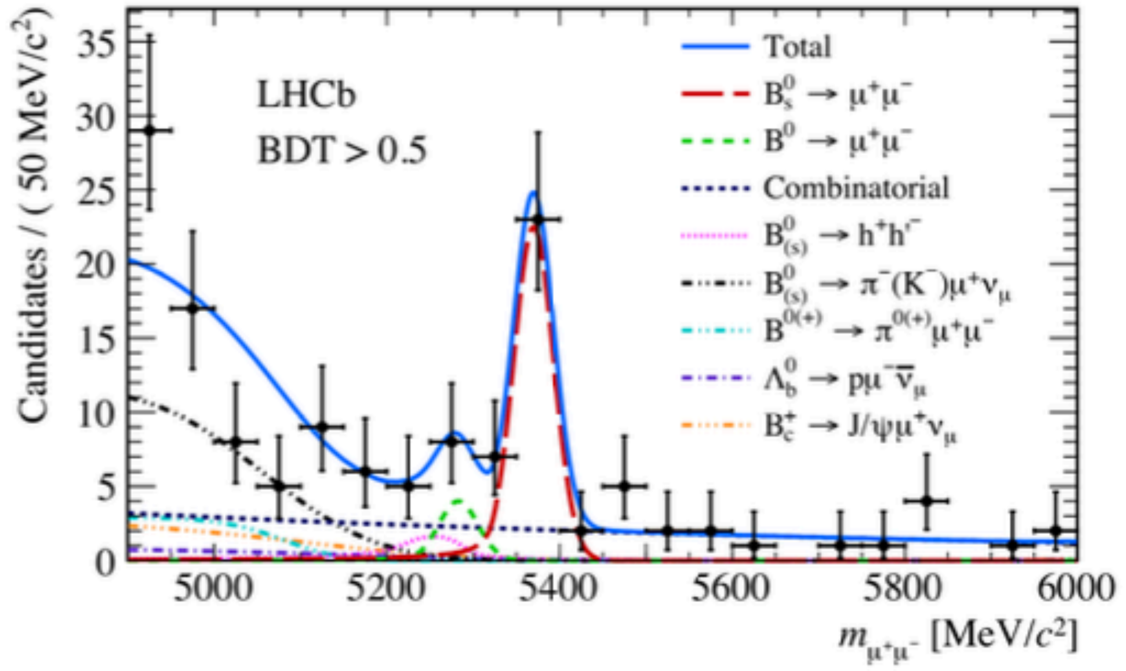
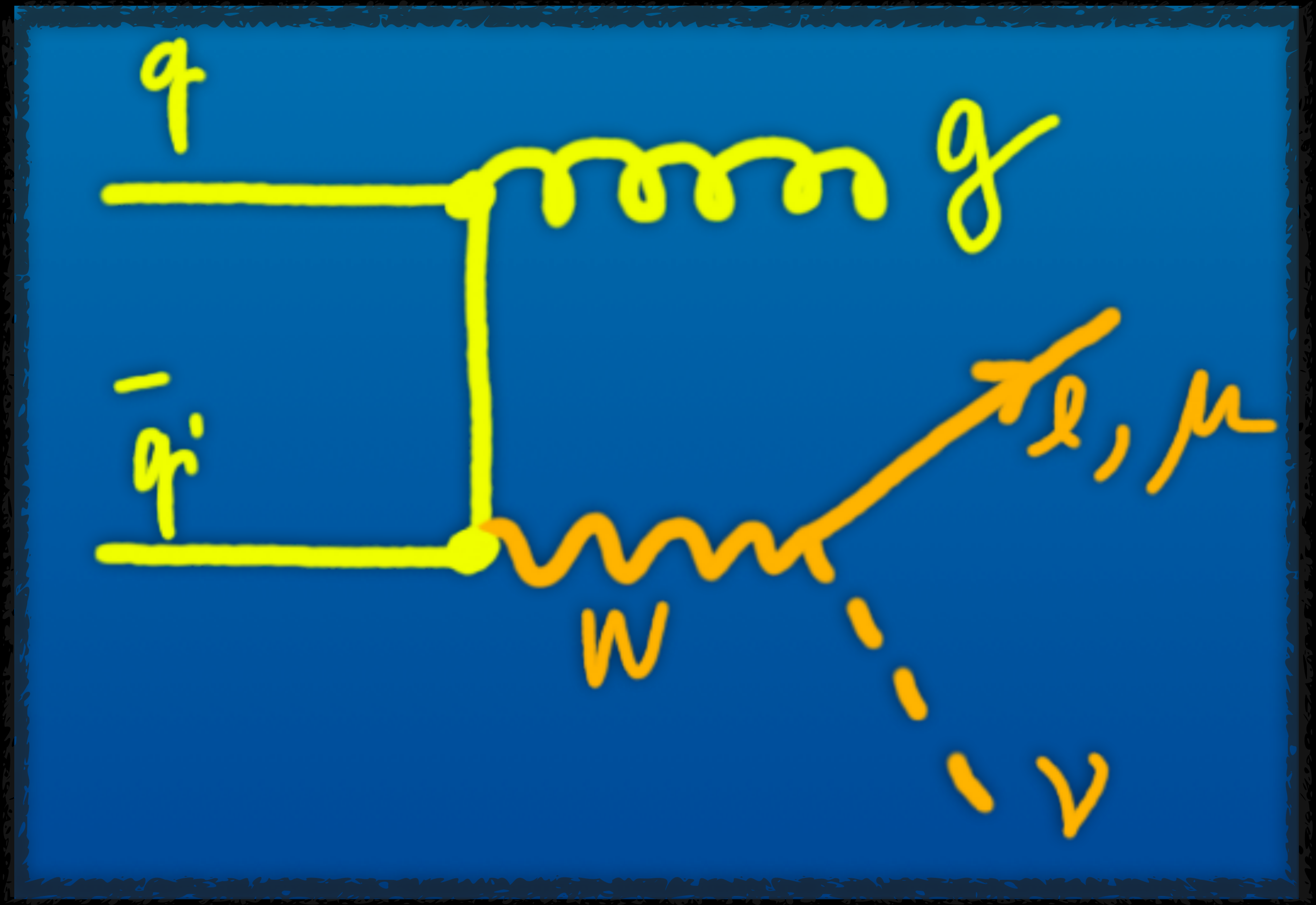


An exclusive analysis scrutinising the Bs mass region

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$



The challenge of the W Mass Measurement

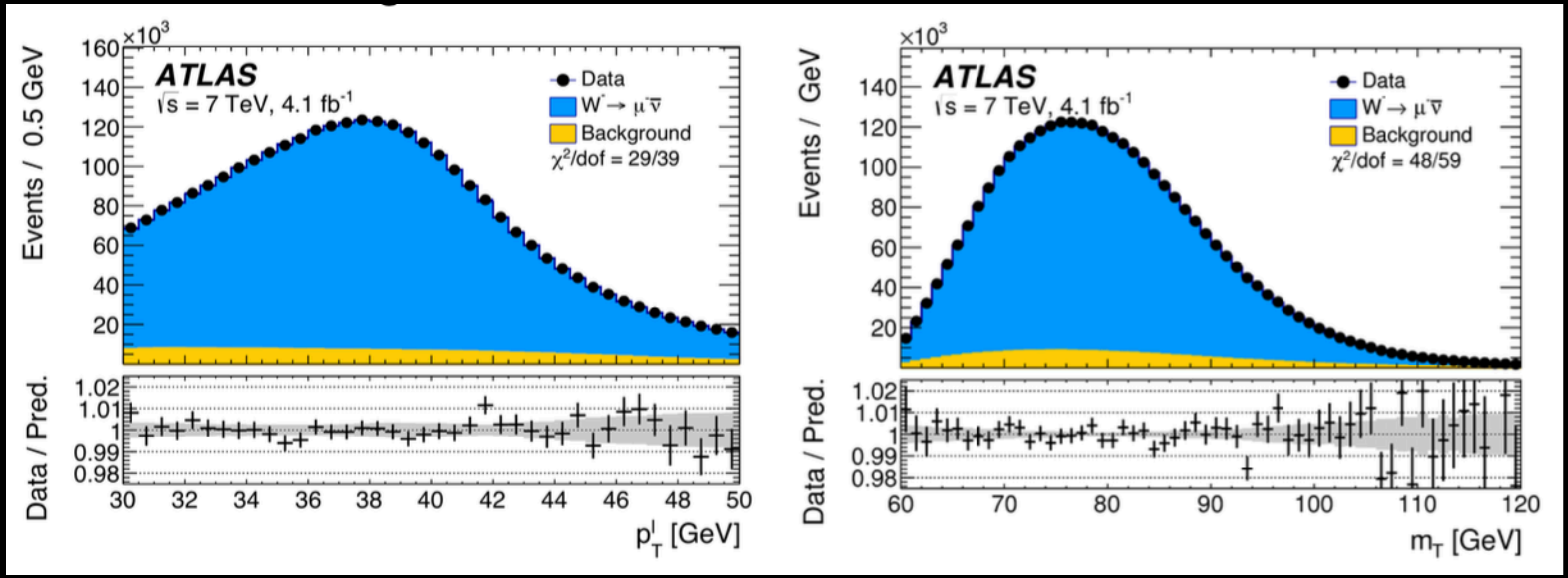


Cannot measure **W mass** directly from its decay particles because the **neutrino** is not measured directly in the detector

Measure **W** recoil precisely

$$m_T = \sqrt{2\, p_T^l\, p_T^{miss}\,(1 - \cos\Delta\varphi)}$$

Strategy: fit two kinematic distributions in several categories



P^l_T: Clean energy measurement, but more sensitive to the modelling of the W transverse momentum

M_T: Less sensitive to modelling but more difficult to reconstruct because of the missing transverse energy

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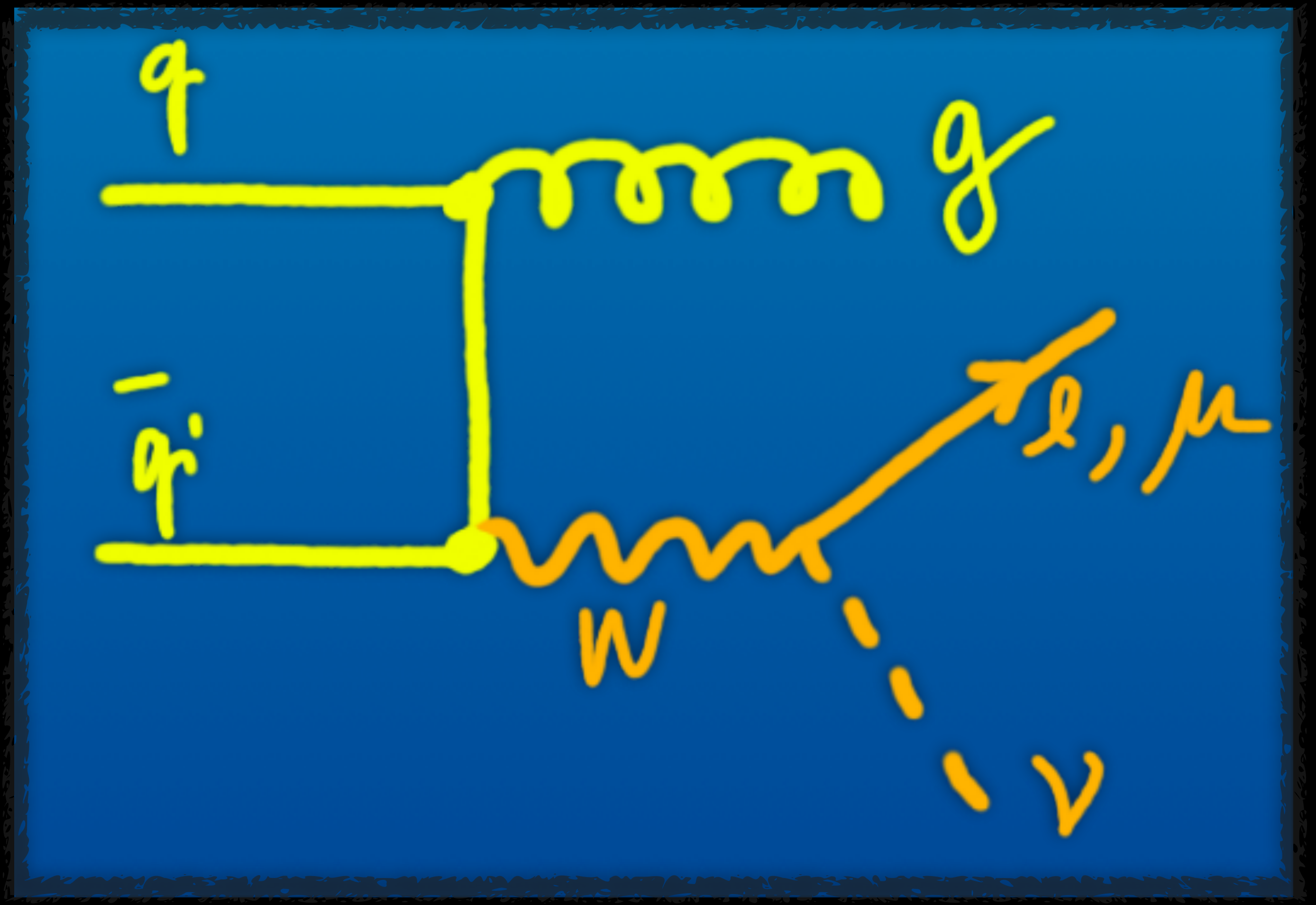

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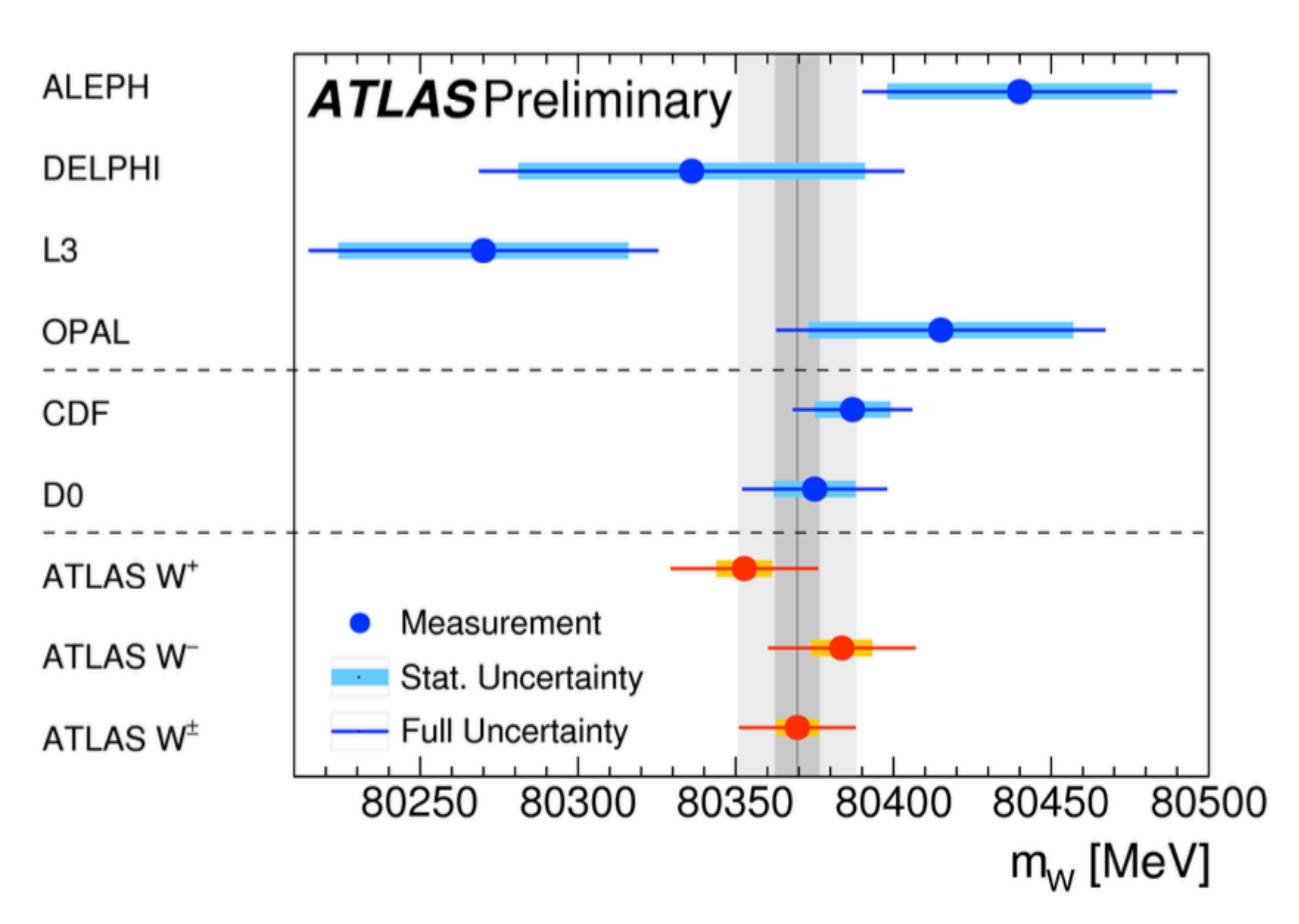
↓

Measure **W** recoil precisely

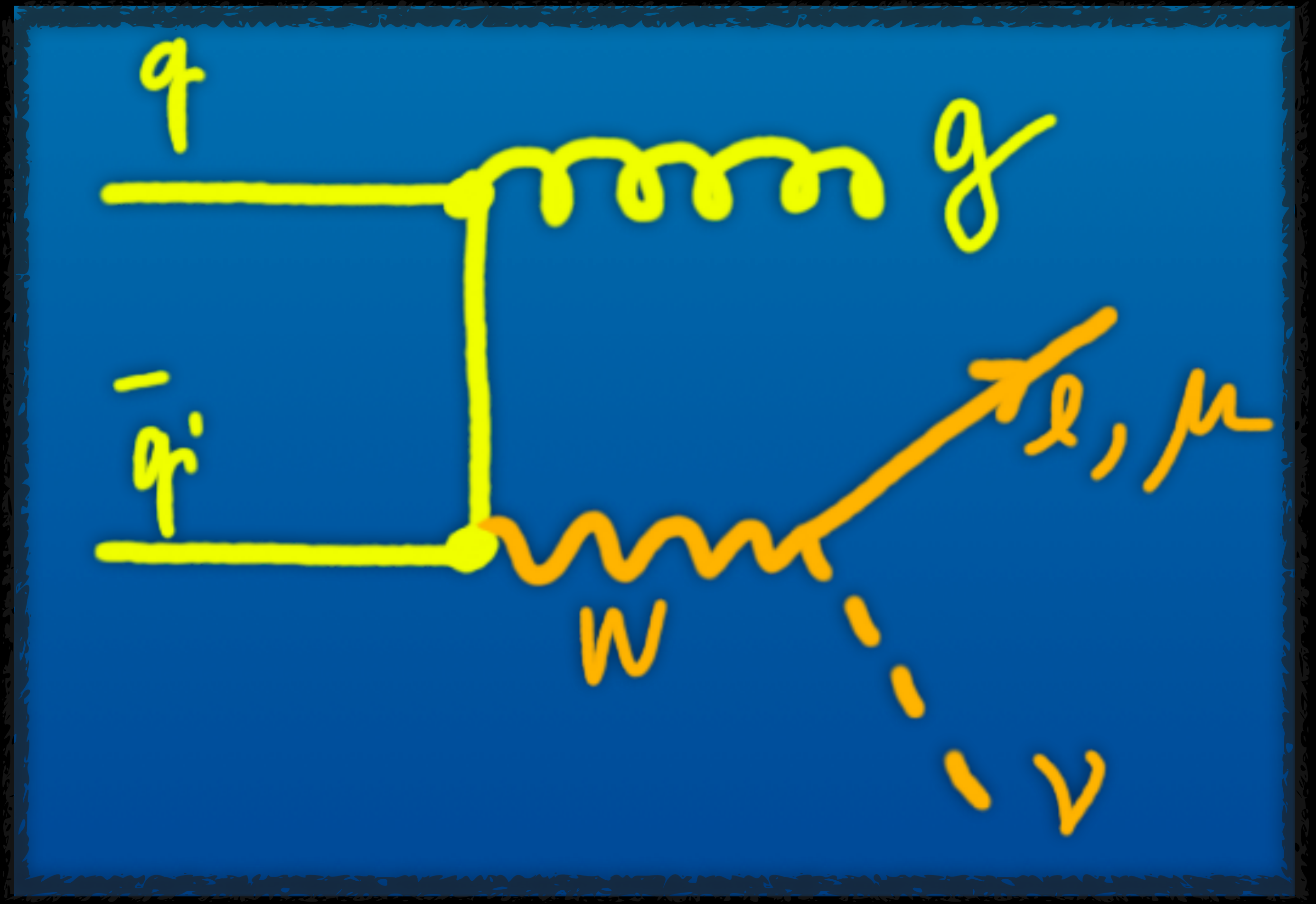
$$m_T = \sqrt{2\, p_T^l\, p_T^{miss}\, (1 - cos\Delta\varphi)}$$

Strategy: fit two kinematic distributions in several categories



m_W = 80369.5 ± 18.5 MeV (large component from modeling)

The challenge of the W Mass Measurement



Cannot measure **W mass** directly from its decay particles because the **neutrino** is not measured directly in the detector

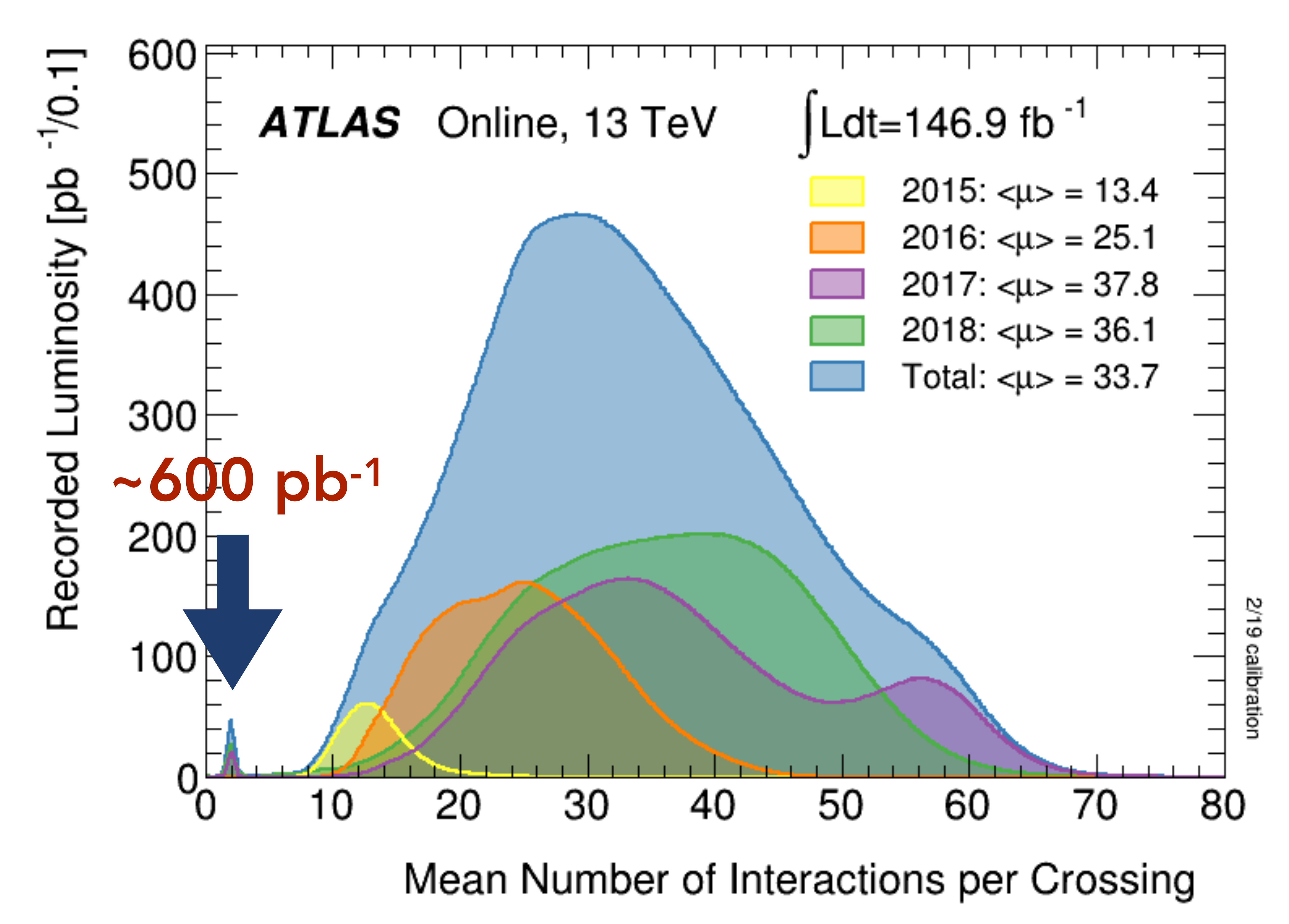
⬇

Measure **W** recoil precisely

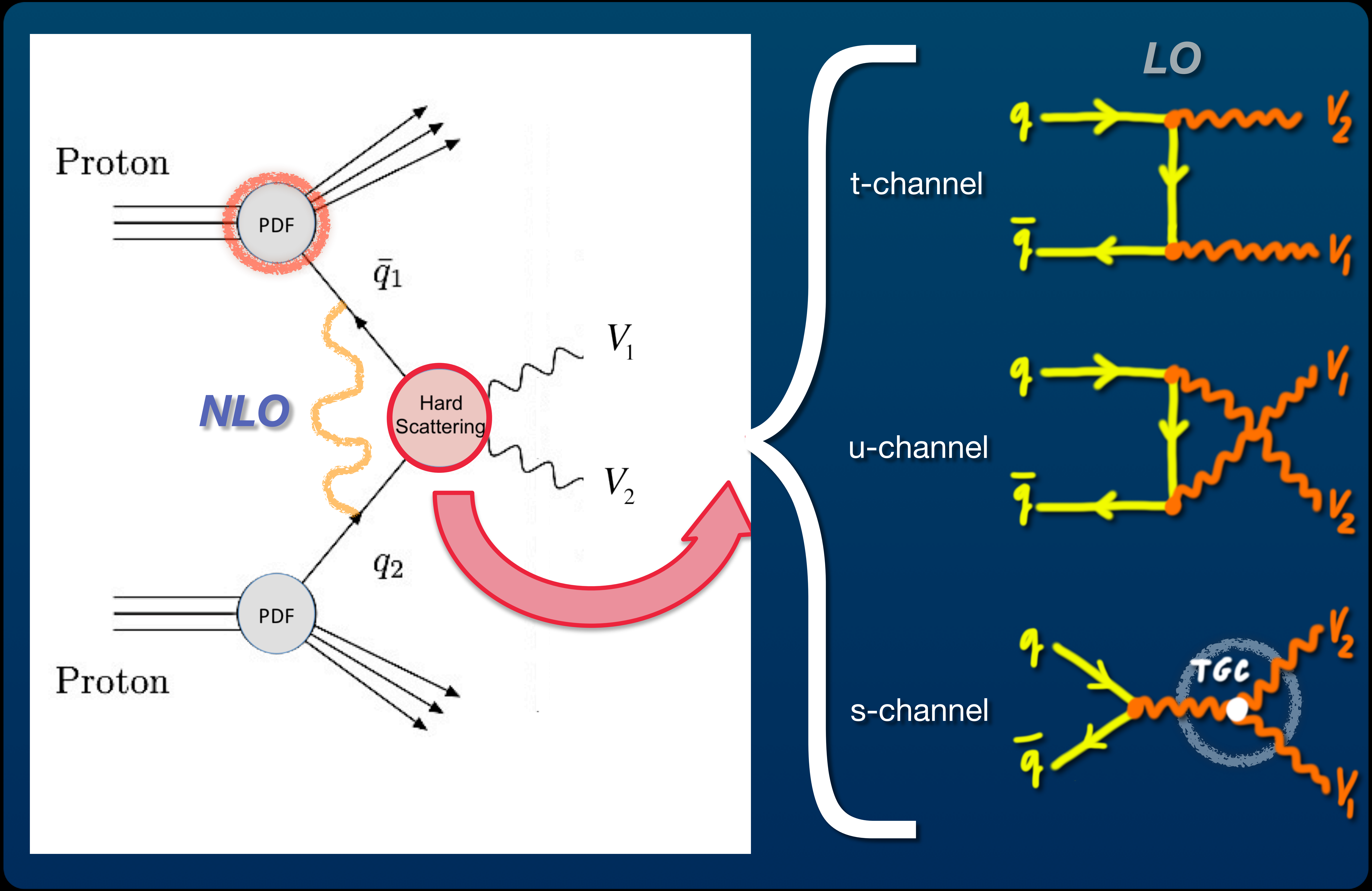
$$m_T = \sqrt{2\, p_T^l\, p_T^{miss}\, (1 - \cos\Delta\varphi)}$$

Strategy: fit two kinematic distributions in several categories

For further improvements:
Special precision-data runs with low pile-up events

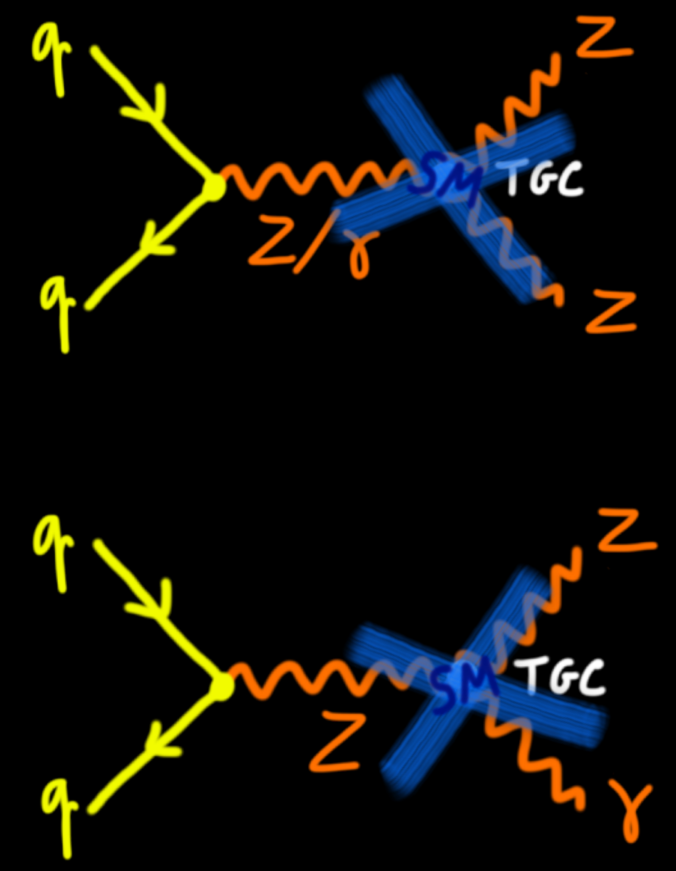


Diboson production at the LHC



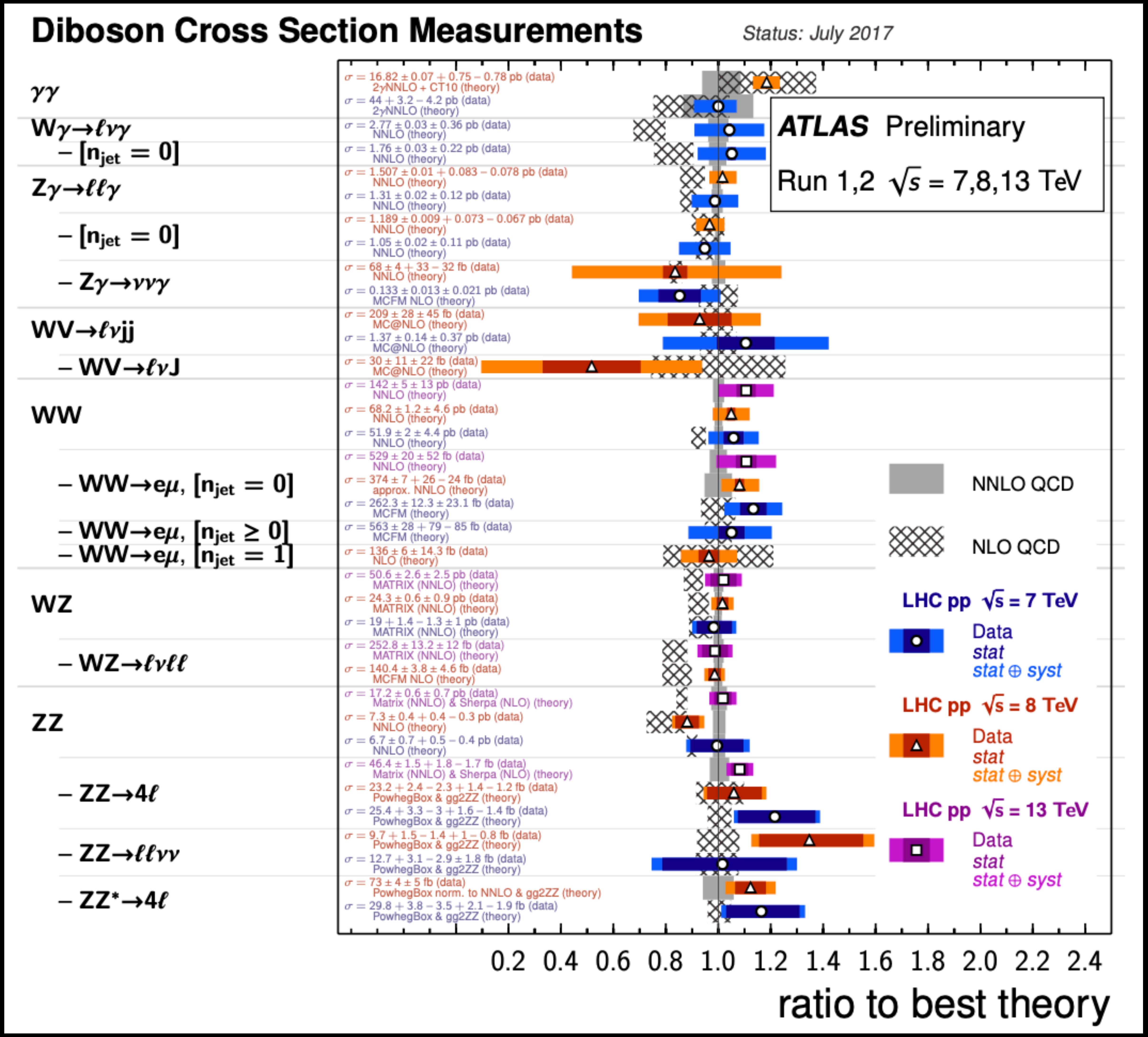
Final states:
WW
WZ
ZZ
Wγ
Zγ

Anomalous Triple Gauge Couplings

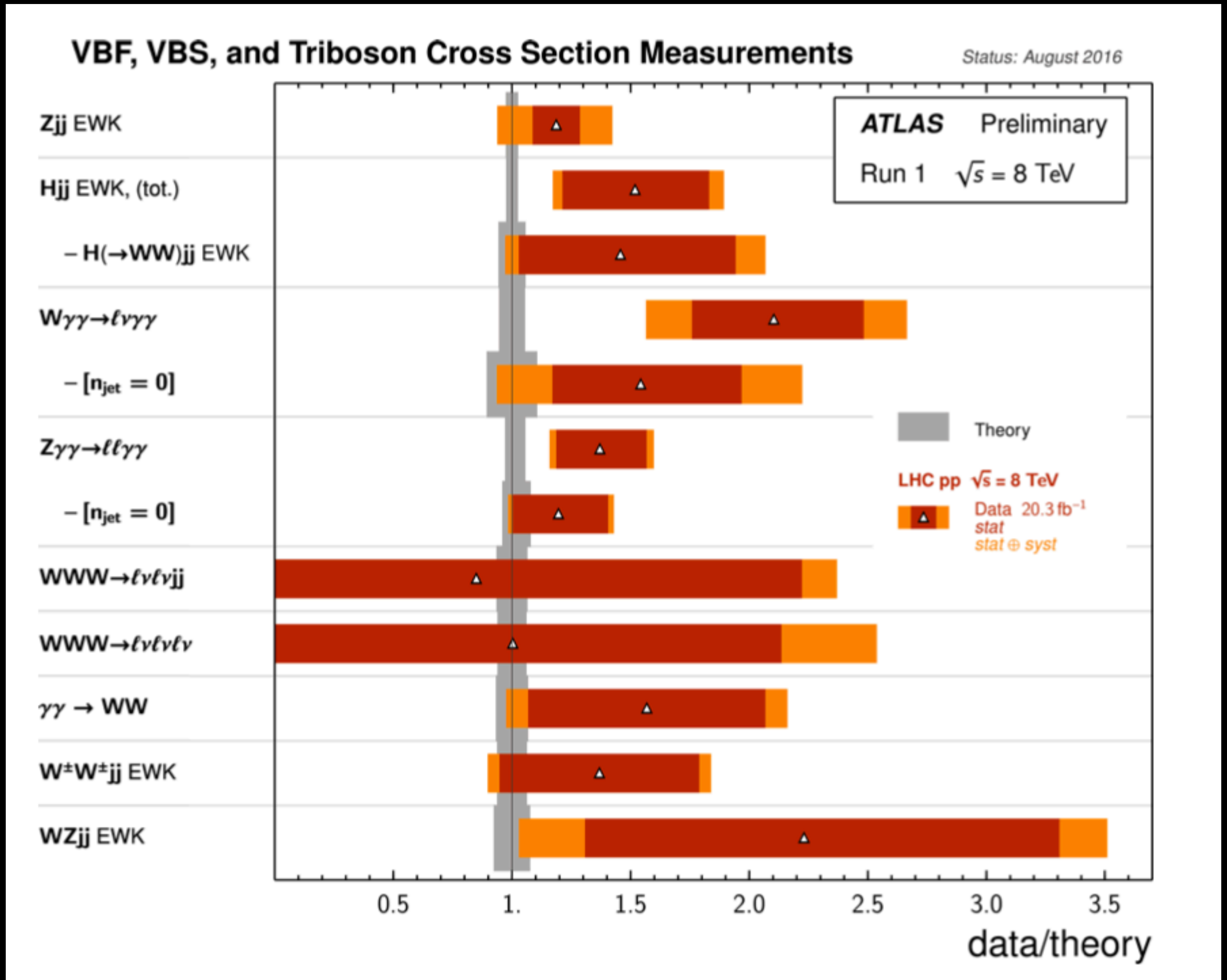


Di- (and Tri-) boson measurements at the LHC

Large number of processes measured and used to constrain anomalous gauge couplings



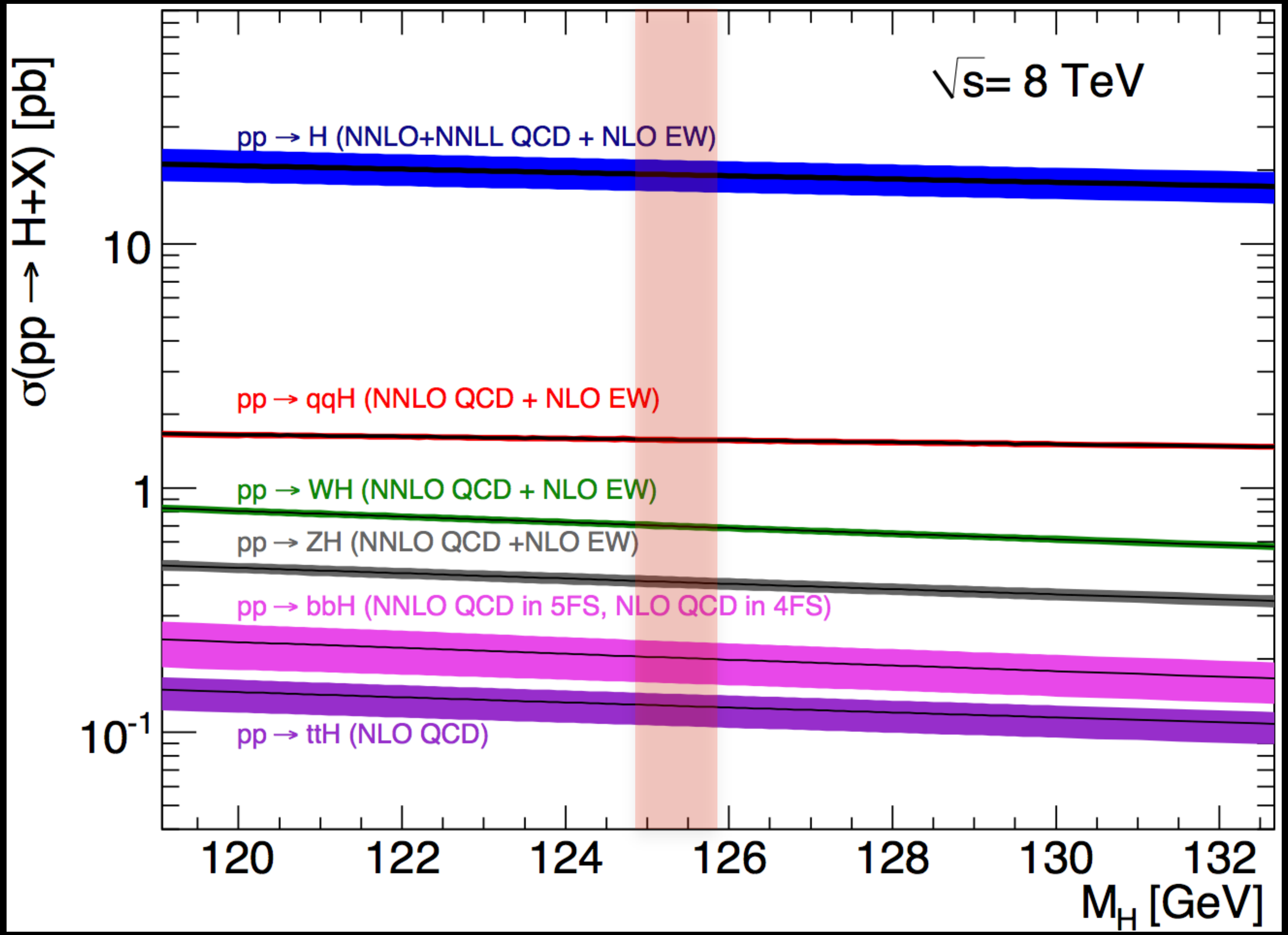
Even more rare processes…



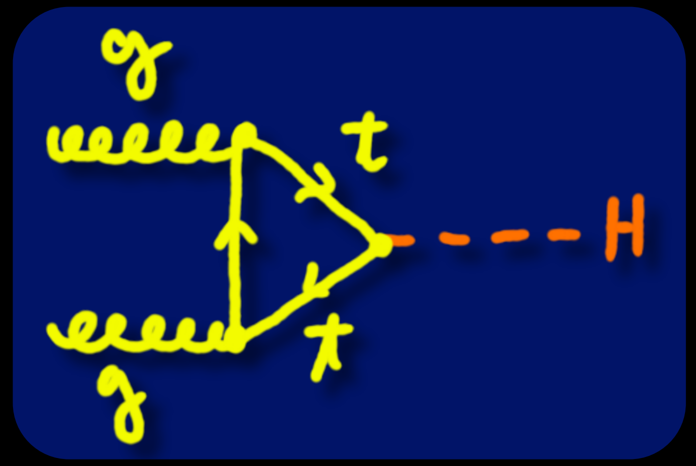
Exposing the need for NNLO QCD calculations

Higgs

Higgs Production at LHC (m_H = 125 GeV)

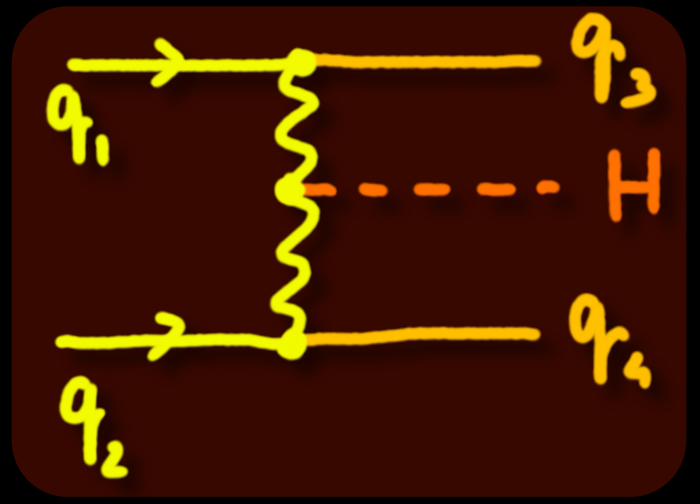


Earlier cross section calculations assumed a full range of Higgs masses



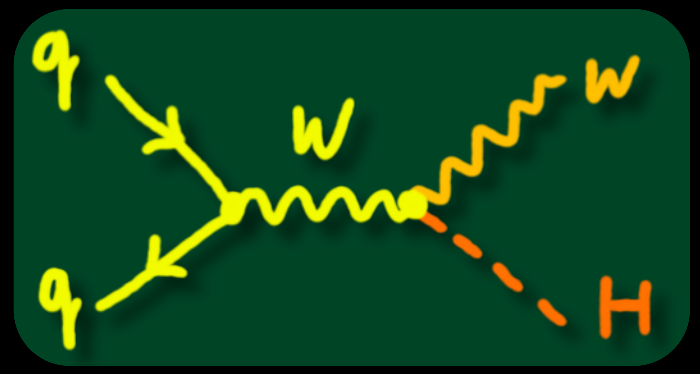
Gluon Fusion (ggF)

NNLO+NNLL QCD
+ NLO EWK



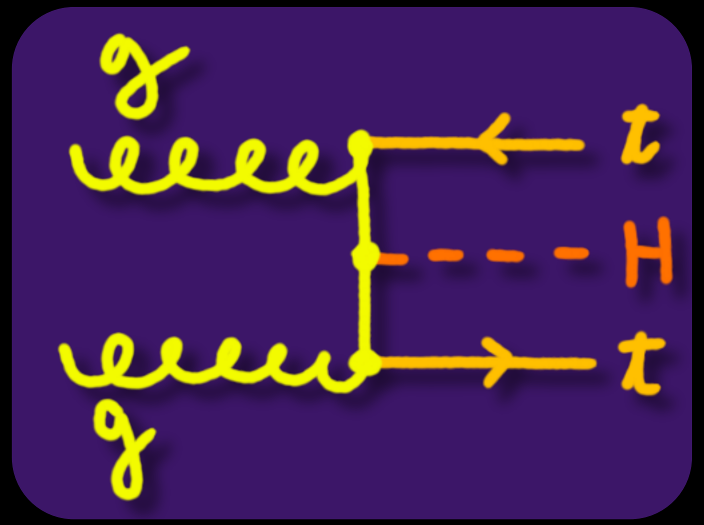
Vector Boson Fusion (ggF)

NNLO QCD
+ NLO EWK



Associate Production (VH)

NNLO QCD
+ NLO EWK



Associate Production (ttH)

NLO QCD

Production Rates in Run 2 (13 TeV) for 150 fb^{-1}

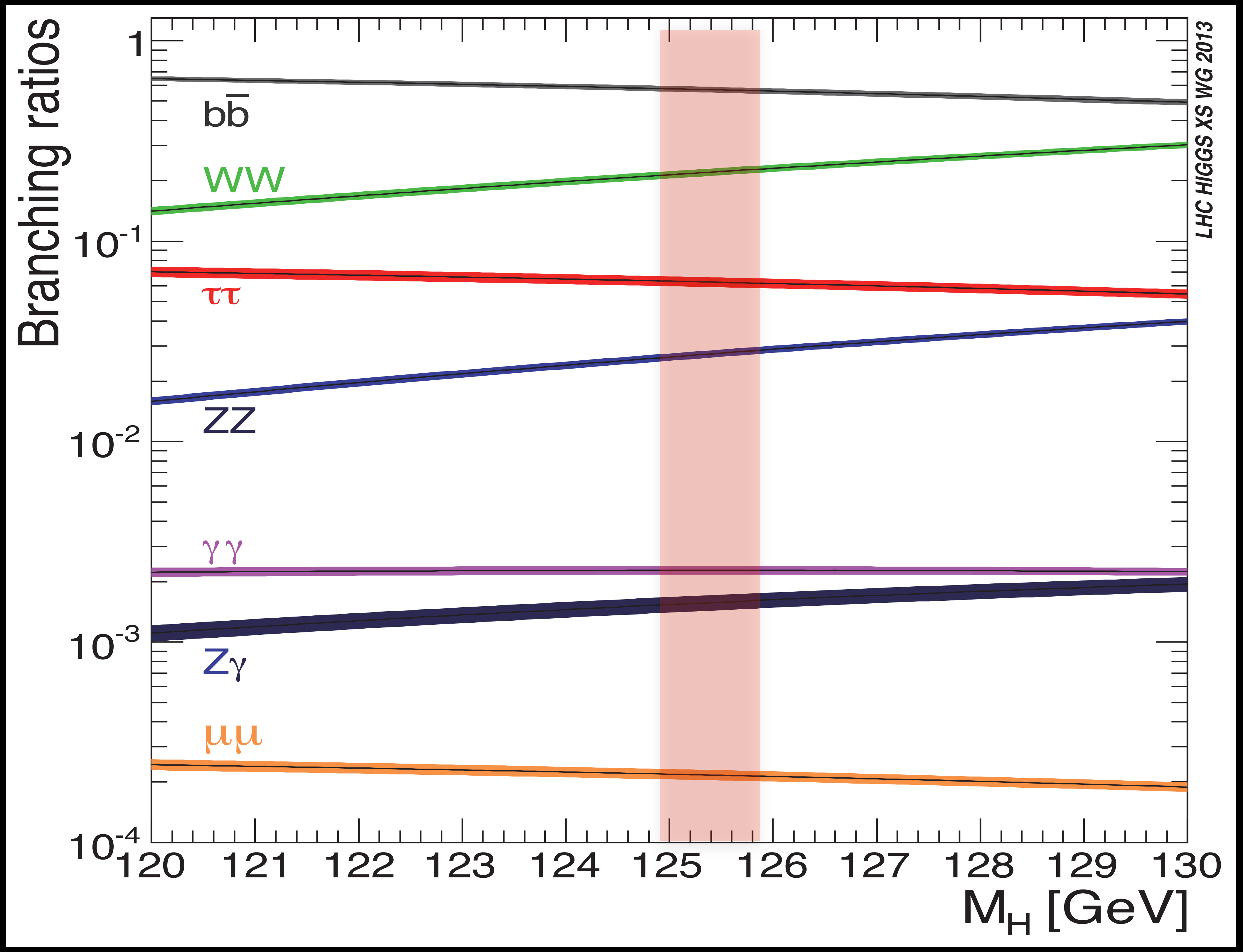
~8M events

~600k events

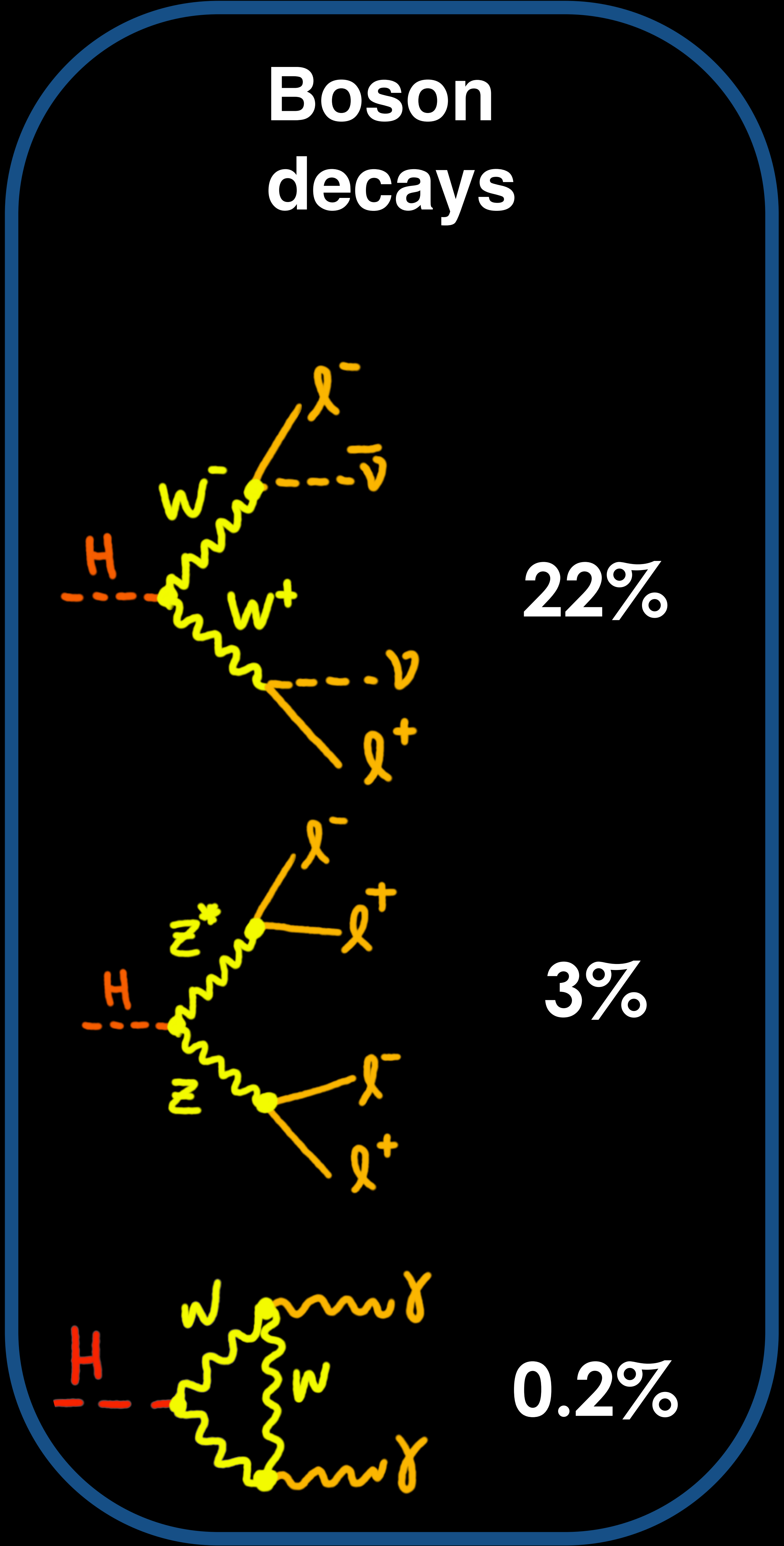
~400k events

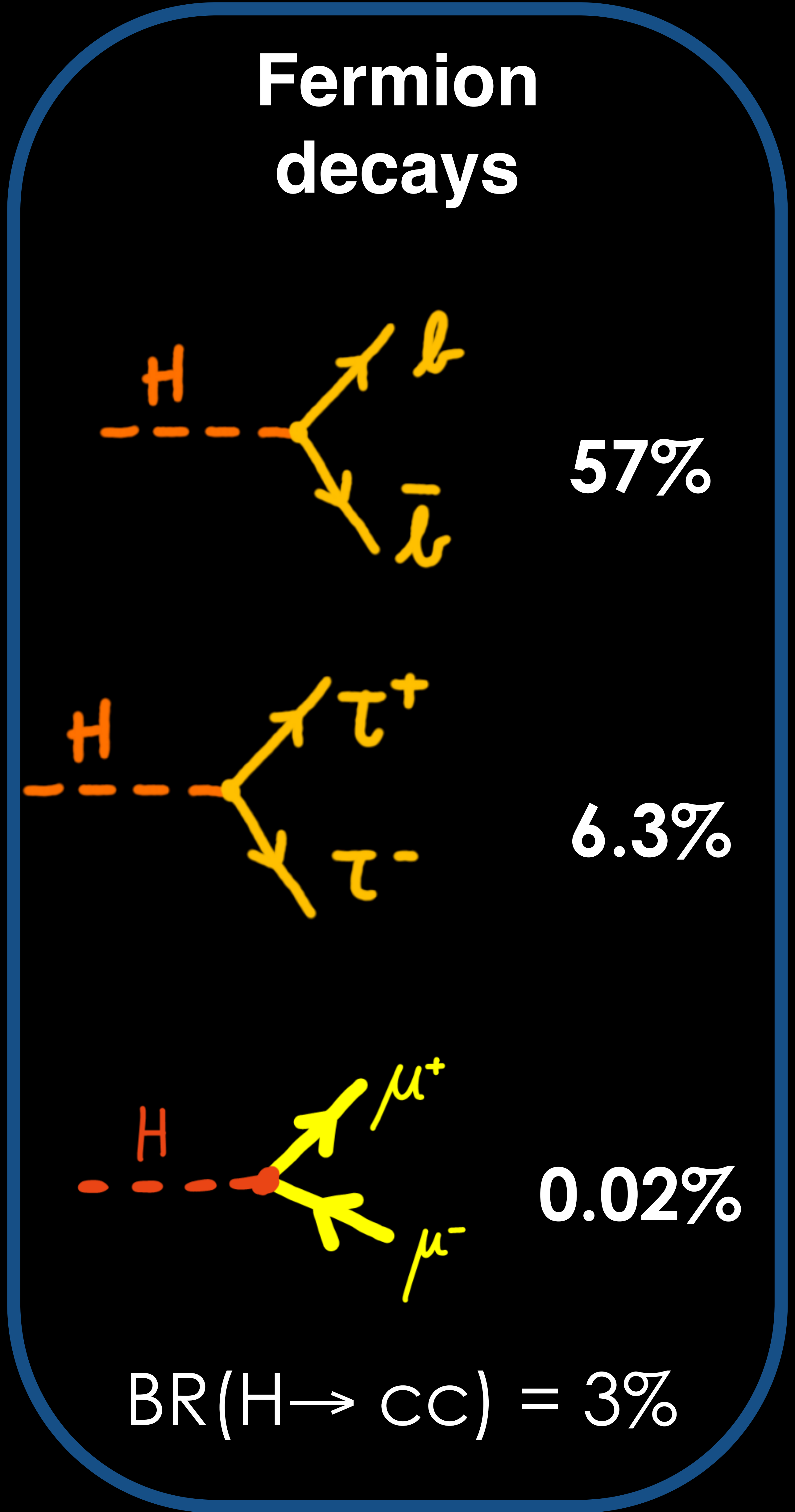
~80k events

Higgs Decay Branching Fractions (m_H = 125 GeV)

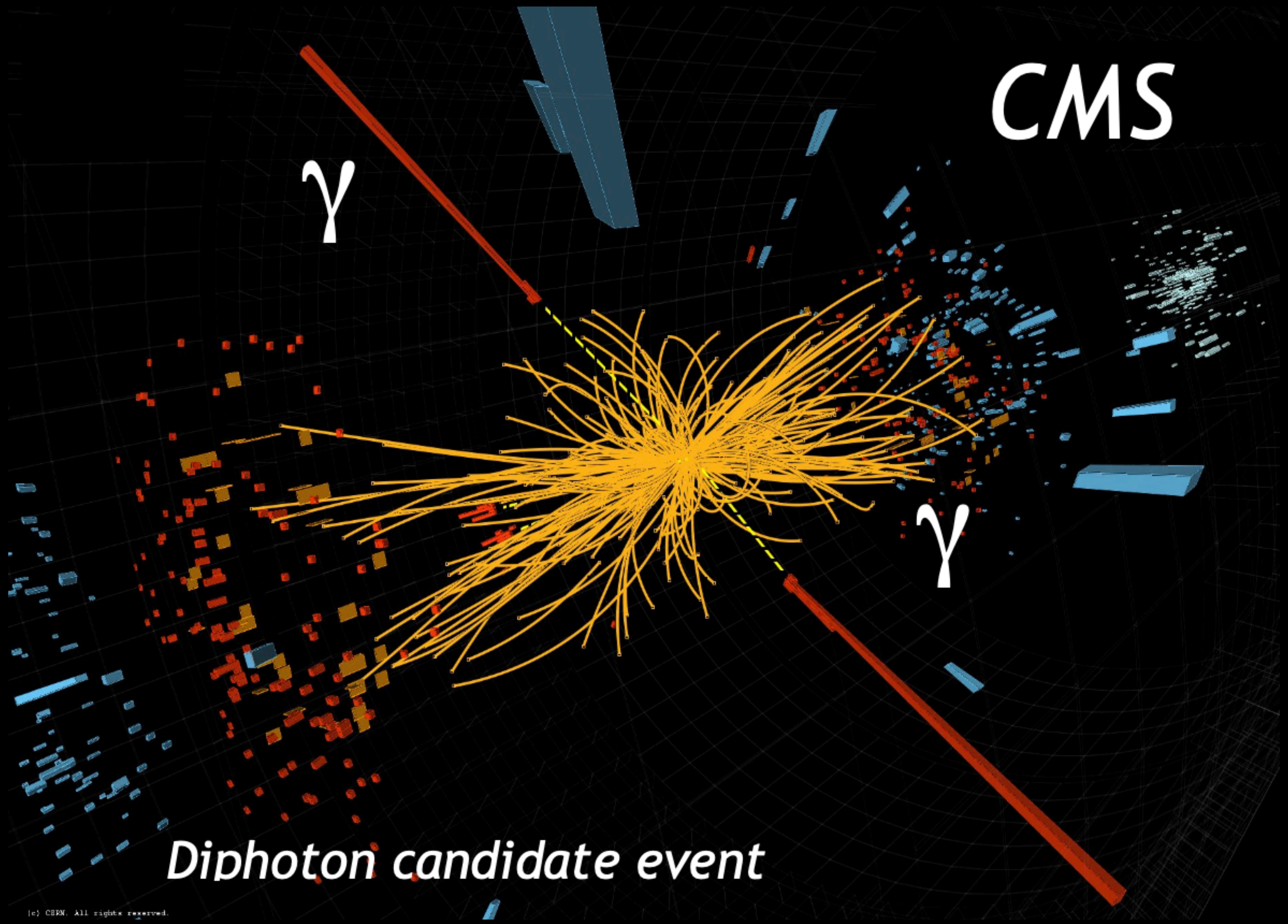


Possible to test Higgs sector with many decay modes

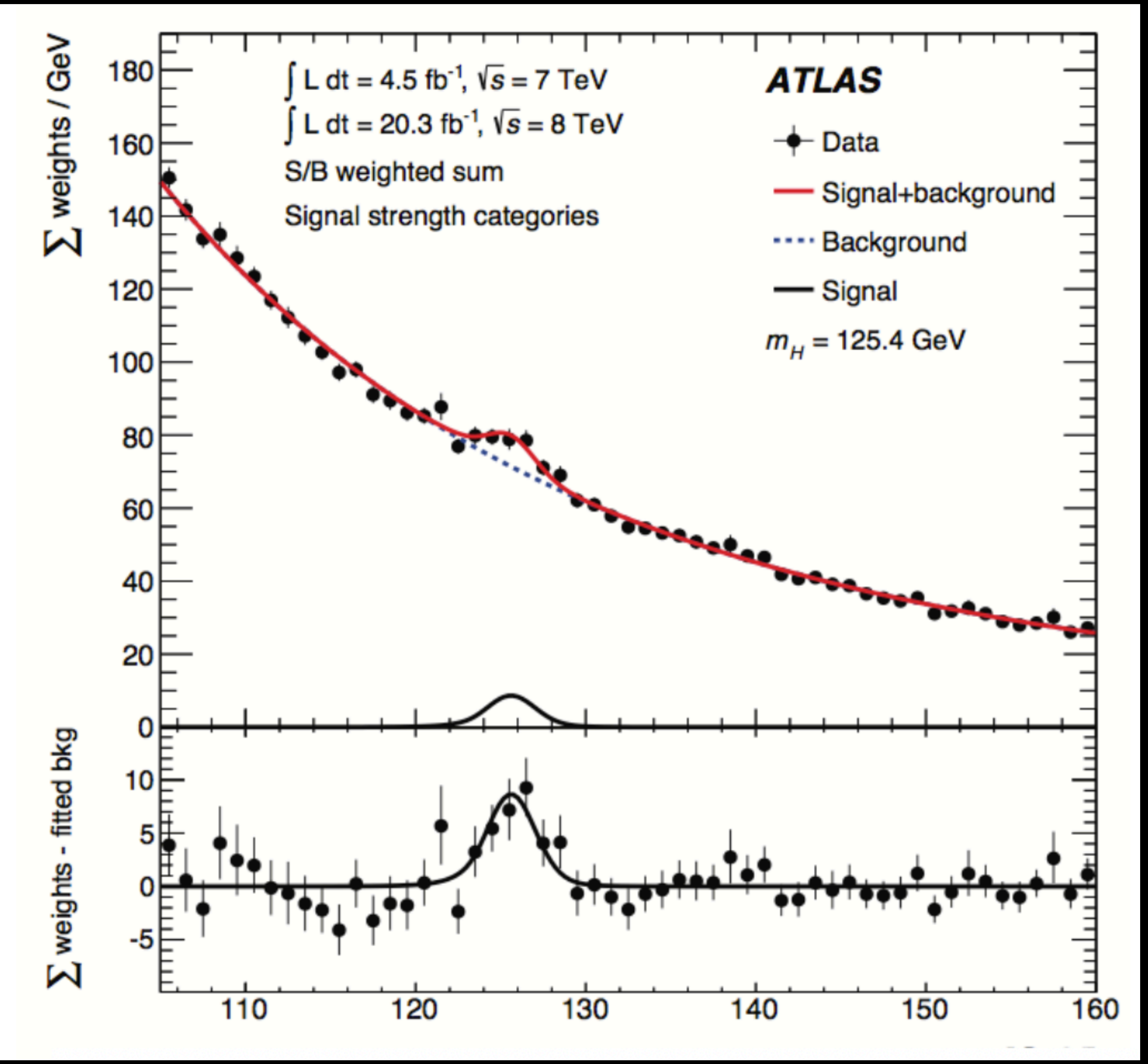


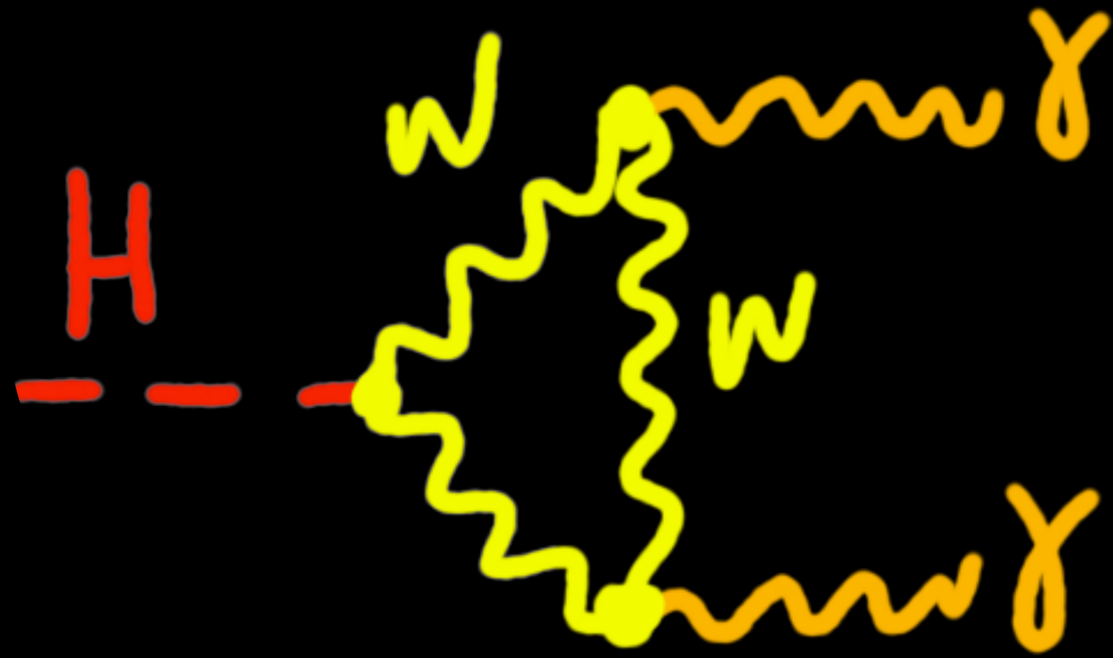


Discovery channel: 2 photons

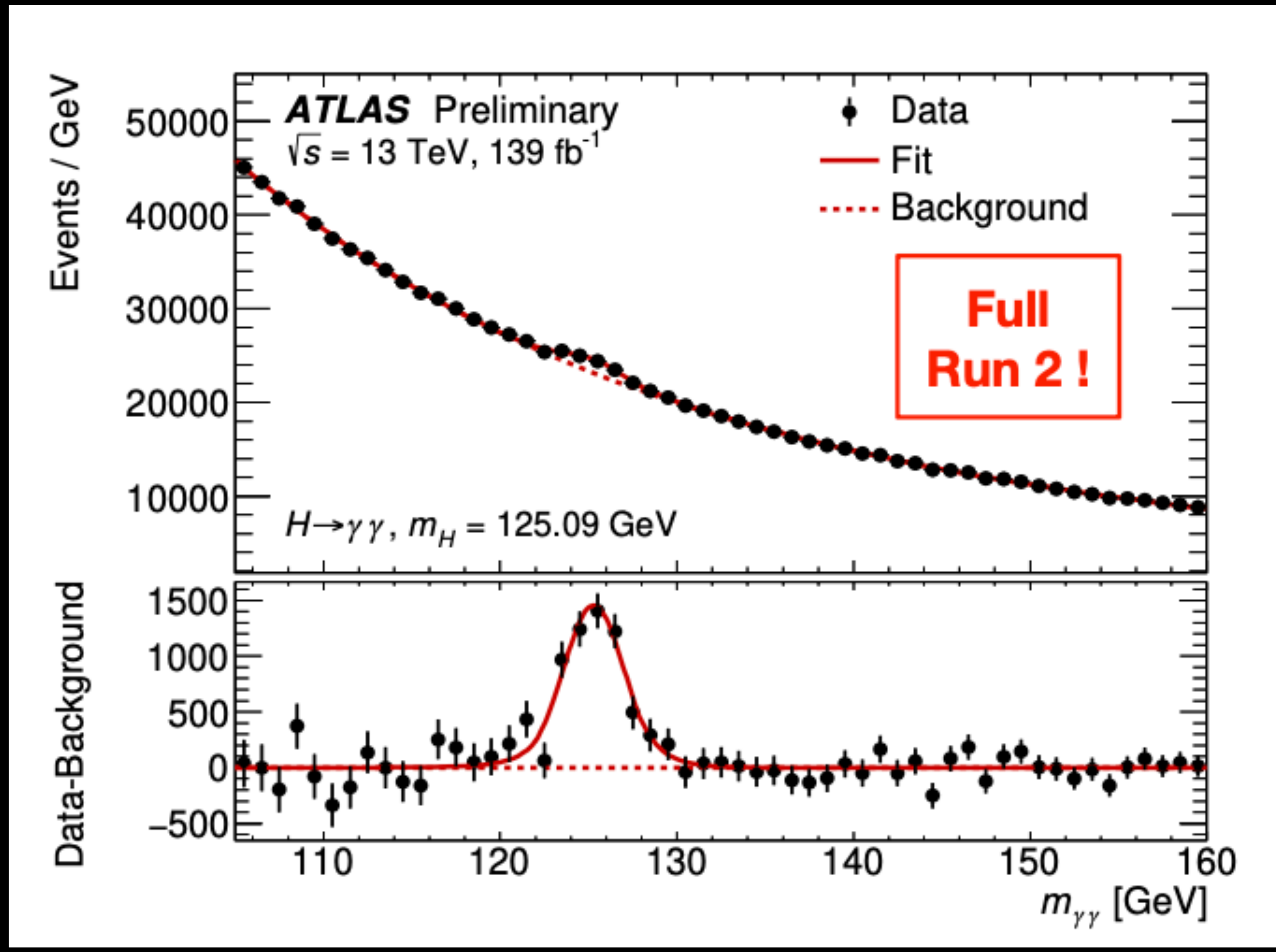


High mass resolution O(1%) allowing data driven estimate of background in the sidebands



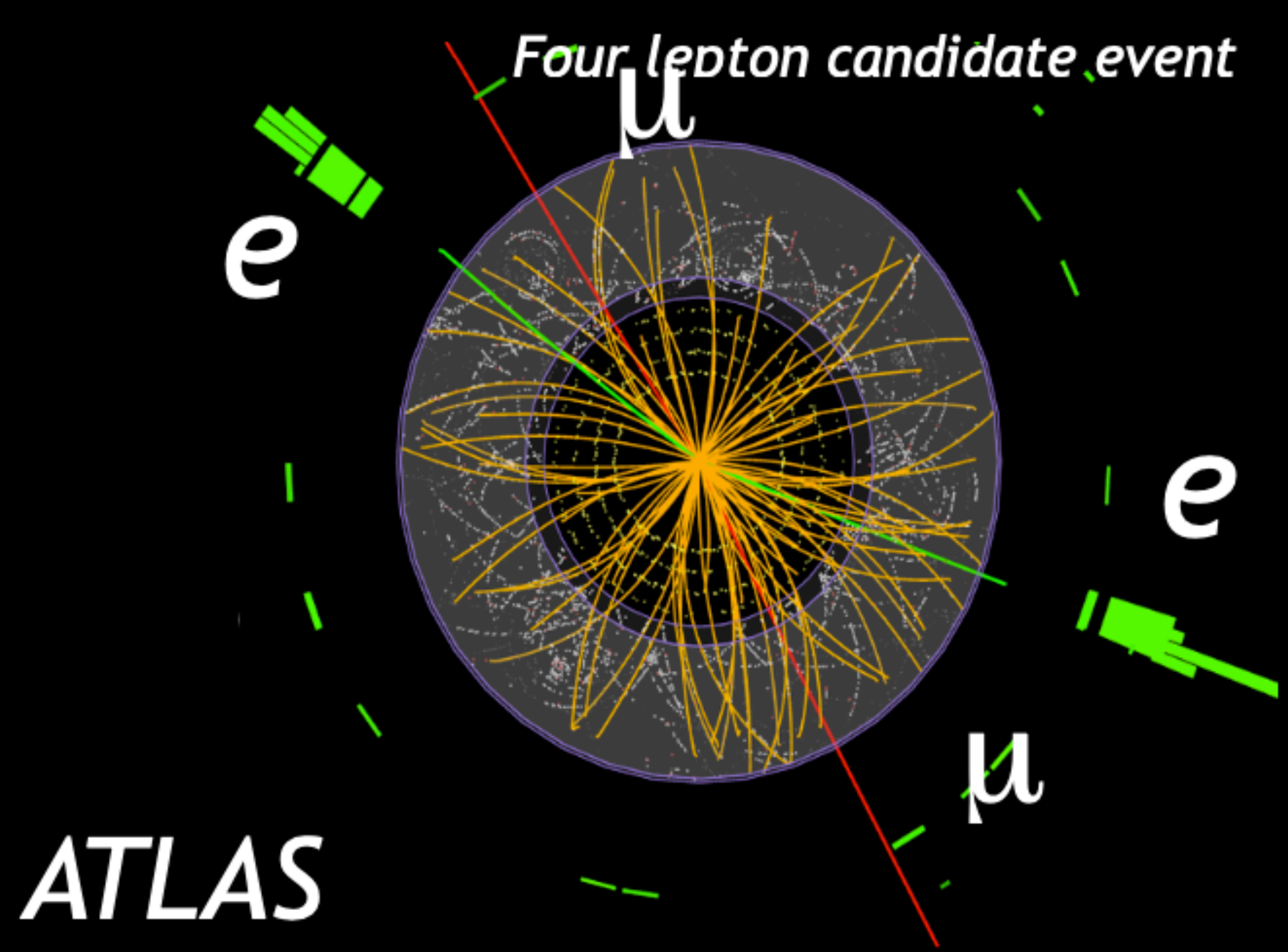


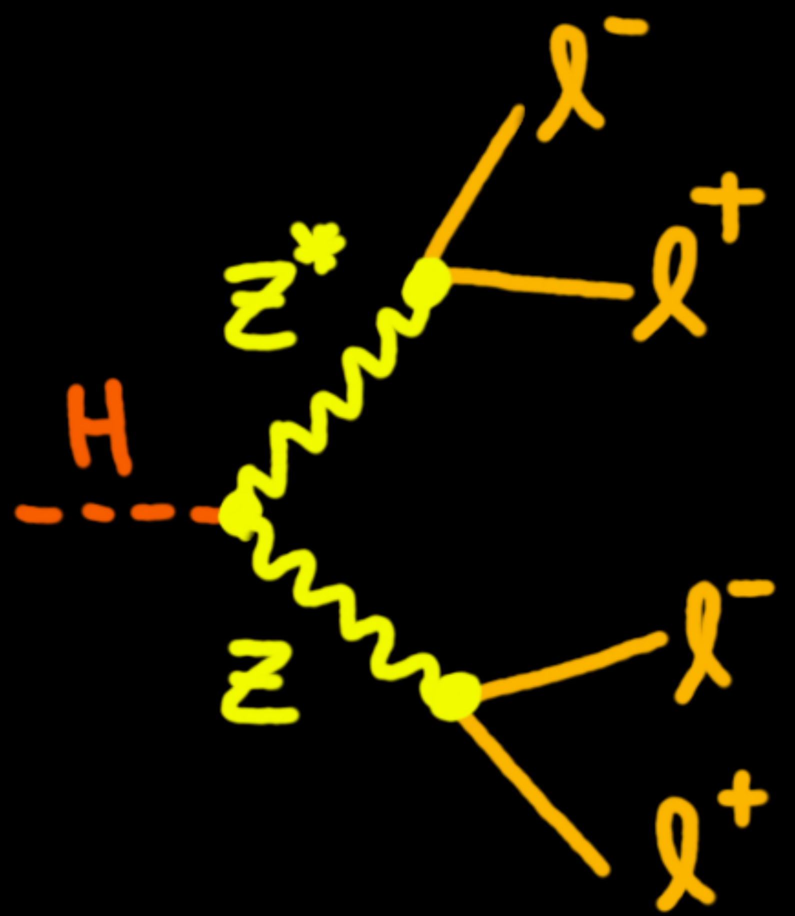
Observation implies that the bump does not originate from spin 1 particle: Landau-Yang theorem



Sensitive to new physics

Discovery channel: 4 leptons

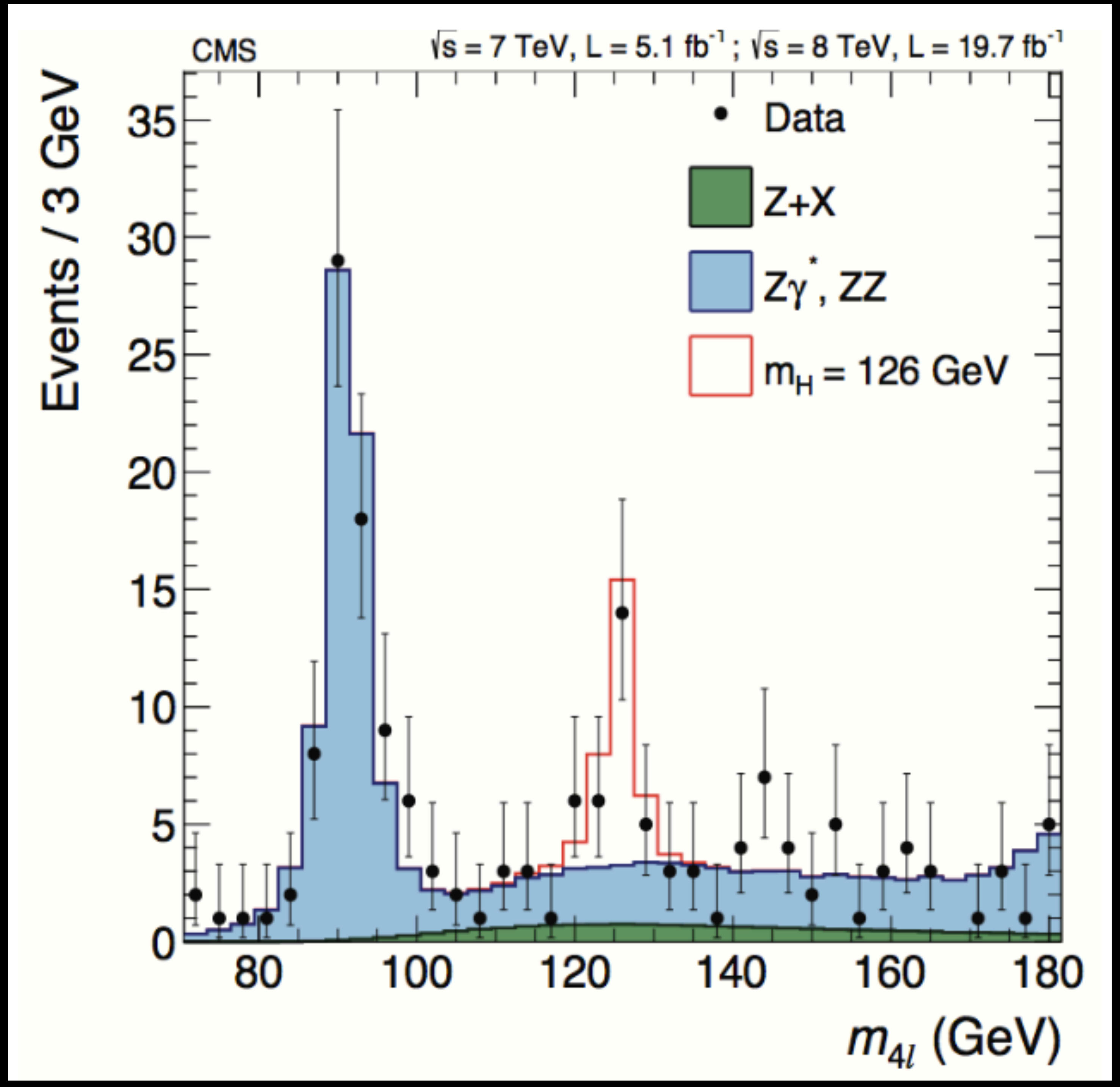


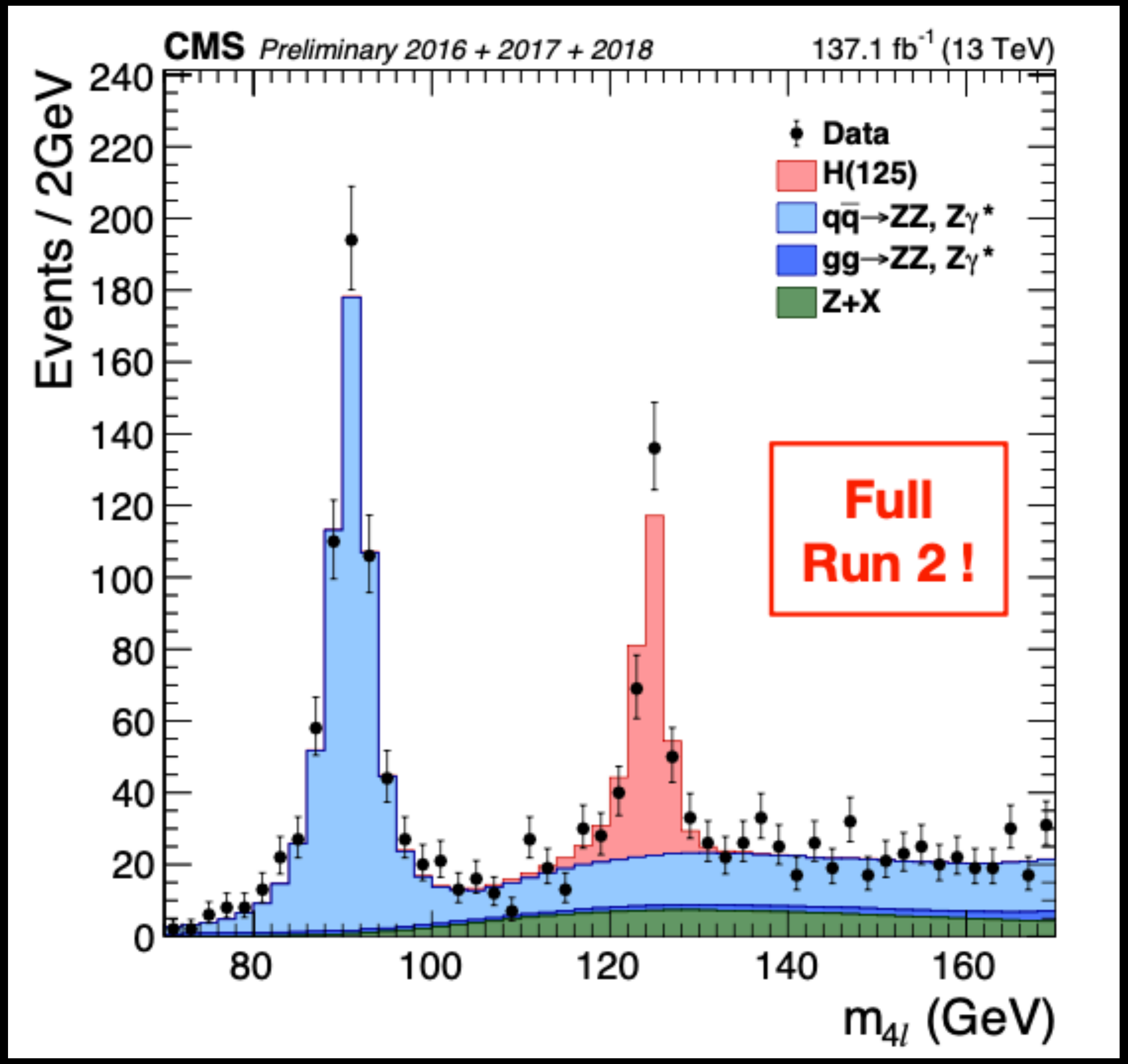


Very high S/B ratio

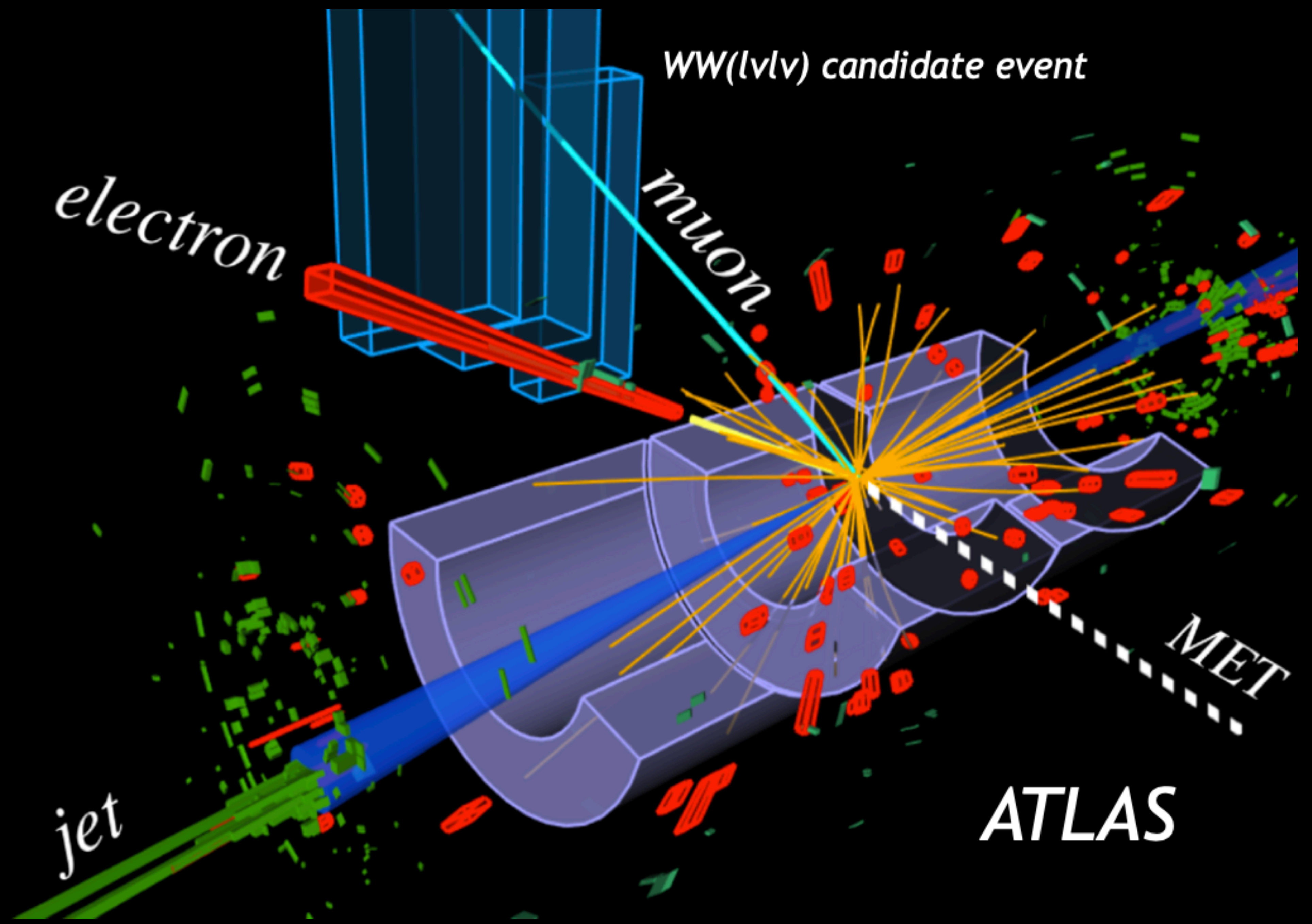
Backgrounds can be estimated from MC

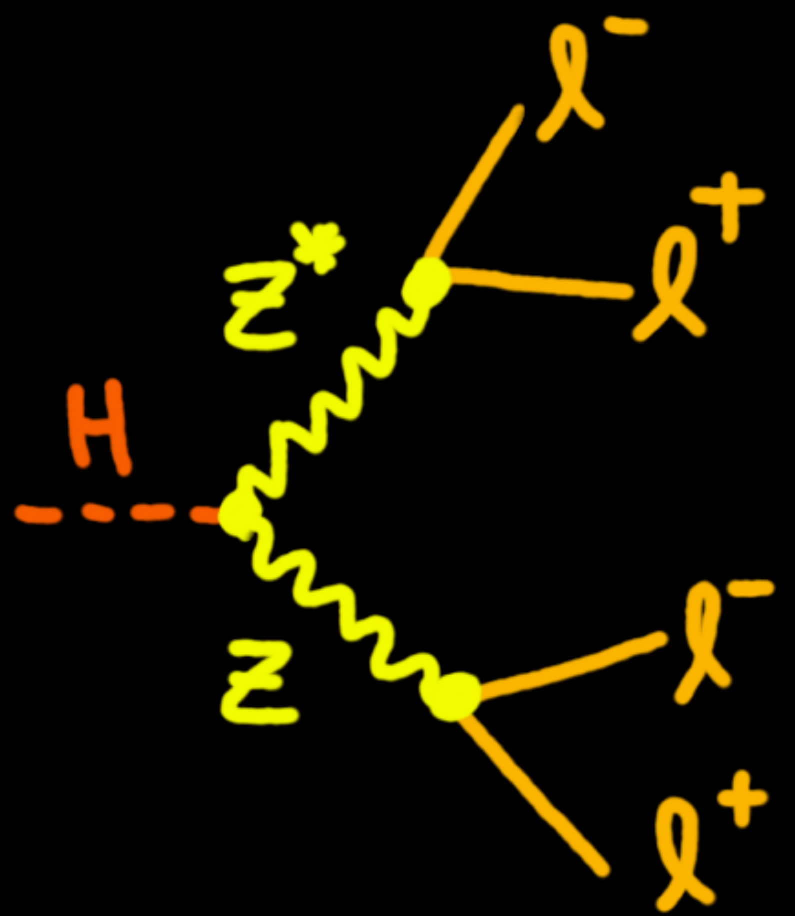
Polarization can be reconstructed





Discovery channel: WW



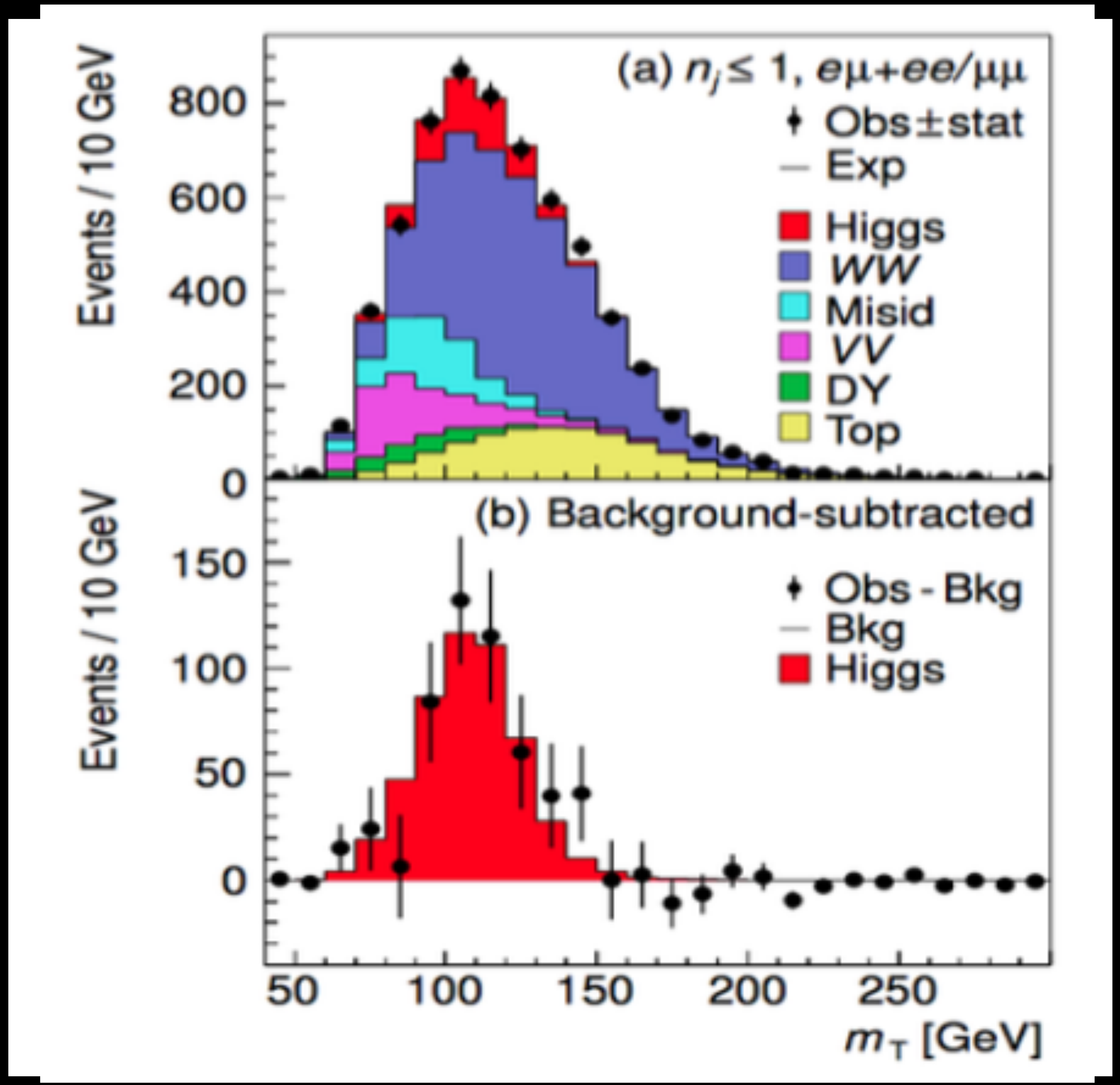


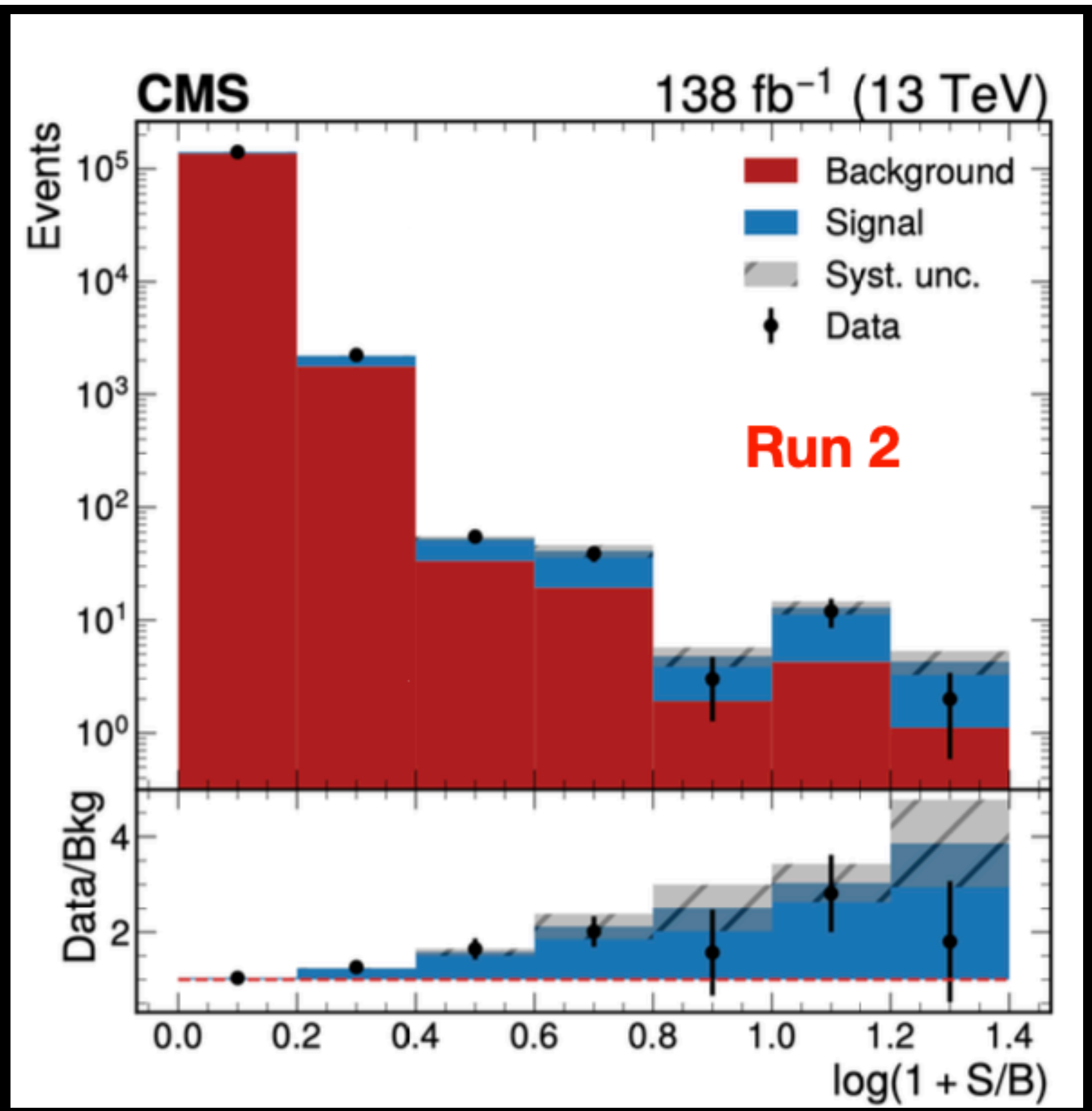
Large event rate

but

Large background from SM WW and top quark production

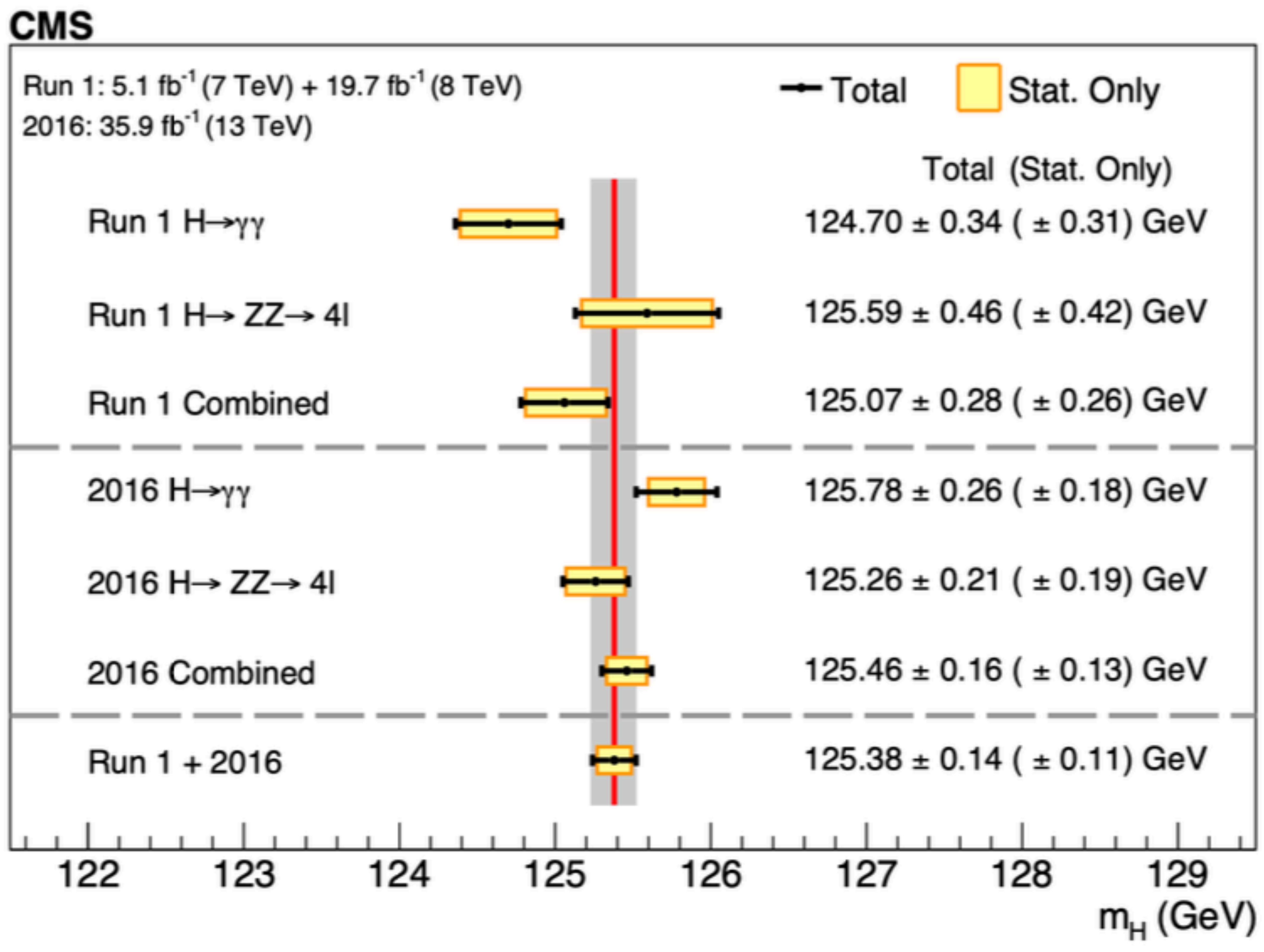
Mass resolution spoiled by the presence of neutrinos

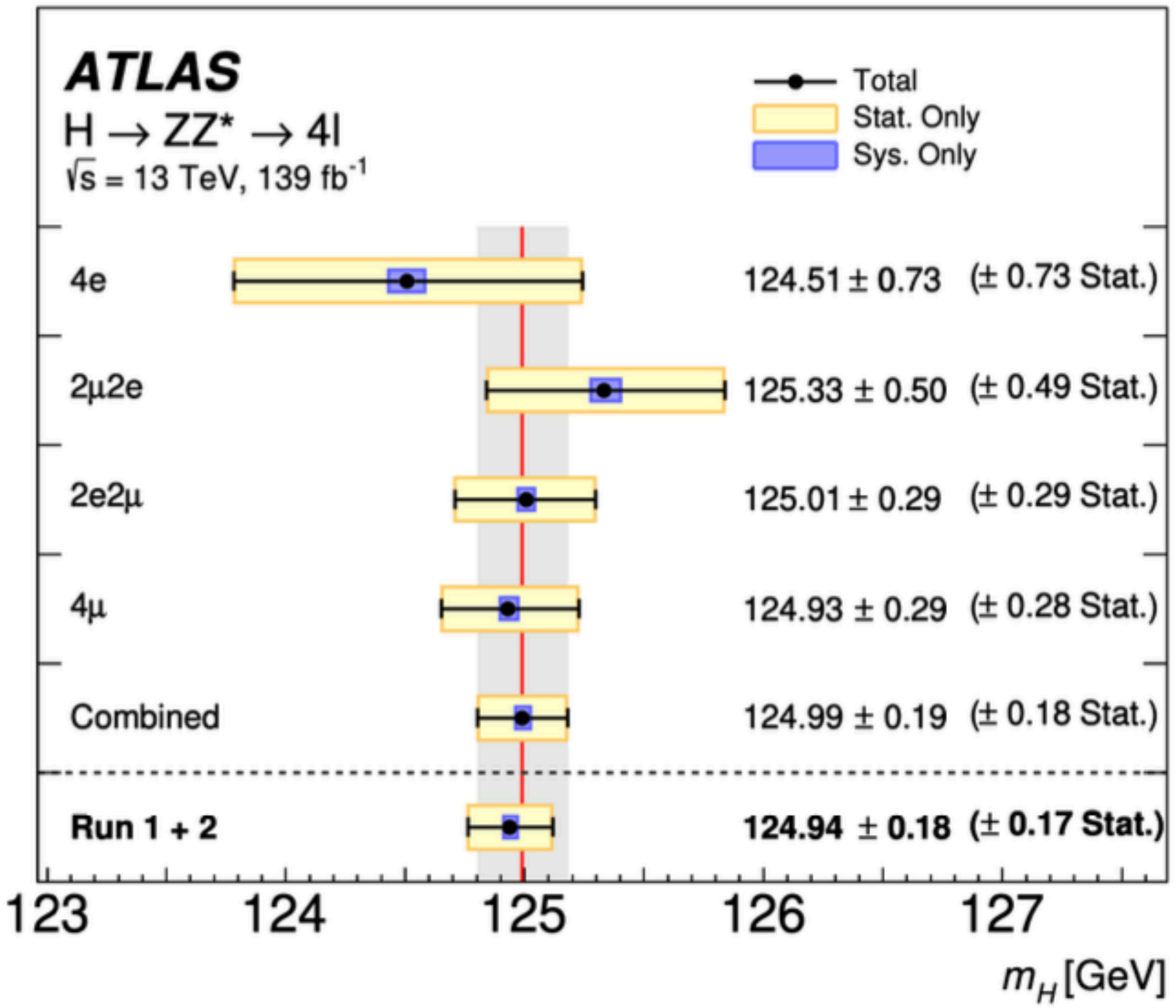




Higgs boson mass

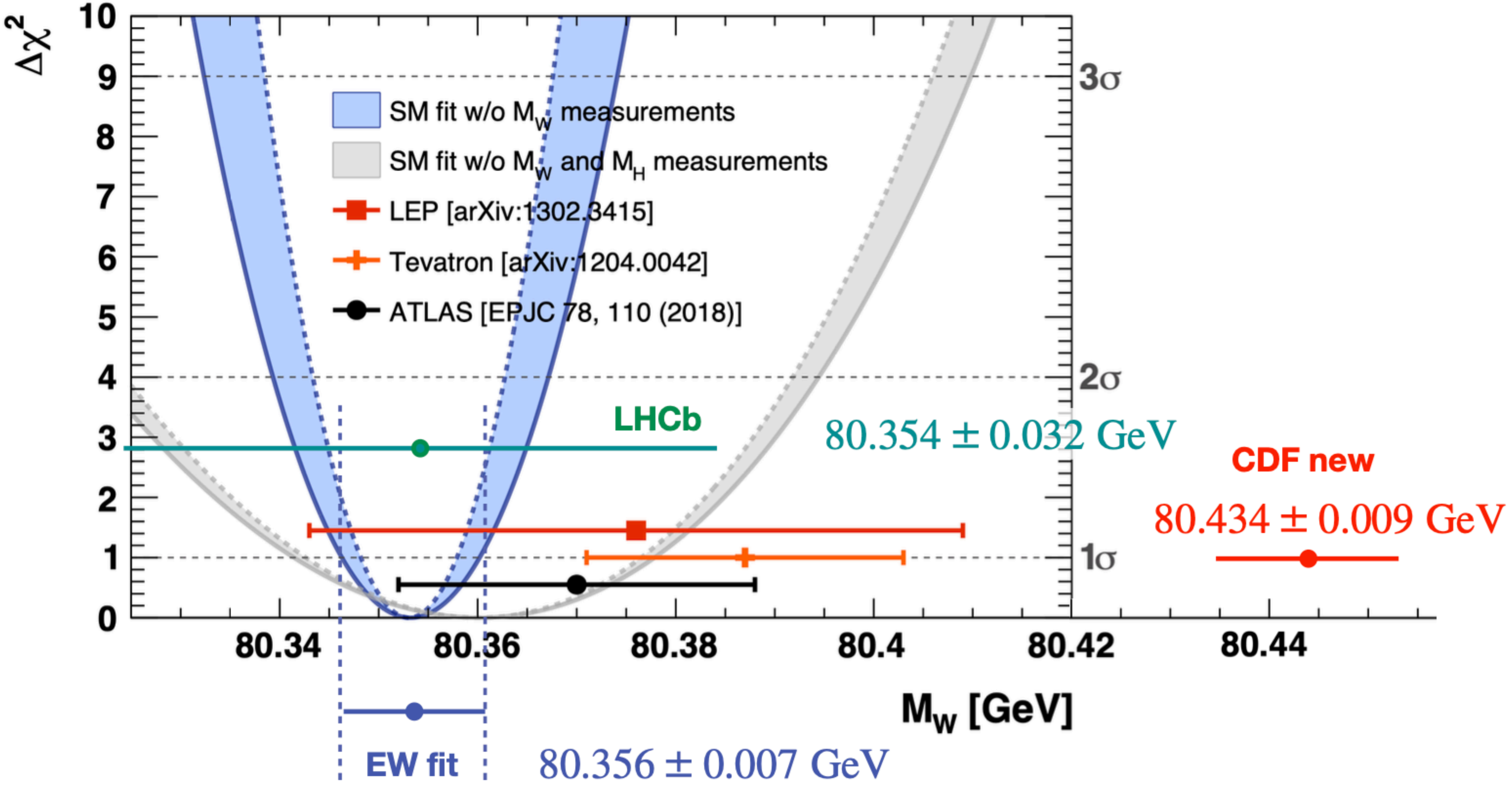
Measurement done exclusively in the di-photon and 4-leptons channels





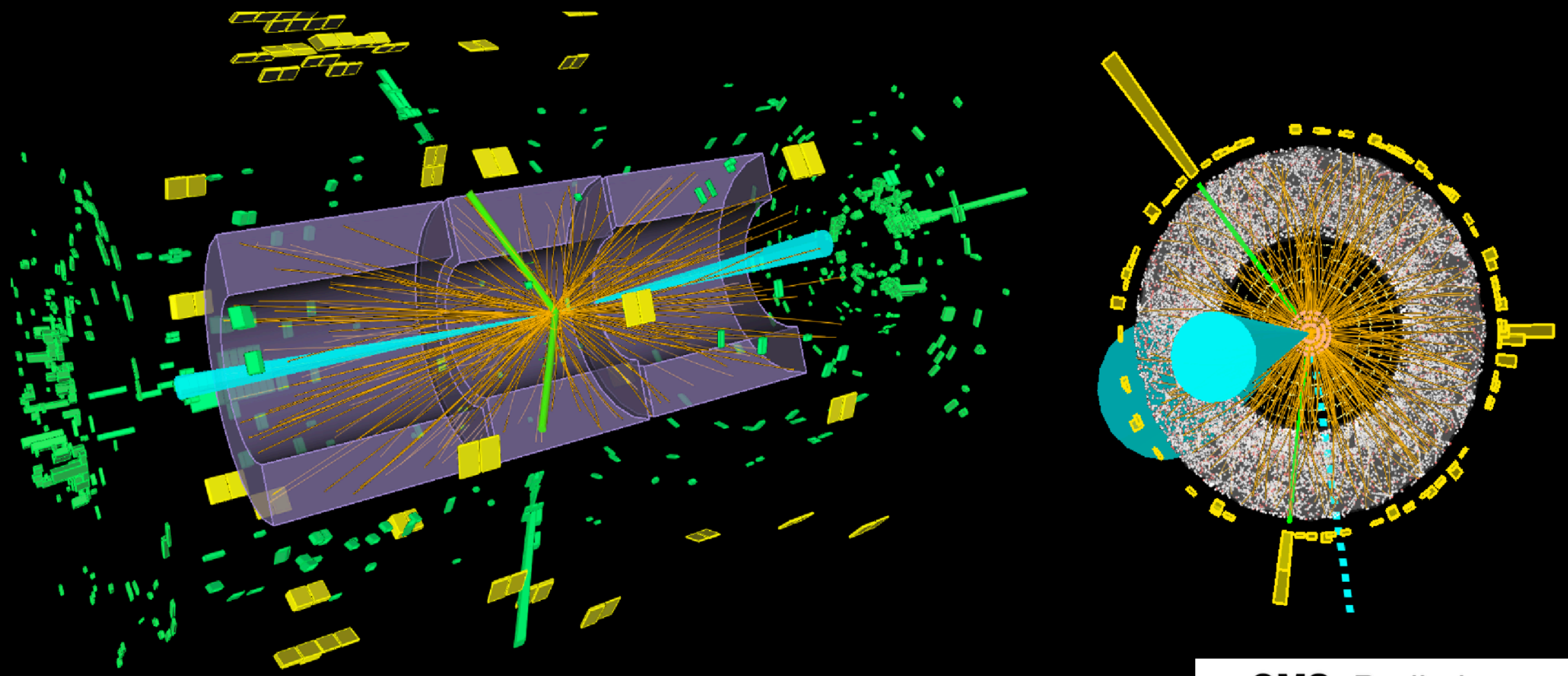
0.11% uncertainty

Precision measurements and predictions

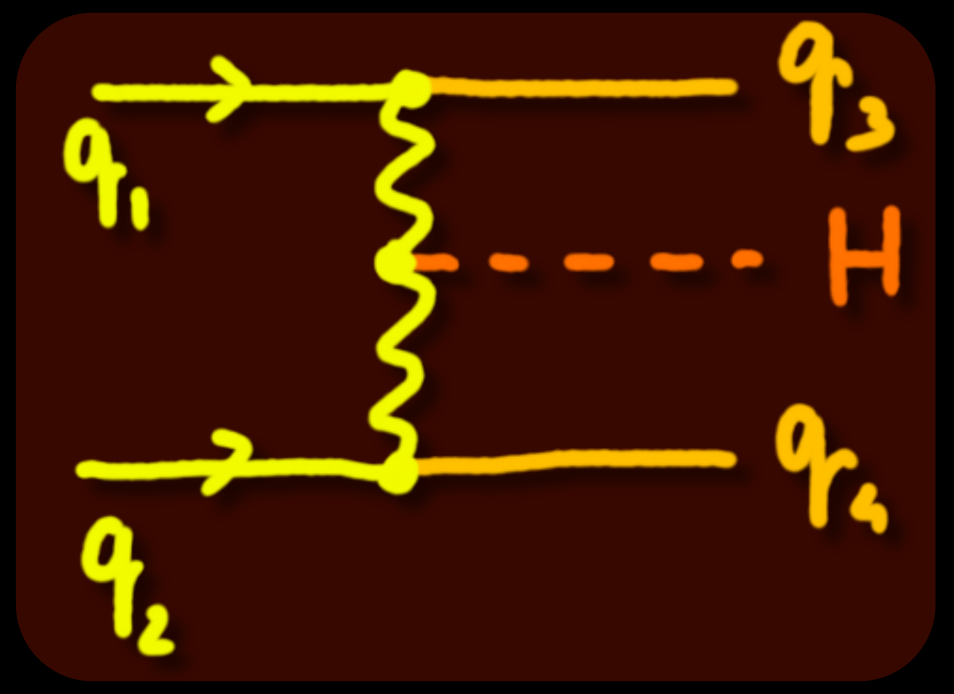


The knowledge of the Higgs mass has large impact on the precision of indirect measurements!

Higgs observation in tau channel

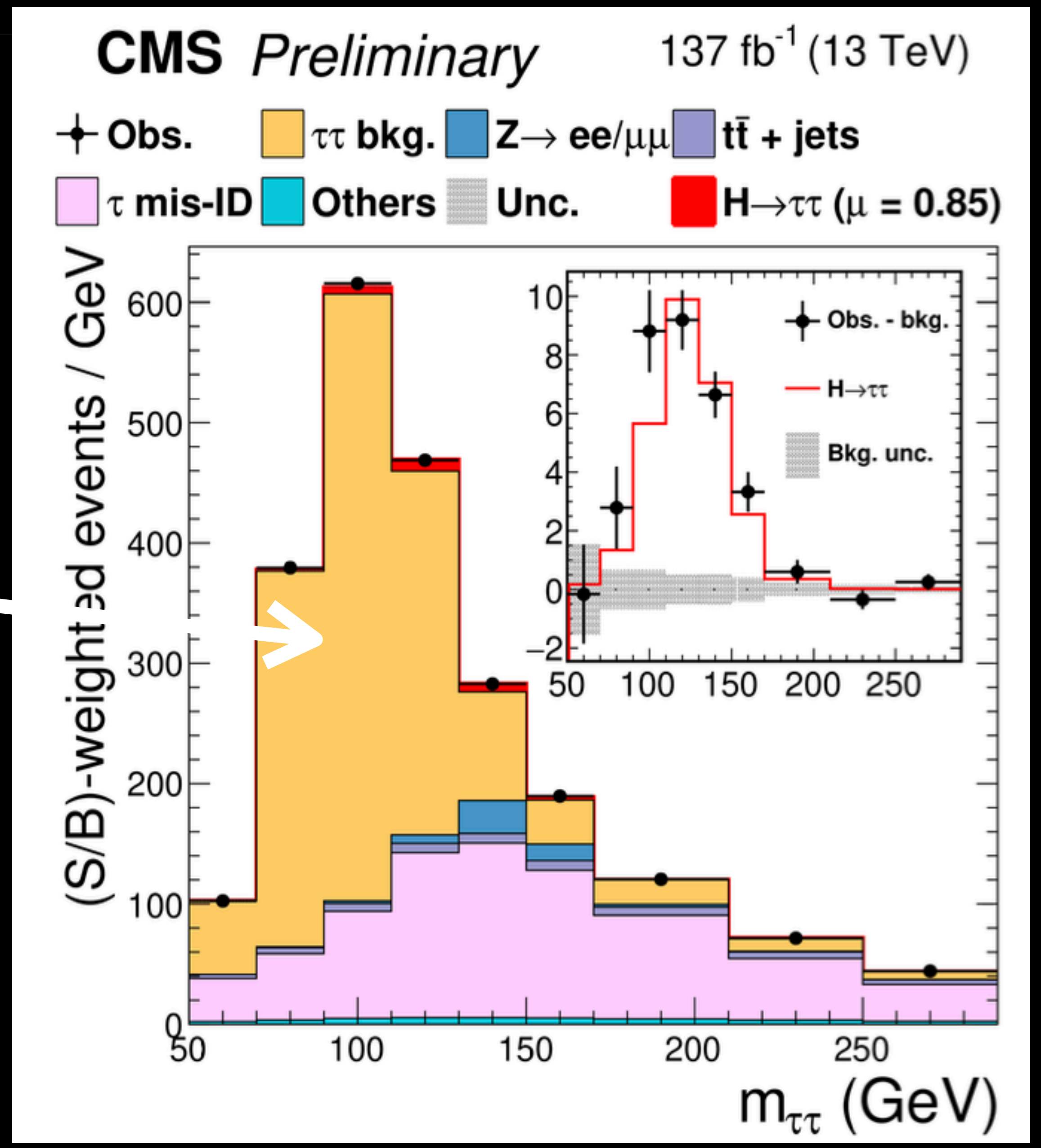


VBF process

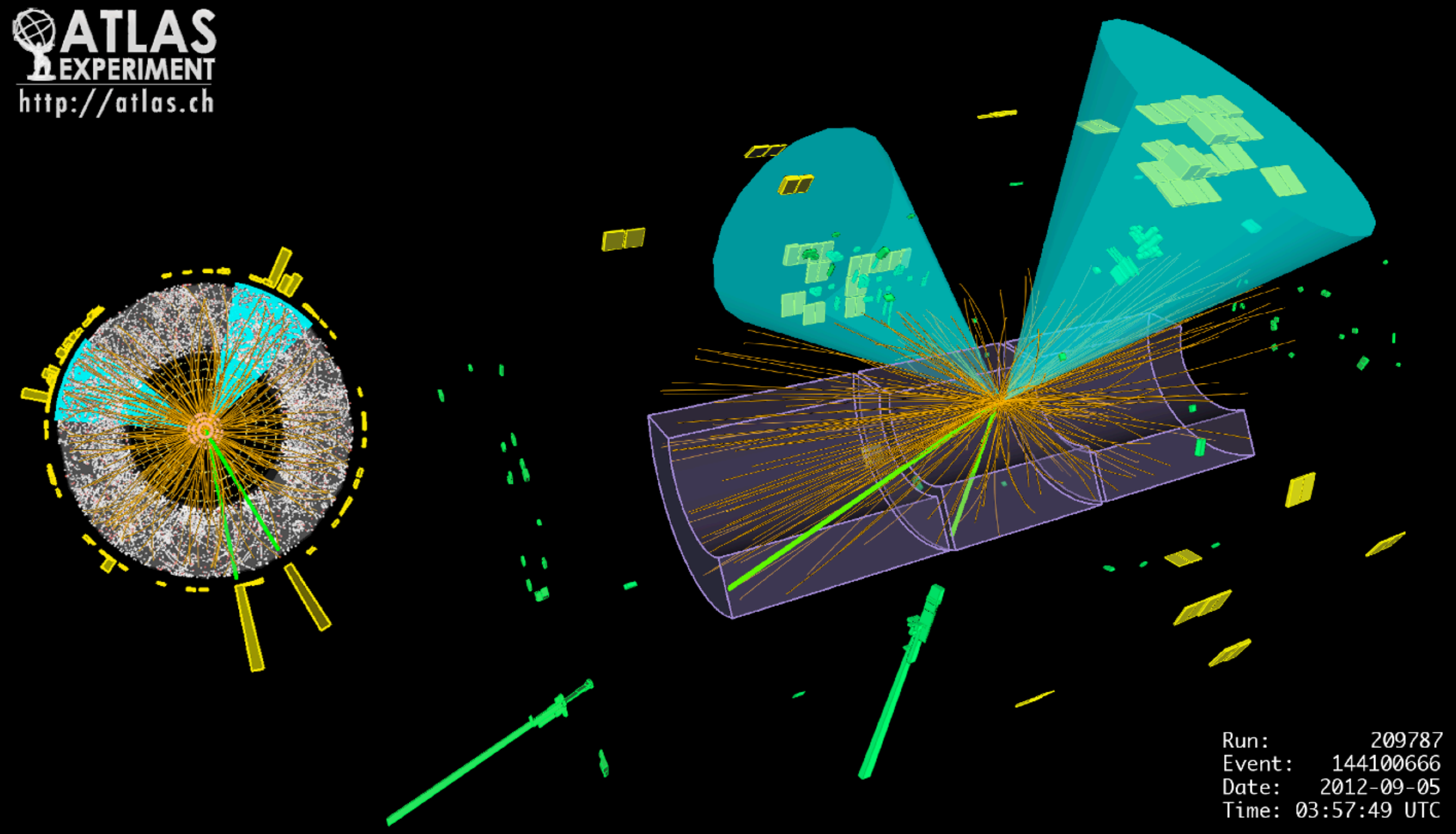


with two forward jets

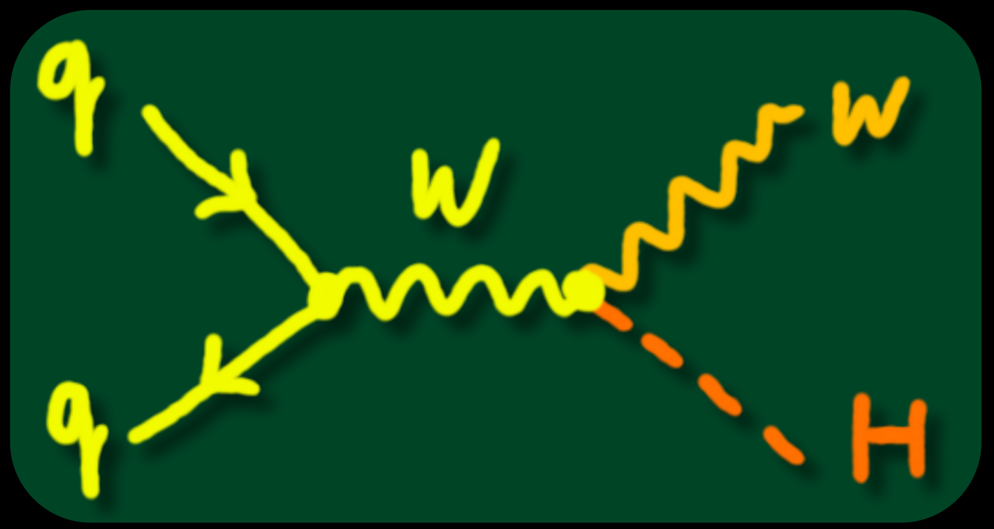
background
from Z production
plus 2 jets

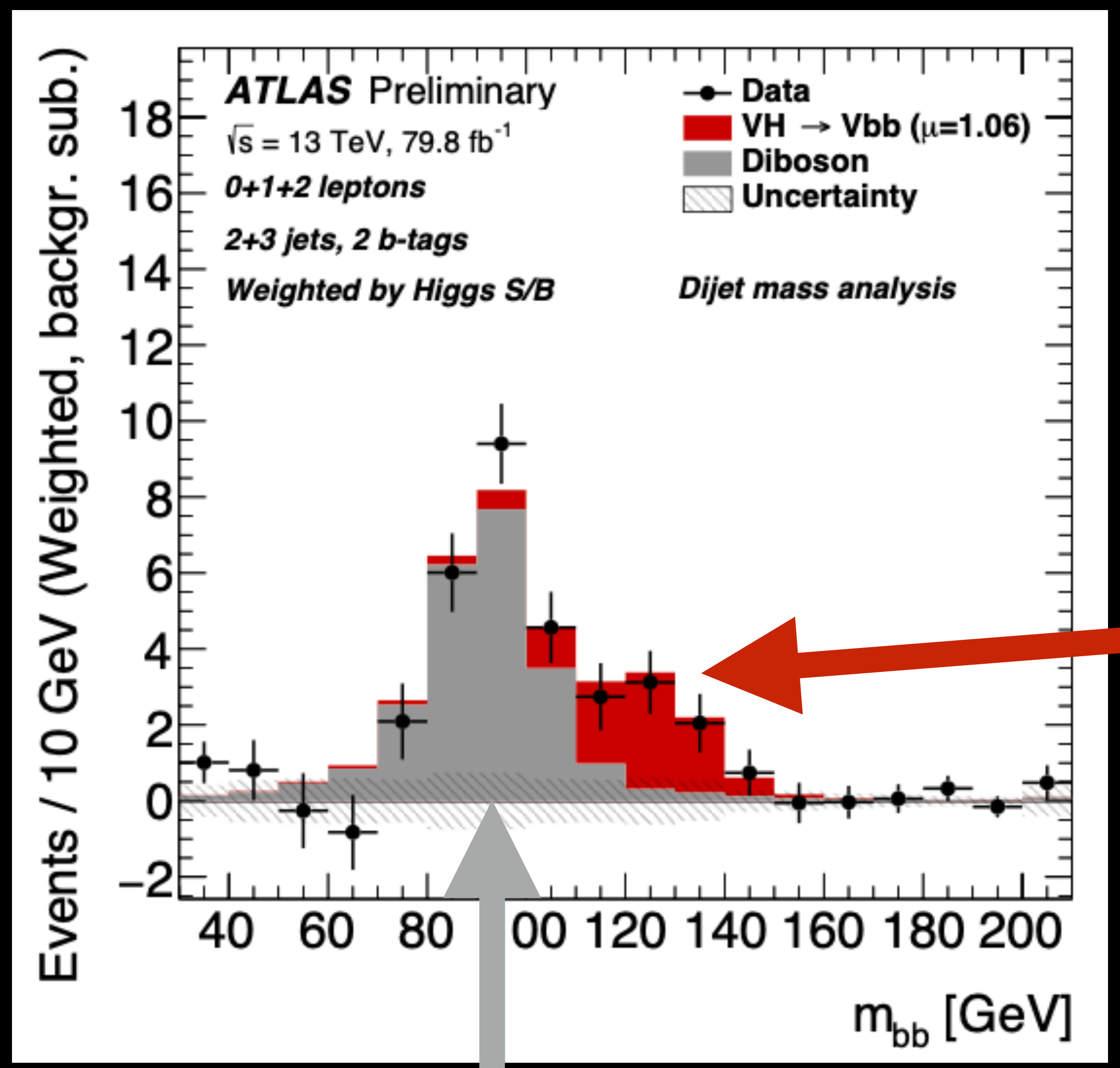


Higgs observation with b-quark decays



W/Z associate process

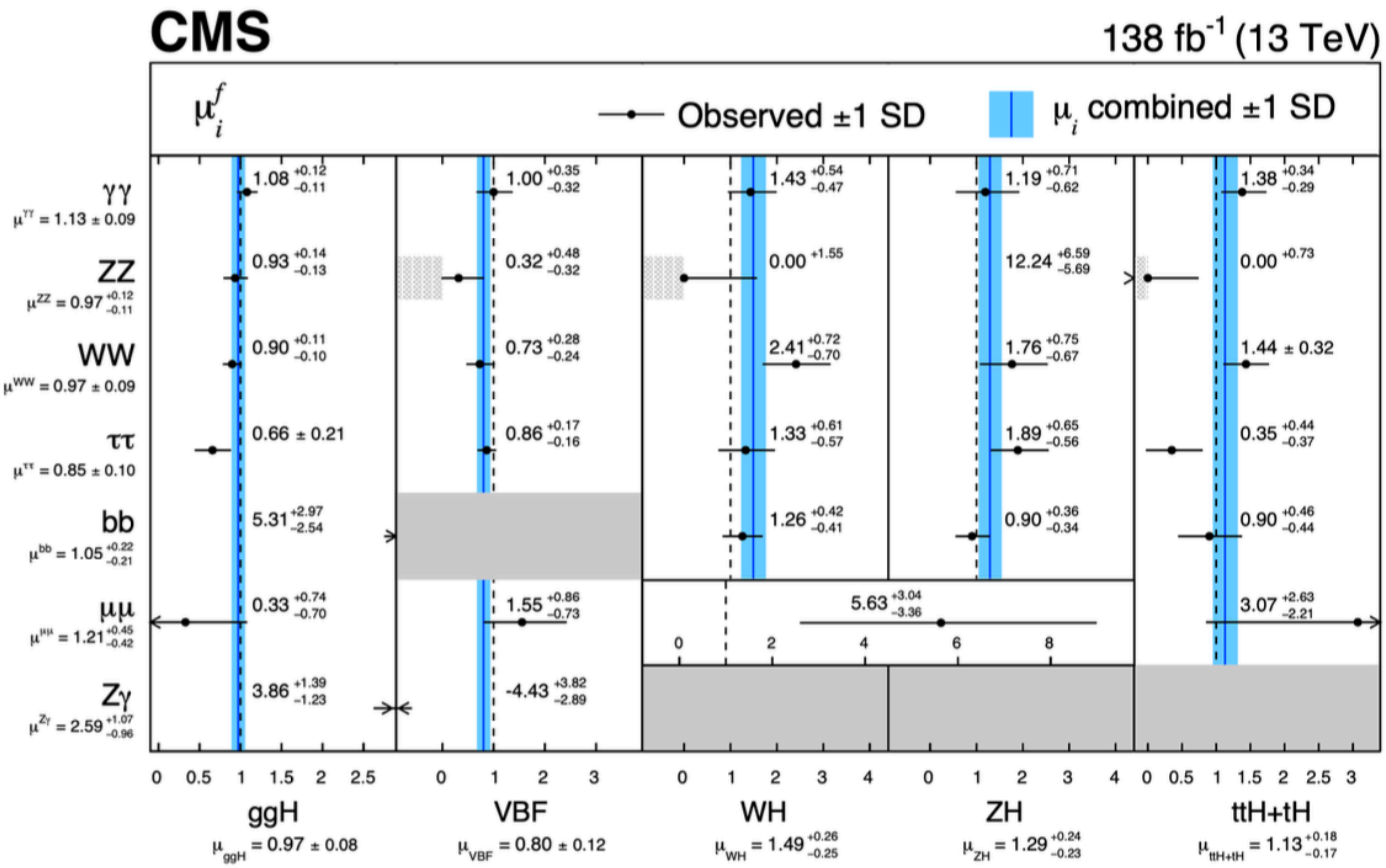




Higgs into b-quarks

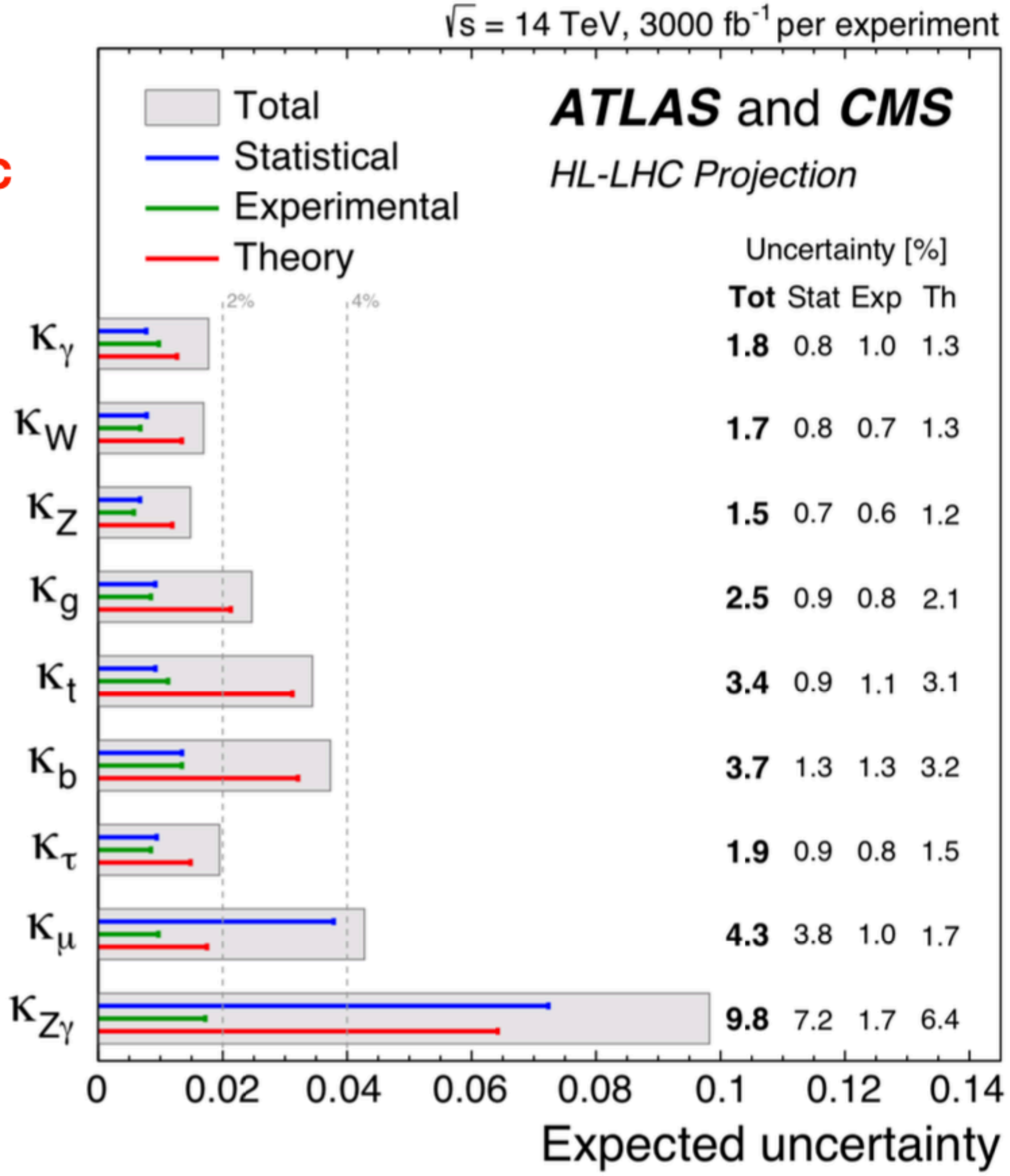
Z decays into b-quarks

Overview of the Higgs Boson exploration



Higgs Boson Coupling Precision at LHC and HL-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

What we know about the Higgs

- Gives mass to the **W** and **Z** bosons
- Gives mass to 3rd generation fermions via Yukawa interaction
- Evidence it couples to the 2nd generation fermions as expected
- Has spin 0
- Not composite (down to 10^{-19} m)

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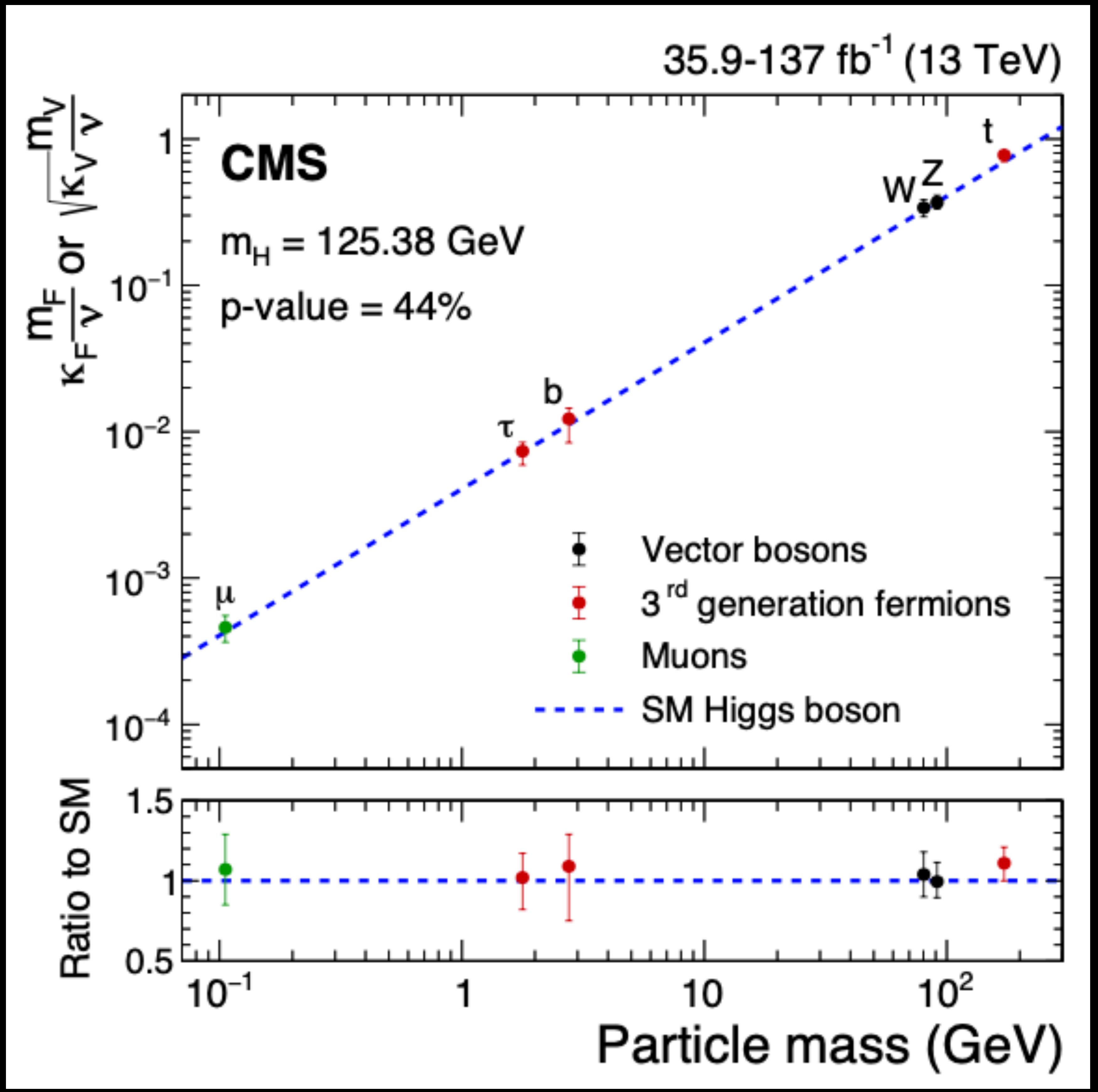
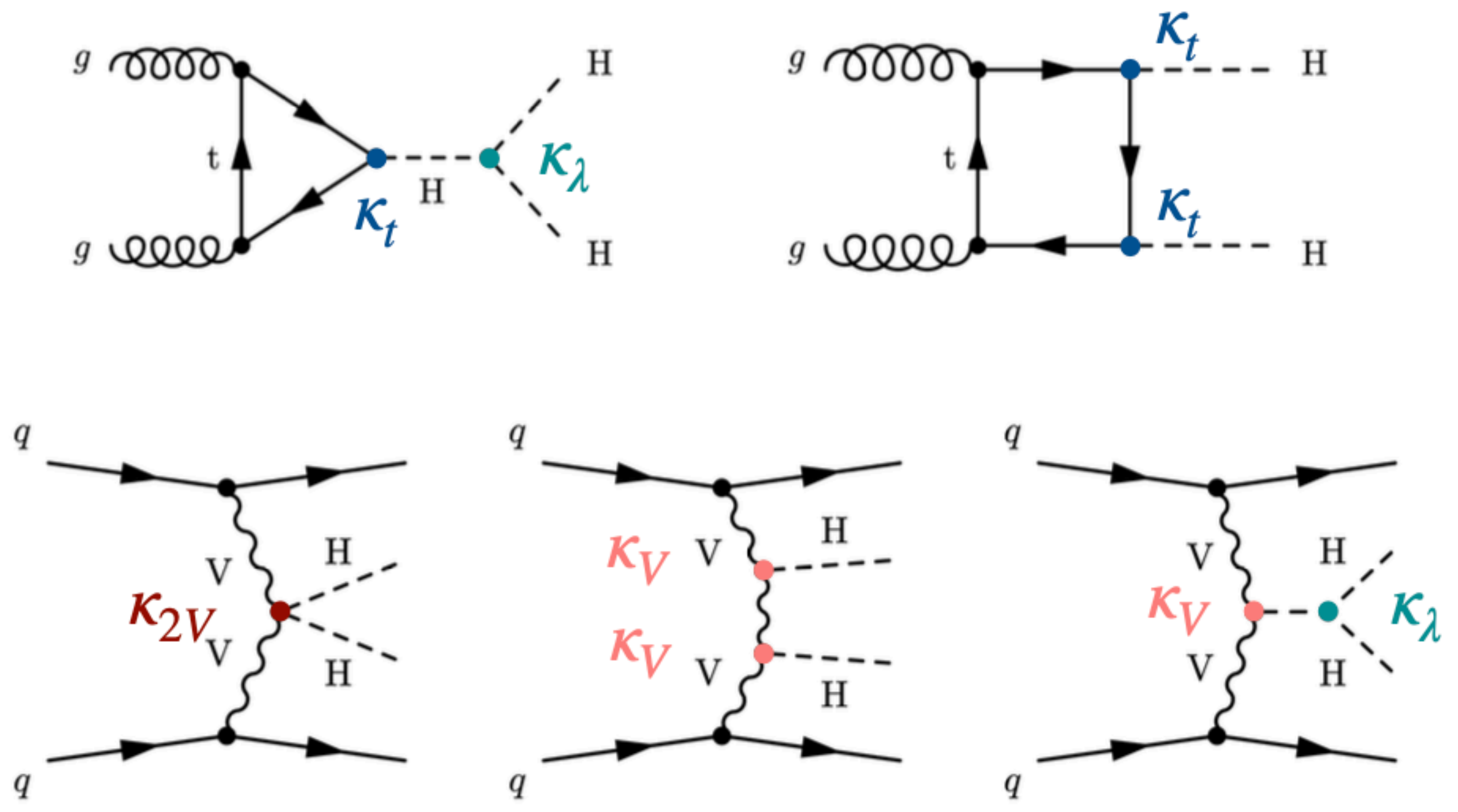


Di-Higgs Production and Higgs Self Coupling

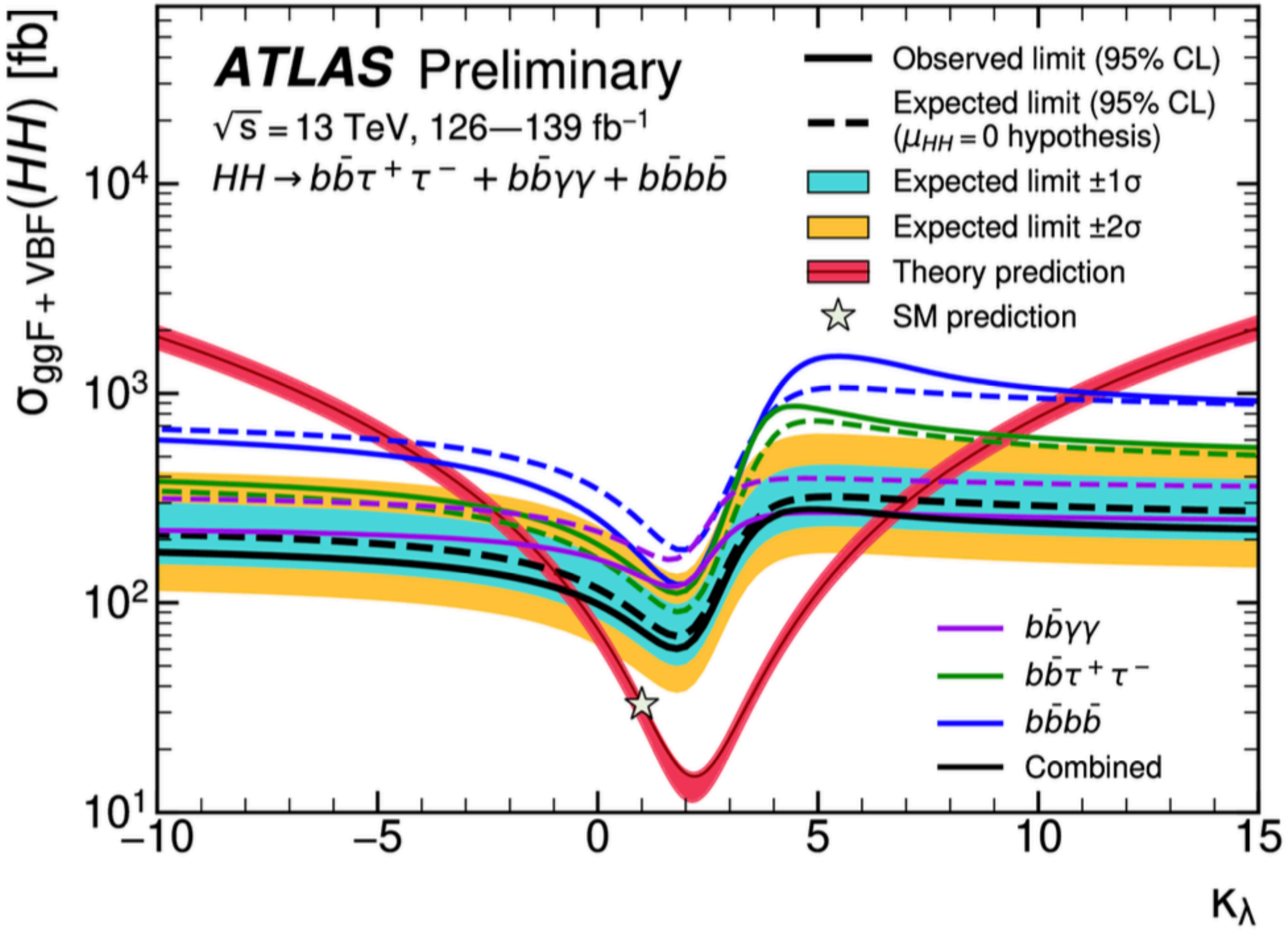
Higgs pair production through gluon fusion and VBF



Cross section ~1000× smaller than Higgs production still

Expect ~100k events produced at HL-LHC

Multiple channels being investigated to maximize sensitivity: bb, γγ, ττ , WW

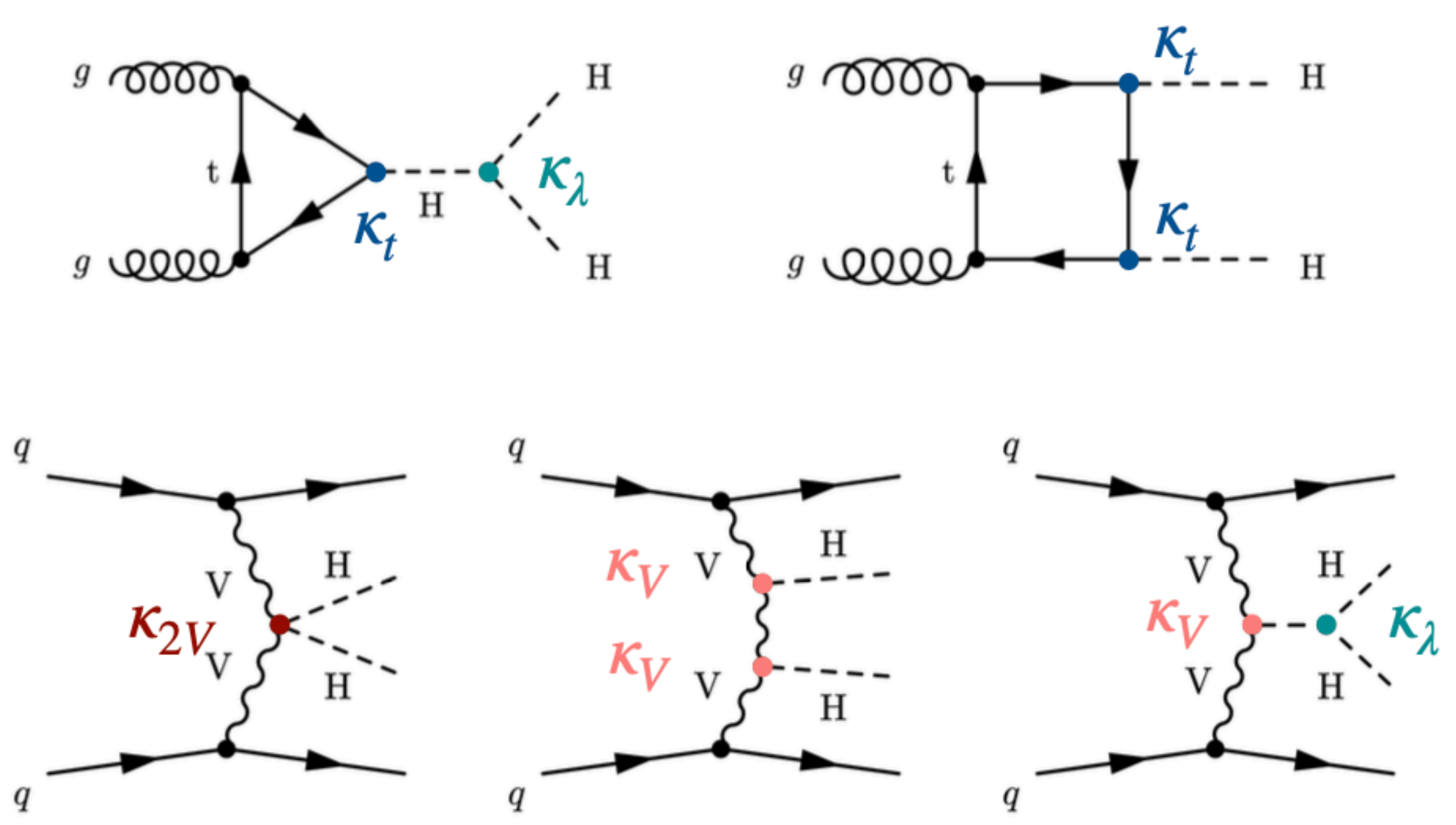


ATLAS

Observed	$-0.4 < \kappa_\lambda < 6.3$
Expected	$-1.9 < \kappa_\lambda < 7.5$

Di-Higgs Production and Higgs Self Coupling

Higgs pair production through gluon fusion and VBF

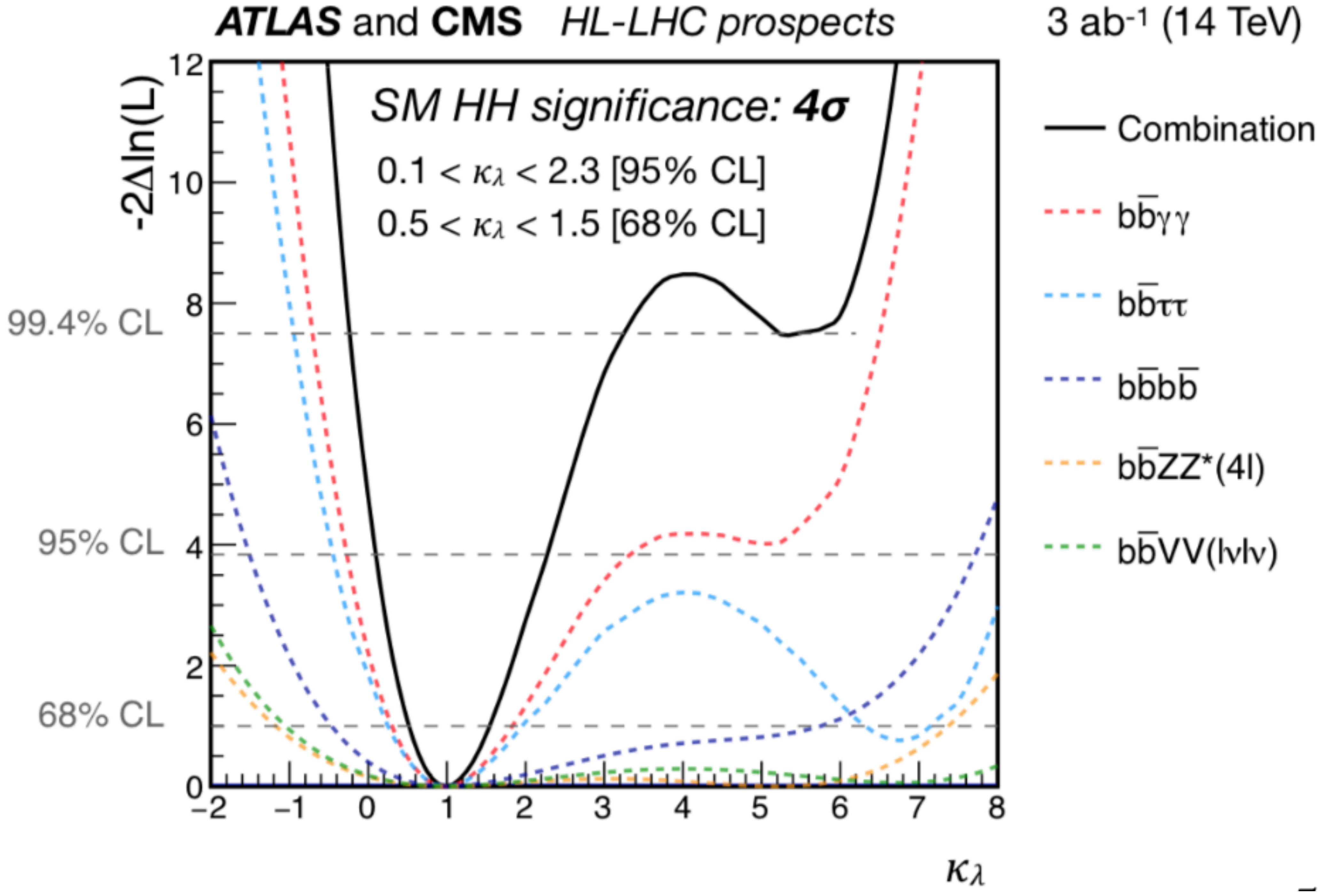


Cross section ~1000× smaller than Higgs production still

Expect ~100k events produced at HL-LHC

Multiple channels being investigated to maximize sensitivity: bb, γγ, ττ , WW

Prospects for HL-LHC



Possible observation of HH signal at 5σ constraint on the Higgs self coupling of $0.5 < k_\lambda < 1.5$

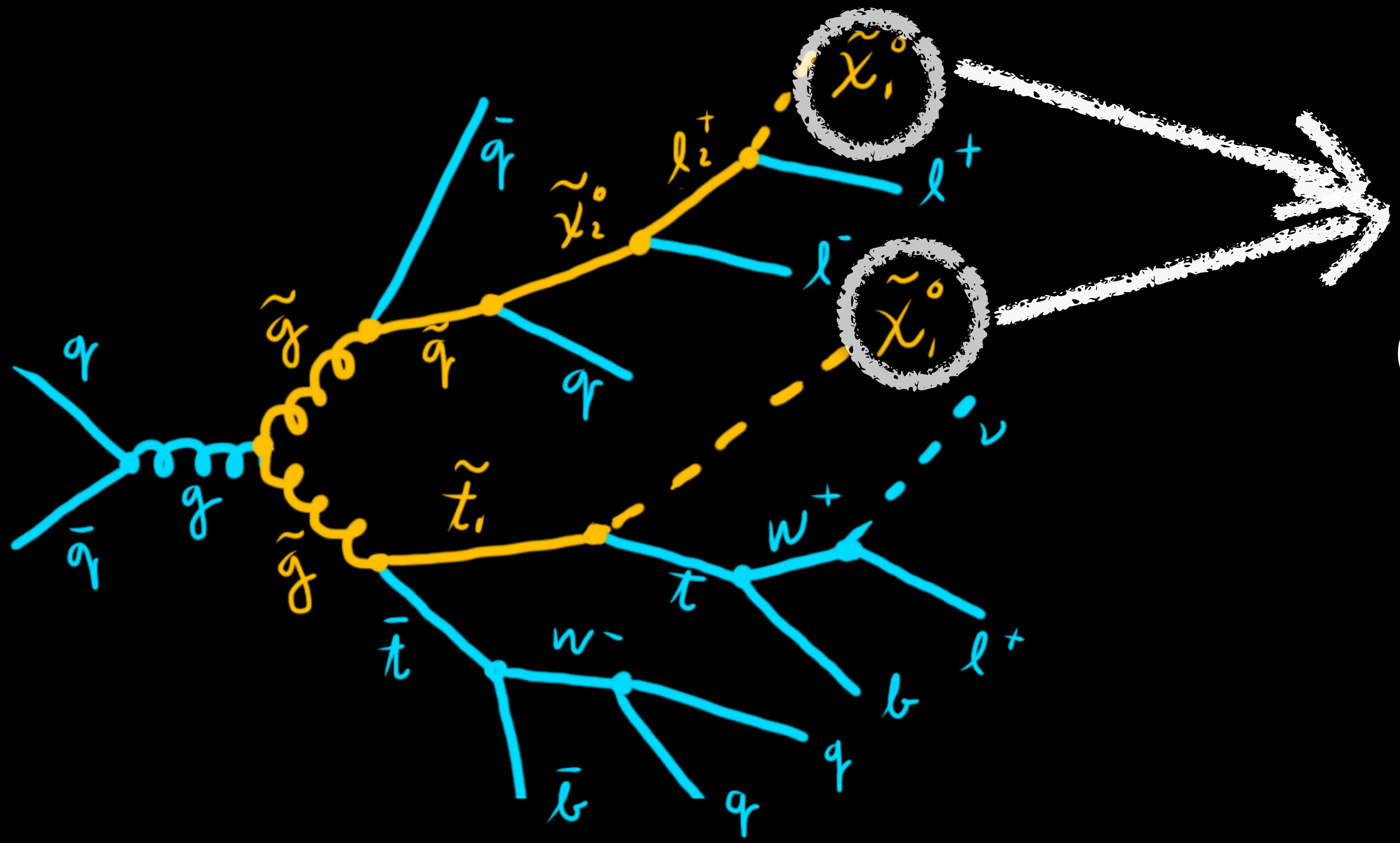
Searches

SUPERSYMMETRY (SUSY)

- **A favorite, ideal, long-time candidate to explain most of questions raised**
  - Symmetry between bosons and fermions, provides dark matter candidate, provides unification of forces, no fine-tuning required for Higgs mass
- **Unfortunately, no evidence for SUSY found yet**

Strong SUSY production

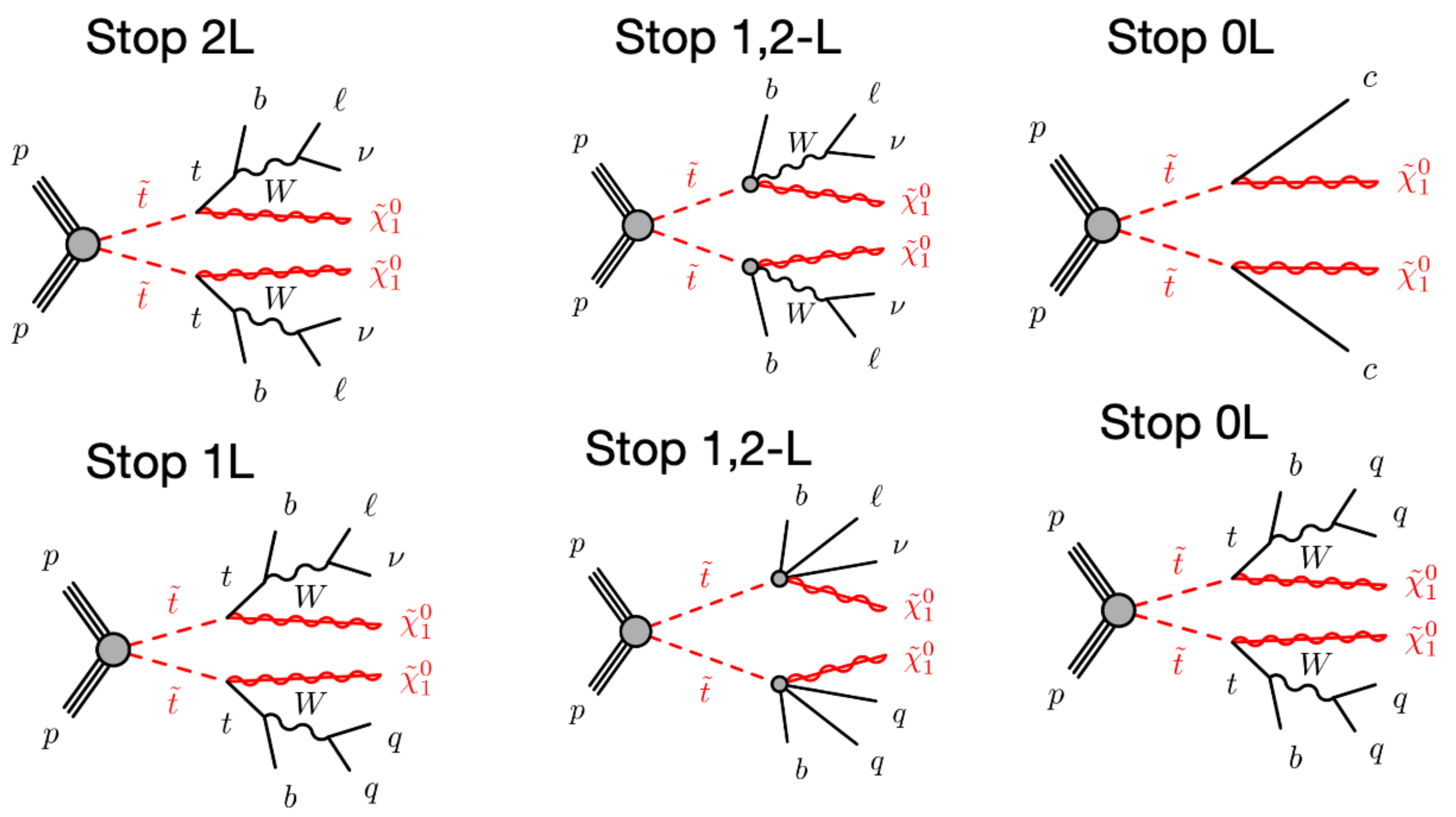
Large cross section



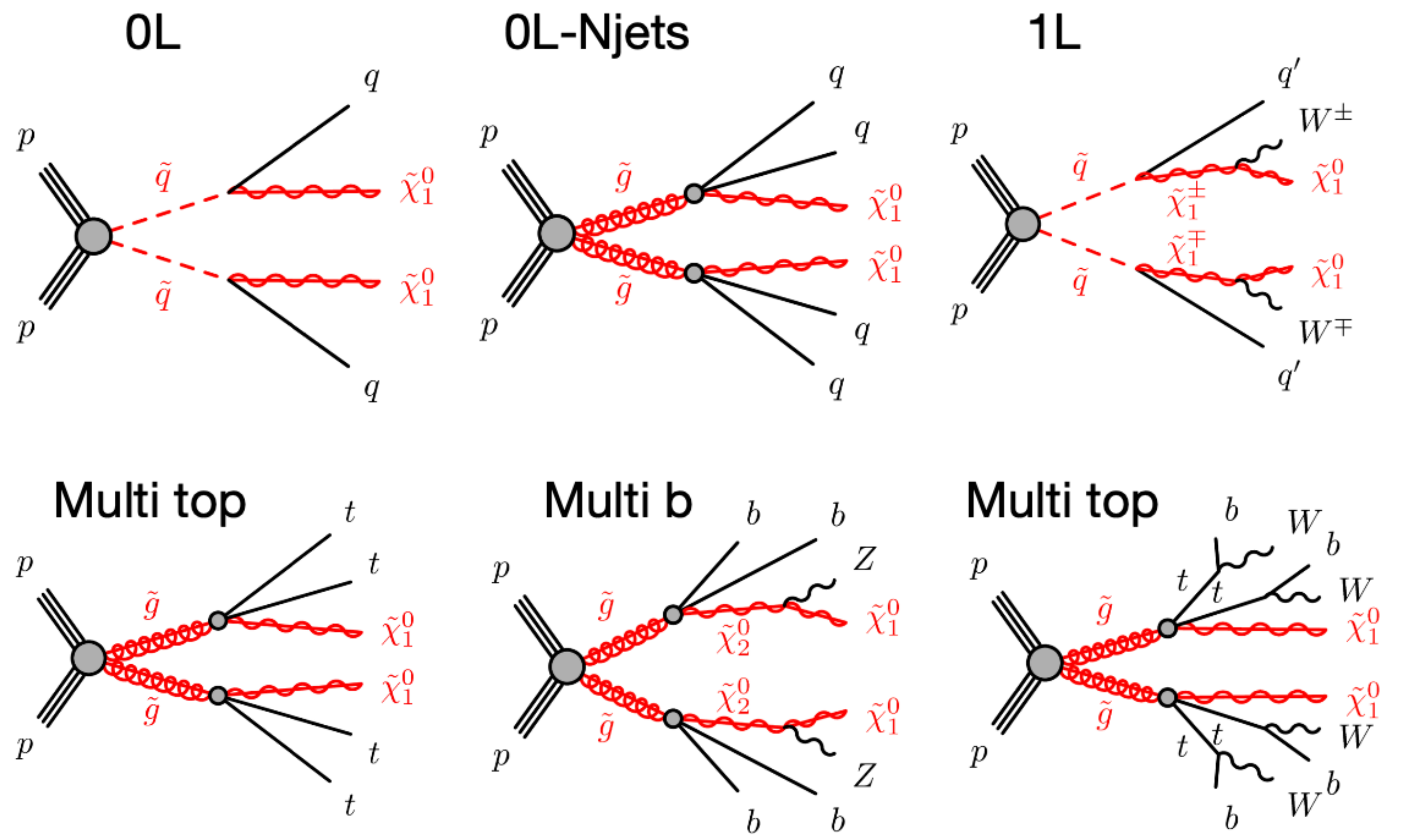
Mass gluino > 2 TeV (depending on models)

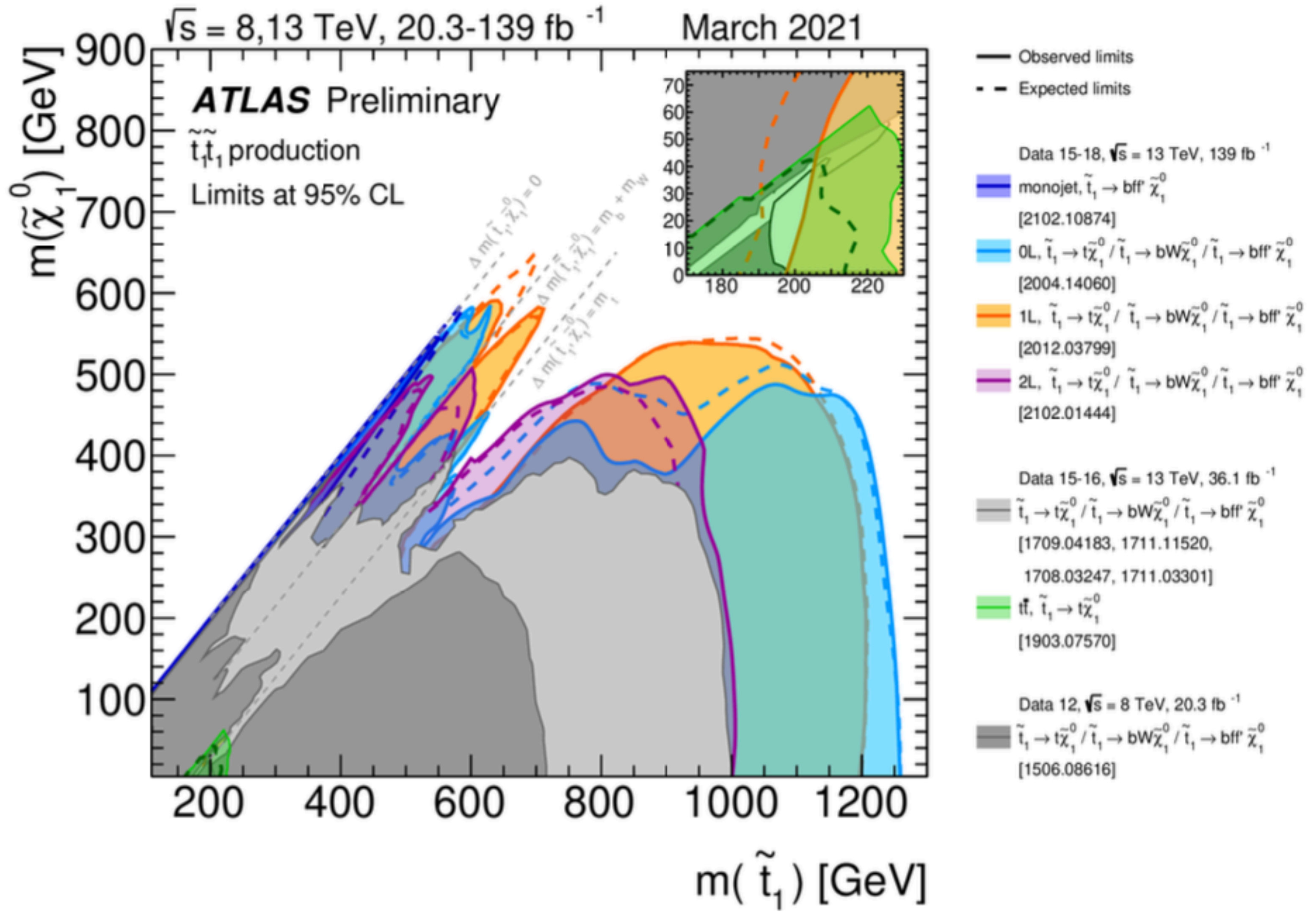
Searches for Natural and Strongly Produced SUSY

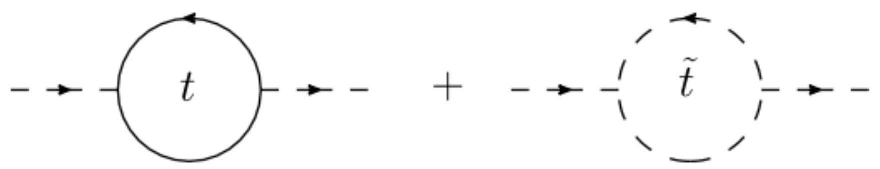
Stop



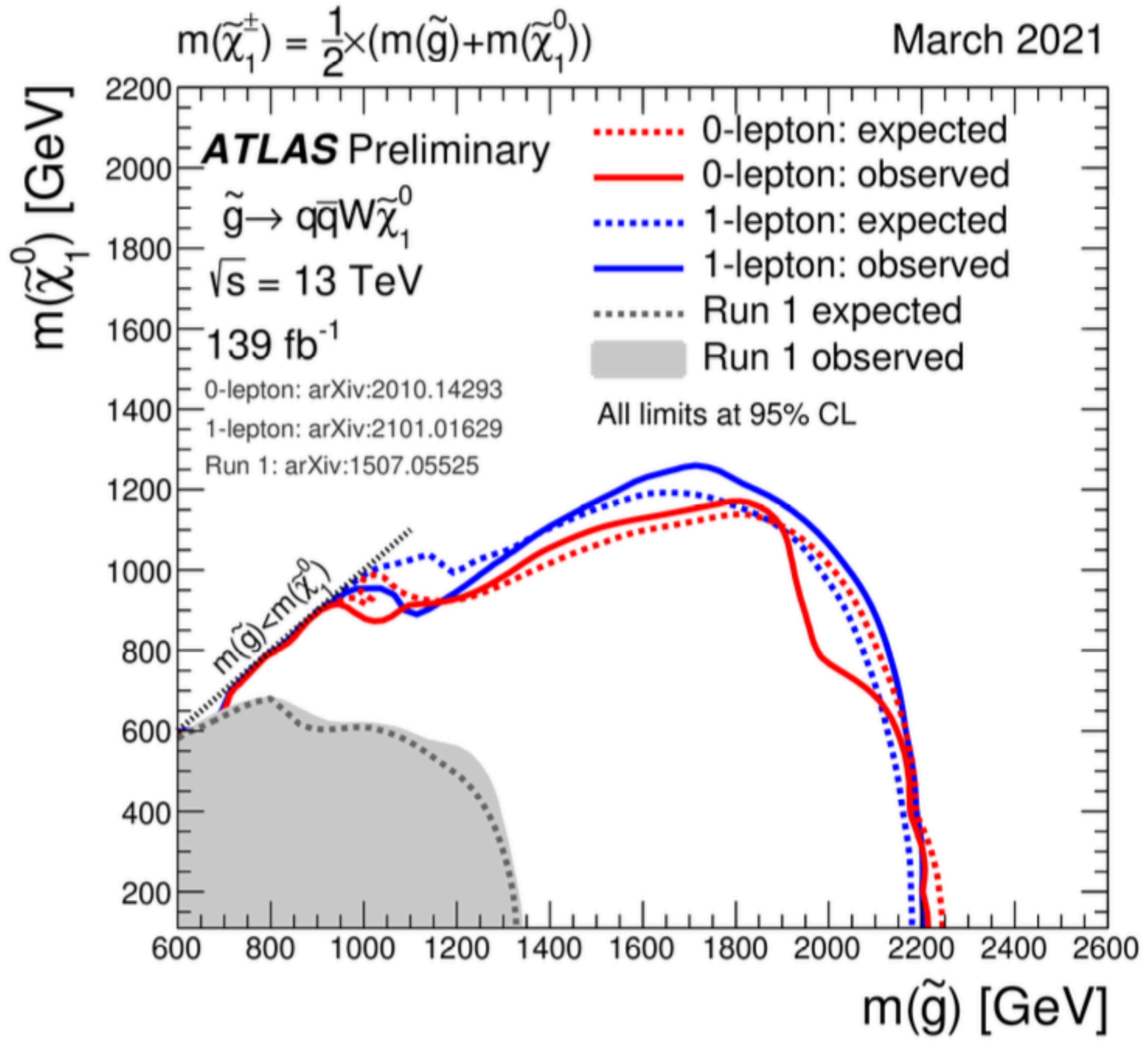
Squarks and gluinos

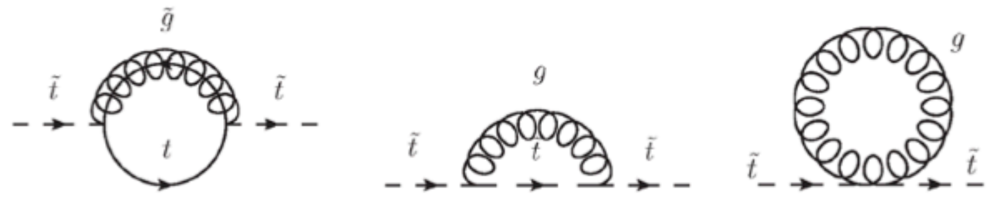






Not so natural SUSY: Stops > 1 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.



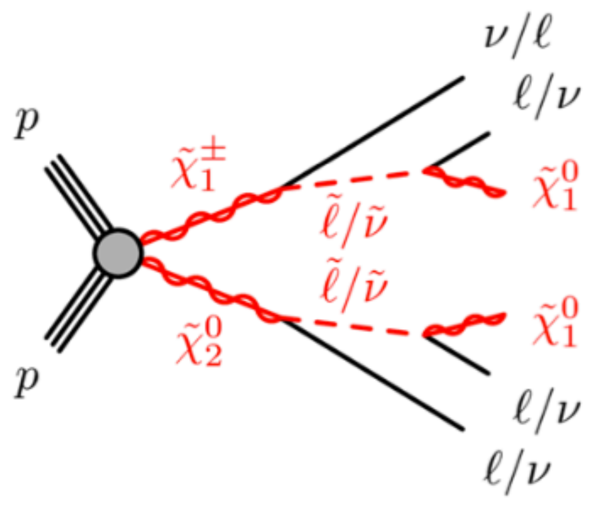


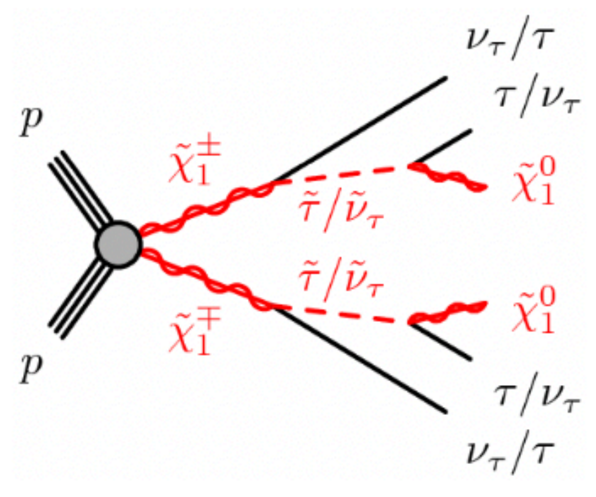
Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

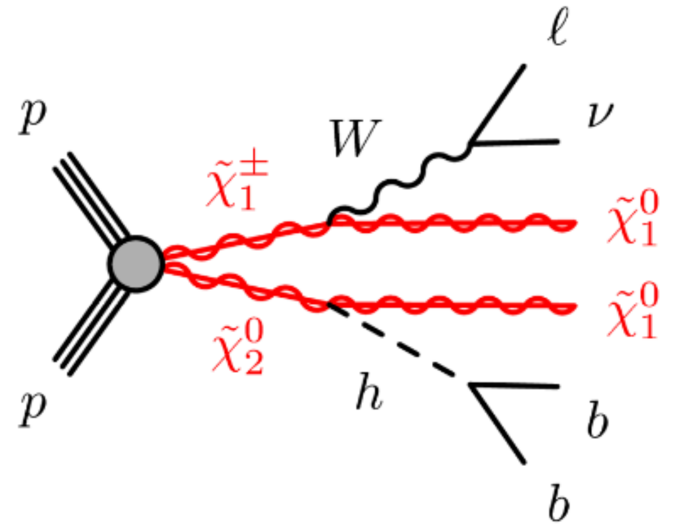
Searches for Weakly Coupled and Complex Scenarios

Weakly produced SUSY

Weak production of charginos, neutralinos and sleptons

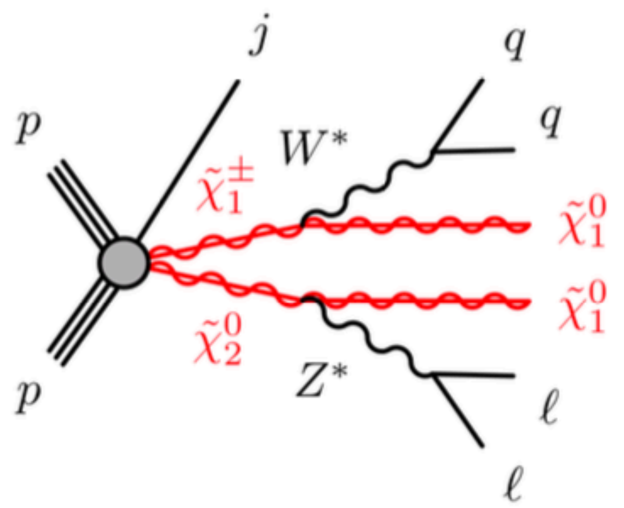


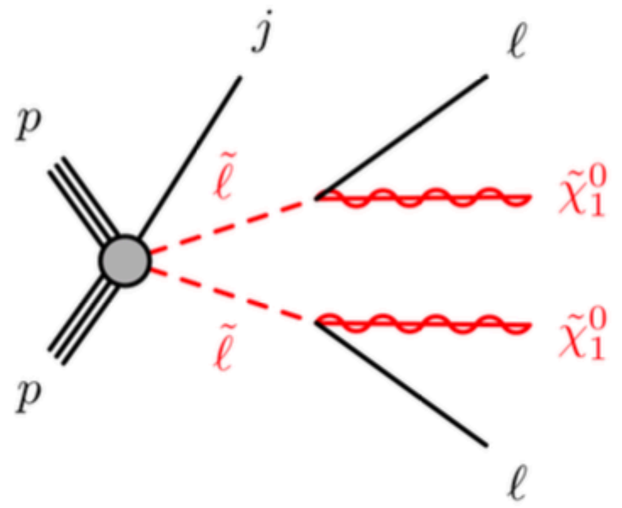




1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

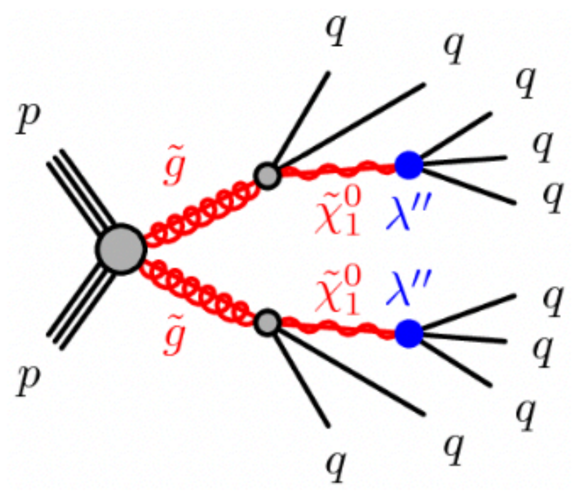
Weak production in **compressed scenarios**

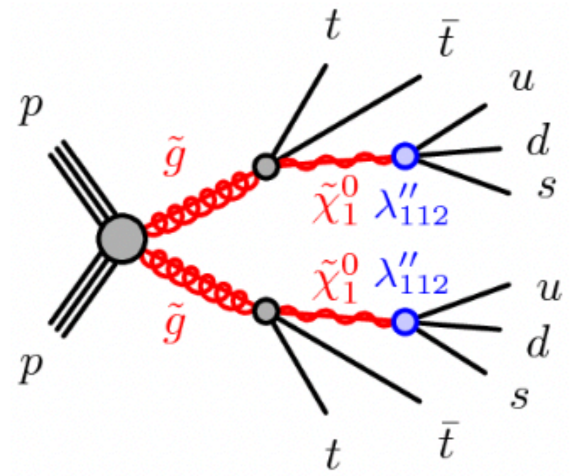


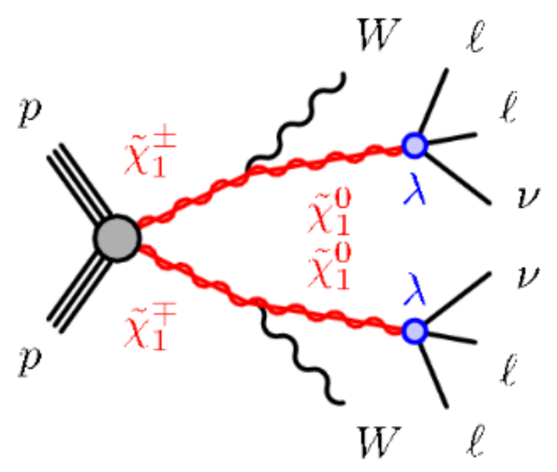


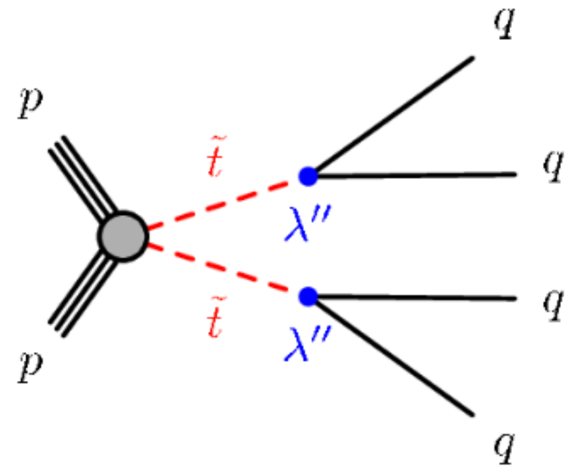
Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY









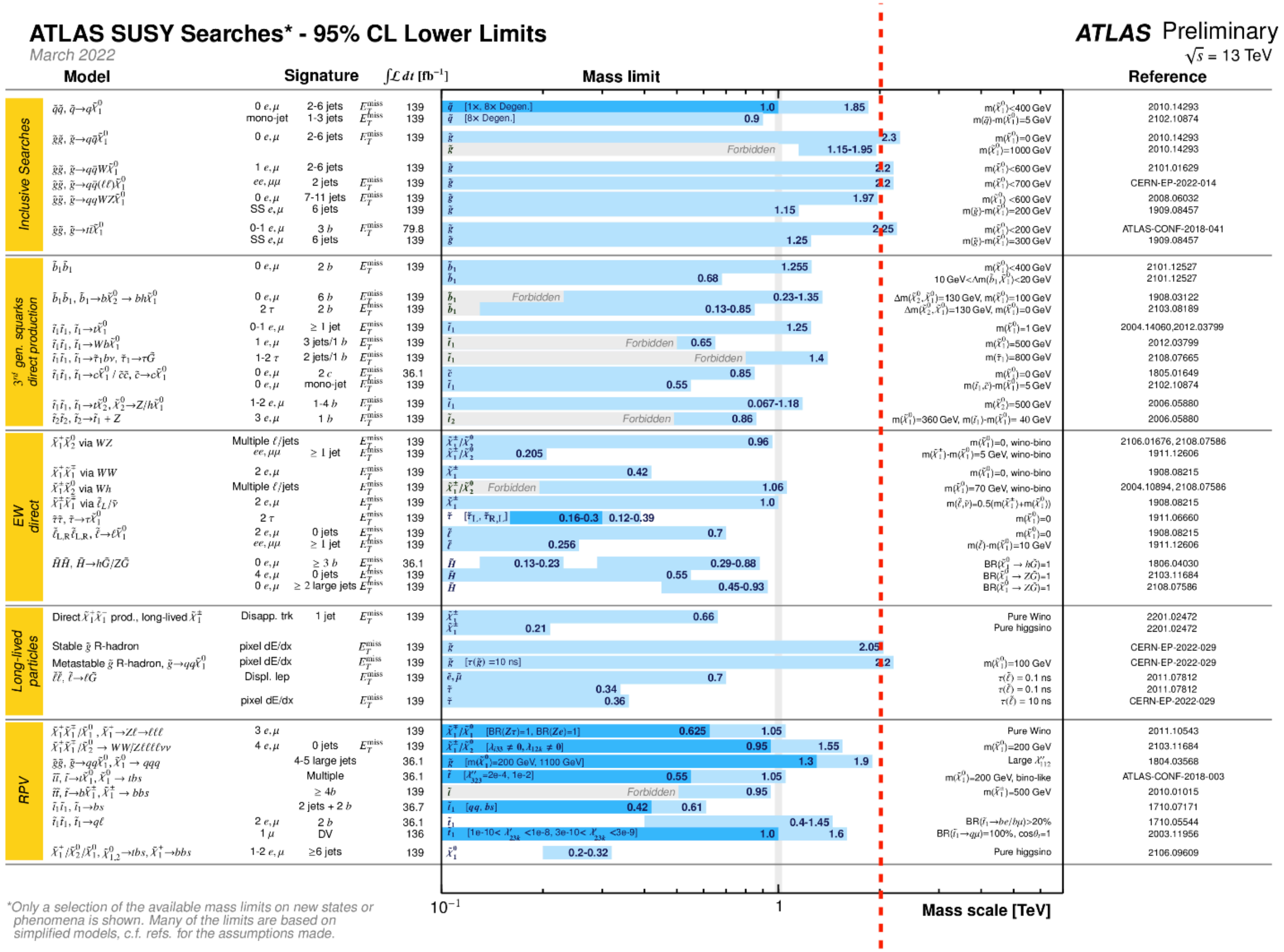
Resulting in topologies without LSP in the final state and therefore no MET.

Rare or complex signatures → more difficult to observe

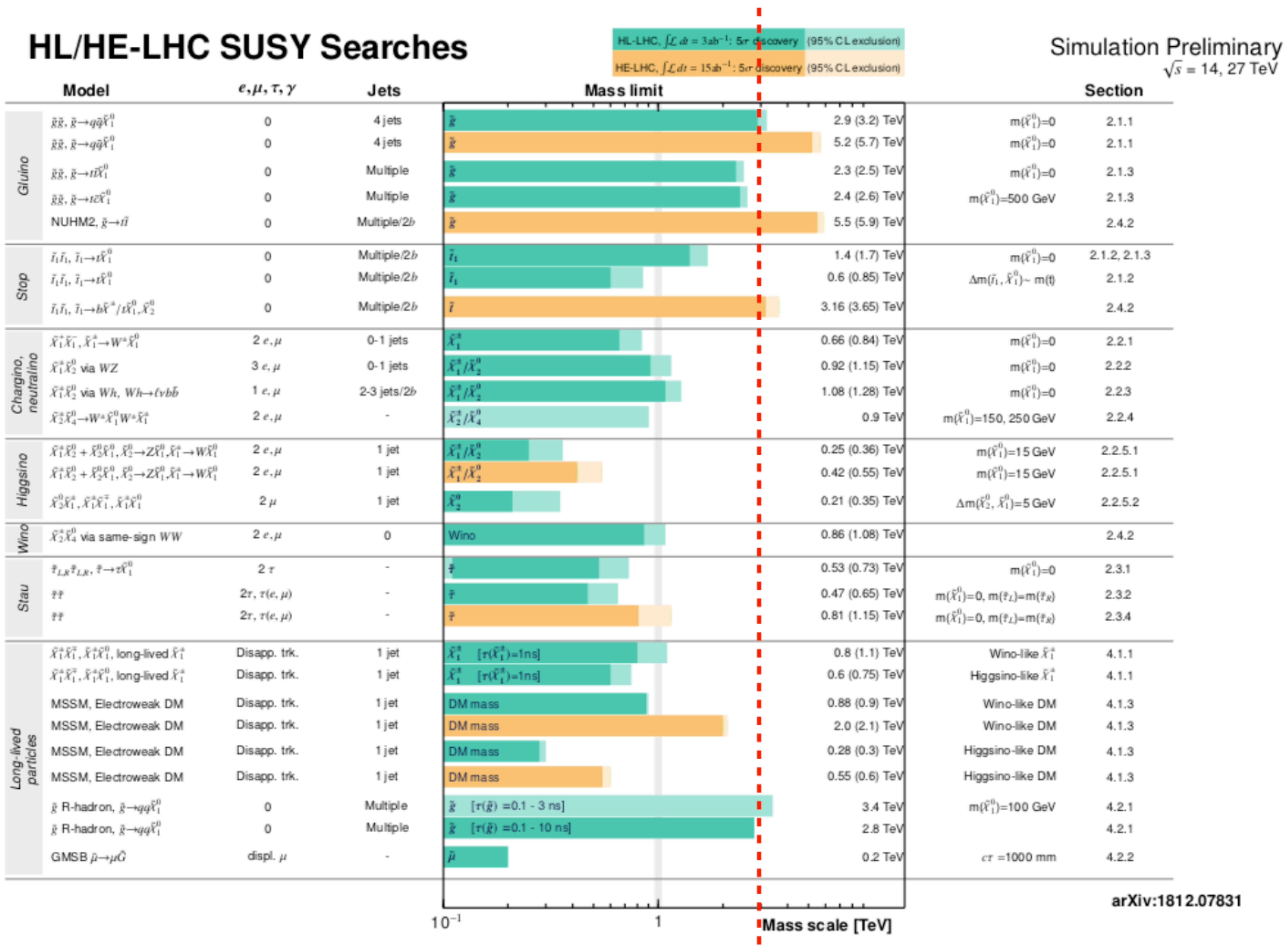
Summary of SUSY Searches

ATLAS Results (similar for CMS)

Prospects for HL-LHC (HE-LHC)



2 TeV



3 TeV

HL-LHC YR

A large variety of topologies and models … no discoveries thus far

SUSY Searches Outcomes:

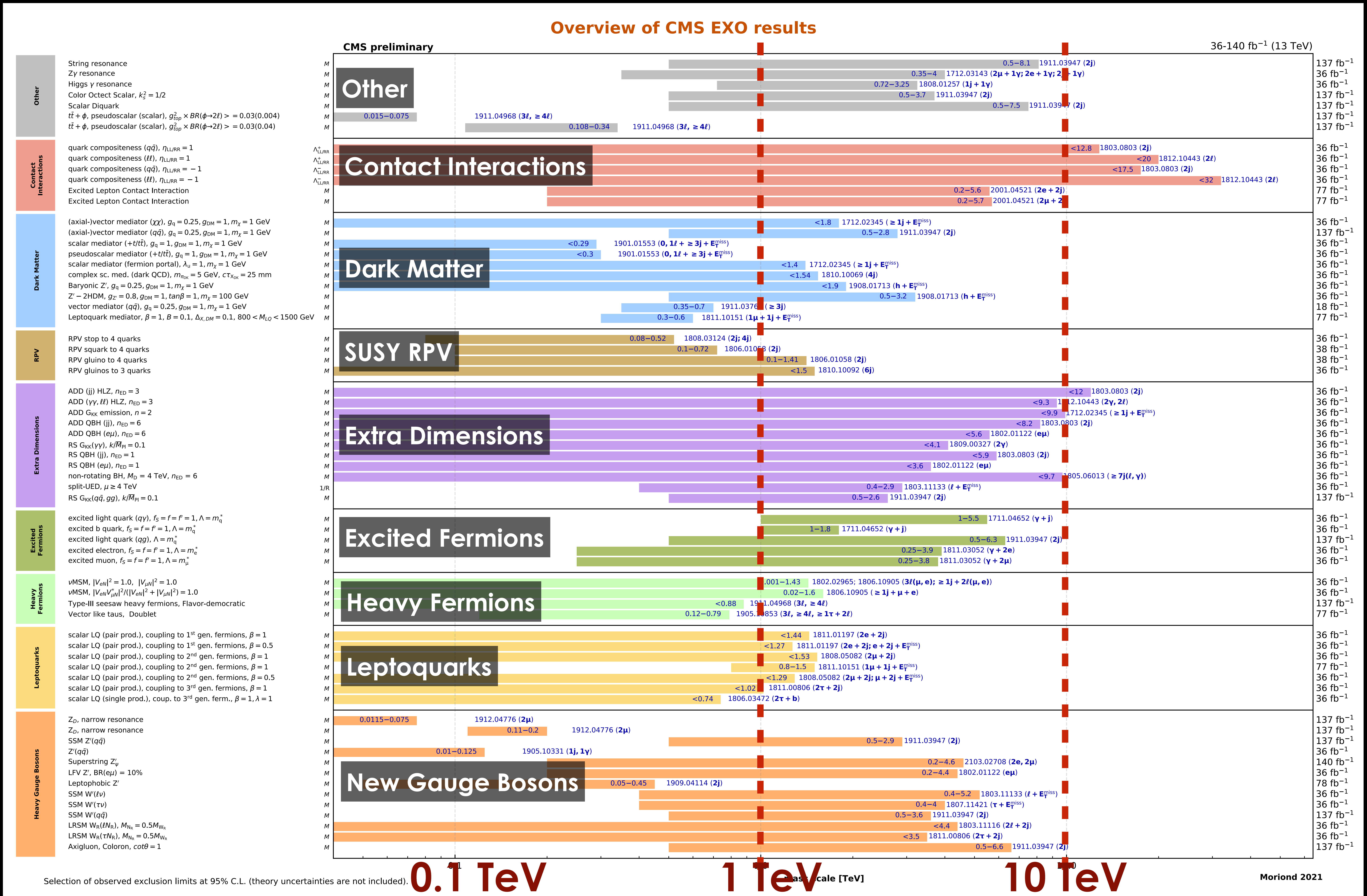
Caveats to be aware of:

- Searches typically assume Branching Fractions of 100% into a specific channel
- Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
- Interpretation is usually done via simplified model framework, not in the full model

Limits might be less stringent that they seem to be

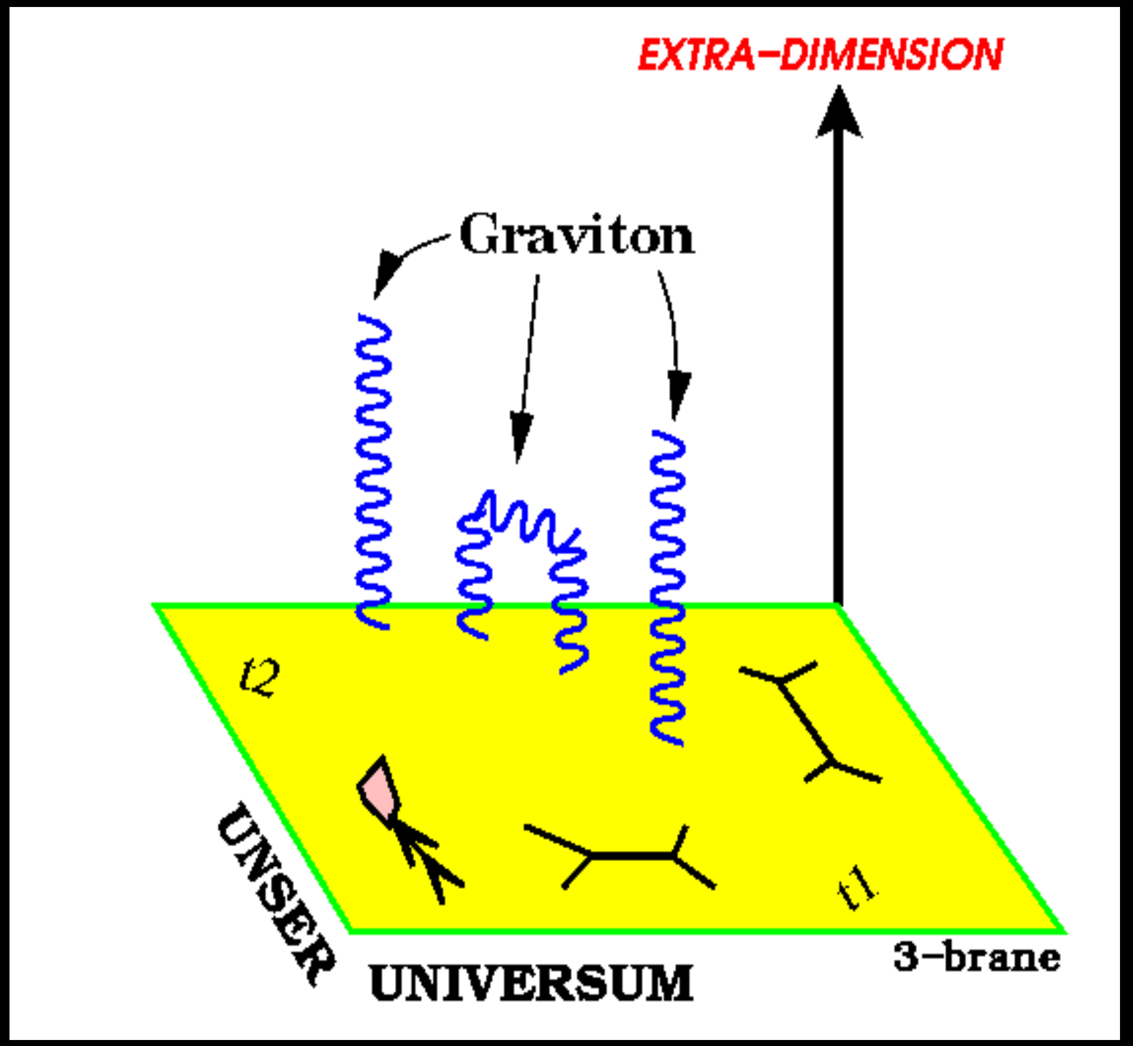
DIRECT NEW PHYSICS SEARCHES FROM LHC

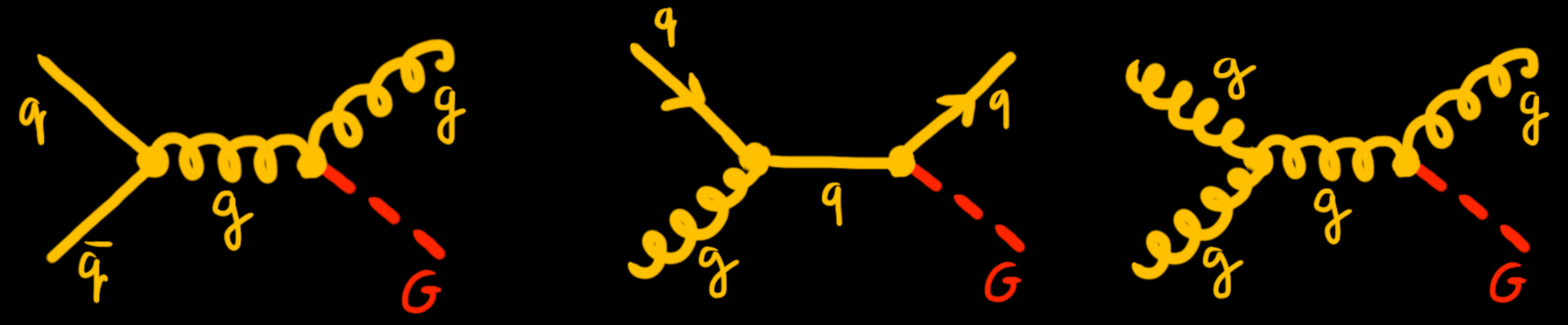
Observed exclusion limits at 95%

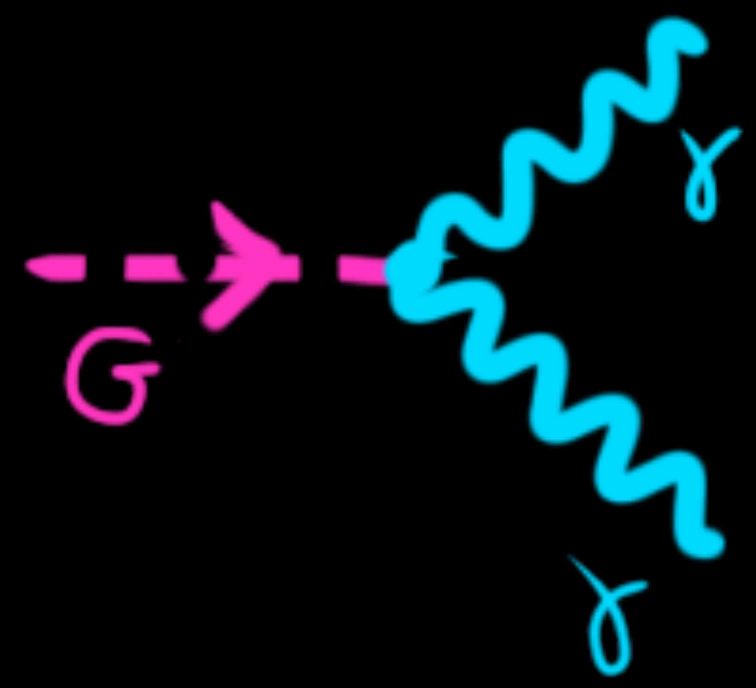


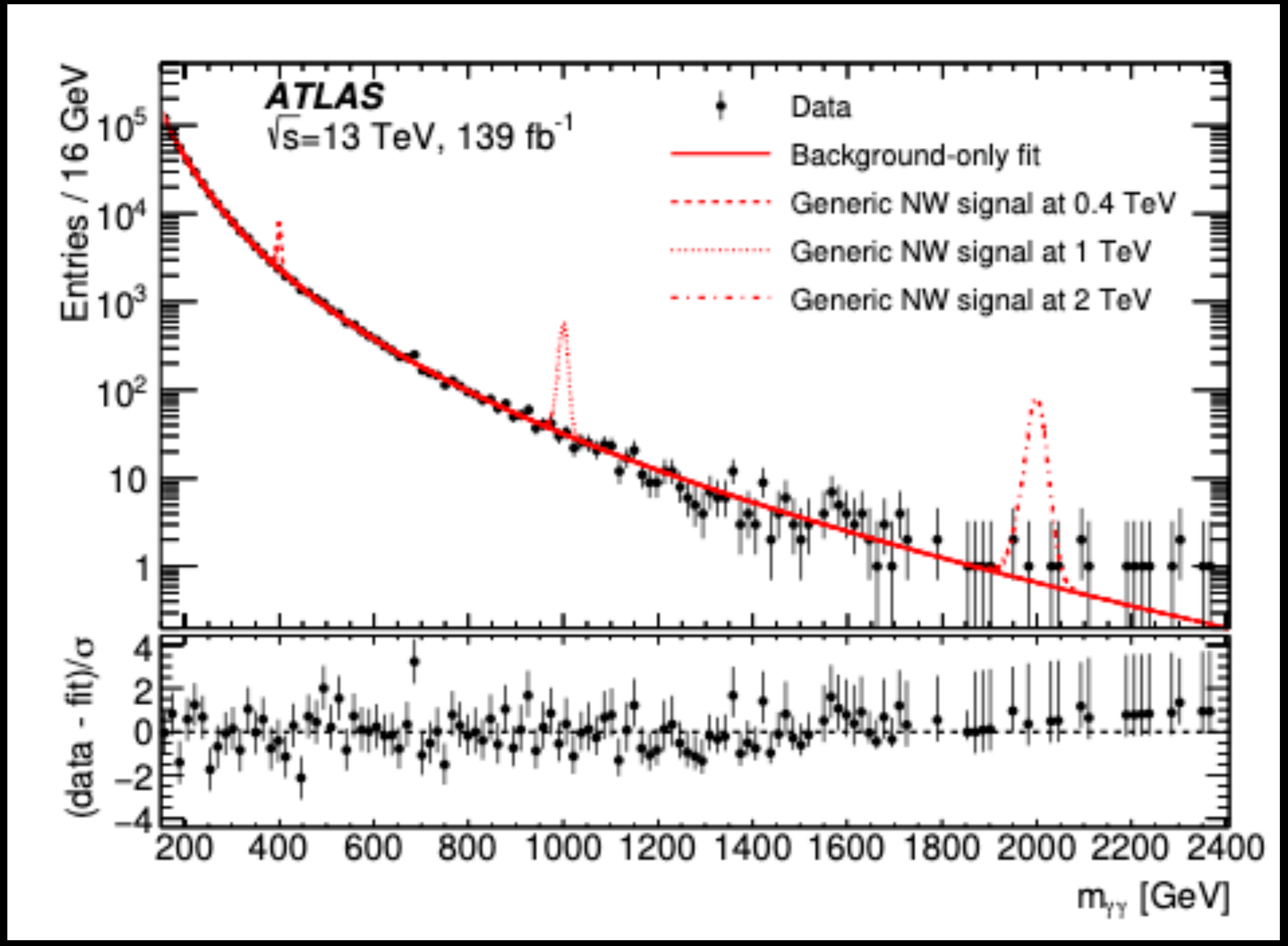
Extra Dimensions - an example of bump hunting

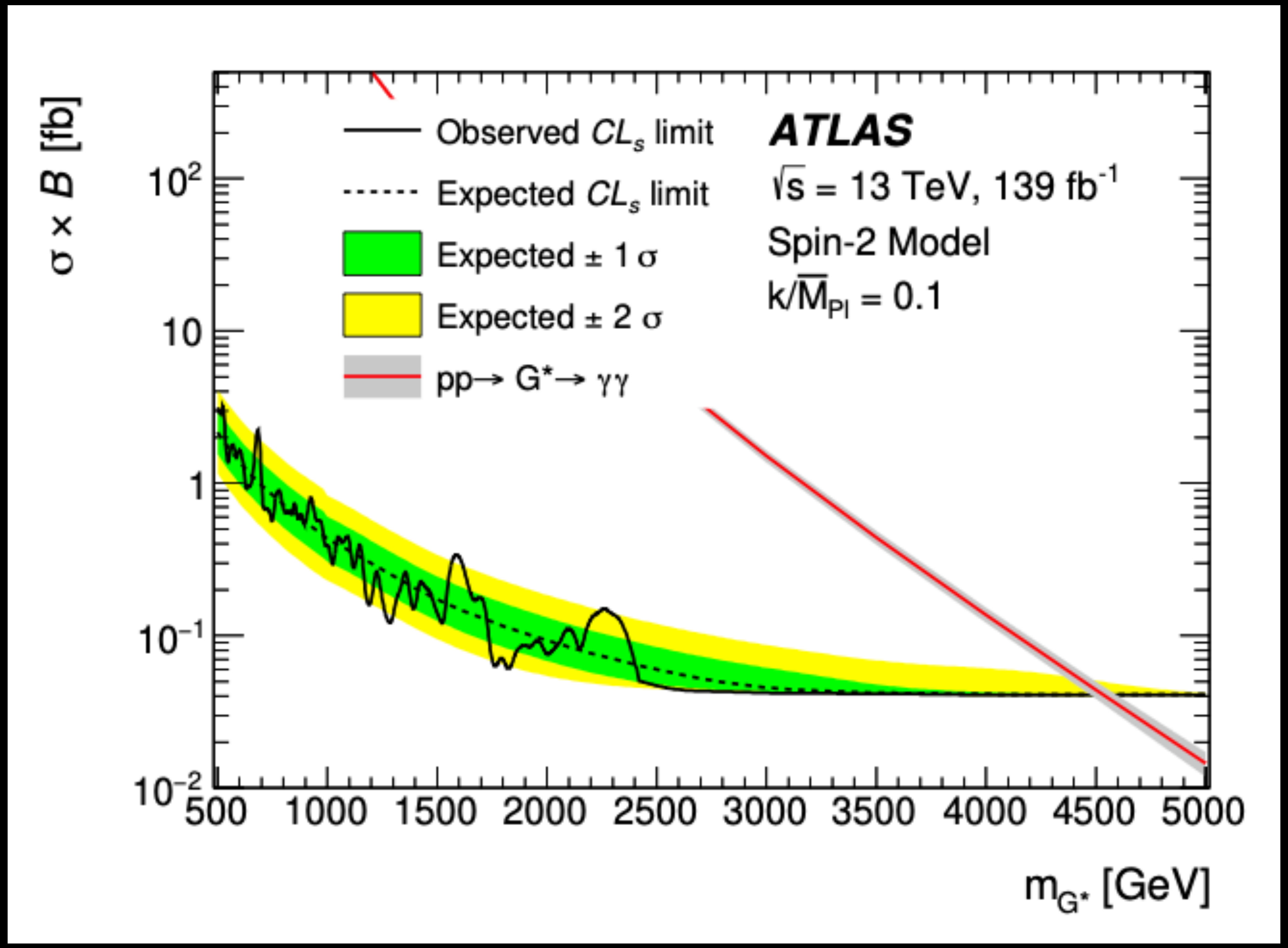
- Hierachy problem solved by bringing down Planck scale
  - n extra dimensions, compactified at radius R
  - SM confined to brane in a higher dimensional space
  - Only gravity can access extra dimensions





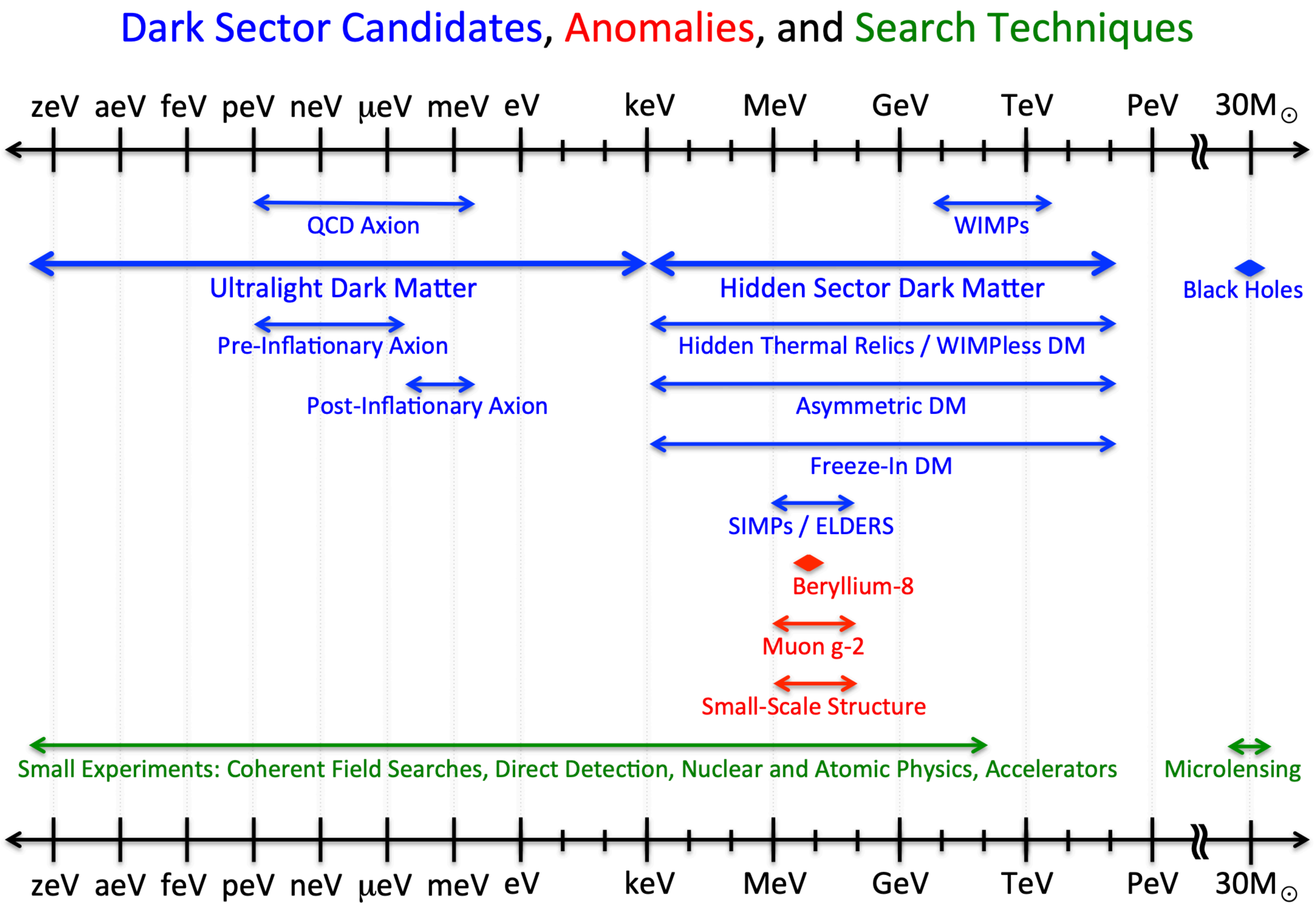






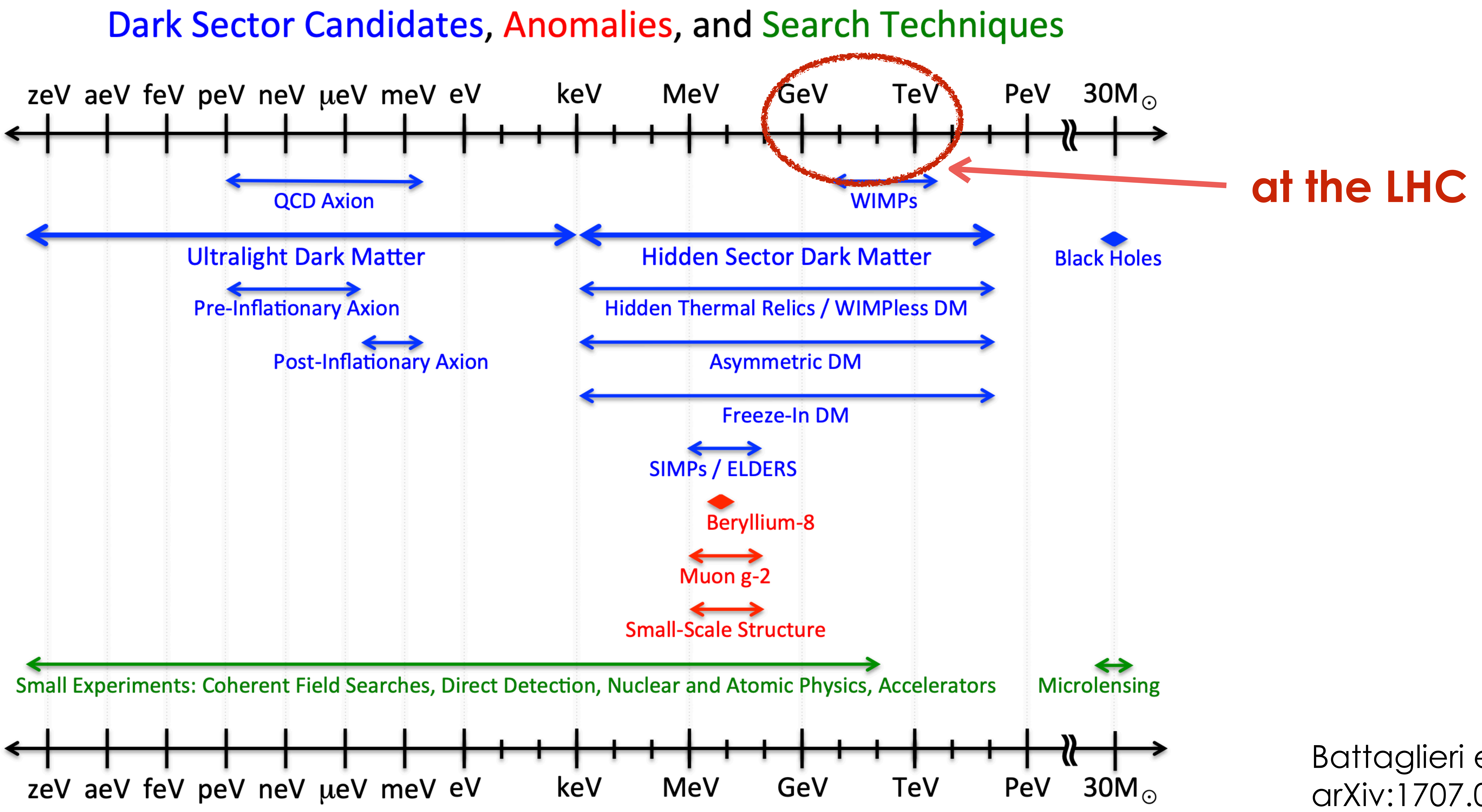
Dark Matter

Dark Matter Landscape



Battaglieri et al., arXiv:1707.04591

Dark Matter Landscape



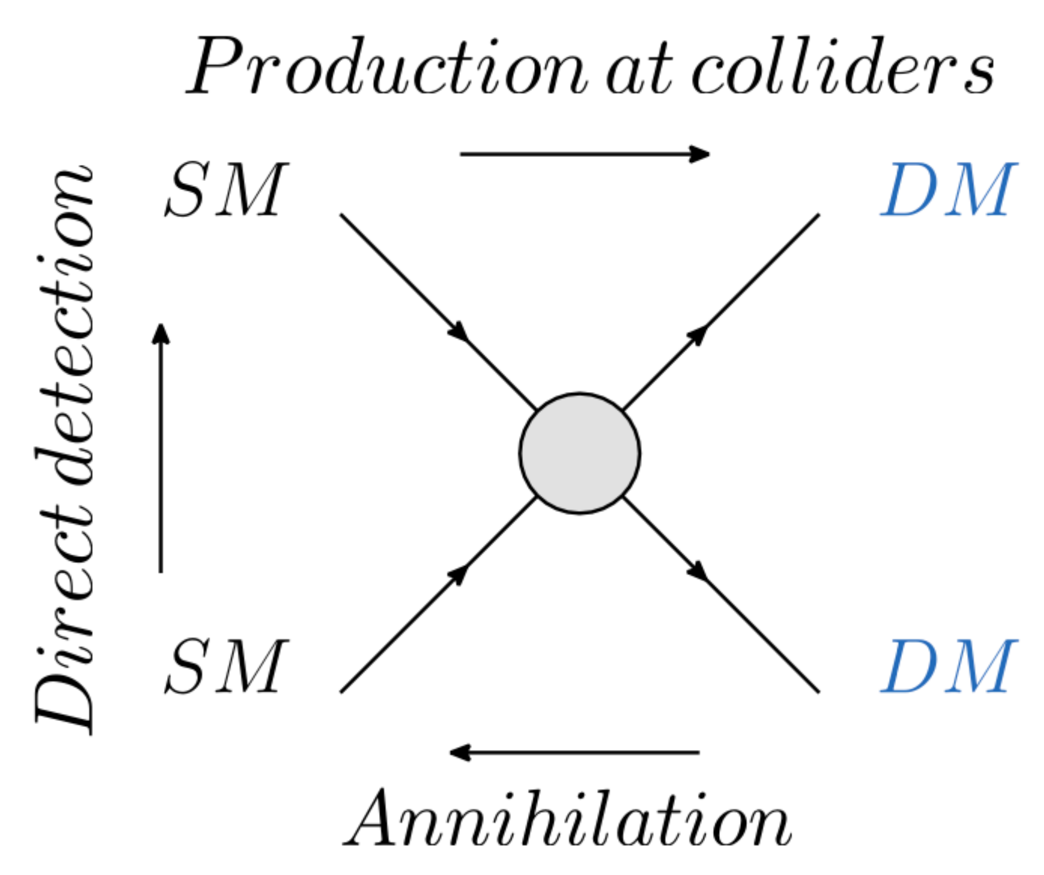
Battaglieri et al., arXiv:1707.04591

Dark Matter Searches at Colliders

There are three main approaches to detect DM:

- Dark Matter-nucleon scattering (direct detection)
- Annihilation (indirect detection)
- Pair production at colliders

All three processes are just topological permutations of the same Feynman diagram



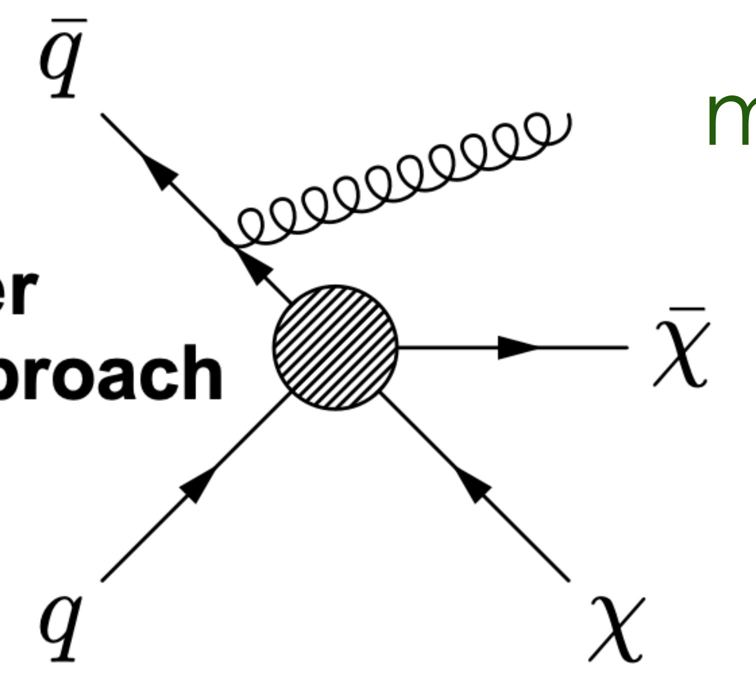
Leads to complementarity of searches

How to trigger on a pair of DM particles in a collider

Use Initial State Radiation (jet, γ, W, Z, …)

Mono-anything analyses:
mono-jet, mono-photon, mono-top,
mono-V, mono-Higgs…

Original paper used EFT approach



mono-jet

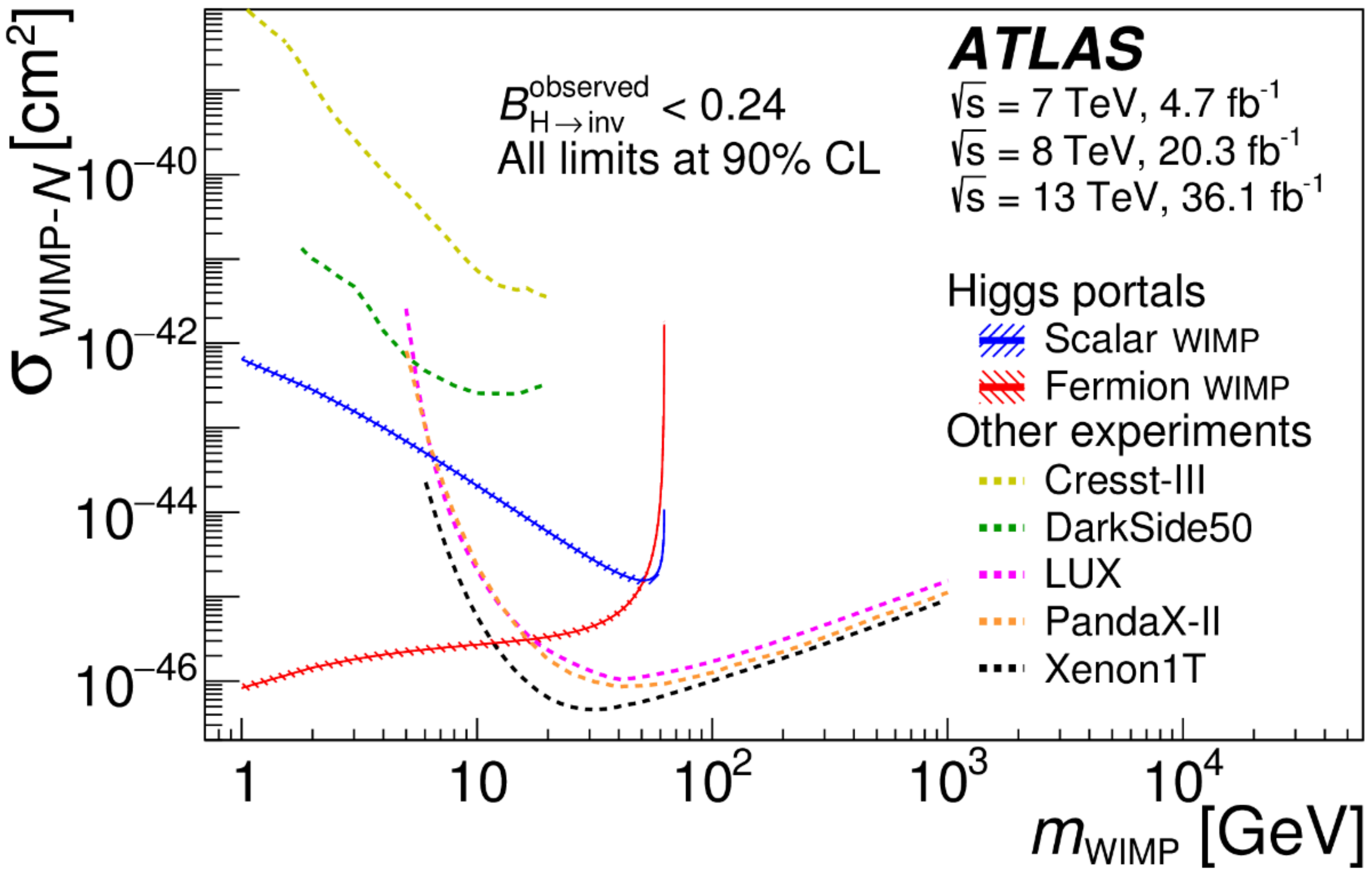
DM → MET

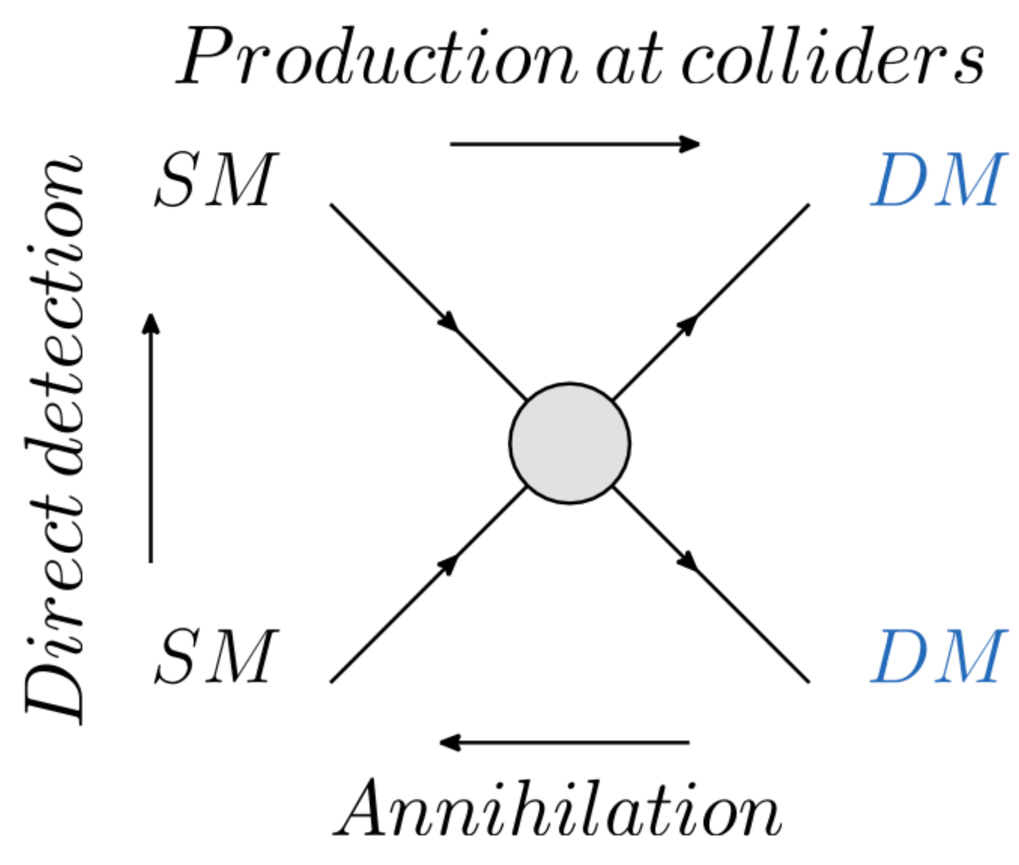
Monojet + MET

Beltran, Hooper, Kolb, Krusberg, and Tait,
"Maverick Dark Matter at Colliders" JHEP 09 (2010) 037

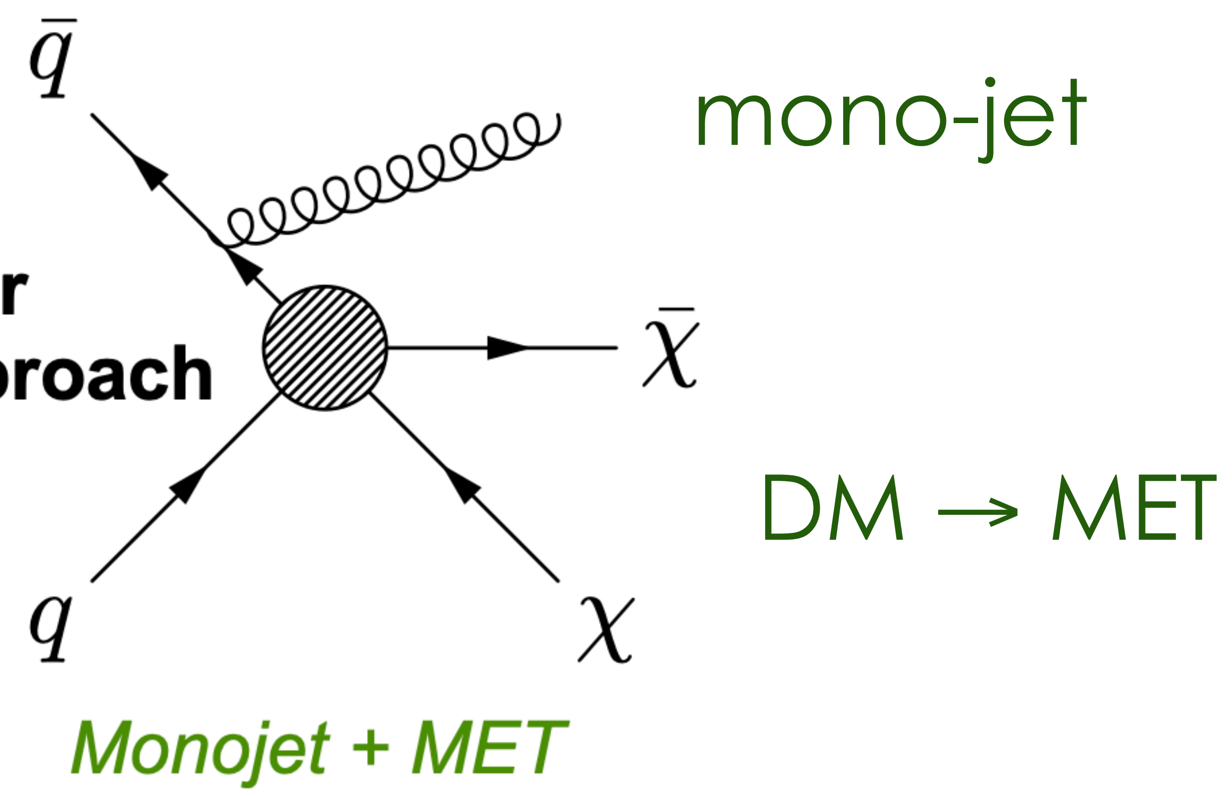

ATLAS
EXPERIMENT
1707 GeV
Monojet event
MET: 1735 GeV
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Dark Matter Searches at Colliders: Higgs → invisible





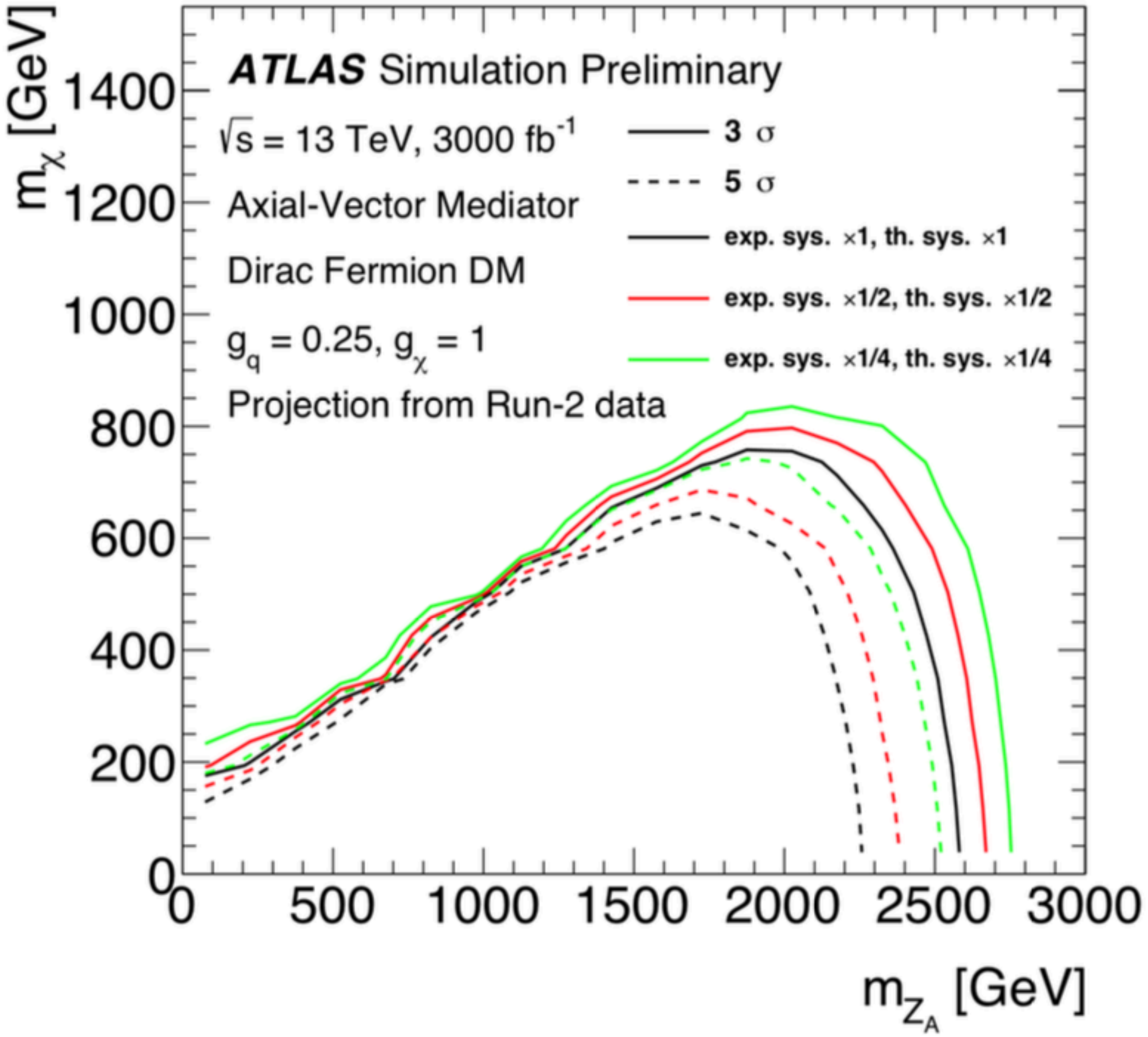
Original paper used EFT approach



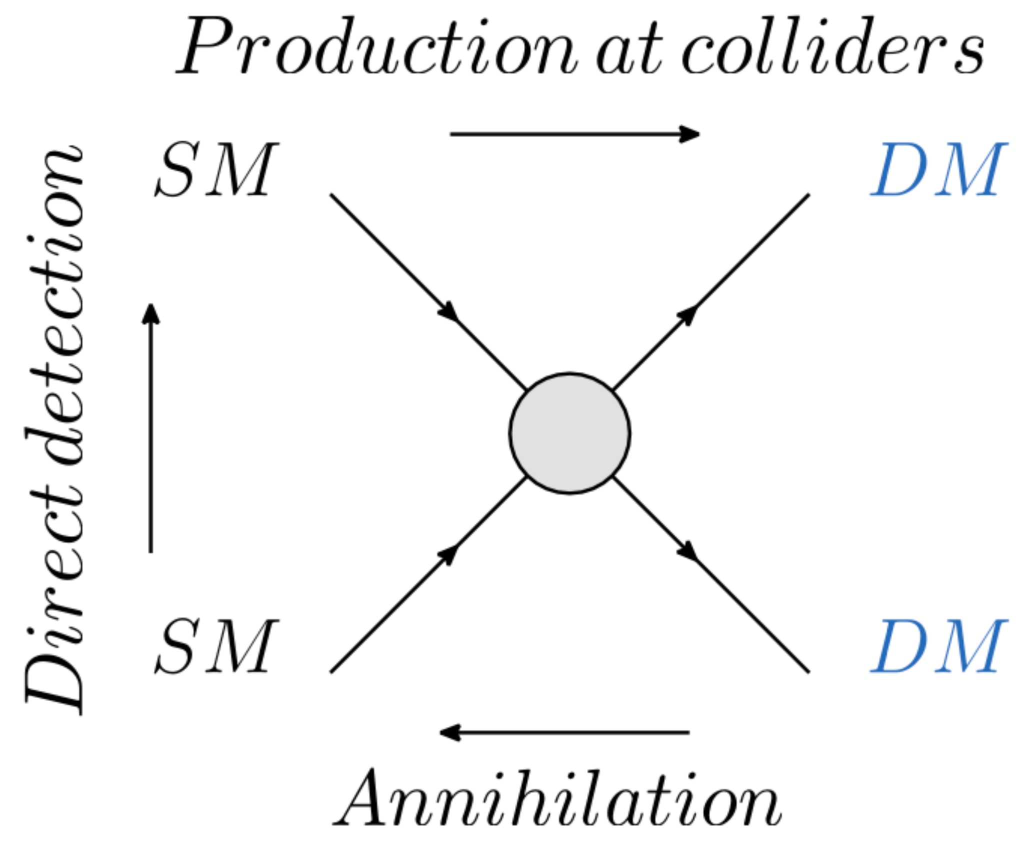
Beltran, Hooper, Kolb, Krusberg, and Tait,
"Maverick Dark Matter at Colliders" JHEP 09 (2010) 037

Dark Matter Searches at Colliders

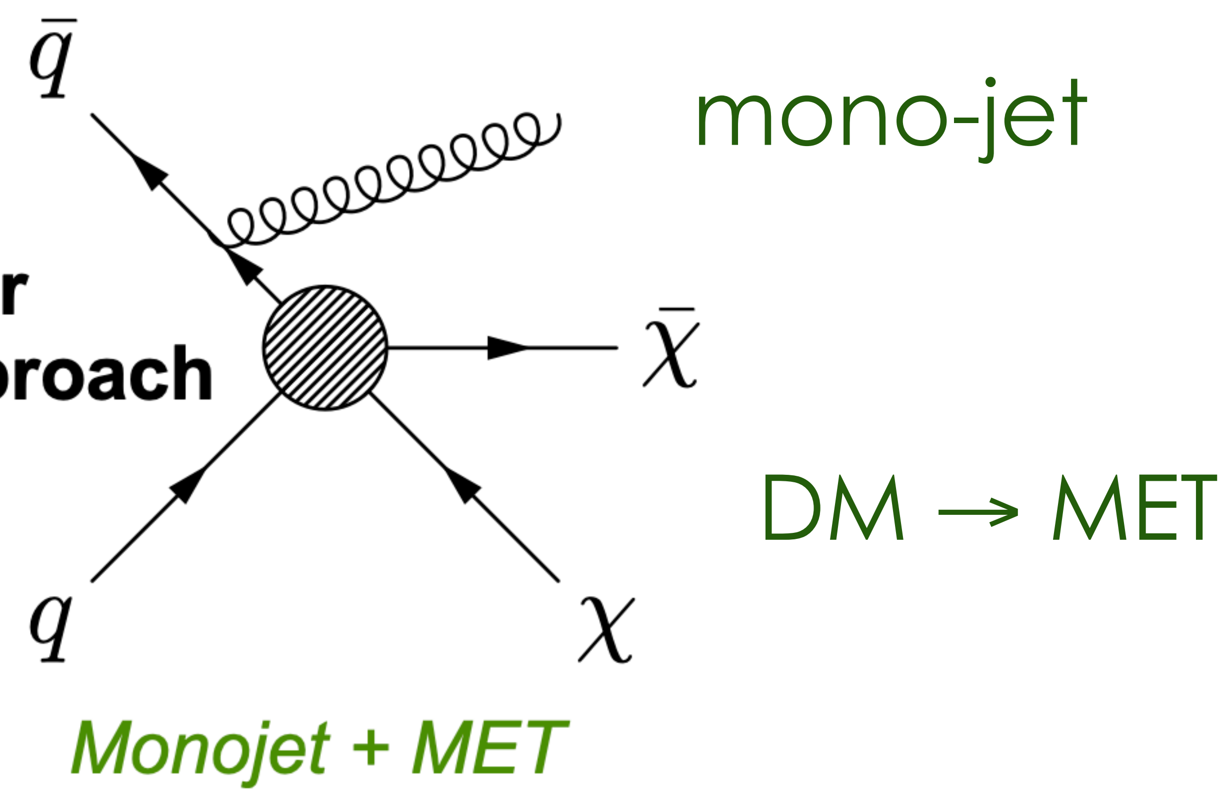
Mono-jets prospects at HL-LHC



Reach TeV range, but model dependent



Original paper used EFT approach

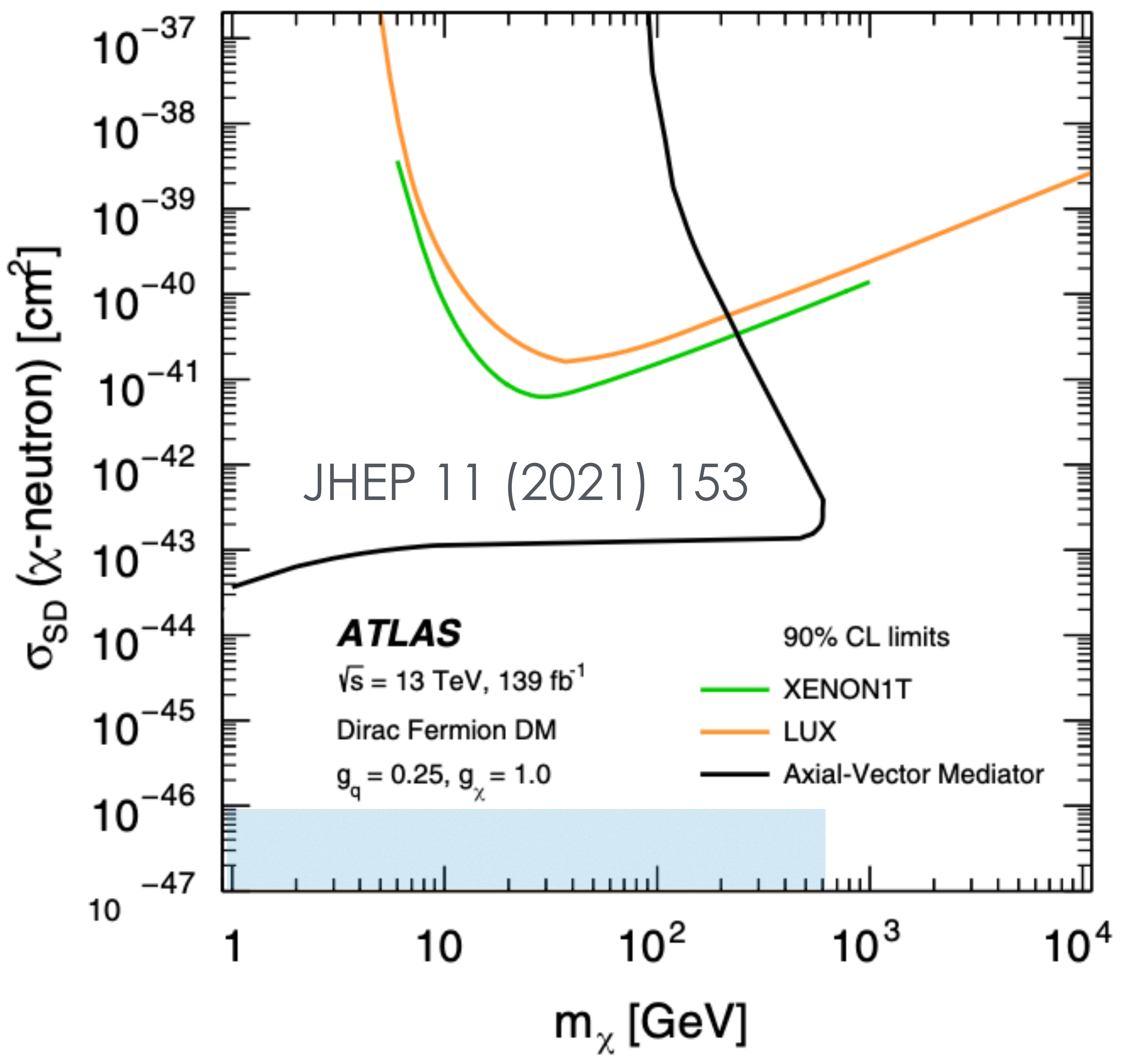


Beltran, Hooper, Kolb, Krusberg, and Tait, "Maverick Dark Matter at Colliders" JHEP 09 (2010) 037

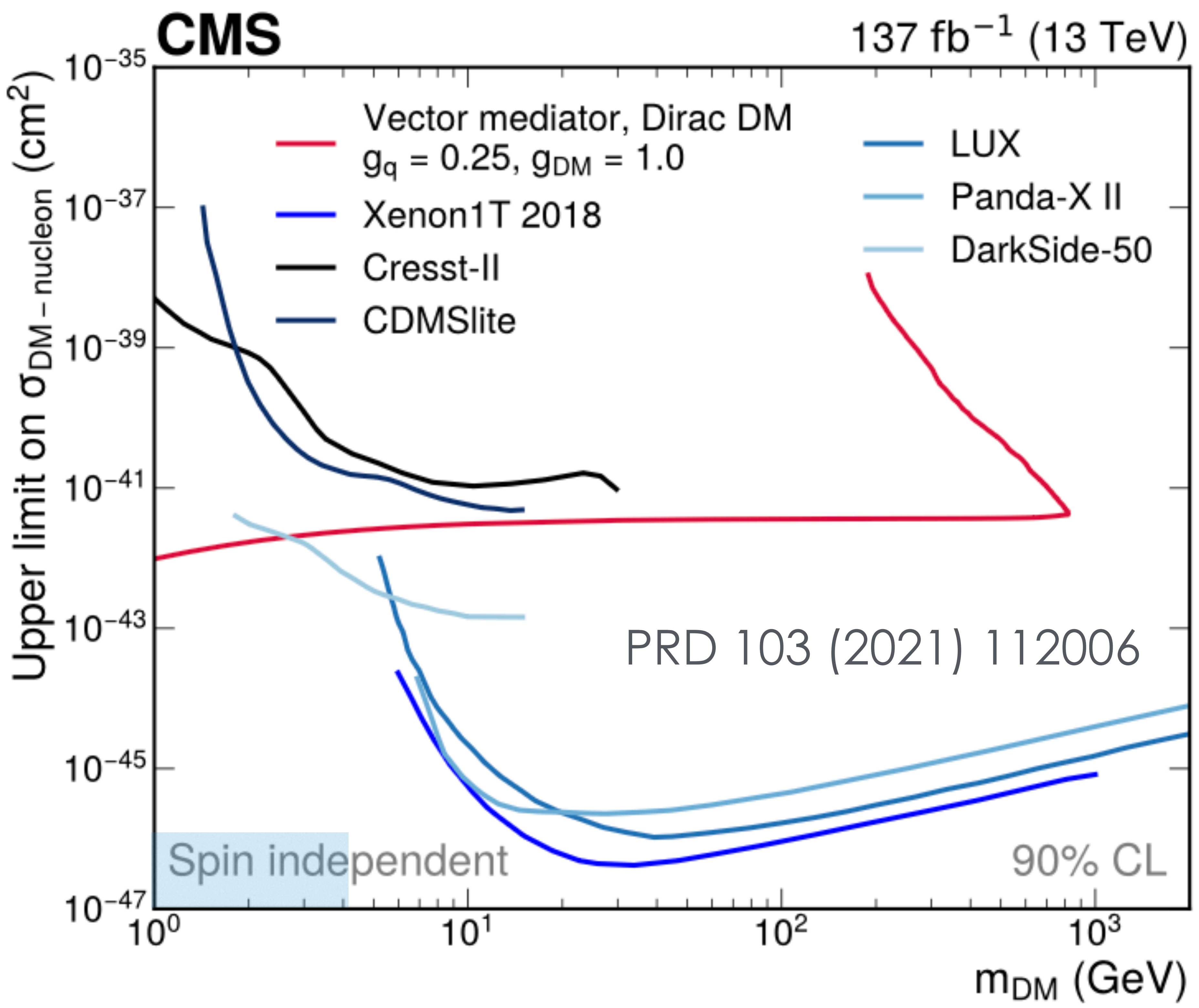
Dark Matter Searches at Colliders

Complementarity to Direct Detection

Collider experiments competitive w/ direct detection ones



Spin Dependent (axial-vector mediator) up to m_{DM} ~500 GeV



Spin Independent (vector mediator) for very light m_{DM} < ~5 GeV

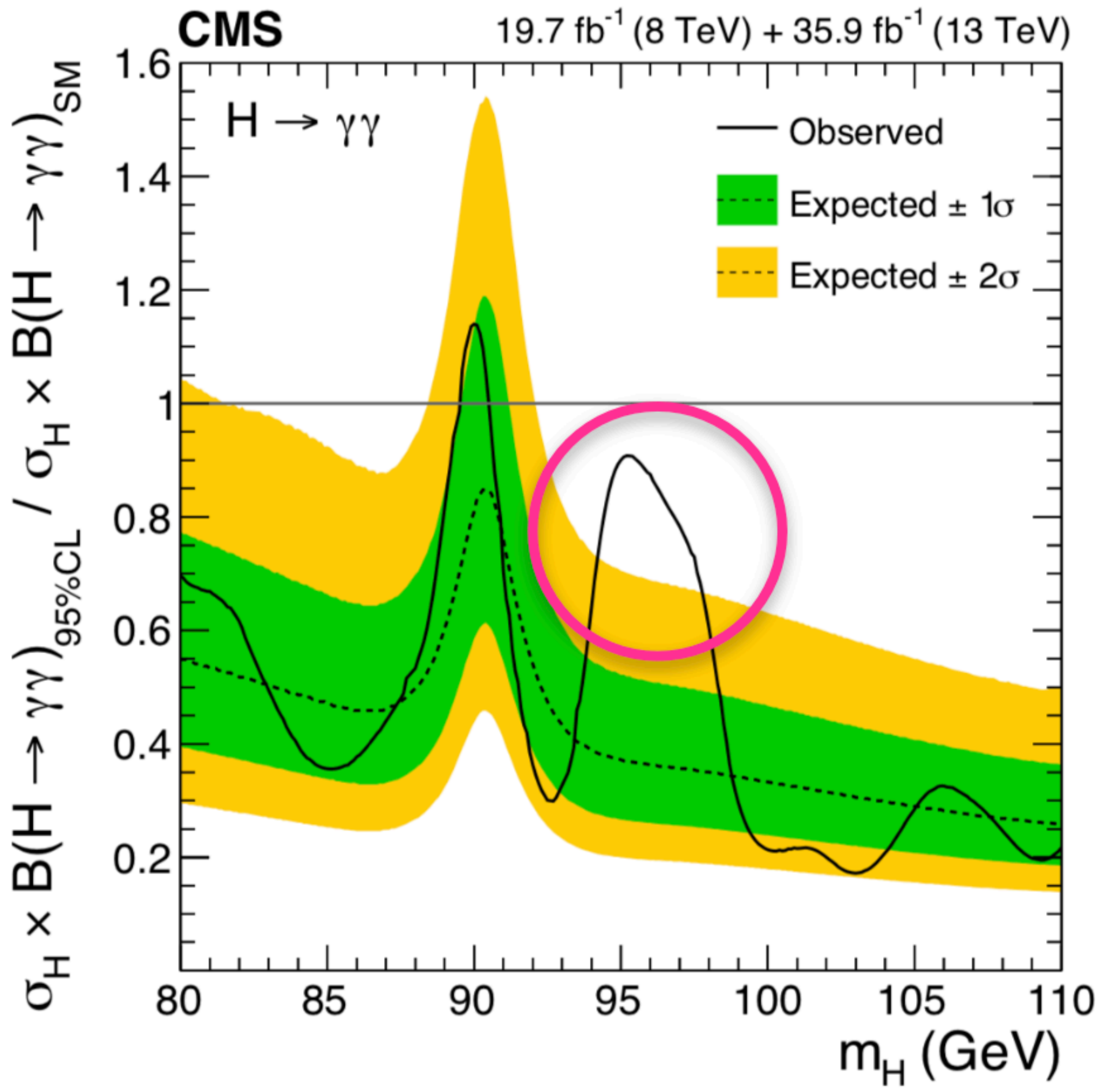
Do anomalies exist in the LHC data?

Anomalies do exist… a few examples

Several 3σ local excesses…

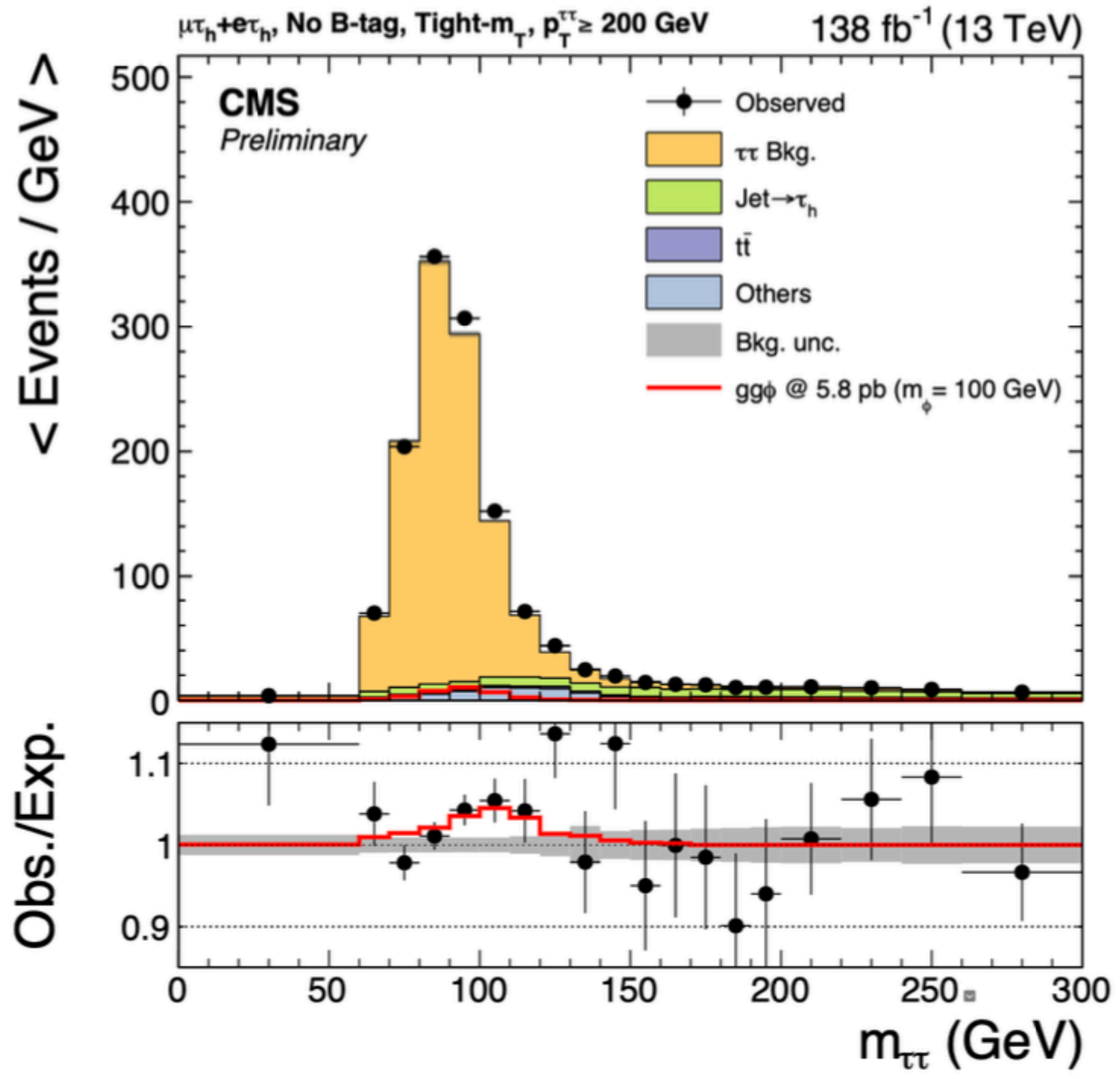
$a \to \gamma\gamma$

Local (global) significance at 95.3 GeV : 2.9σ (**1.5σ**)



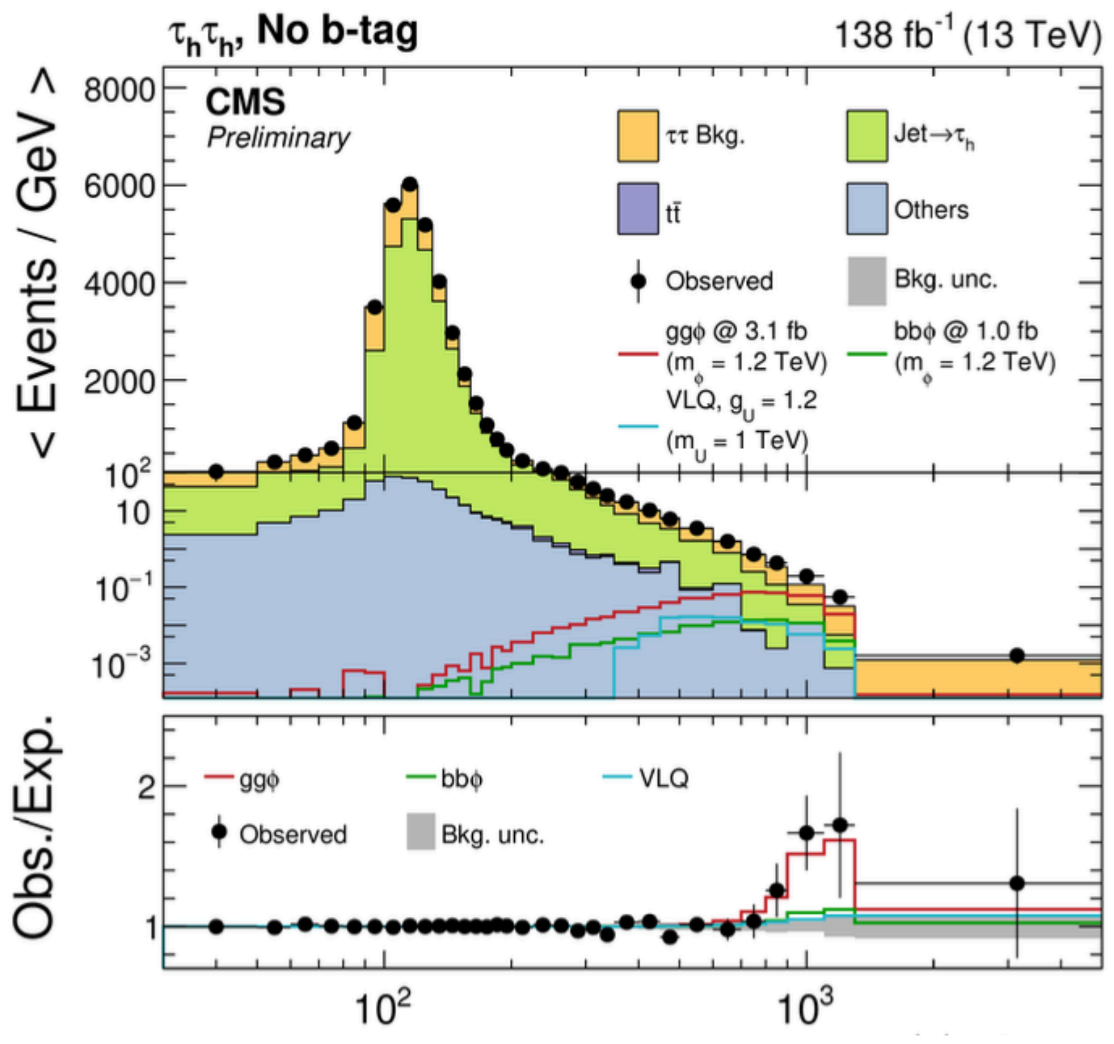
$\phi \to \tau^+\tau^-$

Local (global) significance at 95 TeV : 3.1σ **(2.7σ)**



$\phi \to \tau^+\tau^-$

Local (global) significance at 1.2 TeV : 2.8σ **(2.4σ)**



Warning:

With such large number of searches statical fluctuations are expected and there could be systematic effects!

NO NEW PHYSICS OBSERVED

→ LOOK FURTHER/DEEPER

Explore new tools and techniques

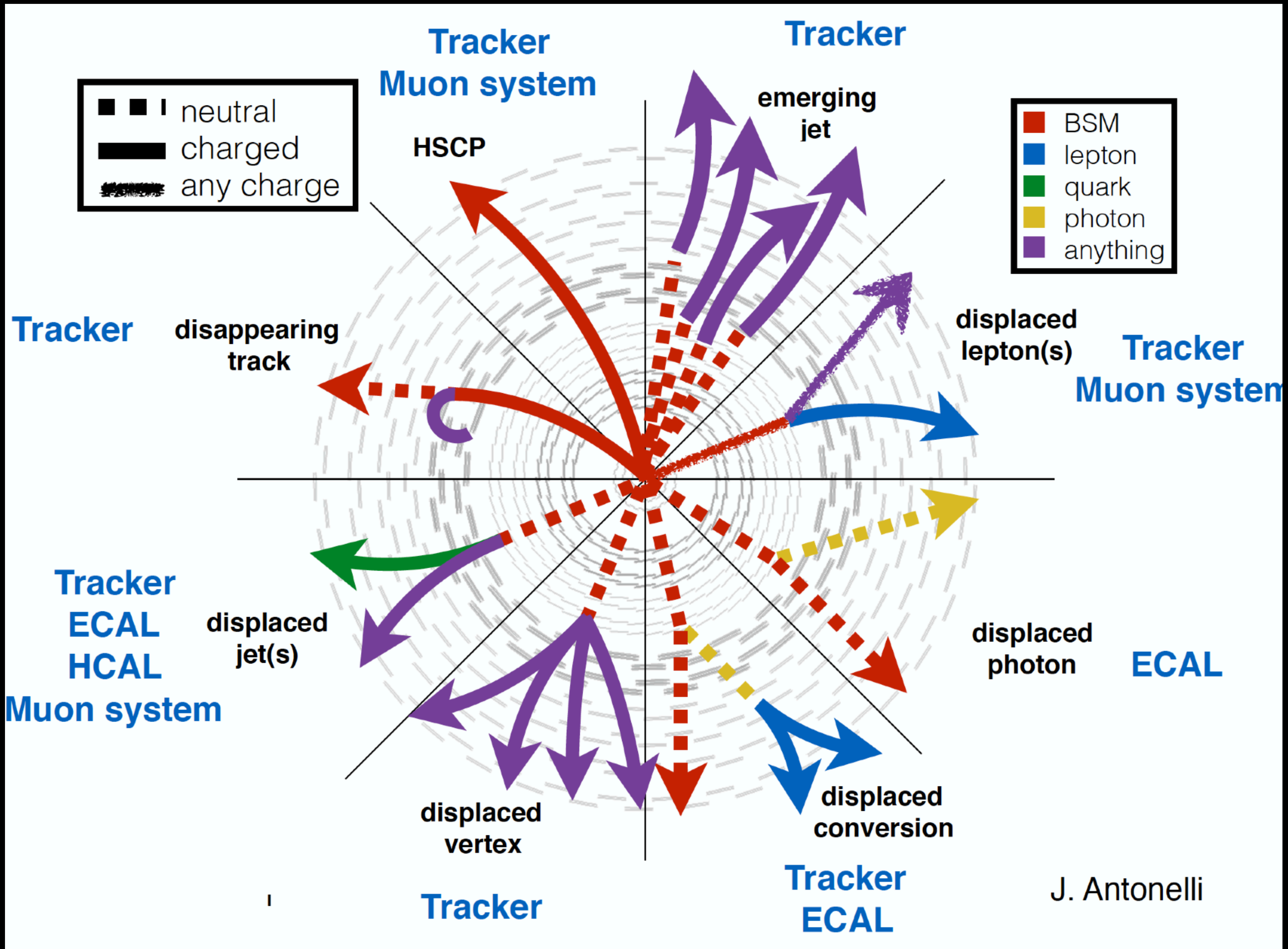
Long-lived particles (LLPs)

Long-lived particles (LLPs) are common in BSM

- Small phase space for decay (e.g. Split SUSY)
- Small couplings to SM particles
  - Suppressed (e.g. Higgs/gauge portal to Dark Sector)
  - Forbidden by symmetry (SUSY R-parity)

Could have escaped observation so far

- Challenges:
  - Often requires new triggers
  - Exotic detector signatures (requiring new tools)
  - Non-standard backgrounds



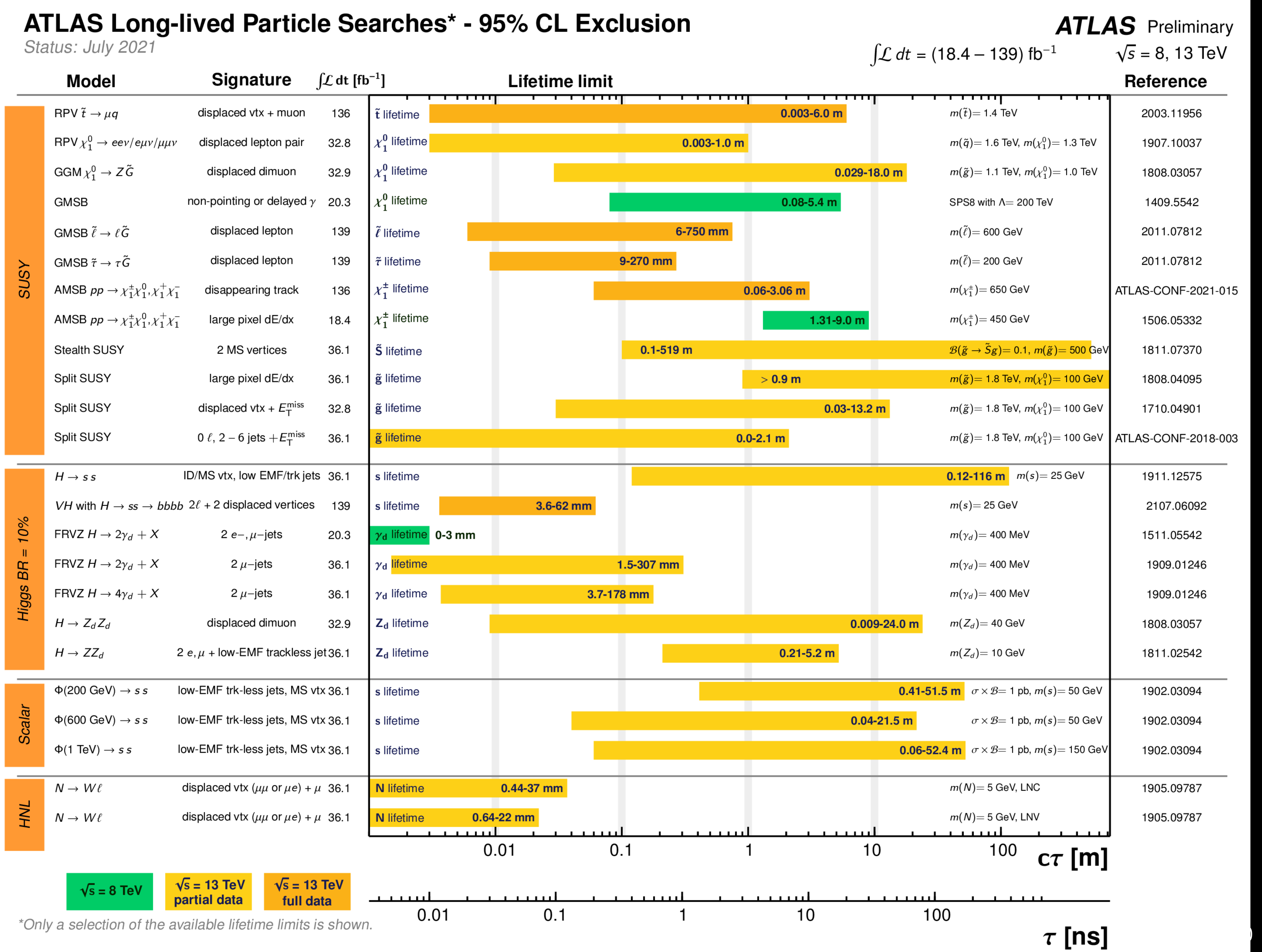
Displaced leptons

Disappearing track

Large pixel dE/dx

Track-less jets

Displaced vertices



NO NEW PHYSICS OBSERVED

→ LOOK FURTHER/DEEPER

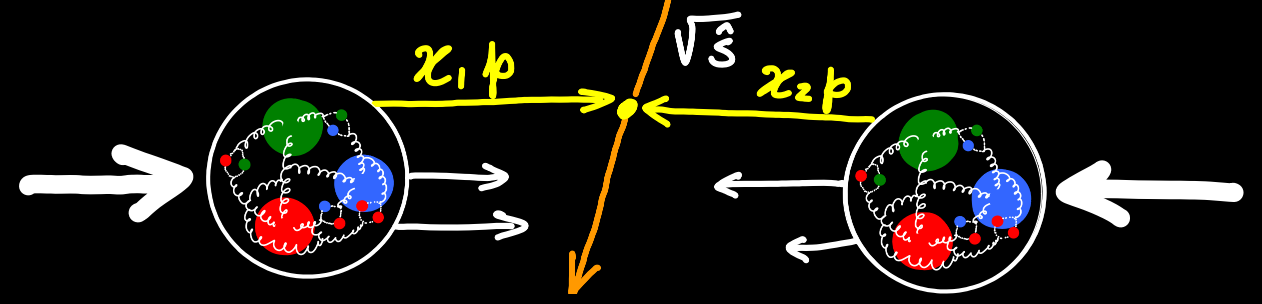
Explore new tools and techniques

The highest energy possible

The highest luminosity possible

As low backgrounds as possible

THE LARGE HADRON COLLIDER



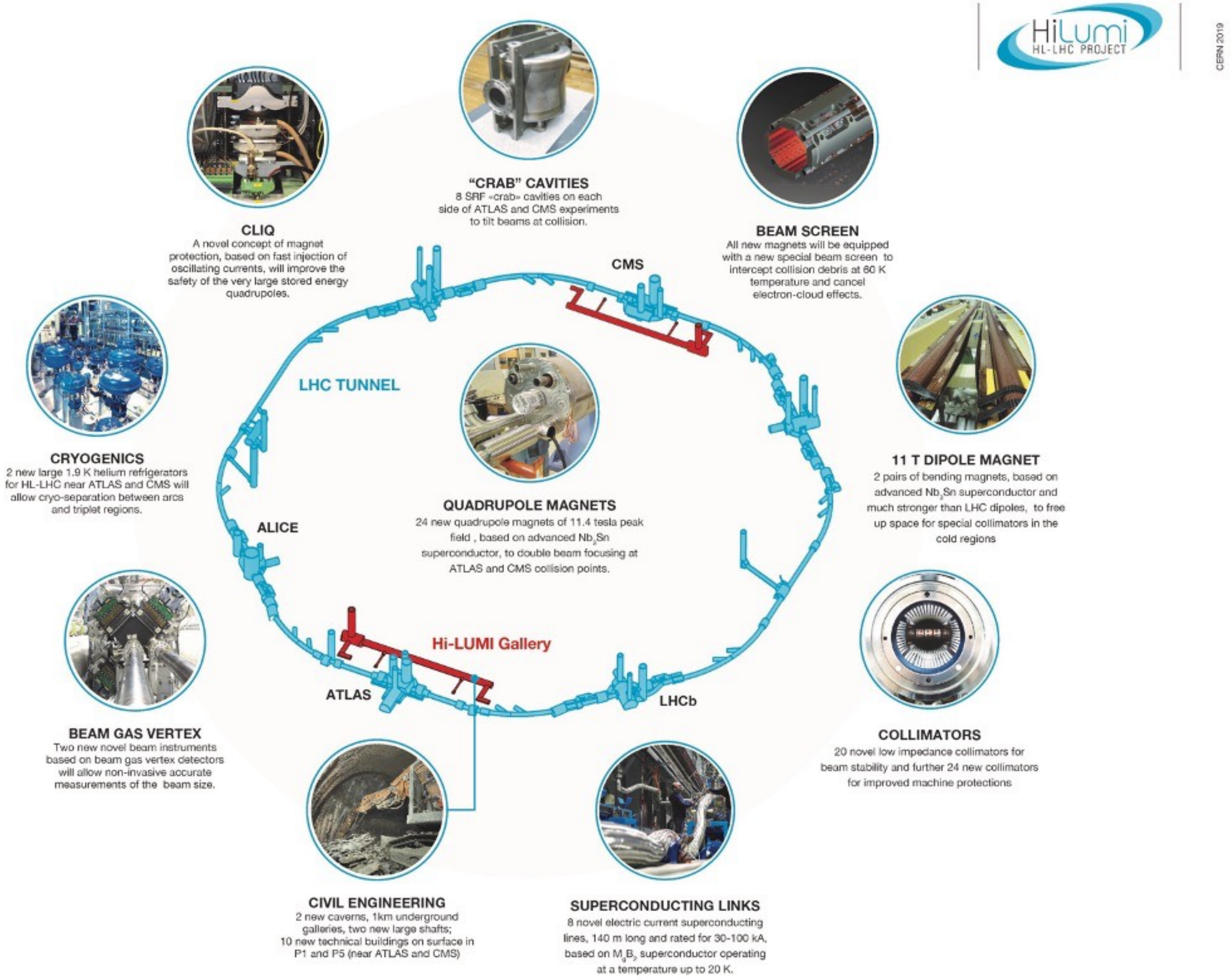
LHC and experiments being upgraded

HL-LHC starting in 2029: 3000-4000 fb^{-1}

Center of mass energy: 14 TeV

HL-LHC Upgrade

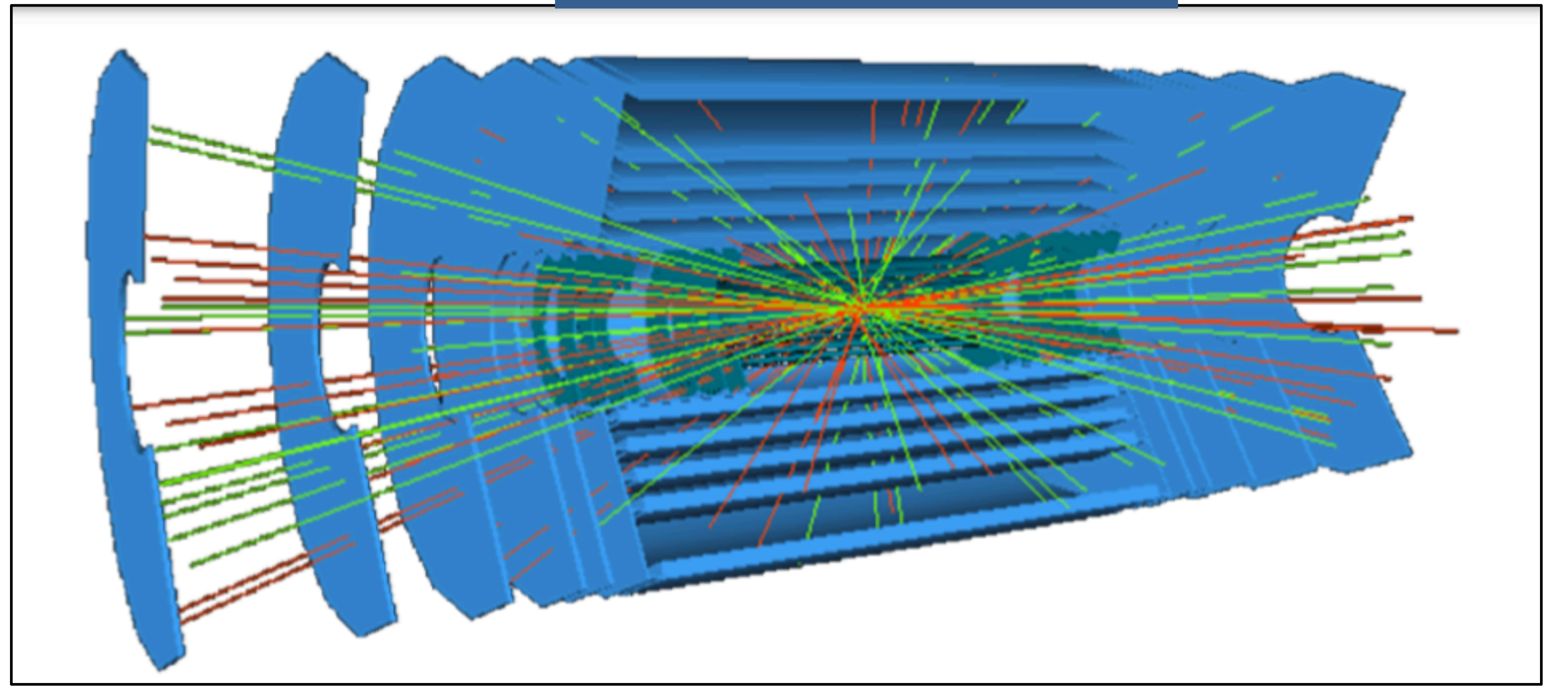
~1.2 km of accelerator
will be upgraded



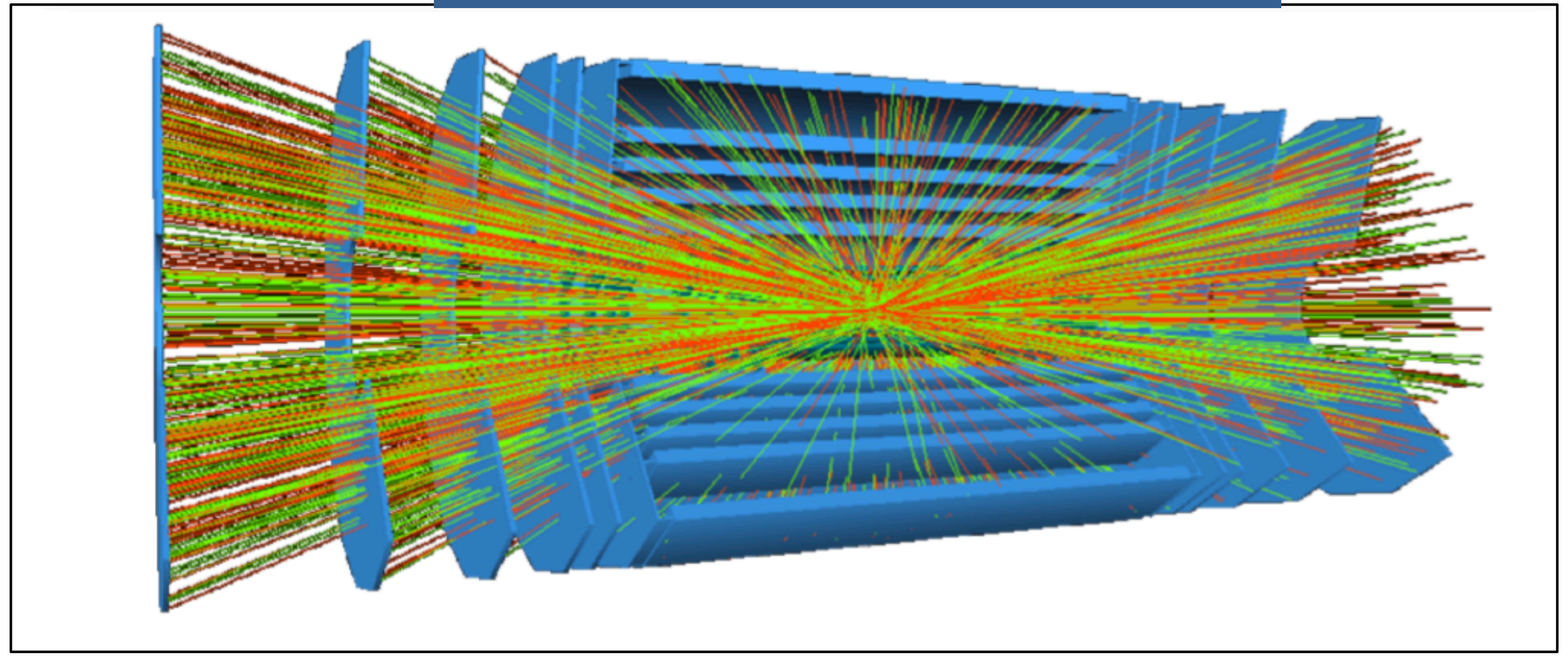
Challenging Phase-II Upgrades of ATLAS and CMS

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment

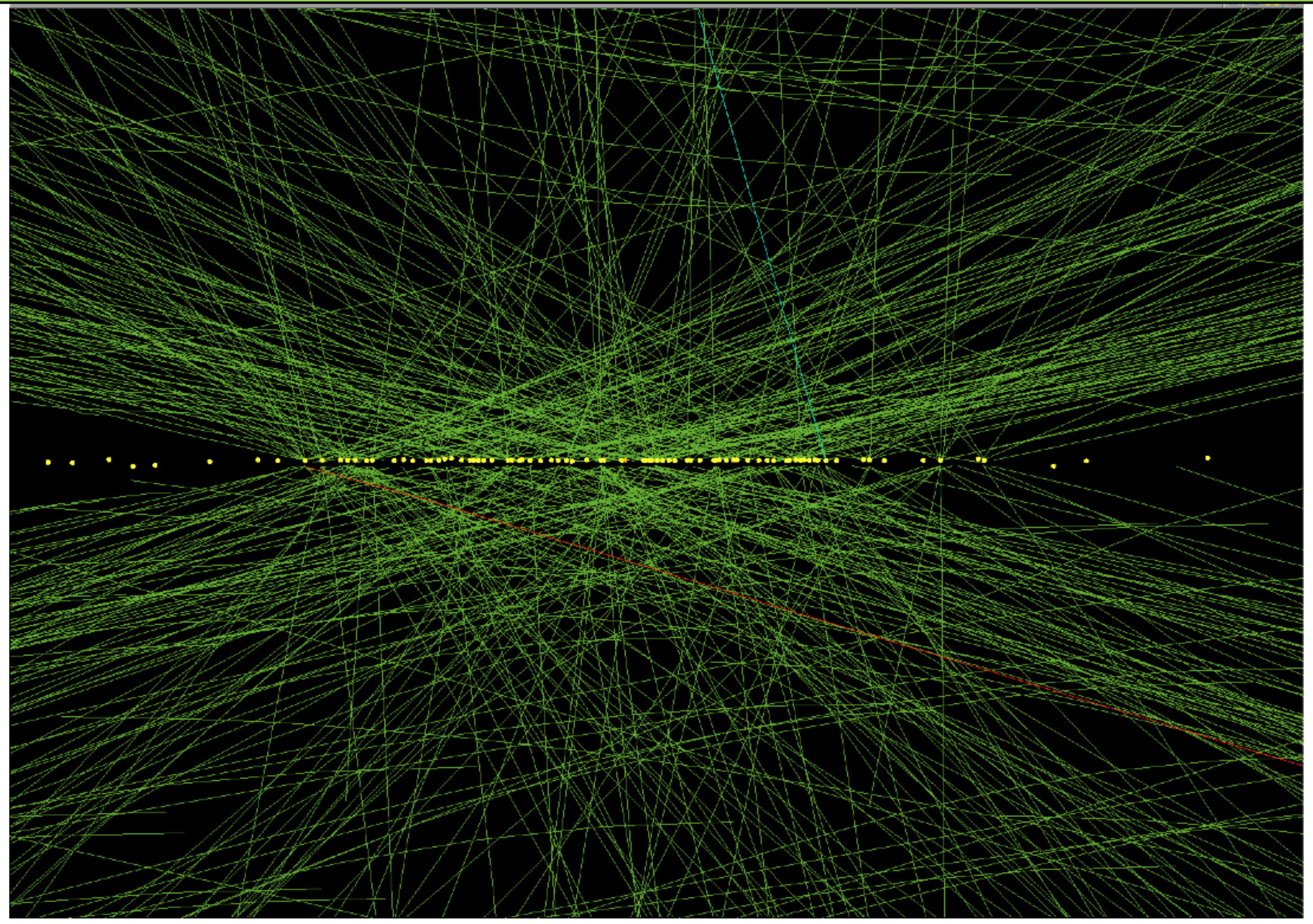
LHC: ~ 30 evts/x-ing



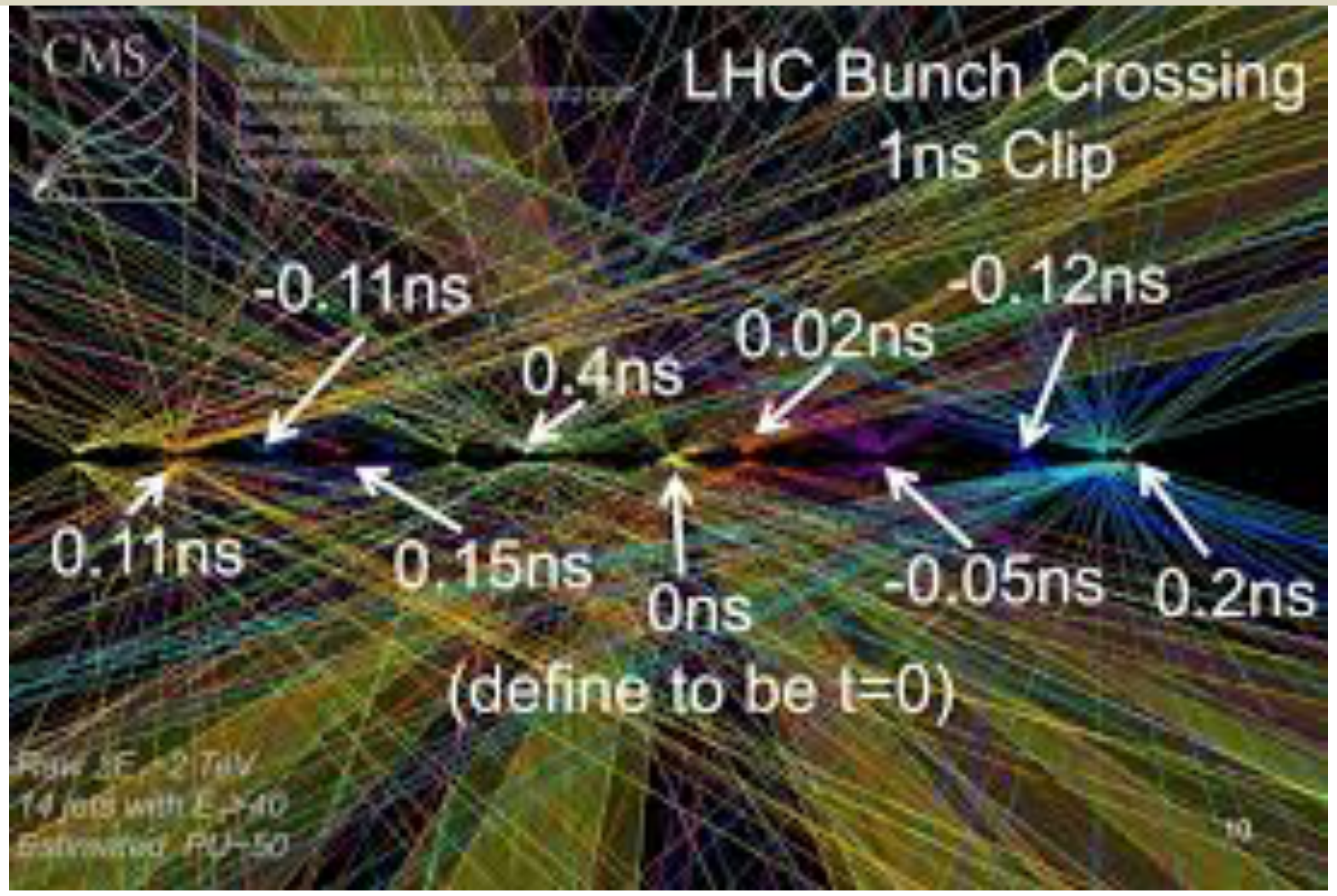
HL-LHC: ~ 140-200 evts/x-ing



Event with 78 reconstructed vertices (CMS Run 2 data)
Note: ~ 20 expected when detectors were designed

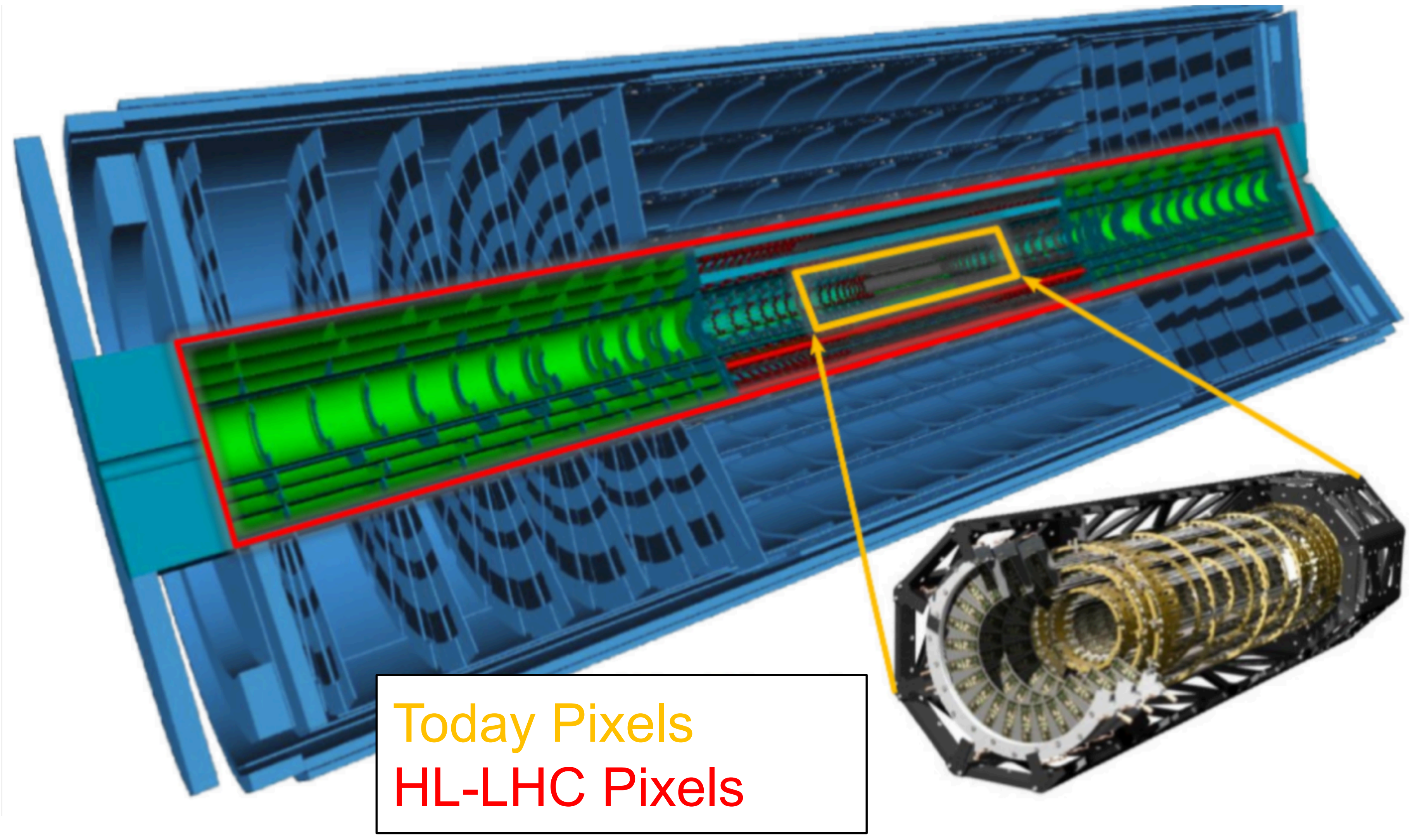


New timing detectors with resolution ~ 30 ps in both experiments will allow 4-dimensional identification of primary vertex



Challenging Phase-II Upgrades of ATLAS and CMS

ATLAS tracker (ITk)

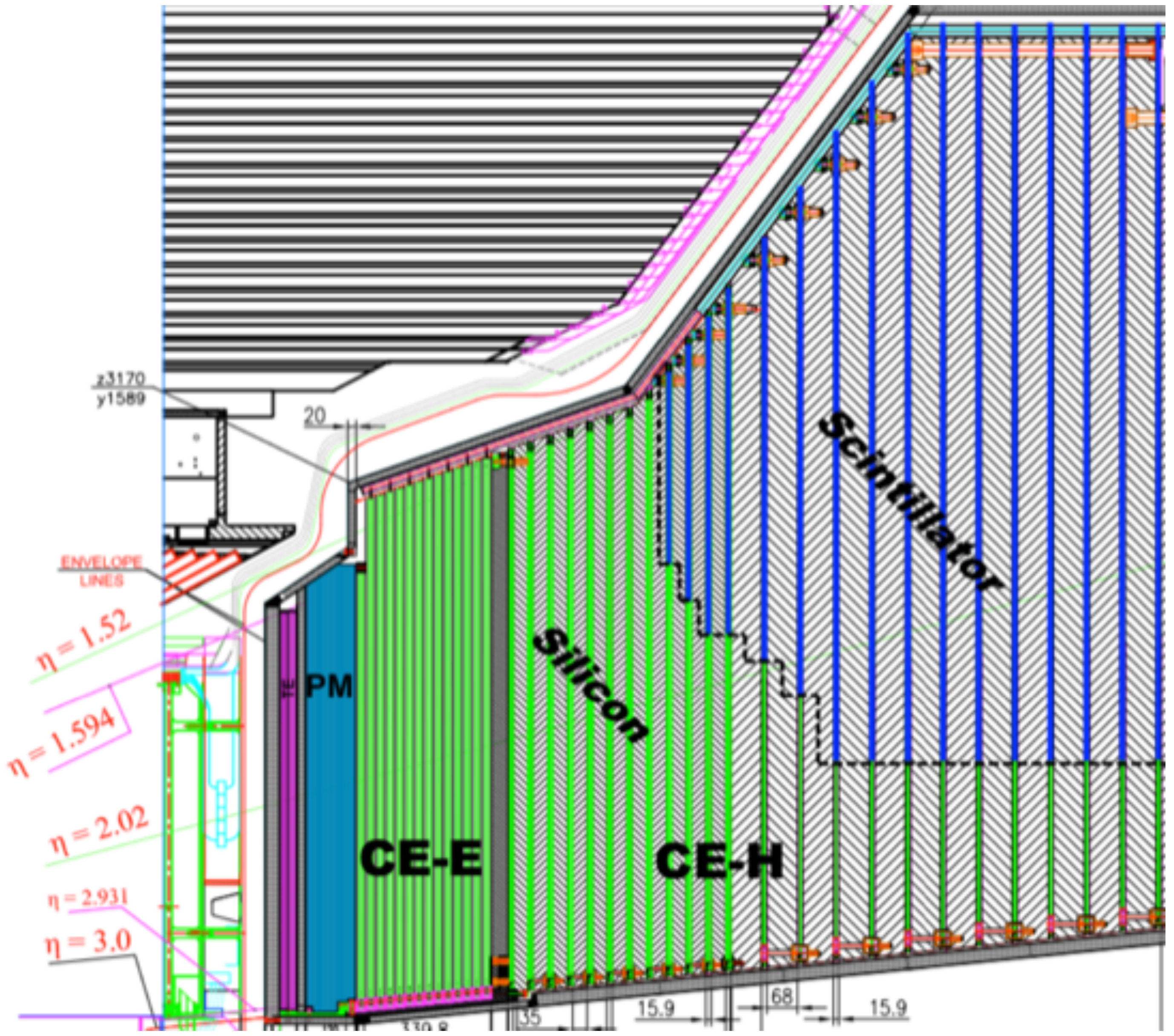


$|\eta| < 4$

Low mass, rad hard
Barrel: 5 pixel + 4 strip layers
End-cap: up to 23 pixel + 6 strip rings
Pixel size: 25 x 100 μm^2 and 50 x 50 μm^2
Strip size (barrel): ~ 75 μm x 24-42 mm

Total Si area: ~ 180 m^2
Total # of channels: ~ 5 billion (50 x today)

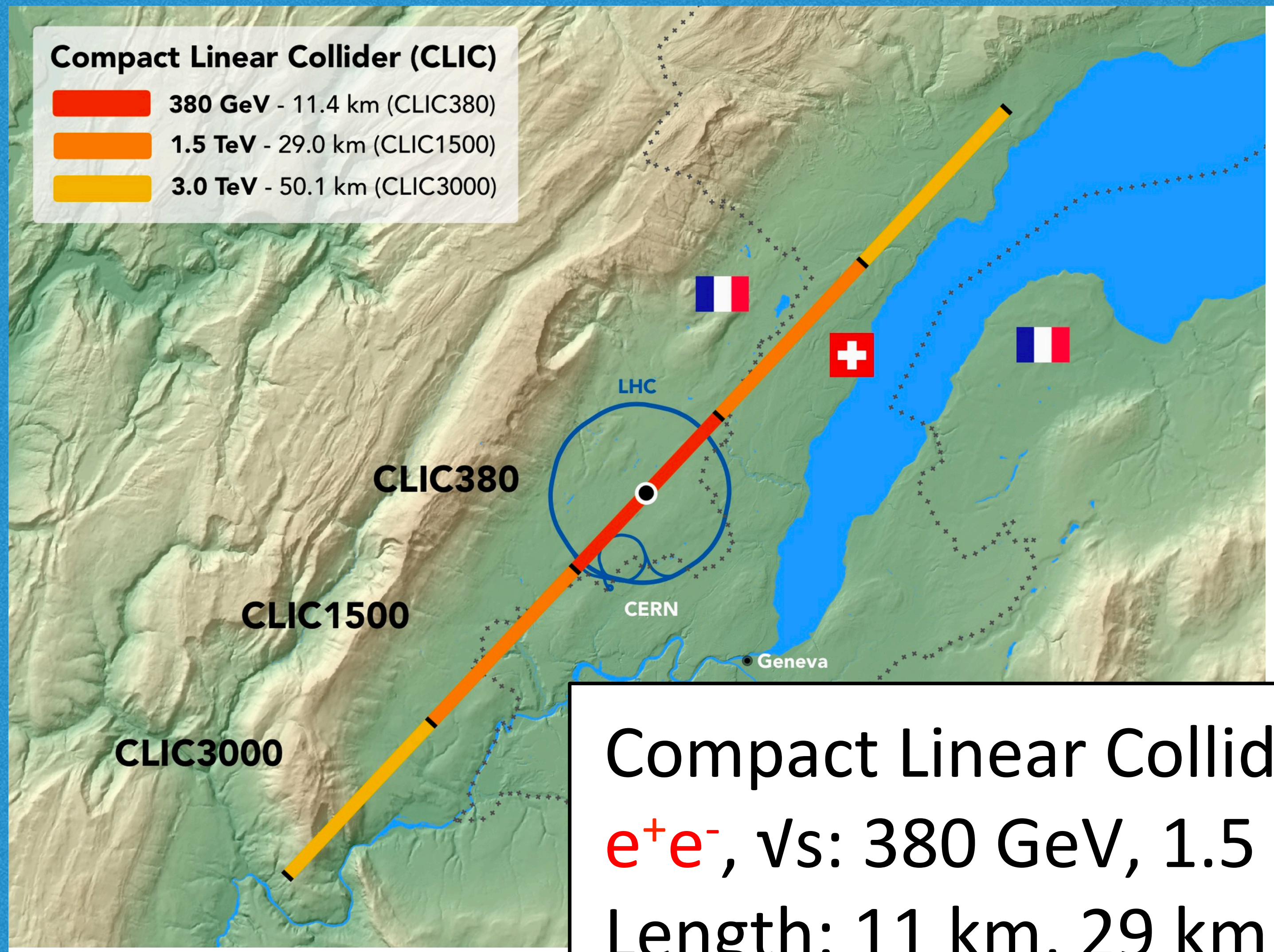
CMS end-cap calorimeter (HGCAL)



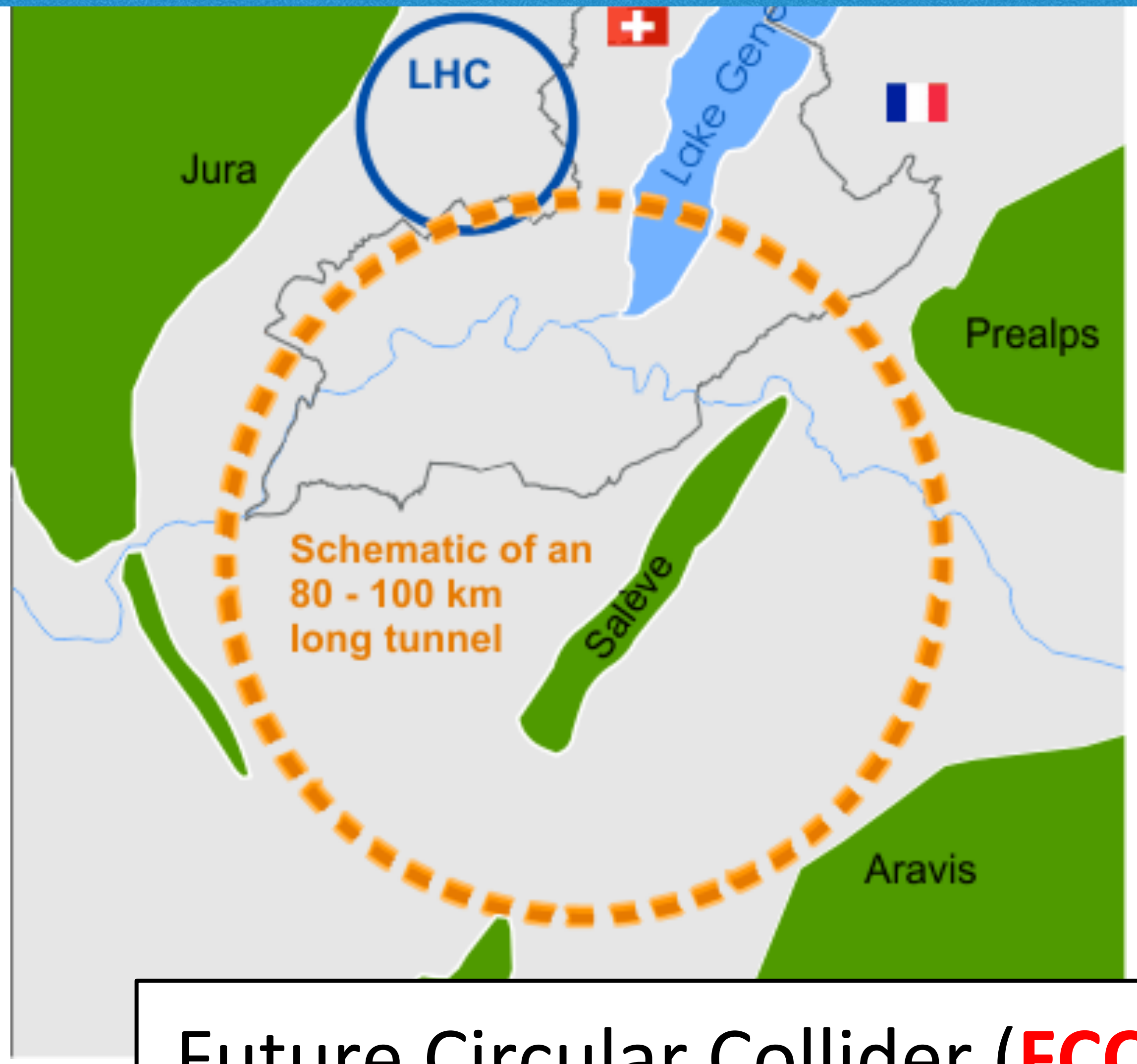
$1.5 < |\eta| < 3$

Unprecedented lat. and long. segmentation (ILC-type)
Time resolution ~ 30 ps
EM part (CE-E): Si pads, Cu/CuW/Pb absorber
26 layers, 25 X_0
HAD part (CE-H): Si and scintillator, steel absorber
21 layers, 8.5 λ
~ 600 m^2 of Si pads (0.5-1 cm^2)
10^6 channels

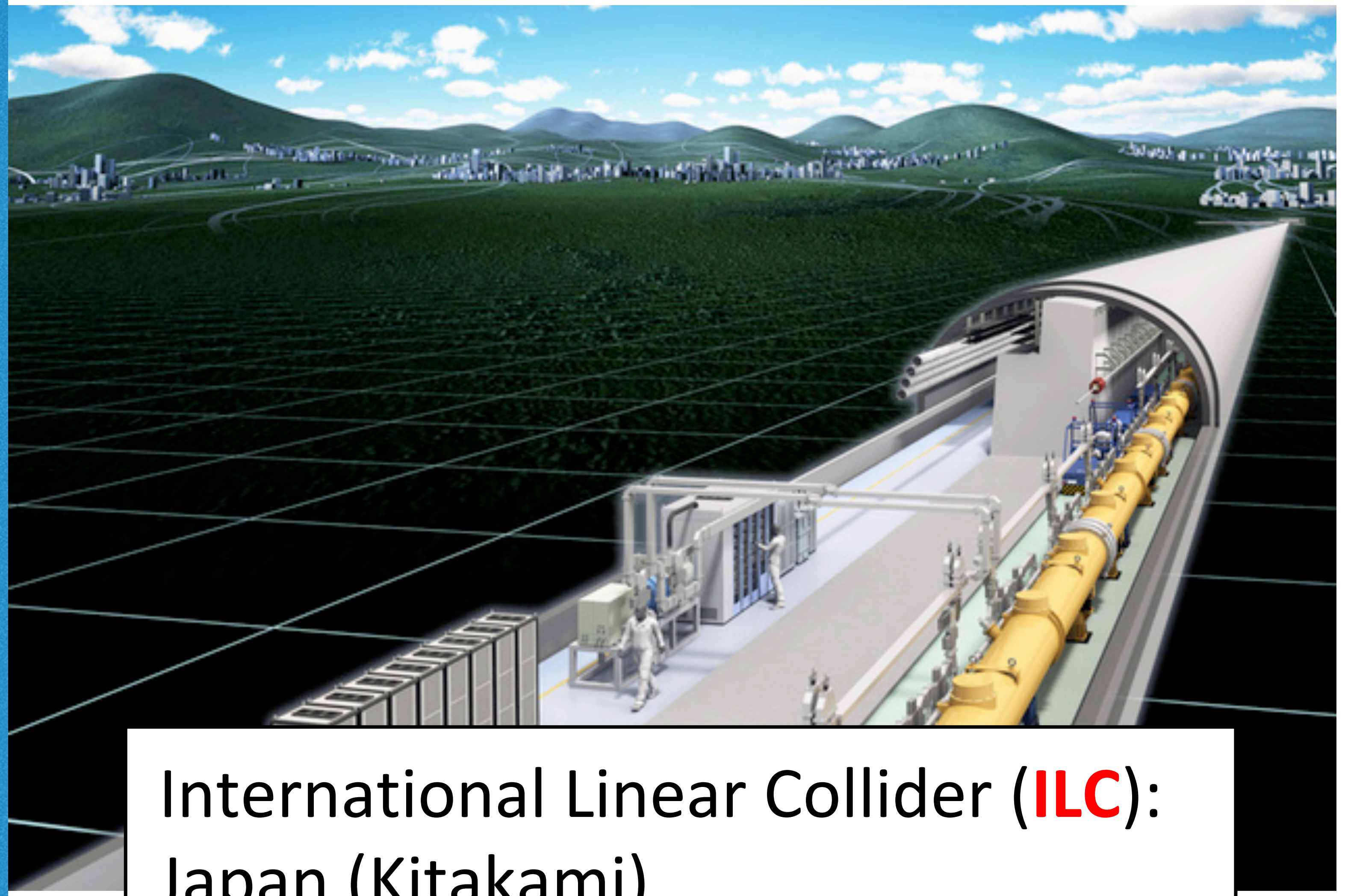
New High-Energy Collider Projects



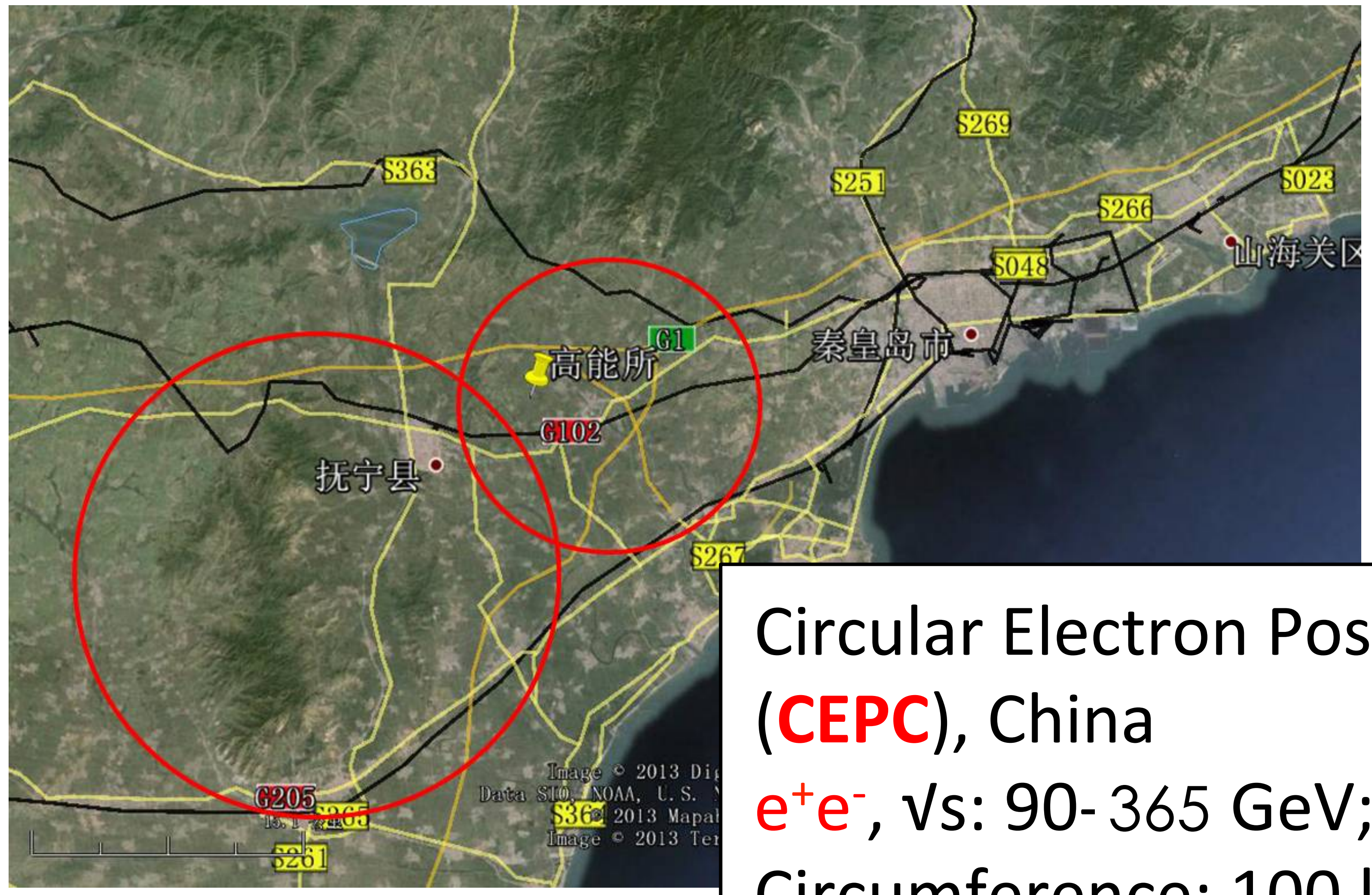
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 (365) GeV; FCC-hh pp
Circumference: 97.75 km

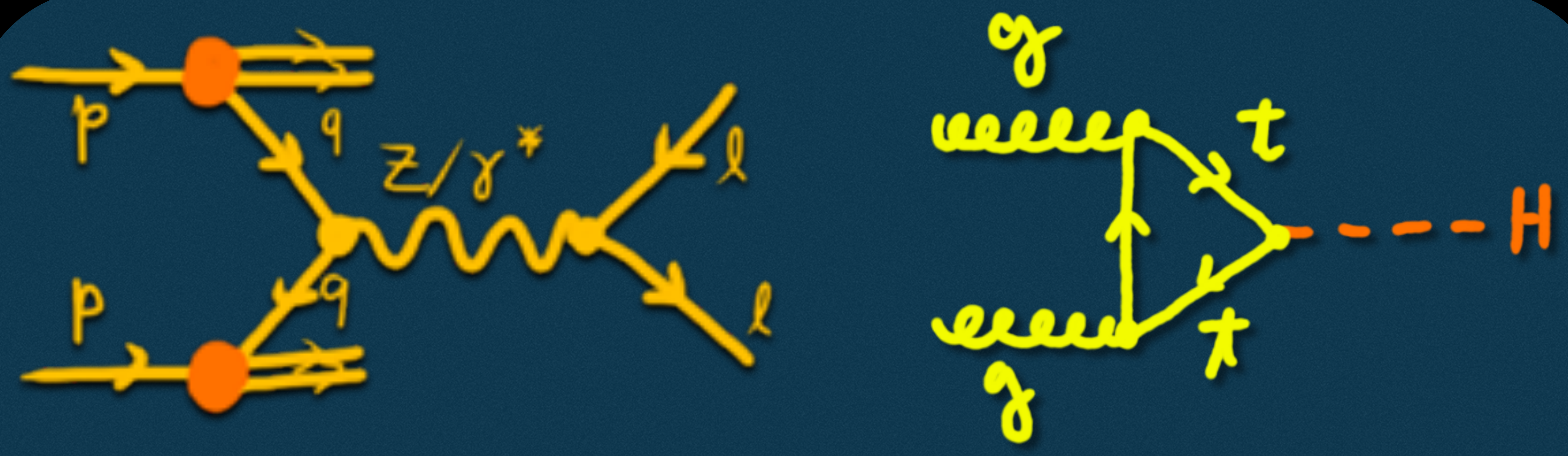


International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



Circular Electron Positron Collider
(**CEPC**), China
e^+e^-, $\sqrt{s}$: 90- 365 GeV; SPPC pp,
Circumference: 100 km

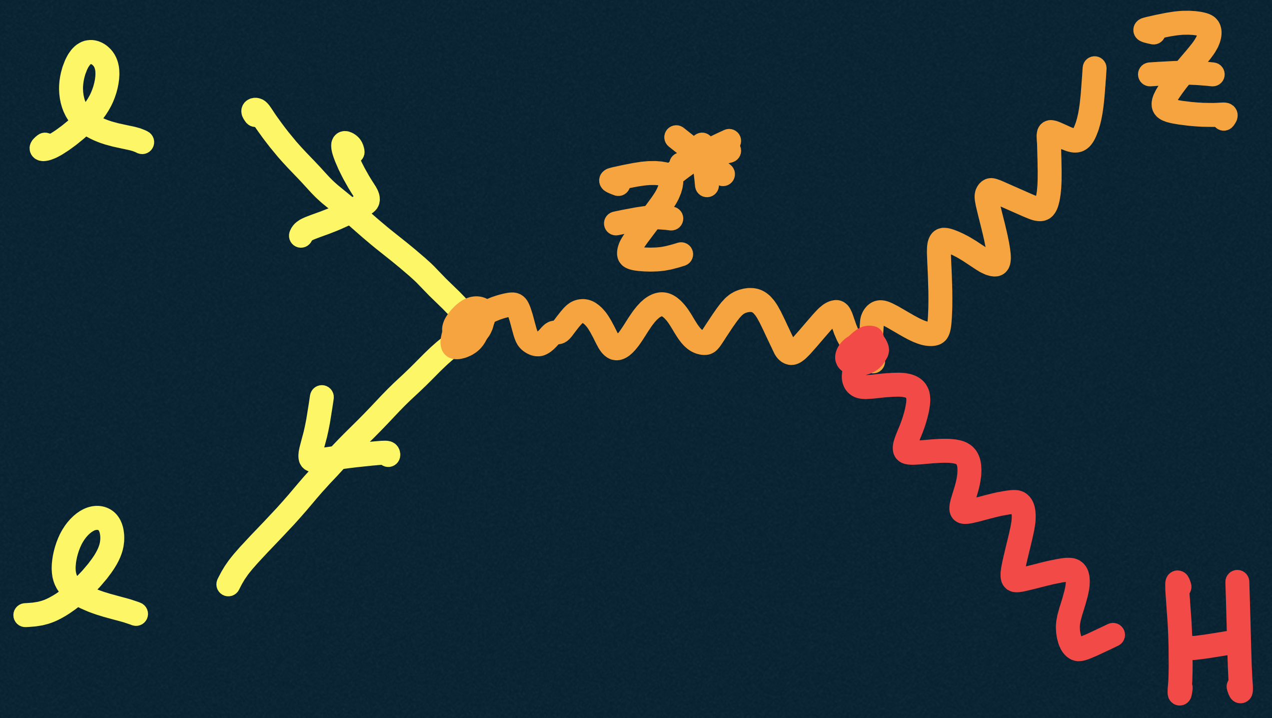
Hadron versus lepton colliders



1. Proton are compound objects
   - Initial state unknown (particle and momentum)
   - Limits achievable precision
2. High rates of QCD background

   S/B ~ 10^{-10}

   - Complex triggers
   - High levels of radiation
     - Detector design focus on radiation hardness of many sub-detectors
3. Very high-energy circular colliders feasible



1. Electrons are point-like particles
   - Initial state well-defined (particle, energy, polarization…)
   - High-precision measurements
2. Clean experimental environment

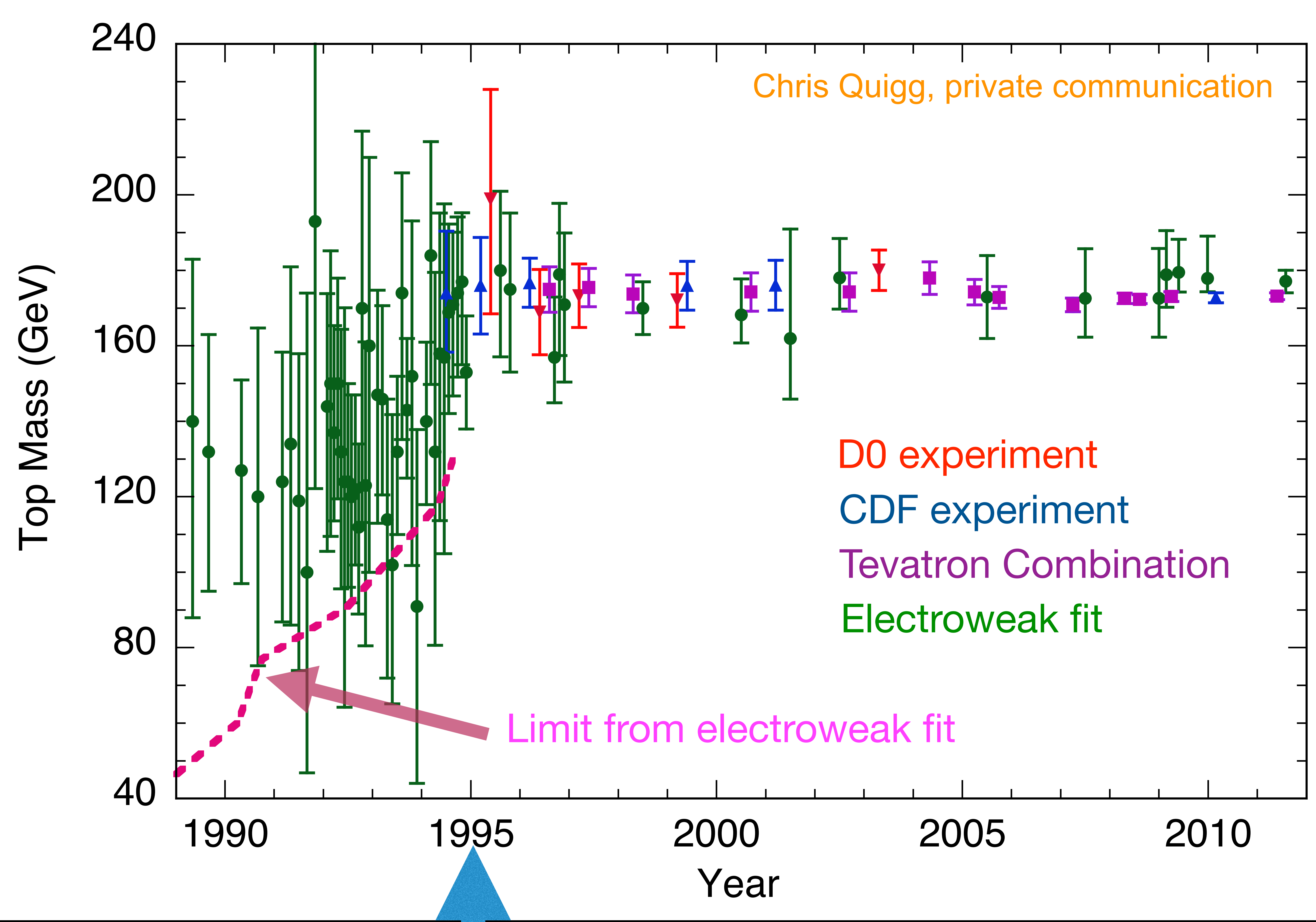
   S/B ~ 10^{-3}

   - No (less) need for triggers
   - Lower levels of radiation
3. Very high-energies require linear colliders

After the Higgs boson discovery, no other new physics found
Need to also pursue outstanding precision

- PRECISION physics can play a key role -

Top Mass Prediction from Precision Electroweak data



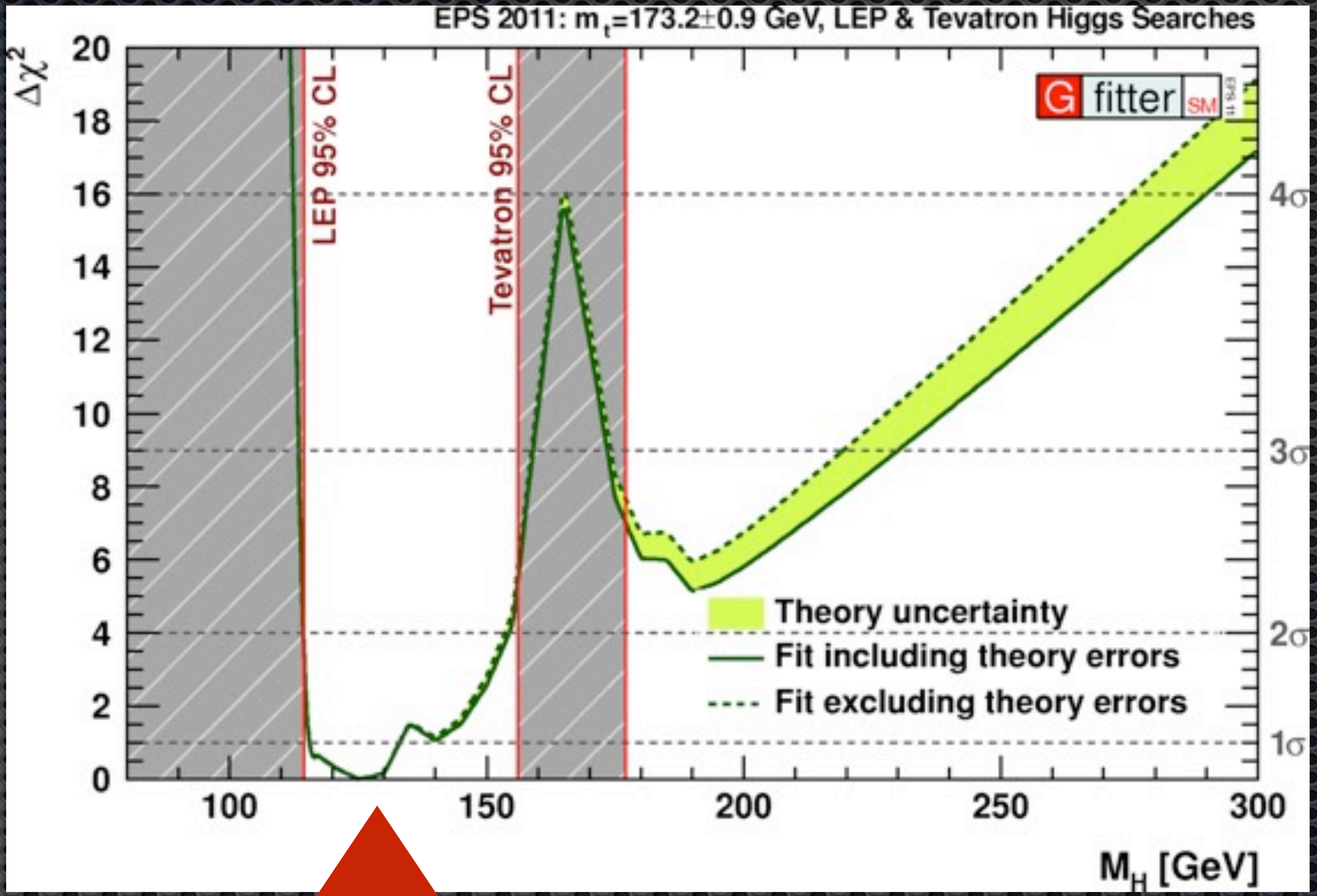
$M_{top} = 175 \longrightarrow 173$ GeV

World average:
$m_{top} = 173.1 \pm 0.6$ GeV
(0.35%)

Top discovery at Tevatron

Overnight update

- **Updated with EPS'01 results**
  - **Excludes direct searches from ATLAS and CMS from EPS**



Standard Fit

m_H (minimum)= 94.5 GeV, Range m_H = [71, 124], m_H < 166.5 GeV @ 95%

Complete Fit

m_H (minimum)= 125.2 GeV, Range m_H = [116, 133], m_H < 153.9 GeV @ 95%

Thanks to Matthias Schott from the GFitter group

July 21-27

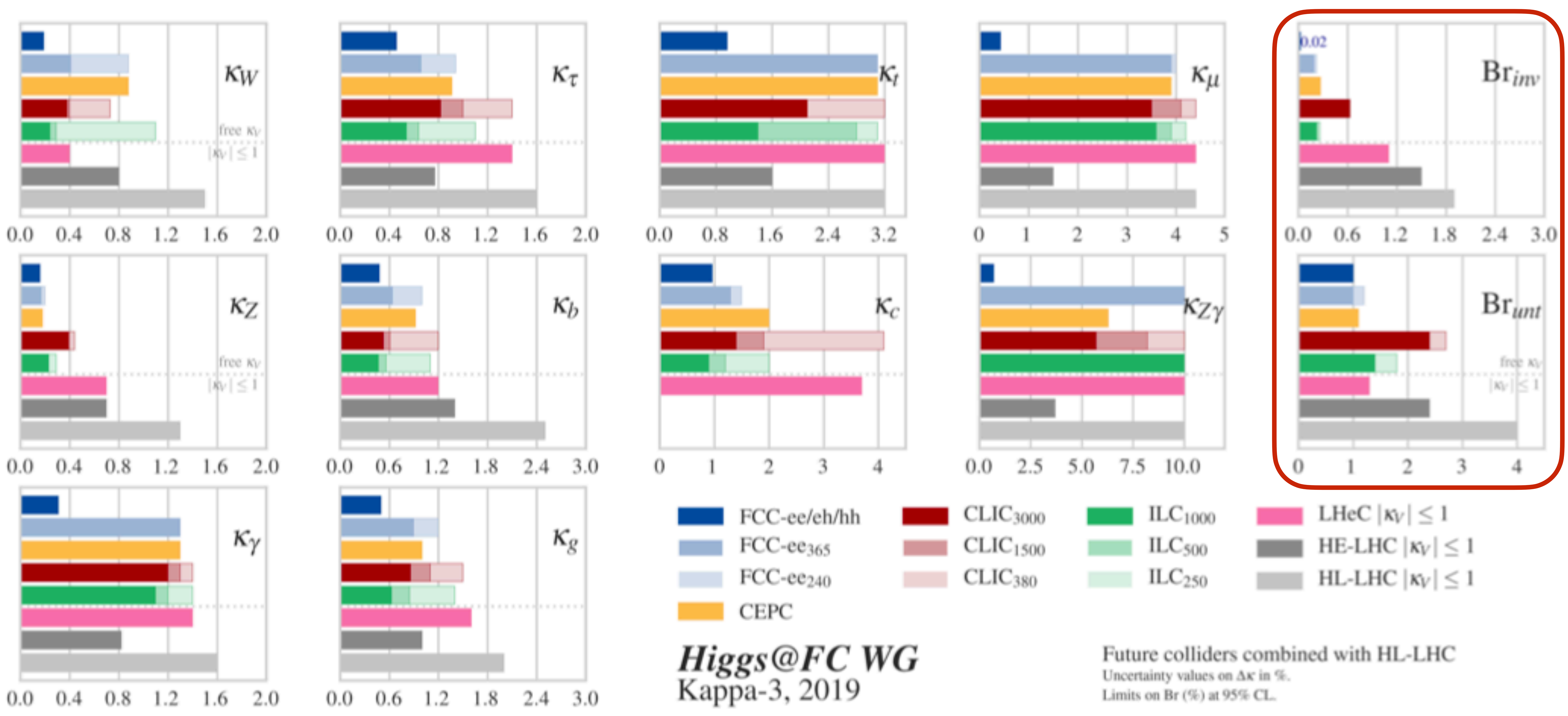
PANIC 2011, July 28, 2011

WARNING: Slide from 2011

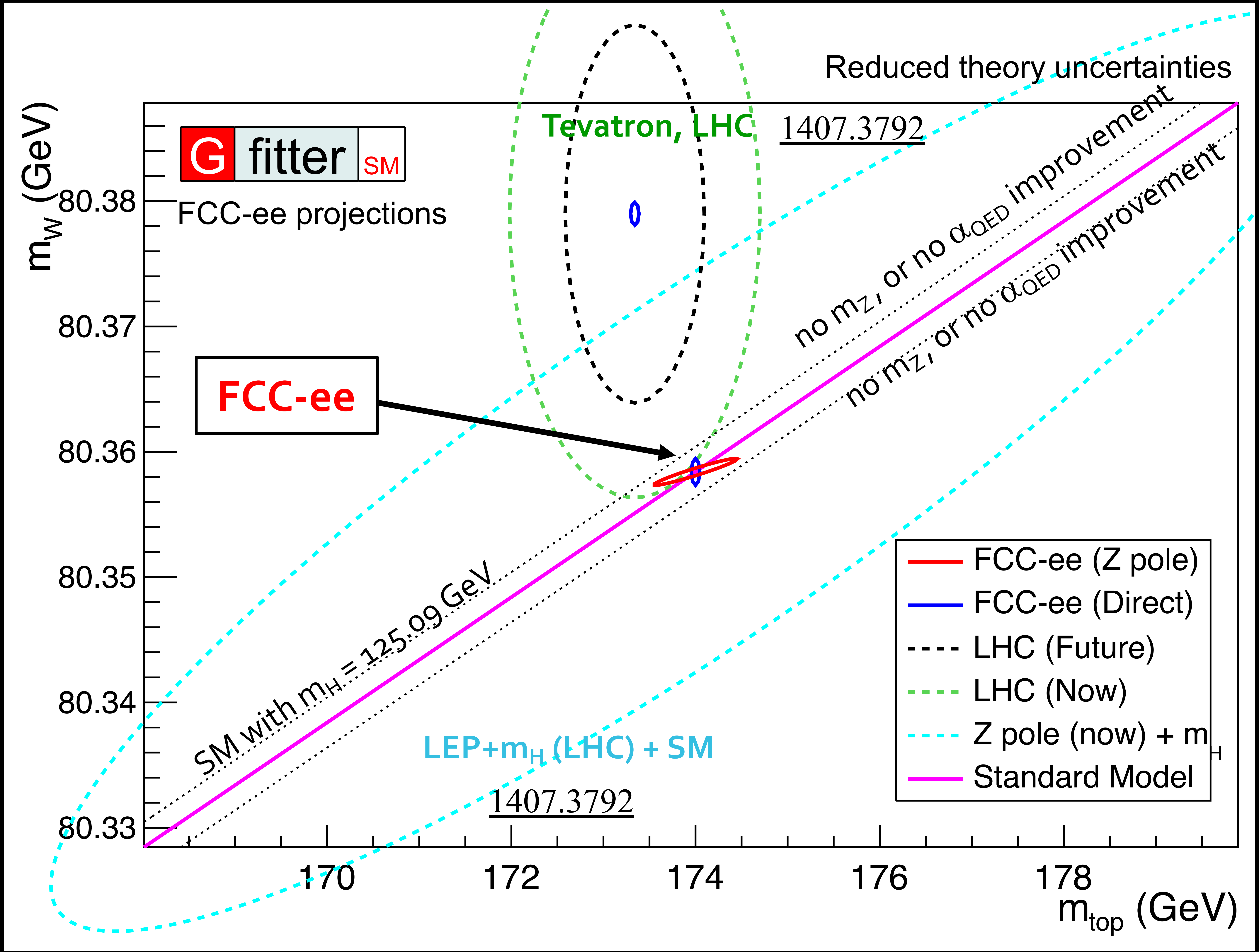
Higgs coupling measurement at future colliders

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

95% CL limits



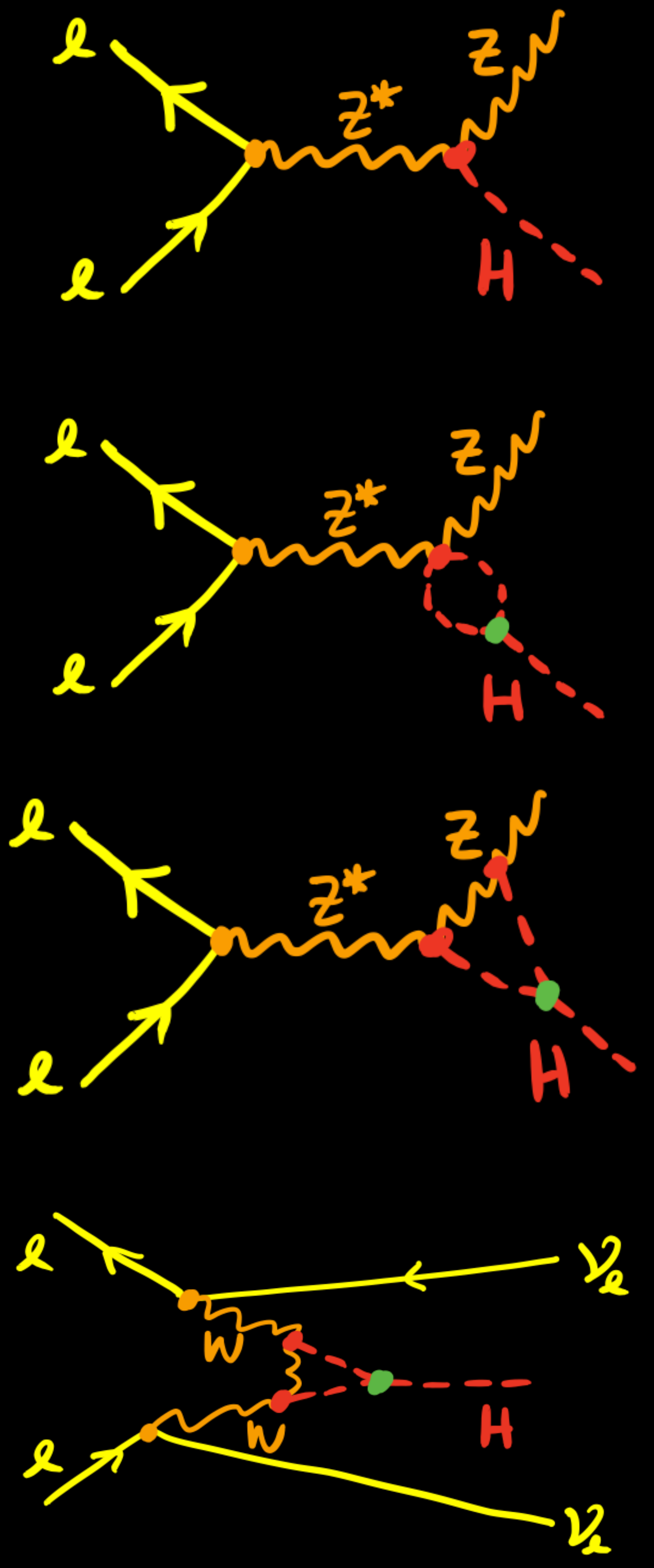
Combination of electroweak measurements

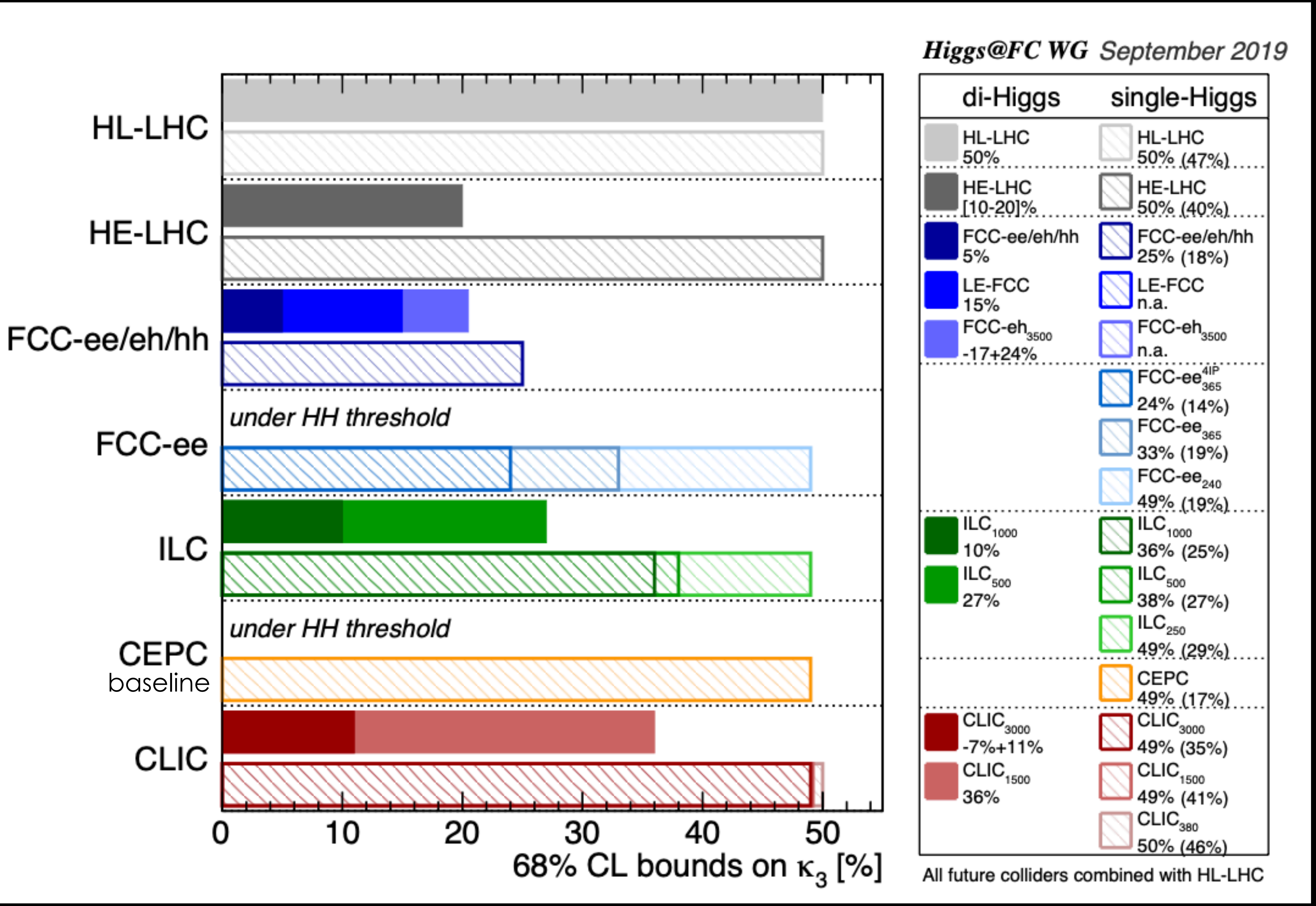


Precision of theory predictions needs to improve to take advantage of this experimental precision for full sensitivity to new physics

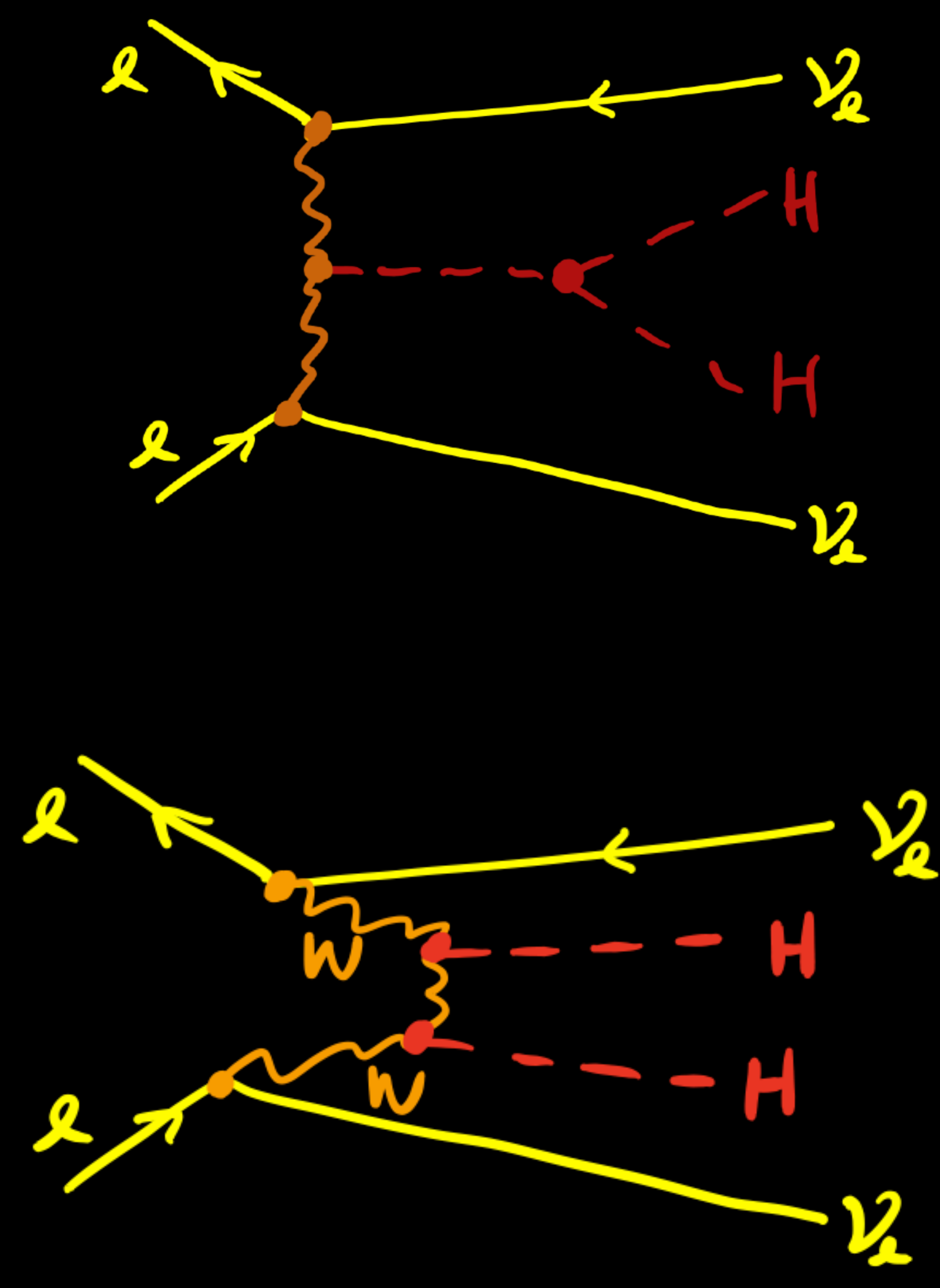
Higgs self-coupling at lepton colliders

Global effective-field-theory analysis can assess Higgs trilinear self-coupling





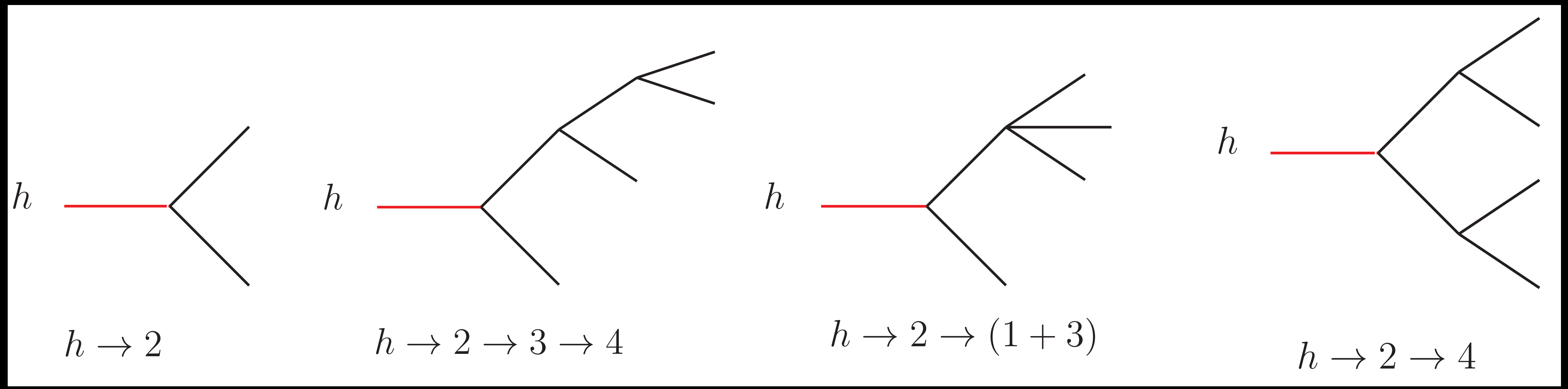
Direct production at ILC and CLIC most important



BSM Physics through Exotic Higgs Decays

General search for BSM

e^+e^- collider better than HL-LHC for MET+hadronic activity final states



Z. Liu, H. Zhang, LT Wang, 1612.09284

Final remarks

The standard Model is well established but many questions remain answered

LHC, including HL-LHC, to provide still 20-30x more data
Hence, small discrepancies can still turn into discoveries

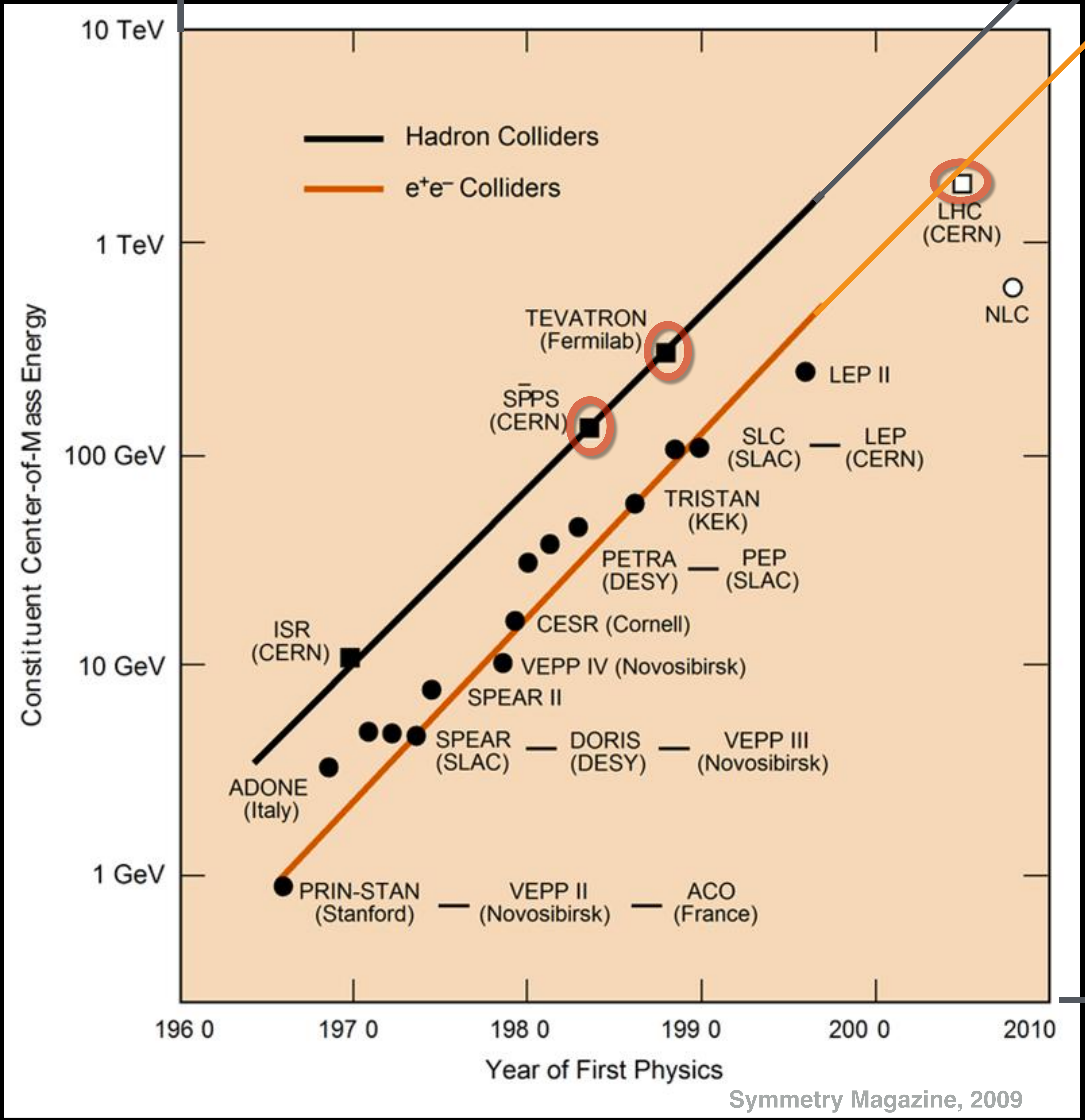
Higgs self coupling measurement at HL-LHC is a major milestone

Planning for the next future accelerators has started

(see Tatsuya Tanaka's lecture tomorrow for details)

Expect new exciting sensitivity for BSM physics and potential discoveries
Higgs will continue to play an essential role

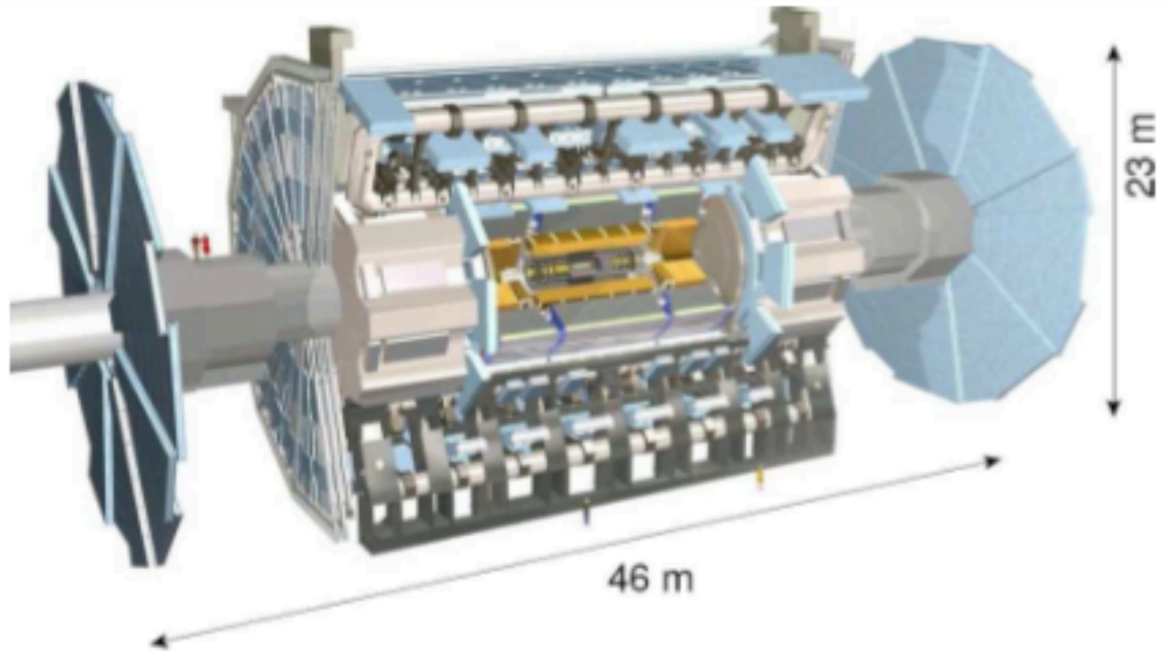
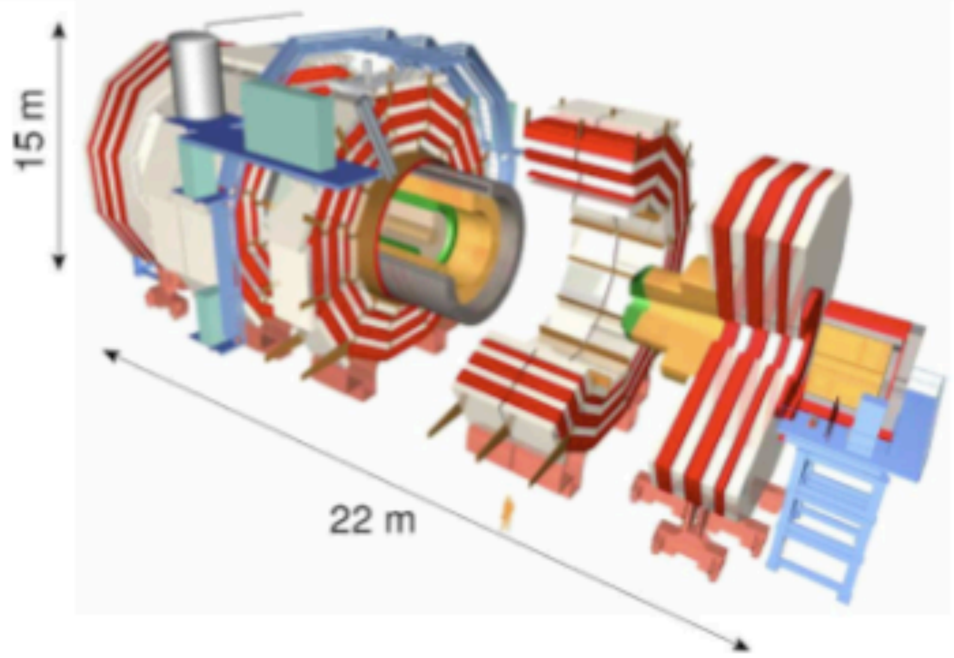
Explore synergies of electron and hadron colliders to maximize physics potential



10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
Constituent Center-of-Mass Energy
Hadron Colliders
e+e− Colliders
LHC
(CERN)
NLC
TEVATRON
(Fermilab)
LEP II
SPPS
(CERN)
SLC
(SLAC)
LEP
(CERN)
TRISTAN
(KEK)
PETRA
(DESY)
PEP
(SLAC)
CESR (Cornell)
ISR
(CERN)
VEPP IV (Novosibirsk)
SPEAR II
SPEAR
(SLAC)
DORIS
(DESY)
VEPP III
(Novosibirsk)
ADONE
(Italy)
PRIN-STAN
(Stanford)
VEPP II
(Novosibirsk)
ACO
(France)
196 0
197 0
198 0
199 0
200 0
2010
Year of First Physics
Symmetry Magazine, 2009

2040 GeV

ATLAS and CMS in more detail

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

How bad does it look?

2012: Z → μμ event