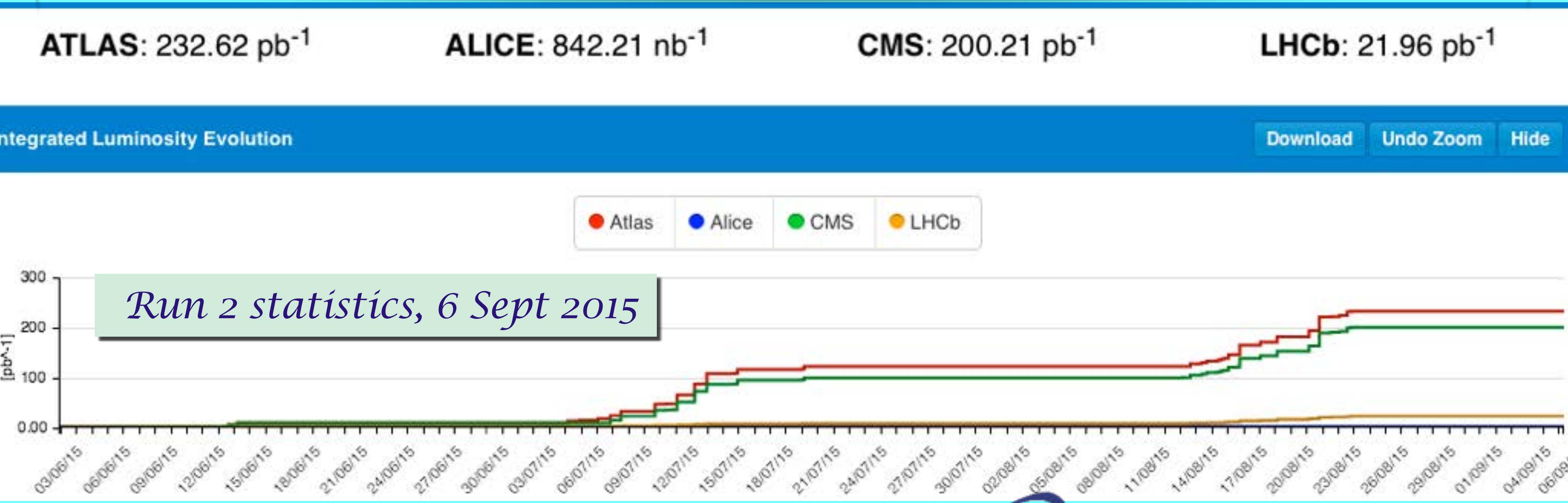
LFC15: Physics Prospects for Linear and other Future Colliders after the Discovery of the Higgs, 7-11 September 2015 , ECT, Trento, Italy*

Approaching a new energy frontier at the LHC



Barbara Mele

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Sezione di Roma

Trento, 7 September 2015

Outline

- Collider Physics : where we stand today
  - SM test "concluded" ! (shell in knowledge completed…)
  - Higgs boson is there ➜ Criticalities (and Opportunities) !
  - A few anomalies at 8-TeV ???
- LHC : present and near future (schedule)
- increase in sensitivity and mass reach
- first Run-2 results
- possible scenarios ahead …
- Outlook

benefitted a lot from summer conferences :
EPS-HEP2015, LP2015, SUSY2015, LHCP2015…

pp collisions: where we stand today

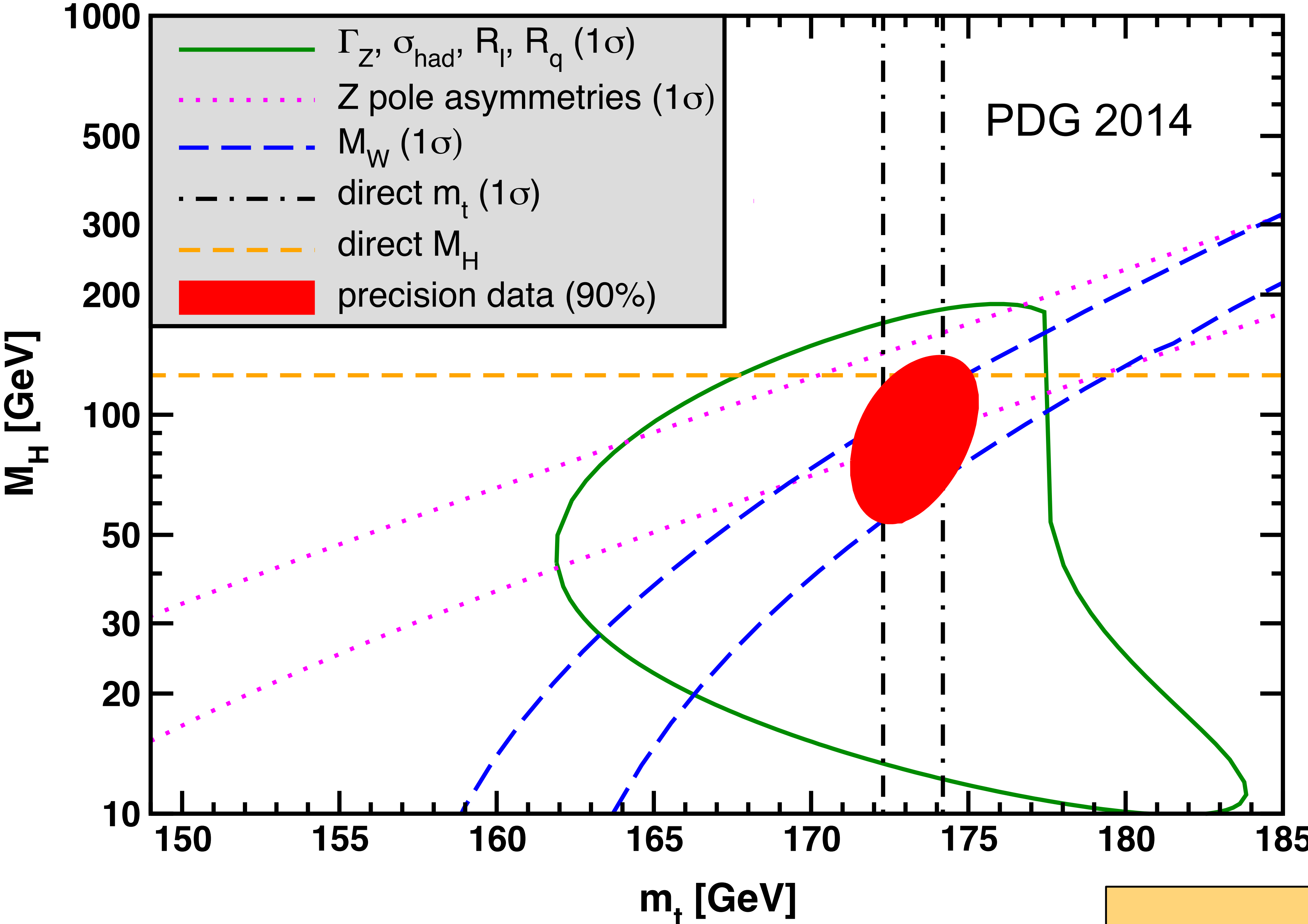
- LHC Run 1 at 7-8 TeV completed (2009-13)

  [in ATLAS/CMS: $\int L \sim 5 + 20$ fb^{-1}/ exp]

  Amazing Performance ! ➜ results well above expectations... (and still a lot to come !)

- SM tested at high accuracy in a new $\sqrt{s}$ range : QCD (many regimes,PDFs), top physics, EW processes, flavor
- "direct" exploration of SM EWSB sector started up with observation of a (quite light) Higgs resonance !!!
  - still a lot of room for a non-SM EWSB sector
- bounds on new heavy states predicted by many BSM models widely extended wrt pre-LHC era
  - hints of BSM physics at 8 TeV ???
- Run 2 at 13 TeV started in June after LS1 ... !

Higgs observation ➜ triumph of SM (and LHC !)



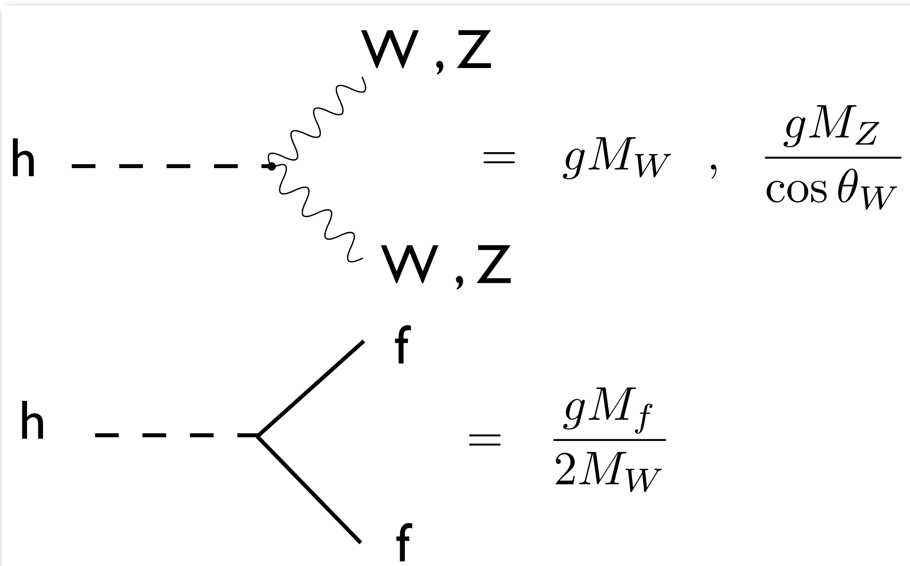
"invisible" width !
(m_H error band)

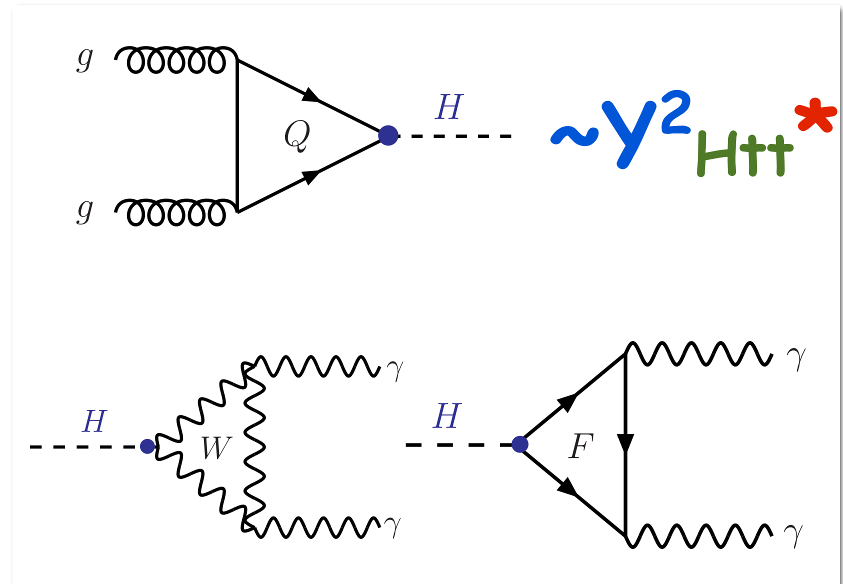
red area is 90% CL
prediction from EWPTs

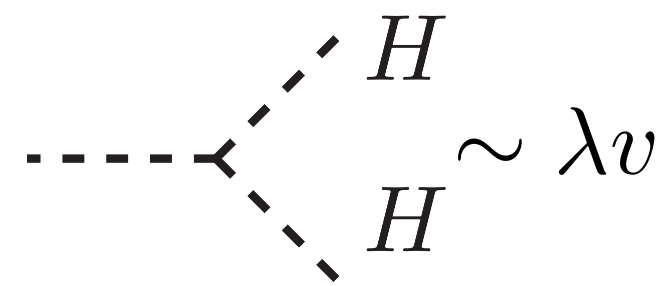
last missing
SM state !

is LHC signal really a SM Higgs ?

- test g_{HXX} (magnitude and structure) to vector bosons (EWSB), to fermions and self-couplings







$m_H \sim 125$ GeV

$\Gamma_H = 4.2$ MeV

$\lambda = (m_H/v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

$H \to bb$ 56%*

$H \to cc$ 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰*

$H \to gg$ 8.5%*

$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

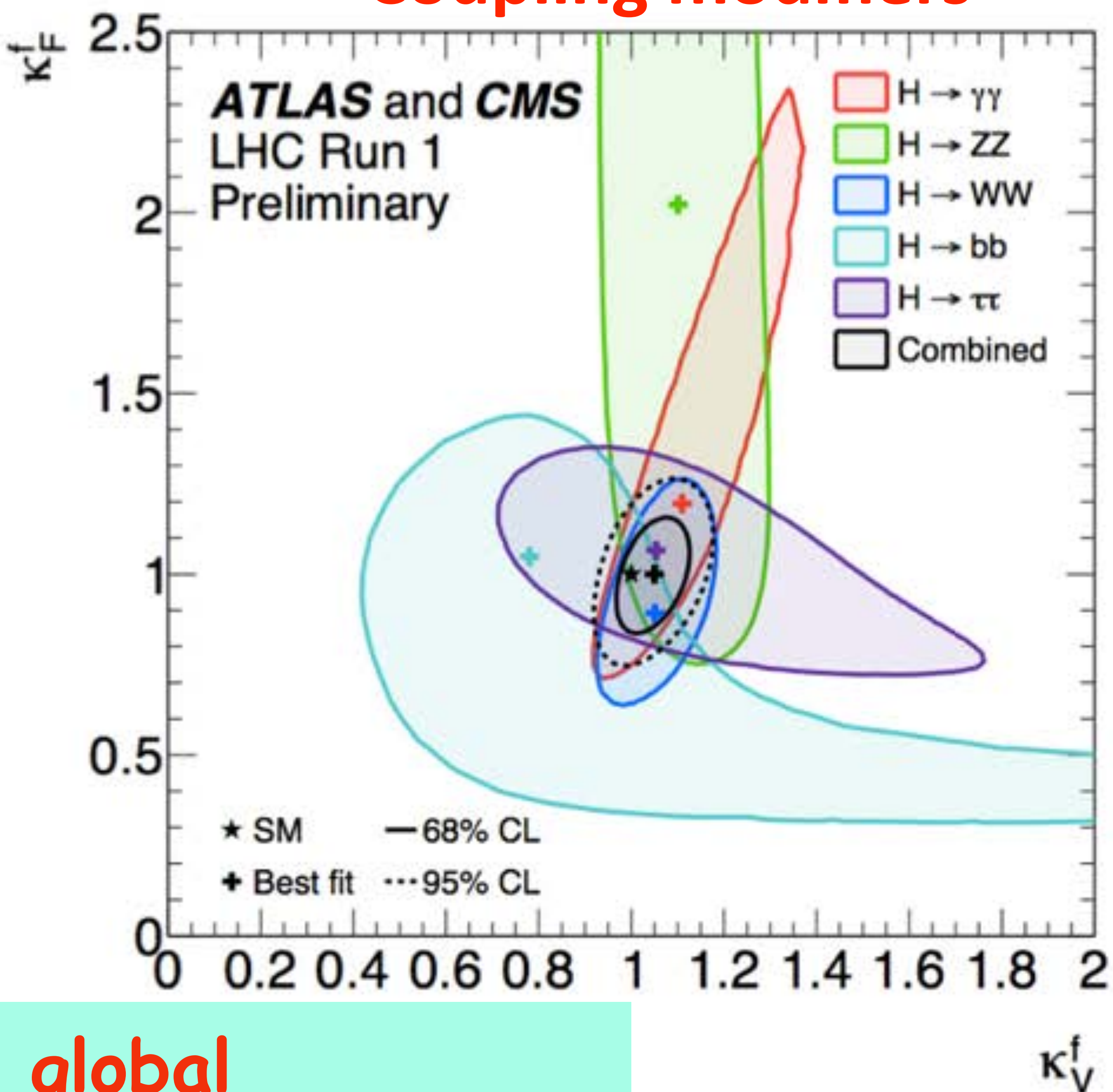
most couplings accessible at LHC (*) !

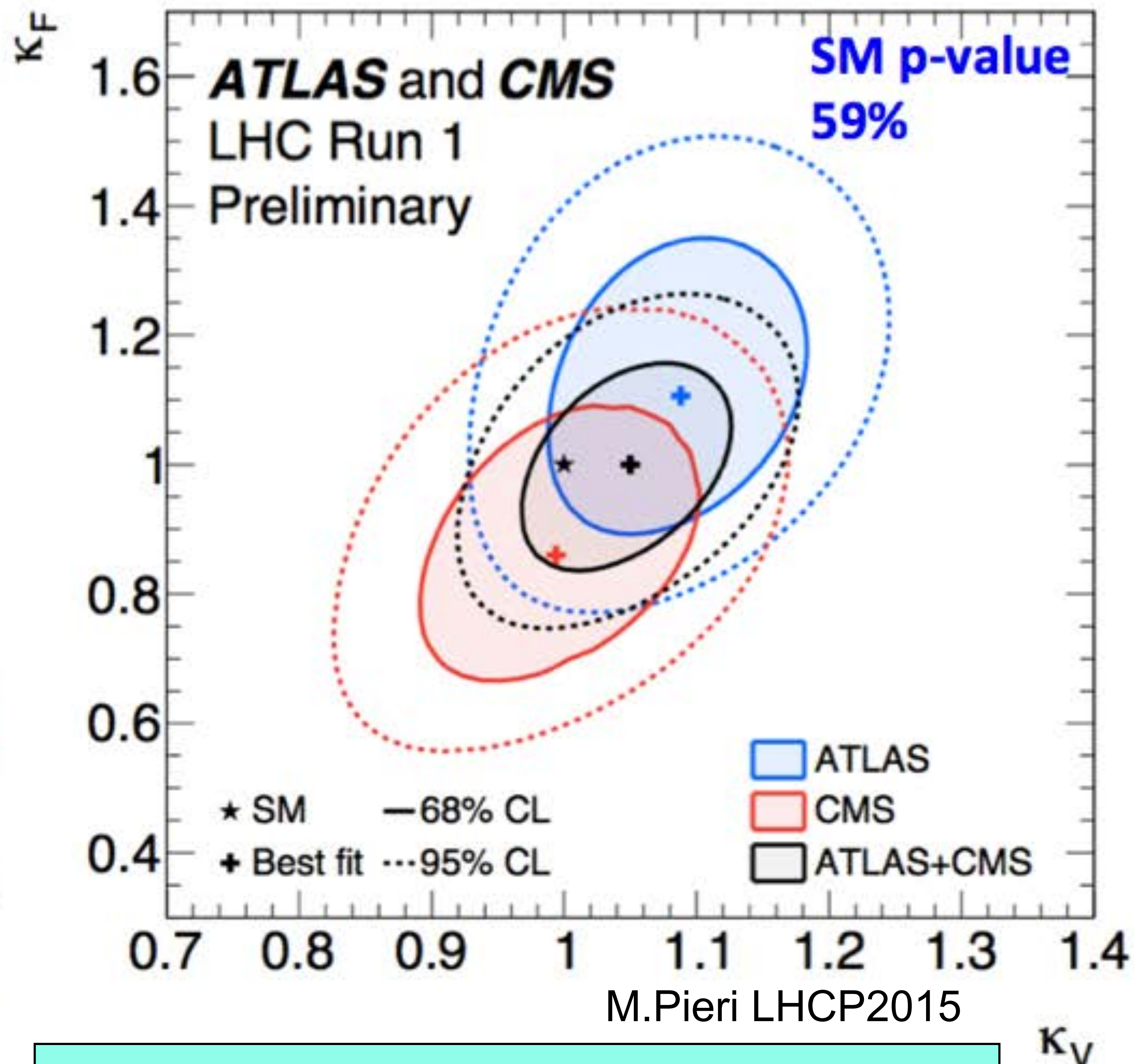
ATLAS + CMS Higgs-coupling combination !

$\sqrt{2} \sim 1.4$ gain in precision (statistics dominated)

CONF Note/PAS:
- ATLAS-CONF-2015-044
- CMS-PAS-HIG-15-002

Coupling modifiers





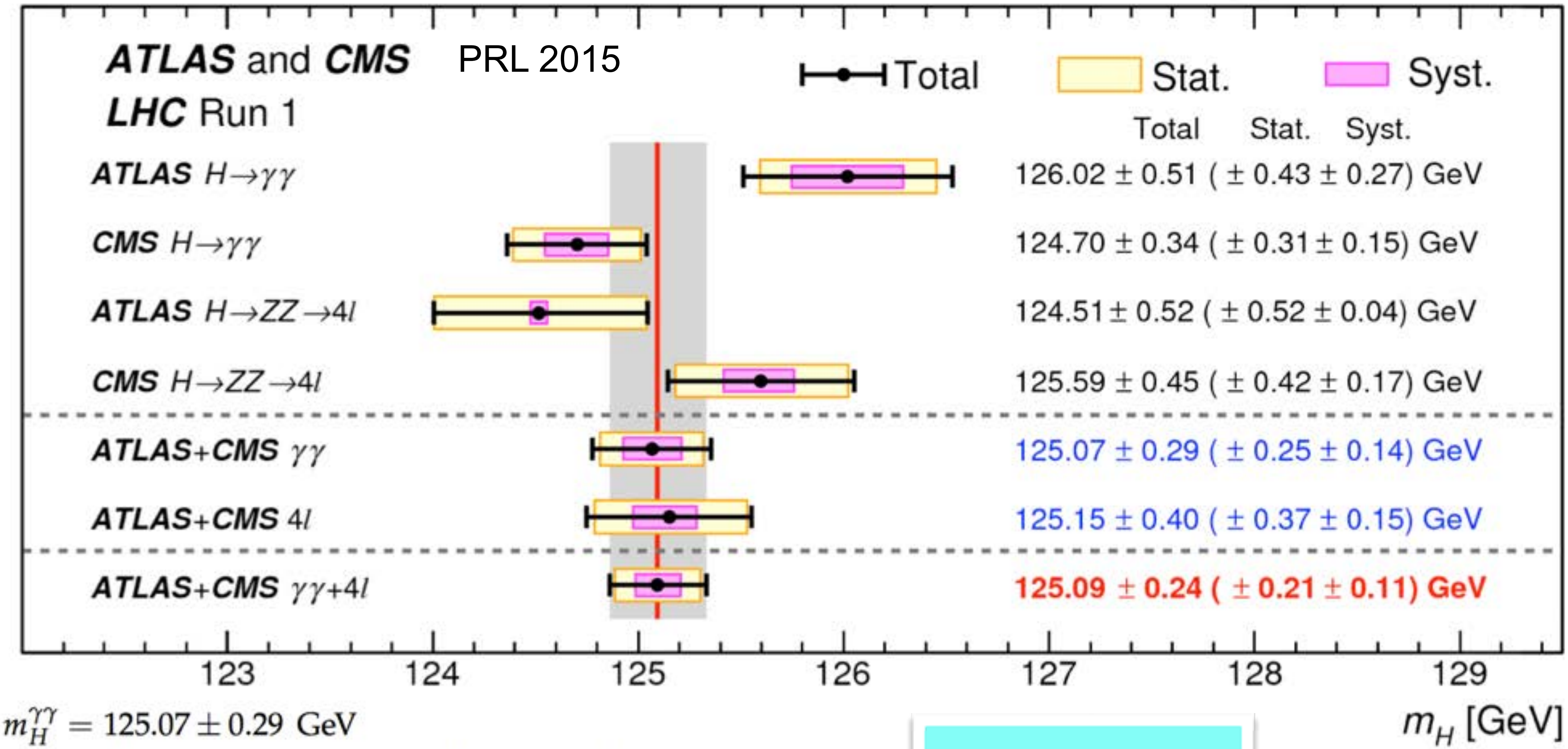
M.Pieri LHCP2015

global signal strength :

$$\mu = 1.09^{+0.11}_{-0.10}$$

SM agreement within 1σ !

ATLAS + CMS Higgs mass combination !



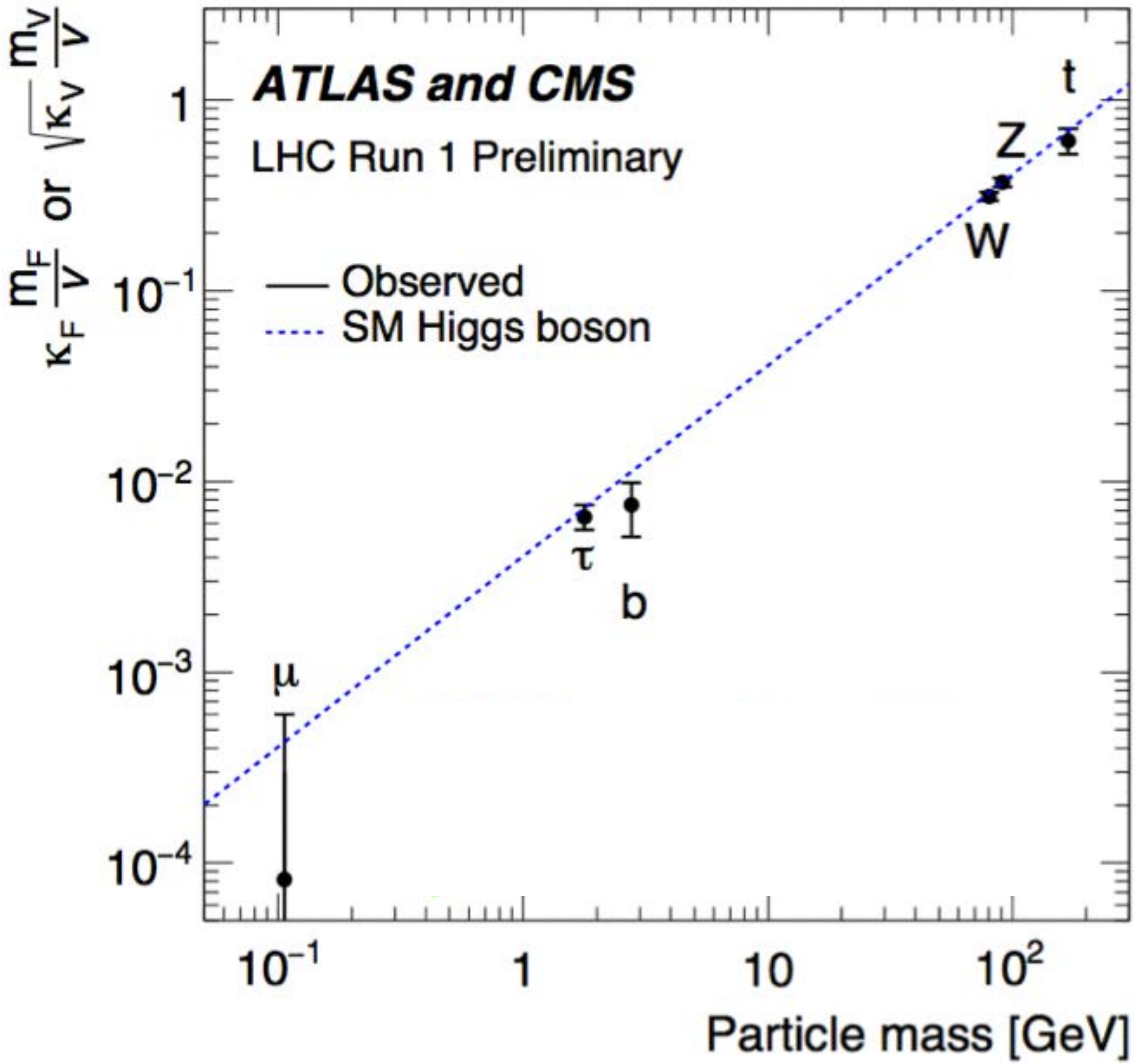
$$m_H^{\gamma\gamma} = 125.07 \pm 0.29\ \text{GeV}$$
$$= 125.07 \pm 0.25\,(\text{stat.}) \pm 0.14\,(\text{syst.})\ \text{GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40\ \text{GeV}$$
$$= 125.15 \pm 0.37\,(\text{stat.}) \pm 0.15\,(\text{syst.})\ \text{GeV}$$

$\Delta M_H \sim 2‰$

$$M_H = 125.09 \pm 0.24\ \text{GeV}$$
$$= \pm 0.21\ (\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}$$

a clear SM footprint is emerging : $g_{HXX} \sim m_X^{(2)}$



it is not a generic scalar state!

SM pattern well matched within errors !

SM-Lagrangian : OK !

SM gauge group :

SU(3)$_{QCD}$ x SU(2)$_L$ x U(1)$_B$

spontaneusly broken via Higgs mechanism

→ SU(3)$_{QCD}$ x U(1)$_{em}$

Higgs Lagrangian :

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) - \bar{\psi}_L\Gamma\psi_R\phi - \bar{\psi}_R\Gamma^\dagger\psi_L\phi^\dagger$$

$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \frac{1}{2}\lambda(\phi^\dagger\phi)^2$$

built up just by imposing

- gauge invariance (L_{SM} singlet of SM group)
- renormalizability [D ≤4 operators]

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

masses fix all Higgs interactions !

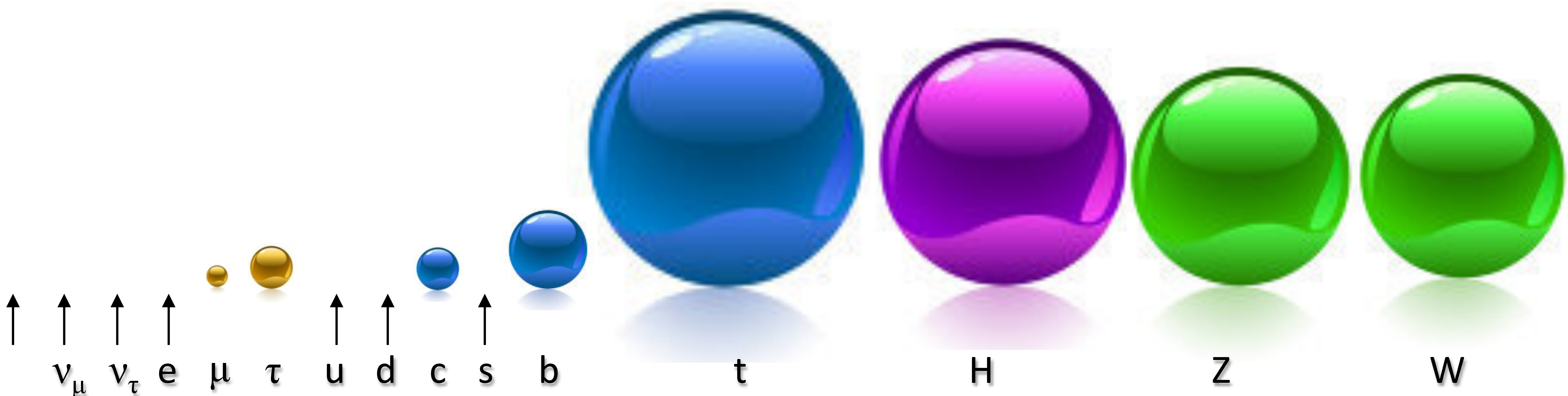
SM Higgs sector criticalities →

- Flavor
- Naturalness
- Self-coupling

Mystery in Hierarchy of SM Yukawa's

$$\mathcal{L}_{Y_f} \sim \frac{m_f}{v} \bar{f} f H$$

m_f's span many orders of magnitudes…



courtesy of R. Chierici

origin of Flavor Symmetry Breaking ?

$$Y_{top} = \frac{\sqrt{2}\, m_t}{v} \simeq 1 \quad (???)$$

SM is not enough !

- SM does not explain a number of things (flavor, strong CP, neutrino sector, baryogenesis, Dark Matter...)

- crucial issue for Collider Physics (and LHC !) :

what is the expected
Energy THReshold (E_{THR}) to go BSM ???

→ Higgs sector gives a hint here...

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

M_H unprotected by Symmetries !

- quadratic divergences on fundamental-scalar mass

drive M_H to the next energy threshold E_{THR} !

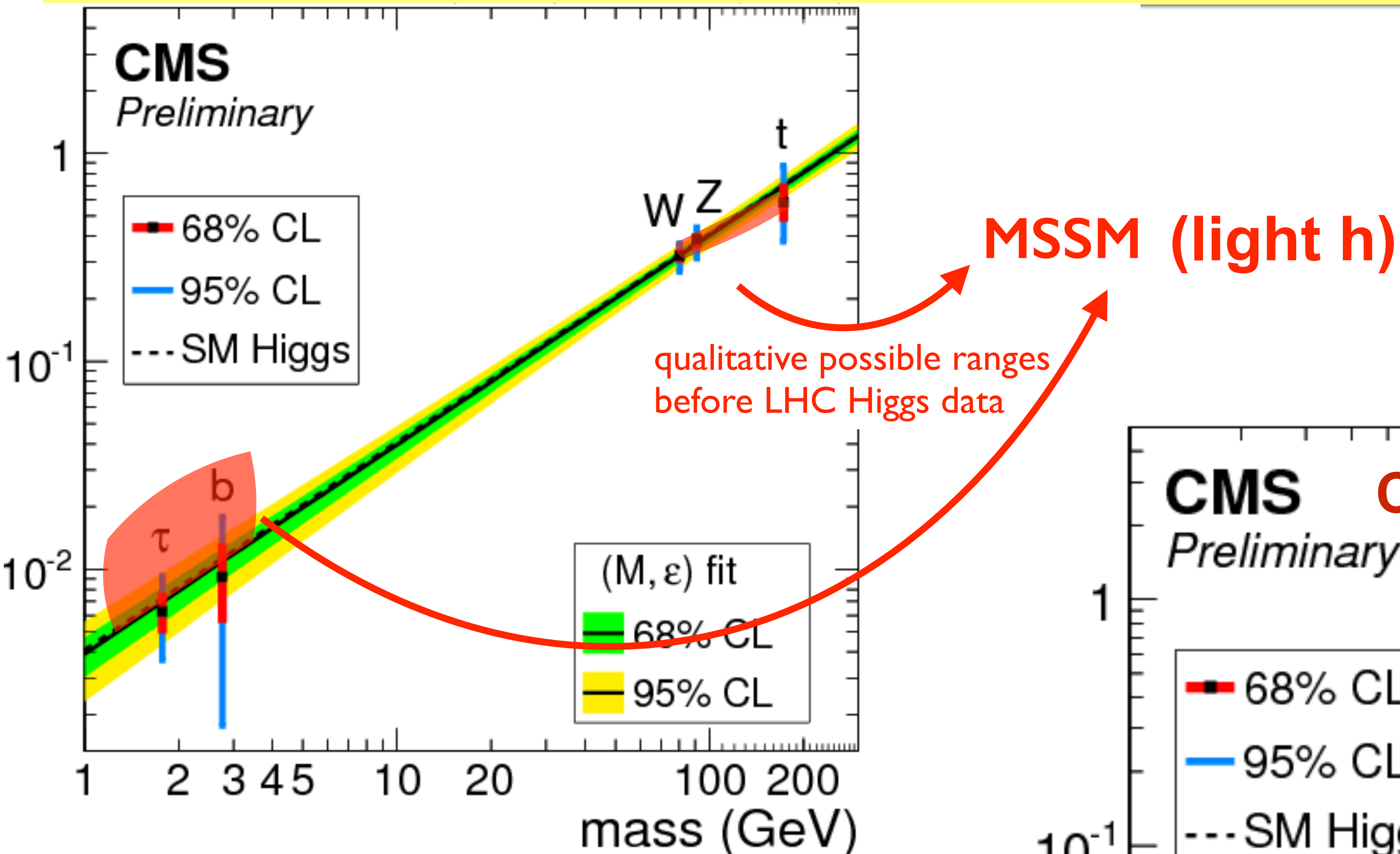
→ to avoid Fine-Tuning of parameters (→ "natural" model)

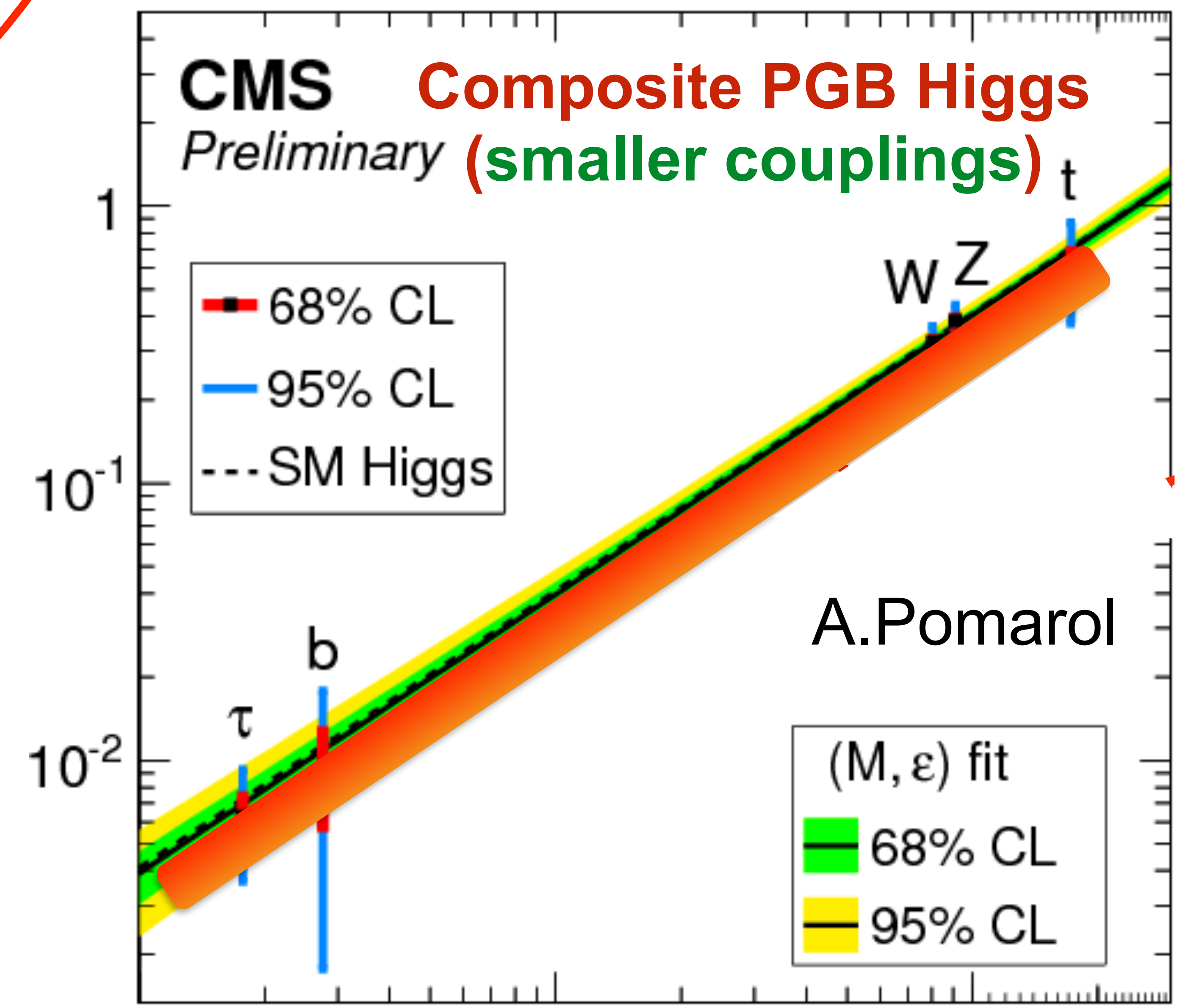
$E_{THR} \sim M_H / g_{coupling} \sim o$ (1 TeV)

WARNING : the exact way E_{THR} "materializes" depends on the actual (yet unknown !) SM extension !

- after LHC Run 1, Simplest Versions of "PROPOSED" Models look quite Fine-Tuned !

Higgs is an invaluable probe of BSM sectors





typical deviations
in H couplings in
'natural' Higgs models:
few % → 10's %

largest contributions to g_{HXX} from BSM

	g^h_{ff}	g^h_{VV}	κ_{GG}	$\kappa_{\gamma\gamma}$	$\kappa_{Z\gamma}$	g_{3h}
MSSM	✓					✓
NMSSM	✓	✓	✓	✓	✓	✓
MCHM	✓	✓			✓	✓
SUSY Composite Higgs	✓	✓				✓
Higgs as a Dilaton			✓	✓	✓	✓
Partly-Composite Higgs			✓	✓	✓	✓
Bosonic TC						✓

Pomarol, arXiv:1412.4410

possible hint of cracks in SM could come before new heavy-states observation !

Higgs self-coupling most exposed to BSM effects !
(impact on : vacuum stability, Baryogenesis from cosmo EWPT ?,…)

a few 3σ anomalies at high Q in Run 1

one example :

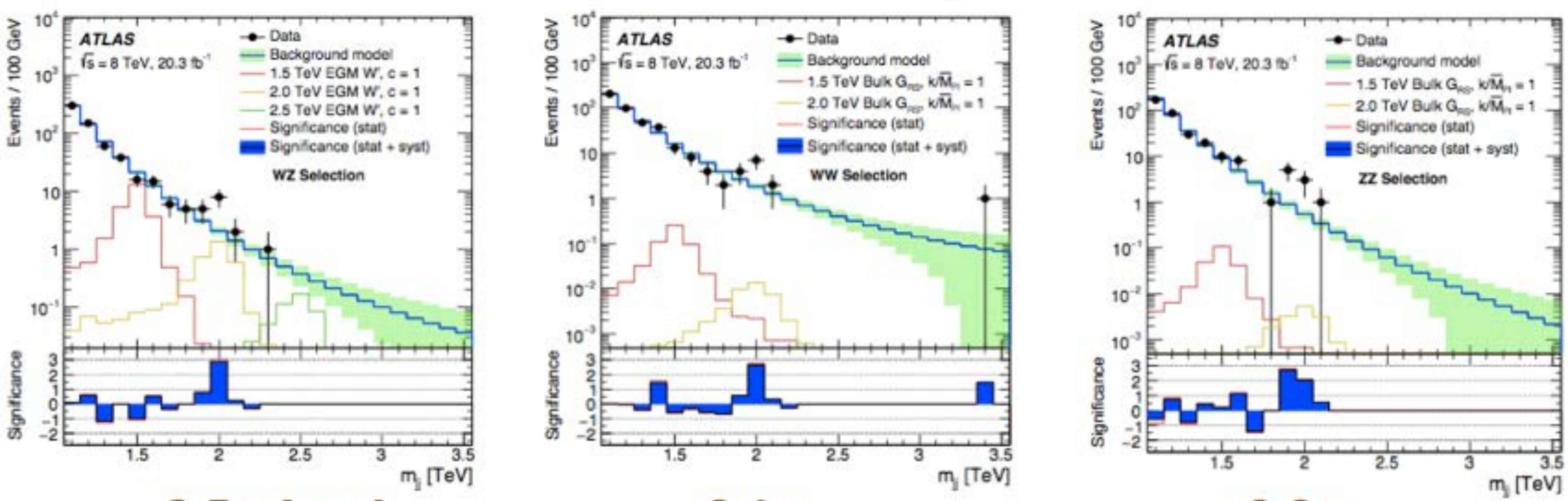
ATLAS, arXiv:1506.00962

(quite a few in Flavor Physics too !)

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

$|m_j - m_V| < 13$ GeV

boosted-object reconstruction more and more crucial in next Runs !



3.5σ *local* | **2.6σ** | **2.9σ**

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

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

M. Mangano

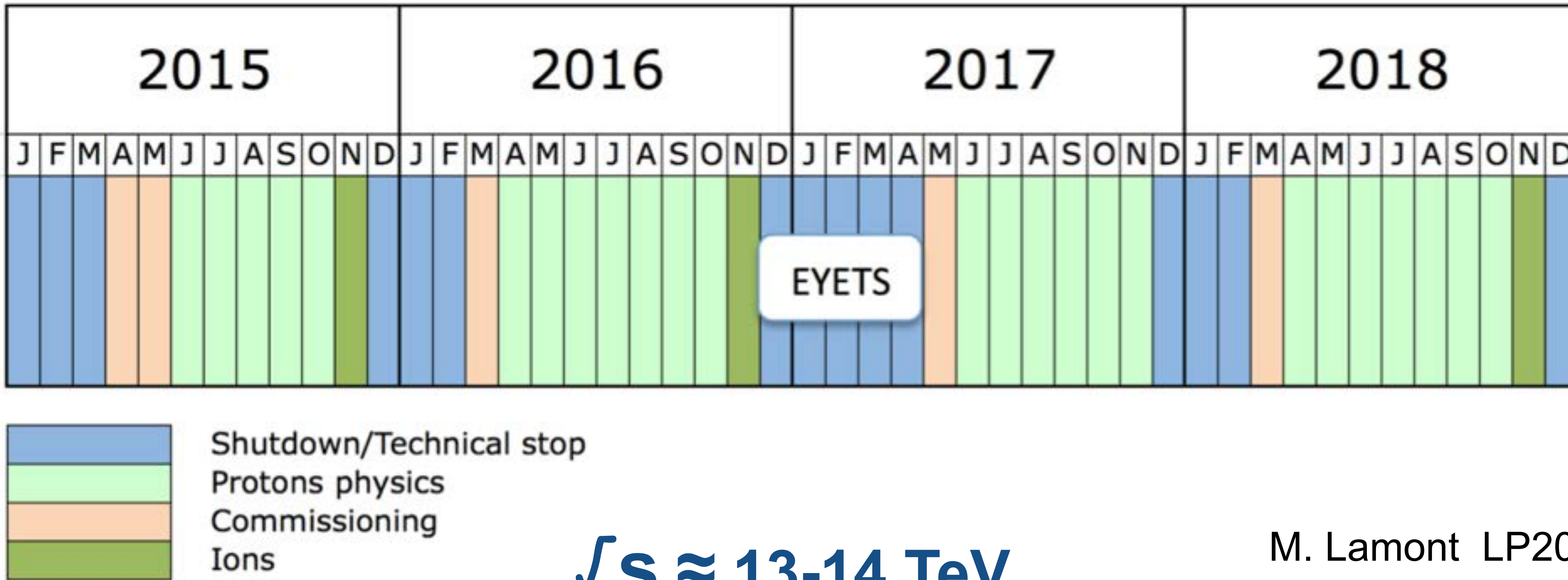
LHC RUN 2 :
8 TeV → 13-14 TeV

62%-75% higher c.m. energy available

yet unexplored domain

→ huge discovery potential !!!

Run 2 *(schedule)*



M. Lamont LP2015

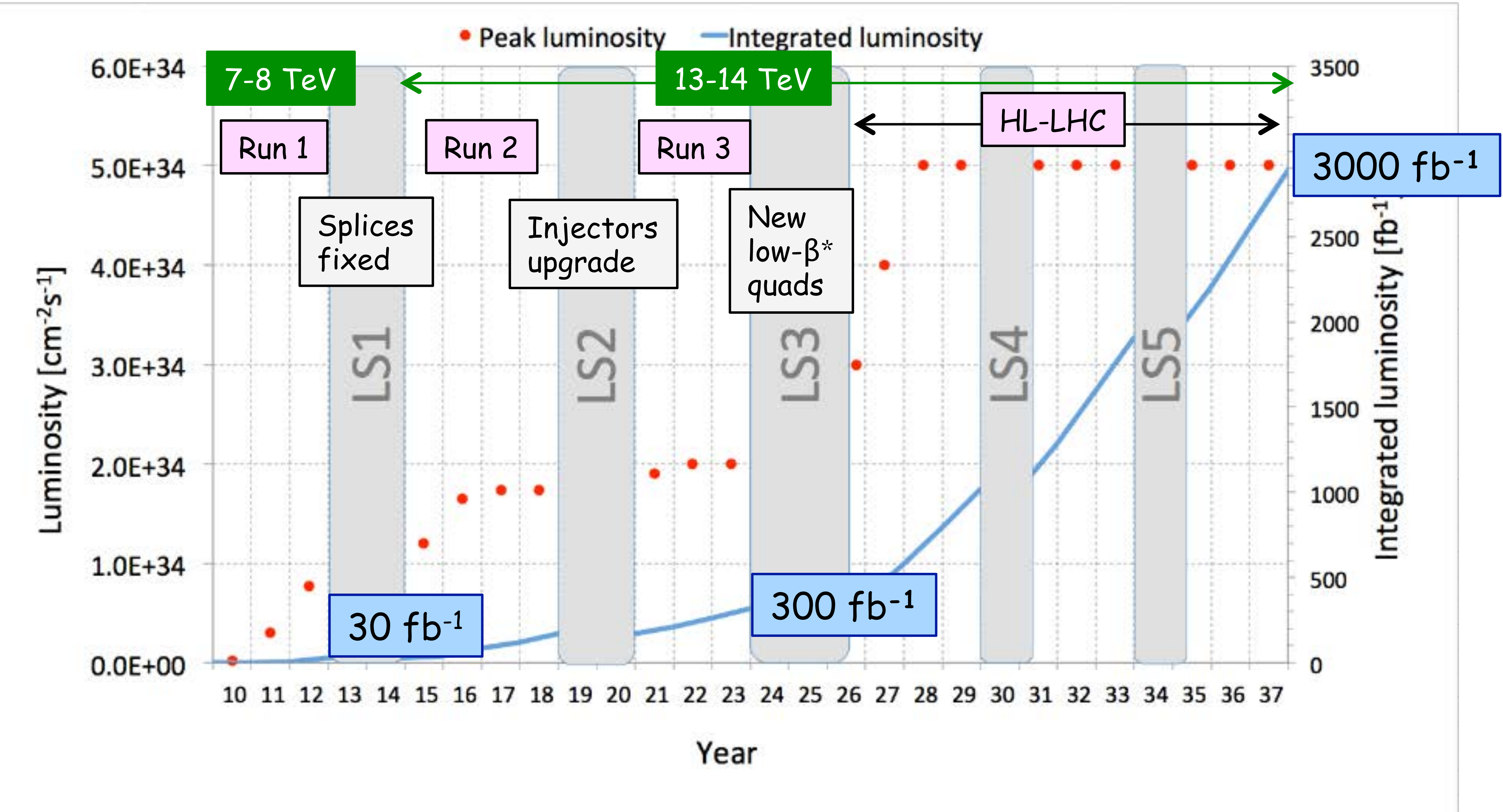
$\sqrt{s} \approx$ 13-14 TeV

ATLAS
CMS

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	36
2018	1.5	160	36

$\int L_{tot} \approx$ 100 fb^{-1}/exp

The present and near/medium-term future: LHC and HL-LHC



LHC is highest-E, highest-L operational collider → full exploitation ($\sqrt{s}$ ~ 14 TeV, 3000/fb) is mandatory

F. Gianotti, EPS2015

M_{BSM}-reach gain at 13/14 TeV vs ∫L

just from PDF's behavior

- M_{high} definition:

$$\frac{N_{\text{signal-events}}(M^2_{\text{high}}, 14\,\text{TeV}, \text{Lumi})}{N_{\text{signal-events}}(M^2_{\text{low}}, 8\,\text{TeV}, 19\text{fb}^{-1})} = 1$$

neglecting scaling differences in background, reconstruction, and detector behavior !!!

- for a resonance of mass M:

Coefficient for ij scattering channel (e.g. $q\bar{q}$, gg)

$$N(M,s) \sim \frac{1}{M^2}\sum_{ij} C_{ij}\mathcal{L}_{ij}(M^2,s)$$

Parton luminosity for ij scattering channel

$$\frac{\mathcal{L}_{ij}(M^2_{\text{high}}, s_{\text{high}})}{\mathcal{L}_{ij}(M^2_{\text{low}}, s_{\text{low}})} \times \frac{\text{lumi}_{\text{high}}}{\text{lumi}_{\text{low}}} = \frac{M^2_{\text{high}}}{M^2_{\text{low}}}$$

$$\mathcal{L}_{ij}(M^2,s) = \int_\tau^1 \frac{dx}{x} x f_i(x,M^2)\frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$

Salam, Weiler, cern.ch/collider-reach

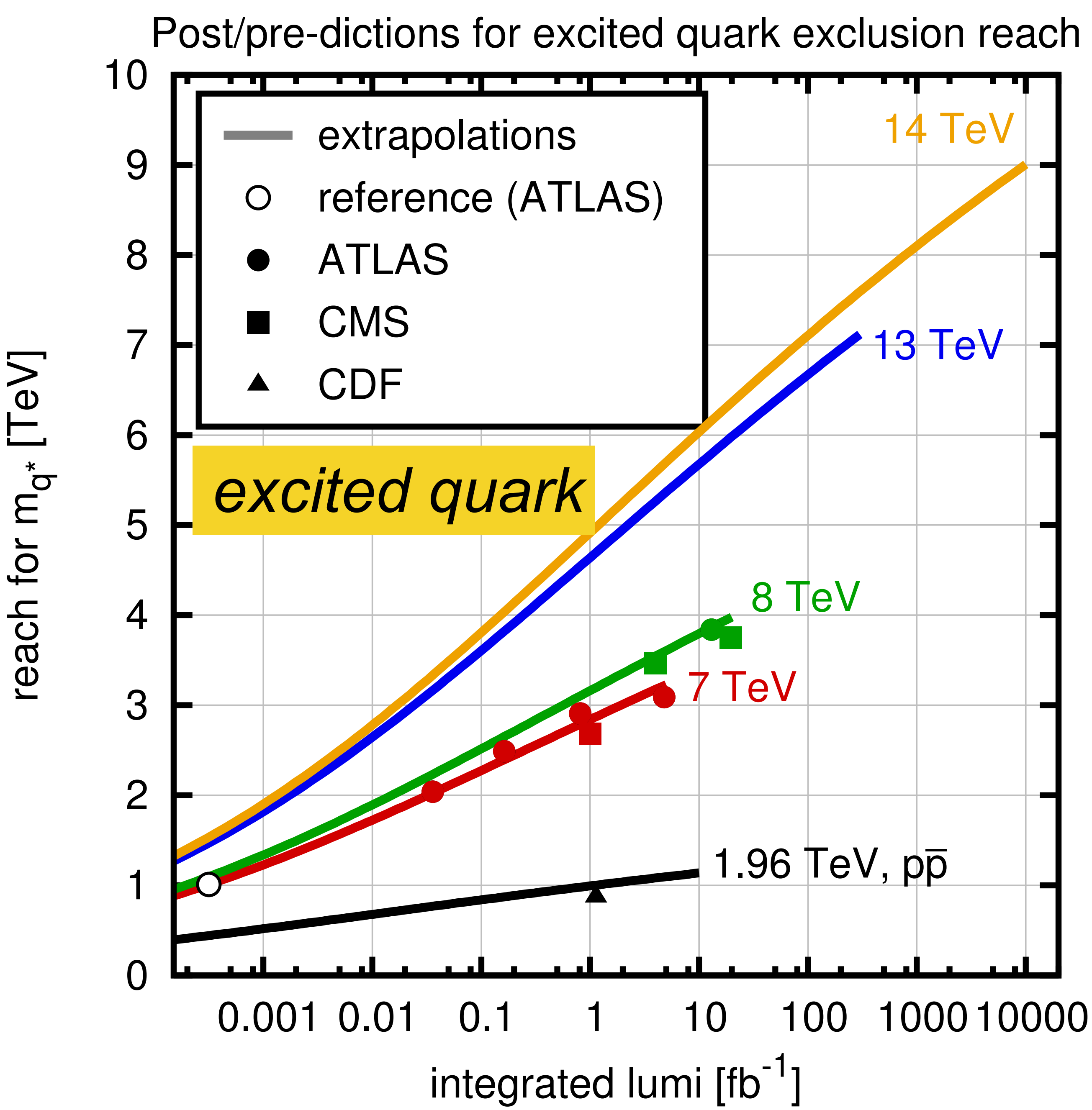
i & j parton

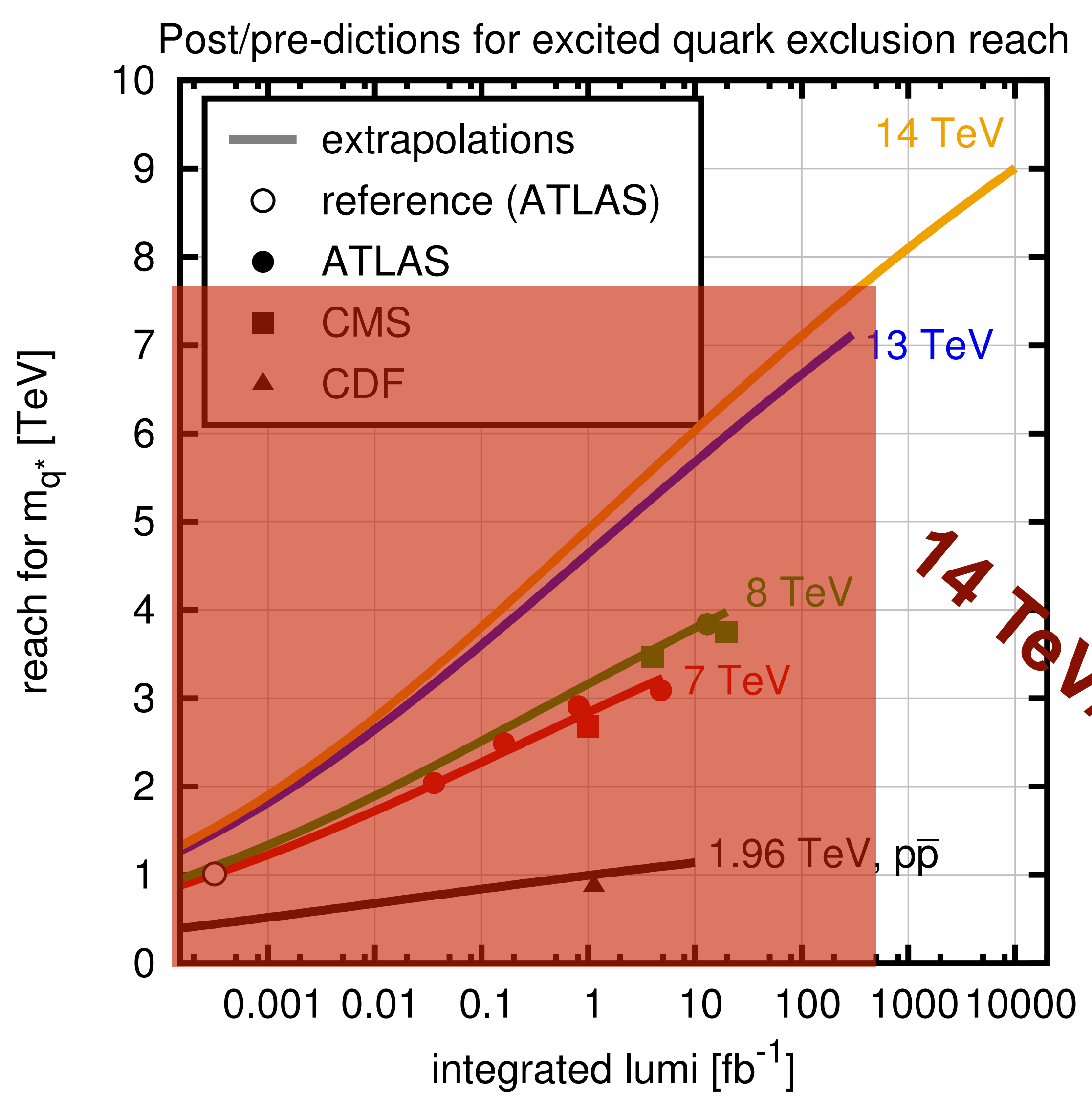
M_{BSM}-reach gain at 13/14 TeV vs $\int L$

$$\frac{\mathcal{L}_{ij}(M^2_{\rm high}, s_{\rm high})}{\mathcal{L}_{ij}(M^2_{\rm low}, s_{\rm low})} \times \frac{\rm lumi_{high}}{\rm lumi_{low}} = \frac{M^2_{\rm high}}{M^2_{\rm low}}$$

just from PDF's

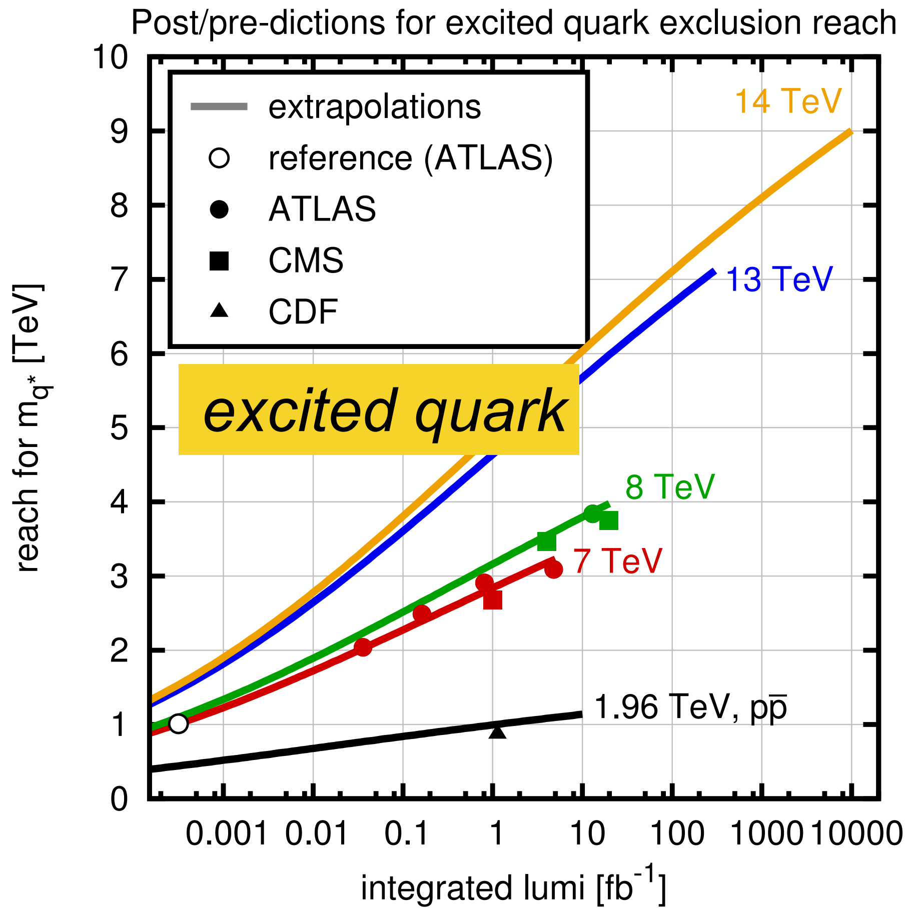
$$\mathcal{L}_{ij}(M^2, s) = \int_\tau^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$

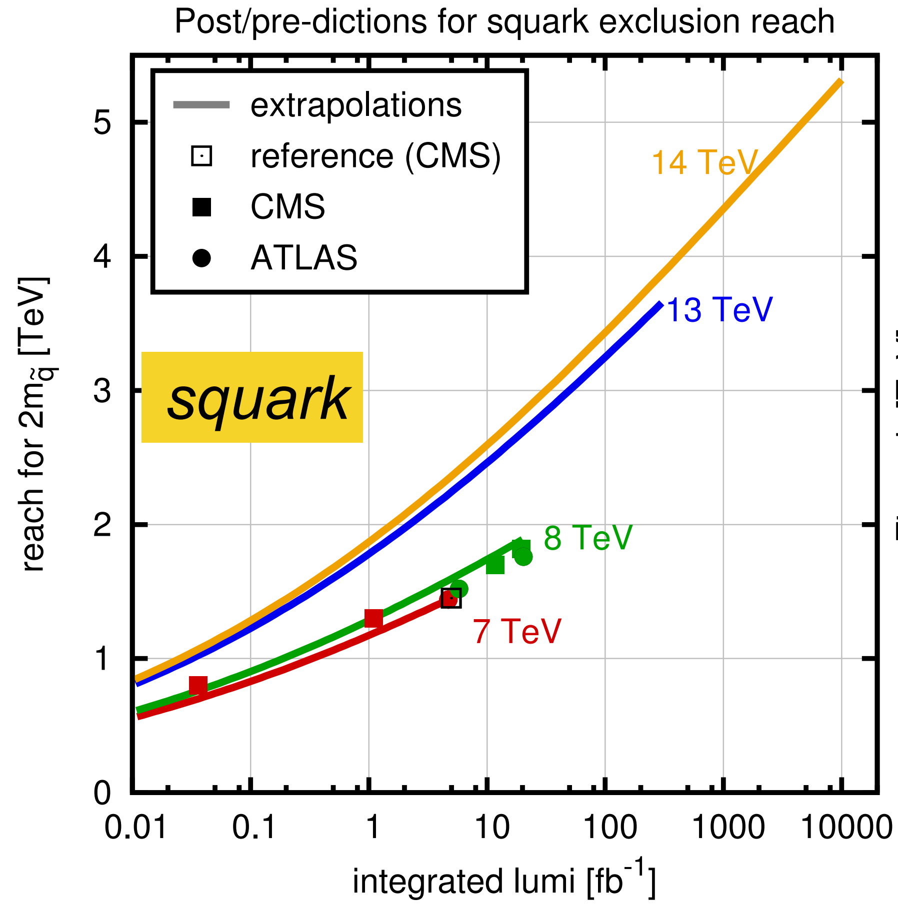


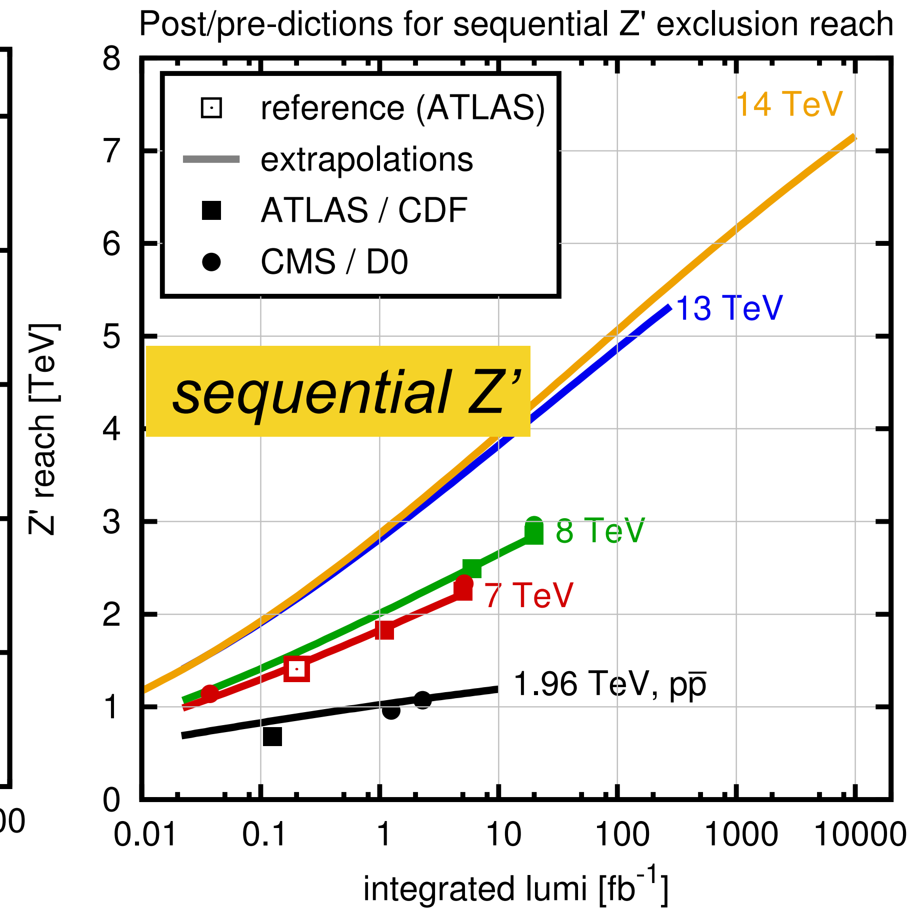


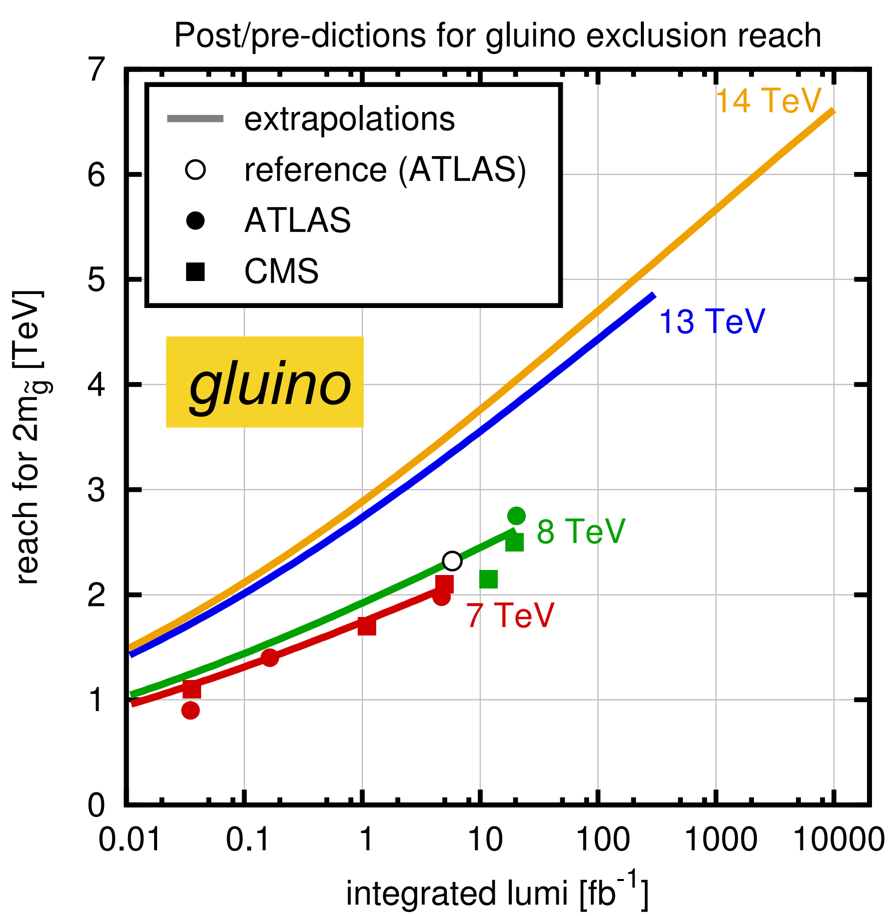
14 TeV/ 300 fb^{-1}

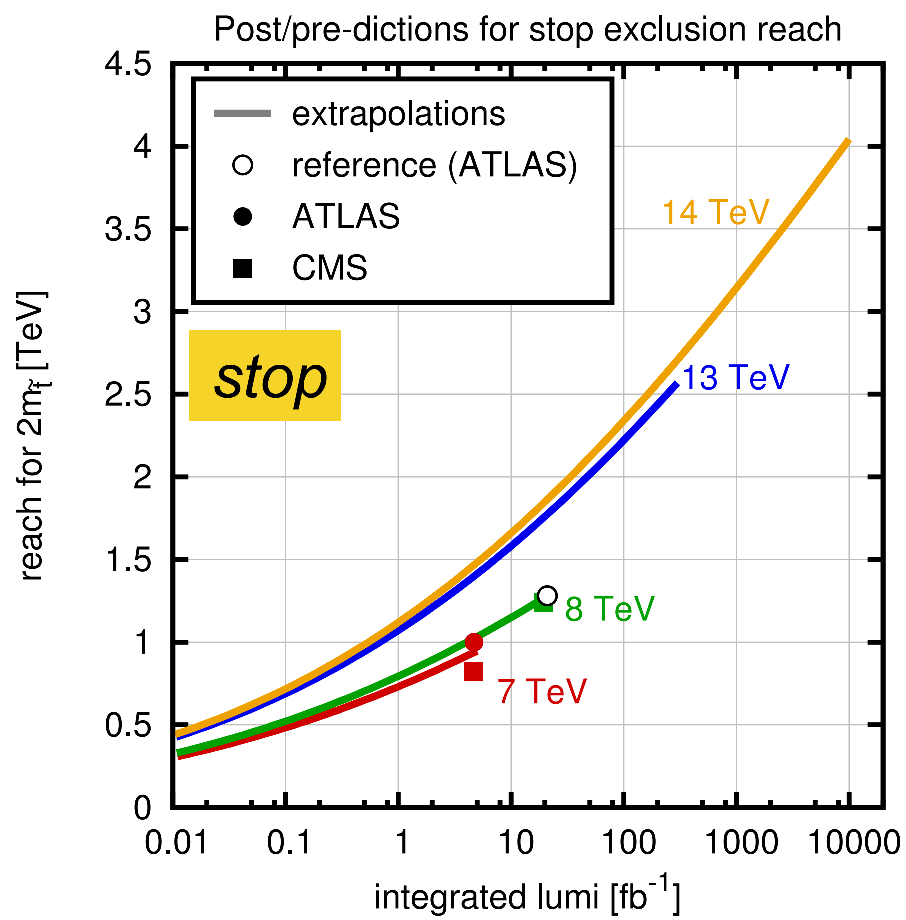
Salam, Weiler, cern.ch/collider-reach

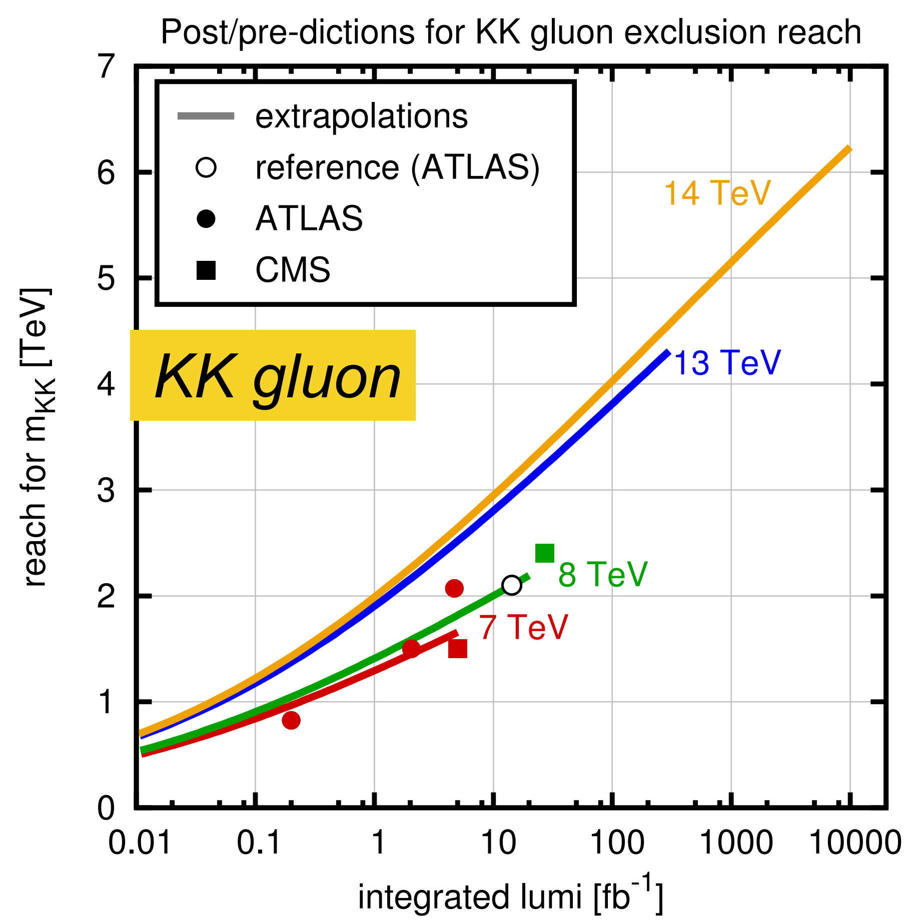

Post/pre-dictions for excited quark exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
CDF
excited quark
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, pp̄
reach for m_{q^*} [TeV]
integrated lumi [fb^{-1}]


Post/pre-dictions for squark exclusion reach
extrapolations
reference (CMS)
CMS
ATLAS
squark
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{q}}$ [TeV]
integrated lumi [fb^{-1}]

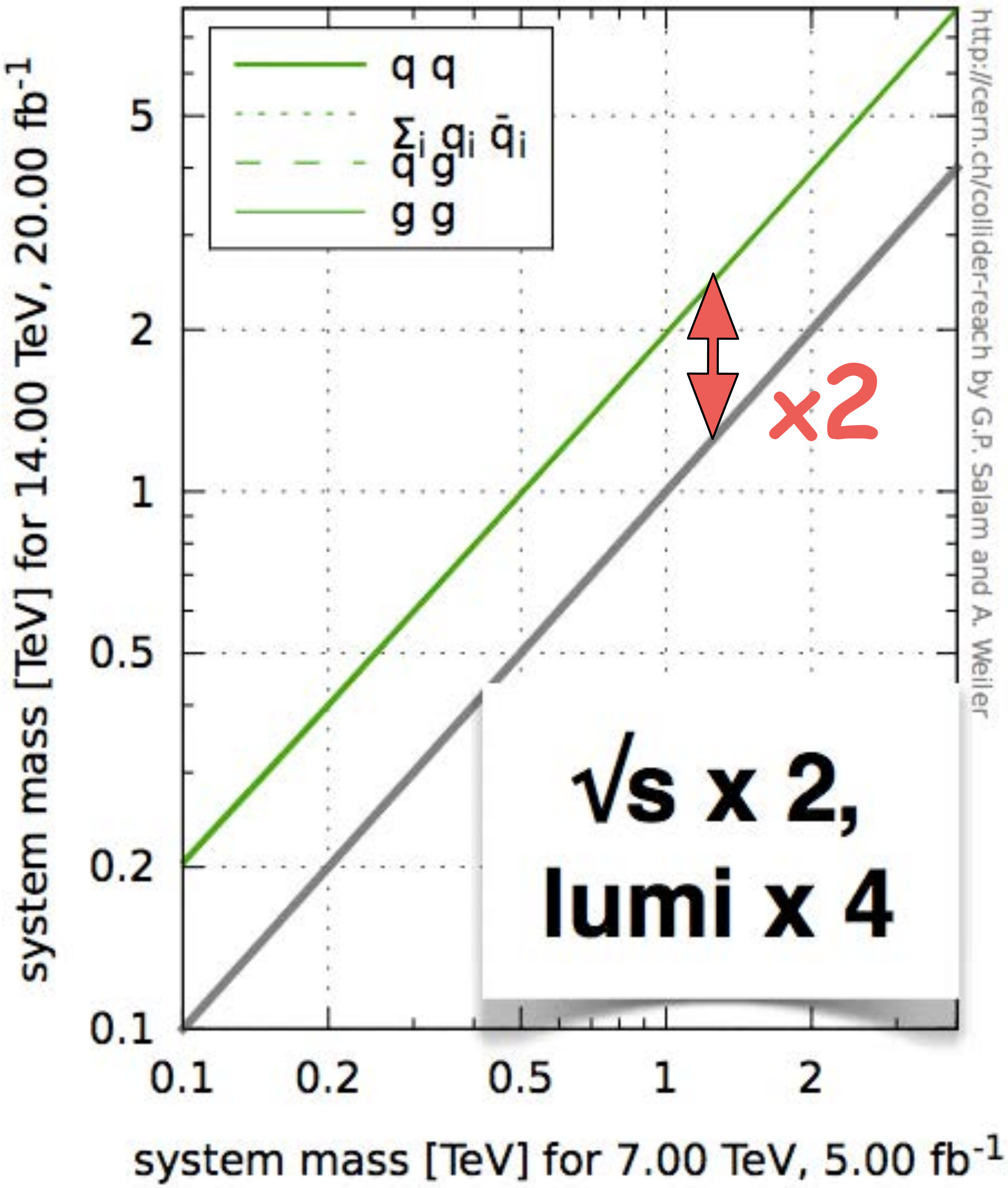

Post/pre-dictions for sequential Z' exclusion reach
reference (ATLAS)
extrapolations
ATLAS / CDF
CMS / D0
sequential Z'
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, pp̄
Z' reach [TeV]
integrated lumi [fb^{-1}]


Post/pre-dictions for gluino exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
gluino
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{g}}$ [TeV]
integrated lumi [fb^{-1}]


Post/pre-dictions for stop exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
stop
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{t}}$ [TeV]
integrated lumi [fb^{-1}]


Post/pre-dictions for KK gluon exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
KK gluon
14 TeV
13 TeV
8 TeV
7 TeV
reach for m_{KK} [TeV]
integrated lumi [fb^{-1}]

approx scaling of mass-reach (1)



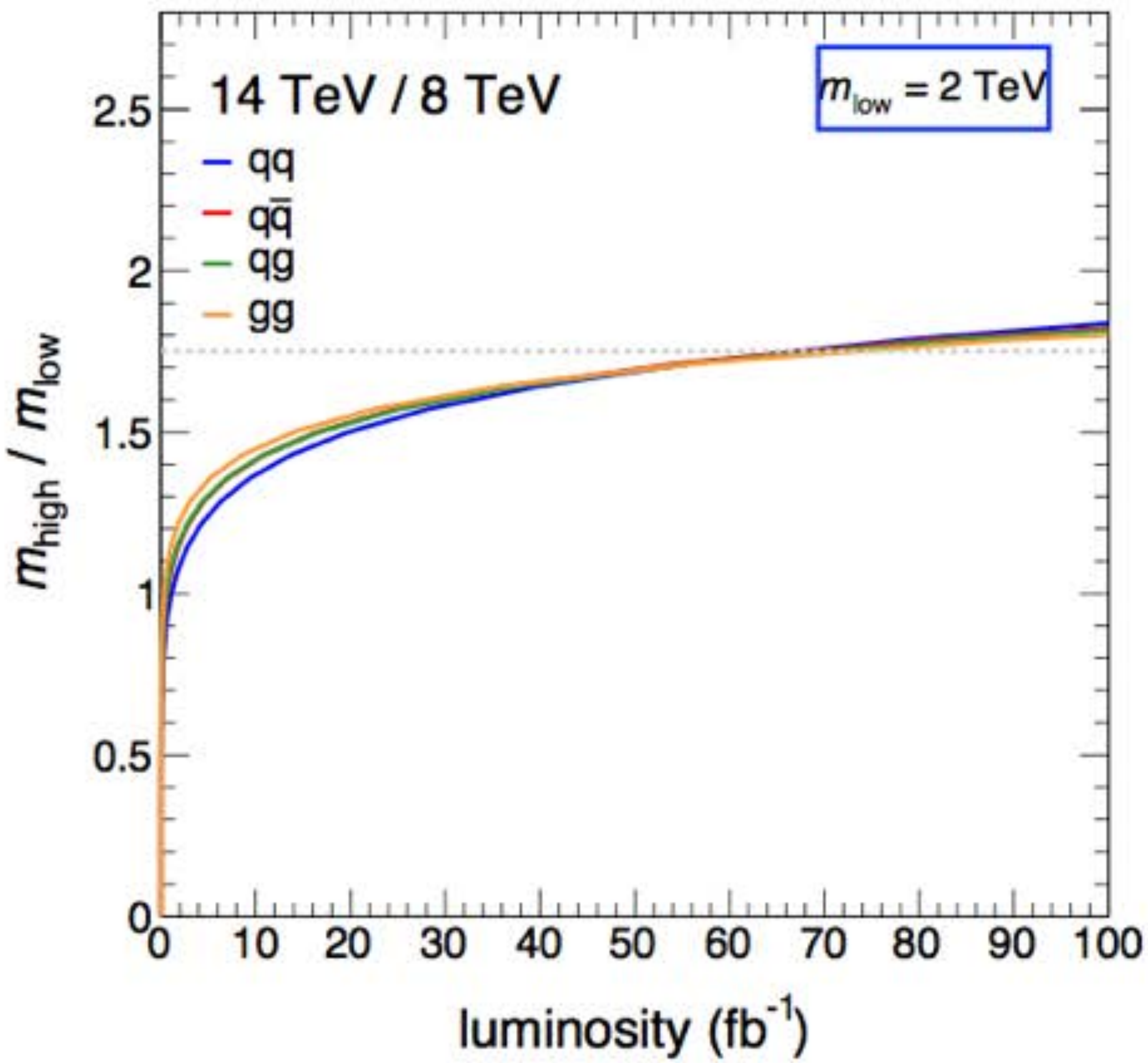
- $\sqrt{S} \rightarrow x \times \sqrt{S}$
- $\int L \rightarrow x^2 \times \int L$

$\Rightarrow M_{high} \rightarrow x \times M_{high}$

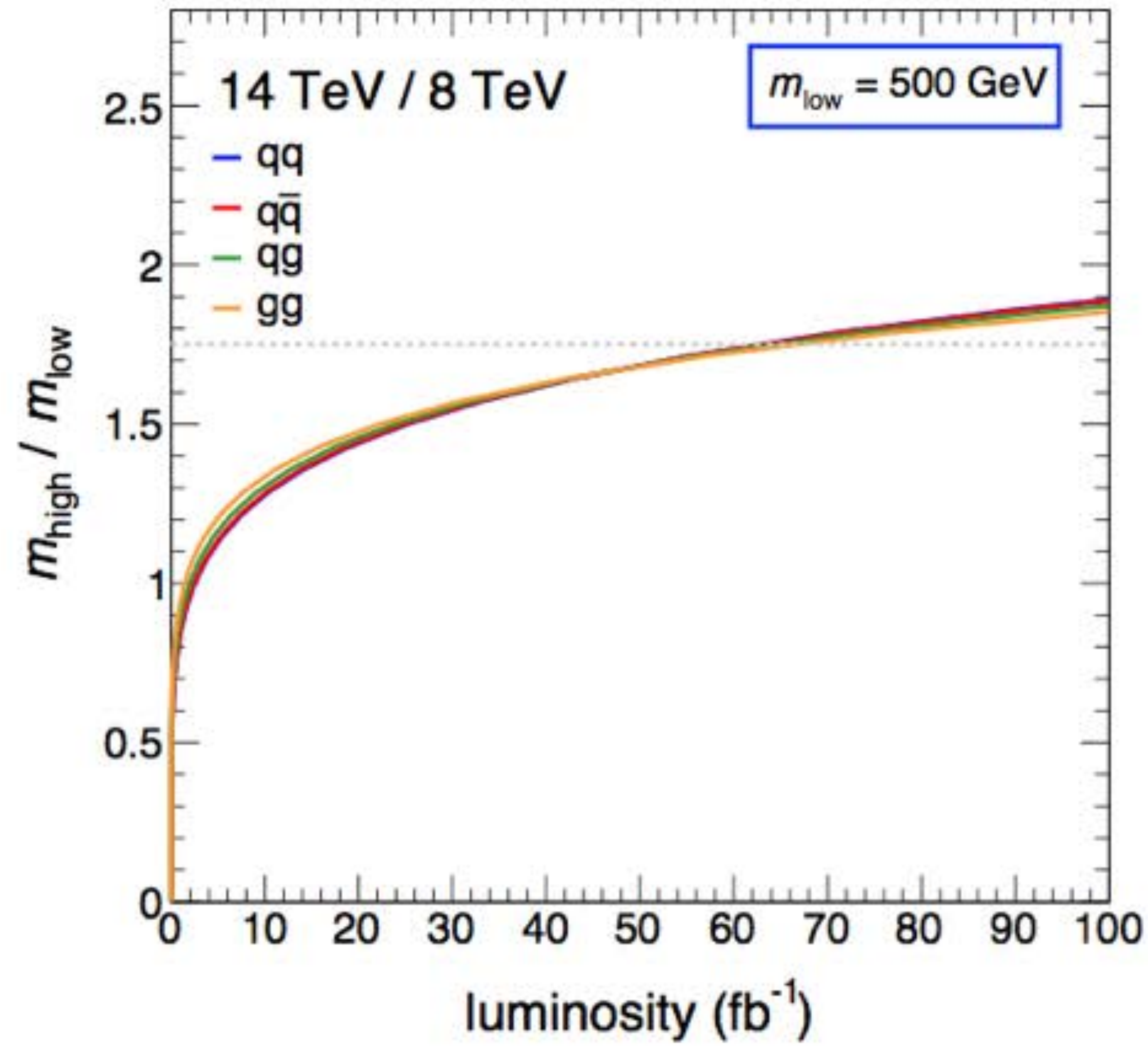
-same Bjorken-x scaling,
-Lumi compensates $1/M^2$

Δ M_{high} ~ Δ log (Lumi)

Run I limit 2 TeV, e.g. pair of 1 TeV gluino.



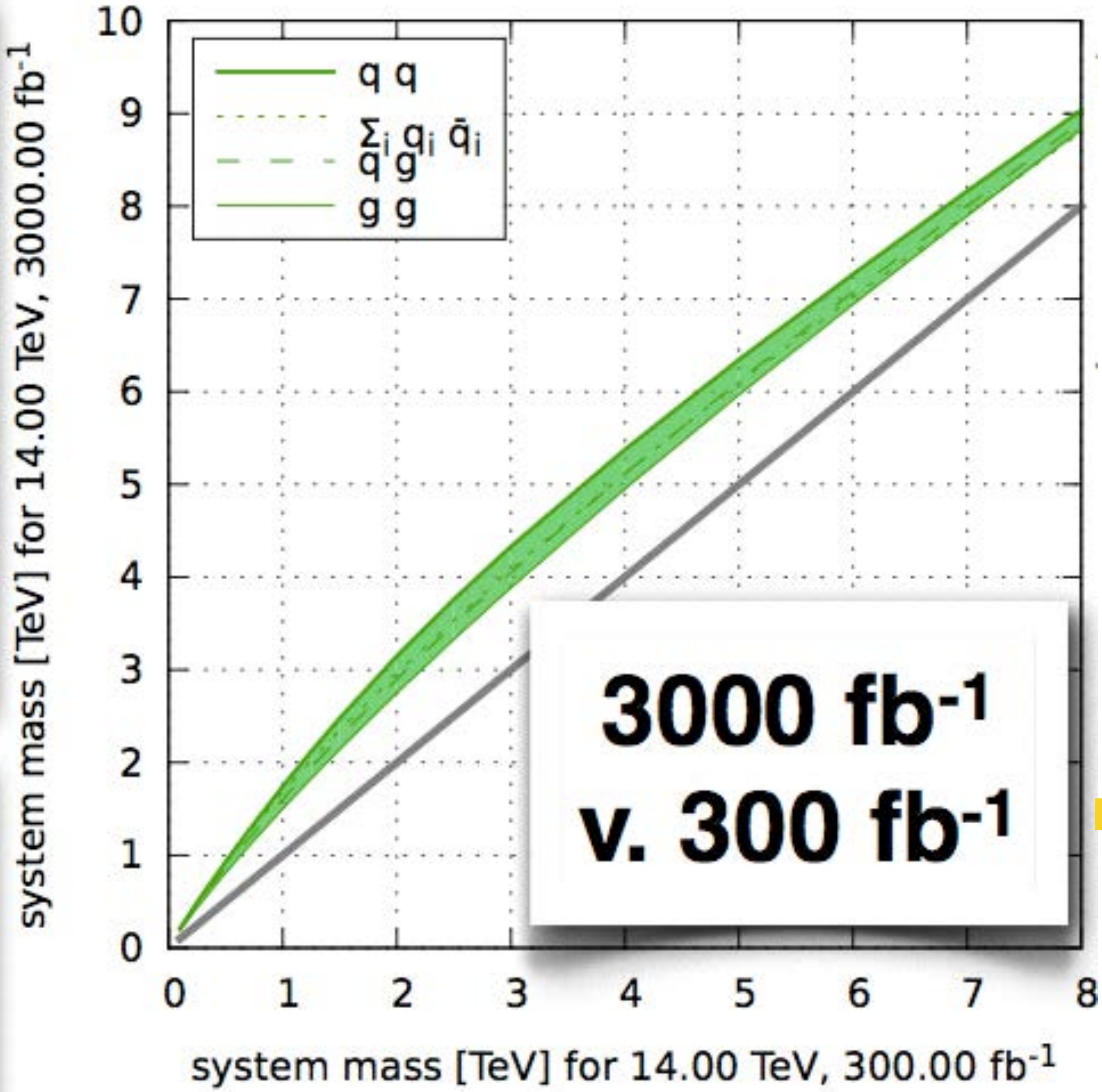
500 GeV, e.g. pair of 250 GeV electroweak-ino



Steep falling PDF ⇒ Rapid gain initial 10 fb^{-1}, slow improvements afterwards.

L.Wang SUSY2015

approx scaling of mass-reach (2)



valid for:
$0.15 \leq M_{high}/\sqrt{S} \leq 0.6$

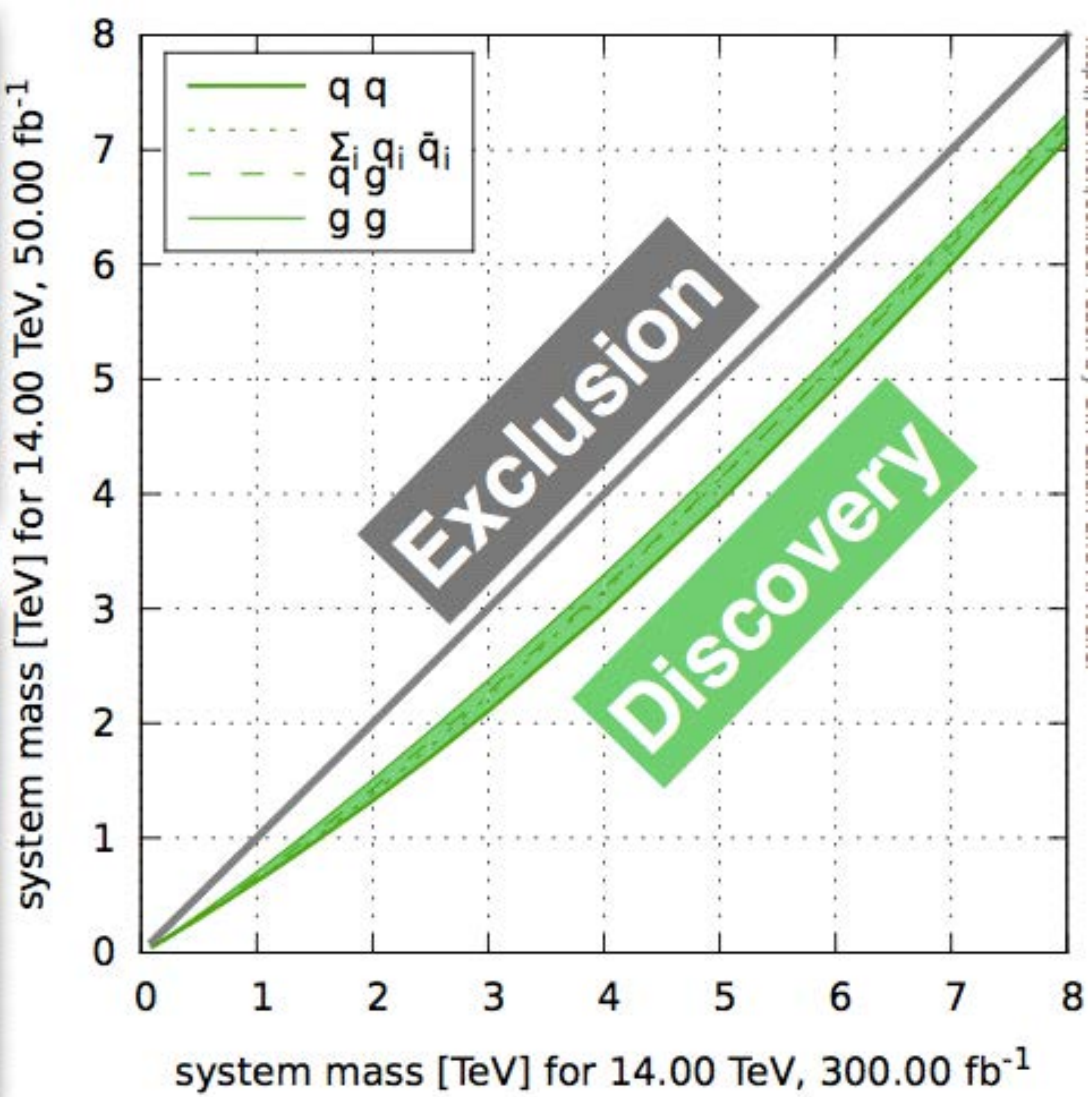
-from PDF's behavior at large x

- at given $\sqrt{S}$, if $\int L \to 10 \times \int L$

$\Delta M_{high} \to 0.07\sqrt{S}$

$= 1\text{TeV} \,|_{\sqrt{S}=14\text{TeV}}$

➜ approx scaling of exclus/discov-reach



~ valid for: $S \lesssim B$

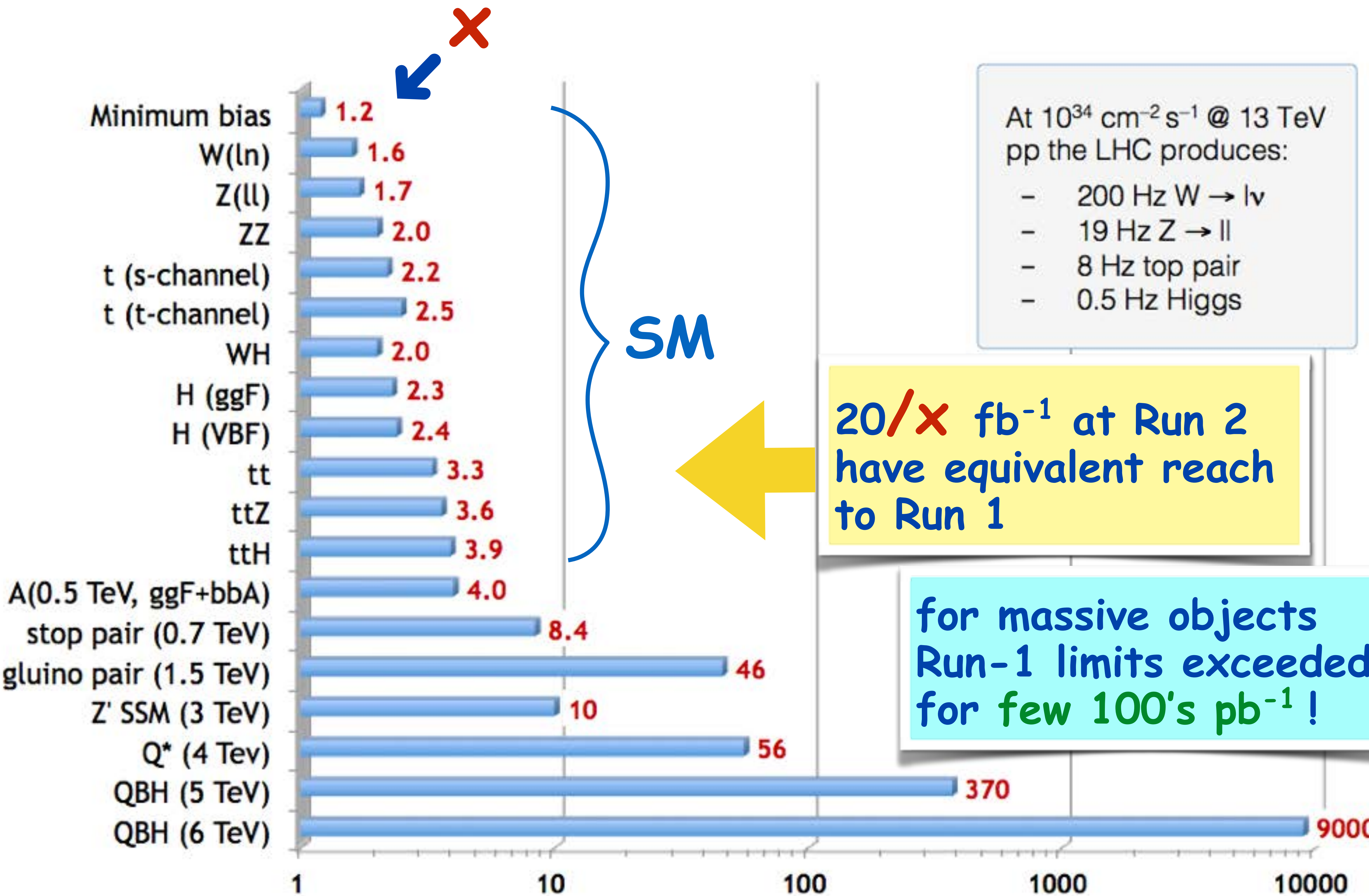
- exclusion ➜ 2-σ
- discovery ➜ 5-σ
- at given M reach :

$\int L_{discov} \sim (5/2)^2 \int L_{excl}$

$M_{disc} \sim M_{excl} - 0.05 \sqrt{S}$

$0.8\,\mathrm{TeV} \,|_{\sqrt{S}=14\,\mathrm{TeV}}$

x = σ(pp→X)$_{13TeV}$ / σ(pp→X)$_{8TeV}$



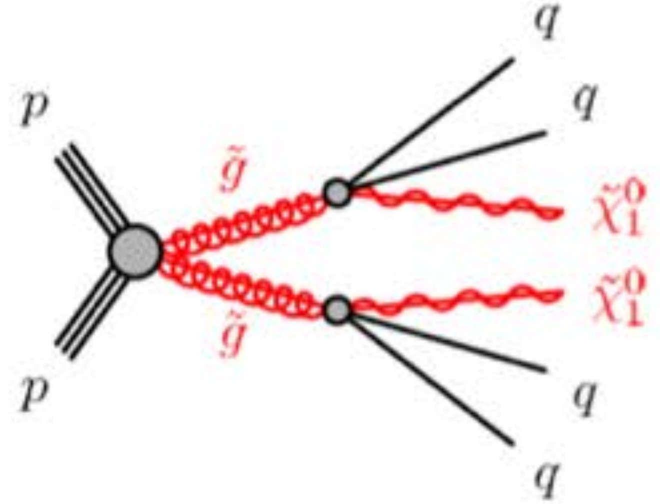
At 10^{34} cm^{-2} s^{-1} @ 13 TeV pp the LHC produces:

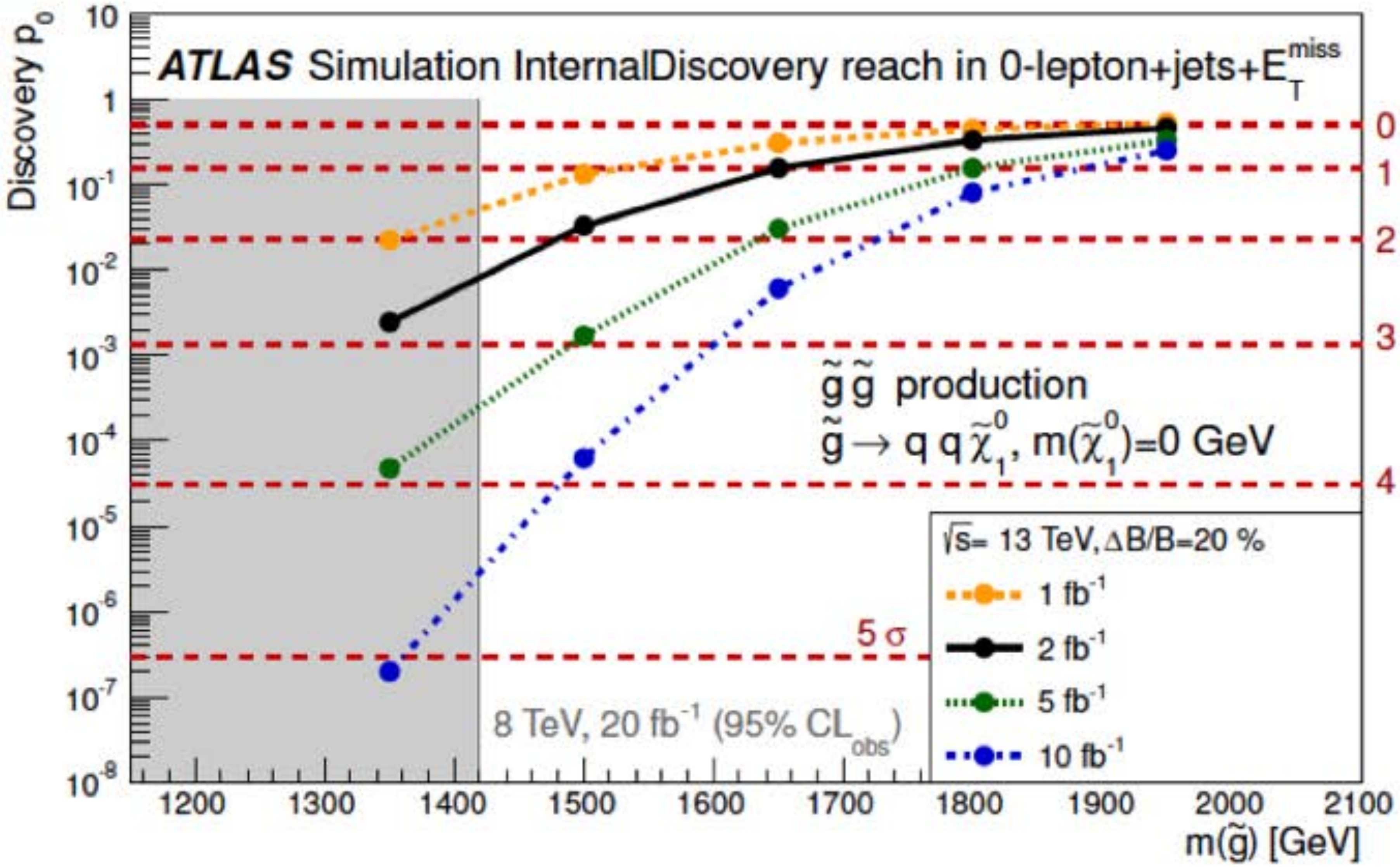
- 200 Hz W → lν
- 19 Hz Z → ll
- 8 Hz top pair
- 0.5 Hz Higgs

20/x fb^{-1} at Run 2 have equivalent reach to Run 1

for massive objects Run-1 limits exceeded for few 100's pb^{-1} !

Searches for new particles





- **Could find evidence (3σ) up to ~1.5 GeV with 5 fb^{-1}**

B. Heinemann LP2015

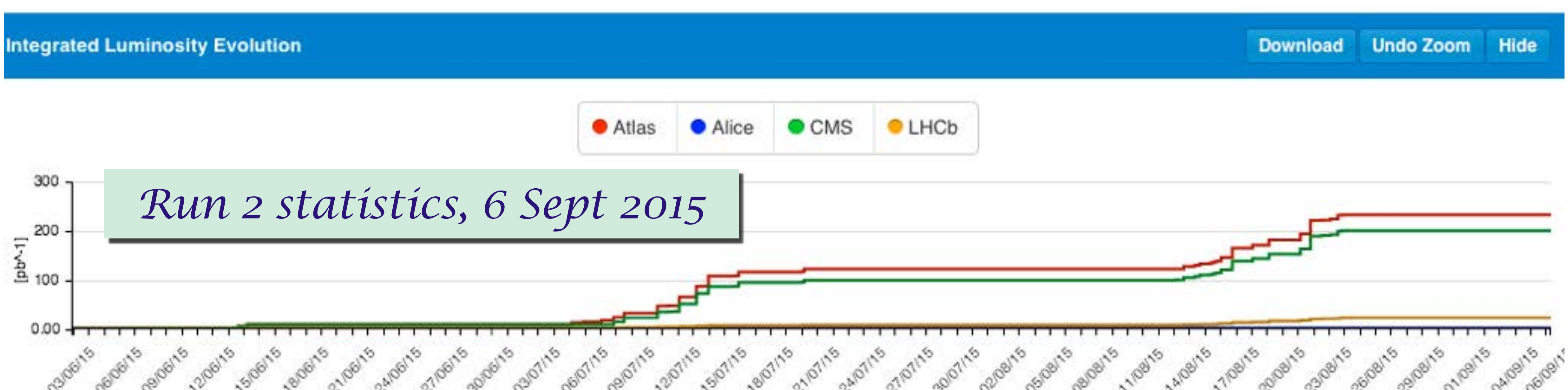
very first results at 13 TeV

(first ones appeared as soon as July !!!)

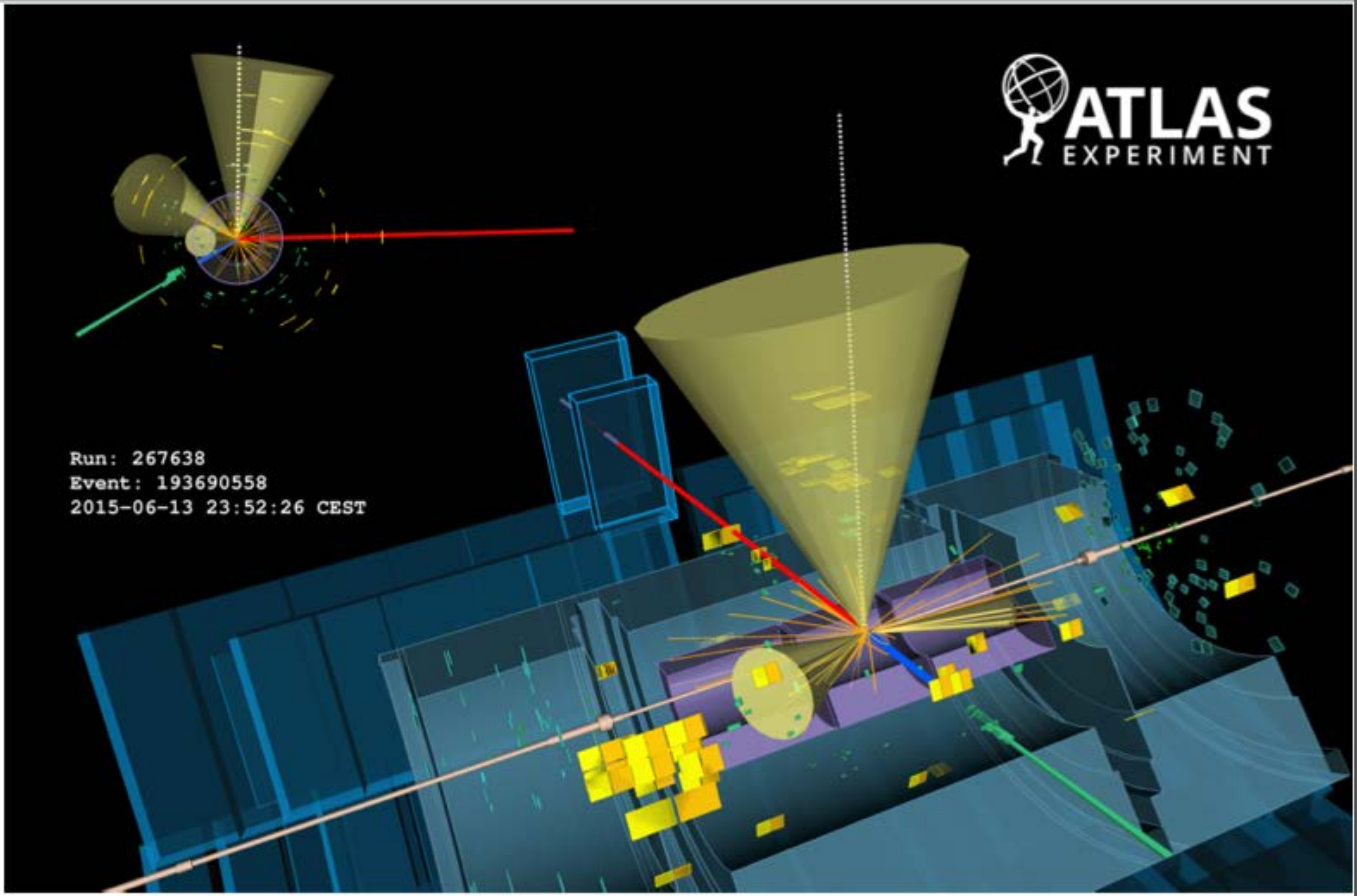
(quite a few) preliminary results at 13 TeV

- focus on ATLAS/CMS (>200 pb^{-1} collected up today)
- commissioning of Physics Objects ongoing
- SM cross sections [soft QCD (σ_{inel}, min bias, p.le correl.s), ee, μμ, inclusive-jet, W, Z, top-pair x-sections)
- di-jet and di-lepton resonances
- multi-jet, photon/lepton+jet, di-photons
- we are just 3 months after first stable beams at 13TeV !!!!!

ATLAS: 232.62 pb^{-1} **ALICE**: 842.21 nb^{-1} **CMS**: 200.21 pb^{-1} **LHCb**: 21.96 pb^{-1}

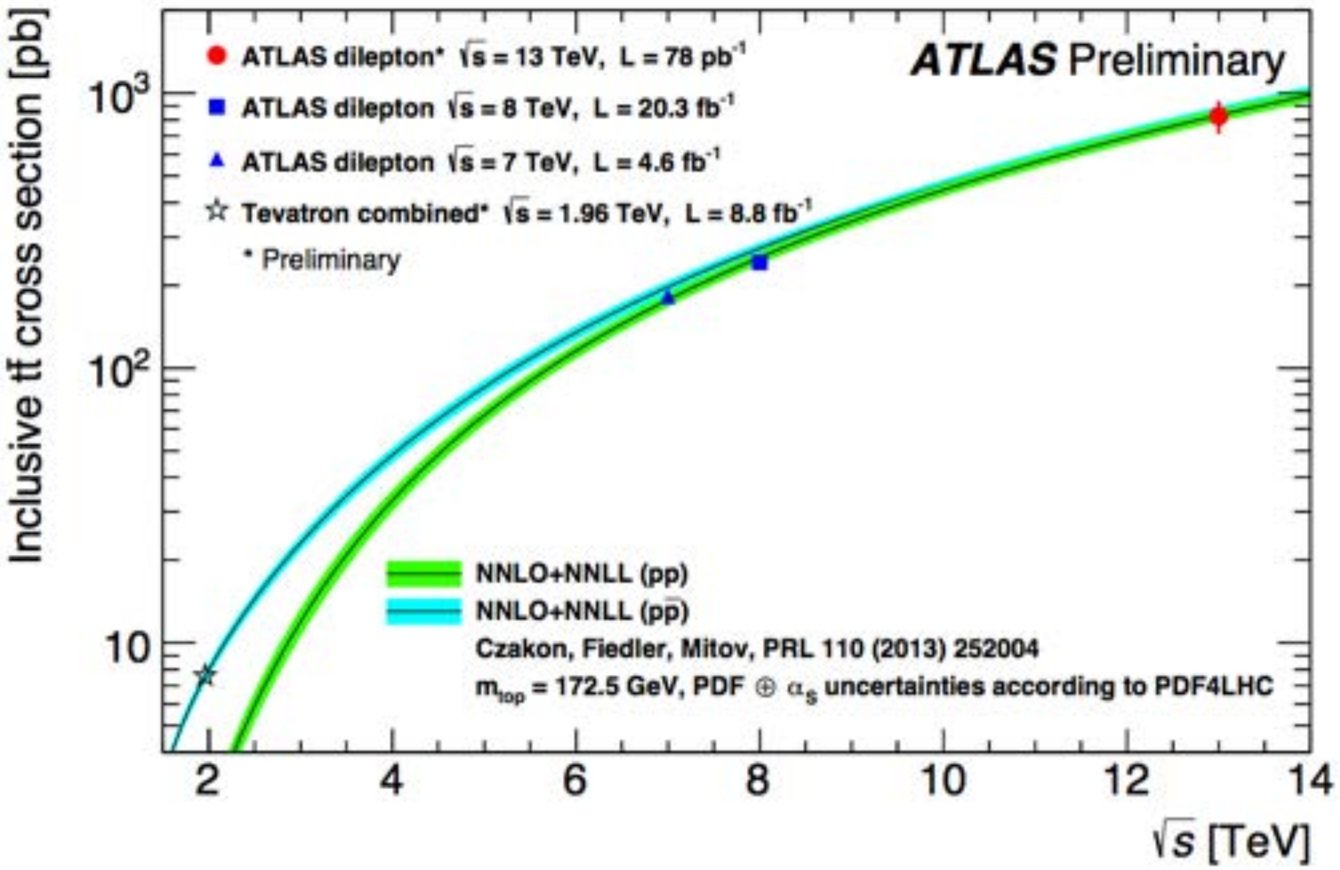


$t\bar{t}$ Production



- Isolated electron and muon, p_T>25 GeV
- 1 or 2 b-jets, p_T>25 GeV

first σ(ttbar) measurements at 13 TeV !

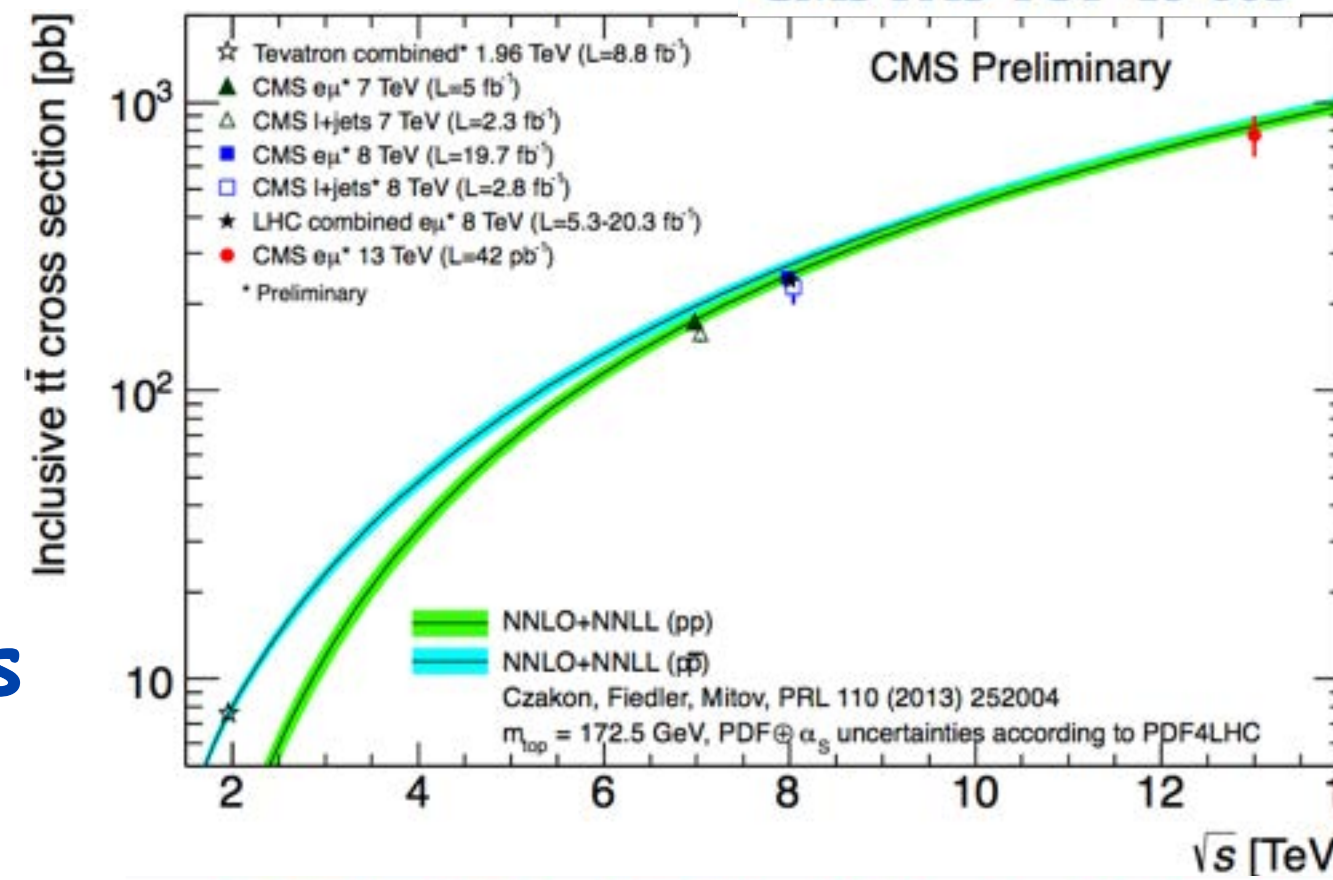


[*] ATLAS-CONF-2015-033

σ_{tt}=825±49 (stat.)±60 (syst.)±83 (lumi.) pb

- pp → t tbar
- 78 pb^{-1}(ATLAS)
- 42 pb^{-1} (CMS)
- di-lepton final states

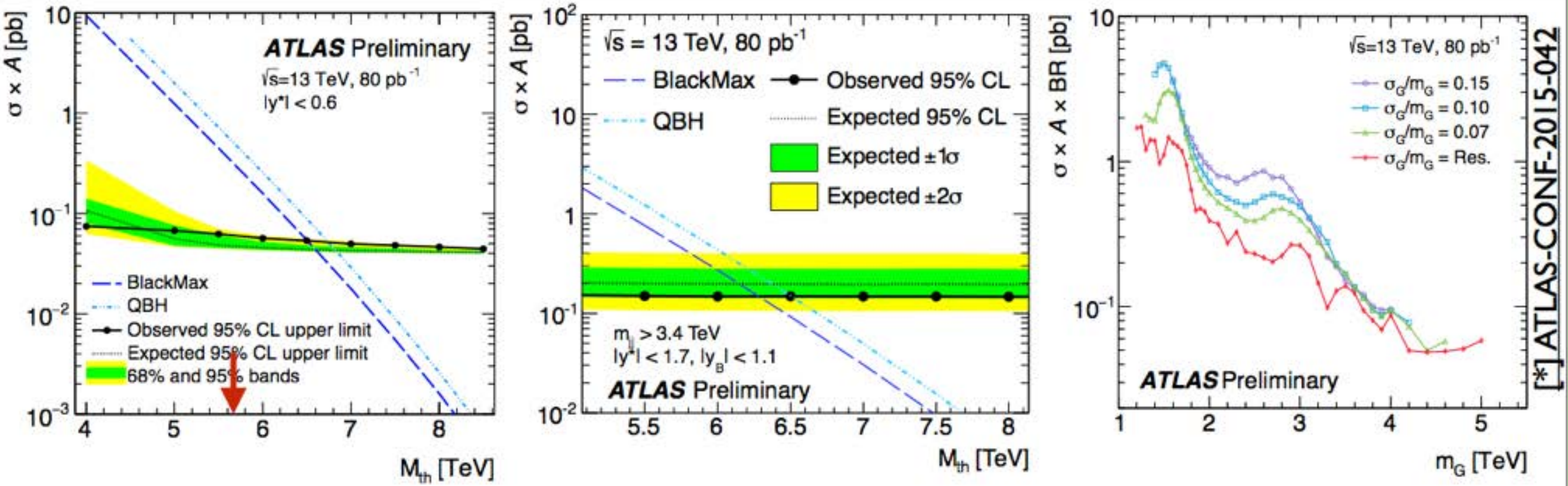
CMS PAS TOP-15-003



σ_{tt}(13TeV)= 772 ± 60 (sta) ± 62 (sys) ± 93 (lum) pb

- nice matching with NNLO+NNLL SM predictions

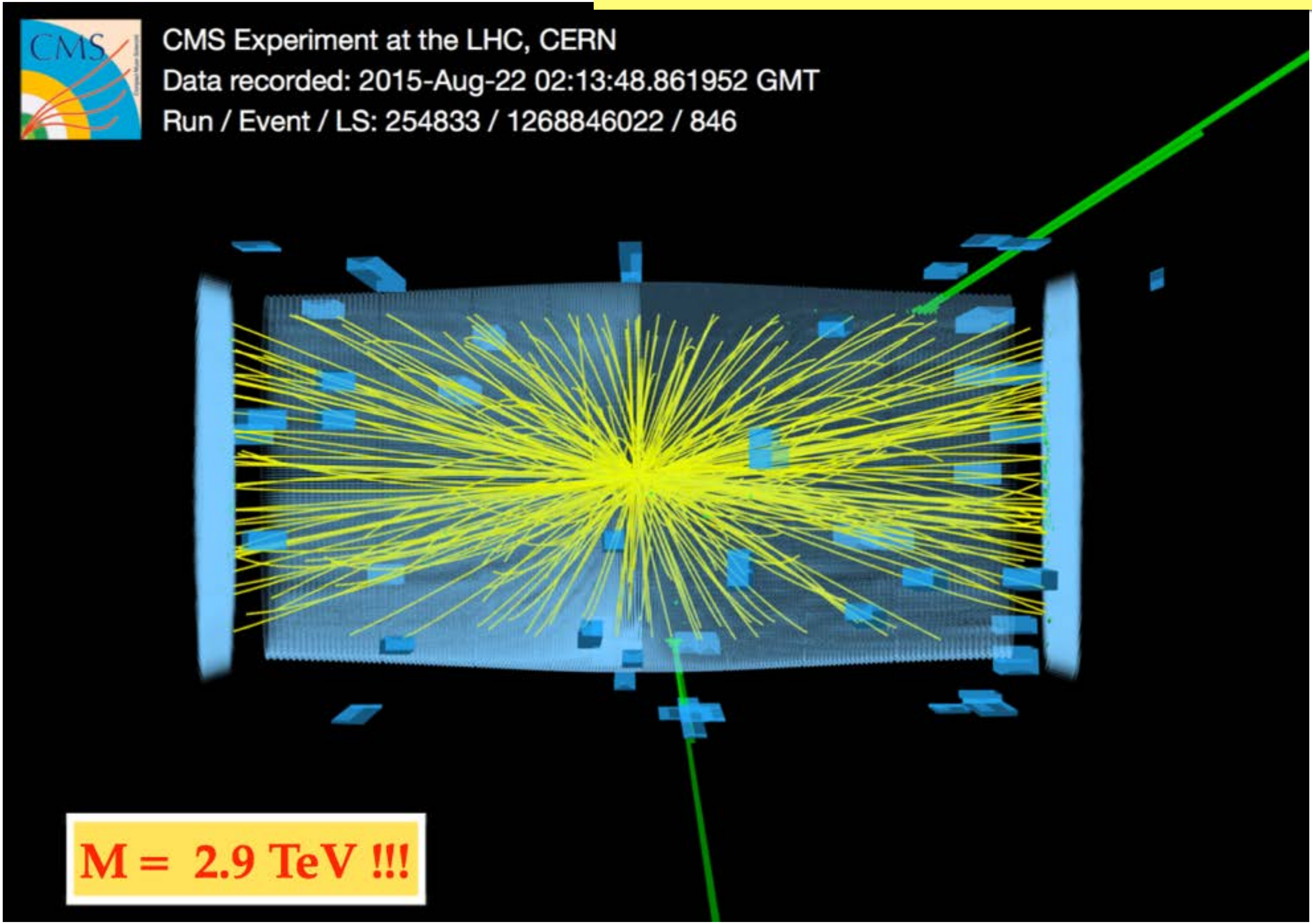
Summary of Limits (Dijet Searches)



- Limits on M_{th} of about 6.5 TeV, depending on model, a 1 TeV improvement with respect to Run 1 limits

- Model-independent limits on resonant cross section weaker than in Run 1, but extending to masses of up to 1 TeV higher (~5 TeV)

Di-electron resonance search

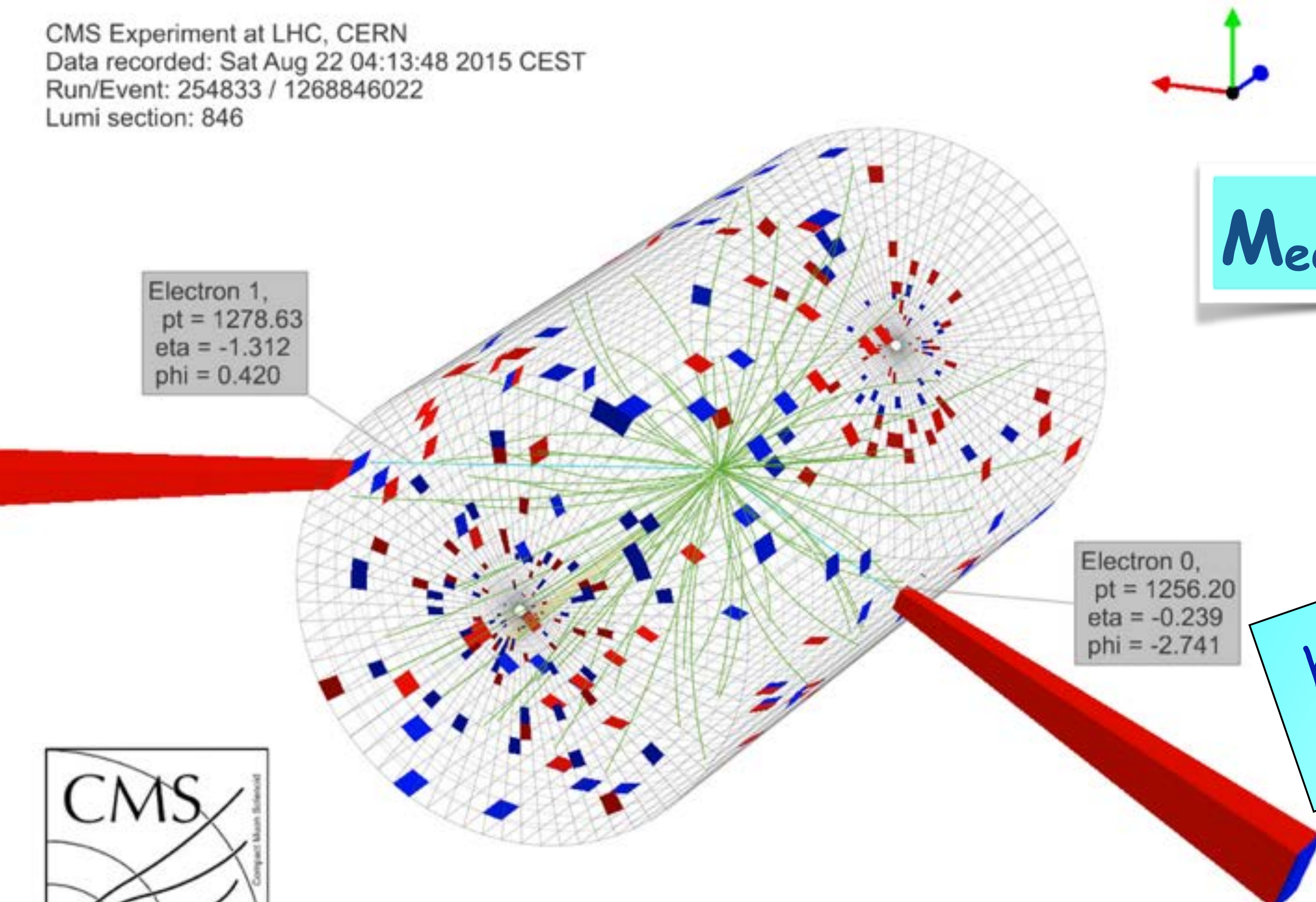


M = 2.9 TeV !!!

Di-electron resonance search at 13 TeV

one large-M_{ee} event observed with ~100 pb^{-1} at 13 TeV

(expected bckgd for M_{ee} > 2.5TeV → 0.002 evs)



M_{ee} = 2.9 TeV

highest M(ee) in whole Run 1 was 1.8 TeV !

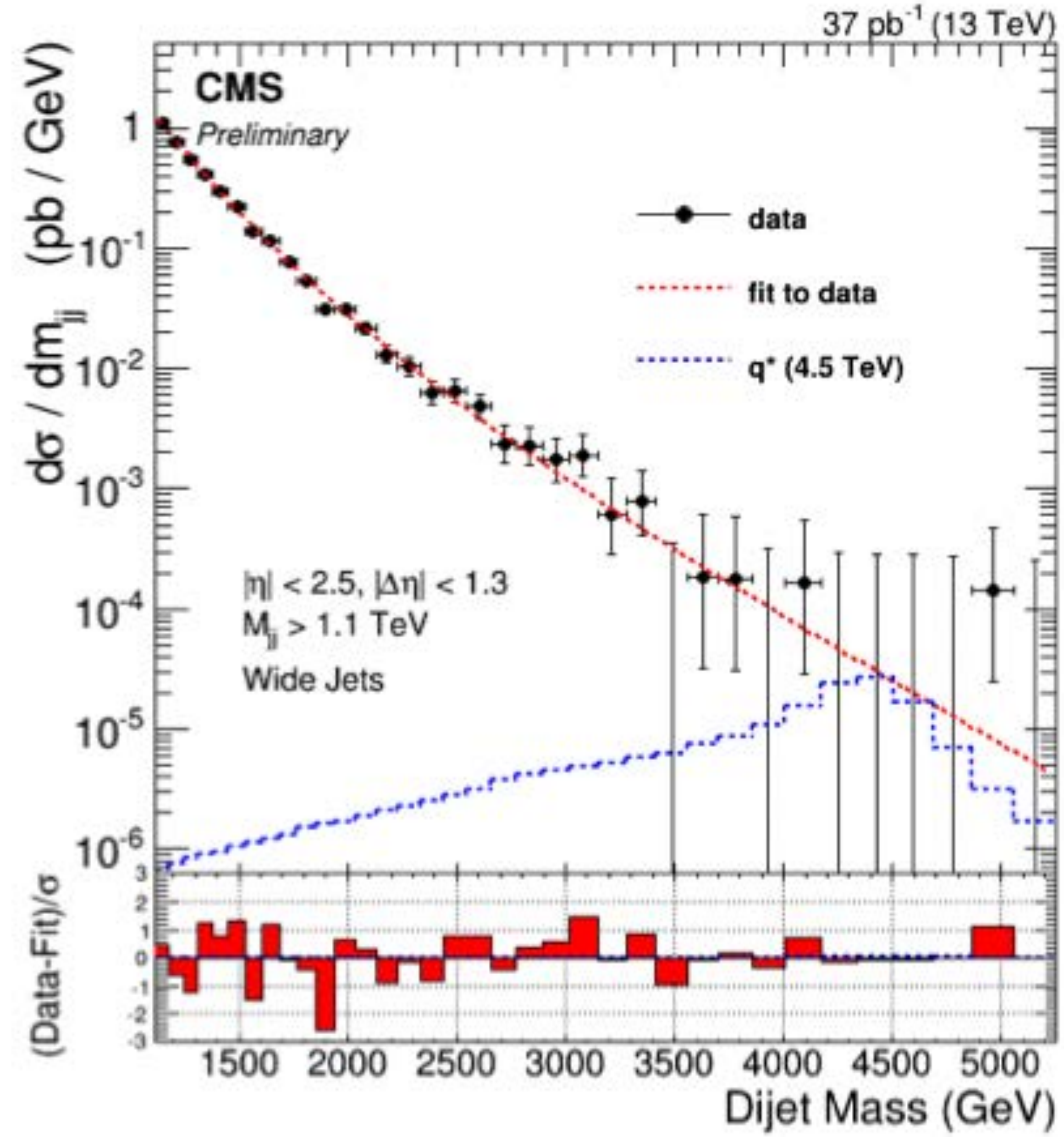
Di-jet resonance search

Fitting function unchanged since Run I

CMS-DP-2015-017/CDS:2037378

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-\frac{m_{jj}}{13000})^{p_1}}{(\frac{m_{jj}}{13000})^{p_2+p_3\ln(\frac{m_{jj}}{13000})}}$$

- Above 3.5 TeV
  - ➡~4.6 background events are expected (from fit to data) and
  - ➡~0.8 events of signal from the considered q* model (4.5 TeV).
  - ➡4 events are observed in data.



- With the current integrated luminosity we expect to exceed the sensitivity of the 8 TeV analyses only for narrow resonances with masses greater than about 5 TeV.

Stay tuned.

Possible Scenarios Ahead

(from next few years LHC outcome…)

possible scenarios ahead

A: one (or more) new Resonance(s) discovered

start to build up extended theory (known framework ? new ideas needed ?)

deep Revolution in Particle Physics !

B: (>3σ) anomalies in σ's/BR's/distrib.s

new forces ? exchange of new states ? (particular focus on Higgs/top/MET processes, most exposed to SM criticalities)

C: both A and B occur

knowledge in Particle Physics improved anyway !

D: no real anomaly in collider data

accuracy in SM phenomena dramatically increased, new energy territory explored

no "discovery" at LEP ! anyway its results gained a Nobel Prize to t'Hooft and Veltmann…

Outlook

- SM: beautifully successful at E < 1TeV BUT it is not enough…
- Higgs boson is the first elementary (?) scalar field observed in nature ➜ it comes together with quite a few criticalities !
  ➜ measurement of Higgs properties is one of the best ways to "indirectly" discover new physics (and discriminate among different BSM's); possibility of exotic signatures/more Higgses
- Higgs boson observation opened up an entire new chapter of BSM exploration ➜ in case of no observation of new heavy states in the next LHC run, precision Higgs physics will have a key role in paving the way for extending the SM theory…
- LHC Run 2 just started with great potential for discoveries !
- however "revolutionary" the LHC outcome at ~14TeV will be, it will lay just the first stage of a new path of exploration (in no way a conclusive one for Particle Physics !)