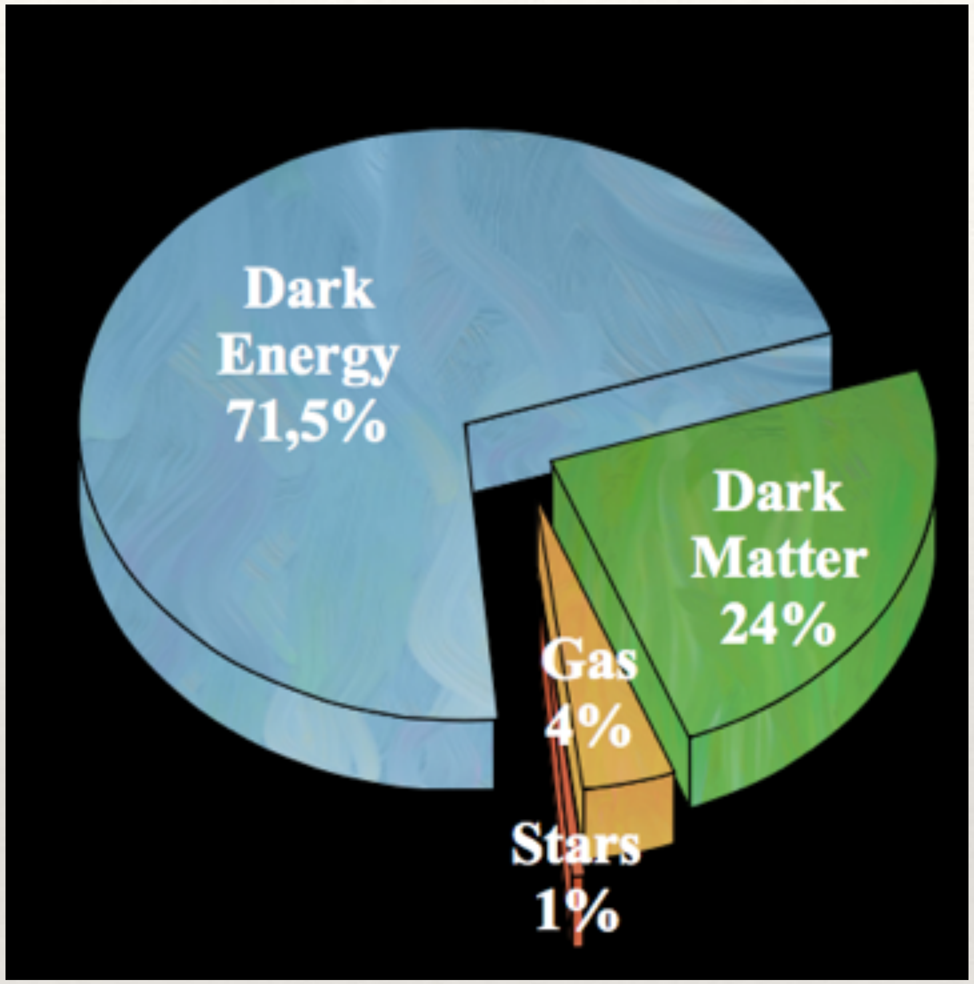
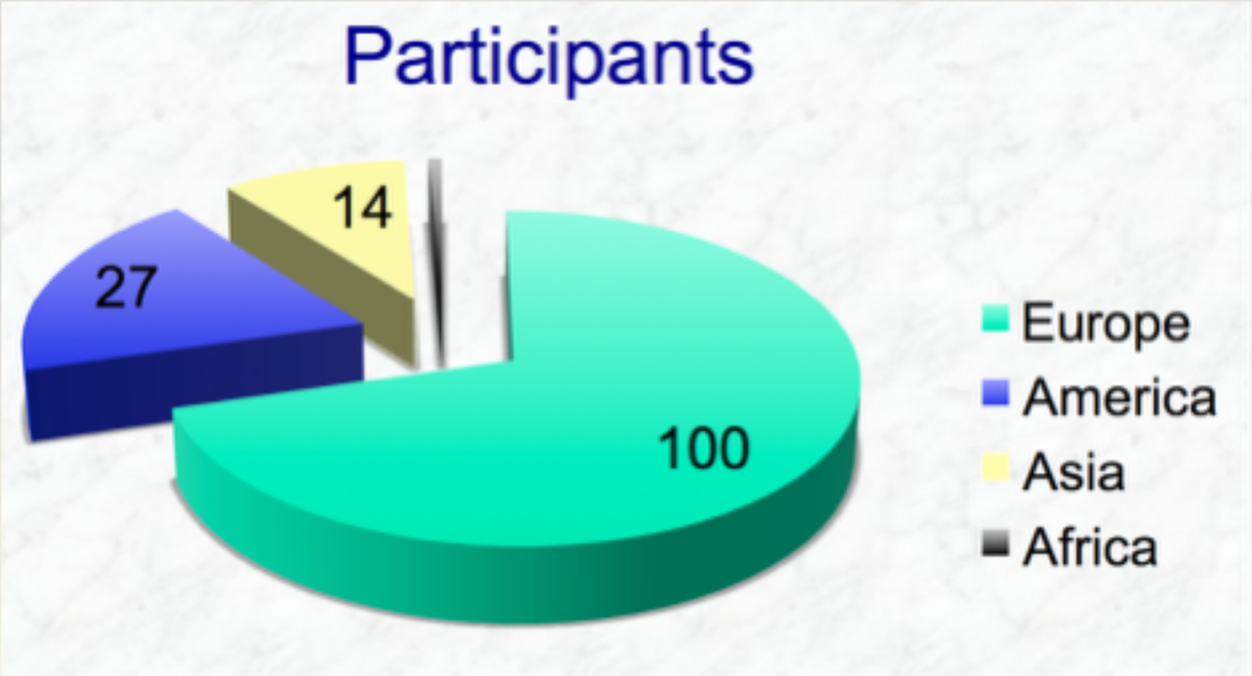
Summary

Gavin Salam (CERN)

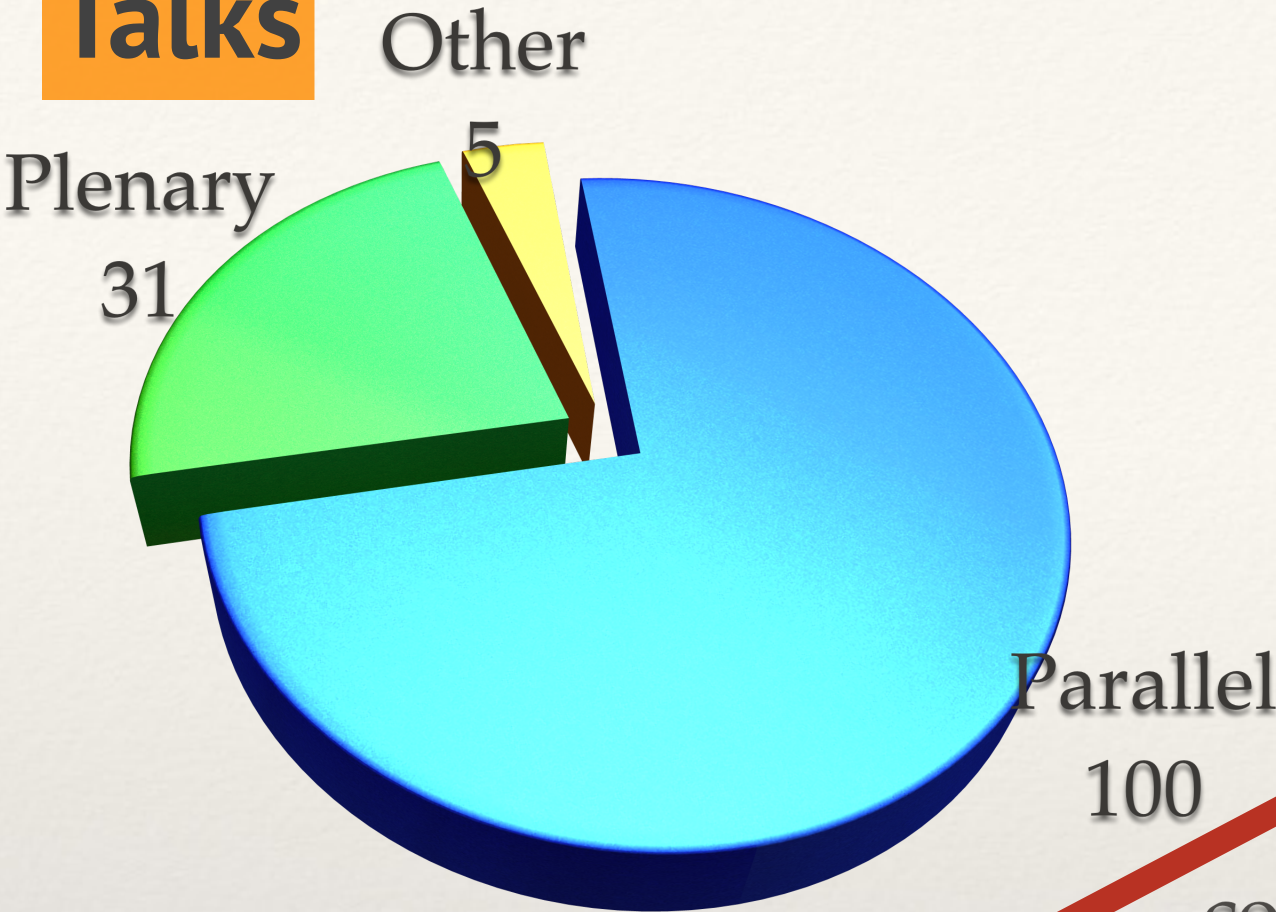
Numbers

Jakobs

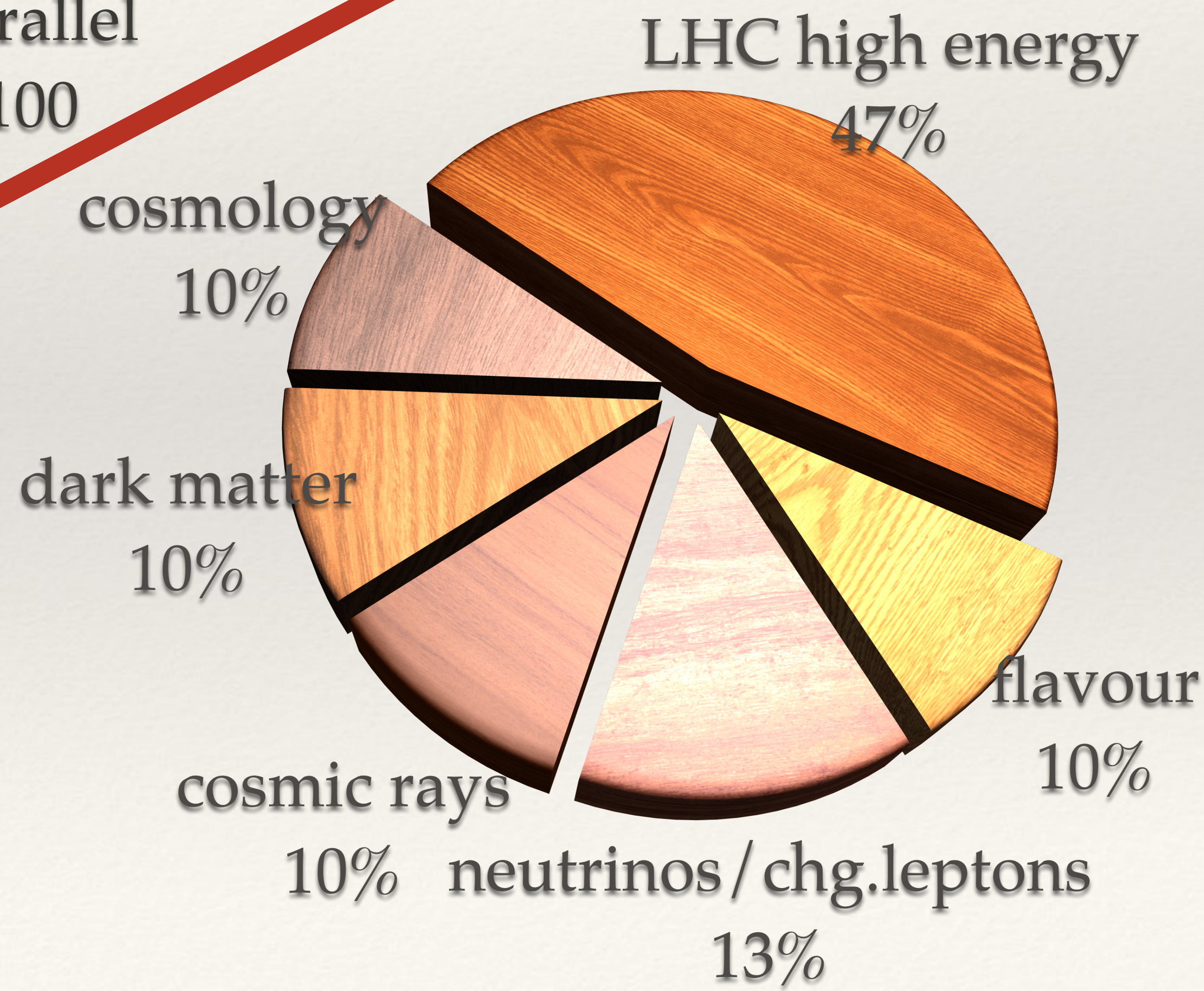


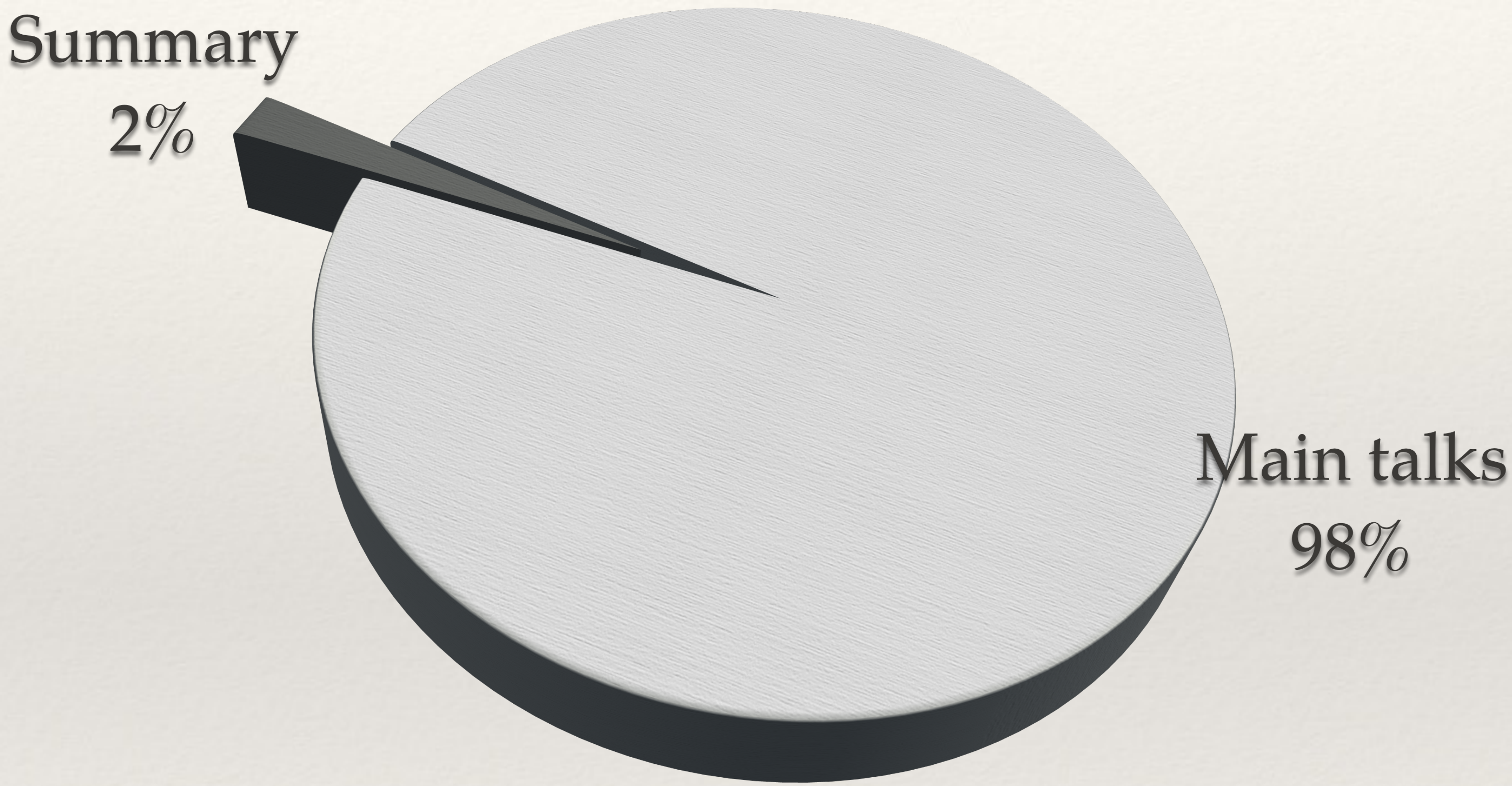


Talks



Plenary subjets

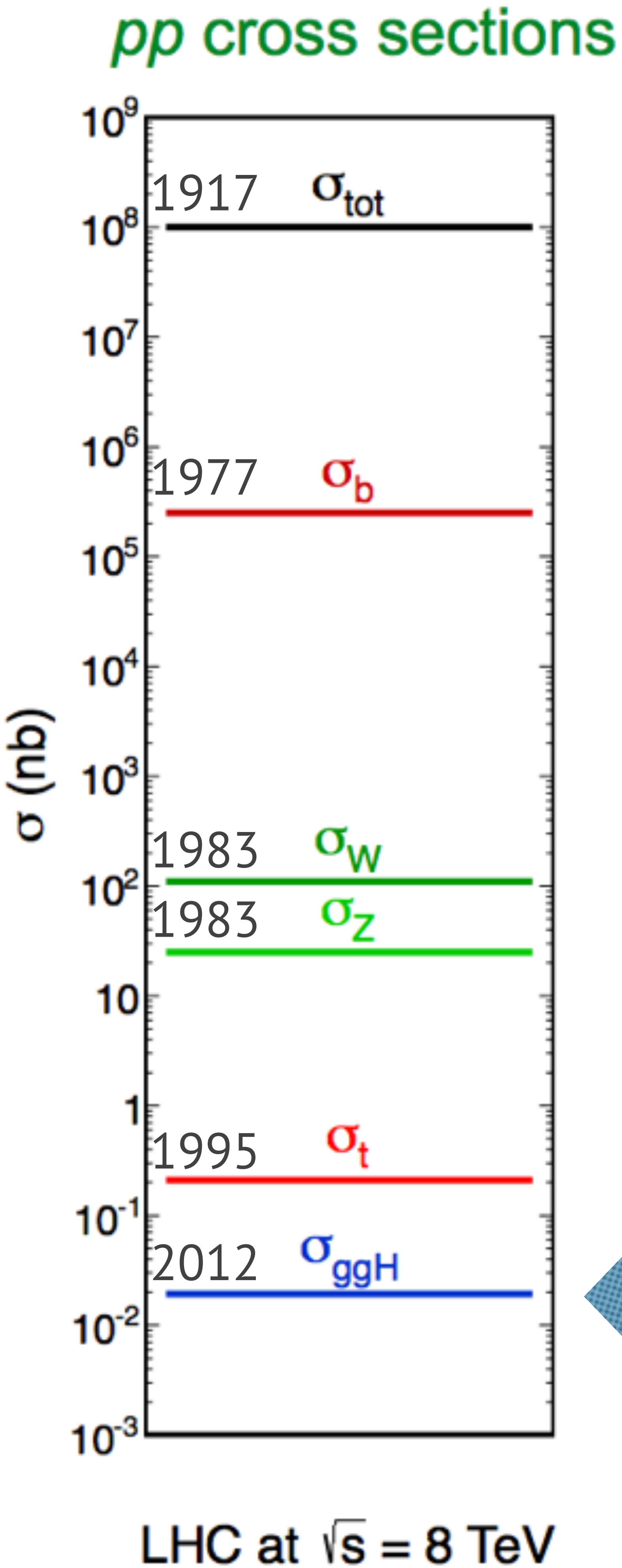


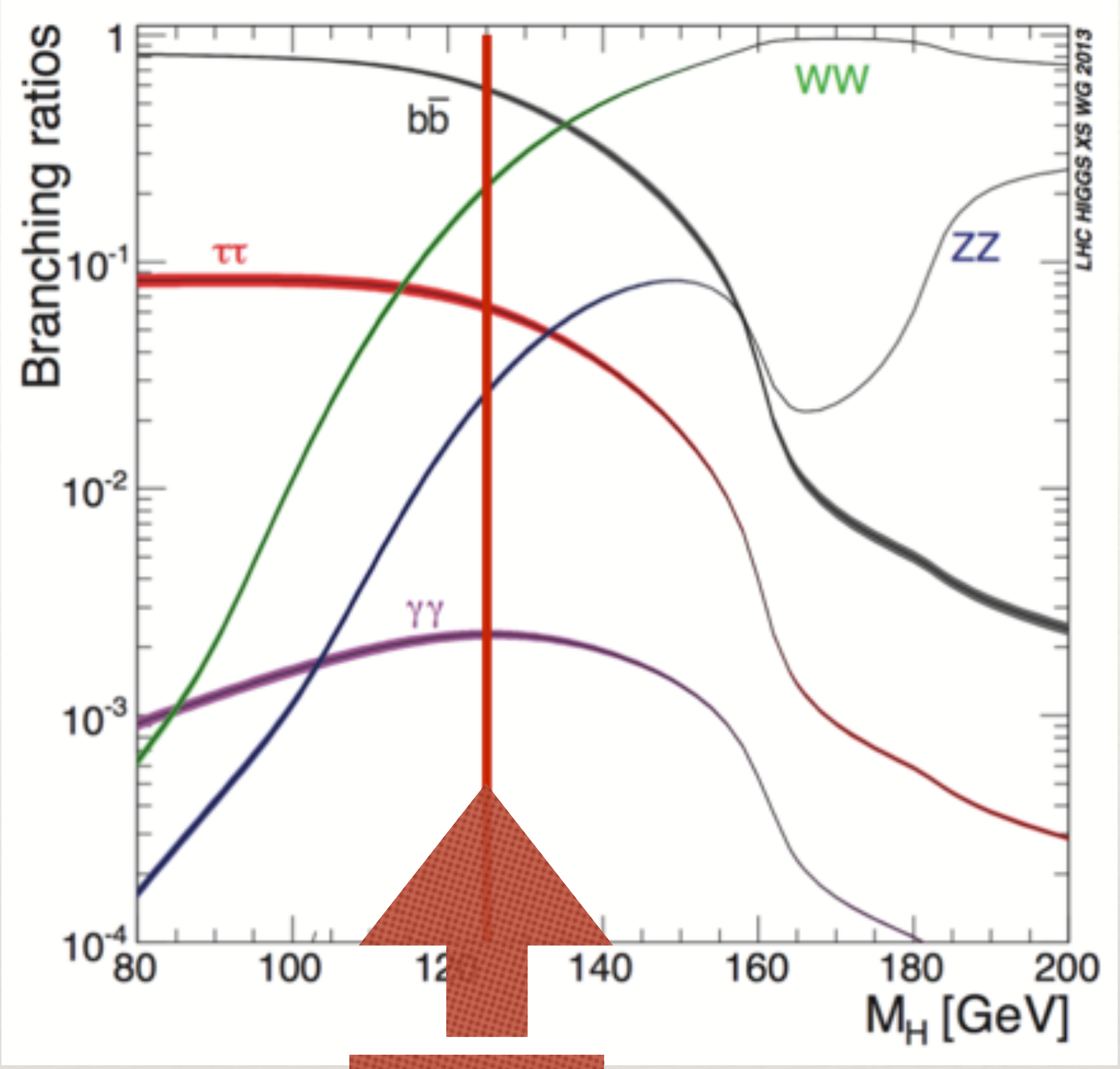

Summary
2%
Main talks
98%

Higgs

barely 3 years old

Peters



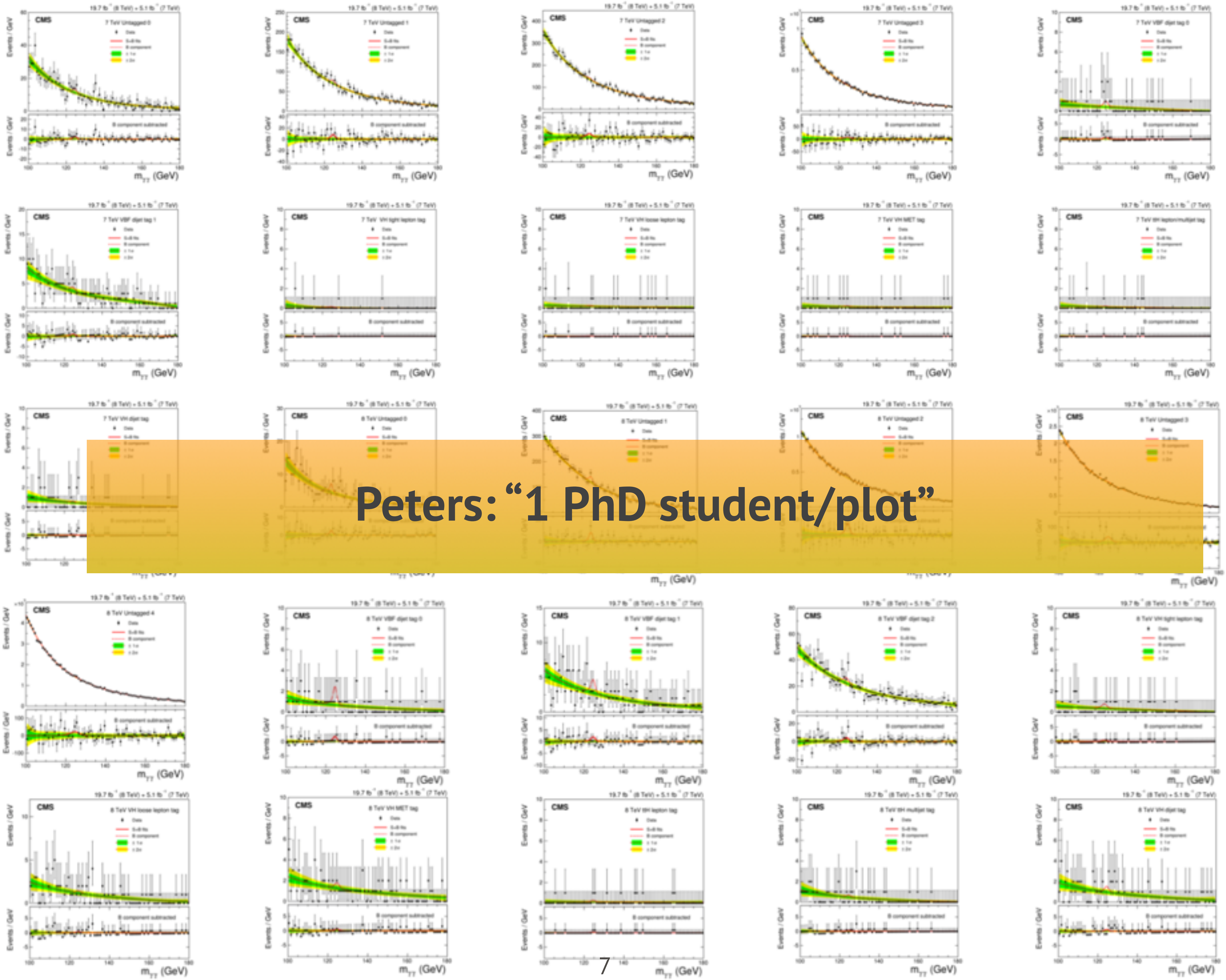


decay

Higgs

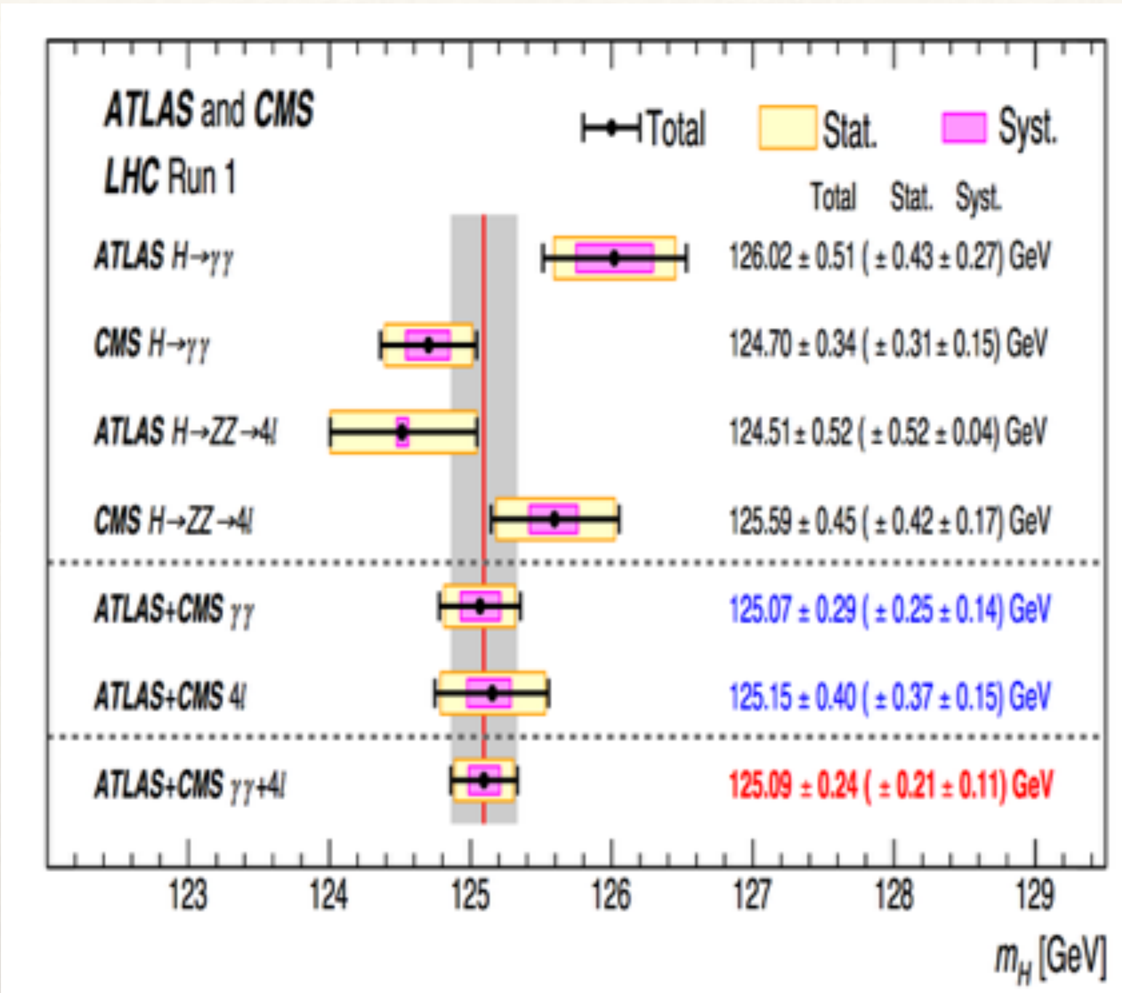
production

The small cross section works against us but the mass is as interesting as could be

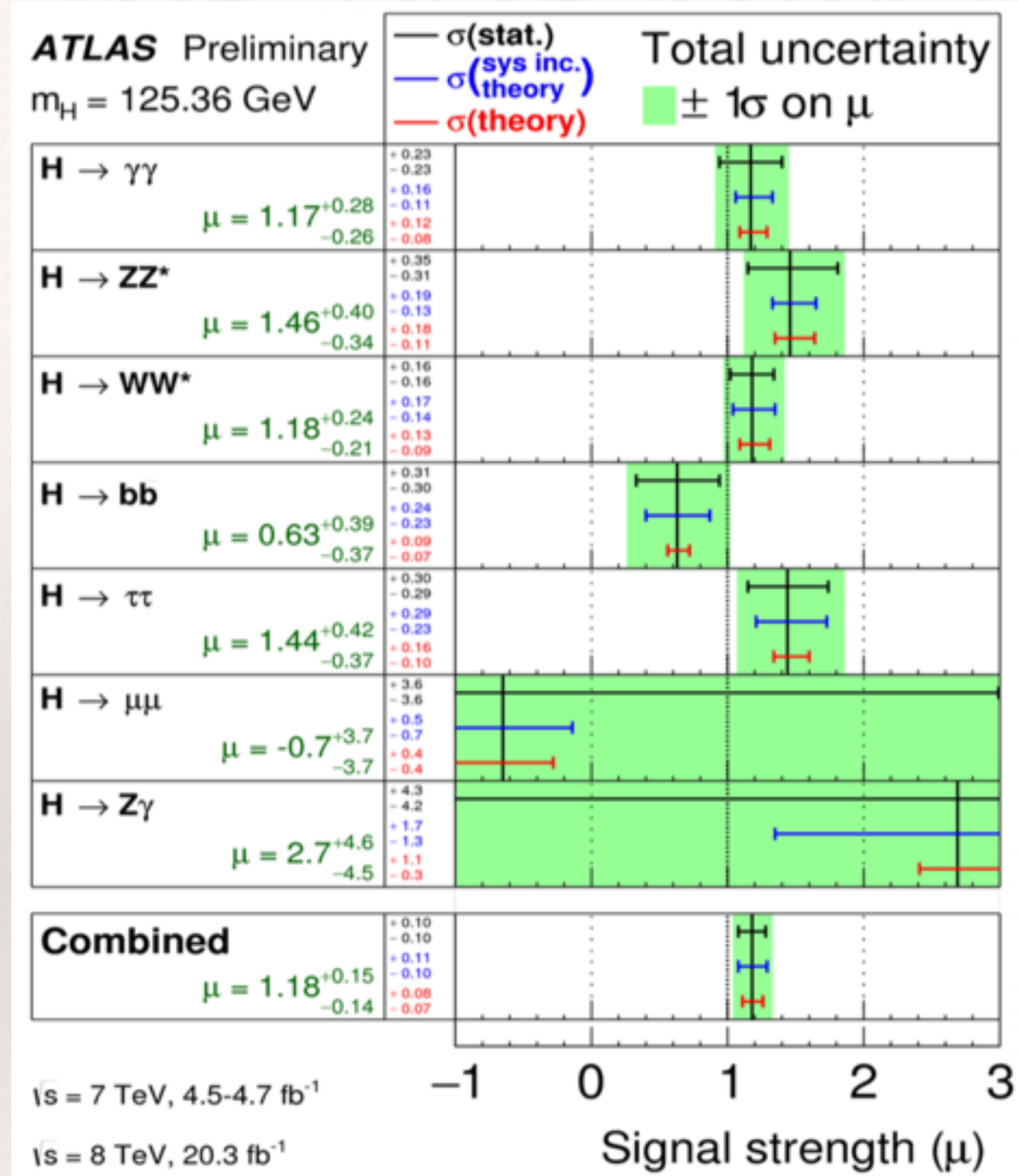


Peters: “1 PhD student/plot”

Mass: known to ~ 0.2%



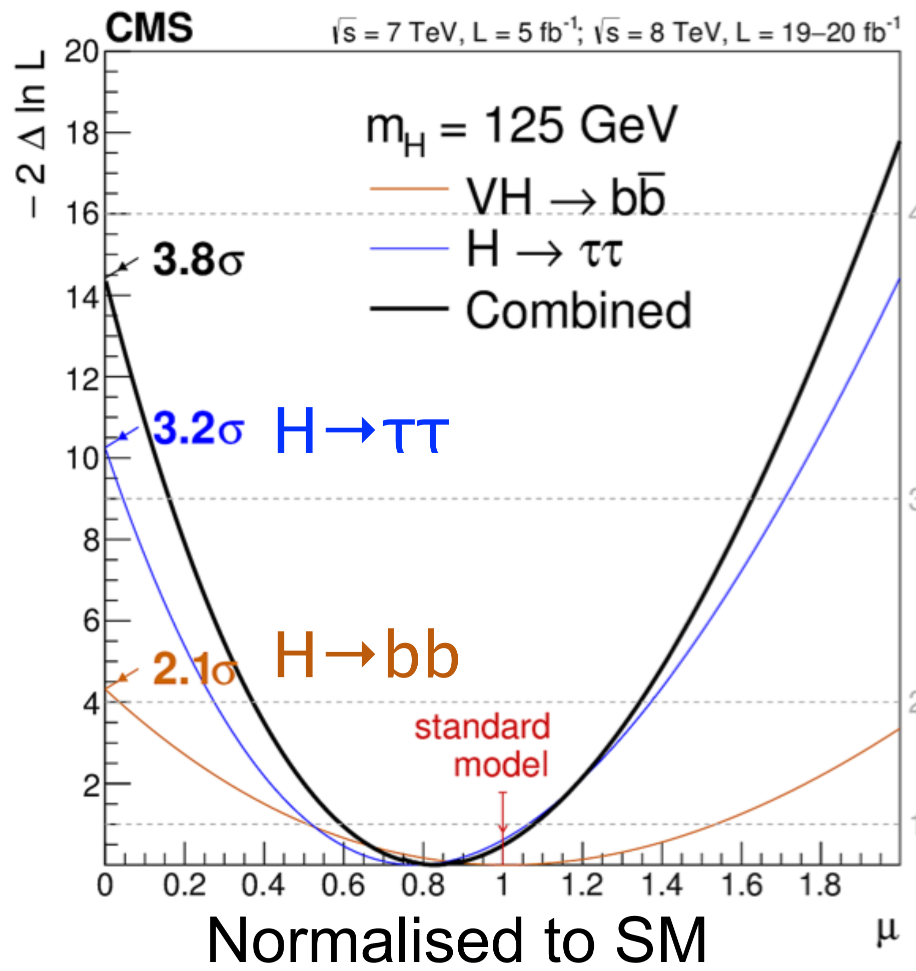
decay "BRs" to 20–40%

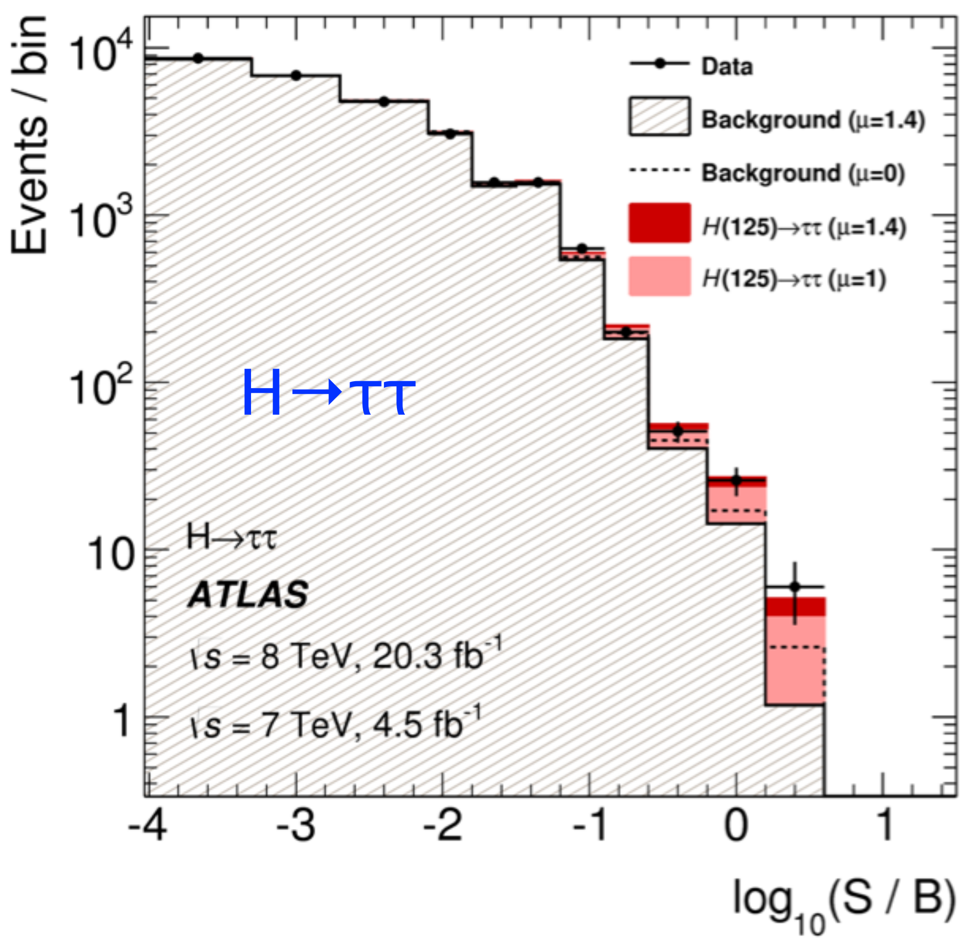


- spin-parity 0^+ consistent with data
  - alternative J^P hypotheses excluded at the 99.9% CL

Direct evidence for Higgs-fermion (Yukawa) coupling

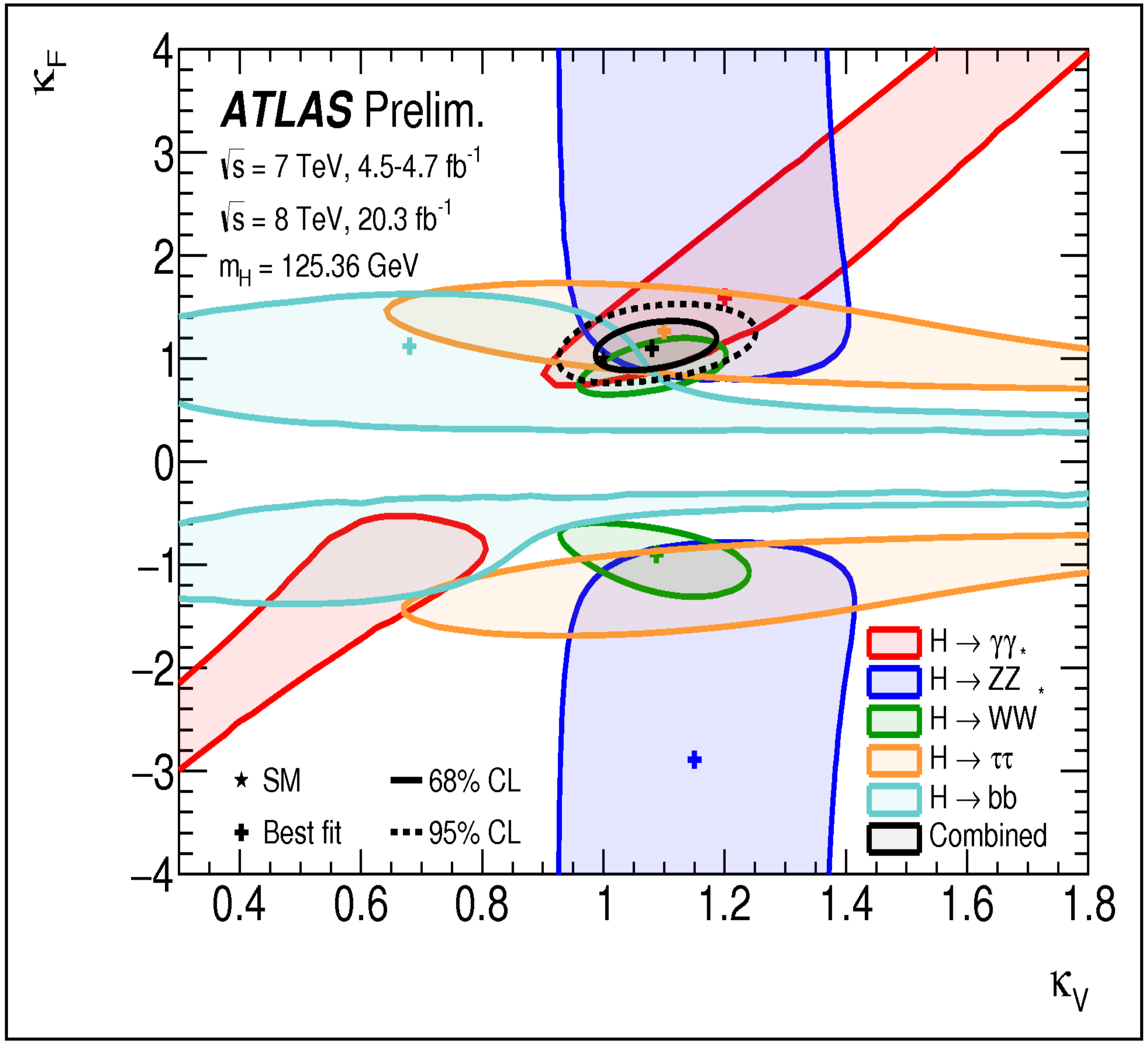
Evidence for Higgs-Yukawa coupling

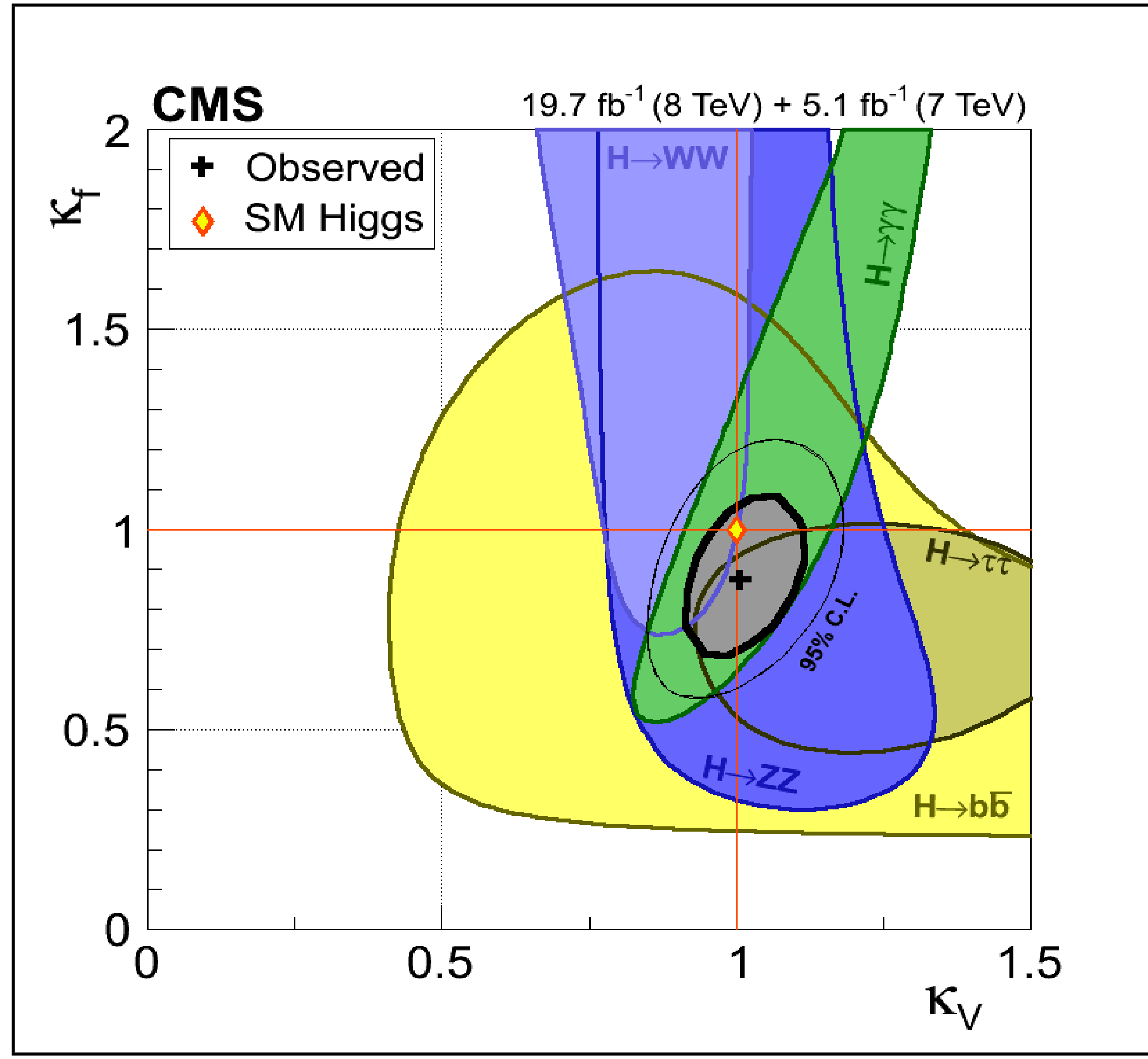




A fundamental part of the Standard Model

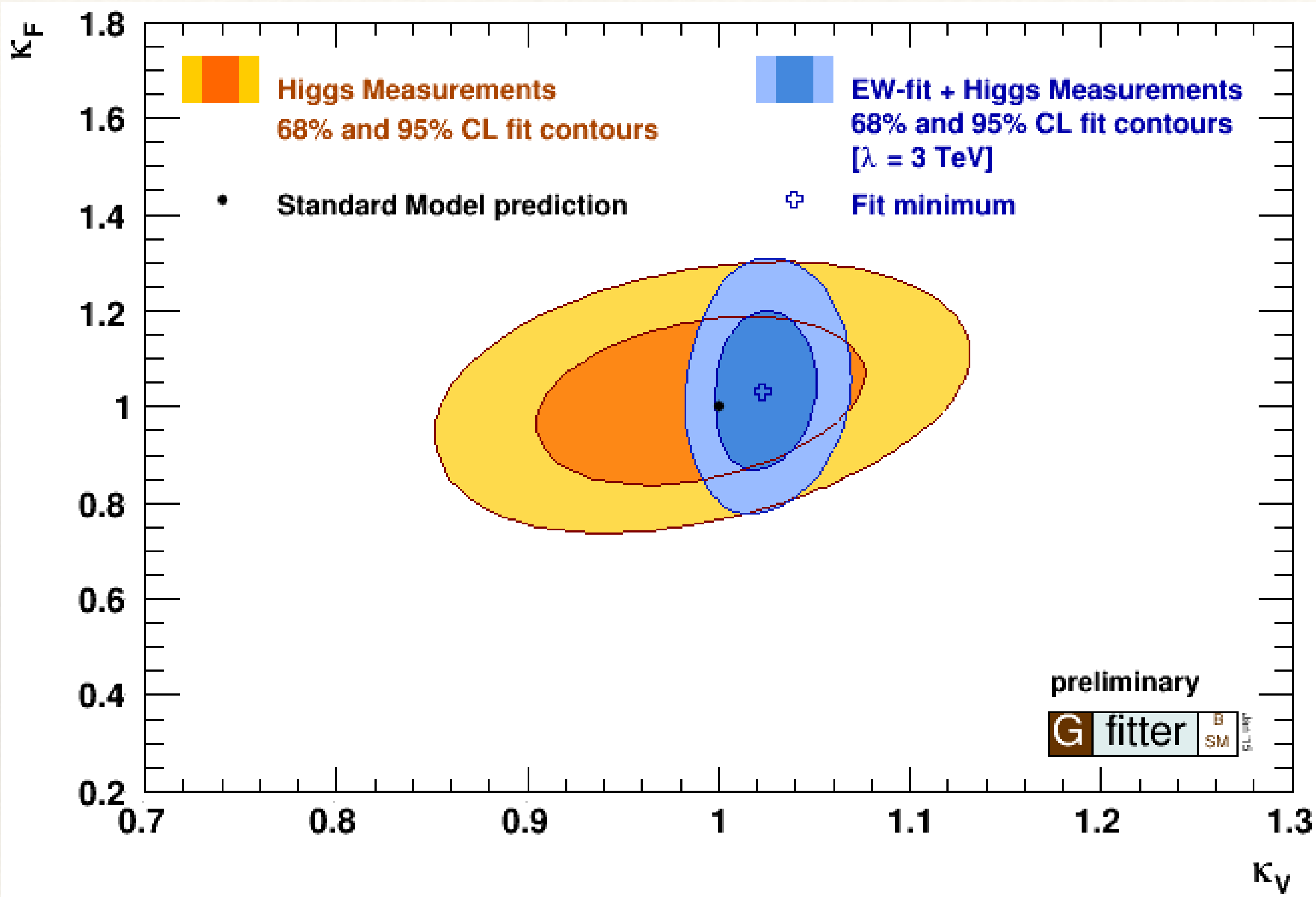
fermion v. vector couplings





Gomez

Direct & EWK prec^{n} Higgs fits

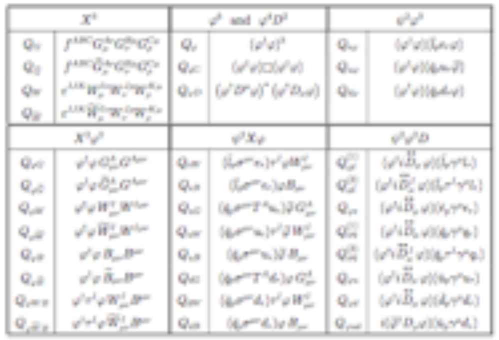


Peiffer

Direct measurements bring most information on fermion couplings

Rosetta Stone

Massò



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

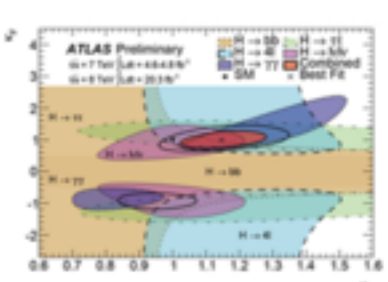
Table 2: Dimension-six operators other than the four-fermion ones.

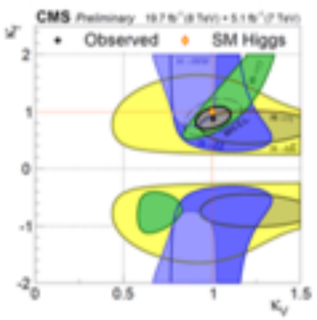
d=6 operators

Looking for a clear relation

Experimental measurements

$\kappa_i \equiv g_i / g_i^{SM}$





Higgs:
theory calculations

K. Peters & G. Gomez:

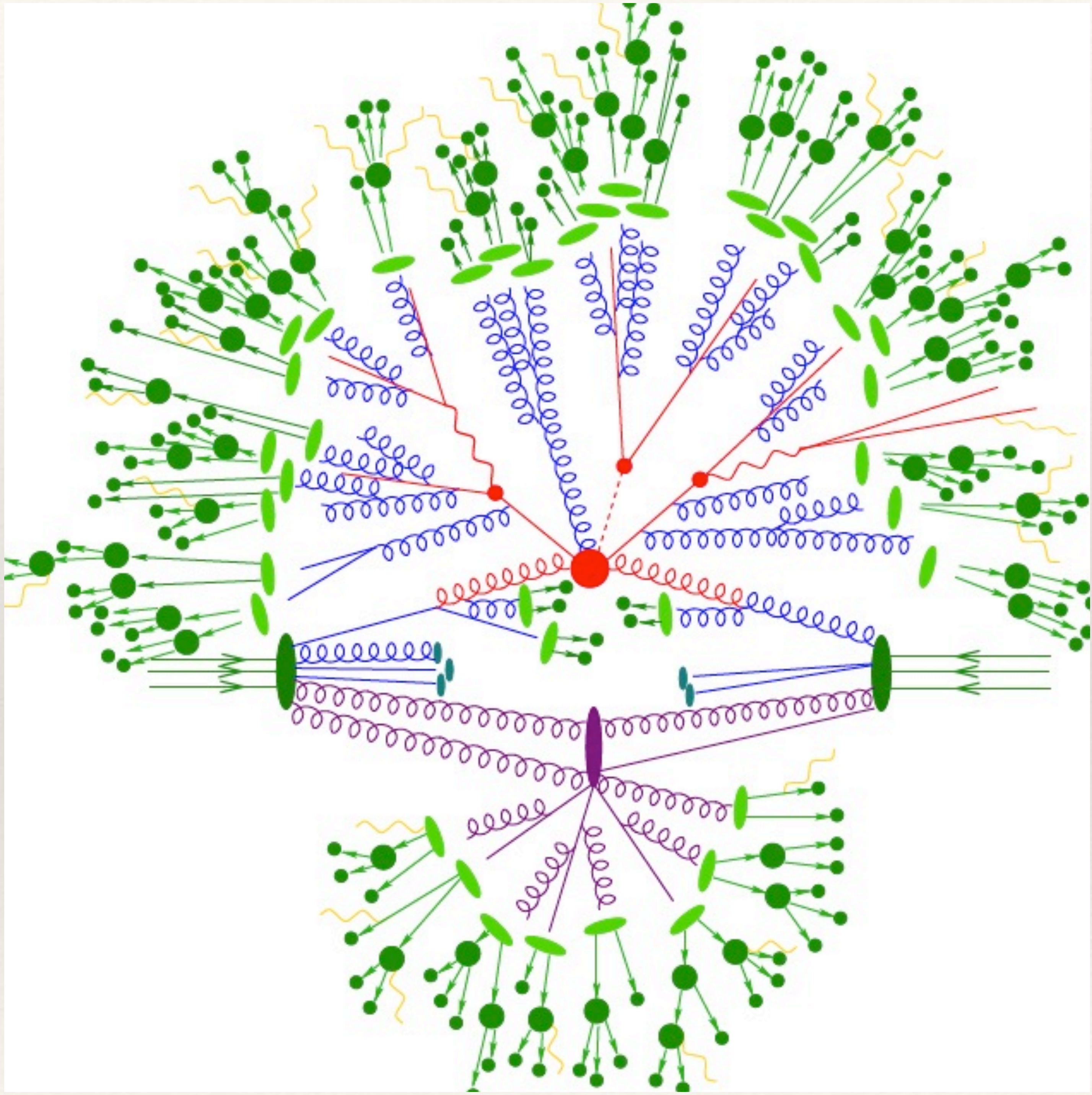
“[we are] at the point where systematics from theory and from experiment are on the same level”

ATLAS: $\mu = 1.18 \pm 0.10\ (stat.) \boxed{\pm 0.07}\ (exp.\ syst.) \boxed{\pm 0.08}\ (theo.\ syst.)$

CMS: $\mu = 1.00 \pm 0.09\ (stat.) \boxed{\pm 0.07}\ (exp.\ syst.) \boxed{\pm 0.08}\ (theo.\ syst.)$

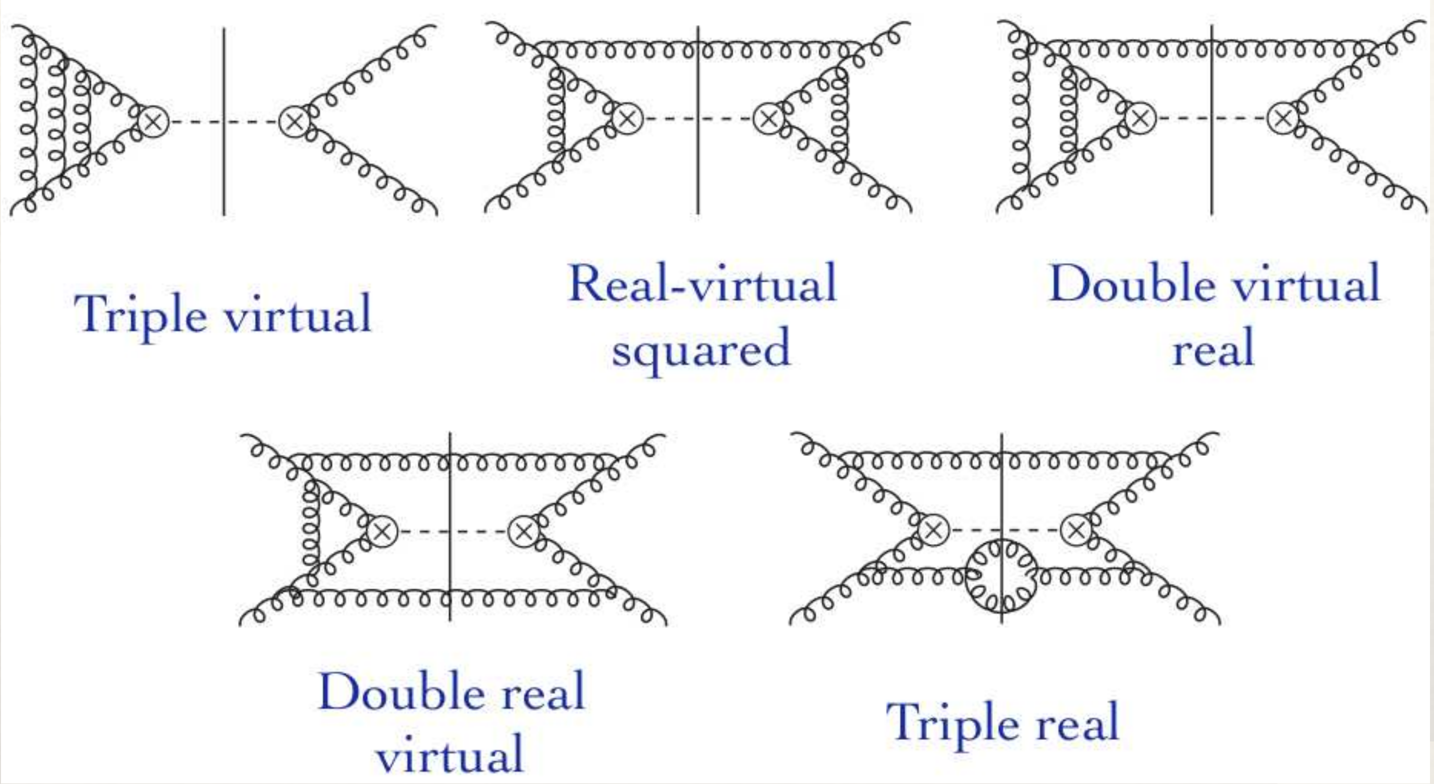
QCD @ LHC is work in progress

A mixture of **rigorous prediction** (perturbation theory, resummation), **measured inputs** (strong coupling, PDFs) and **semi-controlled modelling** (assembly of pieces & non-perturbative hadron-scale physics).



Milestone calc$^{\mathrm{n}}$: Higgs @ NNNLO

- full NNNLO cross section Anastasiou et al. '15

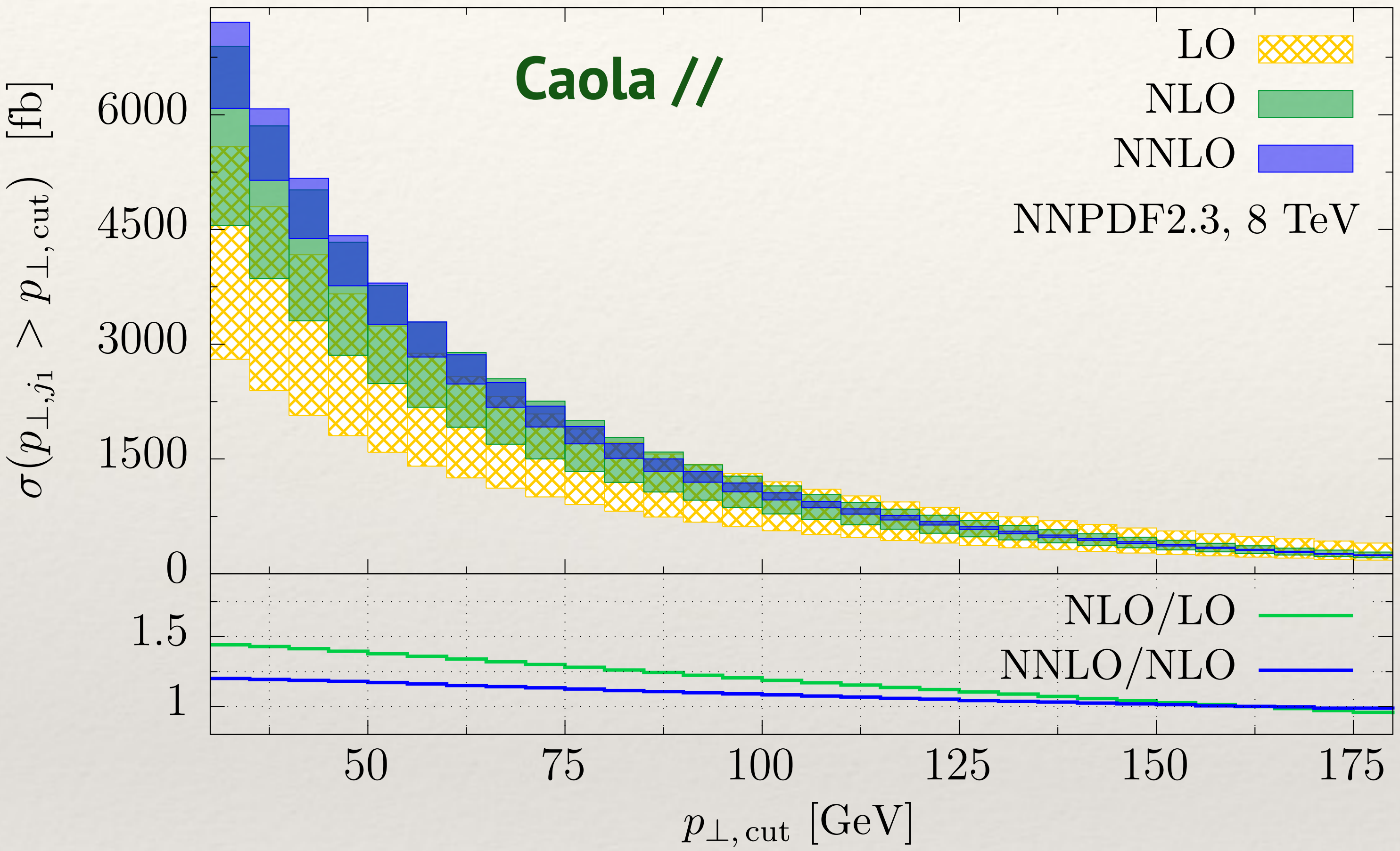


Can only identify Higgs couplings deviations if you know how many Higgses to expect from SM

Mistlberger //
[& Dittmaier's talk]

- scale uncertainty:
  9% @ NNLO $\rightarrow$ 3% @ NNNLO
- correction:
  $\frac{\Delta\sigma_{\mathrm{NNNLO}}}{\sigma_{\mathrm{NNLO}}} = 2.2\%$ @ $\mu = M_{\mathrm{H}}/2$

Milestone: Higgs+jet @ NNLO

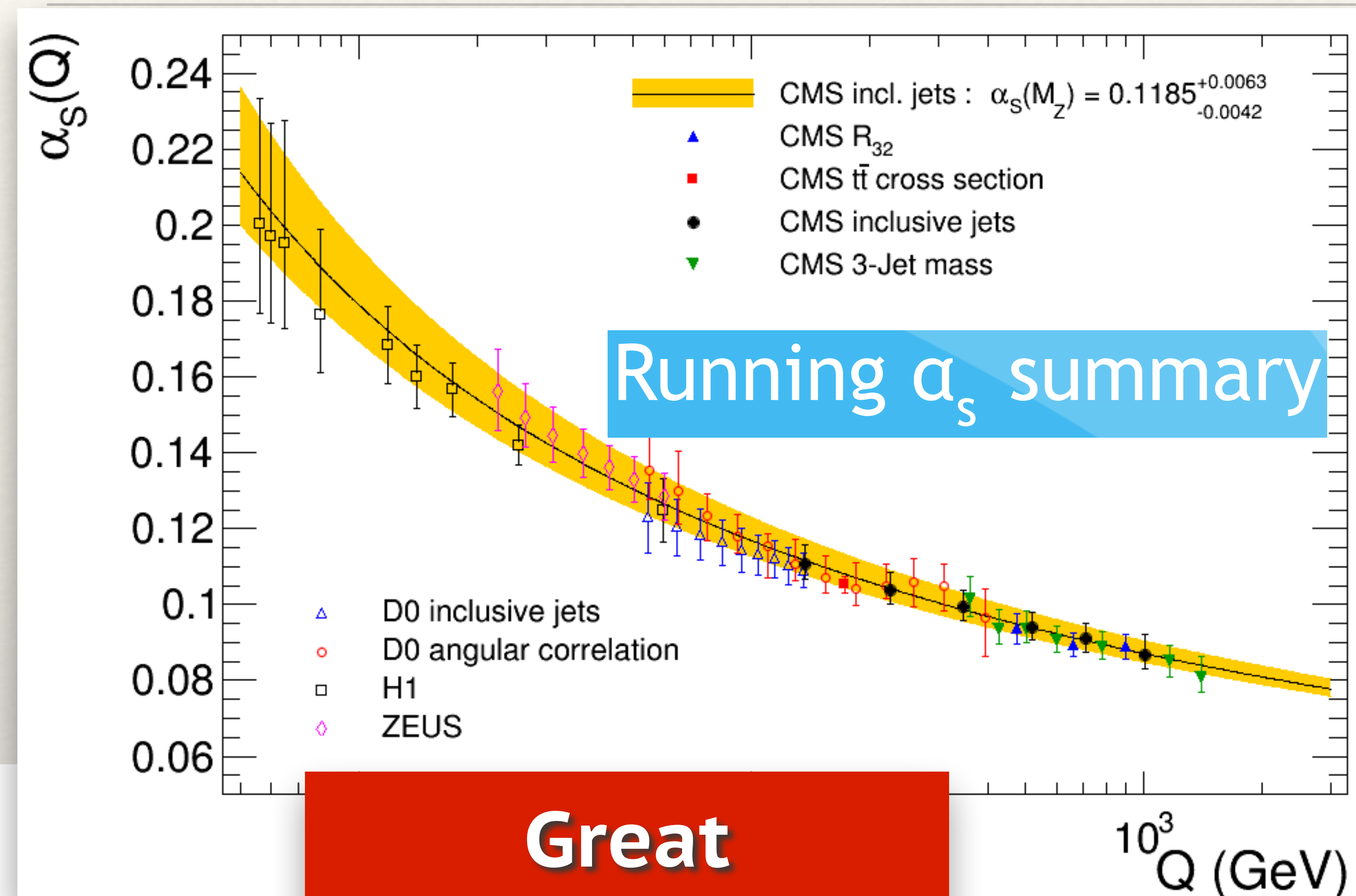


Not just enough to know how many Higgses produced, but also how they're distributed

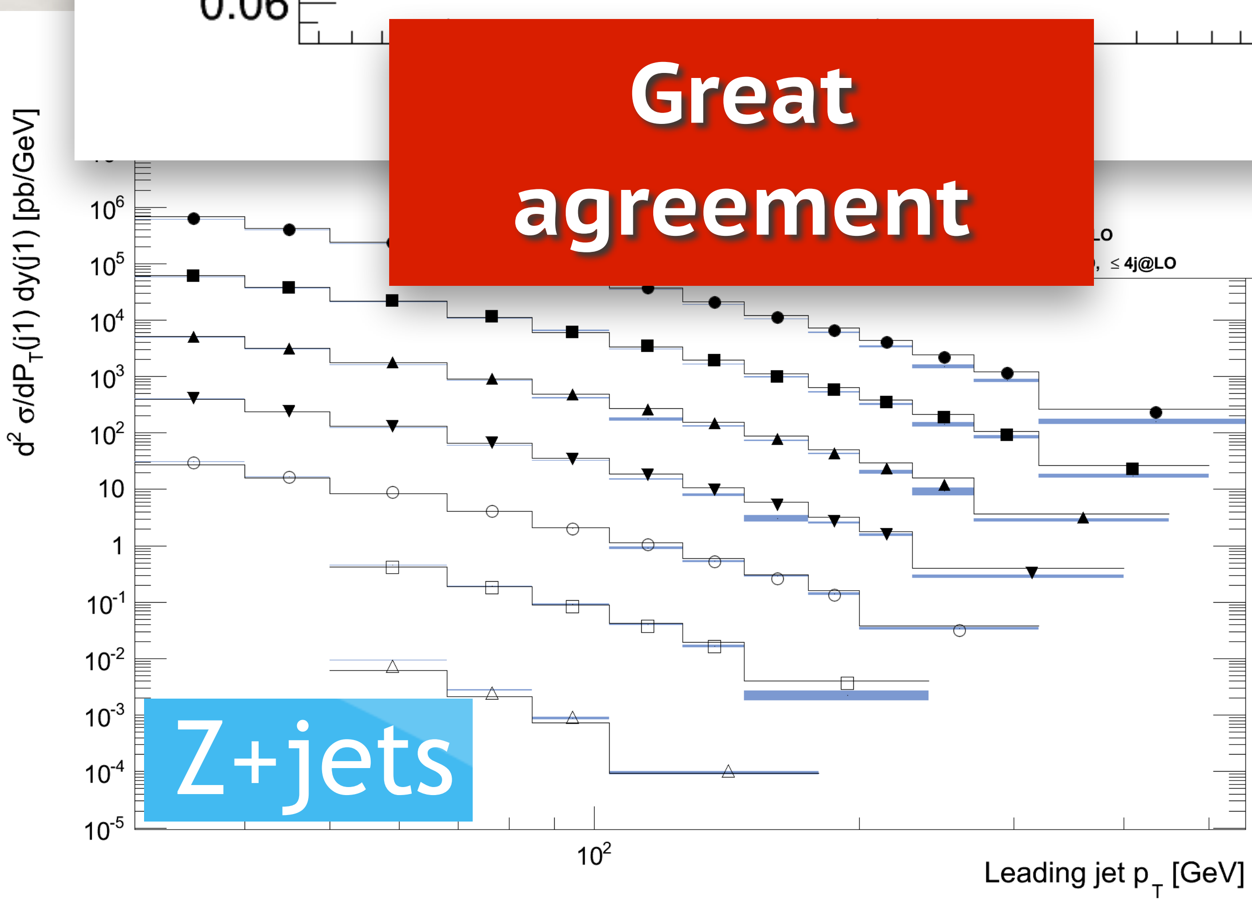
(e.g. momentum distribution, association with other objects like jets)

LHC Run 2 will be accompanied by "Higgs Theory 2"

Experimental validation



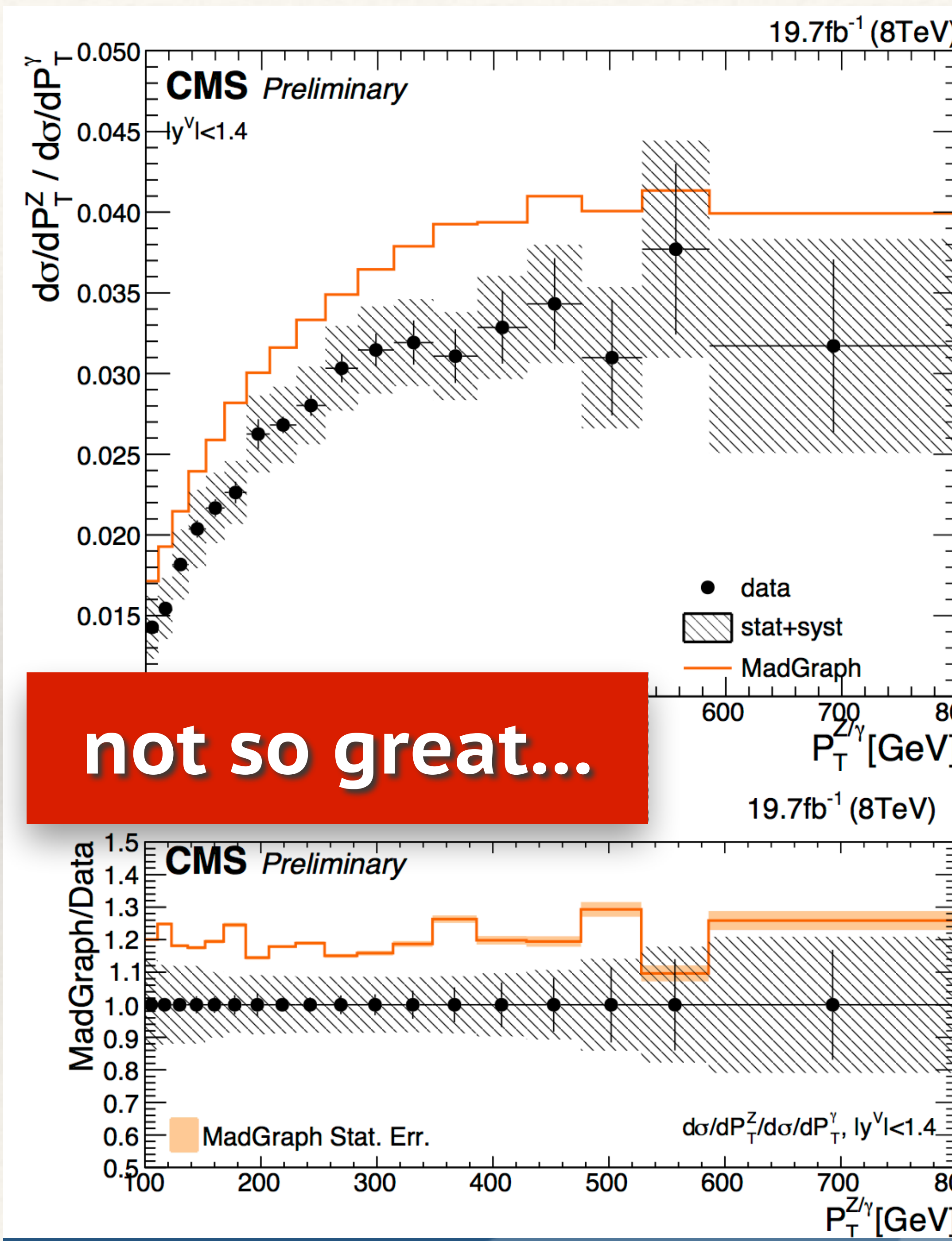
Running α_s summary



Great agreement

Z+jets

Z+jets / gamma + jets

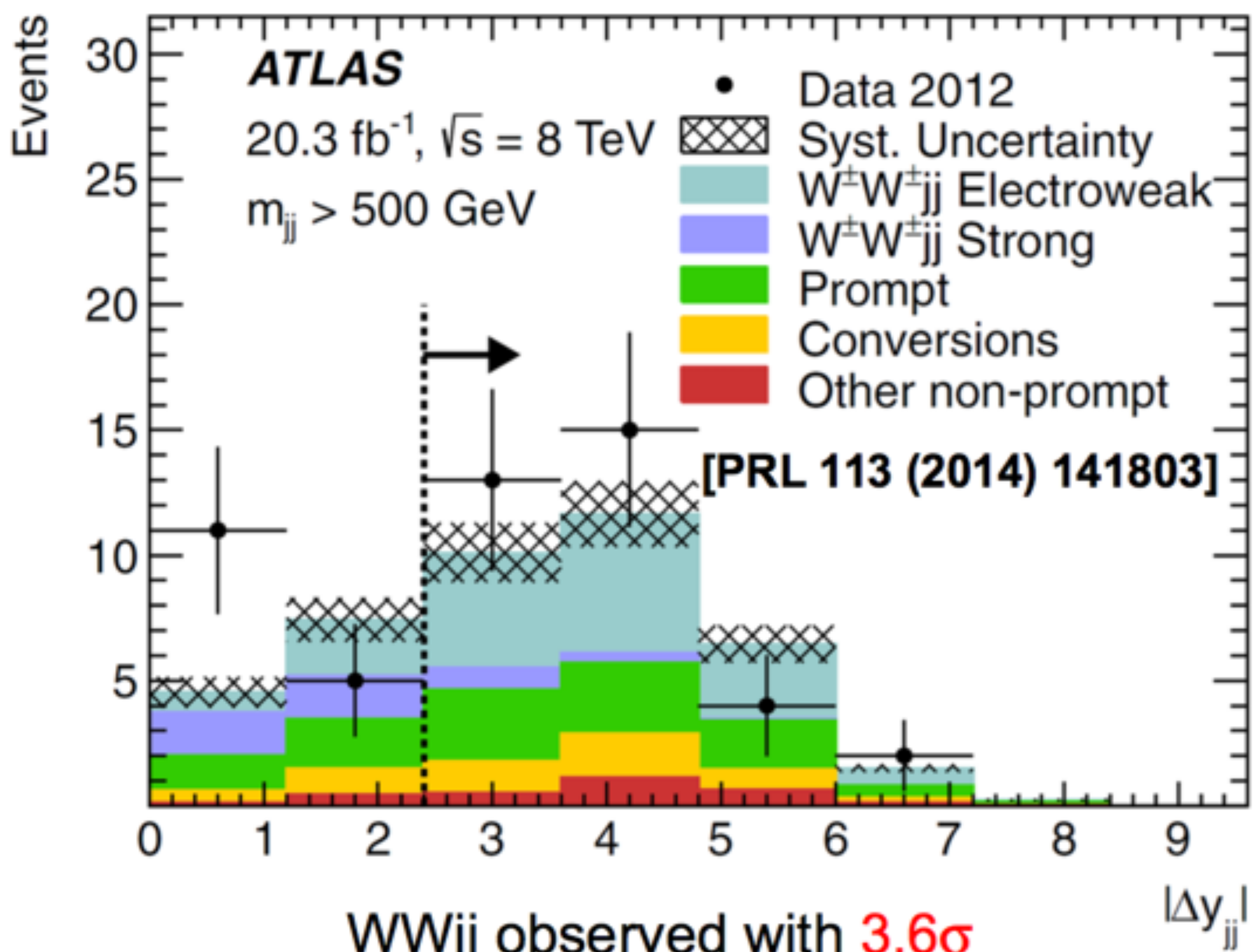


not so great…

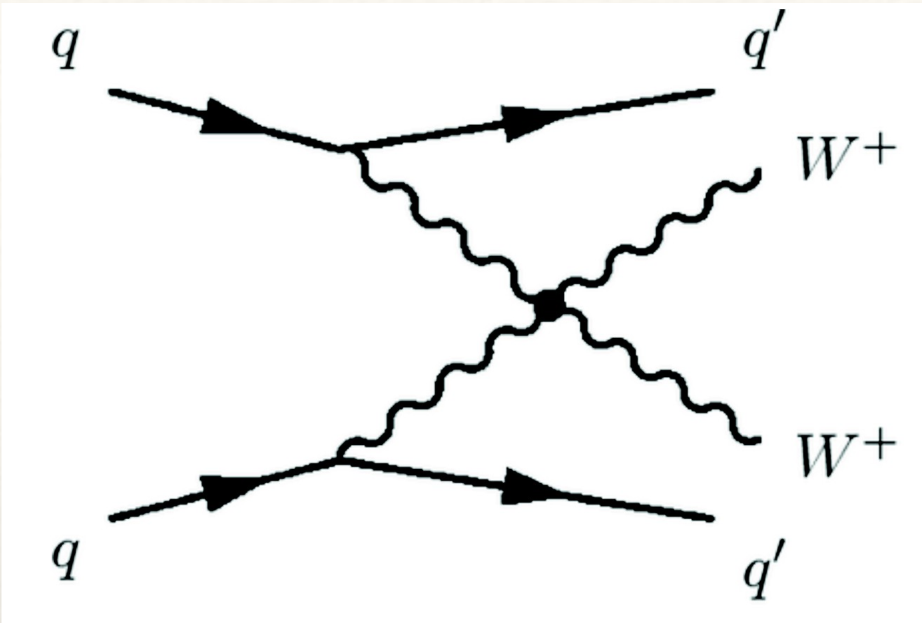
Savin

Vector boson scattering

- First evidence in same sign WW
  - ➔ Same sign dileptons
  - ➔ 2 high pT jets with $|\Delta\eta_{jj}| > 2.4$



WWjj observed with 3.6σ



- WWjj EW production:

ATLAS: $\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb

Predicted: 0.95 ± 0.06 fb

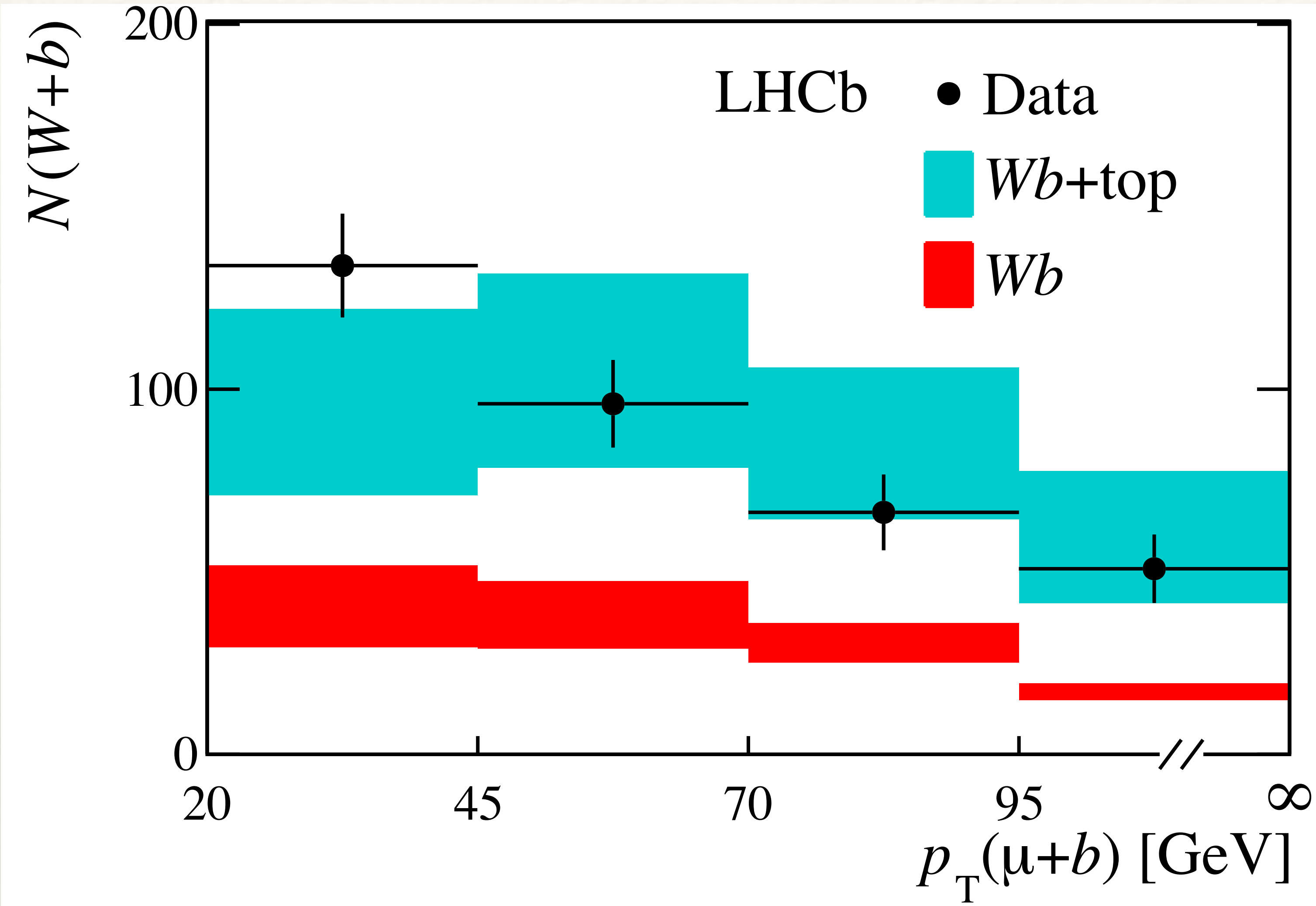
Sauvan

Top
20 years old

- Only place to study the properties of a bare quark
  - Lifetime < hadronisation
- Special role in EWSB?
- First place a new particle could be observed
  - Particularly if new particle couples to mass
- Top is a background to many other searches

Lister

top at LHCb



Top previously seen at CDF, D0, ATLAS & CMS

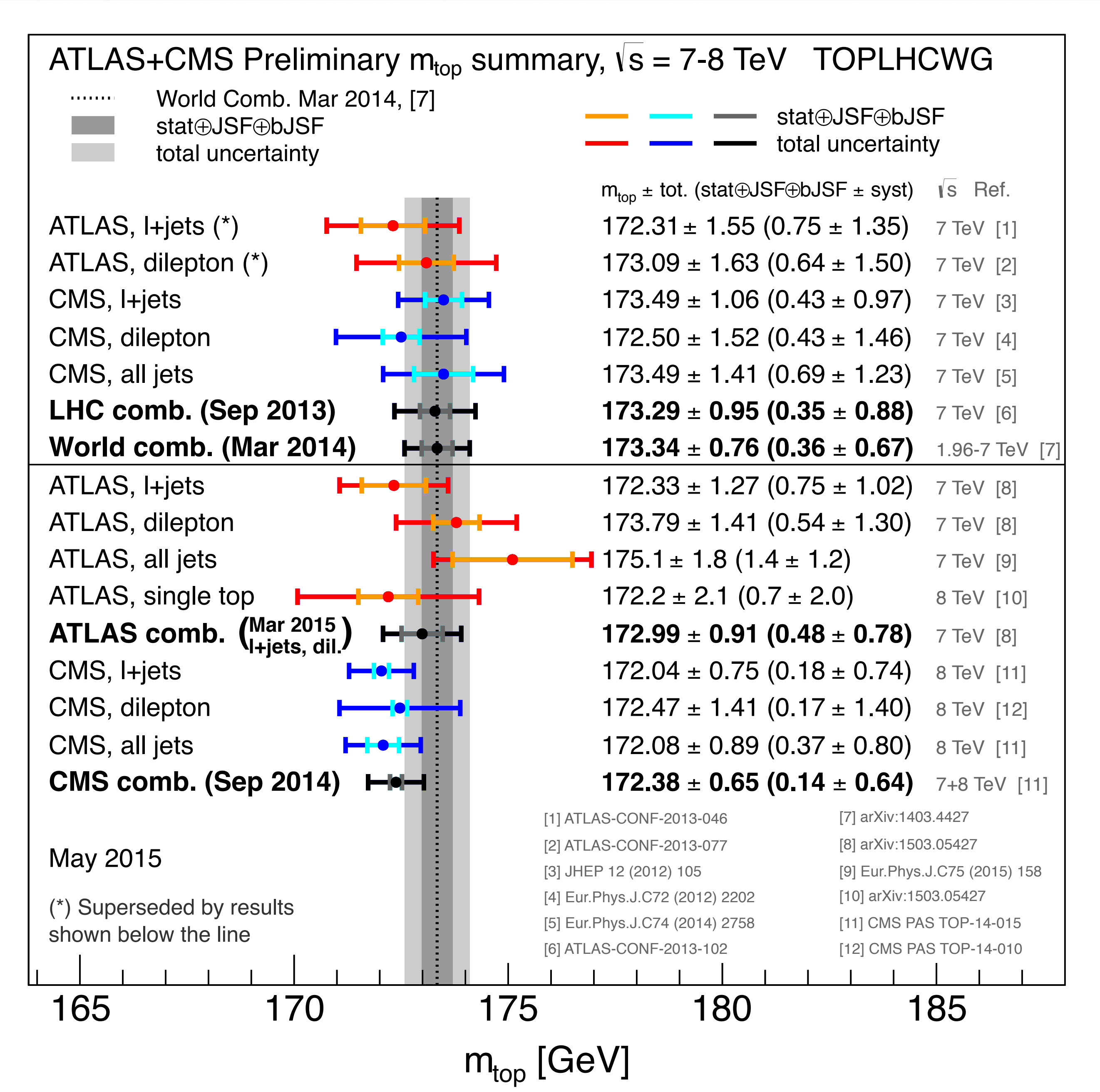
As of Wednesday, LHCb is the 5th experiment to see tops
(in special "forward" region)

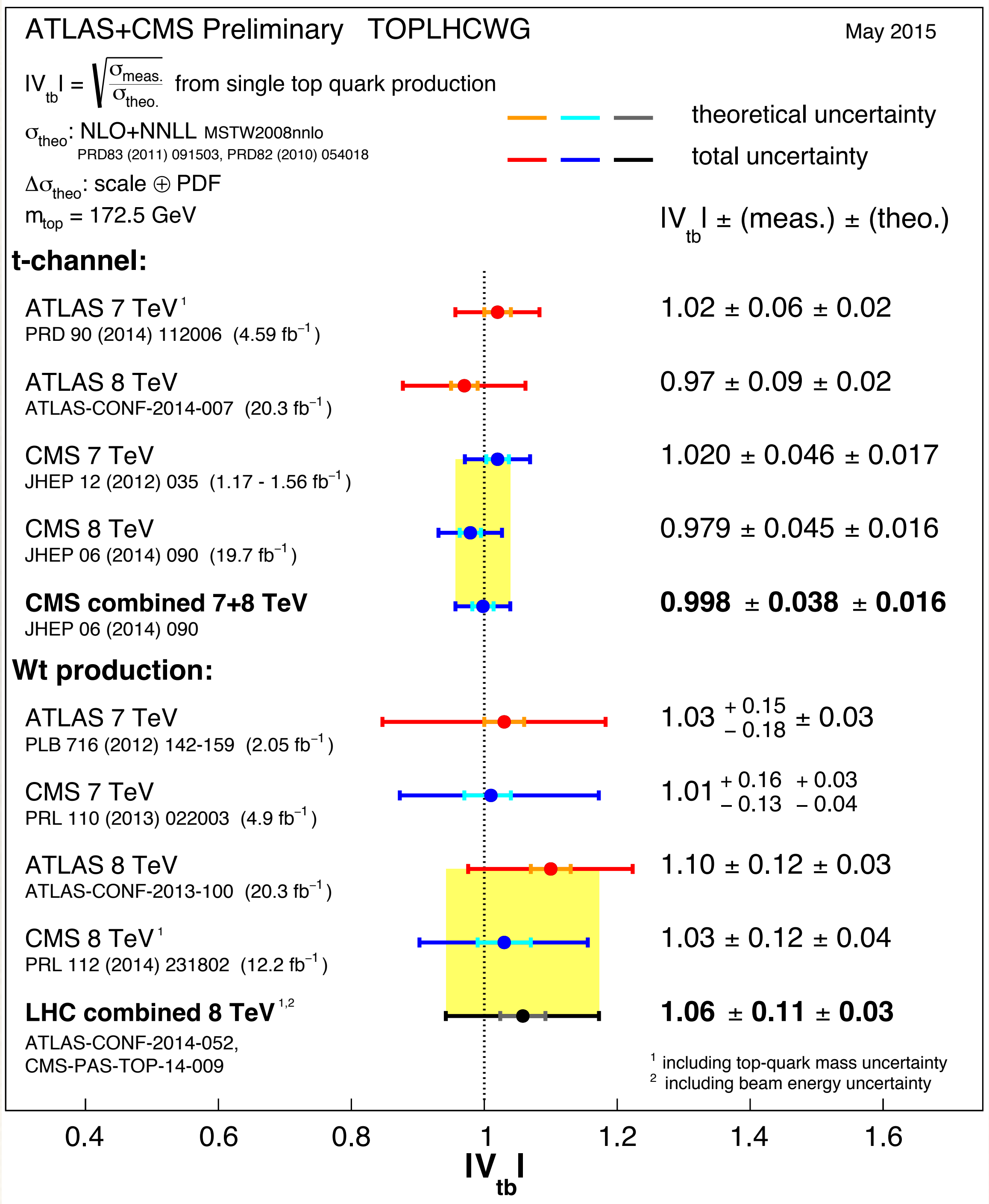
$$\sigma(\mathrm{top})[7\,\mathrm{TeV}] = 239 \pm 53\,(\mathrm{stat}) \pm 38\,(\mathrm{syst})\,\mathrm{fb}\,,$$
$$\sigma(\mathrm{top})[8\,\mathrm{TeV}] = 289 \pm 43\,(\mathrm{stat}) \pm 46\,(\mathrm{syst})\,\mathrm{fb}\,.$$

Top mass & couplings

Top mass: 0.4%

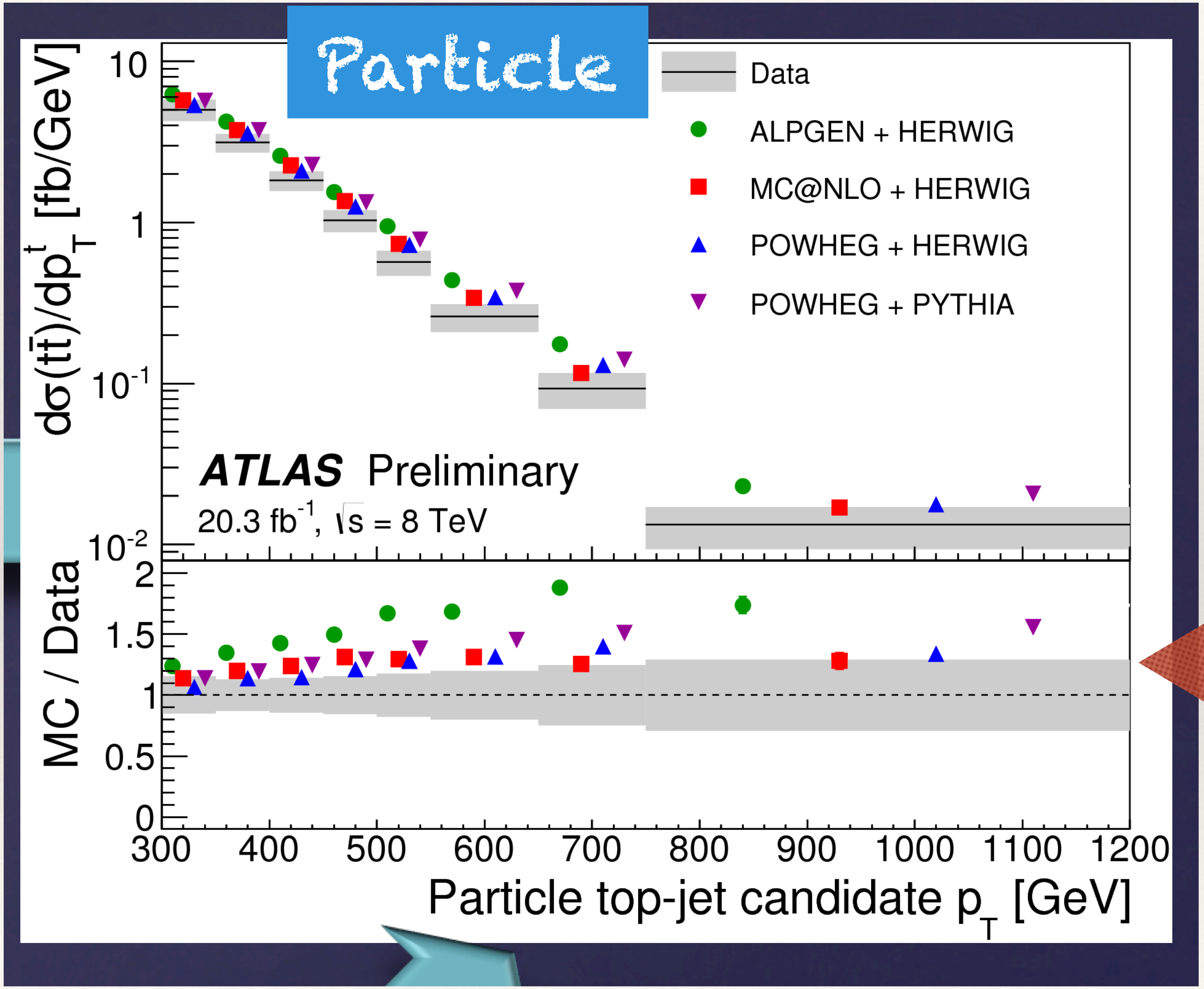
V_{tb}: 11%





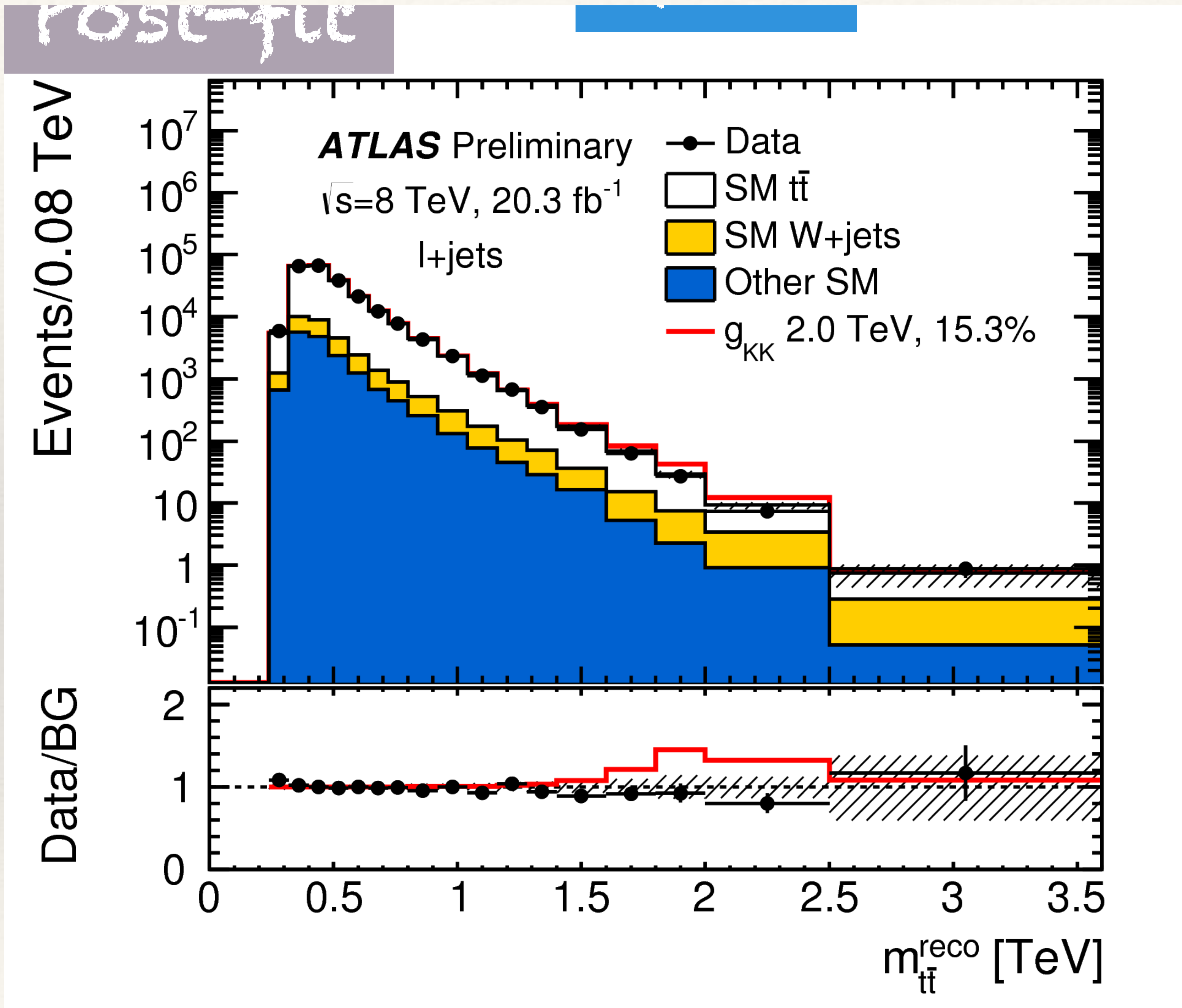
Lister

Top-quark pt



Most QCD predictions are too high

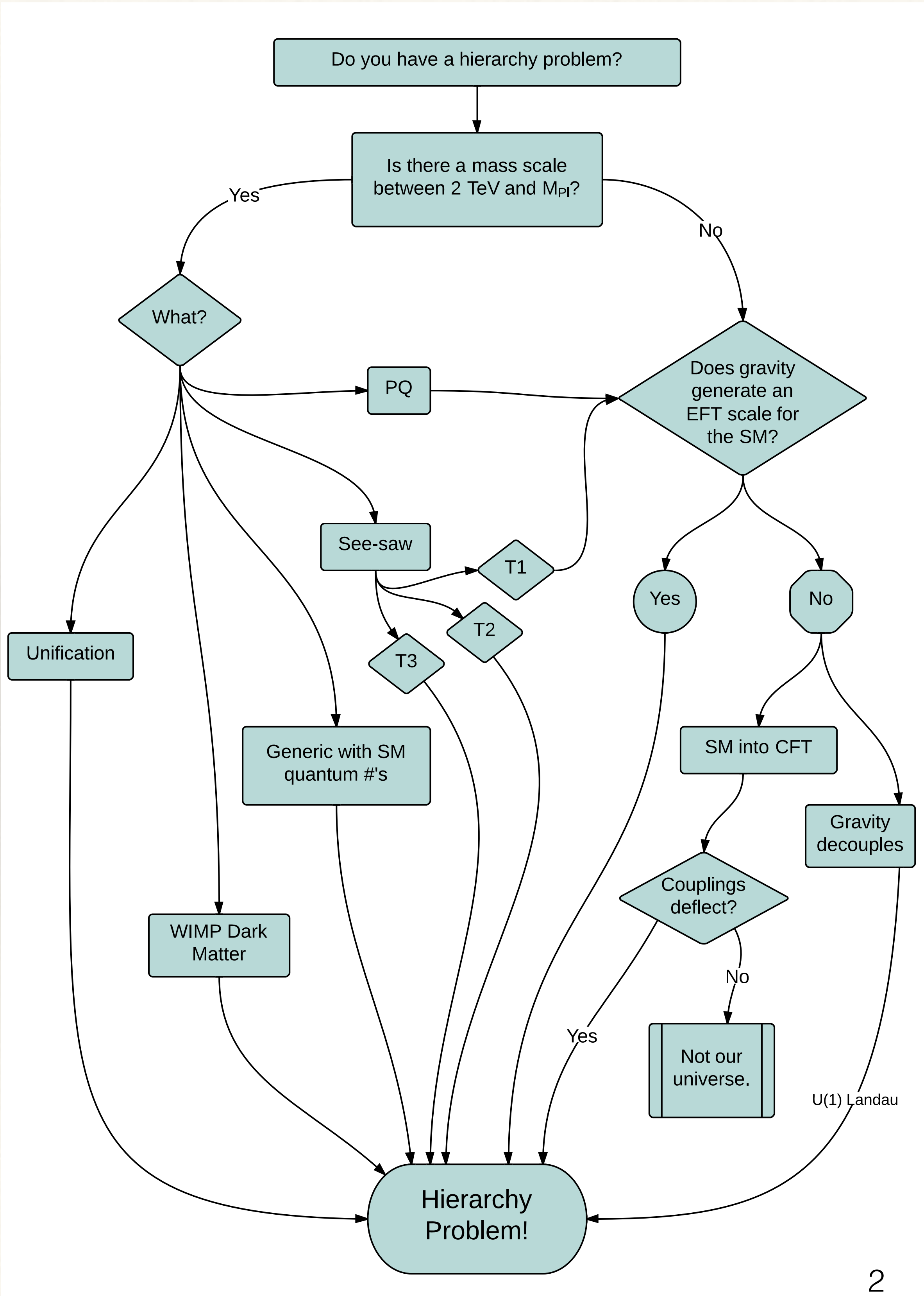
ttbar mass spectrum for searches



LHC new-physics searches
"SUSY" & "exotics"

Hierarchy problem

Craig



Elementary scalars are quadratically sensitive to physics at higher scales.

Independent of regularization scheme.

Model-building scales aside, gravity attests to presence of a higher scale.

No viable proposals for mitigating sensitivity to physics @ Planck scale *without* new physics @ weak scale.

Hierarchy problem only sharpened with the discovery of an elementary SM-like Higgs (+nothing else so far).

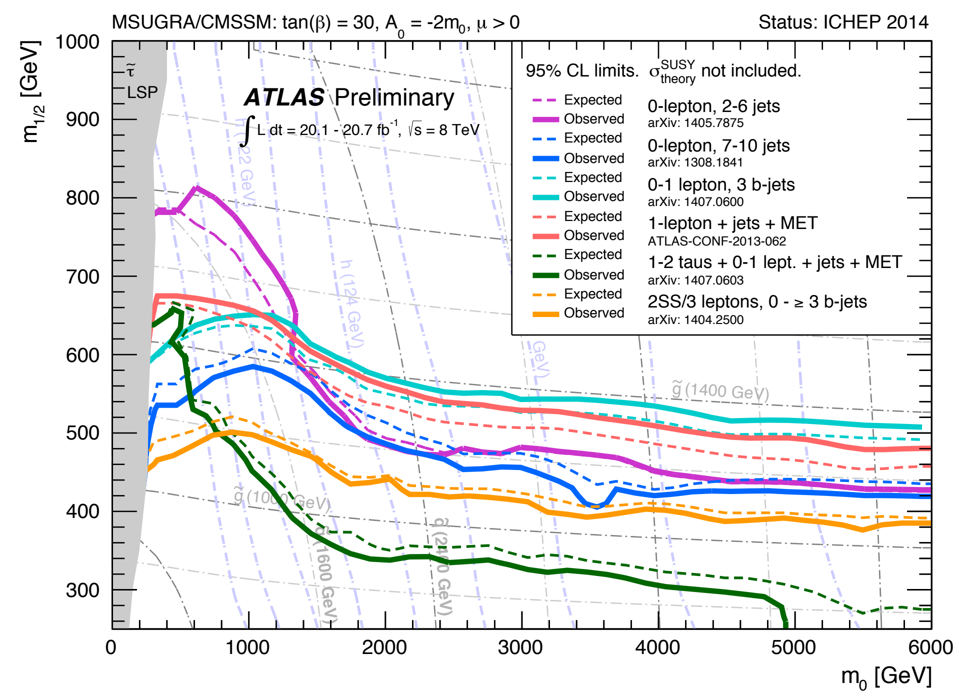
Craig

The case for SUSY

Why SUSY?

- ✓ Naturalness
- ✓ Dark matter
- ✓ Unification
- ✓ Higgs mass
- ✓ Decoupling

Why not?

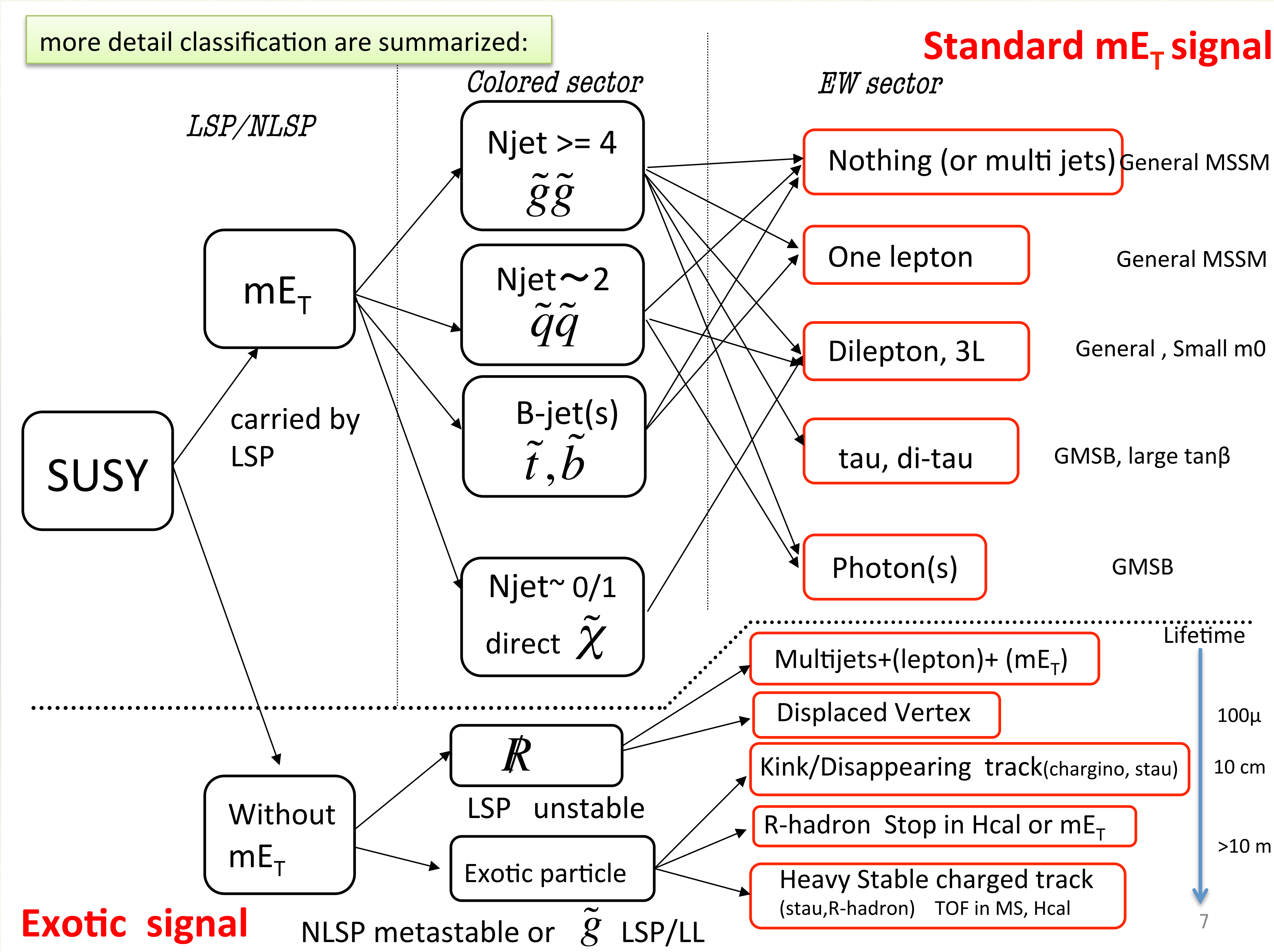


Mass reach for simplest versions out to 1.5 TeV

~1% tuning level

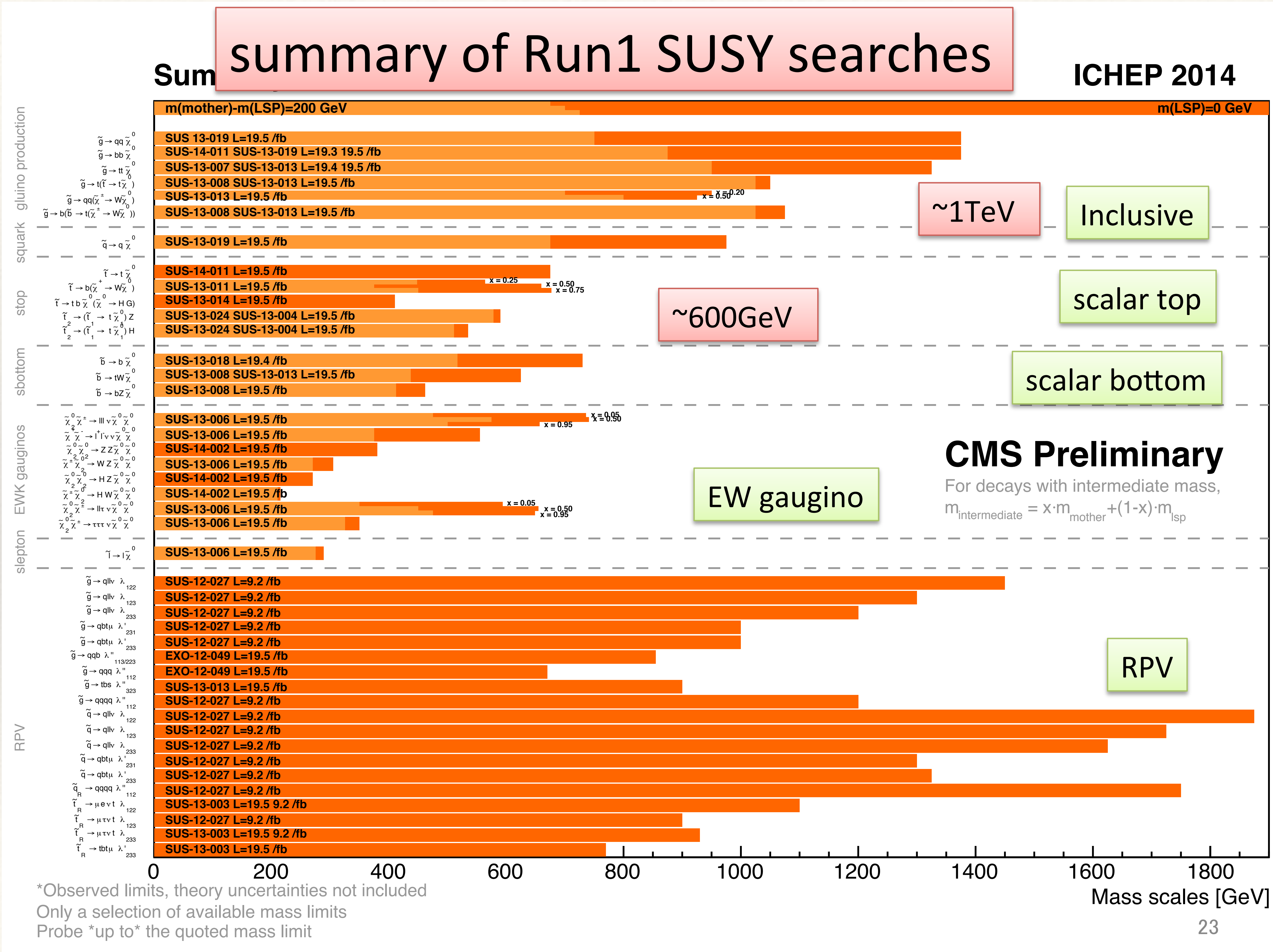
SUSY search organization

Asai



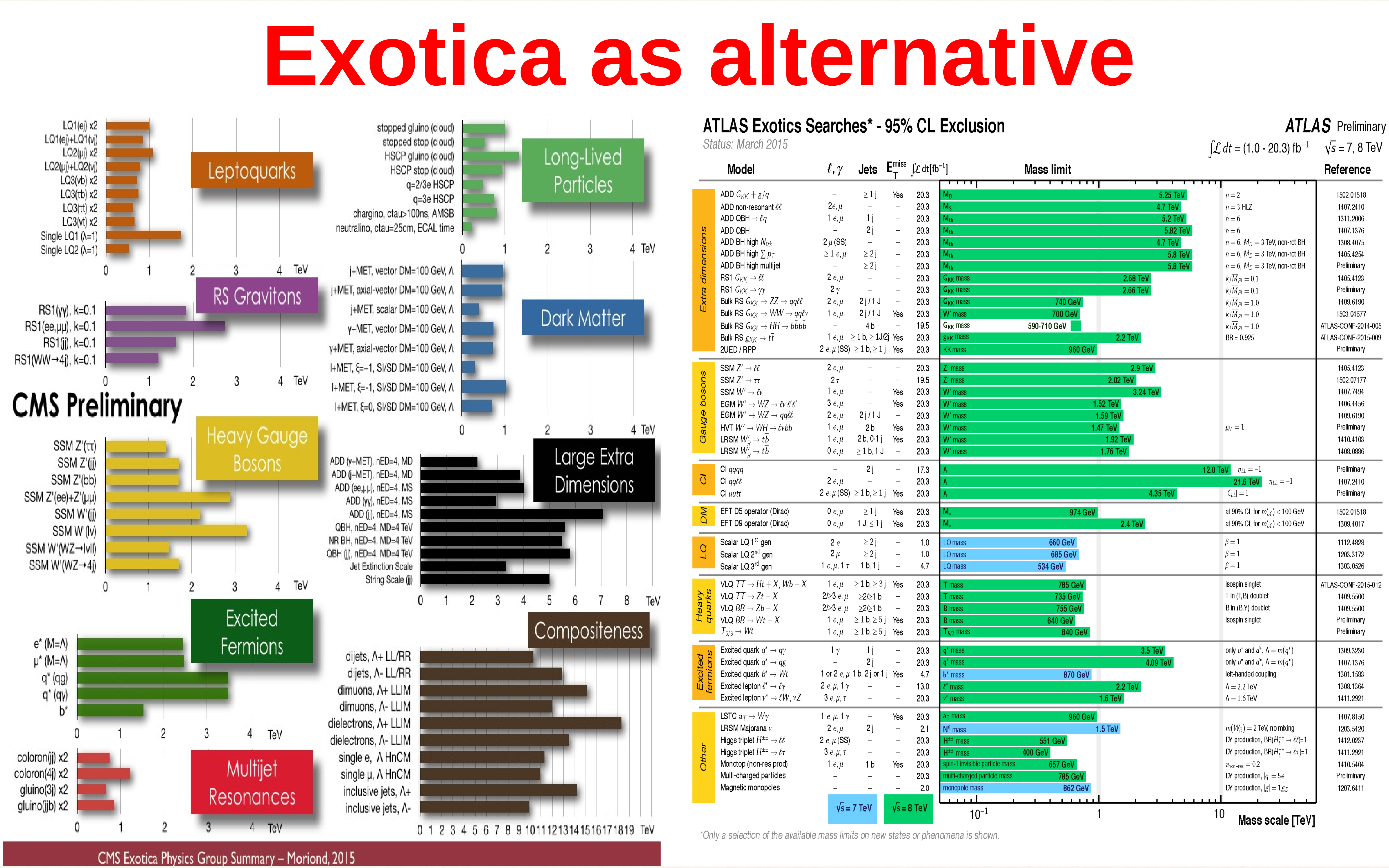
LHC limits: SUSY

Asai



LHC limits: exotics

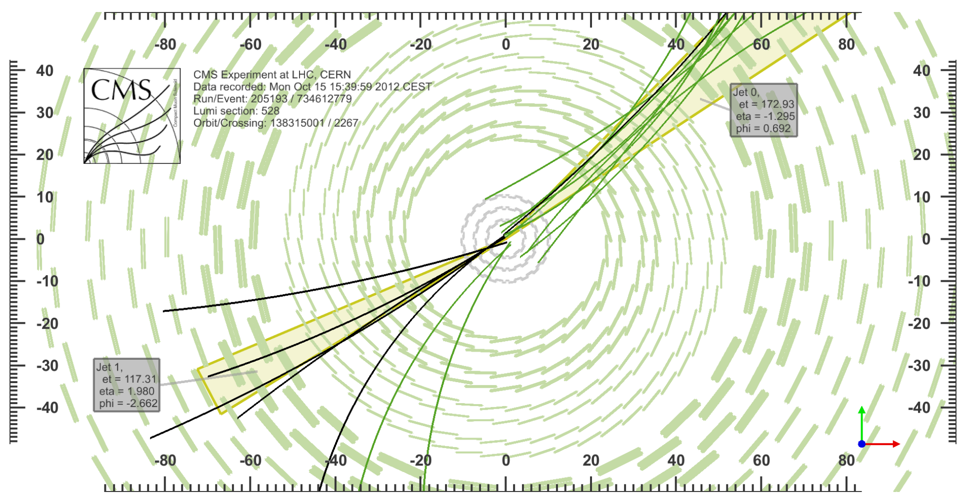
Alcaraz

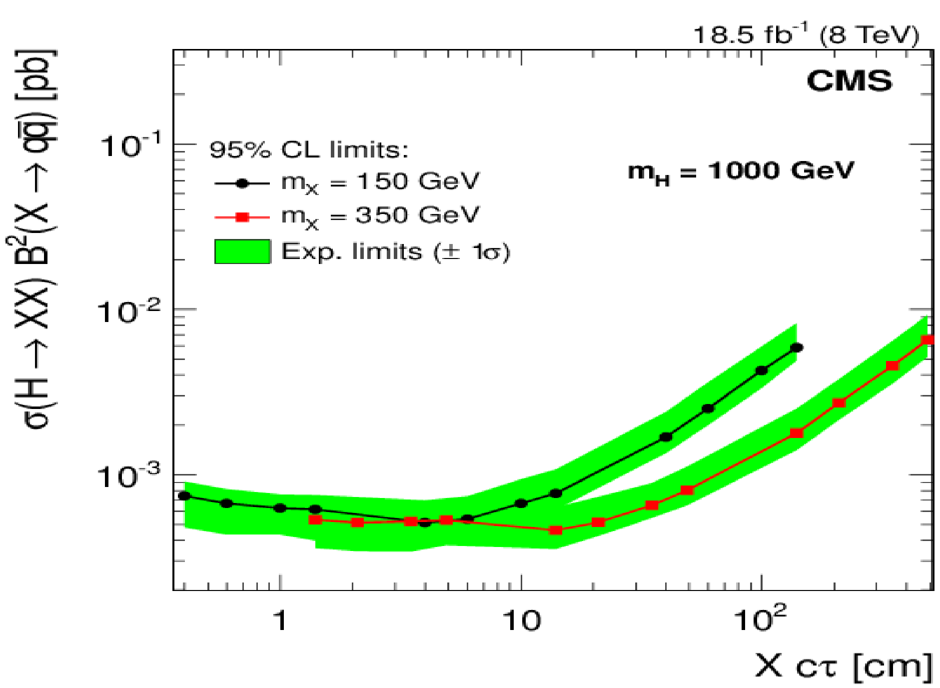


an exotics example

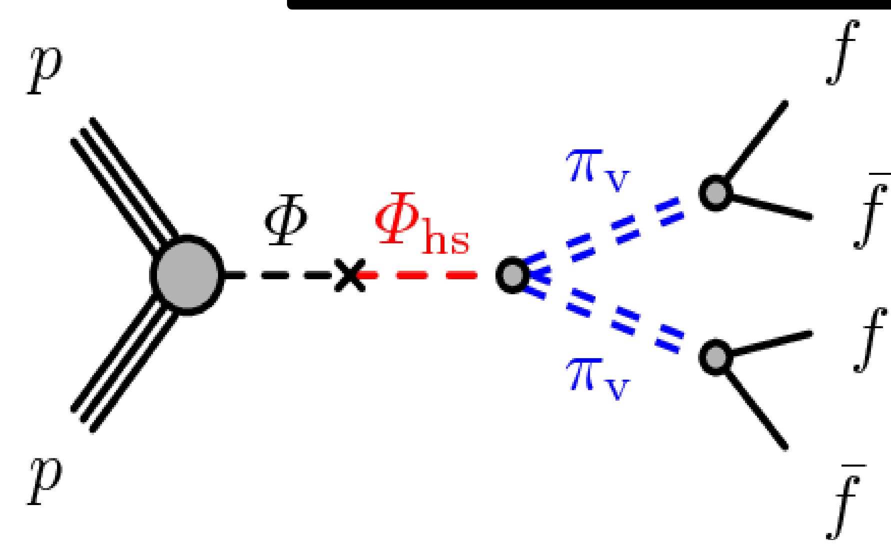
Displaced jets

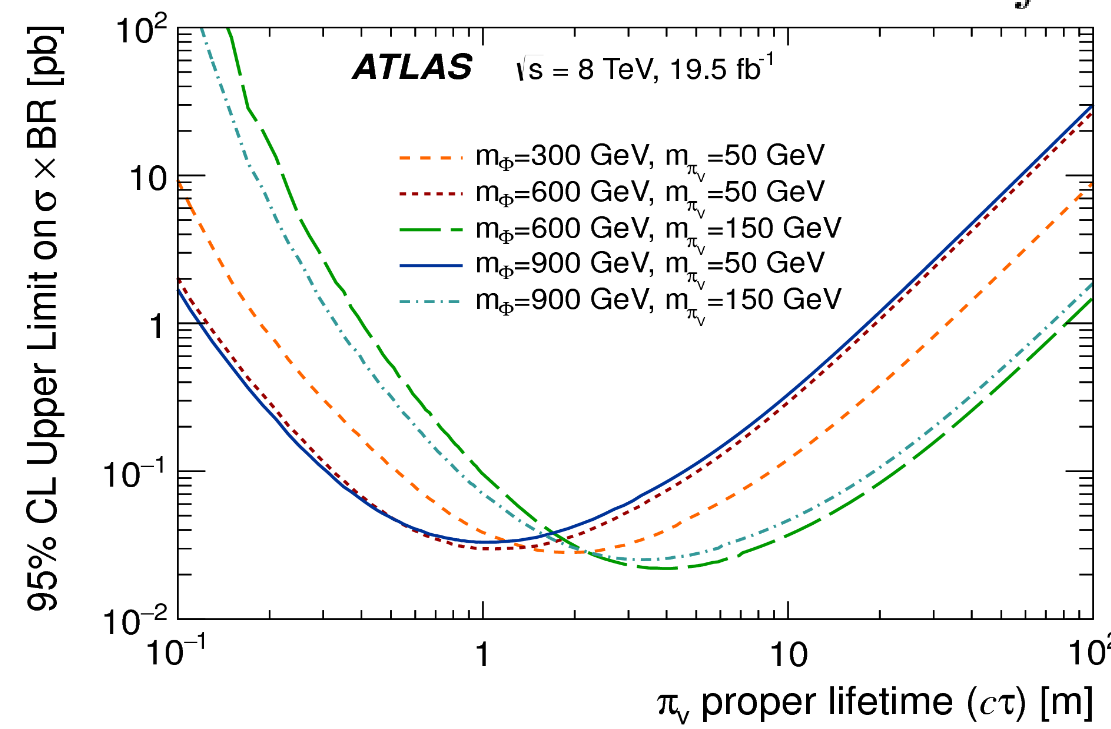
CMS, arXiv:1405.1994





ATLAS, arXiv:1504.03634

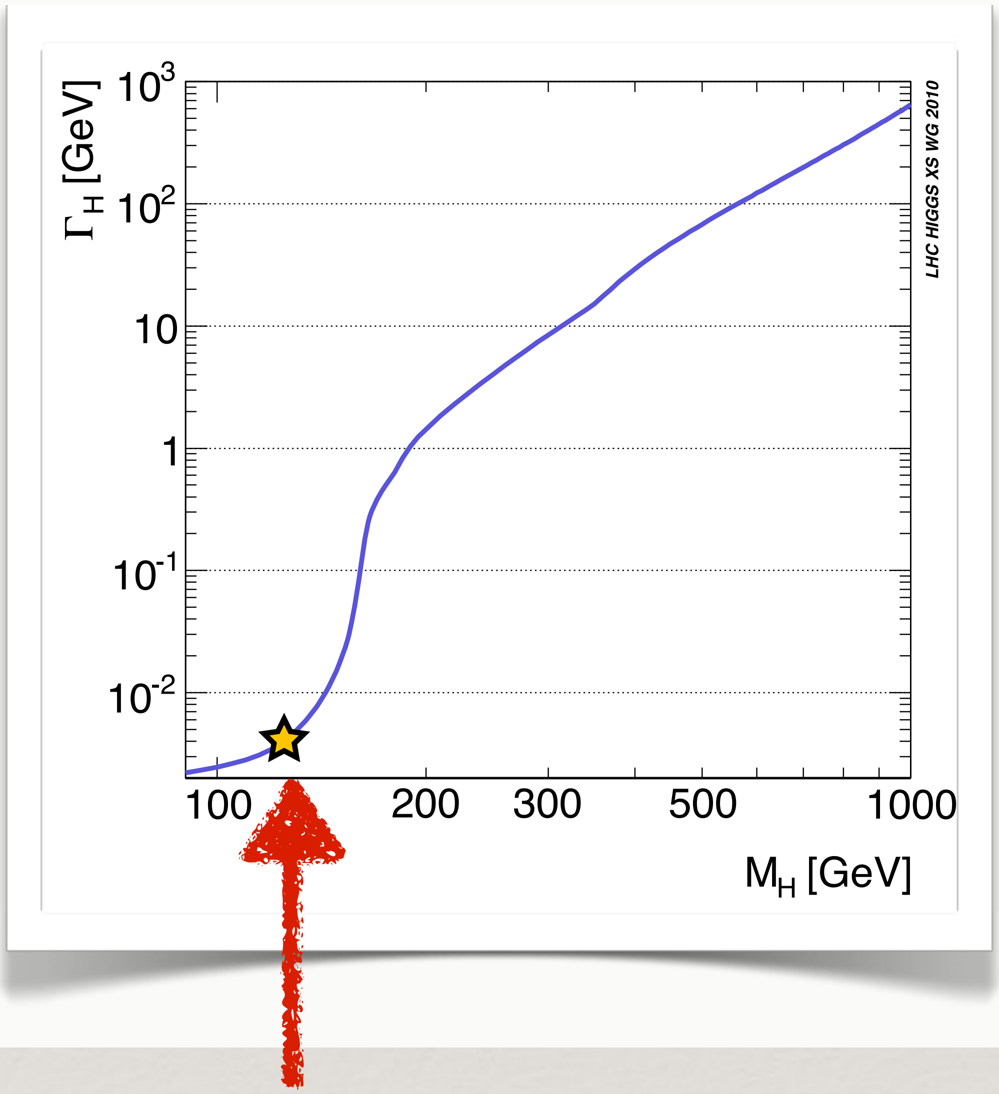




Exploring decay lengths from cm to several m

Higgs:
as BSM portal

- A light SM-like Higgs is narrow:



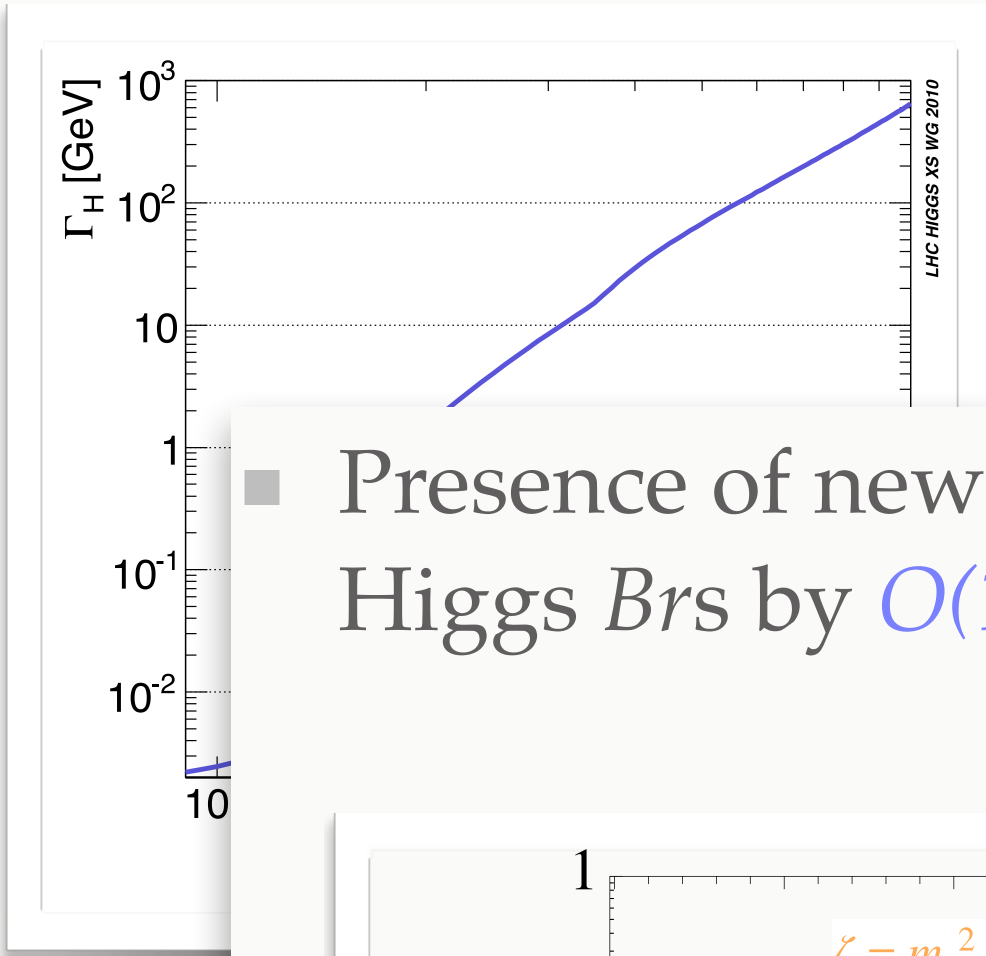
$$\Gamma_h(125\ \mathrm{GeV}) = 4.1\ \mathrm{MeV}$$

Shelton

Comparison:
top, W, Z all have
width of O(1GeV)

Higgs: as BSM portal

- A light SM-like Higgs is narrow:



$\Gamma_h(125$

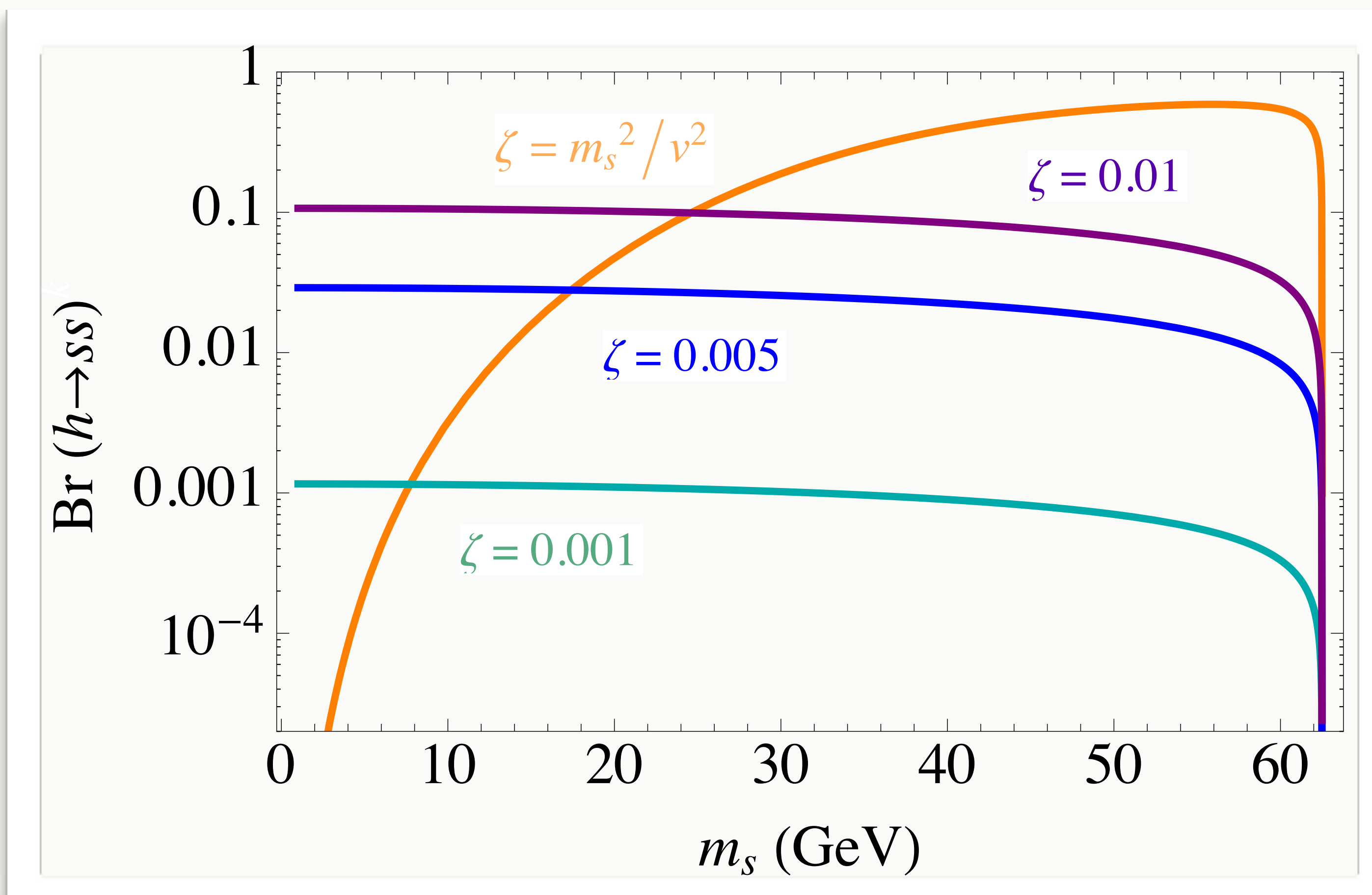
C

top

wid

- Presence of new light degrees of freedom can distort Higgs *Brs* by *O(1)* even for small couplings

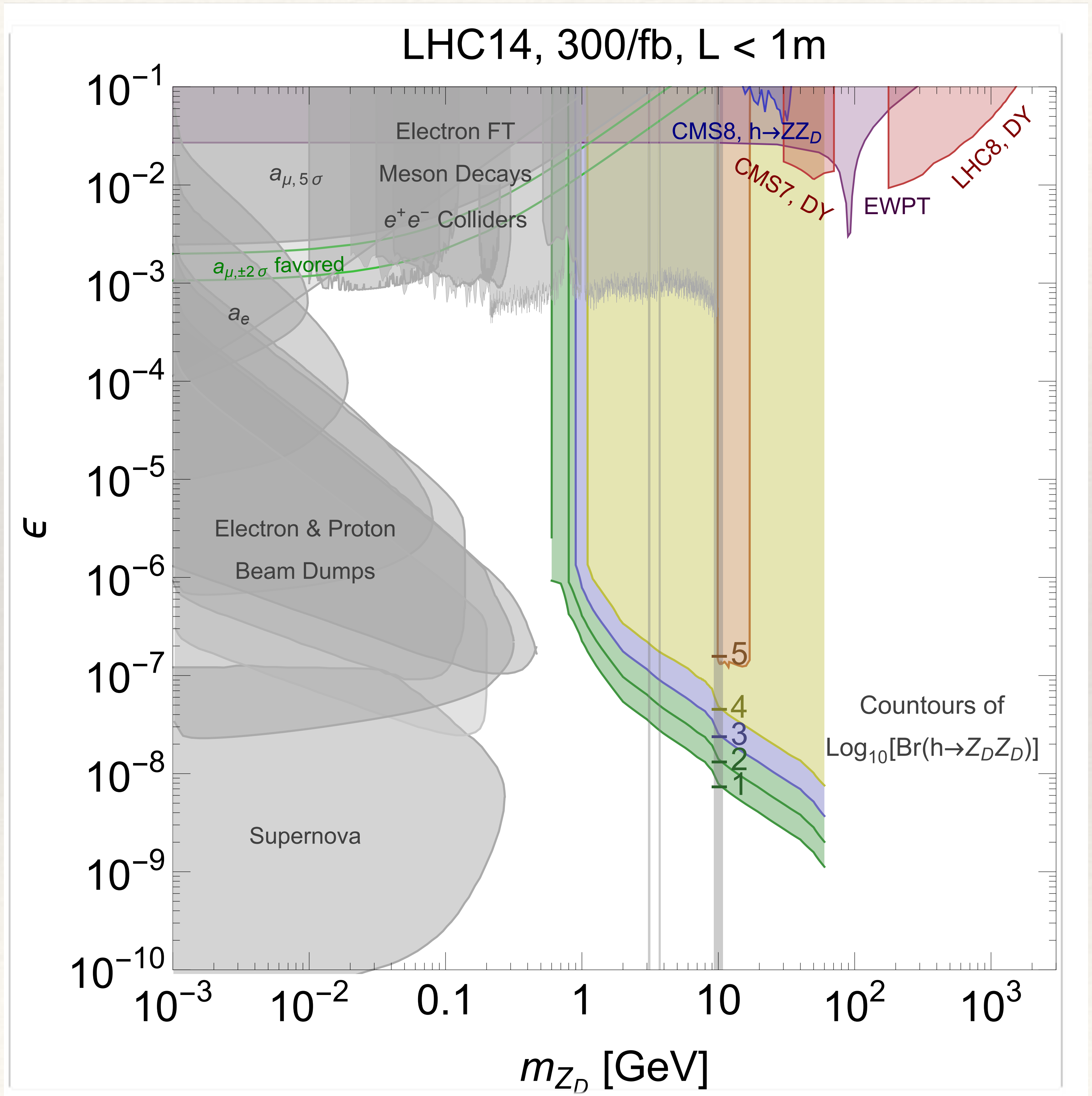
Shelton



Simple example: one new scalar

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

Higgs portal window into dark sectors



A dark U(1)

Shelton

Recasting

Papucci

The LHC experiments don't usually publish their raw data

(CMS has released 0.2% of its raw data + analysis tools)

- 250-300 analyses SUSY+exotica, CMS+ATLAS, 7+8TeV
- no significant deviation from the Standard Model, but incredibly extensive and valuable information to constrain the Beyond the Standard Model panorama
- Large amount of results brings new challenges in understanding consequences for beyond the Standard Model physics

CheckMATE, Drees et al. 1312.2591

Atom, I.W.Kim, M.P., K.Sakurai, A.Weiler, to be released soon

MadAnalysis, … Conte et al, 1206.1599, 1405.3982, 1407.3278

Recasting

Papucci

Take search X setting limits for model A

Extrapolation!!

Write code to mock up search X
(not enough info → introduce approximations)

Use mocked-up analysis with model B

Generate events for model A, use them with mocked-up analysis, compare results with published experimental results

Extract approximate limits of search X for model B

Validation (most time consuming part)

Repeat for 100's of analyses…

Have we found a scalable / sustainable model yet?

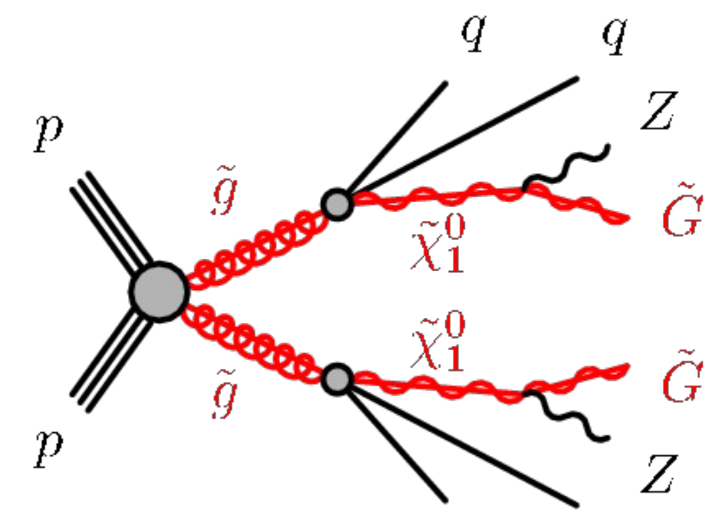
LHC discrepancies?

mET + jets + Z(→ll)

Asai

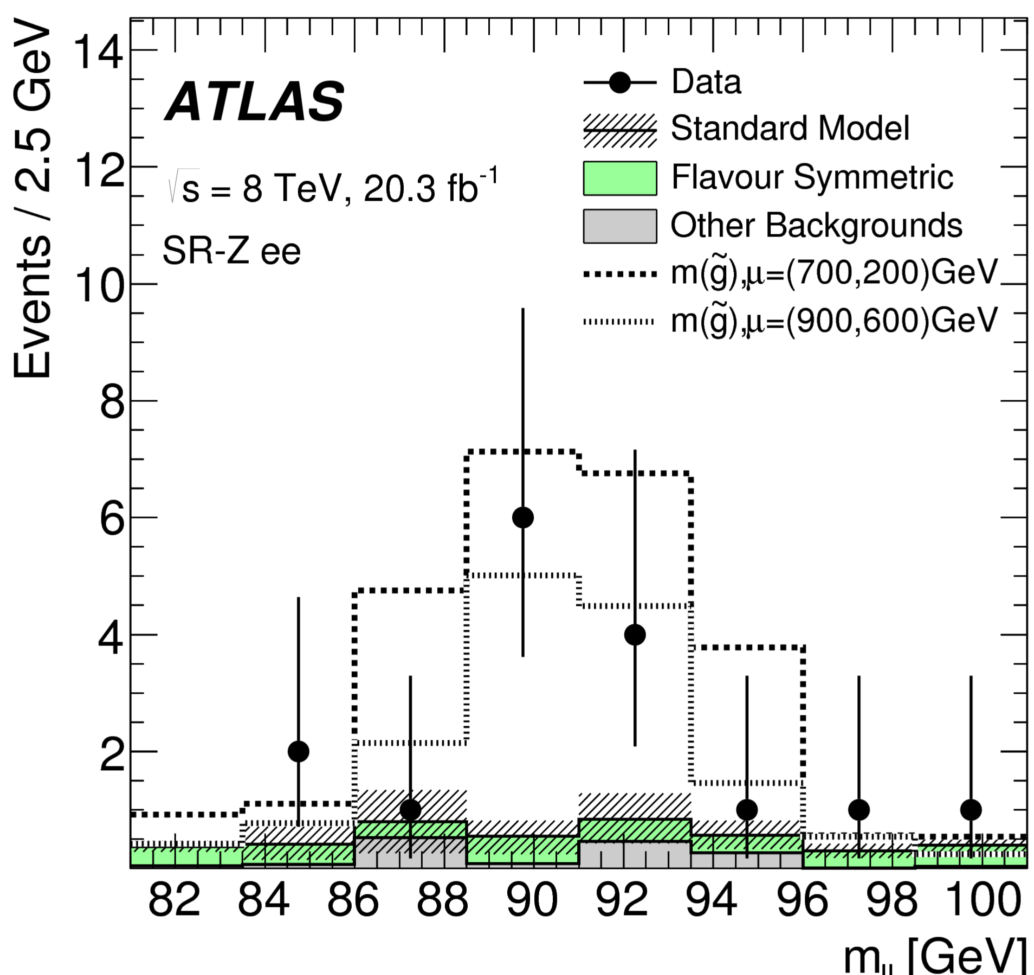
3 σ excess is found

mET+jets+Z(→ll)

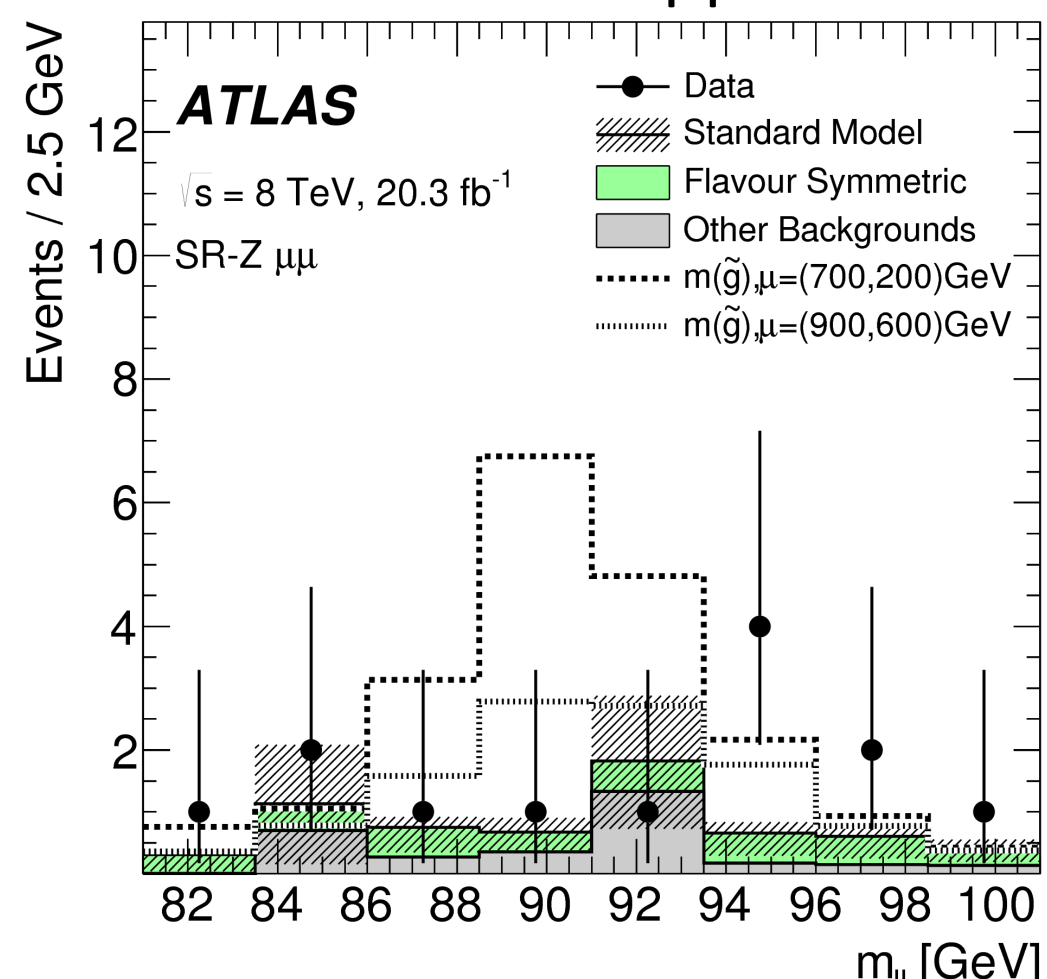


At least 2jets (PT>35GeV)   HT>600GeV(high jet activity)
mET > 225GeV
then select SFOS lepton pair (ee, μμ)
M(ll)=Mz+-10GeV

3σ excess in ee channel

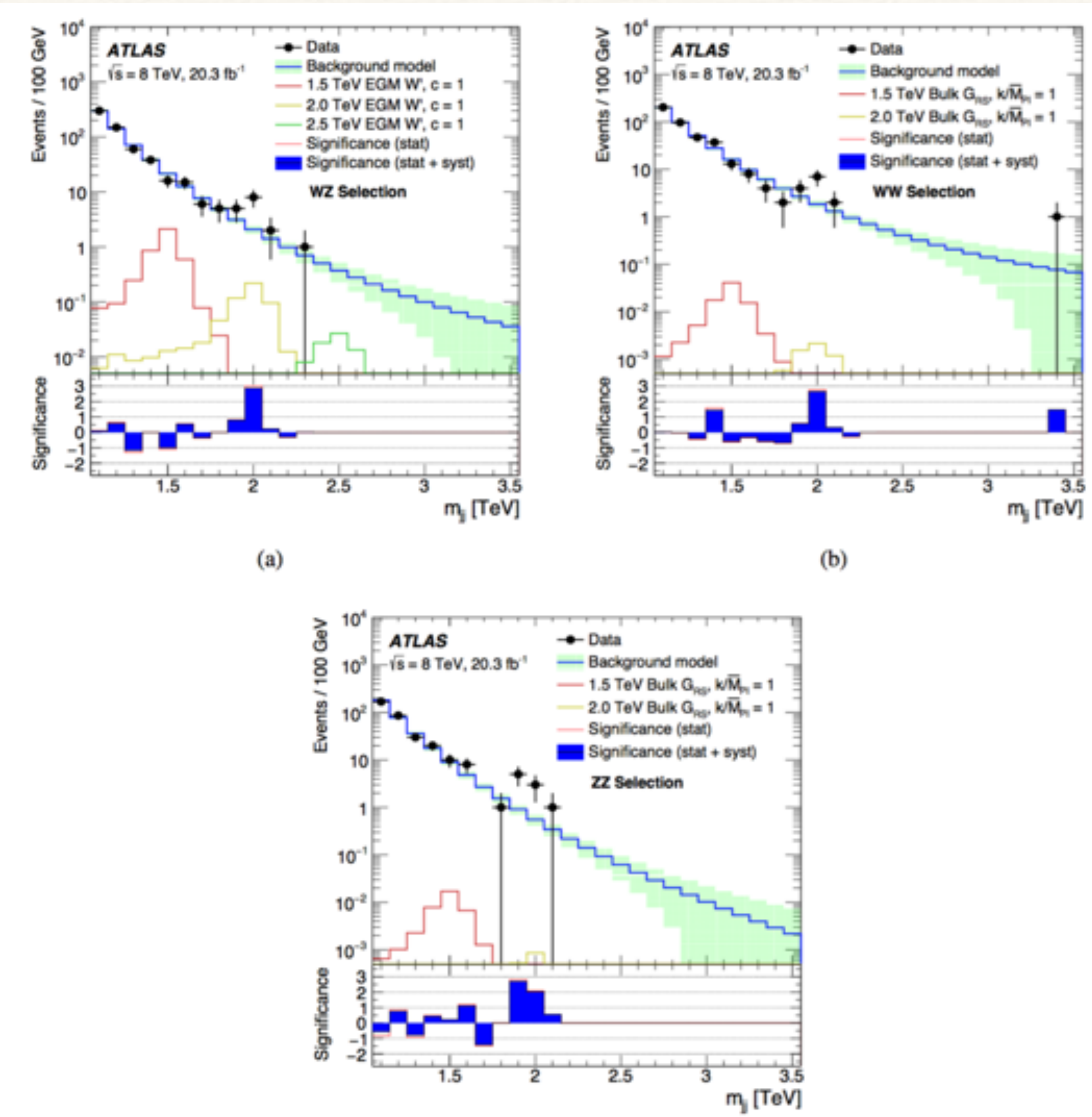


1.7 σ excess in μμ channel



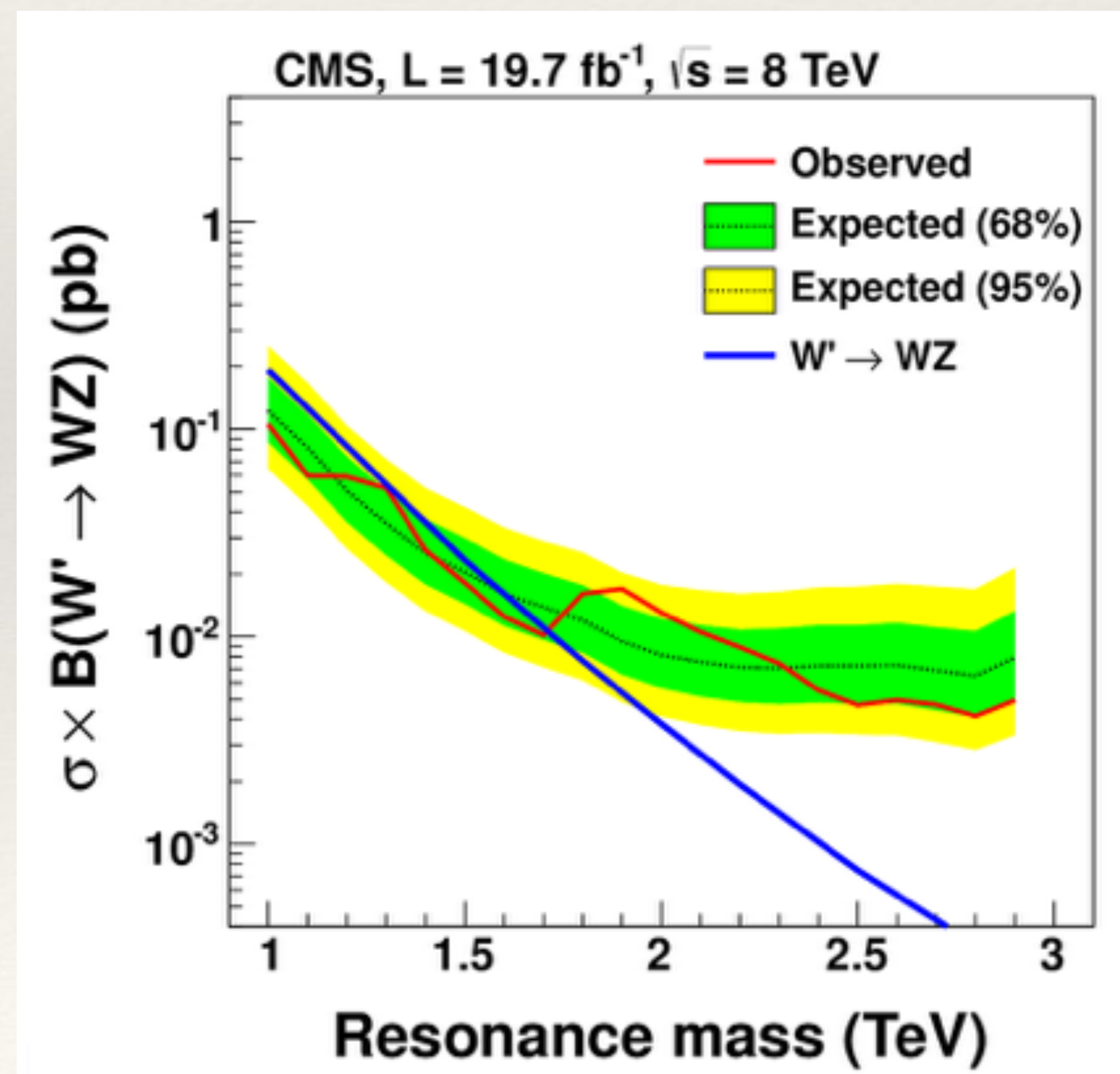
But No excess was found in CMS data

VV resonances



Both ATLAS & CMS have a small excess around 2 TeV

1.5 – 3 σ

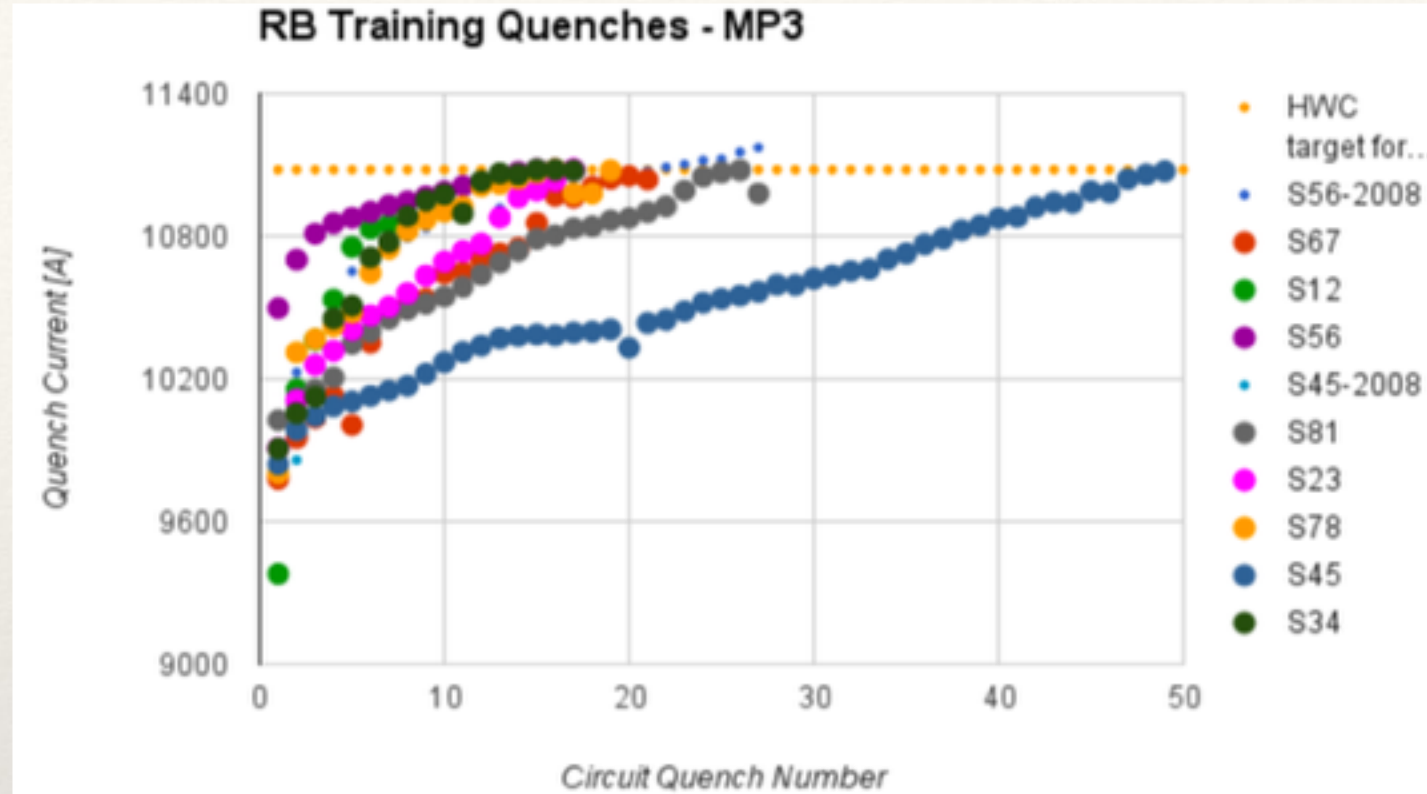


But ATLAS & CMS bumps probably not quite in same place

LHC prospects

Lamont

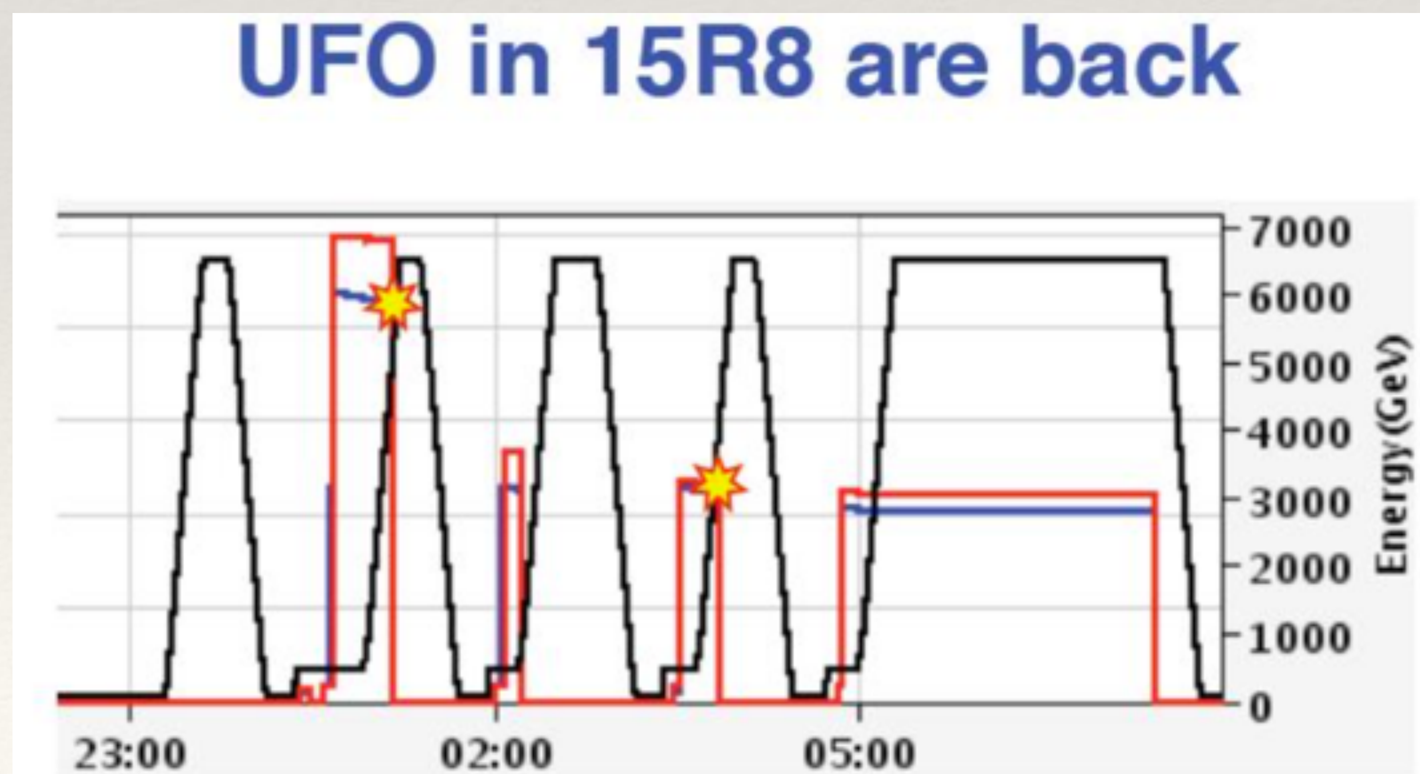
➟ LHC @ 13 TeV



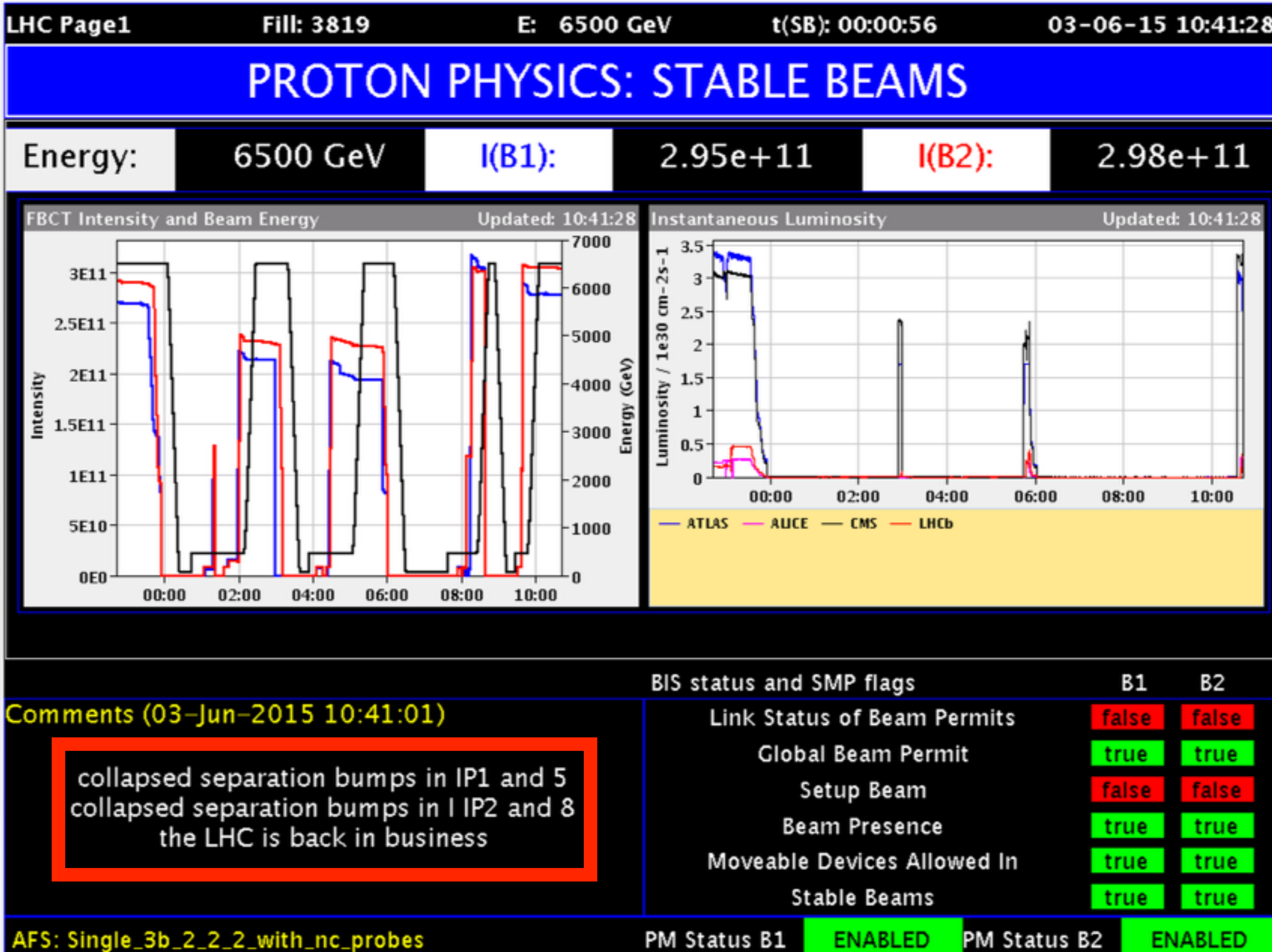
Milestones

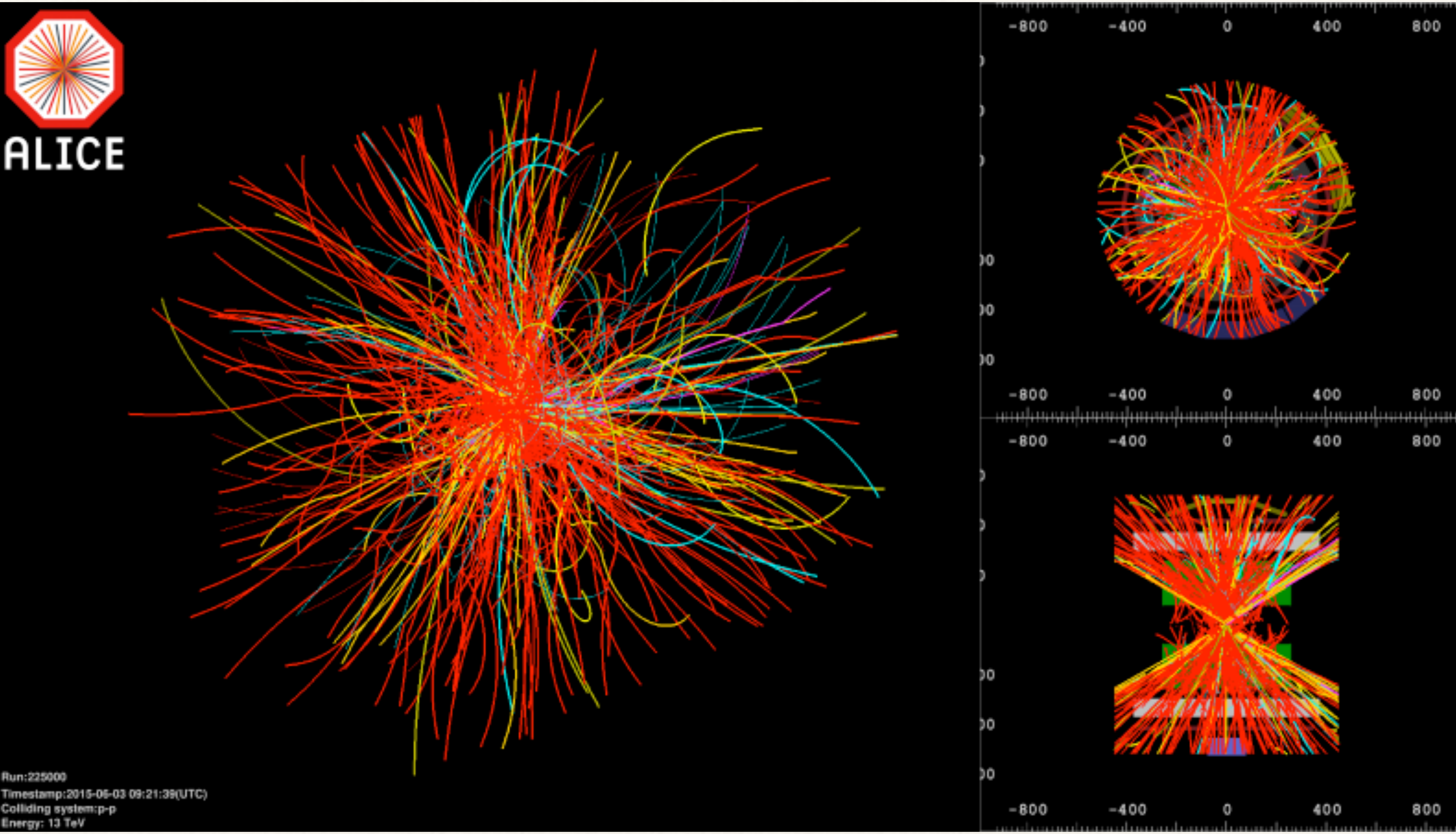
Circulating beam	Sunday 5th April
Ramp to 6.5 TeV	Friday 10th April
First 13 TeV collisions	Wednesday 20th May
First Stable beams	Wednesday 3rd June

THIS IS NOT BAD!



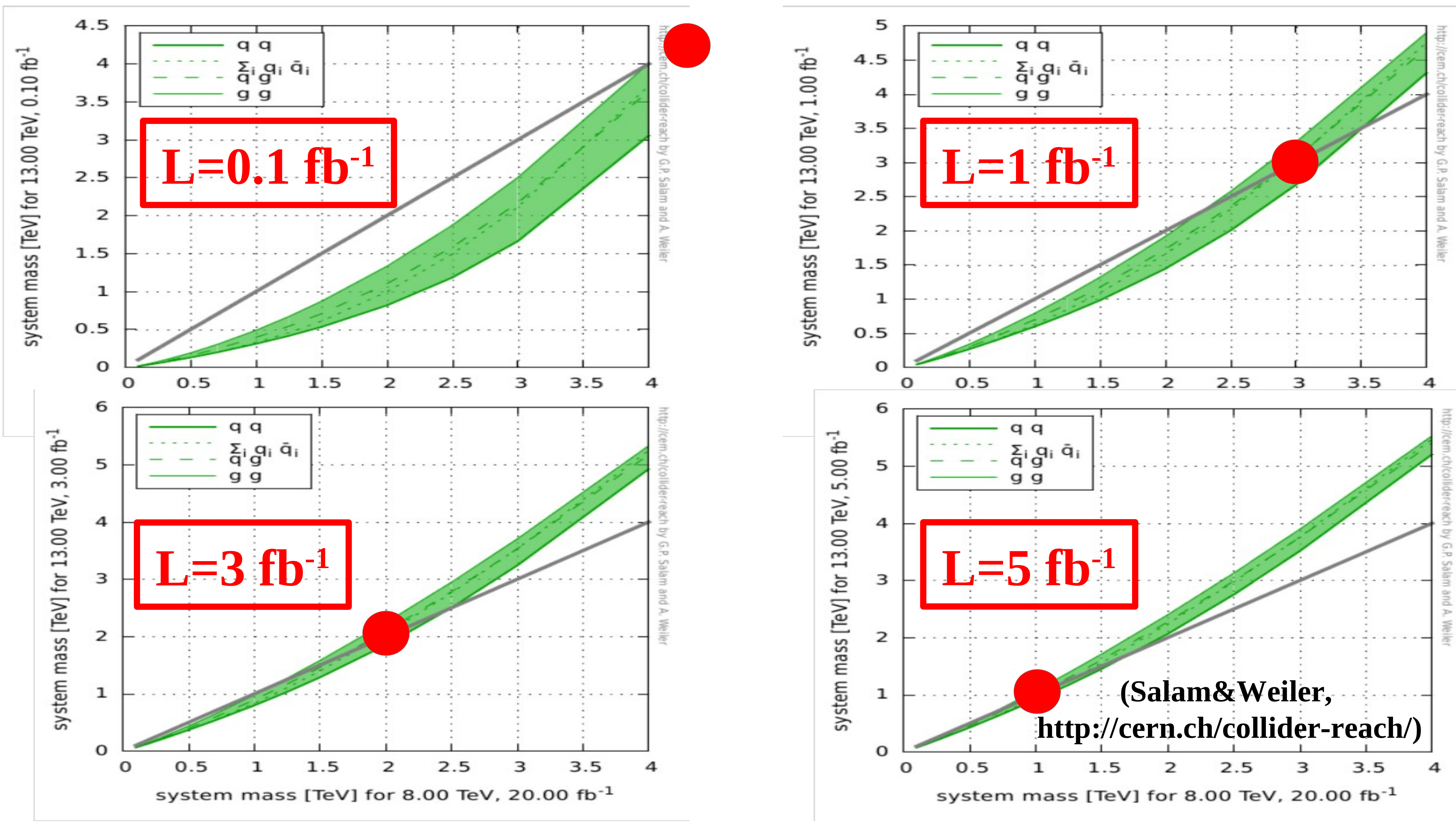
Wednesday: start of LHC Run 2




ALICE
-800 -400 0 400 800
-800 -400 0 400 800
-800 -400 0 400 800
-800 -400 0 400 800
Run:225000
Timestamp:2015-06-03 09:21:39(UTC)
Colliding system:p-p
Energy: 13 TeV

When does Run 2 match Run 1?

Physics: resonances in LHC Run2



- More sensitive than Run1 to masses ≳3 TeV with just 1 fb^{-1} in Run2
- Essentially better than Run1 for most searches with 5 fb^{-1} !

Alcaraz

13 TeV LHC through to 2018

(Current status today: 5+20fb^{-1} at 7+8TeV)

	Peak lumi E34 cm^{-2}s^{-1}	Days proton physics	Approx. int lumi [fb^{-1}]
2015	1.2	70	5 - 10
2016	1.5	160	35
2017	1.7	160	45
2018	1.7	40	10

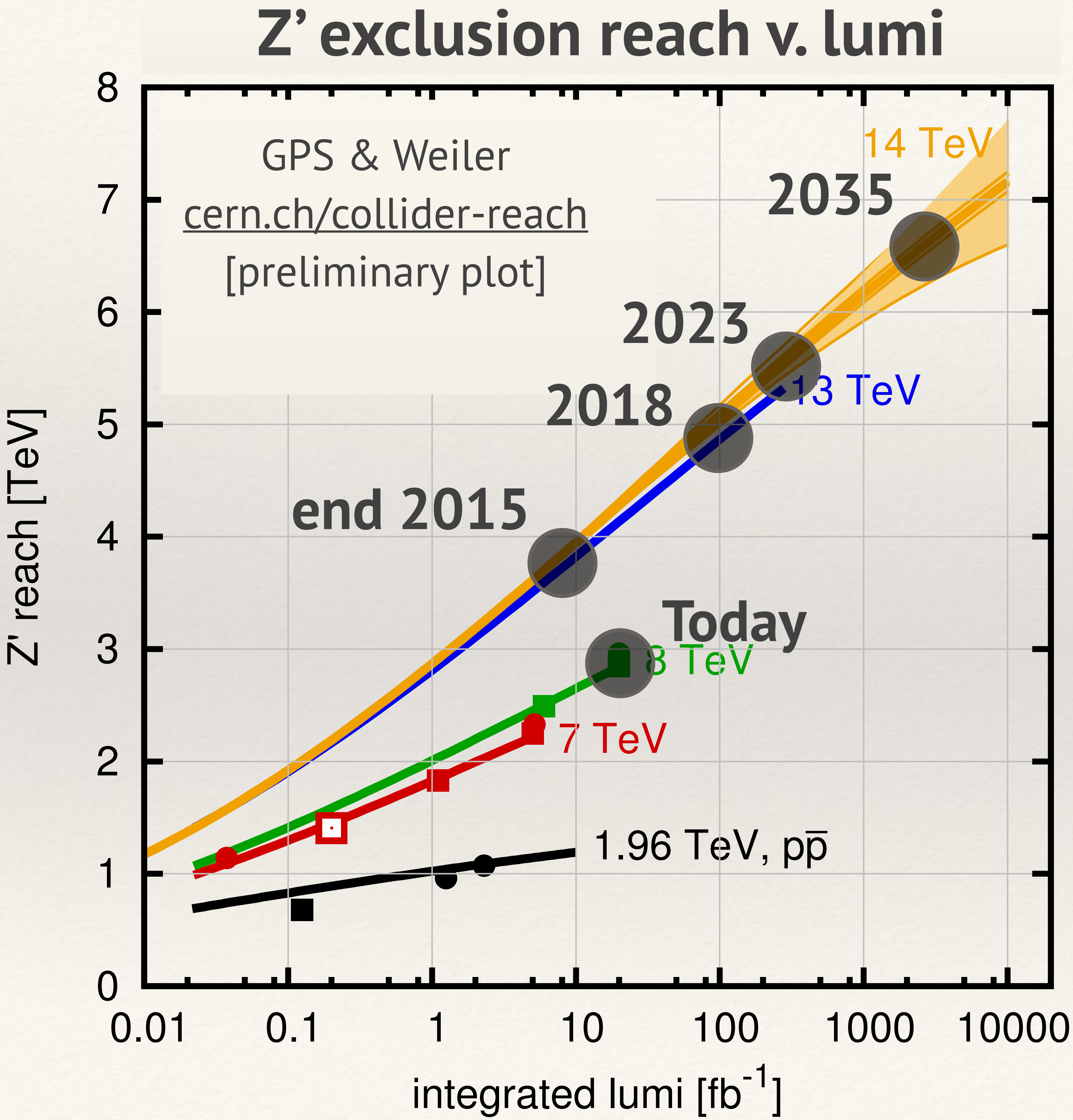
Lamont

total: 100 fb^{-1}

Impact for Higgs physics: 5x lumi, 2x cross section

→ roughly 10x more events

Implications for searches



By the end of the year, most searches will beat 8 TeV results

[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]

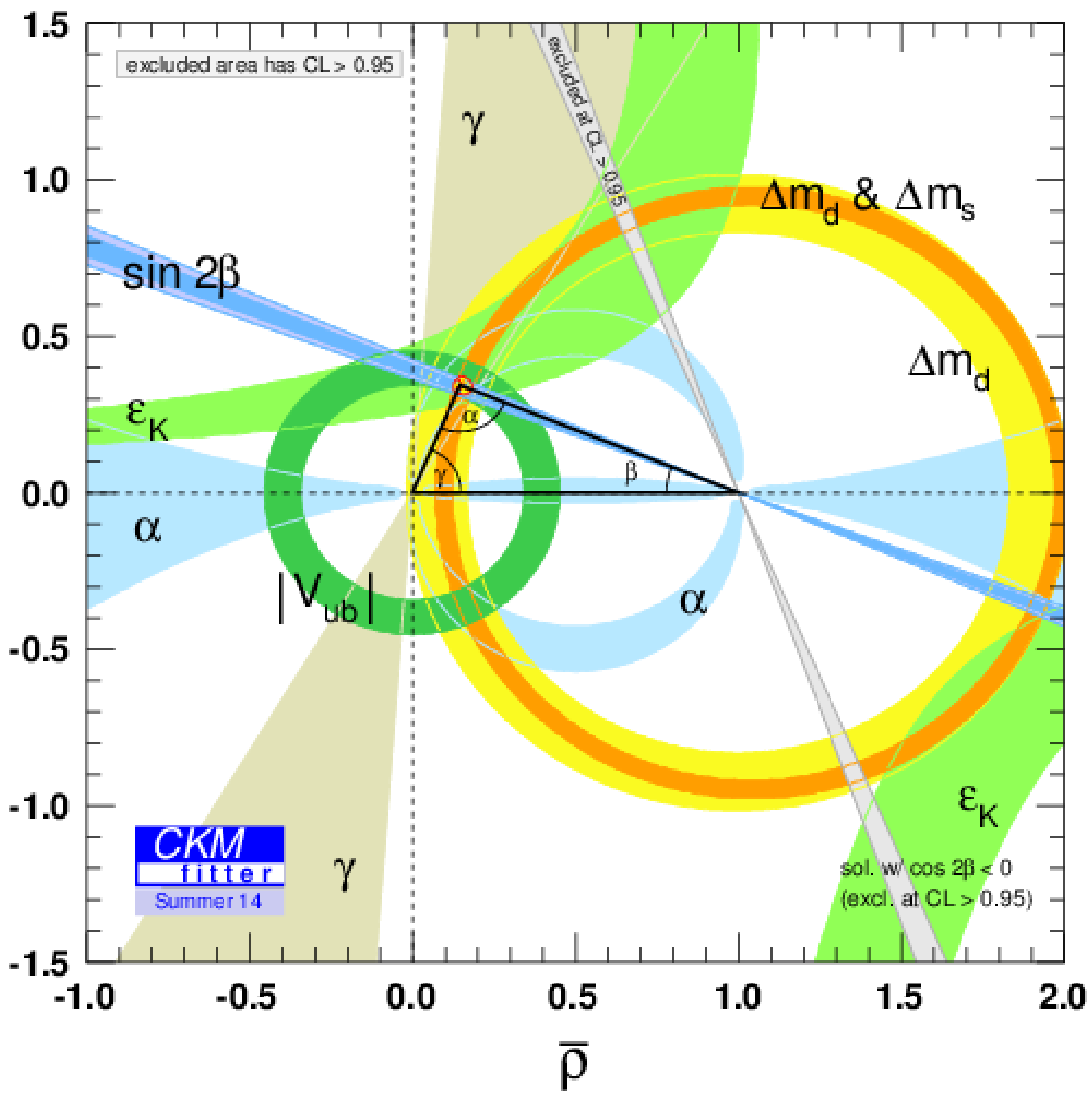
Subsequent years bring steady improvement

[quark] **flavour sector**

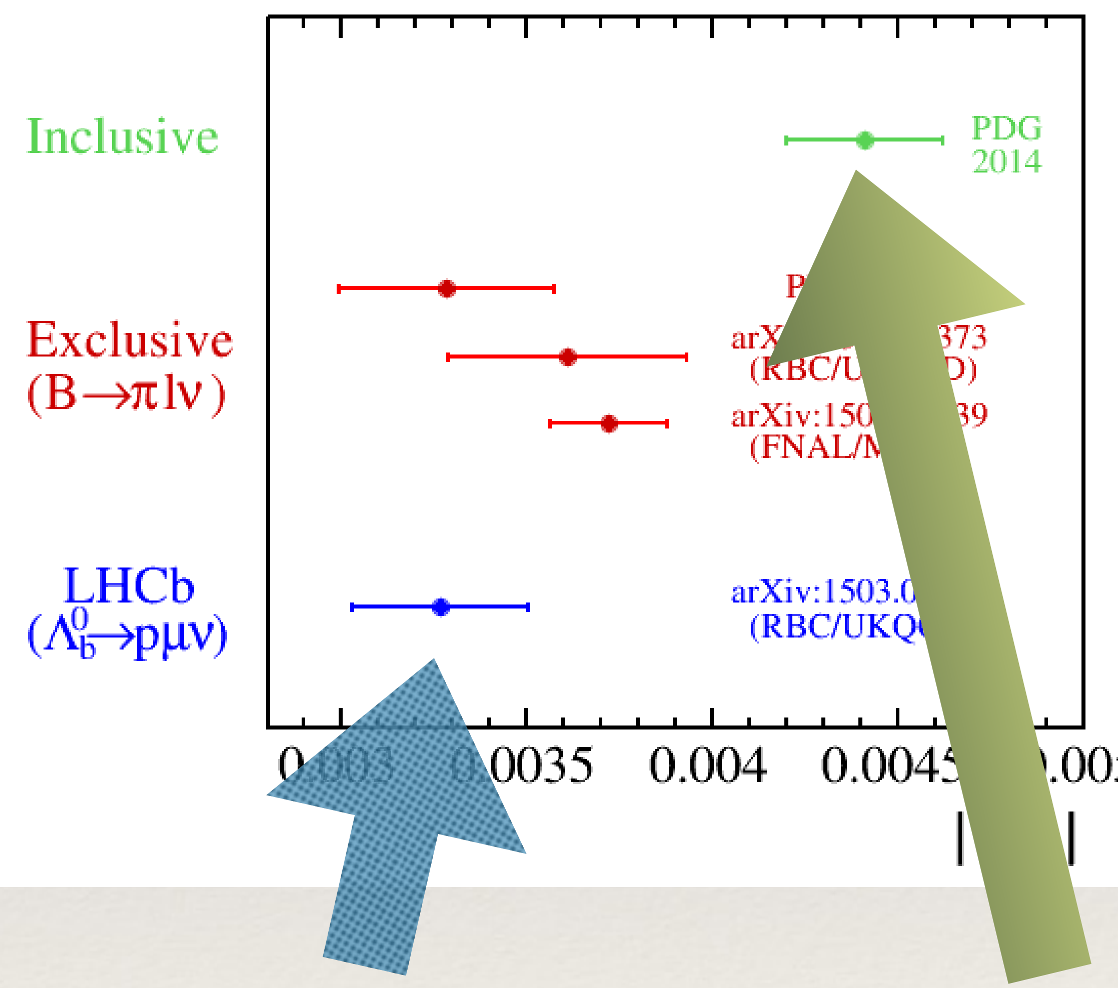
Gershon

CKM matrix

http://ckmfitter.in2p3.fr
see also http://www.utfit.org



$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$



Persistent tension between incl. & excl. V_{ub} confirmed in exclusive B-baryon decays

Rare decays

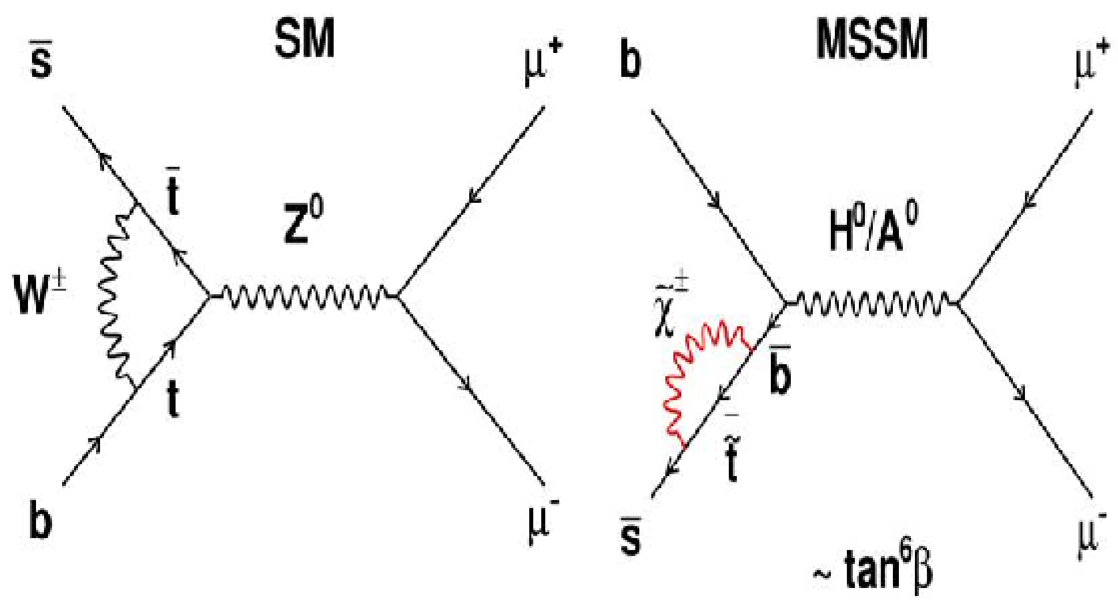
$$B_s \to \mu^+\mu^-$$

Nature 522 (2015) 68

Killer app. for new physics discovery

Very rare in Standard Model due to
- absence of tree-level FCNC
- helicity suppression
- CKM suppression

… all features which are not necessarily reproduced in extended models



$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.66 \pm 0.23) \times 10^{-9}$

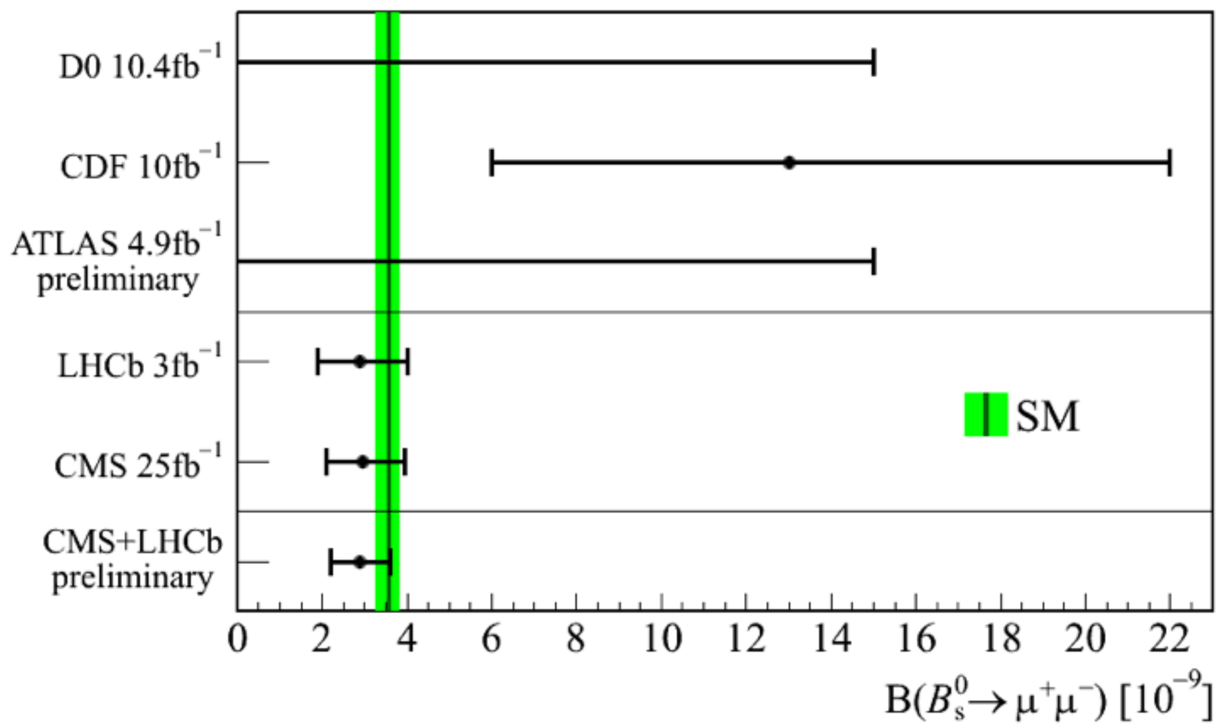
$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$

Recall Shelton's point about narrow Higgs width and how that makes Higgs decays sensitive to new physics

Flavour v. Higgs

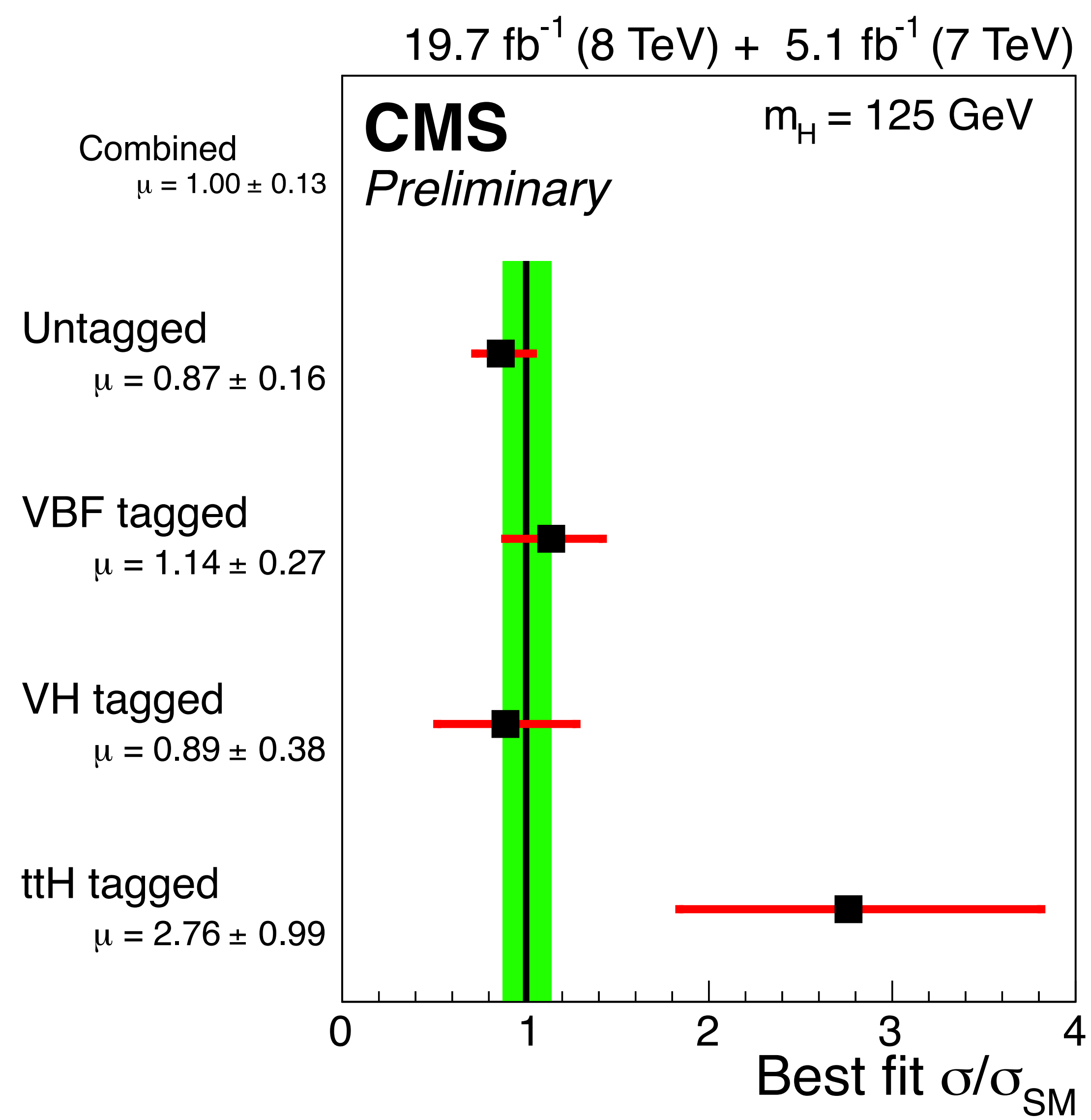
Haisch

Flavor data



$$\mu_{B_s \to \mu^+\mu^-} = 0.79 \pm 0.20$$

Higgs data

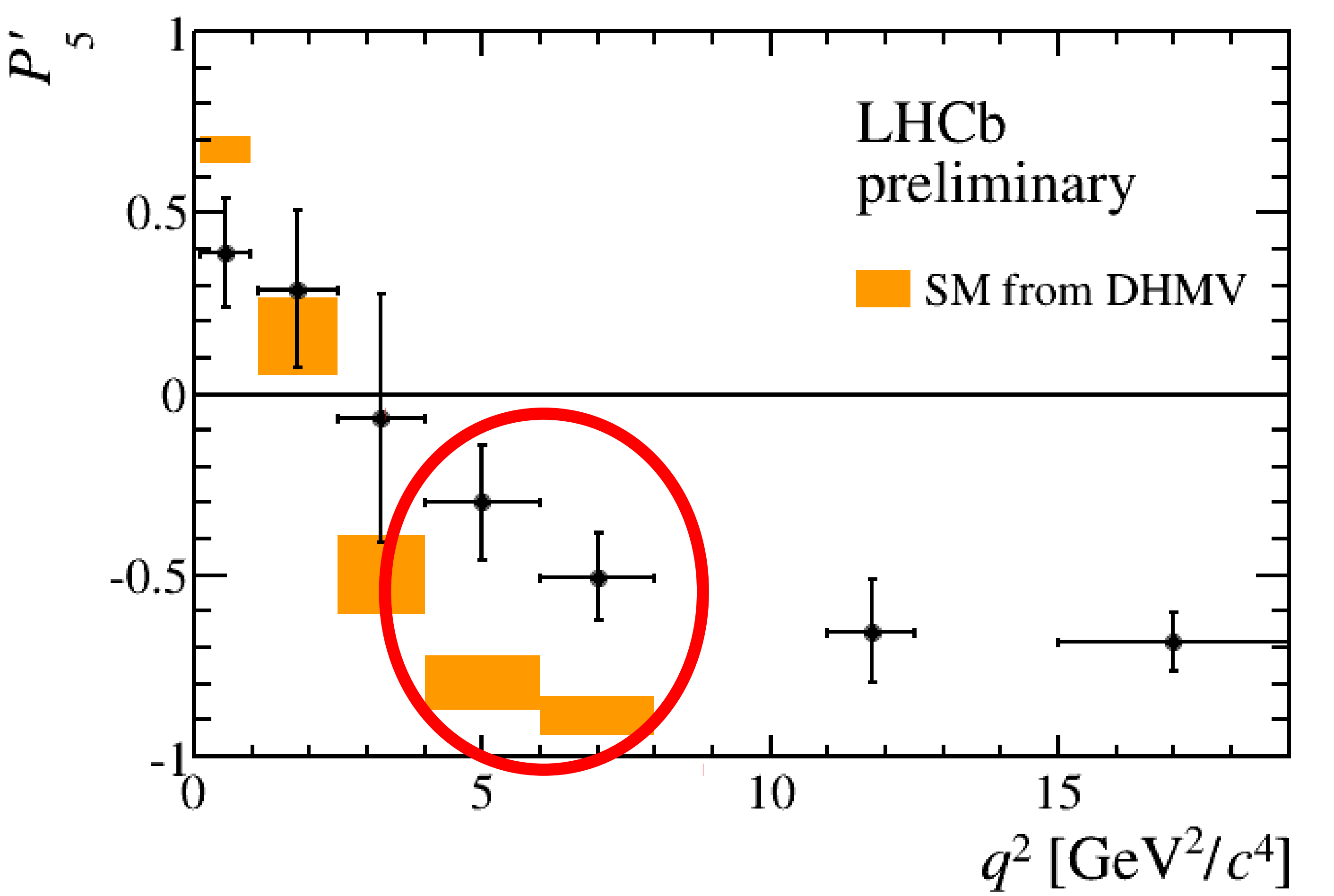


$$\mu_{\text{Higgs}} = 1.1 \pm 0.1$$

Comparable precisions; comparable BSM scale sensitivity $\gtrsim$ 0.6-0.8 TeV

Tensions

$B^0 \to K^{*0}\mu^+\mu^-$ Tension in P_5'

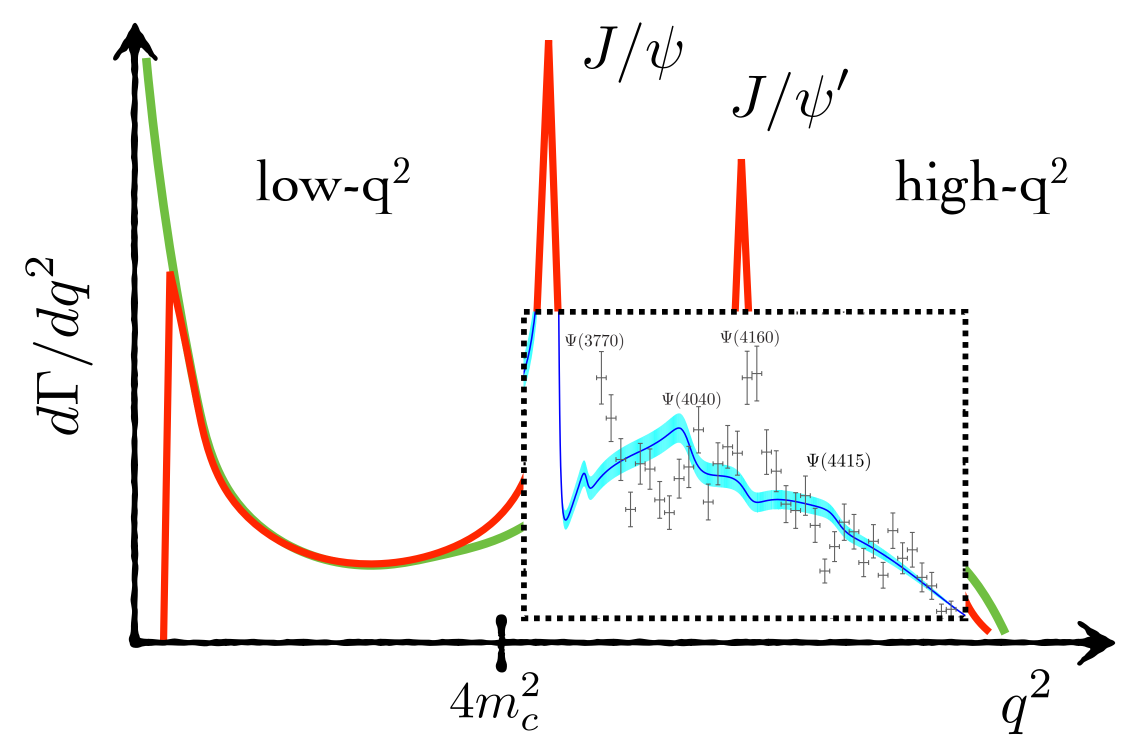


Gershon LHCb results

- Error budget of P_5' in [4, 6] GeV^2 bin:

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$

A closer look



Haisch: > 10pages of backup discussion

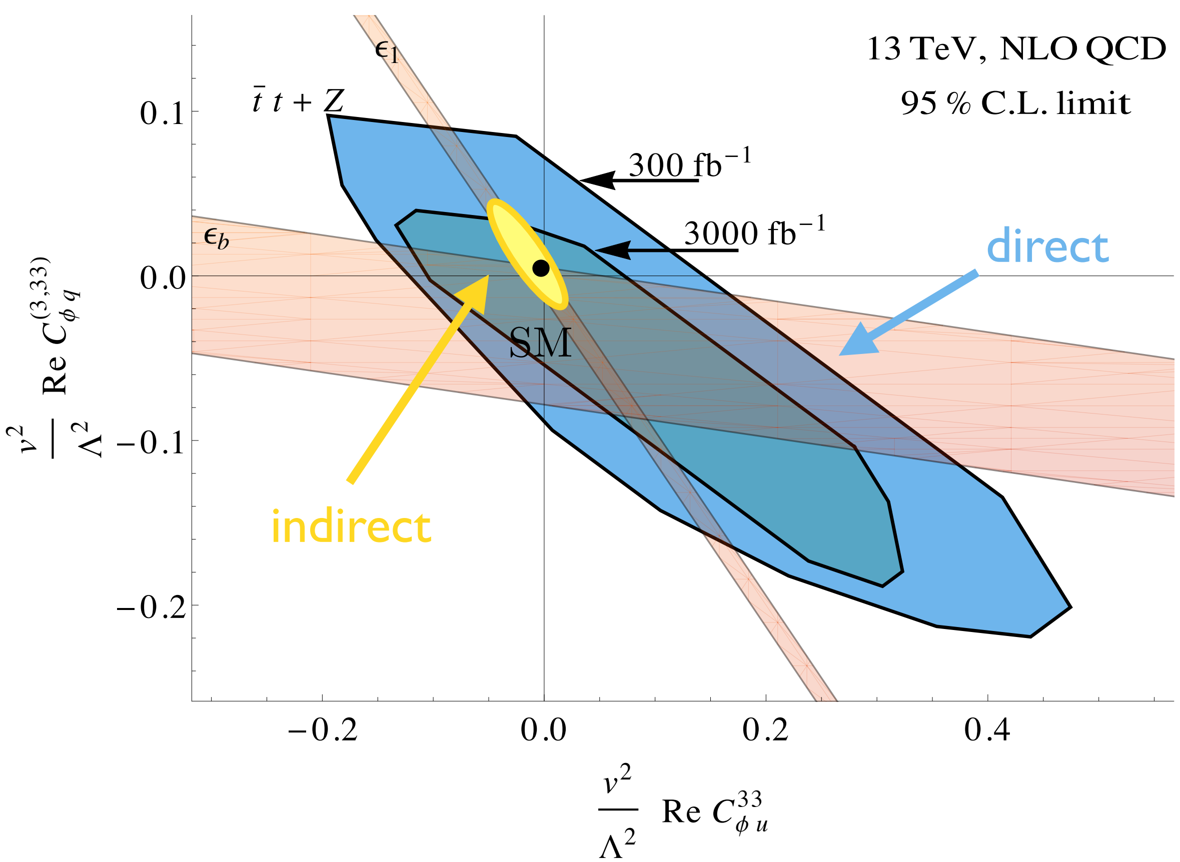
XYZ spires

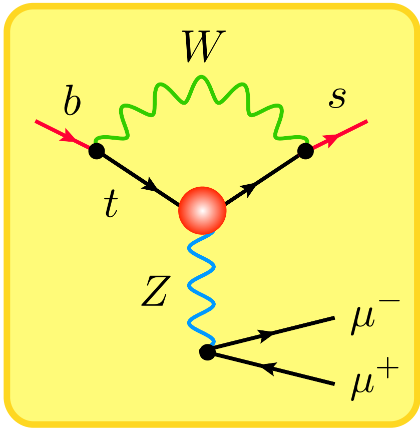
hadron physics is tough

top getting into the flavour game

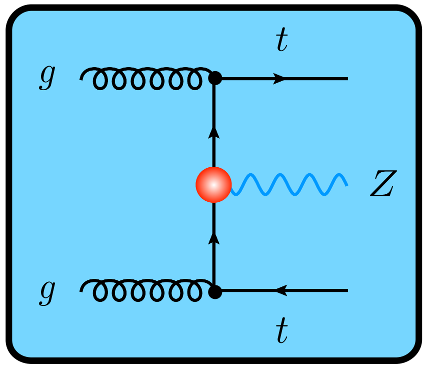
Haisch

$t\bar{t}Z$ couplings: Comparison





[Brod et al., 1408.0792]



[Röntsch & Schulze, 1404.1005]

- Indirect bounds stronger than direct limits for $t\bar{t}Z$ couplings. Still worth looking at $pp \to t\bar{t}Z$, as cancellation in former case possible

14/28

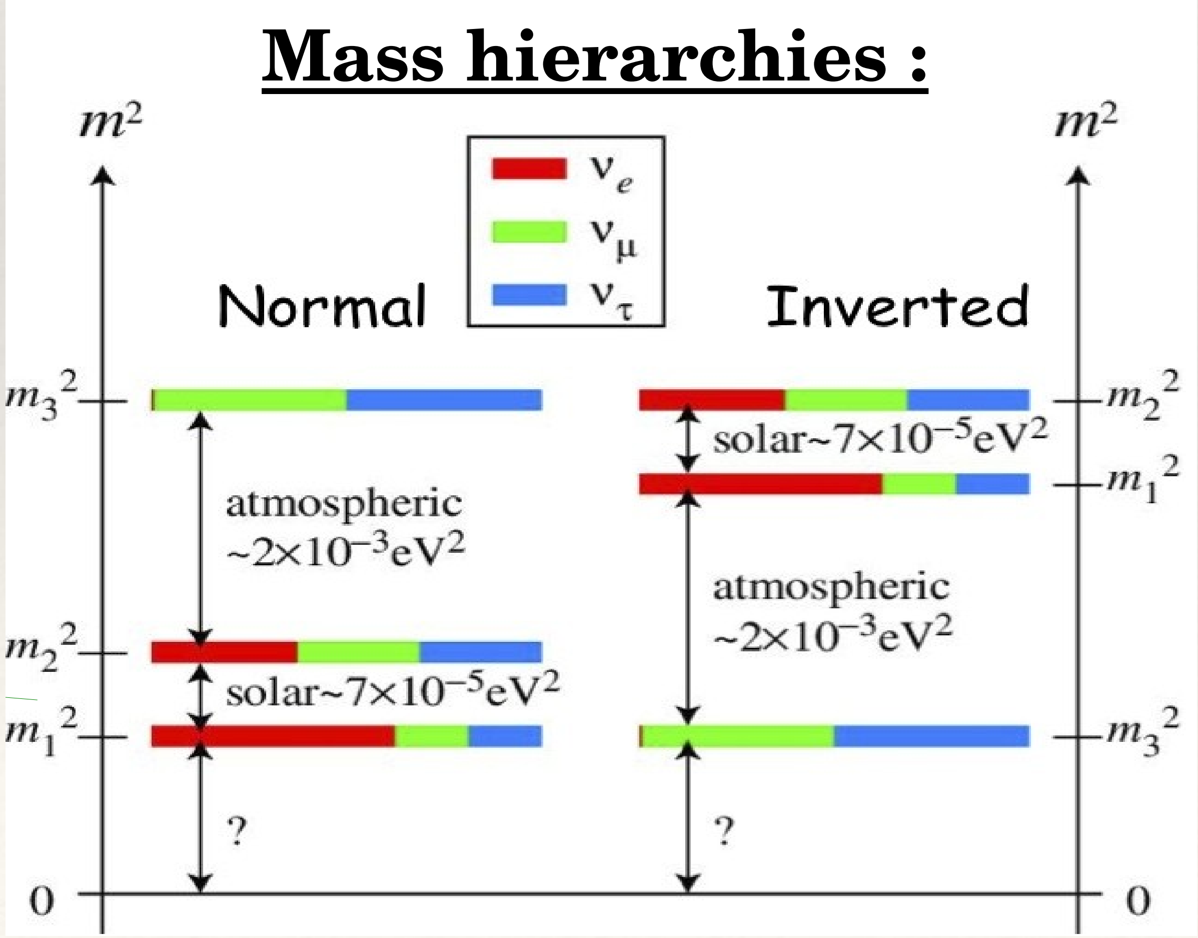
neutrinos

(& lepton sector more generally)

could large CP violation in neutrino sector account for baryon asymmetry of universe?

status

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$



Key open questions

Absolute mass scale

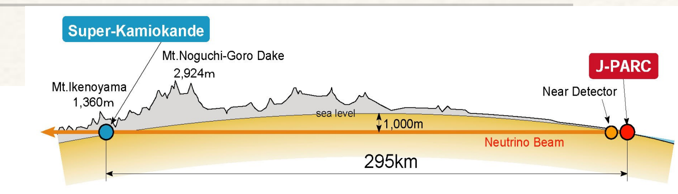
Mass hierarchy

Amount of CP violation
(some 2σ hints that it's large)

Majorana or Dirac?

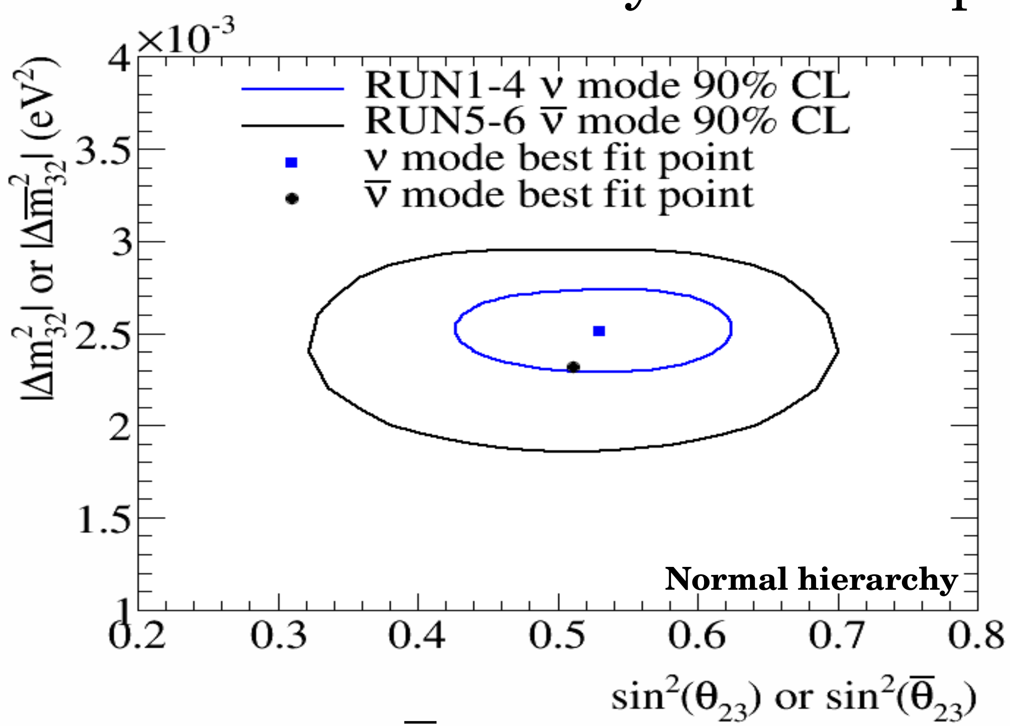
Sterile neutrinos?

New T2K $\bar{\nu}_\mu$ disappearance



1) w/ the T2K ν_μ disappearance results (using 6.6 x 10^{20} POT)

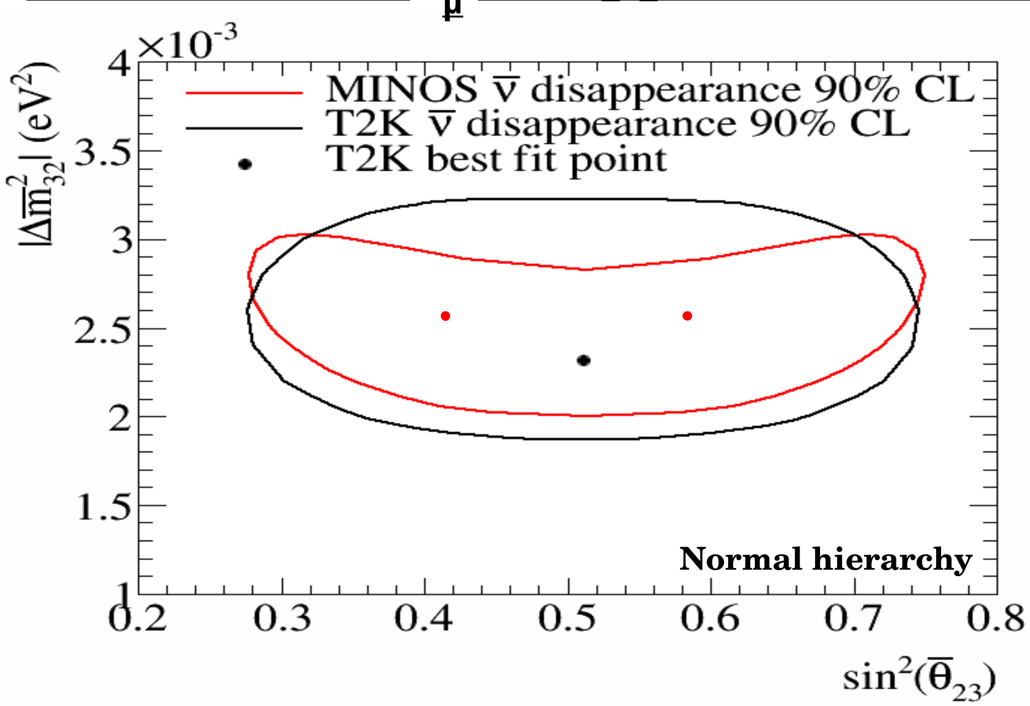
→ CPT can be directly tested comparing neutrino / antineutrino disappearance :



$$P(\nu_\mu \rightarrow \nu_\mu) \xrightarrow{\text{CPT}} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

Neutrino and antineutrino results are perfectly consistent within the errors
=> No hint of CPT violation

2) w/ MINOS $\bar{\nu}_\mu$ disappearance results

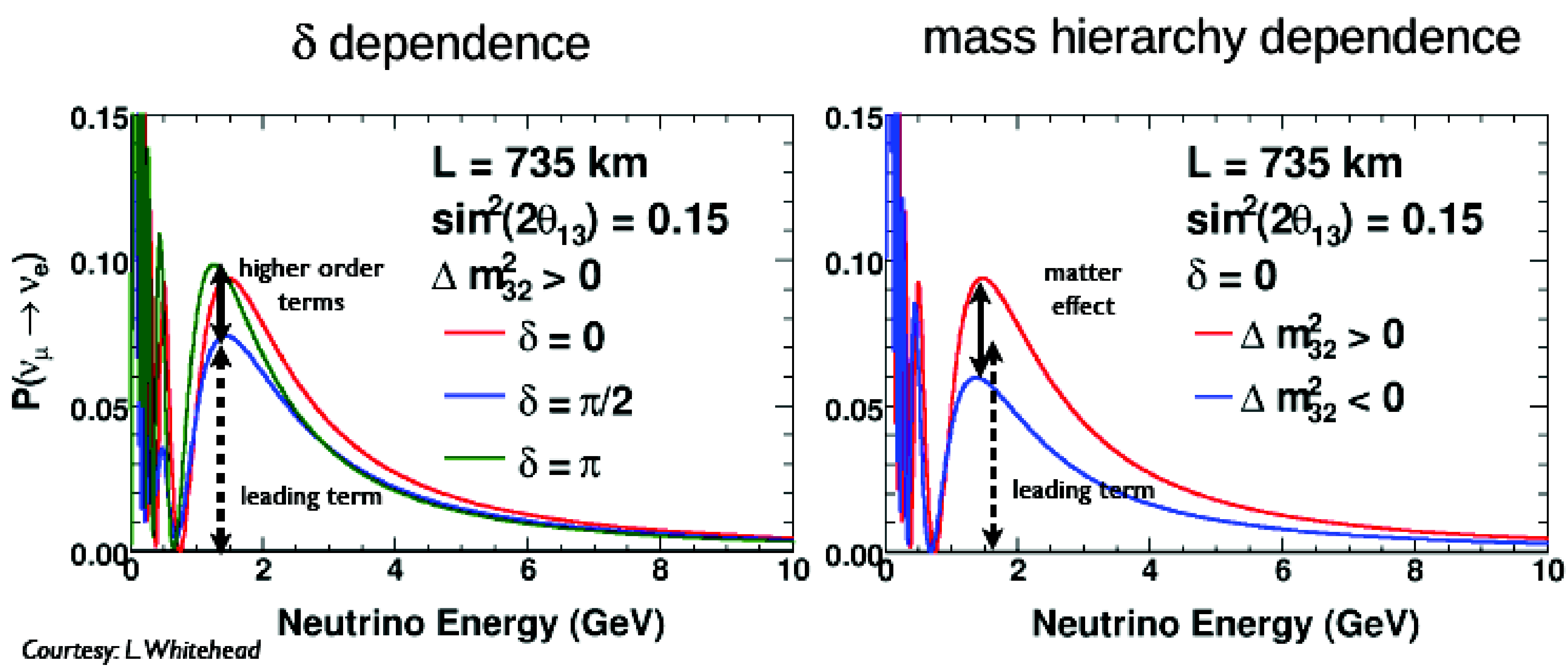


1. **Sensitivity to $\bar{\Theta}_{23}$ already comparable to MINOS**

2. **No significant discrepancy between MINOS & T2K in $\bar{\nu}_\mu$**
(though MINOS prefer non maximal-mixing)

Get CP phase δ and hierarchy?

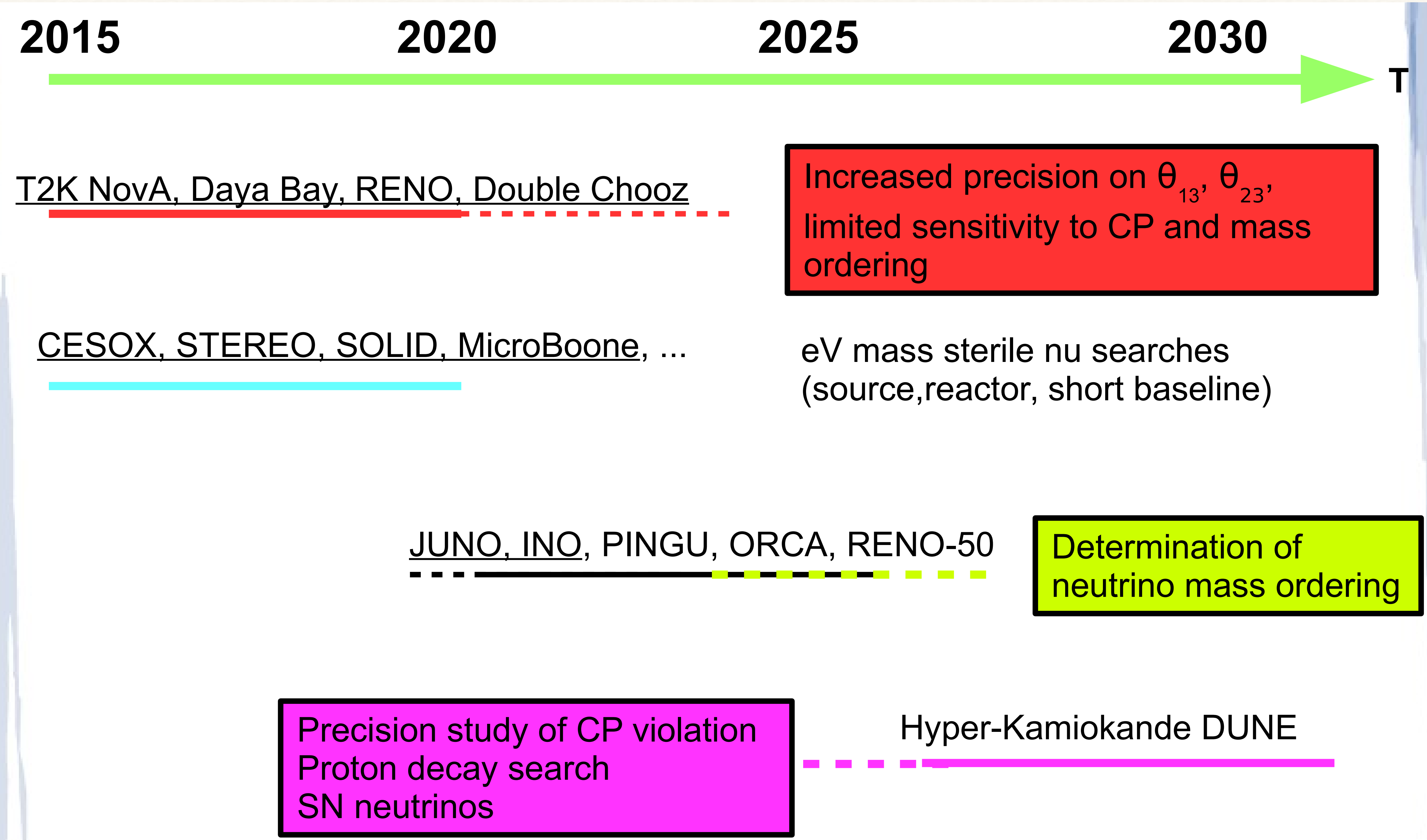
The matter with CP



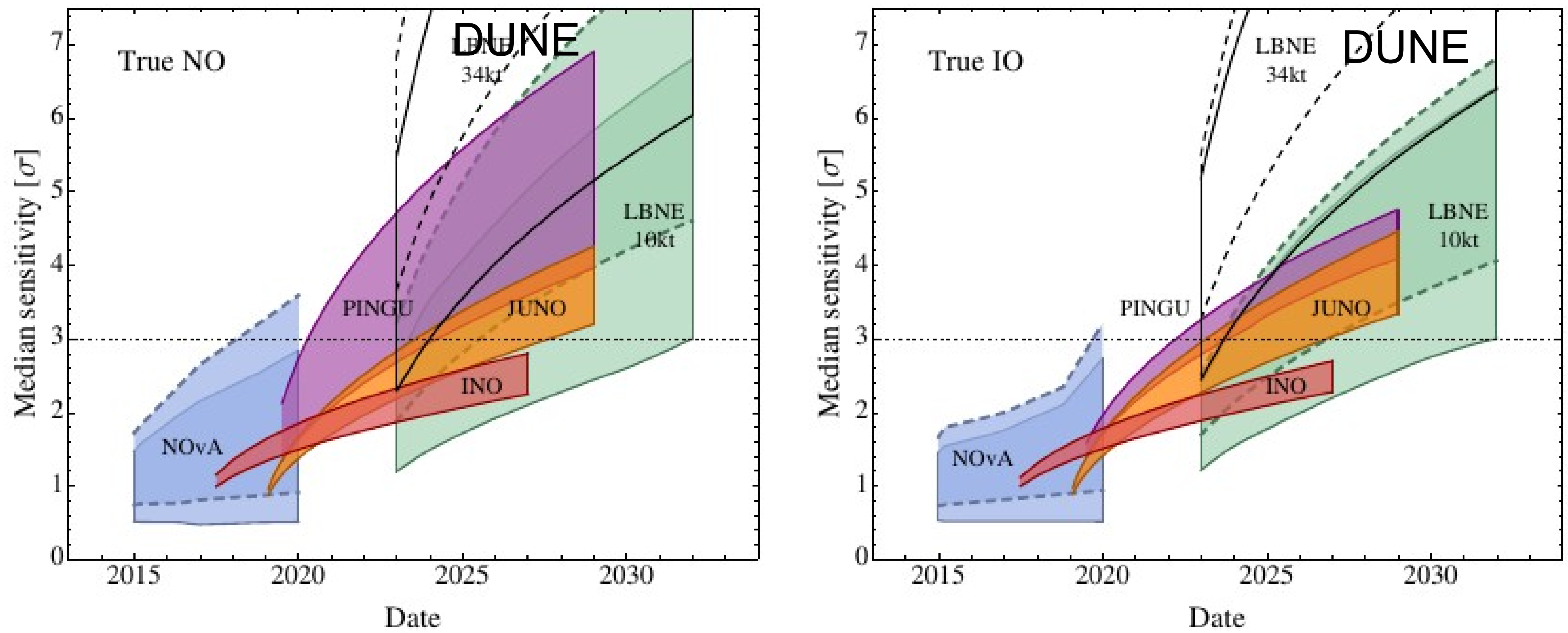
signal is difference in neutrino and anti-neutrino muon → electron appearance rate

Difficulty: matter effects do the same & depend on hierarchy

ν physics timeline



Mass ordering timeline



Caution: median sensitivity, starting dates indicative.

absolute mass scale?

Gonzalez-Garcia

Presently only Bounds

- From Tritium β decay (Mainz & Troisk expe)

  $m_{\nu_e} < 2.2$ eV (95%)

  Katrin (2016?) Sensitivity to $m_{\nu_e} \sim 0.2\,\text{eV}$

- From $0\nu\beta\beta$ decay for Majorana Neutrinos

  $m_{ee} < 0.14 - 0.76$ eV (90%)

  Goal of Next Decade $\Rightarrow$ m_{ee} at IO

- From Analysis of Cosmological data

  Bound on $\sum m_\nu$ changes with:

  cosmo parameters fix in analysis

  cosmo observables considered

Model	Observables	Σm_ν (eV) 95%
$\Lambda\text{CDM} + m_\nu$	Planck TT + lowP	≤ 0.72
$\Lambda\text{CDM} + m_\nu$	Planck TT + lowP + lensing	≤ 0.68
$\Lambda\text{CDM} + m_\nu$	Planck TT,TE,EE + lowP+lensing	≤ 0.59
$\Lambda\text{CDM} + m_\nu$	Planck TT,TE,EE + lowP	≤ 0.49
$\Lambda\text{CDM} + m_\nu$	Planck TT + lowP + lensing + BAO + SN + H_0	≤ 0.23
$\Lambda\text{CDM} + m_\nu$	Planck TT,TE,EE + lowP+ BAO	≤ 0.17

Charged lepton sector

Feruglio

muon, the major player

	present upper bound		future sensitivity	
$BR(\mu^+ \to e^+\gamma)$	5.7×10^{-13}	[MEG]	6×10^{-14}	[MEG ~2018]
$BR(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}	[SINDRUM]	$\approx10^{-16}$	[Mu3e>2019]
$CR(\mu^- Ti \to e^- Ti)$	4.3×10^{-12}	[SINDRUM II]		
$CR(\mu^- Au \to e^- Au)$	7.0×10^{-13}	[SINDRUM II]		
$CR(\mu^- Al \to e^- Al)$			$(2\div6)\times10^{-17}$	[Mu2e>2018]
$CR(\mu^- Al \to e^- Al)$			$\approx3\times10^{-17}$	[COMET>2019]

great improvements expected within this decade
4-5 orders of magnitude: a golden age for CLFV searches

more ambicious project under Study both at FNAL and at J-PARC aiming at 10^{-18}

l	$d_l(e\,cm)$
e	$<8.7\times10^{-29}$
μ	$<1.8\times10^{-19}$
τ	$<10^{-16}$

l	$\Delta a_l = a_l^{EXP} - a_l^{SM}$
e	$(-10.5\pm8.1)\times10^{-13}$
μ	$(29\pm9)\times10^{-10}$
τ	$-0.007<\Delta a_\tau<0.005$

[more on this later on]

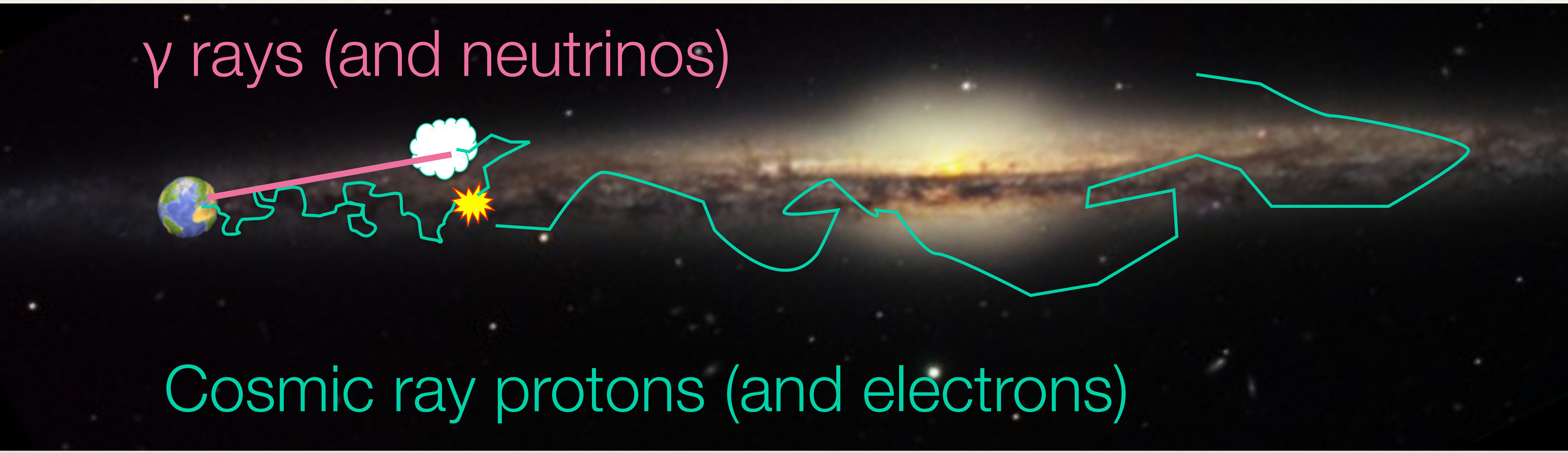
3.2 σ

soon checked by Muon g-2 at Fermilab > 2017 improving accuracy from 0.5 ppm to 0.2 ppm

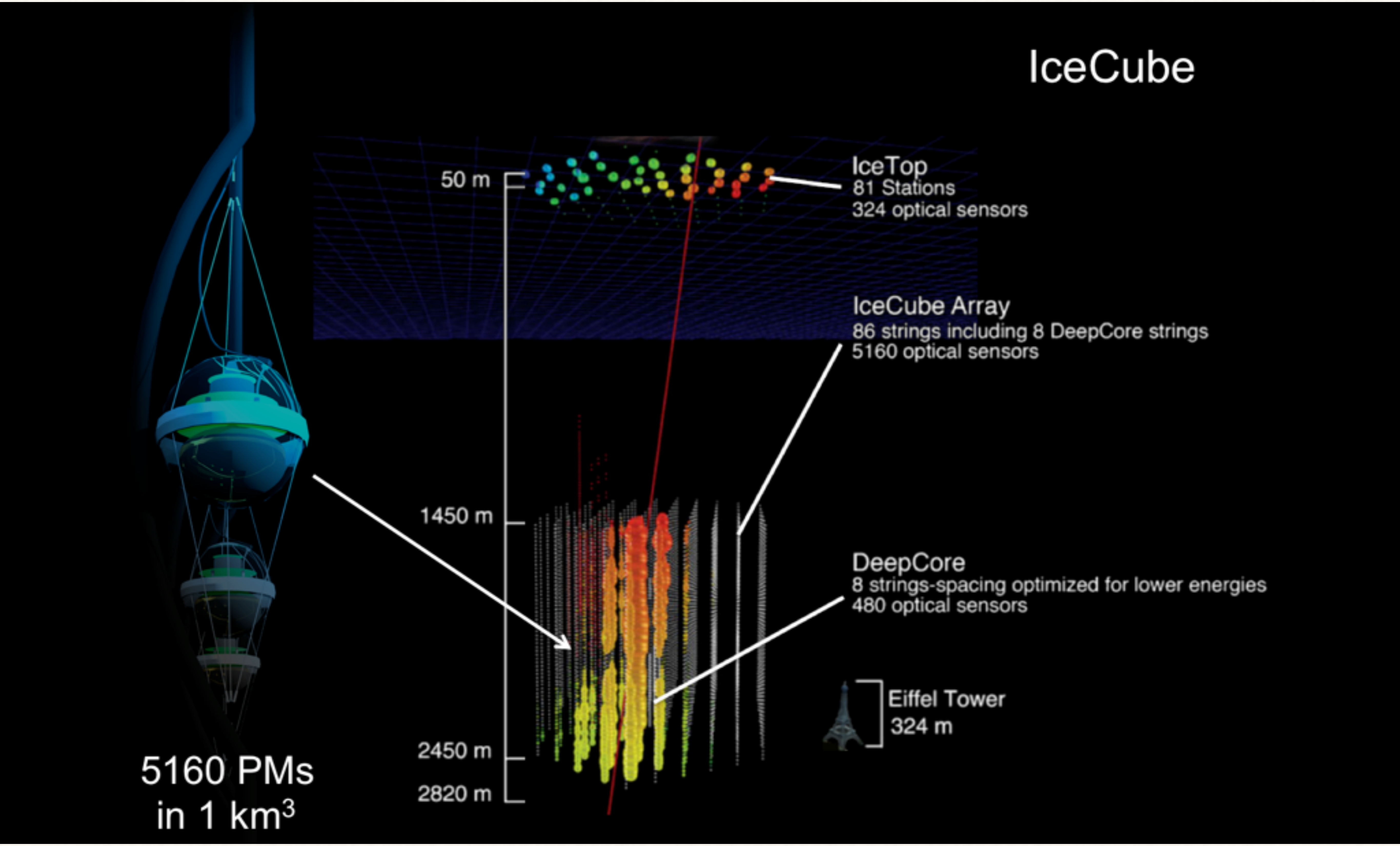
Cosmic-rays

charged v. neutral

Funk



new kid on the block: neutrinos

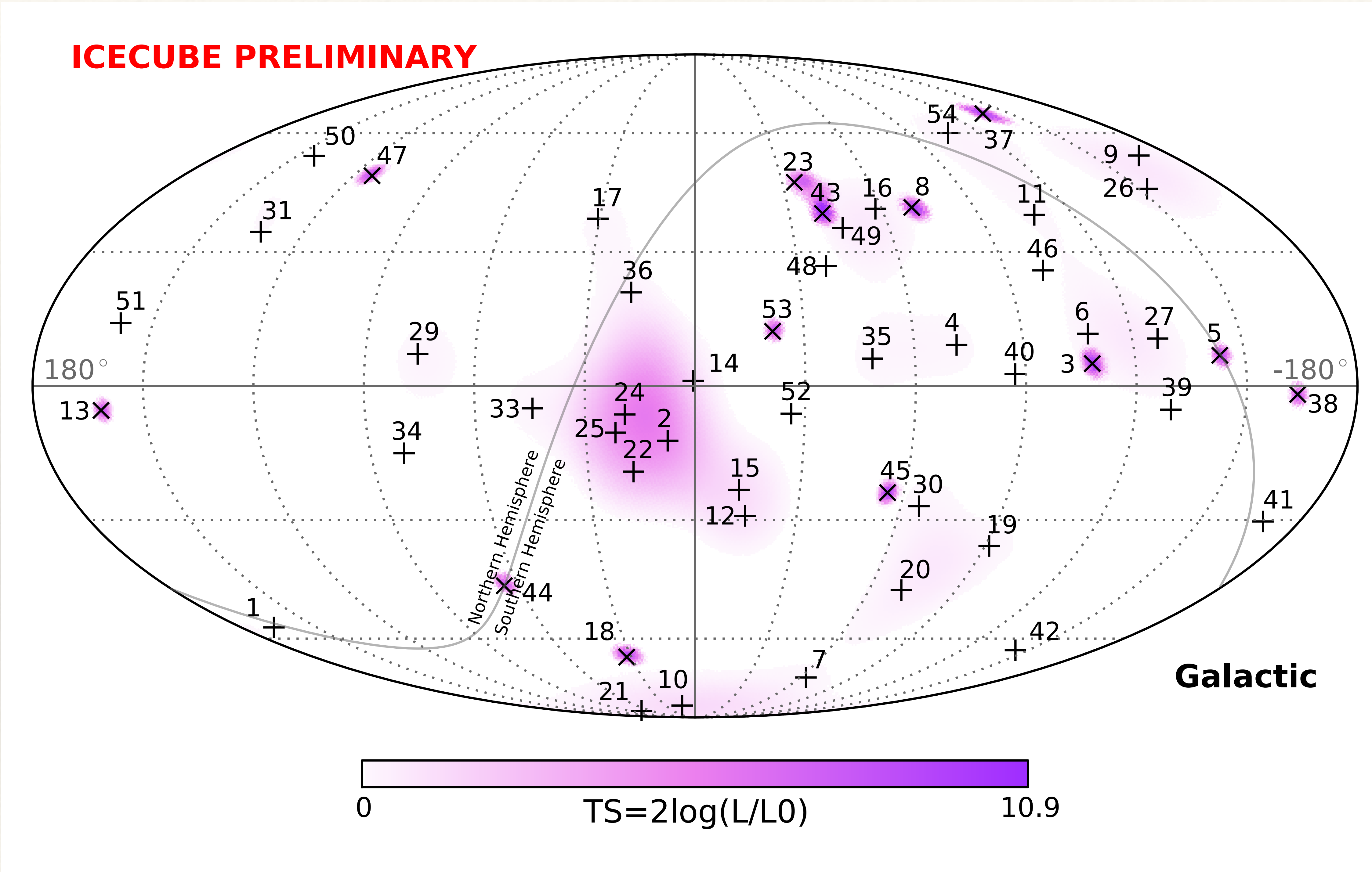


IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km³

Halzen

birth of neutrino astronomy

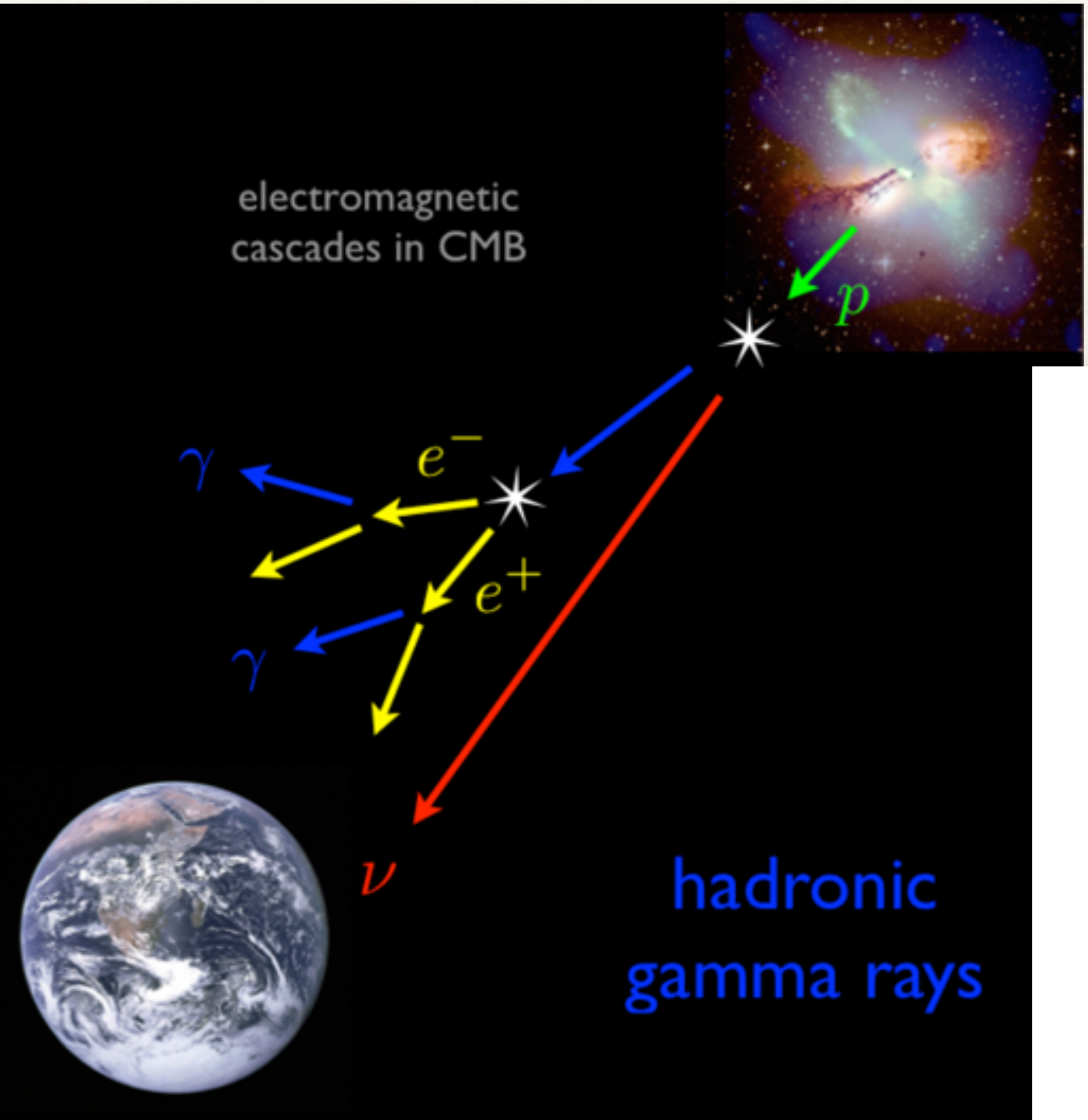
Halzen

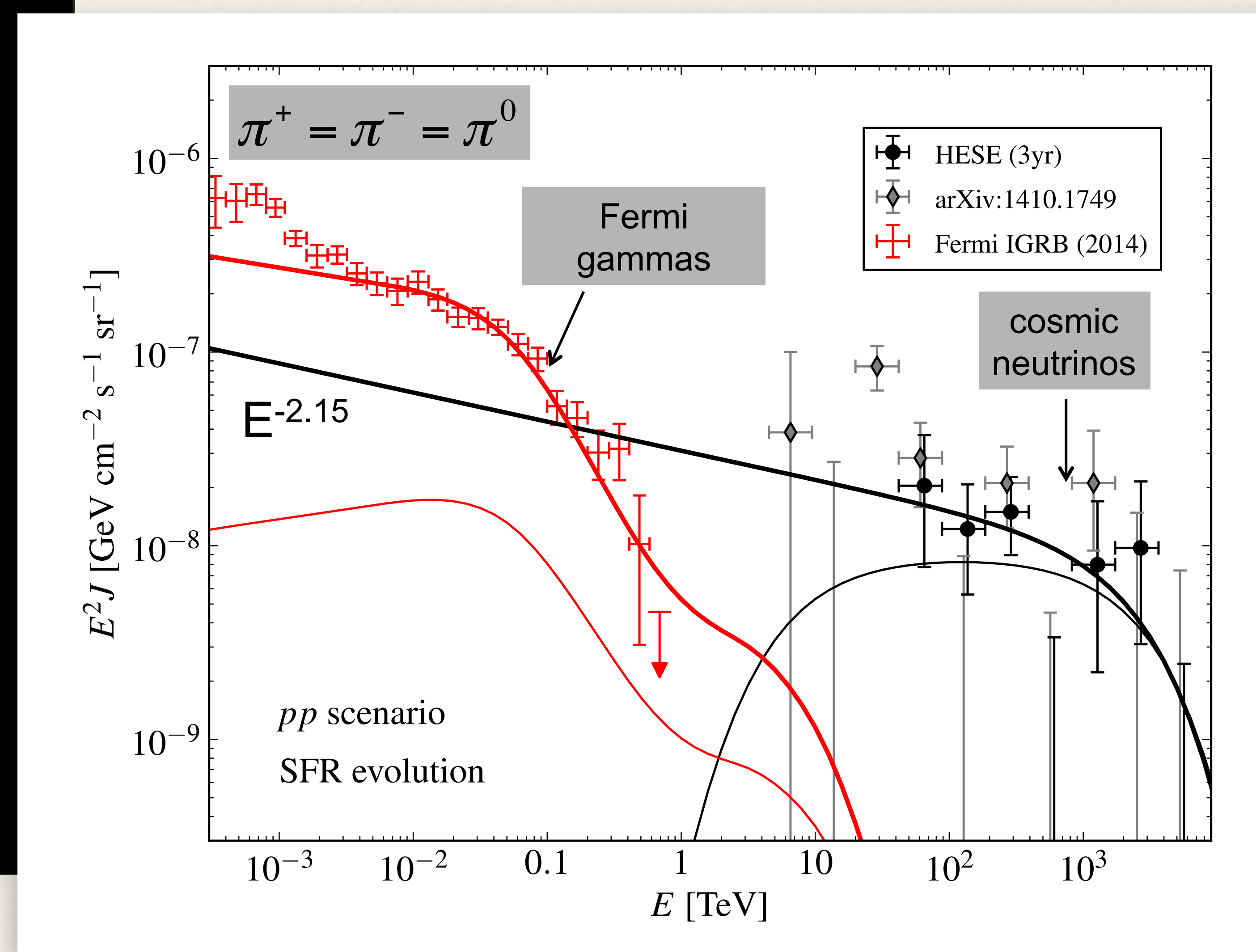


time &/or directional clustering yet to be detected

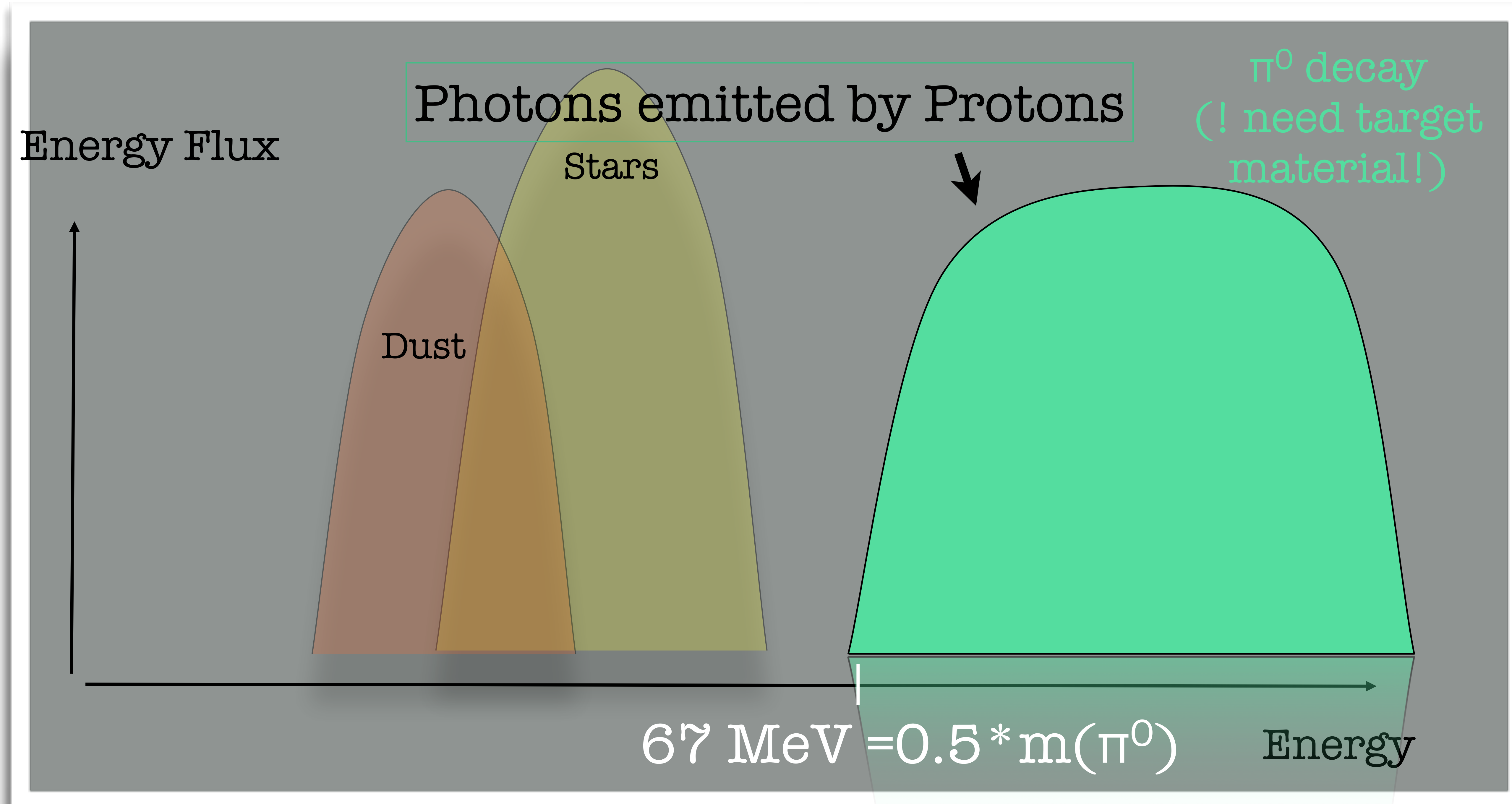
Do gamma rays and neutrinos have same origin?

Halzen

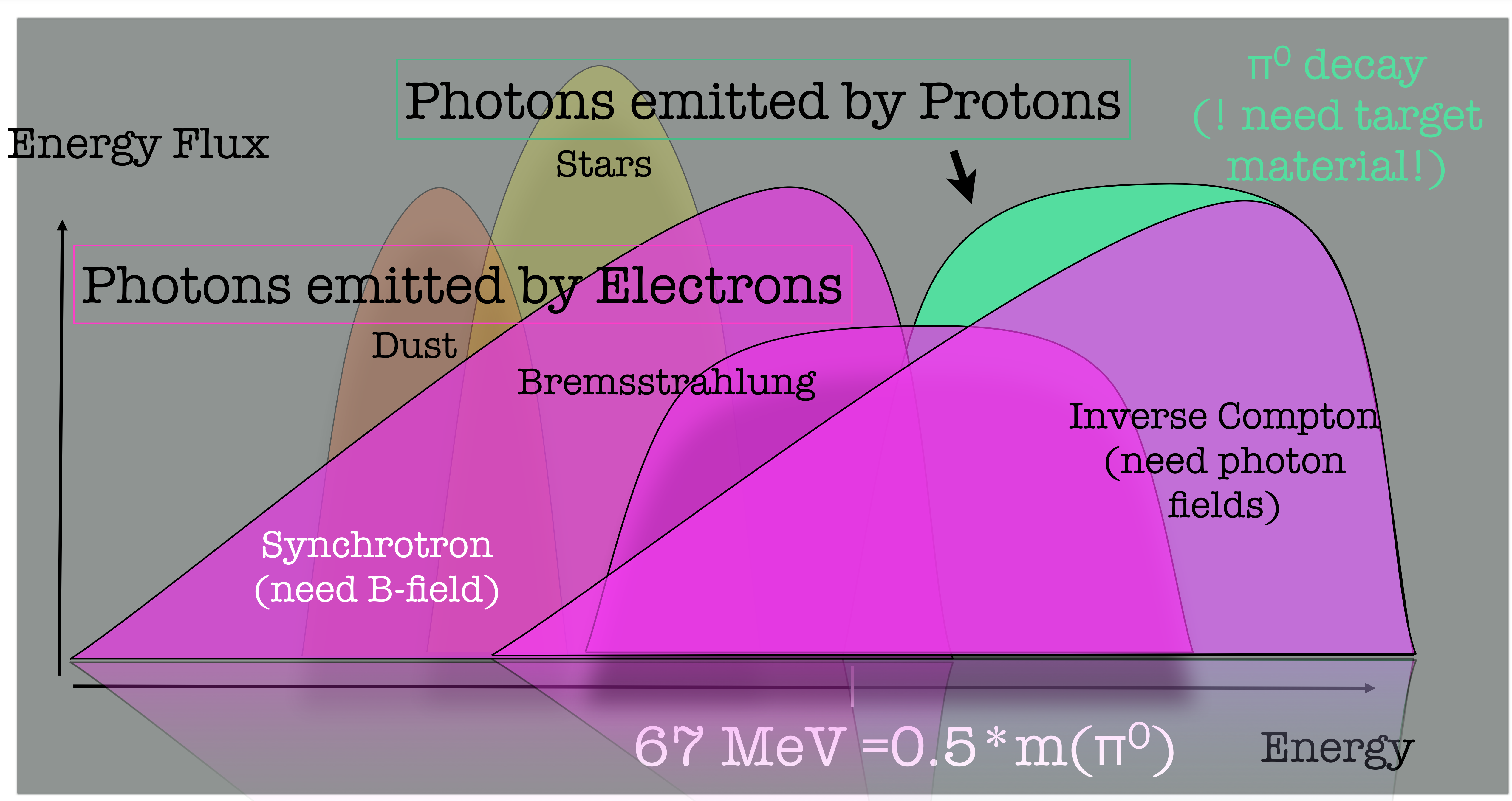




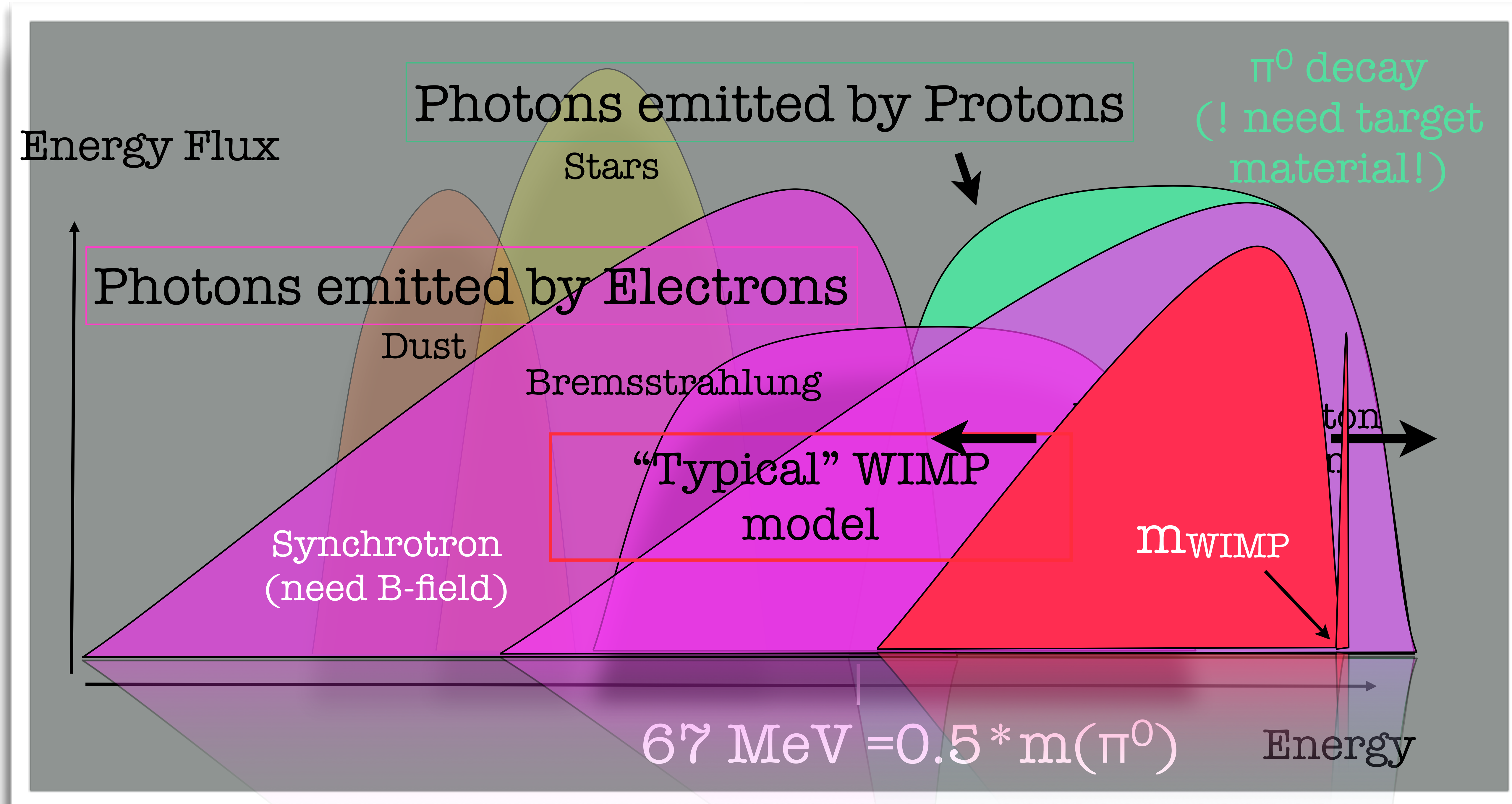
Gamma-ray emission

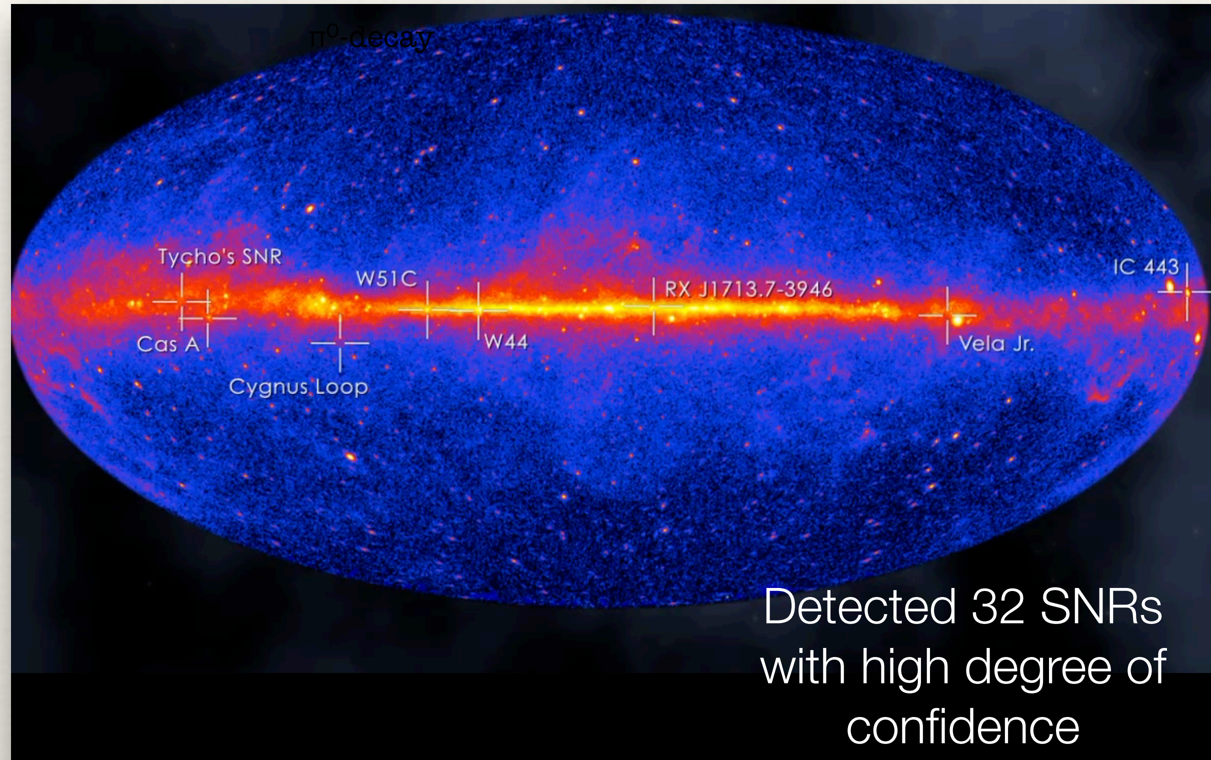


Gamma-ray emission

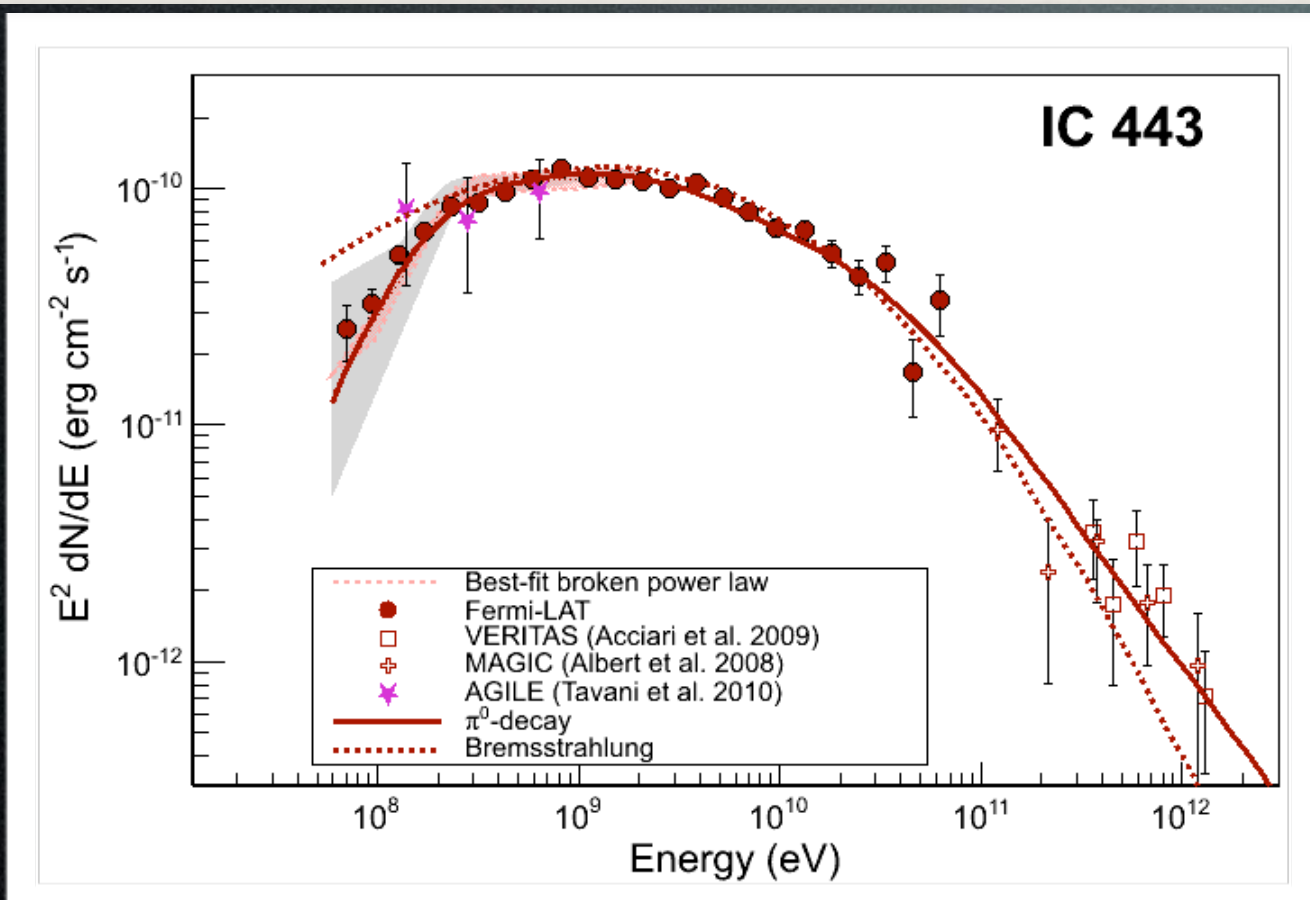


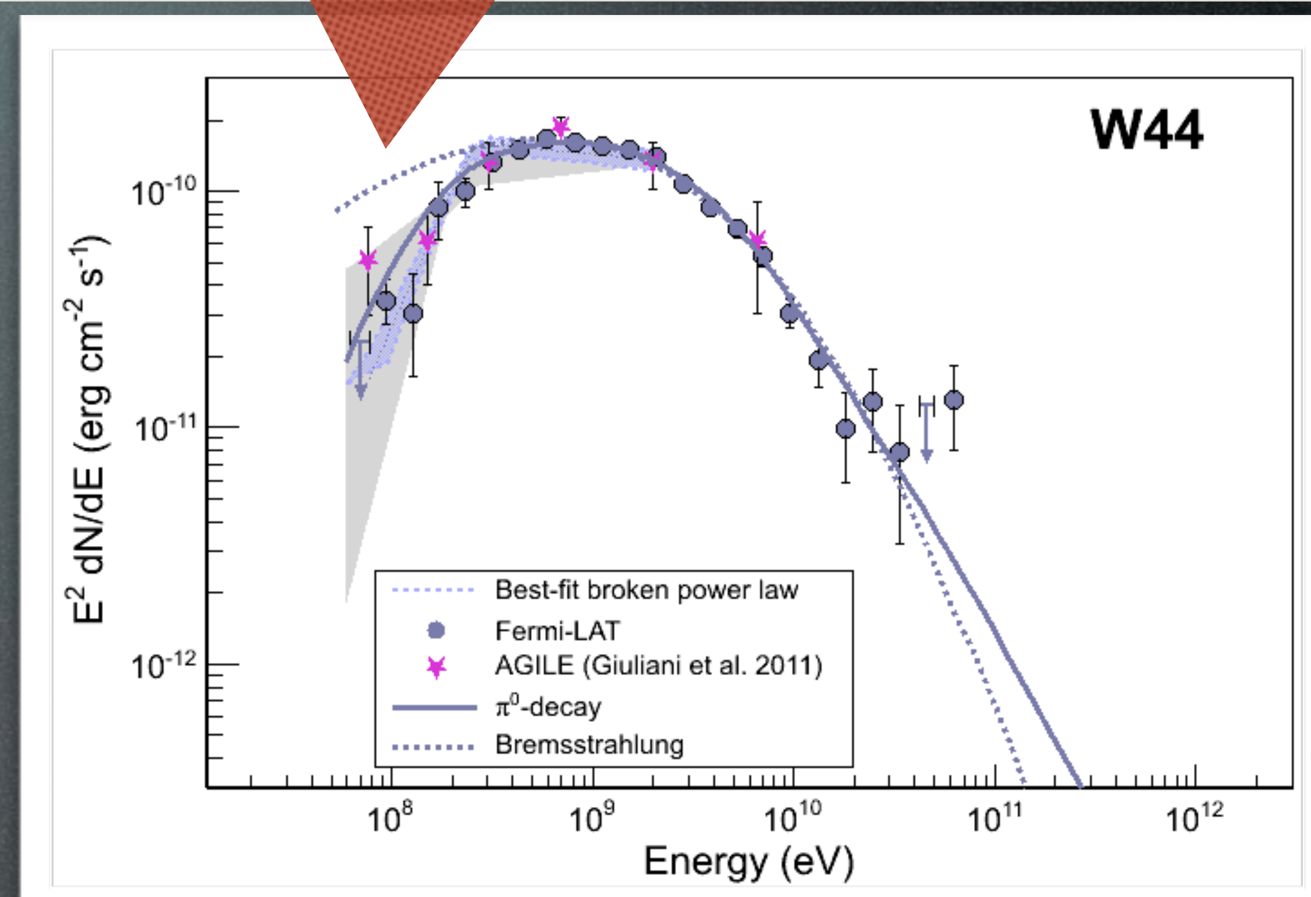
Gamma-ray emission



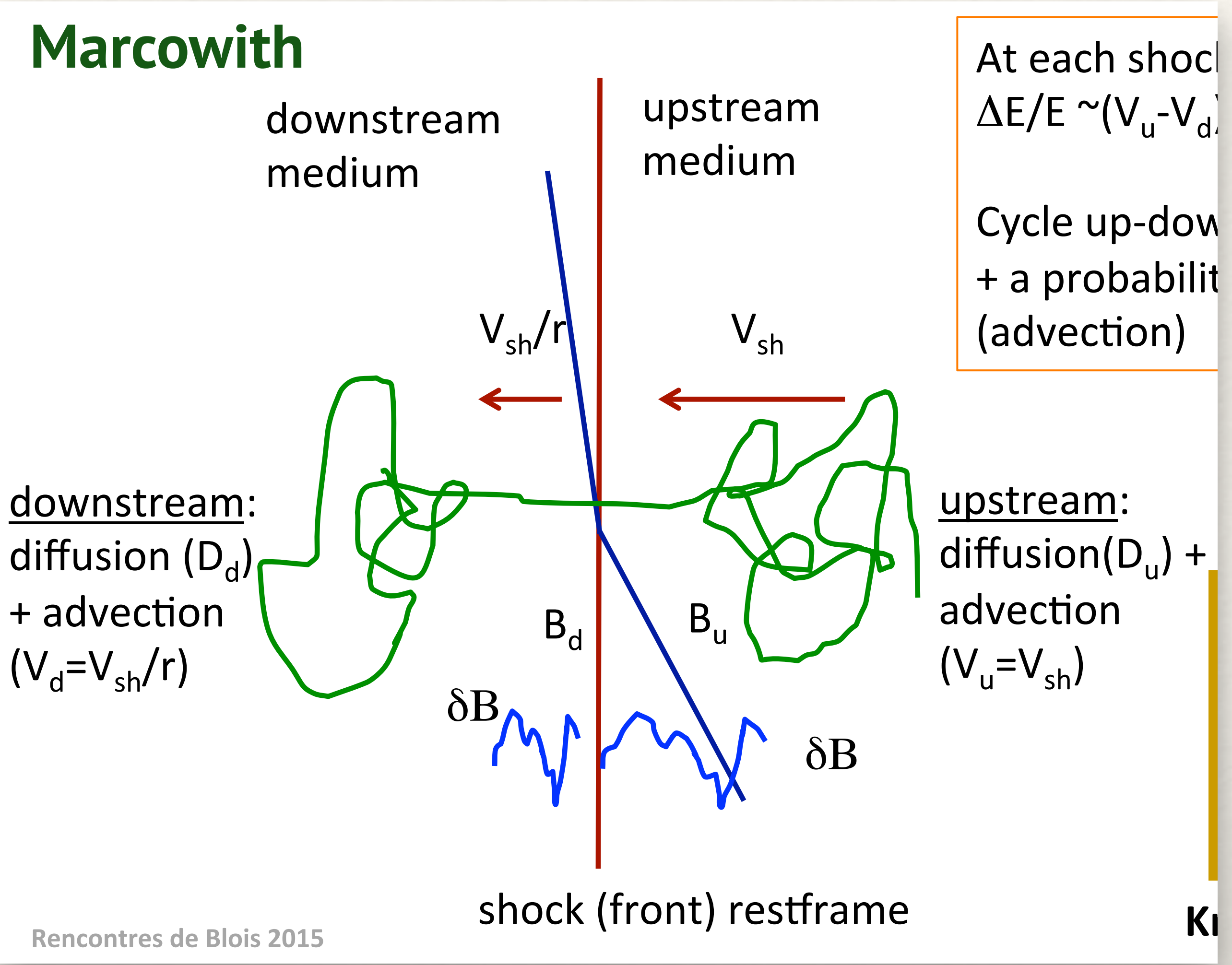


pion bump(?)



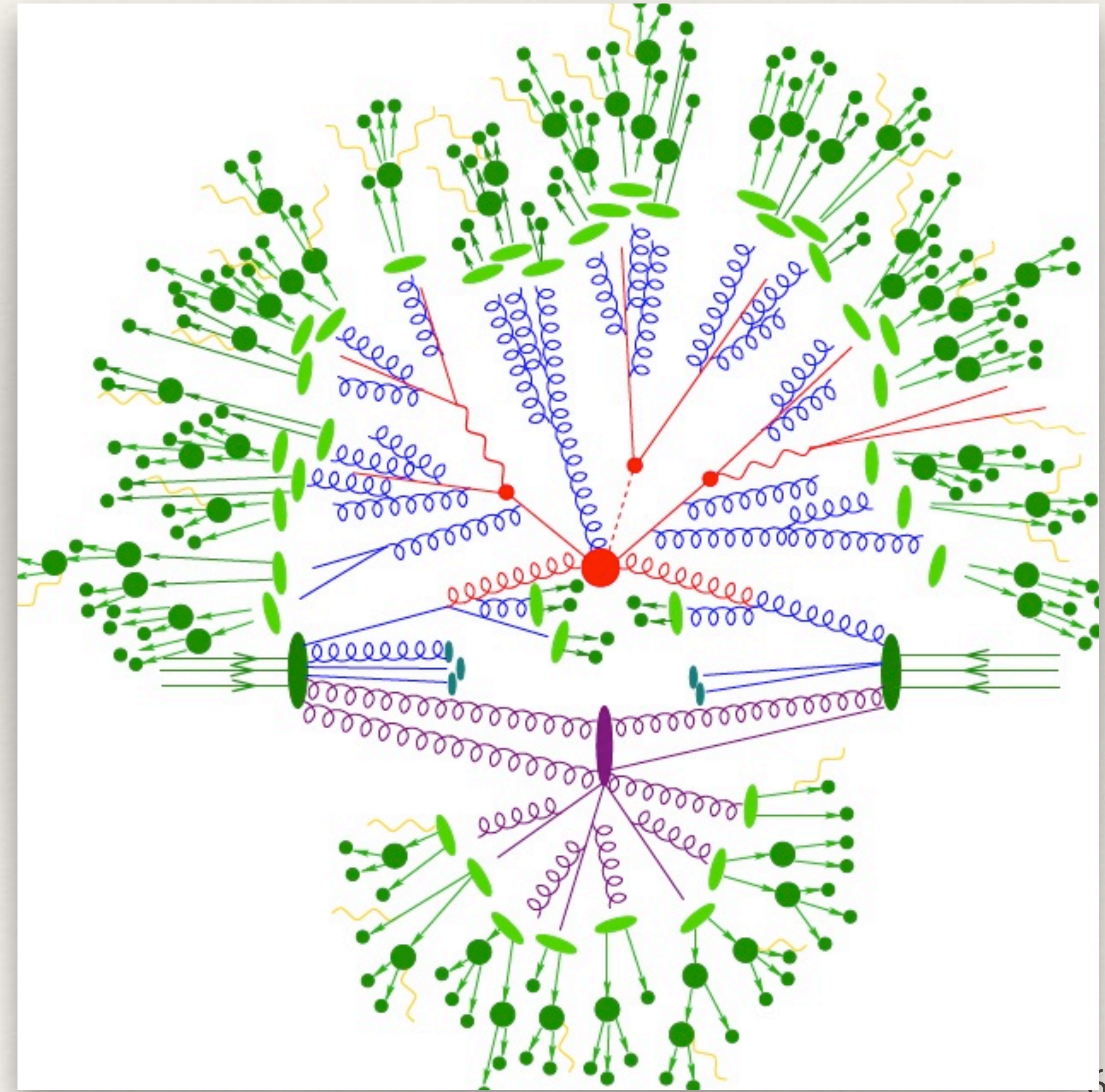


Funk



Cosmic rays.
particle collisions

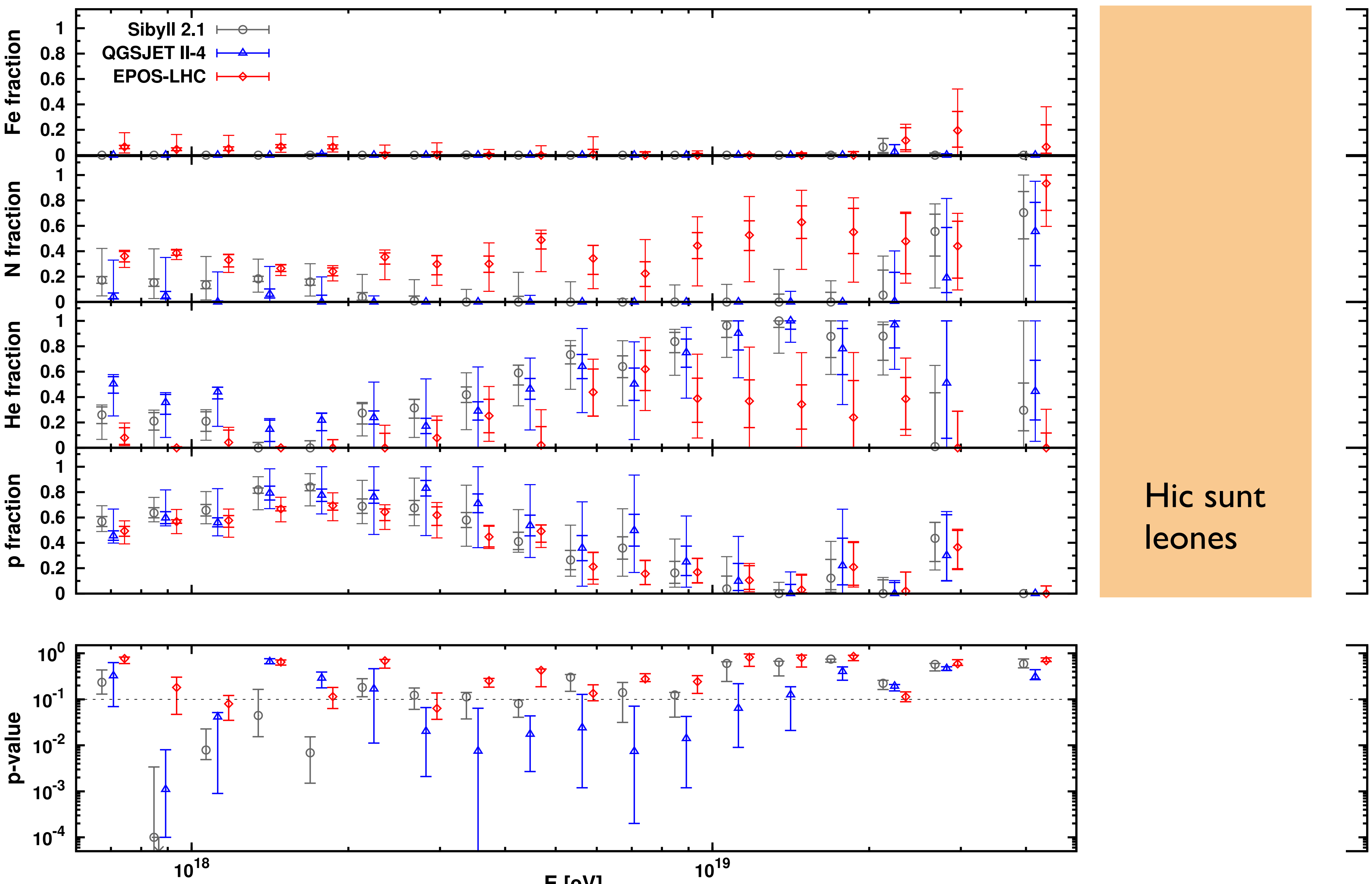
“CRs are likely accelerated at shocks in supernova remnants. But no observational proof yet”



Cosmic ray composition: Auger

Composition Fit (X_{max} distribution)

Data available only up to $< 5\times10^{19}$ eV



Pierre Auger Collaboration, PRD 90 (2014) 12, 122006

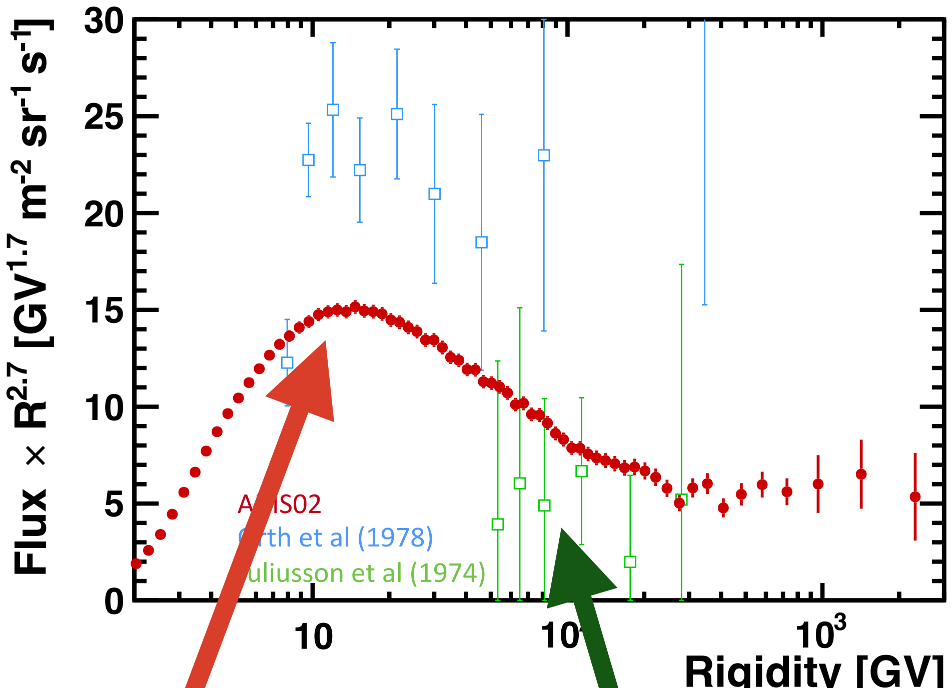
22

Roth

Cosmic ray composition: AMS

AMS Lithium flux

- Like B and Be, Li is produced by spallation processes.
- Sensitive to CR propagation parameters (diffusion, convection, reacceleration…).



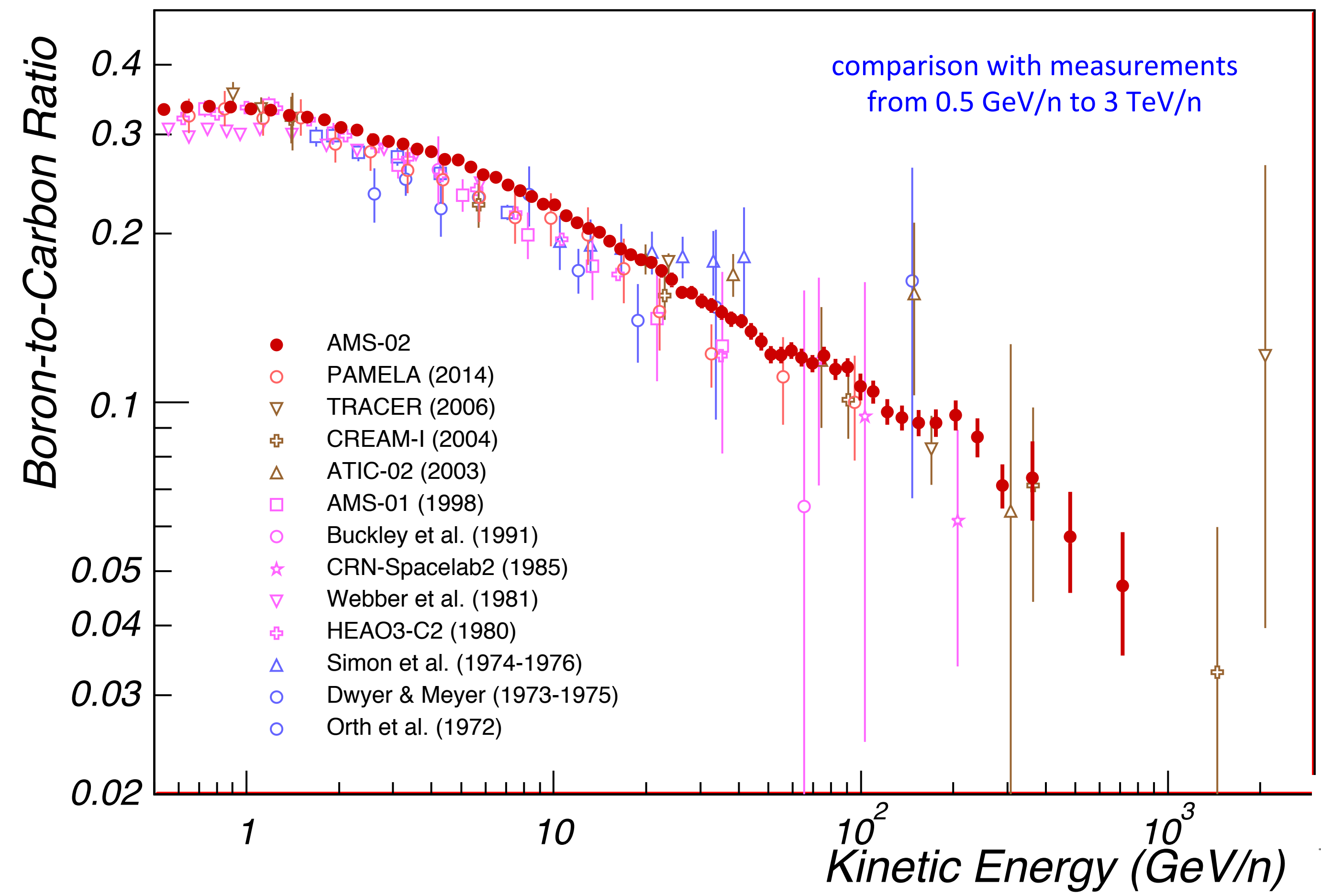
→ Deviation from single power law and hardening of the Lithium flux above 300 GV: new data for CR physics.

AMS

pre-AMS

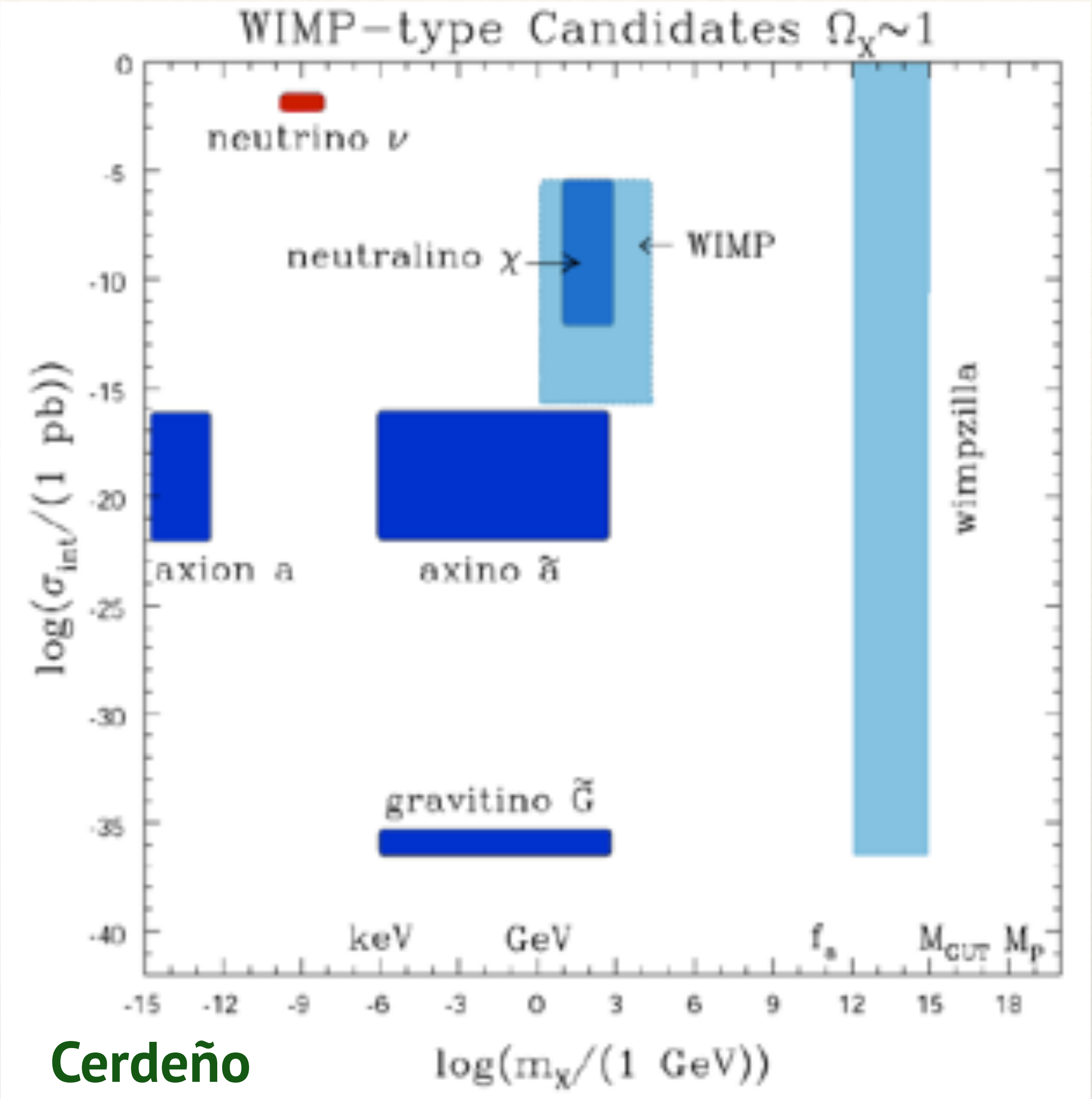
Derome

AMS B/C ratio



→ High precision data for CR physics.

Dark Matter

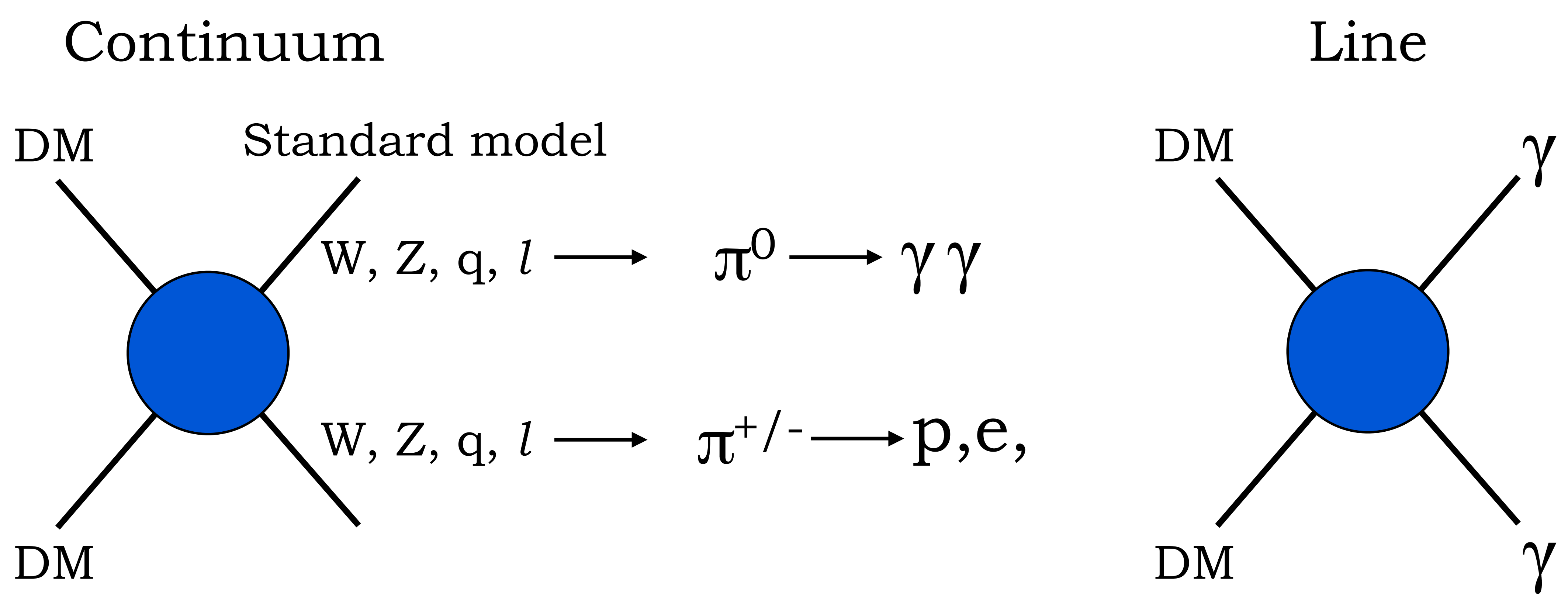


$$\langle \sigma_{\rm ann} v \rangle \approx \frac{3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}}{\Omega_{\rm DM} h^2} \longrightarrow \langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

"Thermal relic scale"

Indirect detection

Indirect dark matter detection: micro-physics



For continuum photon final states:

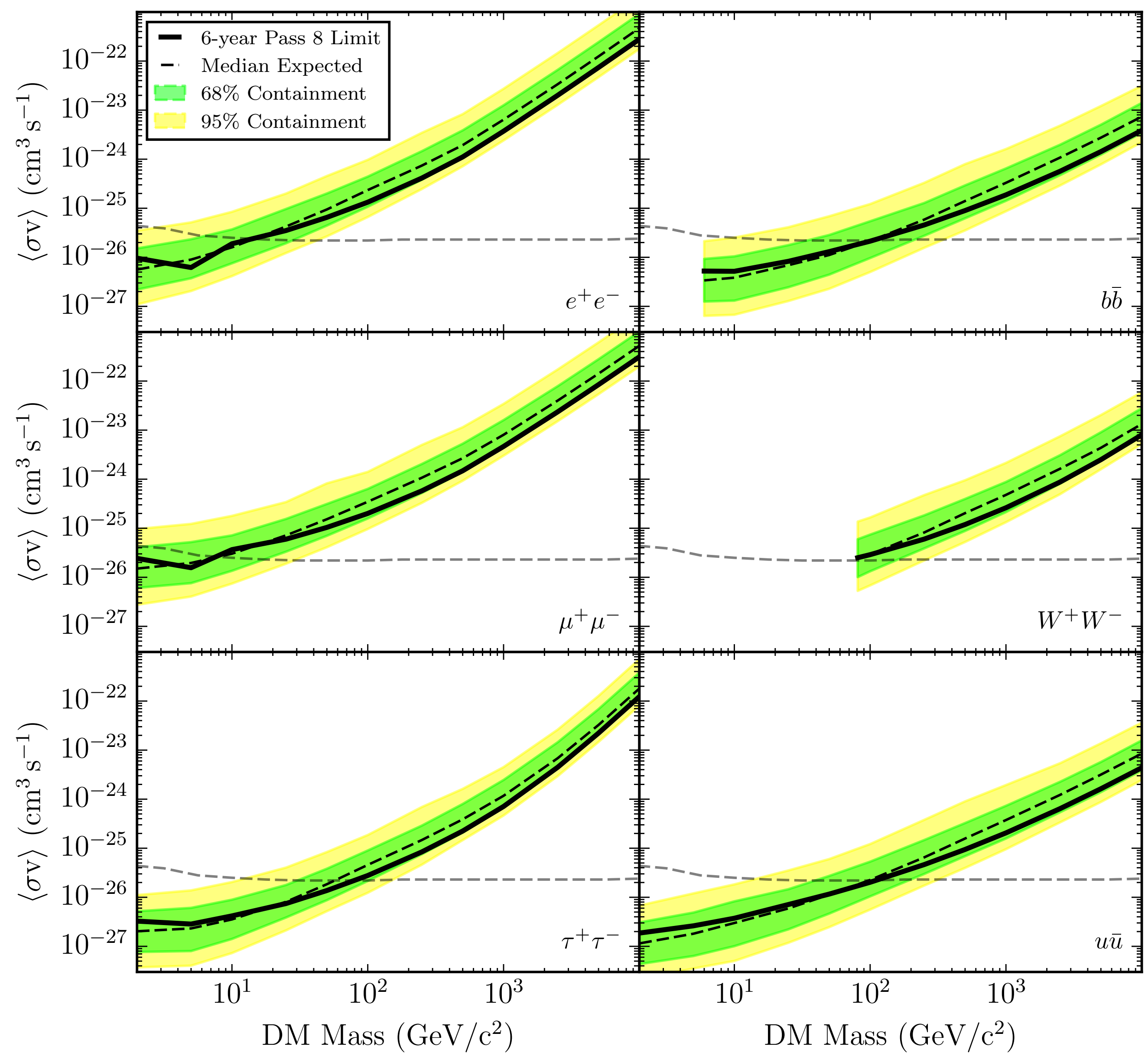
- Tens to hundreds of photons produced per WIMP annihilation
- 100 GeV mass WIMPs gives photons in the gamma-ray band, 10 MeV-10 GeV

Fermi dwarf spheroidal analysis

- Determine the total mass of dark matter from velocities of stars in each satellite

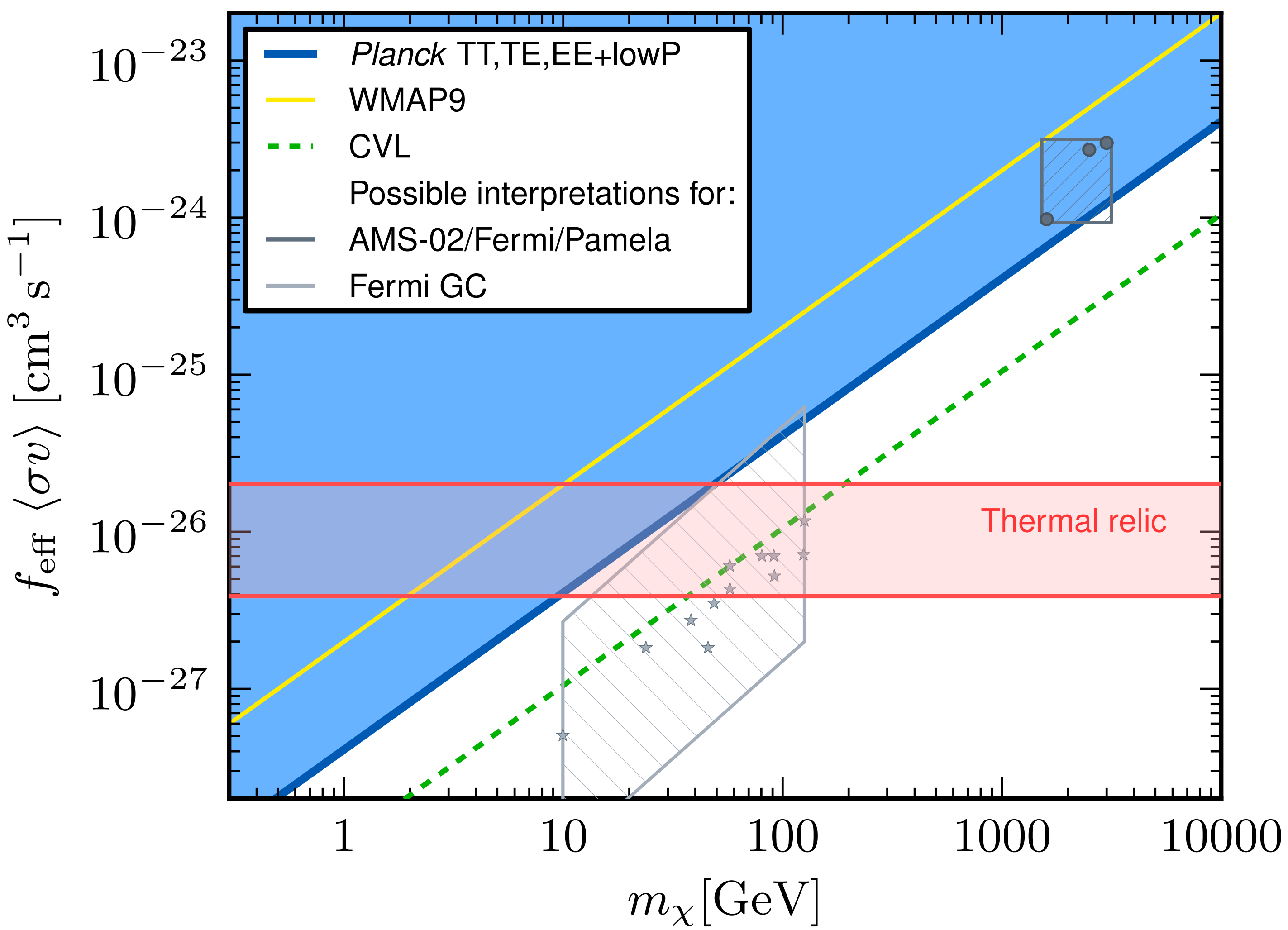
- Combine measured gamma-ray flux upper bound with total dark matter mass in each satellite to get upper bound on annihilation cross section

Fermi-LAT collaboration
PRL, 1108.3546
PRD, 1310.0828
PRL, 1503.02641



Constraints on DM annihilation from CMB

- DM annihilation injects energy into CMB at z ~ 1000.
- Annihilation products lose energy due to interactions with plasma
- Widens the surface of last scattering and alters CMB peaks
- Results are relatively insensitive to annihilation channels. Everything except directly annihilation to just neutrinos strongly constrained
- Also information from polarization

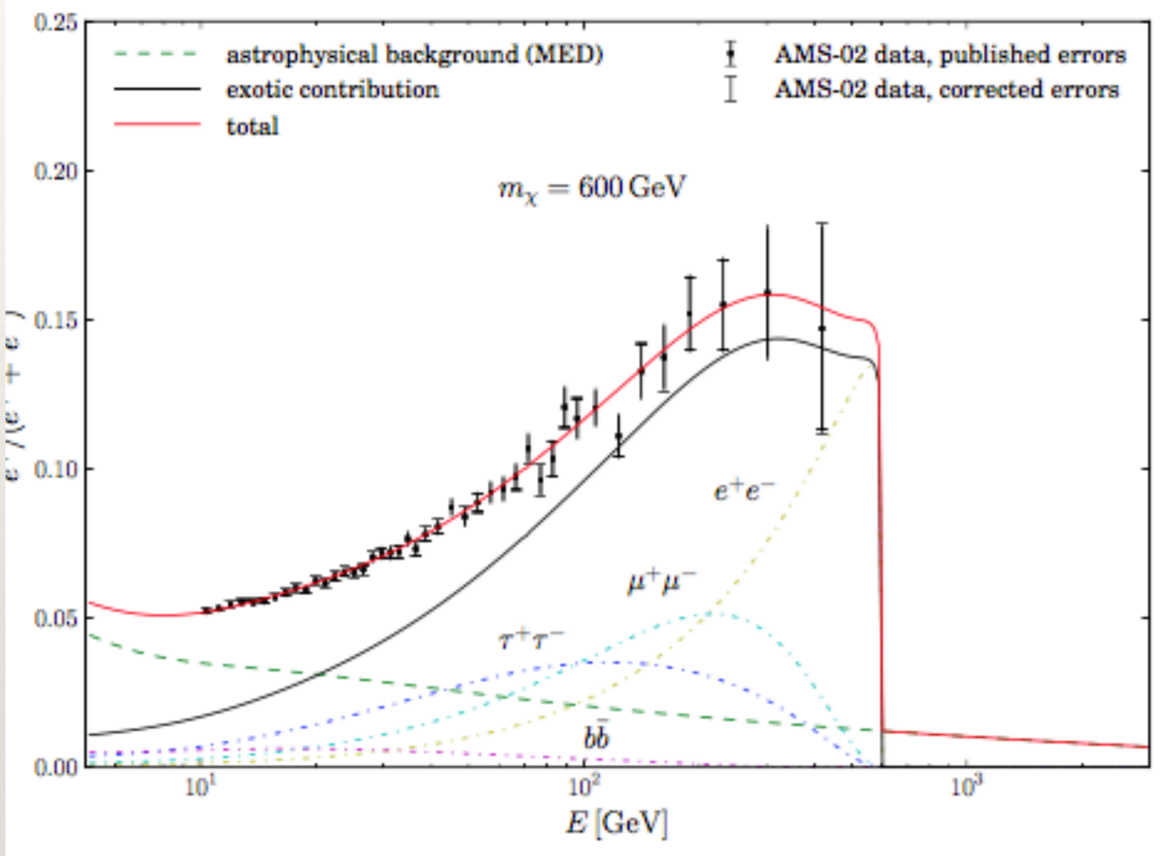


Planck collaboration 1502.01589

AMS positrons

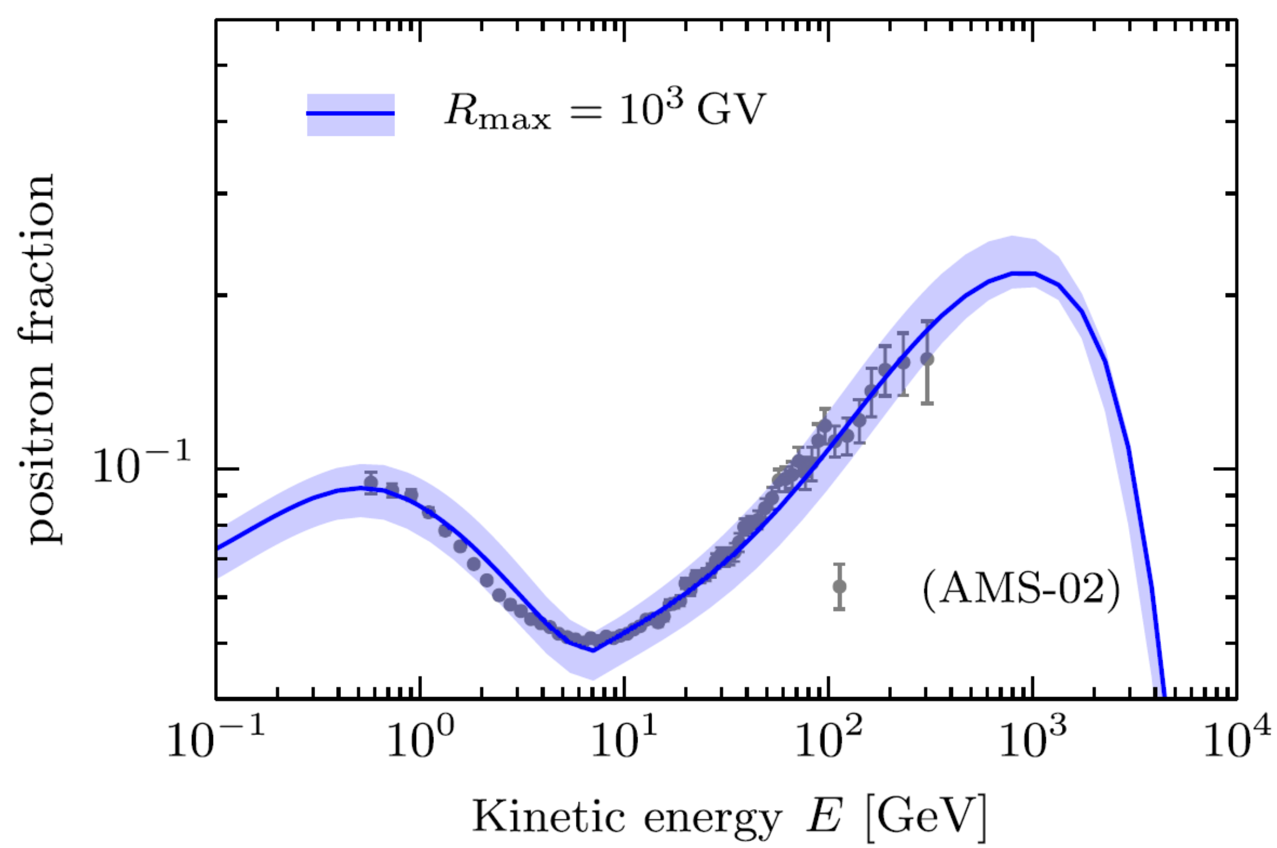
Fit of Positron Fraction with DM signal

Derome



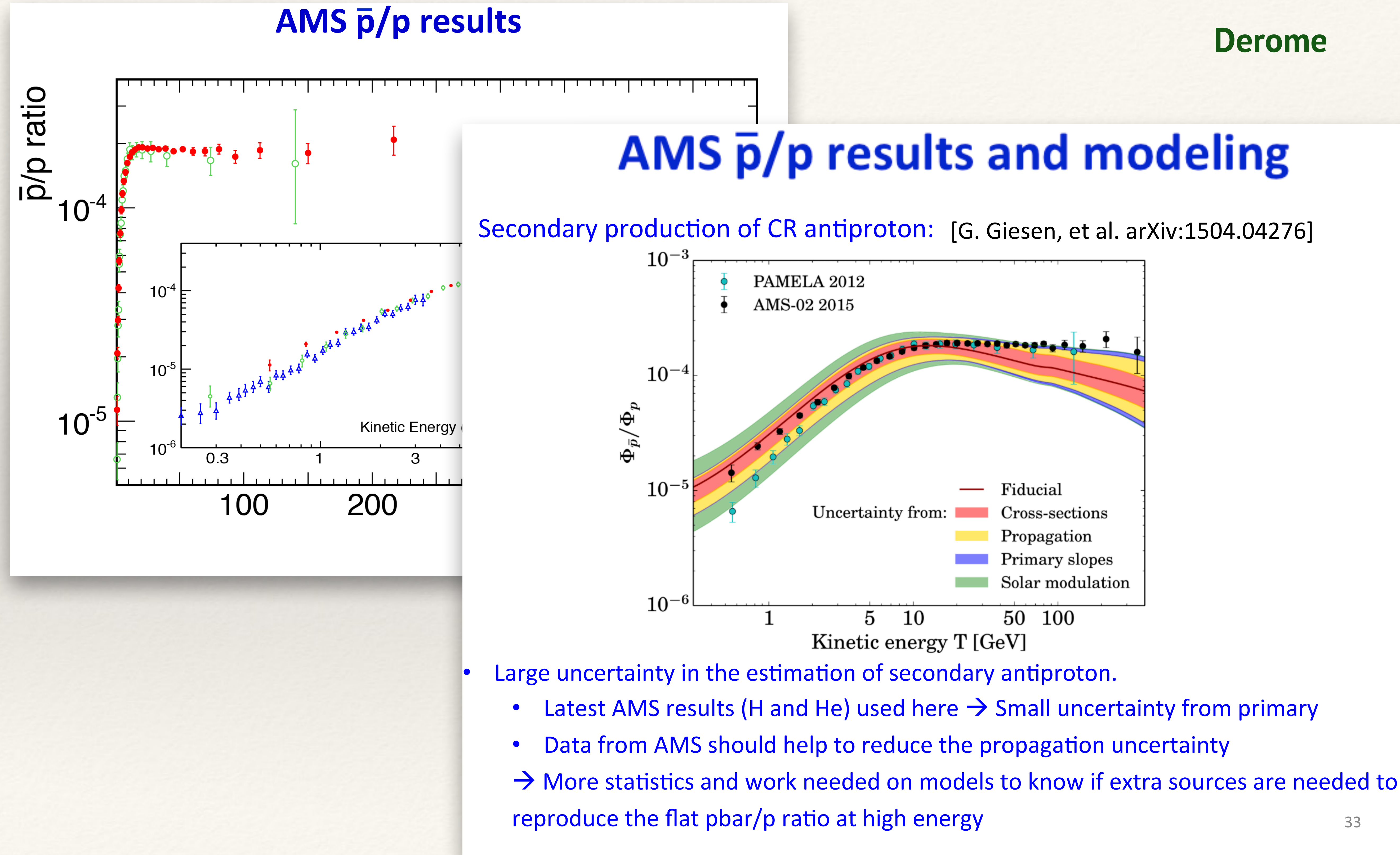
Acceleration and Production in SNR

P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301(R)



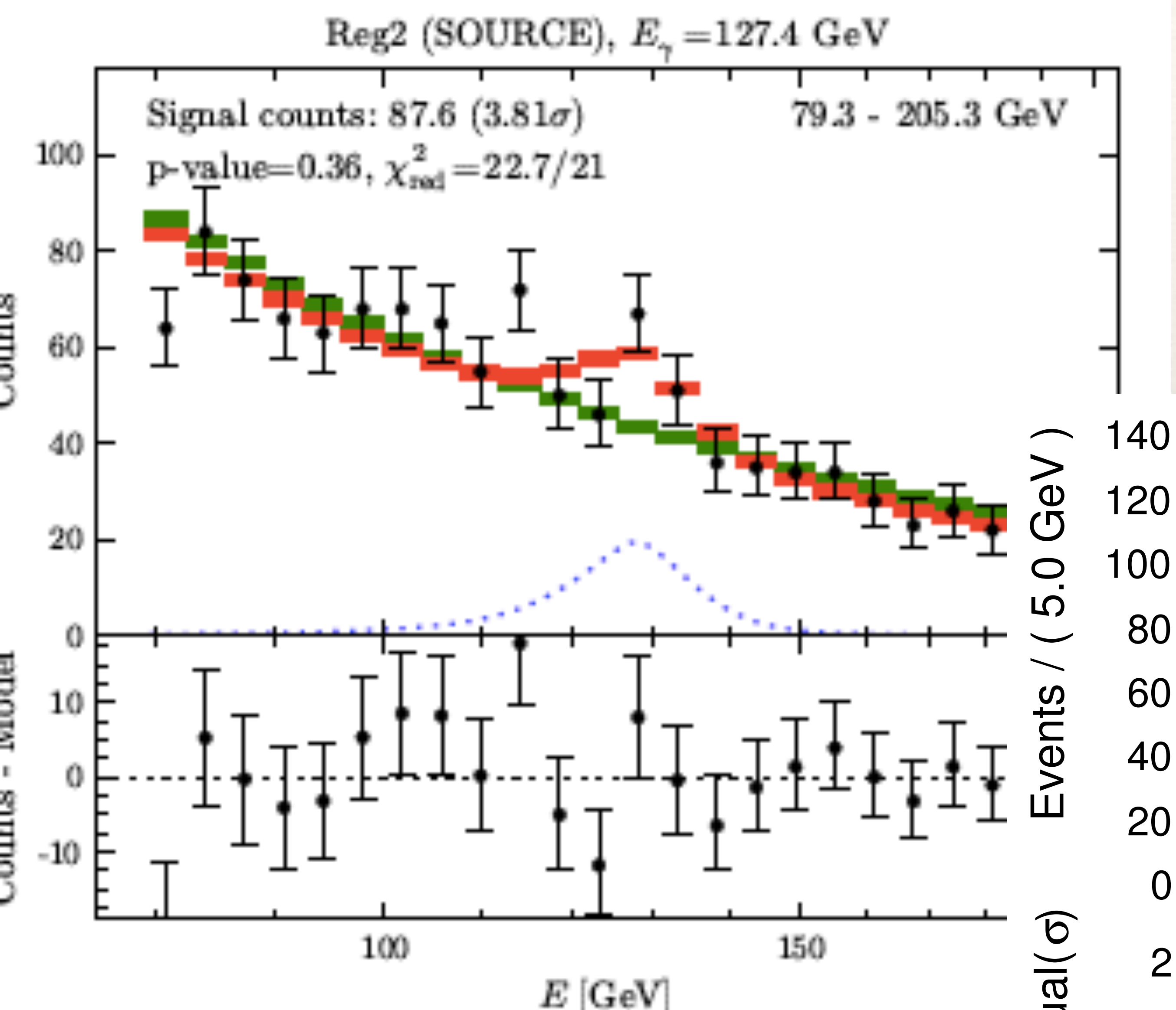
AMS antiprotons

Derome

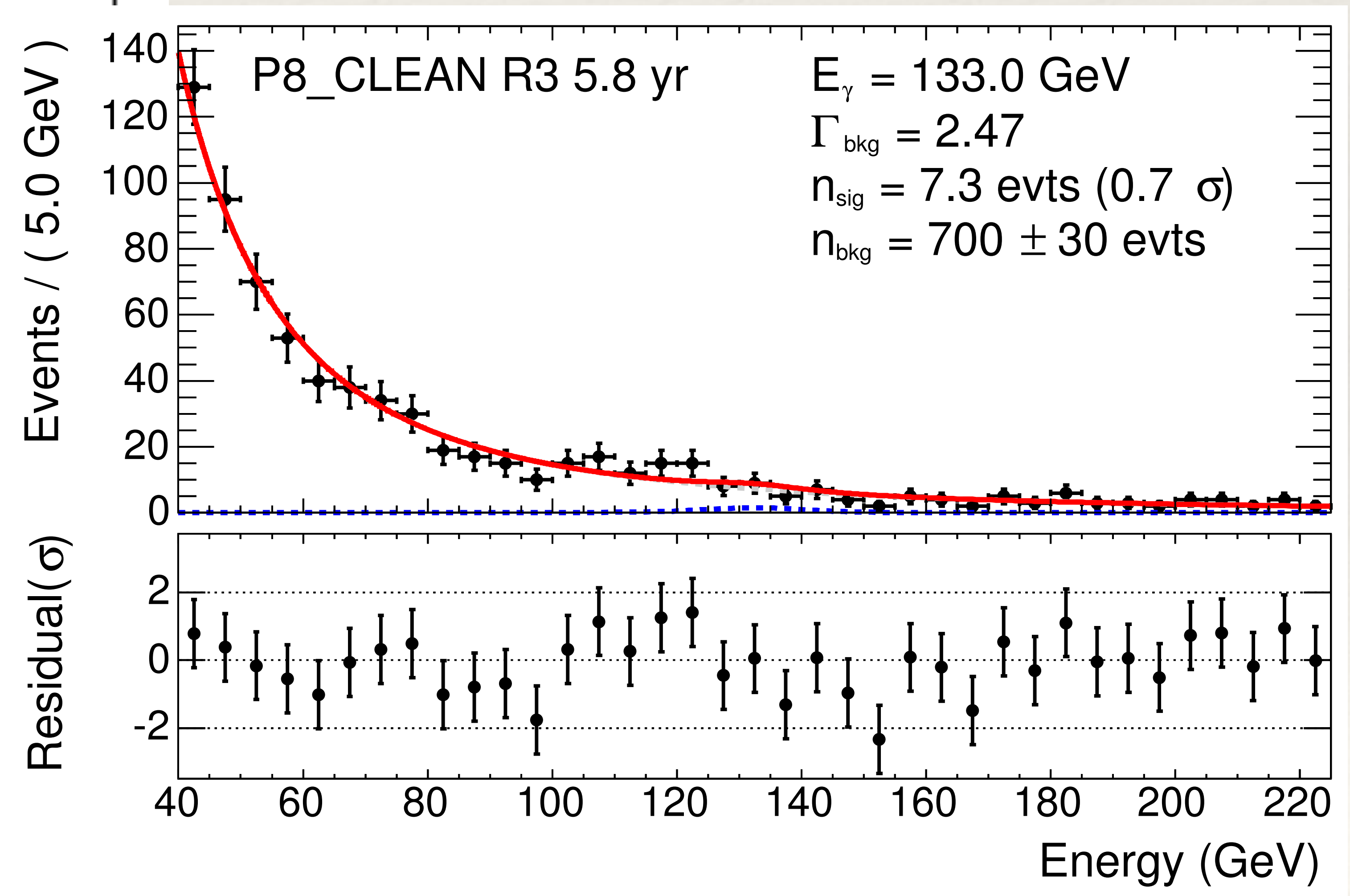


gamma-ray line searches

Weniger 2012



Fermi 2015

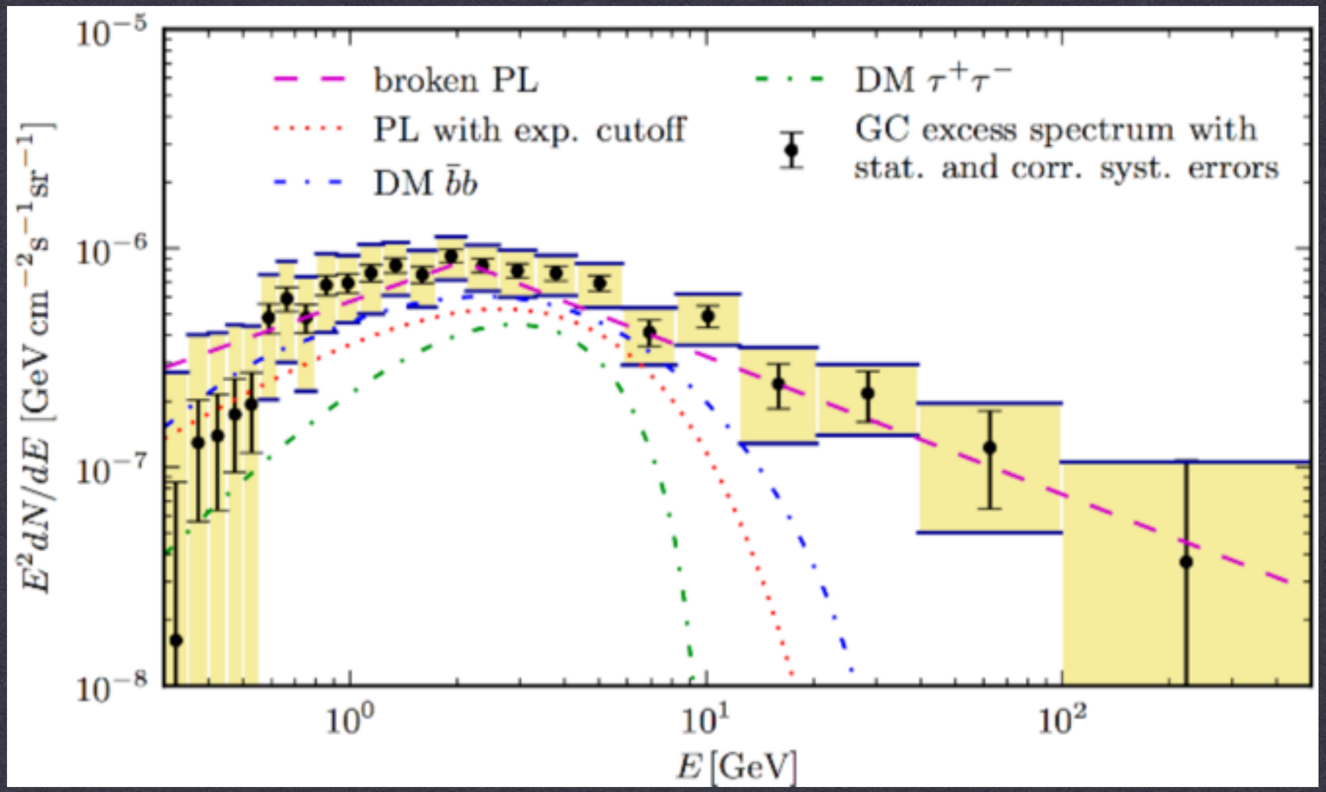


Linden

inner/central-galaxy excess

EXCESS SPECTRUM

Calore et al. (2014, 1409.0042)

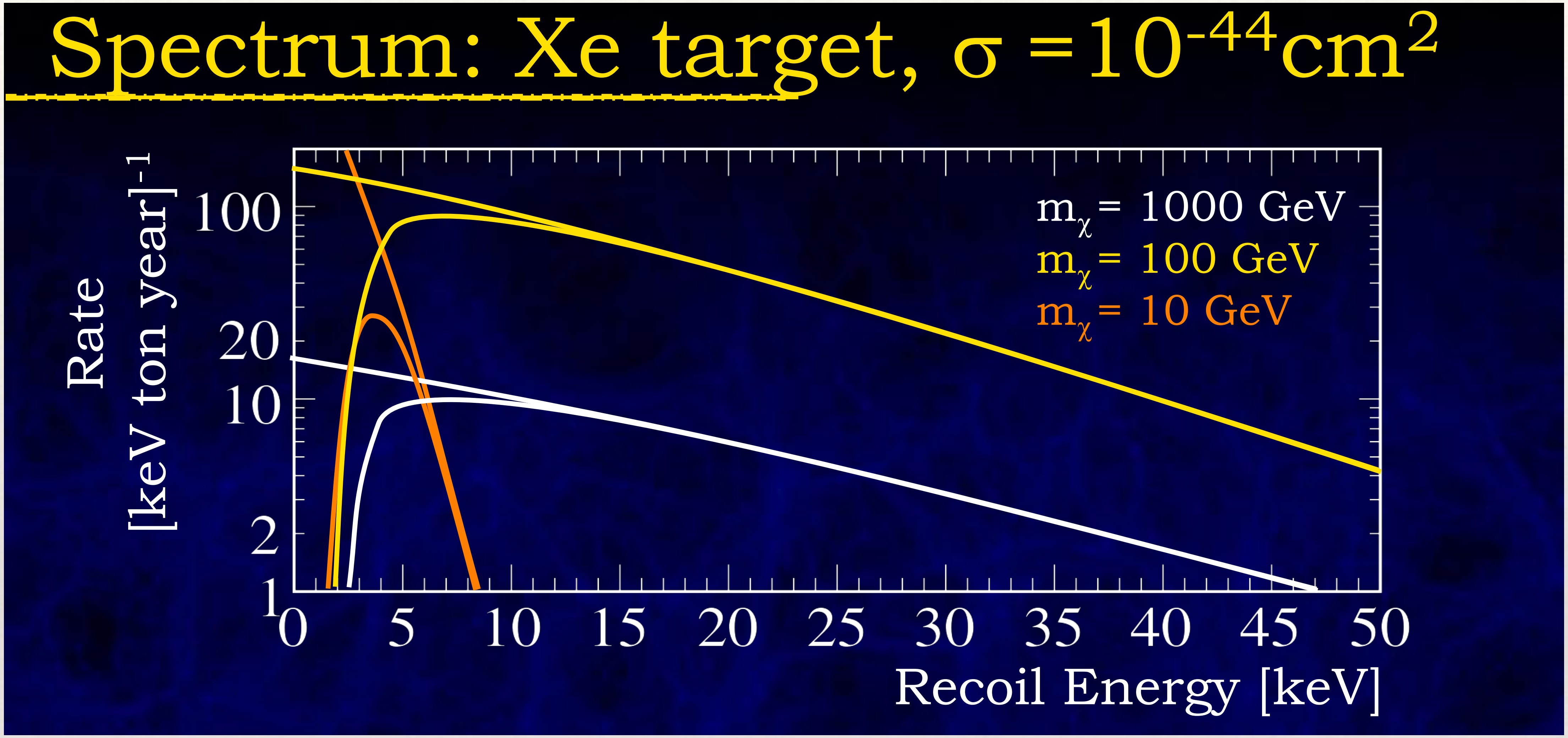


Spectral Model highly resilient to changing systematic background models ~300 models considered here.

Low energy spectrum hard to constrain due to systematics
High energy spectrum difficult due to statistics

One excess (at 10% level) that hasn't yet been explained away

Direct detection



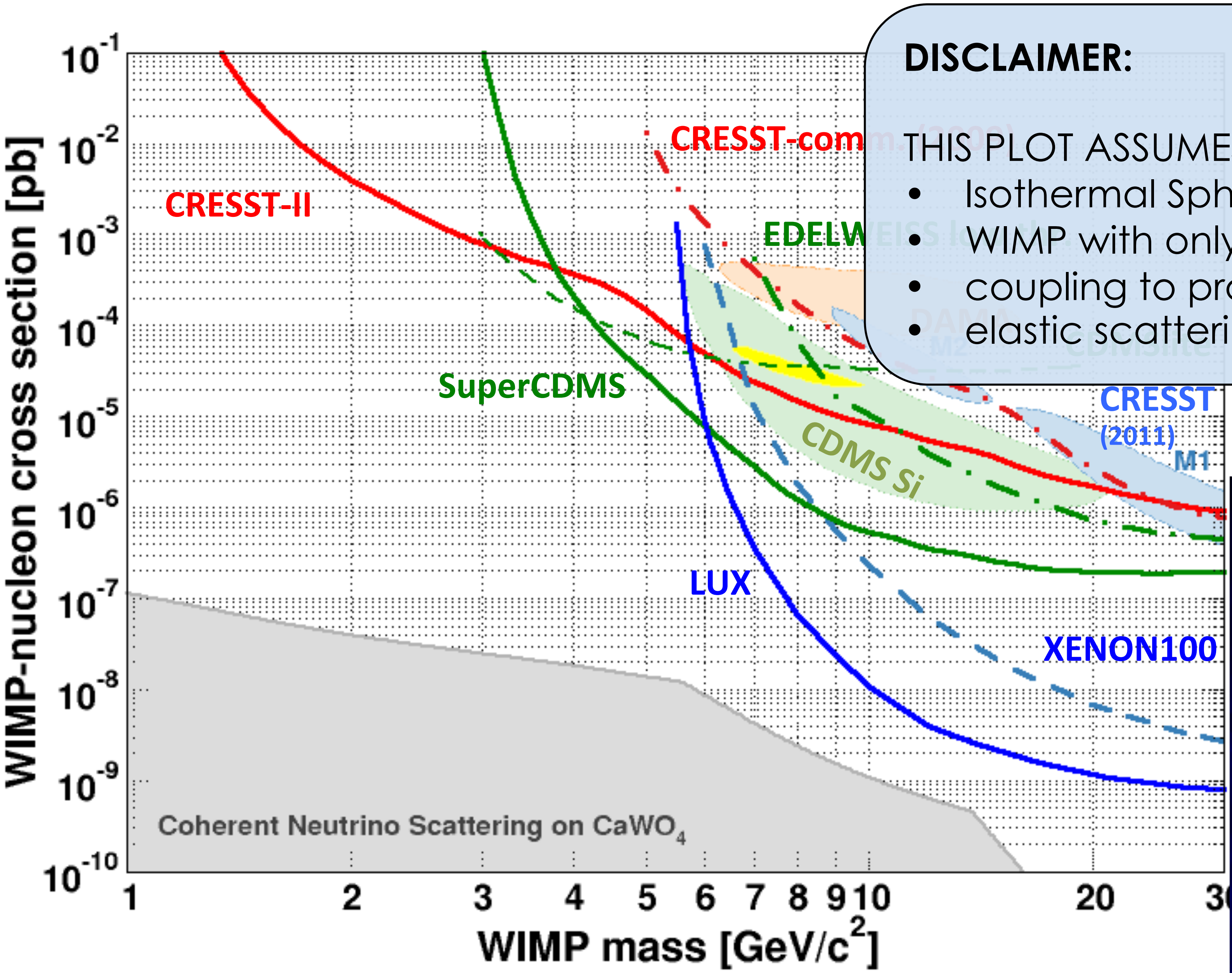
Acceptance necessarily drops to 0 at E_r=0:
Measured signal is a bump after all.

Limits, limits, limits…

Upper bounds on the SI cross section

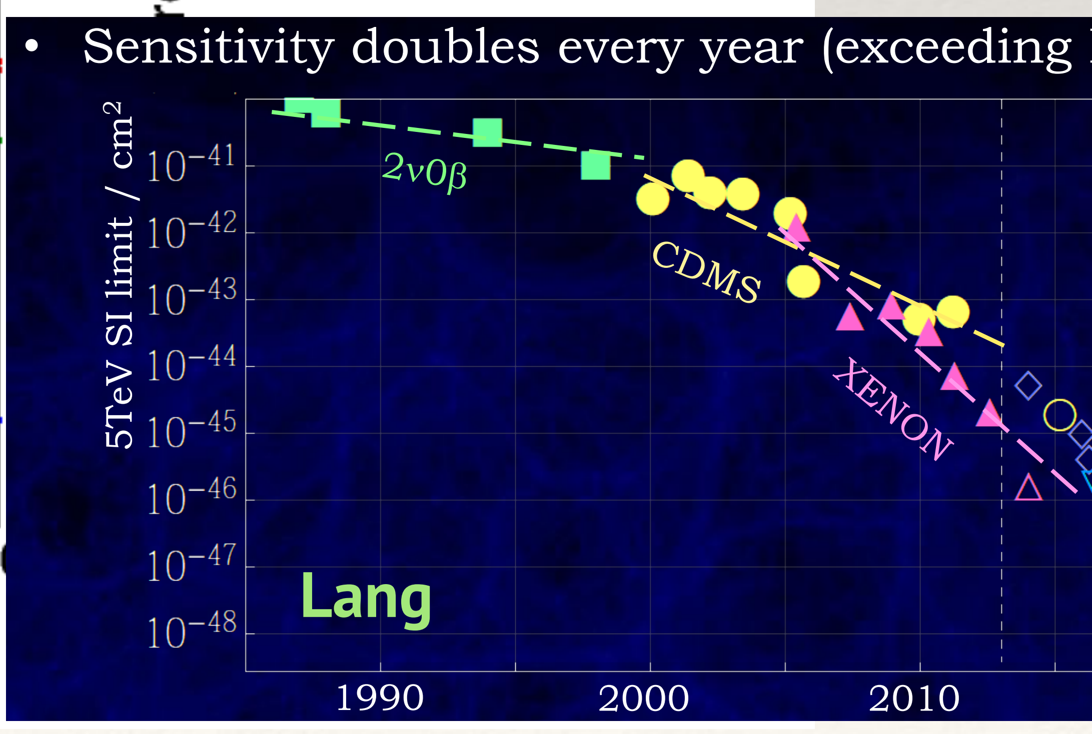
Cerdeño

XENON10, XENON100, LUX (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the scattering cross section

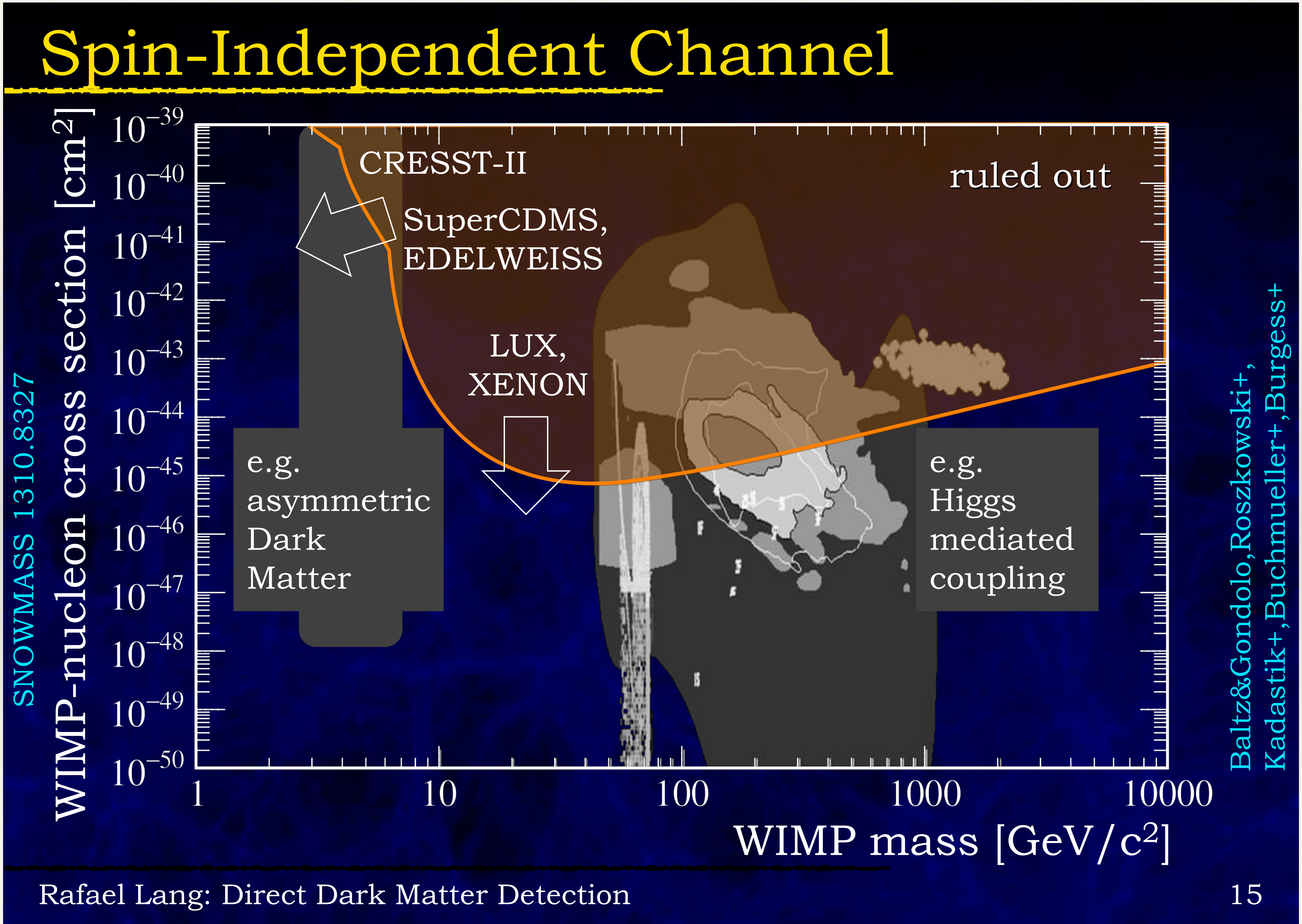


DISCLAIMER:

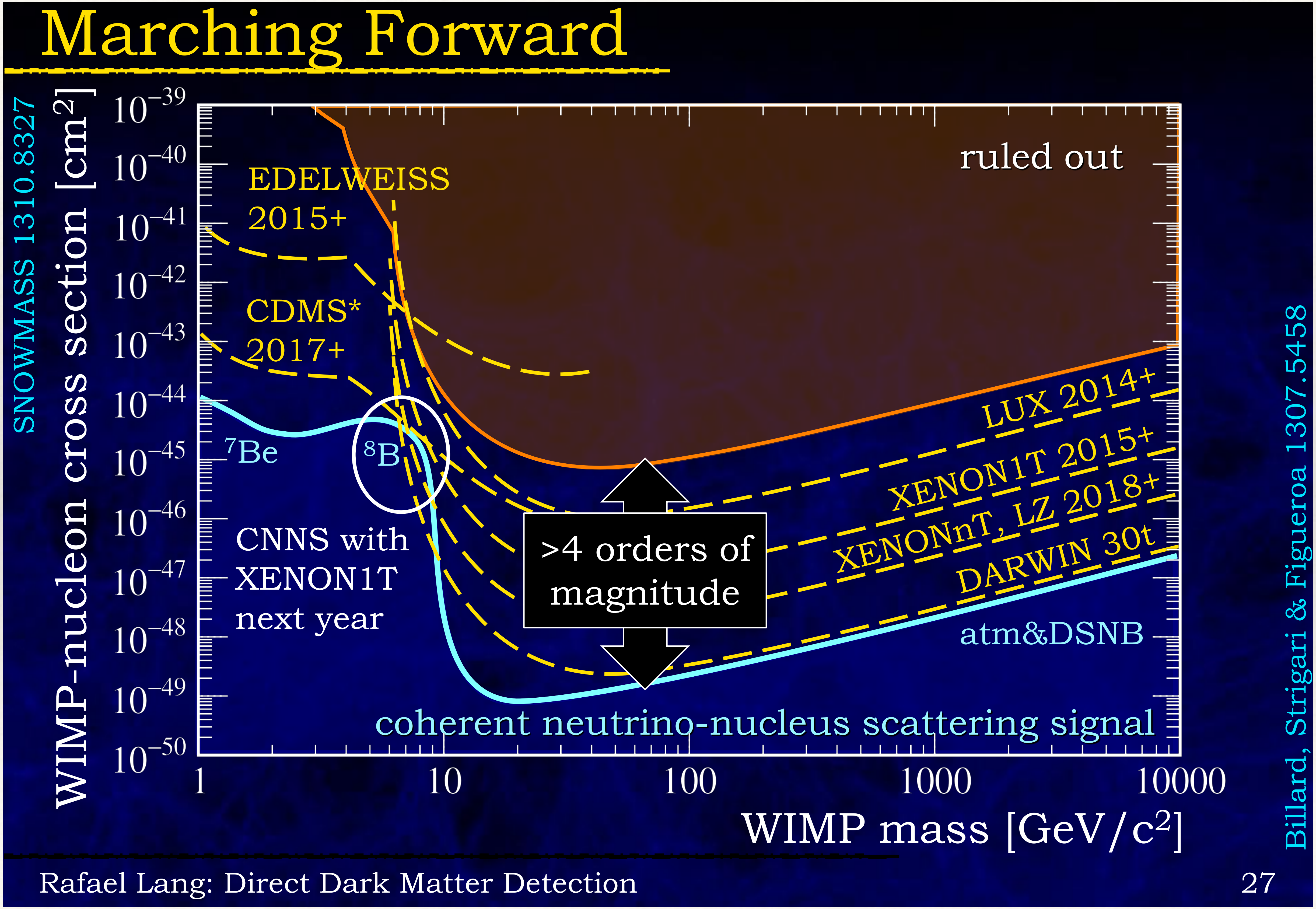
THIS PLOT ASSUMES
- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering



Exclusions v. models



Prospects



Marching Forward
SNOWMASS 1310.8327
WIMP-nucleon cross section [cm²]
EDELWEISS 2015+
CDMS* 2017+
ruled out
LUX 2014+
XENON1T 2015+
XENONnT, LZ 2018+
DARWIN 30t
atm&DSNB
⁷Be
⁸B
CNNS with XENON1T next year
>4 orders of magnitude
coherent neutrino-nucleus scattering signal
WIMP mass [GeV/c²]
Billard, Strigari & Figueroa 1307.5458
Rafael Lang: Direct Dark Matter Detection
27

Are we being too conservative in describing DM-nucleus interactions?

The most general effective Lagrangian contains up to 14 (x2) different operators that induce six types of response functions and two new interference terms

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\, \Psi^*_\chi(\vec{x}) \mathcal{O}_\chi \Psi_\chi(\vec{x})\, \Psi^*_N(\vec{x}) \mathcal{O}_N \Psi_N(\vec{x})$$

Spin-Indep.

$\mathcal{O}_1 = 1_\chi 1_N$

$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

Spin-Dep.

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

Angular momentum of unpaired nucleon

$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

Angular momentum and spin

$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$

$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

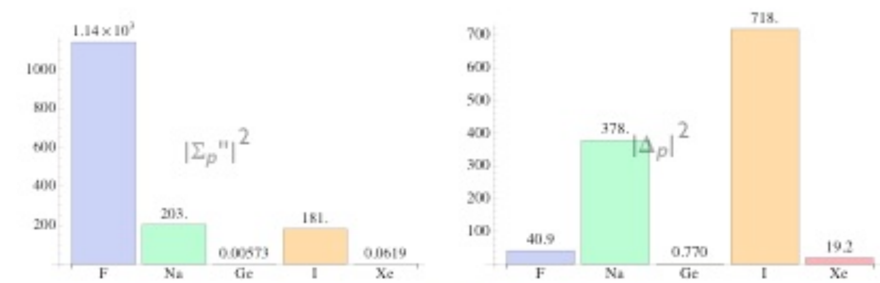
$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$

$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right)\right.$

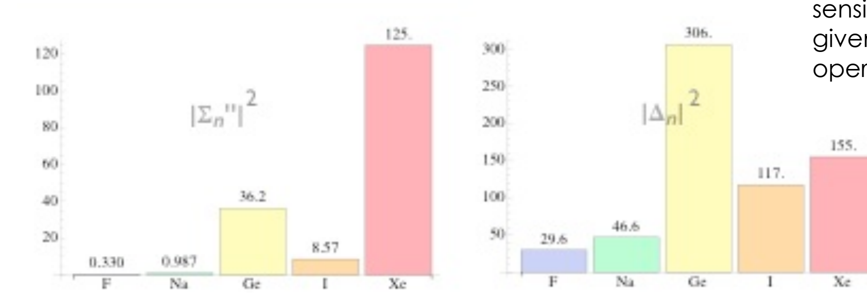
cf. effort taking place for Higgs physics

These are extremely sensitive to the choice of target material, being crucial in the design phase of new experiments.

Vector, proton coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$



Vector, neutron coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$



Some targets have enhanced sensitivities for a given set of operators

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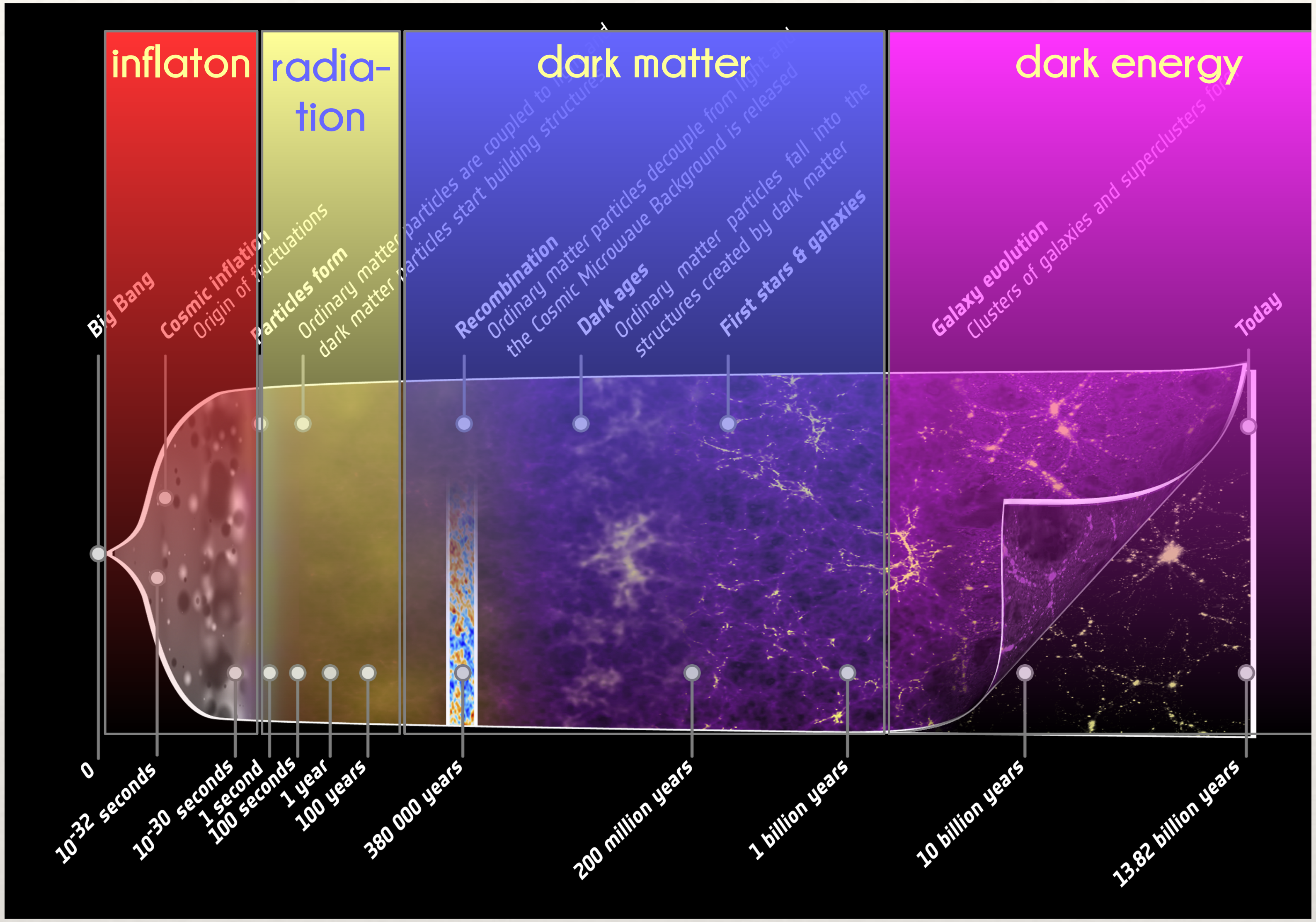
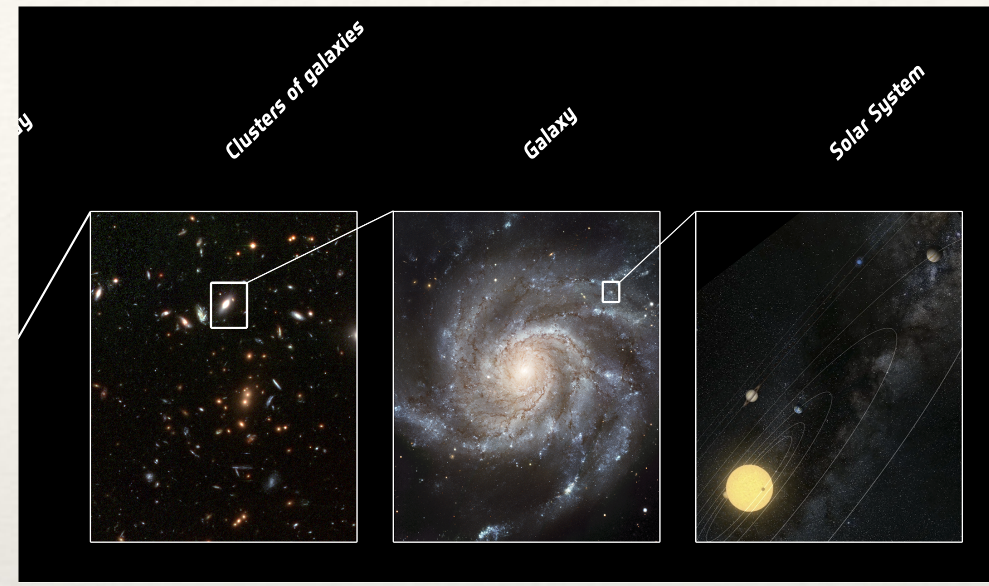
Cerdeño

Cosmology



Ensslin



Peiris

- Don't know the dynamics of inflation: parameterize weakly scale-dependent functions with a few numbers to pin down observationally.

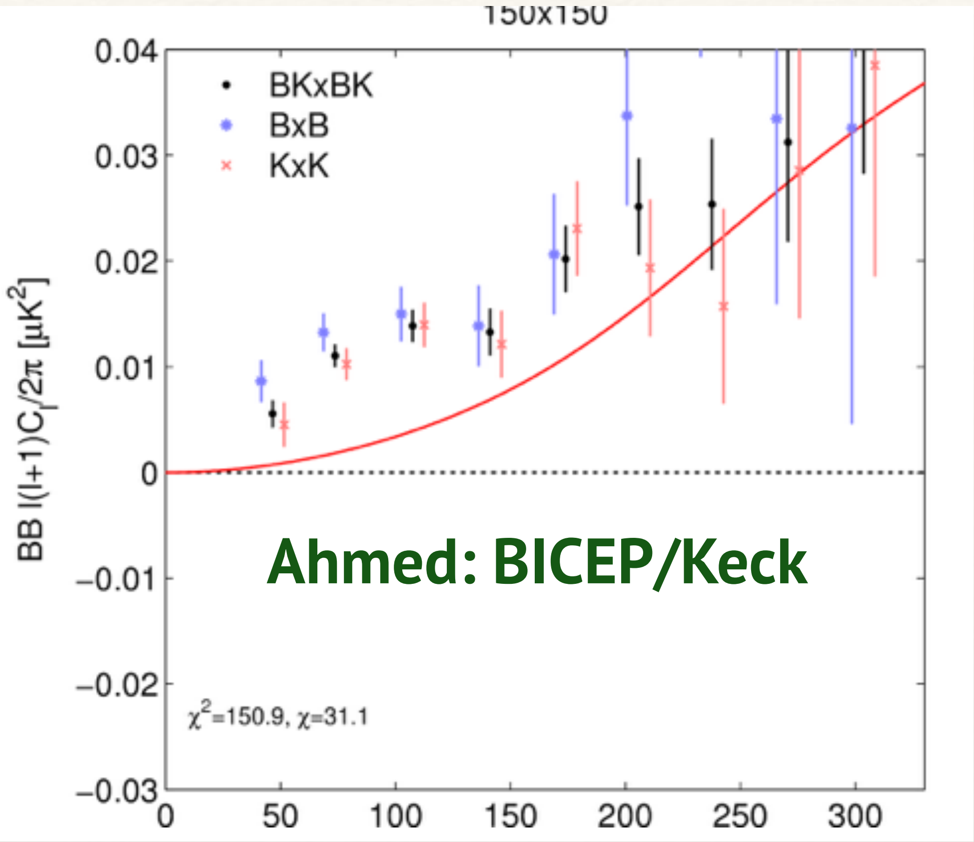
$$P_{\mathcal{R}}(k) \simeq A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \qquad P_h(k) \simeq A_t \left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_{\mathcal{R}}(k_0)}$$

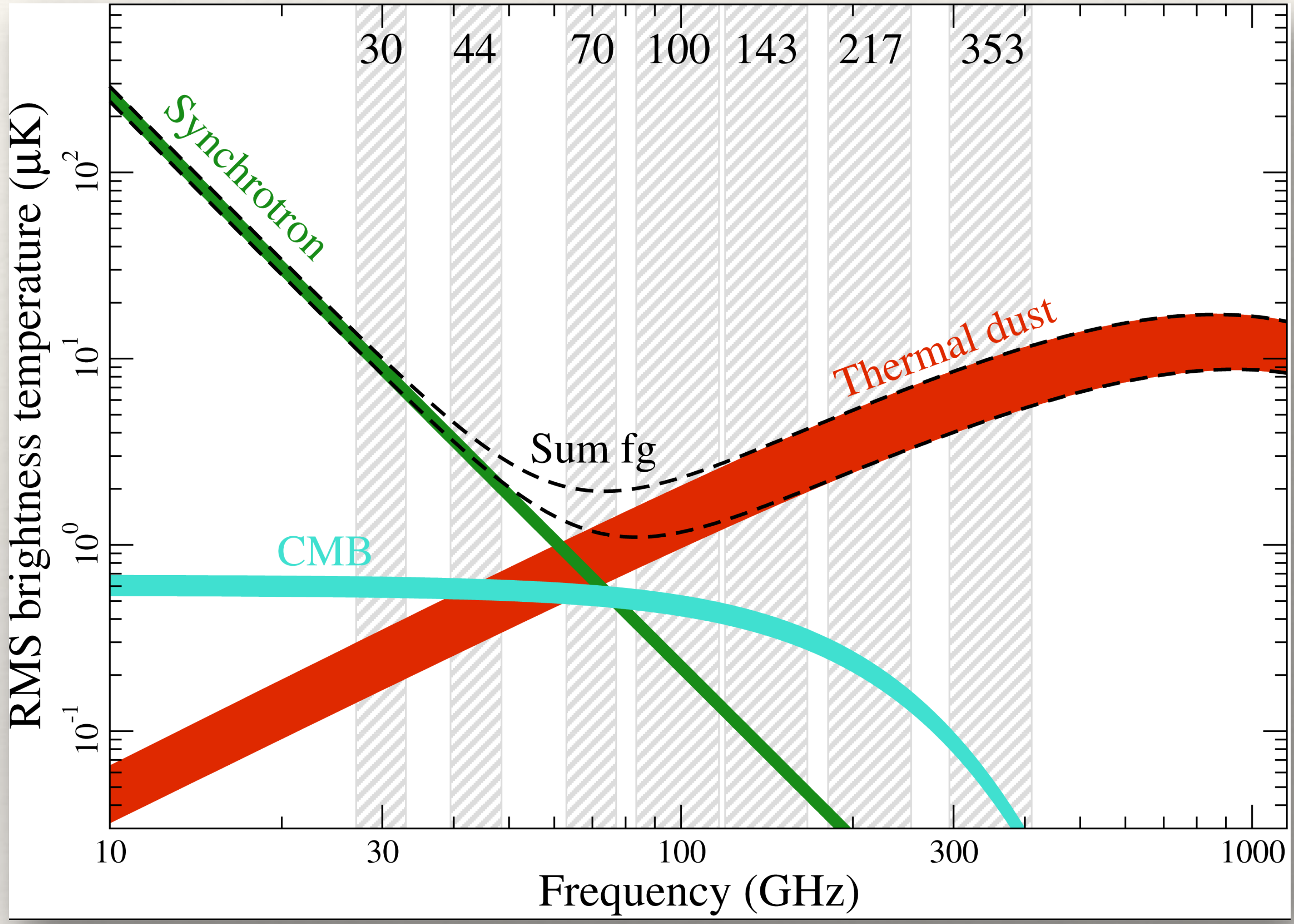
Some Planck results

Enßlin

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

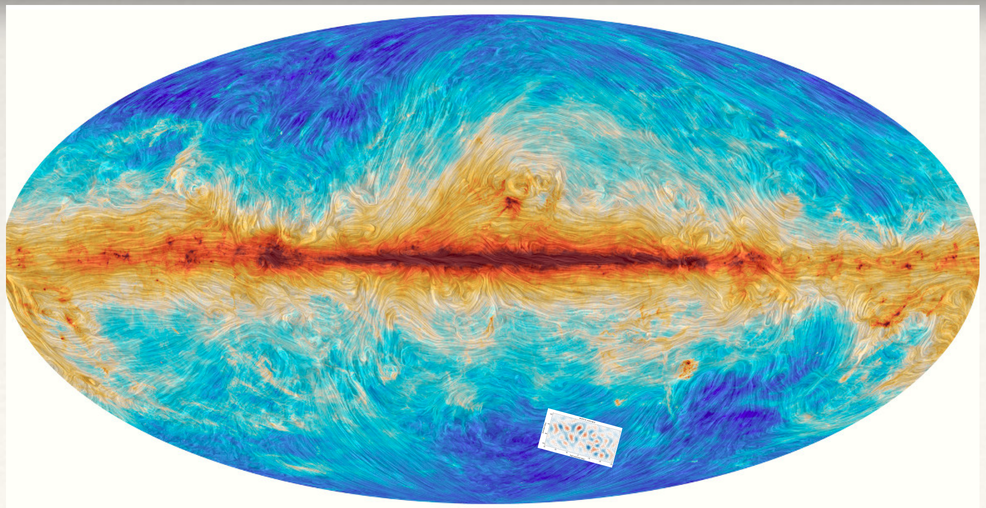
BB power spectrum & gravitational imprint





BB perturbations are there, but what's their origin?

Primordial gravity waves or dust?

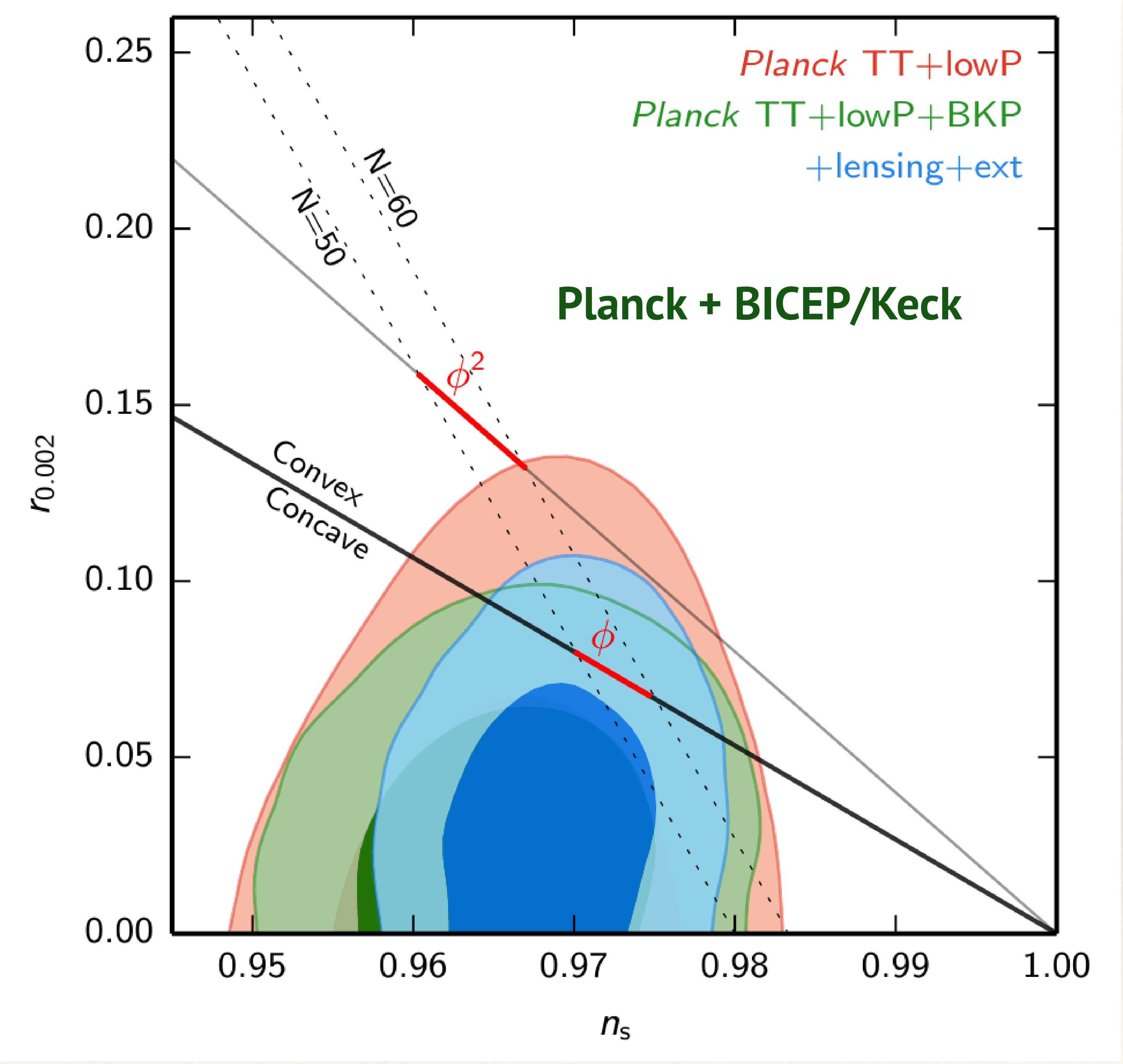


BB power spectrum & gravitational imprint

Enßlin, Peiris, Ahmed

Planck TT+lowP+BKP combined limit:
$r_{0.002} < 0.08$ (95% CL)

no strong evidence yet for primordial gravitational waves in CMB



Inflation: score-card

Peiris

A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \qquad H \simeq \mathrm{const}$$

- Solves:
  - horizon problem
  - flatness problem (flatness tested at <1% level!)
  - monopole problem

  i.e. explains why the Universe is so large, so flat, and so empty

- Predicts:
  - scalar fluctuations in the CMB temperature
    - ✓ nearly but not exactly scale-invariant (>5σ!)
    - ✓ approximately Gaussian (at the 10^{-4} level!)

  ? primordial tensor fluctuations (gravitational waves)

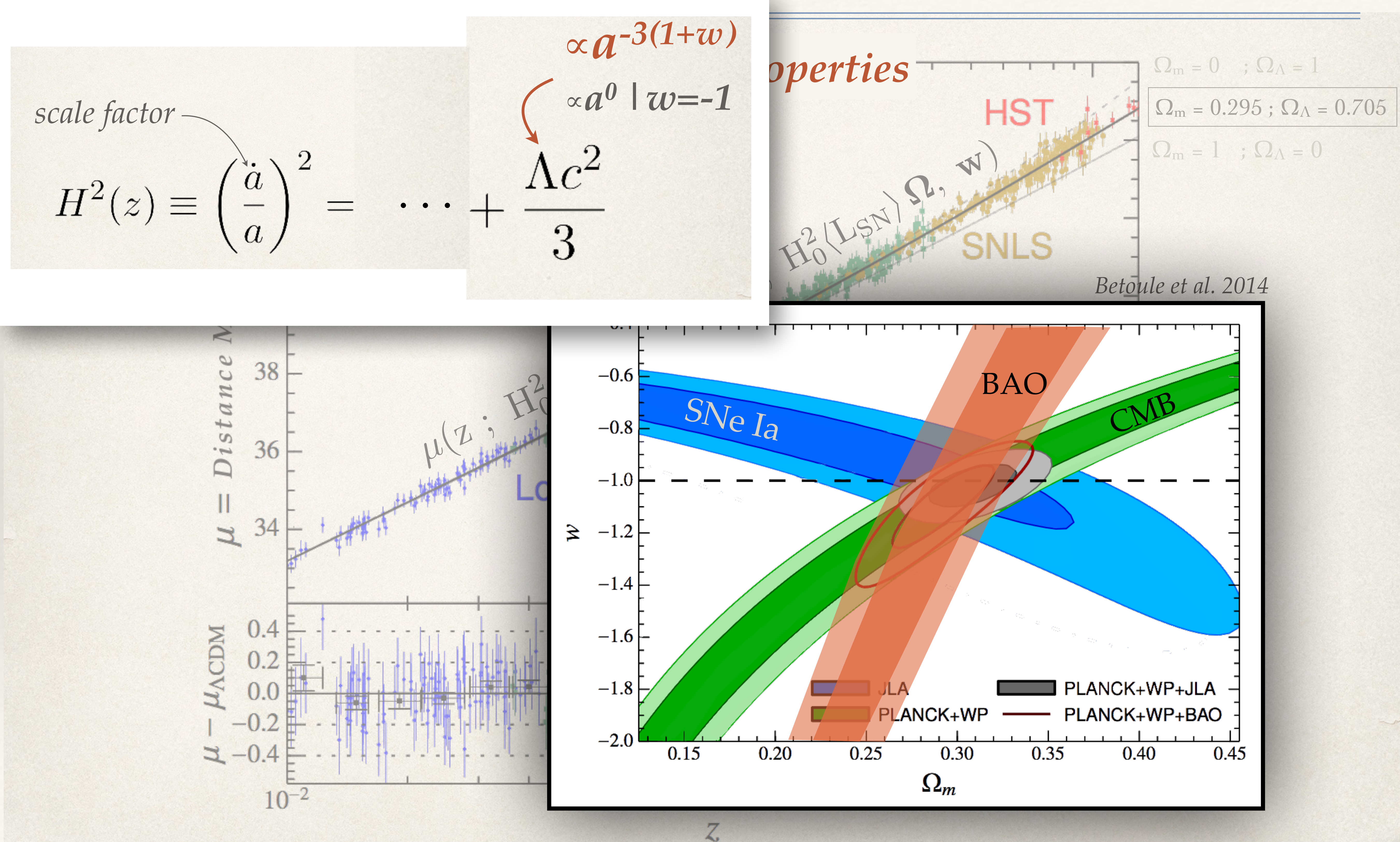
Dark energy equation of state

scale factor

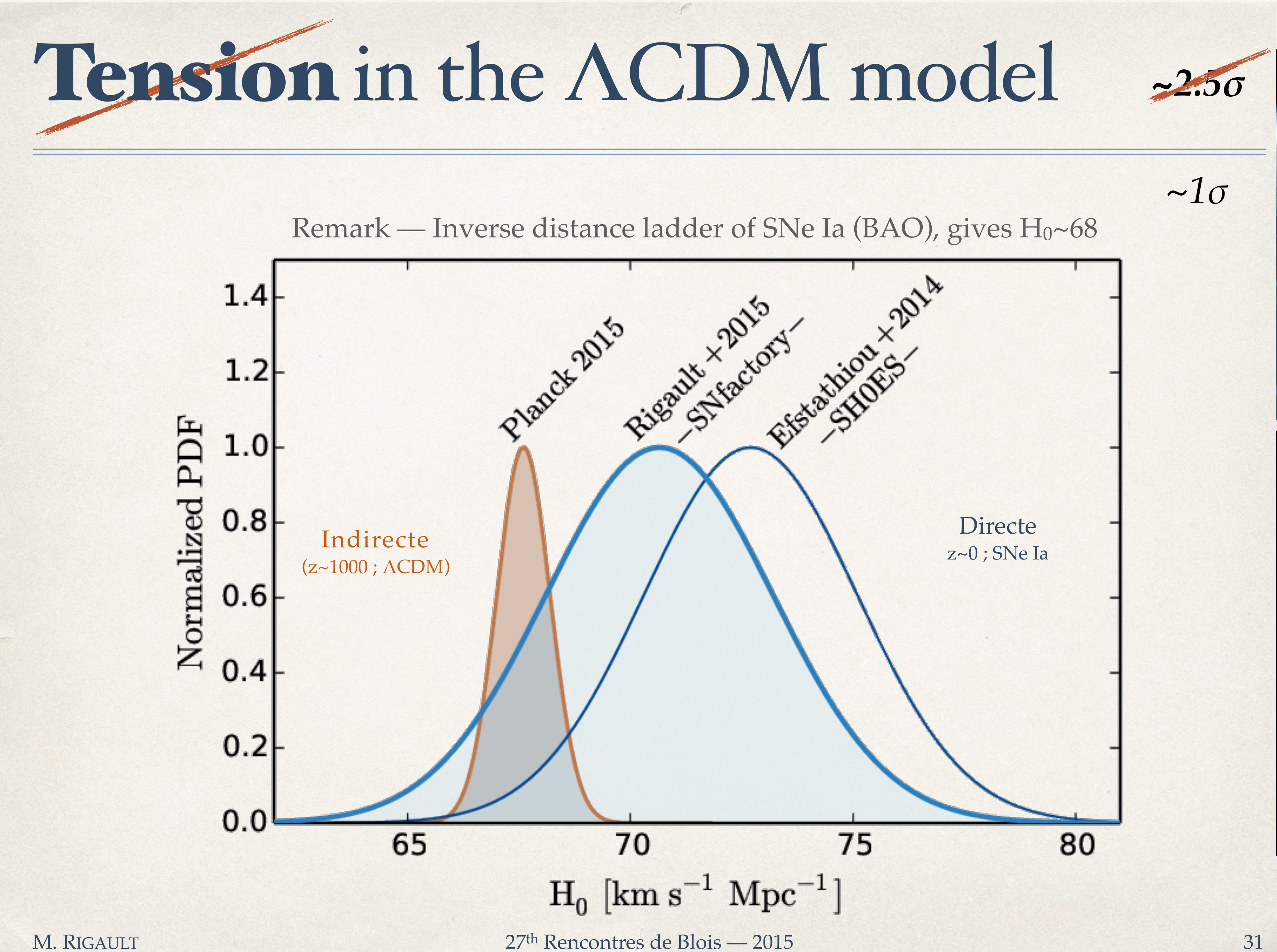
$$H^2(z) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \cdots + \frac{\Lambda c^2}{3}$$

$\propto a^{-3(1+w)}$

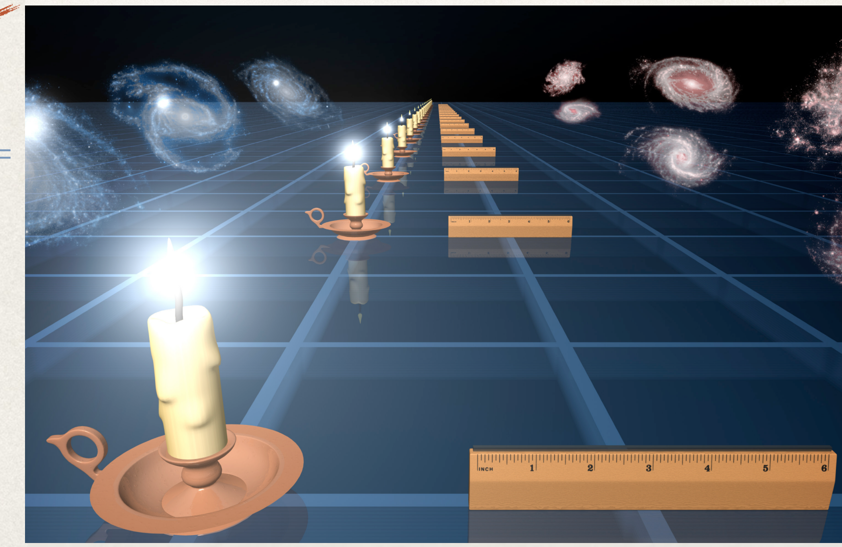
$\propto a^0 \mid w=-1$

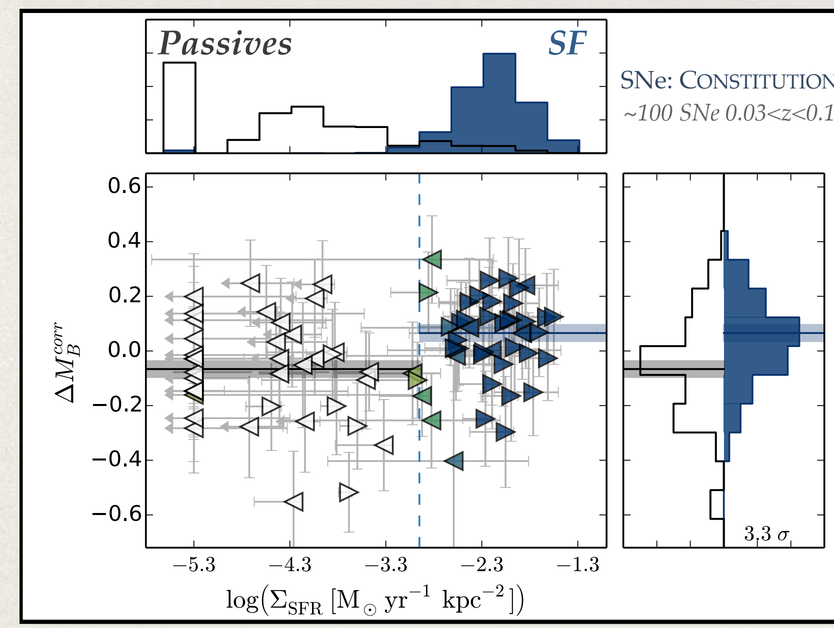


Tension in Hubble const.?



Standard Candles Standard Rulers



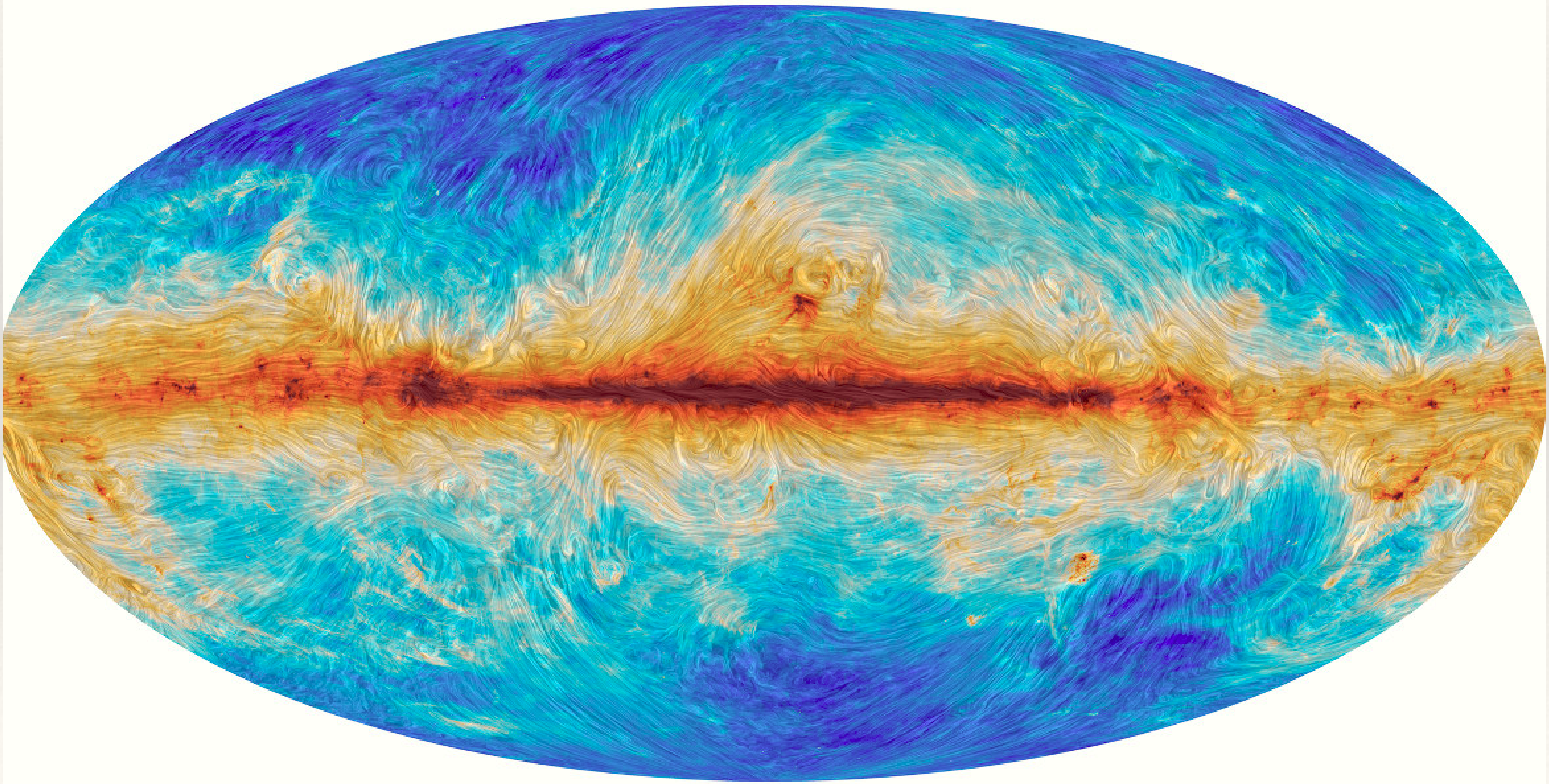


Rigault

Imagery

the ancient Universe

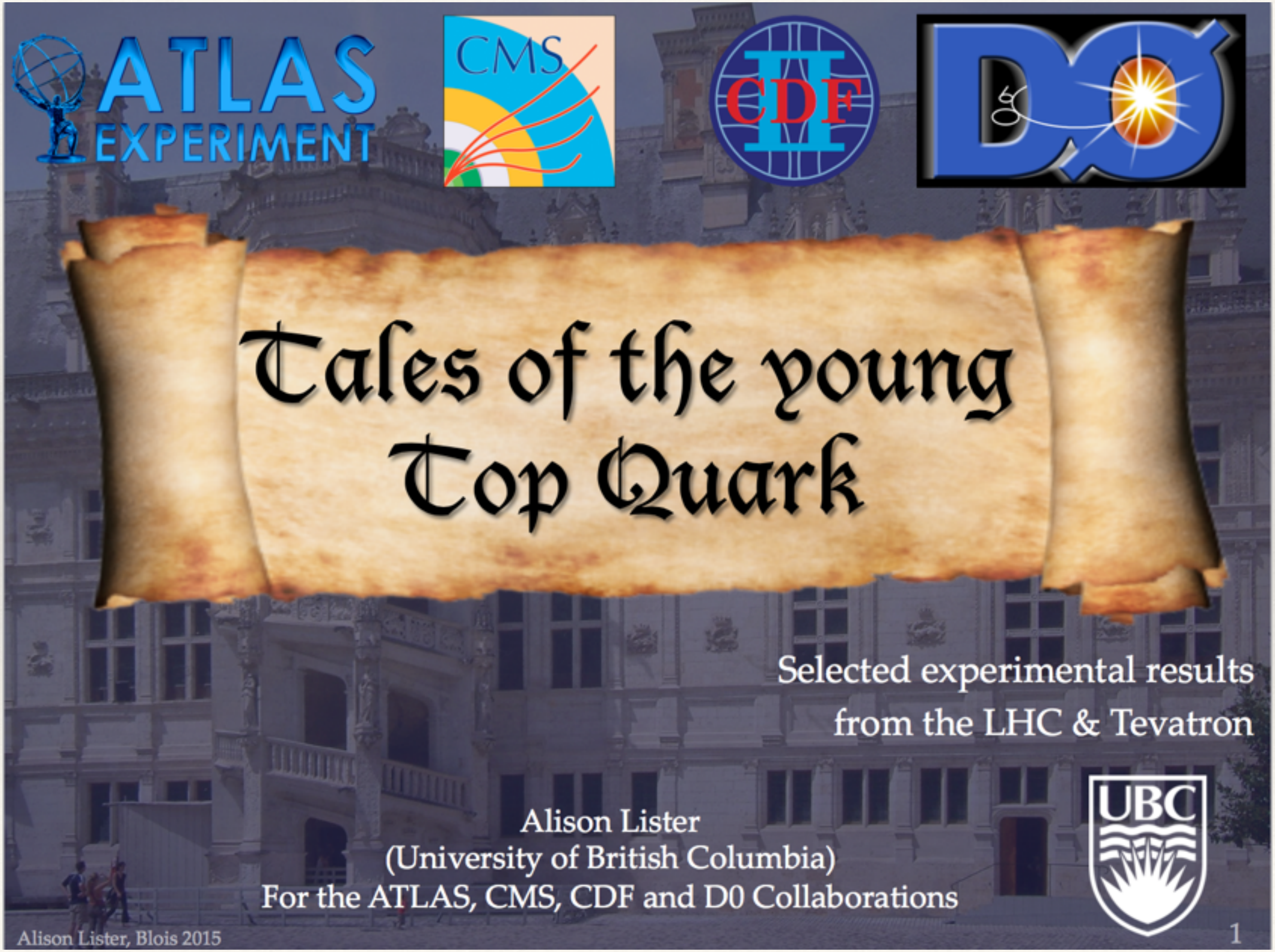
Dust Intensity & Polarization



old representations of old

new representations of old

young or old?


ATLAS EXPERIMENT
CMS
CDF II
DØ
Tales of the young Top Quark
Selected experimental results from the LHC & Tevatron
Alison Lister
(University of British Columbia)
For the ATLAS, CMS, CDF and D0 Collaborations
UBC
Alison Lister, Blois 2015
1

old-testament ancient

Asai

2. The Old Testament

Before LHC, Light SUSY (< 1TeV) is **"Natural"**

There were 3 dogmas

(1) Dark Matter (Bino ∼O(100GeV) /Wino ∼1TeV /Higgsino ∼O(100–1000GeV))
assumption: thermal production

(2) Naturalness of Higgs mass (within 1% tuning)
Scalar top quark (stop) mass ∼ < 1 TeV , Higgsino < O(100GeV)

(3) Unify three Forces (mainly depends on Gaugino ∼ 1–10TeV)

Gaugino/

Before LHC Run1, people believed SUSY is light (< ~ 1 TeV)

Divining / crystal balls

Papaefstathiou

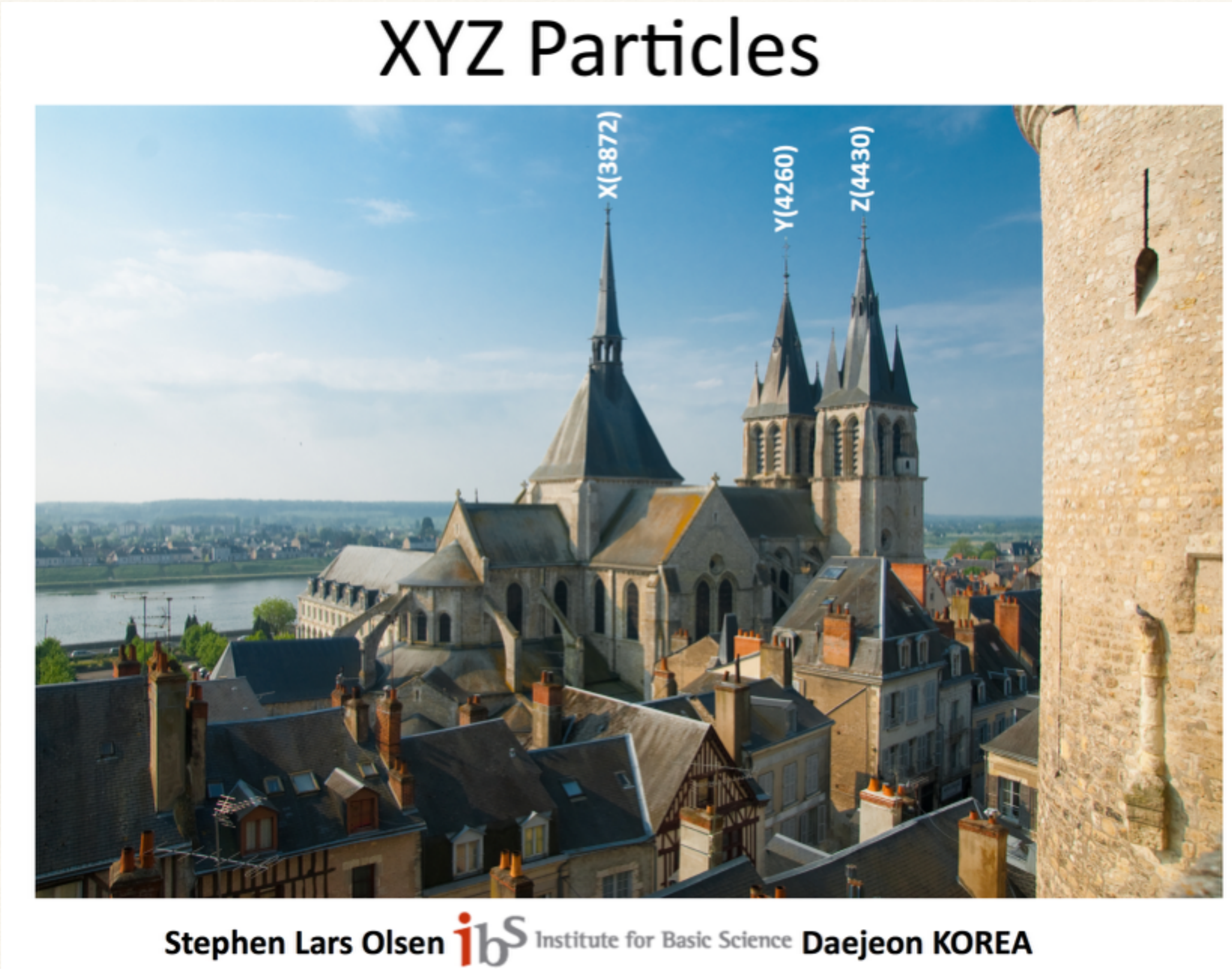
phenomenological projections

- search for **hh** at LHC14 in final states:

	(+)	(-)
$hh \to (b\bar{b})(\tau^+\tau^-)$	low bkgs, large BR	τ-tagging
$hh \to (b\bar{b})(\gamma\gamma)$	v. low bkgs, $m_{\gamma\gamma}$	low σ and j-to-γ
$hh \to (b\bar{b})(W^+W^-)$	leptons+E_{miss}	$t\bar{t}$
$hh \to (b\bar{b})(b\bar{b})$	highest BR (~1/3)	QCD

- discovery of **SM** signal at high-lumi LHC (3000 fb^{-1}) seems very likely!

XYZ castles

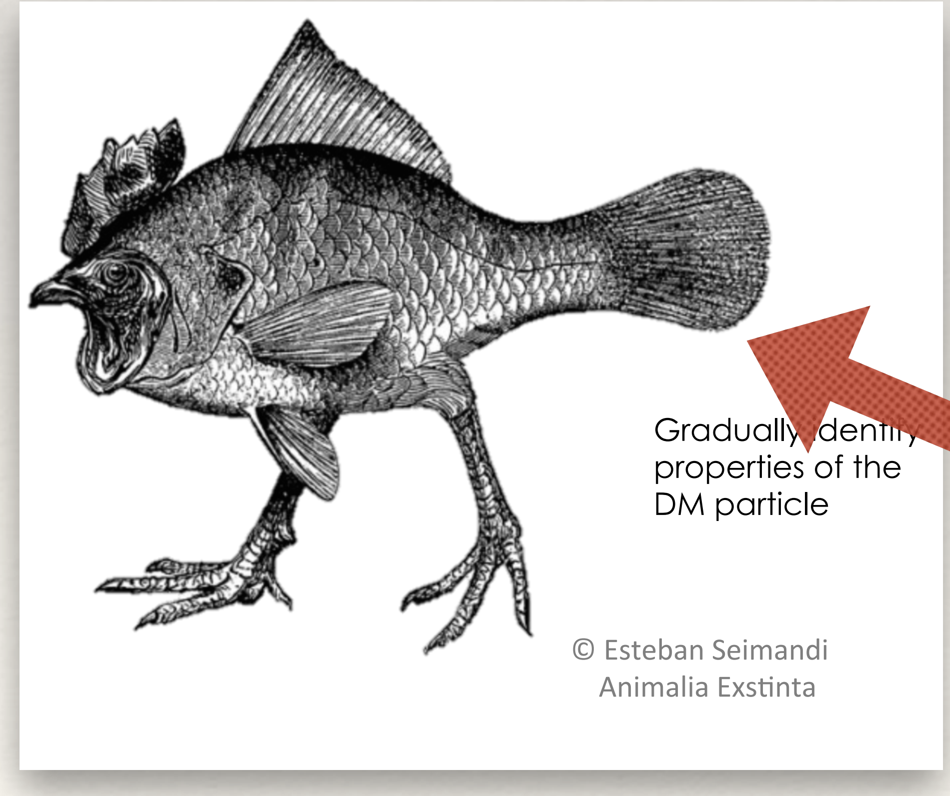


Olsen

Fauna

Lang

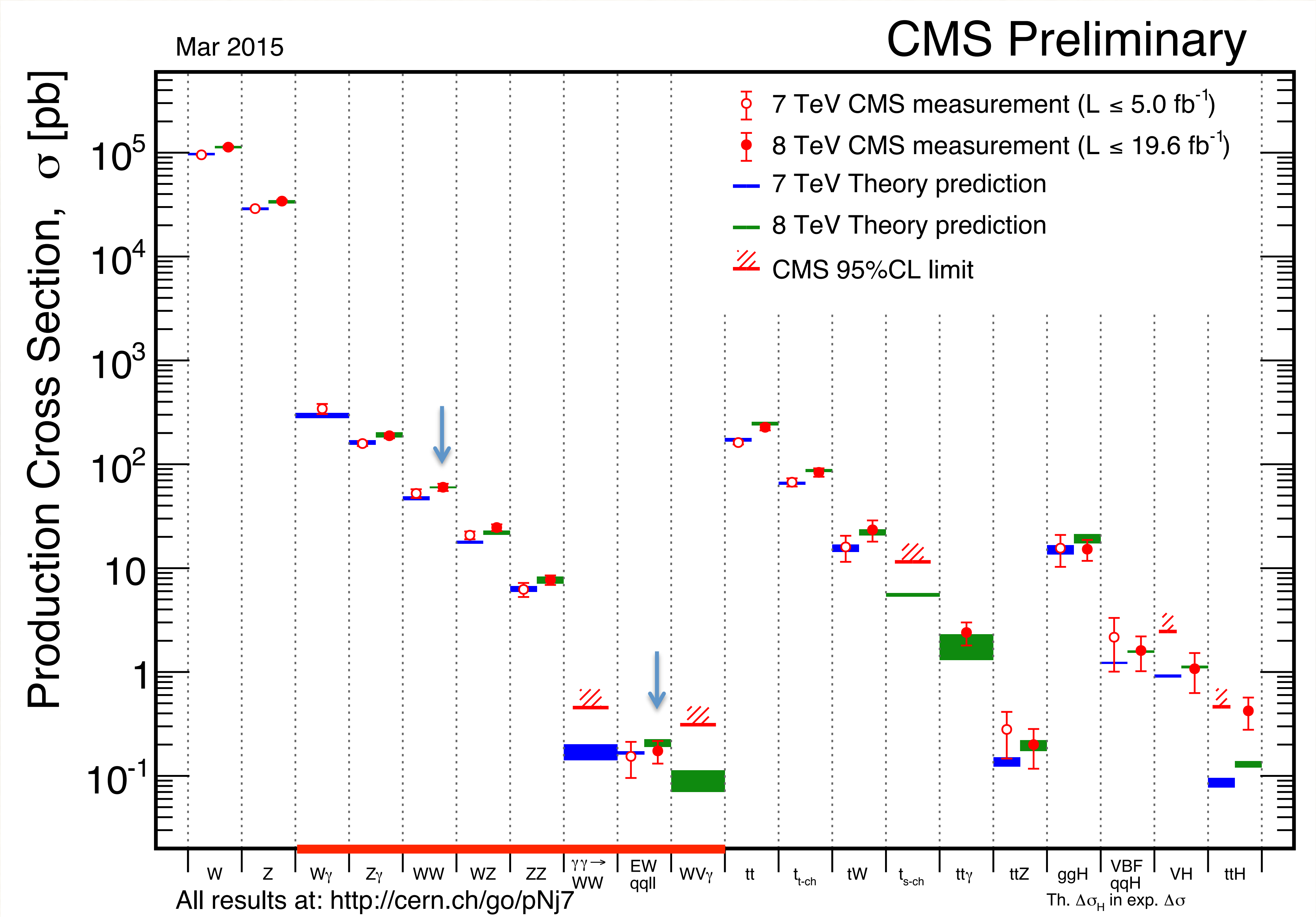
Cerdeño



Natural?

Staircase to heaven

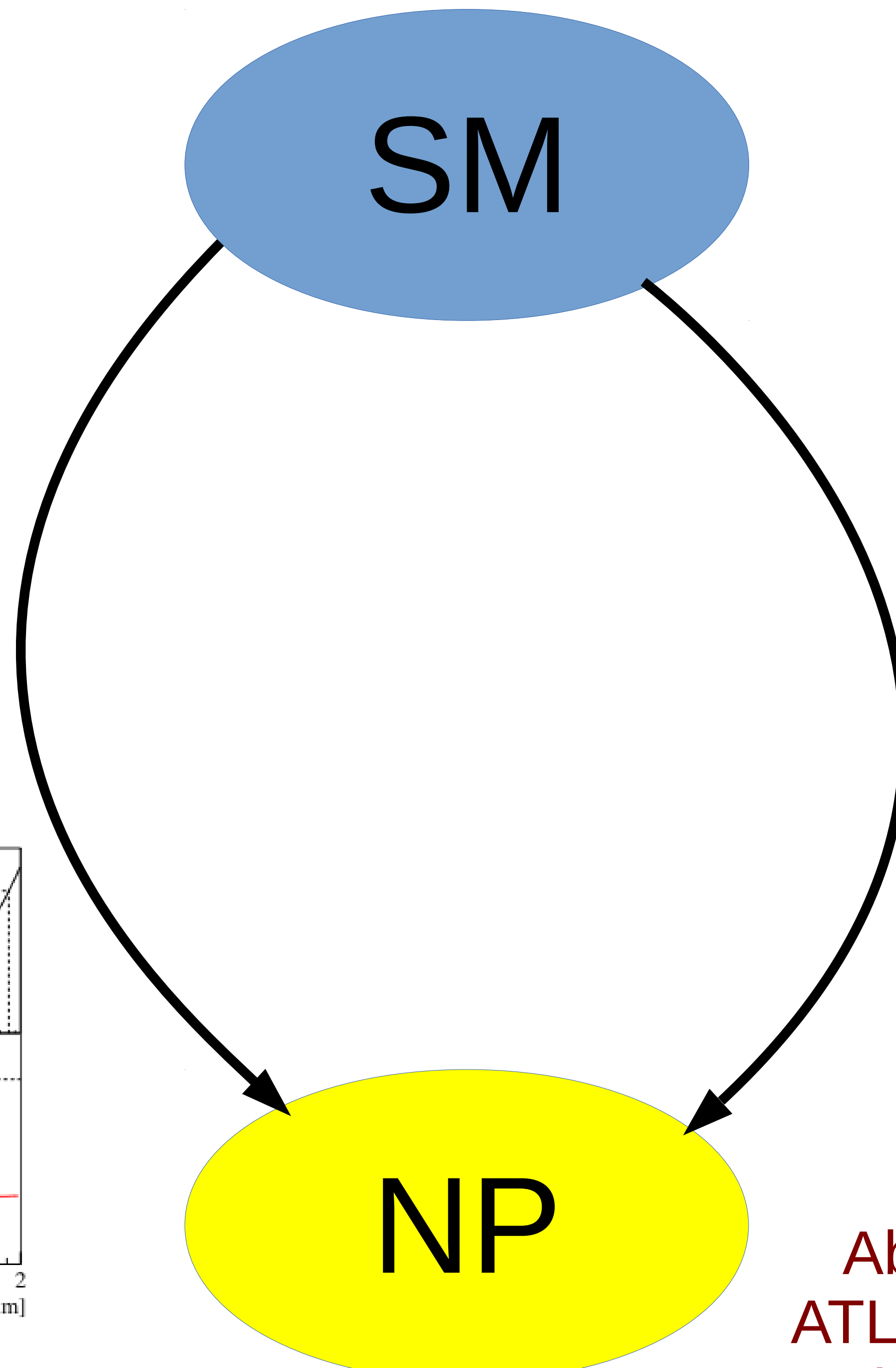
But only if your first script was Arabic, Hebrew, N'ko, etc.



Two routes to heaven

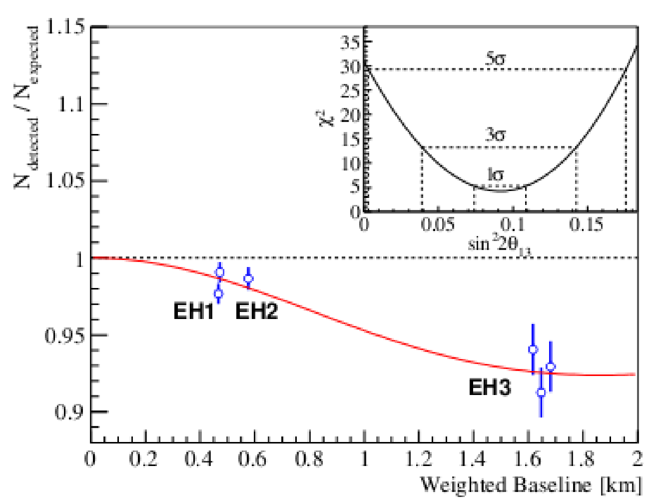
for quark flavour physics

CP violation
(extra sources must exist)

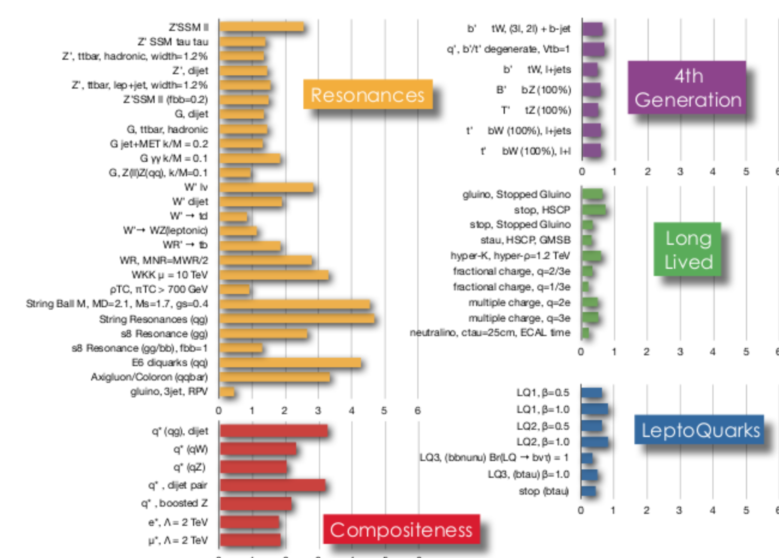


Rare decays
(strong theoretical arguments)

But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}



But
- How high is the NP scale?
- Why have FCNC effects not been seen?



Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

Concluding remarks

- We have puzzles that clearly need solving, e.g. dark matter, hierarchy of scales, baryon asymmetry
- Lack of clues about them, whether in the sky or in colliders, is **frustrating.**
- But powerful, well-executed experiments (and theory calculations) mean we're learning things fast: cosmological parameters, (ν)SM parameters, Higgs properties — amazing progress on many of these fronts.
- Treasure the day-to-day excitement that accompanies this progress, progress that is a prerequisite for the bigger revolutions that we hope to see, sooner or later.

Finally

A big **thank you** to the organizers for putting together such a stimulating and smoothly run workshop in this beautiful location.

Backup slides

Top	Higgs
20 years old	3 years old
0.4% on mass?	0.2% on mass

Wednesday: start of LHC Run 2

10.37am

> A huge cheer and round of applause in #ATLAS Control Room for first #13TeV collisions! Congratulations to the LHC @CERN for this milestone!
>
> — ATLAS Experiment (@ATLASexperiment) June 3, 2015

10.36am

Stable beams are expected in a few minutes - as soon as collisions occur successfullly at the other two interaction points - ALICE and LHCb...

10.34am

Beams now colliding at 13 TeV inside the ATLAS and CMS detectors!

10.34am

The LHC Operations team is preparing for first collisions at 13 TeV - aligning the beams at the four interaction points around the LHC ring.