BSM physics at high energies
– an experimental review

XXI LNF Spring School "Bruno Touschek" in
Nuclear, Subnuclear and Astroparticle Physics

13–17 May 2024

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About these lectures

Content

- 1st lecture: intro – di-X searches – dark matter – SUSY
- 2nd lecture: BSM Higgs – HNLs – long-lived particles – going beyond

Caveats

- very broad subject, impossible to cover all
  - constantly changing
  - personal bias unavoidable
- very diverse subjects come together here
  - many overlaps – no A-Z story
  - attempt to broad picture combined with experimental connection
- stop me if you get lost!
- references

Content Lecture 1

- Introduction
  - the standard model – from SM to BSM – Top-Down versus Bottom-Up
  - the energy frontier – LHC and detectors – how to search the data?
- bread and butter resonance searches
  - dilepton and lepton+MET searches
  - dijet searches and beyond
  - diphotons
- dark matter
  - di-invisible → dark matter
  - direct dark matter searches at LHC
  - di-X interplay with dark matter – beyond the LHC
- supersymmetry
  - appeal
  - strong production: jets+MET
  - weak production: leptons+MET
  - RPV: multijets

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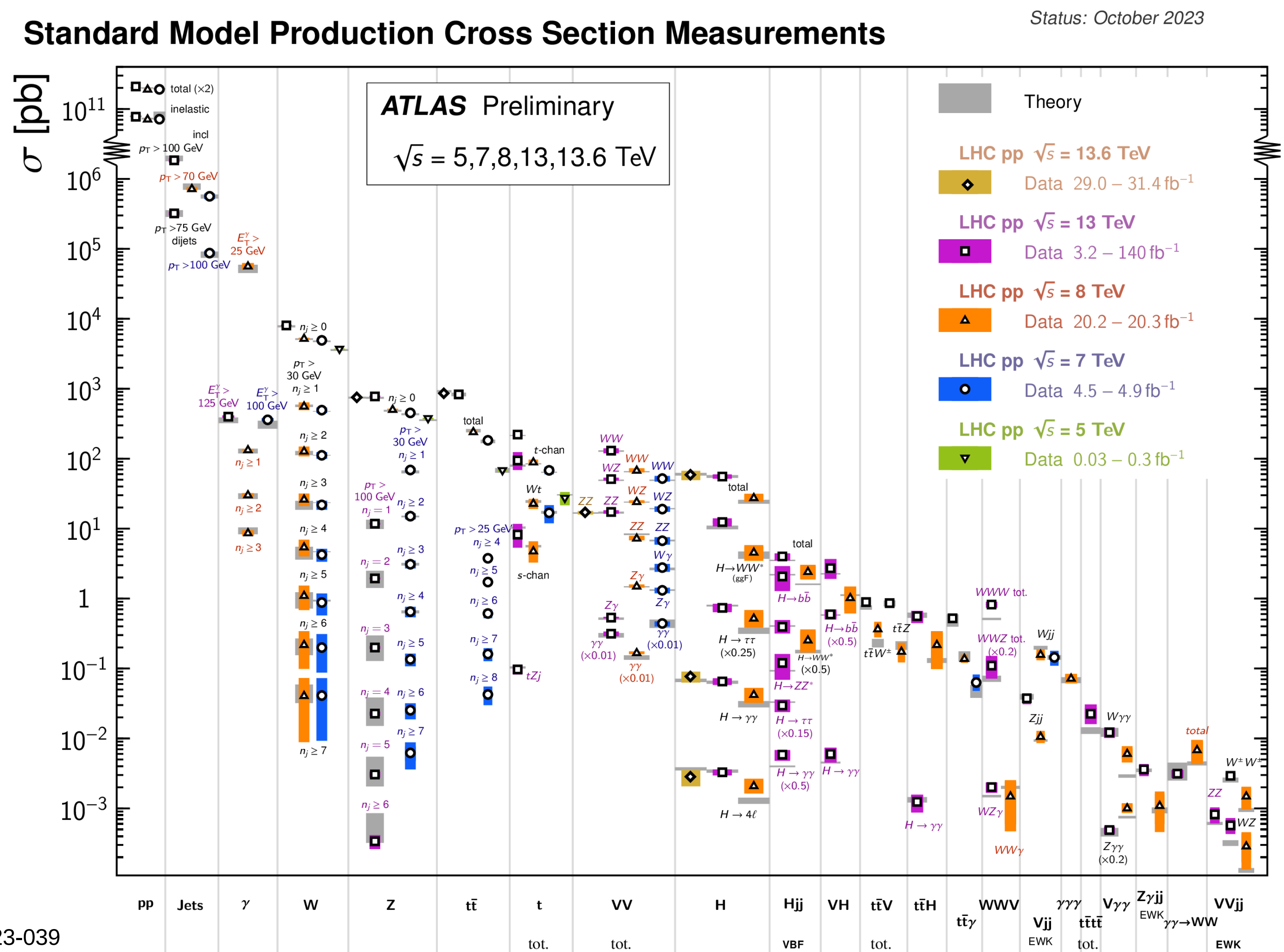
The Standard Model

- the standard model is the most successful scientific theory ever

EM, weak, strong interactions:
all accurately predicted



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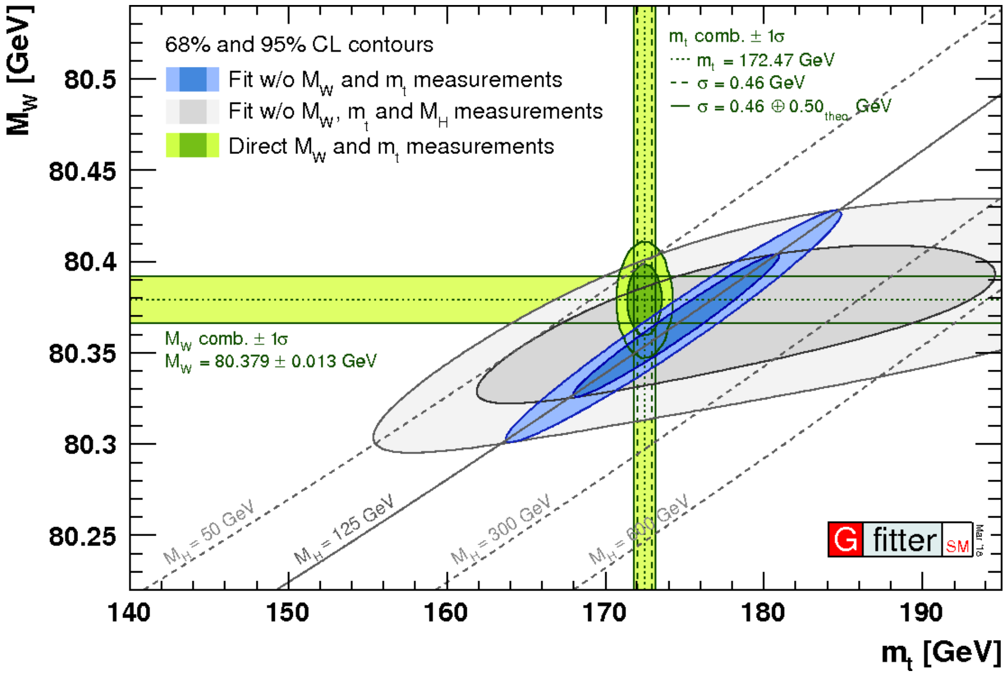
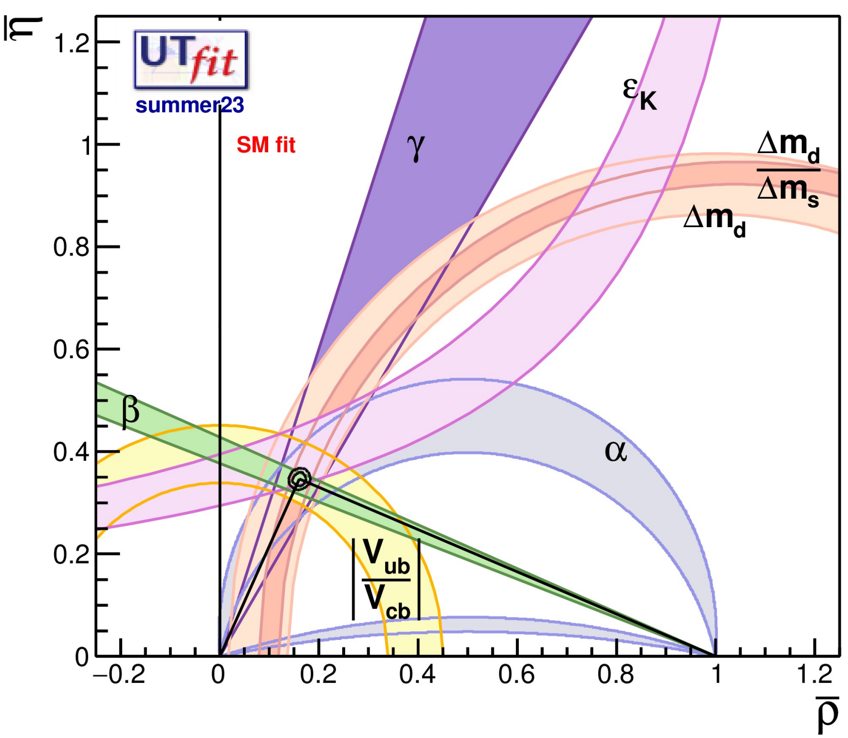


Eur.Phys.J.C 78 (2018) 8, 675

Very overconstrained but still
internally consistent

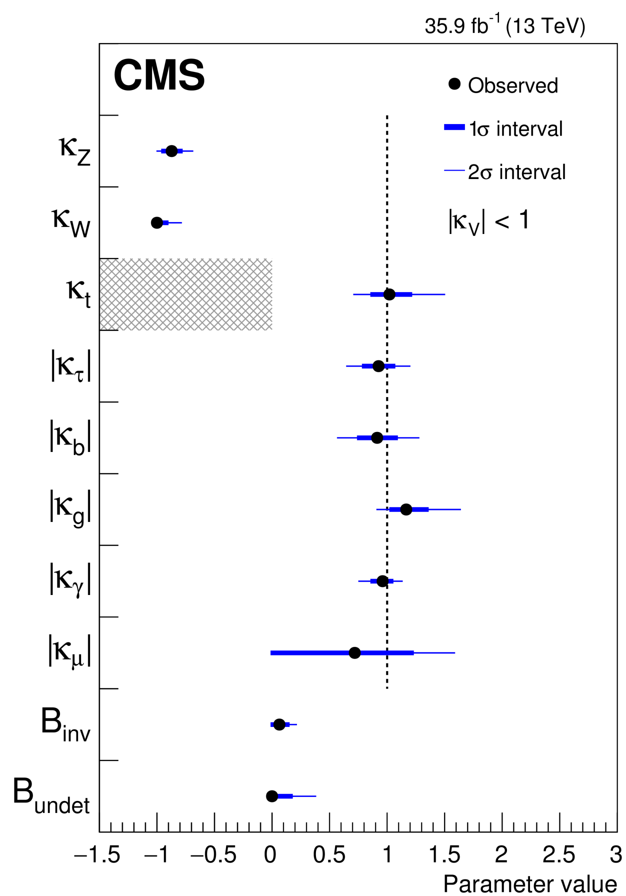
Rend.Lincei Sci.Fis.Nat. 34 (2023) 37-57



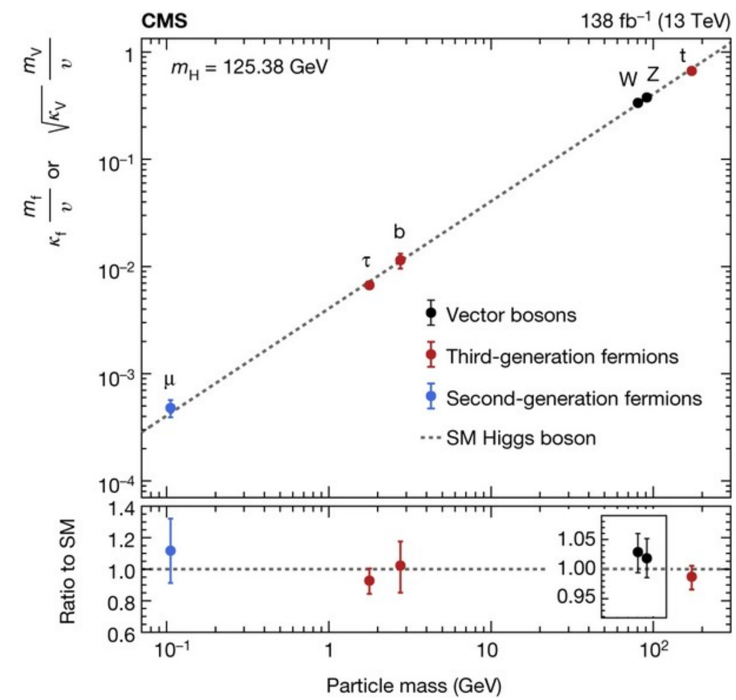
The Standard Model

- the standard model is the most successful scientific theory ever

Prediction, discovery and confirmation of a fundamental scalar (the Higgs boson) arising from the BEH mechanism with Yukawa couplings to fermions



EPJC 79 (2019) 421



Nature volume 607, pages 60–68 (2022)

Beyond the Standard Model?

- experimental evidence for BSM physics
  - gravity
  - neutrino oscillations
  - matter-antimatter asymmetry
  - dark matter *
  - ...

  * all from indirect observations, some with model dependence

- theoretical indications for BSM physics
  - hierarchy problem *
  - why? number of families, number of parameters, gauge group structure *
  - strong CP problem *
  - stability of the EW vacuum *
  - ...

  * severity of the problem depends on the theorist

Beyond the Standard Model?

- experimental anomalies
  - number of anomalies in B-physics
  - number of high-energy anomalies at CMS/ATLAS
  - anomalous magnetic moment muon ("g-2")
  - W mass
  - DAMA/LIBRA dark matter
  - reactor and Gallium anomalies
  - the Beryllium anomaly
  - ...
- all of the above anomalies need confirmation or are even contested
- most of these are actively being researched further

- also many anomalies in astrophysics / cosmology
  - research often links to extensions of the Standard Model

From SM to BSM

- research cycle
  - take the SM as the baseline model
  - add BSM ingredients to solve one or more problems
  - make predictions in new BSM phase space
  - test experimentally with existing data, new data, or new experiments
  - rince and repeat

- potential BSM ingredients
  - new particles
  - new interactions: portals, mixing,...
  - new signatures
- potential observables
  - high-mass / low-mass resonances
  - cross section or branching ratio deviations
  - shape deviations / interference
  - EFT tests

From SM to BSM

- where to go beyond the SM?
  - high energies – limited by colliders' center of mass energies
    - new colored particles
    - new electroweak gauge boson partners
    - new fermions, eg. 4^{th} generation, heavy neutrinos
    - new Higgs bosons
    - ...
  - rare processes – limited by luminosity and data-taking capabilities
    - low-mass resonances with large background
    - small couplings
    - Higgs sector
    - rare decays
    - ...
  - unusual processes – limited by detectors and our ingenuity
    - invisible signatures
    - long-lived particles
    - unusual charges
    - ...
  - and any combination of the above

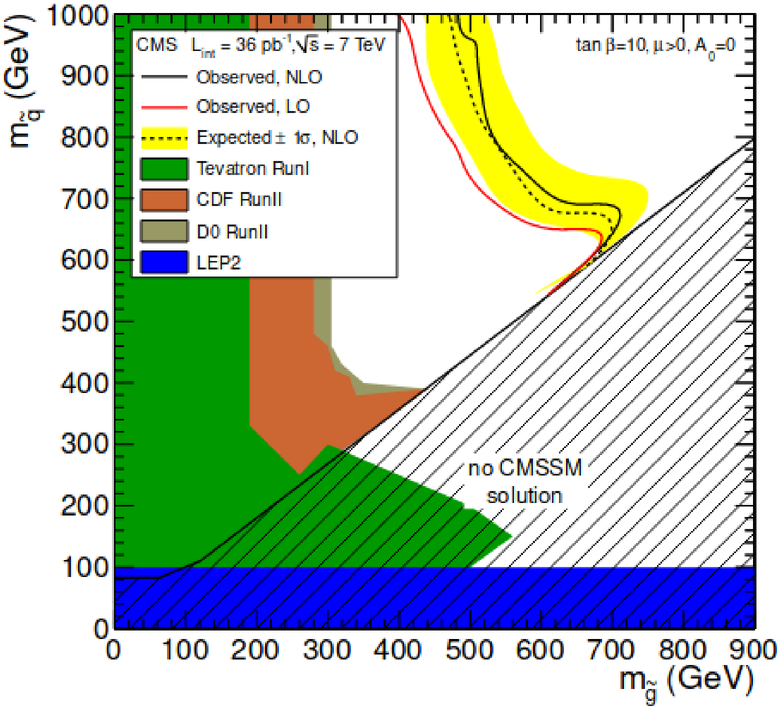
Top-down versus bottom-up

- before LHC (LEP, Tevatron), we mostly worked top-down
  - start from a theoretical principle to address SM problems
  - (mostly) fully consistent BSM models
  - huge parameter space
  - Higgs fate not known yet

- searches were often narrow tests of model specifics
  - hard to re-interpret in other contexts

- examples:
  - supersymmetry
  - technicolor
  - little Higgs
  - extra dimensions

JHEP 08 (2011) 155



Top-down versus bottom-up

- transition to simplified models in 2010 (susy) and 2015 (dark matter)
  - limit to the essence of the BSM aspect of interest
  - focus on experimental signatures
  - easier to re-interpret
  - actually expands the phase space

Simplified Models for LHC New Physics Searches #1
LHC New Physics Working Group • Daniele Alves (SLAC) et al. (May, 2011)
Published in: *J.Phys.G* 39 (2012) 105005 • e-Print: 1105.2838 [hep-ph]
pdf links DOI cite claim reference search 870 citations

Dark Matter benchmark models for early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum #1
Daniele Abercrombie (MIT), Nural Akchurin (Texas Tech.), Ece Akilli (Geneva U.), Juan Alcaraz Maestre (Madrid, CIEMAT), Brandon Allen (MIT) et al. (Jul 3, 2015)
Published in: *Phys.Dark Univ.* 27 (2020) 100371 • e-Print: 1507.00966 [hep-ex]
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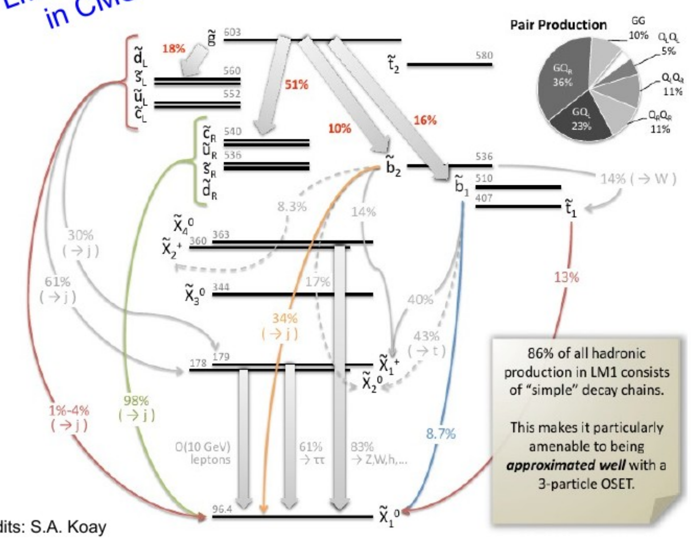
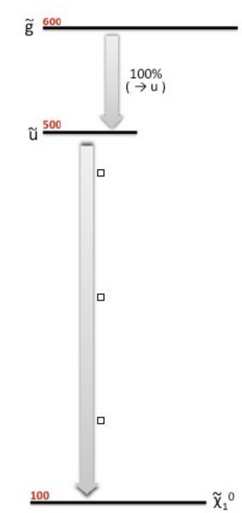
sparticle spectrum LM1 benchmark in CMSSM



credits: S.A. Koay

sparticle spectrum yielding equivalent hadronic observables

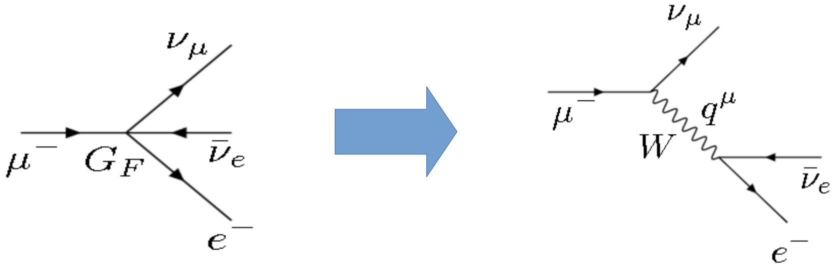


Top-down versus bottom-up

- nowadays strong emphasis on Effective Field Theory (EFT)
  - parametrize our ignorance of the full theory at high energies in "effective" low-energy "operators"

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j + \cdots$$

  - these operators are non-renormalizable, so they cannot be Lagrangian terms in a fully consistent renormalizable theory that works at all energies
  - example: the non-renormalizable Fermi theory with 4-fermion vertices could describe observations because the W mass was at that time still a very high energy scale



- EFT appeal
  - systematically explore how BSM can contribute at low energies

    1 at dim. 5 (L violating) , 59 at dim. 6 (assuming gauge invariance and B and L conservation), etc.
  - empower SM measurements as tests for BSM
  - combine across diversity of analyses

Top-down versus bottom-up

- even truly model-independent sensitivity

High Energy Physics - Experiment

[Submitted on 8 Mar 2023 (v1), last revised 21 Sep 2023 (this version, v2)]

A search for new physics in central exclusive production using the missing mass technique with the CMS detector and the CMS-TOTEM precision proton spectrometer

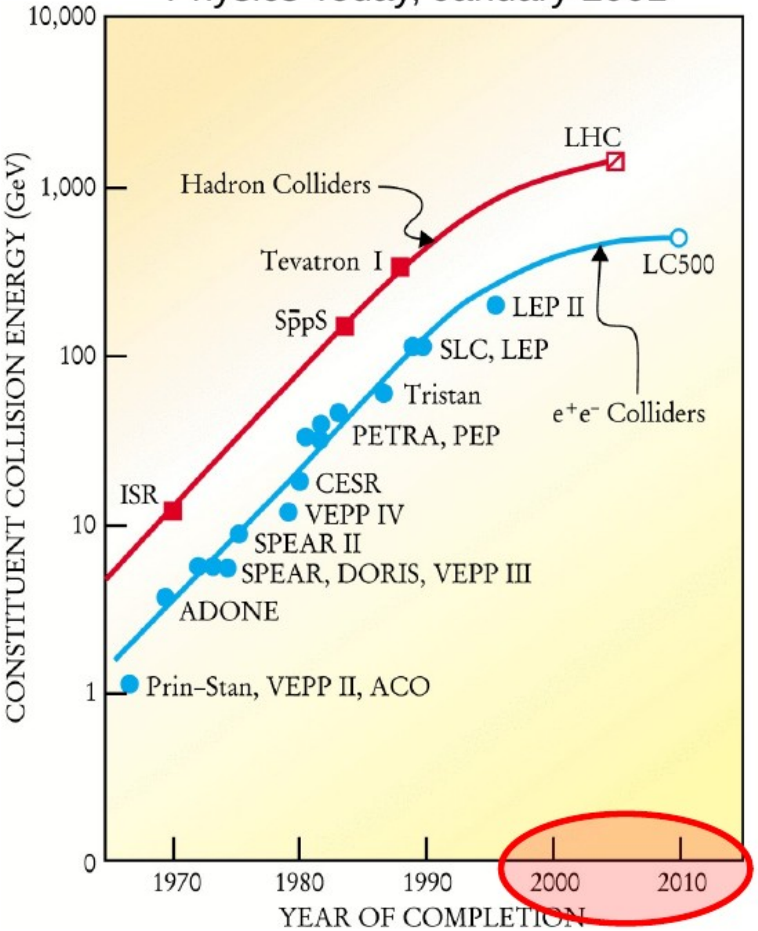
CMS Collaboration, TOTEM Collaboration

A generic search is presented for the associated production of a Z boson or a photon with an additional unspecified massive particle X, pp $\rightarrow$ pp + Z/γ + X, in proton-tagged events from proton-proton collisions at $\sqrt{s}$ = 13 TeV, recorded in 2017 with the CMS detector and the CMS-TOTEM precision proton spectrometer. The missing mass spectrum is analysed in the 600-1600 GeV range and a fit is performed to search for possible deviations from the background expectation. No significant excess in data with respect to the background predictions has been observed. Model-independent upper limits on the visible production cross section of pp $\rightarrow$ pp + Z/γ + X are set.

The energy frontier

- hadron colliders reach higher beam energies compared to lepton colliders
  - but the partons within the hadrons which collide have only a fraction of the beam energy
  - leptons carry the full beam energy! and annihilate without debris
- strong progress over several past decades in accelerator performance
  - slowed down in 21st century due to scale of the projects and no real revolution in the technology which is being applied

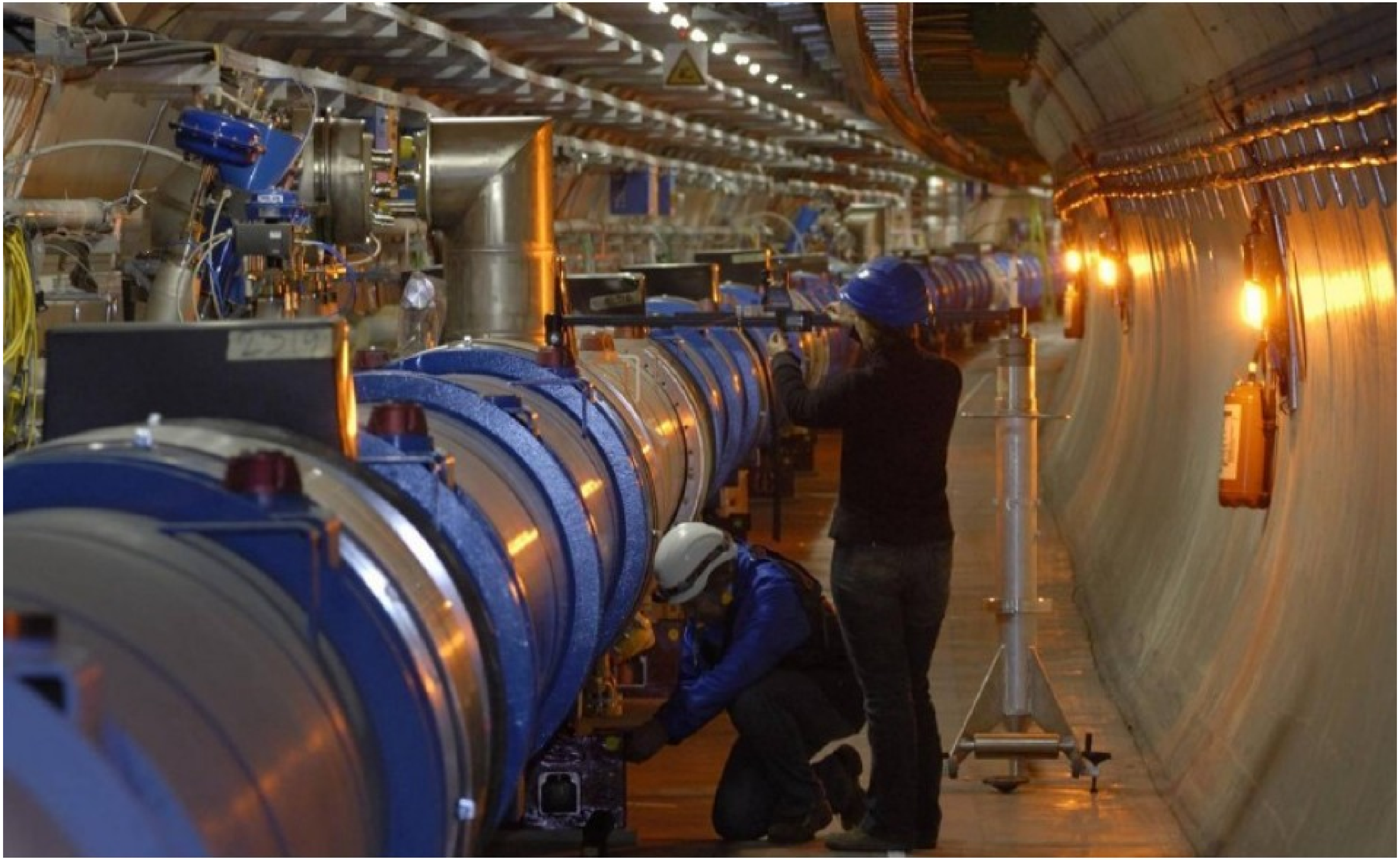
Physics Today, January 2001



reality has been even slower!

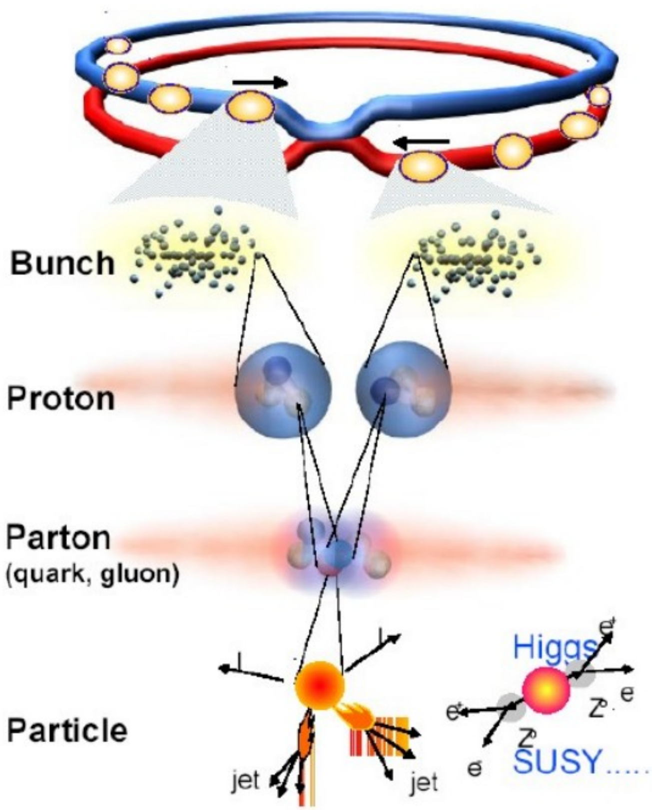
The energy frontier

- the LHC is our current most powerful machine



The energy frontier

- the LHC is our current most powerful machine
  - designed to discover the Higgs boson
  - and more: BSM, B-physics, QGP,...
  - first studies 1982 – approved 1994
    operational since 2009



Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^{7}-10^{9}

The energy frontier

- the LHC is our current most powerful machine
  - world-record energy
  - huge event rates

- rate = σ L

σ – cross-section

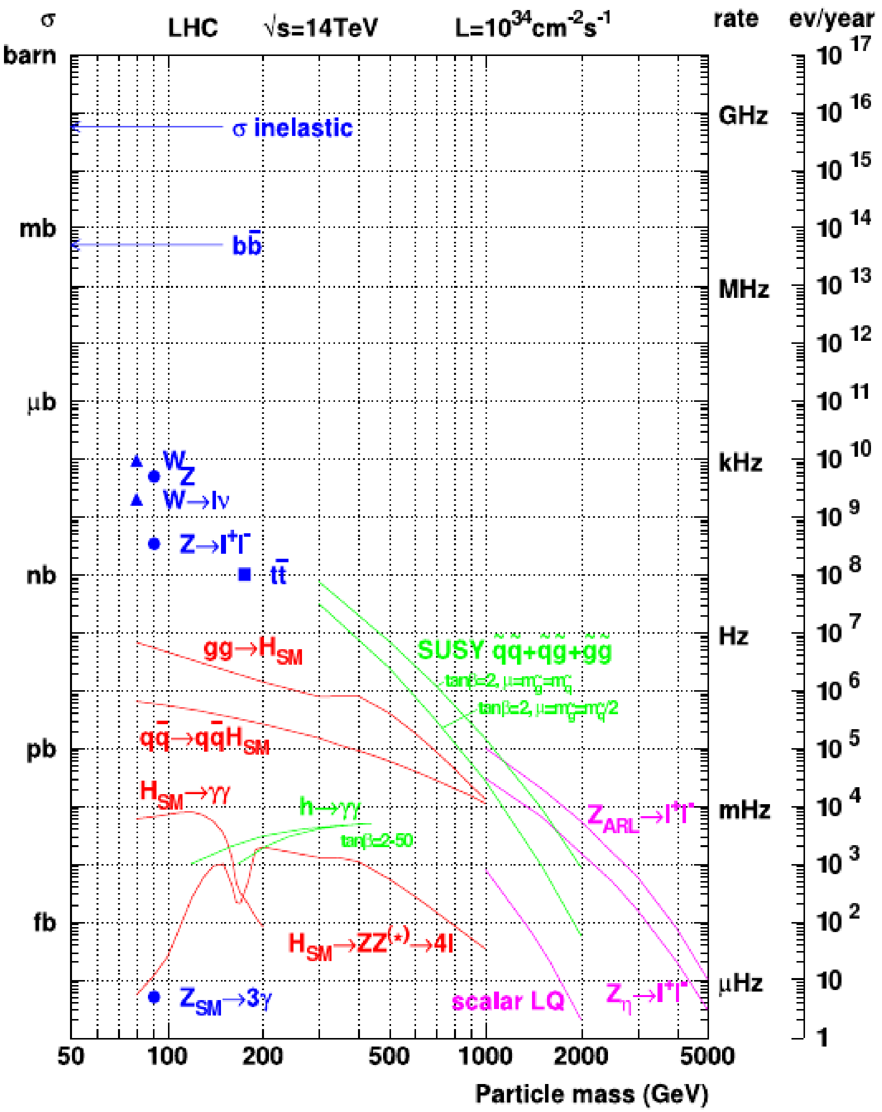
- units of barn = 10^{-24} cm^2
- probability for a physics interaction

L – luminosity

- measure of density of colliding particles

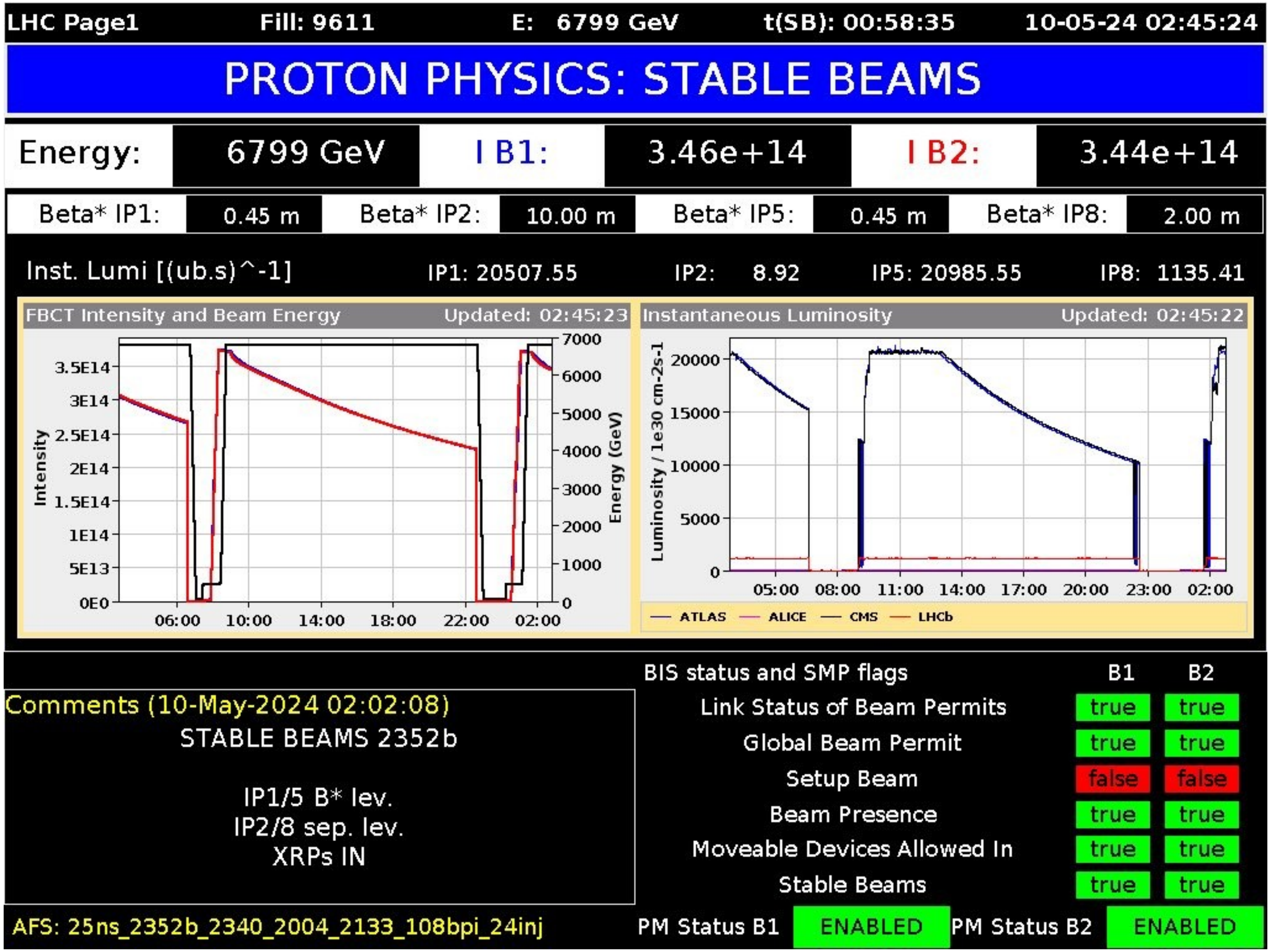
$$L = \frac{f N_1 N_2}{4 \pi \sigma_x \sigma_y}$$

- units of cm^{-2} s^{-1} or $barn^{-1}$ s^{-1}:

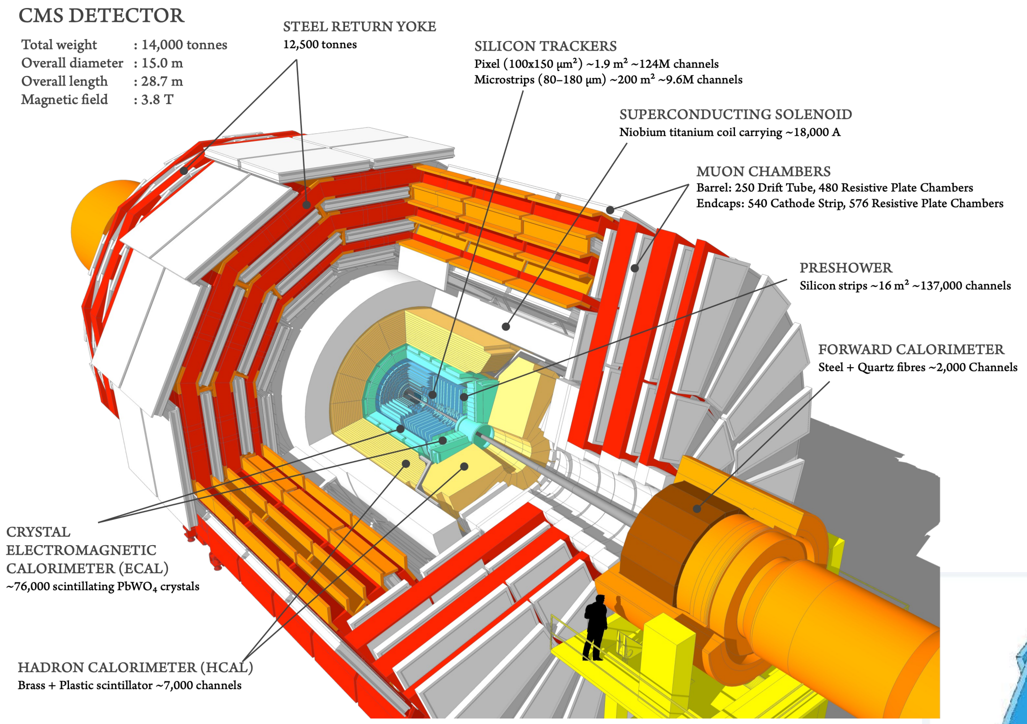


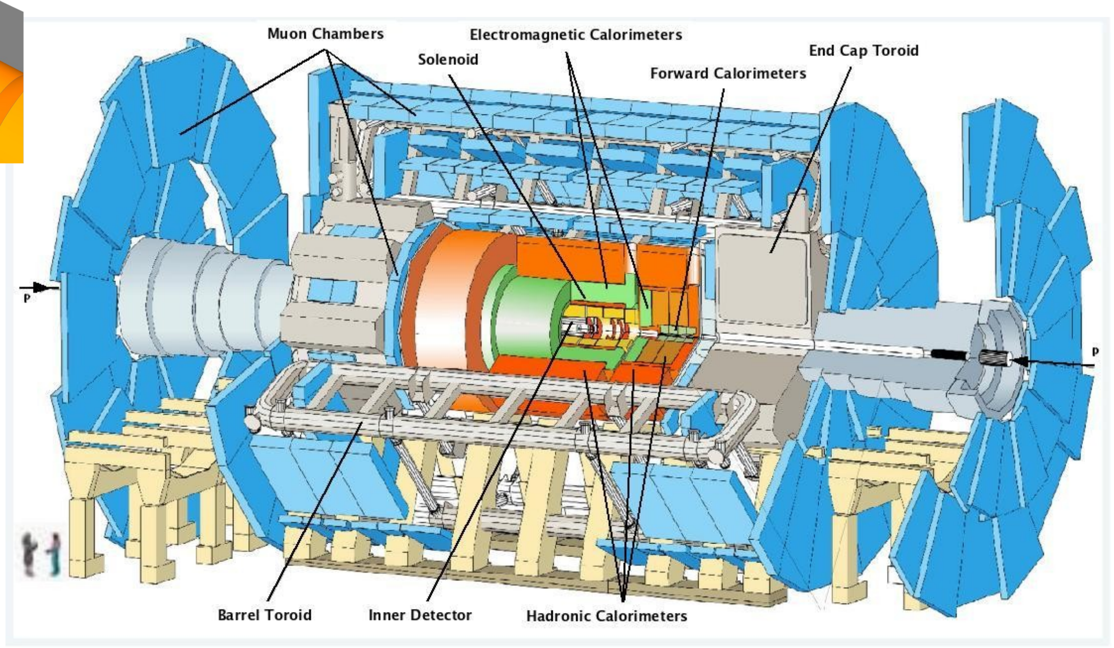
The energy frontier

- the LHC is our current most powerful machine
  - excellent performance!



Detectors at the energy frontier





How do we search for New Physics?

- number of signal events S in a selected event sample is estimated by subtracting the estimated background B from the total number of events N
  - S = N – B

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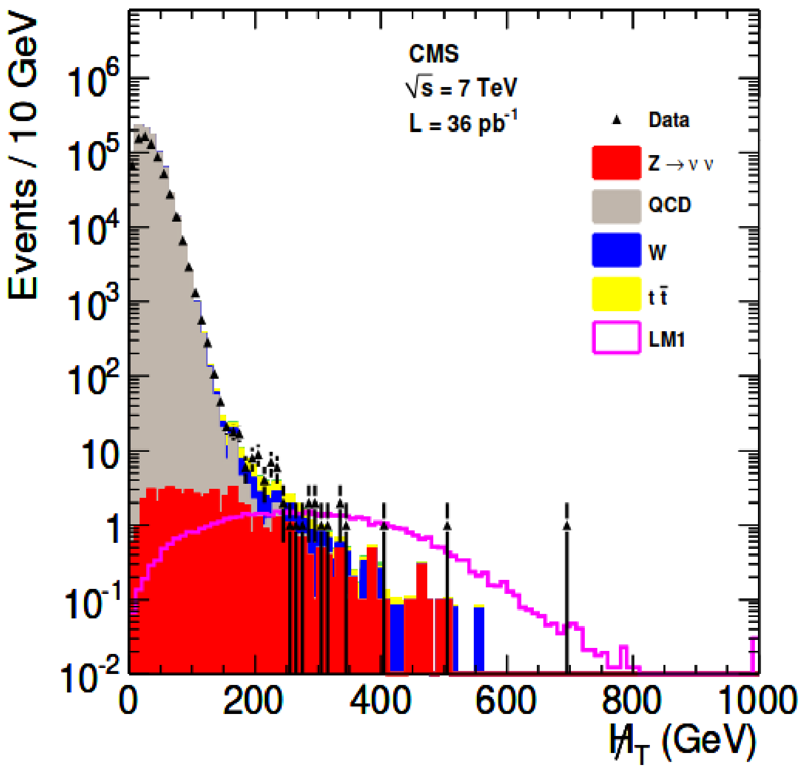

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- number of signal events S in a selected event sample is estimated by subtracting the estimated background B from the total number of events N
  - S = N – B
- statistical uncertainty in the signal estimate S = √N = √(S+B)
  - Poisson statistics
  - ignore systematic uncertainties for now
- statistical significance: S / √(S+B)

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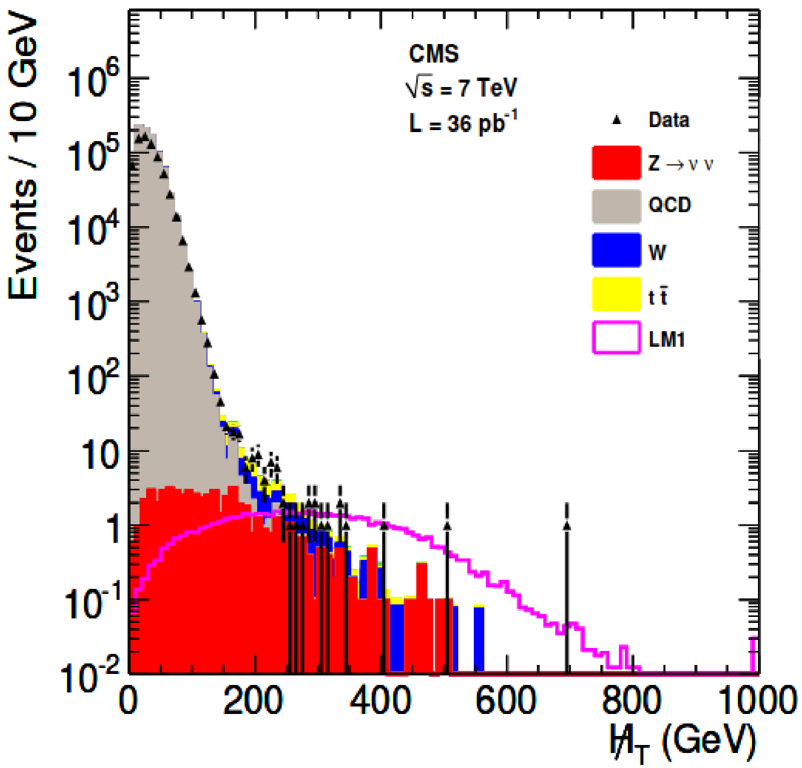

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- statistical significance: S / $\sqrt{(S+B)}$
- goal: maximize significance
  - by keeping signal events
  - while suppressing background

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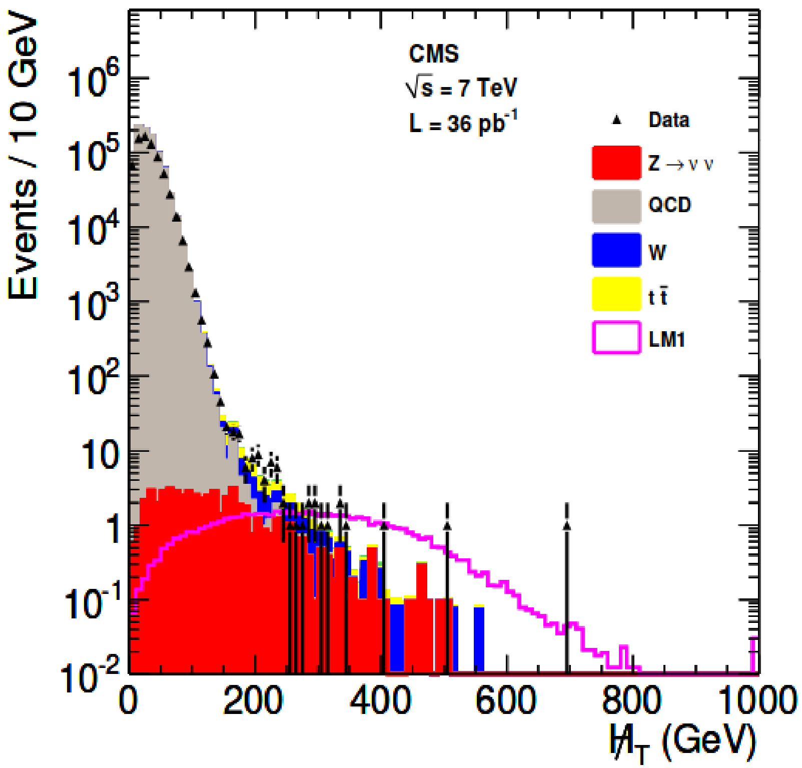
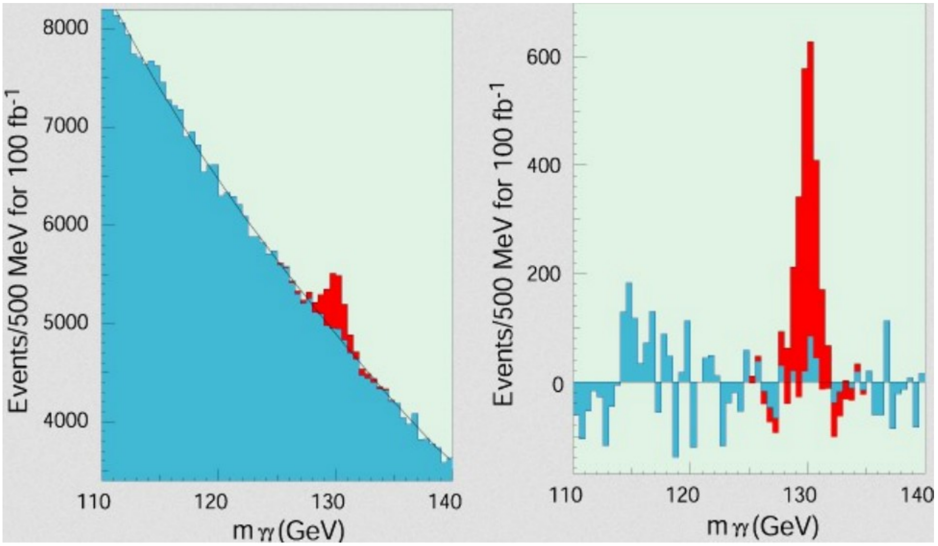


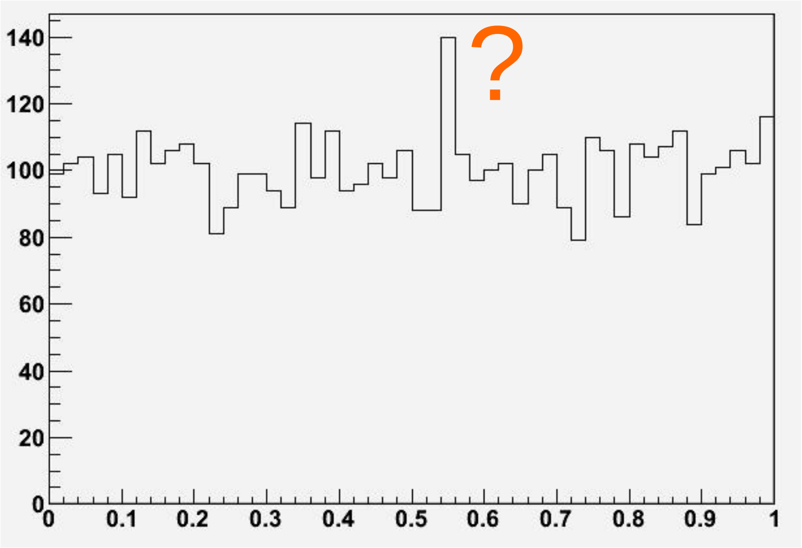
How do we search for New Physics?

- goal: maximize significance $S / \sqrt{(S+B)}$
  - by keeping signal events
  - while suppressing background
- simplest case: resonance peak on smooth background
  - fit background using sidebands
  - estimate background in signal region by extrapolating the fit
- more complex
  - counting experiments
  - shape fitting
  - unbinned fit
  - ...



How do we search for New Physics?

- discovery? be careful!
  - global versus local excess → the “look-elsewhere effect”
- when we search eg. a bump in a mass spectrum
  - we run hypothesis tests as a function of mass
  - the more bins we consider, the more we expect statistical fluctuations to show up!
- non-trivial interplay with resolution on the estimated quantity
  - typically this is estimated numerically with pseudo-experiments
- also: 100's of BSM searches at LHC…
- also also: overestimated systematic uncertainties may hide a real signal
- extrordinary claims require extraordinary evidence
  - human judgment stays indispensible



Content Lecture 1

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  - the standard model – from SM to BSM – Top-Down versus Bottom-Up
  - the energy frontier – LHC and detectors – how to search the data?
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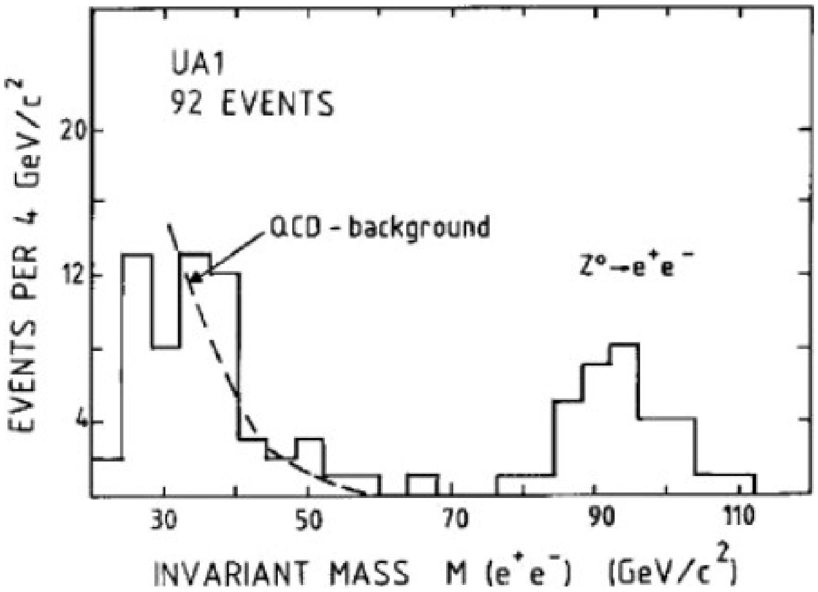
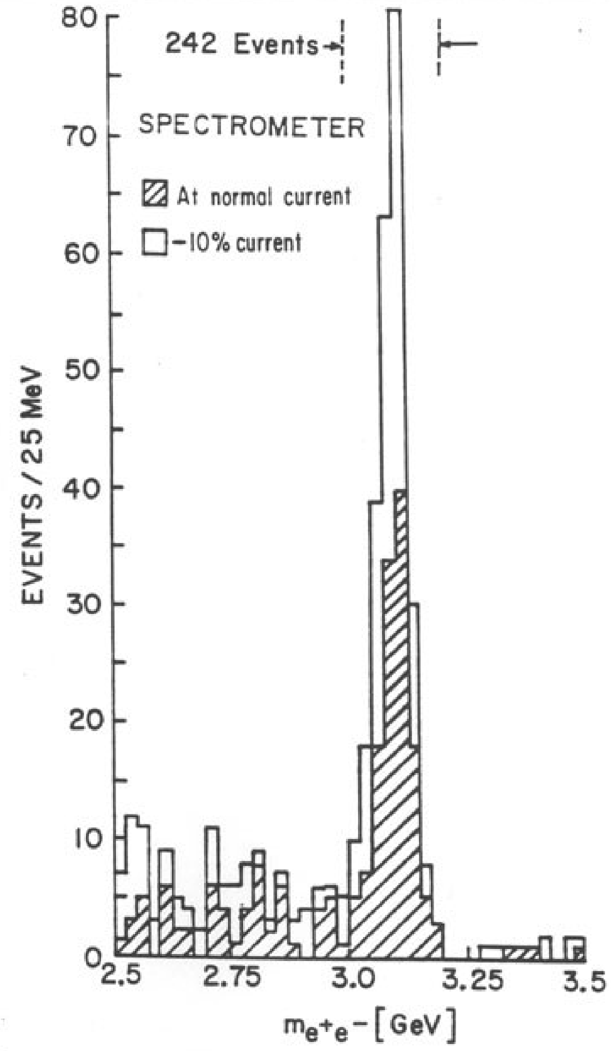
Dilepton searches

- dilepton searches are a historically winning strategy at high energies
- experimentally “easy” to identify and measure
- new particles pop up as peaks in the dilepton mass spectrum





Dilepton searches

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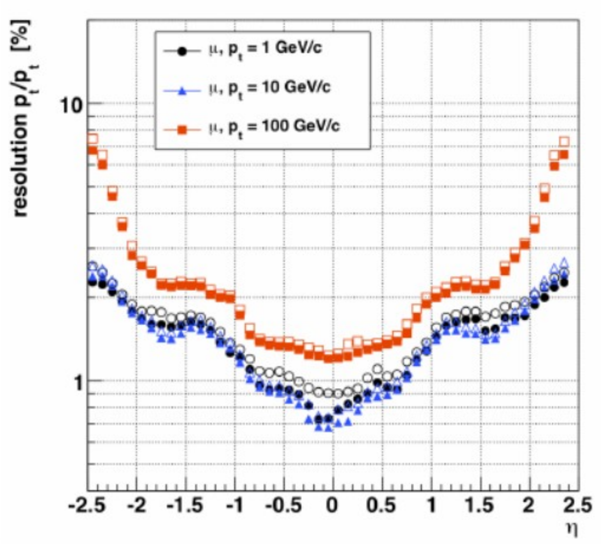
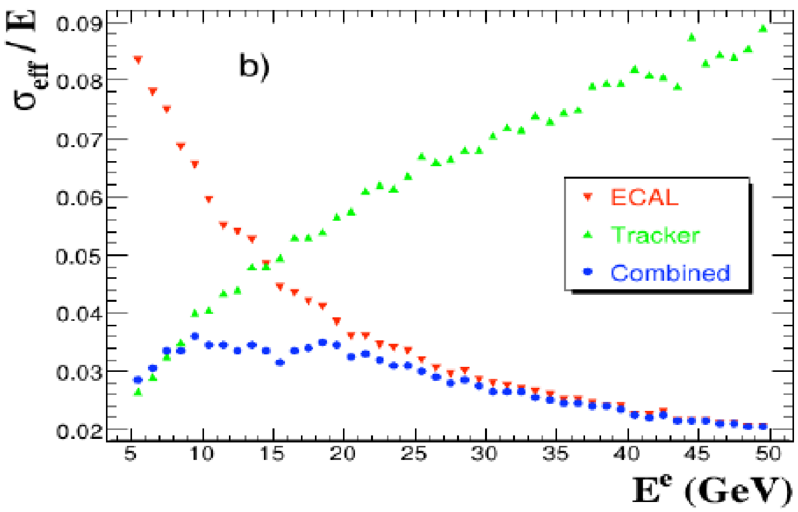
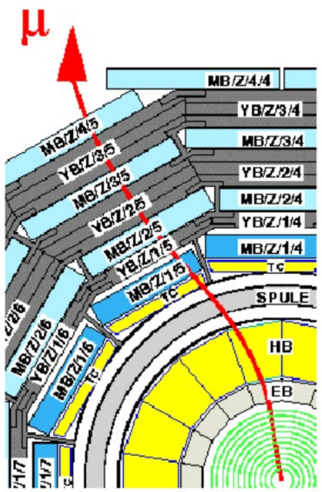
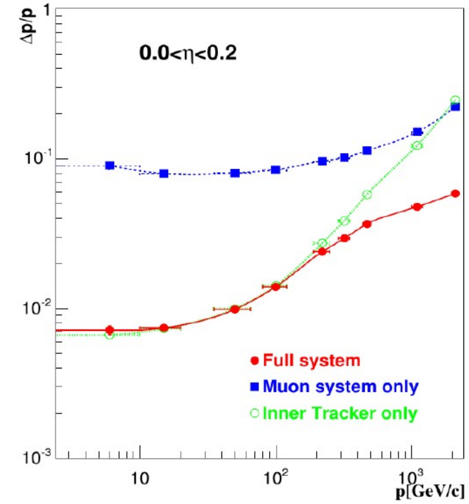
- modern detectors have excellent electron, muon and even tau measurement capabilities



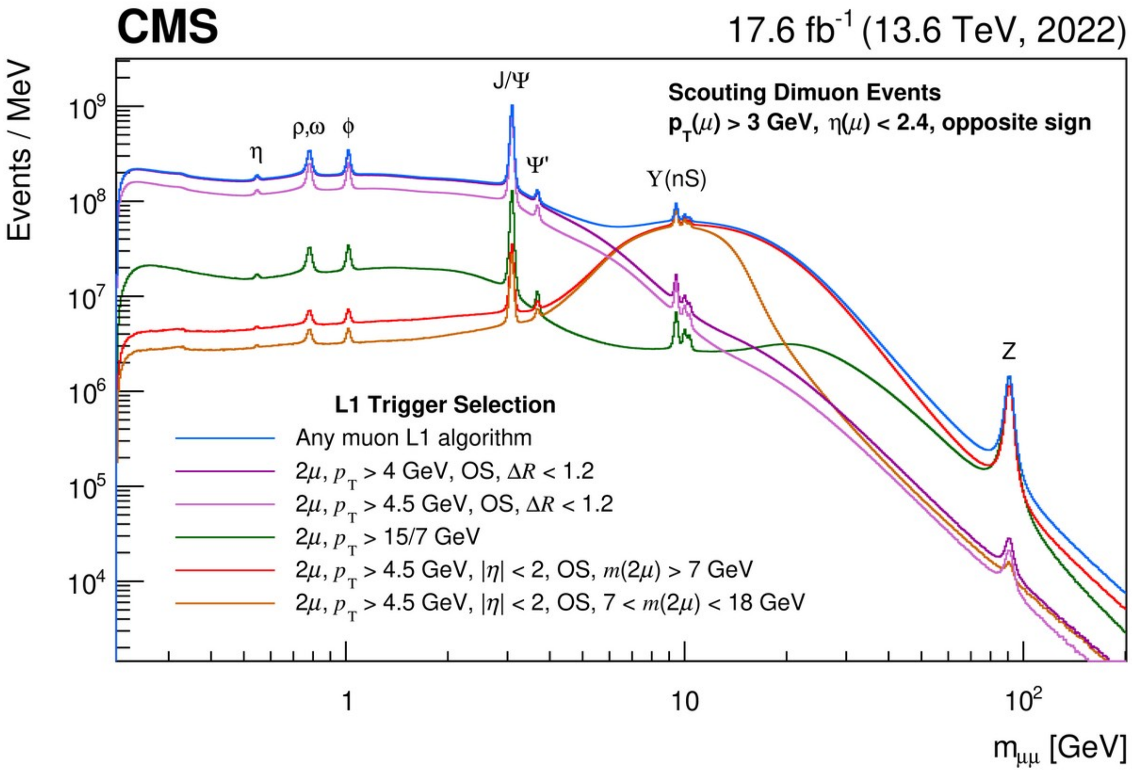






Dilepton searches

- dilepton searches are a historically winning strategy at high energies
- modern detectors have excellent electron, muon and even tau measurement capabilities
  - also for triggering the events



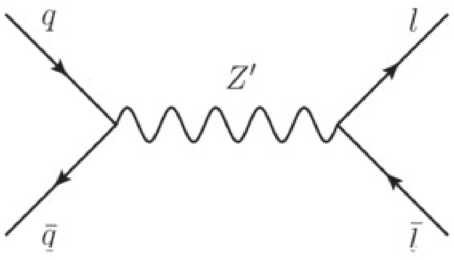
e-Print: 2403.16134 [hep-ex]

Dilepton searches

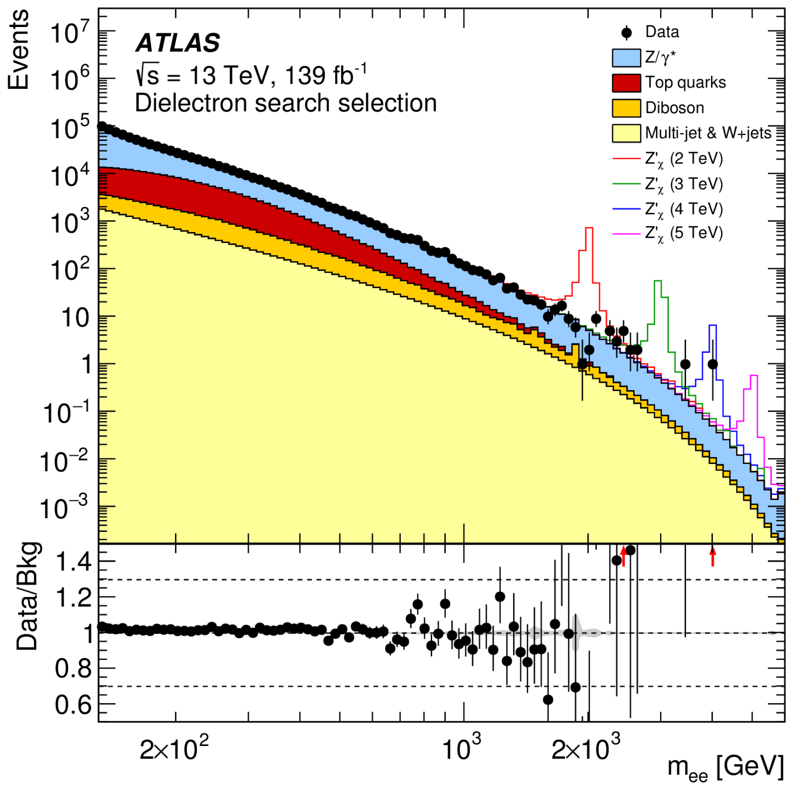
- so let's hunt for new resonances!
  - interpretations in many models

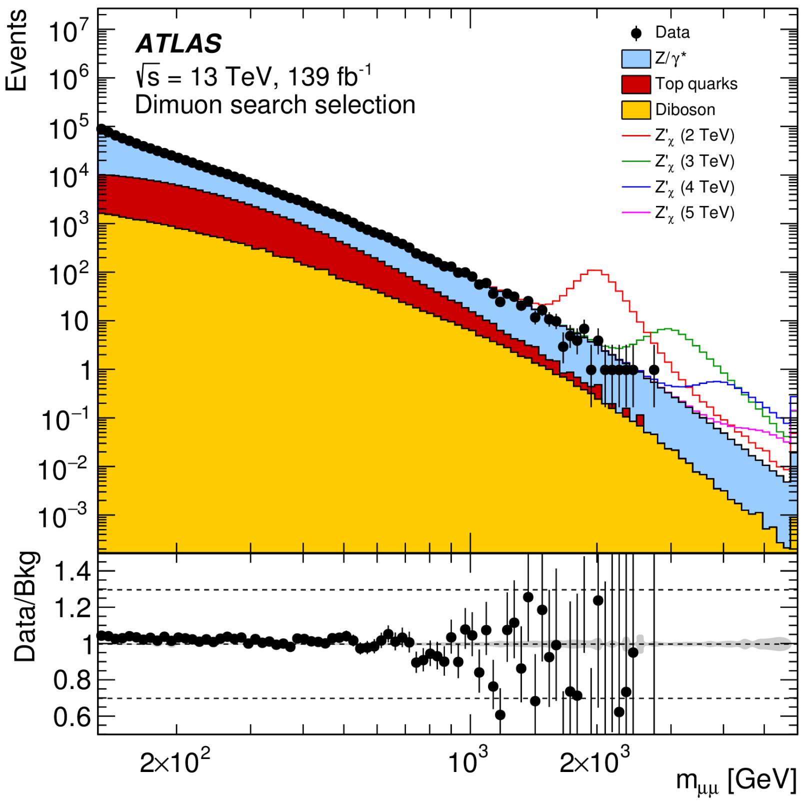
    think of it as a “heavy, narrow Z”
  - electrons and muons complementary

    due to resolution at high energies, backgrounds,...



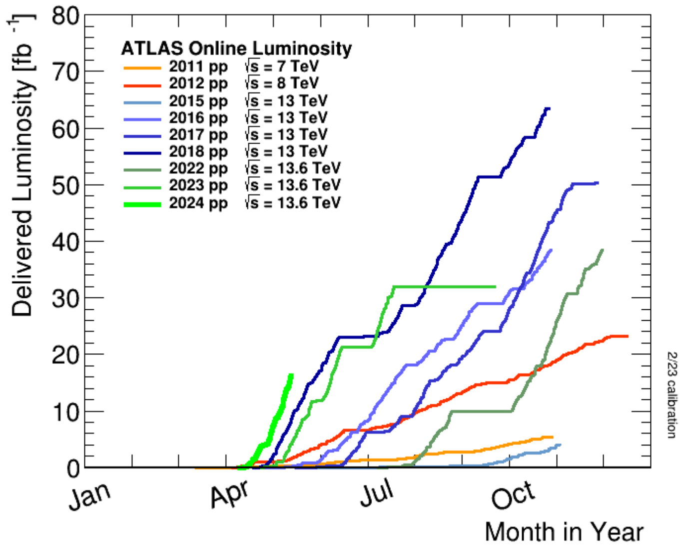
Phys.Lett.B 796 (2019) 68-87

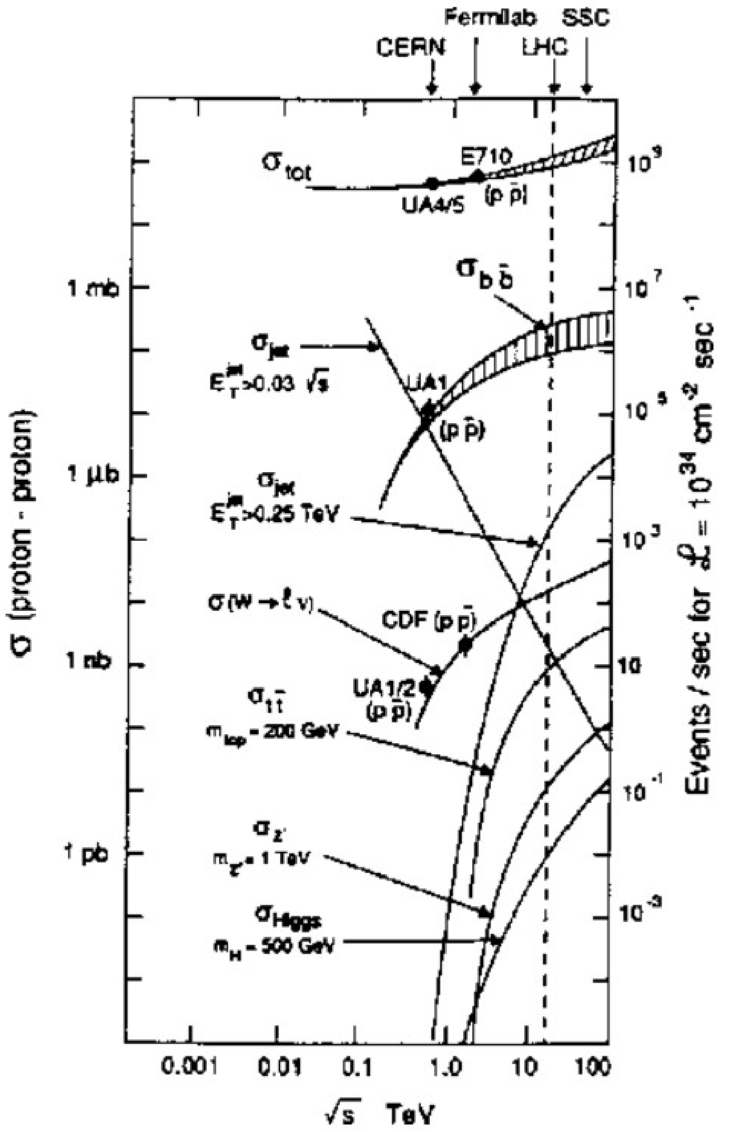




Dilepton searches

- so let's hunt for new resonances!
  - LHC c.o.m. energy is the driving ingredient
    - → 2010-2011: 7 TeV
    - → 2012: 8 TeV
    - → 2015-2018: 13 TeV
    - → 2022-now: 13.6TeV
  - luminosity determines how rare the physics is we can see





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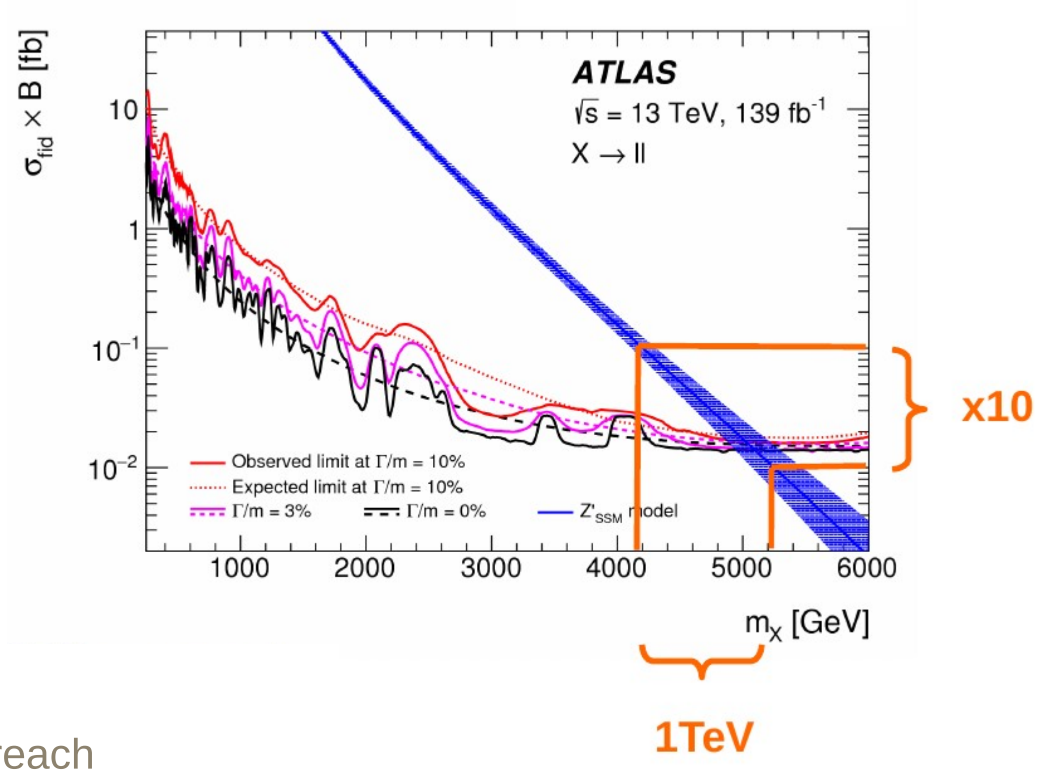
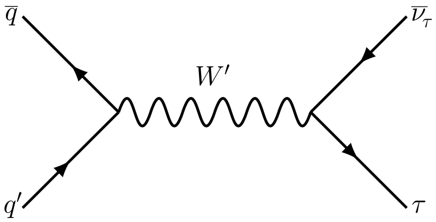
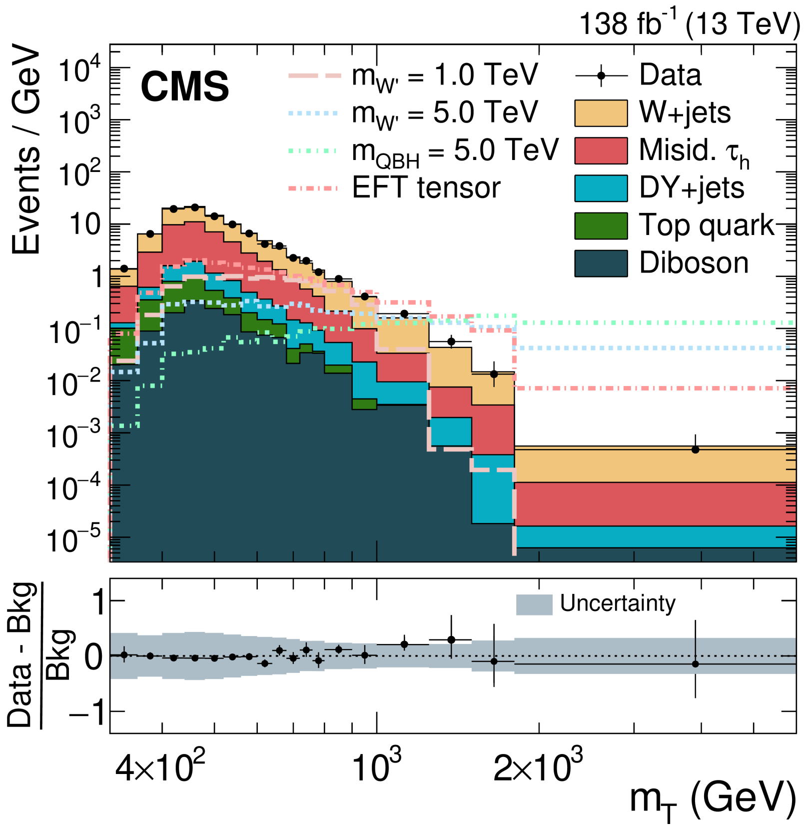


- more data with same energy?
  - factor 10 in luminosity → 1TeV more reach
  - if no hint yet… → no discovery anywhere soon

Dilepton searches

- we did the same with charged lepton + neutrino
  - recent example with taus
  - transverse mass instead of invariant mass



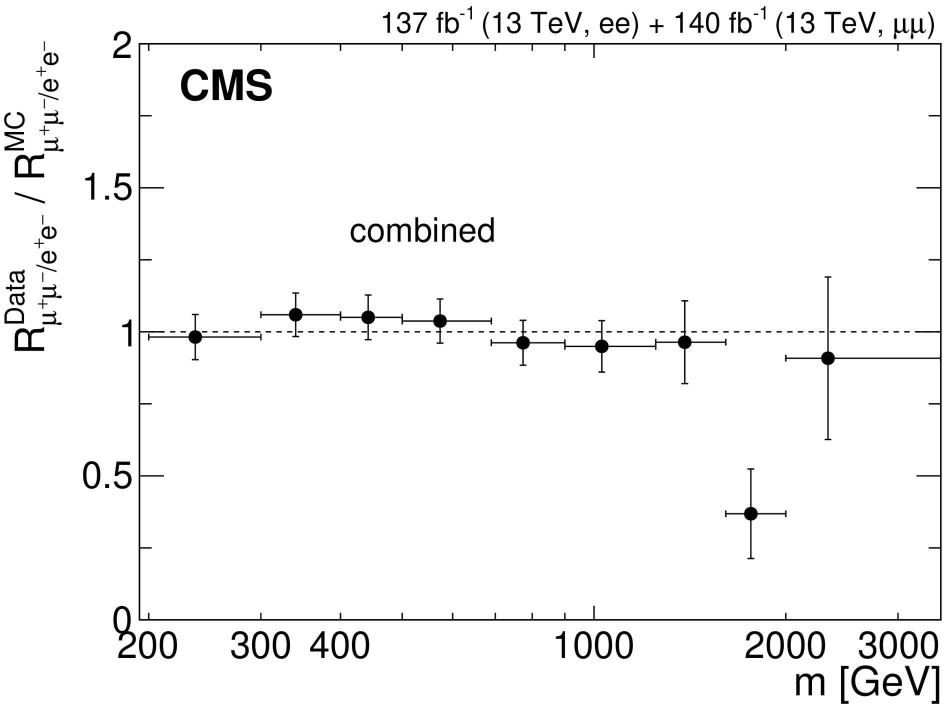


JHEP 09 (2023) 051

Dilepton searches

- what if we compare electrons to muons?
  - some important systematics cancel in the ratio → increased sensitivity
  - exciting...?

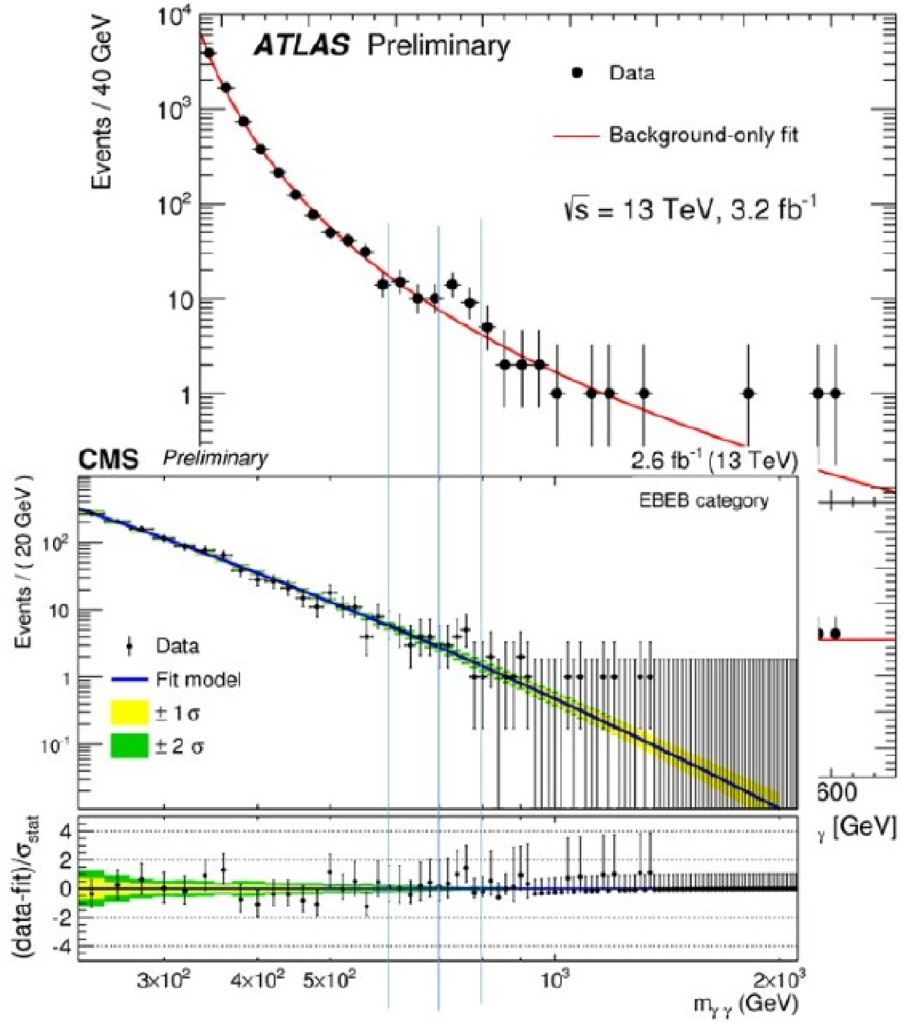
JHEP 07 (2021) 208



- it caught some attention because lepton universality may not hold for BSM at high energies
  - Yukawa-type couplings
  - leptoquarks
  - ...

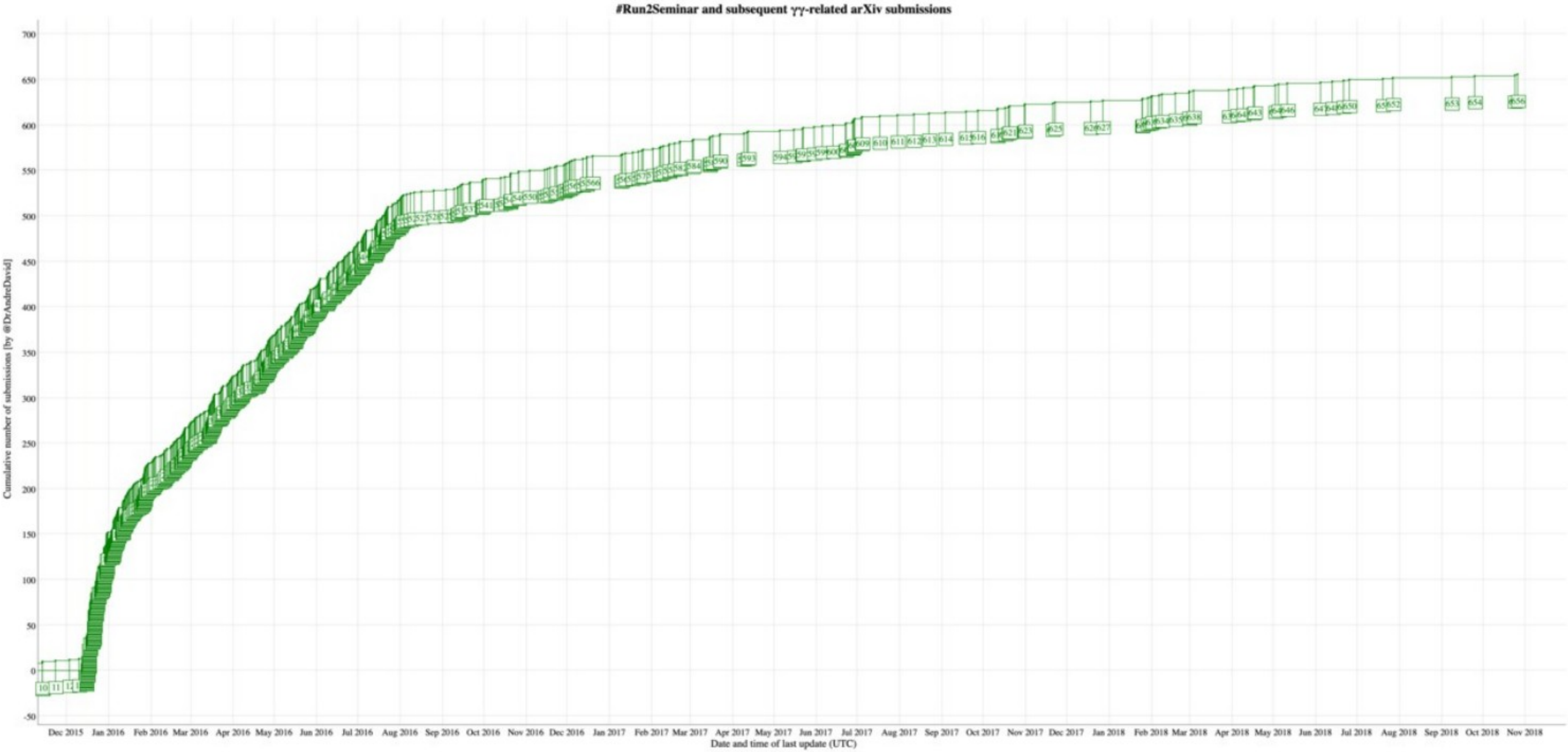
Diphoton searches

- diphotons was a discovery channel for the Higgs boson – what else?
  - Higgs-like bosons
  - axion-like particles
  - gravitons
  - …
- early 2016…



Diphoton searches

- diphotons was a discovery channel for the Higgs boson – what else?
- pheno response...



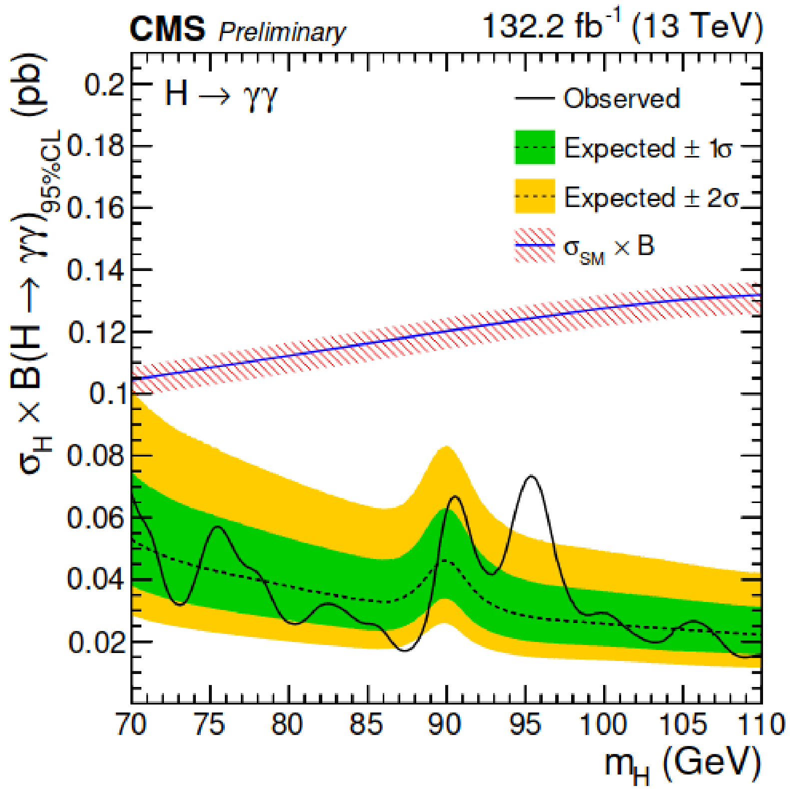
Diphoton searches

- diphotons was a discovery channel for the Higgs boson – what else?

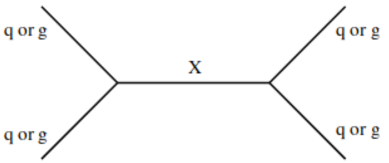
- at highest masses
  - sensitivity from high LHC energy explored
- at low masses
  - increasing datasets
  - improving analysis techniques
  - hunt for rare BSM hidden in background

- excess at 95GeV…?
  - not significant enough on its own

CMS PAS HIG-20-002



Dijet searches

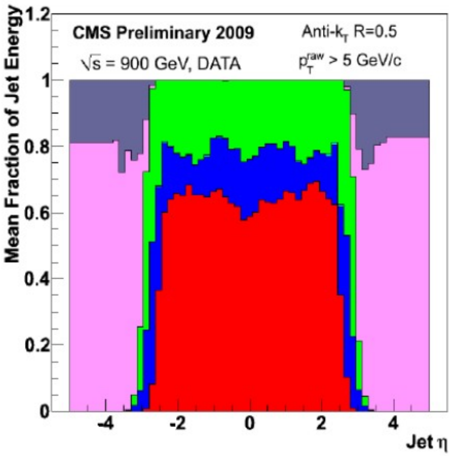


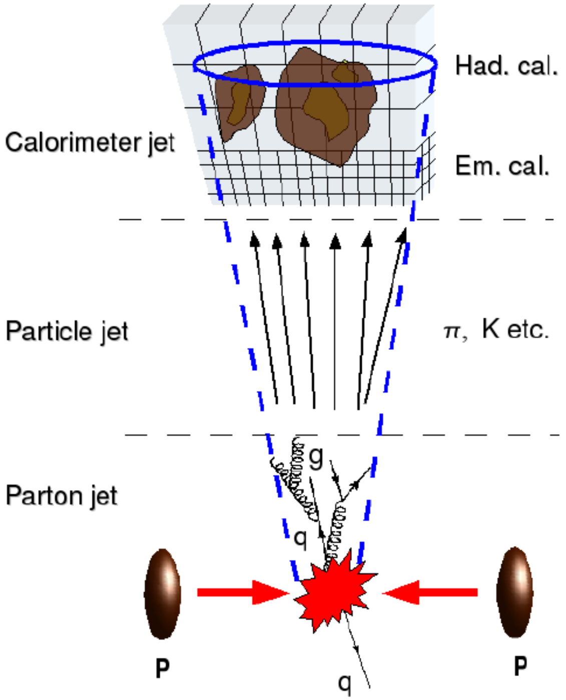
- the LHC is a hadron collider
  - hadronic cross sections are largest: large coupling, color factor
- quarks / gluons hadronize
  - sprays of hadrons, photons,… → jets
  - jet energy measurements are less accurate

neutral hadrons

photons

charged hadrons



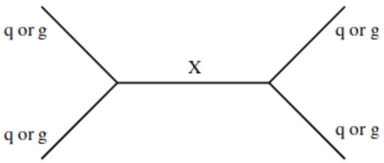


energy showers in the calorimeters

decays, interactions with material, magnetic field

out-of-cone partons underlying event

Dijet searches



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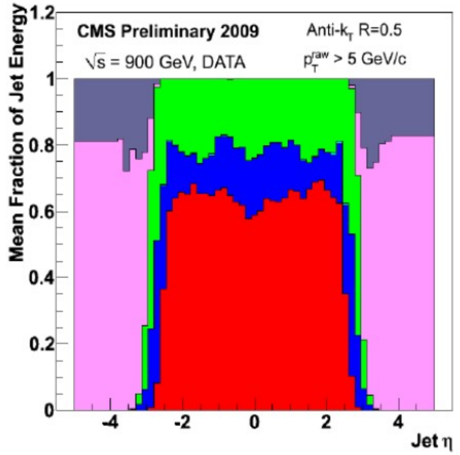
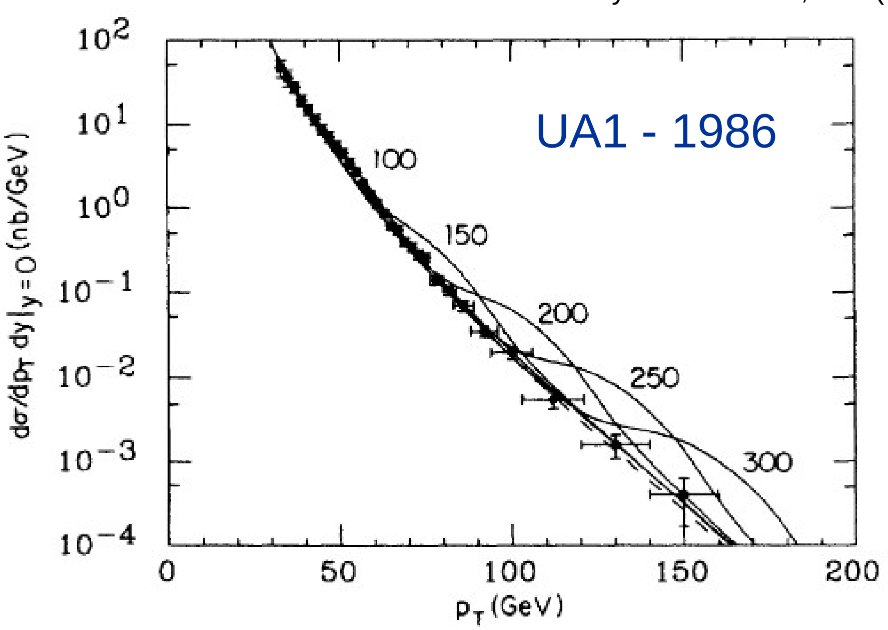


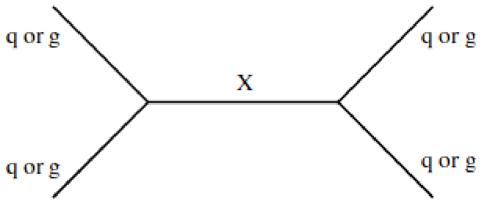
- dijet searches are another standard candle for BSM searches
  - reaches the most energetic collisions ever produced at colliders
  - many models predict production of pair of high-energy jets
  - if we can produce it, then it also decays back
- explored in many past experiments
  - UA1 / UA2 ; CDF / D0 ; LEP

Phys. Lett. B 172, 461 (1986)



Dijet searches

- up to 8TeV in invariant mass
  - backgrounds from strong force
    with extreme proton energy fraction
  - massive energy deposits
- many subtle experimental challenges
  - energy punch-through
  - noise backgrounds
  - tracking inefficiency
  - trigger efficiency
  - ...



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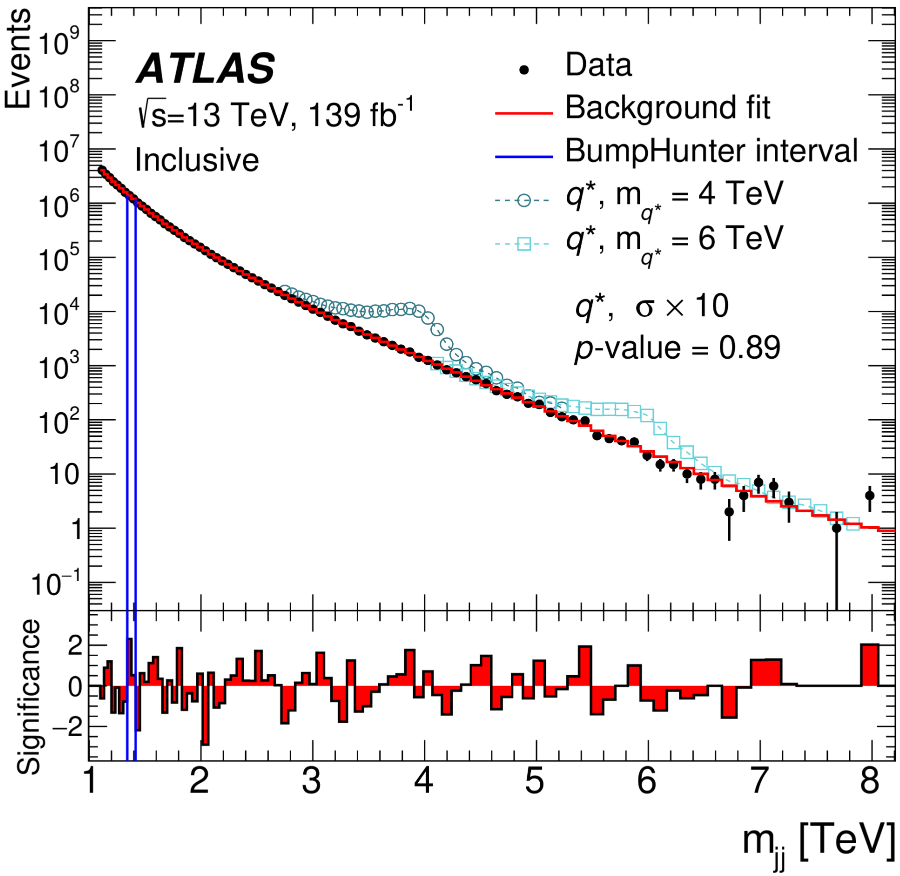
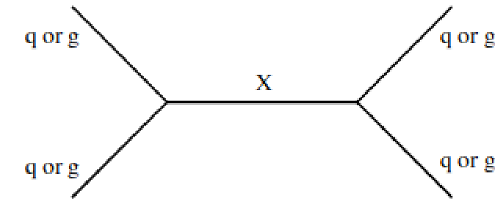
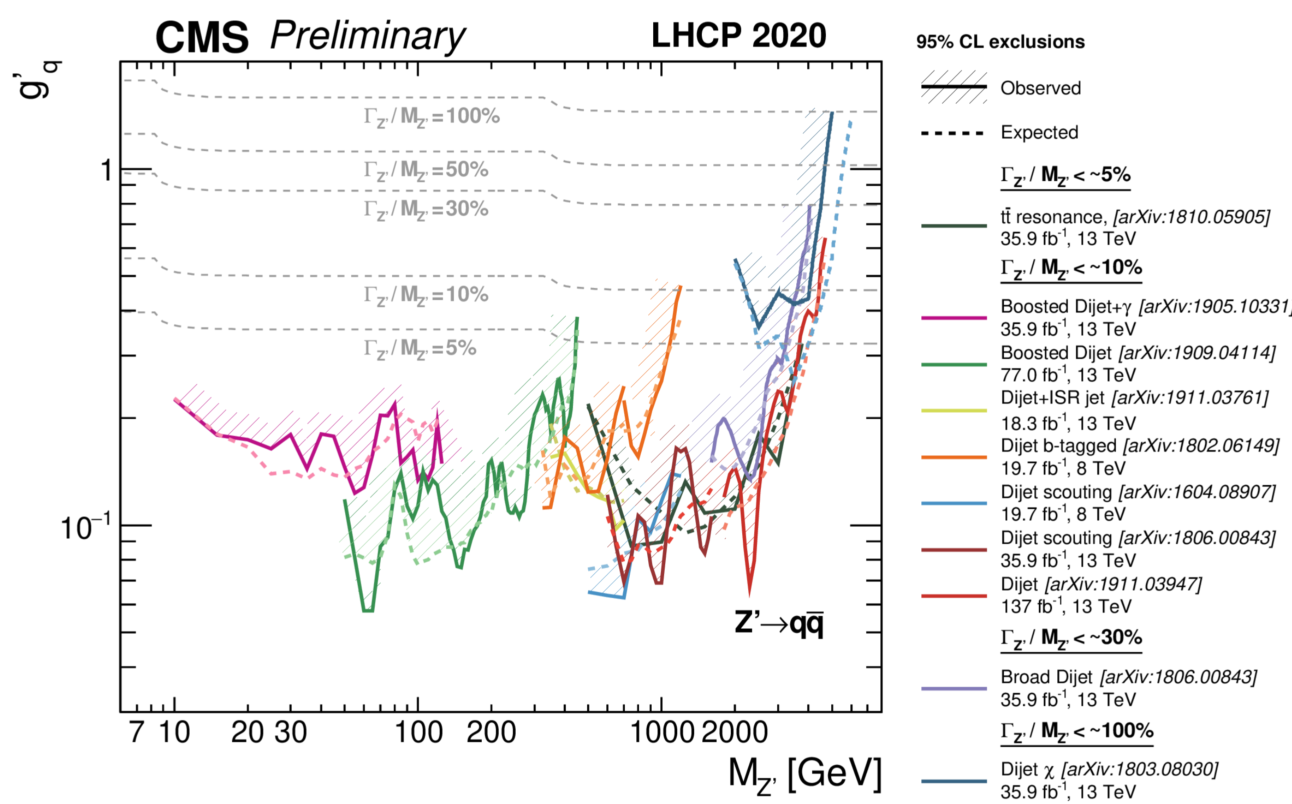


Dijet searches

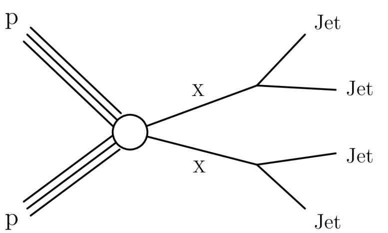


- also the lower masses remain interesting!
  - large backgrounds
  - but signal could be large as well

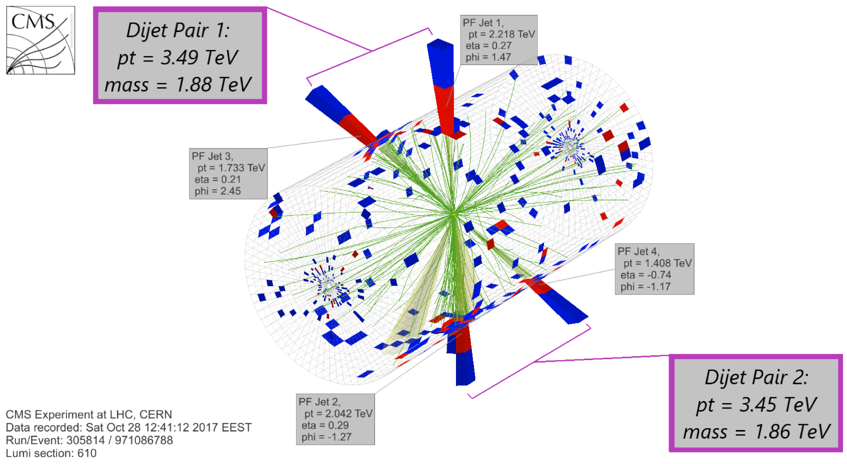
- strategies to reach lower energies
  - “scouting” triggers
  - jet + dijet
  - photon + dijet



Pairs of dijets?



- imagine an extra intermediate particle
  - tantalizing excess!



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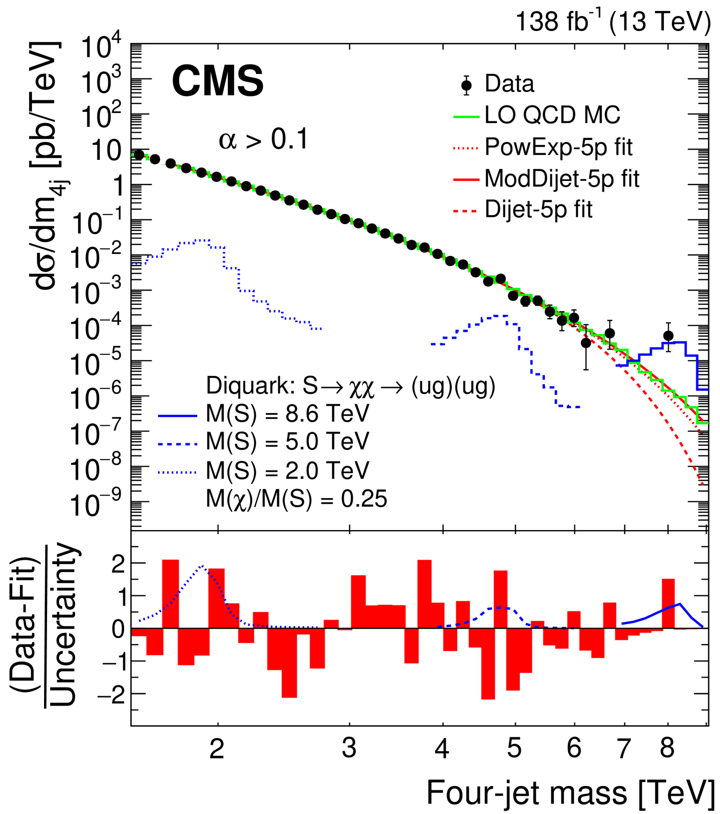

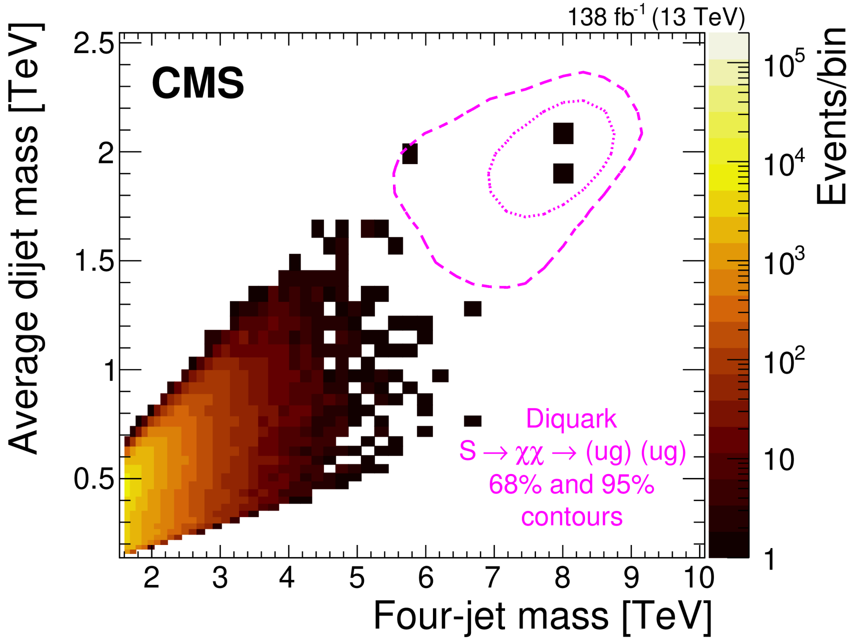

- also searches for trijets, t-channel, ...

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  - di-invisible → dark matter
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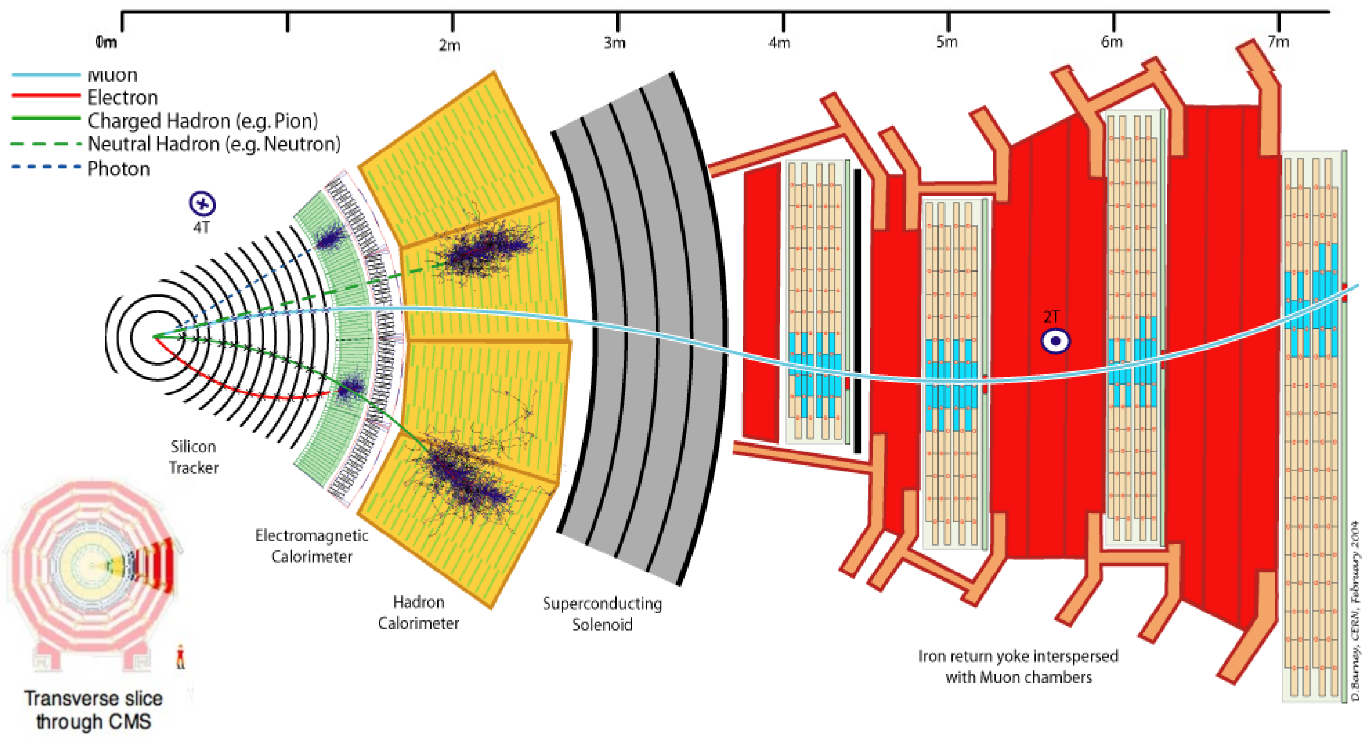
  - weak production: leptons+MET
  - RPV: multijets

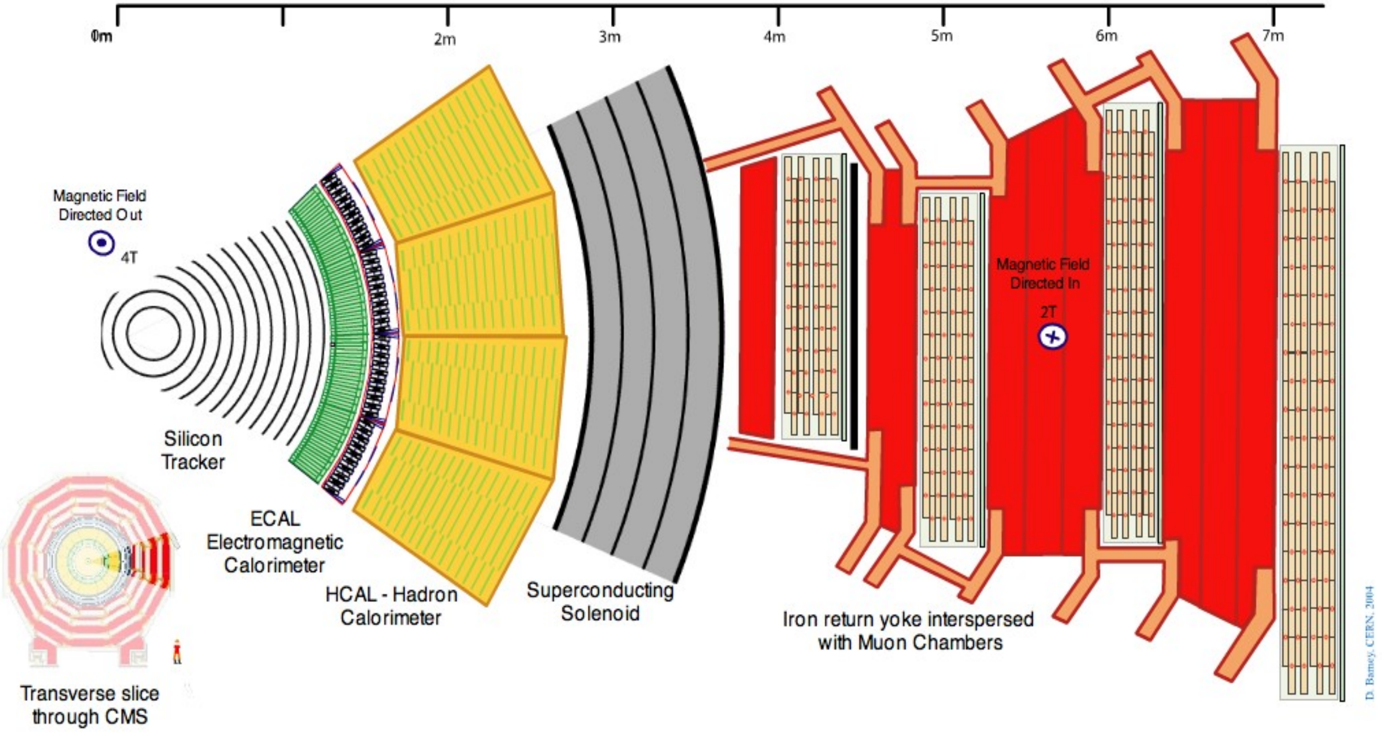
Dark Matter: pairs of ... nothing?

- it's possible we produce particles that don't interact in our detector
  - if very long-lived → dark matter candidate
  - instead of this…:



Dark Matter: pairs of ... nothing?

- it's possible we produce particles that don't interact in our detector
  - if very long-lived → dark matter candidate
  - we see this! "missing energy" (MET)



Dark Matter

- production at colliders can happen if
  - kinematically accessible
  - coupling to quarks/gluons
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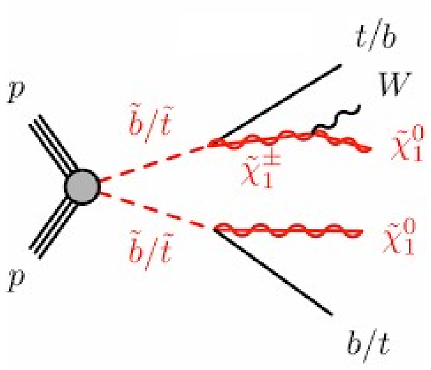
DM from cascade decays

- new particle production
  decay to DM+X
  - typically pair produced
- example: SUSY
  - with R parity always 2 LSP's yielding MET



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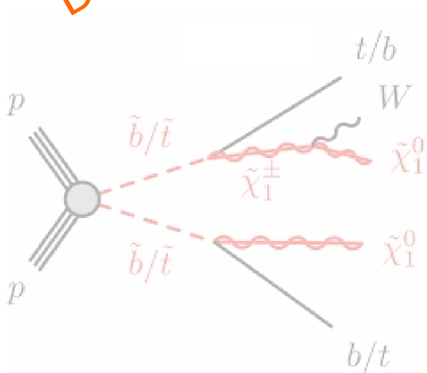
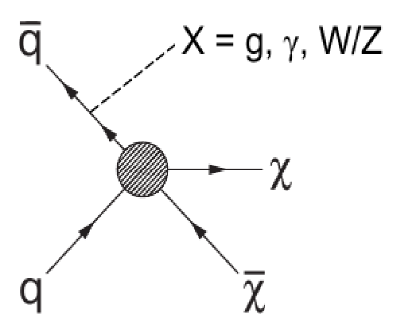
Discussed later



DM produced directly

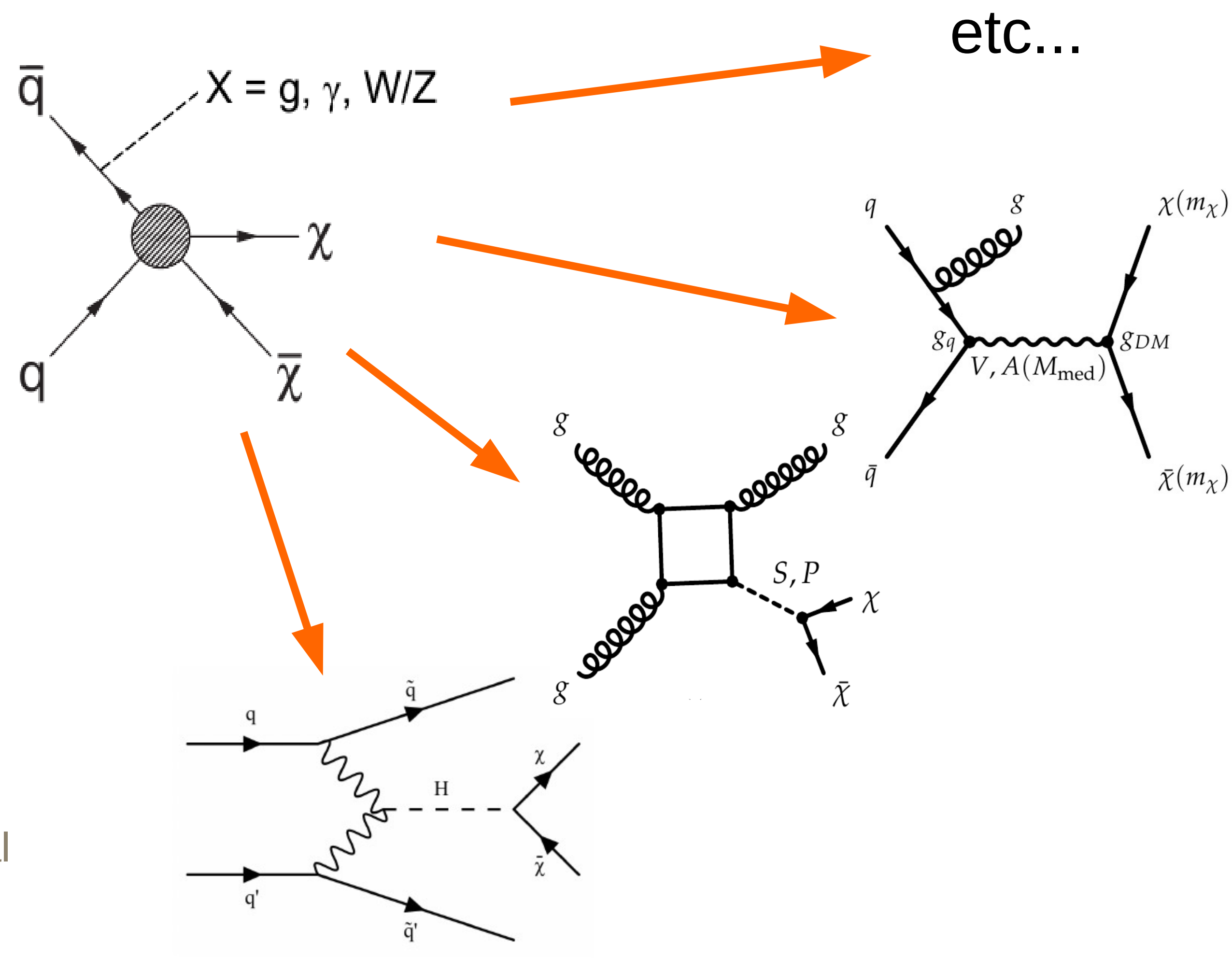
- direct DM pair production through mediator
- but back-to-back DM particles are invisible
  - ISR diagrams provide
    probe recoiling against DM pair



Direct DM searches

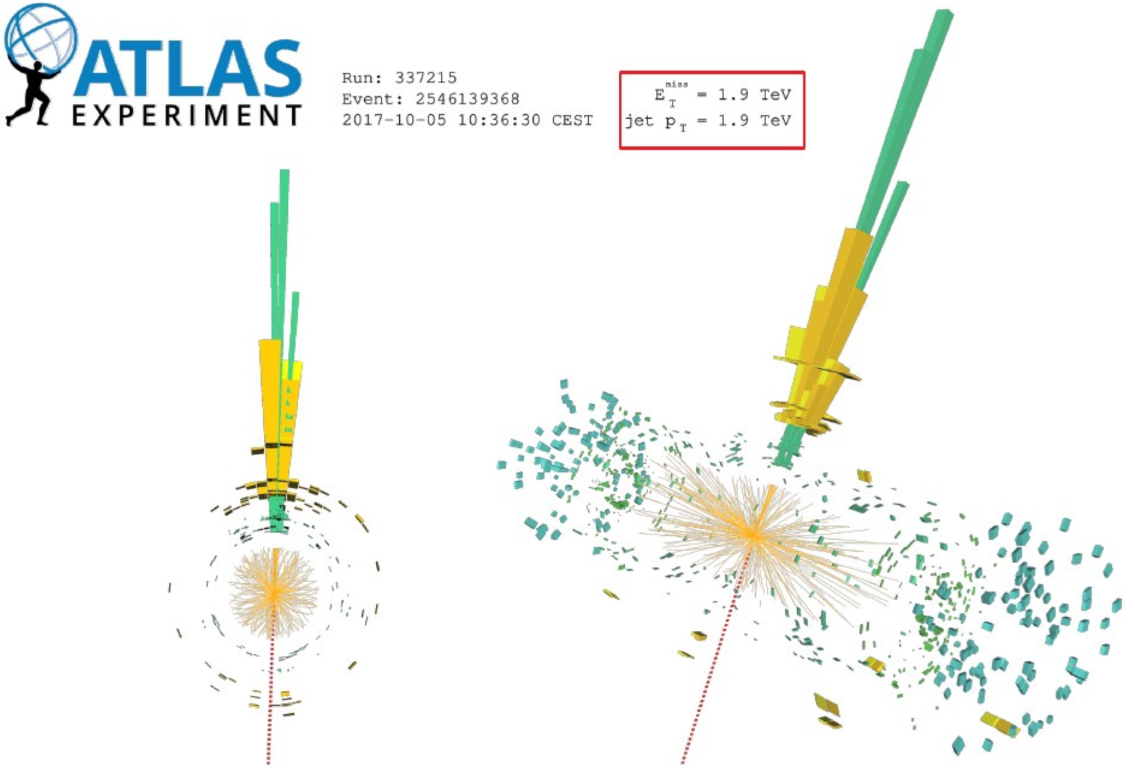
Mediator focus

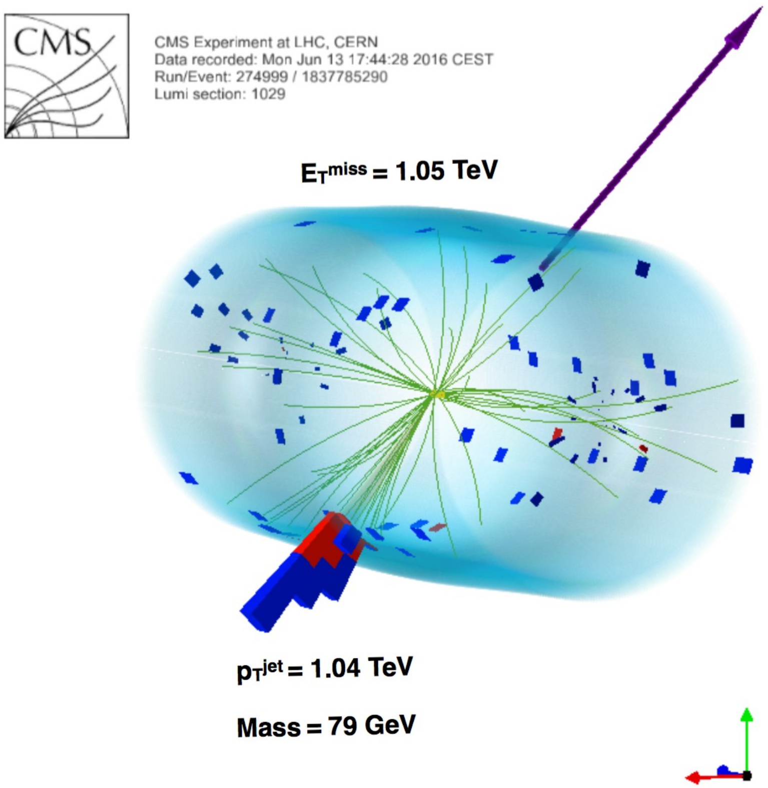
- the LHC's strength is to produce the mediator on-shell
- we must make the mediator explicit
  - an EFT “blob” is not sufficient



- model description
  - mediator type
  - production mode
  - couplings to q and DM
  - mediator and DM mass
  - consider beyond the minimal

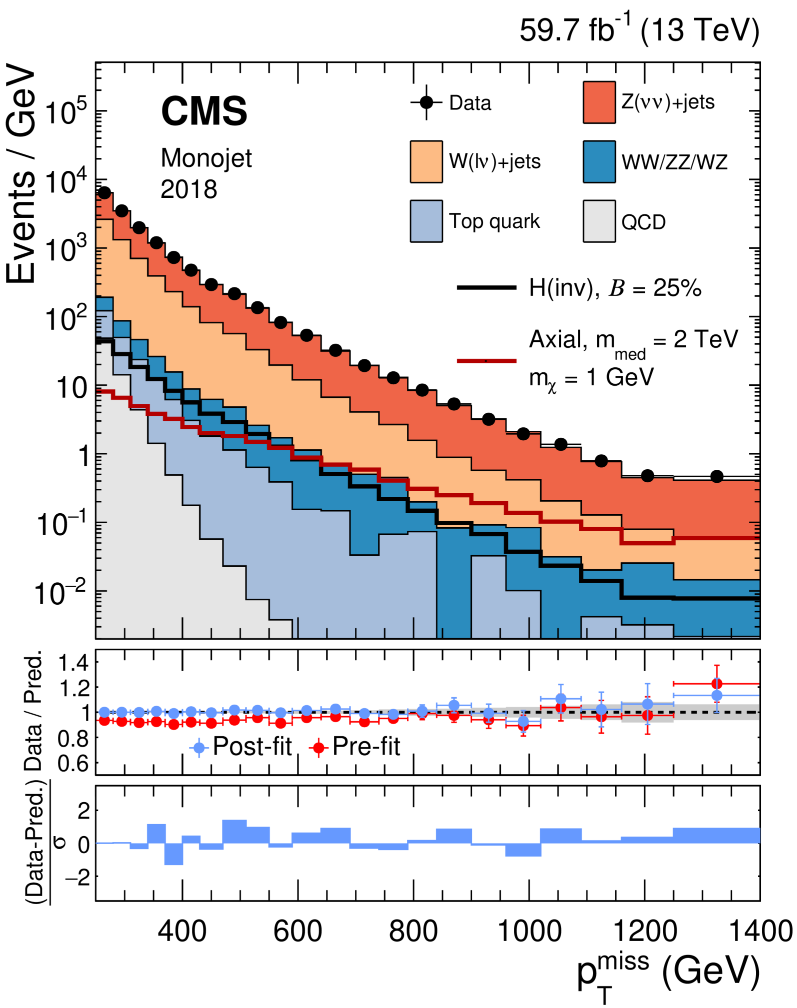
Direct DM searches





Direct DM searches

- Monojet search as the poster child example



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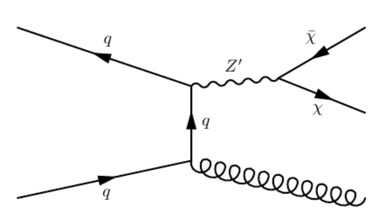
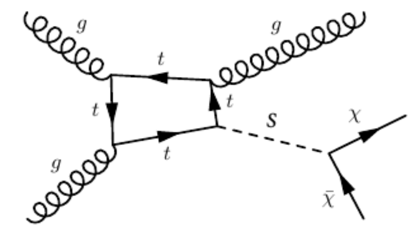
- DM recoils against a jet from QCD ISR

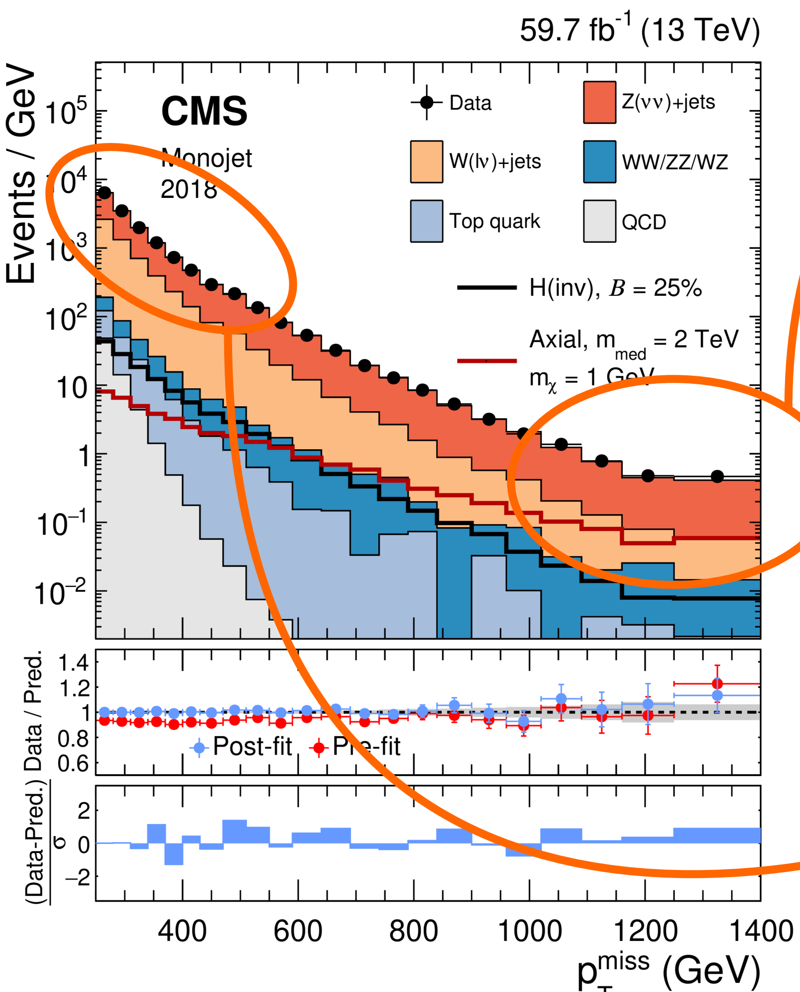


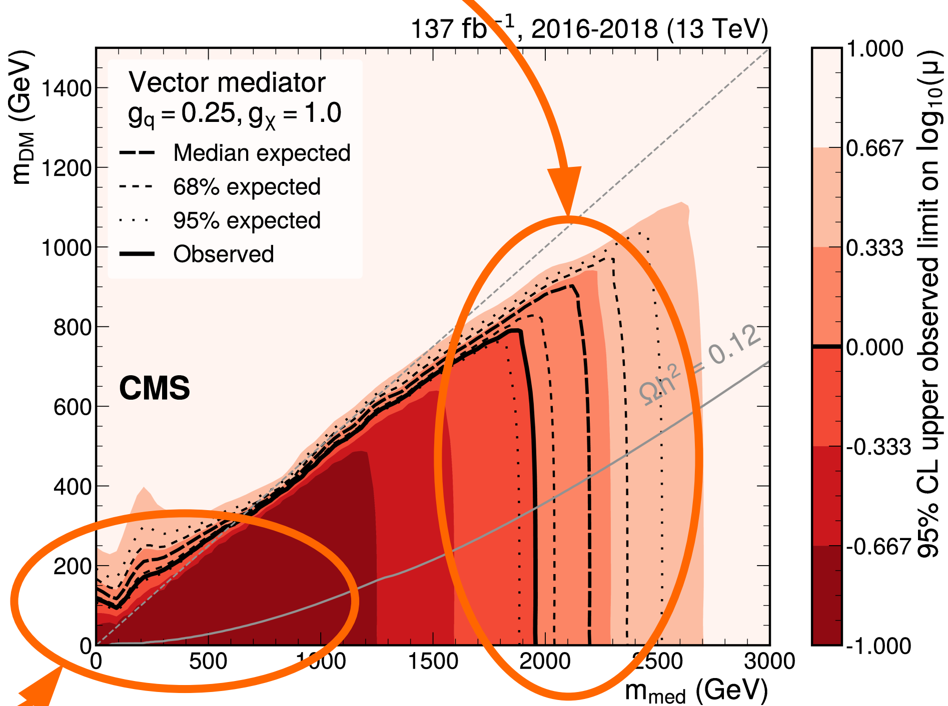


- selection highlights
  - MET as sensitive observable
    cut driven by trigger: MET > 250GeV
  - e/μ/τ and b veto → suppress top / W
  - jets-MET not aligned → suppress QCD
  - jet & MET cleaning → suppress instrum. BG
- irreducible Z→νν dominant BG
- remarkable precision achieved on BG!
  - ~% in bulk, 10% in tails
  - using constraints from Z→μμ, Z→ee, γ+jets, W→μν and W→eν control regions

Direct DM searches

- Monojet search as the poster child example





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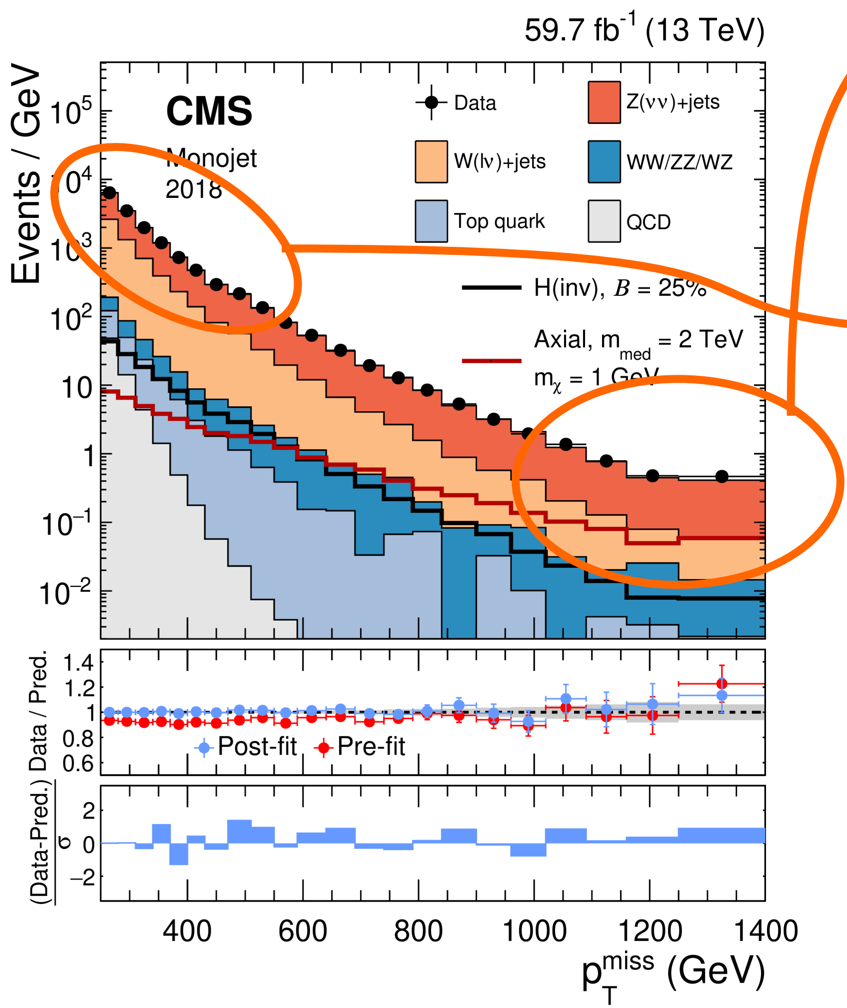
- many interpretations: DM s- and t-channel simp. models, Higgs portal, ADD extra dimensions, LeptoQuarks,...

Direct DM searches

- Monojet search as the poster child example



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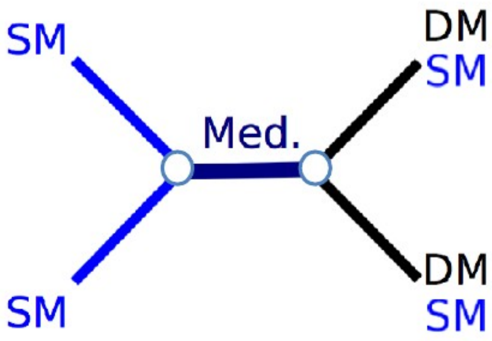
- statistically limited
  - improve slowly with luminosity
- systematically limited
  - no low-hanging fruits left
  - improve with hard work
  - challenges and opportunities at higher lumi
- theoretical uncertainties already very well controlled
  - NLO QCD+EWK
  - arXiv:1705.04664

Di-X search interplay with DM

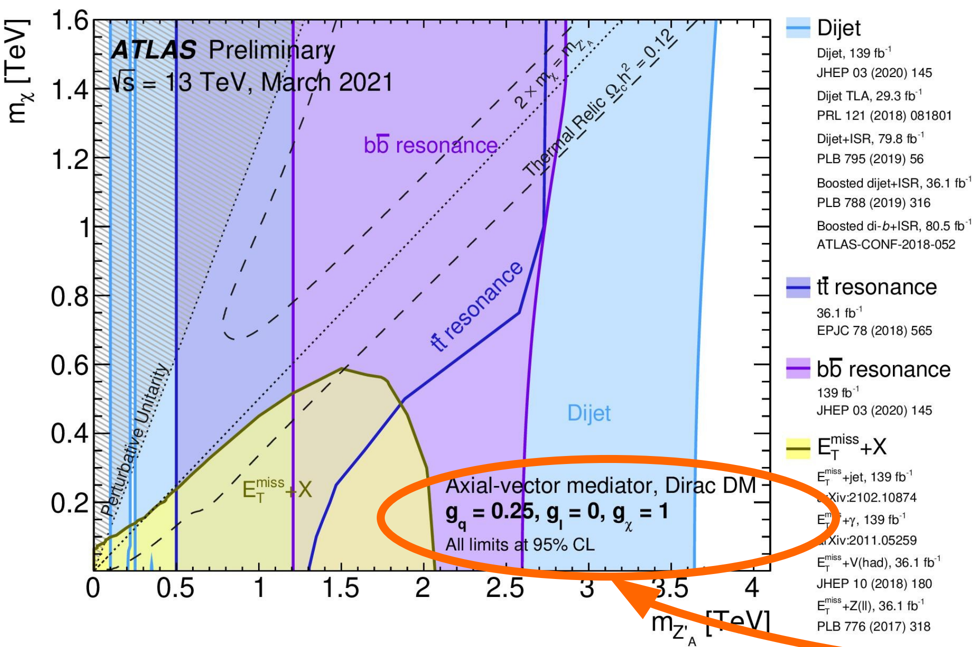
beyond the invisible: link to visible

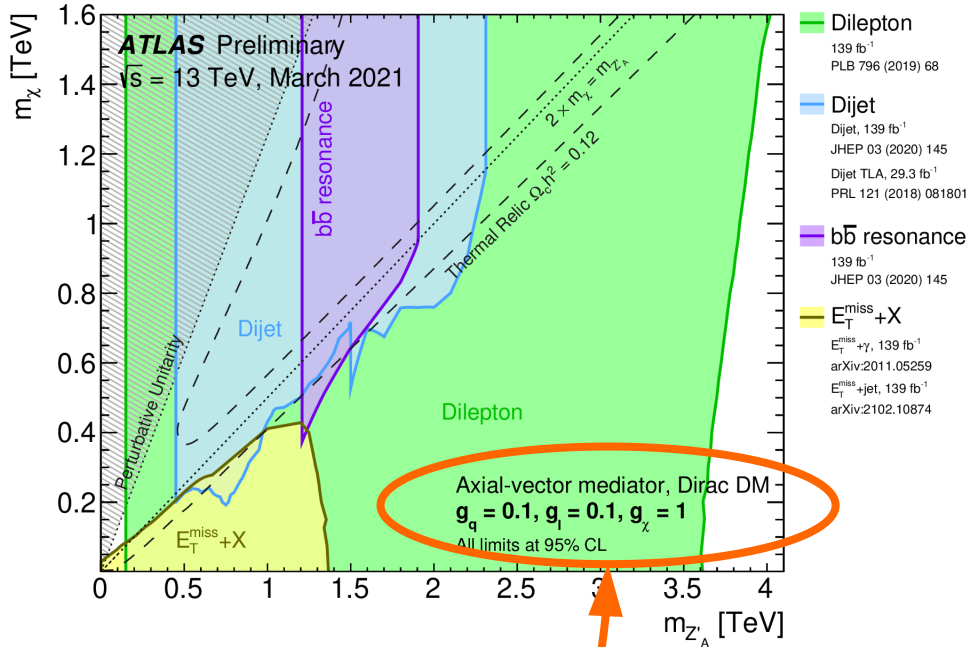
- LHC sensitivity to DM strongest when producing mediator on-shell
- new mediator may still be probed event if dark matter inaccessible (eg. kinematically) at LHC
  - quark (jet) final states guaranteed
  - muon and electron pairs possibly too
- thus we can indirectly constrain dark matter models
  - constraints on couplings
  - from searches in dijet and dilepton final states
  - model dependency!
    → always specify all parameters/assumptions



Di-X search interplay with DM

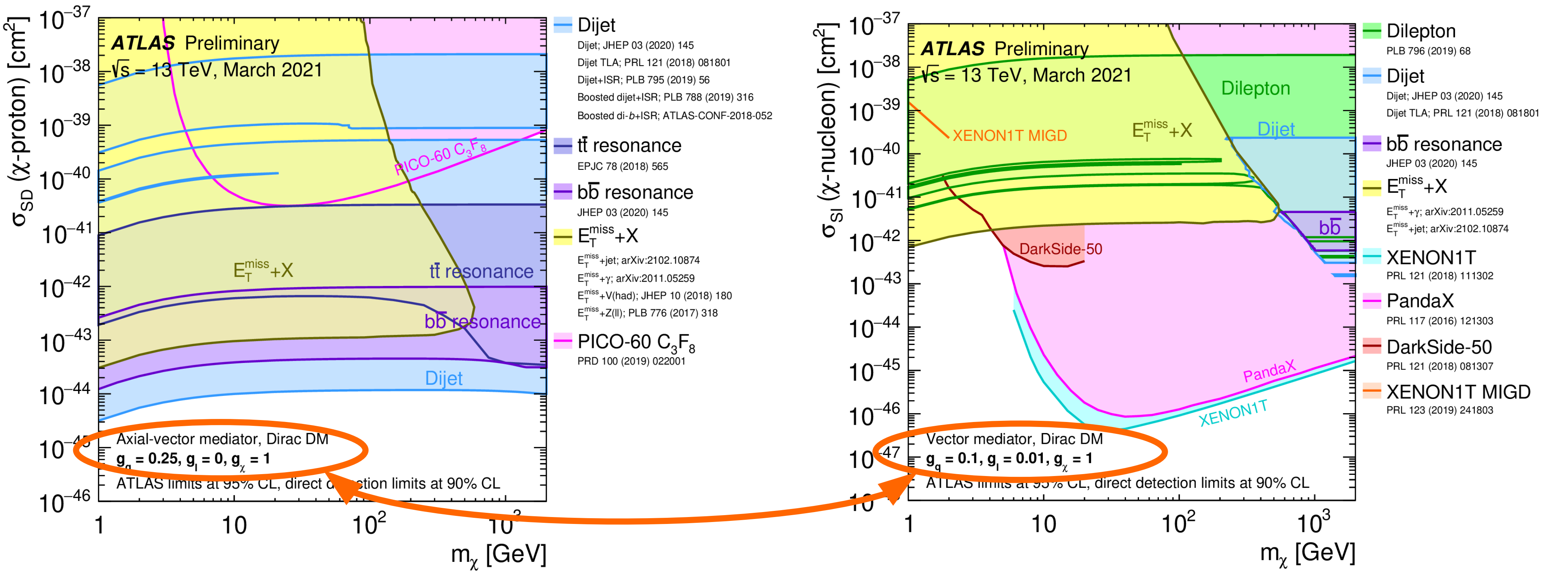
- interpretation in LHC phase space
  - probing mediators to several TeV
  - strong complementarity of invisible and visible channels
- exclusions crucially depend on couplings to SM and DM!





Dark Matter beyond LHC

- translate interpretation in phase space of direct DM detection searches
- take-home message: complementarity
  - best LHC results for low-mass DM, with mediator produced on-shell
- model dependency!



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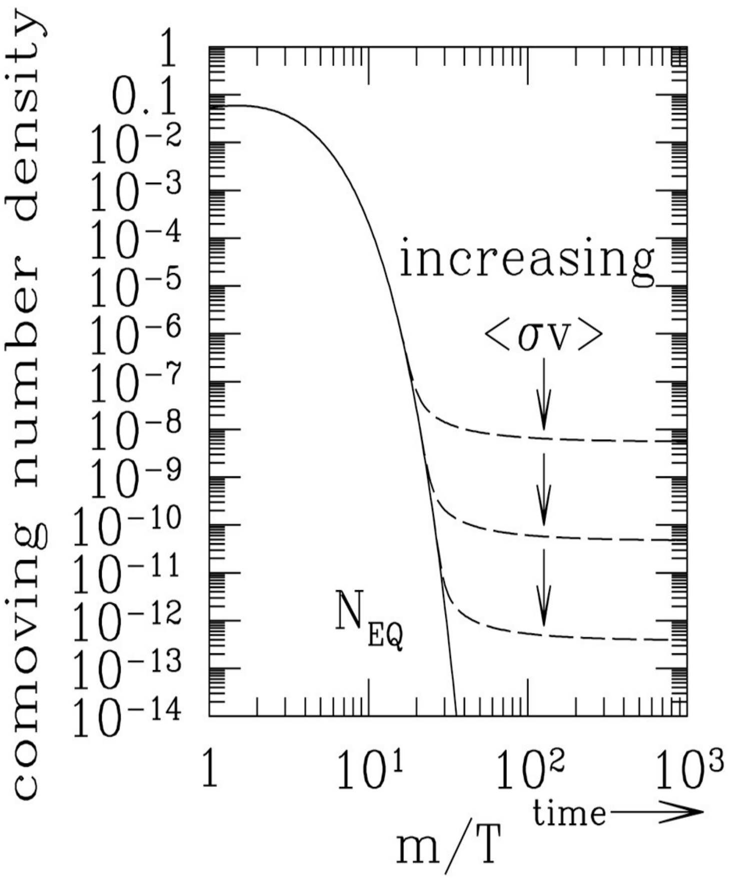
The WIMP miracle

- ...assuming thermal dark matter production...
- ...assuming cold dark matter...
- ...assuming DM to be 1 particle...

- relic dark matter density is inversely proportional to the DM annihilation cross section
  - correct relic density at

    $<\sigma v> \sim 3 \times 10^{-26}$ cm^3 / s
  - this is the cross section of a 100 GeV particle with a coupling like the weak interaction
- so cosmology and particle physics points us independently to a special mass scale, the weak scale
  - special role for the Higgs boson?
  - the superesymmetry neutralino?



Supersymmetry

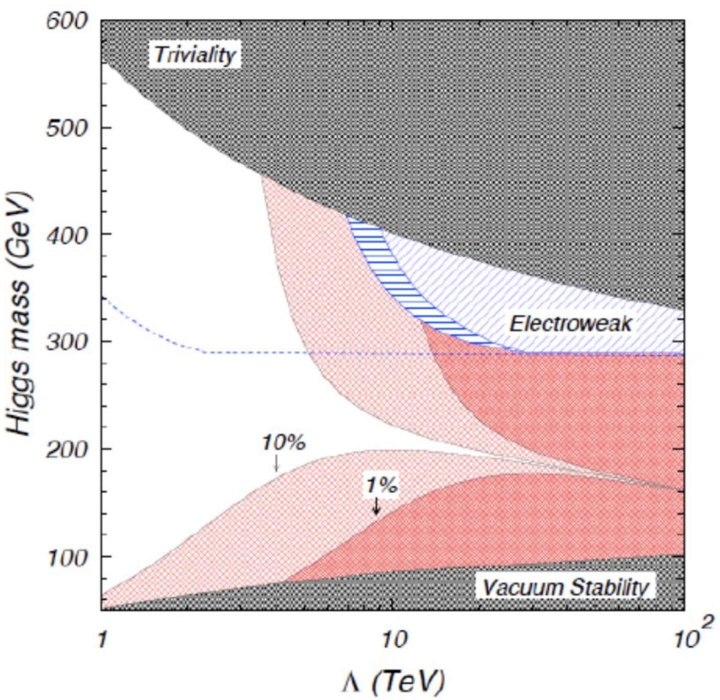
- hierarchy problem: scalar mass sensitive to all scales

  - the integral can be cut off at a momentum scale Λ

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)$$

  - to cancel this radiative correction up to the Planck scale…

    we need to cancel 32 orders of magnitude
    → fine tuning



Supersymmetry

- possible solution: supersymmetry (SUSY):

  add a boson for each fermion, and vice versa

  - scalar quarks and leptons

Names		spin 0	spin 1/2
squarks, quarks	Q	$(\tilde{u}_L \ \ \tilde{d}_L)$	$(u_L \ \ d_L)$
(×3 families)	$\overline{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\overline{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
sleptons, leptons	L	$(\tilde{\nu} \ \ \tilde{e}_L)$	$(\nu \ \ e_L)$
(×3 families)	$\overline{e}$	$\tilde{e}_R^*$	$e_R^\dagger$

Names	spin 1/2	spin 1
gluino, gluon	$\tilde{g}$	g
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$
bino, B boson	$\widetilde{B}^0$	B^0

majorana fermions as
gauge boson partners ("-inos")

extended Higgs sector and
fermionic superpartners

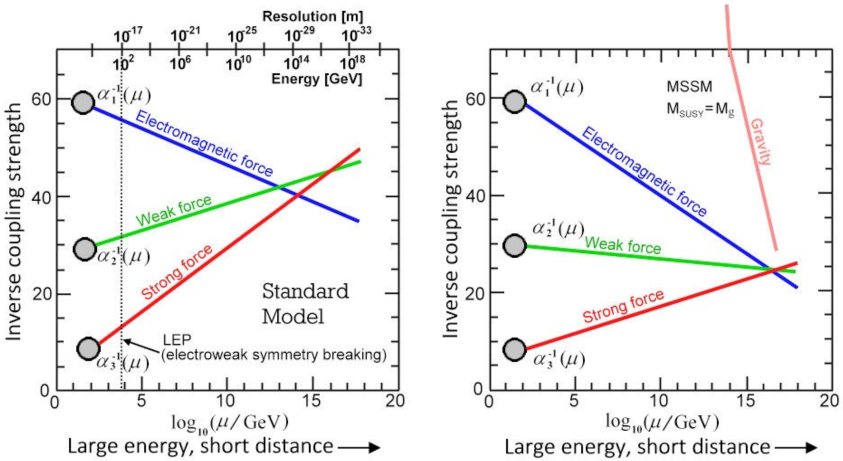
Names		spin 0	spin 1/2
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$

- mixing between bino, winos and Higgsinos → charginos and neutralinos

- no SUSY at same masses observed → no perfect cancellation
  - to save naturalneess and avoid new fine tuning:
    higgsino ~ 100 GeV
    stop ~ 400 GeV
    gluino ~ 2000 GeV

Supersymmetry appeal

- hierarchy problem
- unification of the forces



- EW symmetry breaking can be a natural consequence of SUSY breaking
  - under certain conditions in the Higgs sector
- dark matter
  - gravitational evidence is overwhelming
  - SUSY can provide an ideal WIMP
  - note: dark matter is not a requirement put on SUSY models

    it's the reverse: require proton stability through conservation of R parity

    → SUSY particles must come in pairs

    → the lightest SUSY particle is stable

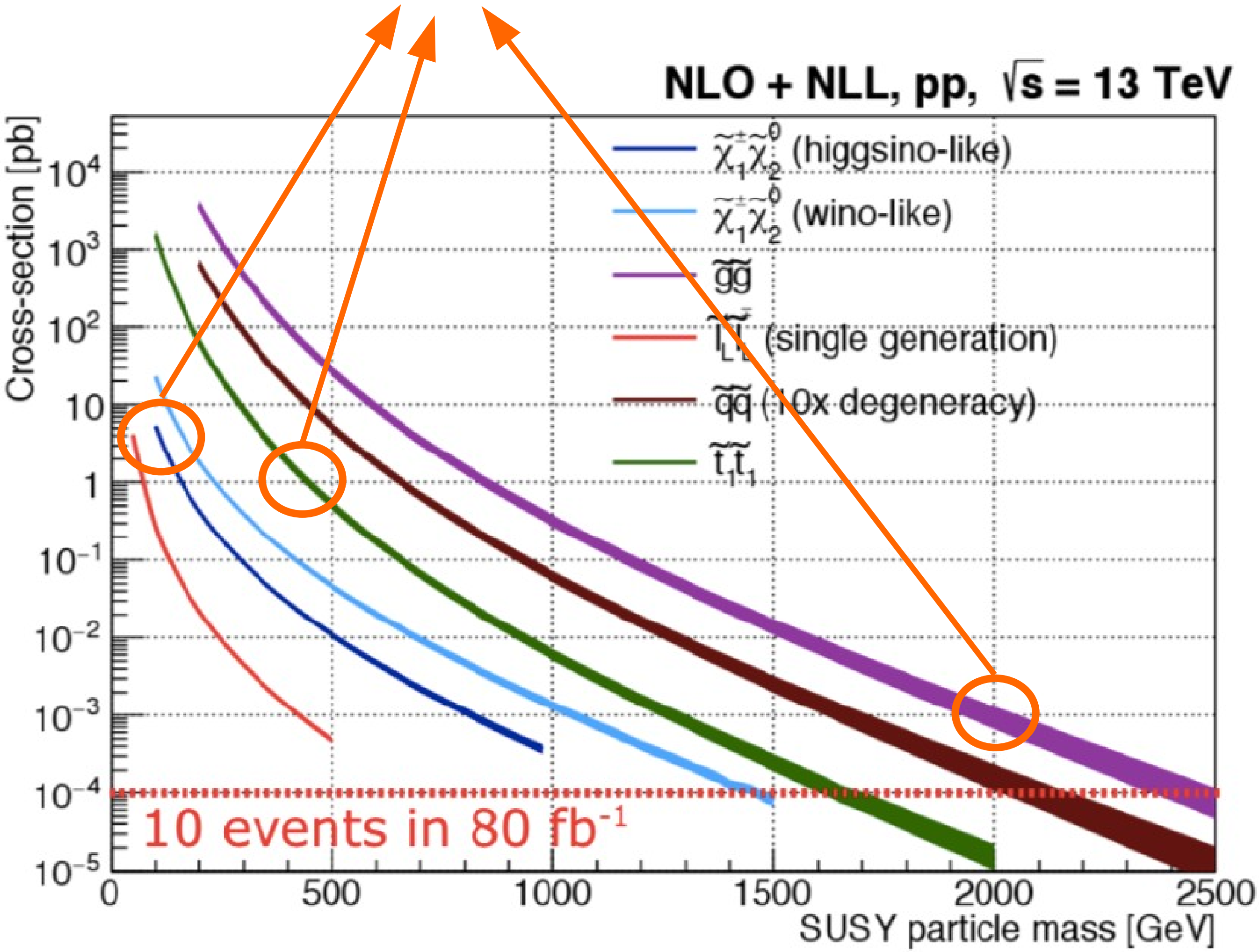
$$P_R = (-1)^{2s+3B+L}$$

- string theory requires SUSY
  - but no indication at what energy scale

Supersymmetry at LHC

- collider cross sections can be quite large
- current LHC energy and luminosity probes natural SUSY directly

- SUSY can still hide in experimentally difficult decays



Supersymmetry at LHC

- high cross sections for strong production of heavy squarks and gluinos
  - the squarks and gluinos then decay depending on the SUSY spectrum of lighter sparticles
  - but since they are coloured, they will always produce quarks or gluons (jets)
  - and the LSP will always give rise to undetected momentum in the detector
  - generic feature: missing energy + jets + possible leptons/photons/...

    a particularly SUSY-like signature are same-charge lepton pairs

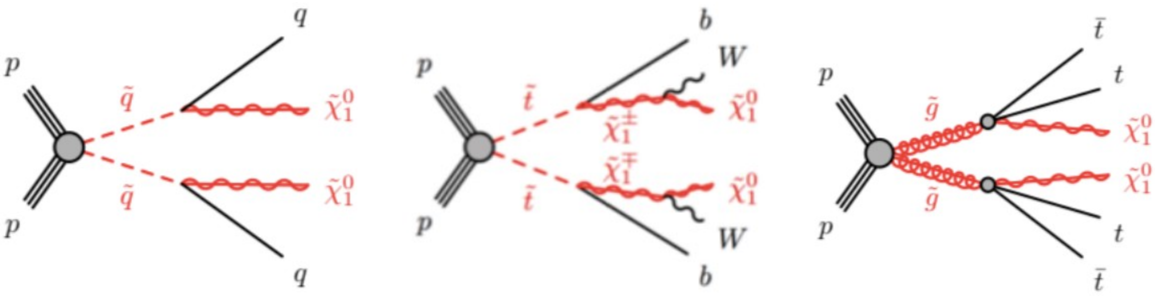
- small cross sections for electroweak production of charginos, neutralinos, and sleptons
  - Z's and W's appear in the decays, or leptons directly from the sleptons → can be used to suppress backgrounds
  - depending on spectrum configurations, final states arise with 2, 3, 4 leptons, with or without Z resonances, same charge or not, same flavour or not
  - generic feature: leptons + MET, but absence of jets

- also Higgs bosons can appear in the decays!

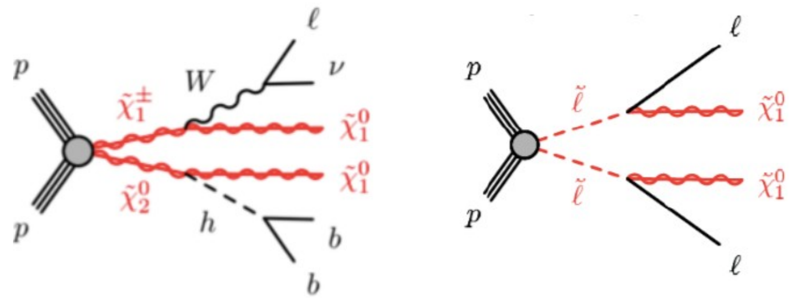
Supersymmetry at LHC

- classic hadronic SUSY signatures
  - jets + MET
  - lepton + jets + MET
  - SS dileptons + jets + MET
  - …

some example diagrams



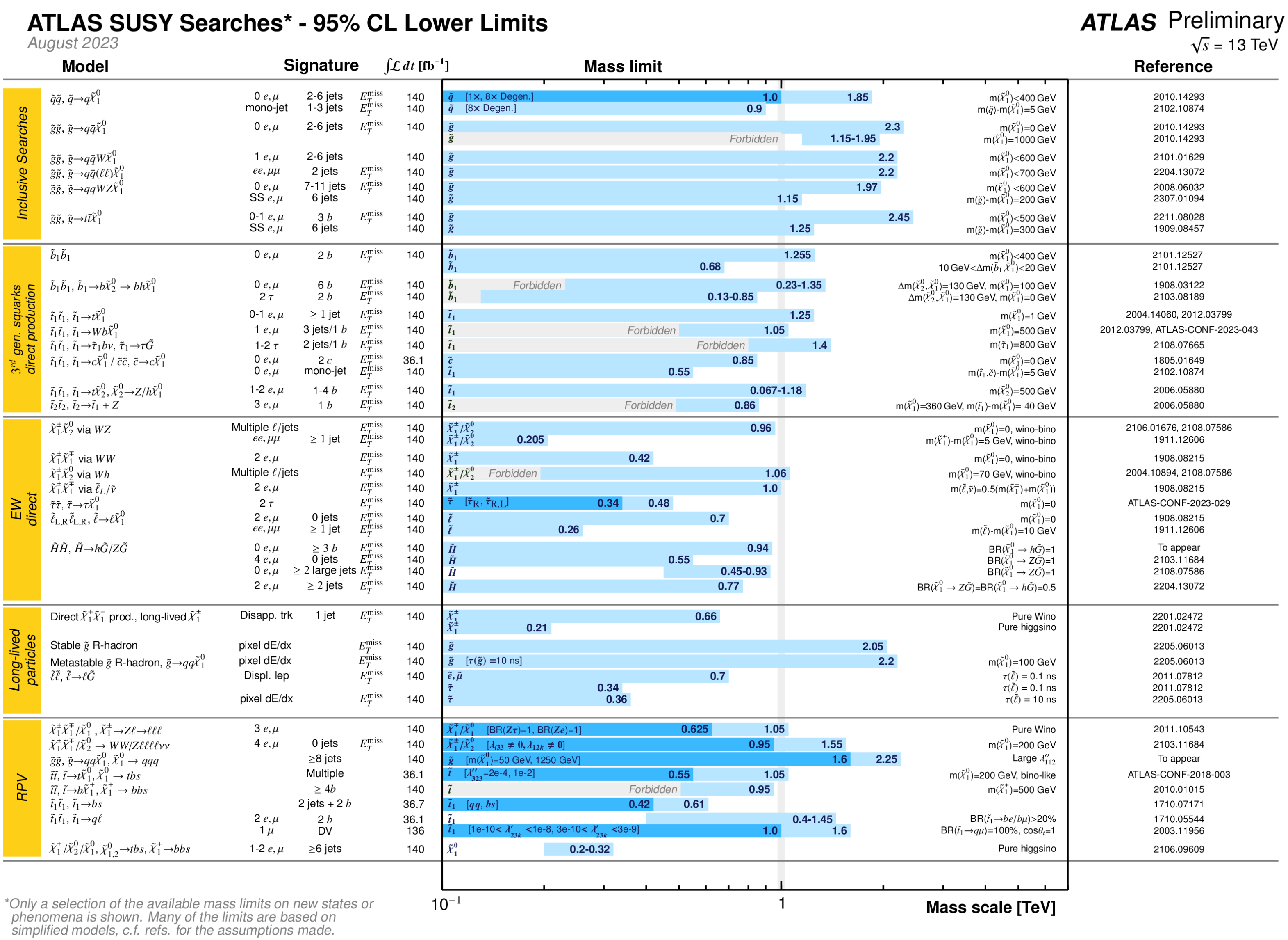
- classic electroweak SUSY signatures
  - Z/W/H + MET
  - dileptons + MET
  - ...



- many 10's of searches, years of work, no hints of SUSY
  - maybe nature chose something else than these classic signatures?

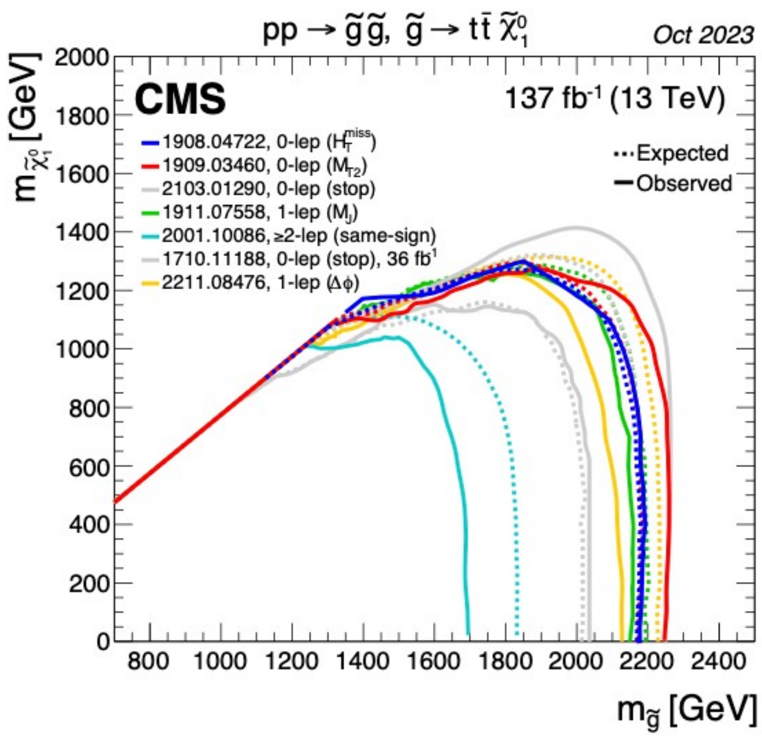
Supersymmetry at LHC

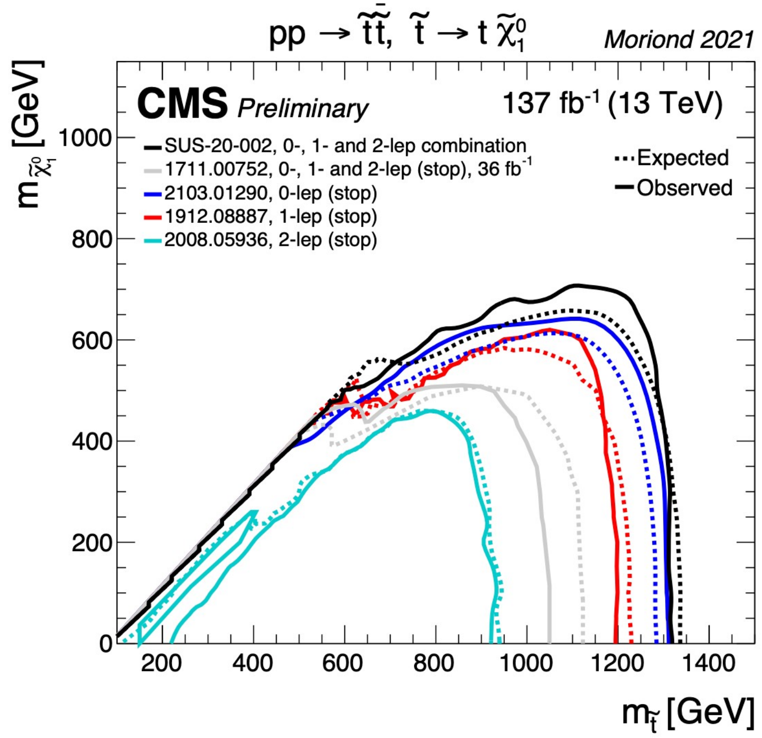
- current experimental situation



Supersymmetry at LHC

- zooming in on gluino and stop searches
  - drivers of the fine-tuning tests





- limits from direct searches are now very stringent
  - fine tuning seems inevitable
  - simple low-mass SUSY solutions losing traction

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