LHC searches for new Physics and Dark Matter : part 2

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The Dark and Visible Side of the Universe ISAPP 2017
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OUTLINE for this week

- **Part A: Tuesday**
- - 1. **Reasons** to go Beyond the Standard Model
- - 2. Experimental **techniques**
- **Part B: Wednesday**
- - 3. Brief overview **Higgs** physics
- - 4. **Searches** for Dark Matter (and BSM), including introduction to Supersymmetry

- Bunches ?

3. Brief overview Higgs physics

The missing piece of the Standard Model:

The Higgs Boson

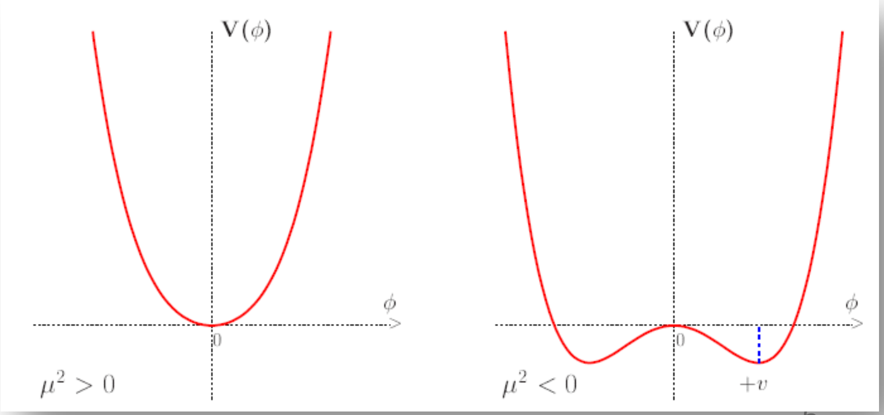
SM Higgs reminder

- Problem with massive W and Z ➔ Simple mass term in Glashow/Salam/Weinberg theory violate (local) gauge invariance (non renormalizable)
- Higgs mechanism explains electroweak symmetry breaking, i.e. why W and Z are massive and the photon is no (and it also allows fermion mass terms)
- A scalar (complex isodublet) field is added with a non-zero vacuum expectation value
- After "electroweak symmetry breaking" this field results in one observable Higgs particle (3 degrees of freedom mix with the W and Z bosons)

In short for a simple scalar field (not SM case):

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)\ ,\ V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

$$\text{if } \mu^2 < 0 \qquad \langle 0|\phi^2|0\rangle \equiv \phi_0^2 = -\frac{\mu^2}{\lambda} \equiv v^2$$



Expand around minima:

$\phi = v + \sigma$ *+ change to unitarity gauge = massive W and Z + massless gamma+ scalar Higgs*

Limits on SM Higgs : Unitarity bound

Optical theorem relates total Cross Section with Im(forward amplitude)

$$\sigma = \frac{1}{s}\,\mathrm{Im}\,[\,A(\theta=0)\,]$$
$$= \frac{16\pi}{s}\sum_{\ell=0}^{\infty}(2\ell+1)|a_\ell|^2$$

→Unitarity bound $|\mathrm{Re}(a_\ell)| < \frac{1}{2}$

(probability not conserved in scattering)

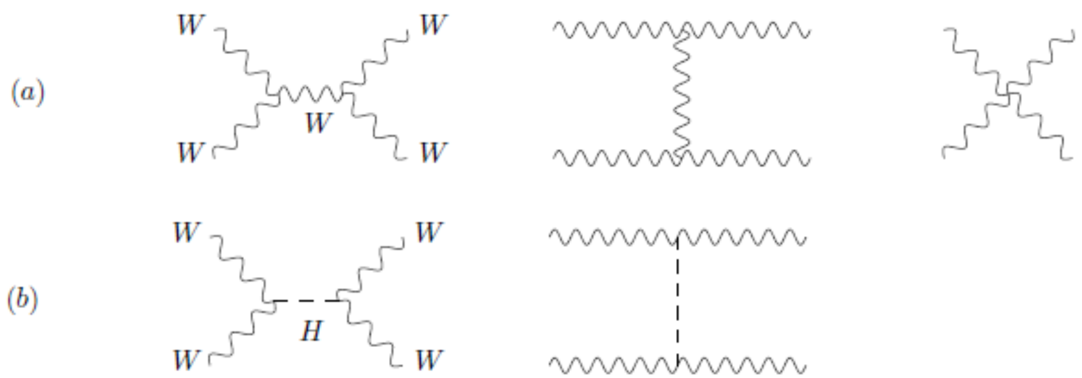


Figure 2.1: *Generic diagrams of elastic WW scattering: (a) pure gauge-boson dynamics, and (b) Higgs-boson exchange.*

Cross section for elastic long. WW scattering grows without light Higgs above unitarity bound
Higgs restores unitarity!

If Higgs would not exist there must be some other mechanism at O(1 TeV) to restore unitarity

Motivation for the Higgs boson was to restore unitarity in $W_L W_L \rightarrow W_L W_L$ scattering.

This requires that the Higgs mass is not too large.

$$M_H^2 \leq 2\sqrt{2}\pi/G_F \sim (850\ \mathrm{GeV})^2$$

B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. Lett. **38** (1977) 883.

Higgs mass "triviality" bound

- Couplings and masses in the SM lagrangian depend on energy

  ➔ Also the case for quartic Higgs self coupling

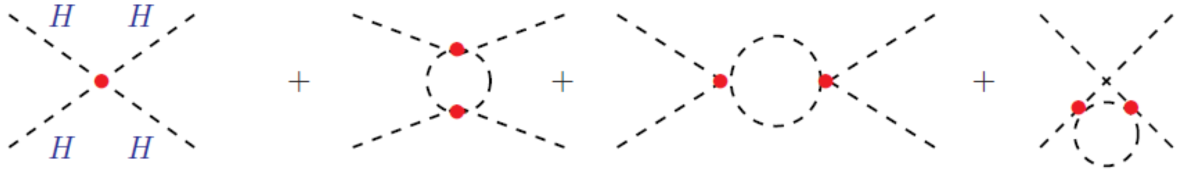


Figure 1.17: Typical Feynman diagrams for the tree–level and one–loop Higgs self–coupling.

RGE describes variation
of Higgs quartic coupling with energy:

$$\frac{d}{dQ^2}\lambda(Q^2) = \frac{3}{4\pi^2}\lambda^2(Q^2) \quad + \text{higher orders}$$

Solution with respect to reference energy v
(ew symmetry breaking scale)

$$\lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

Gives a Landau pole where
coupling becomes infinite at energy:

$$\Lambda_C = v\,\exp\left(\frac{4\pi^2}{3\lambda}\right) = v\,\exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$$

Turn this argument around:
Higgs must be **lighter** to avoid Landau pole
(i.e. energy bound Lamda_c where coupling is still finite)

$$\Lambda_C = M_H$$

$$\Lambda_C \sim 10^{16}\ \text{GeV}\ M_H \lesssim 200\ \text{GeV}$$

Higgs mass: “stability” bound

We also need to consider the effects of gauge bosons and fermions in the “running”

Effect: Coupling Lambda can get too small, even negative due to top quark Contribution

➔Negative Lambda changes Higgs potential and leads to $V(Q^2) < V(v)$
➔Vacuum is not stable anymore

Solution: to keep $\lambda(Q^2) > 0$

$$M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

➔ Strong lower constrain on Higgs mass $\Lambda_C \sim 10^3\ \mathrm{GeV} \Rightarrow M_H \gtrsim 70\ \mathrm{GeV}$

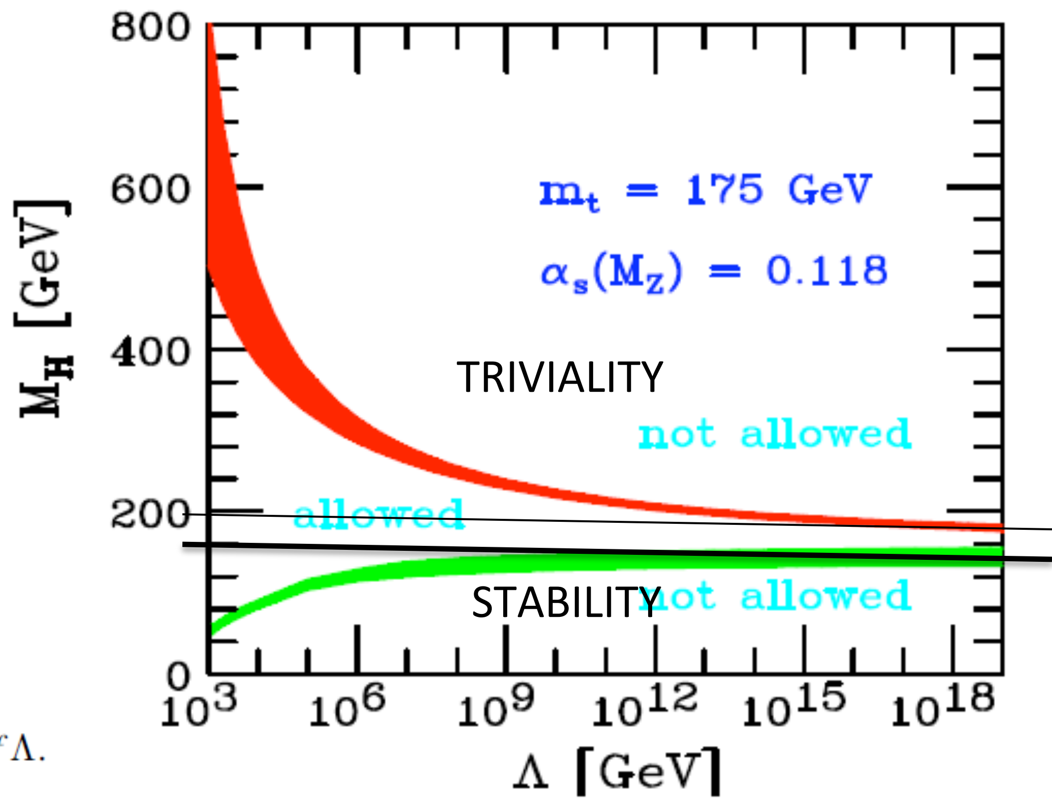
$\Lambda_C \sim 10^{16}\ \mathrm{GeV} \Rightarrow M_H \gtrsim 130\ \mathrm{GeV}$

Higgs mass constrains

Bounds on the Higgs boson mass
Lambda is energy scale at which
SM Higgs with mass M_H becomes
strongly self-interacting (upper bound)
& vacuum stability (lower bound)

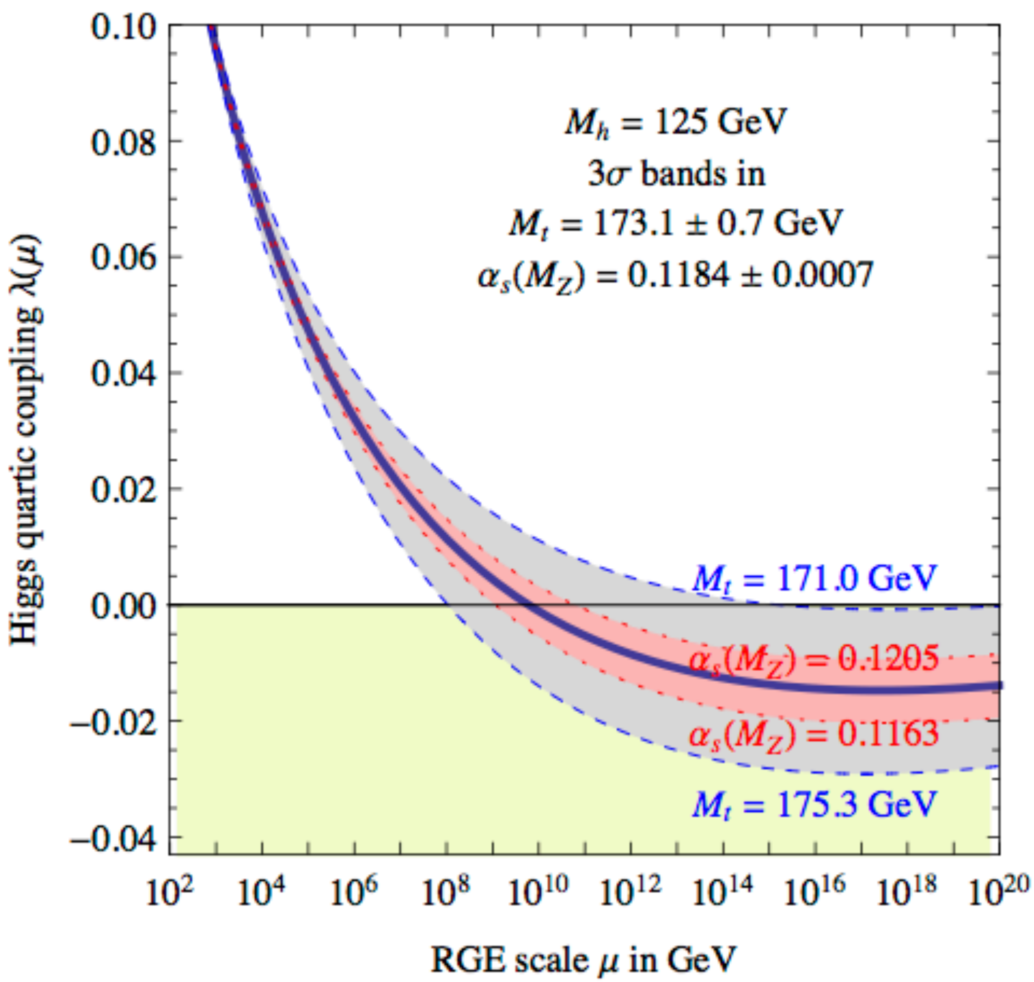
Λ	M_H
1 TeV	60 GeV $\lesssim M_H \lesssim$ 700 GeV
10^{19} GeV	130 GeV $\lesssim M_H \lesssim$ 190 GeV

Higgs mass bounds for two values of the cut-off Λ.



Planck scale bounds need to be fulfilled for SM Higgs
➔ Otherwise new physics at lower scale needed

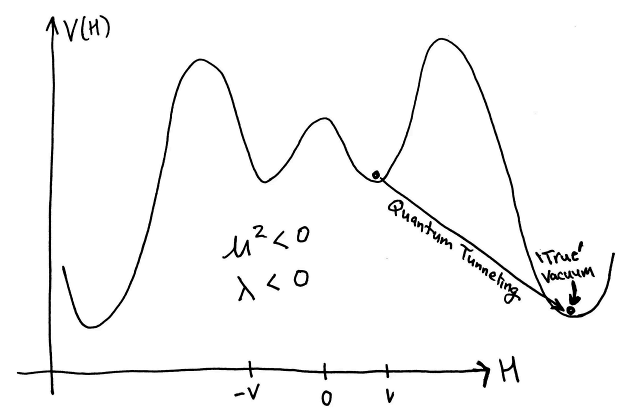
Stability of vacuum



M_h = 125 GeV

With 3 sigma
lambda < 0 around 10^10 GeV

➔ New physics needed to repair that?



Picture by ROBERTO VEGA-MORALES

W, Z, top& Higgs

SM predicts relation between W mass and other observables

Correction Δr on W and Z mass depends on top mass^2

… and on log (m_higgs)

Measure W and top mass
to predict the mass of the Higgs boson within the SM

(additional contributions to Δr may arrise from new particles, e.g. SUSY)

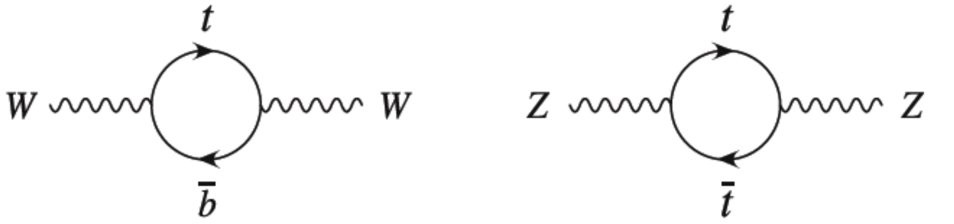


Fig. 8. Virtual top quark loops contributing to the W and Z boson masses

Fig. 9. Virtual Higgs boson loops contributing to the W and Z boson masses

$$\sin^2\theta_W \equiv 1 - \frac{m_W^2}{m_Z^2}\,, \tag{23}$$

the W-boson mass can be expressed as:

$$m_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W(1-\Delta r)}\,, \tag{24}$$

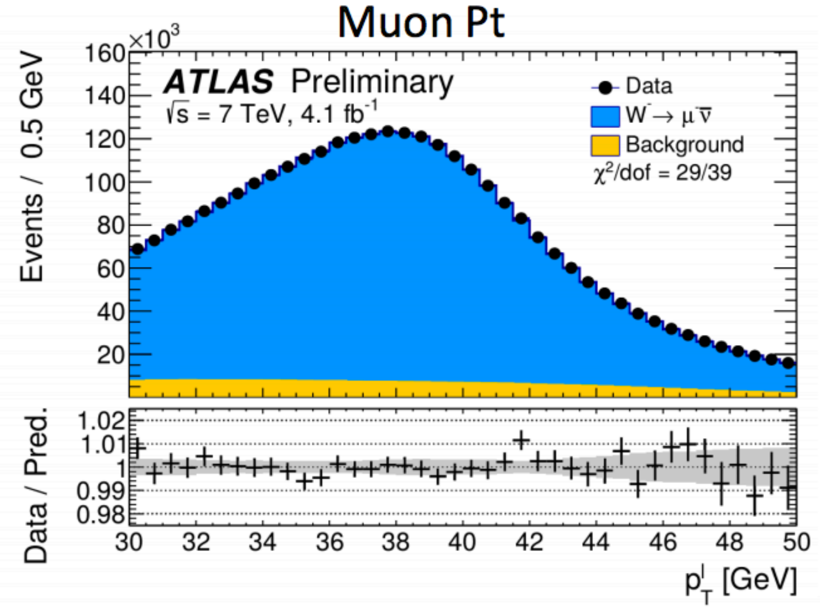
where Δr contains all the one-loop corrections. Contributions to Δr originate from the top quark by the one-loop diagrams shown in Fig. 8, which contribute to the W and Z masses via:

$$(\Delta r)_{top} \simeq -\frac{3G_F}{8\sqrt{2}\pi^2\tan^2\theta_W}m_t^2\,. \tag{25}$$

Measurement of the W-boson mass

arXiv:1701.07240

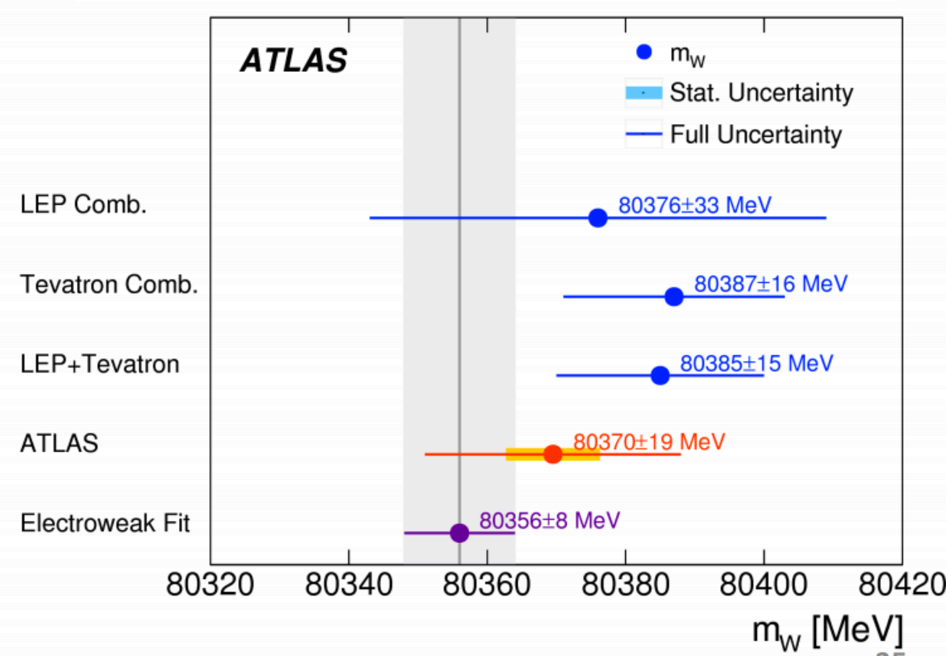
- Based on early data (2011) at √s = 7 TeV (4.6 fb^{-1}) with low Pile-Up
- Huge amount of work to understand detector response and the modelling of kinematic quantities (Mt, P_t^l) (relies on large Z → ℓℓ sample)



Similar precision reached as for current best measurement from CDF

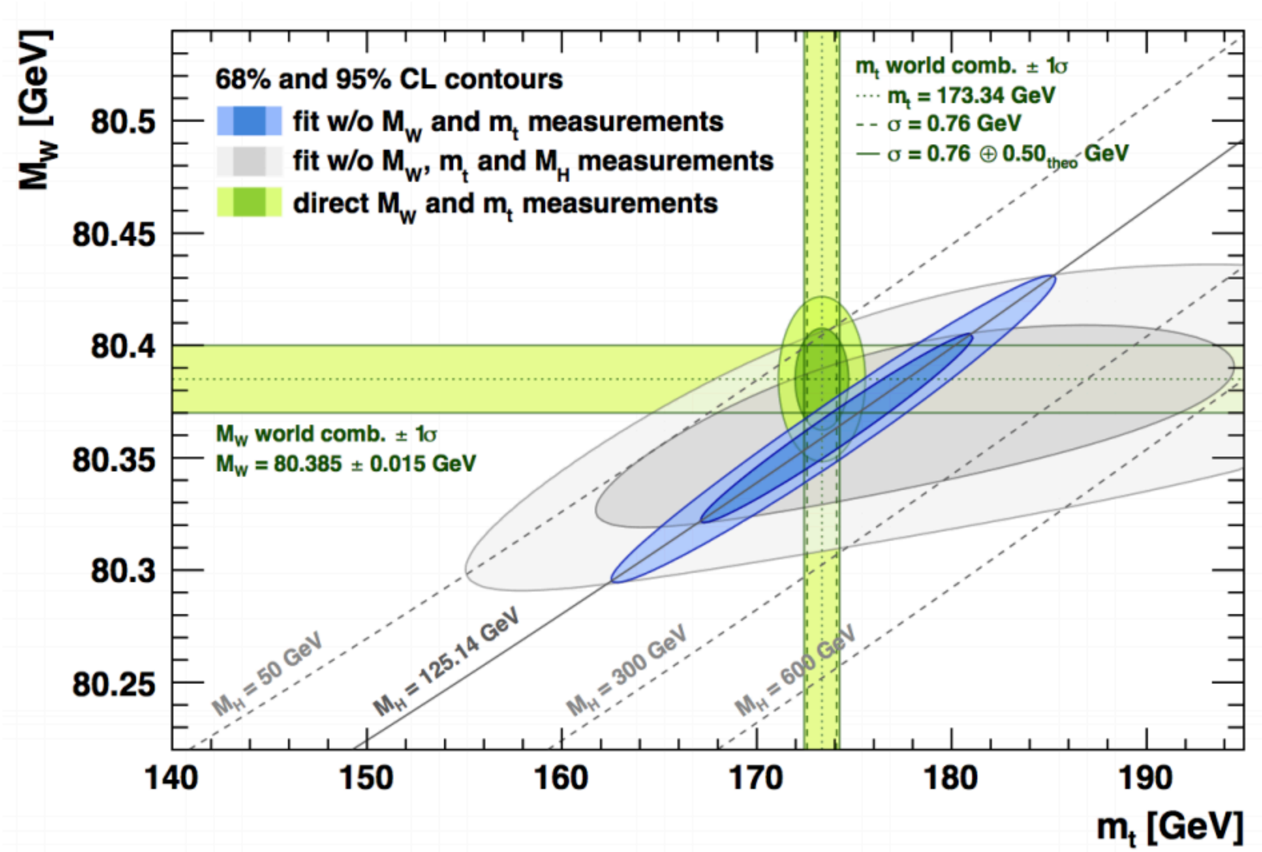
$m_W = 80.370 \pm 0.019$ GeV

± 7 MeV statistical
± 11 MeV systematic
± 14 MeV modeling



M. Boonekamp: W mass

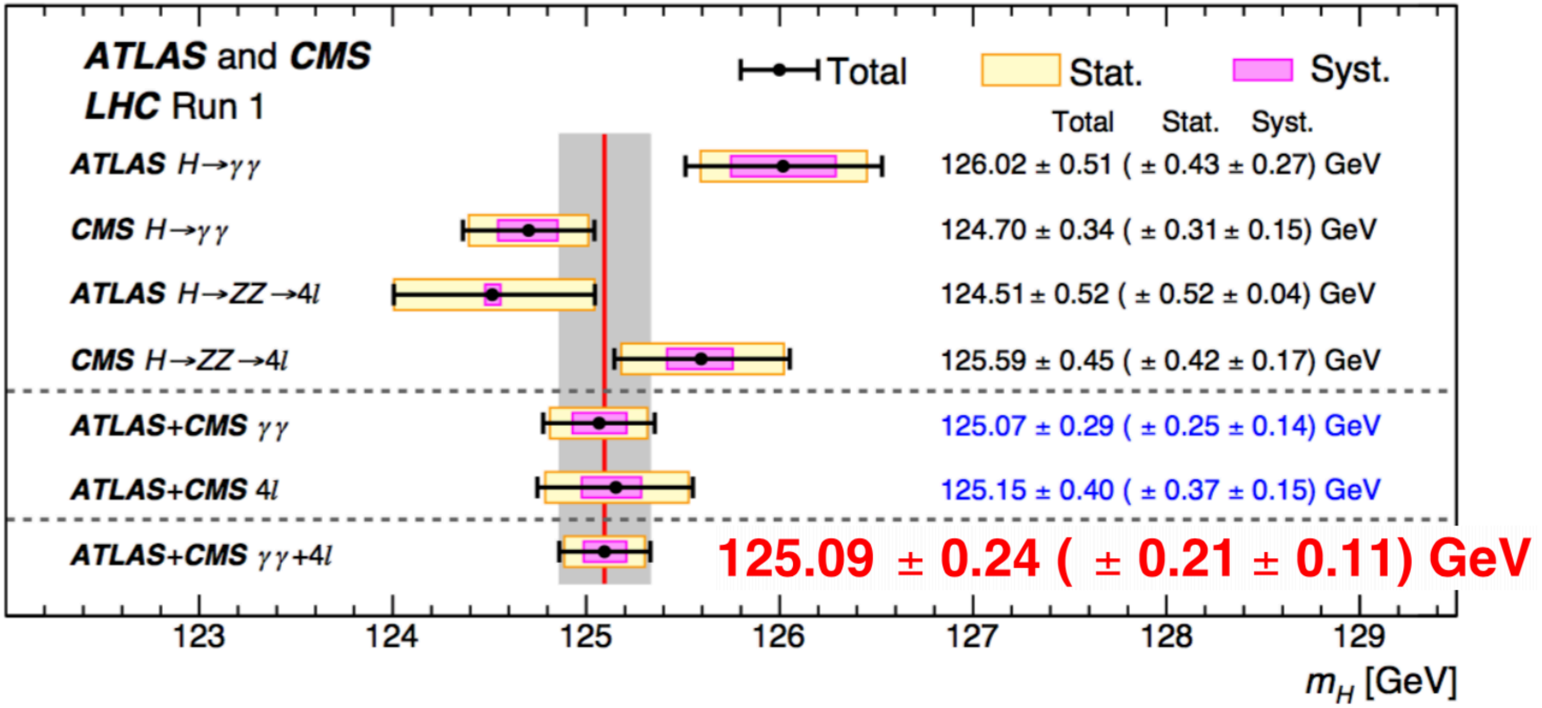
SM fit 2017



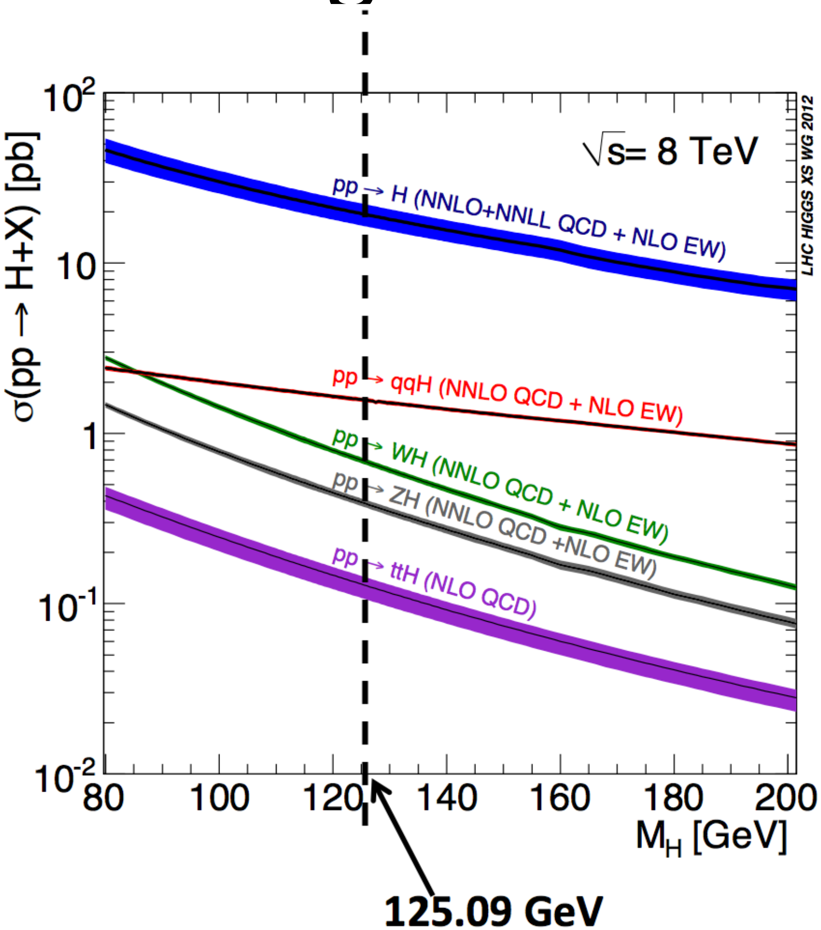
68% and 95% CL contours
fit w/o M_W and m_t measurements
fit w/o M_W, m_t and M_H measurements
direct M_W and m_t measurements
m_t world comb. ± 1σ
m_t = 173.34 GeV
σ = 0.76 GeV
σ = 0.76 ⊕ 0.50_{theo} GeV
M_W world comb. ± 1σ
M_W = 80.385 ± 0.015 GeV
M_H = 50 GeV
M_H = 125.14 GeV
M_H = 300 GeV
M_H = 600 GeV
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190

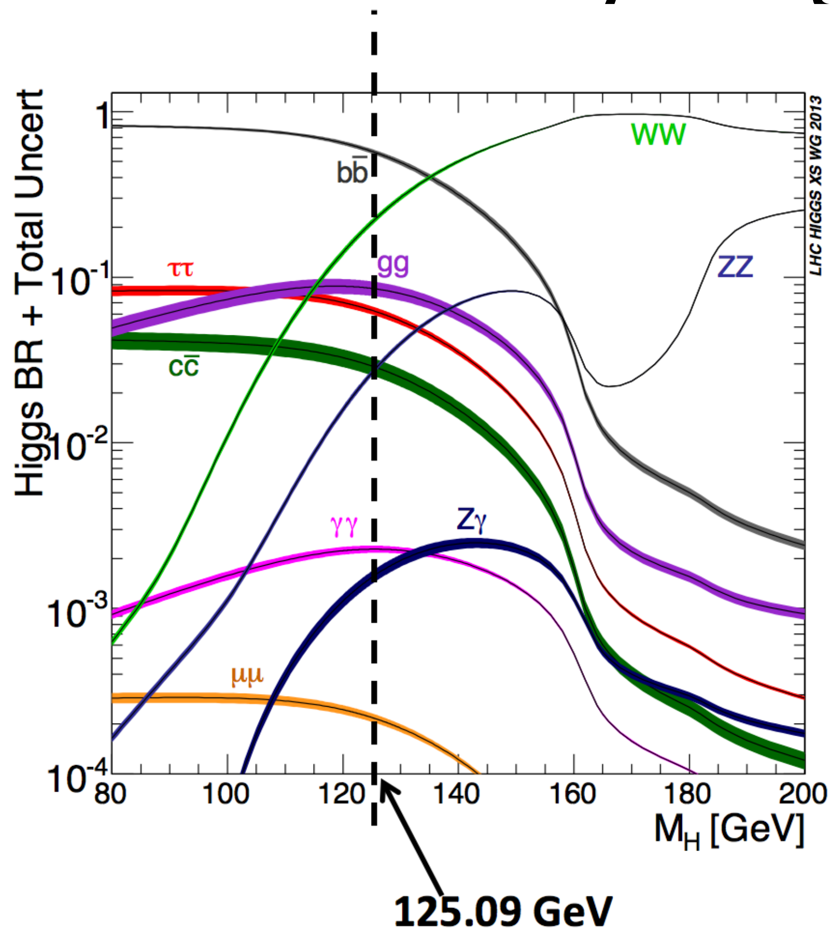
Measurement of the Higgs boson mass

- ATLAS+CMS combination on mass measurement with high-resolution channels: **$H \to \gamma\gamma$ and $H \to ZZ \to 4l$**

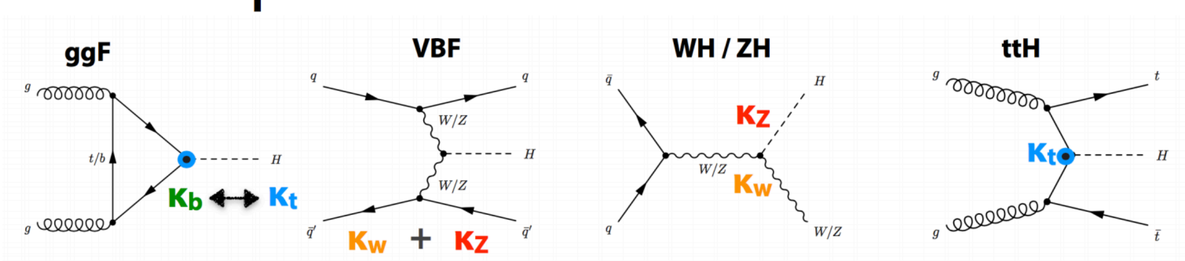


Knowing the mass we know everything





- **Usual suspects:**



Signal strengths, μ

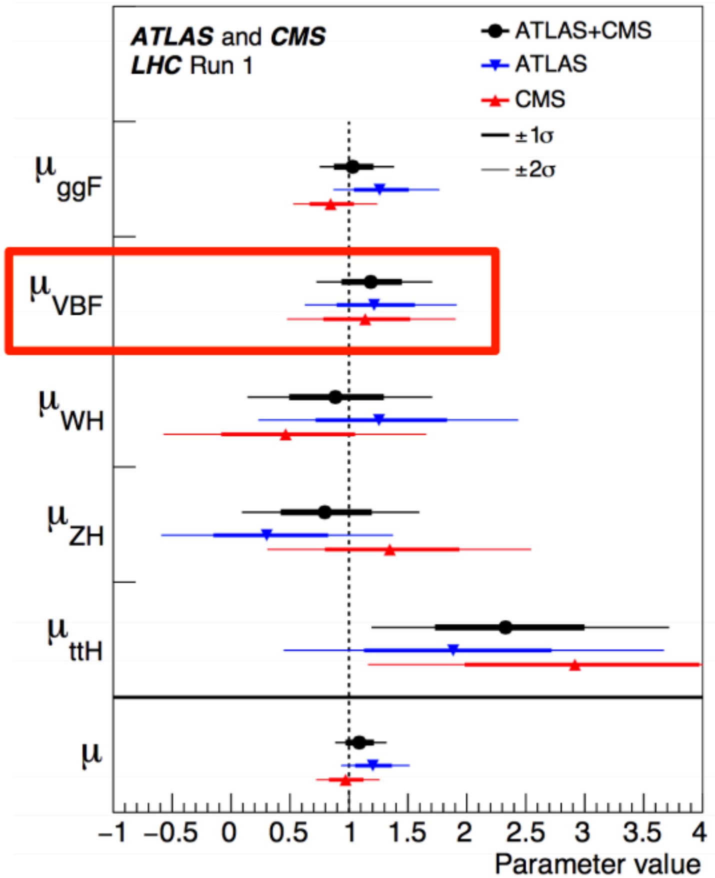
Parameters scale cross sections and BRs relative to SM

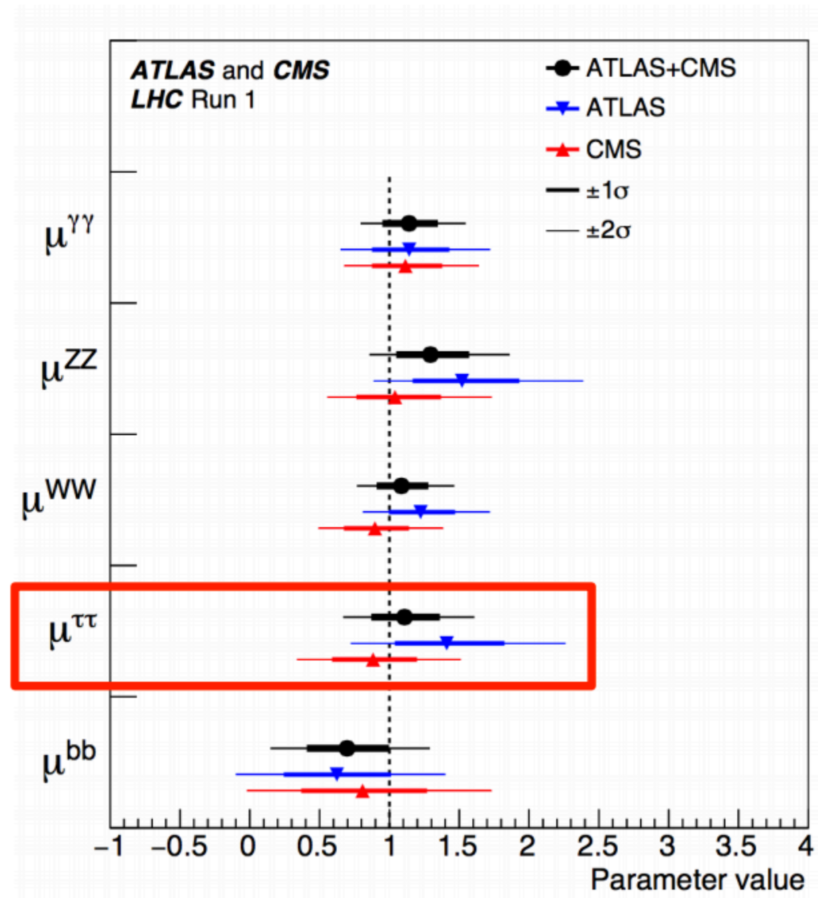
$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

Scaling of generic i → H → f process

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

Signal strengths, μ





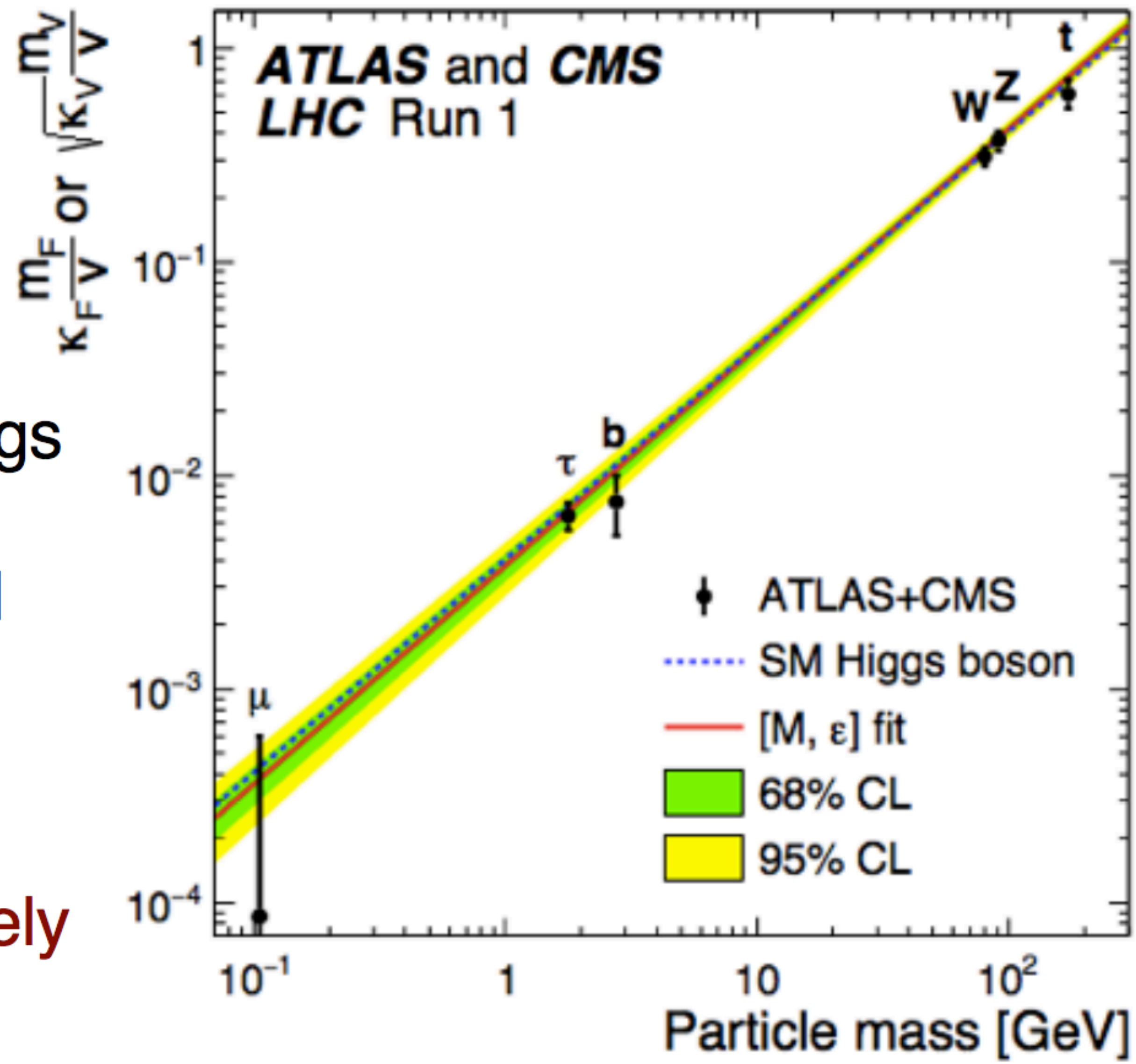
Going from mu to kappa framework now (including production /EFTs)

H→ττ decay mode and VBF process established through the ATLAS+CMS combination

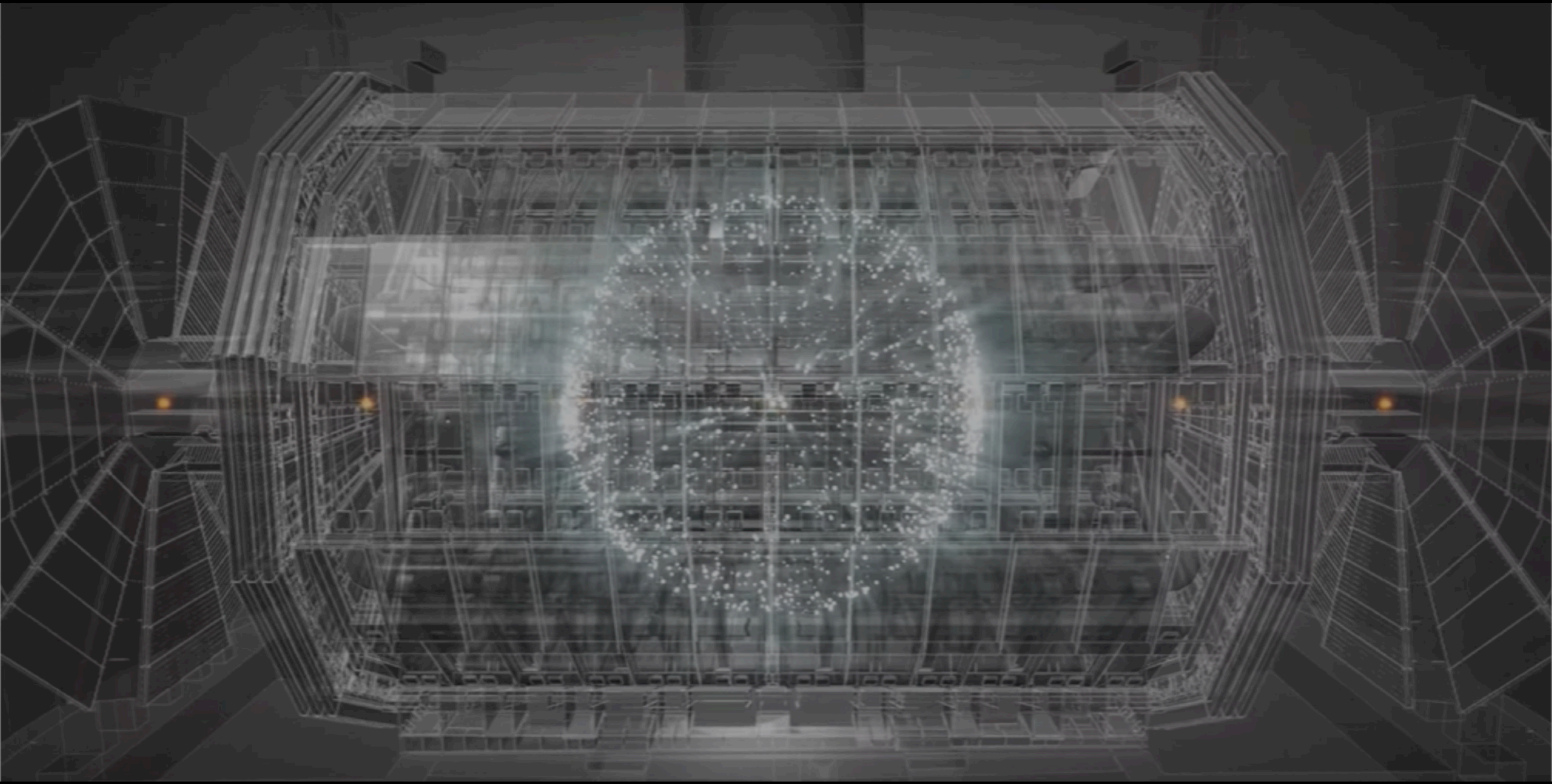
All coupling modifiers are lower than predicted.

low k_b value decreases total Higgs width through dominant Γ_{bb} partial decay width.

Need to measure all couplings precisely

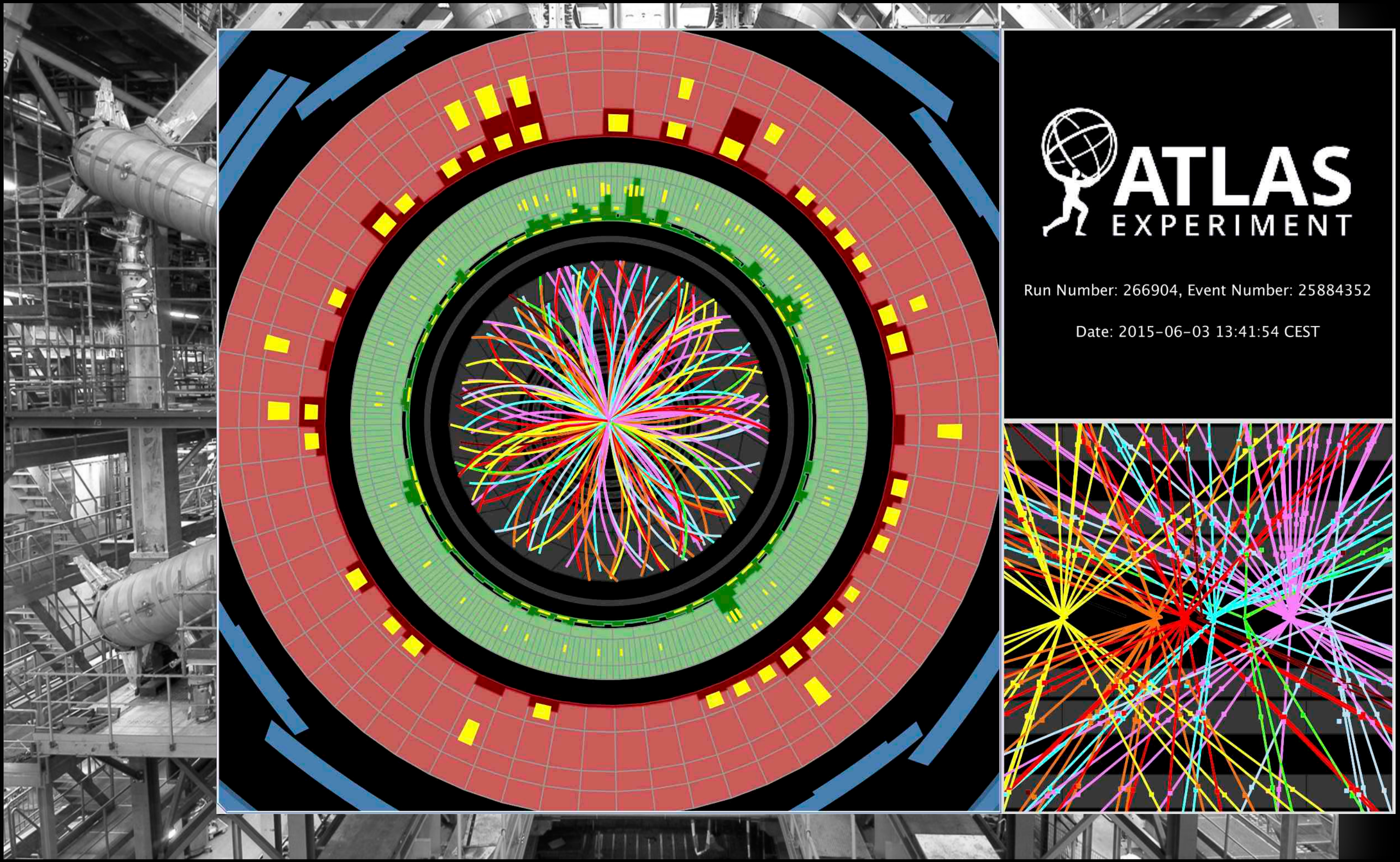


Collisions at the Large Hadron Collider



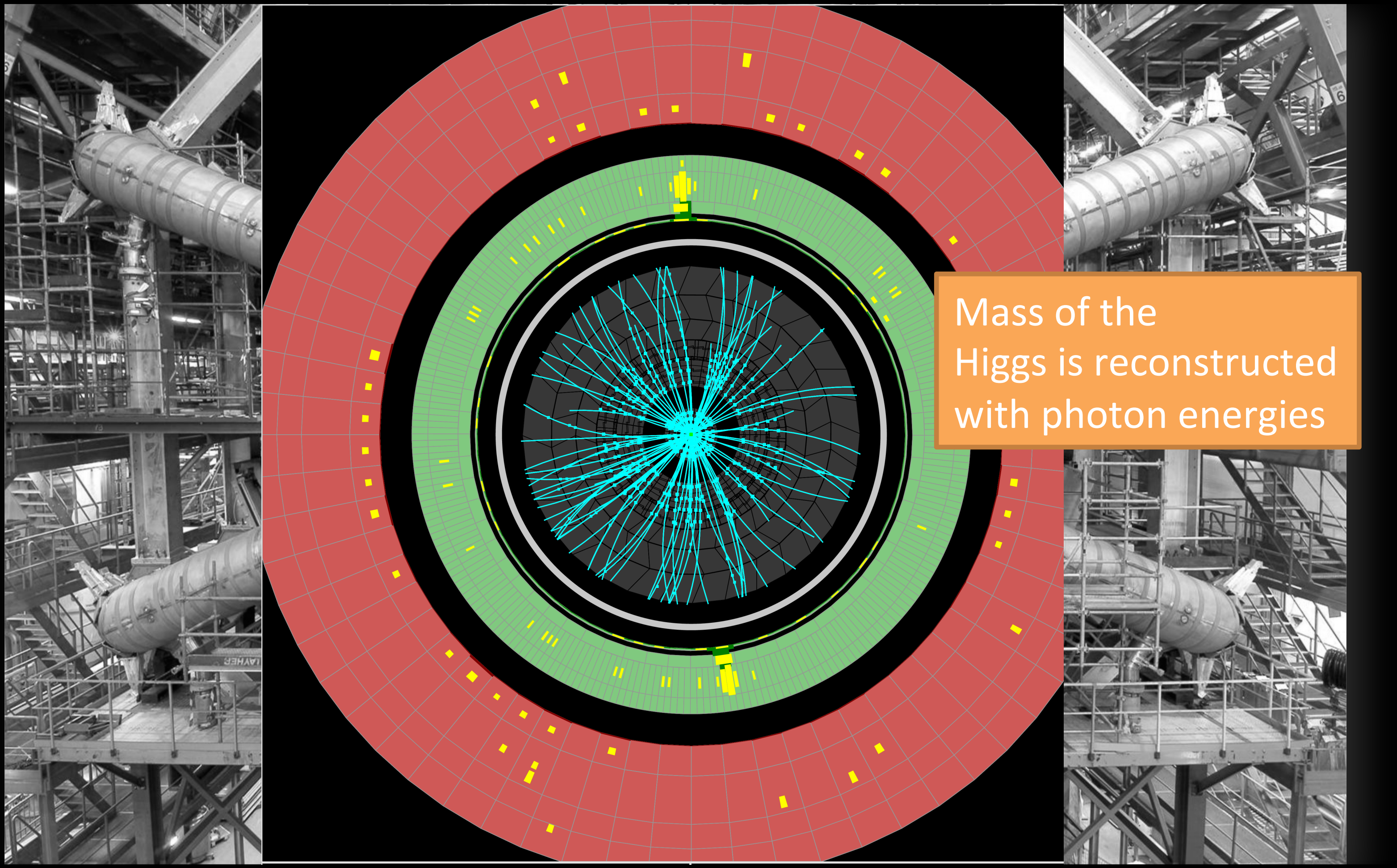
Bunch crossing every 25 ns… many collisions per bunch crossing

Most events look like this…



Event from LHC run-2

1 in >1000 billion events looks like this

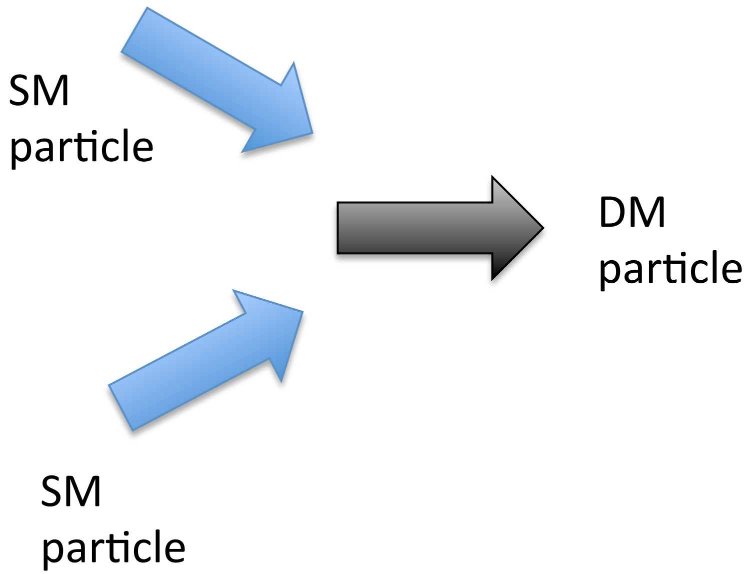


Higgs ->gamma gamma candidate with mass of 125 GeV

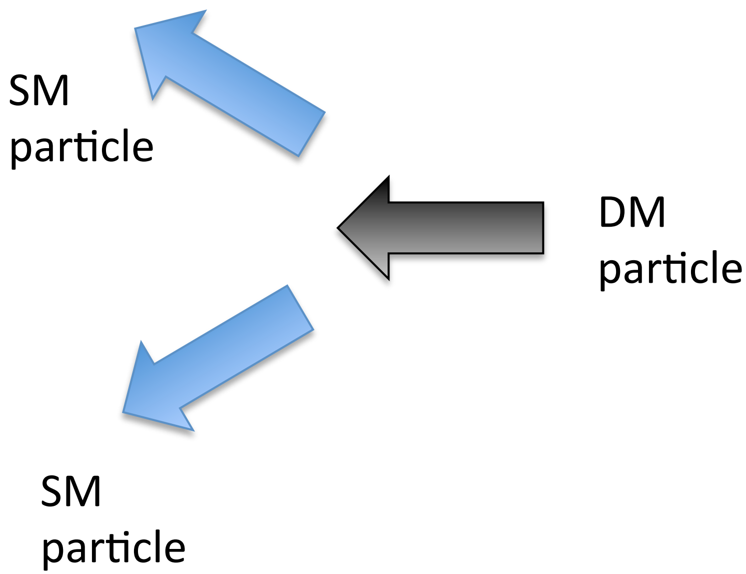
New physics searches at LHC

- Let's start with Dark Matter

Dark Matter production

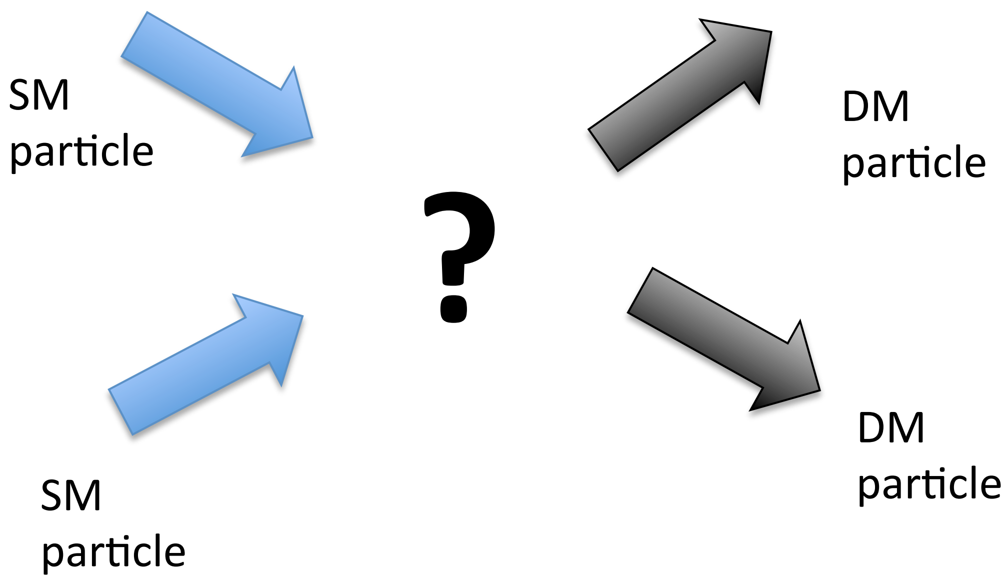


Dark Matter production



DM would likely be unstable

Dark Matter production

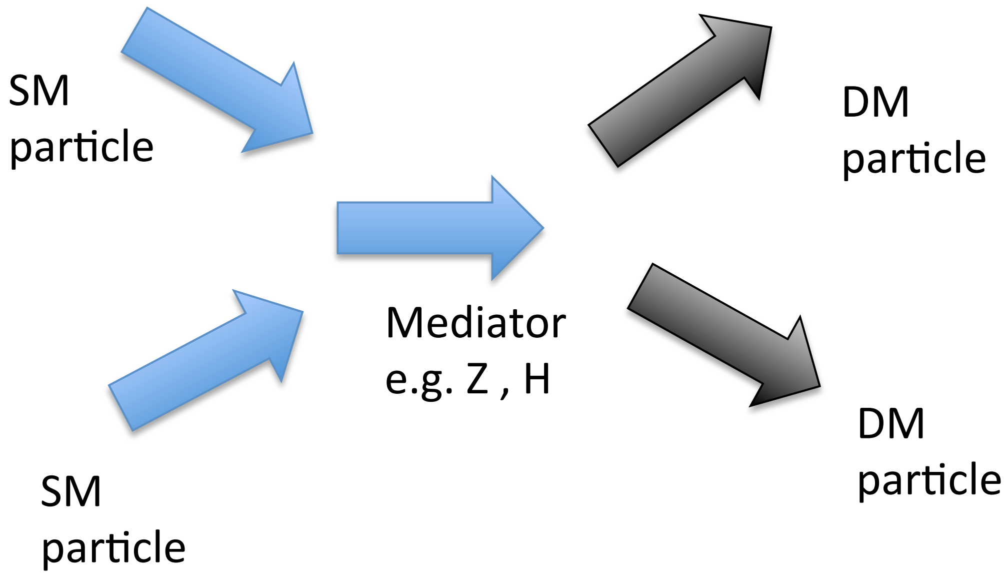


Most WIMP theories have a (Z2-symmetry, e.g. R-parity for SUSY) Quantum Number conservation to forbid too large proton decay rate

→ DM particles produced in pairs

→ DM is then stable!

Dark Matter production



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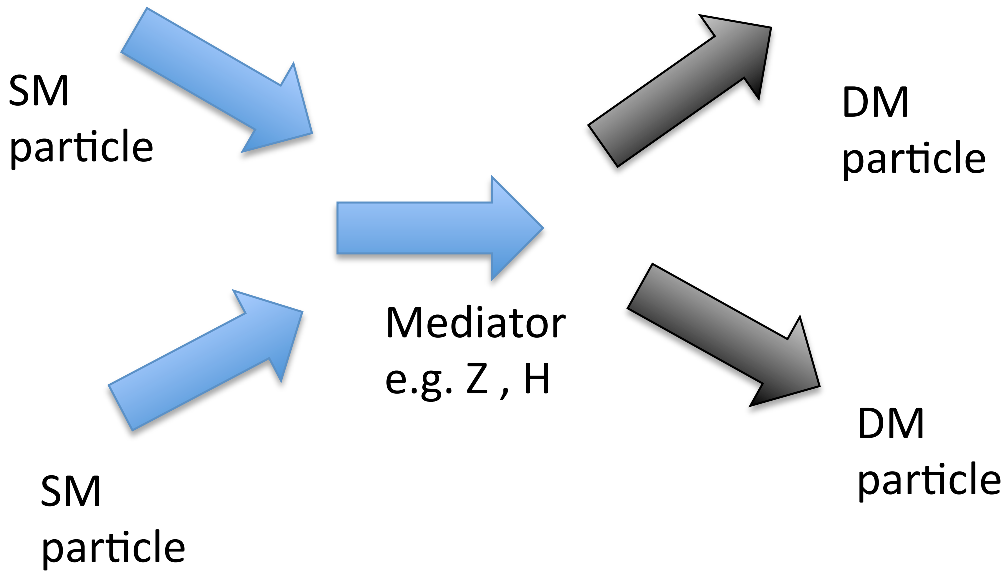
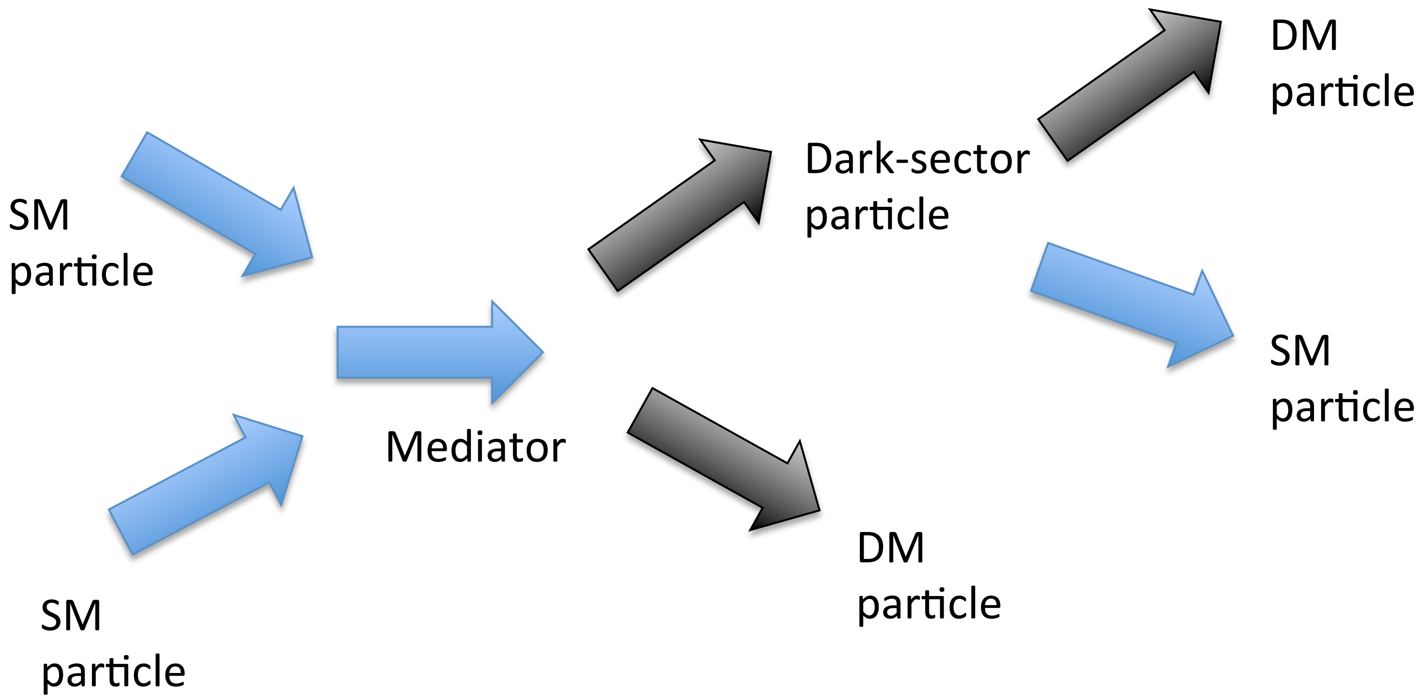
Dark Matter production



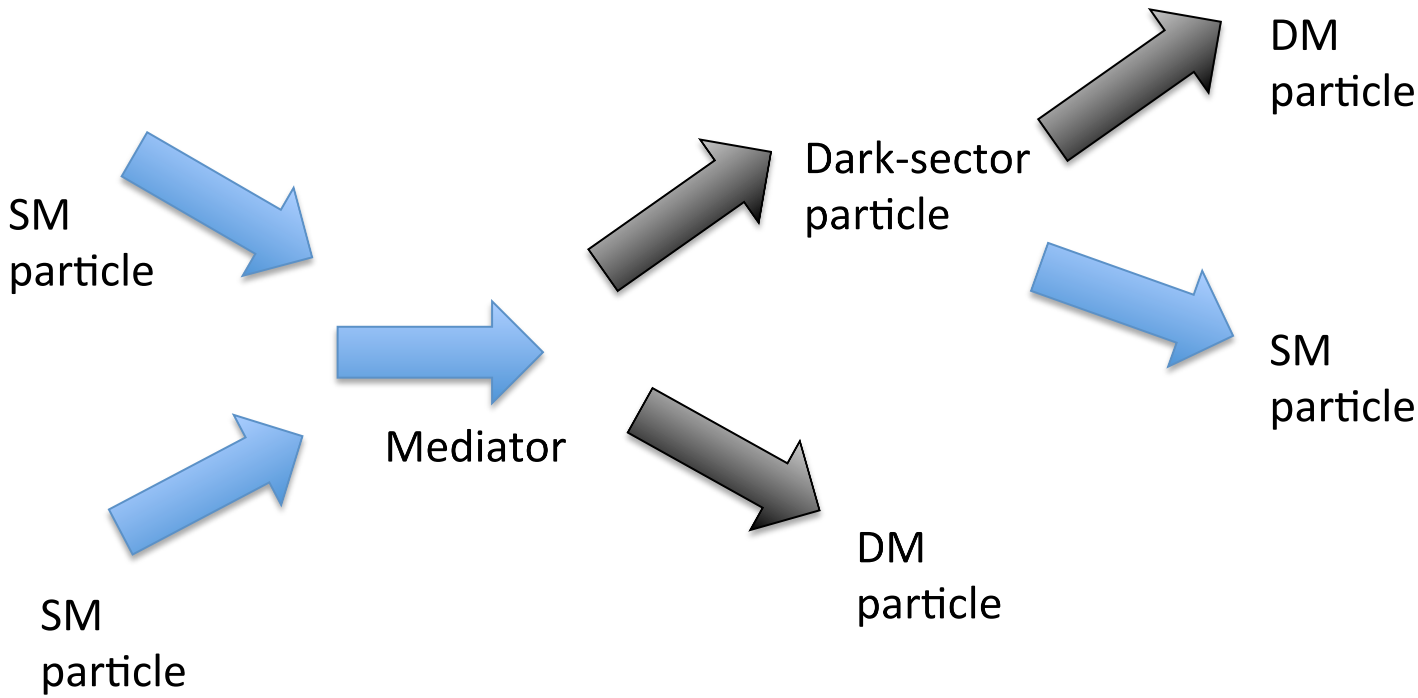
Stable and only weakly Interacting
- → Like neutrino
- → Too low interaction cross section to be visible in LHC detector

We see nothing at LHC

Dark Matter production



Dark Matter production

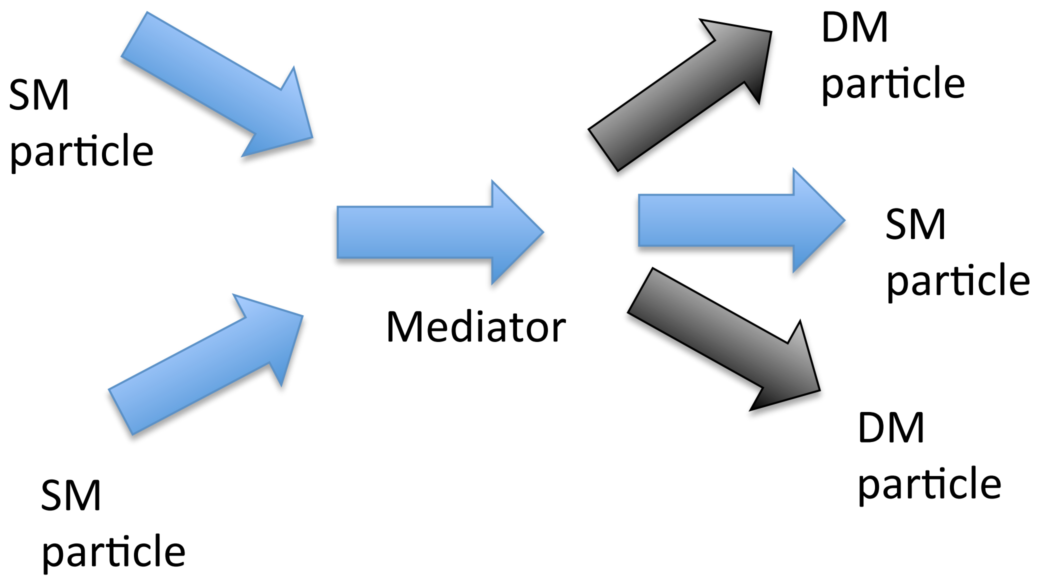


→ SM particle + Missing Momentum

Detectable at LHC if rate high enough !

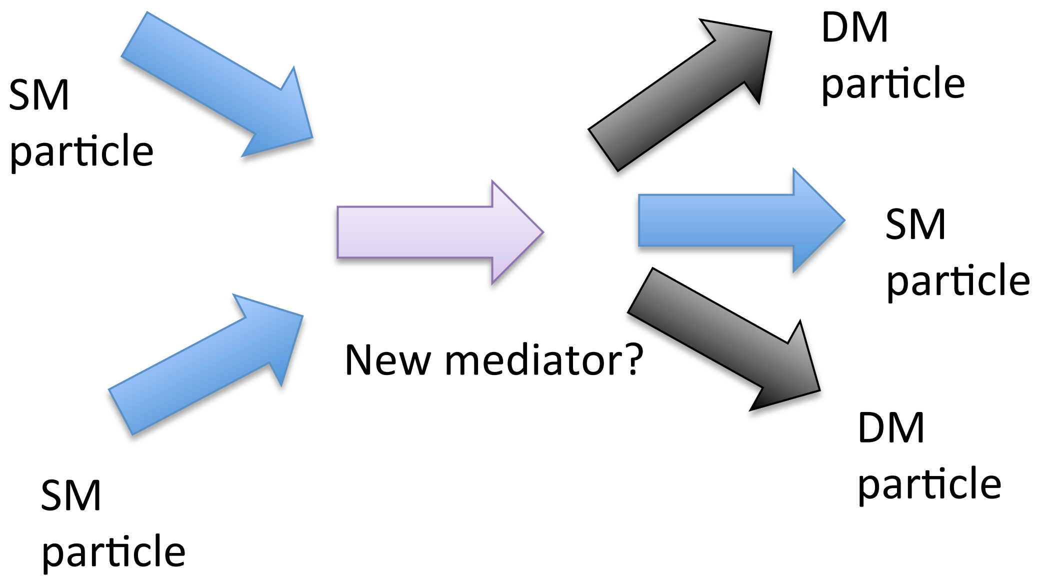
Dark Sector particle example:
SUSY gluino…

Dark Matter production



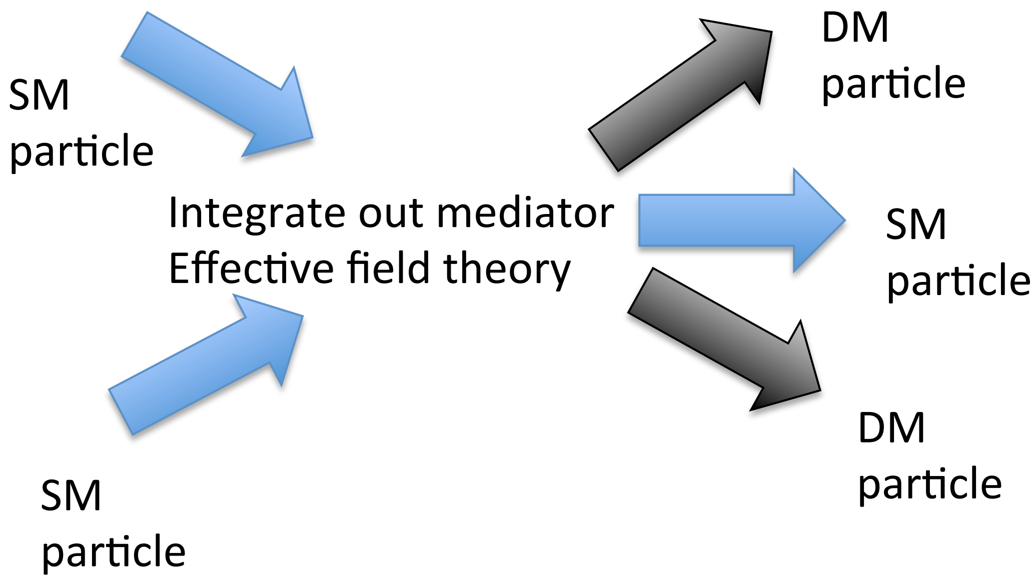
Detectable at LHC
if rate high enough !

Dark Matter production



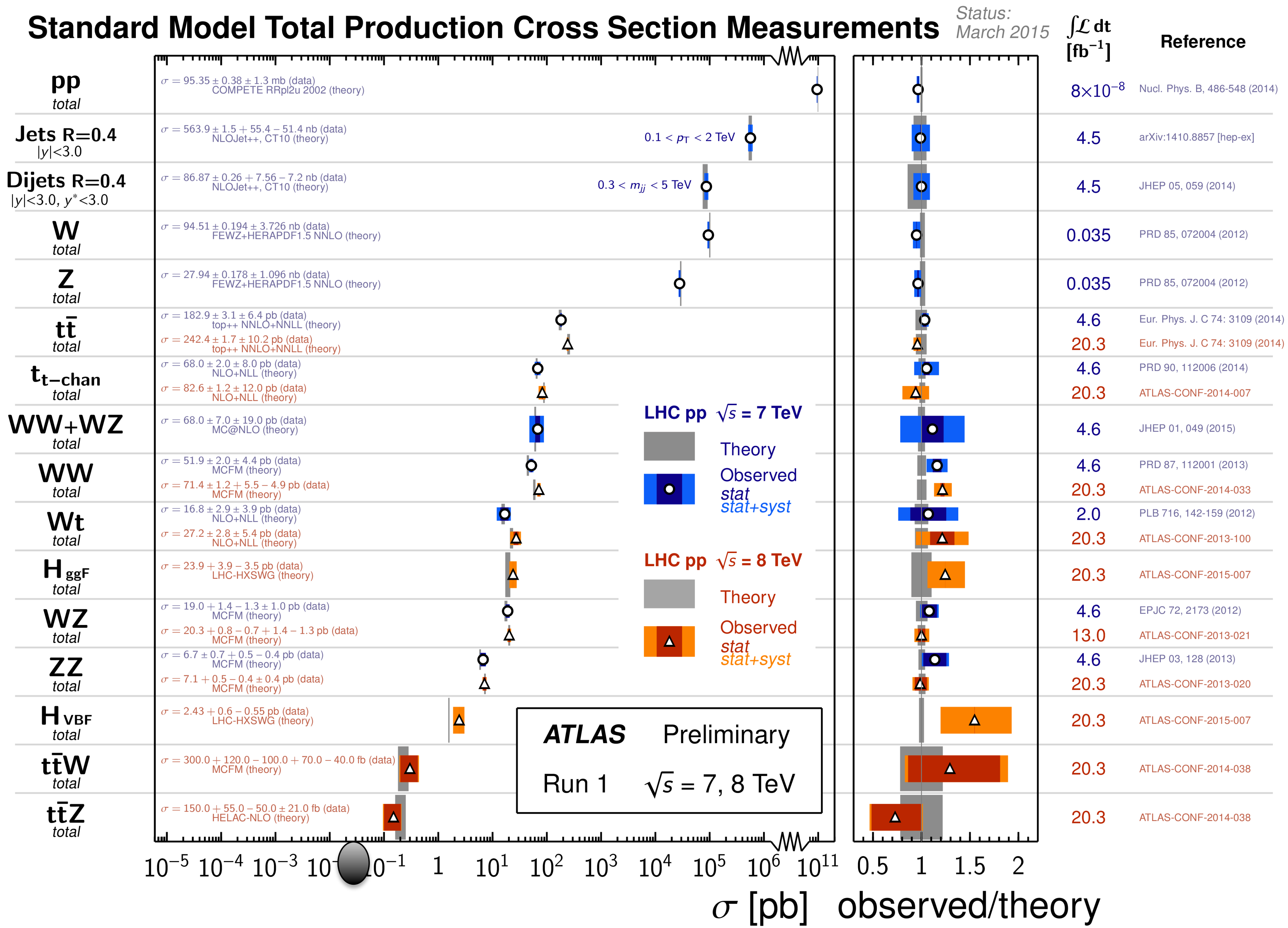
Detectable at LHC
if rate high enough !
New mediator models

Dark Matter production

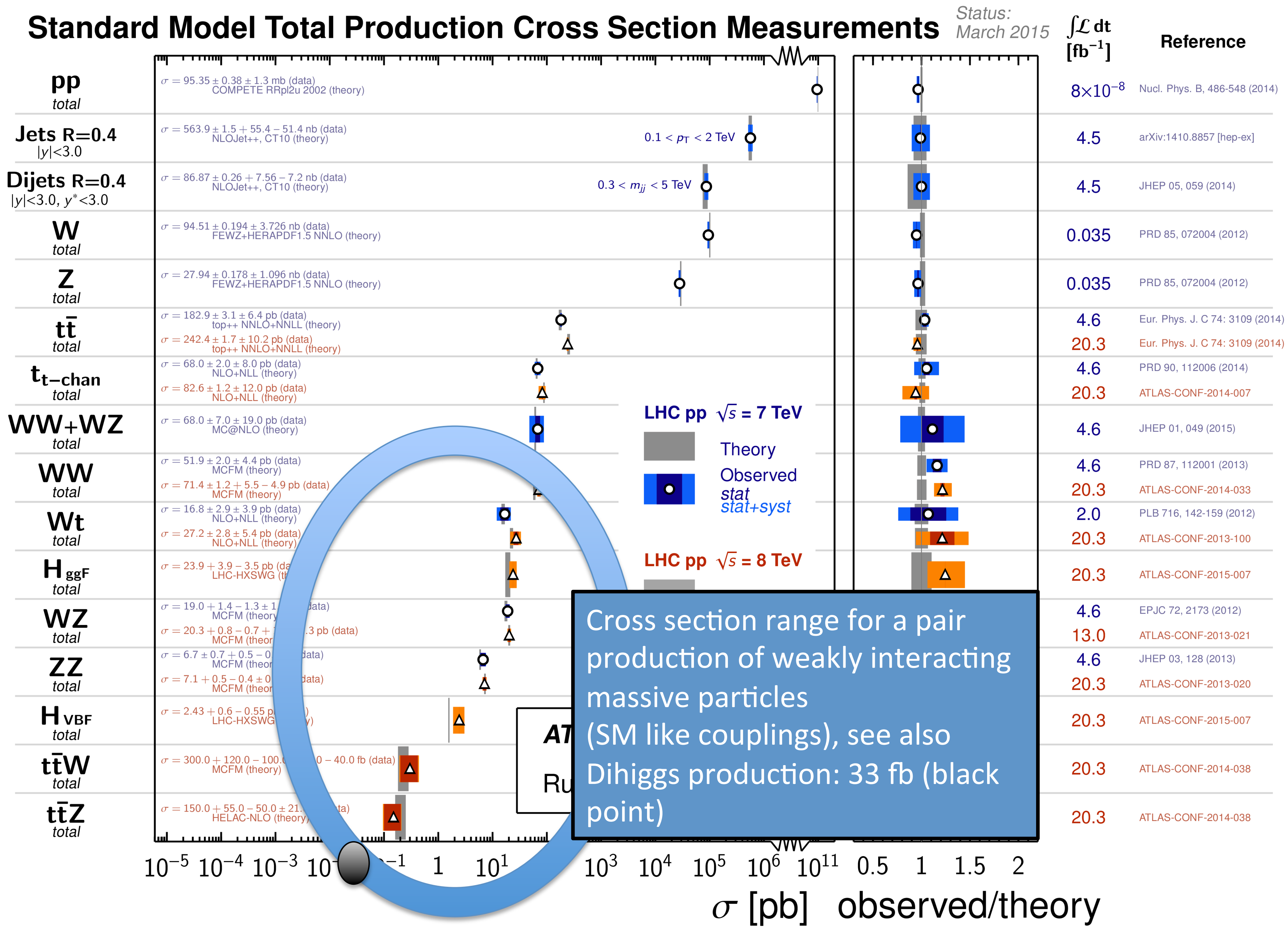


EFT/Contact Interactions work
if mediator is very heavy
Might not be the case at LHC
Is not the case if weakly interacting

How large is the expected WIMP production cross section?



Standard Model Total Production Cross Section Measurements
Status: March 2015
∫ℒ dt [fb⁻¹]
Reference
pp total
σ = 95.35 ± 0.38 ± 1.3 mb (data)
COMPETE RRpl2u 2002 (theory)
8×10⁻⁸
Nucl. Phys. B, 486-548 (2014)
Jets R=0.4 |y|<3.0
σ = 563.9 ± 1.5 + 55.4 − 51.4 nb (data)
NLOJet++, CT10 (theory)
0.1 < pT < 2 TeV
4.5
arXiv:1410.8857 [hep-ex]
Dijets R=0.4 |y|<3.0, y*<3.0
σ = 86.87 ± 0.26 + 7.56 − 7.2 nb (data)
NLOJet++, CT10 (theory)
0.3 < mjj < 5 TeV
4.5
JHEP 05, 059 (2014)
W total
σ = 94.51 ± 0.194 ± 3.726 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
Z total
σ = 27.94 ± 0.178 ± 1.096 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
tt̄ total
σ = 182.9 ± 3.1 ± 6.4 pb (data)
top++ NNLO+NNLL (theory)
4.6
Eur. Phys. J. C 74: 3109 (2014)
σ = 242.4 ± 1.7 ± 10.2 pb (data)
top++ NNLO+NNLL (theory)
20.3
Eur. Phys. J. C 74: 3109 (2014)
tt−chan total
σ = 68.0 ± 2.0 ± 8.0 pb (data)
NLO+NLL (theory)
4.6
PRD 90, 112006 (2014)
σ = 82.6 ± 1.2 ± 12.0 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2014-007
WW+WZ total
σ = 68.0 ± 7.0 ± 19.0 pb (data)
MC@NLO (theory)
4.6
JHEP 01, 049 (2015)
WW total
σ = 51.9 ± 2.0 ± 4.4 pb (data)
MCFM (theory)
4.6
PRD 87, 112001 (2013)
σ = 71.4 ± 1.2 + 5.5 − 4.9 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-033
Wt total
σ = 16.8 ± 2.9 ± 3.9 pb (data)
NLO+NLL (theory)
2.0
PLB 716, 142-159 (2012)
σ = 27.2 ± 2.8 ± 5.4 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2013-100
H ggF total
σ = 23.9 + 3.9 − 3.5 pb (data)
LHC-HXSWG (theory)
20.3
ATLAS-CONF-2015-007
WZ total
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data)
MCFM (theory)
4.6
EPJC 72, 2173 (2012)
σ = 20.3 + 0.8 − 0.7 + 1.4 − 1.3 pb (data)
MCFM (theory)
13.0
ATLAS-CONF-2013-021
ZZ total
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data)
MCFM (theory)
4.6
JHEP 03, 128 (2013)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2013-020
H VBF total
σ = 2.43 + 0.6 − 0.55 pb (data)
LHC-HXSWG (theory)
20.3
ATLAS-CONF-2015-007
tt̄W total
σ = 300.0 + 120.0 − 100.0 + 70.0 − 40.0 fb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-038
tt̄Z total
σ = 150.0 + 55.0 − 50.0 ± 21.0 fb (data)
HELAC-NLO (theory)
20.3
ATLAS-CONF-2014-038
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
0.5 1 1.5 2
σ [pb] observed/theory



Cross section range for a pair production of weakly interacting massive particles (SM like couplings), see also Dihiggs production: 33 fb (black point)

Models for Dark Matter@LHC

- Complete models:

  Supersymmetry (SUSY)

  (much less work on others, Extra Dim, Technicolor, etc.)

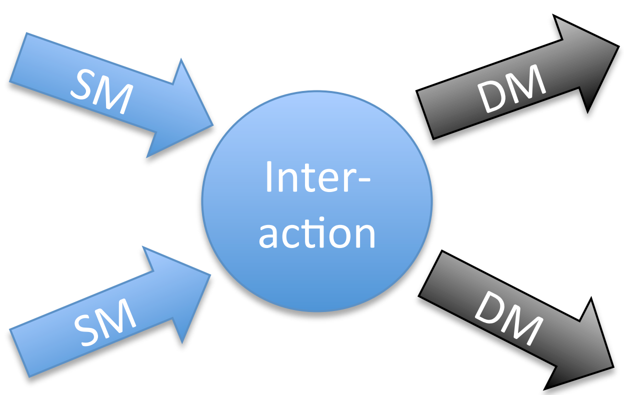
- Trying to be also more general… (but model-dependent!)

  - simplified models
  - effective field theories

Effective Field Theories/ Simplified models /Contact Interactions

- Simplified models: Simple theory with 2-3 parameters, simplification of a full theory

e.g. Mediator, DM, coupling



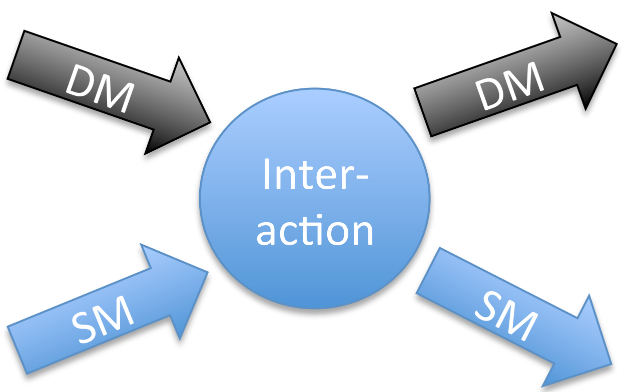
Limit on
Interaction and DM mass

EFT: Assume effective couplings

Effective Field Theories/ Simplified models /Contact Interactions

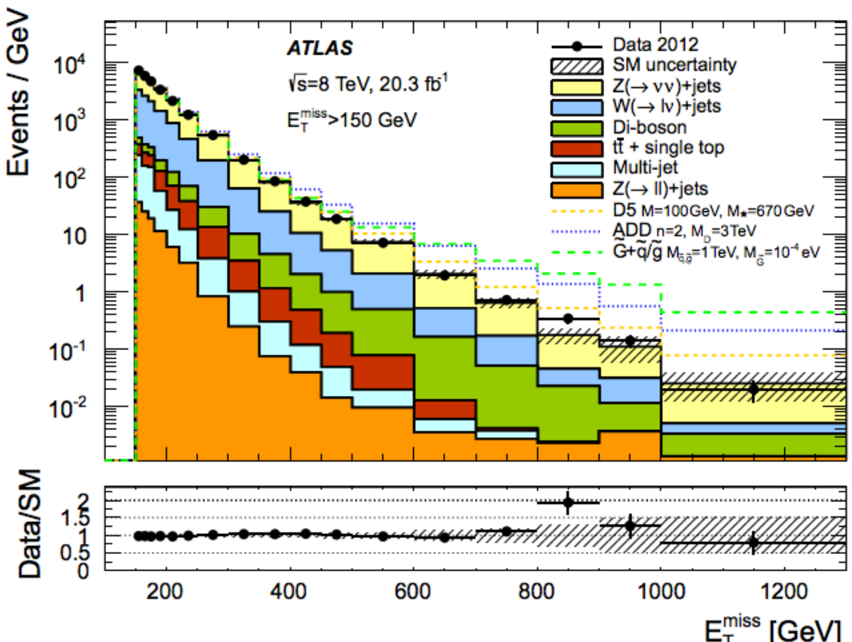
- Simplified models: Simple theory with 2-3 parameters, simplification of a full theory

  e.g. Mediator, DM, coupling



LHC limit can be converted to ***direct DM detection*** experiments

Monojets interpreted with EFTs



(b)

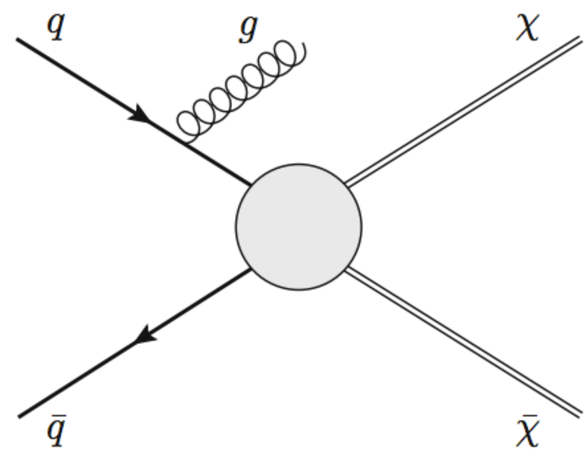
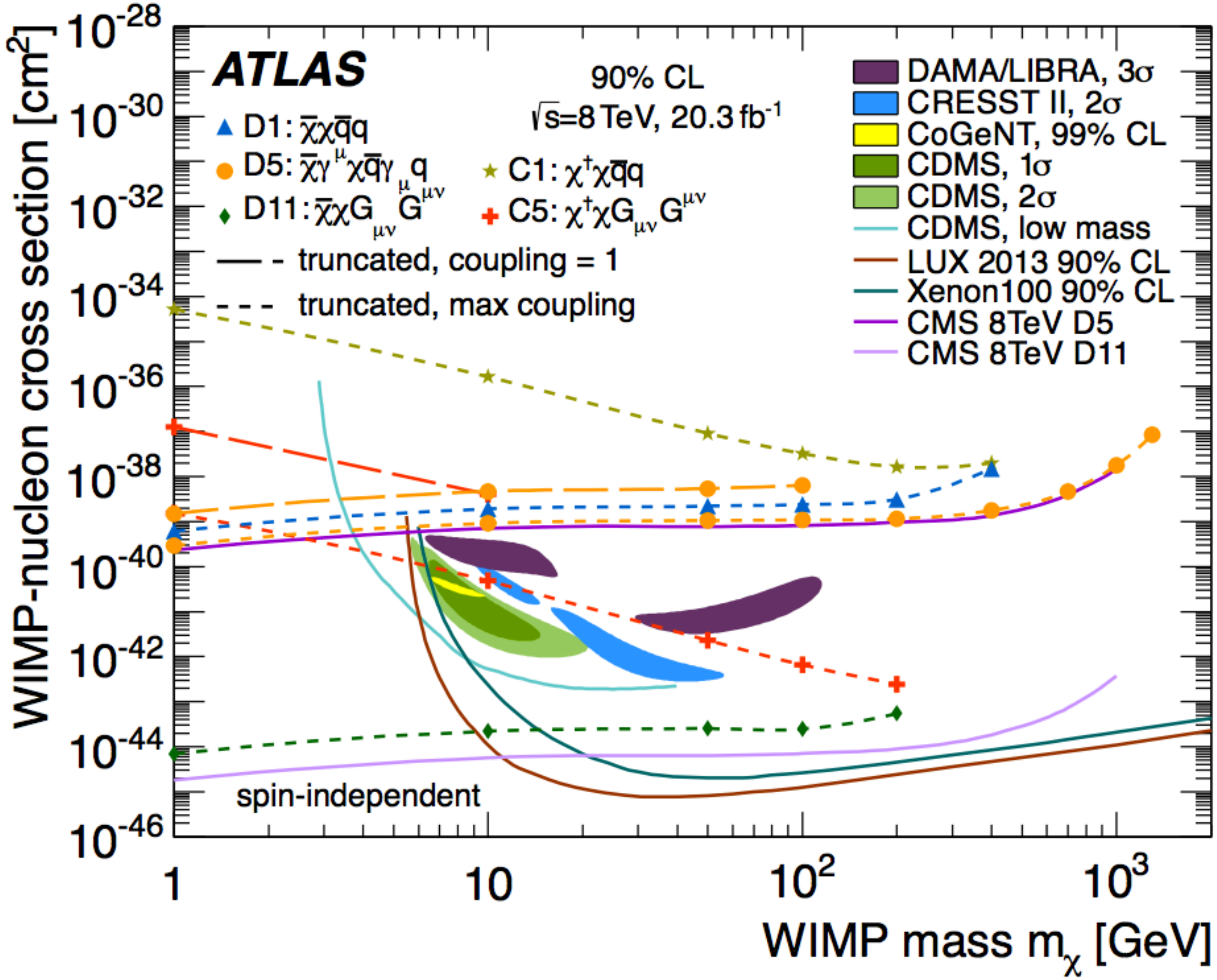


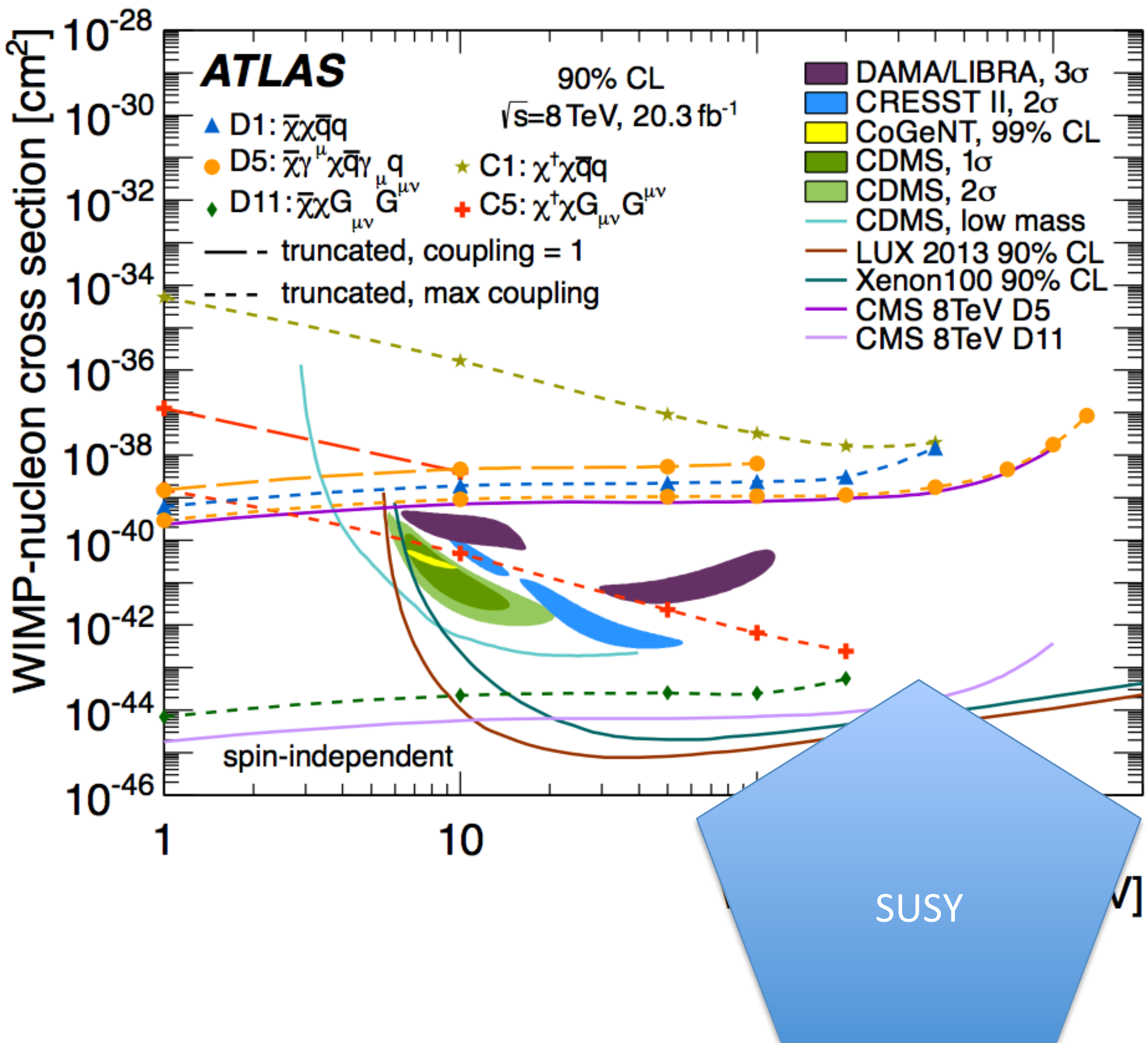
Table 1 Effective interactions coupling WIMPs to Standard Model quarks or gluons, following the formalism in Ref. [41], where $M_\star$ is the suppression scale of the interaction. Operators starting with a D describe Dirac fermion WIMPs, the ones starting with a C are for scalar WIMPs and $G^a_{\mu\nu}$ is the colour field-strength tensor

Name	Initial state	Type	Operator
C1	qq	Scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	Scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	Scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	Vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	Axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	Tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	Scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

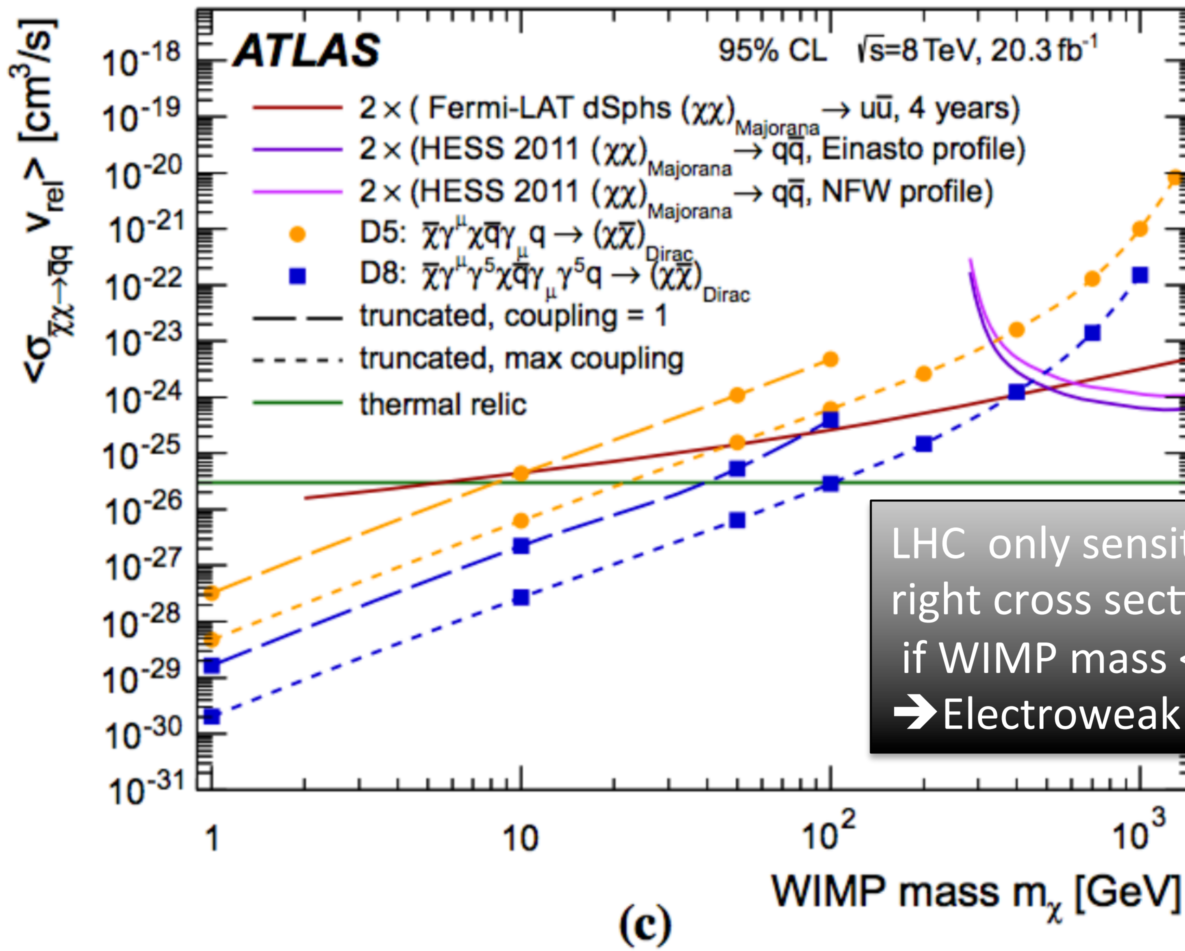
DM limits effective models



DM limits effective models



$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \, \mathrm{s}^{-1}$$



LHC only sensitive to
right cross sections
if WIMP mass < 40 GeV …
➔Electroweak scale not tested yet!

EFT → simplified DM models

- Critics: At LHC likely mediator particle not too heavy →EFT not applicable
- In Run2: Change interpretation from EFT to "simplified DM models", i.e.

  models with mediator M (e.g. Z'), DM mass,

  and couplings

Example : Monojets re-interpretation

- Interpretation with a vector s-channel mediator *V* (Z' type), DM can be dirac fermion of complex scalar:

$$\mathcal{L}_{\text{fermion},V} \supset V_\mu \bar{\chi}\gamma^\mu (g_\chi^V - g_\chi^A \gamma_5)\chi + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f \,,$$

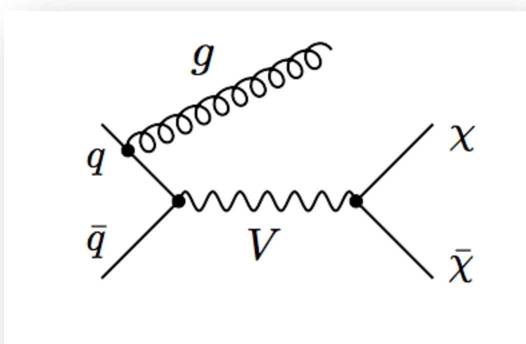
$$\mathcal{L}_{\text{scalar},V} \supset i g_\varphi V_\mu (\varphi^* \partial^\mu \varphi - \varphi \partial^\mu \varphi^*) + \sum_{f=q,\ell,\nu} V_\mu \bar{f}\gamma^\mu (g_f^V - g_f^A \gamma_5) f \,,$$

Parameters:

$$\{m_\chi,\, M_V,\, g_\chi^V,\, g_u^V,\, g_d^V,\, g_\ell^V\} \,,$$

while, in the latter case, the corresponding set is

$$\{m_\chi,\, M_V,\, g_\chi^A,\, g_u^A,\, g_d^A,\, g_\ell^A\} \,.$$



Dark matter + mono-jet

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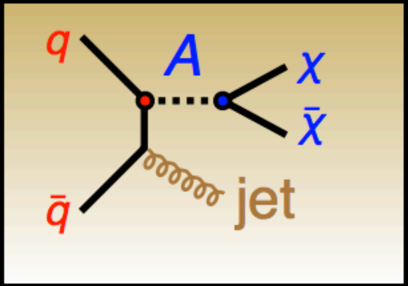
Pittsburgh



Mono-jet

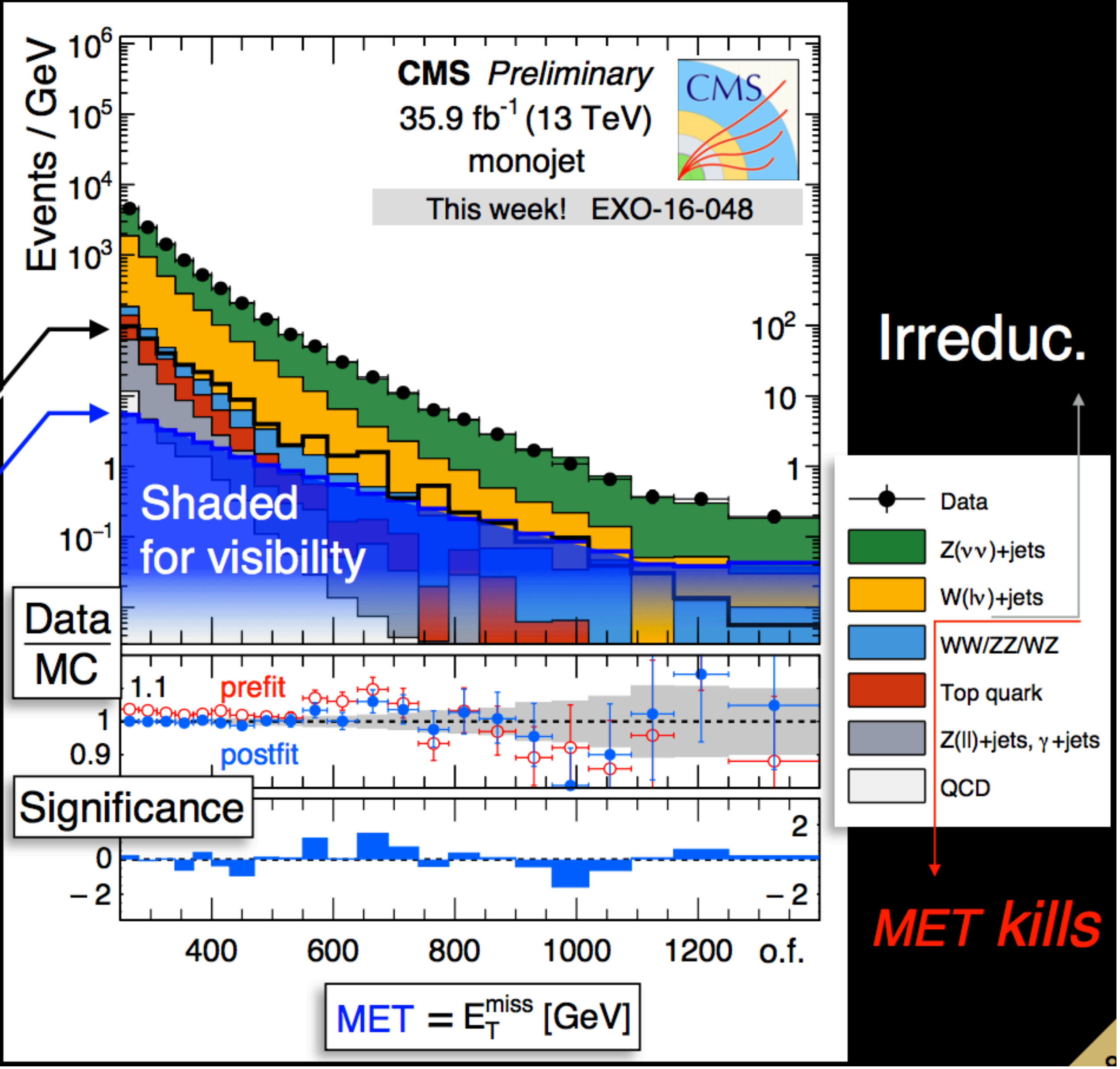
Signal models

Higgs invisible

Axial-vector
$m_{med} = 2$ TeV
(more later)

MET ≳ 200 GeV v. largest processes

- Kills di-jet, multi-jet
- Kills $t\bar{t}$
- Kills W, Z, γ



Irreduc.

MET kills

Mediator resonance search

Mediator via di-jet

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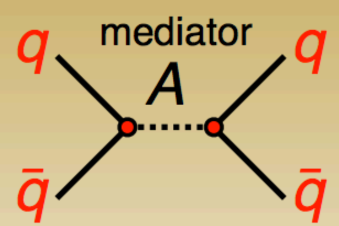


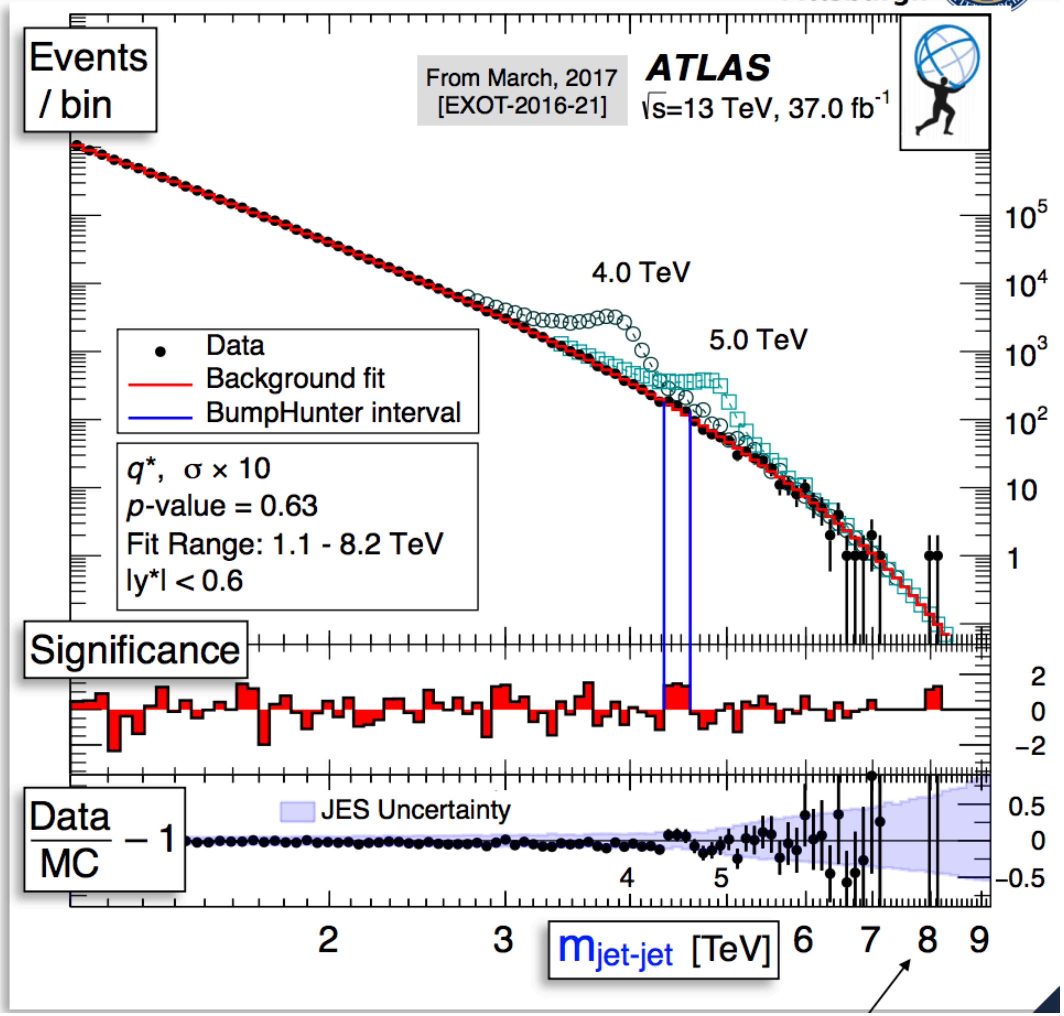
Challenges

- Di-jets high rate
- $m_{jet\text{-}jet}$ threshold

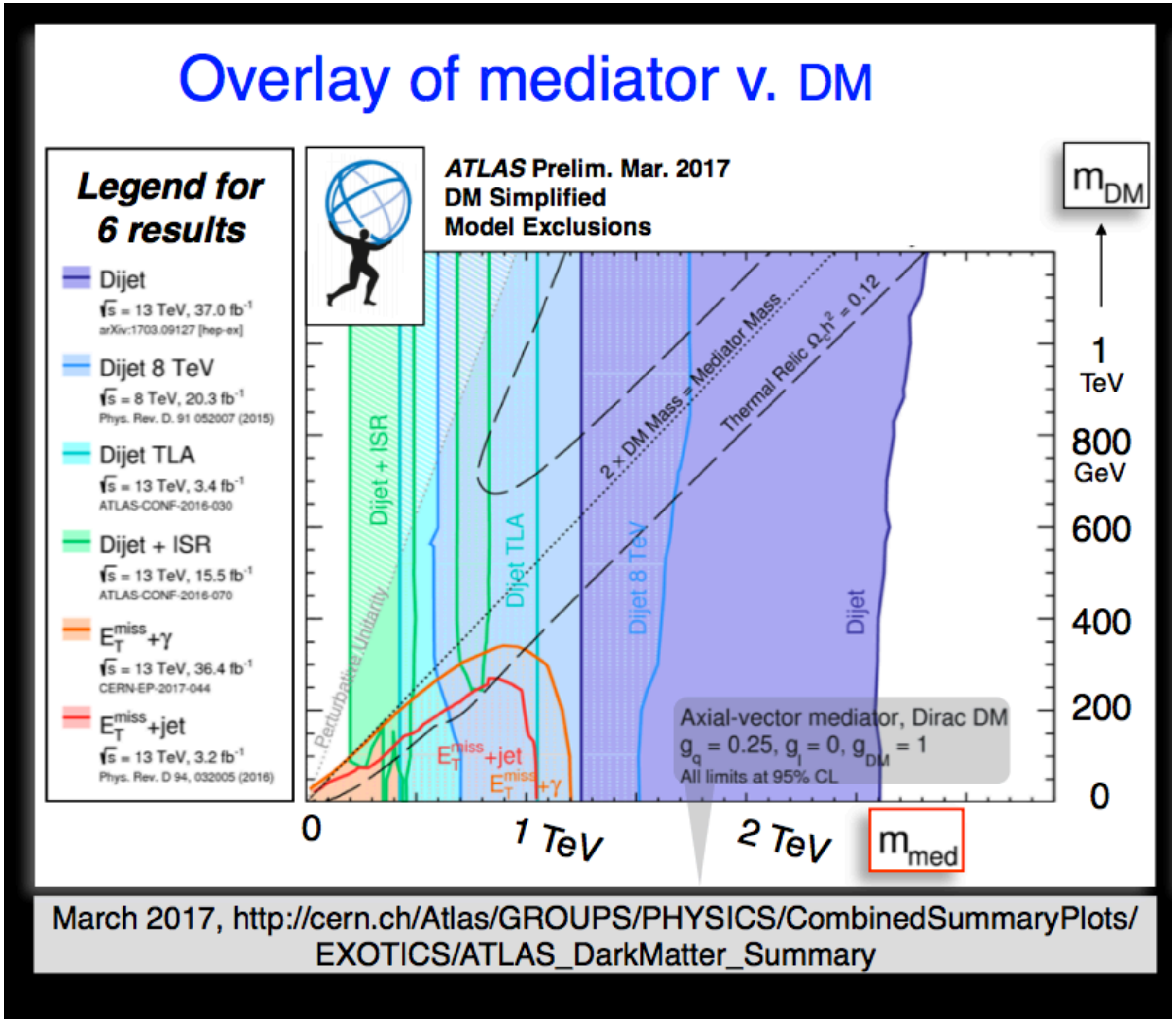
Solutions

- ISR jet / photon
- Boosted jet-jet
- Save trig.-level (more later)

Display of event here next slide



Limits mediator vs DM



Example: Dirac Fermion Dark Matter

$$\mathcal{L}_{\text{fermion},\phi} \supset -g_\chi \phi \bar{\chi}\chi - \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) ,$$

$$\mathcal{L}_{\text{fermion},a} \supset -i g_\chi a \bar{\chi}\gamma_5\chi - \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right) .$$

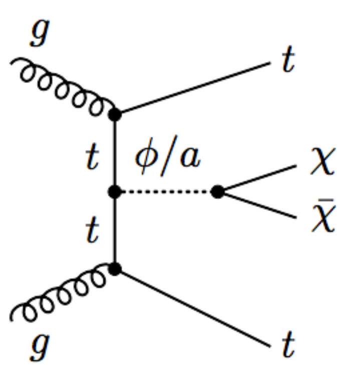
scalar ϕ or pseudoscalar a

$y_i^f = \sqrt{2} m_i^f / v$ with v the Higgs VEV.

Set op parameters:

$$\{m_\chi,\ m_{\phi/a},\ g_\chi,\ g_u,\ g_d,\ g_\ell\} .$$

https://arxiv.org/pdf/1506.03116.pdf



Higgs portal Dark Matter

3 scenarios:

- DM scalar singlet, couples with ^4 interaction with SM Higgs field
- DM is a fermion singler, couples to a scalar phi/a which mixes with the higgs (see previous slide)
- DM is a mixture of singlet and doublet (like in SUSY a bino-higgsino ➔ see SUSY) and then couples with the higgs

The future of invisible Higgs

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Pittsburgh

Luminosity projections

CMS Run-2 VBF results with 2.3 fb^{-1}

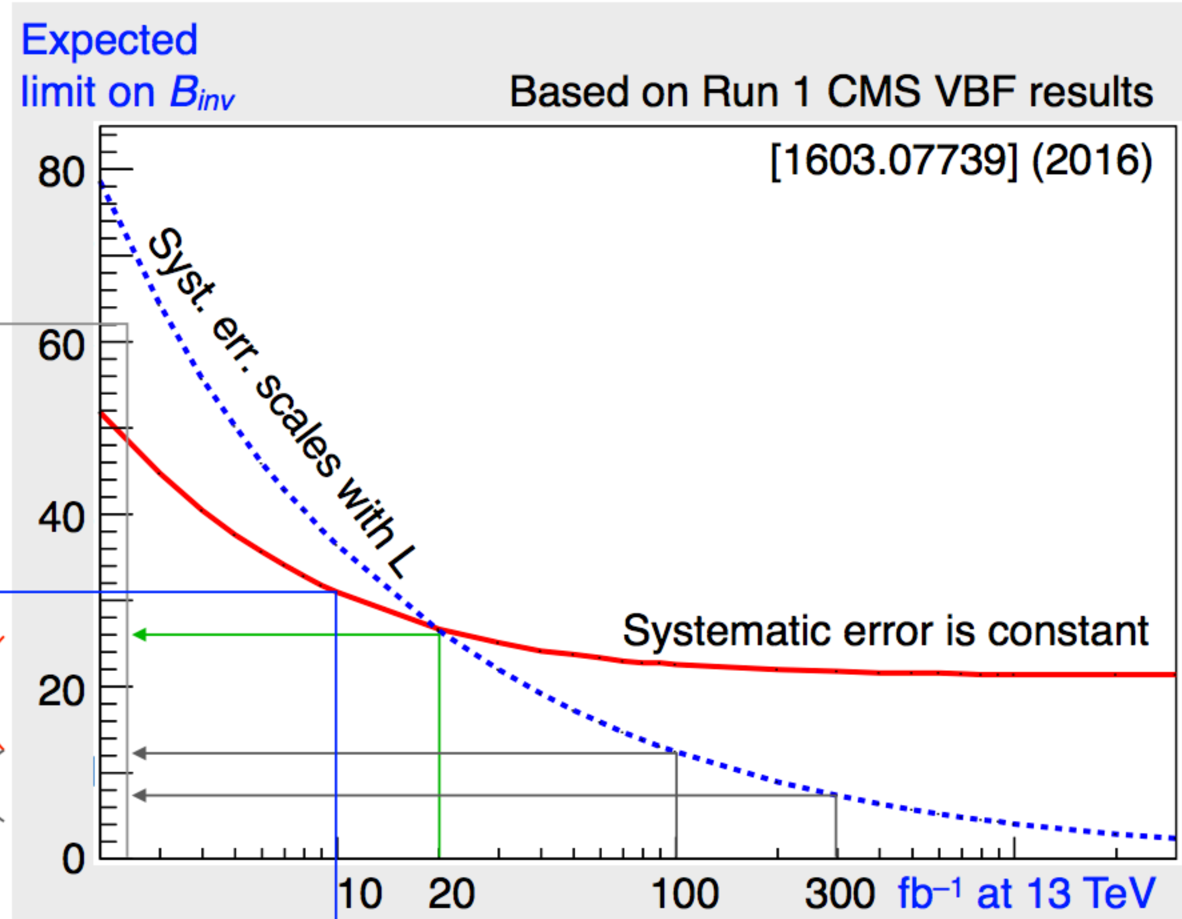
- Limit 69% (62%)
- *Z* norm'd w/ *W*

ATLAS Run-1 VBF

- Limit 28% (31%)
- *Z* norm'd w/ *W*

Run 2 target

Run 3+ target



Need 10 fb^{-1} of 13 TeV reach Run 1

We'll try for < 20% in Run 2

Maybe possible? < 10% in Run 3

Higgs portal scalar singlet and H->invisible

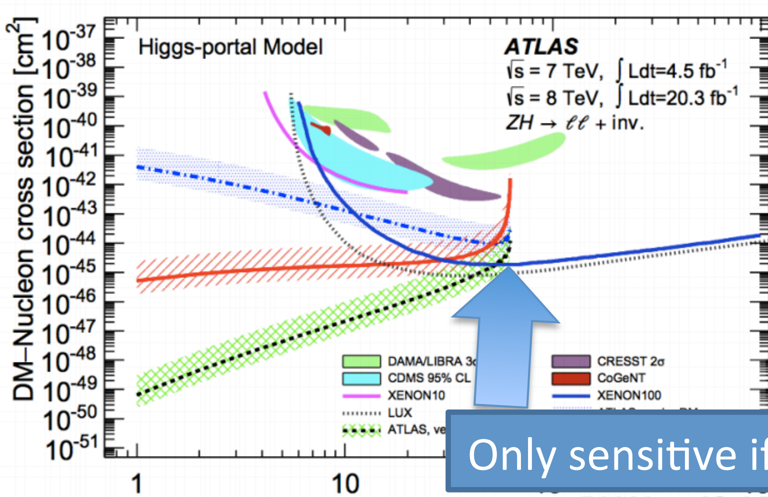
- SM simplest extension: Lagrangian = SM+ DM field
- DM couples to SM only via Higgs

$$\mathcal{L}_S = -\frac{\mu_S^2}{2}S^2 - \frac{\lambda_{hs}}{2}S^2 H^\dagger H - \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{\lambda_S}{4}\lambda_S S^4$$

Higgs invisible decay — Higgs-DM coupling — DM-nucleon xsec

$$\Gamma(h \to \chi\chi) \Leftrightarrow \lambda_{h\chi\chi}^2 \Leftrightarrow \sigma_{N\chi}$$

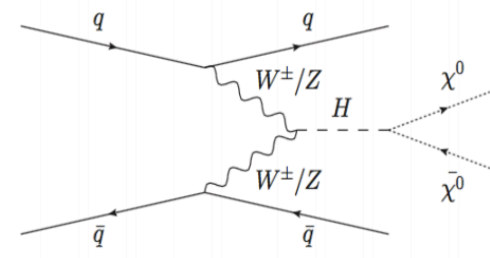
$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$



Only sensitive if DM < M_h/2

VBF

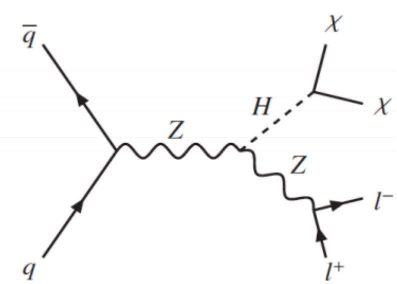
VBF production:

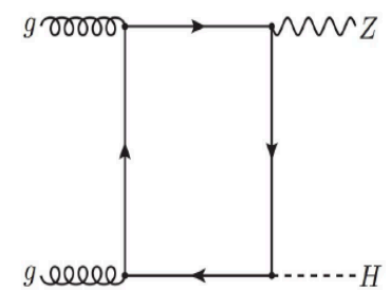


(a) Signal

- Energetic dijets system (Large Δη)+ MET
- Most sensitive channel **BR< 28% RunI**

ZH





Associate Higgs production with a Z boson:

- Opposite charge dilepton+ MET

ean signature **BR < 78% RunI**
BR < 98% RunII ICHEP

abr ecay NIKHEF outing

Neutral third party

Hong
Pittsburgh

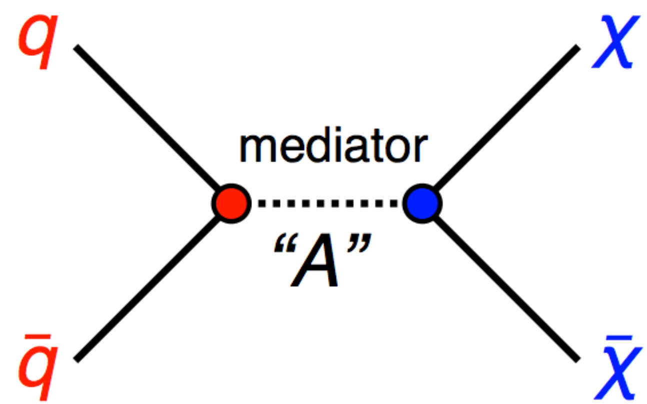
Features of mediator

^ prompt, colorless, etc.

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	∝ mass	∝ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$
Example chan.	mono-b	di-jet

Complementary in channels

Lagrangian parameters



$g_q\, \bar{q}qA$ — matter-mediator

$g_{DM}\, \bar{\chi}\chi A$ — DM-mediator

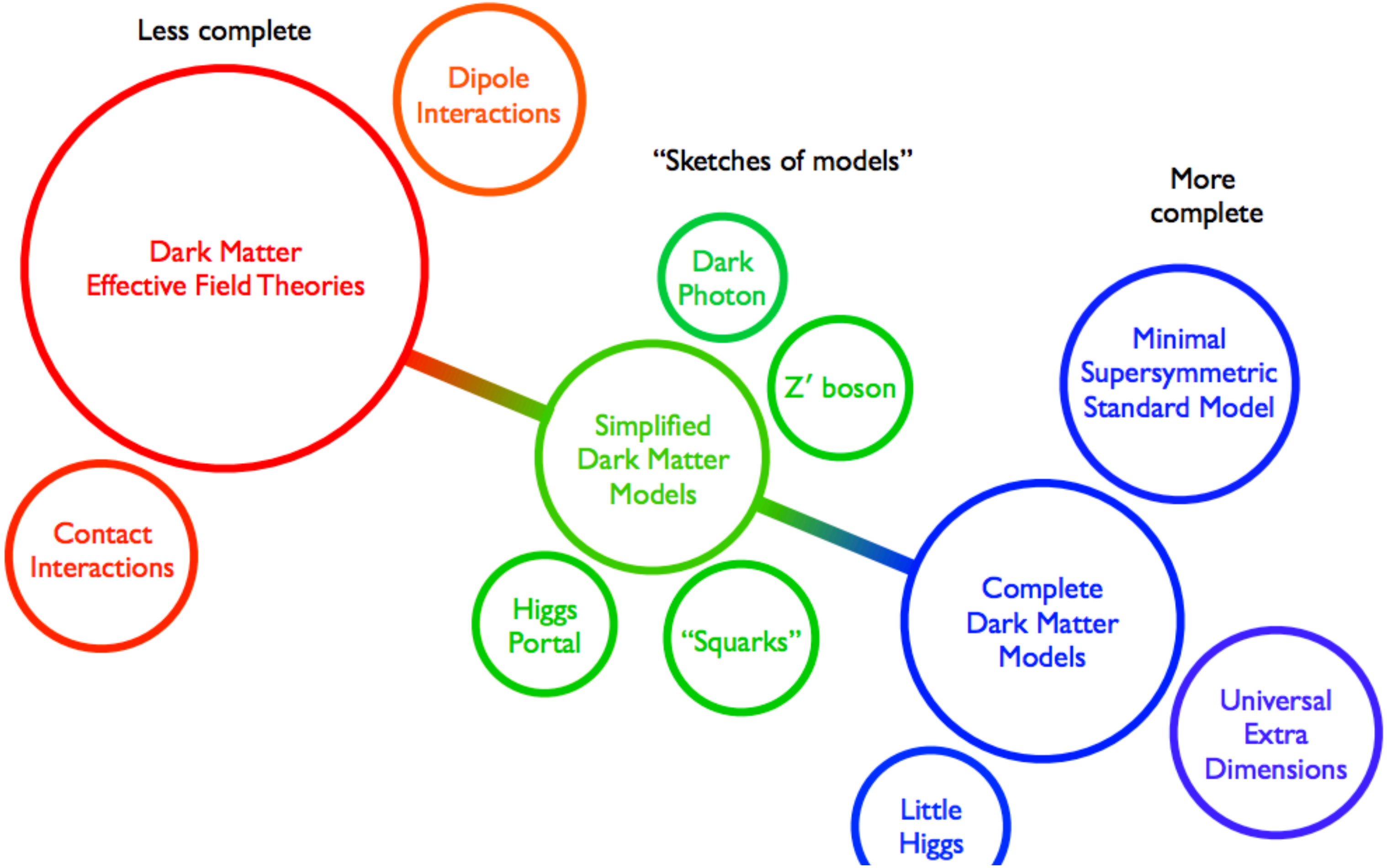
g_q ~~m_q~~ m_{med} g_{DM} m_{DM} ~~m_{med}~~

❶ known ❷ ❸ ❹ redundant

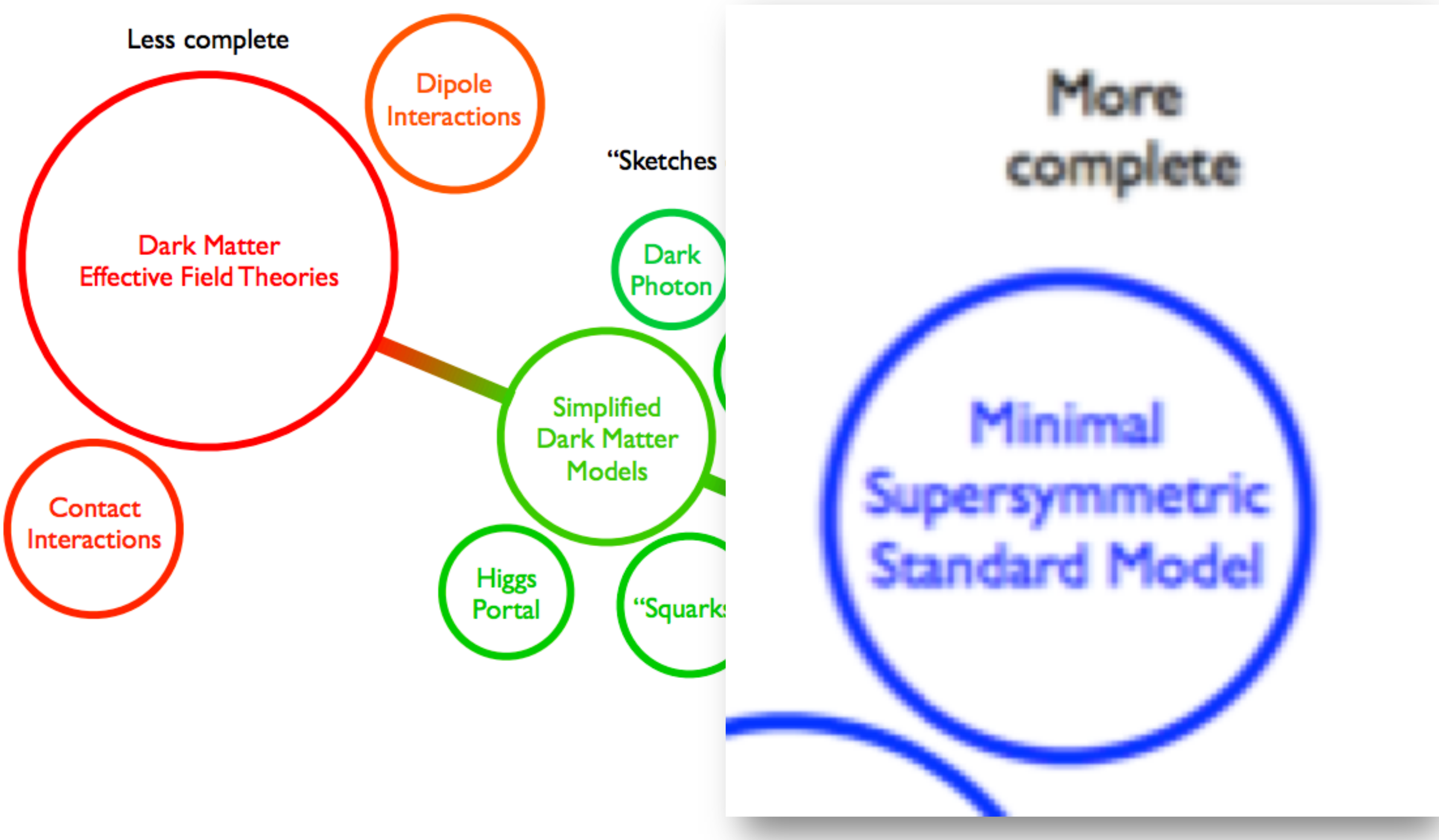
matrix element = 4 parameters

2d plots must assume 2 other param.

Full models


Less complete
Dipole Interactions
Dark Matter Effective Field Theories
Contact Interactions
"Sketches of models"
Dark Photon
Z′ boson
Simplified Dark Matter Models
Higgs Portal
"Squarks"
More complete
Minimal Supersymmetric Standard Model
Complete Dark Matter Models
Universal Extra Dimensions
Little Higgs

Full models



Less complete
Dipole Interactions
Dark Matter Effective Field Theories
Contact Interactions
"Sketches
Dark Photon
Simplified Dark Matter Models
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"Squarks
More complete
Minimal Supersymmetric Standard Model

Quarks (s=1/2)

Leptons (s=1/2)

Fields: Gluon
B and W's fields
(s=1)

Higgs (s=0)

SUSY

Scalar Quarks (s=0)
(squarks)

sLeptons (s=0)

Gluino
Bino, Wino's (s=1/2)

Higgsinos (s=1/2)

Quarks (s=1/2)

Leptons (s=1/2)

Fields: Gluon
B and W’s fields
(s=1)

Higgs (s=0)

Scalar Quarks (s=0)
(squarks)

sLeptons (s=0)

Gluino
Bino, Wino’s (s=1/2)

Higgsinos (s=1/2)

SUSY particles heavier, since
symmetry must be broken to give right Higgs mass!
- Minimal SUSY (MSSM), minimal number of parameters (105!)
- Lightest neutral SUSY particle is Dark Matter candidate

SUSY transformations

A supersymmetry (SUSY) transformation turns a bosonic state into a fermionic state, and vice versa.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle.$$

Operator Q that generates SUSY transformations must be a spinor (like a fermion): *(Why ?)*

Q† (the hermitian conjugate of Q) is also a symmetry
generator. Because Q and Q† are fermionic operators, they carry spin angular momentum ½
➔ supersymmetry must be a spacetime-spin symmetry.

SUSY transformations

Standard Model: chiral fermions (i.e., fermions whose left- and right-handed pieces transform differently under the gauge group) ➔ parity-violating interactions

To make this work the so called Hagen Lopusanski theorem says that the generators Q and Q† must satisfy an algebra of anticommutation (Q are fermionic) and commutation relations:

{Q, Q†} = P_μ
{Q, Q} = {Q†, Q†} = 0
[P_μ,Q] = [P_μ, Q†] = 0

where P_μ is the four-momentum generator of spacetime translation
(and Q has also an index).

$$\hat{P}_\mu = \left(\frac{1}{c}\hat{E}, -\hat{\mathbf{p}}\right) = i\hbar\left(\frac{1}{c}\frac{\partial}{\partial t}, \nabla\right) = i\hbar\partial_\mu$$

➔ SUSY: Space-time Spin symmetry !

SUSY particle states

The single-particle states of a supersymmetric theory fall into Supermultiples: They contains both fermion and boson states, which are commonly known as superpartners of each other.

Since two particle states in the supermultiplet are related by some Q and Q† and thus by P^2

➔ **The superpartners must have the same mass since P^2 is the mass operator**

The supersymmetry generators Q, Q† also commute with the generators of gauge transformations.

➔ **particles in the same supermultiplet must also be in the same representation of the gauge group, and so must have the same electric charges, weak isospin, and color degrees of freedom**.

➔ SUSY particles couple as their SM partners !!!

➔ Couplings are NO free parameters in SUSY !!!

SUSY supermultiplets

Each supermultiplet contains an equal number of fermion and boson degrees of freedom.

Important example:

➔Fermionic quark can be q_L and q_R =➔ Two different scalar quarks q_L and q_R

Simplest possibilities: (Weyl Fermion = solution of massless Dirac equation)

Chiral supermultiplet
- Weyl fermion two spin ½ states with different helicity/chirality
- two scalars (spin 0) , often merged into a complex scalar field, one as partner for each chirality

Gauge supermultiplet:
- one spin=1 field (must be massless gauge boson, i.e two helicity states)
- two spin=1/2 Weyl Fermions (two helicity states) with same gauge properties

(s=3/2 fermion ➔ Not renormalizable)

SUSY supermultiplets

- All SM particles need to be grouped in either a chiral or gauge supermultiplet.

- Quarks and Leptons → ?
- Massless bosons of the SM → ? (which ones?)
- Higgs fields of the SM ?

SUSY supermultiplets

- All SM particles need to be grouped in either a chiral or gauge supermultiplet.

- Quarks and Leptons → Chiral
- Massless bosons of the SM → Gauge
- Higgs fields of the SM → Chiral

Which spin do their SUSY partners have ?

SUSY supermultiplets → Spins

- All SM particles need to be grouped in either a chiral or gauge supermultiplet.

- Quarks and Leptons → Chiral → Spin 0 SUSY partners
- Massless bosons of the SM → Gauge → Spin 1/2
- Higgs fields of the SM → Chiral → Spin 1/2

Which spin do their SUSY partners have ?

SUSY supermultiplets → Names

- All SM particles need to be grouped in either a chiral or gauge supermultiplet.

- → Spin 0 SUSY partners → sfermions (scalar fermions)
- → Spin ½ gauge partners → gauginos
- → Spin ½ higgs partners → Higgsinos

Which spin do their SUSY partners have ?

Sfermions

SUSY partners of the left and right handed parts of electron field are called

left- and right-handed selectrons :

(note that they have NOT a right-handed helicity since they are not fermions but have spin 0, but they have the ***couplings*** *as there superpartners)*

Quarks ➔ squarks

Bottom quark ➔ sbottom

top ➔ stop

Higgs

- Sitting in chiral supermultiplet
- SM has 1 complex doublet higgs field (H_0,H+) giving mass to the W+- and Z0
- However:

In SUSY we need 2 complex doublet fields

sitting in 2 chiral supermultiplets.

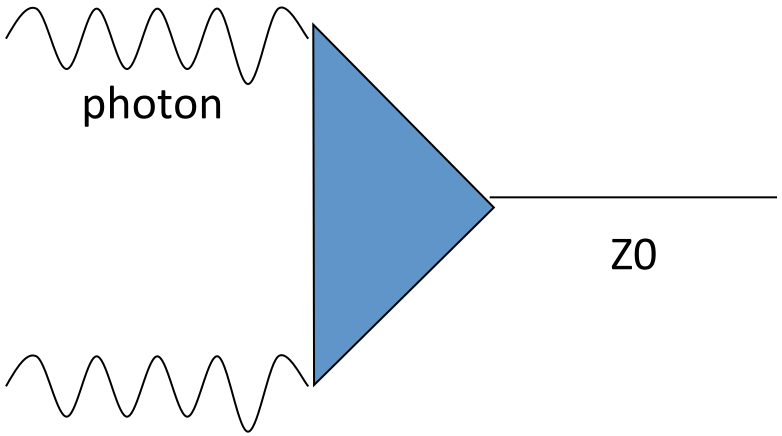
Why 2 Higgs supermultiplets?

- Before electroweak symmetry breaking we have a complex isospin doublet in the SM Higgs sector: H^+ and H^0 with 2 degrees of freedom each and Y=1/2

-> Q makes now the SUSY Higgs-fermions (they have 2 spins directions each) so everything seems to be OK

However so called triangular anomalies will appear!
What is this?
Higher order graphs
become divergent for left handed
fermions
if not Σ Y = 0 (Y is the weak hypercharge)

(vanishes in the SM
for each generation -> Why?)



Solution:
Introduce at least two Higgs (Higgsino) doublets with opposite hypercharge
This is called the 2HDM !

Model building - supermultiplets

Organize fermions and bosons in spin multiplets

Table 1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model.

(Color,chirality,hypercharge = $Q-I_{3L}$)

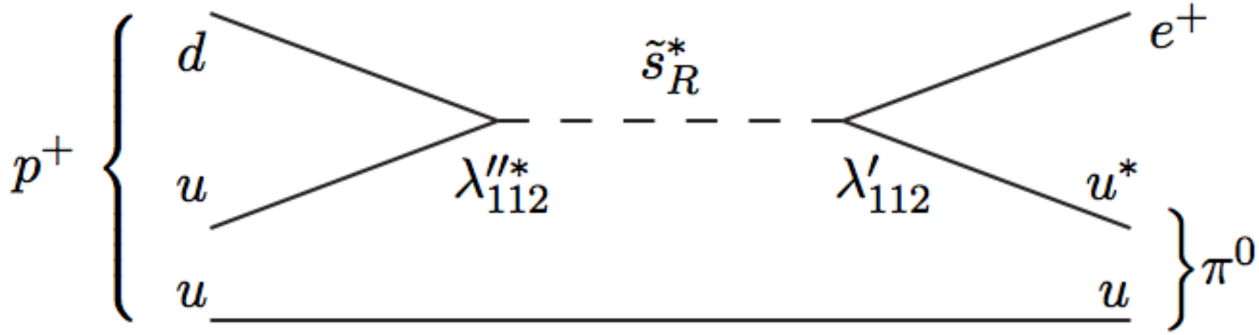
Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

(dimension of the multiplet)

Table 2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Proton decay



In general MSSM both couplings are allowed via
Scalar-fermion-fermion interactions
Proportional to yukawa coupling…
➔These interactions must be tiny since we would otherwise observe proton decay

R-parity

Fast proton decay likely with very general SUSY Lagrangian
→ Solution: assume conservation of a newmultiplicative quantum number called R-parity:

baryon and lepton numbers of particles are no longer assumed to be conserved. Instead R-parity may be conserved, where the R-parity is

$$R = (-1)^{2j+3B+L}.$$

- With spin j, baryons B, and leptons L.
- All Standard Model- like particles have R-parity of 1 while the new “ supersymmetric” particles have R-parity -1.

R-parity conservation consequences

1. Lightest SUSY particle stable
   a candidate for dark matter → Why?

2. Collider signals: SUSY particles are always produced in pairs

The minimal SUSY model (MSSM) is defined to have r-parity conservation

SUSY breaking

Supersymmetry is a broken symmetry

➔ We expect a mechanism similar to electroweak symmetry breaking which yields a broken symmetry at low energies

➔ Mass terms for SUSY particles are introduced due to SUSY breaking
➔ We do not know exactly how ?
➔ Lets be ignorant on the exact mechanism and introduce all allowed Mass terms…

SUSY breaking should be soft (of positive mass dimension) in order to be able to naturally maintain a solution to the hierarchy problem
➔ See later slides on hierarchy problem

Soft breaking terms

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$

Remember:

M3 = Gluino mass
M2 = Wino mass
M1 = Bino mass

Soft breaking terms

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$

$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)$$

➔ Later related to Yukawa couplings

➔ Again 3x3 matrices in family space (with mass dimension)

Soft breaking terms

$$\mathcal{L}_{\rm soft}^{\rm MSSM} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + {\rm c.c.}\right)$$

$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + {\rm c.c.}\right)$$

$$-\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger$$

➔ These are squared 3x3 mass matrices
➔ Different for left and right-handed
➔ Different for u and d-type
➔ Different for squarks and sleptons

Soft breaking terms

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$

$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)$$

$$-\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger$$

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.$$

➔These are additional soft breaking terms for the Higgs

➔Is b (and mu term before SUSY breaking)…

Soft breaking terms summary

Expect:

$$M_1,\, M_2,\, M_3,\, \mathbf{a_u},\, \mathbf{a_d},\, \mathbf{a_e} \sim m_{\rm soft},$$
$$\mathbf{m^2_Q},\, \mathbf{m^2_L},\, \mathbf{m^2_{\overline{u}}},\, \mathbf{m^2_{\overline{d}}},\, \mathbf{m^2_{\overline{e}}},\, m^2_{H_u},\, m^2_{H_d},\, b \sim m^2_{\rm soft},$$

All these terms together yield:

105 new parameters
(masses, phases and mixing angles in the MSSM Lagrangian that cannot be rotated away)

➔ Is this a problem ?

The mass spectrum of the MSSM

MSSM Higgs sector

After the EW symmetry breaking

Gauge and Higgs fields are supersymmetrized before electroweak Symmetry breaking (hence they can be put into multiplets):

Higgs sector in 2HDM:

(H^{+}_{1},H^{0}_{1}) with Y=+1/2 and (H^{0}_{2}, H^{-}_{2}) with Y=-1/2

→After the Higgs-Mechanism (eats 3 degrees of freedom from the 8=2*complex doublet)

These Higgs field mix to 5 observable Higgs bosons:

h0,H0 (neutral, CP even)

A (neutral, CP odd)

H+, H- (charged)

-> In addition we have the Higgsions (8 degress of susy higgs field transform to 4 Higgsinos with spin ½)

$H^{+}_{1},H^{0}_{1},H^{0}_{2},H^{-}_{2}$ (all with a tilde!!, I can't make the tilde in PowerPoint)

In more detail

Scalar potential in the MSSM:

$$V = (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2)$$
$$+ [b\,(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}]$$
$$+\frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2}g^2|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2.$$

Finding minimum ➔ Vacuum expectation values and prediction for Z mass

$$v_u = \langle H_u^0 \rangle, \qquad v_d = \langle H_d^0 \rangle.$$

$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\ \text{GeV})^2.$$

The ratio of the VEVs is traditionally written as

$$\tan\beta \equiv v_u/v_d.$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2.$$

➔ This is the SUSY version of the Hierarchy problem mH_u and mu need to cancel to yield M_Z !

Higgs mass predictions

$$
\begin{aligned}
m_{A^0}^2 &= 2b/\sin(2\beta) = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 \\
m_{h^0,H^0}^2 &= \frac{1}{2}\Big(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2(2\beta)}\Big), \\
m_{H^\pm}^2 &= m_{A^0}^2 + m_W^2.
\end{aligned}
$$

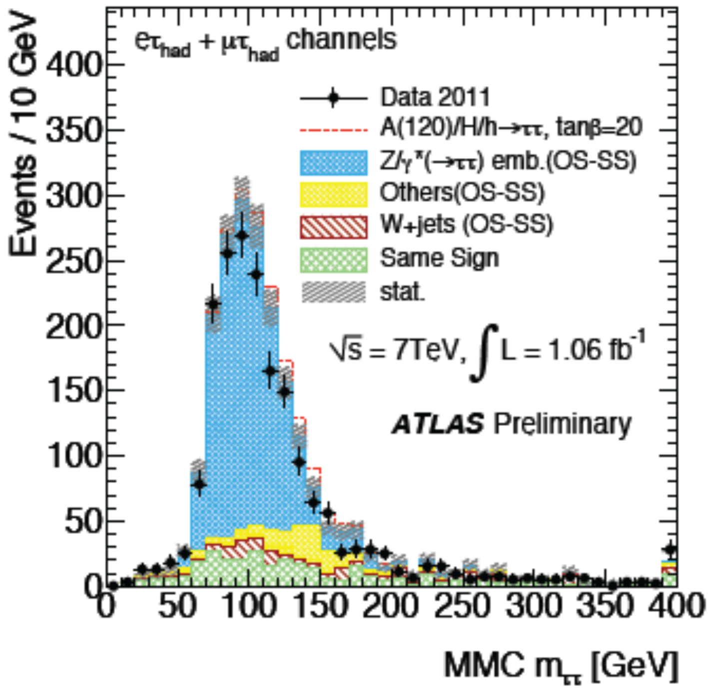
➔Prediction for all 5 Higgs masses

➔Can trade m_Hu , m_Hd and b for

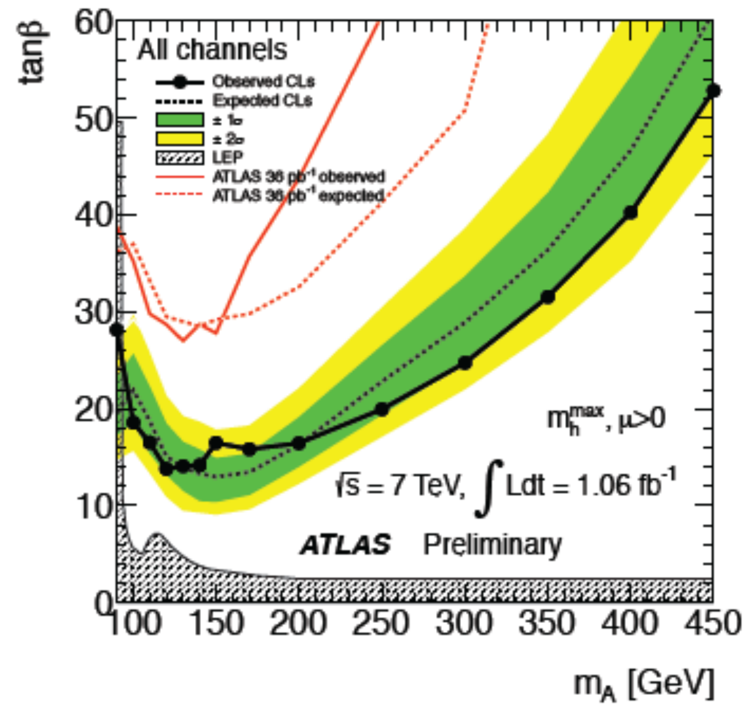
m_A , mu and tan (beta) as pMSSM parameters

Just to show you that there are also special MSSM Higgs searches

MSSM H/A → ττ



Effective mass distribution for $l\tau_{had}$. The data are compared with the background expectation and an added hypothetical signal. "OS-SS" denotes the difference between the opposite-sign and same-sign event yields.



Expected and observed exclusion limits based on CLs in the $m_A - \tan\beta$ plane of the MSSM derived from the combination of the analyses for the eμ, $l\tau_{had}$ and $\tau_{had}\tau_{had}$ final states. The dark green and yellow) bands correspond to the ±1σ and ±2σ error bands, respectively.

Old slide, need to find the newest limits…

Higgs mass prediction

This yields at tree level a prediction for the lightest Higgs mass:

$$m_{h^0} < m_Z |\cos(2\beta)|$$

→ M_higgs < 91 GeV

Higgs mass prediction

Beyond tree level ➔ Loop contributions:

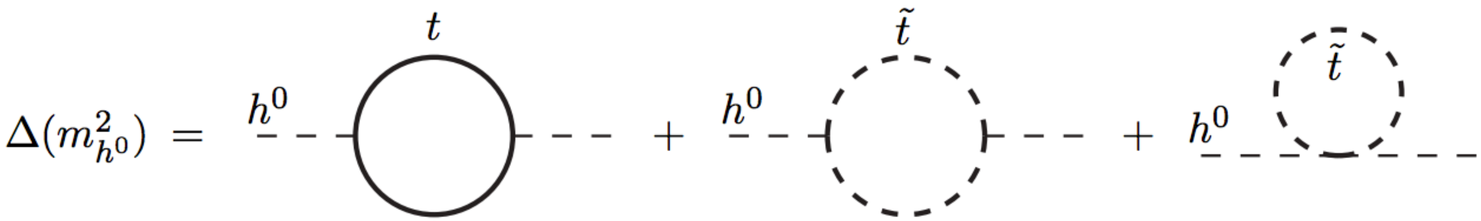


Figure 8.2: Contributions to the MSSM lightest Higgs squared mass from top-quark and top-squark one-loop diagrams. Incomplete cancellation, due to soft supersymmetry breaking, leads to a large positive correction to $m^2_{h^0}$ in the limit of heavy top squarks.

➔ M_higgs < 135 GeV

We know now: M_higgs = 125 GeV

➔ SUSY scale usually > 1 TeV (stops heavy or highly mixed)

MSSM electroweak sector

After the EW symmetry breaking

- Supersymmetrization happens "before" EW symmetry breaking

-> 2 Winos $\tilde{W}^{\pm}$ have same quantum numbers as Higgsinofields H+1, H-2
-> They mix to 4 charginos $\tilde{\chi}^{\pm}_{1,2}$

The neutral Wino and Bino and the Higgsinos H01, H02 mix to 4 neutralinos: $\tilde{\chi}^{0}_{1,2,3,4}$

It may also be that Higgsinos and Winos+Bino stay separate (e.g. if susy would be unbroken)
→ We can get then two neutral Higgsinos + Photino + Zino

Mixing matrix

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T M_{\widetilde{\chi}^0}\,\psi^0 + \text{h.c.}\ ,$$

where

$$\psi^0 = \begin{pmatrix} \widetilde{B} \\ \widetilde{W}^3 \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \end{pmatrix}$$

and

$$M_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_{\theta_W} m_Z & s_\beta s_{\theta_W} m_Z \\ 0 & M_2 & c_\beta c_{\theta_W} m_Z & -s_\beta c_{\theta_W} m_Z \\ -c_\beta s_{\theta_W} m_Z & c_\beta c_{\theta_W} m_Z & 0 & -\mu \\ s_\beta s_{\theta_W} m_Z & -s_\beta c_{\theta_W} m_Z & -\mu & 0 \end{pmatrix}.$$

Here we have introduced abbreviations $s_\beta = \sin\beta$, $c_\beta = \cos\beta$, $s_W = \sin\theta_W$, and $c_W = \cos\theta_W$. The mass matrix $\mathbf{M}_{\widetilde{N}}$ can be diagonalized by a unitary matrix $\mathbf{N}$ to obtain mass eigenstates:

$$\widetilde{N}_i = \mathbf{N}_{ij}\psi_j^0, \tag{8.2.4}$$

so that

$$\mathbf{N}^*\mathbf{M}_{\widetilde{N}}\mathbf{N}^{-1} = \begin{pmatrix} m_{\widetilde{N}_1} & 0 & 0 & 0 \\ 0 & m_{\widetilde{N}_2} & 0 & 0 \\ 0 & 0 & m_{\widetilde{N}_3} & 0 \\ 0 & 0 & 0 & m_{\widetilde{N}_4} \end{pmatrix} \tag{8.2.5}$$

Mixing matrix simplified

Regime	Composition neutralinos	Composition charginos
$M_1 < M_2 < \|\mu\|$	$(\tilde{B}, \widetilde{W}, \tilde{H}, \tilde{H})$	$(\widetilde{W}, \tilde{H})$
$M_1 < \|\mu\| < M_2$	$(\tilde{B}, \tilde{H}, \tilde{H}, \widetilde{W})$	$(\tilde{H}, \widetilde{W})$
$\|\mu\| < M_1 < M_2$	$(\tilde{H}, \tilde{H}, \tilde{B}, \widetilde{W})$	$(\tilde{H}, \widetilde{W})$
$\|\mu\| < M_2 < M_1$	$(\tilde{H}, \tilde{H}, \widetilde{W}, \tilde{B})$	$(\tilde{H}, \widetilde{W})$
$M_2 < \|\mu\| < M_1$	$(\widetilde{W}, \tilde{H}, \tilde{H}, \tilde{B})$	$(\widetilde{W}, \tilde{H})$
$M_2 < M_1 < \|\mu\|$	$(\widetilde{W}, \tilde{B}, \tilde{H}, \tilde{H})$	$(\widetilde{W}, \tilde{H})$

Table 1: Composition of the neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$ and charginos $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$.

Couplings matrix Chargino/Neutralino

	$\widetilde{B}$	$\widetilde{W}^3$	$\widetilde{H}^0_S$	$\widetilde{H}^0_A$	$\widetilde{W}^\pm$	$\widetilde{H}^\pm_{u/d}$
$\widetilde{B}$			h^0, H^0, A^0	h^0, H^0, A^0		$H^\mp$
$\widetilde{W}^3$			h^0, H^0, A^0	h^0, H^0, A^0	$W^\mp$	$H^\mp$
$\widetilde{H}^0_S$	h^0, H^0, A^0	h^0, H^0, A^0		Z	$H^\mp$	$W^\mp$
$\widetilde{H}^0_A$	h^0, H^0, A^0	h^0, H^0, A^0	Z		$H^\mp$	$W^\mp$
$\widetilde{W}^\pm$		$W^\mp$	$H^\mp$	$H^\mp$	Z	h^0, H^0, A^0
$\widetilde{H}^\pm_{u/d}$	$H^\mp$	$H^\mp$	$W^\mp$	$W^\mp$	h^0, H^0, A^0	Z

Table 2: Interactions between the Binos, Winos and Higgsinos. The entries indicate which fields are involved in the interaction.

MSSM - Particle Content

Particle content of the MSSM:

Superpartners for Standard Model particles:

$$\left[u,d,c,s,t,b\right]_{L,R} \quad \left[e,\mu,\tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}\right]_{L,R} \quad \left[\tilde{e},\tilde{\mu},\tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector:
Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

Generating SUSY breaking

No time to discuss this:

Examples:

Gravity mediated SUSY breaking: (Minimal Supergravity or MSUGRA)
Susy breaking through gravity at the Planck scale, gravitino is very heavy

Gauge mediated SUSY breaking: (GMSB)
Mediators are ‘normal’ gauge bosons, gravitino is lightest susy particle

Anomaly mediated SUSY breaking: (AMSB)
Breaking in higher dimensions

+ many others

My conclusion: We do not really know the MSSM mass spectrum

What is the CMSSM?

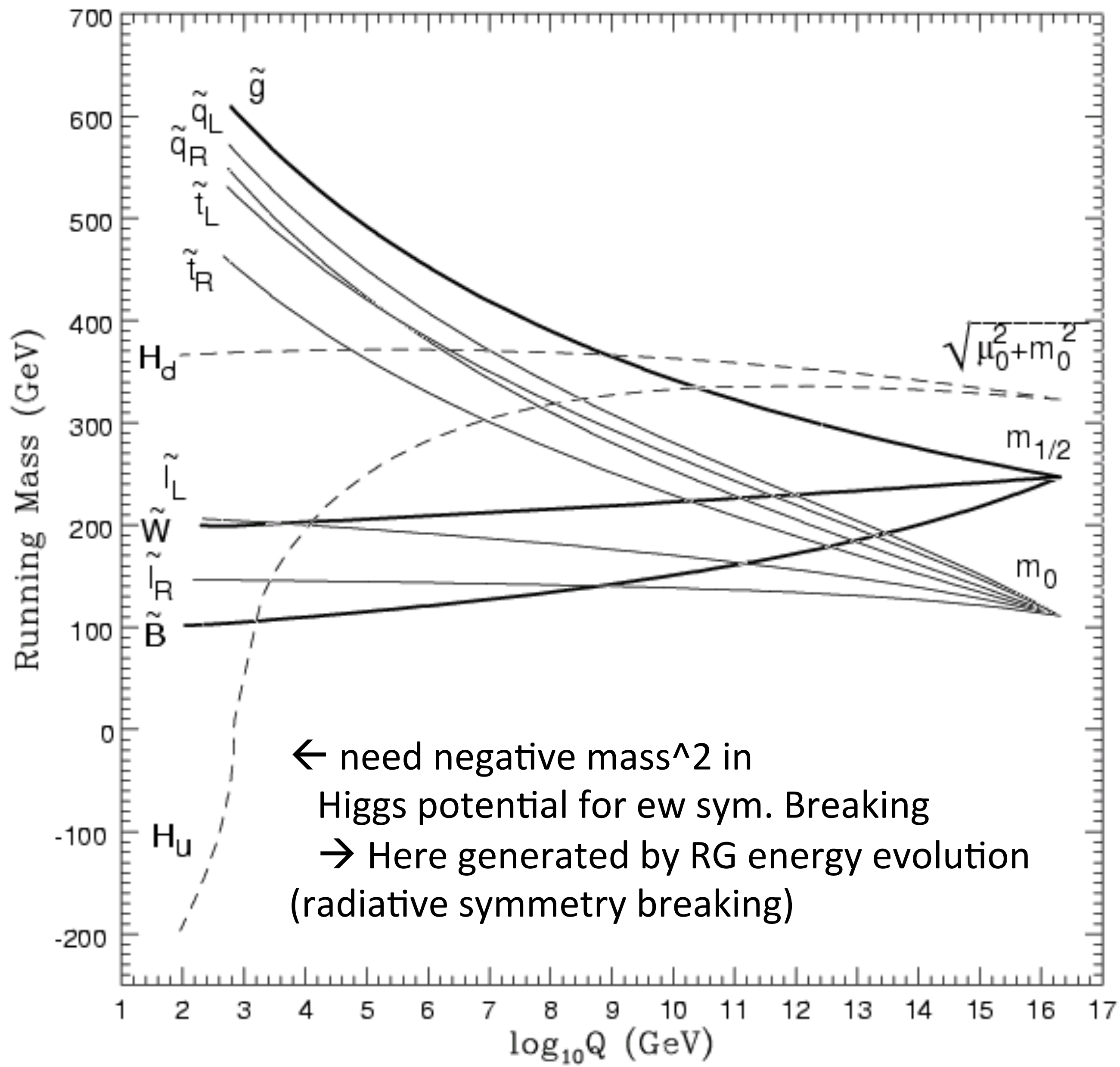
- Constrained Minimal Supersymmetric SM

  (also called minimal supergravity = MSugra)

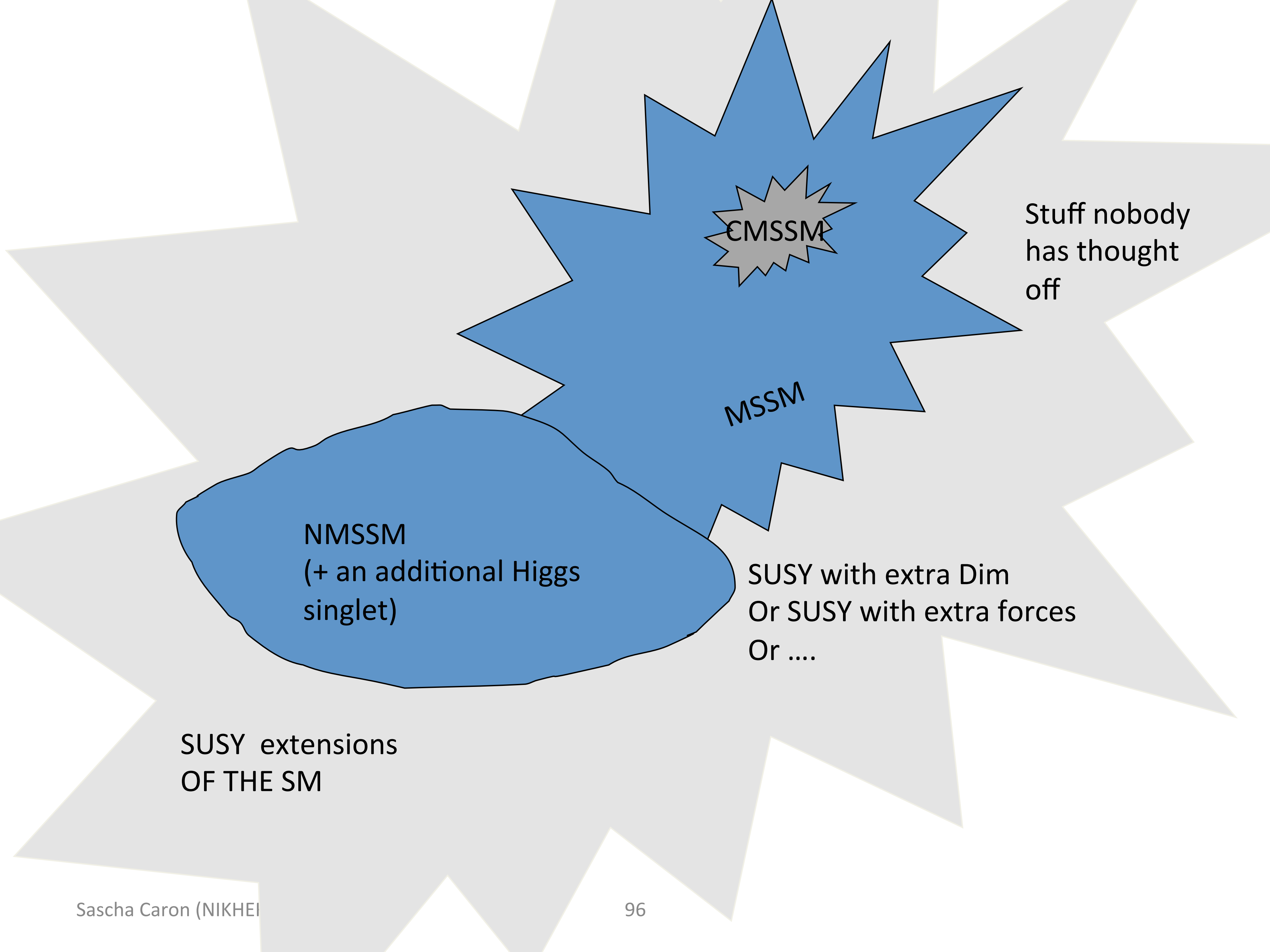
Assume at M_X : all scalar masses are the same = m_0
all gaugino masses are the same = $m_{1/2}$

- universal trilinear coupling A0
- Tan beta
- Sign of susy higgs parameter μ (|μ| constrained by M_z)

→4 ½ parameters : m^2_0 , $m_{1/2}$, A0, tan beta , sign(μ)



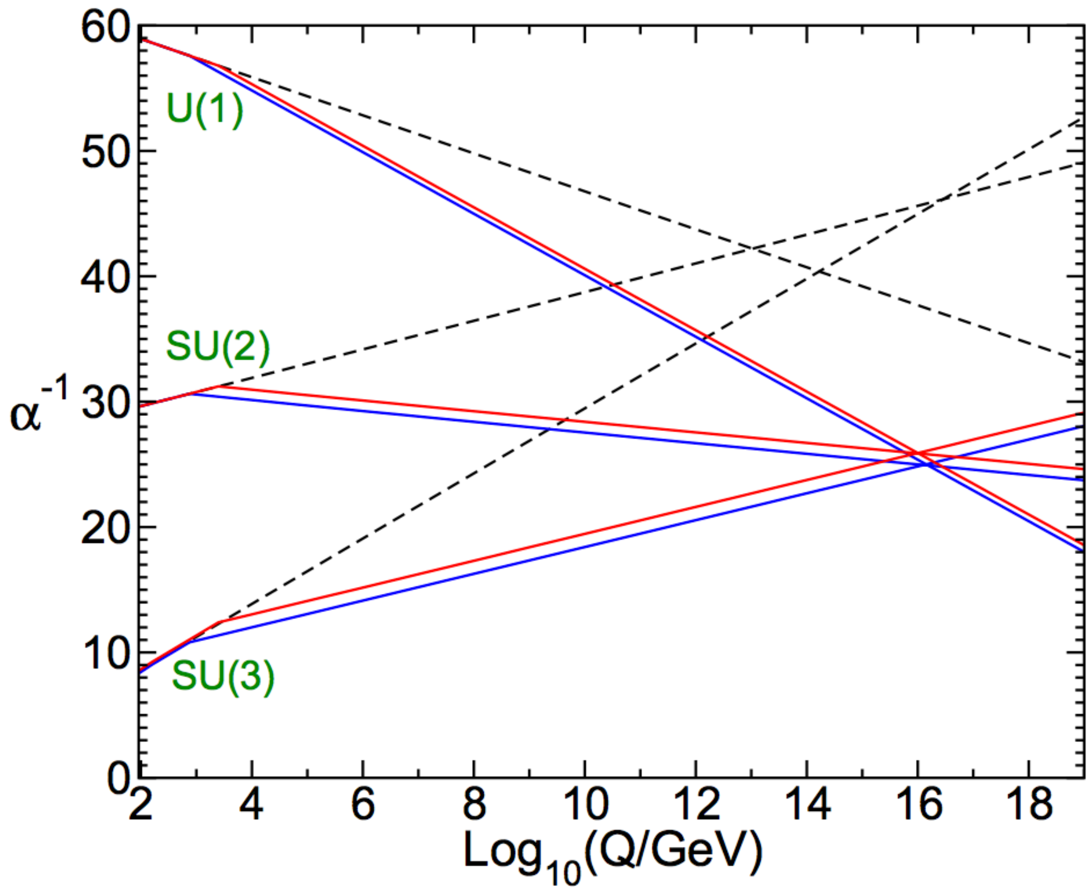
← need negative mass^2 in
Higgs potential for ew sym. Breaking
→ Here generated by RG energy evolution
(radiative symmetry breaking)


CMSSM
MSSM
Stuff nobody has thought off
NMSSM (+ an additional Higgs singlet)
SUSY with extra Dim
Or SUSY with extra forces
Or ….
SUSY extensions OF THE SM

Why Supersymmetry ?

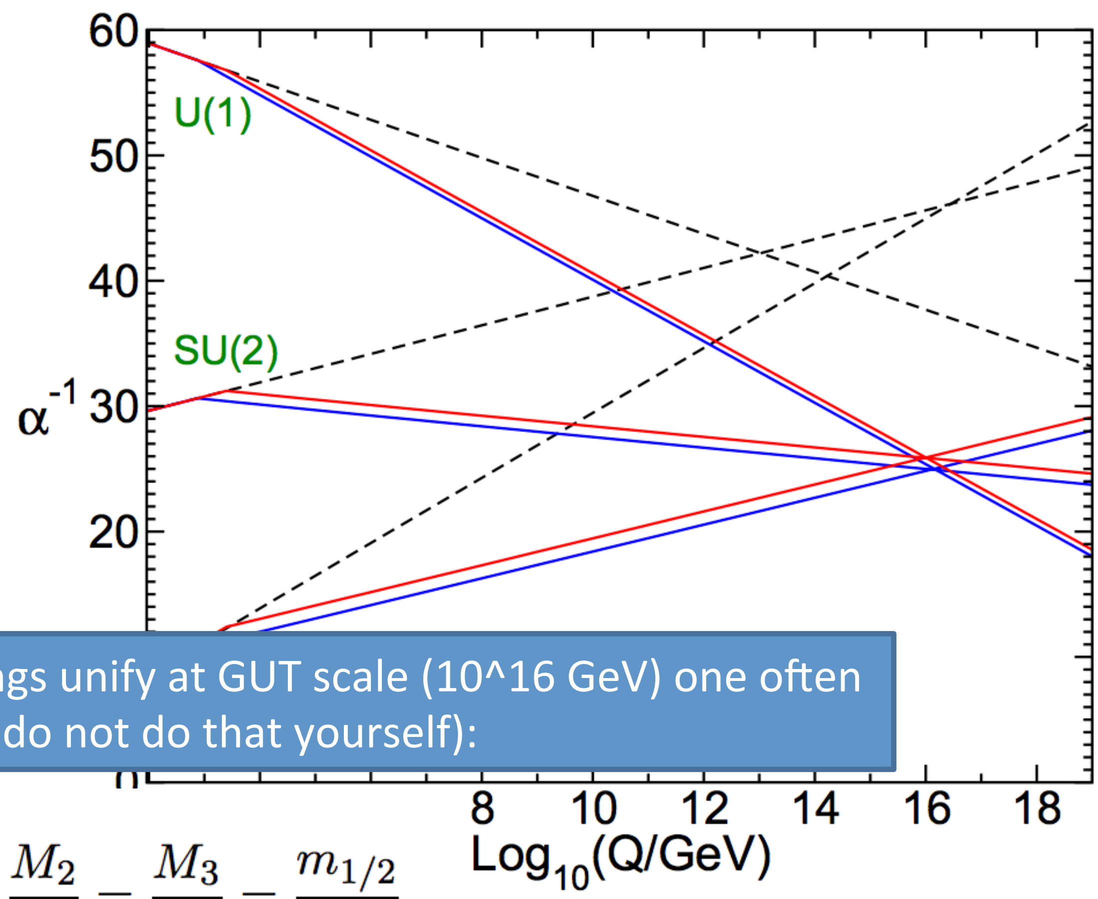
Gauge couplings

Figure 6.8: Two-loop renormalization group evolution of the inverse gauge couplings $\alpha_a^{-1}(Q)$ in the Standard Model (dashed lines) and the MSSM (solid lines). In the MSSM case, the sparticle masses are treated as a common threshold varied between 750 GeV and 2.5 TeV, and $\alpha_3(m_Z)$ is varied between 0.117 and 0.120.



Gauge couplings

Figure 6.8: Two-loop renormalization group evolution of the inverse gauge couplings $\alpha_a^{-1}(Q)$ in the Standard Model (dashed lines) and the MSSM (solid lines). In the MSSM case, the sparticle masses are treated as a common threshold varied between 750 GeV and 2.5 TeV, and $\alpha_3(m_Z)$ is vari
0.117 and 0.120.



Since the couplings unify at GUT scale (10^16 GeV) one often assumes (Please do not do that yourself):

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} = \frac{m_{1/2}}{g_U^2}$$

Dark Matter

Dark Matter candidates in the MSSM

Which ones ?

Dark Matter

Dark Matter candidates in the MSSM

Neutralino_1: **Perfect candidate ? How perfect?**

Sneutrinos : Not possible in MSSM, if light seen in Z decays, if heavy excluded by direct detection (only possible beyond MSSM)

Fine tuning in SUSY

Higgs mass = Z mass + Quantum Corrections (M_SUSY)
125 = 91 + Quantum Corrections (M_SUSY)

Fine tuning of Higgs mass can be rewritten in fine-tuning of Z mass
Z mass = Higgs mass – Quantum Corrections (M_SUSY)

$$\mathrm{FT} = \Delta_{\mathrm{EW}} = \max_i \left| \frac{C_i}{m_Z^2/2} \right|, \tag{2}$$

where the C_i are defined as:

$$C_{m_{H_d}} = \frac{m_{H_d}^2}{\tan^2\beta - 1}, \quad C_{m_{H_u}} = \frac{-m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}, \quad C_\mu = -\mu^2$$

$$C_{\Sigma_d^d} = \frac{\max(\Sigma_d^d)}{\tan^2\beta - 1}, \quad C_{\Sigma_u^u} = \frac{-\max(\Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1}.$$

How can we determine if SUSY is fine-tuned already ?

We determine how much a **parameter set** of the MSSM is fine tuned via:

FT = max. Quantum-Corrections^2 / M_Z^2

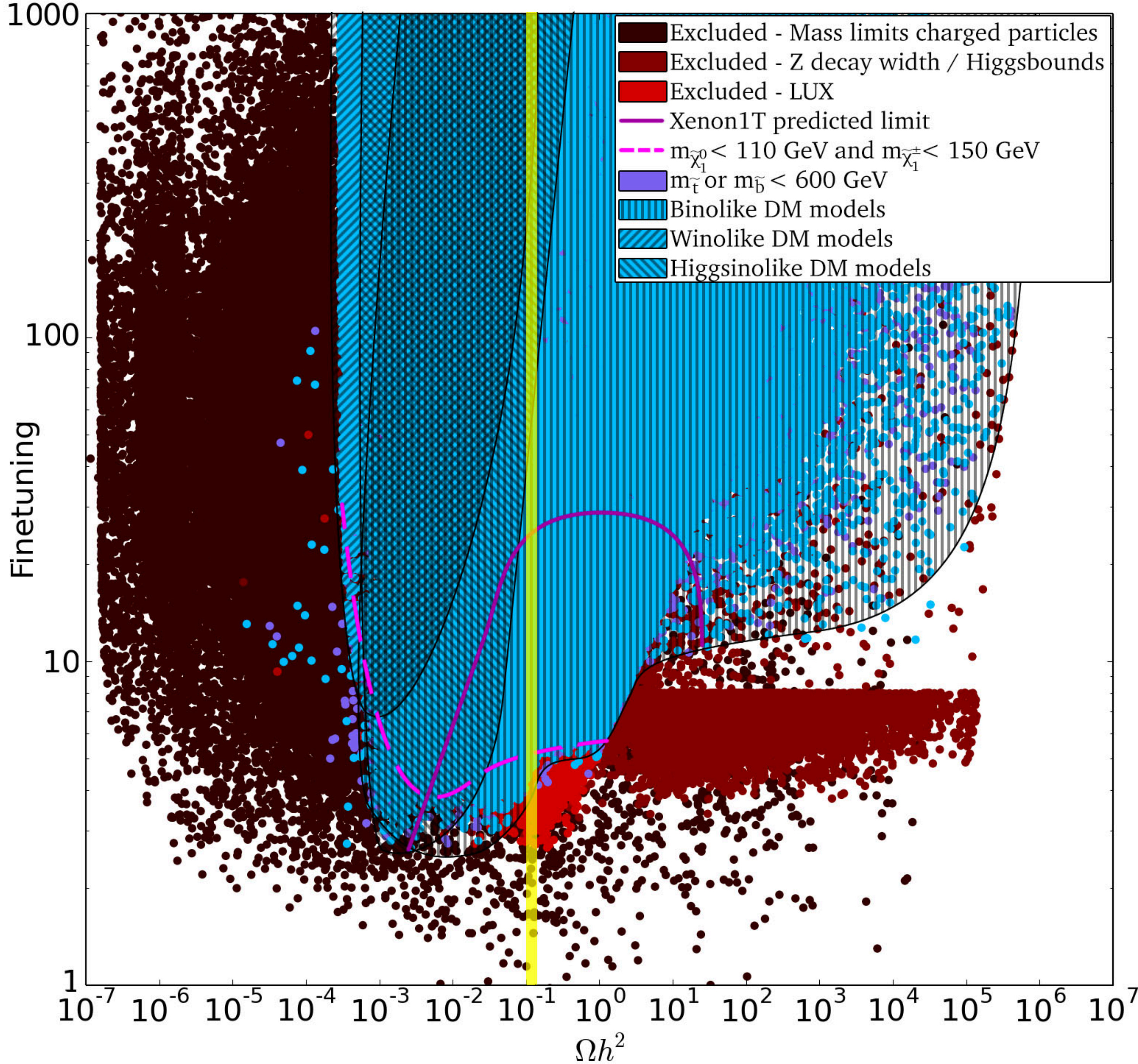
FT = 1-10 ➔ Natural, **perfect** !

FT = 10-100 ➔ a bit of tuning, **so la la**

FT = 100-1000 ➔ **not so good.**

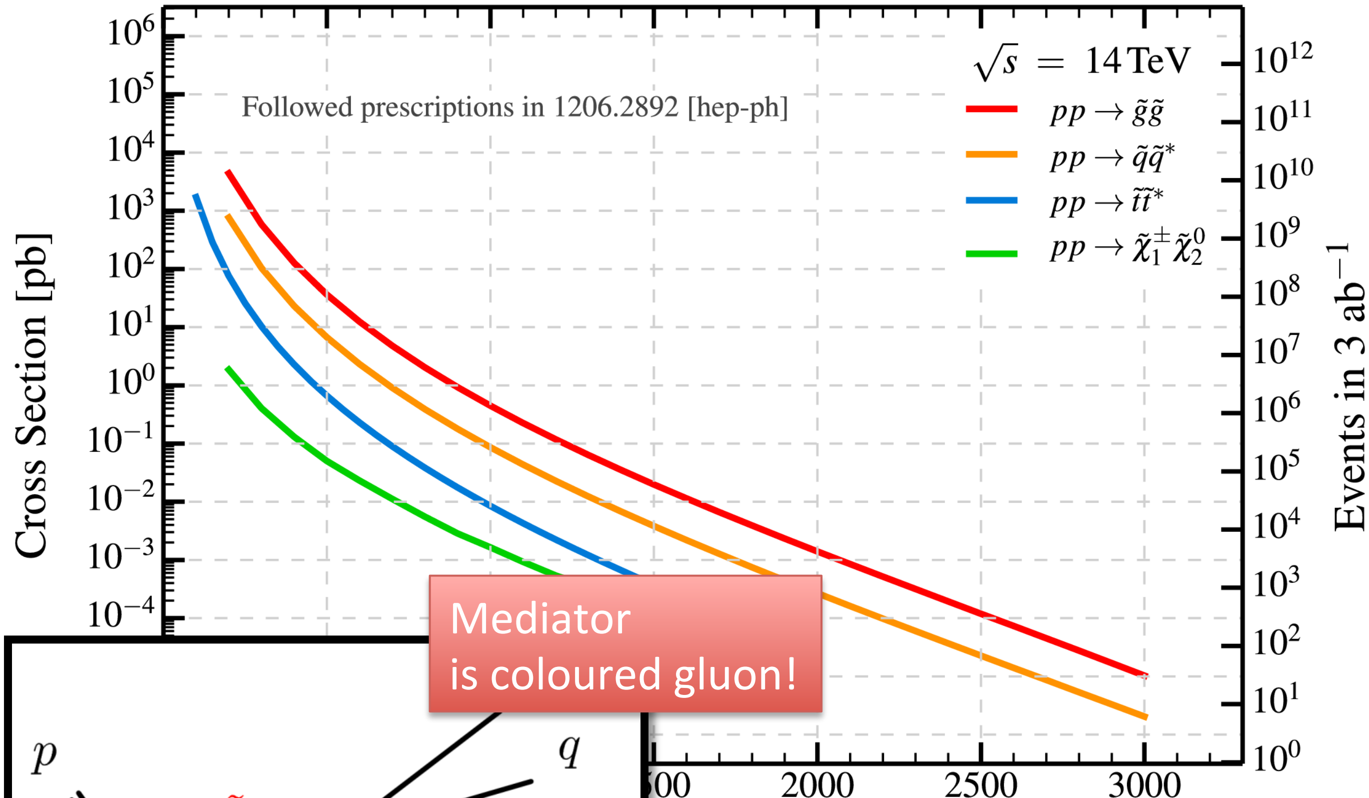
FT > 10^(10) ➔ highly FT models, **bad**...

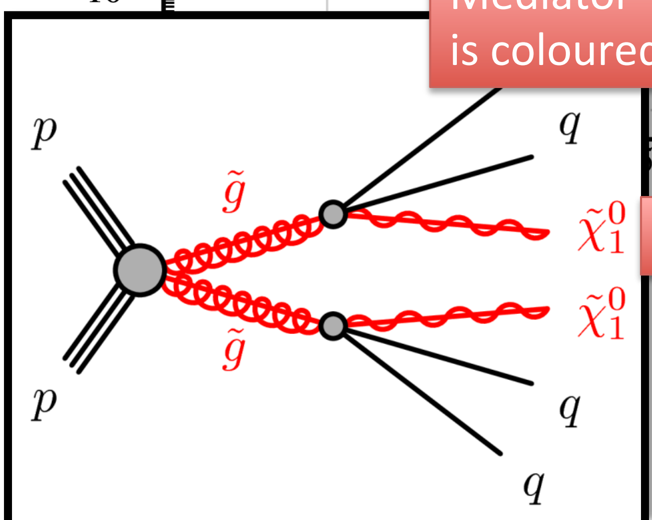
Dark Matter relic density



LHC SUSY searches

Production rate: Supersymmetry

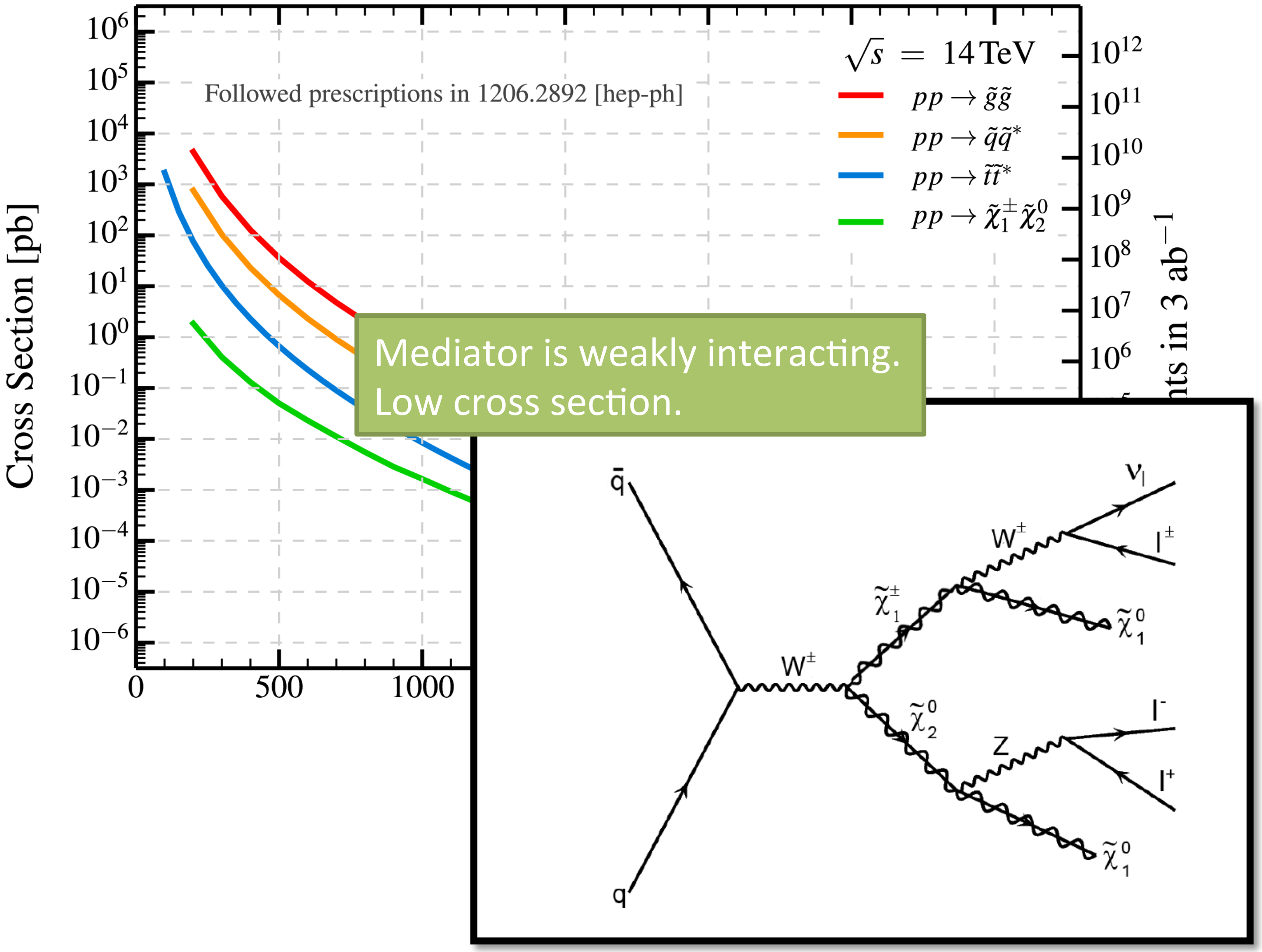




Mediator
is coloured gluon!

Large Cross section

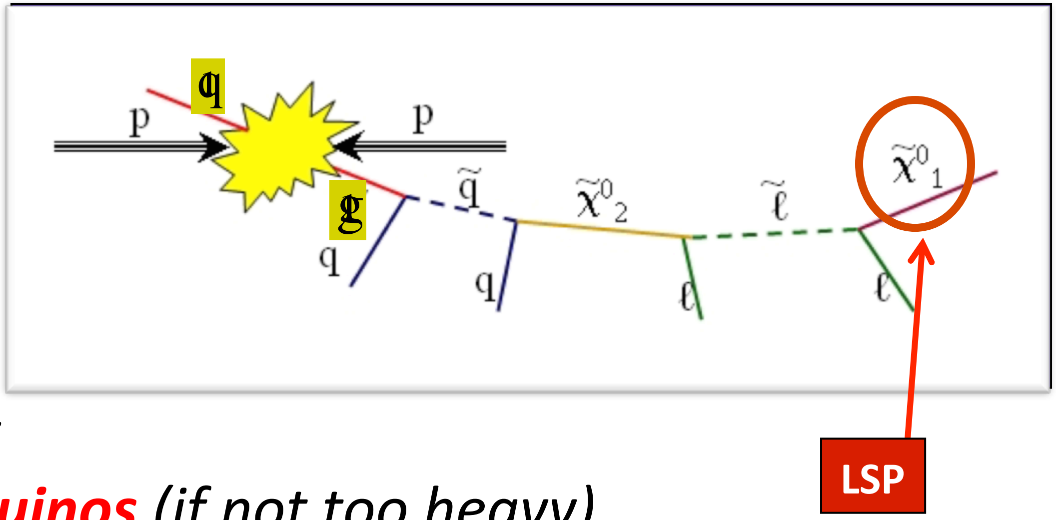
Production rate: Supersymmetry



Mediator is weakly interacting.
Low cross section.

SUSY and the LHC : Signal

If R-Parity is conserved then SUSY particles are pair produced



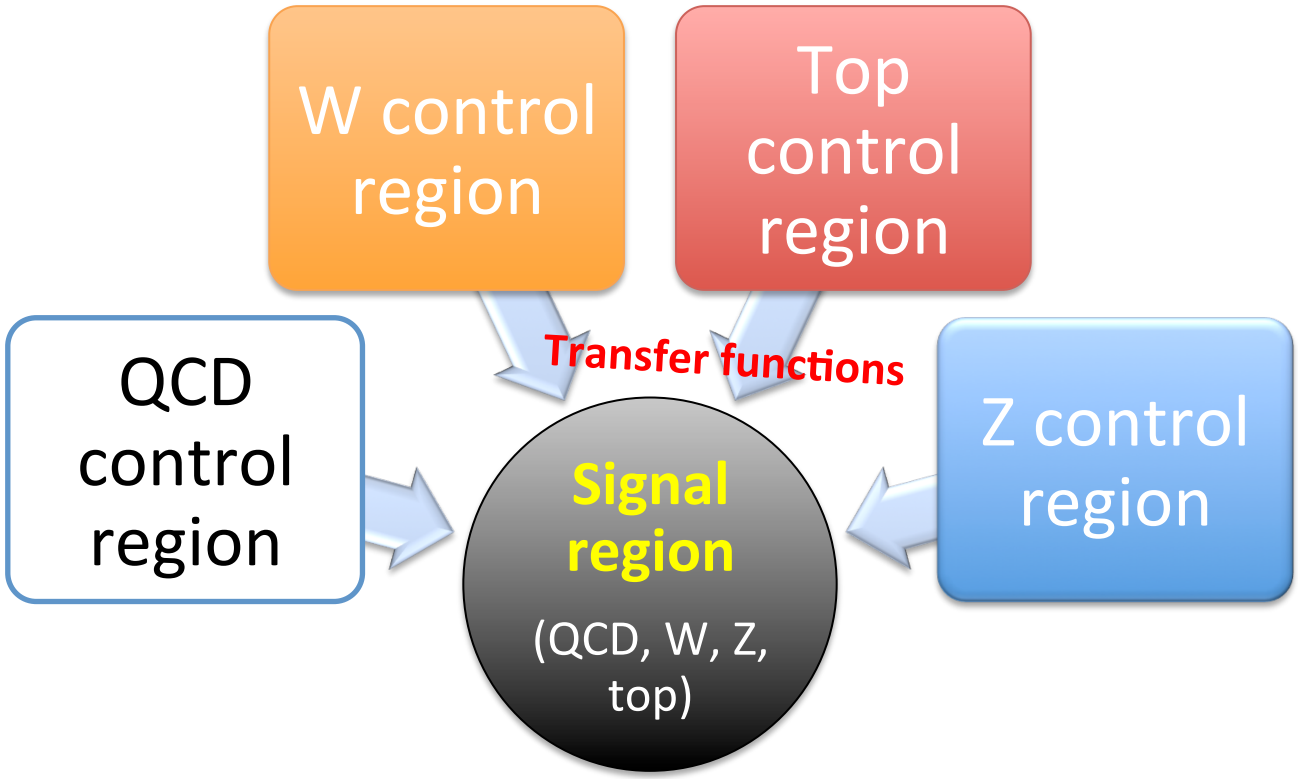
LHC:

*Due to strong force dominant production of **squarks** and **gluinos** (if not too heavy)*
Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

Similar conclusions /channels For many other models (Universal Extra Dimension, ADD, Little Higgs, ….)

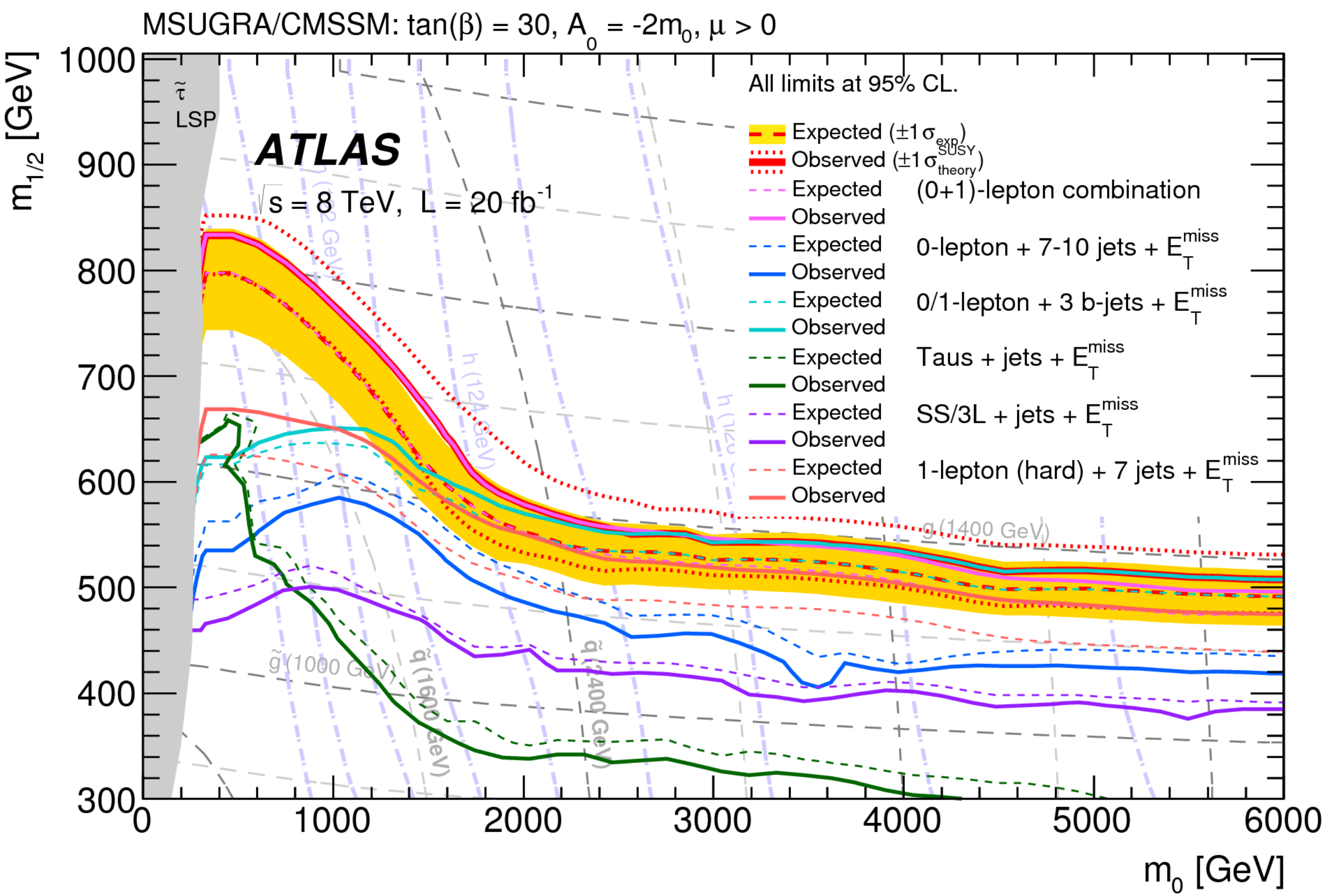
Mass pattern in general SUSY unknown ! Searches need to be quite general and model-parameter-independent

Analysis model - control regions



- Measure number of events in control selections
- Predict number of events in signal region via a fit to control regions
- Important : Test model and transfer functions
  (e.g. by alternative control regions or methods)

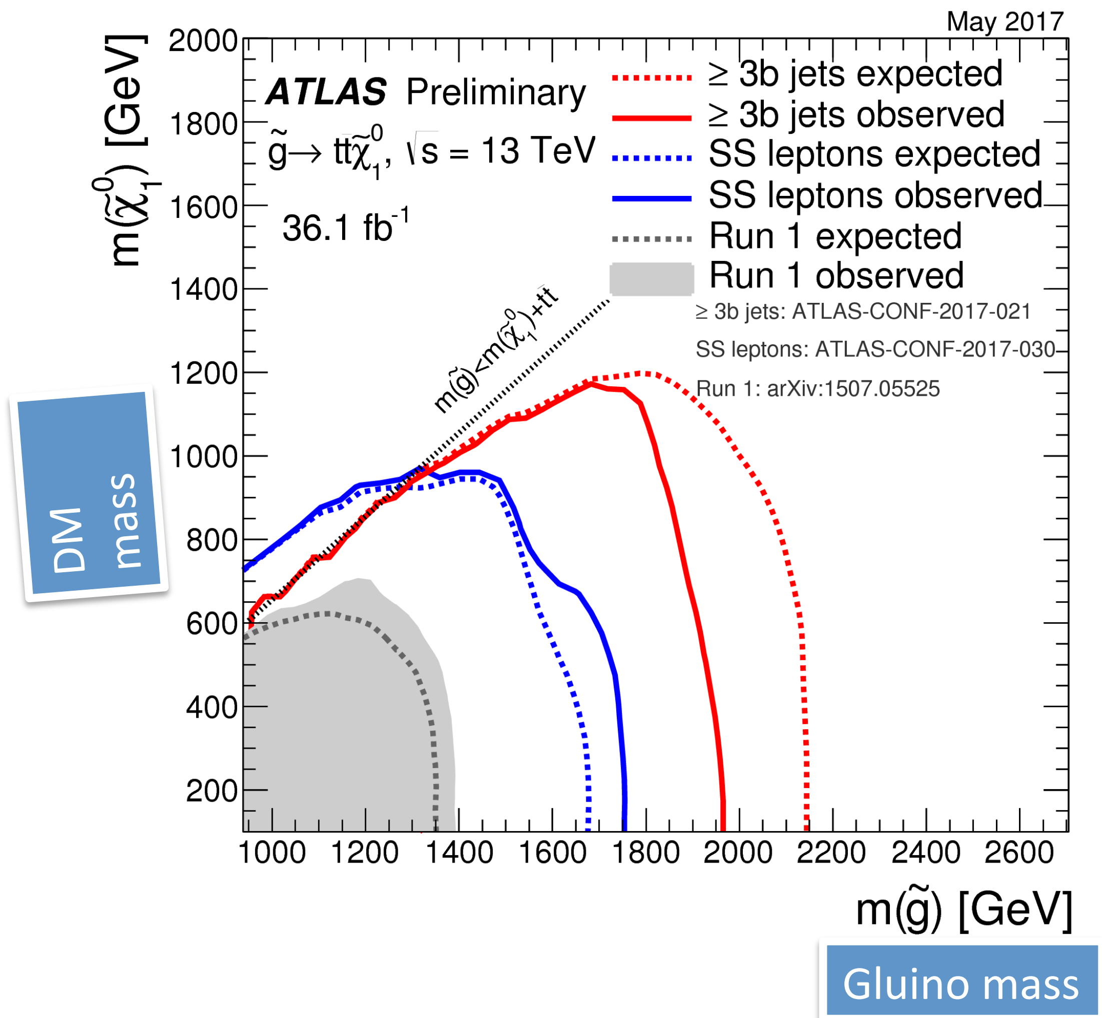
Run-1 results "constrained" MSSM



Run-2 limits gluino

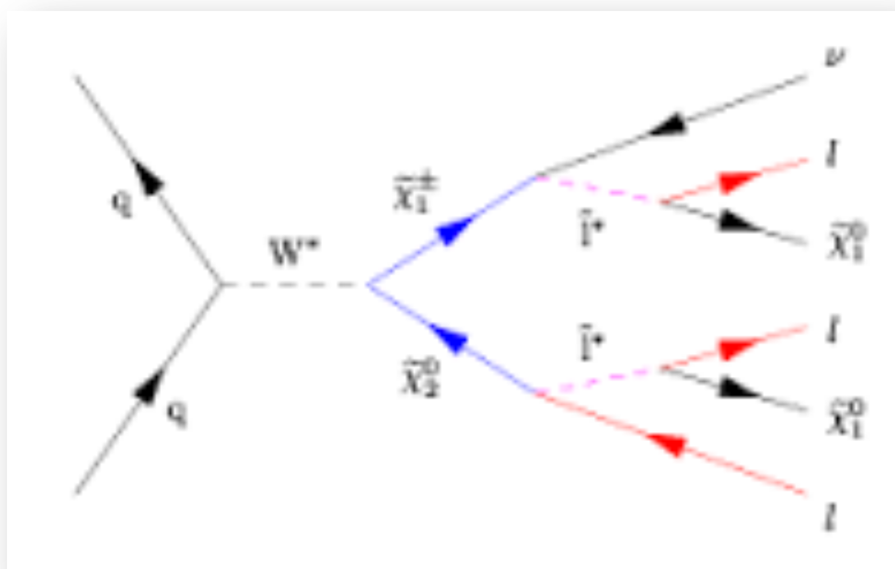
Limits for processes with colored particles slightly improved by 500 GeV

➔ Gluino likely heavy,
➔ Same for 1st, 2nd generation squarks

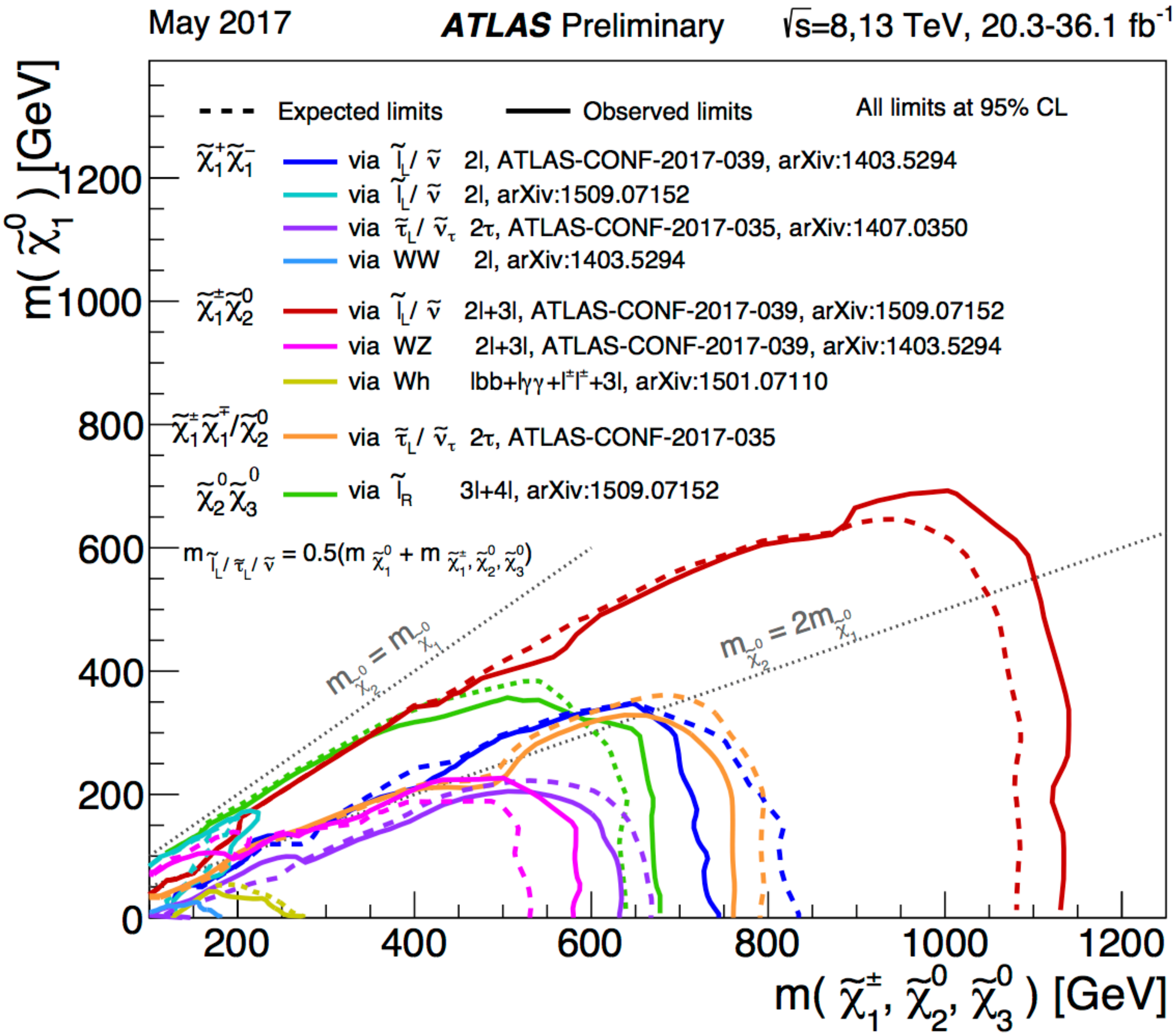


Electroweak sector

- Searches for Charginos and Neutralinos usually look at multi-lepton production via the production of a chargino and a neutralino_2 (with or without light slepton)



Run-2 Limit chargino/neutralino

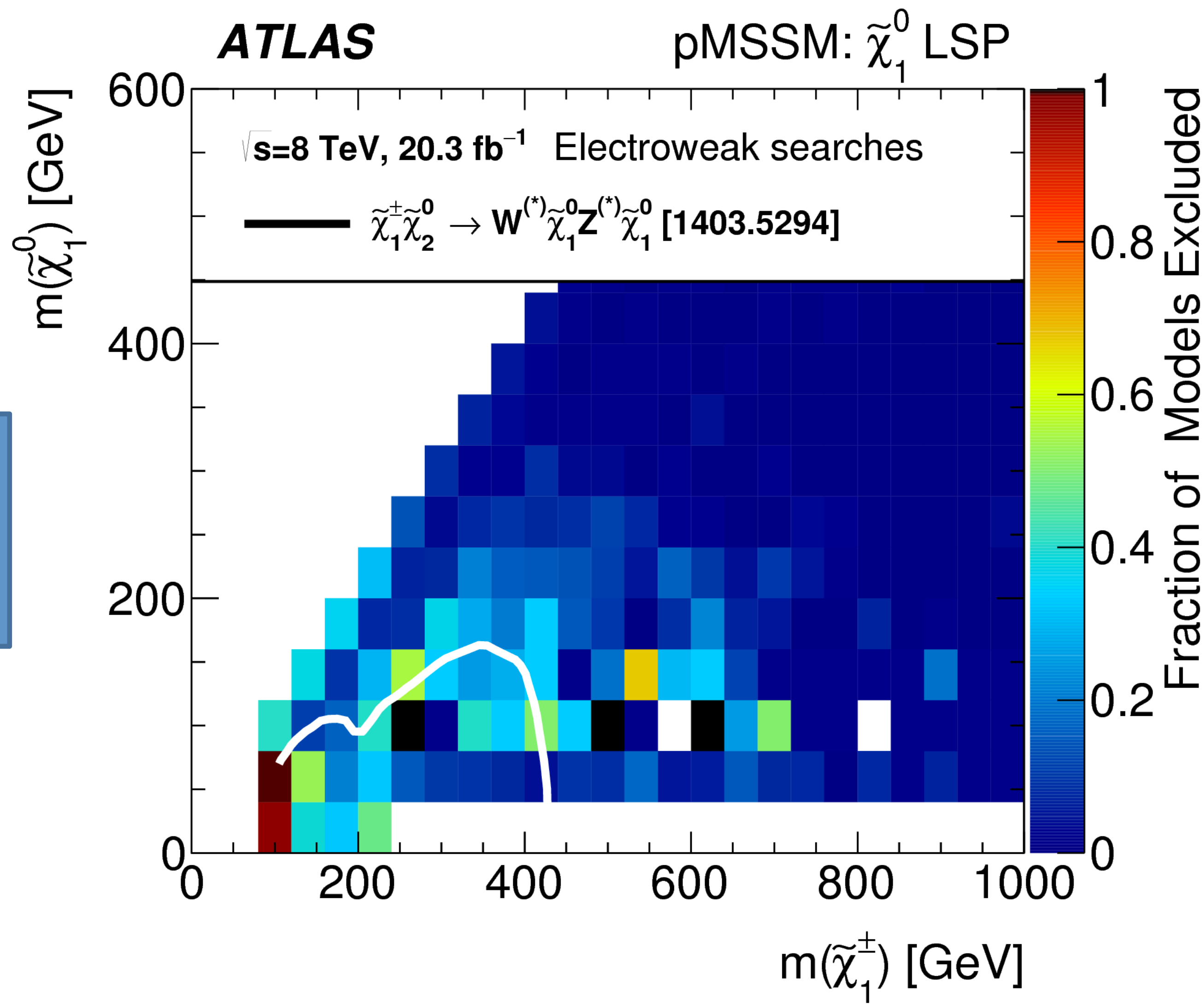


Be careful:

Usually assuming
-“simple decay”
-BR =1
-Maximum
(Wino) cross section

OK, what do we see in less simplified SUSY models ?

No real constrain on WIMP
100 GeV
DM particles…

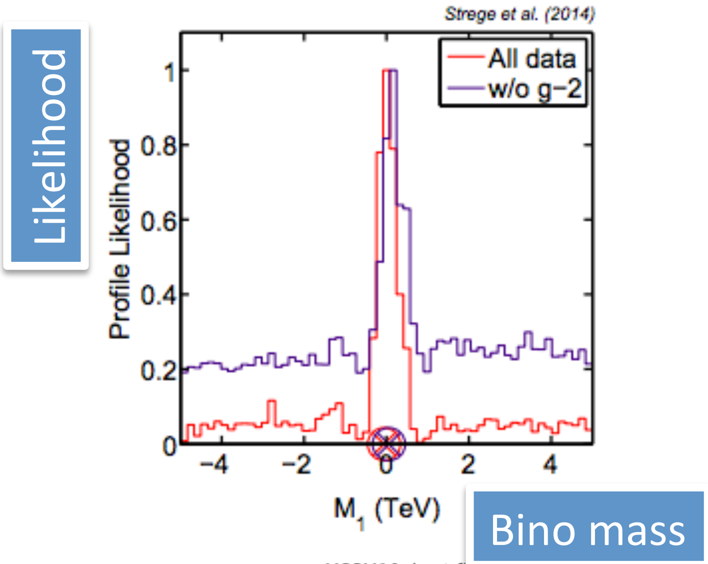


Our personal favored model: Global fits and the 100 GeV Bino

Global Fits for Dark Matter

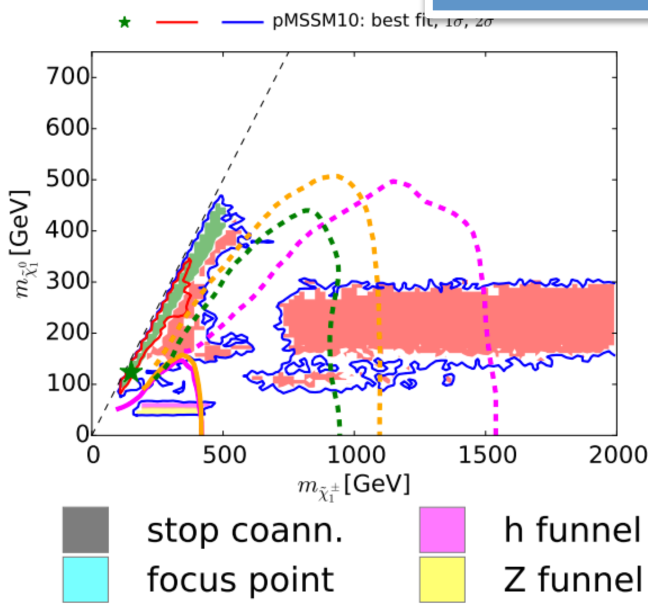
JHEP 1409 (2014) 081

Fit in MSSM model with 18 parameters using all worldwide data, but no LHC and Fermi-LAT



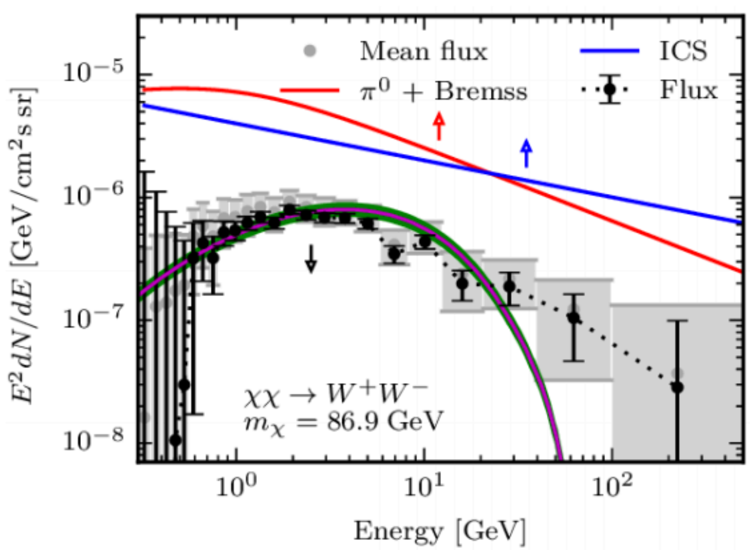
Eur.Phys.J. C75 (2015) 500
Mastercode collaboration:

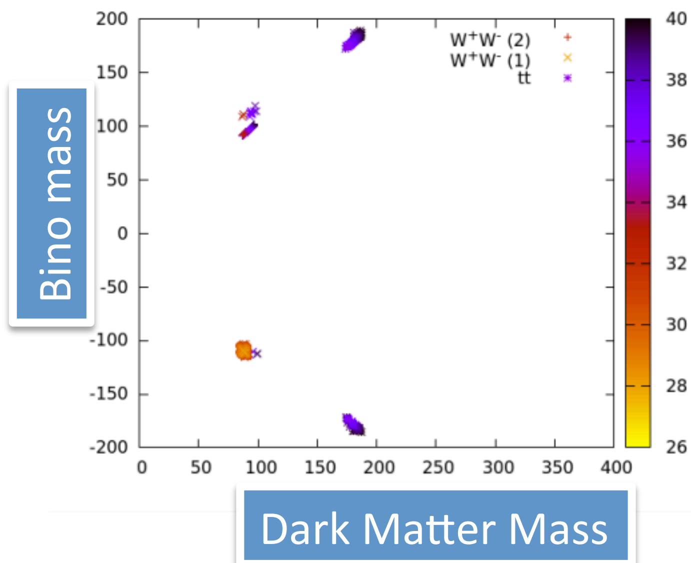
Fit in MSSM model with 10 parameters using all worldwide data, but no Fermi-LAT



Galactic Center excess

JCAP 1508 (2015) 08, 006 and arxiv1507.07008





Galactic Center gamma-ray excess can be described with Neutralino DM of approx. 80-90 GeV annihilating into W+W-

Fit using GC excess
Higgs, LEP, Lux, Icecube data "only" !
➔ Right DM relic density

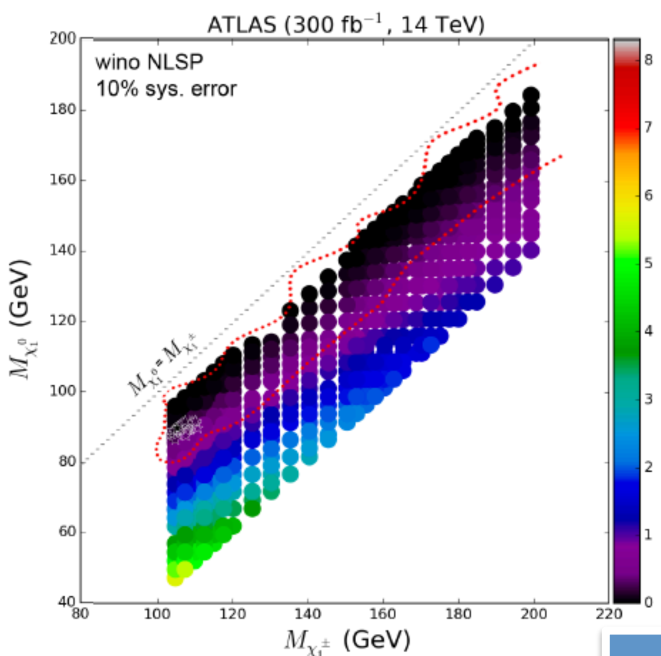
Best solution is 85 GeV Bino-Higgsino or Bino-Wino….

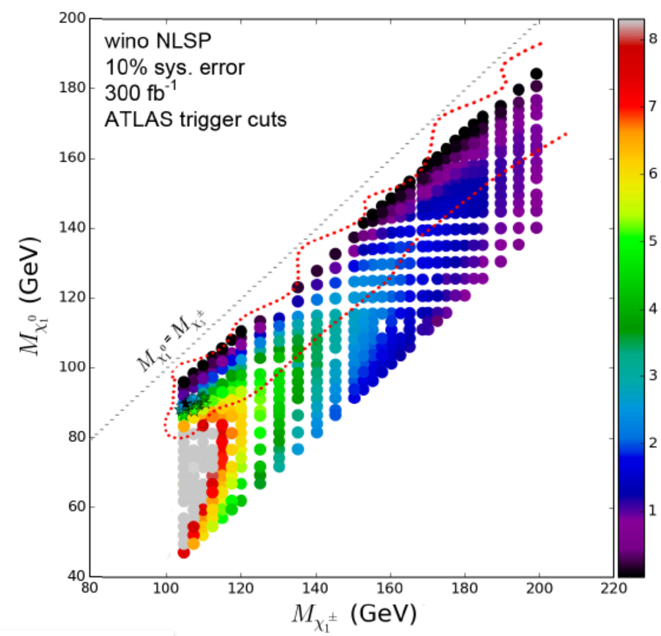
The case for a 100 GeV Bino

MSSM global fits and Galactic Center excess prefer region of approx. 100 GeV Bino Dark Matter, compressed with a chargino yielding the correct DM density

Dedicated search ("low MET") would yield sensitivity in this Region!
(on arxiv later this week)

Bino mass





Wino mass

(a)

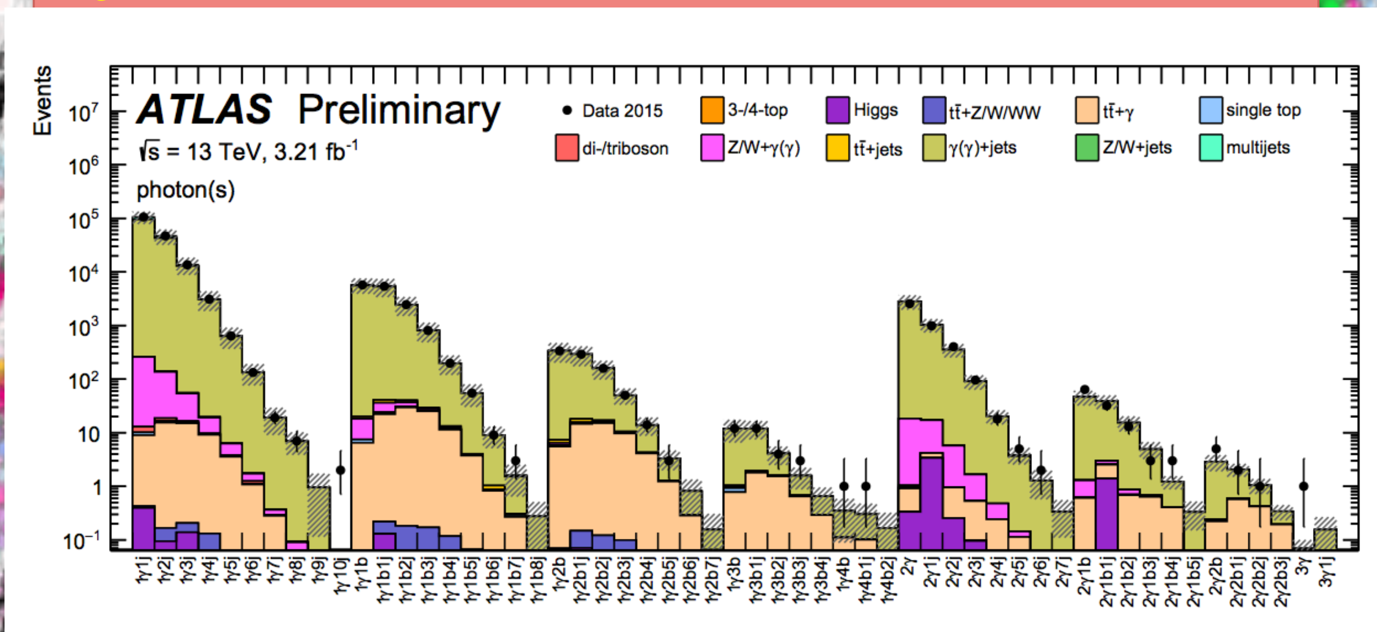
Summary

- No new physics yet
- Coloured particles and Z'/W' etc. likely heavy
- Weakly coupling particles less constrained
- SUSY could still rule with 100 GeV Dark Matter
- Are we missing the right model ?

(generic search with automized algorithm):

The question of my life:

Is there <u>any</u> anomaly
In LHC data which we have not seen yet ?
Model independent approach (see below)
Can we improve on that by using auxiliary information ?



Sara Aldeweireld, Jeroen Schouwenberg

- Most sensitive at early LHC:

  SUSY search for squarks and gluinos

Many parameters?

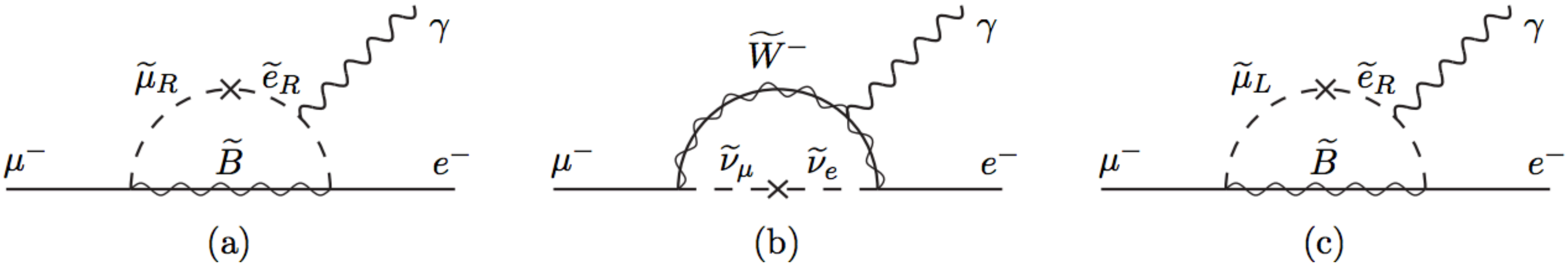
The true SUSY model (if existing) has likely much less parameters.

We see that random setting of some offdiagonal elements of the mass matrices yield again e.g. lepton number violation

➔ Can reduce amount of "effective" parameters since we know that offdiagonal elements must be very small....

Constraints of offdiagonal elements

Mu => e gamma



K0 mixing:

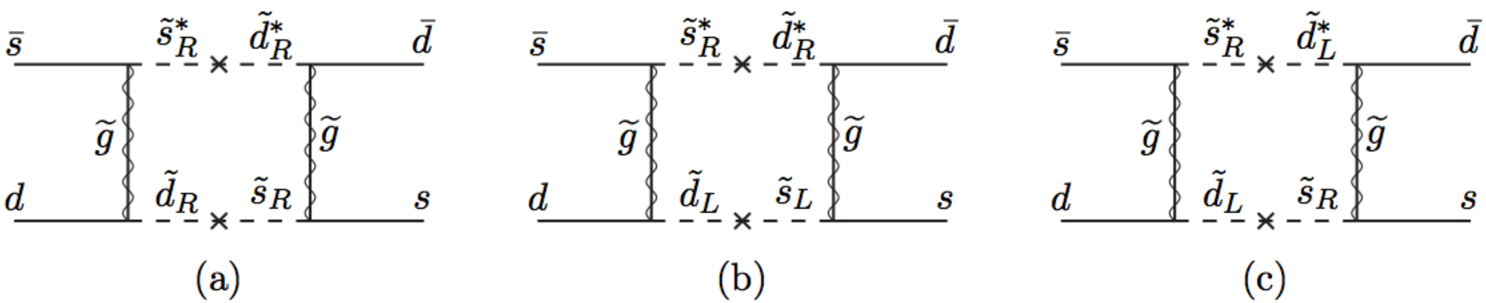


Figure 6.7: Some of the diagrams that contribute to $K^0 \leftrightarrow \overline{K}^0$ mixing in models with strangeness-

Phenomenological MSSM

$$\mathbf{m^2_Q} = m^2_Q \mathbf{1}, \quad \mathbf{m^2_{\bar{u}}} = m^2_{\bar{u}} \mathbf{1}, \quad \mathbf{m^2_{\bar{d}}} = m^2_{\bar{d}} \mathbf{1}, \quad \mathbf{m^2_L} = m^2_L \mathbf{1}, \quad \mathbf{m^2_{\bar{e}}} = m^2_{\bar{e}} \mathbf{1}.$$

$$\mathbf{a_u} = A_{u0}\, \mathbf{y_u}, \qquad \mathbf{a_d} = A_{d0}\, \mathbf{y_d}, \qquad \mathbf{a_e} = A_{e0}\, \mathbf{y_e},$$

➔ Only the squarks and sleptons of the third family can have large (scalar)^3 couplings.

Assume that CP violation only due to phase of CKM Matrix

=➔ Now typically about 15 – 25 parameters
➔ We call this phenomenolocially relevant MSSM
➔ pMSSM is a not a model, but a collection of possible SUSY models

Phenomenological MSSM

Usually: $$\mathbf{m_Q^2} \approx \begin{pmatrix} m_{Q_1}^2 & 0 & 0 \\ 0 & m_{Q_1}^2 & 0 \\ 0 & 0 & m_{Q_3}^2 \end{pmatrix}, \qquad \mathbf{m_{\bar{u}}^2} \approx \begin{pmatrix} m_{\bar{u}_1}^2 & 0 & 0 \\ 0 & m_{\bar{u}_1}^2 & 0 \\ 0 & 0 & m_{\bar{u}_3}^2 \end{pmatrix},$$

$$\mathbf{a_u} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_t \end{pmatrix}, \qquad \mathbf{a_d} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_b \end{pmatrix}, \qquad \mathbf{a_e} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_\tau \end{pmatrix}$$

➔ Only the squarks and sleptons of the third family can have large (scalar)^3 couplings.

Assume that CP violation only due to phase of CKM Matrix

=➔ Now typically about 15 – 25 parameters

➔ We call this phenomenolocially relevant MSSM

➔ pMSSM is a not a model, but a collection of possible SUSY models

This looks like a mess ?

The MSSM should be seen as our theoretical constraints of SUSY.

The “true” SUSY model is likely much simpler in structure and that is the reason why many of the 105 parameters are likely not relevant and should be set to specific values.

Baryon and Lepton number violating terms

Need to forbid baryon or Lepton number violating terms (or both):

$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^i L_i H_u$$
$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

L etc. are chiral supermultiplets

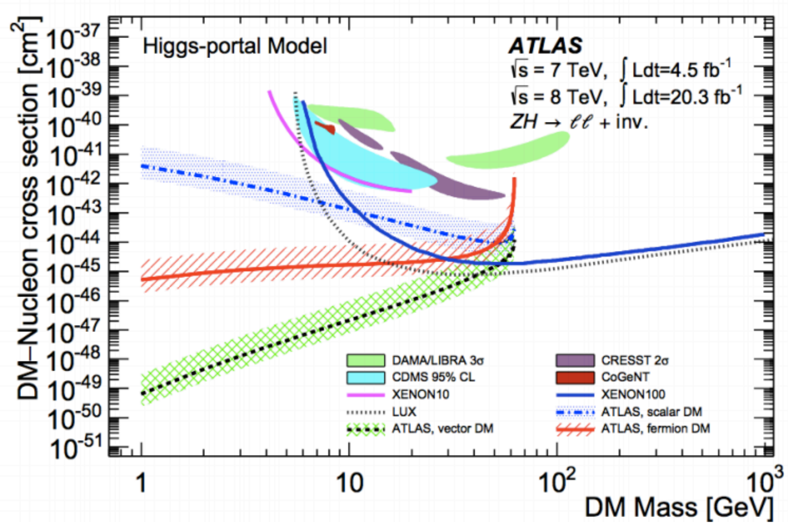
Higgs portal scalar singlet and BR for H->invisible

- SM simplest extension: Lagrangian = SM+ DM field
- DM couples to SM only via Higgs

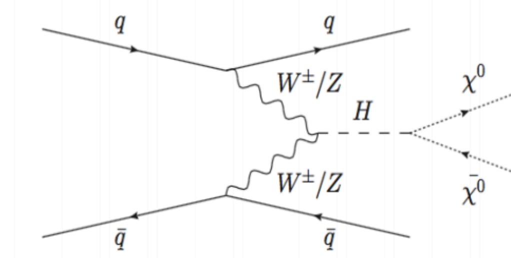
$$\mathcal{L}_S = -\frac{\mu_S^2}{2}S^2 - \frac{\lambda_{hs}}{2}S^2H^\dagger H - \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{\lambda_S}{4}\lambda_S S^4$$

Higgs invisible decay		Higgs-DM coupling		DM-nucleon xsec
$\Gamma(h \to \chi\chi)$	$\Leftrightarrow$	$\lambda^2_{h\chi\chi}$	$\Leftrightarrow$	$\sigma_{N\chi}$

$$BR(h\to\chi\chi) = \frac{\Gamma(h\to\chi\chi)}{\Gamma(h\to\chi\chi)+\Gamma(h\to SM)}$$



VBF

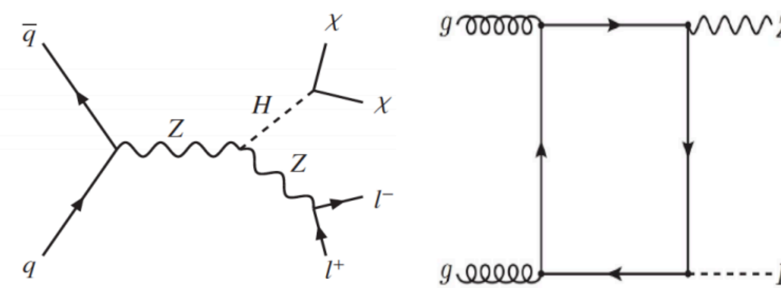


(a) Signal

VBF production:

- Energetic dijets system (Large Δη)+ MET
- Most sensitive channel **BR< 28% RunI**

ZH



Associate Higgs production with a Z boson:

- Opposite charge dilepton+ MET
- Clean signature **BR < 78% RunI**
  BR < 98% RunII ICHEP