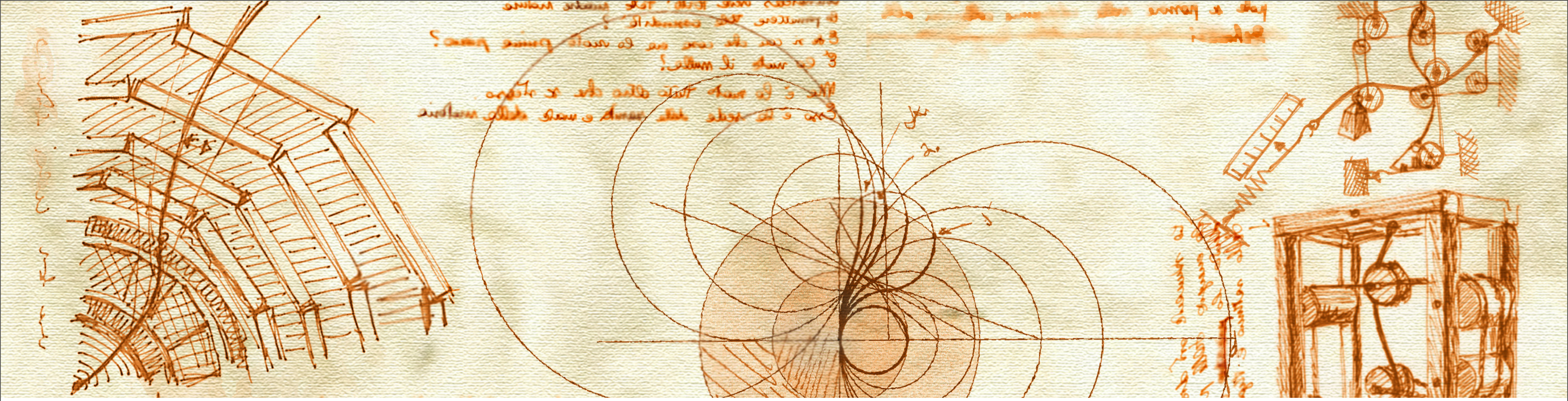
CMS-PHO-OREACH-2009-001

Search for exotic new physics in CMS

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20th November, 2017

TIFR, Mumbai, India

Physics Institute III A

RWTH AACHEN UNIVERSITY

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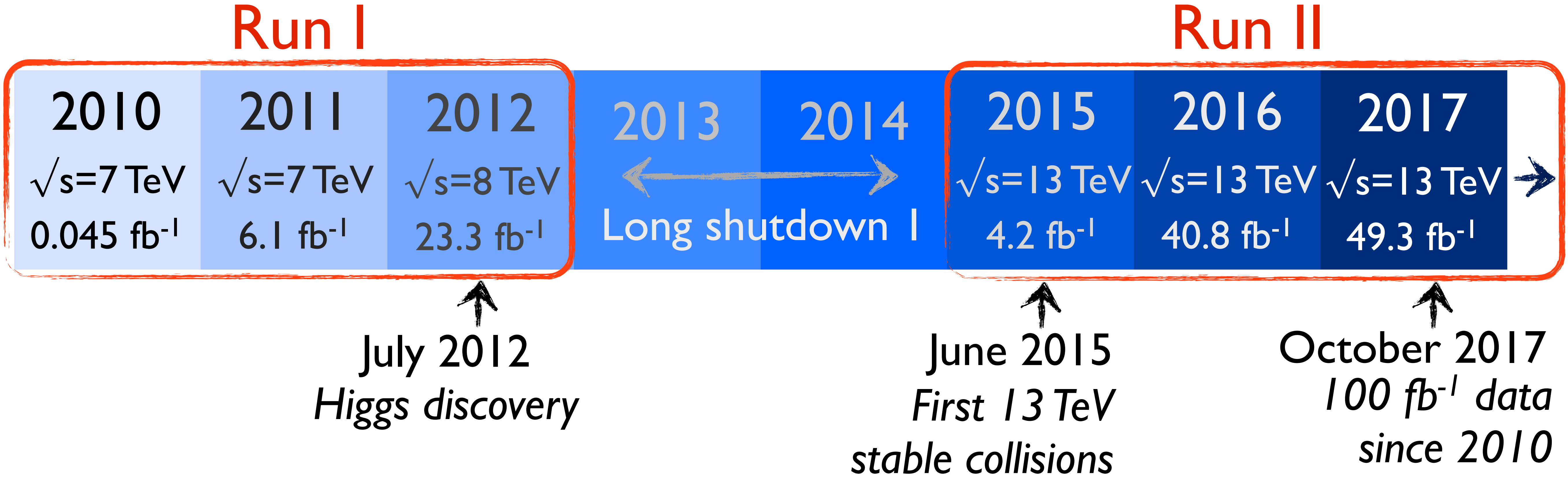
CMS Compact Muon Solenoid

Introduction



Run I

Run II

2010	2011	2012	2013	2014	2015	2016	2017
$\sqrt{s}$=7 TeV	$\sqrt{s}$=7 TeV	$\sqrt{s}$=8 TeV	Long shutdown 1		$\sqrt{s}$=13 TeV	$\sqrt{s}$=13 TeV	$\sqrt{s}$=13 TeV
0.045 fb^{-1}	6.1 fb^{-1}	23.3 fb^{-1}			4.2 fb^{-1}	40.8 fb^{-1}	49.3 fb^{-1}

July 2012
Higgs discovery

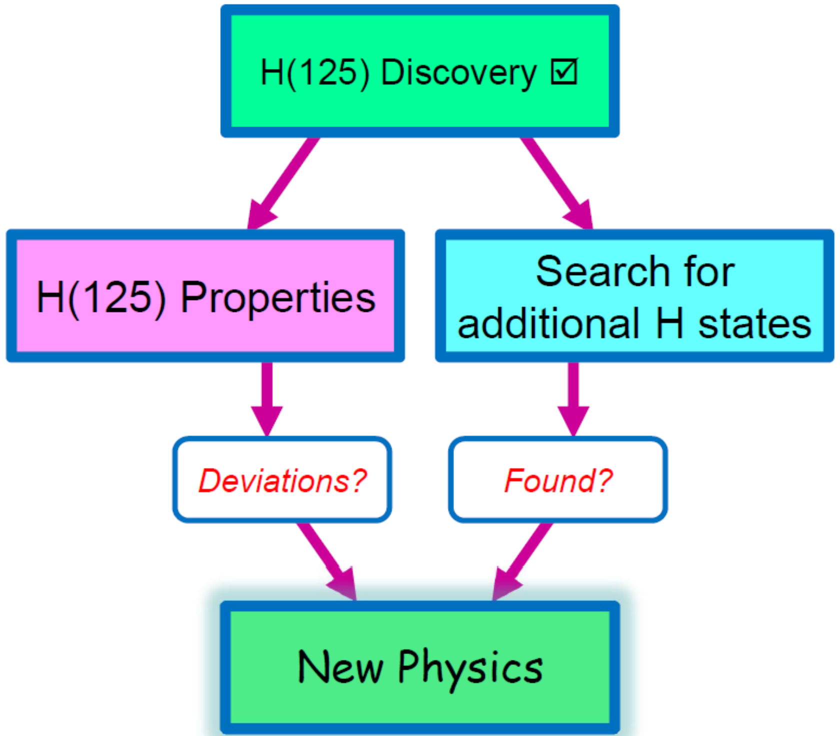
June 2015
First 13 TeV stable collisions

October 2017
100 fb^{-1} data since 2010

- LHC is delivering (primarily) p-p collision data since 2010
- Increase in center-of-mass energy in run-II significantly extends reach of run-I
  - Higgs production(ggH): 19.3 pb → 43.9 pb (x2.3)
- Experimentally more challenging
  - Increased instantaneous luminosity
    - Increased overlapping p-p collisions (pile-up)
    - Increased event rate

Lessons from Run-1

- There is a Higgs boson
  - It is standard model like
  - An obvious lamp-post to look under
  - In run-II, perform precision measurements of the Higgs properties
    - example: measure Higgs differential cross-sections
- No clear indication of new physics
  - In run-II, search in as many final states as possible, covering large range of masses
- Excellent understanding of
  - Detector/ Reconstruction/ Calibration
  - Standard Model physics



H(125) Discovery ☑

H(125) Properties

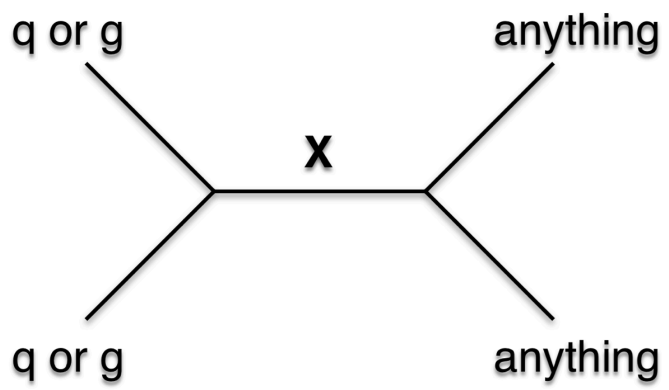
Search for additional H states

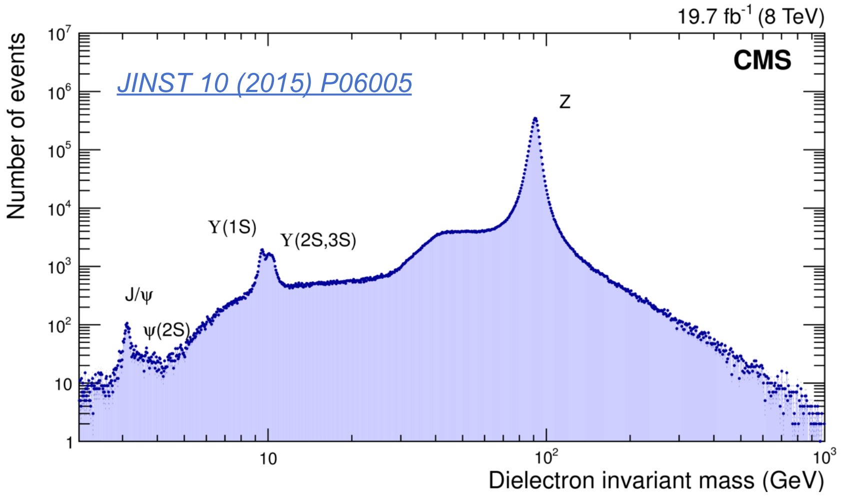
Deviations?

Found?

New Physics

from R. Mankel



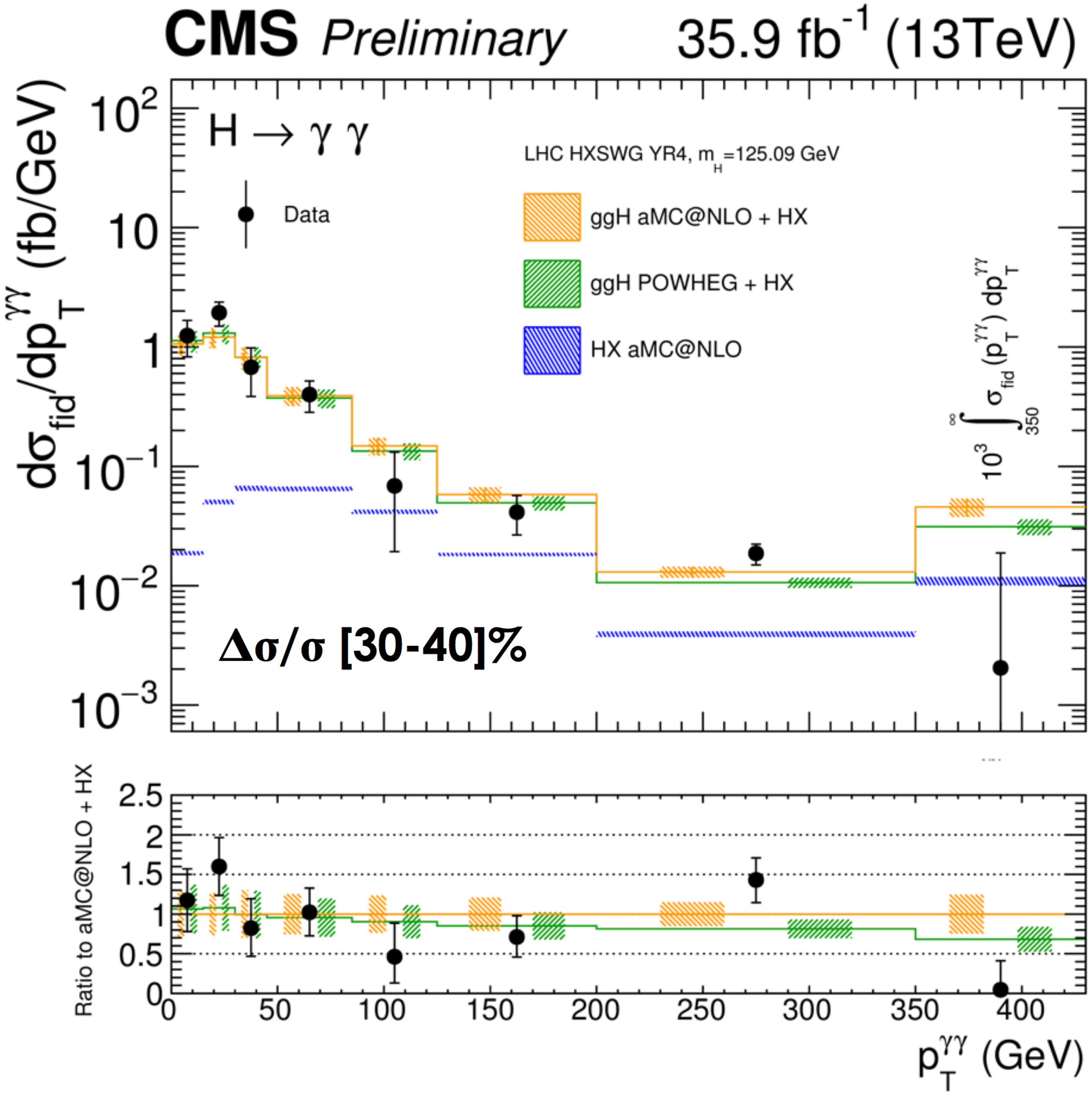


Higgs differential cross section

in γγ channel

- Small branching (≈10^{-3}) but very clean channel
- Good mass resolution (1-2% at 125 GeV)
- Direct test of perturbative QCD calculations in the Higgs sector
- Good agreement with QCD predictions within uncertainty
- Statistical uncertainty still dominant over systematics
- No hint yet of extra contributions from new processes

CMS-HIG-17-015



Many other Higgs analyses performed...

Precision measurement

- Width

$$\boxed{\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f}$$

- Signal strength (μ_i^f) in different production and decay modes
- Coupling modifiers (κ)

$$\boxed{\sigma \cdot B(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\right)}$$

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad \kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$$

Production **Decay** **Total width**

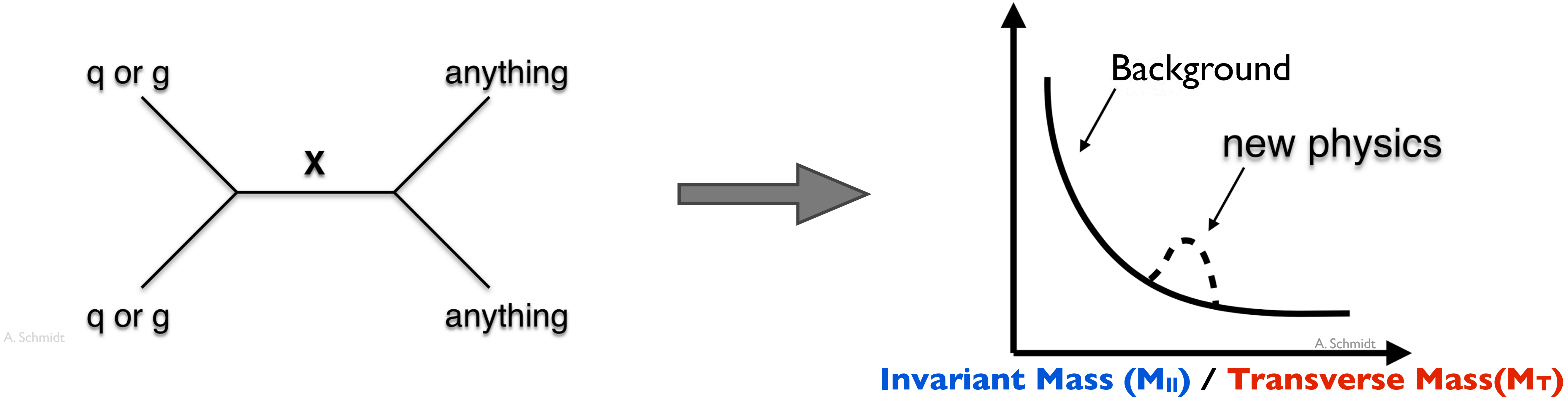
- Spin, Parity

Searches

- rare decays of Higgs
  - LFV channels, di-muon, di-electron etc..
  - di-Higgs in different final states

no hint of new physics

Searches for New Physics *in Bump-Hunt technique*



Bump hunt

Fully reconstructed final state

eg. X→e+μ

Final state not fully reconstructed

MET in the final state

eg. X→e+ν

$X \rightarrow e\mu$ Lepton Flavor Violating (LFV) decay

CMS PAS EXO-16-001

13 TeV

2.7 fb^{-1}

Experimental Signature

- e and μ → High p_T, isolated

No other signal-specific cut in order to stay **model independent**

Generic and inclusive search strategy. Many possible theoretical interpretations.

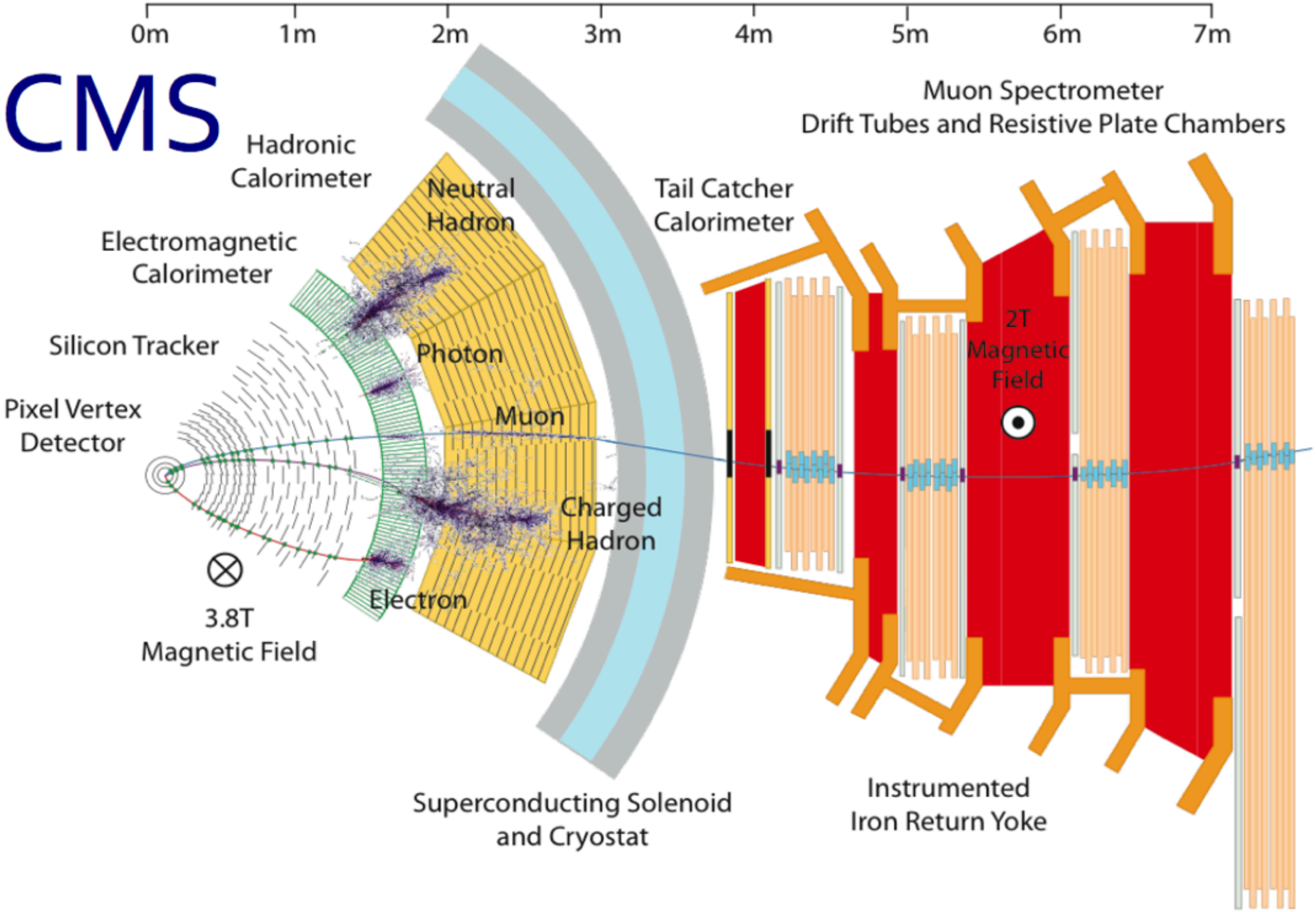
Three basic elements → Charged particle tracks | Calorimeter clusters | Muon tracks

↑

Combine information from different sub-detectors to reconstruct particles with better resolution

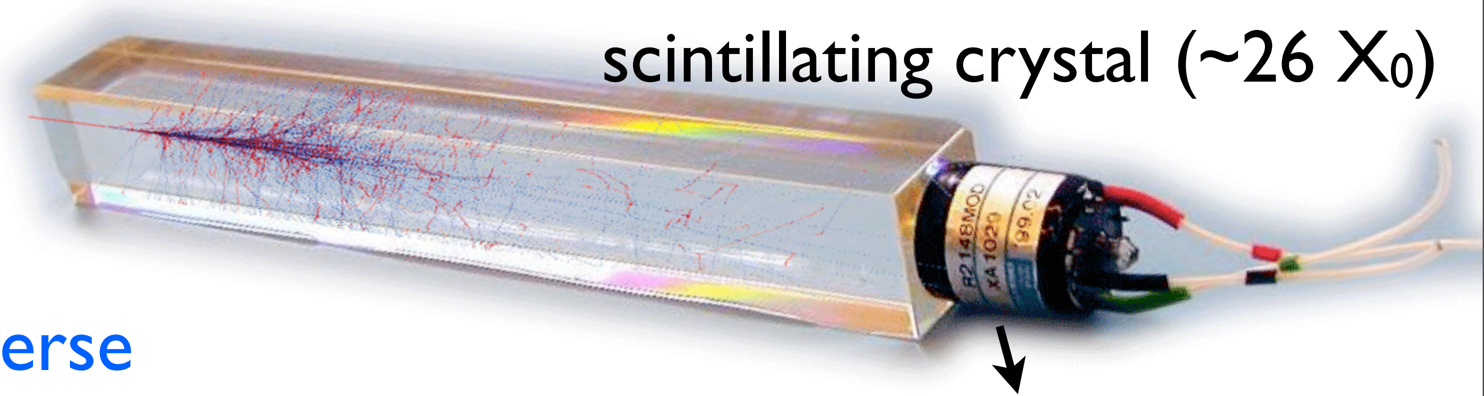
↑

Particle Flow



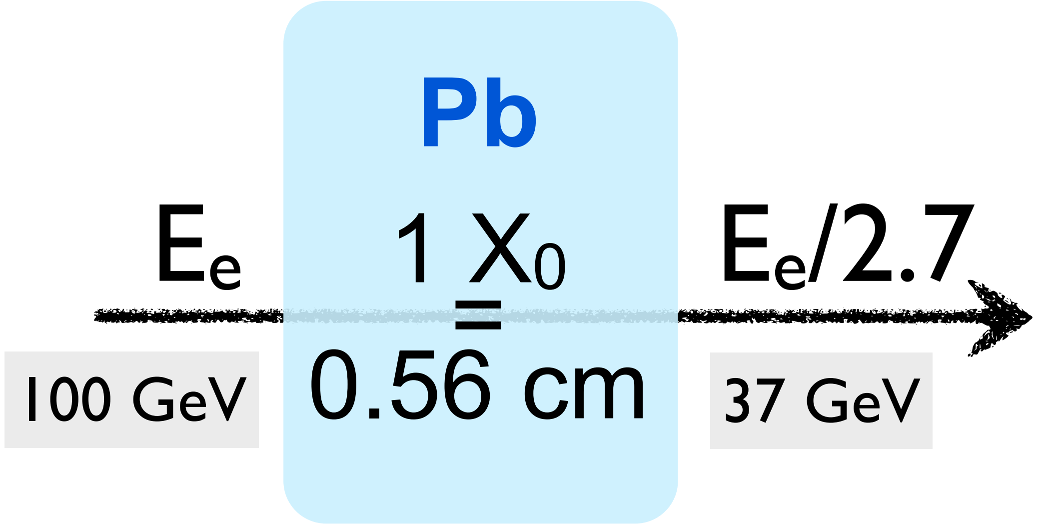
Electrons in CMS

- Electrons deposits energy in ECAL
  - Homogeneous, compact, high transverse granularity
- Pixel and silicon-strip tracker to reconstruct electron tracks
- Bremsstrahlung radiation due to tracker material in front of ECAL
- Search for the highest ET crystal
- Narrow η - larger φ window around the seed
- Superclusters built collecting all the crystals in the road
- Information from HCAL also useful for electron/jet discrimination. Electrons deposit most of their energy in the ECAL➜ E_{HCAL}/E_{ECAL} small



PbWO4 scintillating crystal (~26 X_0)

Light detector (VPT or APD)

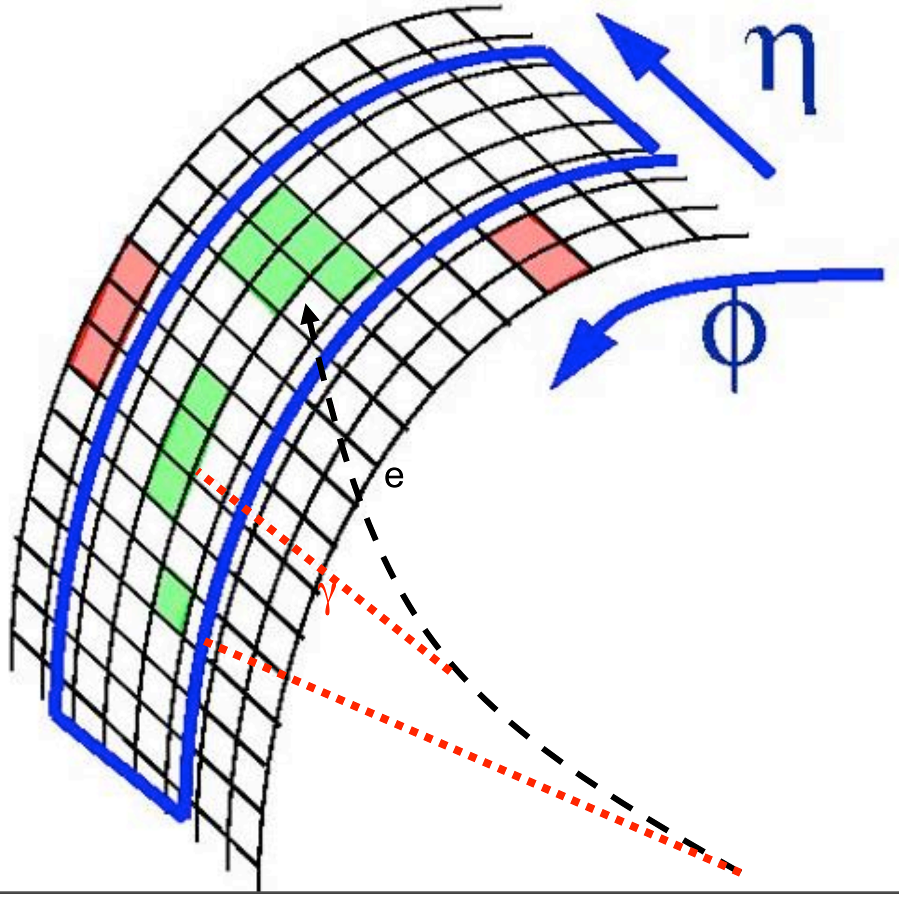


Pb

E_e 100 GeV

$1\ X_0 = 0.56$ cm

$E_e/2.7$ 37 GeV

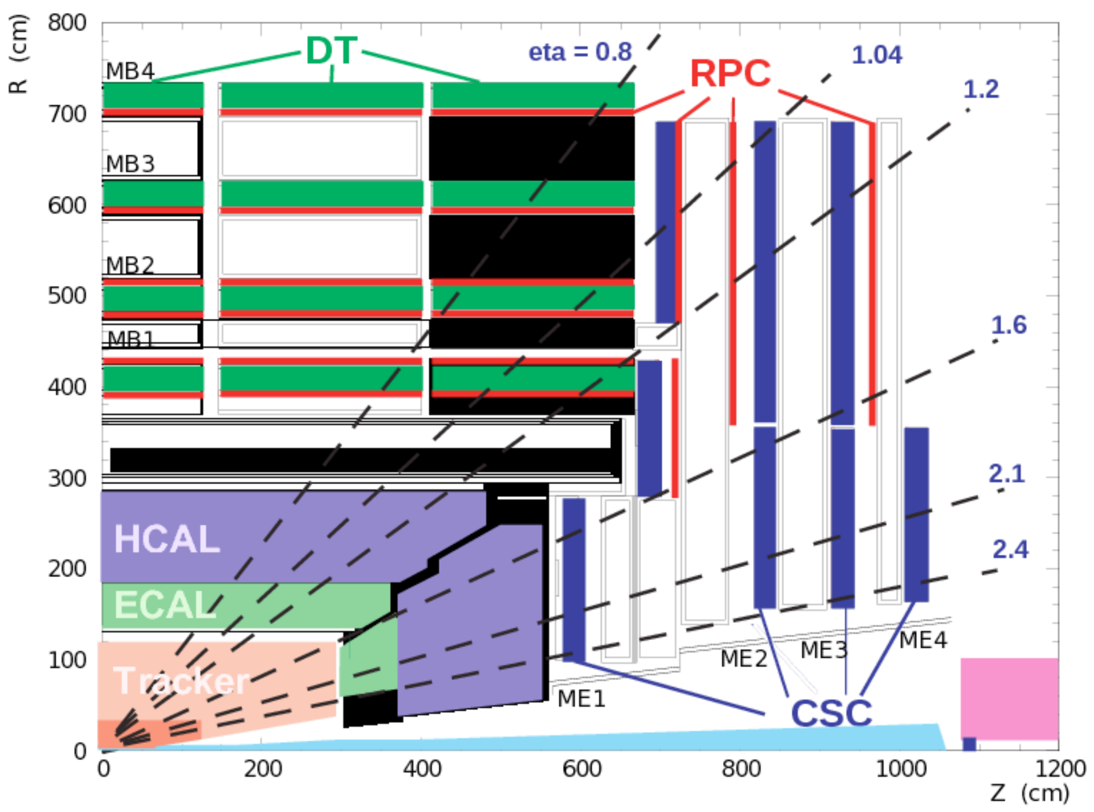


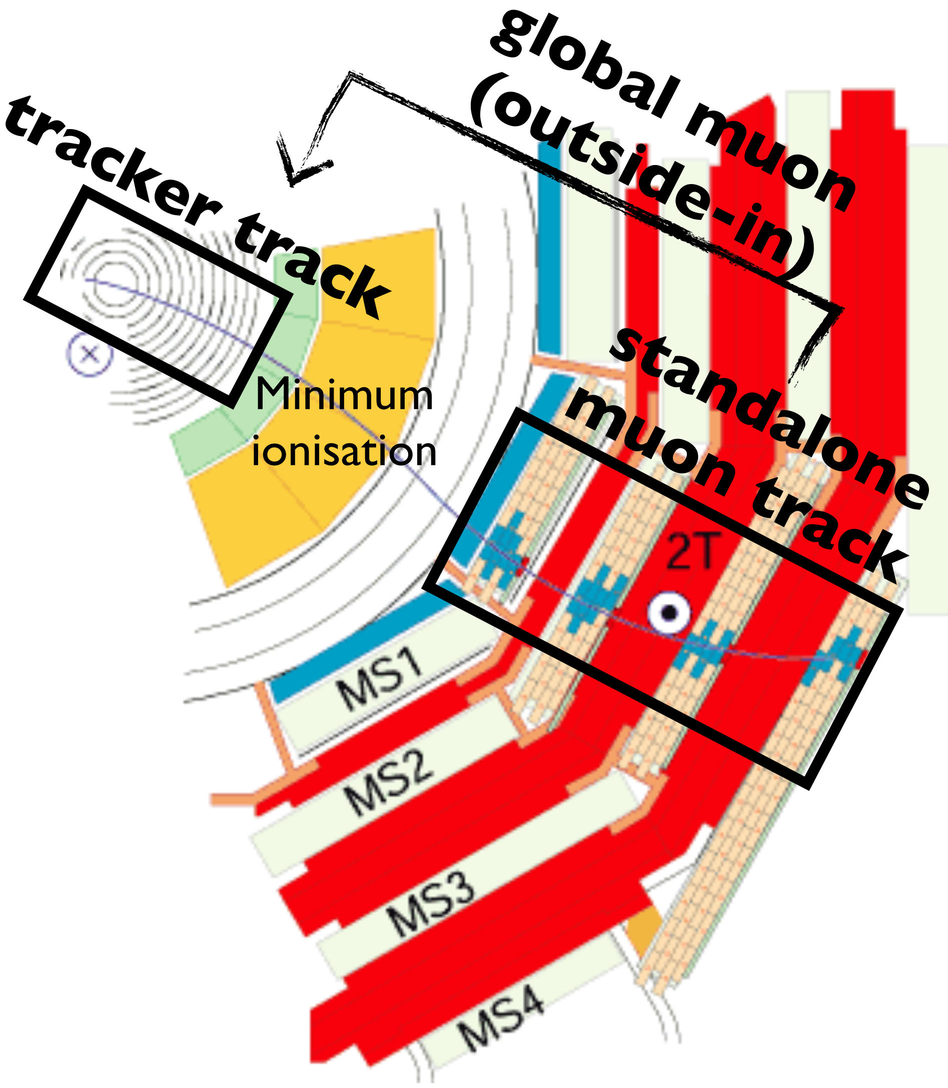
σ(E)/E ~ 2% for 50 GeV electron

Muons in CMS

- Redundant muon measurement
  - **Muon system**
    - Drift Tubes (DT) in central barrel
    - Cathode Strip Chambers (CSC) in endcap
    - Resistive Plate Chambers (RPC) in barrel and endcap
  - **Inner tracker**
- 3 muon reconstruction algorithms
  - standalone muon: reconstructed in muon system only **Important for long-lived searches**
  - global muon: outside-in (standalone muon to inner track)
  - tracker muon: inside-out (inner track to muon detector)

Muon momentum resolution 2-10%





X→eμ Lepton Flavor Violating (LFV) decay

13 TeV

2.7 fb^{-1}

Cut-based e and μ identification

<u>Background</u>

- Dominant
  - TTbar, Diboson
- Other
  - Single Top
  - Drell-Yan

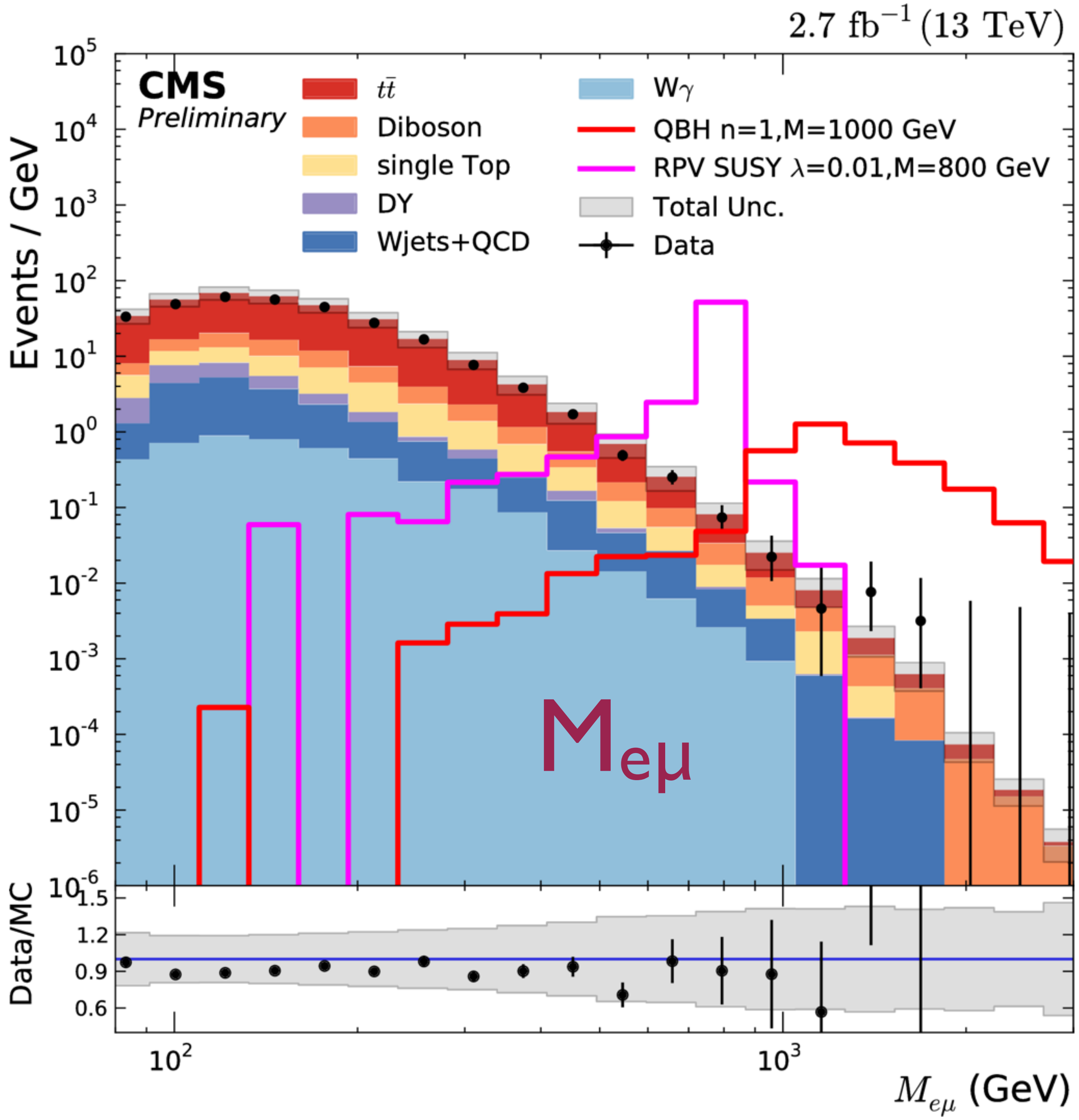
Real Leptons

- Wɣ

ɣ mis-identified as e

- W+Jets, QCD

Jet mis-identified as electron (Data-driven)



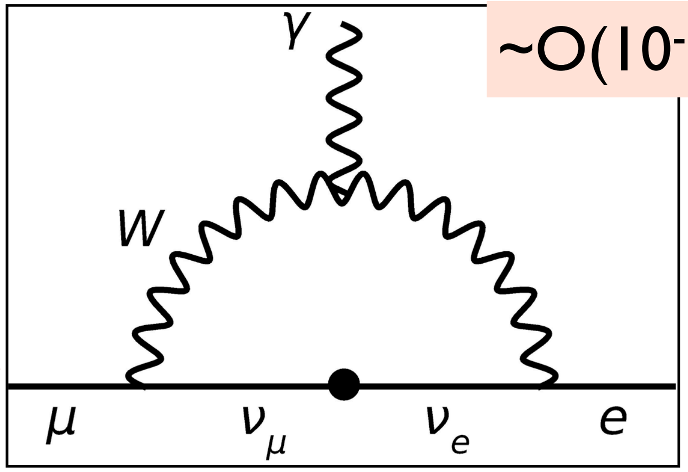
Discriminating Variable : Meμ

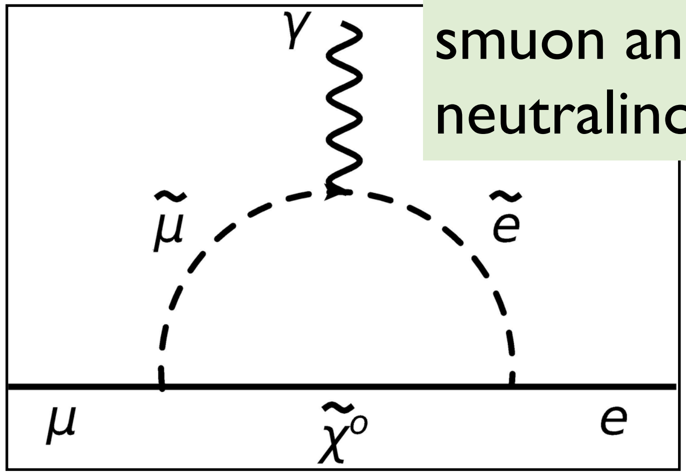
No significant excess

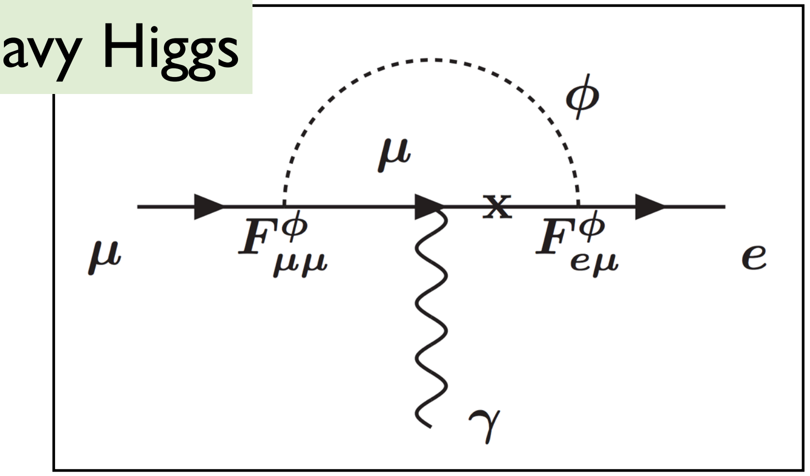
Why is LFV important?

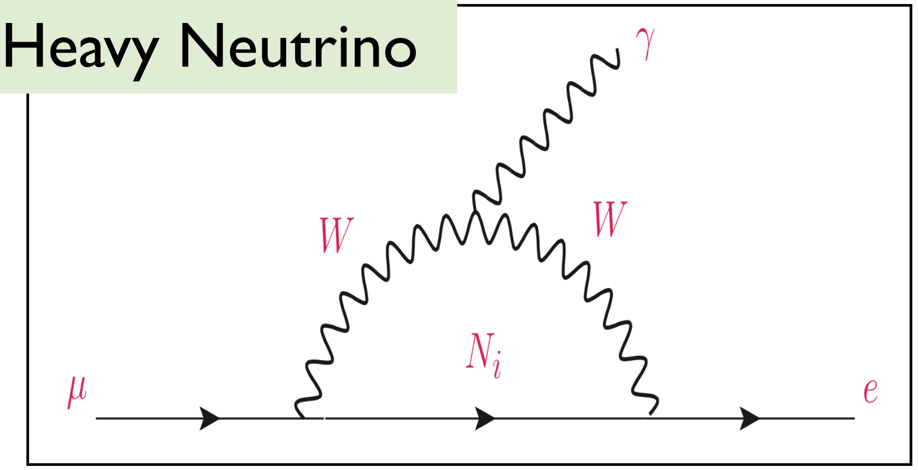
- Neutral Lepton Flavour Violation (LFV) observed → neutrino oscillation
- Charged LFV not observed
- Example $\mu \to e\gamma$
- Branching Ratio from known physics $\sim O(10^{-54})$
- Can be enhanced in presence of New Physics
- Many extensions of SM with new states at TeV scale generates charged LFV

- Strong limit from indirect searches in some cases.
- Can be degraded by cancellation of LFV effects from other new physics.
- Direct search is complementary to limits obtained from searches at lower energies.


$\sim O(10^{-54})$


smuon and neutralino

Heavy Higgs


Heavy Neutrino


LFV in R-Parity Violating (RPV) SUSY

In SUSY, most generic super-potential allows terms like this

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}\underset{\overset{\longleftrightarrow}{\text{LLE}}}{L_iL_j\bar{e}_k} + \lambda'_{ijk}\underset{\overset{\longleftrightarrow}{\text{LQD}}}{L_iQ_j\bar{d}_k} + \mu'_iL_iH_u$$

λ and λ' terms violate lepton number (and also lepton flavor)

They also violate R-parity.

R-parity (R) = $(-1)^{3B+L+2s}$

R=(+1) for SM, R=(-1) for SUSY particles

R-Parity Conserving SUSY: Proton always stable

If only L (or B) is violated, then the proton would be still stable!

B → baryon num.
L → lepton num.
s → particle spin

In RPV SUSY, the Lightest SUSY Particle (LSP) is unstable → low MET in event

X→eμ

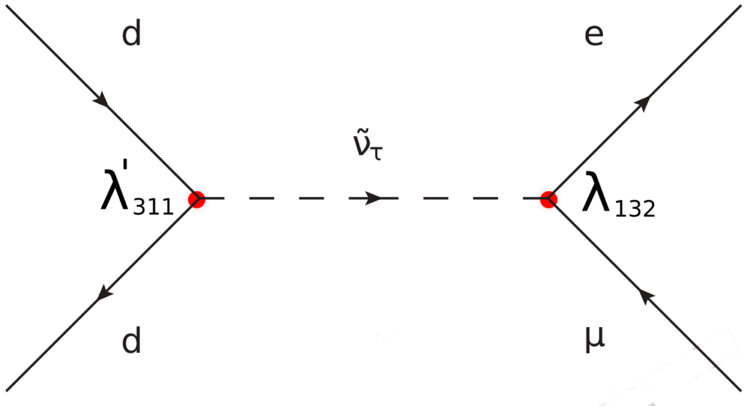
13 TeV 2.7 fb^{-1}

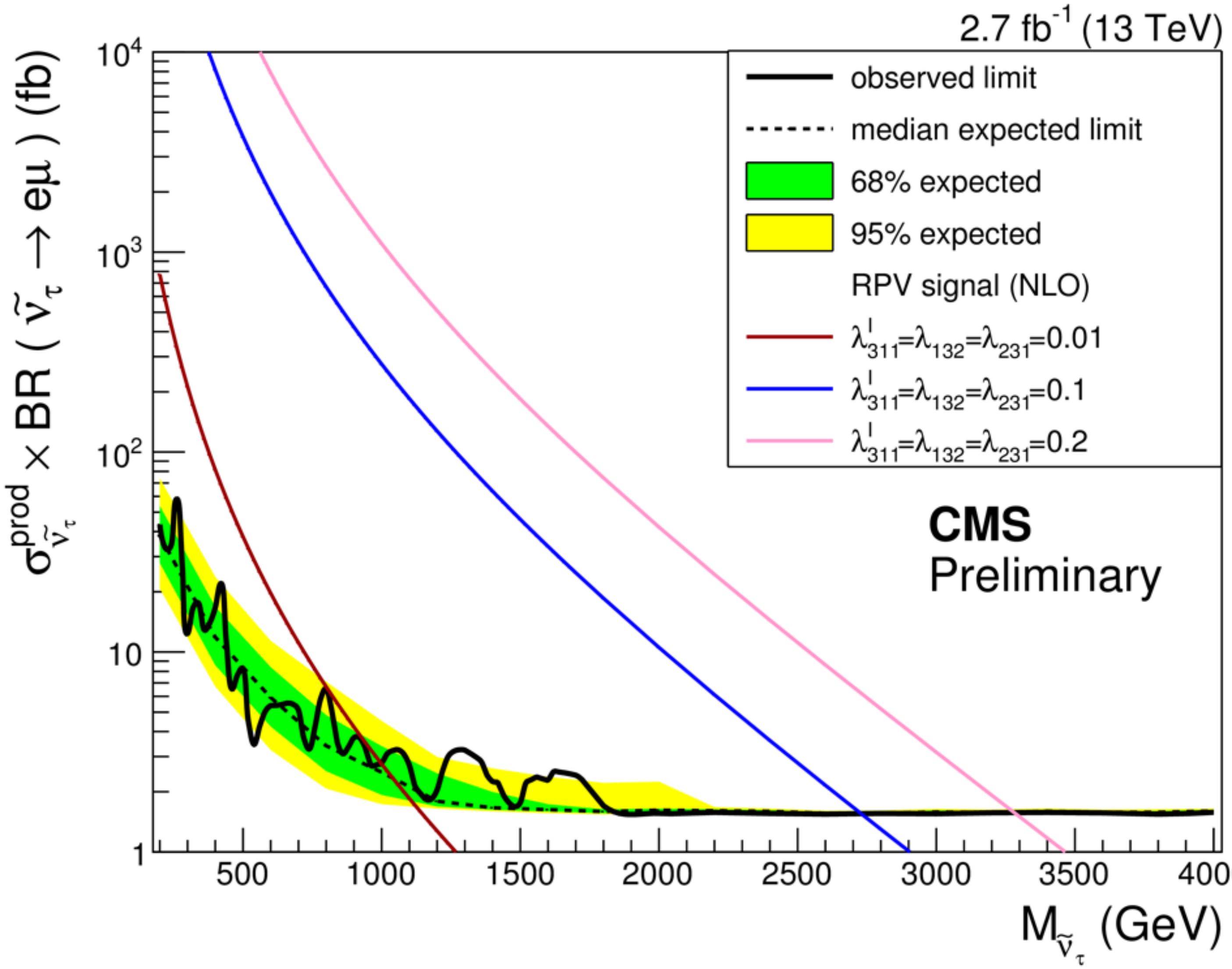
$$\lambda_{132}\lambda'_{311} < 3.3\times10^{-7}\ (M_{\tilde{\nu}_\tau}/1\,\text{TeV})^2 \text{ at } 90\%\text{ CL}$$

Strong limits from low-energy muon conversion experiments

RPV SUSY interpretation

- Resonant production of **τ** sneutrino **Lightest SUSY Particle**
- Decay to eμ
- Assume all RPV couplings vanish, except λ'_{311}, λ_{132}, λ_{231}





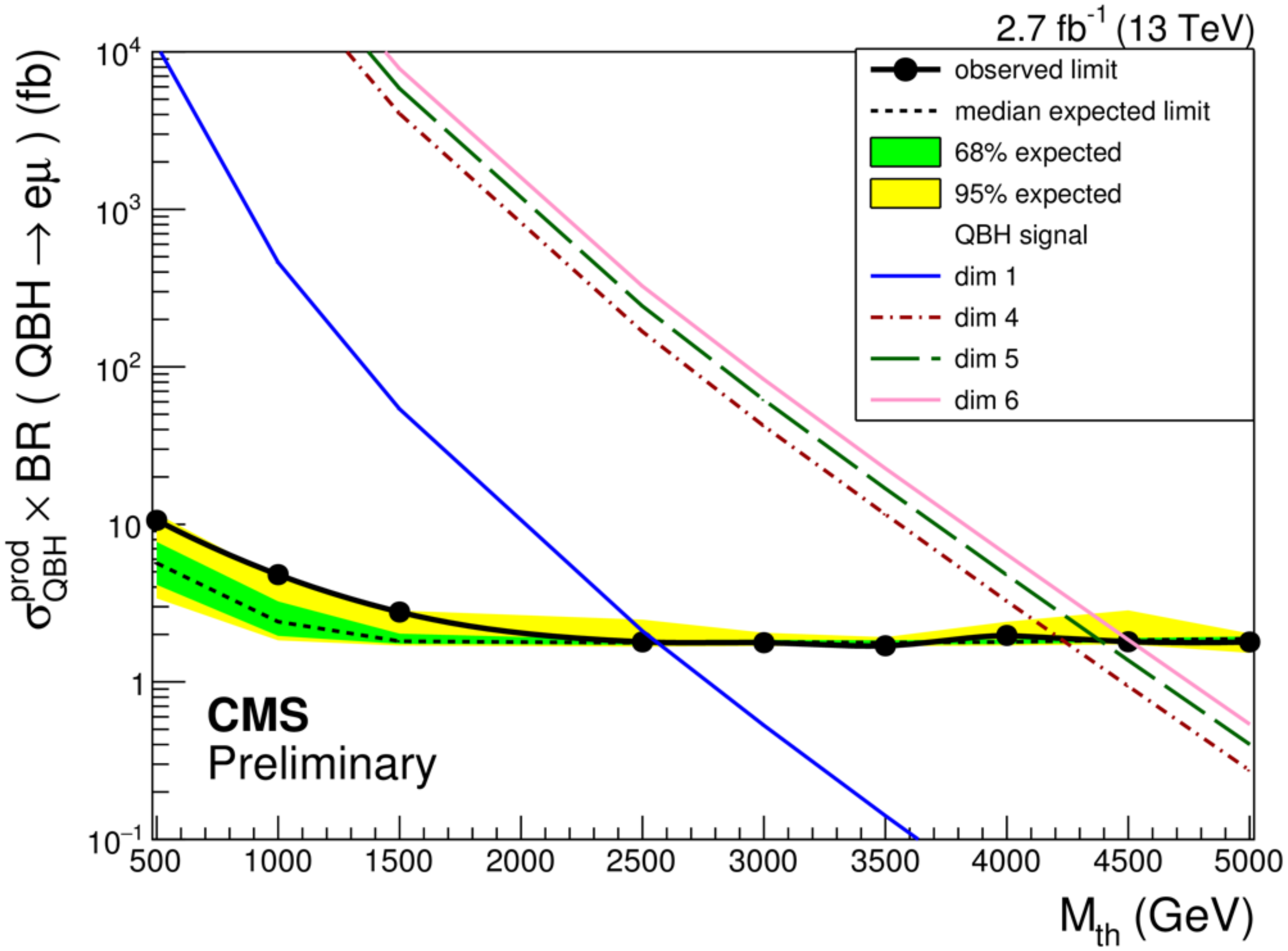
RPV coupling	τ sneutrino mass
$\lambda' = \lambda = \mathbf{0.01}$	1.0 TeV
$\lambda' = \lambda = \mathbf{0.1}$	2.7 TeV
$\lambda' = \lambda = \mathbf{0.2}$	3.3 TeV

X→eμ

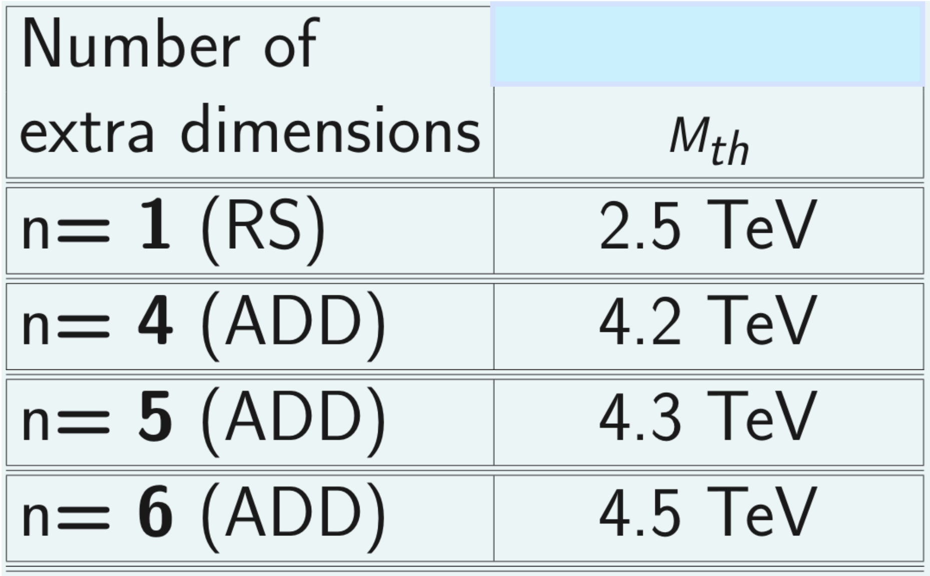
13 TeV 2.7 fb^{-1}

Quantum Blackhole (QBH)

- Extra dimension(s) → Fundamental Planck scale lowered to TeV region (M_P~1 TeV)
- QBH produced if $\sqrt{s} > M_P$
- Spin-0, colorless, charge-neutral QBH
- Cross section depends on threshold mass for QBH production ($M_{th}=M_P$) and number of extra dimensions (n)



- n=1 : Randall-Sundrum (RS) model
- n=4,5,6 : Arkani-Hamed-Dimopoulos-Dvali (ADD) model



Number of extra dimensions	M_{th}
n= **1** (RS)	2.5 TeV
n= **4** (ADD)	4.2 TeV
n= **5** (ADD)	4.3 TeV
n= **6** (ADD)	4.5 TeV

QBH generator by Douglas M. Gingrich arxiv 0911.5370

Electric charge, QCD color, spin conserved

$X \to e/\mu/\tau_{had}$+MET

Experimental Signature

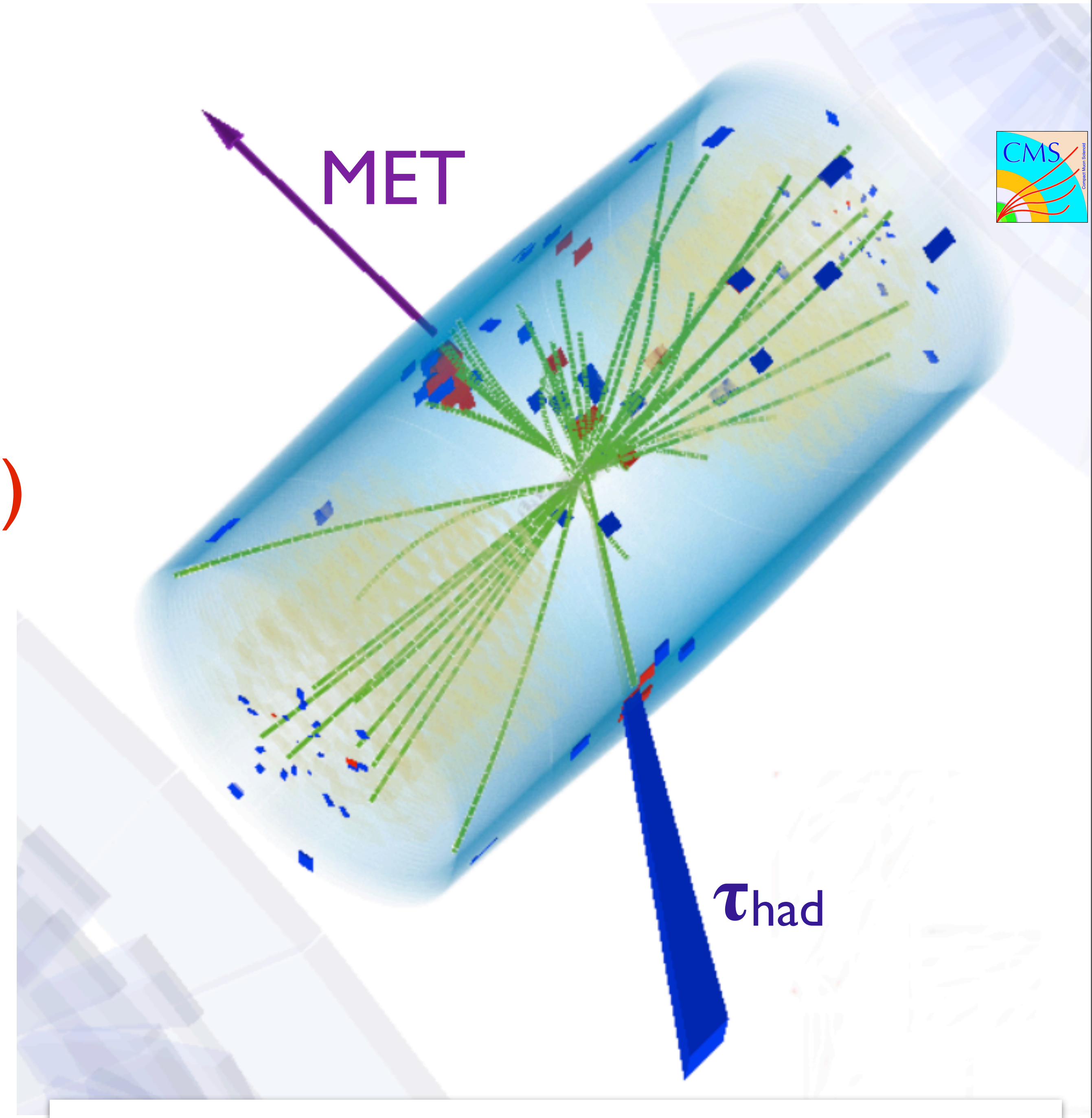
❖ High-p_T, isolated $e/\mu/\tau_{had}$

❖ Missing Transverse Energy (MET)

Back-to-back: $\Delta\Phi(\ell, \text{MET})$ high

Balanced in p_T: $p_T(\ell)$/MET close to 1

- τ_{had} **and MET** are experimentally challenging
- Uses information from full detector (Particle-flow)
- **HCAL is important**



Event display of the highest M_T τ+MET event

Data recorded: Oct. 9, 2015

$pT(\tau)$: 509 GeV,

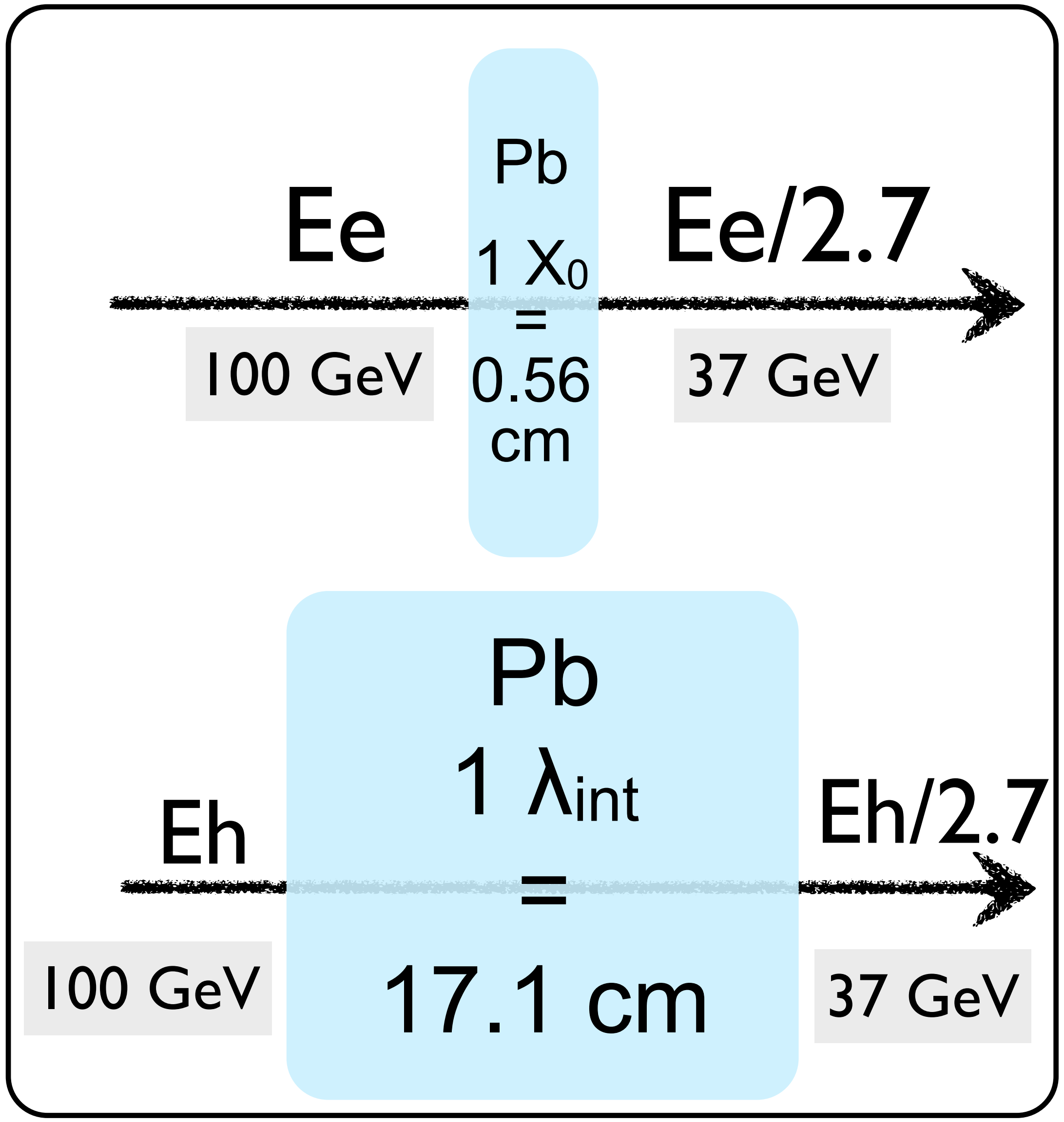
MET : 540 GeV

CMS HCAL

- Hadronic showers more complex. Need more material to contain them.
- Homogeneous calorimeter not possible.
- Brass(passive absorber) / Plastic scintillator(active) sampling calorimeter
- Hadronic shower has EM component from $\pi^0 \rightarrow \gamma\gamma$
- Resolution is best if the HCAL has similar energy response to electrons as charged pions (e/h~1).
- But generally e/h>1 (CMS case)

$\sigma(E)/E \sim 18\%$ for 50 GeV $\pi^{+/-}$

Showers: EM vs hadronic



Ee

100 GeV

Pb

$1\ X_0$

=

0.56 cm

Ee/2.7

37 GeV

Eh

100 GeV

Pb

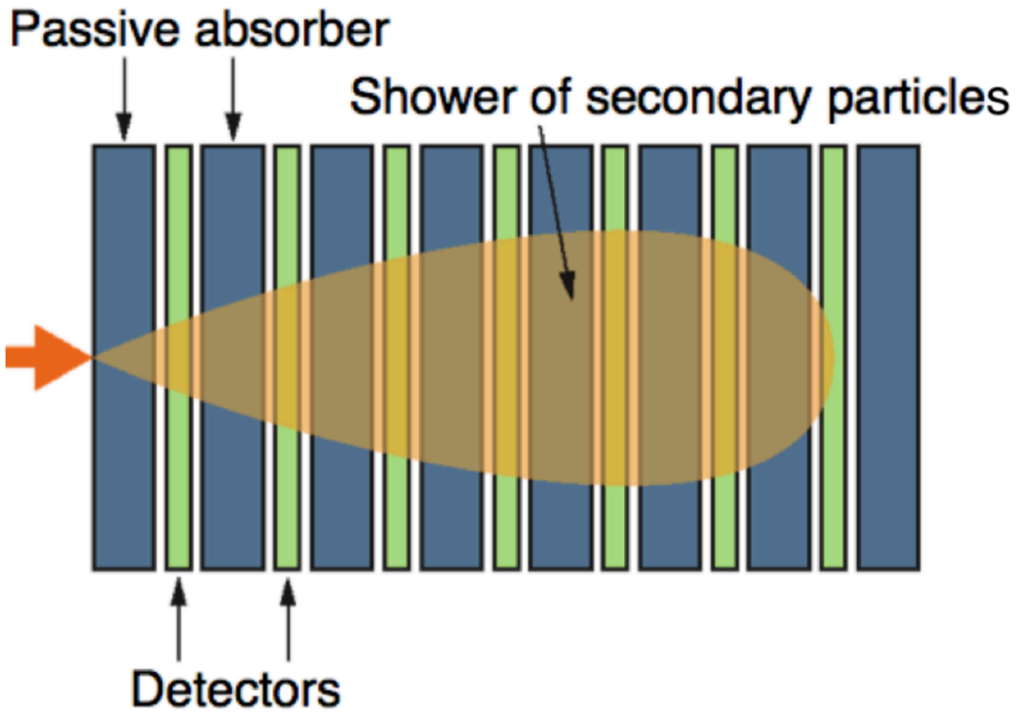
$1\ \lambda_{int}$

=

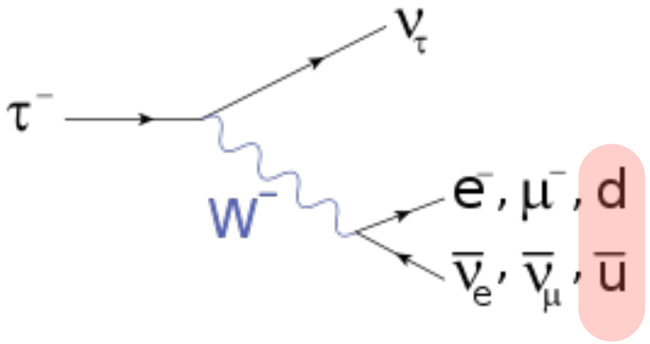
17.1 cm

Eh/2.7

37 GeV

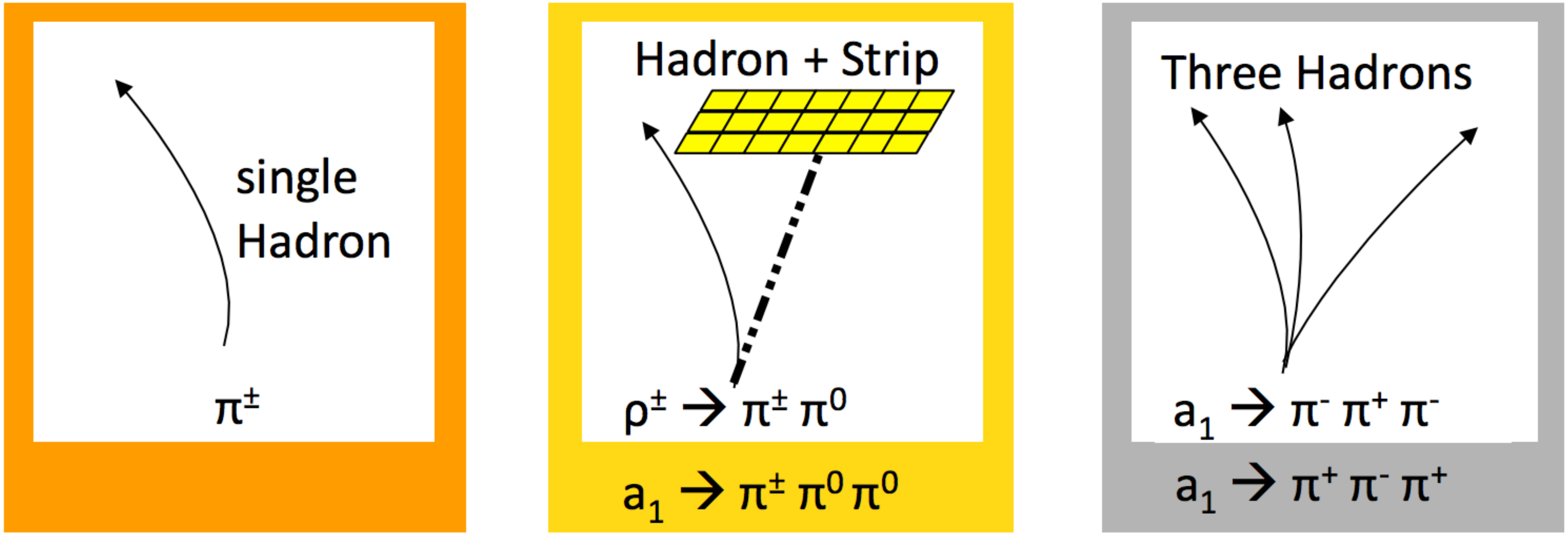


Hadronic taus in CMS



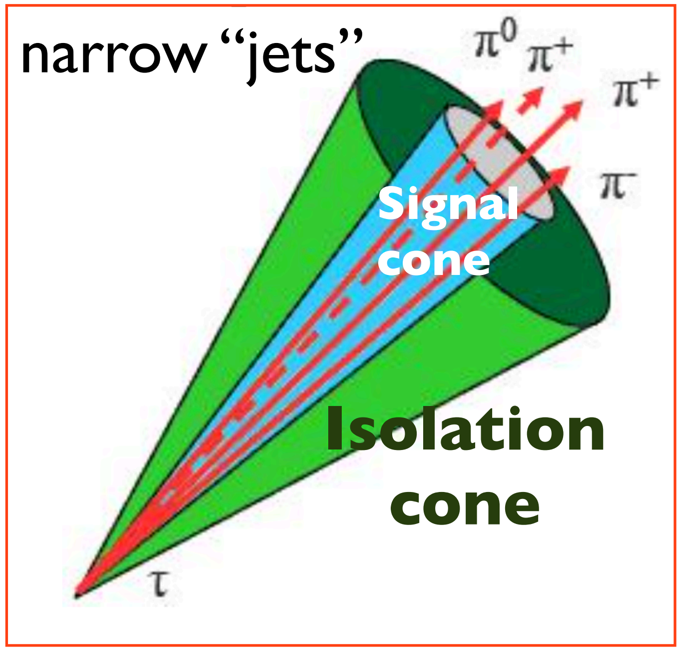
Many possible hadronic tau decays.
Group them into three families

1-prong, **1-prong+nπ^0**, **3-prong**



strips = $\pi^0 \to \gamma\gamma$ candidates

demand tracks (1 or 3) and neutral particles are within signal cone

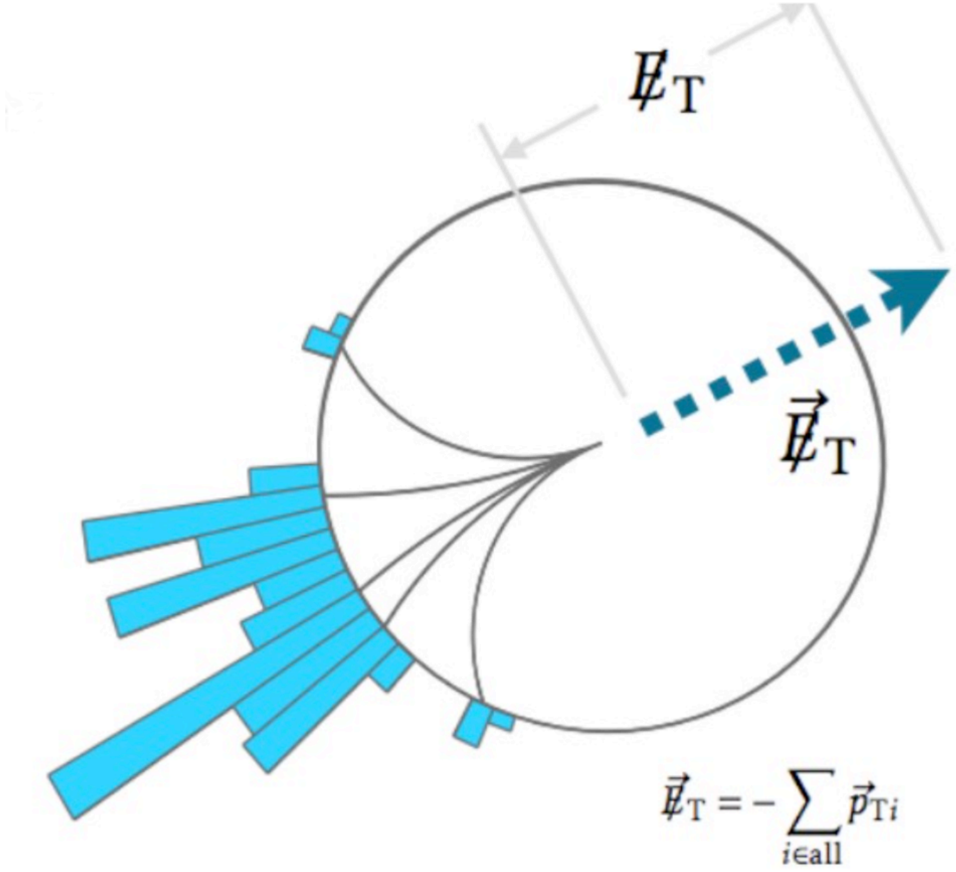


Main handle in τ_h discrimination against QCD jets: isolation

	Efficiency	Mis-identification rate
Jet-Rejection (Tight)	~60%	<1%
Electron-Rejection (Tight)	~75%	~0.1%

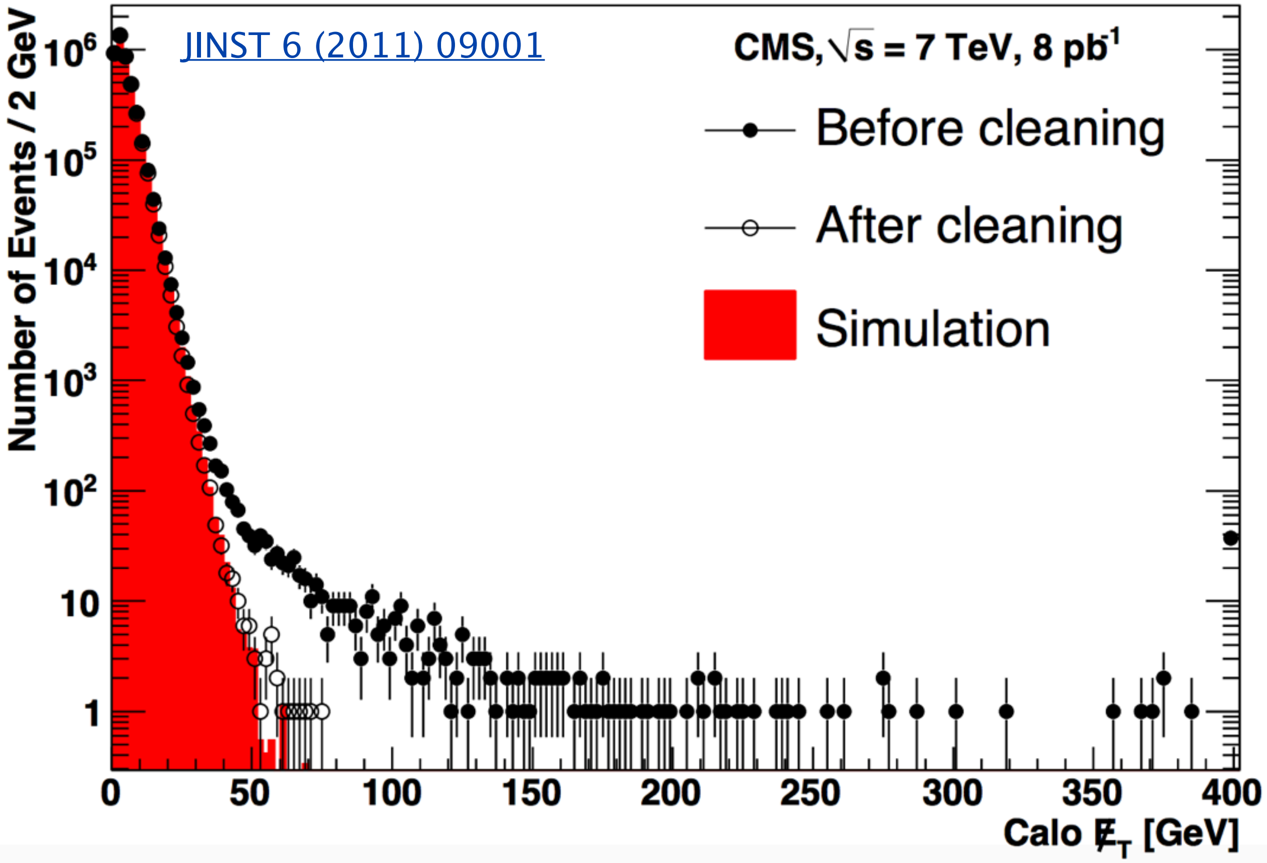
MET in CMS

Particle escaping the detector undetected gives rise to MET → imbalance in p_T of all reconstructed particles in an event



$$\vec{\not{E}}_T = -\sum_{i \in \mathrm{all}} \vec{p}_{Ti}$$

- Well understood MET important for many new physics searches
- Many sources of fake MET
  - Dead / hot calorimeter cells
  - Jet whose hardest hadron enters a crack in the calorimeter
  - "beam halo"
  - Cosmic muon
- Apply clean up cuts to remove fake high MET events



JINST 6 (2011) 09001

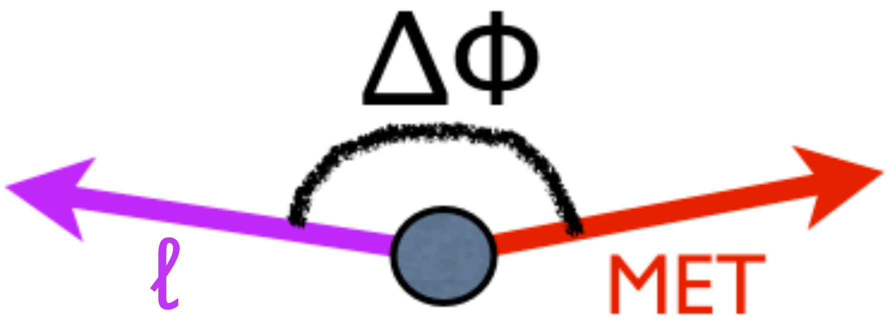
MET well understood in CMS data

$X \rightarrow e/\mu/\tau_{had}$+MET

2.3 fb^{-1} 2015 data

Experimental Signature

- High-p_T, isolated $e/\mu/\tau_{had}$ and MET
- Back-to-back → Cut on $\Delta\Phi(\ell, \mathrm{MET})$
- Balanced in p_T → Cut on $p_T(\ell)/\mathrm{MET}$



Background

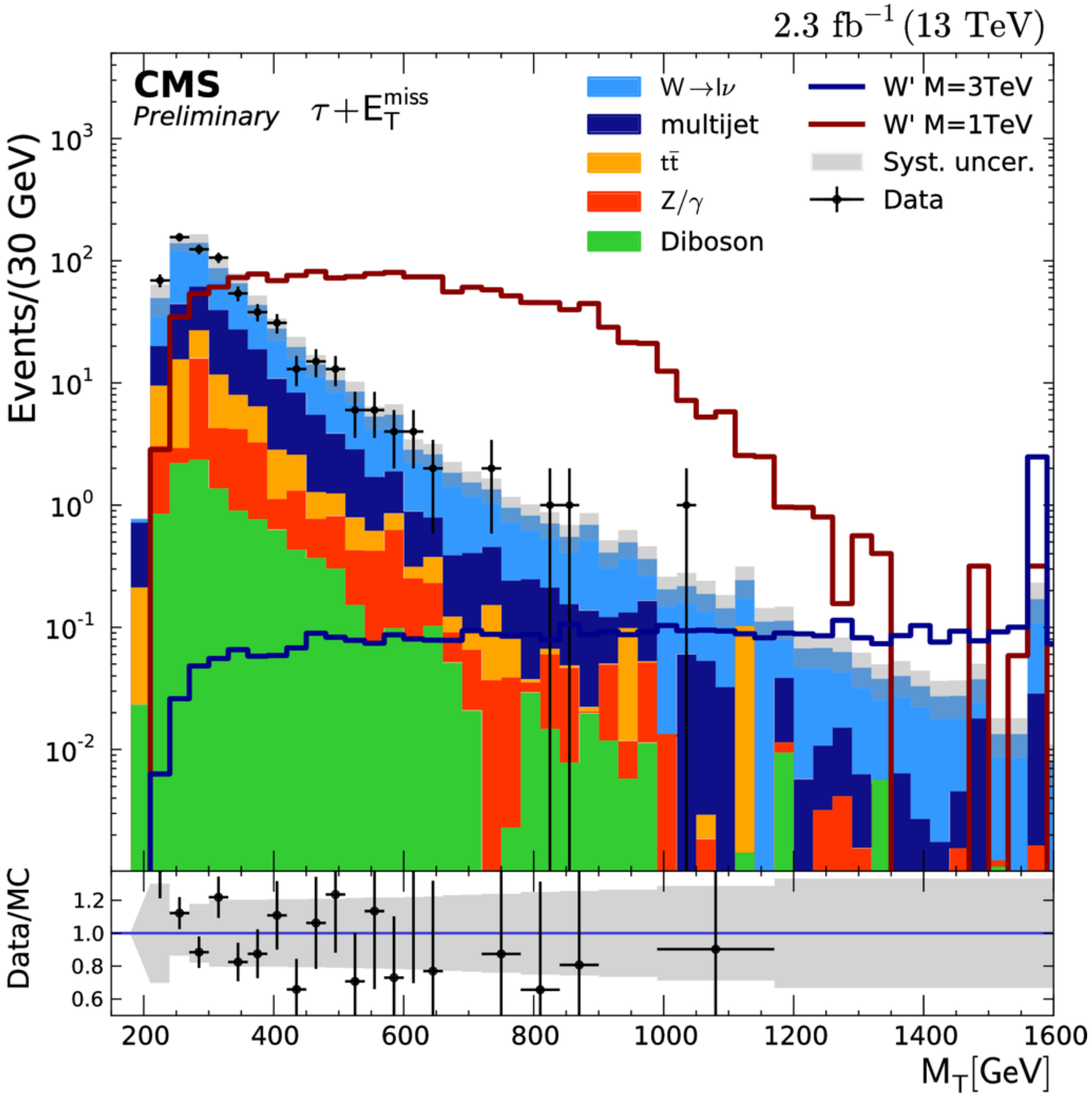
- Dominant
  - $W \rightarrow \ell + \nu$ (irreducible)
- Other
  - Top production
  - Drell-Yan
  - Diboson

Real Leptons

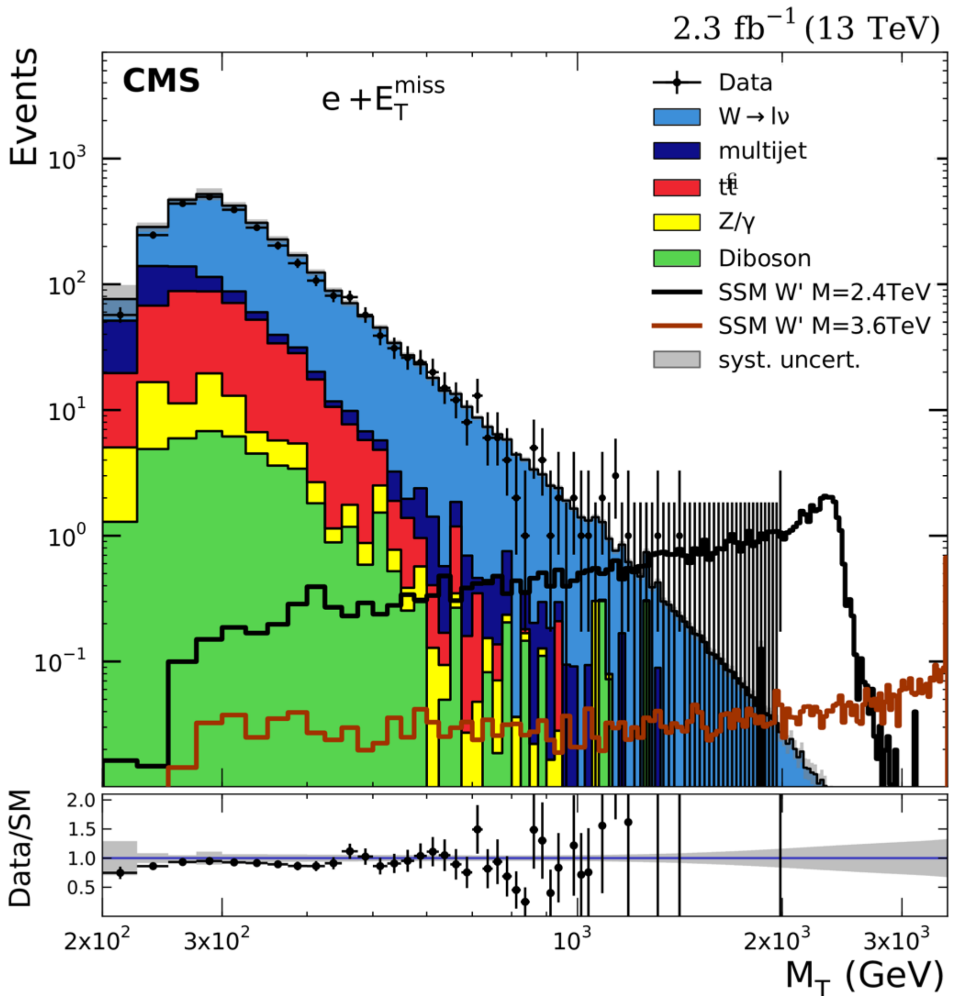
- QCD (e and τ channel)

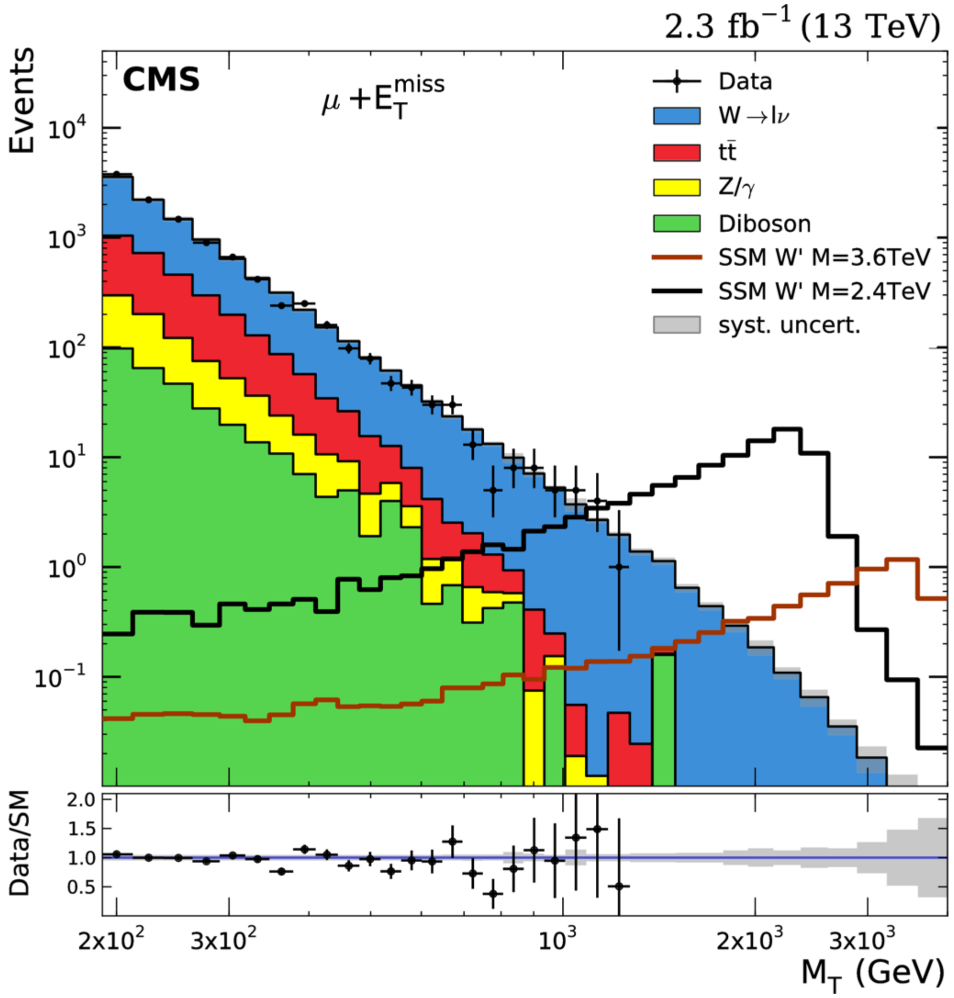
Jet faking lepton Data-driven

W’→e/μ/τ_{had}+MET



No significant excess





Discriminating variable :

$$M_T = \sqrt{2 p_T^l E_T^{miss}\left(1 - \cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})]\right)}$$

2015 data

2.3 fb^{-1}

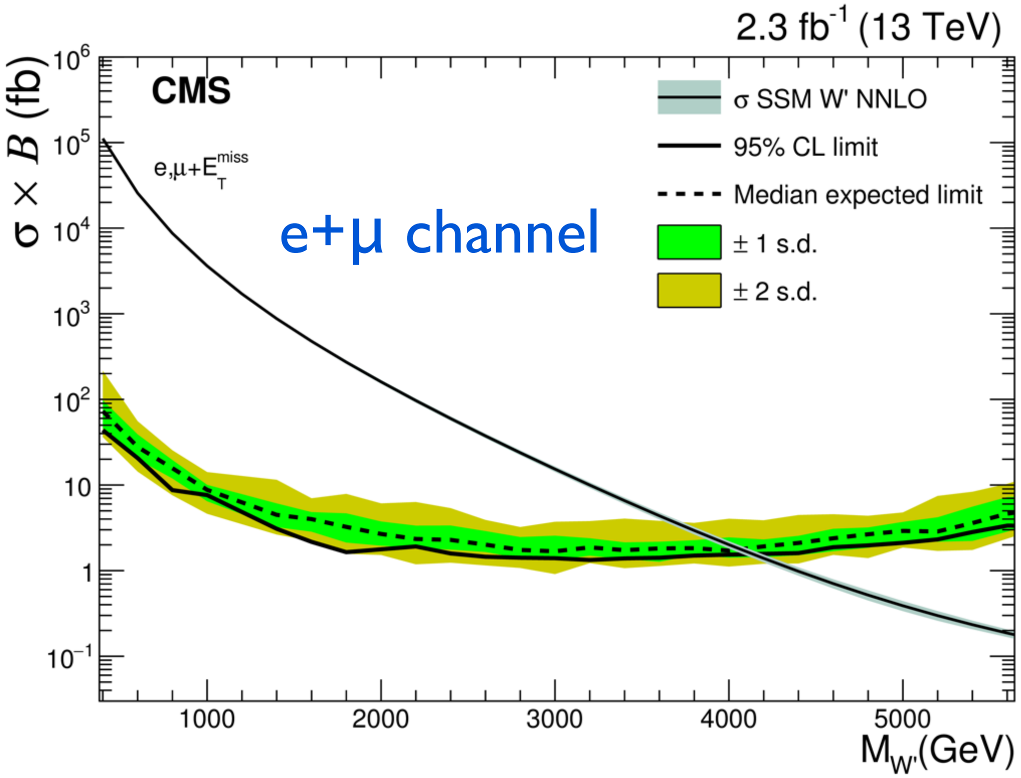
W’→e/μ/τ_{had}+MET

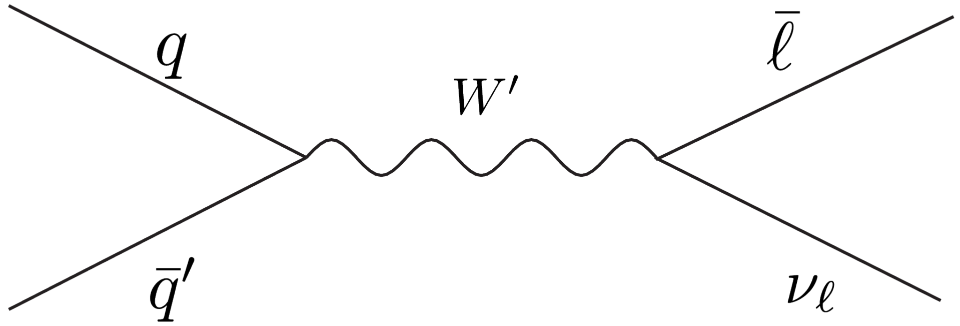
2.3 fb^{-1}

2015 data

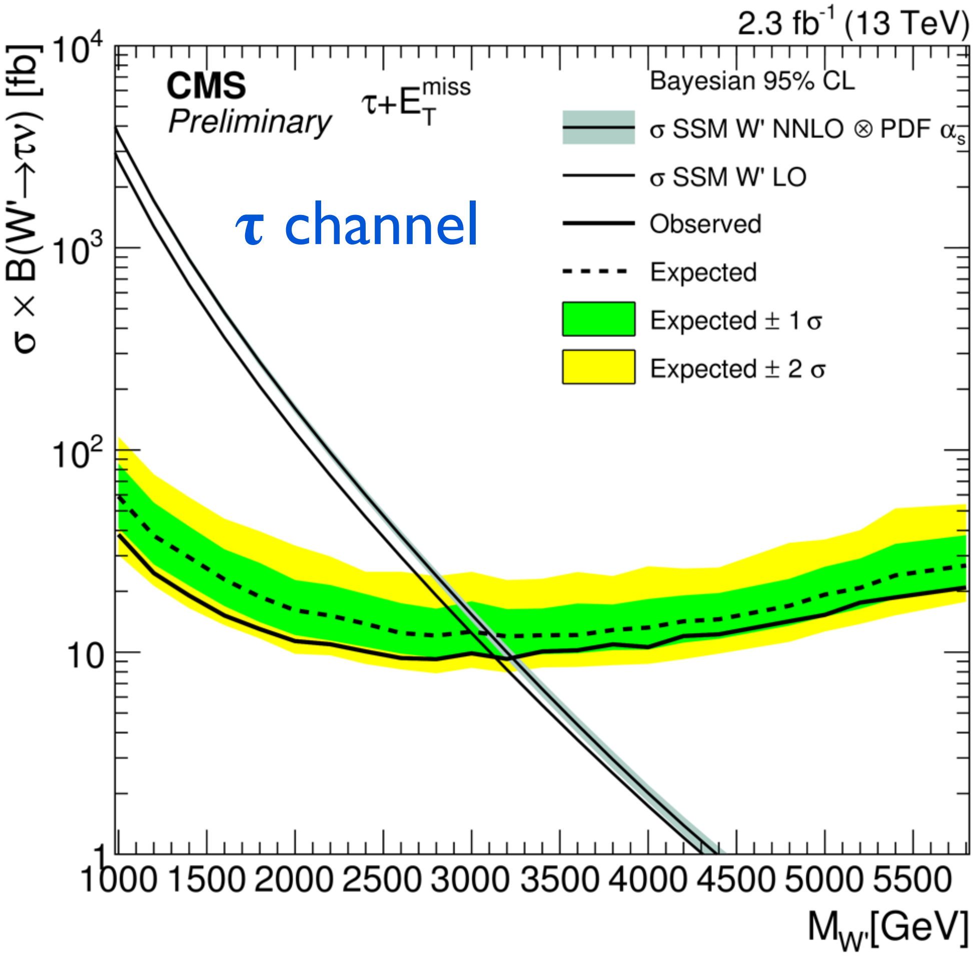
Theoretical Interpretation

- Sequential Standard Model (SSM) predicts new massive boson W’
- Same couplings as SM W boson, but decays to bosons (W, Z, H) assumed to be suppressed
- W’→tb allowed if W’ sufficiently massive
- No interference with SM W boson





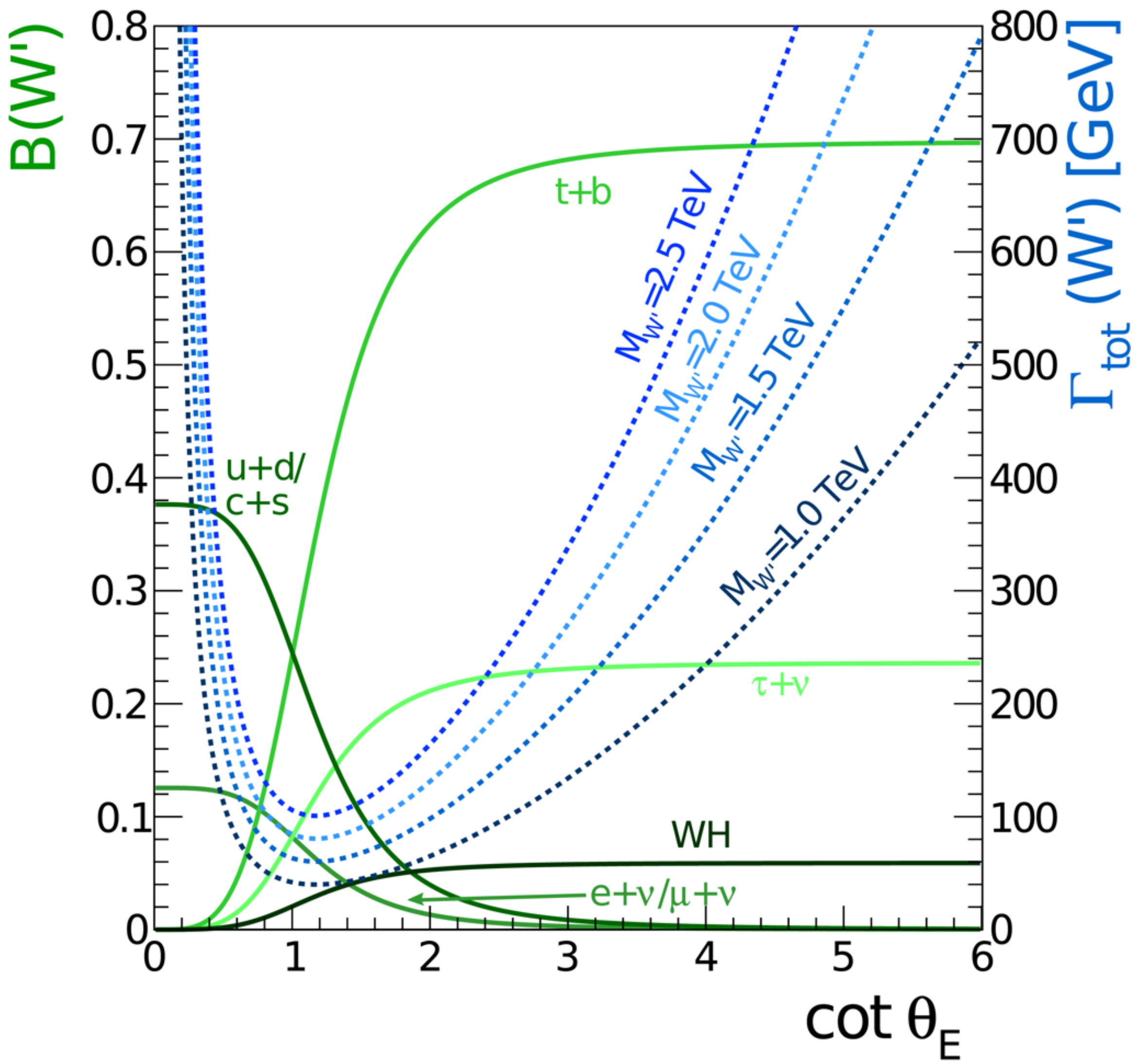
	SSM W’ lower limit on mass
e+μ channel	4.1
τ channel	3.3

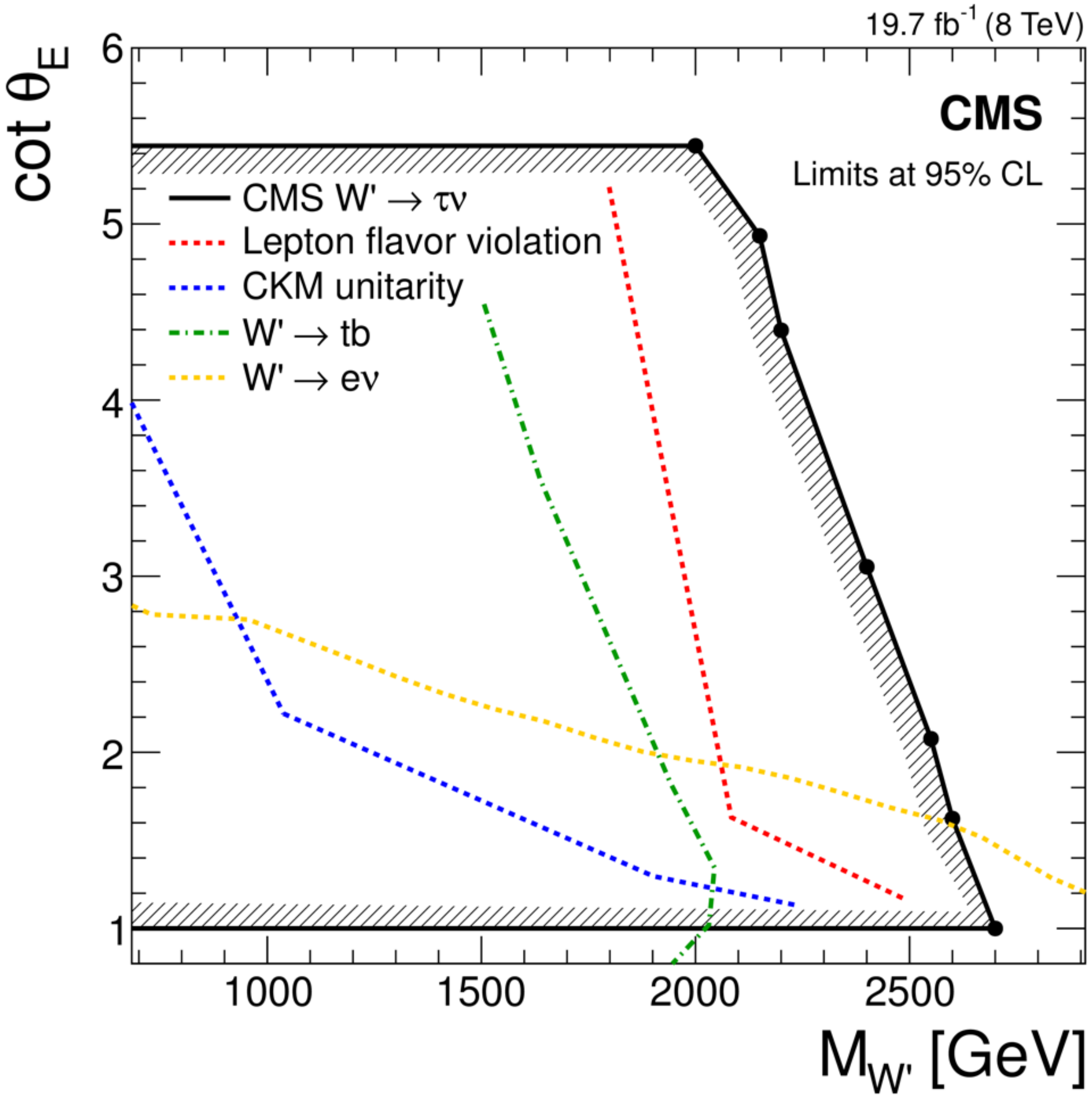


W’→τ_{had}+MET: Enhanced coupling to 3rd generation

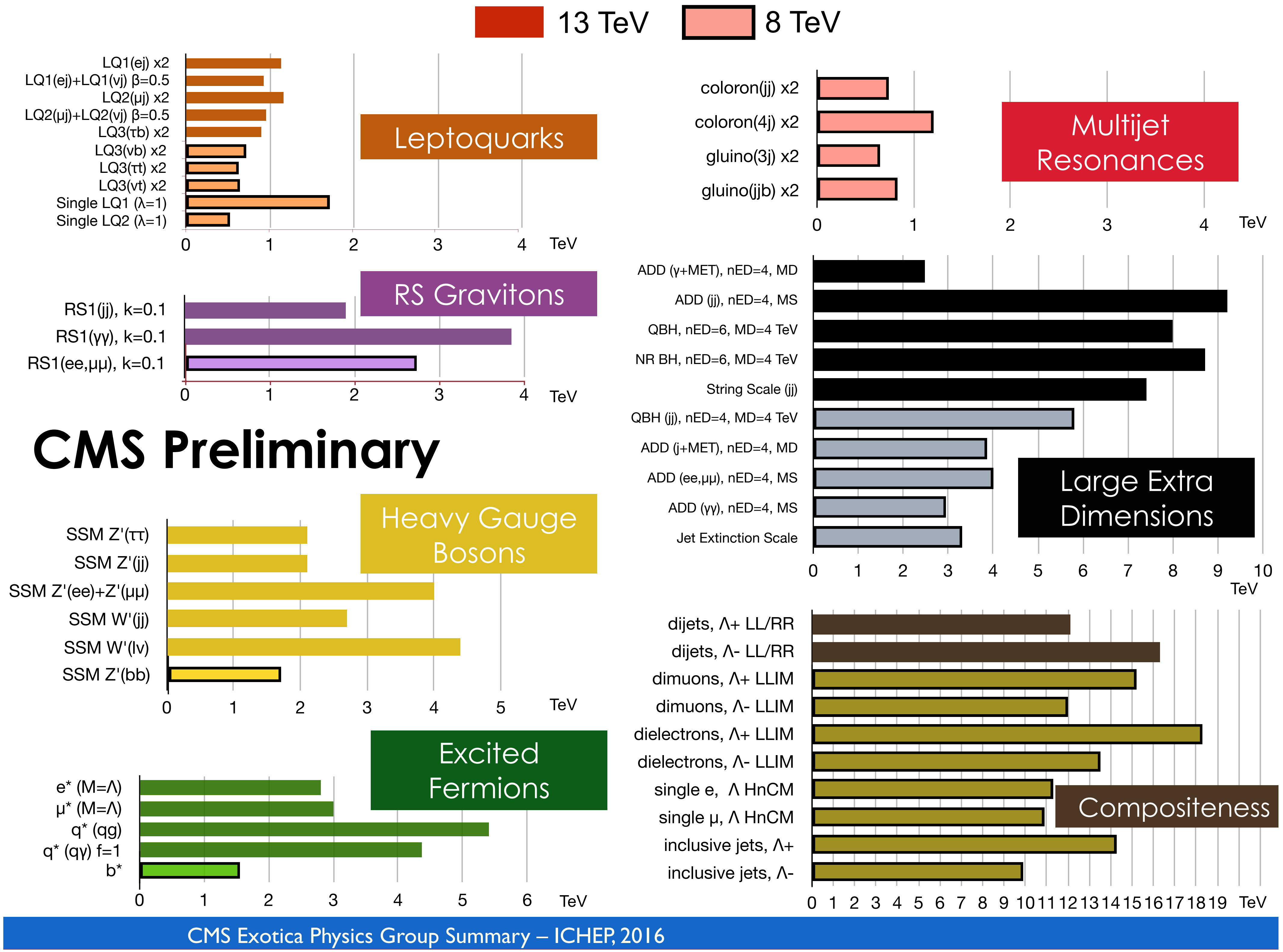
- W’→τ_{had}+MET search allows to test models with enhanced coupling to 3rd generation
- Light SU(2)$_l$ (couples to 1st and 2nd generation) and a heavy SU(2)$_h$ (couples to 3rd generation)→ mixing angle θ_E
- SM-like SU(2)$_W$ and extended group SU(2)$_E$ exist → SU(2)$_E$ gives rise to W’

$$\Gamma_{W'} = \Gamma_{Z'} = \Gamma_{W'}^{SSM} \times \frac{(4+\frac{1}{4})\cot^2\theta_E + 8\tan^2\theta_E}{12+\frac{1}{4}}$$





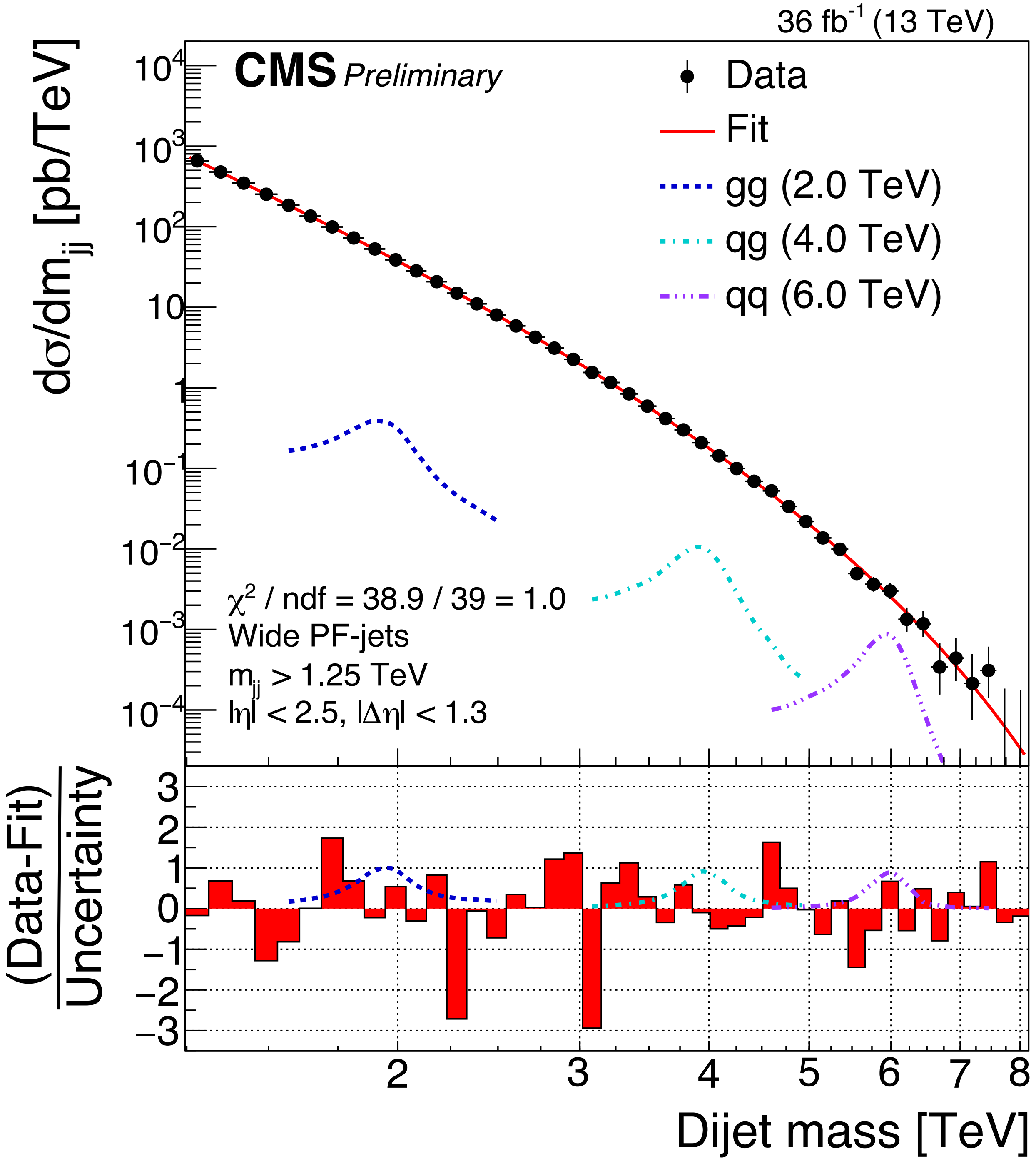
Searches in many other channels



Null results so far

Where is new physics hiding? (1)

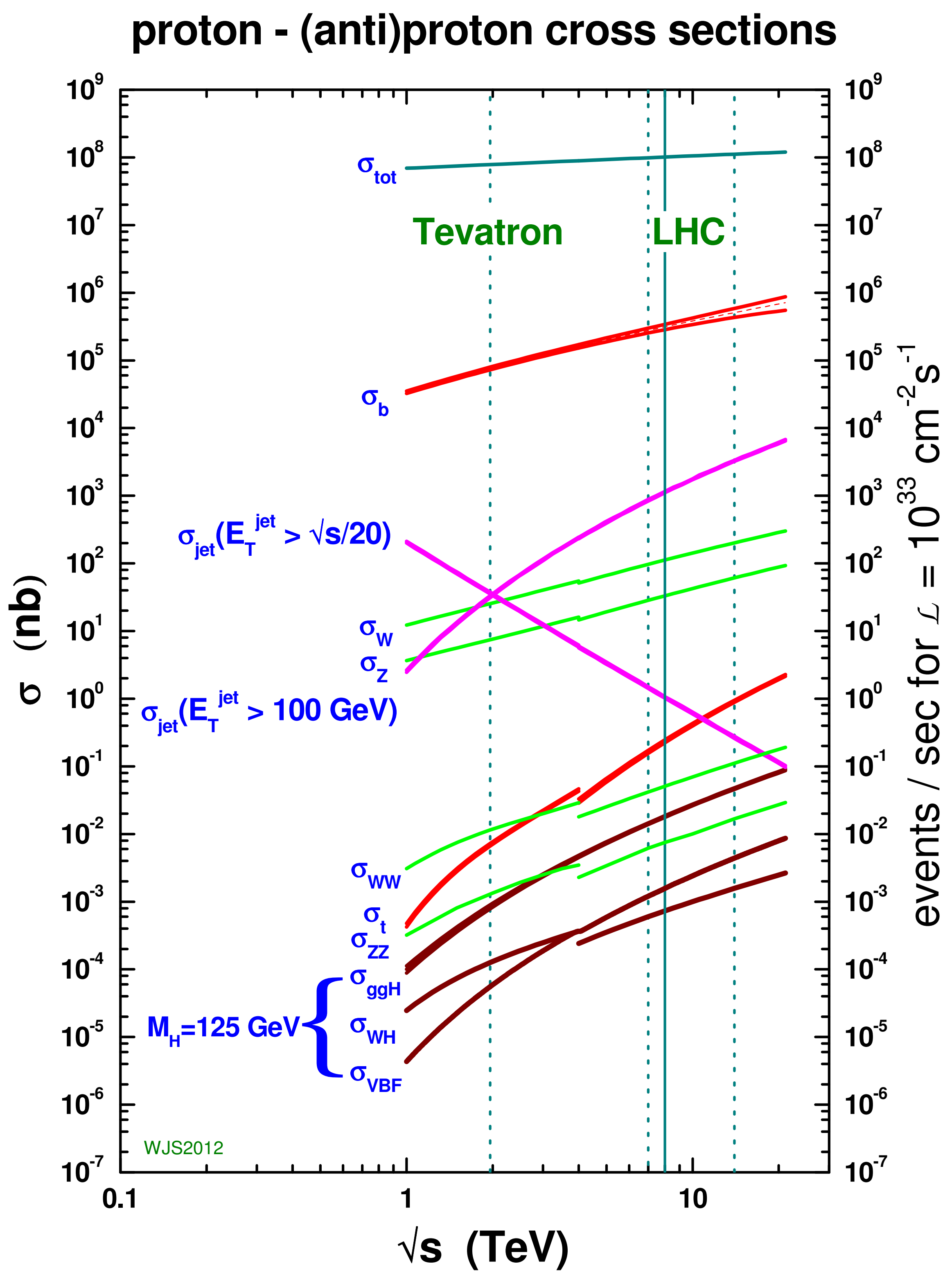
- Many searches can't probe low / intermediate masses because of trigger threshold
- One prime example is di-jet resonance search
- Search starts from ~1.2 TeV (using nominal triggers)



Why trigger threshold is an issue in LHC ?

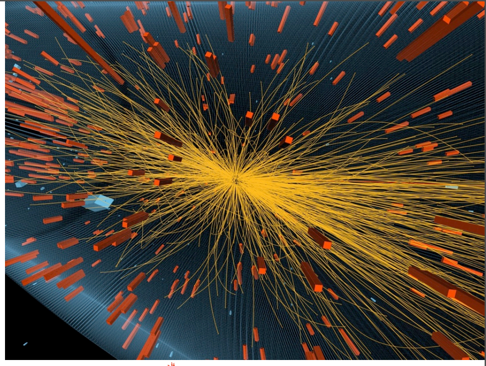
Why trigger threshold is an issue in LHC ?

- At instantaneous luminosity of $1.2\text{X}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$, LHC produces ~1 billion p-p collisions per second
- To save all these collision events, CMS would need to read, process, transfer, and store, tens of TB per second
- Do we even need such large amount of data ?
- Interesting processes are much rarer than the p-p scattering !
- Filter out un-interesting events
  - TRIGGER !
- End up selecting events with high-pT objects



A detour to CMS trigger system

- LHC collide proton bunches each 25 ns, with rate up to 40 MHz
- CMS experiment uses a two-level trigger system to reduce the data volume
- Level 1 (L1) Trigger
    - hardware-based, fast read-out of detector with coarse granularity.
    - 40 MHz→L1→100 kHz.
    - Only simplified event information available (no tracker information).
- High Level Trigger (HLT)
    - Software-based (CMS software written in C++), full readout of detector with full granularity
    - 100 kHz→HLT→1 kHz.
- Events accepted by HLT are transferred to Tier-0, reconstructed offline (prompt RECO) and stored world-wide.
    - Performance of HLT quite close to the offline reconstruction
    - Similar algorithms and calibrations, optimized for speed

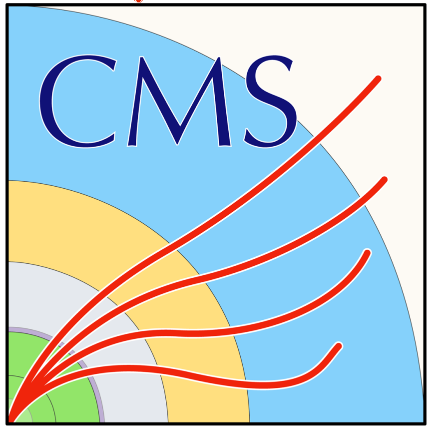


40 MHz

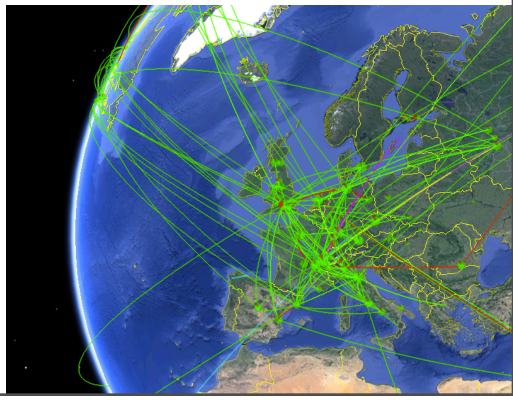
L1

100 kHz

HLT



1 kHz
Offline
reconstruction



Triggers *designed for physics analysis*

L1 triggers (some examples)

L1_SingleMu22

L1_SingleEG34

L1_SingleTau120er

L1_DoubleMu_12_5

L1_SingleJet170

L1_HTT300

L1_DoubleEG_23_10

High Level triggers (some examples)

HLT_Mu50

HLT_Photon175

HLT_PFJet450

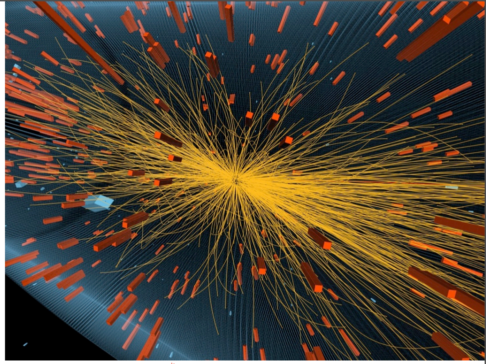
HLT_PFHT900 ← di-jet search

HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90

HLT_DoubleMu38NoFiltersNoVtx

HLT_VLooseIsoPFTau140_Trk50_eta2p1

Events that are not selected by trigger system are lost, **forever**!

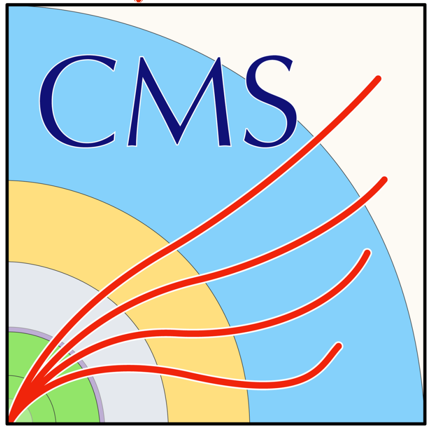


↓ 40 MHz

L1

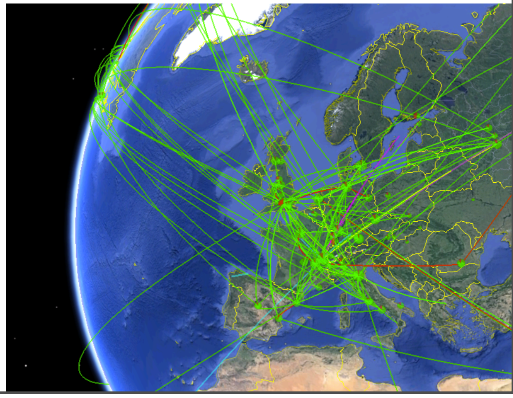
↓ 100 kHz

HLT



↓ **1 kHz**

Offline reconstruction



Can we still probe low mass di-jet resonances ?

YES. In two ways:

- Require a high p_T ISR jet or photon, which helps to surpass trigger threshold
  - Most sensitive in low masses
    - 50-250 GeV (ISR+merged di-jet)
    - 250-600 GeV (ISR+resolved di-jet)
- **Data scouting: new paradigm in trigger**
  - Most sensitive in intermediate masses
    - 600 GeV-1.6 TeV

di-jet+ISR	**Data scouting**	Usual di-jet search
<600	600-1600	>1600

→ M_{jj} in GeV

The actual limitation...

We are limited by

Trigger Bandwidth = Event Rate × Event Size

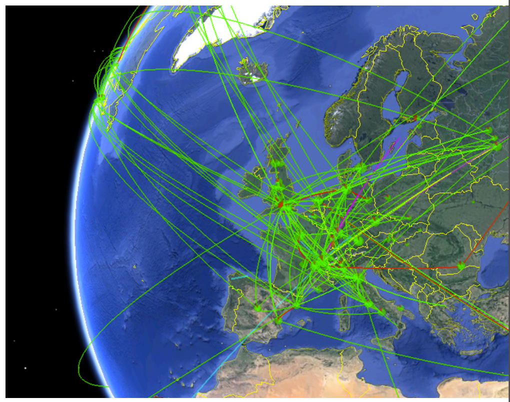
~1 kHz × ~1 MB

≈1 GB/sec

HLT

1 kHz

Offline reconstruction



A way out...

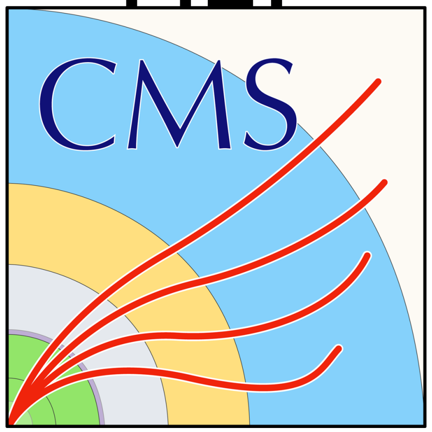
Trigger Bandwidth = Event Rate × Event Size

~1 kHz × ~1 MB

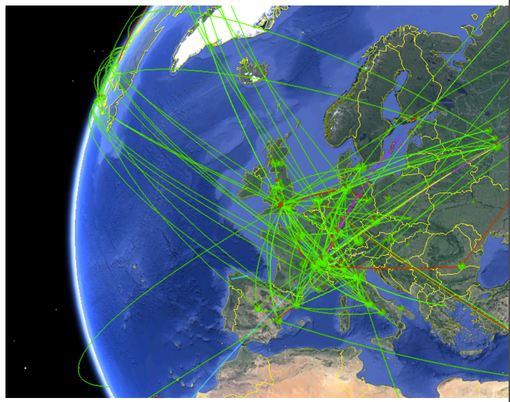
If we want to increase rate (i.e. decrease threshold)

We need to decrease event size

HLT



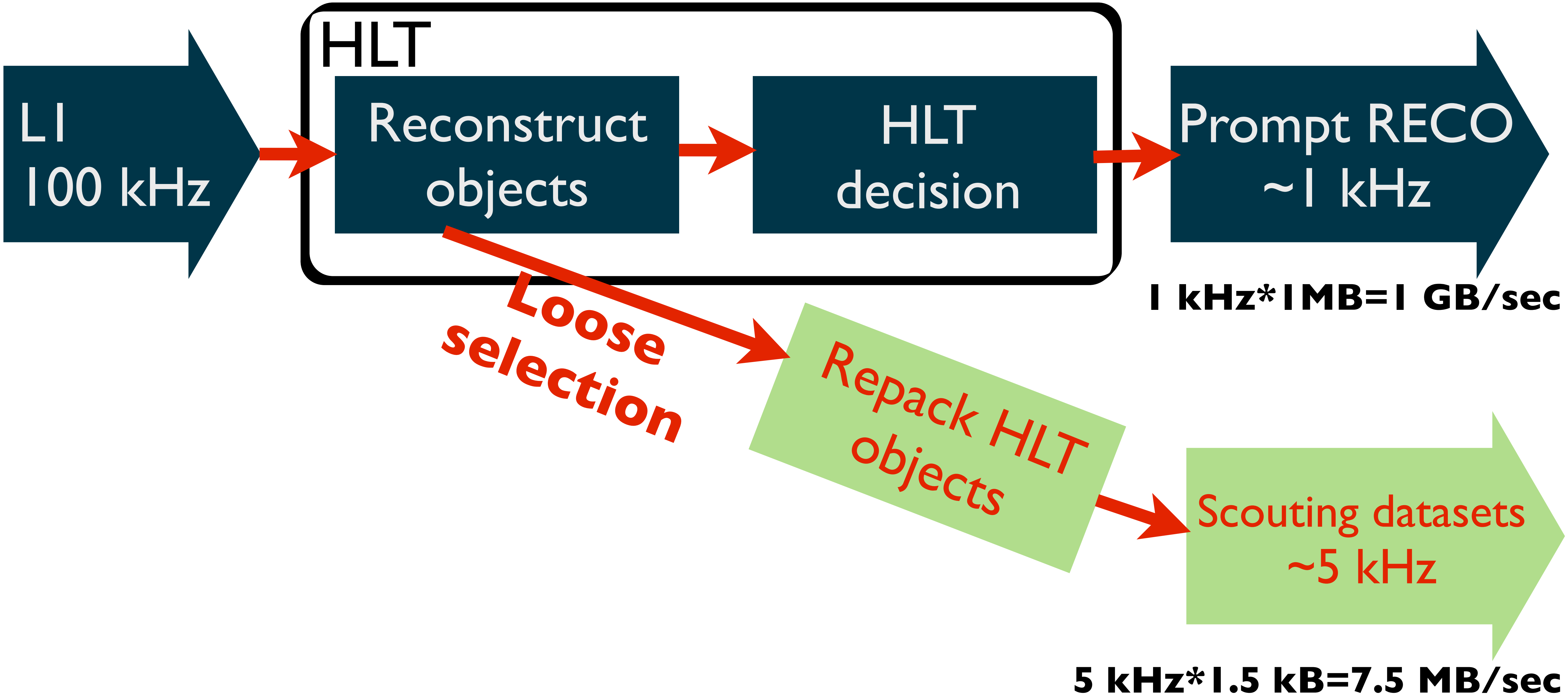
1 kHz Offline reconstruction



This is the idea of data scouting

For di-jet, dropping everything else except calo-jet, MET, primary vertex allows to go from HT=900 GeV to HT=250 GeV at the HLT level

Data Scouting



HLT

L1
100 kHz

Reconstruct objects

HLT decision

Prompt RECO
~1 kHz

1 kHz*1MB=1 GB/sec

Loose selection

Repack HLT objects

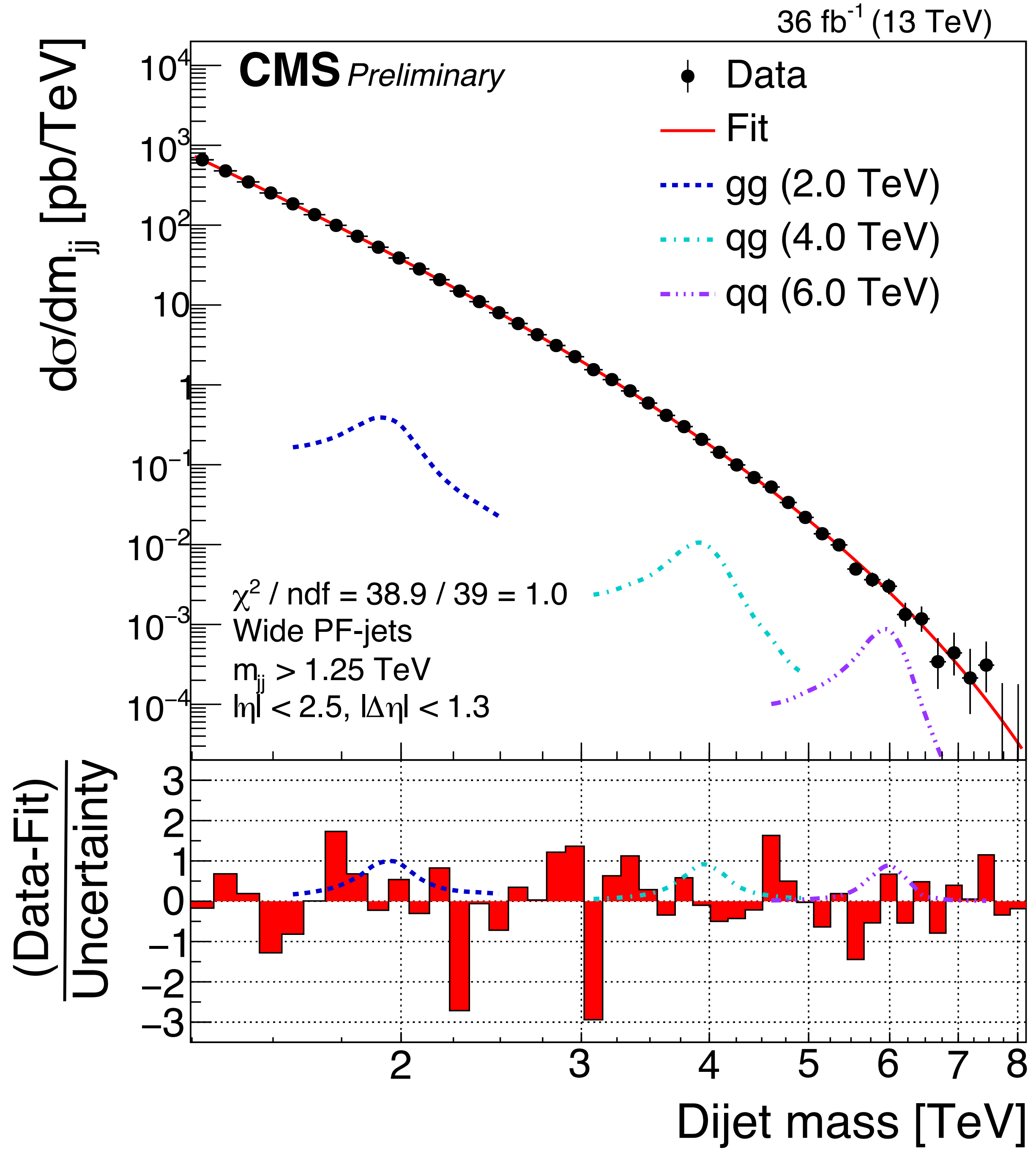
Scouting datasets
~5 kHz

5 kHz*1.5 kB=7.5 MB/sec

- In data scouting, we reconstruct at HLT level, all physics objects needed for an offline analysis
- After a loose trigger selection, the HLT objects are saved directly for offline use
- The events are not sent to prompt RECO, and no RAW data is saved

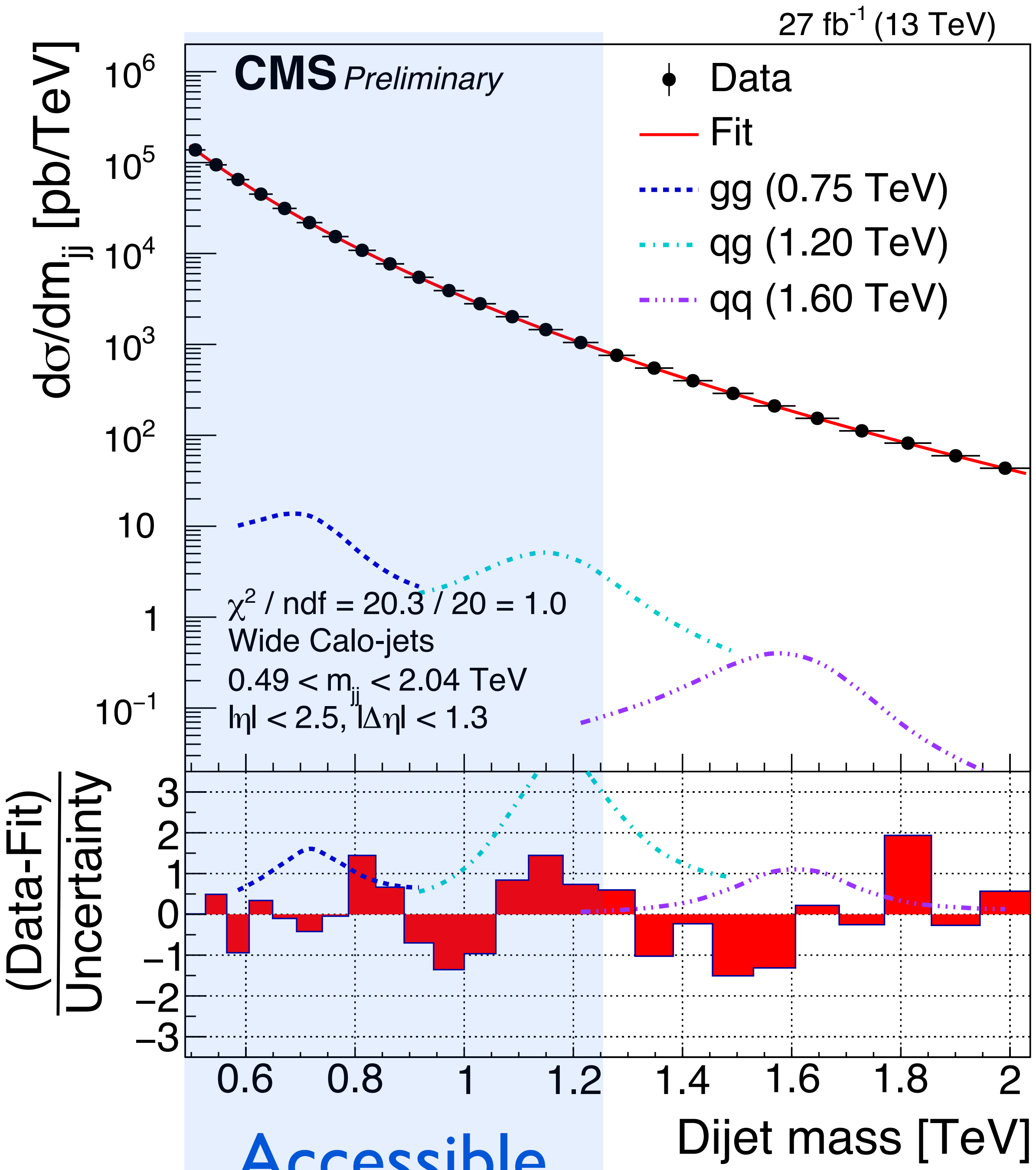
dijet search: nominal and scouting

HLT_PFHT900



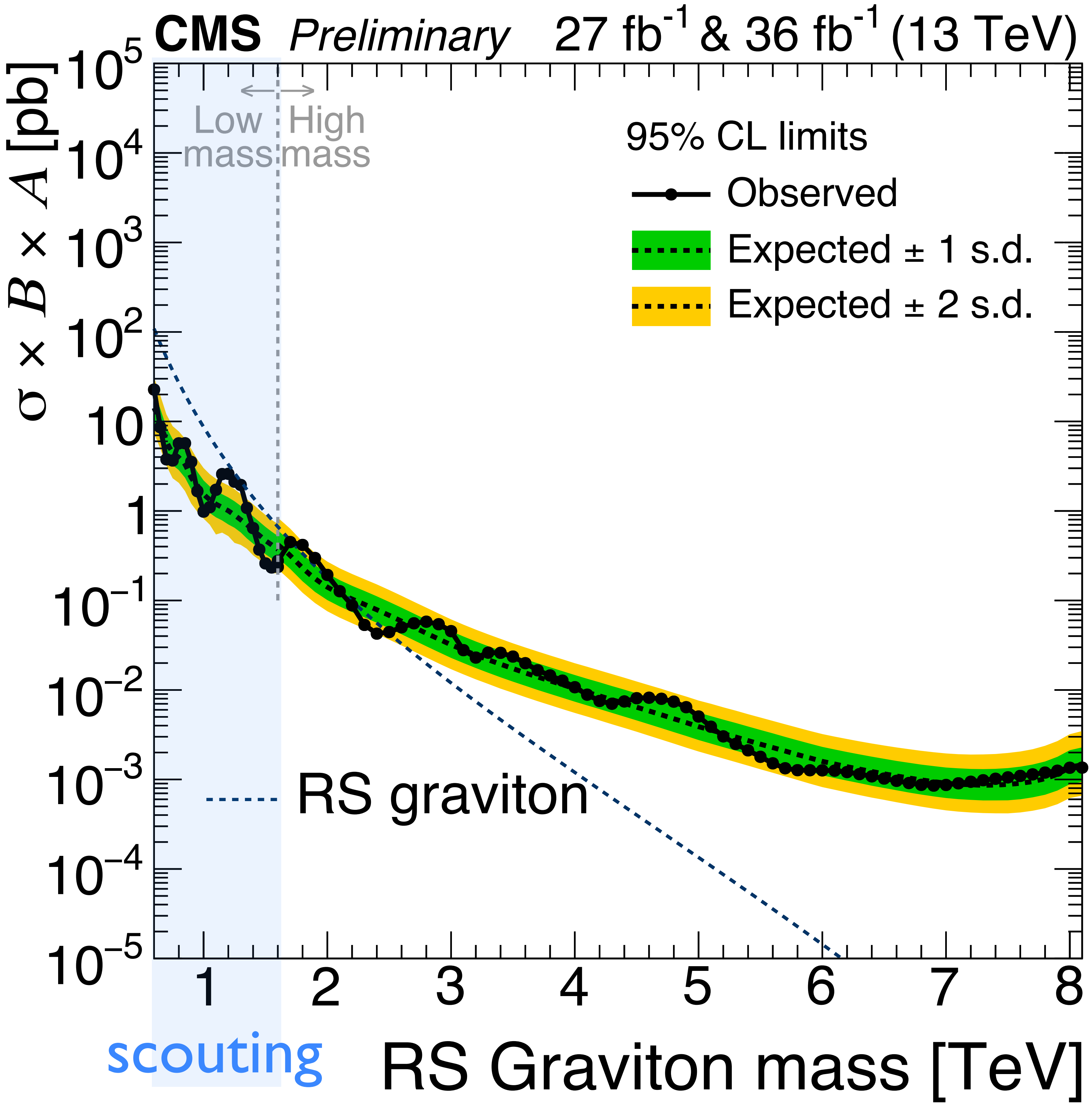
No excess found

DST_HT250_CaloScouting



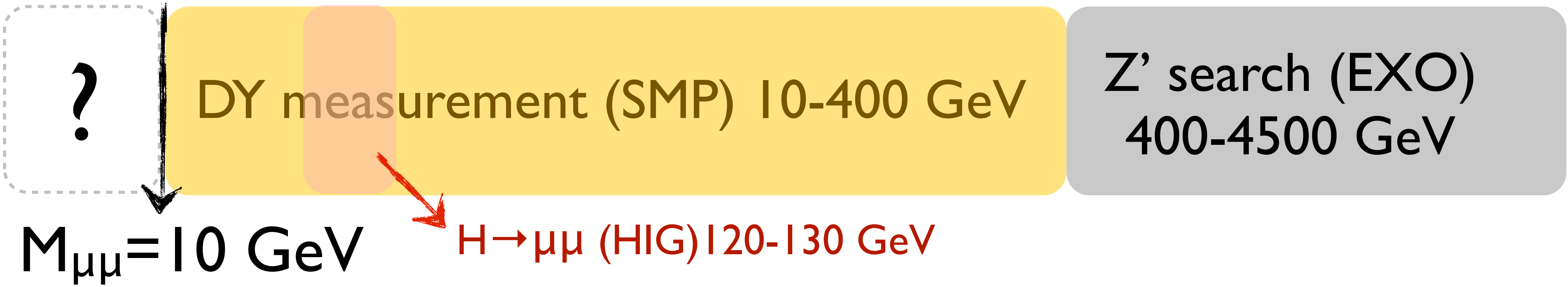
Accessible only by scouting

Di-jet limits



Going beyond dijet: *di-muon scouting*

- Until now, di-jet analysis is the only (public) application of scouting in CMS
- However, CMS has put major efforts in di-muon scouting recently
- With nominal triggers, CMS covers ~10 GeV-4.5 TeV di-muon masses
- Masses below 10 GeV not probed, no suitable trigger available
  - B-physics group has triggers focussing on low mass resonances, not useful for searches



?

DY measurement (SMP) 10-400 GeV

Z’ search (EXO) 400-4500 GeV

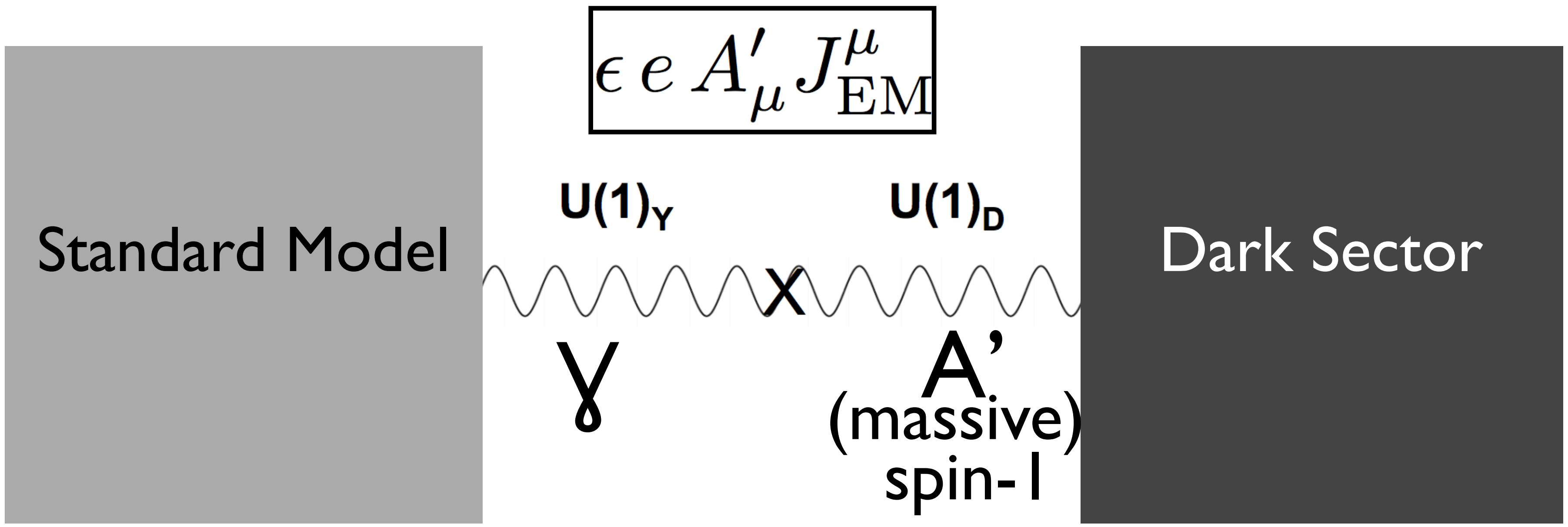
$M_{\mu\mu}=10$ GeV

$H\to\mu\mu$ (HIG)120-130 GeV

Theoretical Motivation *of di-muon scouting*

- Many dark matter models introduce new ‘dark’ sector
- Dark sector may contain new particles that do not couple directly to SM, but there are “portals” between dark sector and SM.
- Dark sectors with extra U(1), kinetic mixing with SM U(1), mixing strength ϵ
- Dark photons (A’) are the corresponding U(1) gauge bosons, mediating this dark force.
- Dark-photon phenomenology explained in arxiv1603.08926 by P. Ilten, Y. Soreq, J. Thaler, M. Williams, W. Xue

$$\boxed{A' \rightarrow \mu\mu}$$



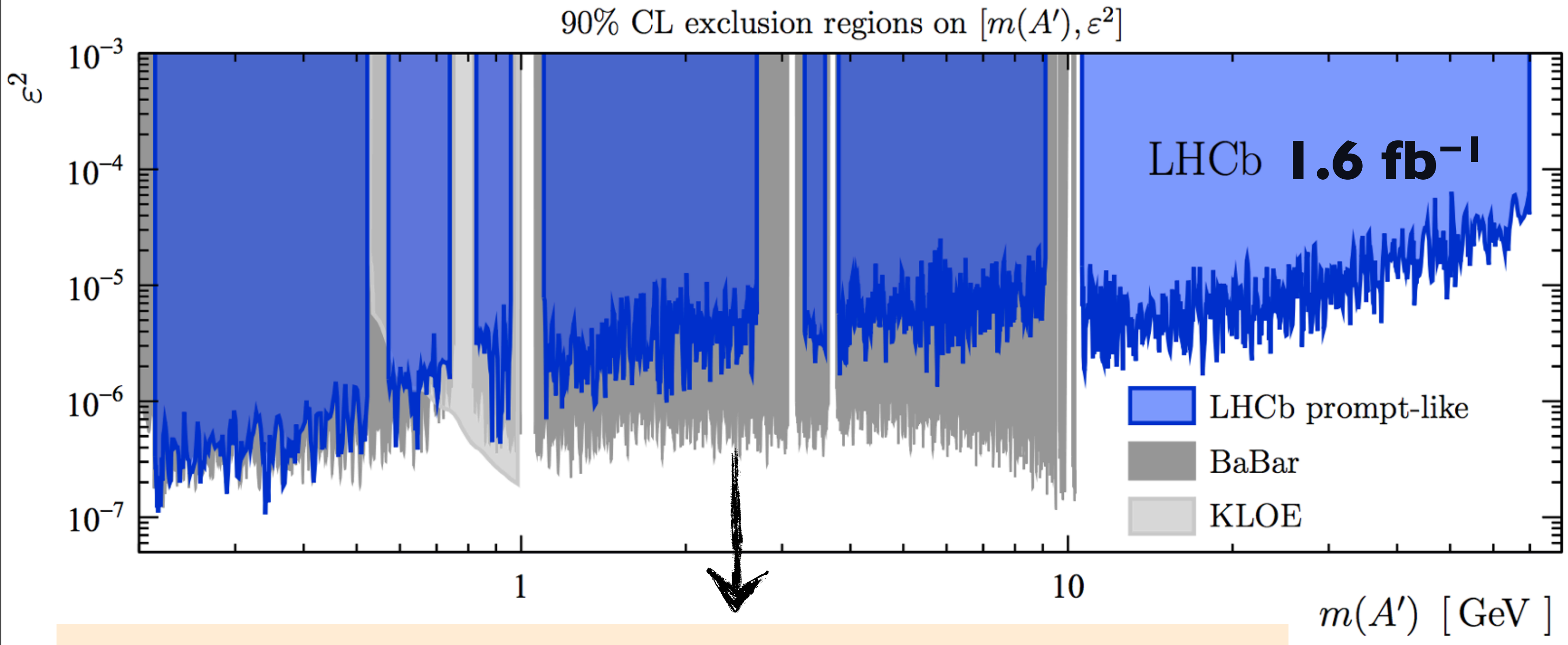
$$\boxed{\epsilon\, e\, A'_{\mu} J^{\mu}_{\mathrm{EM}}}$$

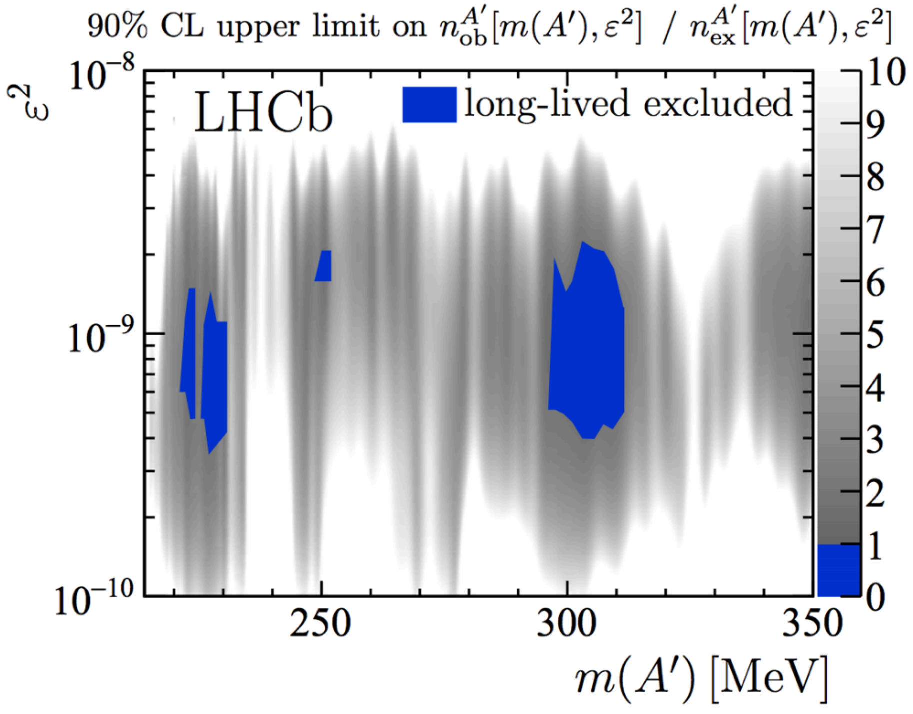
If ϵ is small, A’ can be long-lived

→displaced muon-pair

Previous searches of A'→μμ

LHCb collaboration arxiv1710.02867 (Oct 2017)





BABAR search: A'→μμ, ee using 514 fb^{-1} of data

Energy frontier capabilities are unique and complementary to those at Intensity frontiers

- CMS dark-photon search in di-muon channel: work-in-progress
- Expect similar or better sensitivity than LHCb
- Dedicated di-muon scouting trigger designed for prompt and displaced di-muon search, and placed online
- Aim for 2018 summer conference

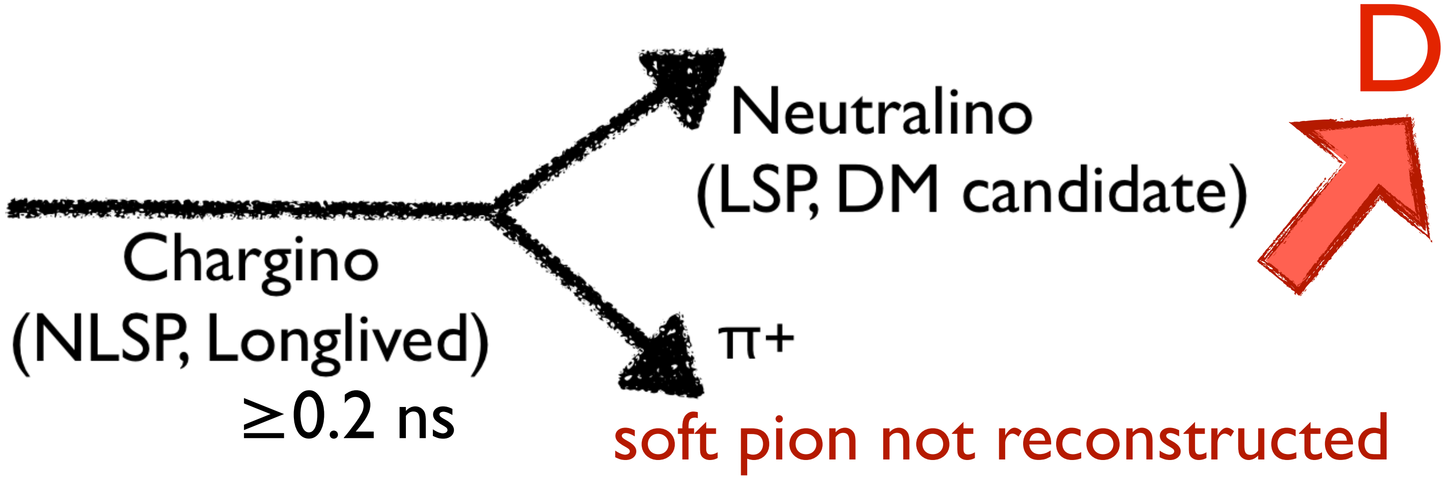
Where is new physics hiding? (II)

(I) Low mass

(II) Long-lived signatures

- Easy to miss unless dedicated effort is made
- Striking signatures in detector
- Often need special trigger

<u>One (exotic) example</u>



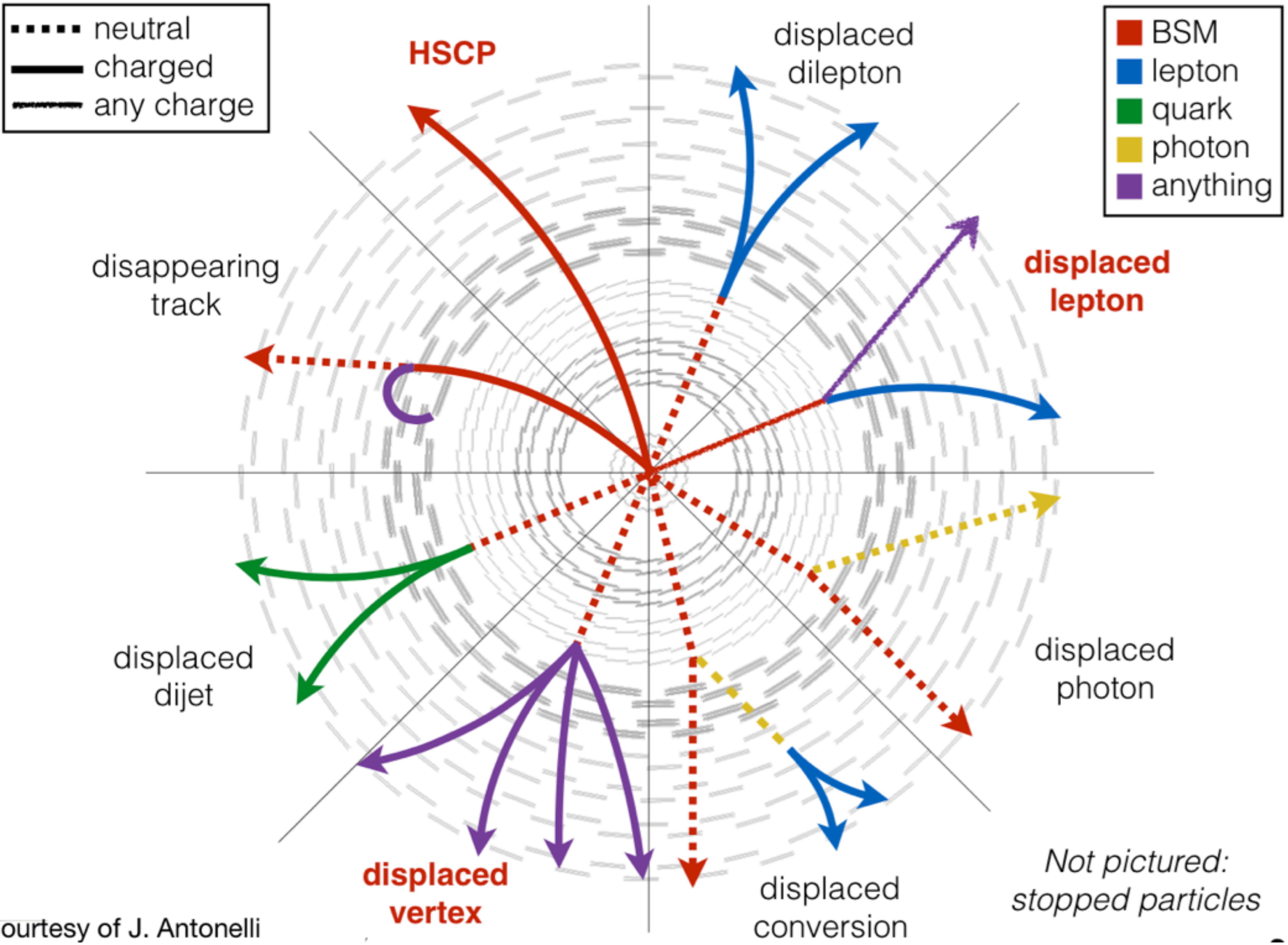
Disappearing track

(AMSB)

Constrained mass spectrum.

Masses of lightest chargino and lightest neutralino are nearly degenerate.

Longlived searches in CMS



Not pictured: stopped particles

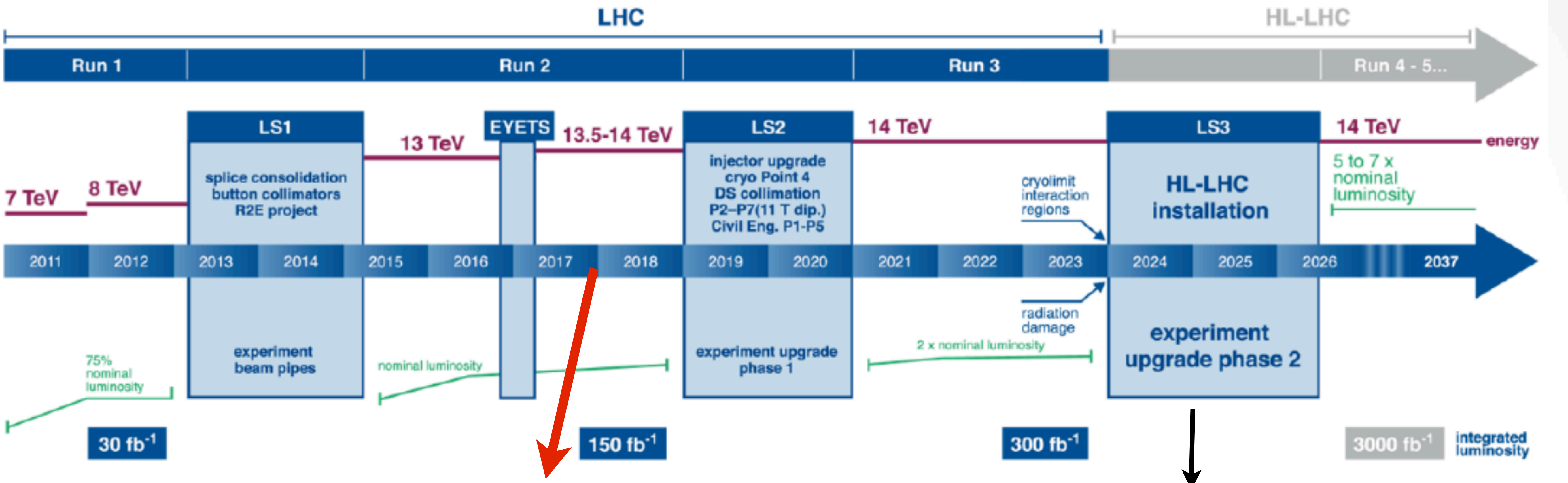
Courtesy of J. Antonelli

Null results so far. More long-lived searches planned.

What’s Next ?

- Wide program for new physics search in CMS.
  - Stringent limits on BSM scenarios
  - Development / extensive use of novel techniques
  - No hint of new particles until now

But, LHC has particle physics program until ~2040

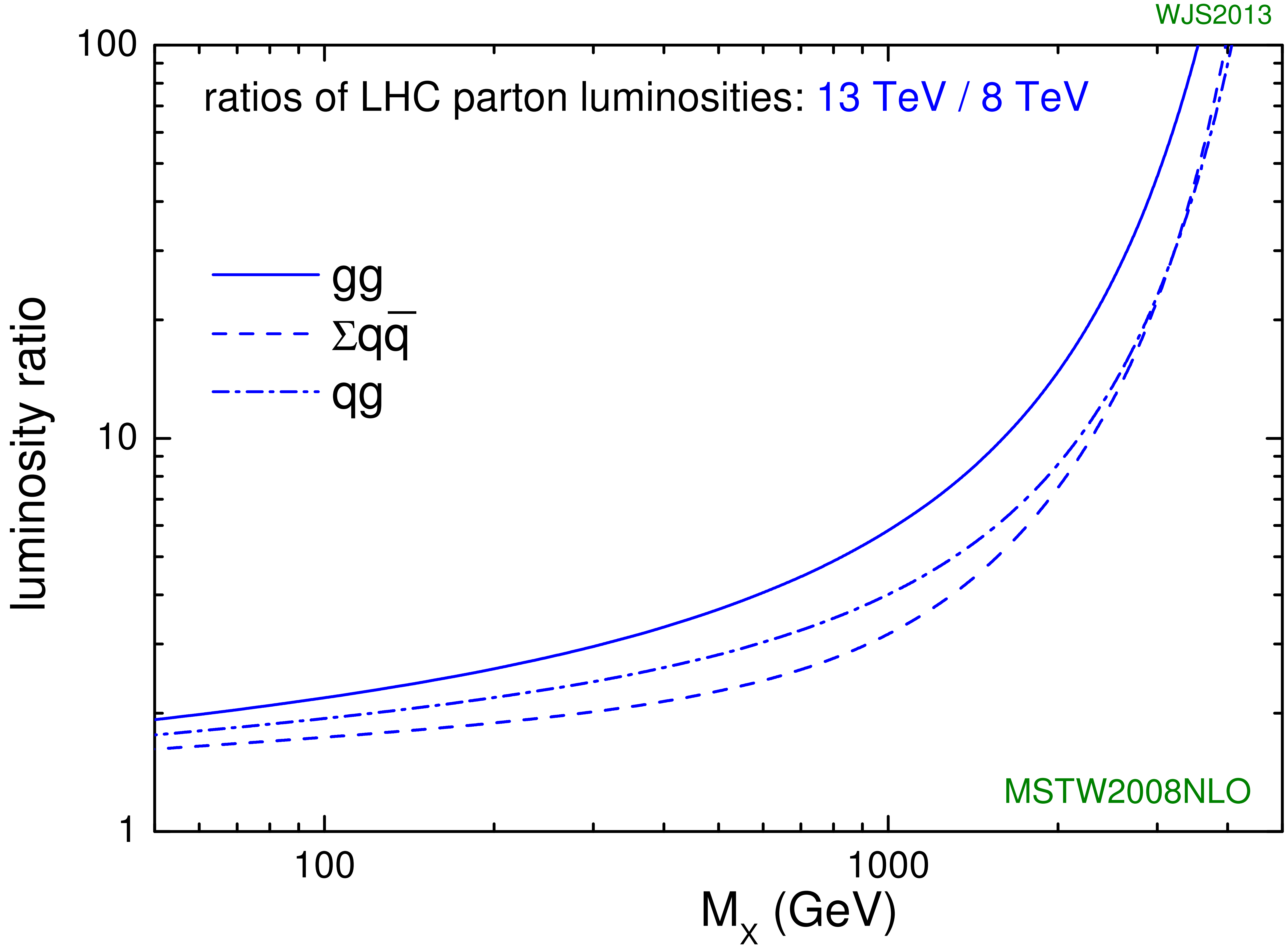


We are here

High-Luminosity LHC

Current amount of data is only a small part of full LHC data expected

Extra Slides


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

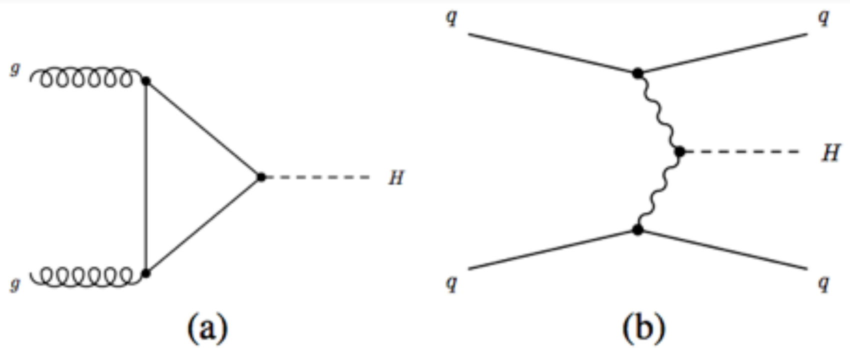


Figure 1: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) *gg*F and (b) VBF production processes.

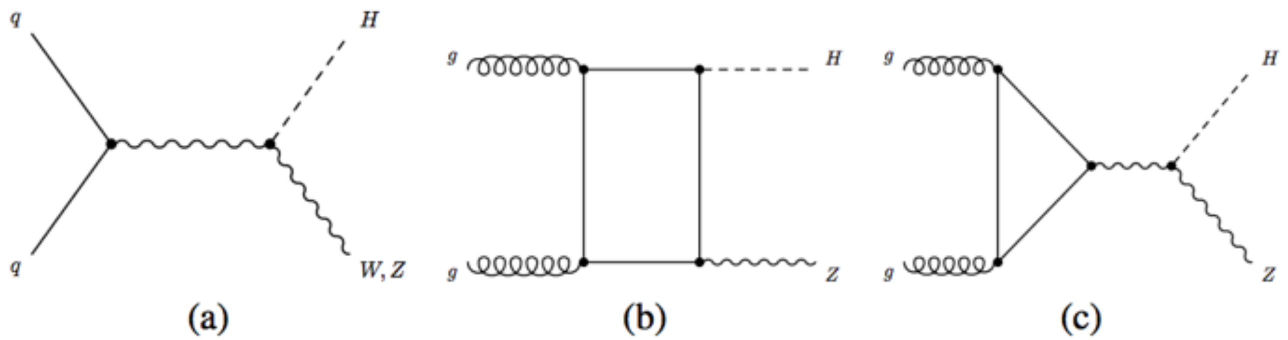


Figure 2: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) $qq \to VH$ and (b, c) $gg \to ZH$ production processes.

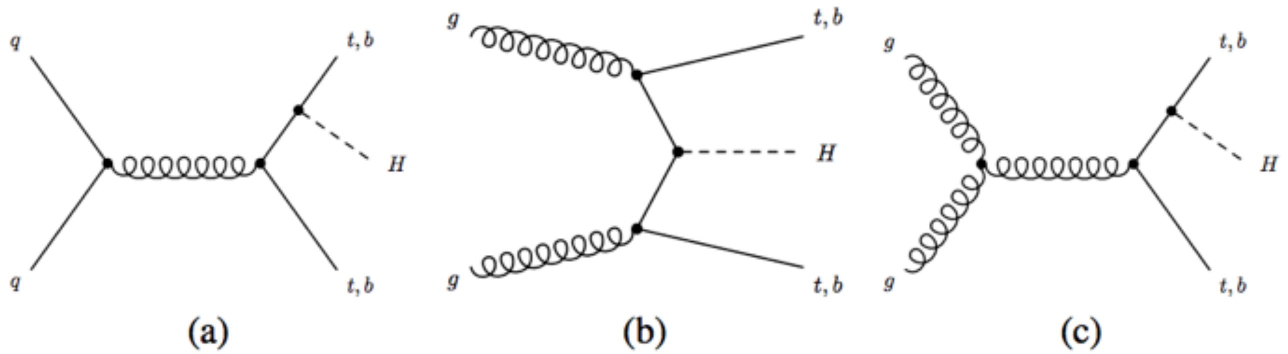


Figure 3: Examples of leading-order Feynman diagrams for Higgs boson production via the $qq/gg \to ttH$ and $qq/gg \to bbH$ processes.

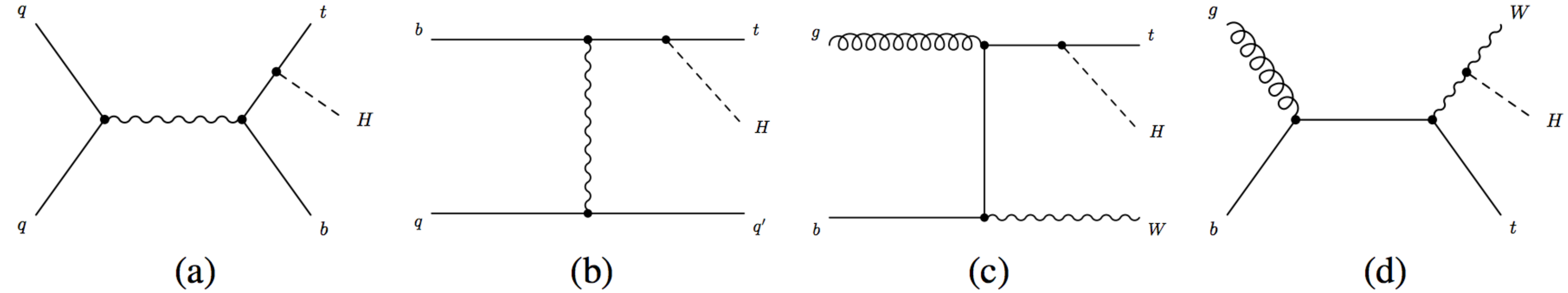
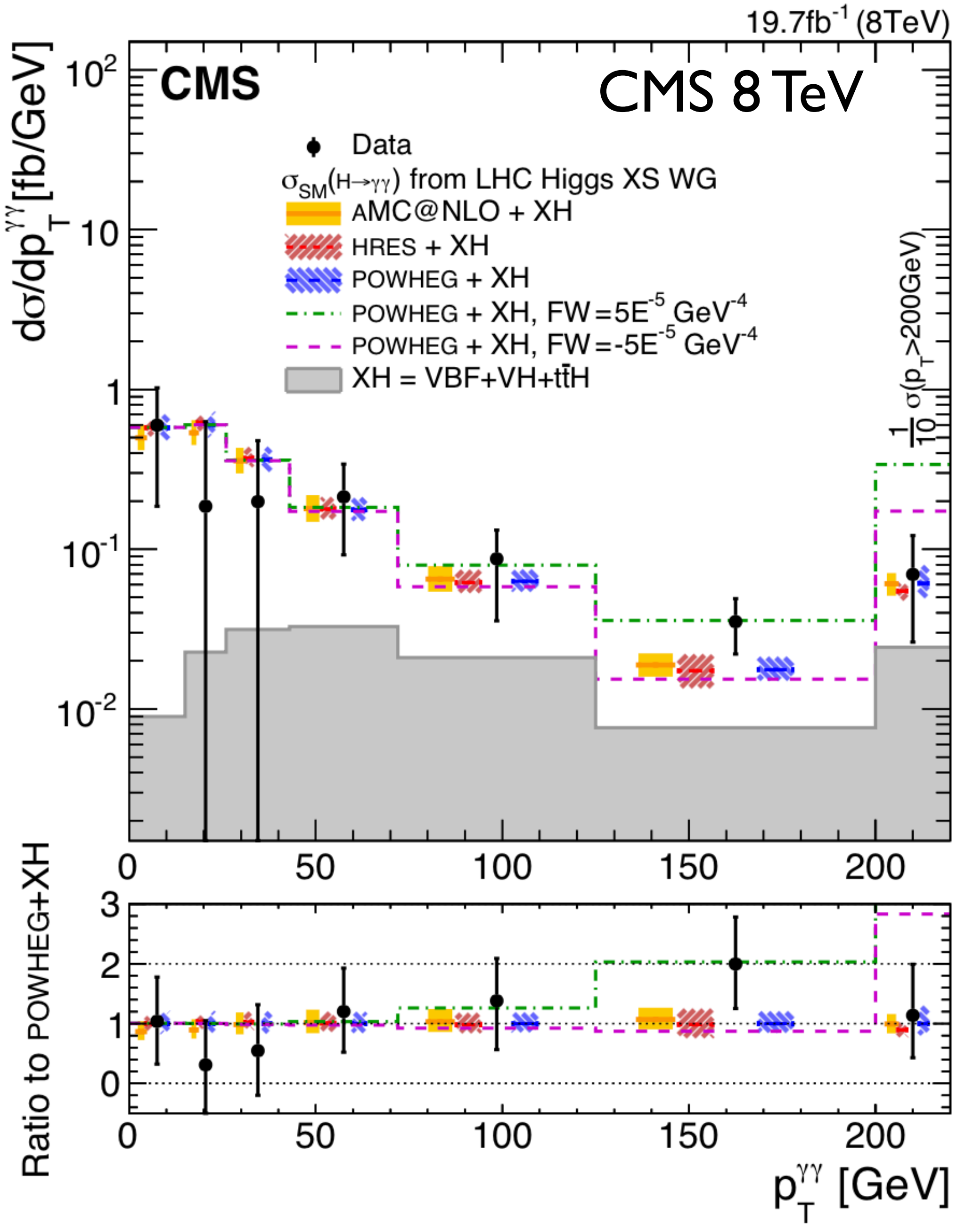
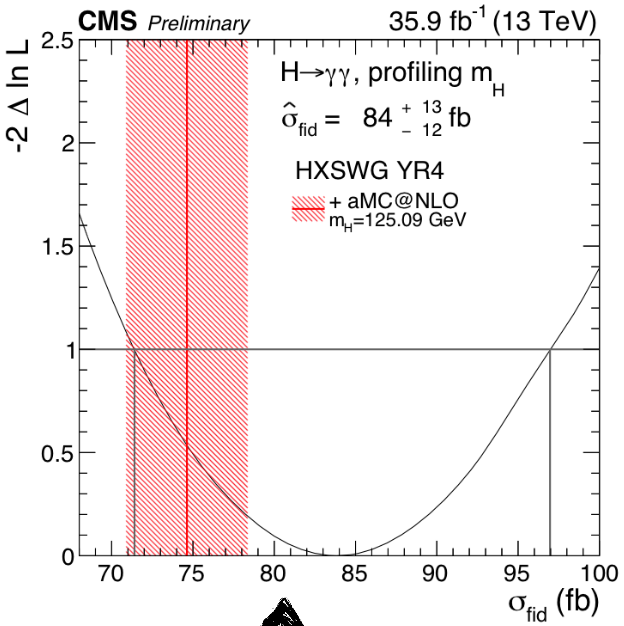
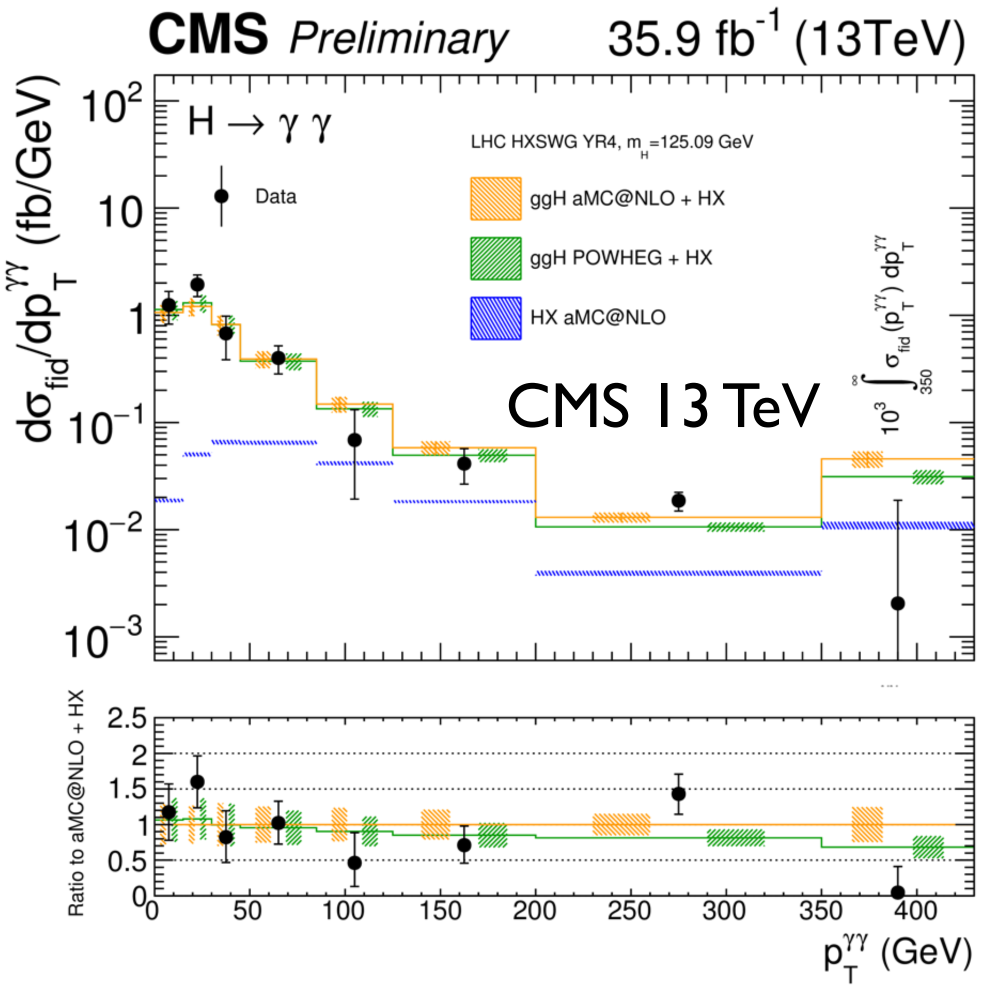


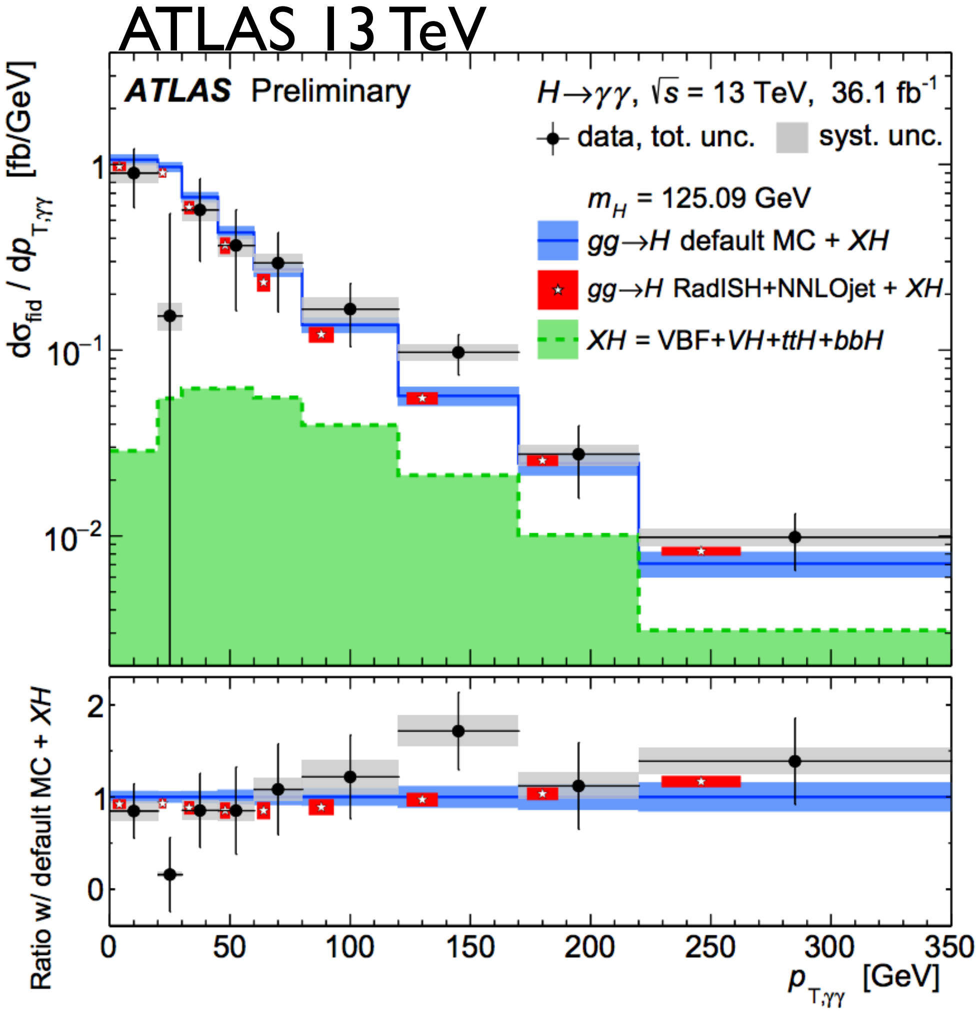
Figure 4: Examples of leading-order Feynman diagrams for Higgs boson production in association with a single top quark via the (a, b) tHq and (c, d) tHW production processes.

Higgs to diphoton differential cross section







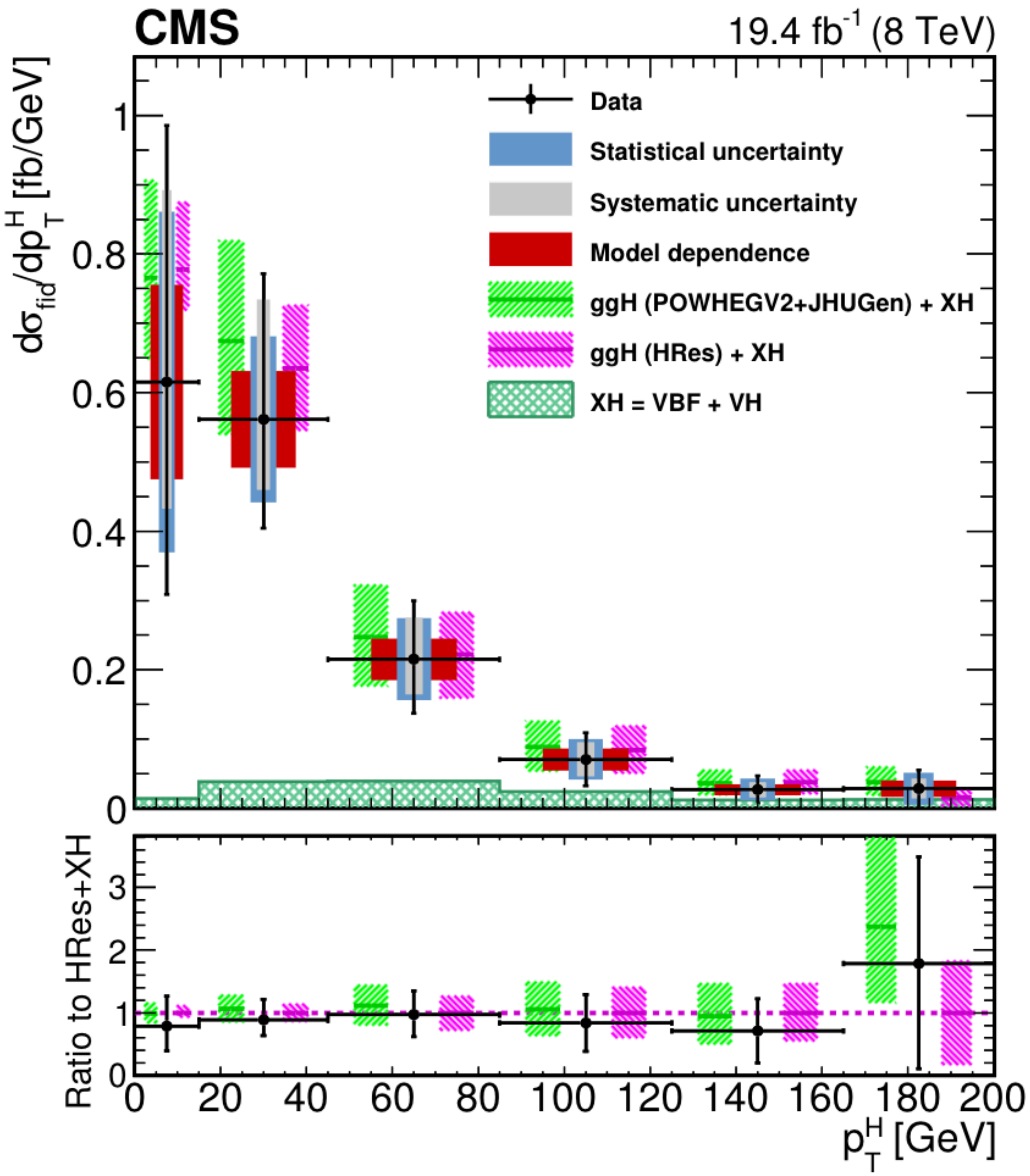


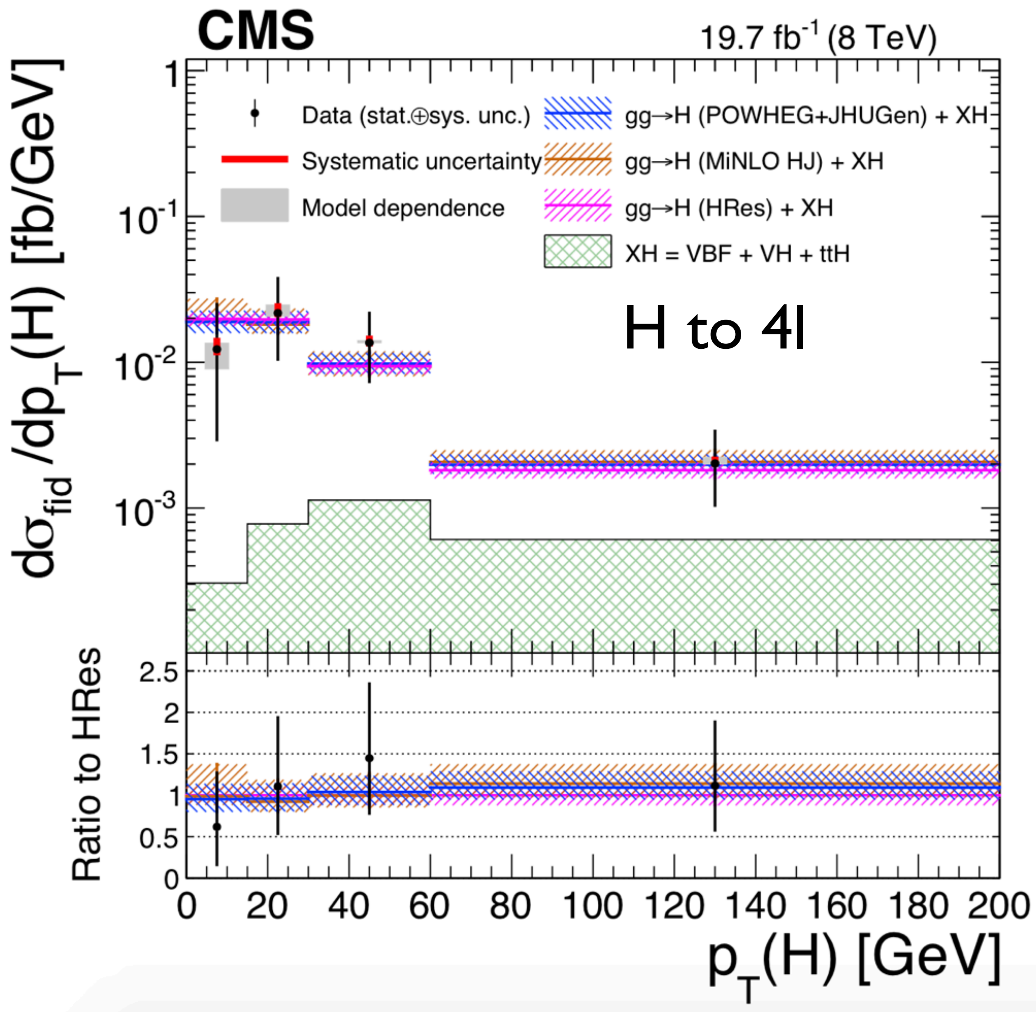
$$\boxed{\sigma_{\rm obs} = 32^{+10}_{-10}\,({\rm stat})^{+3}_{-3}\,({\rm syst})\ {\rm fb},}$$ CMS 8 TeV

$$\boxed{\hat\sigma_{\rm fiducial} = 84 \pm 11\ ({\rm stat}) \pm 7\ ({\rm syst})\ {\rm fb}}$$ CMS 13 TeV

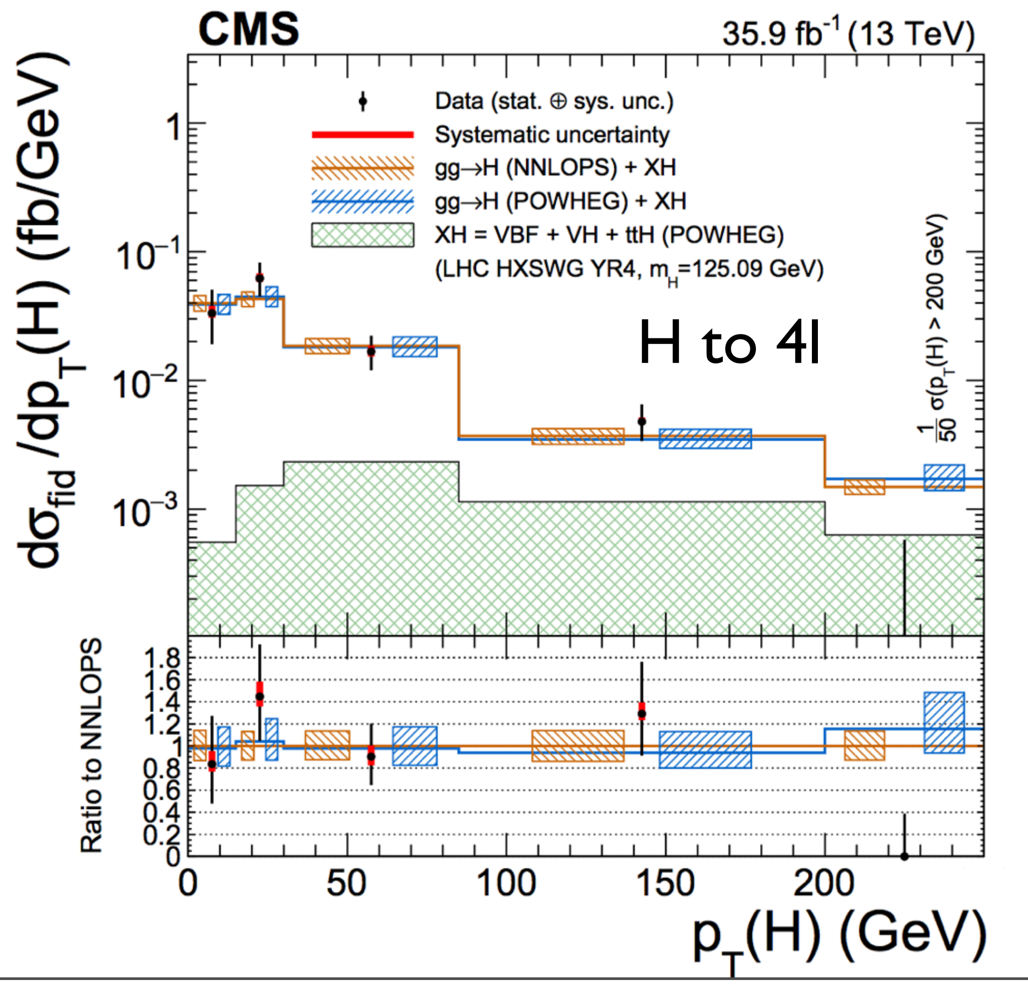
differential cross section

H to W(e)W(μ)





H to 4l

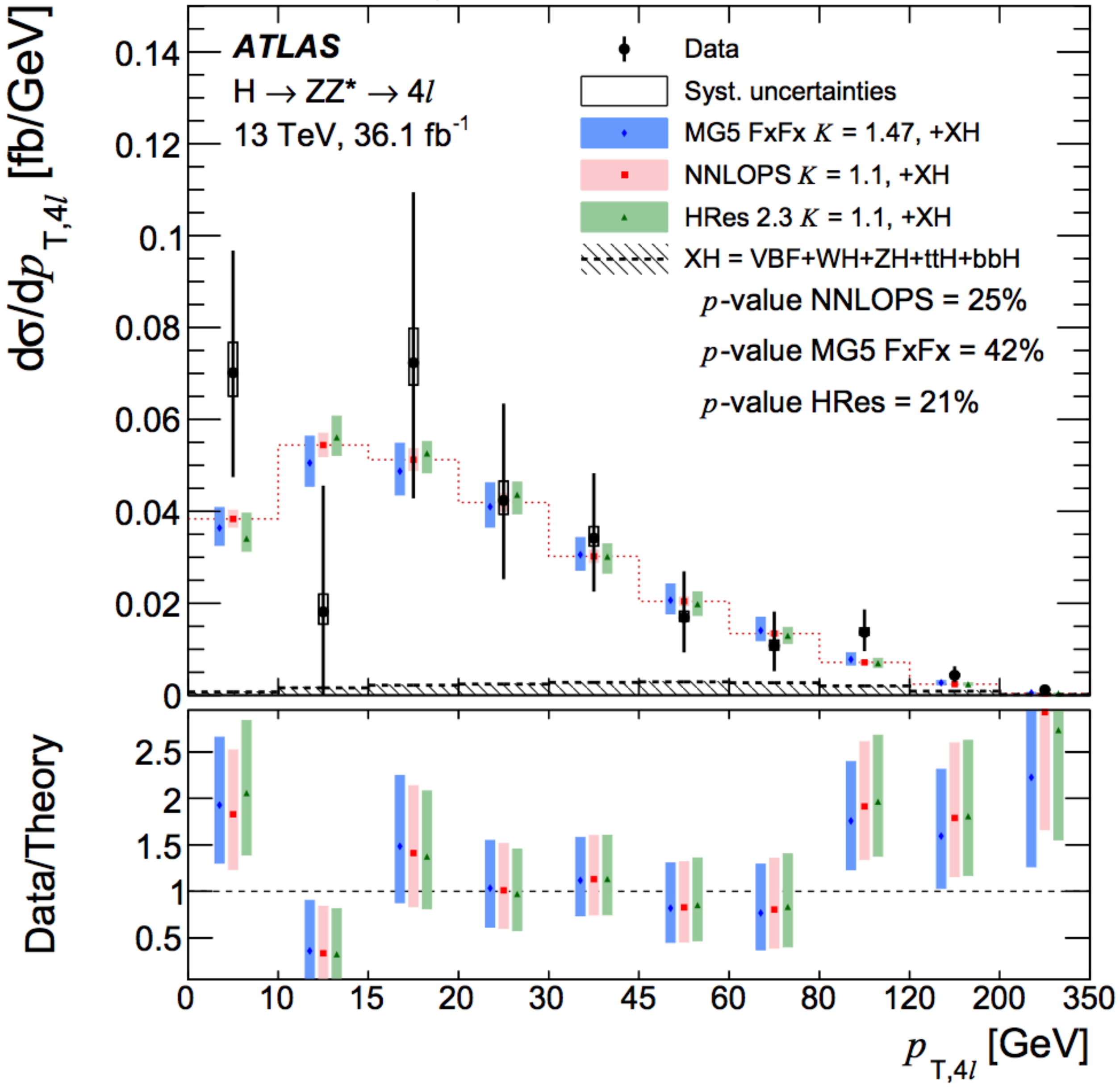


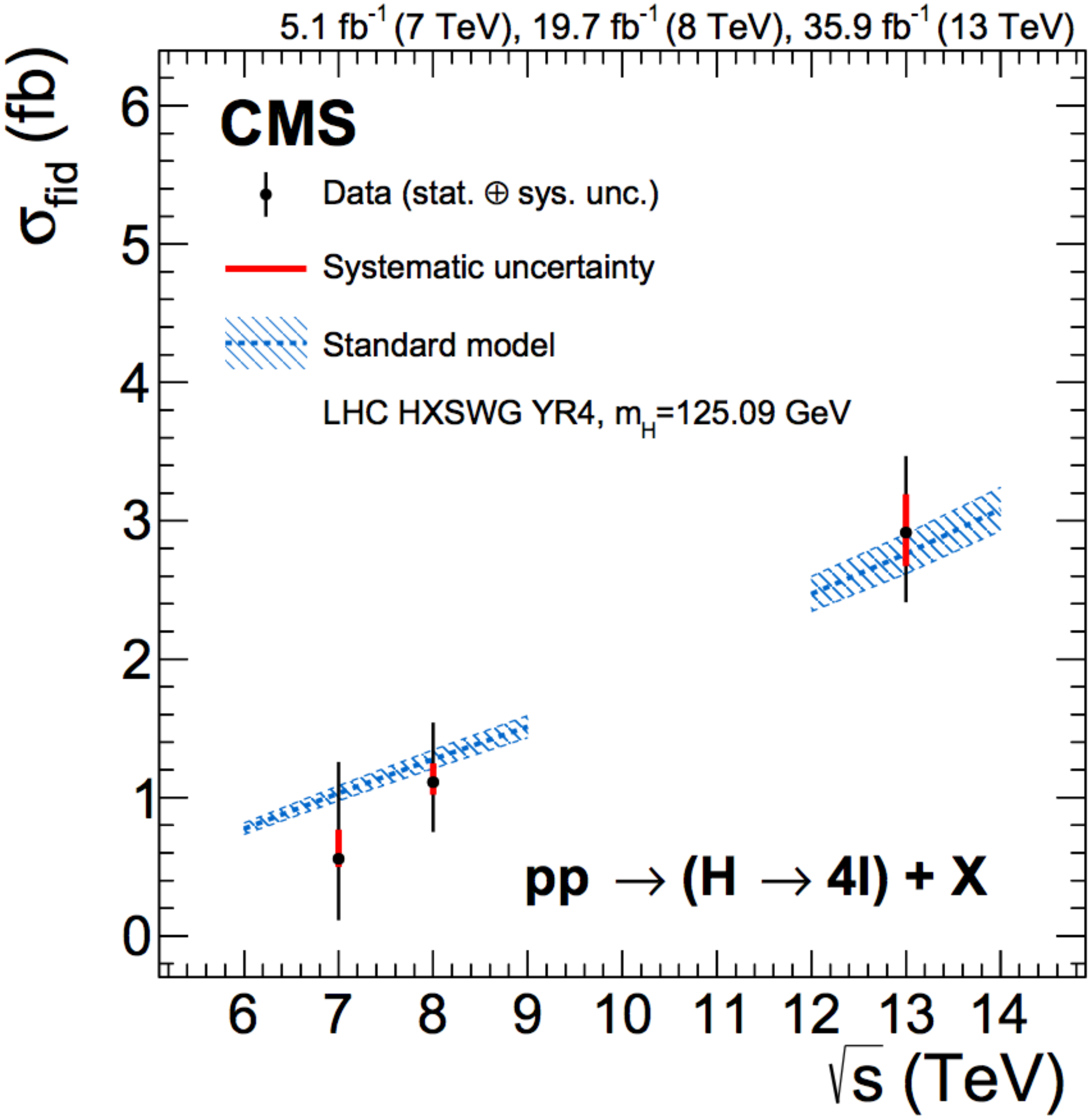
H to 4l

differential cross section

H to 4l

ATLAS

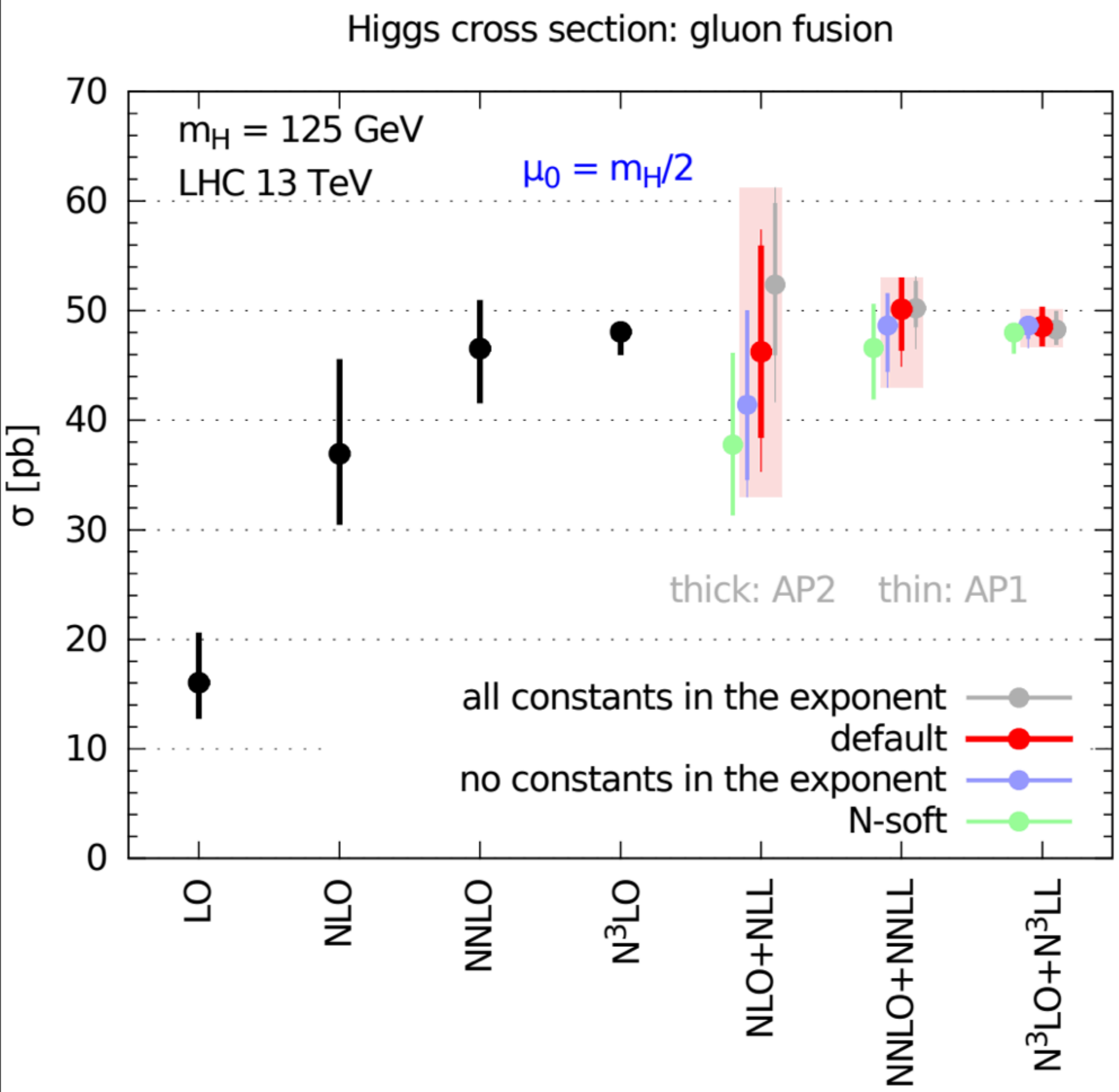


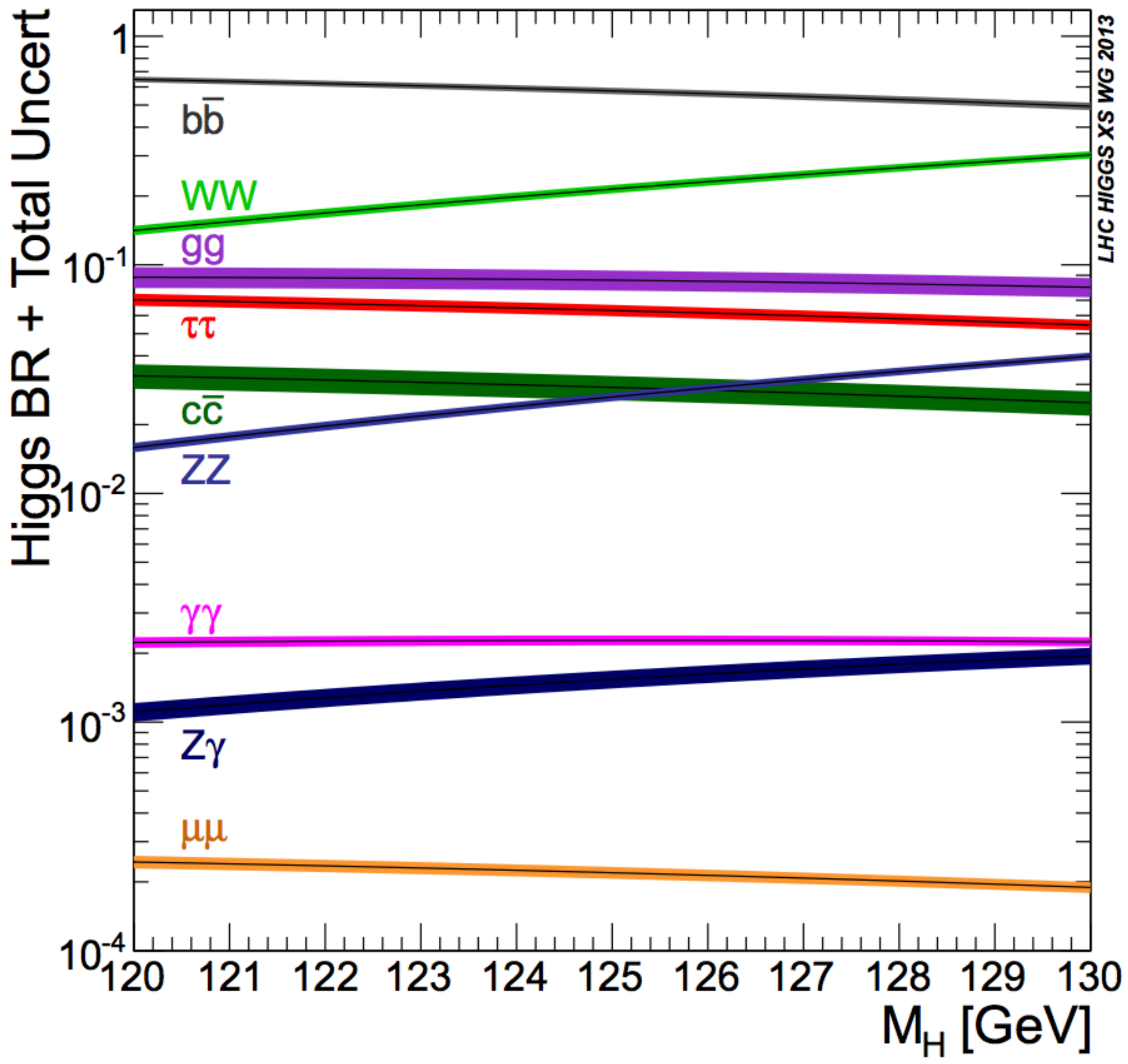


LHC Higgs Cross Section Working Group arXiv:1610.07922

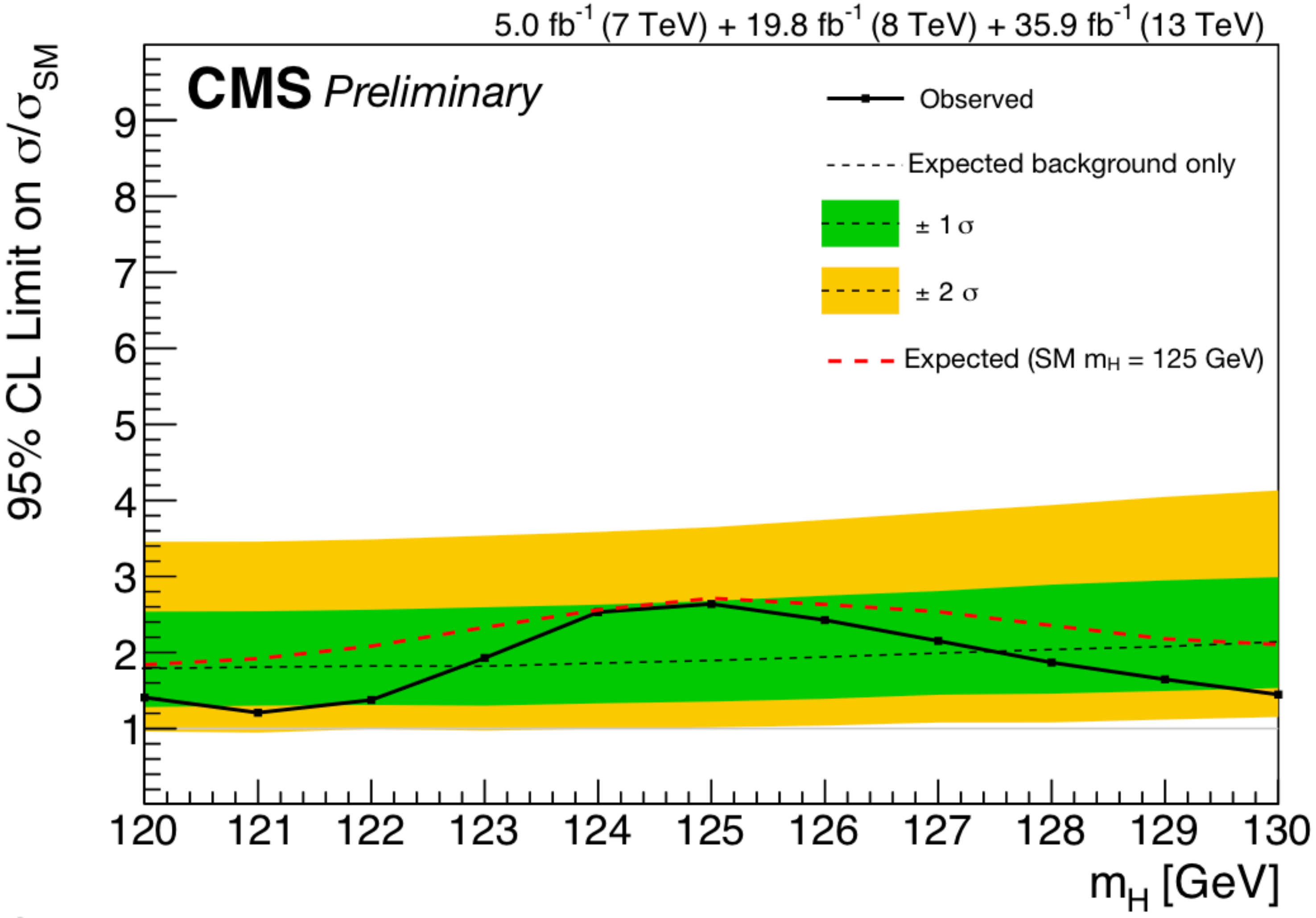
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF}+\alpha_s)\,.$$

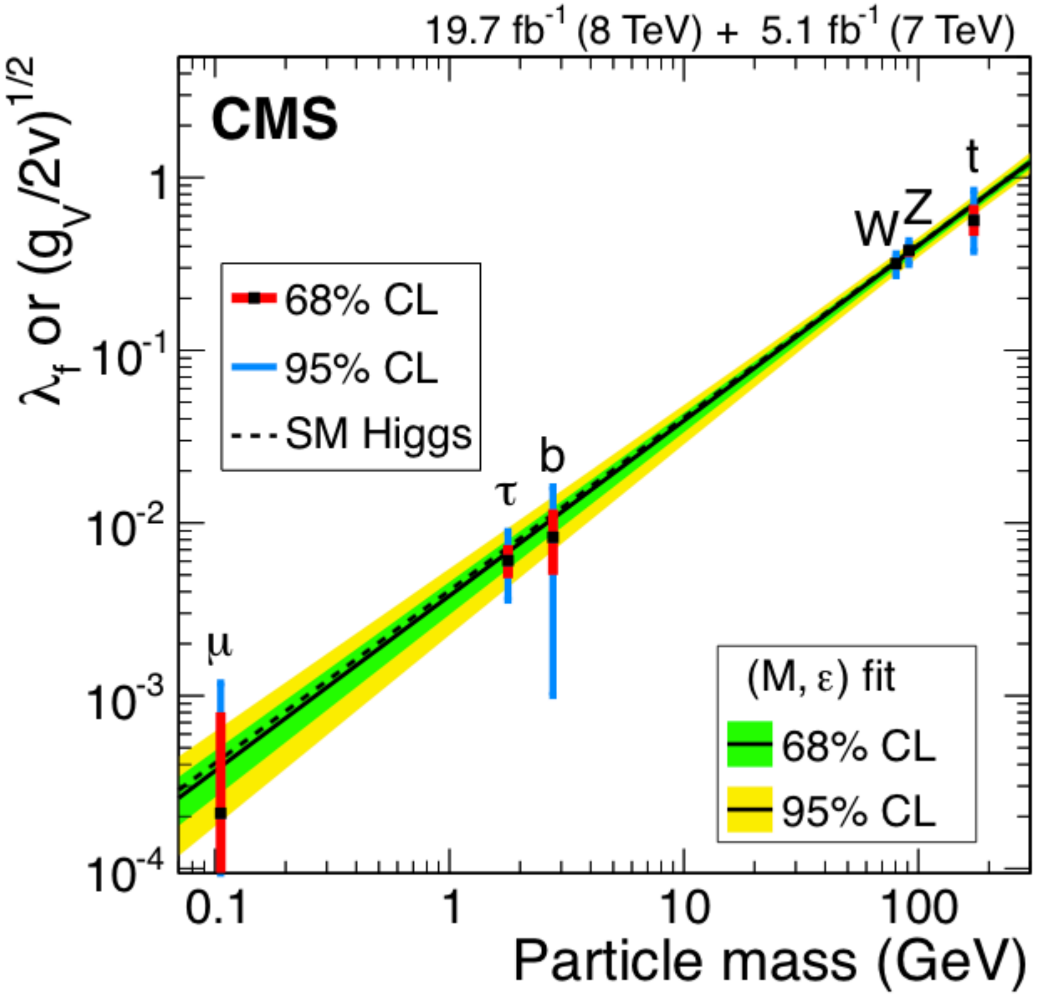
gluon fusion: N3LO
VBF, VH: NNLO
ttH: NLO

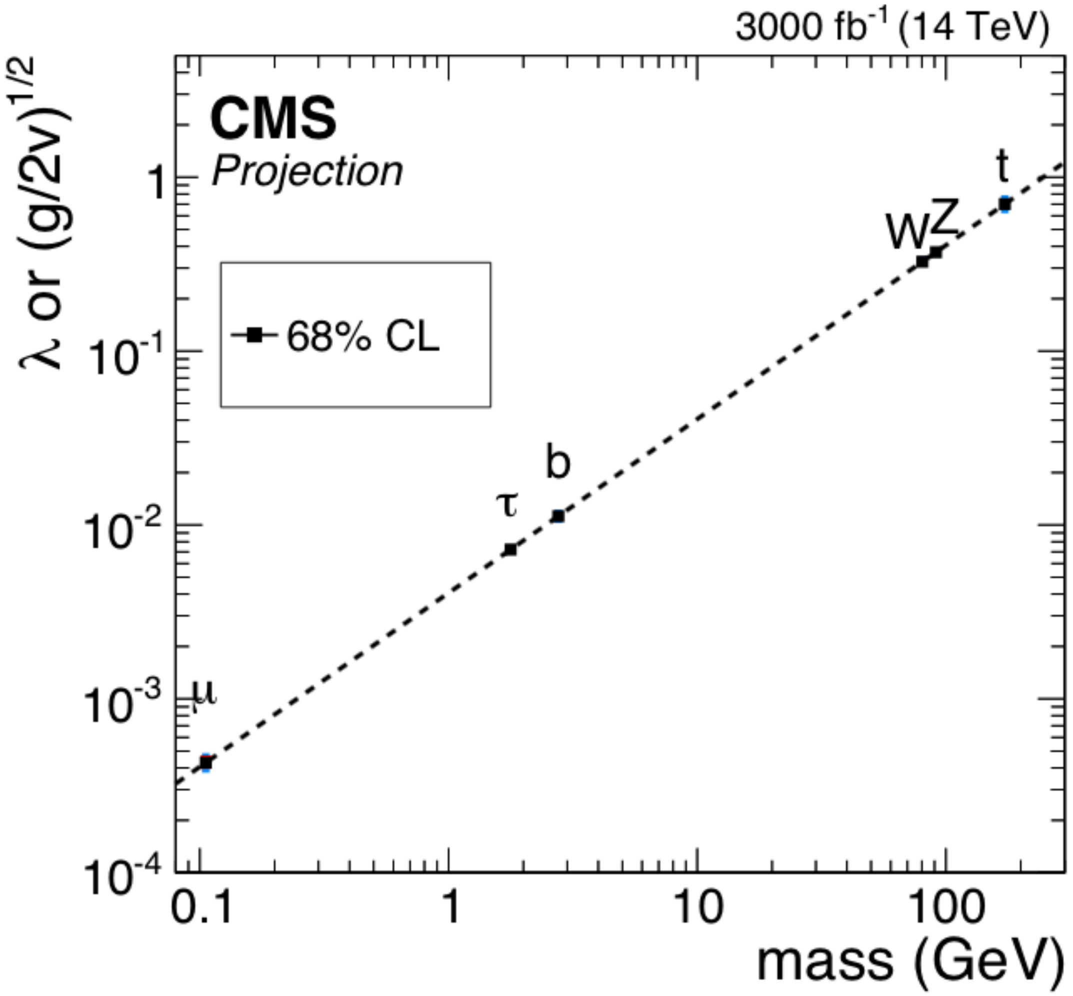




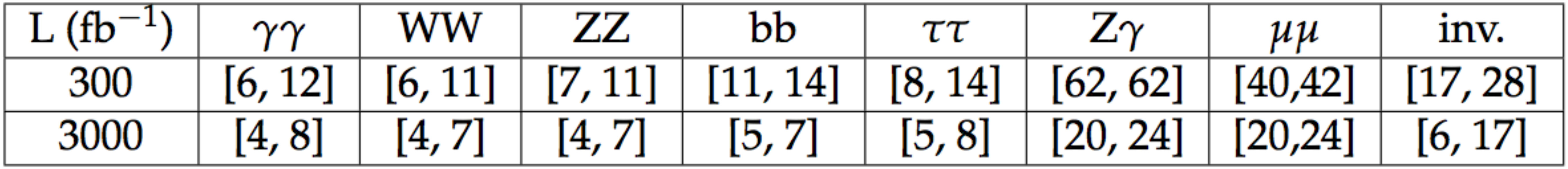
Higgs to mu mu





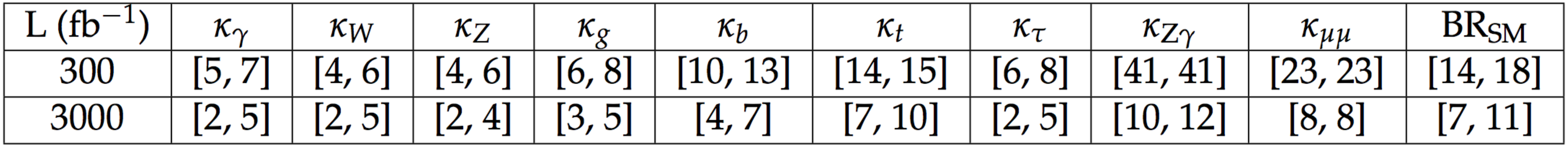


Precision on signal strength



L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

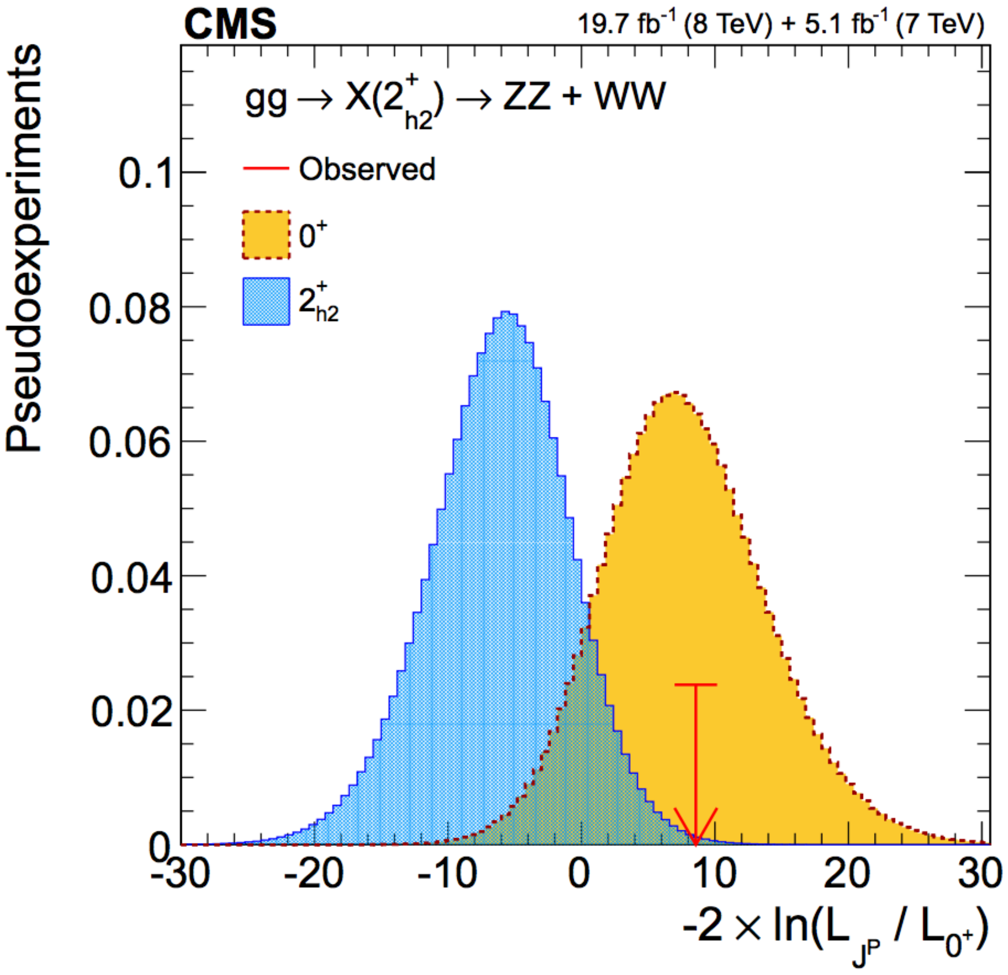
Precision on coupling modifier (K)

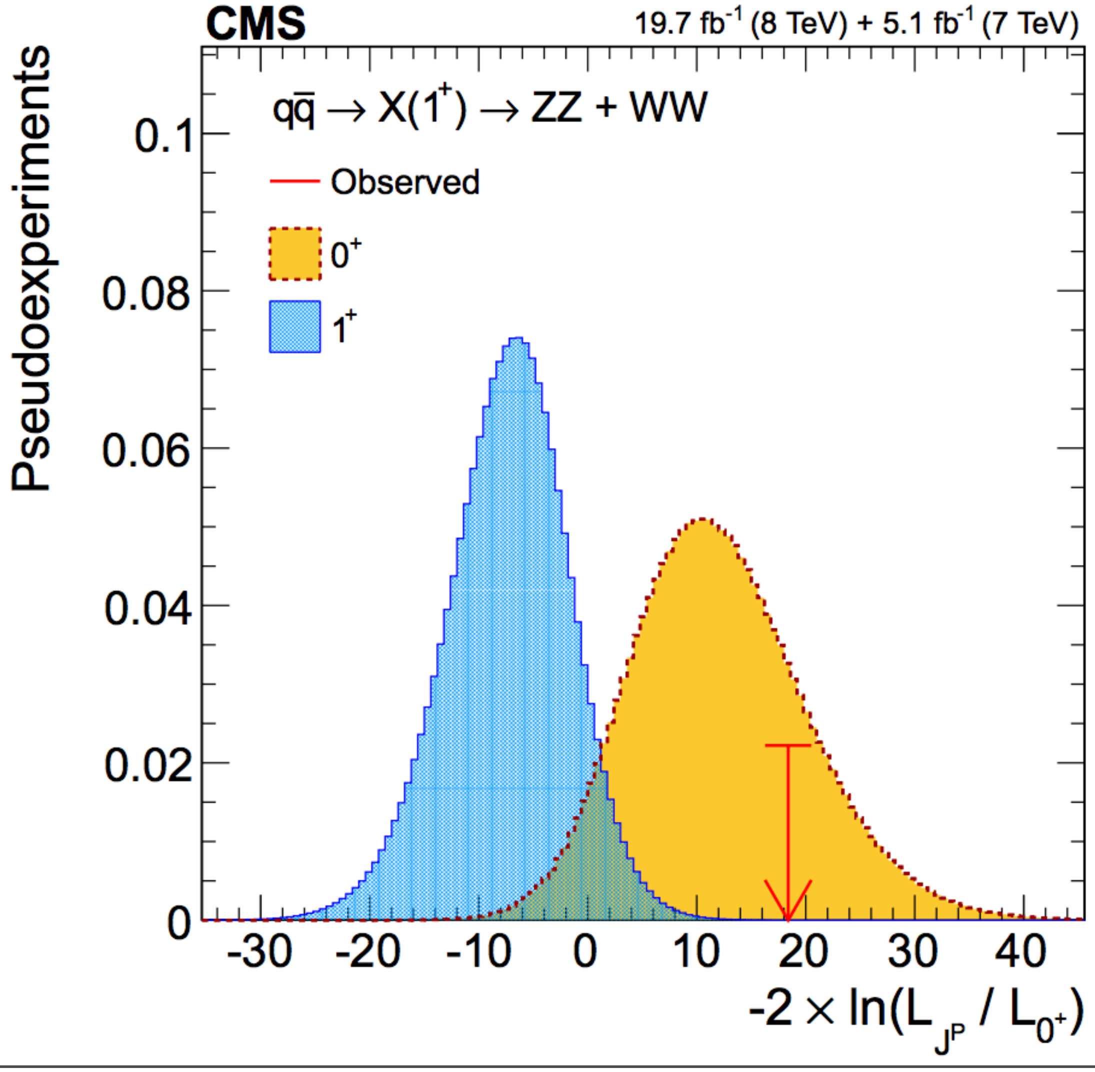


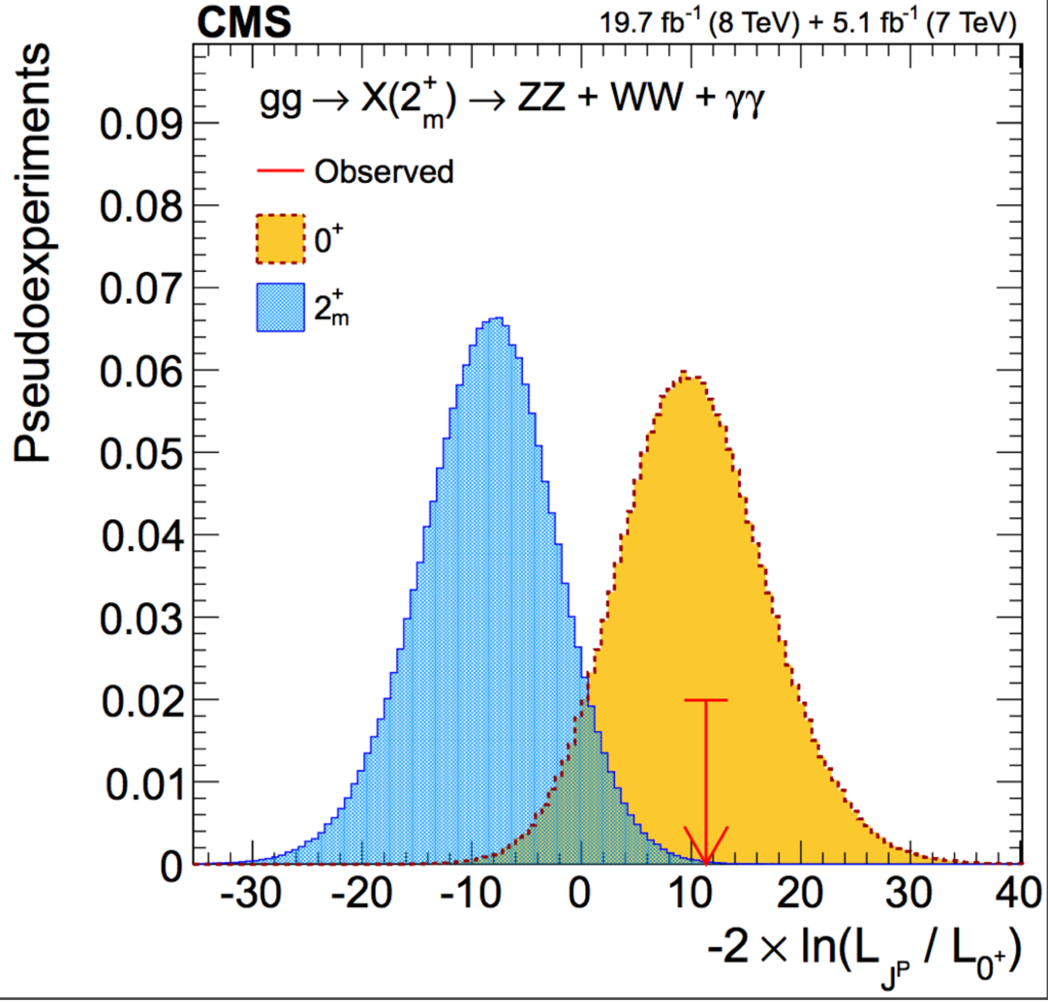
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

Higgs spin parity

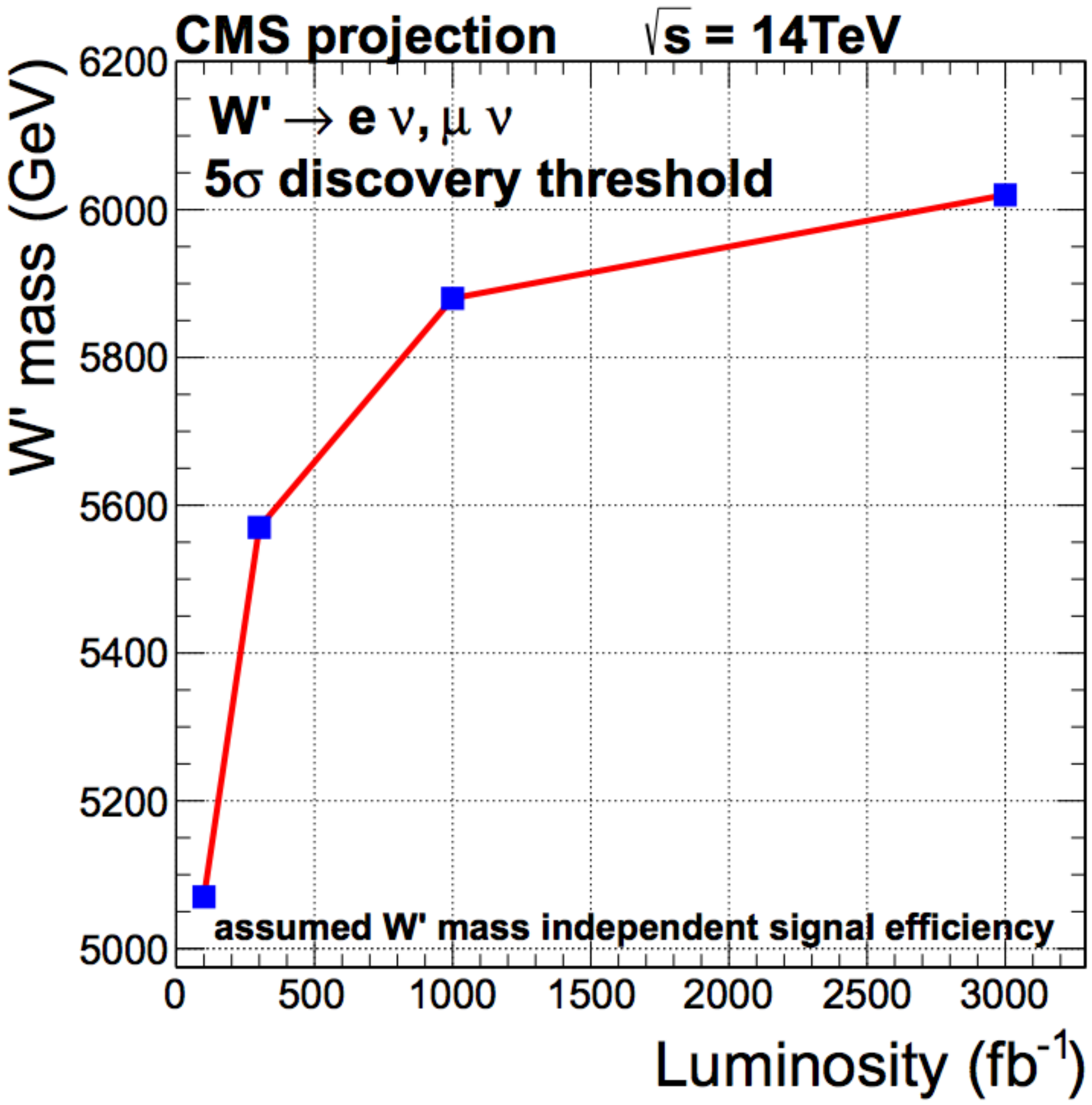
J^P Model	$gg \to X$ Couplings	$q\bar{q} \to X$ Couplings	$X \to VV$ Couplings
2^+_m	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} = c_5^{VV} \neq 0$
2^+_{h2}	$c_2^{gg} \neq 0$	$\rho_1 \neq 0$	$c_2^{VV} \neq 0$
2^+_{h3}	$c_3^{gg} \neq 0$	$\rho_1 \neq 0$	$c_3^{VV} \neq 0$
2^+_h	$c_4^{gg} \neq 0$	$\rho_1 \neq 0$	$c_4^{VV} \neq 0$
2^+_b	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} \ll c_5^{VV} \neq 0$
2^+_{h6}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_6^{VV} \neq 0$
2^+_{h7}	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_7^{VV} \neq 0$
2^-_h	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_8^{VV} \neq 0$
2^-_{h9}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_9^{VV} \neq 0$
2^-_{h10}	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_{10}^{VV} \neq 0$

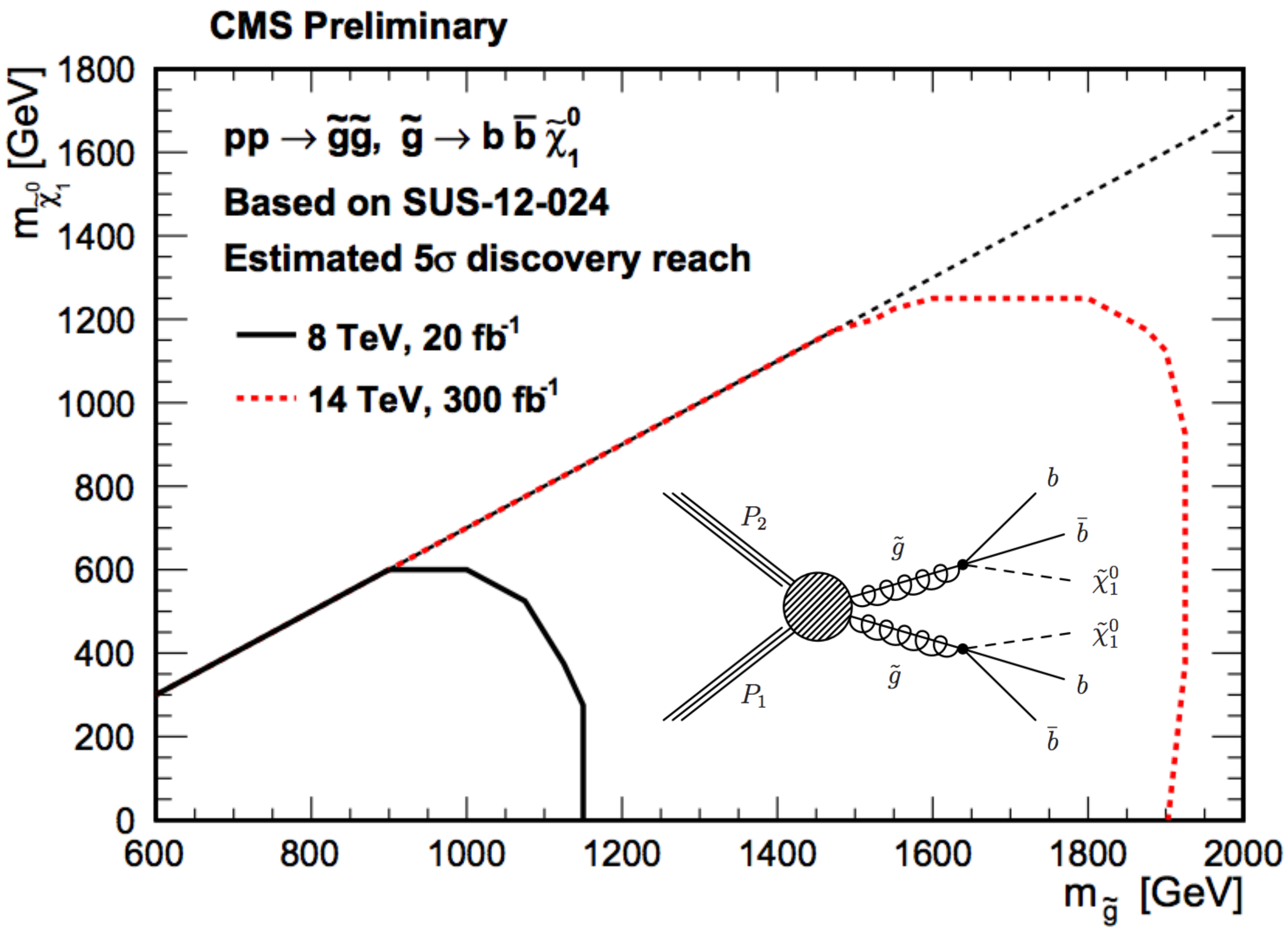




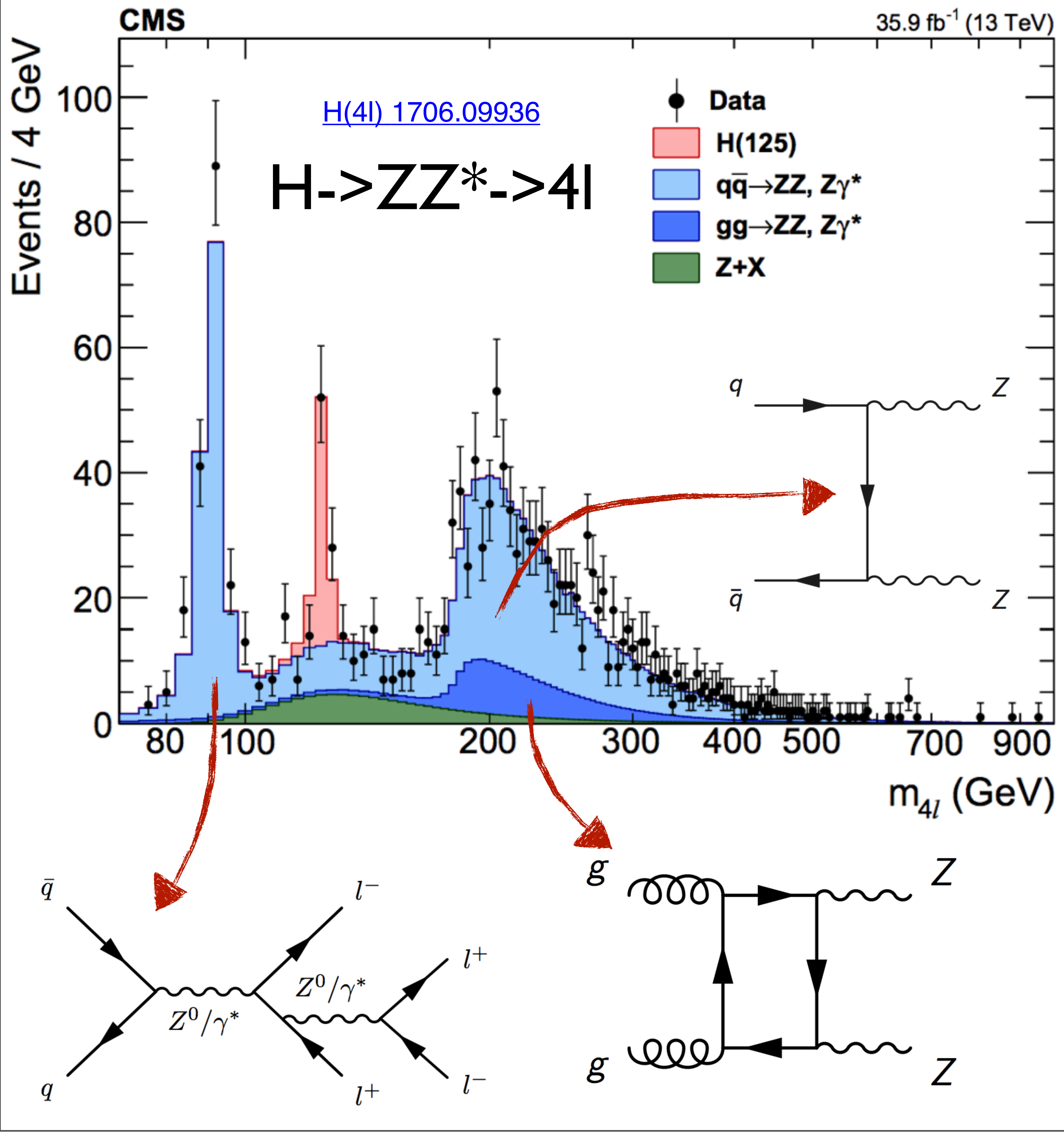


Projection: New Physics

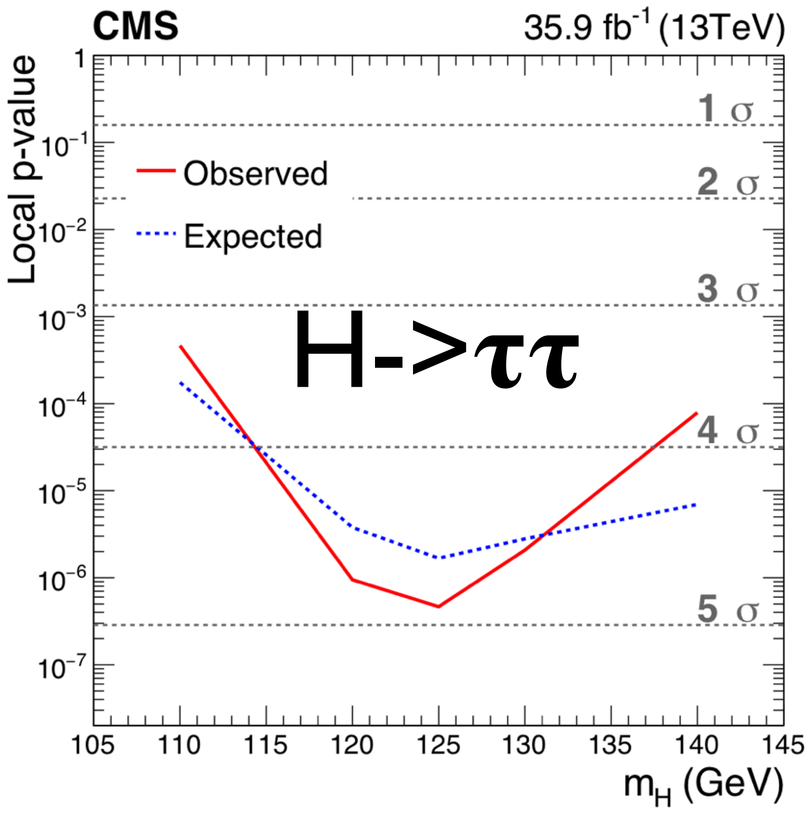




Rediscovery of Higgs with 2016 data


H(4l) 1706.09936

H->ZZ*->4l

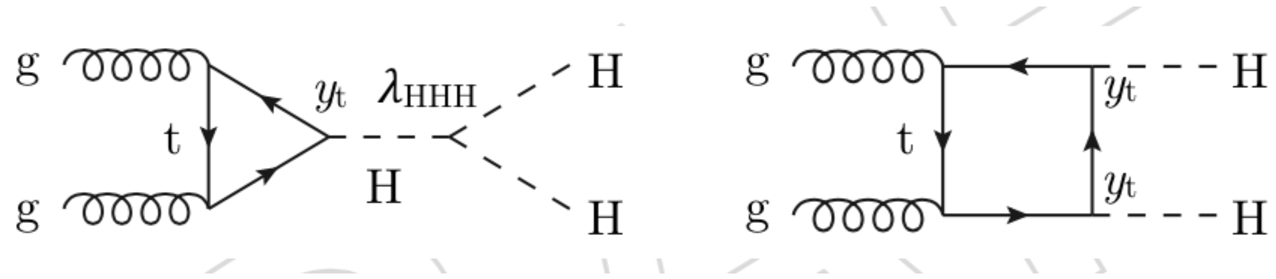

H->ττ

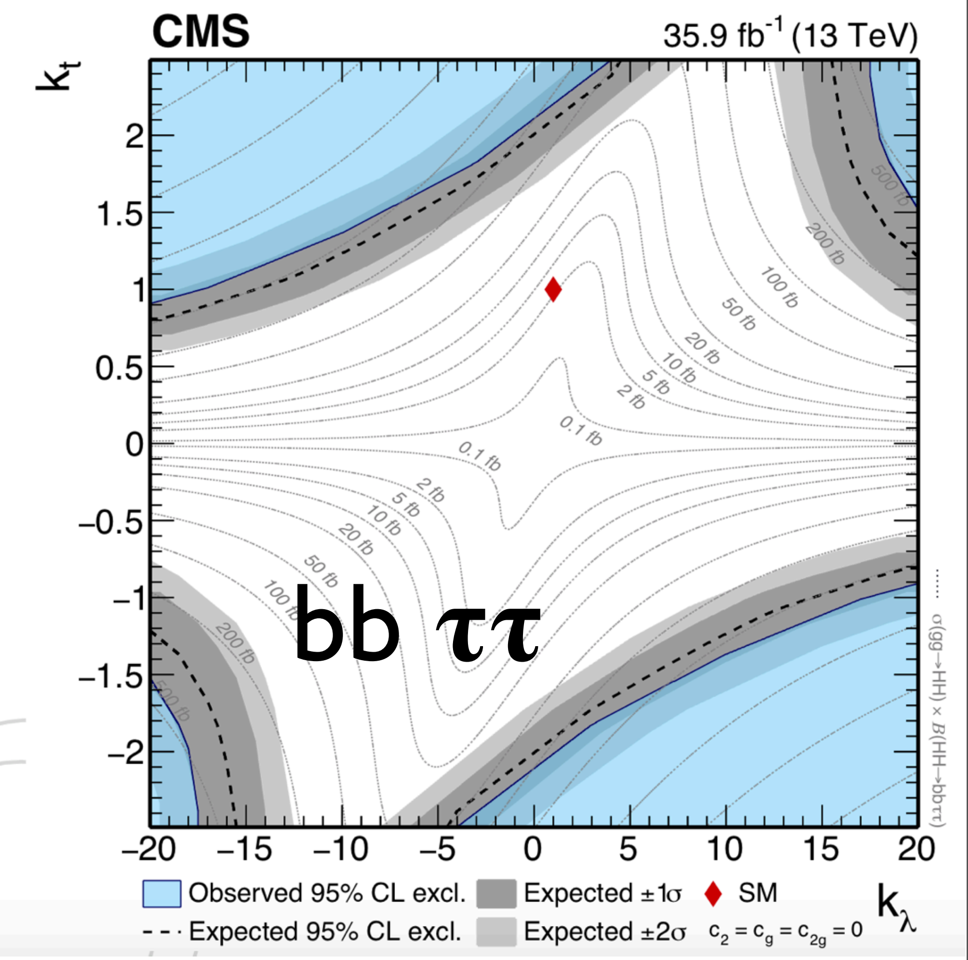
Di-Higgs

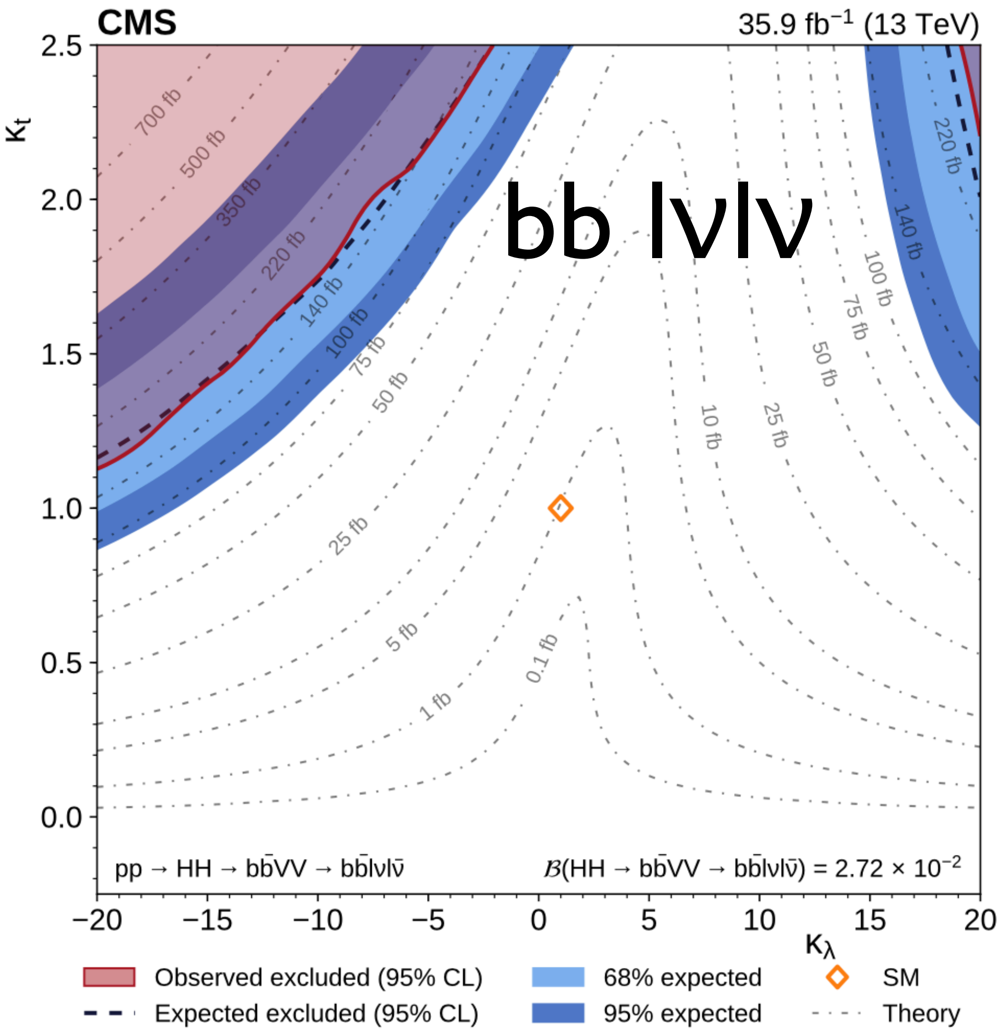
SM prediction (NNLO)

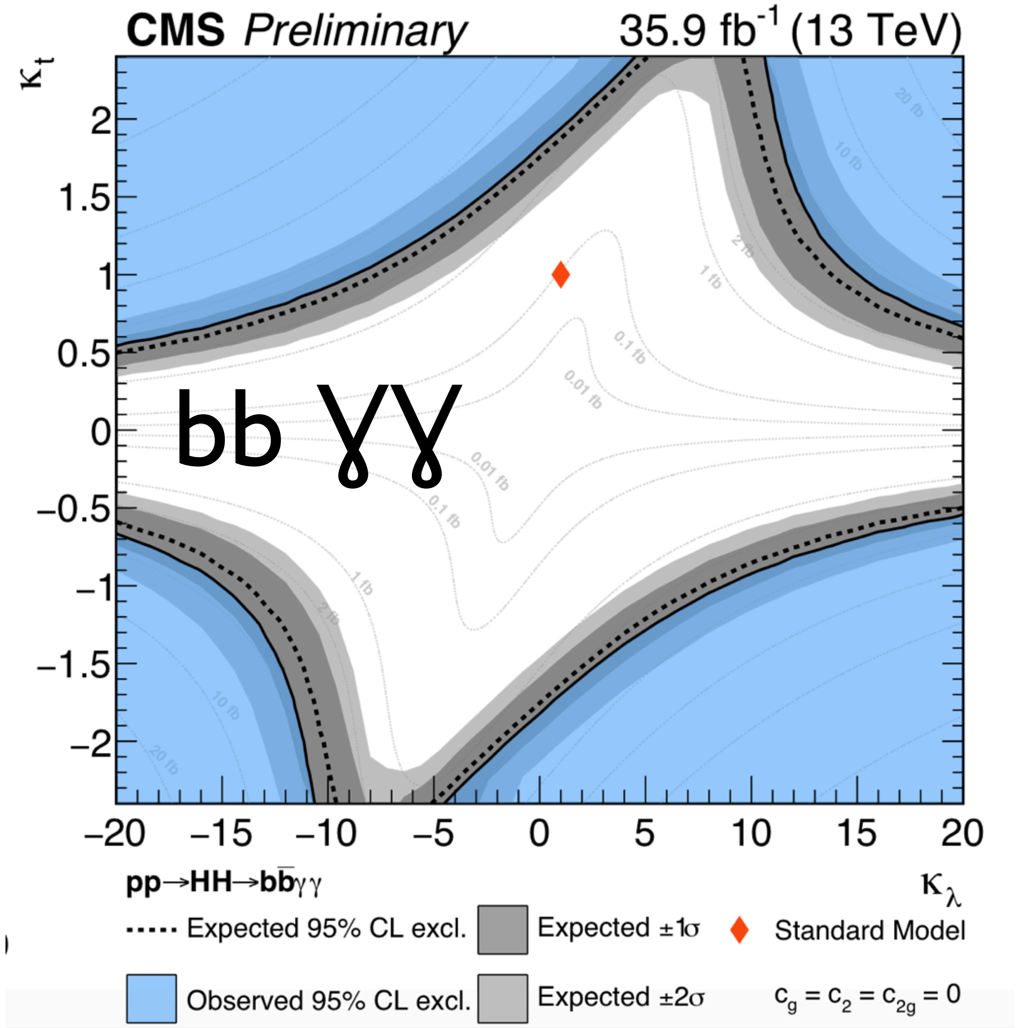
$$\sigma_{\mathrm{HH}} = 33.49^{+4.3\%}_{-6.0\%}\,(\mathrm{scale}) \pm 5.9\%\,(\mathrm{theo})\ \mathrm{fb}$$

$$k_\lambda = \lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH}}^{\mathrm{SM}} \text{ and } k_t = y_t/y_t^{\mathrm{SM}}$$




bb ττ


bb lνlν


bb γγ

$$\underbrace{P(B|A)}_{\text{Posterior}} = \frac{\overset{\text{Likelihood}}{P(A|B)}\,\overset{\text{Prior}}{P(B)}}{P(A)}$$

B is the theory

A is the measurement

$$P(n|s+b) = \frac{e^{-(s+b)}(s+b)^n}{n!}$$

$$p(\mathcal{H}|x) = \frac{\mathcal{L}(x|\mathcal{H}) \times \pi(\mathcal{H})}{\int \mathcal{L}(x|\mathcal{H}')\pi(\mathcal{H}')d\mathcal{H}'},$$

$$p(\theta,\nu|x) = \frac{\mathcal{L}(x|\theta) \times \pi(\theta) \times \pi(\nu)}{\int \mathcal{L}(x|\theta')\pi(\theta') \times \pi(\nu')d\theta'}.$$

$$p(\theta|x) = \frac{\int \mathcal{L}(x|\theta) \times \pi(\theta) \times \pi(\nu)d\nu}{\int\int \mathcal{L}(x|\theta')\pi(\theta') \times \pi(\nu')d\theta' d\nu'}.$$

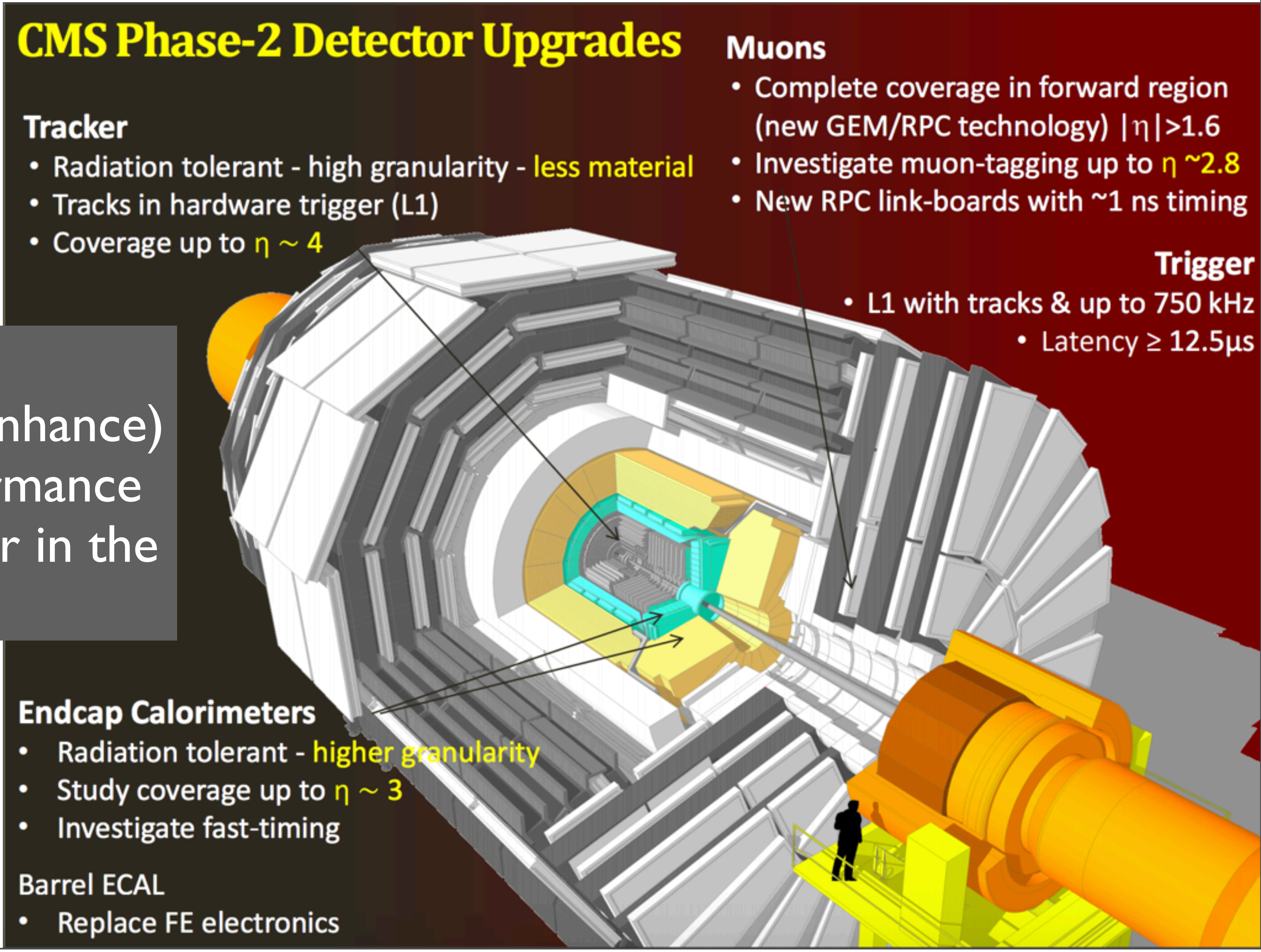
$$1 - \alpha = \int_{\theta_{\mathrm{down}}}^{\theta_{\mathrm{up}}} p(\theta|x)d\theta$$

From LHC to HL-LHC

Radiation six times higher than nominal LHC design

~8x more pileup

Replace detector components that suffer from radiation damage
Tracker and forward region with highest radiation



CMS Phase-2 Detector Upgrades

Tracker

- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons

- Complete coverage in forward region (new GEM/RPC technology) |η|>1.6
- Investigate muon-tagging up to η ~2.8
- New RPC link-boards with ~1 ns timing

Trigger

- L1 with tracks & up to 750 kHz
- Latency ≥ 12.5μs

Endcap Calorimeters

- Radiation tolerant - higher granularity
- Study coverage up to η ~ 3
- Investigate fast-timing

Barrel ECAL

- Replace FE electronics

<u>Basic goal</u>
maintain (possibly enhance) the excellent performance of the CMS detector in the harsher conditions

Concluding Remarks

LHC permits exploration of the "energy frontier"
Discovery of new physics did not happen till now
But we are just getting started