Is there Life after Higgs?

Beyond SM?

How do we achieve our goal?

QCD

John Ellis

KING'S College LONDON

Tests of SM

Top physics

- Mass, A_{FB}, …?

Producing new particles

- e.g., Higgs

Possible signals

- e.g., boosted jets

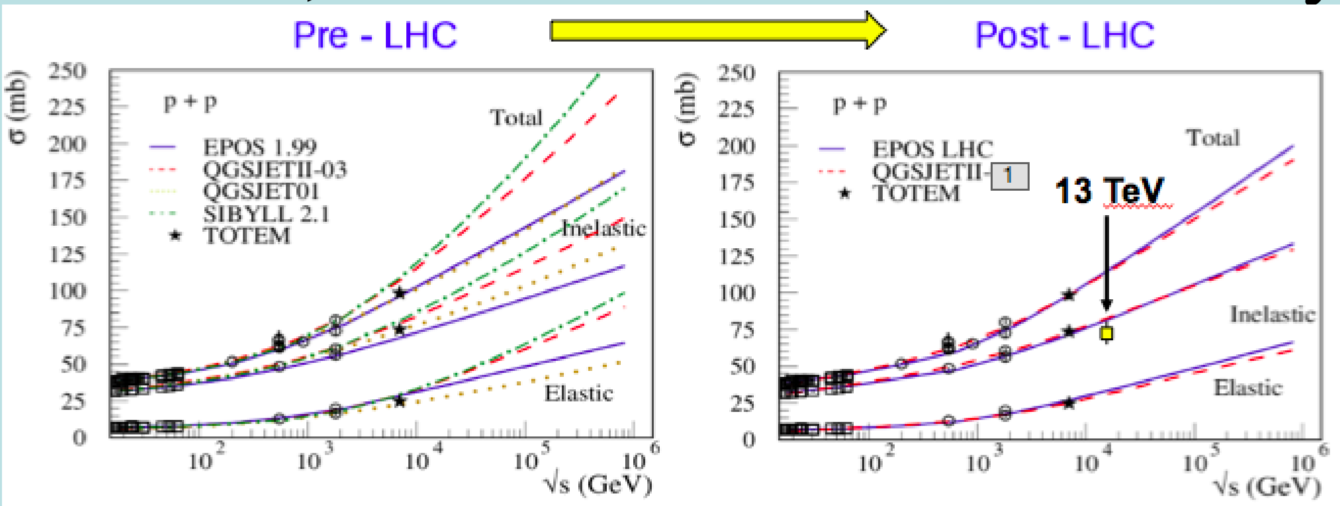
Backgrounds

- e.g., pile-up

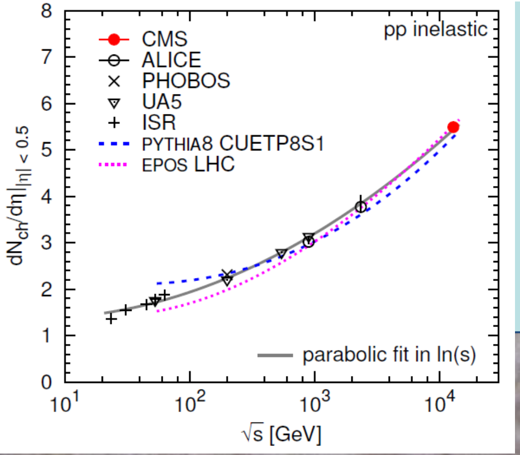
The basis for everything at the LHC

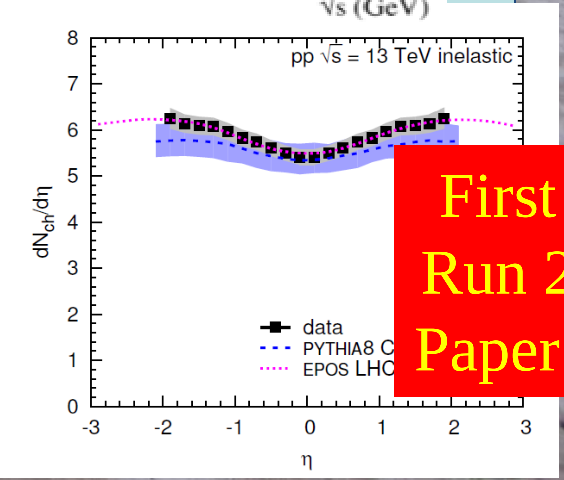
Soft QCD at the LHC

- Needed to model backgrounds for precise measurements, discoveries – also cosmic rays
- σ_{tot}



- Multiplicity $\frac{dN}{d\eta}$





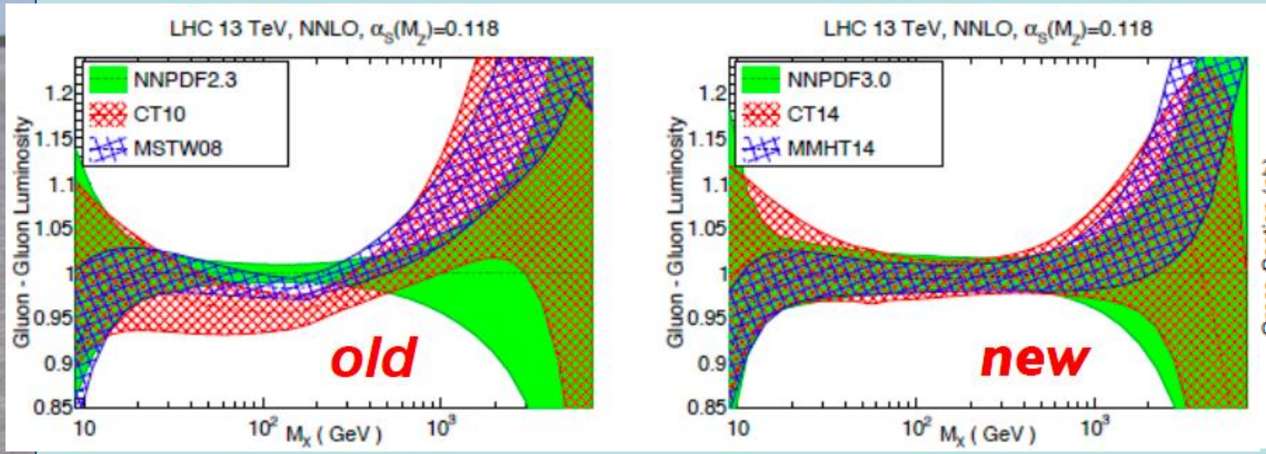
First Run 2 Paper!

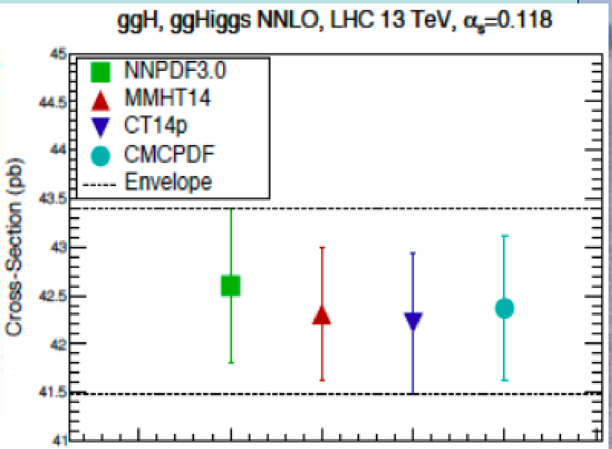
Grosse-Oetringhaus

Hard QCD at the LHC

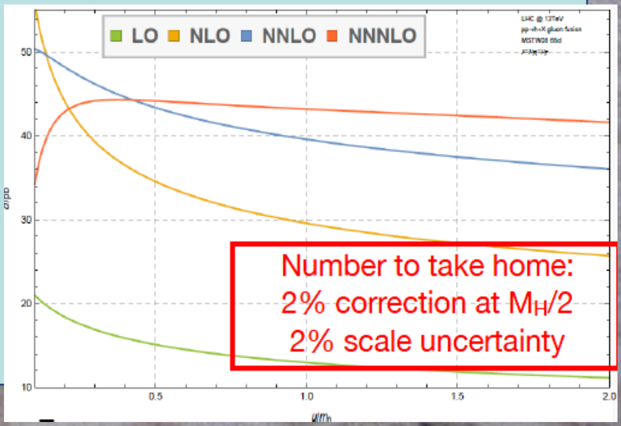
de Visscher

- PDF uncertainties greatly reduced thanks to LHC



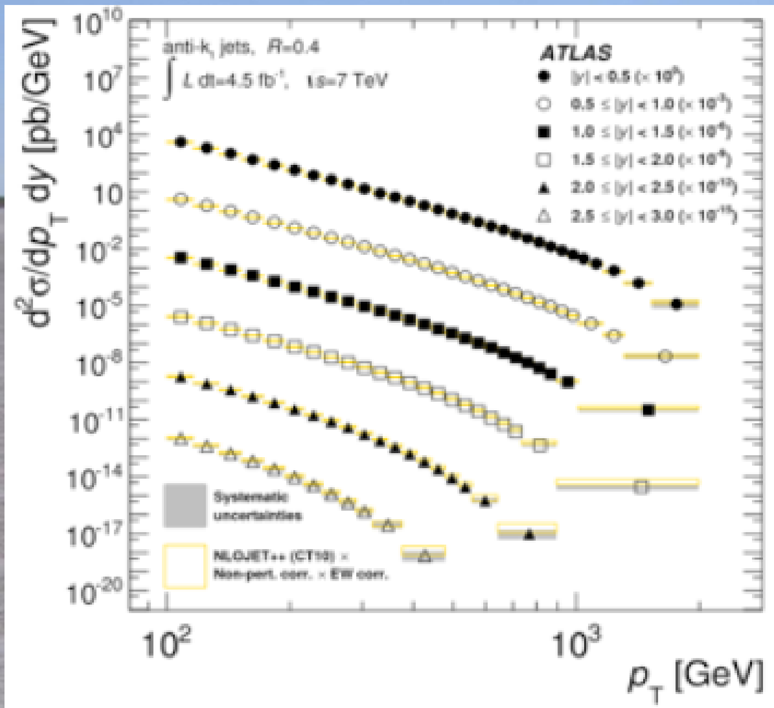


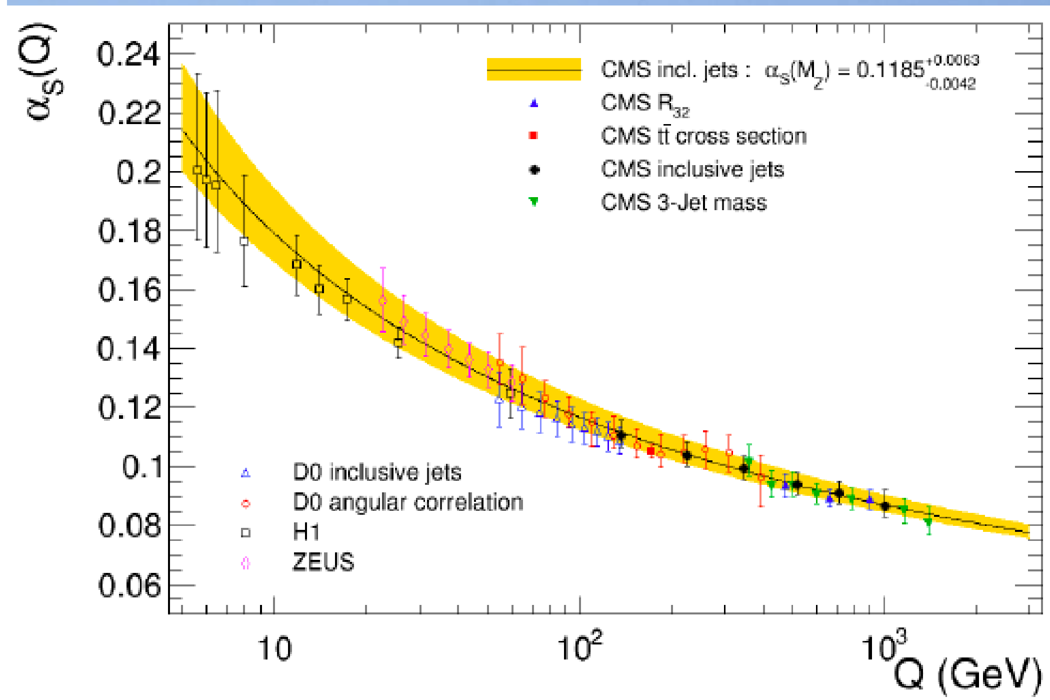
- State-of-the-art calculations NNLO, NLO EW
- N3LO Higgs σ
- NNLO kinematic distributions
- **New era in precision H physics**



Zanderighi

QCD Tests at the LHC

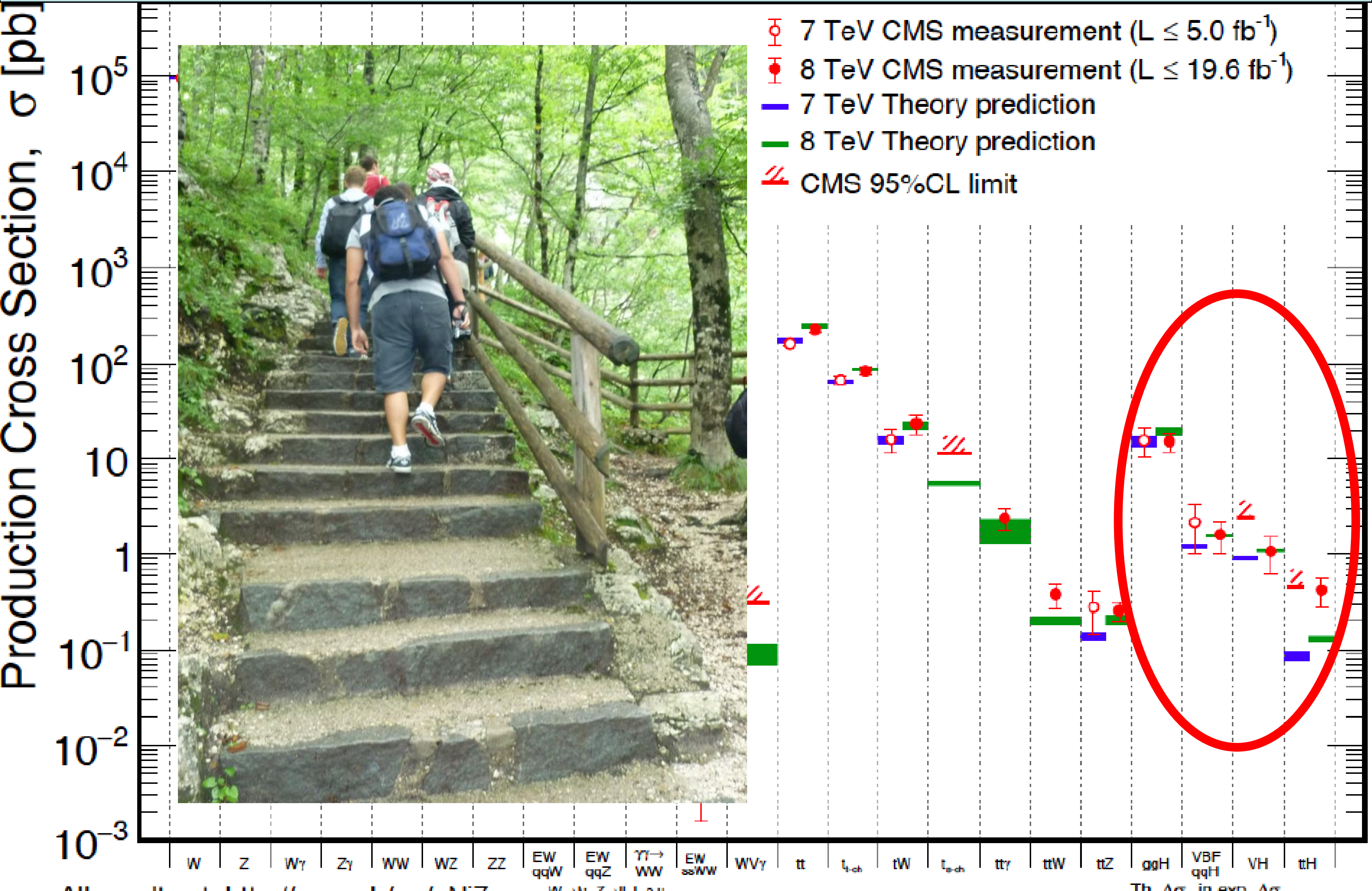




- QCD predictions successful over many orders of magnitude
- **α_s runs beyond the TeV scale**: into a GUT?
- Consistent with world average

De Visscher

Standard Model Cross-Sections @ LHC



All results at: http://cern.ch/go/pNj7

Melnikov, Meyer

Hard QCD: the Top Mass

- Basic parameter of SM; **stability of EW vacuum?**
- World average:

m_t = 173.34 ± 0.76 GeV

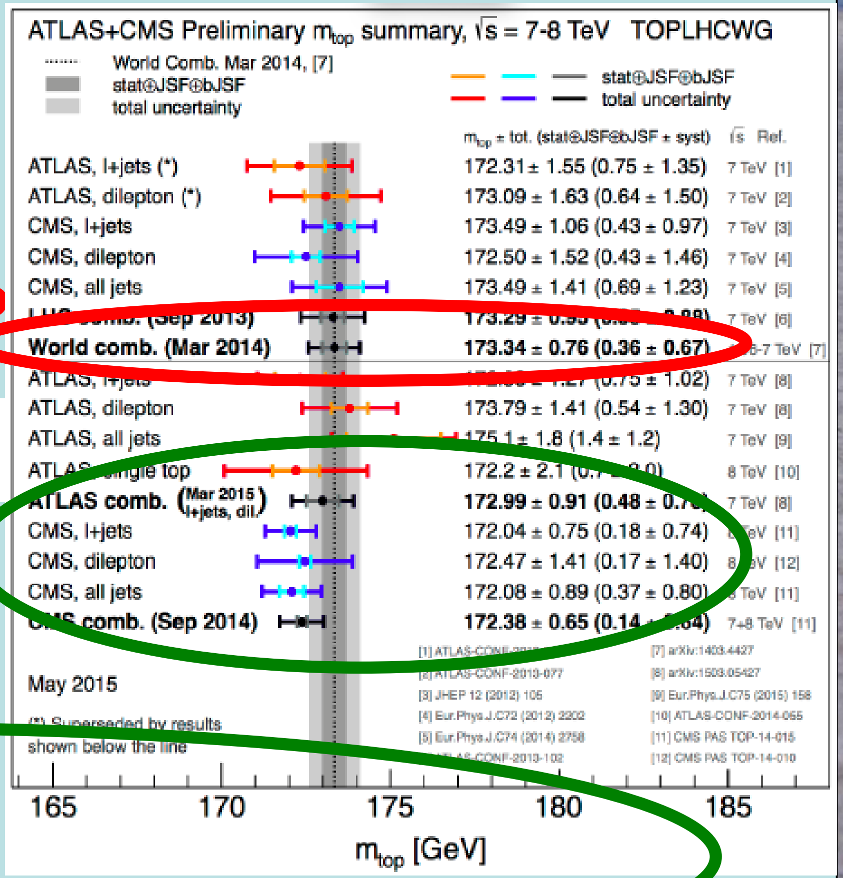
- **Running → pole mass OK?**

$$+ 7.557 + 1.617 + 0.501 + 0.195)$$

- Monte Carlo mass?!
- New measurements:

ATLAS: 172.99±0.91 GeV

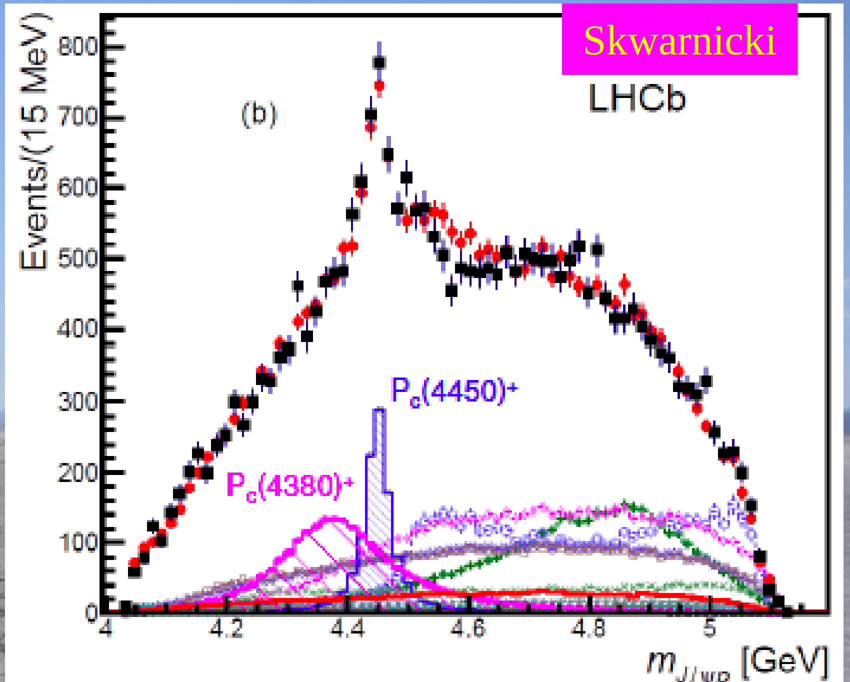
CMS: 172.38±0.65, D0: 174.98±0.58±0.49 GeV

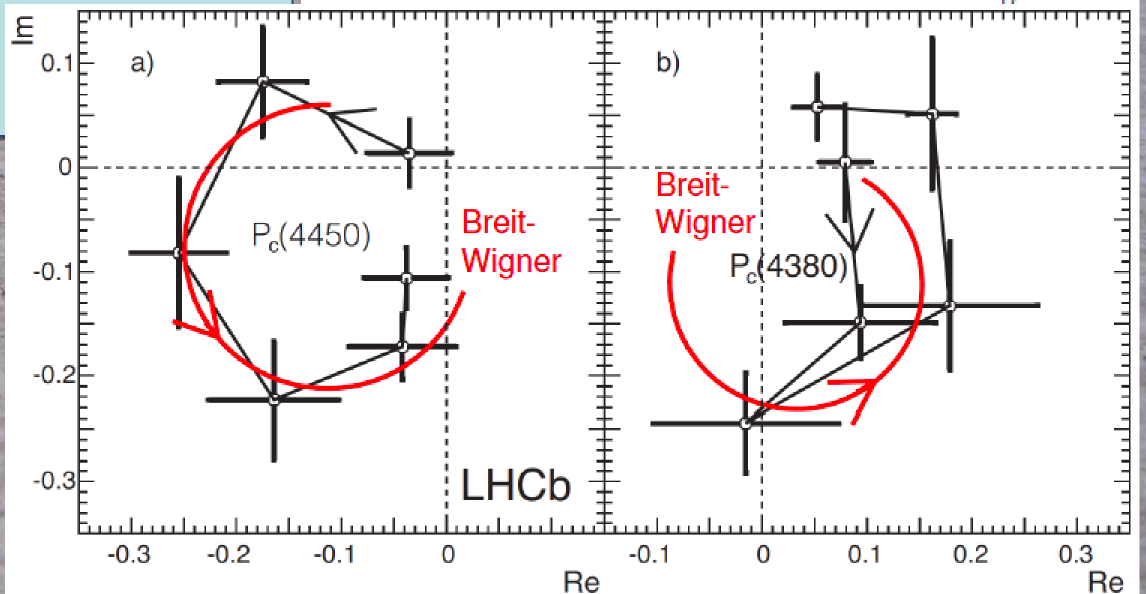


To Pentaquark or not to Pentaquark?

- Surely something there
- One nice Argand diagram
- One not so nice

But are they states with 4 q + 1 qbar In a single "bag"?





- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

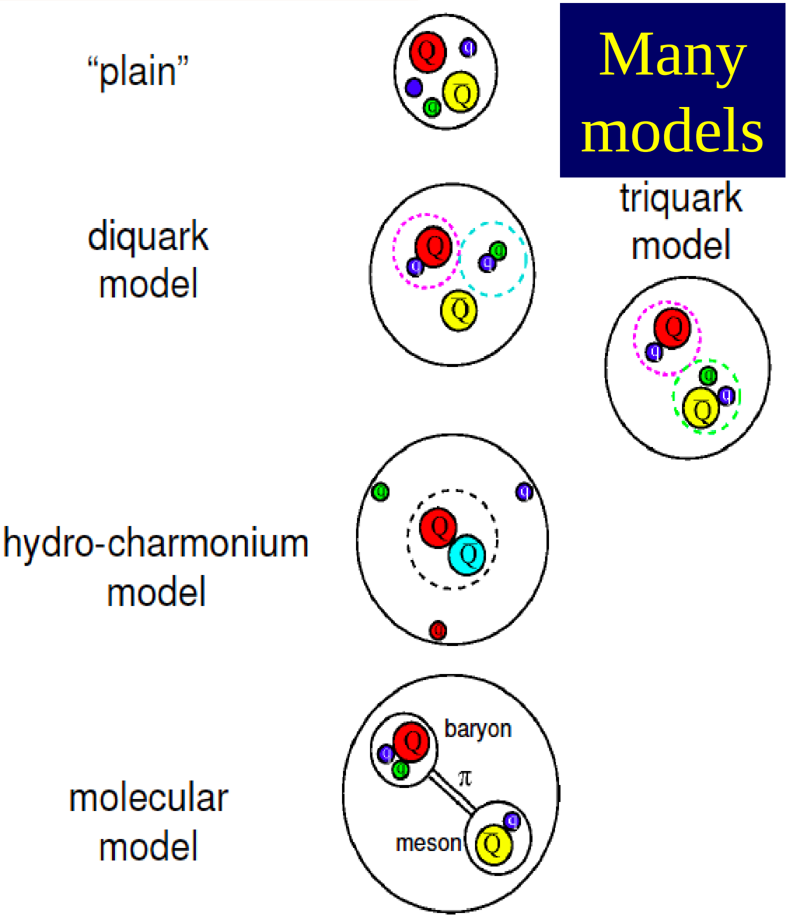
Skwarnicki, Bondar

To Pentaquark or not to Pentaquark?

4380±8±29	205±18±86
4449.8±1.7±2.5	39±5±19

- Why is 4450 MeV state so narrow, despite having 400 MeV of phase space?
- Barely bound state of Σ_c D^*?
- Analogous to "tetraquarks"?
- If so, many more to see!
- **Detect in photoproduction at JLAB?**

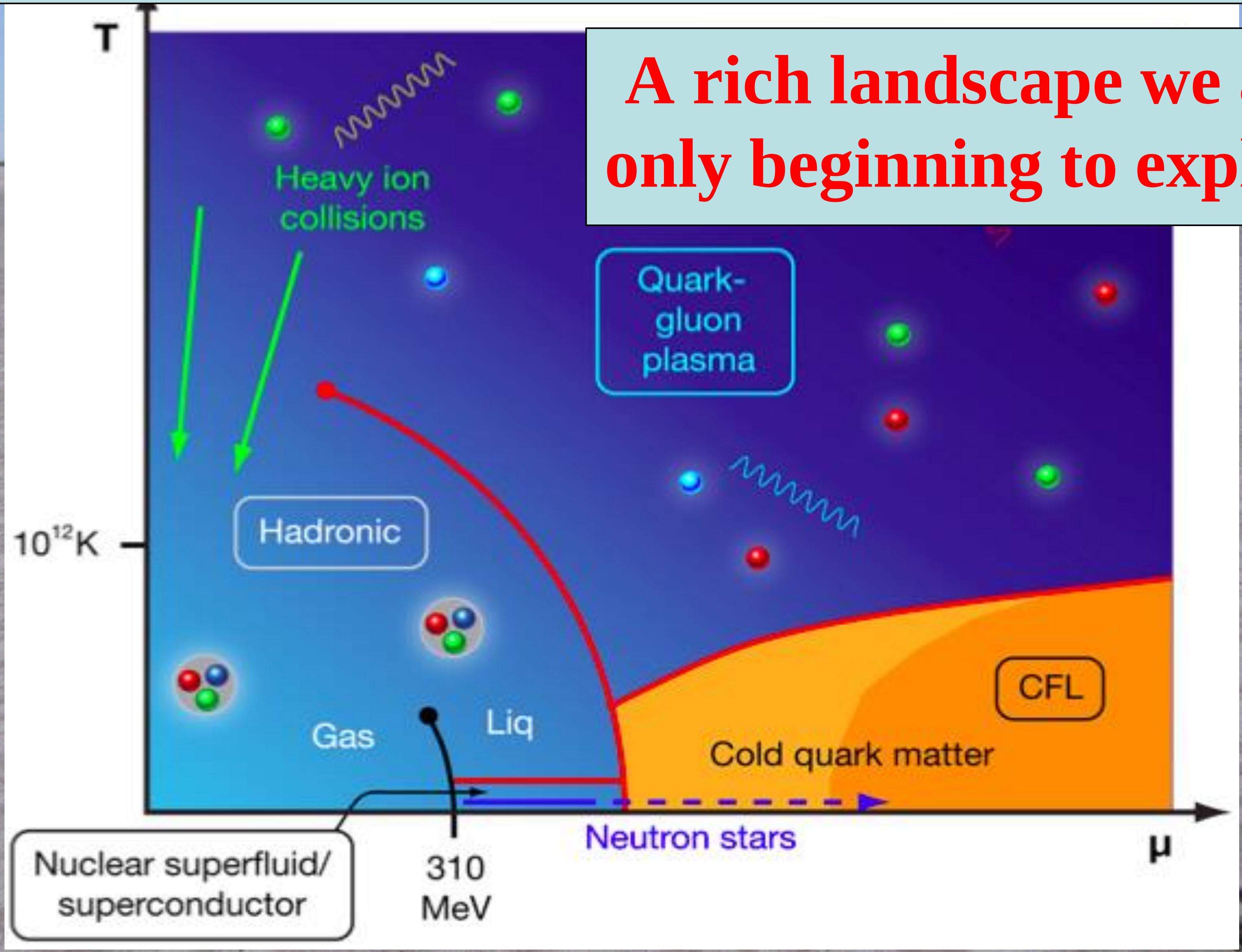
Many models



Vuorinen, Arnaldi

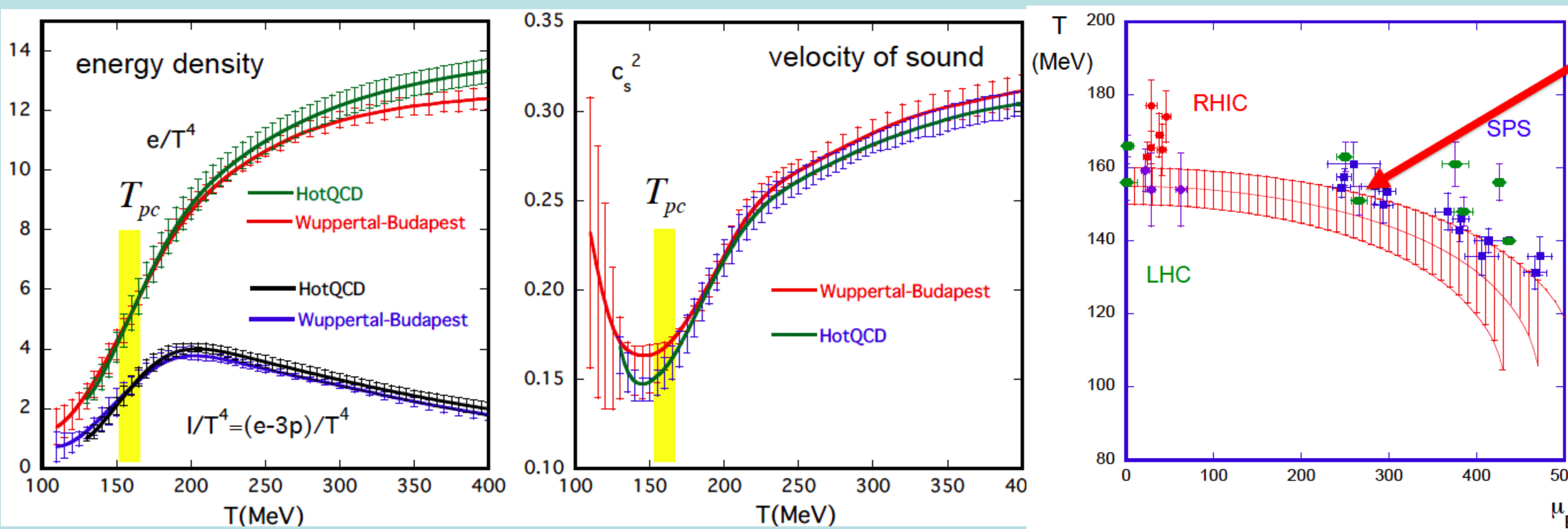
Phase Diagram of Nuclear Matter

A rich landscape we are only beginning to explore



Lattice at Finite T, μ_B

Ukawa

- ~~QCD phase transition~~: crossover T = 155±5 MeV
- 

- Extrapolation to $\mu_B \neq 0$: T < chemical freeze-out?

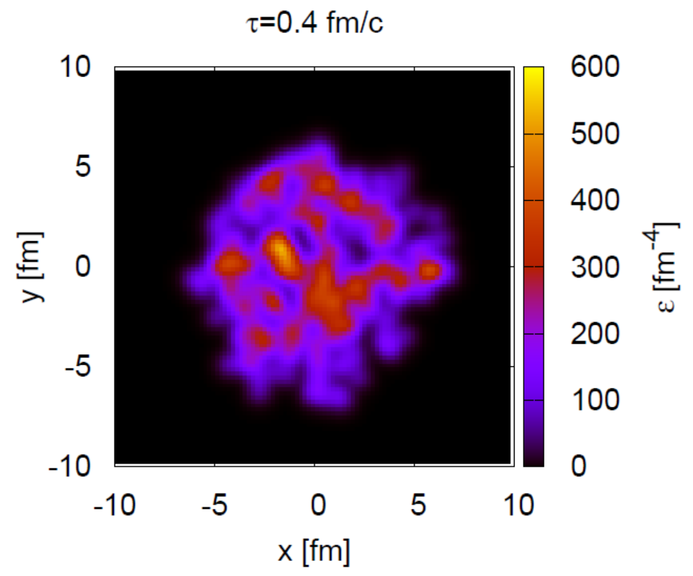
  (Charge fluctuations yield T ≈ hadron abundances)
- No reliable calculation of critical end point

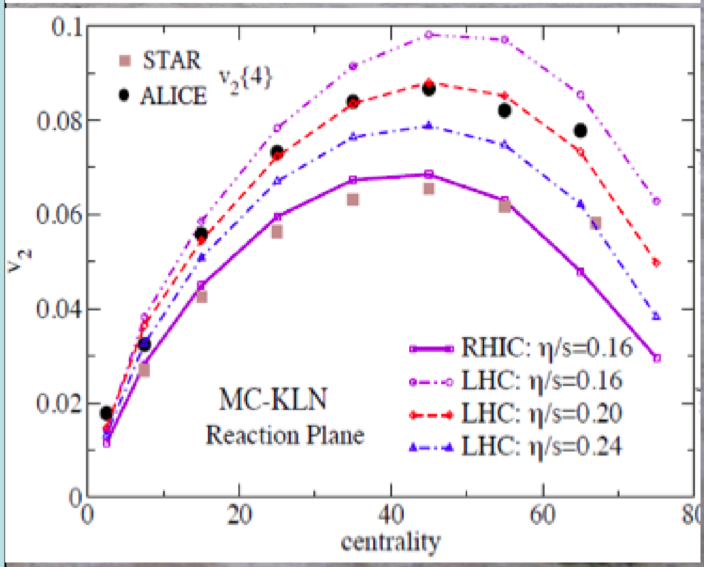
Vuorinen

Anisotropies in Little Bangs

- Many anisotropies $v_n \neq 0$
- Collective hydrodynamic flow
- Constraints on viscosity η
  - η/s < 0.2: lowest known?
- **Value close to lower limit from stringy AdS/CFT**

  η/s = 1/4π
- Increase from RHIC to LHC?
- Interpolation towards perturbative QCD?

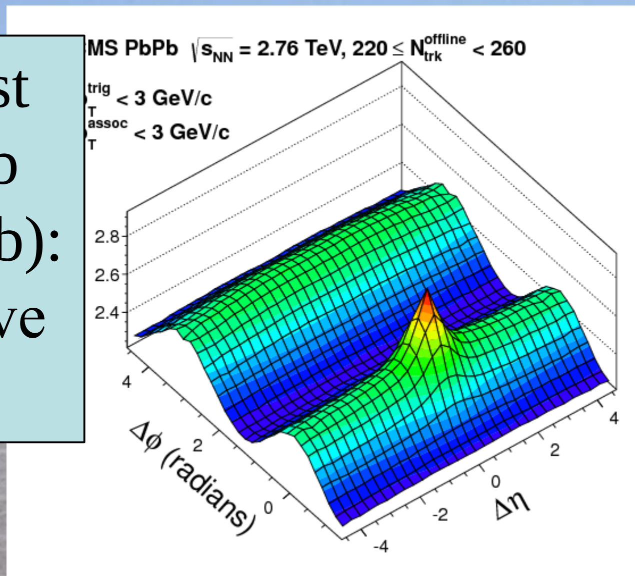




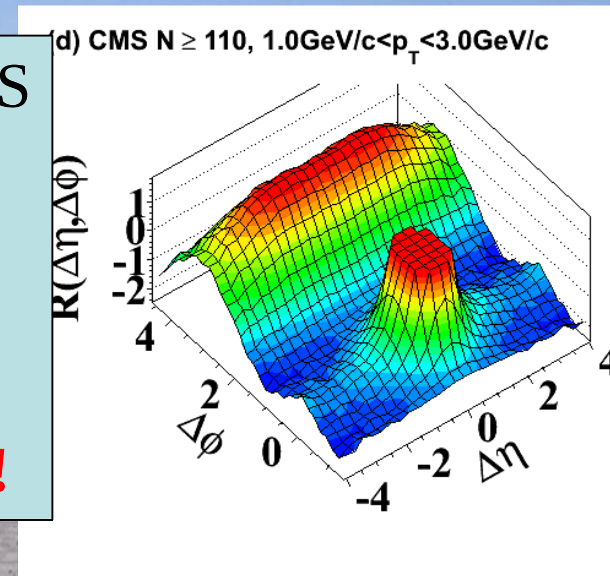
Grosse-Oetringhaus

"Ridge": Collective Effect in pp?!

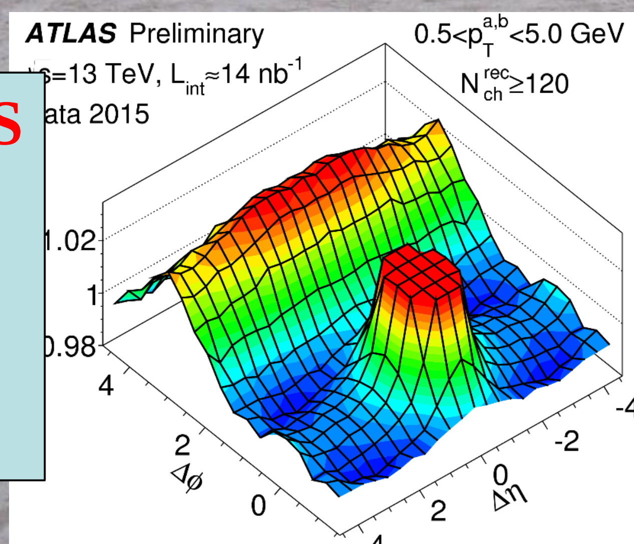
Seen first in Pb-Pb (later p-Pb): "collective effect"



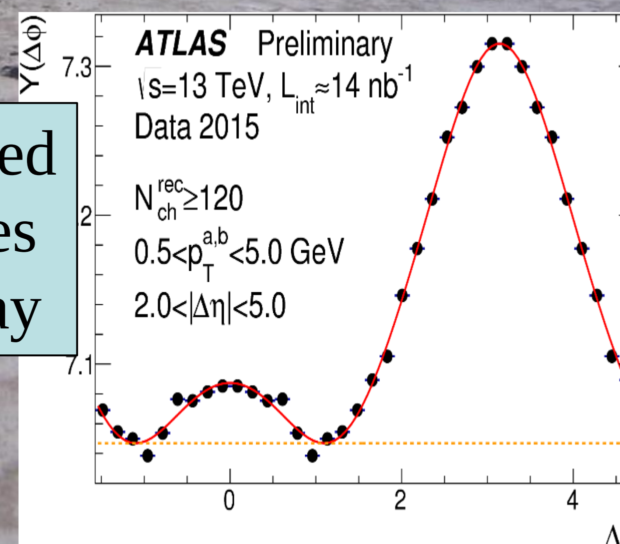
Then by CMS in high-multiplicity pp events: **BIG SURPRISE!**



Now by ATLAS in high-multiplicity pp events at 13 TeV



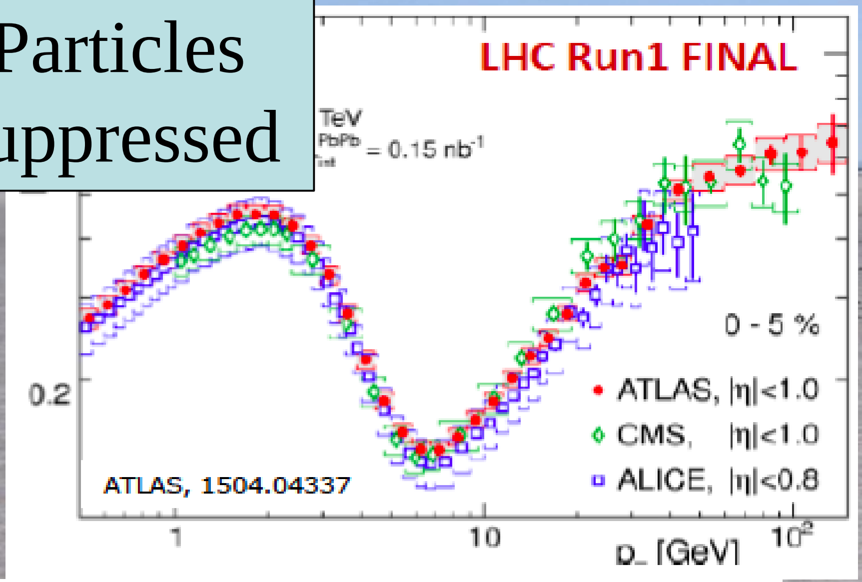
Detailed studies on way



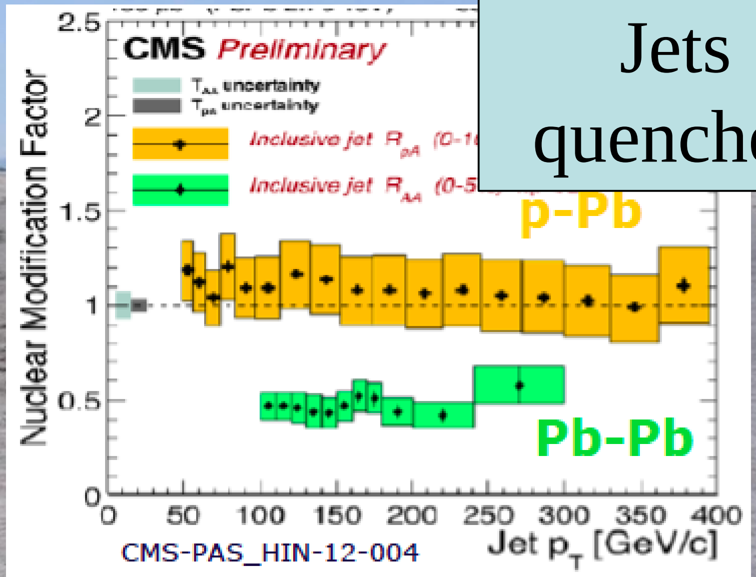
Arnaldi

Many Impressive Suppressions!

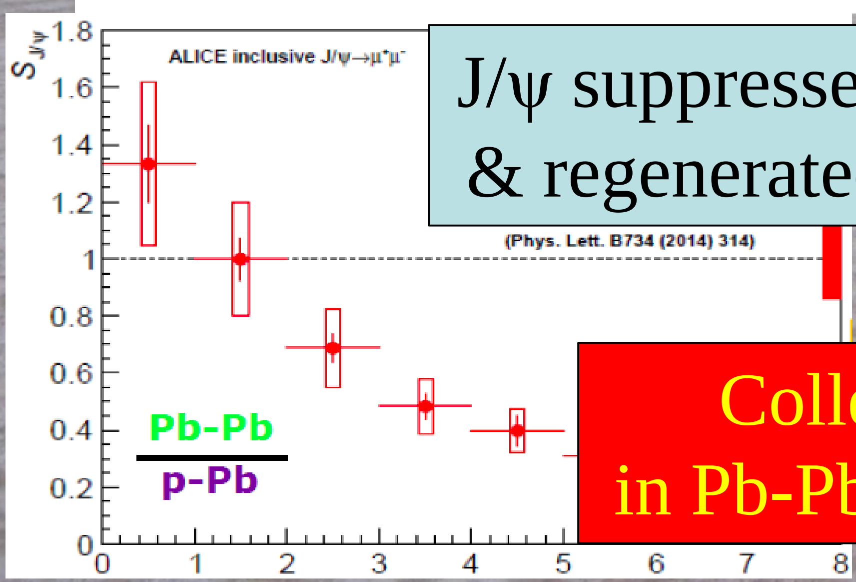
Particles suppressed



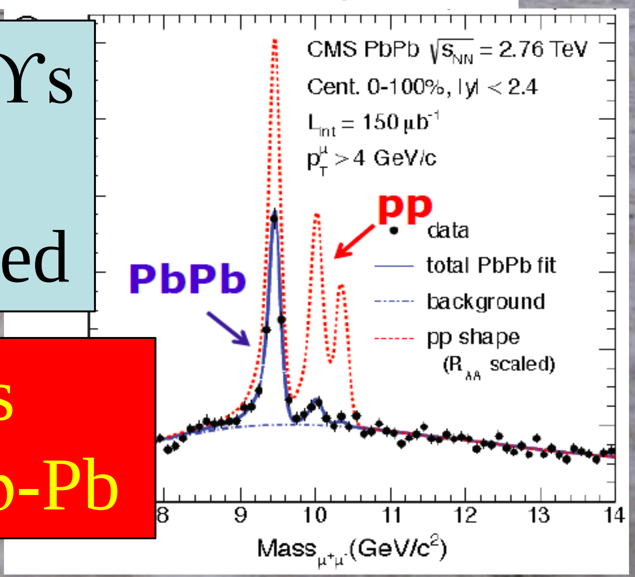
Jets quenched



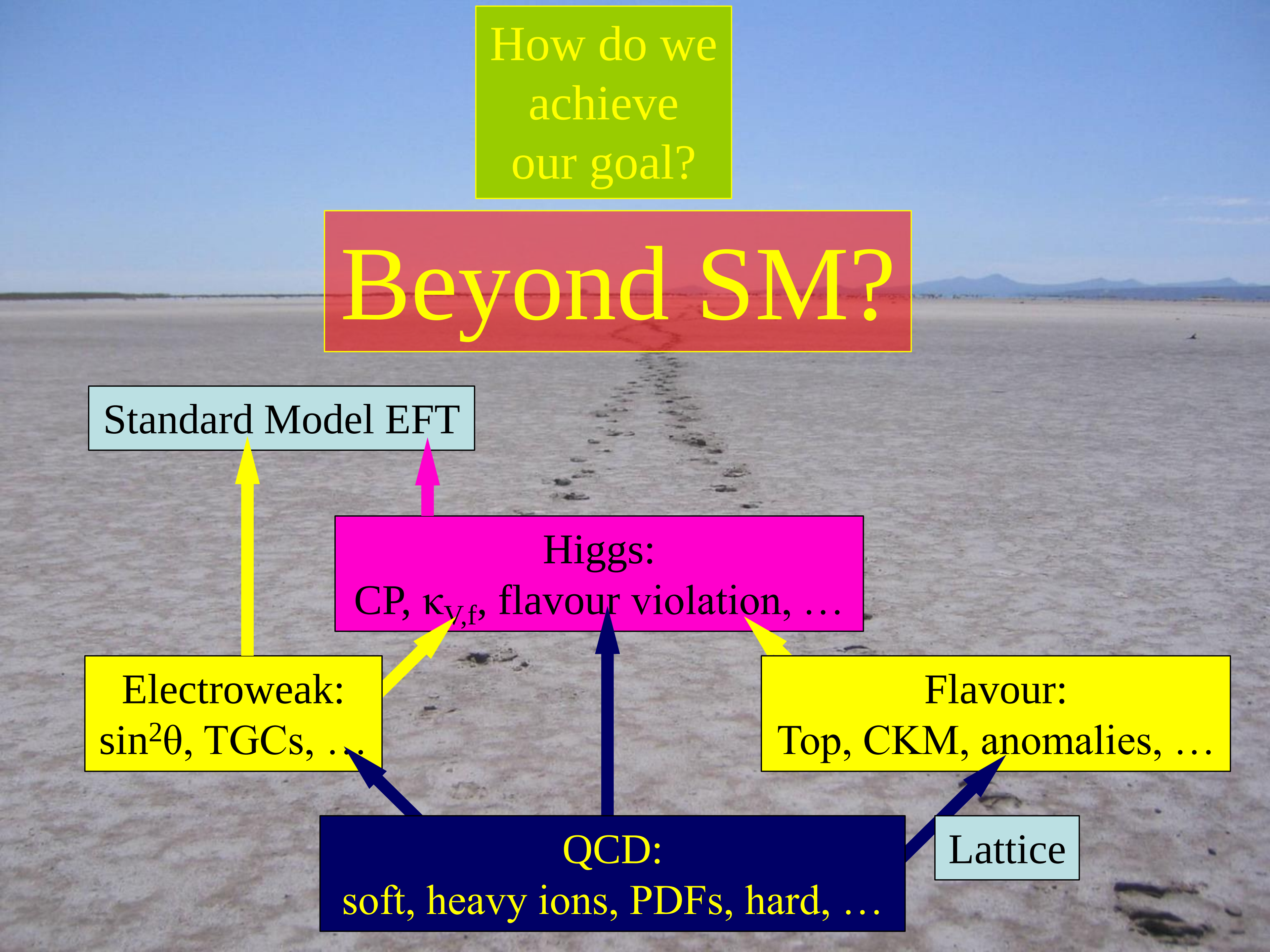
J/ψ suppressed & regenerated



Heavier ϒs more suppressed



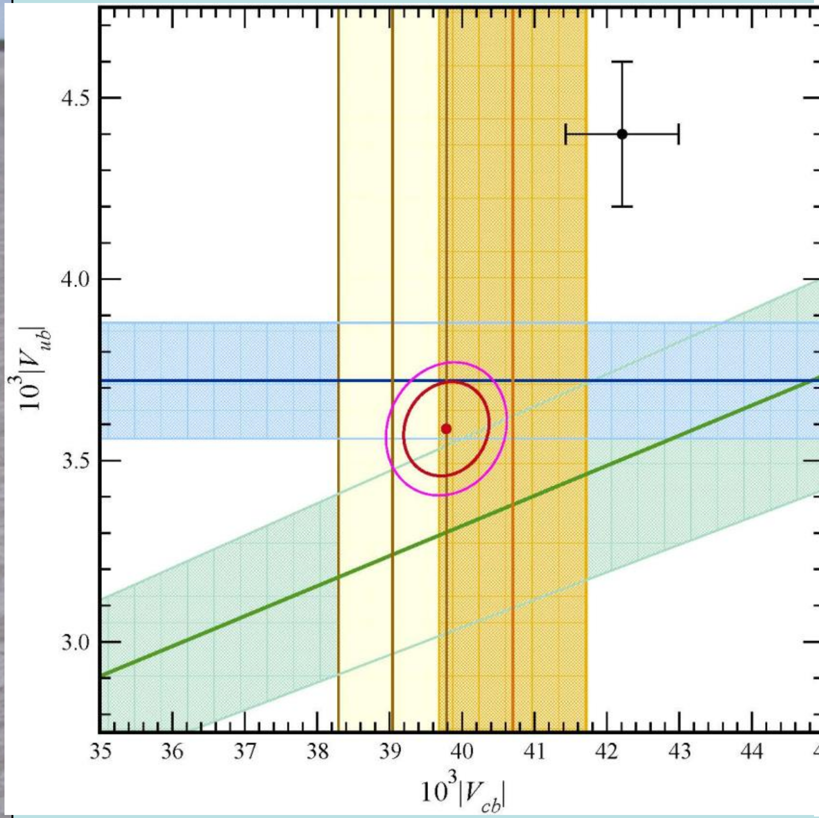
Collective effects in Pb-Pb ≠ those in p-Pb

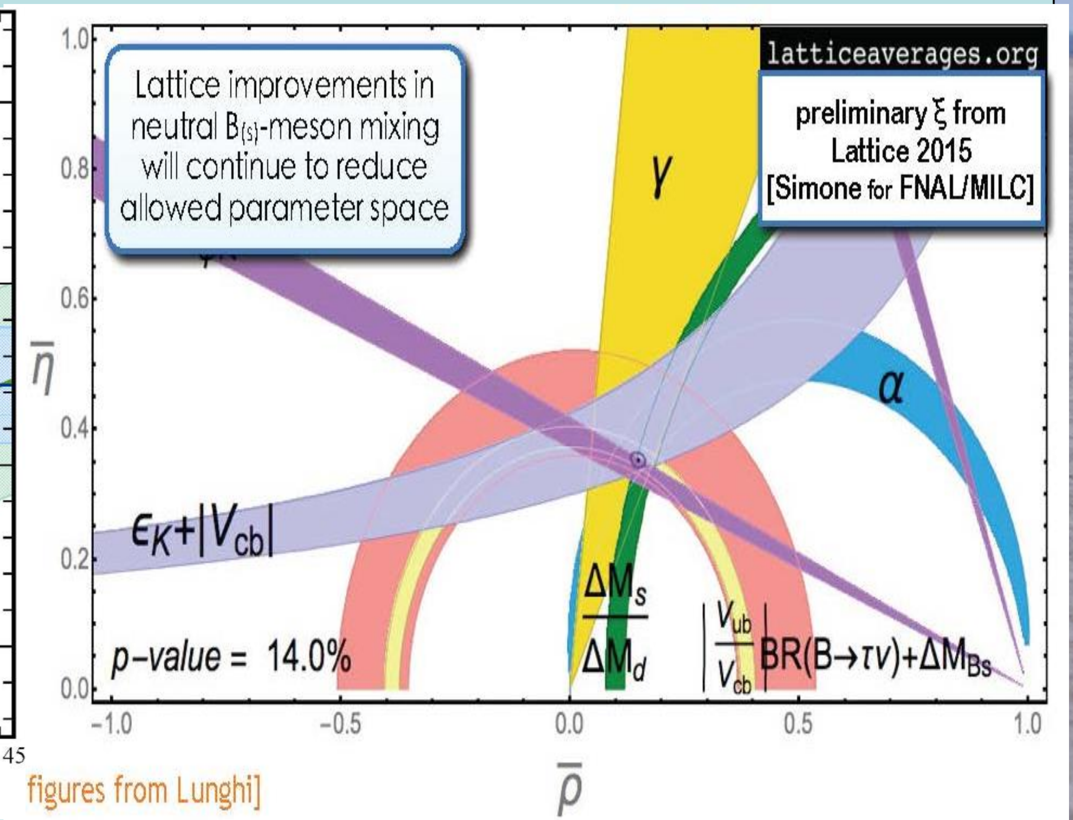

How do we achieve our goal?
Beyond SM?
Standard Model EFT
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Flavour:
Top, CKM, anomalies, …
QCD:
soft, heavy ions, PDFs, hard, …
Lattice

Unitarity Triangle 2015

- V_{ub}, V_{cb}: exclusive vs inclusive

Miyabayashi, Ligeti, DeTar





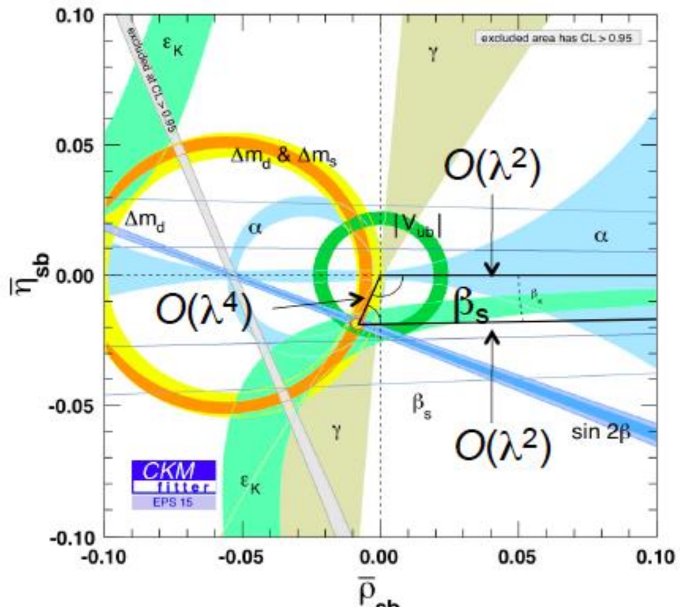
figures from Lunghi]

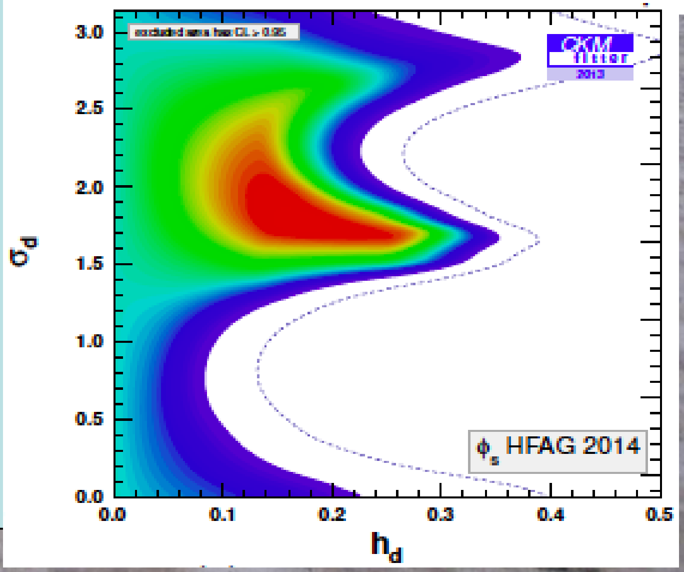
Lattice input crucial for exclusive V_{ub}, B_s mixing

Flavour Physics

Miyabayashi, Ligeti

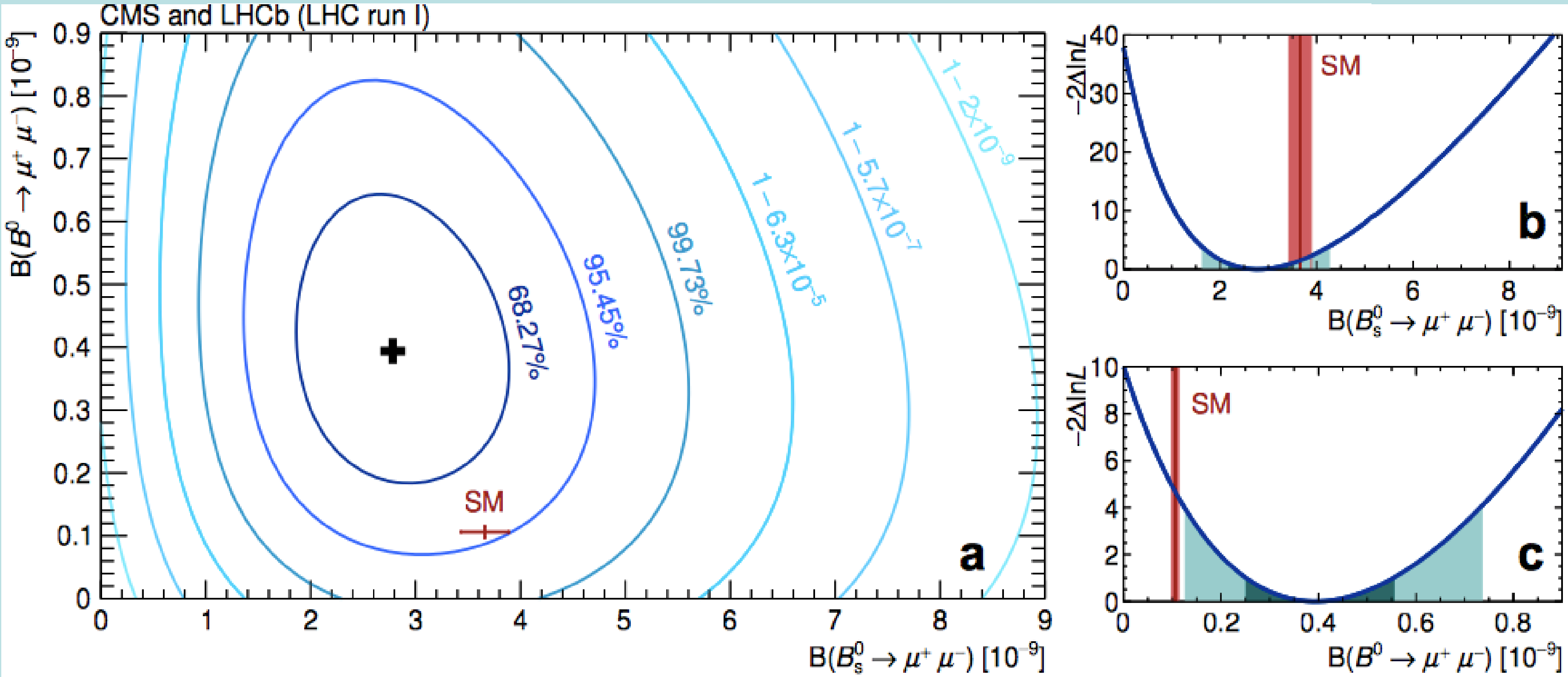
- CKM picture works very well
- **Second unitarity triangle?**
- Many successful predictions:
  - Many modes of CPV
  - No sign of CPV in charm ☹
- Could still be substantial BSM contributions to B physics
- Does TeV physics copy CKM?
  - Minimal flavour violation?





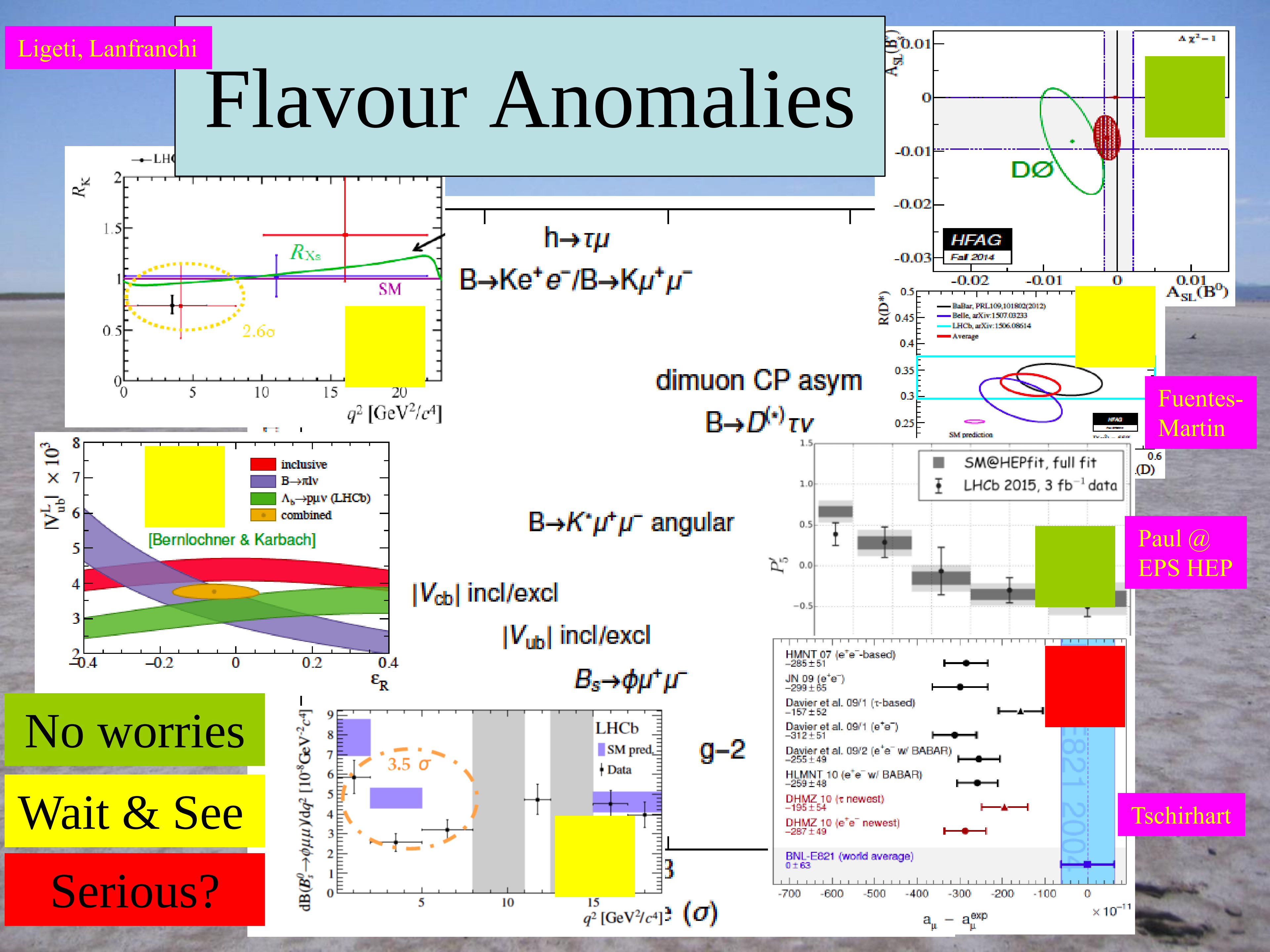
$B_{s,d} \rightarrow \mu^+\mu^-$ Decays

- $B_s \rightarrow \mu^+\mu^-$ success for CKM



- $B_d \rightarrow \mu^+\mu^- >$ CKM?
  - Would require non-minimal flavour violation

Lanfranchi



Ligeti, Lanfranchi
Flavour Anomalies
h→τμ
B→Ke⁺e⁻/B→Kμ⁺μ⁻
dimuon CP asym
B→D(*)τν
B→K*μ⁺μ⁻ angular
|Vcb| incl/excl
|Vub| incl/excl
Bs→φμ⁺μ⁻
g−2
No worries
Wait & See
Serious?
Fuentes-Martin
Paul @ EPS HEP
Tschirhart
RXs
SM
2.6σ
q² [GeV²/c⁴]
DØ
HFAG
Fall 2014
ASL(B⁰)
BaBar, PRL109,101802(2012)
Belle, arXiv:1507.03233
LHCb, arXiv:1506.08614
Average
SM prediction
inclusive
B→πlν
Λb→pμν (LHCb)
combined
[Bernlochner & Karbach]
εR
SM@HEPfit, full fit
LHCb 2015, 3 fb⁻¹ data
3.5 σ
LHCb
SM pred.
Data
HMNT 07 (e⁺e⁻-based) −285±51
JN 09 (e⁺e⁻) −299±65
Davier et al. 09/1 (τ-based) −157±52
Davier et al. 09/1 (e⁺e⁻) −312±51
Davier et al. 09/2 (e⁺e⁻ w/ BABAR) −255±49
HLMNT 10 (e⁺e⁻ w/ BABAR) −259±48
DHMZ 10 (τ newest) −195±54
DHMZ 10 (e⁺e⁻ newest) −287±49
BNL-E821 (world average) 0±63

Miller

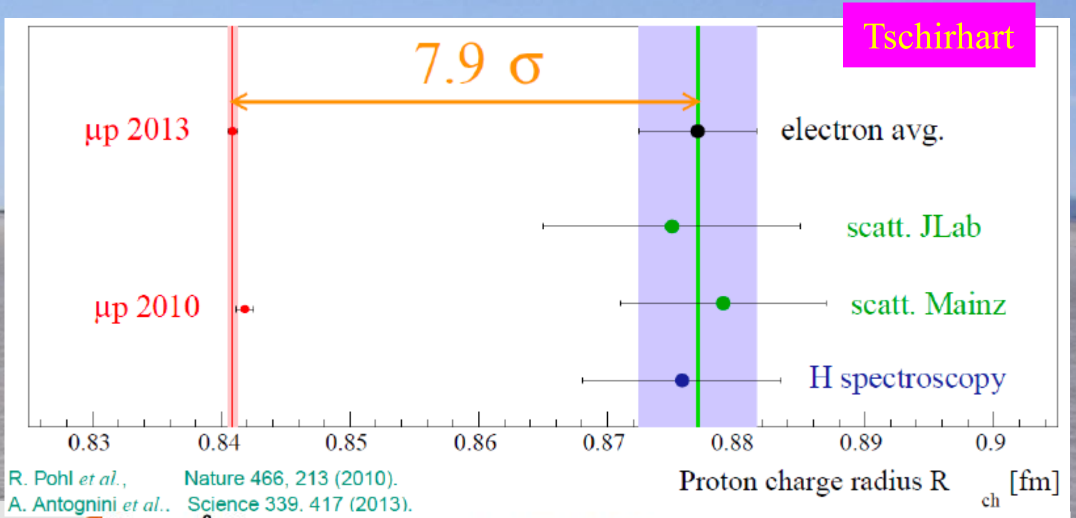
Charged Lepton Flavour Violation

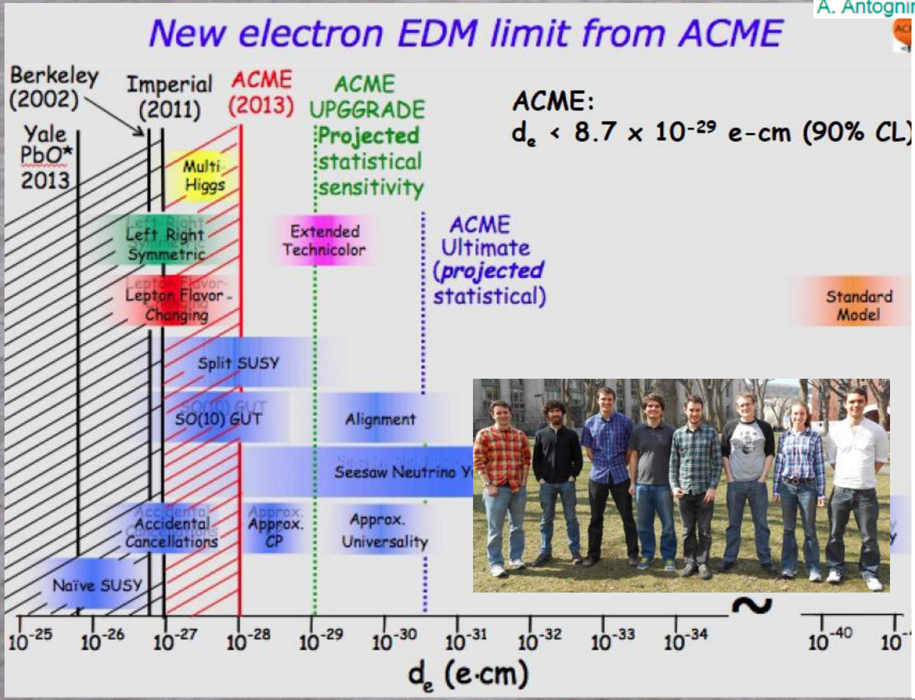
Observable in SUSY models with ν masses?

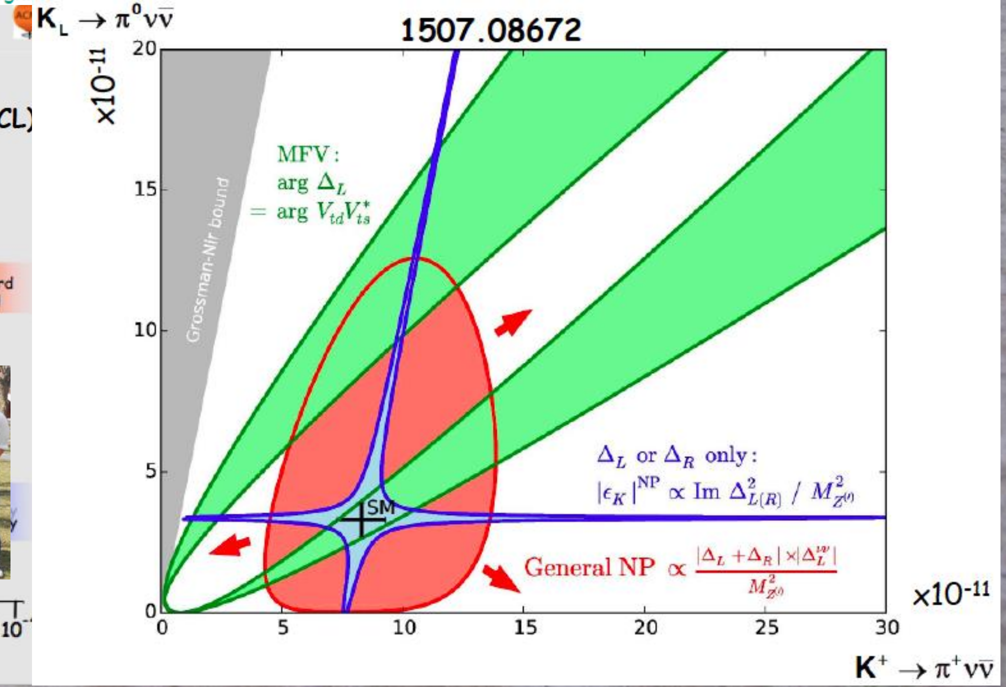
Reaction	Current Limit	Future limit	Who/where?
$\mu \to e\gamma$	5.7×10^{-13}	$<6\times10^{-14}$	MEG at PSI
$\mu \to eee$	1.0×10^{-12}	$<10^{-15}$-10^{-16}	PSI
$\mu N \to eN$ (Au)	7×10^{-13}	$<10^{-18}$	PRISM/ Mu2e II
$\mu N \to eN$ (Al)	-----	$<10^{-16}$ /10^{-18}	Mu2e, COMET/ upgrades
$\mu N \to eN$ (Ti)	4.3×10^{-12}	$<10^{-18}$	PRISM/ Mu2eX
$\mu^+e^- \to \mu^-e^+$	8.3×10^{-11}		
$\tau \to \mu\gamma$	4.4×10^{-8}	$<10^{-9}$	Flavor factory
$\tau \to e\gamma$	3.3×10^{-8}	$<10^{-9}$	Flavor factory
$\tau \to \mu\mu\mu$	2.1×10^{-8}	$<10^{-9}$-10^{-10}	Flavor factory
$\tau \to eee$	2.7×10^{-8}	$<10^{-9}$-10^{-10}	Flavor factory
$\tau \to \mu ee$	1.5×10^{-8}	$<10^{-9}$-10^{-10}	Flavor factory

Other Low-Energy Physics

- p charge radius
- EDMs
- K➔πνν







EW Physics at Tevatron & LHC

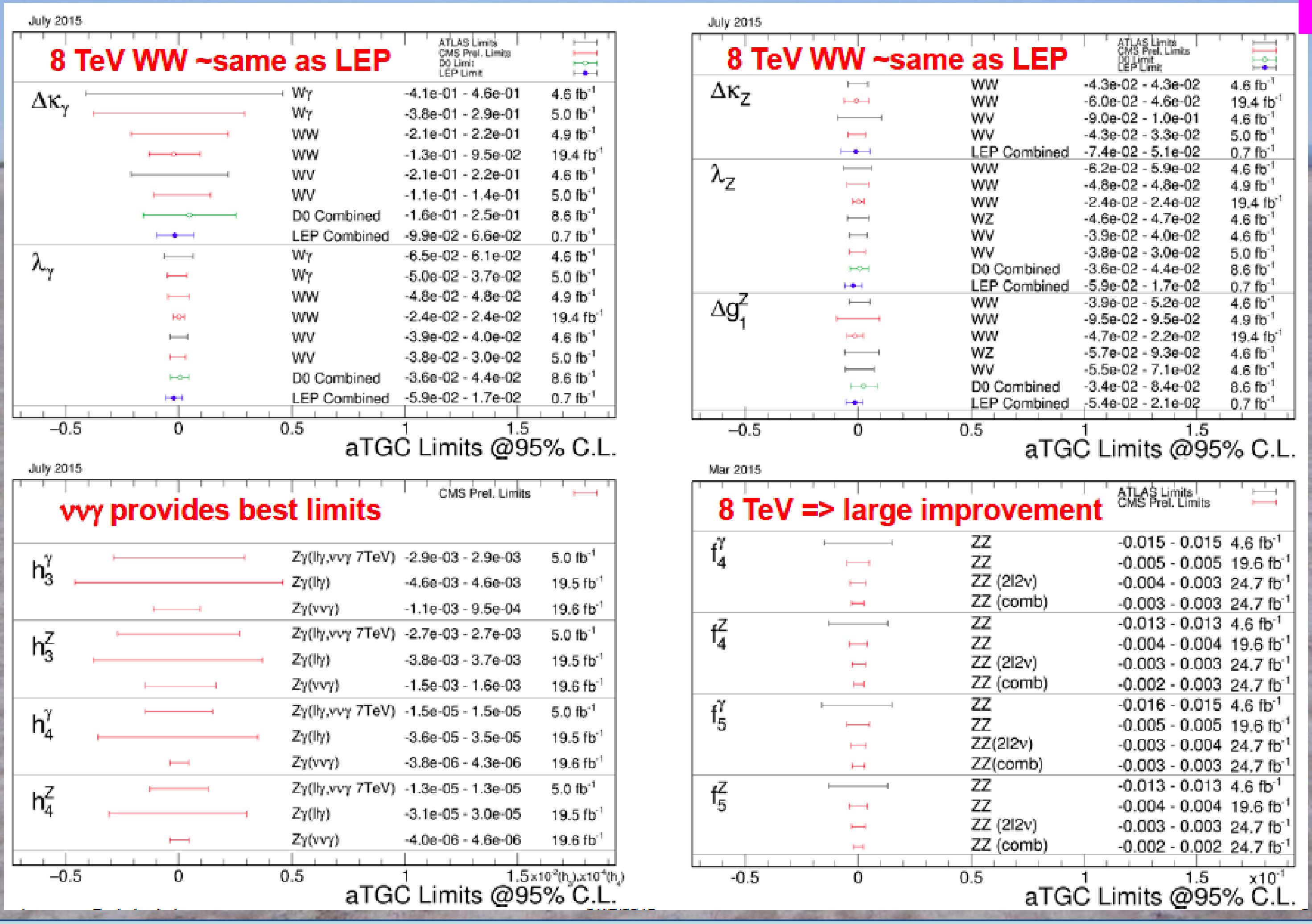
Einsweiler

- Forward-backward asymmetry in Z production at Tevatron gives precision in $\sin^2\theta$ in same ball-park as LEP or SLC
- Could do better by combining CDF, D0 using e^+e^- and $\mu^+\mu^-$
- **Challenge for LHC!**

	$\sin^2\theta_{\rm eff}^{\rm lept}$
ATLAS	0.2308 ± 0.0012
CMS [6]	0.2287 ± 0.0032
D0 [5]	0.23146 ± 0.00047
CDF [4]	0.2315 ± 0.0010
LEP, $A_{\rm FB}^{0,b}$ [3]	0.23221 ± 0.00029
LEP, $A_{\rm FB}^{0,l}$ [3]	0.23099 ± 0.00053
SLC, $A_{\rm LR}$ [3]	0.23098 ± 0.00026
LEP+SLC [3]	0.23153 ± 0.00016
PDG global fit [46]	0.23146 ± 0.00012

Triple-Gauge Couplings at LHC

Einsweiler

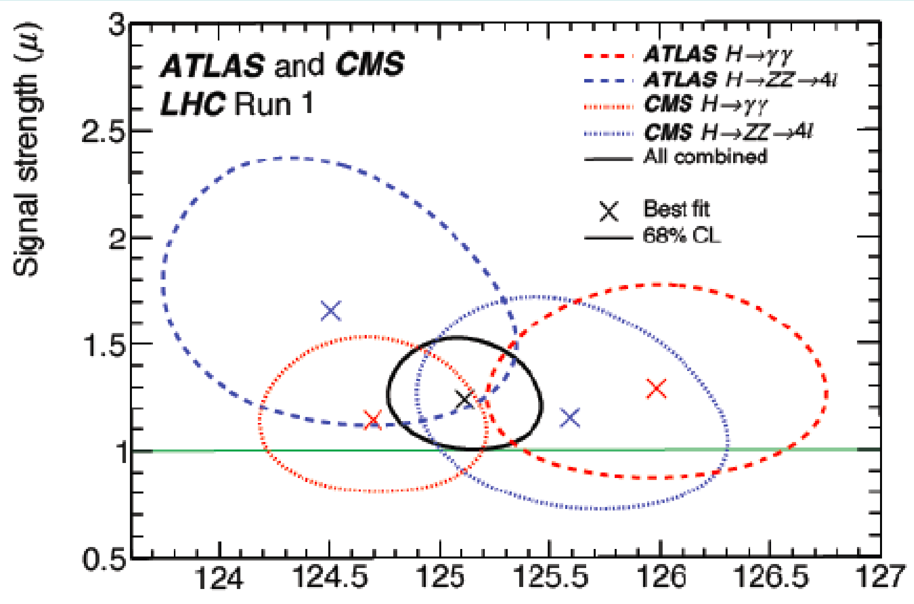


Important ingredients in global fits to SM EFT

Higgs Mass Measurements

Farrington

- ATLAS + CMS ZZ^* and $\gamma\gamma$ final states



$$125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$$

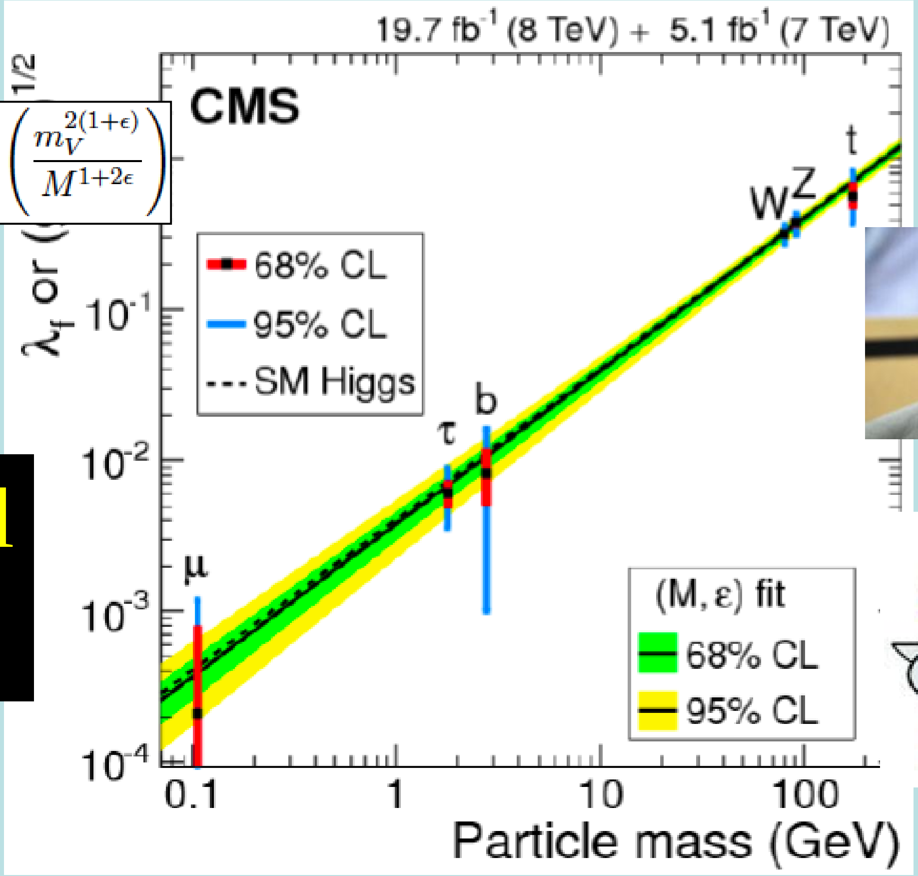
- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

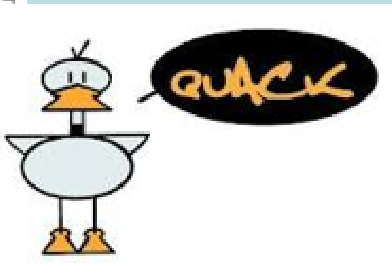
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

Farrington

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



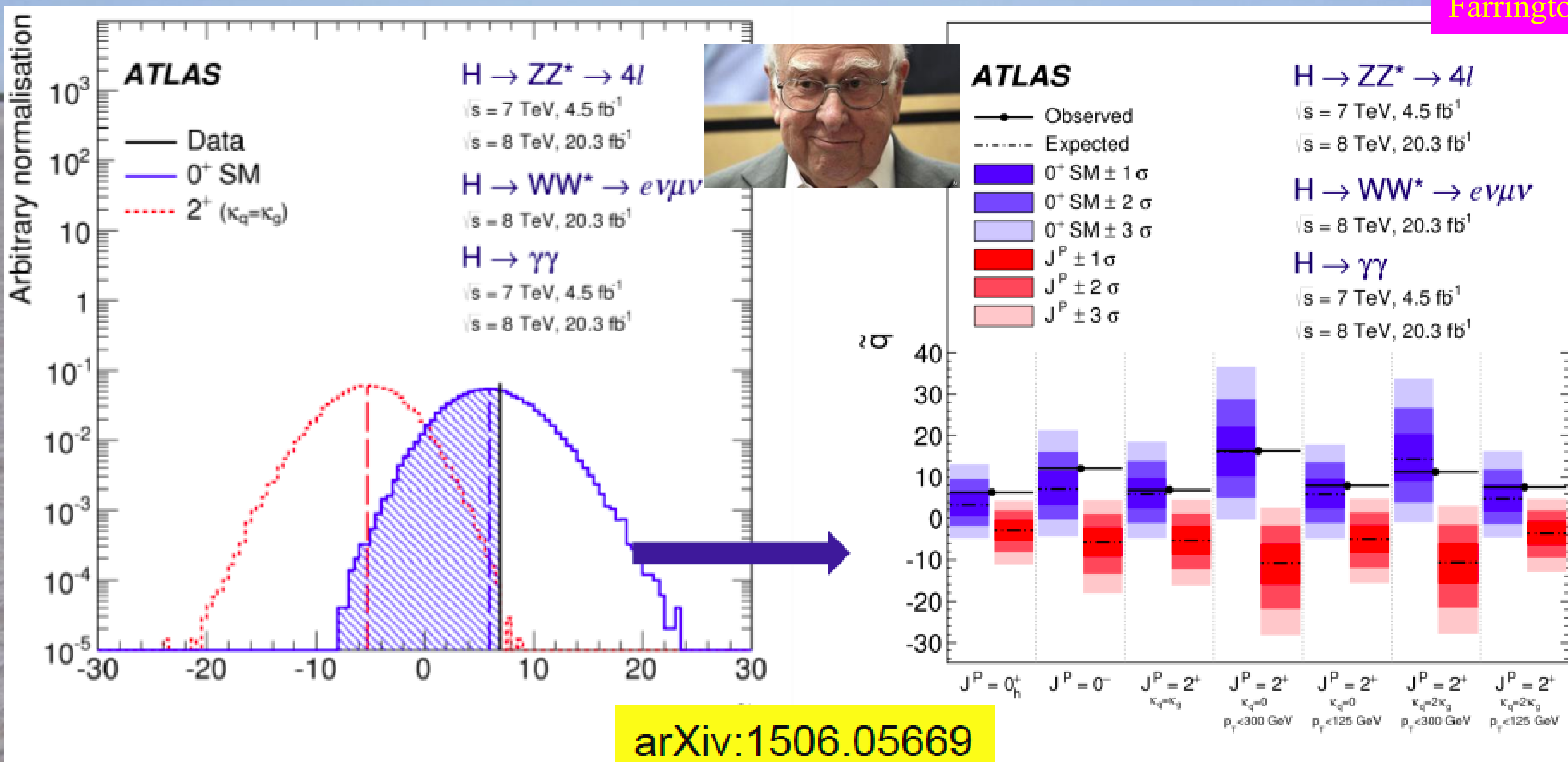


Global fit

- **Solid line = SM**, dashed line = best fit

H Spin-Parity Tests: 0^+ AOK

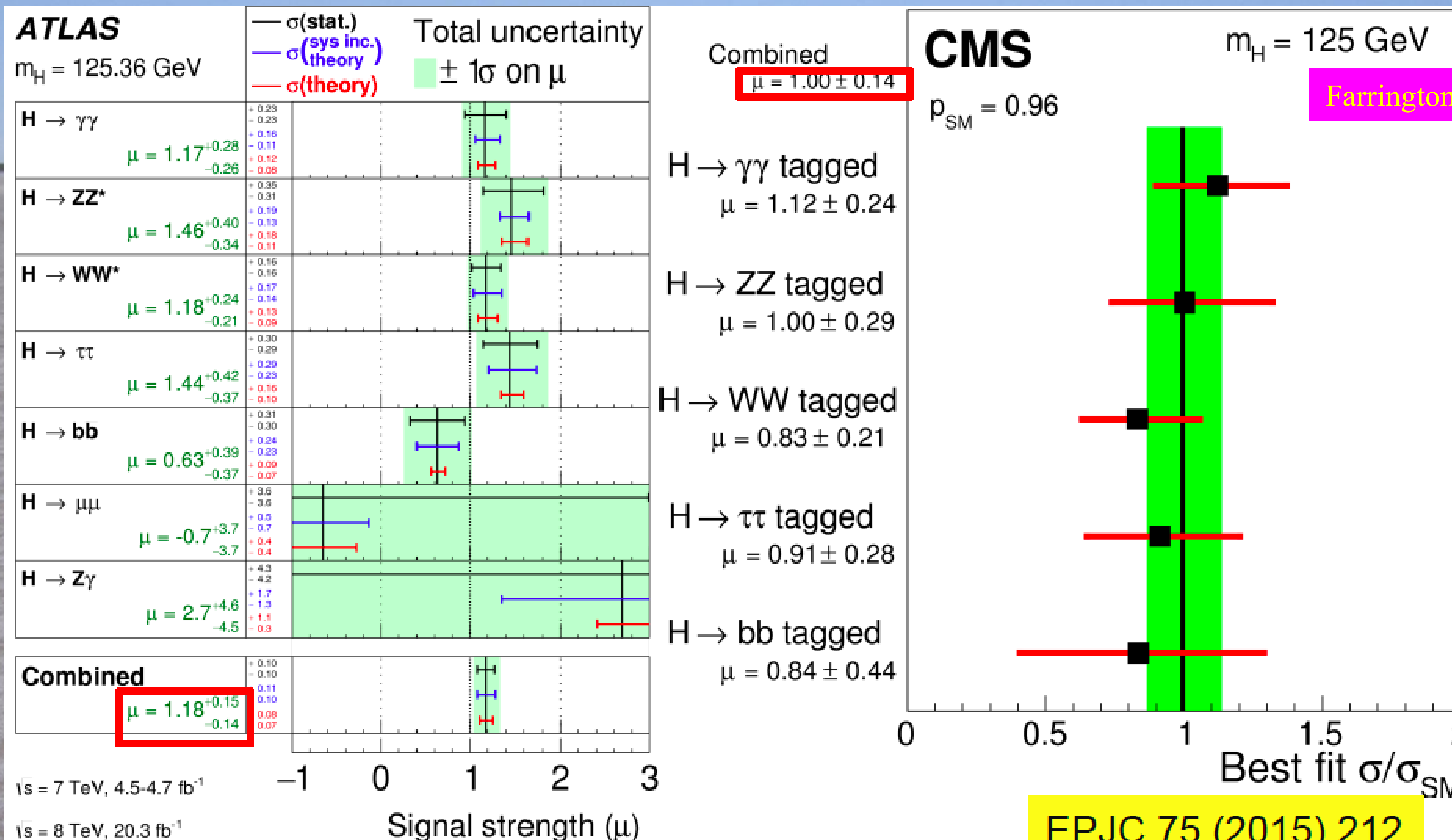
Farrington



arXiv:1506.05669

- Alternative spin-parities disfavoured > 99.9%

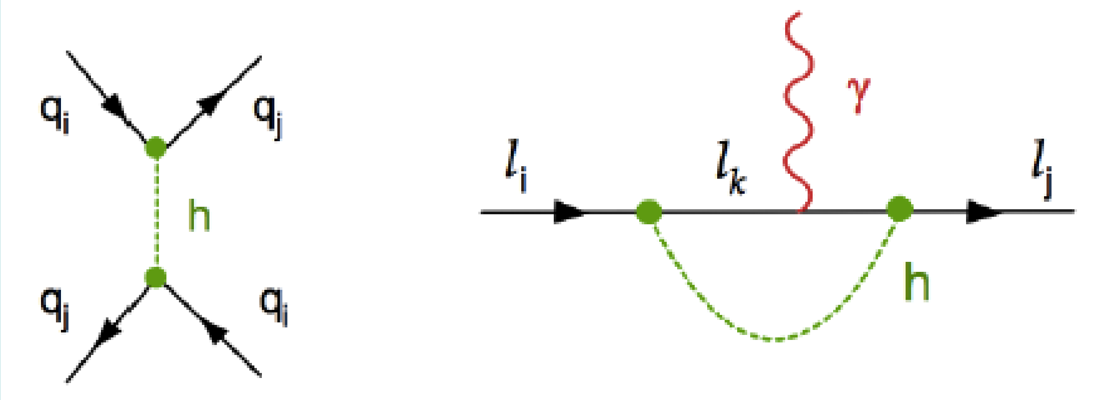
Higgs Signal Strengths



- Globally, Standard Model OK @ 10% level

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

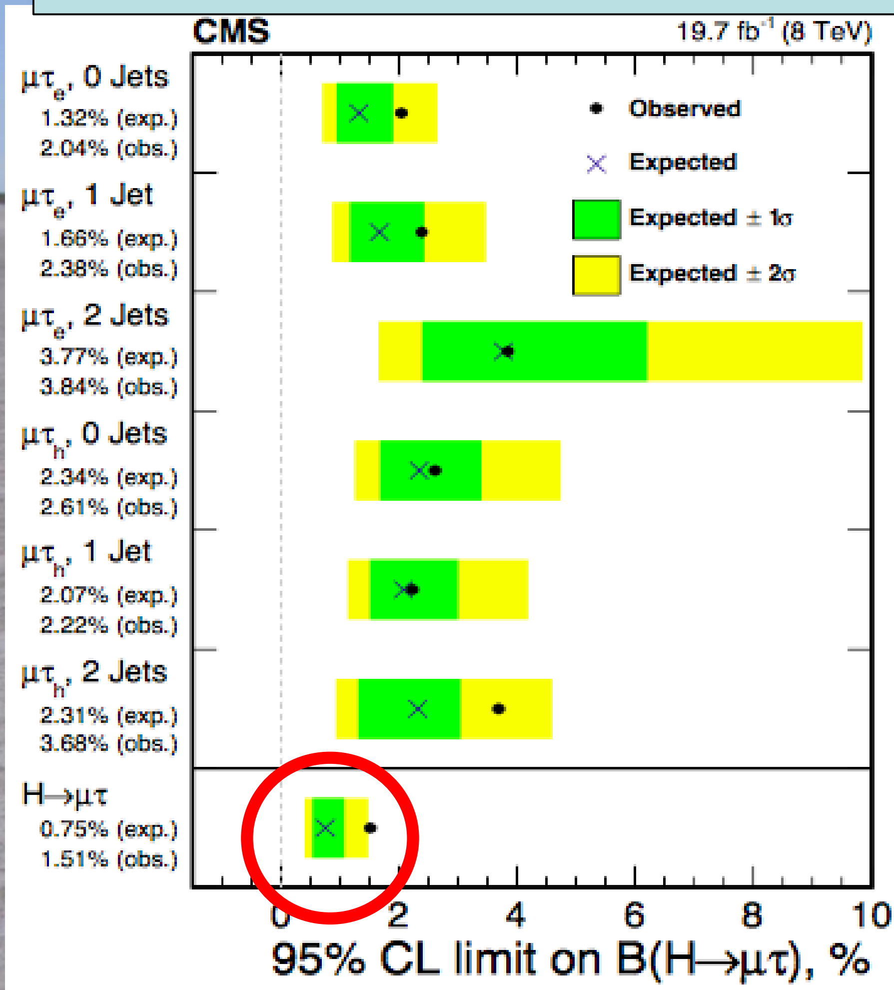
Either BR(τμ) or BR(τe) could be O(10)%

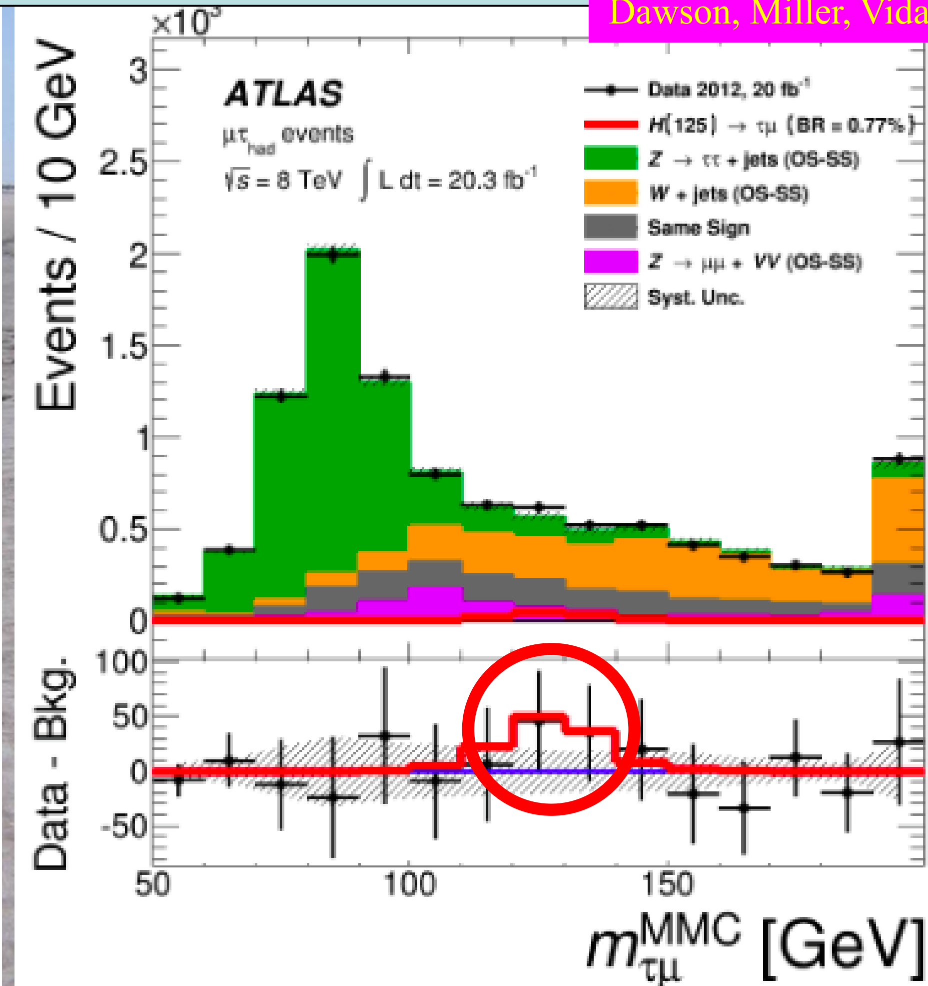
Blankenburg, JE, Isidori: arXiv:1202.5704
Harnik, Kopp, Zupan: arXiv:1209.1397

B BR(μe) must be < 2×10^{-5}

Flavour-Changing Higgs Couplings?

Dawson, Miller, Vidal





$$\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

$$\mathrm{Br}(H \to \mu\tau) = (0.77 \pm 0.62)\%$$

Also: BR(eτ) < 0.69%, BR(eμ) < 0.036%

CMS @ DPF

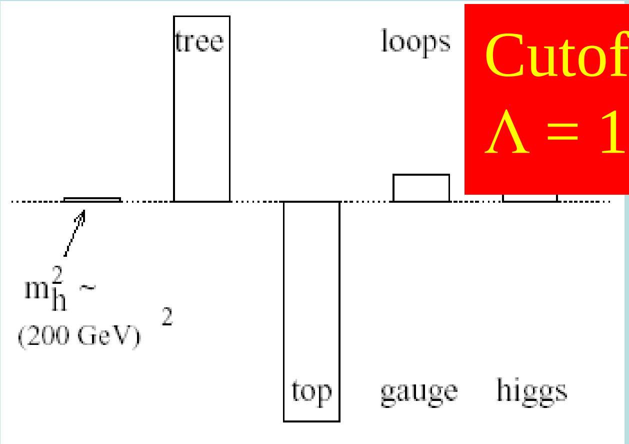
Elementary Higgs or Composite?

McCullough

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

Cut-off $\Lambda \sim$ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

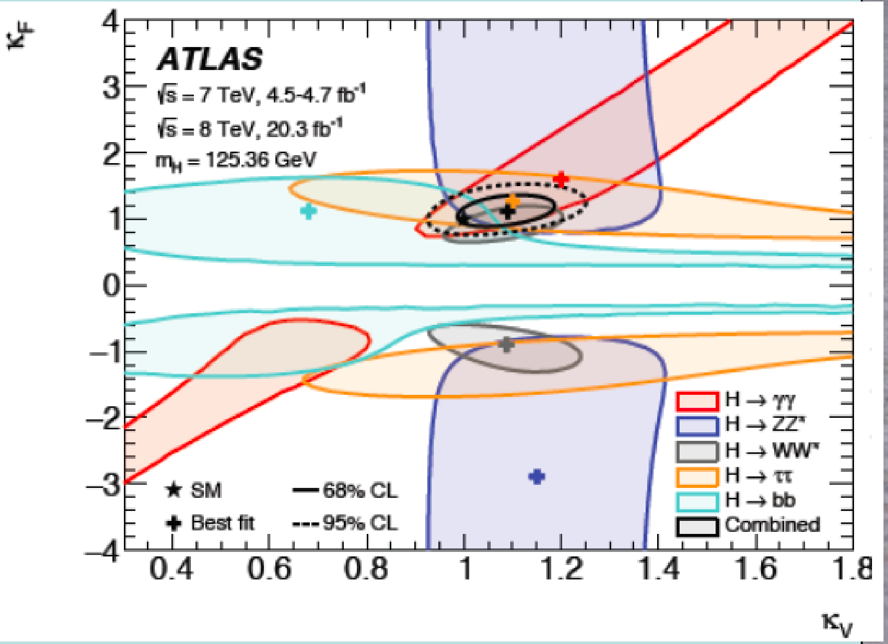
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?
- Little Higgs, …

Global Analysis of Higgs-like Models

Farrington

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$

Production	Loops	Interference	Expression in terms of fundamental coupling strengths
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(VBF)$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.$[illegible]$4 \cdot \kappa_Z\kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.$[illegible]$1 \cdot \kappa_t\kappa_W$
$\sigma(qb \to tHq')$	-	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.9$[illegible]$\cdot \kappa_t\kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma_{Z\gamma}$	✓	$W-t$	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.1$[illegible]$\cdot \kappa_W\kappa_t$

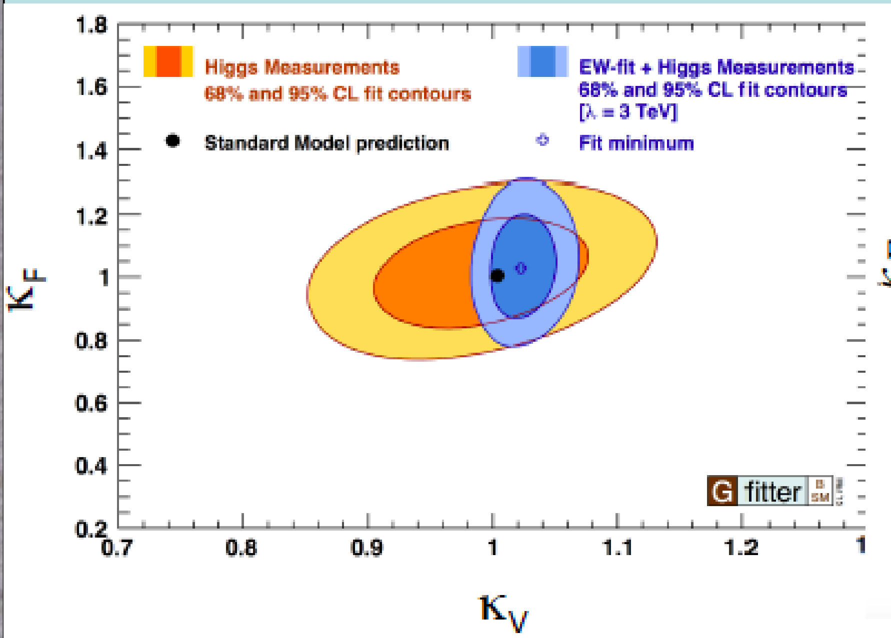


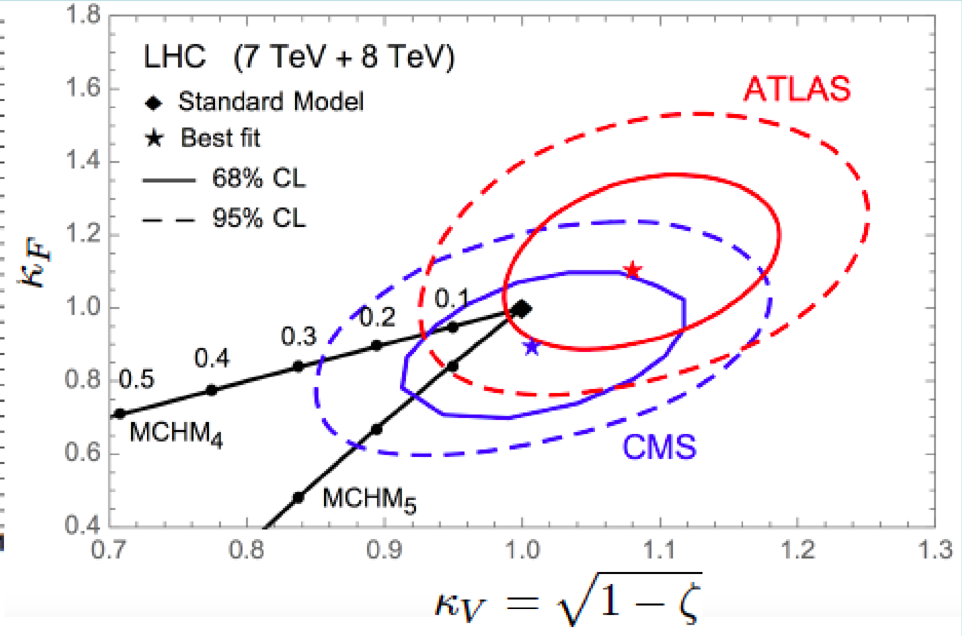
- Sensitive to relative sign: interference in gg, γγ, tH, Zγ

Global Analysis of Higgs-like Models

Dawson

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$





- Consistency between Higgs and EW measurements
- Must tune composite models to look like SM

Why is there Nothing rather than Something?

Ciuchini

- Higher-dimensional operators as relics of higher-energy physics: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

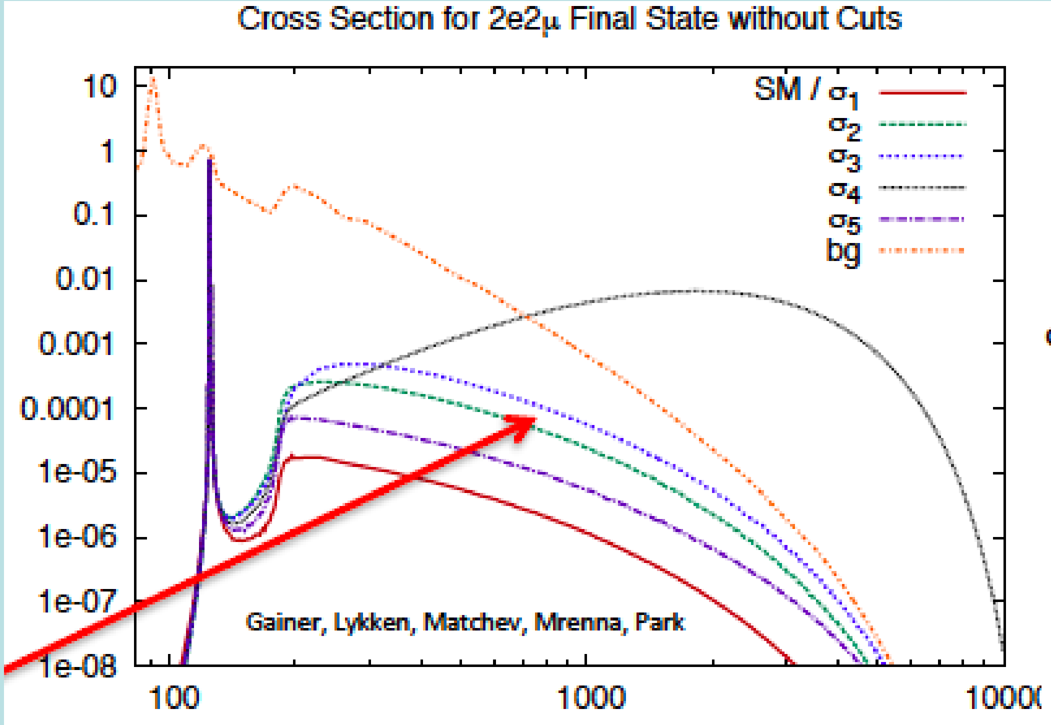
$$
\begin{aligned}
\mathcal{L} \supset \; & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\;\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\;\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+ \; & \frac{2ig\;\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\;\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
+ \; & \frac{ig\;\bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\;\bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
+ \; & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\;\Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\;\Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\;\Phi^\dagger\Phi\;\Phi\cdot\bar{L}_L\tau_R
\end{aligned}
$$

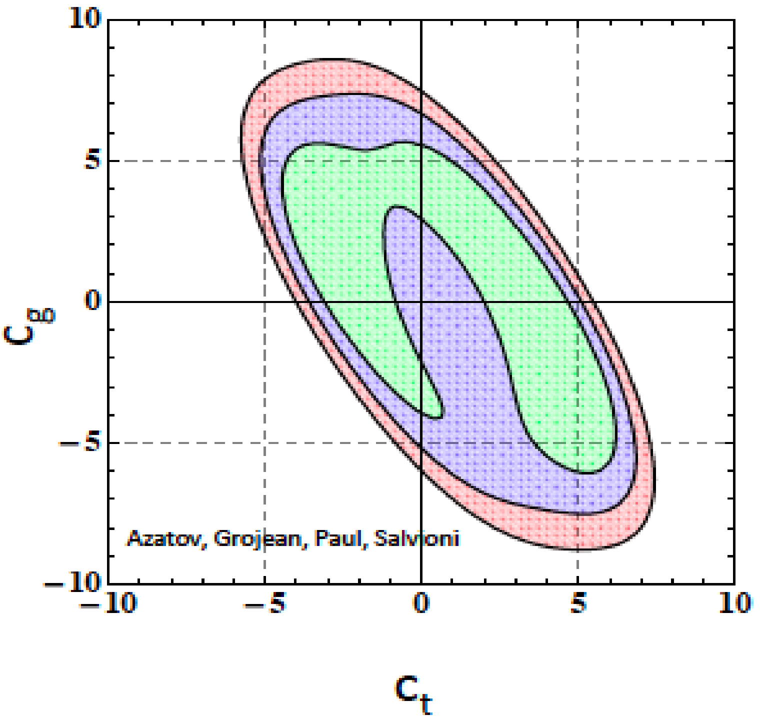
- Constrain with precision EW, Higgs data, TGCs …

Off-Shell Higgs Production & Γ_H

Farrington, Dawson

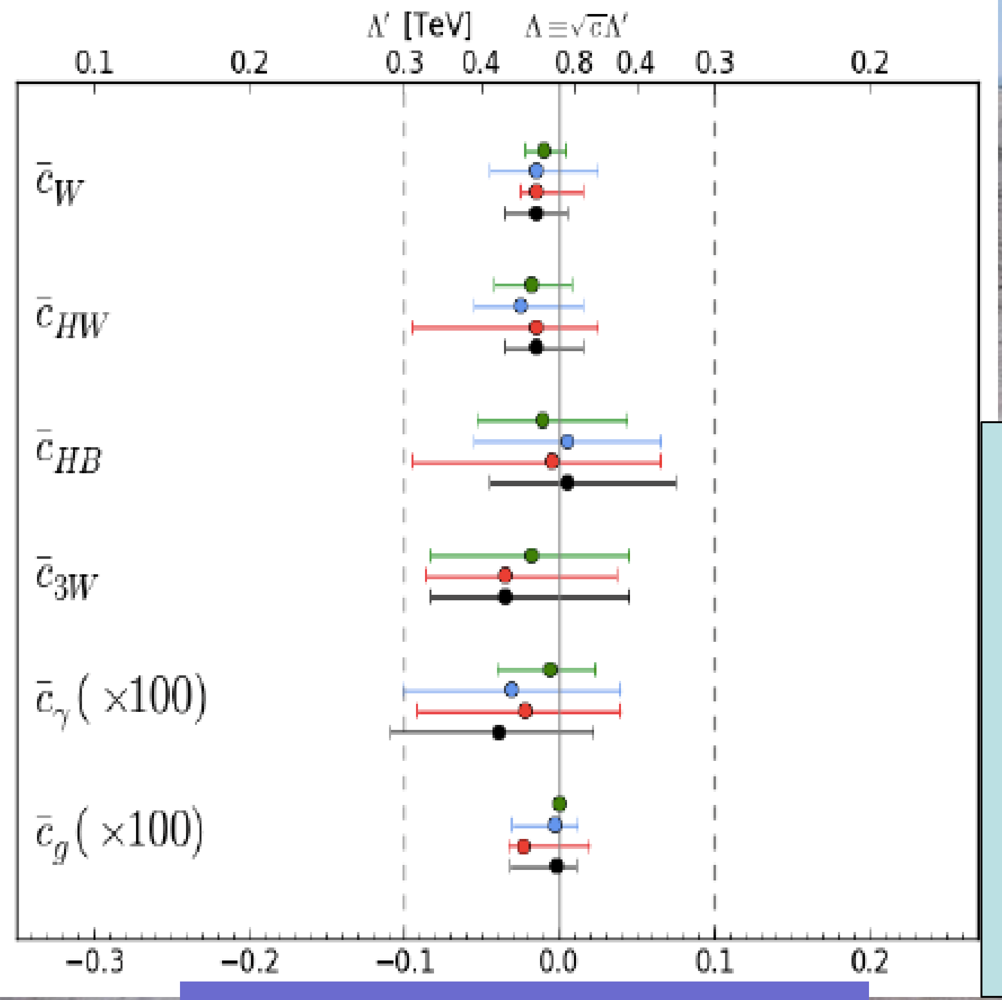
- If off-shell couplings = on-shell: $\Gamma_H < 5.4, 5.5 \times$ SM
- BUT: beware higher-dimensional operators in EFT





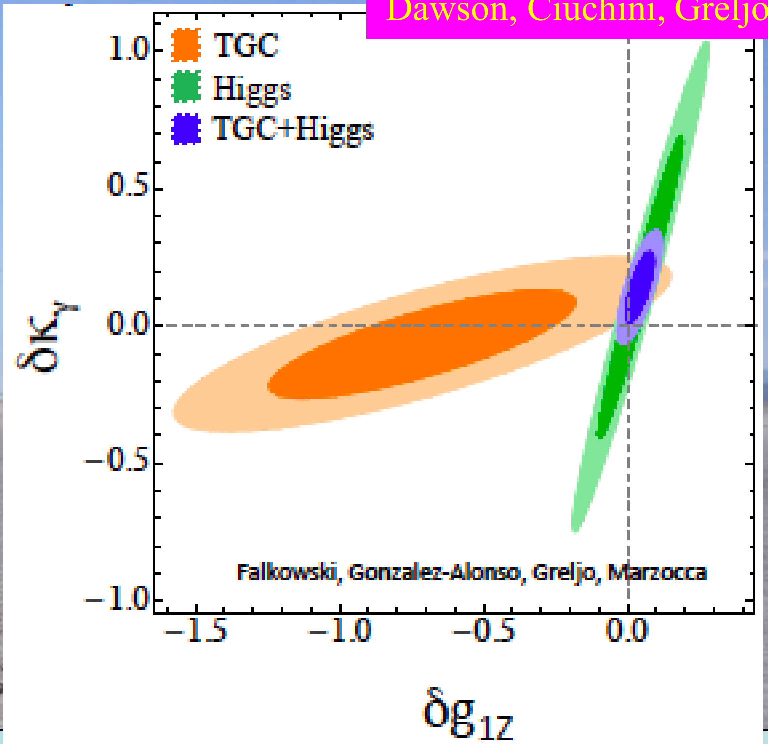
- EFT coefficients constrained by combination

Global Fits including LHC TGCs

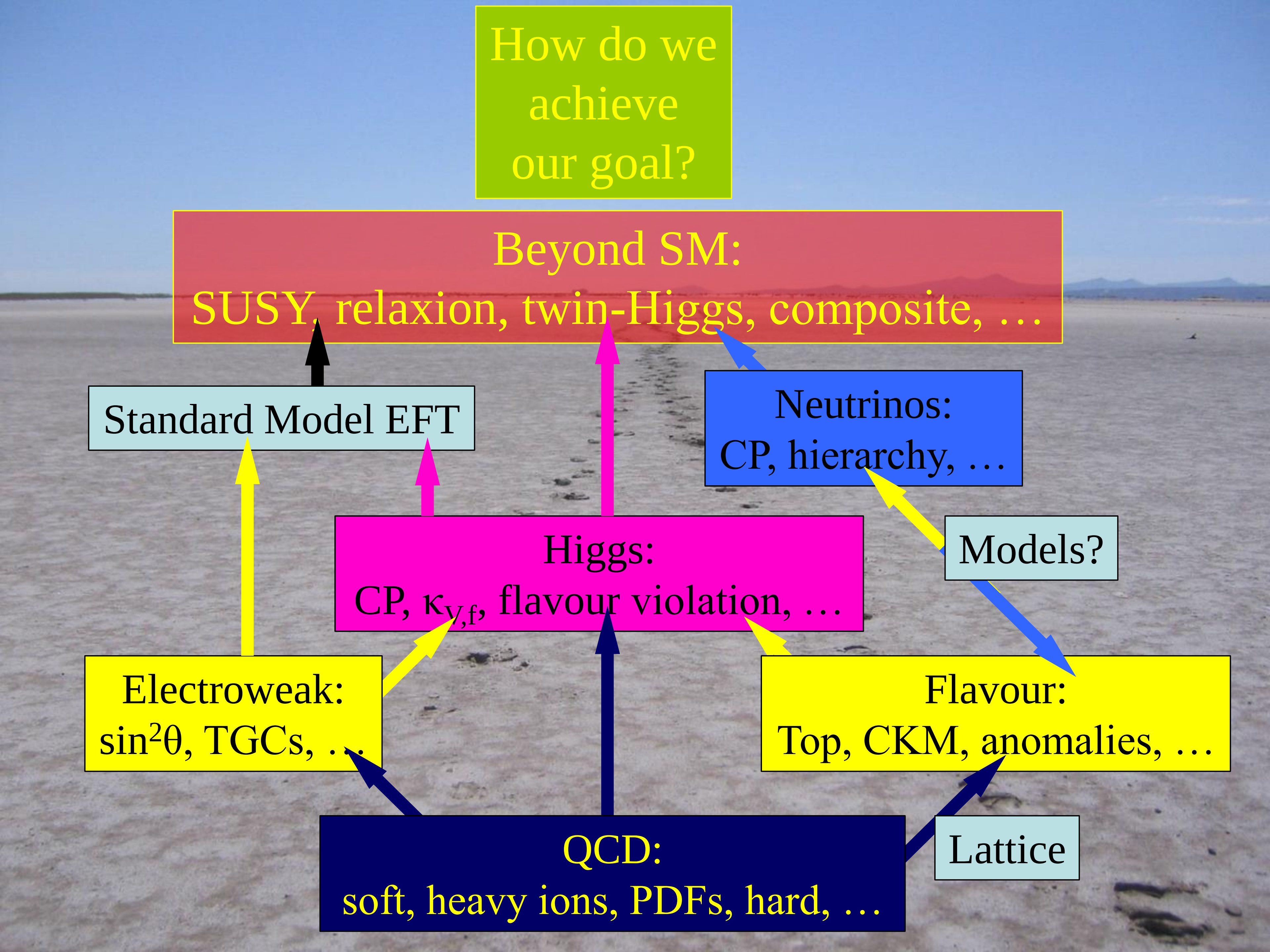


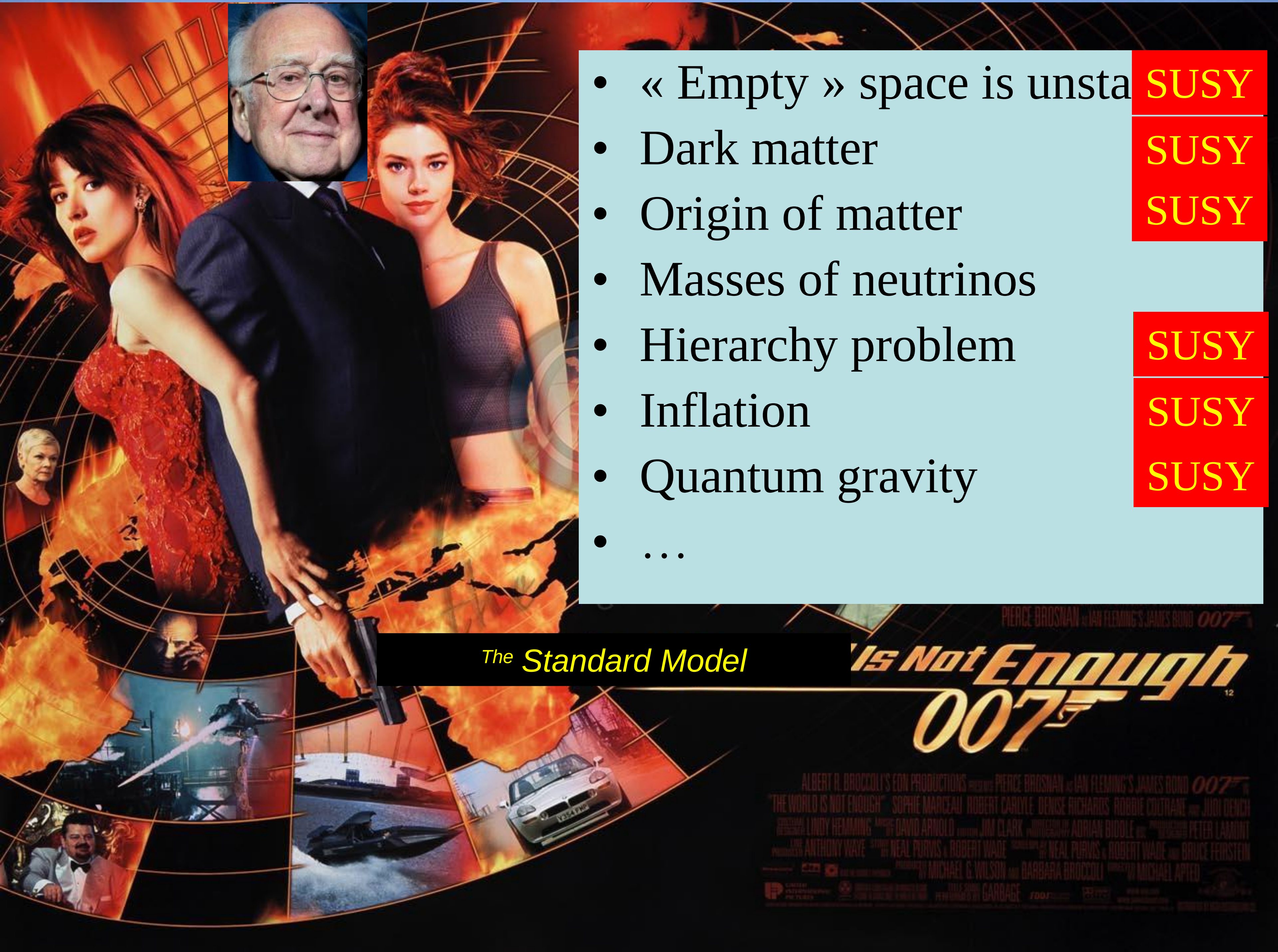
JE, Sanz & Tevong You, arXiv:1410.7703

Dawson, Ciuchini, Greljo



- **Associated production**
- **LHC Triple-gauge couplings**
- Global combination
- **Individual operators**

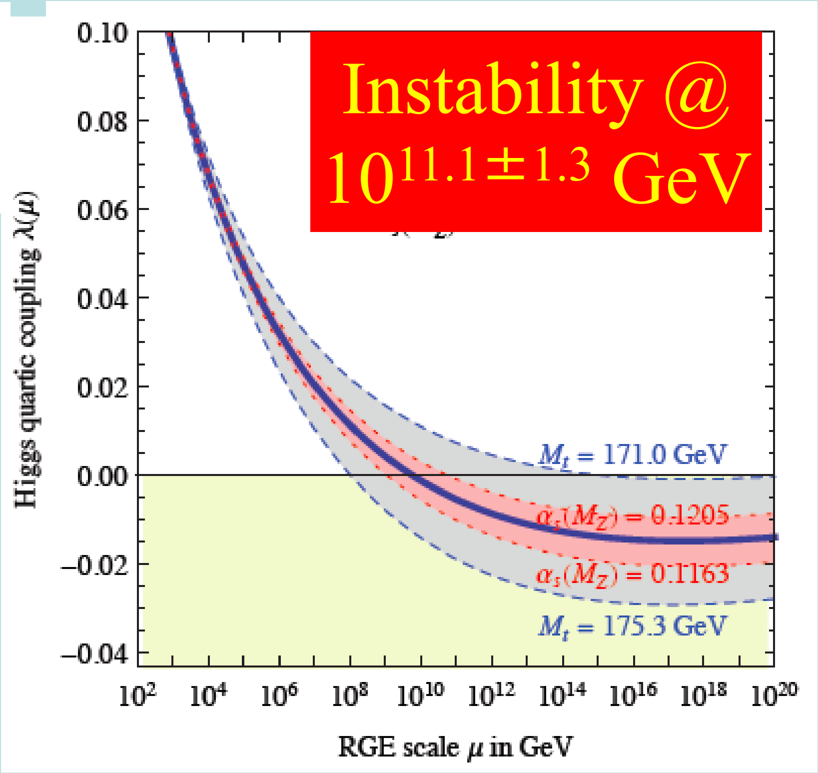

How do we achieve our goal?
Beyond SM:
SUSY, relaxion, twin-Higgs, composite, …
Standard Model EFT
Neutrinos:
CP, hierarchy, …
Models?
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Flavour:
Top, CKM, anomalies, …
QCD:
soft, heavy ions, PDFs, hard, …
Lattice


« Empty » space is unsta
SUSY
Dark matter
SUSY
Origin of matter
SUSY
Masses of neutrinos
Hierarchy problem
SUSY
Inflation
SUSY
Quantum gravity
SUSY
…
The Standard Model
Is Not Enough
007

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$



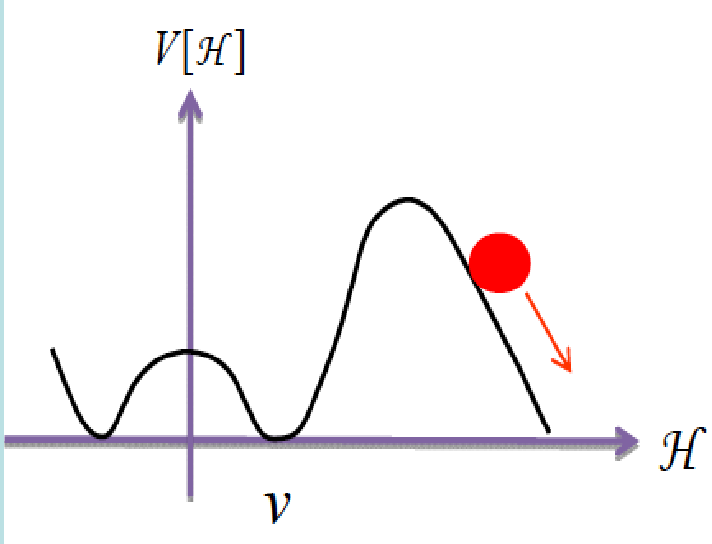
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

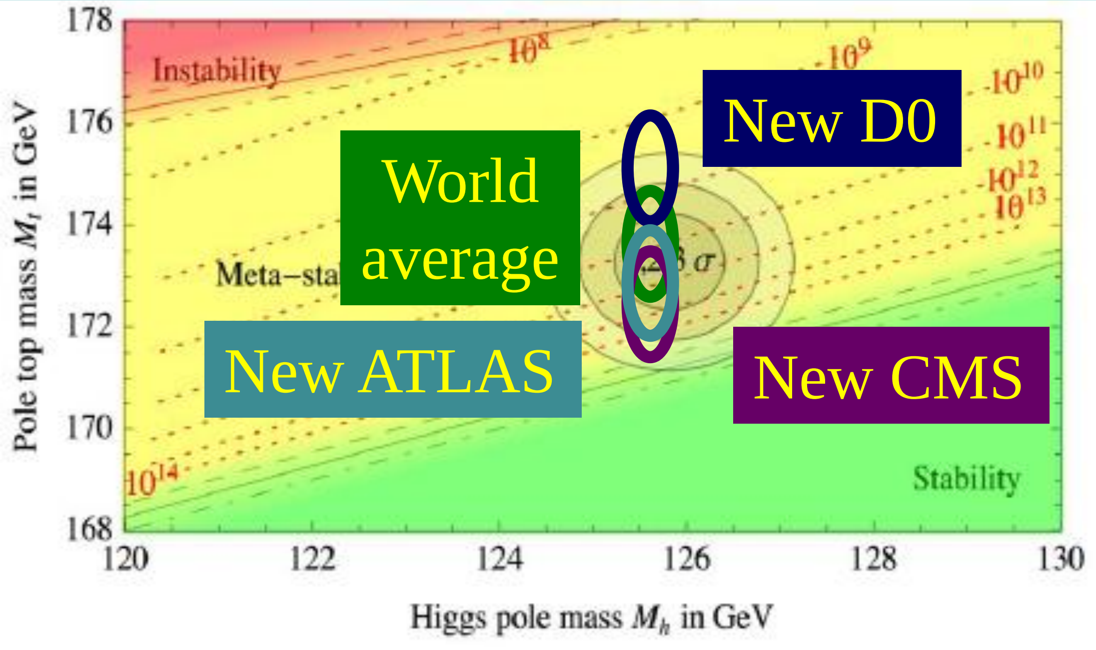
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H

Melnikov, Meyer





- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

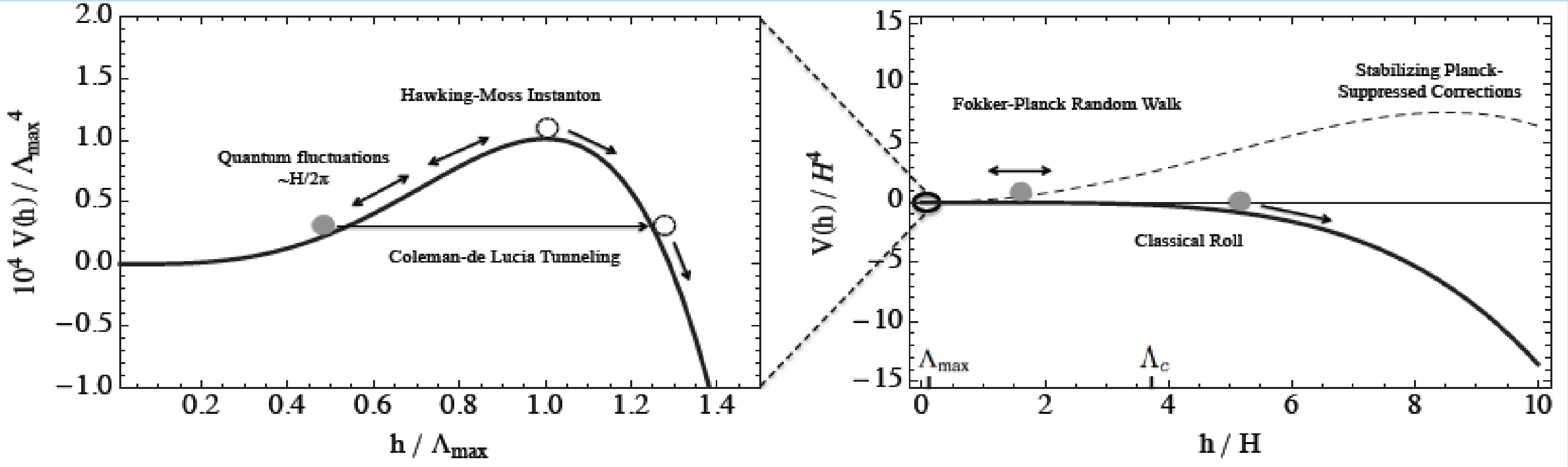
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

m_t = 173.3 ± 1.0 GeV → $\log_{10}(\Lambda/\text{GeV})$ = 11.1 ± 1.3

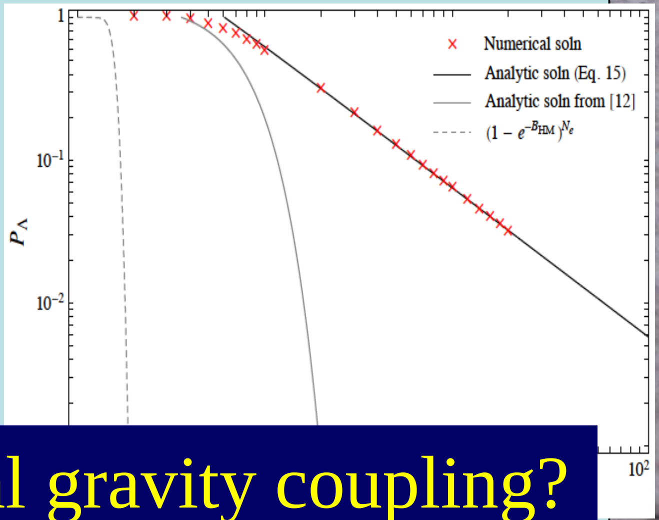
Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so
  - If not, OK if more inflation



OK if dim-6 operator? Non-minimal gravity coupling?

Shchutska

SUSY: Dusk or Dawn?

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

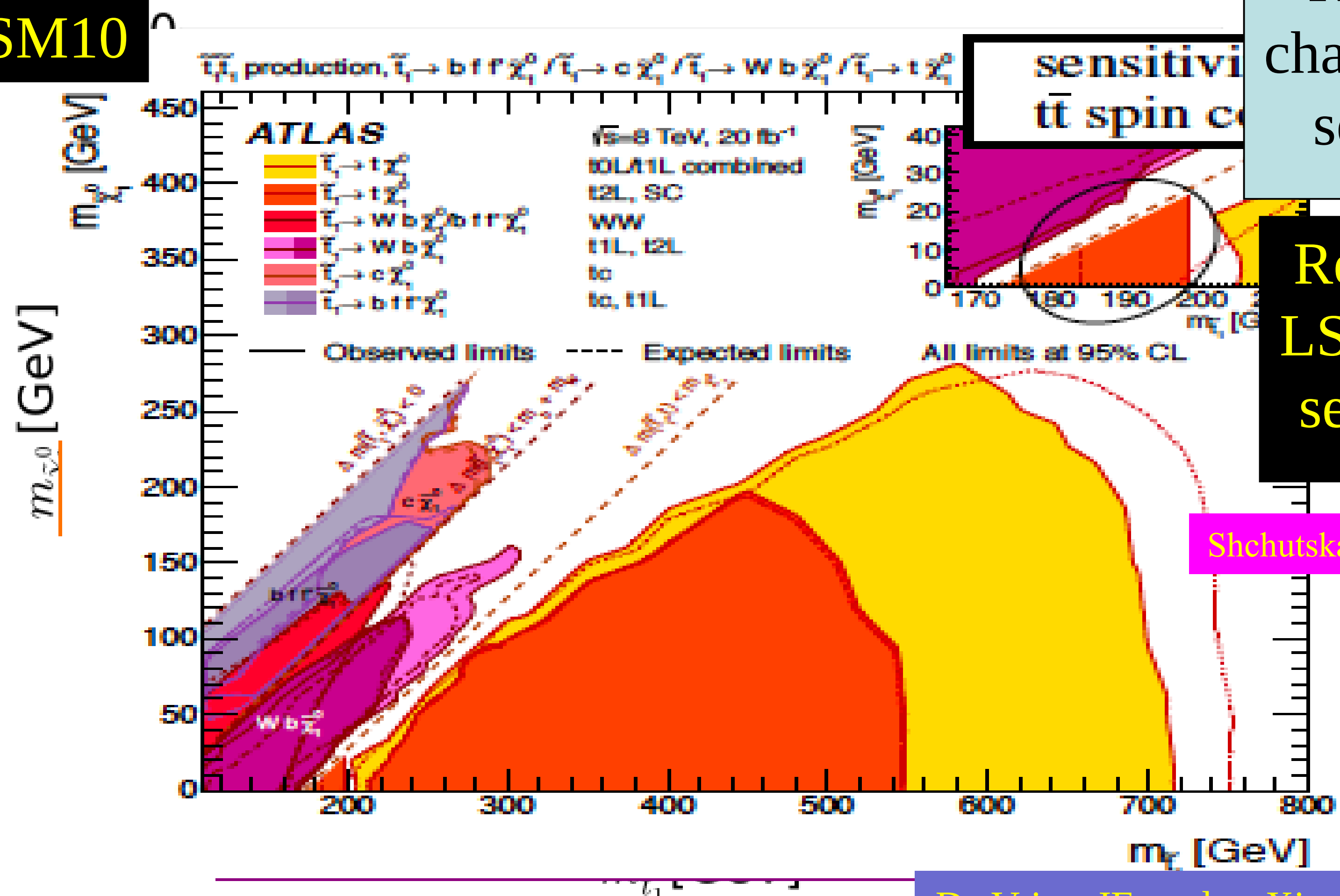
- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

"… better known, and still well-motivated … MSSM" McCullough

Exploring Light Stops @ Run 2

2012 ATLAS + CMS with 20/fb of LHC Data

pMSSM10



Reach of chargino + b searches

Reach of LSP + top searches

Shchutska, Cristinziani

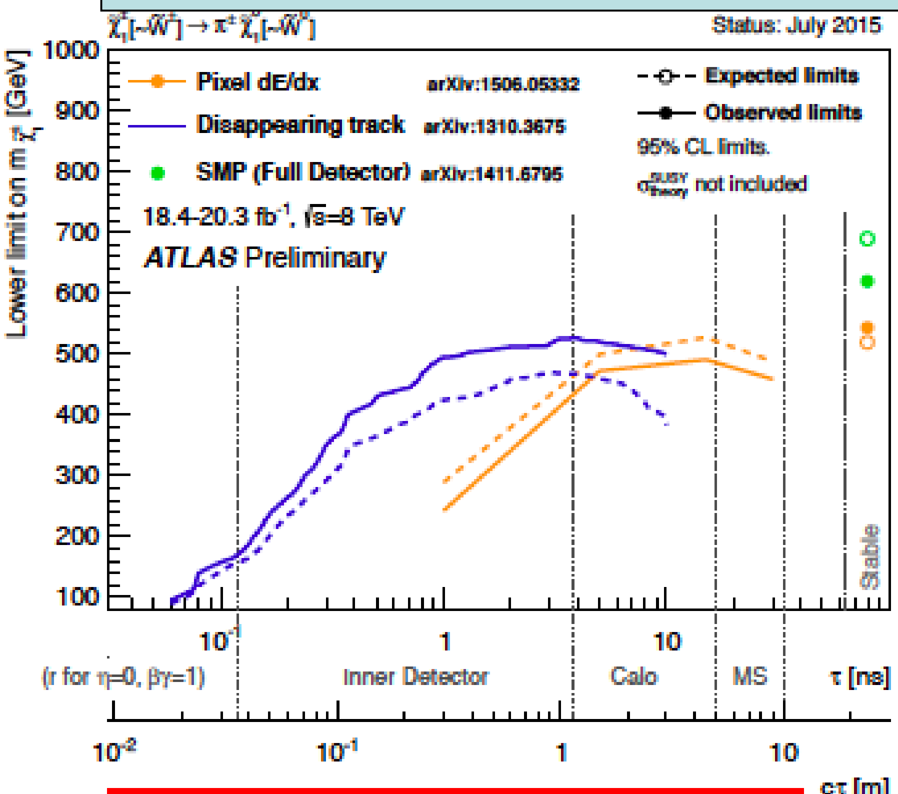
De Vries, JE et al: arXiv:1504.03260

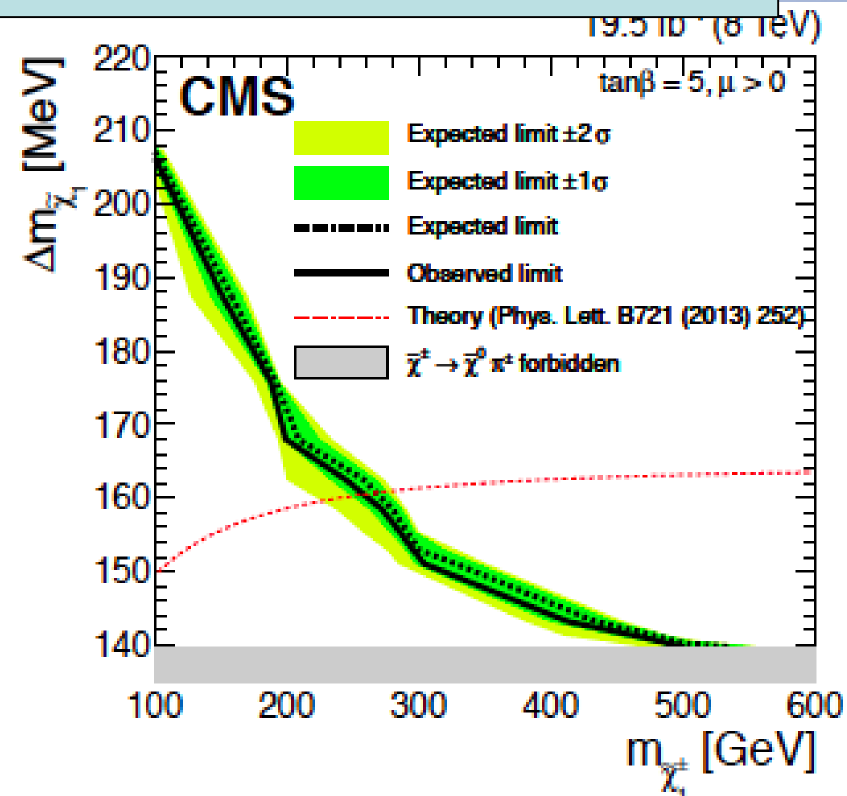
Part of region of light "natural" stop weighing ~ 400 GeV can be covered

Searches for Long-Lived Sparticles

Shchutska

- Interpretations given for long-lived charginos





Sensitive up to $m_{\tilde\chi^\pm} \approx 500$ GeV
for wid

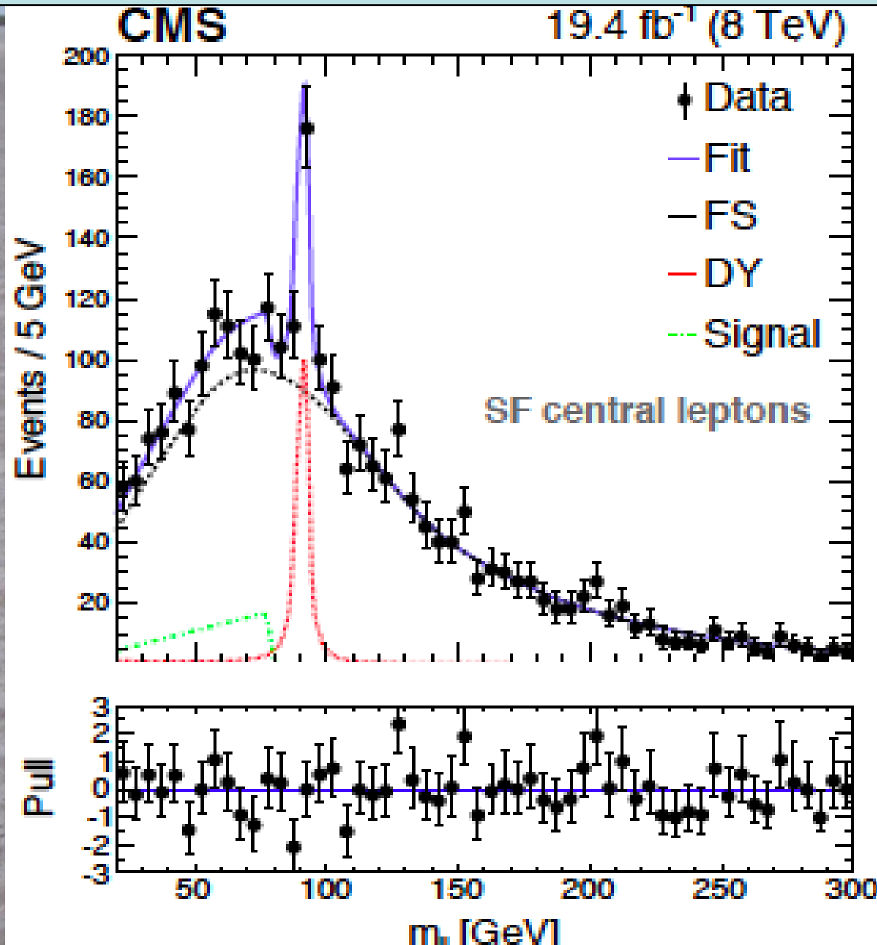
Similar result from CMS shown

low 260 GeV

Also interesting for long-lived staus

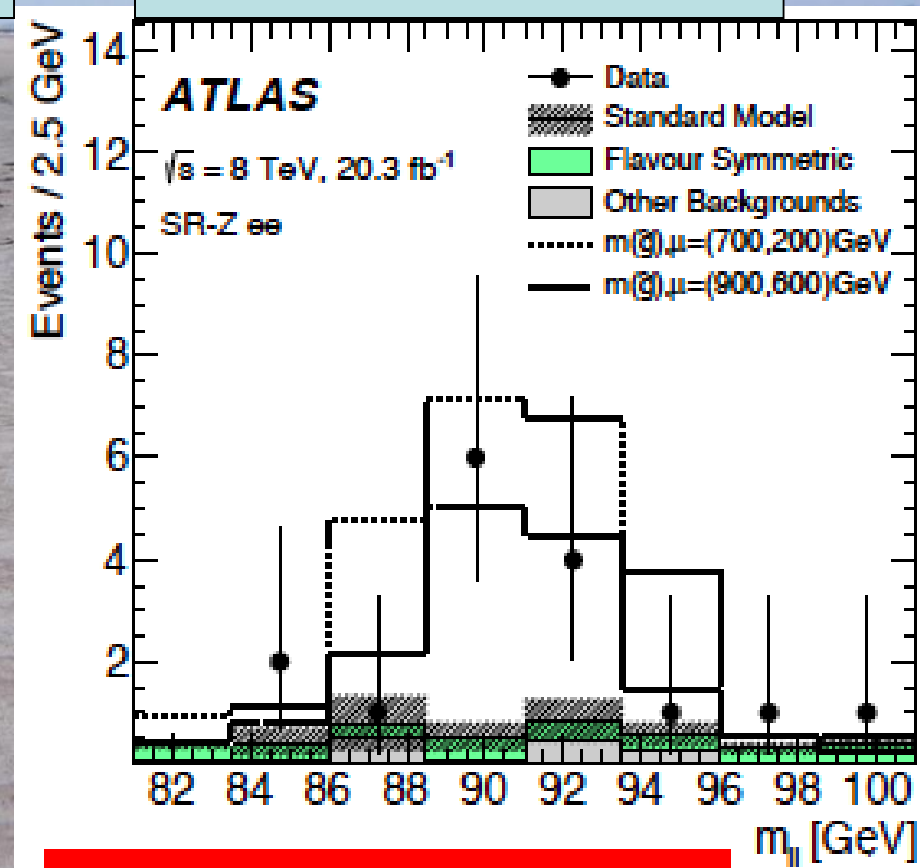
Anomalies with Missing E_T

- Dilepton edge below Z



- Z + missing E_T

Shchutska

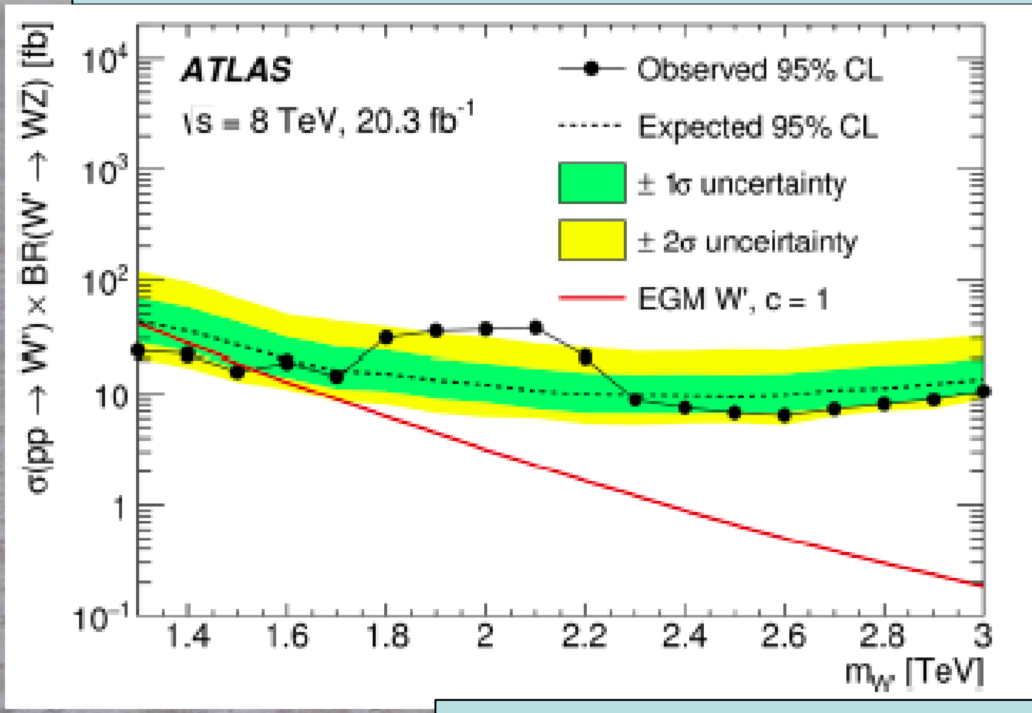


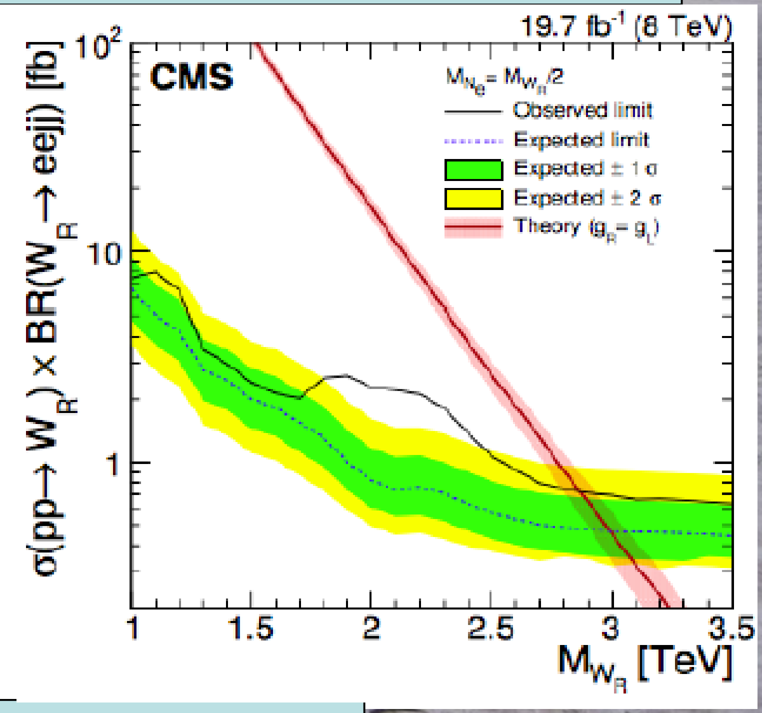
Wait & see @ Run 2!

Exotic High-Mass Anomalies

Kersevan

- Diboson "bump": VV ➔jjjj around 2 TeV?
  - 3.4σ local significance, 2.5σ global significance





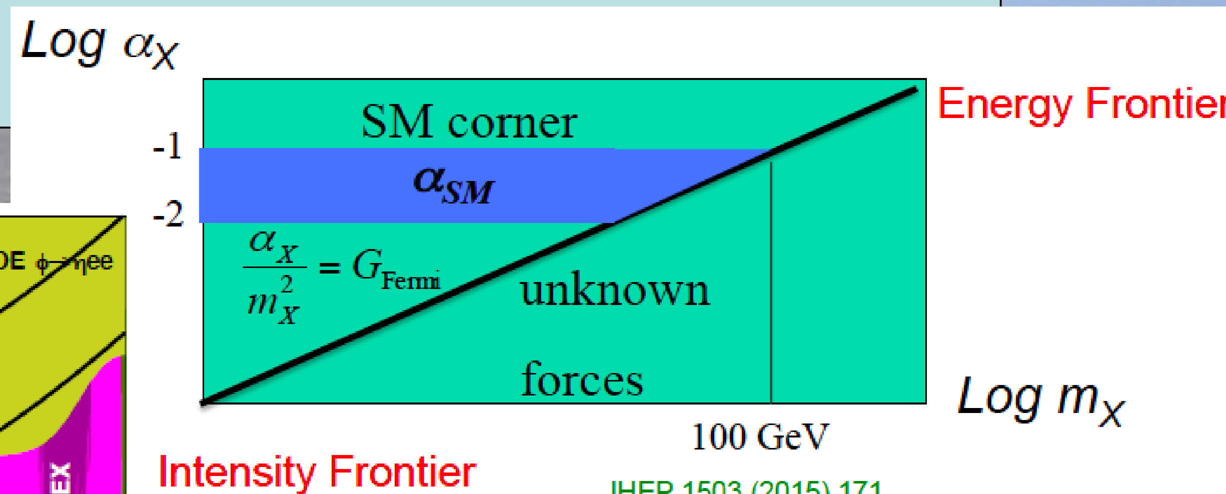
- W_R ➔eejj?
  - (2.8σ local significance)

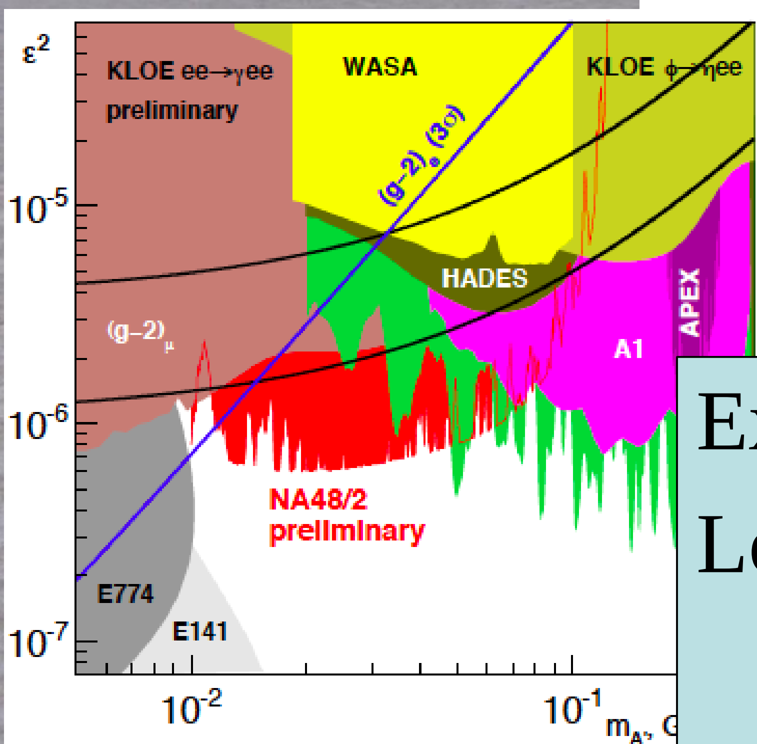
Wait & see @ Run 2!

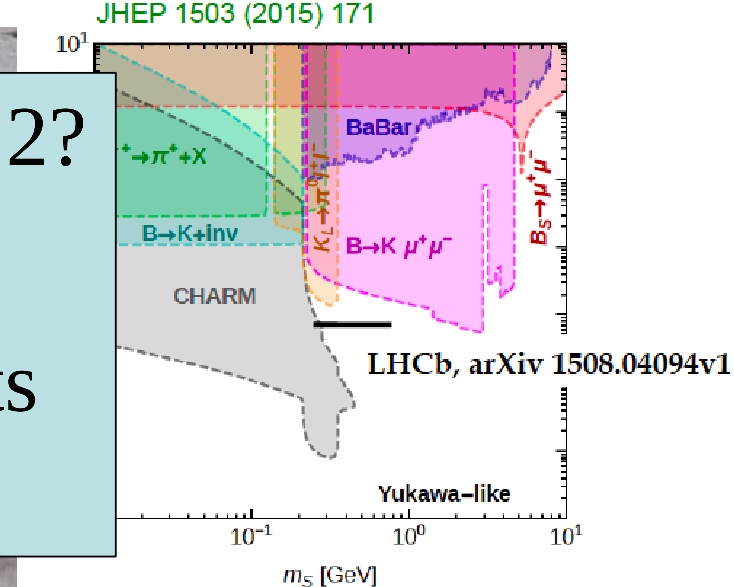
Energy Frontier vs Intensity Frontier

- Light weakly-interacting particles difficult to see at LHC

Pospelov







Explain $g_\mu - 2$?

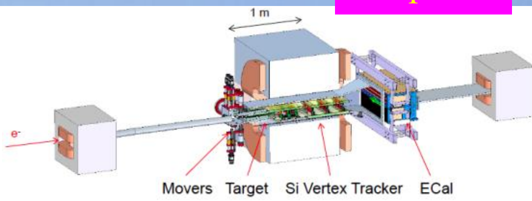
Low-energy constraints

& LHCb

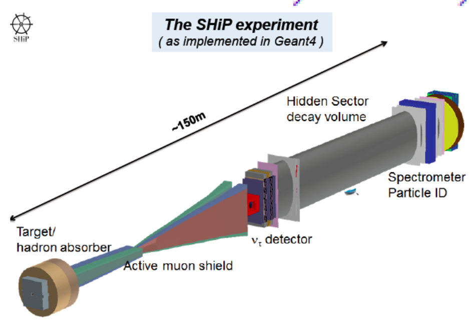
Projects for Future Experiments

Pospelov

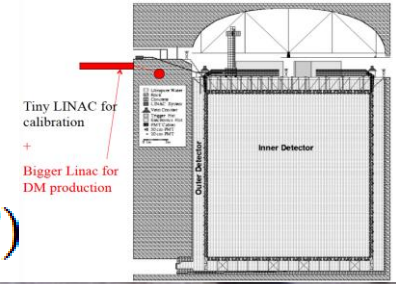
Fixed Target/beam dump experiments sensitive to



- Dark Photons: HPS, DarkLight, APEX, Mainz, SHiP…
- Light dark matter production + scattering: MiniBoNE, BDX, SHiP…



- Right-handed neutrinos: SHiP
- Missing energy via DM production: NA62 ($K \rightarrow \pi\nu\nu$ mode), positron beam dumps…

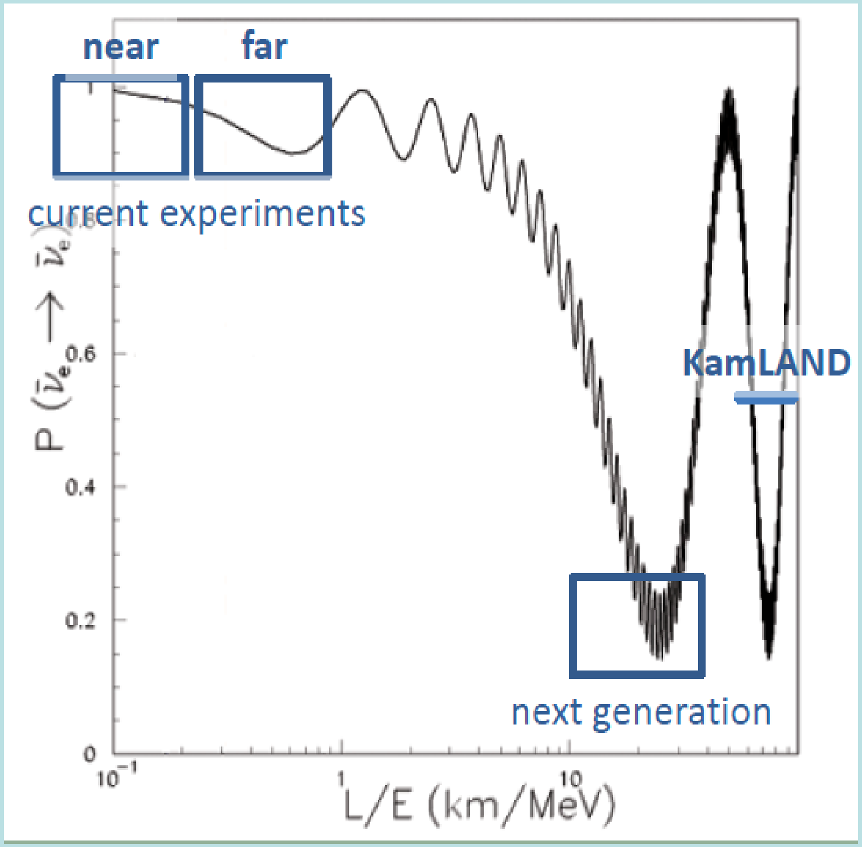


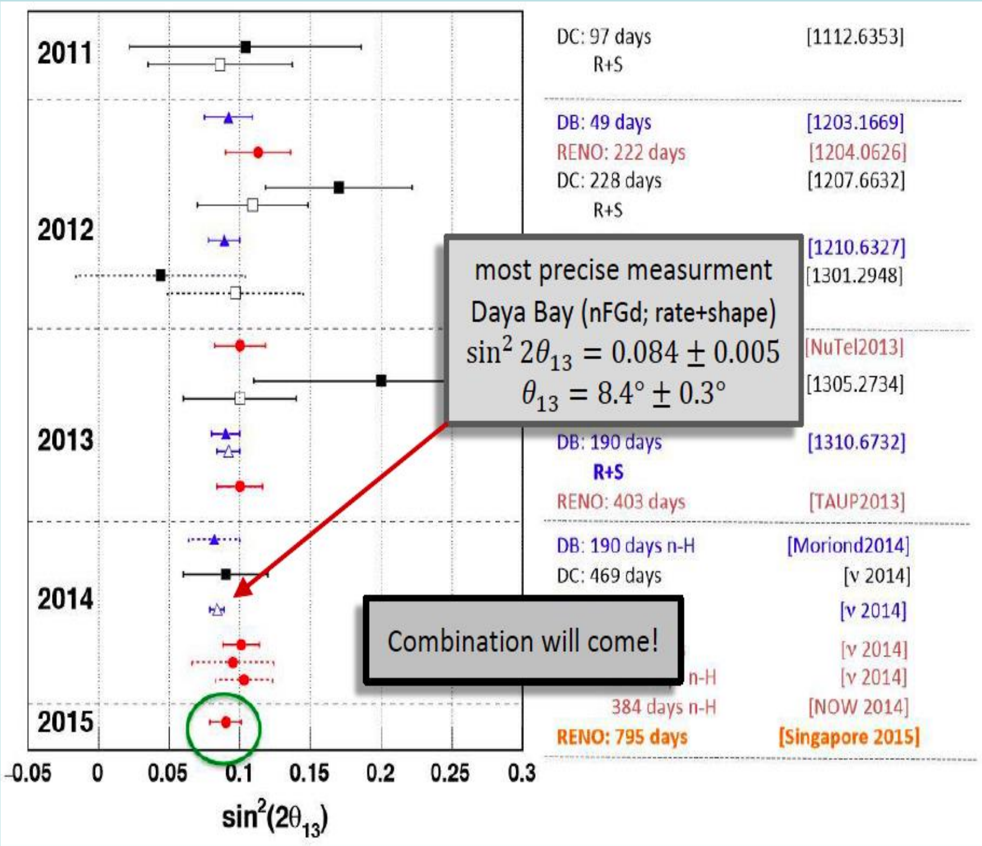
- Extra Z' in neutrino scattering: DUNE near detector (?)

Reactor Neutrino Experiments

Stahl

- **Great progress since previous Lepton-Photon**



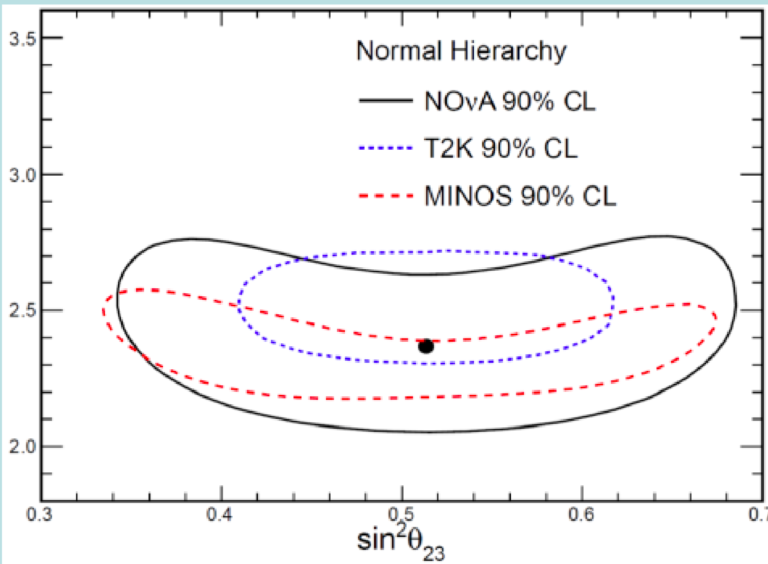


- Anomaly in ν flux ≠ oscillations

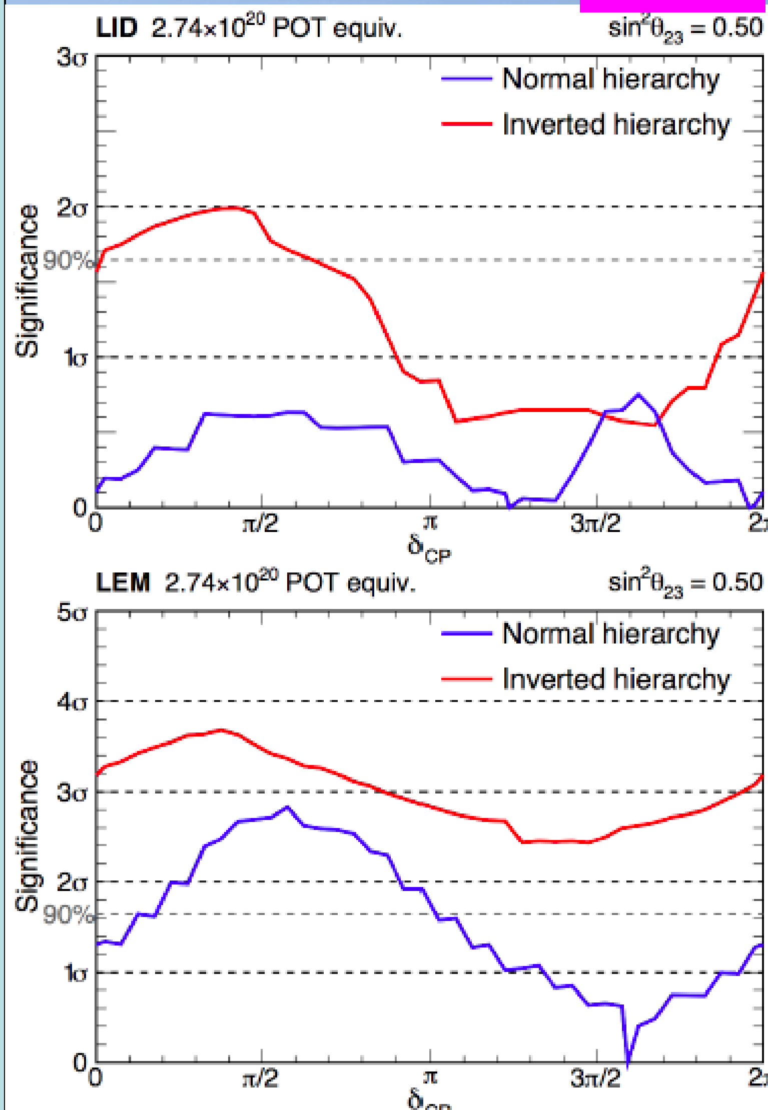
Accelerator + Atmospheric νs

Shanahan

- **5σ $\nu_\mu \rightarrow \nu_\tau$ from OPERA**
- **First Light from NOνA**



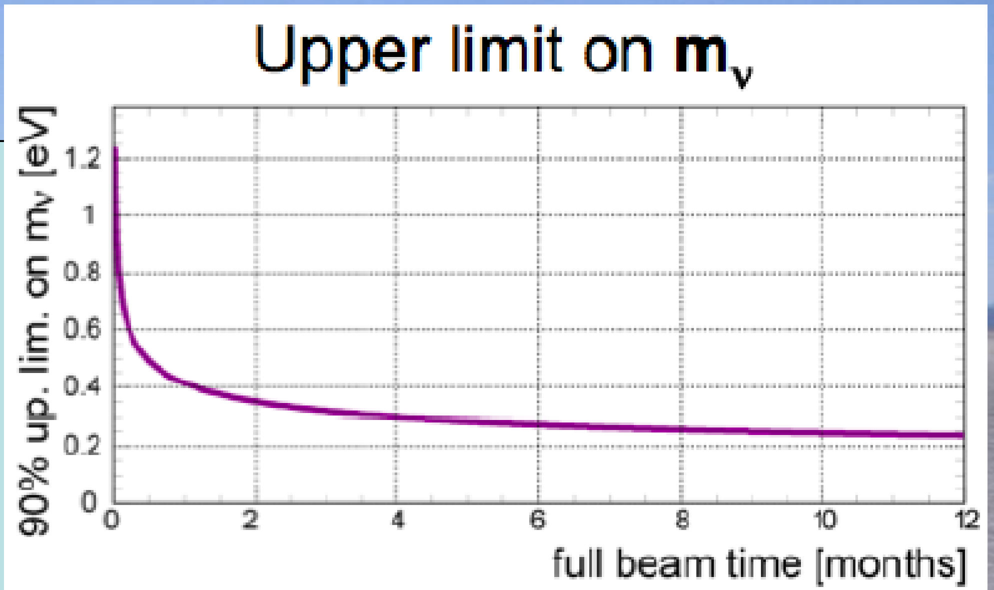
- Consistent with previous mild preferences for normal hierarchy, $\delta_{CP} \approx 3\pi/2$?

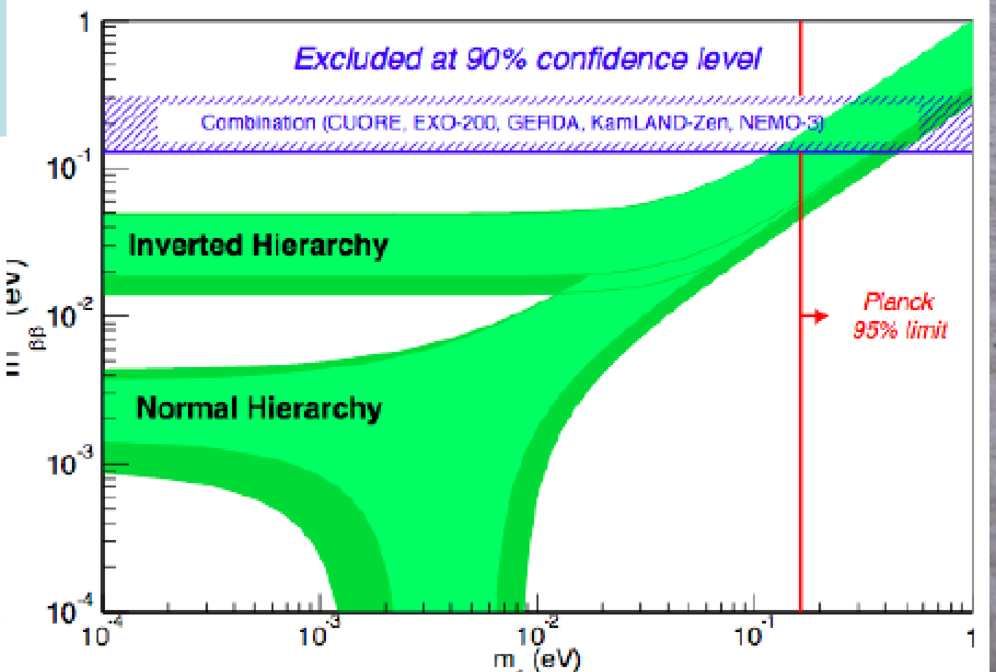


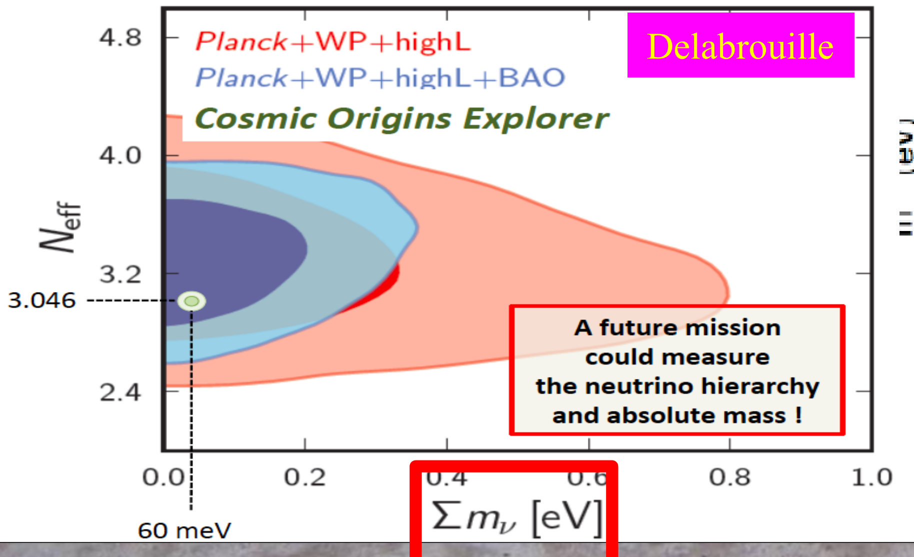
Zavatarelli

Absolute m_ν

- Tritium β spectrum:
  - Katrin to start in 2016
  - e^- capture on ^{163}Ho
- ν-less ββ decay
- **Using the CMB**







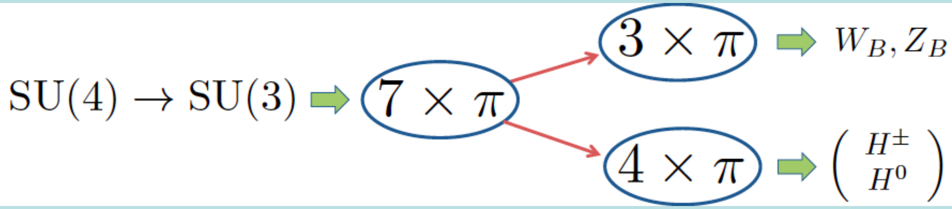
Novel Idea # 1: “Twin Higgs”

McCullough

- **Higgs sector links 2 copies of Standard Model:**

$$V_{\text{Higgs}} = \lambda\left(|H_A|^2 + |H_B|^2\right)^2$$

- SM quadratic divergences cancelled by SM-neutral particles: “neutral naturalness”
- Postulate negative mass^2 in SM_B sector



- “our” Higgs is pseudo-Nambu-Goldstone boson
- Novel LHC phenomenology
  - Higgs ➔B-sector glueballs? Displaced vertices?

Novel Idea # 2: “Relaxion”

McCullough

- Add “axion-like” field to Standard Model

$$\mathcal{L} \sim (M^2 - g\phi)|H| - gM^2\phi + f_\pi^3 \lambda_q \langle h \rangle \cos\left(\frac{\phi}{f}\right)$$

- Chiral symmetry breaking potential
- Depends on quark mass, hence Higgs vev
- Evolution of “axion-like” field
- Gets trapped with non-zero vev
- Also Higgs vev, naturally small
- 10^{40} inflation efolds, $\theta_{QCD} \neq 0$!!
- Need epicycles (new QCD’, …)

Composite Vector (Gauge) Bosons?

Komargodski

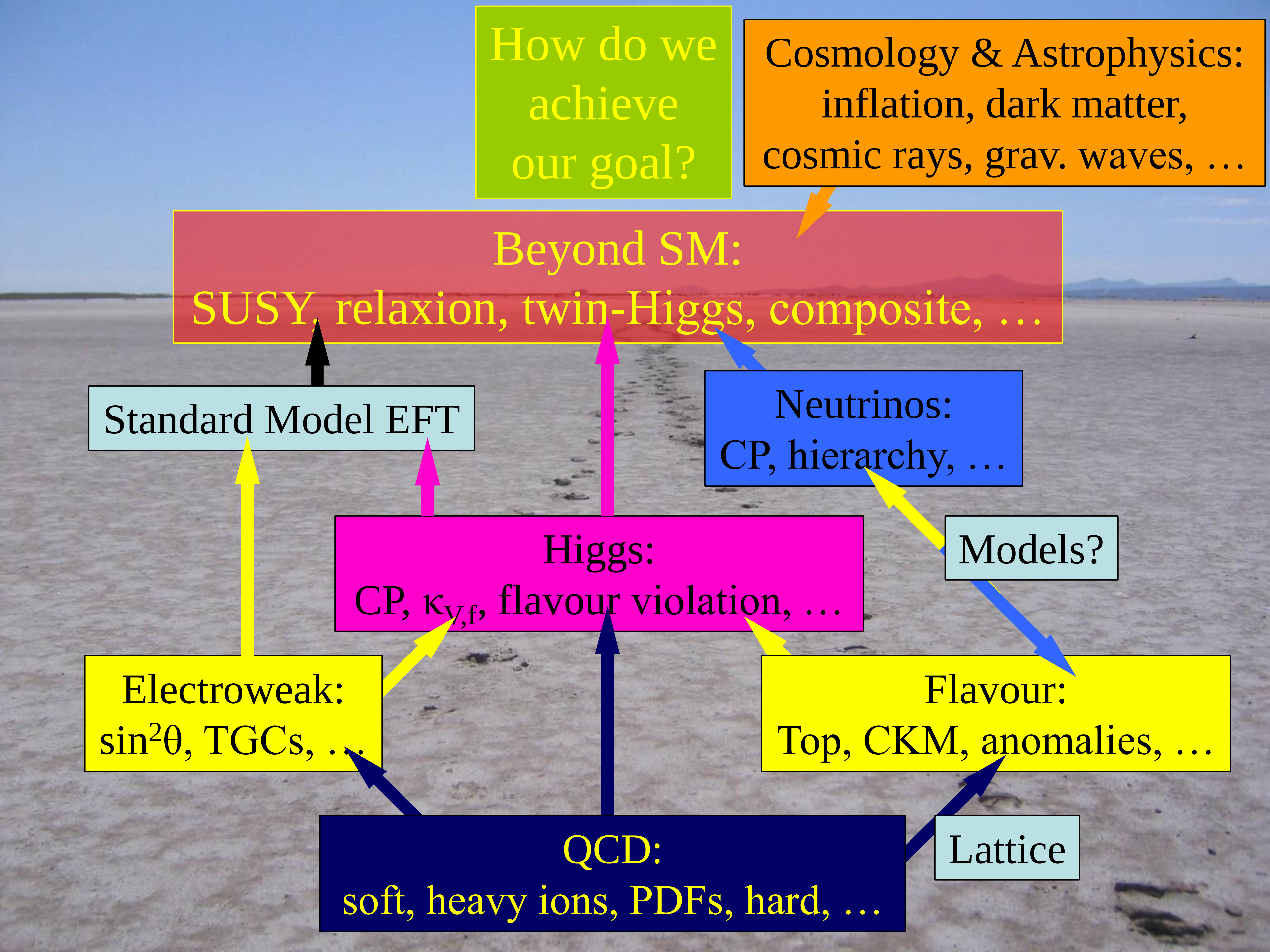
- Massless spin-1 bosons can be composite
  - – Explicit supersymmetric example:
    - SU(4) + 6 **4** + **4bar** ➔SU(2) + 12 **2** fermions + 32 **1** scalars
- Example of strong-weak duality, proof uses

$$(p,p)^2(q,q)^2 \int \prod_{i=1,..,4} [dr_i] \frac{\prod_{i,j\leq 4} \Gamma(\mu_i r_j, 1/(\tilde{\mu}_i r_j), p, q)}{\prod_{i,j\leq 4} \Gamma(r_i/r_j, r_j/r_i, p, q)}$$

$$= \left[\prod_{i,j\leq 2} \Gamma(\mu_i/\tilde{\mu}_j, p, q)\right] \int \prod_{i=1,2} [dr_i] \frac{\prod_{i,j\leq 2} \Gamma(\mu_i r_j, 1/(\tilde{\mu}_i r_j), p, q)}{\prod_{i,j\leq 2} \Gamma(r_i/r_j, r_j/r_i, p, q)}$$

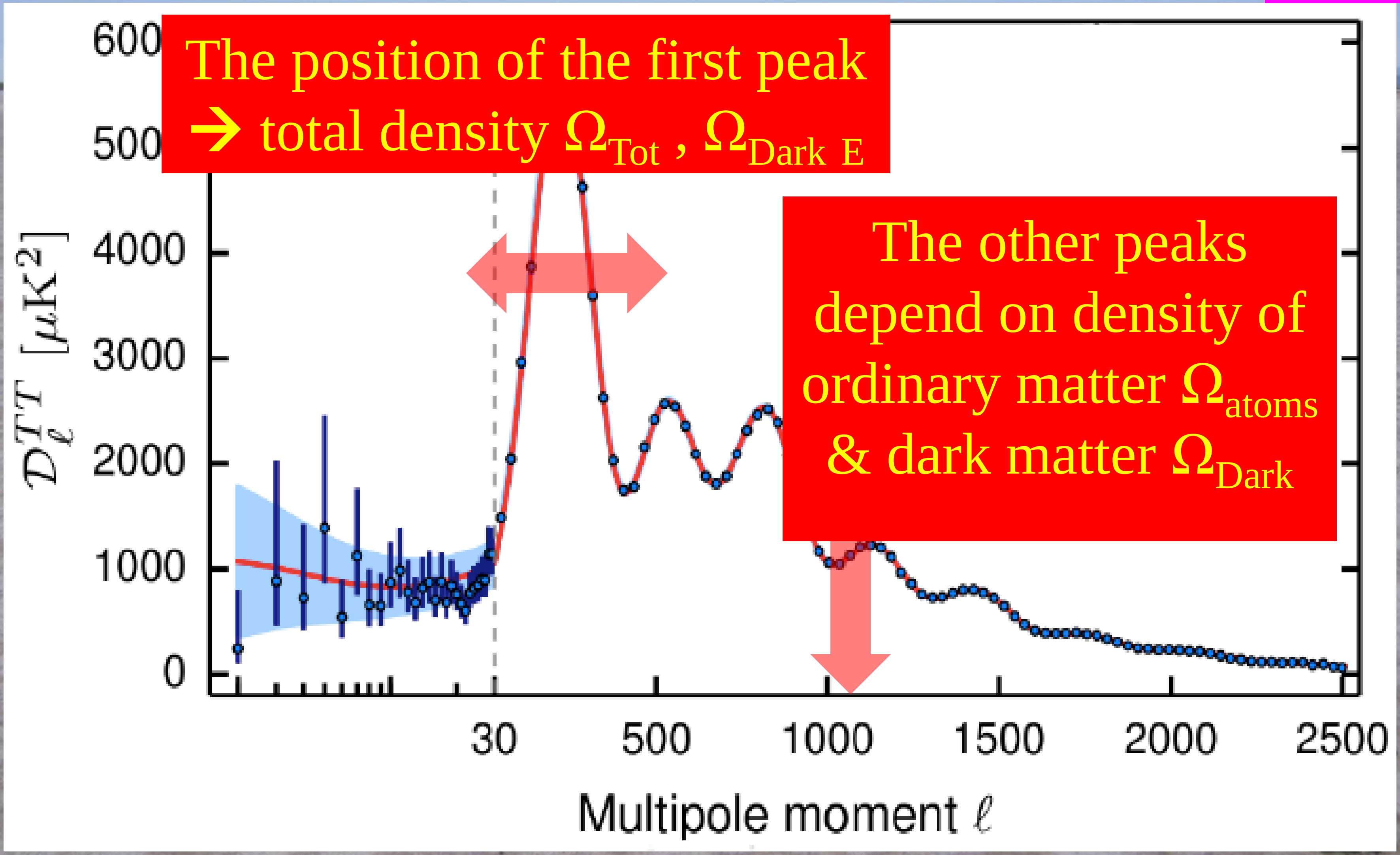
Elliptic hypergeometric Gamma functions and q-Pochhammer symbols

- Applicable to ρ meson of QCD?
- Applicable to gauge bosons of Standard Model?
- **“No experimental motivation” – Look for it!**


How do we achieve our goal?
Cosmology & Astrophysics: inflation, dark matter, cosmic rays, grav. waves, …
Beyond SM: SUSY, relaxion, twin-Higgs, composite, …
Standard Model EFT
Neutrinos: CP, hierarchy, …
Higgs: CP, $\kappa_{V,f}$, flavour violation, …
Models?
Electroweak: $\sin^2\theta$, TGCs, …
Flavour: Top, CKM, anomalies, …
QCD: soft, heavy ions, PDFs, hard, …
Lattice

The Spectrum of Fluctuations in the Cosmic Microwave Background

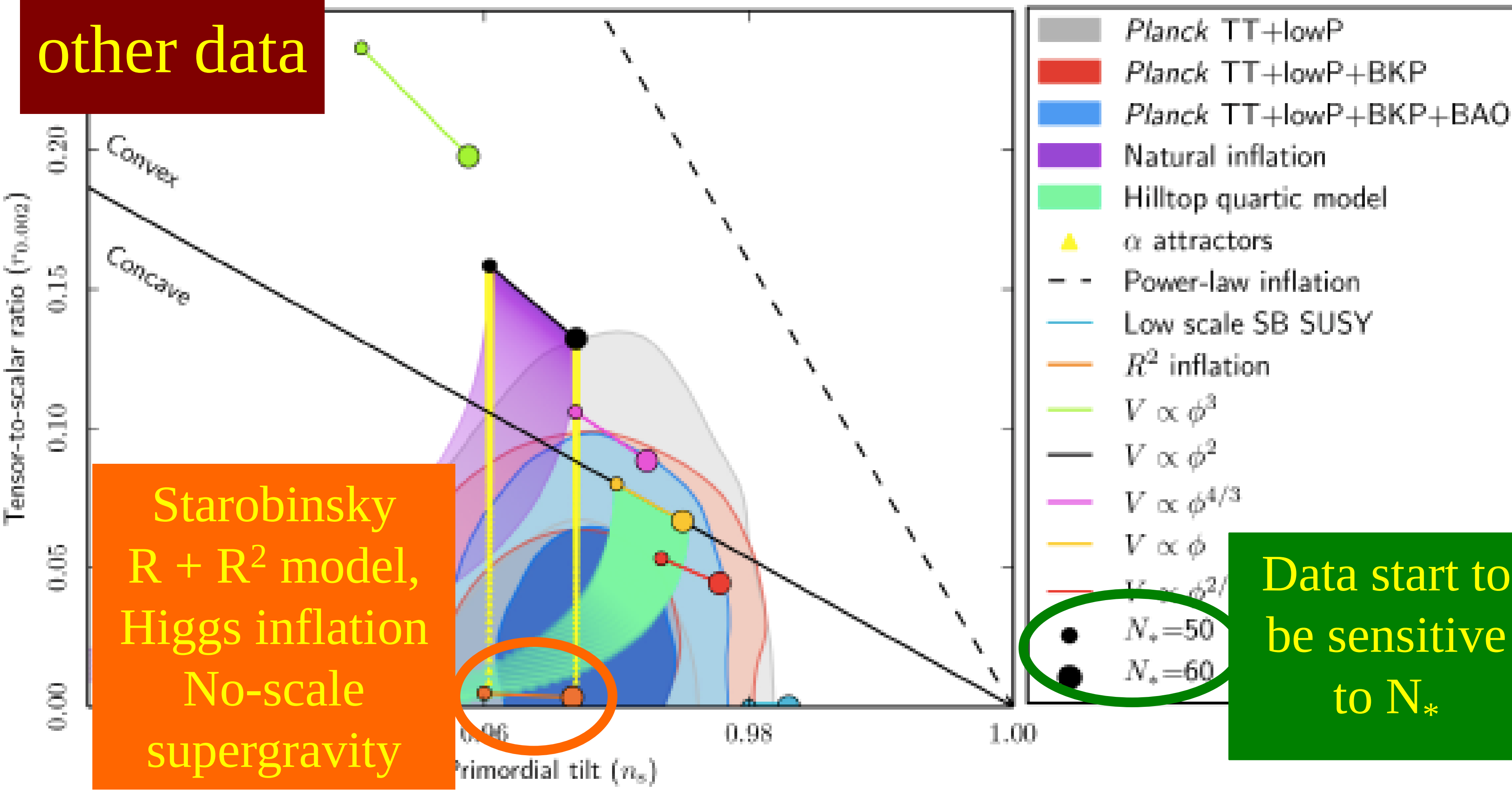
Delabrouille



Inflationary Landscape

Guth

Planck + other data

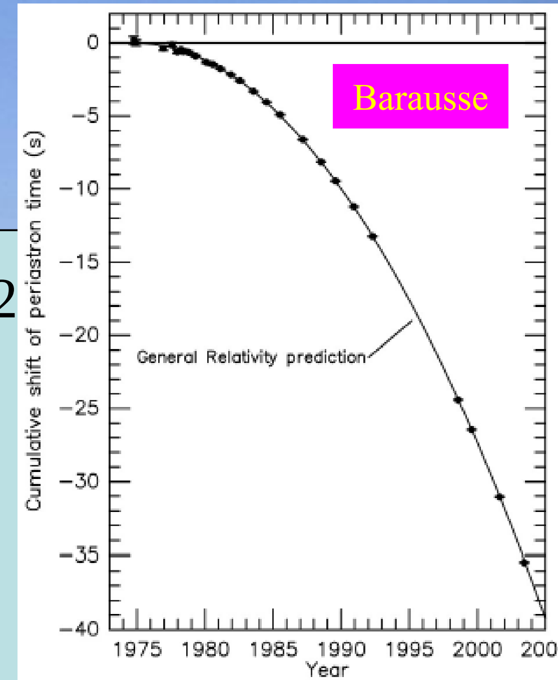


Starobinsky
$R + R^2$ model,
Higgs inflation
No-scale
supergravity

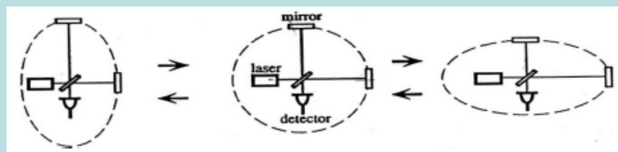
Data start to be sensitive to N_*

Need new space mission to probe Starobinsky et al.

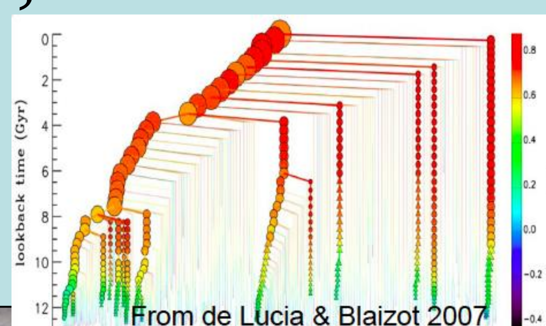
Gravitational Waves

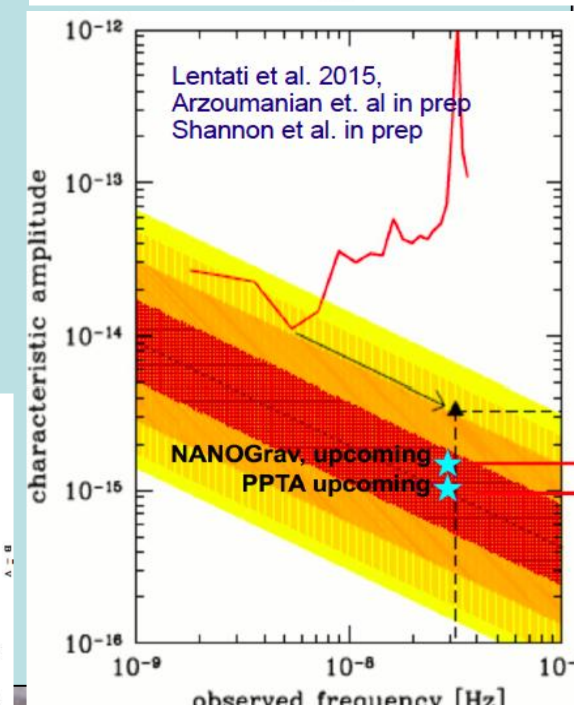


- Quadrupole radiation: $< \frac{MR^2}{\tau^3} \sim \frac{Mv^2}{\tau} >^2$
- Indirect binary pulsars evidence
- GW in the CMB? BICEP2 ☹
- Searches:



- LIGO, Virgo, GEO600, KAGRA:
  - NS/BH binaries **(nuclear EOS)**
- Pulsar timing array, eLISA:
  - massive BH mergers
- **GW astronomy!**

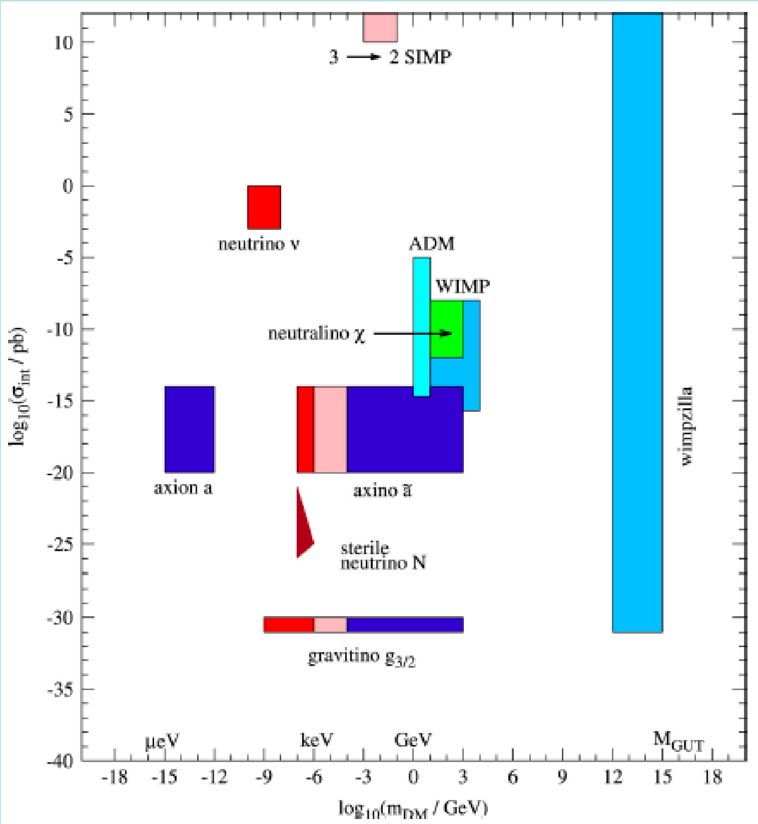


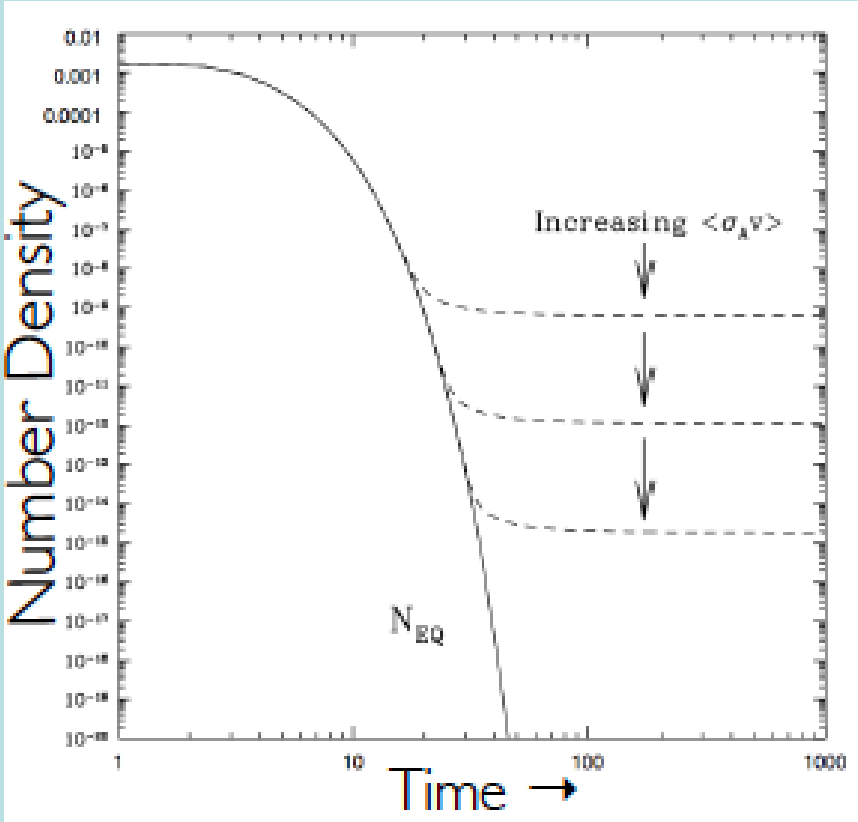


Landscape of Dark Matter Candidates

Volansky

- Candidates with large range of mass, coupling
- Focus on fashionable WIMP scenario

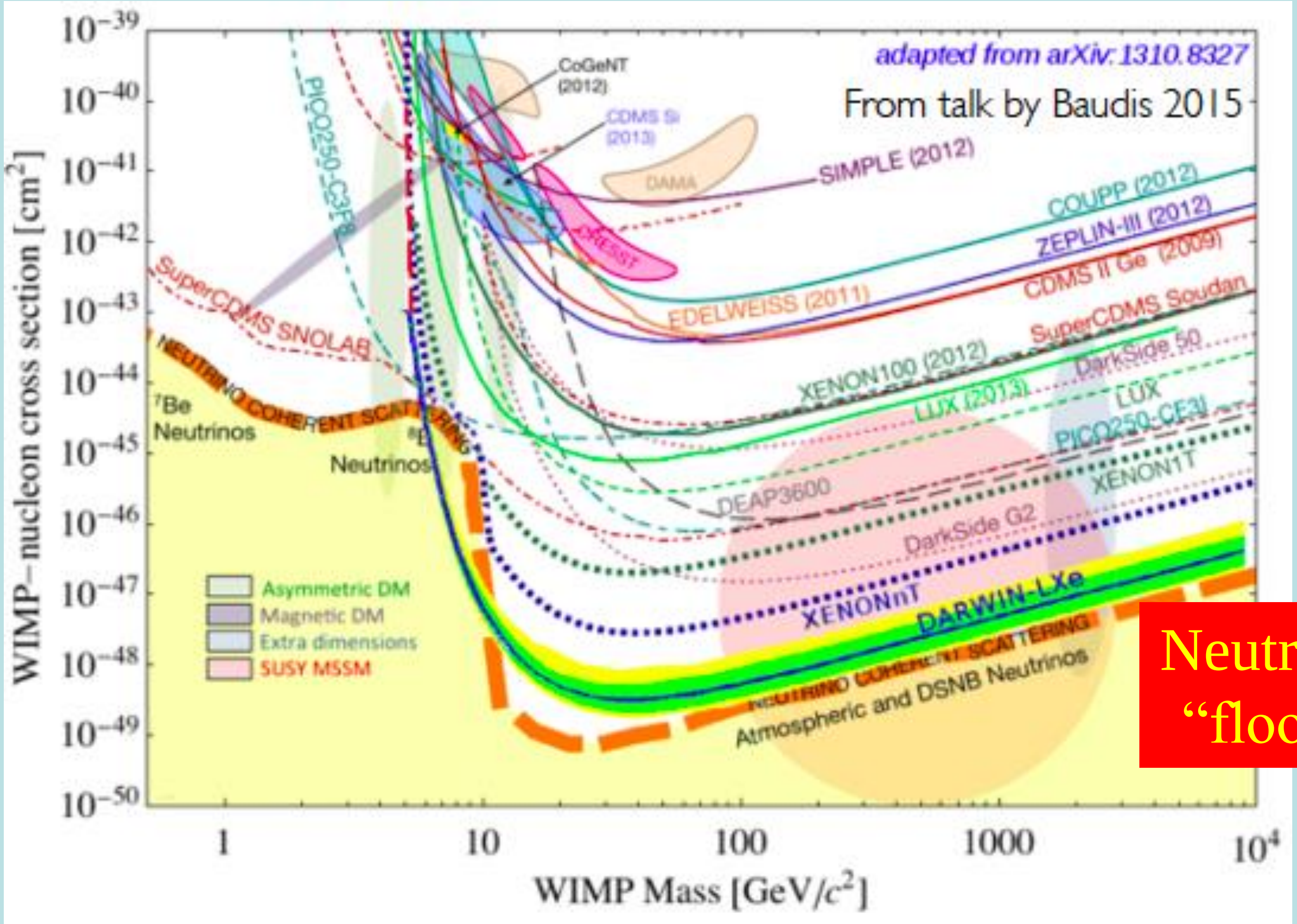




Direct Dark Matter Searches

Baudis

- Compilation of present and future sensitivities

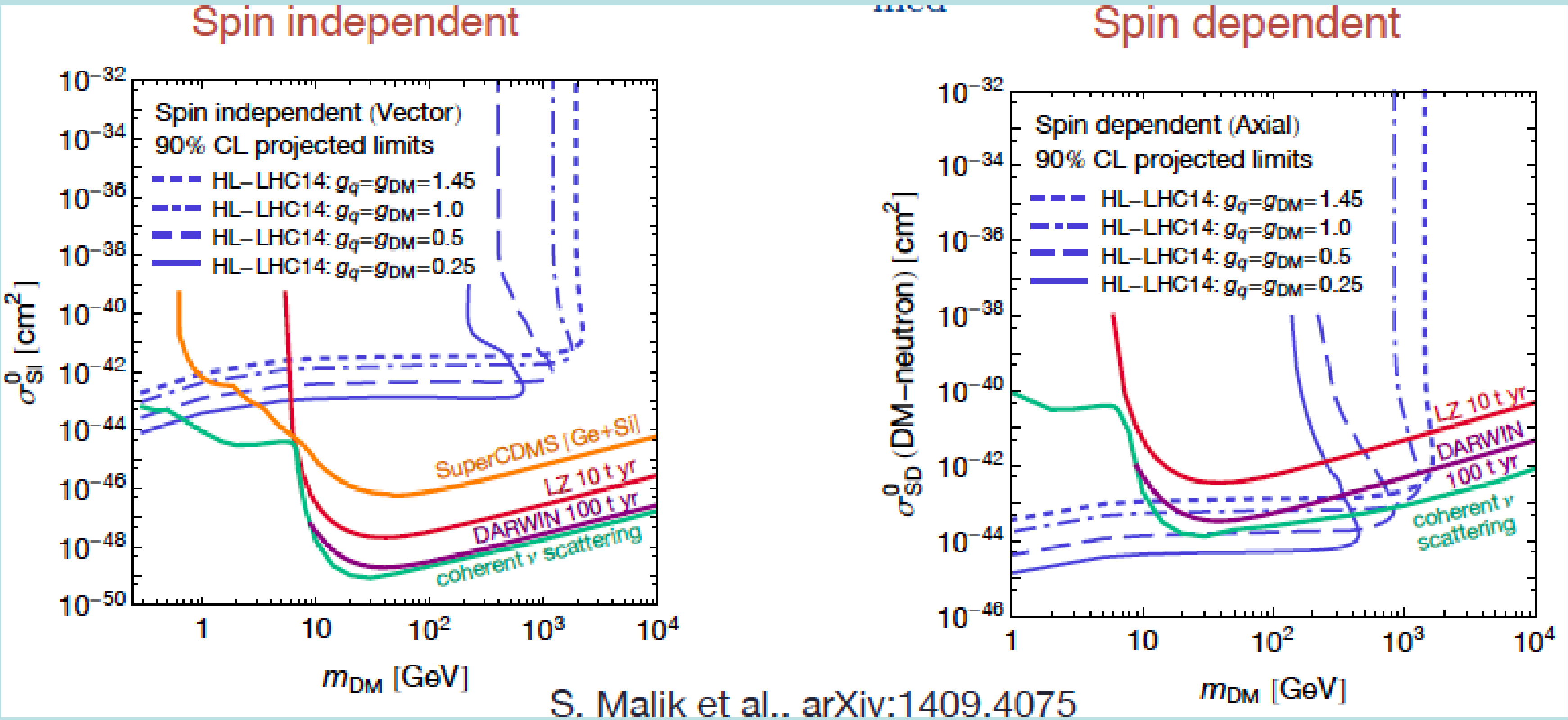


Neutrino "floor"

LHC vs Dark Matter Searches

Baudis, Kersevan

- Compilation of present "mono-jet" sensitivities



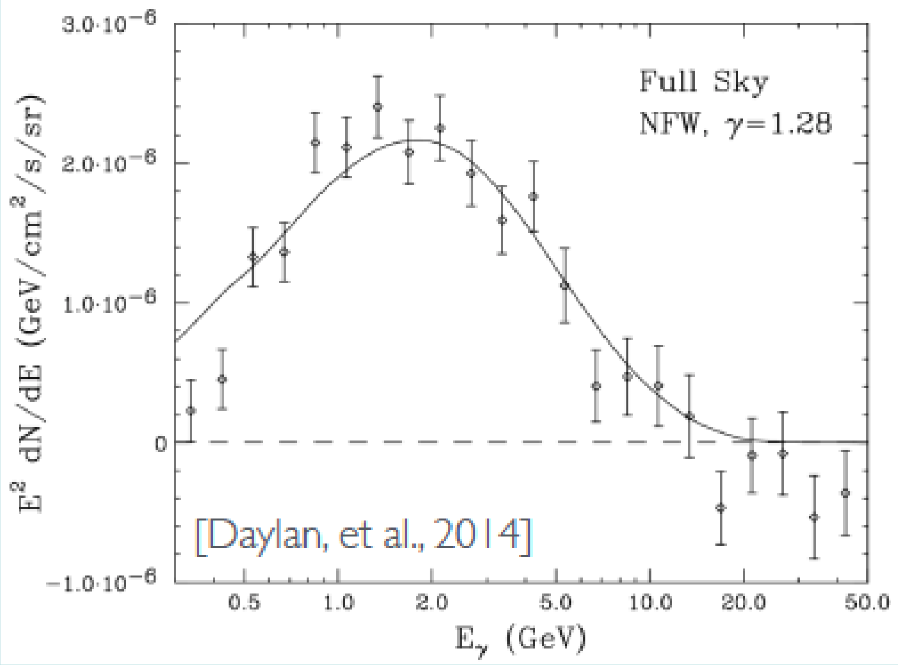
- LHC wins for spin-independent, except small m_{DM}

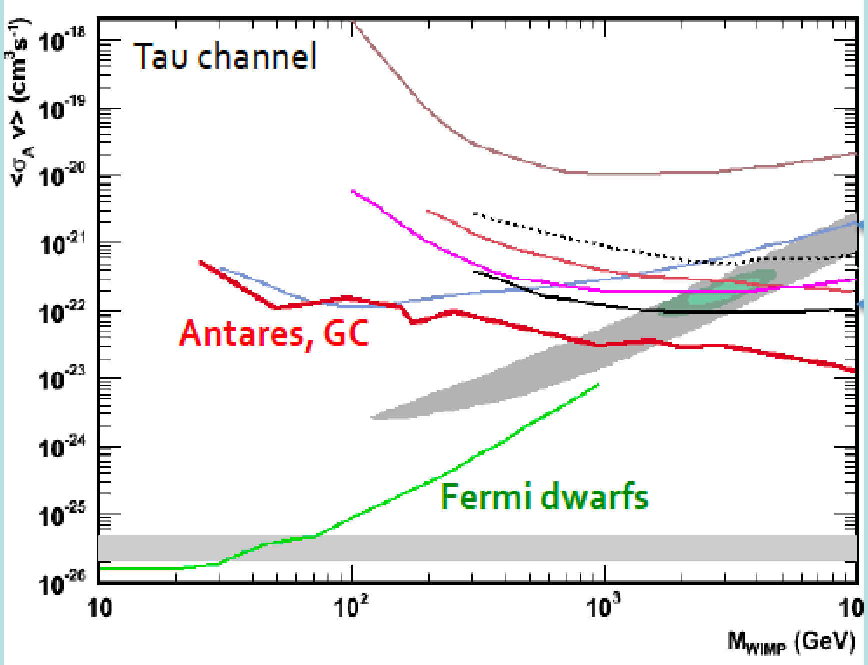
NB: Model dependence

Indirect Searches for Dark Matter

Sanchez Conde, Berge

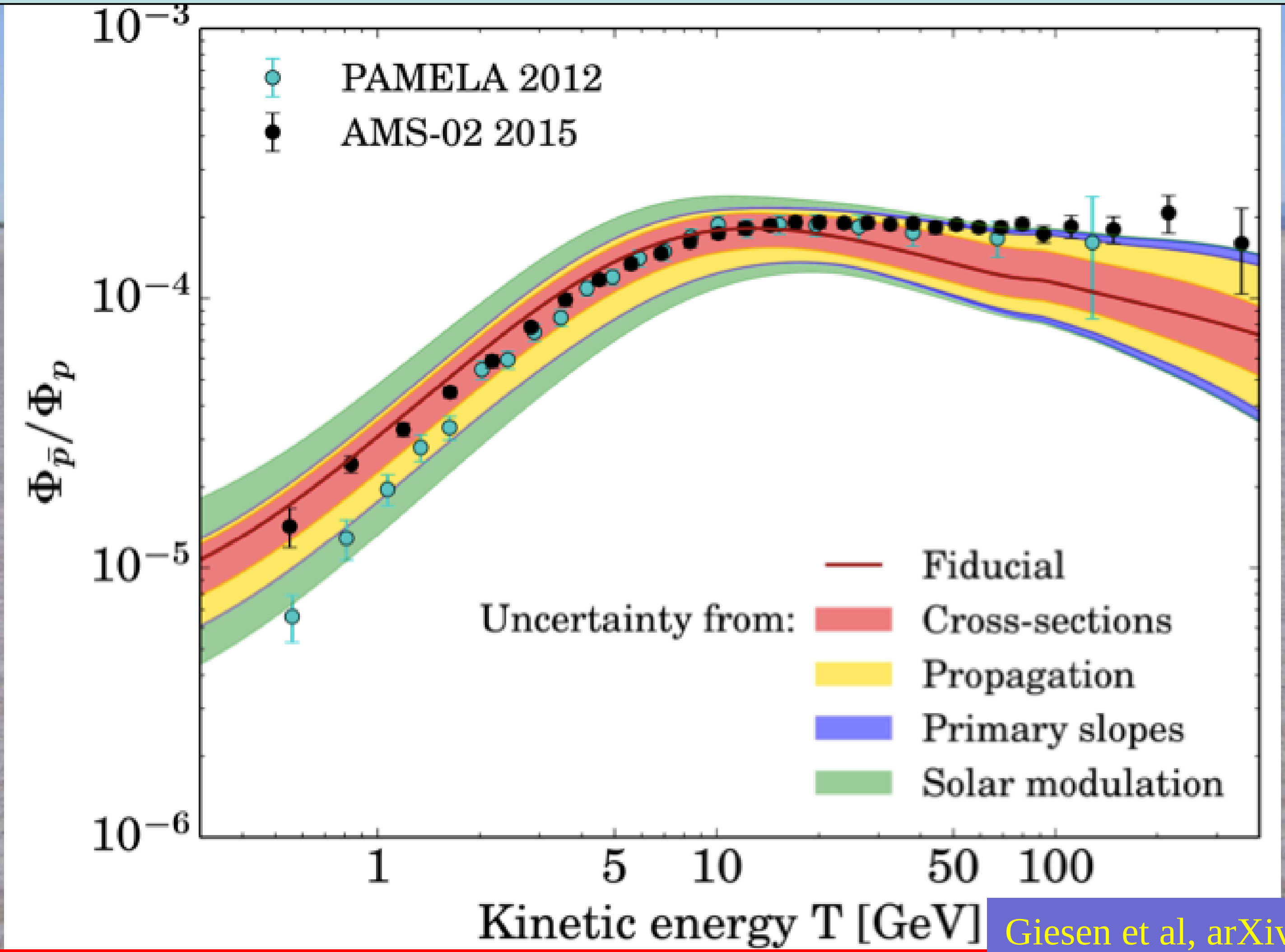
- Well-established GeV γ excess from Galaxy
  - **But could be unresolved point sources**





- Searches for γs from dwarfs reach dark matter σ
  - More sensitive than neutrino limits

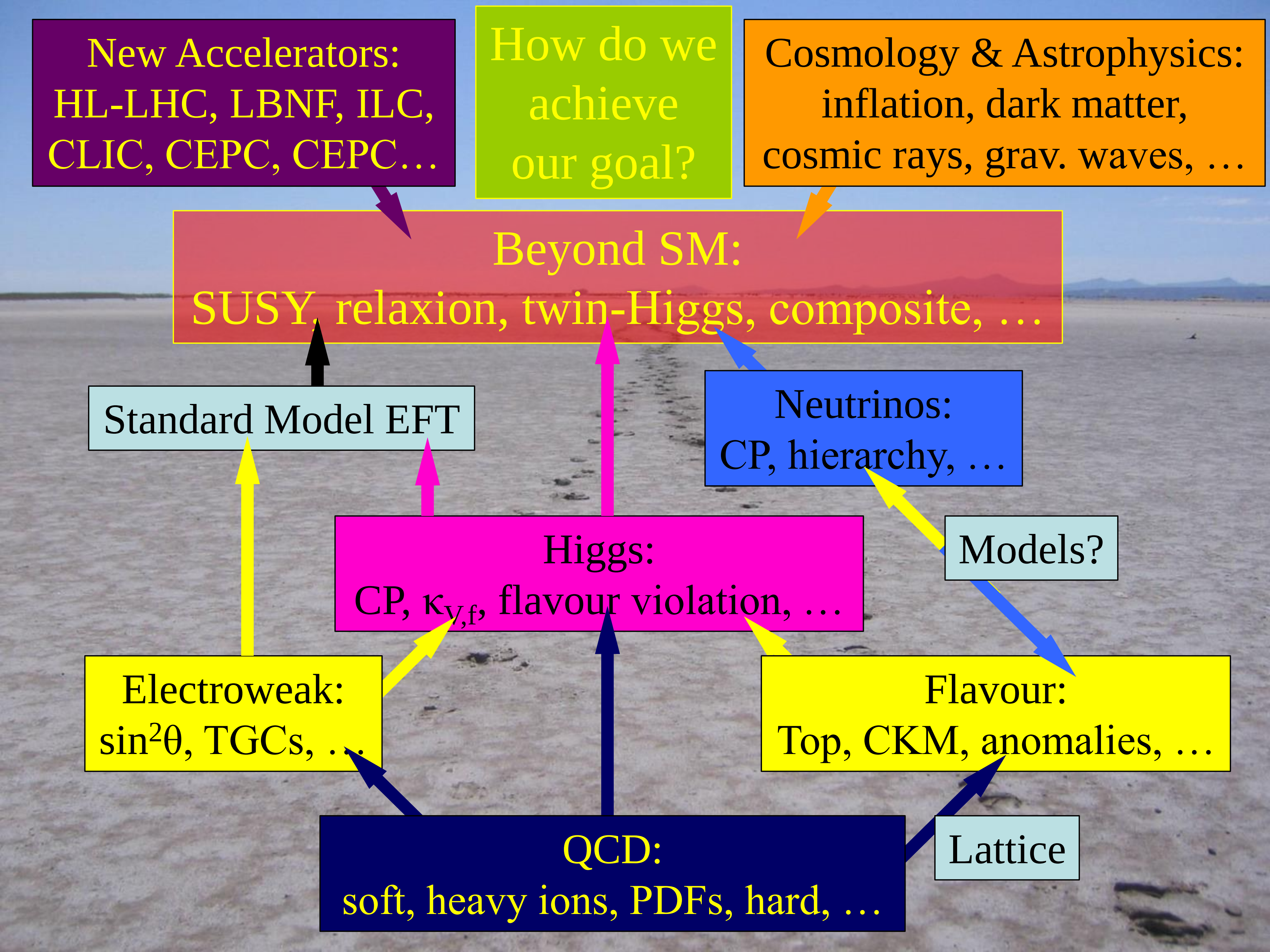
Antiproton/Proton Ratio



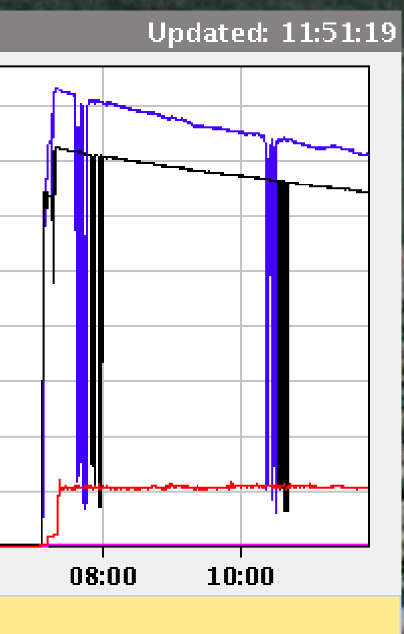
Li

Giesen et al, arXiv:1504.04274

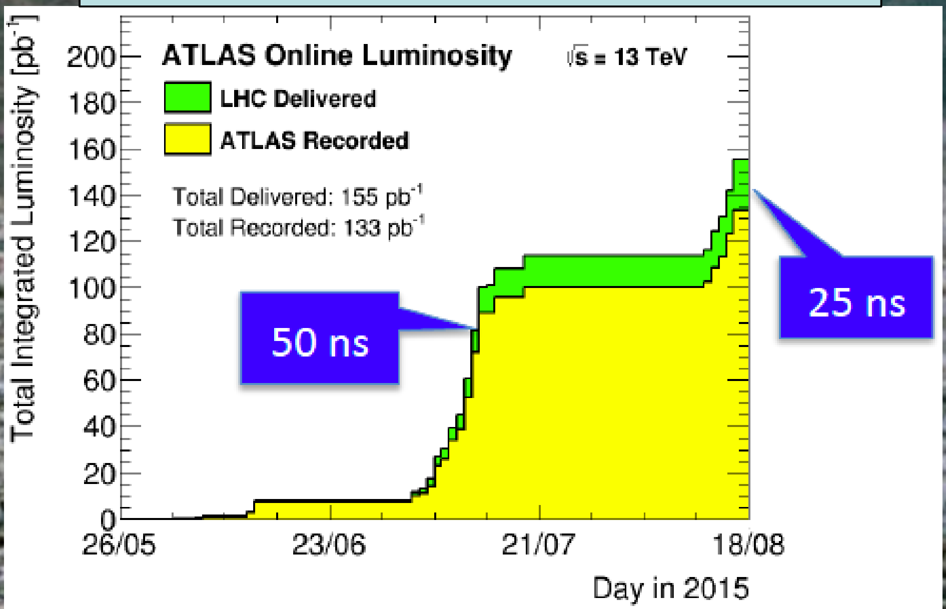
Secondary production compatible with AMS-02


New Accelerators:
HL-LHC, LBNF, ILC,
CLIC, CEPC, CEPC…
How do we
achieve
our goal?
Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM:
SUSY, relaxion, twin-Higgs, composite, …
Standard Model EFT
Neutrinos:
CP, hierarchy, …
Models?
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Flavour:
Top, CKM, anomalies, …
QCD:
soft, heavy ions, PDFs, hard, …
Lattice

Frustrations with SEUs in QPS, TDIs, UFOs, ULO, earth faults



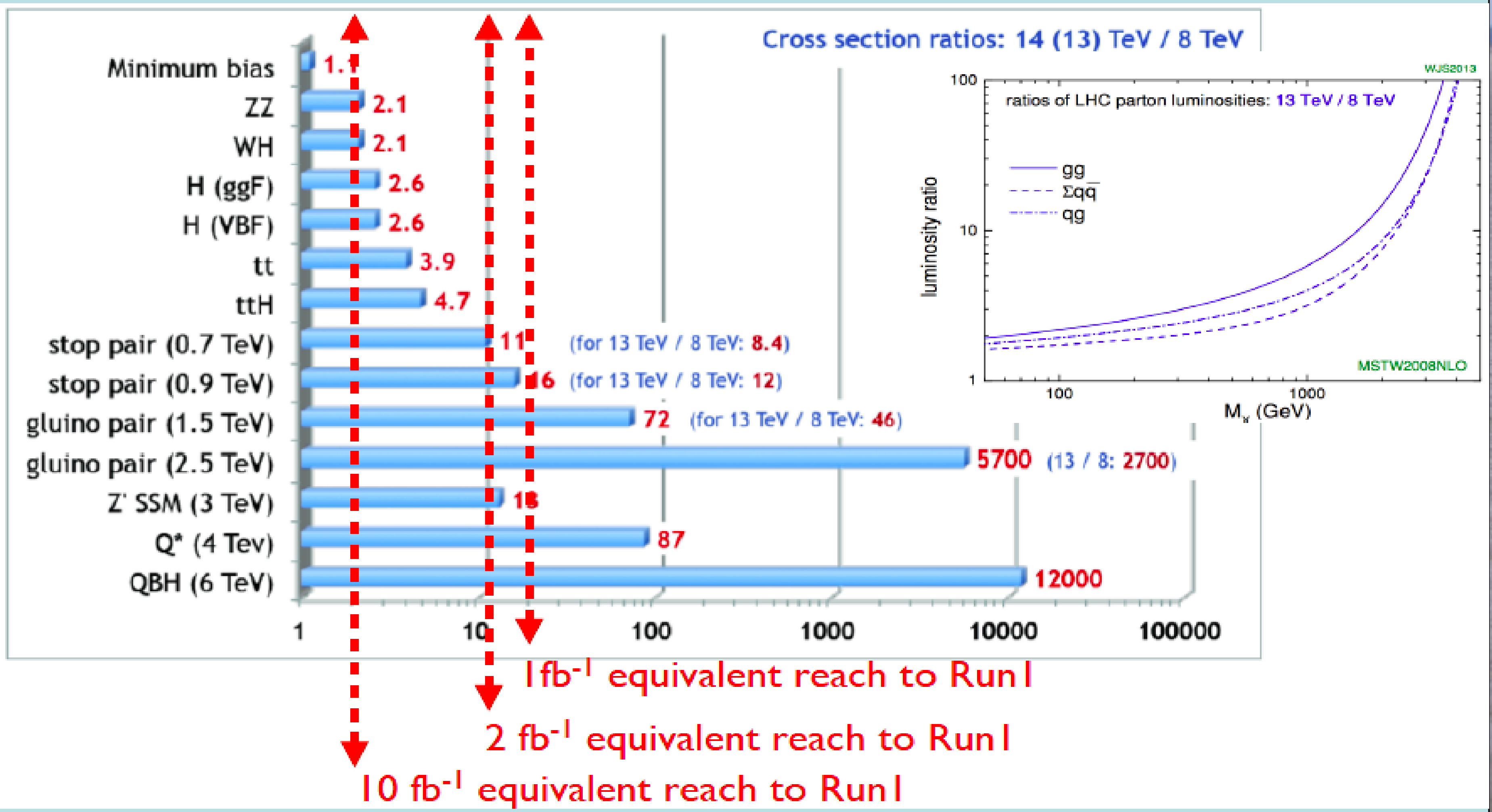
Sometimes the magic works



Why we are so excited by Run 2

Heinemann, Malgeri

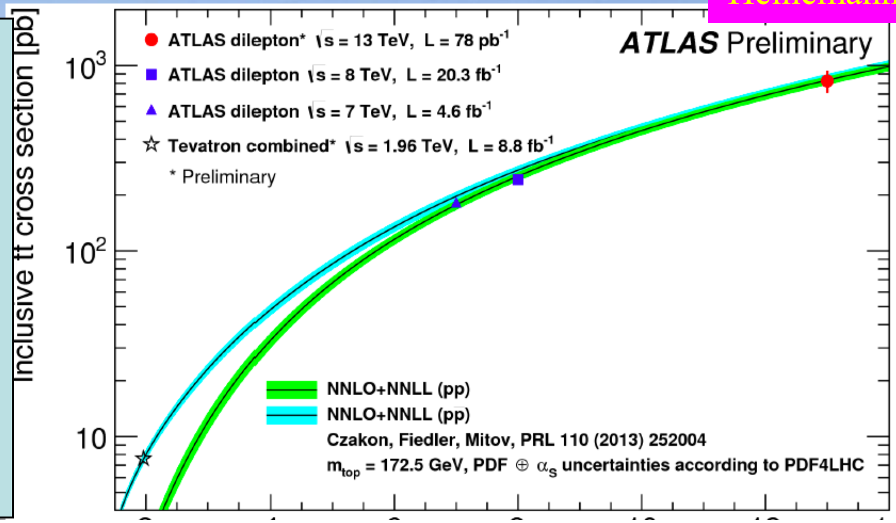
- Expected 2015 Luminosity explores new physics

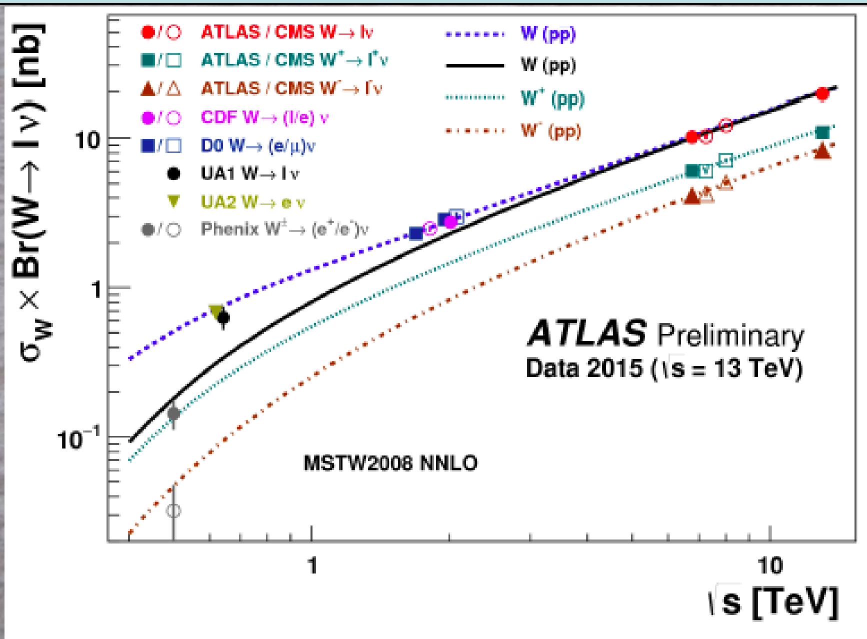


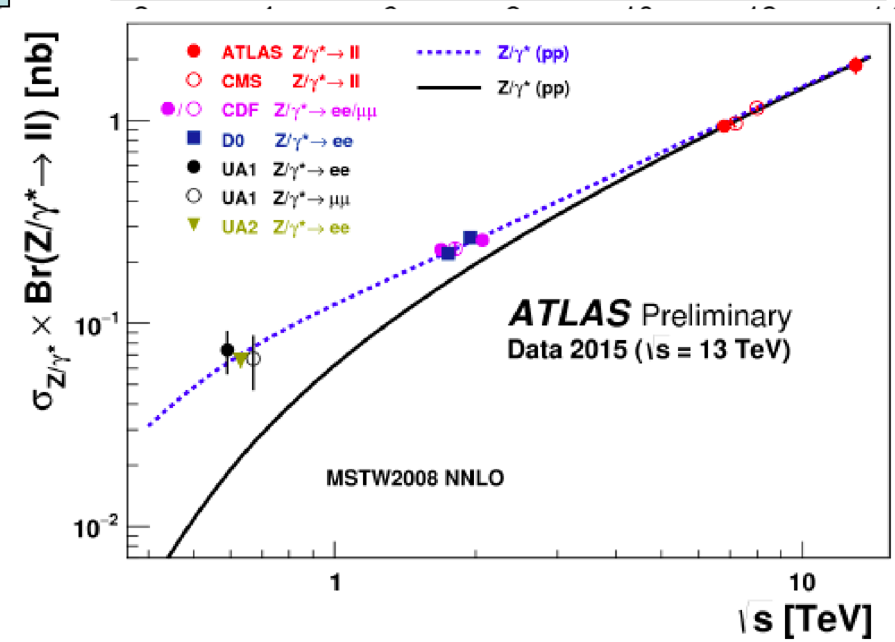
First ATLAS Results from Run 2

Heinemann

- In addition to many "softer" results:
  - Cross-sections for t tbar, W± and Z



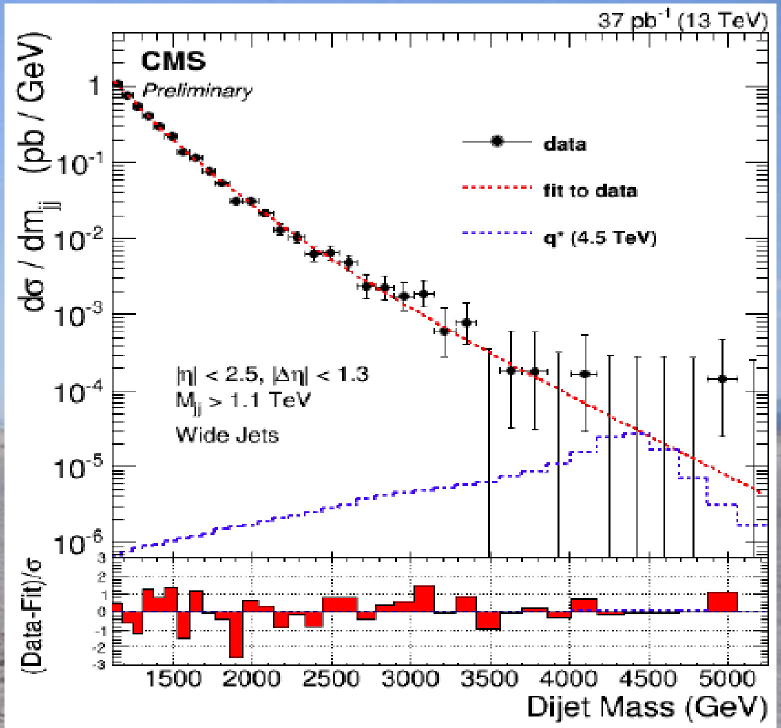


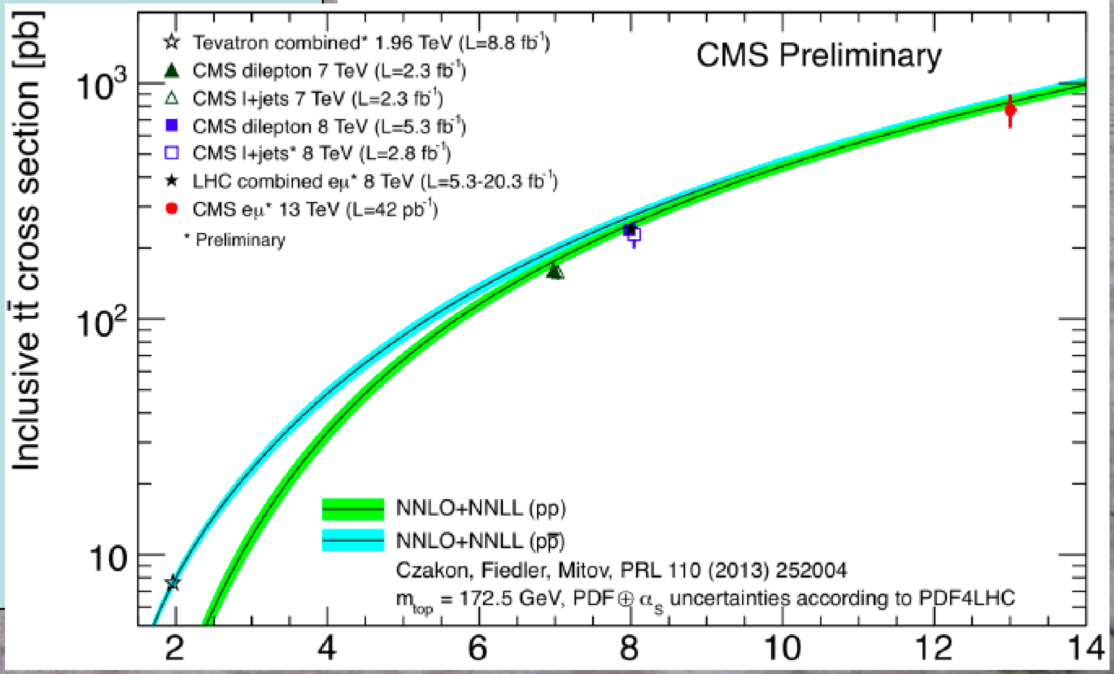


Malgeri

First CMS Results from Run 2

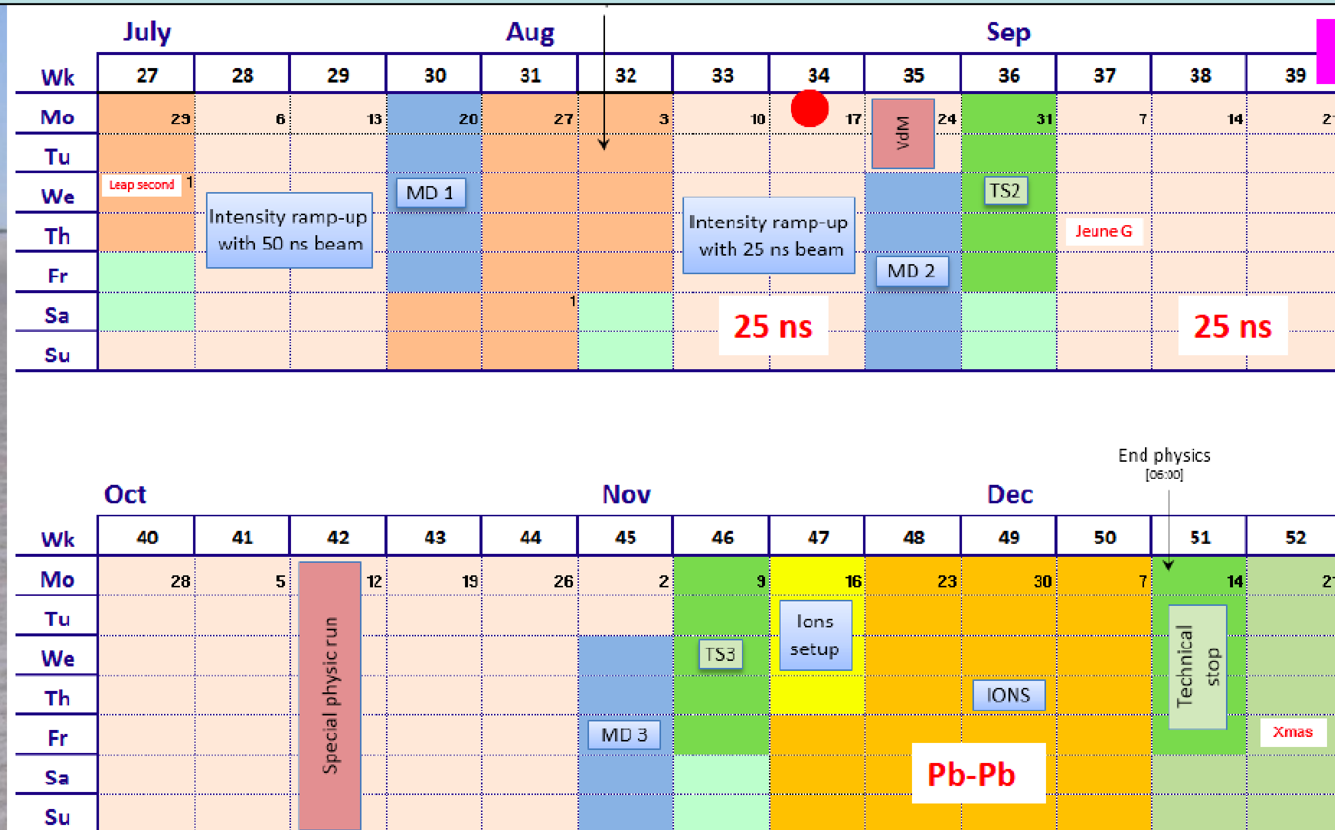
- In addition to many "softer" results:
  - Dijet mass distribution
  - Cross-section for t tbar





Prospects for Rest of 2015

Lamont

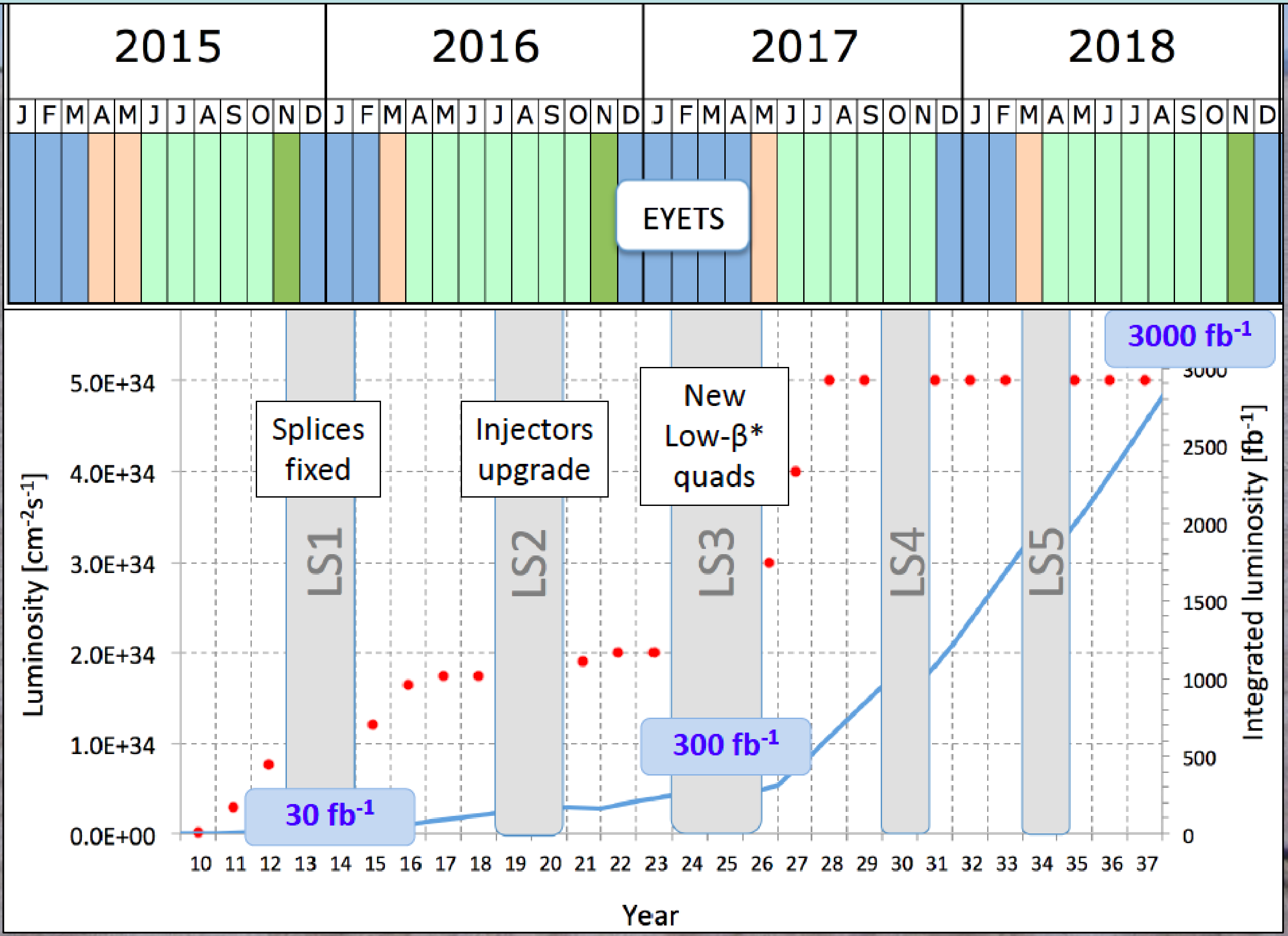


	Nc	Beta *	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	476	80	1.1e11	1.8	1.6e33	14	0.1 fb^{-1}	27
2015.1	1200	80	1.2e11	3.5	3.6e33	50	~2.3 fb^{-1}	21
2015.2	1200	60	1.2e11	2.3	5.6e34	47	~3.4 fb^{-1}	33

And in Future Years

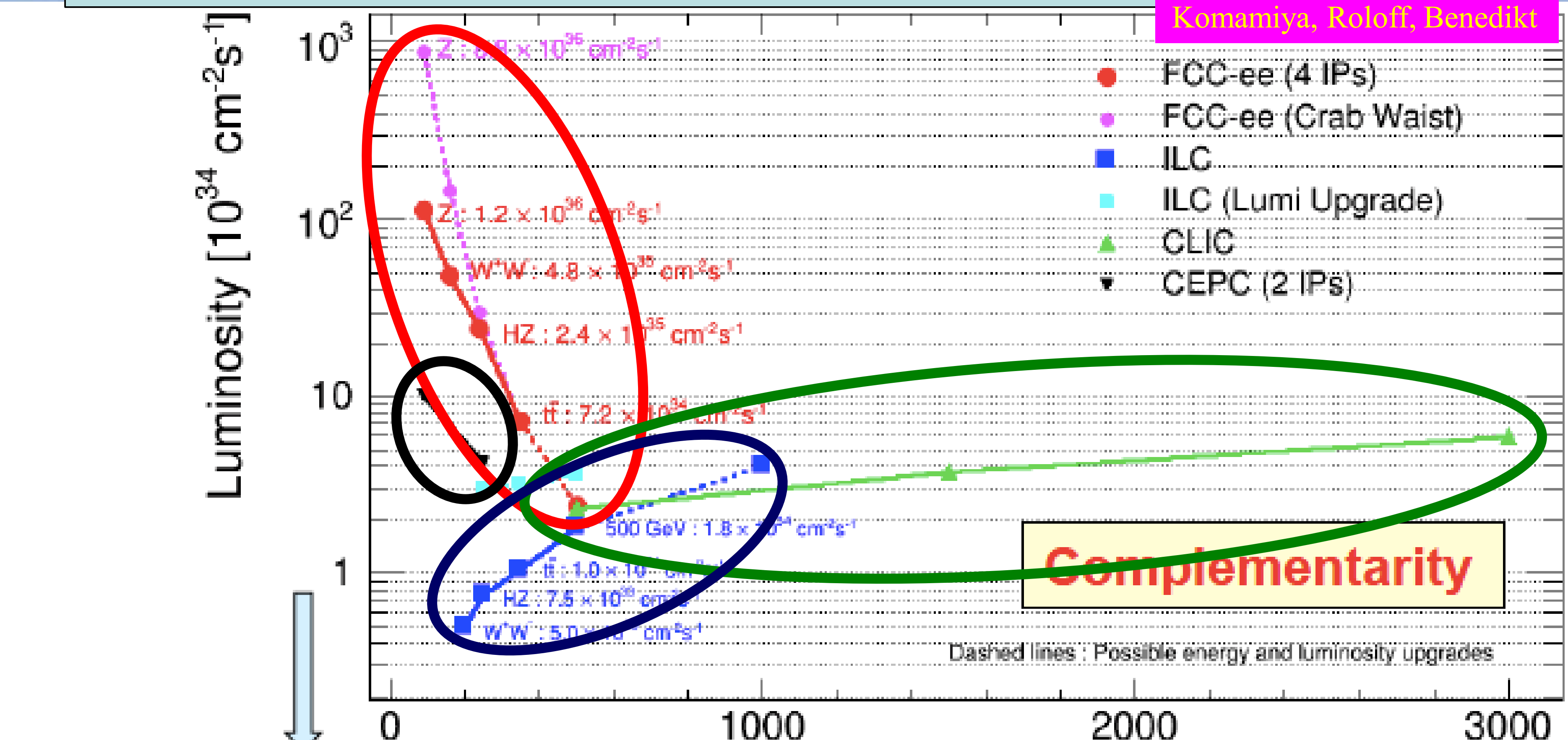
Lamont

- Present limitations not seen as fundamental



Projected e^+e^- Colliders: Luminosity vs Energy

Komamiya, Roloff, Benedikt



LEP: 0.001 – 0.0

Prioritize energy or luminosity at low E?
LHC Run 2 will guide us

Benedikt

FCC hh ee he

CEPC-SPPC

Preliminary Conceptual Design Report

Future Circular Colliders

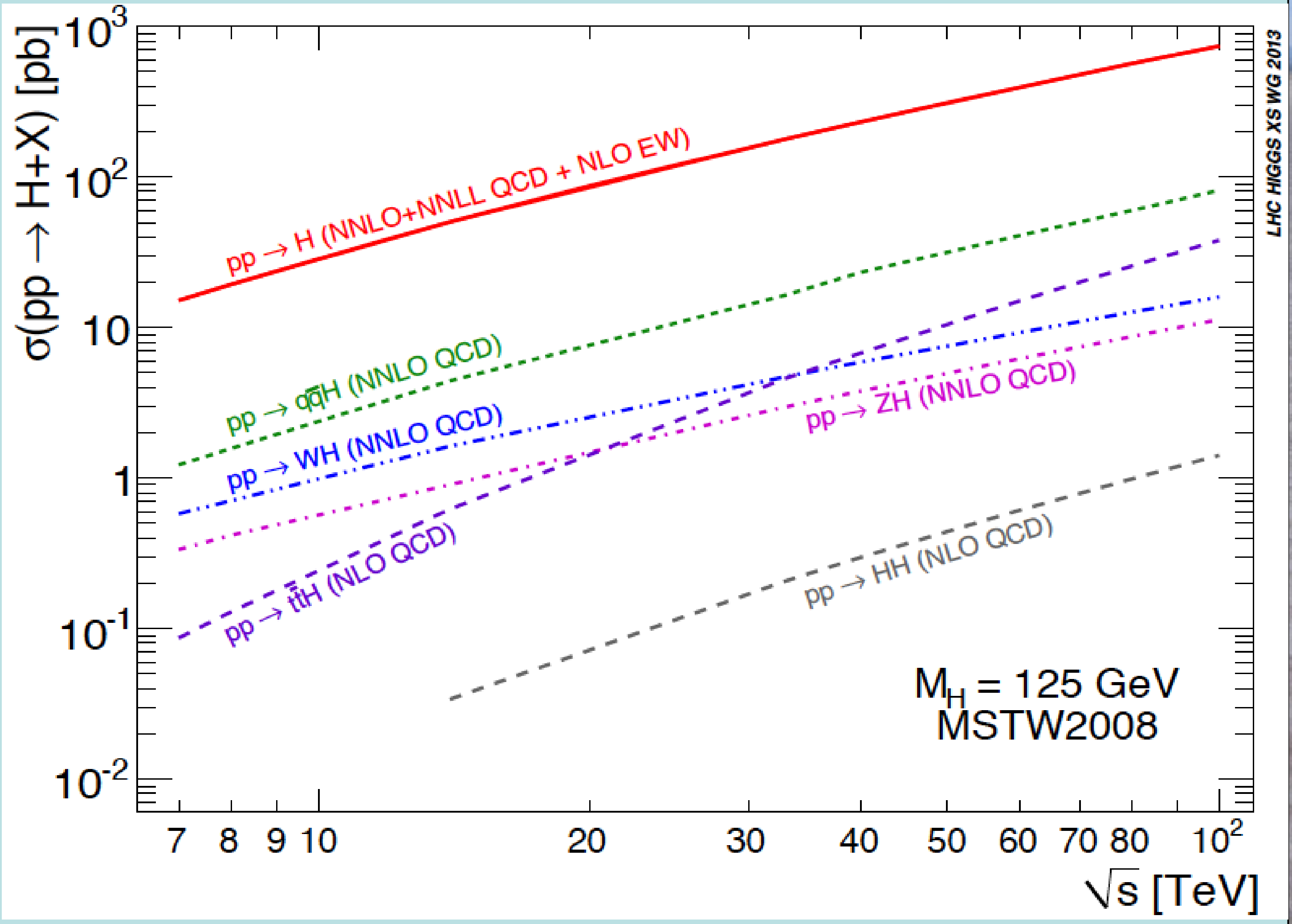
The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Higgs Cross Sections

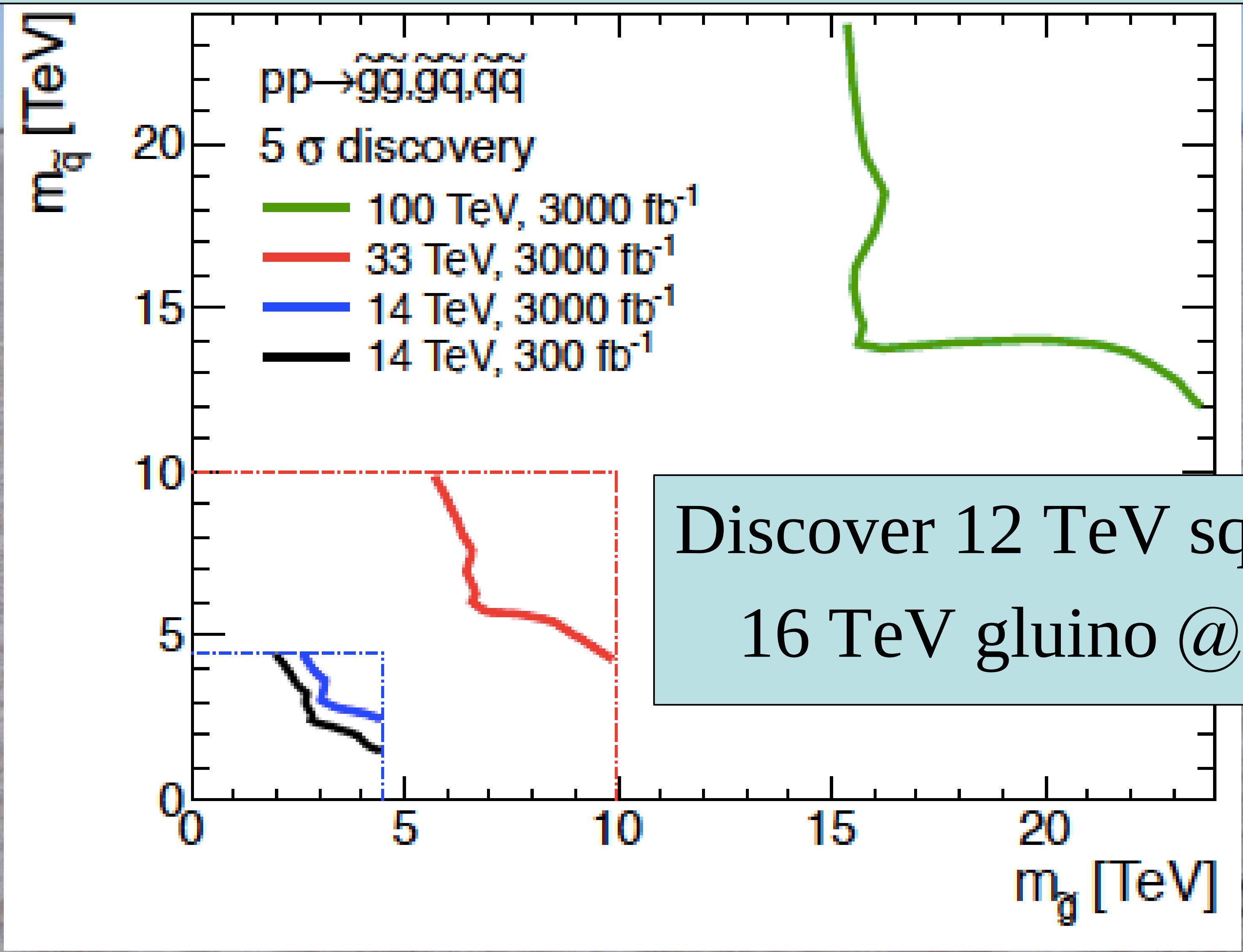
Benedikt

- At the LHC and beyond:



Squark-Gluino Plane

Benedikt



Discover 12 TeV squark, 16 TeV gluino @ 5σ

New Accelerators:
HL-LHC, LBNF, ILC, CLIC, CEPC, CEPC…

How do we achieve our goal?

Cosmology & Astrophysics:
inflation, dark matter, cosmic rays, grav. waves, …

Beyond SM:
SUSY, relaxion, twin-Higgs, composit

Standard Model EFT

Neutrinos
CP, hierarchy

Higgs:
CP, $\kappa_{V,f}$, flavour violation, …

New regions
New generations

Electroweak:
$\sin^2\theta$, TGCs, …

Flavour:
Top, CKM, anomalies, …

QCD:
soft, heavy ions, PDFs, hard, …

Lattice