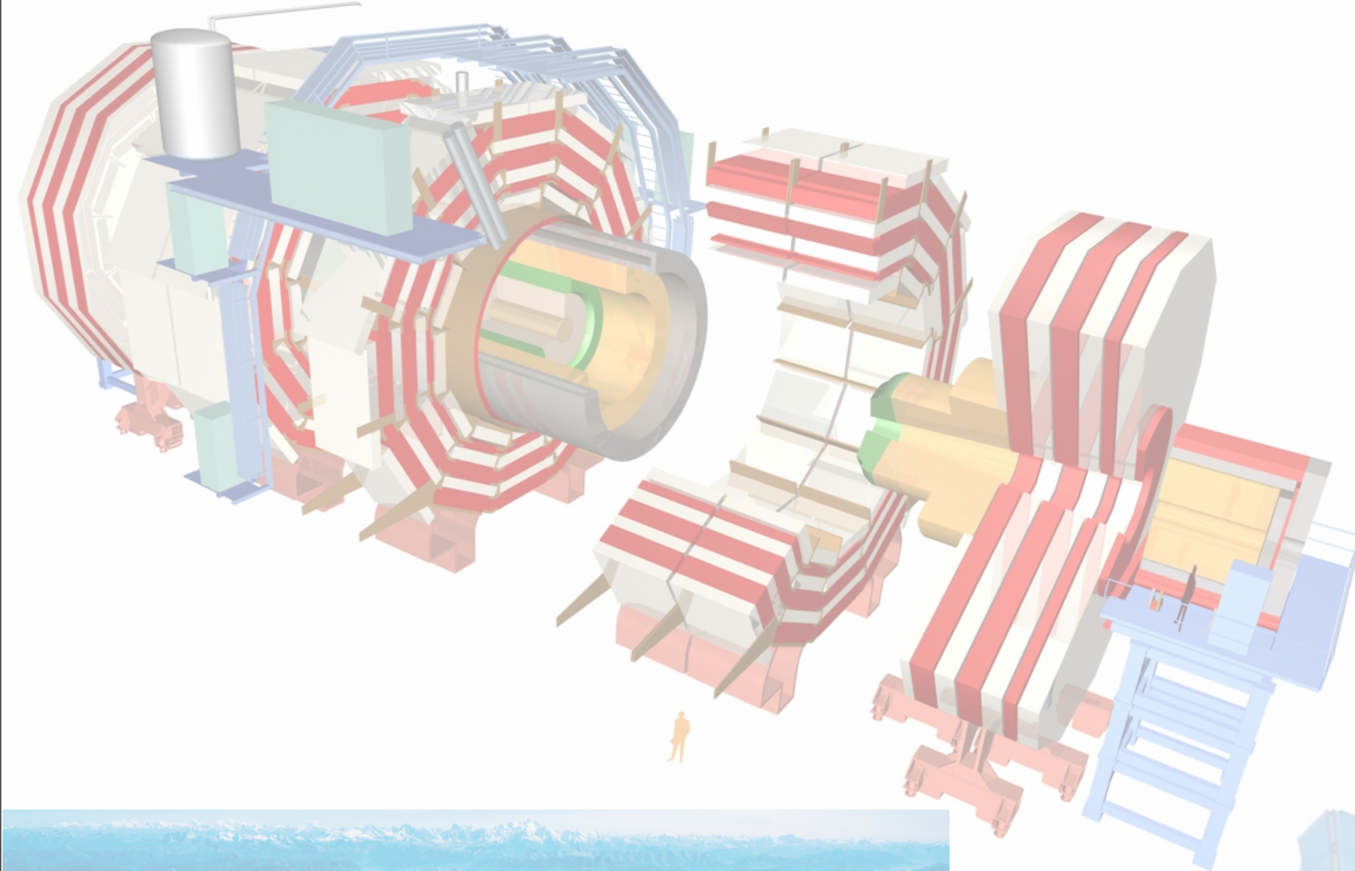
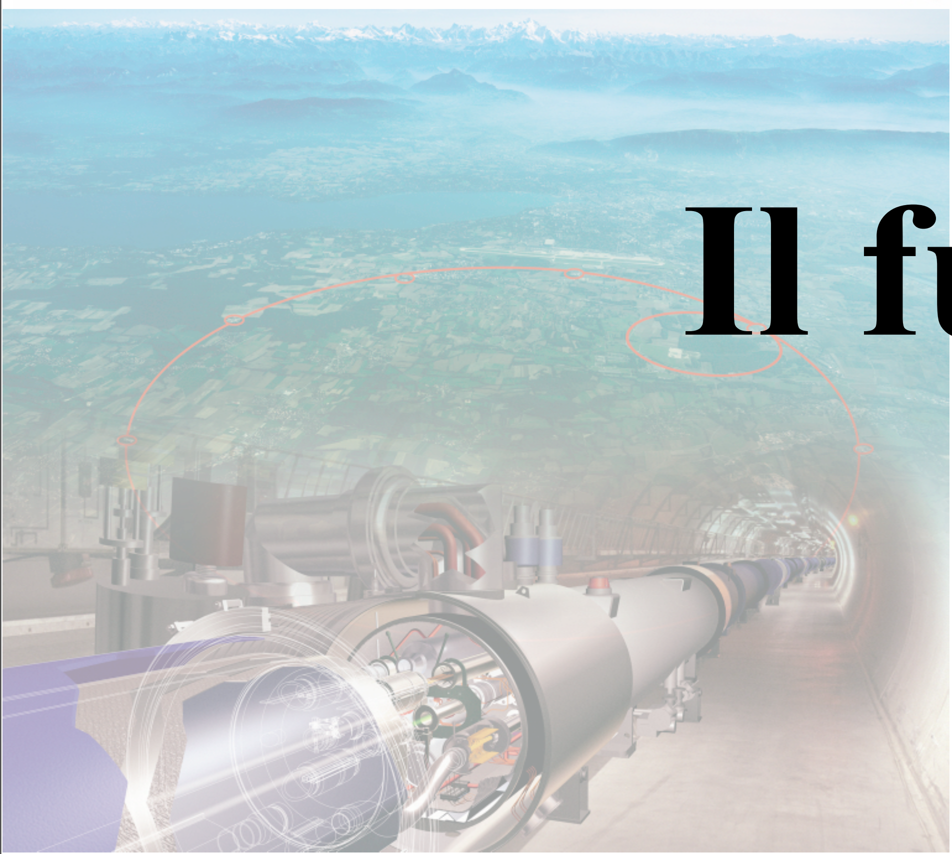
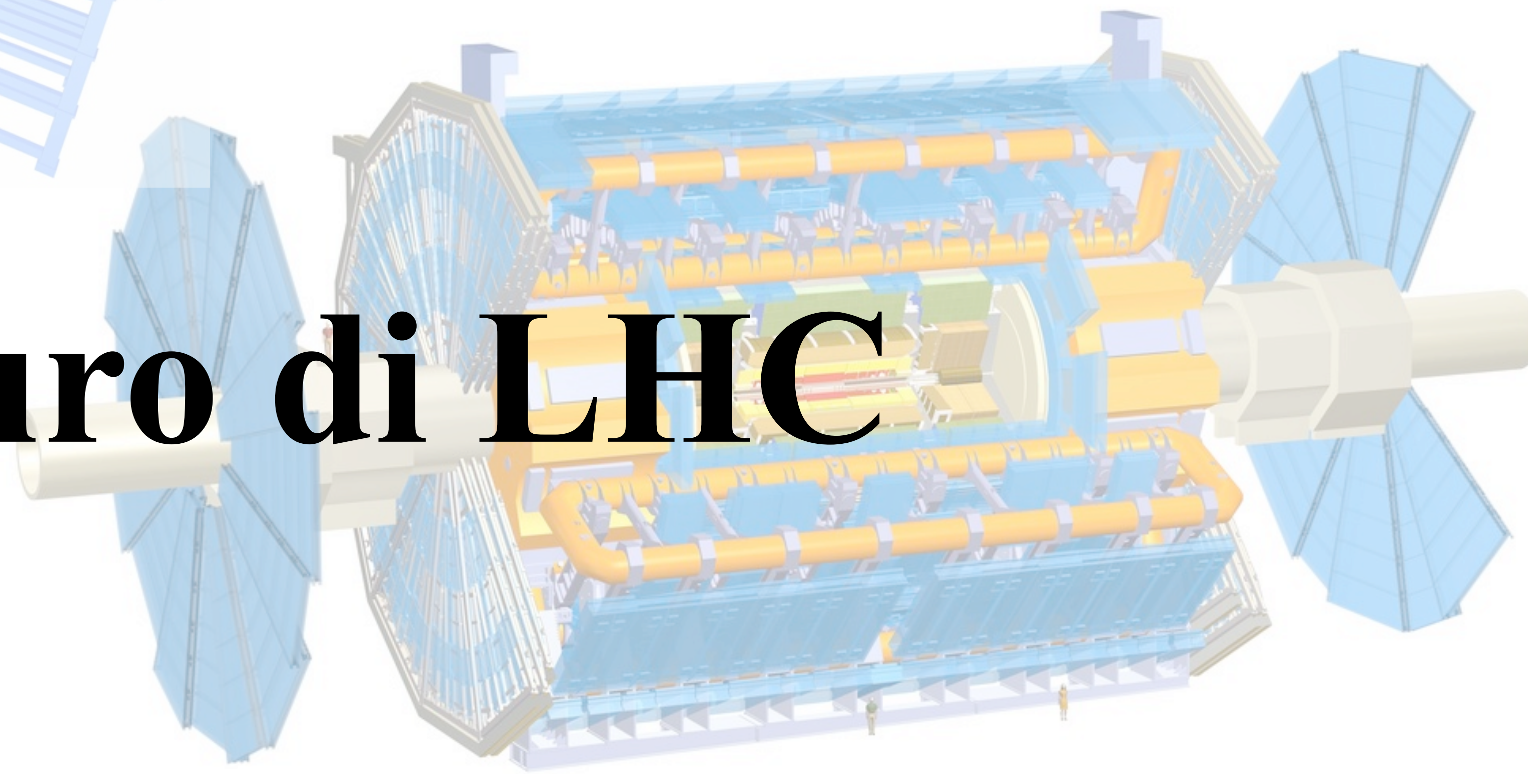






Il futuro di LHC

Paolo Giacomelli (INFN Bologna)
Giovedí, 4 Luglio, 2013

Outline

- Evoluzione futura di LHC e HL-LHC
- Programma di fisica
- Upgrades dei rivelatori CMS e ATLAS
- Misure di precisione del bosone di Higgs
- Decadimenti rari del bosone di Higgs
- Auto-accoppiamento del bosone di Higgs
- VV scattering
- Prospettive di SUSY
- Prospettive per fisica oltre il Modello Standard

<u>Nota</u>

Tratterò solo gli esperimenti ATLAS e CMS

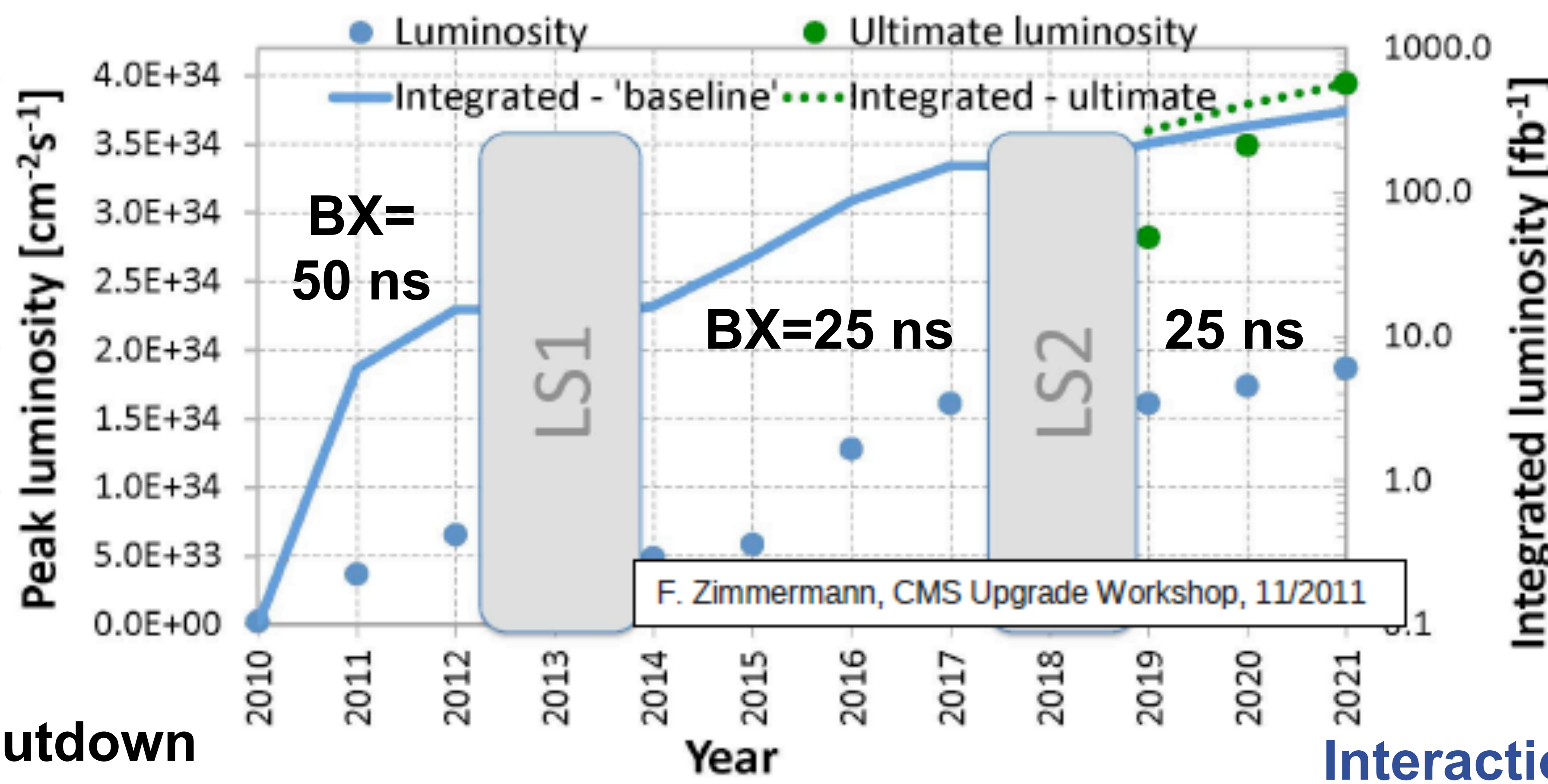
LHC e HL-LHC

LHC | **Energy increase 8 TeV to 13/14 TeV** | **Injection upgrade** | **HL-LHC**

$PU = \begin{Bmatrix} 100@25ns \\ 200@50ns \end{Bmatrix}$ →

$PU = \begin{Bmatrix} 50@25ns \\ 100@50ns \end{Bmatrix}$ →

$PU = \begin{Bmatrix} 25@25ns \\ 50@50ns \end{Bmatrix}$ →



Luminosity-leveled at 5×10^{34} cm^{-2}s^{-1} in HL-LHC

LS= Long Shutdown

Interaction region upgrade

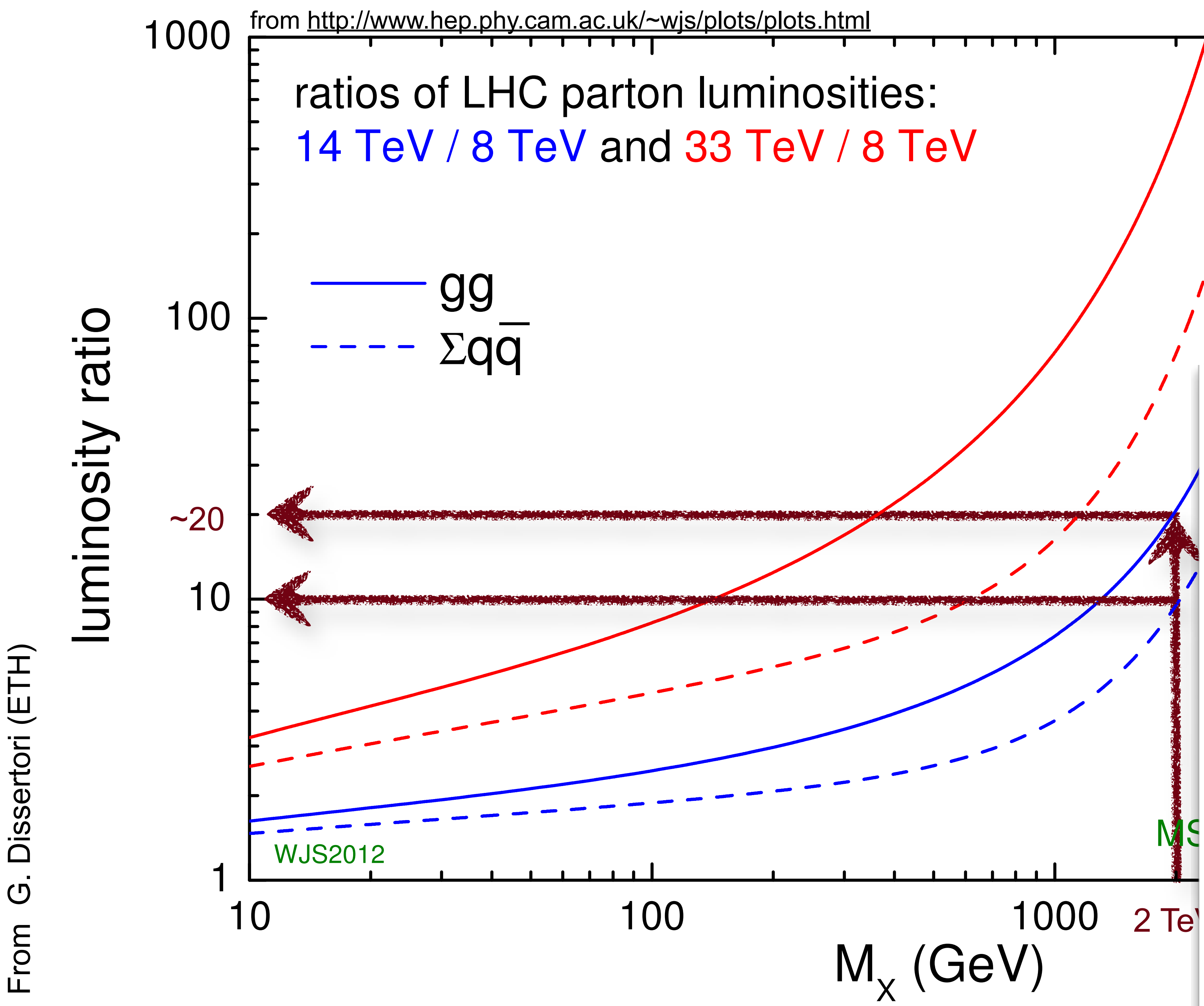
	LHC		LHC (after LS1)		HL-LHC (after LS3)
Listantanea	8×10^{33} Hz/cm^2		2×10^{34} Hz/cm^2		5×10^{34} Hz/cm^2
Lintegrata	30 fb^{-1}	LS1	300 fb^{-1}	LS3	3000 fb^{-1}
Pile Up	PU ~40		PU ~50		PU ~140

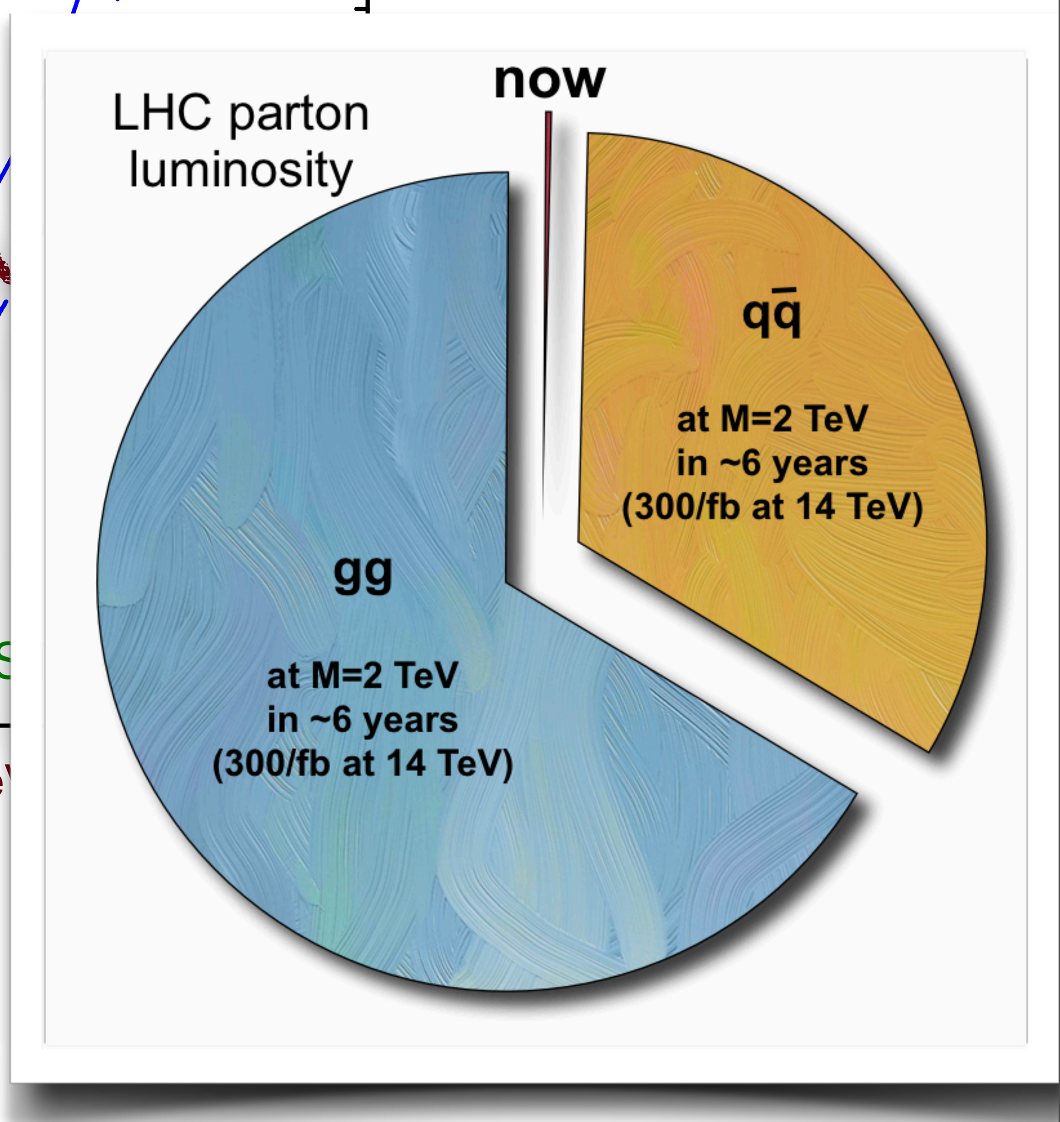
ATLAS, CMS Upgrade plan

Phase 1 Upgrade →

Phase 2 Upgrade →

LHC dopo LS1





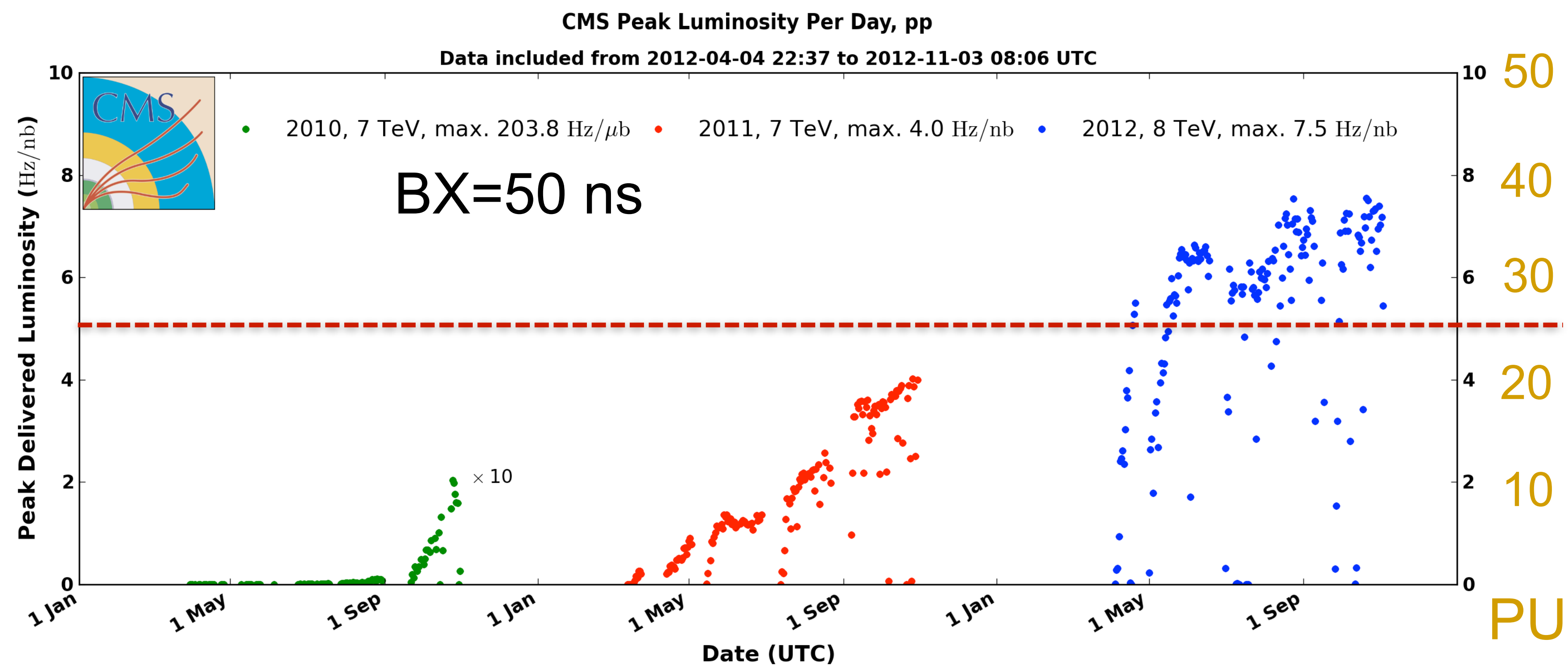
Stiamo per esplorare un territorio nuovo!!

Sfide sperimentali

- Servono detectors e trigger ad alte prestazioni da basse fino ad alte scale di energia
  - Misure del bosone SM-like a 125 GeV
  - Ricerca di nuova fisica oltre al TeV
- Phase 1 Upgrade: due volte la luminosità di disegno di LHC
  - Pileup di eventi raggiunge ~50 collisioni per beam crossing (@ 25 ns)
  - Fattore 5 di aumento delle frequenze di trigger rispetto al run del 2012
- Phase 2 Upgrade: 5x la luminosità di disegno di LHC
  - Pileup di eventi raggiunge ~140 collisioni per beam crossing (@ 25 ns)
  - Servono soluzioni per operare con altissime frequenze (10-15 x 2012), radiazione e pileup

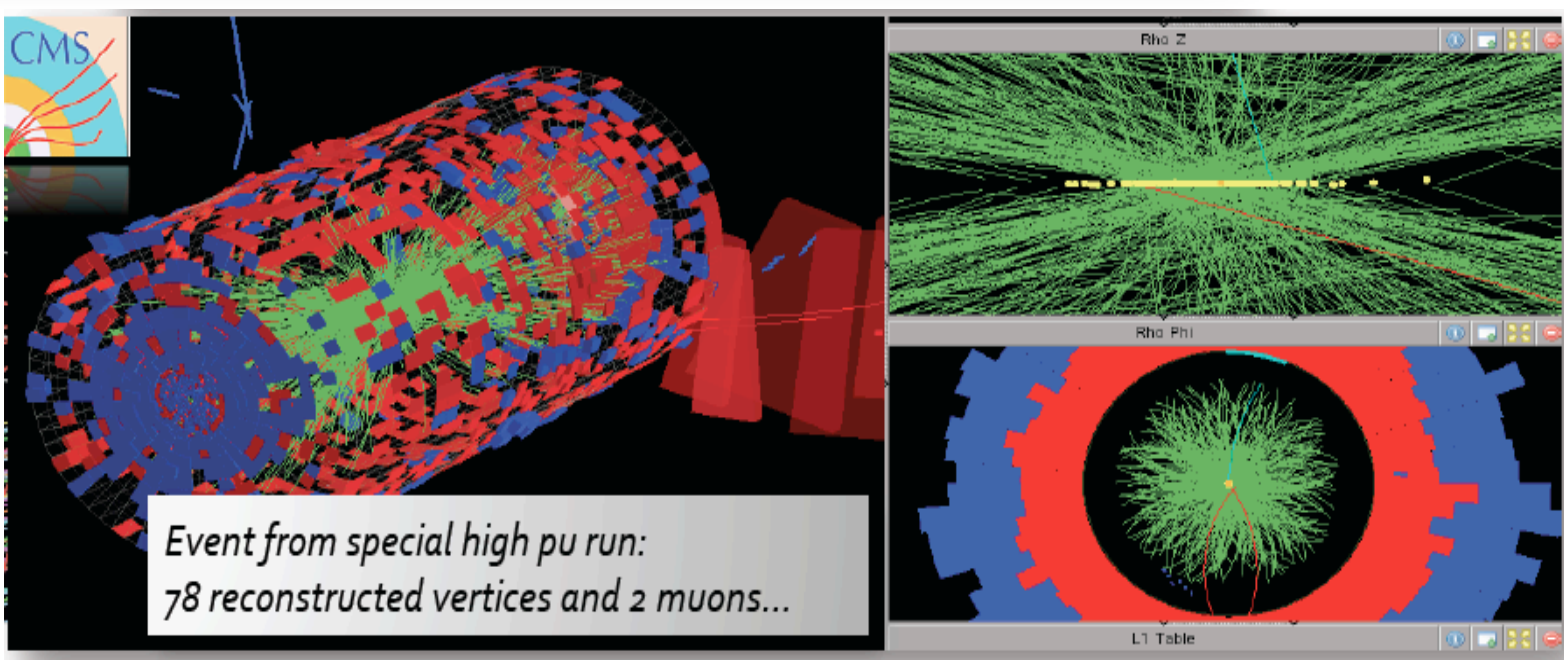
ATLAS e CMS sono stati progettati per L= 1-2 x10^{34} cm^{-2}s^{-1}

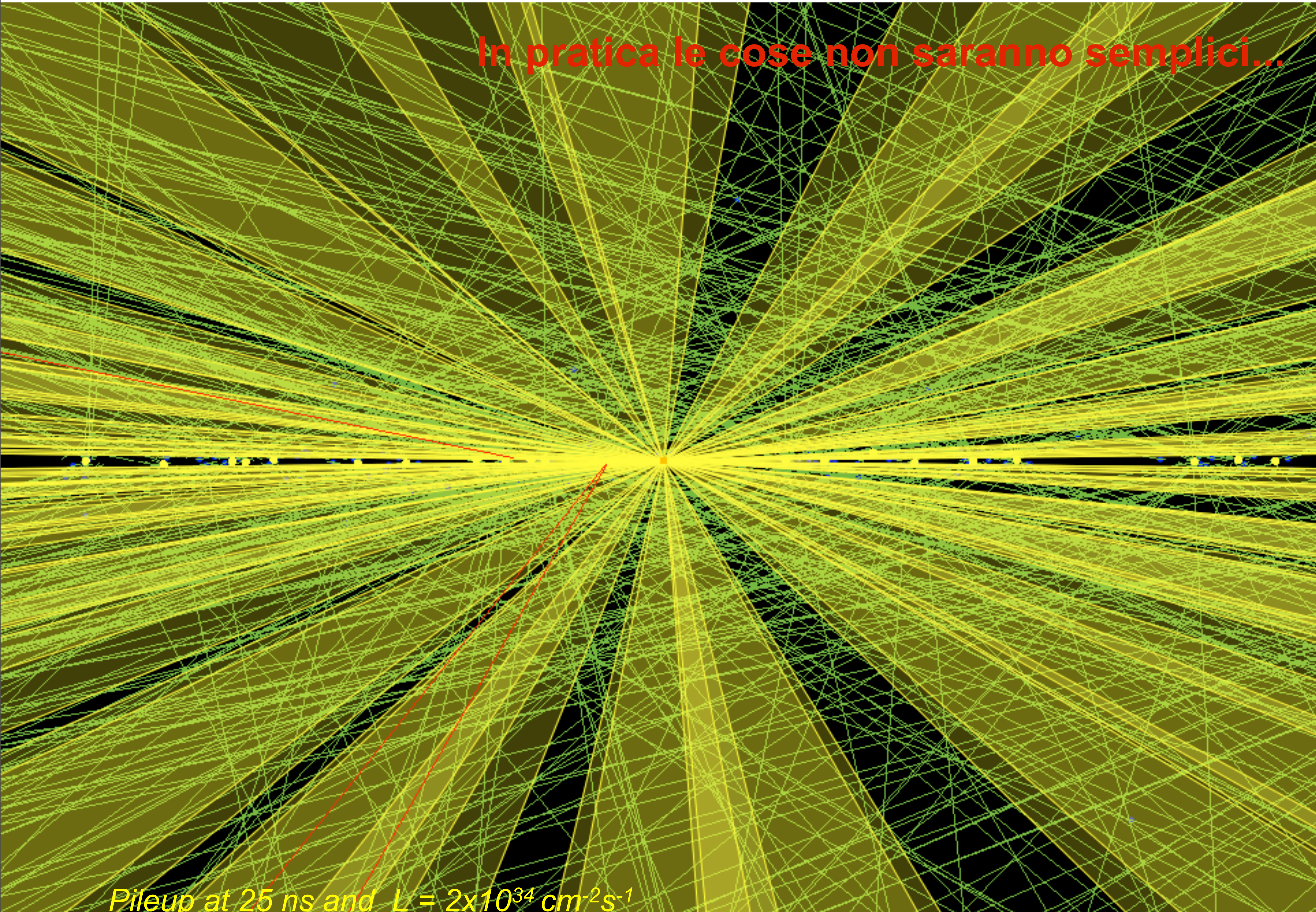
Pileup nel 2012



Peak: 37 pileup events

Design value
25 pileup events
(L=10^{34}, BX=25 ns)




In pratica le cose non saranno semplici...
Pileup at 25 ns and L = $2x10^{34}$ $cm^{-2}s^{-1}$

Programma di fisica

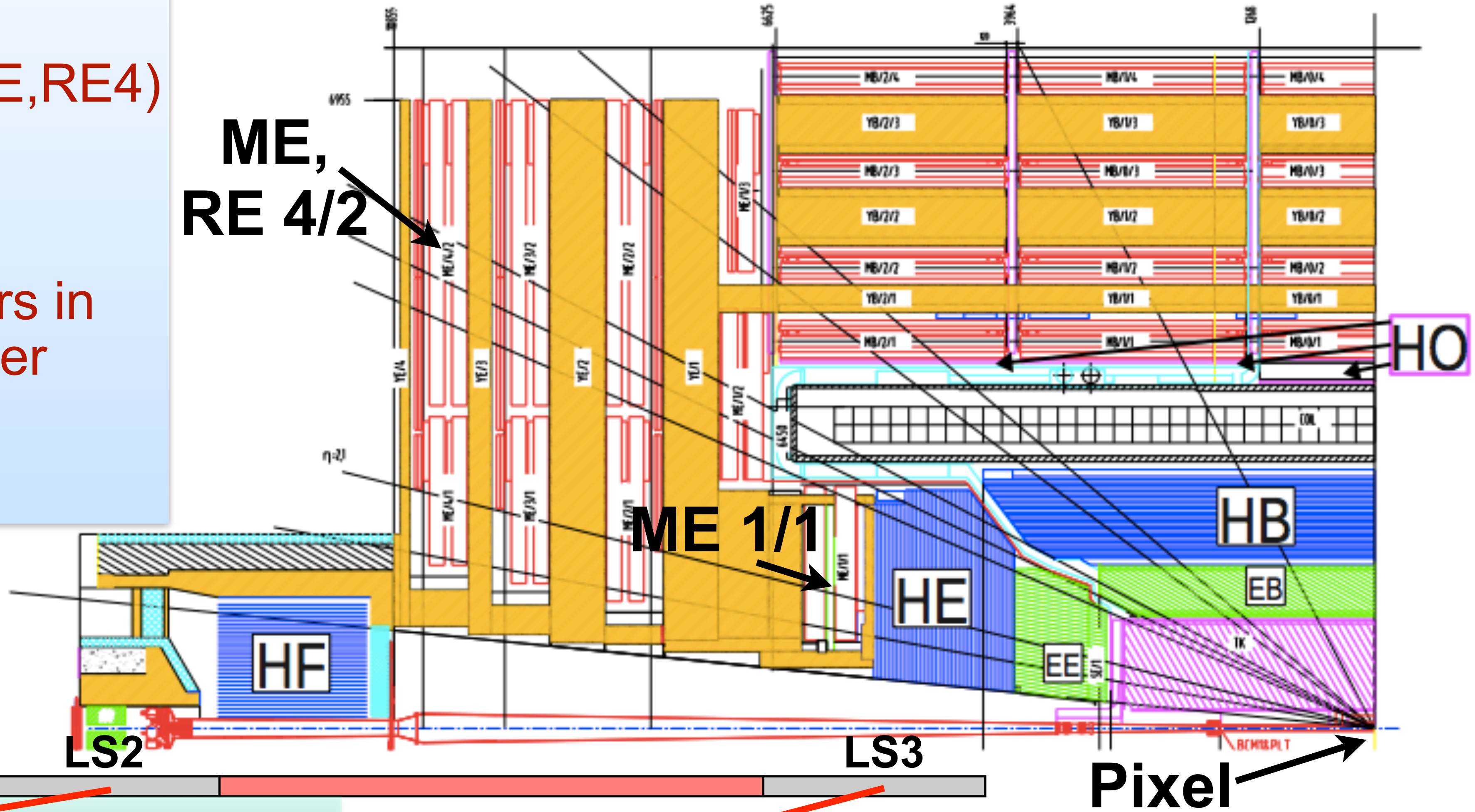
La scoperta di un bosone scalare SM-like con m_H~125 GeV definisce le priorità di fisica

- Con i dati di LHC 13/14 TeV fino al ~2022 (~300 fb^{-1})
  - Misure delle proprietà del bosone di Higgs SM-like
    - massa, J^{PC}
    - accoppiamenti individuali con una precisione del 5-15%
  - Ricerca di nuova fisica ad una nuova scala di energie
    - SUSY
    - Exotica (fisica oltre il Modello Standard)
- Con i dati di HL-LHC a 14 TeV fino al ~2032 (~3000 fb^{-1})
  - Misure di alta precisione del bosone di Higgs
  - Studi dei decadimenti rari del bosone di Higgs e degli auto-accoppiamenti
  - Studi di VV scattering
  - Caratterizzare eventuale Nuova Fisica scoperta durante la Phase 1 a 14 TeV

CMS upgrade program

LS1 Projects

- Complete Muon coverage (ME,RE4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)
- DAQ1→DAQ2



LS1 LS2 LS3

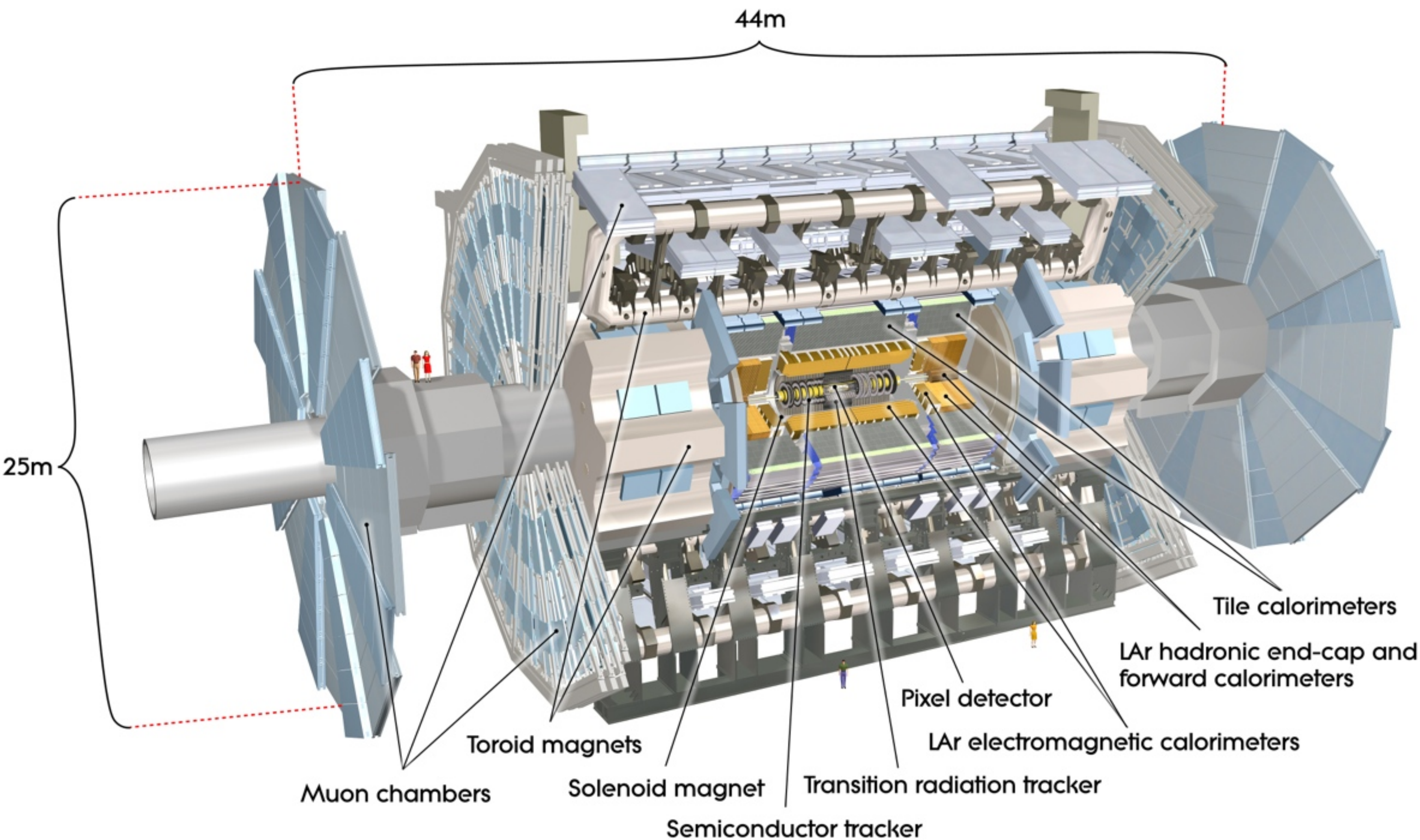
Phase 1 Upgrades

- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon det. under review
- Preparatory work during LS1
  - New beam pipe for pixel upgrade
  - Install test slices of pixel, HCAL, L1-trigger
  - Install ECAL optical splitters for L1-trigger

Phase 2: being defined now

- Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade
- Further DAQ upgrade

ATLAS detector



ATLAS upgrade program

2009 2010 2011 2012 **2013 2014** 2015 2016 2017 **2018** 2019 2020 2021 **2022 2023** … 2030

Prepare for: Phase 0,I **LS1** Phase I,II **LS2** Phase II **LS3**

"Phase-0" upgrade: consolidation
$\sqrt{s}$ = 13~14 TeV, 25ns bunch spacing
$L_{inst} \simeq 1 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 27.5$)
$\int L_{inst} \simeq 50$ fb^{-1}

"Phase-I" upgrades:
ultimate luminosity
$L_{inst} \simeq 2\text{-}3 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 55\text{-}81$)
$\int L_{inst} \gtrsim 350$ fb^{-1}

"Phase-II" upgrades:
$L_{inst} \simeq 5 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 140$) w. leveling
$\simeq 6\text{-}7 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 192$) no level.
$\int L_{inst} \simeq 3000$ fb^{-1}

ATLAS has devised a 3 stage upgrade program

- New insertable pixel b-layer (IBL)
- New Al beam pipe
- New pixel services
- Complete installation of EE muon chambers
- New evaporative cooling plant
- Consolidation of detector services
- Specific neutron shielding
- Upgrade magnet cryogenics

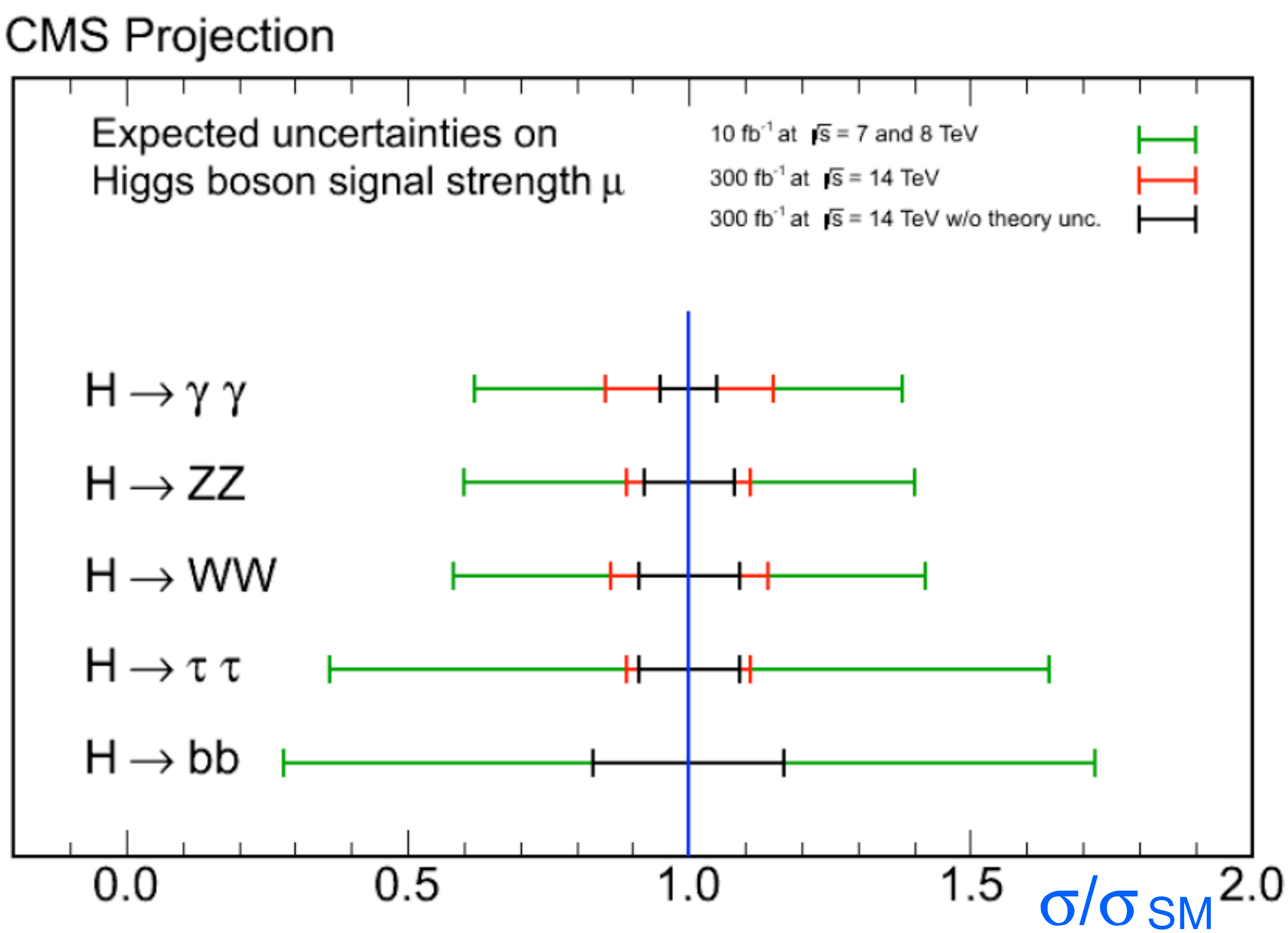
- New Small Wheel (nSW) for the forward muon Spectrometer
- High Precision Calorimeter L1-Trigger
- Fast TracKing (FTK) for L2-trigger
- Topological L1-trigger processors
- New forward diffractive physics detectors (AFP)

- Completely new tracking detector
- Calorimeter electronics upgrades
- Upgrade part of the muon system
- Possible L1-trigger track trigger
- Possible changes to the forward calorimeters

From M. Diemoz

Misure dell'Higgs con 300 fb^{-1}

- Si assume che un detector upgraded mantenga le prestazioni del 2012
- Tre scenari:
  - Scenario 1: stesse incertezze sistematiche del 2012
  - Scenario 2: incertezza teorica ridotta di un fattore 2, altre incertezze ri-normalizzate con $1/\sqrt{L}$
  - Scenario 3: stesse incert. exp. del 2012, nessuna incertezza teorica

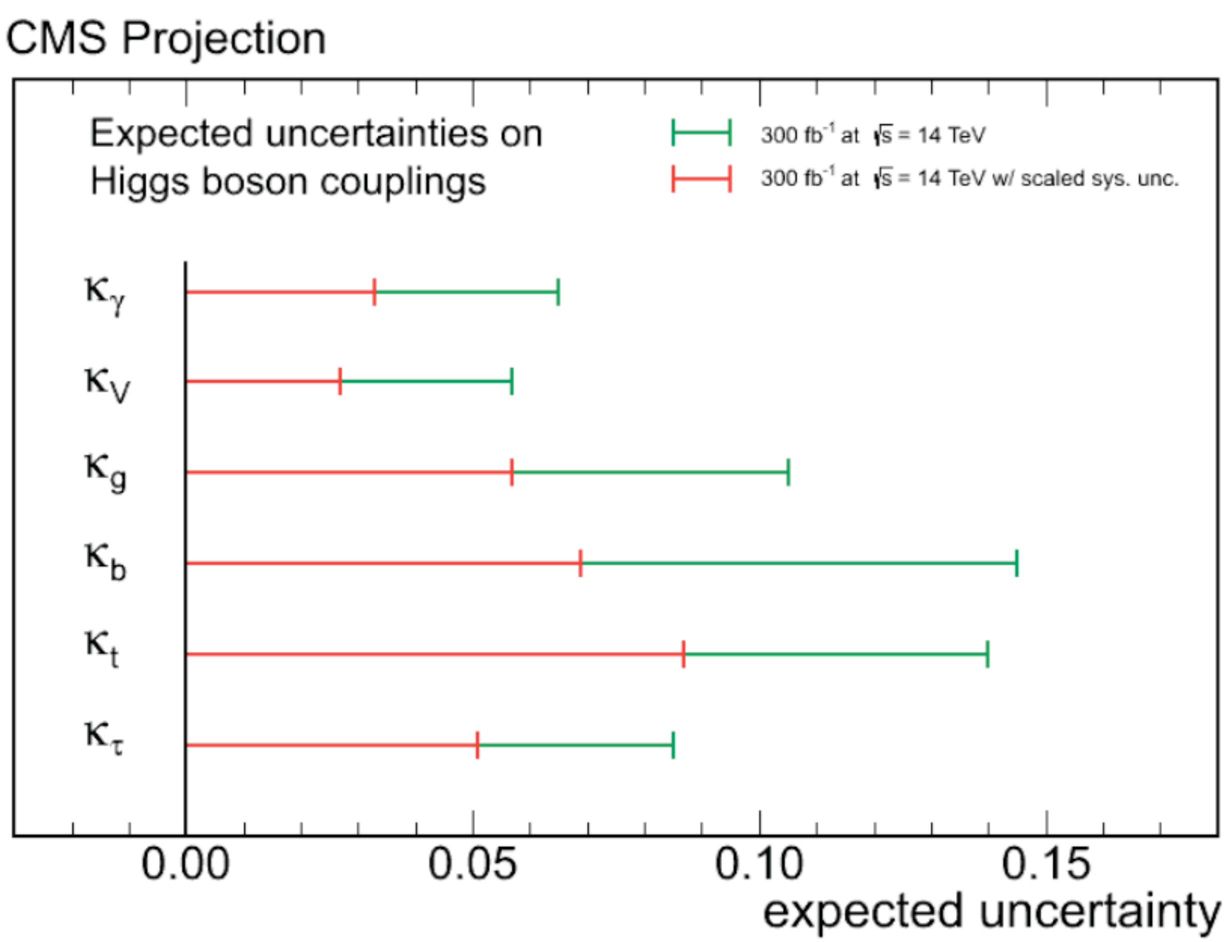


10 fb^{-1}, 7 and 8 TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 3)

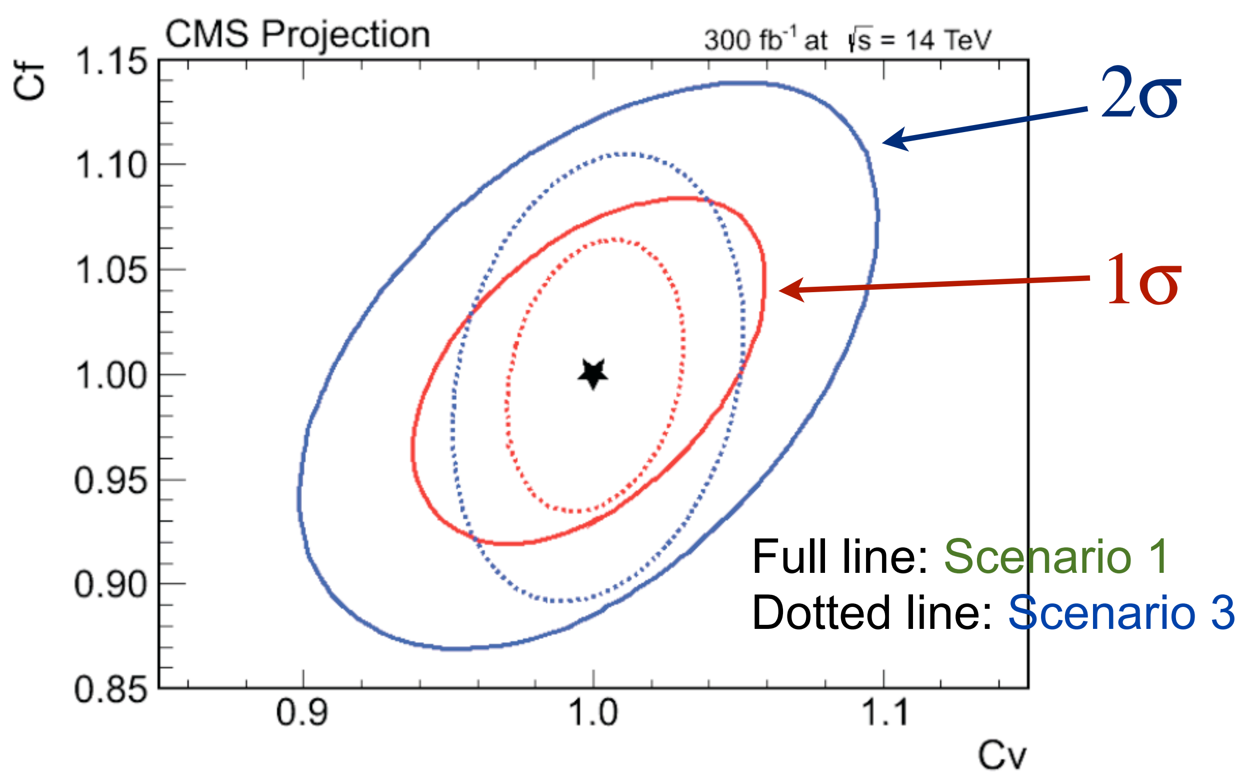
Con 300 fb^{-1} la precisione sulla "signal strength" (σ/σ_{SM}) sarà di 10-15% per canale

Accoppiamenti dell'Higgs @300 fb^{-1}

- Tre scenari:
  - Scenario 1: stesse incertezze sistematiche del 2012
  - Scenario 2: incertezza teorica ridotta di un fattore 2, altre incertezze ri-normalizzate con $1/\sqrt{L}$
  - Scenario 3: stesse incert. exp. del 2012, nessuna incertezza teorica



300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2



Con 300 fb^{-1} le incertezze sugli accoppiamenti dell'Higgs saranno

$\sigma(\kappa_V) \sim$ 3-6%

$\sigma(\kappa_f) \sim$ 5-15%

HL-LHC accoppiamenti @3000 fb^{-1}

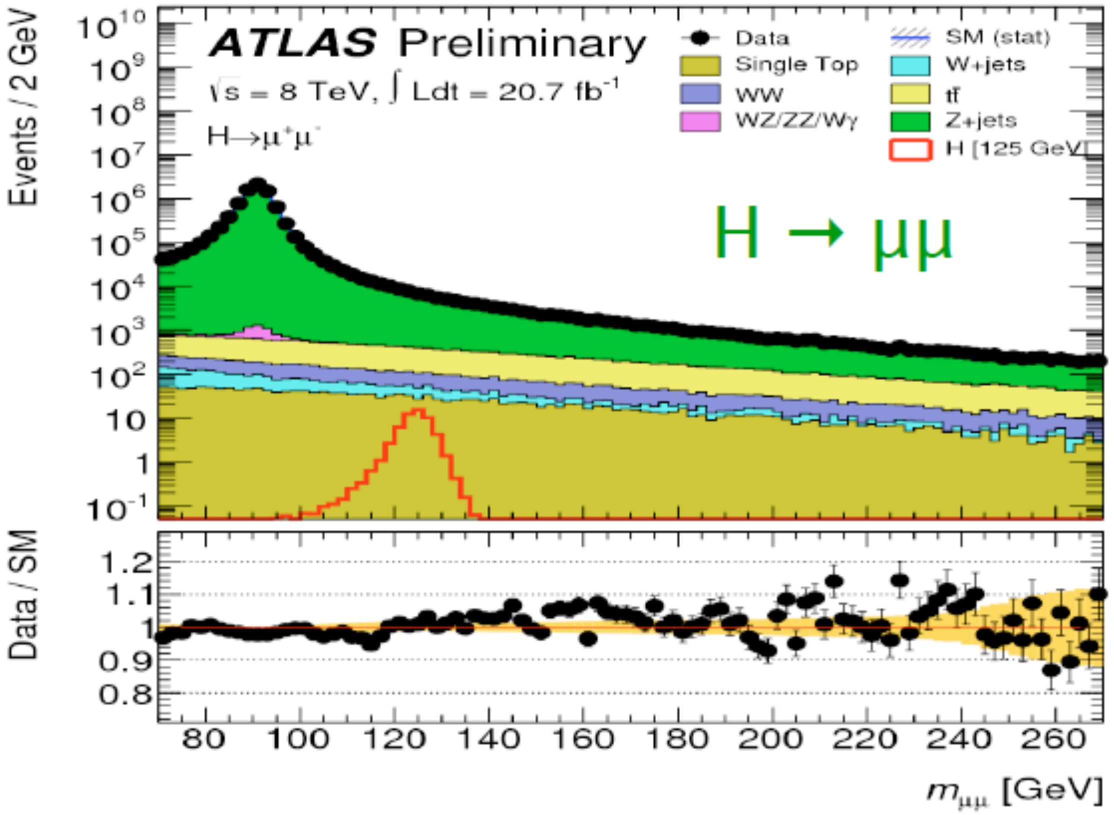
- Estrapolazione di due ordini di grandezza a luminosità più elevate
  - e' soggetta a grandi incertezze
  - gli scenari 1 e 2 si possono considerare come limite superiore ed inferiore
- Esperienze al LEP e Tevatron mostrano che uno scaling $1/\sqrt{L}$ non e' irreale

CMS Coupling	Uncertainty (%) 3000 fb^{-1} Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

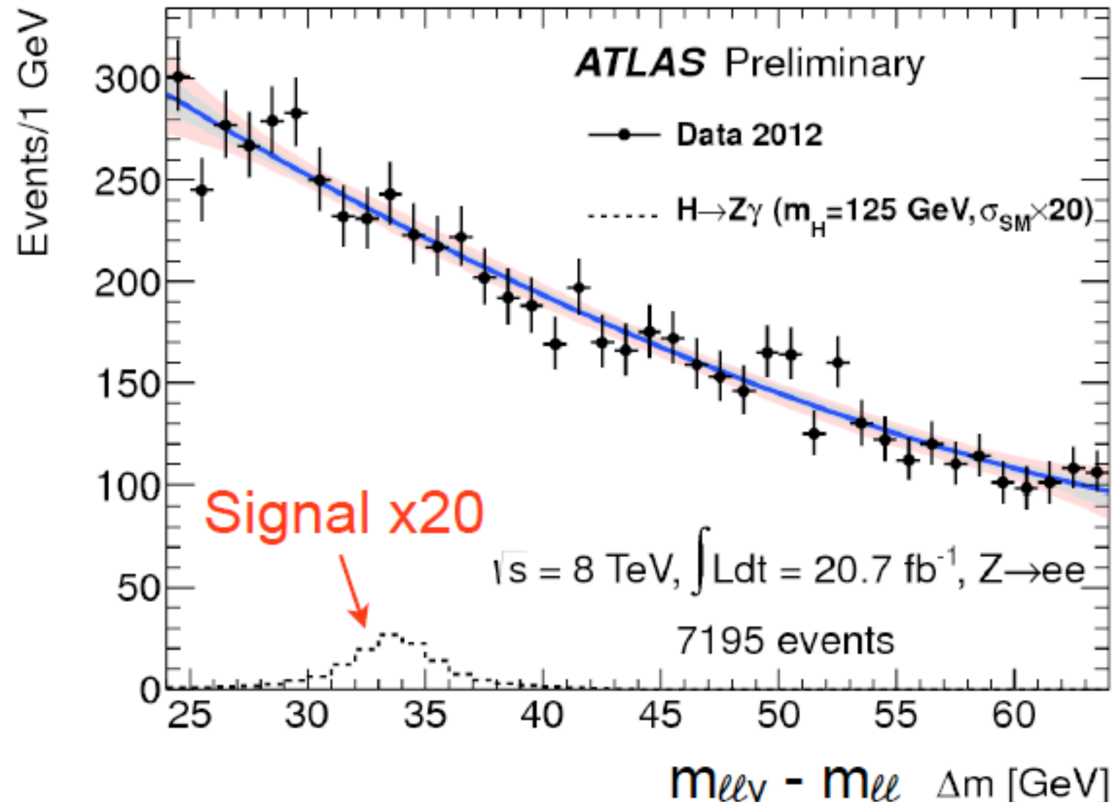
- Con 3000 fb^{-1} gli accoppiamenti del bosone di Higgs possono essere determinati con alta precisione (1-4%)

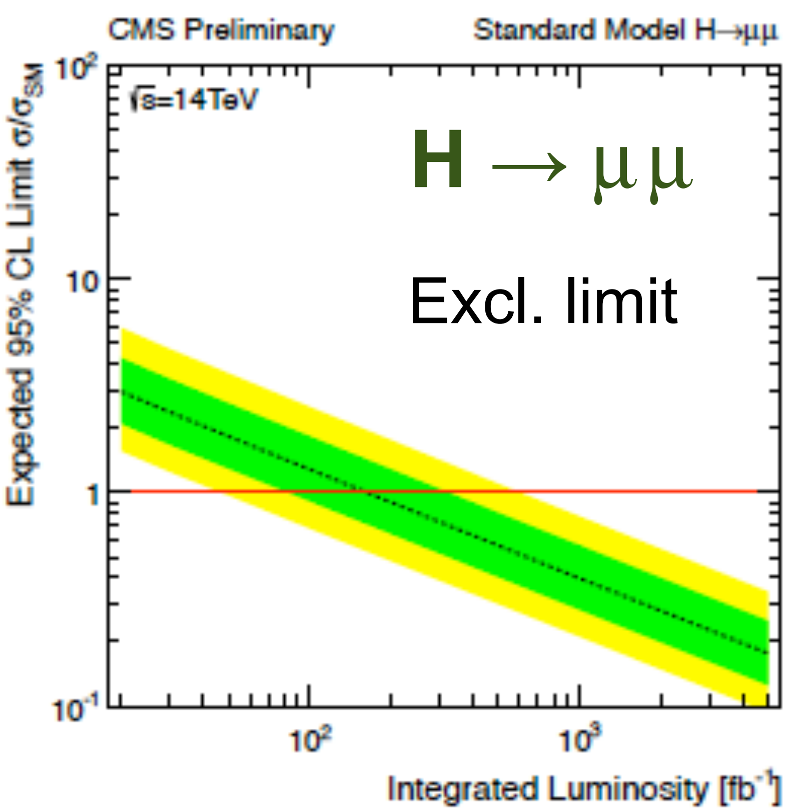
Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$

Decadimenti rari del bosone di Higgs

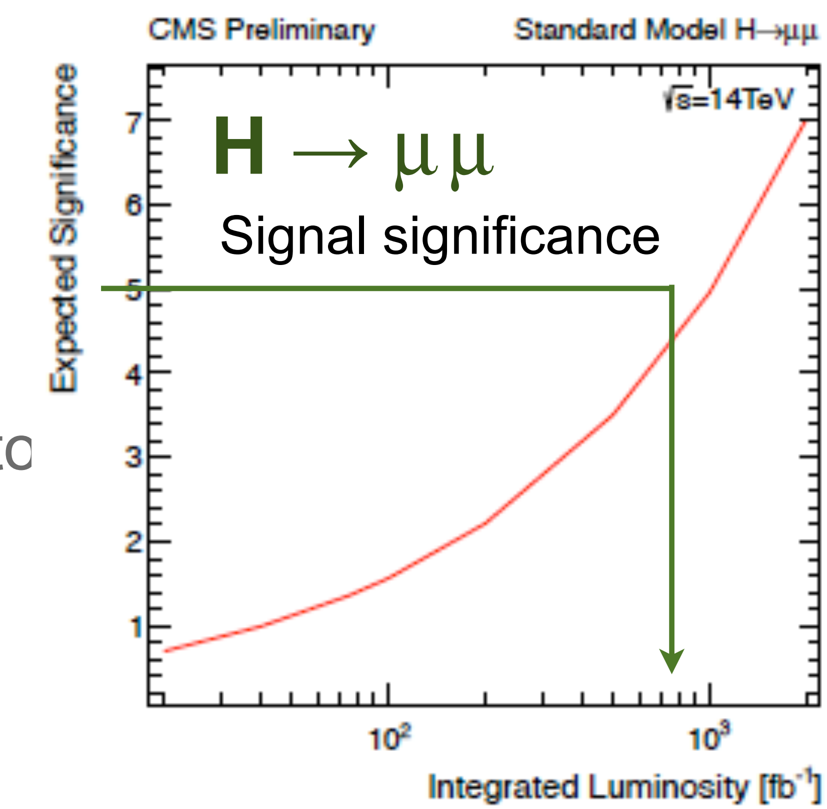


H → Z(ee)γ



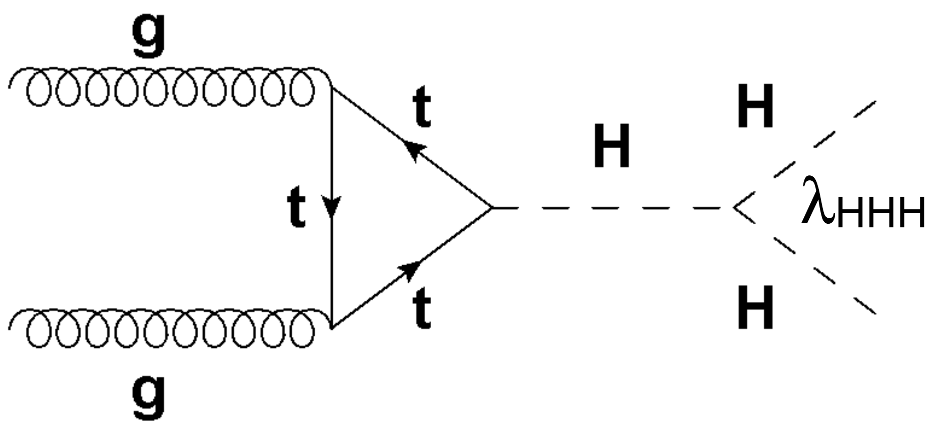


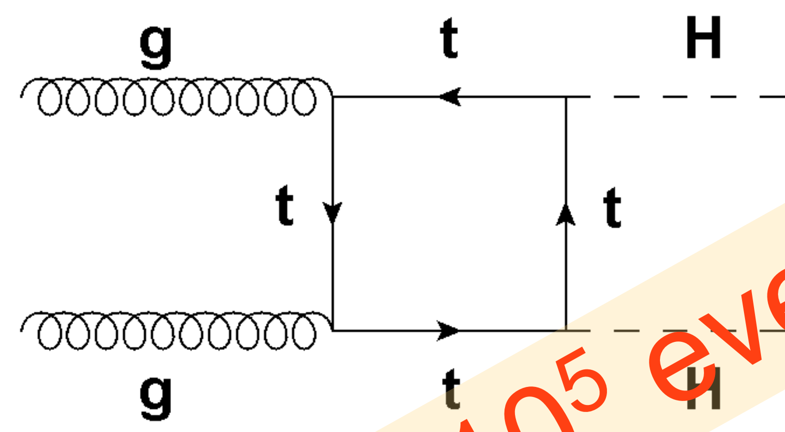
- Il decadimento H→μμ può essere osservato con una significatività di 5 sigma
  - misura dell'accoppiamento Hμμ con una precisione di ~10%



Higgs boson self-coupling

Destructive interference between the two diagrams





Taken from **"Higgs self-coupling measurements at the LHC"** by M. J. Dolan, C. Englert and M. Spannowsky, JHEP 10 (2012 112.

Many channels to investigate. Most promising ones:

$b\bar{b}W^+W^-$ (large BR but large bkg.)

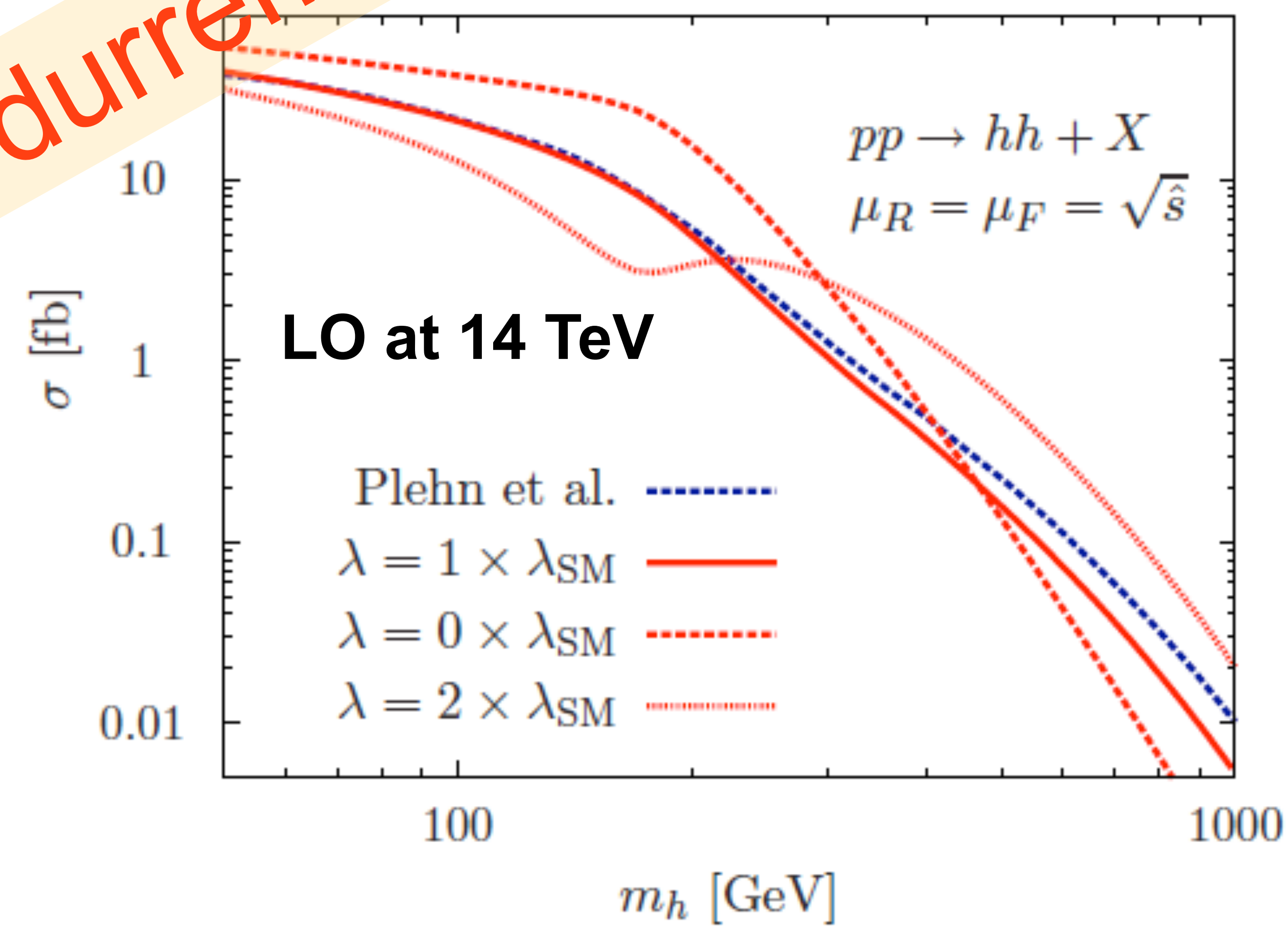
$b\bar{b}\gamma\gamma$ (clean but small BR)

$b\bar{b}\tau^+\tau^-$

$b\bar{b}\mu^+\mu^-$ also being considered

$b\bar{b}b\bar{b}$

Con L=3000 fb^{-1} produrremo 10^5 eventi HH

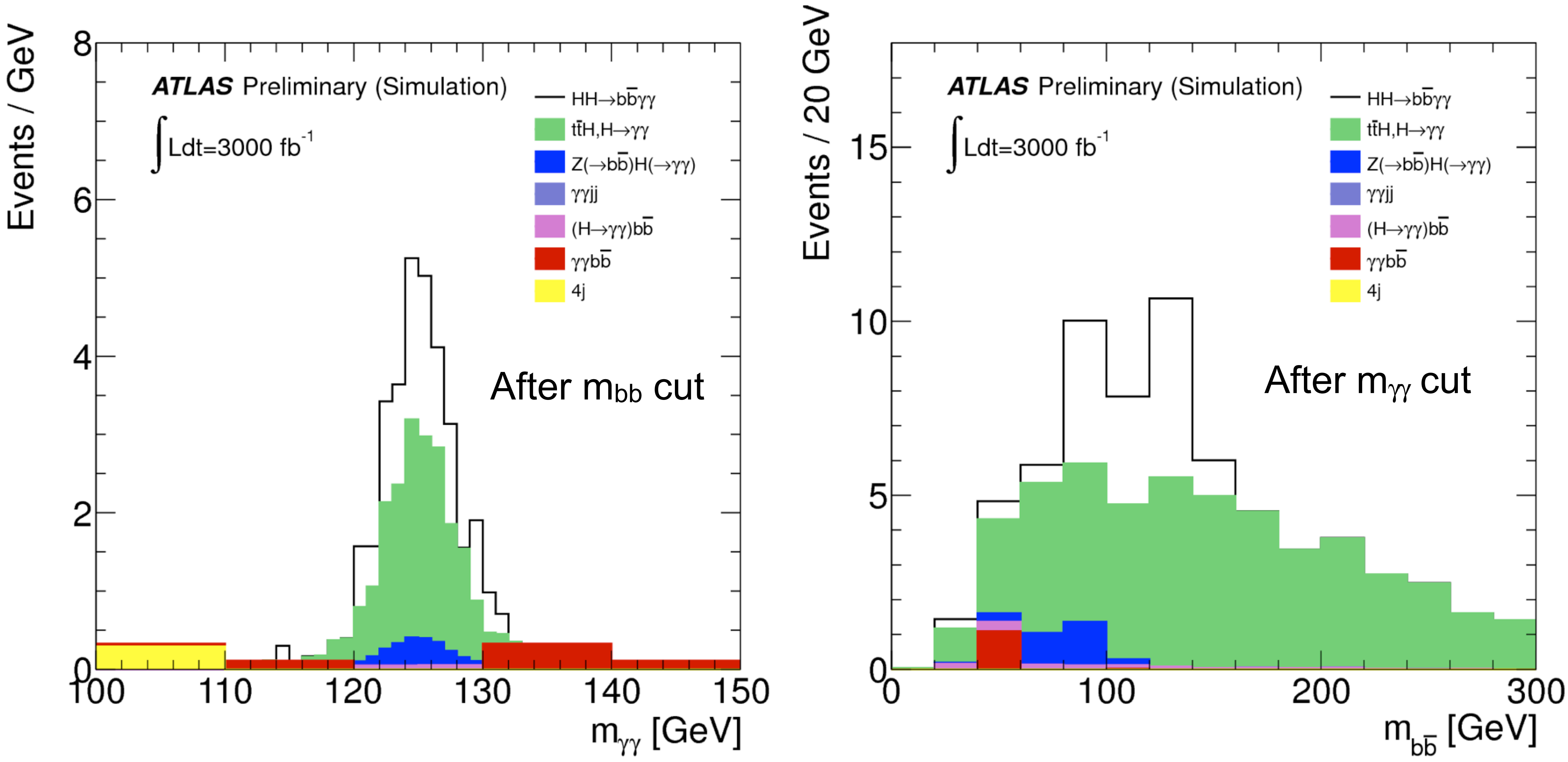


NLO cross-section at m_H=125 GeV:

σ = 34 fb$^{+18\%}_{-15\%}$ (QCD scale) ± 7% (PDF+α_s) ± 10% (EFT)

Higgs boson self-coupling

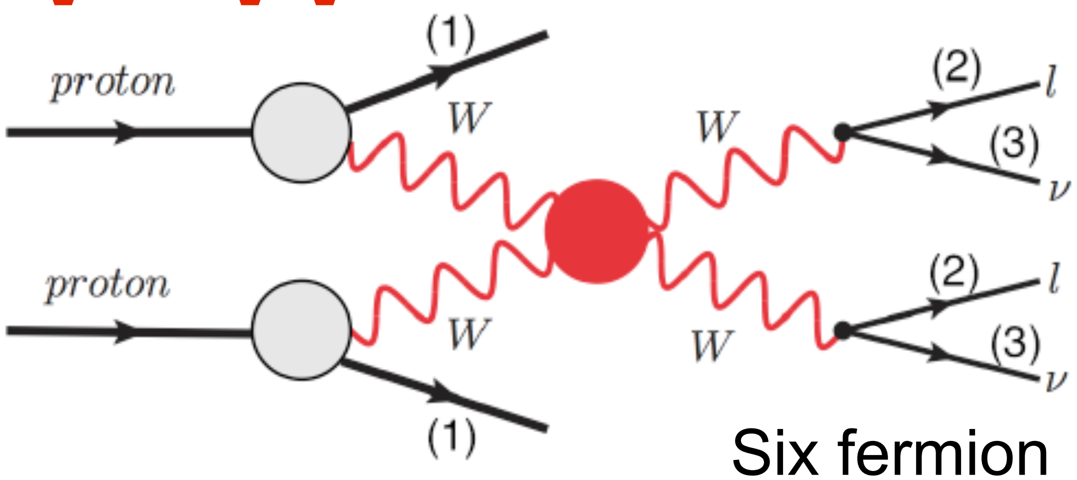
$HH \to b\bar{b}\gamma\gamma$



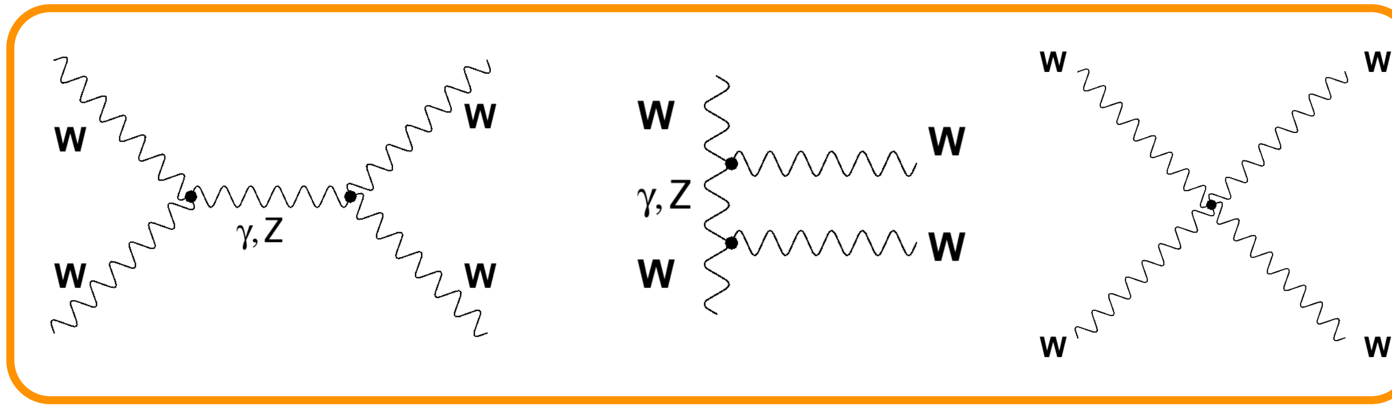
Con L=3000 fb^{-1} si otterrà una sensibilità di 3σ per esperimento

VV scattering: violazione unitarietà

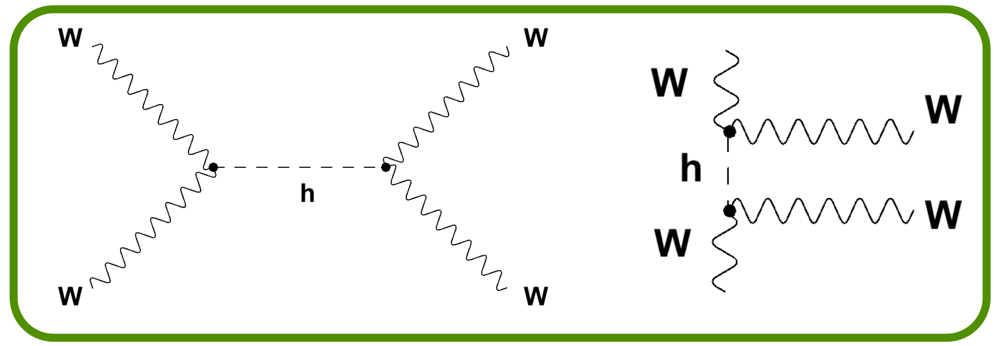
VV→VV



Six fermion final state



S channel **T channel** **QGC**



Senza il bosone di Higgs, $W^+_L W^-_L \to W^+_L W^-_L$ viola l'unitarietà a $\sqrt{s} \geq 1.2$ TeV

masse W, Z (→ gradi di libertà longitudinali) derivano dal meccanismo di Higgs:

$$A\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) \approx \frac{1}{v^2}\left(-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

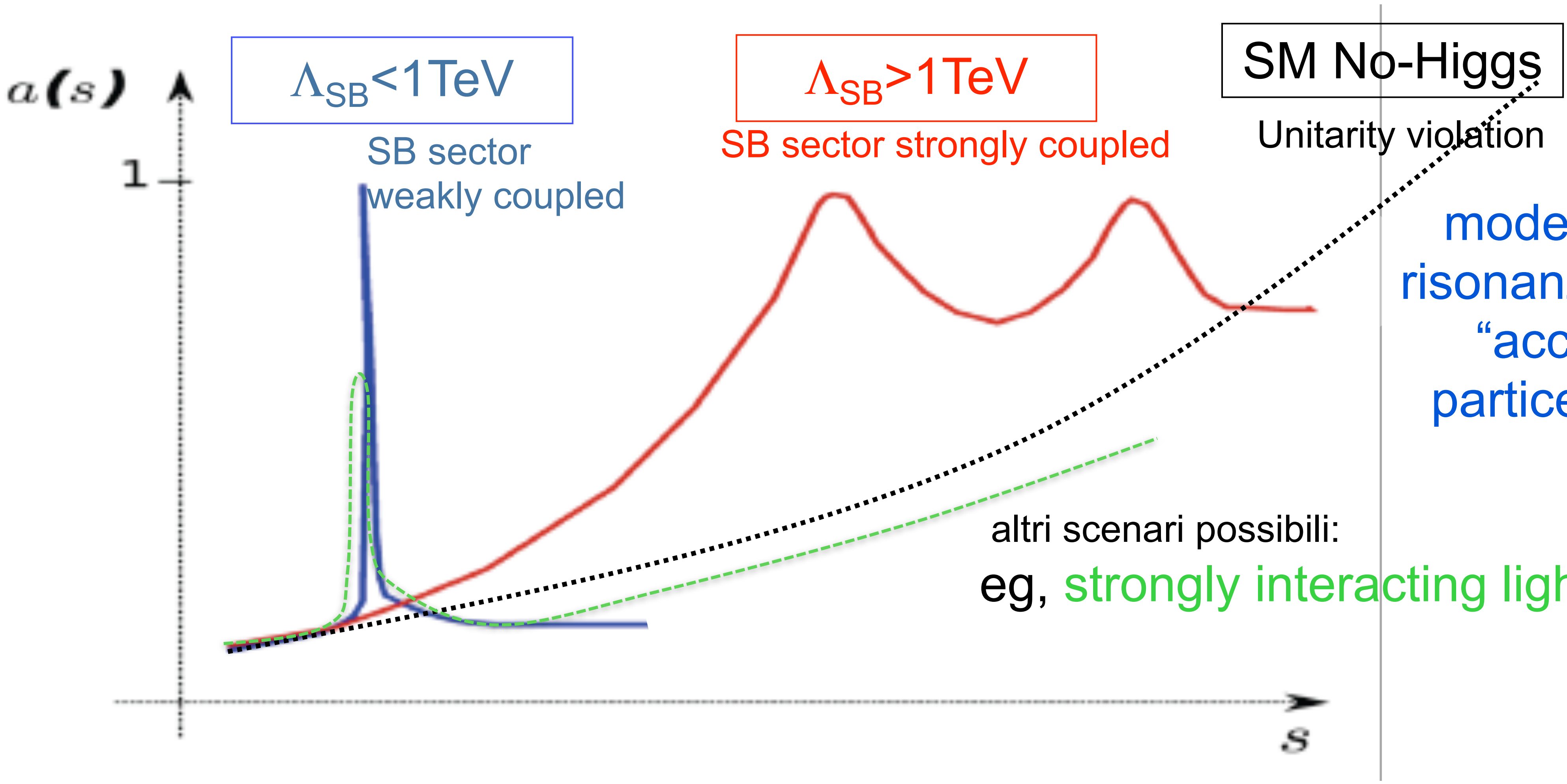
VV scattering is the smoking gun for EW Symmetry Breaking!

Taken from **"Prospects for VV scattering: latest news"** by S. Bolognesi (JHU) talk at Implications of LHC results for TeV-Scale physics (March 2012)

VV scattering come sonda per EWSB

VV Scattering spectrum, σ(VV→VV) vs M(VV)

e' la sonda fondamentale per verificare la natura del bosone di Higgs o per trovare un meccanismo alternativo dell'EW Symmetry Breaking

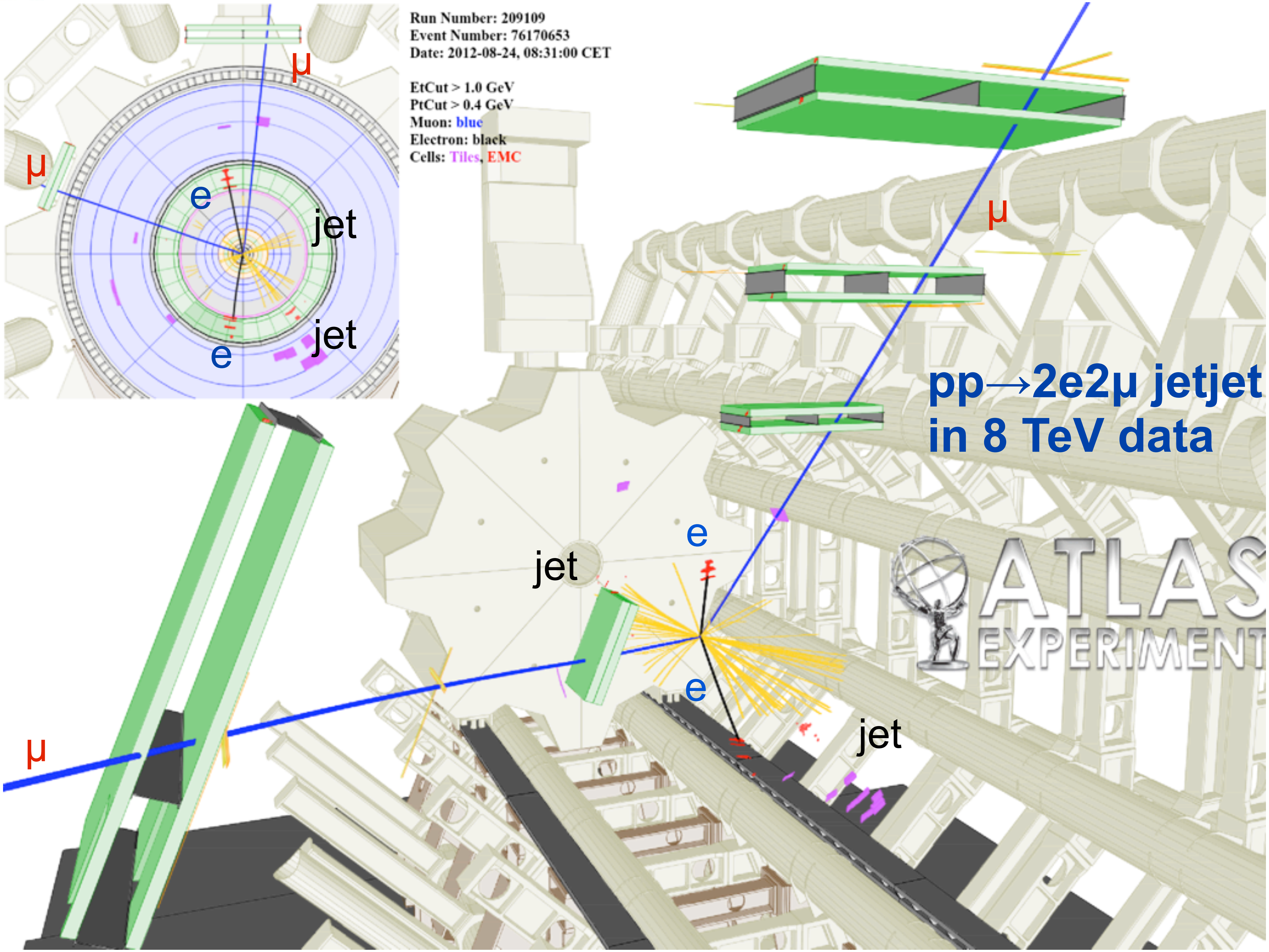


modelli BSM prevedono risonanze alla scala del TeV "accoppiate" con una particella scalare leggera

Ricerca di ulteriori risonanze nello spettro VBF

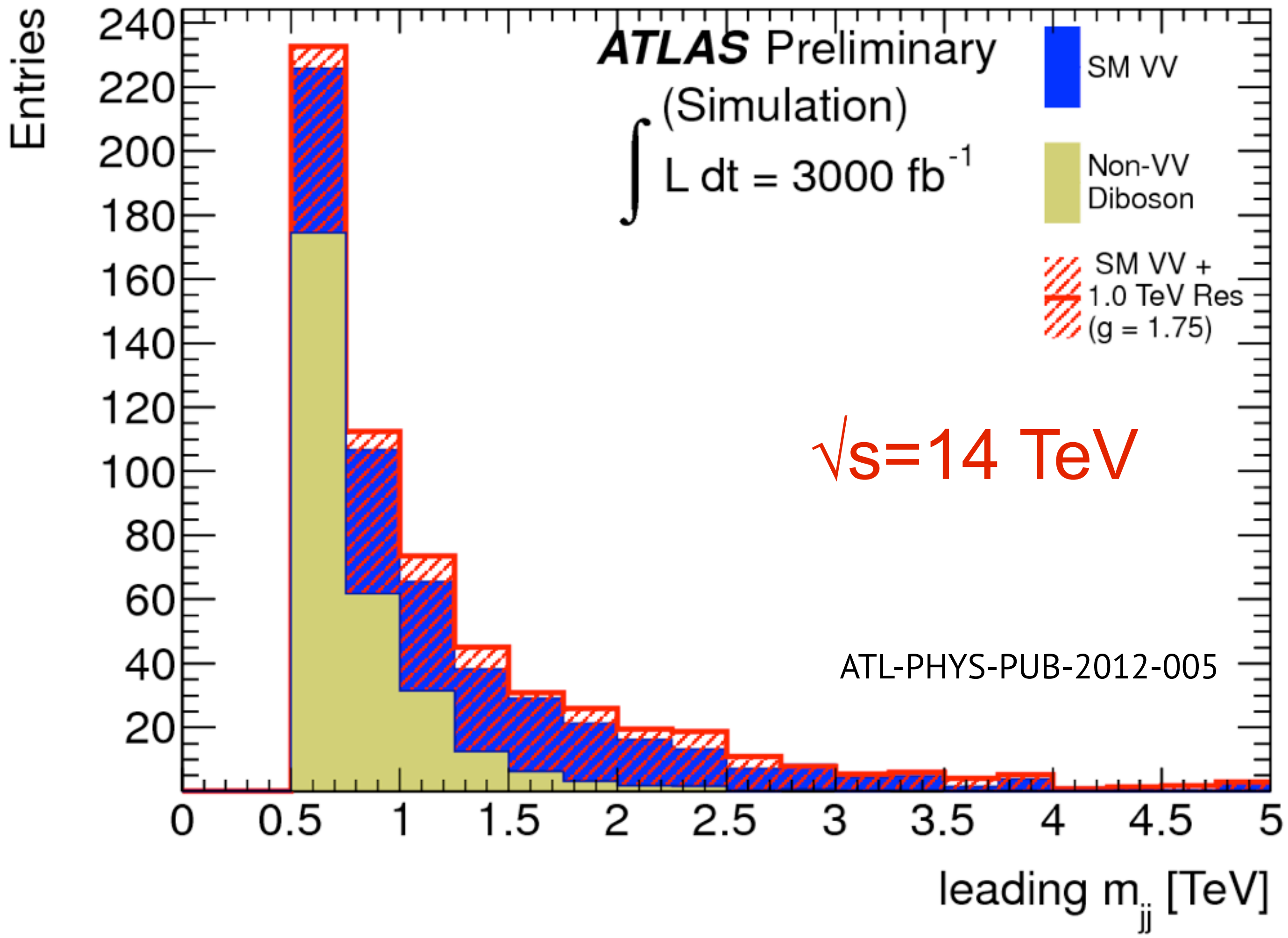
Adaptation from **"Boson Boson scattering analysis"** by A.Ballestrero (INFN Torino) talk at First LHC to Terascale Workshop (Sept 2011):

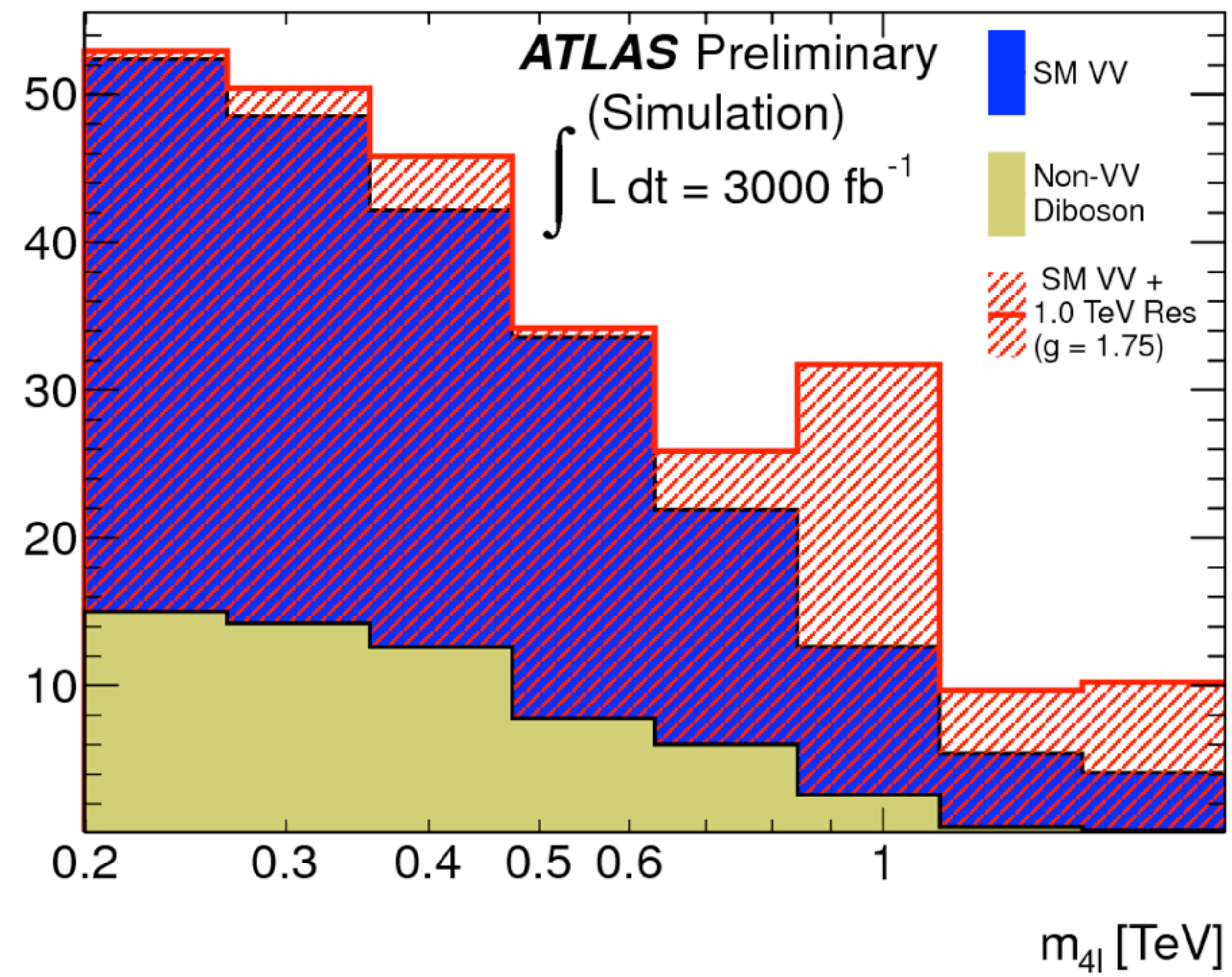
VBF 2e2μ candidate event



ZZ risonanze

pp→ZZ+2j→4ℓ+2j channel

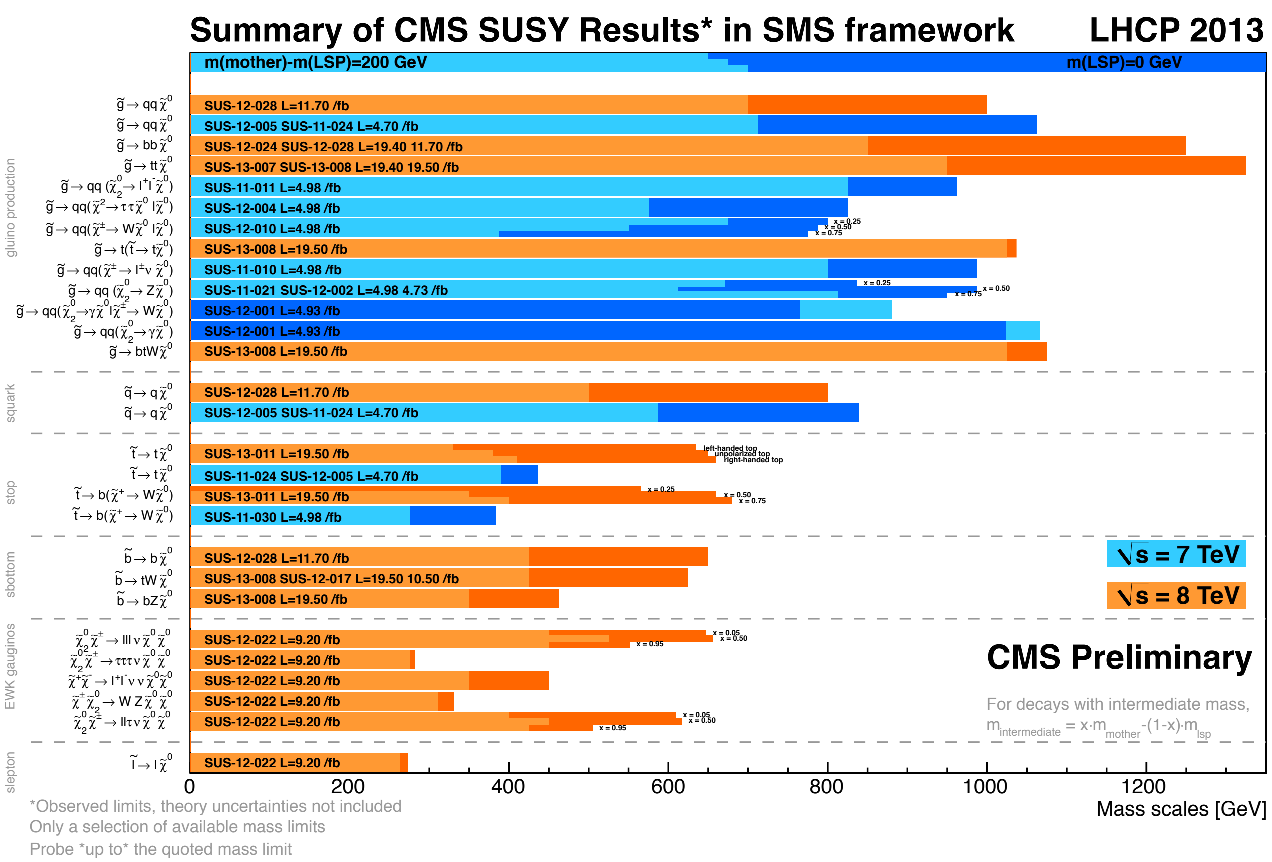


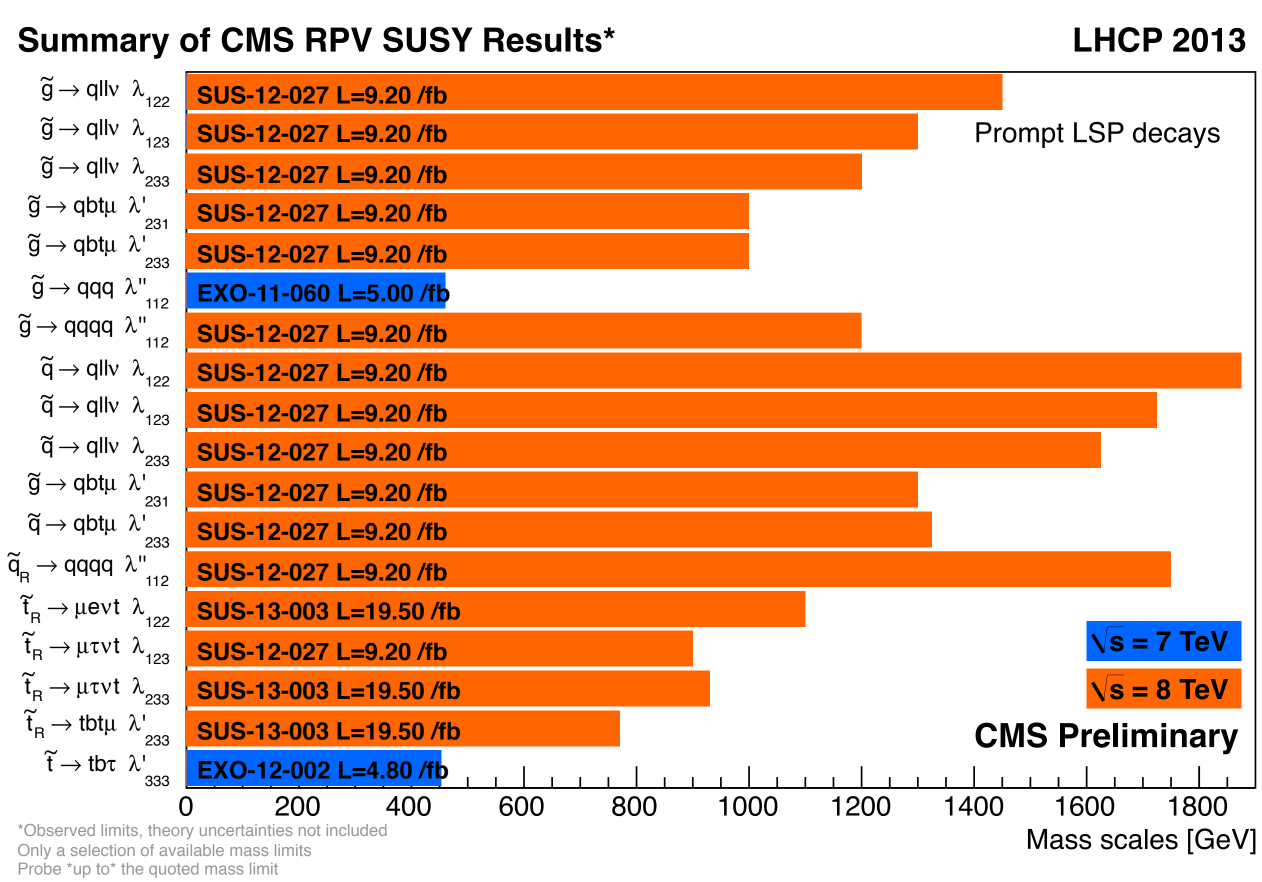


model	300 fb^{-1}	3000 fb^{-1}
$m_{resonance}$ = 500 GeV, $g = 1.0$	2.4σ	7.5σ
$m_{resonance}$ = 1 TeV, $g = 1.75$	1.7σ	5.5σ
$m_{resonance}$ = 1 TeV, $g = 2.5$	3.0σ	9.4σ

Sensibilità a risonanze anomale ZZ in Vector boson scattering

SUSY



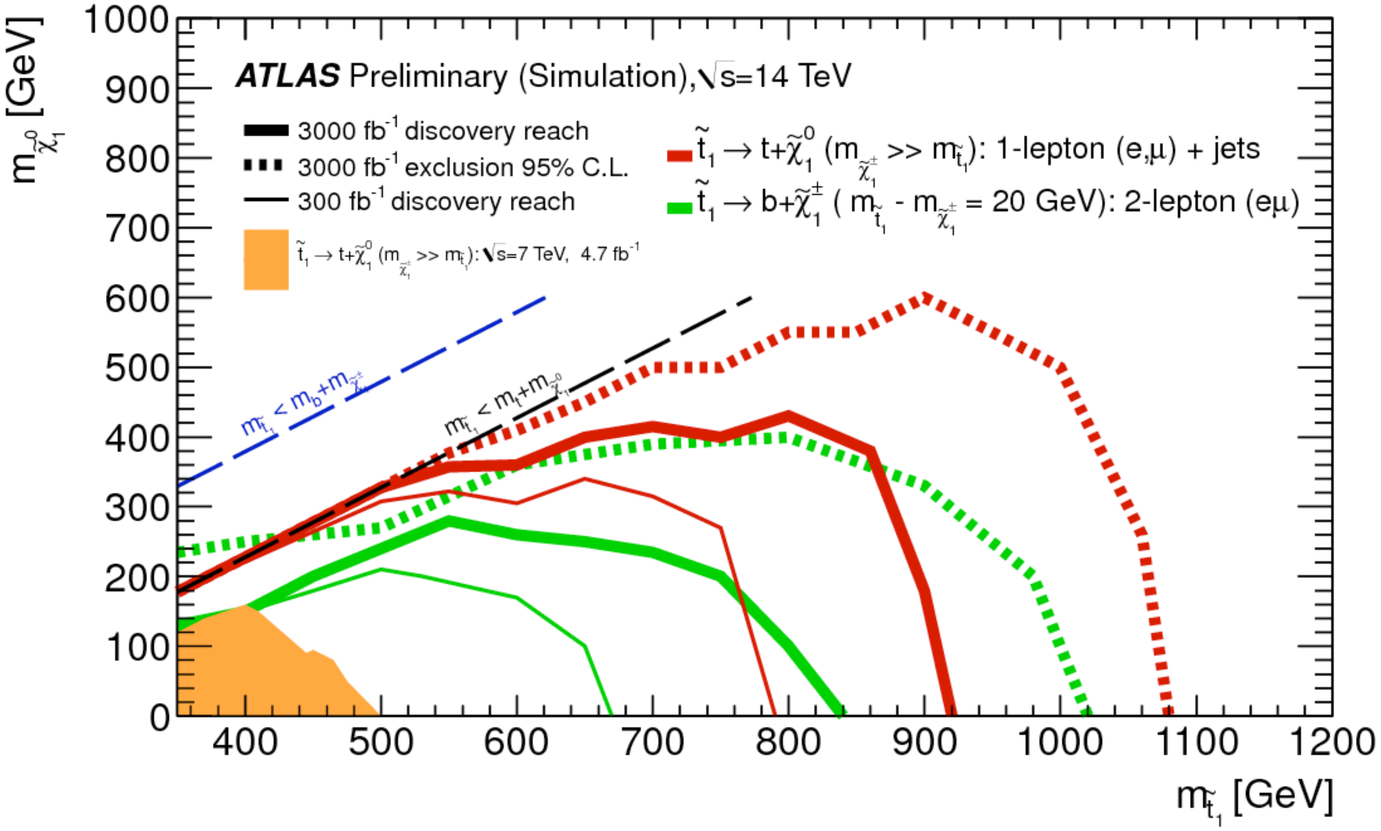


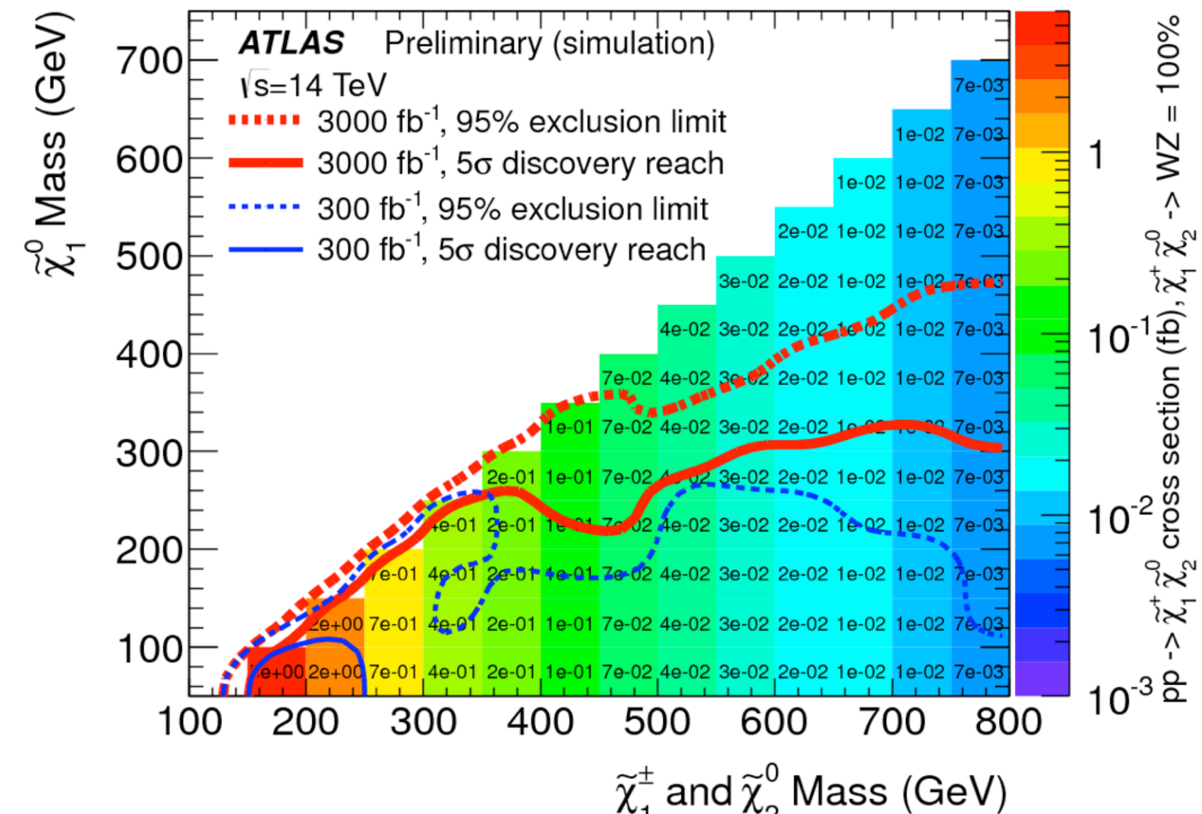
Purtroppo nessun segnale...

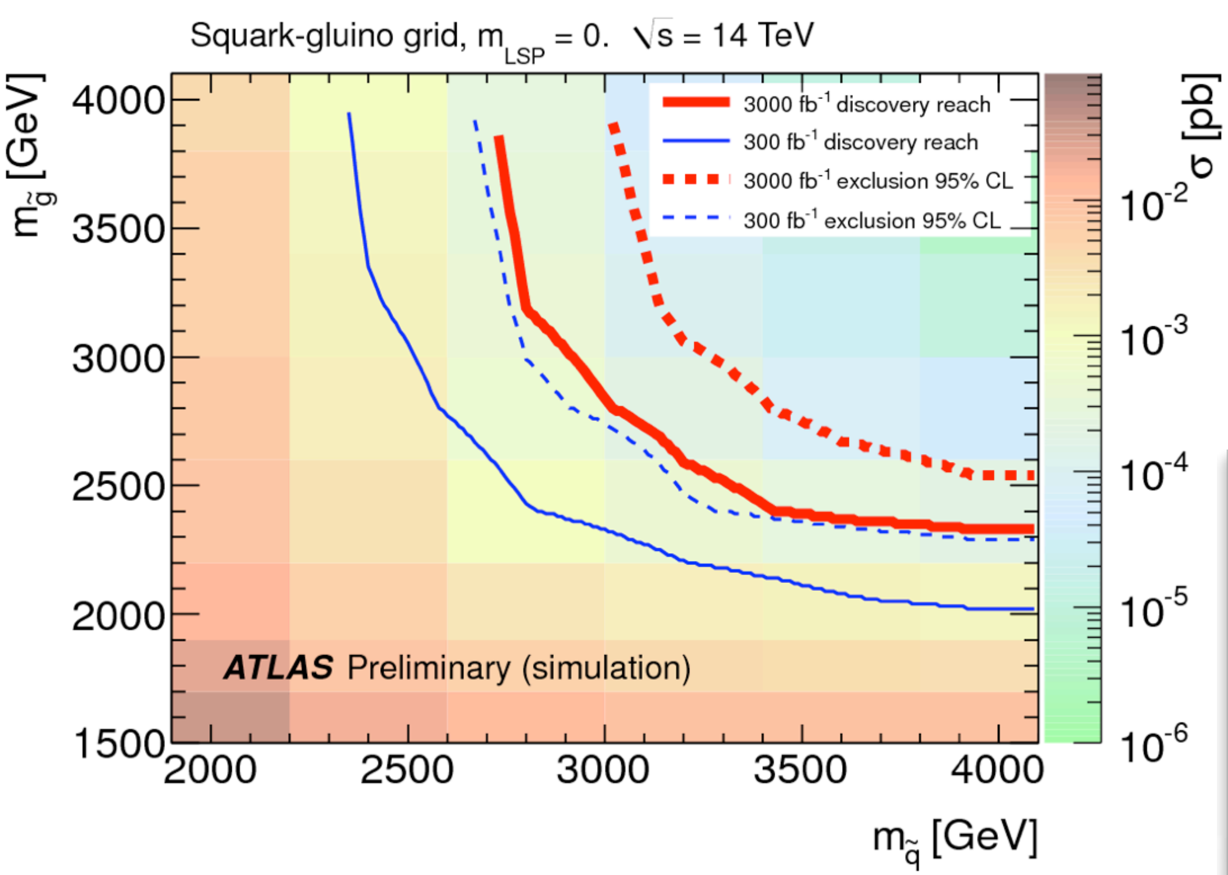
SUSY limiti odierni

EWKinos	~200-400 GeV
Stop, sbottoms	~200-600 GeV
Squarks, gluinos	~600-1300 GeV

SUSY reach at higher luminosity





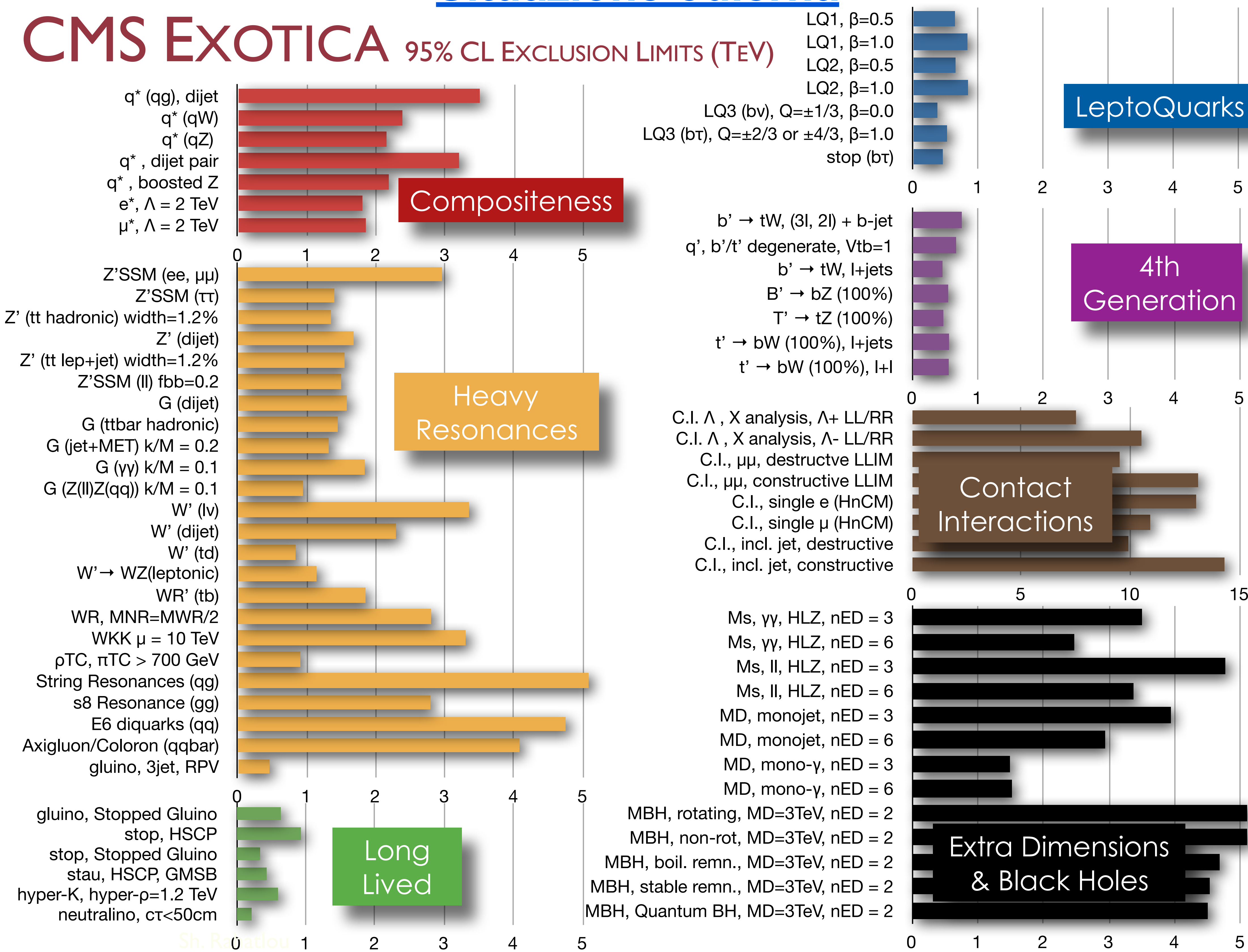


SUSY reach with 300 fb^{-1}
EWKinos fino a ~ 800 GeV
Stops,sbottoms fino a ~ 1TeV
squarks,gluinos fino a ~2.5 TeV

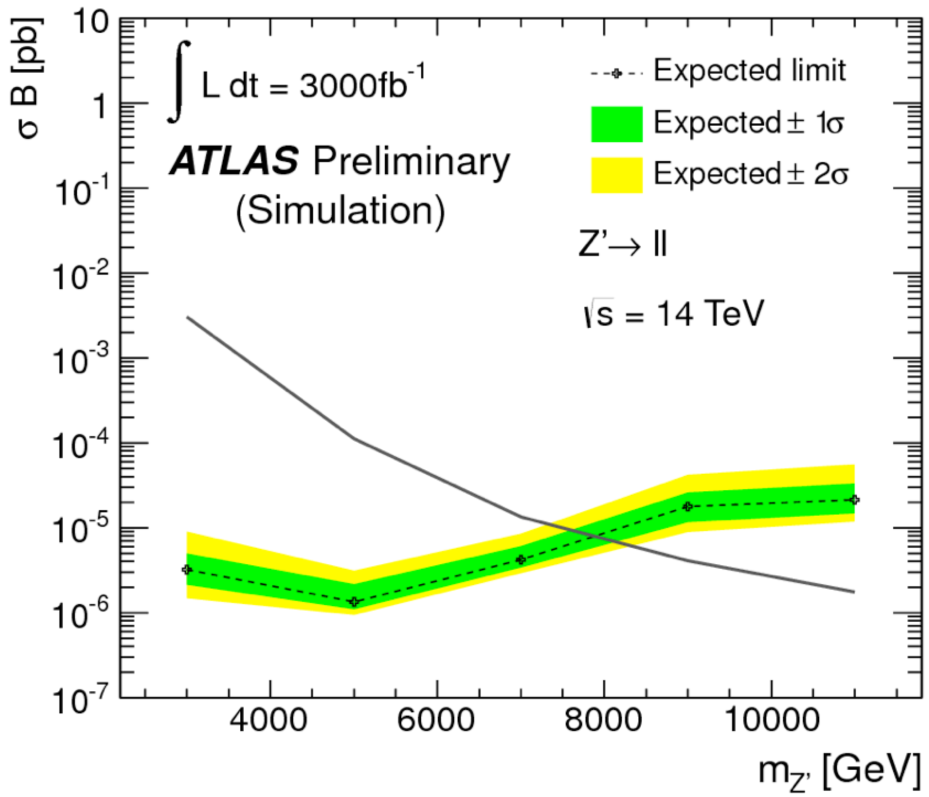
Andado da L=300 fb^{-1} a L=3000 fb^{-1} la sensibilità a squarks di 1^a and 2^a gen. e ai gluinos migliora di ~400-500 GeV, mentre per gli stops di circa 200 GeV

Fisica oltre il Modello Standard

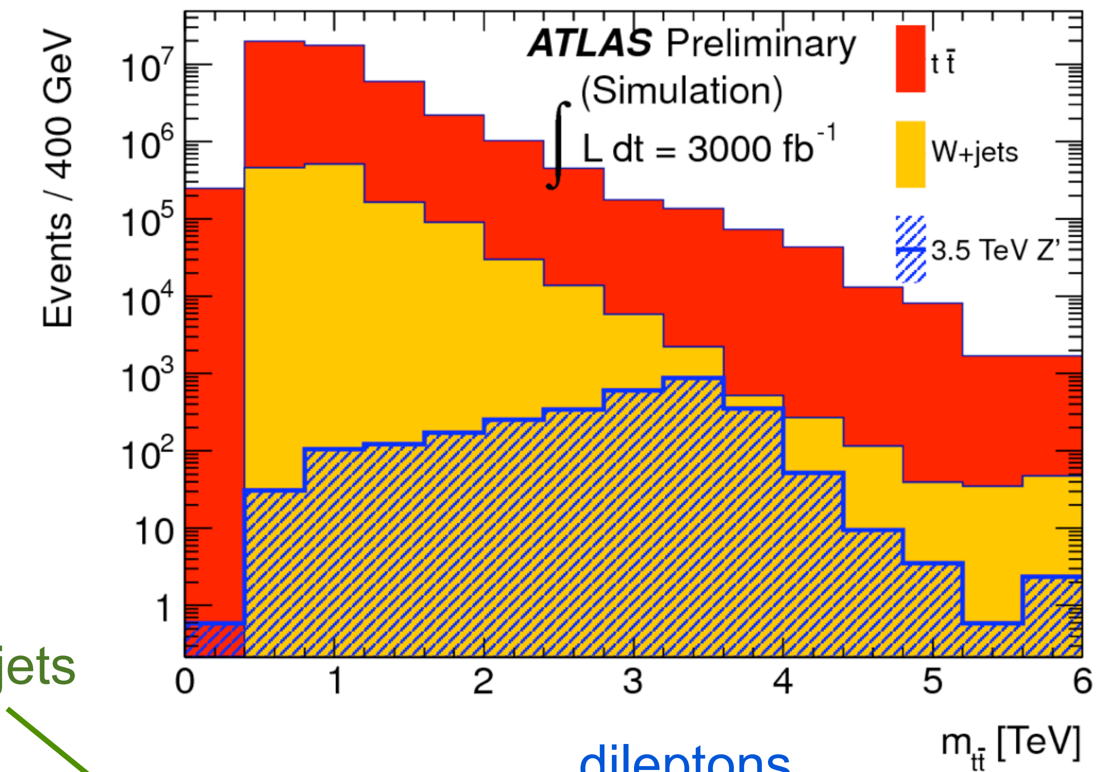
Situazione odierna



Fisica oltre lo SM a HL-LHC



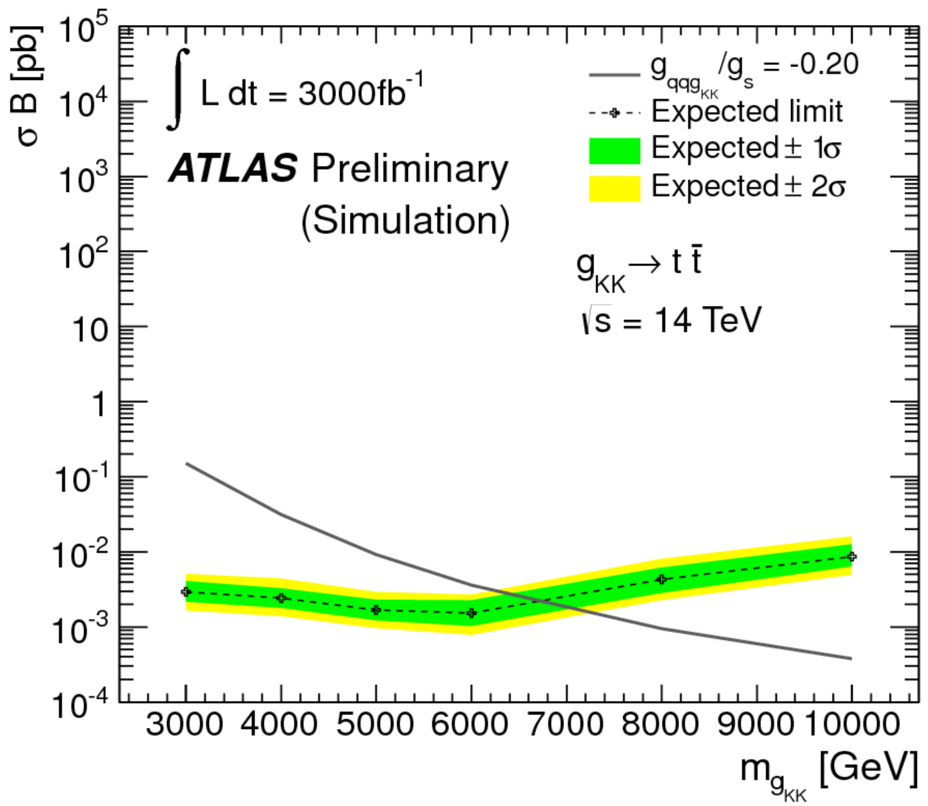
Z' Topcolour



lepton+jets

dileptons

Kaluza-Klein gluons in extra-dimensional models



model	$300\ fb^{-1}$	$1000\ fb^{-1}$	$3000\ fb^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{Topcolour}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

Limiti attesi per varie topologie nello Sequential Standard Model. Tutti i limiti in massa sono in TeV.

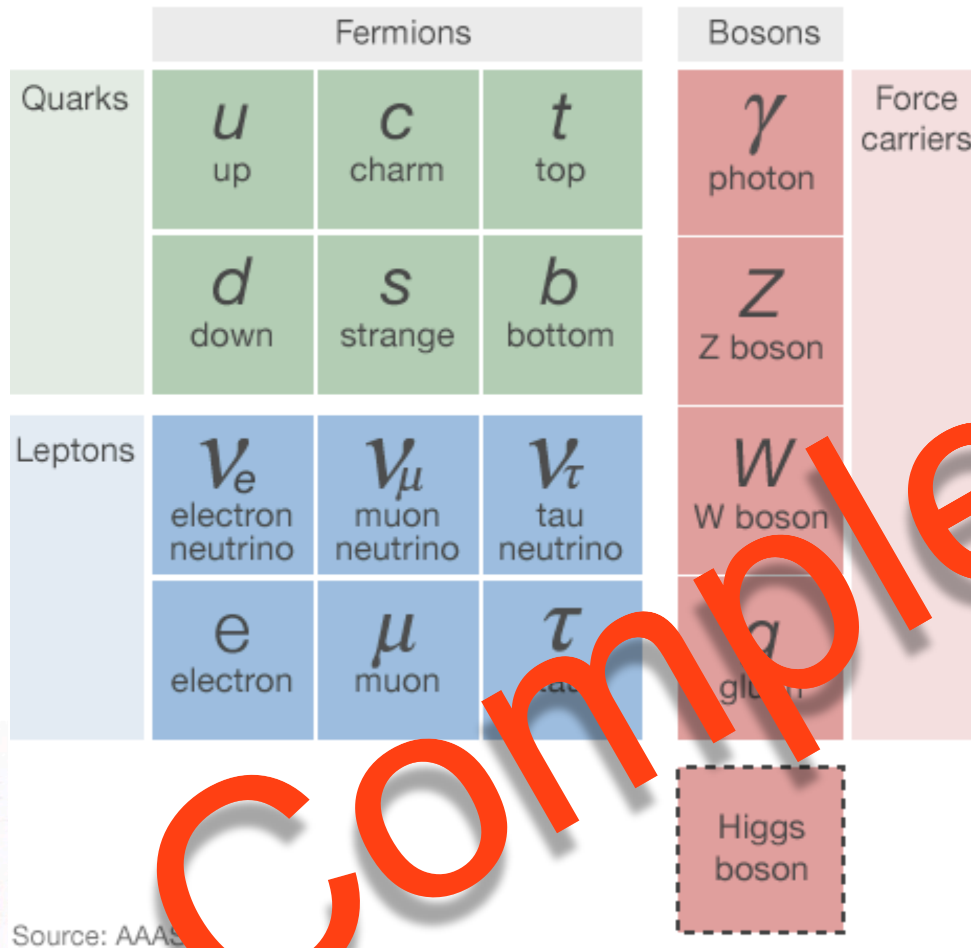
Conclusioni

- ATLAS e CMS hanno superato le previsioni nel primo run di presa dati a LHC.
- Questo ha portato alla scoperta di un nuovo bosone compatibile con il bosone di Higgs del Modello Standard.
- La nuova energia nel centro di massa prevista per il 2015 apre una nuova interessantissima finestra su fisica oltre il Modello Standard.
- Un ambizioso programma di upgrade dei rivelatori e' cominciato per assicurare il funzionamento nei futuri runs ad alta luminosità in condizioni sperimentalmente assai più difficili.
- HL-LHC permetterà di misurare con alta precisione le caratteristiche del nuovo bosone e di studiare fenomeni estremamente rari.

LHC ha un programma di fisica estremamente interessante per i prossimi 20 anni!

Higgs memorabilia...

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



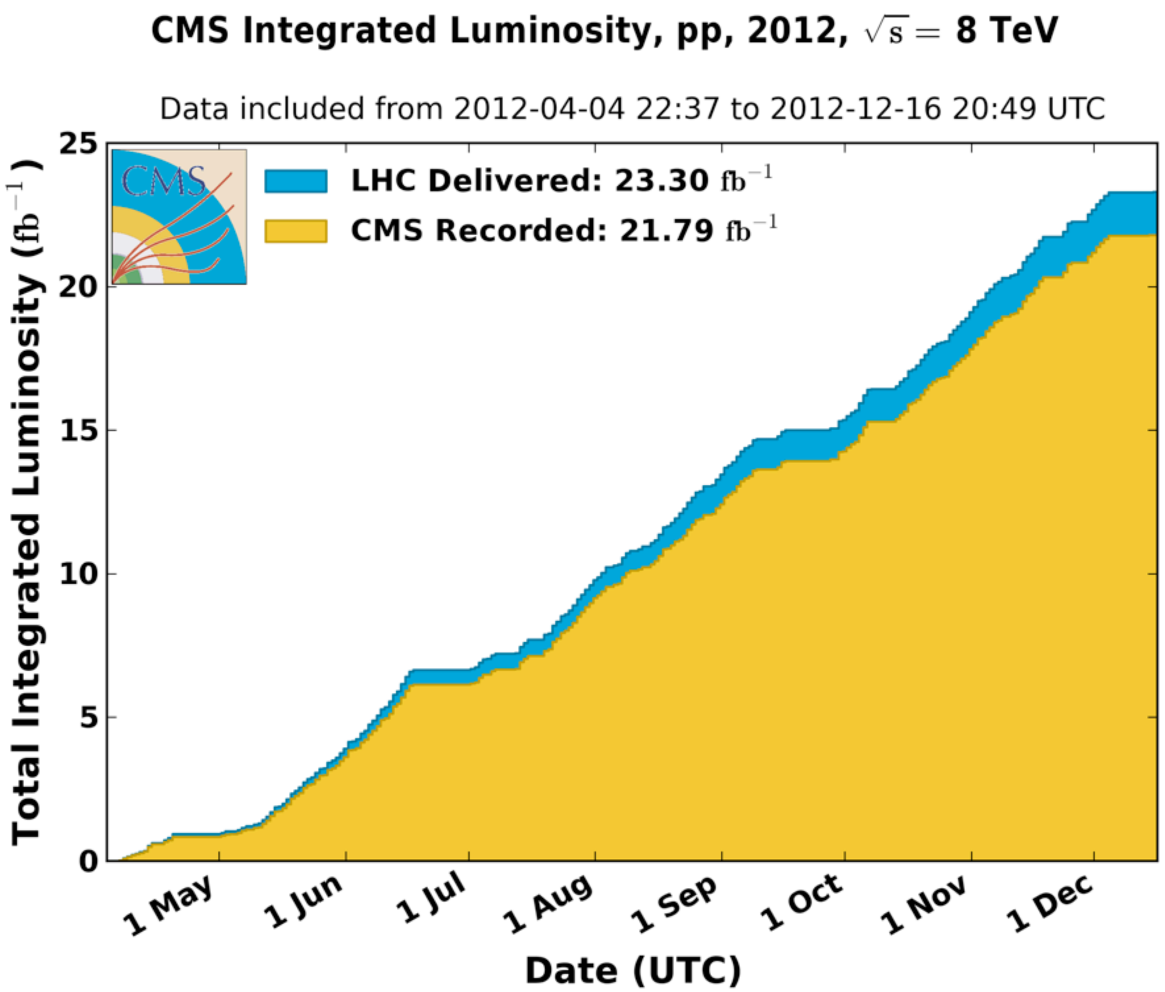
Buon Compleanno!

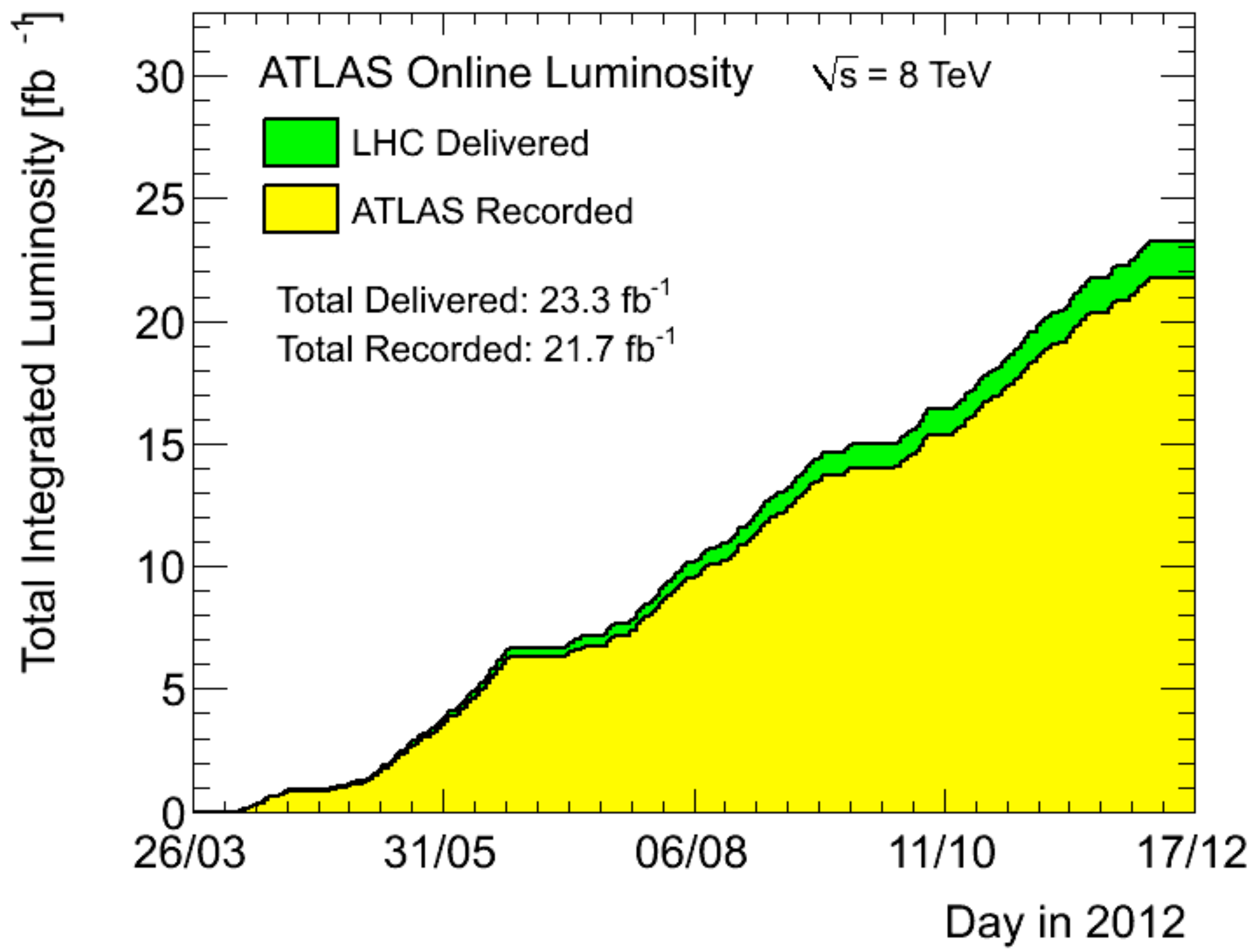
Backup

Integrated luminosity in 2012

Integrated luminosity recorded in 2012: **~22 fb^{-1}**

2011: L=~6 fb^{-1}





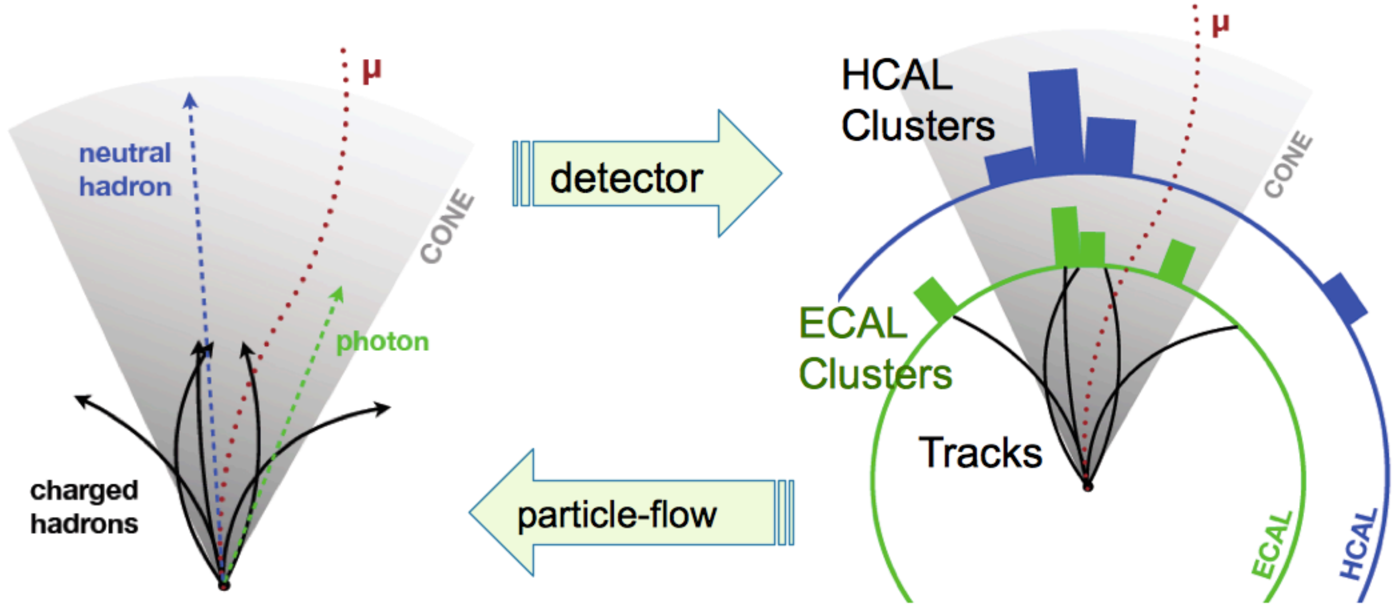
Total delivered luminosity: **~30 fb^{-1}**

Total recorded luminosity: **~27 fb^{-1}**

Excellent LHC performance and very high data-taking efficiency of the two detectors

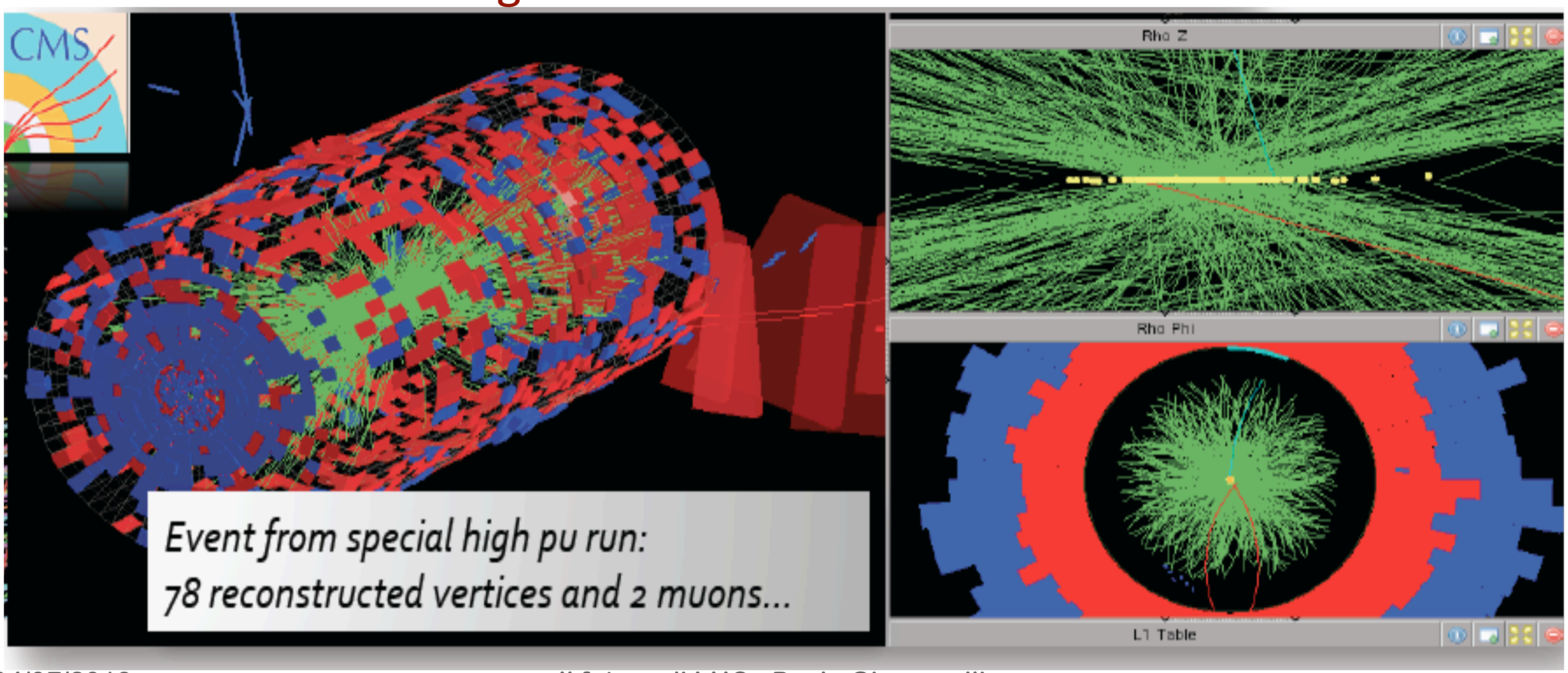
Upgrade challenges and recipe

Maintain low trigger thresholds, efficient particle and physics object reconstruction at high rate and pile-up



Need new technology R&Ds to:

- Increase granularity
- Increase data bandwidth
- Increase processing power
- Improve radiation hardness
- Minimize material in tracking devices

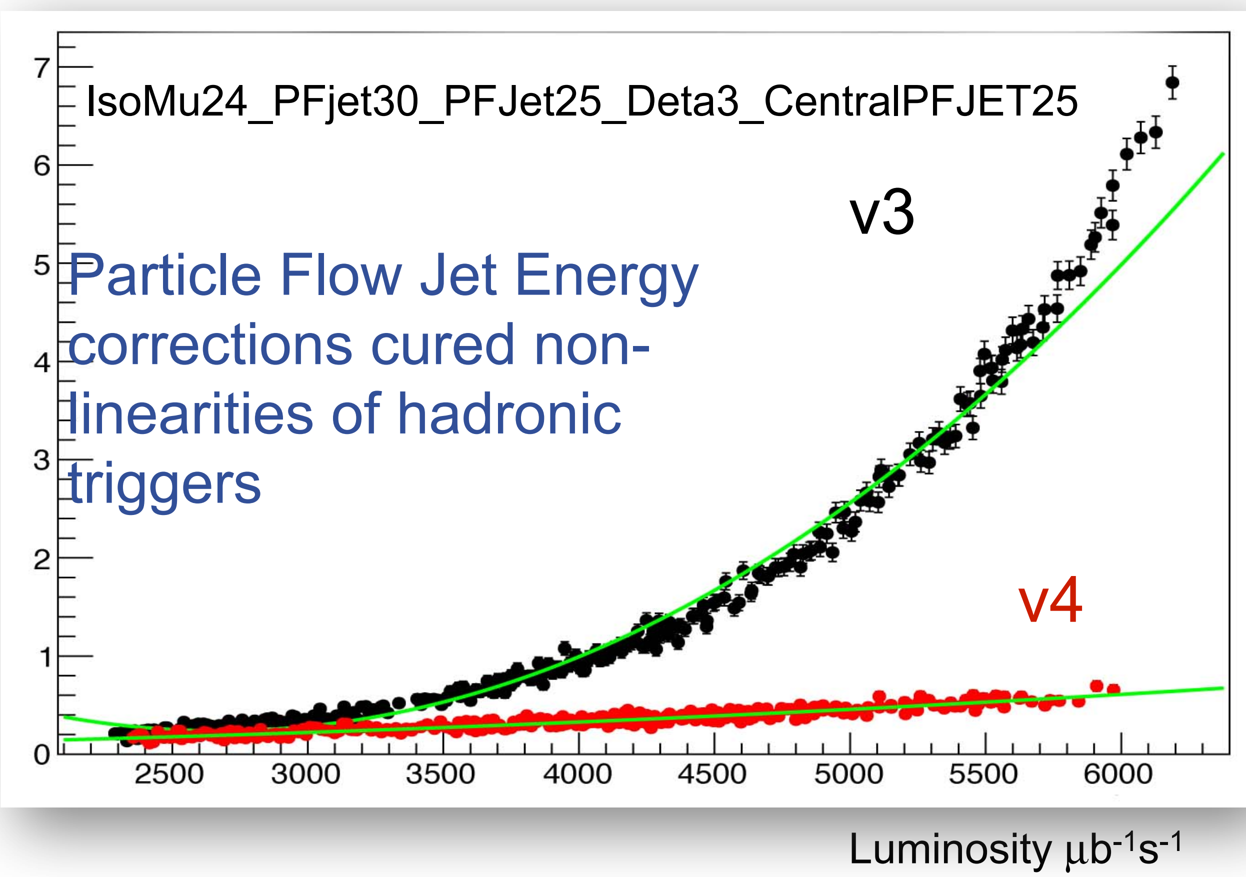


Trigger challenge in 2012

Maintaining high trigger efficiency while keeping the trigger rate within budget was one of the biggest challenges of the CMS experiment in 2012

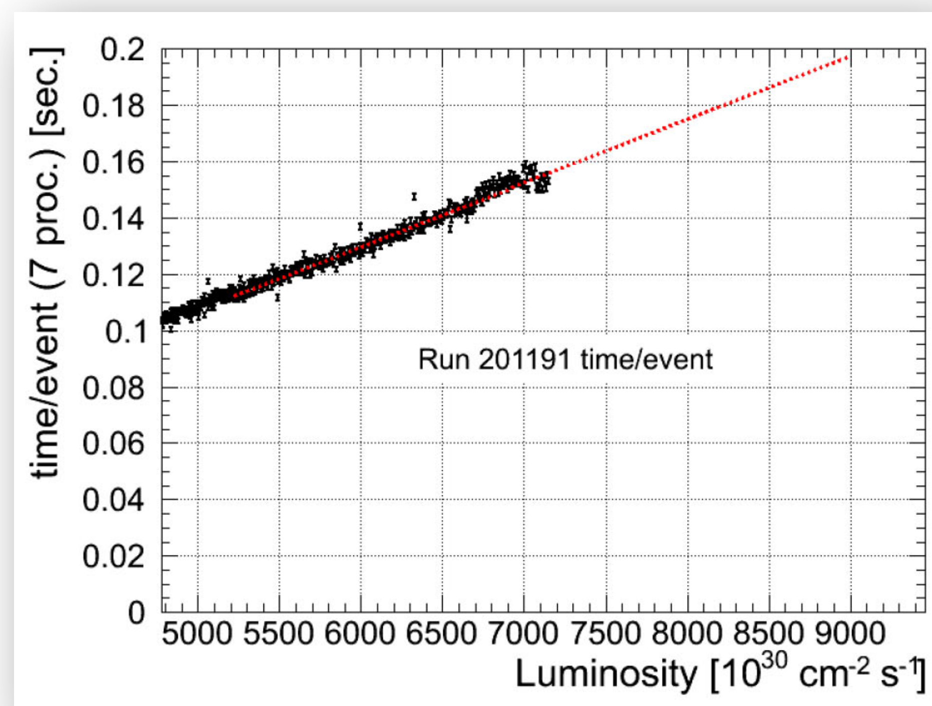
The experience obtained in 2012 with peak pileup of ~35 events gives us confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:



HLT CPU time:

- linear with PU, no signs of runaway

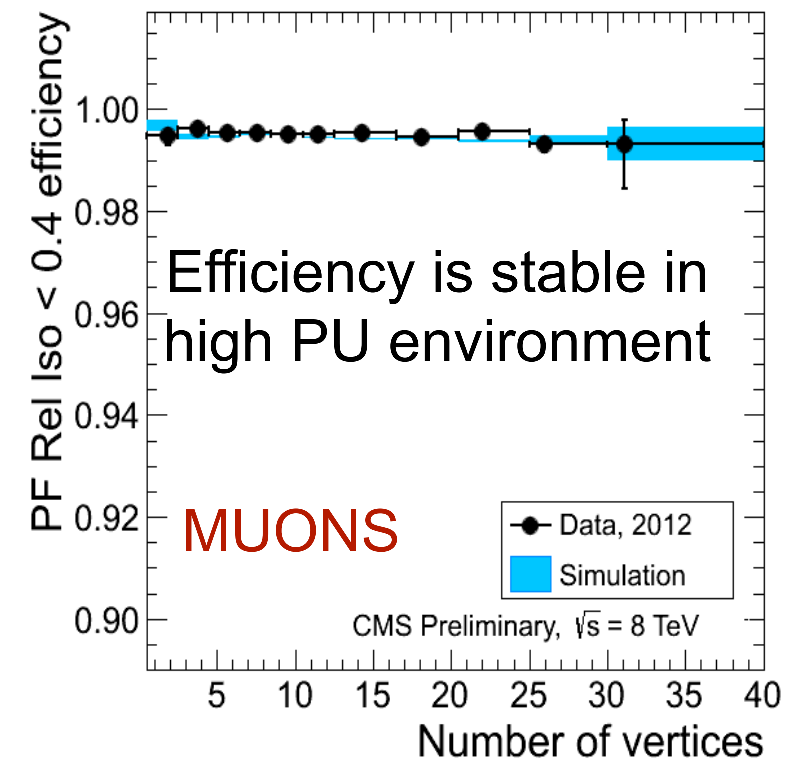


Pileup challenges

Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity:

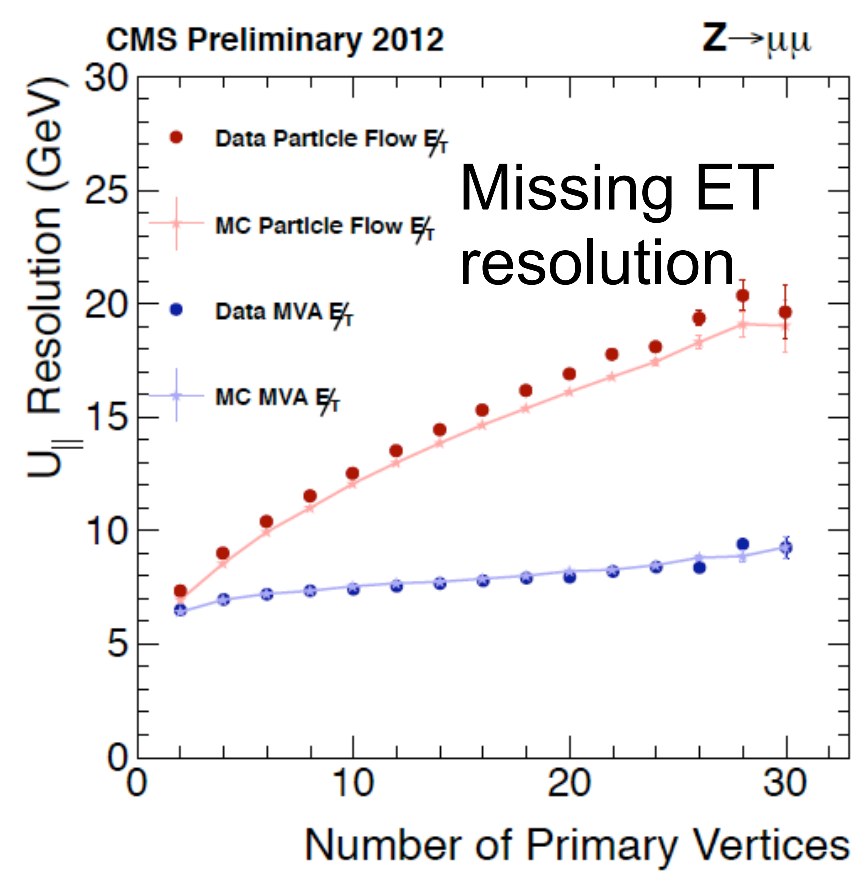
- efficient association of charged tracks to collision vertices
- reconstruction of charged and neutral particles in jets
- pileup neutrals corrected w/global energy density (ρ)

Muon isolation



Physics with high pileup requires full particle flow reconstruction assuring:

- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation



Very efficient reconstruction code is needed to stay within computing budget

From 2013 to HL-LHC

- From 30 to 3000 fb^{-1}: two orders of magnitude extrapolation in luminosity

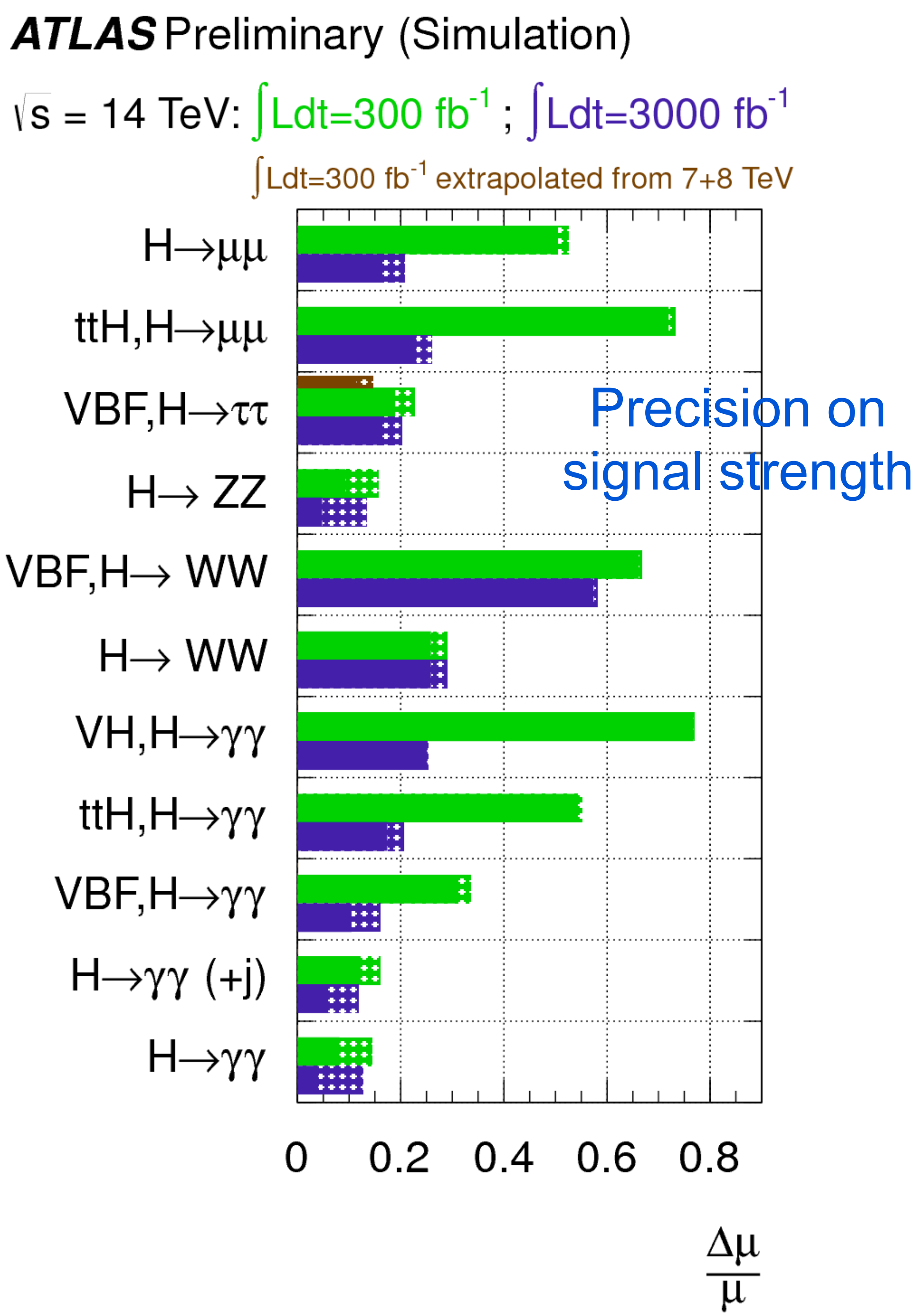
To calculate physics projections at HL-LHC

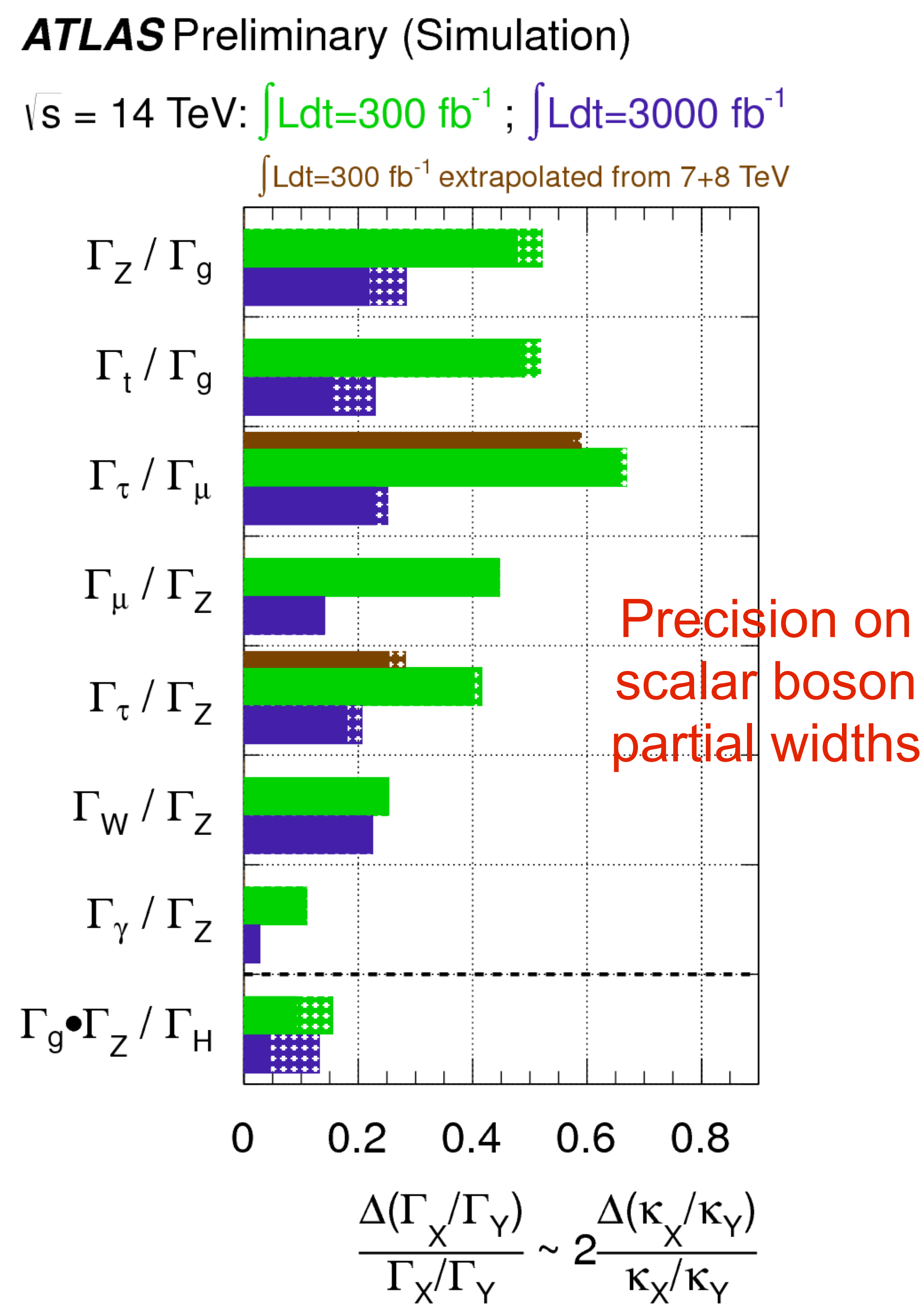
Similar trigger and reconstruction peformances as in 2012

Need upgraded detectors to offset the much harsher LHC conditions and radiation damage

ATLAS and CMS have launched a comprehensive upgrade program

Higgs boson couplings @3000 fb^{-1}

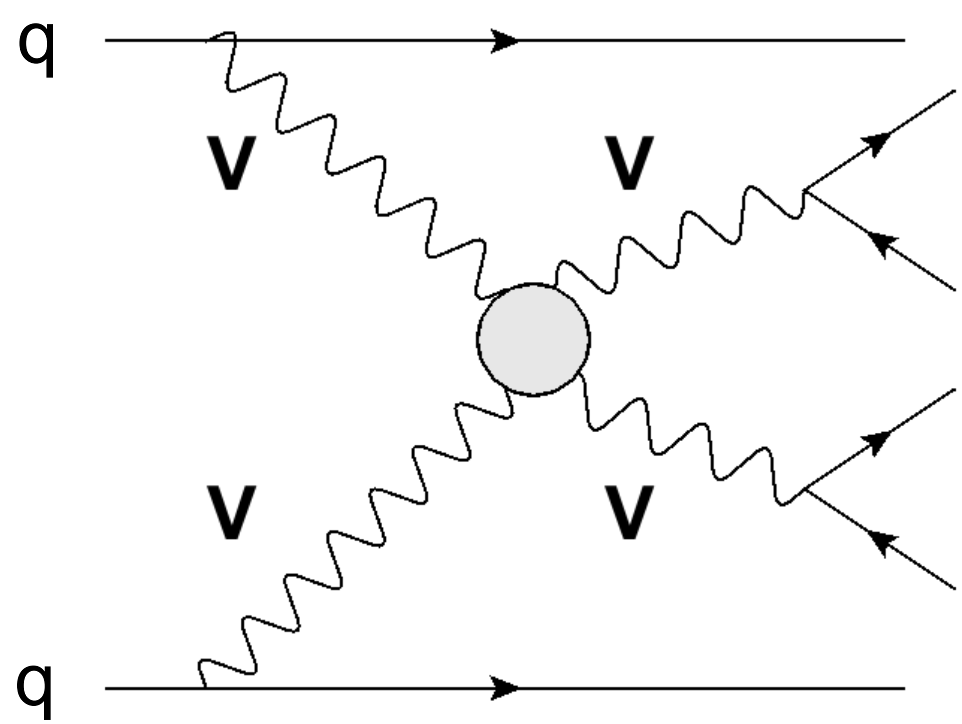




- With 3000 fb^{-1} the couplings can be determined with high precision (a few %)

Vector Boson Fusion (VBF)

Generic diagram for vector boson fusion (VBF) process



Signature: forward-backward "spectator" jets with very high energy

- Once the vector bosons decay, we have a six-fermion final state
- The full set of $qq \rightarrow 6$ fermions diagrams has to be considered
- In order to investigate EWSB, one has to isolate VV processes from all other six-fermion final states

➡ Apply tight kinematic cuts

Typical kin. cuts

$p_{T,j} > 20$ GeV $|\eta_j|<5$ $p_T^{tag} > 30$ GeV $|\eta_{j1}-\eta_{j2}|>4.0$

$\eta_{j1} \cdot \eta_{j2} < 0$ $m_{jj} > 600$ GeV

VV scattering: semileptonic

Semileptonic is most promising: reasonable signal yield

Number of events for 20 fb^{-1} (fully MC based, no systematics, 14 TeV)

WV -> lnjj

ATLAS	N sign.	N back.
500 GeV	6.2	16
800 GeV	13	17
1.1 TeV	4.8	9.2

CMS	N sign.	N back.
500 GeV	337	20759
>1 TeV	45	3281

ZV -> lljj

CMS	N sign.	N back.
500 GeV	62	3415
>1 TeV	5	348

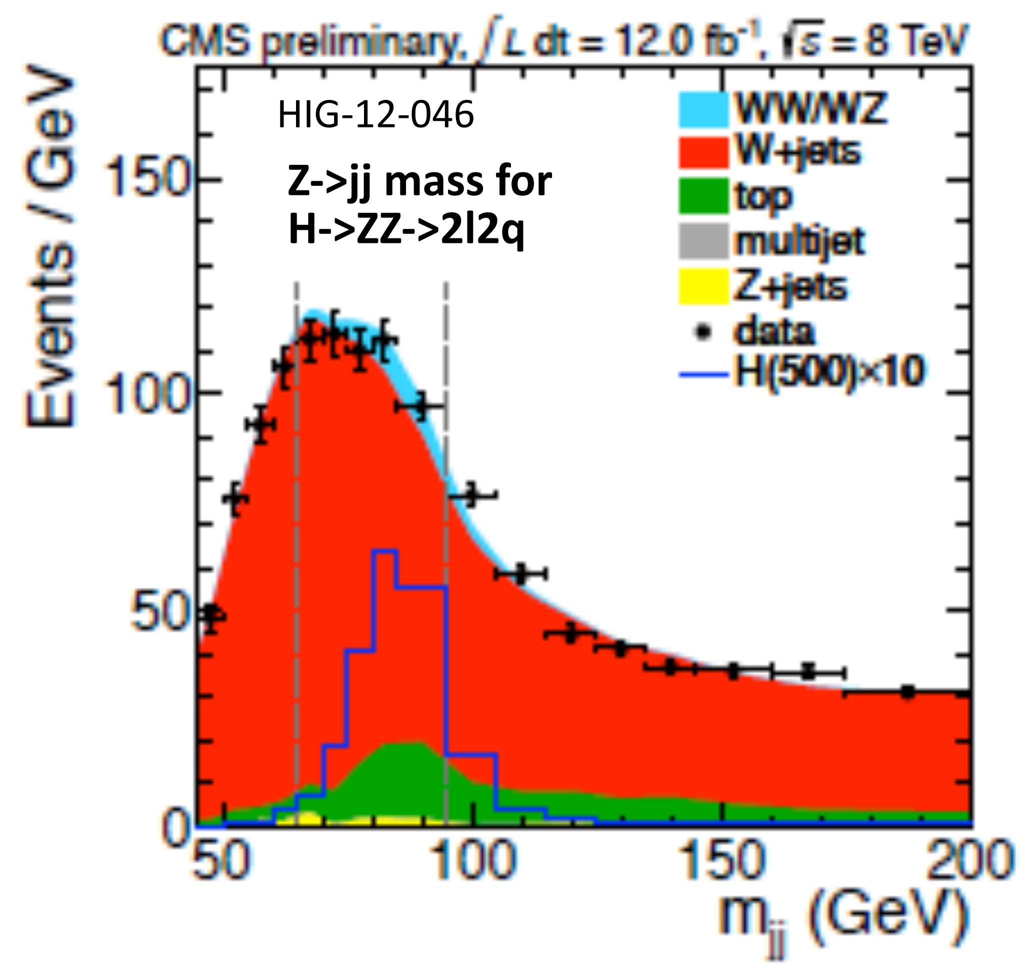
CERN-OPEN-2008-020

For recent inclusive Higgs search:

- more sophisticated analysis developed
(btag categories, angular analyses,
$m_{jj} = m_Z$ kinematic fit)

- data driven background

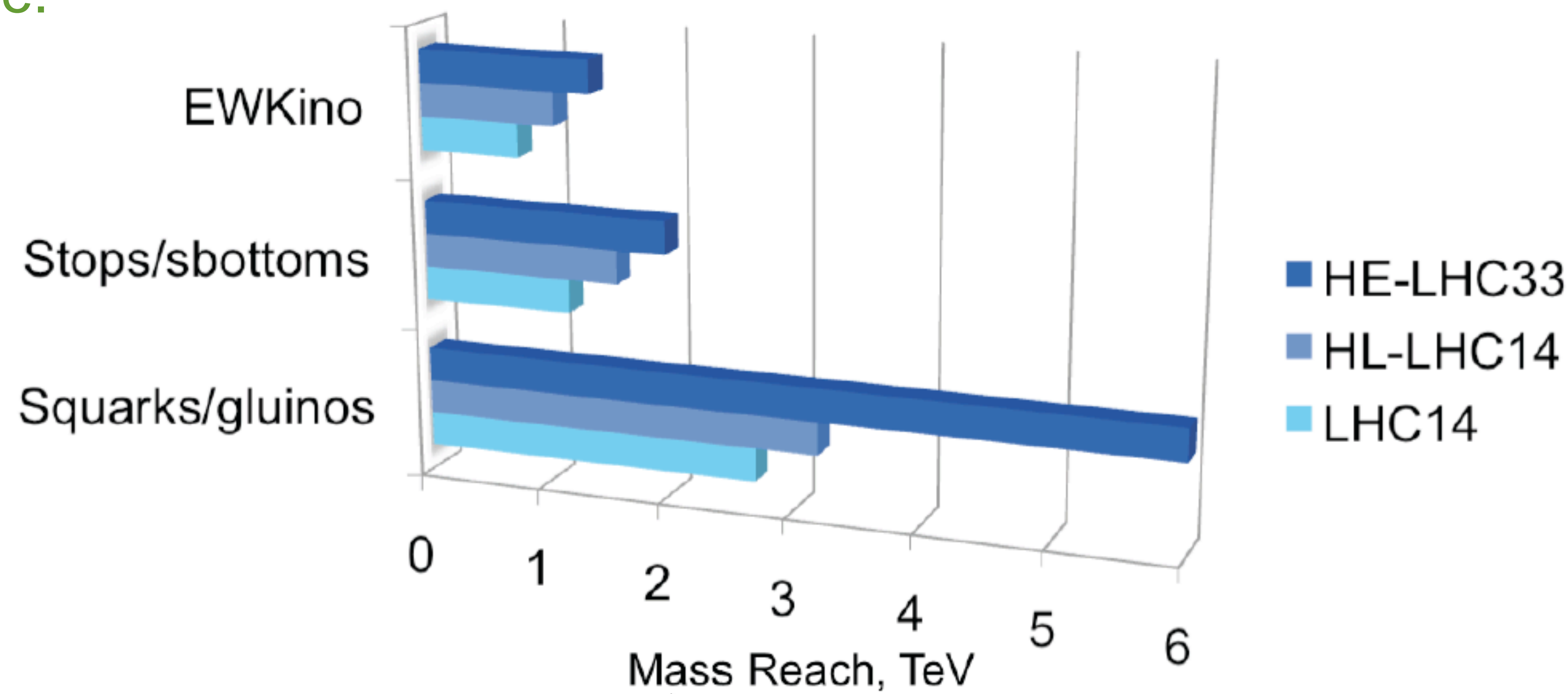
Improved JES: m_{jj} reso from 20-25% to 10-15%



SUSY reach at higher luminosity

LHC at 14 TeV expands the reach for SUSY particles to much higher masses. (HE-LHC at 33 TeV does it even more)

As expected, the gain with HL-LHC is more modest (~25%) in this case.



SUSY reach with 300 fb^{-1}
EWKinos up to ~ 800 GeV
Stops,sbottoms up to ~ 1TeV
squarks,gluinos up to ~2.5 TeV