After the Higgs discovery: perspectives on HEP

Future Research Infrastructures: Challenges and Opportunities
Villa Monastero, Varenna,
8-11 July 2015

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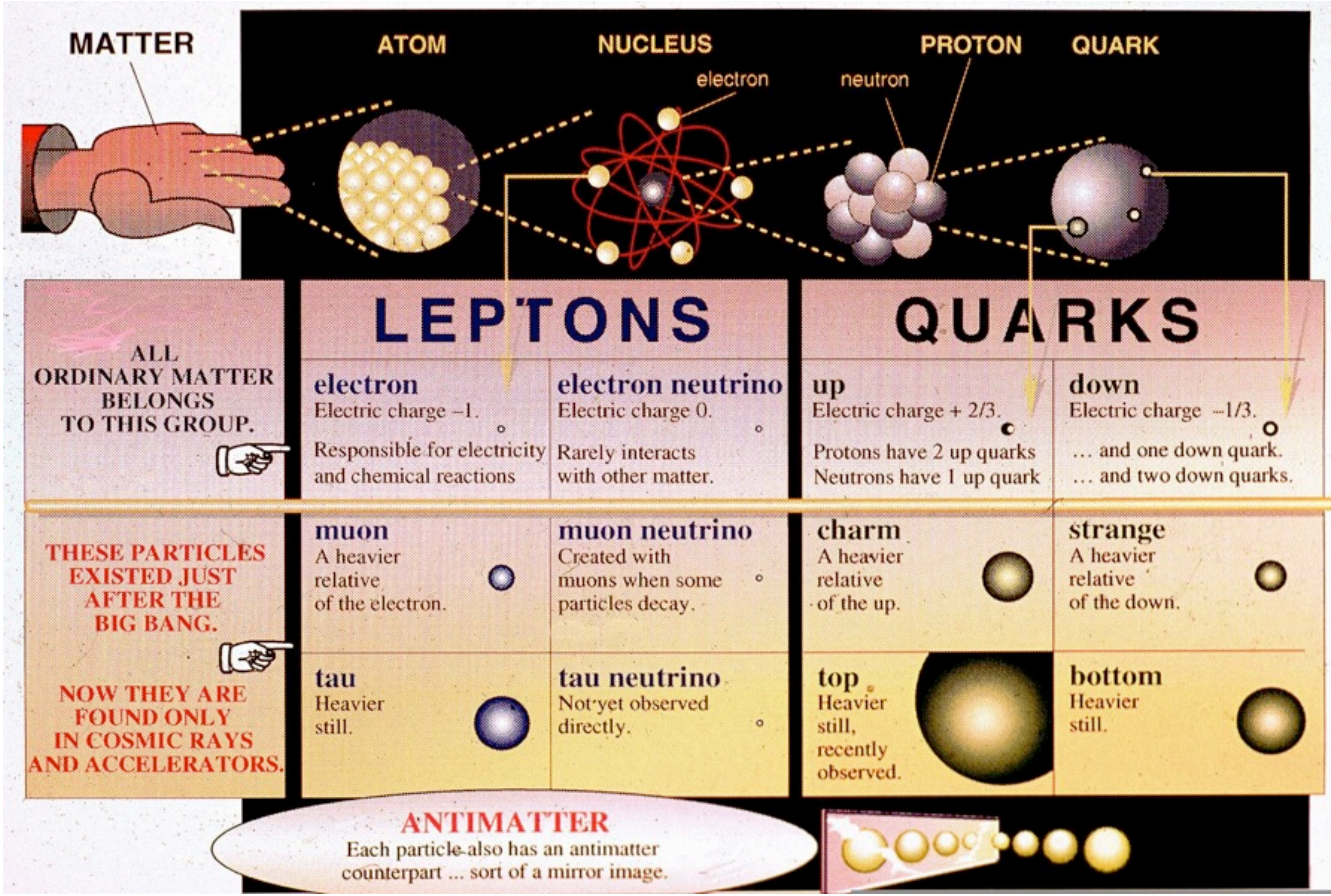
CERN, PH-TH

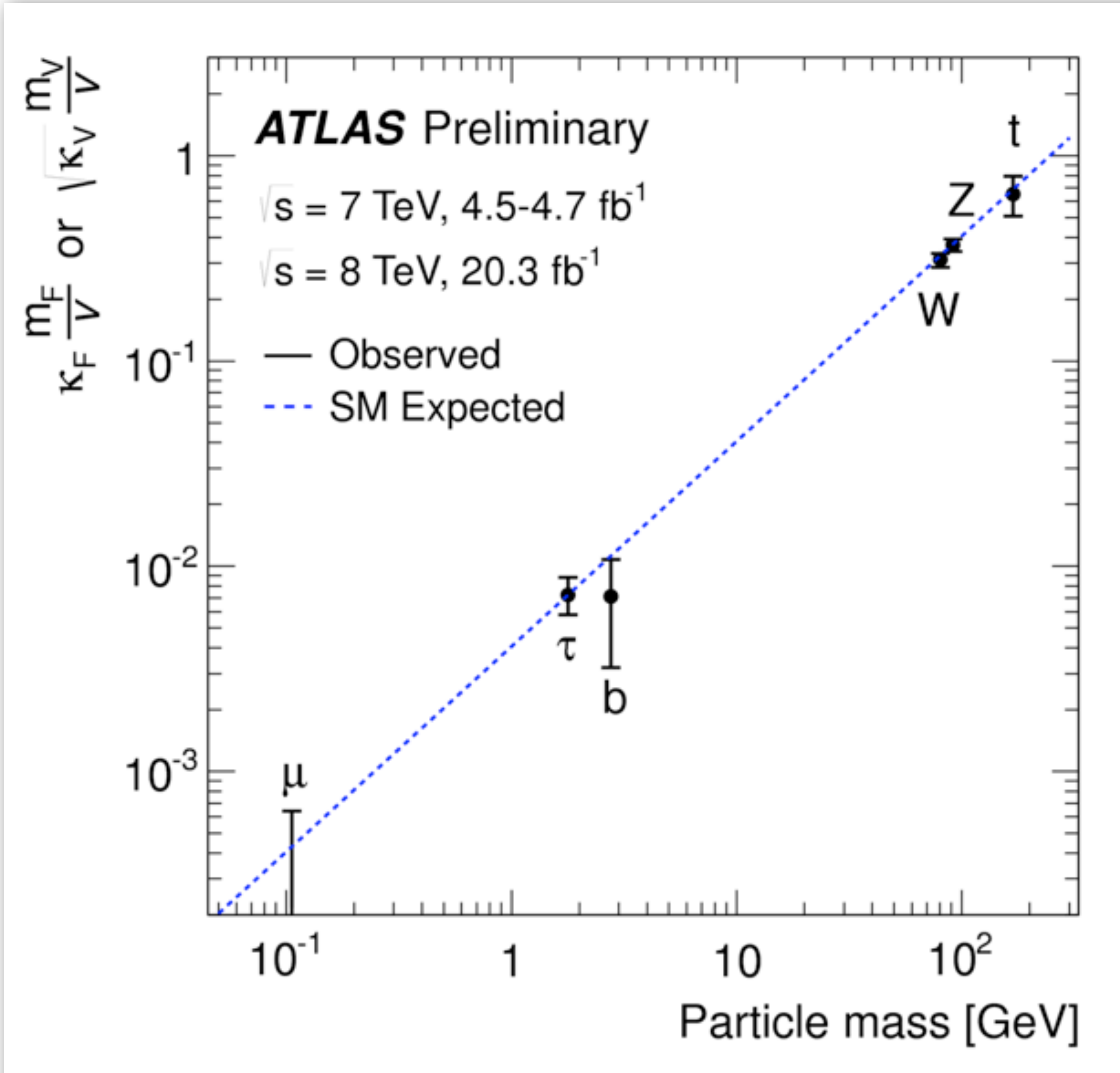
The Standard Model of particle physics



Status of the Standard Model

- **< 1973: theoretical foundations of the SM**
  - renormalizability of SU(2)xU(1) with Higgs mechanism for EWSB
  - asymptotic freedom, QCD as gauge theory of strong interactions
  - KM description of CP violation
- **Followed by 40 years of consolidation:**
  - **experimental** verification, via **discovery** of
    - **Fermions**: charm, tau, bottom, top (all discovered in the USA)
    - **Bosons**: gluon, W and Z, **Higgs** (all discovered in Europe)
  - **technical theoretical advances** (higher-order calculations, lattice QCD, ...)
  - **experimental** consolidation, via precision **measurement** of
    - EW radiative corrections
    - running of α_S
    - CKM parameters, ...
- **Remains to be verified:**
  - ***mechanism at the origin of particles' masses: is the Higgs boson dynamics what prescribed by the SM, or are there other phenomena at work?***

Run 1 of the LHC determined, with a precision of ±20%, that the Higgs boson gives a mass to SM particles



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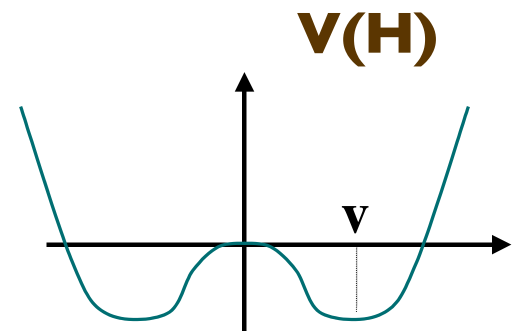
5. ***What gives mass to the Higgs?***

   Obvious question, with a trivial answer in the SM: the Higgs gives mass to itself!
   But less trivial answers can arise in beyond-the-SM scenarios

Higgs selfcouplings

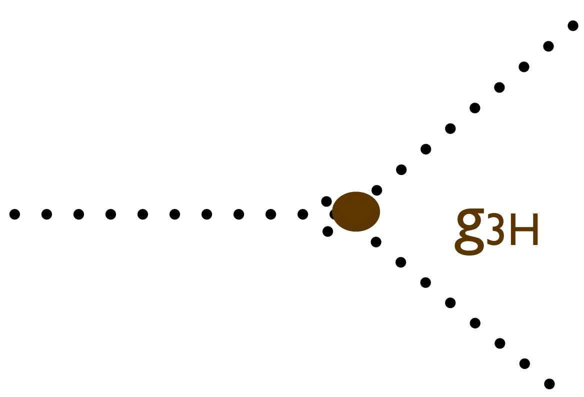
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

$$V_{SM}(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

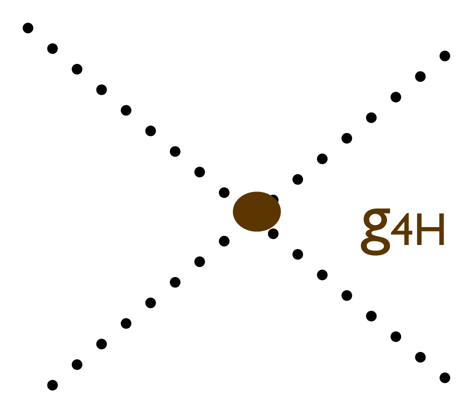


$$\frac{\partial V_{SM}(H)}{\partial H}\Big|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}\Big|_{H=v} \quad \Rightarrow \quad \begin{aligned} \mu &= m_H \\ \lambda &= \frac{m_H^2}{2v^2} \end{aligned}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



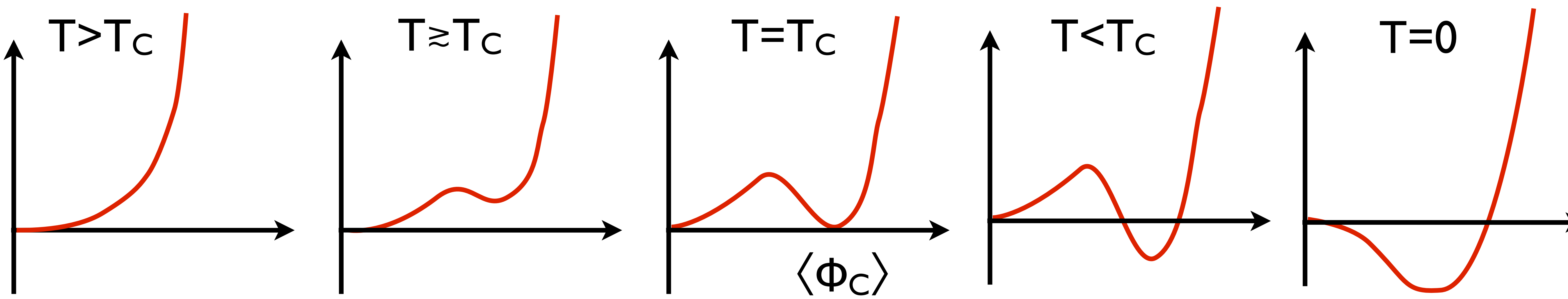
$g_{3H} \Rightarrow 6\lambda\, v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

The nature of the EW phase transition



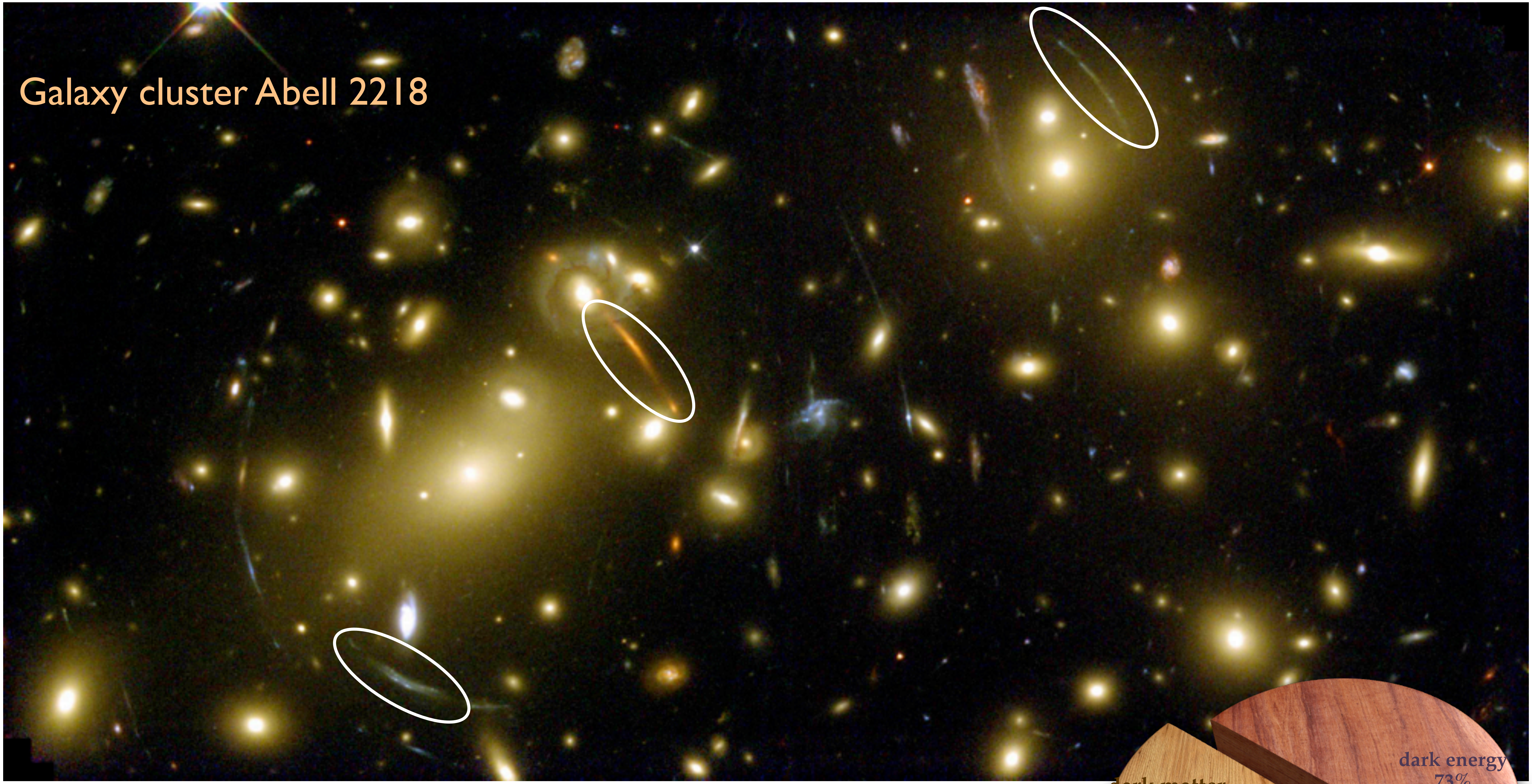
Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV ⇒ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible

Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for future accelerators

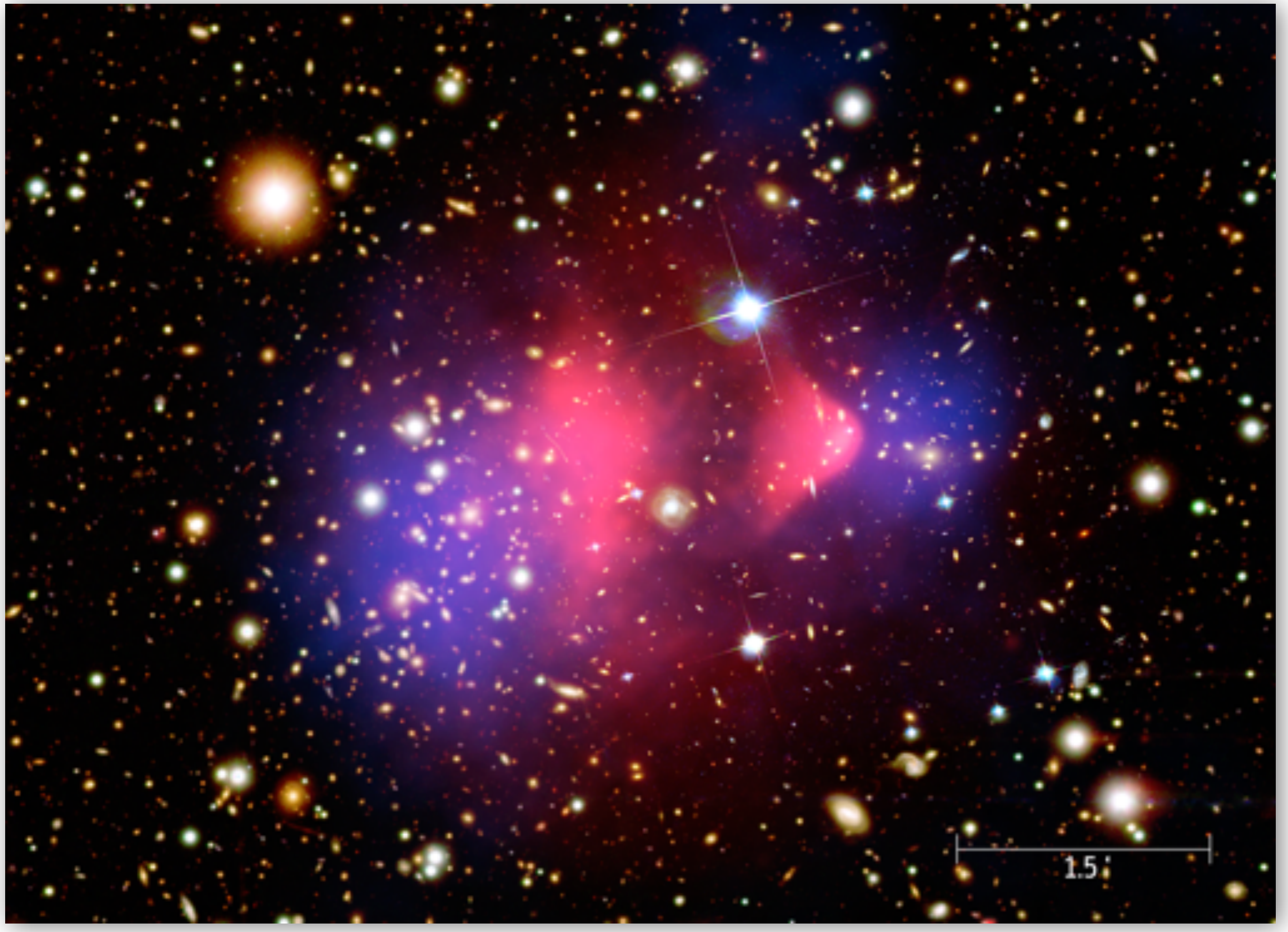
- Experimental probes:
  - study of triple-Higgs couplings (... and quadruple, etc)
  - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
  - search for new sources of CP violation, originating from (or affecting) Higgs interactions

What is Dark Matter?



The modeling of Dark Matter has become more and more articulate. From a single source (WIMP, axion, neutrino, ...) to the possibility of dark hidden worlds

Evidence building up for self-interacting DM



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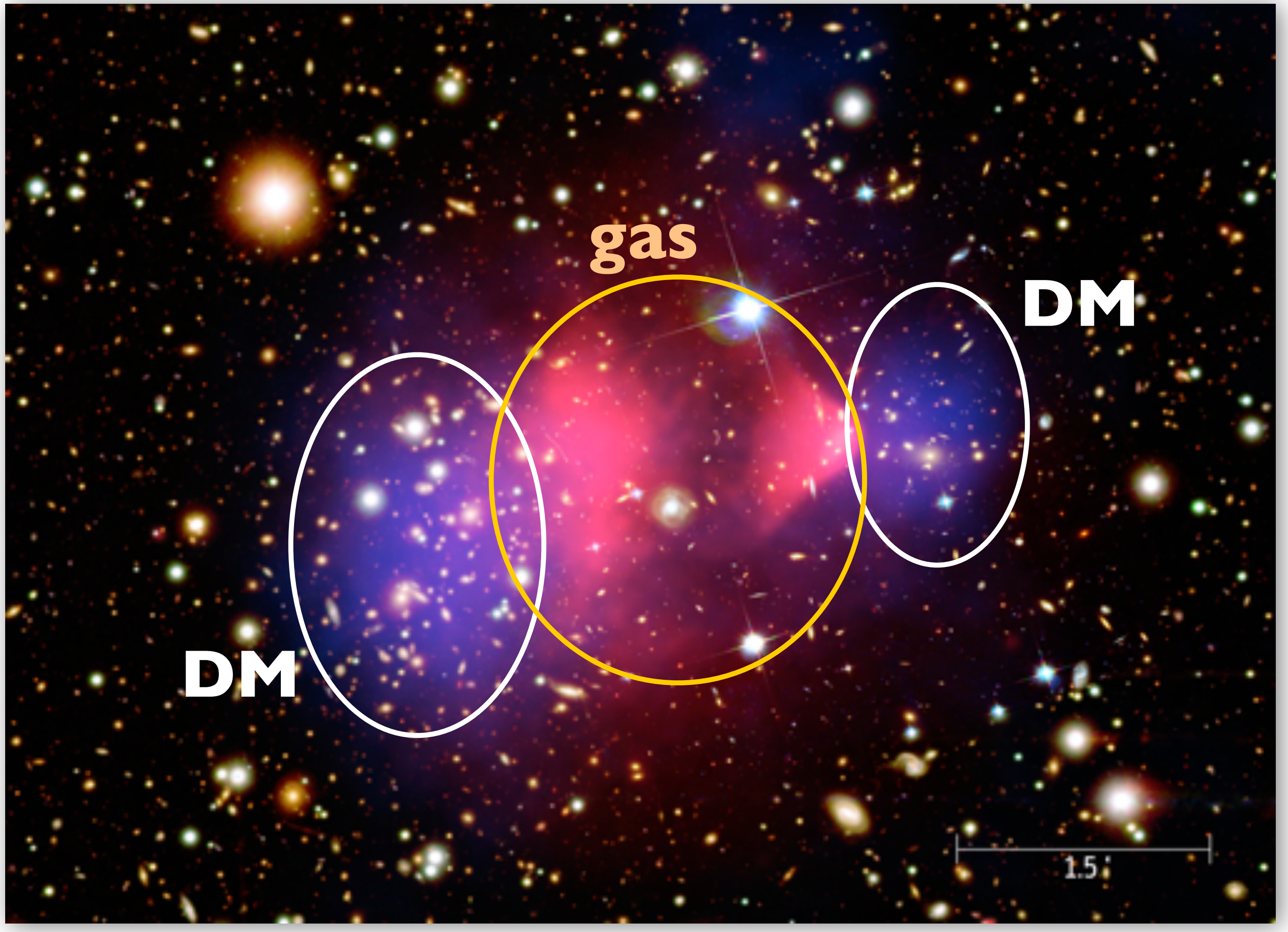

$\sigma \sim 1 cm^2 (m_\chi/g) \sim 2\times10^{-24} cm^2 (m_\chi/GeV)$

For a WIMP: $\sigma \sim 10^{-38} cm^2 (m_\chi/100\ GeV)$

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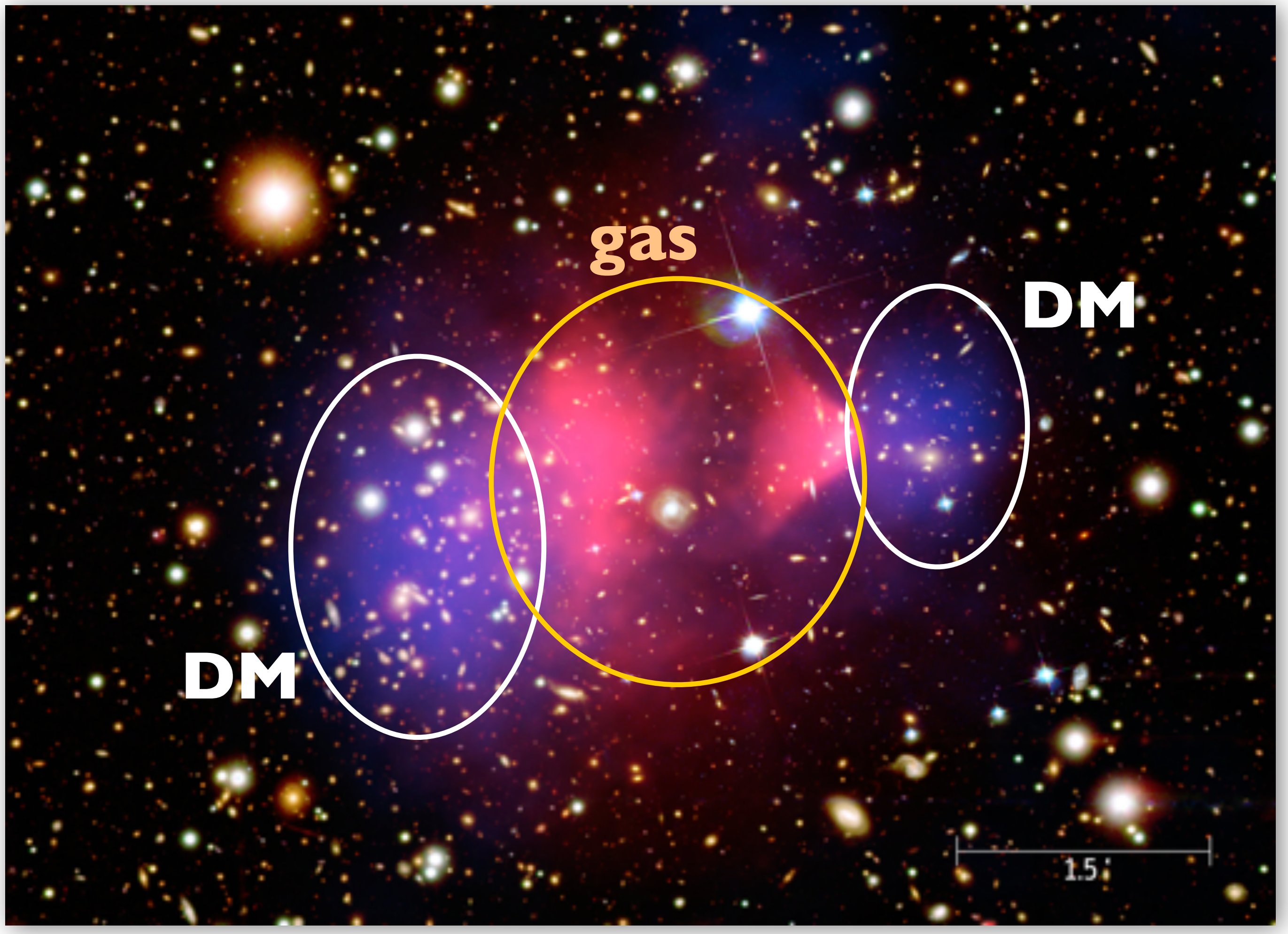

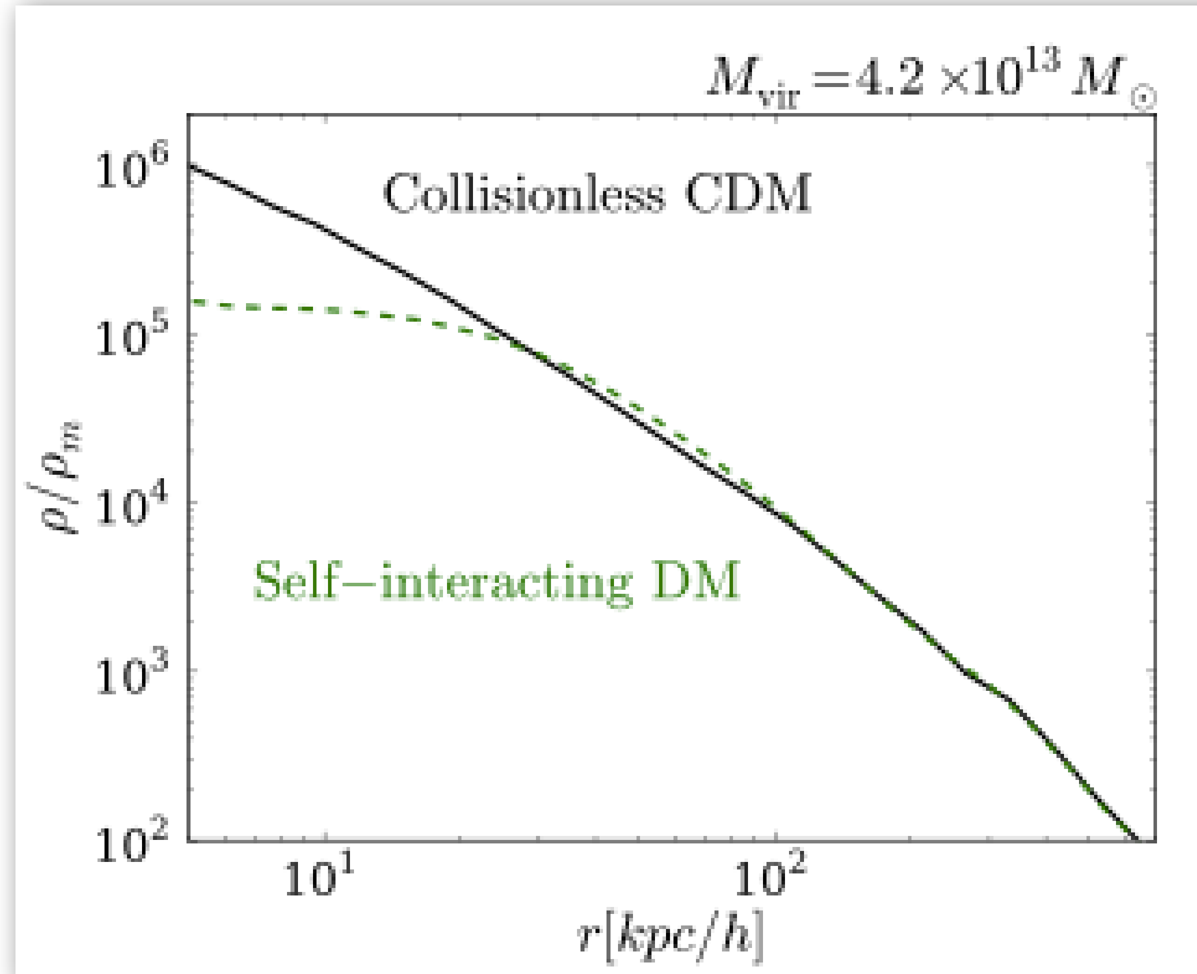

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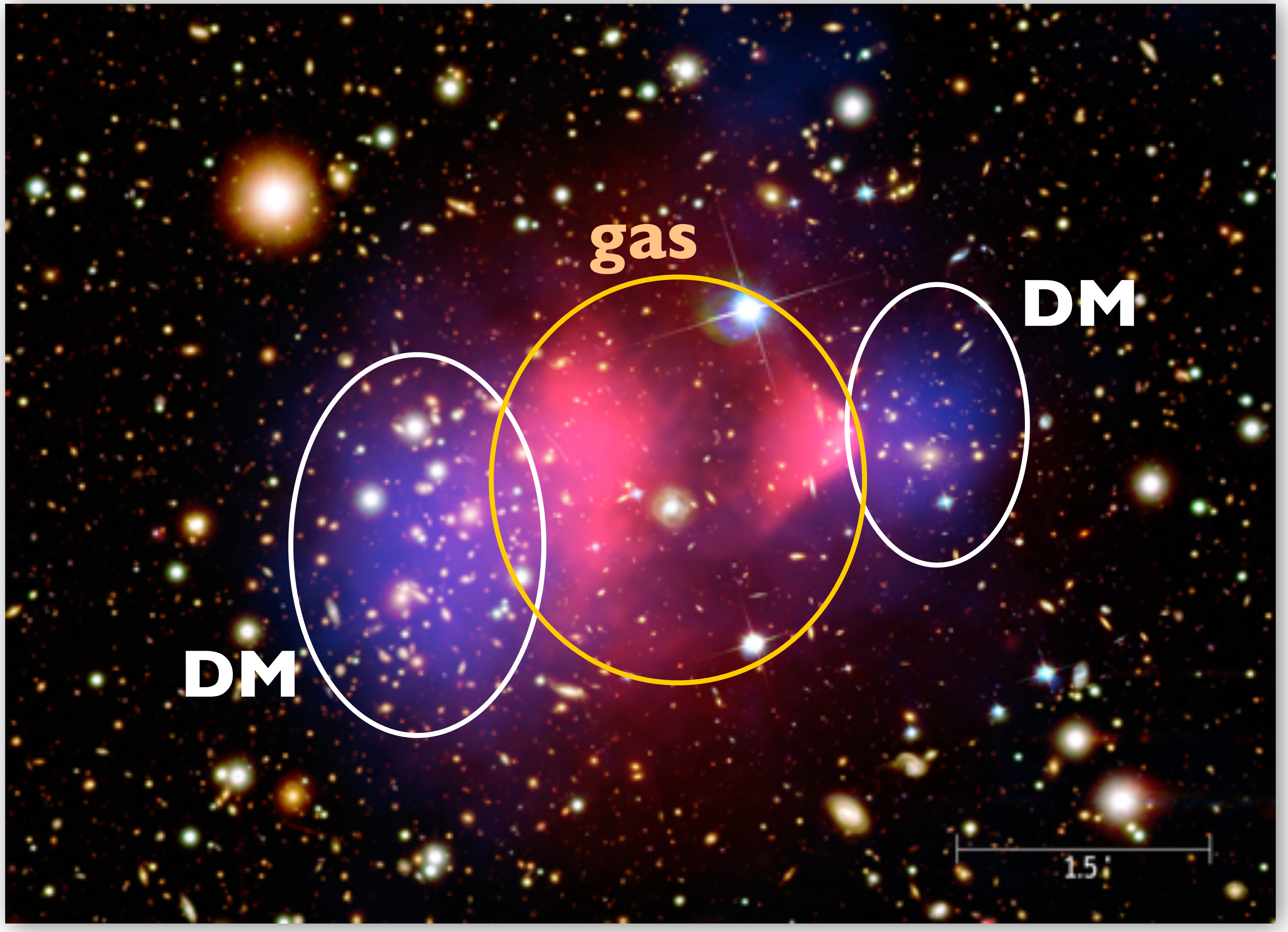

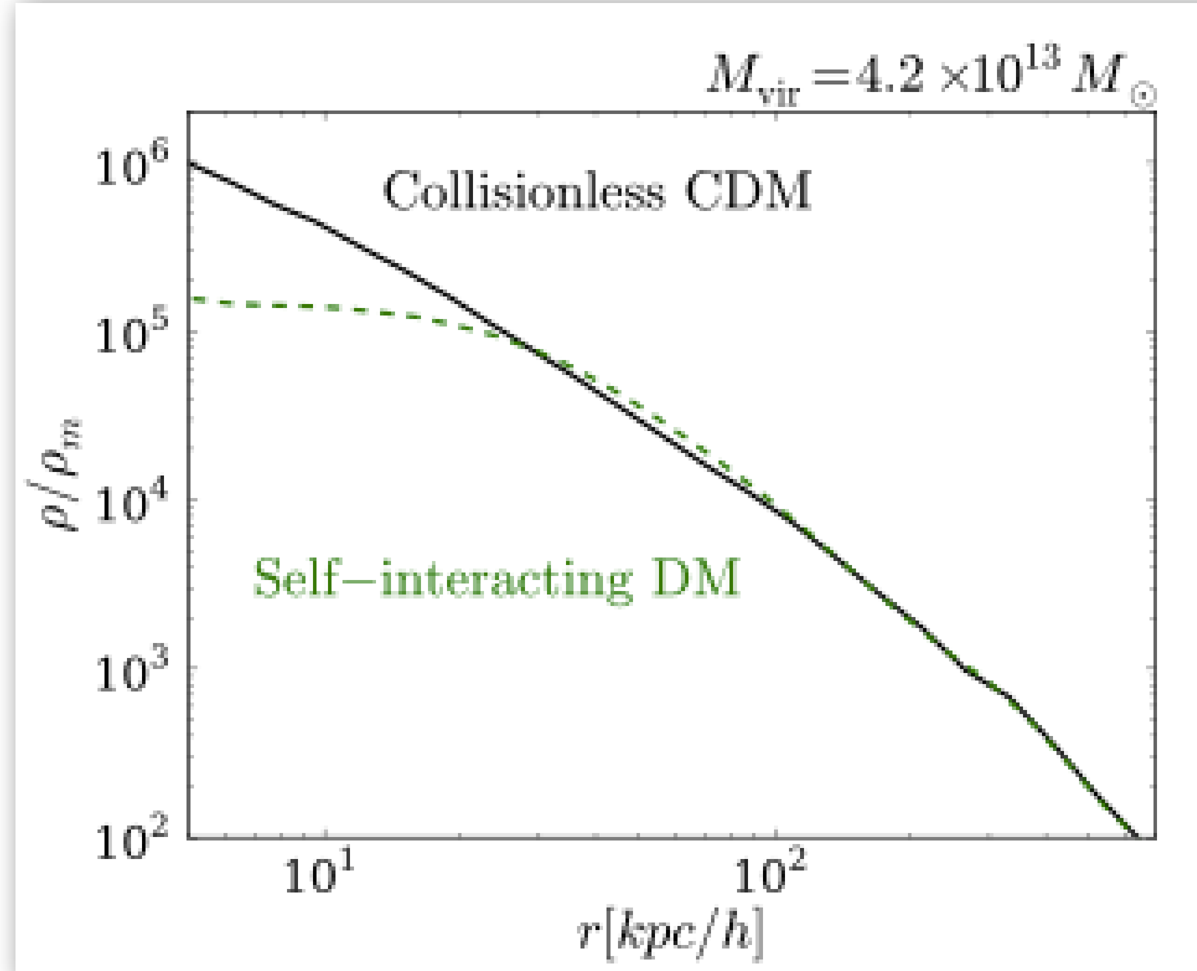

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Growing interest in models with rich sectors of "dark" particles, coupled to the SM ones via <u>weakly interacting</u> "portals"

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The opportunities for testing and discovering such scenarios at the LHC, beyond and elsewhere are under study

Pending items after LHC Run 1

Anomalies in flavour phenomena

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$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

LHCb, arXiv:1406.6482

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stat syst

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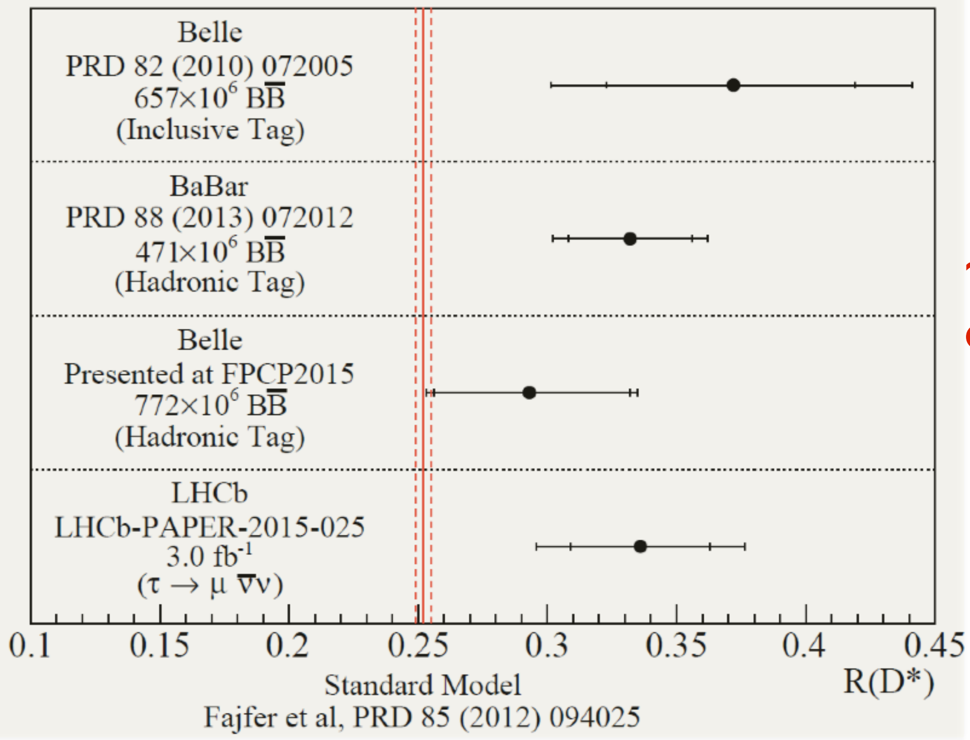
$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

SM: $R(D^*) = 0.252(3)$

LHCb, arXiv:1506.08614:

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

2.1σ



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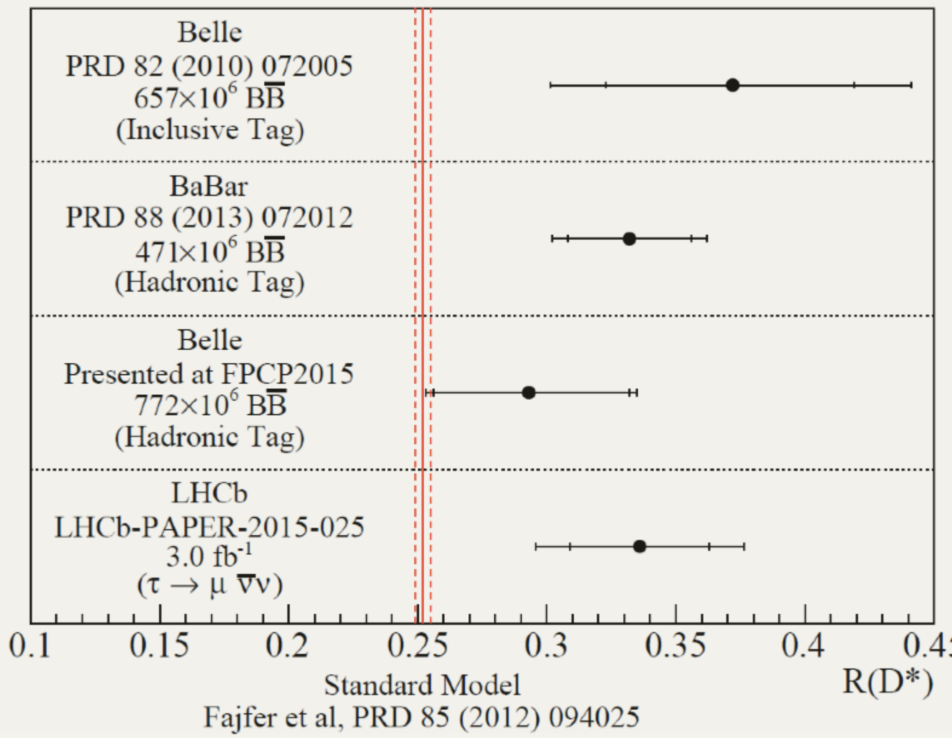

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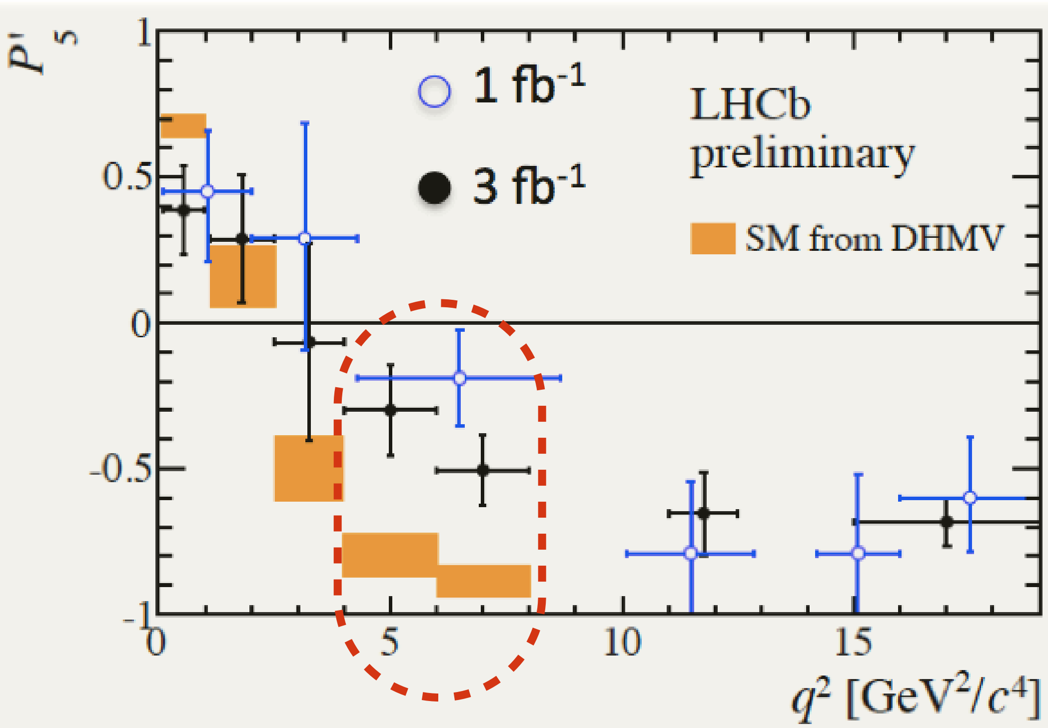

• $B \to K_* \mu^+\mu^-$ anomaly

LHCb, arXiv:1308.1707 and
3fb^{-1} update LHCb−CONF−2015−002

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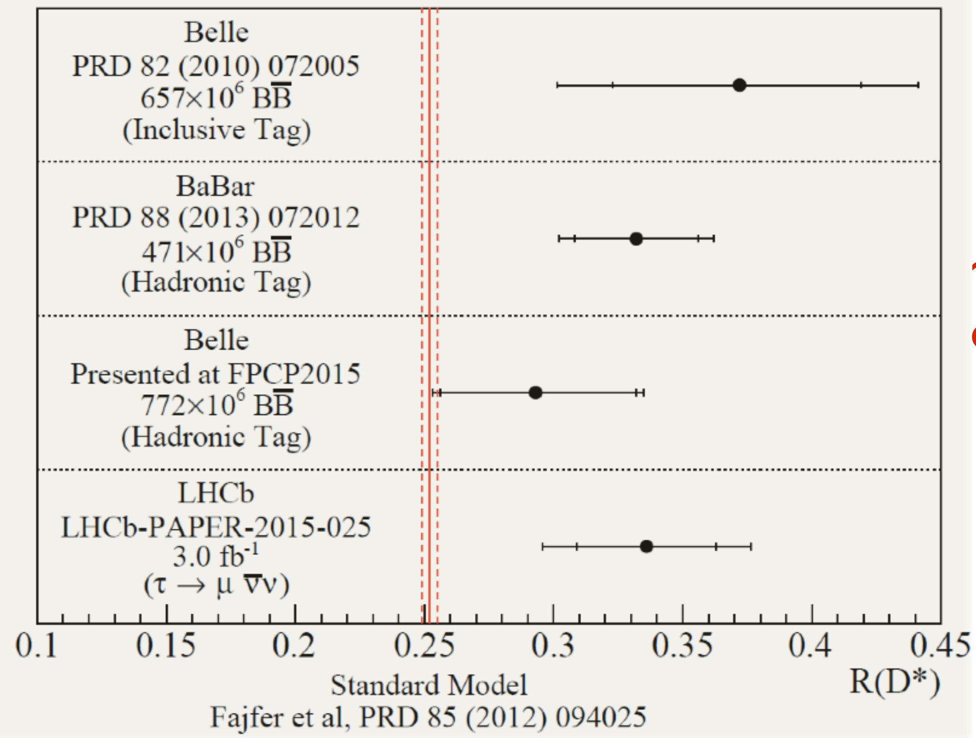

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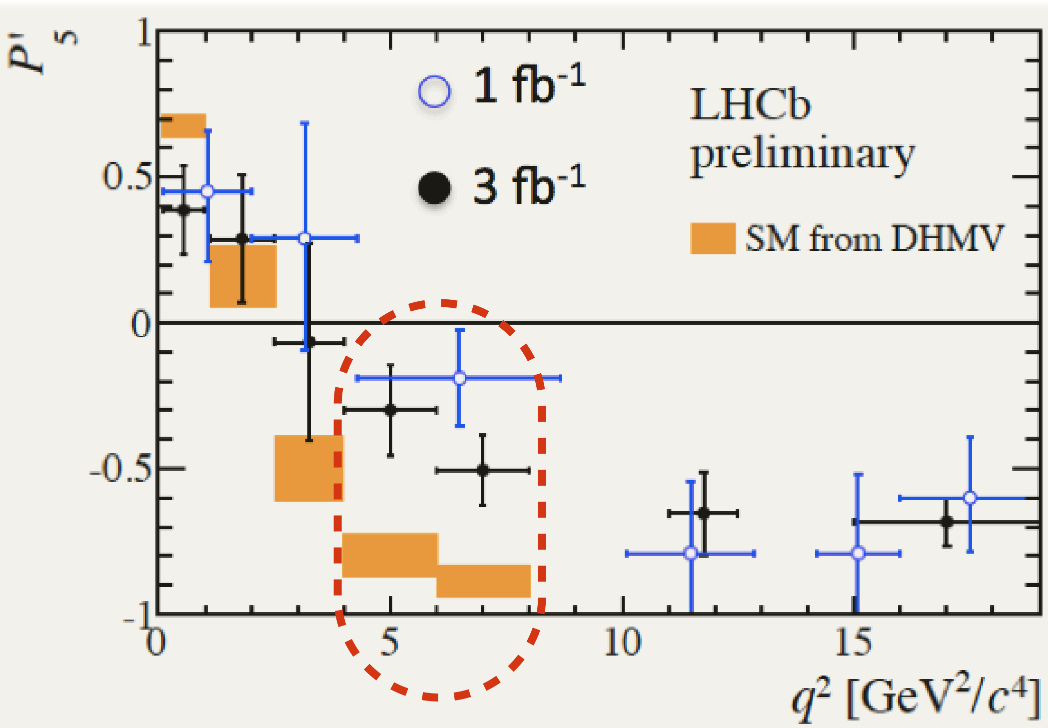


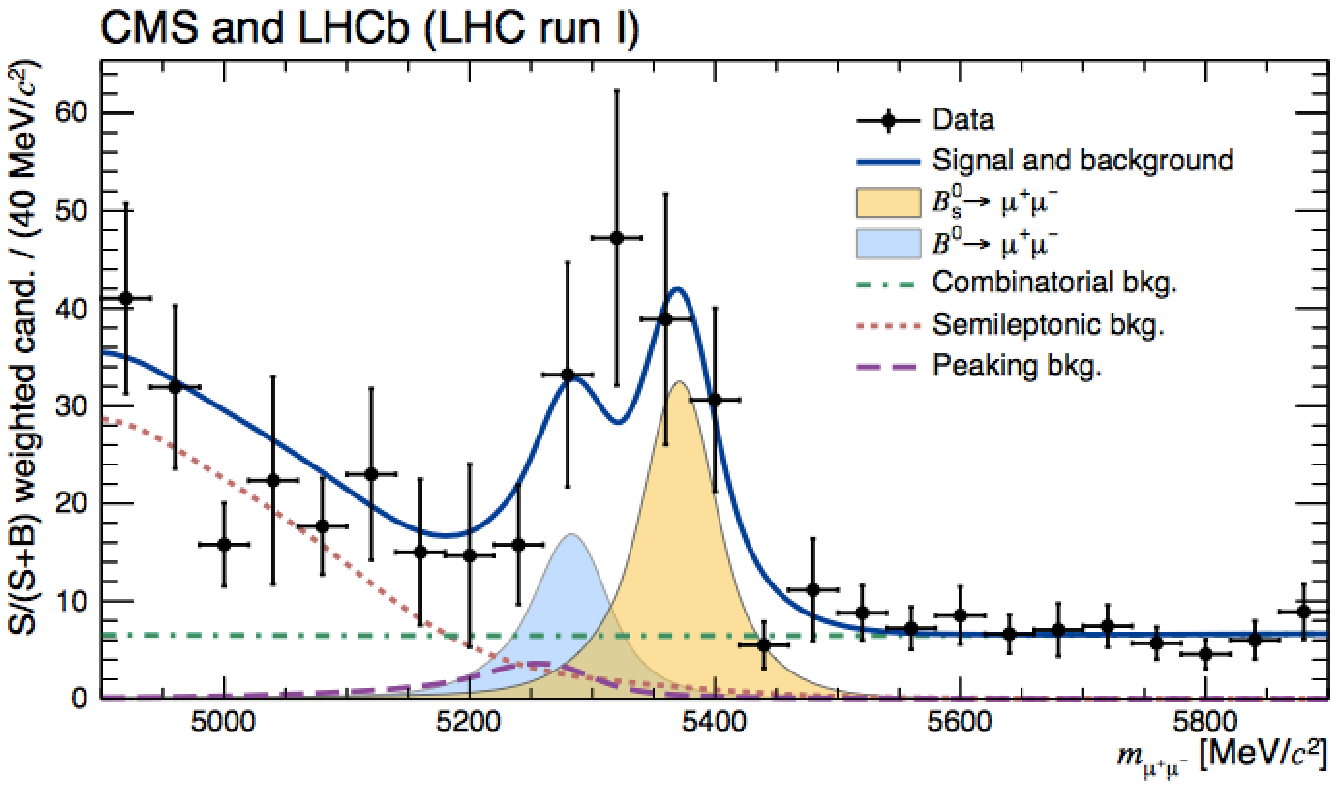
- B → K* μ+μ− anomaly

LHCb, arXiv:1308.1707 and 3fb^{-1} update LHCb−CONF−2015−002

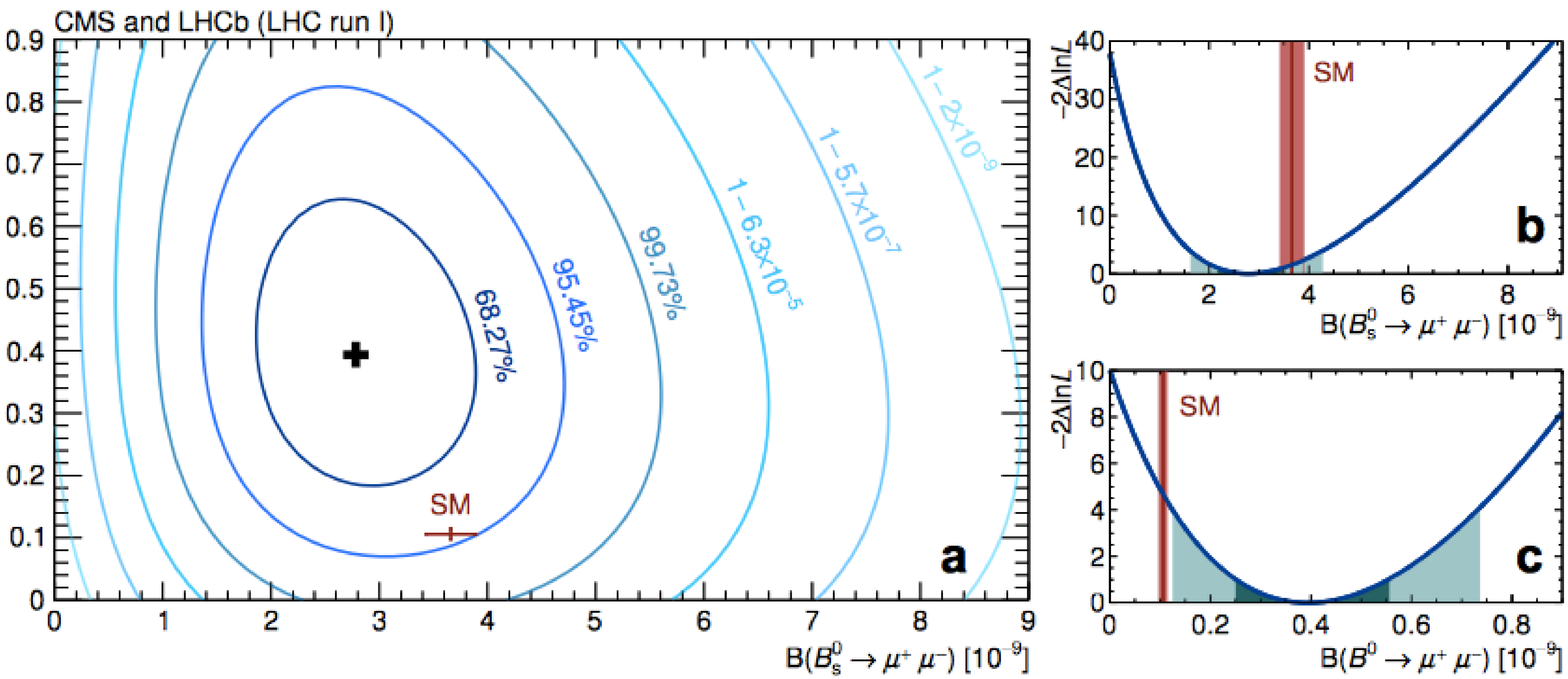
$$\text{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\%$$

CMS-PAS-HIG-14-005

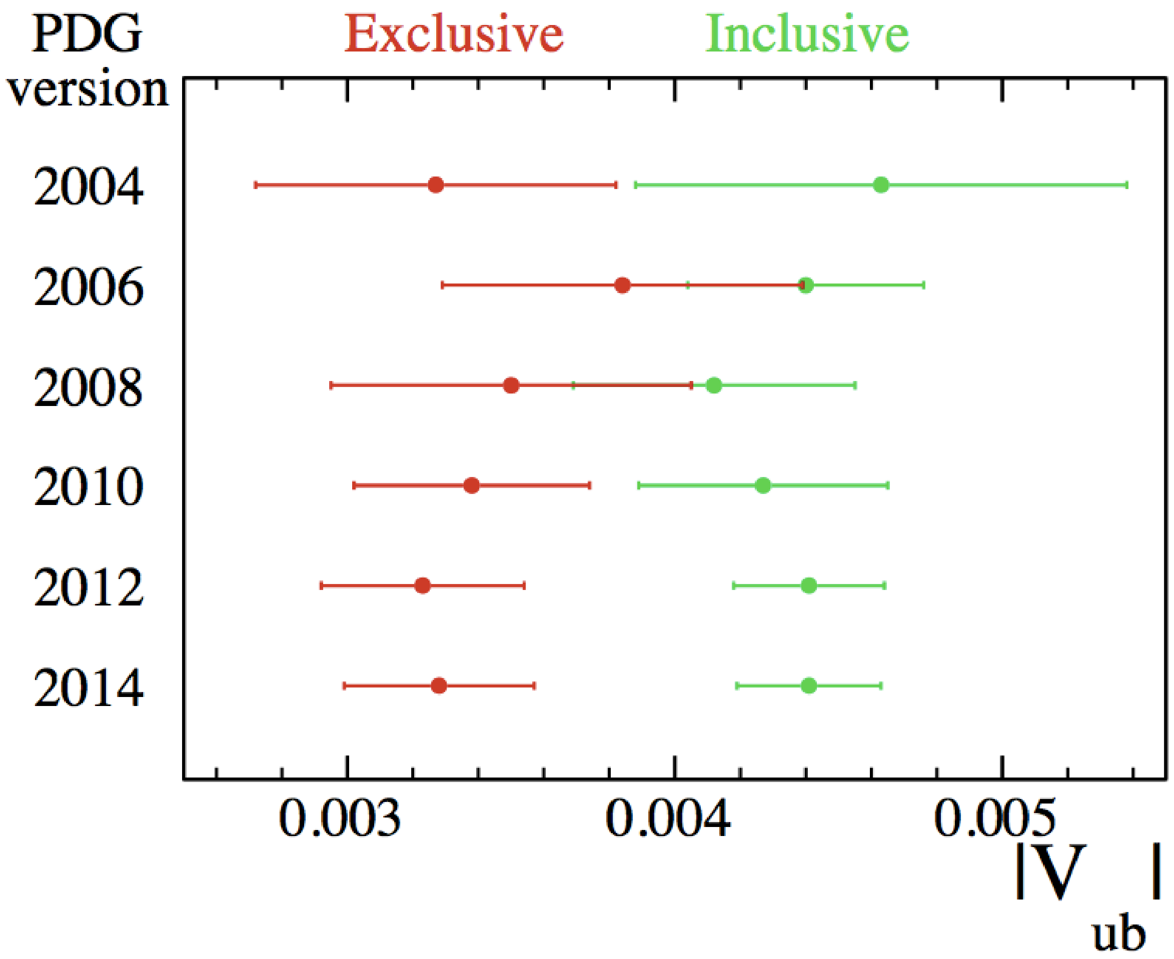
CMS/LHCb $B_{(S)} \to \mu^+\mu^-$



$$\frac{BR(B \to \mu^+\mu^-)}{BR(B_S \to \mu^+\mu^-)}$$ 2.3σ high w.r.t. SM



V_{ub} puzzle


PDG version
Exclusive
Inclusive
2004
2006
2008
2010
2012
2014
0.003
0.004
0.005
|V_ub|

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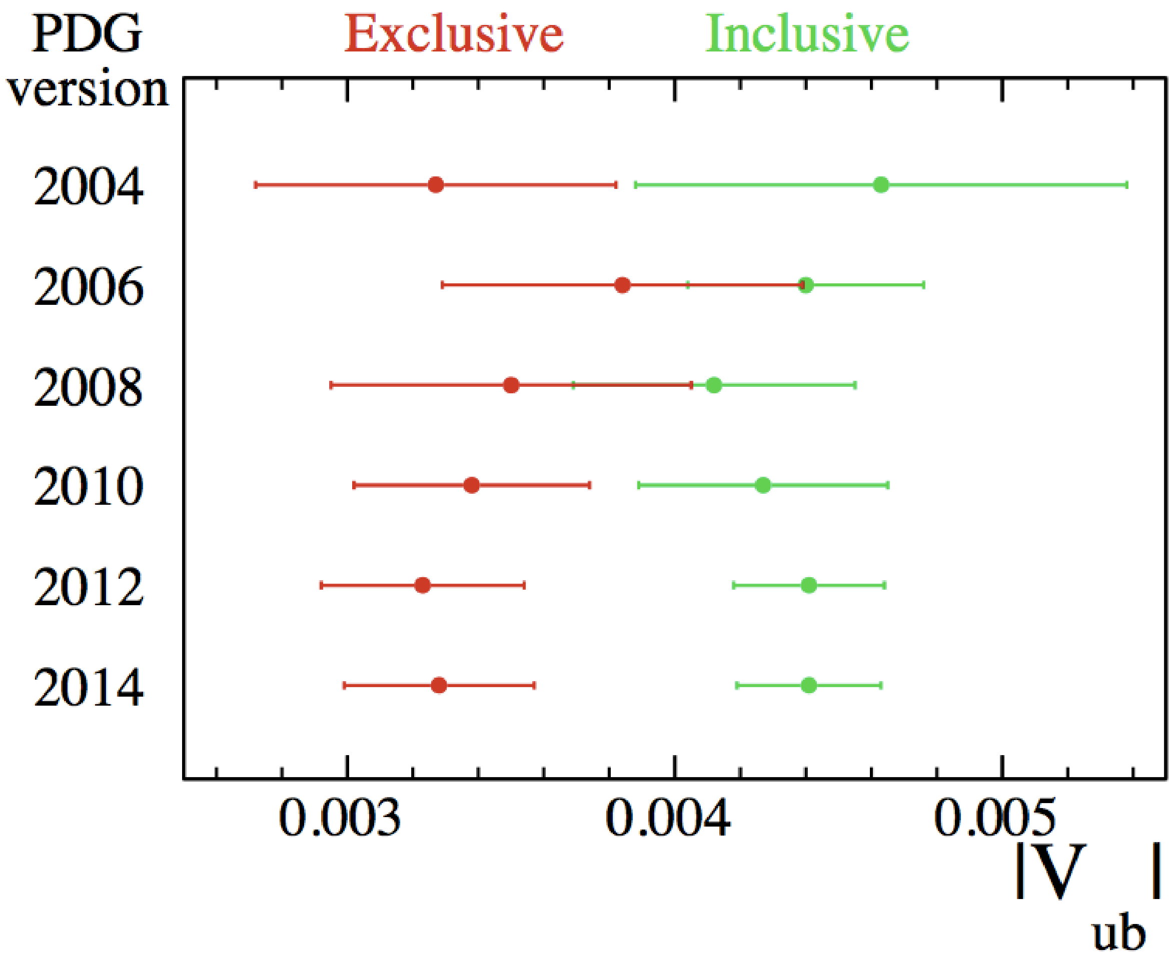
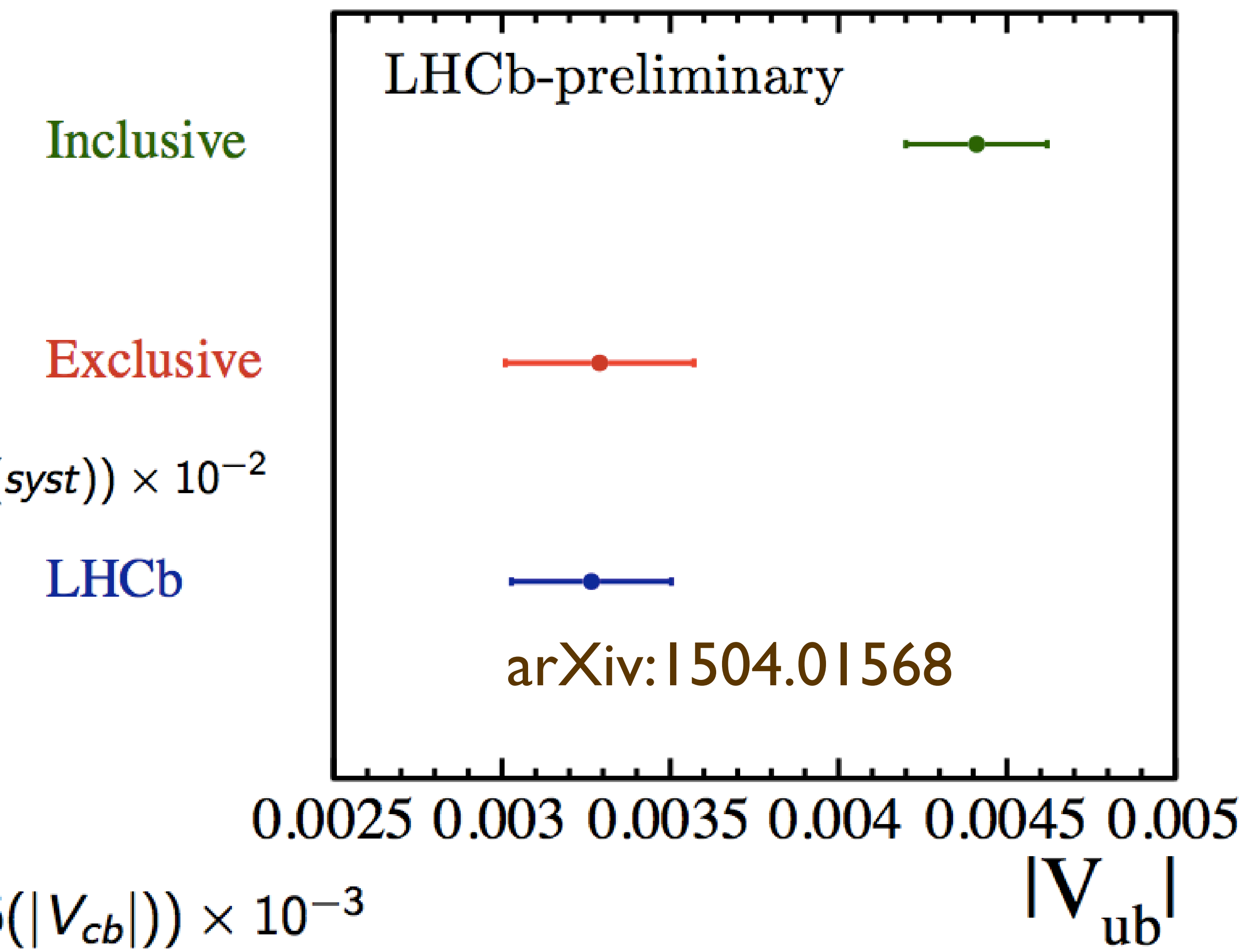


$\Lambda_b \to p\mu\nu$ at LHCb

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

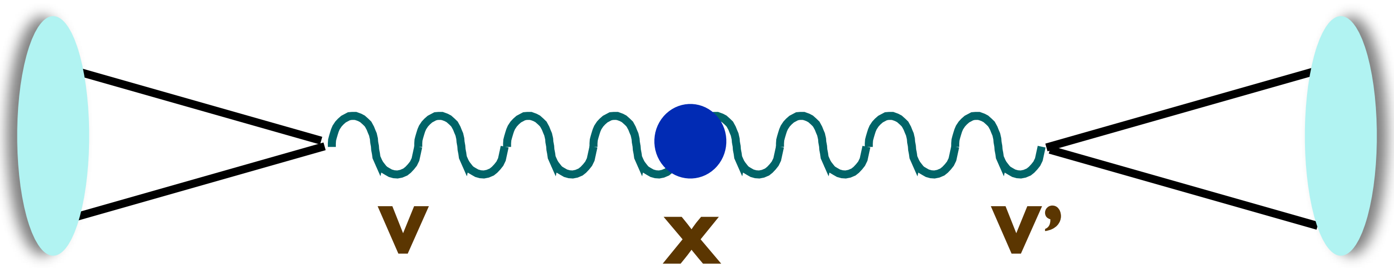
$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$



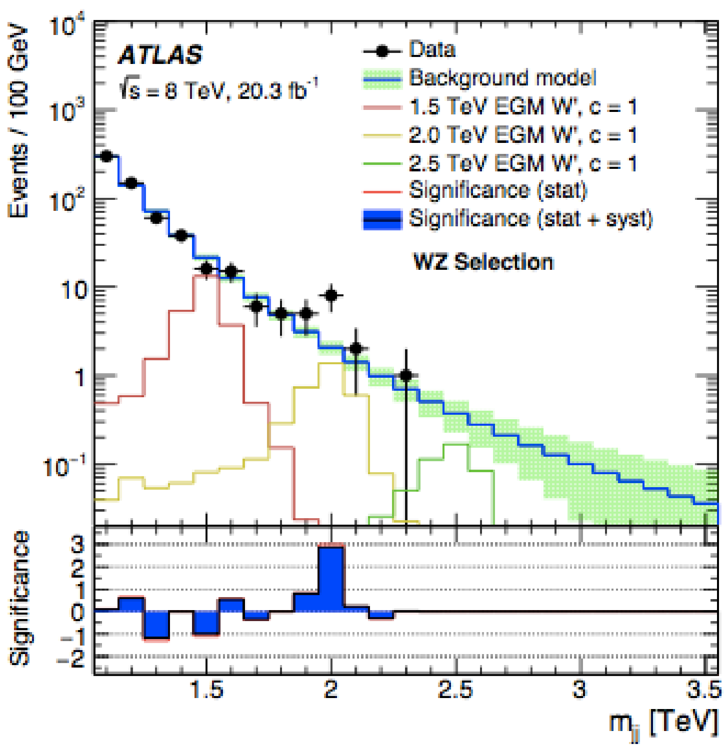
Anomalies left over from run 1, examples at large Q

ATLAS, arXiv:1506.00962

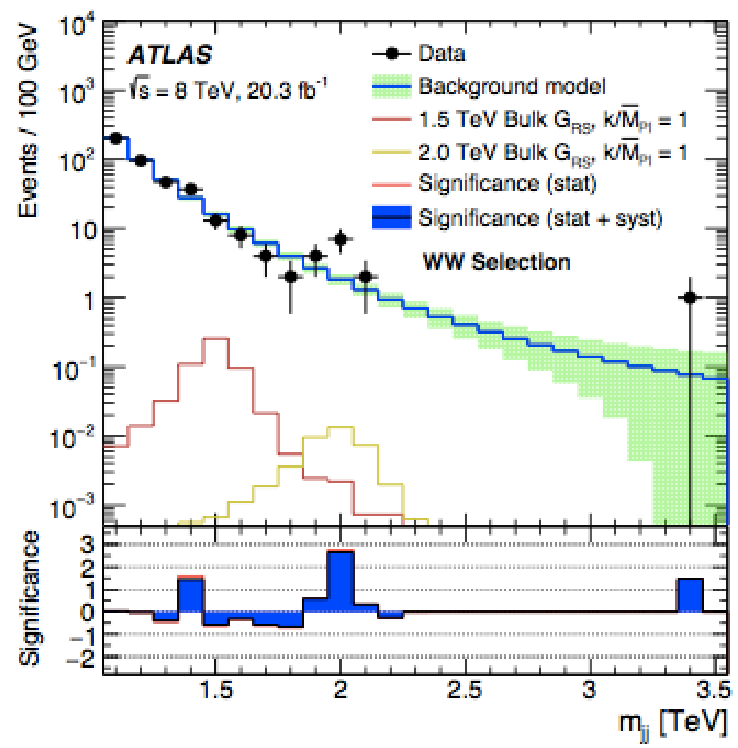
pp→X→VV' →jet jet, with V(')=W,Z fully hadronic decays



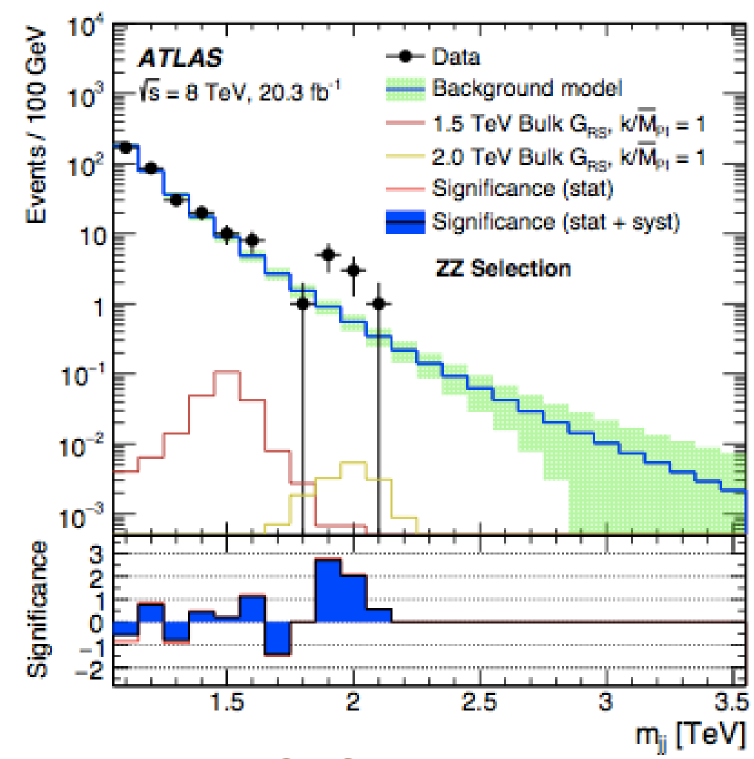
$| m_j – m_V | < 13$ GeV



3.5σ *local*



2.6σ



2.9σ

→**2.4σ *global***, accounting for the whole range of m_{jj} and for ZZ, WW, WZ modes

NB: the excesses are strongly correlated: $| m_j – m_V | < 13$ GeV allows the same event to belong to more than one selection among WZ, WW and ZZ

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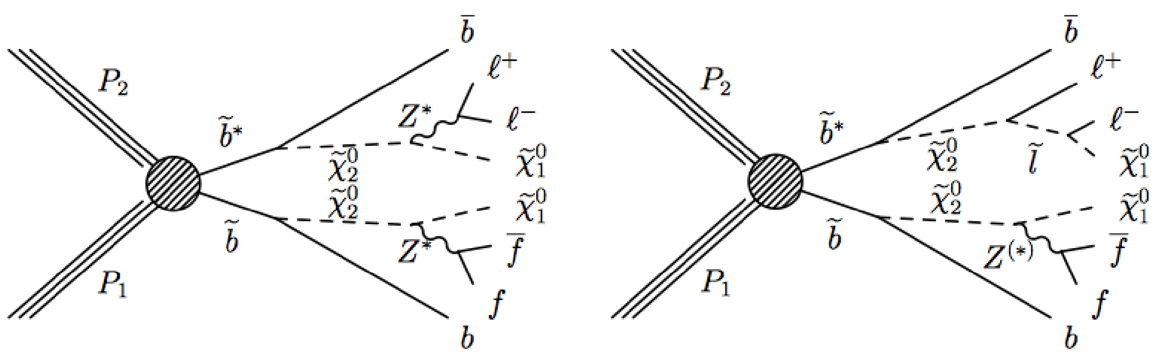
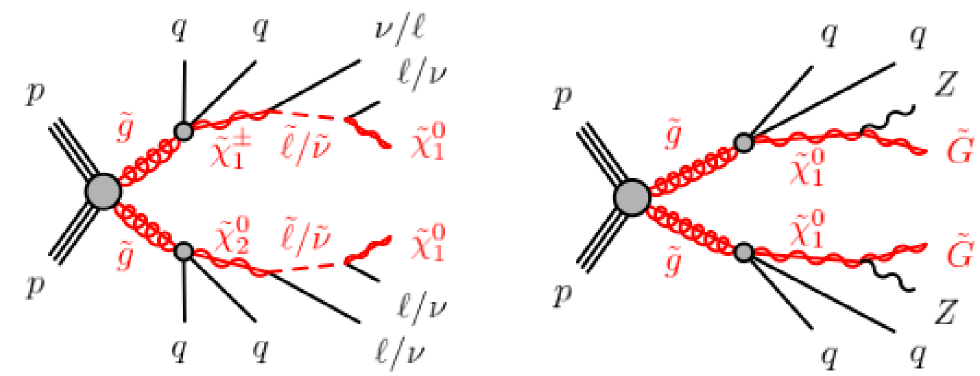
Dileptons + jets + MET (SUSY searches)



CMS, http://arxiv.org/abs/1502.06031



ATLAS, http://arxiv.org/abs/1503.03290

$N_{jets\ (p_T>40\ GeV)} \geq 2$, $E_T^{miss} > 150$ GeV
or
$N_{jets\ (p_T>40\ GeV)} \geq 3$, $E_T^{miss} > 100$ GeV

low mass: m_{ll} = (20–70) GeV
On-Z: m_{ll} = (81–101) GeV

$N_{jets\ (p_T>35\ GeV)} \geq 2$, $E_T^{miss} > 225$ GeV
$H_T > 600$ GeV

On-Z: m_{ll} = (81–101) GeV

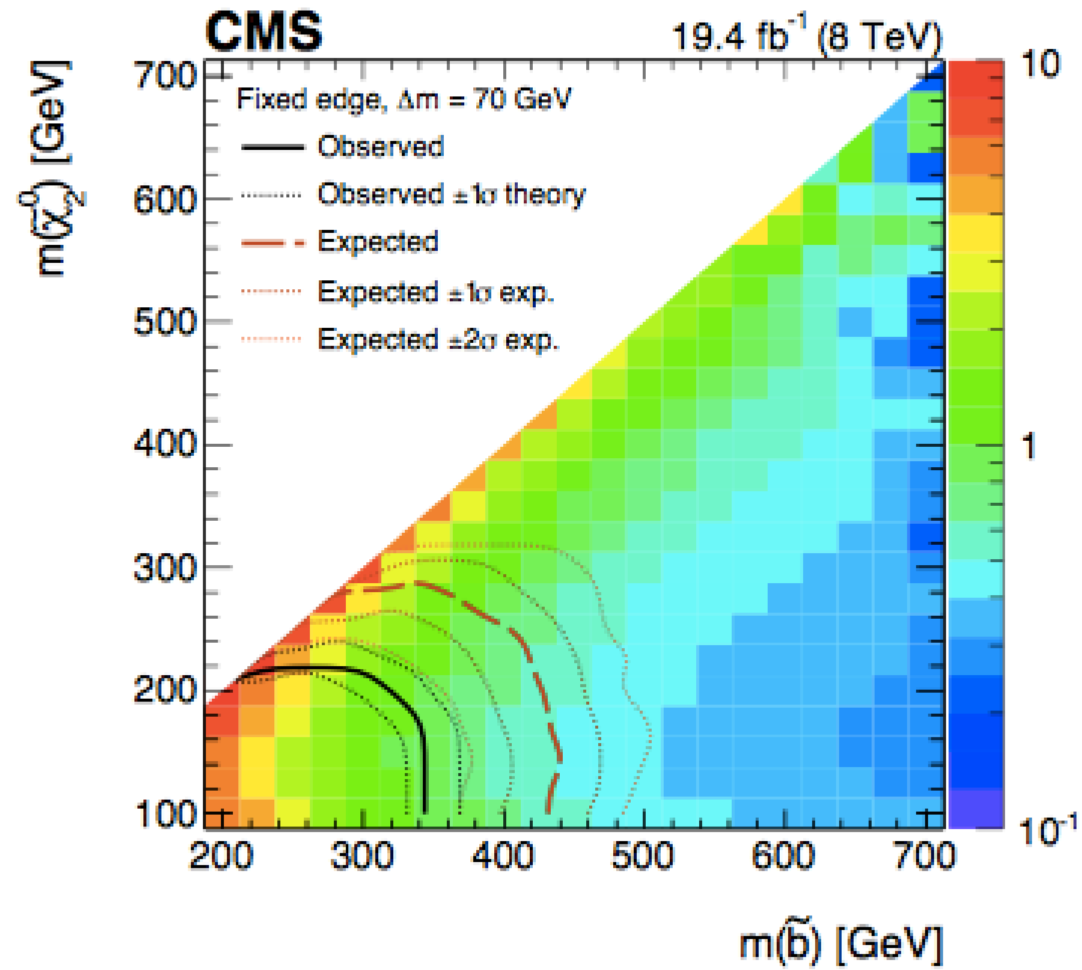
CMS, http://arxiv.org/abs/1502.06031

	Low-mass		On-Z	
	Central	Forward	Central	Forward
Observed	860	163	487	170
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$
Drell–Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17
Observed − estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}
Significance	$2.6\,\sigma$	$0.3\,\sigma$	$0.4\,\sigma$	$<0.1\,\sigma$

$\Rightarrow$2.6 σ

... no signal on-peak

σ(350 GeV) ratio 13TeV/8TeV ~ 4.5



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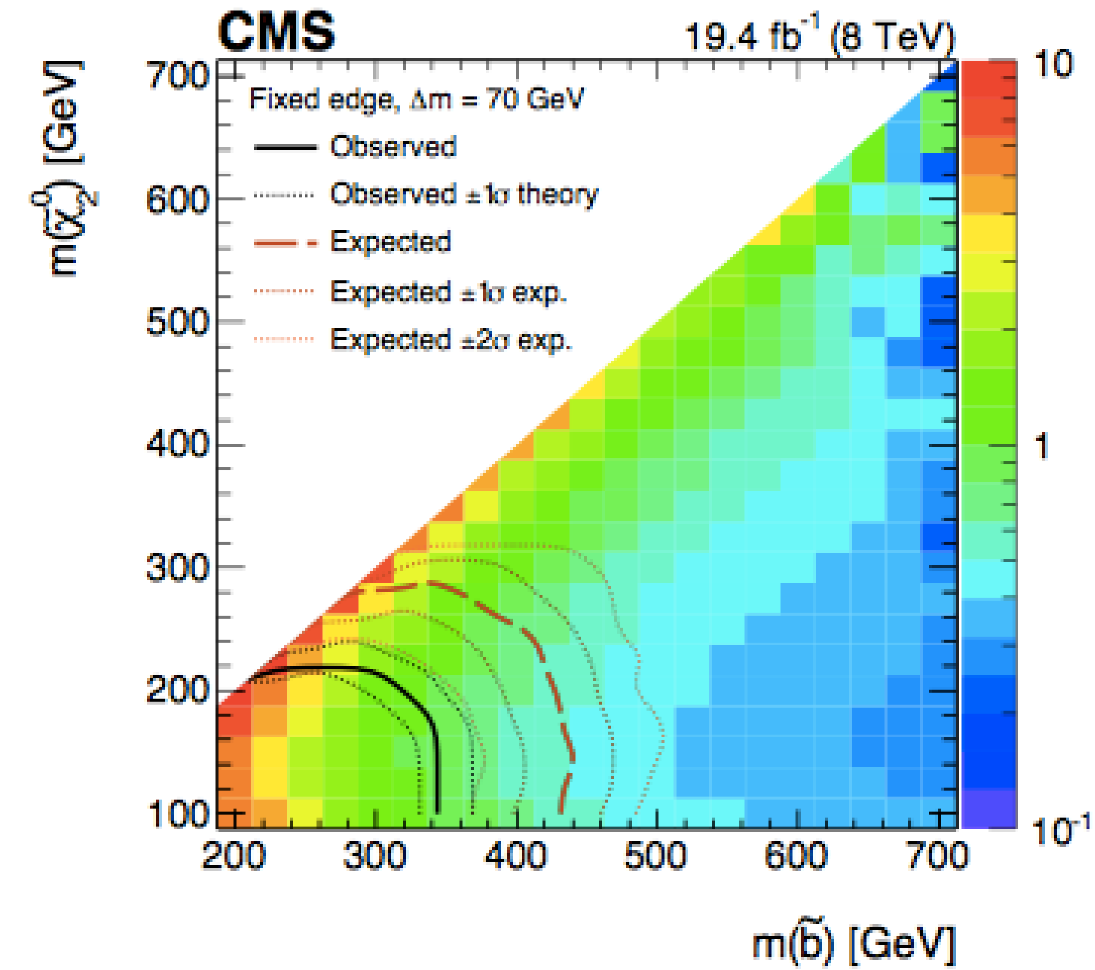
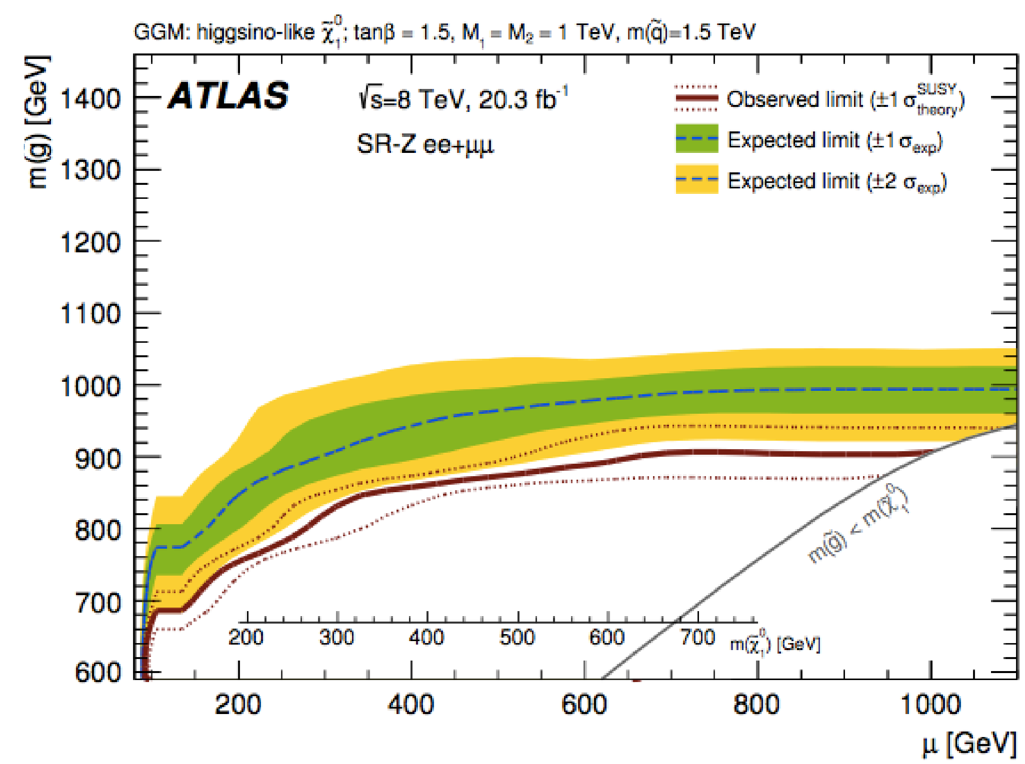


ATLAS, http://arxiv.org/abs/1503.03290

Channel	SR-Z *ee*	SR-Z *μμ*	SR-Z same-flavour combined
Observed events	16 **⇒3.0 σ**	13 **⇒1.6 σ**	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ^* + jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

... but no signal off-peak

σ(800 GeV) ratio 13TeV/8TeV ~ 8.5



Already more than 10 TH interpretation papers on arXiv ....

Why do we need the HL-LHC?

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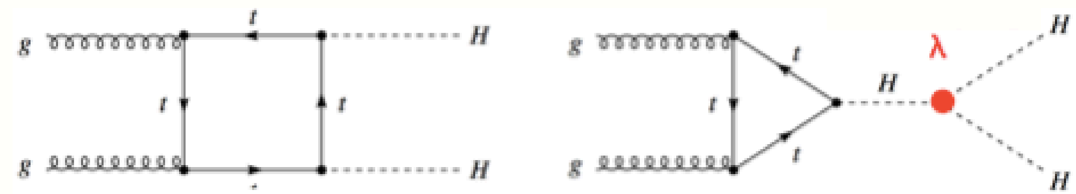
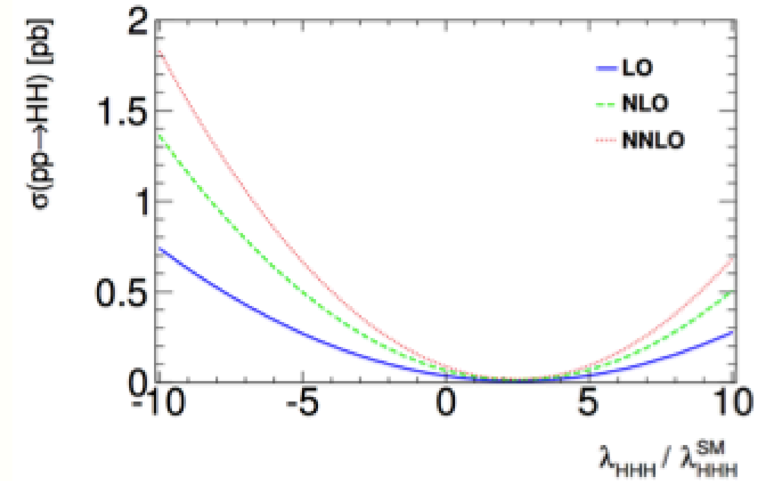
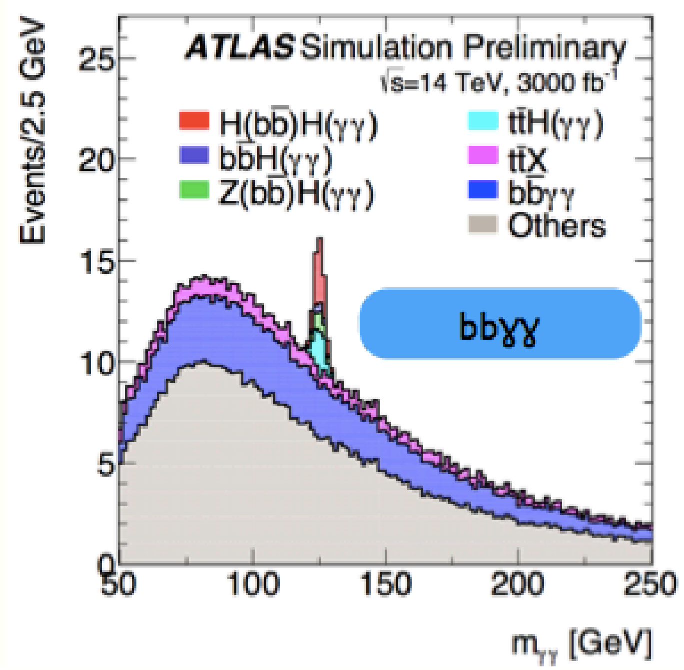
The key deliverable of HL-LHC: Higgs selfcoupling

HH→bbγγ

- Measurement of the Higgs pair production to probe the trilinear coupling and thus the Higgs potential
- Negative interference between the box and s-channel leading to suppression of event yield



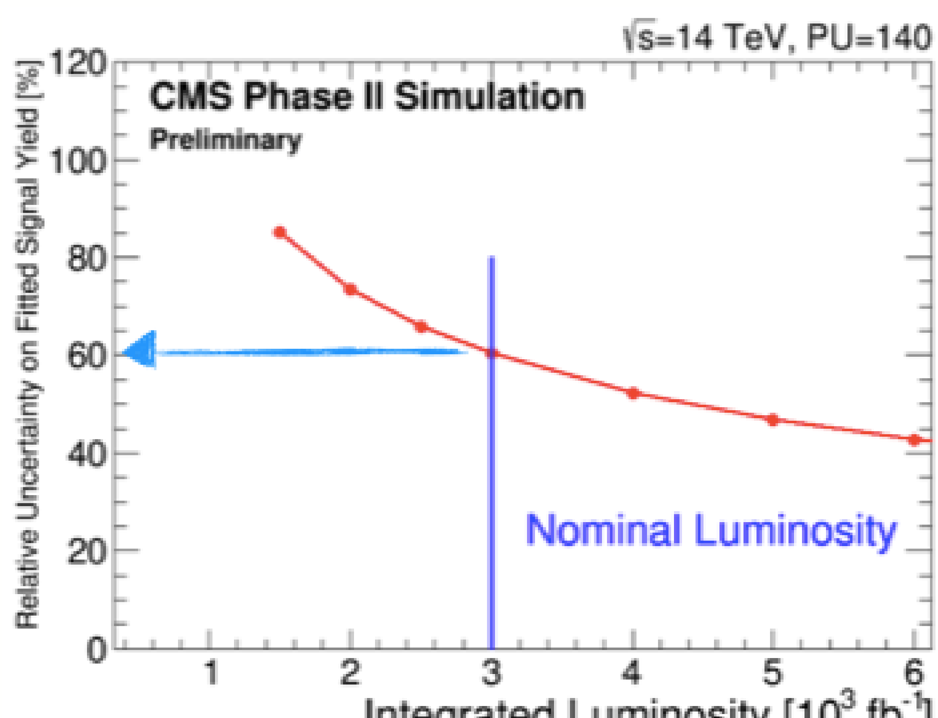




PHYS-PUB-2014-019

process	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2
S/√B (split barrel and endcap)	1.3

Physics Performance for 2nd ECFA workshop



3ab^{-1}: 60% precision on signal yield (SM coupling)
→ 40% with 2 expts
→ 30% including other channels?
→ 25% with experience?
→ ?? %

must be optimistic!

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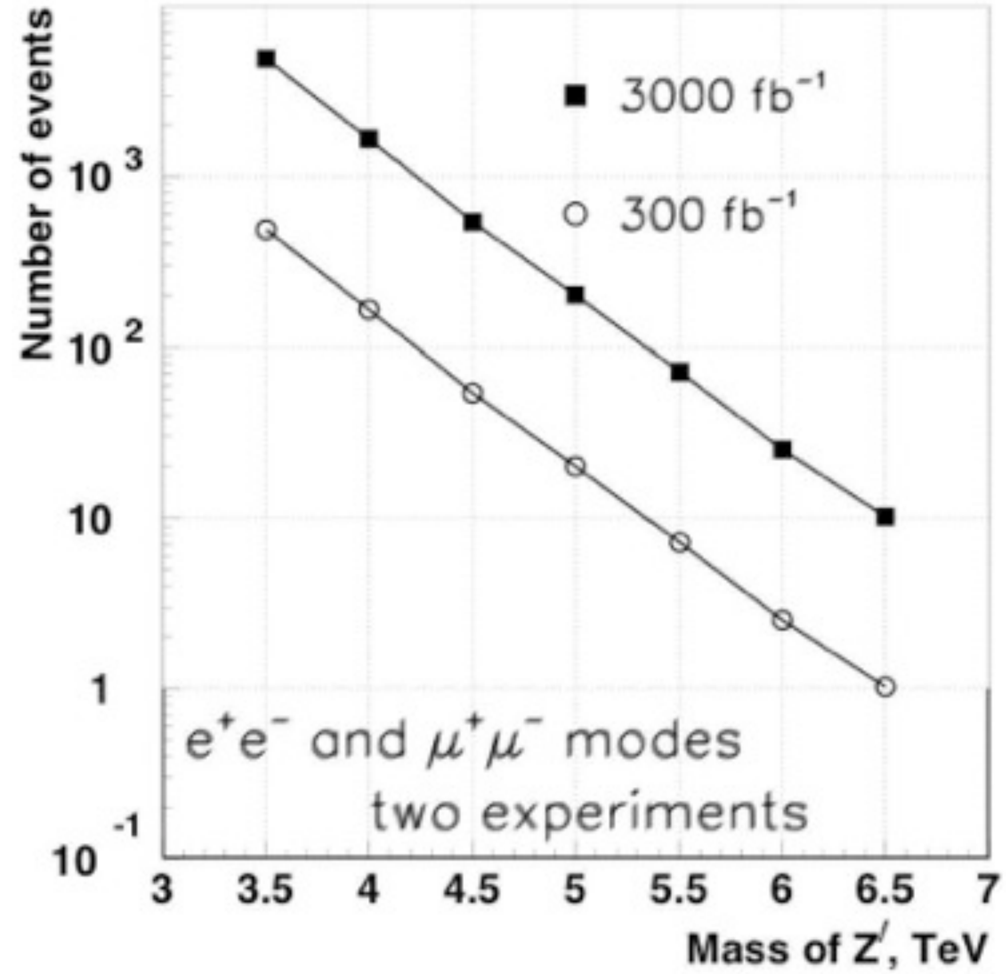
Searching new forces: W', Z'

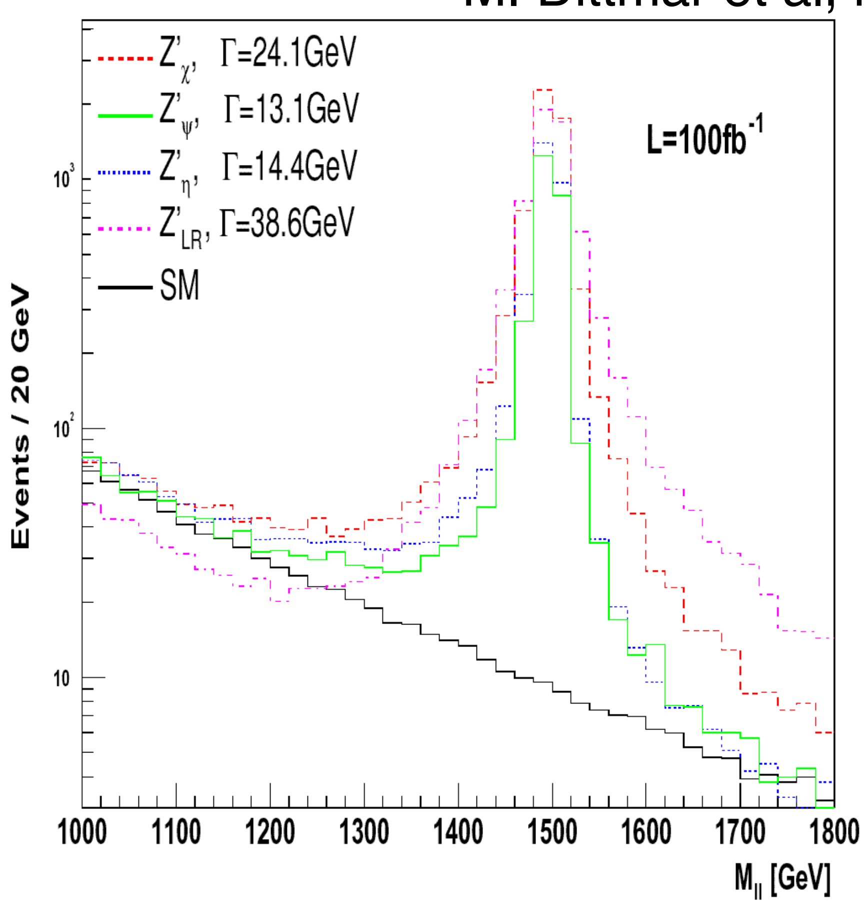
E.g. a W' coupling to R-handed fermions, to reestablish at high energy the R/L symmetry

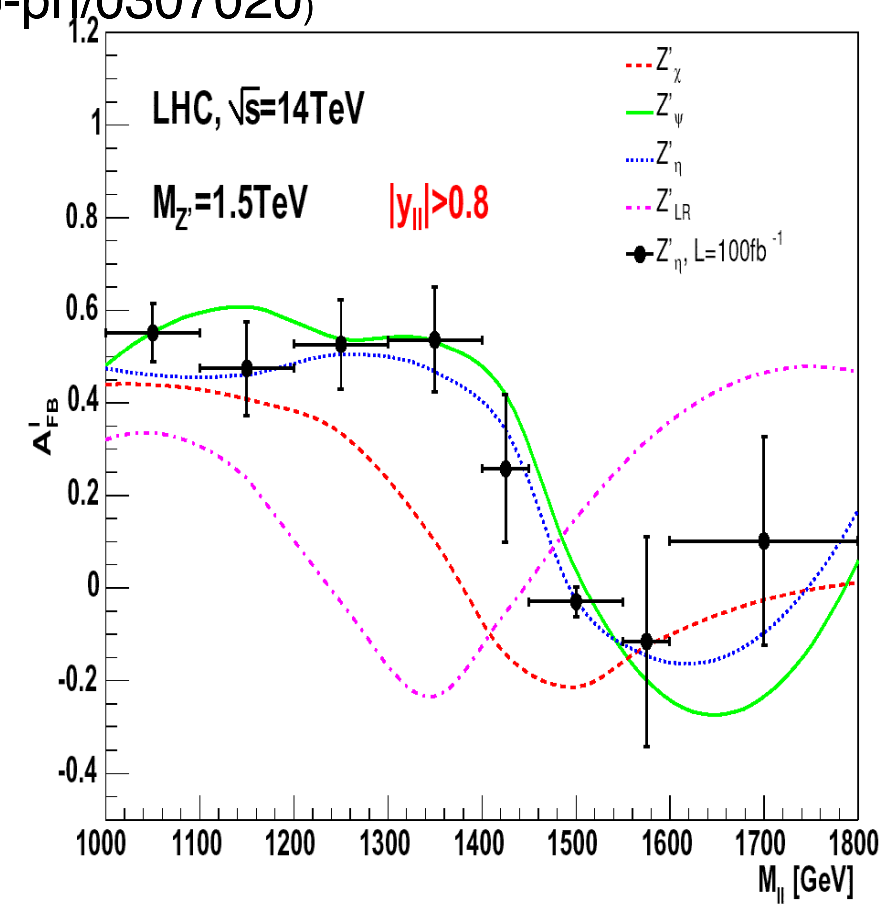


100 fb^{-1} discovery reach up to ~ 5.5 TeV

Differentiating among different Z' models:

M. Dittmar et al, hep-ph/0307020)





100 fb^{-1} model discrimination up to 2.5 TeV

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- **The "*still-don't-know-what's-next*" scenario**
  - LHC is the only guaranteed machine we have. If nothing else is approved within the next 10-15 years, we must rely on HL-LHC and possible further evolutions of the LHC complex to guarantee the future of our exploration

Why do we need to go beyond the HL-LHC?

Goal: finding the answer to key questions such as

- **What's the origin of Dark matter ?**
- **What's the origin of matter/antimatter asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What determines the number and interactions of different families of quarks and leptons?**
- **...**

The “tools”

- Direct exploration of physics at the weak scale through high-energy colliders (linear/circular, ee/pp/ep/μμ)
- Quarks: flavour physics, EDM’s
- Neutrinos: CP violation, mass hierarchy and absolute scale, majorana nature
- Charged leptons: flavour violation, g–2, EDMs
- Axions, axion-like’s (ALPs), dark photons, ...

There is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee to find an answer to any of the questions above

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$\Rightarrow$

- target broad and well justified scenarios
- consider the potential of given facilities to provide conclusive answers to relevant (*and answerable!*) questions
  - can we identify forms of *no-lose theorems ?*
- weigh the value of knowledge that will be acquired, no matter what, by a given facility (*the value of "measurements"*)

Most of the "big questions" touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future exptl facilities. E.g.

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- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

Why do we need to go beyond the HL-LHC?

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…. because 14 TeV are not enough to guarantee the answer to any of these questions

The exploration of the high-energy frontier beyond the LHC can provide conclusive answers to most of those questions

- **A complete study of the Higgs boson, of its interactions and of EWSB is a guaranteed deliverable of this programme ...**
- **... accompanied by an ambitious discovery potential, sensitive to possible manifestations of new physics at the TeV scale**

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To address the scenarios raised by the question of "why don't we see new physics at the LHC" (i.e. (i) scale of new physics is too large, or (ii) signals are elusive), future facilities should guarantee

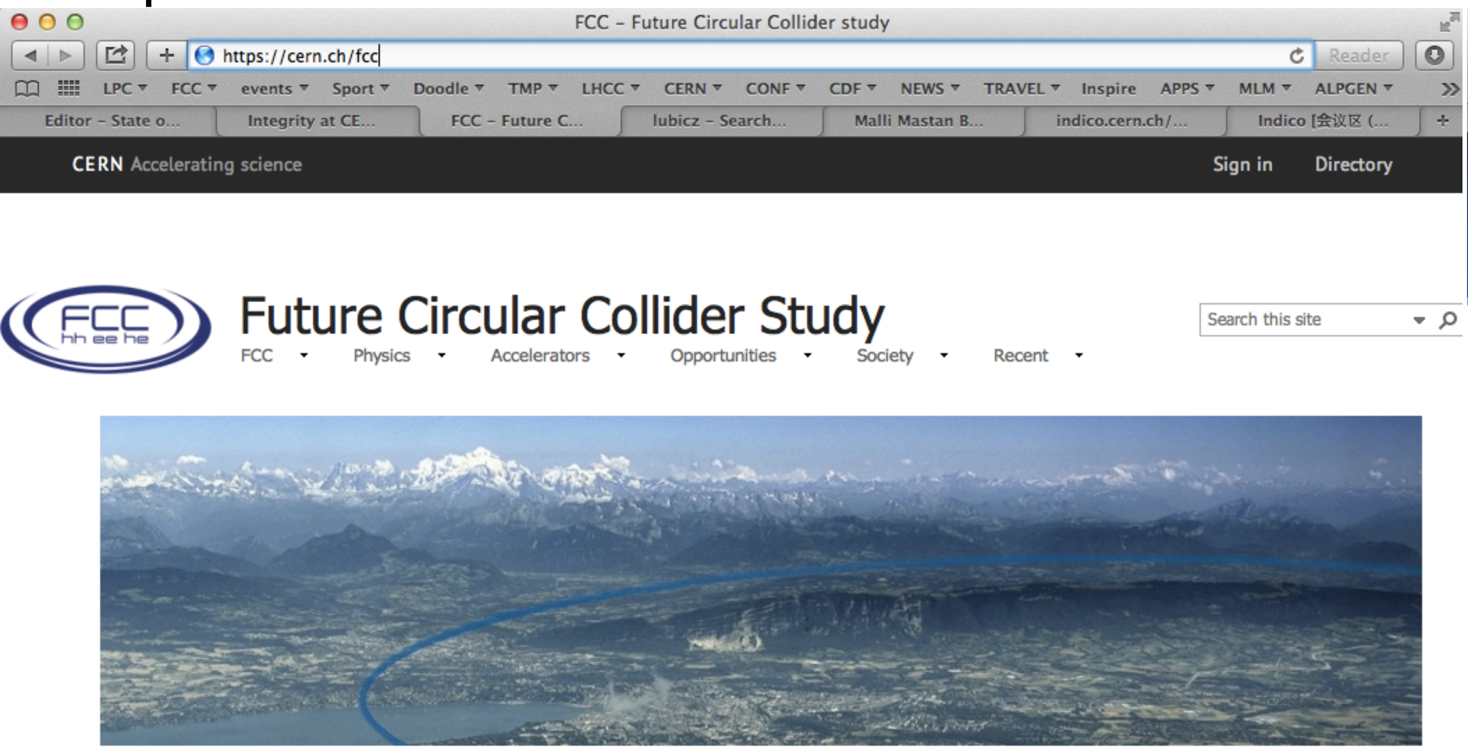
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

The known faces at the energy frontier are the linear e^+e^- colliders, namely ILC and CLIC

The new kids in town: **circular colliders**

… and two efforts are formalized and develop into studies towards Conceptual Design Reports

http://cern.ch/fcc



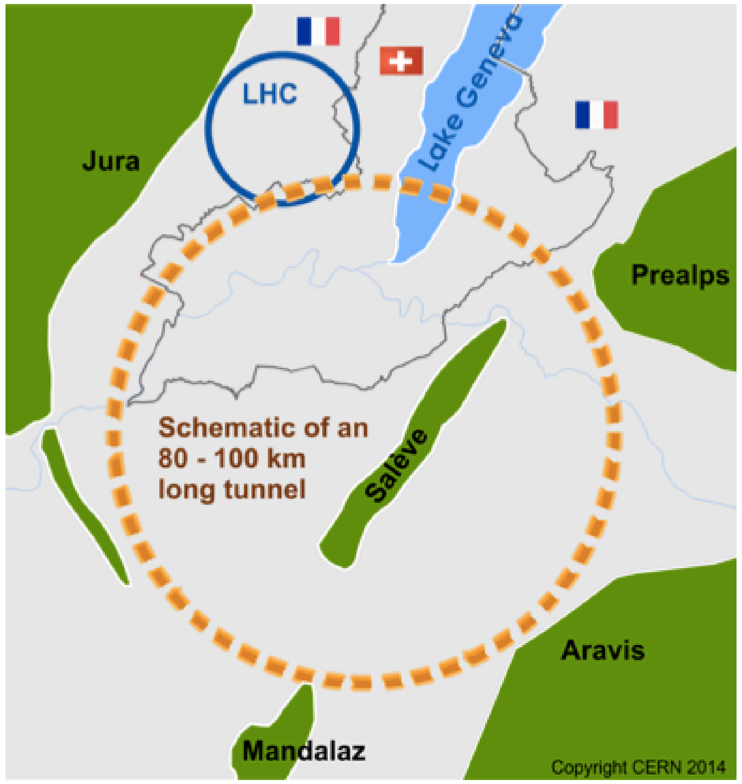
http://cepc.ihep.ac.cn

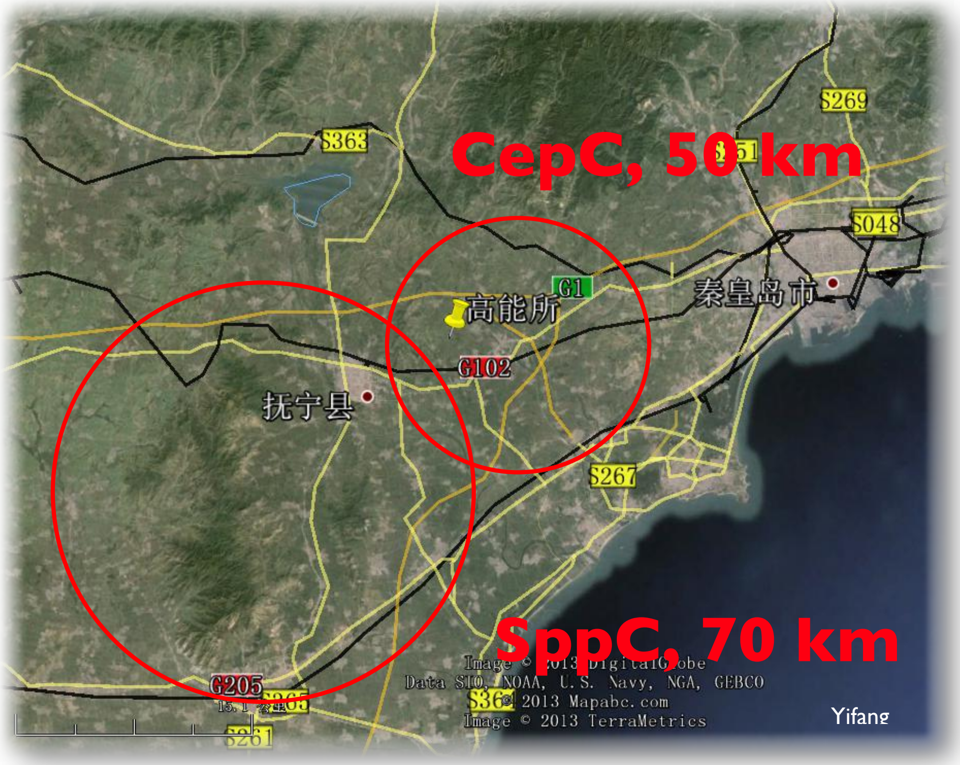
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e*⁺*e*⁻ collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area





FCC-hh parameters and lum goals

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} cm^{-2}s^{-1} (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} cm^{-2}s^{-1} (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

Higgs boson HZ studies
+ WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @5 10^34 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

Top quark mass
Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   → transverse polarization of 'single' bunches for precise E_beam calibration
   2 years

$M_Z, \Gamma_Z R_b$ etc…
Precision tests and rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

M_W, and W properties etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

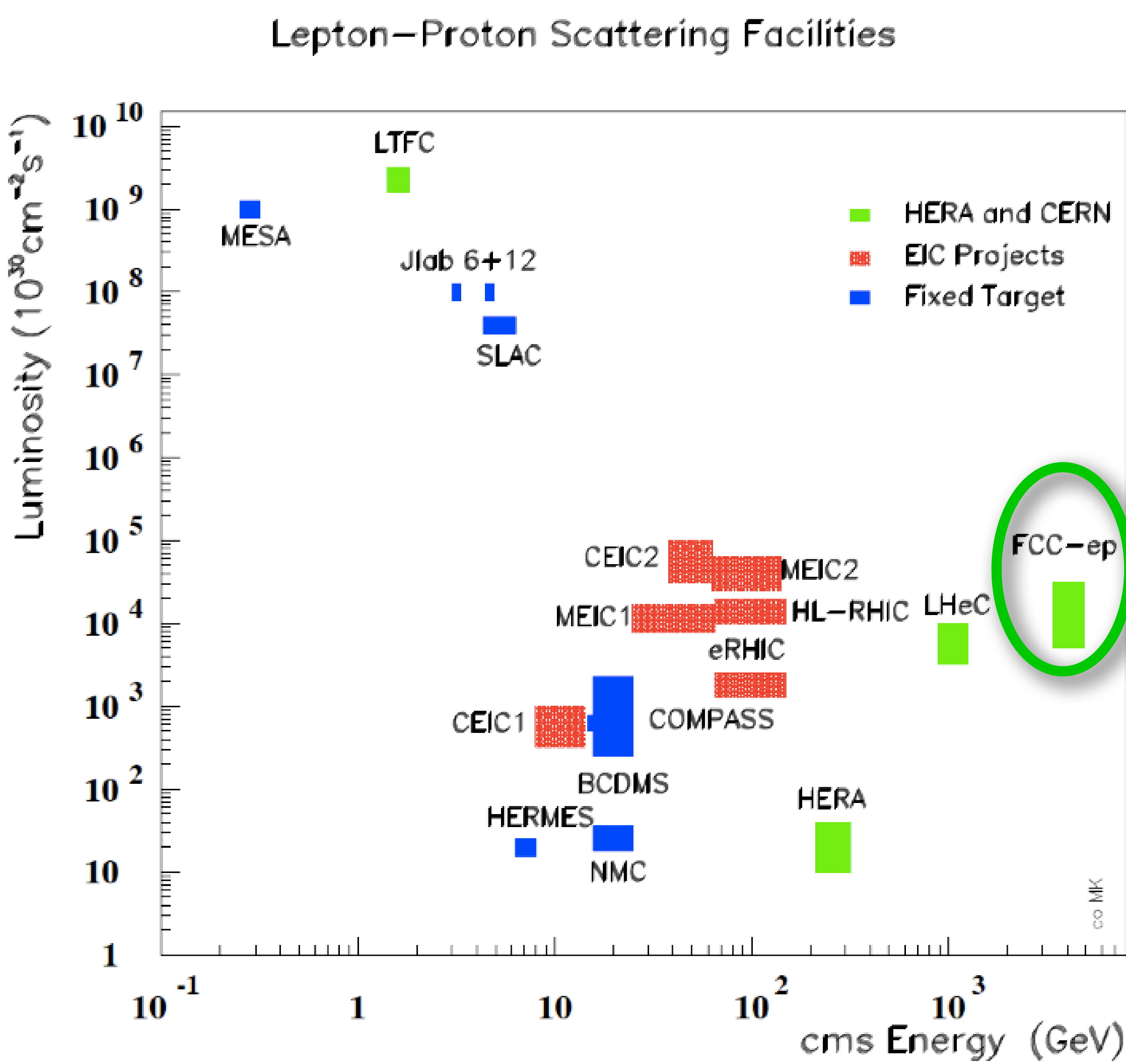
A_{LR}, A_{FB}^{pol} etc

6. more and upgrades….

P.Janot

NB: **TLEP = FCC-ee**

FCC-eh parameters and lum goals



175 GeV e- beam from FCC-ee and 50 TeV p beam from FCC-hh
Highest centre-of-mass energy ep collider, ~6 TeV
Luminosity ~10^{34}cm^{-2}s^{-1}

Higgs precision projections

g_{HXY}	FCC-ee
ZZ	0.16%
WW	0.85%
$\gamma\gamma$	1.7%
$Z\gamma$	
tt	
bb	0.88%
$\tau\tau$	0.94%
cc	1.0%
ss	$H\to V\gamma$, in progr.
$\mu\mu$	6.4%
uu,dd	$H\to V\gamma$, in progr.
ee	$e^+e^-\to H$, in progr.
HH	
BR_{exo}	0.48%

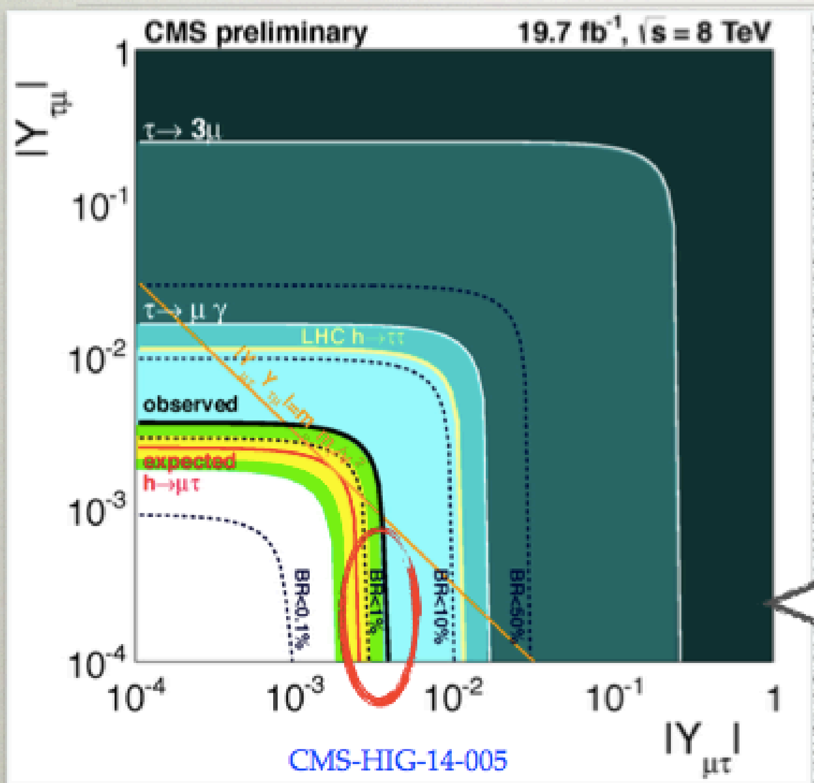
Higgs precision projections

	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

g_{HXY}	FCC-ee	FCC-hh	
ZZ	0.16%		
WW	0.85%		
γ γ	1.7%		
Zγ		1% ?	→ extrapolation from HL-LHC estimates
tt		1% ?	→ from ttH/ttZ
bb	0.88%		
τ τ	0.94%		
cc	1.0%		
ss	H→Vγ, in progr.		
μμ	6.4%	2% ?	→ extrapolation from HL-LHC estimates
uu,dd	H→Vγ, in progr.		
ee	e^+e^-→H, in progr.		
HH		5% ?	→ from HH → bb γγ
BR_{exo}	0.48%	< 10^{-6} ?	→ for specific channels, like H→eμ, ...

FCC-hh ambitious but possible targets?

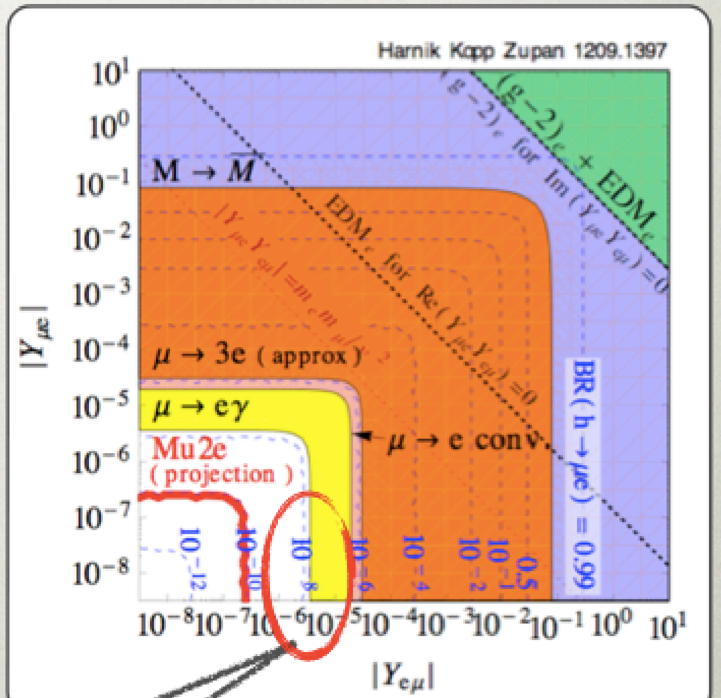
$h \to \tau\mu$



- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ *h?* ***LHC8*** $\Rightarrow$ ***100 TeV 3 ab***$^{-1}$
- assume same scaling for signal and bckg
  - $Br{\sim}10^{-2} \Rightarrow Br{\sim}10^{-4}$
  - $\Lambda{\sim}0.2\ TeV \Rightarrow \Lambda{\sim}2 TeV$
- if bckg free
  - $Br{\sim}10^{-2} \Rightarrow Br{\sim}10^{-6}$
  - $\Lambda{\sim}0.2\ TeV \Rightarrow \Lambda{\sim}20 TeV$
    $(Y_{\mu\tau}\, Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2)$

$h \to \mu e$

- indirect bounds better than LHC
- $h \to \mu e$ very clean channel

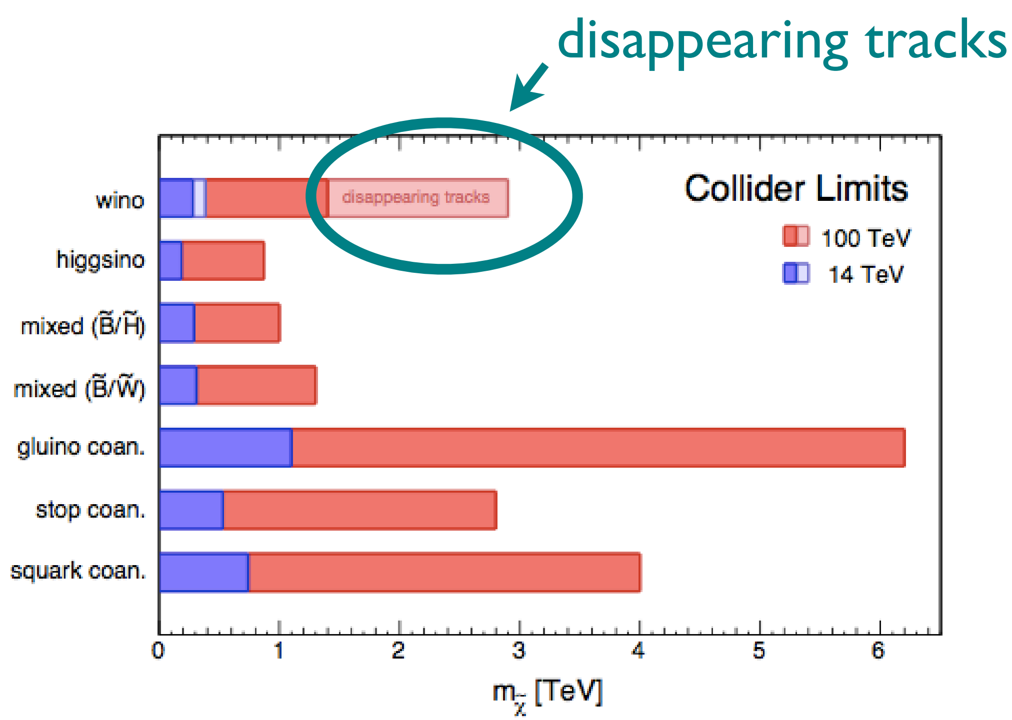


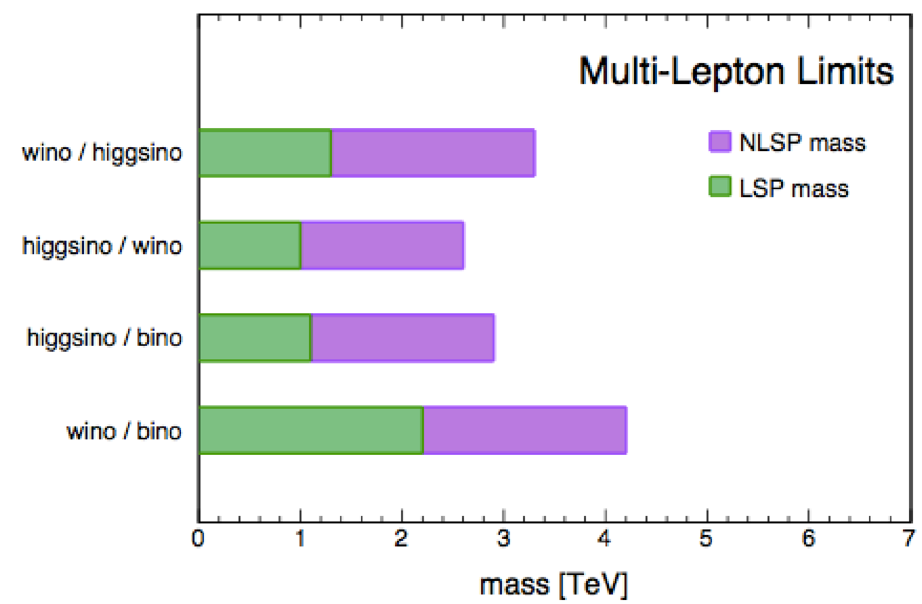
- what can one do with 10^9 Higgses @100TeV?

Towards no-lose arguments for Dark Matter scenarios:

WIMP searches at colliders

L.Wang @ FCC week





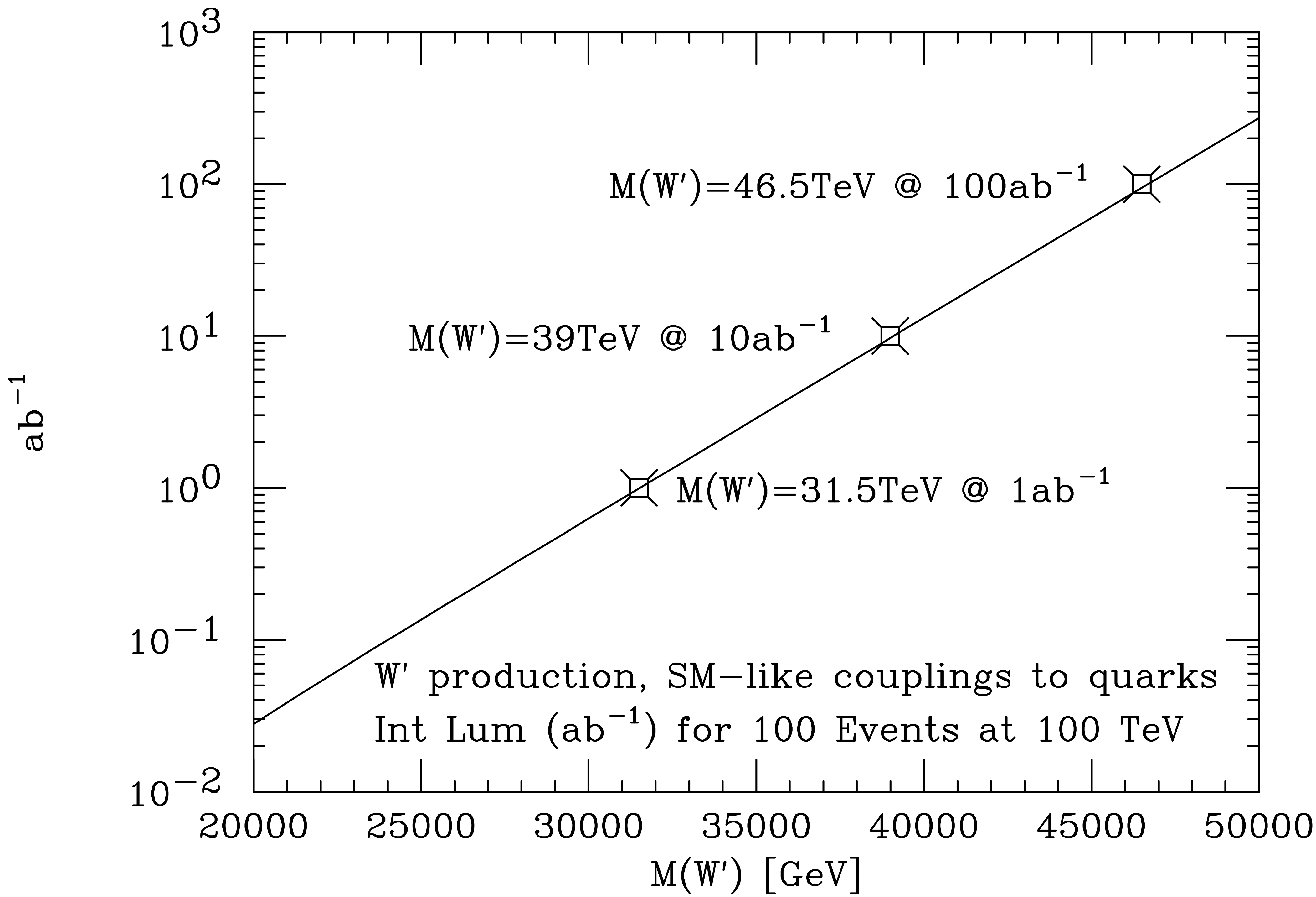
$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\ \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

Extension of the discovery reach at high mass

Example: discovery reach of W’ with SM-like couplings

NB For SM-like Z’, $\sigma_{Z'}\, BR_{lept} \sim 0.1 \times \sigma_{W'}\, BR_{lept}$, ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

From the global programme of FCC-ee, 1–2 orders of magnitude more precise measurements of EW parameters

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_l	α_s , δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(105/161)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho$, ε_3 ,$\Delta\alpha$** **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	**$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$** **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

Conclusions and final remarks

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- The success of the SM and the Higgs discovery give us a robust framework to interpret and assess the value and possible implications of current puzzles in physics, from the smoking-gun evidence for DM or ν masses, to the more subtle and ambiguous scattered anomalies, to the purely theoretical concerns (hierarchy problem, flavour problem, etc.)
- While crucial inputs are coming and will come from sources other than accelerator-based experiments, these are irreplaceable to guarantee progress towards answering most of the key outstanding questions of HEP