Hunting for new Physics at the LHC

Run 2 and Future Prospects

Pedro Ferreira da Silva (CERN)

European School of High Energy Physics
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Outline

- How did we arrive to the LHC?
- Where do we {stand,go}?
- Experimental signatures and challenges in the hunt for new physics

How did we arrive at the LHC?

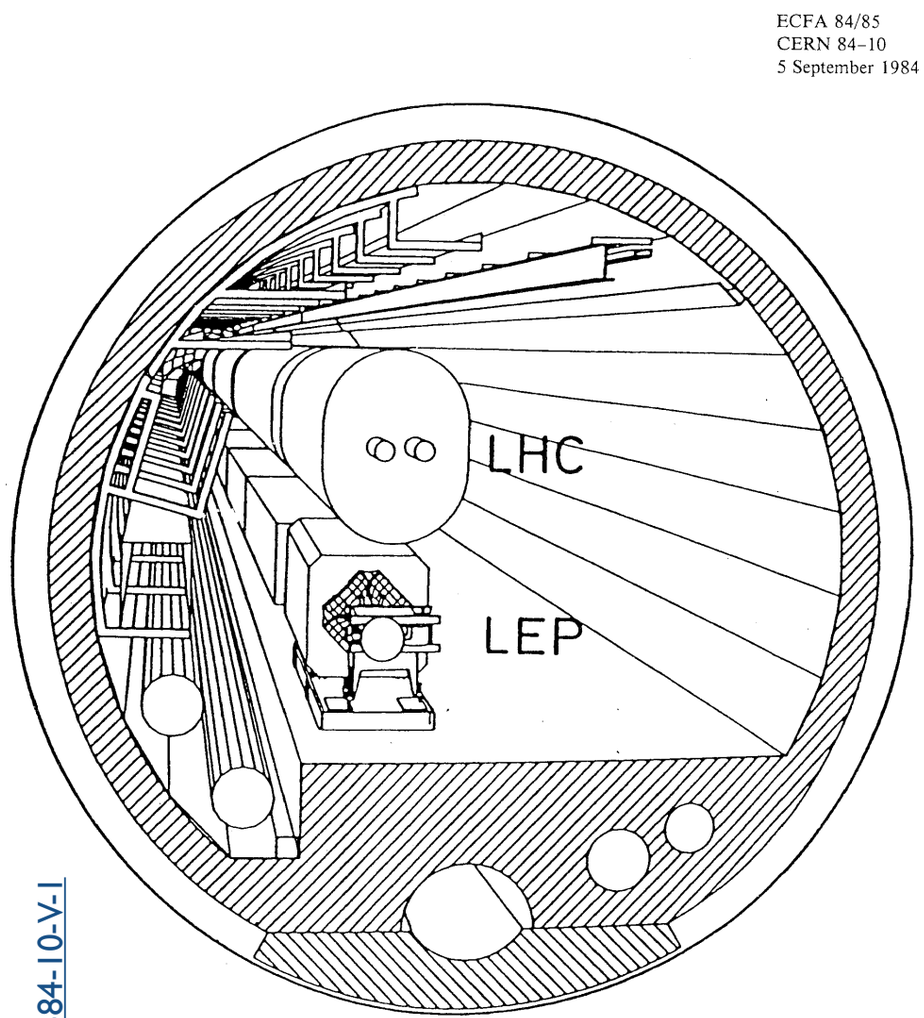
Machine design and potential

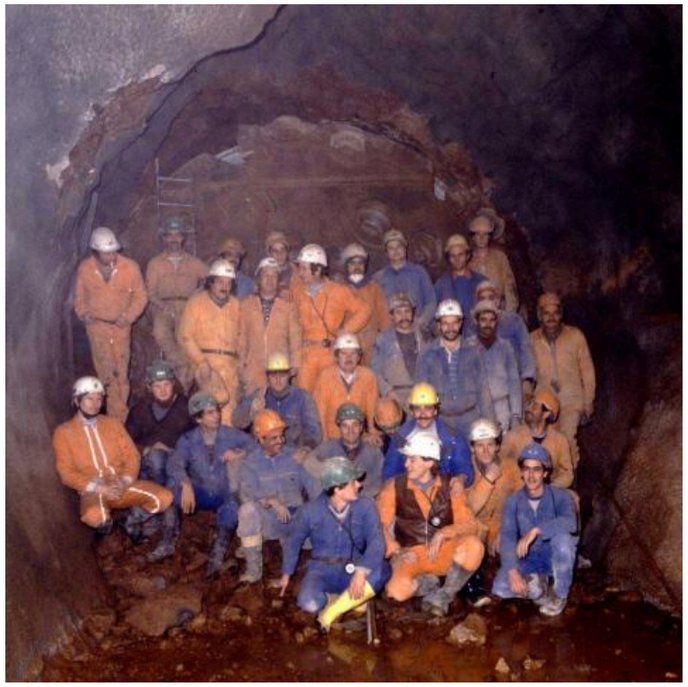
General purpose detector design

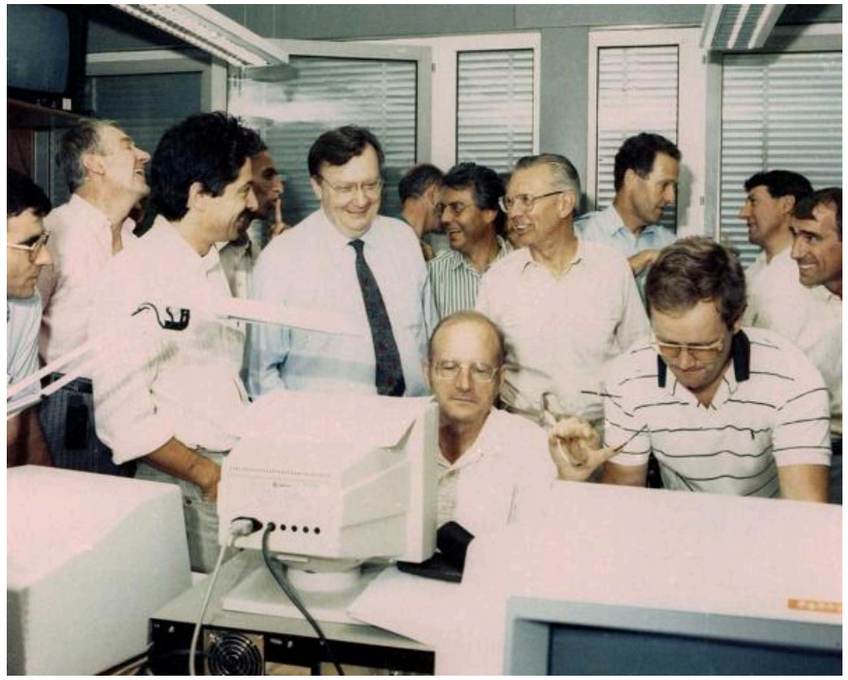
Current performances

Towards a Large Hadron Collider

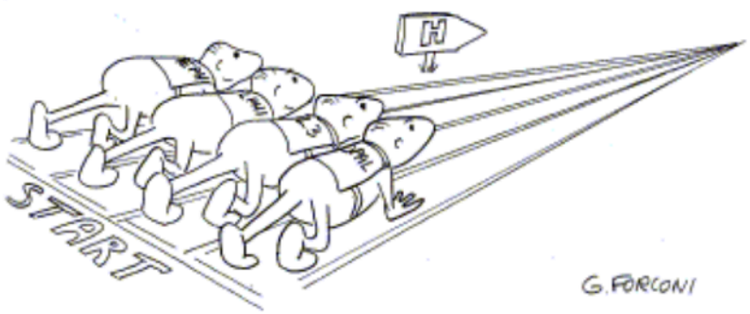
- **Lausanne (CH), 1984: 1 year past the W and Z discovery comes the LHC proposal**
  - LEP tunnel was chosen already in view of the highest energy possible @ the LHC
  - excavation of the 27 km ± 1 cm ring is completed in **February 1988**
  - first beams for LEP injected **July 1989**







1989: The race is ON!

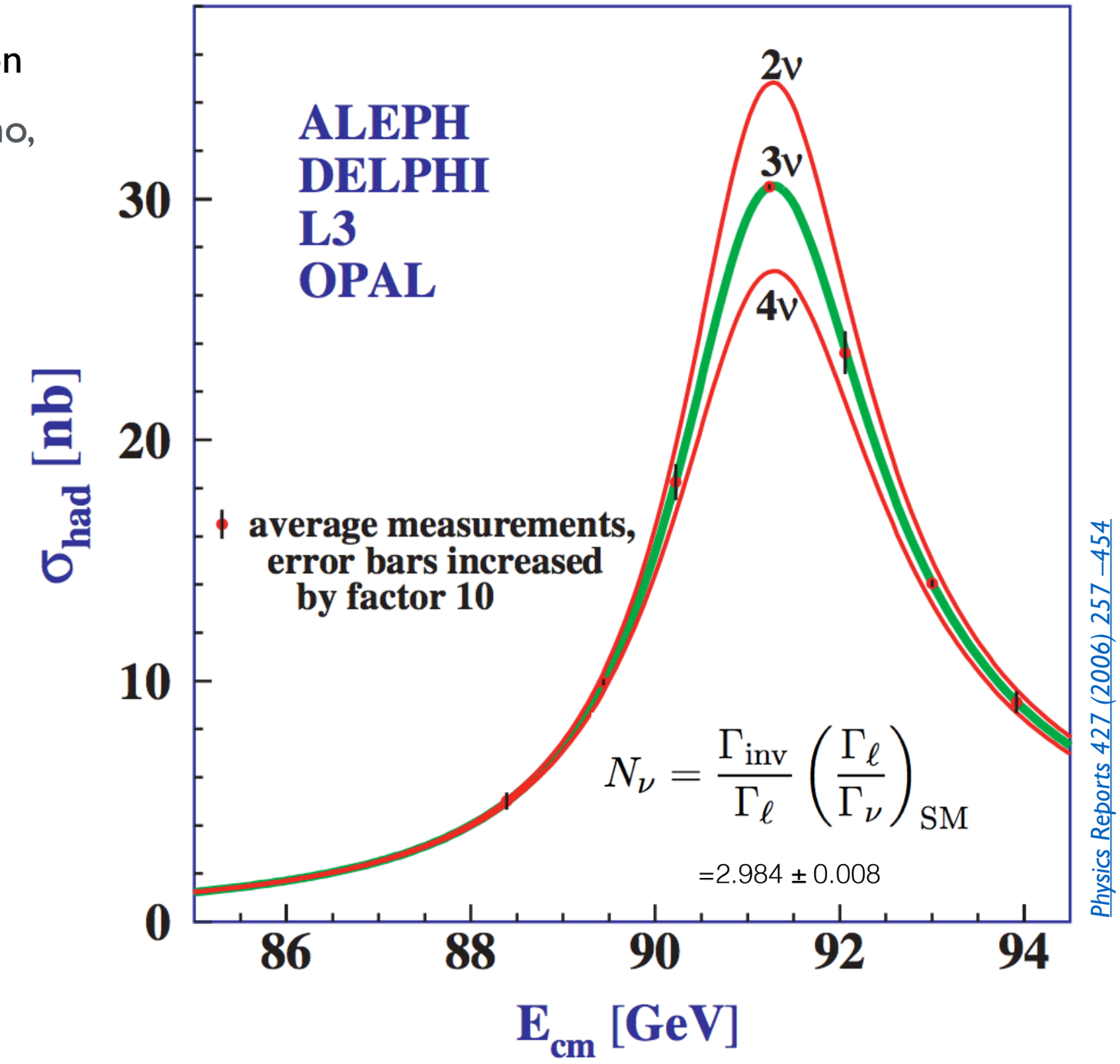


Particle physics at the dawn of the LHC I

- **After the LEP and SLC programmes ended**
  - SM tested to unprecedented precision

    e.g. Γ_Z => 3 families of active neutrino,

    determination of α_S at N^3LO, …



Physics Reports 427 (2006) 257–454

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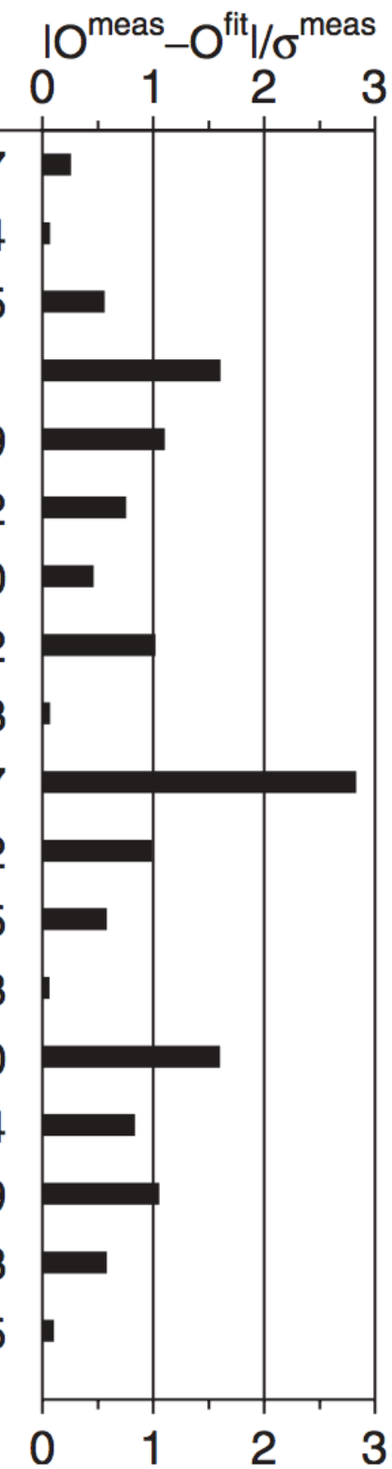
  - no strong tension between data and the SM

    modulo the forward-backward asymmetry

    under the Z pole, i.e. $A_{fb}^{0,b}$…

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



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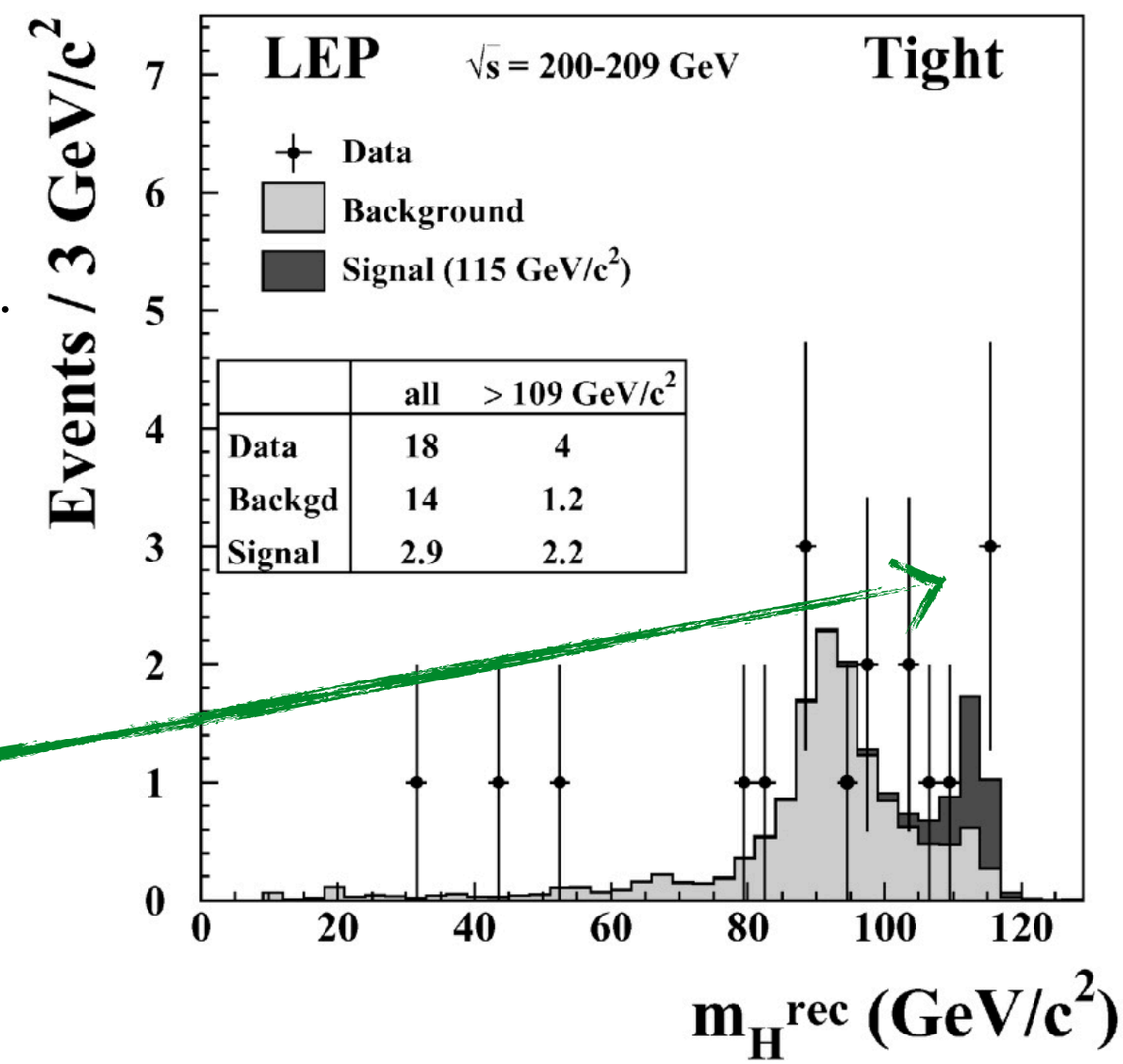
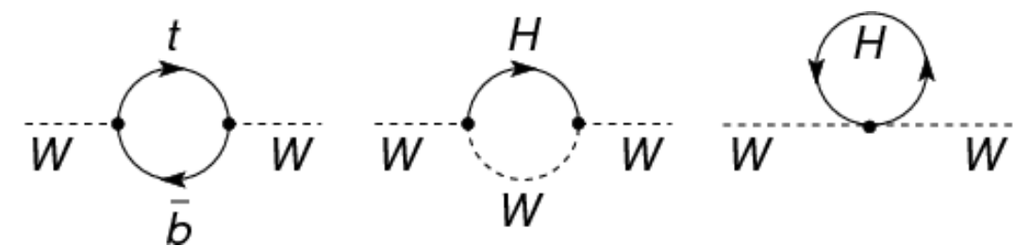
    e.g. Γ_Z => 3 families of active neutrino,
    determination of α_S at N^3LO, …
  - no strong tension between data and the SM
    modulo the forward-backward asymmetry
    under the Z pole, i.e. $A_{fb}^{0,b}$…
  - direct searches excluded m_H<114 GeV at 95% CL…

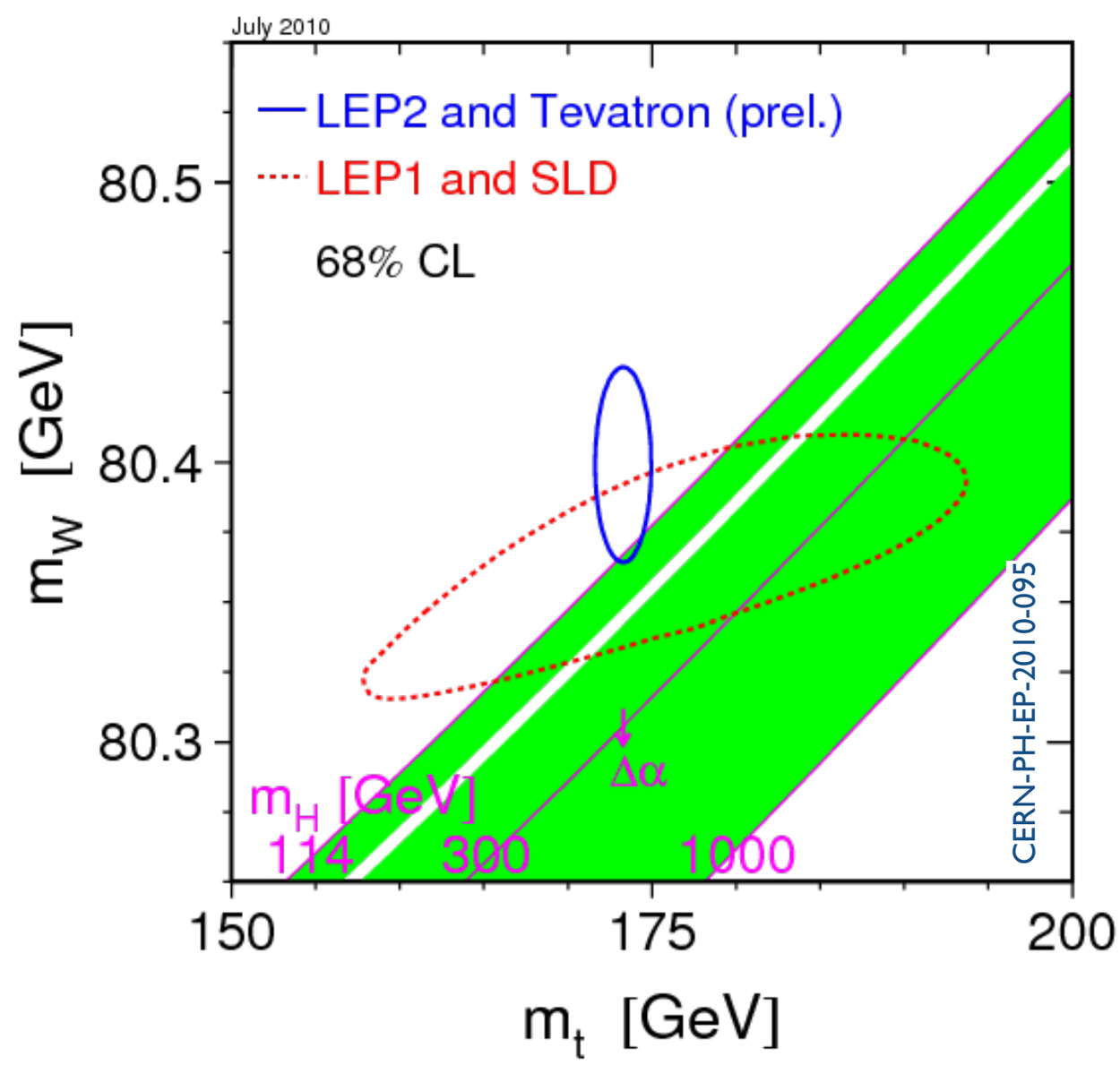
Phys.Lett. B565 (2003) 61-75



Particle physics at the dawn of the LHC II

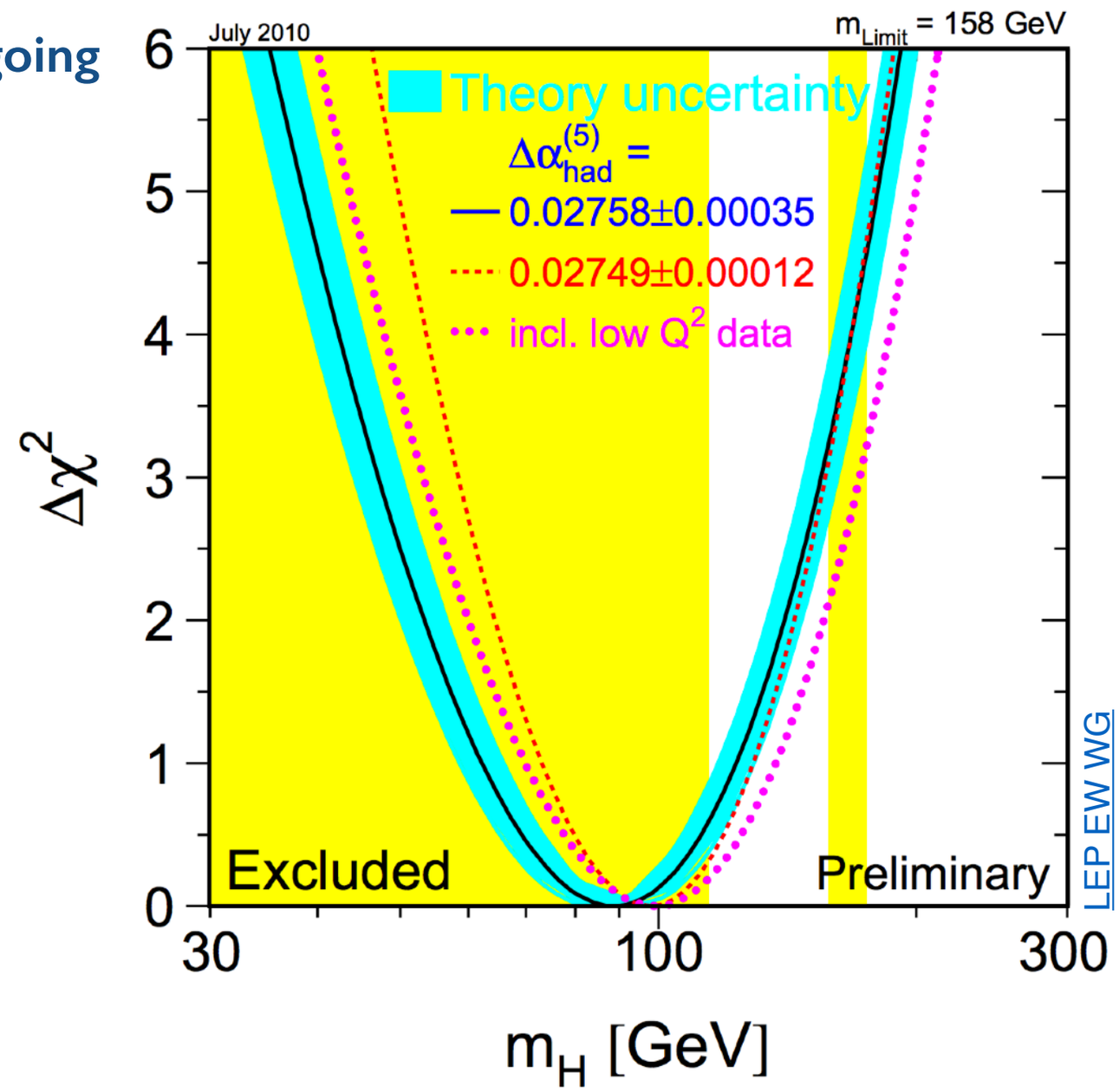
- **Fermilab's Tevatron ($p\bar{p}$) : Run 2 is still on-going**
  - discovery of the top quark
  - m_t measured to <1% precision





Particle physics at the dawn of the LHC II

- **Fermilab's Tevatron ($p\bar{p}$) : Run 2 is still on-going**
  - discovery of the top quark
  - m_t measured to <1% precision
  - not yet sensitive to Higgs
    (apart m_H~165 GeV)
  - no hints of new physics (BSM)
    (but slight tensions in combined EWK fits)

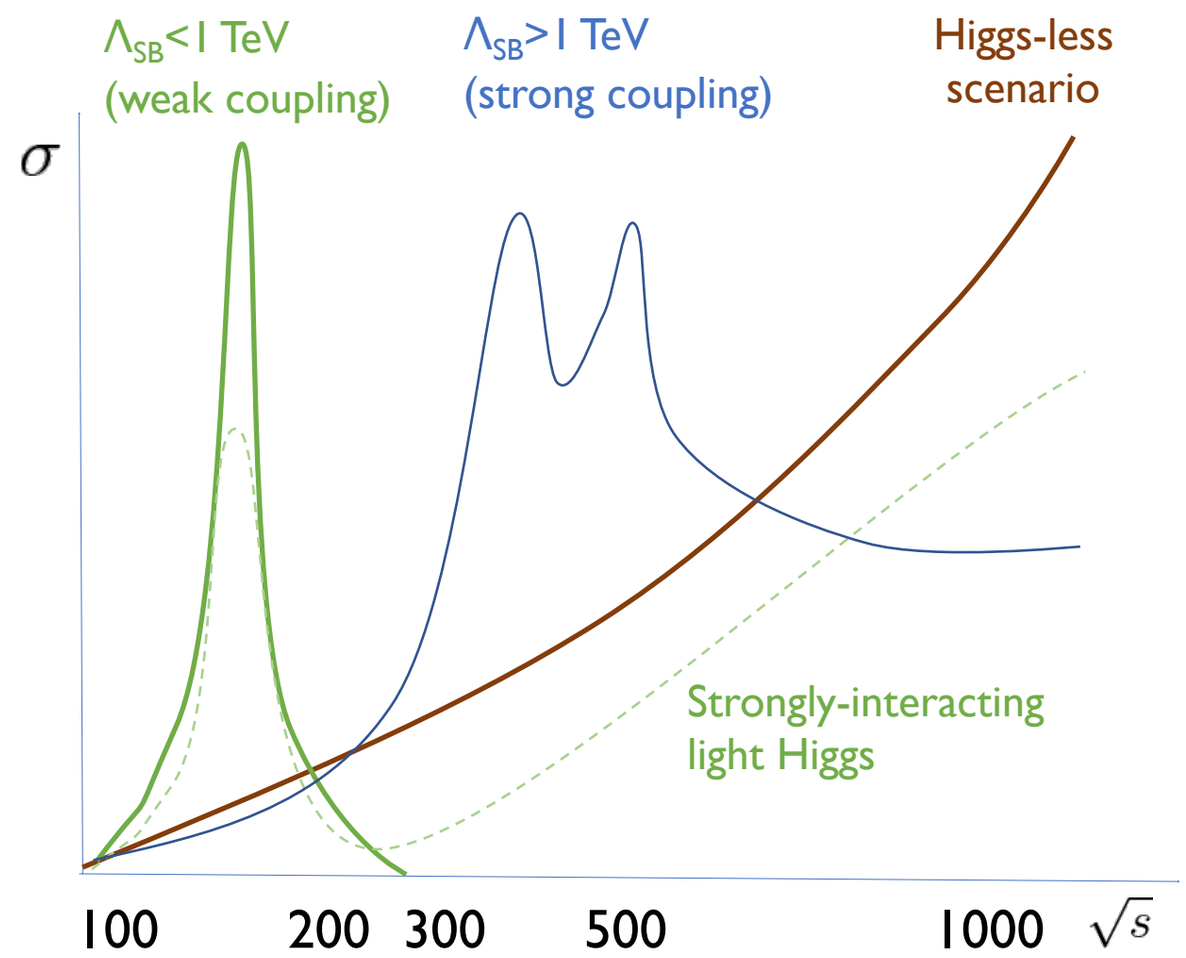


- **In addition, no hints of BSM from precision B-physics (Tevatron, Belle, BABAR)**

Enters the LHC: a collider designed to test EWSB…

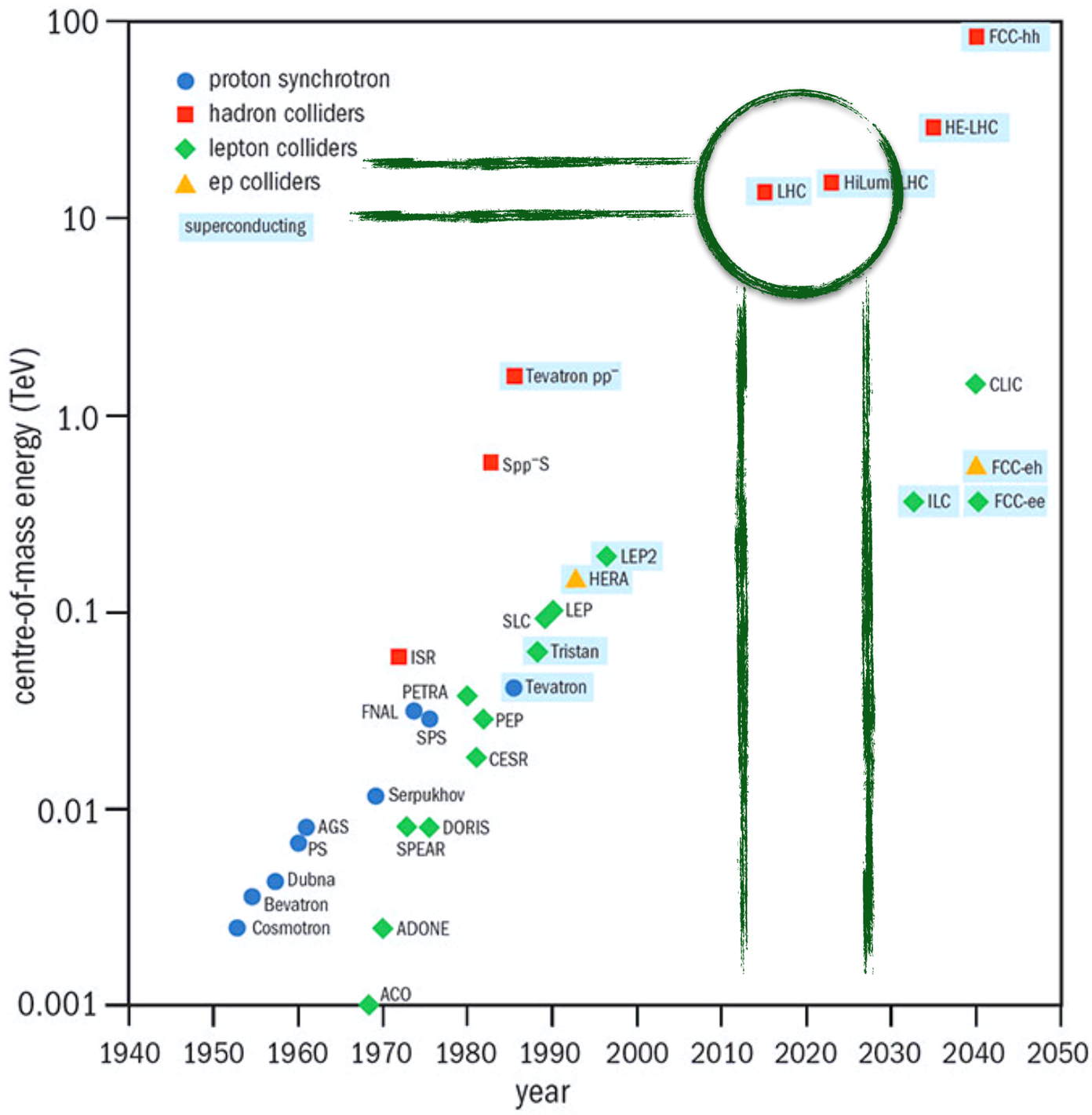
- **Initially designed to uncover what happens at the TeV energy scale:**
  - ensure coverage to produce a Higgs boson candidate
  - bridge LEP's M_H>114.4 GeV @ 95%CL up to 1 TeV
  - maximal sensitivity below WW threshold (favored by indirect fits)
- **What if no Higgs candidate? something should happen in $\sigma(W_L W_L)$**

$$A(W^+W^- \to W^+W^-) \to \frac{1}{v^2}\left[s + t - \frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2}\right]$$



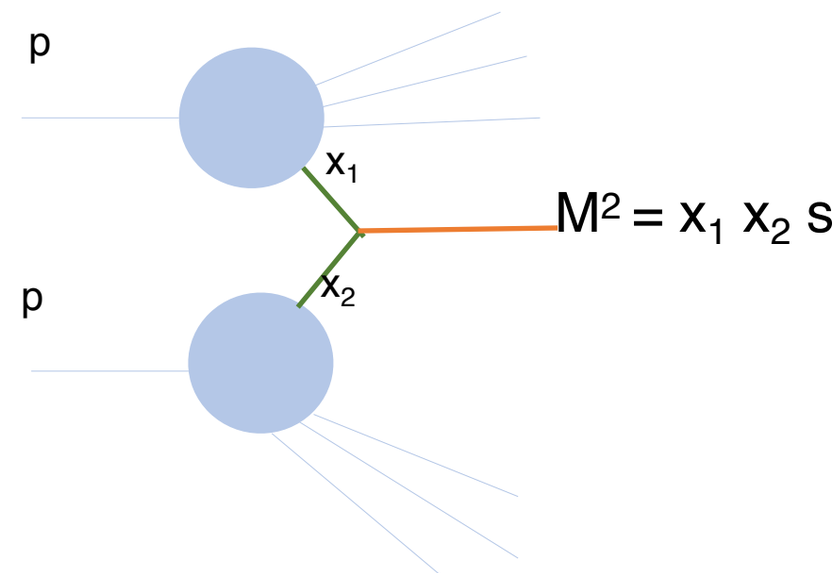
…at the energy frontier…

- **Replace electrons with protons**
  - scan partonic $s^{1/2}$ up to TeV scale



…at the energy frontier…

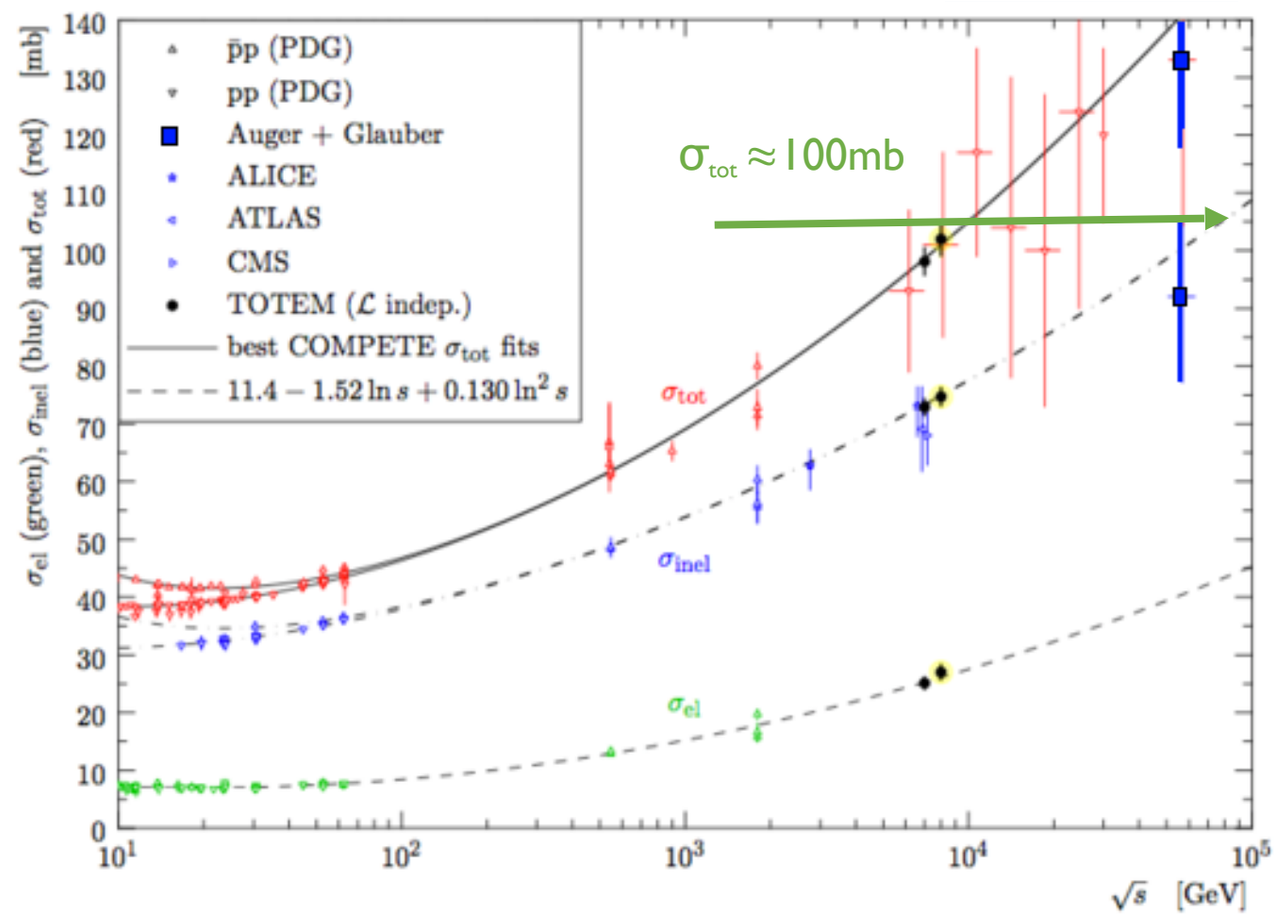
- **Replace electrons with protons**
  - scan partonic $s^{1/2}$ up to TeV scale
  - each collision is unique in energy and remnants
  - need knowledge on the PDF, UE, α_S



(parton distribution functions / underlying event / strong coupling constant)

- **Large total cross section: O(100 mb)**

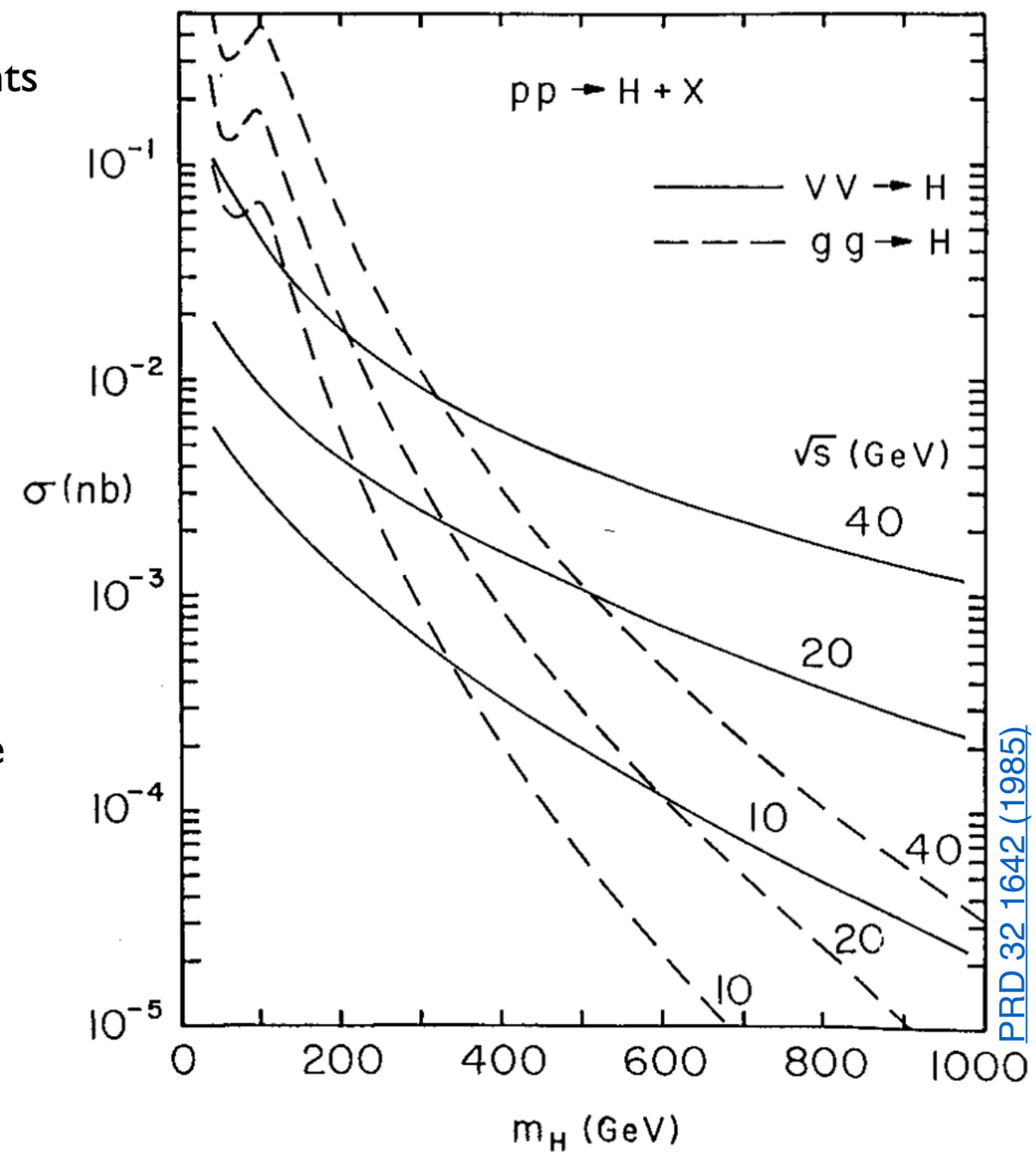
arXiv:1305.6131



…at the energy frontier…

- **Replace electrons with protons**
  - scan partonic $s^{1/2}$ up to TeV scale
  - each collision is unique in energy and remnants
  - need knowledge on the PDF, UE, α_S
- **Large total cross section: O(100 mb)**
- **Processes of interest are O(10pb)**
  - theory needs to cover >14 orders magnitude
  - experiments need online selection

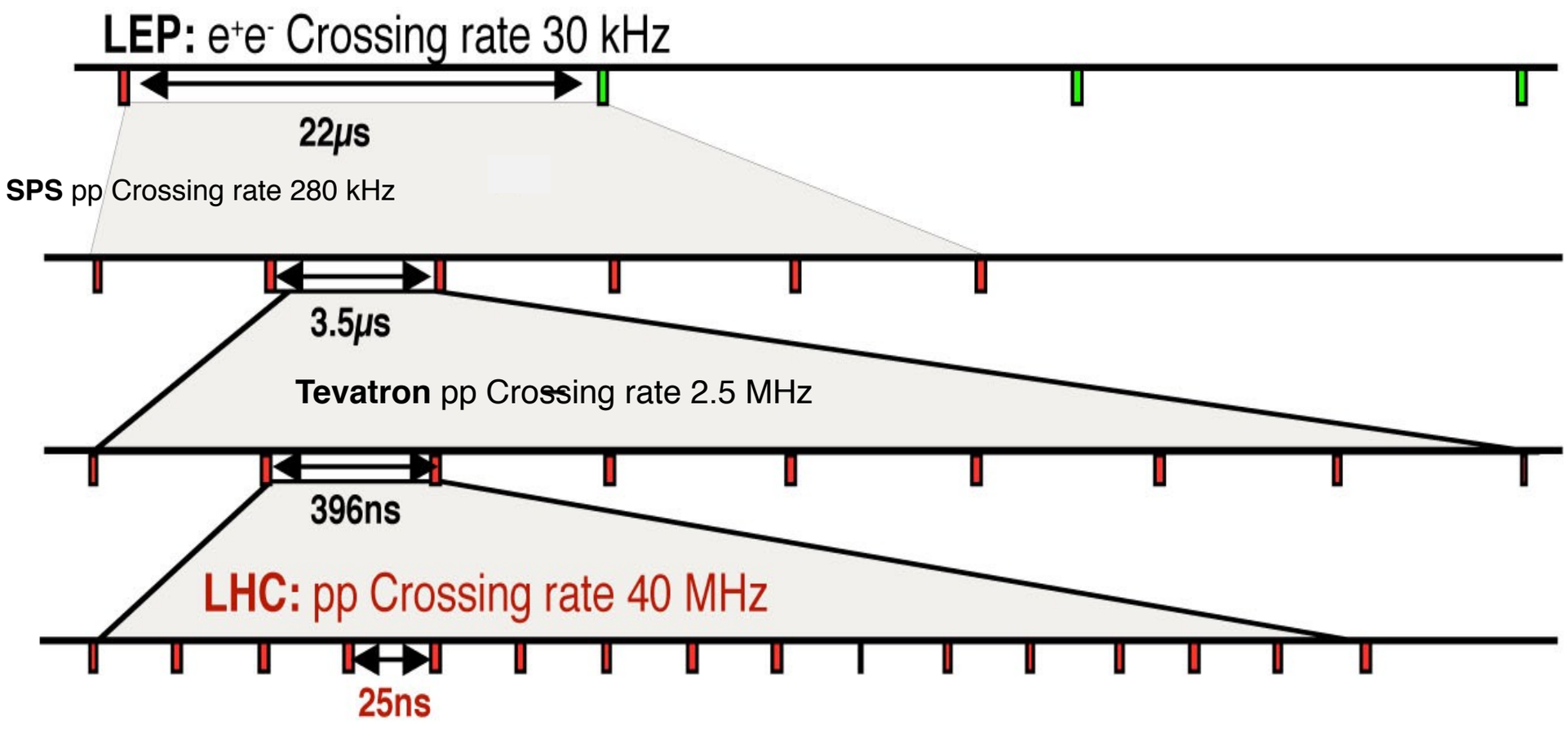
Can it ever be precise enough?



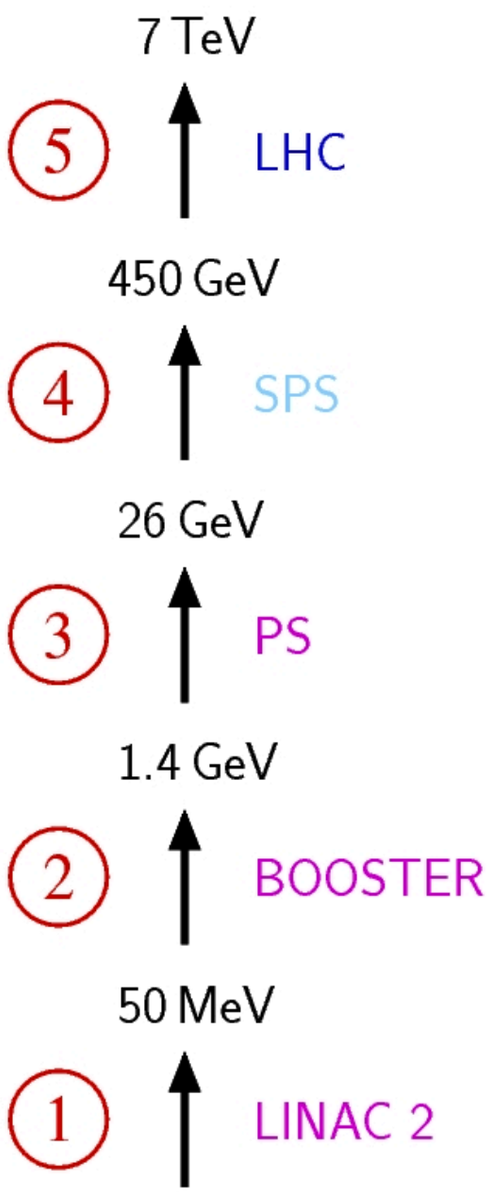
PRD 32 1642 (1985)

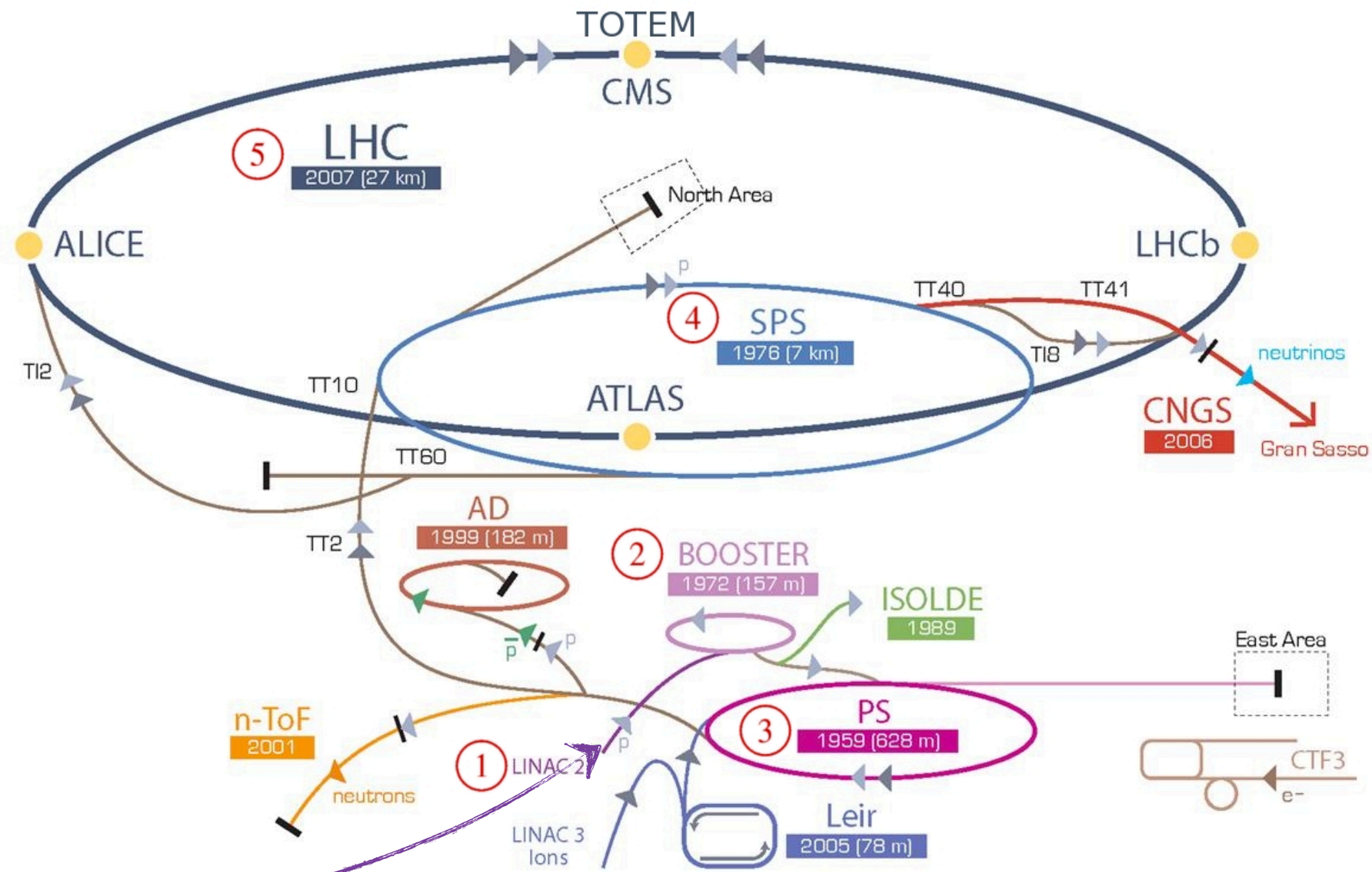
…and breaking intensity records

- **High integrated luminosity needed to produce the processes of interest**
  - instantaneous luminosity 10^{34} cm^{-2} s^{-1} ⇒ 10^7 Hz/mb ⇒ O(10^2-10^3 MHz) collision rate!
  - crossing rate >10^3 larger than LEP with ~25 interactions/crossing
- **Challenging for detectors: front-end, trigger and data acquisition systems**



Main endpoint of the CERN accelerator complex





p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Luminosity is the key ingredient

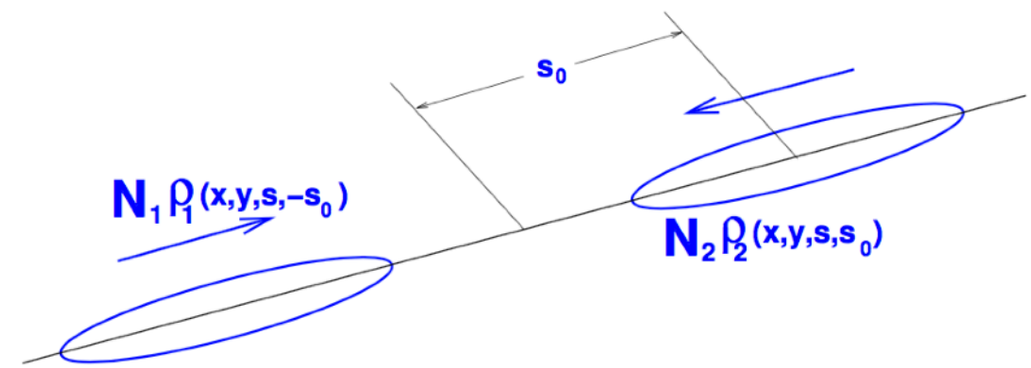
- **Master formula for the event rate expected:**

$$\dot{N} = \mathcal{L} \cdot \sigma$$

luminosity

cross section

- **Depends on the flux of particles in the beam**
  - results from the convolution of the two beam densities
  - simplest case: heads-on collisions, gaussian profiles,…



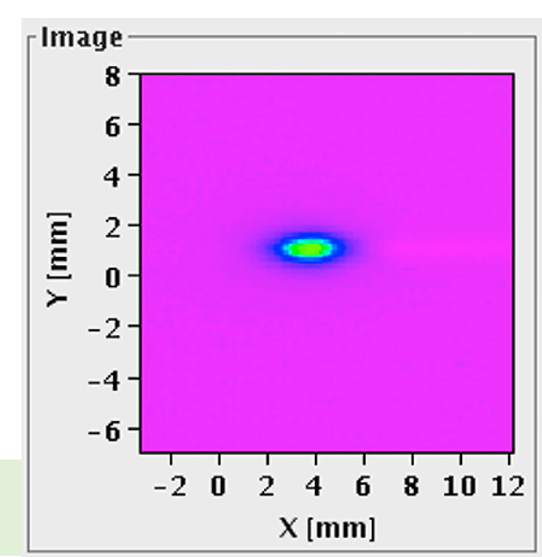
$$\mathcal{L} = \frac{2 \cdot N_p N_p f N_b}{(\sqrt{2\pi})^6 \sigma_s^2 \sigma_x^2 \sigma_y^2} \iiiint e^{-\frac{x^2}{\sigma_x^2}} e^{-\frac{y^2}{\sigma_y^2}} e^{-\frac{s^2}{\sigma_s^2}} e^{-\frac{s_0^2}{\sigma_s^2}} dx dy ds ds_0$$

$$= \frac{1}{4\pi} (f N_b N_p) \frac{N_p}{\sigma_x \sigma_y}$$

Number of particles in bunch

beam current

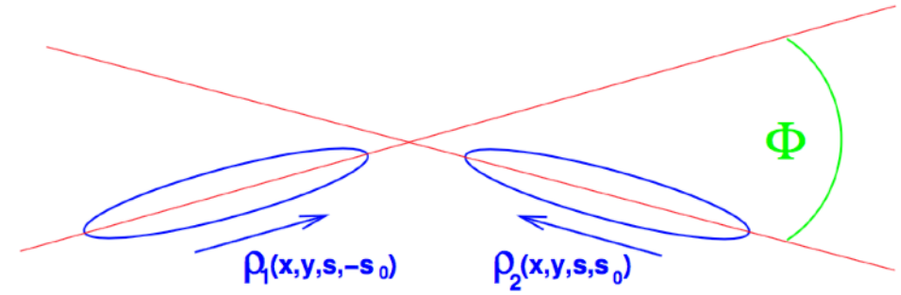
beam xy width

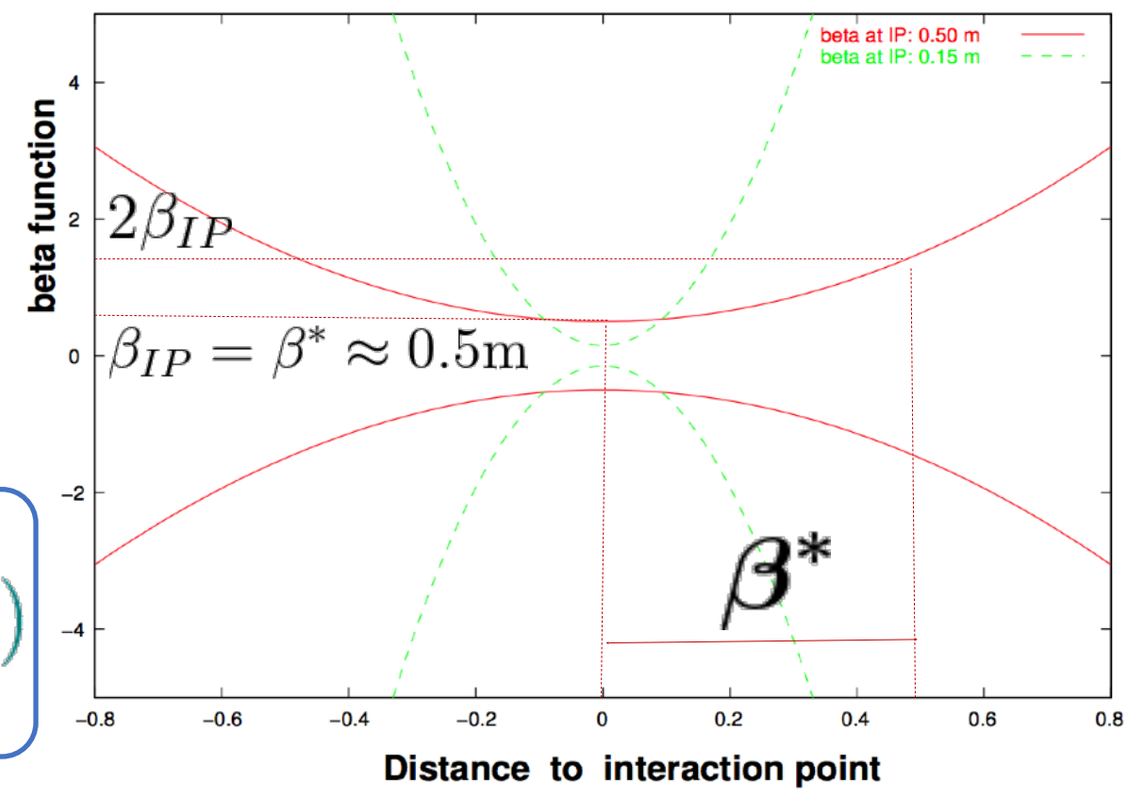


Luminosity in real life

- **At the LHC the beams have however:**
  - a crossing angle ($\varphi \approx 300$ rad)
  - distance-dependent profile

    (aka hourglass effect)
  - non-gaussianities, offsets,…





- **Usually becomes expressed as:**

$$\mathcal{L} = \frac{1}{4\pi}(f N_b N_p)\frac{N_p}{\varepsilon_N}\frac{\gamma}{\beta^*}R(\phi, \beta^*, \varepsilon, \sigma_z)$$

beam current

Brightness (ε-emmitance)

*Energy and β**

Reduction factor

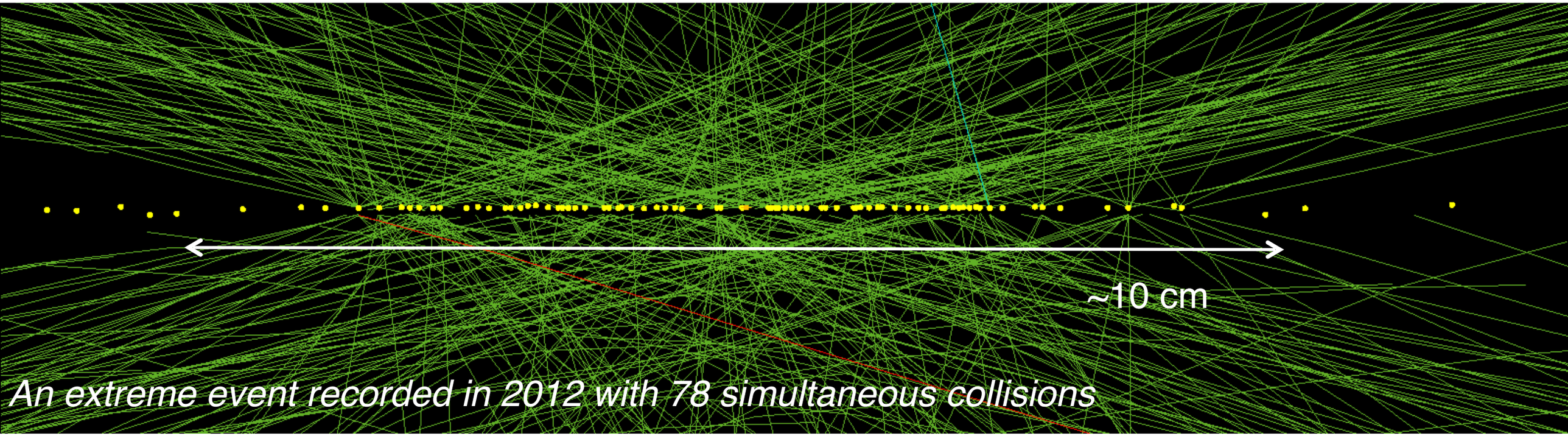
Online tool to estimate it is provided by the CERN LPC - link

Pileup: one side-product of instantaneous luminosity

- **High instantaneous luminosity does not come for free**
  - the average number of events per crossing is currently

$$\mu = \frac{\sigma \cdot \mathcal{L}}{f \cdot N_b} = \frac{80\ \mathrm{mb} \cdot 10\ \mathrm{nb\ s^{-1}}}{11245\ \mathrm{s^{-1}} \cdot 2808} \approx 25$$

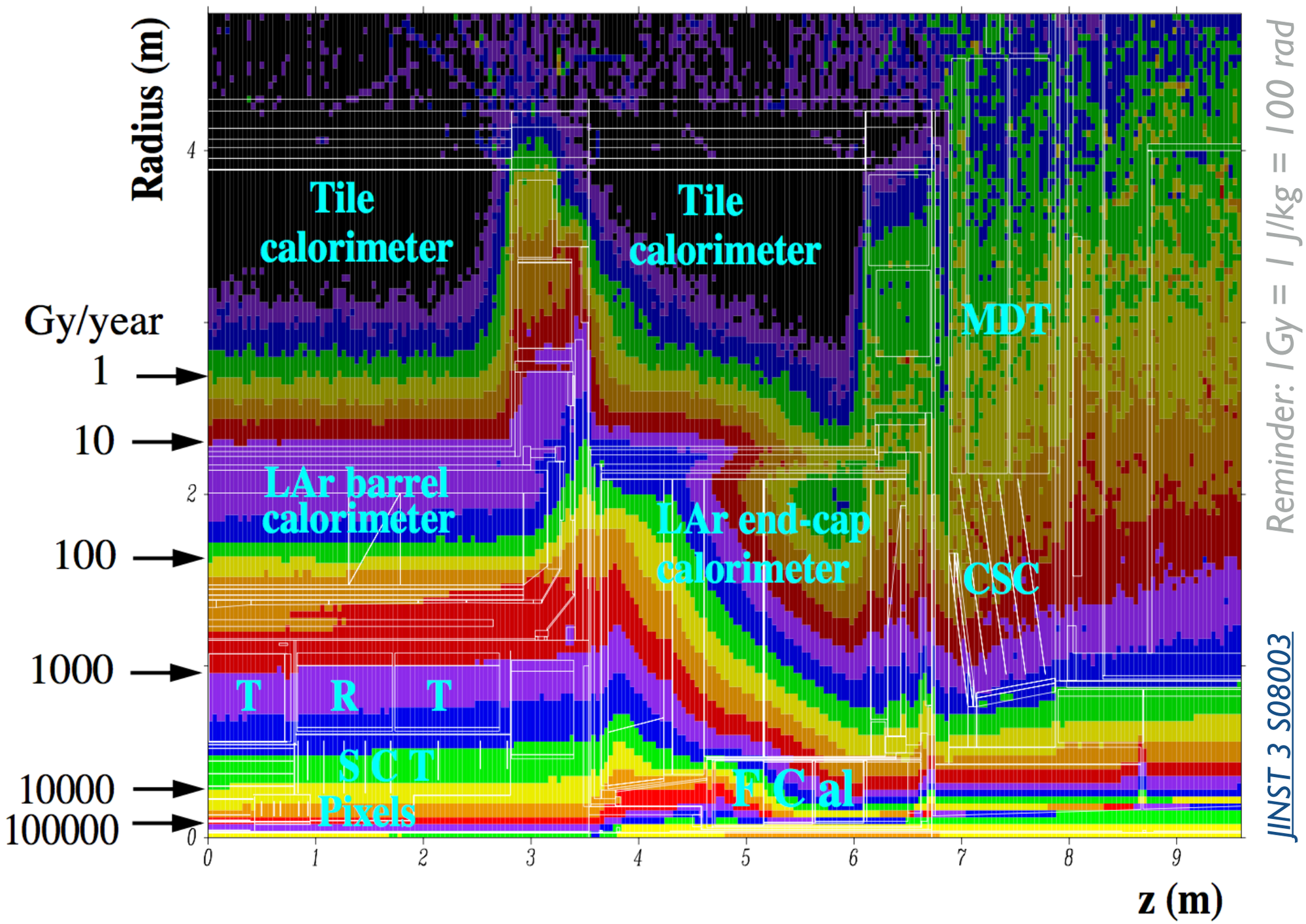
  - expected to increase by a factor of 6 at the HL-LHC



An extreme event recorded in 2012 with 78 simultaneous collisions

Radiation levels: a challenge for detectors and electronics

- Activation of materials, impurities, loss of transparency/response, spurious hits …
  - additional shielding/moderators needed to limit radiation impact in the detectors



Parton distribution functions are crucial at the LHC

- **How effectively can the beam energy be converted in physics?**
- **The cross section is determined by:**
  - short-distance interaction between the proton constituents

    (Feynman rules for the process will determine its strength)
  - parton distribution functions (PDFs)

    (parametrize probability of constituent carrying a fraction of the energy)
  - Valid in all pQCD orders, up to power corrections ~ $p_n(\Lambda_{QCD}/Q)^n$

Partonic cross section

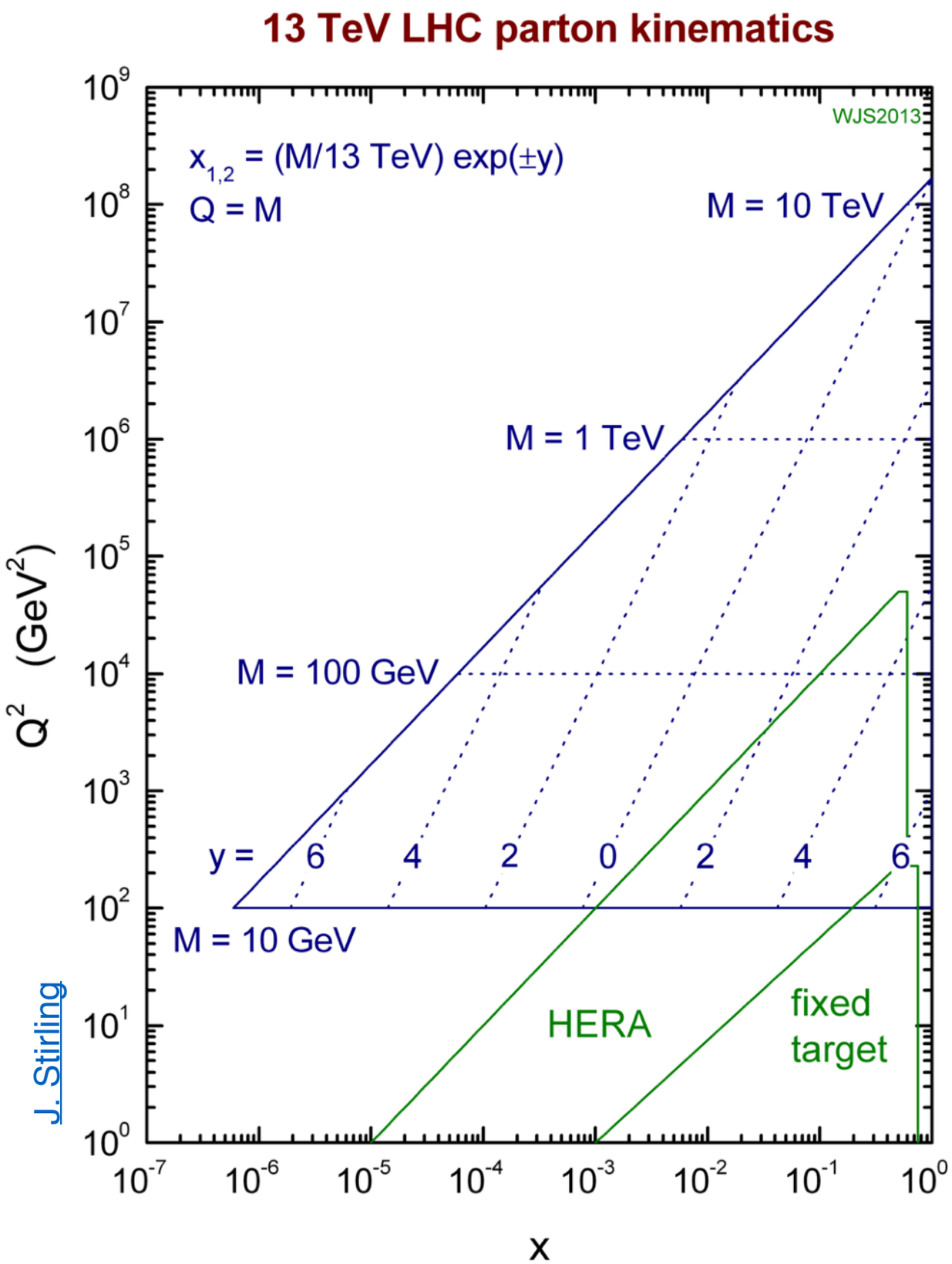
$$\sigma = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}\left(\frac{Q^2}{\mu^2}\right)$$

PDF for species i

Factorization scale: separates hard-process from soft-process

Scale of the hard scattering process: e.g. m_H, m_{top}

PDF coverage



- Usually expressed in the (x,Q^2)-plane
- Previous measurements from HERA/fixed target covered only a portion of what needs to be explored at the LHC

Parton luminosities

- **A convenient way to write σ is:**

$$\sigma = \sum_{(ij)} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \frac{1}{s} \frac{dL_{ij}}{d\tau} \hat{s}\hat{\sigma}_{ij}\left(\frac{Q^2}{\mu^2}\right)$$

sum over possible parton pairs

$\tau = x_1 x_2$: energy fraction converted in the hard process

Parton luminosity

$\hat{s} = \tau s$:partonic center-of-mass energy

- The parton luminosity results from the integration of the PDFs

$$\tau \frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 \left[x_1 f_i(x_1,\mu^2) x_2 f_j(x_2,\mu^2) + (1 \leftrightarrow 2)\right] \delta(\tau - x_1 x_2)$$

- **We can use this compact definition almost as a look-up-table to evaluate**
  - cross sections (starting from an already existing partonic cross section value)
  - the reach of a hadron collider

Dijet rate at the LHC as an example

- **Consider the production of two gluon jets with p_T>0.5 TeV:** $\sigma(pp \to gg, p_T^g > 0.5 \text{ TeV})$

$$\sigma = \sum_{(ij)} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \frac{1}{s} \frac{dL_{ij}}{d\tau} \hat{s}\hat{\sigma}_{ij}\left(\frac{Q^2}{\mu^2}\right)$$

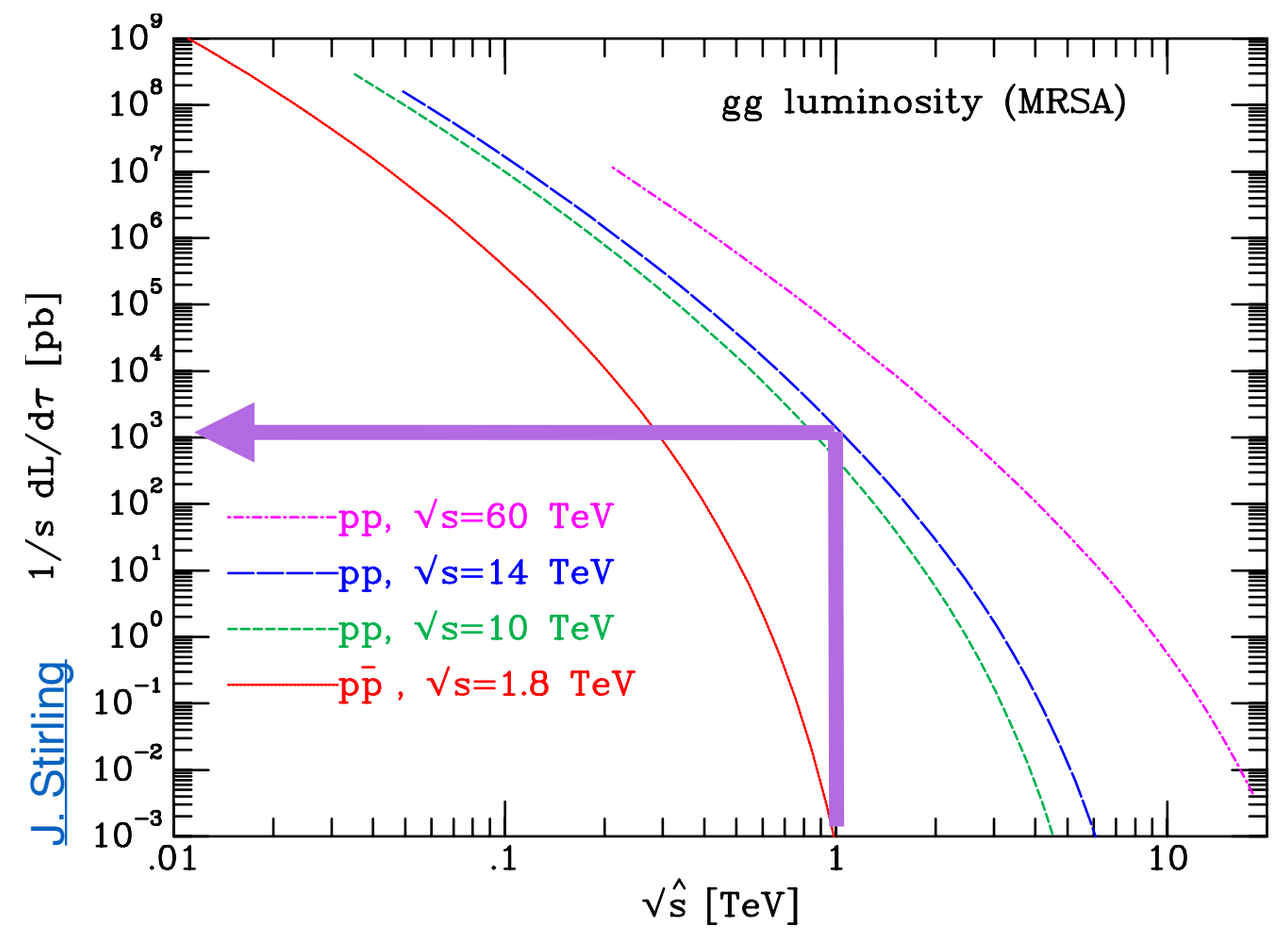
10^3 pb 1 TeV *orders of magnitude*

1 0.01

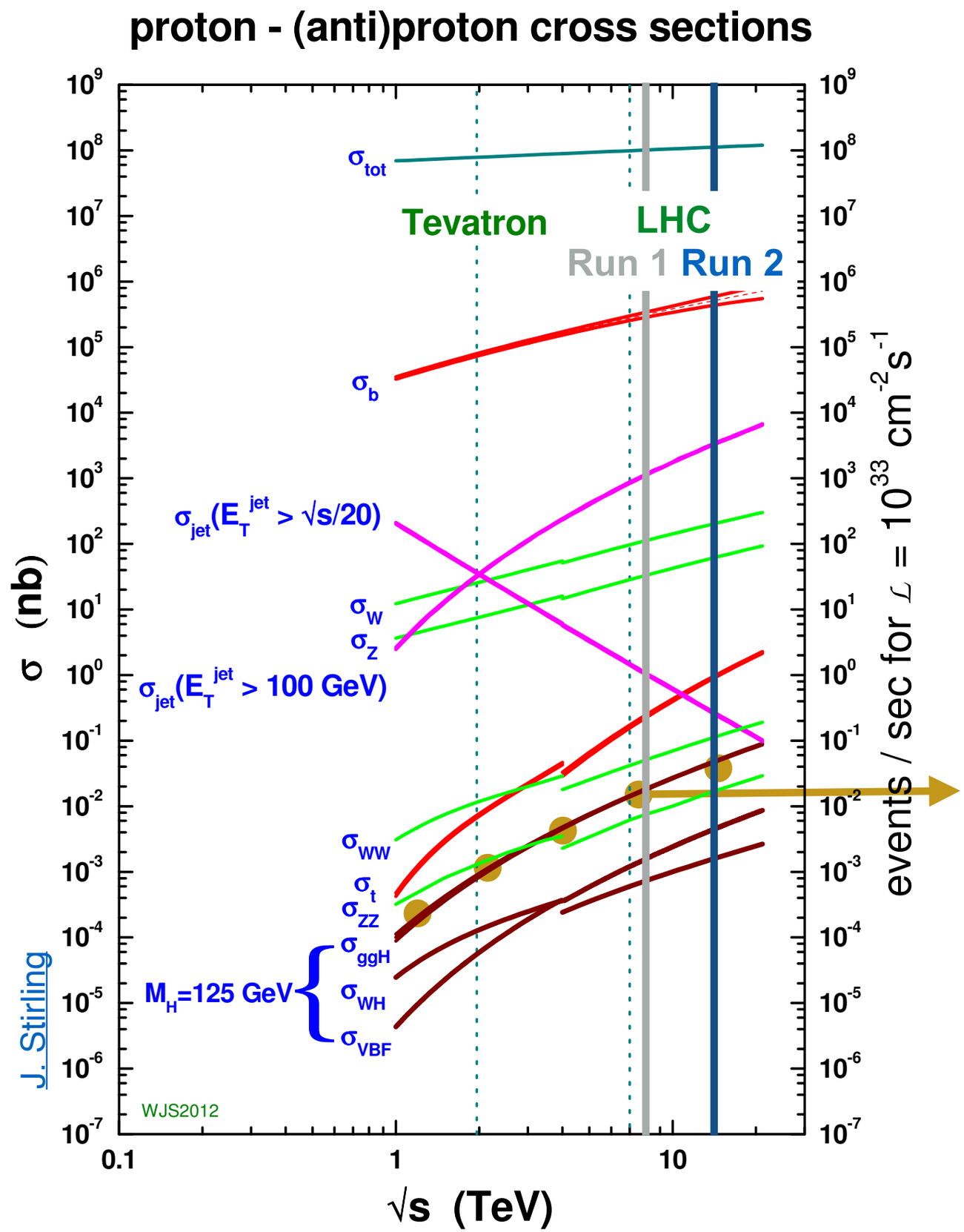
- Multiplying all the factors we get σ=10pb

For L=10^{34} cm^{-2} s^{-1} that is

O(1 event / 1s) at the LHC



Expected cross sections and rates in hadron colliders



- Strong processes dominate
- **Higgs: O(5 Hz) production rate**

  ⇒ Need to reject 10^9 orders of magnitude to find the "golden" events!
- **New physics <Hz production rate**

  ⇒ Need to collect high statistics: O($ab^{-1} = 10^6\ pb^{-1}$)

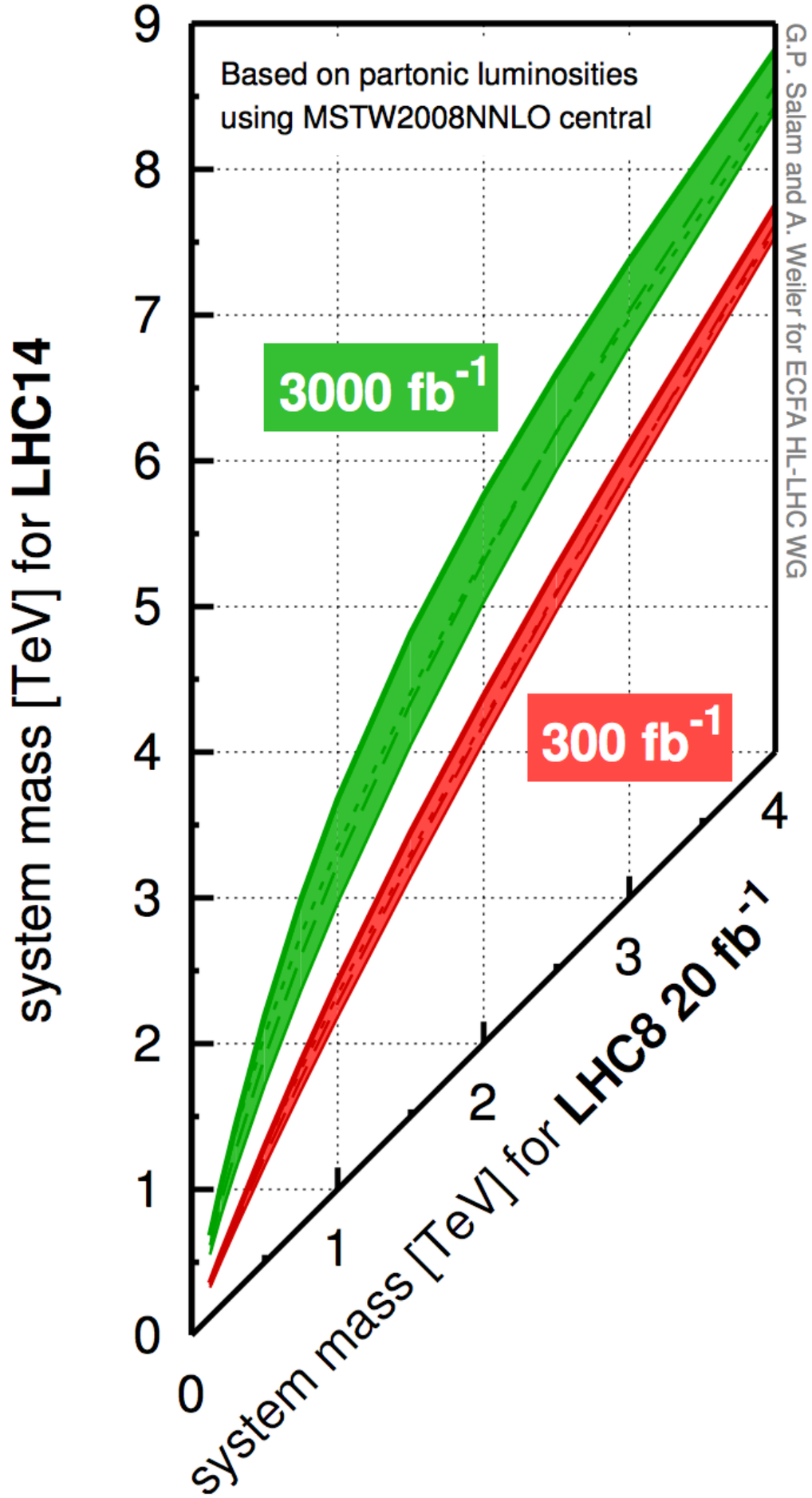
Collider reach

- Use parton luminosities to estimate reach
  - ratio at different $s^{1/2}$ estimates the gain in σ
  - use to find the (mass,luminosity)-equivalent
- Example:
  - during the 8 TeV run (20 fb^{-1}) we have a sequential Z' up to M ≈ 2.8 TeV
  - this would correspond @ 14 TeV to

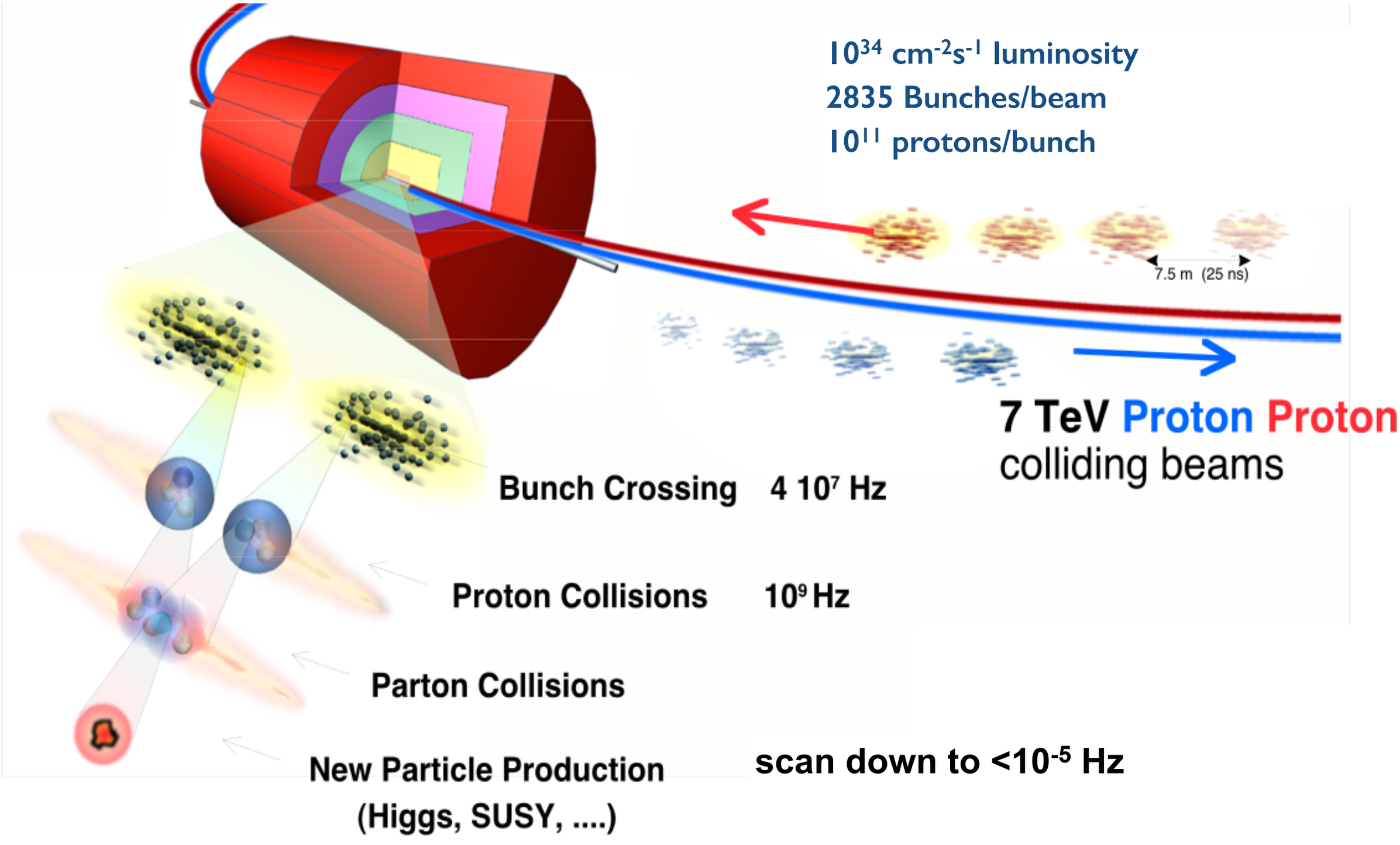
Mass [TeV]	4.2	5.7	7.0
Luminosity [fb]	20	300	3000

- Useful online tool is available

  @ collider-reach



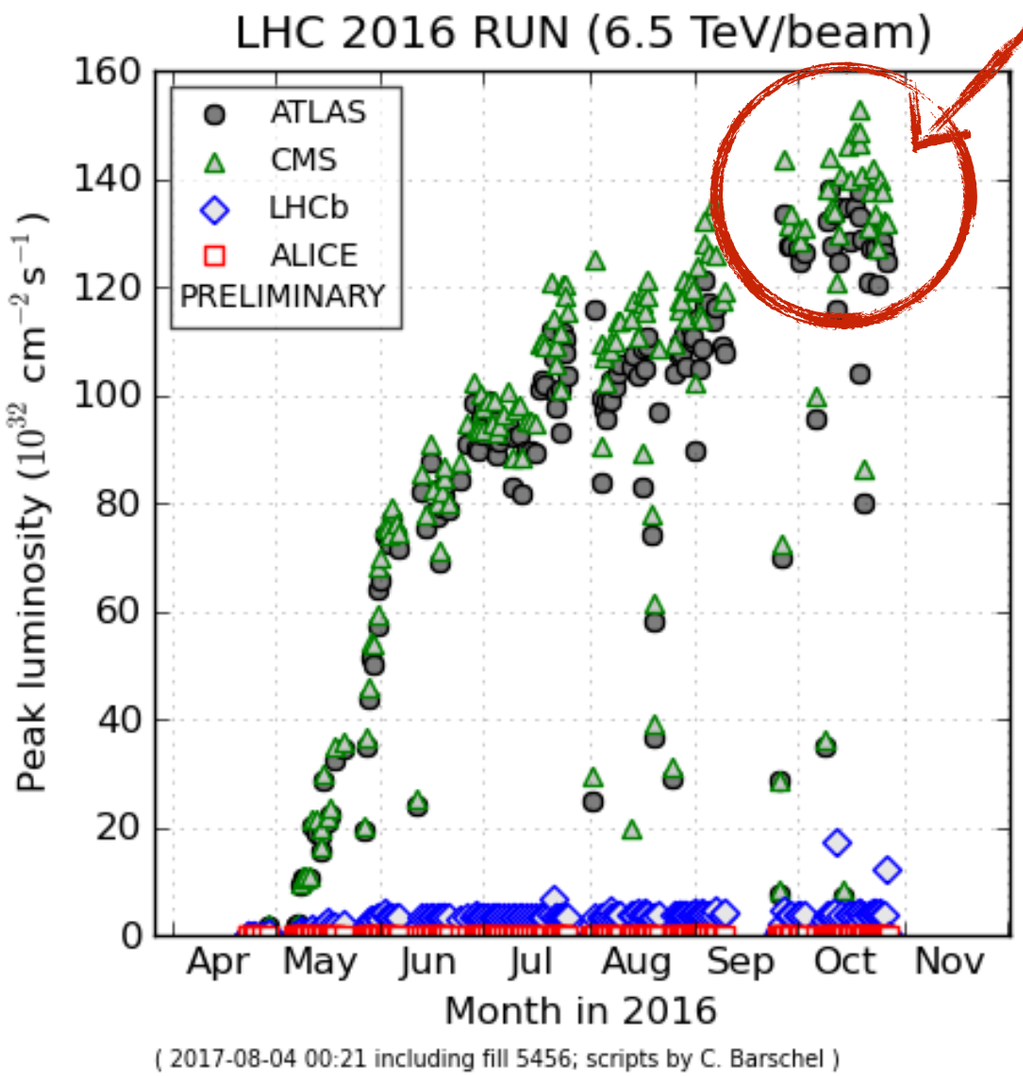
Collisions at the LHC: a summary

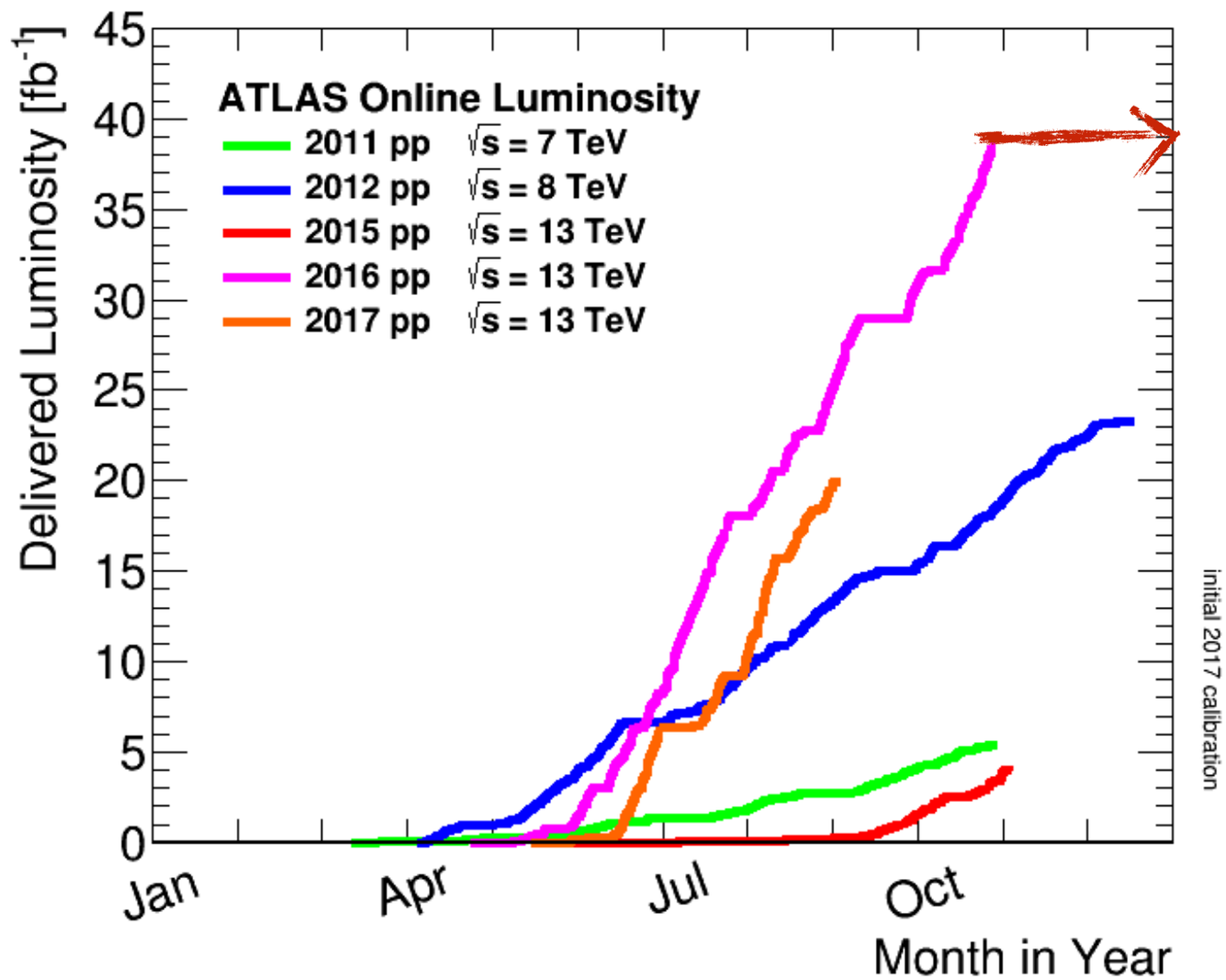


Need to select 1 / 10^{13} events produced and reject pileup!

LHC Run 2 performance overview

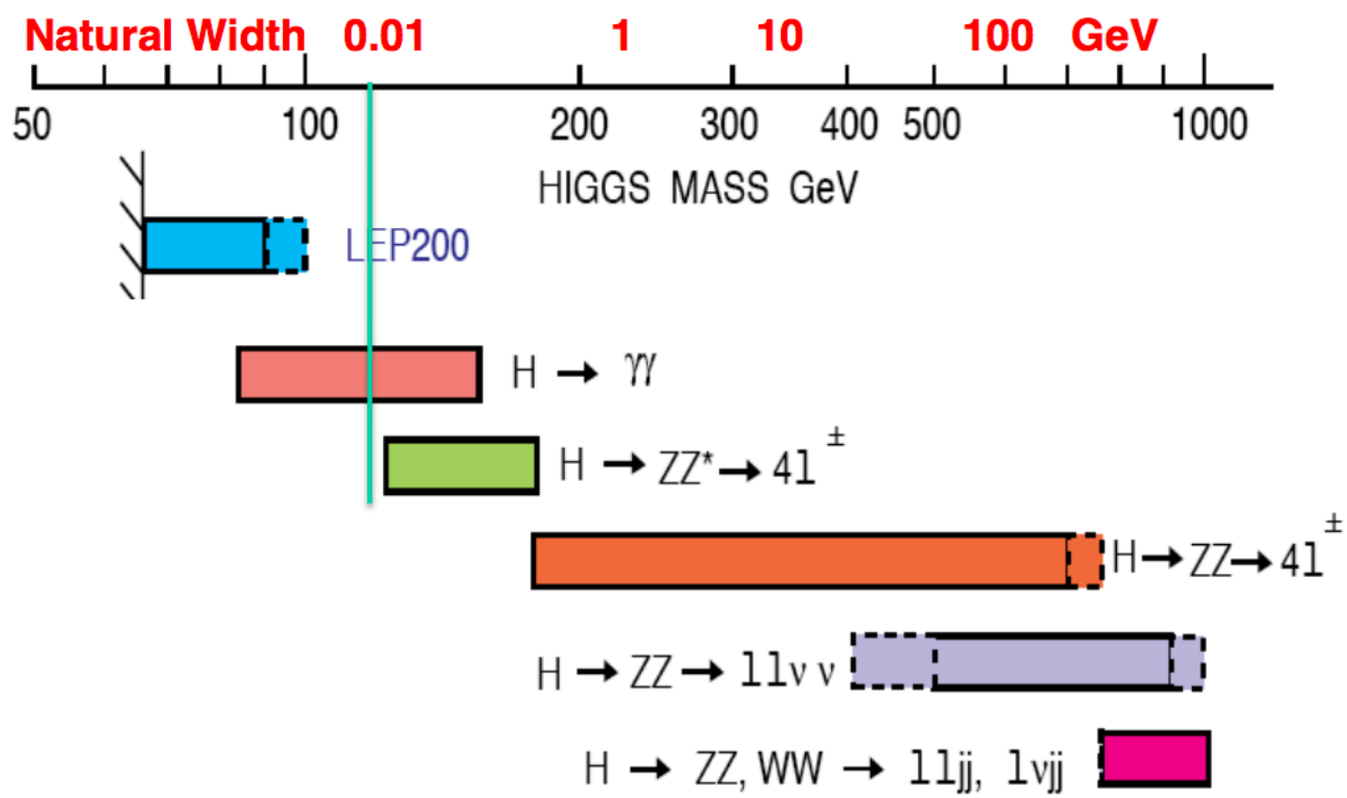
- **Run 2 of the LHC at 13 TeV surpasses completely in luminosity Run 1 (7 and 8 TeV)**
  - >2 times more luminosity than initially expected in 2016
  - total number of bunches not yet at maximum allowed: peak lumi. reaching ~1.4×10^{34} $cm^{-2}s^{-1}$
  - also successful 570 μb^{-1} PbPb (2015) and 180 nb^{-1} pPb (2016) runs





The general-purpose detectors concept

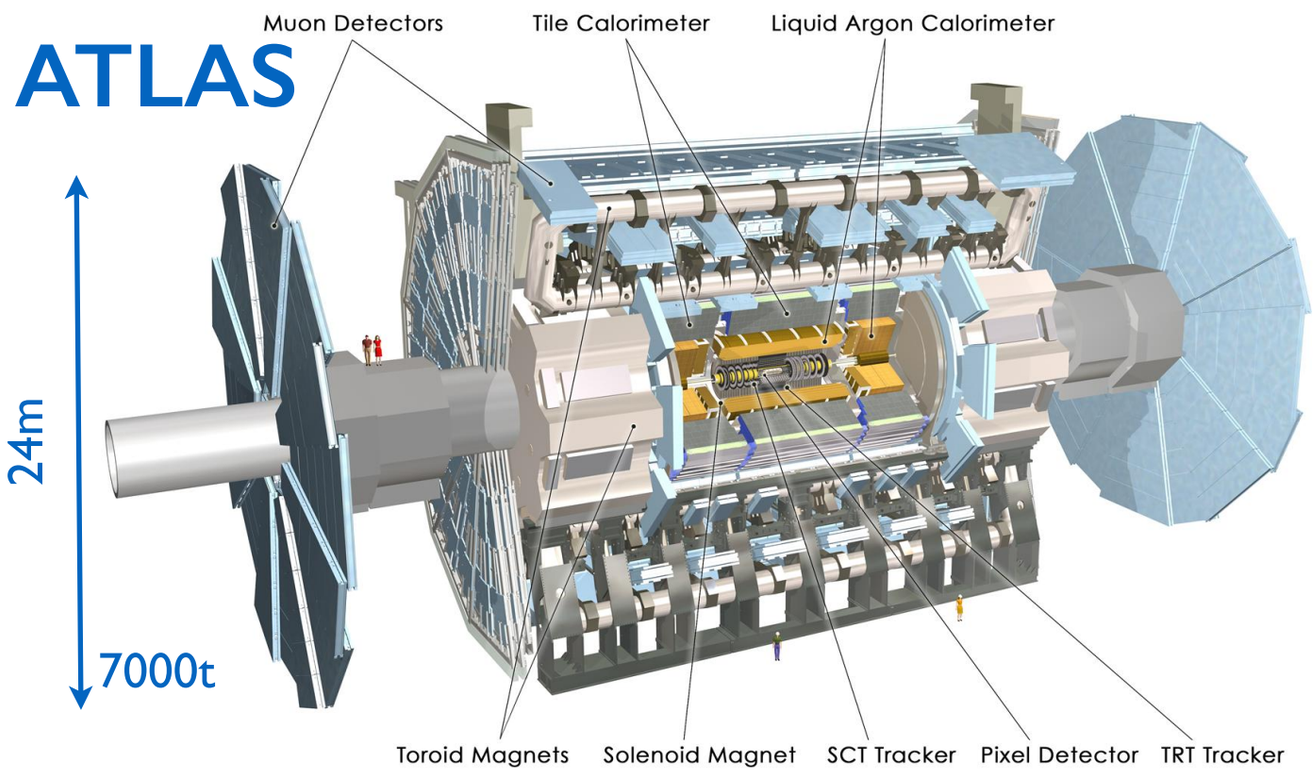
- The Higgs mass is not fixed in the SM: different signatures to be expected
- 4π-hermetic general purpose detectors are needed covering: leptons, photons, jets

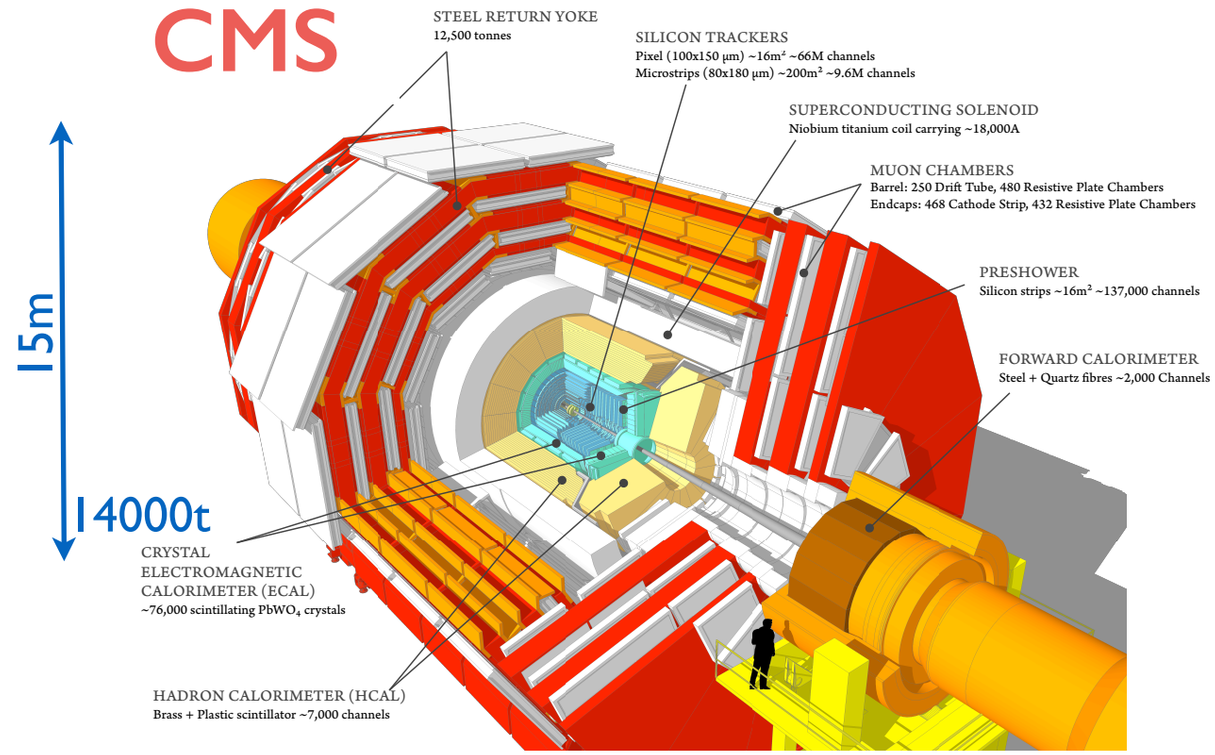


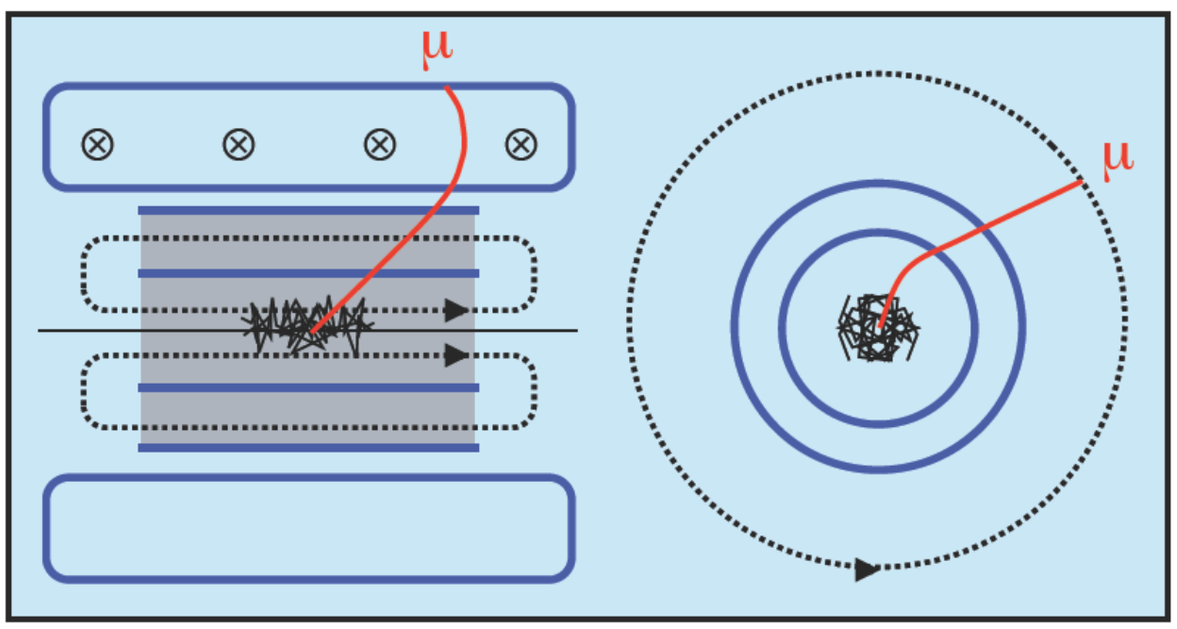
Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	±2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	±3.2	±2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	±3.2	±3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	±2.7	±2.4

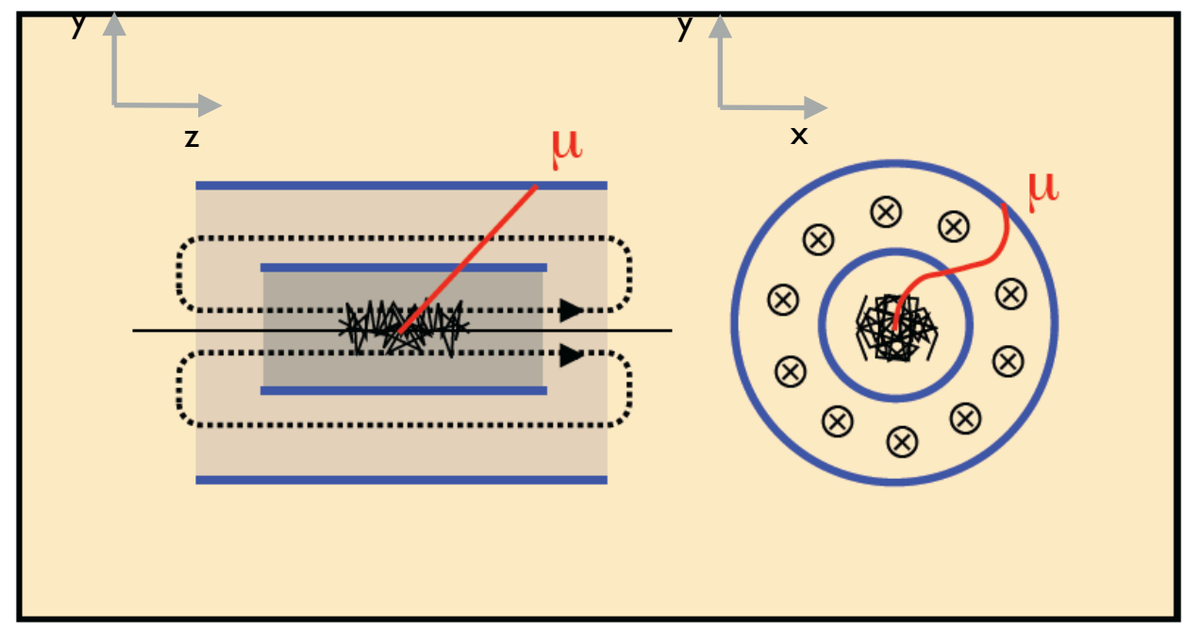
ATLAS performance goals from JINST 3 S08003

The two general purpose detectors







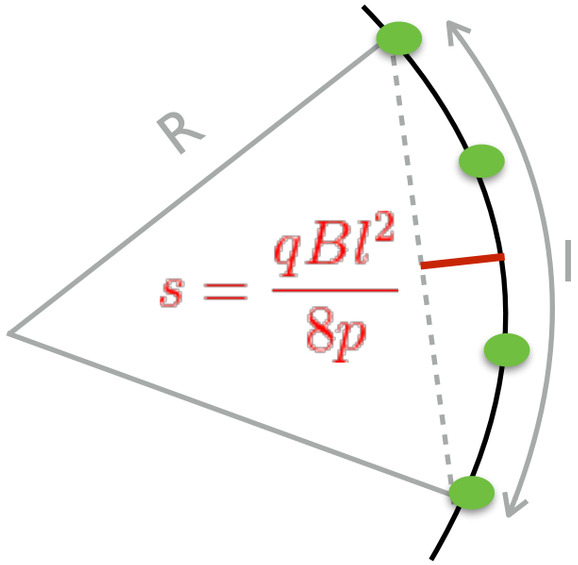


- Standalone measurement of p(μ)
- Resolution is flat in η and independent of pileup

- Two complementary p(μ) measurements
- Tracks point to primary vertex

The magnet is the heart of an experiment I

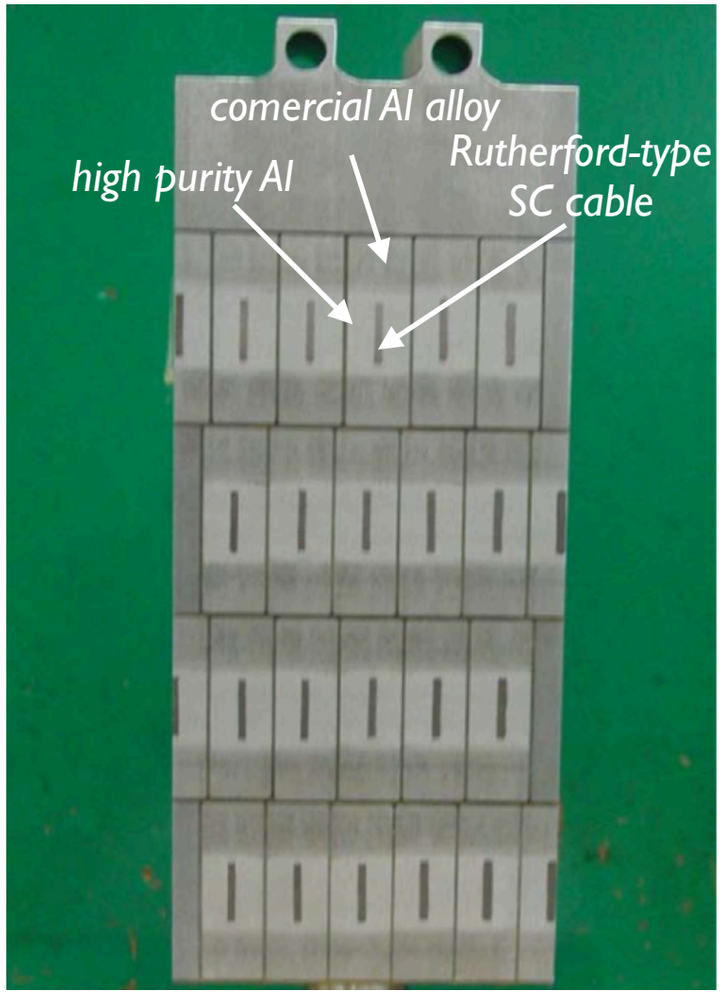
- Goal: measure 1 TeV muons with $\delta p_T/p_T$=10% without charge error
  - $$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3Bl^2}\sigma_s$$ this implies ~50μm uncertainty in measuring *s*
  - either use "continuous tracking" or "extreme field"



- **From Ampere's theorem:** $\oint \vec{B} \cdot d\vec{s} = \mu_0 I \Rightarrow B = \mu_0 n I$

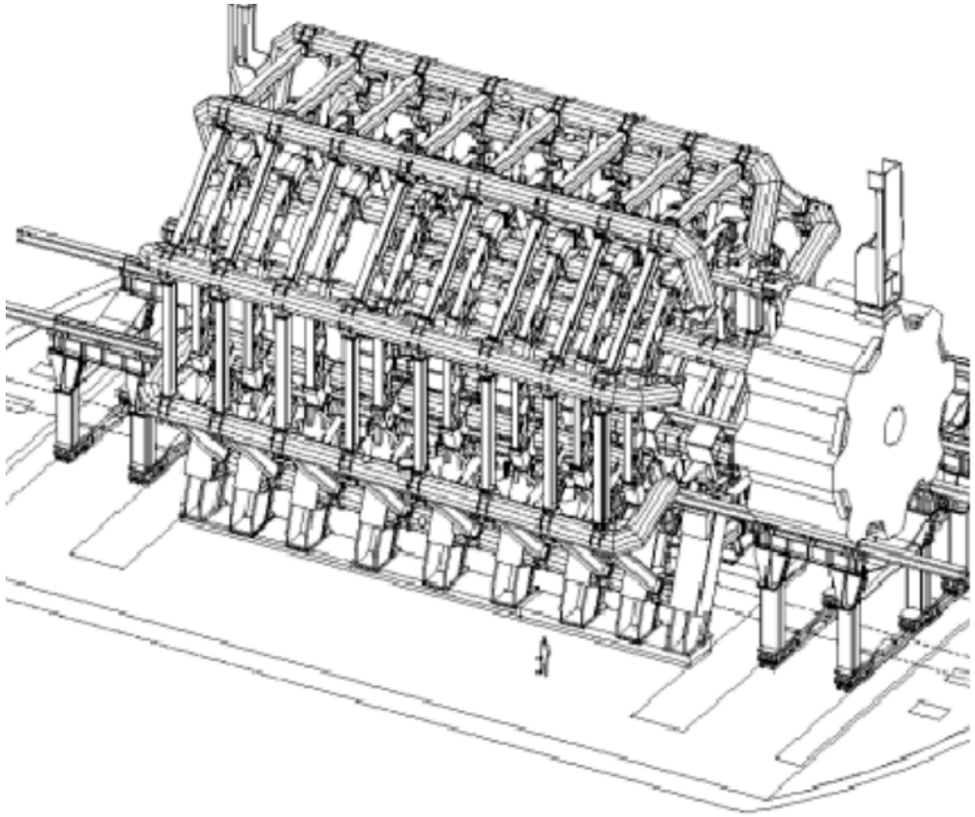
  ⇒ n= 2168 (120) turns per coil in CMS (ATLAS)

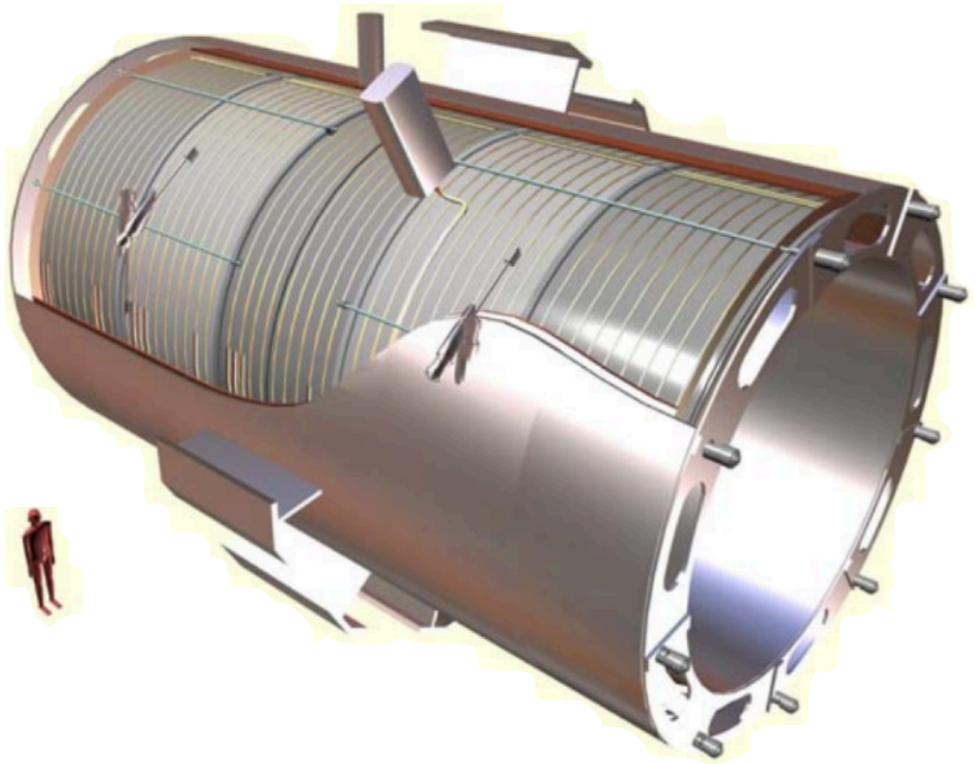
  - special design needed for superconducting cable in CMS
  - size limited by magnetic pressure (P≈6.4 MPa)



JINST 3 (2008) S08004

The magnet is the heart of an experiment II

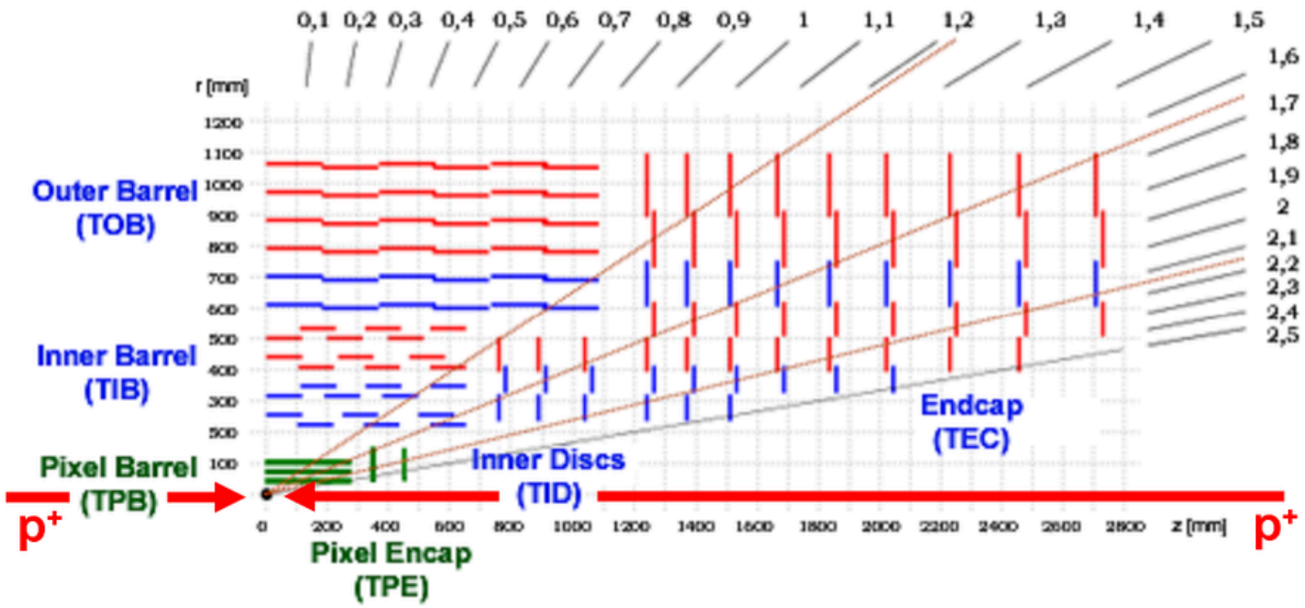




	ATLAS	CMS
B	0.6T (8 coils, 2x2x30 turns)	4T (1 coil, 2168 turns/m)
Challenges	• spatial/alignment precision over large surface • 1.5GJ energy stored	• design and winding of the cable • 2.7GJ energy stored
Drawbacks	• limited pointing capabilities • non-trivial B • additional solenoid (2T) needed for tracking • space needed	• limits space available for calorimetry • no photomultipliers for calorimeters • multiple scattering in iron core • poor bending at large angles

Si-based trackers

- **General requirements:**
  - 0.5% (10%) p_T resolution at 1 GeV (TeV)
  - allow lepton charge @ p~2 TeV
  - keep narrow signals narrow ($H\to4\mu$, $Z\to\ell\ell$)
  - keep $Z'\to\ell\ell$ searches competitive

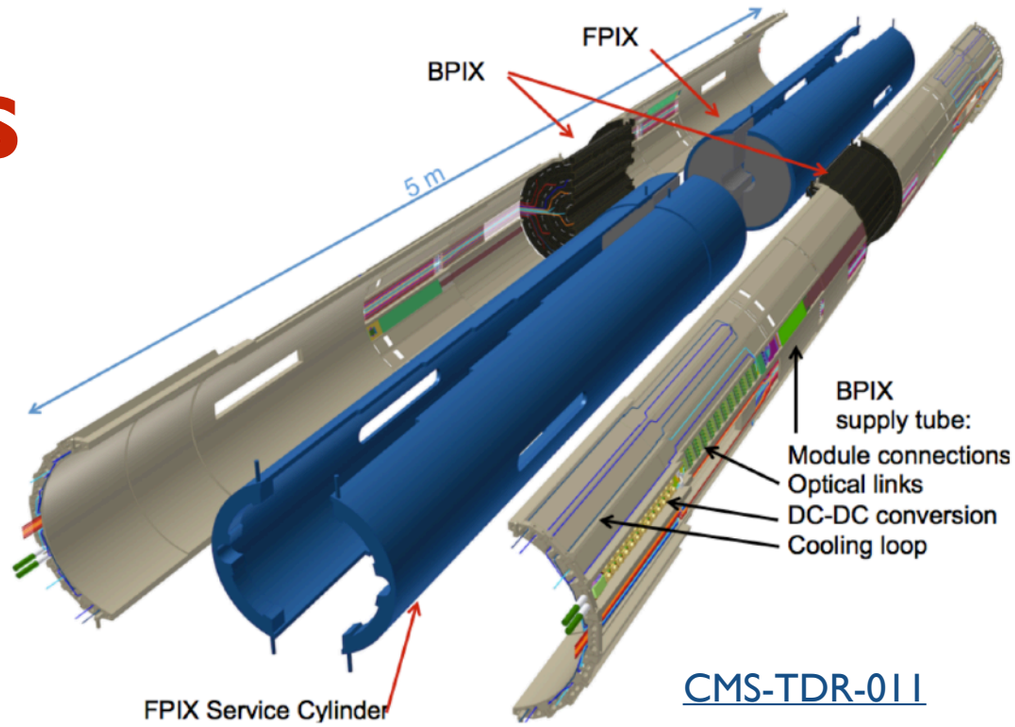


- **Continuous tracking (ATLAS) or few accurate points (CMS)?**

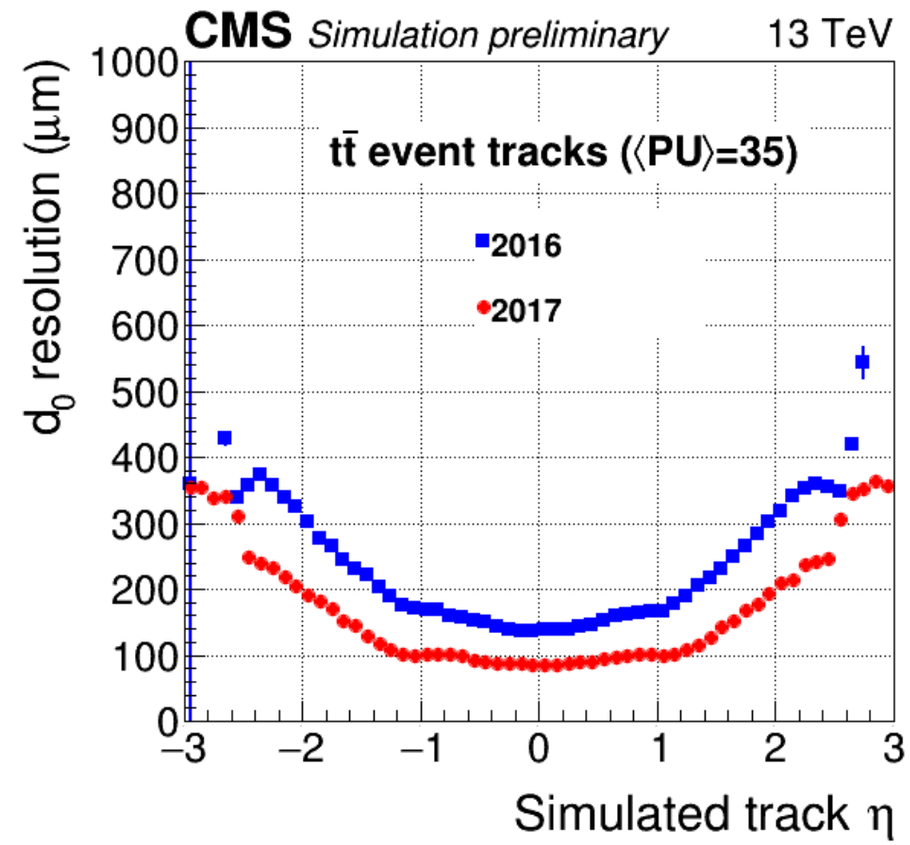
	ATLAS	CMS
R_{in} [cm]	5	4.4
R_{out} [m]	1.1	1.1
Length [m]	5.4	5.8
B [T]	2	4
X_0 @ $\eta\approx0$ (1.4)	0.3 (2.3)	0.4 (1.8)
σ_{p_T}/p_T @ 1 (100) GeV	1.3% (3.8%)	0.7% (1.5%)
"outer" $\sigma_{r\phi}$	130 μm/straw	35 μm/strip

Refurbished pixels in Run 2

CMS

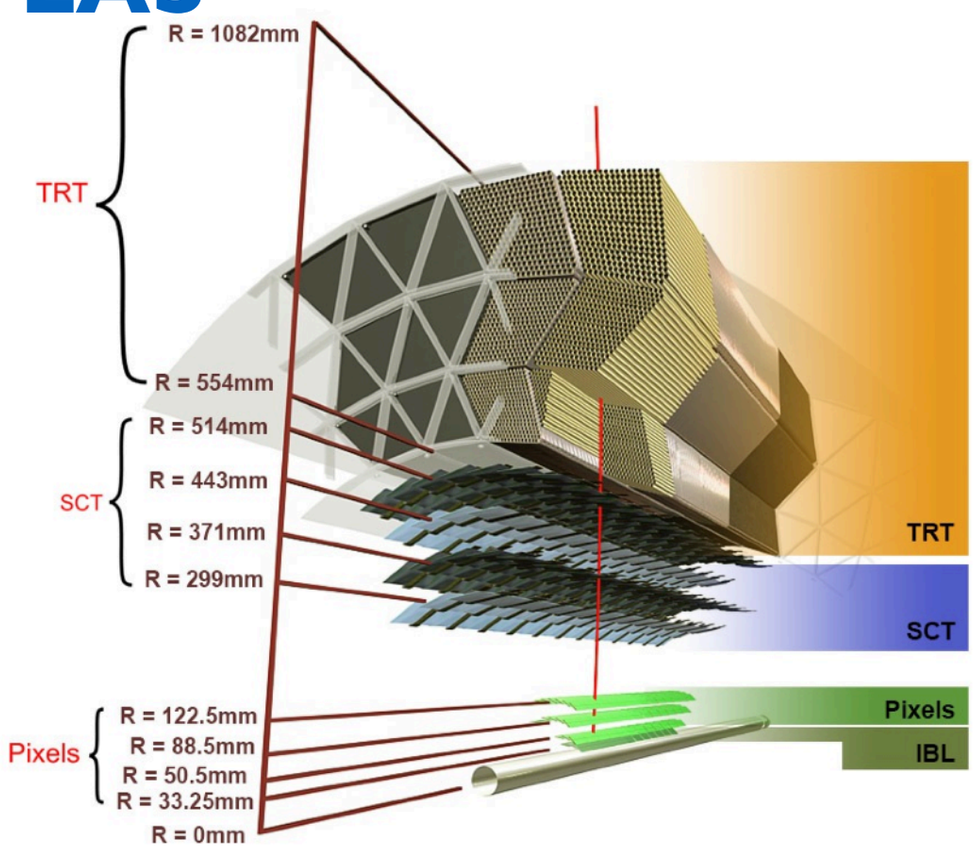


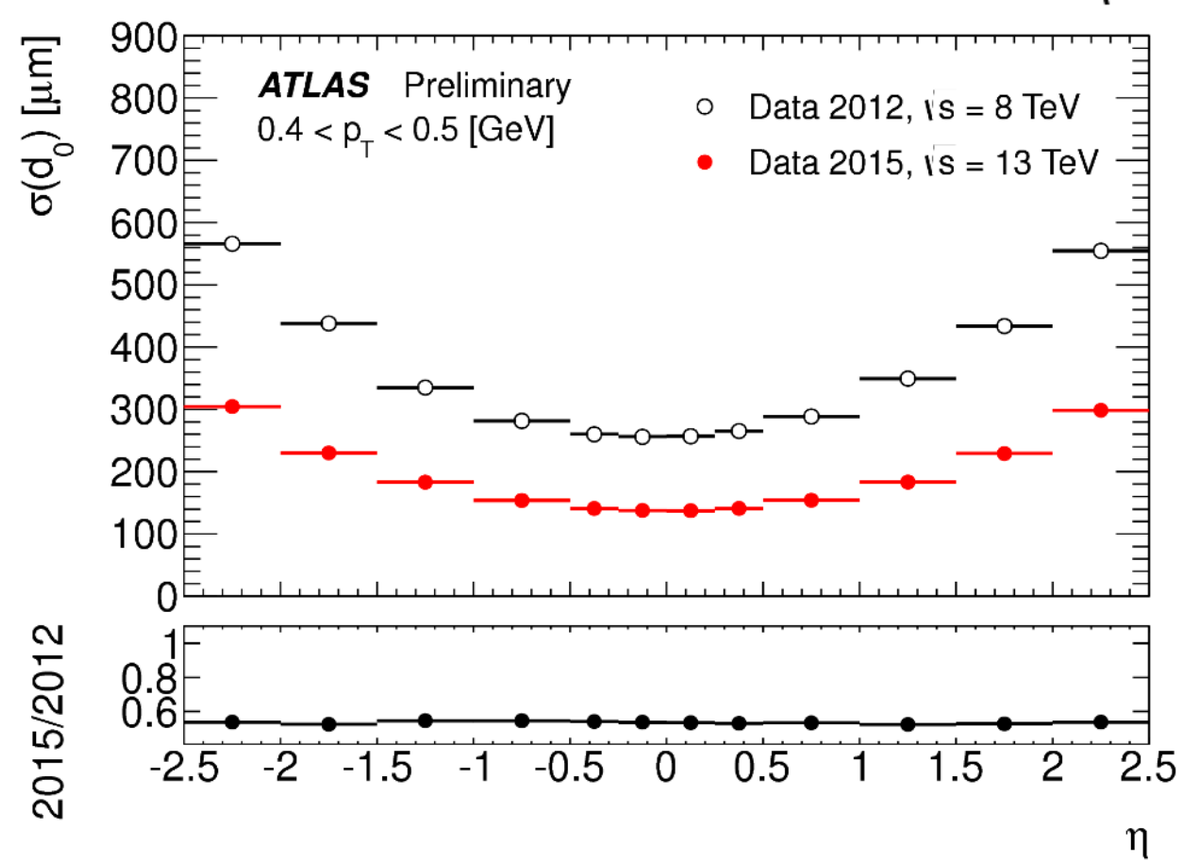
CMS-TDR-011



2017 TRK performance

ATLAS





IDTR-2015-007

Calorimeters

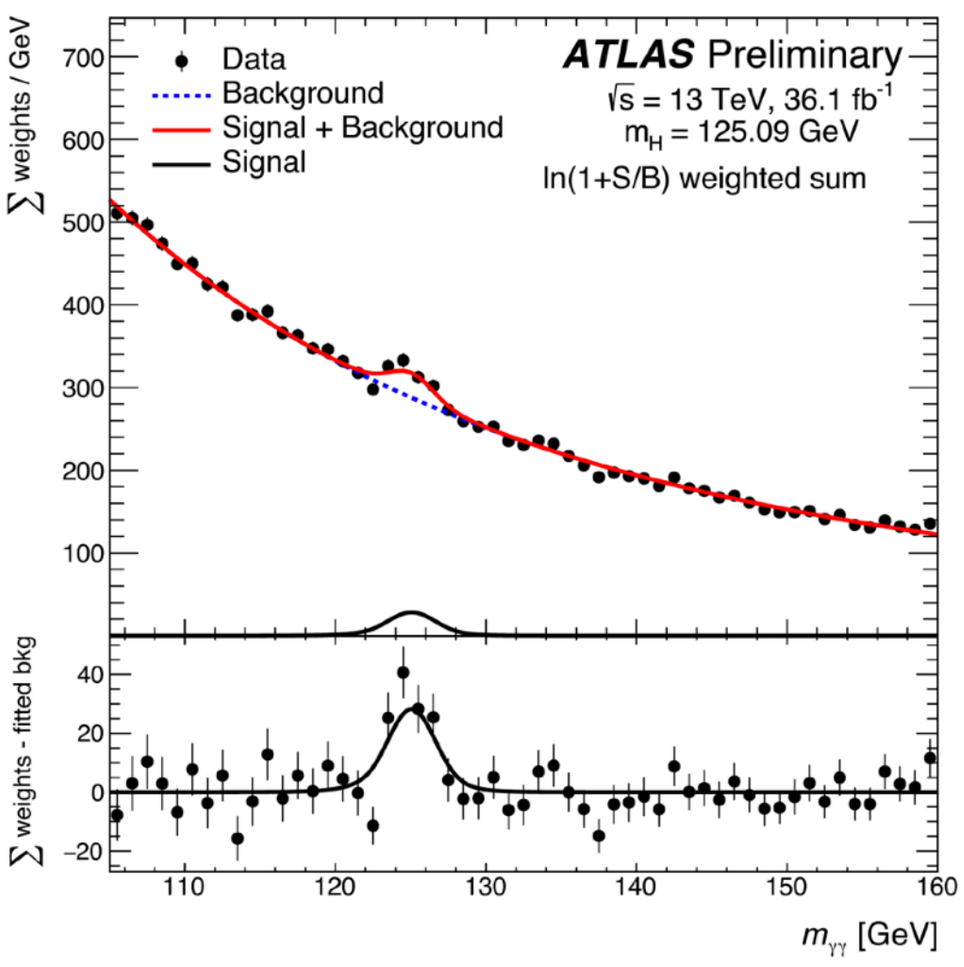
- **Di-object invariant mass performance is often the figure of merit**

$$m_{\alpha\alpha'} = \sqrt{2E_\alpha E_{\alpha'}(1-\cos\zeta)} \Rightarrow \frac{\delta m_{\alpha\alpha'}}{m_{\alpha\alpha'}} \propto \frac{\delta E_\alpha}{E_\alpha} \oplus \sin\zeta \cdot \delta\zeta$$

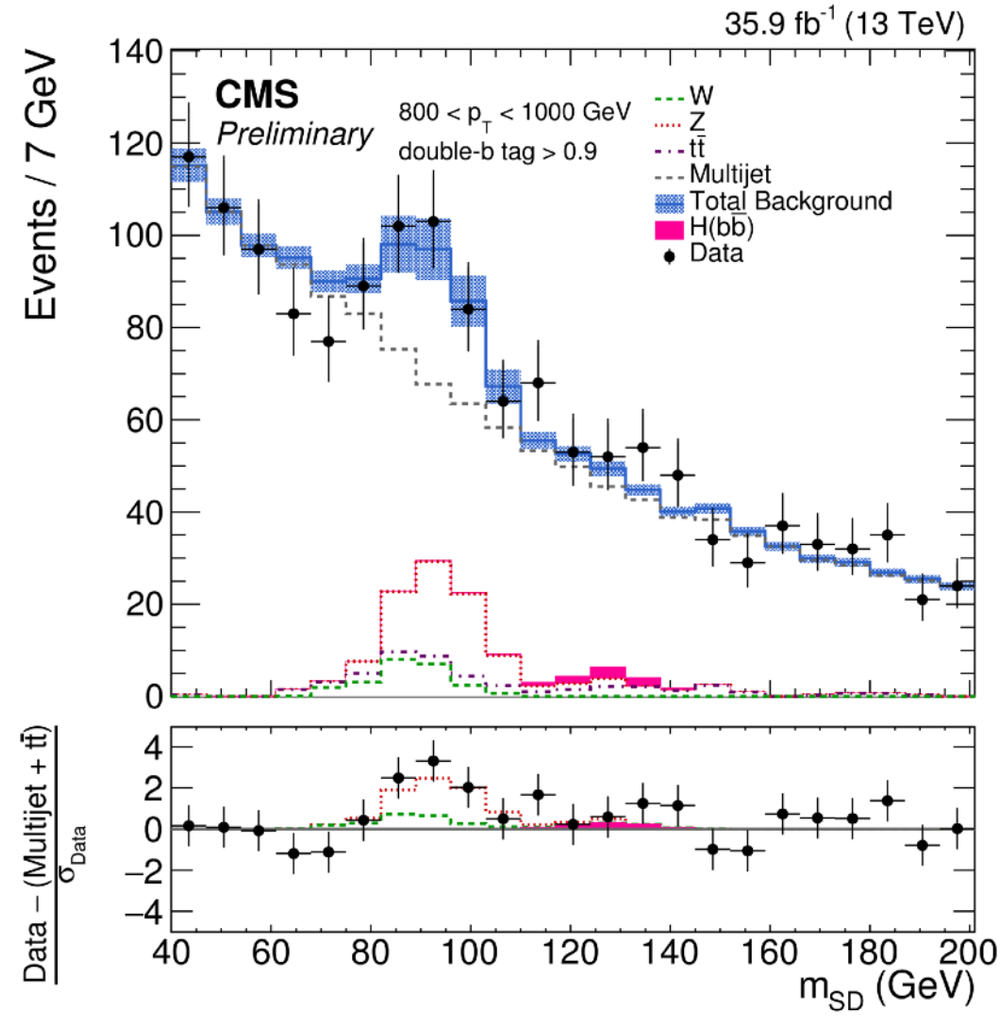
Particle	σ_E/E
γ	~3-10%/$E^{1/2}$
hadrons	~50-100/$E^{1/2}$

pileup mitigation from pointing and timing capabilities + fast charge integration

fine segmentation to resolve $\pi^0 \to \gamma\gamma$, jet substructure

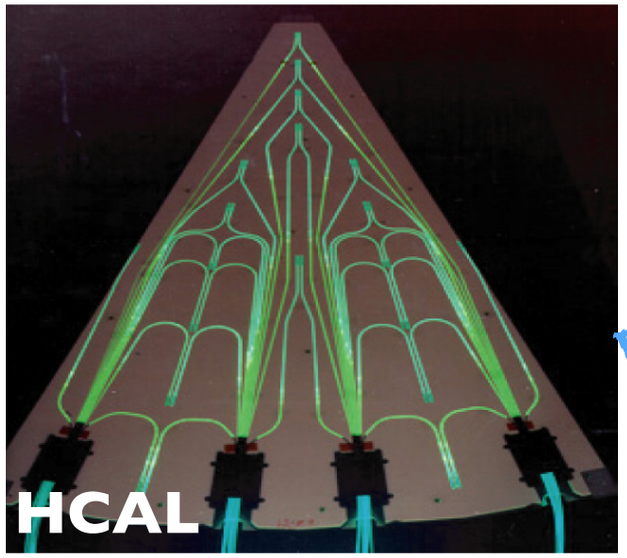


ATLAS-CONF-2017-045

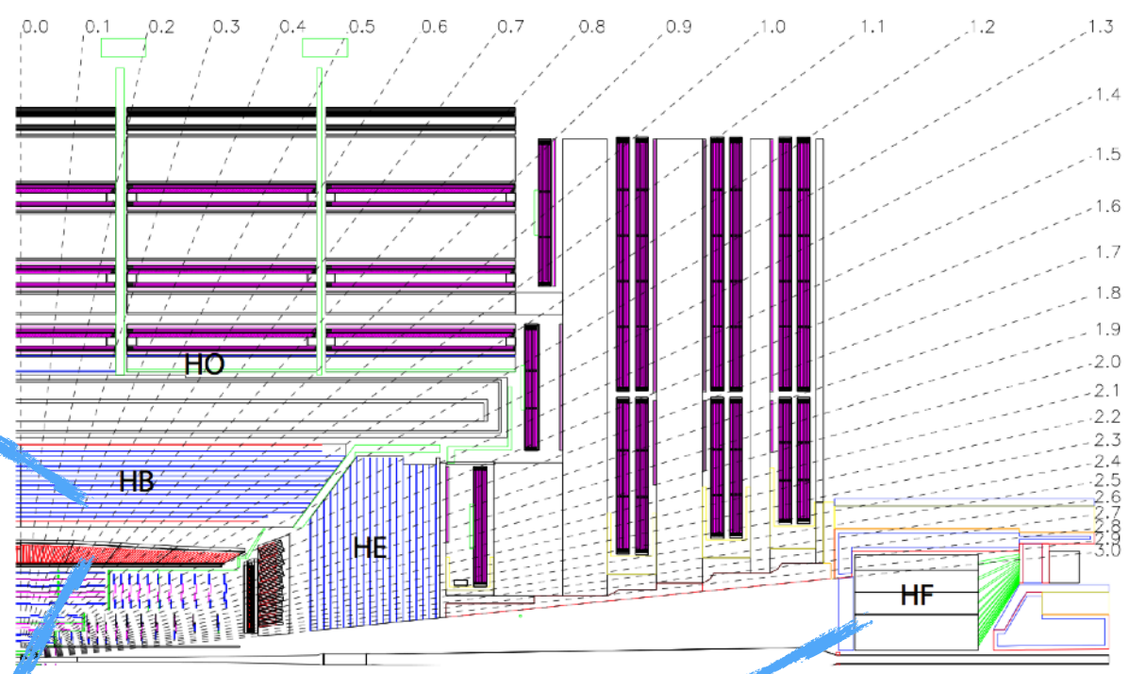


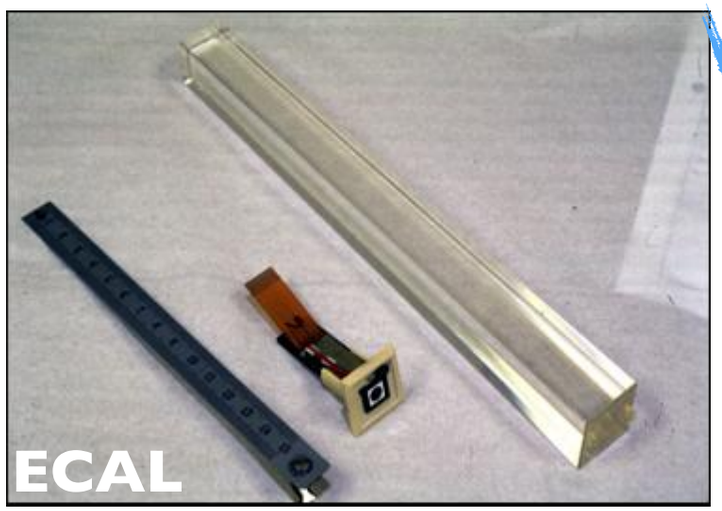
CMS-HIG-17-010

CMS calorimetry system



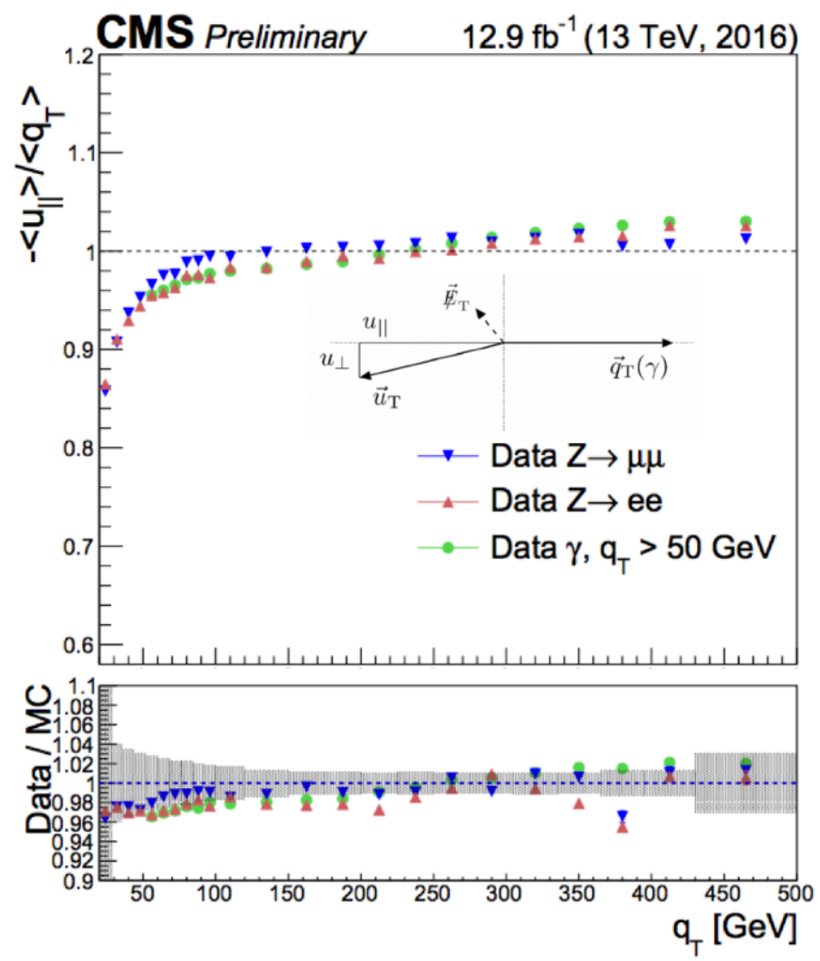
- Brass and scintillator
- Si photomultipliers (Run 2)





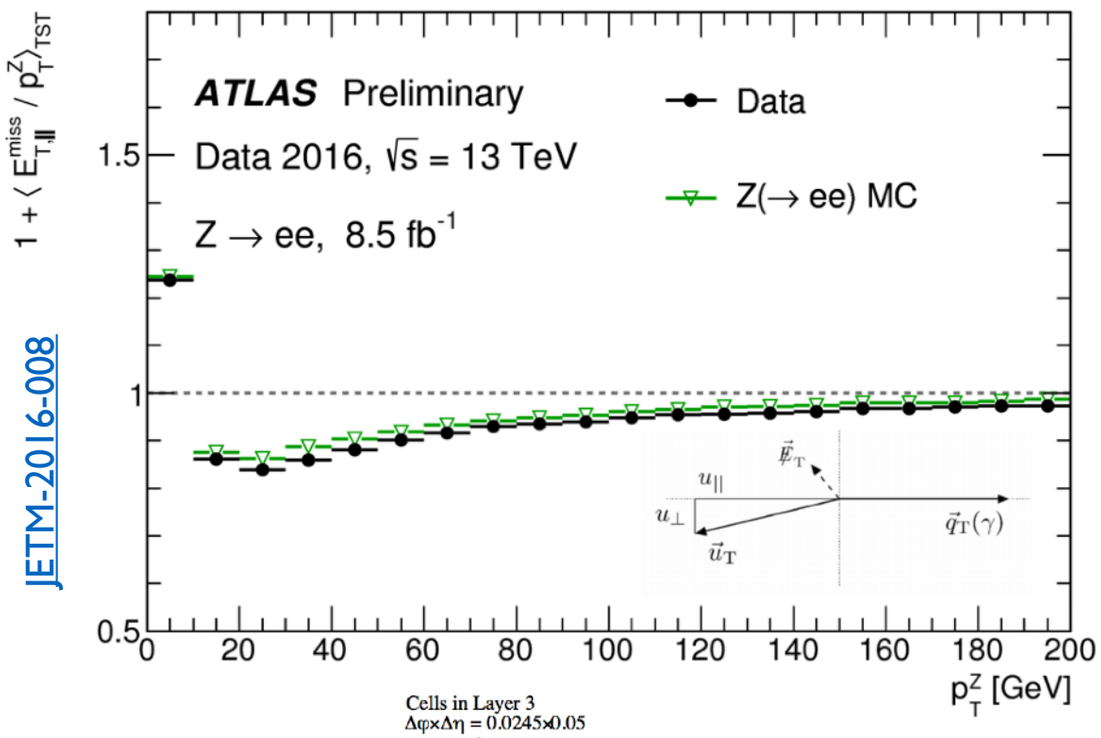
- $PbWO_4$ crystals
- Avalanche photodiodes
- Projective geometry

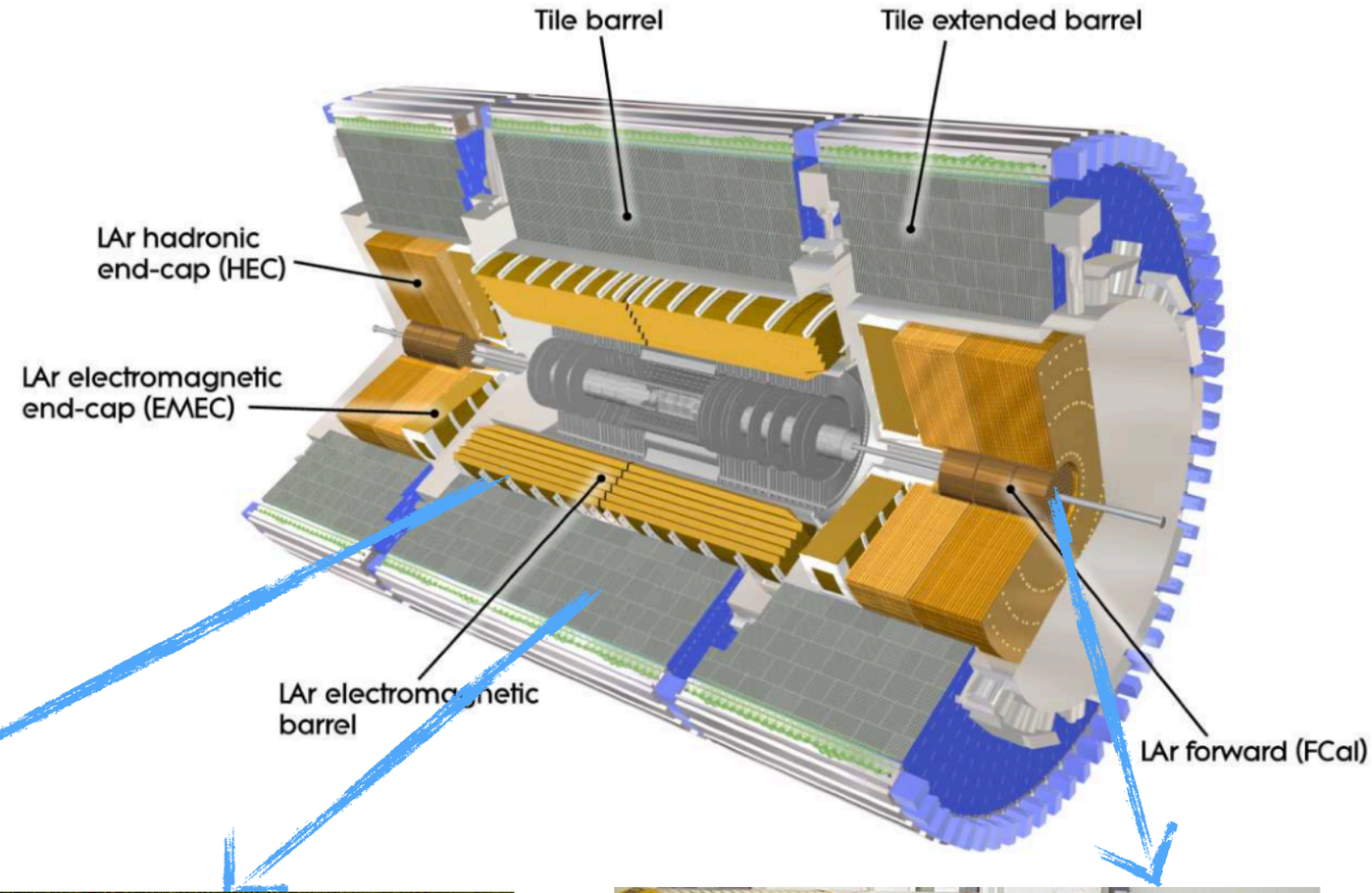
- Quartz fibers and steel
- Multi-anode photomultipliers

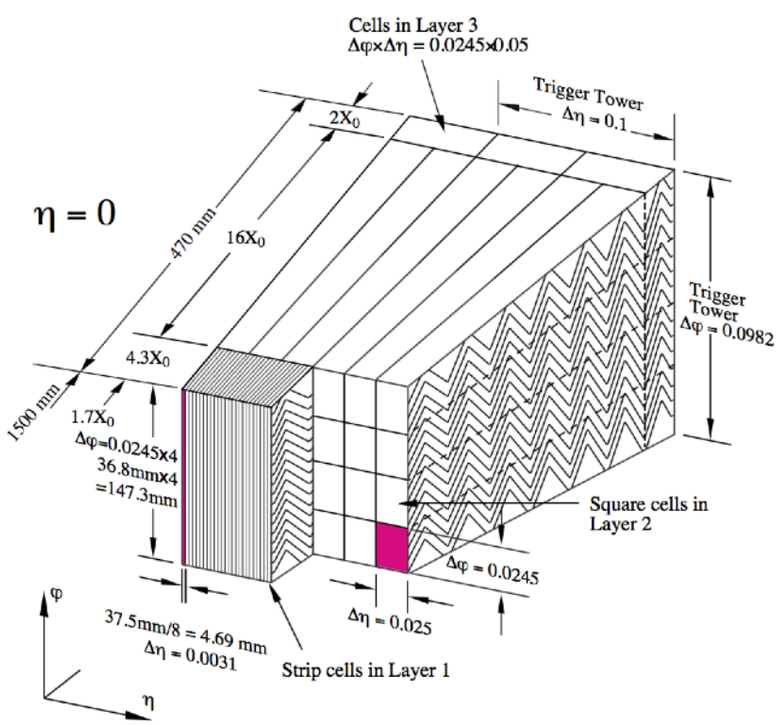


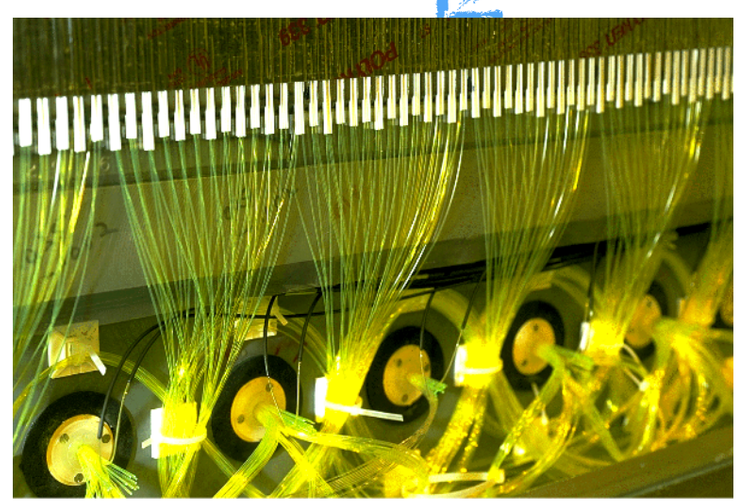
CMS-JME-16-004

ATLAS calorimetry overview









ECAL

- Lead and liquid Argon
- accordion geometry

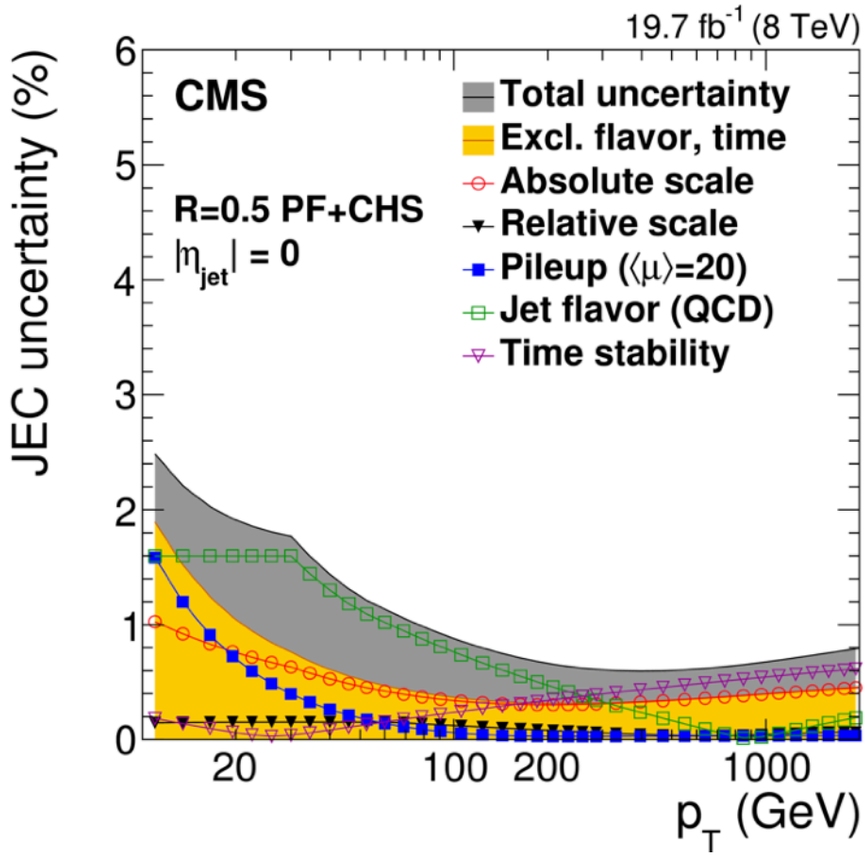
HCAL

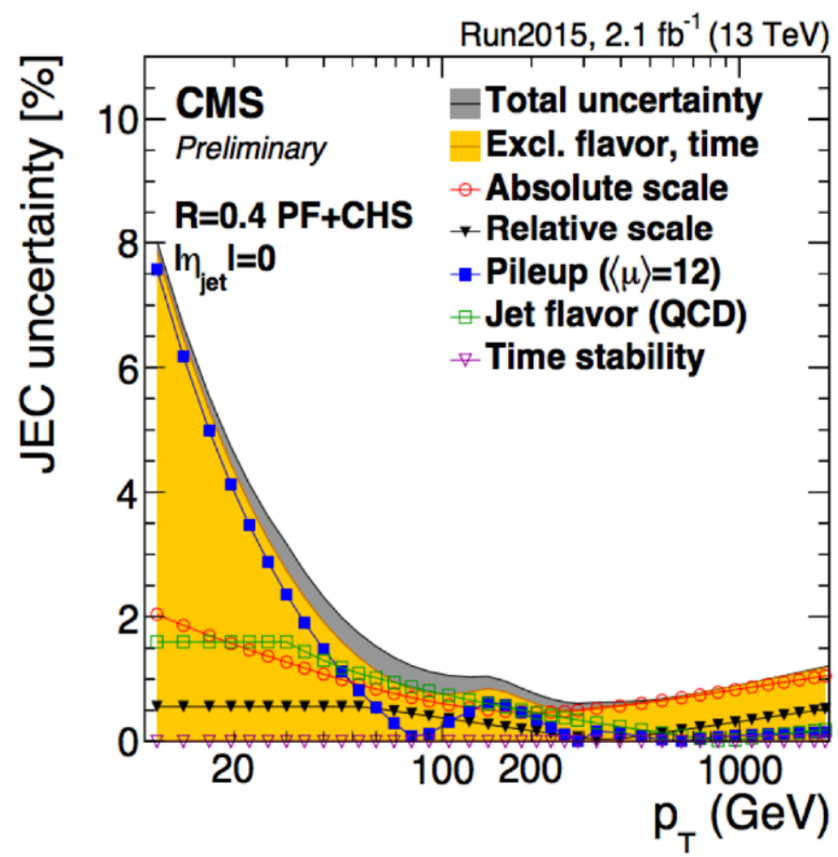
- Steel and scintillating tiles
- WLS readout by PMTs

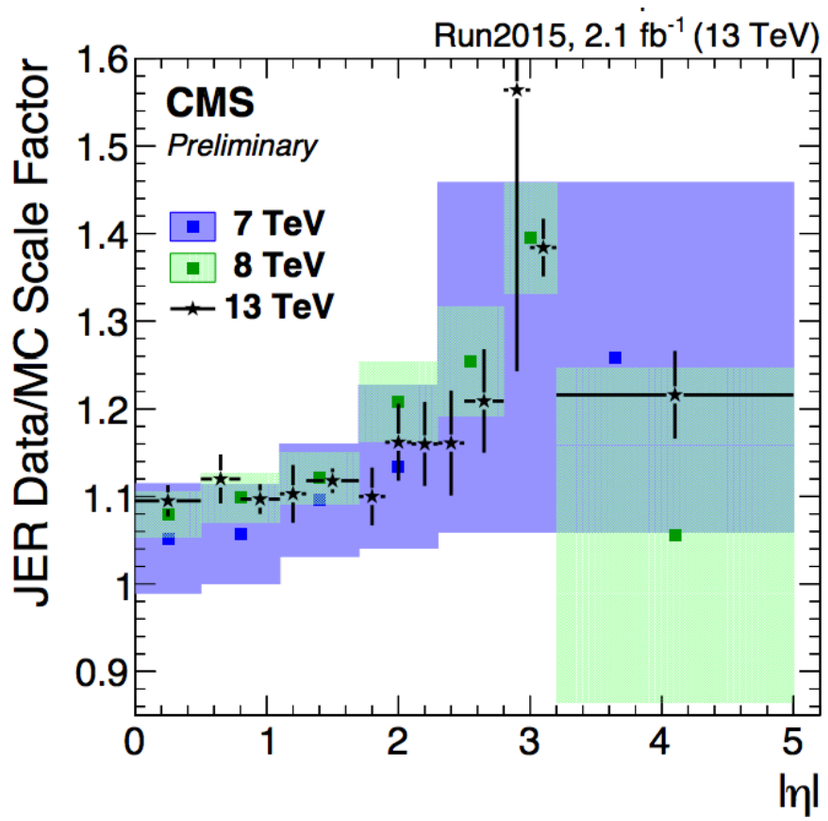
Forward HCAL

- Copper/W and liquid Argon

Jet performance: Run I vs Run II







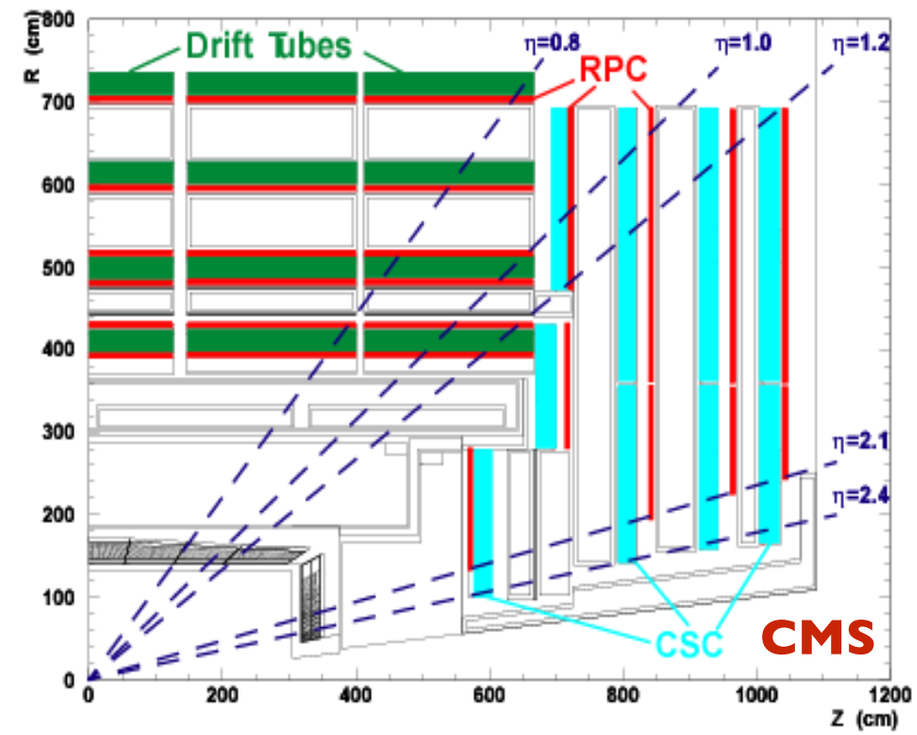
- **Jet energy scale**
  - Pileup: 25ns (Run I) vs 50ns (Run II) more work needed to mitigate out-of-time pileup contribution
  - Absolute/relative scale: more data needed in Run II
- **Jet energy resolution**
  - similar performance (driven by single particle resolutions)

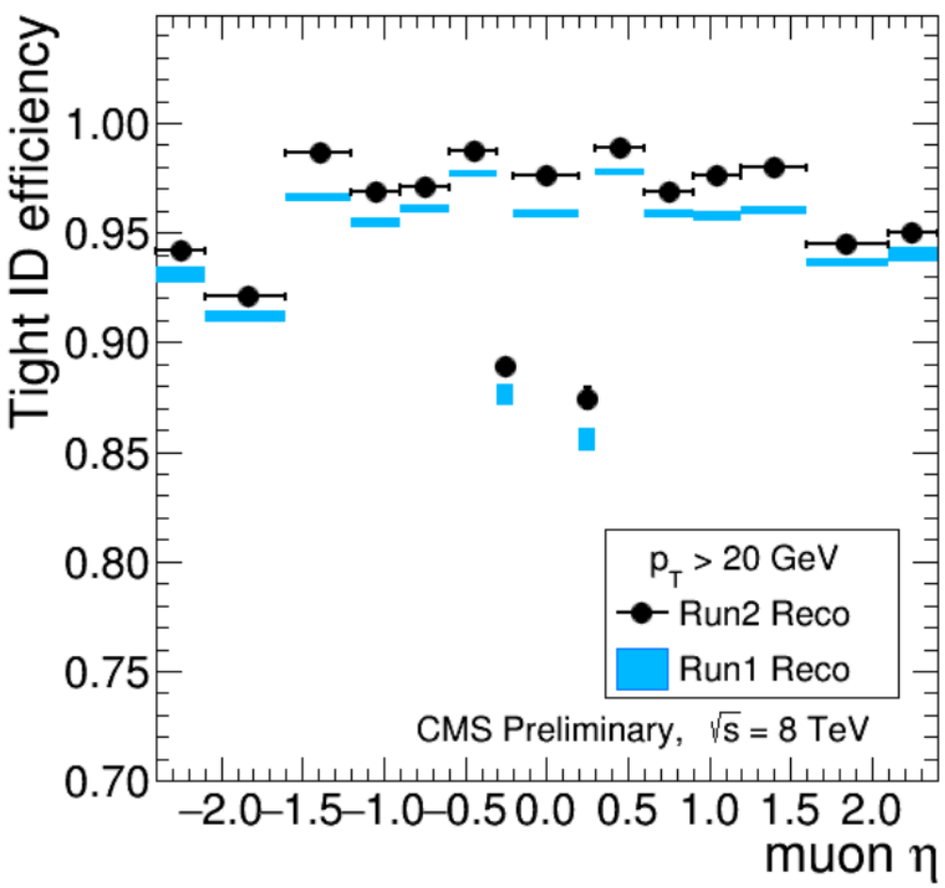
JINST 12 (2017) P02014, CMS DP 2016/020

Muon reconstruction

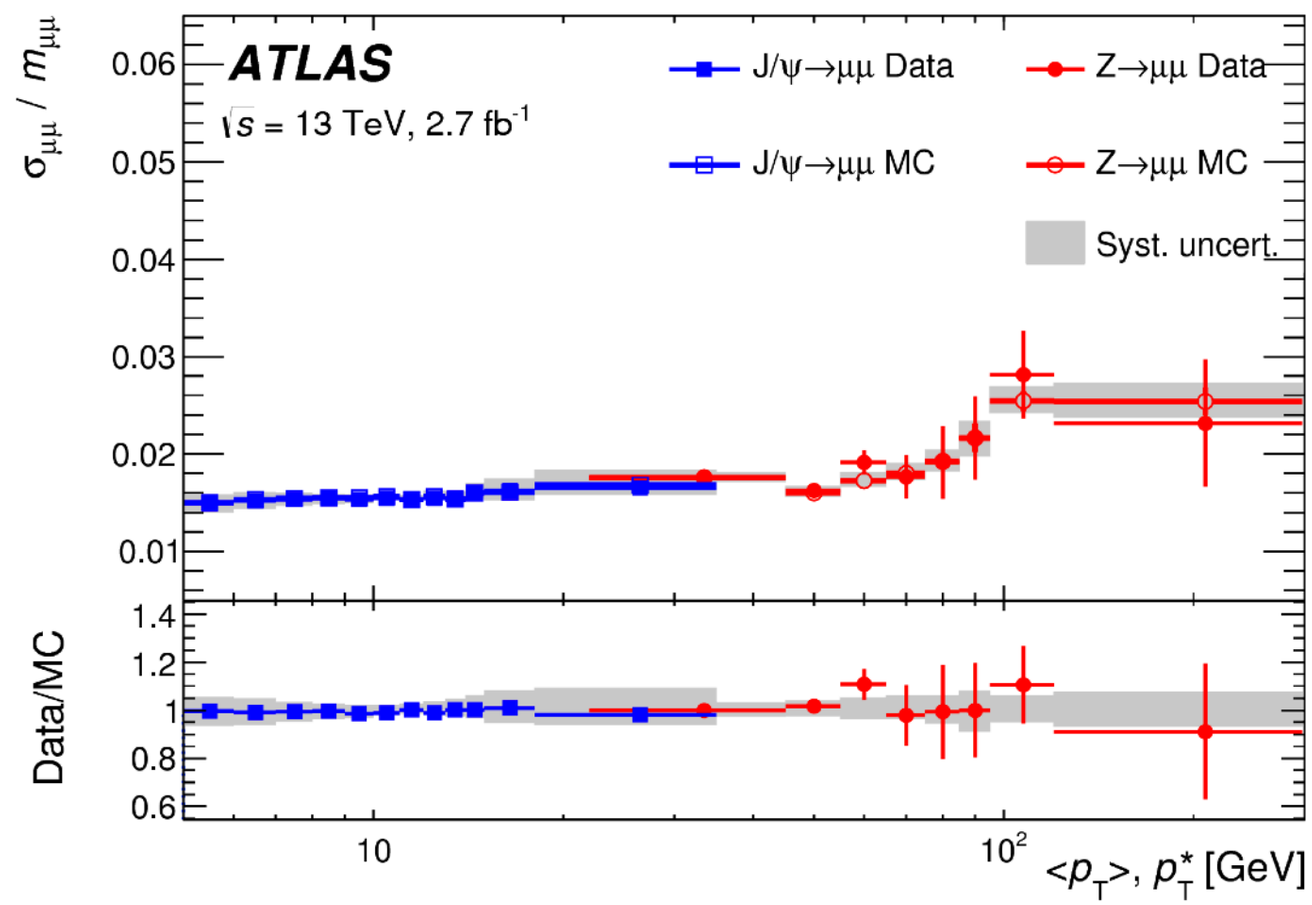
- **External tracking for muons is used in both detectors**
  - mostly based on gaseous ionization chambers used
  - provide easy id at high integrated luminosities
  - good momentum resolution for level-1 trigger

    (significantly improved in CMS after matching to tracker)
- δ-rays, punch-throughs, *n* may trick pattern recognition
- lower p_T b,c→μ decays have high trigger rates



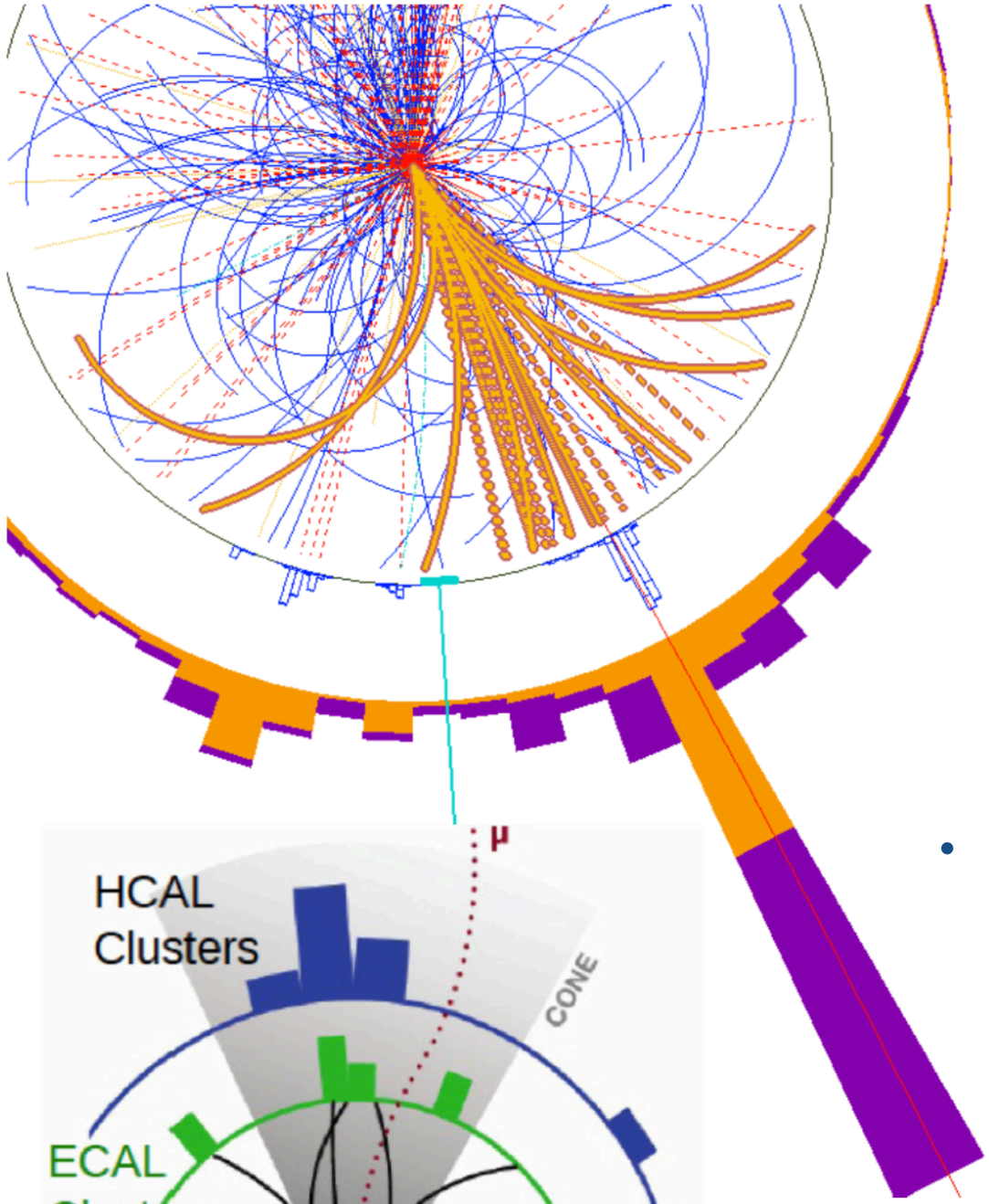


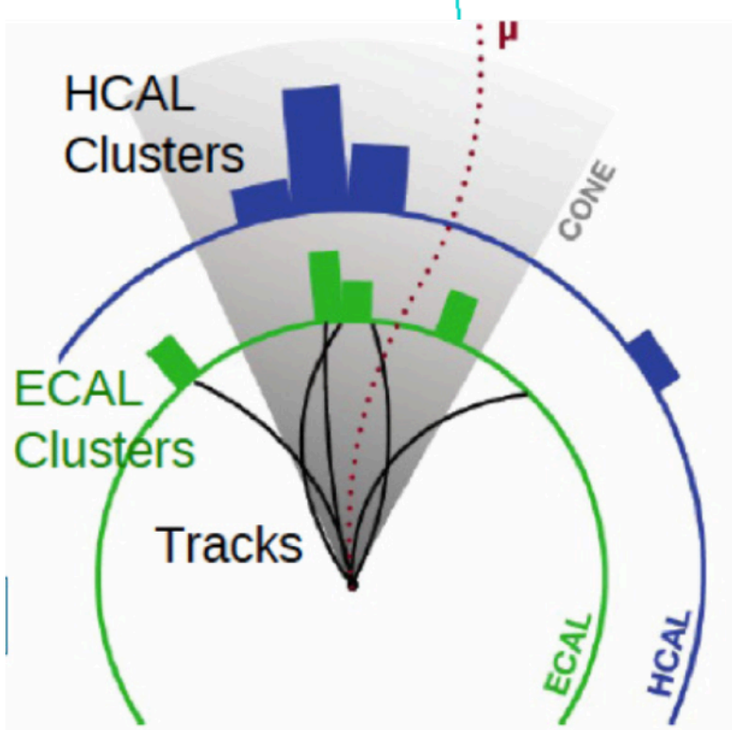
CMS-DP-2015/015

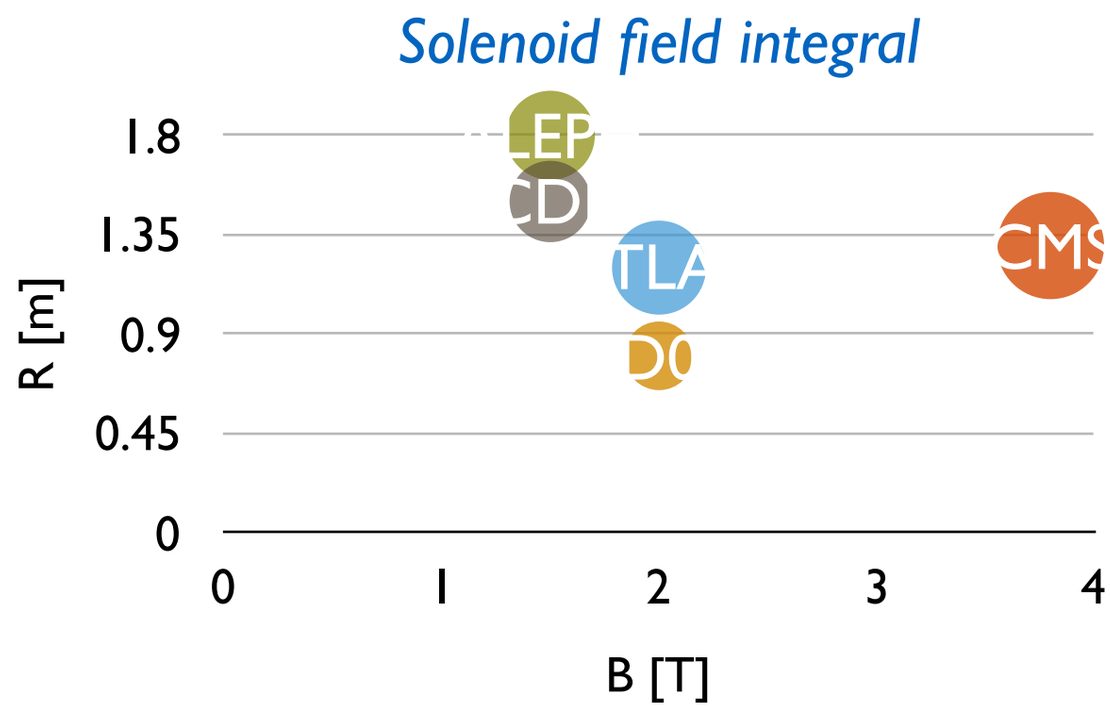


ATLAS-PERF-2015-10

Field integral and particle flow



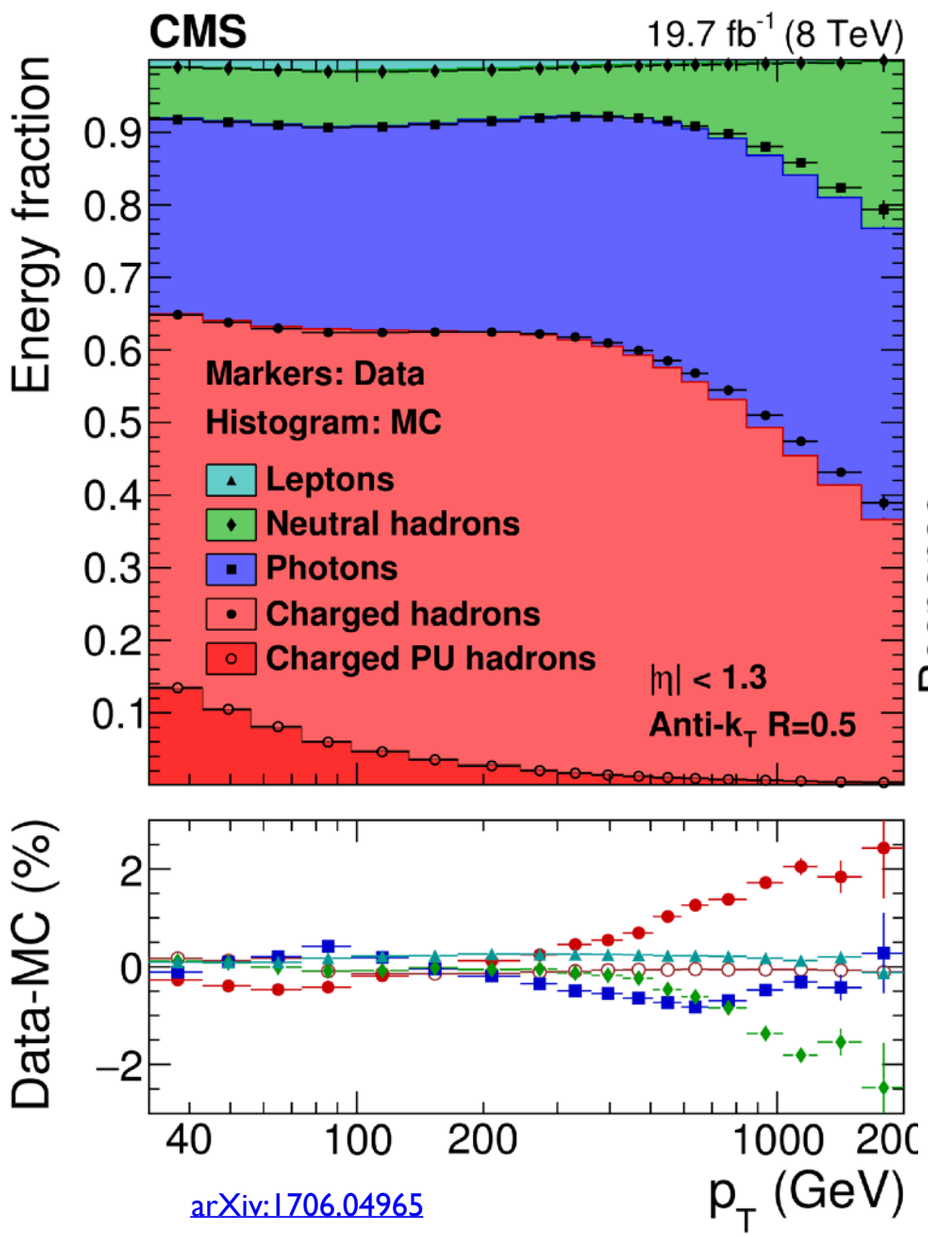




- **Particle flow algorithms benefit from larger B.R**
  - well separated tracks
  - reconstruct conversions, nuclear interactions, V^0 decays
  - easier to link with calorimeter deposits
  - dedicated calibrations from identified π^+, K^0, e, γ, μ

Particle flow performance

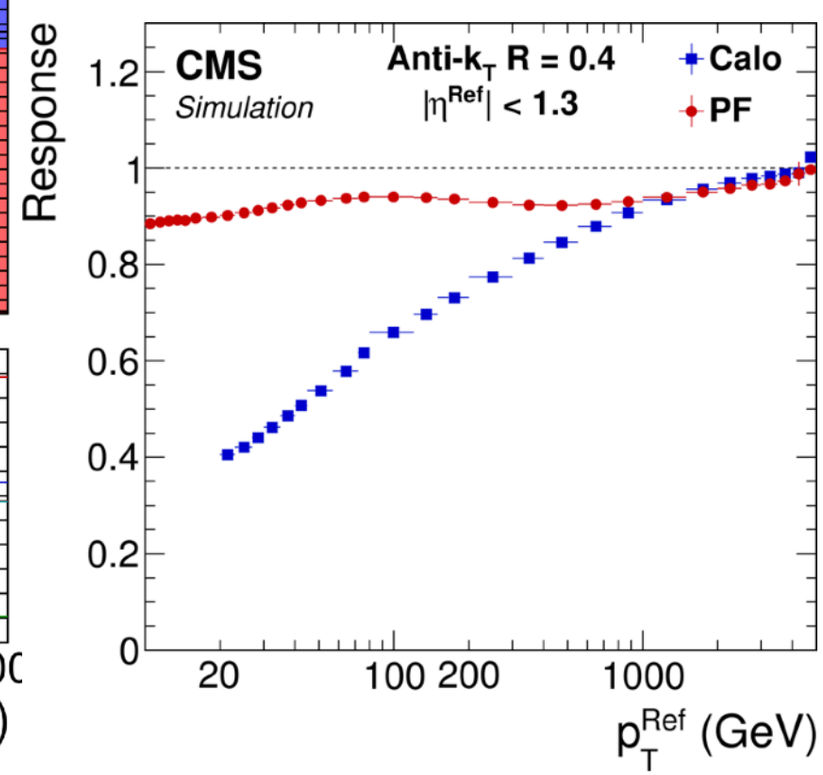
- **>80% of the jet components are reconstructed using high resolution detectors**
  - *tracking*: π^+,K^+ and other charged hadrons are approximately O(60%)
  - *ECAL*: by isospin symmetry $\pi \rightarrow \gamma\gamma$ contribute in second place with O(20%)

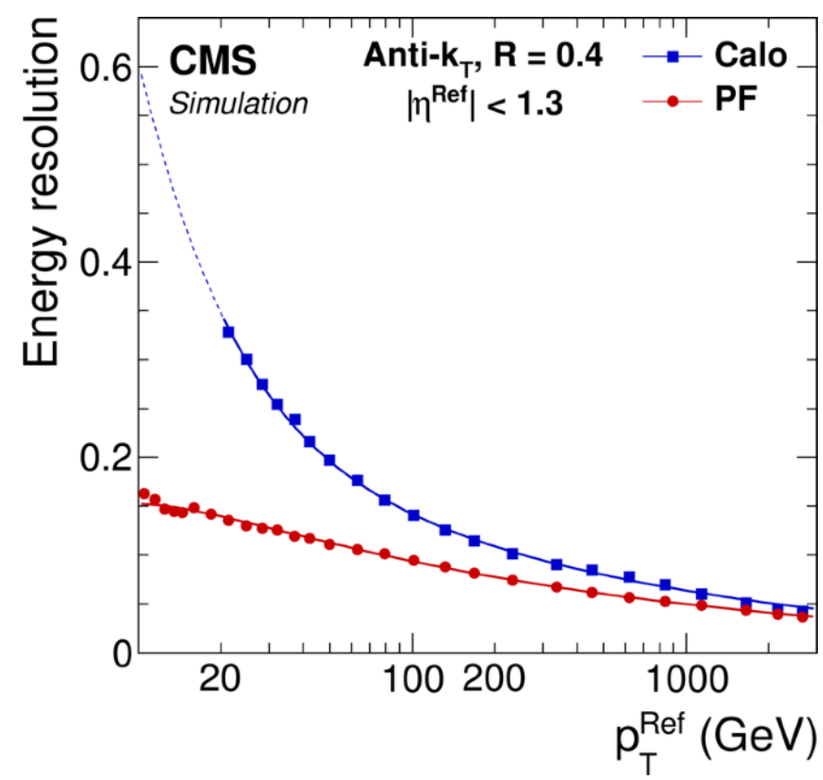


arXiv:1706.04965

Excellent out-of-the-box response (p_T^{reco}/p_T^{ref})

Ability to reconstruct jets at lower pT, gain>60% in resolution ($\Delta p_T/p_T^{ref}$)

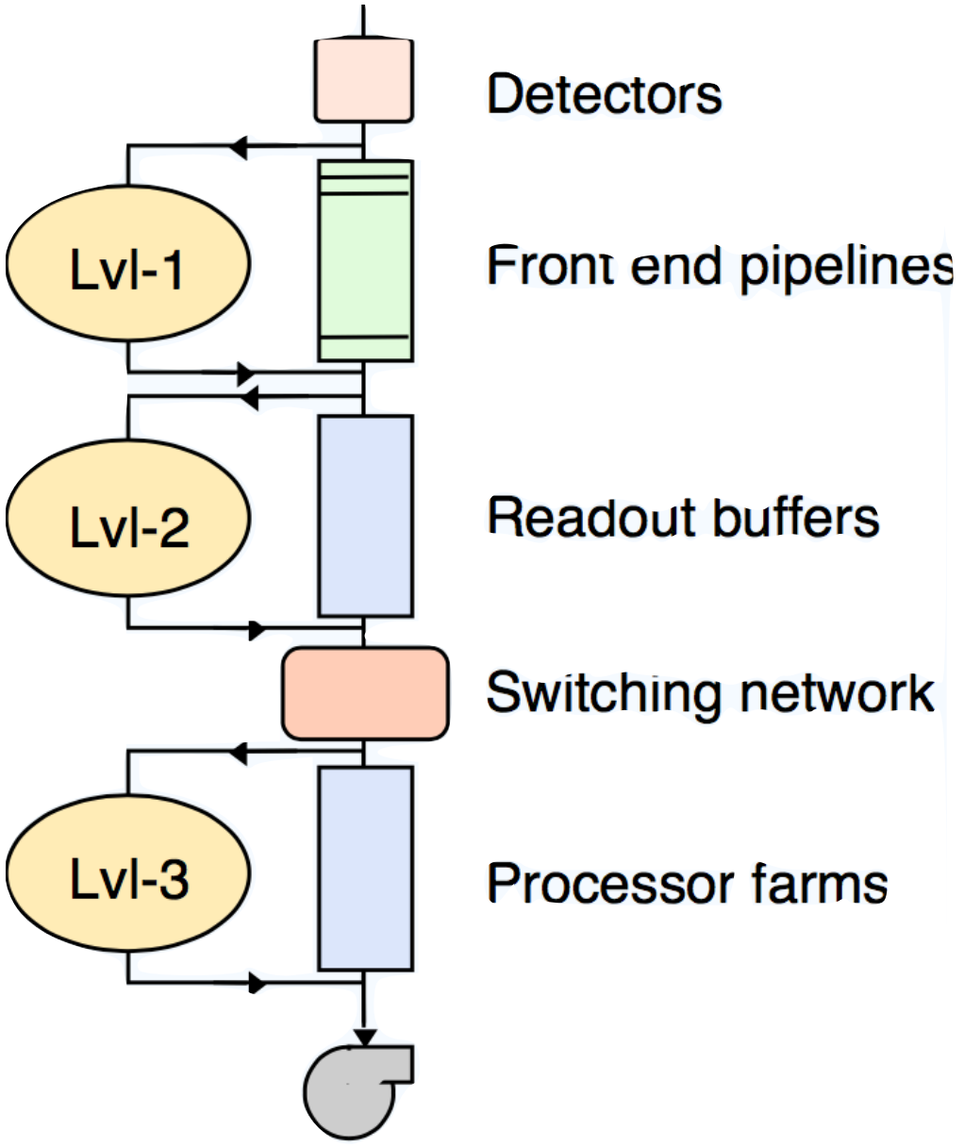




Trigger is the brain of the experiment

- **Ultimately decides what is experimentally accessible at the LHC**
  - ADCs must be in synch with beam crossings @ 40 MHz
  - can only use a sub-set of information (coarser granularity)
- **Intermediate buffers are the trick**
  - de-randomize incoming event rate
  - decouple slow readout from fast front-end
- **L1/L2 trigger implemented in hardware**
  - combine information from sub-detectors
  - accept @ 100kHz
- **HLT implemented in a CPU farm**
  - partial or full reconstruction from raw data
  - ultimate decision if data goes to tape @300Hz

ATLAS-Run I architecture



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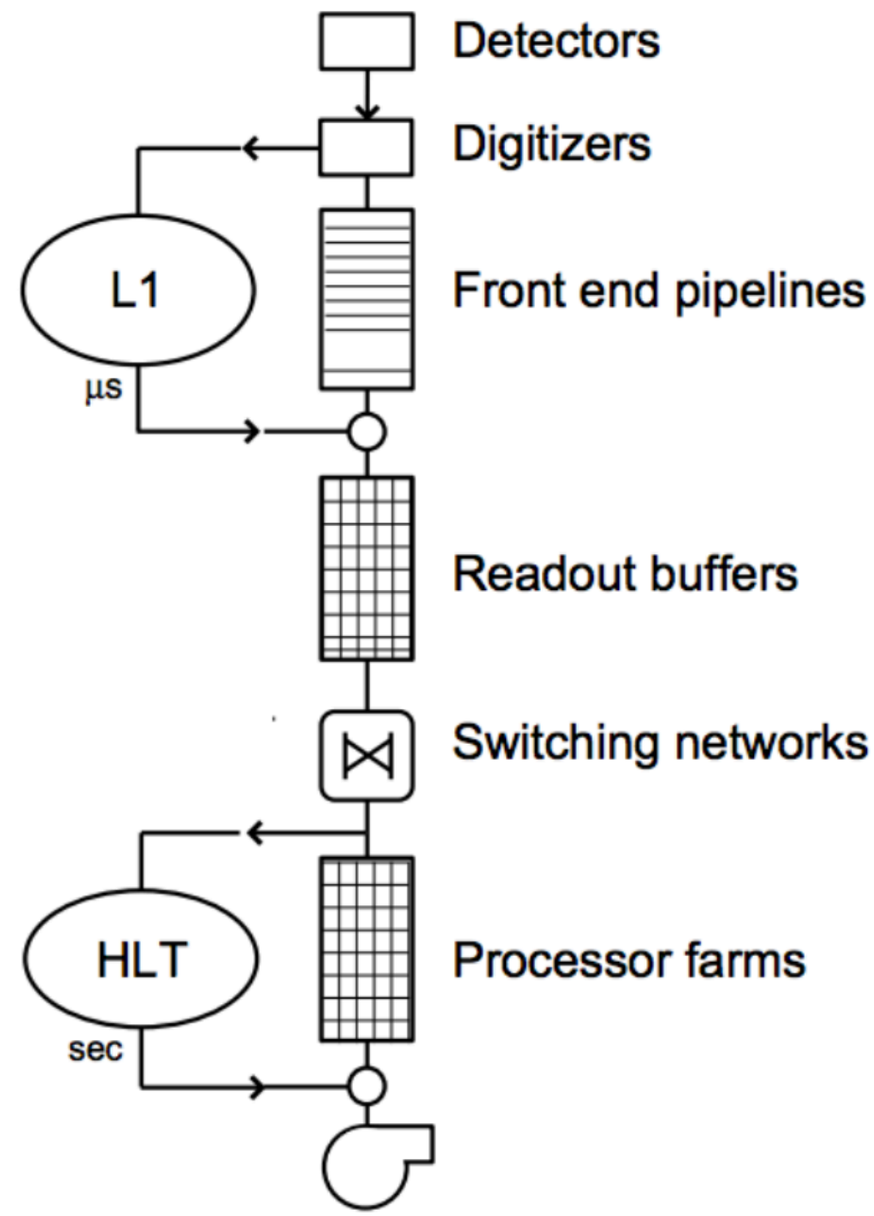
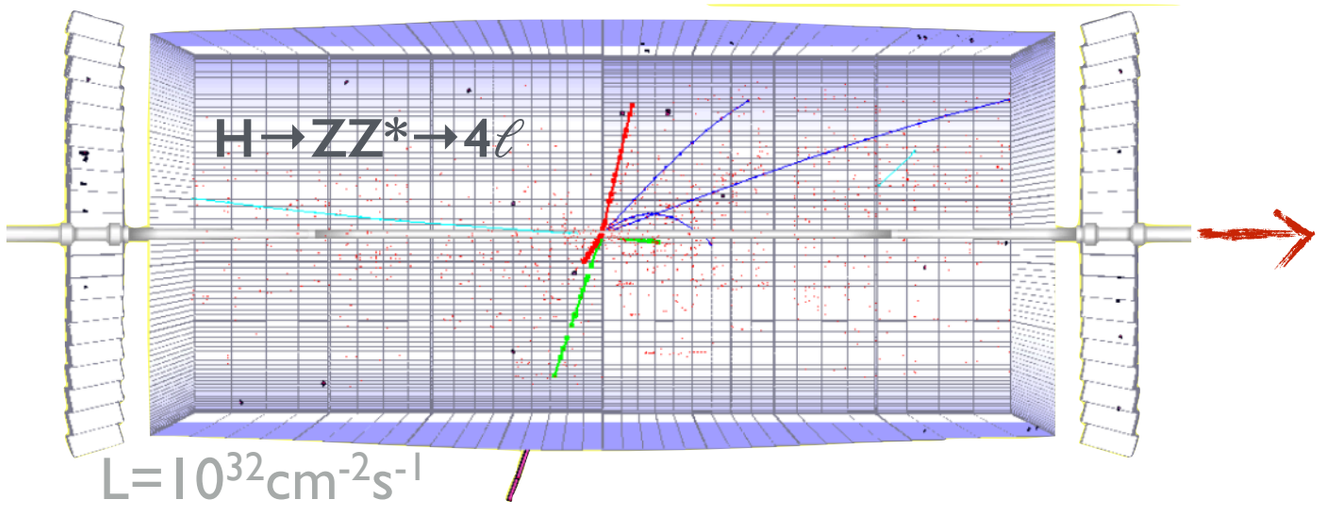
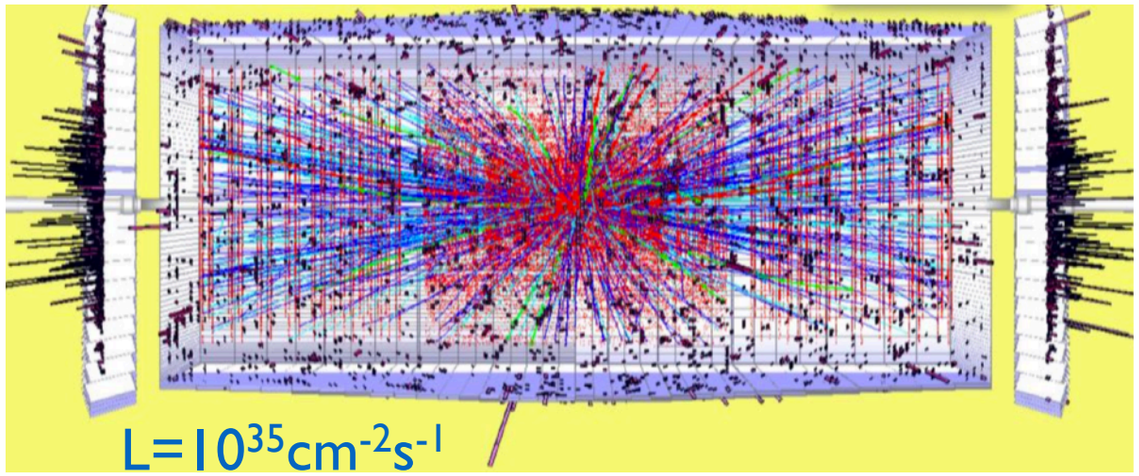
CMS architecture



Road ahead for detector upgrades





Phase 0
2013-2014

Consolidate detectors, address operational issues, prepare for high pileup

- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- **CMS** : Replace HCAL forward PMTs and outer HPD → SiPM
- **ATLAS** : Diamond beam monitor, additional pixel layer 2013-2014 2018-2019

Phase I
2018-2019

Mantain / improve performance at high pileup

- **CMS**: new pixels, HCAL SiPMs, electronics, and L1-Trigger
- **ATLAS**: L1 trigger improvement, fast track trigger at L2, new muon small wheels

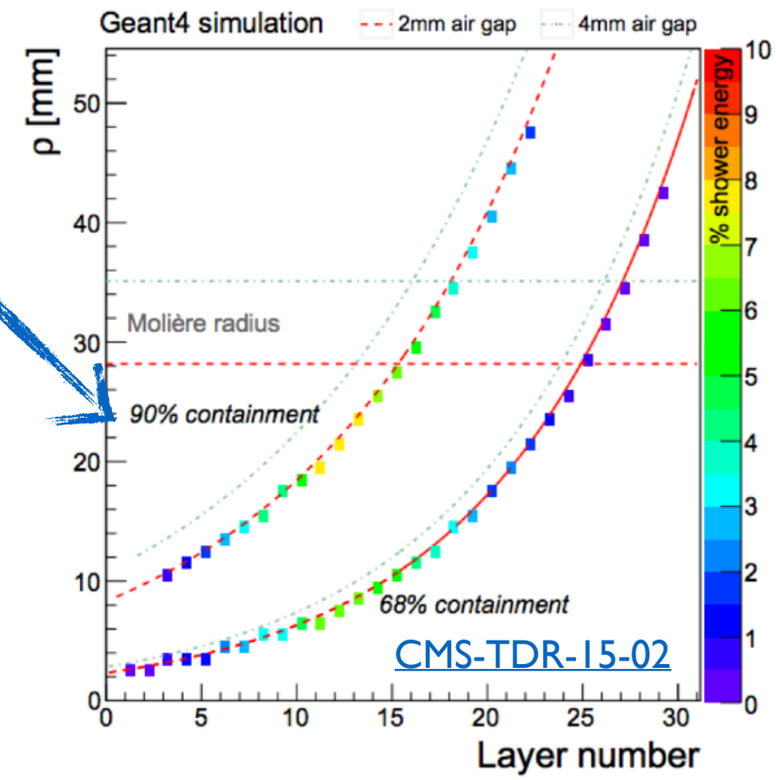
Phase II
2023-2024

Mantain / improve performance at extreme pileup : sustain rate + radiation doses

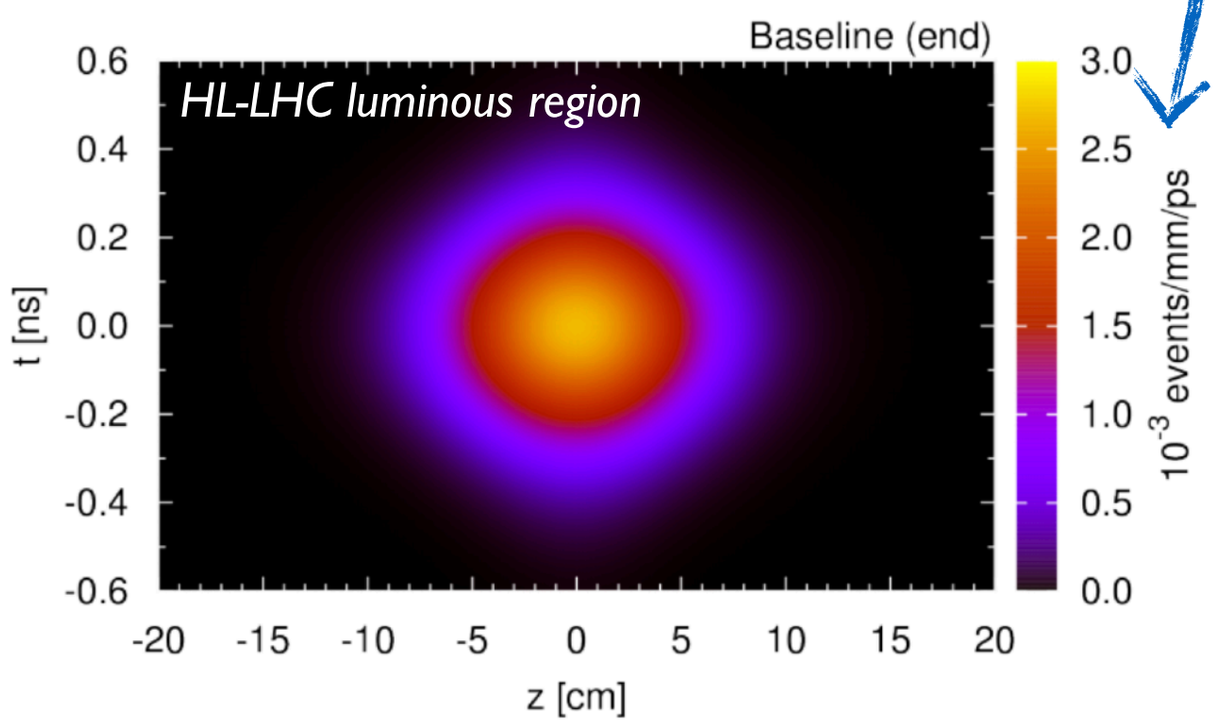
- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- **CMS**: track trigger, replace endcap calorimeters
- **ATLAS**: replace inner tracker, new forward calorimeter

Detector strategies to mitigate pileup at HL-LHC

- **Use fine granular detectors**
  - *transverse*: reduce flux per calorimeter cell, resolve fine structures
  - *longitudinal*: absorb low energy pileup in the first layers
  - *3D reconstruction+timing*: associate deposits to primary vertices

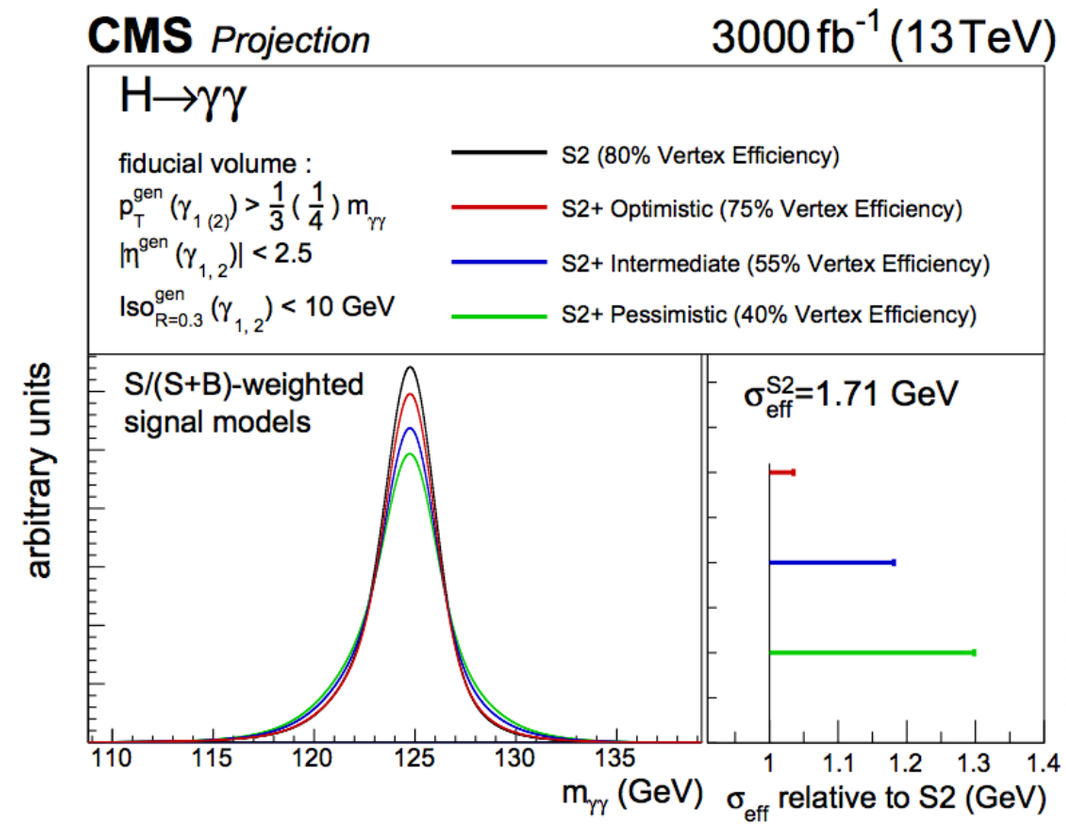


CMS-TDR-15-02



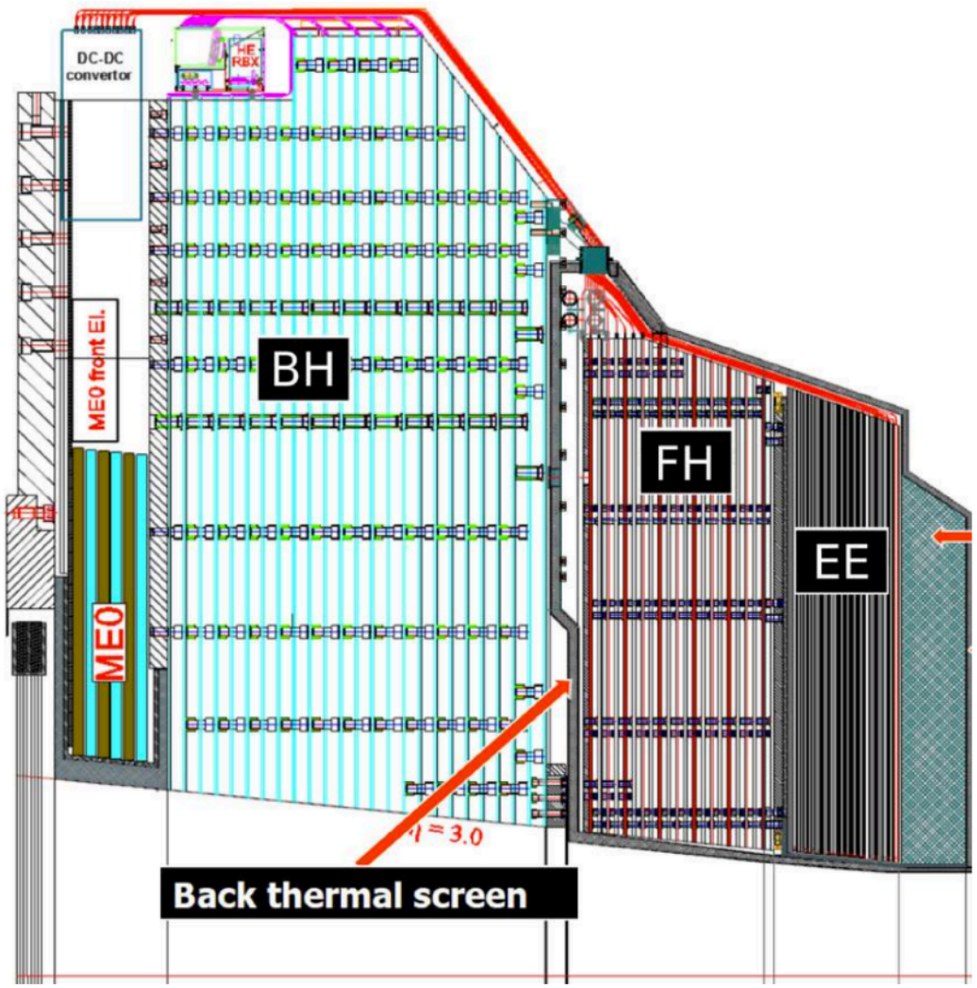
- **Example: H→$\gamma\gamma$ association to primary vertex**
  - loose 30% in resolution with "tracker only" informat

    ⇒ up to 20% larger uncertainty in cross section



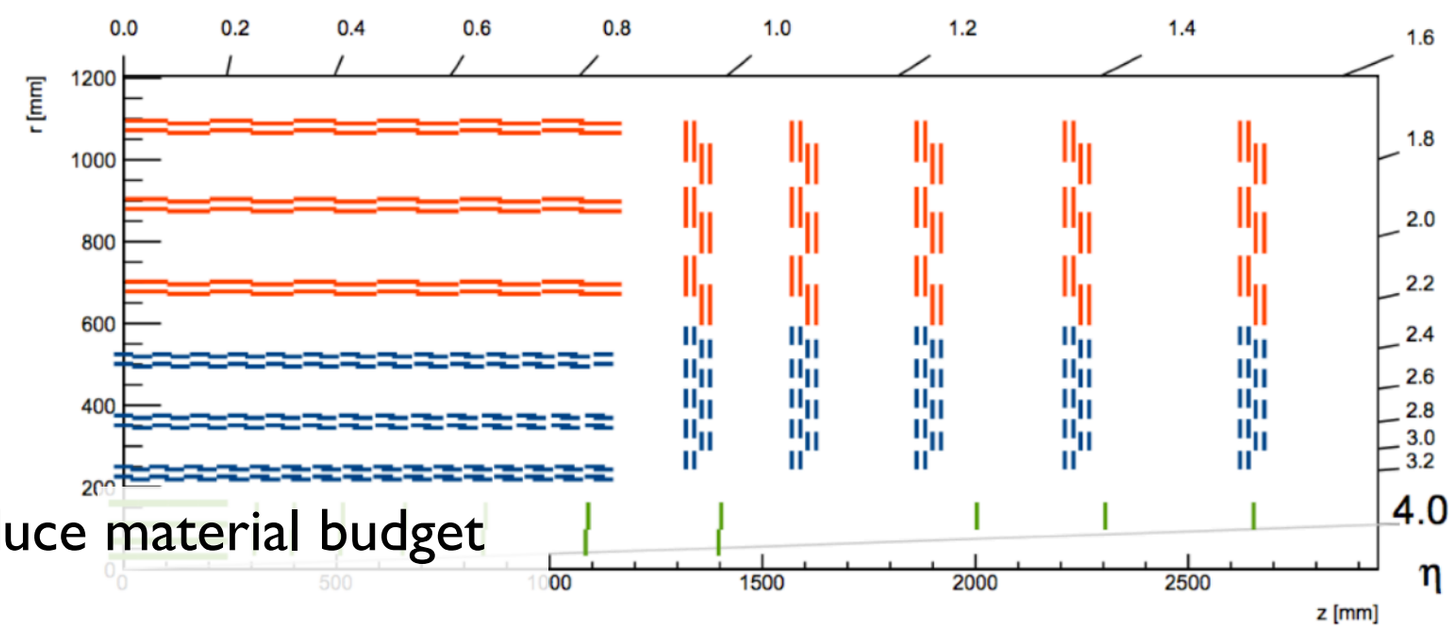
CMS-PAS-FTR-16-002

Example of detector challenges ahead



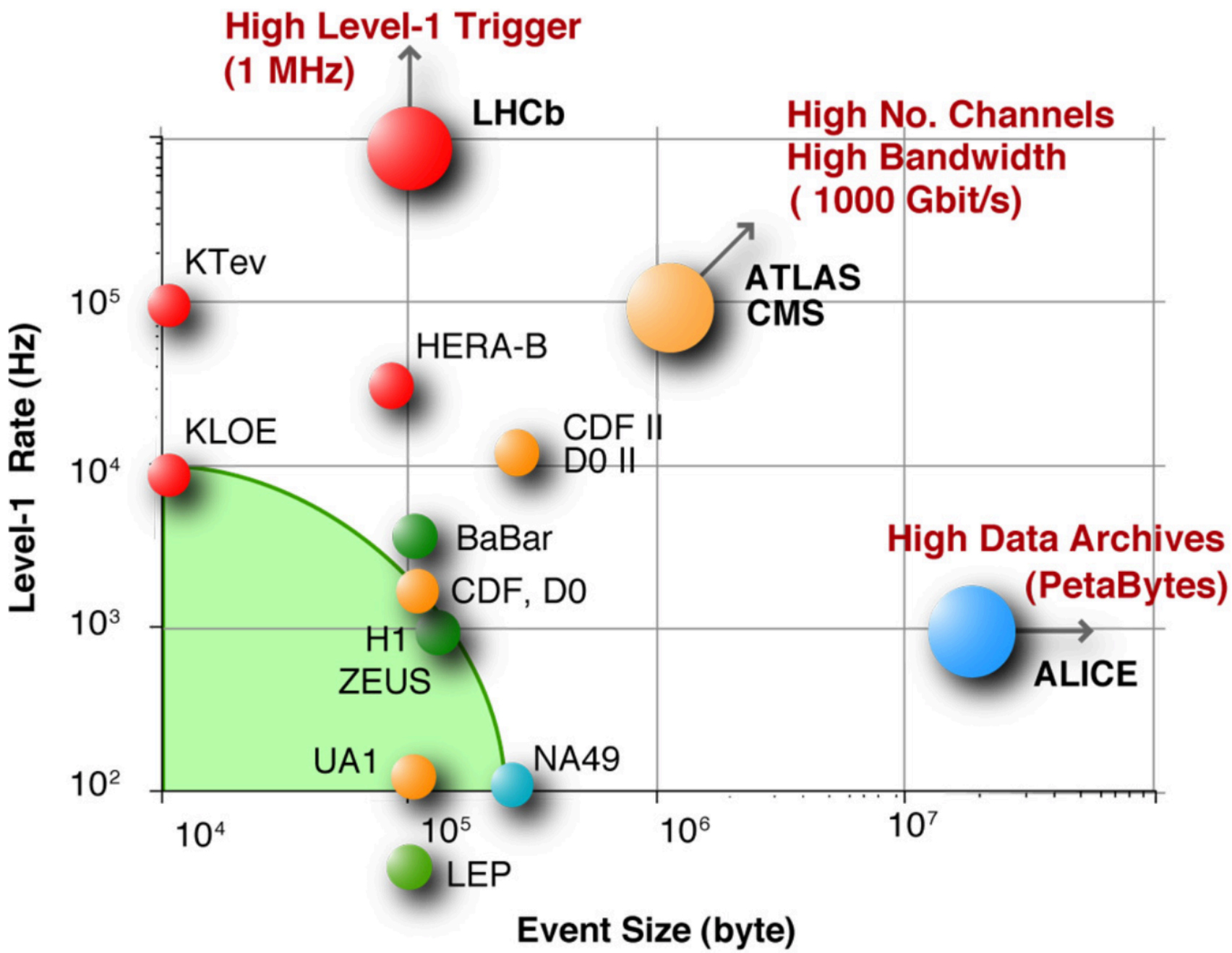
CMS-TDR-15-02

- **High granular calorimeter for CMS endcap**
  - $>10^6$ channels measuring: E, t and x,y,z
  - trigger (data) flow @ 40 MHz (up to 750 kHz)
  - keep intercalibration unc. below 3%
  - clock distribution for timing capabilities (30ps/cell)
  - cooling, mechanics,…



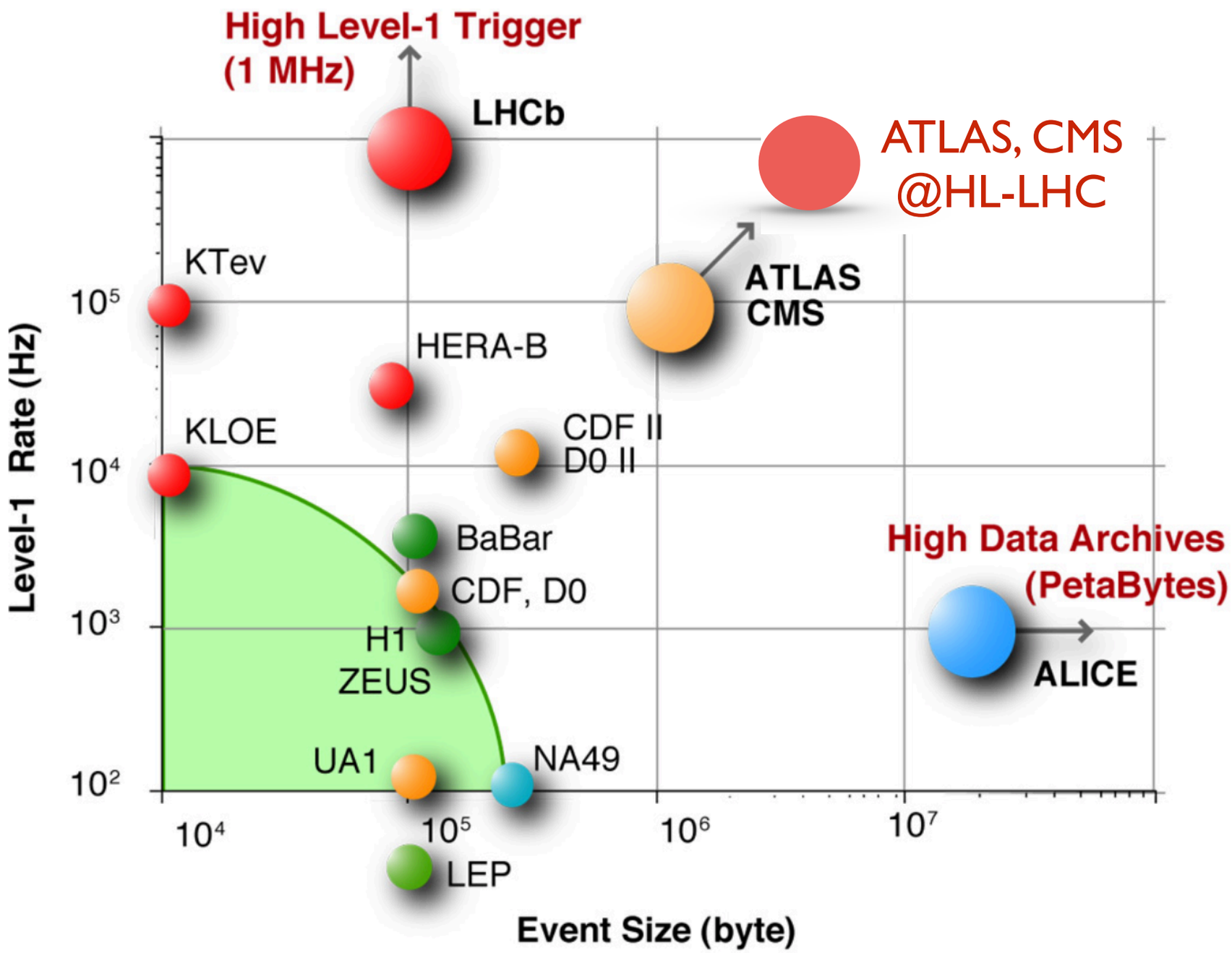
- **Tracker**
  - extend to higher rapidities and reduce material budget
  - reduce hit merging (improve track separation)
  - provide robust, fast pattern recognition (for L1 and HLT)

Future of Trigger and DAQ systems?



- To sustain the HL-LHC rates refined information is needed: track trigger, crystal level

Future of Trigger and DAQ systems?



- Unavoidable increase in bandwidth: up to ~7.5x higher at L1 and HLT
- Storage throughput increasing by ~10x ⇒ 42Gb/s @ HL-LHC

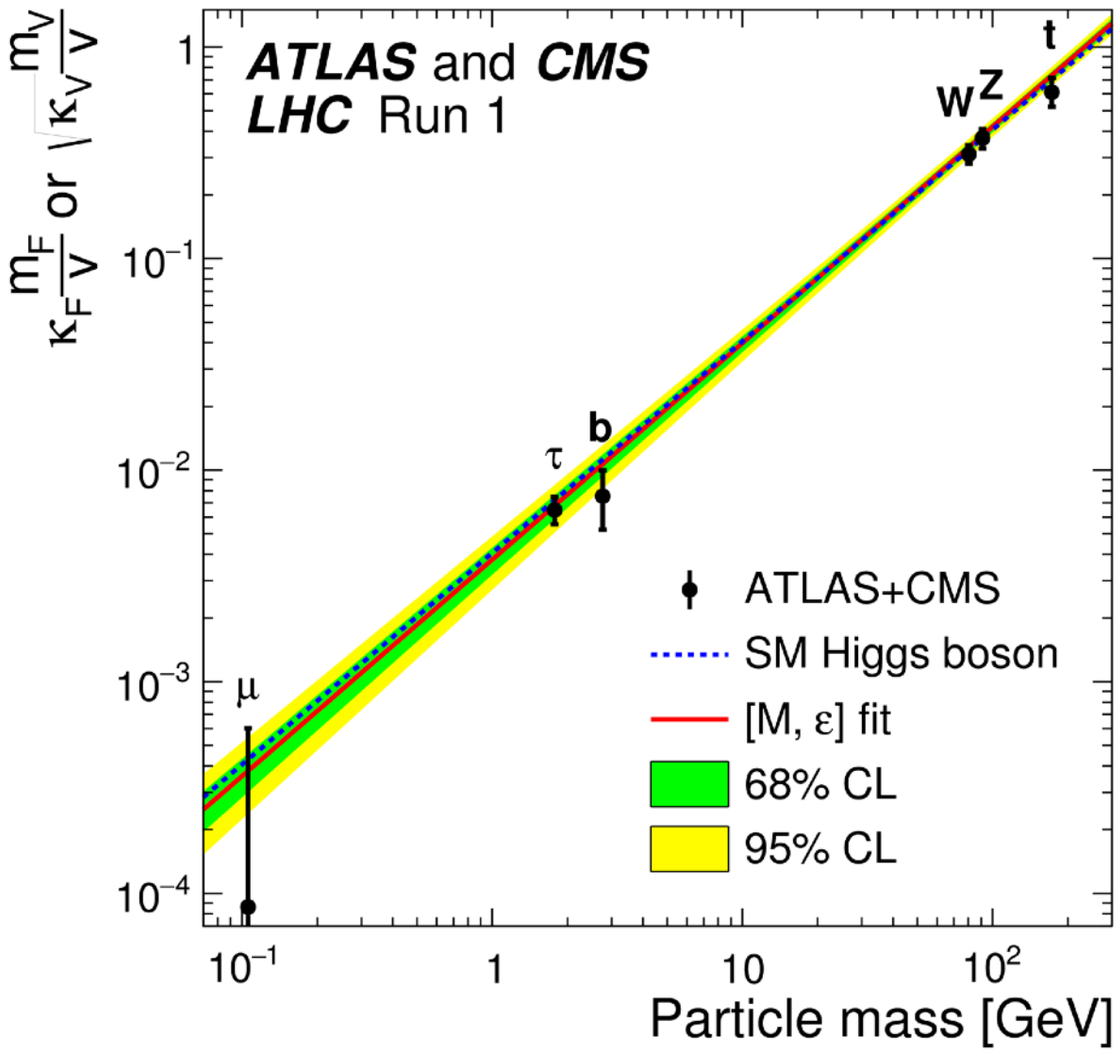
Where do we {stand, go} ?

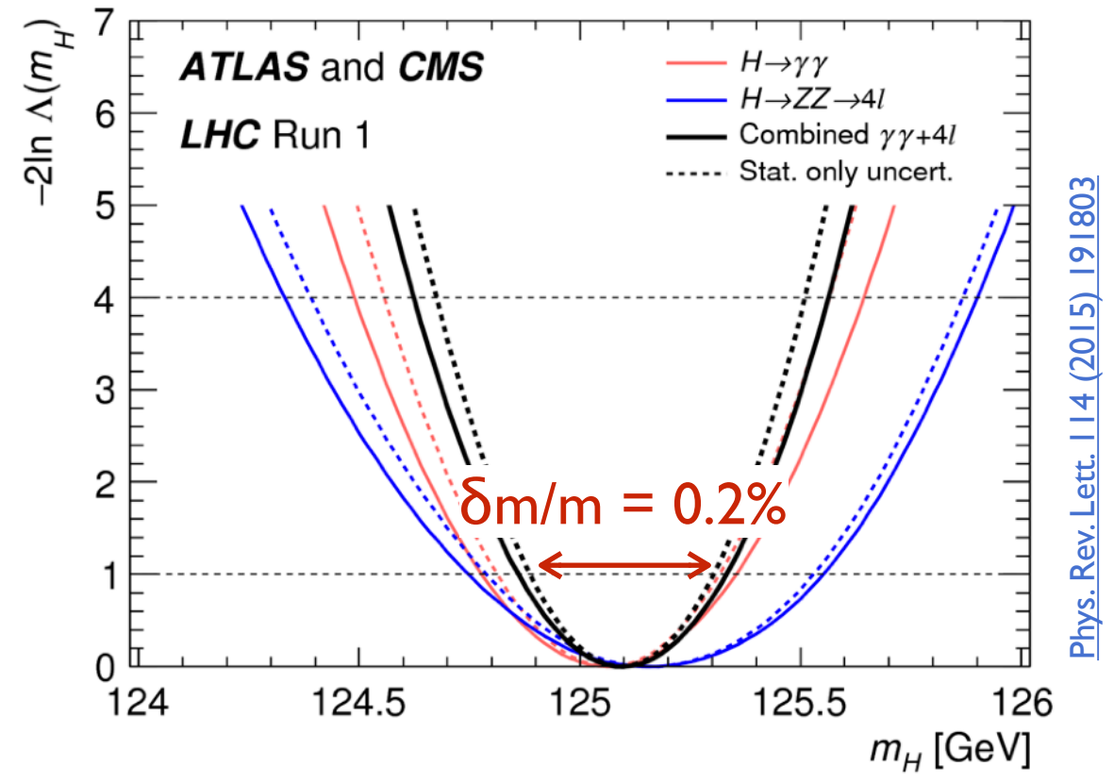
O(4%) of the pieces identified

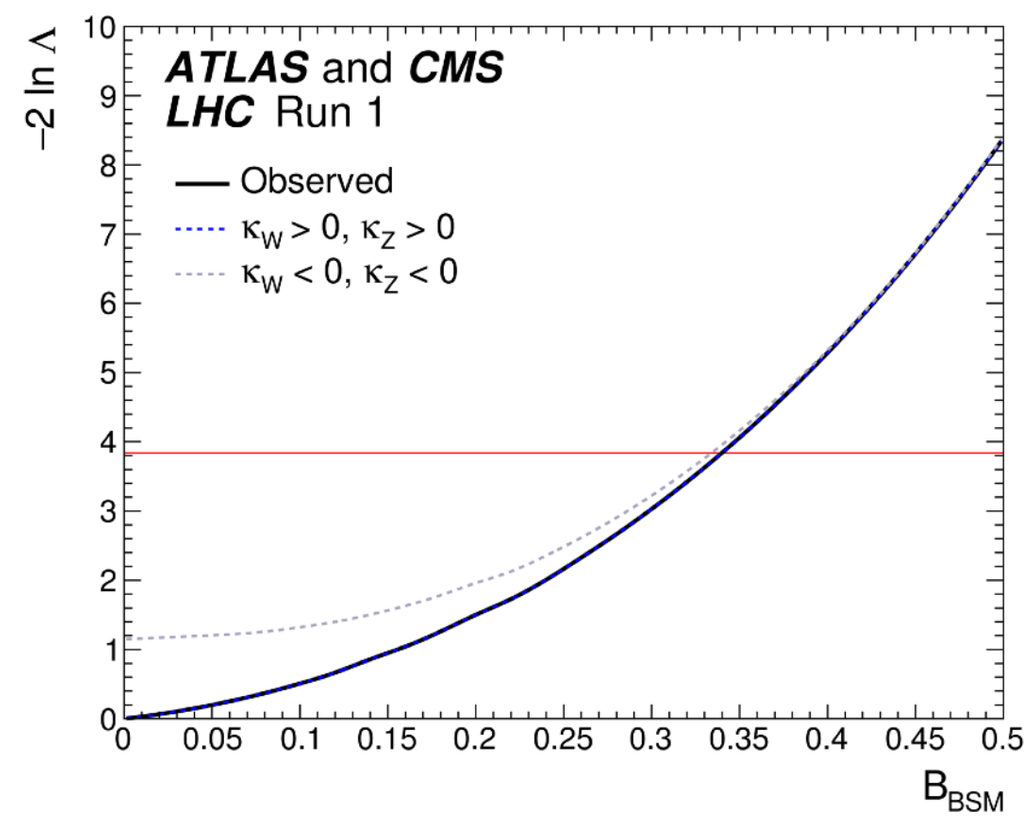
O(96%) to be found

(c) Todd McLellan

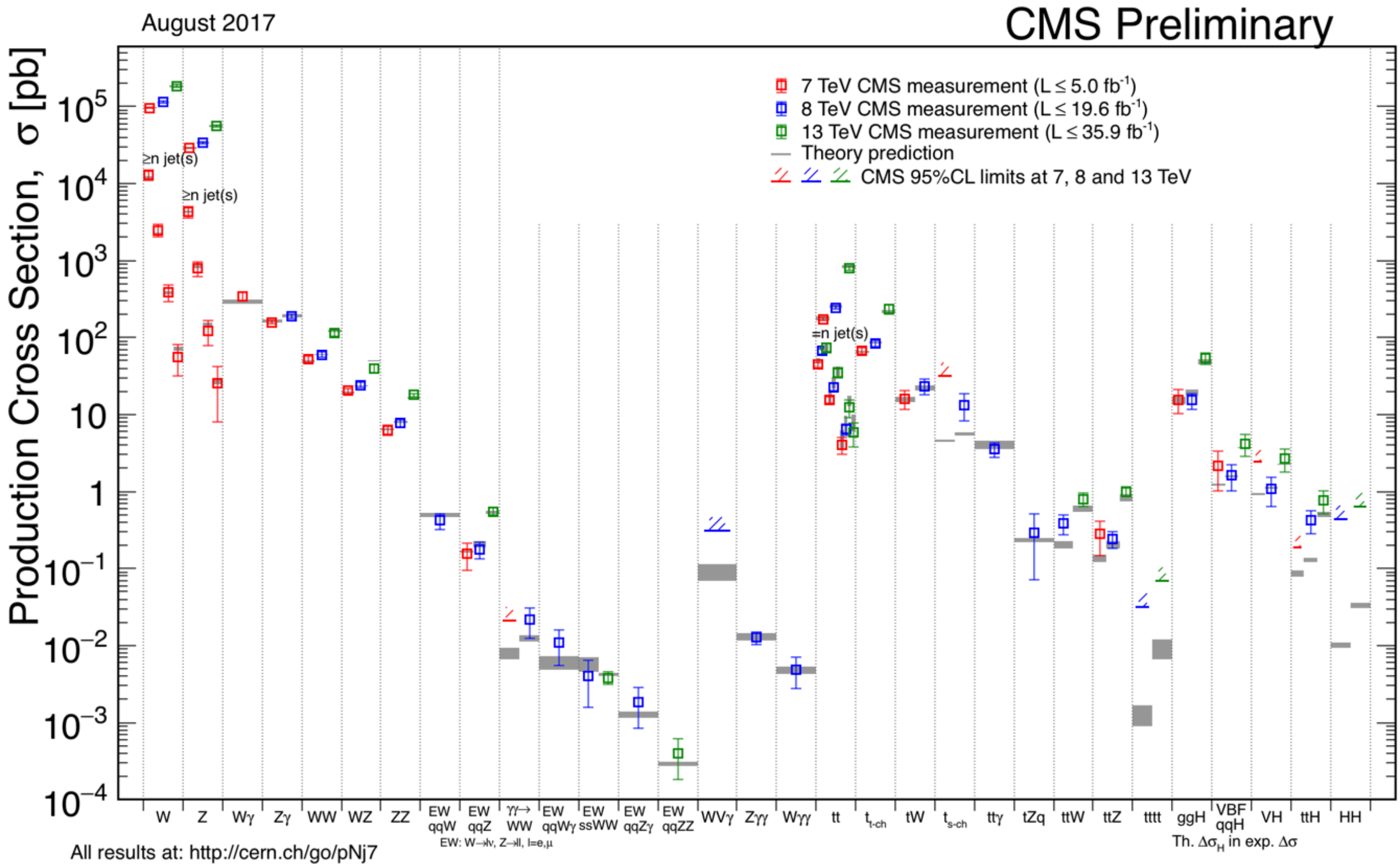
With the Higgs boson the SM is now complete







- **Run I discovery behaving like the SM Higgs**
  - not all couplings are yet measured
  - no coupling is measured to the % level
  - still a large room for BSM contributions

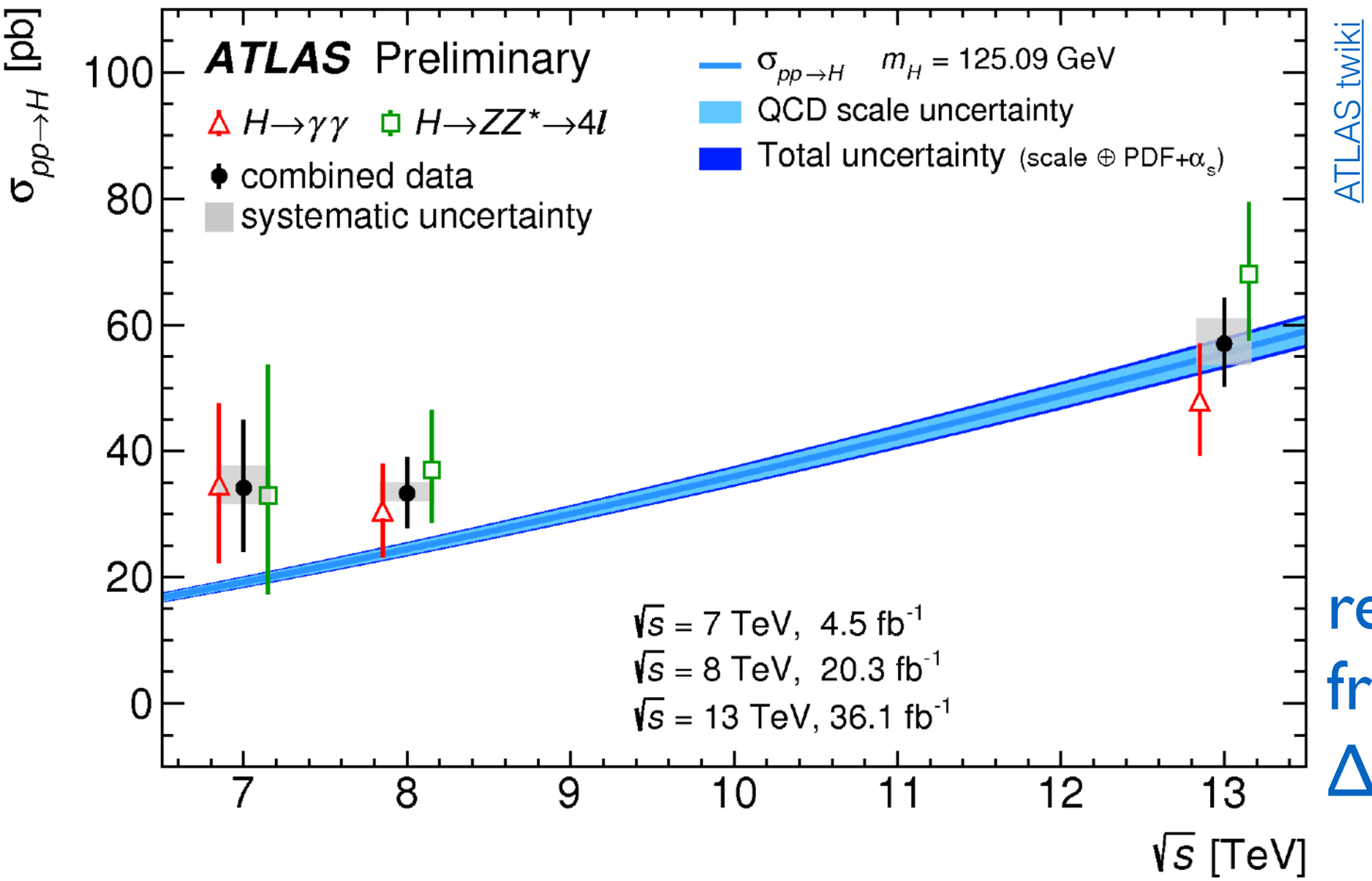


Electroweak bosons

Top

Higgs

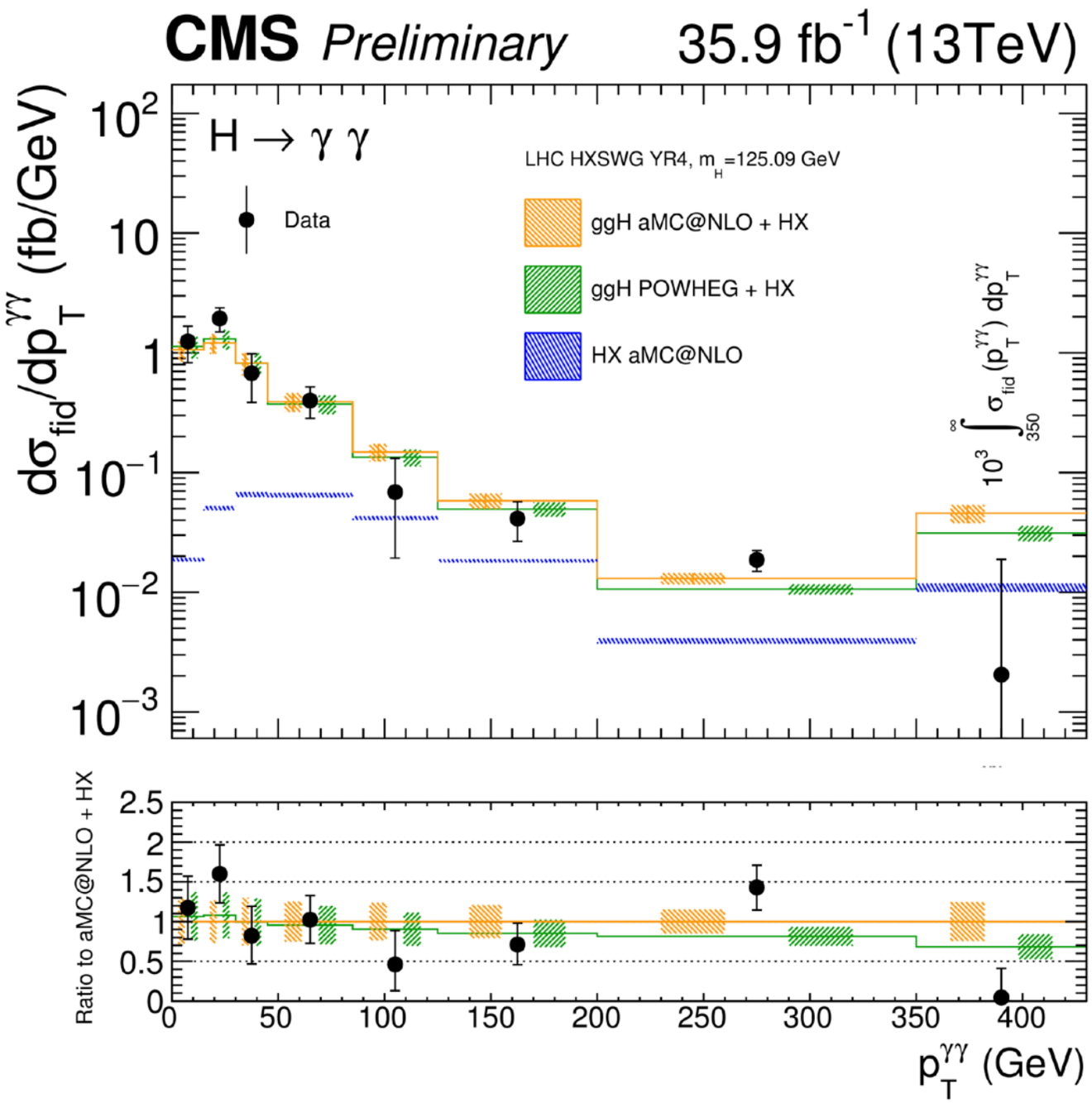
Some highlights from Higgs in Run 2



ATLAS twiki

re-discovering recent friends at new $s^{1/2}$: $\Delta\sigma/\sigma \sim 30\%$

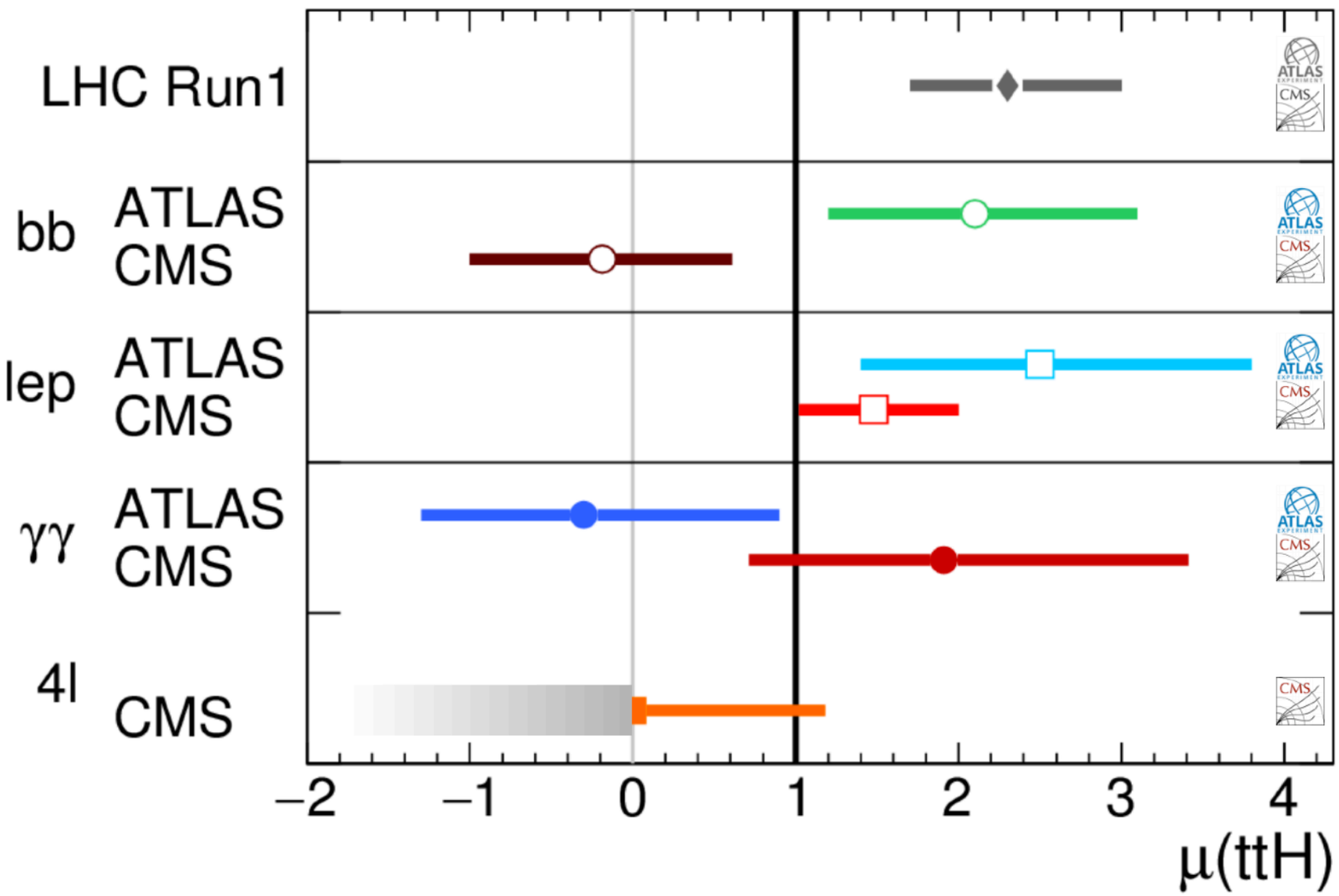
Some highlights from Higgs in Run 2



CMS-PAS-HIG-17-015

programme of differential measurements gaining thrust: fiducial measurements comparing to state-of-the-art MC: fair agreement with predictions

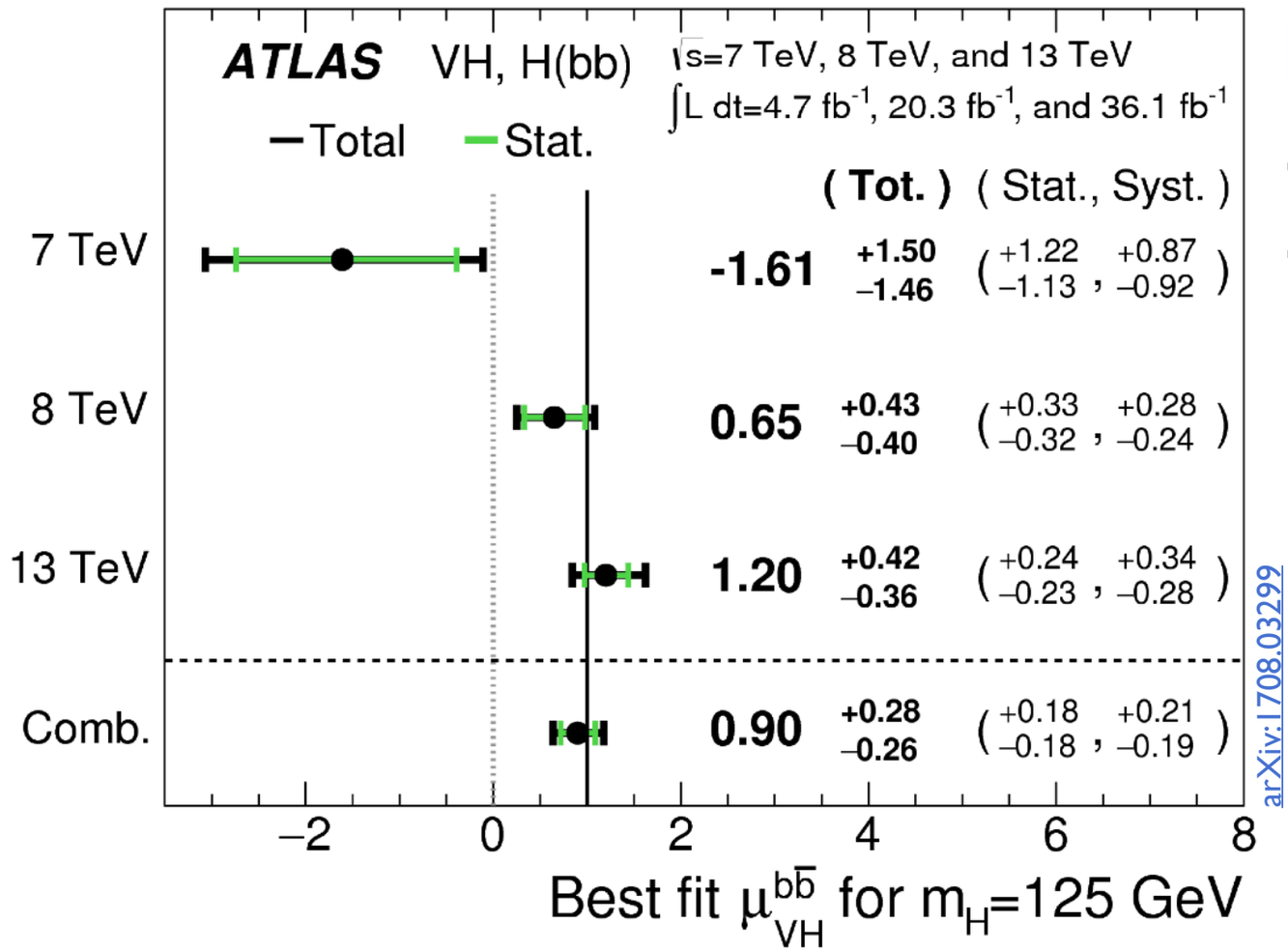
Some highlights from Higgs in Run 2



from G. Petrucciani @ Moriond EW'17

Observation for ttH? Maybe, if combined…
…but missing a flagship final state.

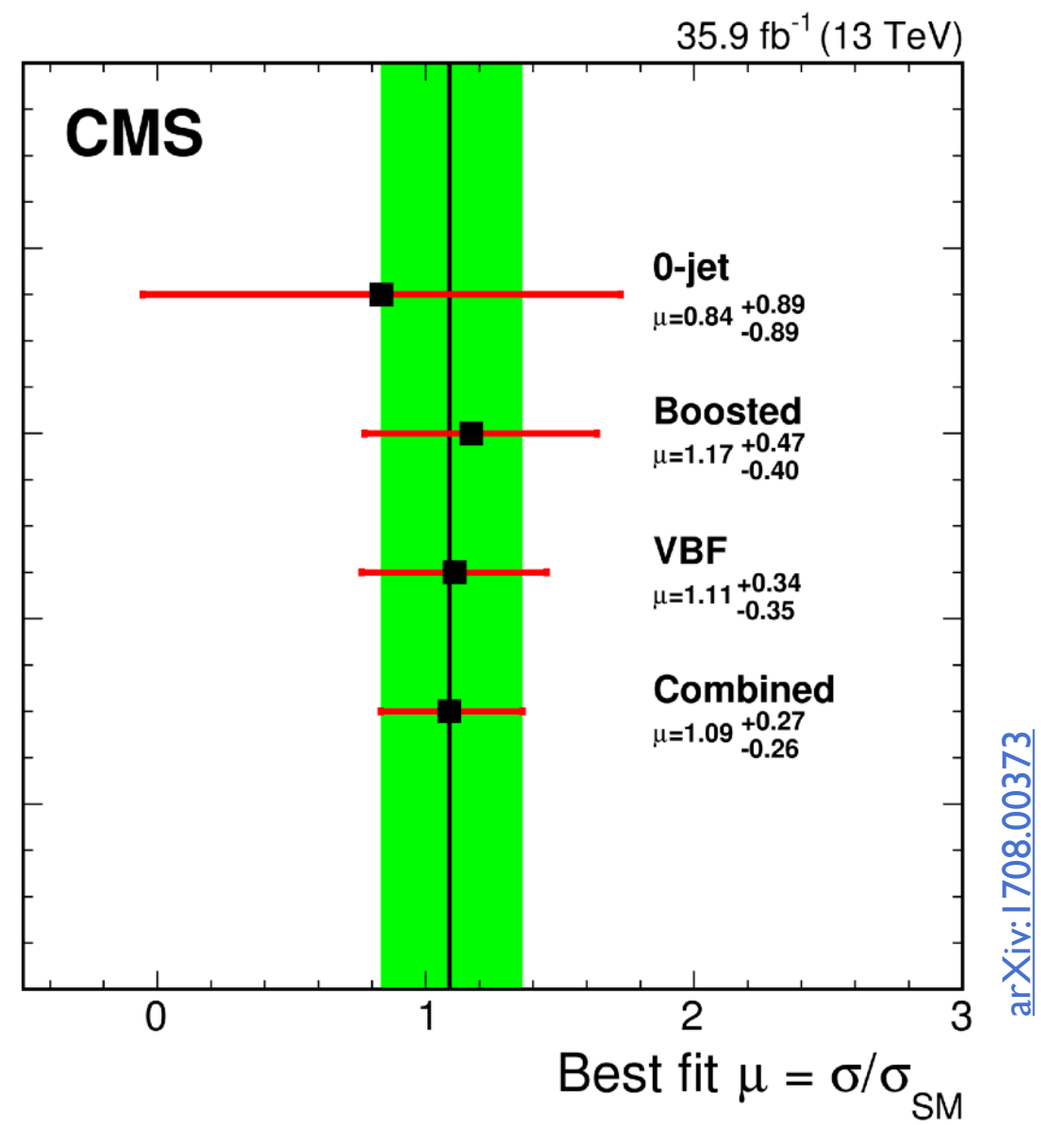
Some highlights from Higgs in Run 2



Evidence for VH→bb

3.5σ significance in Run II

3.6σ significance combining with Run I



Observation for H→ττ

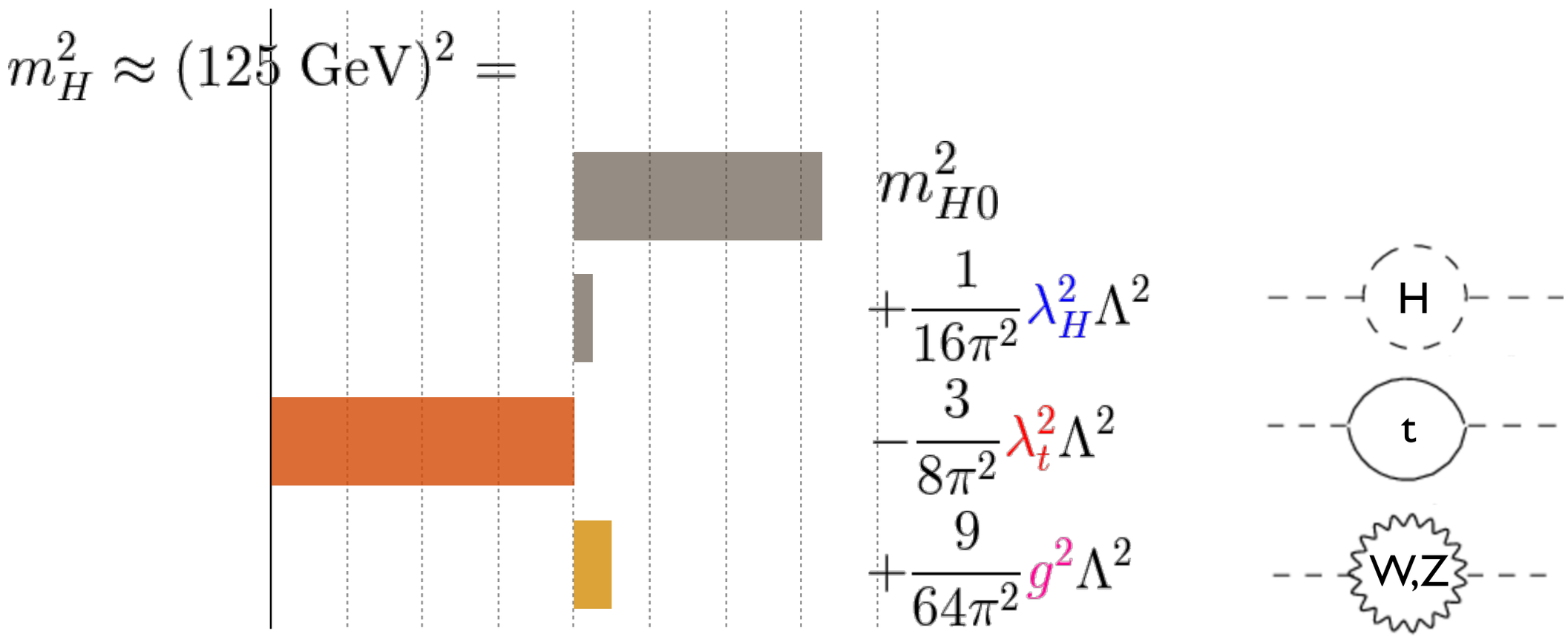
4.9σ significance in Run II

5.9σ significance combining with Run I

With the Higgs the SM is now incomplete

Corrections to Higgs mass from loops:

un-natural balance with the top quark in the SM



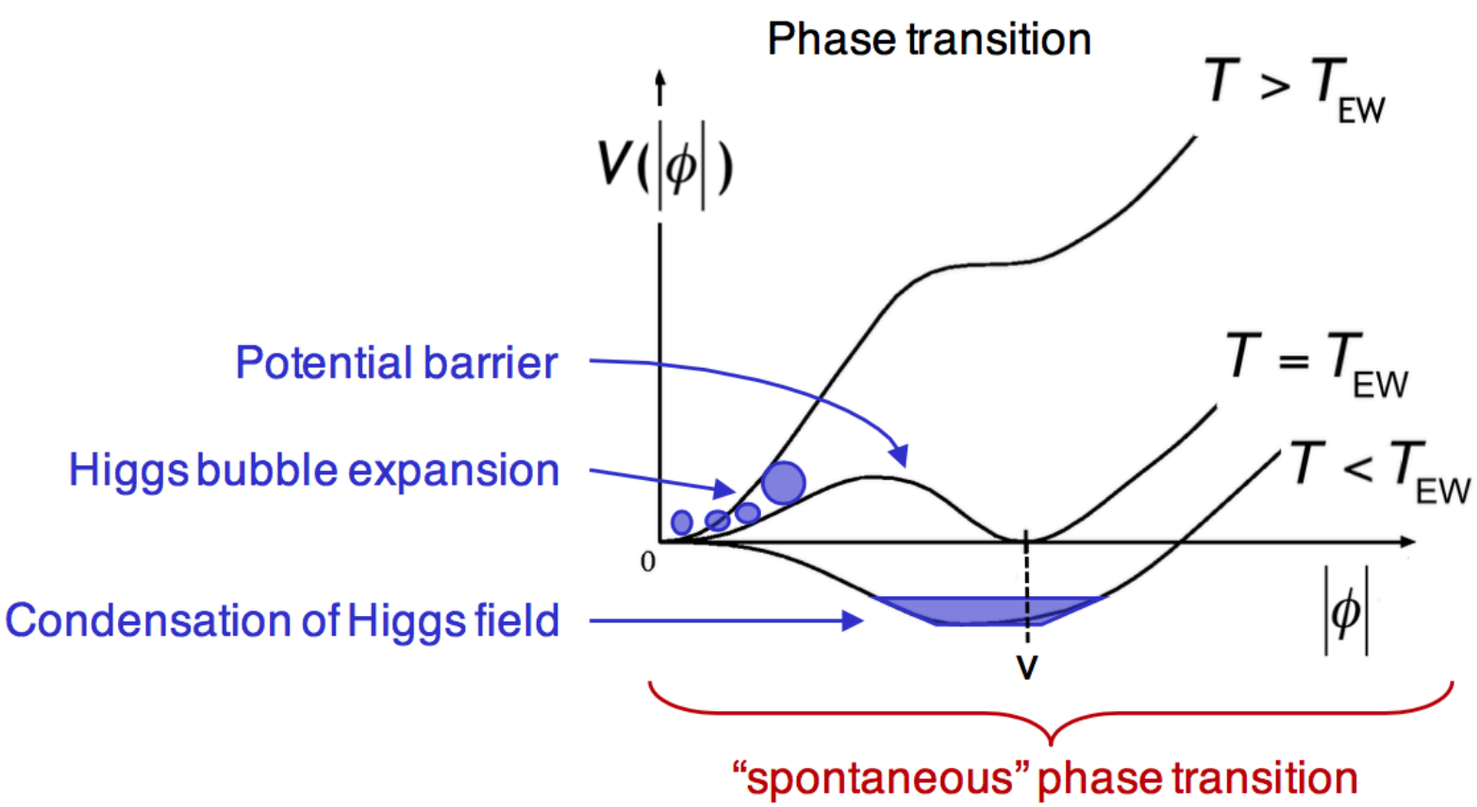
⇒ part of the clues are in the Higgs self-interaction and m_t

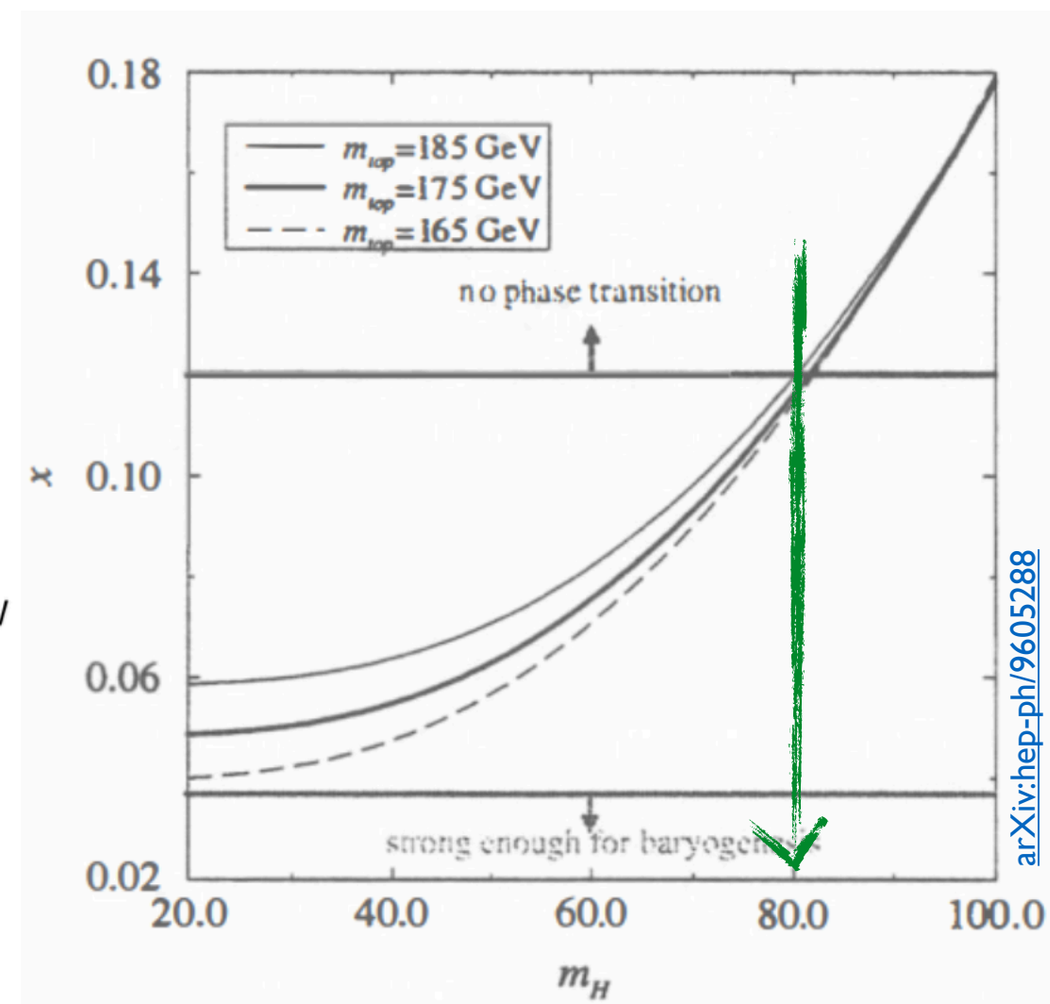
Tracing back from the early universe

- **A phase transition must occur for T_{EW} (~10^{-10}s after the big bang)**
  - strong first order transition is possible if $\langle\phi_C\rangle > T_{EW}$
  - in the SM this implies that m_H<80 GeV but experimental evidence contradicts this

    m_H~125 GeV and cosmological remnants from the electroweak epoch exist

⇒ new physics coupling to H at the TeV scale?

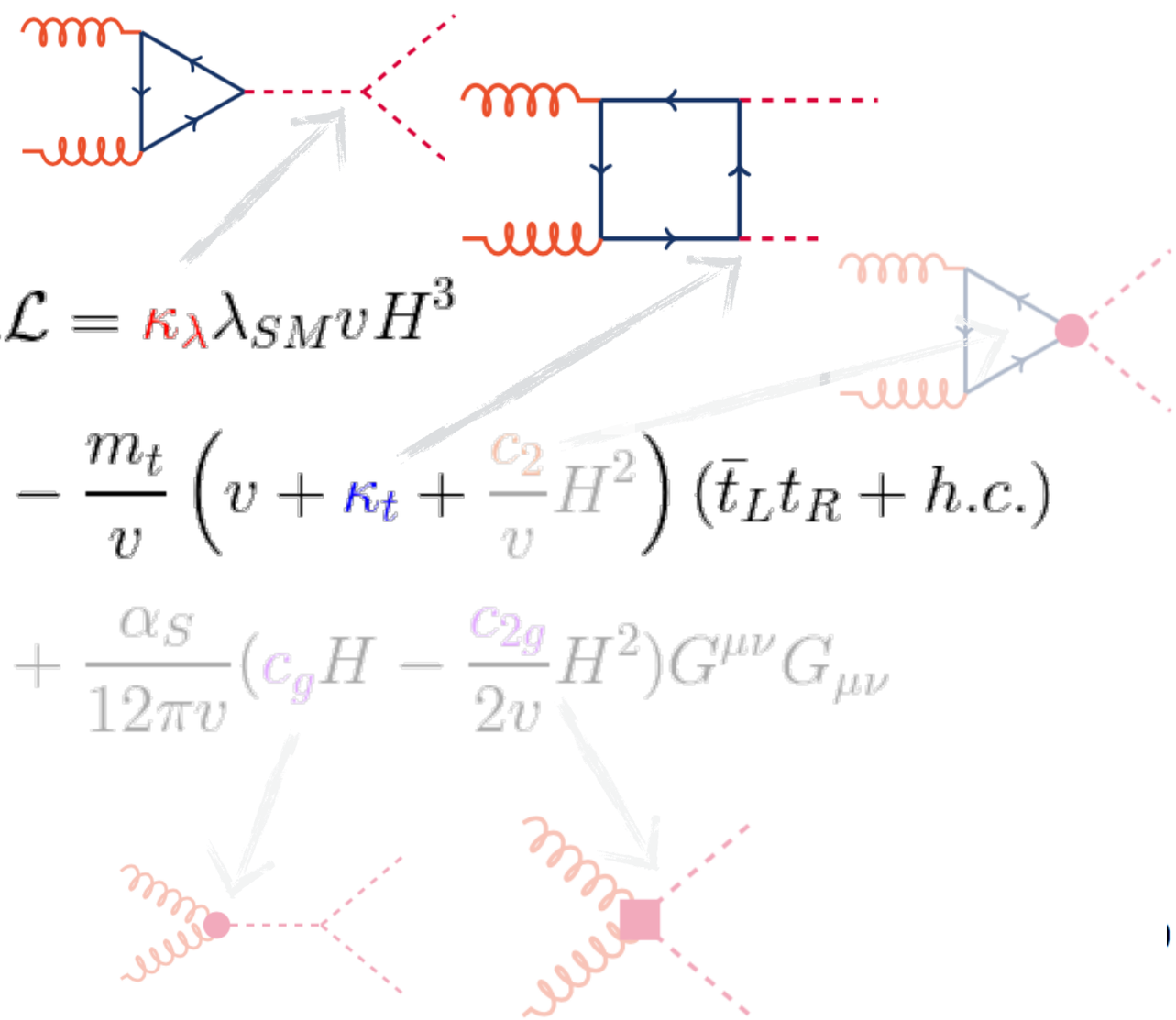




arXiv:hep-ph/9605288

Testing the origin of M_H at the LHC

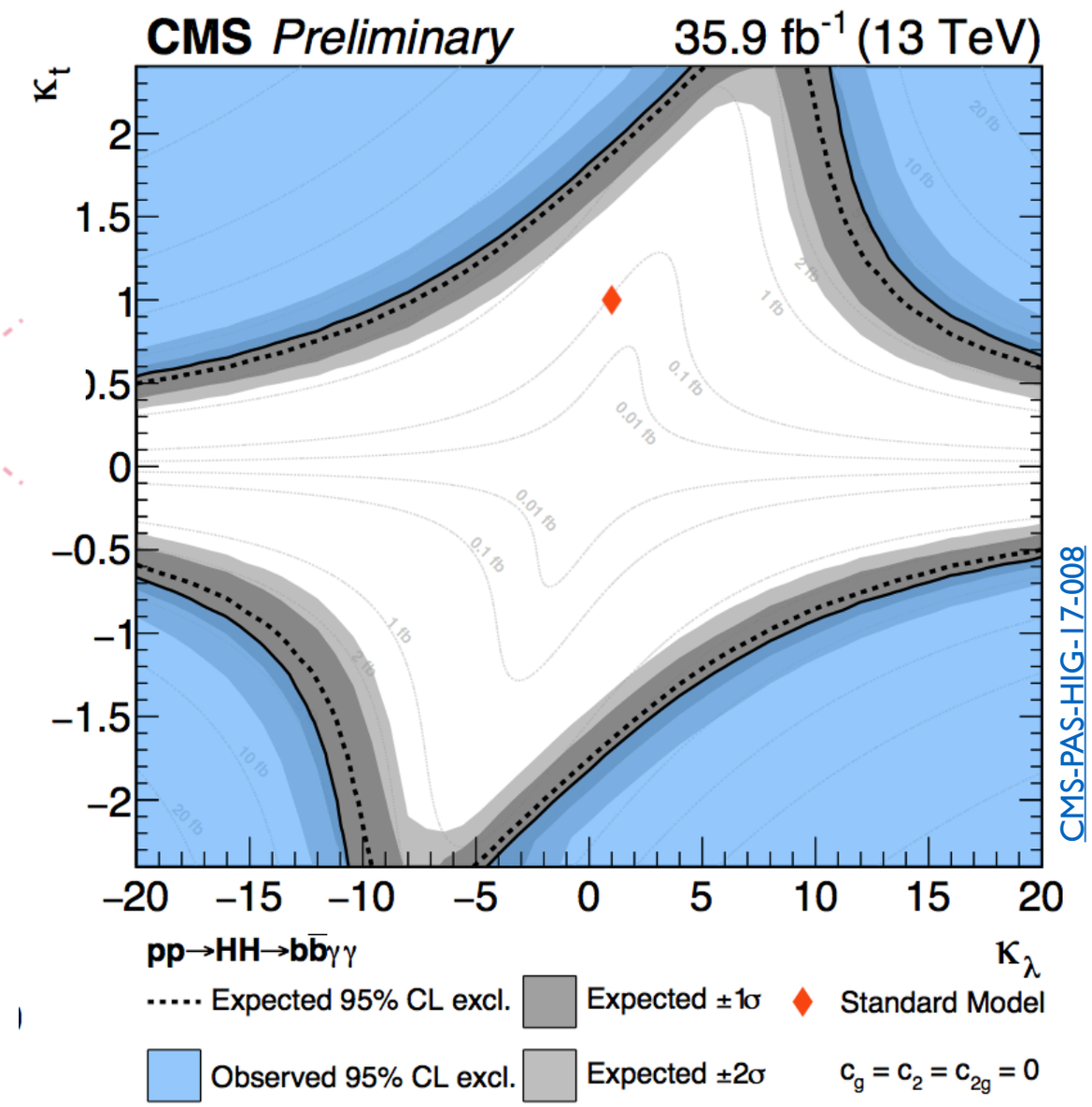
- **Measuring the self-couplings of the Higgs at the LHC will require the HL-LHC**
  - HH production: low cross sections, non-trivial backgrounds and competition with $(y_t)^2$
  - nevertheless new physics may be contributing to it resonantly or not
  - current Run2 testing O(20-30)x the SM expectations for triple H couplings



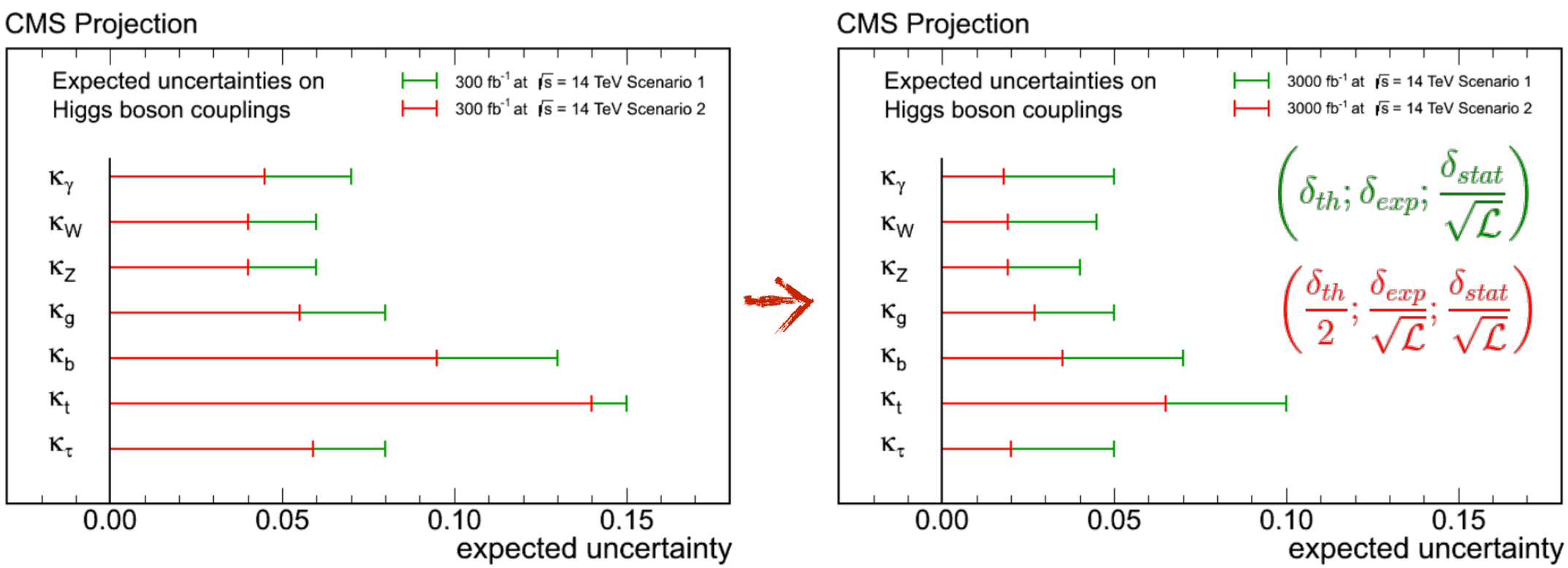
$$\Delta\mathcal{L} = \kappa_\lambda \lambda_{SM} v H^3$$

$$- \frac{m_t}{v}\left(v + \kappa_t + \frac{c_2}{v}H^2\right)(\bar{t}_L t_R + h.c.)$$

$$+ \frac{\alpha_S}{12\pi v}\left(c_g H - \frac{c_{2g}}{2v}H^2\right)G^{\mu\nu}G_{\mu\nu}$$



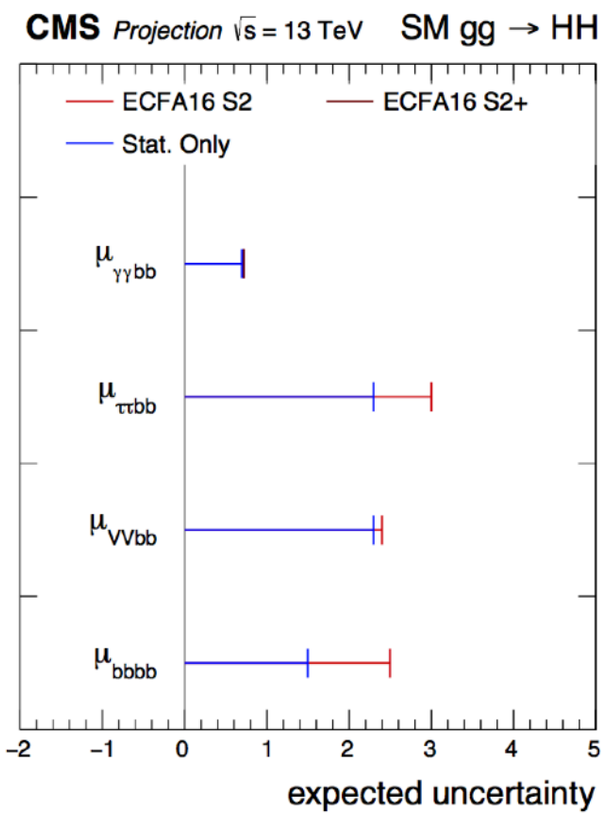
Where are we aiming for regarding the Higgs couplings?



CMS-TDR-15-02

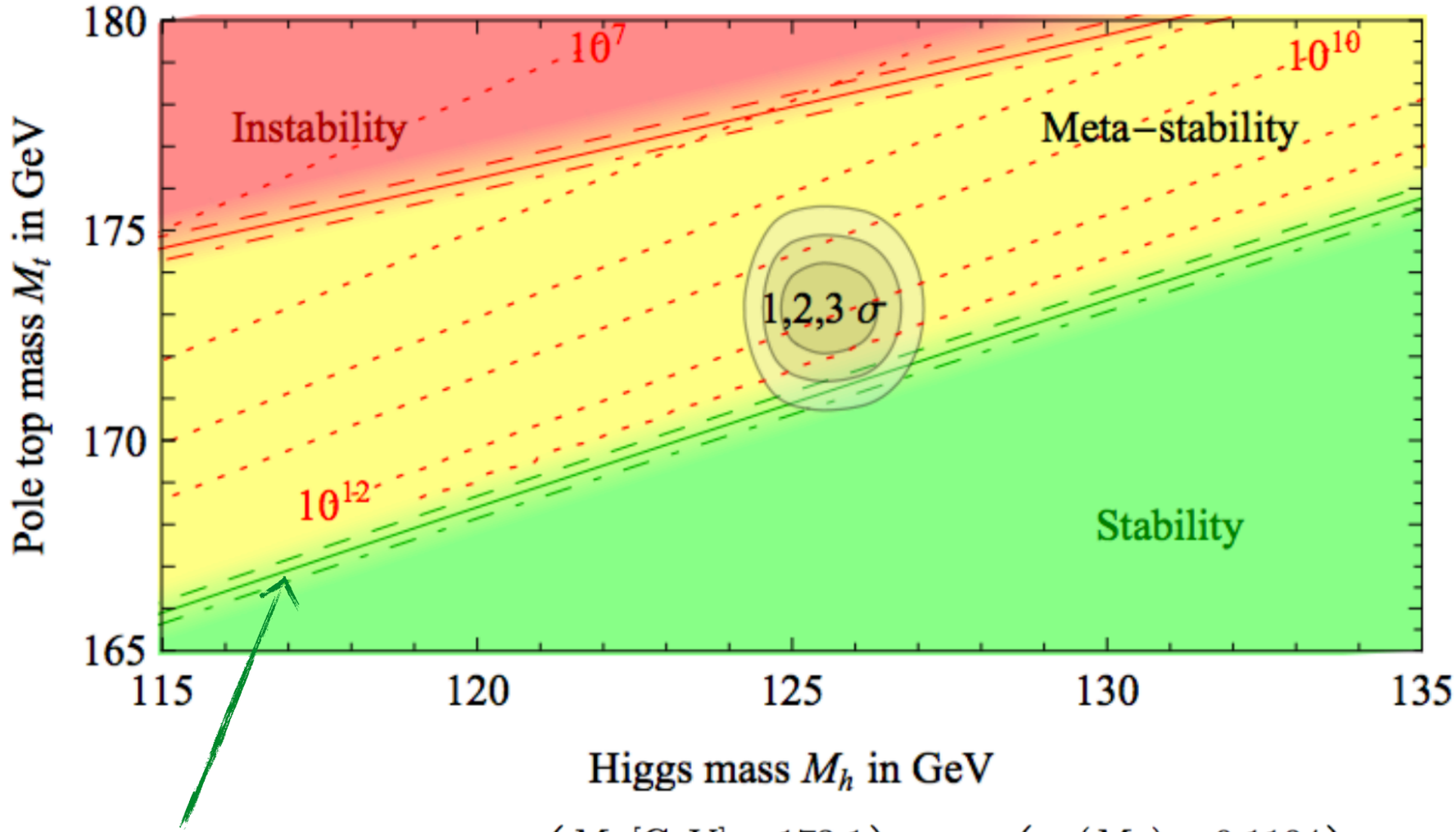
- **Establishing the Higgs couplings to bosons and fermions**
  - <5-10% (<10-15%) level end of HL-LHC (Run 2)
  - H→μμ measured with 5-8% uncertainty
- **Higgs self-couplings long road ahead**
  - HH @ 3σ after combinations?

Theory needs to accompany - how far can we get?



CMS-PAS-FTR-16-002

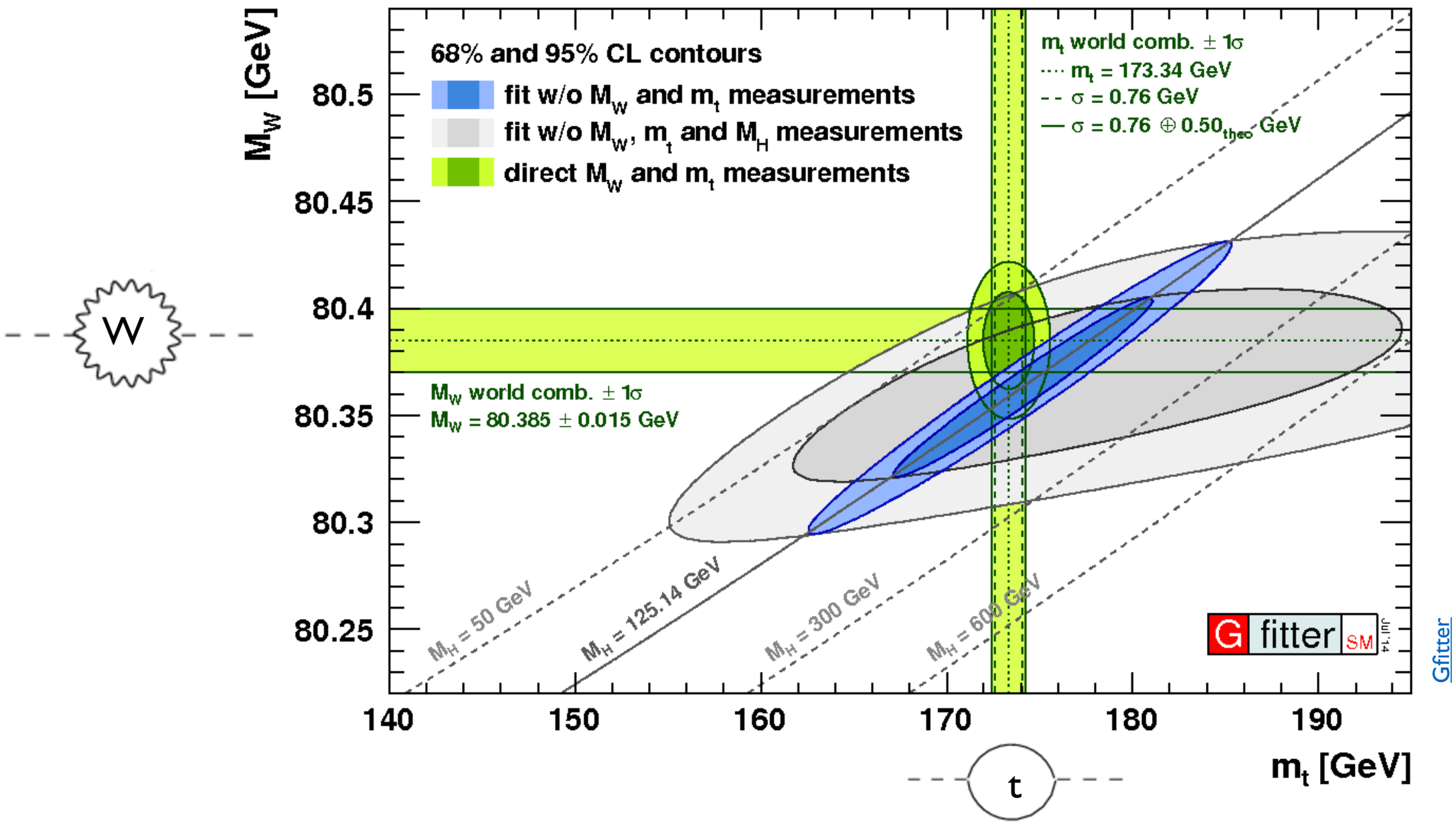
Tracing back from the early universe - cont.



$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

- **Running λ and m_H to the Planck scale : some tension regarding the vacuum stability**
  - experimentally δM_H ~100 MeV is within reach (10x smaller than theory prediction)
  - how far can we get in the experimental sources: **top quark mass** and α_S?

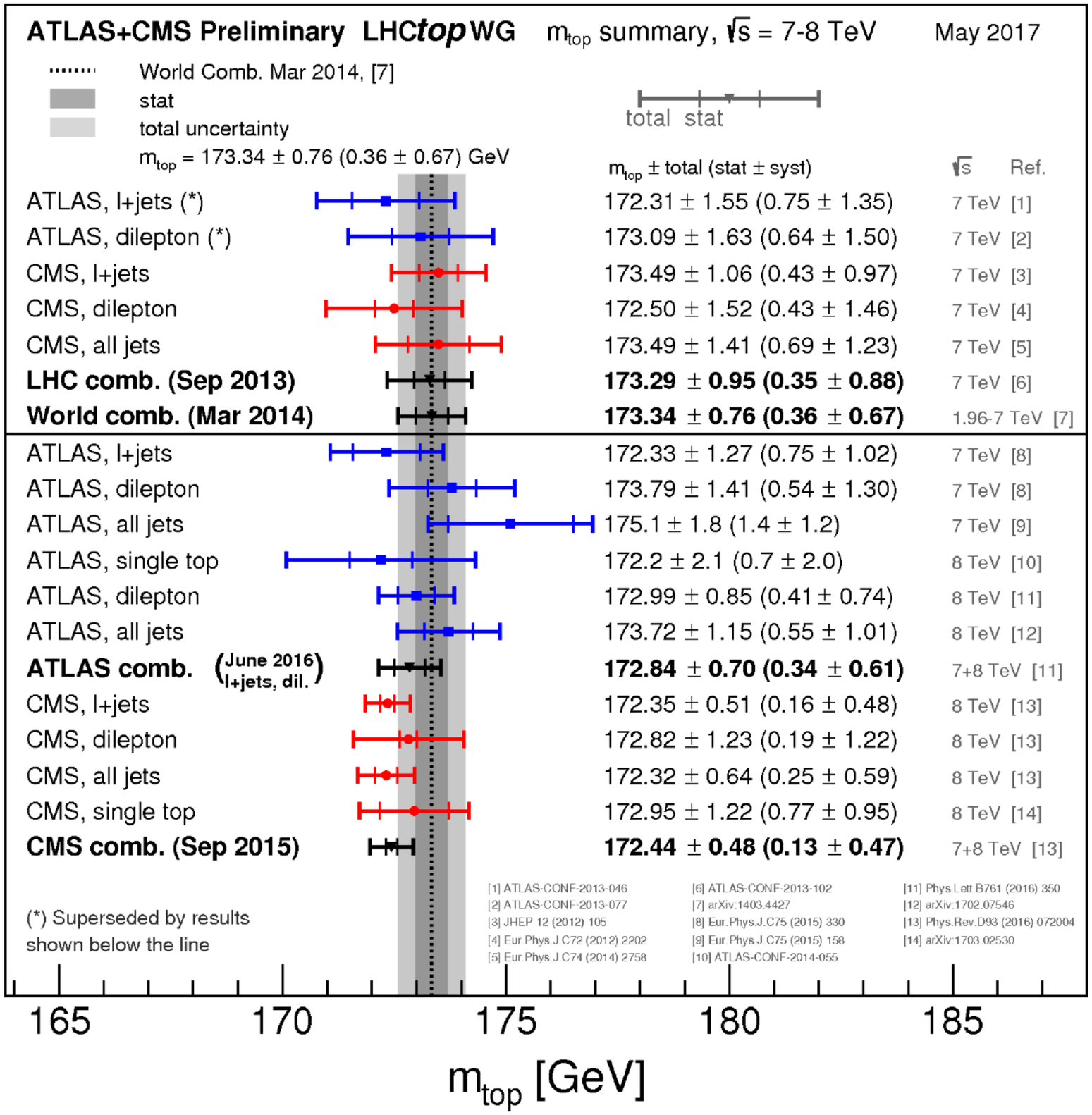
Testing further the SM consistency through m_H



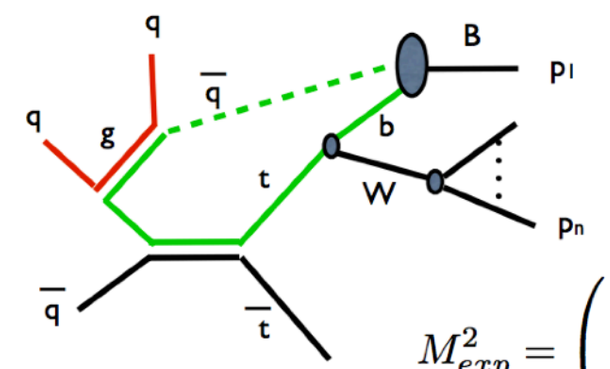
- The top mass uncertainty is the most significant blocker to untie this situation
  - δm_W~0.02%: unlikely to see a 0.5% shift in future measurements?
  - δm_t~0.4%$_{exp}$+0.4%$_{interpretation}$: can reference MCs be calibrated to pole mass?

how far can we push m_W and m_t at the LHC?

Direct m_t measurements circa 2017



LHCTopWG twiki



$$M^2_{exp} = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

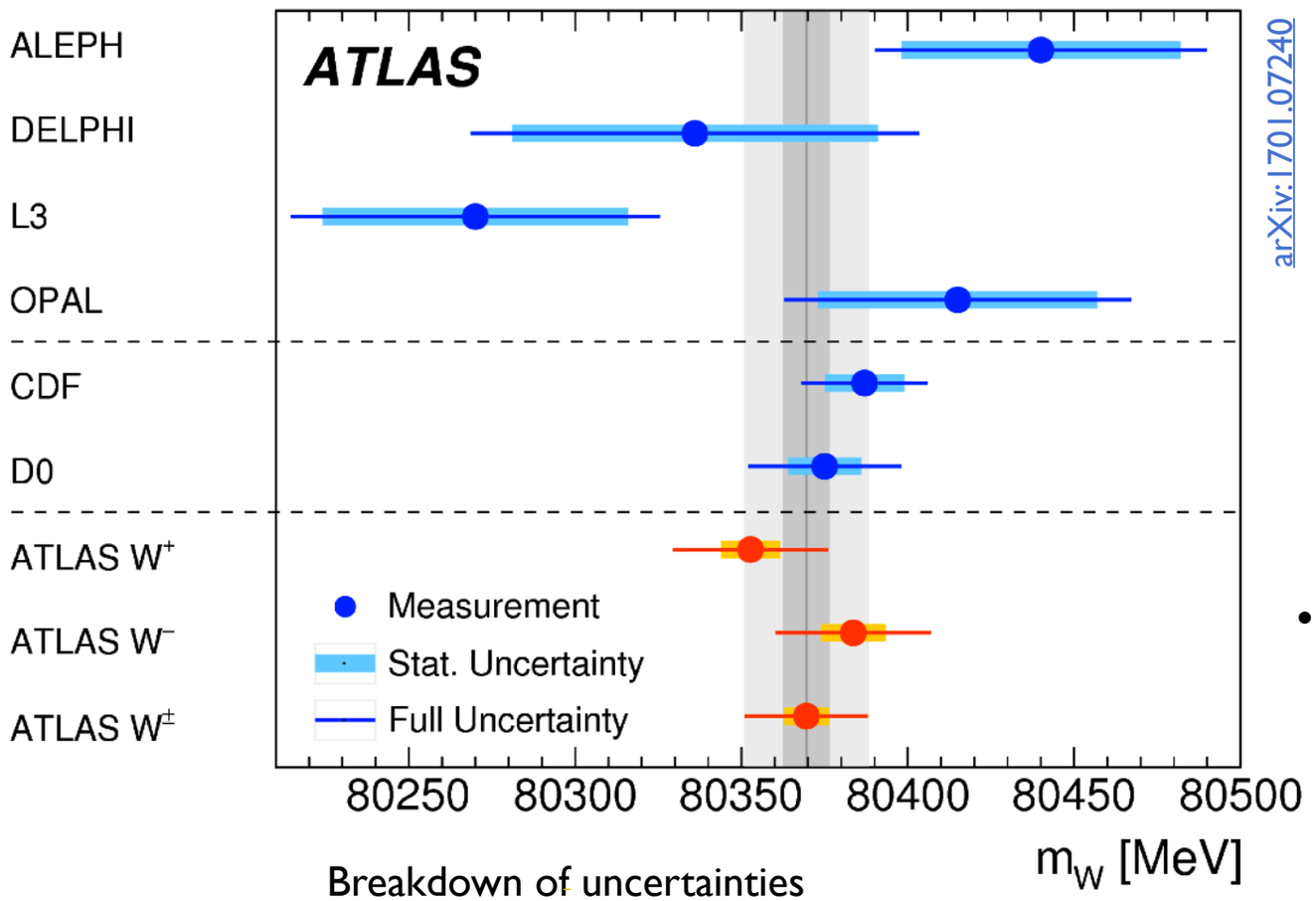
(c) MLM

- **LHC rapidly caught up with precise mass measurements**
  - 500 MeV (0.3%) level
  - ambiguity at the level of Λ_{QCD}
  - calibrated to a simulation

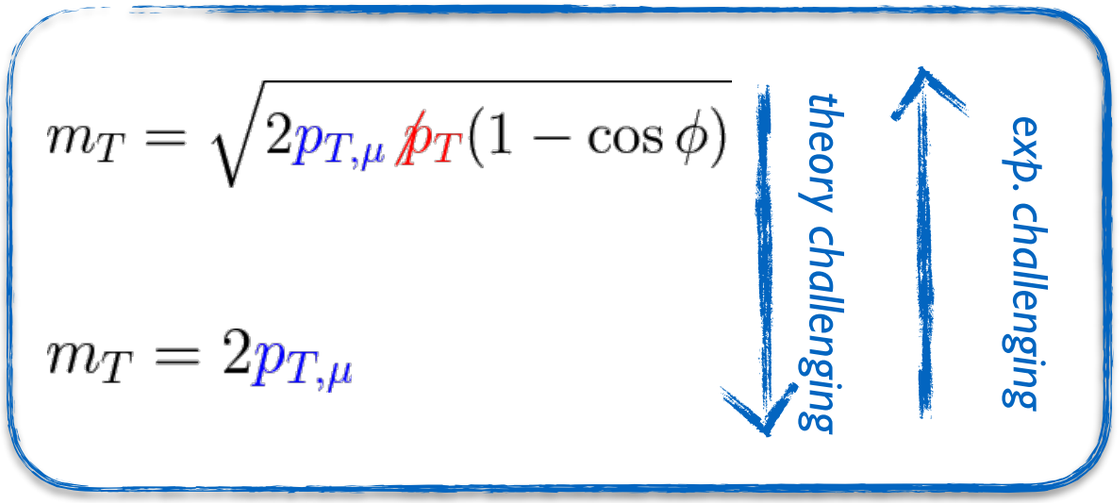
    ⇒ npQCD + parton shower

Translate precisely to m_t^{pole}?

First W mass at the LHC !



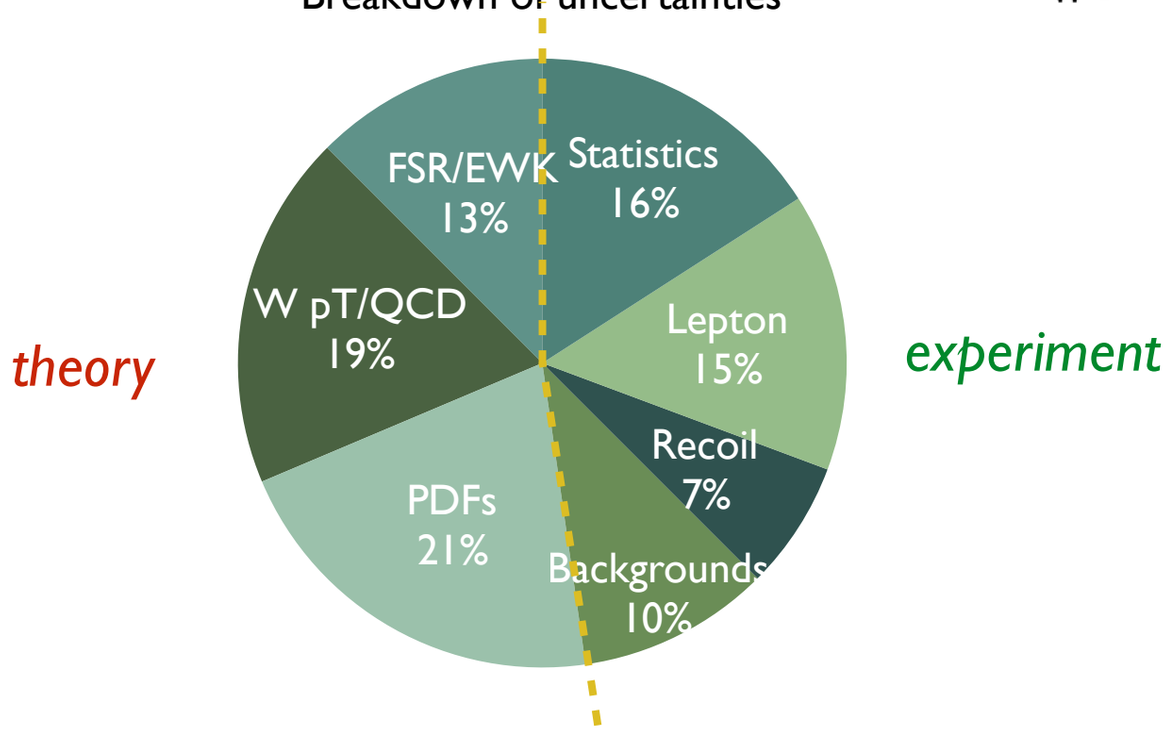
arXiv:1701.07240



- **Several ingredients involved**
  - Lepton calibration: J/ψ, Z data
  - Modelling of the recoil: Z data
  - W p_T: calibrate predictions on Z p_T

    (but also angular distributions and FSR)
  - PDFs : sea/valence quark ratios

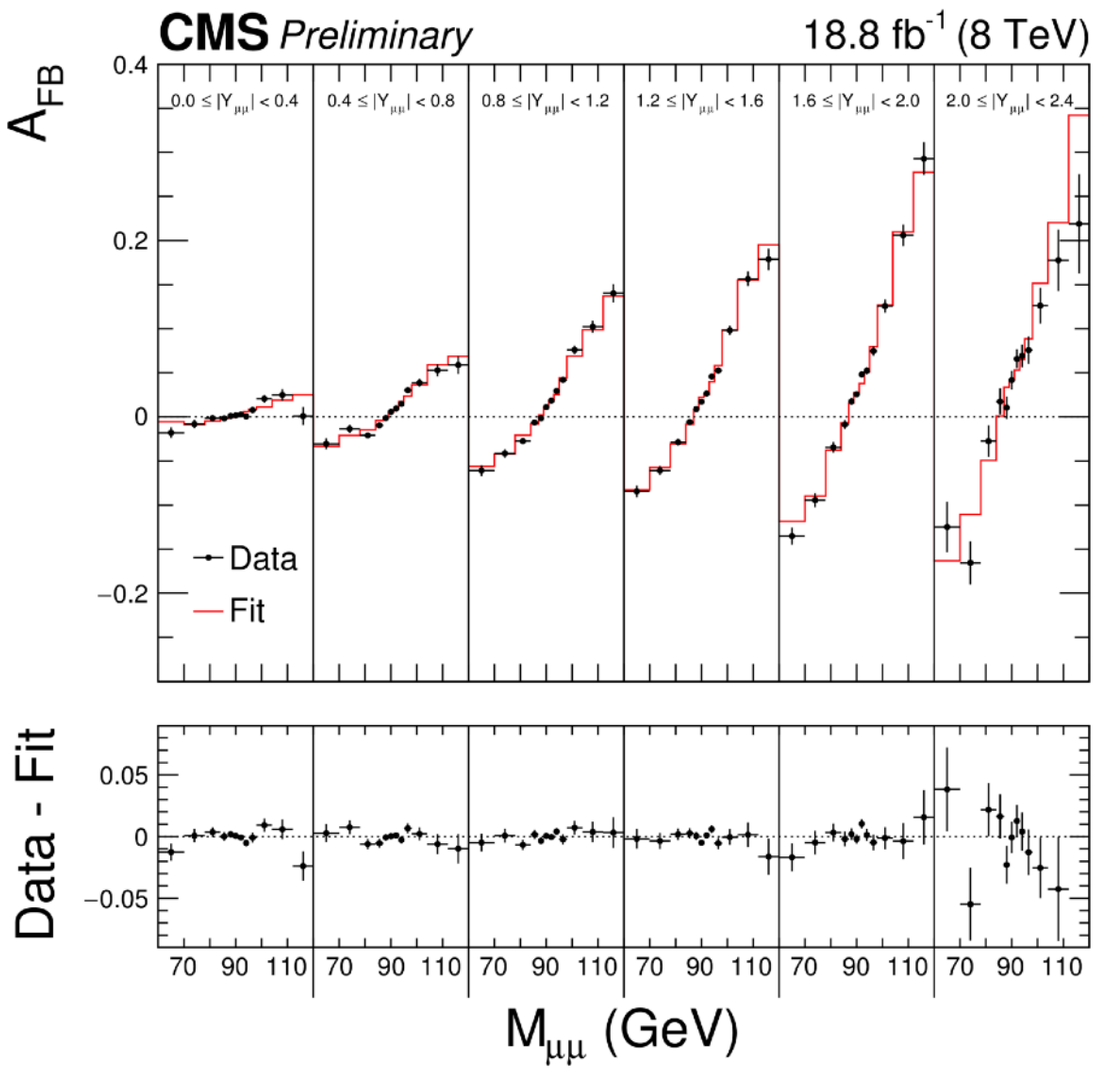
Breakdown of uncertainties



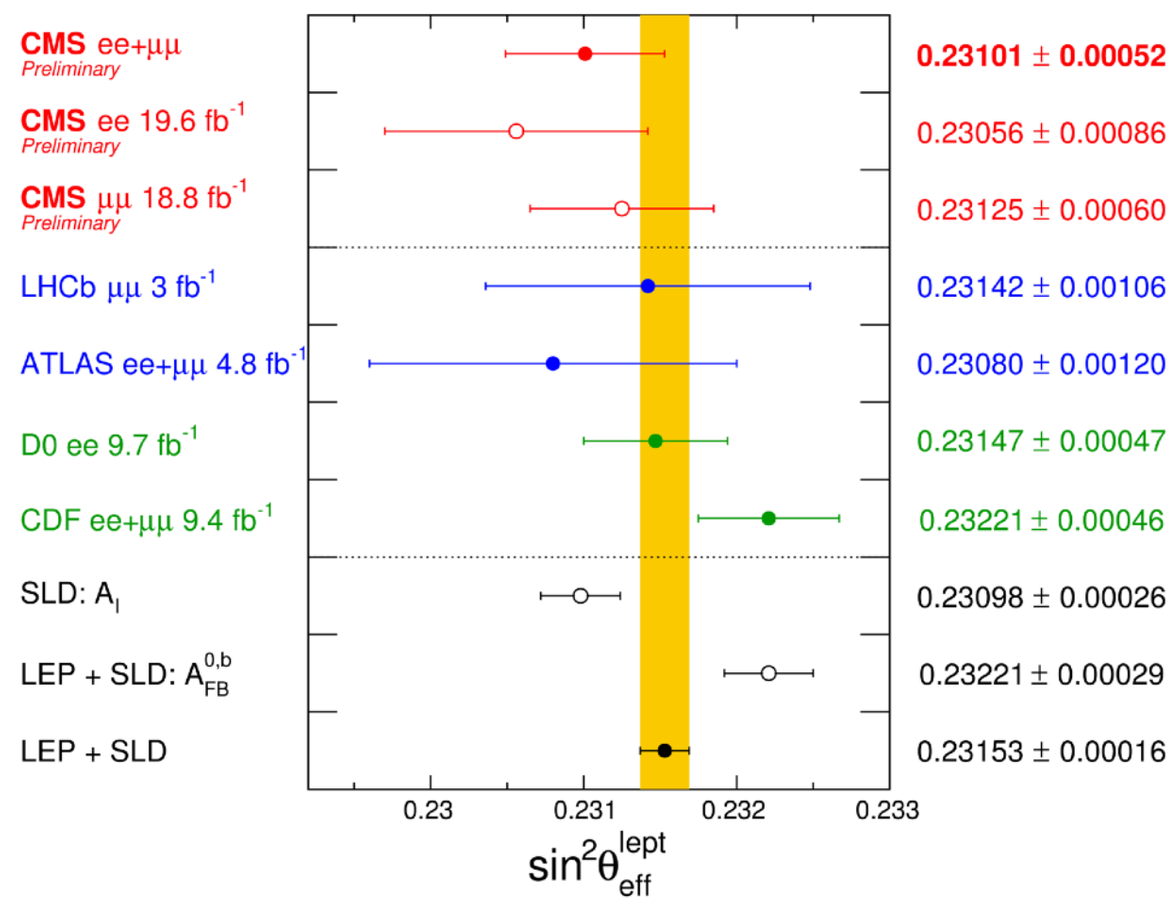
Free of ambiguities: decay products are pure EWK

But calibration involves non-trivial QCD predictions

Latest on the weak mixing angle



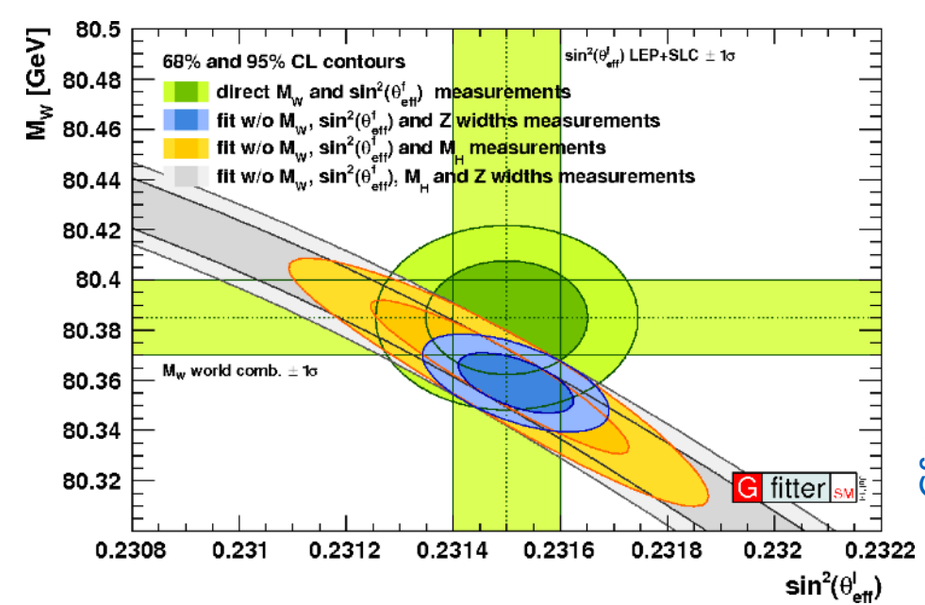
$$\sin^2\theta^{lept}_{eff} = 0.23101 \pm 0.00036_{\rm stat} \pm 0.00018_{\rm syst} \pm 0.00016_{\rm th} \pm 0.00030_{\rm pdf}$$



CMS-PAS-SMP-16-007

- **Forward-Backward asymmetry in $Z/\gamma^* \to \ell\ell$**
  - sensitive to the weak mixing angle $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$
  - still room for improvement at the LHC

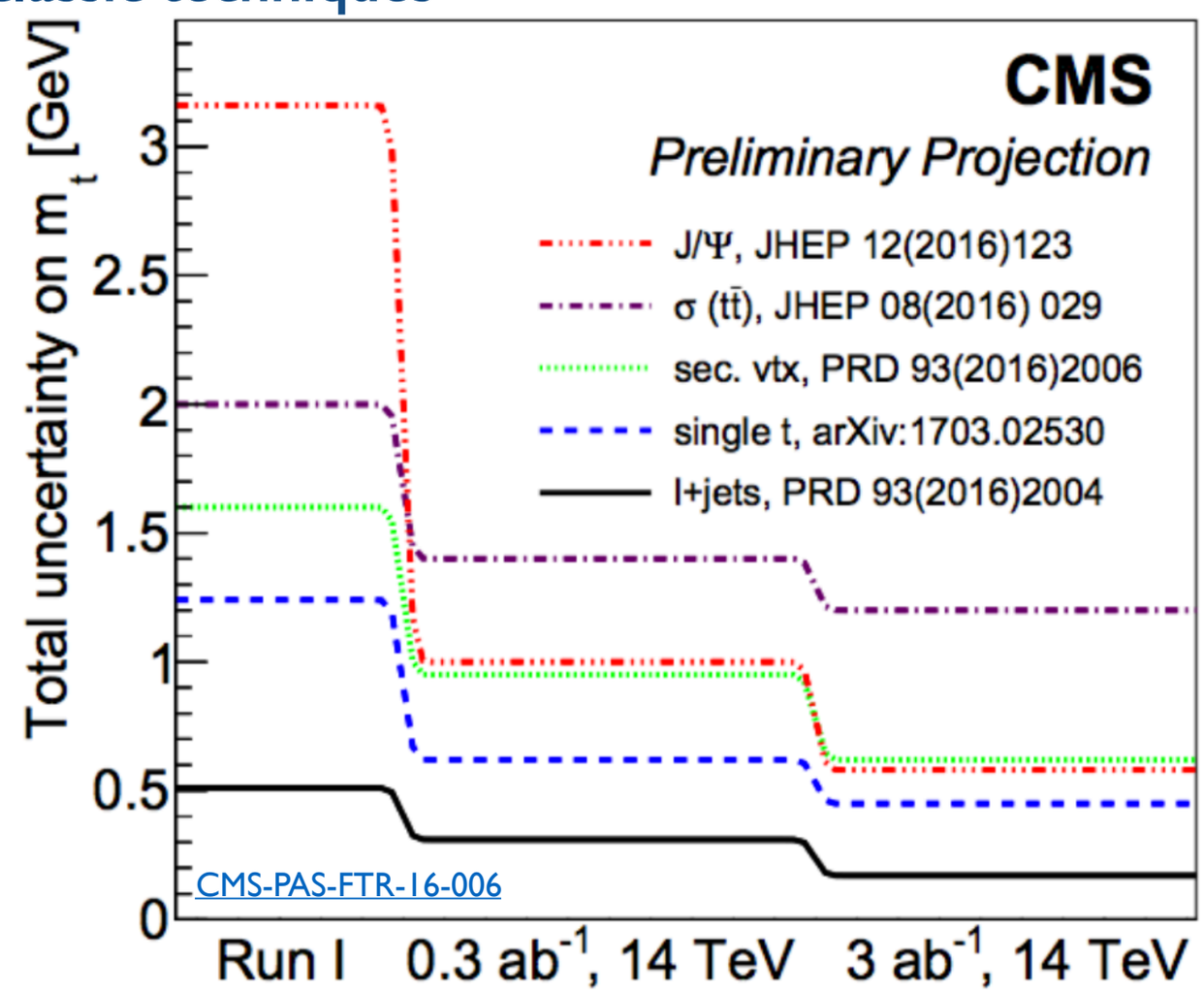
common theory/PDF uncertainties with W mass



Gfitter

What are we aiming for with m_t, m_W?

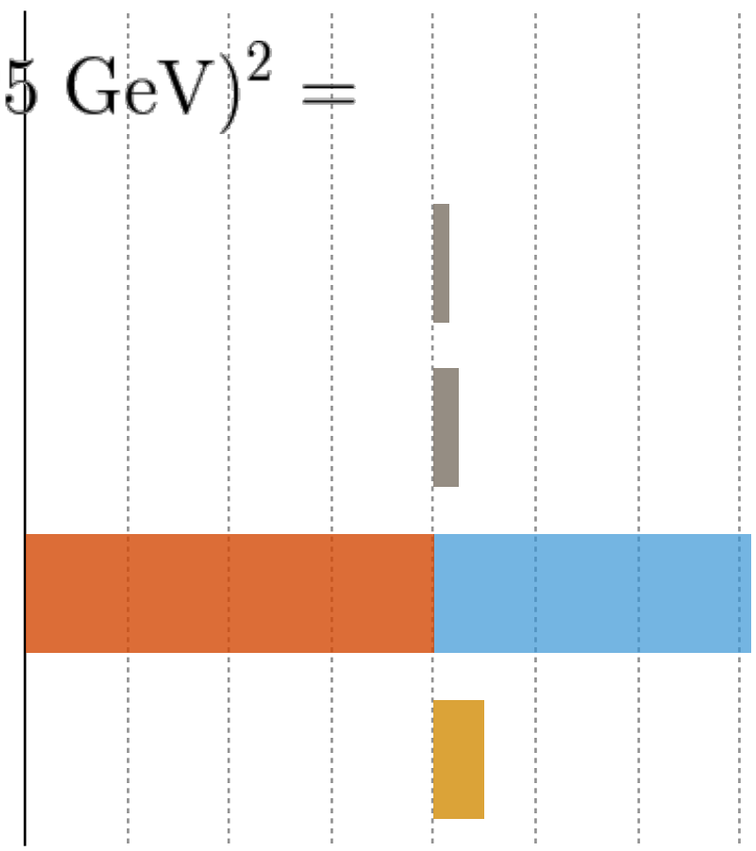
- **m_W : fresh start! uncertainty already competitive with Tevatron**
  - recoil estimate from data becomes harder in more recent and future datasets due to pileup
  - benefit from higher statistics for higher p_T W's evading the npQCD uncertainties
  - 5-10 MeV (may be optimistic?)
- **m_t : Λ_{QCD} within experimental reach using classic techniques**
  - combination with alternative methods
  - evolve towards differential m_t
  - but theory needs to accompany interpretation
  - 200 MeV

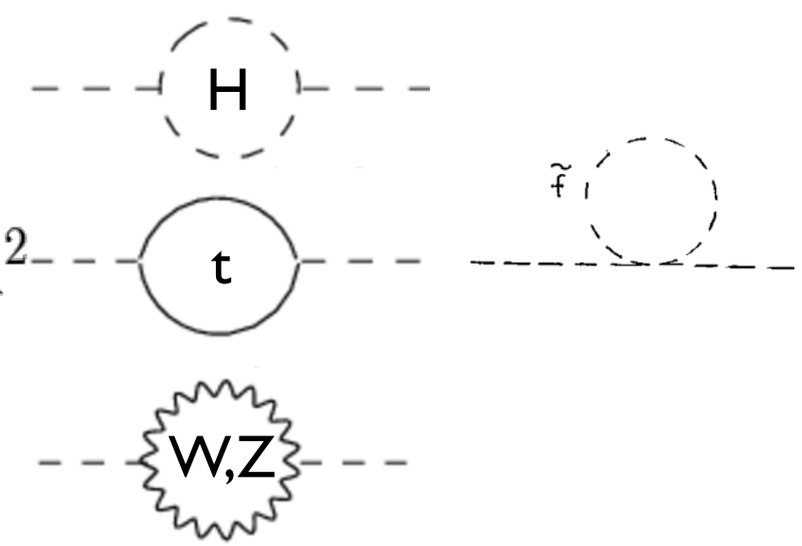


In both cases: rich programme of experimental and theory challenges ahead!

With the Higgs the SM is now incomplete - reprise

$$m_H^2 \approx (125\ \mathrm{GeV})^2 = m_{H0}^2 + \frac{1}{16\pi^2}\lambda_H^2\Lambda^2 - \frac{3}{8\pi^2}\left(\lambda_t^2 - \lambda_{\tilde{t}}^2\right)\Lambda^2 + \frac{9}{64\pi^2}g^2\Lambda^2$$

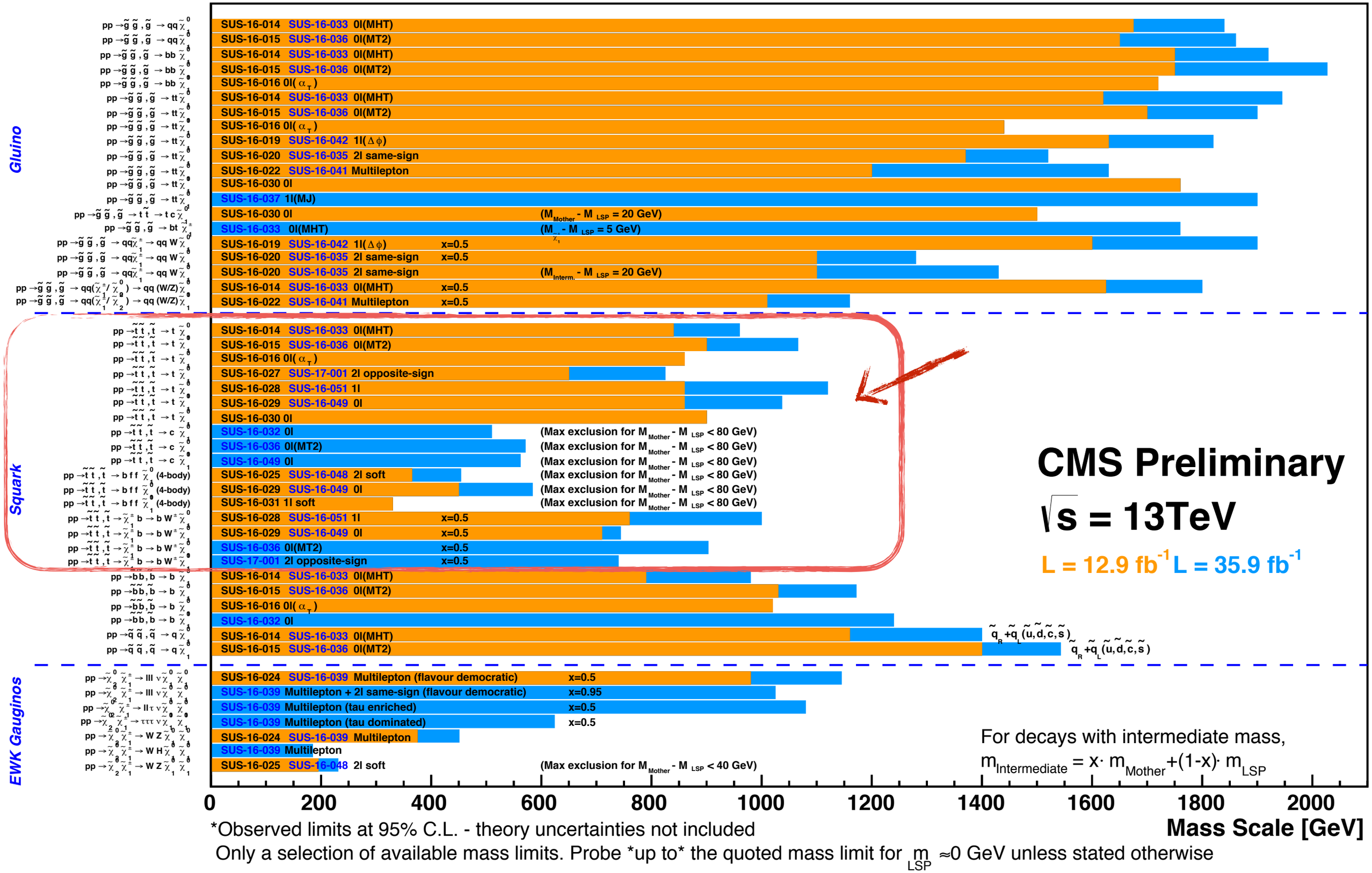




⇒ a top quark partner at the TeV scale?

Selected CMS SUSY Results* - SMS Interpretation

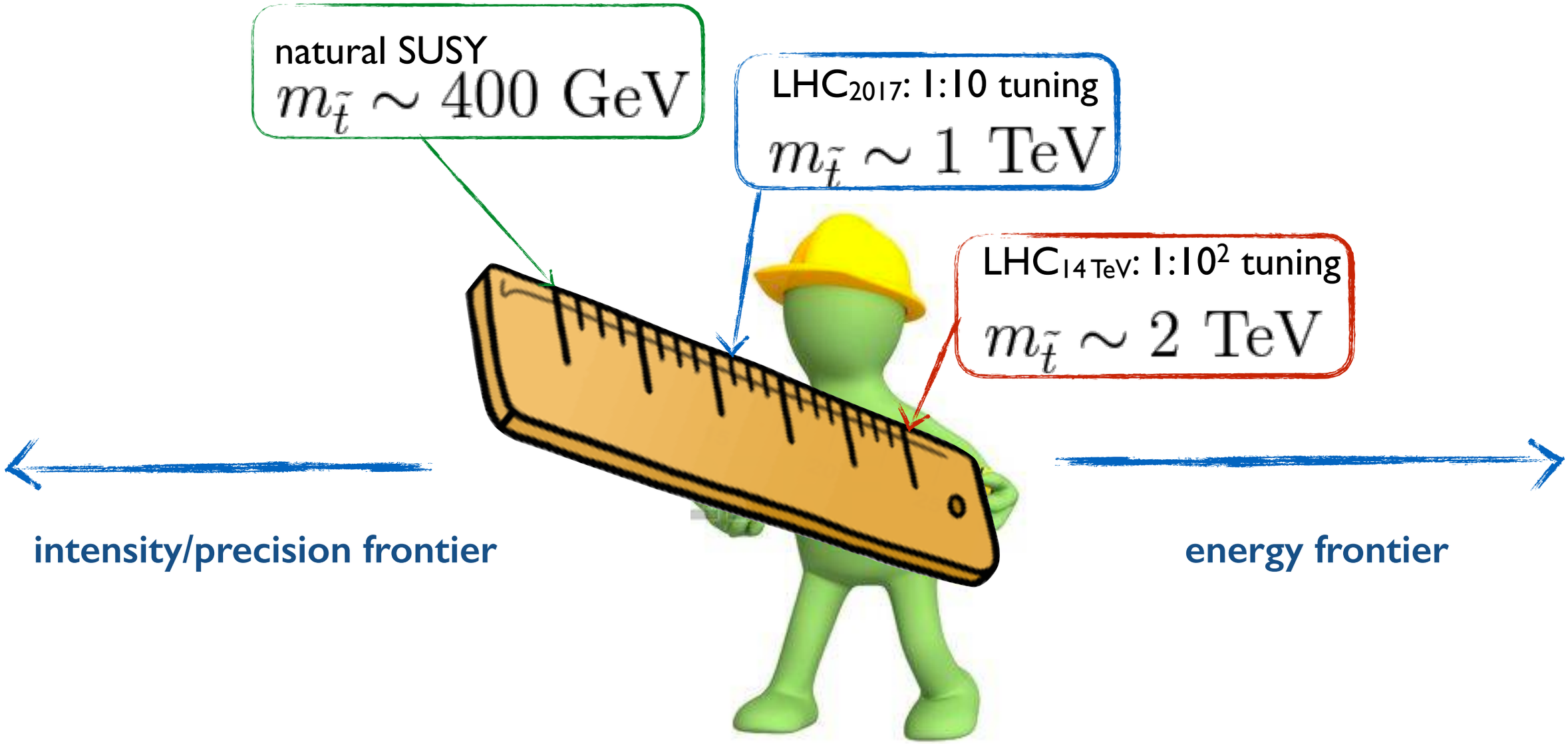
ICHEP '16 - Moriond '17



*Observed limits at 95% C.L. - theory uncertainties not included

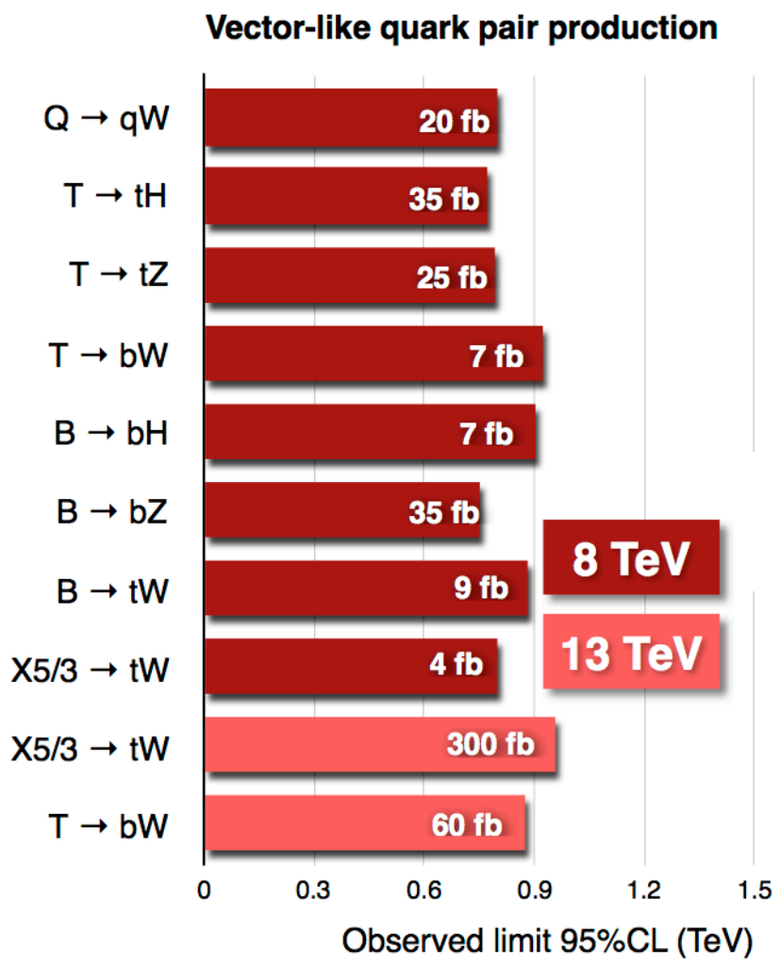
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

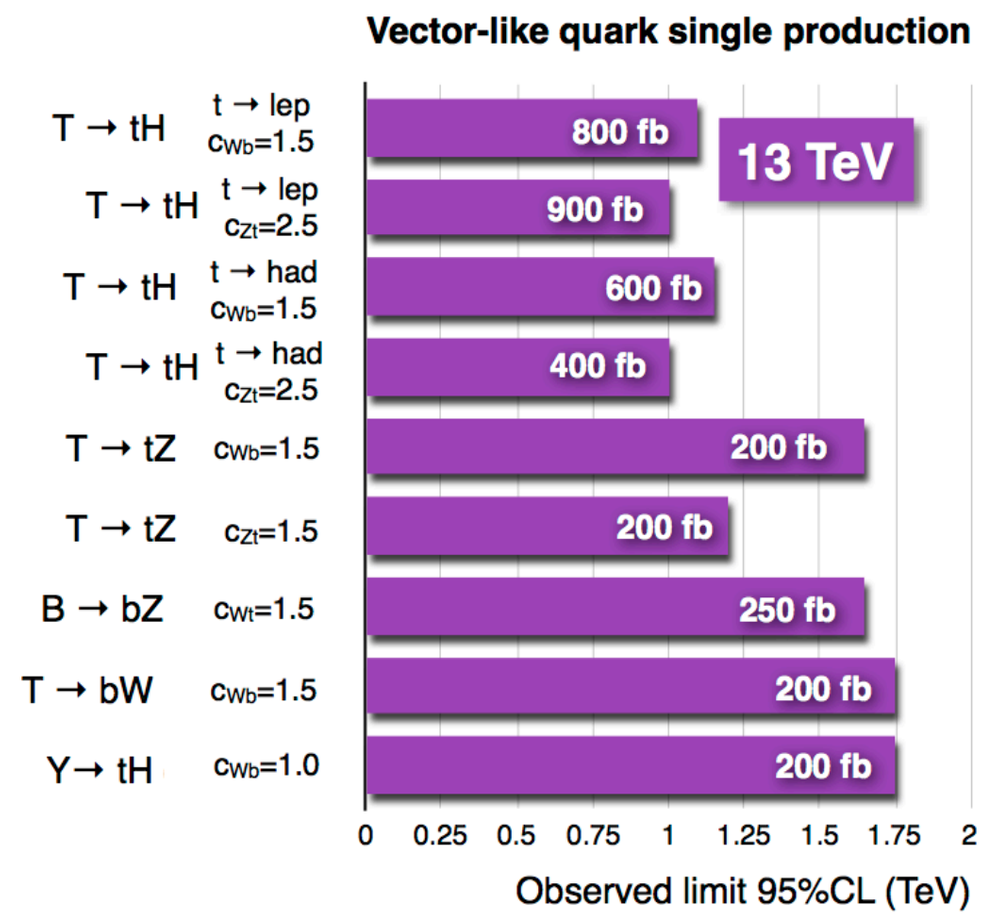
Desperately searching for SUSY?



- **Although nothing striking is above the standard model expectations**
  - we have only analysed ~2% of the data to come
  - still room to find a stop quark in a "moderate fine-tuned scenario"
- **Intensity/precision frontier : common challenges with Higgs, EWK, flavour**

Vector-like quarks I

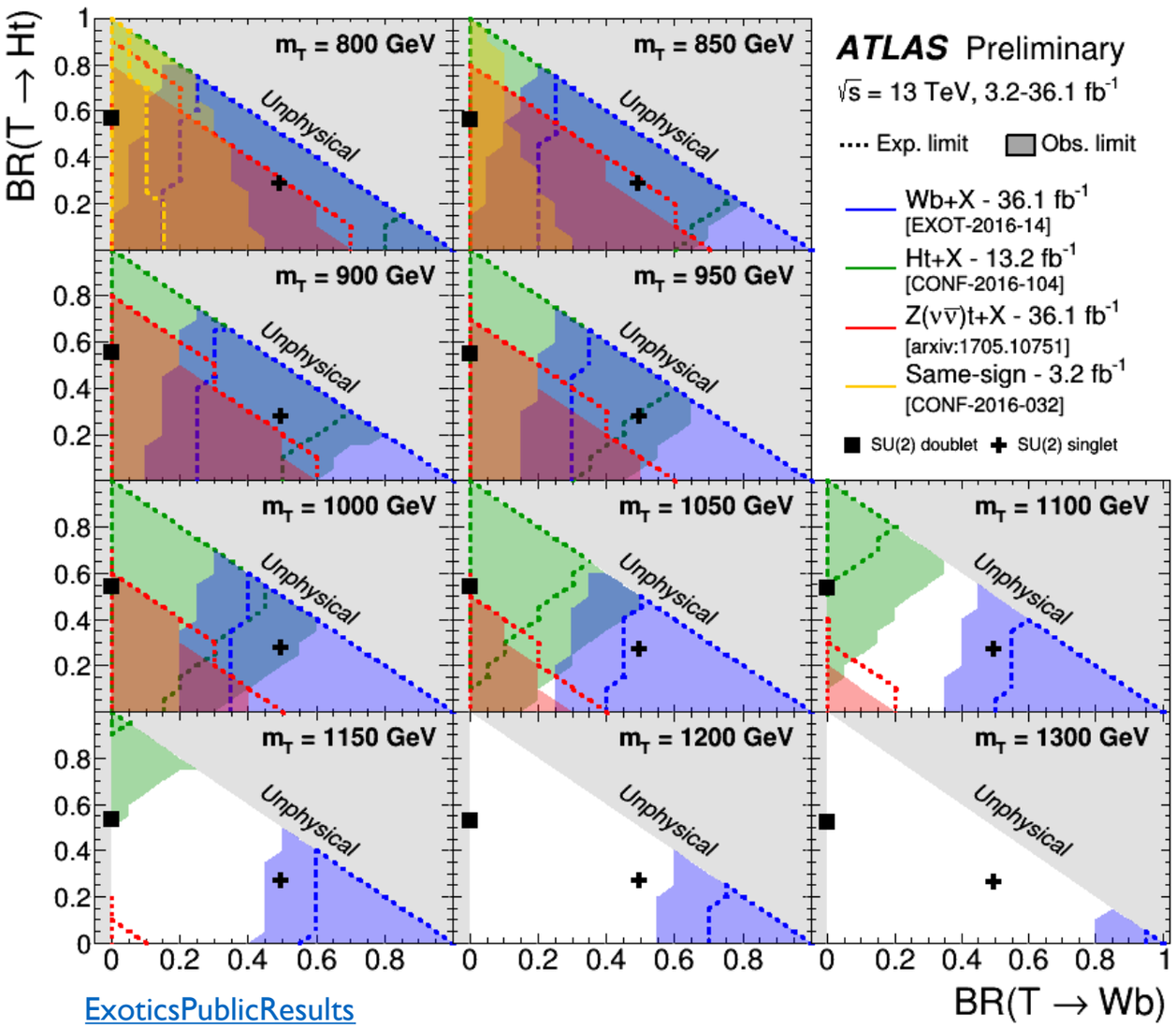




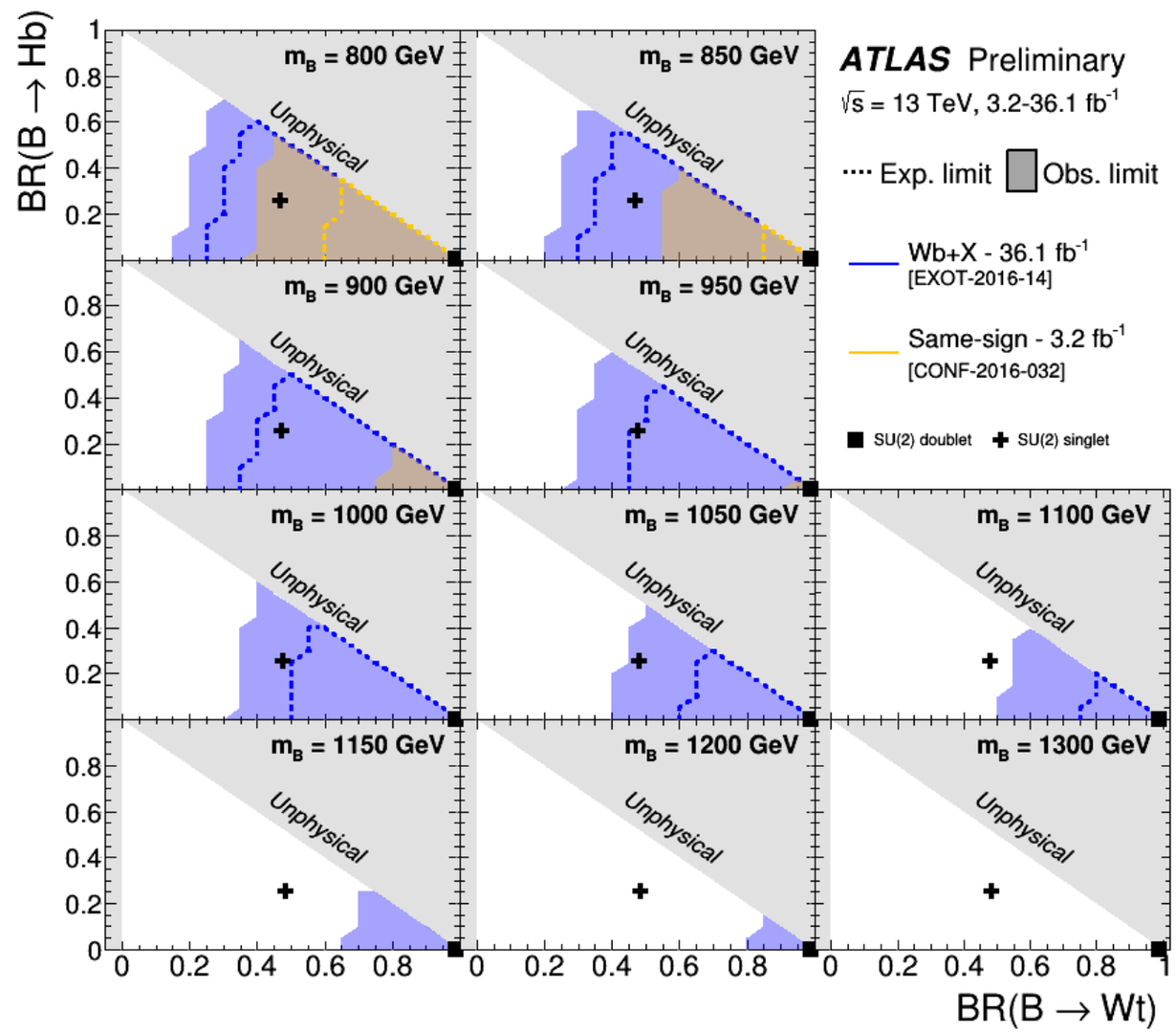
PhysicsResultsB2G

- **Extra fermion partners may contribute to cancel divergences in m_H**
  - unlike SM fermions have left- and right-handed charged currents
  - Yukawa-type coupling to SM fermions
  - reach signatures with bottoms/tops and bosons in the final state
- **Typical of composite Higgs, little Higgs-like theories, extra dimensions**

Vector-like quarks II



ExoticsPublicResults



- **Uncharted territory - leave no stone unturned**
  - cover all possible final states and scan the couplings

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \rightarrow \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \rightarrow tt$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	$1\ e, \mu$	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \rightarrow WV \rightarrow qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \rightarrow tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e, μ	$\geq$1 b, $\geq$1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \rightarrow Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	1705.10751
	VLQ $TT \rightarrow Wb + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \rightarrow Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	1409.5500
	VLQ $BB \rightarrow Wt + X$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \rightarrow WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Should the new physics scale be at the LHC reach?

- K^0, D^0, B^0, B^0_s mass splittings yield tight constraints on new physics contributions

$$\delta\mathcal{L} = \frac{z_{qq'}}{\Lambda^2}\left(\bar{q}_L\gamma_\mu q'_L\right)^2 \Rightarrow \frac{\Delta m_h}{m_h} \sim \frac{|z_{qq'}|}{3}\left(\frac{f_h}{\Lambda}\right)^2$$

- If flavour structure is trivial (z~1)

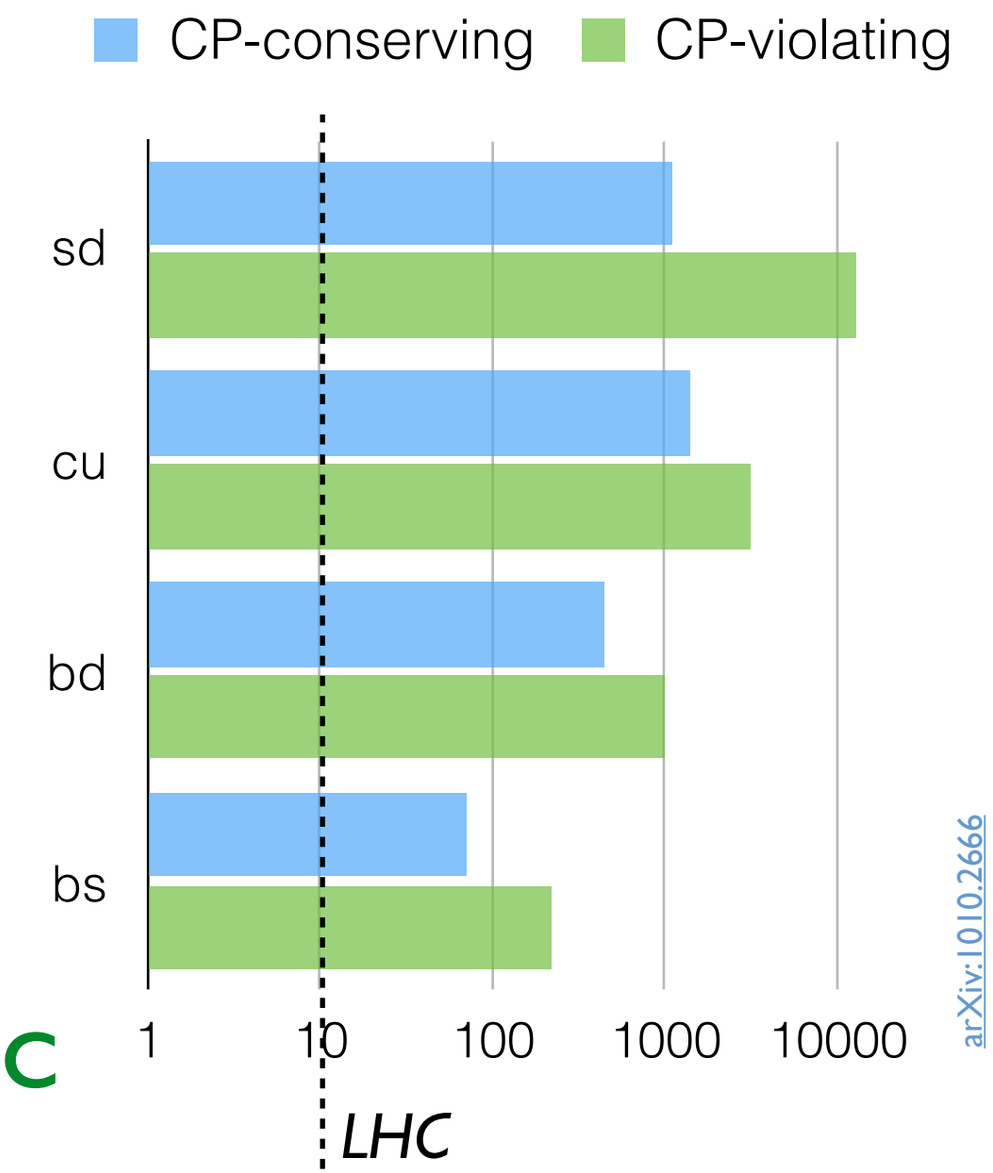
  $\Lambda \gtrsim$ O(100 TeV)

  ⇒ only glimpses of NP observed at the LHC?

- If $\Lambda \sim$ O(1 TeV)

  NP flavour structure is far from trivial

  ⇒ flavour measurements are good probe of NP



Both cases ⇒ higher precision at the LHC

Searching for subtle NP effects in data

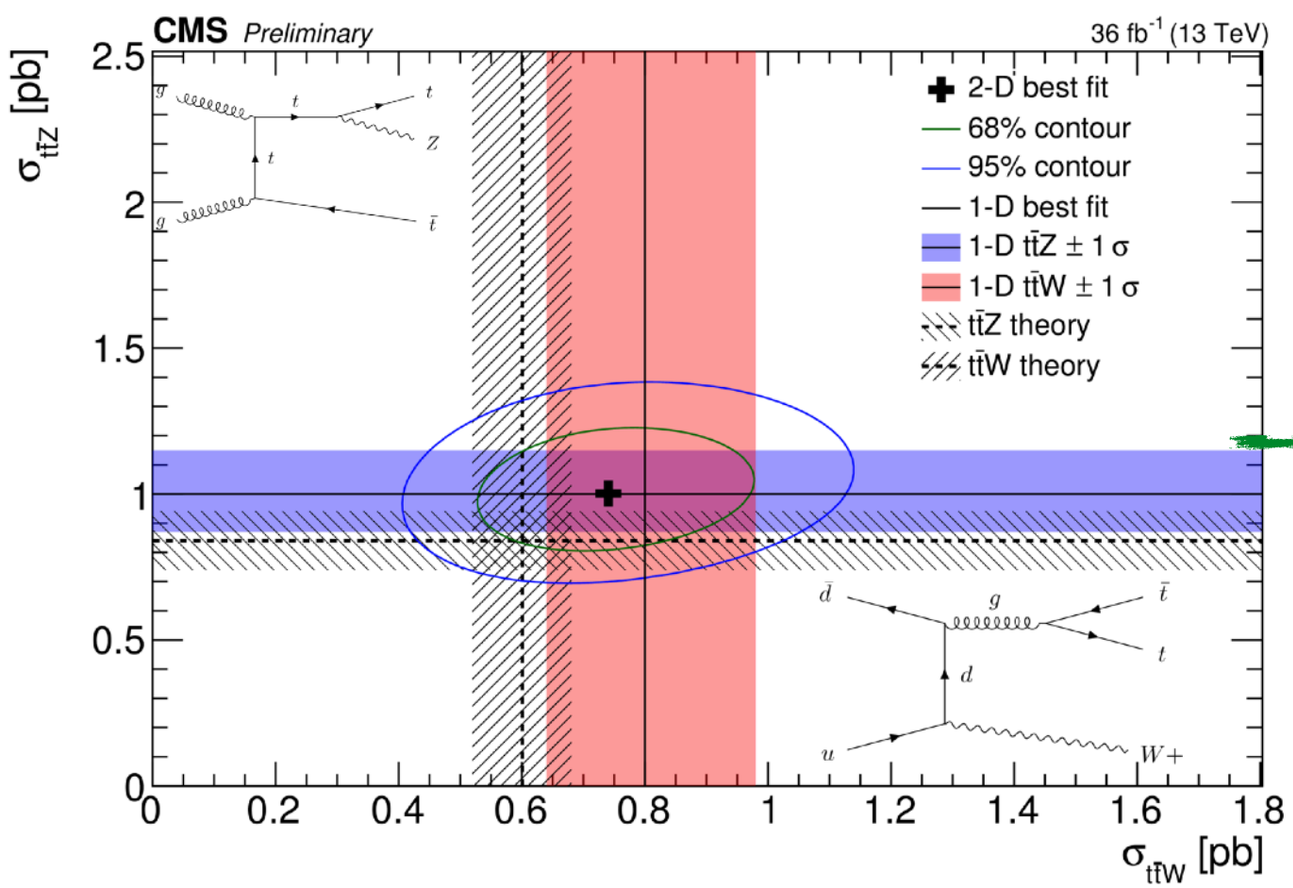
- **If the energy probed does not yet resolve the mass of the new particles**
  - look for deviations induced by Fermi-like interactions

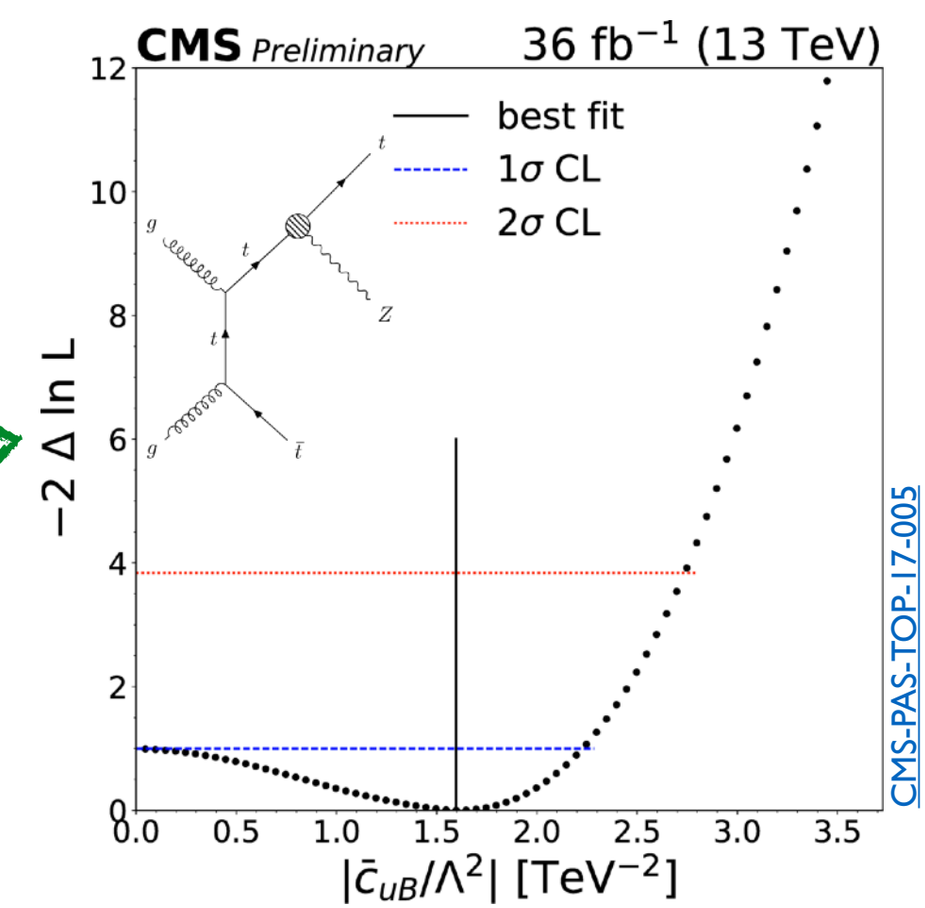
$$\delta\mathcal{L} = \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right) \longrightarrow \delta\sigma = \sum \frac{c_i^2}{\Lambda^2}\sigma_i + \sum \frac{c_i c_j}{\Lambda^4}\sigma_{ij} + \ldots$$

interference with the SM expectations

pure NP contribution
although suppressed by $1/\Lambda^4$ may be non-negligible!

- **Several start moving in the direction of a a global scan of allowed NP contributions**

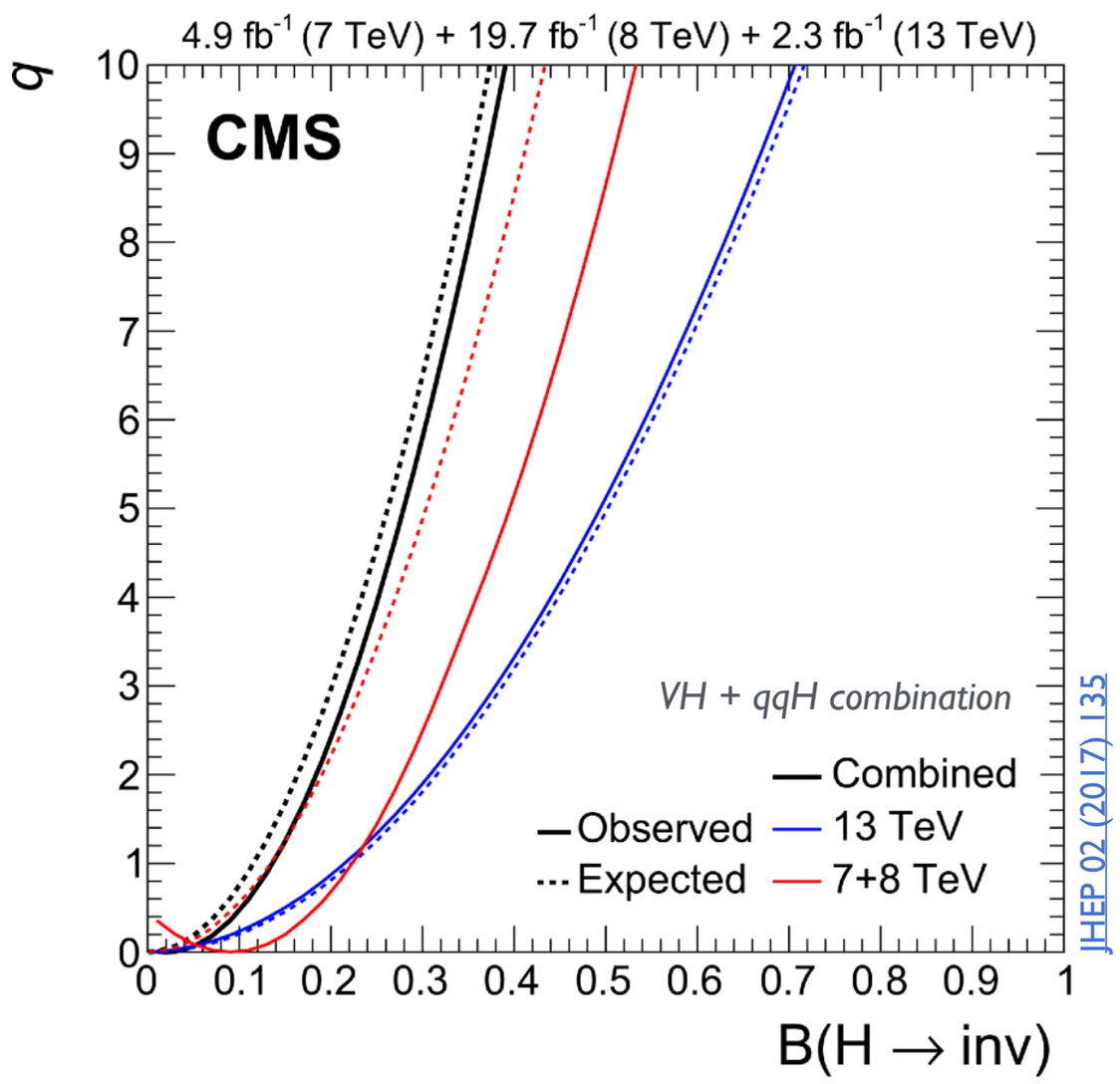


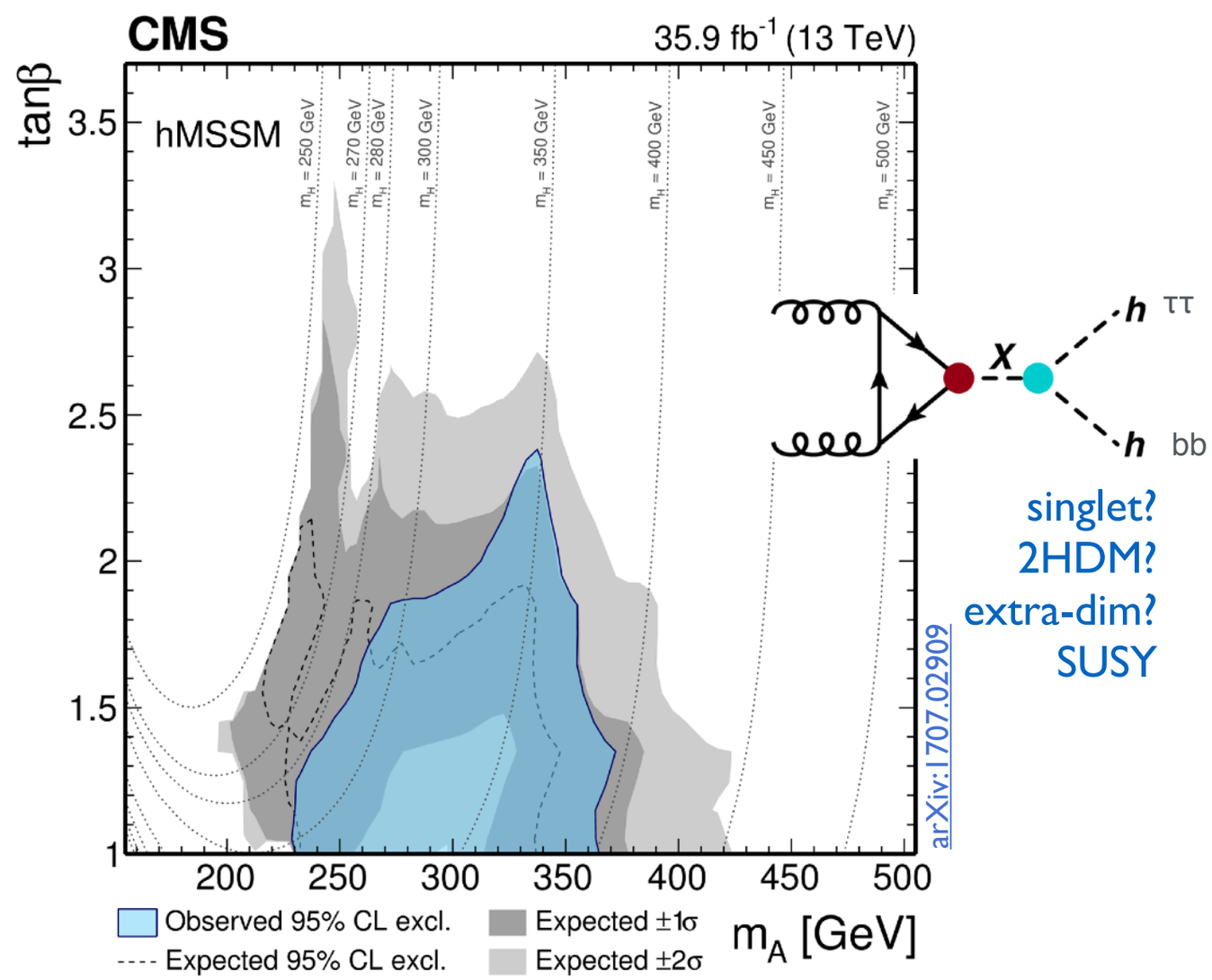


CMS-PAS-TOP-17-005

Higgs as a portal

- **Still a (experimental) large room for invisible Higgs decays: BR<0.24 @ 95%CL**
  - significant changes in this BR could be due to new neutral particles : dark matter?
- **It may also be that the Higgs sector is more complex and accompanied by partners**
  - resonant associated (VH) and hh production, high-mass diboson resonances, ….





Dark matter and Higgs

- **The limits on the invisible BR of the Higgs can be re-casted to limits dark matter production**

$$\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2},$$

$$\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}.$$

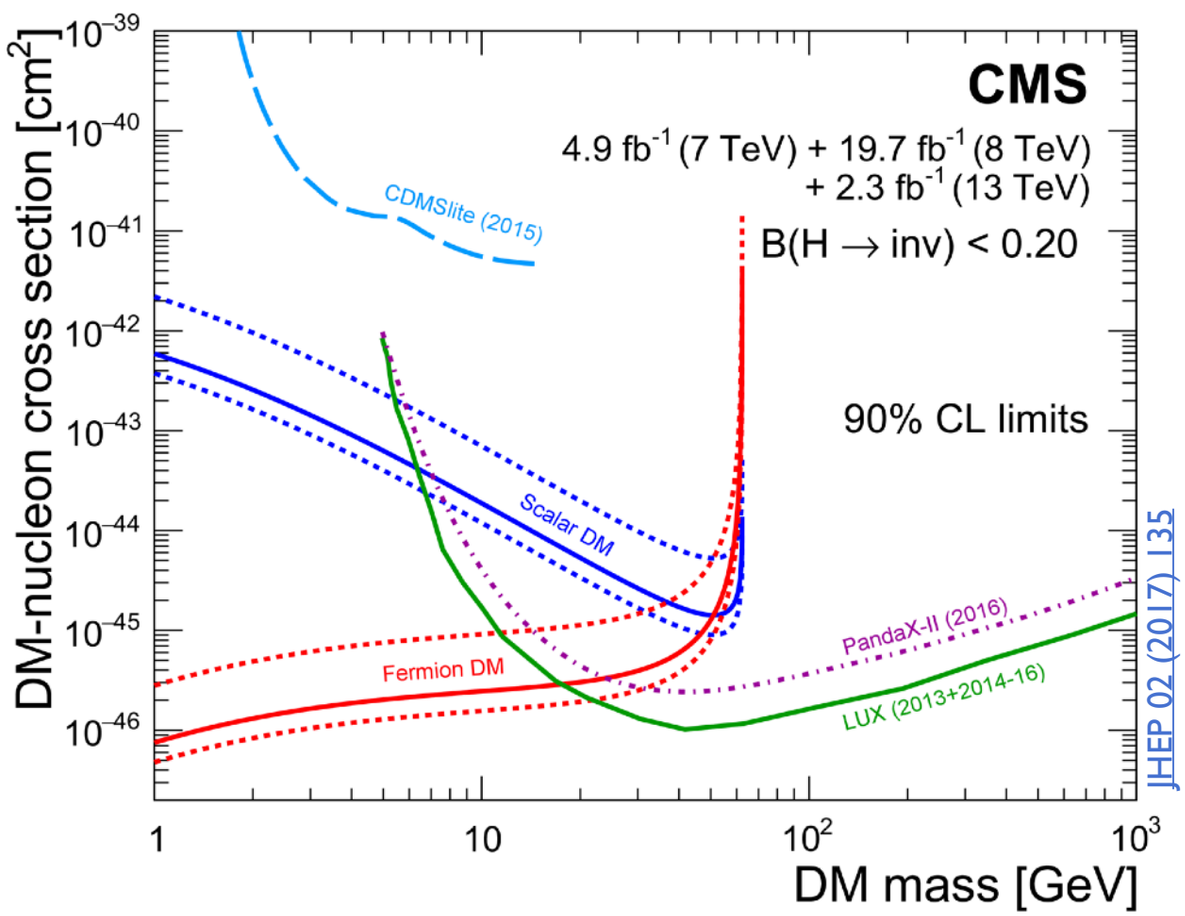
m_N - nucleon mass ~0.939 GeV
$v=246/\sqrt{2}$ GeV (vev)
f_N~0.326 central value for coupling (from lattice*)

$\beta = \sqrt{1 - 4M_\chi^2/m_H^2}.$

$\Gamma_{inv} = \Gamma_{SM}\, BR_{inv}/(1-BR_{inv})$

*PRD 81(2010) 014503, PRL 103(2009) 122002

- **Latest re-interpretations in terms of mediator-WIMP mass** (see **CERN-LPCC-2016-001**)



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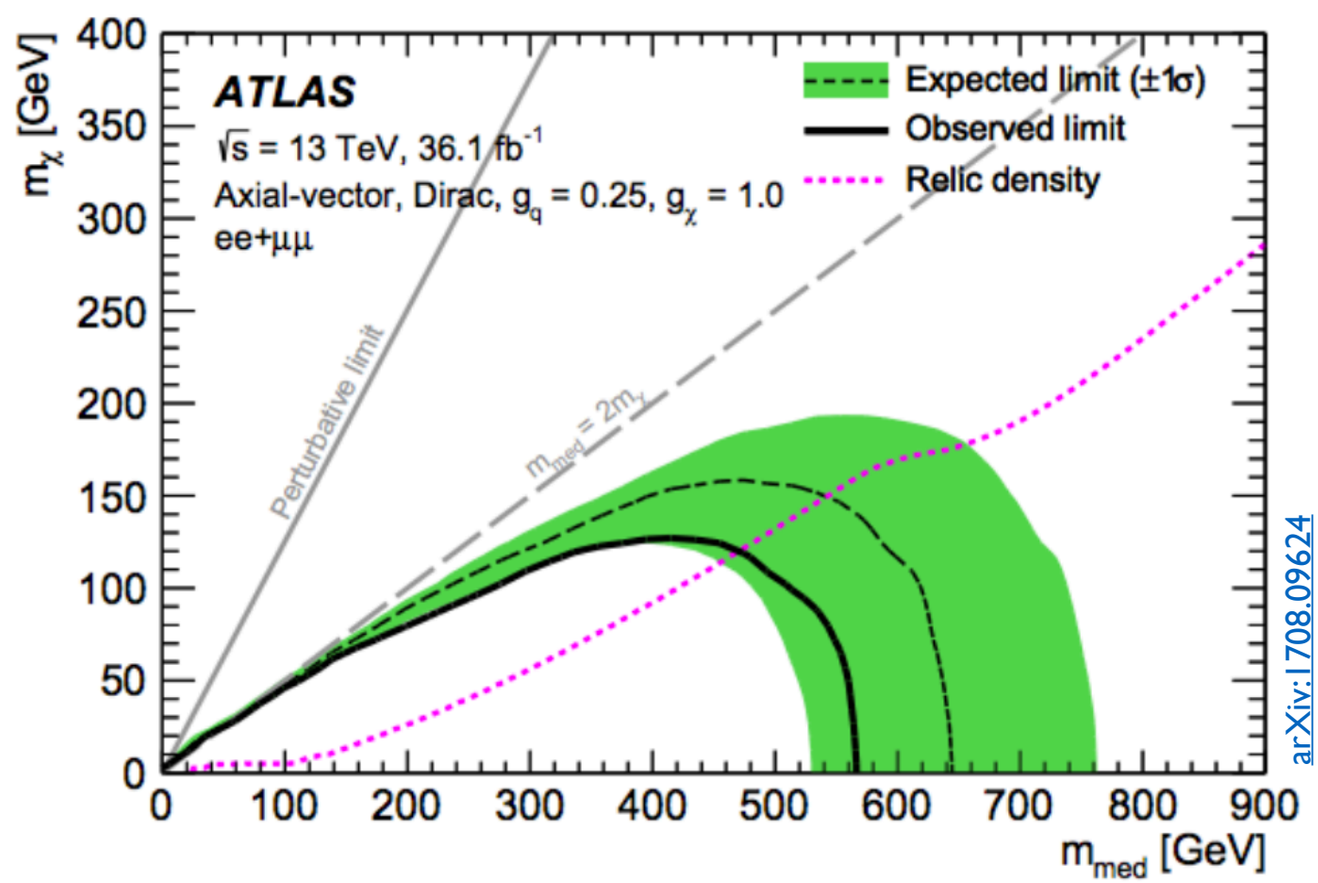
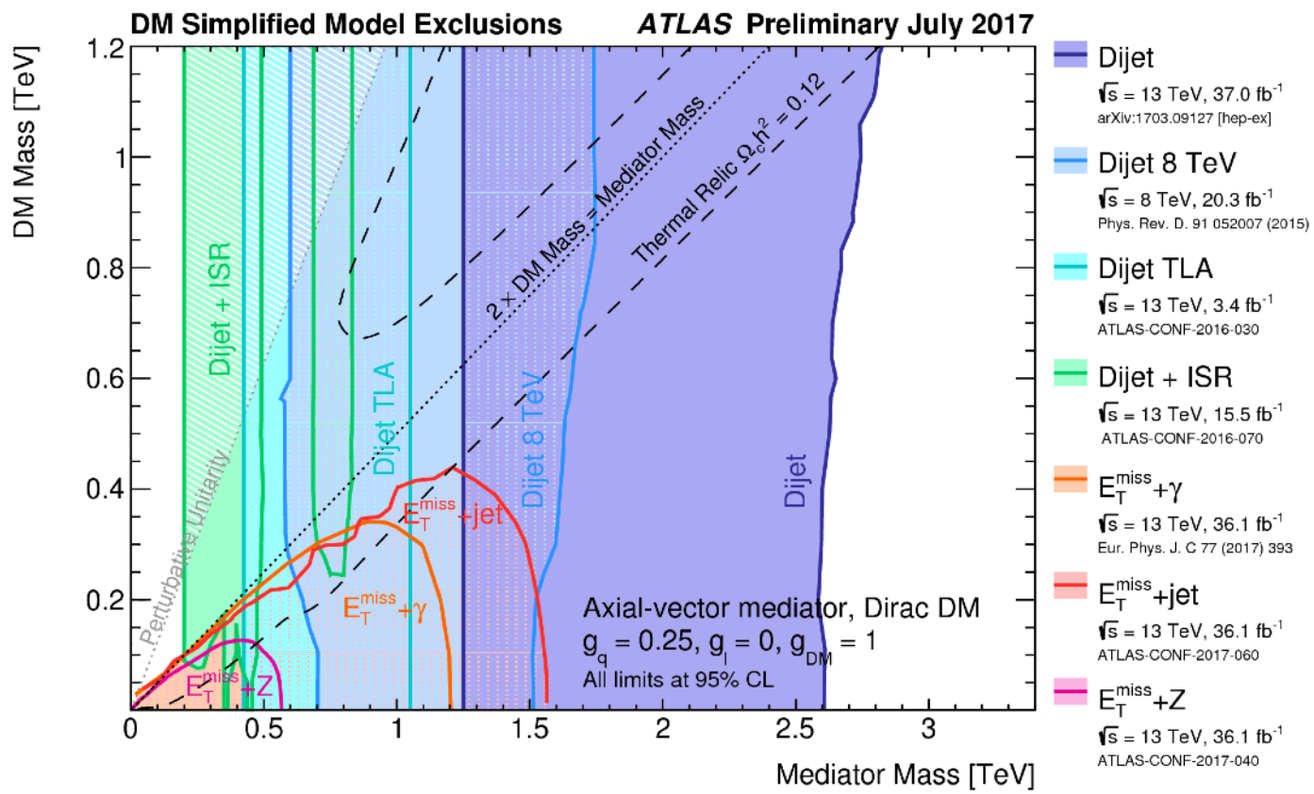
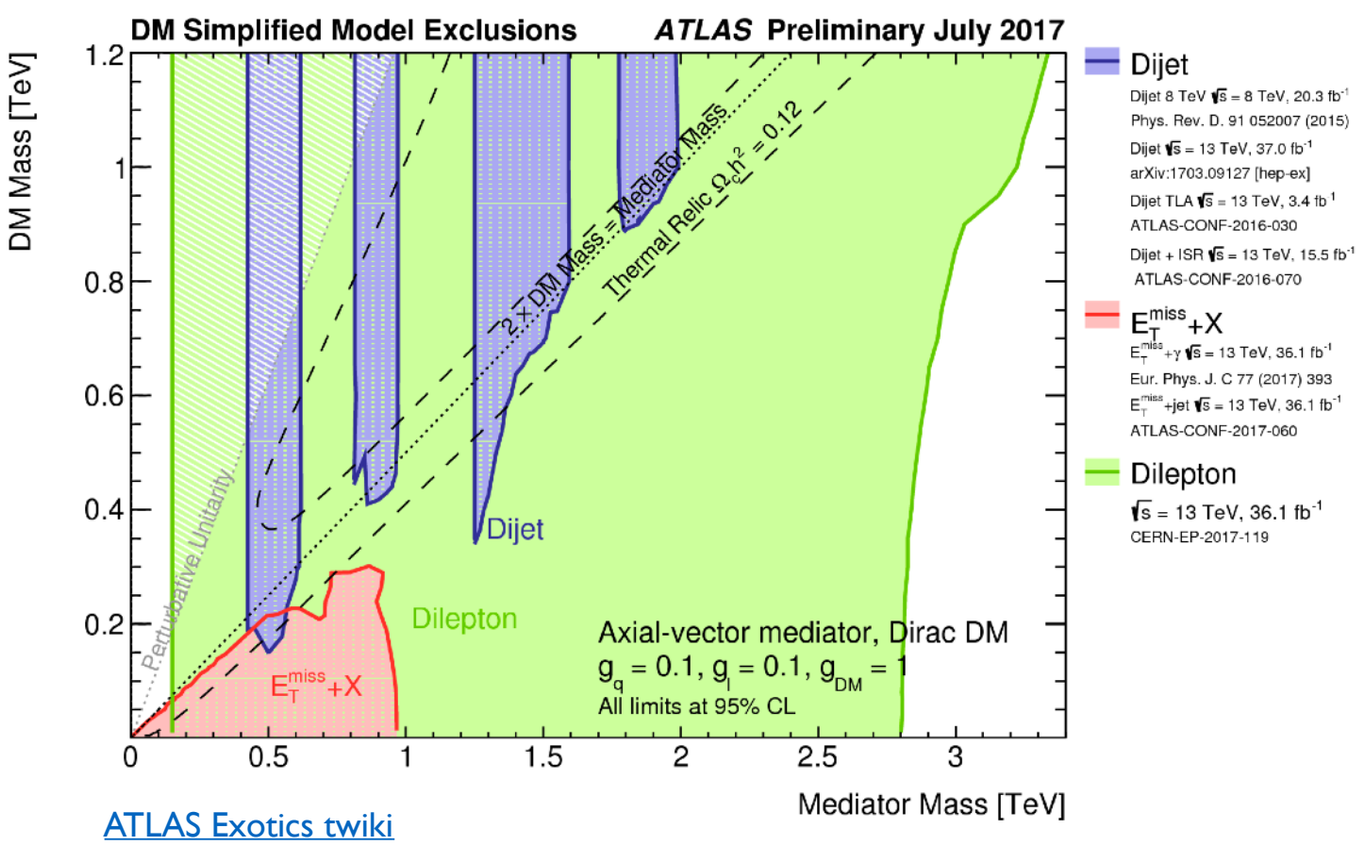


arXiv:1708.09624

Dark matter at the LHC

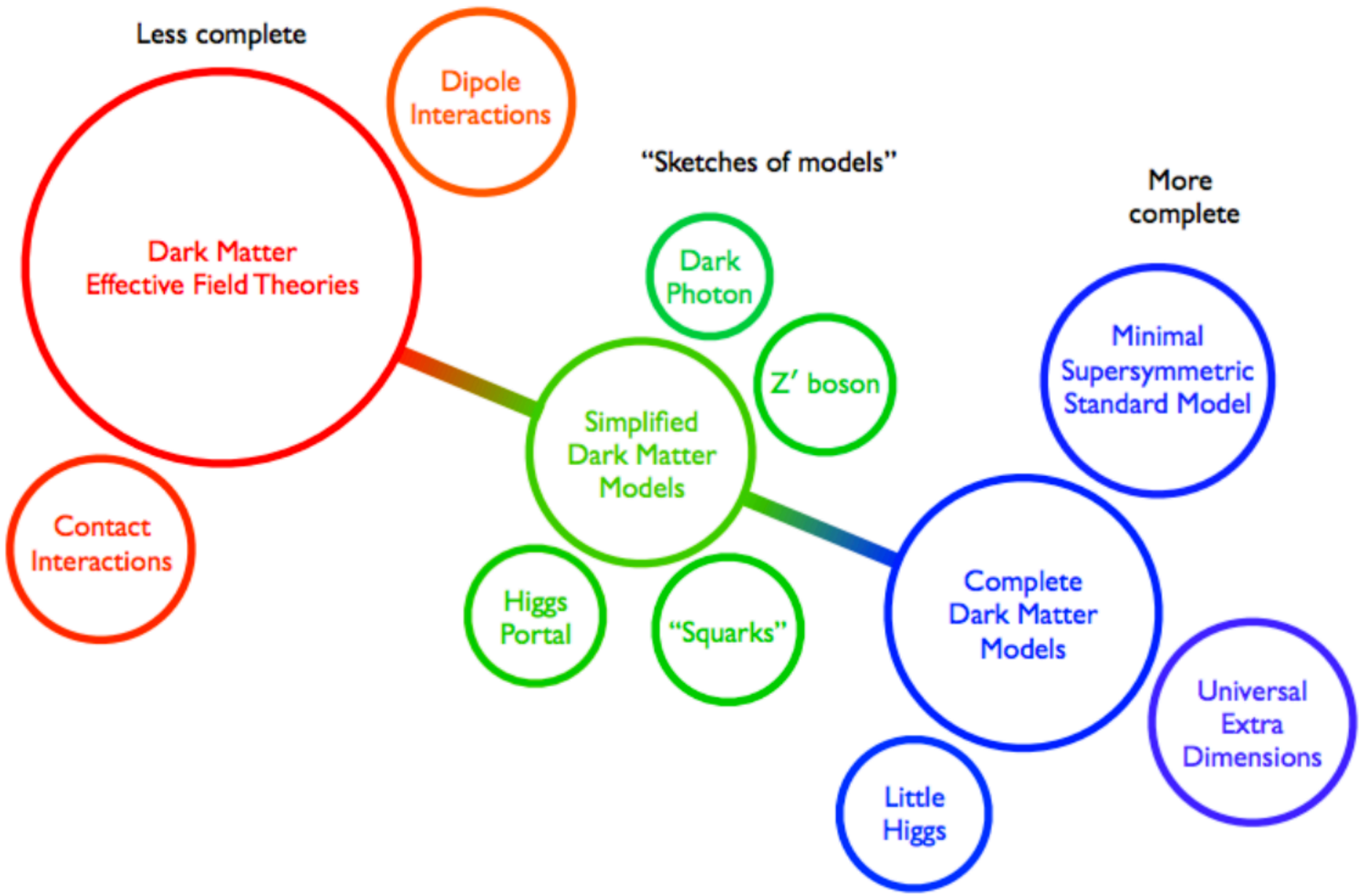




ATLAS Exotics twiki

- **Wide range of searches for associated production of dark matter: mono-X, jet+ISR, top, H**
  - spin-dependent re-interpretation is unavoidable
  - nevertheless, nicely complements direct searches from dedicated experiments

Data, models, what is the nature of BSM?



Phys. Dark Univ. 9-10 (2015) 8-23

- **Experimentalists rely on this type of model landscape to gauge their findings**
  - but the point is not so much what we plot/quote as limit
  - we want to fill in the puzzle by leaving no stone unturned

Outstanding questions - LHC dawn

Electroweak symmetry breaking

- does the Higgs boson exist?

Dark matter

- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
- one type or more ?
- only gravitational or other interactions ?

Quarks and leptons

- why 3 families ?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Neutrinos

- ν masses, their origin - Higgs role?
- Majorana or Dirac ?
- CP violation
- additional species?
- sterile ν ?

Physics at the highest E-scales:

- how is gravity connected with the other forces ?
- do forces unify at high energy ?

Universe's accelerated expansion:

- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

adapted. from I. Shipsey @ ICHEP2016

Outstanding questions - LHC Run 2

Electroweak symmetry breaking

- m_H natural or fine-tuned ?
- if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition

Dark matter

- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
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be happily unsettled and search for new physics