New Physics in the Early LHC

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Outline

- LHC -- An overview of the machine
- What happens when protons collide?
- Will the LHC be able to see the Higgs?
- Will the LHC be able to see supersymmetry?
- How about more exotic new physics?

Basic Quantities

Instantaneous Luminosity

$$\mathcal{L} = \frac{f_{\text{rev}} N_p^2 n_b}{4\pi w_b^2} F$$

Typically measured in $\text{cm}^{-2}\text{s}^{-1}$

Event Rate

$$R = \sigma_{\text{proc}} \mathcal{L}$$

Typically measured in number per second

Integrated Luminosity

$$\mathcal{L}_{\text{int}} = \int \mathcal{L} dt$$

Typically measured in $\{p,f\}b^{-1}$

Number detected

$$N = \epsilon_{\text{detect}} \sigma_{\text{proc}} \int \mathcal{L} dt + N_{\text{background}}$$

$$1\text{cm}^2 = 10^{24}\text{barns} = 10^{36}\text{pb} = 10^{39}\text{fb}$$

Ideal LHC

Design parameters:

	Tevatron	LHC
Energy per Beam	0.98 TeV	7.0 TeV
# of Bunches	36	2808
Protons / bunch	2×10^{11}	1×10^{11}
Luminosity	3×10^{32} cm^{-2}s^{-1}	1×10^{34} cm^{-2}s^{-1}
Magnetic Field	4.2 T	8.3 T
Temperature	4.2 K	1.9 K
Circumference	6.3 km	27.0 km

Ideal integrated LHC luminosity of ~100 fb^{-1}/yr

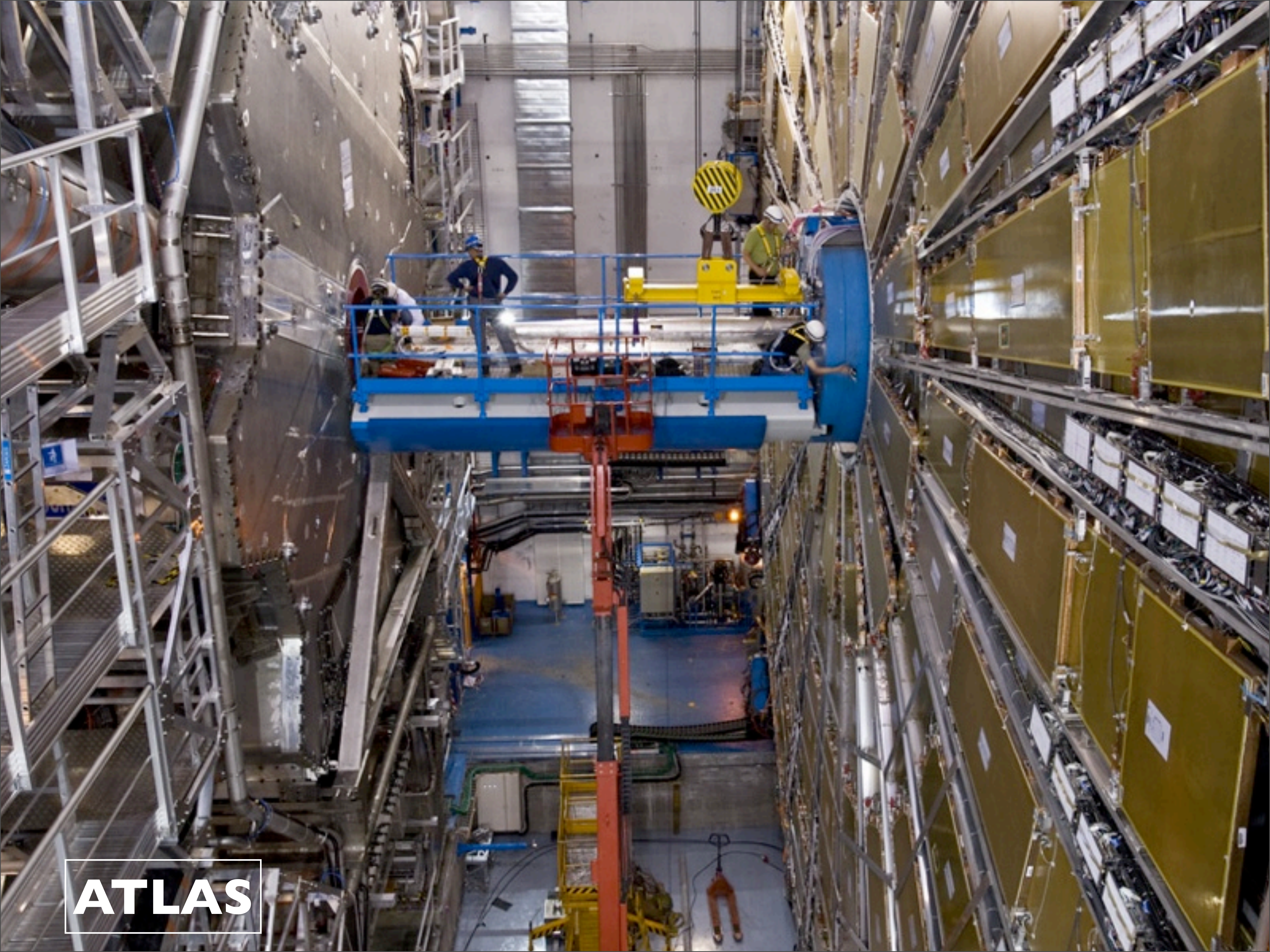

Beam Pipe

LHC Experiments

There are four detectors. All have been “ready” since 2008.

ATLAS	General purpose -- Higgs and supersymmetry.
CMS	General purpose -- Higgs and supersymmetry.
ALICE	Quark-gluon plasma.
LHCb	B Mesons. Matter-antimatter asymmetry.

The physics in this talk will focus on ATLAS and CMS.

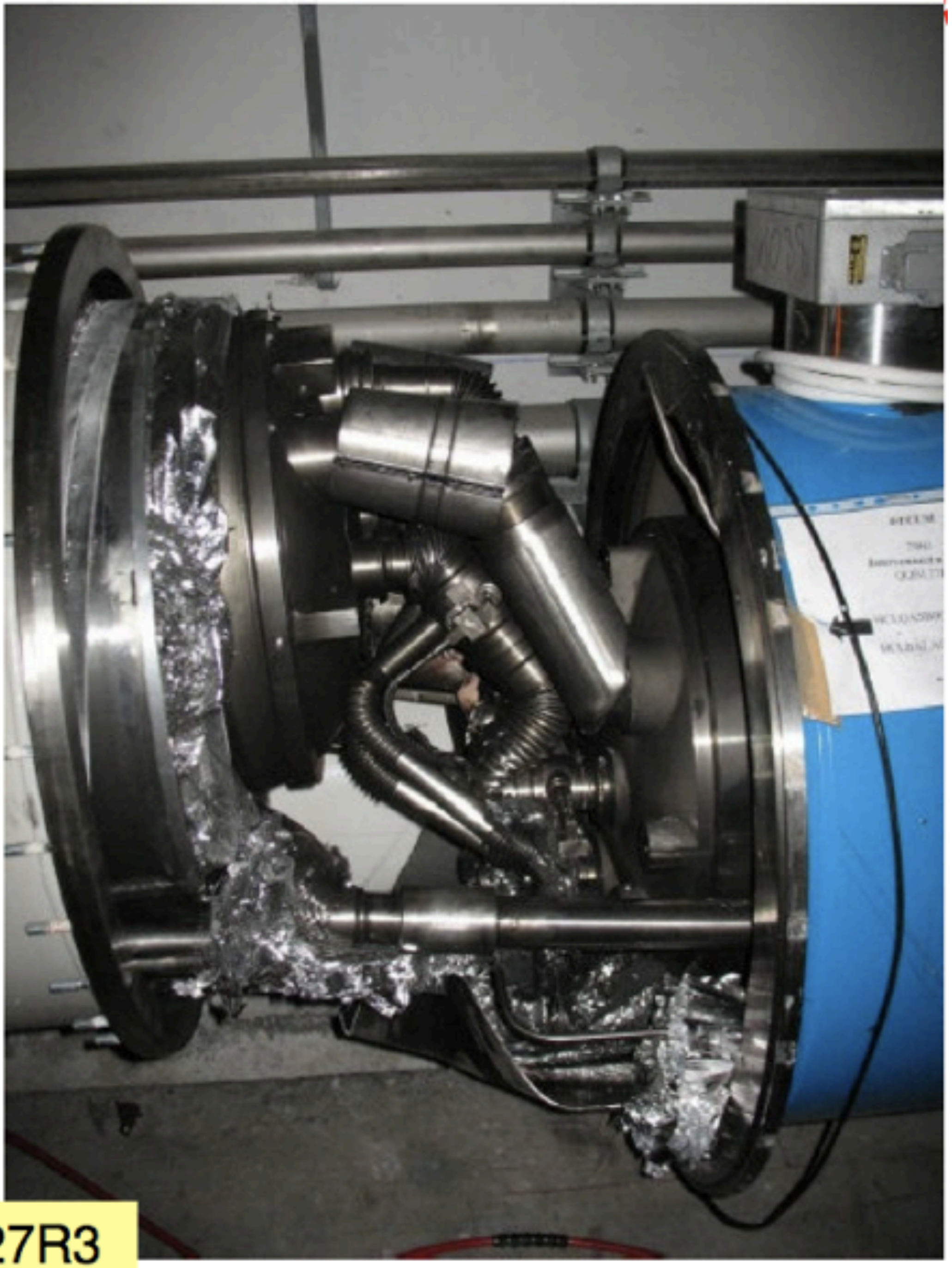

ATLAS


JLG LIFTLUX 153-12
CMS


Welding an
Interconnection

LHC Timeline: Part 1

- 1994: Formal approval from CERN
- 1995: Technical Design Report completed
- 2002: Magnet production transferred to industry
- 2005: First magnet lowered
- 2007: Last magnet lowered, interconnections complete
- 2008: Construction complete, cool down ring
- Sept 10, 2008: First beam injection, splash events observed
- Sept 11-18, 2008: Beam studies and ramping in energy
- Sept 19, 2008: A problem develops...



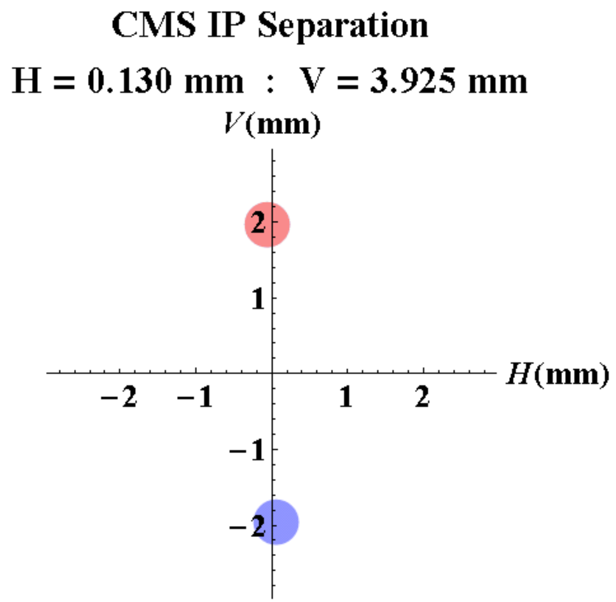
QQBI.27R3


FEIN Elektrowe
FEIN Electric Power

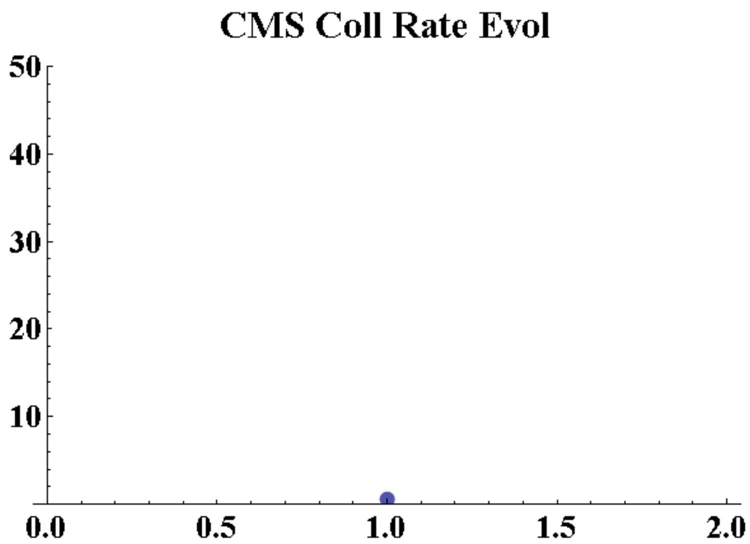
LHC Timeline: Part 2

- October 2008 - October 2009: Repairs, installation of new safety features, re-cooling of magnets
- October 26, 2009: First new beam injection tests
- November 20, 2009: Circulating beams in each direction
- November 23, 2009: First collisions, at 900 GeV c.m.e.
- November 30, 2009: Beams to 1.18 TeV each (world record)
- December 2009: Millions of collision events recorded
- February 3, 2010: Decision to cap at 3.5 TeV / beam for first run
- March 19, 2010: Beams ramp to 3.5 TeV each
- March 30, 2010: Collisions at 7 TeV c.m.e.
- *Until ~Fall 2011: Collisions, beam studies, luminosity improvements*
- *Until ~December 2012: Technical stop for upgrades*
- *December 2012 and onward: Collisions at 14TeV*

LHC Timeline: Recent

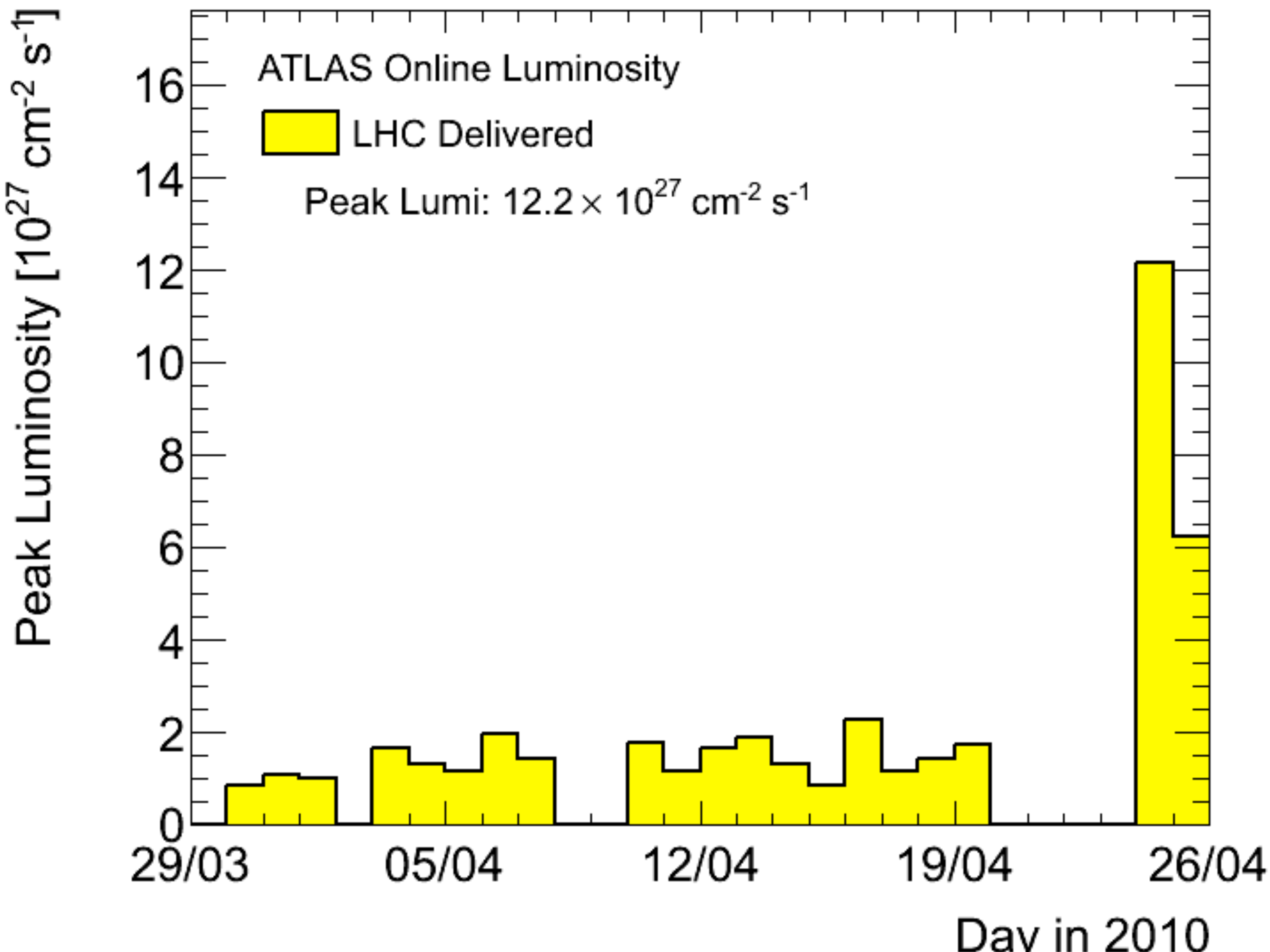


March-April: Work on beam overlap.

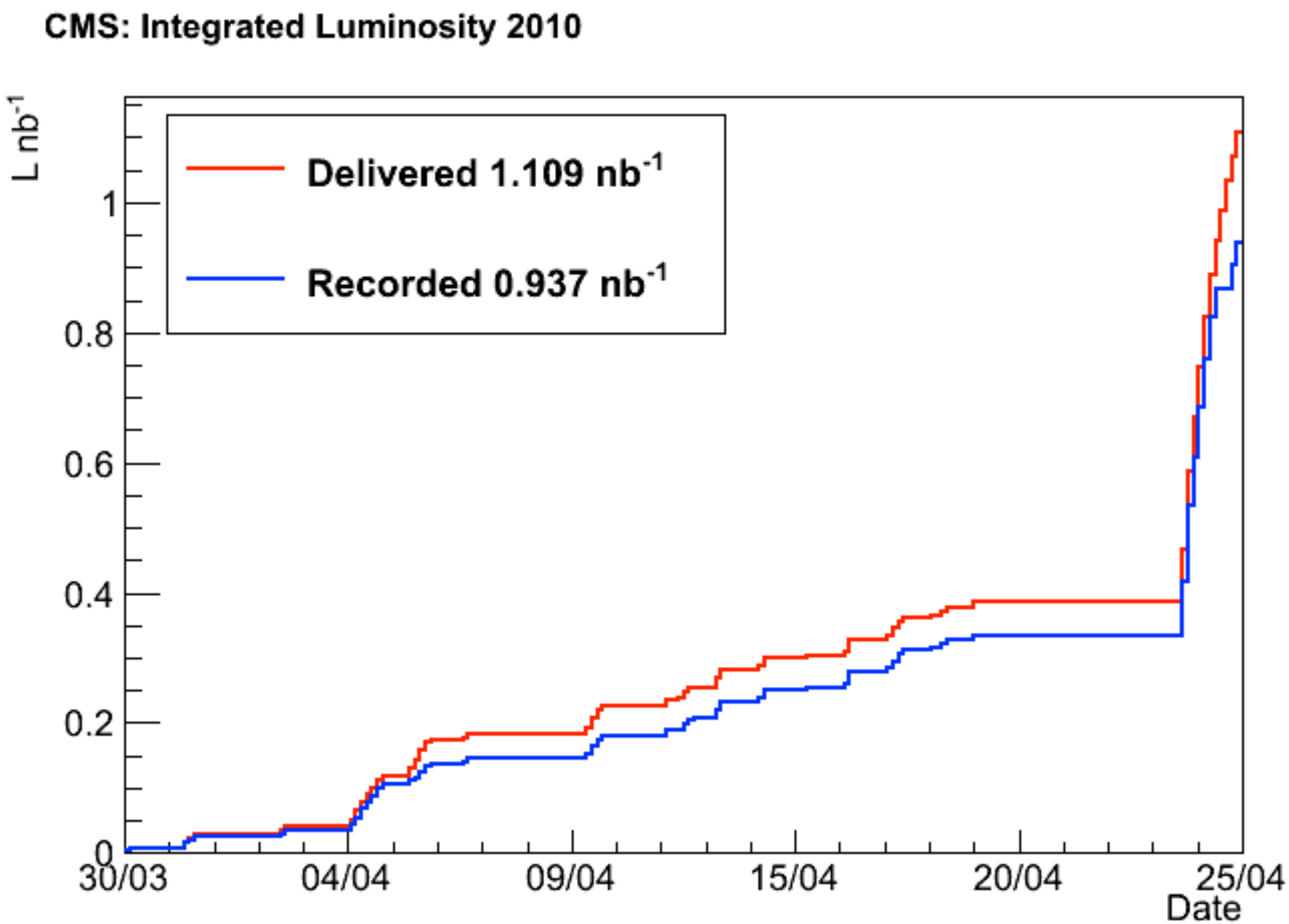


LHC Timeline: Recent

End of April: Work on "squeezed beams" to increase luminosity.



LHC Timeline: Luminosity Timeline



Note: $\mathrm{nb}^{-1} = 10^{-6}\mathrm{fb}^{-1}$

LHC Timeline: Luminosity Timeline

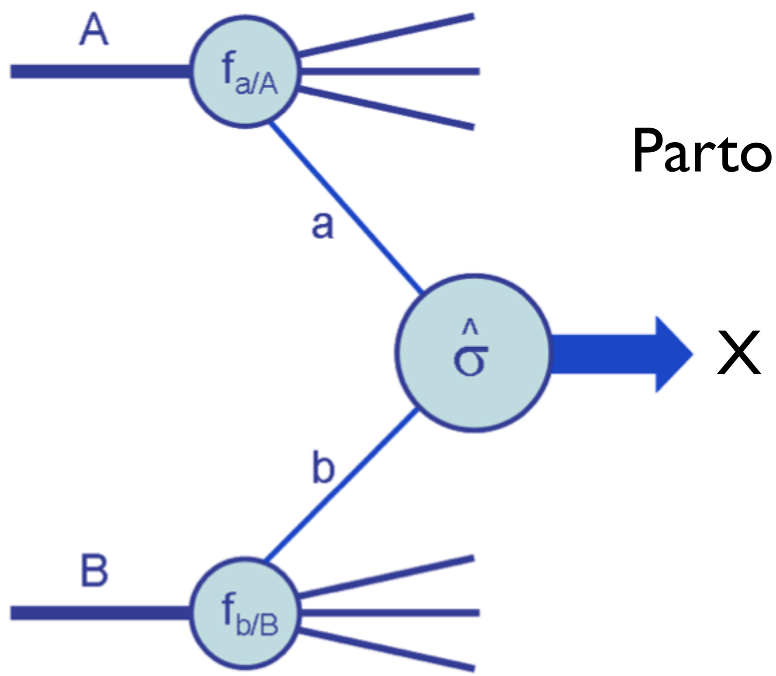
Step	Comment	Turn around time	Max number bunches	Protons/Bunch	% nom. intensity	Min beta*	Peak Luminosity $cm^{-2}s^{-1}$	Integrated Luminosity per month	events/X
1	Beam commissioning							First collisions	
2	Pilot physics, partial squeeze, gentle increase in bunch intensity, avaialbility low	Long	43	3×10^{10}		4 m	8.6×10^{29}	100 - 200 nb^{-1}	
3		5	43	5×10^{10}		4 m	2.4×10^{30}	~ 1 pb^{-1}	
4		5	156	5×10^{10}	**2.5**	2 m	1.7×10^{31}	~9 pb^{-1}	
5a	No crossing angle - could at this stage push intensity see 5b	5	156	7×10^{10}	**3.4**	2 m	3.4×10^{31}	~18 pb^{-1}	0.8
7	No crossing angle.	5	156	7×10^{10}	**3.4**	2 m	4.9×10^{31}	~26 pb^{-1}	
8	50 ns - nominal crossing angle - aperture restricts squeezing further - note limited complement of bunches.	5	144	7×10^{10}	**3.1**	2 m	4.4×10^{31}	~23 pb^{-1}	
9	50 ns	5	288	7×10^{10}	**6.2**	2 m	8.8×10^{31}	~46 pb^{-1}	
10	50 ns*	5	432	7×10^{10}	**9.4**	2 m	1.3×10^{32}	~69 pb^{-1}	
(11)	50 ns*	5	432	9×10^{10}	**11.5***	2 m	2.1×10^{32}	~110 pb^{-1}	

(an early plan for 3.5 TeV/beam energy)

Note final luminosity

Collisions: Proton Interactions

Protons are messy objects with unpleasant structure. Would like to simplify.



Parton Model

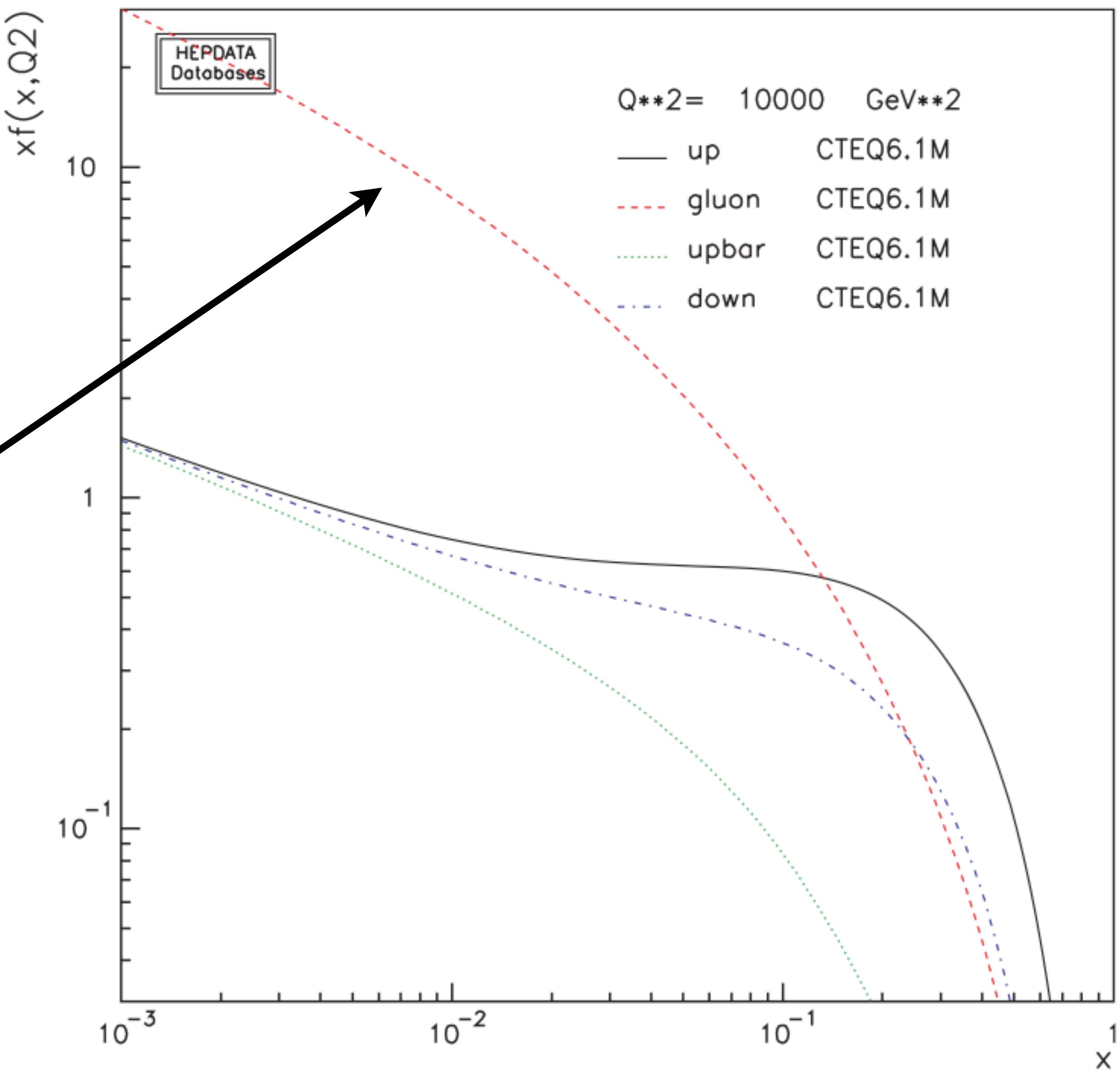
$$\sigma_{A+B\to X} = \int \hat{\sigma}_{a+b\to X} f_{\mathrm{a/A}}(x_1, Q) f_{\mathrm{b/B}}(x_2, Q) dx_1 dx_2$$

f_i = Parton Distribution Function, the probability density of finding particle type i carrying fraction x_i of proton's momentum.

$$\hat{s} = x_1 x_2 s$$

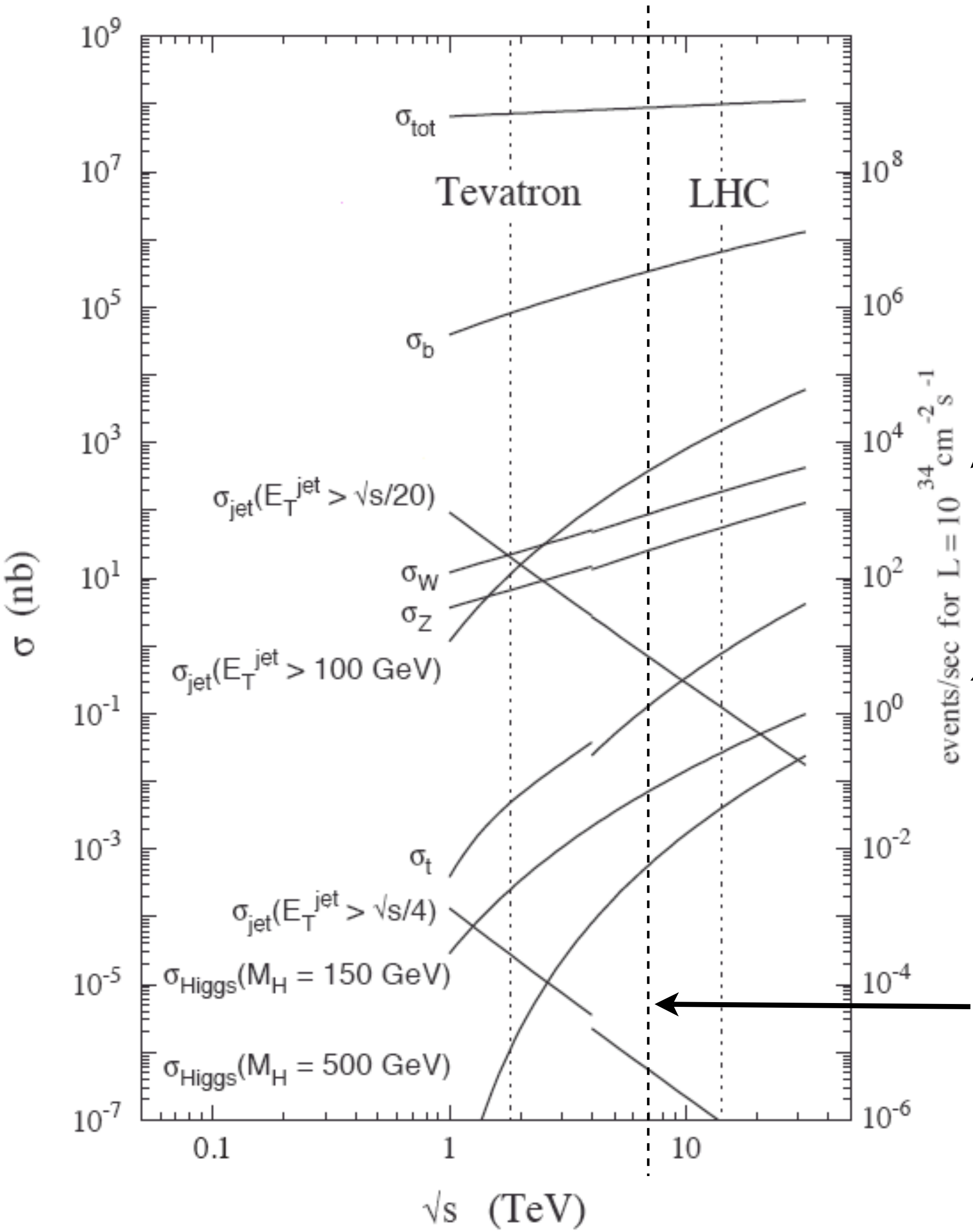
Collisions: Proton Interactions

PDFs depend on energy scale Q (typically the momentum transfer scale).



LHC mostly collides gluons

Collisions: Standard Cross-Sections



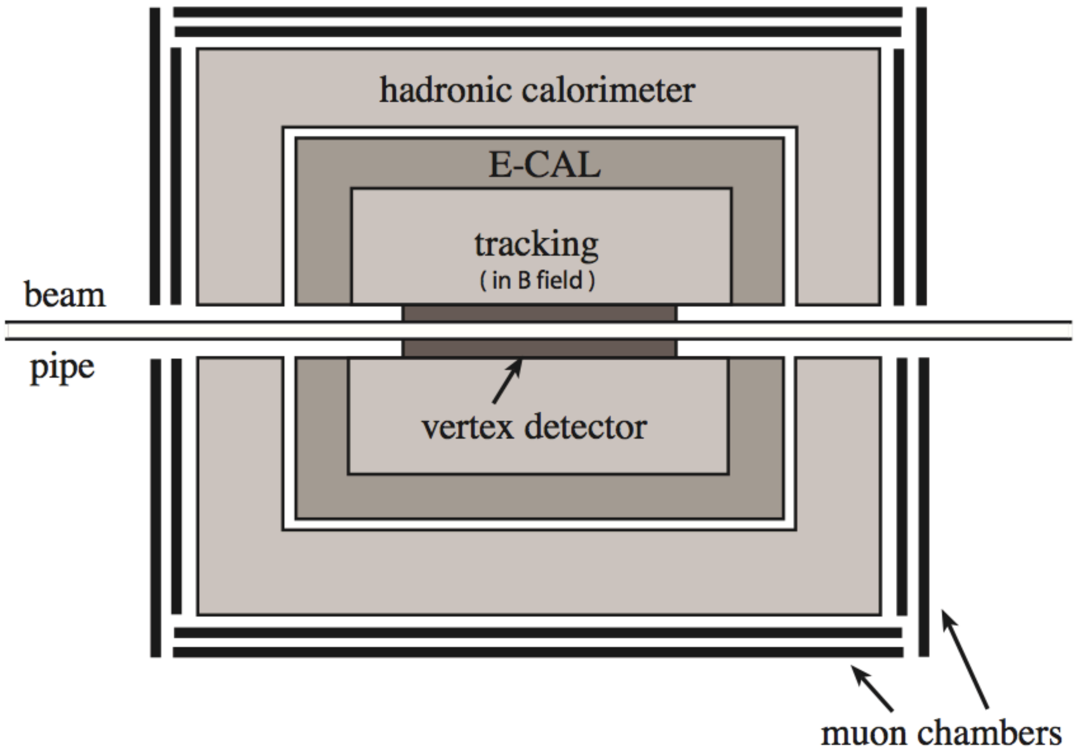
Current luminosity more like 10^{28} $cm^{-2}s^{-1}$

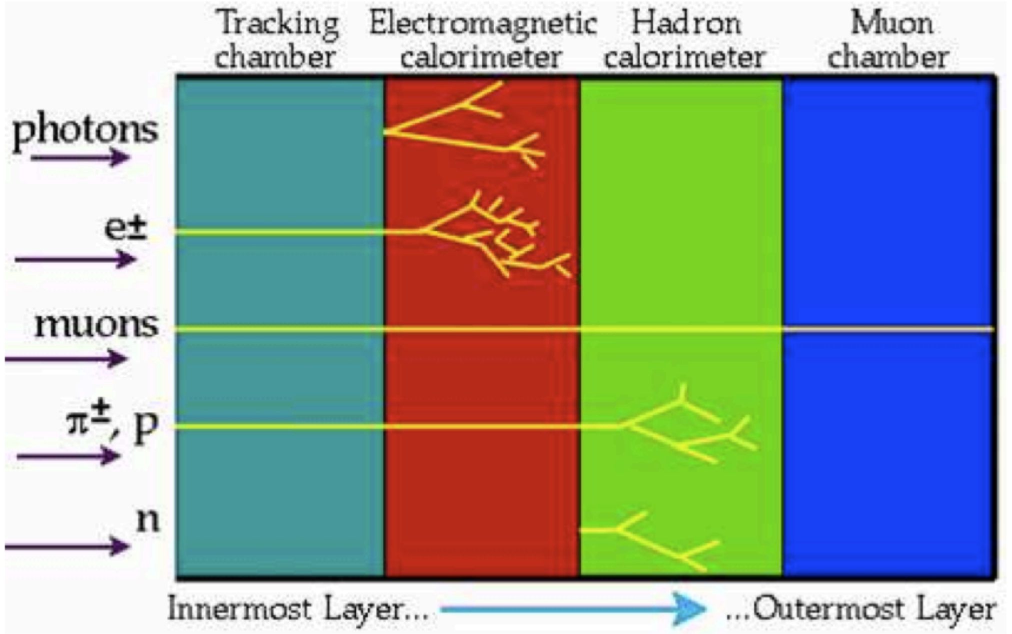
So read as events/month instead of events/s

Early LHC

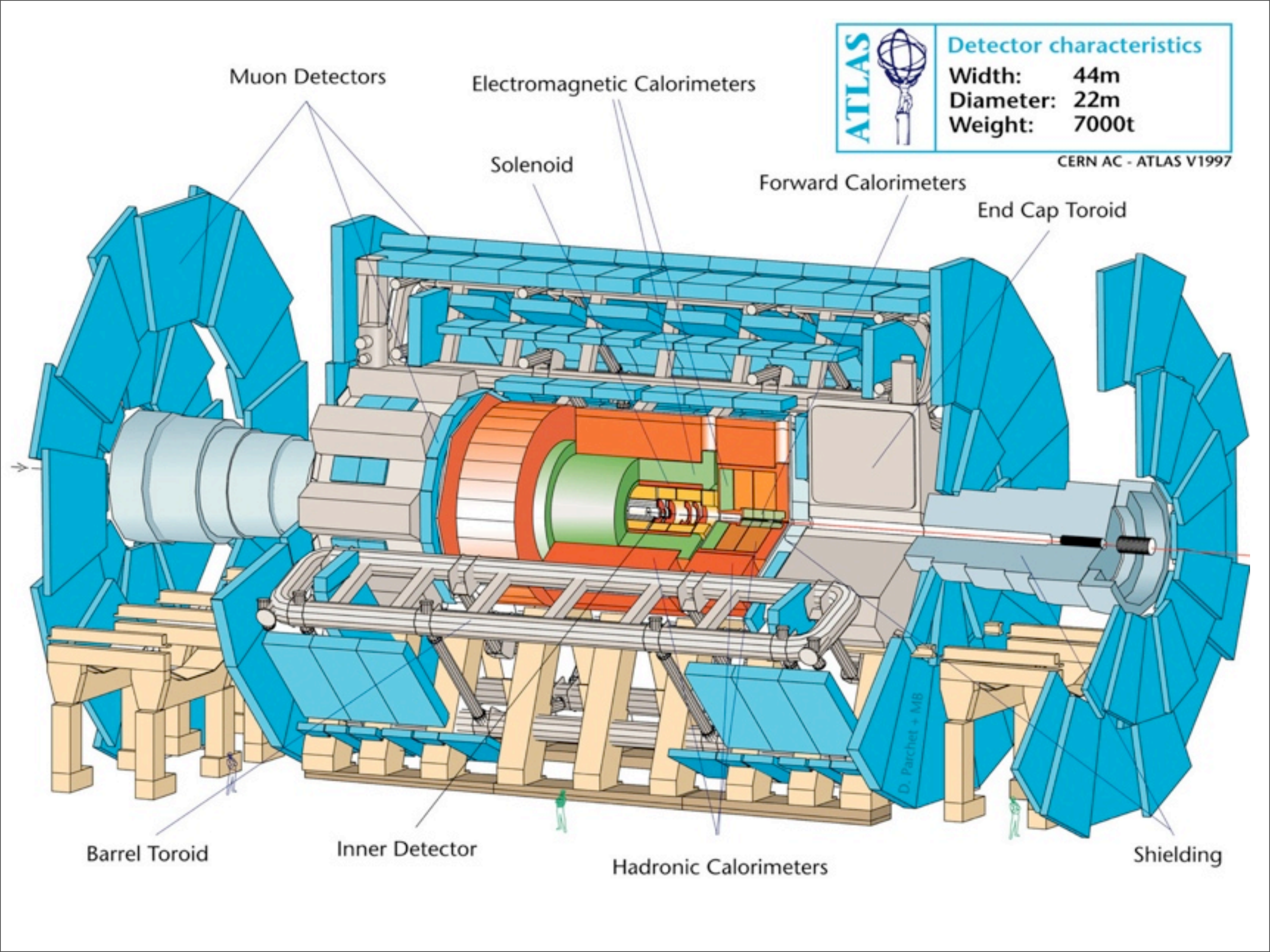
Collisions: Final State Products

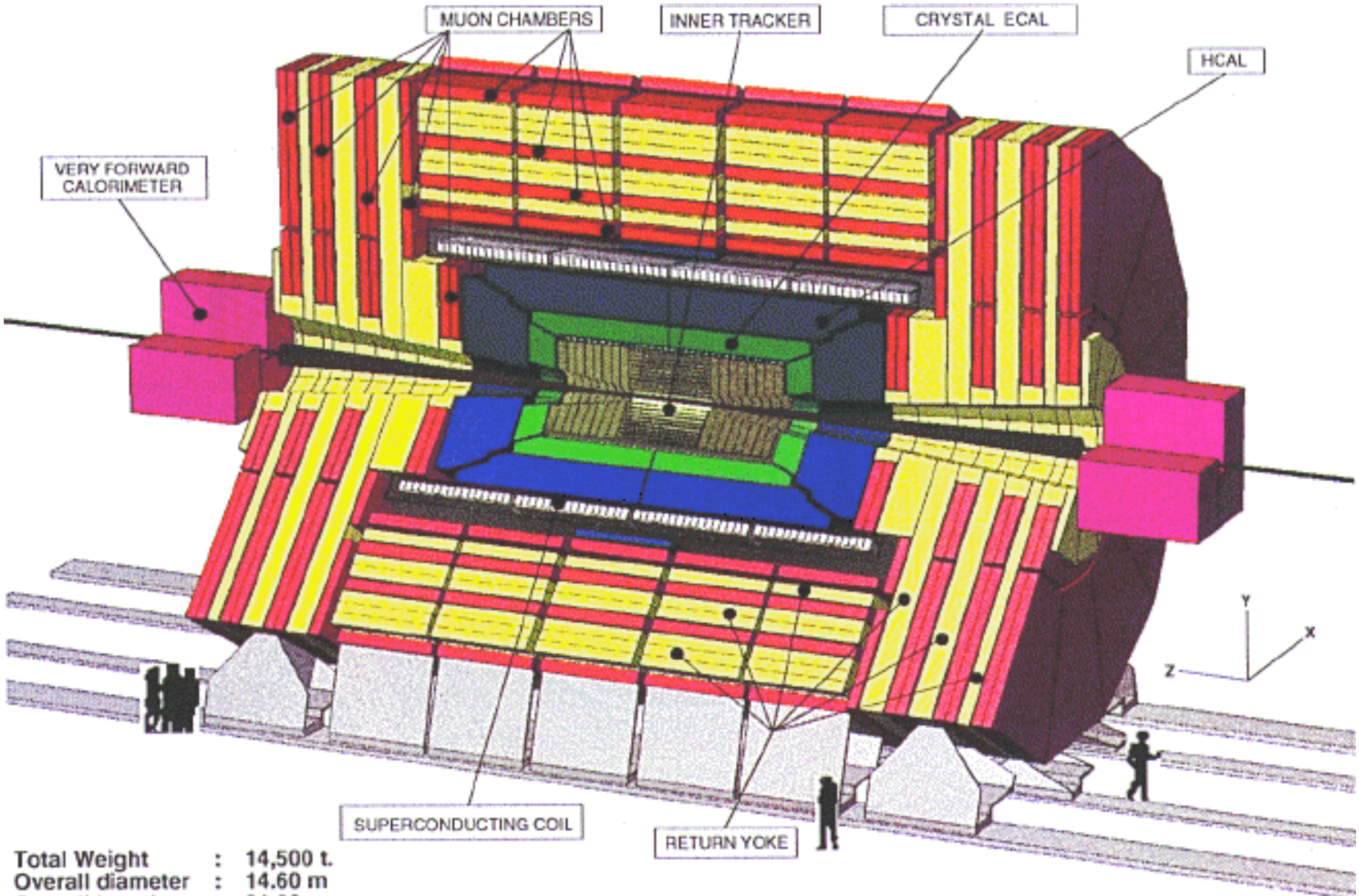
Most unstable particles decay rapidly within detector.
Can only observe the decay products.



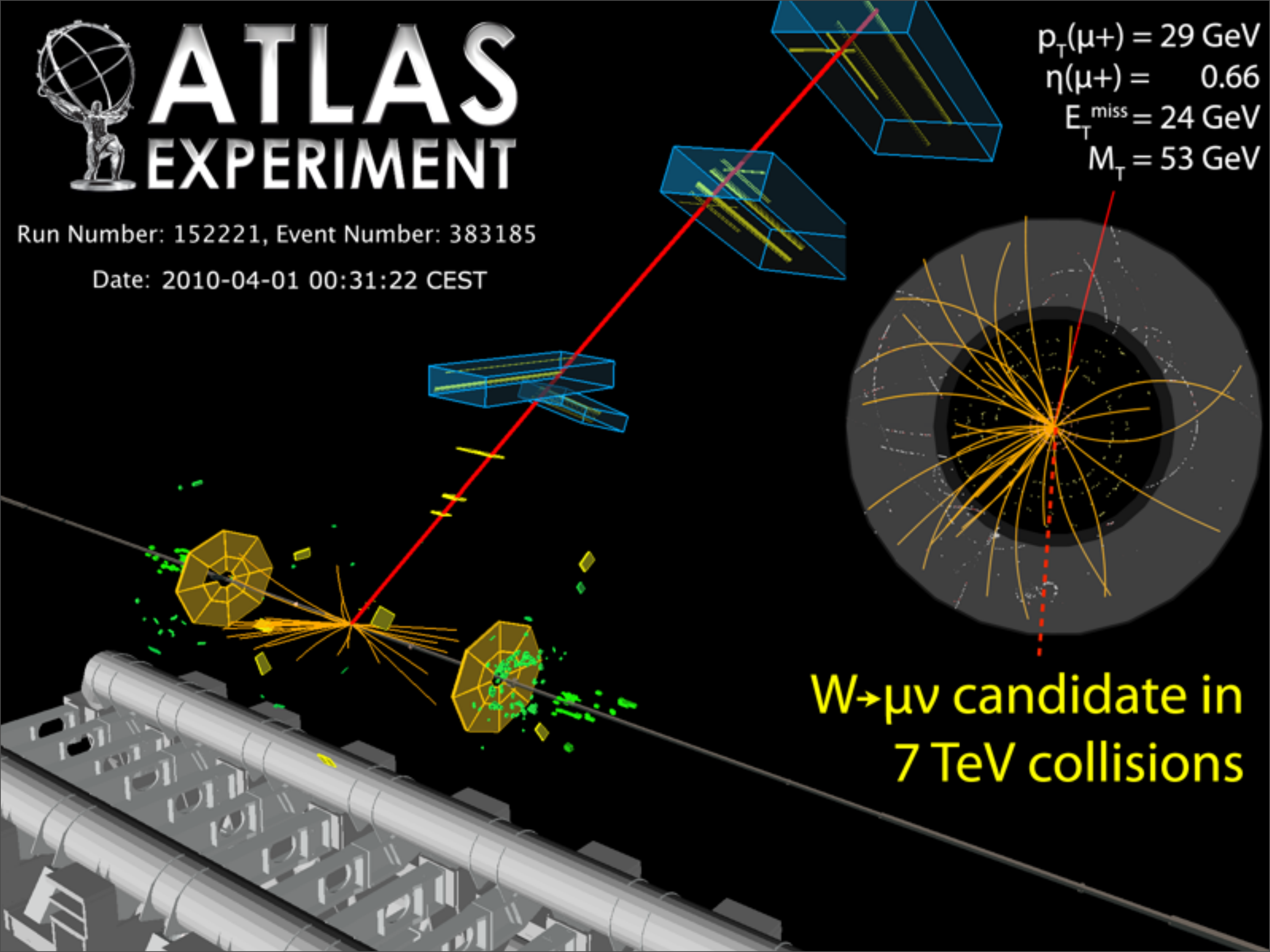


Reconstruction of the underlying events is a challenging task.

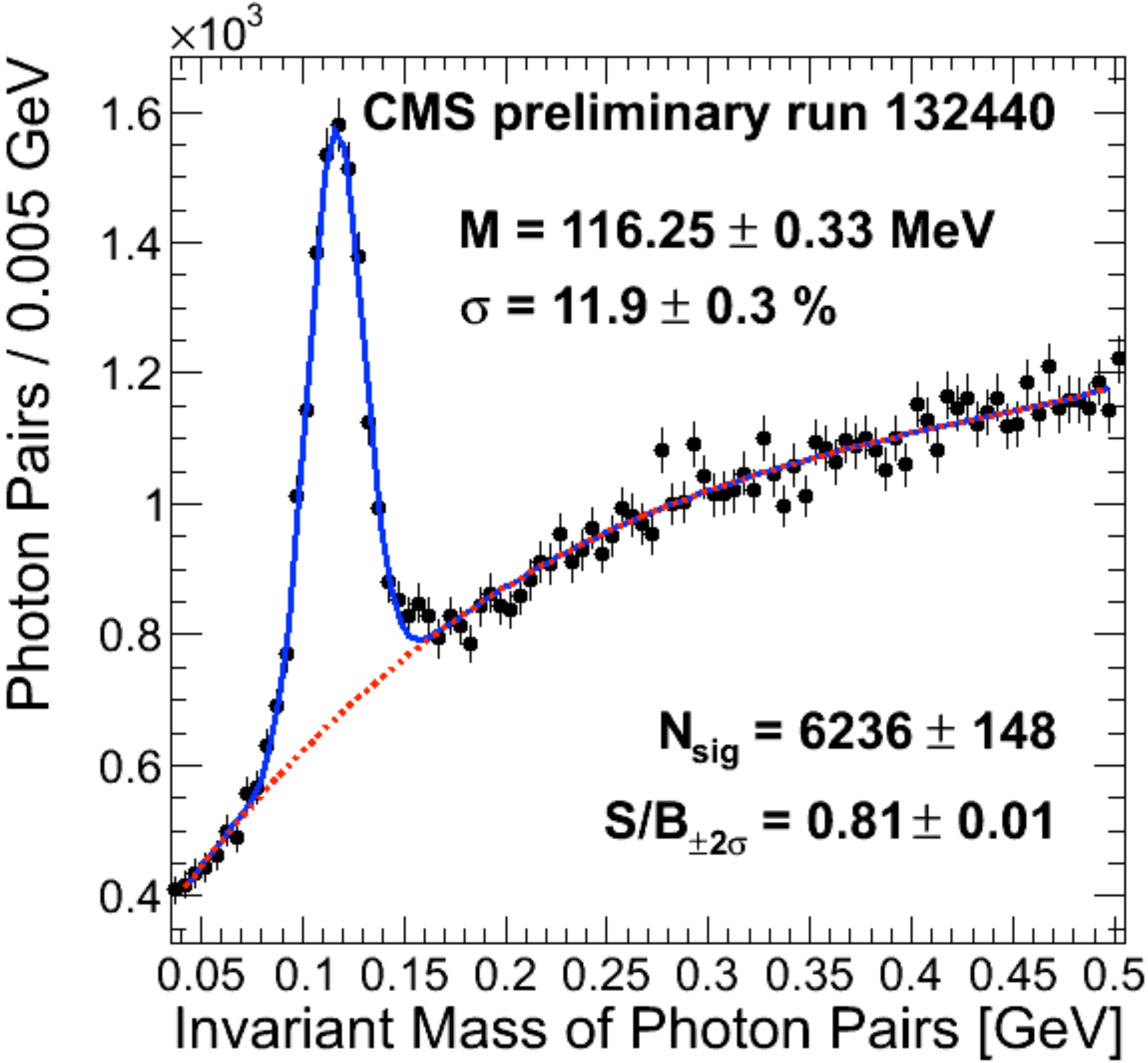

ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding



Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla



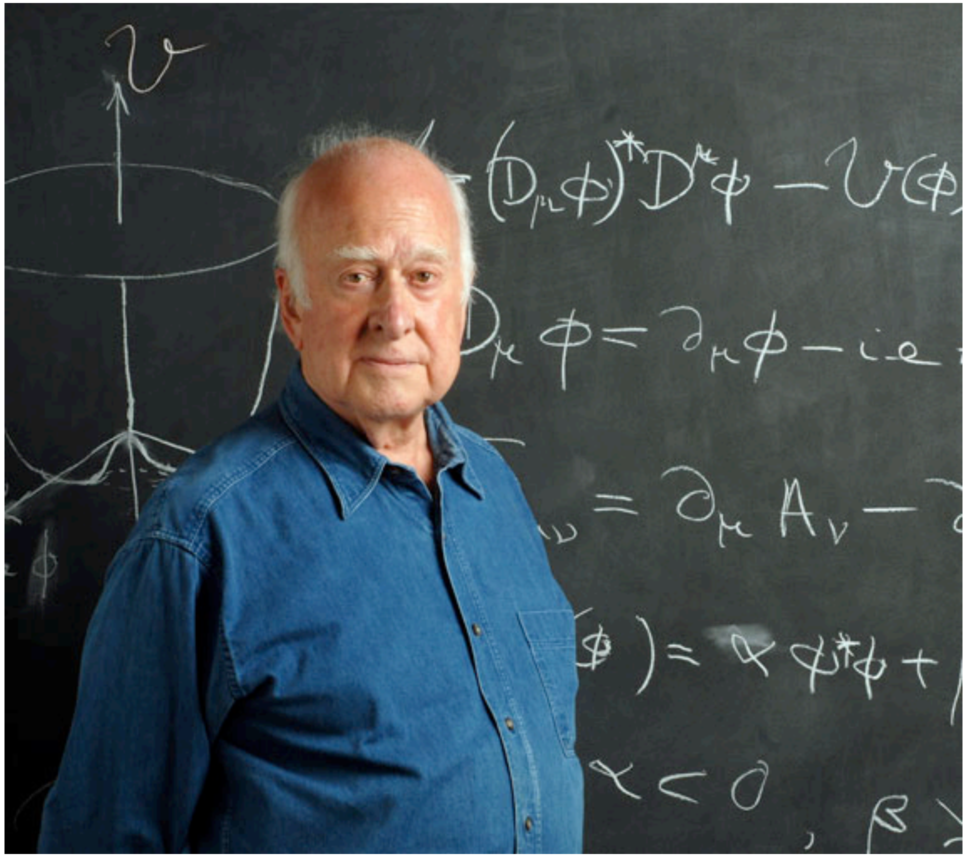
ATLAS
EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+)$ = 29 GeV
$\eta(\mu+)$ = 0.66
E_T^{miss} = 24 GeV
M_T = 53 GeV
W→μν candidate in 7 TeV collisions



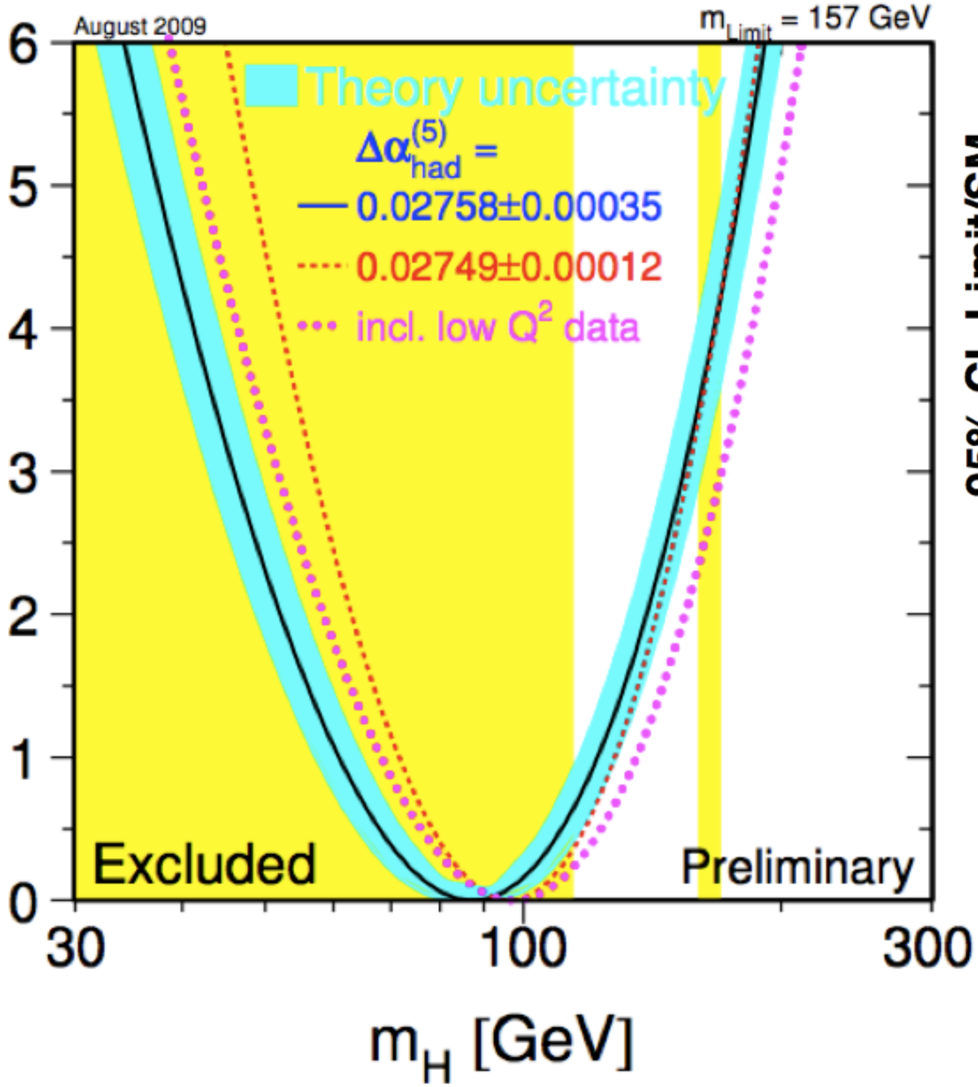
(presumably uncalibrated)

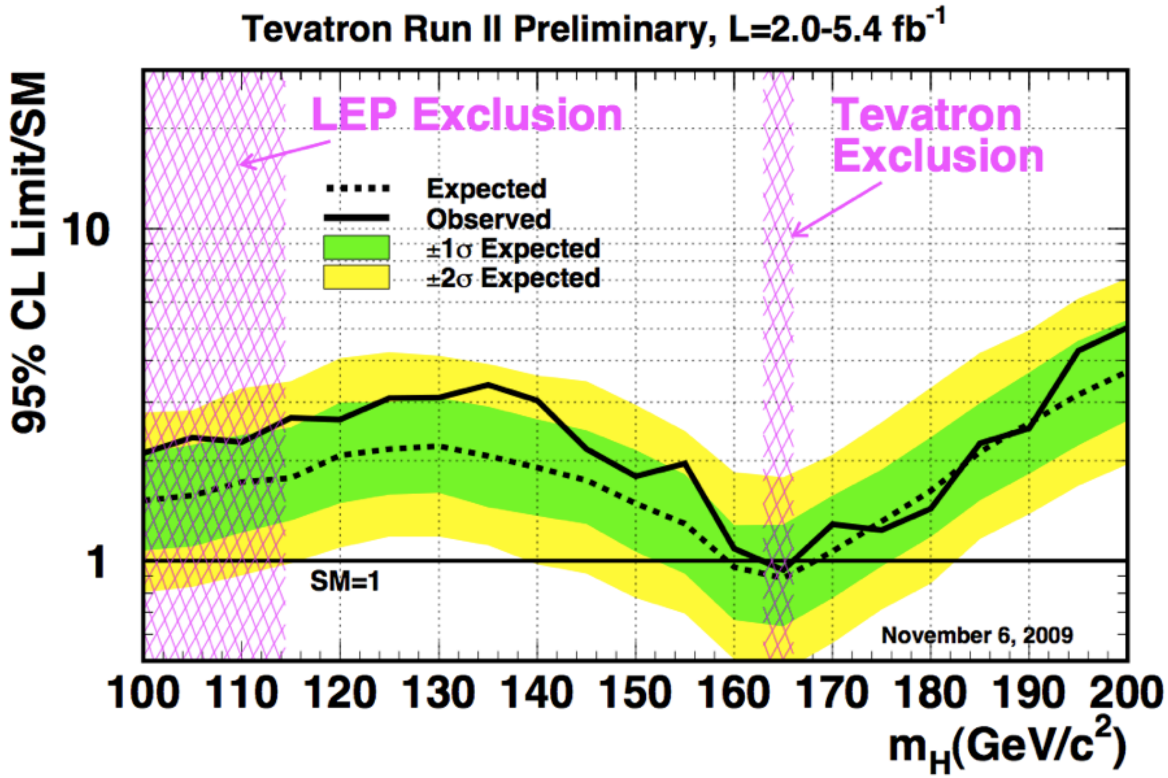
Standard Model Higgs

- Scalar degree of freedom which emerges from spontaneous symmetry breaking of electroweak sector.
- Results from the simplest method of generating mass terms.
- Coupling to fermions is proportional to their mass.



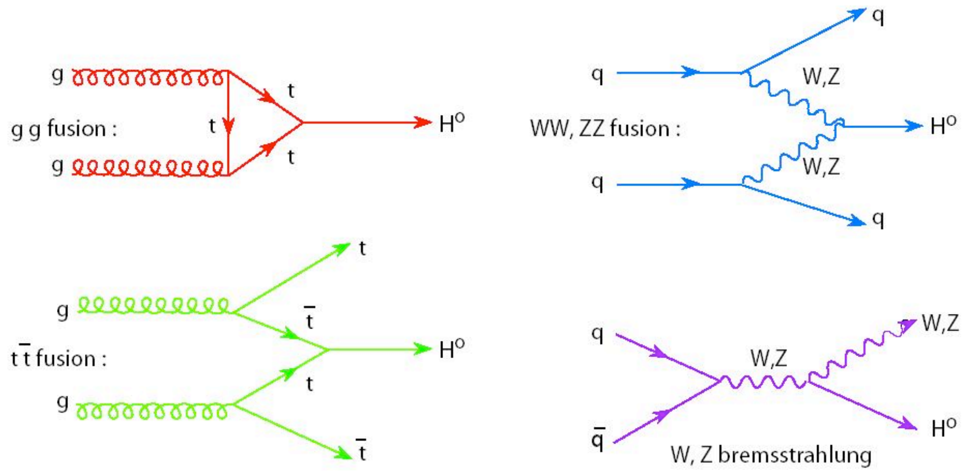
SM Higgs: Current Constraints

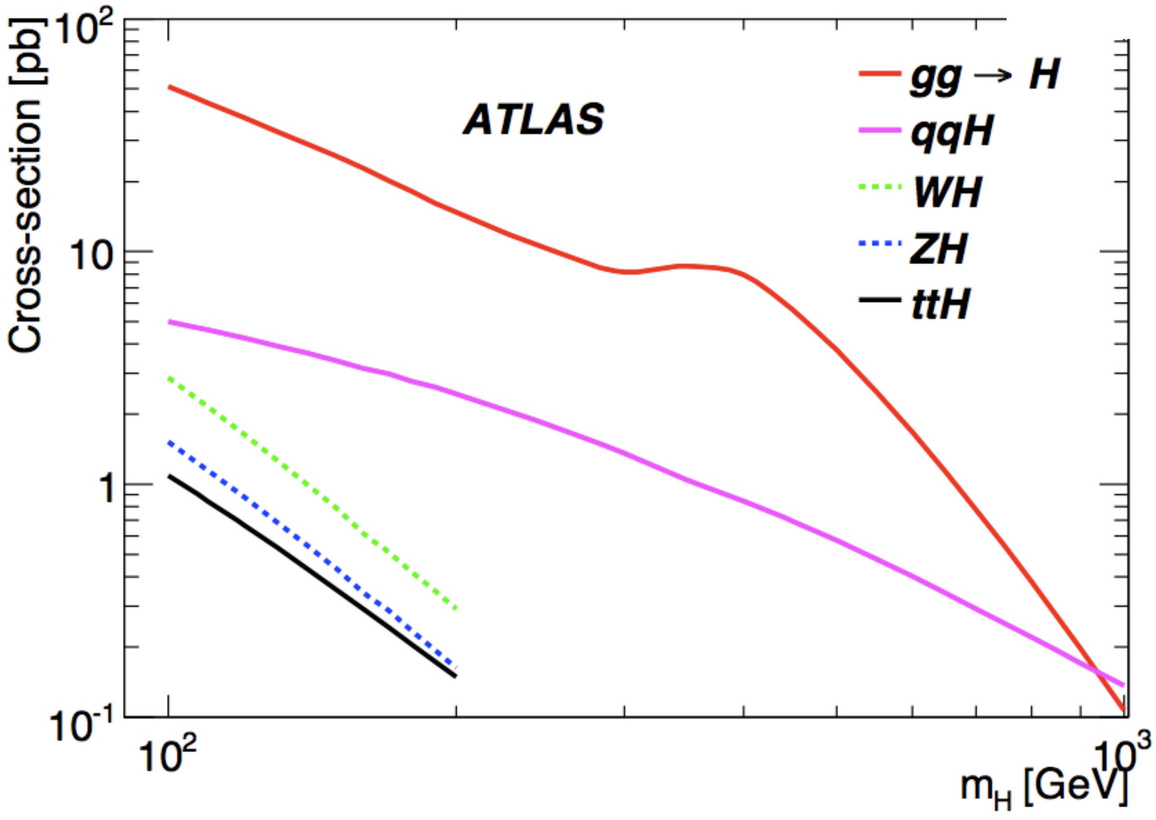




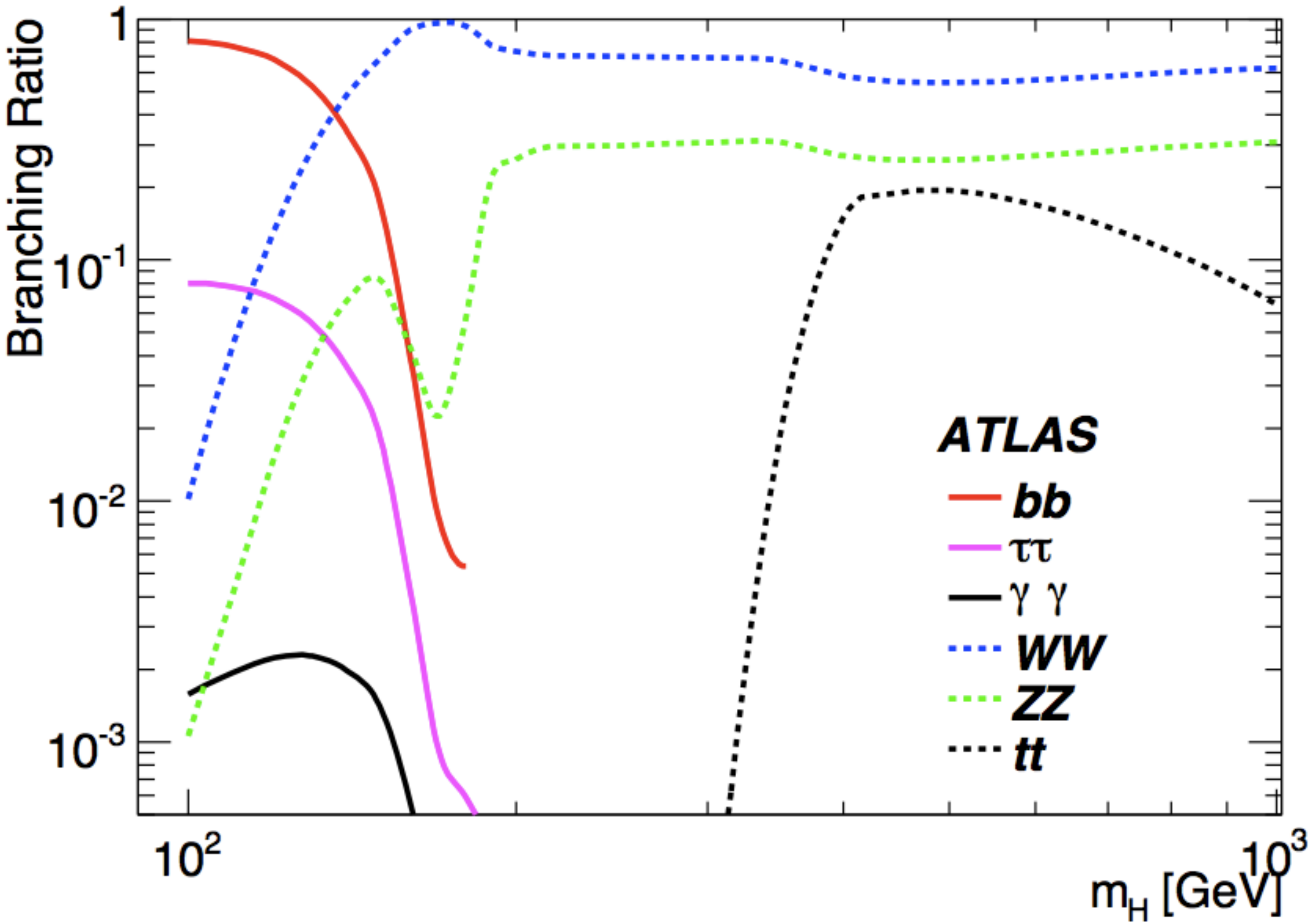
SM Higgs: How to Make Them

Main production channels

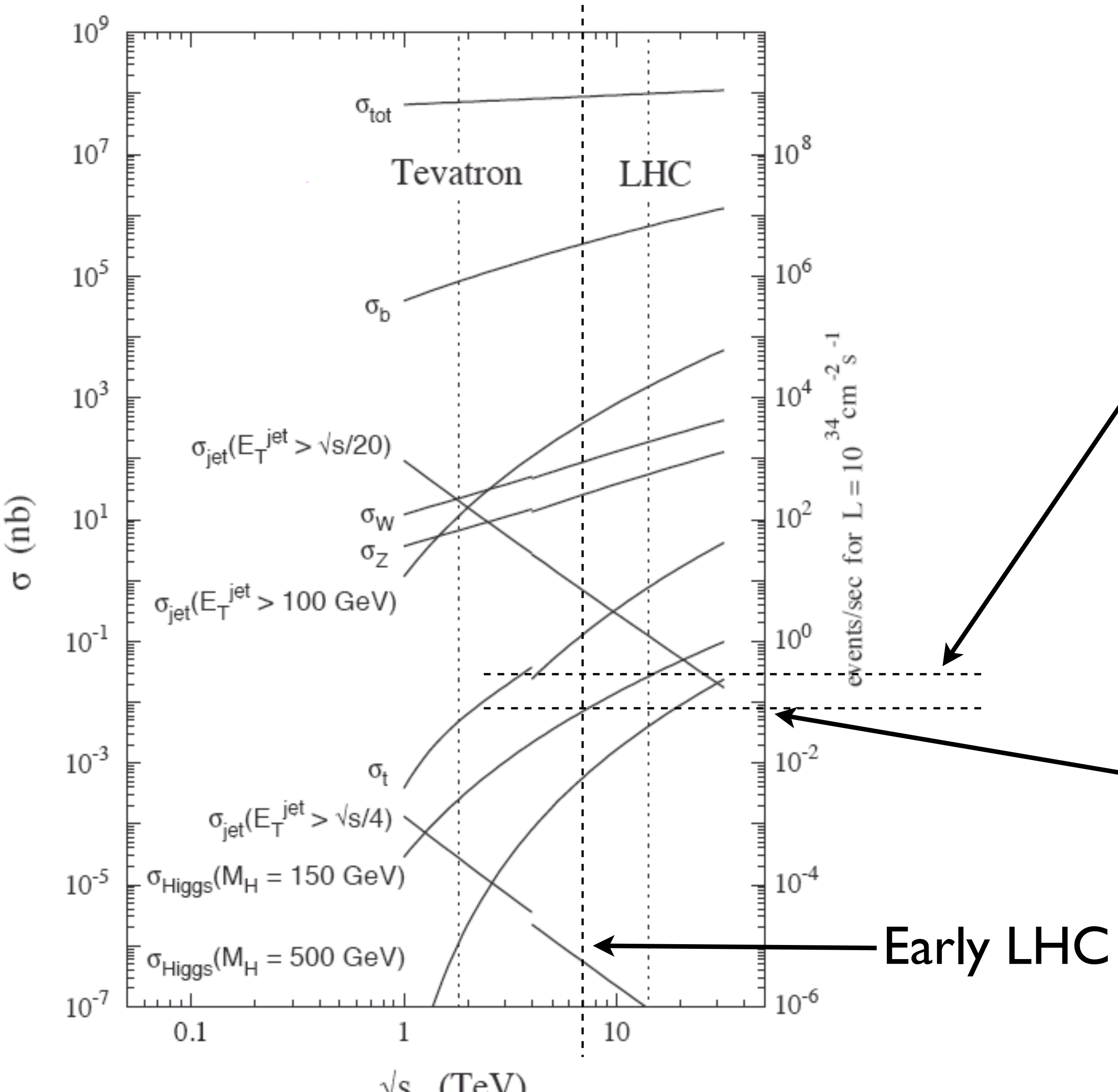




SM Higgs: How to See Them



SM Higgs: Early LHC Problems

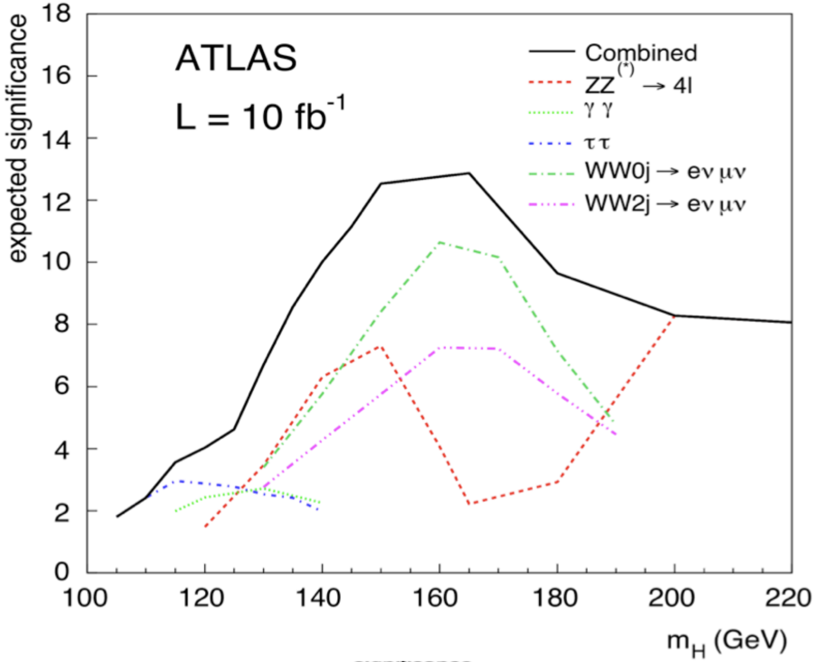


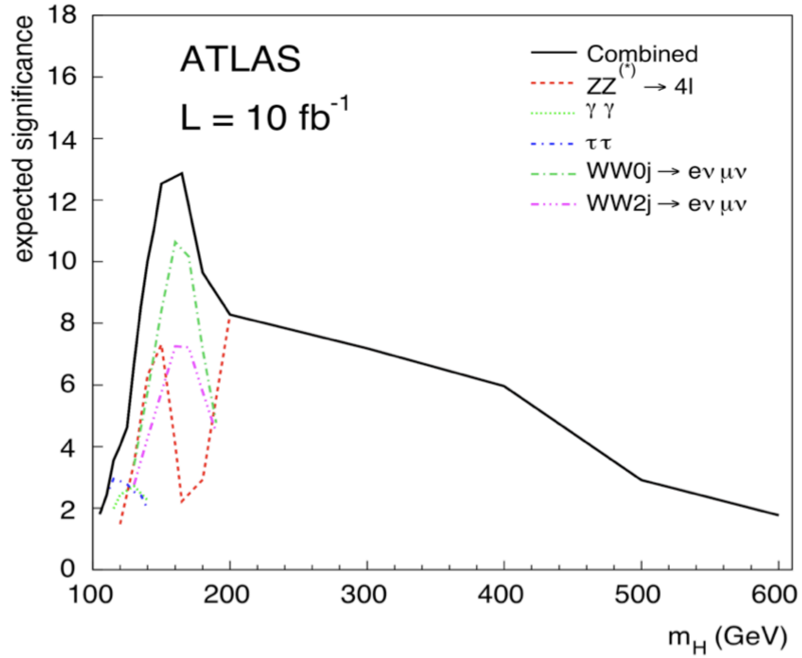
"Naive analysis"

Production rate down by a factor of ~5

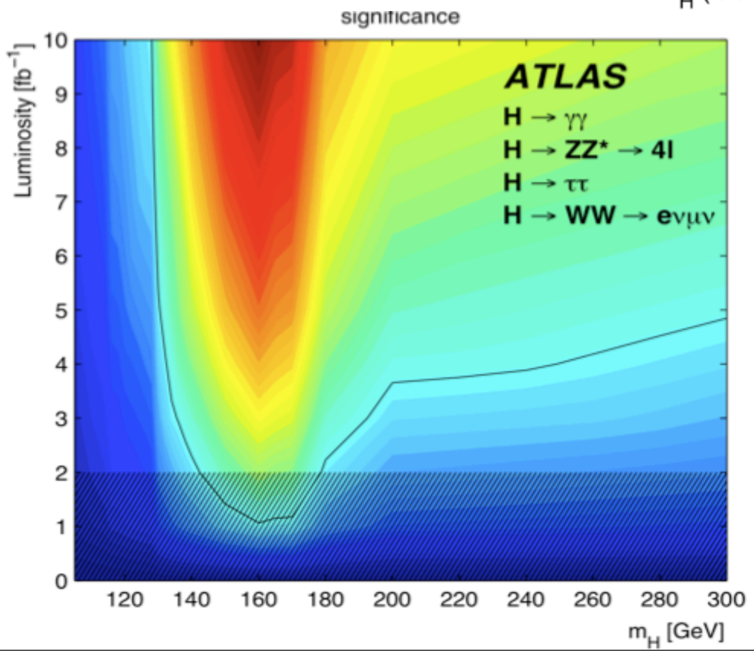
One Higgs per few months at current lumi. How long to get luminosity up?

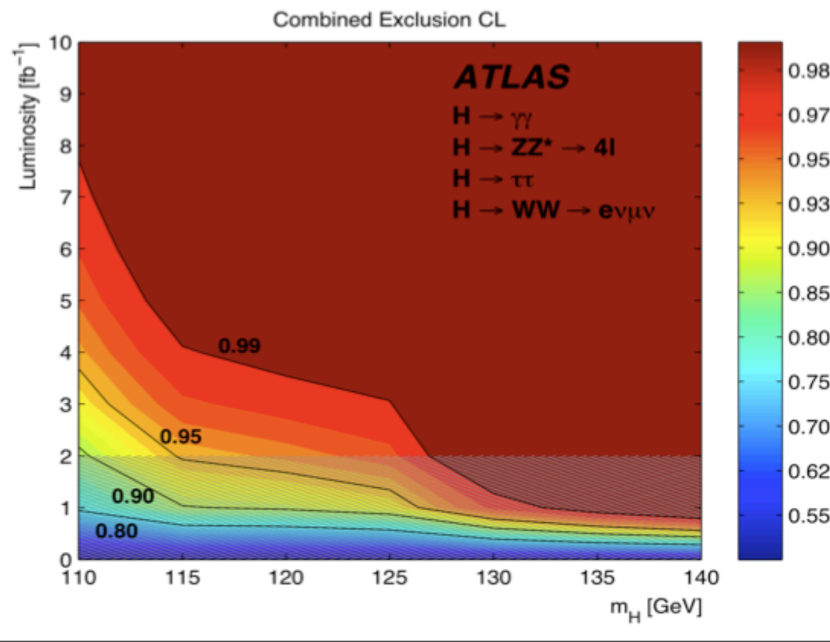
SM Higgs: Ideal ATLAS Observation



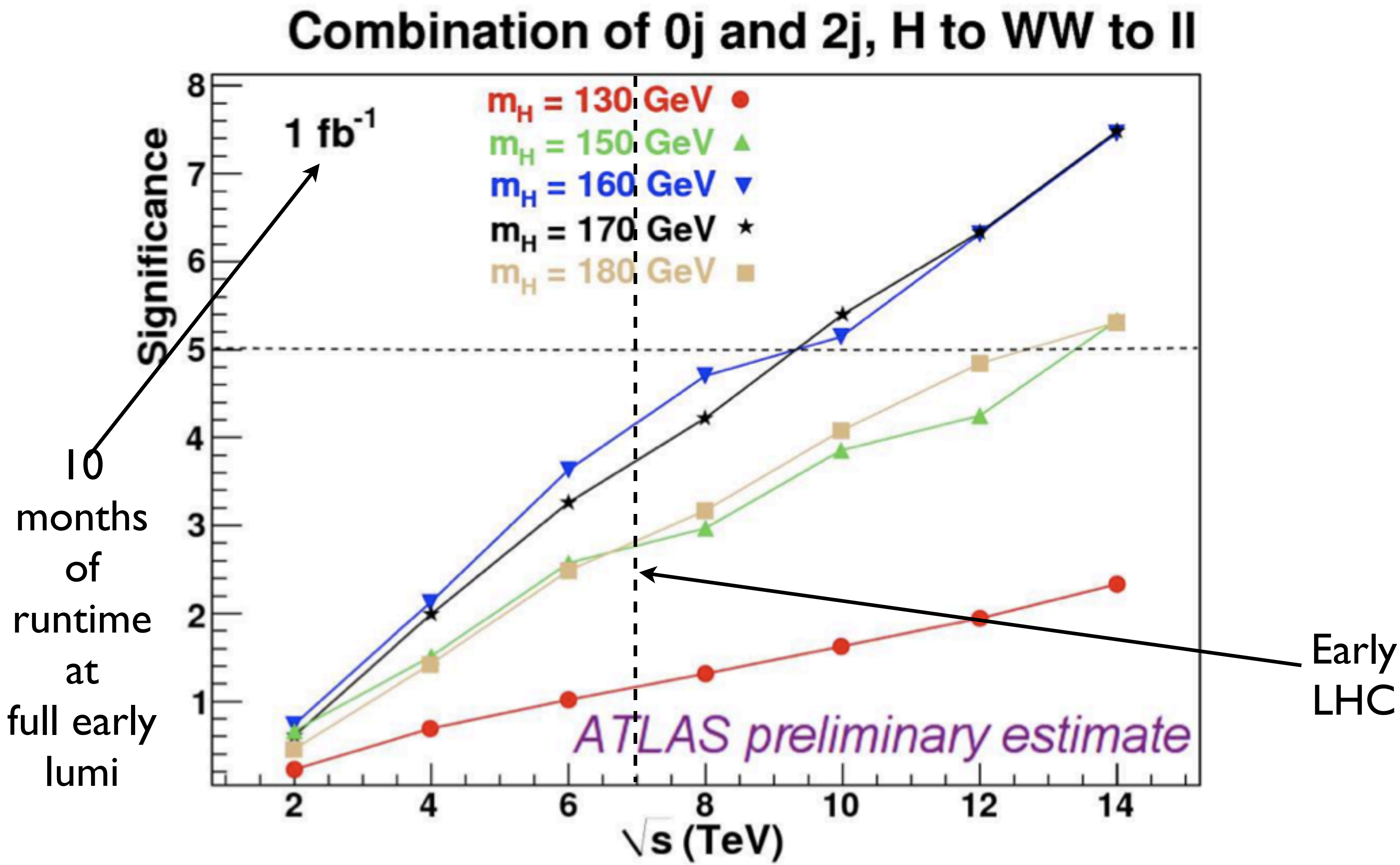


Results for **14 TeV**

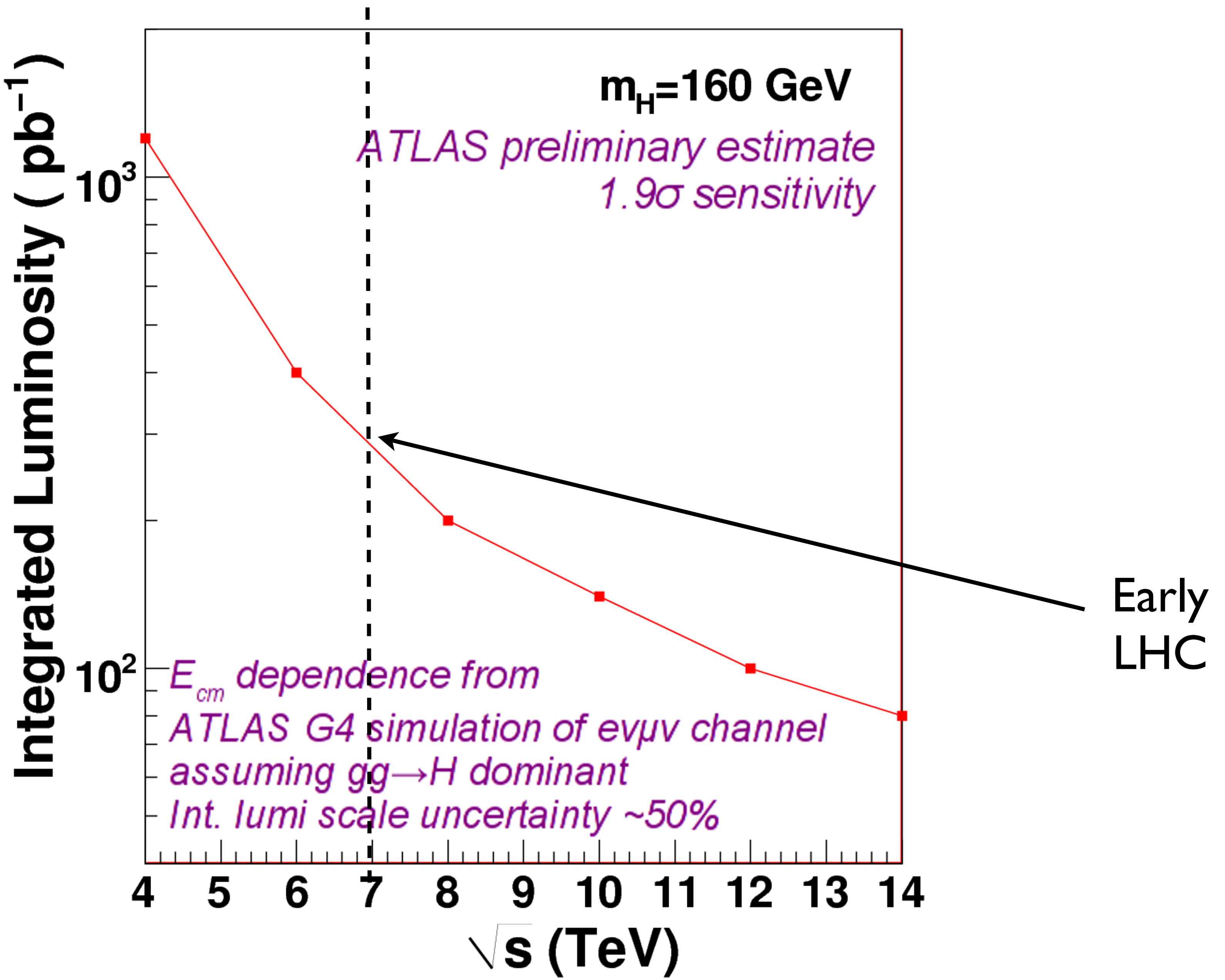




SM Higgs: ATLAS At Lower Energies



SM Higgs: ATLAS At Lower Energies



SM Higgs: Early LHC Potential

- Dependent on rate at which luminosity increases
- If achieve target luminosity with ~1 year of runtime, begin to generate significant results.
- Easiest areas to probe are in the Tevatron range.
- Most likely to confirm or slightly extend the region around Tevatron exclusion.
- Early LHC results will put LHC "on the map" of the Higgs search.

Supersymmetry

- Supersymmetry is theoretically motivated to address various problems in the Standard Model (naturalness of Higgs mass, dark matter, etc).
- Each SM particle has a heavier superpartner.
- Superpartners are produced in pairs.
- mSUGRA is a theoretically motivated version of SUSY that dramatically simplifies the parameter space.
- Characterized by 5 parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}(\mu)$

Recent work by Baer et al, arXiv:1004.3594 (April 20, 2010)

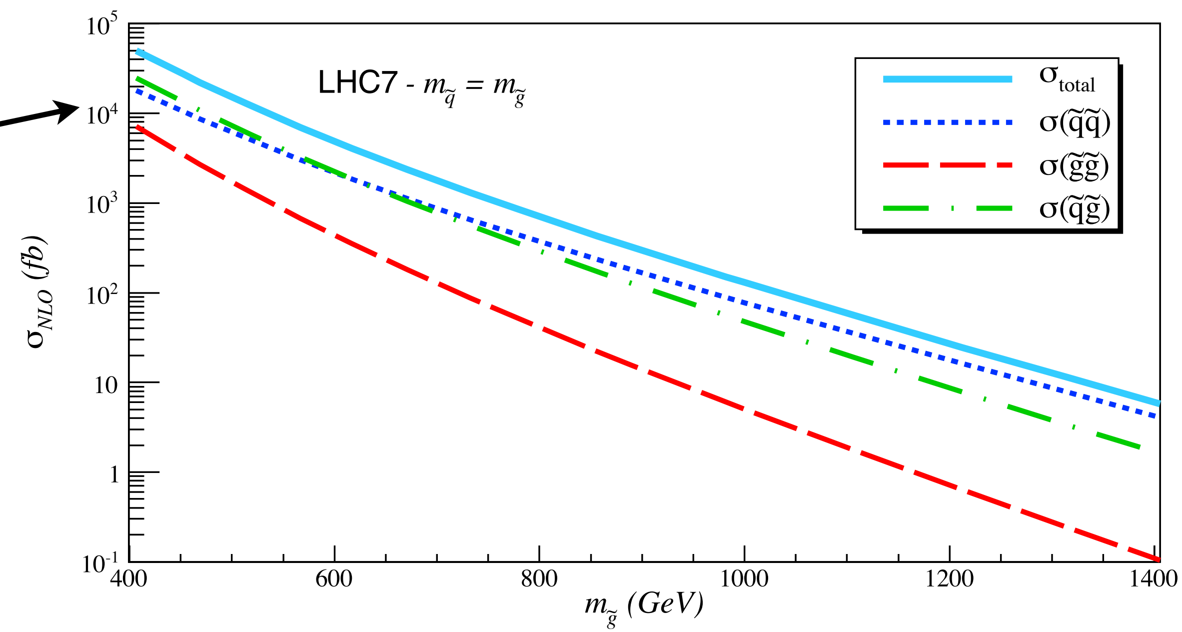
Supersymmetry

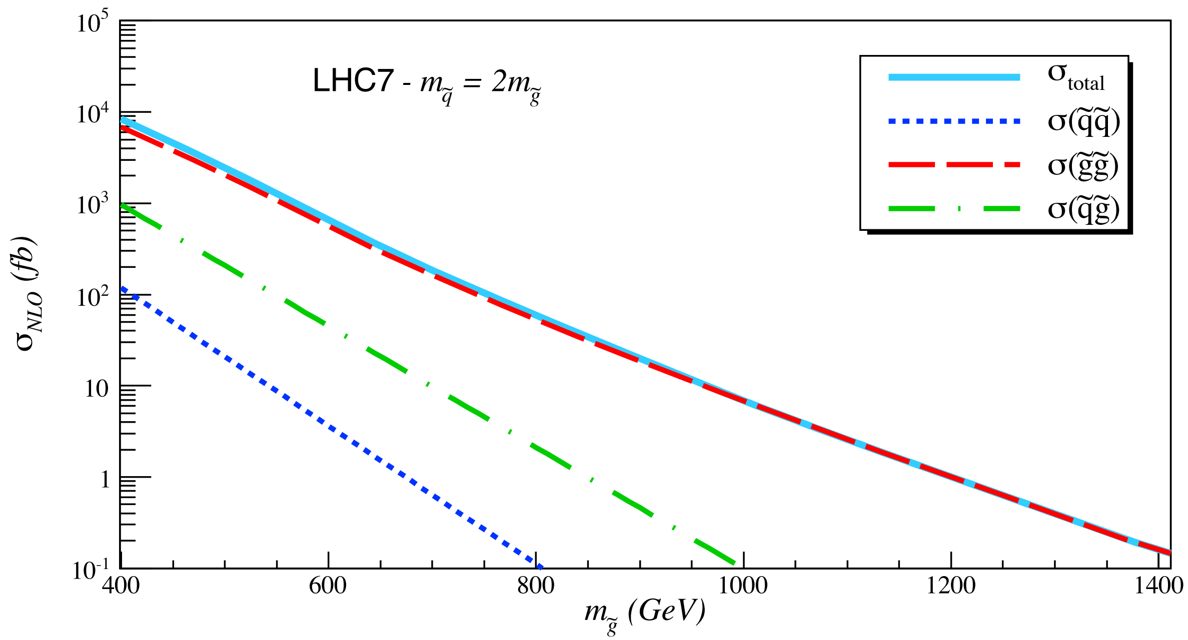
Recent work by Baer et al, arXiv:1004.3594 (April 20)

- Focused on 7 TeV and <~ 2 fb^{-1} of data
- Not an official ATLAS or CMS study
- Used established event generators for underlying events and backgrounds.
- Modeled detector response and efficiencies.
- Applied a series of optimized cuts.
- Assumed poor accuracy in energy measurements.

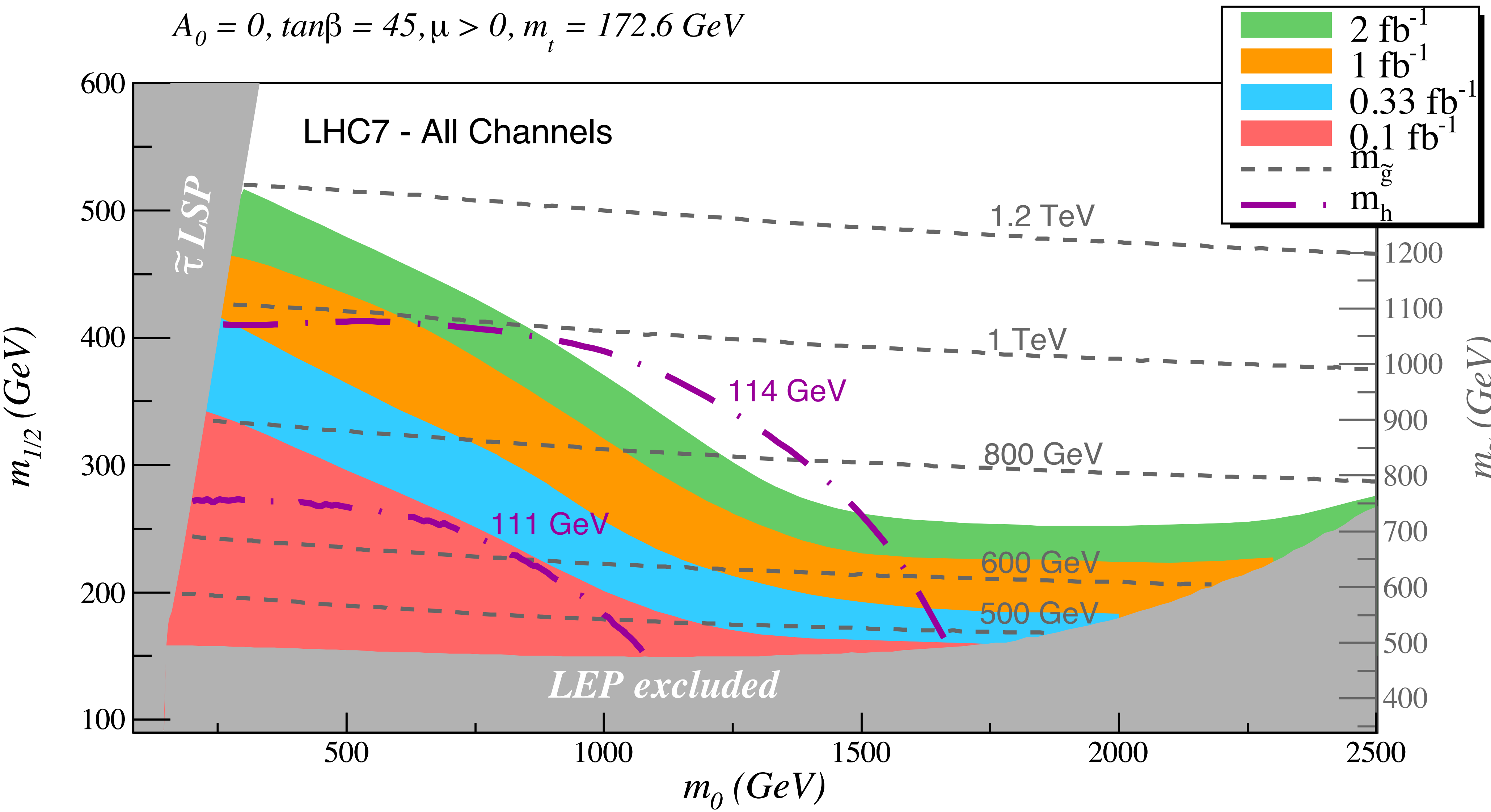
Supersymmetry

If gluino mass is below a TeV, production cross-sections are significant.

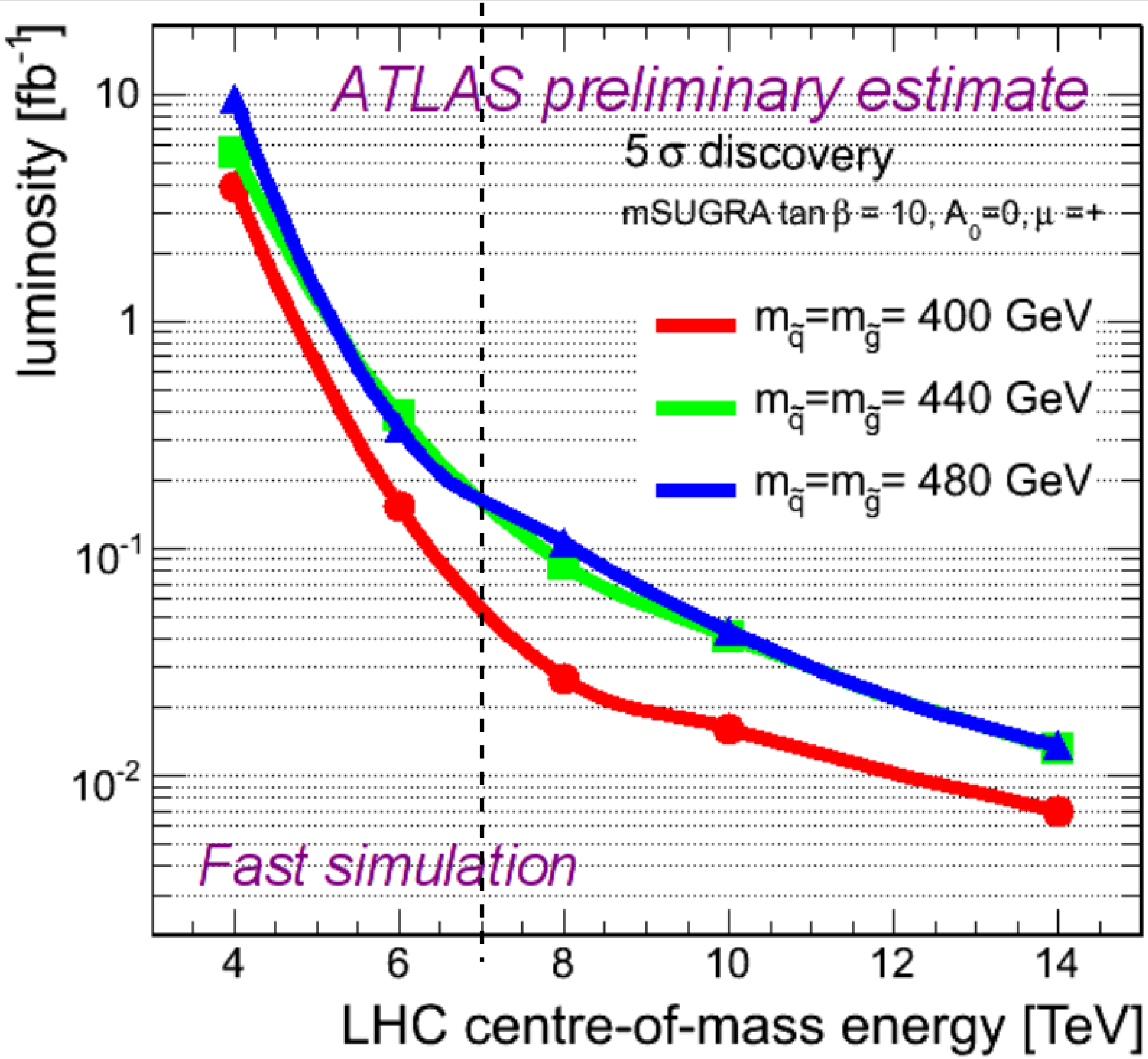




Supersymmetry



Supersymmetry



The Z'

- Gauge boson corresponding to a new U(1).
- A variety of models contain such a new gauge group: GUTs, string compactifications, composite Higgs models, etc.
- May mix with the Z of the standard model.
- Characterized by 3 parameters: $m_{Z'}$, g_Y, g_{BL}.

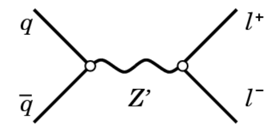
Recent work by Salvioni et al, arXiv:0909.1320v2 (Oct 30 2009)

The Z'

Defining the couplings:

$$\mathcal{L} = -\frac{1}{4}\, F^i_{\mu\nu}\, F^{i\,\mu\nu} + \frac{1}{2}\, M_i^2 A^{i\mu}\, A^i_\mu + A^i_\mu\, J^\mu_i + \dots \qquad i = \gamma, Z, Z'$$

$$J^\mu_{Z'^0} = \sum_f \left[g_Y\, Y(f) + g_{BL}\,(B-L)(f)\right] \overline{f}\gamma^\mu f$$



Tevatron/LHC

	(u,d)	u^c	d^c	(ν,e)	ν^c	e^c
T_{3L}	$(+\frac{1}{2},-\frac{1}{2})$	0	0	$(+\frac{1}{2},-\frac{1}{2})$	0	0
Y	$+\frac{1}{6}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{2}$	0	$+1$
$B-L$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	$+1$	$+1$
$Q_{Z'}$	$\frac{1}{6}\widetilde{g}_Y + \frac{1}{3}\widetilde{g}_{BL}$	$-\frac{2}{3}\widetilde{g}_Y - \frac{1}{3}\widetilde{g}_{BL}$	$\frac{1}{3}\widetilde{g}_Y - \frac{1}{3}\widetilde{g}_{BL}$	$-\frac{1}{2}\widetilde{g}_Y - \widetilde{g}_{BL}$	$\widetilde{g}_{BL}$	$\widetilde{g}_Y + \widetilde{g}_{BL}$

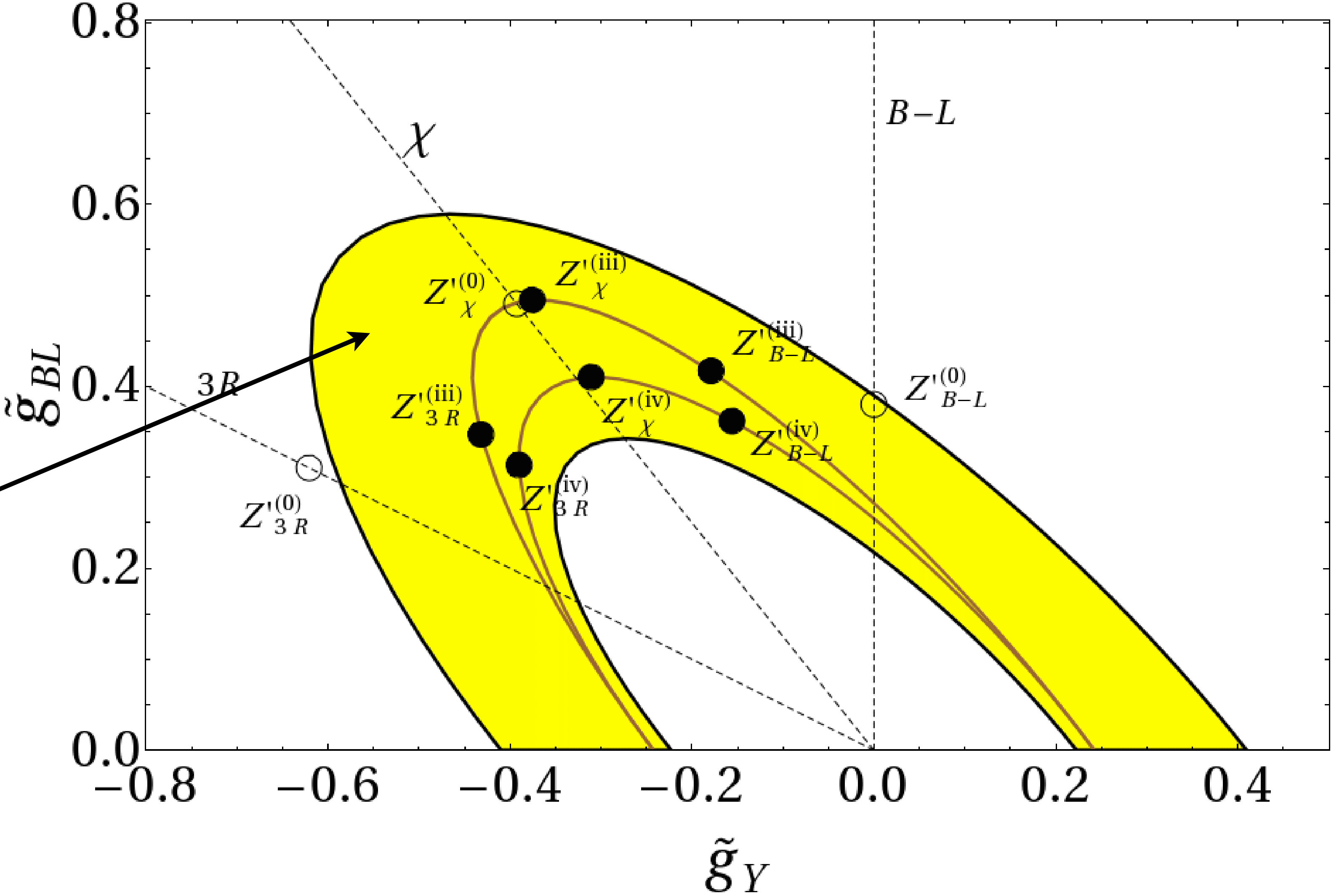
Commonly-studied models:

	Z_{B-L}	Z_χ	Z_{3R}
g_Y	0	$-\frac{2}{\sqrt{10}}g_{Z'}$	$-\,g_{Z'}$
g_{B-L}	$\sqrt{\frac{3}{8}}g_{Z'}$	$\frac{5}{2\sqrt{10}}g_{Z'}$	$\frac{1}{2}g_{Z'}$

"GUT value"

$$g_{Z'} = \sqrt{5/3}\, g'$$

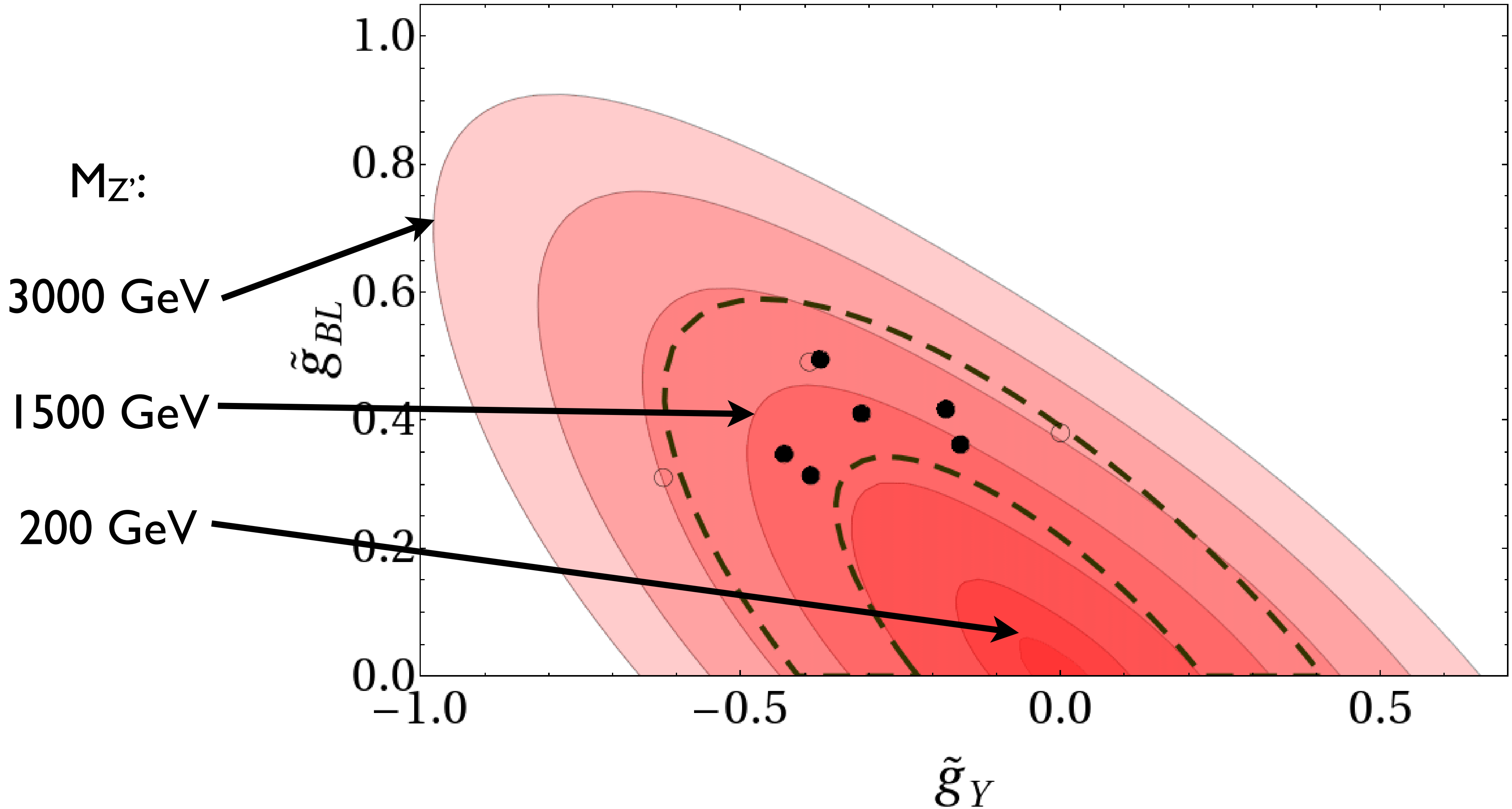
The Z': Favored Region



Favored by GUT theories

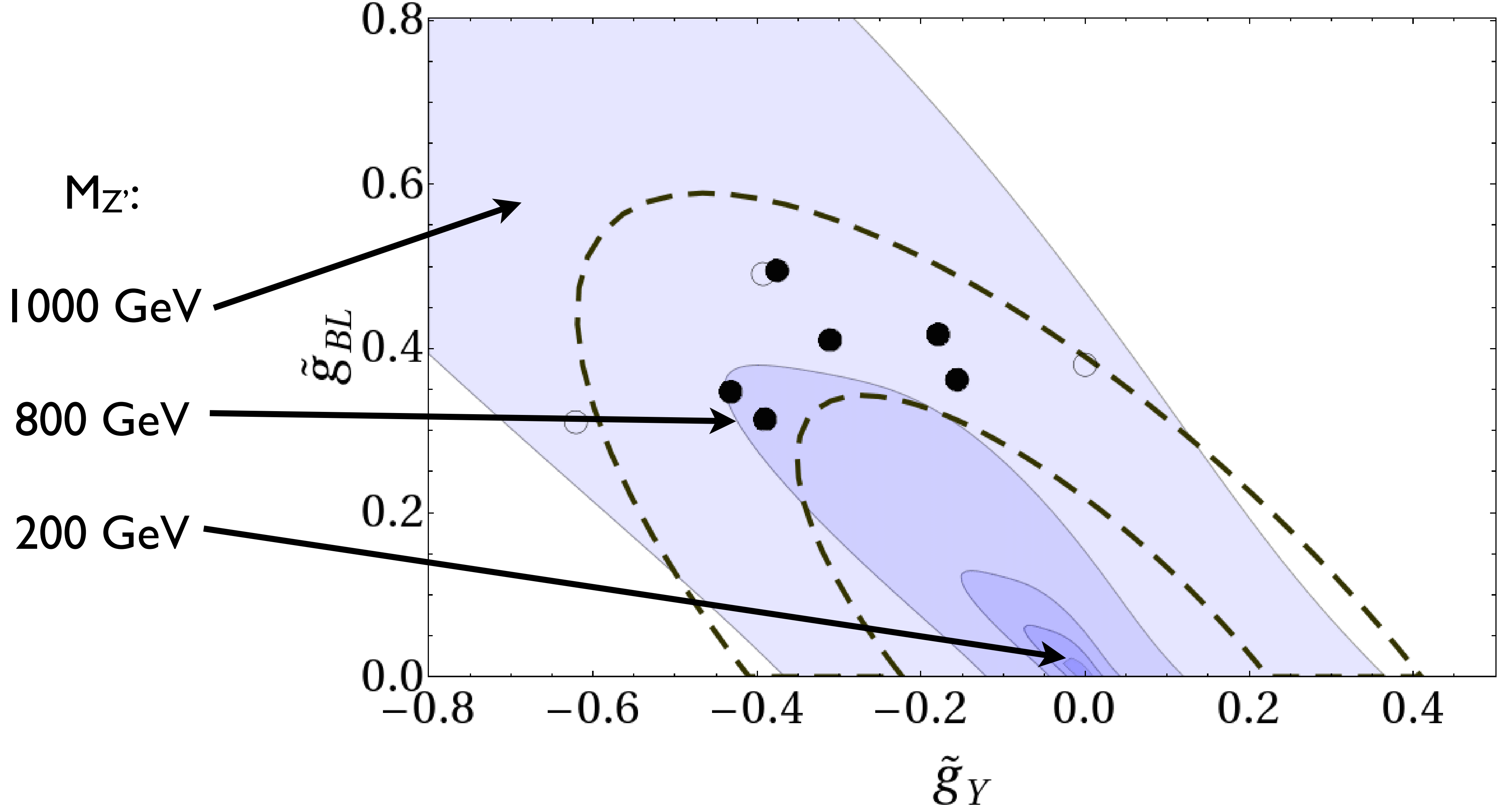
The Z': Electroweak Constraints

Region allowed by electroweak precision tests, at 95% CL.



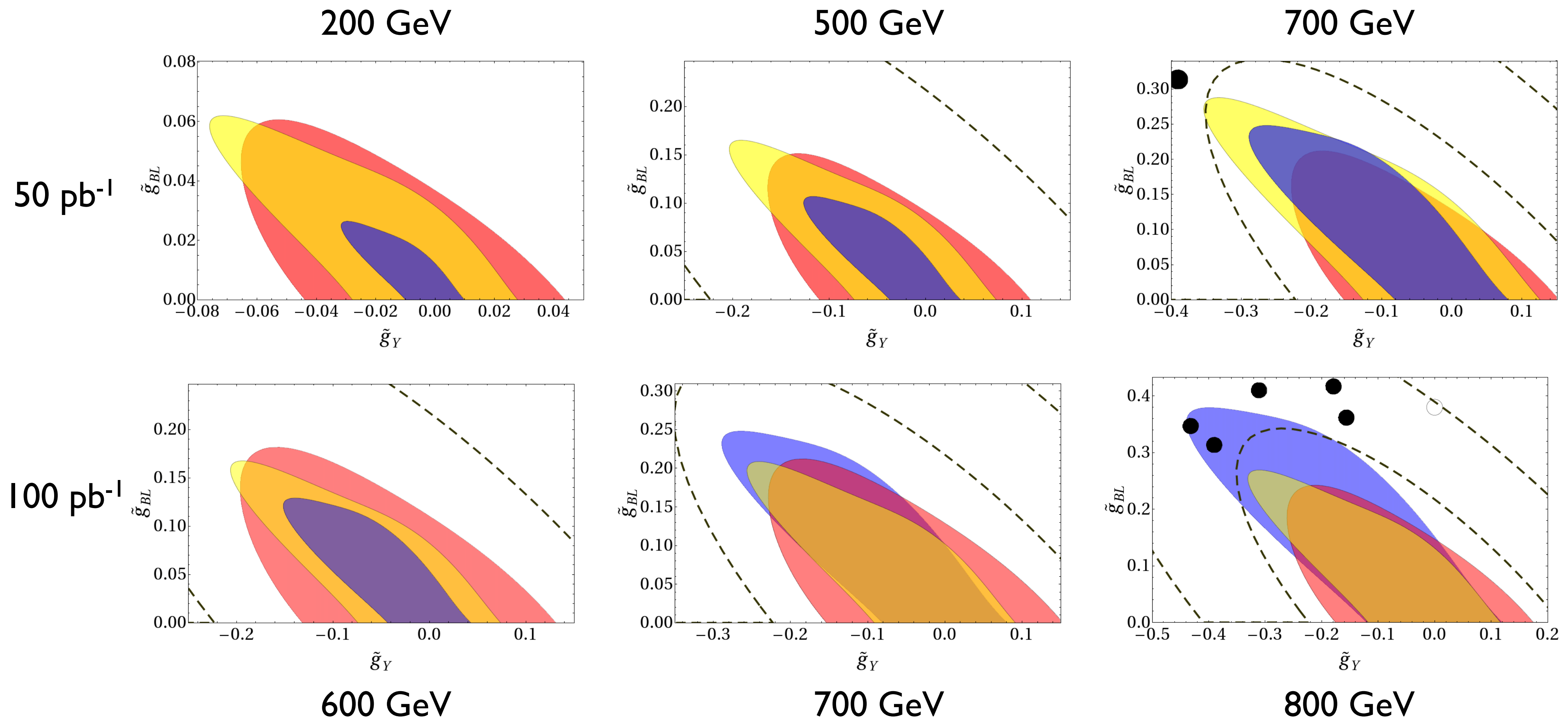
The Z': Tevatron Constraints

Region allowed by Tevatron direct searches, at 95% CL.



The Z': Early LHC Constraints

Region allowed by LHC direct searches with 7 TeV collisions.

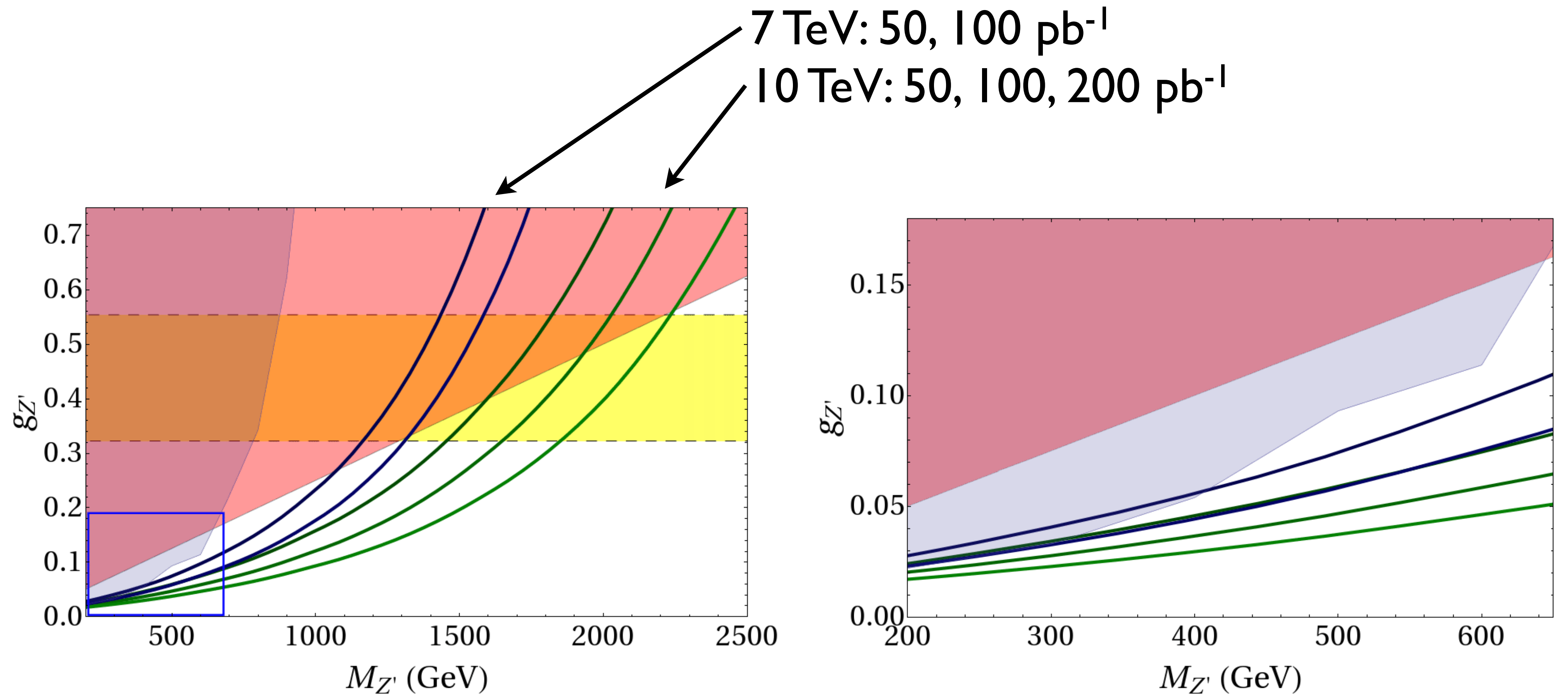


Red = Allowed by electroweak.   Blue = Allowed by Tevatron

Yellow = Not within 5σ discovery at LHC

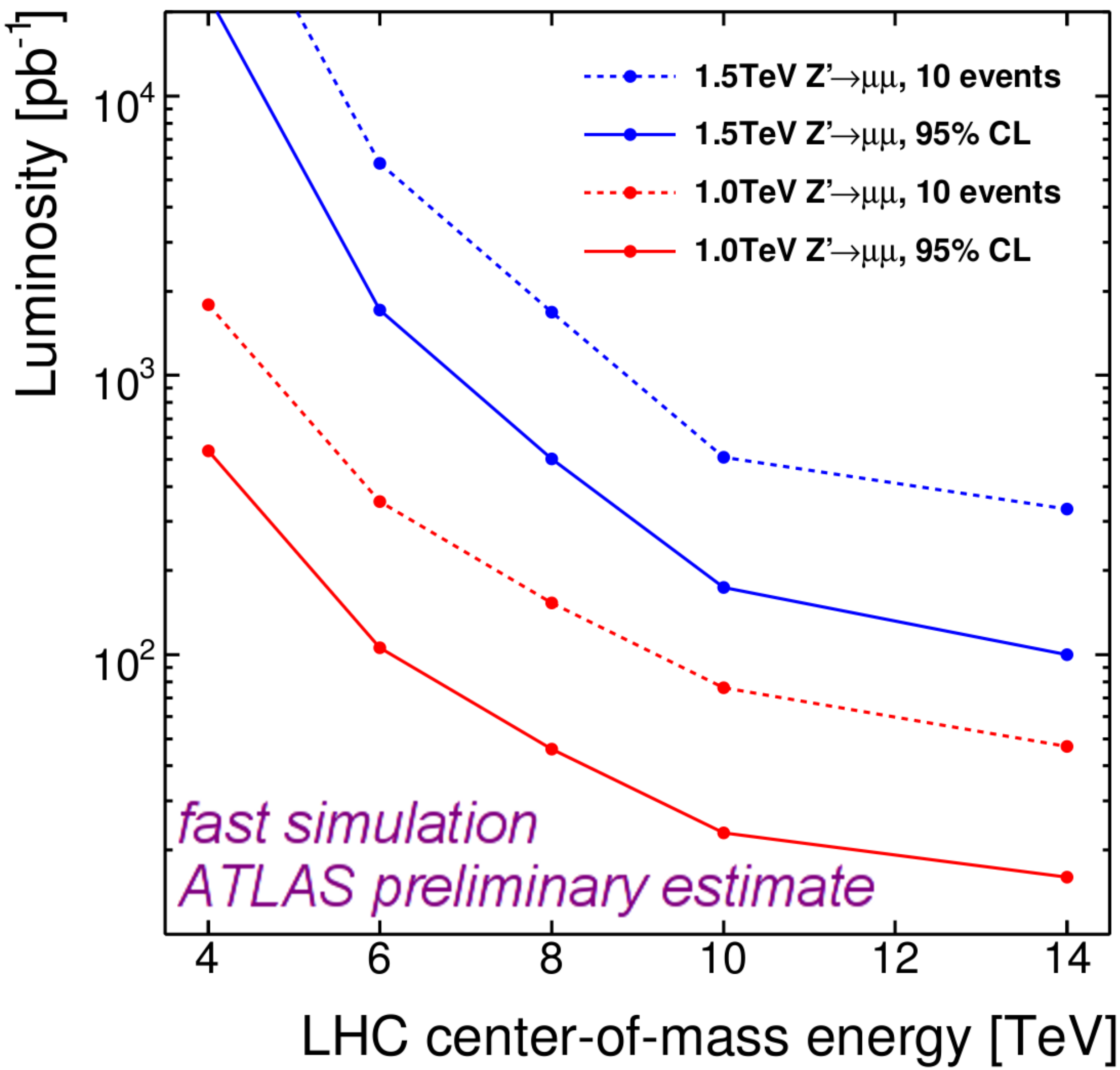
The Z': Early LHC Constraints

Region excluded by LHC direct searches with, at 95% CL.



Red = Excluded by electroweak. Blue = Excluded by Tevatron
Yellow = GUT-preferred band

The Z': Early LHC Constraints



The Z': Early LHC Potential

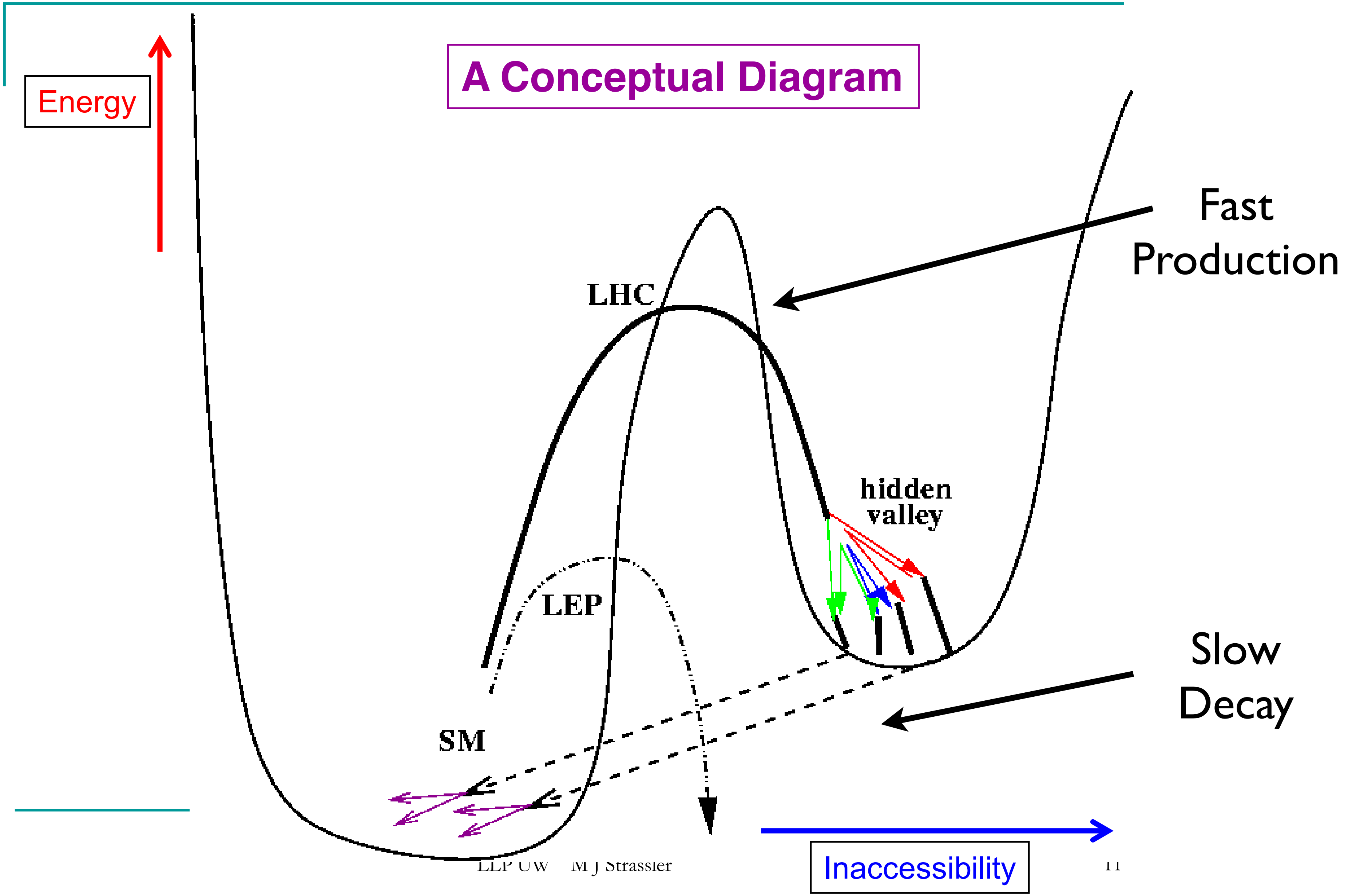
- LHC is sensitive to new U(1) gauge groups with large masses, even at lower collision energy and luminosity.
- Will be competitive with best current constraints (electroweak).
- Potential for discovery, particularly for masses around 800 GeV.

Hidden Valleys

- A hidden sector of particles that have carry charge from a "Valley" gauge group, but are SM singlets.
- Allows new *light* states.
- Communicate with the SM by a heavy messenger.
- High energy gets over the messenger particle and creates long-lived particles in the valley, which eventually decay back into SM particles.
- Distinctive displaced vertices in the LHC. May also produce large MET.
- A threshold-like signal -- very clear signals are soon as barrier is breached.

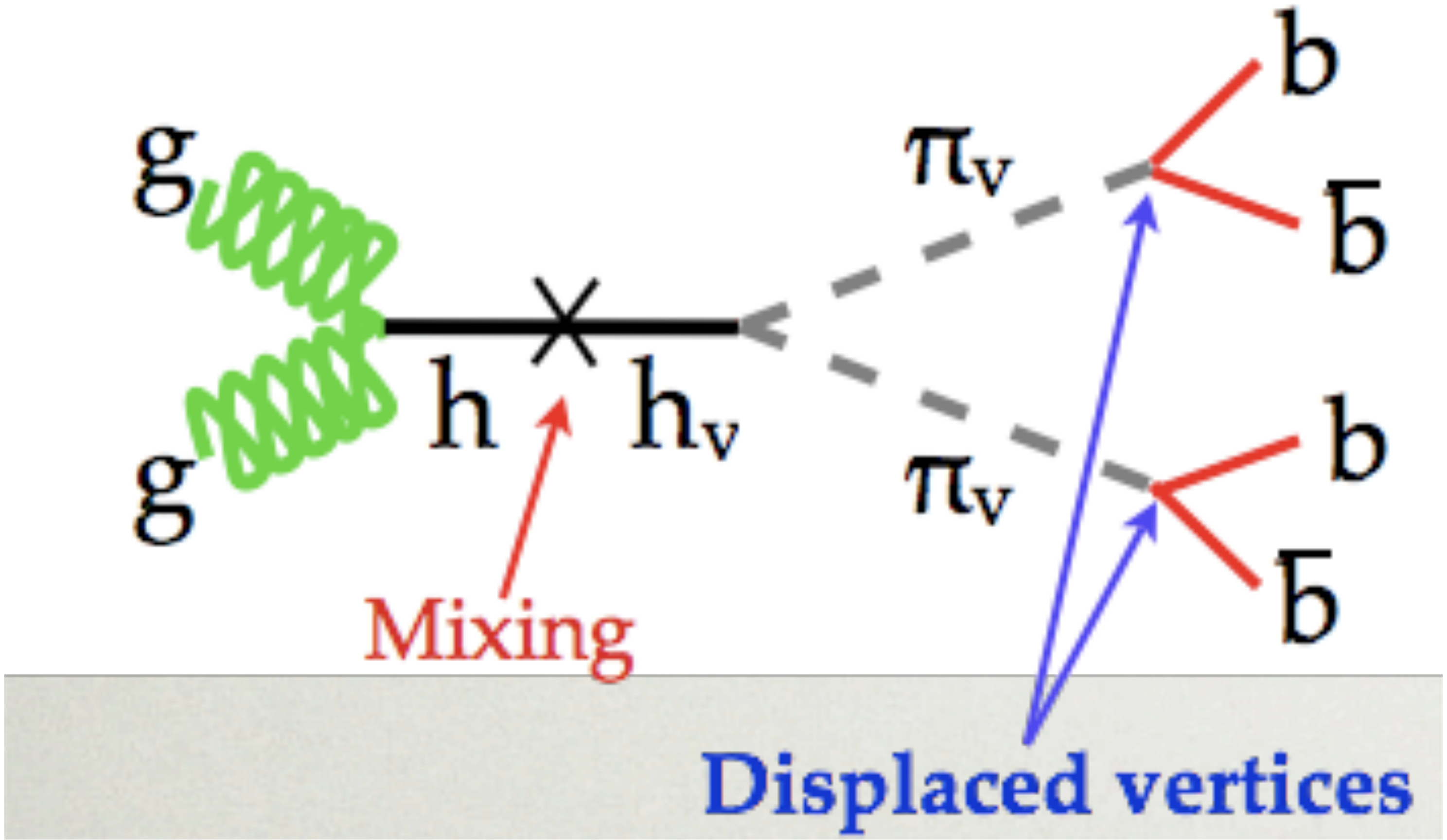
Long-time work by Matt Strassler, Kathryn Zurek, Dan Ventura and others.

Hidden Valleys

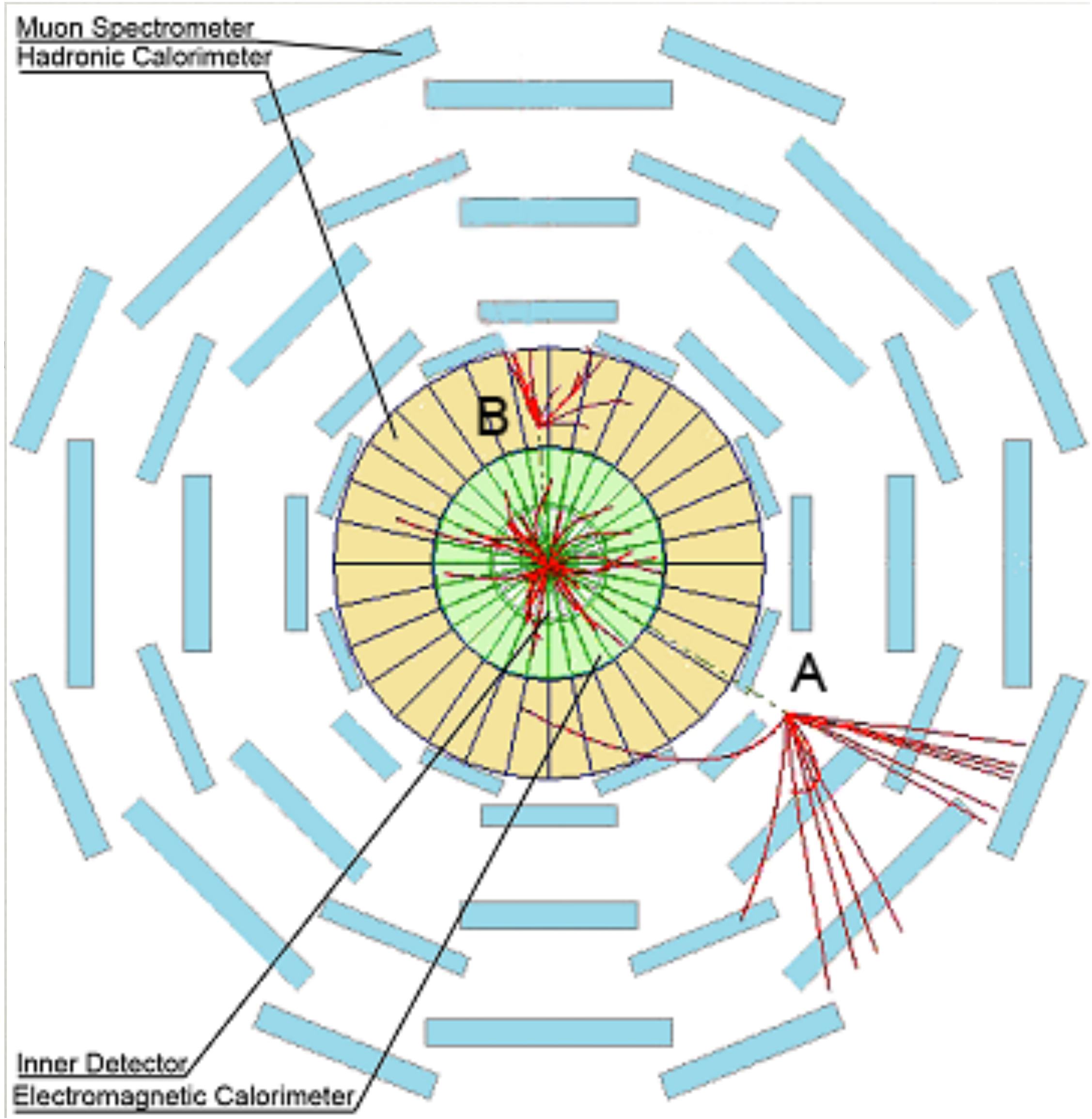


Hidden Valleys: Production

Typical setup involves mixing of scalars through a vertex whose coupling is suppressed by a large scale.



Hidden Valleys: Decay in Detector

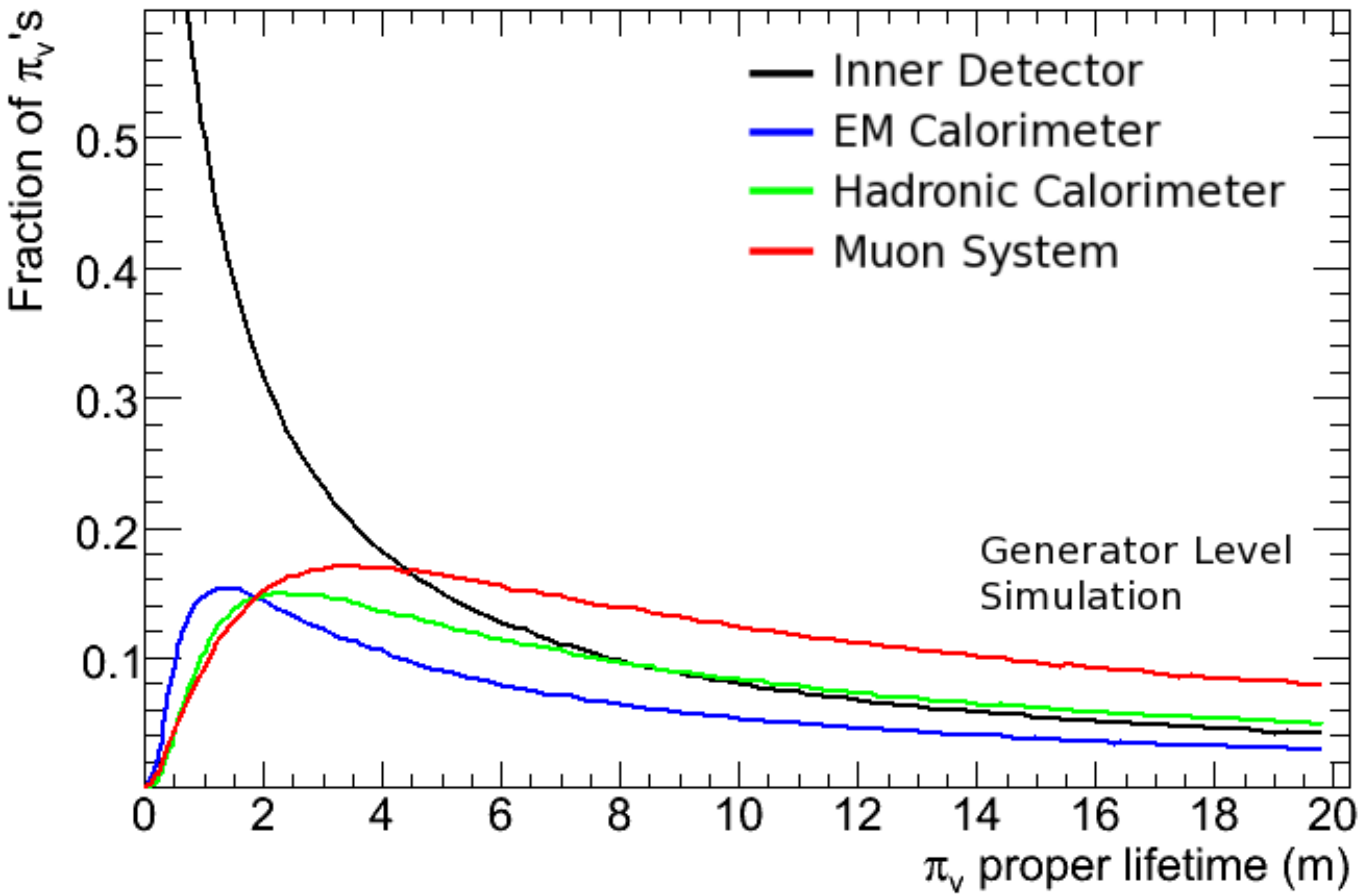


A: Displaced vertex decay in the muon system

B: Displaced vertex decay in the hadron calorimeter

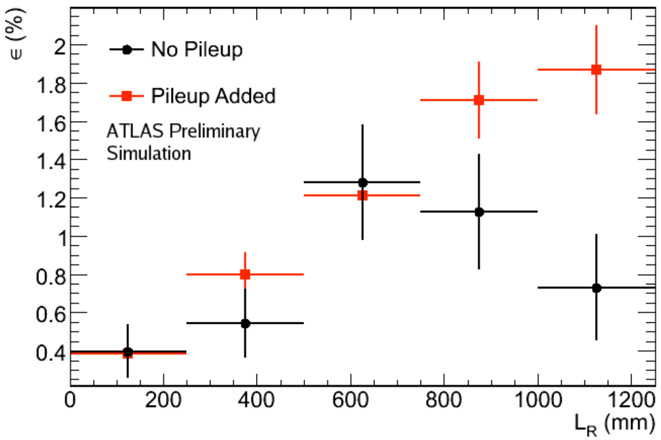
Hidden Valleys: Decay in Detector

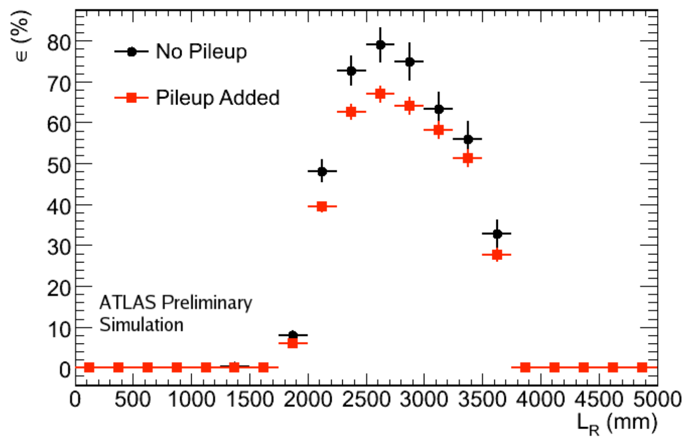
Distribution of location of displaced vertices:

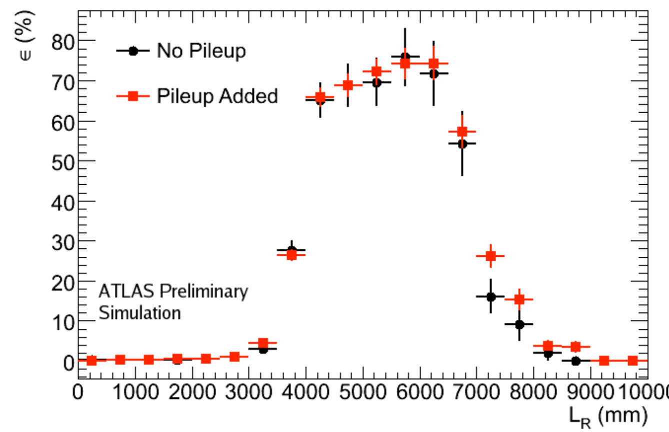


Hidden Valleys: Trigger Efficiencies

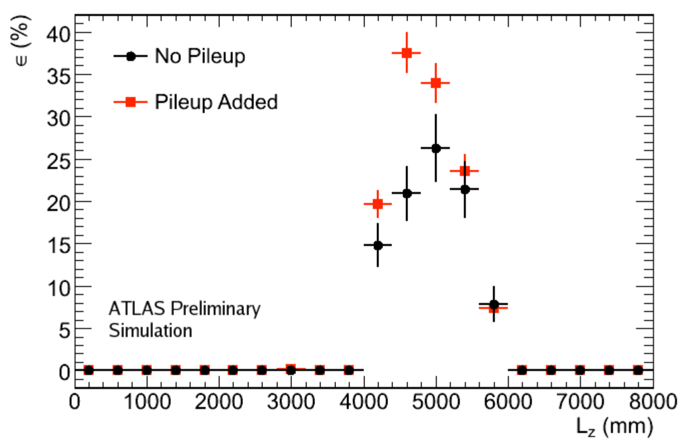
Increasing distance from beam pipe

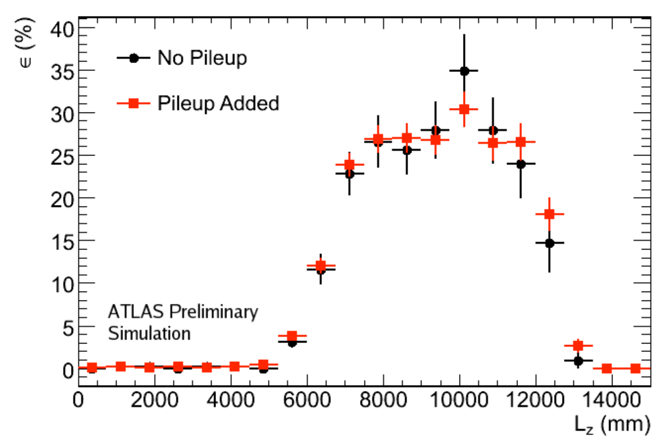




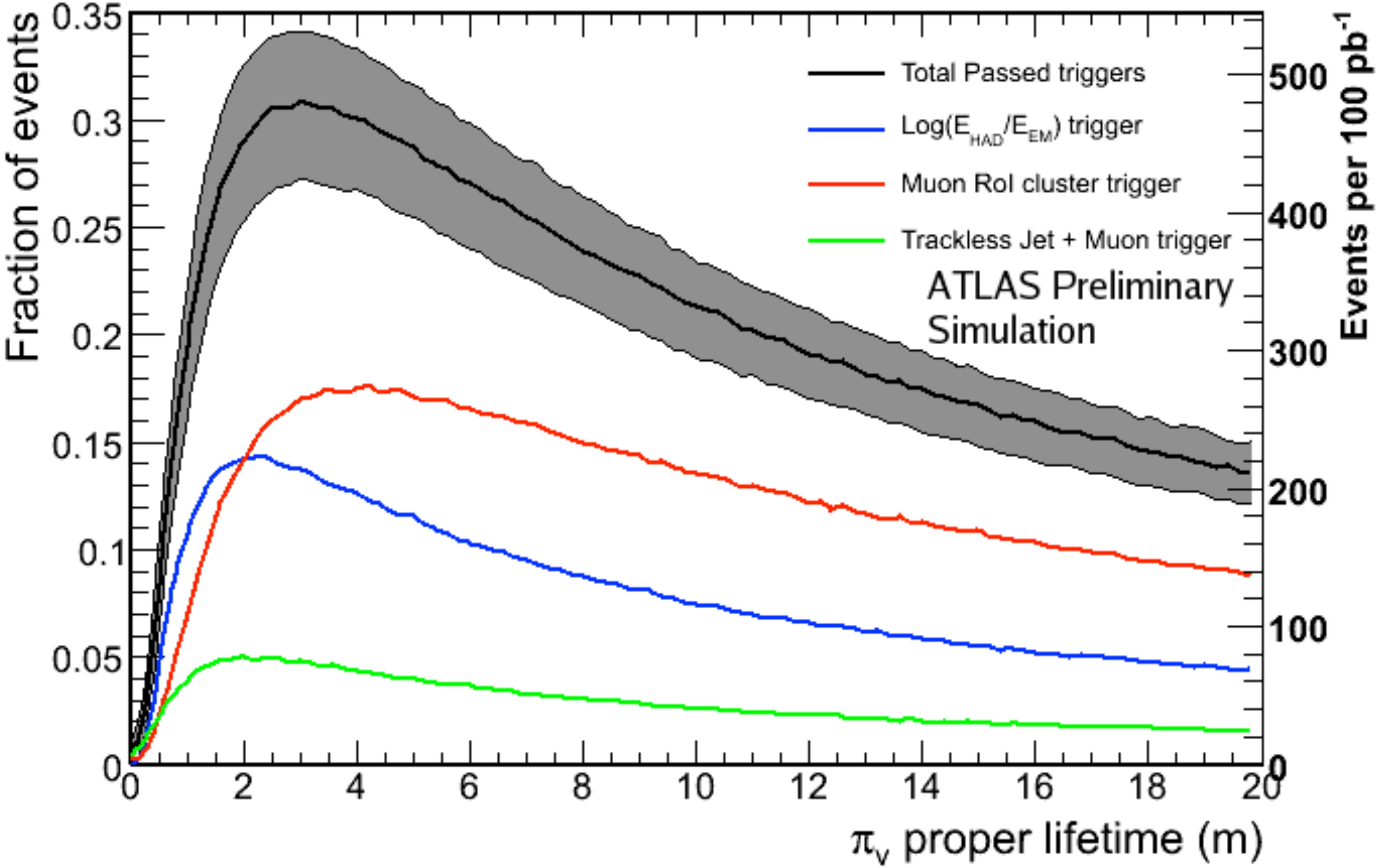


Top Row: Barrel
Bottom Row: Endcap





Hidden Valleys: Trigger Efficiencies



Hidden Valleys: Early LHC Potential

- Distinctive signature.
- If such a sector exists with a typical messenger mass scale of ~TeV, shows up clearly in early LHC data.
- Not motivated by solving problems in the Standard Model -- makes Hidden Valley models less compelling.

Early LHC: Conclusions

- 18 months of running at 7 TeV, including beam commissioning.
- Reach for new physics depends on how rapidly LHC is able to achieve increased luminosity.
- **Higgs**: Significant integrated luminosity requirements. Not likely to achieve reach well beyond Tevatron until restart in 2012.
- **Supersymmetry**: Retains moderate reach into regions of mSUGRA parameter space for modest luminosities. Some discovery potential.
- **Z'**: Good reach for heavy new gauge bosons, > 800 GeV. Some discovery potential.
- **Hidden Valleys**: Excellent reach for this less-well-motivated theory. Some discovery potential.