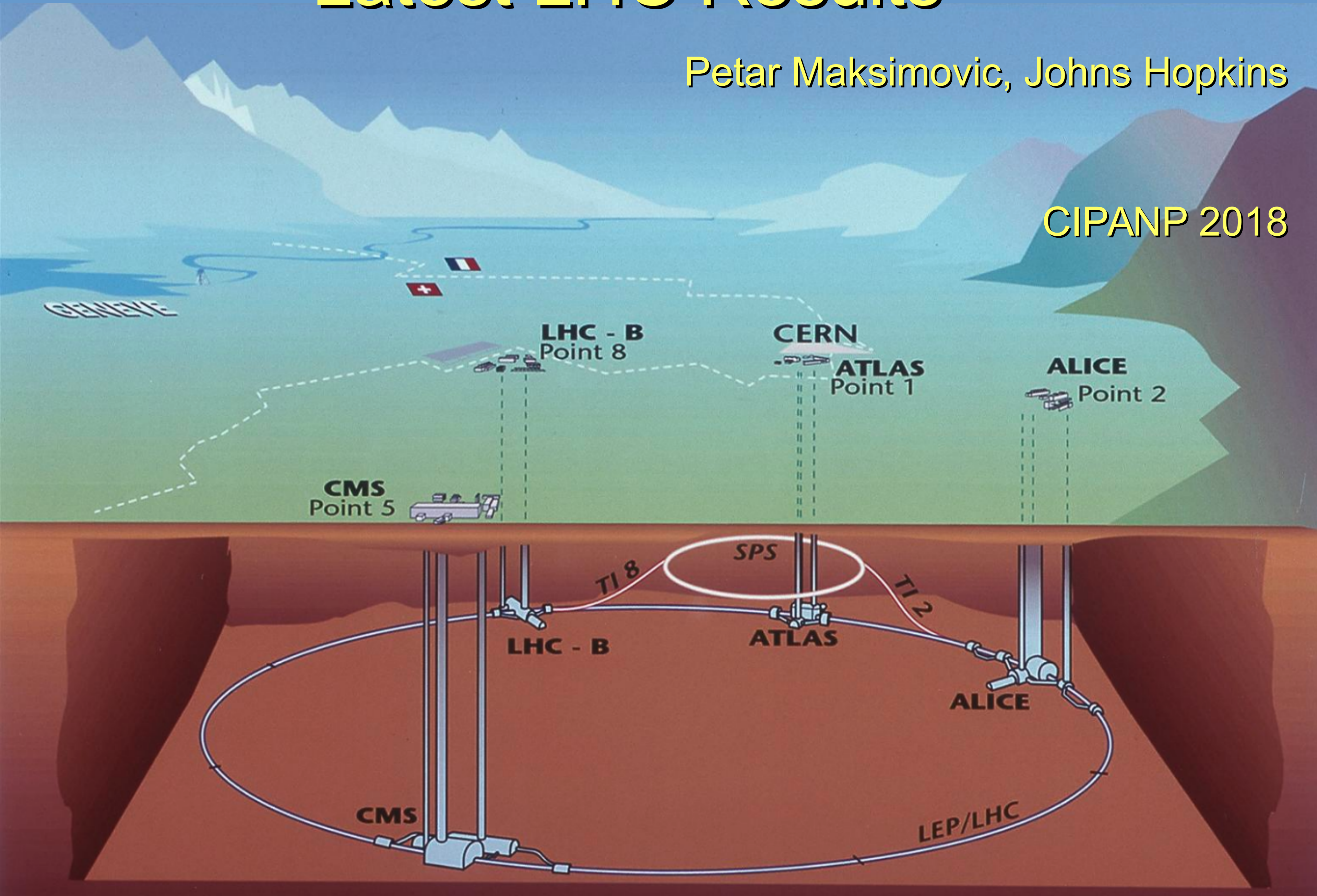
Latest LHC Results

Petar Maksimovic, Johns Hopkins

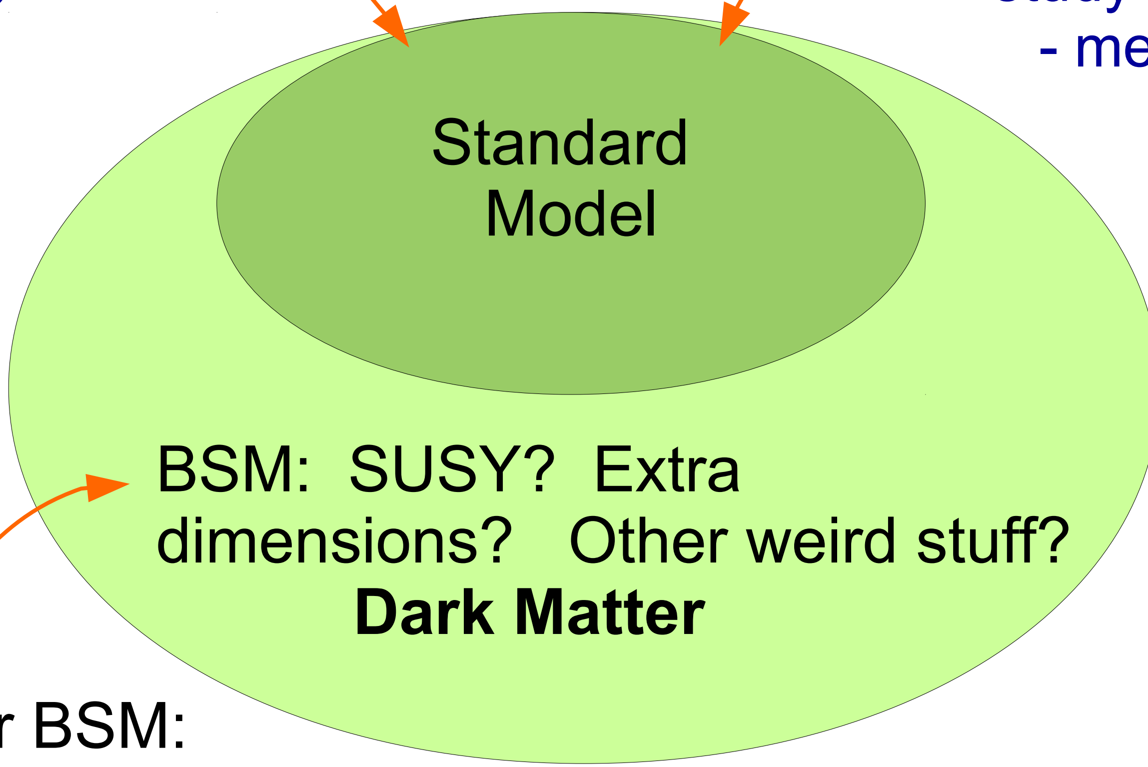
CIPANP 2018



LHC goals

Precision tests of Standard Model
- top, electroweak, QCD
- flavor physics

Study EWSB:
- find Higgs ✓
- study its properties
  - measure Higgs potential

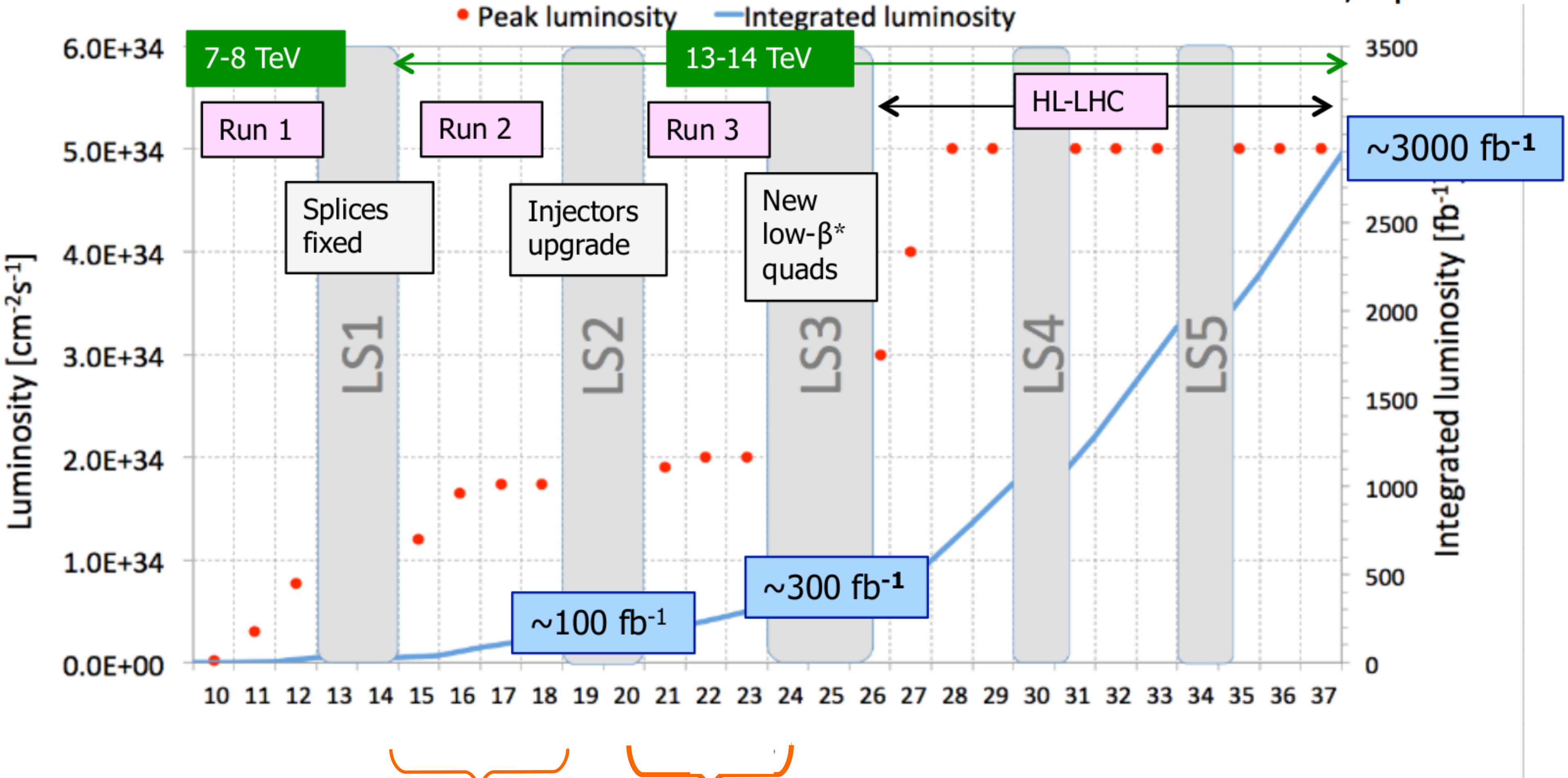


Search for BSM:
- directly
- indirectly (in precision measurements)

Study strongly interacting matter at extreme energy densities.

LHC Roadmap

F. Gianotti, April 2016

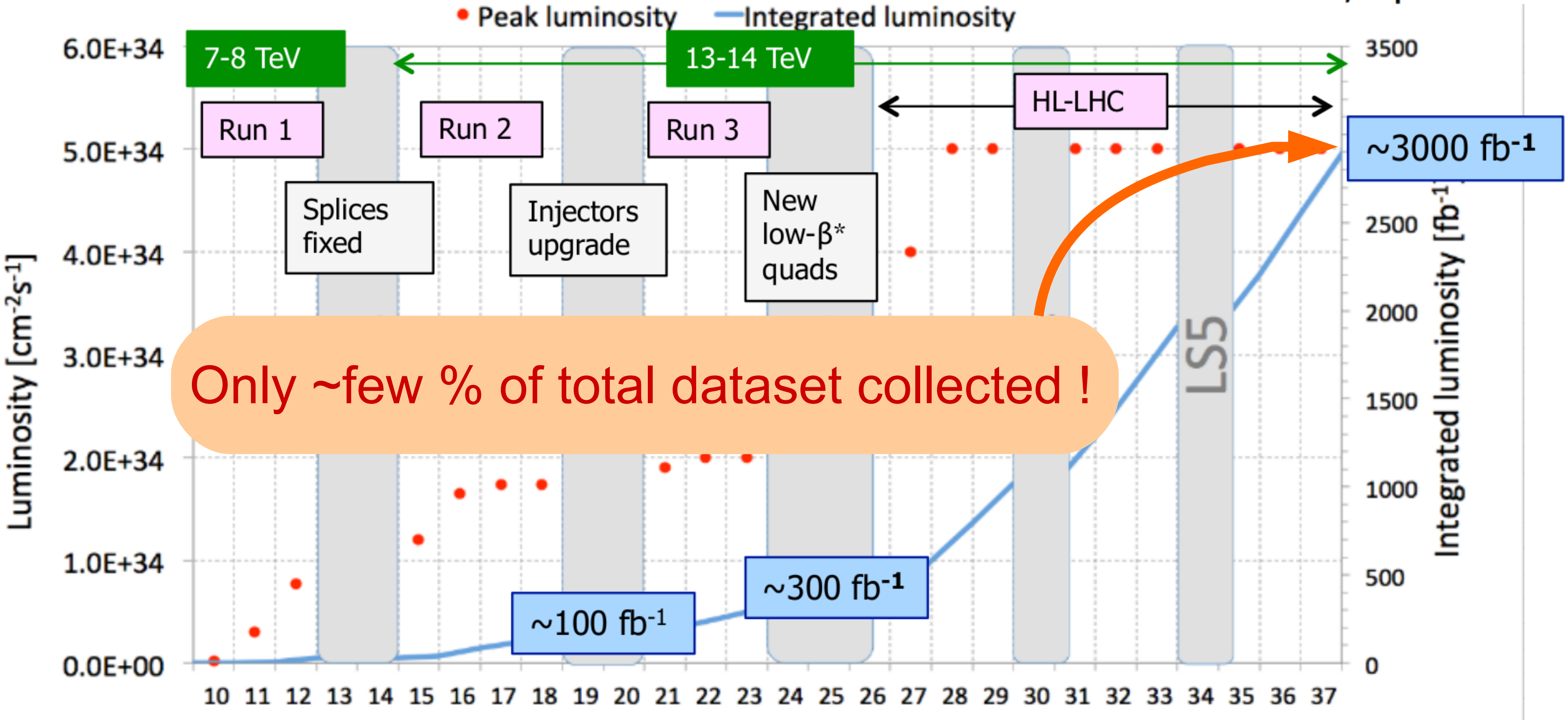


Collected so far @13 TeV ~ 100 fb^{-1}

Run 3 ~ x 3

LHC Roadmap

F. Gianotti, April 2016



Collected so far @13 TeV ~ 100 fb^{-1}

Run 3 ~ x 3

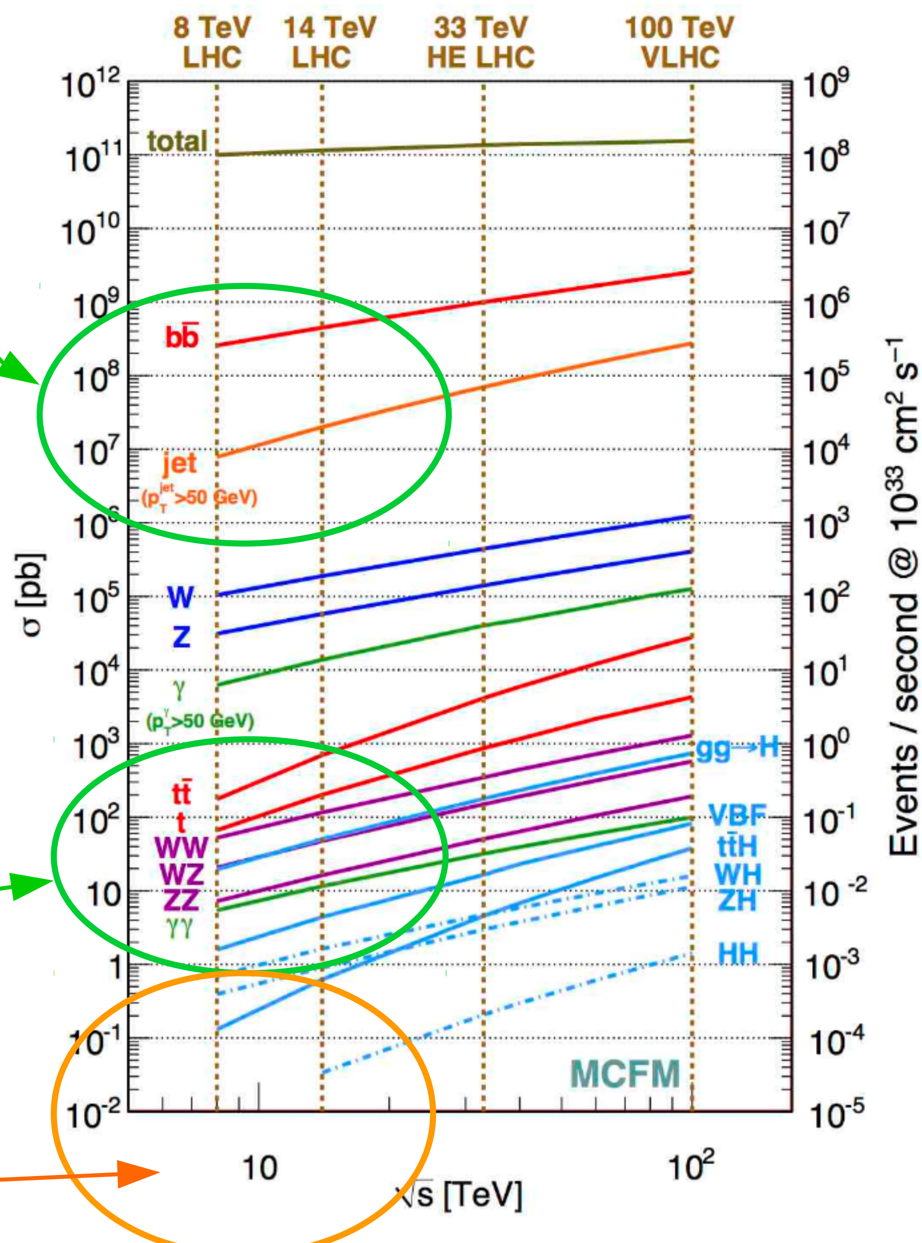
HL-LHC ~ x 30 !

Preamble to pp: life on the trigger's edge

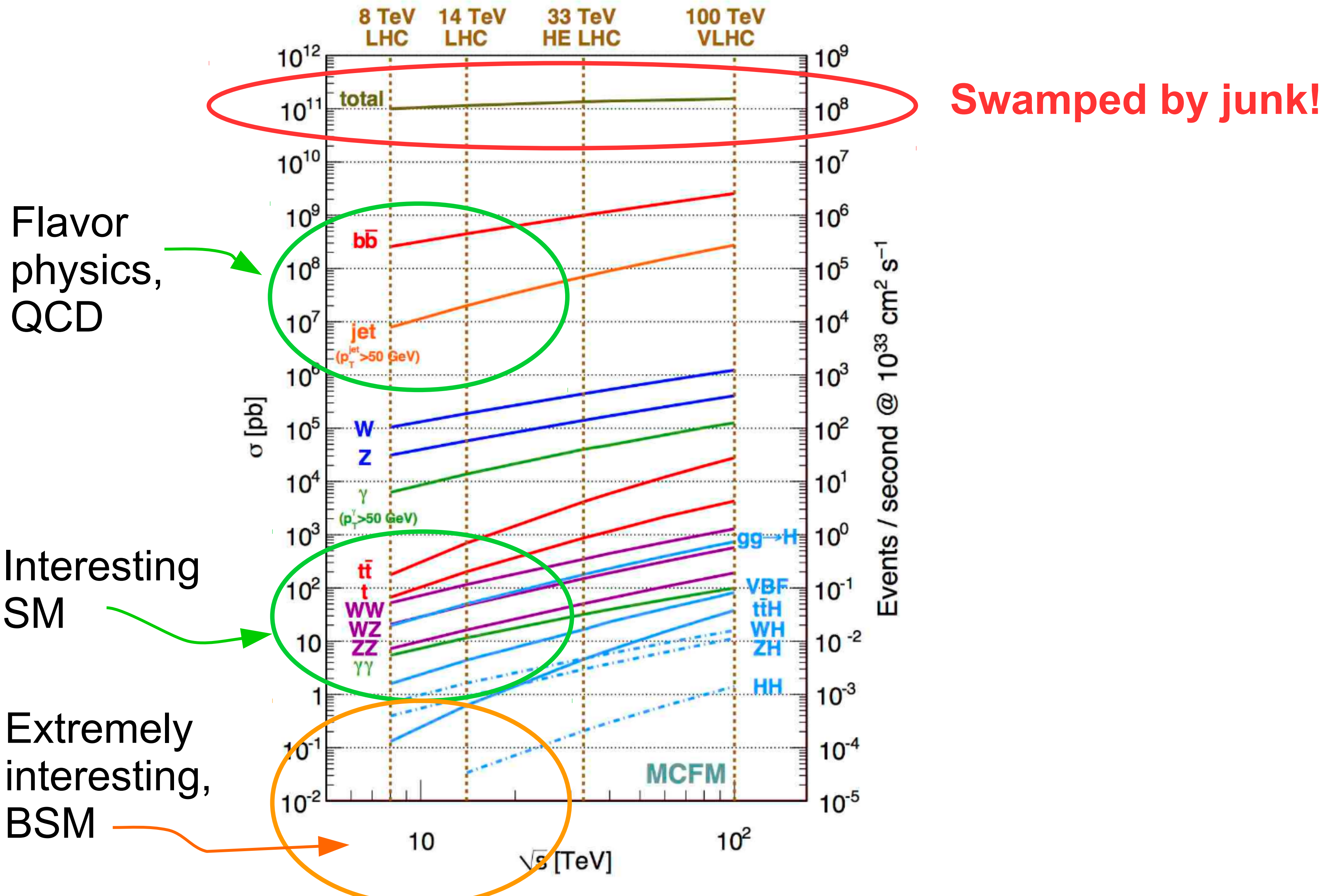
Flavor physics, QCD

Interesting SM

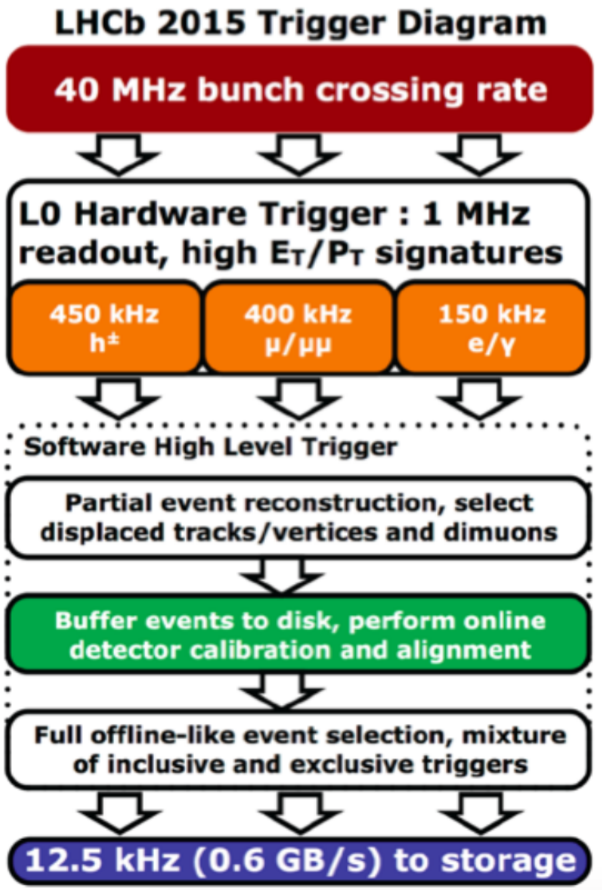
Extremely interesting, BSM



Preamble to pp: life on the trigger's edge



Preamble to pp: life on the trigger's edge

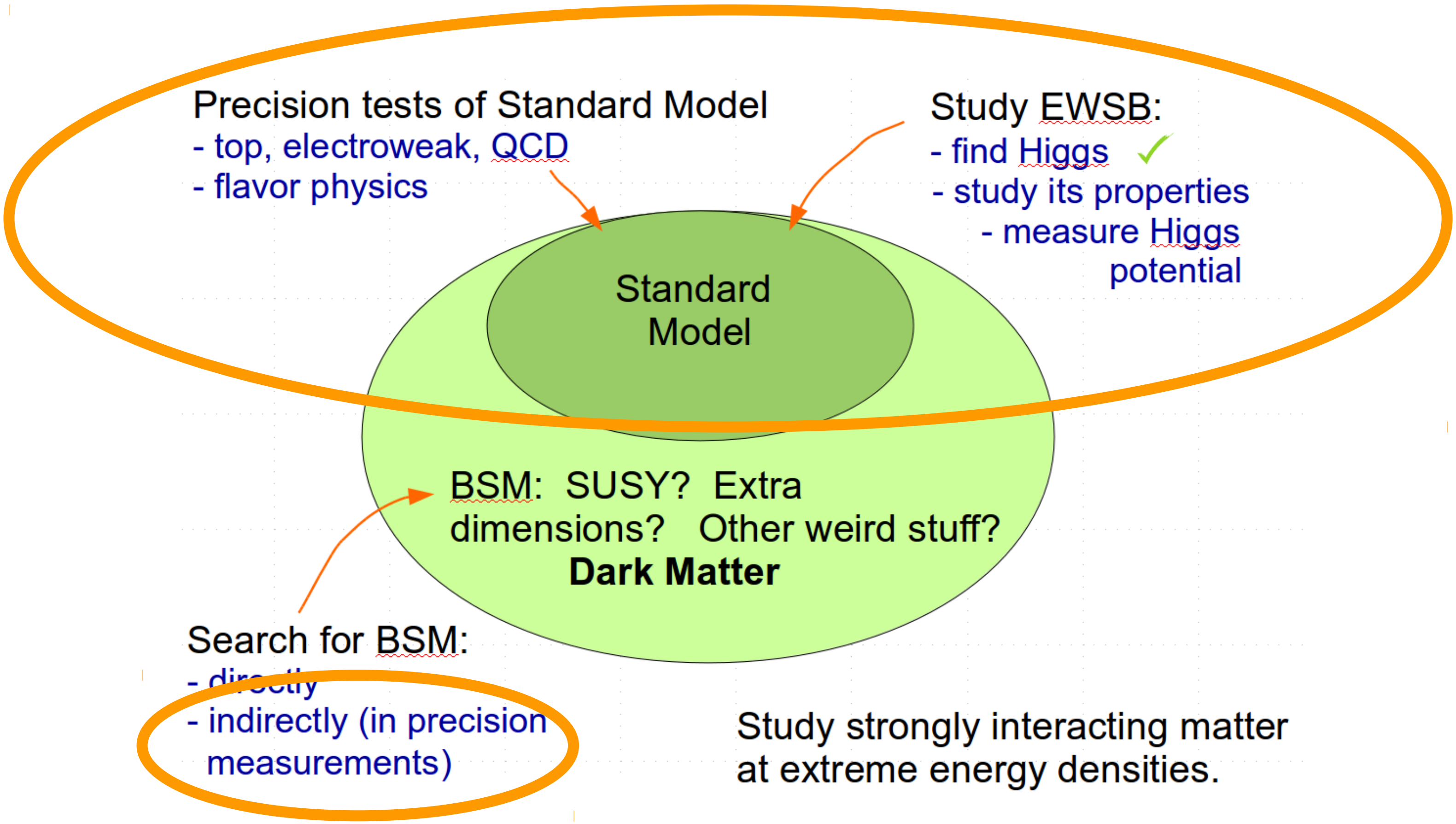


- Trigger: filter events online, throw away most of them
  - ATLAS, CMS keep ~ 1 in 1,000,000
- Triggers + fast detectors and DAQ enable most of physics in pp collisions

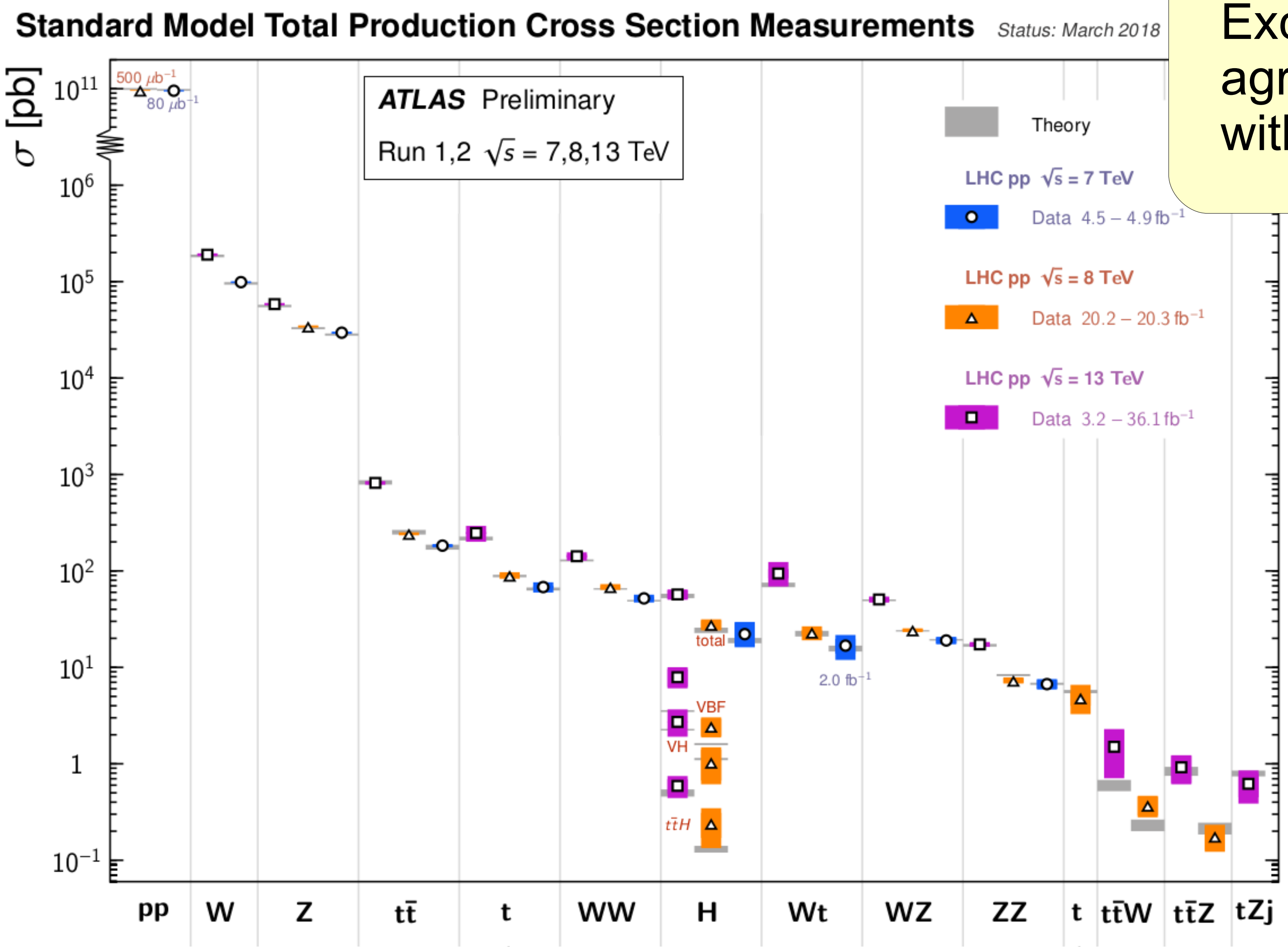
No trigger = no data = no measurement

- BSM can hide where we have no triggers or no detectors
  - That thought stimulates new approaches and new ideas

Part I: Standard Model & Precision Tests



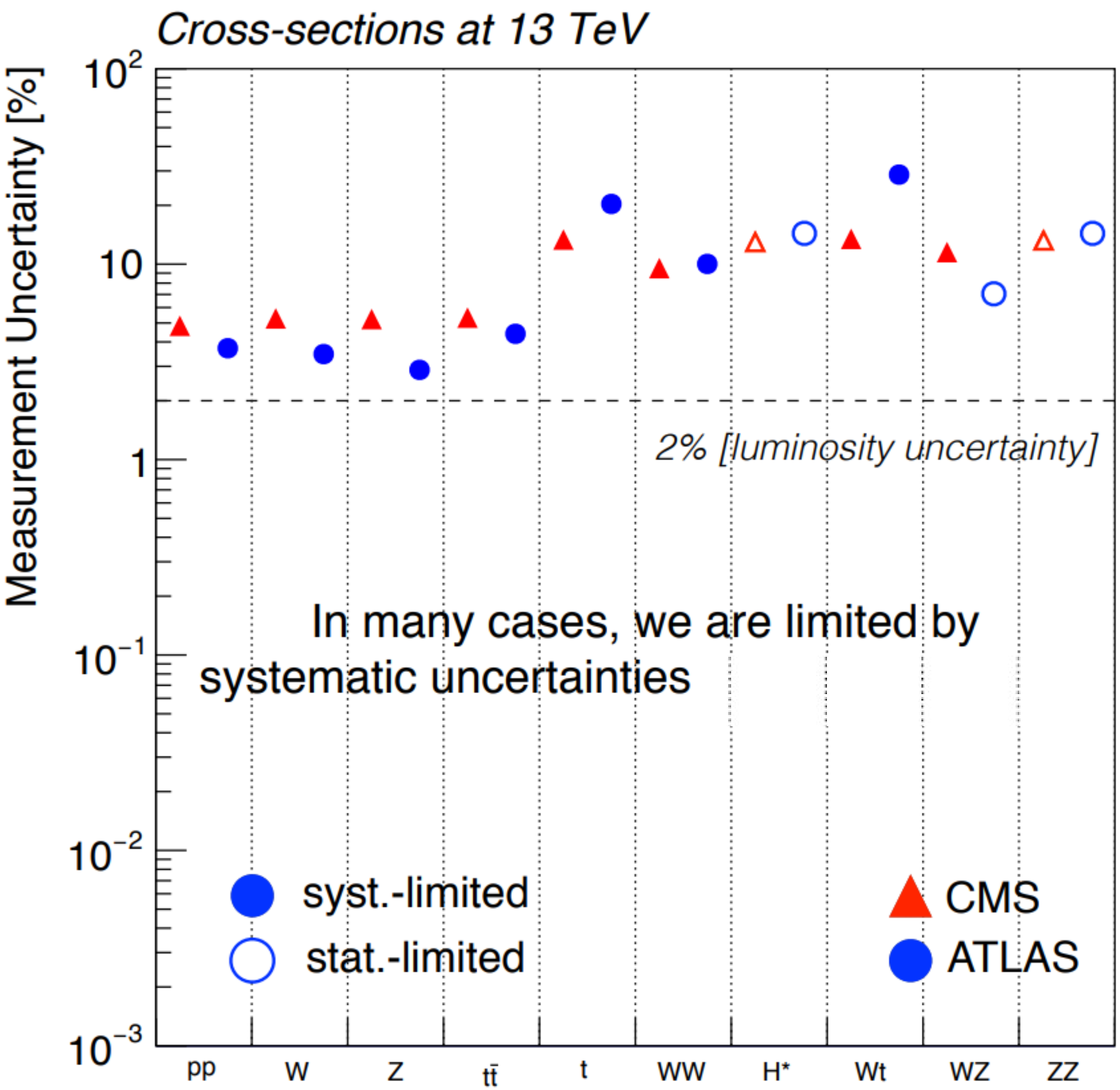
SM production cross-sections



Excellent agreement with theory

SM production cross-sections: uncertainties

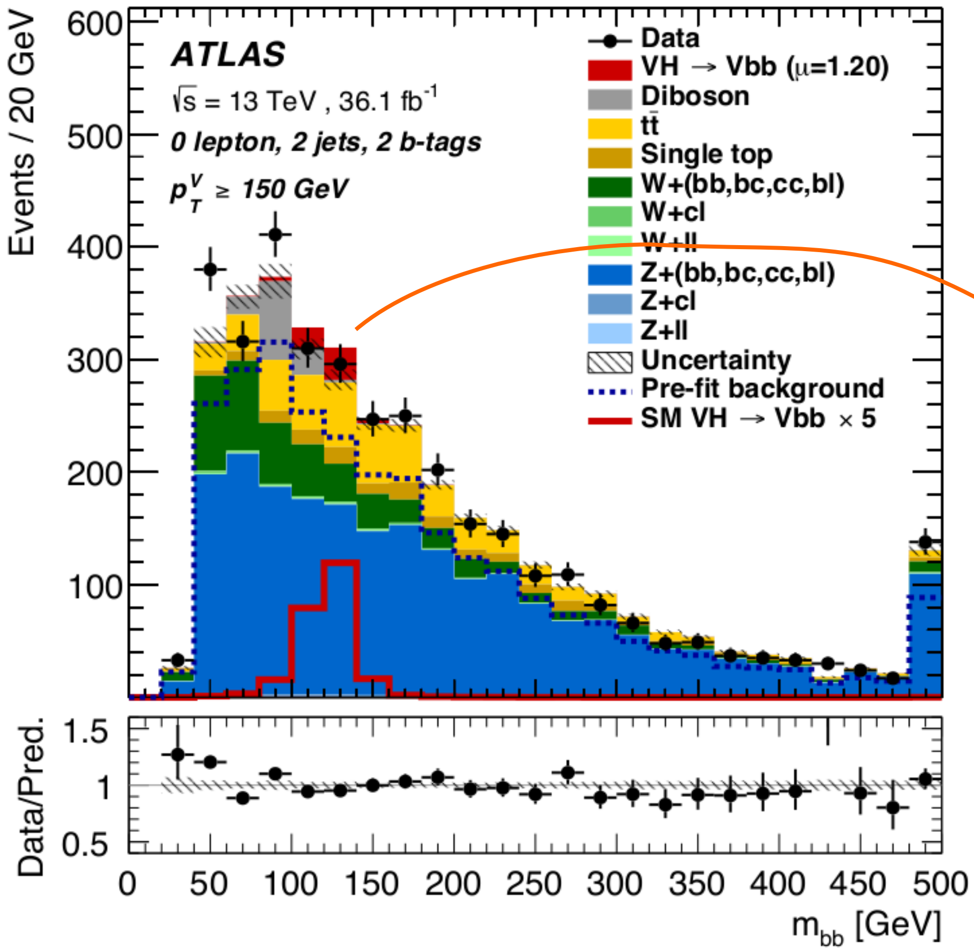
- Many are systematics limited
- Statistics needed for
  - WZ, ZZ
  - Everything Higgs



VH, H→bb

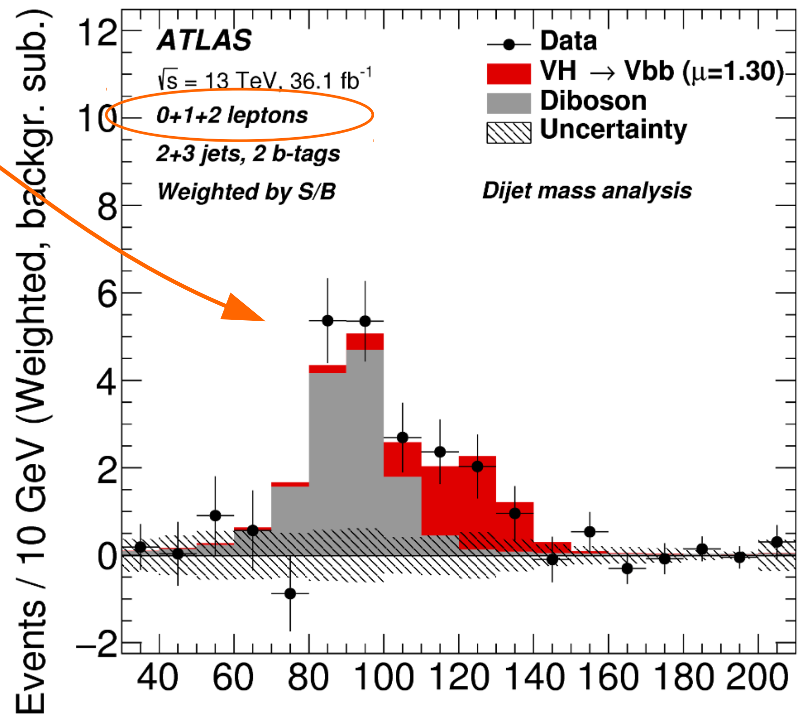
- Higgs physics: in some areas, started to reach precision era. In others: still in "search" mode.

Challenging backgrounds!



- 3.6σ after combining all channels.

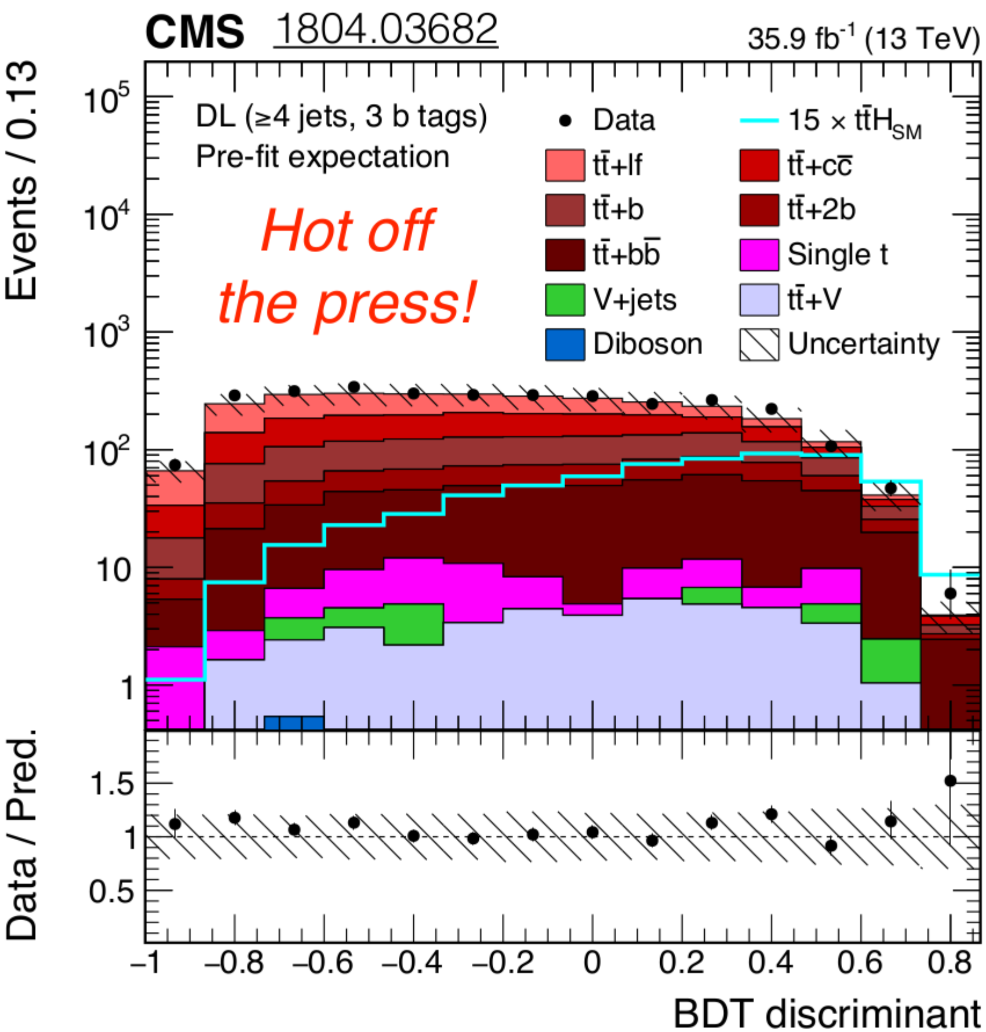
(Background subtracted)

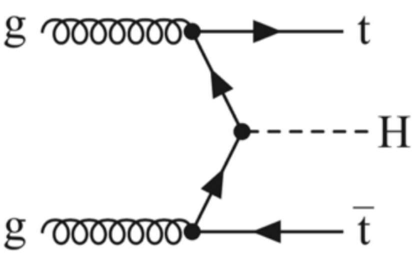


JHEP 12 (2017) 024

ttH, H→bb

- Higgs physics: in some areas, started to reach precision era. In others: still in "search" mode.





- Complex final state. BDT for classification.
- ~ 60% uncertainty

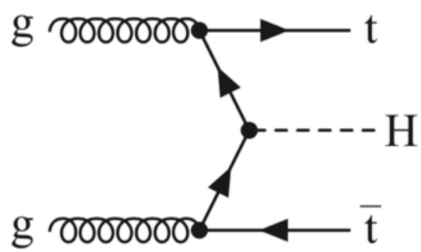
  (stat. > syst.)

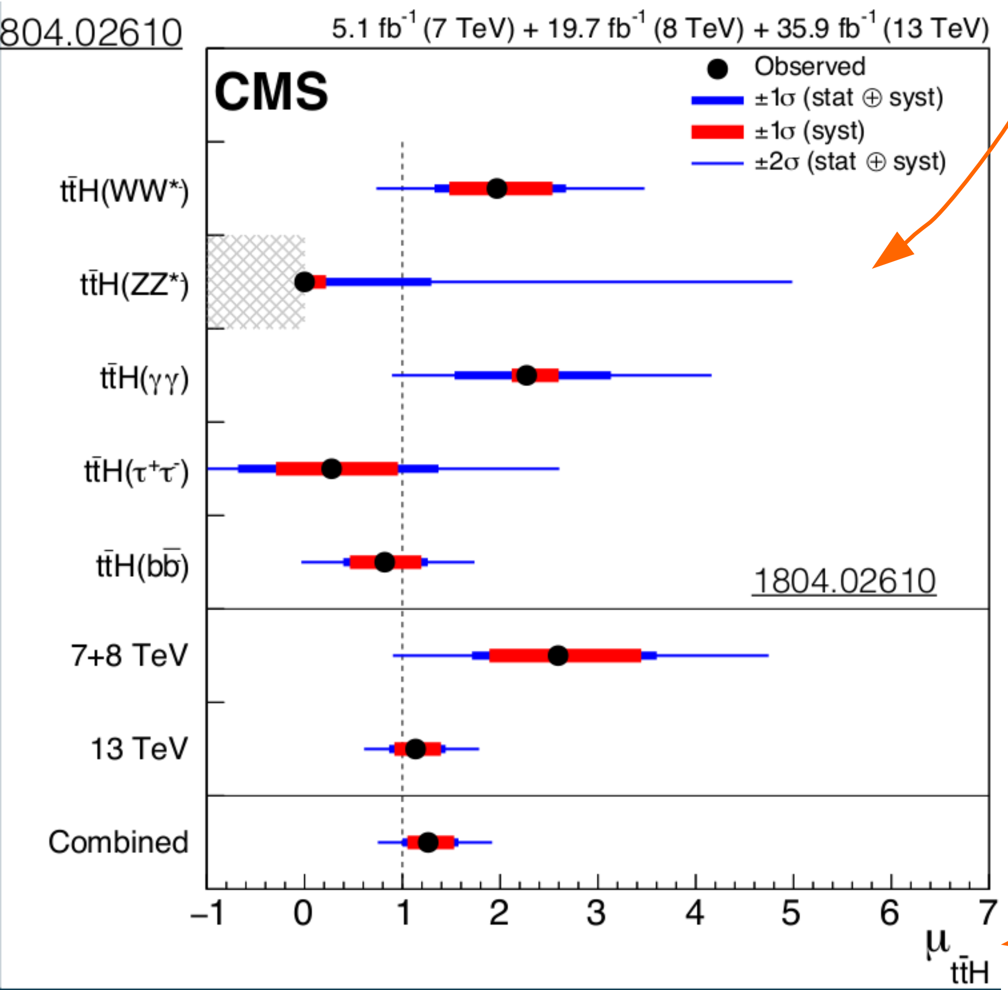
- ATLAS result:

  Phys. Rev. D 97, 072016

ttH, many H decay channels

- When search becomes measurement…
- Complex combination of all channels

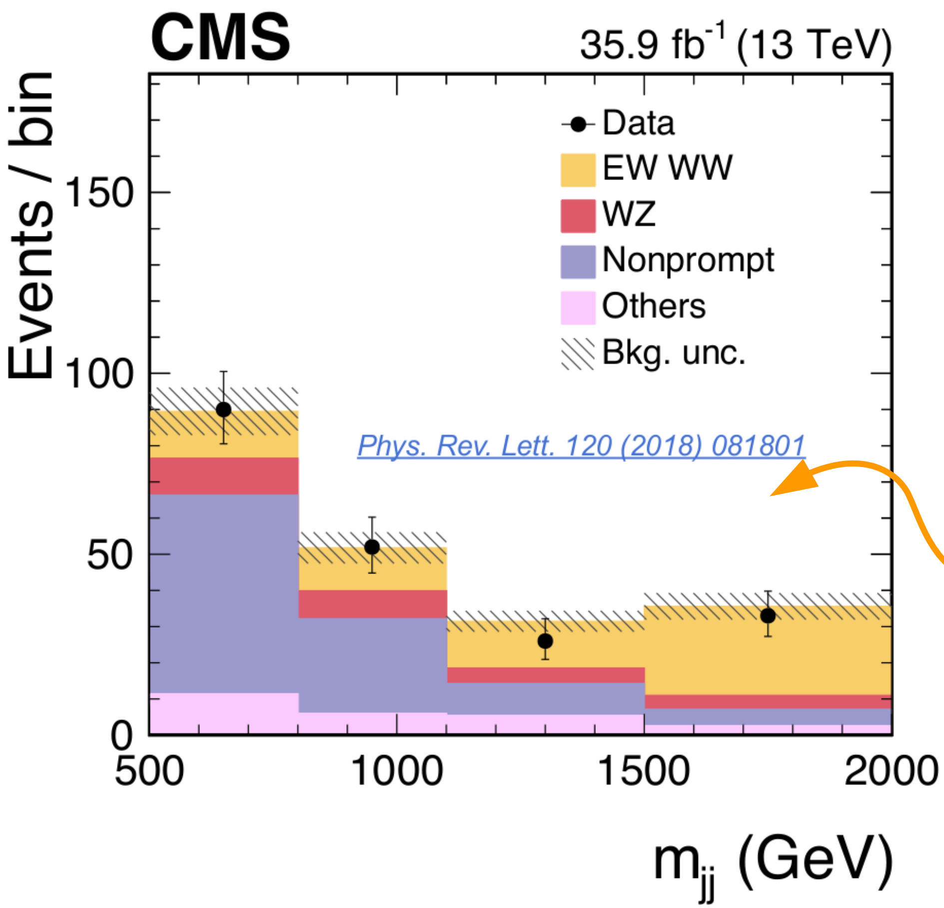




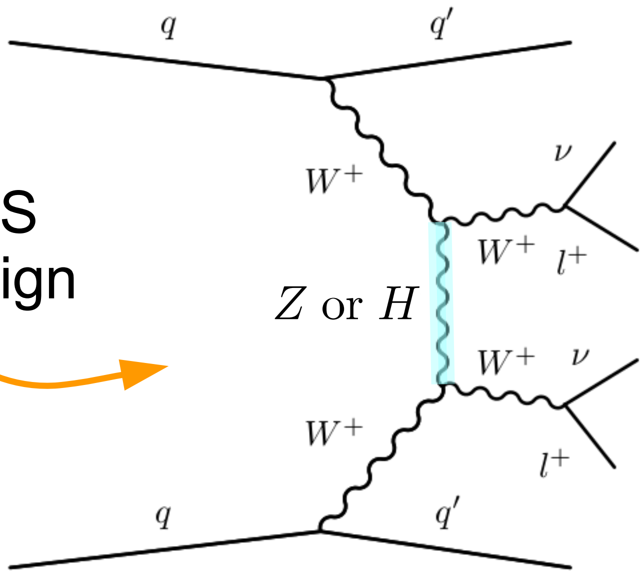
- CMS: 5σ
  - 4.2σ expected
- ATLAS: 4.2σ
  - 3.8σ expected

Signal strength w.r.t. SM

Vector Boson Scattering



Access VBS via same-sign WW



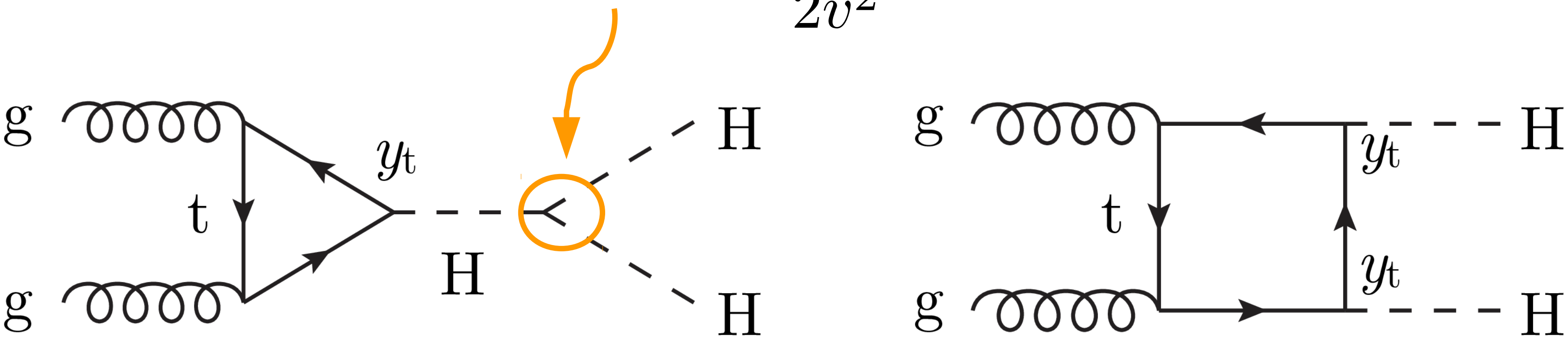
- First observation, now > 5σ
- Longitudinal scattering x-sec.
- Anomalous couplings
- Input to Higgs couplings

HH in the SM

- Measurement of Higgs boson self-coupling
  = a fundamental test of SM!

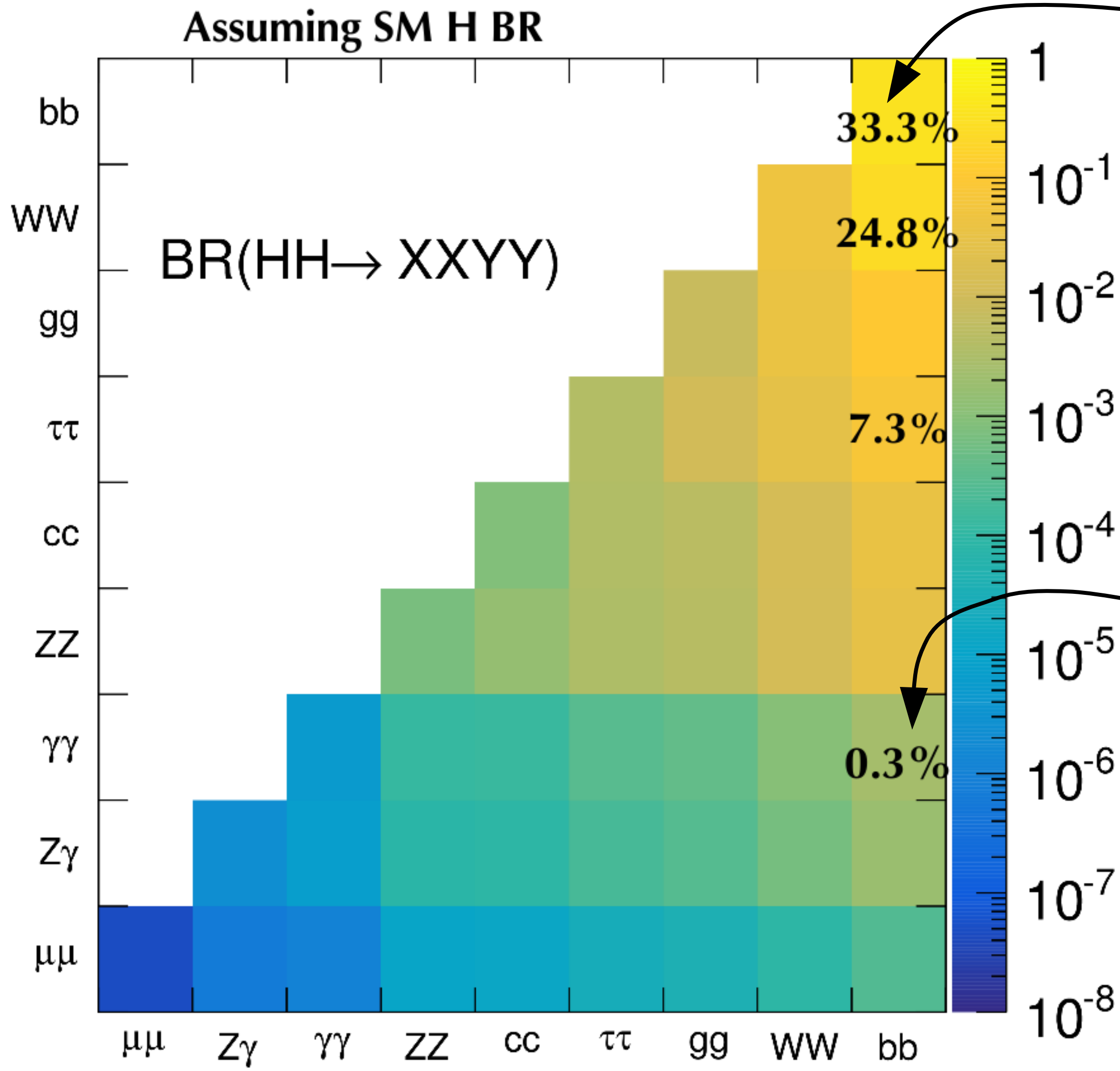
- HHH probes the shape of the Higgs potential!

$$\lambda_{\mathrm{HHH}} = \frac{m_H^2}{2v^2}$$



- SM predicts extremely small cross-section for HH prod.
  - 33.5 fb @ 13 TeV

Complementarity of HH channels

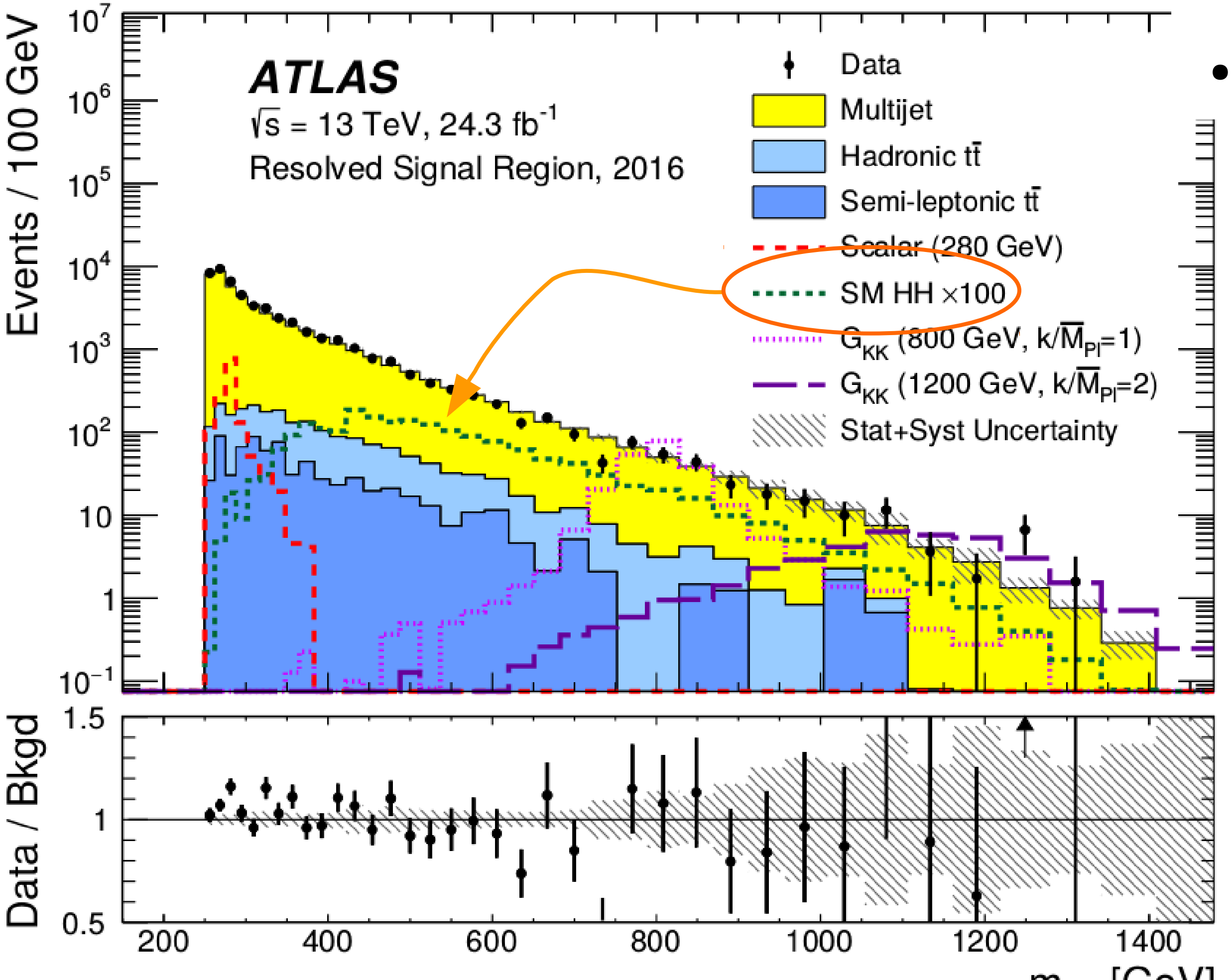


- H(bb)
  - largest BR
  - high ϵ_b, low fake rate suppress light QCD background
  - but, bb QCD still high
- H(γγ)
  - low BR, but
  - low backgrounds
  - excellent mass resolution

HH in SM

- ATLAS $\mathrm{H}(b\bar{b})\mathrm{H}(b\bar{b})$:
  - < 13*SM

Best single limit!

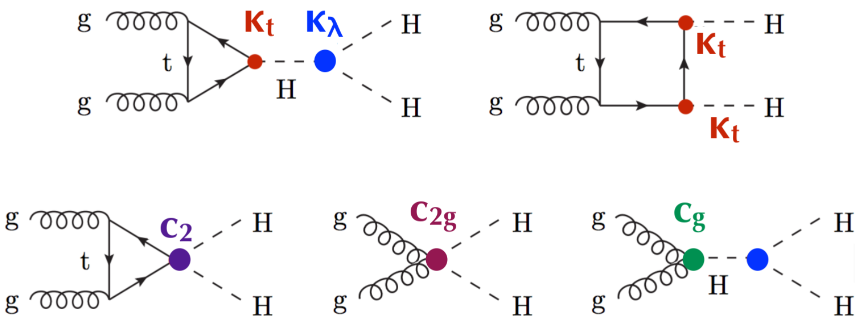


arXiv: 1804.06174

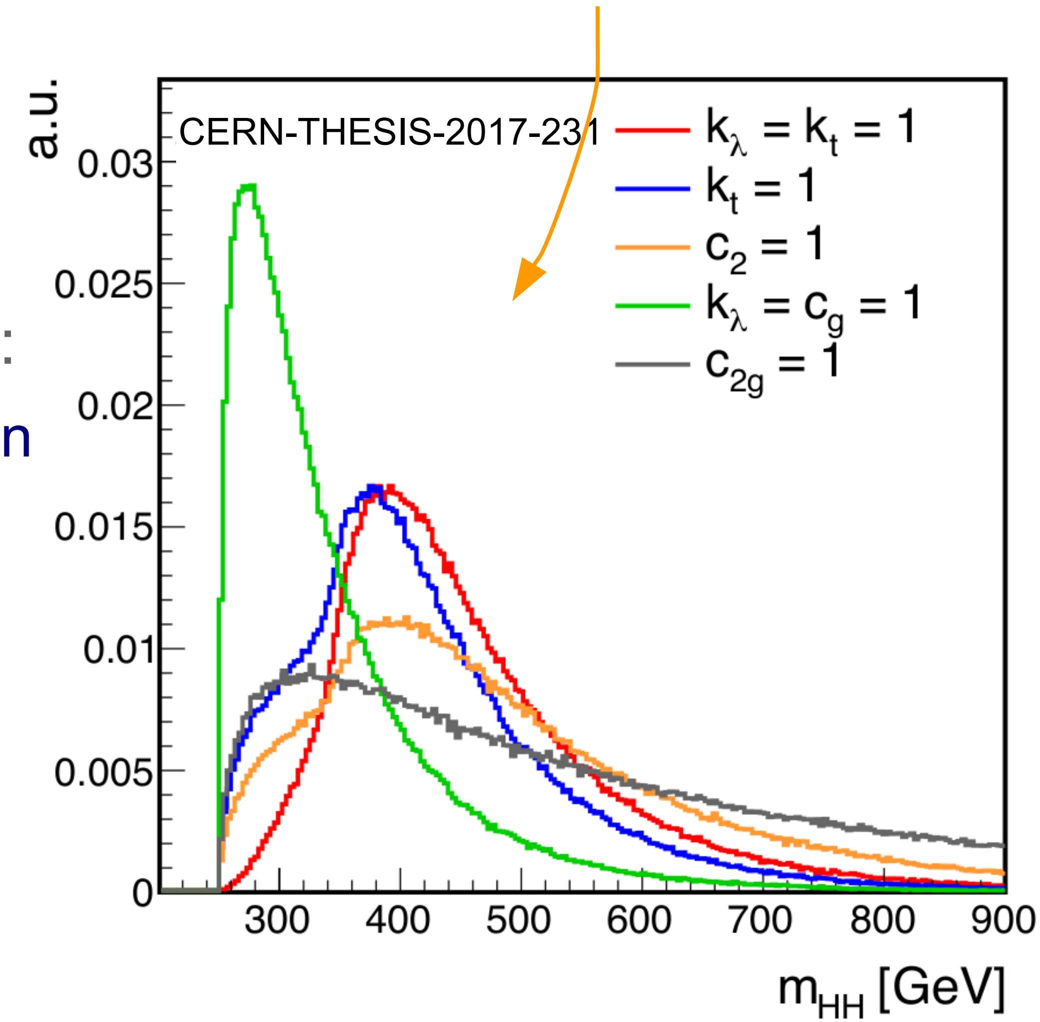
- CMS:
  - $\mathrm{H}(\gamma\gamma)\mathrm{H}(b\bar{b})$: < 19*SM
  - $\mathrm{H}(\tau\tau)\mathrm{H}(b\bar{b})$: < 30*SM
  - $\mathrm{H}(VV^* \to \ell\nu\ell\nu)\mathrm{H}(b\bar{b})$: < 79*SM

SM HH spread out: an absolute bkgd estimate is the key!

HH in BSM (non-resonant)



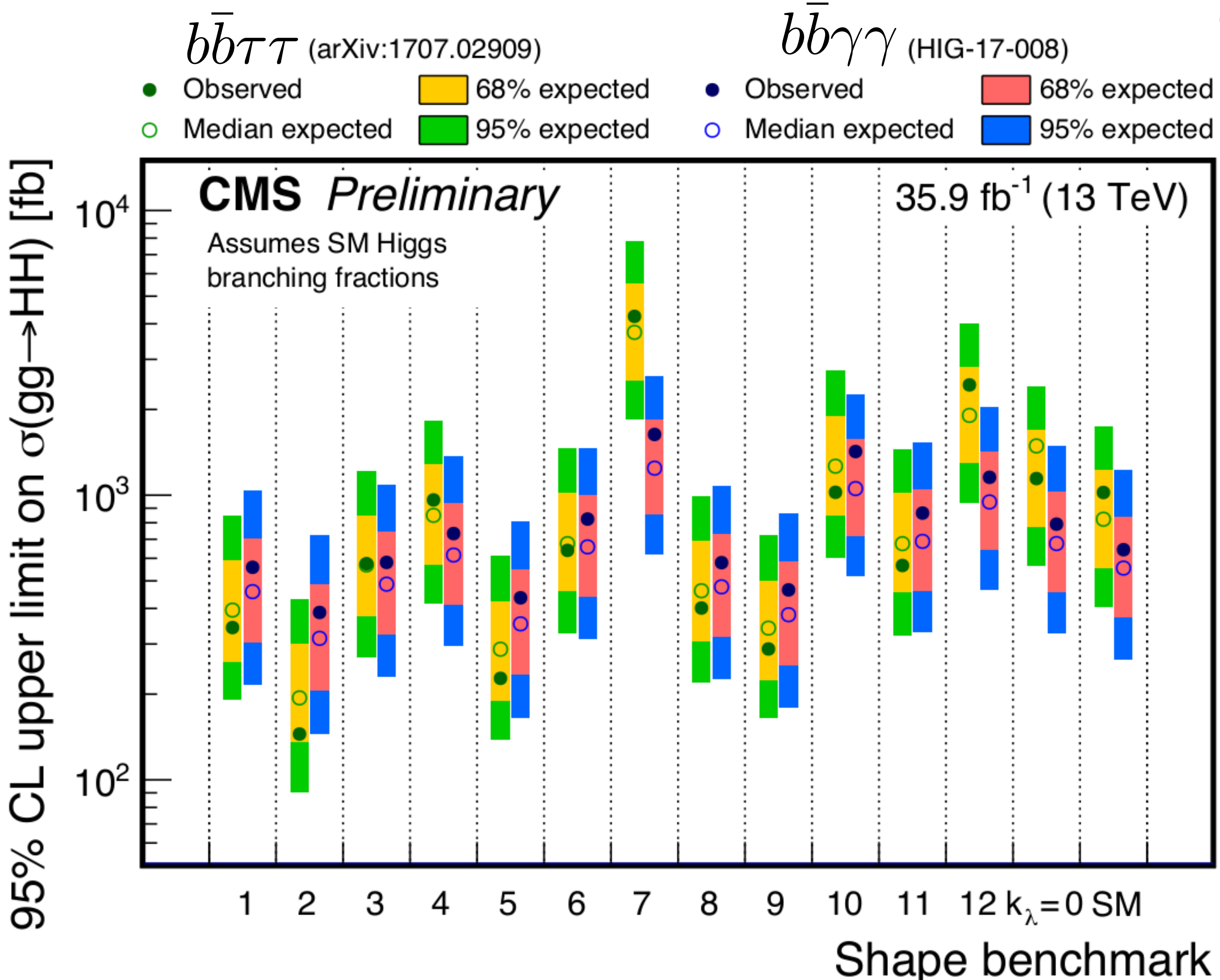
- Strong effects on cross-section and m_{HH} shape!

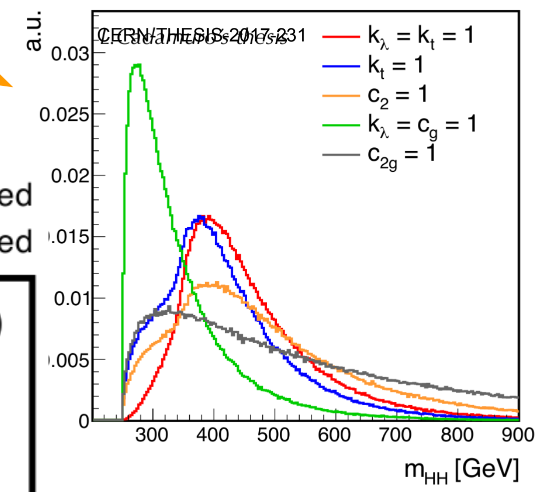


- To see deviation from SM:
  - Better than 20% precision on λ_{HHH}
  - [1305.6397]
- Less for NMSSM
  - [1505.05488]

BSM limits for $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$

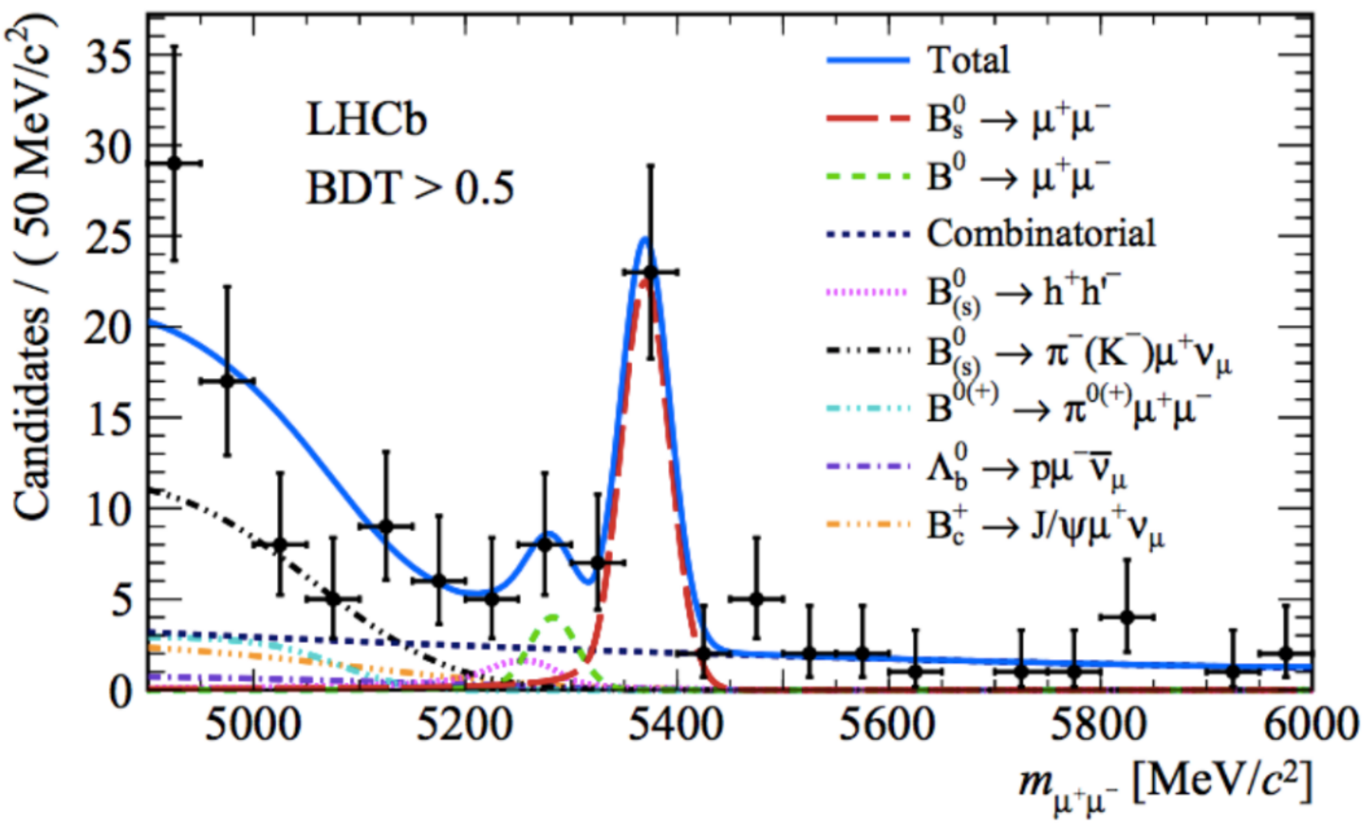
- BSM: 12 "benchmark points"

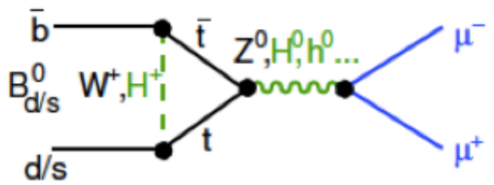


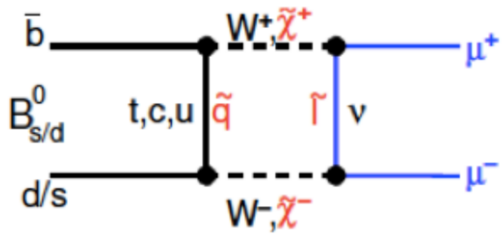


Flavor Physics: $B_s \to \mu^+\mu^-$

- Observation by LHCb alone! (7.8σ)
  - previously by LHCb + CMS combination
  - BDT to identify two μ from same vertex







Consistent with SM predictions.

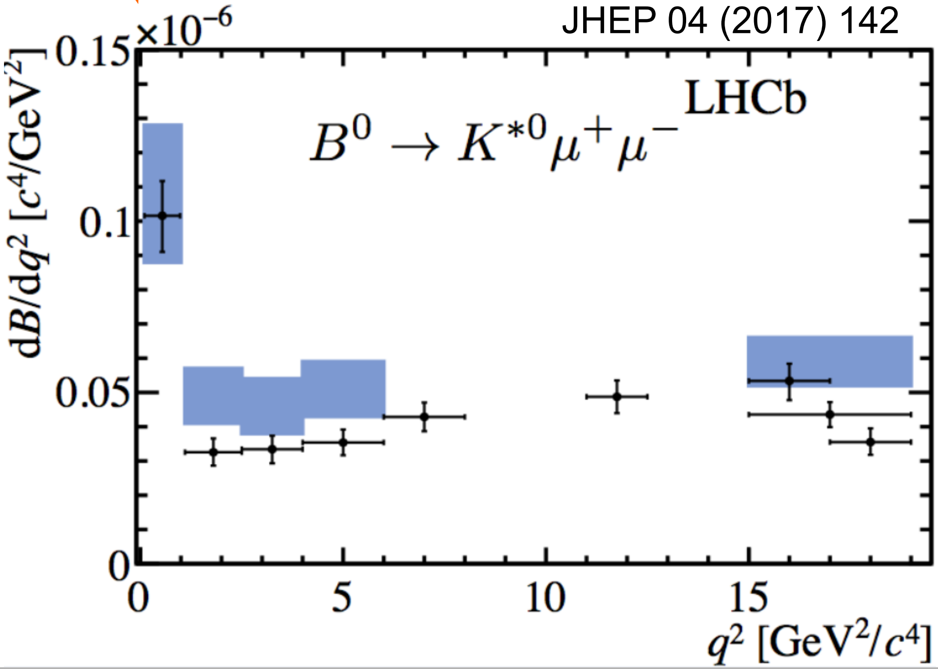
Set stringent limits on possible BSM models

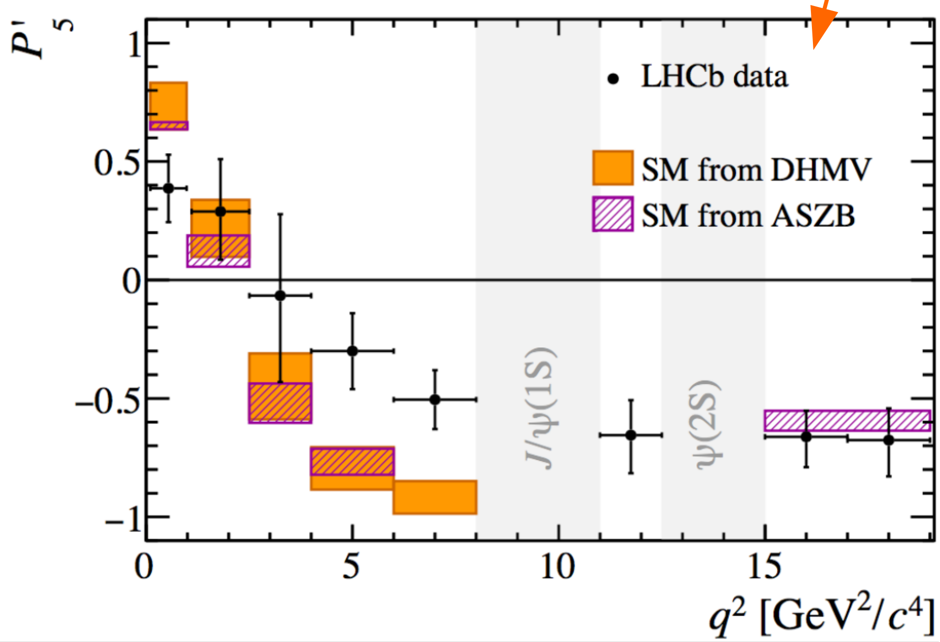
Phys. Rev. Lett. 118, 191801 (2017)

Flavor Physics: anomalies in $b \to s\ell^+\ell^-$

- Differential BR in several $b \to s\ell^+\ell^-$ processes systematically lower than SM predictions.
- Angular analysis (e.g. P_5' from Run 1, 3 fb-1) also show tension with SM.

JHEP 04 (2017) 142



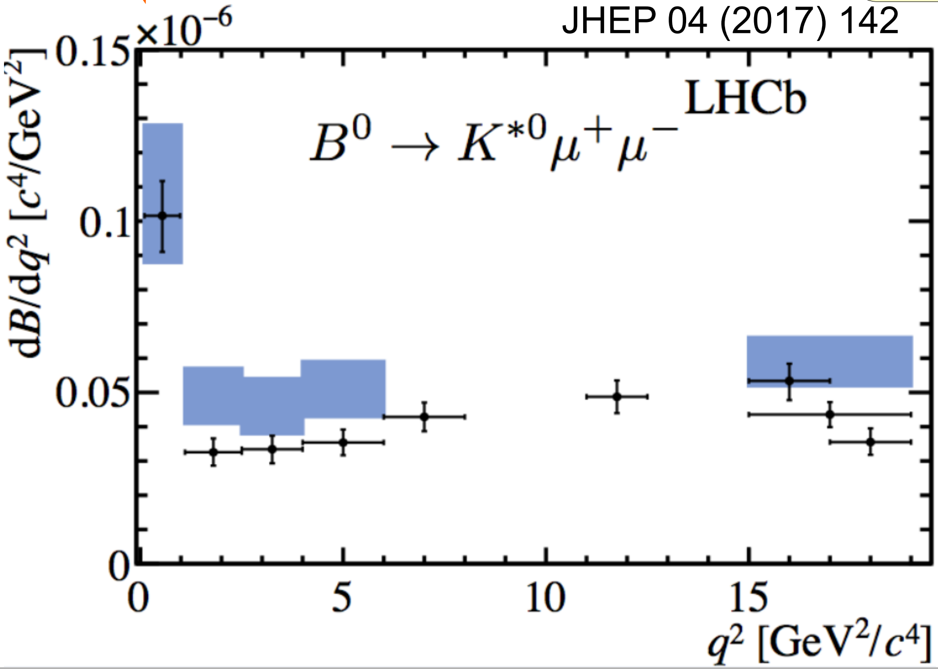


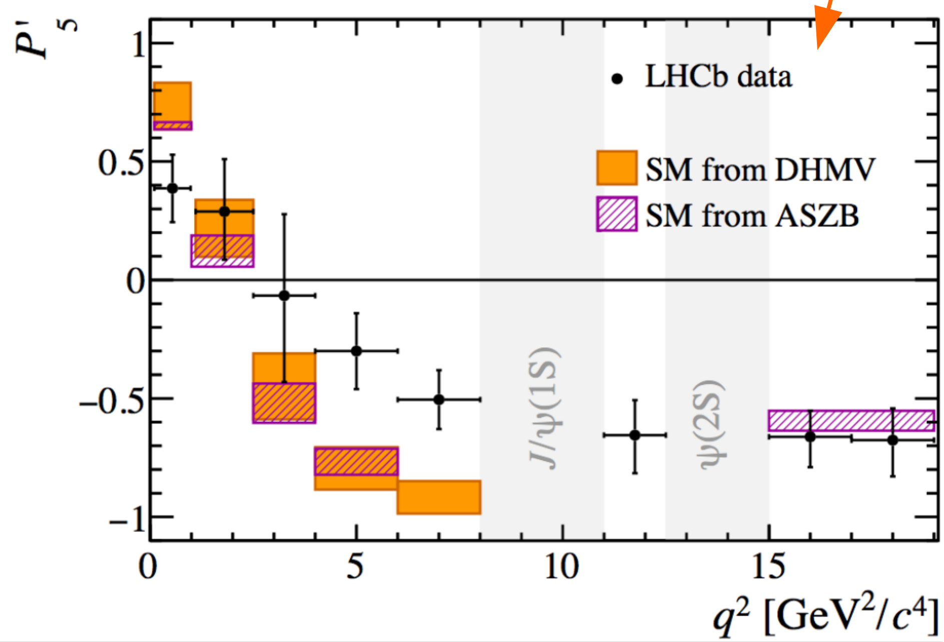
Flavor Physics: anomalies in $b \to s\ell^+\ell^-$

- Differential BR in several $b \to s\ell^+\ell^-$ processes systematically lower than SM predictions.
- Angular analysis (e.g. P_5' from Run 1, 3 fb-1) also show tension with SM.

Hints of BSM physics, or… underestimated QCD uncertainties?

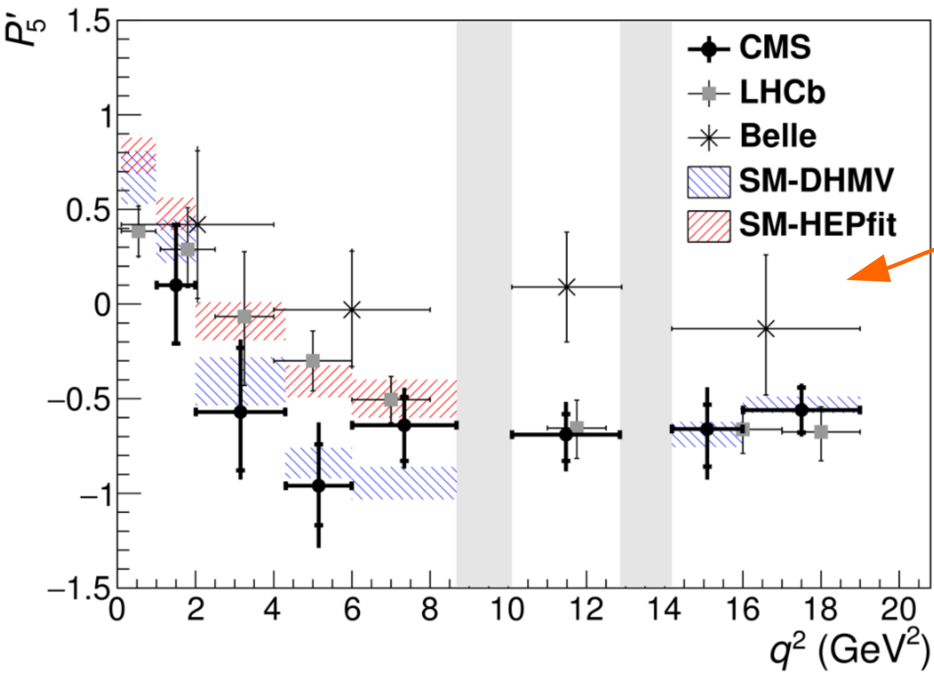
JHEP 04 (2017) 142



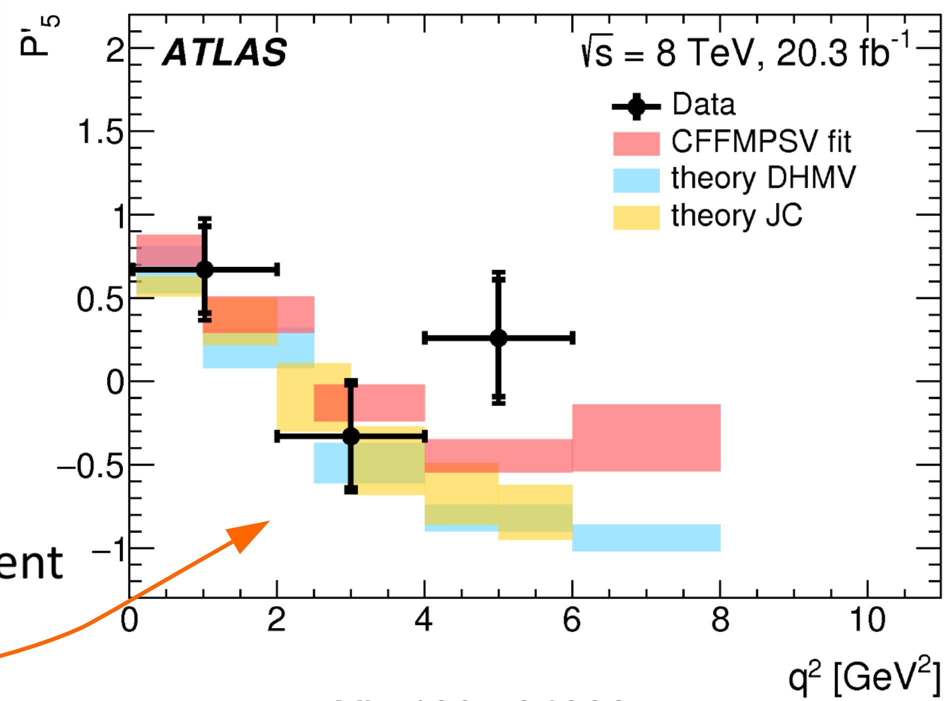


Flavor Physics: anomalies in $b \to s\ell^+\ell^-$

- Angular analysis parameter P_5' also measured by ATLAS and CMS in $B^0 \to K^*\mu^+\mu^-$ decay.



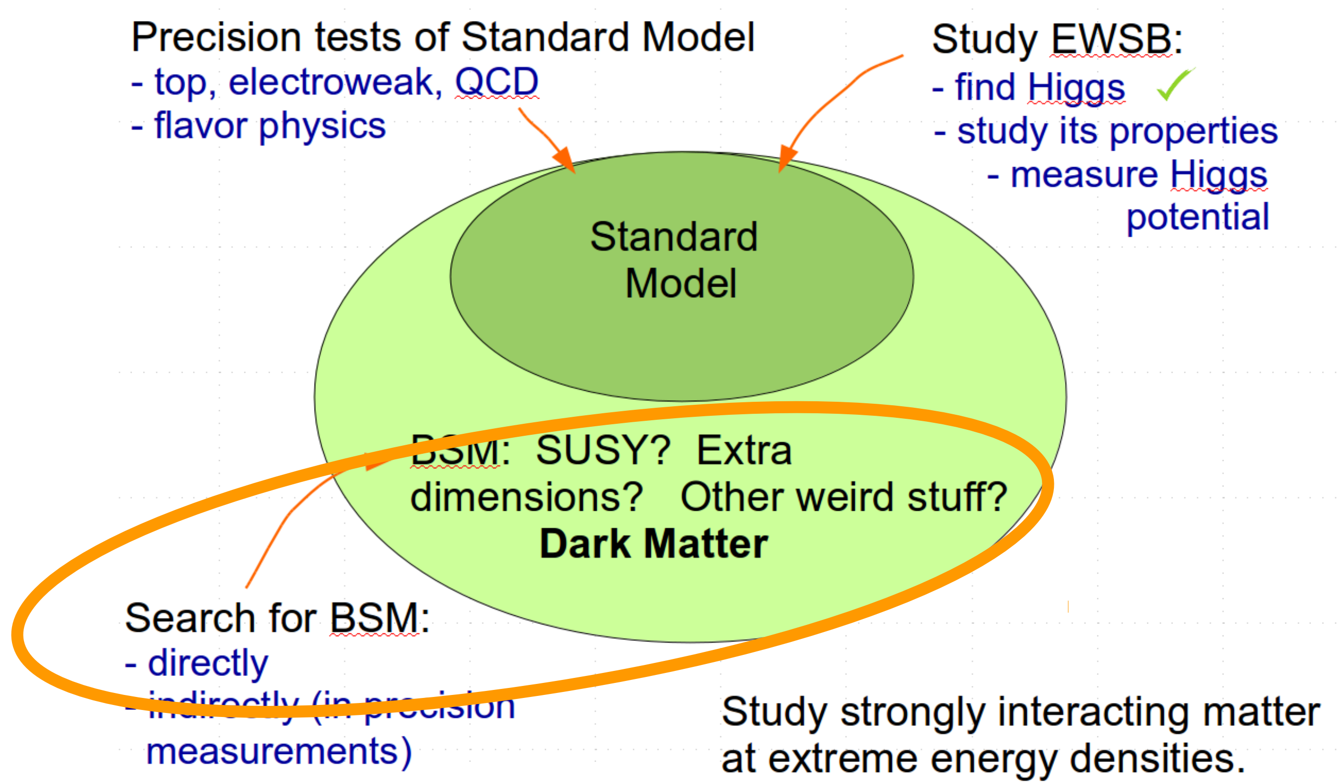
CMS: data compatible with SM predictions in the whole range



ATLAS: generally in good agreement with SM, except a ~2.5 sigma deviation in 1 bin

arXiv:1805.04000

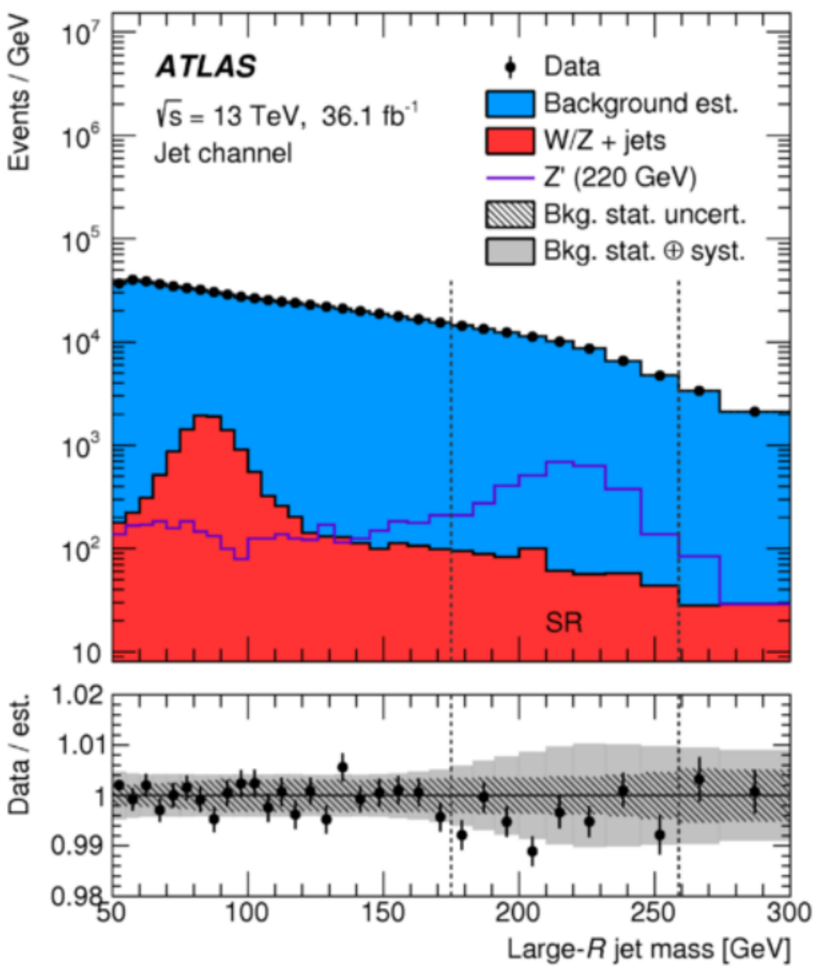
Part II: BSM Searches

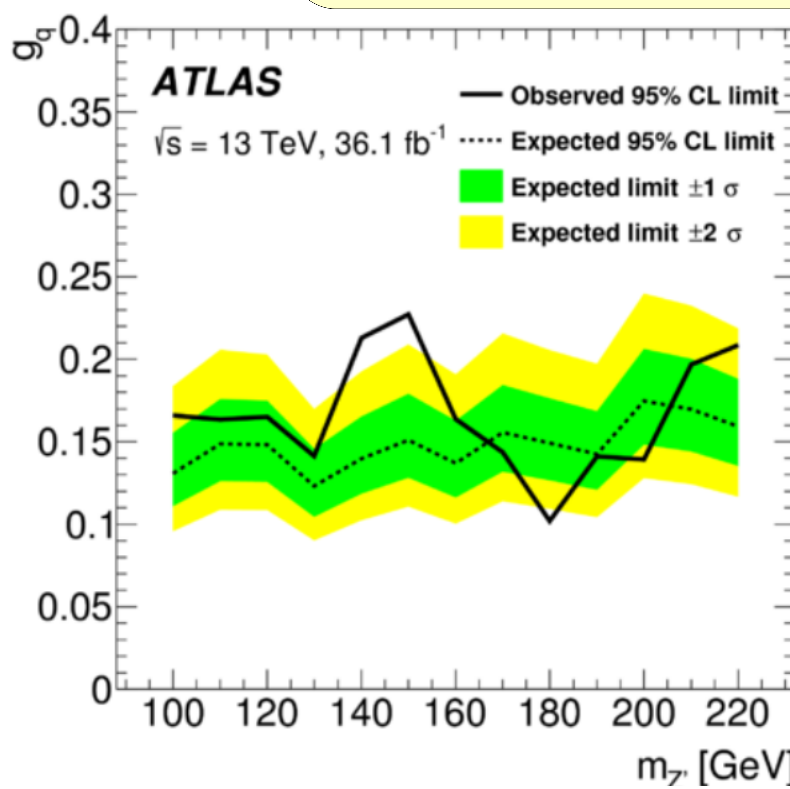


Light X → qq

- Light X recoils against ISR jet / photon

Jet has two “prongs”. Use substructure to isolate signal from QCD



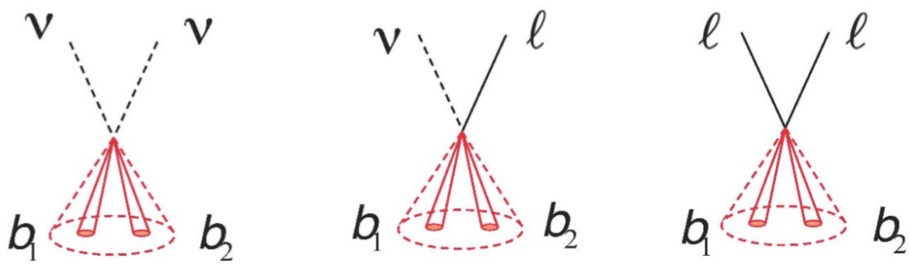


2.4σ deviation at 140 GeV
(1.2σ global)

ATLAS: arXiv:1801.08769 (see also CMS: EXO-17-001)

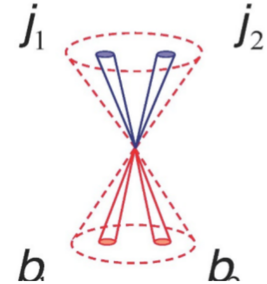
Diboson resonances

With leptons, MET

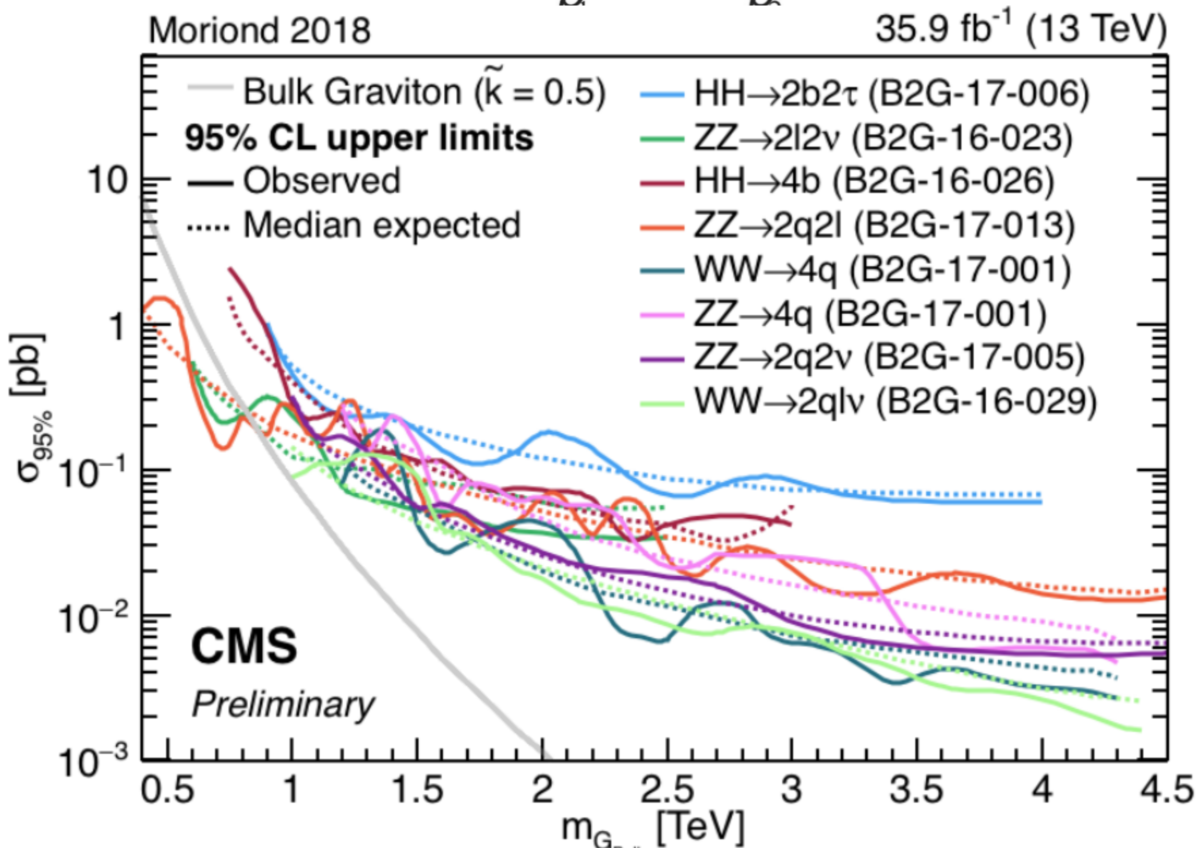


ZH (with Z to νν) WH (with W to lν) ZH (Z to ll)

All hadronic

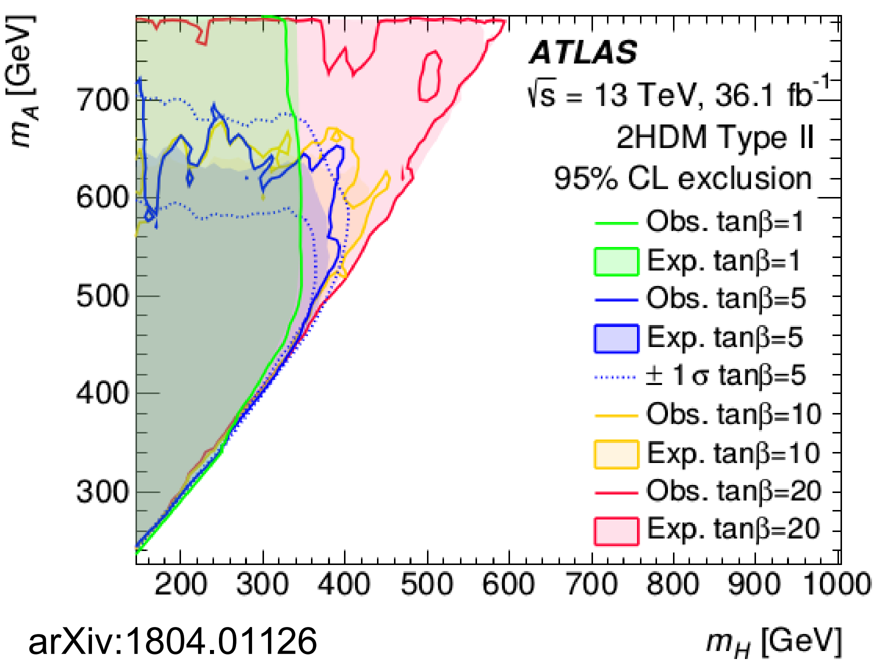


- Heavy use of jet substructure for merged jets from
  - V→ qq
  - H→bb

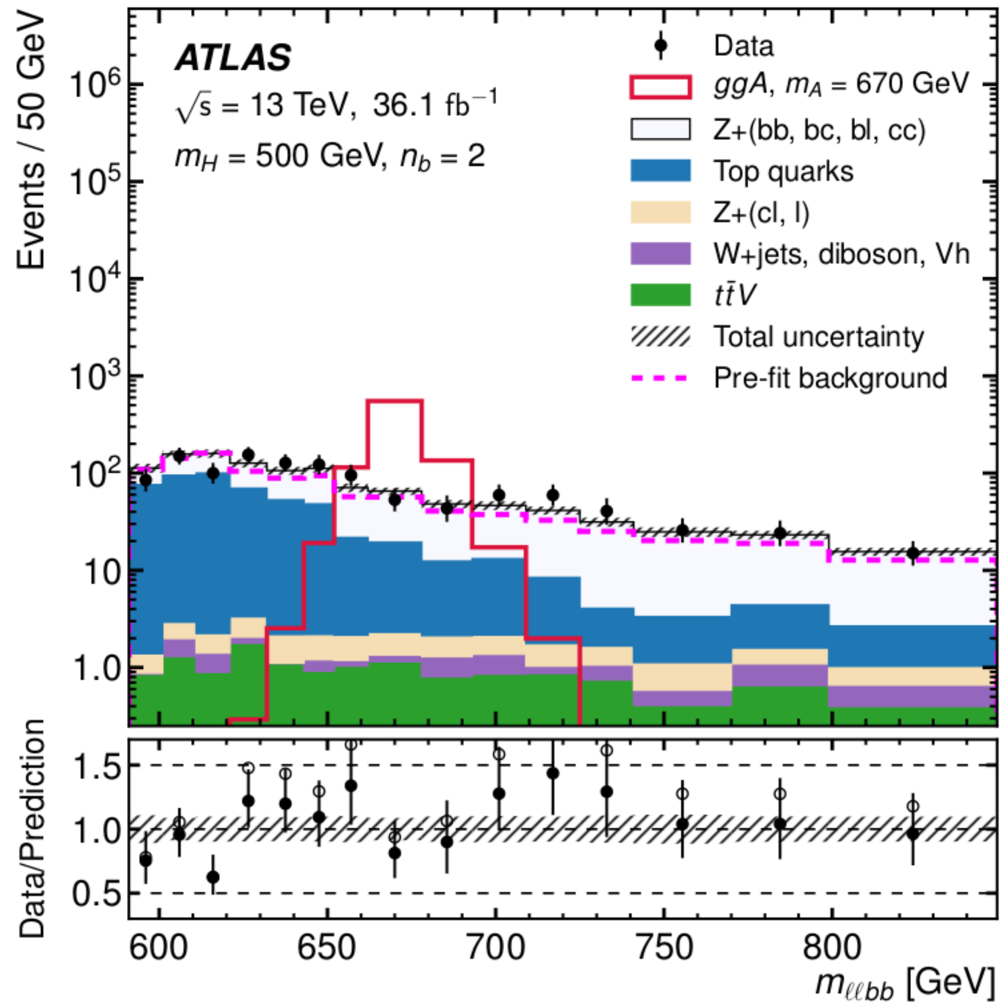


$A \to ZH_{heavy} \to (\ell\ell)(b\bar{b})$

- Additional Higgs bosons well-motivated in many BSM scenarios
  - (e.g. 2HDM)
- Here, two heavy Higgs bosons: $m_A \neq m_{H_{heavy}}$

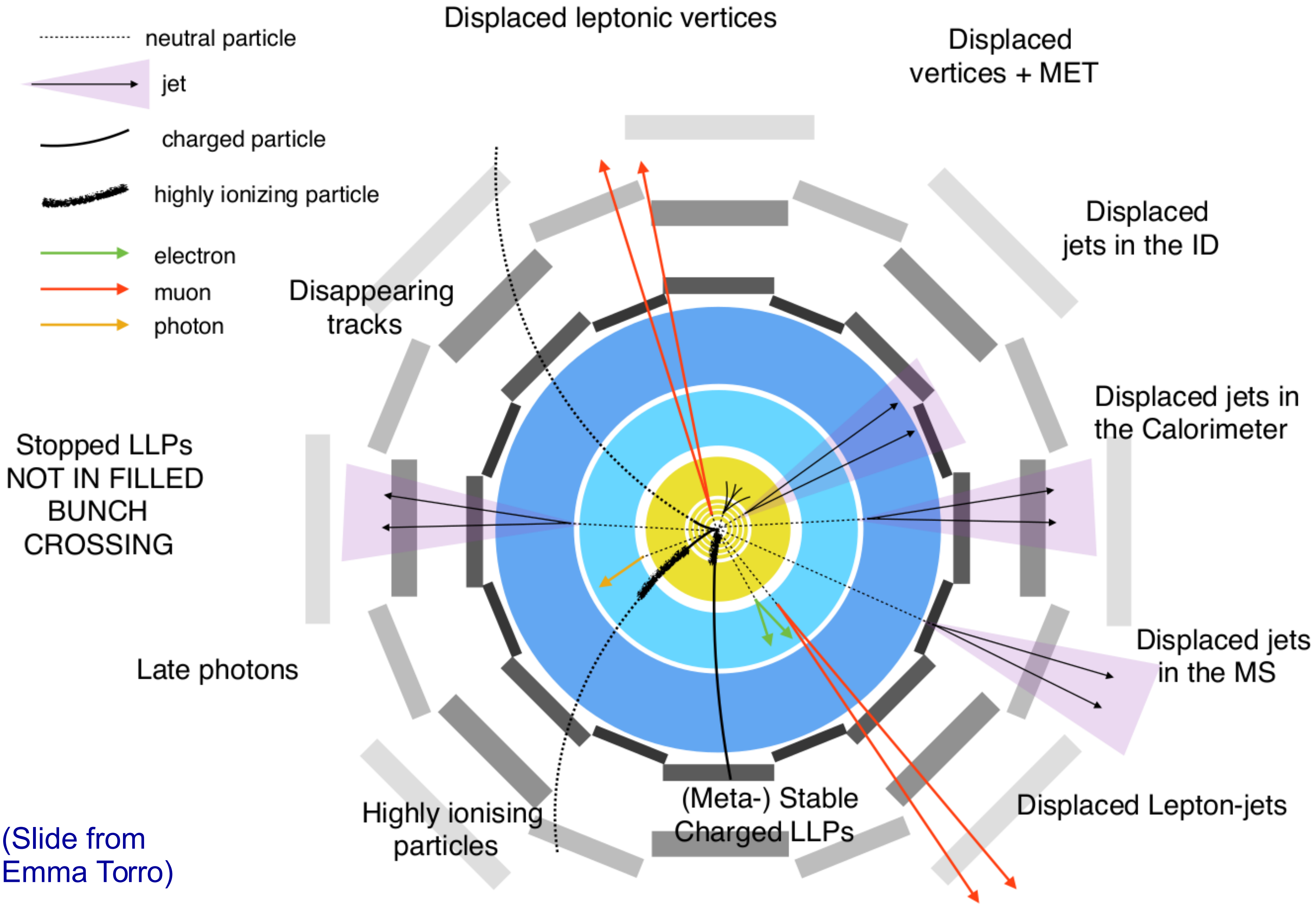


arXiv:1804.01126



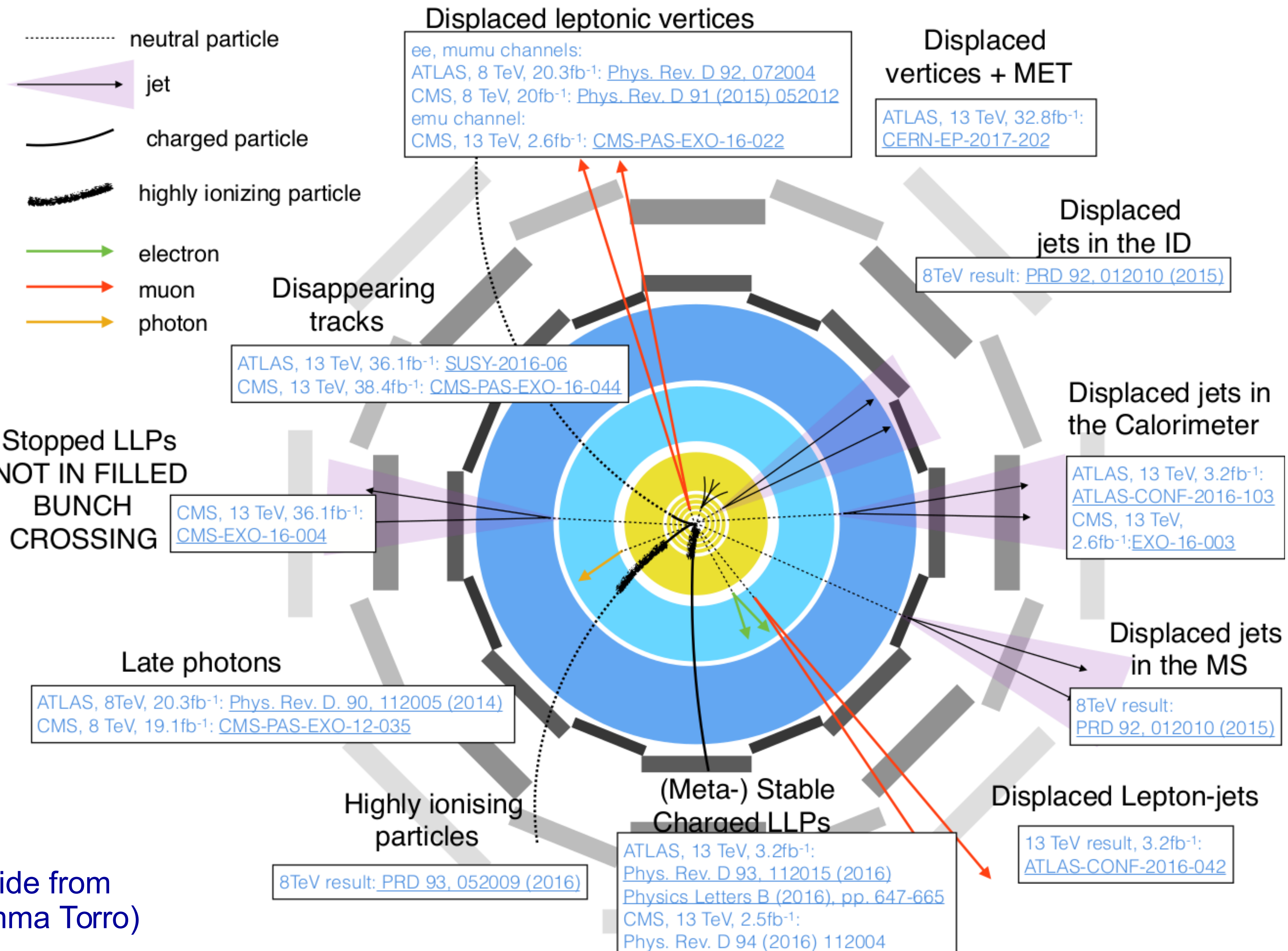
Hopefully, the first in a series of X→YZ searches. (Many models.)

Long-Lived Particles



(Slide from Emma Torro)

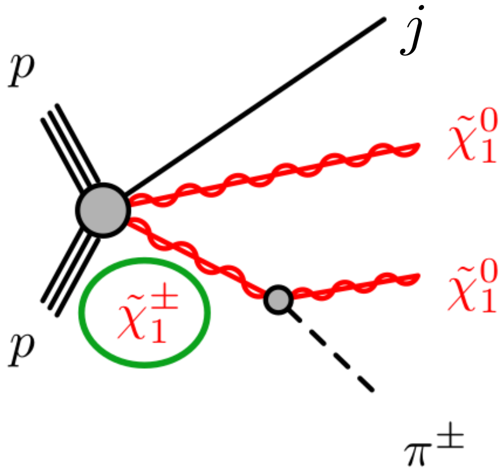
Long-Lived Particles

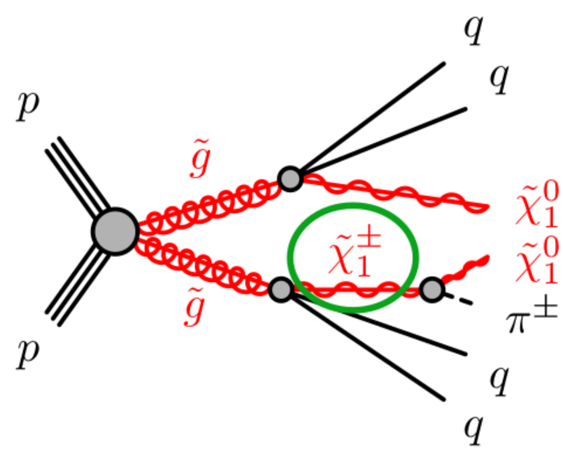


(Slide from Emma Torro)

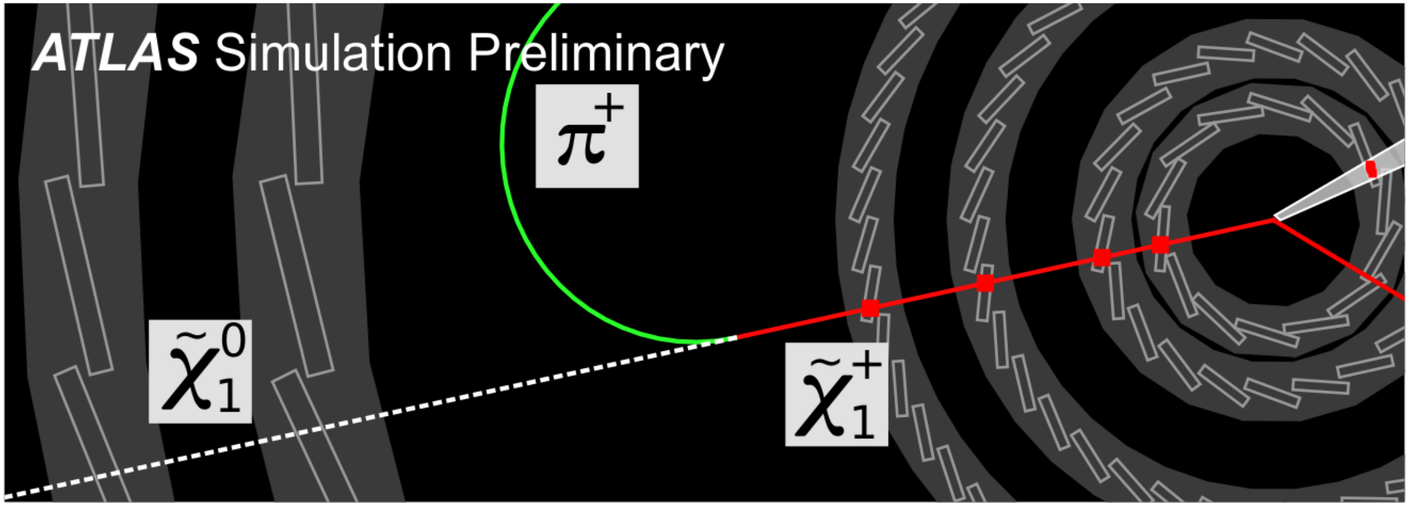
Disappearing tracks

- Anomaly-Mediated SUSY Breaking:
  - almost degenerate neutralino and chargino, Δm ~ 100 MeV



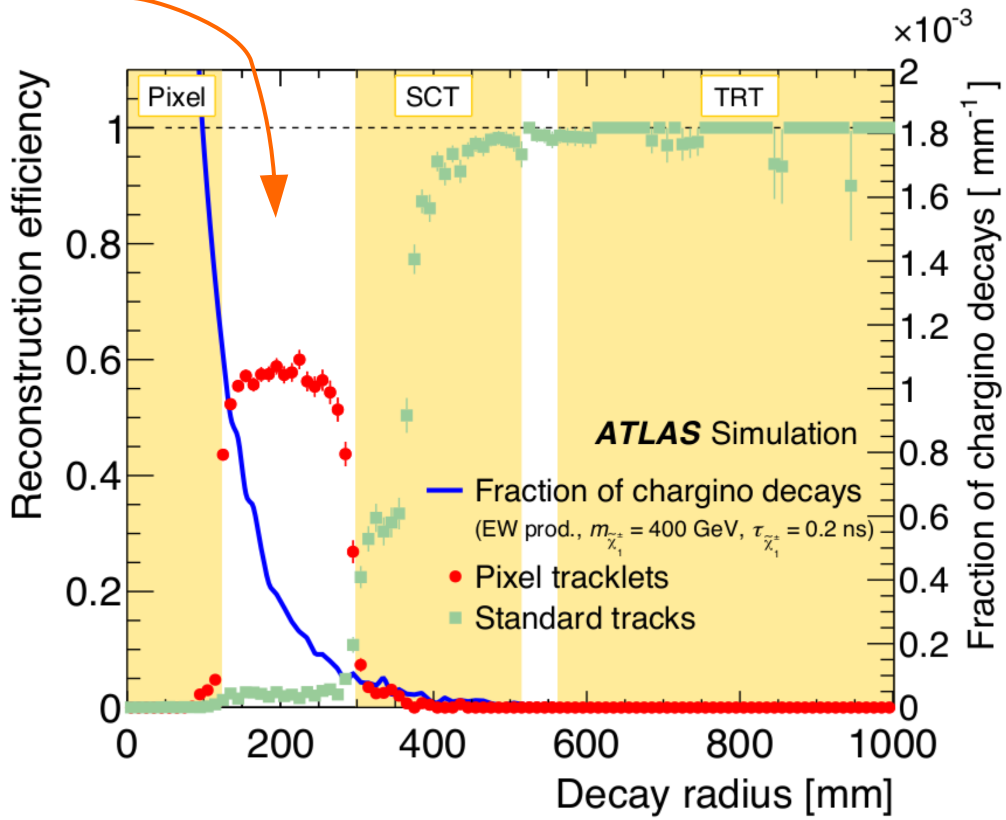


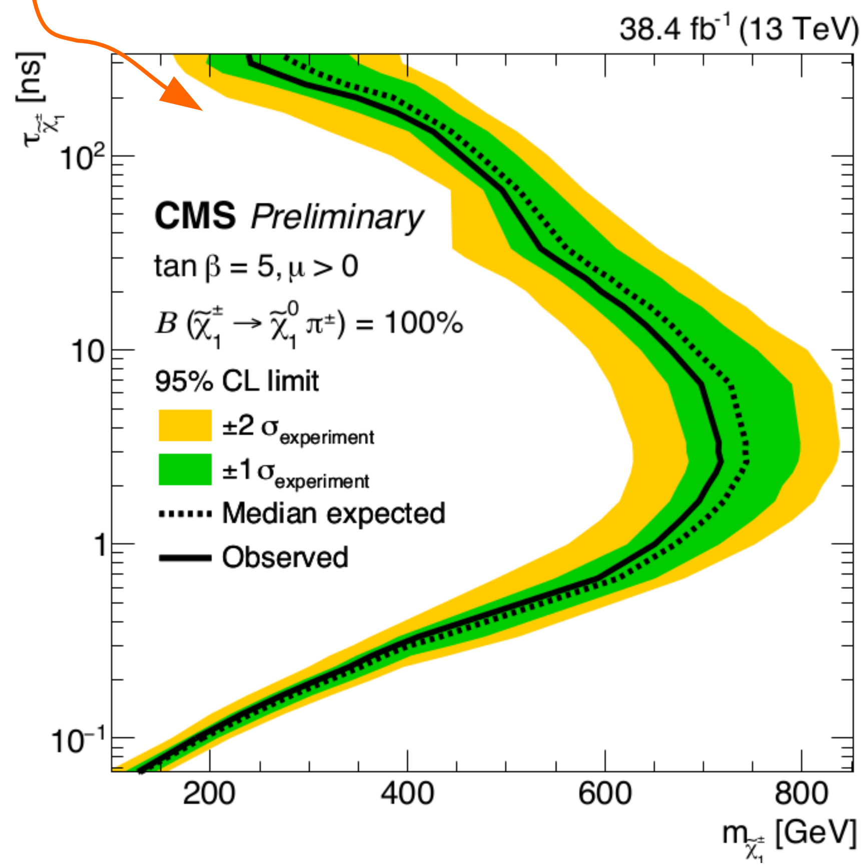
A feat of dedicated tracking technology



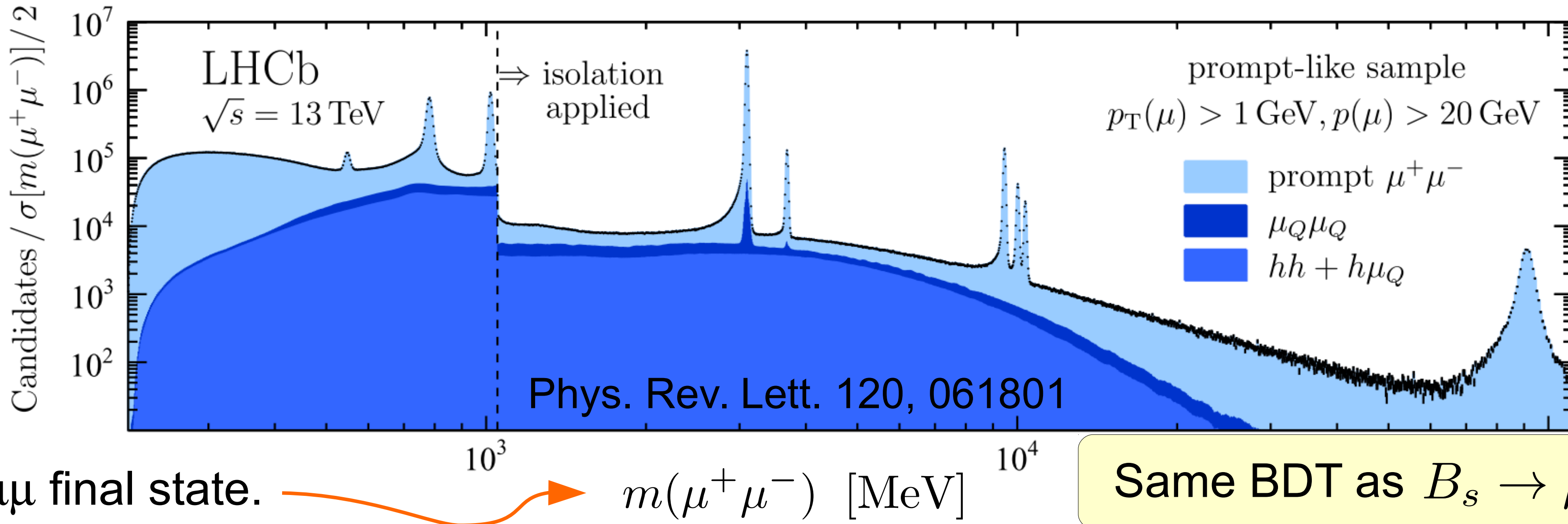
Disappearing tracks

- Search sensitive to LLP lifetime of 10ps to 10 ns
- Limits of chargino mass vs its lifetime



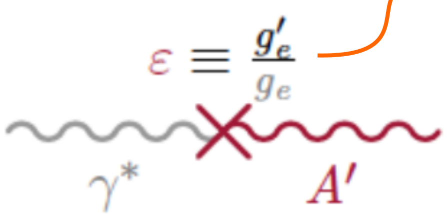


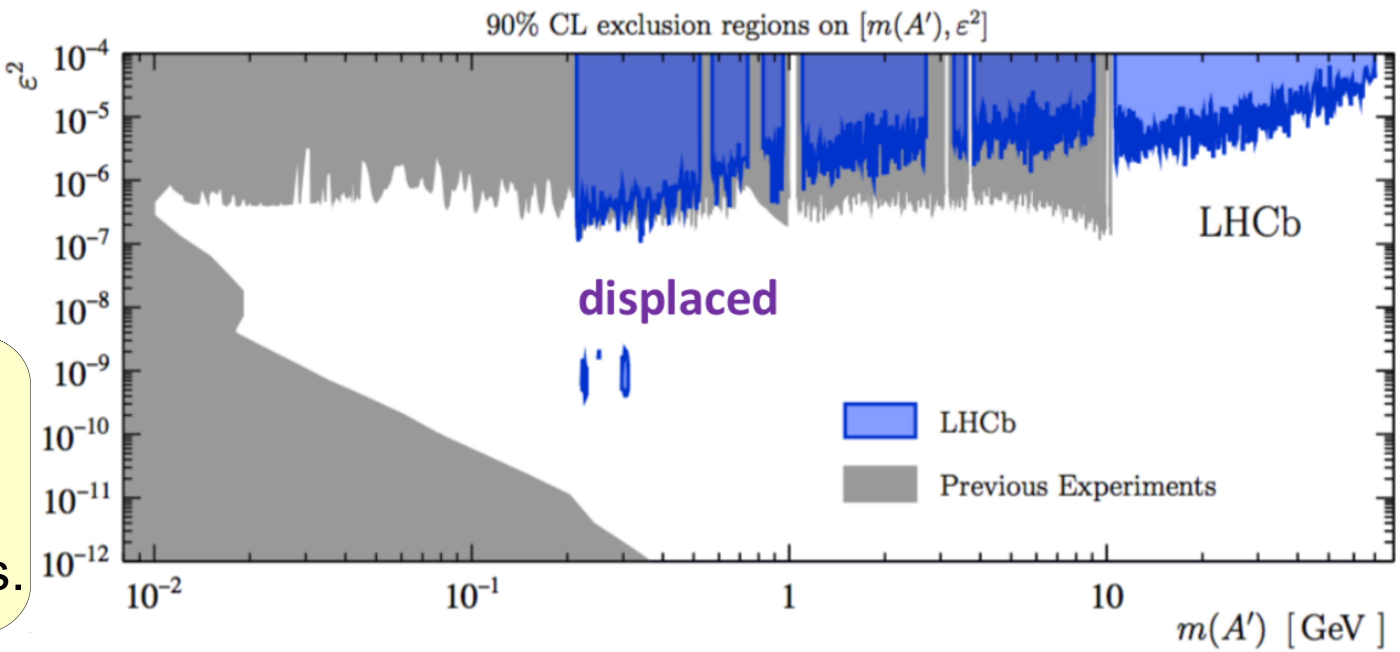
Massive Dark Photons – a dark sector portal



Same BDT as $B_s \to \mu\mu$

μμ final state.
Both prompt and displaced.

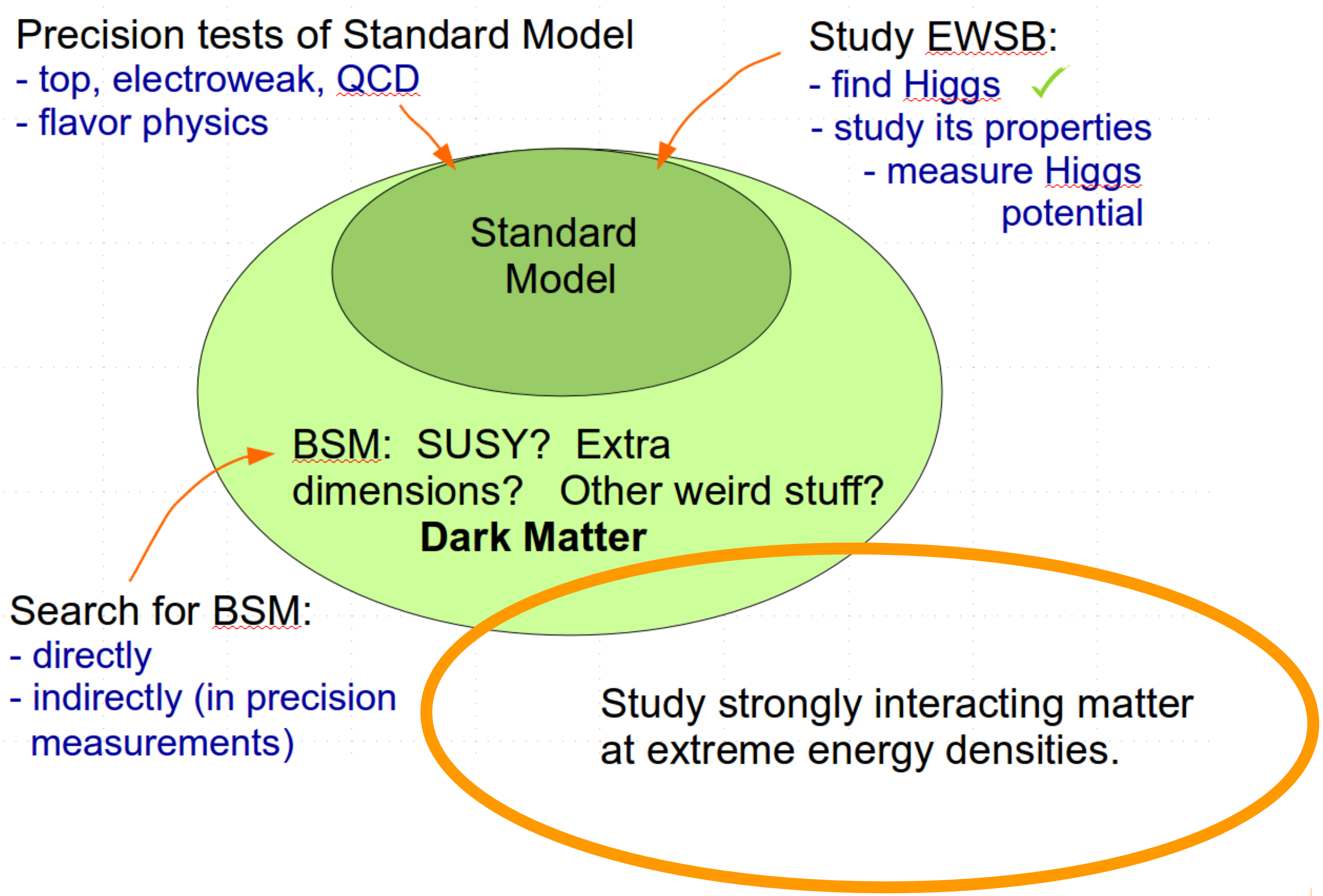




World's best limits
10.6 – 70 GeV

First displaced limits.

Part III: Heavy Ion Physics

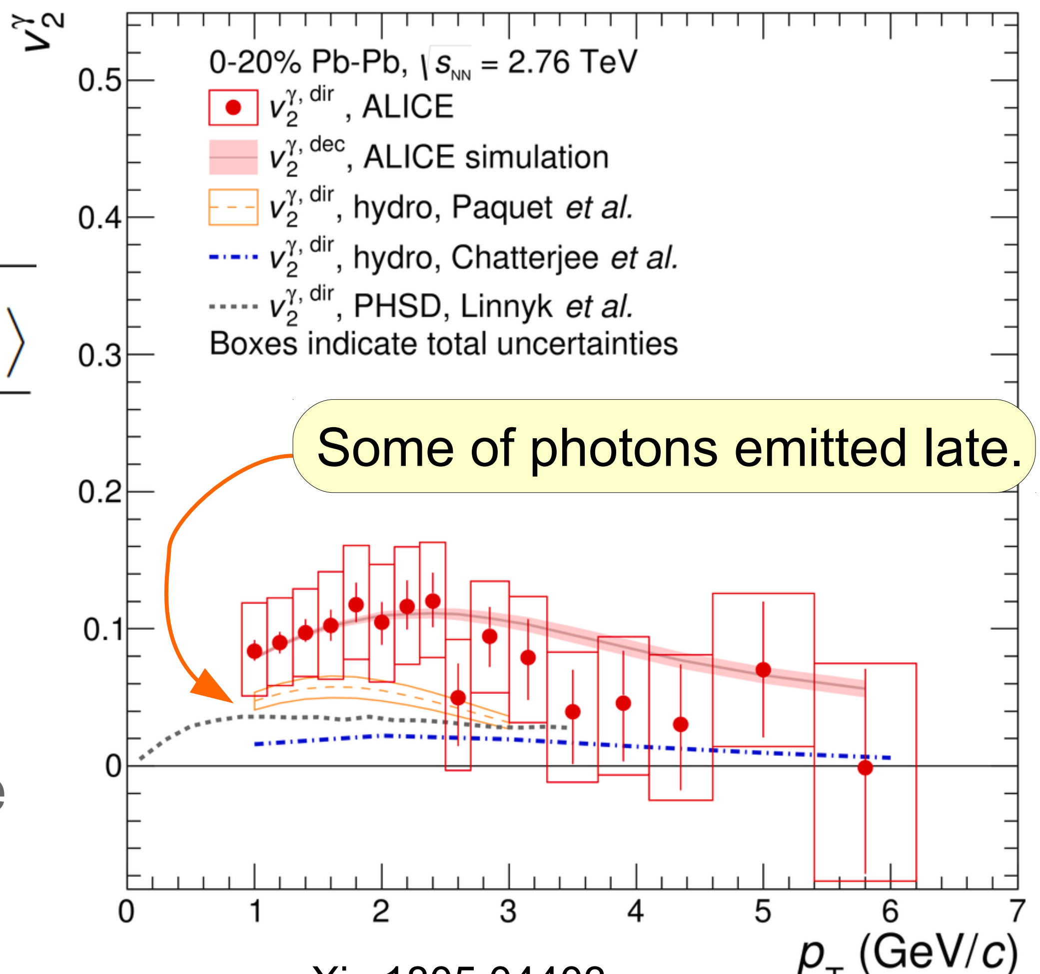


Collective flow, using direct photons

- Study QGP, photons escape the collision zone unaffected
- Carry info on conditions at production time, and on the development of collective flow.

Eliptic flow:

$$v_2 = \sqrt{\frac{\left\langle\left\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{A*}}{M_A} \right\rangle\right\rangle \left\langle\left\langle \vec{u}_2 \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle\right\rangle}{\left\langle \frac{\vec{Q}_2^{A}}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \right\rangle}}$$



arXiv:1805.04403

Challenge: must subtract large decay photon bkg!

- Need more stats to settle "direct photon puzzle".

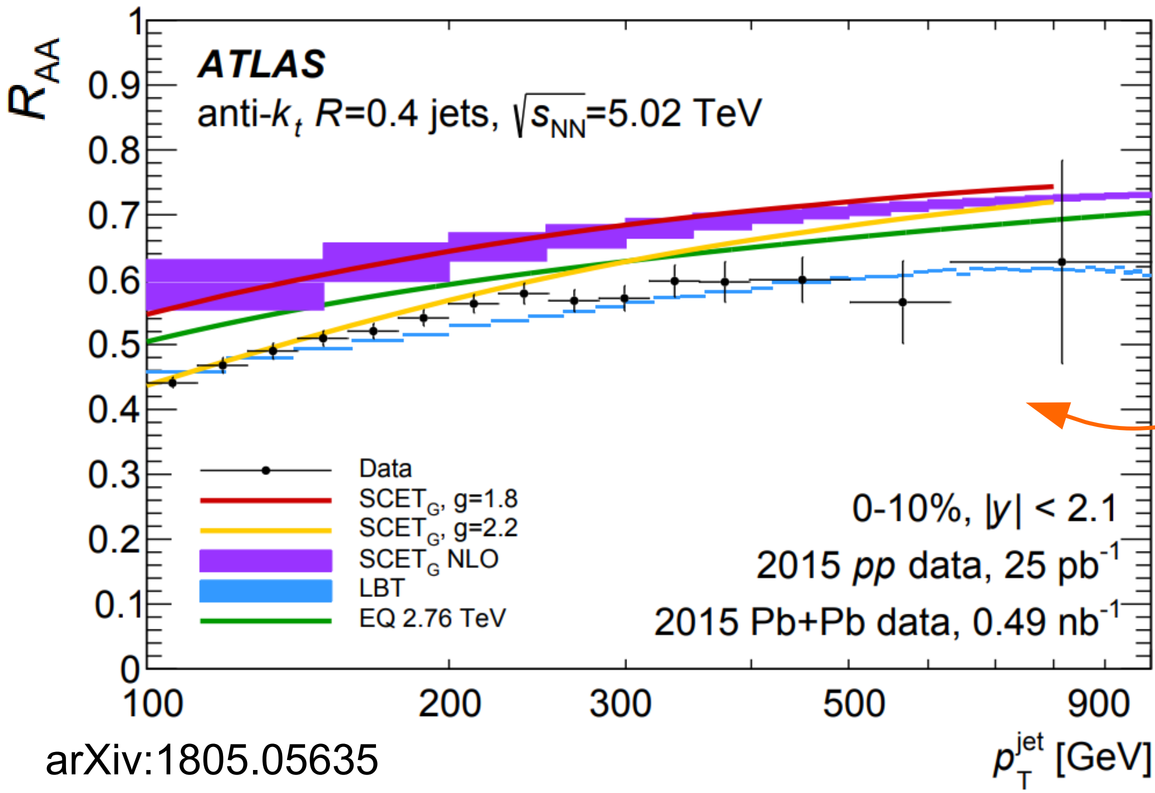
Nuclear modification factor, R_{AA}

- Jet quenching = hard partons lose energy in QGP medium
- Normalize double-differential rate:

(suppression of jet yields in central collisions relative to pp)

$$R_{AA} = \frac{\left.\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{AA}\rangle \left.\frac{\mathrm{d}^2\sigma_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{pp}}$$

(mean nuclear thickness function)



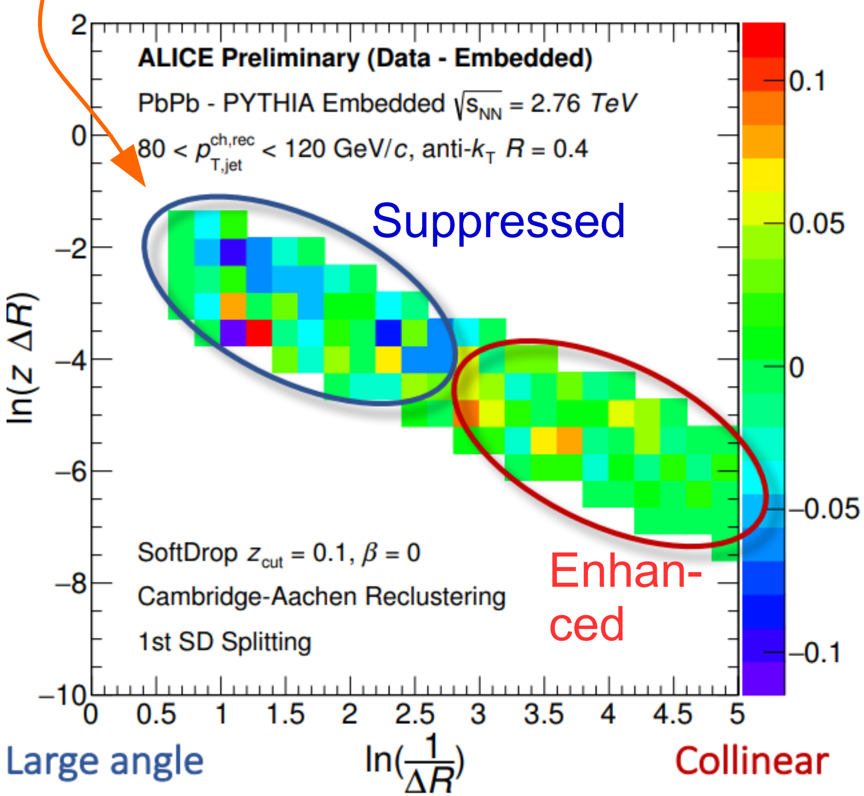
arXiv:1805.05635

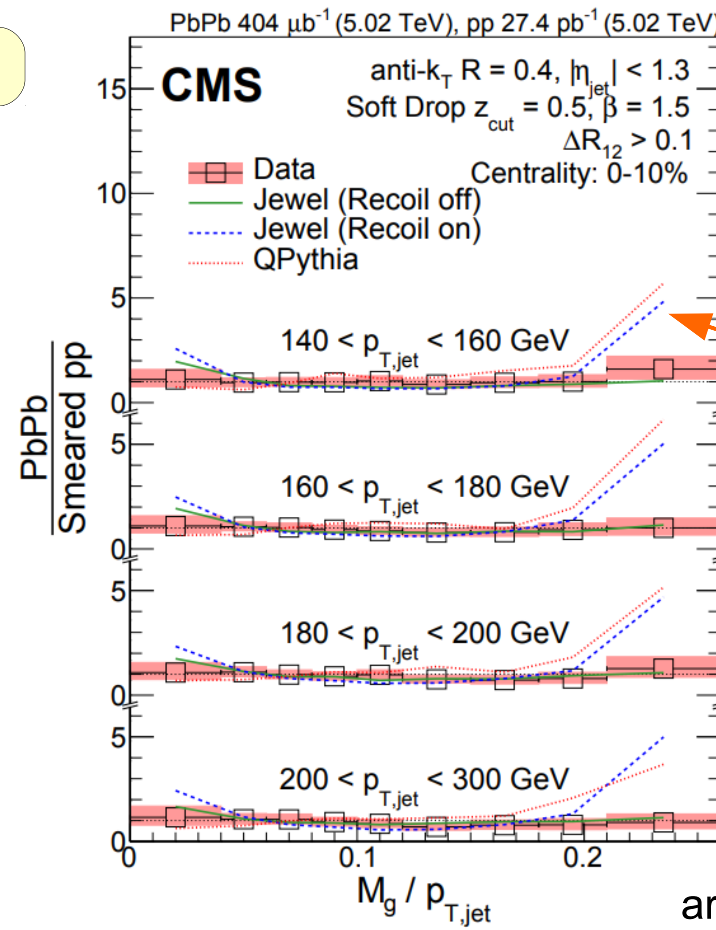
Comparison with models of QGP

Studies of QGP using “jet grooming”

- Jet grooming: remove large-angle, soft radiation inside a jet
  - reveals underlying hard structure
  - study interactions of hard partons with QGP

Modification of z_g distribution in PbPb



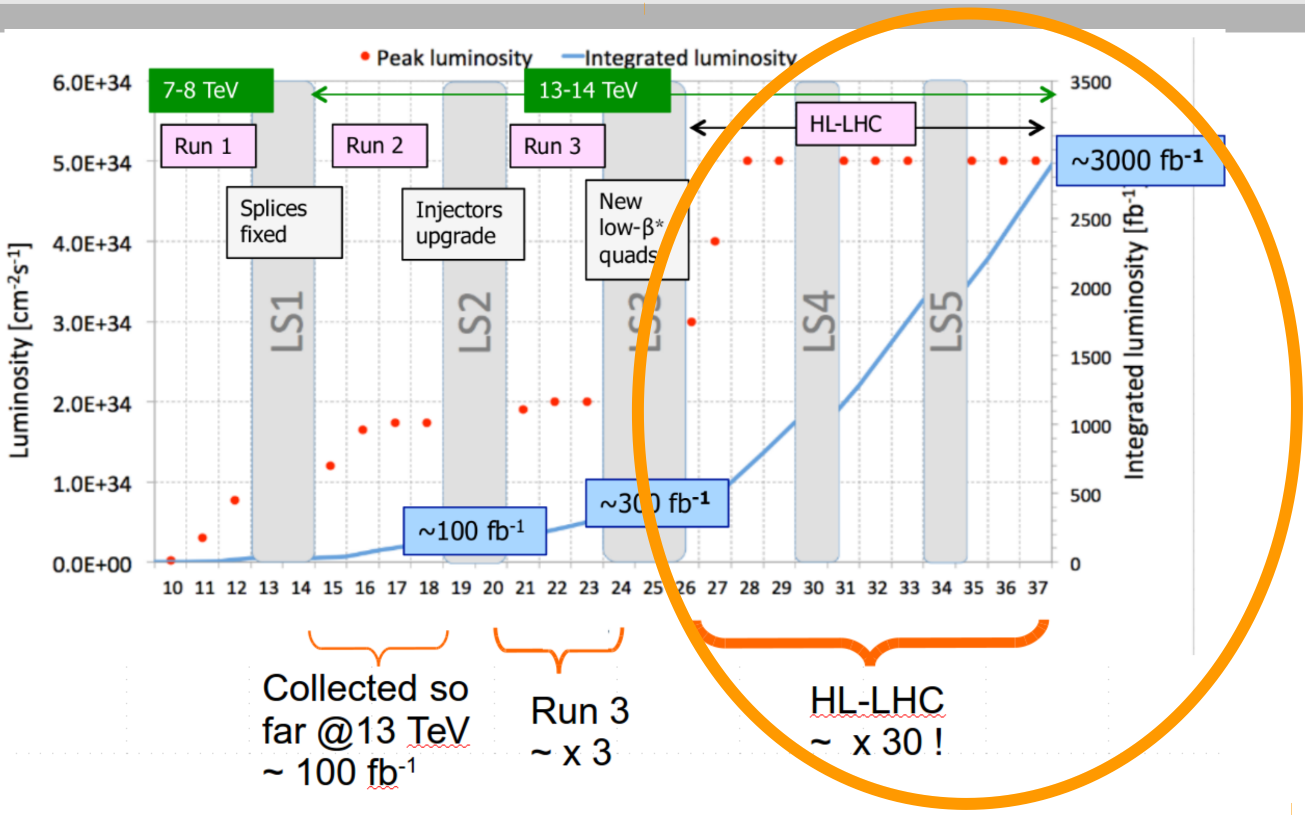


Groomed $m_{\rm jet}/p_T$ in QGP

Comparison with models of QGP

arXiv:1805.05145

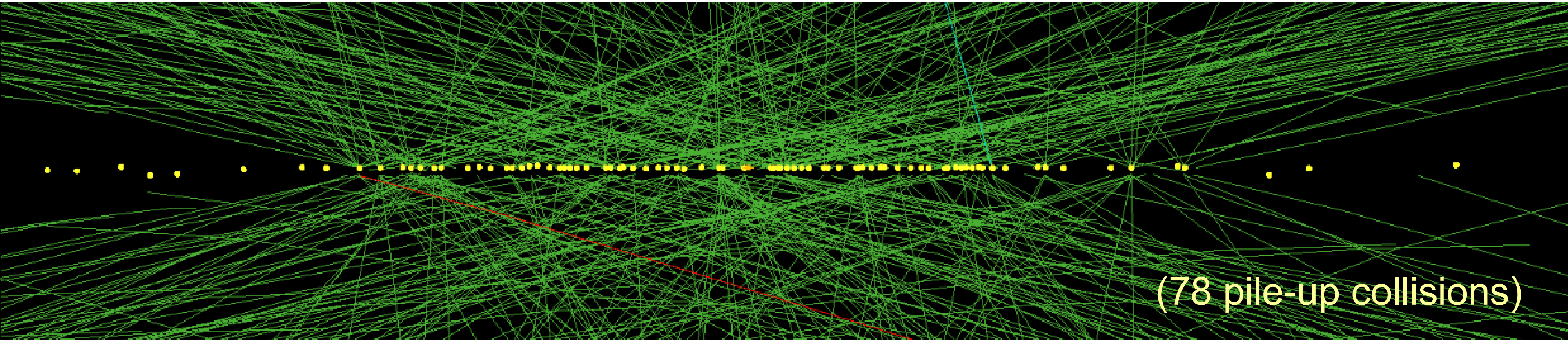
Part IV: The future



- With x30 statistics, greatly extend reach of all searches!
- Greater luminosity: a blessing and a curse
- Upgrade detectors to cope, but also to improve capabilities

Upgrades for HL-LHC

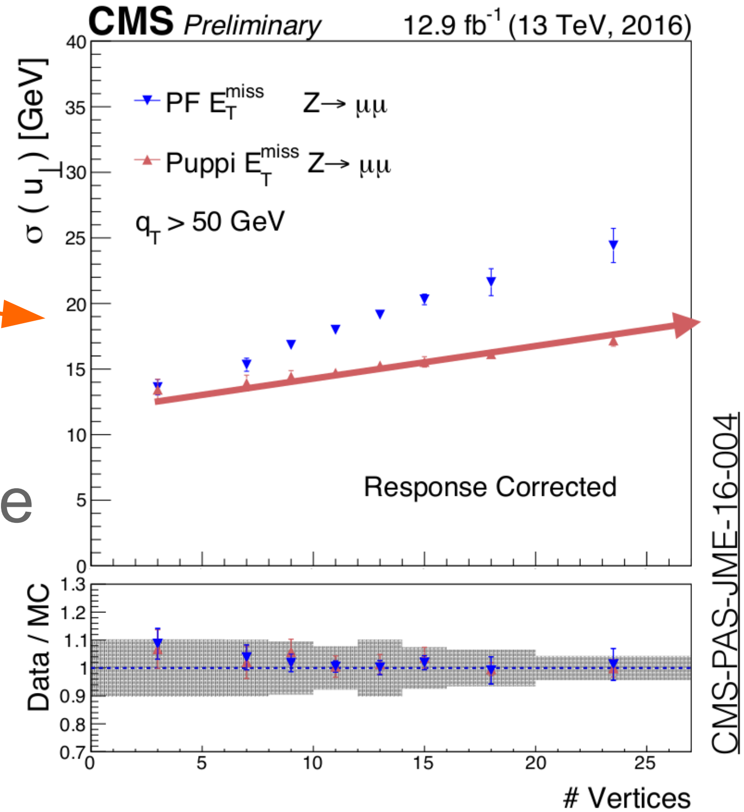
- “Pile-up” = additional interactions in the same bunch crossing
- High Luminosity $\Leftrightarrow$ Large number of pile-up interactions



- Pile-up trouble:
  - Energy added to jets
  - Many spurious hits in the tracker
  - Larger data volume
  - Larger trigger rates
  - Much more radiation damage

Upgrades for HL-LHC

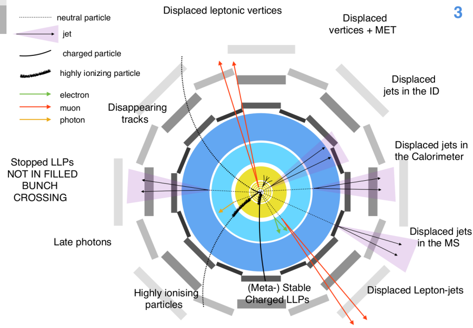
- Pile-up mitigation #1: software
  - clever algorithms to remove & correct effect of PU *offline*
  - data still needs to be read out



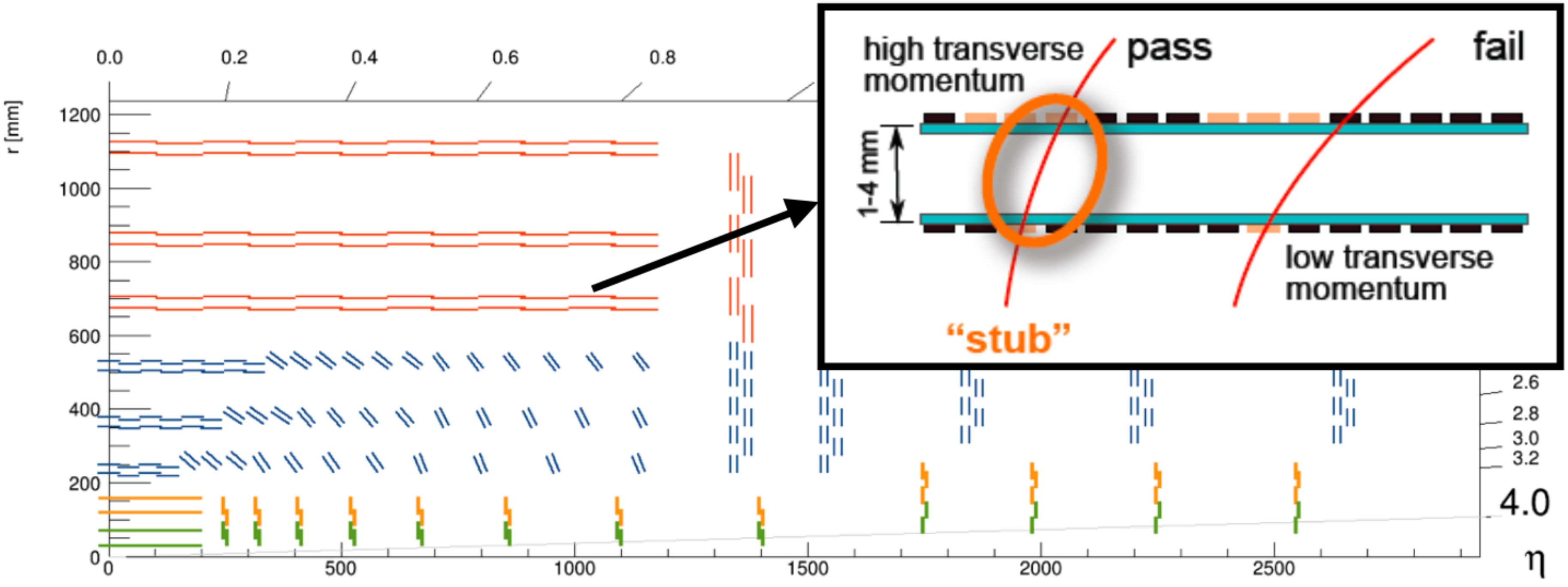
- Pile-up mitigation #2: better hardware
  - smaller granularity
  - more rad-hard
  - faster read-out
- Main goal: maintain performance @ very high # of pile-up.
- However, can improve physics too!
  - new detector systems, new triggers

HL-LHC: trigger on displaced particles

- Displaced tracks: rich physics program



- ATLAS and CMS both adding track triggers



- Tracking information improves other triggers (e.g. leptons)

Summary

- LHC has a rich program in searches for solutions to many remaining questions.

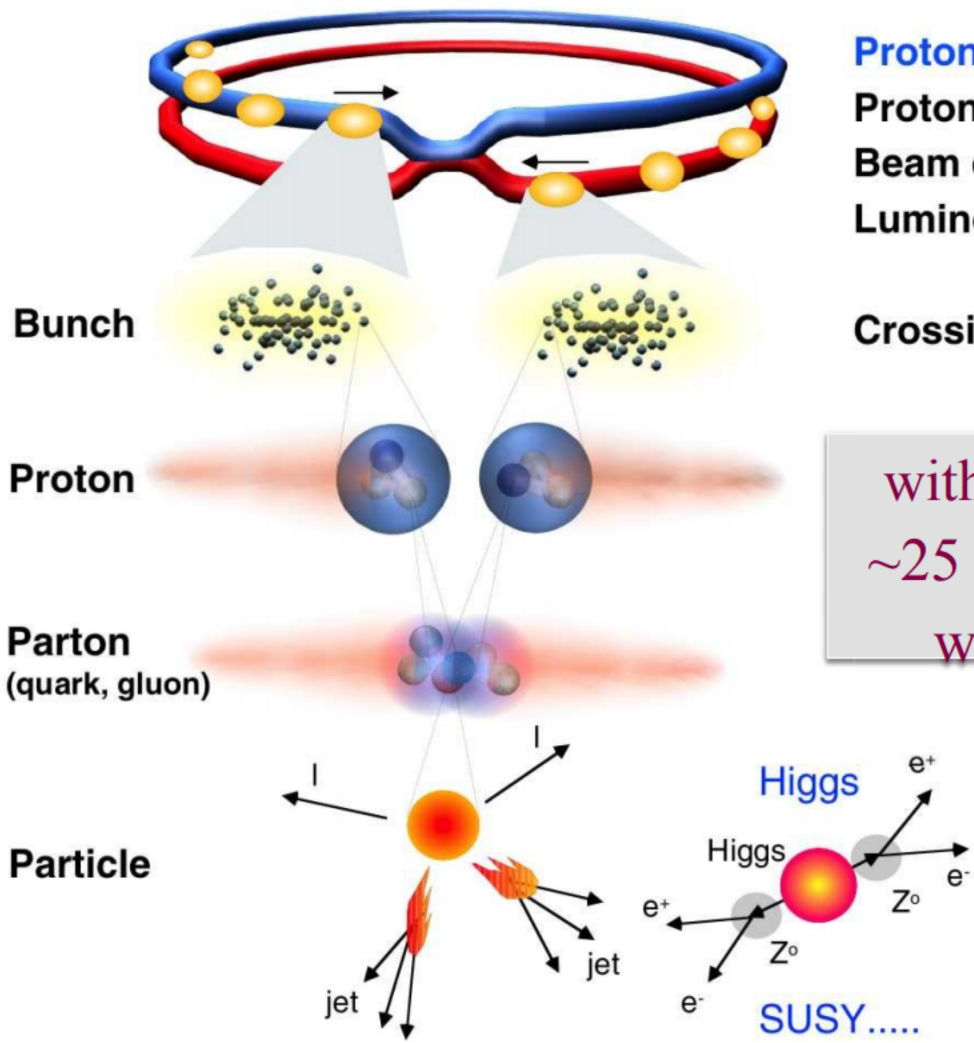
- Run 2 @ 13 TeV = a new territory
  - Lots of things to watch with the new 2017, 2018 datasets

- New ideas and new techniques
  - look in areas not previously accessible
  - high mass, low mass, or displaced

- Still to collect ~ 97% of LHC data. We are only getting started!

BACKUP MATERIAL

LHC overview



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz

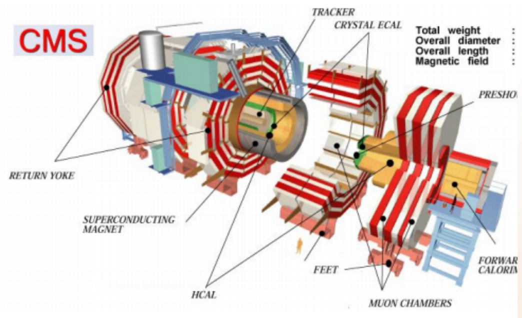
with every bunch crossing
~25 Minimum Bias events
with ~2000 particles
produced

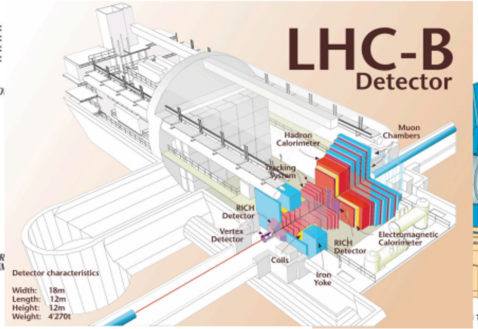
Selection of 1 in
10,000,000,000,000

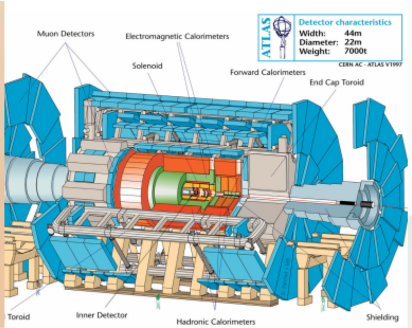
(Slide: W. Smith)

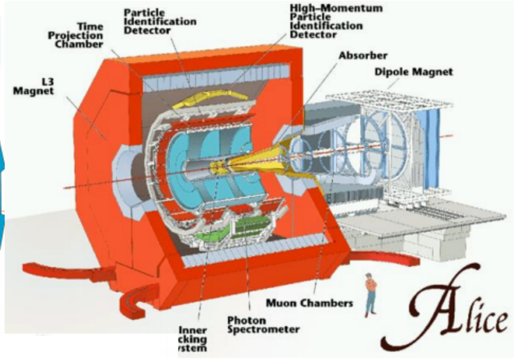
LHC: the cast of characters

- ATLAS, CMS:
  - 4π detectors, excellent coverage in central area, sophisticated trigger system
- LHCb:
  - all forward: high-η coverage, dedicated triggers for B physics
- ALICE:
  - 4π, coverage in central area, but optimized for lower DAQ rate of Heavy Ion collisions

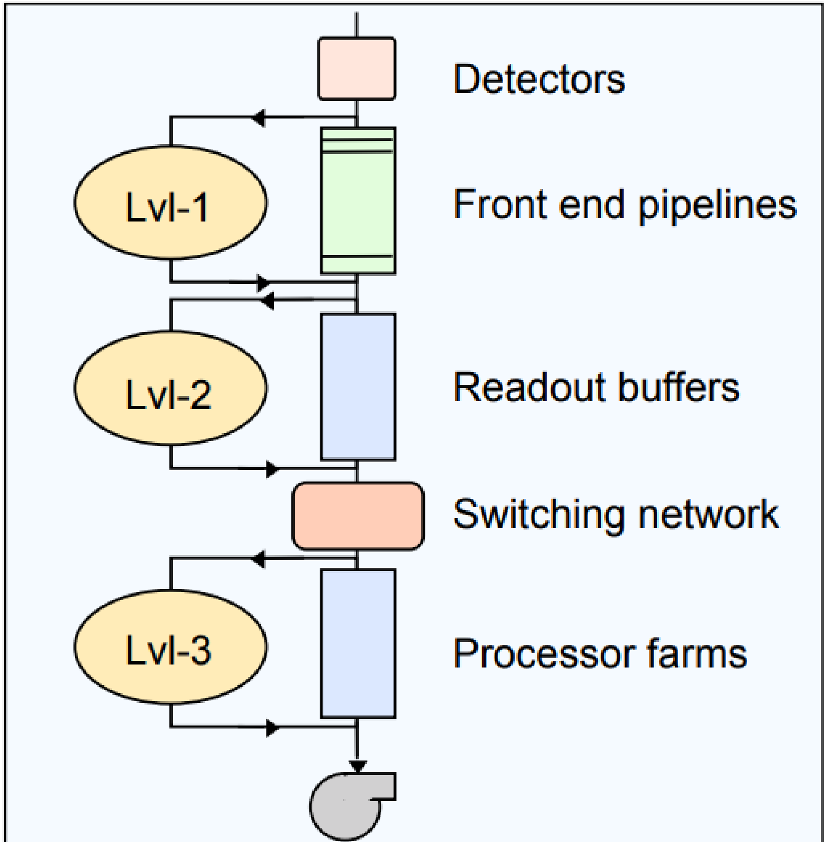




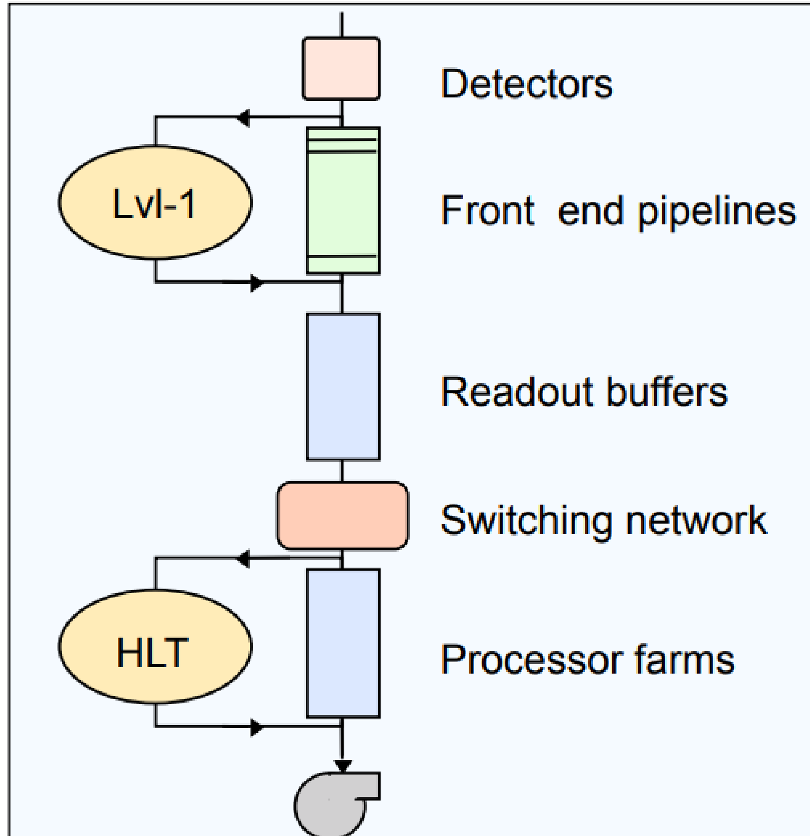




ATLAS and CMS Trigger systems



Run 1 ATLAS: 3 physical levels

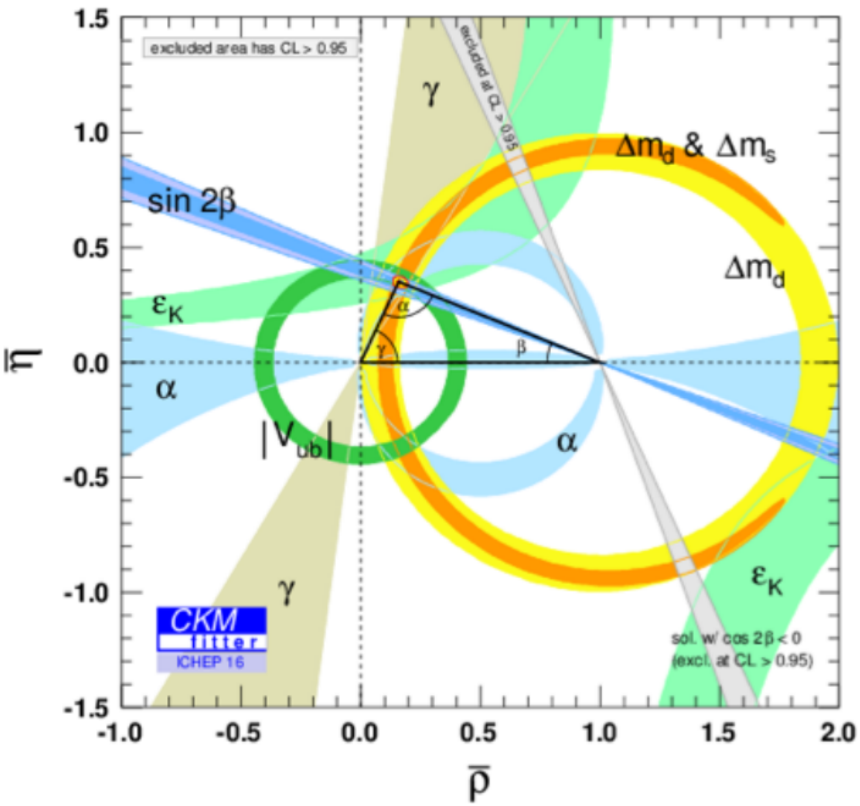


CMS: 2 physical levels

(Slide: W. Smith)

Flavor Physics: CKM

- CKM: status in 2018: all is well, at O(10%)



	Direct	CKM fit
α	$\alpha = \left(87.6^{+3.5}_{-3.3}\right)^o$	$\left(92.1^{+1.5}_{-1.1}\right)^o$
β	$\beta = (22.2 \pm 0.7)^\circ$	$\left(23.74^{+1.13}_{-0.98}\right)^o$
γ	$\gamma = \left(76.2^{+4.7}_{-5.0}\right)^o$	$\left(65.9^{+0.96}_{-2.54}\right)^o$
$-2\beta_s$	$-2\beta_s = -0.021 \pm 0.031$	-0.0370 ± 0.0006

Sensitive to BSM contributions directly. (~ 0 in SM)

- Search for small deviations in:
  - precisely predicted SM processes
  - forbidden processes that can only occur through BSM
    - (new particles at loop or tree level).

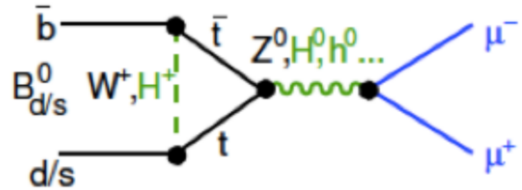
Flavor Physics: Bs → μμ

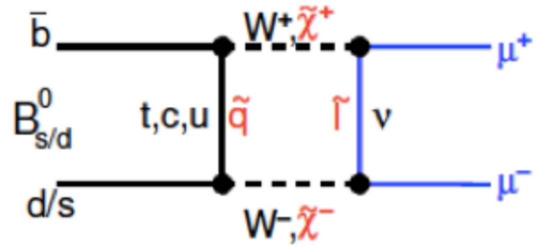
- Observations by LHCb and CMS consistent with SM:

$$Br(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad 6.2\sigma$$

$$Br(B_s^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

arXiv: 1411.4413
Nature 522 (2015) 68

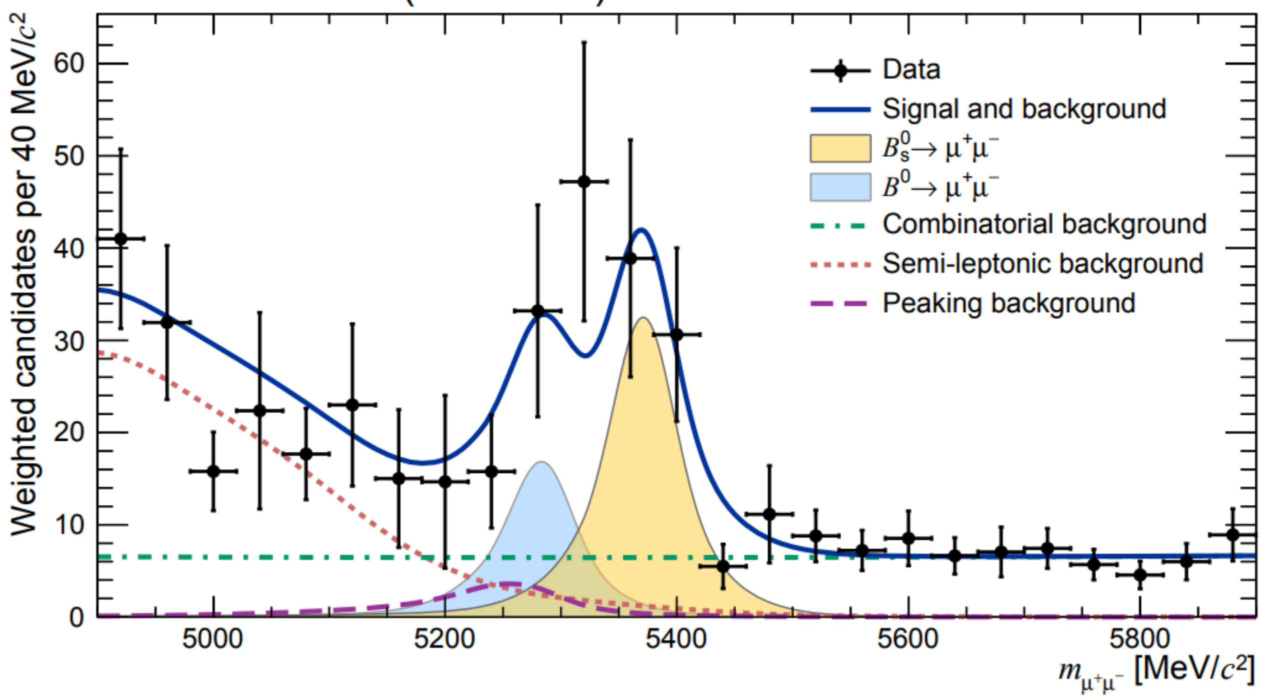




$$ATLAS: Br(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

Eur. Phys. J. C76(2016) no. 9, 513

CMS and LHCb (LHC run I)

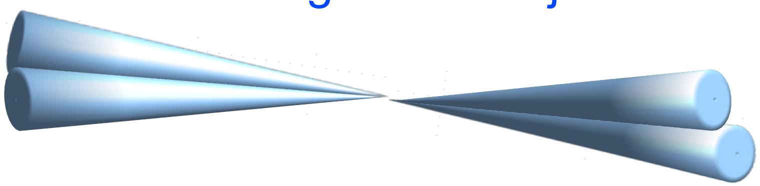


Both CMS and LHCb benefit from dedicated μμ triggers

$\mathrm{H}(b\bar{b})\mathrm{H}(b\bar{b})$

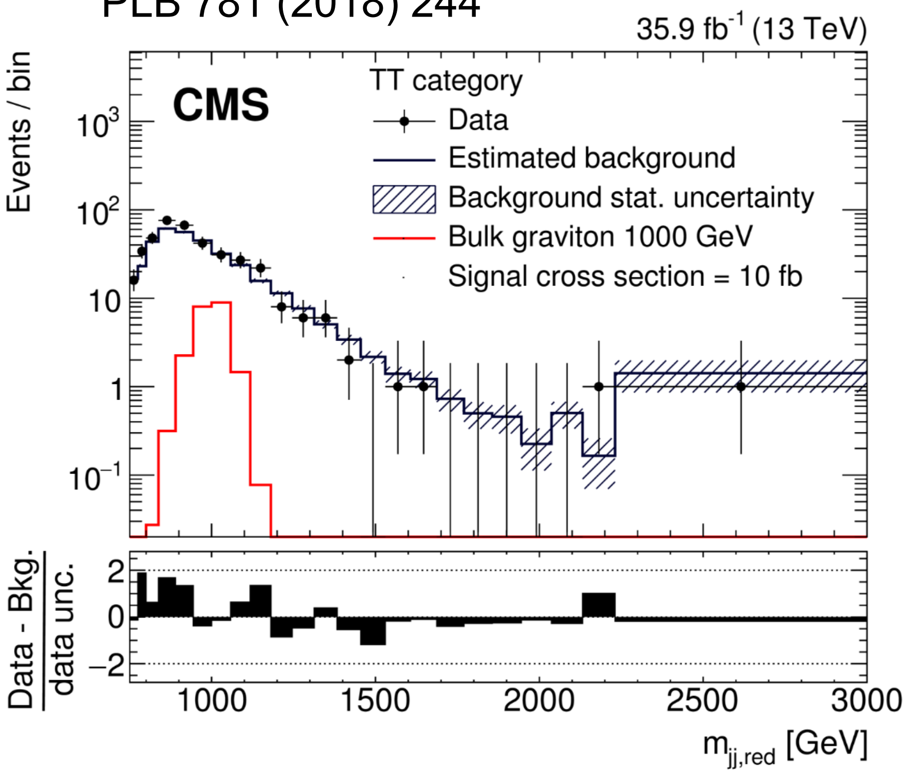
- "Boosted" channel: Improve access to large m_{HH}

Two merged H→bb jets



- b tagging, jet substructure
- Resonant X→HH and nonresonant (SM and BSM)

PLB 781 (2018) 244



arXiv:1804.06174