Exploring New Physics with Top Quarks

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TOP QUARK

— Since —

1995

Leptons

Electron Neutrino
<2.2 eV

Muon Neutrino
<0.17 MeV

Tau Neutrino
<15.5 MeV

Electron
0.51 MeV

Muon
105 MeV

Tau
1.77 GeV

Quarks

Up
2.3 MeV

Charm
1.275 GeV

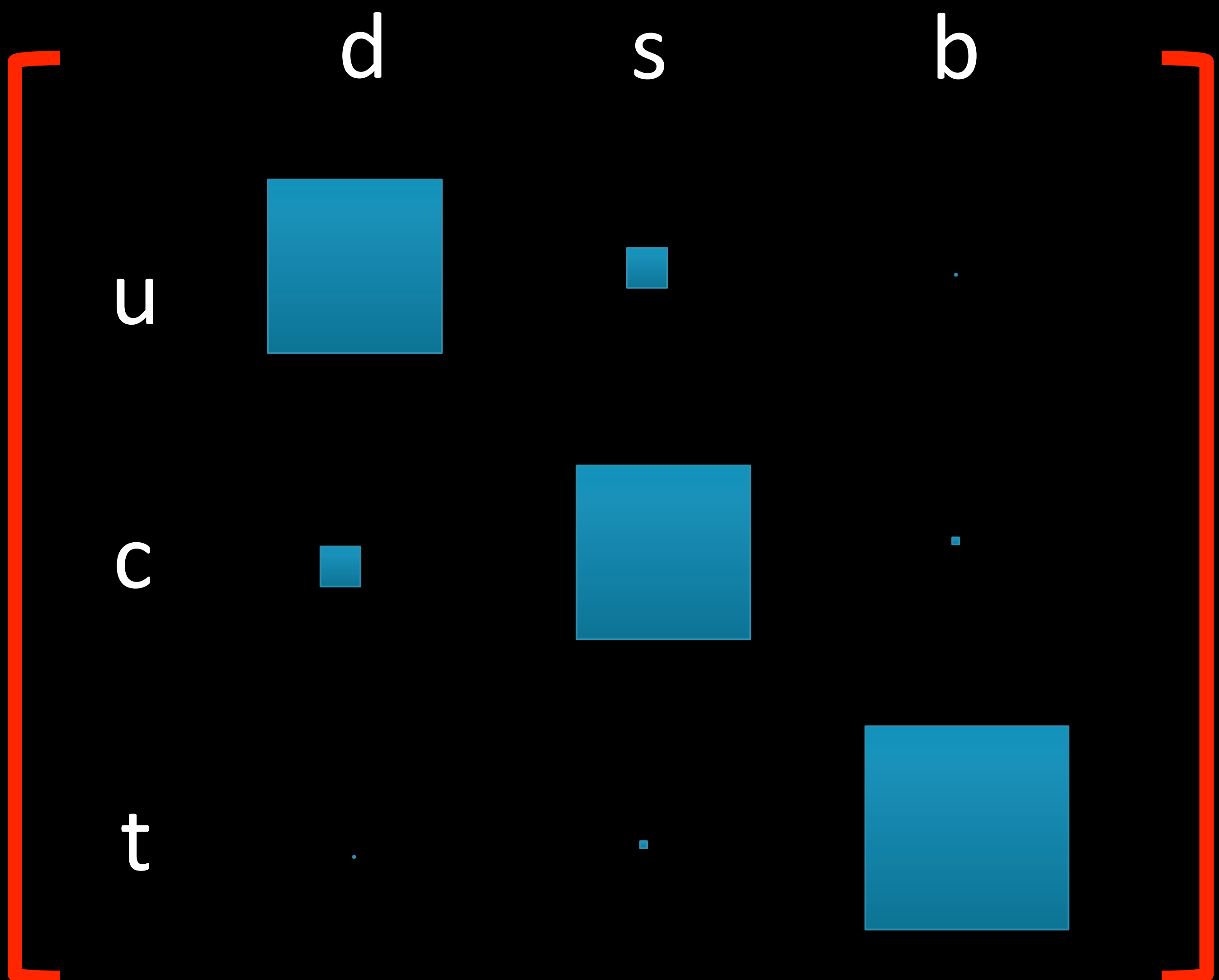
Top
173 GeV

Down
4.8 MeV

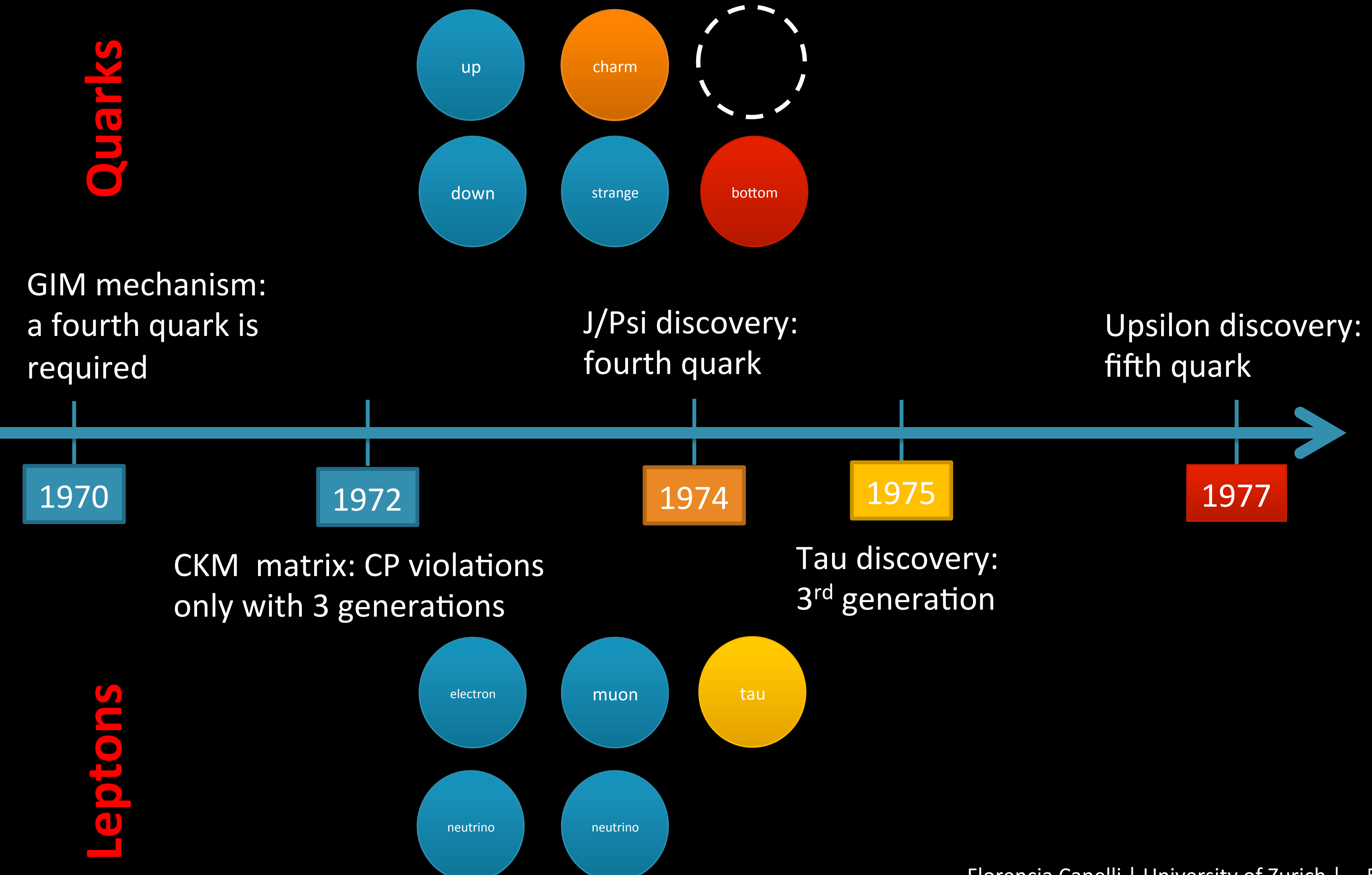
Strange
95 MeV

Bottom
4.18 GeV

The origin of flavor



The road to discovery



The road to discovery

PETRA (DESY):
e^+e^-, $\sqrt{s} \leq 46.8$ GeV
$m_{top} > 23.3$ GeV

SppS (CERN):
ppbar, $\sqrt{s} \leq 630$ GeV
$m_{top} > 69$ GeV

Tevatron (Fermilab):
ppbar, $\sqrt{s} \leq 1800$ GeV
$m_{top} > 92$ GeV

1986

1990

1992

1994

1995

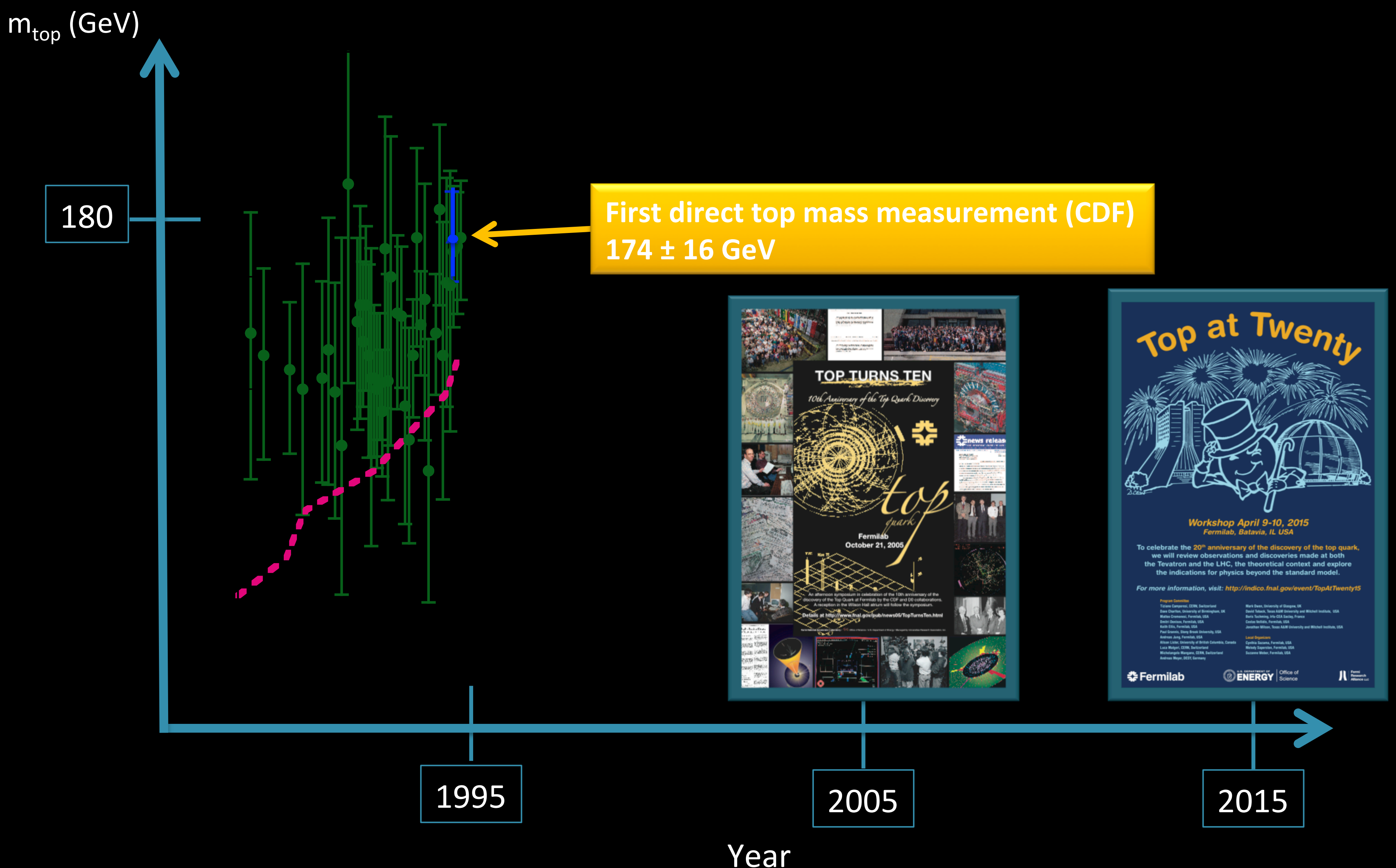
TRISTAN (KEK):
e^+e^-, $\sqrt{s} \leq 61.4$ GeV
$m_{top} > 30.4$ GeV

SLC (SLAC):
e^+e^-, $\sqrt{s} \sim 90$ GeV
$m_{top} > 45.8$ GeV

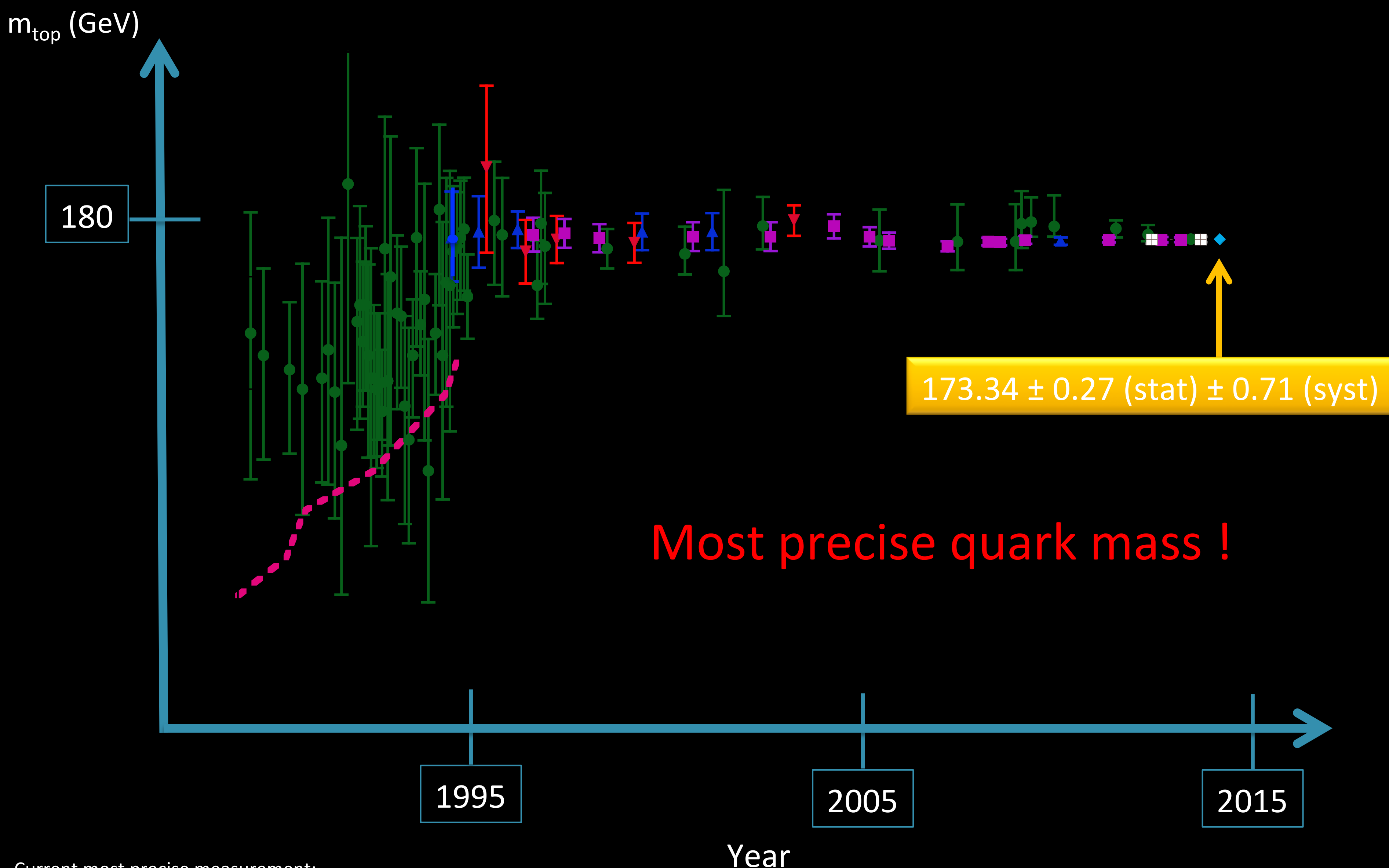
CDF and D0
Discovery

CDF (Tevatron)
Evidence
(2.8 sigma)

Top quark mass

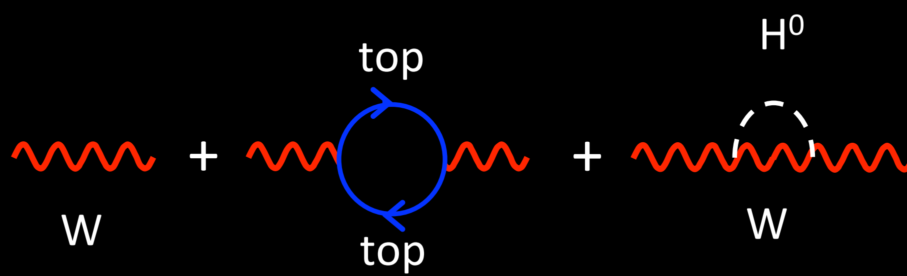


Top quark mass



Current most precise measurement:
CMS combination 172.44 ± 0.13 (stat) ± 0.47 (syst) GeV

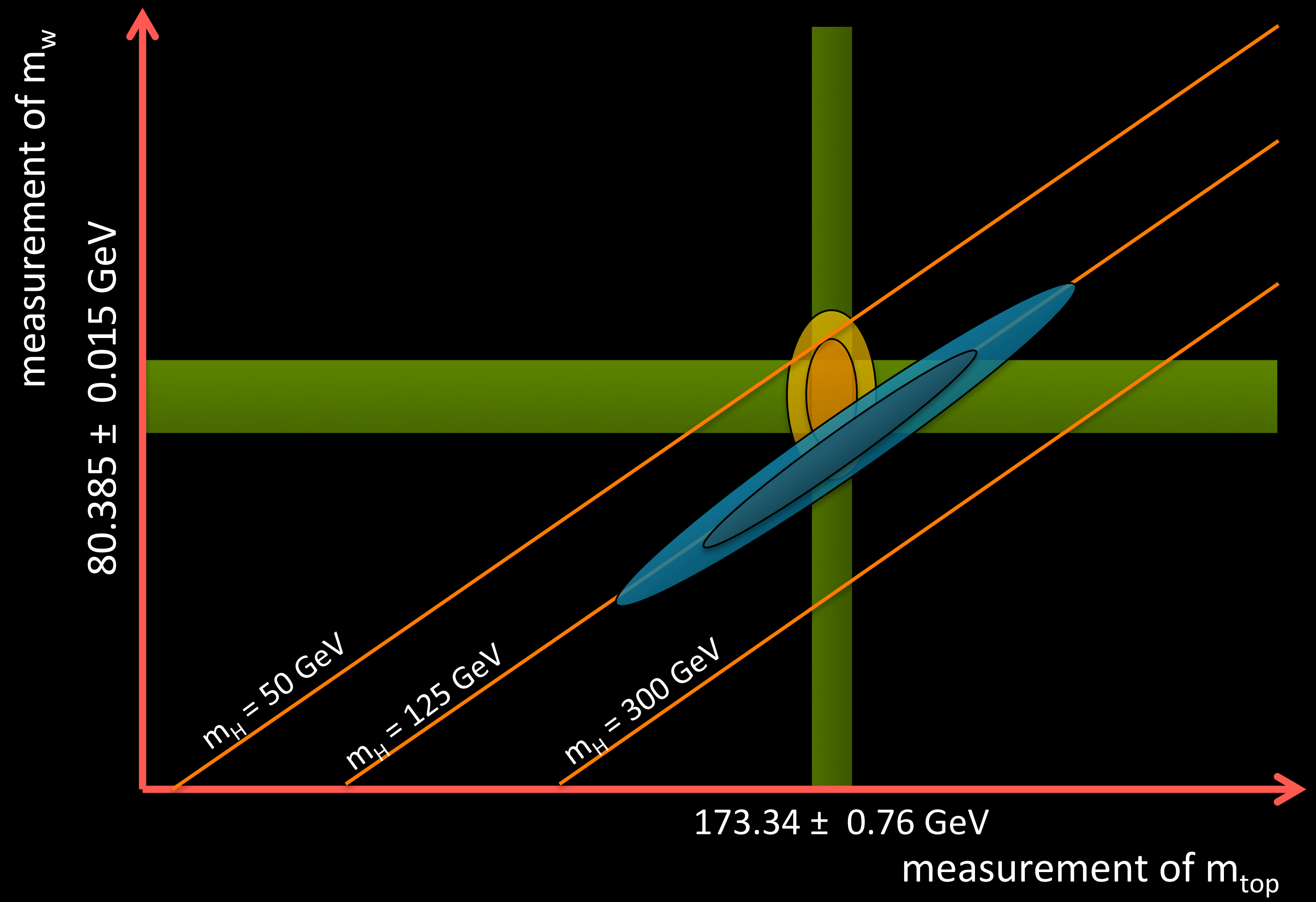
Constraining the theory



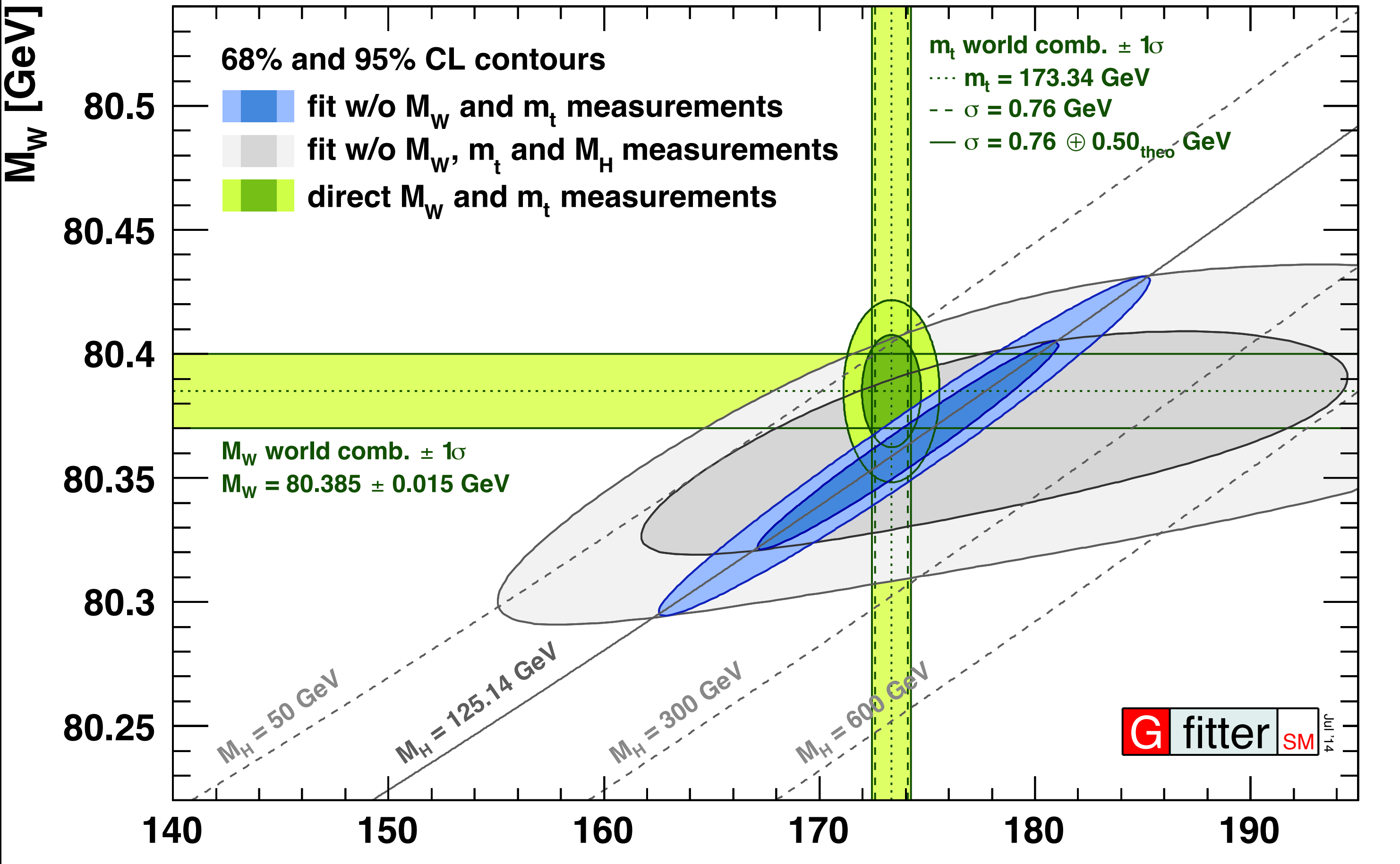
$$m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)$$

The top quark mass enters many electroweak parameters, with sizeable corrections.

Constraining the theory

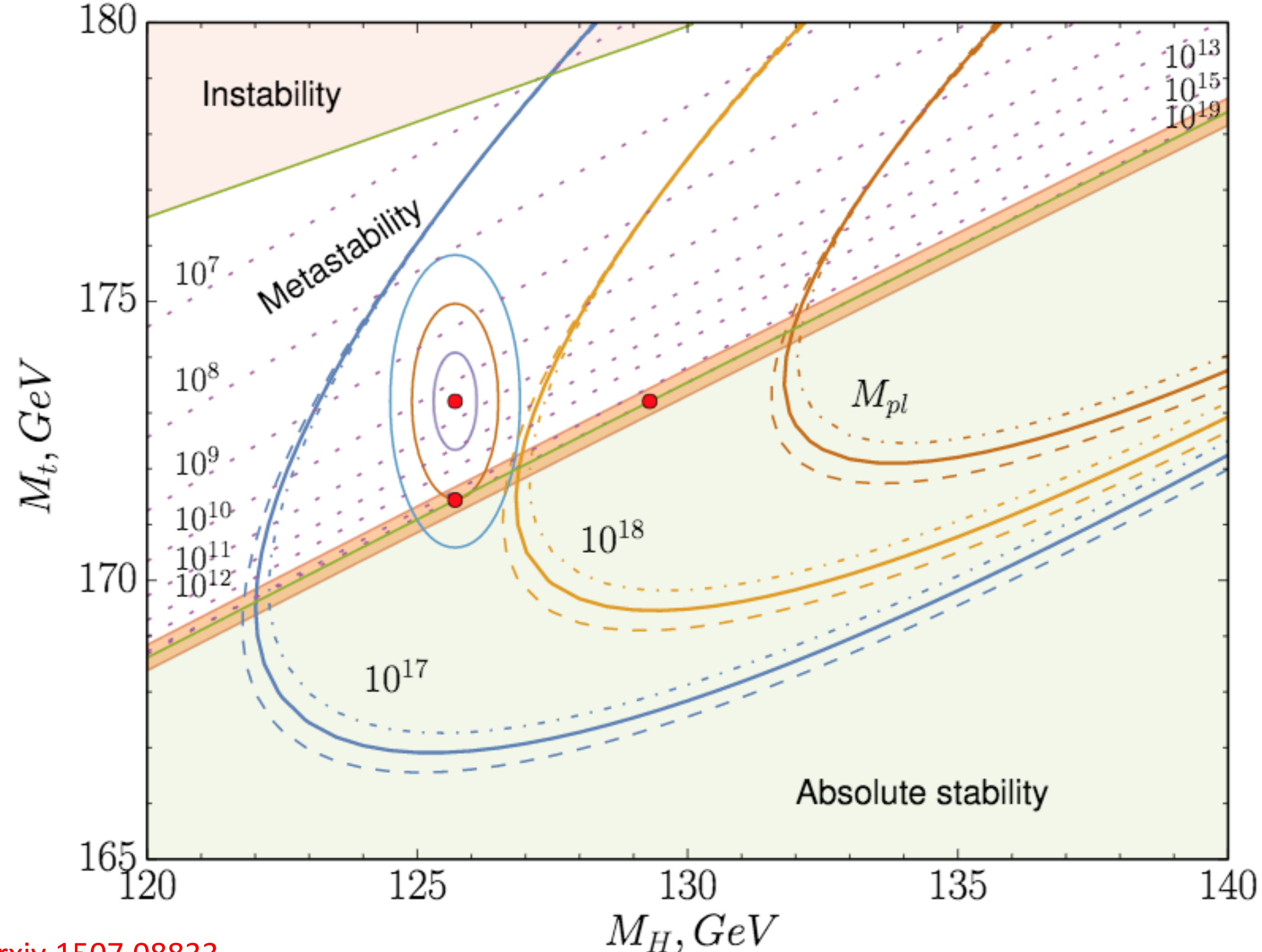


Constraining the theory



http://project-gfitter.web.cern.ch/project-gfitter/

The fate of the Universe



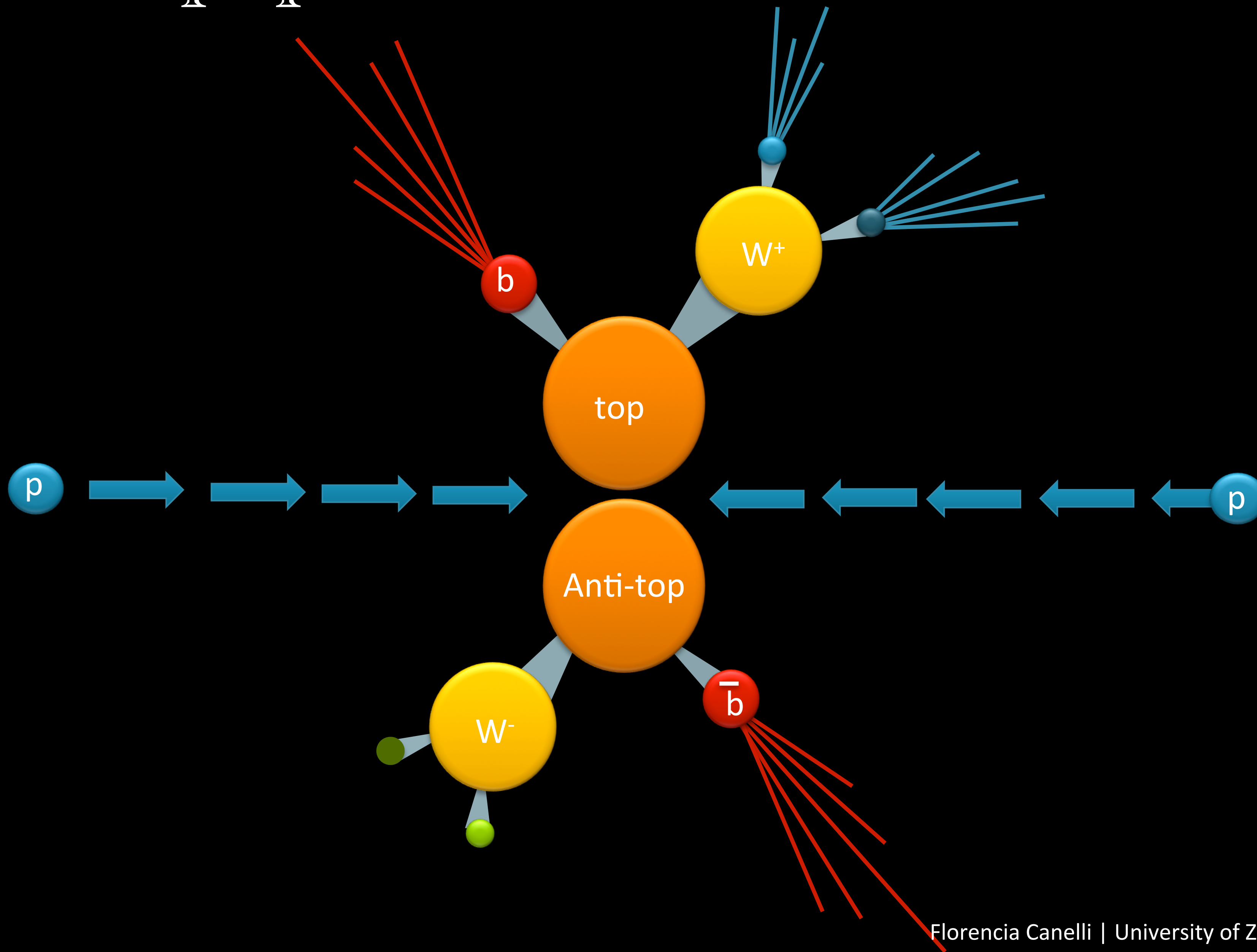
arxiv.1507.08833

Top production and decay at the Large Hadron Collider

Run I 2010-2012: 7 and 8 TeV collected ~5 fb^{-1} and ~20 fb^{-1}

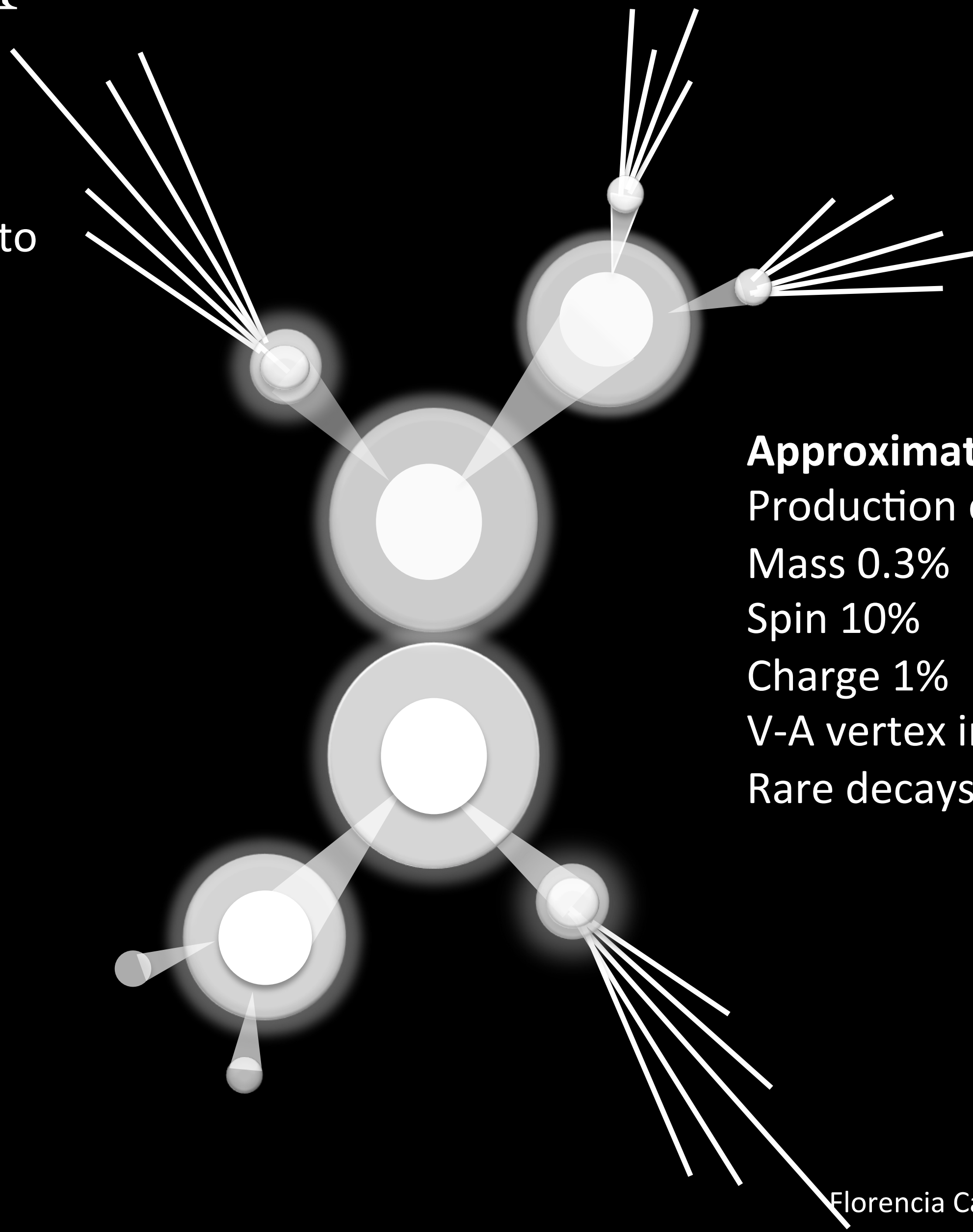
Run II 2015 – present: 13 TeV collected >40 fb^{-1}

Top production and decay



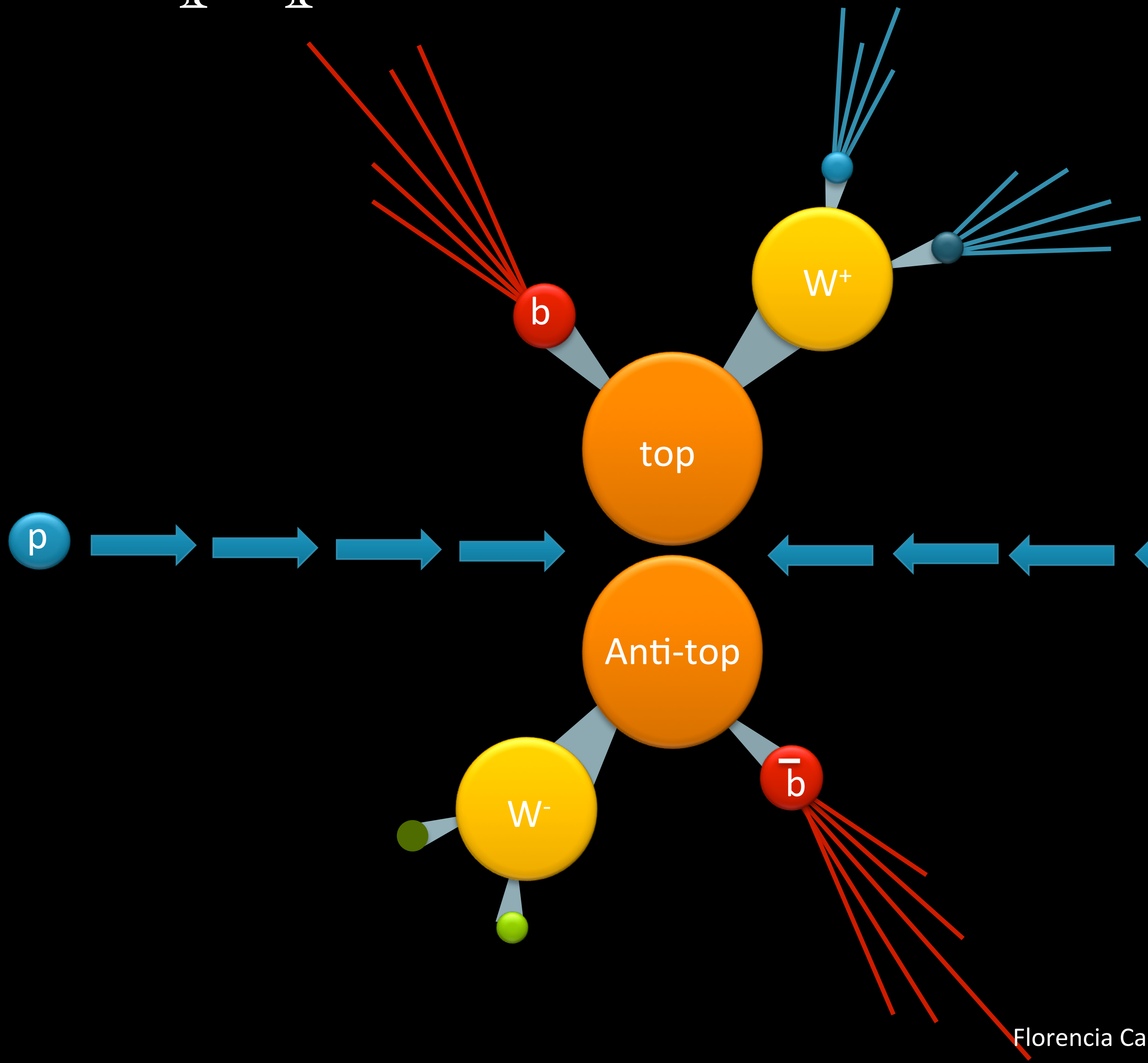
Top production and decay

More than 80 million top quarks produced to date at LHC



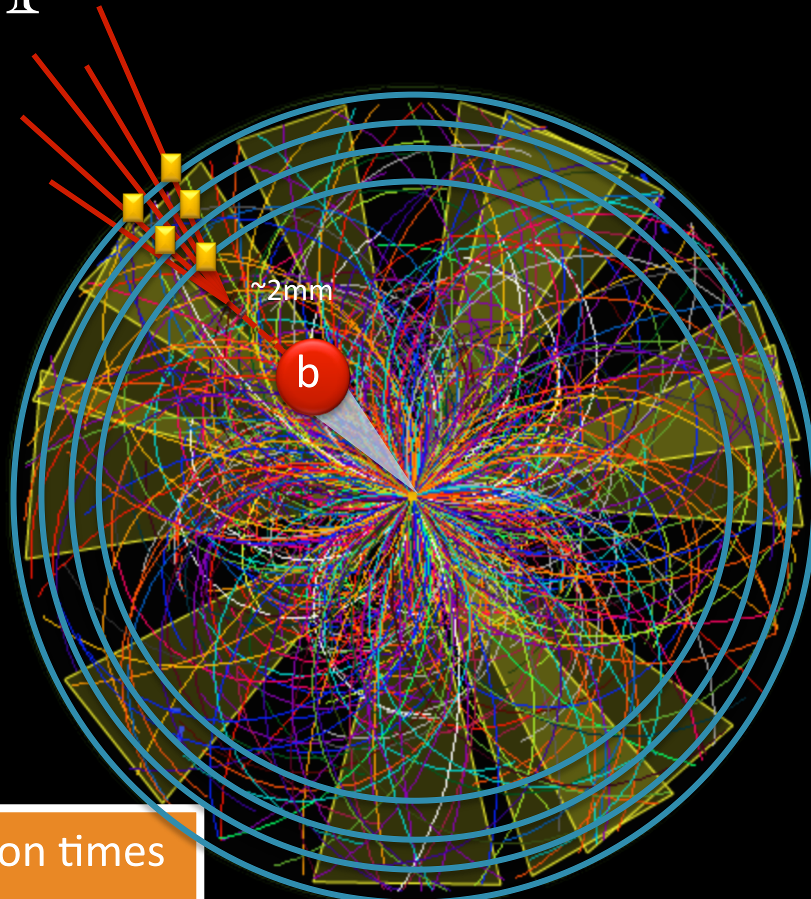
Approximate precision:
Production cross section 4%
Mass 0.3%
Spin 10%
Charge 1%
V-A vertex in decay 4%
Rare decays <1% (at 95 %C.L.)

Top production and decay



Top production and decay

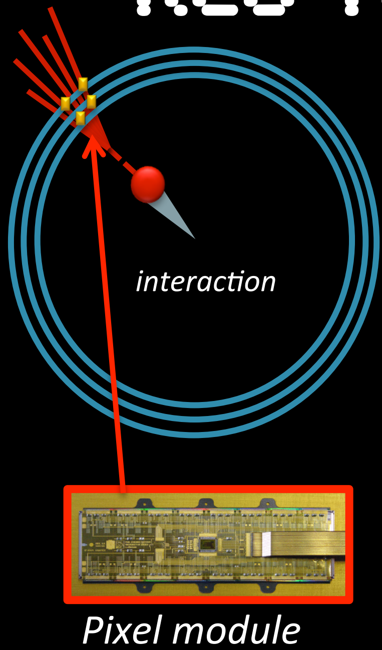
B-tagging and vertexing



Pixel detector provides a precise measurement of particle trajectory and identifies the secondary vertex where particles B mesons decay

Protons cross 40 million times per second.
In each crossing, >30 of interactions are possible. The pixel detector disentangles these interactions and identifies the primary vertex

KEY TECHNOLOGY: PIXEL DETECTORS

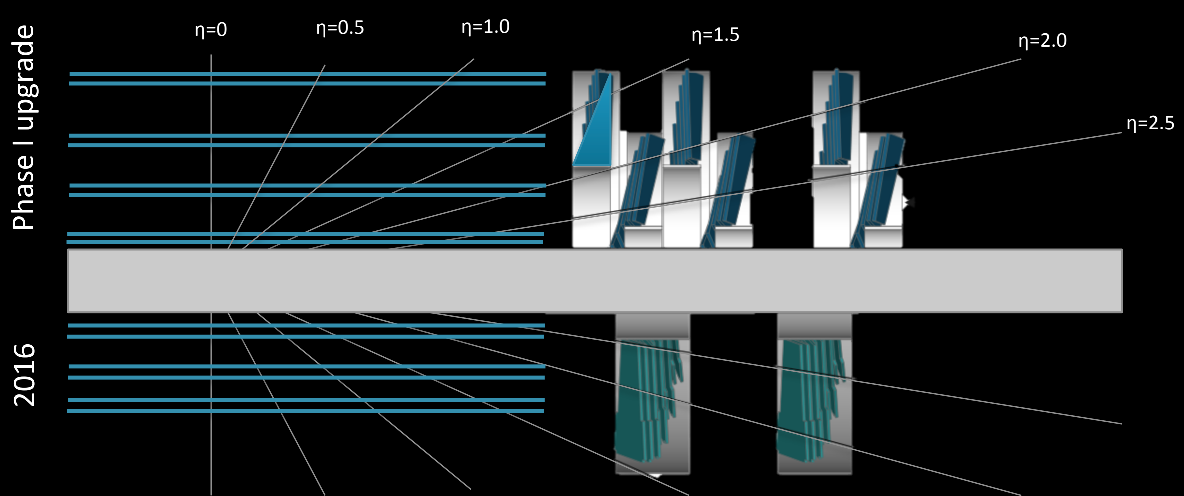


Pixel Detector :

Determines position, time, pulse height of traversing charged particles

- ~100 million channels
- Reads out data at 40 MHz

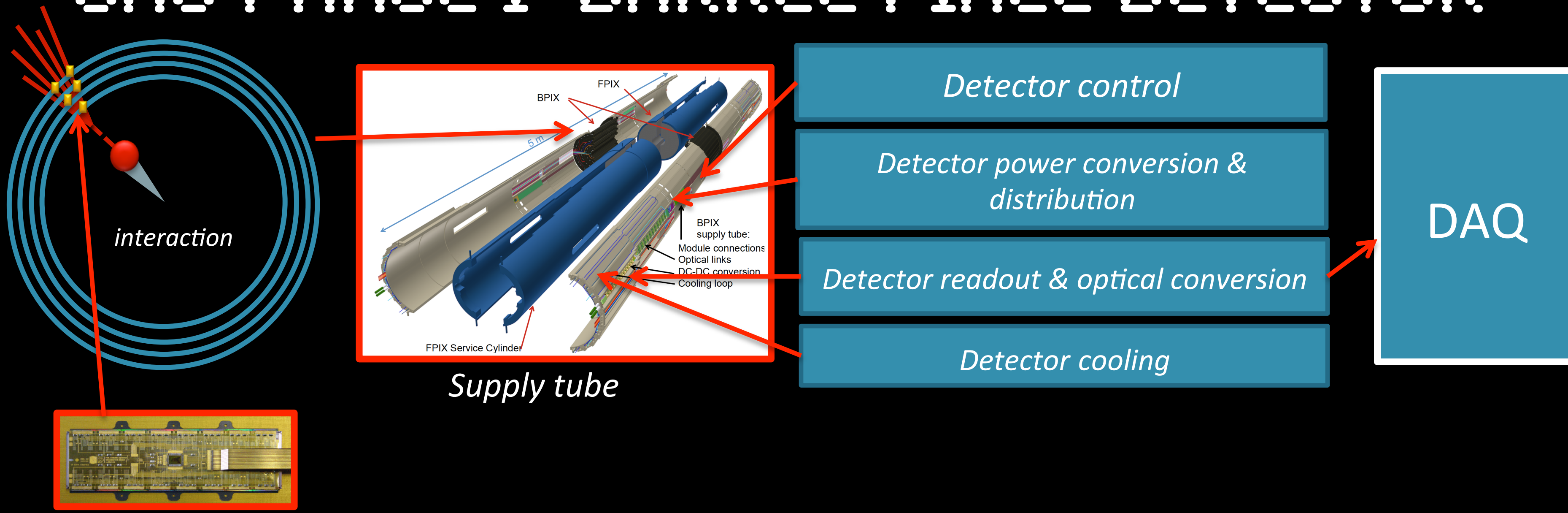
Starting in June 2017 the instantaneous data rate of the LHC increases such that the pixel detector needed to be replaced in order to maintain the excellent tracking of CMS



Phase I upgrade of the pixel detector (2010-2017):

- additional layer,
- less material,
- new readout electronics,
- better cooling

CMS PHASE I BARREL PIXEL DETECTOR



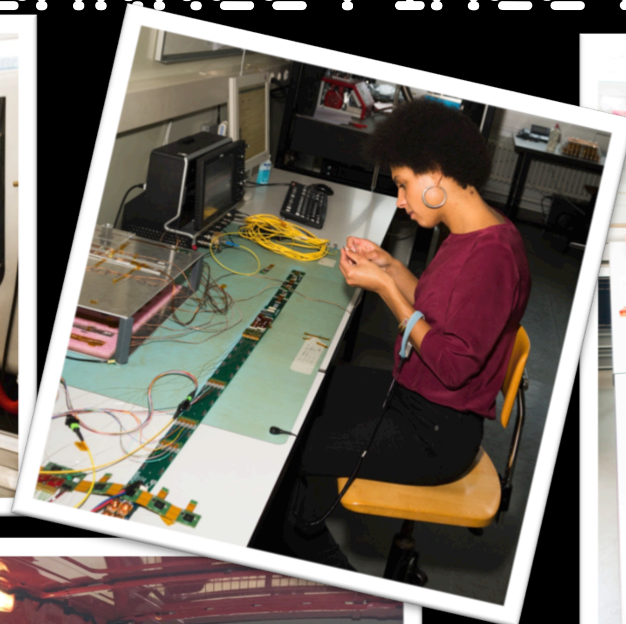
Supply tube

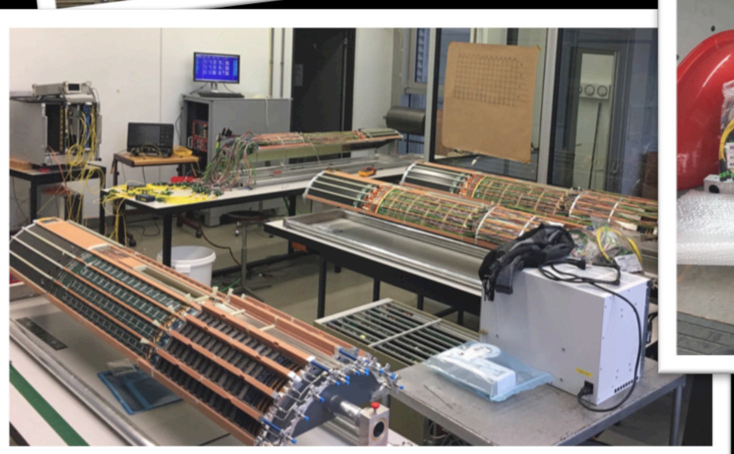
Pixel module

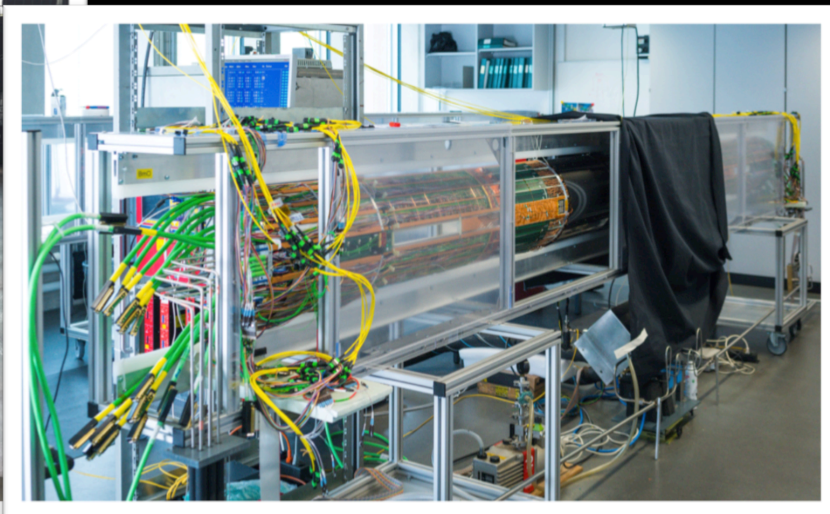
Supply Tube System:

- **Control** : state machine signals, loading calibration constants for detector
- **Power** : Down-conversion of power, distribution of power, control of power for detector
- **Readout** : receives data from detector, assembles, converts to optical, transmits to DAQ
- **Cooling** : supplies cooling to detector

CMS PHASE I BARREL PIXEL DETECTOR





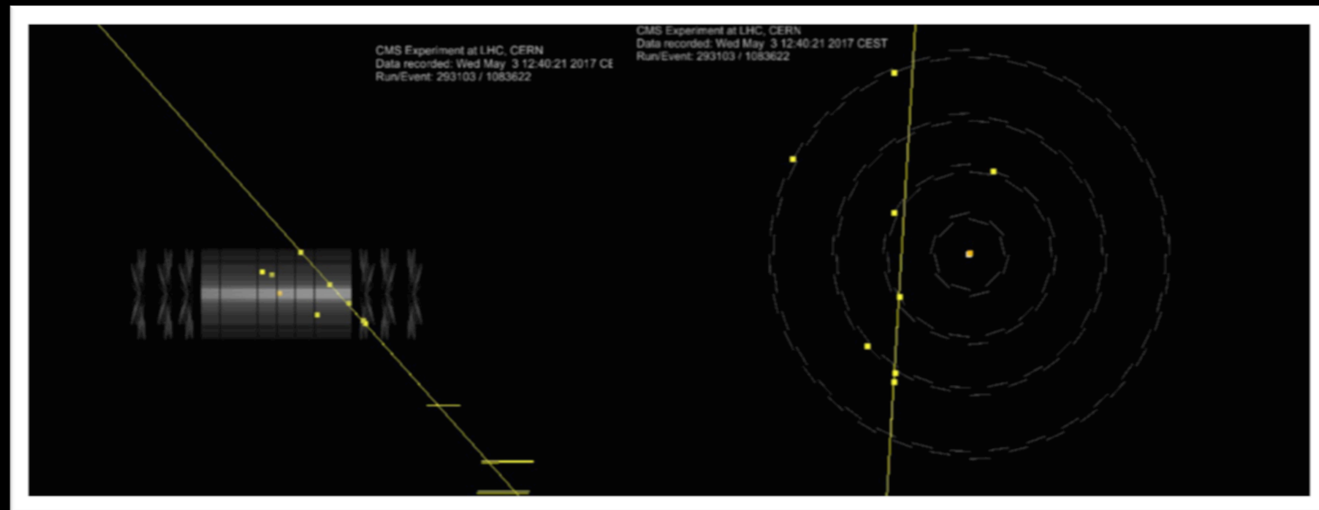


CMS PHASE I BARREL PIXEL INSTALLATION

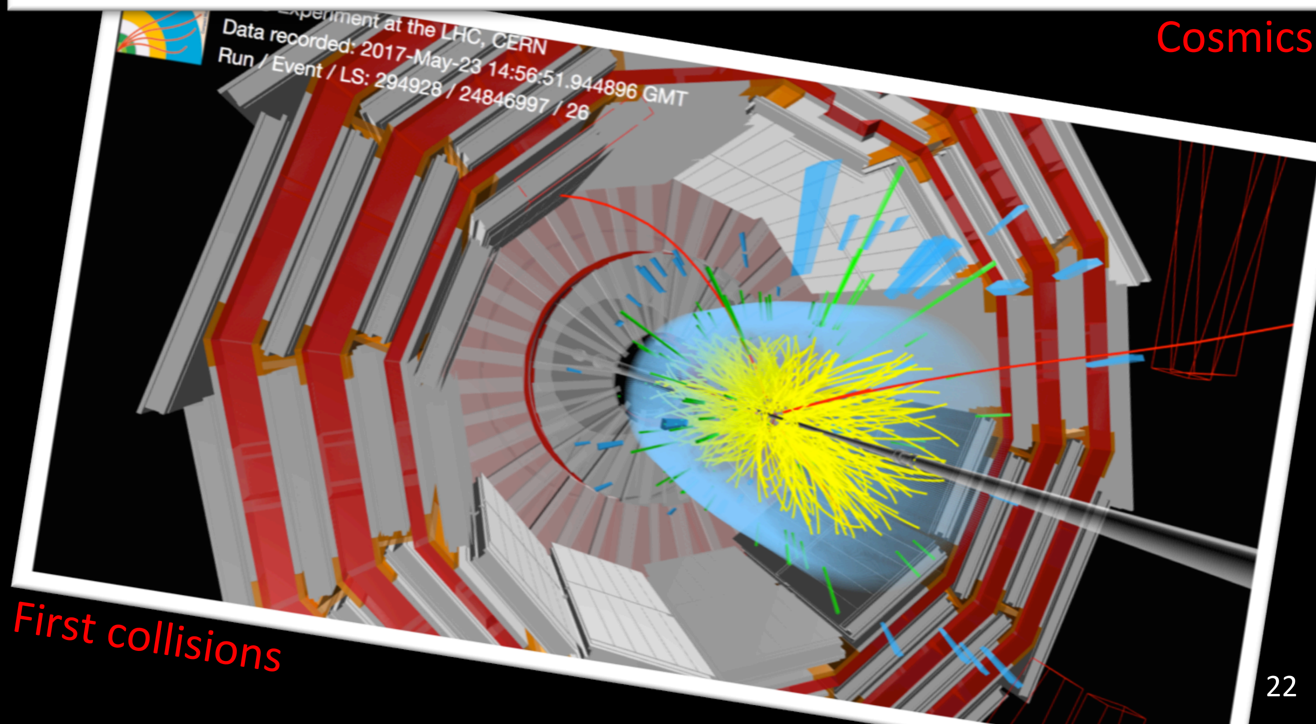
CMS Phase I Barrel Pixel Data

Successfully commissioned and integrated in CMS global taking

Phase I pixel detector is taking its first data in collisions now with more than 95% active channels



Cosmics



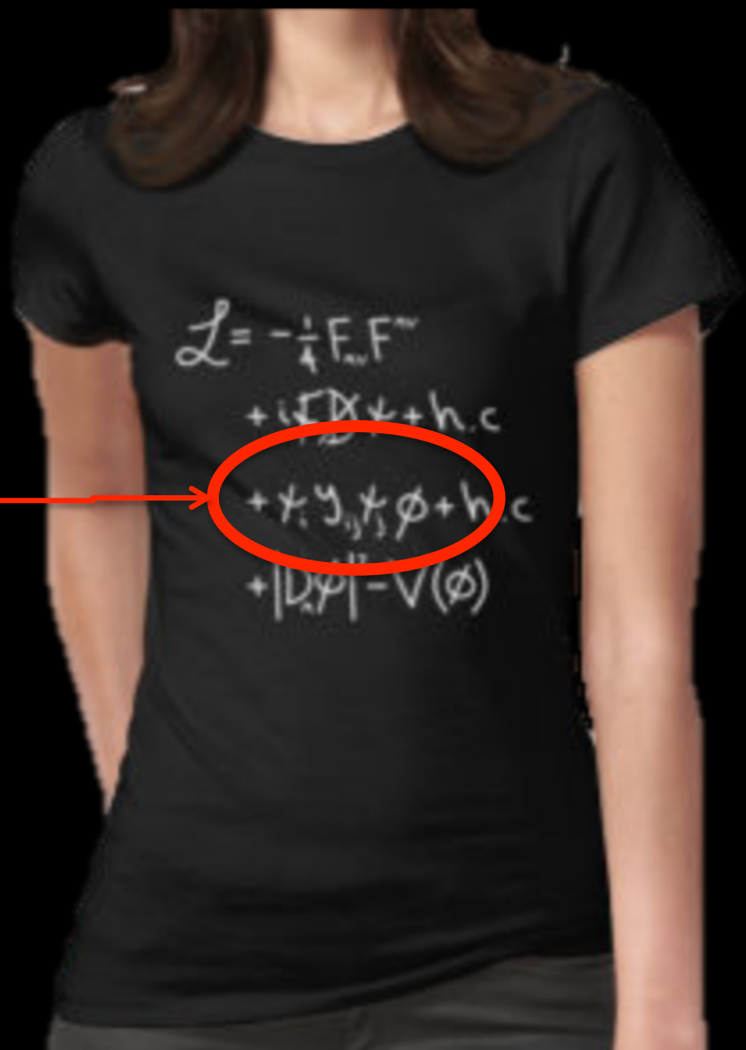
First collisions

The Standard Model

Yukawa sector, y:

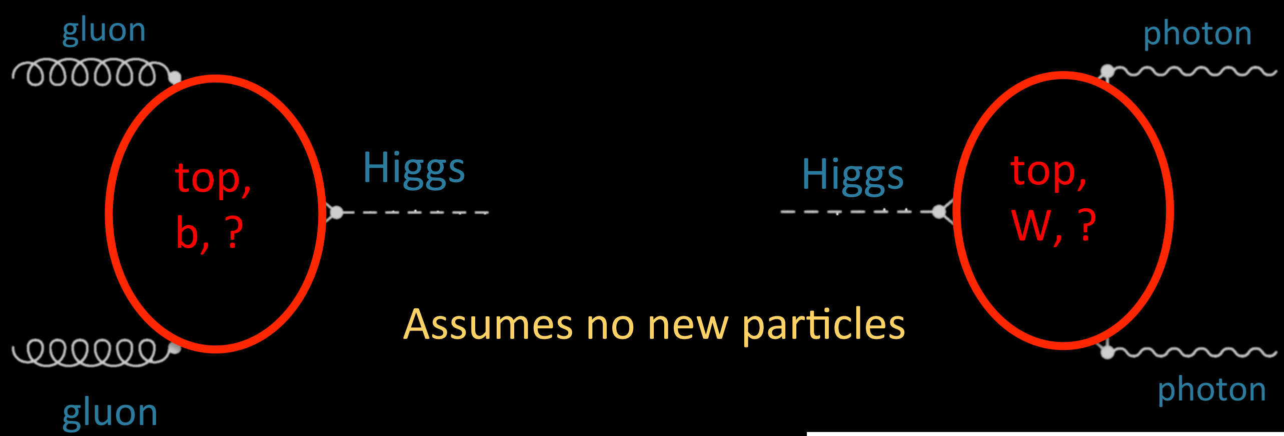
$$\psi_i y_{ij} \psi_j \varphi$$

incorporates interactions between the matter fields and the scalar field Φ that is responsible for giving fermions their masses when electroweak symmetry breaking occurs



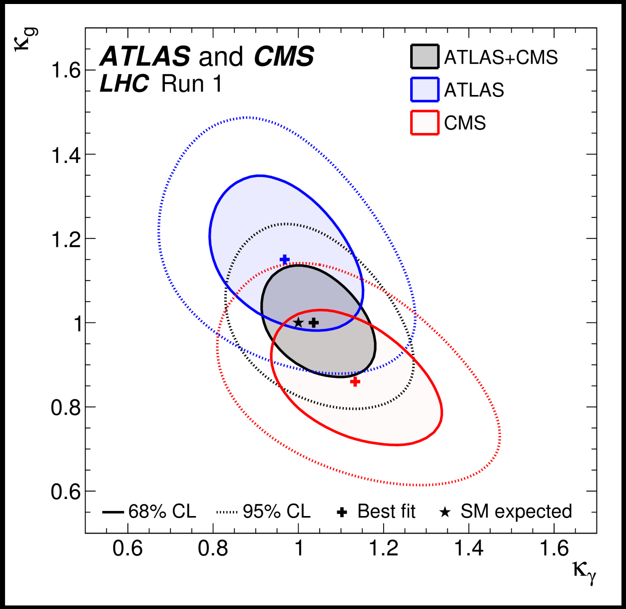
Top and Higgs

The top quark is the most strongly-coupled SM particle to the Higgs boson : y_t ~1



Top-Higgs Yukawa coupling, y_t:

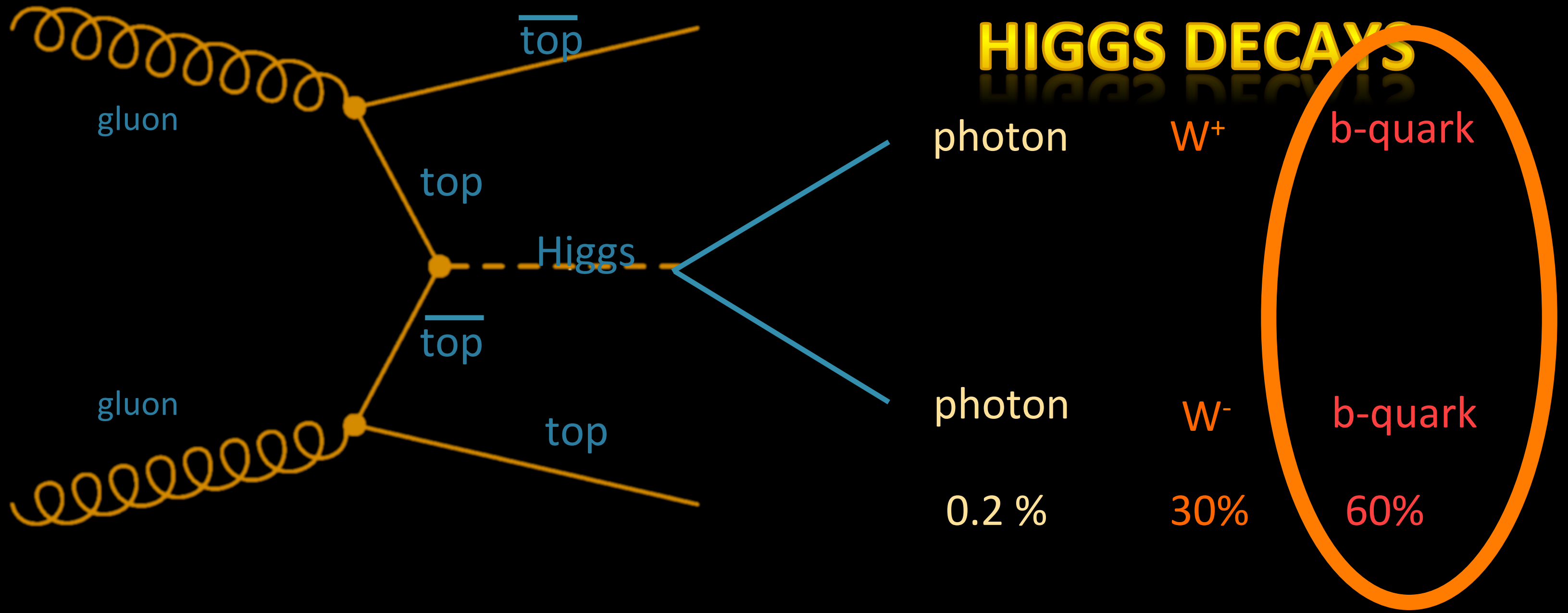
Indirect constraints on the top-Higgs Yukawa coupling can be extracted from channels involving the ggH and γγH vertices



Top and Higgs

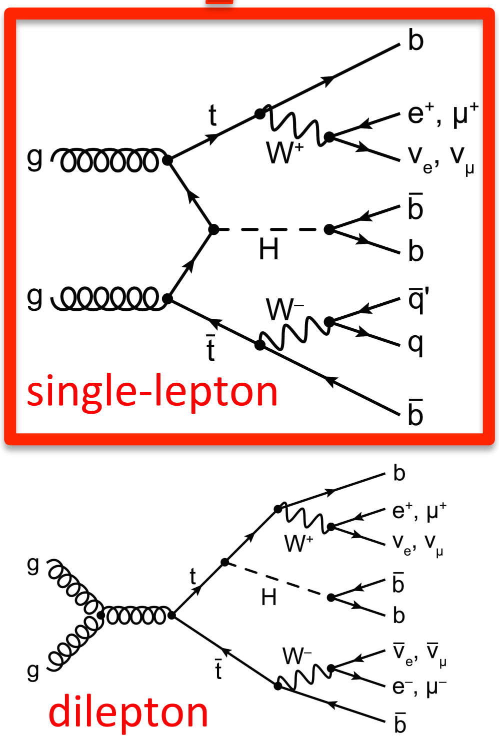
Top-Higgs Yukawa coupling can be measured directly

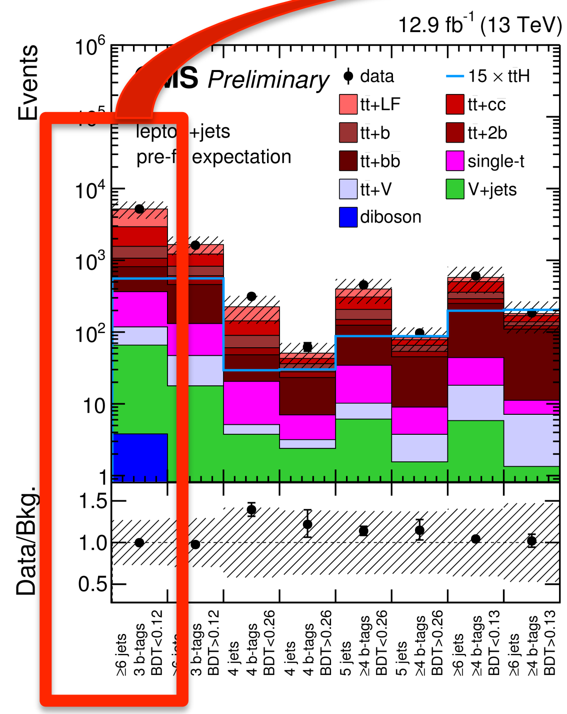
$$\sigma(t\bar{t}H) \propto y_t^2$$

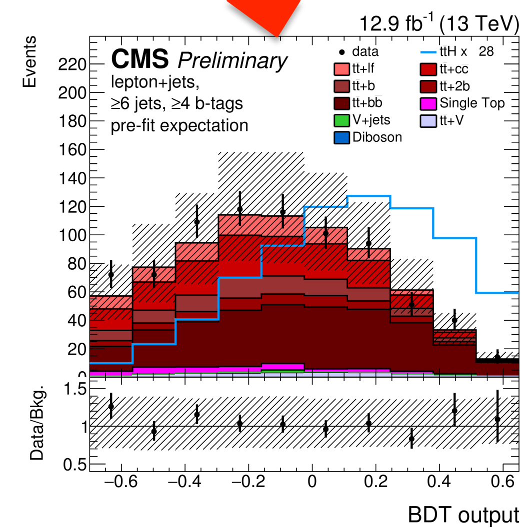


Top and Higgs

Categorize events using number of leptons and b-jets



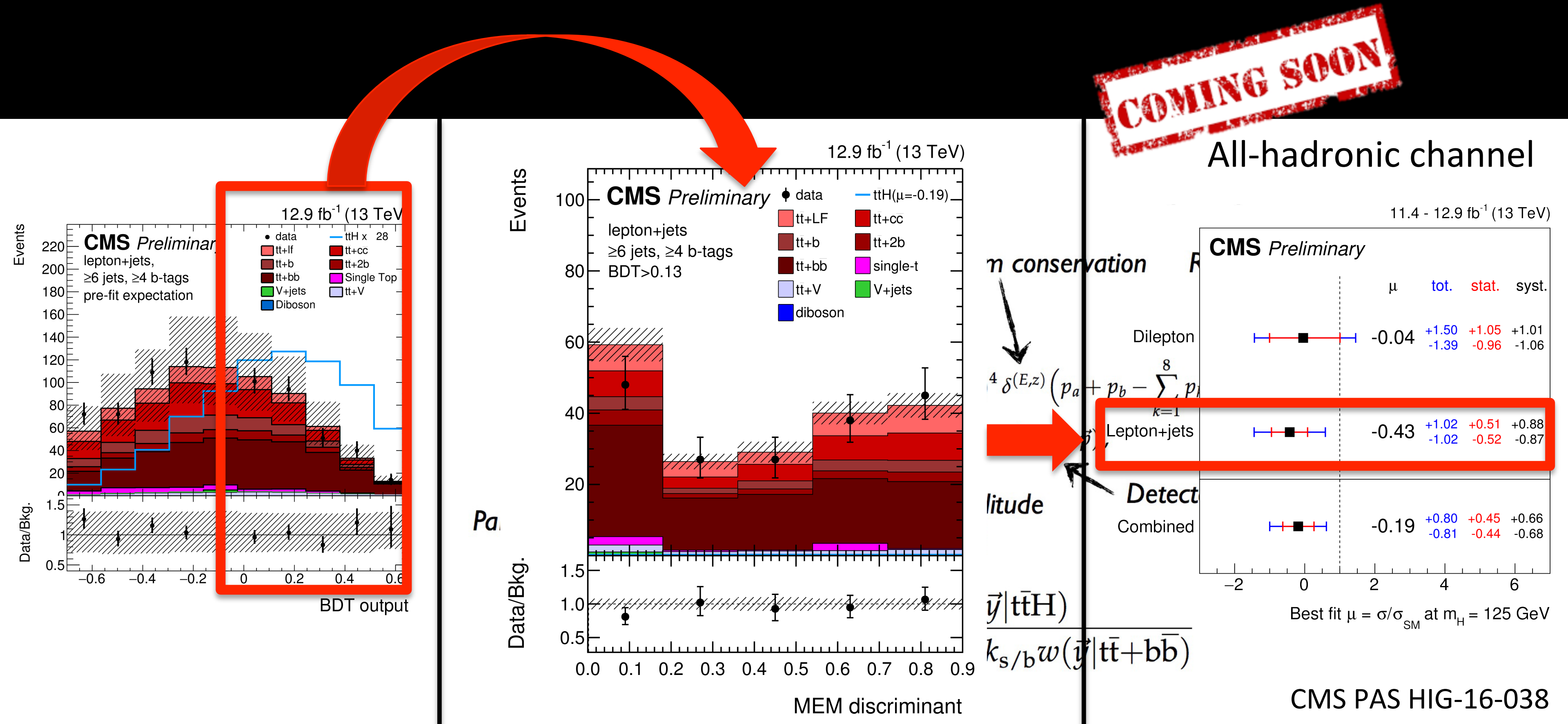




CMS PAS HIG-16-038

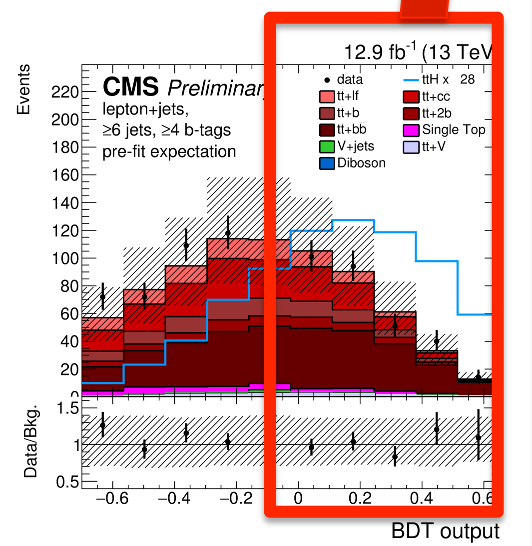
Boosted decision tree to further separate ttH vs sum of backgrounds

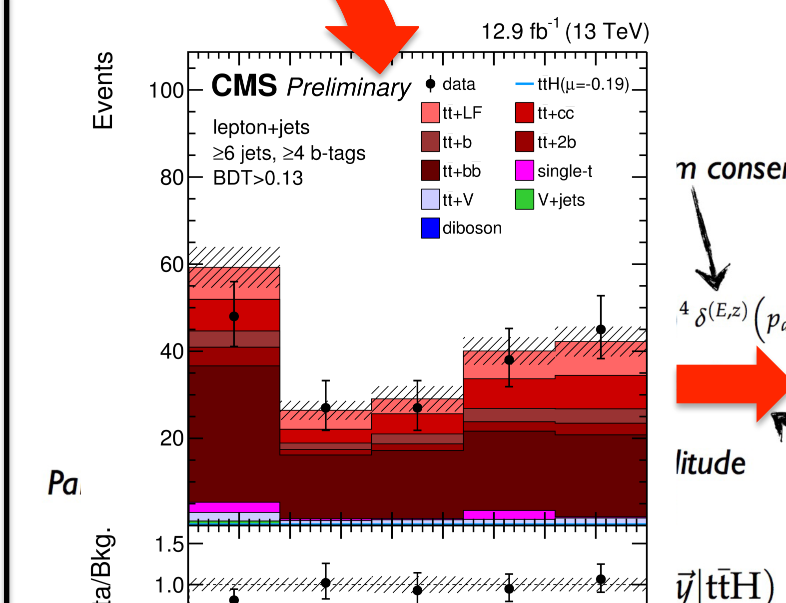
Top and Higgs



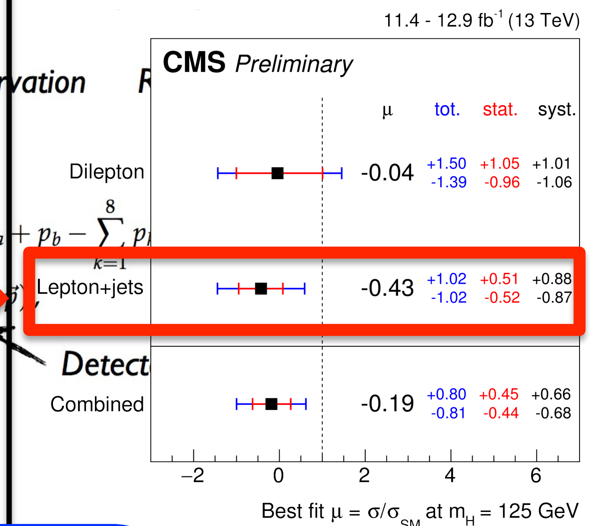
With high BDT output events construct per-event signal-background probability using full kinematics information in an analytical approach

Top and Higgs





All-hadronic channel



CMS PAS HIG-16-038

All channels (H to bb) combined

$$\mu = \frac{\sigma_{measured}}{\sigma_{SM}} = -0.19^{+0.45}_{-0.44}{}^{+0.66}_{-0.68}$$

stat syst

With high … nd probability
using full

Top and Higgs

there's not yet a single analysis with a strong & unambiguous ttH signal, and it will take time and effort to get there

Mainly dominated by understanding and modeling of tt+(b-)jets
(important interaction with theory & MC experts)
Continuous improvement of the signal extraction methods to reduce statistically and systematic

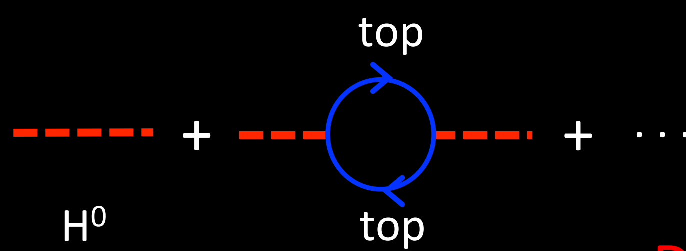
All channels (H to bb) combin

$$\mu = \frac{\sigma_{measured}}{\sigma_{SM}} = -0.19^{+0.45}_{-0.44}\,^{+0.66}_{-0.68}$$

stat syst

Hierarchy problem

The Higgs mass set the electroweak scale.
It receives contributions from the top loops.

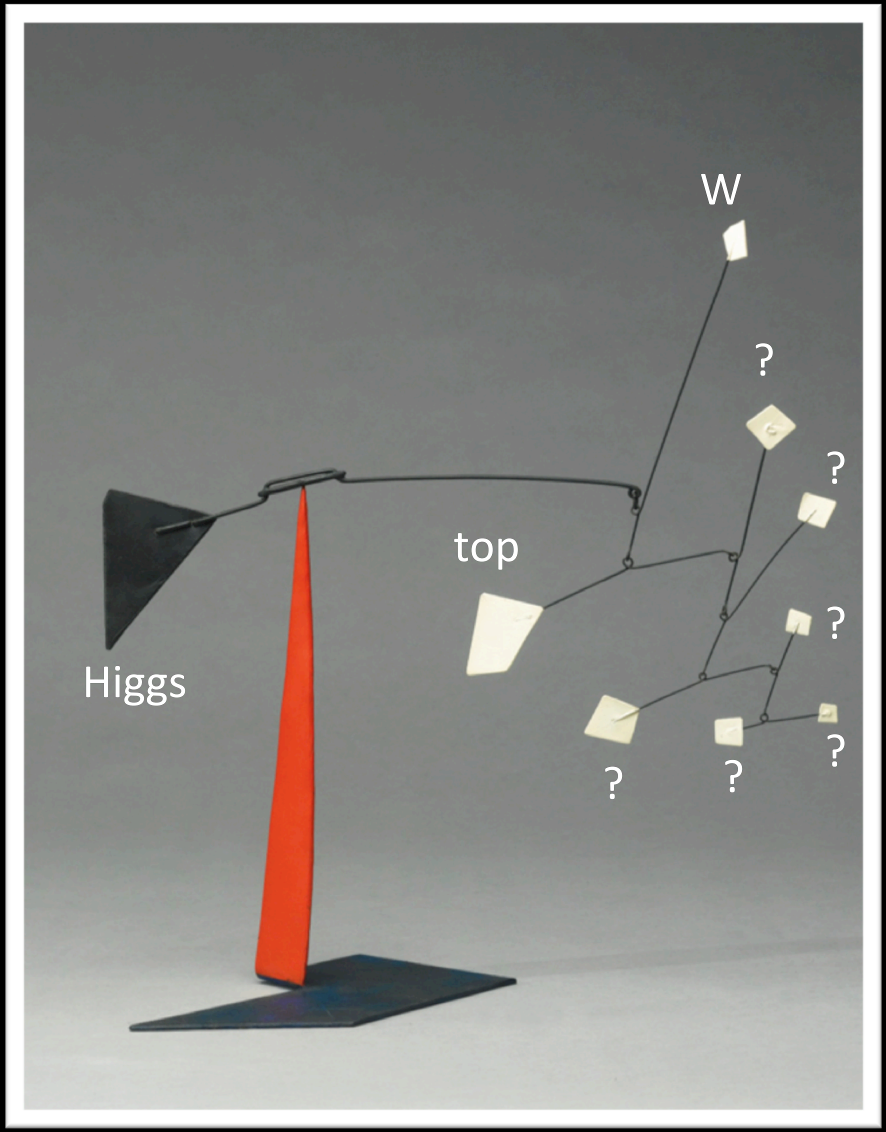


Divergent correction

$$m_H^2 = m_{H^0}^2 - \frac{3}{8\pi^2} |y_t|^2 \Lambda^2 + \ldots$$

Λ Is the scale at which the Standard Model is valid. It could be up to 10^{19} times the mass of the proton (Planck scale) !

Hierarchy problem



There should be new physics that eliminates the large loop contributions from top above the TeV scale

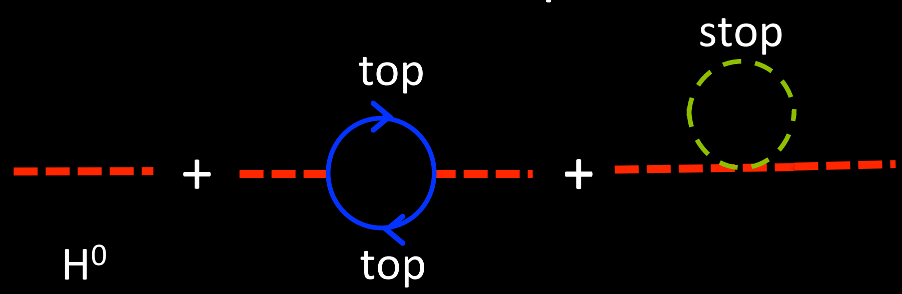
concept: F. Blekman. art: A. Calder, 1964

Hierarchy problem

Solutions

Most popular: Supersymmetry

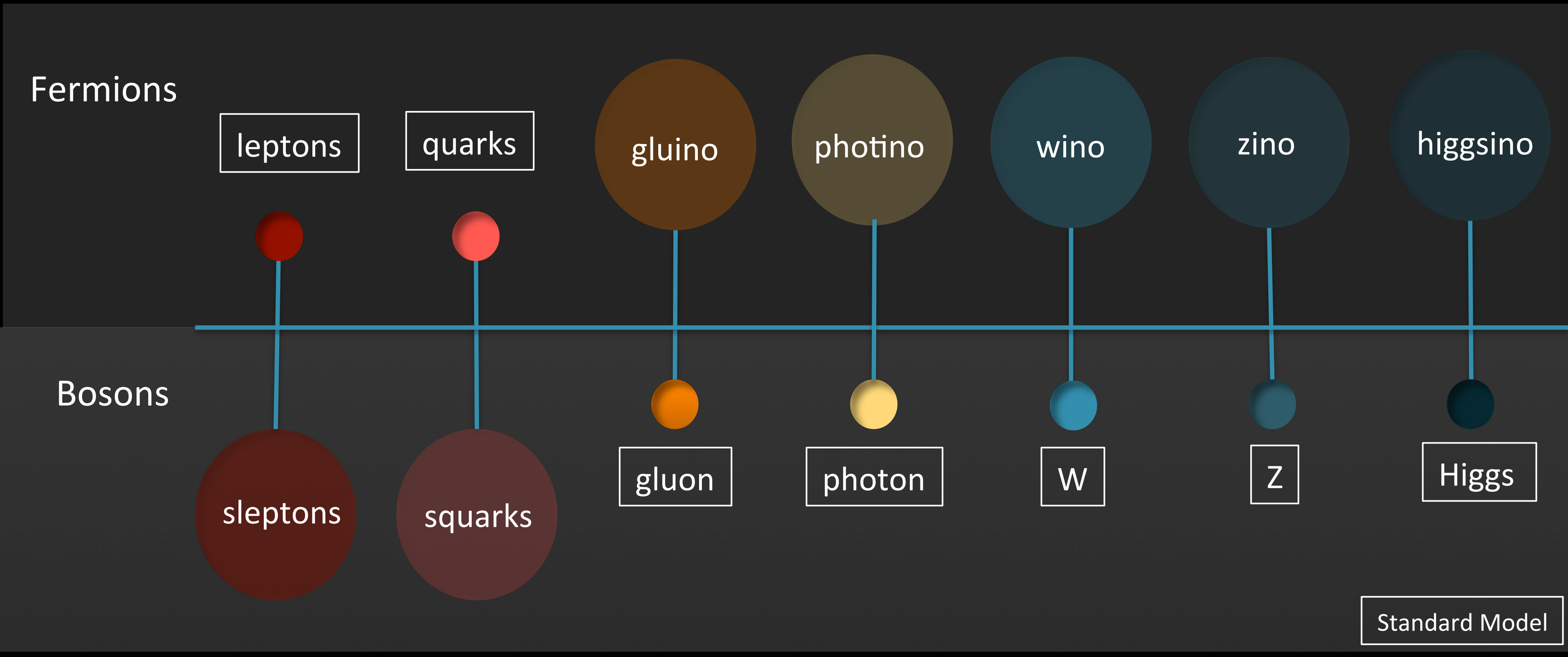
- symmetry that turns bosons into fermions, and vice versa
- Invokes the existence of a bosonic partner of the top quark



$$m_H^2 = m_{H^0}^2 - \frac{3}{8\pi^2}|y_t|^2\Lambda^2 + \frac{3}{16\pi^2}y_s\Lambda^2 + \ldots$$

$$|y_t|^2 = y_s$$

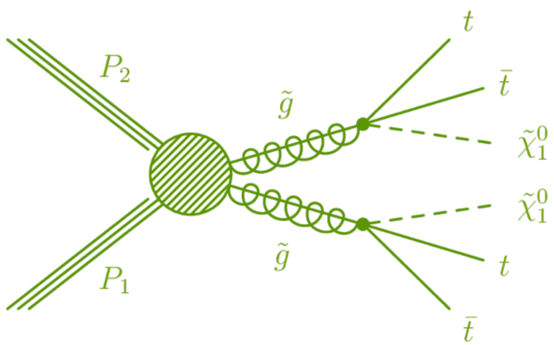
Supersymmetry



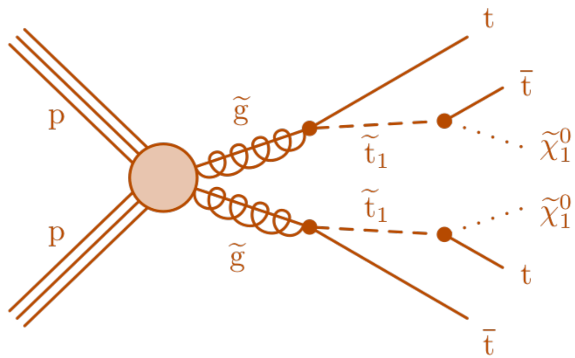
Top and SUSY

Many supersymmetric particles can decay to top quarks

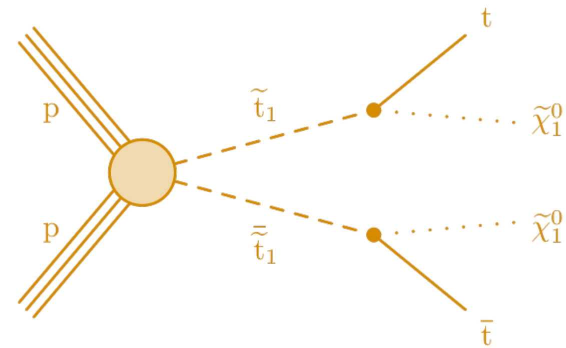
- In the context of a simplified theory SUSY particles are produced in pairs
- The lightest-supersymmetric-particle (LSP, χ) in the decay escapes detection



Gluinos are produced and decay through a top and a virtual stop going to top and LSP



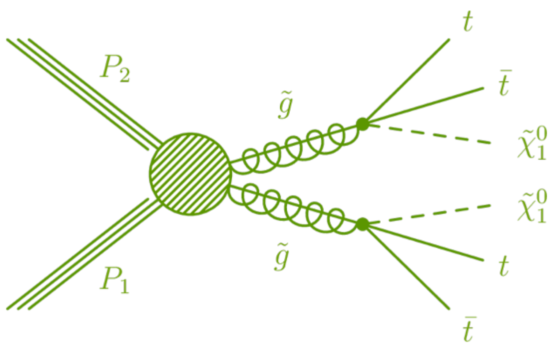
Gluinos are produced and decay through a top and a real stop going to top and LSP



STOP decays to top and LSP

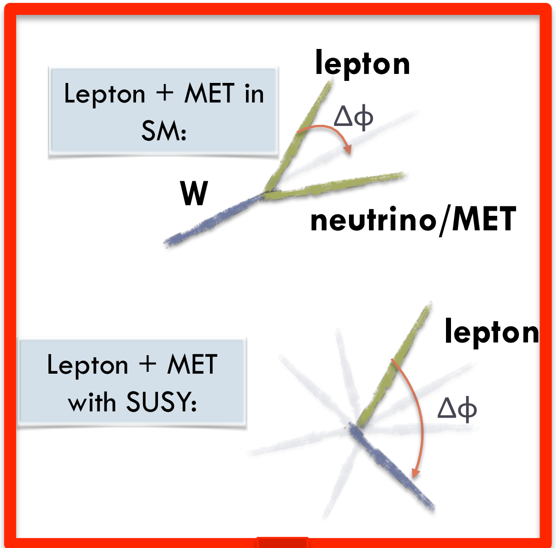
Search for decay chains with two or four top quarks in the final state

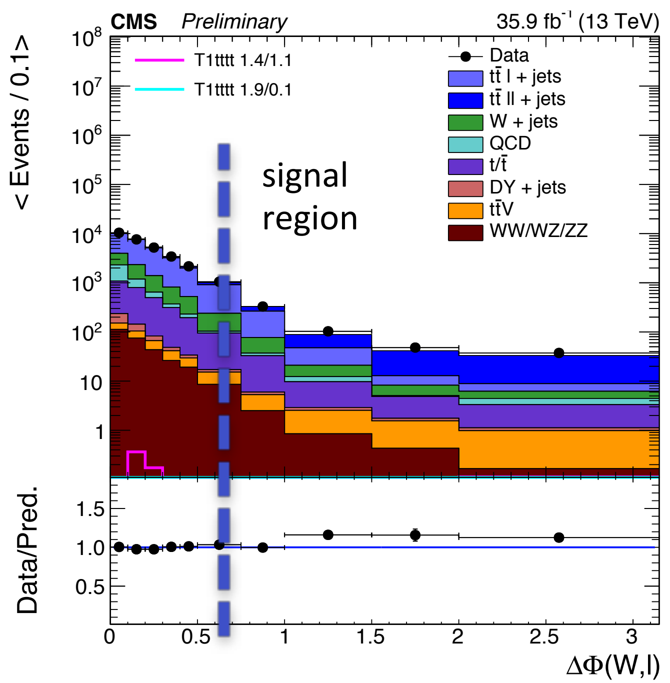
Top and SUSY



One lepton final state : high branching ratio and smaller background dominated by tt production

Main discriminating variable **Δϕ**: Angle between lepton and reconstructed W



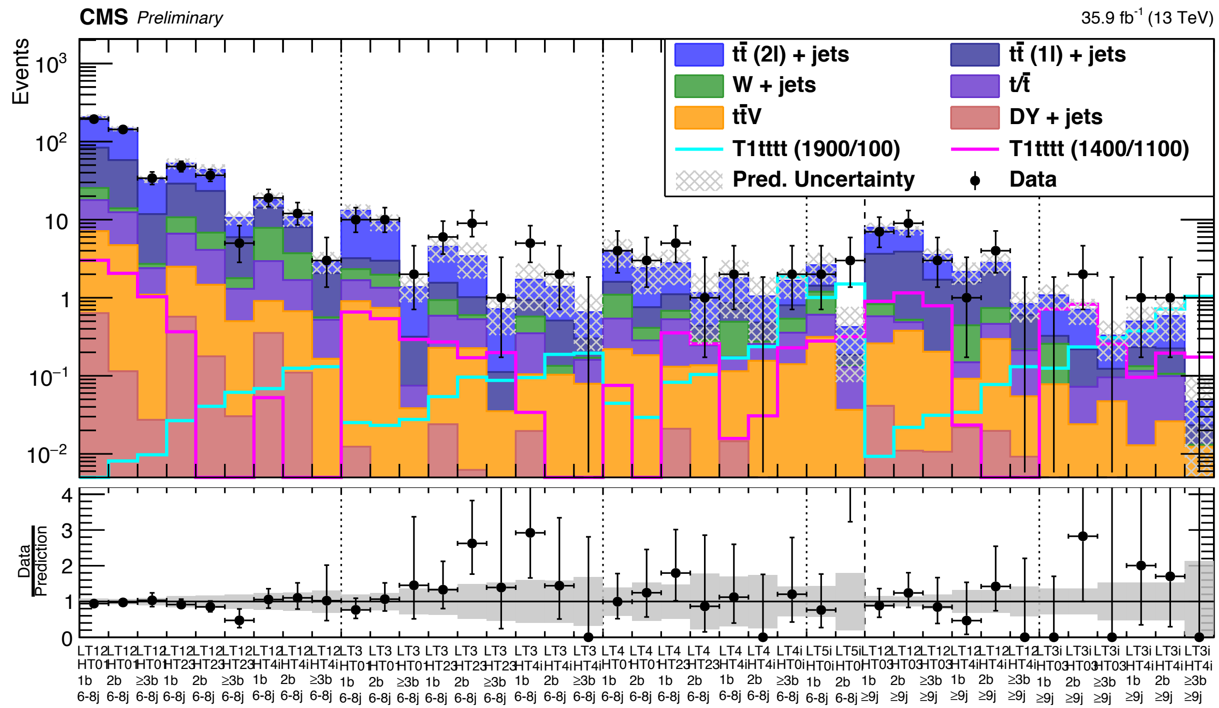


CMS-PAS-SUS-16-042

Top and SUSY

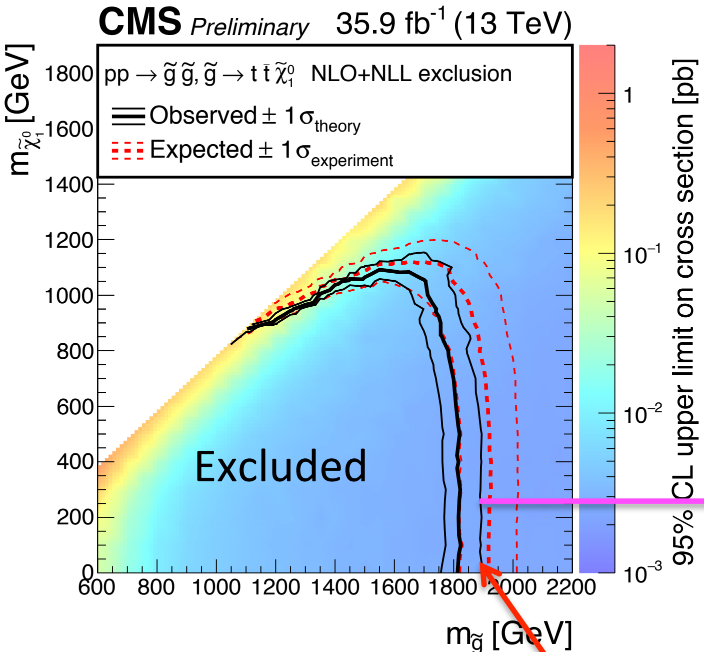
Categorize events in 30 exclusive regions defined to optimize the signal over background:

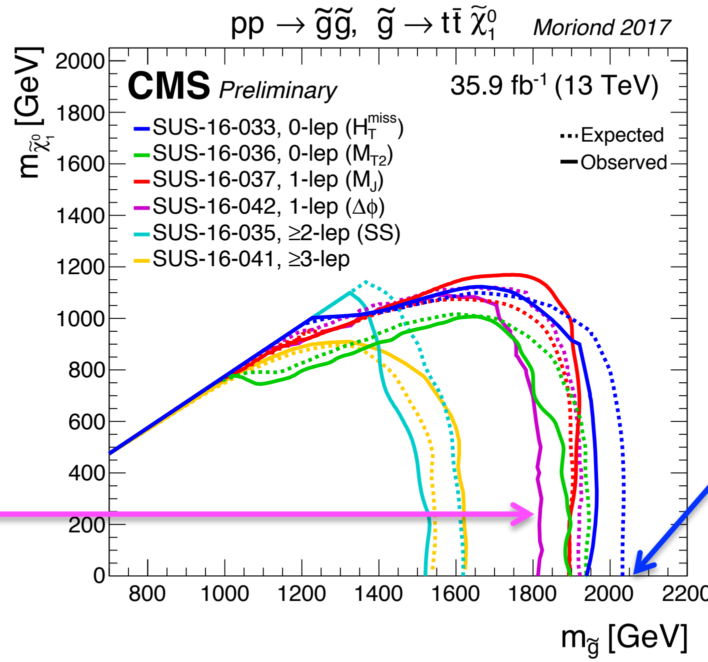
- Number of jets and b-jets,
- Sum p_T of all Jets = H_T, and
- Lepton p_T + MET = L_T



Top and SUSY

Two mass parameters of interest: masses of the gluino ($m_{\tilde{g}}$) and LSP (m_{χ})





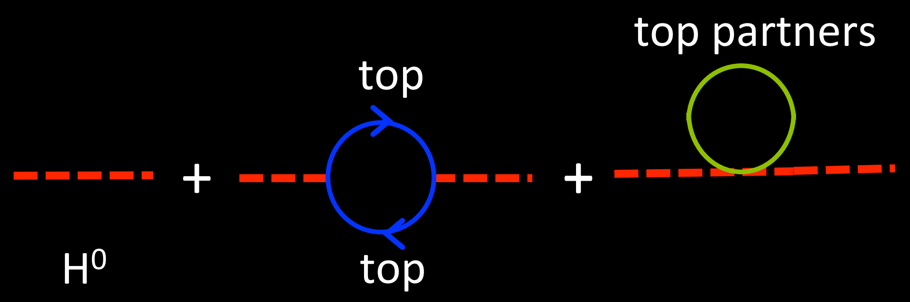
All hadronic channel

Reaching about 2 TeV for gluinos and 1 TeV for stops

Hierarchy problem

Solutions

- Many theories predict the presence of top quark partners (vector-like fermions) which have the same spin and mainly couple top top and b quarks



$$m_H^2 = m_{H^0}^2 - \frac{3}{8\pi^2} m_{tp}^2 \log\Lambda + \ldots$$

summation over loops containing the new fermions cancels the divergence of the top quark loop.
"It looks like magic, but it is guided by the underlying symmetry." –M. Peskin

Top Partners

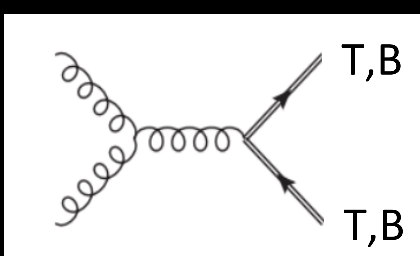
Vector like fermions: New quarks that receive mass through direct mass term (independent of Higgs) and have both left- and right-handed charged currents (in contrast to chiral SM matter)

Configurations

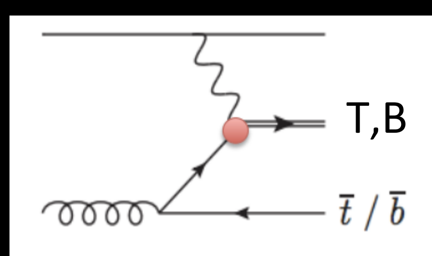
Isospin / hypercharge

Singlets	Doublets	Triplets
$\mathbf{1}_{2/3} = T$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	
$\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$

Production

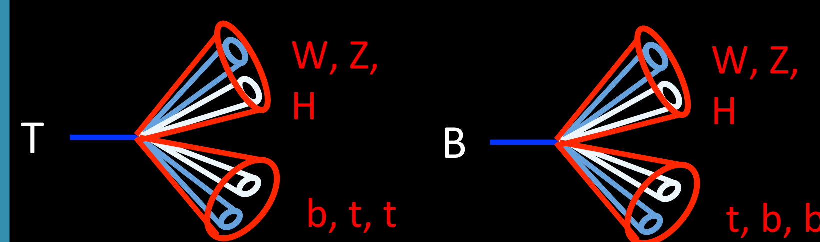


Pair-production, strong mechanism, model independent



Single production, electroweak, depends on the mixing with SM quarks

Decay

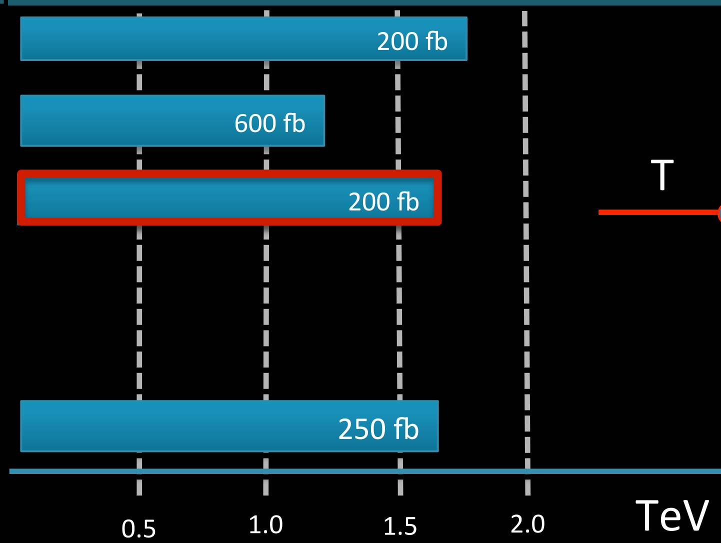


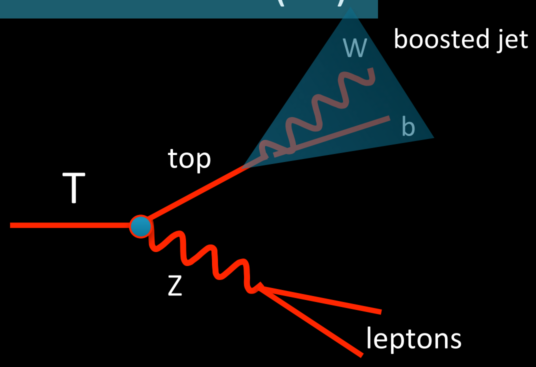
Present boosted signatures

Tops Partners

Particle (*)	Allowed decays
$T^{2/3}$	bW (BR=0.5)
	tH (BR = 0.25)***
	tZ (BR =0.25)
$B^{-1/3}$	tW (BR=0.5)
	bH (BR = 0.25)
	bZ (BR =0.25)

Observed limit 95% CL, CMS 13 TeV results(**)



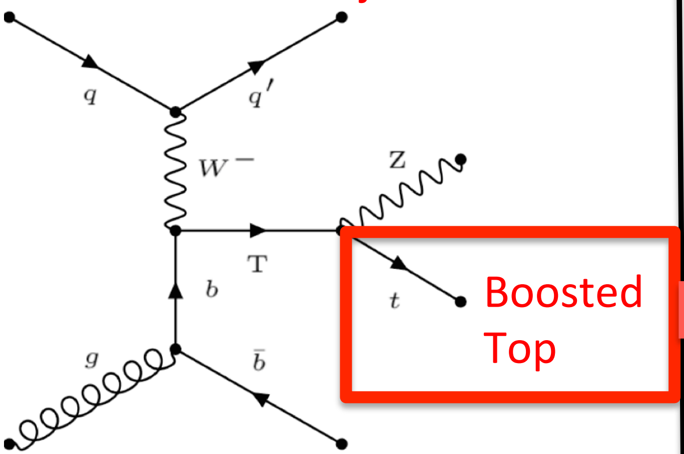


(*) in singlets. Note that $X^{5/3}$ and $Y^{4/3}$ appear in doublets and triplets configurations. Total 7 configurations allowed.

(**) http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/

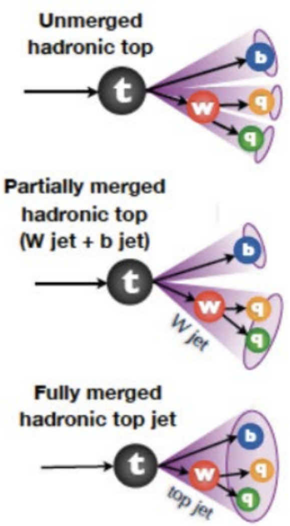
(***) in t→hadronic but also done in leptonic channel

Tops Partners

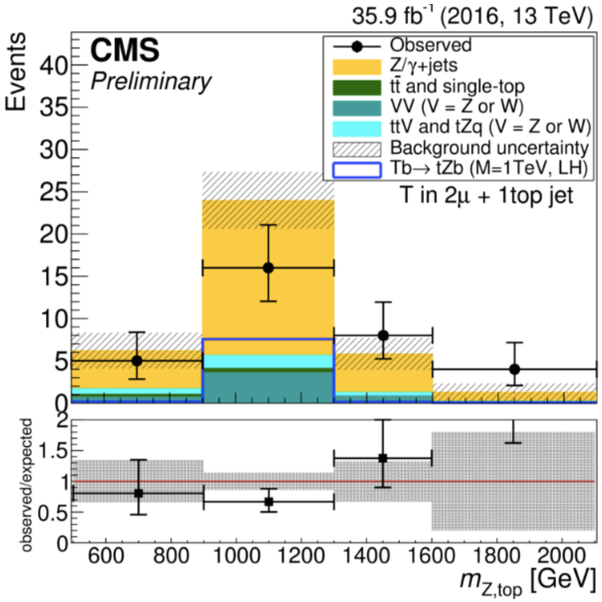


Select Z->ee/μμ + jets with at least 1b-jet tag

Categorize events based on # of W, t-tags and forward jets

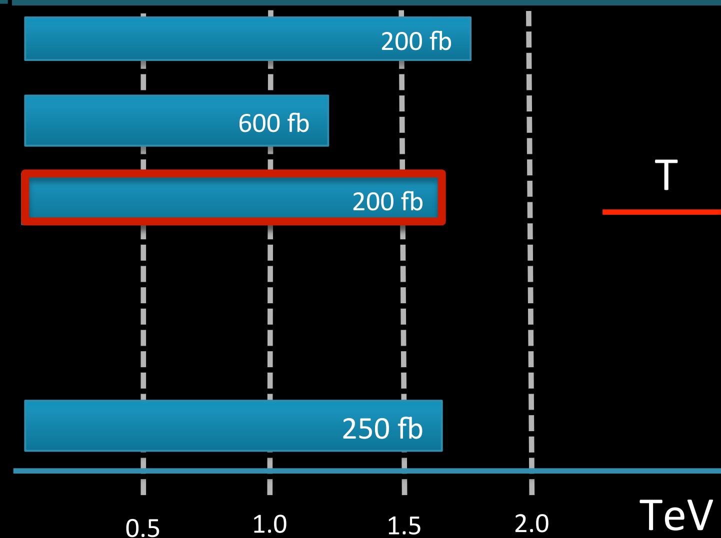


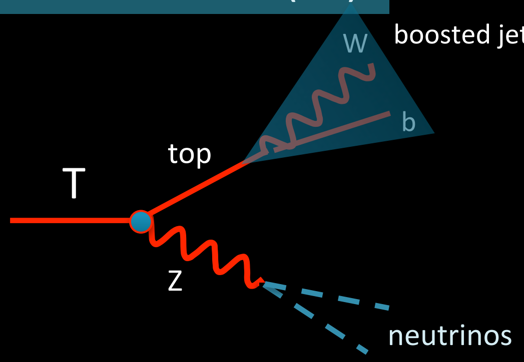
Reconstruct mass of the T quark as M(tZ)



Tops Partners

Particle (*)	Allowed decays	Observed limit 95% CL, CMS 13 TeV results (**)
$T^{2/3}$	bW (BR=0.5)	200 fb
	tH (BR = 0.25)***	600 fb
	tZ (BR =0.25)	200 fb
$B^{-1/3}$	tW (BR=0.5)	
	bH (BR = 0.25)	
	bZ (BR =0.25)	250 fb





Work in progress: More favorable channel in high energy regime

(*) in singlets. Note that $X^{5/3}$ and $Y^{4/3}$ appear in doublets and triplets configurations. Total 7 configurations allowed.

(**) http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/

(***) in t→hadronic but also done in leptonic channel

Tops Partners

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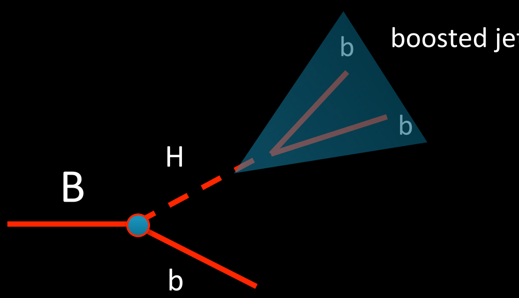
	tZ (BR =0.25)	200 fb
$B^{-1/3}$	tW (BR=0.5)	
	bH (BR = 0.25)	
	bZ (BR =0.25)	250 fb

0.5 1.0 1.5 2.0 TeV



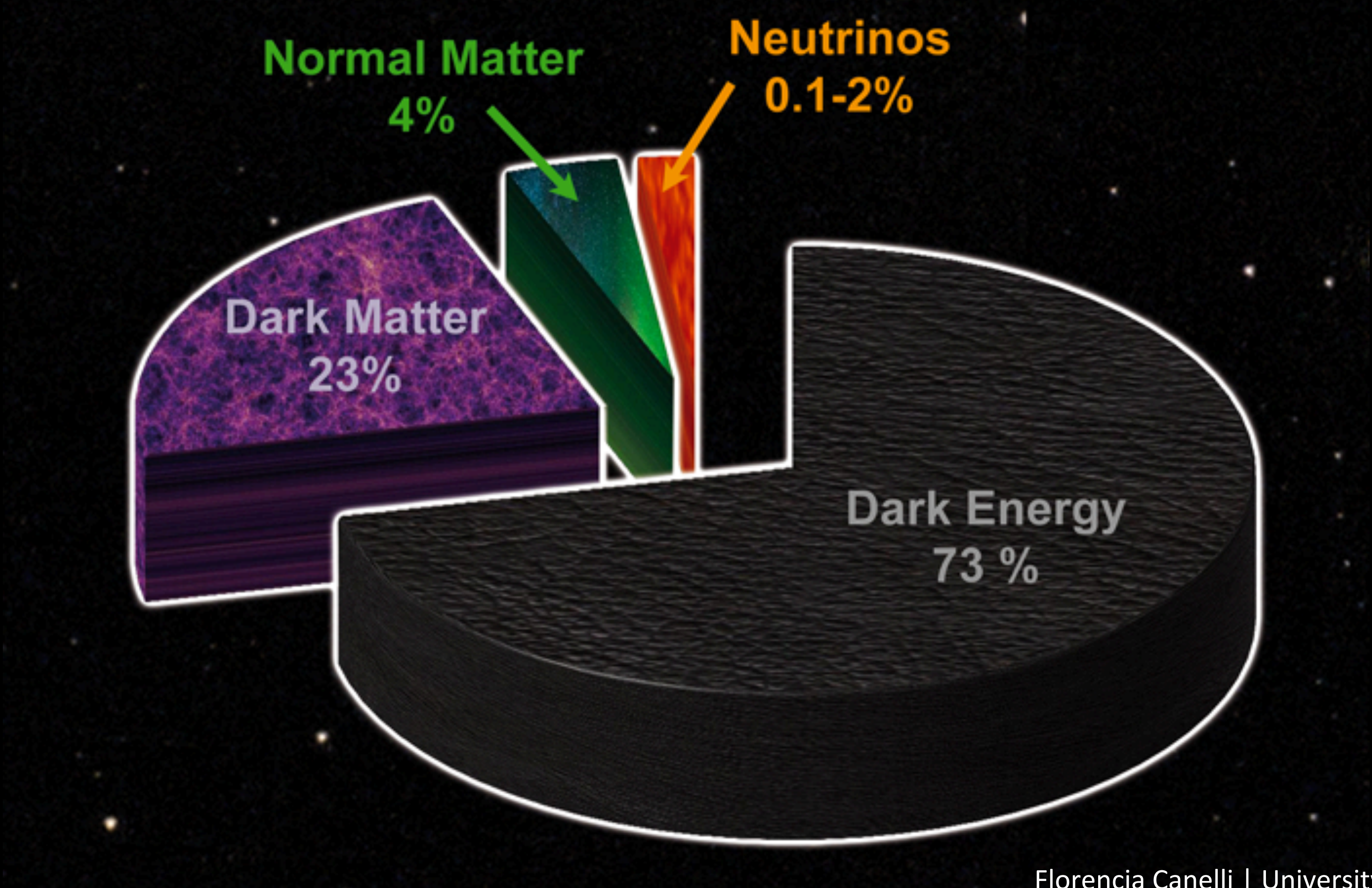
Work in progress: A very challenging signature ! New in LHC

(*) in singlets. Note that $X^{5/3}$ and $Y^{4/3}$ appear in doublets and triplets configurations. Total 7 configurations allowed.

(**) http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/

(***) in t→hadronic but also done in leptonic channel

CONTENT OF THE UNIVERSE



So far we don't know what dark matter is

But
we know that interacts gravitationally
and is at most weakly interacting

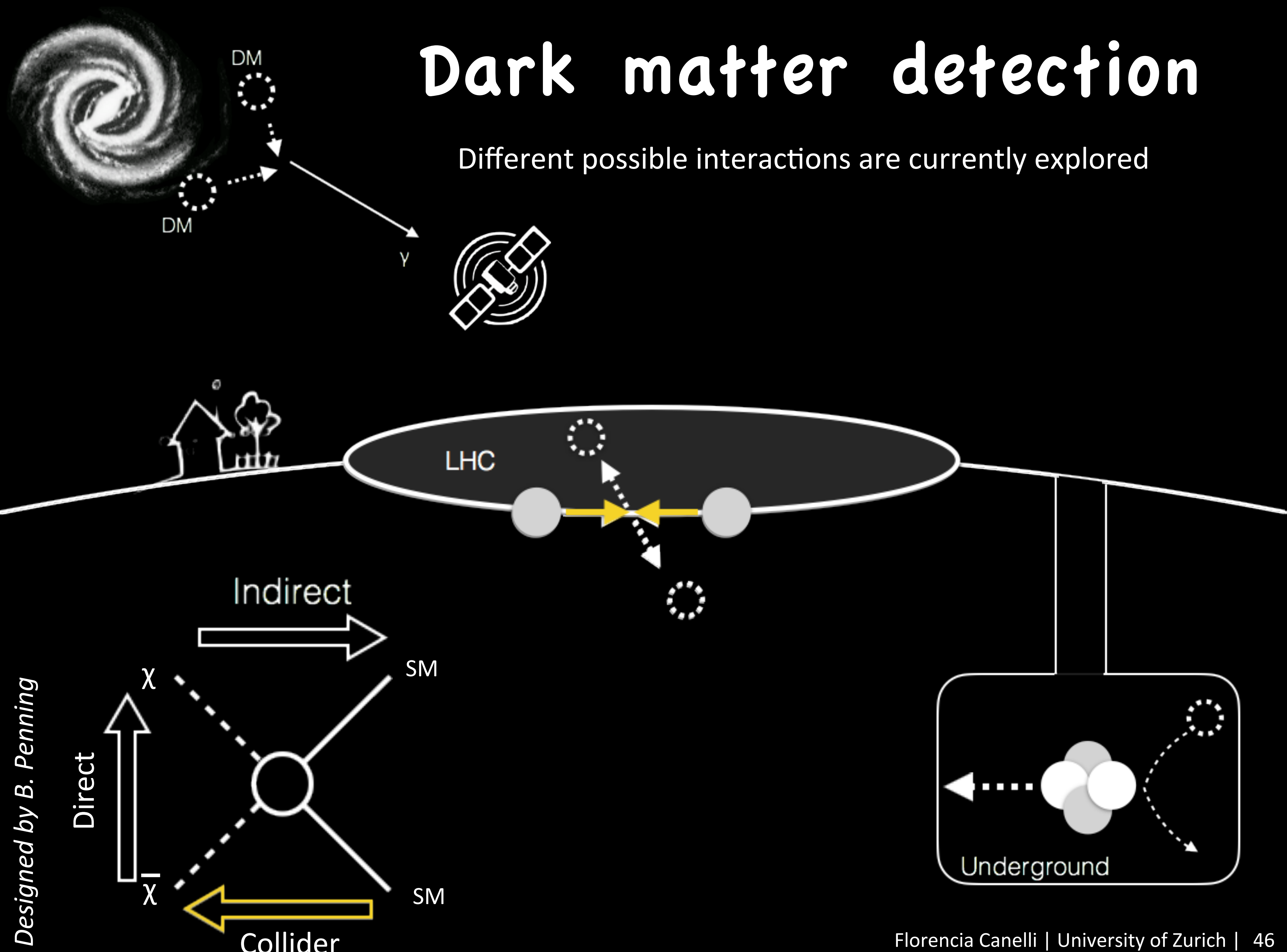
we think that it should have reasonably large coupling some of the SM, in order to explain its abundance in the Universe

The weakly-interacting-massive-particle (WIMP, χ) is among the most popular candidates particles for dark matter

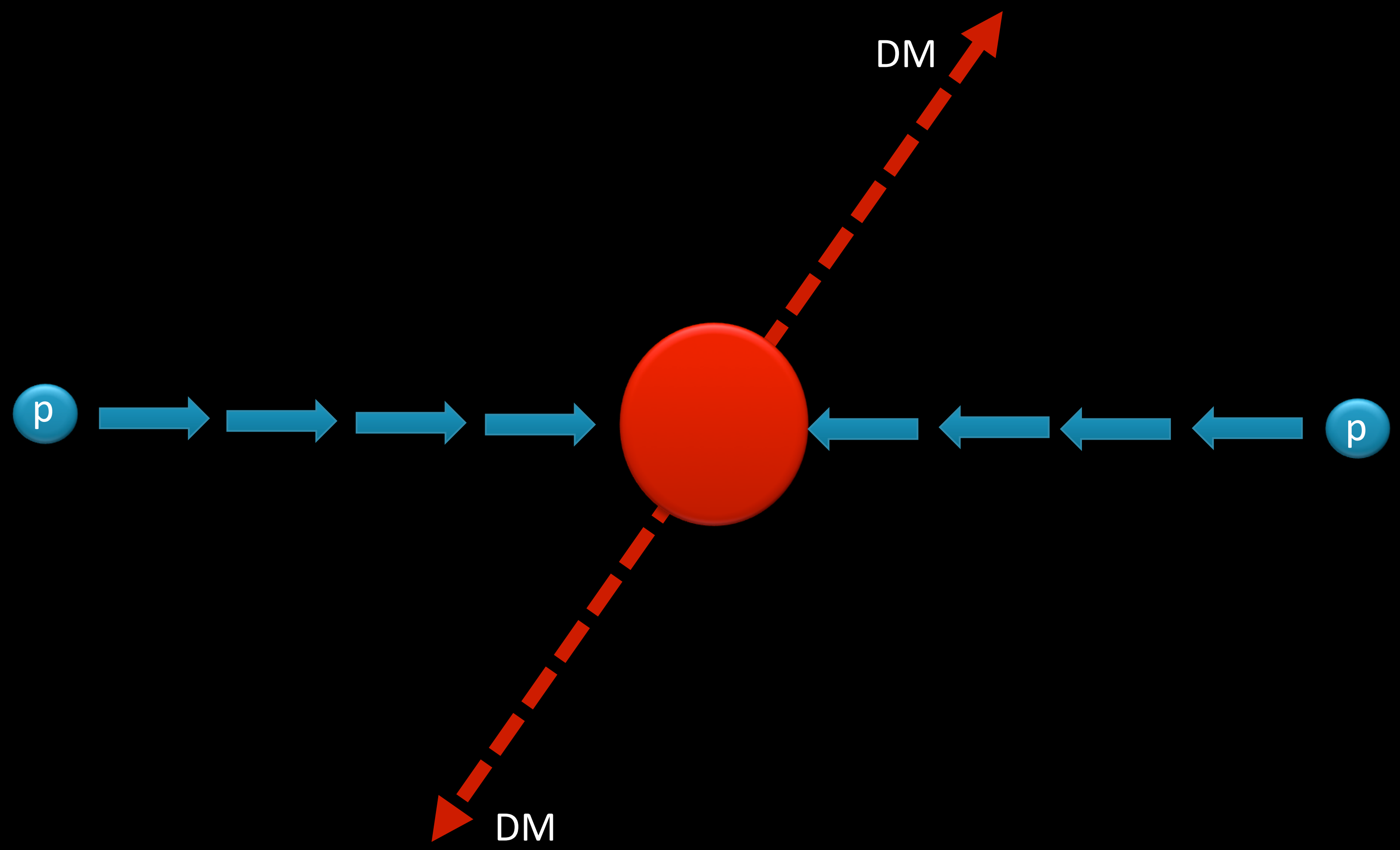
WIMPs appears in many models as the lightest and neutral and ~stable

Dark matter detection

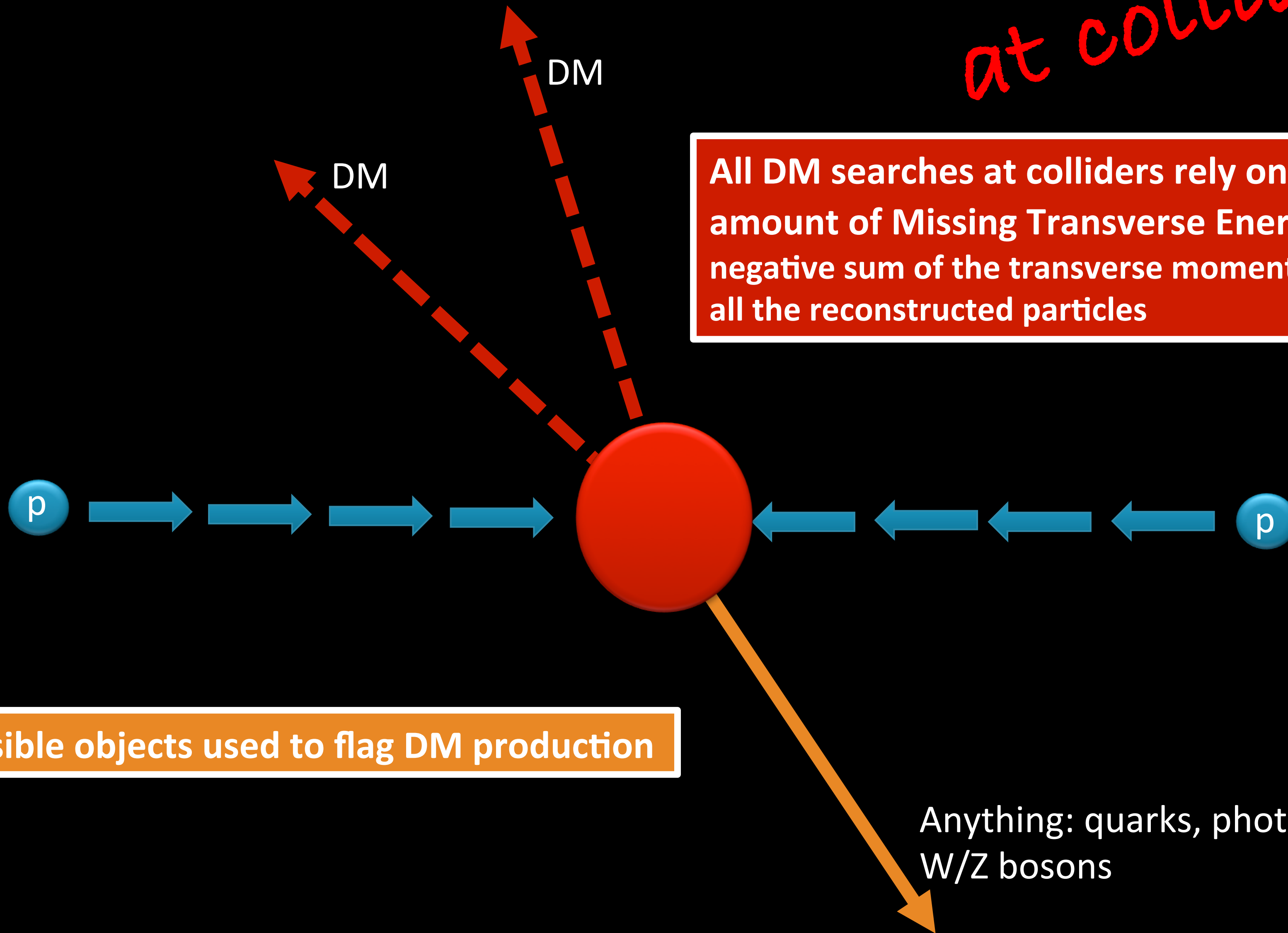
Different possible interactions are currently explored



Dark Matter production at colliders



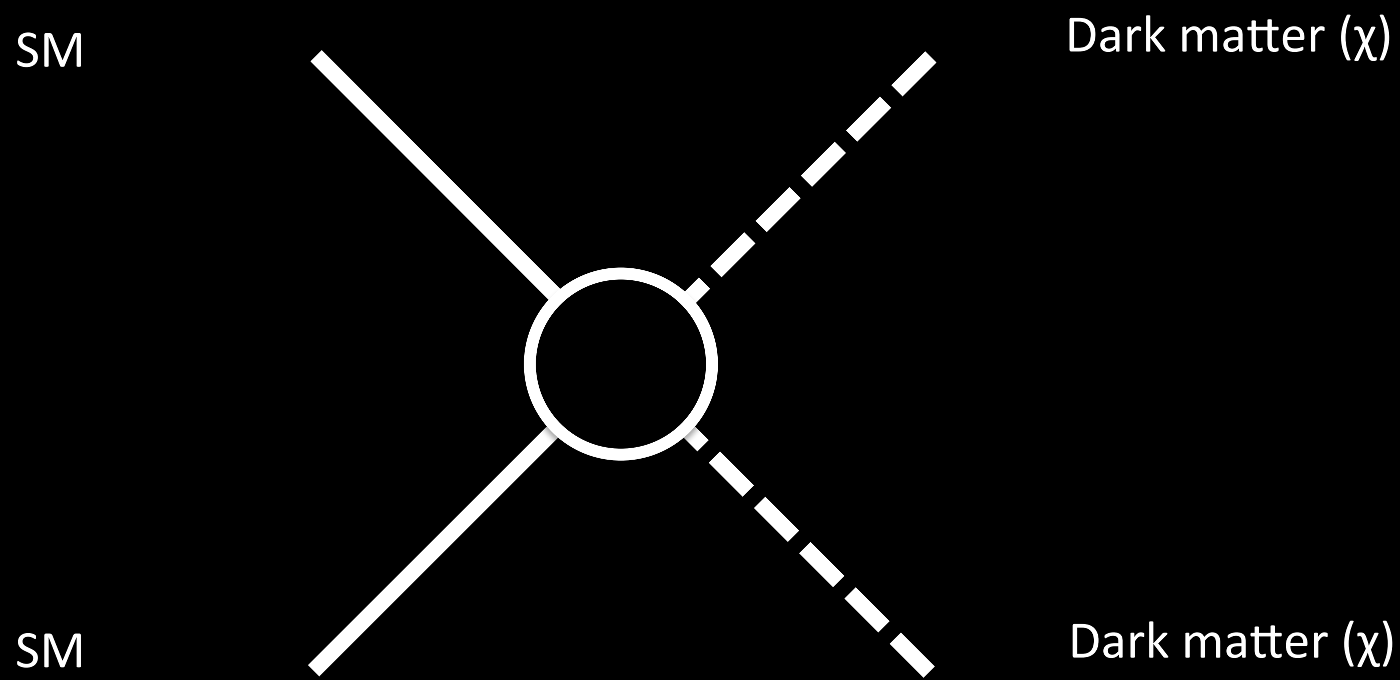
Dark Matter production *at colliders*



All DM searches at colliders rely on large amount of Missing Transverse Energy:
negative sum of the transverse momenta of all the reconstructed particles

Visible objects used to flag DM production

Dark matter phenomenology

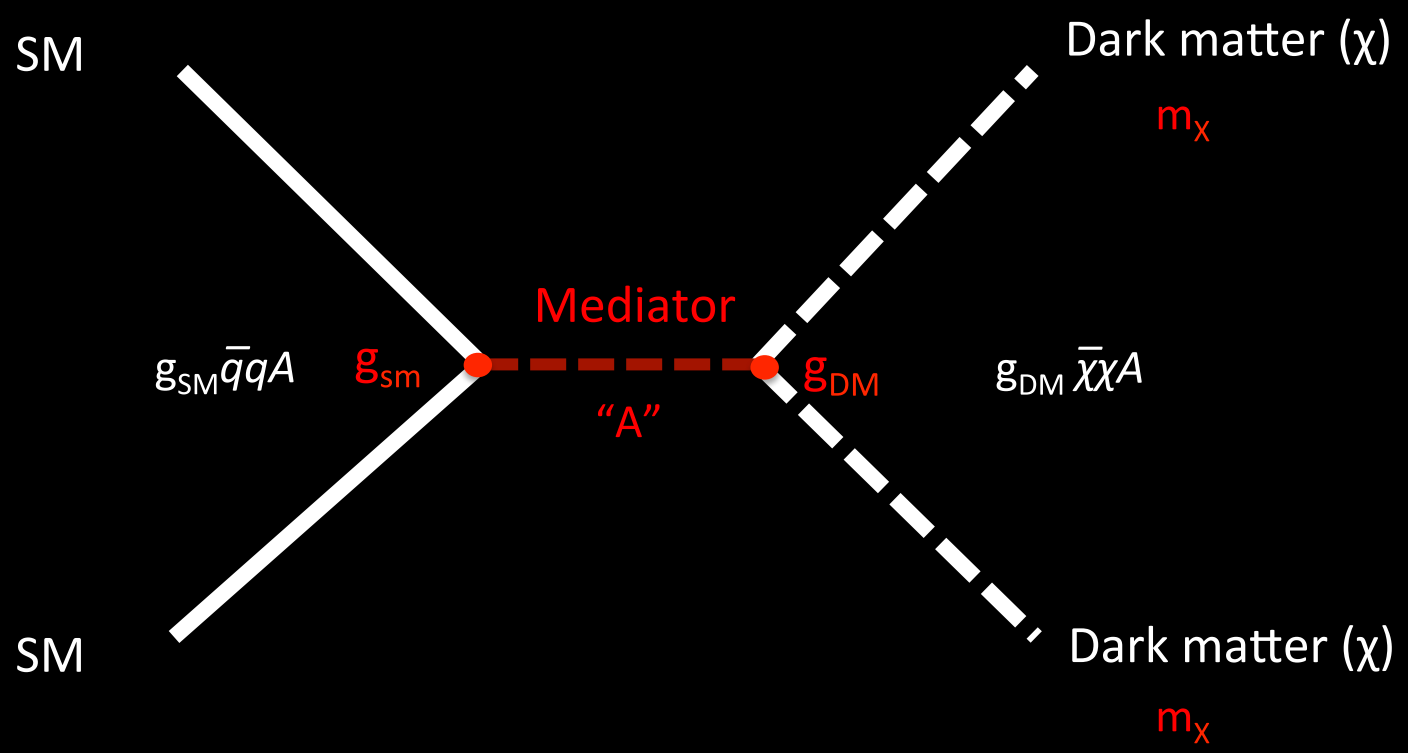


Simplified models[1507.00966]

Dark matter phenomenology

We parametrize all possible interactions that have potential signal strengths:

g_q, g_{DM}, m_{X}, $M_{mediator}$



Simplified models[1507.00966]

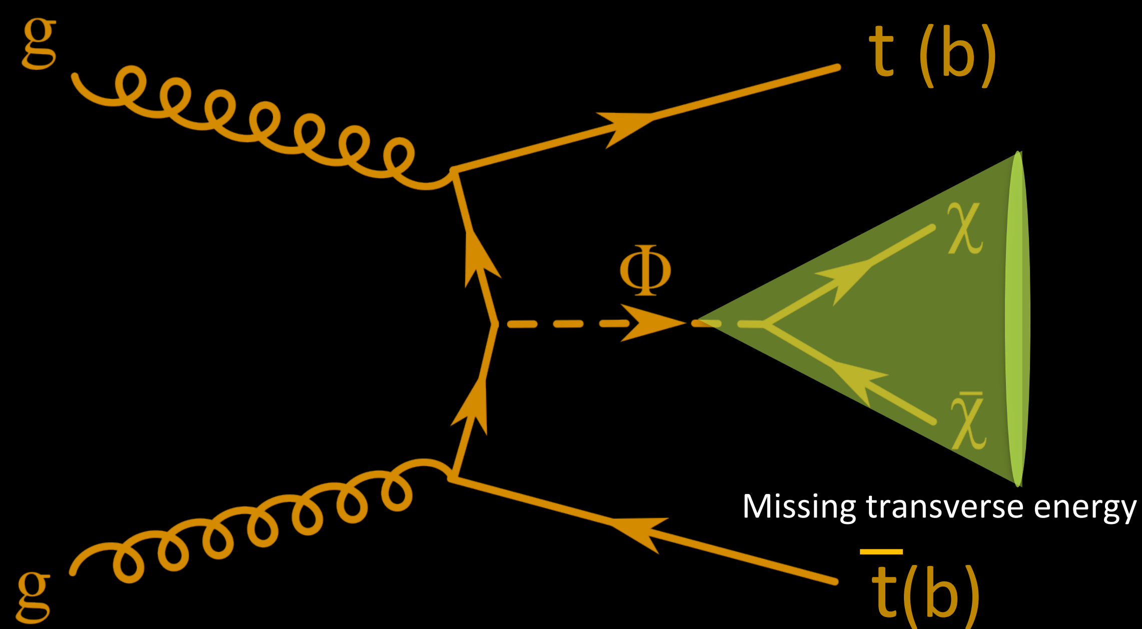
Dark matter phenomenology

LHC program considers a comprehensive set of diagrams for the mediator

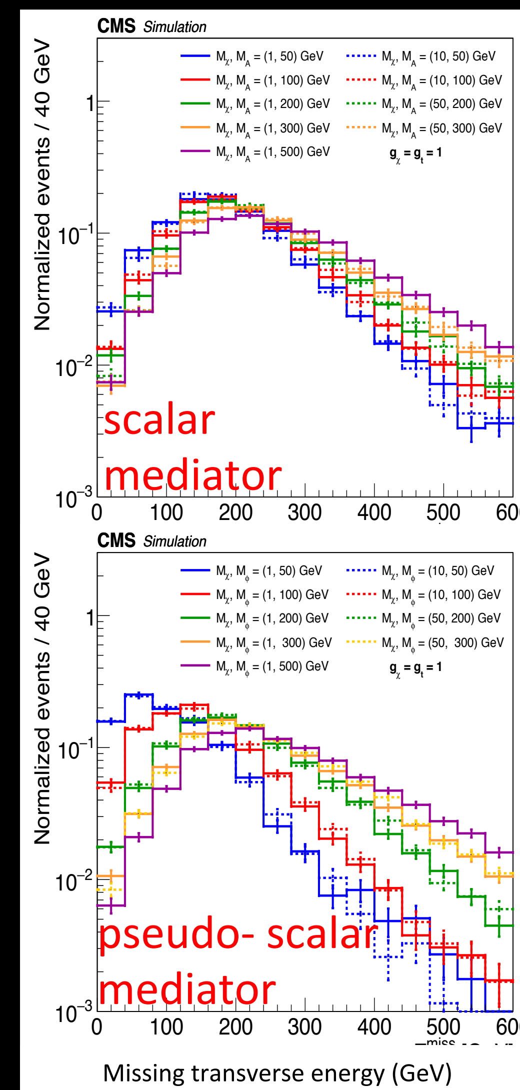
Spin -1	**Vector** $g_{DM} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$	**Axial vector** $g_{DM} Z'_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$
	EWK style coupling (equal to all leptons)	
	Besides very low DM masses direct detection wins clearly over collider	Direct detection and collider are equal in overall sensitivity but probe different regions of parameter space
Spin -0	**Scalar** $g_{DM} S \bar{\chi} \chi$	**Pseudoscalar** $g_{DM} P \bar{\chi} \gamma^{5} \chi$
	Yukawa style coupling (mass based coupling)	
	Direct detection and colliders are equal in overall sensitivity but probe different regions of parameter space	No limits from direct detection, only indirect detection. Collider provides limits similar to scalar couplings

TOP AND DARK MATTER

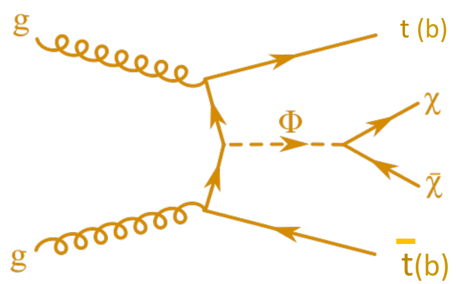
Because only the top quark Yukawa is of O(1), WIMP DM preferentially couples to the heavy top quark



Missing transverse energy spectrum for different dark matter and mediator masses

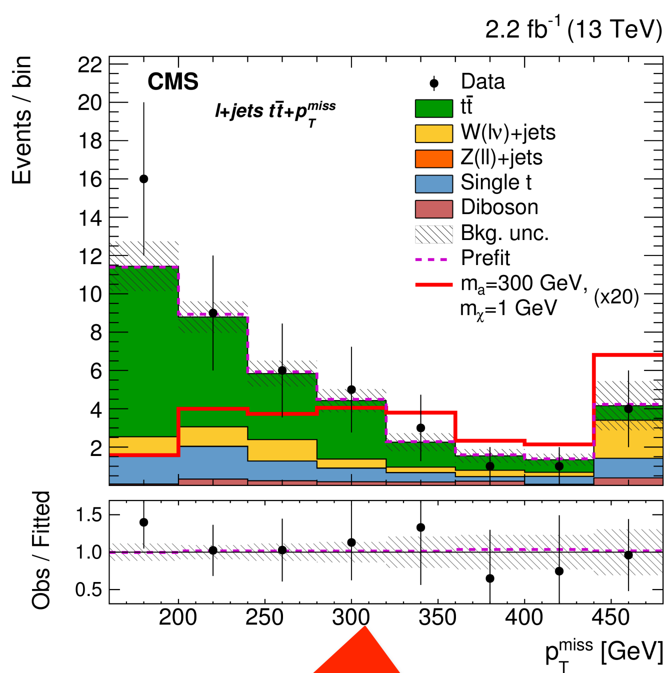


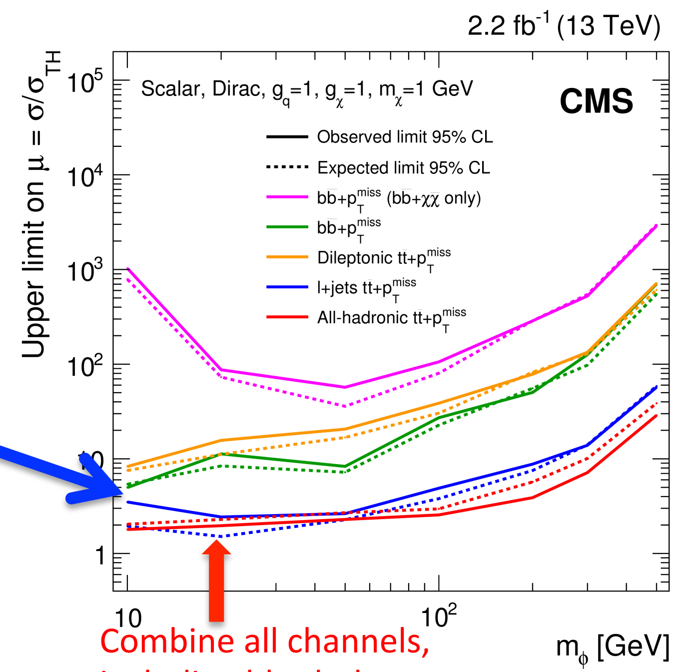
TOP AND DARK MATTER



Analyze all 3 possible decay channels of tt:

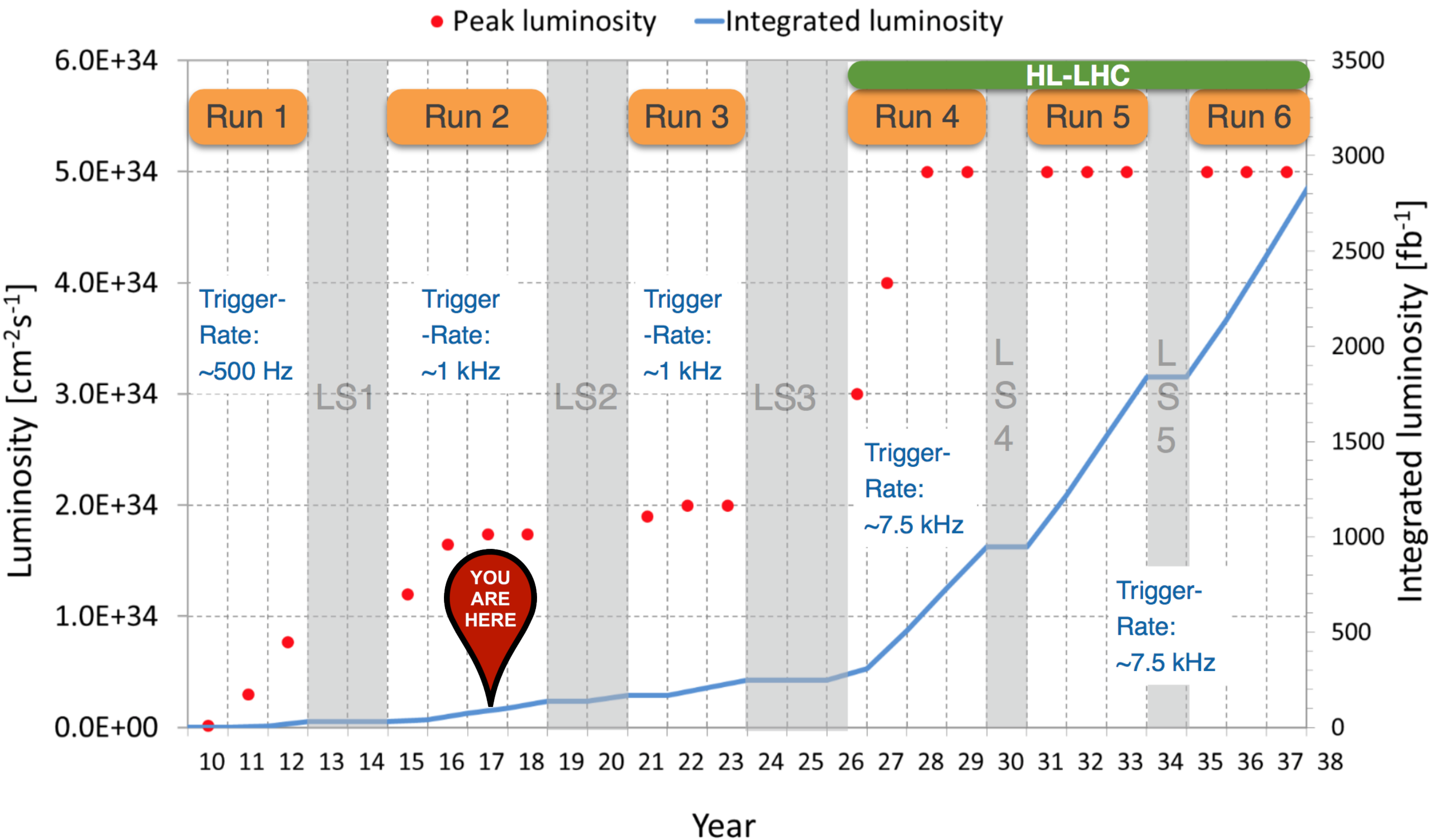
- Hadronic
- Single lepton
- Dilepton





Also done for pseudo-scalar

LHC Data



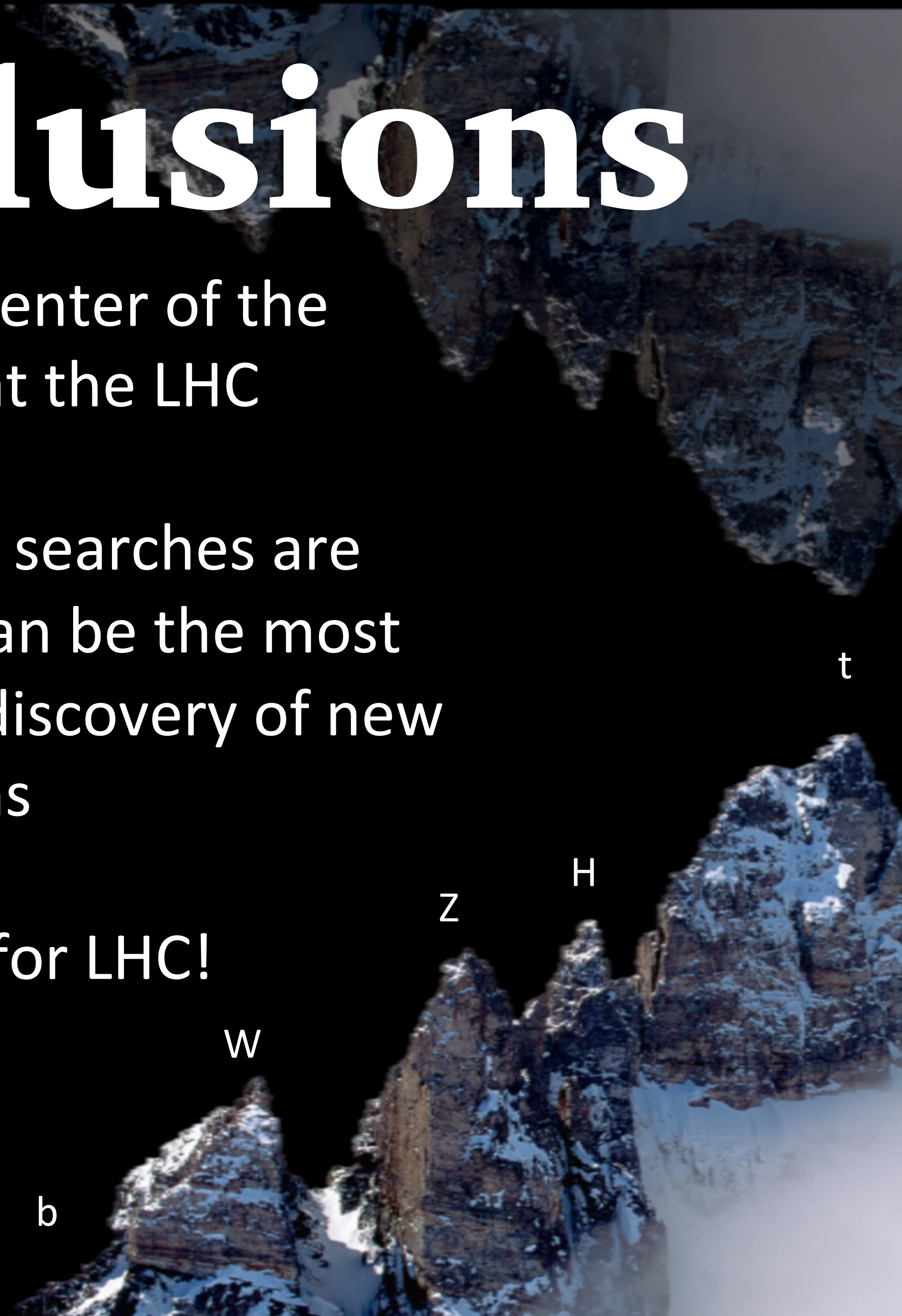
Peak luminosity
Integrated luminosity
HL-LHC
Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
LS1
LS2
LS3
LS4
LS5
Trigger-Rate: ~500 Hz
Trigger-Rate: ~1 kHz
Trigger-Rate: ~1 kHz
Trigger-Rate: ~7.5 kHz
Trigger-Rate: ~7.5 kHz
YOU ARE HERE
Luminosity [cm^{-2}s^{-1}]
Integrated luminosity [fb^{-1}]
Year
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38

Conclusions

The top quark is at the center of the search for new physics at the LHC

Its precision and related searches are key for understanding can be the most important route to the discovery of new fundamental interactions

Very exciting prospects for LHC!



credit: F. Margaroli

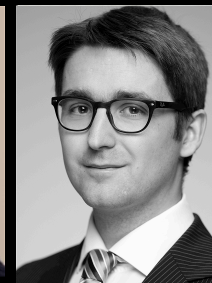
Credits

Top and Higgs

L. Bianchini (ETH)

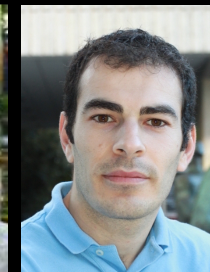
L. Caminada

S. Donato



G. Kasieczka

J. Pata



D. Salerno

Top and Susy

C. Seitz

Top and other Tops

G. Giannini

G. Rauco

+ A. de Cosa

Top and dark matter

A. De Cosa

D. Pinna

A. Zucchetta