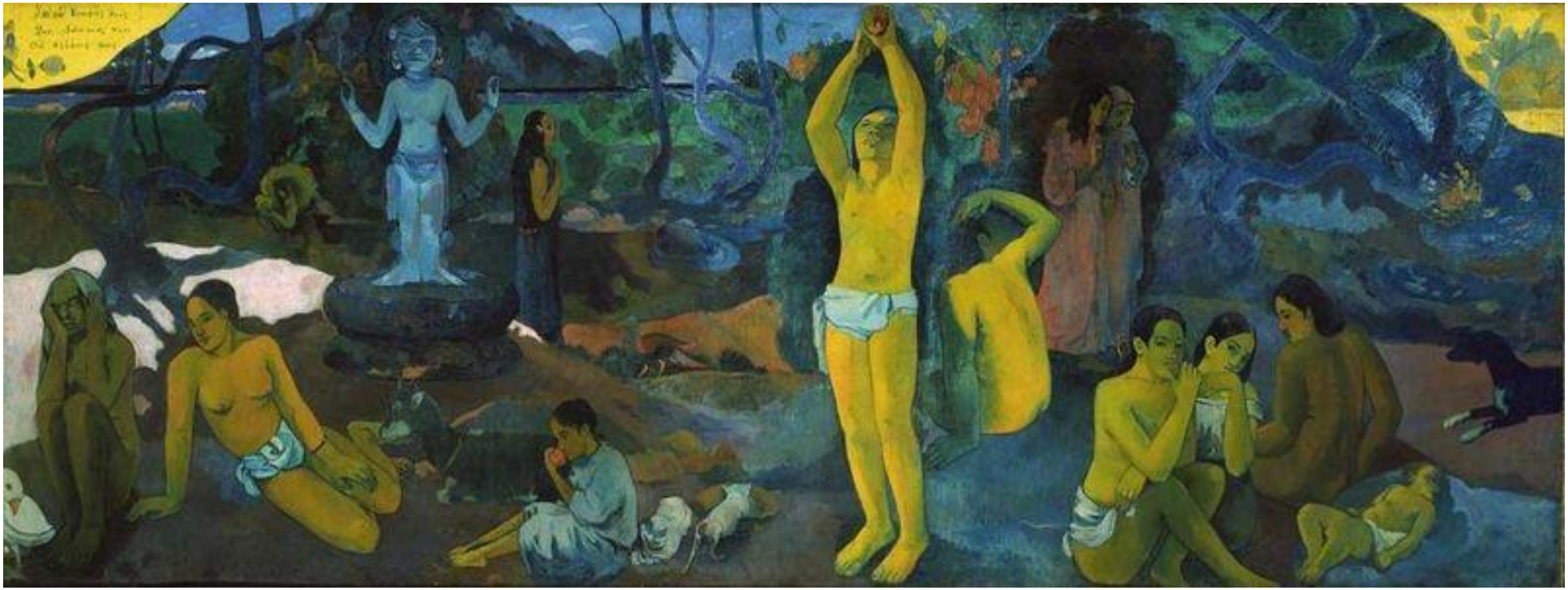
(Selected) Experimental Summary

- **Introduction and a look back**
- **Selected Highlights from LHC and the present**
- **Prospects at LHC and beyond**

Where do we come from, ~~What~~ Where are we, Where are we going?

The blue idol represents
"The Beyond"

Paul Gauguin



D'où Venons Nous / Que Sommes Nous / Où Allons Nous

2014: A special 50th anniversary year

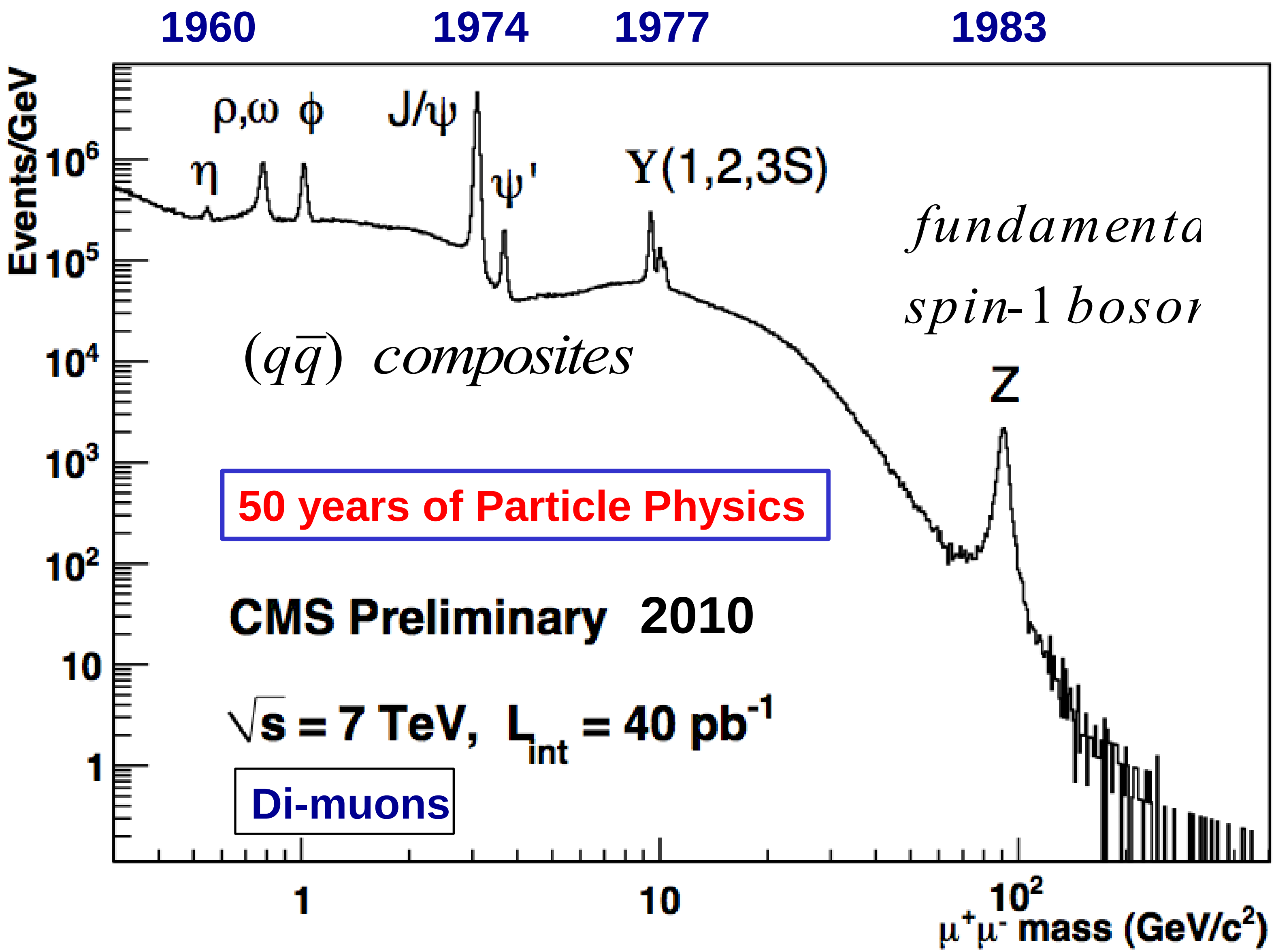
S. Glashow (2009): Highlights from 1964 - 50 years ago

- **January**: Gell-Mann suggested quarks as hadron constituents, but not specifying whether they were mathematical fictions or real particles.
- **February:** Nick Samios discovered the Ω particle, whose existence and properties Murray had predicted.
- **July:** Fitch, Cronin et al. discovered CP violation in kaon decay, an effect that was entirely unanticipated.
- **August:** James Bjorken and I proposed the existence of a fourth (charmed) quark to establish lepton-quark symmetry.
- **October:** Oskar Greenberg proposed the additional quark attribute that would evolve to become quark color.
- **And in August, October and November**: Three seminal papers appeared in Volume 13 of the Physical Review Letters. Taken together, they established what is now known as the ~~Higgs~~ mechanism.

BEH

Talk at CERN Dec. 2009

Harvest from the 1st few months of LHC Run 1



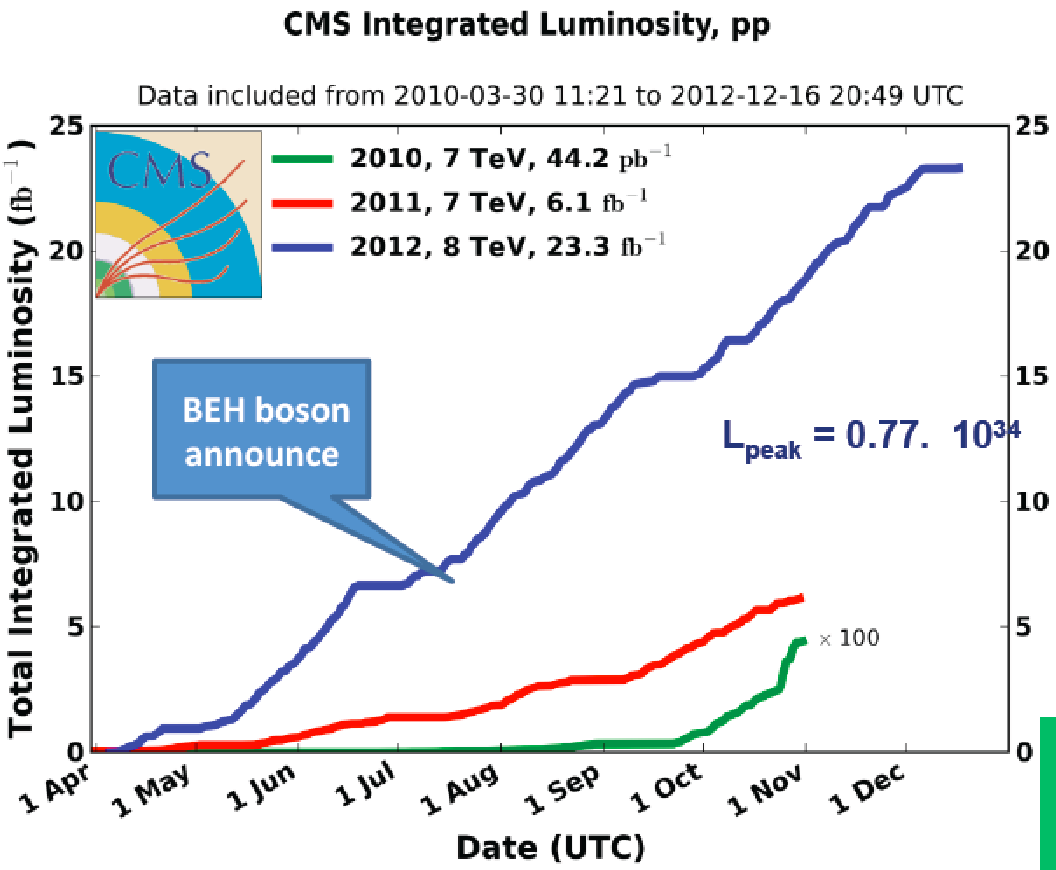
Peak performance through the years

	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

M. Lamont

Run I : Integrated Luminosity

2010-2012 (Run 1): LHC integrated luminosity



3 Memorable Years

2010: **0.04 fb^{-1}**
7 TeV CoM
Commissioning

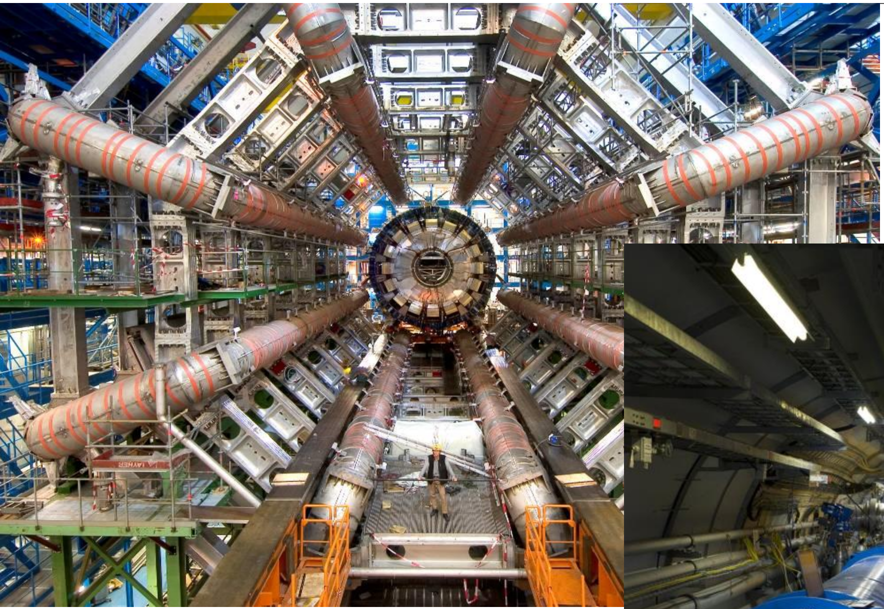
2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits

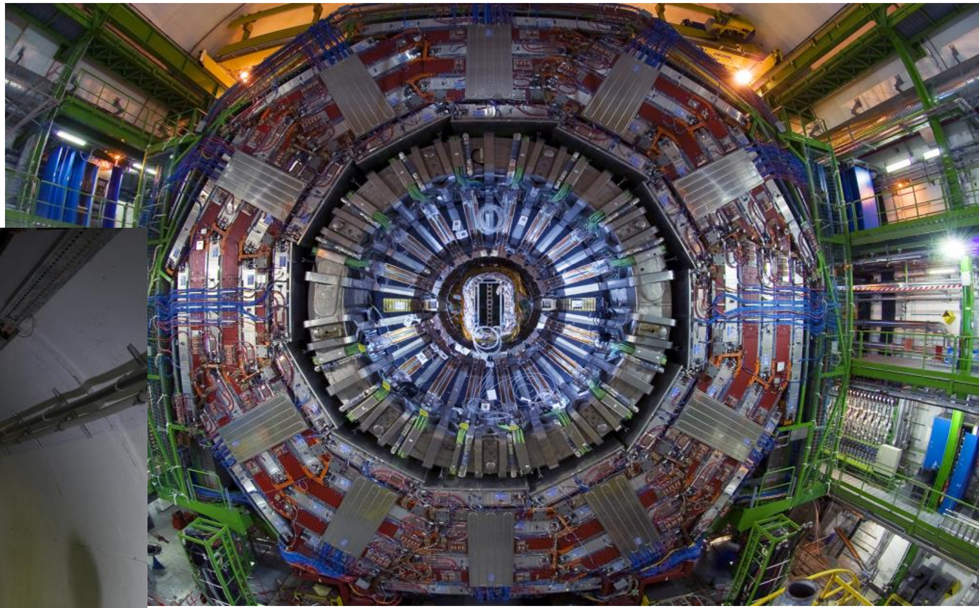
2012: **23.3 fb^{-1}**
8 TeV CoM
… production

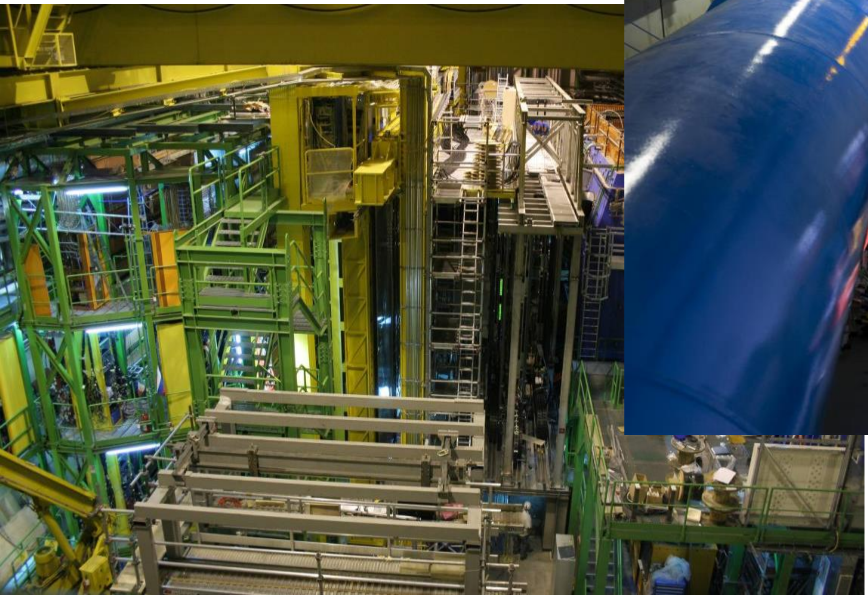
7 TeV and 8 TeV in 2012
Up to 1380 bunches
with1.5 10^{11} protons

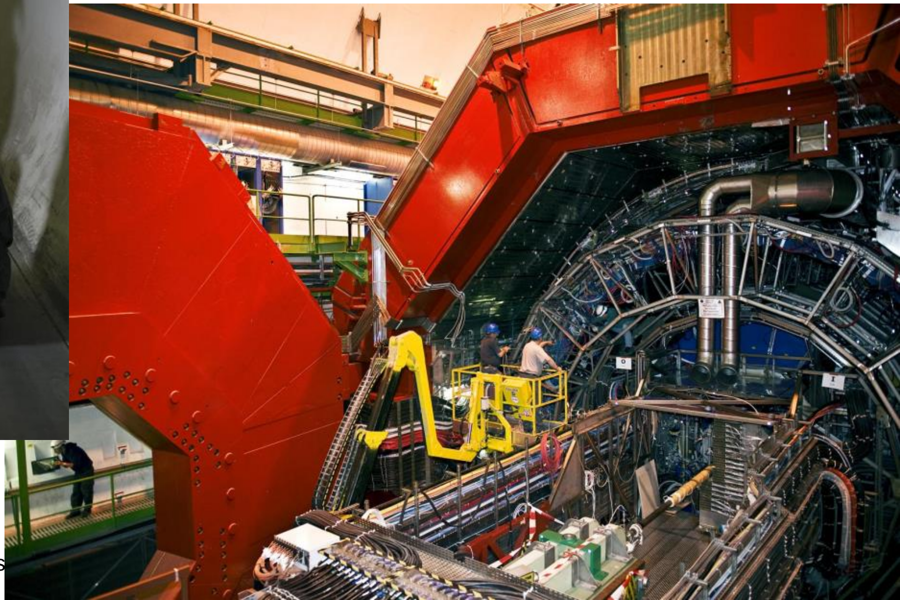
Imperial College London

The LHC Accelerator and Experiments Have Performed Exceedingly Well

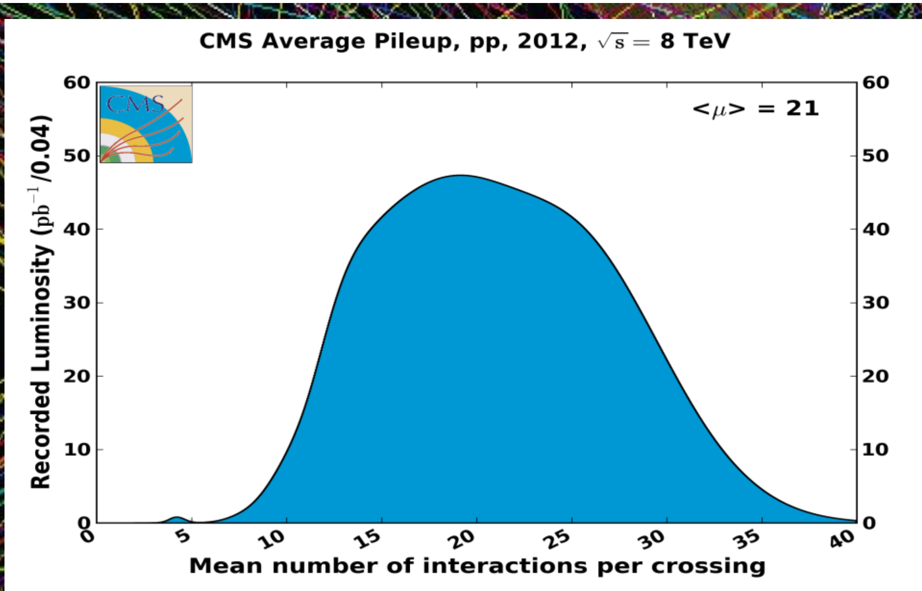


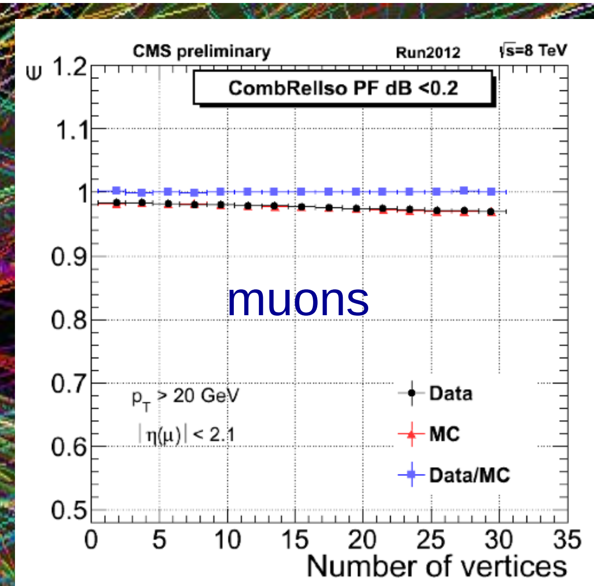




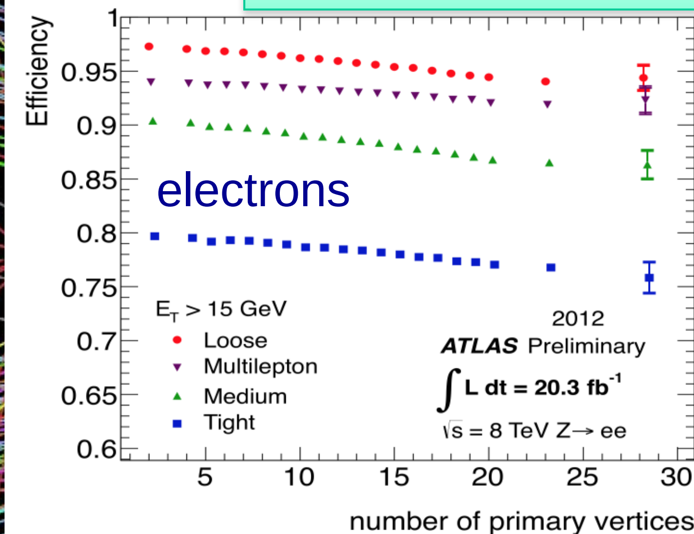


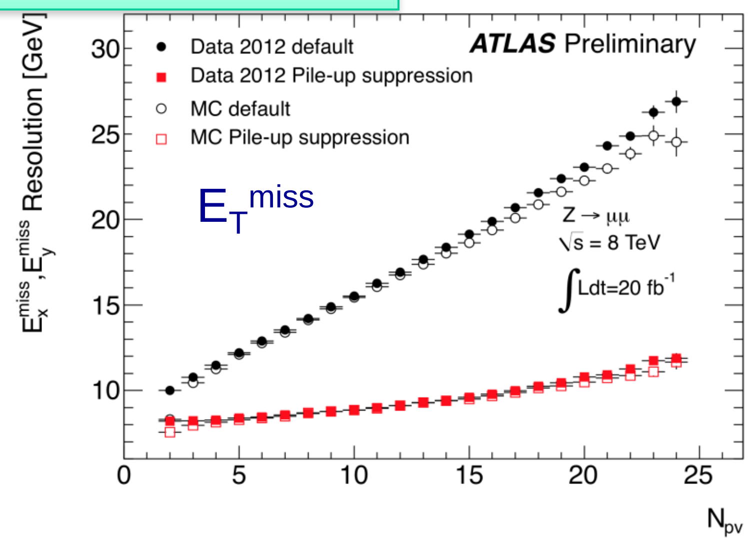
Good Performance under Ferocious Conditions





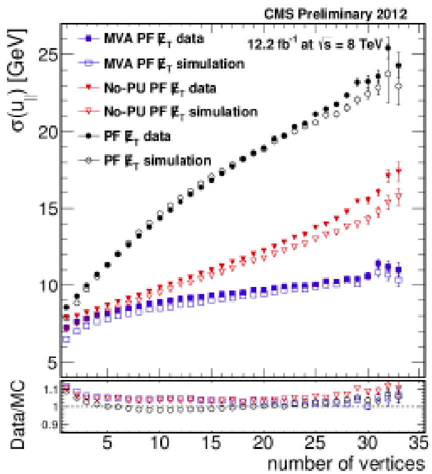
Leptons and MET : almost insensitive to pileup



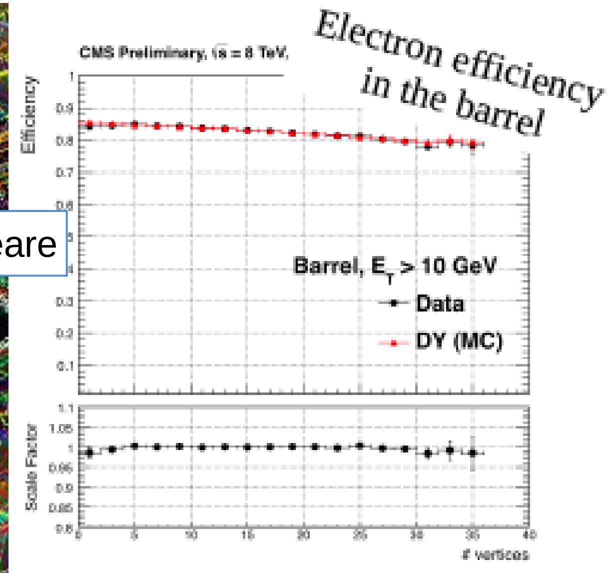


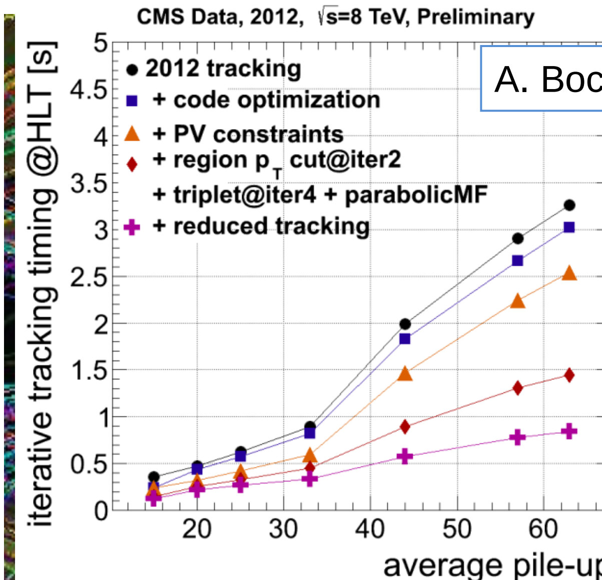
Good performance expected even under more ferocious conditions of Run 2

MET resolution is only slightly affected by pileup when using the most advanced reconstruction method.



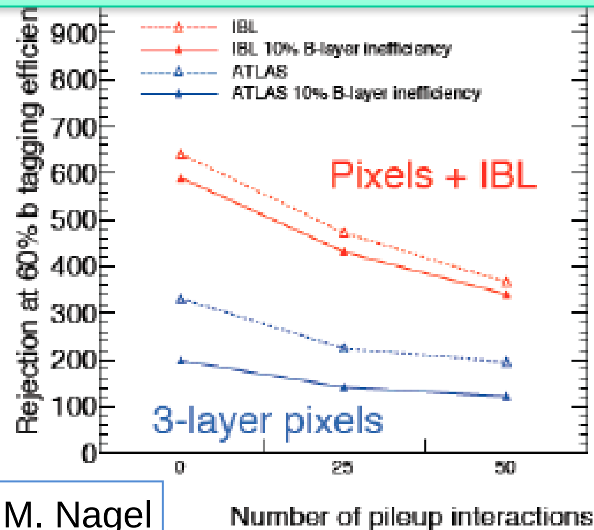
C. Delaeare



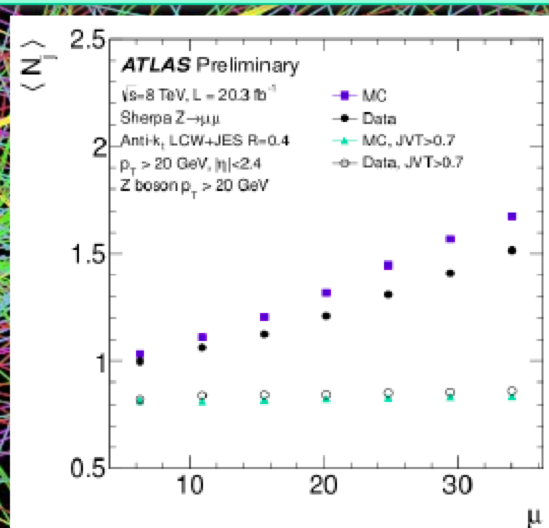


A. Bocci

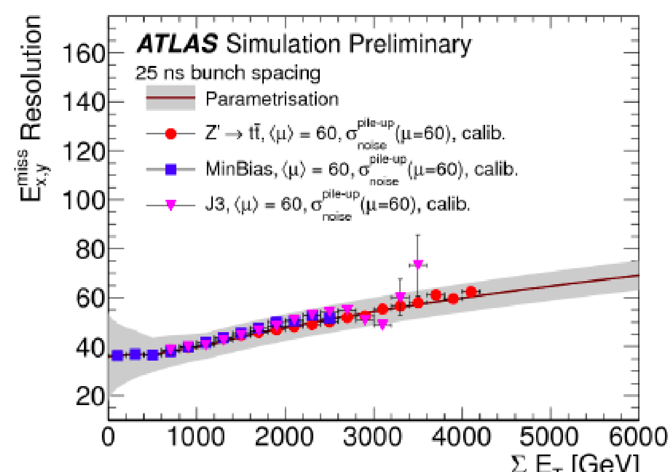
With the improvements performance expected to be similar or better than in Run 1



M. Nagel



Note: Plot uses calorimeter clusters for unmatched objects

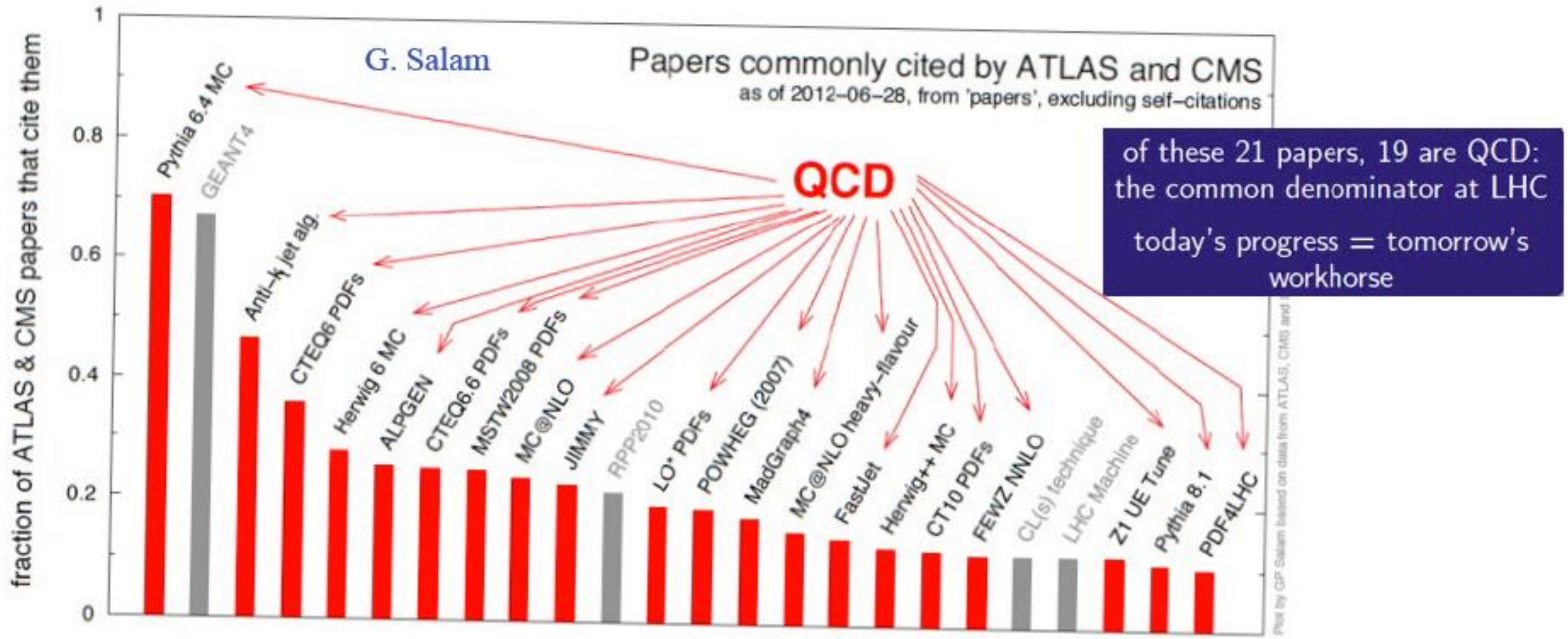


ATL-PHYS-PUB-2013-009

Theoretical Inputs

Radja Boughezal
LHCP 2014

Why do we care about QCD



No real understanding of LHC physics is possible without sophisticated QCD calculations!

The Best is still to come!

Wide range of measurements have shown that **SM predictions for known physics have been essentially spot on.**

This is a tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.

- **Two caveats:**
  - **despite the success of the LHC programme during run-1, we are still learning how to do precision measurements in ATLAS and CMS**
  - **this is why we have not digested fully yet to the best of our understanding, neither our detector performance nor how well we can constrain the theoretical uncertainties (eg PDFs) from our own data.**

  Le meilleur est encore à venir!

D. Froidevaux
M. Mulders

Imperial College London

Particle Spectroscopy !

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

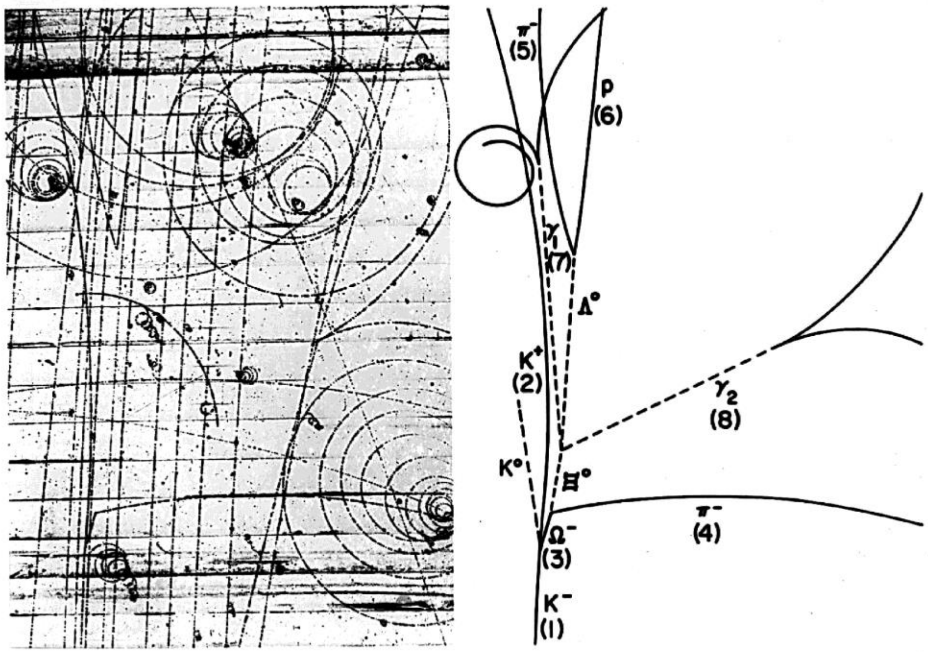
Received 4 January 1964

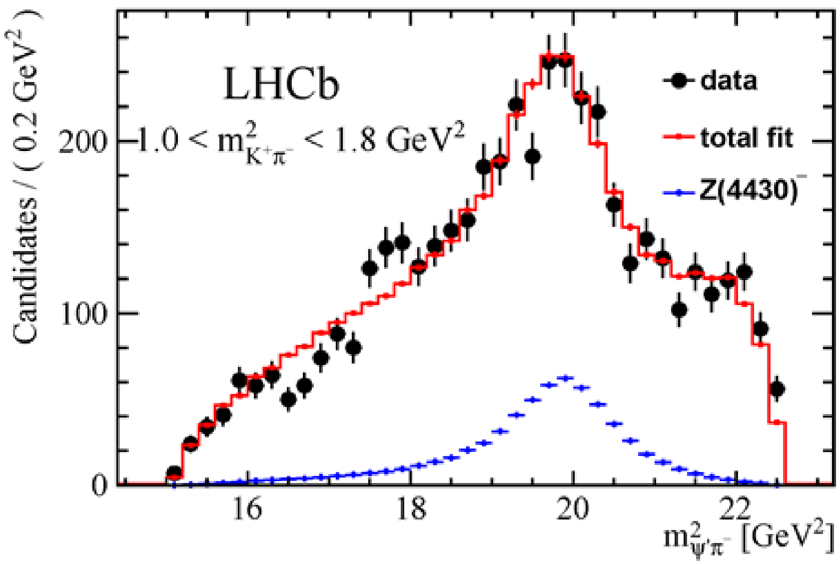
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

Exotic State $Z^+(4430)$

Must contain *c-c bar quarks* ($Z^+ \rightarrow \psi(2S)\,\pi^+$) but also *u* and *d quarks* (it is charged).

Is it a **tetra-quark** state ?





4 tsv

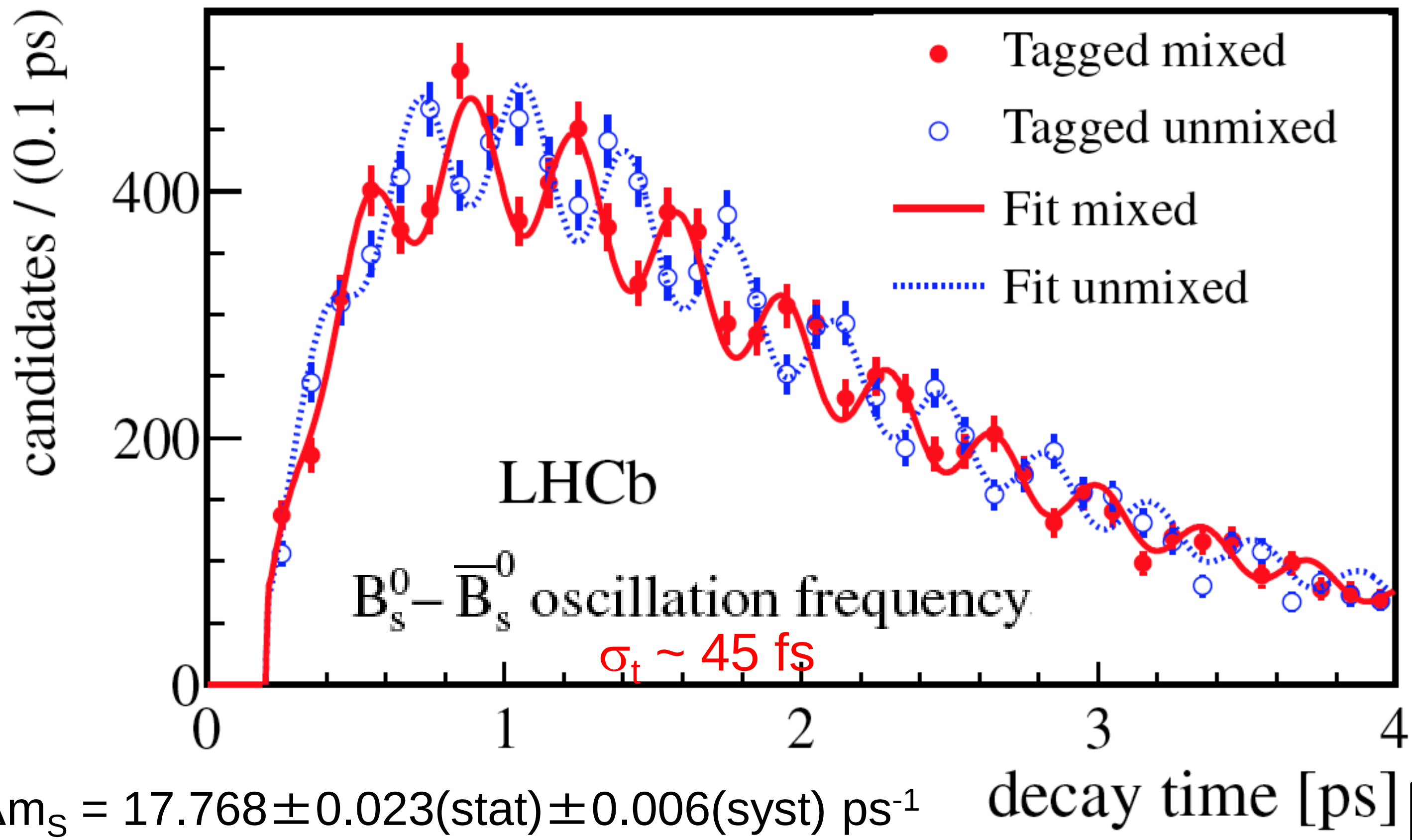
arXiv:1404.1903

CP Violation and Rare Decays

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)



Δm_S = 17.768±0.023(stat)±0.006(syst) ps^{-1}

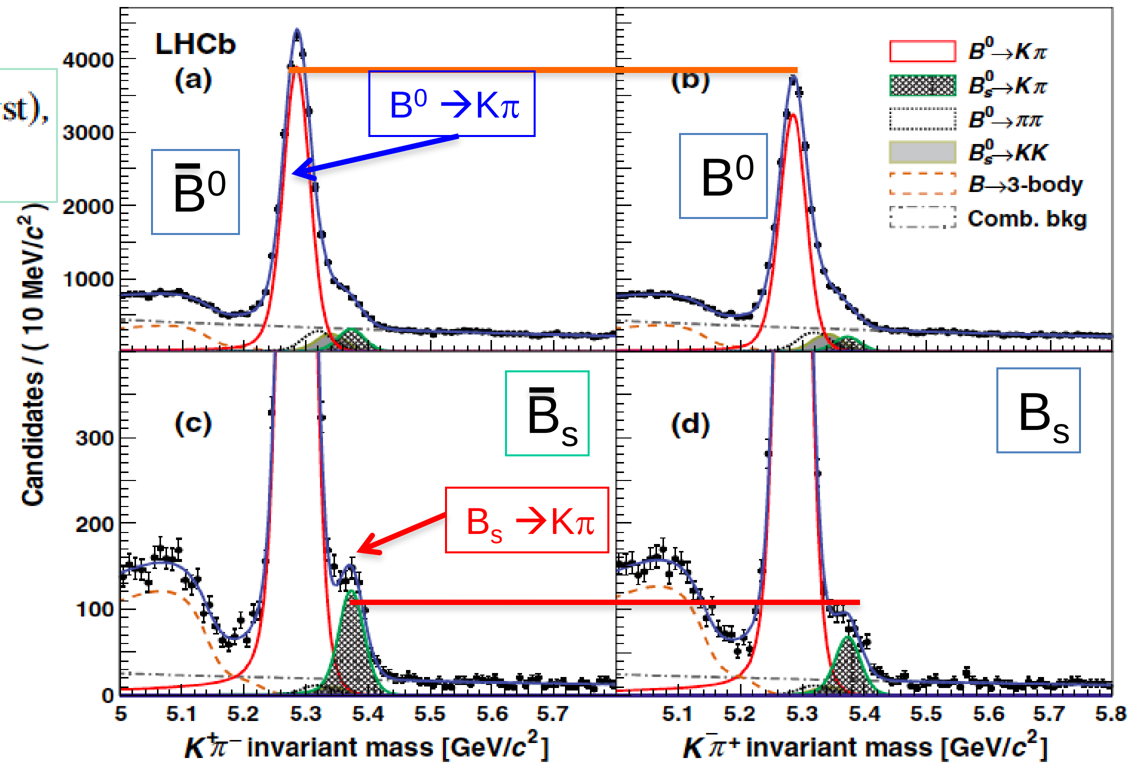
NJP 15 (2013) 05302

Direct CP Violation in $B_{d(s)} \to hh$ Decays

Study of charmless B decays (interesting as dominated by penguin diagrams)

Raw asymmetries

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst}),$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$



First 5σ observation of direct CPV in B_s decays

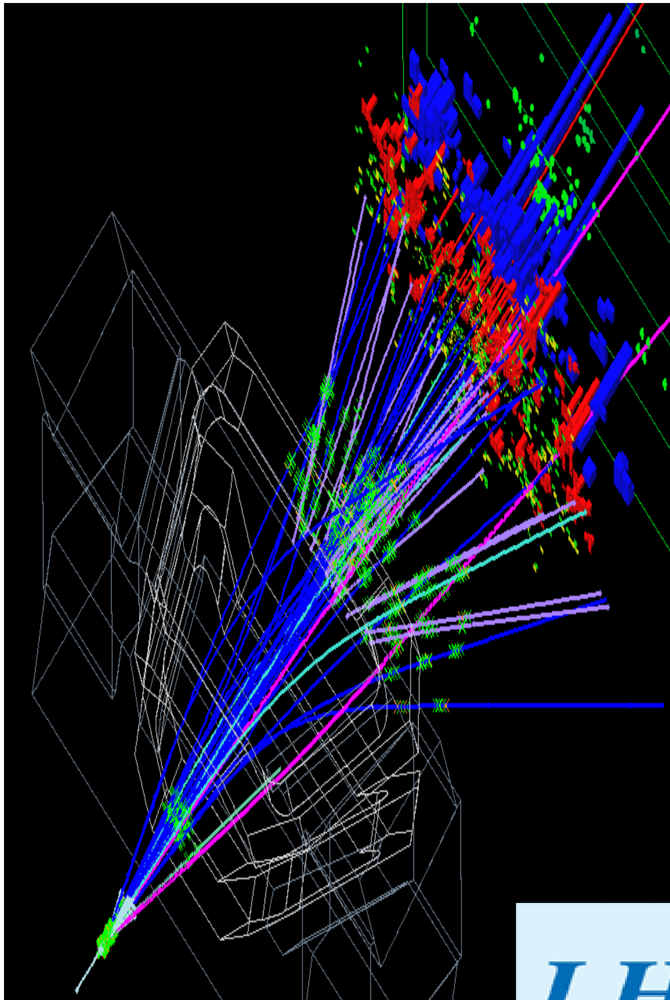
B_s is the 4th particle known to show direct CP violation after K^0 [1964] , B^0 [2000] and $B^\pm$ [2012]

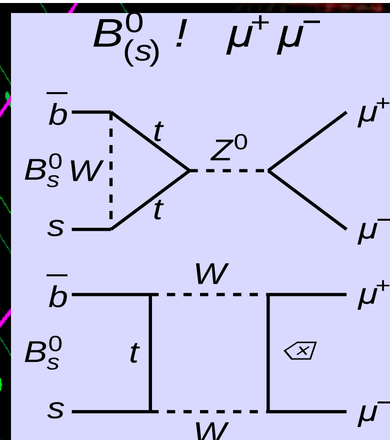
Stringent test of SM A_{CP} (Lipkin)

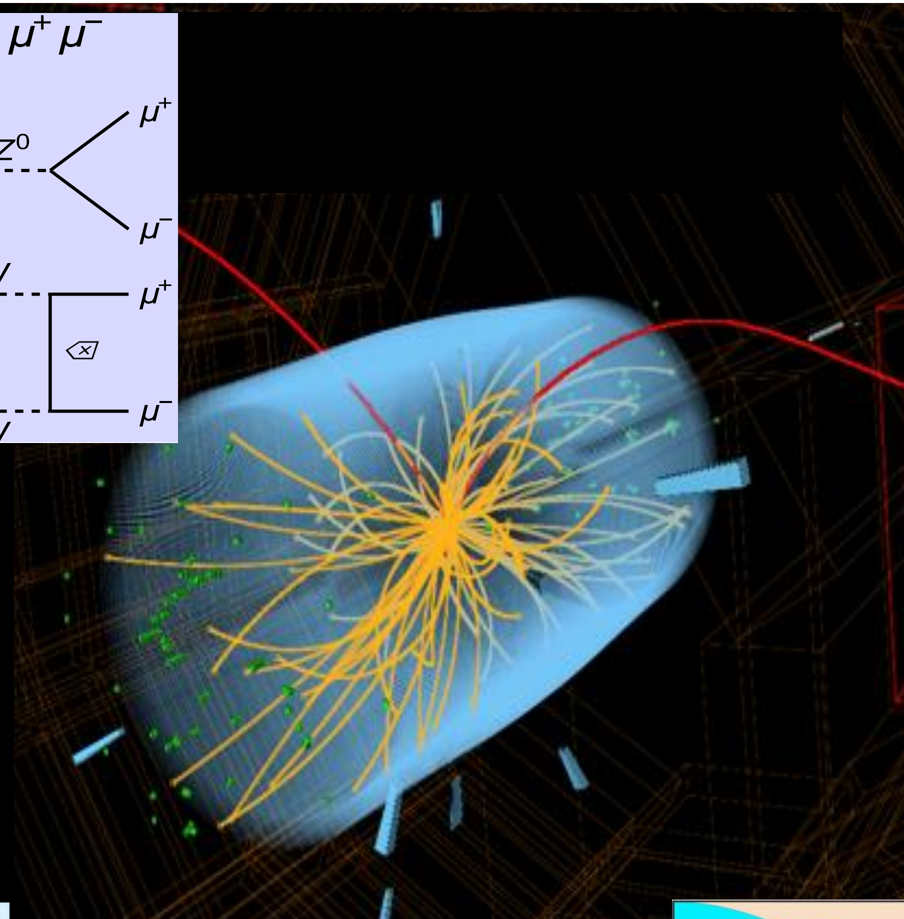
$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = -0.02 \pm 0.05 \pm 0.04.$$

PRL 110 (2013) 221601

Rare Decays: B → μμ







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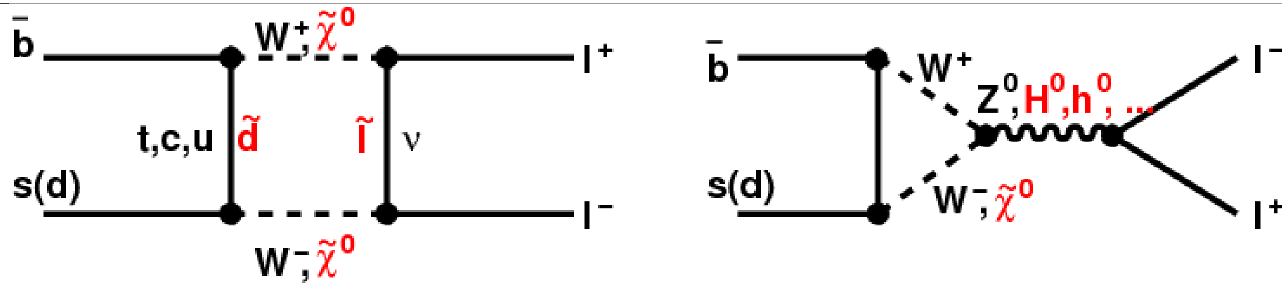
Rare Decays: B → μμ



Sensitive to New Physics, can be strongly enhanced in SUSY with scalar H exchange

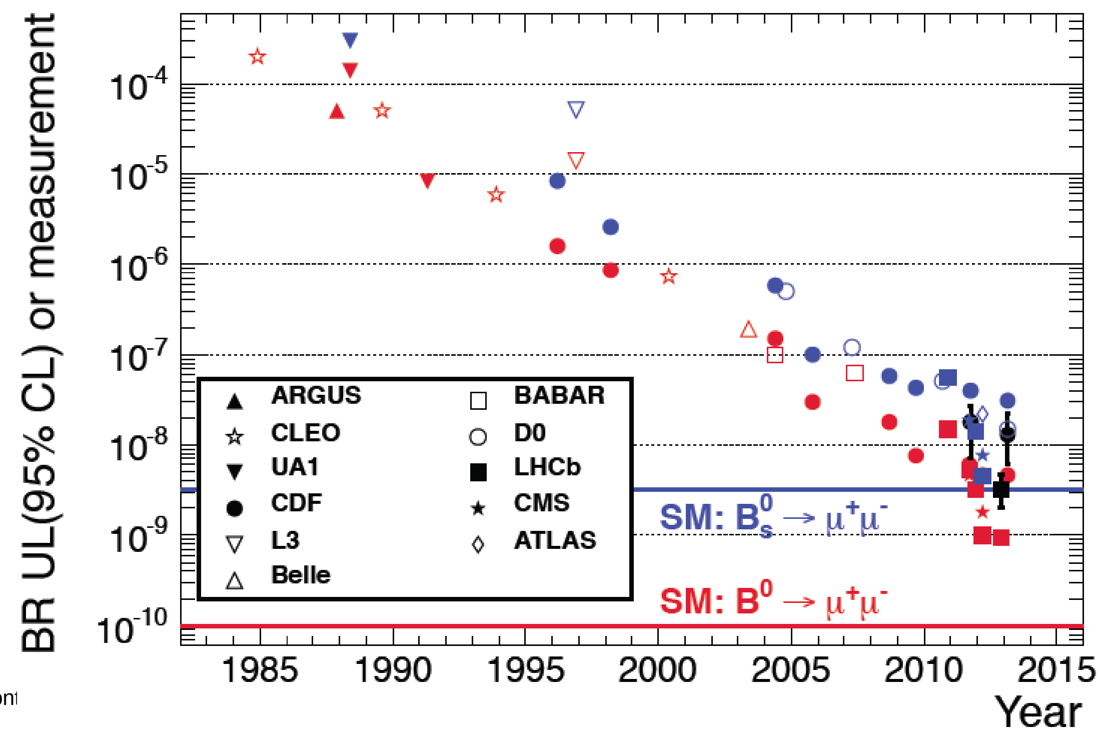
Sensitive probe for MSSM with large tanβ: $B(B_S \rightarrow \mu^+\mu^-) \sim \tan\beta^{\,6} / M_A^{\,4}$

In Standard Model:

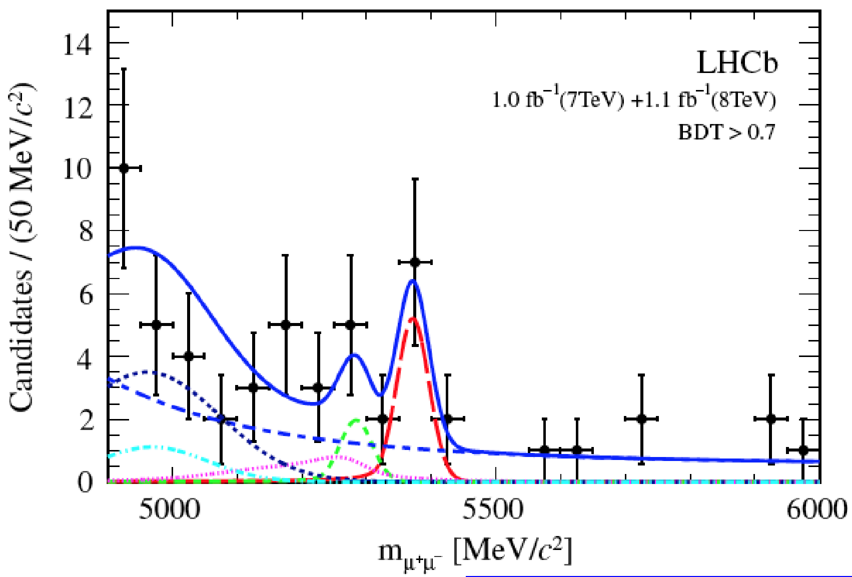
$B(B_d \rightarrow \mu\,\mu) = (0.10 \pm 0.01)\times 10^{-9}$

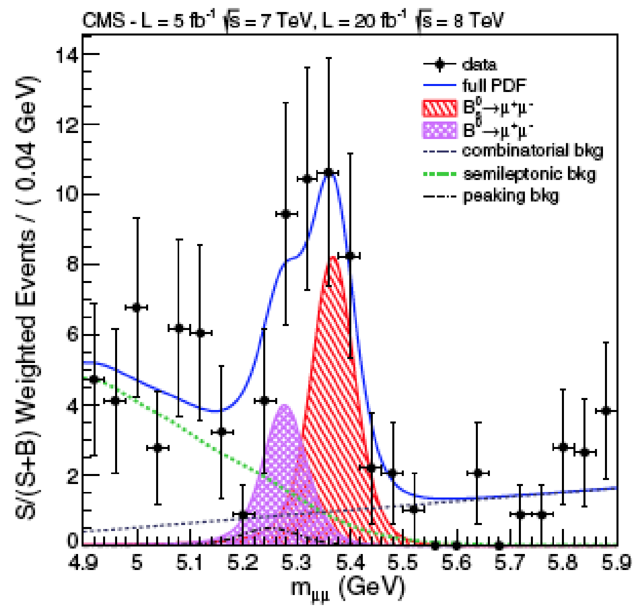
$B(B_s \rightarrow \mu\,\mu) = (3.2 \pm 0.2)\times 10^{-9}$

[A.J.Buras: arXiv:1012.1447]



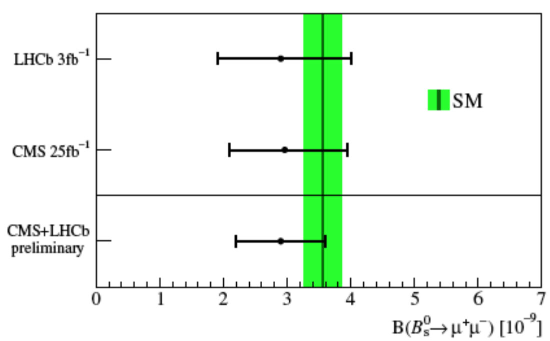
Observation of $B_s \to \mu\mu$

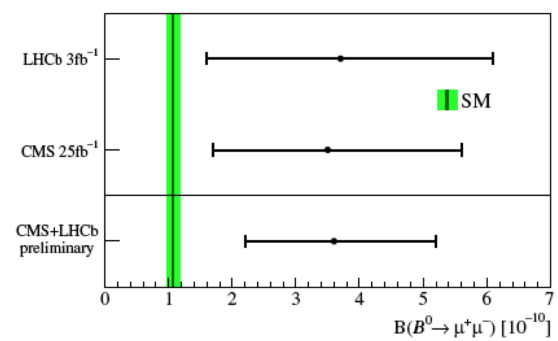


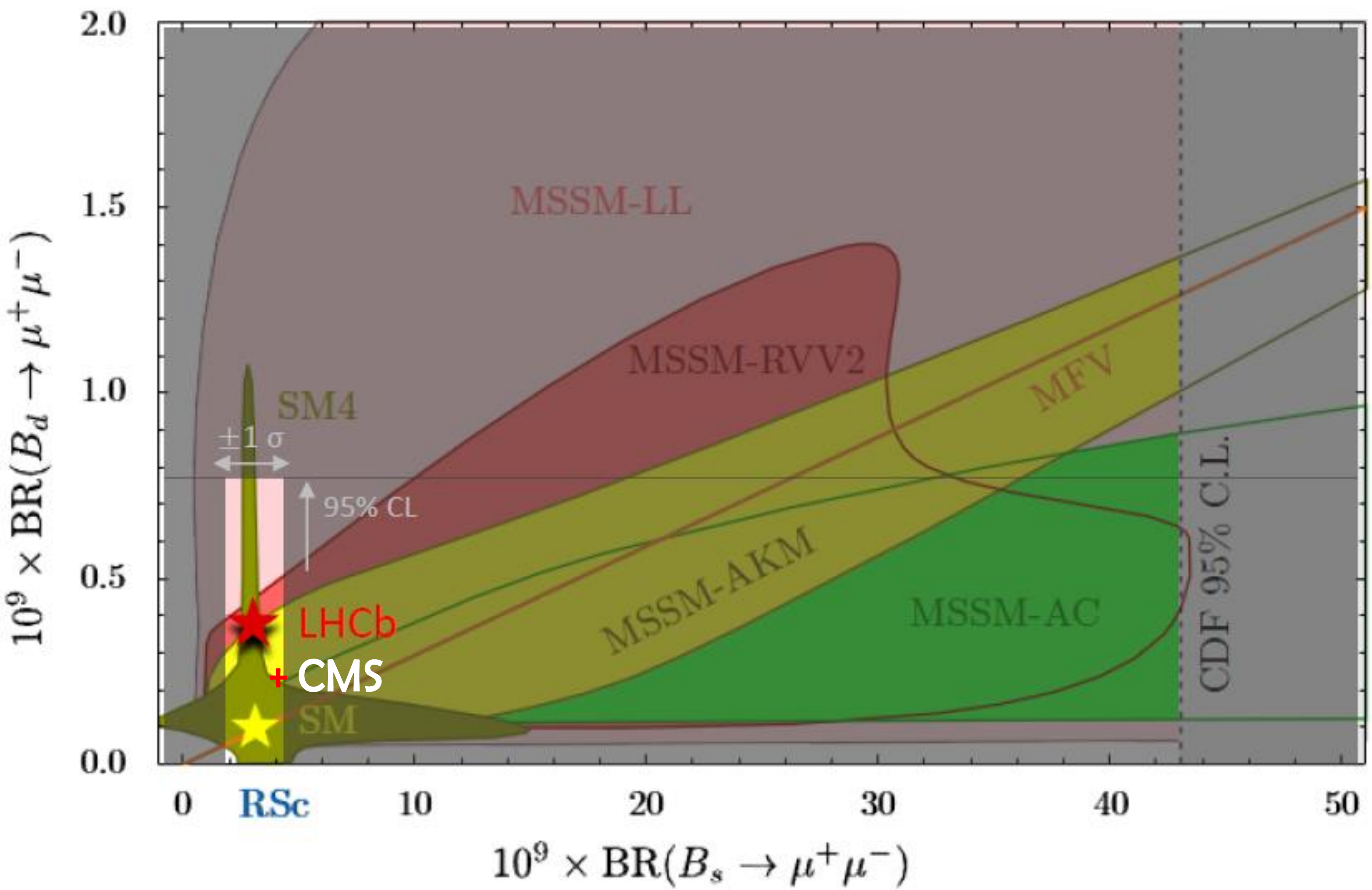


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

CMS PAS BPH-13-007
LHCb-CONF-2013-012

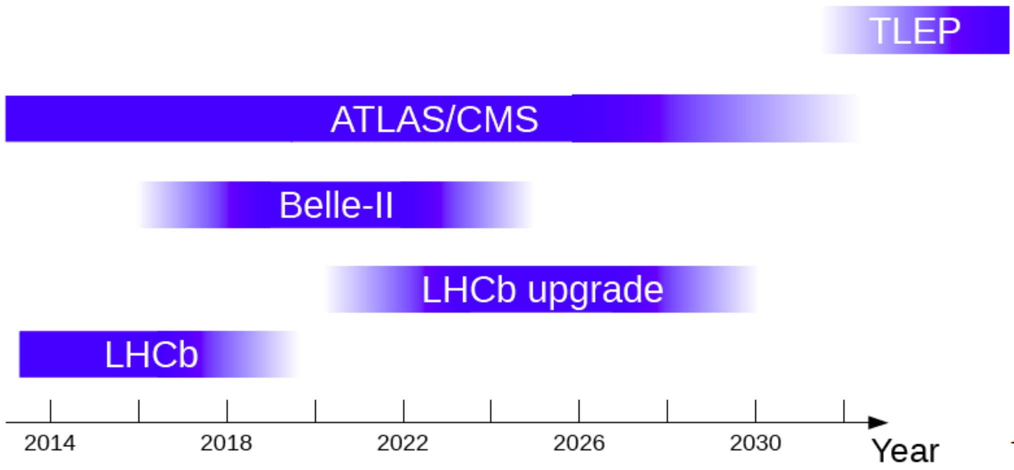






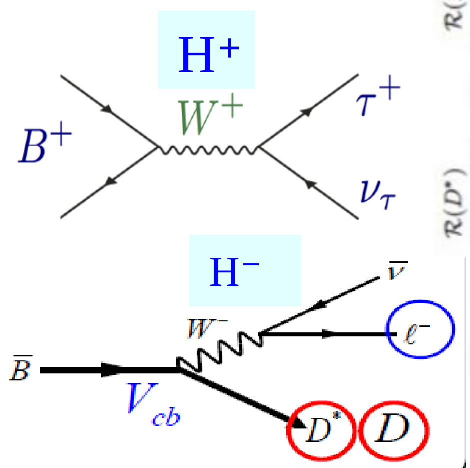
Take account generally of these measurements in building “acceptable” SUSY models

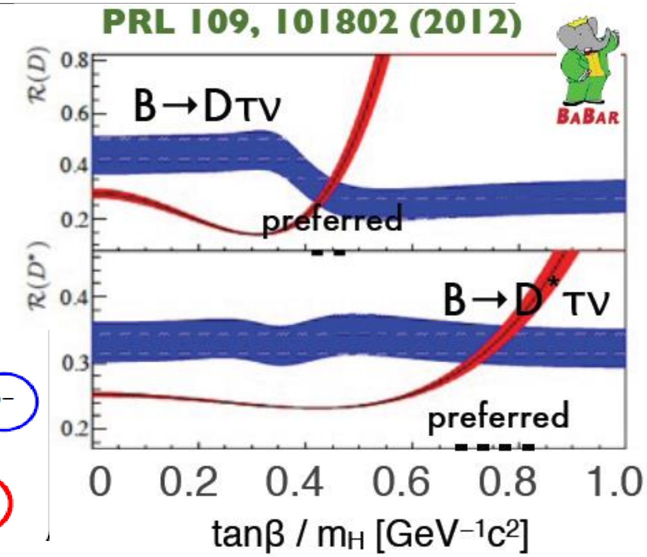
Rich Future: Flavour Physics



U. Egede

G. Hou





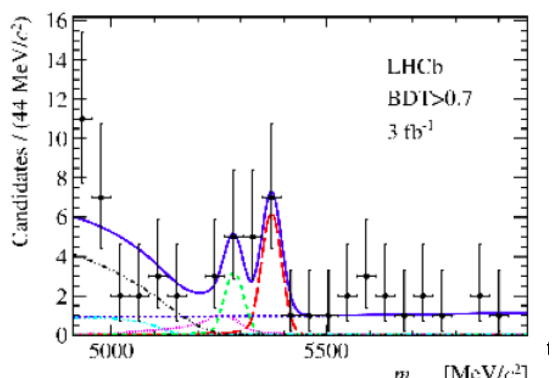
Observing $B^0 \to \mu^+\mu^-$

Following $B^0_s \to \mu^+\mu^-$ observation, challenge now is to observe for $B^0 \to \mu^+\mu^-$

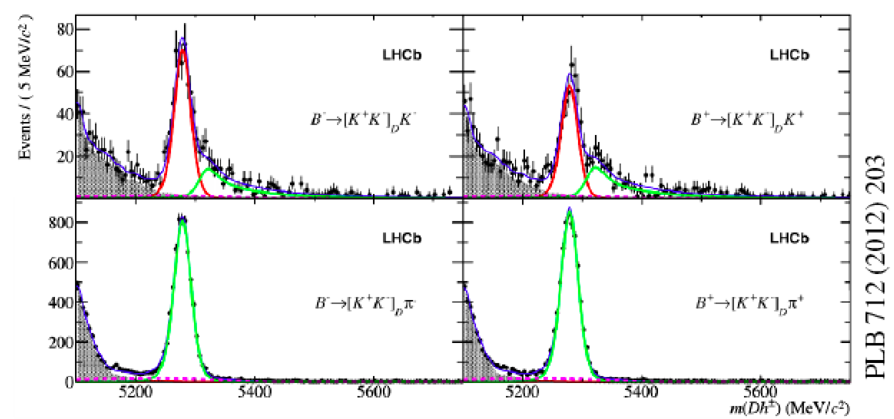
- In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
- New physics not following this pattern may manifest itself as a higher $B^0 \to \mu^+\mu^-$ rate

Lower rate and peaking backgrounds now a real issue

- CMS
  - BF <1.1 10^{-9}
- LHCb
  - BF <0.7 10^{-9}



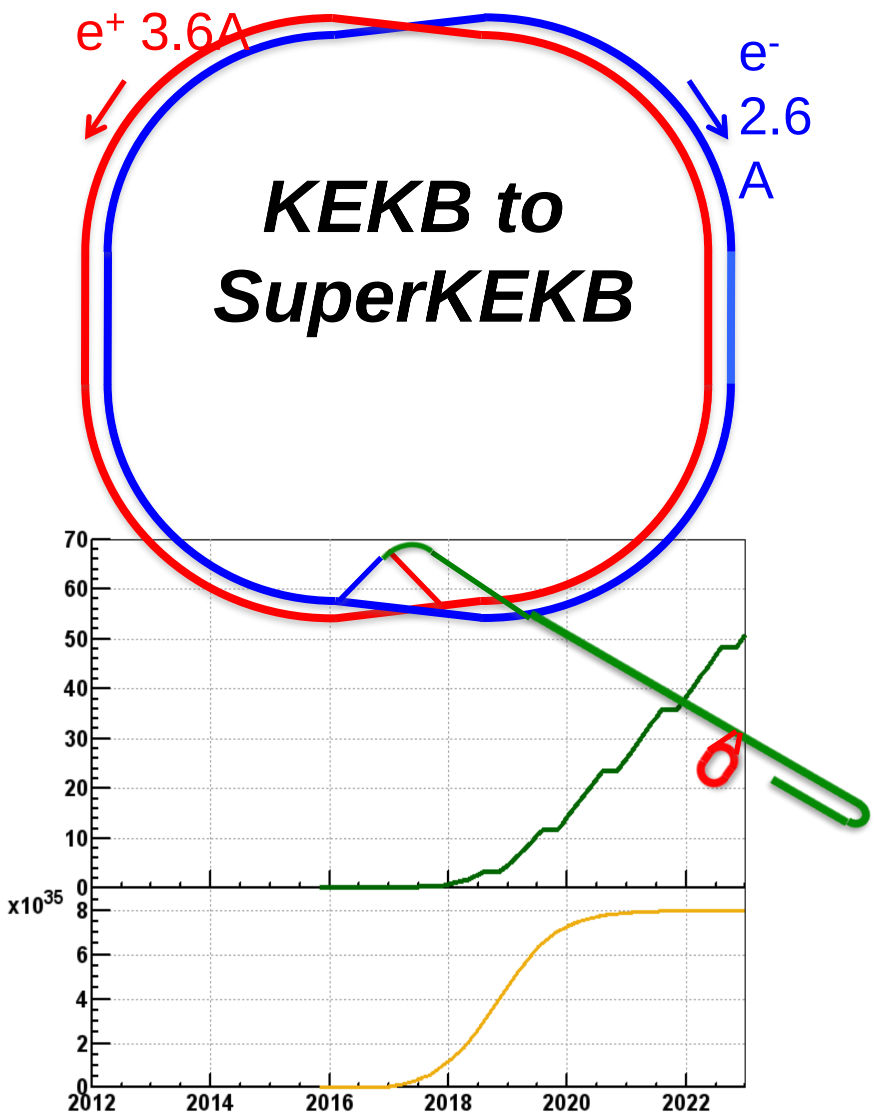
Determination of CP angle γ



Need to understand relative signal yield in the different final states

- Statistical reach for Belle-II is 2°, for LHCb upgrade 1°

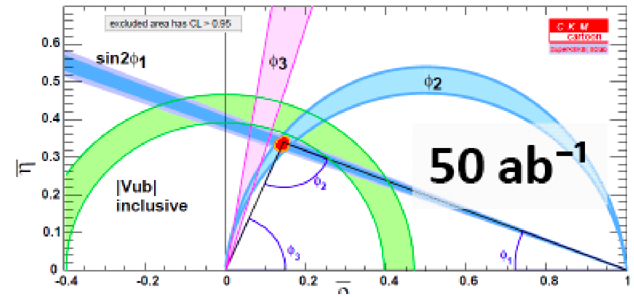
Physics Reach of Belle II and LHCb Upgraded



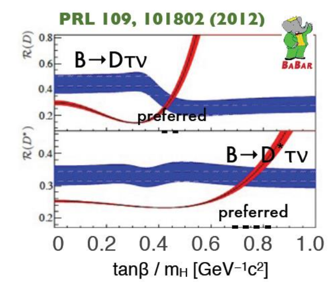
Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		$1.5°$	Belle II
ϕ_3	***	$3°$	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	$1.5°$	Belle II

Remarks: Heavy Flavours

If CKM unitarity is violated Belle 2, with 50 ab^{-1} will reveal it



Look out for significant deviations from SM in loop processes



Pay attention to:

Measurement of angle γ with and without penguin contributions

$B \rightarrow \tau\nu, \mu\nu$

Top – "the new Flavour Frontier" [G. Hou] e.g. $t \rightarrow c\, h^0$

B_s, $B_d \rightarrow \mu\mu$ – precise measurements. Need help from Belle 2 – precise and absolute measurements of some BR

L (fb^{-1})	No. of B_s^0	No. of B^0	$\delta\mathcal{B}/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\rightarrow\mu^+\mu^-)}{\mathcal{B}(B_s^0\rightarrow\mu^+\mu^-)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

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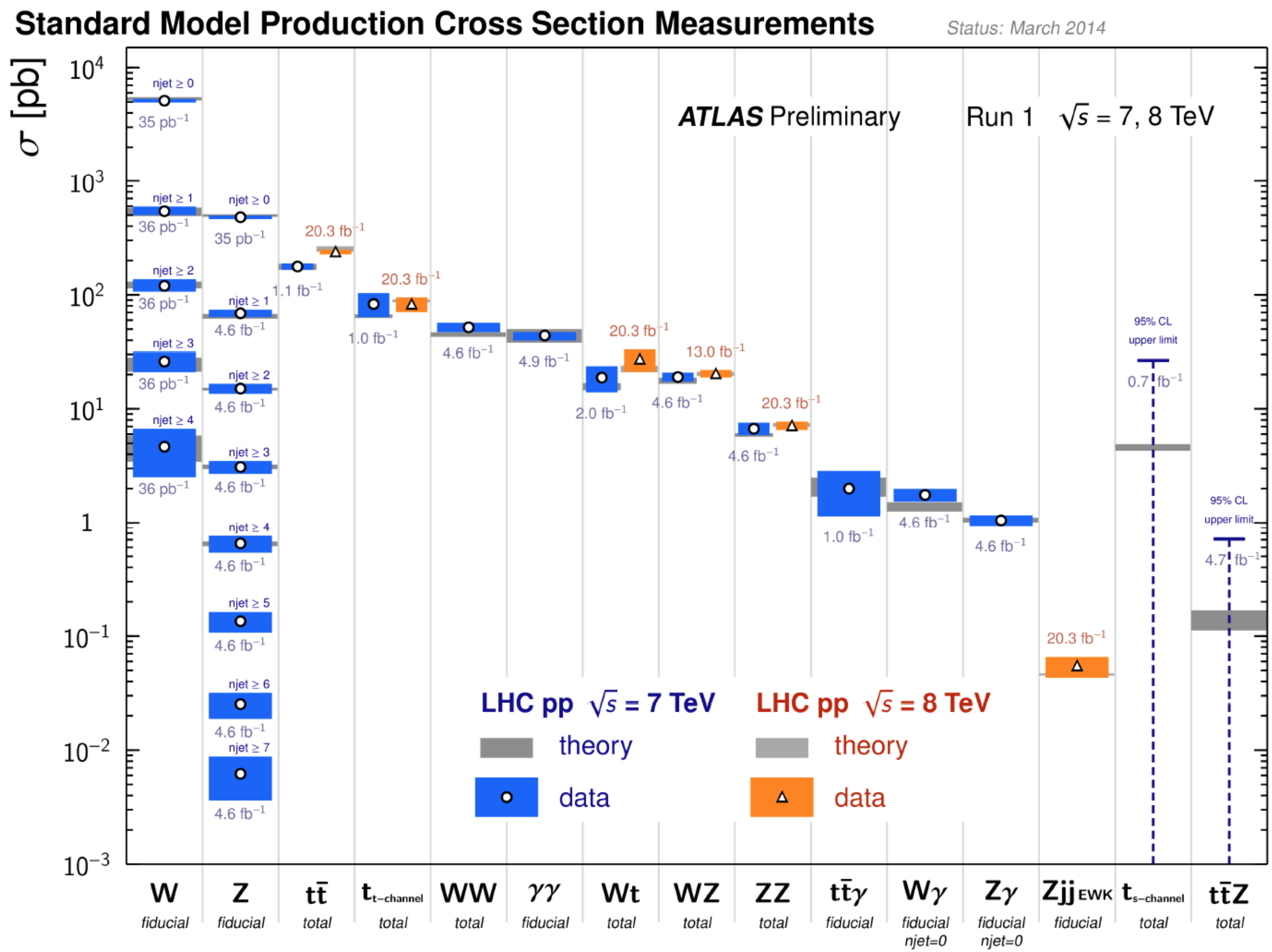
Standard Model and Electroweak Physics



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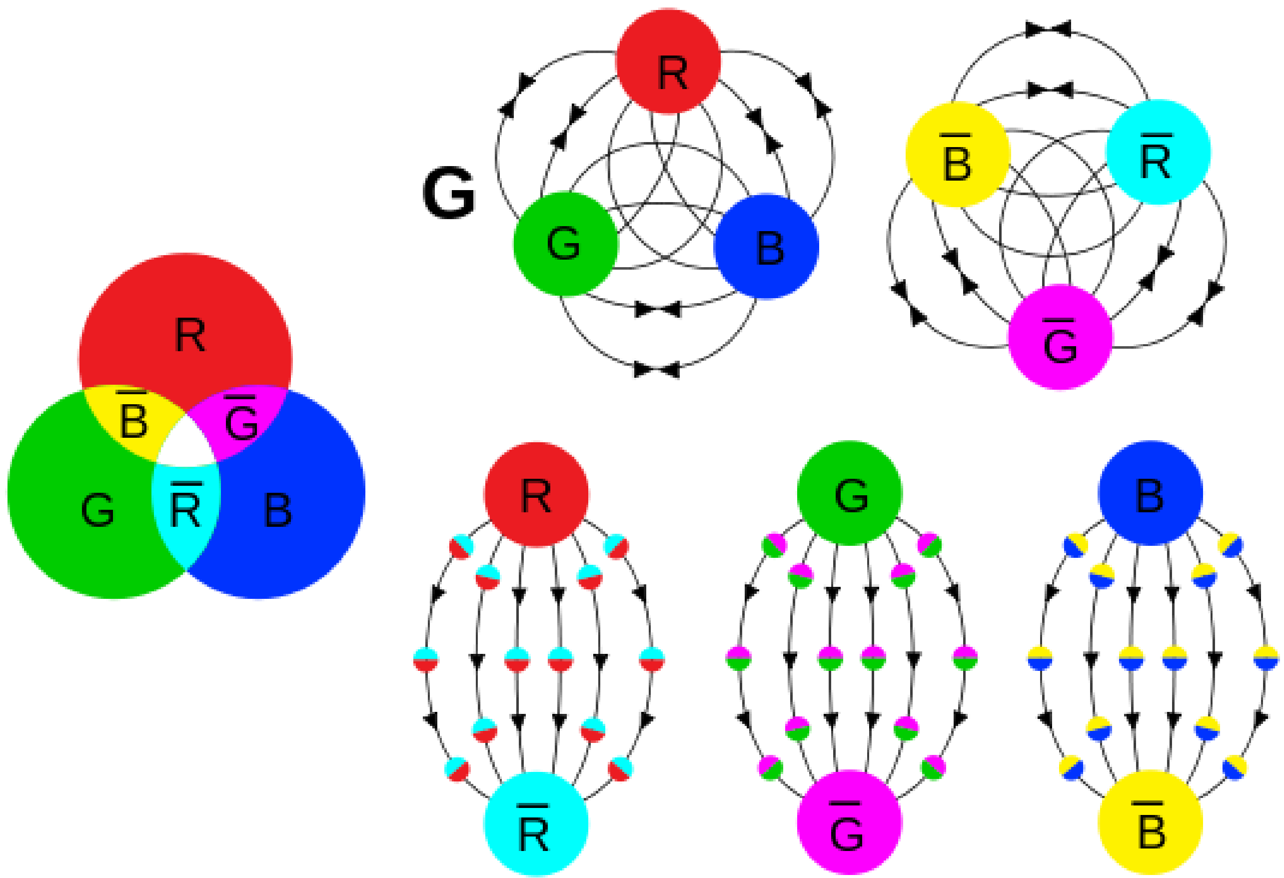
Colour and QCD



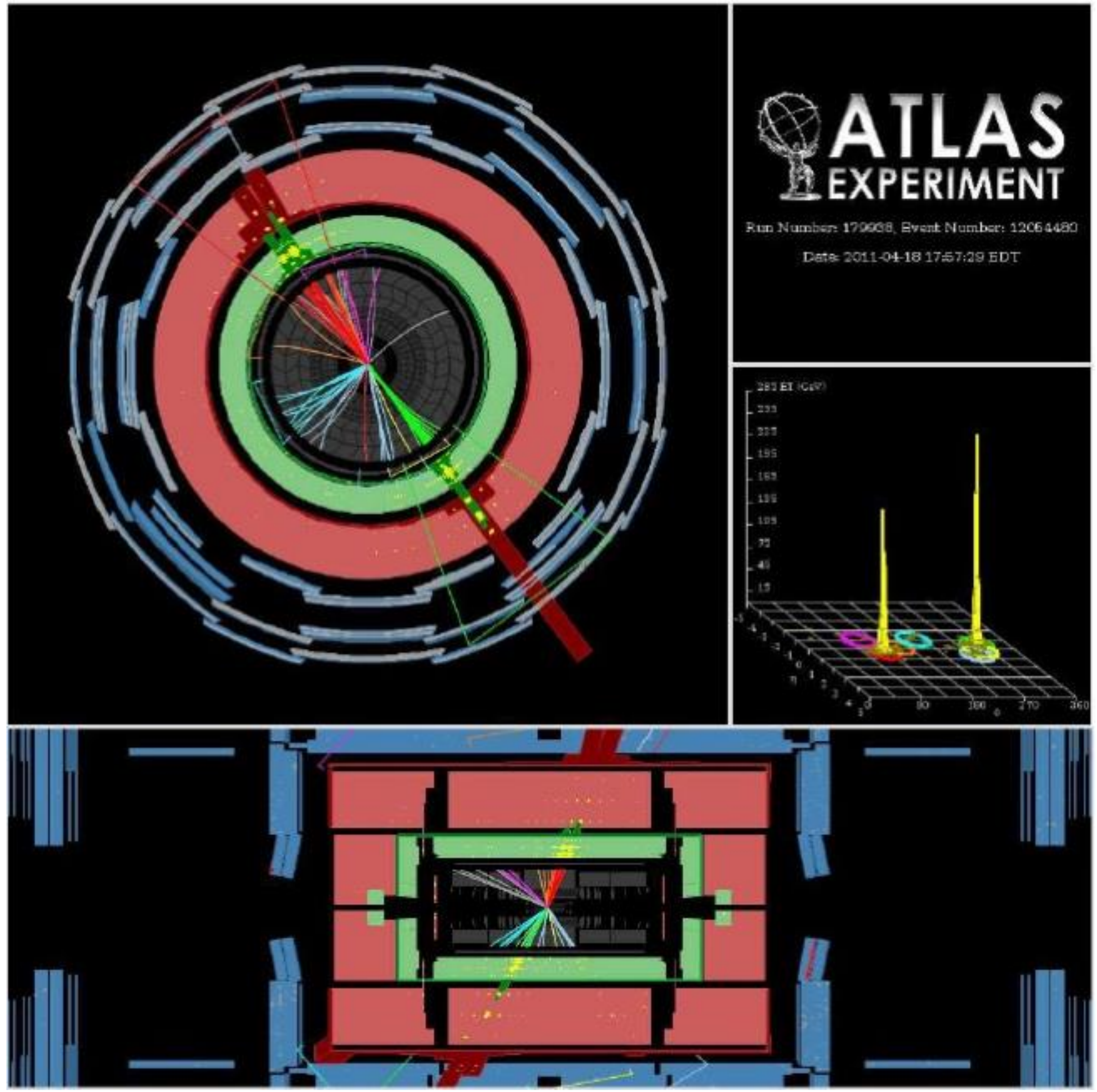
October 1964: Oskar Greenberg proposed the additional quark attribute that would evolve to become quark color.

Quark and Gluon Interactions - Jets

M_{jj} = 4.04 TeV

P_T^1 = 1850 GeV, η= 0.32

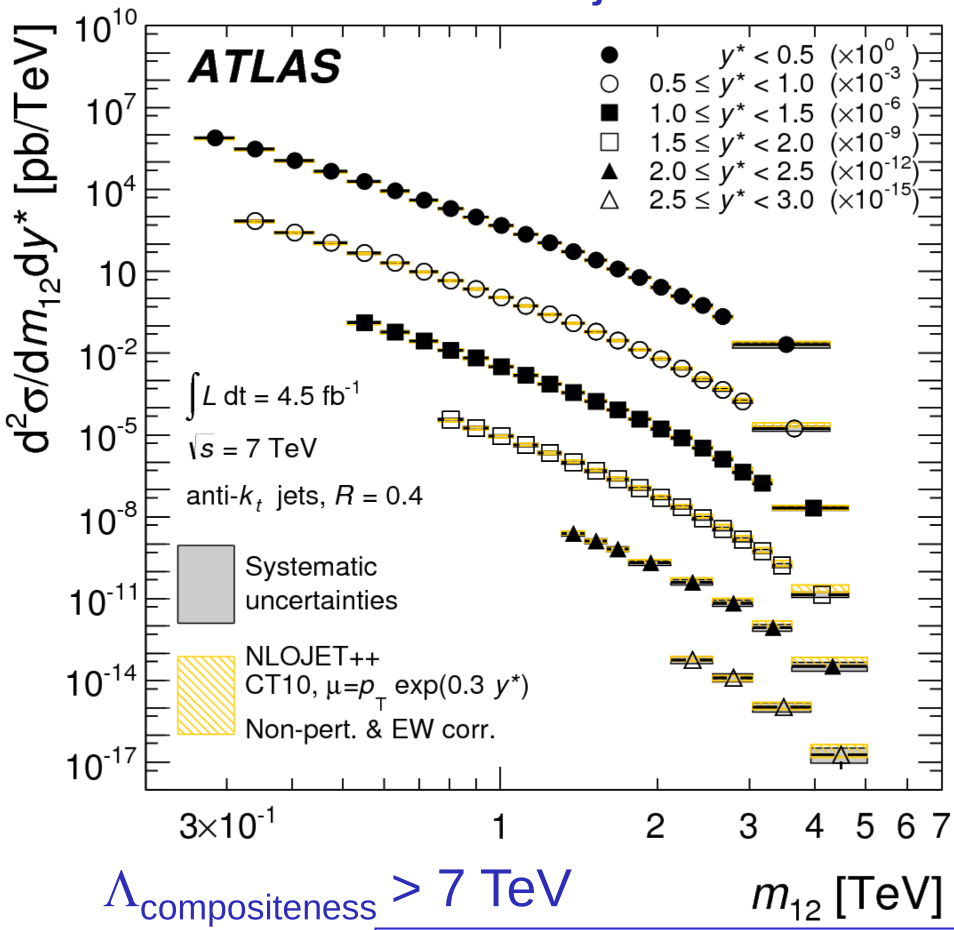
P_T^2 =1840 GeV, η=-0.53



LHC and Testing QCD

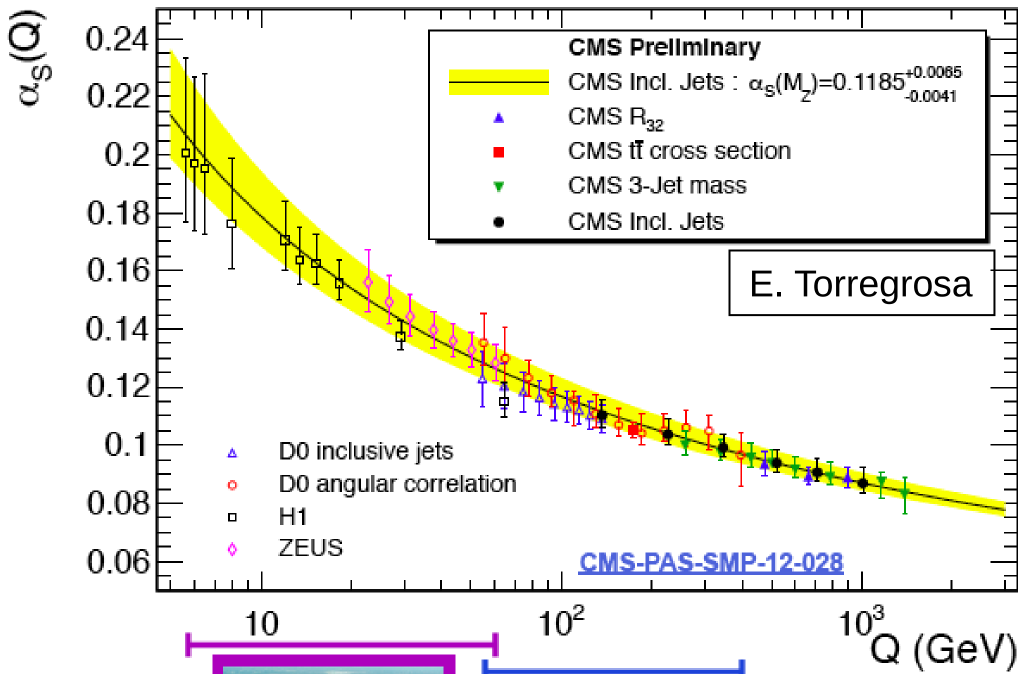
Routinely and successfully analyse physics at the high energy frontier in terms of quarks and gluons!

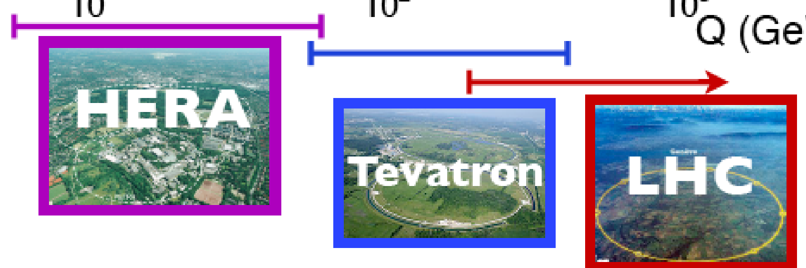
Double Differential Di-jet cross section



$\Lambda_{compositeness}$ > 7 TeV

The strong coupling constant



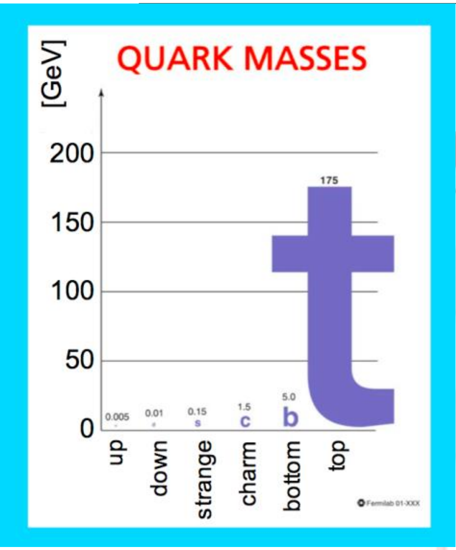


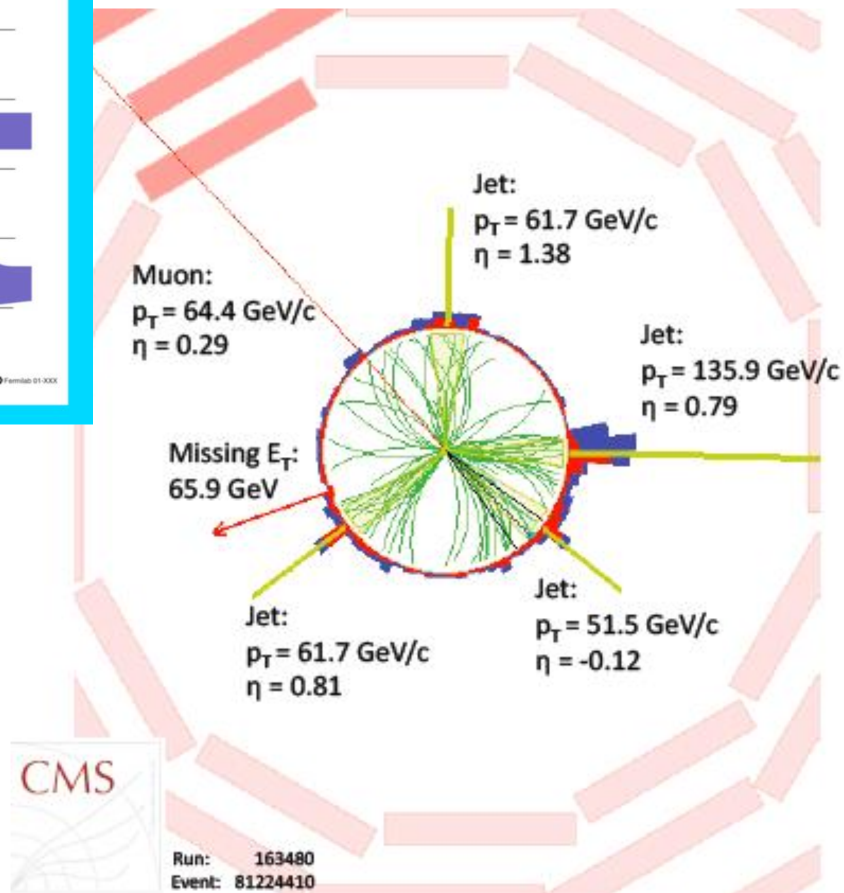
JHEP05(2014)059

Excellent description by QCD

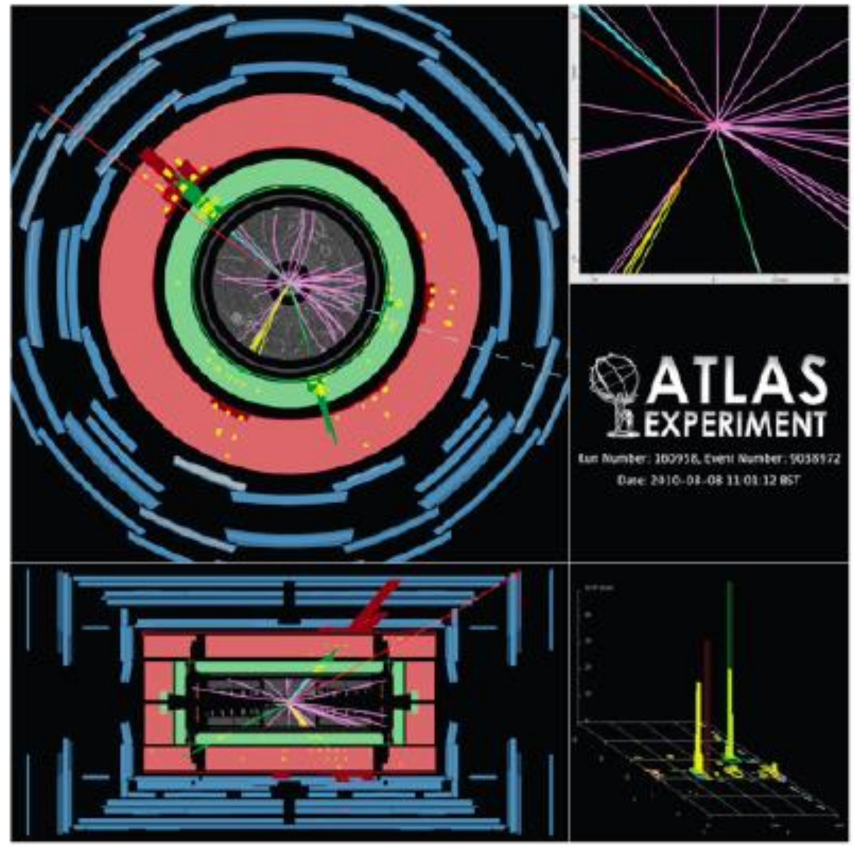
Asymptotic freedom- α_S runs

The most complex SM signal: the Top



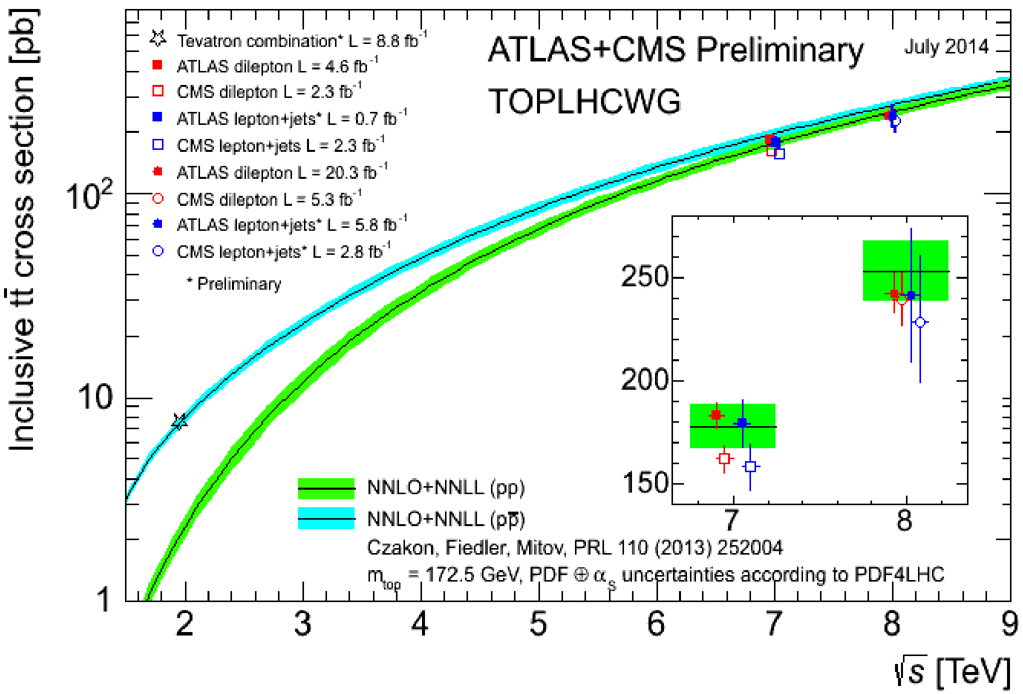


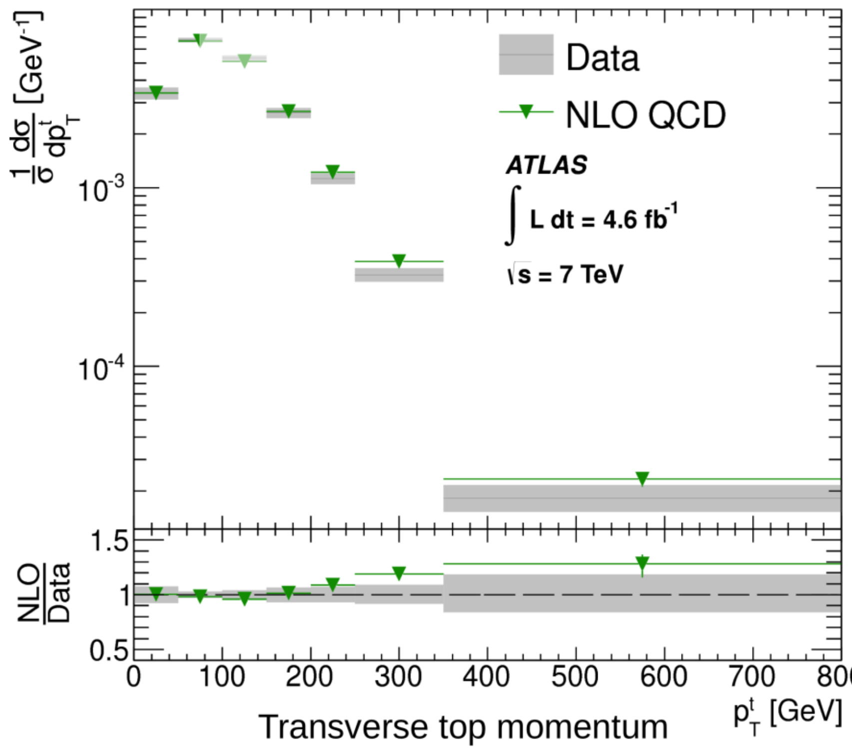
muon+jets event



electron+muon event

Top Studies: e.g. cross sections



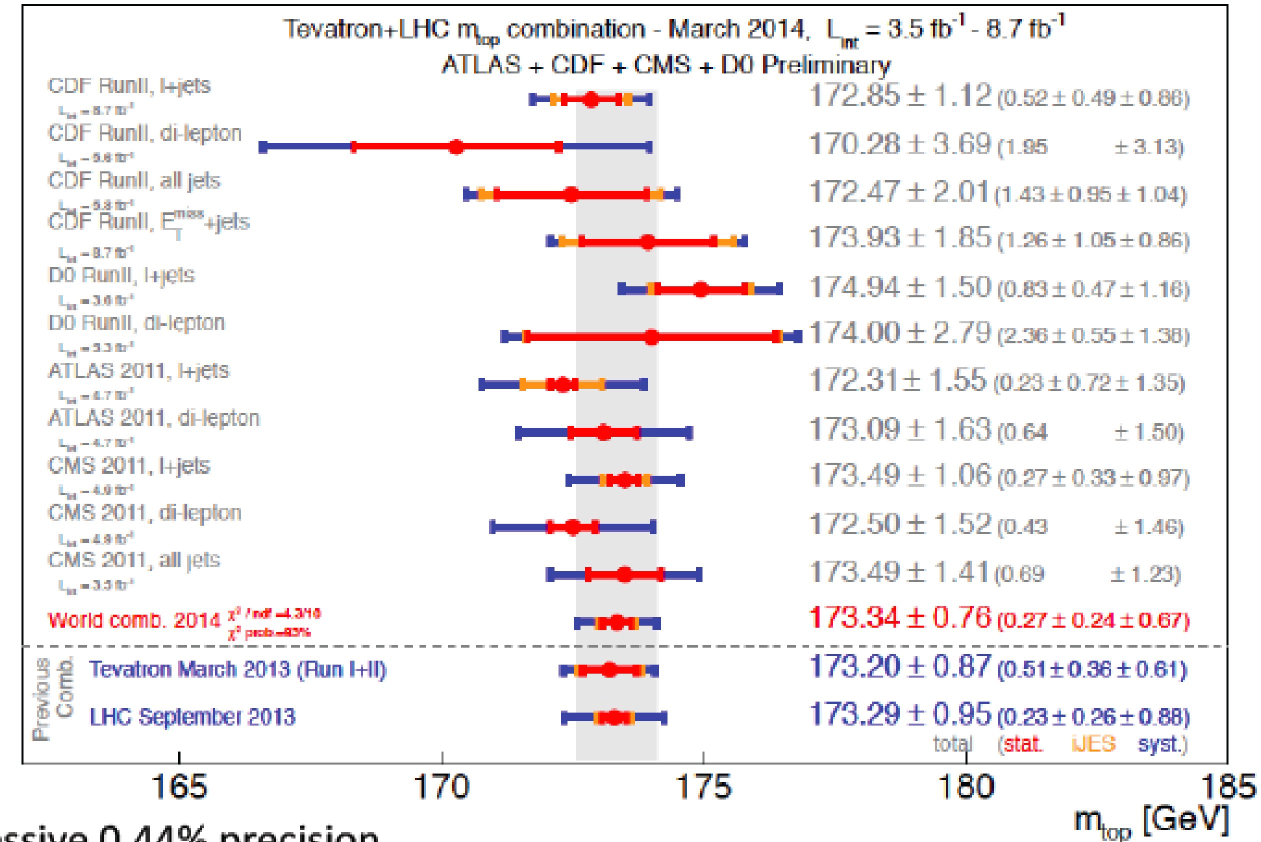


108’000 events in 19.5 fb^{-1}
at 8 TeV selected
(2’500 at Tevatron)

Mass of the Top Quark

R. Tenchini

World combination of m_{top}

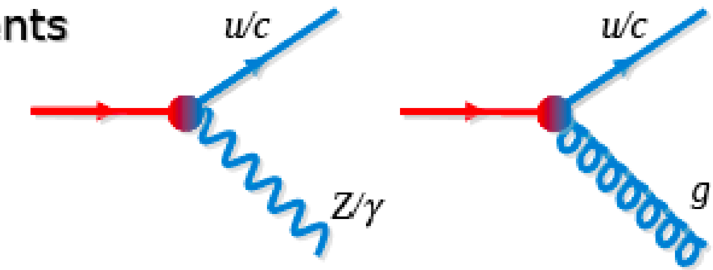


- An impressive 0.44% precision
- Some of the most precise measurements non included yet, e.g.
    - D0 full statistics, matrix element method, arXiv:1405.1756, m_t=174.98±0.76
    - CMS l+jets at 8 TeV, L=19.6 fb^{-1} CMS-TOP-2014-001, m_t=172.04±0.77

Search for non-SM couplings of top in FCNC decays

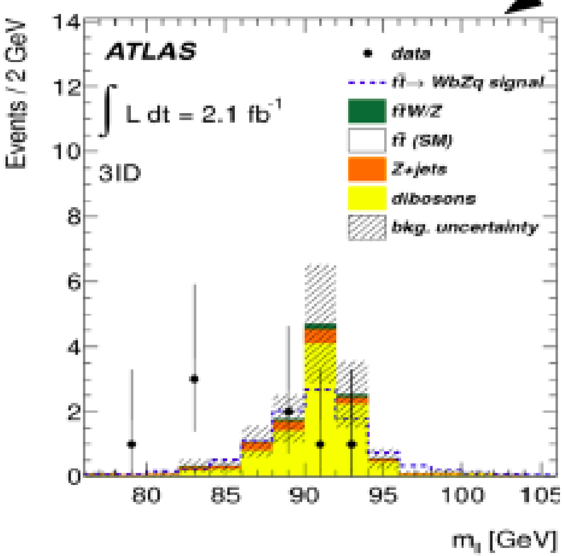
A. Iorio

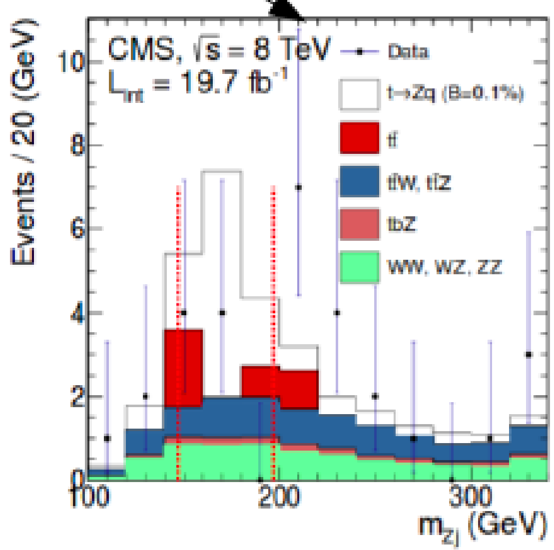
- FCNC can give t->u/c + g/z/γ :Can be searched for in events with 2 tops



- Several BSM theories can be parametrised through similar dimension-6 operators.

- CMS and Atlas look for events with 3 leptons, 2 of which generating a Z boson resonance.





BR(t→Zq) < **0.73% (Atlas)** /

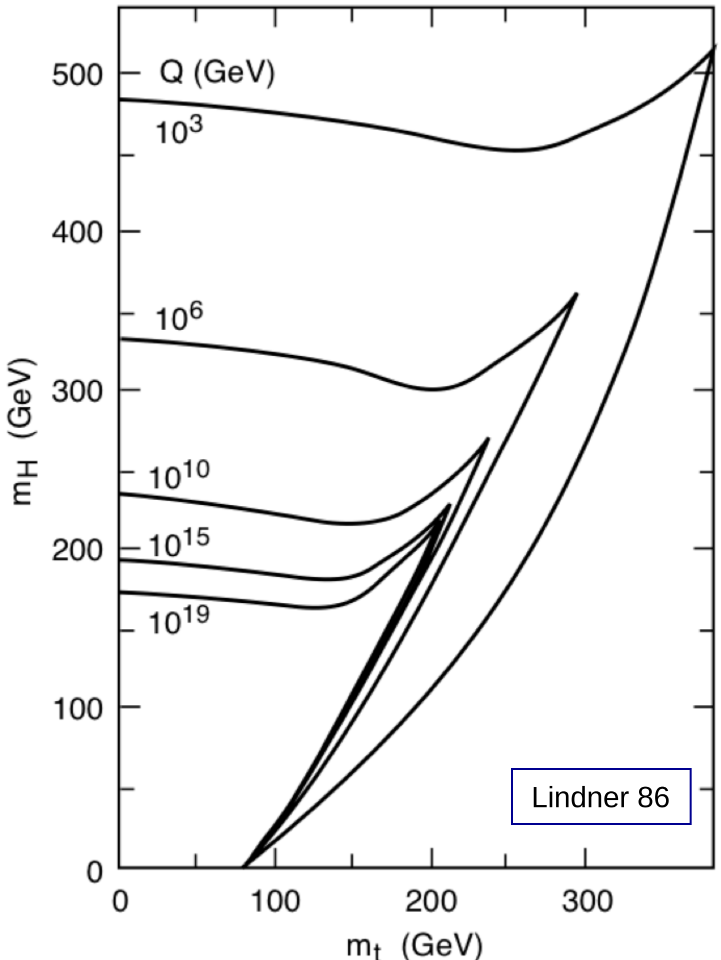
< **0.05% (CMS)**

PLB 716(2012)142-159

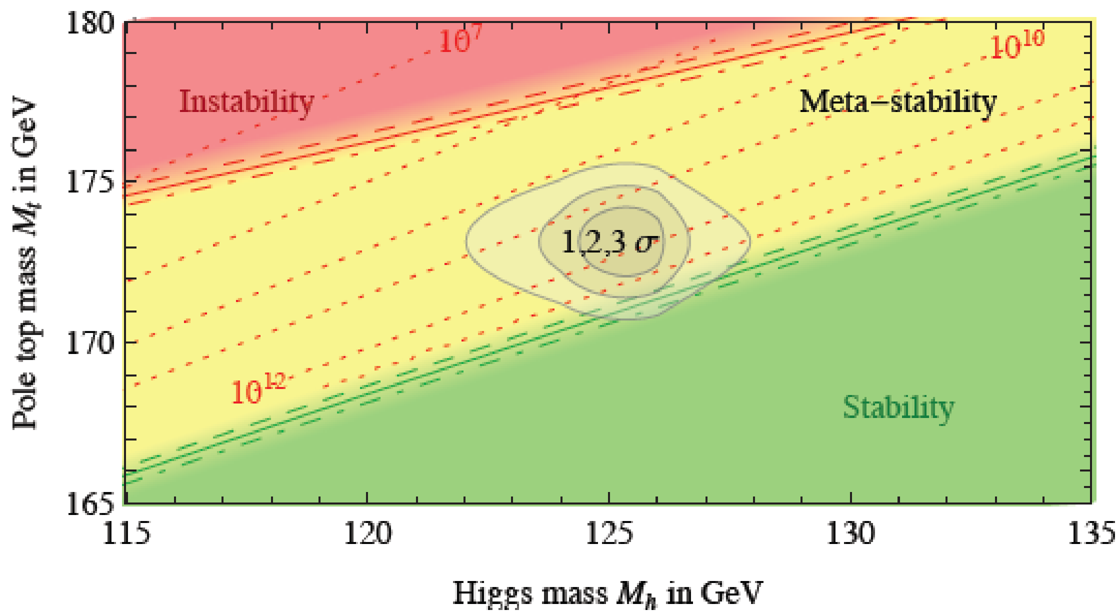
PRL 112(2014)171802

Top and Fate

$$\mu\frac{d}{d\mu}\lambda \approx \frac{1}{16\pi^2}\left(24\lambda^2 - 6y_t^4\right)$$



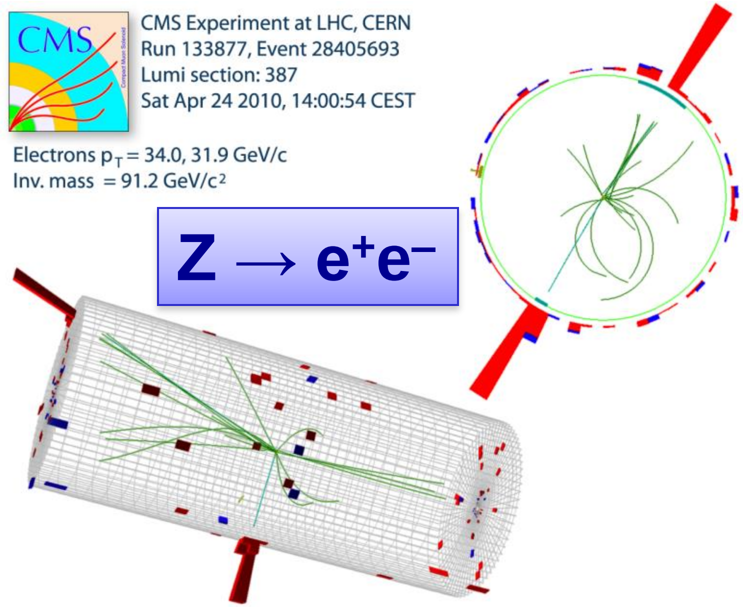
High precision top mass:
A fundamental input to the understanding of the SM
(fateful cosmological implications ?)

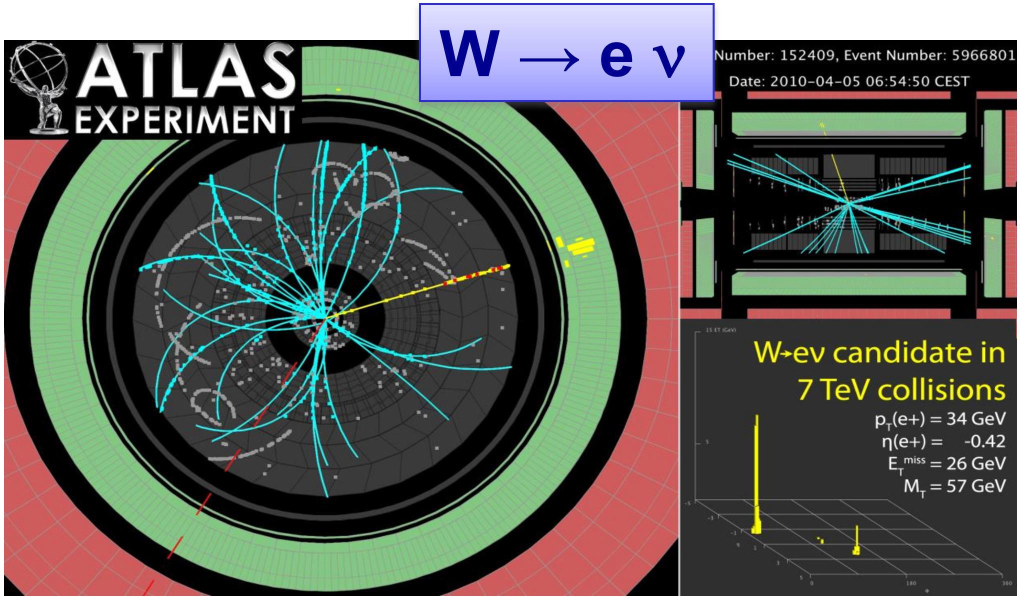


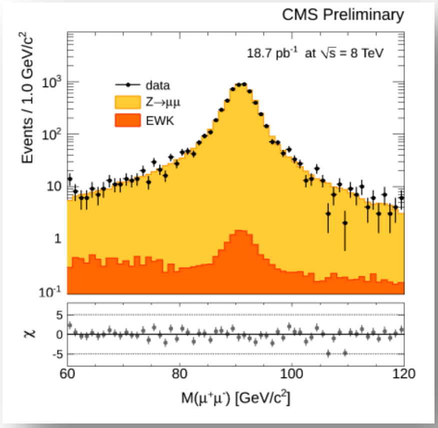
Degrassi et al. ArXiv:1205.6497, arXiv:1307.3536

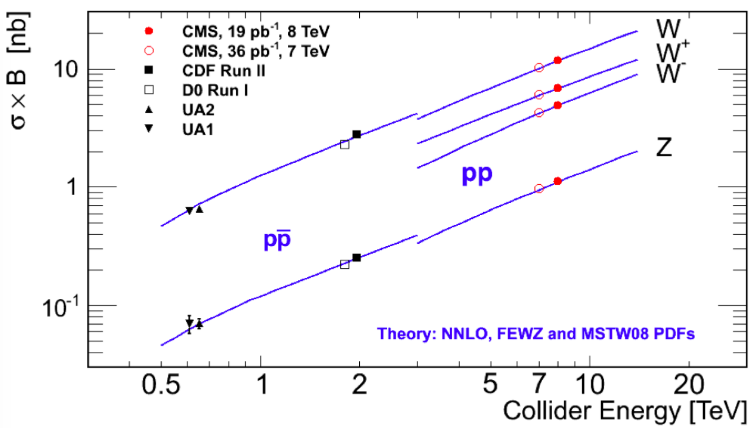
Imperial College London

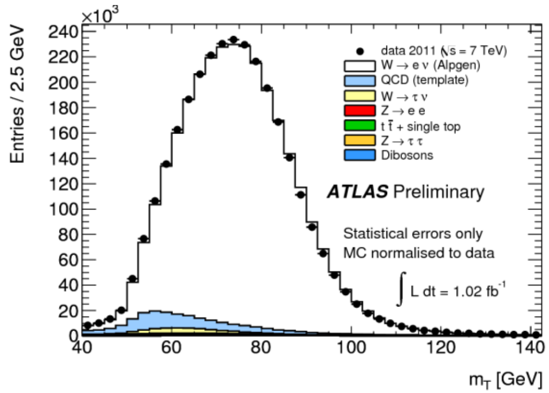
W and Z at 7/8 TeV: (still) clean and beautiful







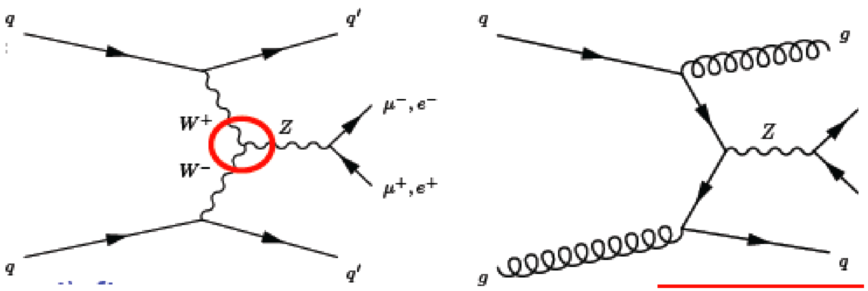




Standard Model: VBF production of Z bosons

Important reaction in order to establish whether the newly found Higgs boson is fully responsible for unitarization of VV scattering (background and techniques).

S. C. Hsu



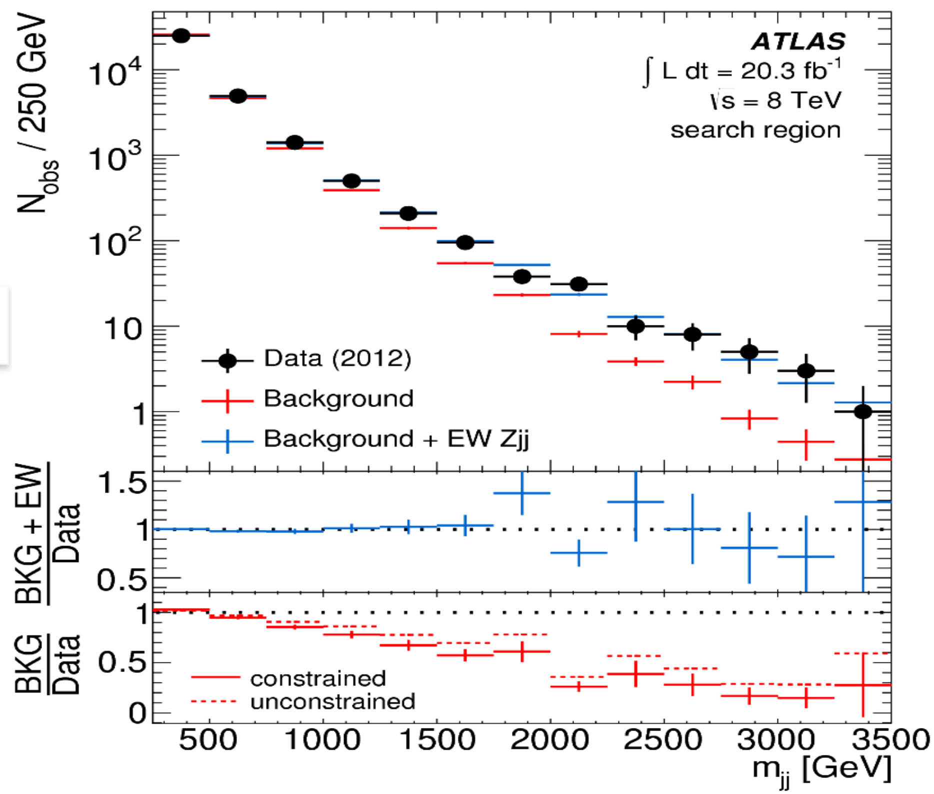
EW~0.01nb QCD~1nb

CMS – 7 TeV: Bkg. Hypothesis excluded at 2.6 σ

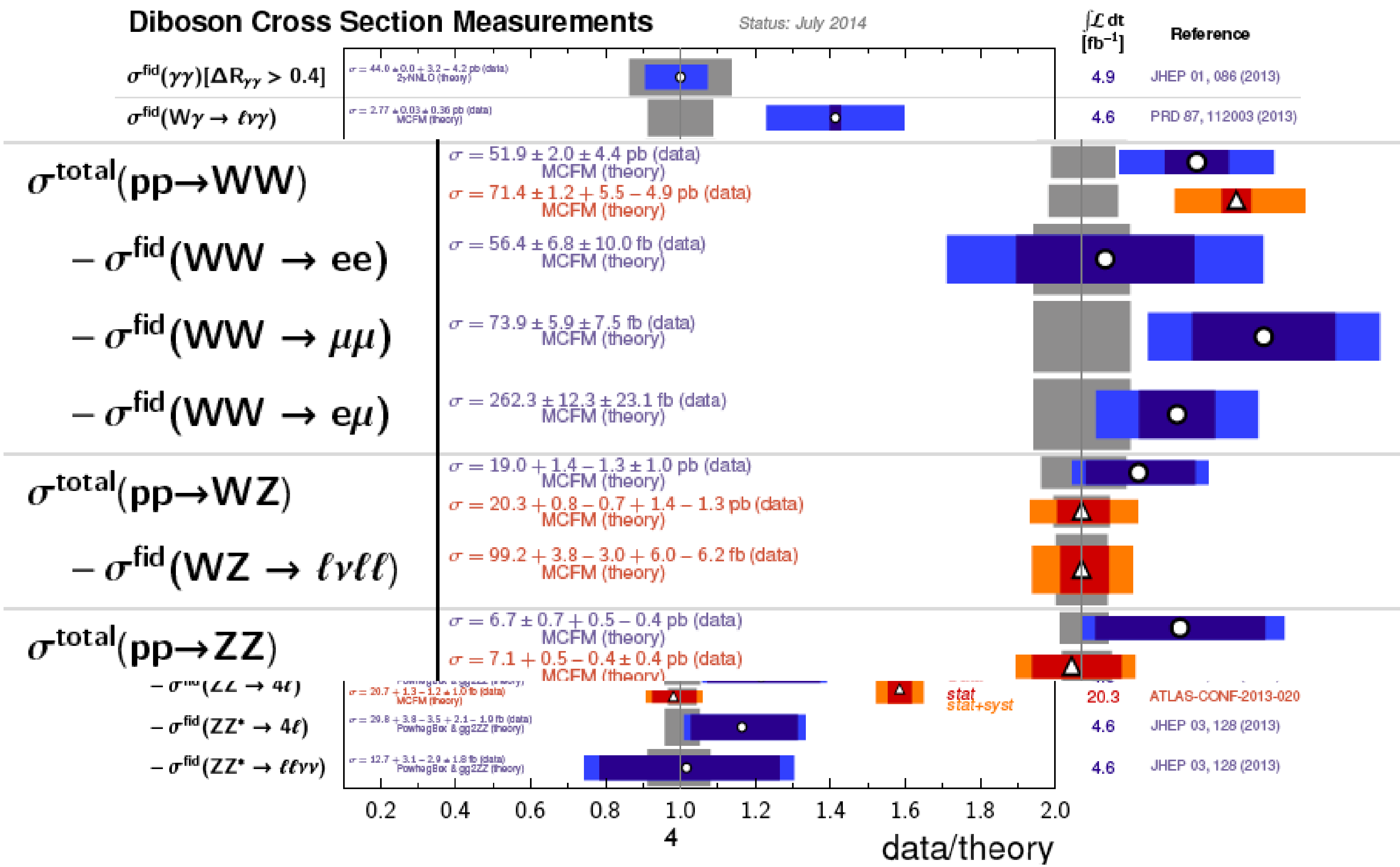
CMS-PAS FSQ-12-019

ATLAS Observation of EW production of Z+jets at > 5σ

$\sigma_{EW}(m_{jj}>1\text{TeV})$
$= 10.7\pm0.9(\text{stat}) \pm1.9(\text{syst}) \pm0.3(\text{lumi})$ fb
cf POWHEG: 9.5 ± 0.4 fb



Di-boson Production



Completing the SM: A Higgs boson

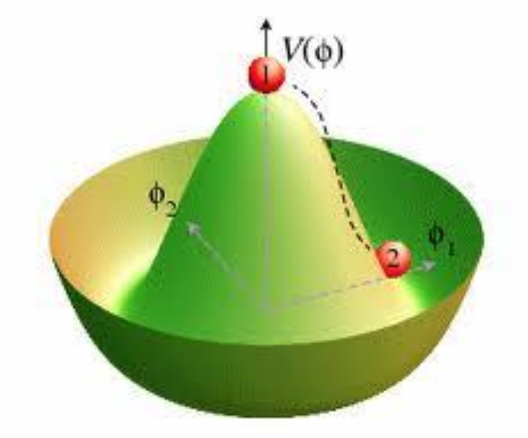
August 1964

[1] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 321, doi:10.1103/PhysRevLett.13.321.

[2] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9.

[3] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508.

[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, "Global conservation laws and massless particles", *Phys. Rev. Lett.* **13** (1964) 585, doi:10.1103/PhysRevLett.13.585.

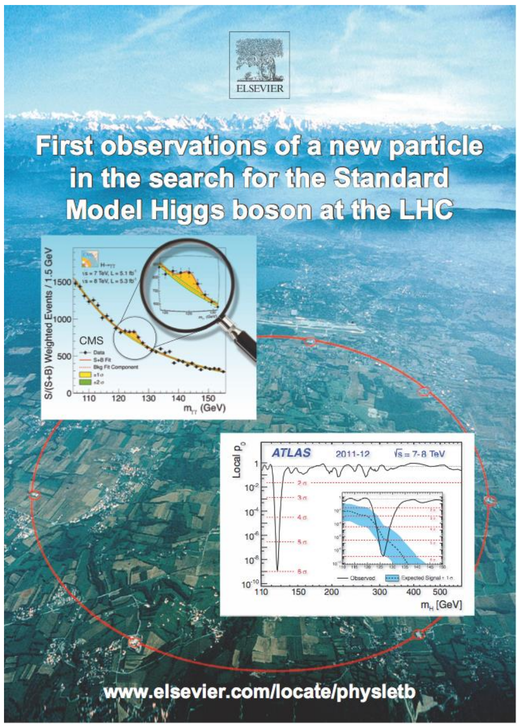


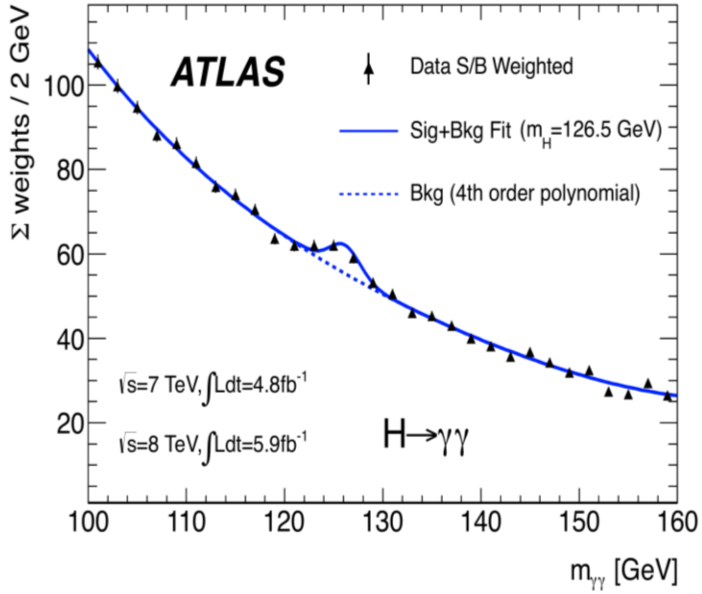
These papers on the *spontaneous symmetry breaking mechanism* attracted very little attention at the time. The *boson* attracted even less interest (T. Kibble, 2011).

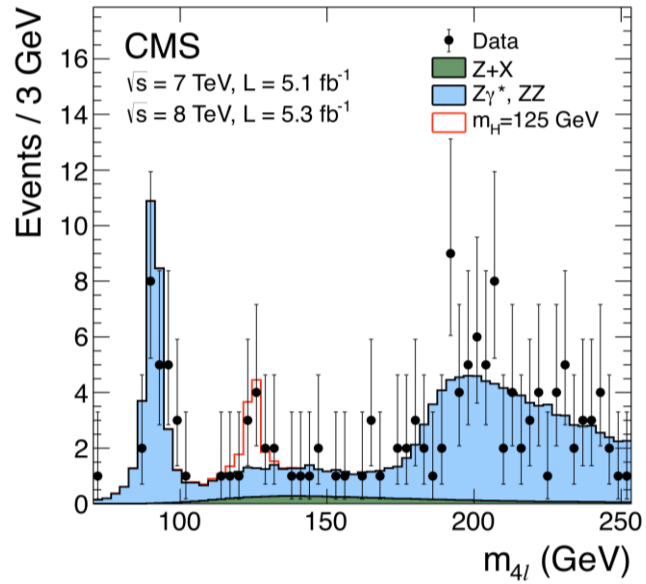
Imperial College London

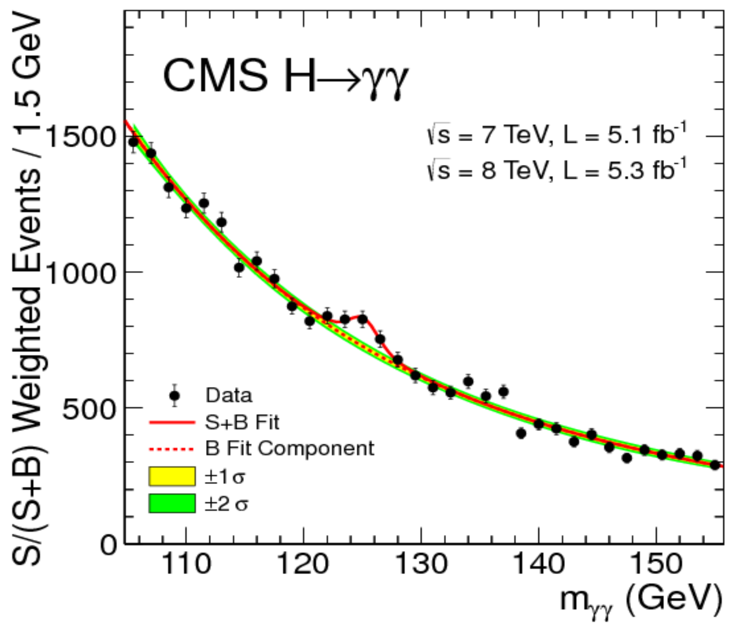
Completing the particle content of SM
A Higgs boson is Born

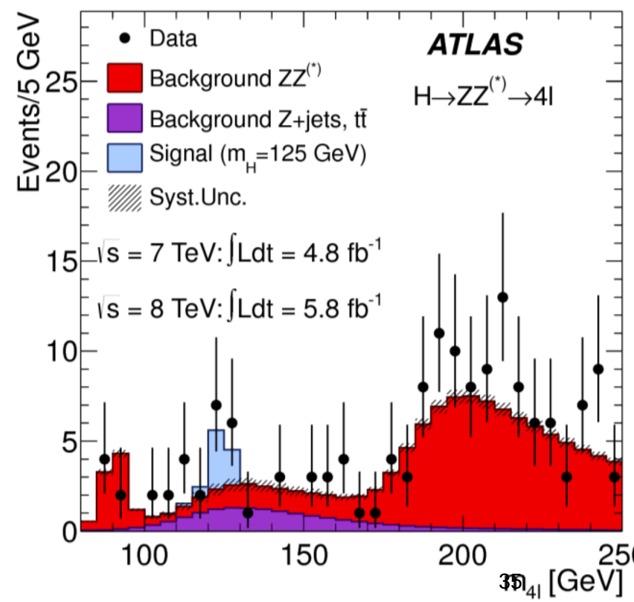
July 4th 2012





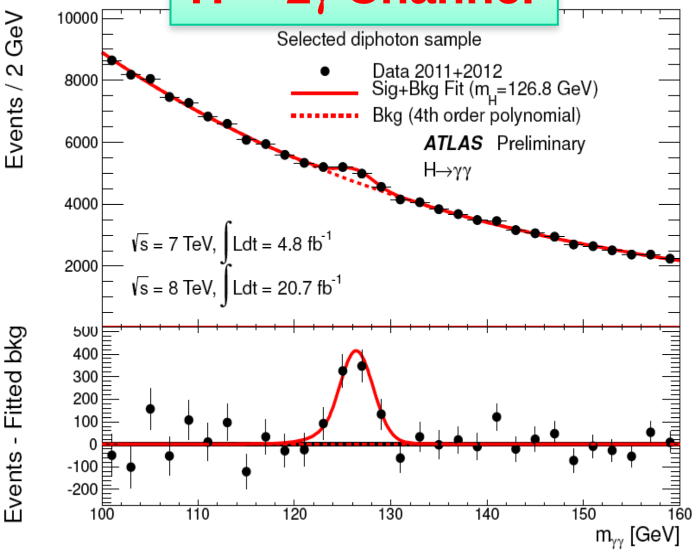




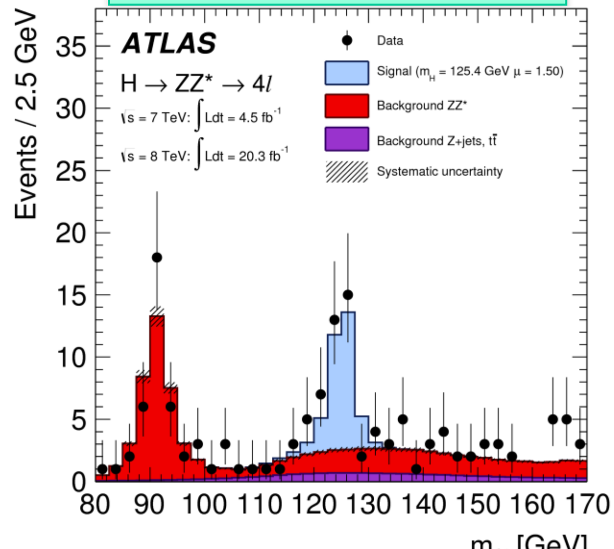


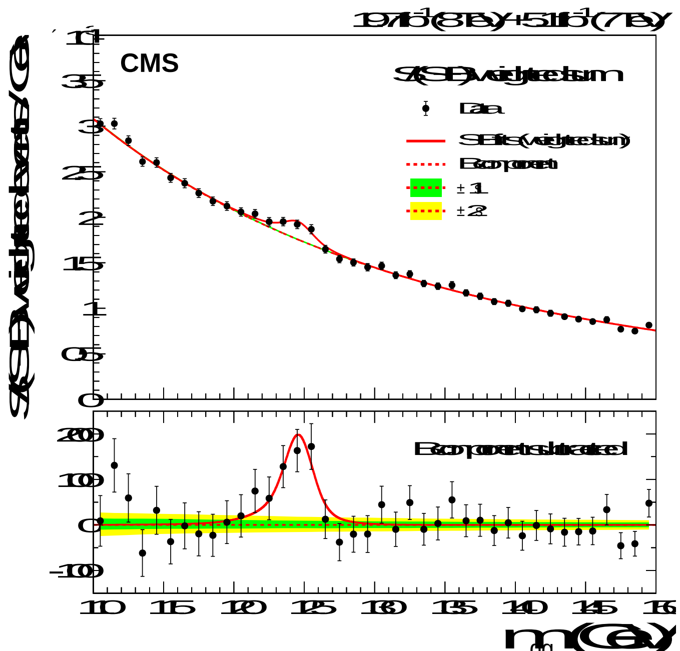
Final Legacy Results: H Decays to bosons

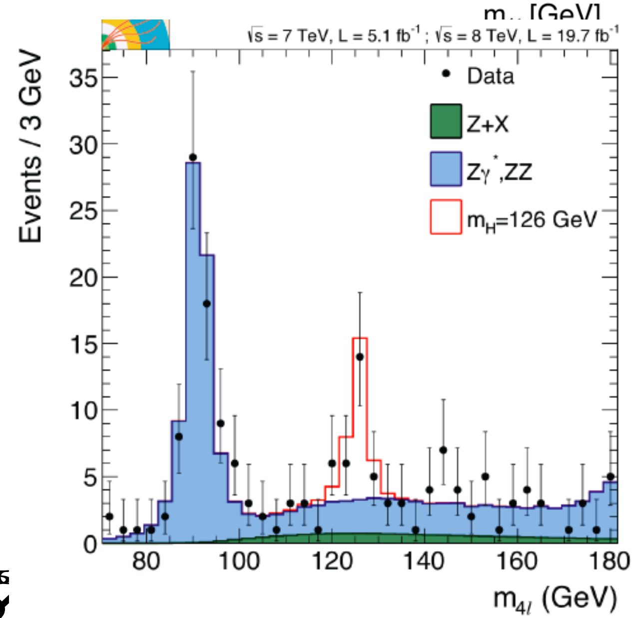
H→ 2γ Channel



H→Z→4*l* Channel







H→ 2γ Channel

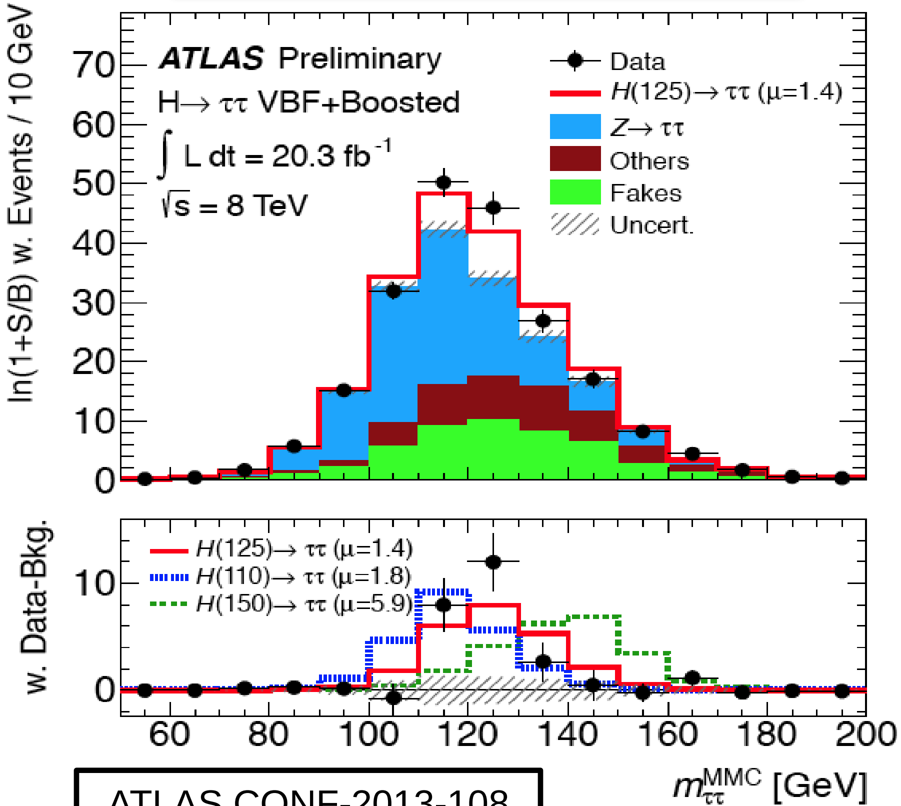
Sign/Exp	Exp	Obs
ATLAS	4.1 σ	7.1 σ
CMS	4.2 σ	5.7 σ

H→Z→4*l* Channel

Sign/Exp	Exp	Obs
ATLAS	4.4 σ	6.6 σ
CMS	6.7 σ	6.8 σ

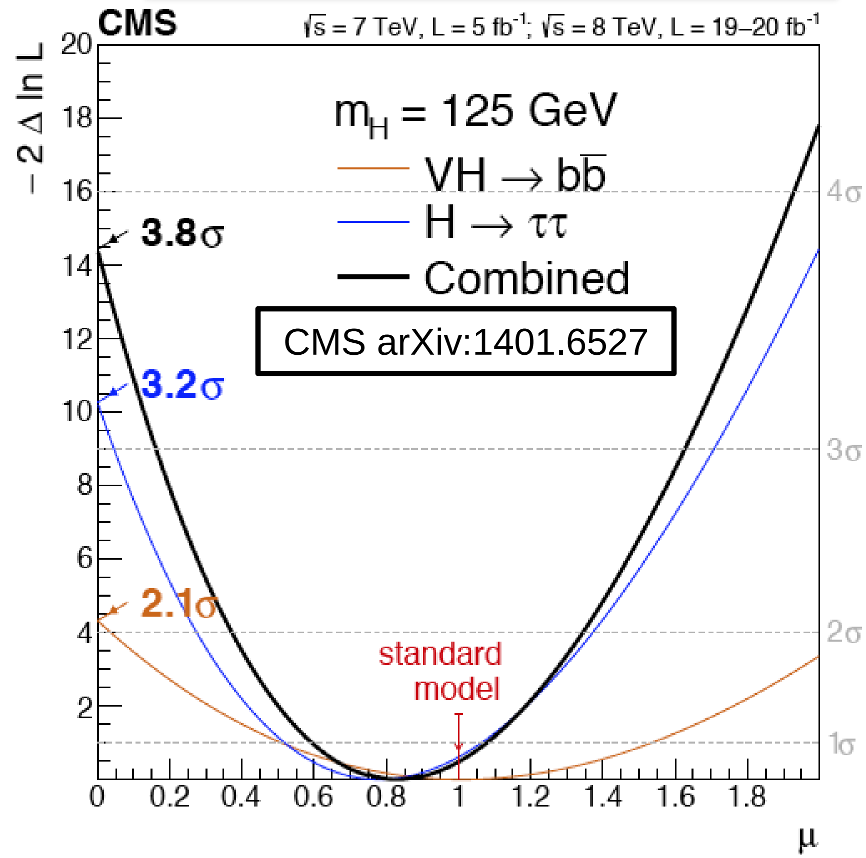
Higgs boson Decays to Fermions

ATLAS: H→ ττ Channel



ATLAS CONF-2013-108

CMS: H→ ττ, bb Channels



Significance	Exp	Obs
ATLAS (ττ)	3.2 σ	4.1 σ

Significance	Exp	Obs
CMS (ττ)	3.4 σ	3.2 σ
CMS (bb)	2.1 σ	2.1 σ

Tevatron: exp (2.1σ), obs (3.0σ)

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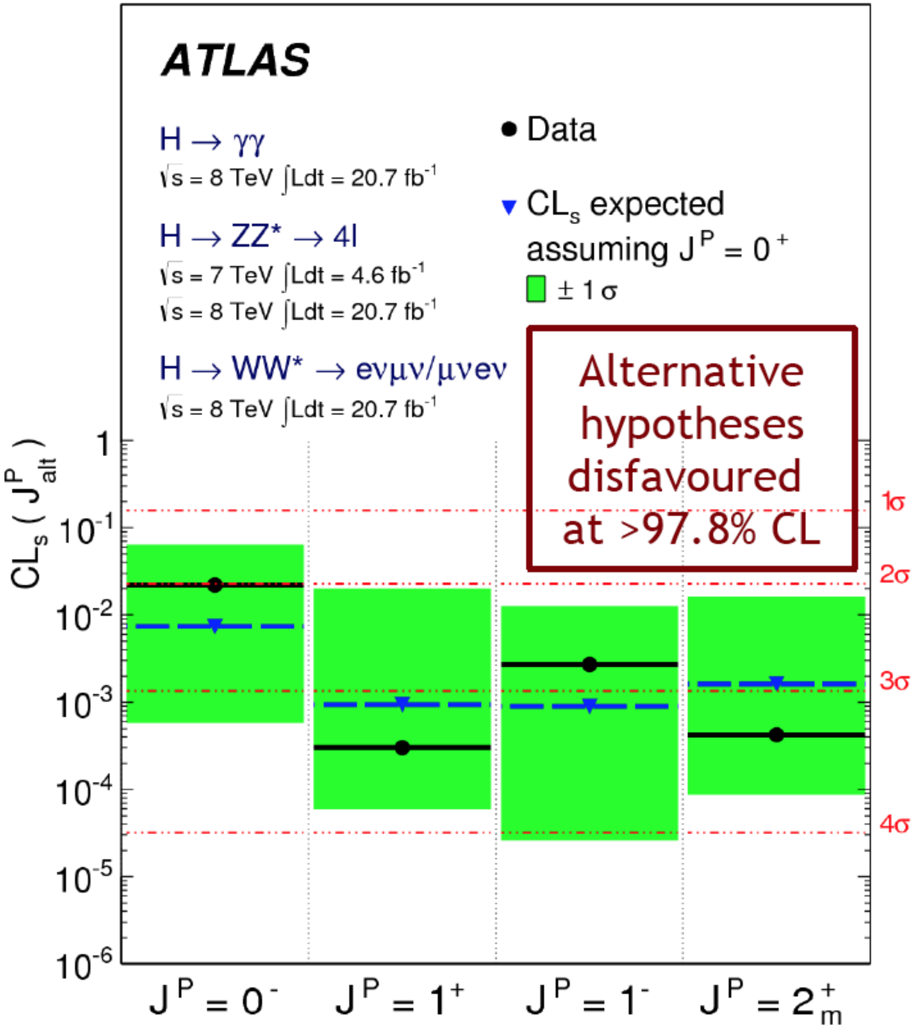
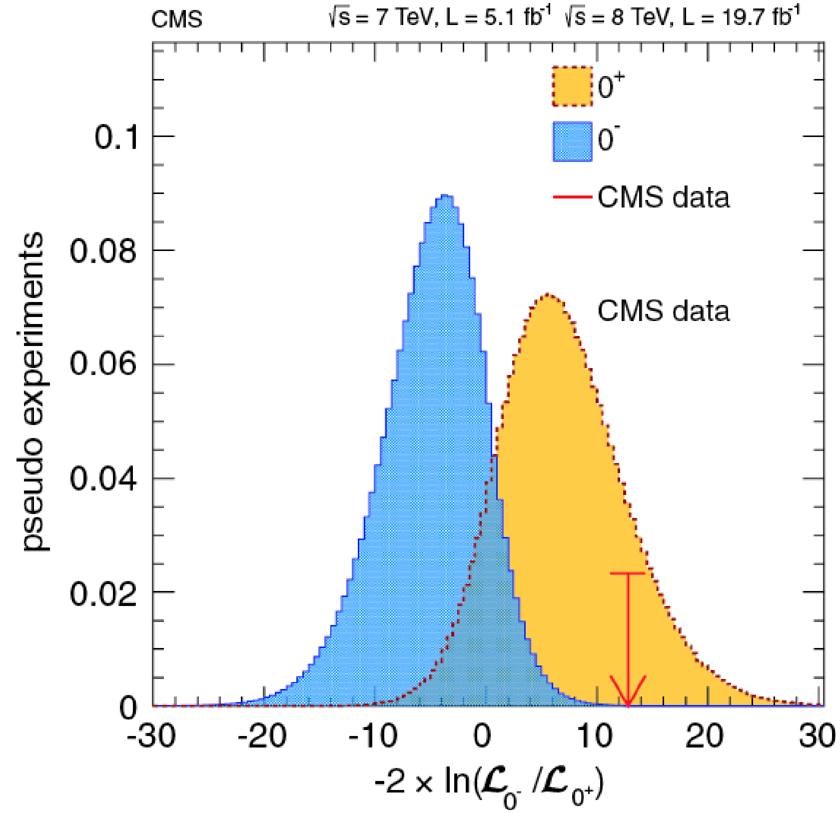
Properties: Spin-Parity – 0^+ Favoured



ATLAS PLB 726(2013)120

CMS: H→Z→4*l* Channel

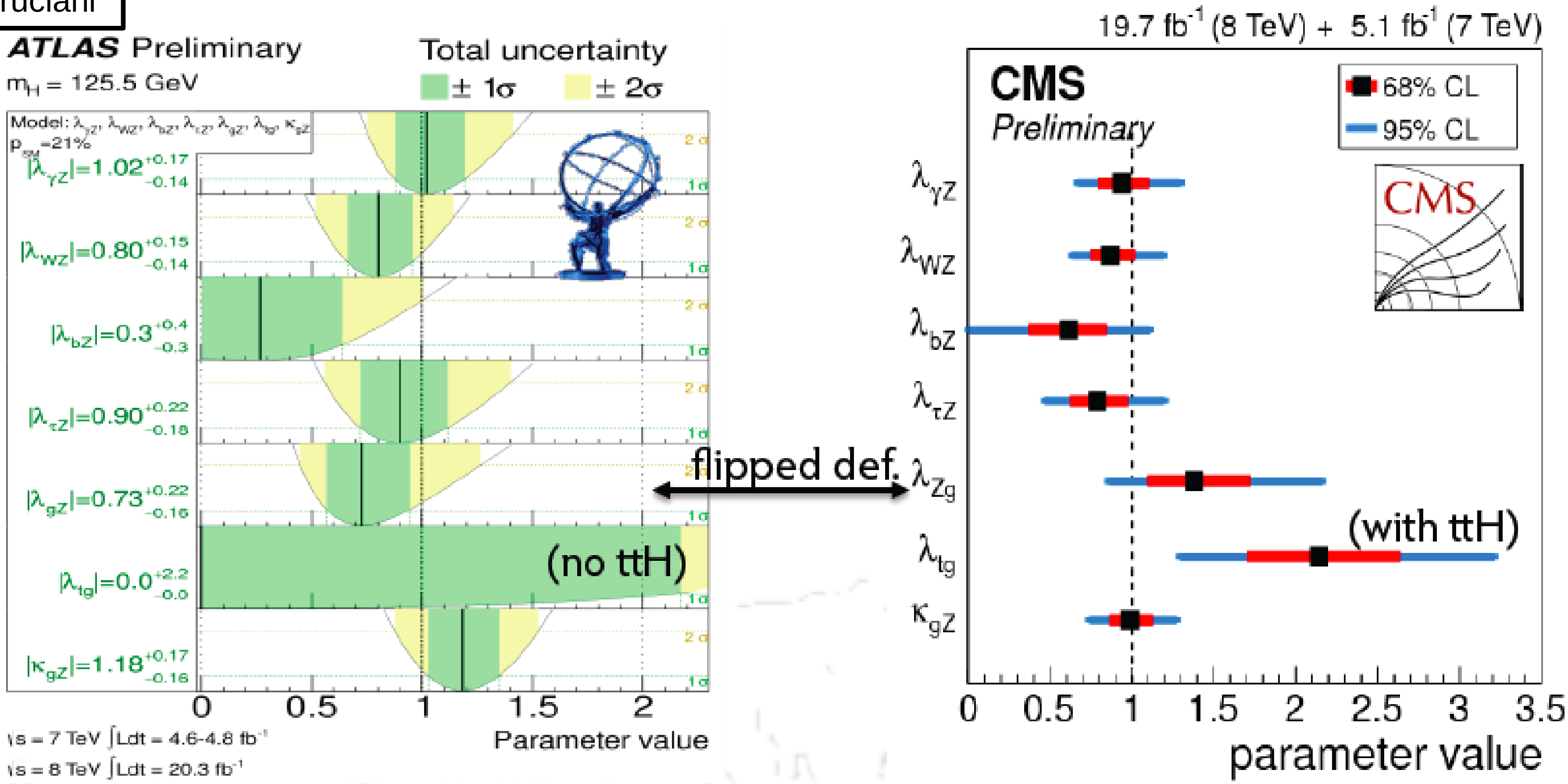


All alternative spin-1 (spin-2) hypotheses tested are excluded at 99% (95) CL or higher

PR D89(2014)092007

Higgs boson: Couplings

G. Pettruciani



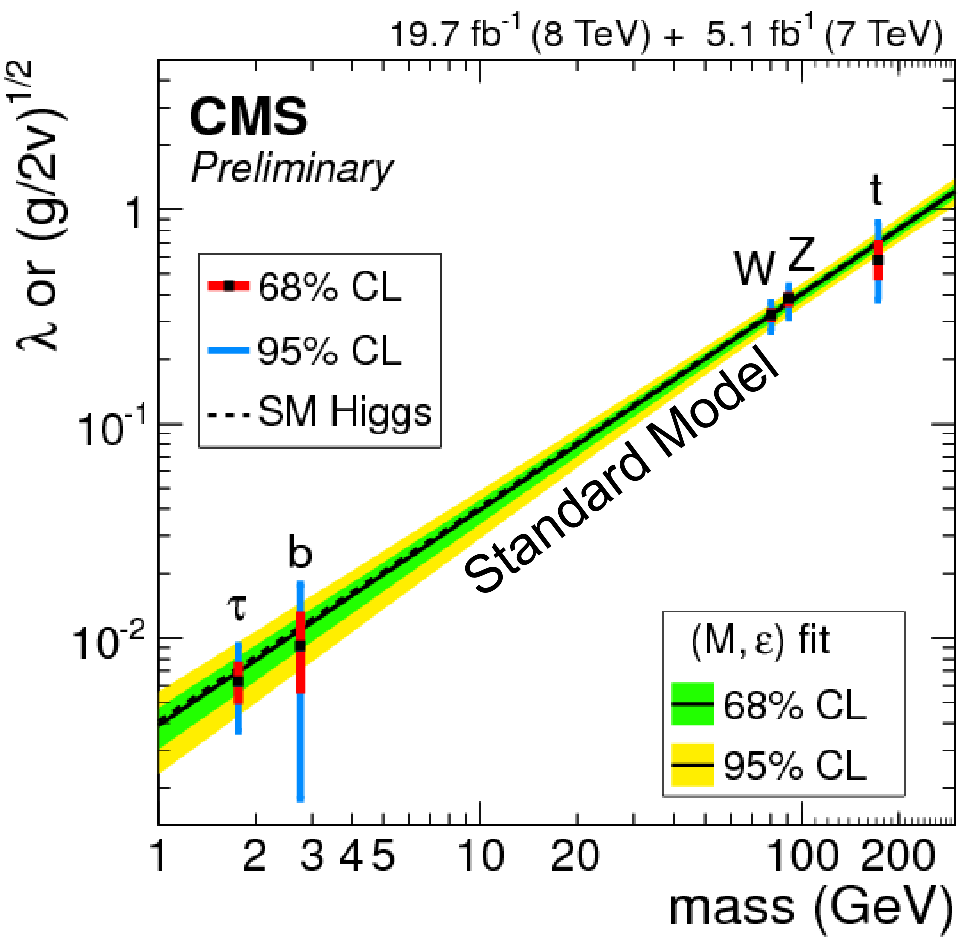
$$m^{(CMS)} = 1.00 \pm 0.09\ (\text{stat}) \pm {}^{0.08}_{0.07} (\text{theo}) \pm 0.07 (\text{syst})$$

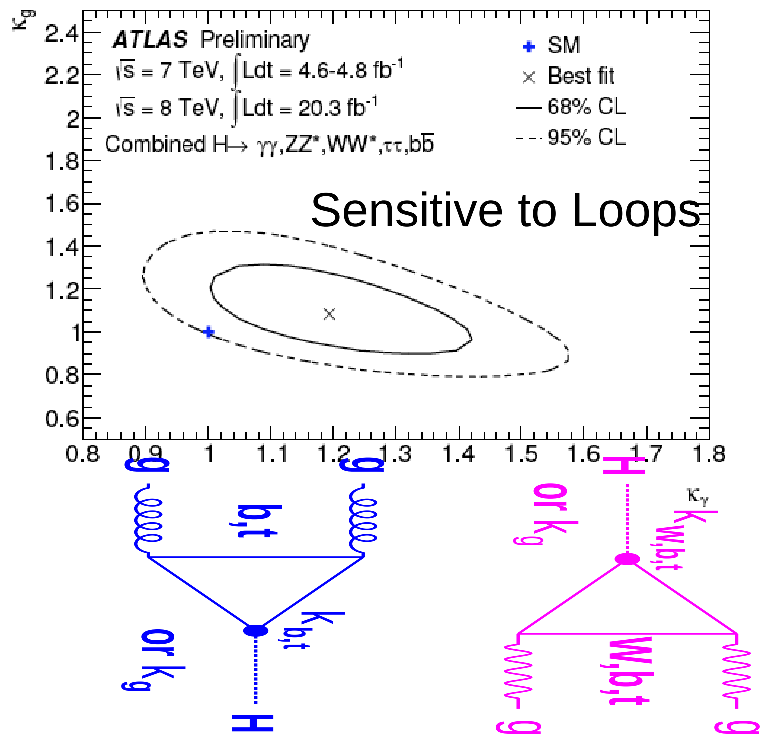
$$m^{(ATLAS)} = 1.30 \pm 0.12\ (\text{stat}) \pm 0.10 (\text{theo}) \pm 0.09 (\text{syst})$$

Mass and Couplings

$$M_H^{(CMS)} = 125.03 \pm^{0.26}_{0.27} \text{ (stat)} \pm^{0.13}_{0.15} \text{ (syst) GeV}$$

$$M_H^{(ATLAS)} = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst) GeV}$$

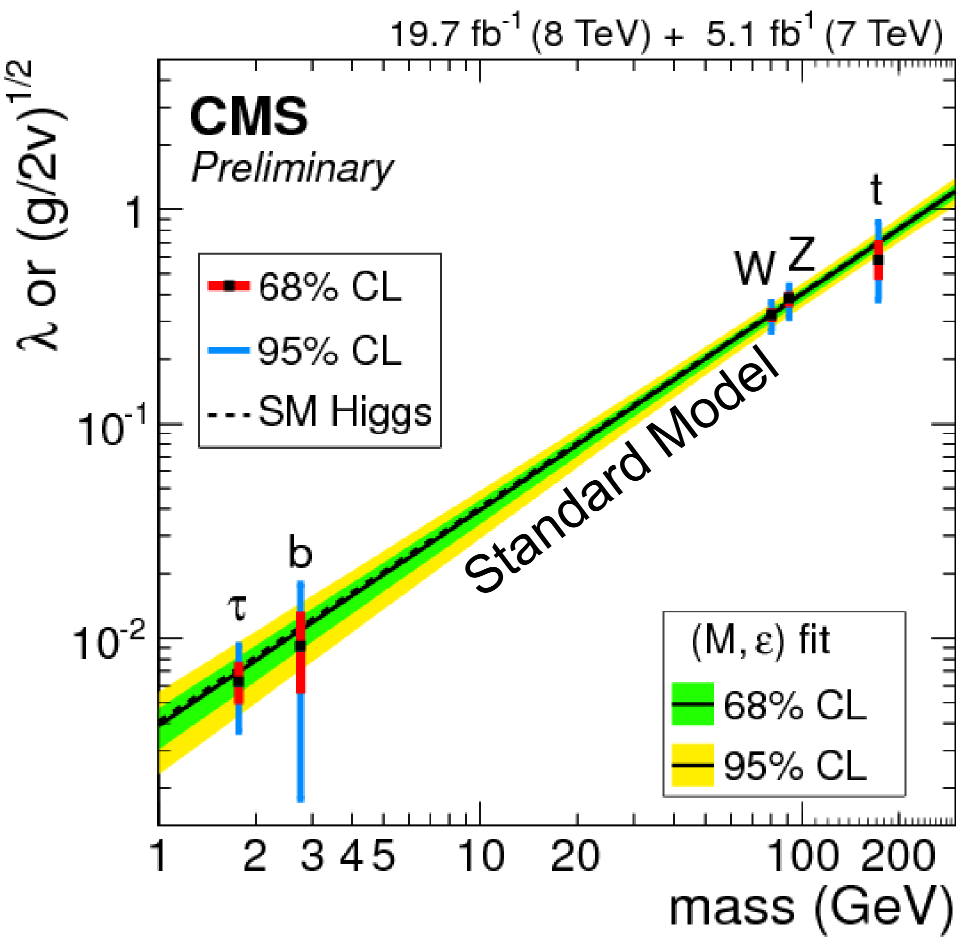




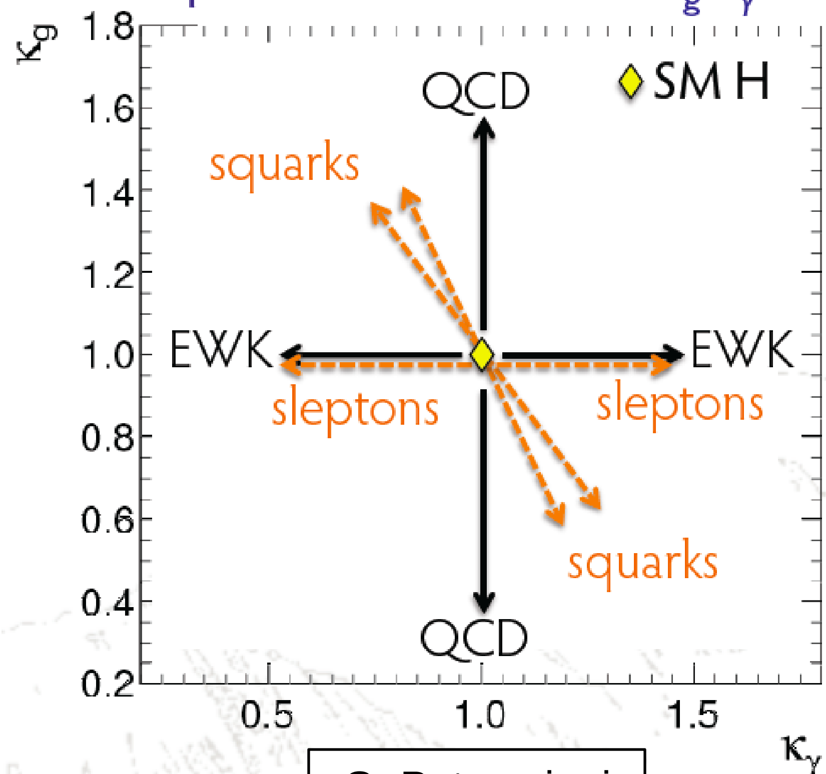
Mass and Couplings

$$M_H^{(CMS)} = 125.03 \pm^{0.26}_{0.27} \text{ (stat)} \pm^{0.13}_{0.15} \text{ (syst) GeV}$$

$$M_H^{(ATLAS)} = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst) GeV}$$



A qualitative sketch of possible deviations in κ_g κ_γ



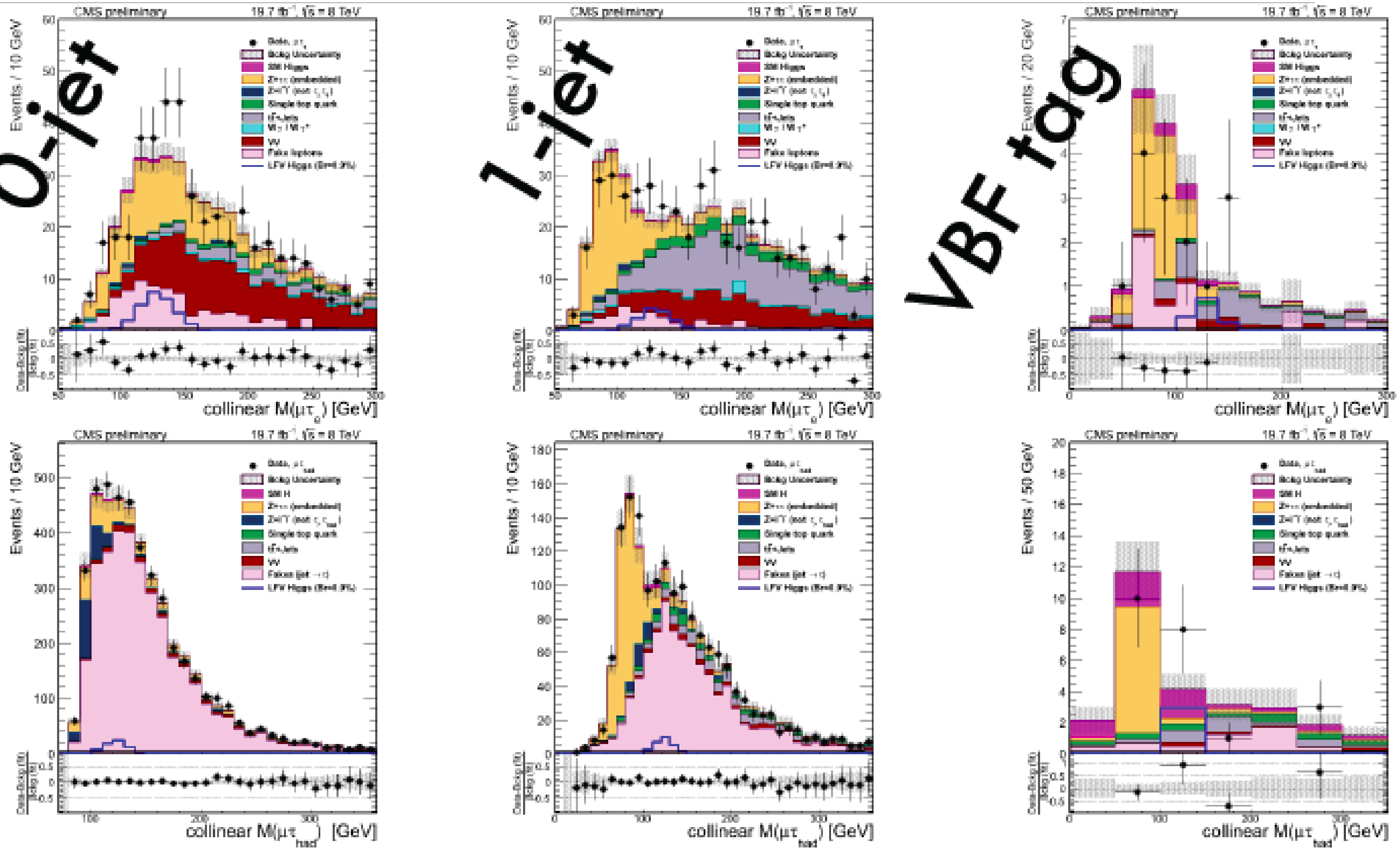
G. Petrucciani

Imperial College London

Exotic Decays of the Higgs boson: $H \to \mu\tau$?

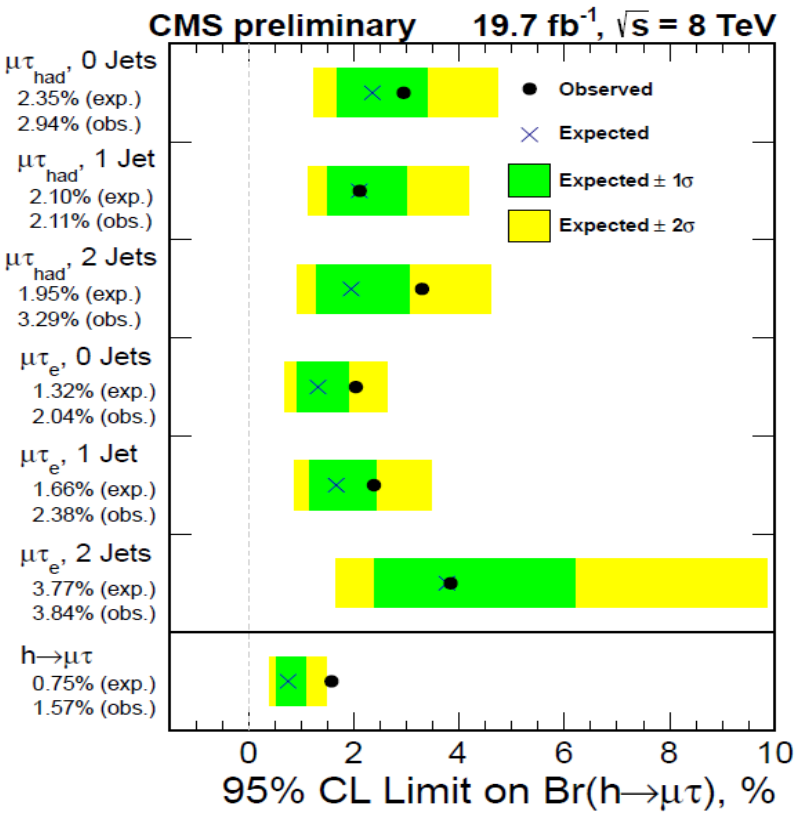
$\mu\tau_e$

$\mu\tau_{had}$



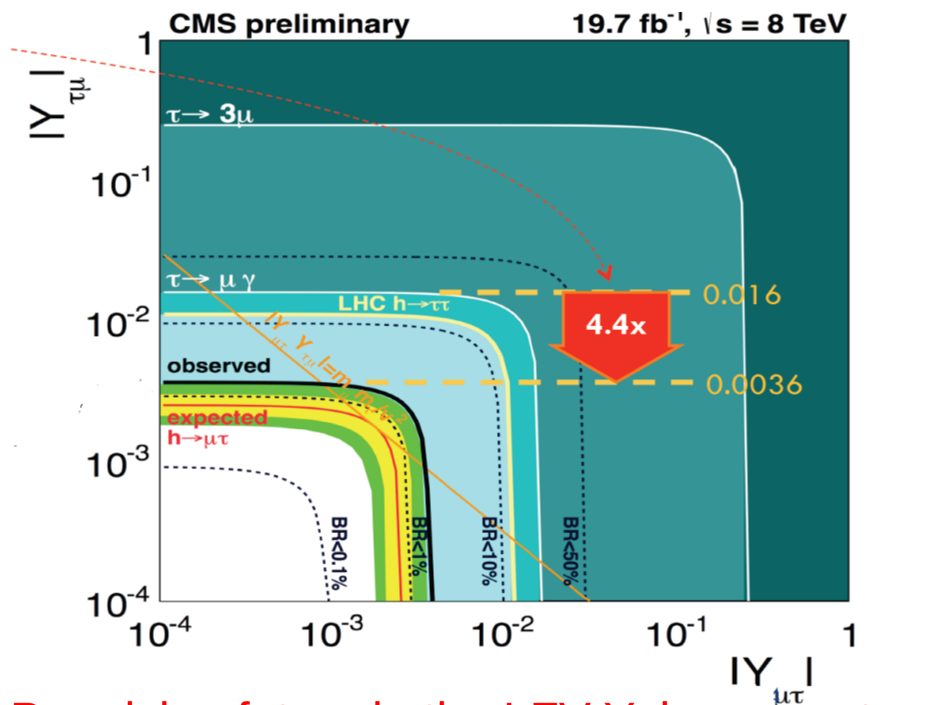
- τ lepton flavor violation not as well constrained as μe (MEG).
- Based on SM $H \to \tau\tau$ analysis. **Different kinematics allows good SM H rejection.**
  - BR($H \to \mu\tau$) < 1.57% at 95%CL (expected limit of 0.75%)

Exotic Decays of the Higgs boson: H→μτ?



M. Titov

Constraint on B(H → μτ) interpreted in terms of LFV Higgs Yukawa couplings



Promising future in the LFV Yukawa sector

BR (H → τμ) < 1.57% @ 95 CL observed

(expected B(H → μτ) < (0.75 ± 0.38)%)

Best fit: B(H → μτ) = (0.89±0.40)%

Significant improvemen (4.4x) wrt. indirect measurements

- Previous best limit from τ→μγ: $\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 0.016$
- Observed limit: $\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 0.0036$

Mild excess in data at the level of 2.5σ

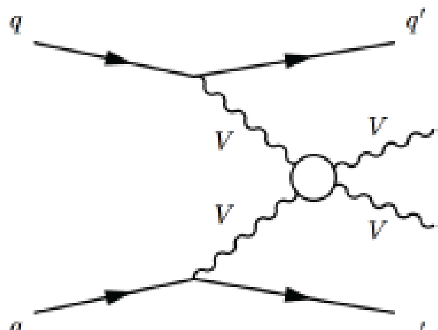
→ still compatible with the SM

Best limits on τ anomalous Yukawa couplings to date

Vector Boson Scattering $W_L W_L \rightarrow W_L W_L$

Several models predict SM-like Higgs but different physics at high energy

- Direct access to EW theory in the unbroken regime ($\sqrt{s} \gg v = 246$ GeV) is a crucial closure test of the SM
  - does H(125) regularize the theory
  - or is there any new dynamics: anomalous quatric couplings or resonances

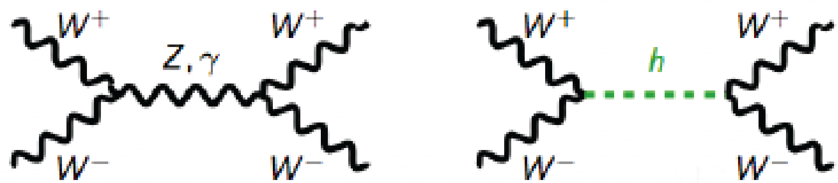


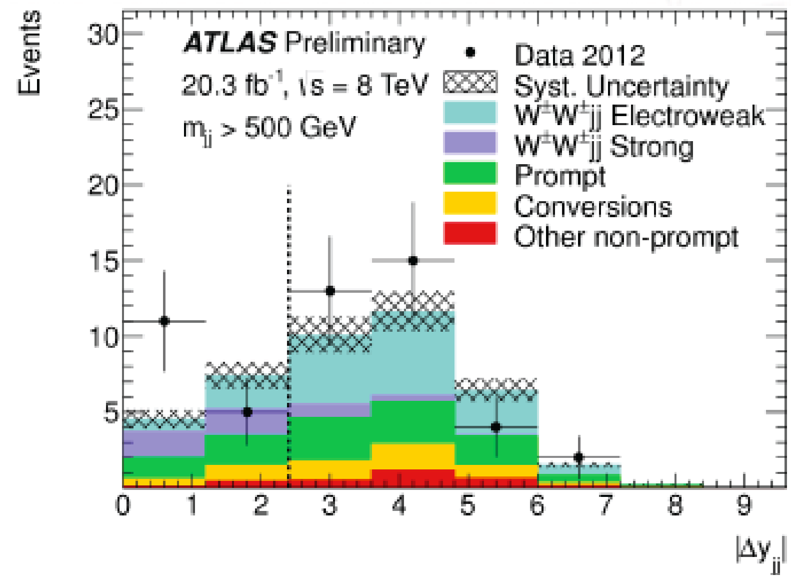
Need $|\eta| \geq 6$ at 100 TeV

10% precision on the SM VBS cross-section (discovery if NP observed at 1 TeV) can be reached with HL-LHC

S. Ganjour

$V_L V_L \rightarrow V_L V_L$ violates unitarity at TeV scale without Higgs exchange diagram





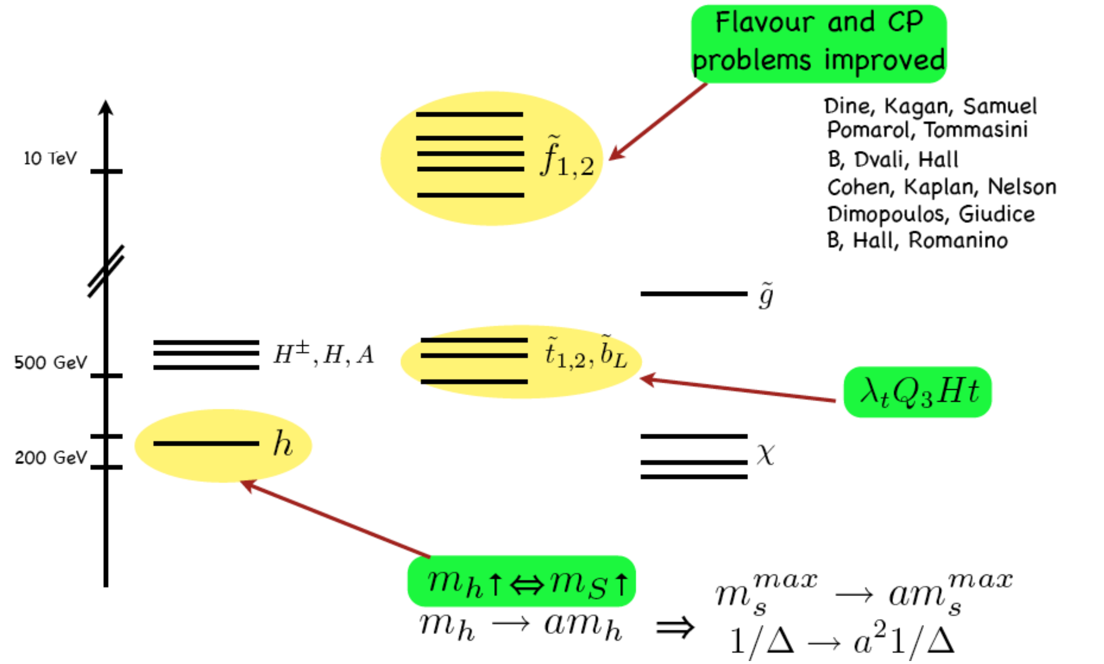
Evidence 3.6 σ for EW VBS having 2 same-sign leptons and 2 high mass forward jets

When LHC started Operating …..

Beyond the MSSM
A motivated spectrum

(discussed in non-suspect times, i.e. before the LHC data)

Barbieri B, Bertuzzo, Farina, Lodone, Pappadopulo



Prior to LHC startup there was much "theoretical" anticipation of new physics. No evidence has yet been found.

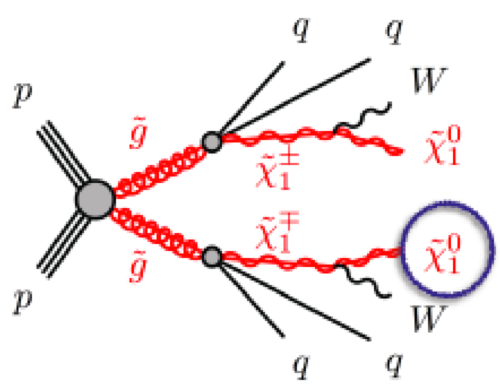
e.g. No sight of SUSY has led to a change of perspective

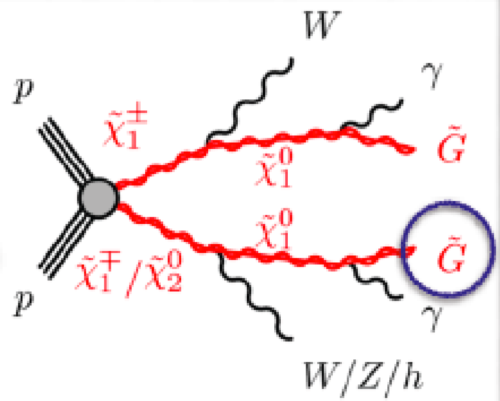
It is quite conceivable that SUSY will make an appearance at 13-14 TeV?

Imperial College London

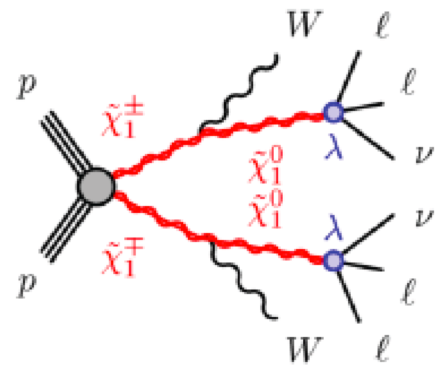
Phenomenology of SUSY

- R-parity conserved (RPC)
  - SUSY particles created in pairs
  - Stable lightest SUSY particle (LSP)
  - Expect large MET from escaping LSPs

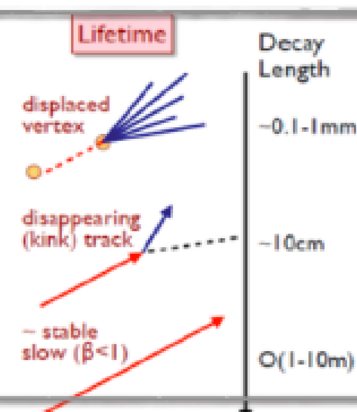




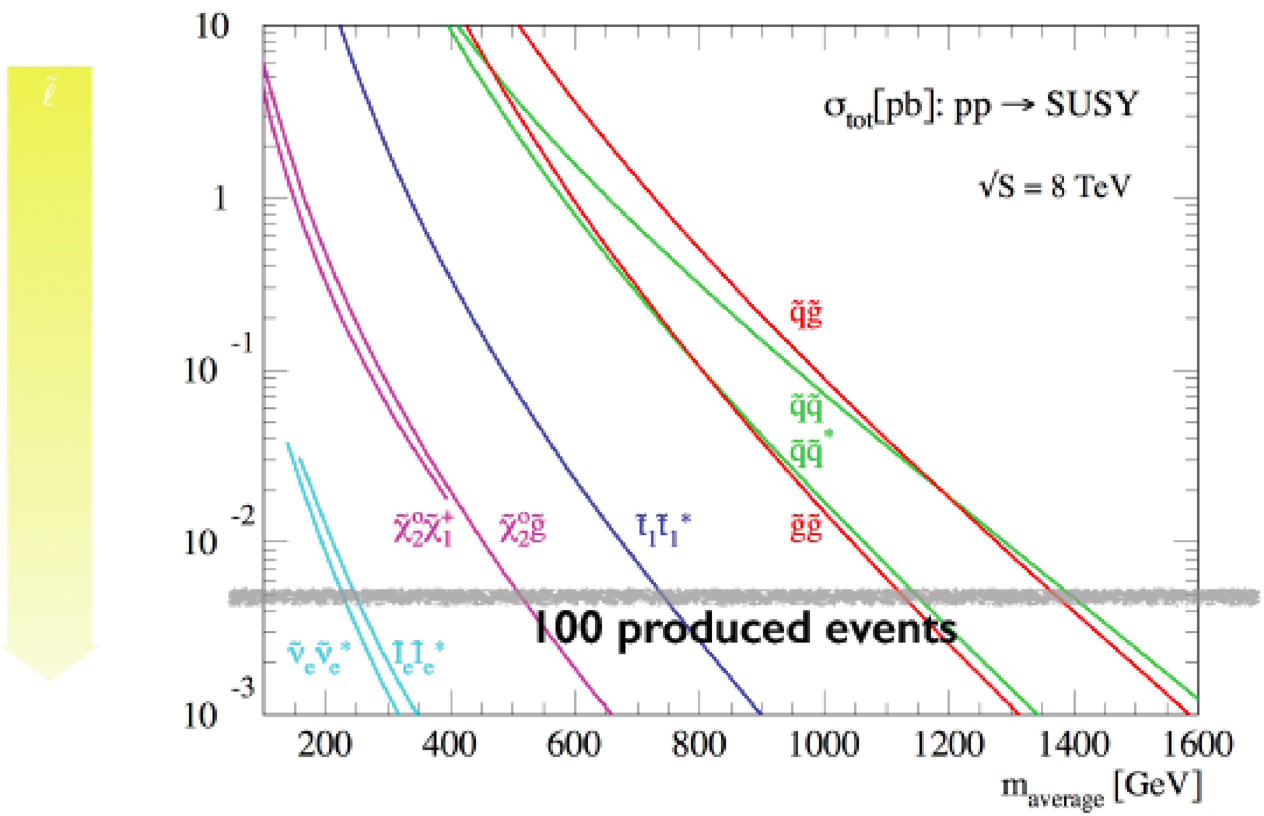
- R-parity violated (RPV)
  - RPC pair-production, but decaying LSP
  - Loss of MET, but large object multiplicity and resonances



- Long Lived (LL) particles (in both RPC and RPV)
  - Meta-stable LSP due to small RPV coupling
  - Compressed spectra
  - Metastable / collider stable sparticles



Seeking SUSY!



A. Canepa

EWK-inos expected sensitivity up to 0.5TeV

Stop expected sensitivity up to 0.7 TeV

Squarks-gluino sensitivity up expected up to 1.2 TeV

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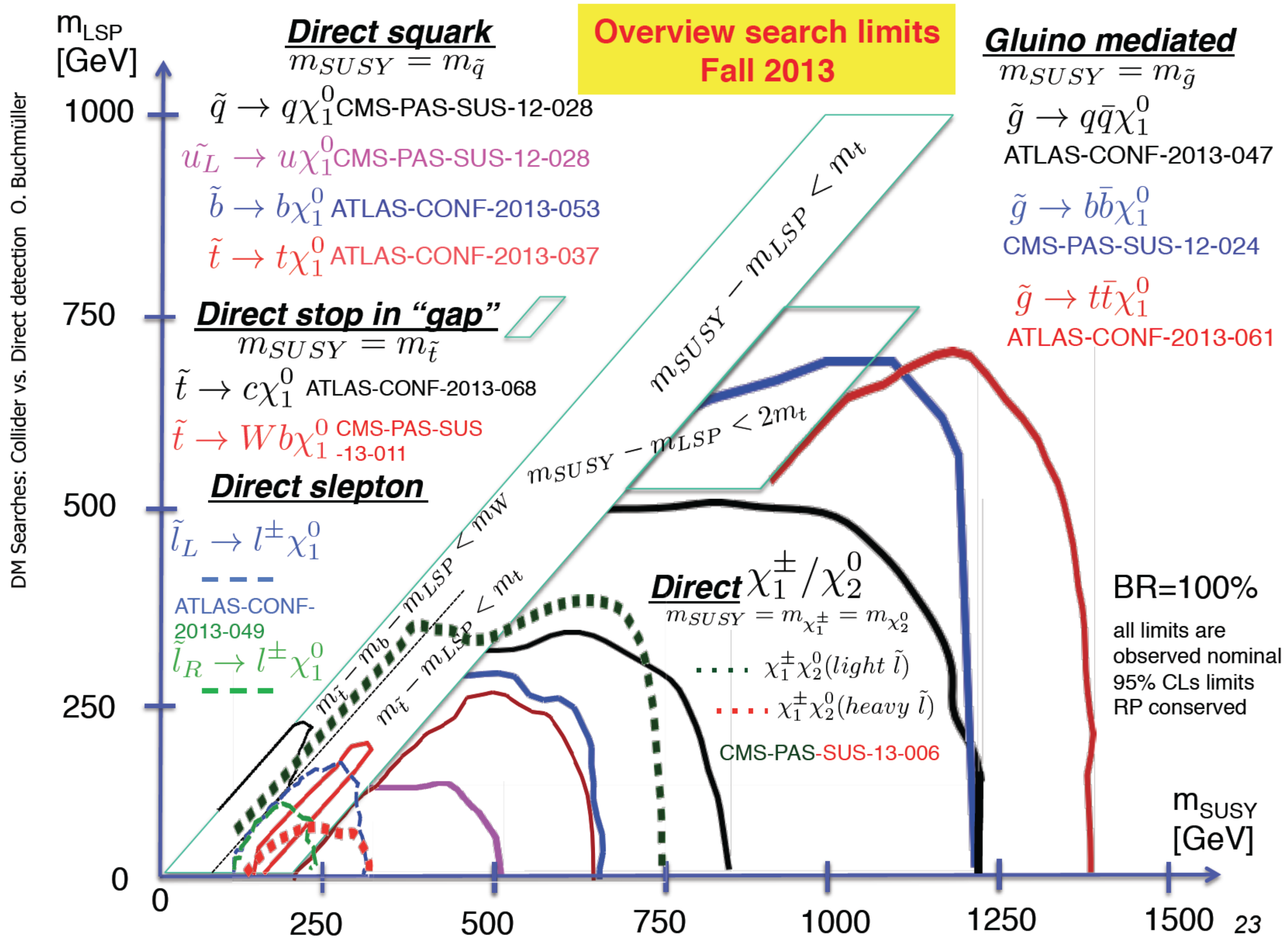
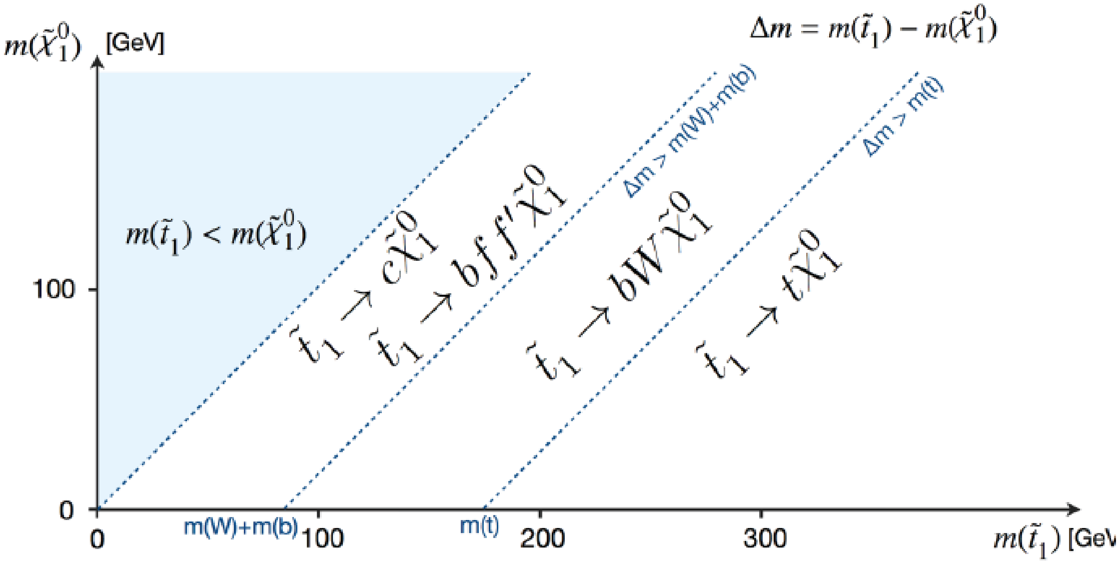
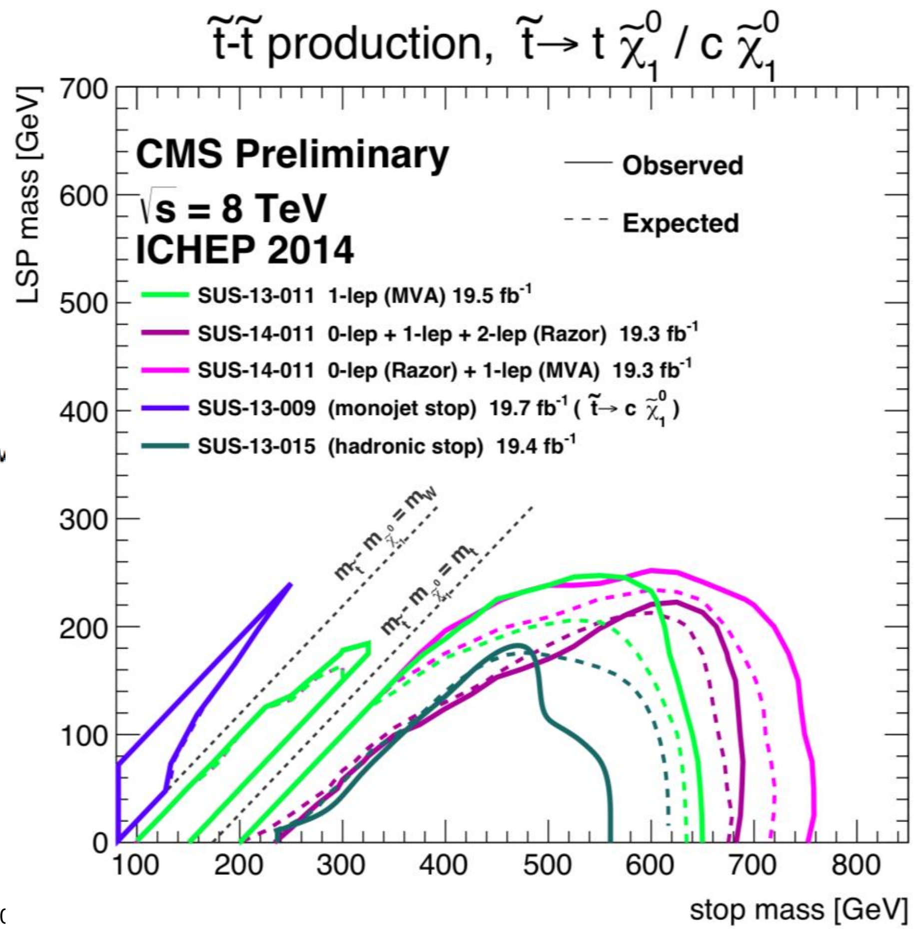
Seeking SUSY



“Stop”- Supposed Key to Naturalness: Exploring Corridors

- cross section is suppressed, 10pb to 1fb from 200 to 900 GeV stops
- sensitivity highly dependent on the decay mode, the mass hierarchy of “sparticles” participating (and to some extent on the stop “handiness”)

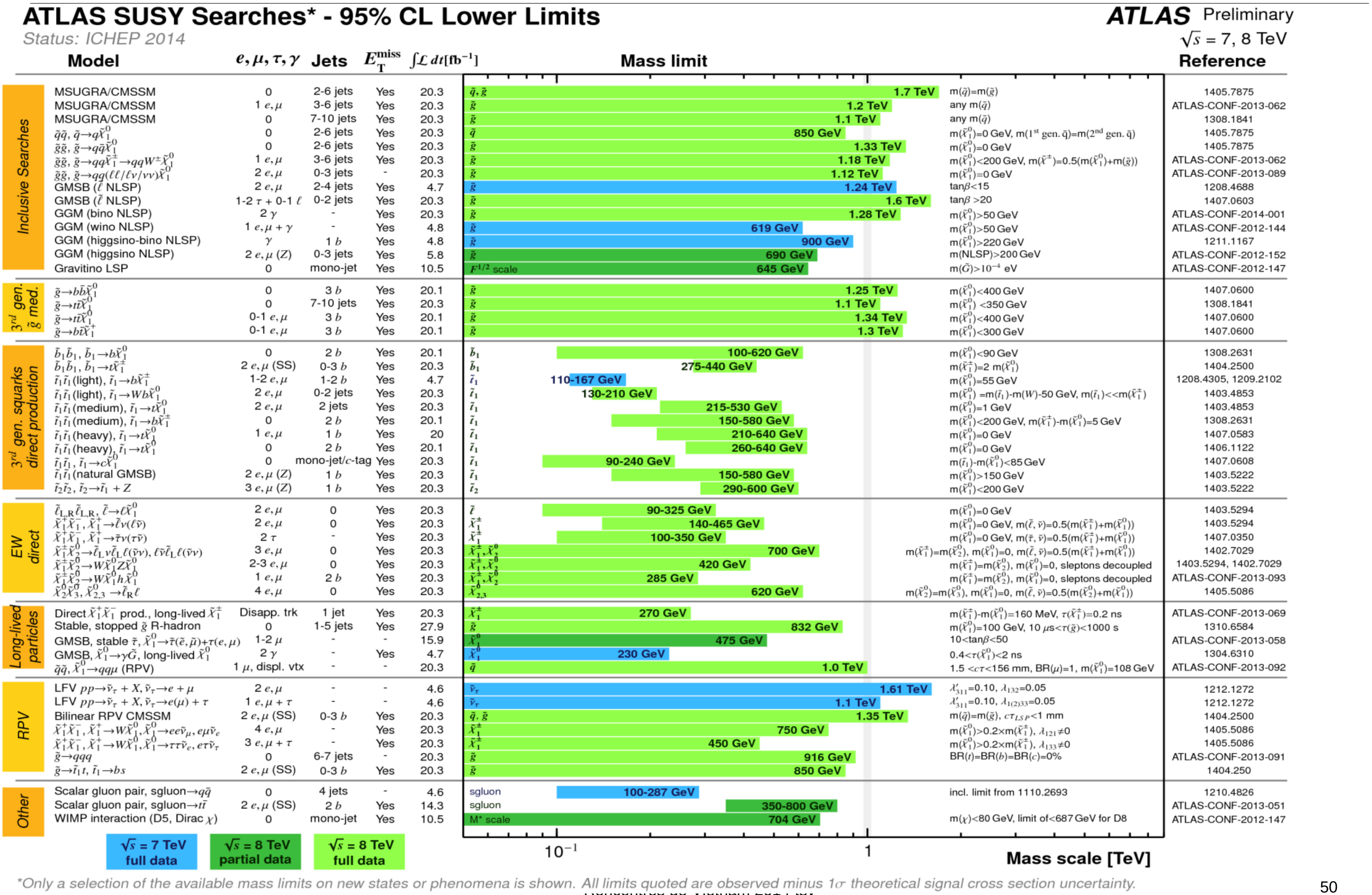


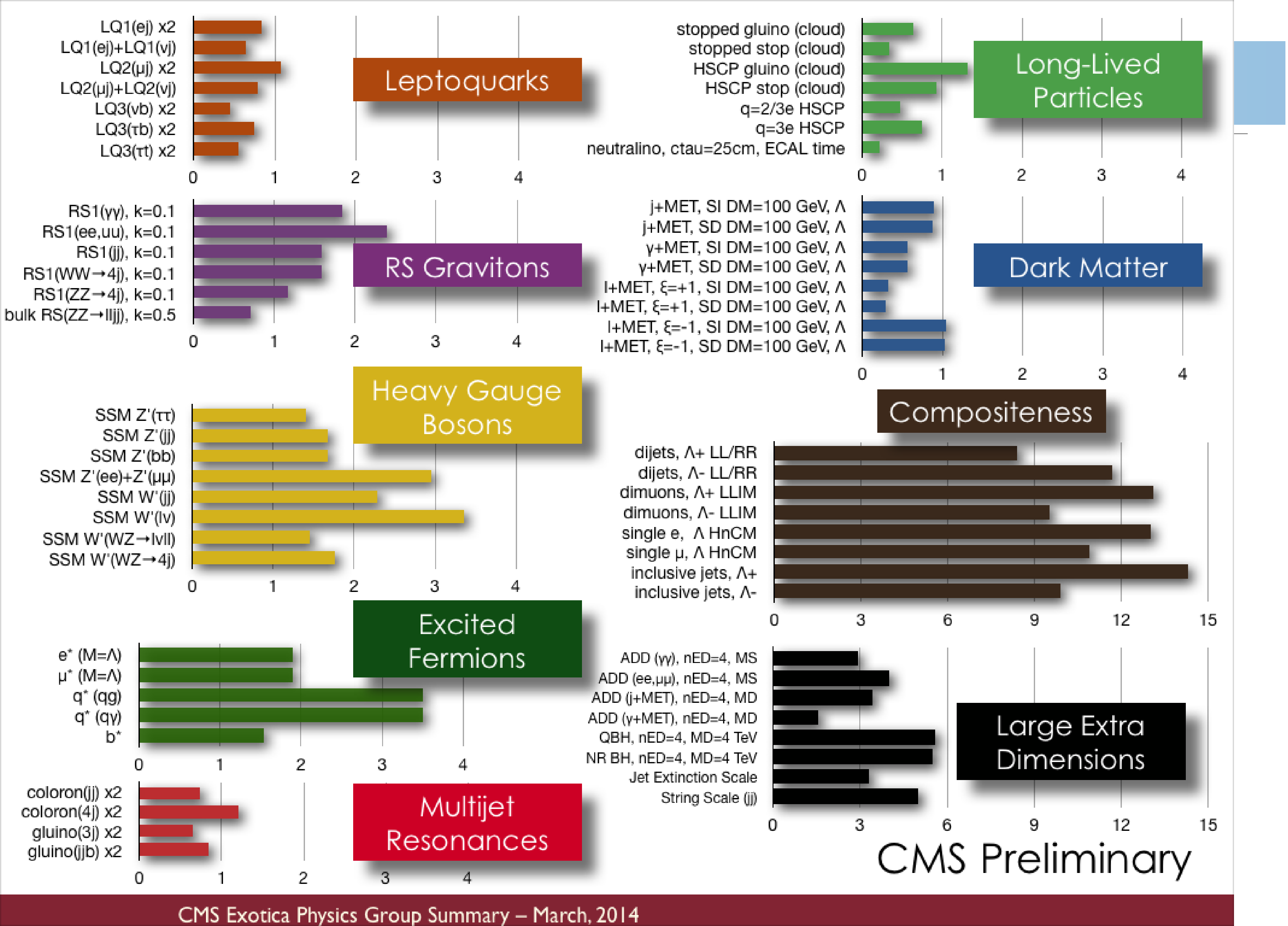


A. Canepa

Imperial College London

Beyond the Standard Model: SUSY





Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
0 1 2 3 4
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
0 1 2 3 4
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5
0 1 2 3 4
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
0 1 2 3 4
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 3 6 9 12 15
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 3 6 9 12 15
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4
CMS Preliminary
CMS Exotica Physics Group Summary – March, 2014

Prospects

“The Beyond”

+ “The Crystal Ball”

Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone:

next question is "Why is (Higgs) mass so low"?

If a new symmetry (Supersymmetry) is the answer, it must show up at O(**1TeV)**

5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Physics Outlook: Using P5 Science Drivers

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

- **Use the Higgs boson as a new tool for discovery**

Answer will be found at **LHC energies**

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

- **Identify the new physics of dark matter**

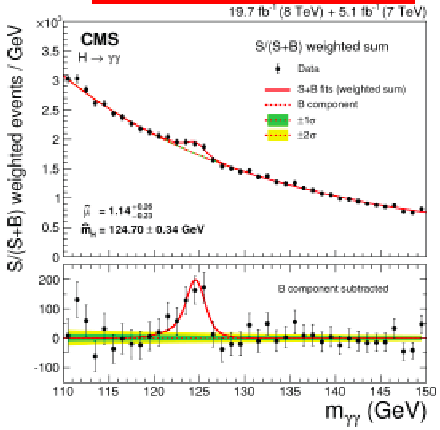
*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV***)*

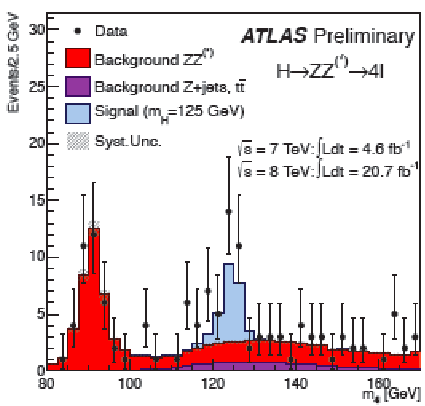
5. Search for new physics at the TeV scale

- **Explore the unknown: new particles, interactions, and physical principles.**

Frontiers of Particle Physics (PP)

$\mathbf{m_H \simeq 125GeV, \hat{\mu} \simeq 1}$

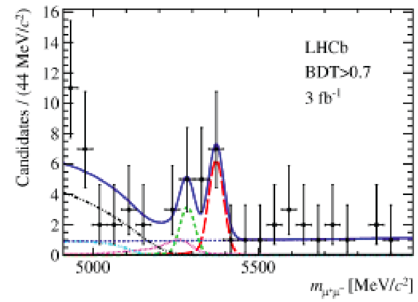




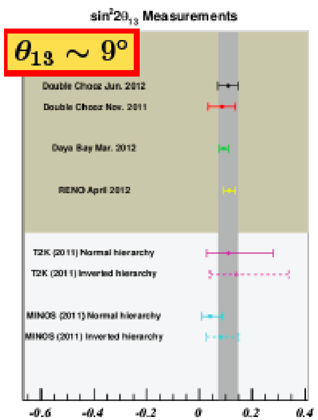
Data strongly favor the scalar 0^+ hypothesis

Precision measurements and reaching higher energy are the Frontiers of PP

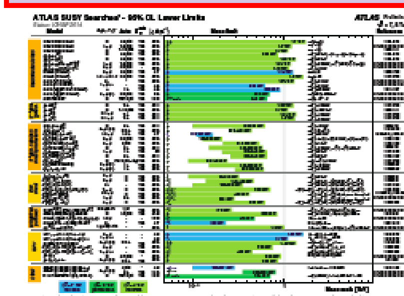
$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

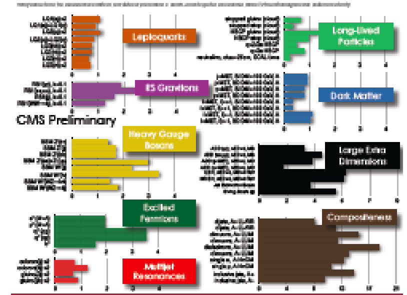


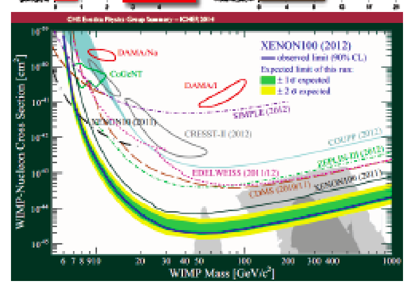
$\theta_{13} \sim 9^\circ$



No evidence of NP in range 200-3000 GeV depending on its type







Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM.

Neutrino masses (oscillations), dark matter, matter-antimatter asymmetry, (Low Higgs boson mass?)

Previously theory “always” showed a nearby new physics scale

Next scale could be anywhere between 1 TeV and very high scale (10^{12}-10^{15} GeV)

The new physics scale can be much lower than the scale Λ that we measure through precision physics

Flavour violation	1 – 10^5 TeV
EDMs	1 – 100 TeV
Neutrino masses	1 – 10^{12} TeV

Precision BEH boson physics is particularly interesting and promising:

This is a new world.

Excellent portal to new physics.

K. Choi

Neutrinos

- Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades.

- Many aspects of neutrino physics are puzzling:
  - What are the origin of neutrino mass?
  - What are the masses?
  - How are the masses ordered (mass hierarchy)?
  - Do neutrinos and antineutrinos oscillate differently? (CP)
  - Are there additional neutrino types or interactions?
  - Are neutrinos their own antiparticles?

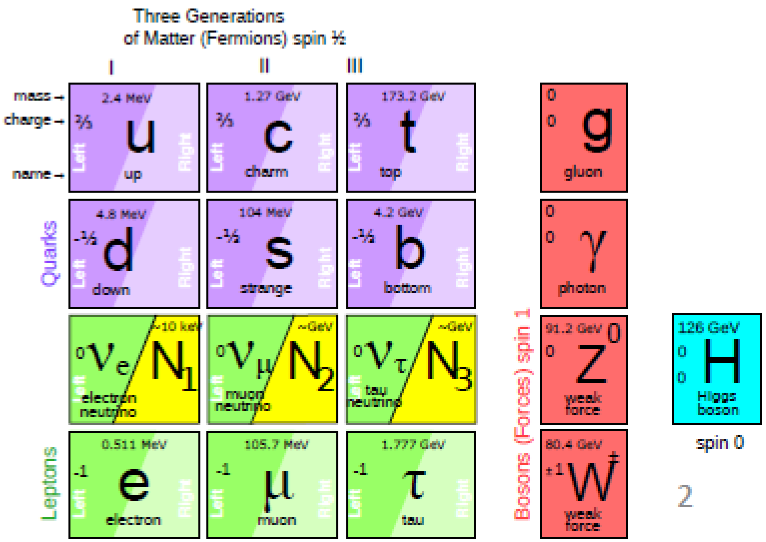
Y.K. Kim ICHEP14

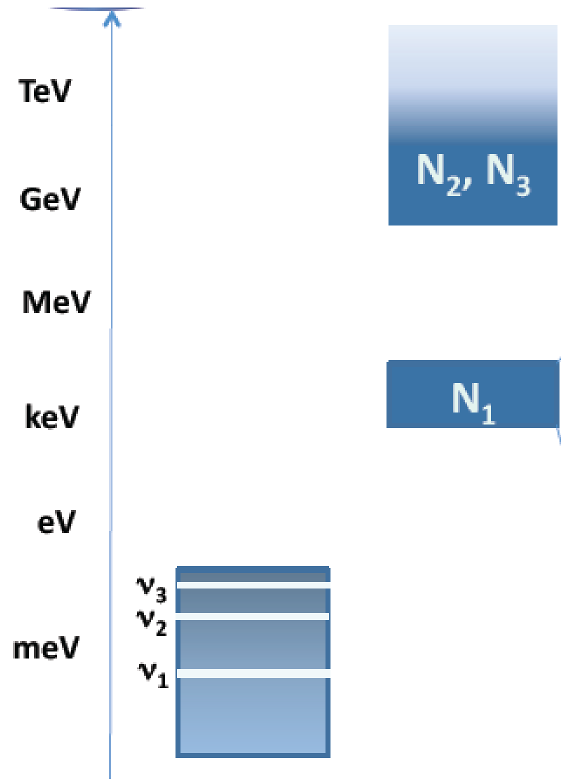
Imperial College London

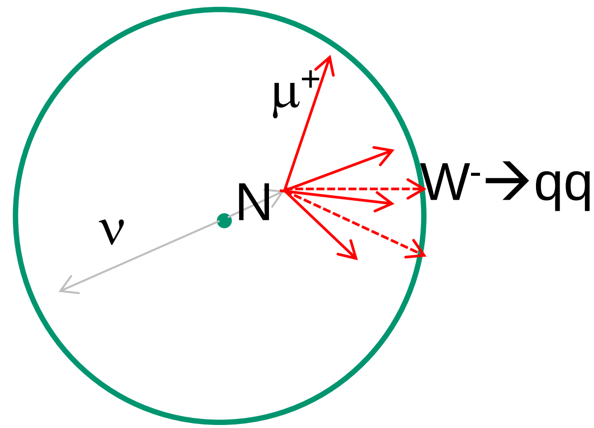
Can neutrinos bring more surprises?

A. Blondel

Completeness of the SM?







Large neutrino mass ~ M

In a large part of the interesting region expect displaced vertices.

l+jets, $l^+ + l^-$, l+τ

Search in ATLAS/CMS ?

$3000 fb^{-1} \to 10^{11}$-5.10^{11} (Z/W)

Decay

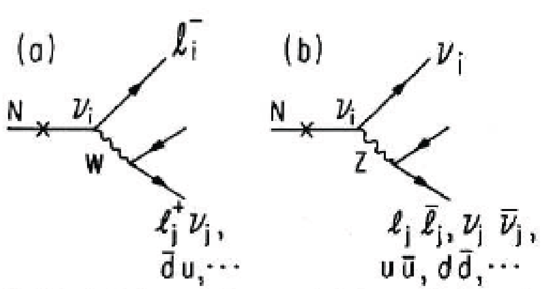


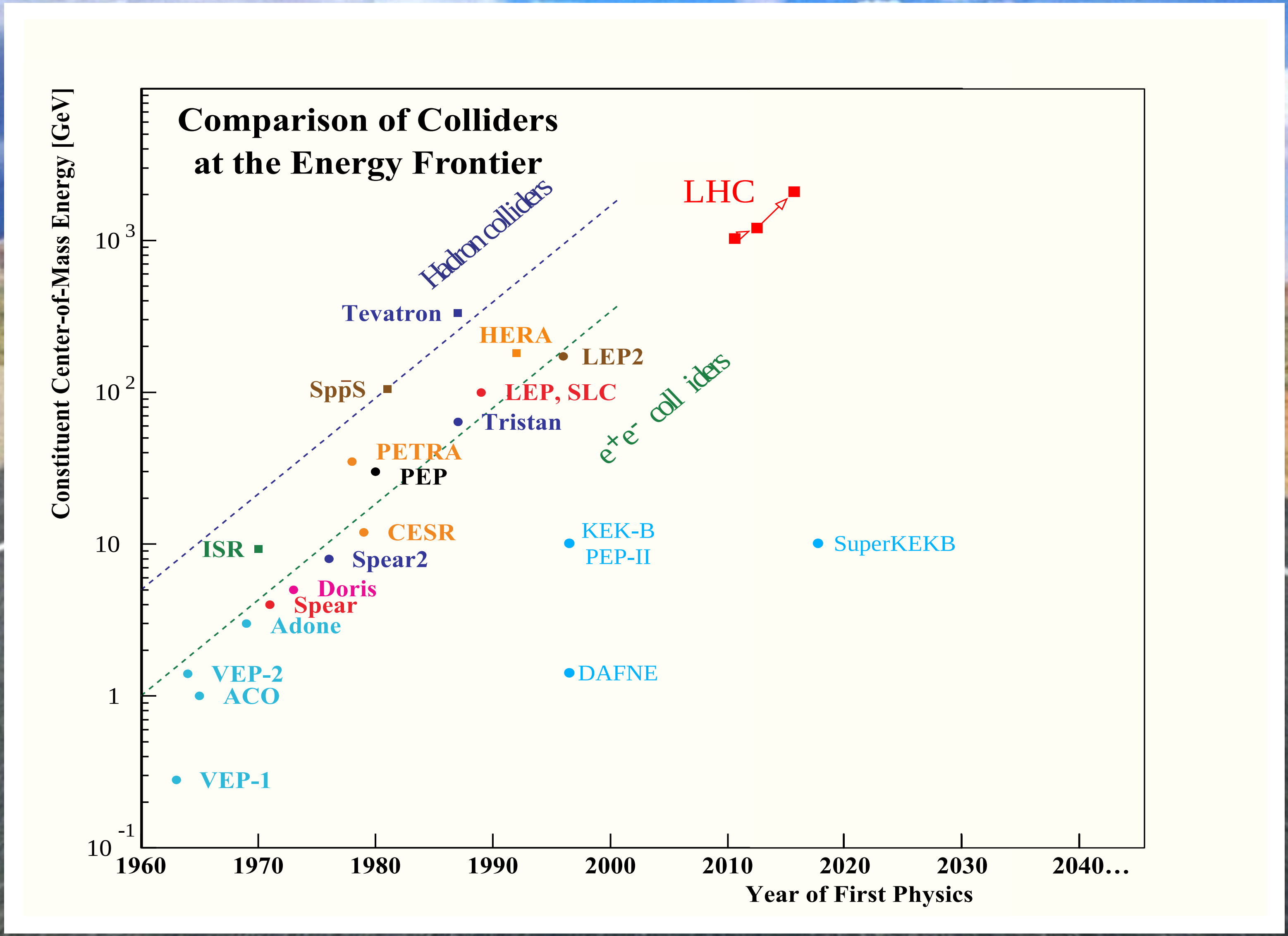
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

$$L \approx \frac{3\ \text{cm}}{|U|^2\ (m_{\nu_m}(\text{GeV}/c^2))^6}$$

NB CC decay always leads to ≥ 2 charged tracks

Past, Present



LHC - 2015

- Target energy: 6.5 TeV
  - to be confirmed at end of powering tests
- Bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit around 50)
- Beta*: 80 to 40 cm

Energy

- Lower quench margins
- Lower tolerance to beam loss
- Lower intensity set-up beams
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

- E-cloud, UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

M. Lamont

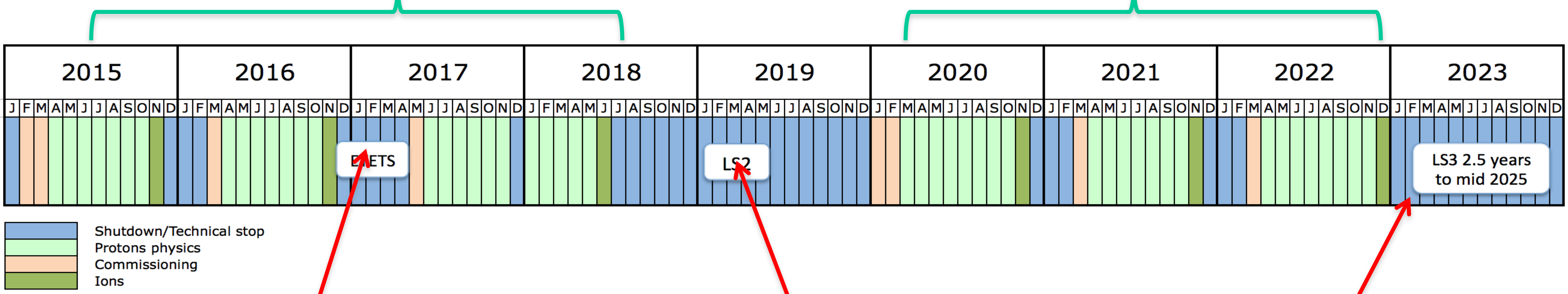
Imperial College London

LHC: 10 year plan

- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7×10^{34} $cm^{-2}\ s^{-1}$

Run 3: 14 TeV c.m. with peak luminosity of ~2×10^{34} $cm^{-2}\ s^{-1}$



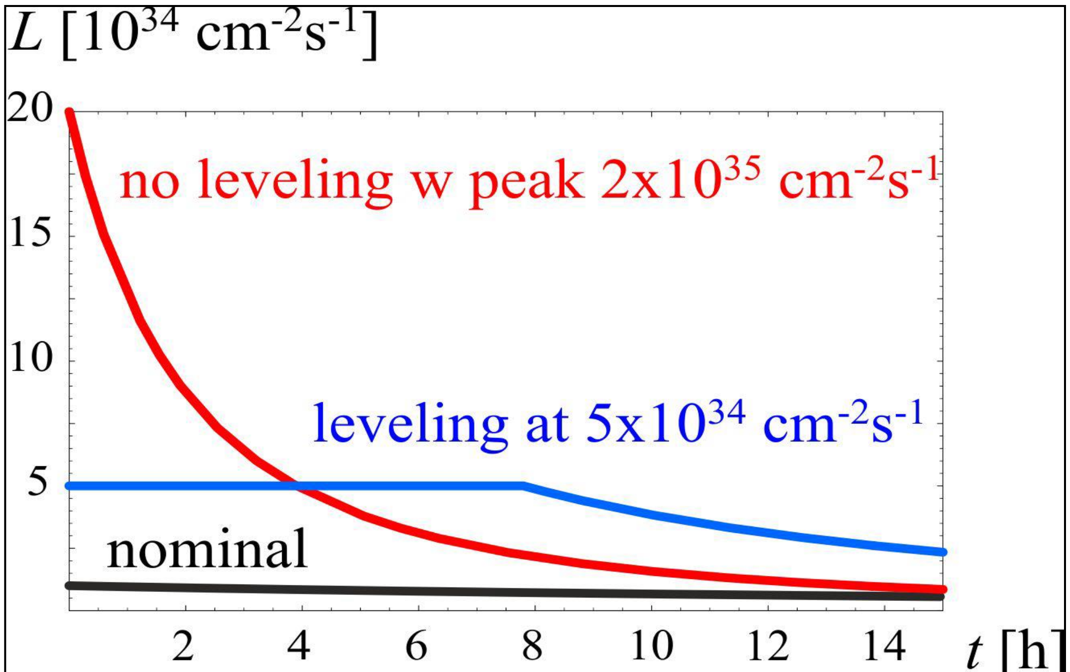
EYETS ~5 months
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

HL-LHC

- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen



M. Lamont and O. Bruning

5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity
Pile-up ~140
3 fb^{-1} per day
~250 fb^{-1} /year

Imperial College London

LHC roadmap to achieve full potential

Last update December 2013

2009 — LHC startup, $\sqrt{s}$ 900 GeV

2010–2012 — $\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns — Run 1, ~25 fb^{-1}

2013–2014 — LS1 — Go to design energy, nominal luminosity - Phase 0

2015–2018 — $\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns — Run 2, ~75-100 fb^{-1}

2018–2019 — LS2 — Injector + LHC Phase I upgrade to ultimate design luminosity

2020–2022 — $\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns — Run 3, ~350 fb^{-1}

2023–2025 — LS3 — HL-LHC Phase II upgrade: Interaction Region, crab cavities?

2025 … 2035? — $\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling — ~3000 fb^{-1}

14 TeV vs 8 TeV – Gain Factors

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: Factor ~2

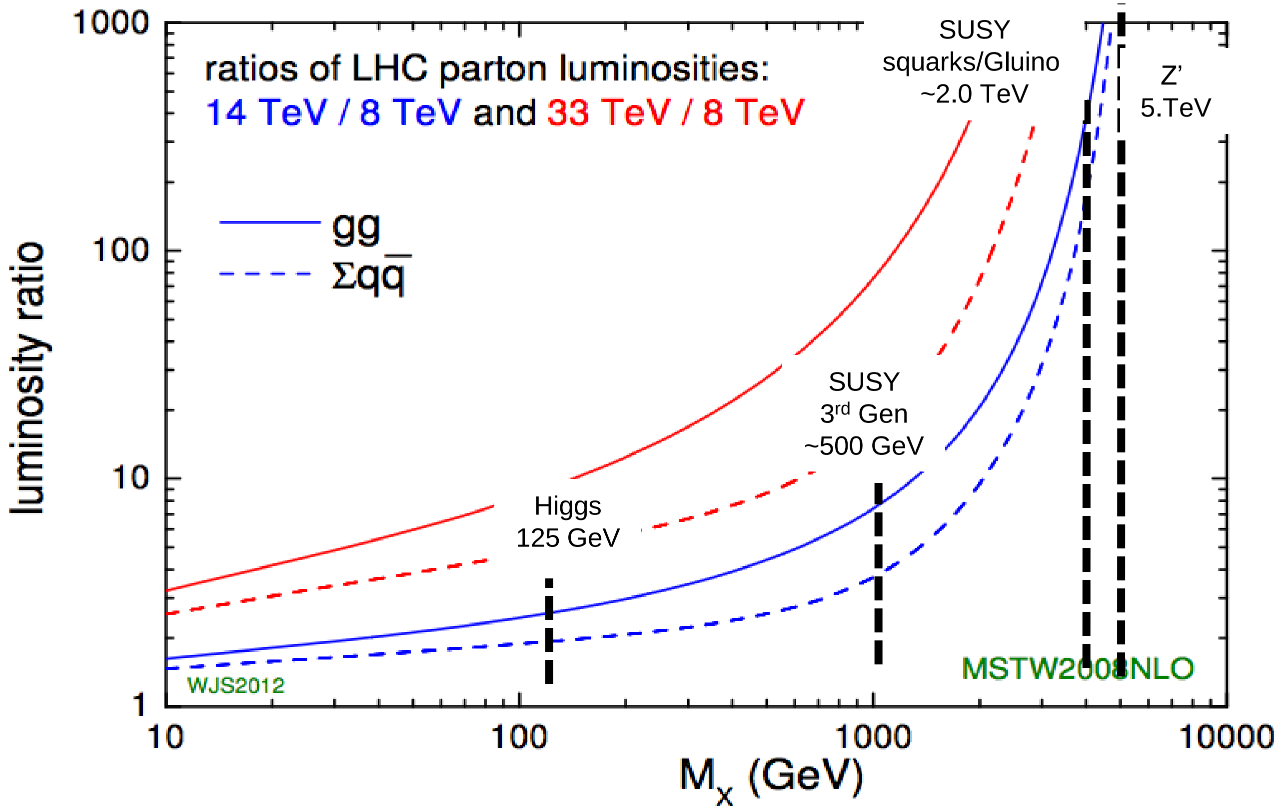
SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: Factor ~ 8

SUSY – Squarks/Gluino:
Mass scale ~ 2.0 TeV
qq,gg,qg: Factor ~300

Z′ :
Mass scale ~ 5 TeV
qq: Factor ~1000

O. Buchmuller

J. Stirling



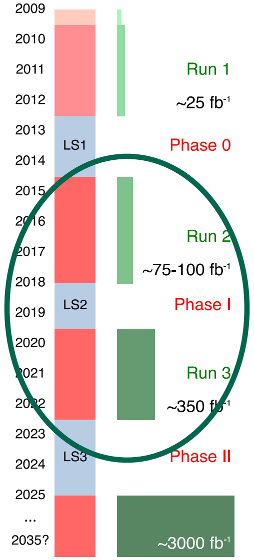
For the searches increase in energy will help a lot!

Looking Ahead to Phase 1

Runs II and III

- **Conduct detailed studies of the properties of the found Higgs boson.** Run II will produce > 5M Higgs bosons
- Search for exotic decays of Higgs boson?

300 fb^{-1}



Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ
ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]
CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]

- **Couplings Precision ~ 5-15%**

Effect of New Physics on couplings:

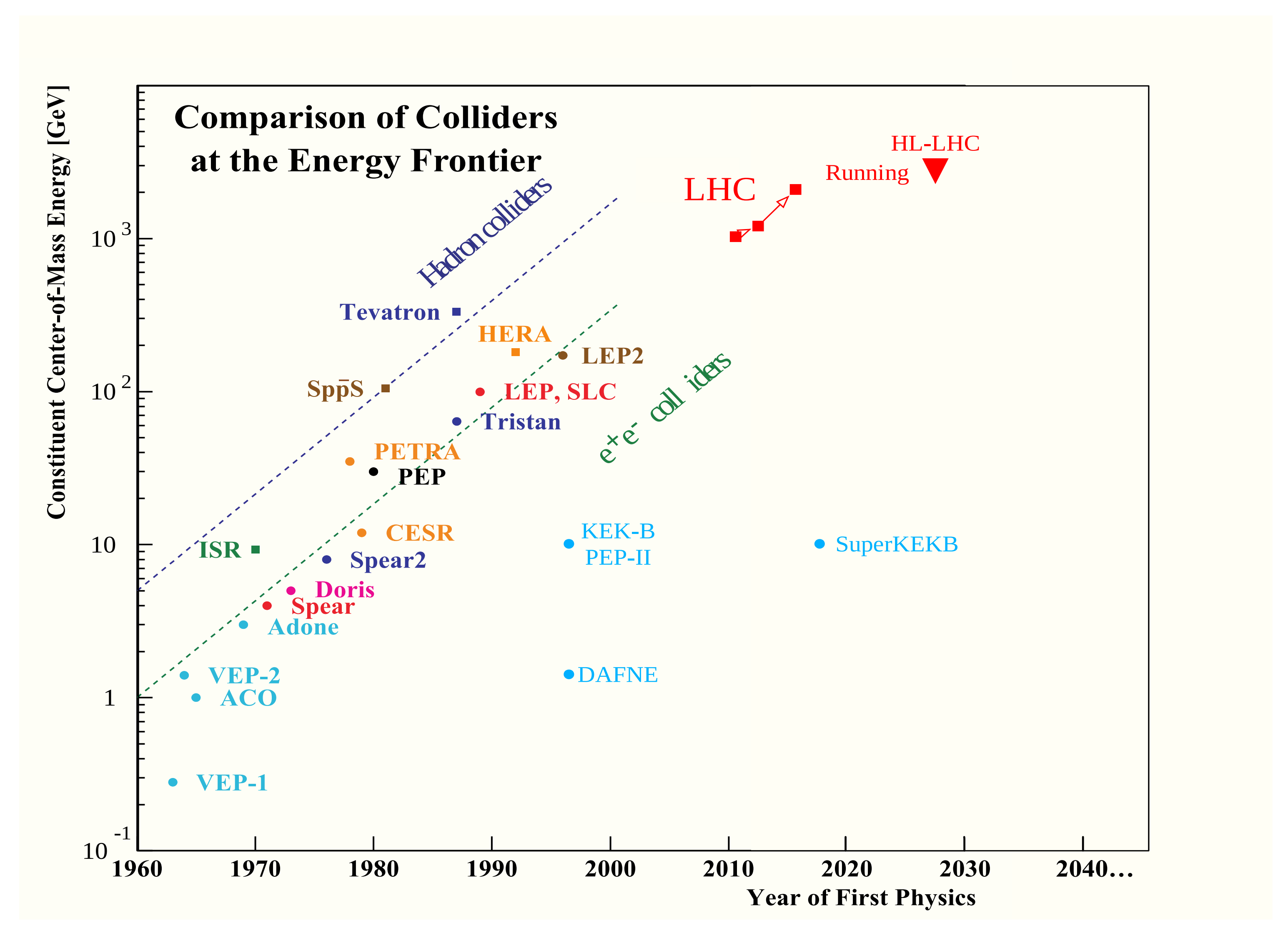
$$\Delta g_{HXX}/g_{HXX} \leq 5\% \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2$$

- **Search for new physics: resonances, supersymmetry, exotica, yet unknown.**

It is conceivable that we find new heavy particle(s) in Phase 1.

- **Look for deviations from the standard model – precision SM measurements**

Past, Present, Future



HL-LHC aka SLHC

EP-TH Faculty Meeting

Challenges for pp GPDs

- LHC design luminosity,
- L ~ 10^{35} cm^{-2}s^{-1},
- Higher c.o.m energy

Implications for Detector R&D

- LHC design energy and luminosity - Upgrades (~ 2009)
- L ~ 10^{35} cm^{-2}s^{-1} - Major Upgrades (~ 2012)
- Higher energy – next generation of detectors (20??)

Conclusions

Looking Further Ahead to Phase 2 (HL-LHC)

Topmost Priority – exploitation of the full potential of the LHC

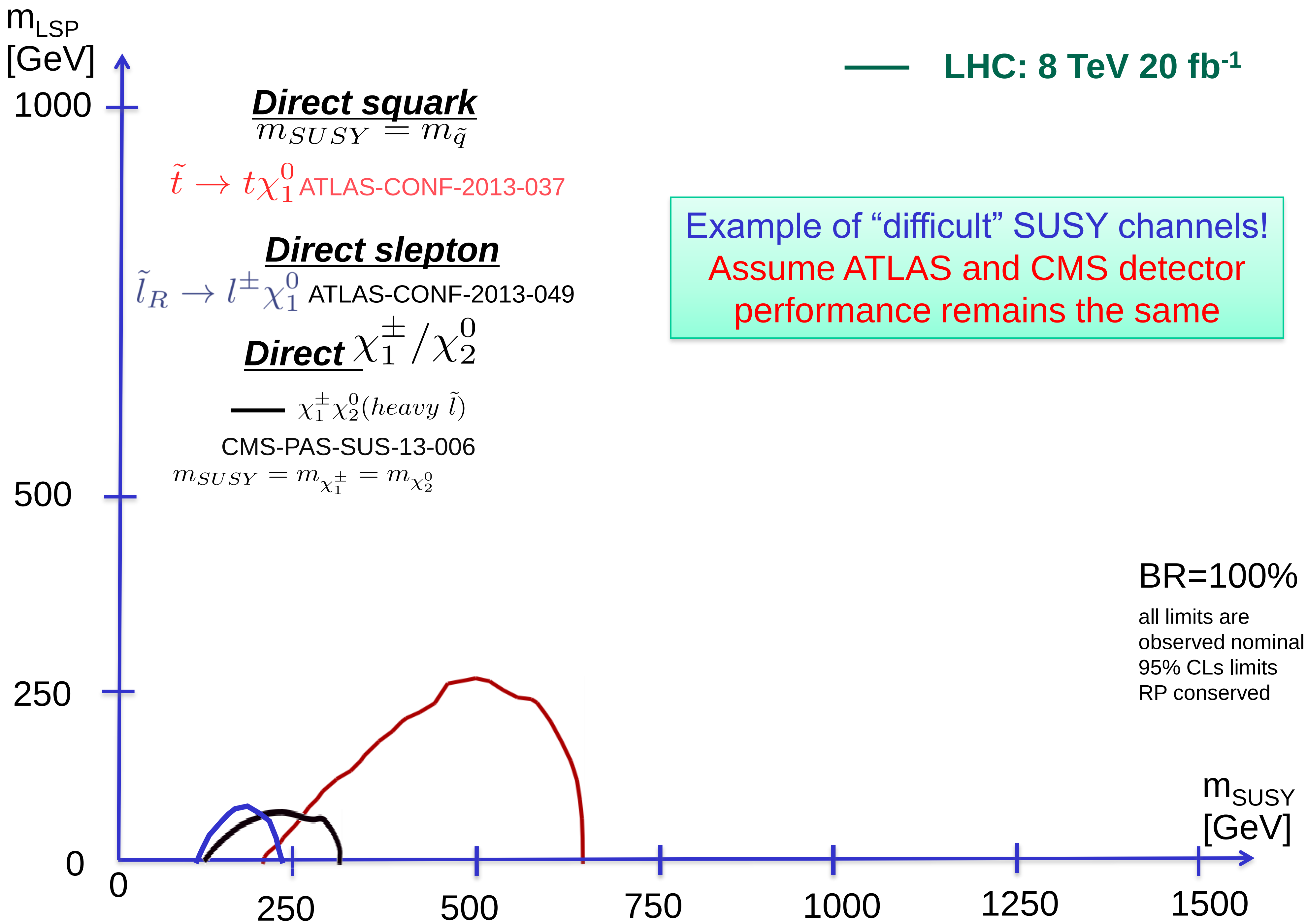
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

Conduct detailed studies of the properties of the found Higgs boson.
How much does it contribute to restoring unitarity in VBF, rare decays (e.g. $H\rightarrow\mu\mu$), and treat the Higgs boson as today we treat the b-quark
LHC → HL-LHC (HL-LHC will be a Higgs factory! 100M produced $3ab^{-1}$)

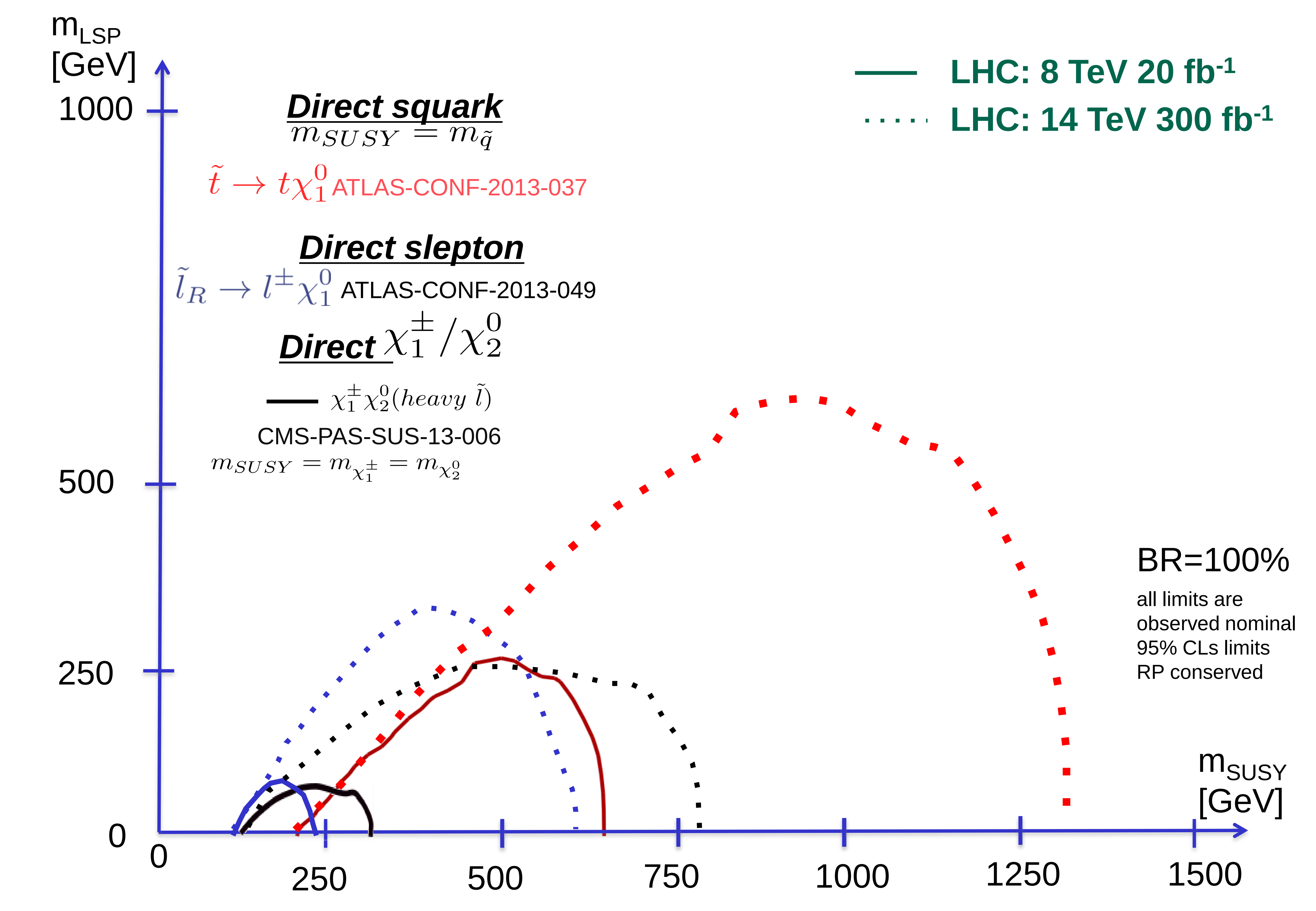
$L(fb^{-1})$	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Couplings Precision ~ 2-10%, H self coupling ~30% (further study)

Continue searching for new physics. If new physics has been found by the end of Phase 1, associated particle(s) will be heavy. Then conduct detailed studies in Phase 3 (HL-LHC).



m_{LSP} [GeV]
LHC: 8 TeV 20 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
Example of “difficult” SUSY channels!
Assume ATLAS and CMS detector performance remains the same
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]



m_{LSP} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
LHC: 8 TeV 20 fb^{-1}
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Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
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BR=100%
all limits are
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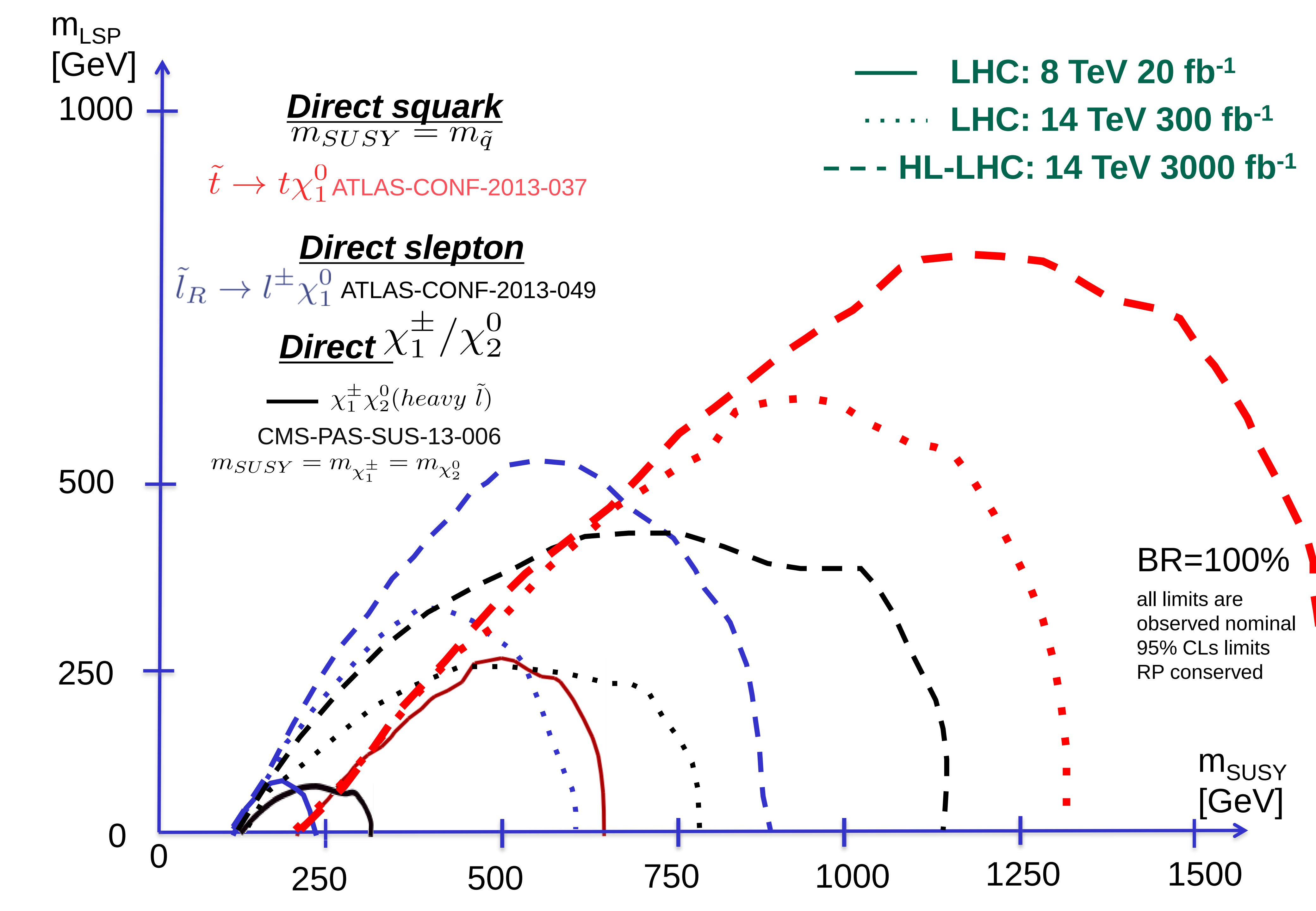

m_{LSP} [GeV]
1000
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750
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1250
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LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
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Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
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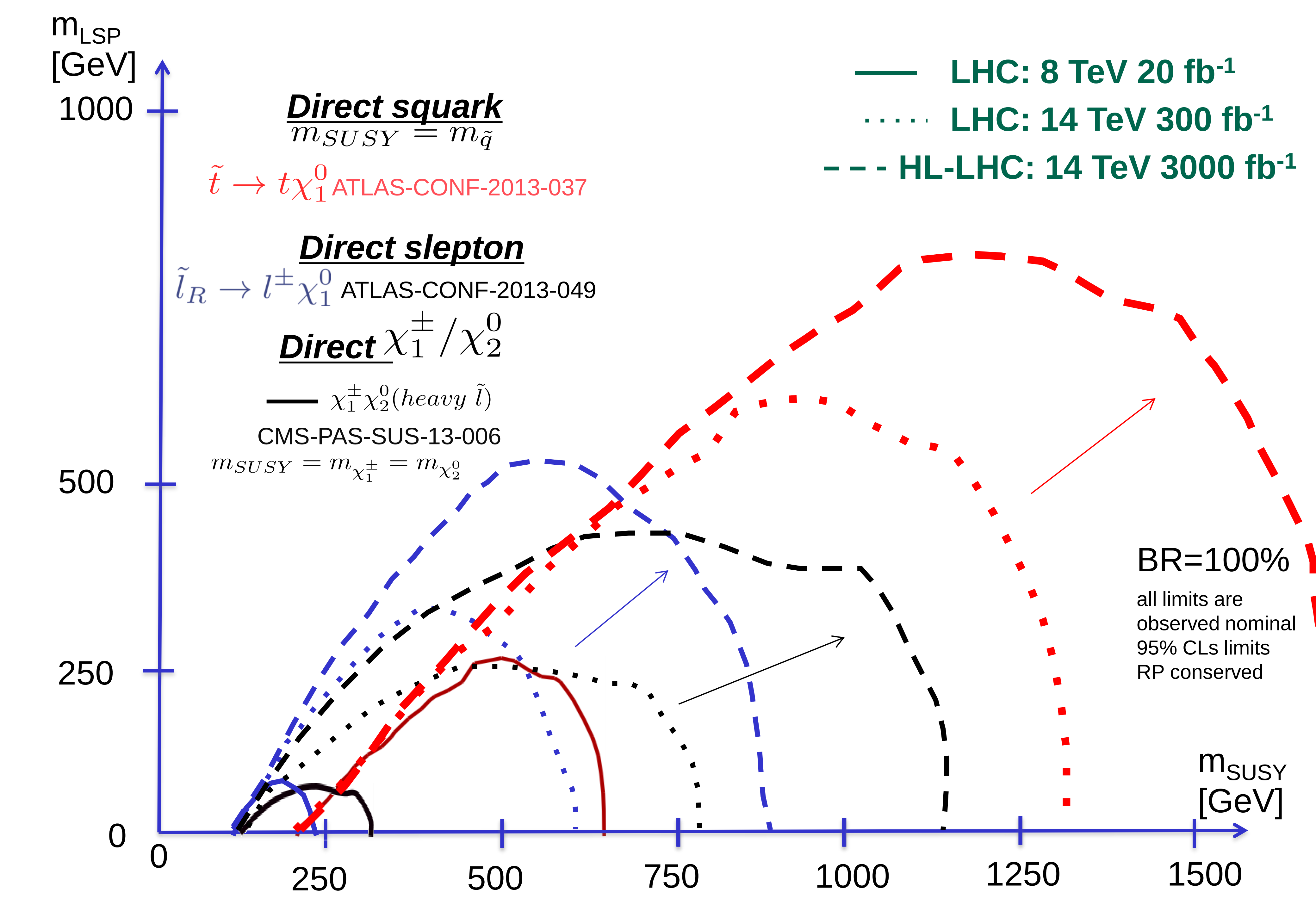

m_{LSP} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
Direct squark
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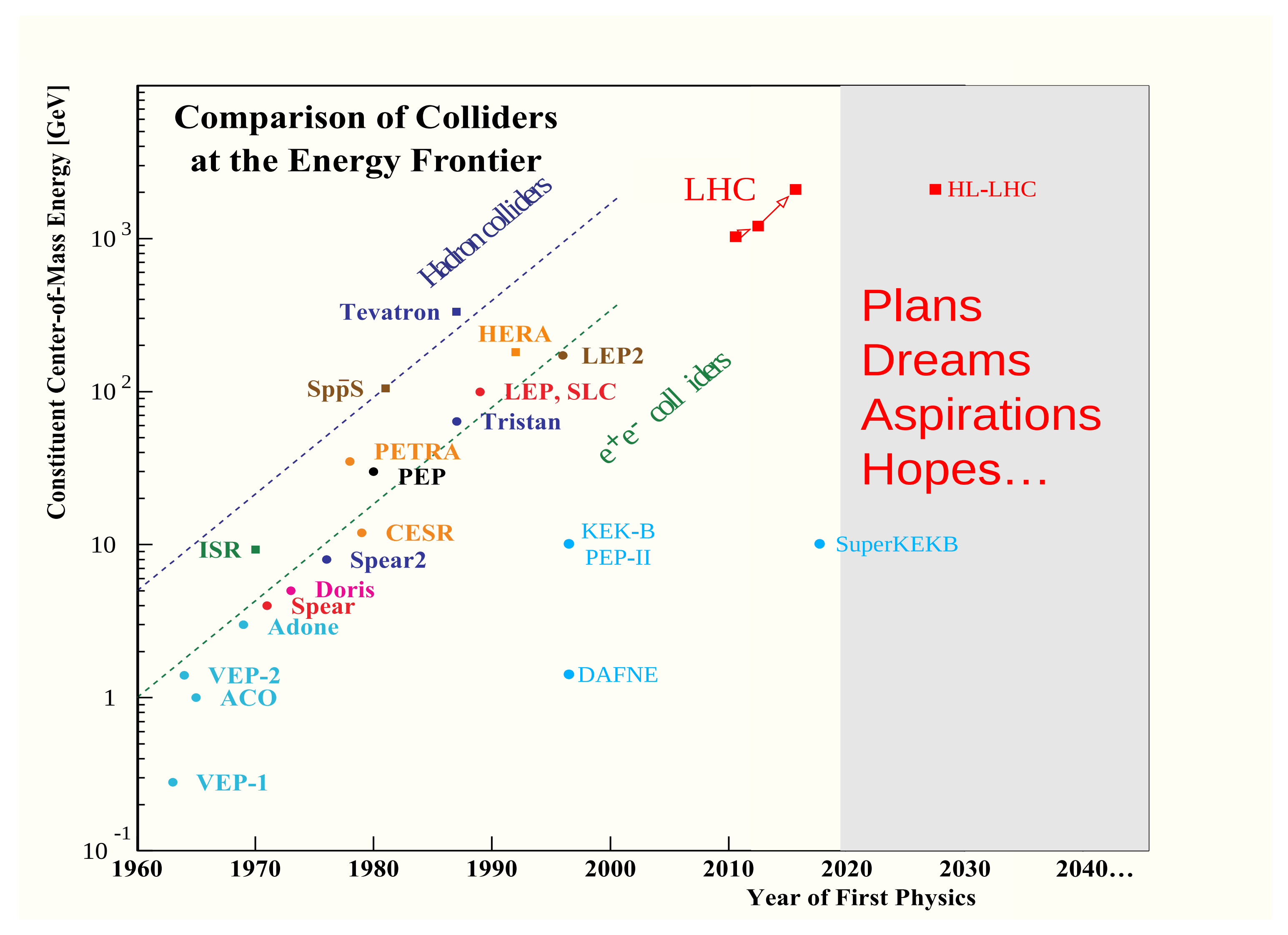
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

Past, Present, Future

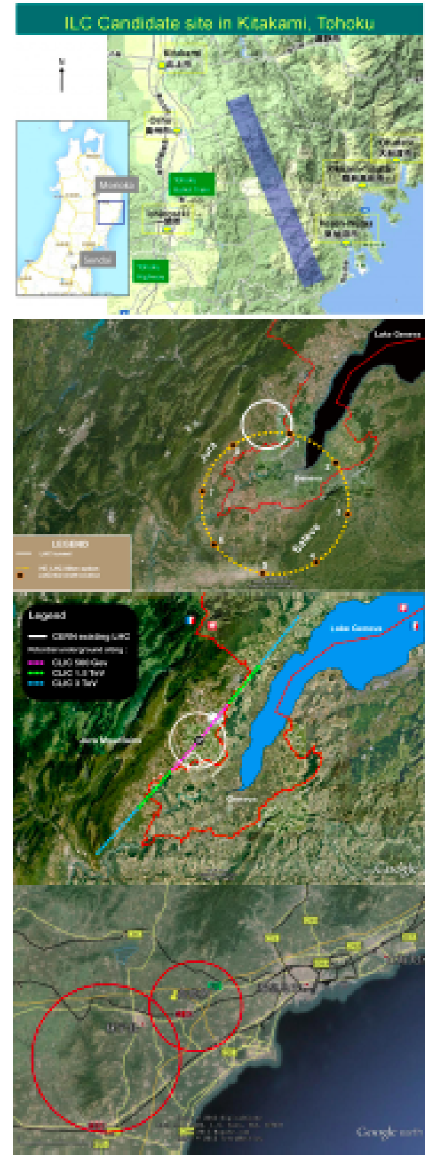


N. Walker ICHEP14

Future Accelerators

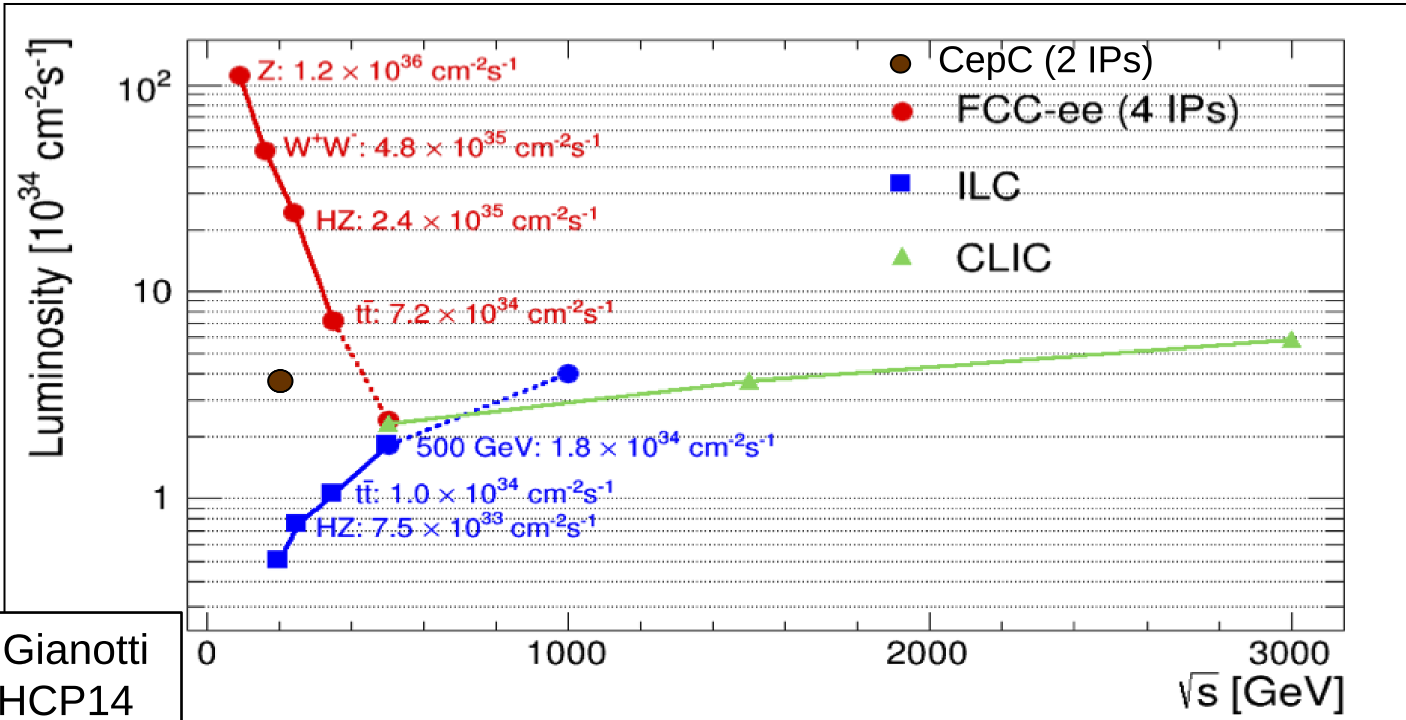
Possible High Energy Frontier Machines

- Next generation linear collider in Japan
  - **International Linear Collider-ILC:** e^+e^- collisions up to 1 TeV
- Post-LHC accelerator projects at CERN
  - **Future Circular Collider-FCC:** FCC-hh (100 TeV), FCC-e^+e^- (350 GeV), possibly ep
  - **Compact LInear Collider-CLIC:** e^+e^- collisions up to 3 TeV
- Circular Collider project in China
  - **Circular Electron Positron Collider-CEPC:** CEPC e^+e^- (250 GeV), SppC pp collider (70-90 TeV)
- **Muon collider** $\leq$5 TeV, US (Neutrino Factory first step)



S. Ganjour

Electron-Positron Colliders



F. Gianotti
LHCP14

M. Klute

FCC-ee v. high statistics e.g. expected statistical uncertainty
m_{top} = 10 MeV
Γ_{top} = 11 MeV
λ_{top} = 13%

	Size km	$\sqrt{s}$ GeV	RF MV/m	L per IP 10^{34}	Bunch/train x-ing rate(Hz)	σ_x μm	σ_y nm	Lumi within 1% of $\sqrt{s}$	Polarisation e^-/e^+
CEPC	54	240	20	1.8	4×10^5	74	160	>99%	considered
FCC-ee	100	240	20	6	2×10^7	22	45	>99%	considered
ILC	31	250	14.7	0.75	5	0.7	7.7	87%	80%/30%
ILC		500	31.5	1.8	5	0.5	5.9	58%	80%/30%
CLIC	48	3000	100	6	50	0.04	1	33%	80%/considered

Hadron Colliders

F. Gianotti LHCP14

	Ring (km)	Magnets (T)	√s (TeV)	L (10^{34})
LHC	27	8.3	14	up to 5
HE-LHC	27	16-20	26-33	5
SppC-1	50	12	50	2
SppC-2	70	19	90	2.8
FCC-hh	100	16	100	≥ 5

More parameters of 100 TeV FCC-hh

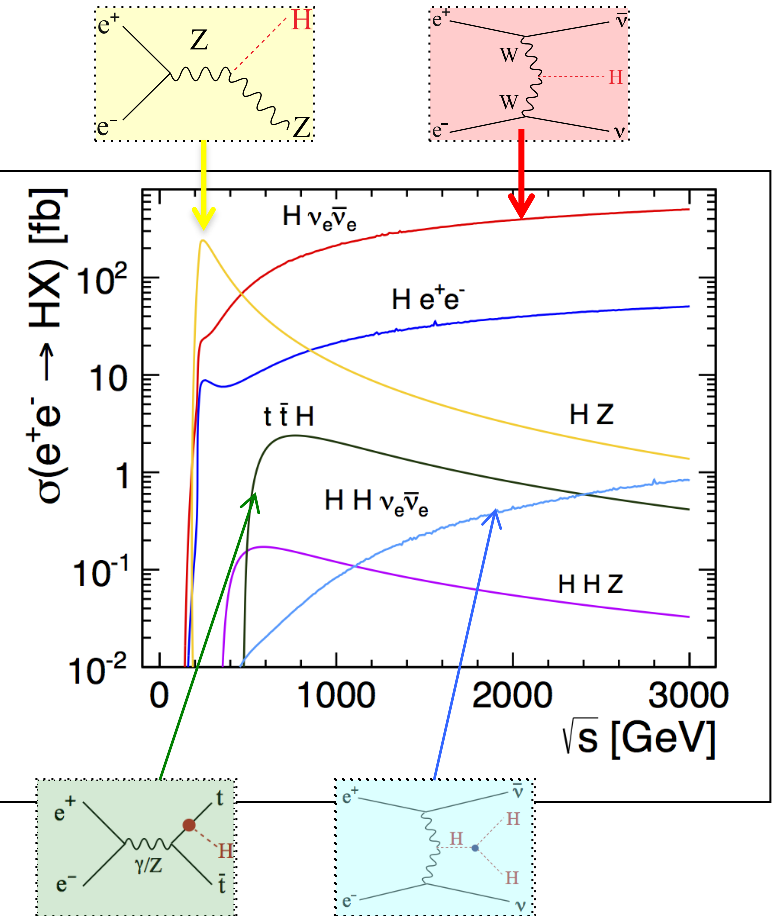
	HL-LHC	FCC-hh
Bunch spacing	25	25
N. of bunches	2808	10600
Pile-up	140	170
E_{loss}/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

5 ns also considered to mitigate e-cloud

How precisely do we need to know the Higgs boson couplings?

F. Gianotti LHCP14

→ 0.1-1% precision needed for discovery



Scenarii with no new particles observable at LHC

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Integrated luminosities correspond to 3-5 years of running at each √s for e+e- and 5 years with 2 experiments for pp

	√s (TeV)	L (ab^{-1})	N_H (10^6)	N_{ttH}	N_{HH}
FCC-ee*	0.24+0.35	10	2	--	--
ILC	0.25+0.5	0.75	0.2	1000	100
ILC_{1TeV}	0.25+0.5+1	1.75	0.5	3000	400
CLIC	0.35+1.4+3	3.5	1.5	3000	3000
				→ tt©©, tt4l	→
bb©©					
HL-LHC	14	3	180	3600 tt©©	250
FCC-hh	100	6	5400	12000 tt4l	20000

* 4 IP

<10% of events usable

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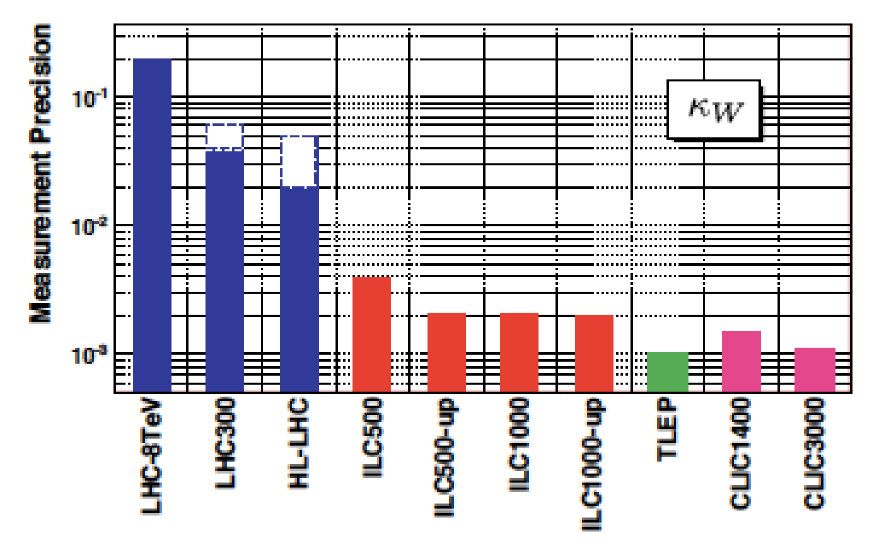
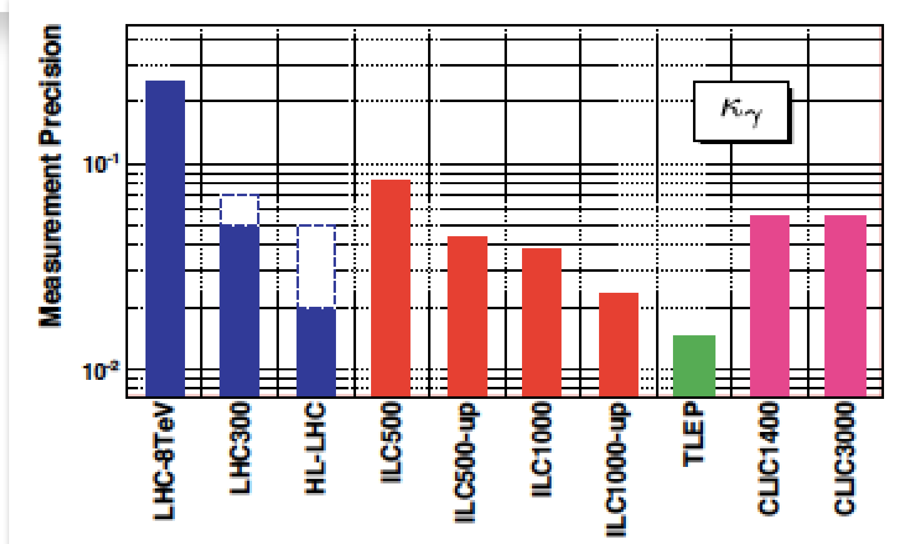
Precision of the Higgs couplings

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%





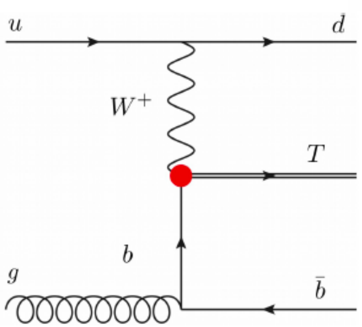
Theory uncertainties need to be improved to match expected good experimental precision and sensitivity to new physics

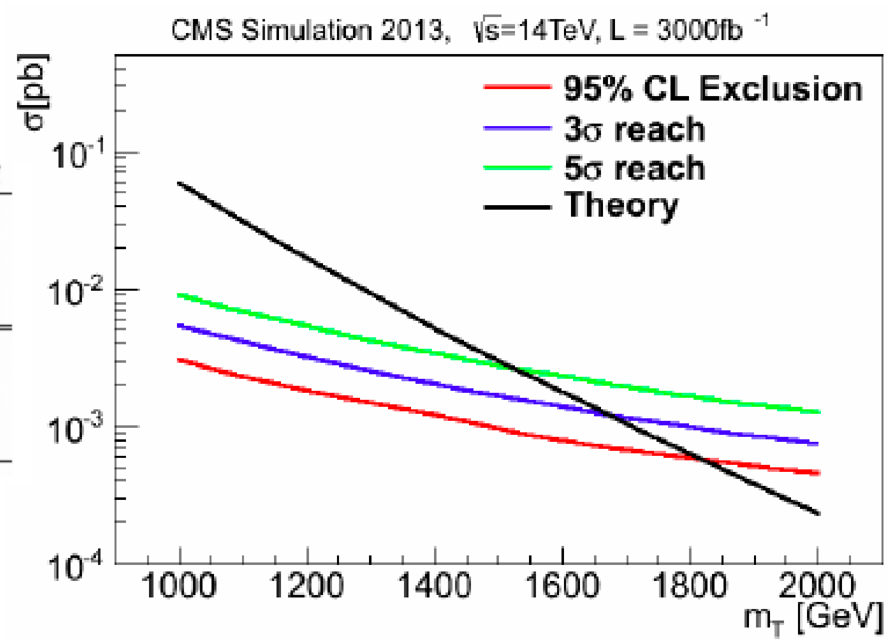
M. Klute

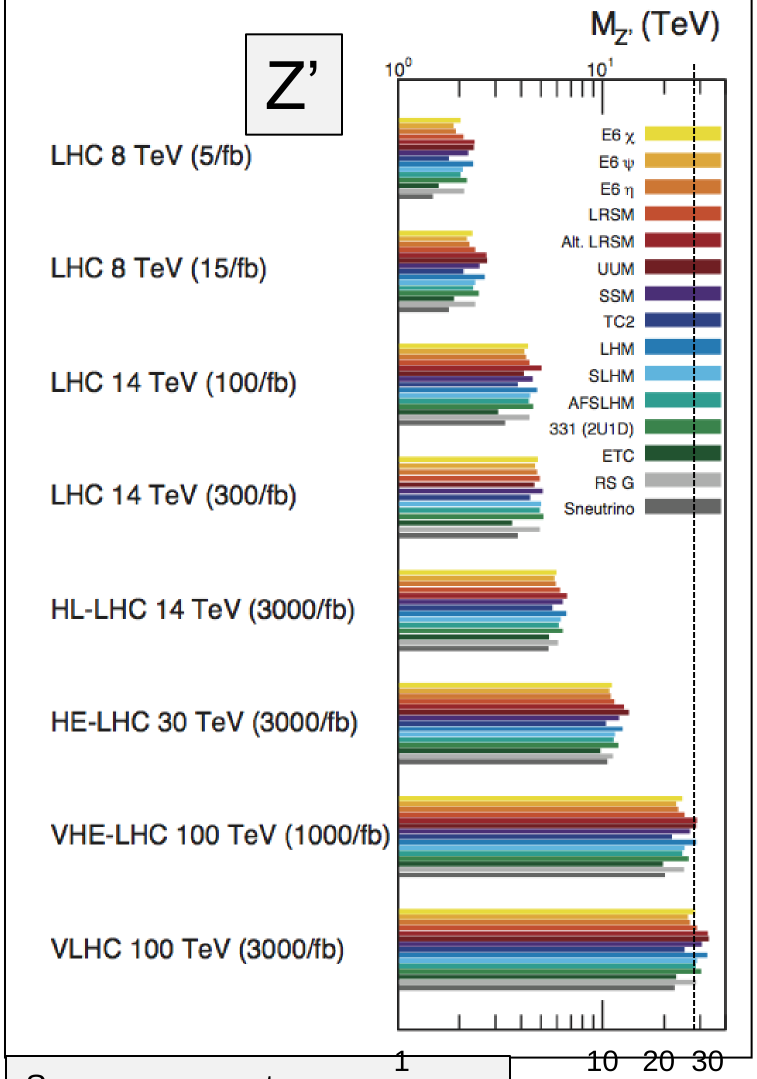
New Physics e.g. Z': Mass Reach

ATLAS projections

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6







Snowmass report:
arXiv:1309.1688

The Detector Challenge: Phase II

Detector Challenge: Maintain/improve on detector performance achieved in Phase I, under more hostile conditions.

Apply lessons from the past – finish a directed programme of R&D and prototyping before starting construction.

HL-LHC: High-level Summary

Inner Trackers Replacement

Endcap/Forward Calorimeters Replacement

Level-1 Trigger: using a “good” set is of utmost importance
Keep thresholds Low, Increase Accept Rate, Bring in tracking info

Changes to Front-end Electronics to allow high L1 accept rate.

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CMS Phase 2 Upgrades

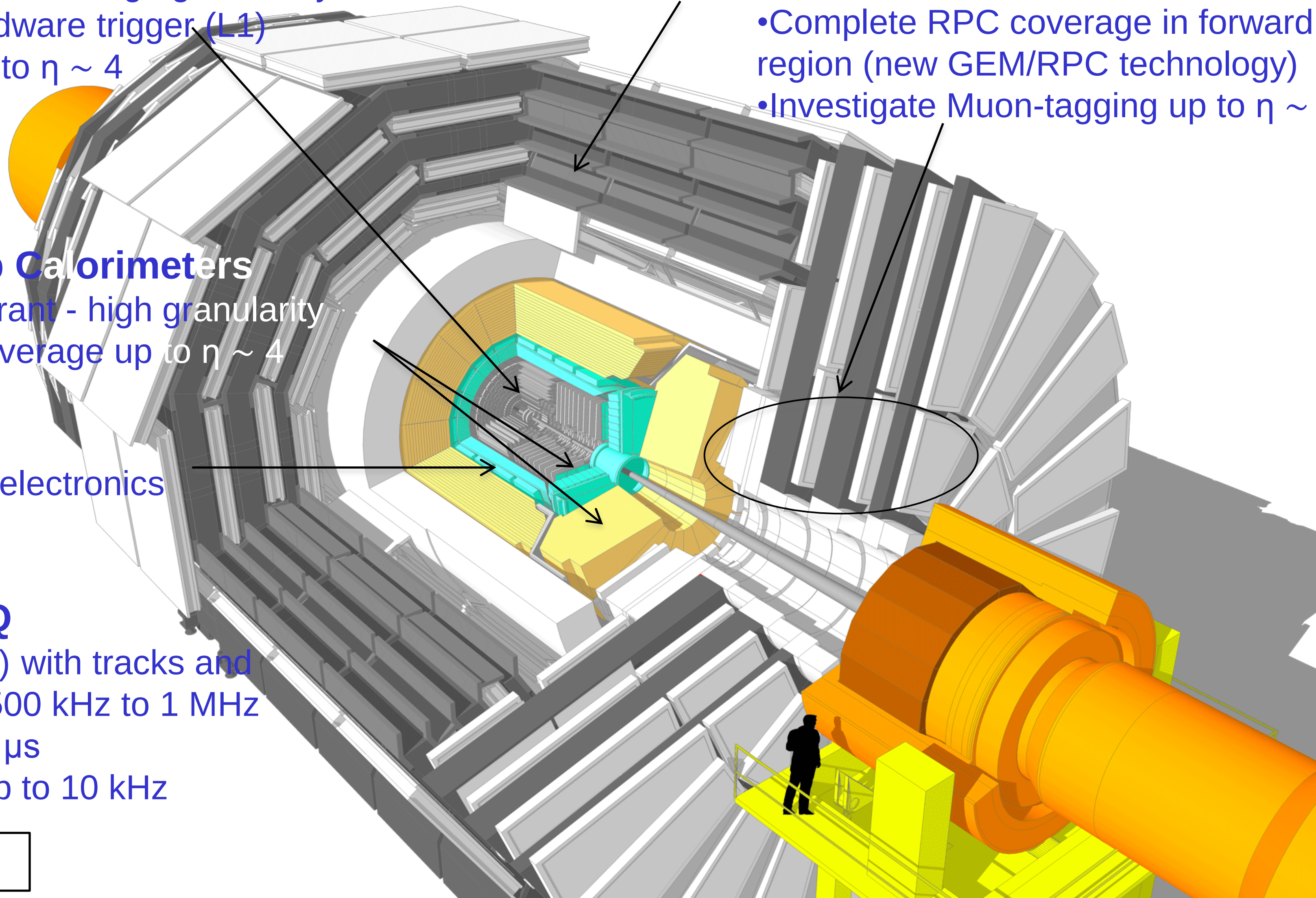
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4

New Endcap Calorimeters
- Radiation tolerant - high granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10 μs
- HLT output up to 10 kHz

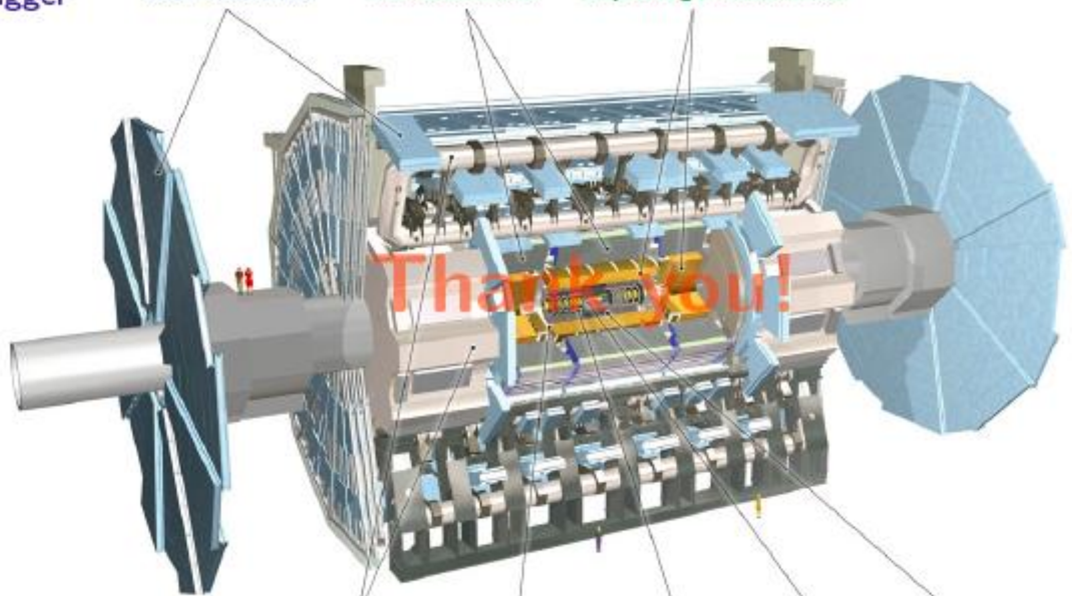


D. Abbaneo

ATLAS: Phase 2 Upgrades

Muon spectrometer
- New Small Wheel
- Additionnal BMG chambers sectors 12&14
- BIS 7-8 RPCs in transition region
- Replacement of read-out electronics
- MDT-based trigger

Calorimeter system
- New L1 trigger (Super Cells)
- LAr and Tile electronics replacement
- Replacement of HEC cold electronics, FCAL?

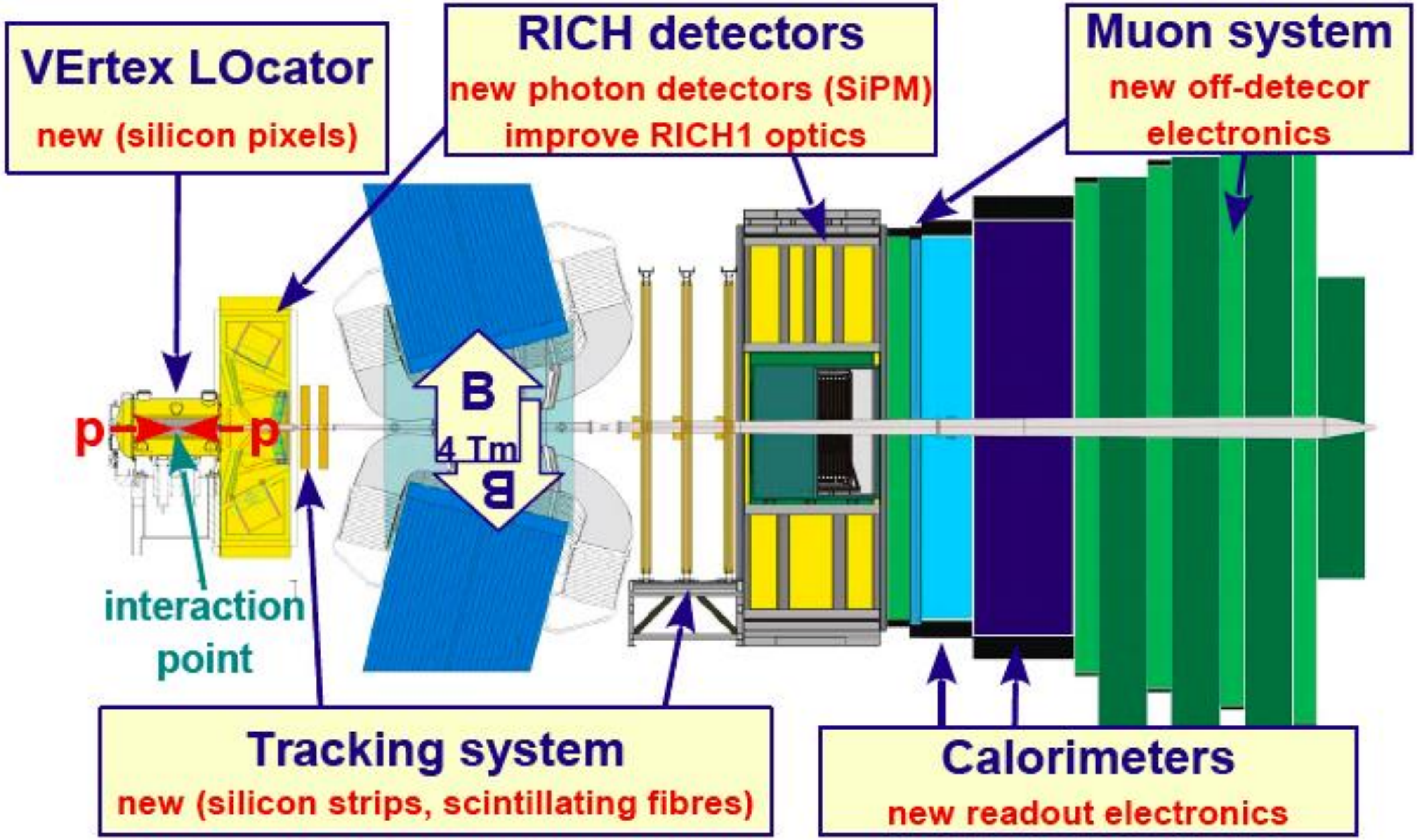


M. Hagel

Inner Detector (ID)
- Fast Tracker for L2 trigger
- New All-Silicon Inner Tracker

Two Level Trigger system
- L0: 1MHz, 6/10μs latency
- L1: 300-400kHz, 30/60μs latency

LHCb: Upgrades



readout full detector at 40 MHz
full software trigger with 20 kHz output rate

“Reconstructing the Universe”

Session and Discussions on Future Accelerators

at Guggenheim, New York

Remarks from Discussions on Future Accelerators 1

- **Where does our Science stand today?**
- **We have made a major discovery - a Higgs boson – a particle like no other.** And we have no evidence for BSM physics at the LHC.
- **The only established new physics beyond the SM has been seen arguably in the neutrino sector, BAU, in the form of dark matter and dark energy… BUT what scale(s)?**

- **IF new physics** (or strong indications) is discovered at the LHC14 – then it is likely to be the lowest of coloured states or the lowest of a series of resonant states – and will be quite heavy. This implies the full spectrum will have even heavier particles and the only sure way to explore that spectrum will to go to a high energy hadron collider (e.g. 100 TeV pp collider – (R.Aleksan- LHC magnets in a 100 km tunnel already gives ~ 55 TeV).

- **IF NO new physics** (beyond the Higgs boson) is found (e.g. in Run 2) then we must continue searching and looking for cracks in the SM in all areas (HL-LHC, neutrinos, EDM, dark matter,…). The found Higgs boson and the associated field are new to fundamental physics. It behoves us to study it in depth and its implications (some of which may go beyond particle physics).

- **Where does it point us? What tools/experiments do we have today: HL-LHC, neutrino experiments, rare processes experiments, dark matter searches, etc.**

Remarks from Discussions on Future Accelerators 2

- **HL-LHC – full exploitation of the potential of LHC**

(Note: the GPD Upgrades funding is not secured yet – and we must make the upgrades a success)

- The LHC provides a broad platform for performing Higgs (studies) and other precision measurements. It is a b-quark, W/Z, top-quark, Higgs factory – the only one we have for the foreseeable future (+ Belle2). Should aim to keep the doubling time short: below ~ one (longish) LHC run. So at some suitable integrated luminosity perhaps push the LHC accelerator and the experiments to the limit ➔ design upgrades beyond $3ab^{-1}$ (say $5\ ab^{-1}$)?

- **Crucial to have a wide range of (unprejudiced) experimental programme (Y. Nomura)**

- **Neutrinos**
- Through experiments probing their nature, the origin of their masses and hierarchy, leptonic CP violation, the unitarity of the PMNS matrix and whether there are additional species.

The US-P5 report provides an opportunity to shape a global neutrino programme with possibly complementary long-baseline experiments. Can the world afford two such experiments (e.g. in US and Japan)? The potential physics payoff seems to point that way.

- **Other complementary experiments** (astroparticle, neutrinoless β-decay, EDM, dark matter, etc)

New Accelerators

Any new (high energy) accelerator will require substantial resources (human and financial).

Need

1) Scientifically persuasive (better still - compelling) case – compare with what is projected to be known in ~ 2030 from the upgraded HL-LHC and elsewhere. And secure consensus/buy-in by most of our community (as was the case for the LHC)
2) Support/understanding from other scientific disciplines
3) Probably international sharing of cost
4) Public support

Remarks from Discussions on Future Accelerators 3

▪**Electron-positron colliders**
The LHC results already limit the sub-TeV colliders mostly to a justification based on precision studies of the Z, W, Higgs boson and ttH.
(TeV or multi-TeV accelerators?)

▪ILC in Japan: $\sqrt{s}$=0.5 TeV: Await decision in Japan. The report of the Japanese Science Council (K. Yokoya) requested a 2-3 year study to provide:
- Clearer and more persuasive arguments – including the relation with the (upgraded) LHC
- A “budget” framework that does not …..stagnate… progress in other academic fields
- International cost sharing
- Public support

▪ CepC: Recent article in Nature (S. Chattopaday) – China is a candidate to build 250 GeV electron–positron collider. Yifang Wang – “You can’t just talk about a project which is 20 years from now”. Proposing to use international participation to increase radius/energy (ee/pp).

▪ Can one of these accelerators be built without support from all regions? Does this imply substantial supplementary funding beyond existing resources?

Remarks from Discussions on Future Accelerators 4

- **Hadron colliders**

Today these seem to be the only reasonable way to probe energy scales some 5-10 times higher than the LHC.

- There is ne a need to proceed vigorously with R&D on **affordable** high field SC dipole magnets.

- The development of 16-20T magnets in the next decade opens up options.

The possibility of going for HE-LHC
or a truly global collider (e.g. pp-FCC).
(As already noted current LHC magnets in an FCC already gives 55 TeV).

Remarks from Discussions on Future Accelerators 5

The next large accelerator?

- A case can be made for an e^+e^- accelerator on the basis of precision measurements (searching for deviations and/or checking the self-consistency of SM) but appears to require a high luminosity and broad energy reach - from Z mass upwards.

- A discovery at LHC/HL-LHC would make a compelling for a high energy hadron collider (with $\sim\sqrt{s_{LHC}}$x5-10) . However, a case can always be made on the basis of unknowns/searches at the next frontier for an energy frontier accelerator.

- The path to follow will depend on the strength of the scientific case, that takes account of results from LHC14, including HL-LHC, and other experiments seeking cracks in the SM, the accelerator's technical, cost and schedule, the regional and global context/involvement, and the longevity of scientific exploitation.

- **Great care, patience, thought and wisdom will be needed to reach a correct and consensual decision within our community, that can be well explained further afield.**

Summary: Physics at the LHC and Beyond

- **At the LHC, after twenty years of design and construction we are firmly in the 2nd half of the journey – the extraction of the science.**

- **A "massive" discovery has been made – a Higgs boson.** The boson appears just to be the one predicted by the SM.

- **No evidence found yet of physics BSM.** The Standard Model with a single "elementary" scalar doublet seems to work well (too well)

- The start of Run 2 will be just as exciting as the original startup. We must be well prepared.

- **We must fully exploit the potential of the HL-LHC and so must make a success of the HL-LHC – our future may well depend on this.**

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Summary: Physics at the LHC and Beyond

- **The "novelty" and the "lightness" of this Higgs boson calls for its in-depth studies, and beyond, at the HL-LHC and the circular and linear e^+e^- colliders (with differing pros and cons).**

- **Must take a holistic view of particle physics – whether we find BSM physics at the LHC or not – and select the path to follow in a prudent manner.**
  - Precision measurements (not only of the new boson, and not only at the LHC)
  - Searches for new particles and phenomena, and their in-depth study if found

- **Above all we hope that new physics appears in Run II at 13-14 TeV.**