TitleTheory II:
BSM physics: direct production and indirect sensitivity

- Why is the SM not sufficient?
- Prospects for SUSY
- Dark Matter Searches
- What about the excess at 750 GeV at the LHC?
- Conclusions

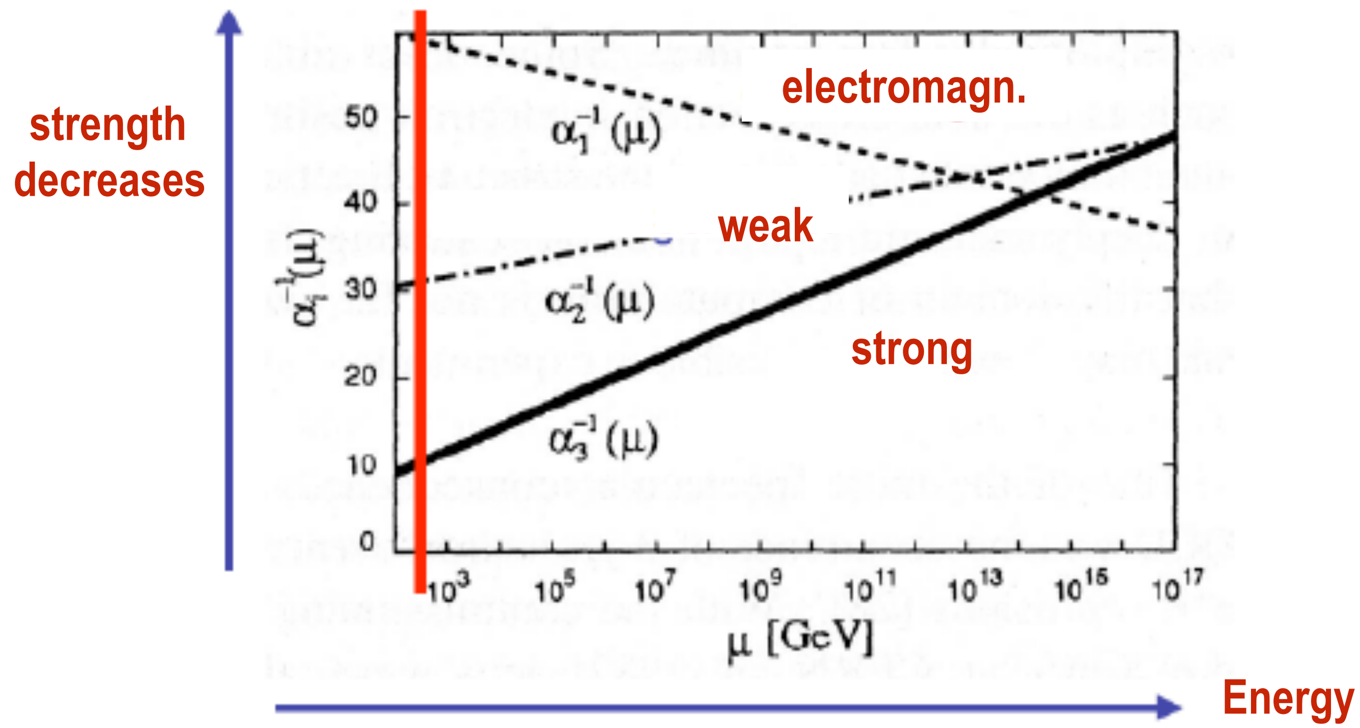
Let's start the BSM snooker now ....

Open questions:

- **Particle discovered with m_H~125 GeV – Higgs@SM?**
  - The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics
  - We still need precision measurements of couplings, potential, CP properties,…
- **In addition**

  The SM does not contain
  - Unification
  - Dark matter
  - Baryon/Antibaryon Asymmetry
  - Neutrino masses
  - Gravity

  Cosmo constant
  - Extreme fine tuning



- **The SM offers no satisfying answers to those open issues**
- **Compelling solutions via `Beyond Standard Model' Physics?**

Experimental hints for physics beyond the SM?

- Currently several flavour anomalies:
  - ➢ b-> c τ ν_τ , b-> s l- l+, b→sμμ,… : always 2-4 σ level
- Excess at 750 GeV at the LHC:
  - ➢ not yet established, but already well studied ….
- Whole Neutrino sector; θ_{13} rather large…

Obviously, there is BSM around, but there is no consistent picture or experimental hints where to look.

- Many different models have been analyzed
  - ➢ with more or less physics potential for solving the open questions ….

But what's the status? Which interpretations are possible? What are the technical requirements that might be essential for resolving the puzzle,….let's start

Status physics

- **Current physics case for e+e-:**
  - Higgs precision physics
  - Top precision physics

  guaranteed physics!

  - Light electroweak particles/DM searches
  - BSM detection in general, complementary to LHC

  well motivated

- **HEP-e+e-: ILC, CLIC or CepC or Fcc-ee**
  - ILC, $\sqrt{s}$=90-500 (1000) GeV, 163 MW, 31 km, polarized beams, t⩾2032
  - CLIC: $\sqrt{s}$=500 GeV,1.5, 3 TeV, 560 MW, 48 km, polarized beams,t≥2035
  - CepC: $\sqrt{s}$=240 GeV, 500 MW, 54 km, polarization unclear, t⩾2028
  - FCC-ee: $\sqrt{s}$=350 GeV, 500 MW, 100km, no polarization at 350, t⩾2035?

P. Burrows

W. Chou, EPS15

- *My guess: only one project has a chance,…if at all*

Current Status

- So far: Higgs boson mH=125 GeV behaves SM-like……
  - ➢no deviations so far within current experimental accuracy
- No new particles found so far: do we live in a decoupling limit?
  - ➢Interpretation: Any BSM must contain a light SM-like scalar particle; fundamental or composite?
  - ➢puts strong constraints on all BSM models!
- Two possibilities within general 2HDM:
  - ➢Decoupling limit: all but one scalar particle are heavy, $m_H \sim m_A \sim m_{H+} \gg v$ and $m_h \sim m_{hSM}$
  - ➢Alignment limit: either h or H is completely aligned with v, i.e. $h \sim h_{SM}$ but H, A, H^+ not necessarily heavy
- No clear situation, no preferred direction to BSM:
  - ➢ looking for 'needle in haystack'
- *Strategy: case studies, and need to be prepared for the unknown !*

Complements of the Standard Model

large parameter space

beautiful but restrictive

only valid up to specific scale

bottom-up: concrete BSM models

top-down: GUTs

effective field theories

SM

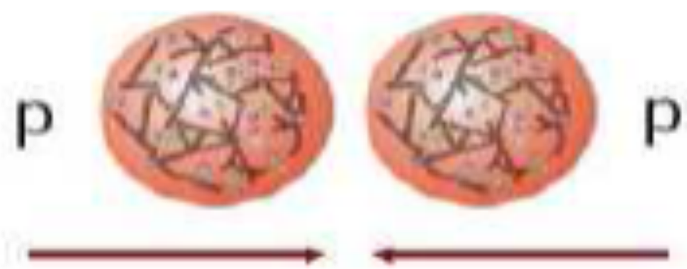
simplified models

deviations from SM

no consistent model

only indirect hints for BSM models

Comparison: pp and e+e- collisions



Characteristics of pp collider

composite particles collide

E(CM) < 2 E(beam)

strong interaction in initial state

`no' polarization applicable

LHC: $\sqrt{s}$ = 14TeV,

used $\hat{s} = x_1 x_2 s$ few TeV

small fraction of events analyzed

multiple triggers

superposition with spectator jets

Large potential for direct discovery

and of the e +e-(γe, γ γ) collider

Pointlike particles collide

Known E(CM) = 2 E(beam)

well defined initial state

polarized initial e- and e+ beams

B-fac ~ O(10)GeV,ILC~90-500GeV , 1 TeV, tunable

CepC~240, FCC-ee~350, CLIC~0.5, 1.5, 3 TeV

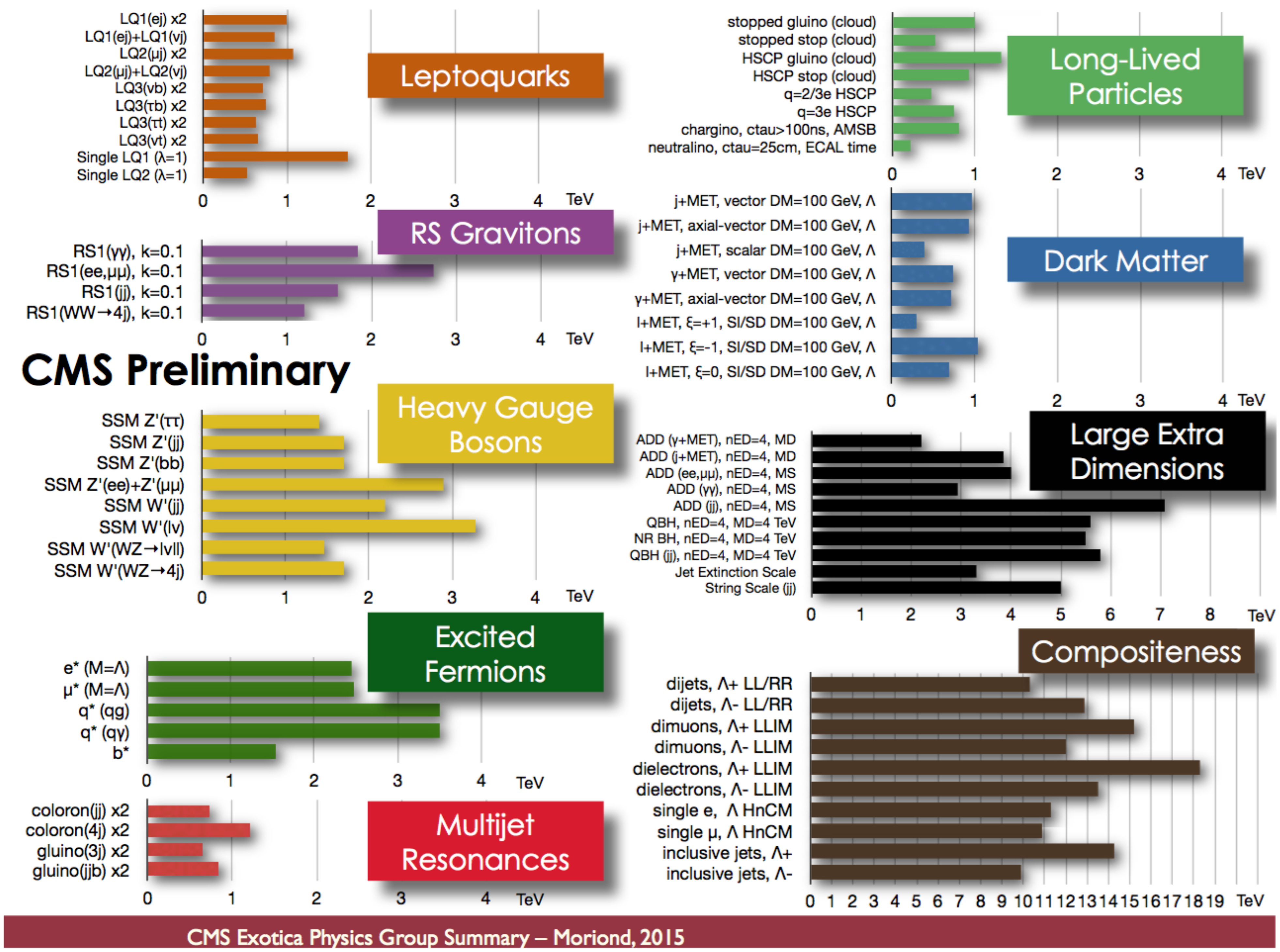
most events in detector analyzed

no triggers required

clean +fully reconstructable events

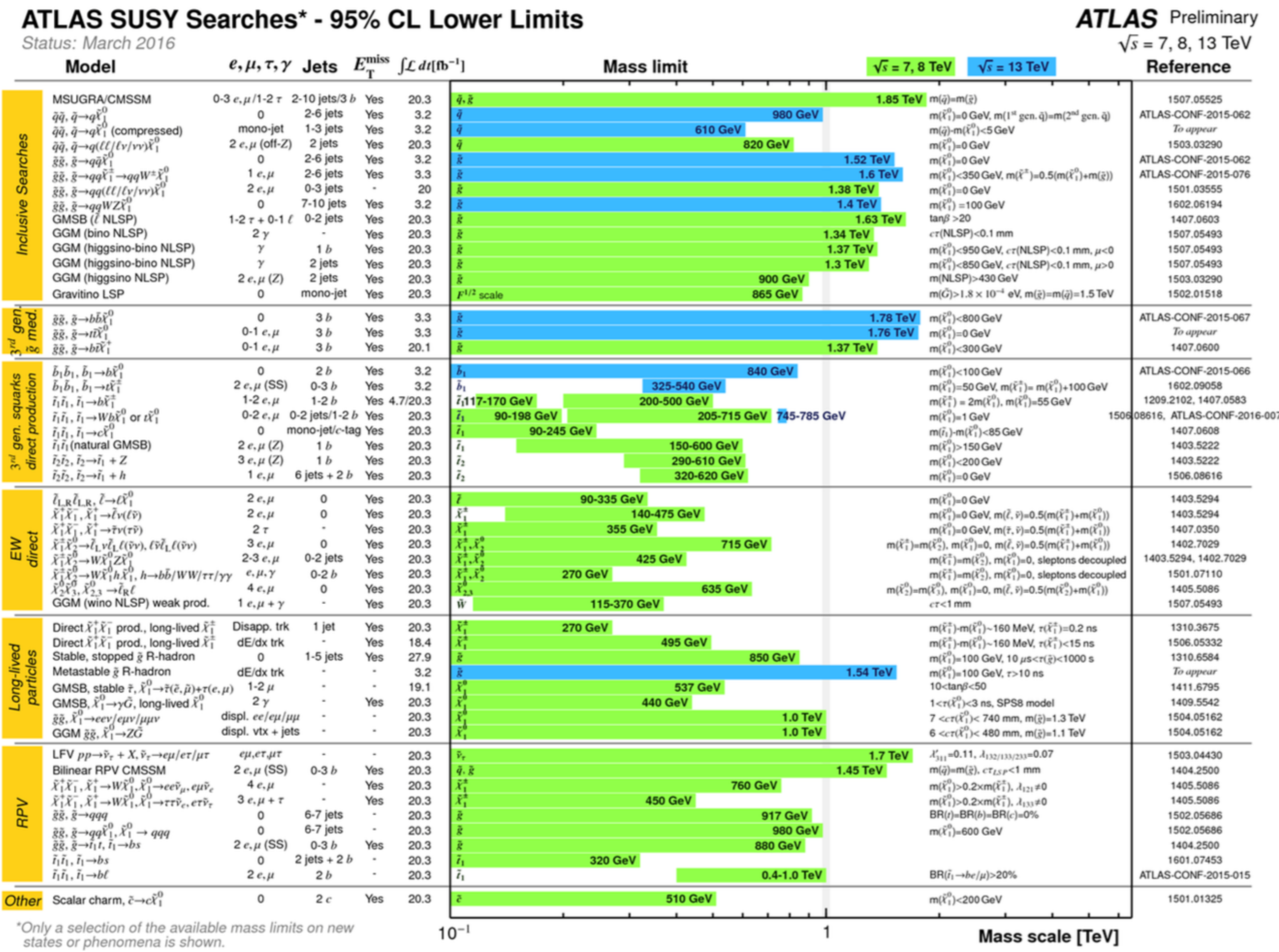
Large potential for discovery also via high precision

Current experimental result from LHC (CMS)



High mass limits, but how generic?

Current experimental result from LHC (ATLAS)

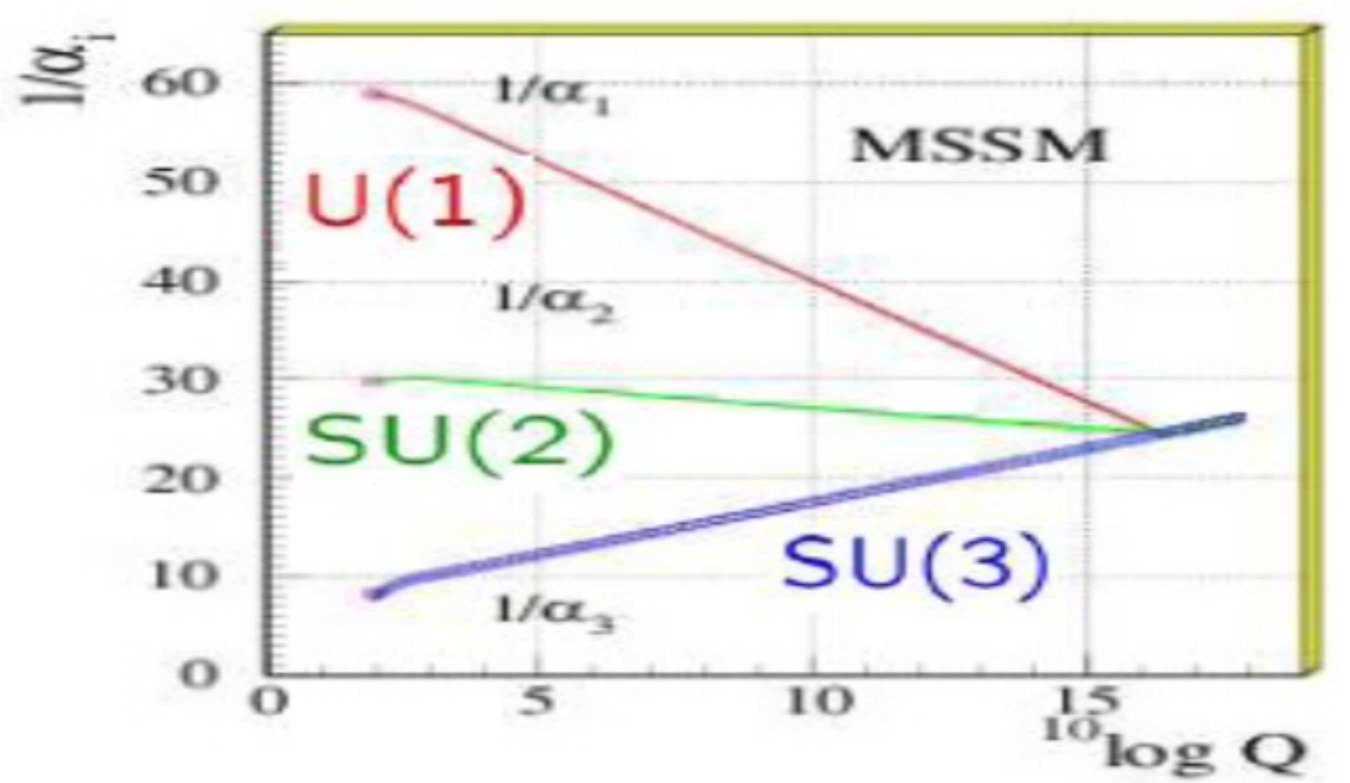


All simplified models!

SUSY as one of the best studied examples…. what does it tell us for e+e- machines?

BSM Example: Supersymmetry

- **Idea:**
  - New SUSY particles change energy dependence of interactions

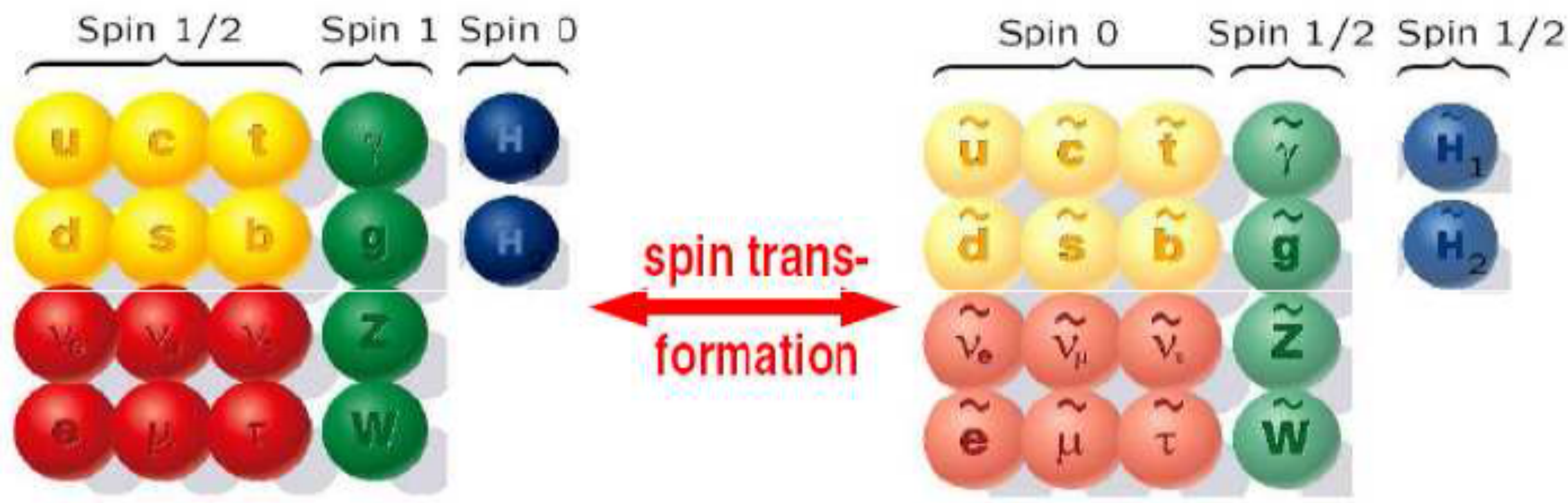


- Unification possible!
- SUSY provides candidate for dark matter
- SUSY predicts even 5 Higgs particles …… so stay tuned!
- SUSY provides new sources for CP violation

➢ But no specific SUSY hints so far at LHC ….. dead already?
Is this a bug or a feature? ….What do the experimental results really tell us?

Example for physics beyond the Standard Model

- Symmetry between fermions and bosons



'The search for SUSY is one of the biggest adventures in present-day physics.' Ed Witten (1999)

- **SUSY structure:** *same gauge structure, SM ↔ SUSY same coupling, different spin*
  - ➢ discovering SUSY requires proving such a structure!
- **Caveat: due to SUSY breaking 105 new free parameters are imposed**
  - ➢ **Strong assumptions on breaking mechanism lead to models of only ~5 parameters**

SUSY breaking schemes

Strongly constrained models, but still respect SUSY structure!

`Hidden sector': → Visible sector:

SUSY breaking → MSSM

` Gravity-mediated': mSUGRA

`Gauge-mediated': GMSB

`Anomaly-mediated': AMSB

.....

4-5 free para- meters

also hybrid- solutions studied !

- SUGRA: mediating interactions are gravitational
- GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions
- AMSB: SUSY breaking happens on a different brane in a higher-dimensional theory

- Feature of schemes: lead to 'characteristic' mass spectra

➢ **But these are strong assumptions…. !**

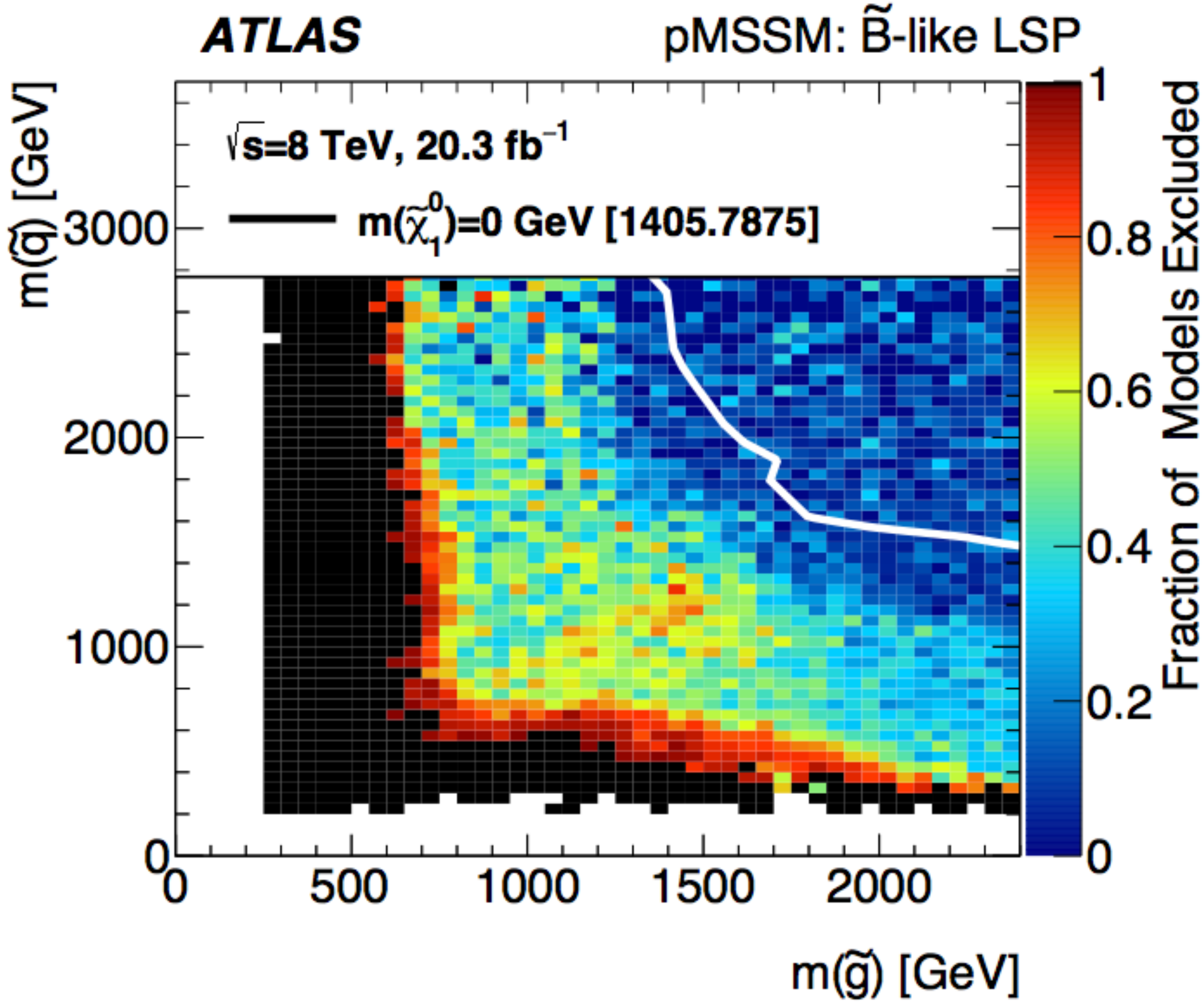
Impact of model assumptions

Often used models:

- **Constrained models: very restrictive in mass spectra**
  - ➢ exclusion limits only valid in the specific parameter point
  - ➢not transferable to full parameter regions
  - ➢but: if new particles found within these analyses still the model structure testable!
- **Simplified models: strong assumptions on masses and branching ratios**
  - ➢do not respect the structure of actual BSM models ……'auxiliary tool' for setting limits
  - ➢exclusion limits correspond to ``best case" scenarios
  - ➢realistic models can be tested with simplified-model limits; constraints in general much weaker

Caution!!!

- **MSSM with 18 parameters: respects the model structure, more general mass hierarchies**
  - ➢no CP-phases,….ok, but phenomenologically a good starting point !
  - ➢however: sampling of parameter random scans is of limited validity



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- **MSSM with 18 parameters: respects the model structure, more general mass hierarchies**
  - ➢no CP-phases,….ok, but phenomenologically a good starting point !
  - ➢however: sampling of parameter random scans are of limited validity
  - ➢depend on the resolution of the scan but in nature only one parameter point will be realized, iff……

So, stay tuned, SUSY@LHC is still highly motivated: do further hints from nature exist?

Any arguments for light SUSY?

- **Minimization of 1-loop Higgs Potential:**

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

- **To keep EWFT ~ 3%:**
  - rather small μ (~200 GeV) required
  - 'naturalness'
  - Several 'natural' scenarios: light stops and light higgsinos,…
  - degenerate masses ~200 GeV range expected *not excluded by LHC!*
- **Consistent with results from low energy, $(g\text{-}2)_\mu$**
  - Favours also rather low SUSY masses in electroweak sector

$$\delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$

- *Required experimental features: ISR technique, precise mass measurements, powerful detector magnets for resolution …*

Requirements of new physics features

E.g. light but mass-degenerate new particles: 'light higgsinos'

- Theoretically easily embedded in hybrid gauge-gravity mediated models
- Higgsino masses ~160 GeV range with typically $\Delta m(_{\chi\pm-\chi 0})$~1 GeV
- Leads to experimental challenges: many π's, soft γ, E_{miss} from decay
- Solution: apply ISR and use recoil mass: $\Delta m_{res}(_{\chi\pm-\chi 0})$<1 GeV *'mono-photon'*

E.g. revealing the underlying structure of the model:

- determine chiral quantum properties of new particles
- prove the coupling structure
- prove the spin structure of the model
- Solution: apply polarized $e^{\pm}$-beams and precise angle distributions+cross sections

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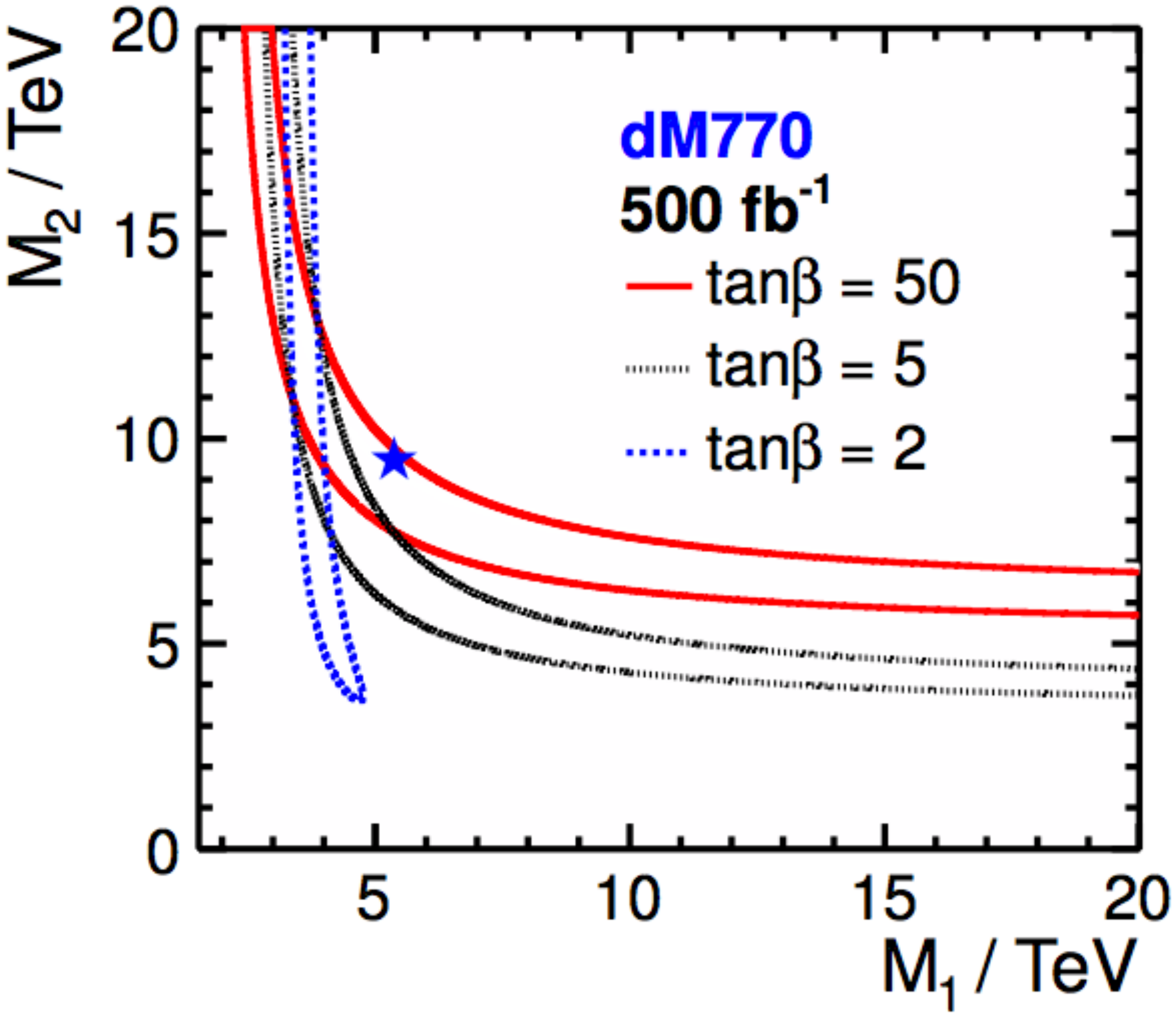
Berggren et al.

- measure masses of the light higgsinos
- measure cross section ($X^0_1 X^0_2$)~ O(%) with polarized beams

➢ determine Δμ~ 4 %

➢ infer M_1,M_2 even in TeV range depending on tanβ

Would be an absolute nightmare scenario for LHC on its own!!!



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Requirements of new physics features

- **Determination of chiral quantum properties of new particles**

Moortgat-Pick et al

New particles are carry quantum numbers

➢have to be proven experimentally

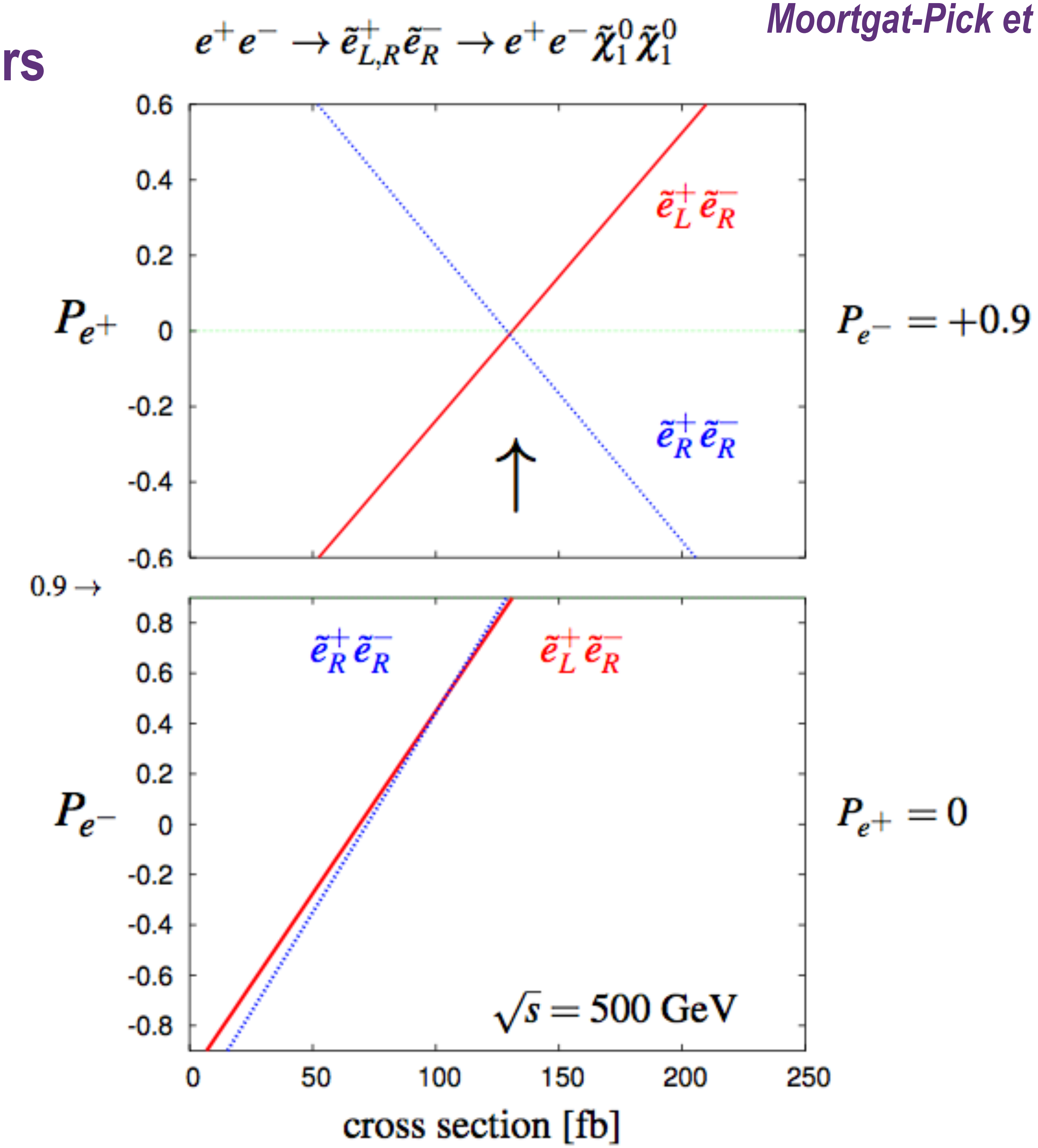
Here: *scalar particles are associated to chiral quantum numbers*

Beam polarization is 'chirality analyzer'

- based on measurement of masses and polarized cross sections

➢*unique identification of associated chiral quantum !*

Experimental verification of such quantum properties not possible at LHC!



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Requirements of new physics features

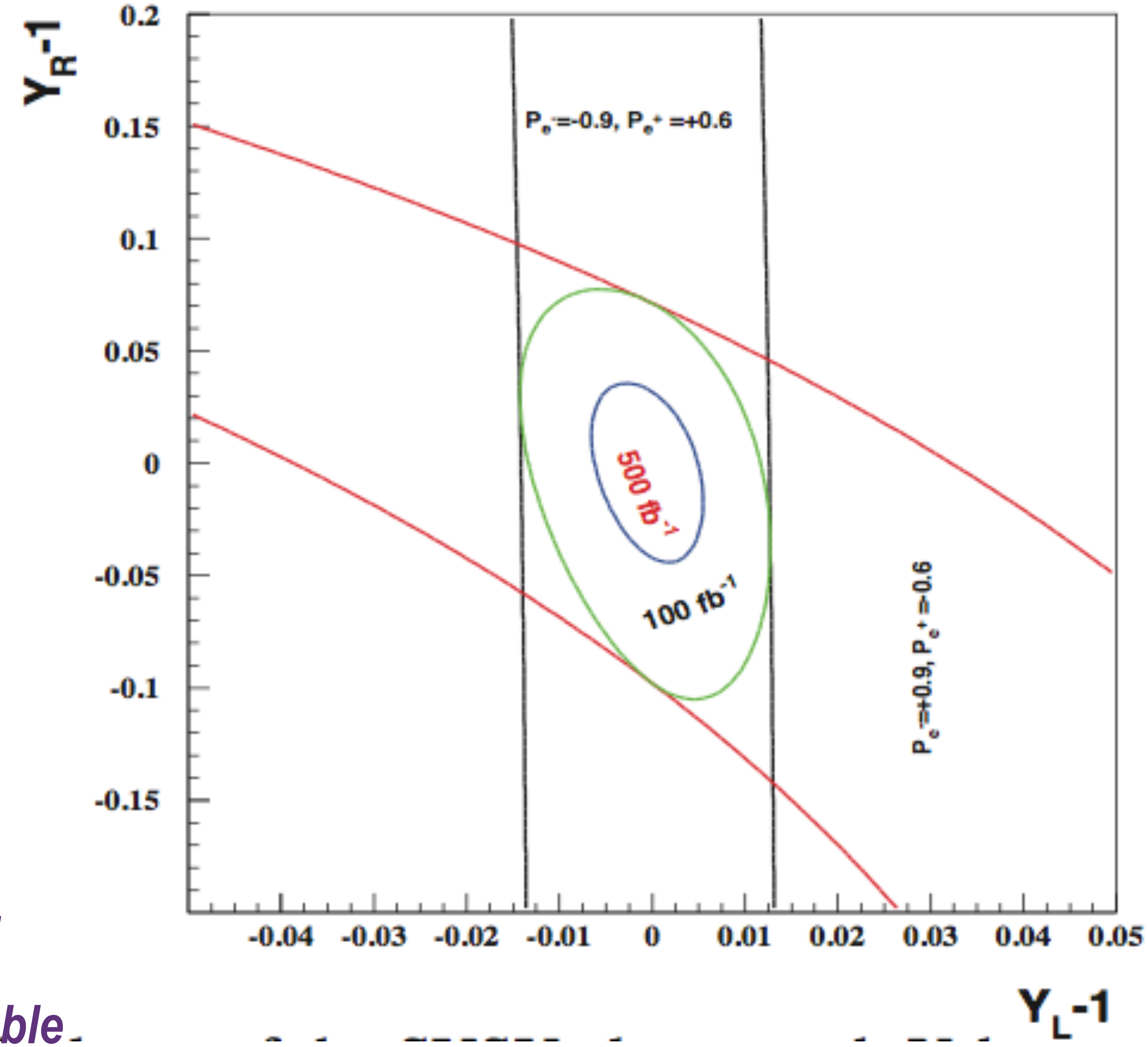
- **Determination of the coupling structure of the model**

Choi, S.Y. et al

Example here:

- Equivalence of electroweak Yukawa couplings g_{wino}, g_{bino} with SU(2) and U(1) gauge couplings g,g'
  $Y_L = g_{wino}/g$, $Y_R = g_{bino}/g'$

- Contour plots of measured polarized cross sections allow the test at %-level, depending on luminosity and polarization



Similar studies for coloured Yukawas exist via determination of gq,gg,qq at LHC, however with larger uncertainties.
If accomplished by LC 5-10% level achievable.

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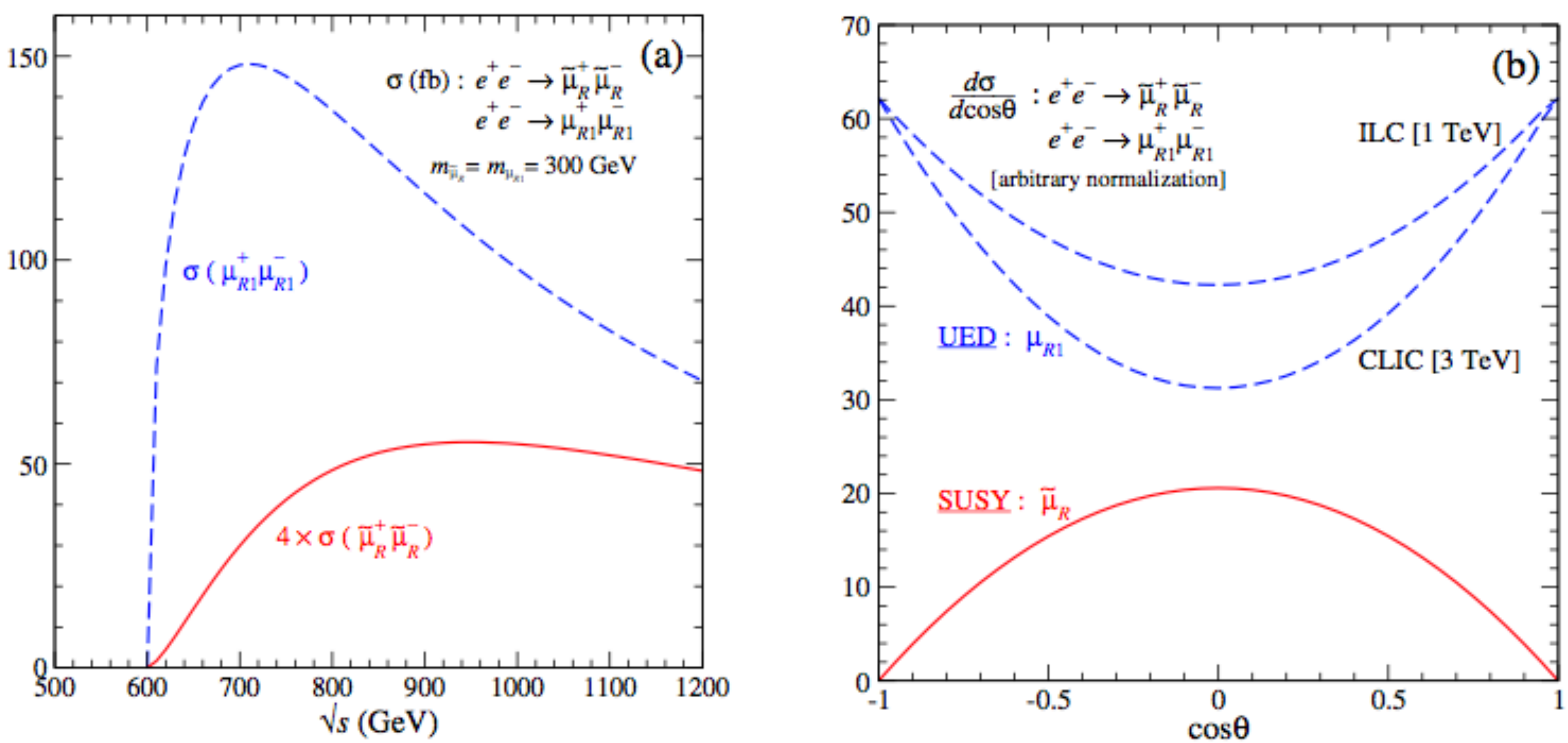
Requirements of new physics features

- **Proving the spin structure of the model**

Choi, S.Y. et al

Threshold excitation



Angular distribution

Smuon pair production in SUSY and an UED model: clear separation possible via both

➢ **thresholds excitation curves, requires tunable energy: p-wave character obvious**

➢ **precise measurement of production angle distributions: $\sin^2\theta$-dependence unique sign for spin**

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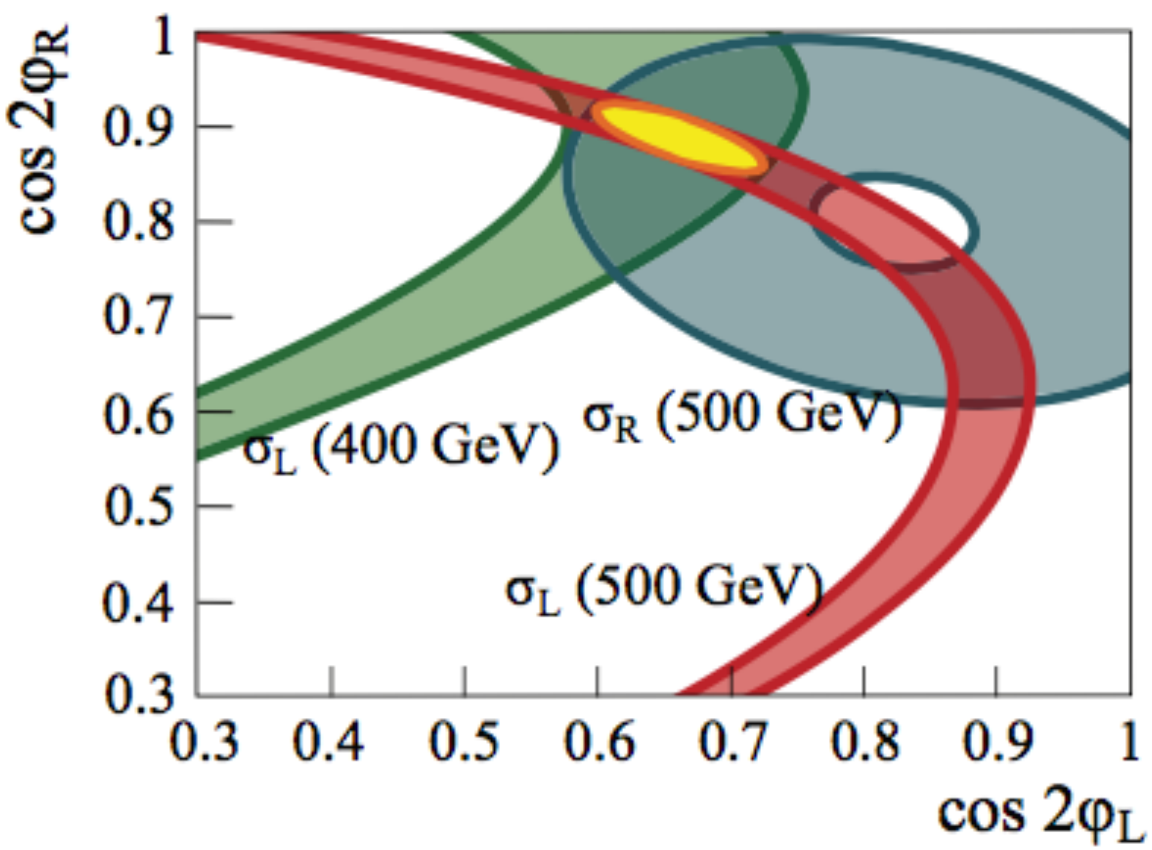
Requirements of new physics features

Determination of fundamental mixing angles

➢ can be converted in fundamental parameters

Based on measurements of the light charginos only

- masses+polarized cross sections
- different cms energies



Choi, S.Y. et al

Model-independent parameter determination: very challenging at LHC !

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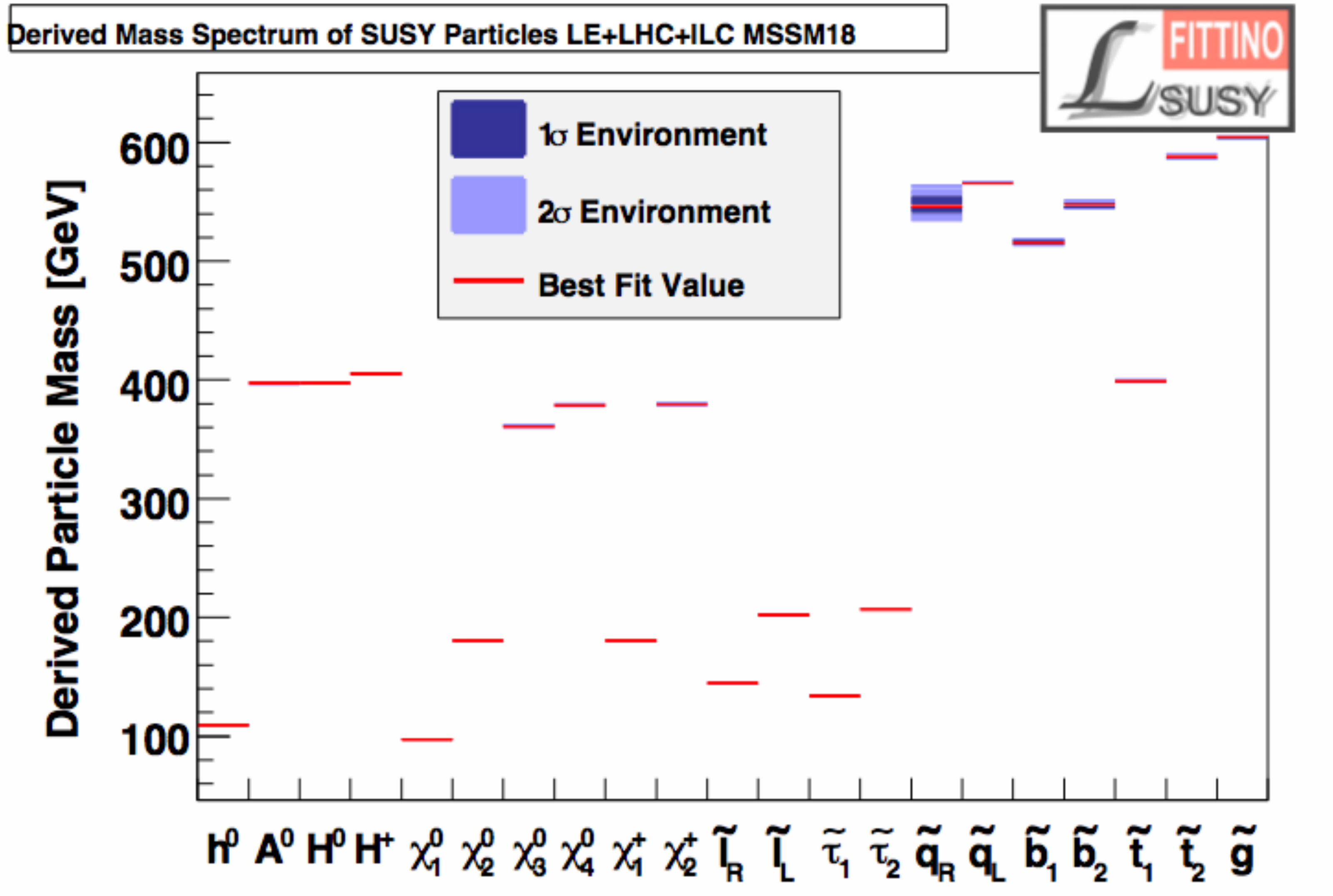

Bechtle et al

Parameter fit in the MSSM18 using
- input from LHC 300
- input from ILC
- constraints from LE

➢ *very precise mass spectrum derived*

E.g. handling of a large number of new model parameters:

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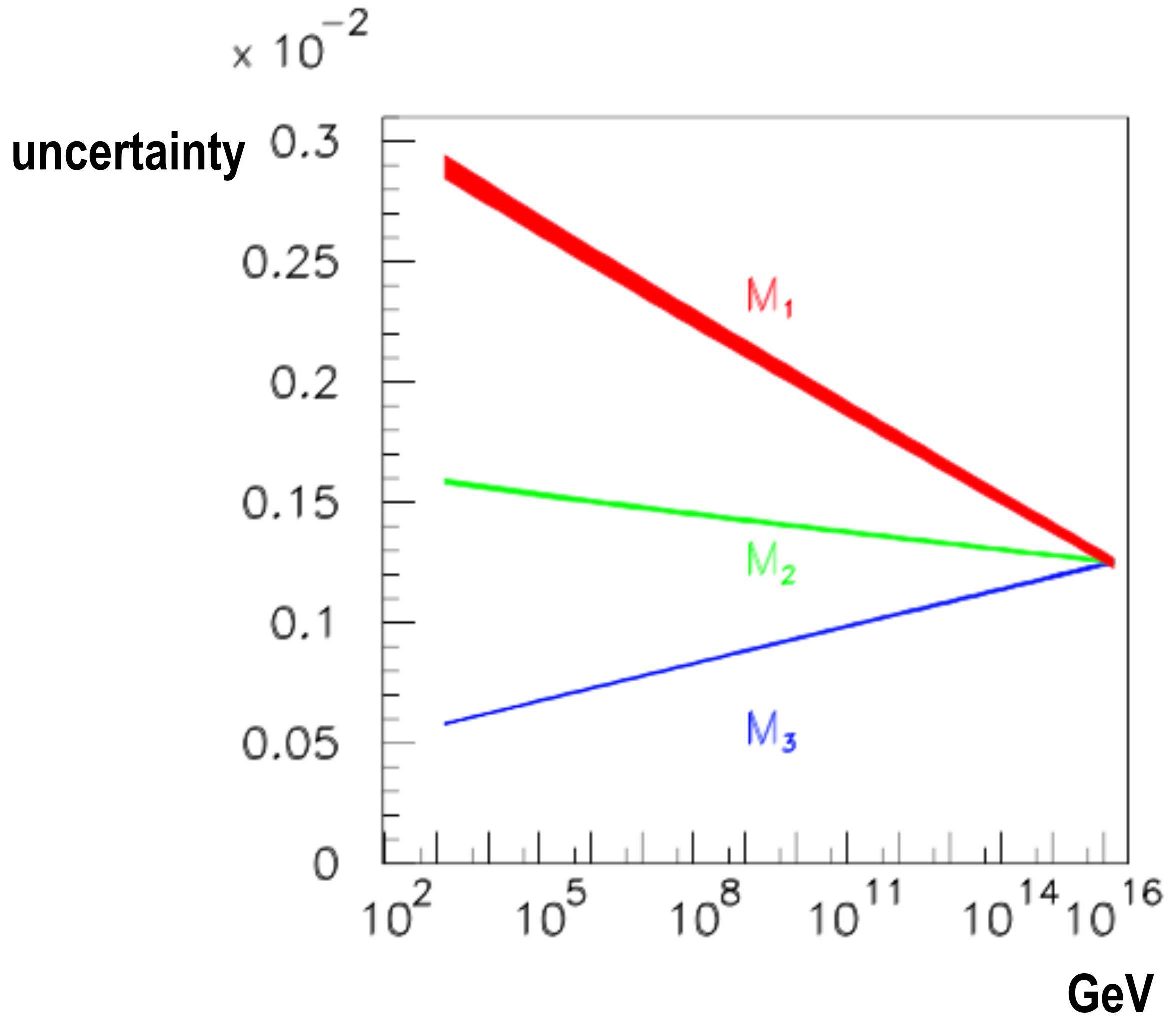
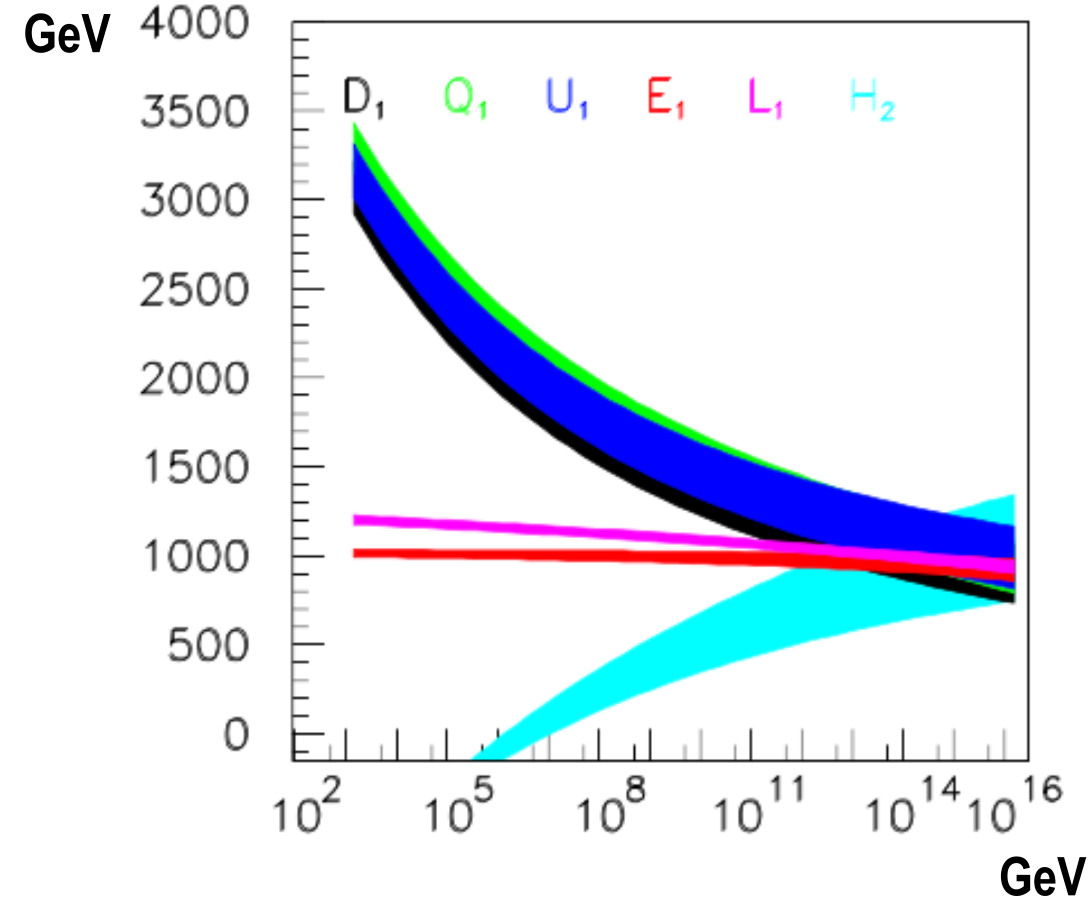
Requirements of new physics features

Linssen et al
Blair et al





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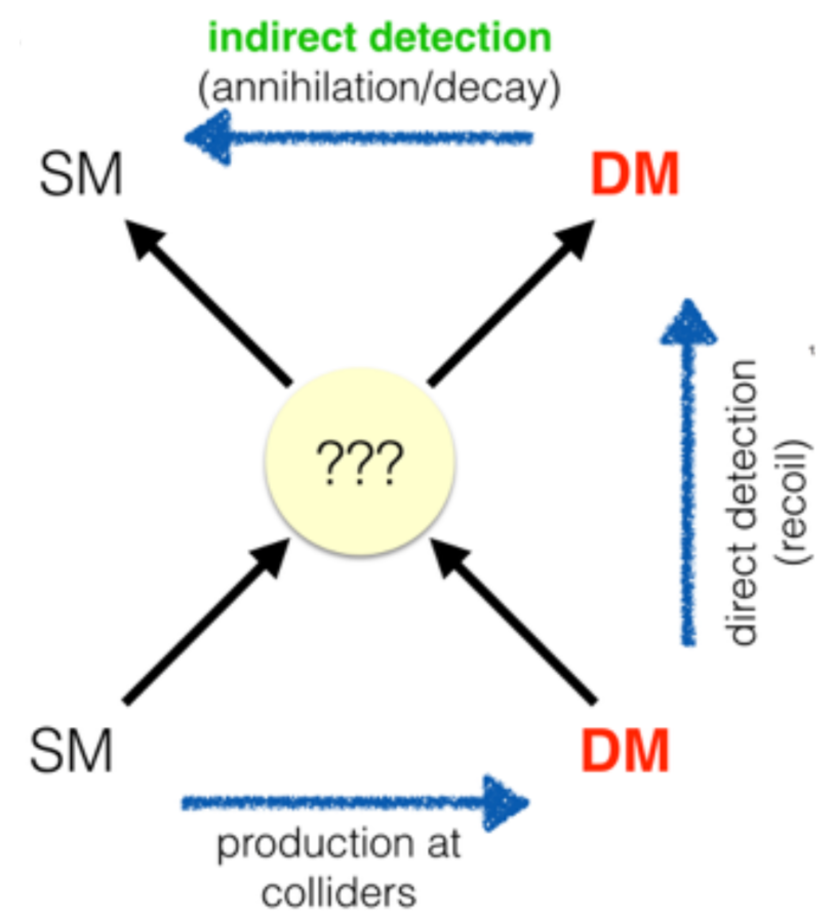
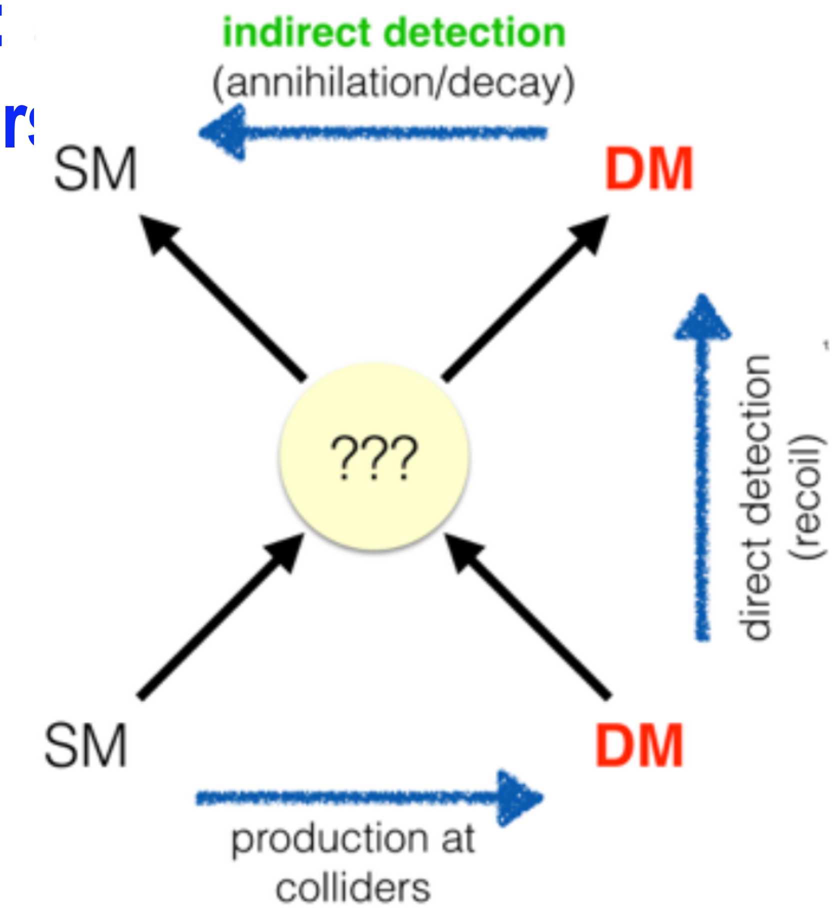
Dark matter (DM) aspects

- **Most compelling reason for BSM is evidence for dark matter:**
  - rather flat rotation curves of galaxy in the halo of DM
  - gravitational lensing point also to gravitational potentials from DM
  - total matter and baryon density from cosmic microwave background: $\Omega h^2 = 0.1196 \pm 0.0031$
- **Constraints from direct searches**
  - DM scattering off nuclei
  - two classes: spin-dependent σ_{SD}, spin-independent σ_{SI}
    - ➢ σ_{SI} gets contributions from H, Z,new coloured F/S
    - ➢ σ_{SD} gets contributions Z, new coloured F/S
  - several experiments: excess compatible with m_{DM}~5-30 GeV
    - ➢ in conflict with XENON, LUX,…
- **Constraints from indirect searches**
  - very important for testing the WIMP paradigm
    - ➢Fermi-LAT sensitive to few tens of GeV
    - ➢forecast: O(100GeV) within decade of data
    - ➢caveat: based on assumptions on astrophysical foregrounds
    - ➢active field: remember discussion about ~130 GeV γ-ray line



Dark matter (DM) prospects

- Candidates —should be stable or long-lived— for DM:
- If weakly interacting: chance to produce DM at colliders
  - SM candidates practically excluded, i.e. not sufficient:
    - ➢baryons and neutrinos ($\Omega_\nu h^2$=0.004)
  - SUSY candidates: LSP (R-parity conserv.) X^0_1
    - ➢pp $\rightarrow X^0_1 X^0_1 \gamma$ or $X^0_1 X^0_1 j$
    - ➢ e+e- $\rightarrow X^0_1 X^0_1 \gamma$
    - ➢*precise MET and polarized beams important*
  - Universal extra dimensions: lightest KK-odd particle
    - ➢ i.g. a vector particle B_1 with mass n/R
    - ➢ *important Higgs mass and couplings: limit on R*
  - Higgs portal models, i.e. 'Higgs connects DM sector to SM':
    - ➢ S with <S>=0 or vector field X_μ, and Majorana fermion χ
    - ➢ imposing Z_2-parity: Higgs responsible for DM annihilation+elastic scattering of DM
    - ➢ *important Higgs invisible width!*
  - Extended scalar sector, e.g. the inert doublet model:
    - ➢ DM either S or P, low (<60GeV), intermediate and heavy mass region (>500GeV)
    - ➢ *crucial invisible Higgs decays, modified $H\gamma\gamma$-rate*

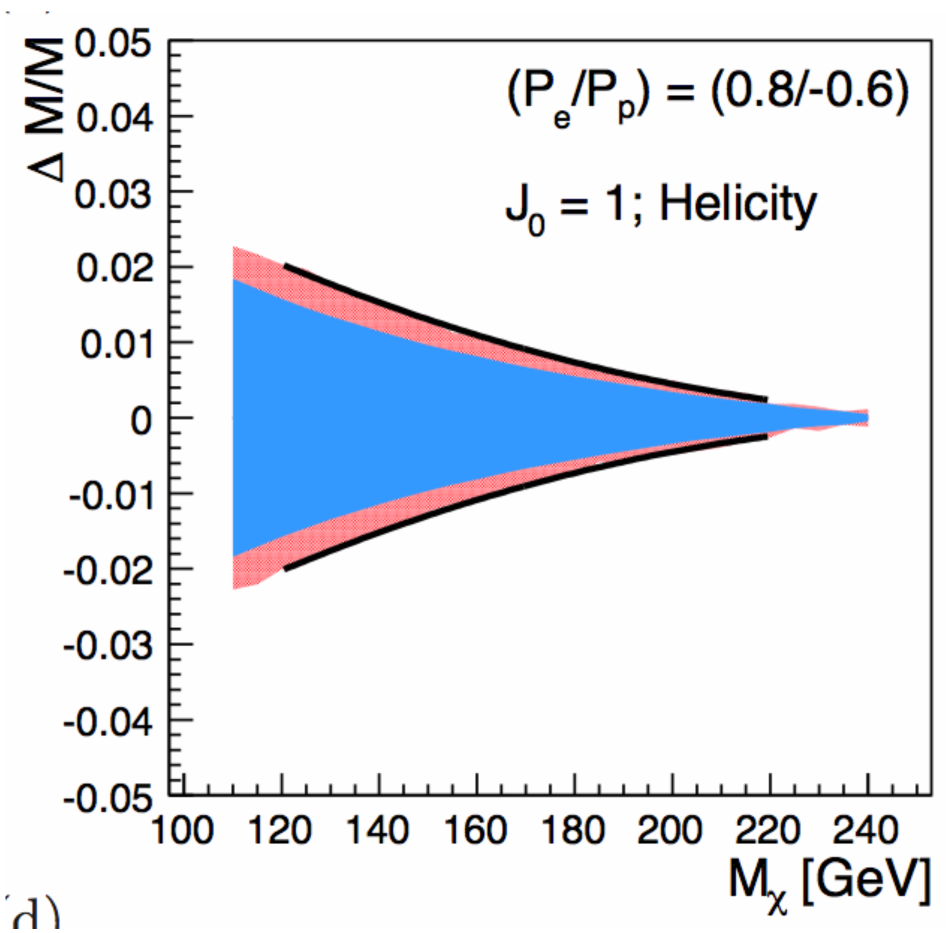


Dark matter (DM) prospects at e+e- colliders

- Resolving the mystery of DM

  - E.g. SUSY candidates: LSP ~ X^0_1
    if no hints for new particles at LHC, but $\sqrt{s_{ee}} > m_{X01}$
    - ➢ e+e- $\rightarrow X^0_1 X^0_1 \gamma$ very promising!
    - ➢ signal is high energy γ only
    - ➢ background e+e- $\rightarrow \nu\nu\gamma$
    - ➢ *beam polarization essential to reduce background and enhance the signal*
    - ➢ exploit energy spectrum: precise m_{DM}, σ_{DM}

Bartels et al.



  - If $m_{DM} < m_{h/2}$
    Invisible Higgs width provides unique opportunity
    - ➢ essential for σ_{SI} in models dominated via Higgs exchange
    - ➢ requires precise determination of BR(H→invisible) and T_{invis}

Dark matter (DM) prospects at e+e- colliders

Dreiner et al.

- **Resolving the mystery of DM**
  - E.g. SUSY candidates: LSP ~ χ^0_1

    if no hints for new particles at LHC, but $\sqrt{s_{ee}} > m_{\chi 01}$

    ➢ different approach: parametrize DM interactions via effective operators

    ➢ SM+DM: heavy mediators only

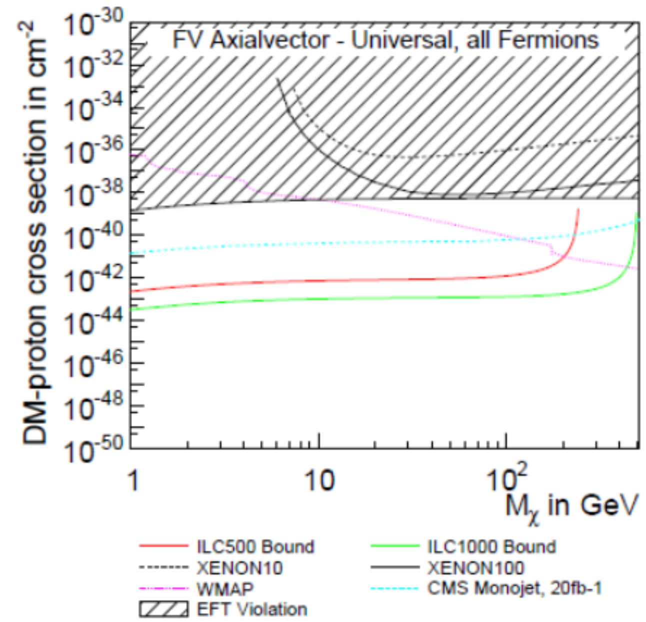
    ➢ still e+e- $\rightarrow \chi^0_1 \chi^0_1 \gamma$ very promising!

    ➢ signal is high energy γ only

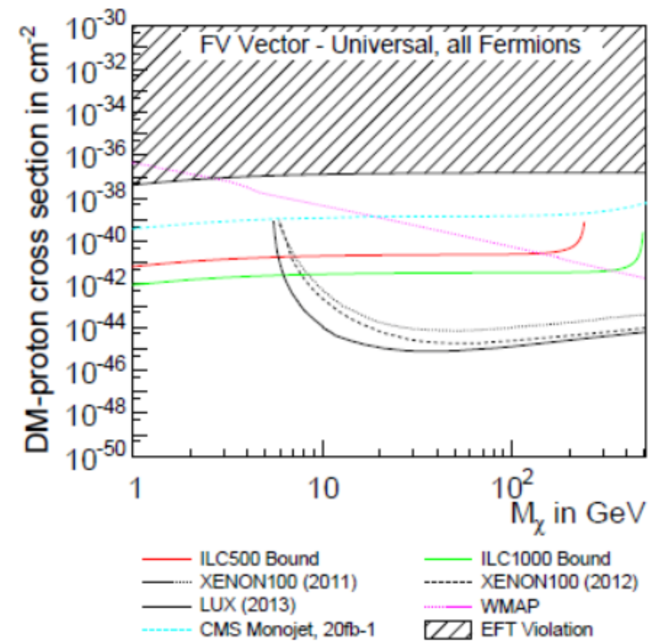
    ➢ background e+e- $\rightarrow \nu\nu\gamma$
  - In some parts of the parameter space:

    bounds from LC (SI DM <10 GeV, SD DM <100): unique opportunity

SD:



SI:



- **Determination of DM (and co-produced particles) properties**

  ➢ precise mass measurements of X's, e.g. via threshold scans in associated production

  ➢ measurements of mass splittings via endpoints

  ➢ measurement of mixing character of DM and test of $\Delta(\Omega h^2)$~10%

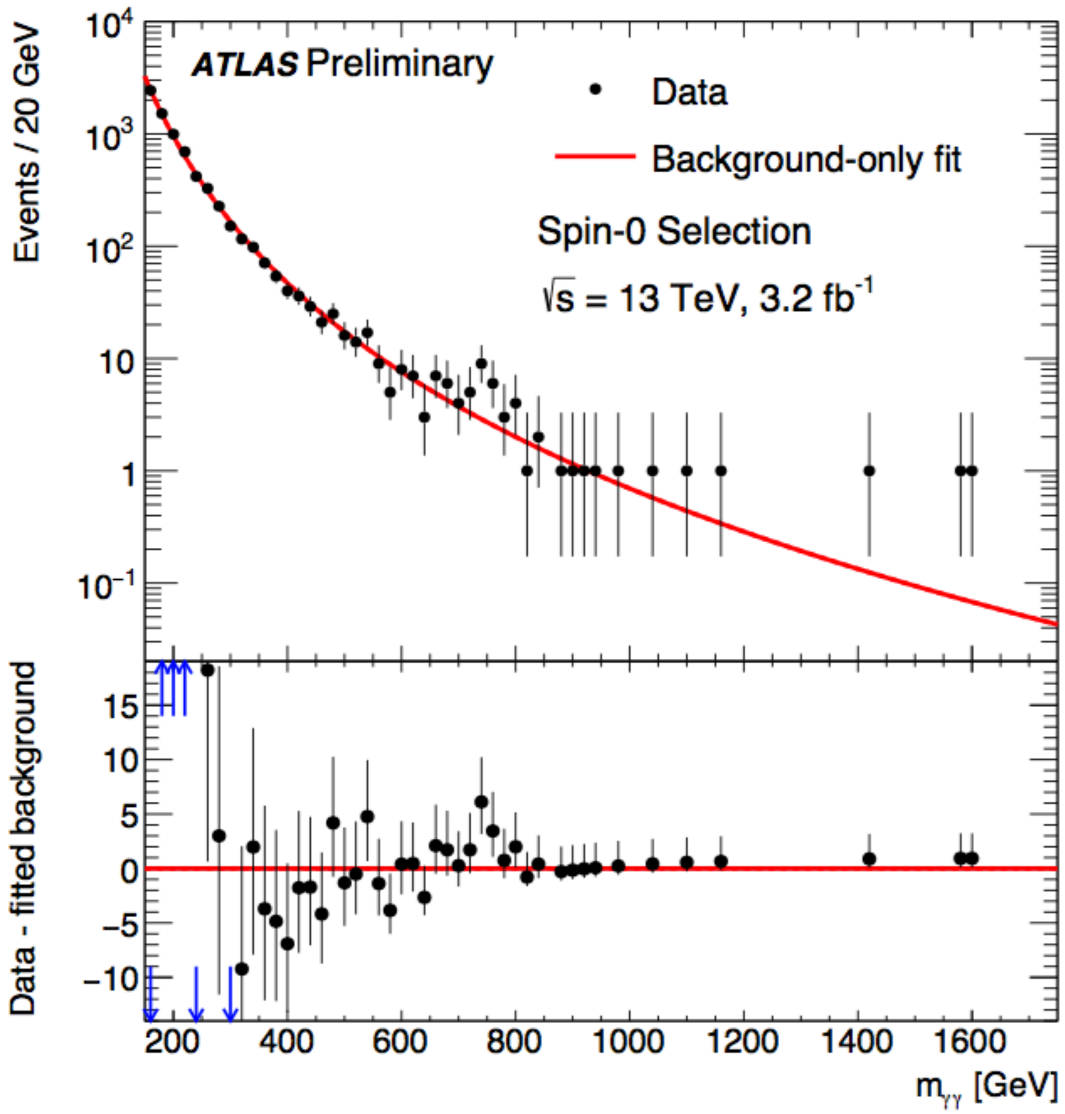
Implications of 750 GeV events in $\gamma\gamma$ channel

What's the status?

[ATLAS Collaboration, Moriond '16]

SPIN-0 ANALYSIS

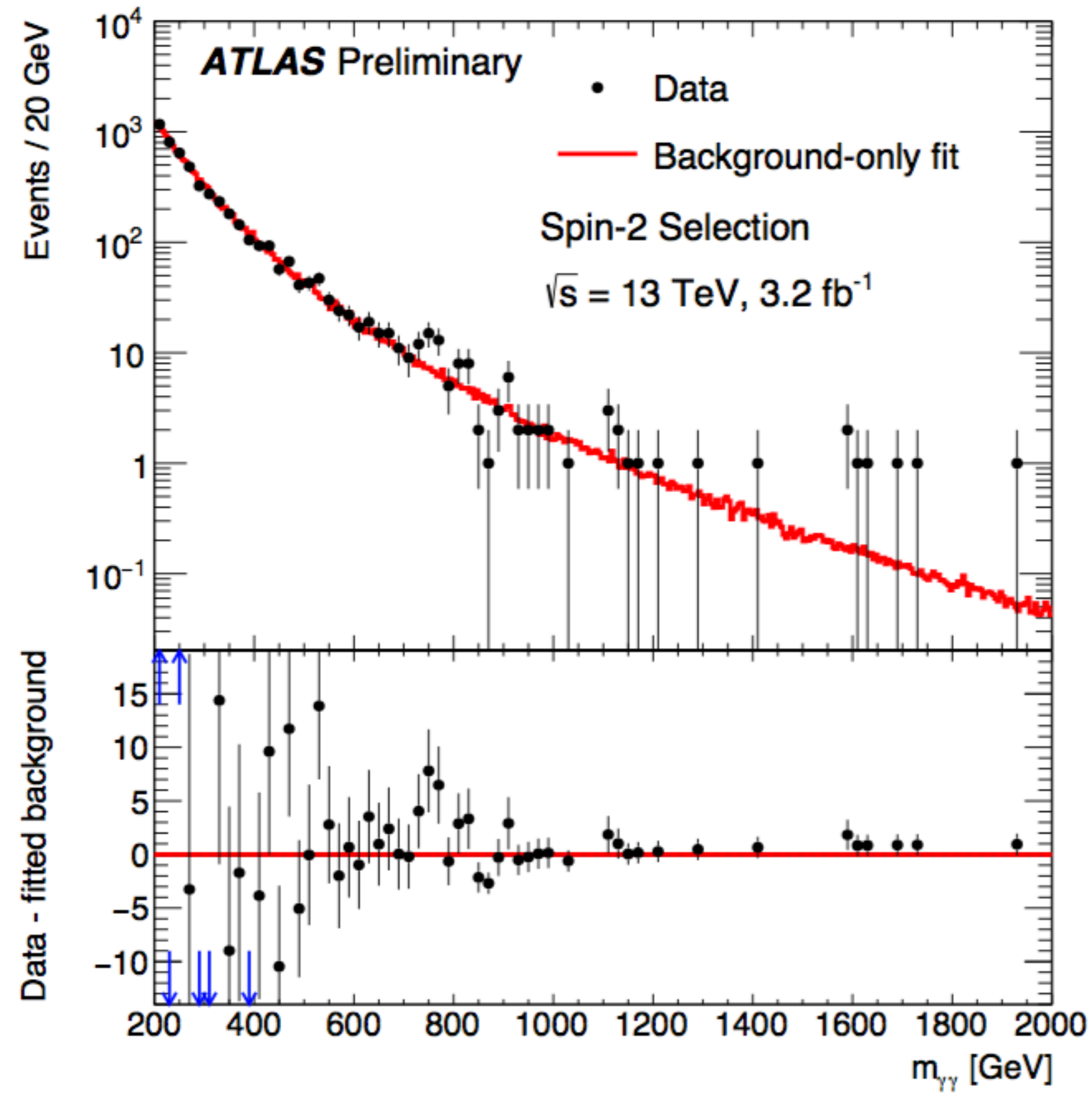
background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

SPIN-2 ANALYSIS

background-only fit

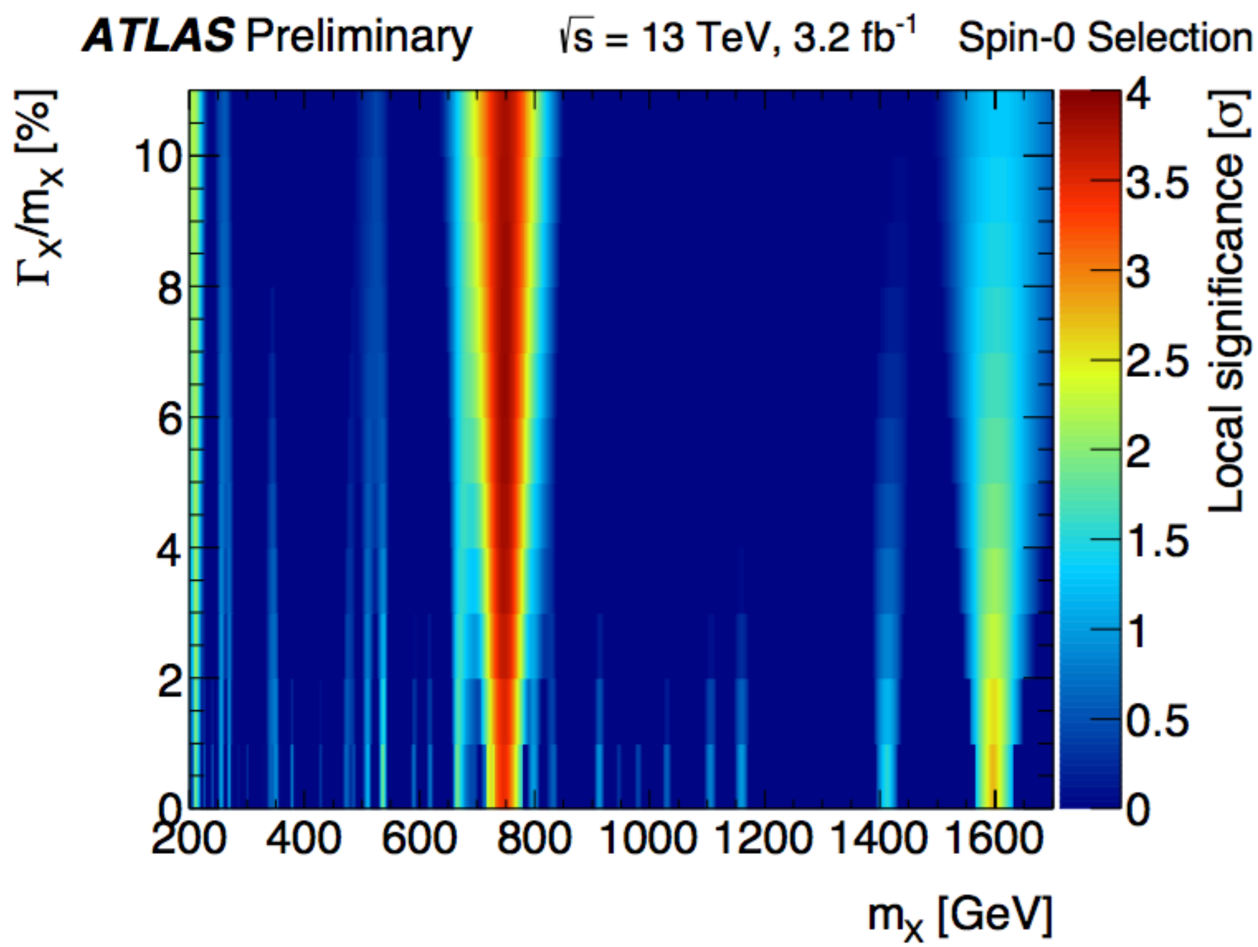


5066 events ($m_{\gamma\gamma}$ > 200 GeV)

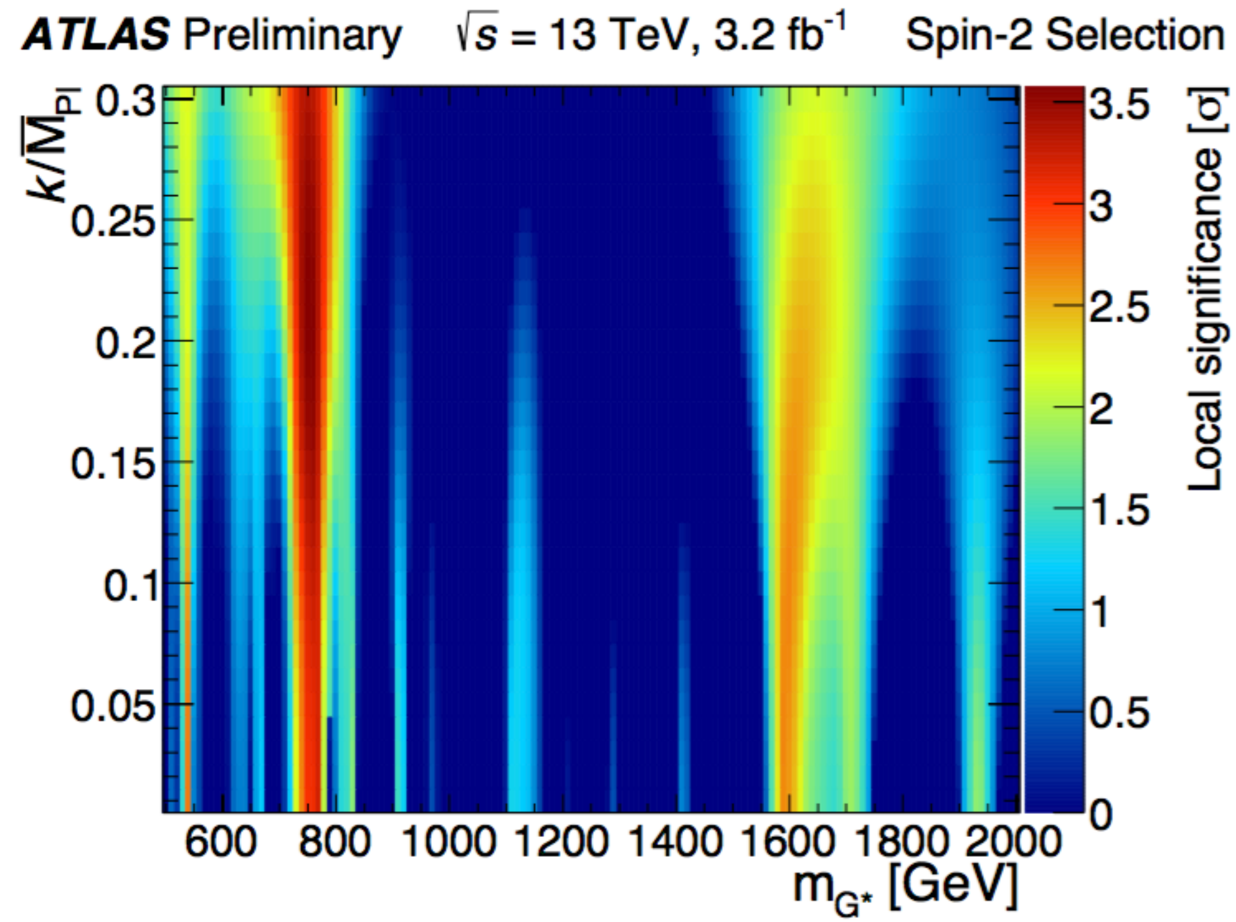
Fluctuation or signal,……that's the question….

Implications of 750 GeV events in γγ channel

What's the status?



- Largest deviation from B-only hypothesis
  - ✓ $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

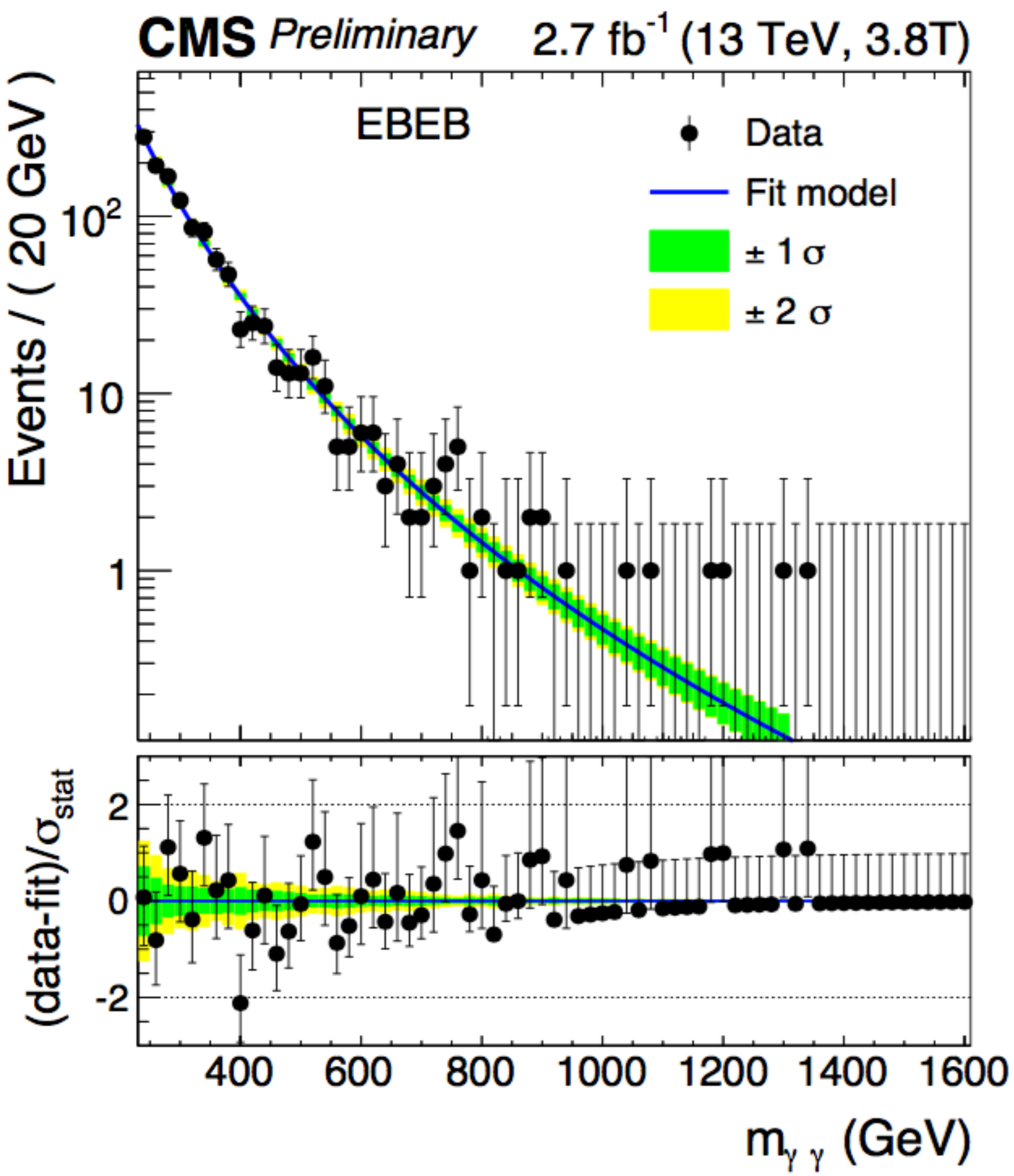


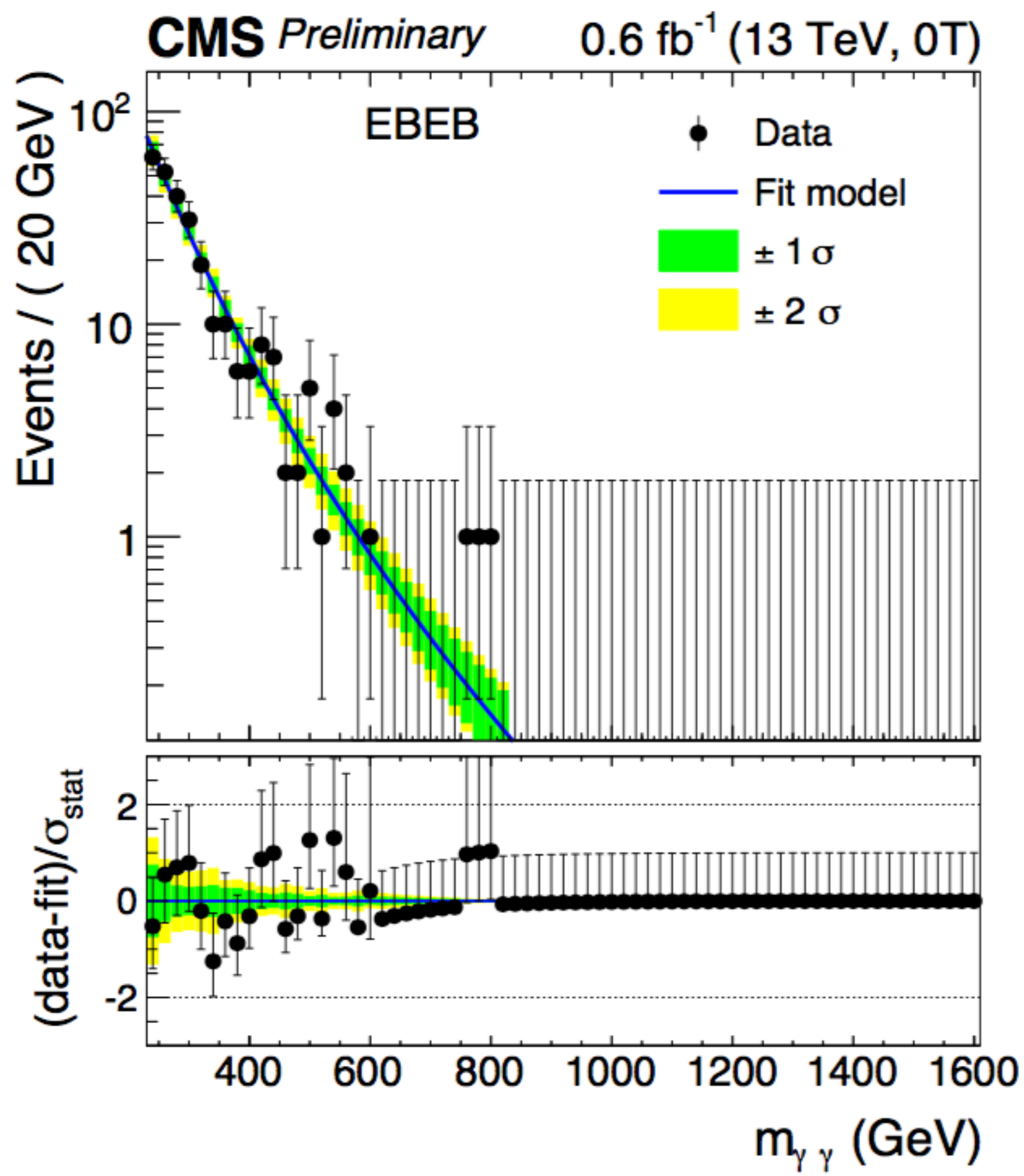
- Largest deviation from B-only hypothesis
  - ✓ $m_G \sim 750$ GeV, $\kappa/M_{Pl} \sim 0.2$ ($\Gamma_G \sim 6\%\ m_G$)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**
    - m_X = [500 GeV – 3.5 TeV]
    - κ/M_{Pl} = [0.01 – 0.3]

CMS: invariant mass spectra at 13 TeV

What's the status?

CMS collaboration, Moriond'16





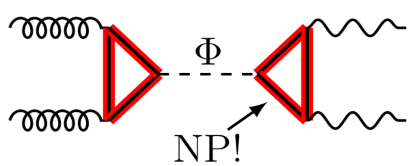
CMS: two events categories

- both photons in ECAL barrel
- one photon in ECAL barrel, one photon in ECAL endcap

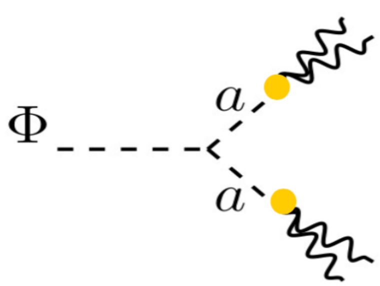
Implications of 750 GeV events in γγ channel

What can be done at e+e- colliders if, iff, iff-f,…………that's a true signal?

- Is it a new resonance at 750 GeV?
  - ➢ either spin 0 (most cases) or spin 2
  - ➢ but in generic models (SUSY, 2HDM) not easy to get only enhancement in γγ finale state and nowhere else
  - ➢ *extra F/S needed in loops,* in that case also contributions to WW, ZZ, Zγ expected,…..so stay tuned



  - ➢ But what if width is large?
    Maybe it's a new strong interaction?
    Could be reflected in Higgs couplings
  - ➢ But what if final state is not 2 photons?
    Could happen in the (plain) NMSSM !



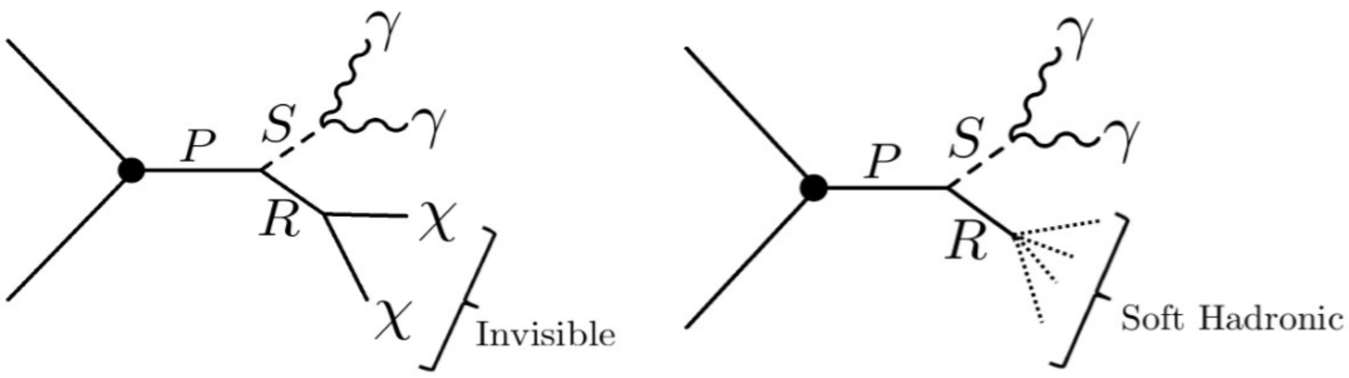
Could be very collimated γ

Depends on mass and coupling of a

Implications of 750 GeV events in γγ channel

More possibilities?

- Could it be a parent resonance ?



➢*If there is a real signal, there should be more new physics!*

- 2016 data@LHC will tell us more, but in case the signal gets stronger:

➢ a ~1TeV LC could provide the γγ-option for precise analysis of that state

➢potentially precise measurements of additional states

Nothing known yet, data 2016 will reveal this mystery, … maybe more mysteries will show up in the next years:

➢ *But the bonus options at the LC γγ-, eγ-collision should technically not be precluded! Keep such a flexibility!*

Conclusions

- **BSM is well motivated, too many open questions in the SM**
  - ➢ lots of models on the market
  - ➢ but 'no clue' which model is most likely to be realized in nature
- **Current results at LHC do not point to a specific scale for BSM**
  - ➢ caution: not guaranteed that new scale is ever known!
  - ➢ but one should not wait any longer: physics case is well established … !

- **Any BSM has new features/structure**
  - ➢ chiral structure, spin, coupling properties have to be experimentally analyzed and tested
  - ➢ direct and indirect test of BSM go hand-in-hand
  - ➢ e+e- machines offer variable tools and high flexibility
  - ➢ tuneable precise energy, polarized beams, '4π detector', bonus options (GigaZ, γγ, eγ)
- **LC offers highest flexibility…..technical design should not preclude options**
  - ➢ *well prepared for the 'Known' but also for the 'Unknown' !*

LHC + LC mandatory to resolve the BSM snooker !

Very special event just ahead!

Don't forget to reserve in time!

Free Parameters in the MSSM

- mass matrices are 3 x 3 hermitian

  → m_Q^2 , m_u^2 , m_d^2 , m_L^2 , m_e^2 : 45 parameters
- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m^2_{Hu}, m^2_{Hd} : 2

→ altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ $\boxed{\text{remain 105 free new parameters in the MSSM!}}$