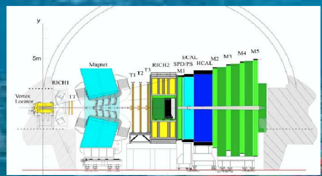
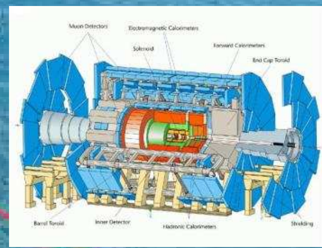
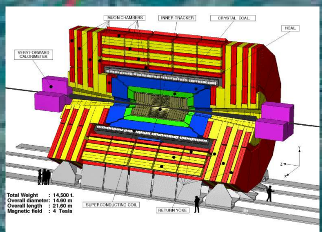
LHC Physics





Jim Rohlf
Boston University



Outline

- Introduction
- Event Rates and Triggering
- Higgs
- Supersymmetry
- Z'
- Extra dimensions
- Techicolor
- Compositeness
- Outlook

LHC parameters

pp c.m. energy	14 TeV
luminosity	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
collision rate	1 GHz
W/Z^0 *rate*	1 kHz
bunch spacing	25 ns
interactions per crossing	20
$\frac{dN_{\mathrm{ch}}}{d\eta}$ *per crossing*	$10^{5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
track flux @ 1 m	$10^{5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
rad. dose @ 1 m *for* $2500\ \mathrm{fb}^{-1}$	1 kGy

First physics expected at "low luminosity":

$2 \times 10^{33}\ \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

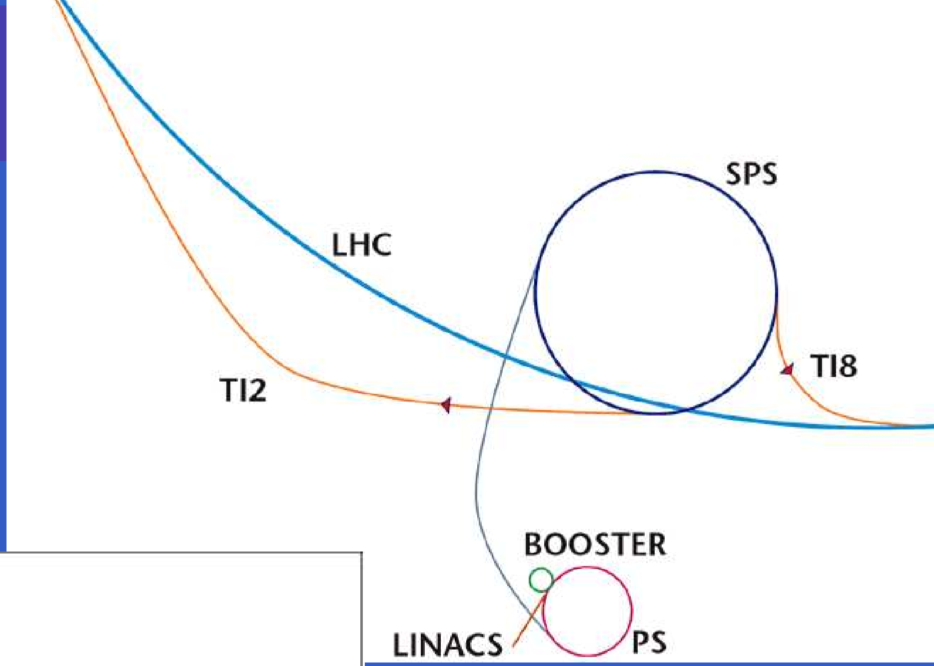
LHC Protons

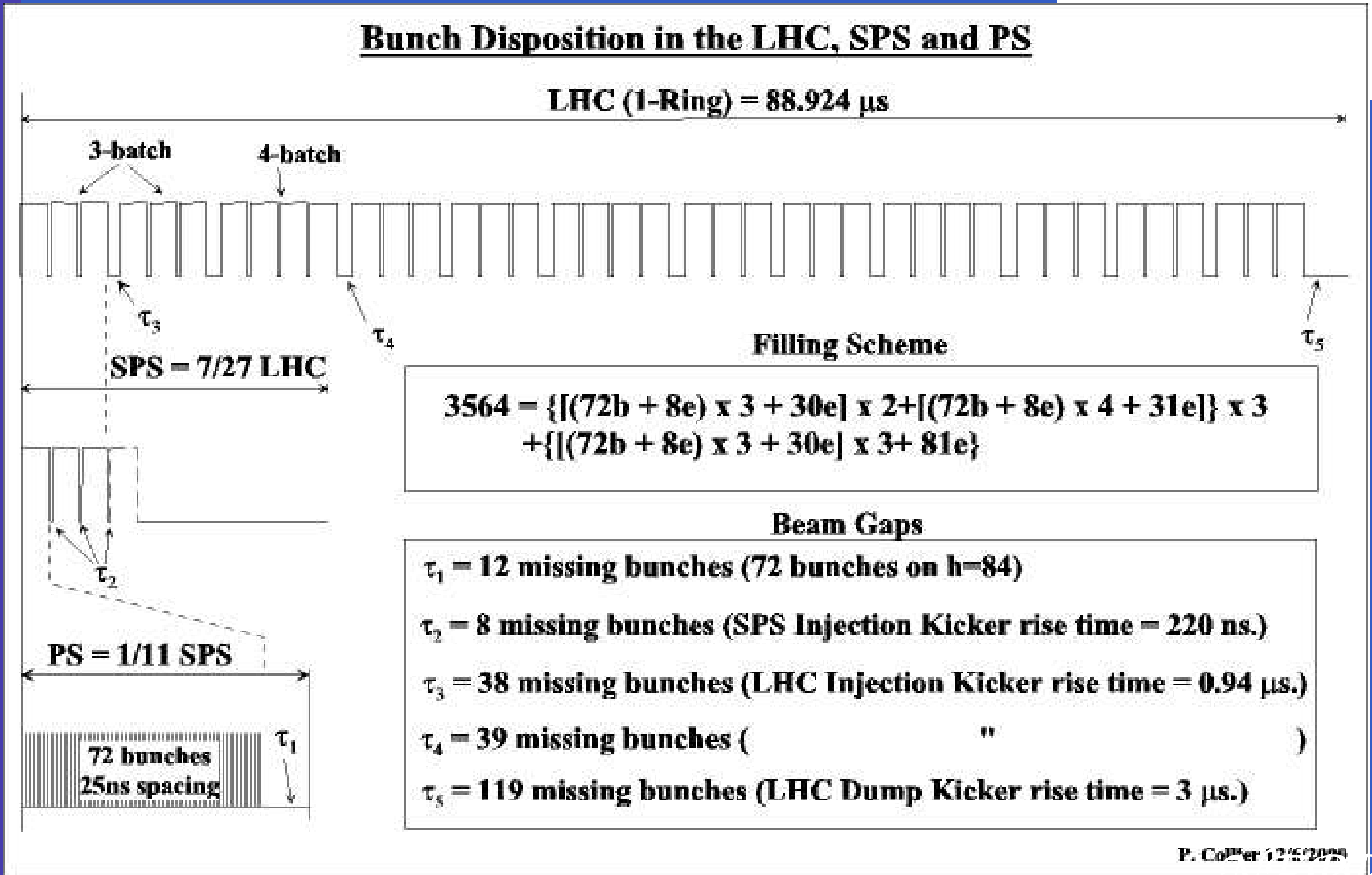
The gaps are important for synchronization!

LHC/PS = 42.4

(39 PS fill) (72 bunches/PS fill)

= 2808 bunches



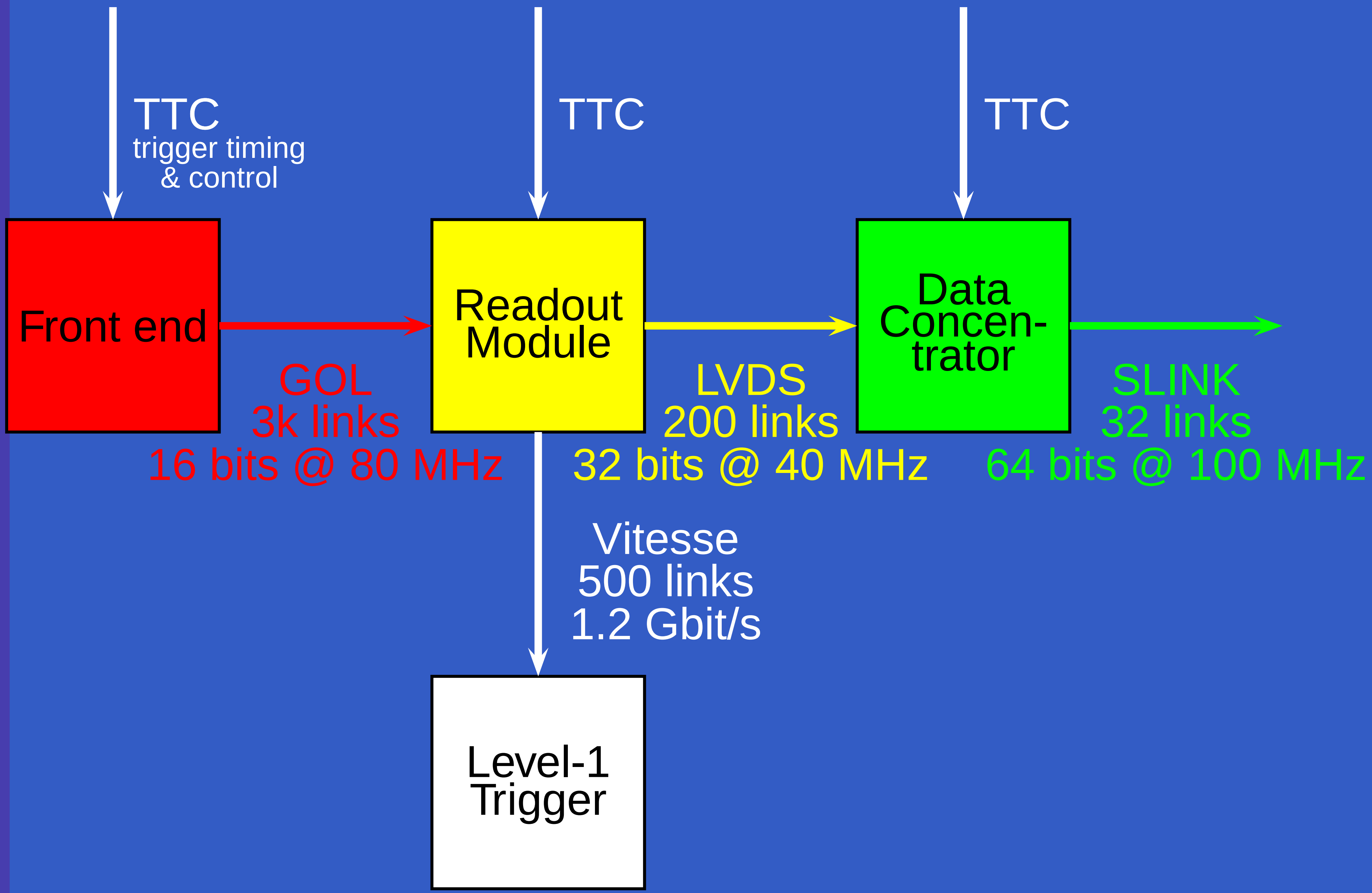


$$\Delta t = \frac{88924 \text{ ns}}{3564 \text{ ns}}$$

$$= 24.95 \text{ ns}$$

“Abort gap” = 3 μs used for fast reset

CMS HCAL Data flow



Stored energy unprecedented

$$E = 2E_{\rm p}N_{\rm b}N_{\rm p}$$

$$E = (2)(1.5 \times 10^{13}\ {\rm eV})(1.6 \times 10^{-19}\ {\rm J/eV})(2808)(1.1 \times 10^{11}) \simeq 1.5\ {\rm GJ}$$

The problem becomes even more severe for the next proton machine!

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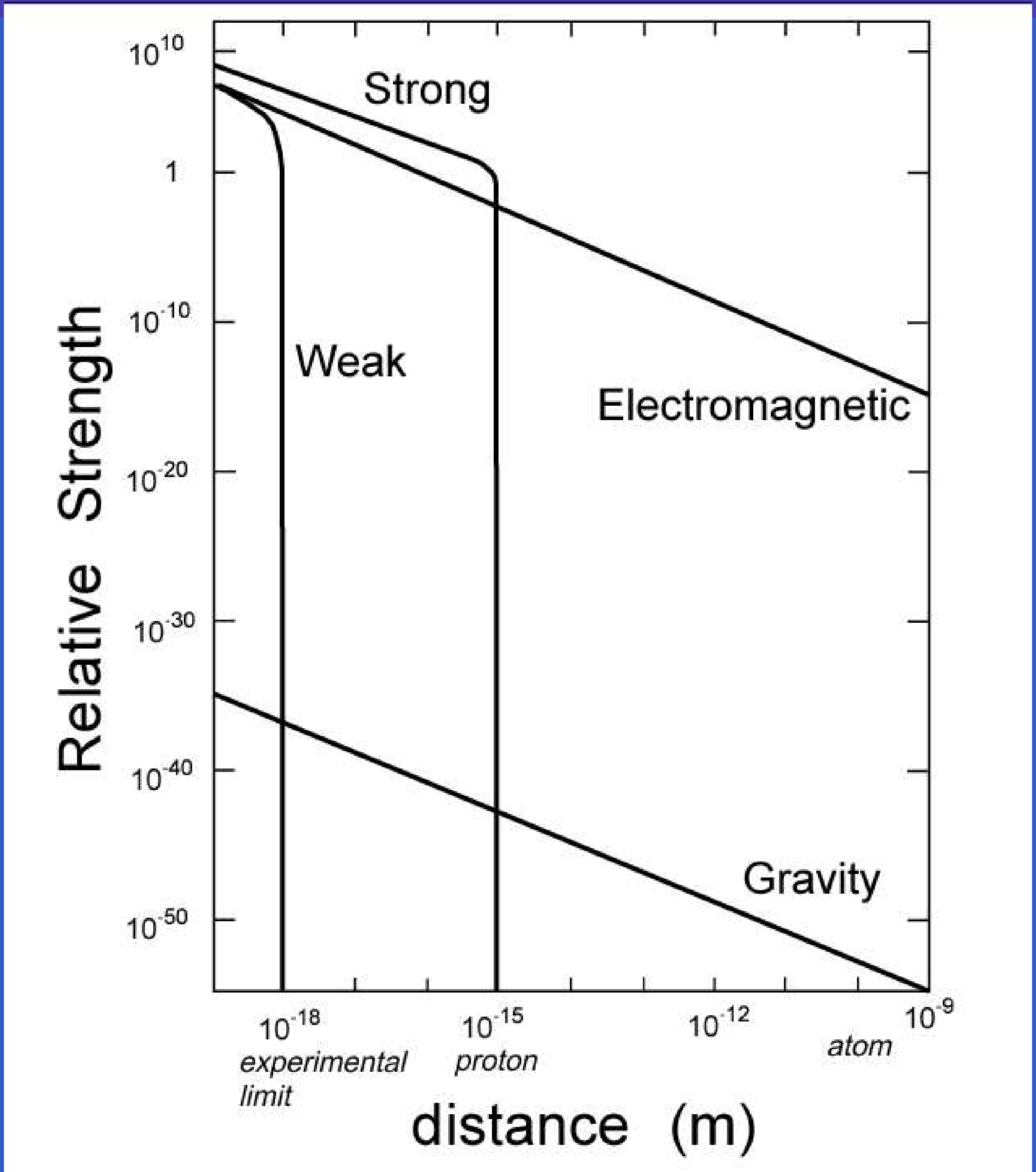
Kuznetsov

$$m = 55,000\ \mathrm{tons}$$

same kinetic energy at 15 knots as the LHC beams!

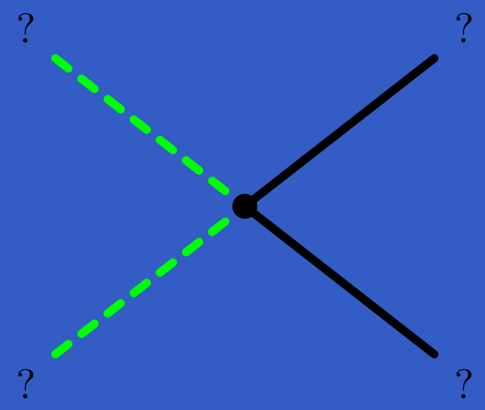
The problem becomes even more severe for the next proton machine!

Forces and Distance



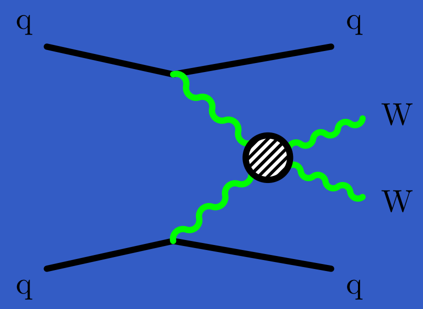
Big Picture

FIRST look at the TeV/c^2 mass scale to find a clue to the hierarchy problem... *What lies between the weak scale and the Planck mass?*



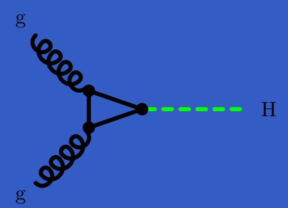
Medium Picture

EXPLORE the mechanism for electroweak symmetry breaking... *How do the* W/Z^0 *interact at high energies?*



Small Picture

NAIL down the elusive Higgs boson...



Links

http://cmsdoc.cern.ch/cms.html
http://atlasinfo.cern.ch/

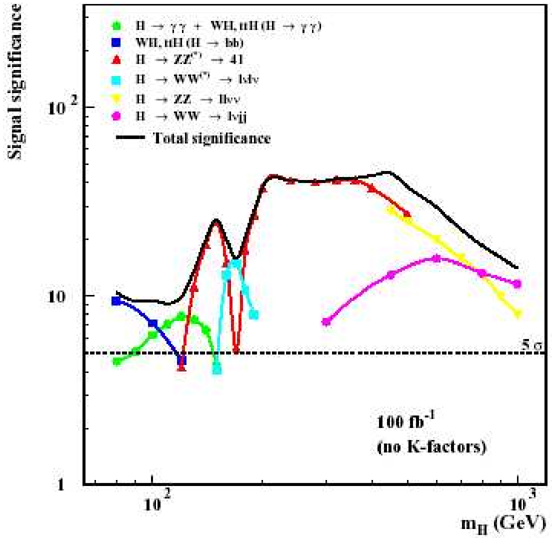
http://conferences.fnal.gov/lhc2003/index.html

- J. Rohlf, CMS: Physics reach at High and Very High Luminosities
- B. Zhou, ATLAS: Physics reach at High and Very High Luminosities

Documents

ATLAS

ATLAS DETECTOR AND PHYSICS PERFORMANCE



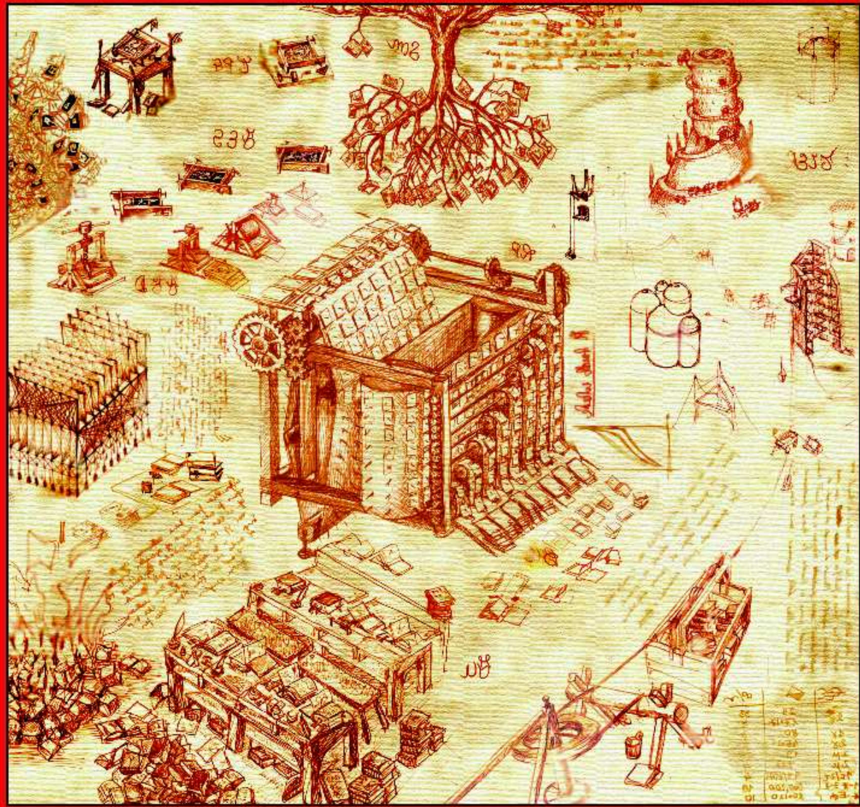
Technical Design Report

Issue:	1
Revision:	0
Reference:	ATLAS TDR 15, CERN/LHCC 99-15
Created:	25 May 1999
Last modified:	25 May 1999
Prepared By:	ATLAS Collaboration

Volume II

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CERN/LHCC 2002-26
CMS TDR 6.2
15 December 2002

CMS

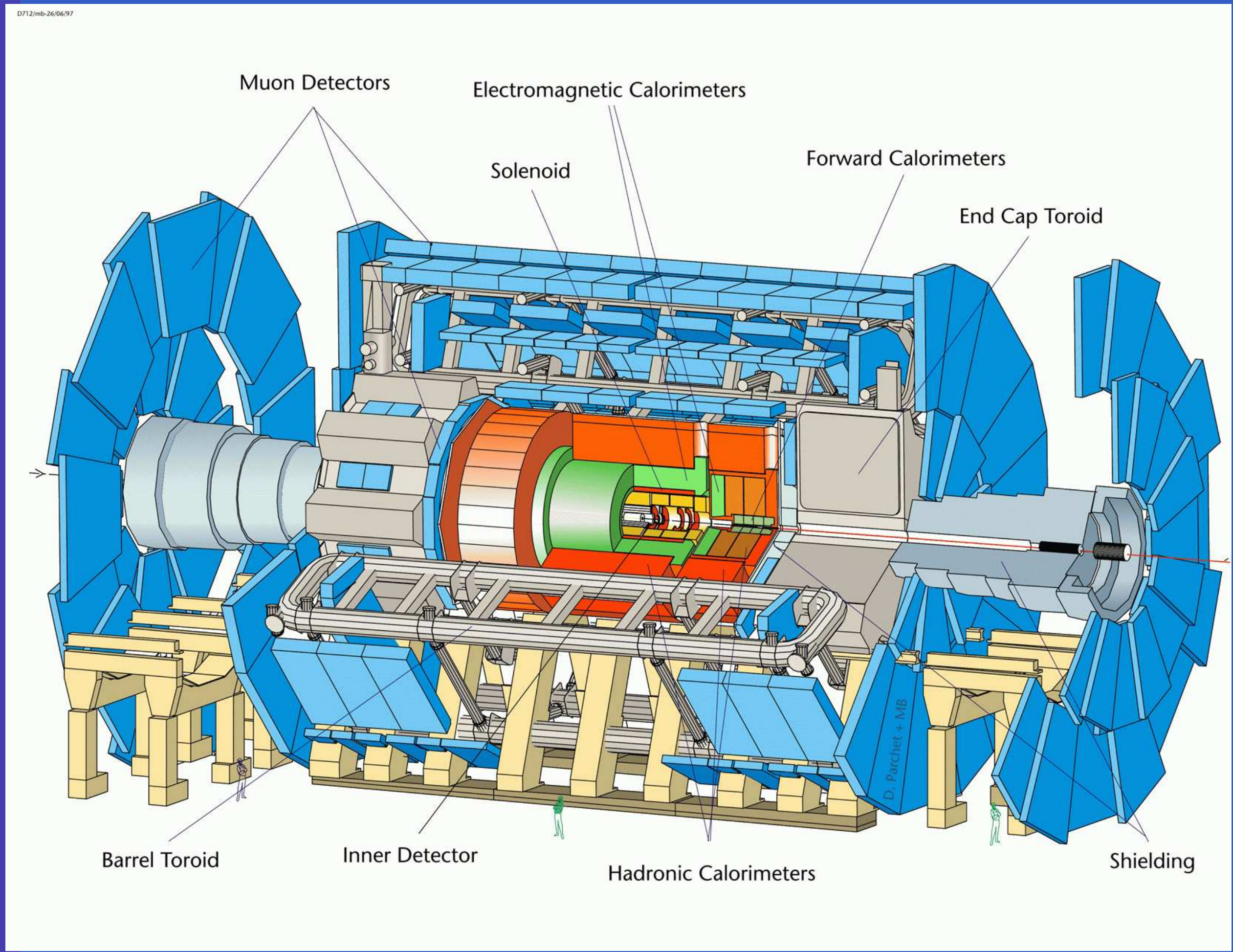


The Trigger and Data Acquisition project, Volume II

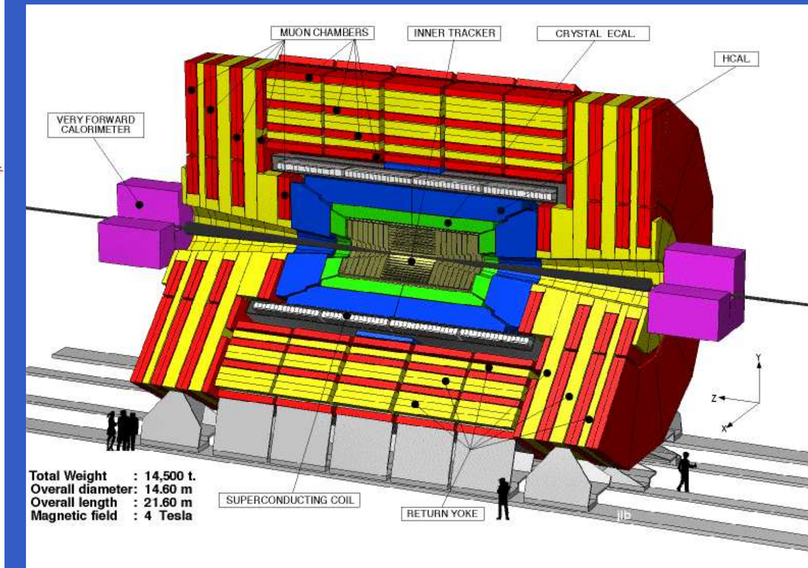
Data Acquisition & High-Level Trigger

Technical Design Report

Detectors overview



- tracking in B field
- EM calorimetery
- had. calorimetry
- muon detectors



A Toroidal Large hadron collider ApparatuS (ATLAS) 7 kTons
0.5 T toroid, 2 T solenoid
25 m × 46 m

Compact Muon Solenoid (CMS) 14 kTons
4 T solenoid
15 m × 22 m

ATLAS and CMS zeroth-order difference

ATLAS

Large magnet cost (40%)

- good stand-alone muon resolution (BL^2)
- less resources spent on ECAL and tracking

CMS

Lower magnet cost (25%)

- high-resolution tracker
- high-performance ECAL

CMS magnet

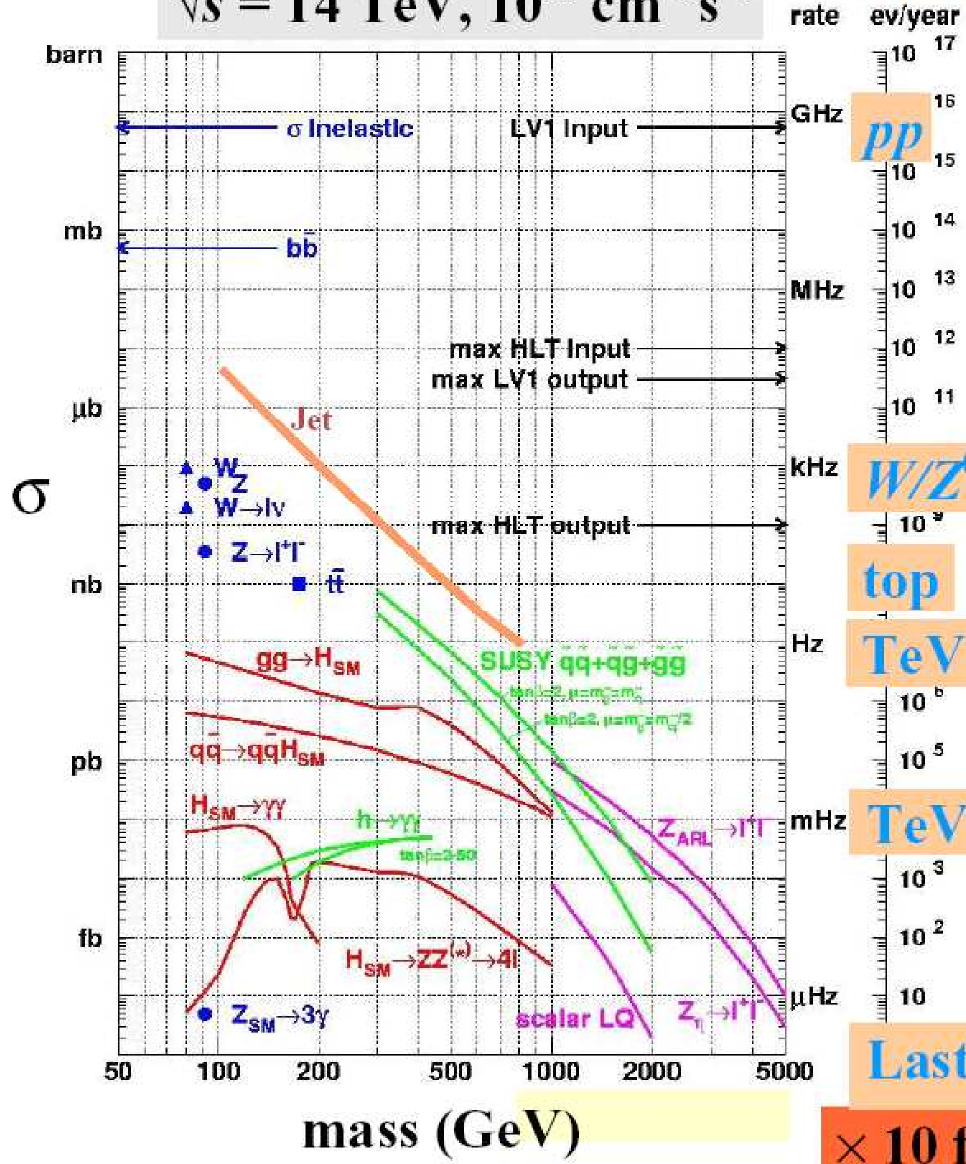
ATLAS magnet

Detector technology

		CMS	ATLAS
Tracking:	inner	pixels	pixels
	barrel	silicon strips	silicon strips / straw tubes
	endcap	silicon strips	silicon strips / straw tubes
ECAL:	barrel	crystals $(\mathrm{PbWO_4})$	liquid argon / Pb
	end cap	crystals $(\mathrm{PbWO_4})$	liquid argon / Pb
HCAL:	barrel	scintillator / brass	scintillator / Fe
	end cap	scintillator / brass	liquid argon / Cu
	forward	quartz / Fe	liquid argon / Cu-W
Muon:	barrel	drift chambers	drift tubes
		+resistive plate	+resistive plate
	end cap	cathode strip	cathode strip
		+ resistive plate	+ thin gap

LHC Rates

$\sqrt{s}$ = 14 TeV, 10^{34} $cm^{-2}s^{-1}$



high lum.

pp

W/Z⁰

top

TeV jets

TeV exotica

Last event: $x_F = ½$

× 10 for super-high lum.

level-1 hardware

level-2/3 software

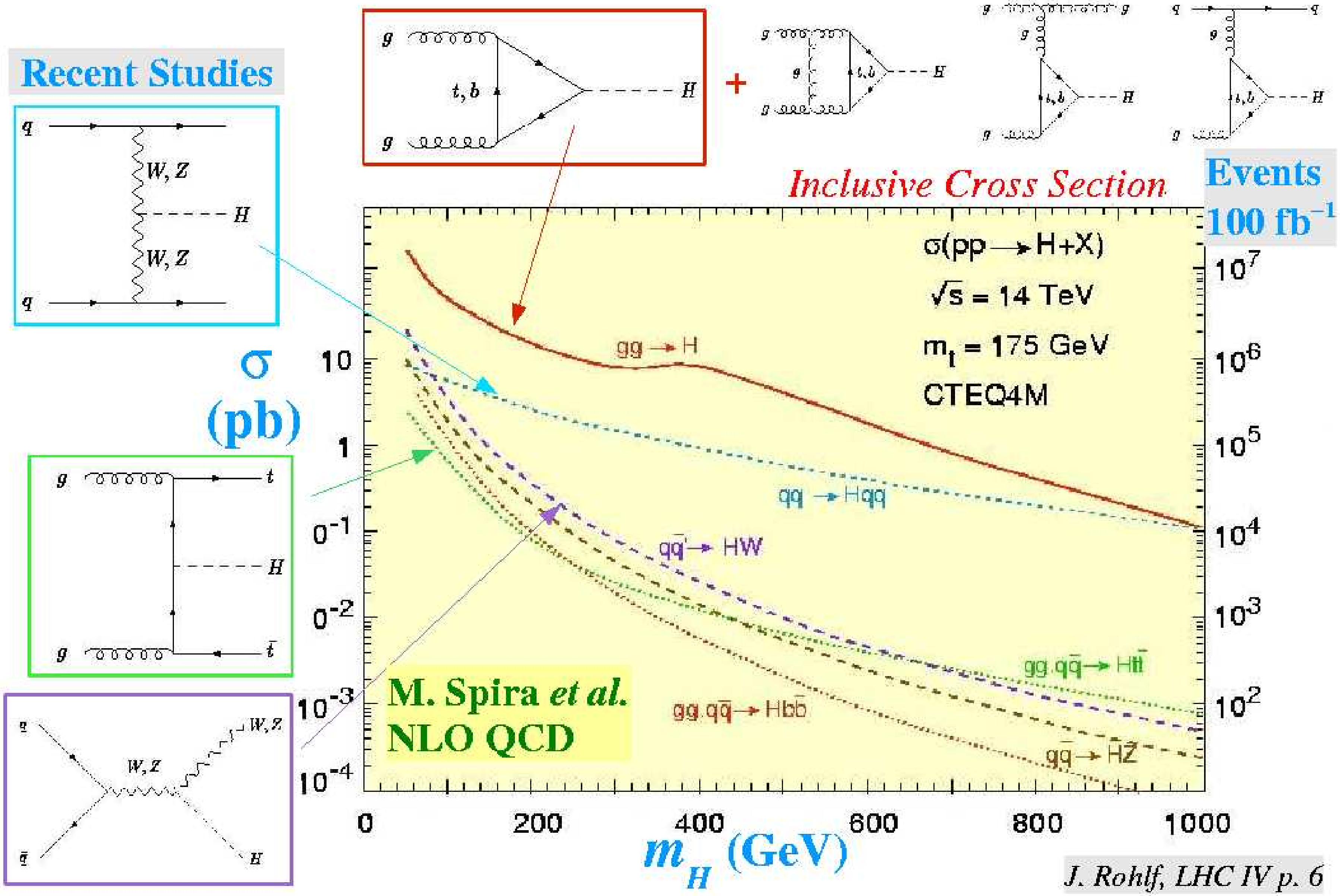
L1 trigger (high lum.)

Trigger	(GeV) *Thresh.*	(kHz) *Rate*
iso. e/γ	34	6.5
2 e/γ	19	3.3
iso. μ	29	6.2
2μ	5	1.7
τ	101	5.3
2τ	67	3.6
jet	250	1.0
3jet	110	1.0
4jet	95	1.0
jet•E_T^{miss}	113/70	4.5
e•jet	25/57	1.3
μ•jet	15/40	0.8
min. bias		1.0
total (10% overlap)		33.5

(designed for 100 kHz with ×3 safety)

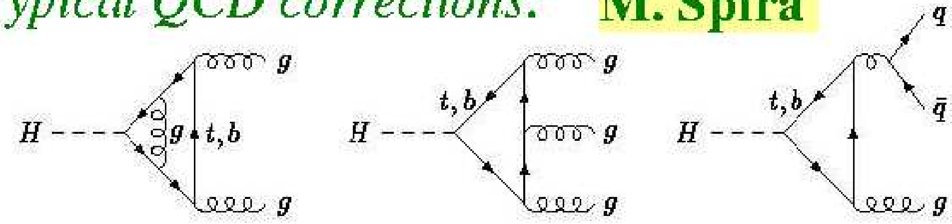
J. Rohlf, LHC IV p. 4

Standard-Model Higgs

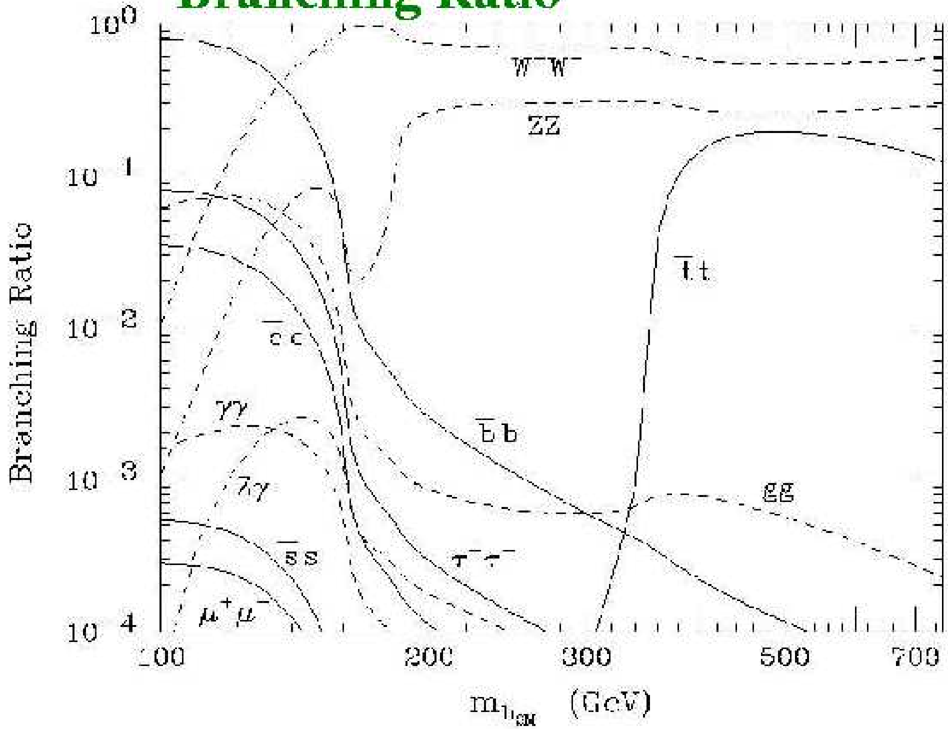


SM: H^0 Branching Ratio and Width

Typical QCD corrections: **M. Spira**

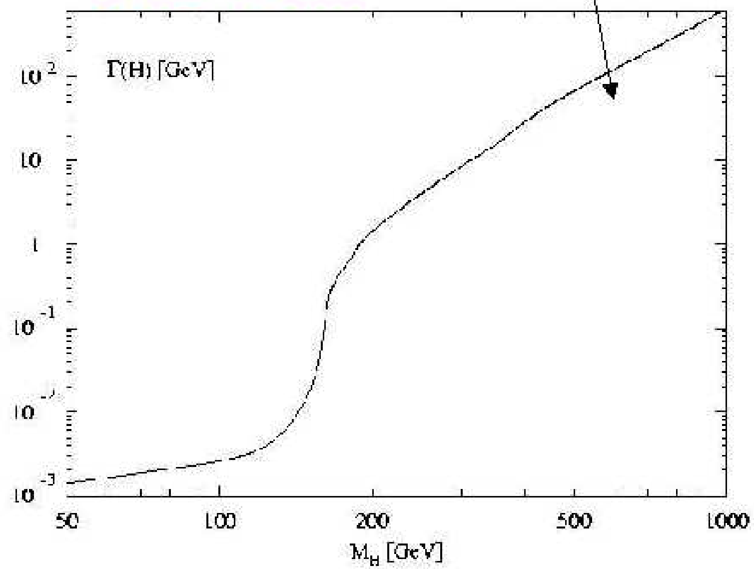


Branching Ratio



"toilet bowl"

Total Width

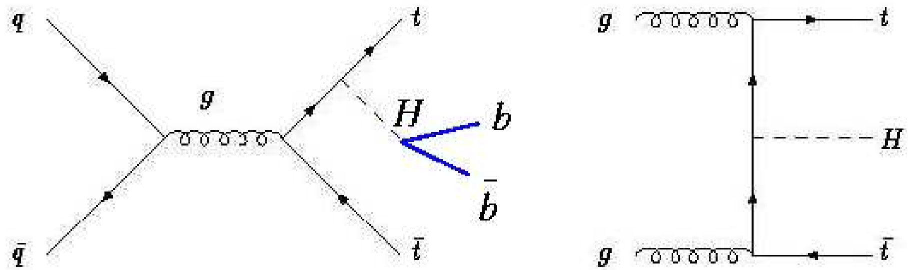


J. Rohlf, LHC IV p. 7

SM: $t\bar{t}H^0$

final state:

$q\bar{q}b\ l\nu\bar{b}\ b\bar{b}$



main backgrounds:

$t\bar{t}b\bar{b}$, $t\bar{t}Z$

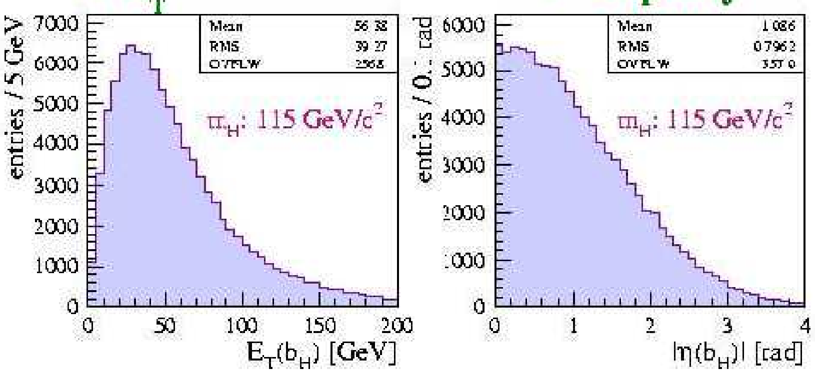
event selection:

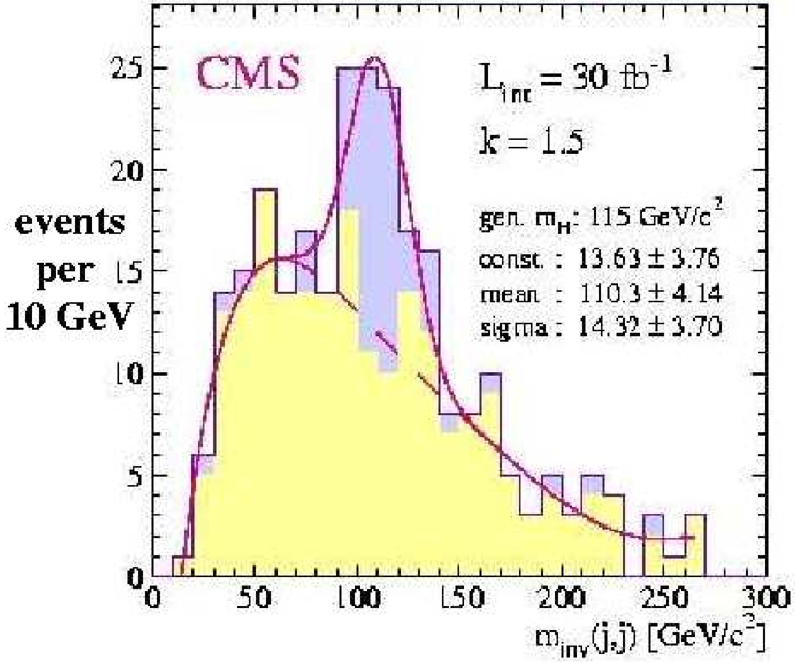
lepton, 4 *b*-tag jets, 2 non-*b* jets,

***W* mass, *t* mass (2)**

V. Drollinger *et al.*

$b\ E_T$ **b Rapidity**





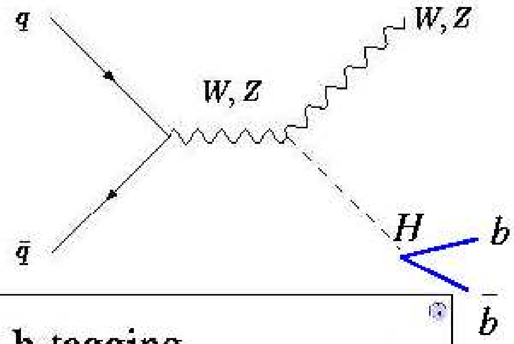
efficiency:

$t\bar{t}H$ (115 GeV)	1.3%
$t\bar{t}b\bar{b}$	0.4%
$t\bar{t}Z$	0.2%

J. Rohlf, LHC IV p. 9

SM: $WH^0 \rightarrow Wb\bar{b}$

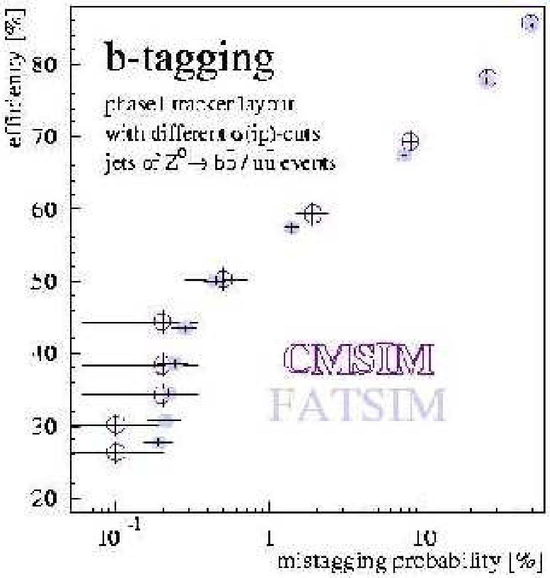
final state: $l^{\pm}\nu\, \bar{b}b$



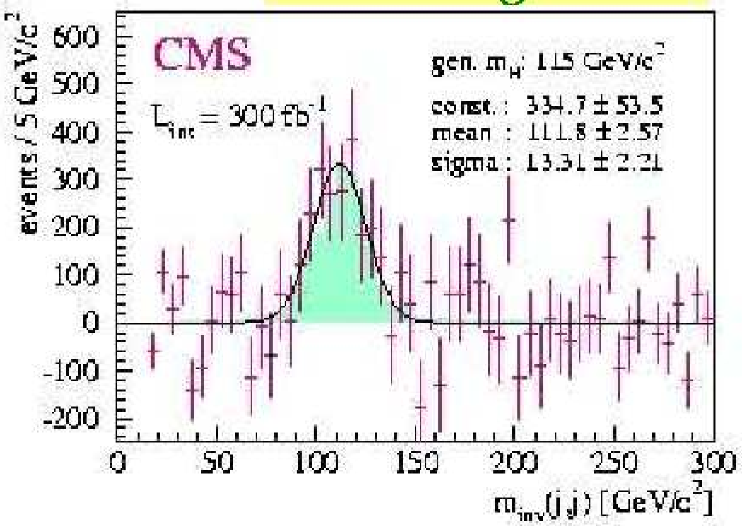
σ = 2.5 pb at M_H=100 GeV,

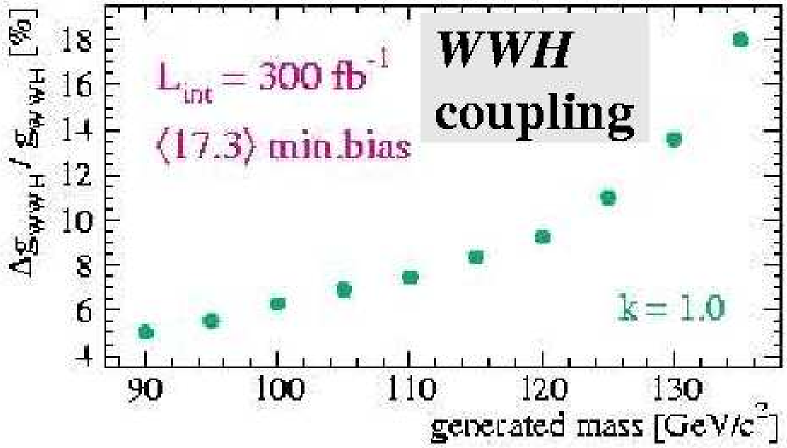
huge backgrounds from:
$t\bar{t}$ (570 pb), $t\bar{b}$ (320 pb),
Wjj (30 pb), WZ (27 pb)

***b*-tag is important**



V. Drollinger *et al.*





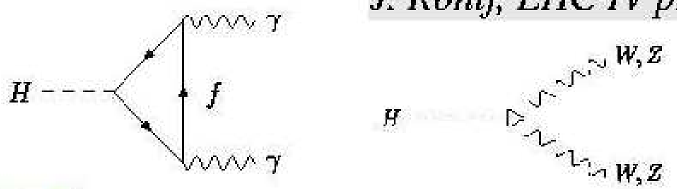
J. Rohlf, LHC IV p. 10

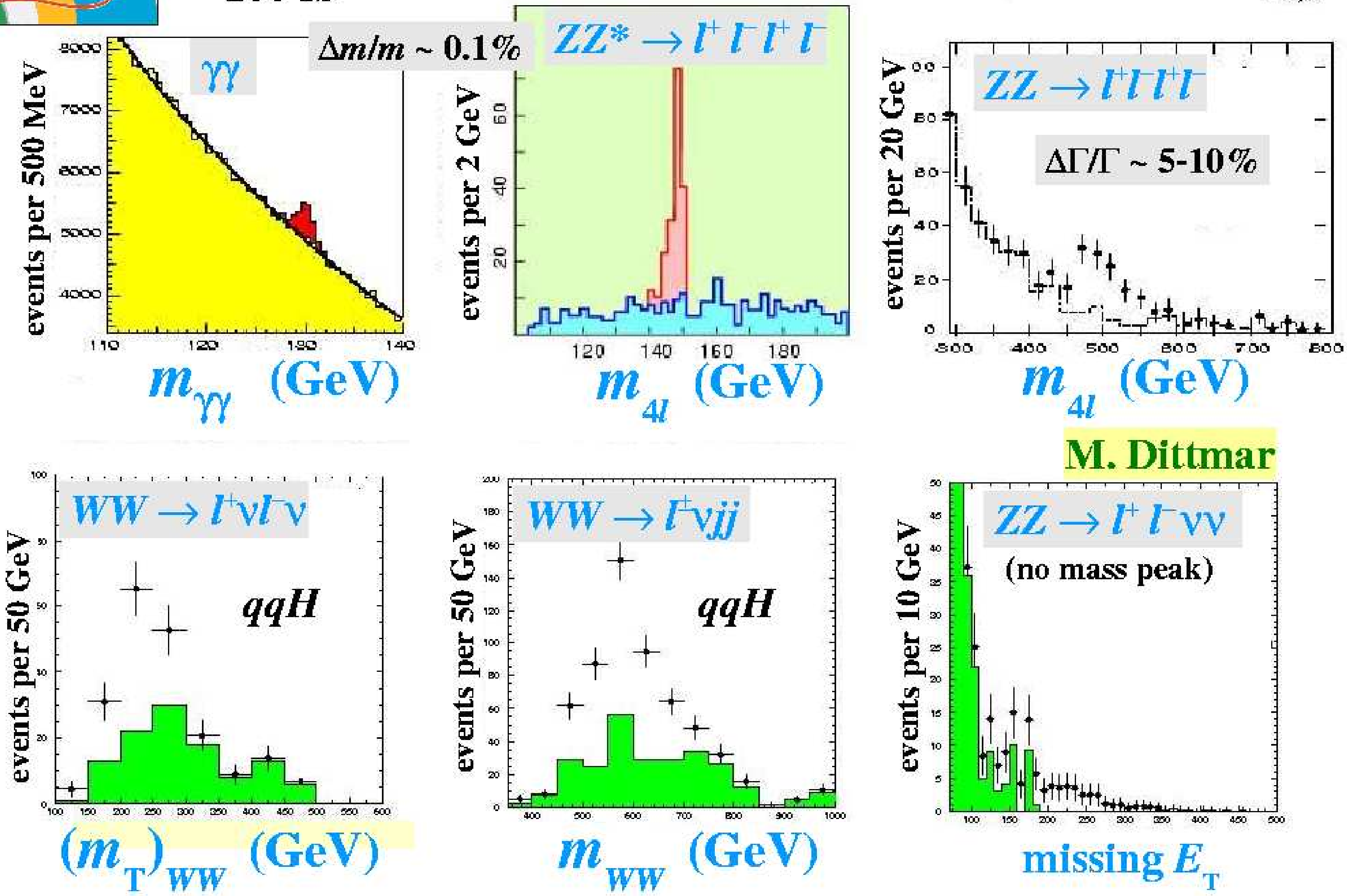
SM: $\gamma\gamma$, WW, Z Z

J. Rohlf, LHC IV p. 11

CMS Warhorses

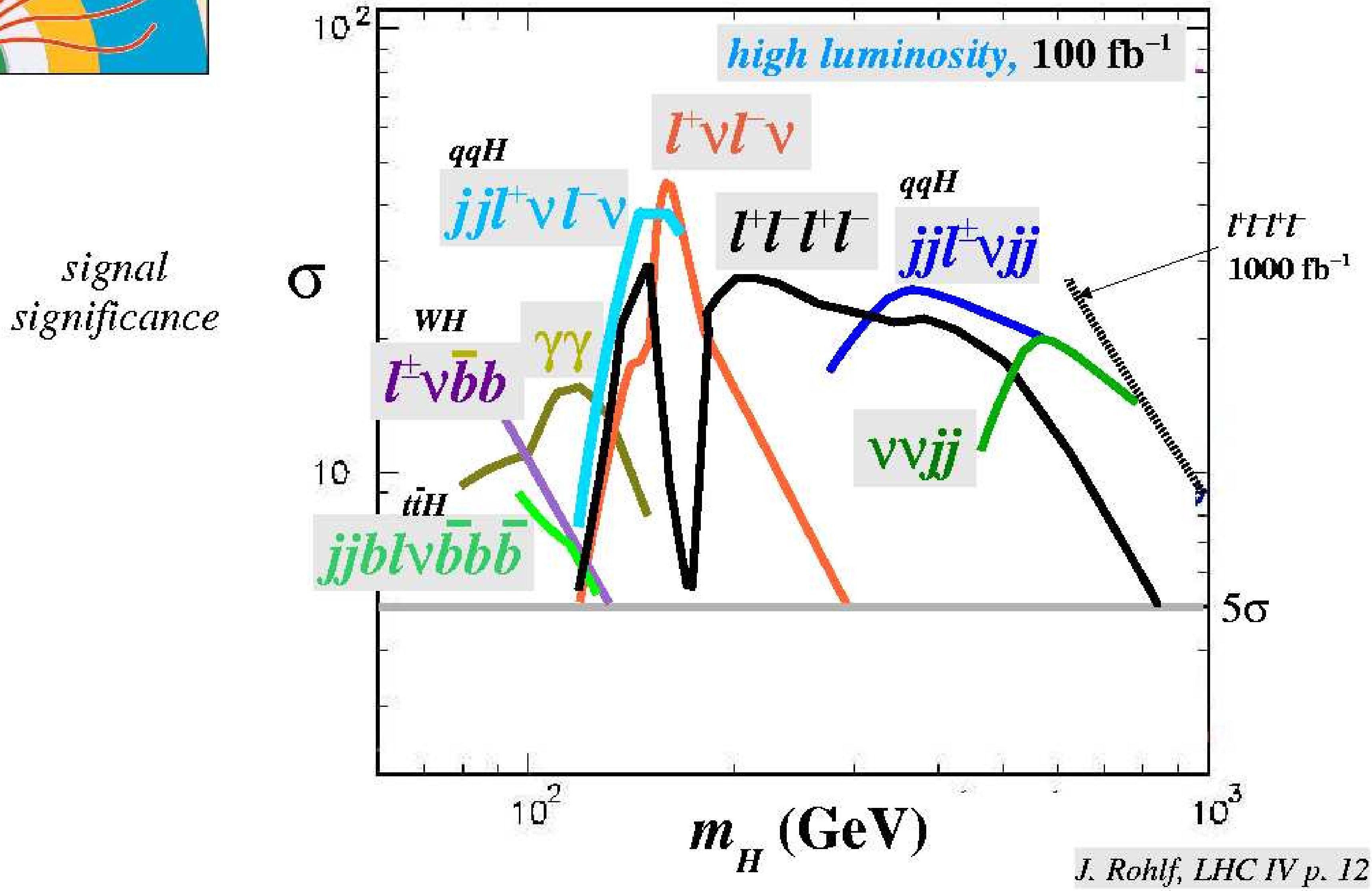
100 fb^{-1}



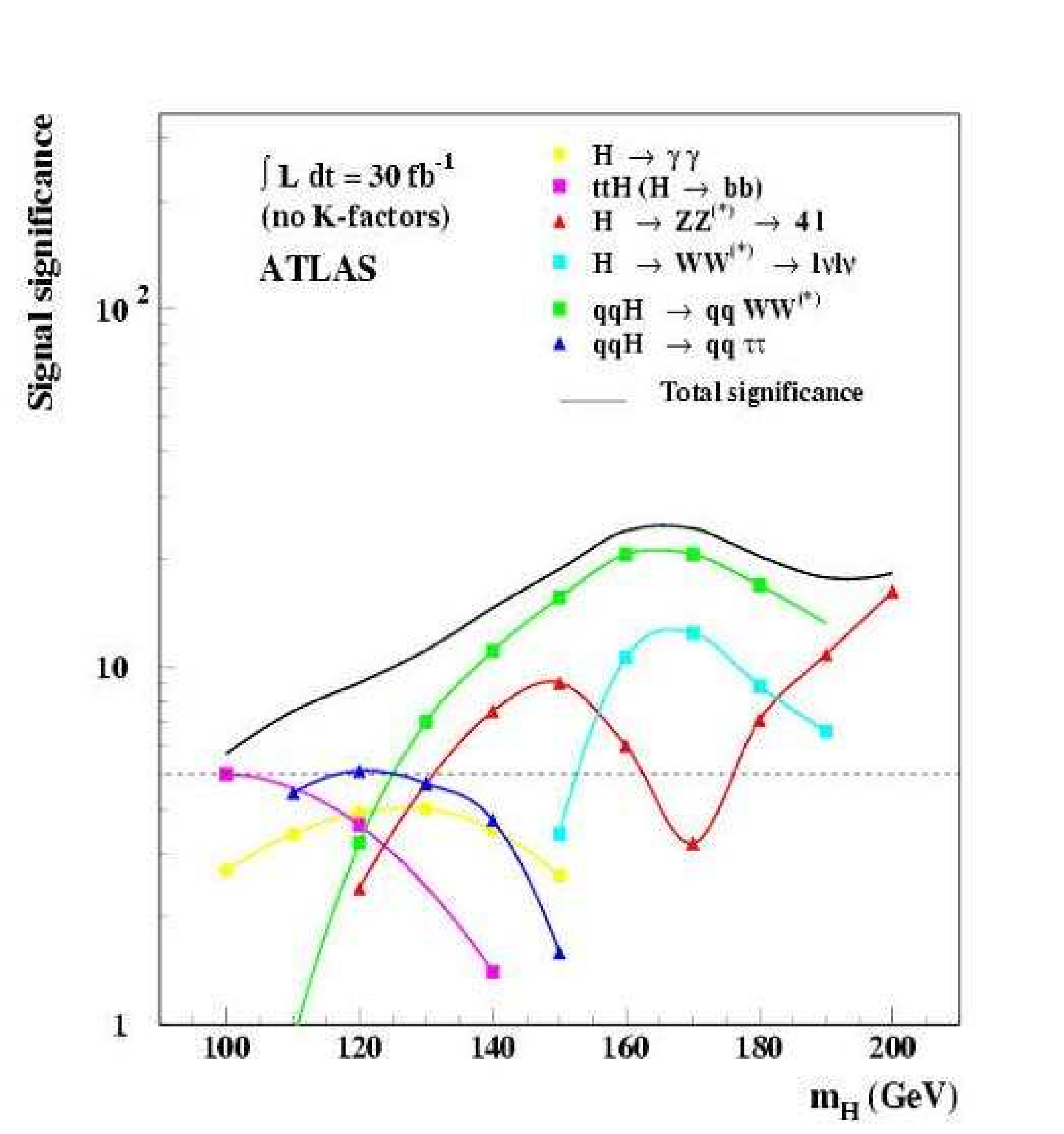


SM Higgs: Summary

Observable in multiple modes over entire mass range.



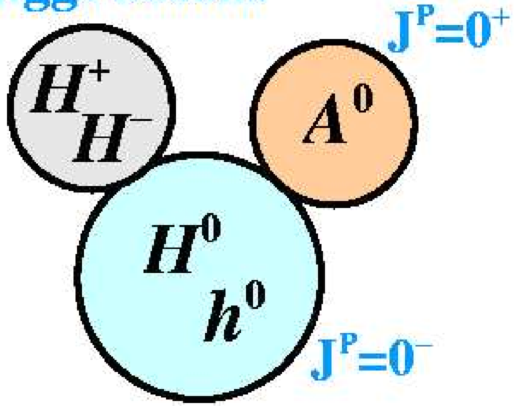
Higgs reach ATLAS



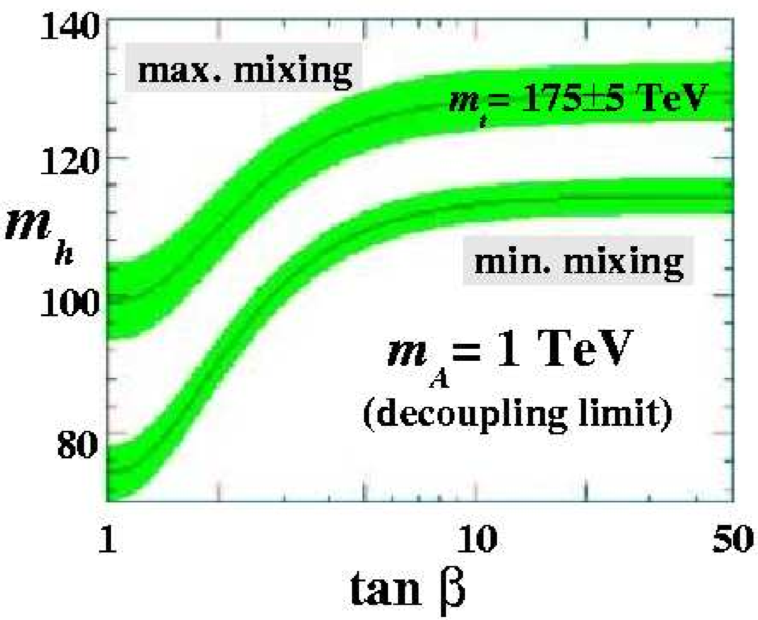
MSSM Higgs

Minimal Supersymmetric Standard Model

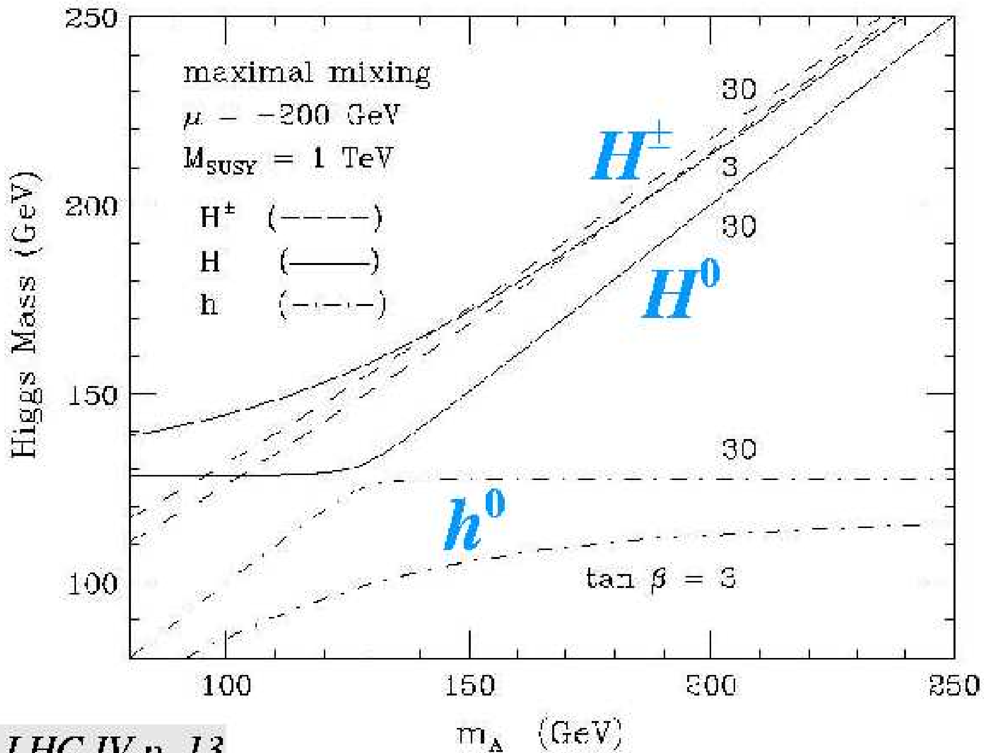
... a 3-ring circus of Higgs bosons



- **Two parameters:**
  $\tan\beta = \frac{v_u}{v_d}$ (where $v_u = \sqrt{2}\langle\Phi_u^0\rangle, v_d = \sqrt{2}\langle\Phi_d^0\rangle$) and m_{A^0}
- **LEP limits are substantial!**
  ⇒ stay alive with maximal top-squark mixing
- **h^0 behaves like *SM*-Higgs and is light**
  ⇒ low-mass *SM* channels are important



Review of Higgs Physics:
J. Gunion PASCOS 03.

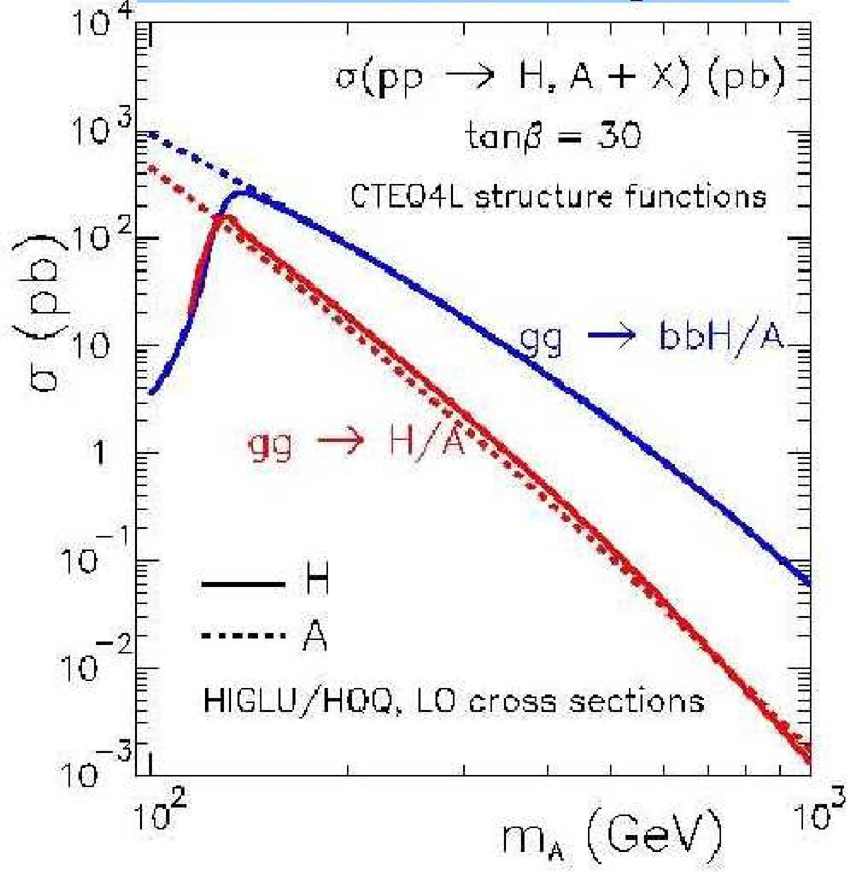


J. Rohlf, LHC IV p. 13

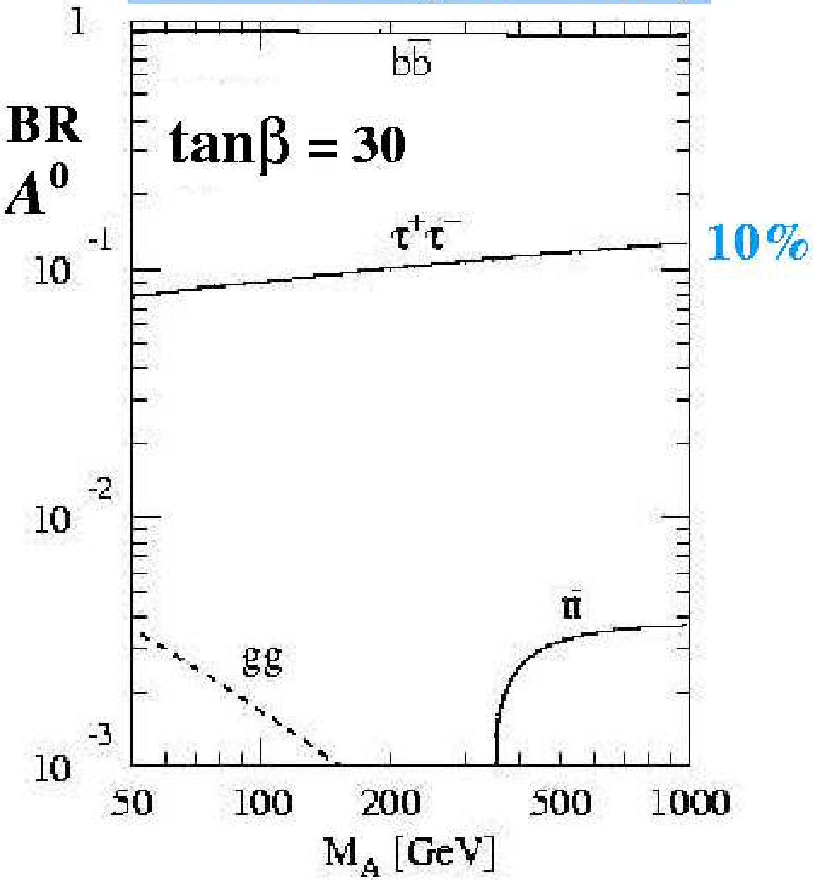
MSSM Higgs

couplings:
$b\bar{b}H^0, b\bar{b}A^0 \sim \tan\beta$
$\tau^+\tau^- H^0, \tau^+\tau^- A^0 \sim \tan\beta$

Radiation from b's is important



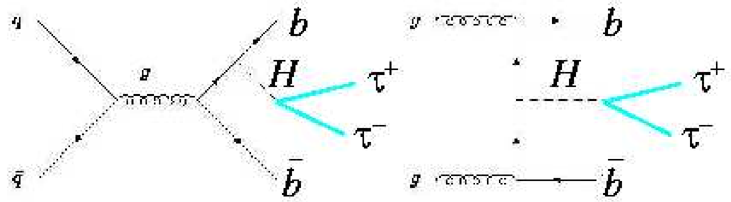
$\tau^+\tau^-$ also an important decay

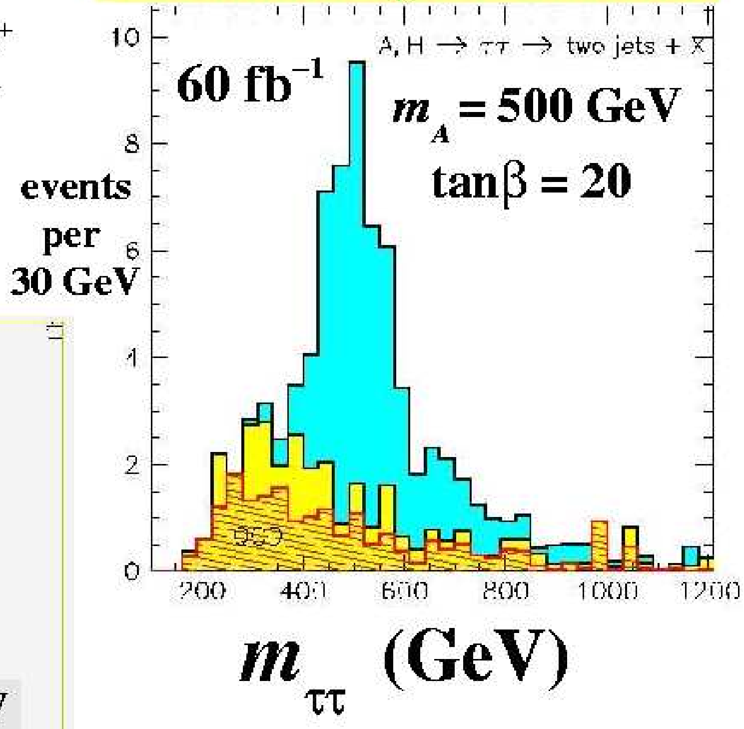


J. Rohlf, LHC IV p. 14

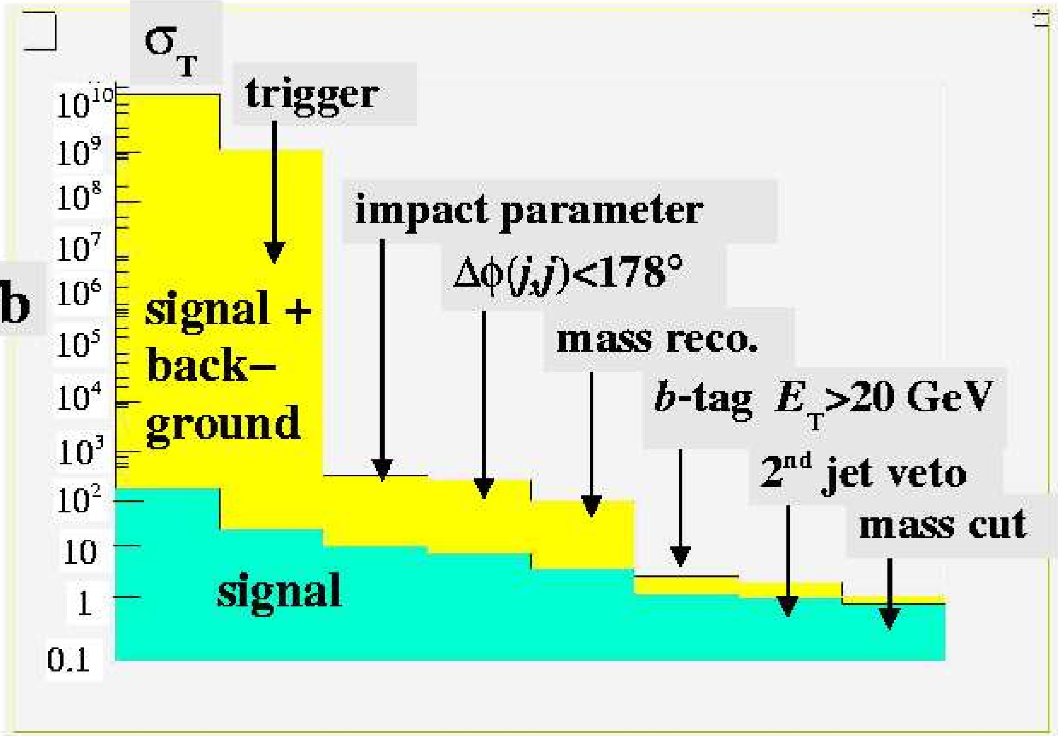
MSSM: $b\bar{b}H^0/A \rightarrow b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}jj$

R. Kinnunen, A. Nikitenko





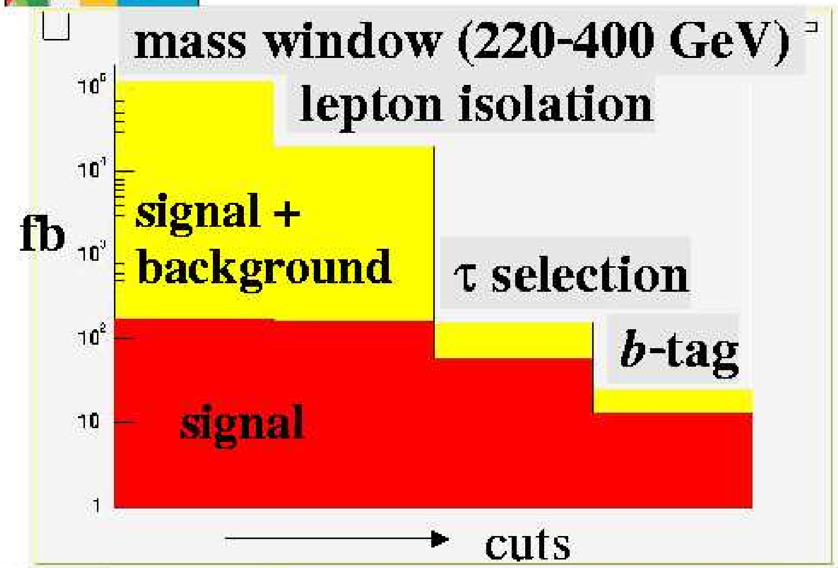
Background dominated by QCD



20% background from *W*, *Z*, top after cuts

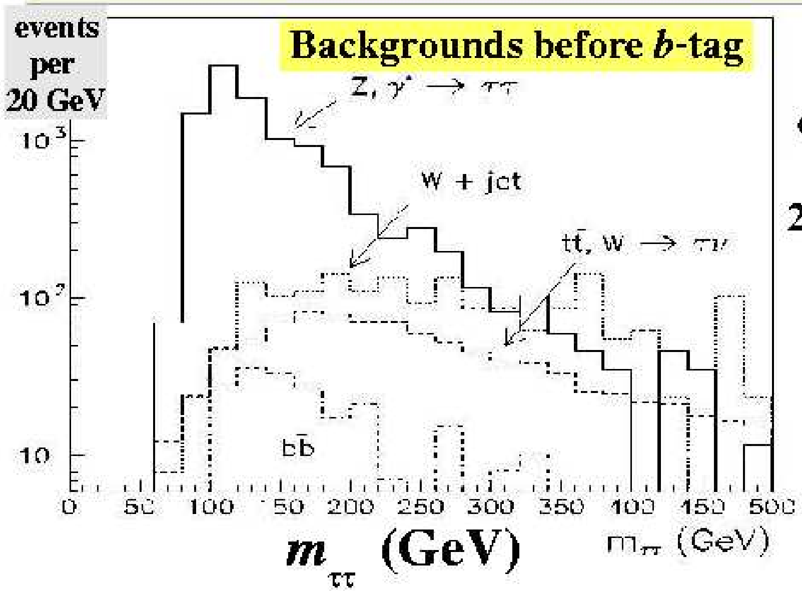
J. Rohlf, LHC IV p. 15

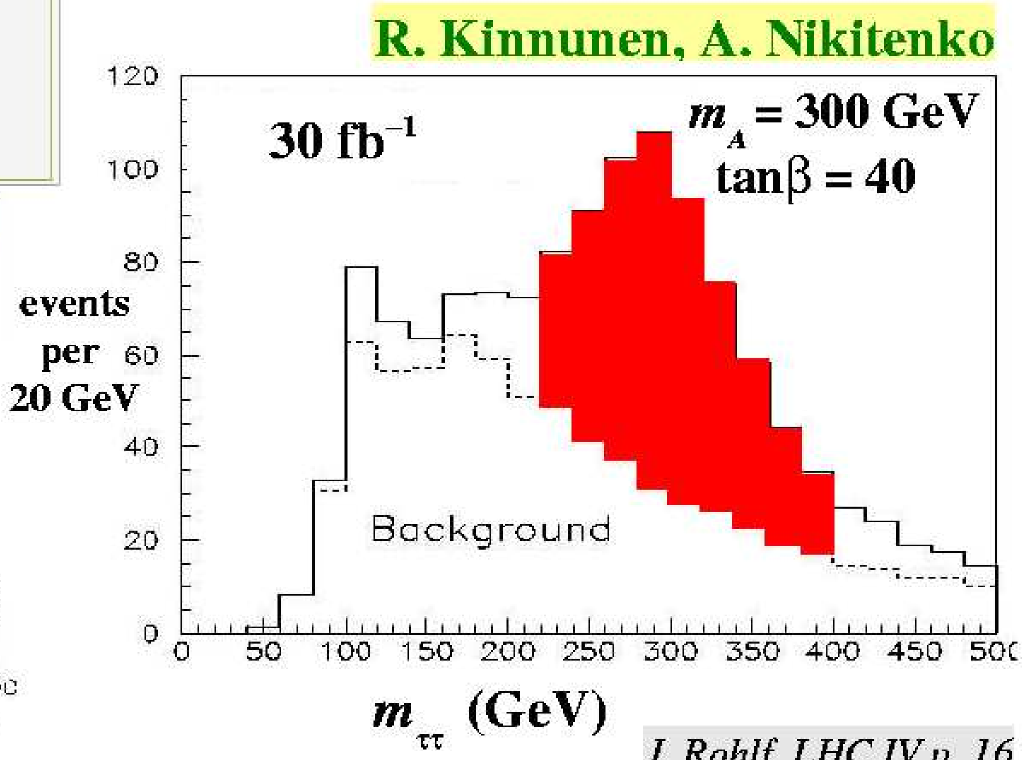
MSSM: $b\bar{b}H^0/A \rightarrow b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}l^{\pm}j$



τ-selection reduces *b* background
b-tag reduces *W/Z* background

After cuts, $W \rightarrow \tau$ from top dominates background





J. Rohlf, LHC IV p. 16

MSSM: $b\bar{b}H^0/A^0 \rightarrow b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}e\mu$

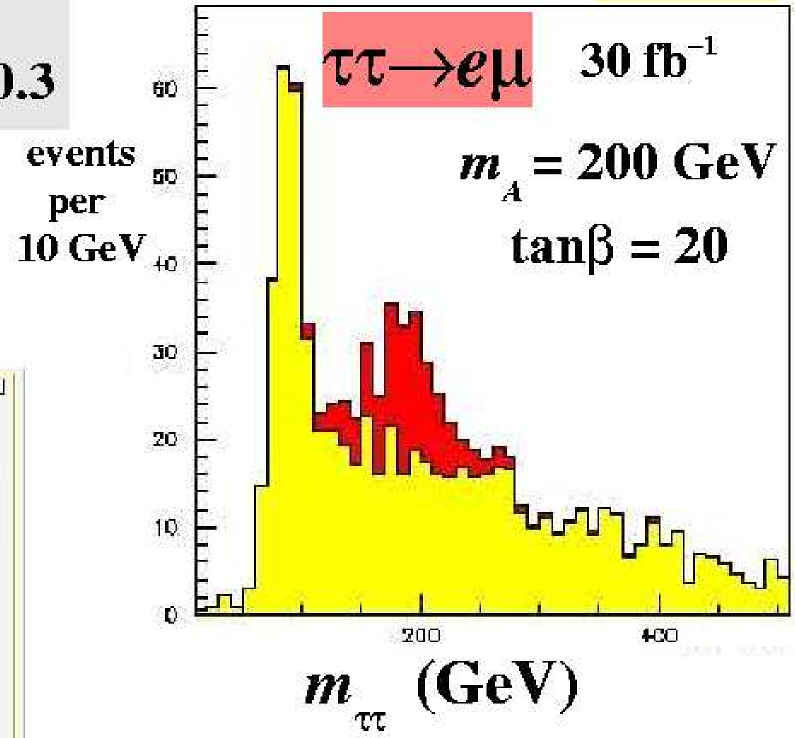
2 isolated high-p_T leptons:

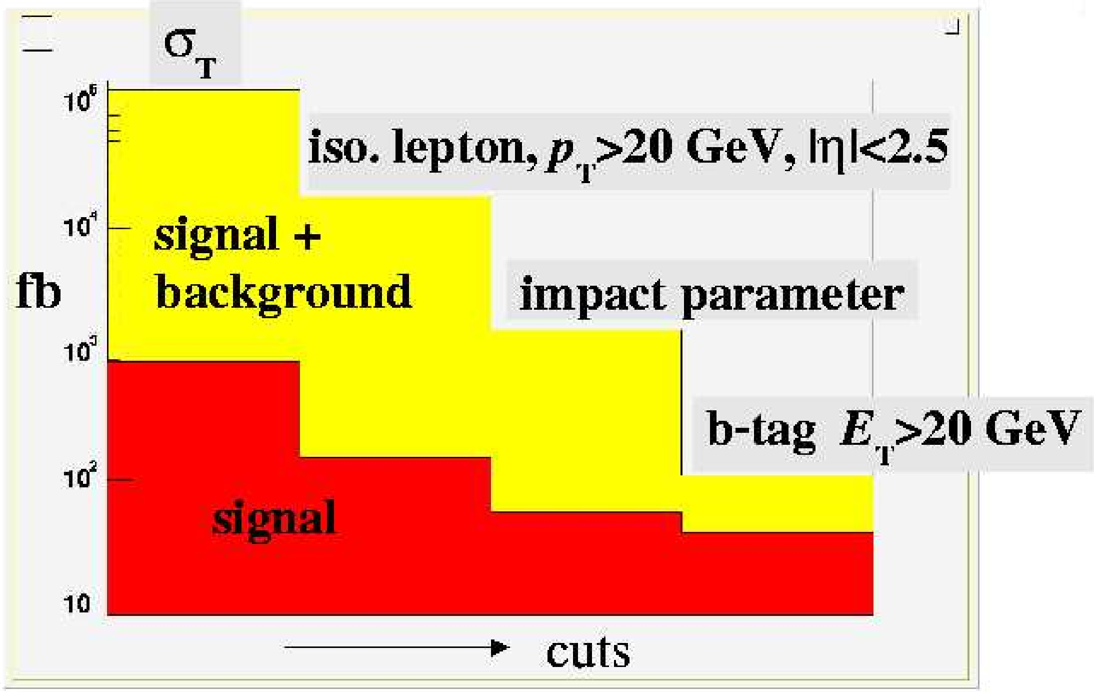
no track p_T>2 GeV with $\Delta R < 0.3$

S. Lehti

main background from top, *Z*

b-tag suppresses the *WW* background



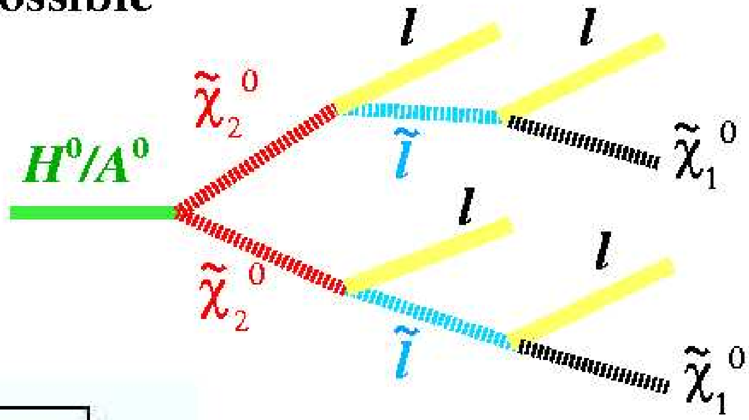


(e^+e^- and $\mu^+\mu^-$ suffer from high DY background)

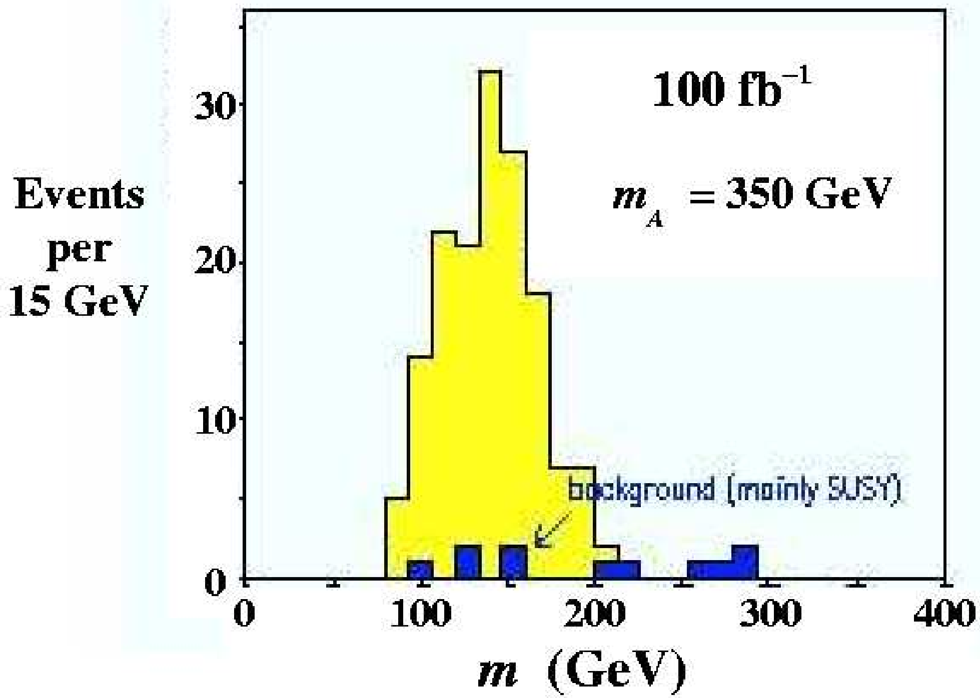
J. Rohlf, LHC IV p. 17

MSSM: $H^0/A^0 \rightarrow \chi^0\chi^0 \rightarrow 4l$

Easy target if kinematically possible



Backgrounds from SM ($t\bar{t}$, ZZ, $Zb\bar{b}$, $Zc\bar{c}$, $Wt\bar{b}$) and SUSY are suppressed with jet and Z veto

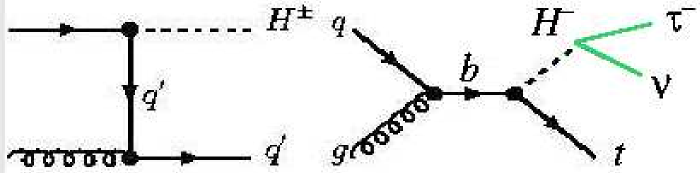


J. Rohlf, LHC IV p. 18

MSSM: $tH^- \to t\tau^-\nu$
$\bar{t}H^+ \to \bar{t}\tau^+\nu$

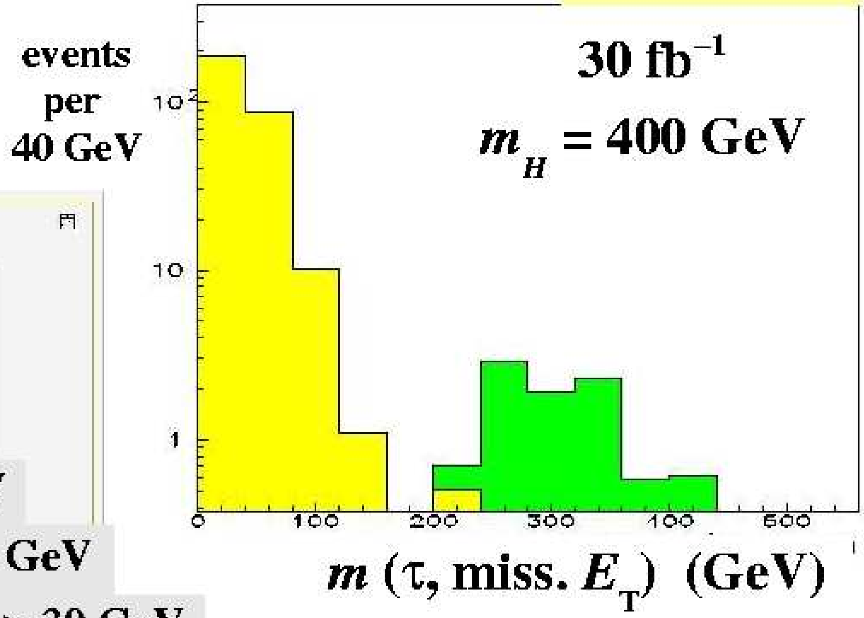
hadronic tau decay

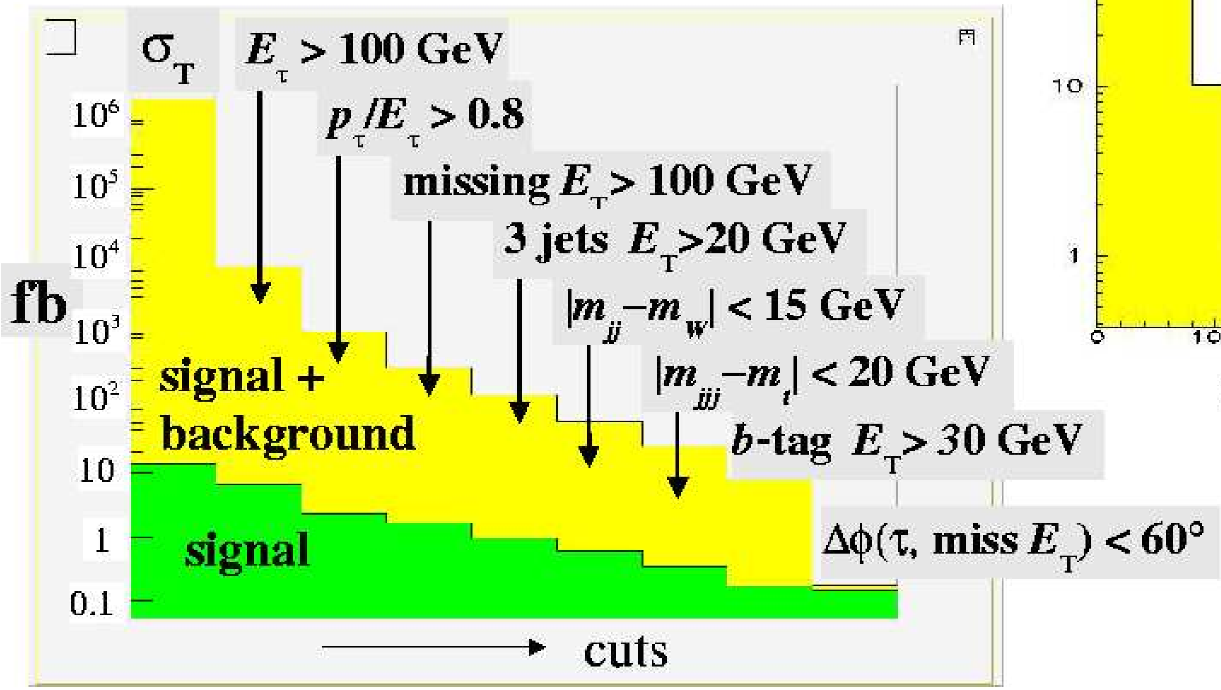
Radiation from a b-quark



Main backgrounds:
$t\bar{t}$, $W + X$

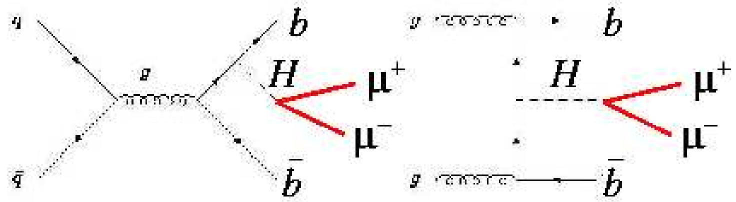
R. Kinnunen





J. Rohlf, LHC IV p. 20

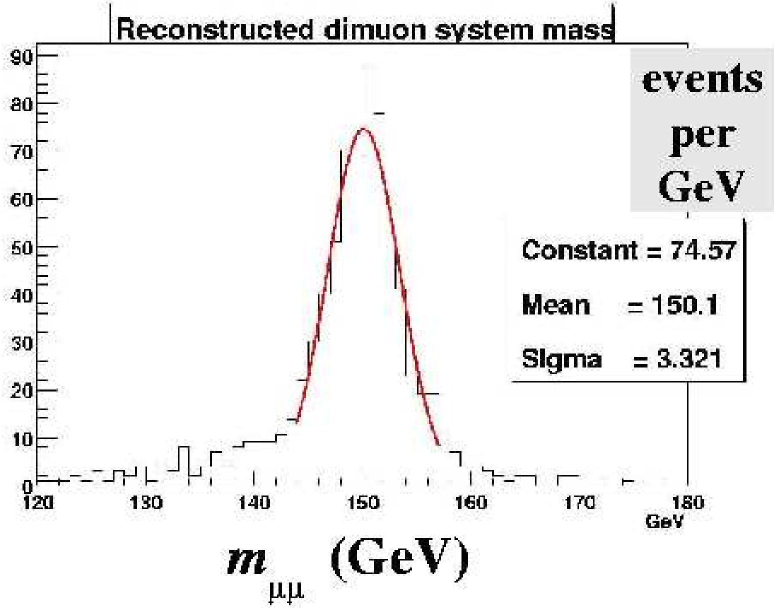
MSSM: $b\bar{b}H^0/A^0 \rightarrow b\bar{b}\mu^+\mu^-$



small BR:

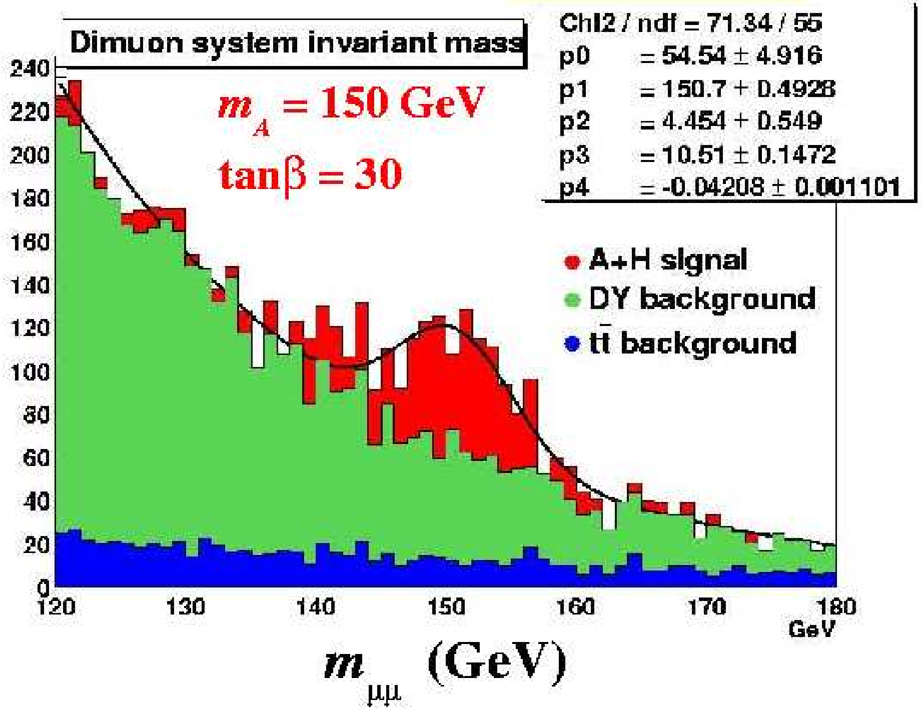
$(m_\mu/m_\tau)^2 = 4\times10^{-3}$

clean signature



20 fb^{-1}

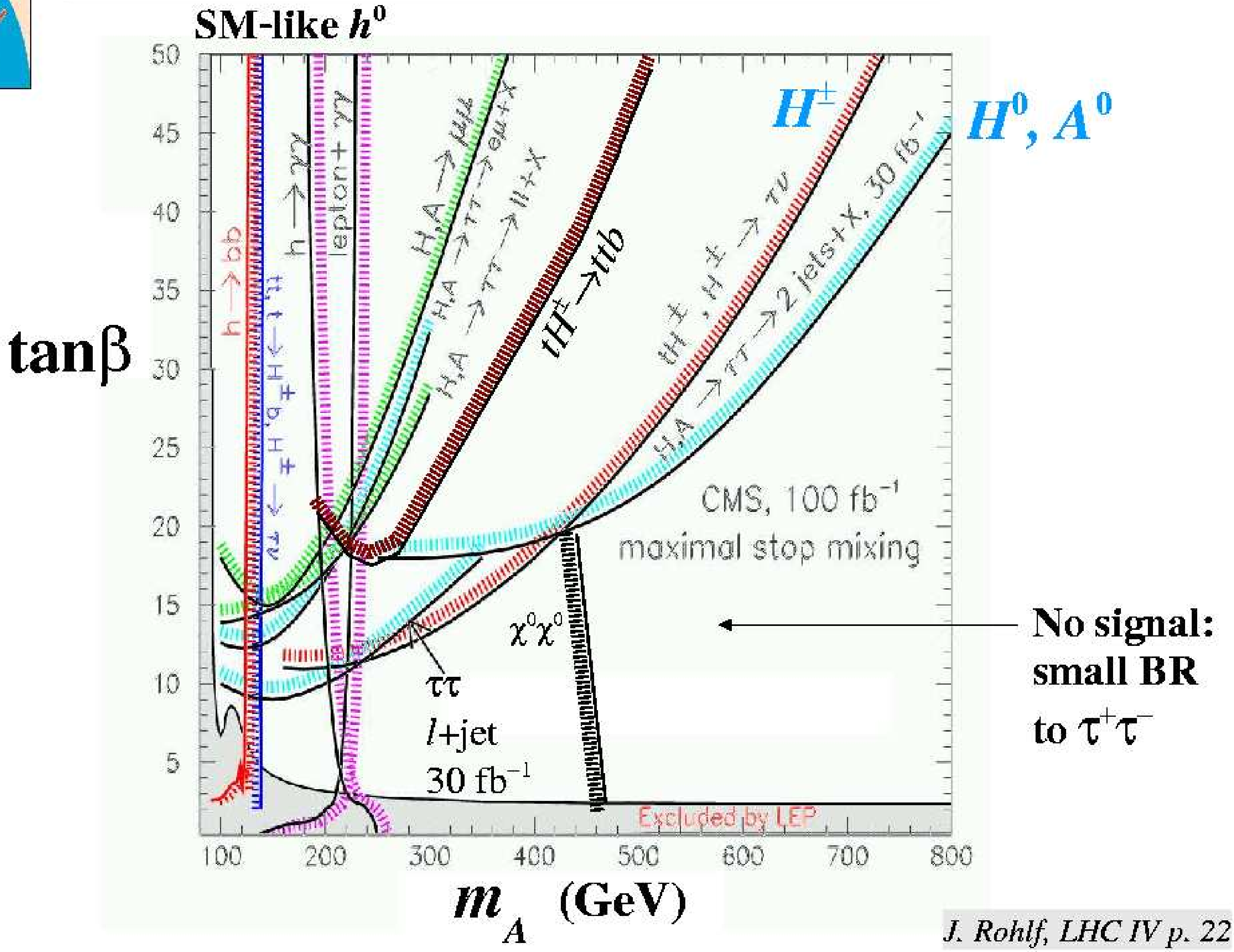
R. Kinnunen



J. Rohlf, LHC IV p. 21

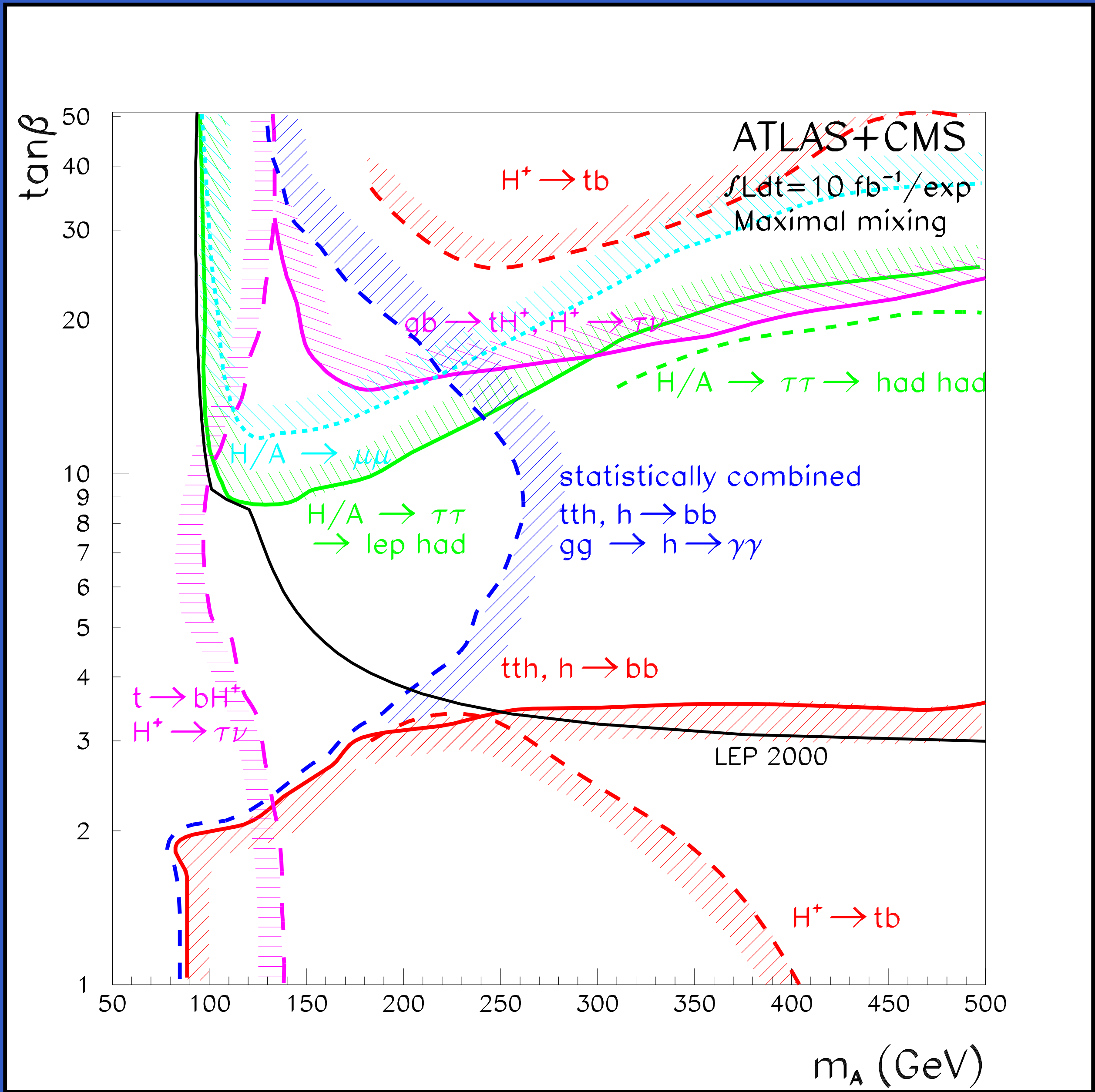
$t\bar{t}$ background reduced with central jet veto

MSSM Higgs: Summary



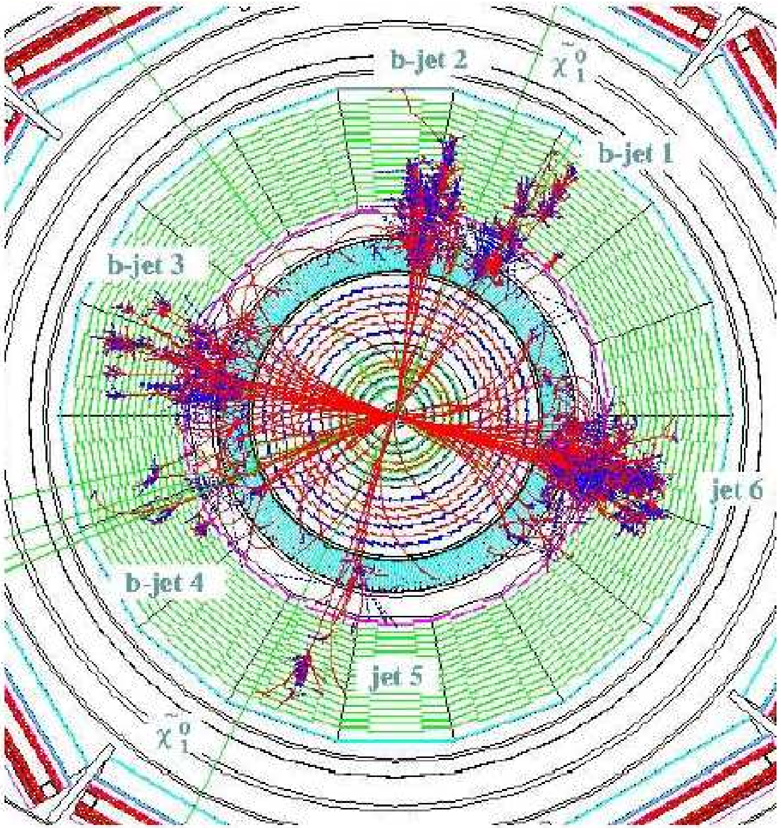
J. Rohlf, LHC IV p. 22

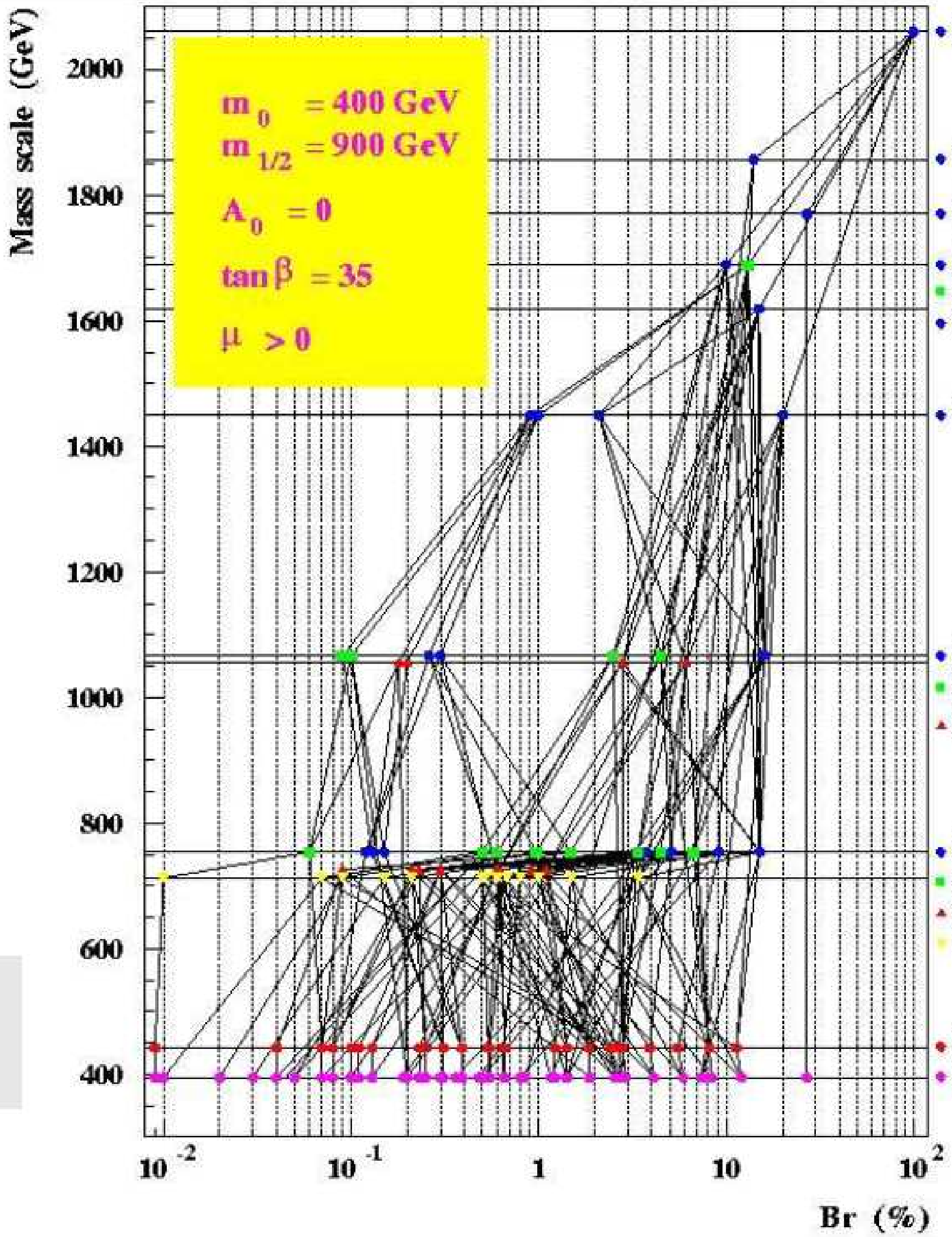
ATLAS+CMS $10\ \mathrm{fb}^{-1}$



SUSY: Sparticle Search

Supersymmetry



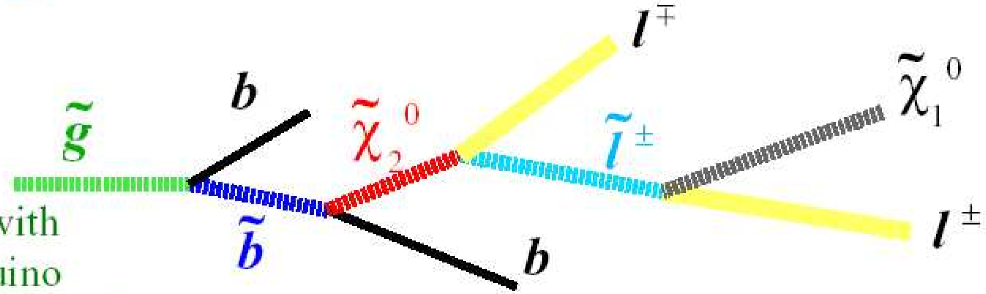


Distinctive signature of leptons, jets, missing E_T for some events

J. Rohlf, LHC IV p. 23

Sparticle Reconstruction

J. Rohlf, LHC IV p. 24



pair–produced with squark or 2[nd] gluino (1 or 2 jets + missing E_T)

Event signature:

2 leptons, p_T>15 GeV, $|\eta|$< 2.4

2 b-jets, p_T>20 GeV, $|\eta|$< 2.0

Large Missing E_T

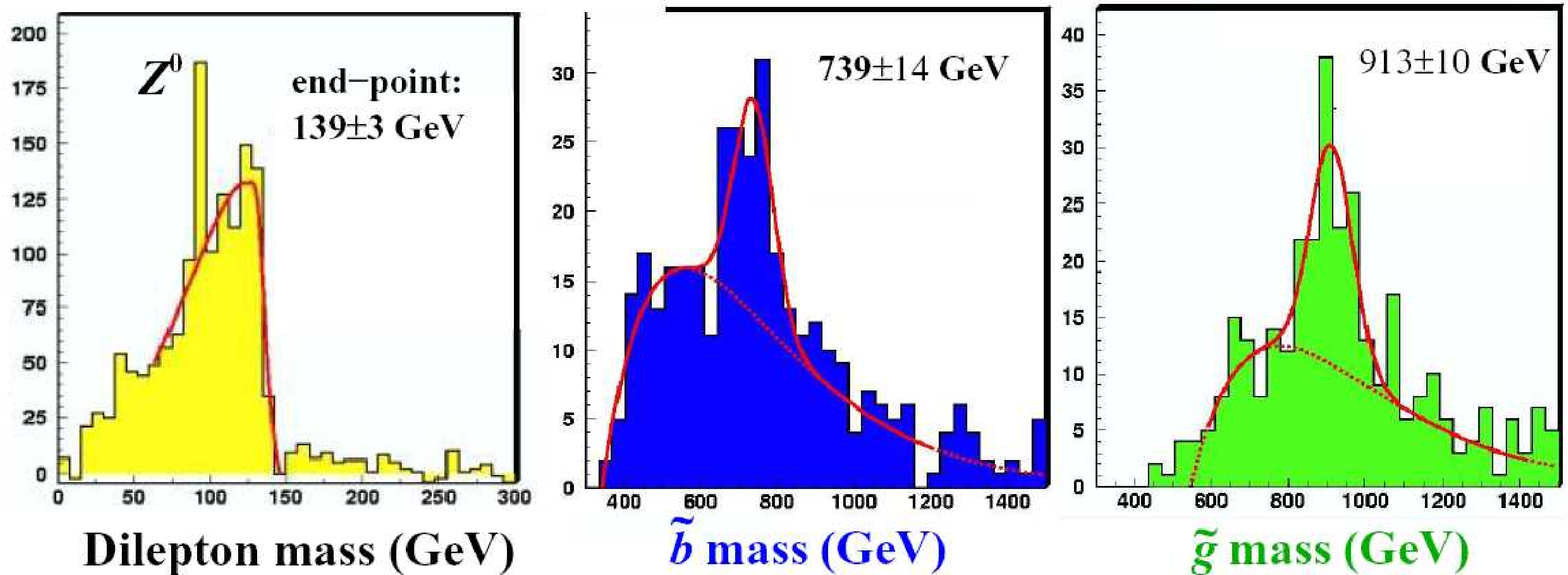
SM backgrounds:

$t\bar{t}$, Z+jet, W+jet, ZZ, WW, ZW

Example: $m_{1/2}$ = 375 GeV, m_0 = 120 GeV, tanβ = 20

500 fb^{-1} **missing E_T > 250 GeV**

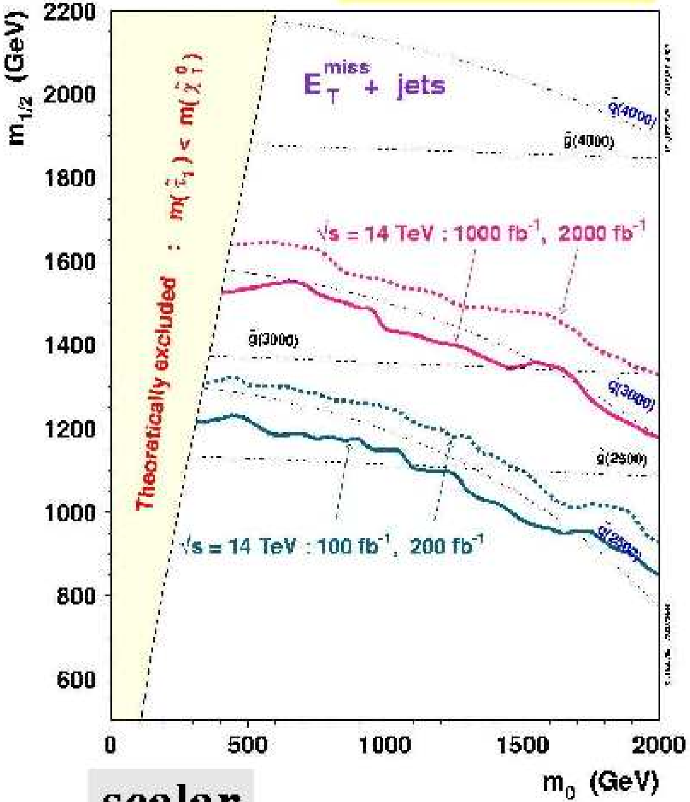
A. Tricomi *et al.*



mSUGRA *Minimal Supergravity*

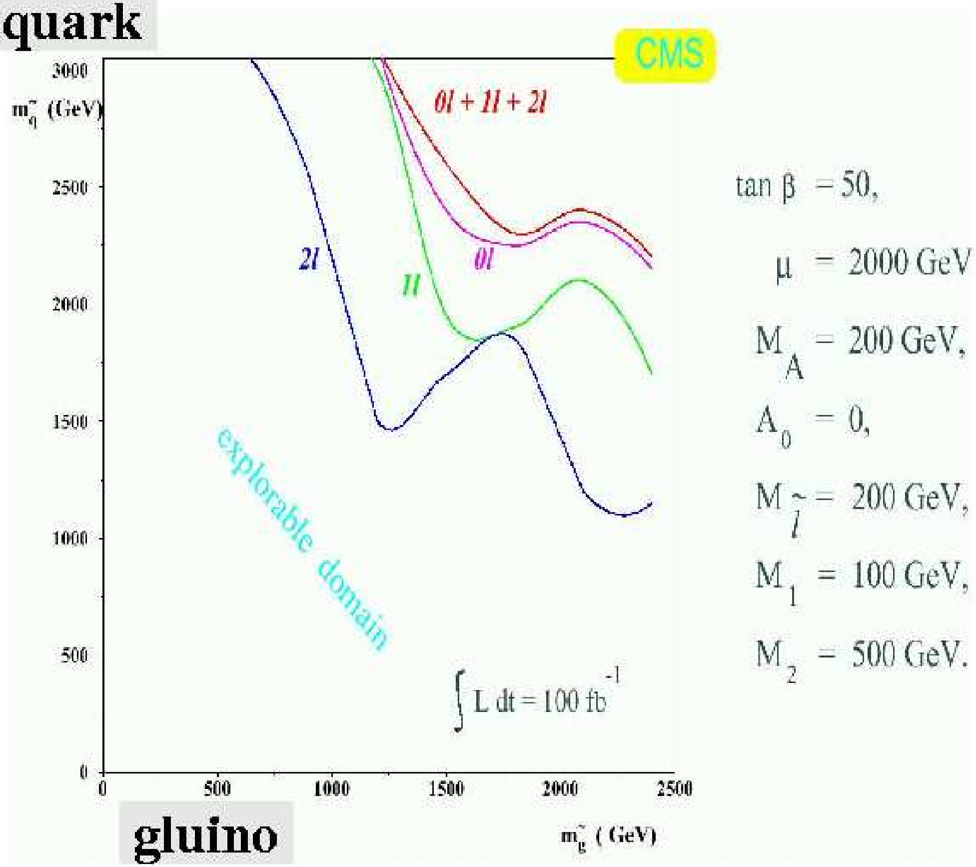
gaugino

S. Abdoulline



scalar

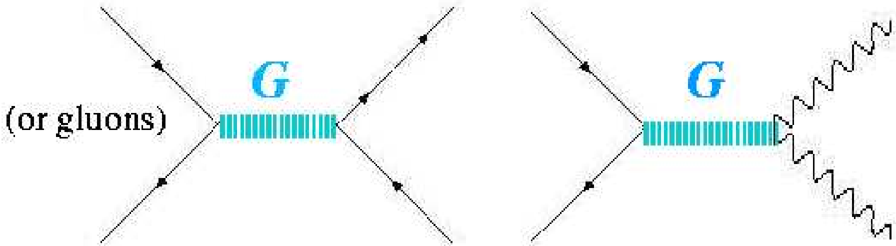
squark



gluino

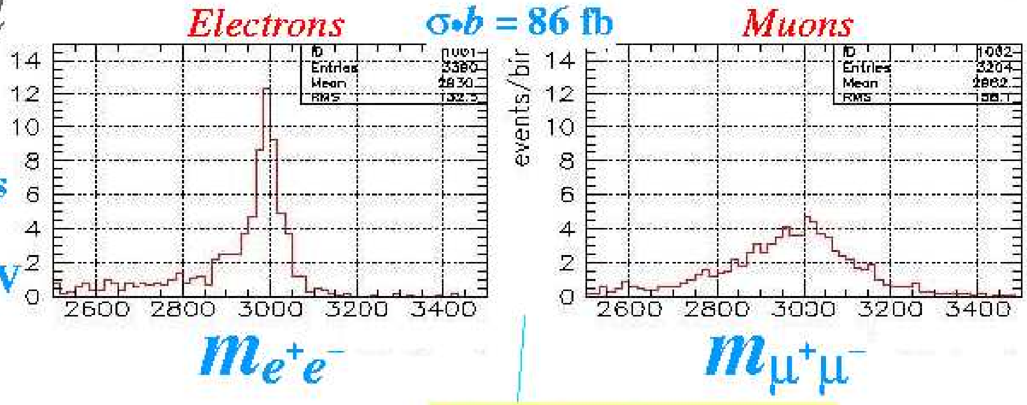
J. Rohlf, LHC IV p. 25

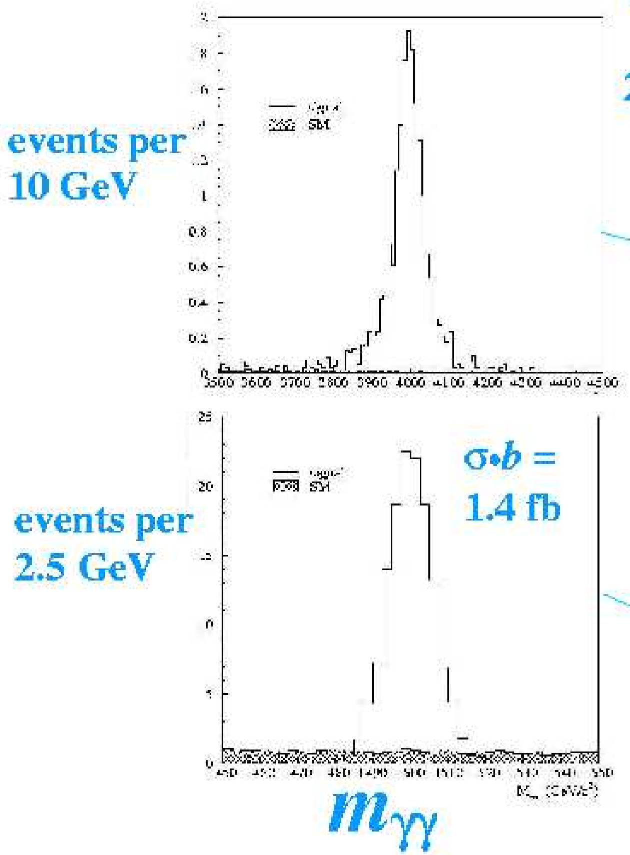
Kaluza-Klein Graviton

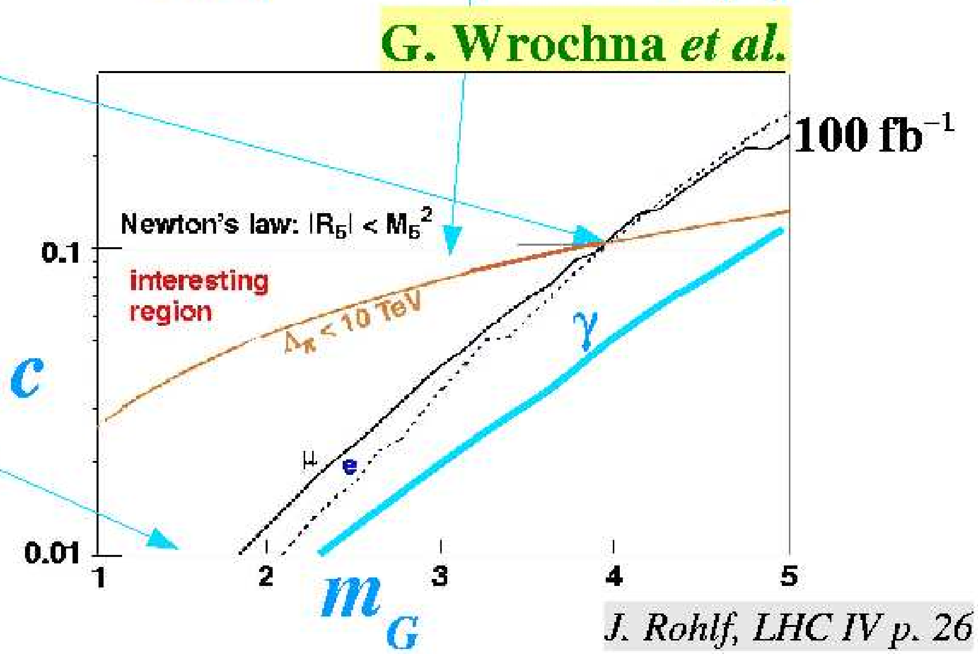


Randall-Sundrum Model

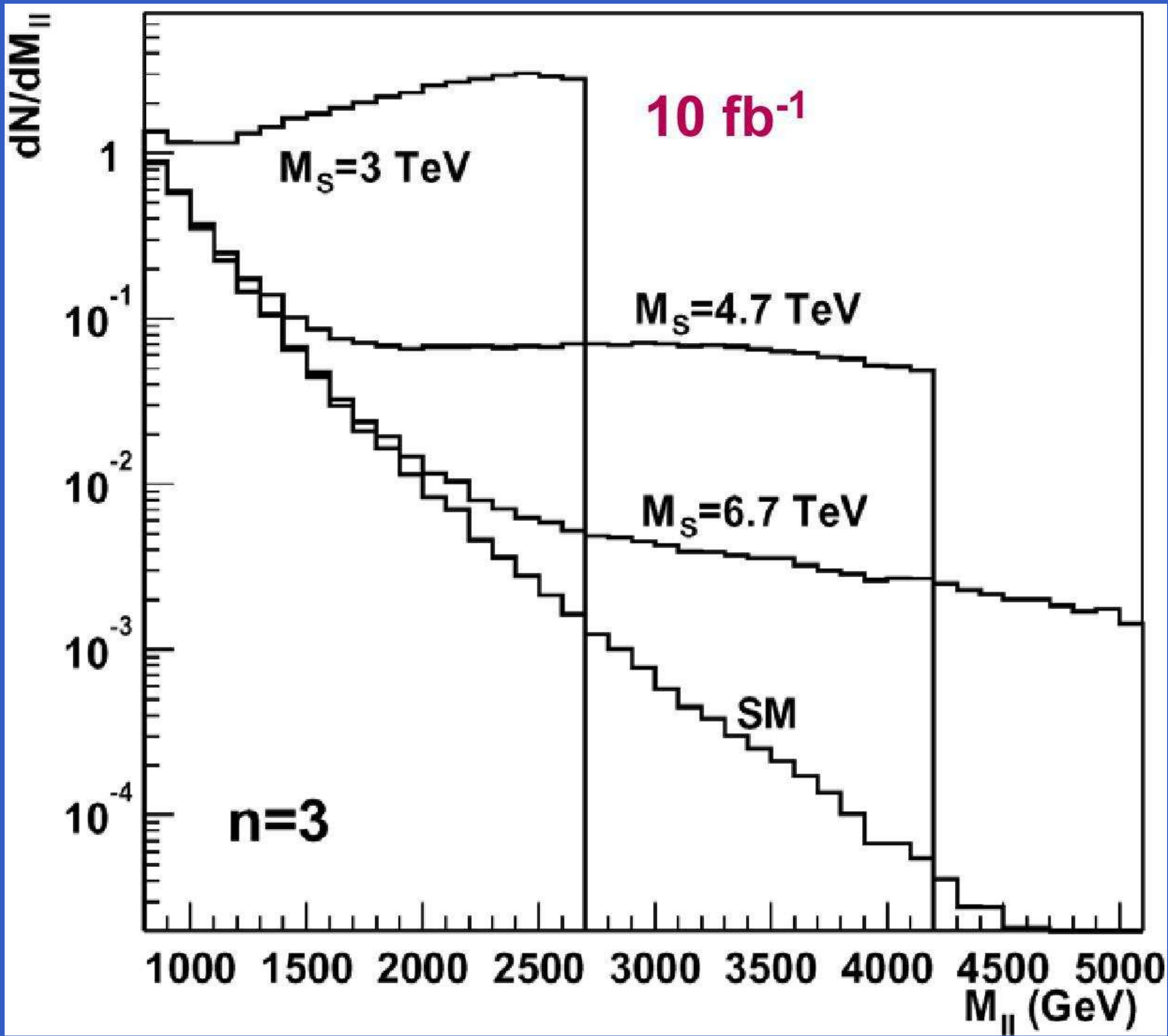
Exploiting the geometry of spacetime to solve the hierarchy problem.



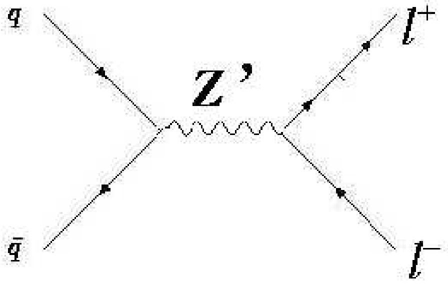


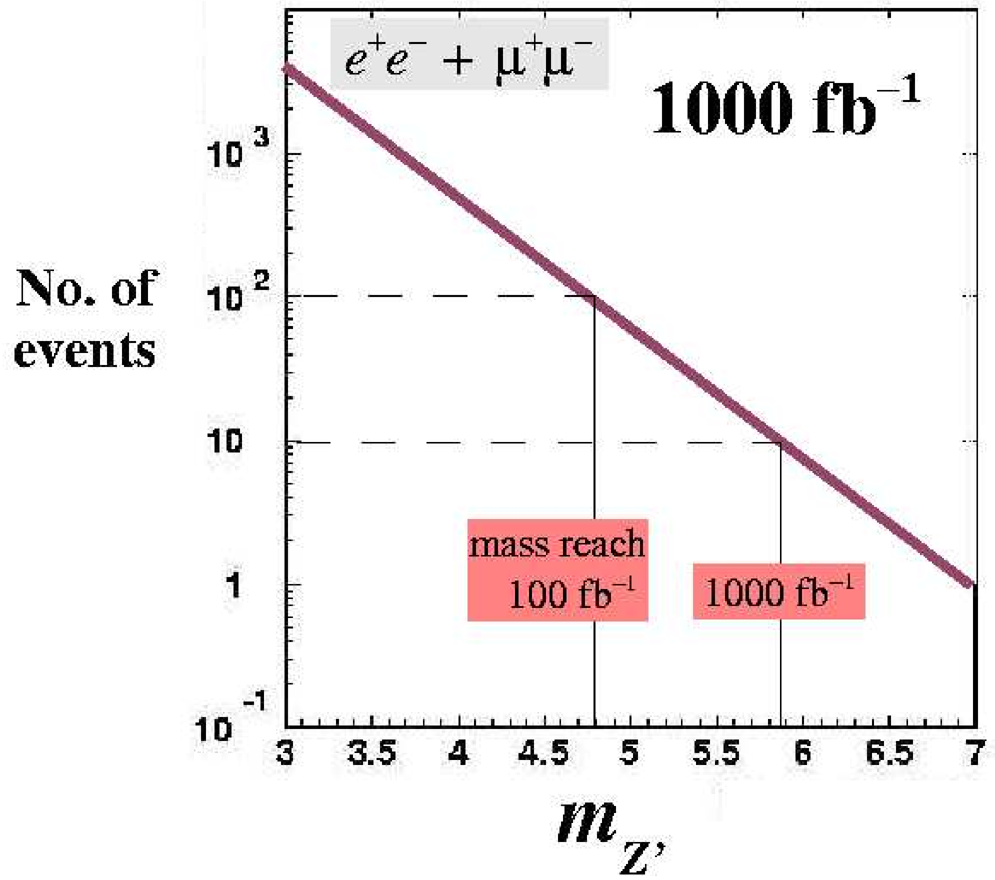


ATLAS extra dimensions



Z'





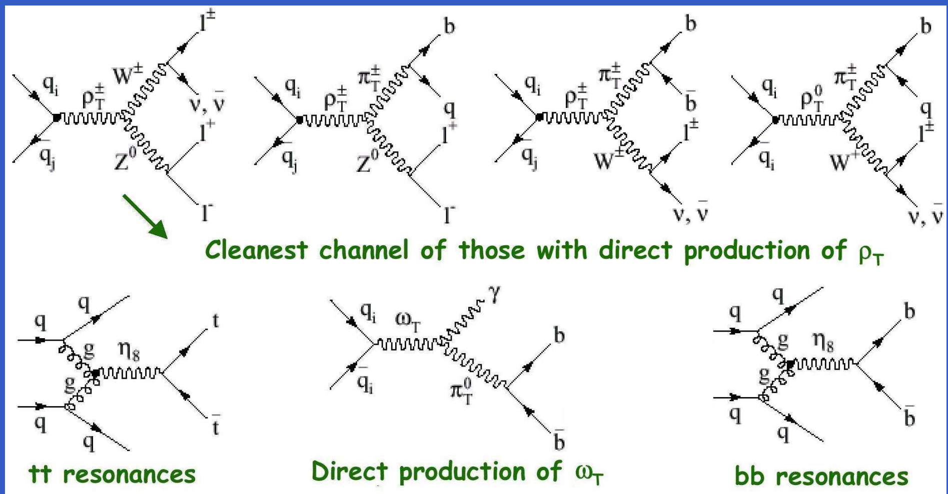
Corrected for:

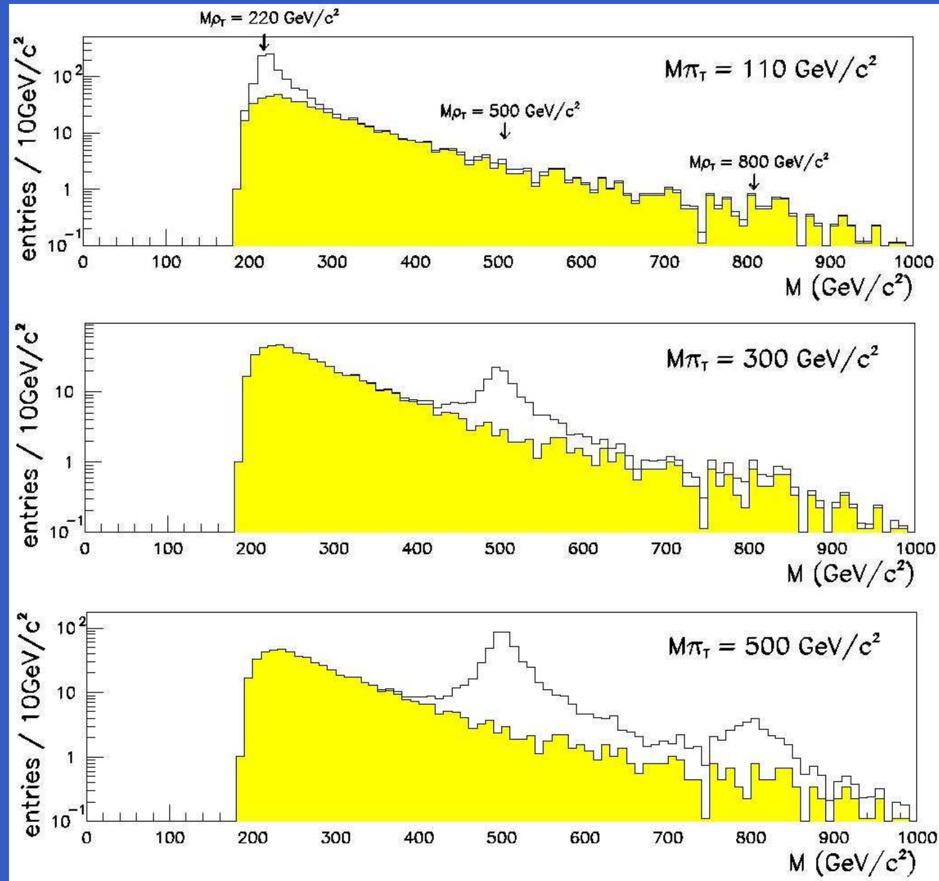
- acceptance
- reconstruction efficiency
- resolution
- crystal saturation
- pileup at 10^{35} $cm^{-2}s^{-1}$

Backgrounds:
Drell-Yan 2%
$t\bar{t} < 1\%$

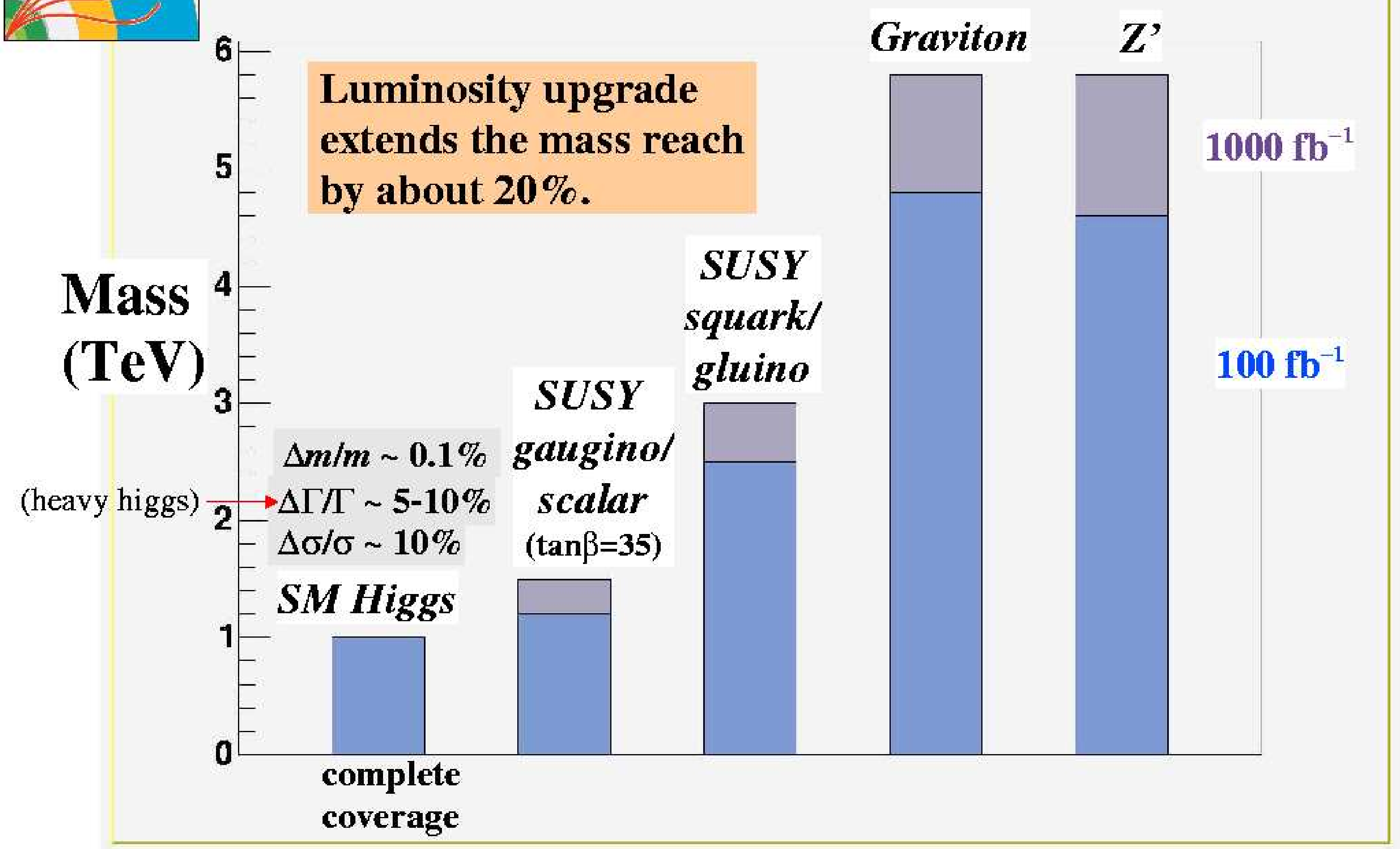
J. Rohlf, LHC IV p. 27

Technicolor ATLAS





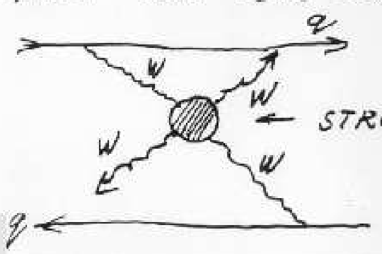
CMS Mass Reach: Summary



J. Rohlf, LHC IV p. 28

Longitudinal W/Z^0 Scattering

UNITARITY LIMIT : $\sqrt{s} = 1.7$ TeV
$G_F s = 8\sqrt{2}\pi$, NOT $G_F s = 1$.
SEARCH FOR $W_L W_L$ SCATTERING



L. Okun
ITEP
Moscow
09.10.89

HISTORIC ANALOGY

1. CLASSICAL RADIUS OF ELECTRON
$r_0 = e^2/mc^2 \simeq 10^{-13}$ cm
AT $r < r_0$ CED FAILED.

5

BUT THERE IS NOTHING SPECIAL at $r \sim 10^{-13}$ cm OR $p \sim 400$ MeV/c
r_0 – "A PAPER TIGER"

2. HOWEVER AT $r_B = r_0/\alpha^2 = \hbar^2/me^2$
NEW FUNDAMENTAL PRINCIPLE
QUANTUM MECHANICS

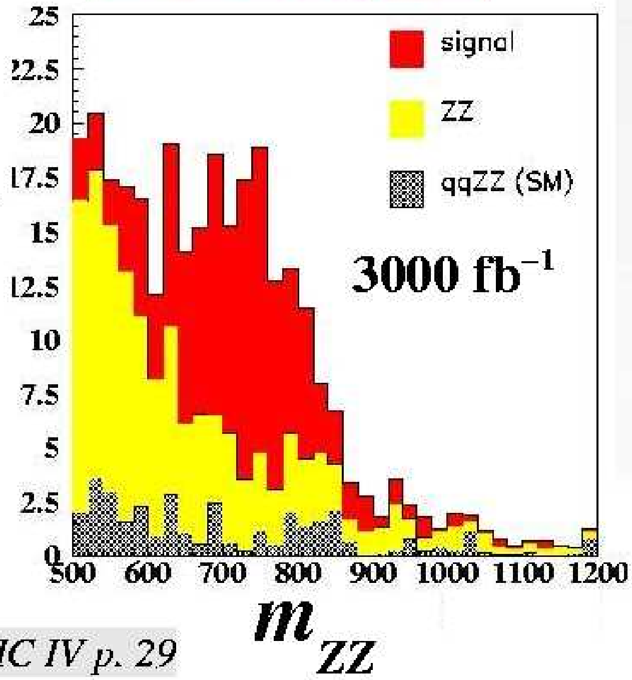
3. AND AT $\lambda_C = r_0/\alpha = \hbar/mc$
RELATIVISTIC QUANTUM FIELD THEORY

r_B and λ_C WERE REAL "TIGERS"

Possible scenario:

$Z^0Z^0 \rightarrow$ 4 leptons

events per 20 GeV

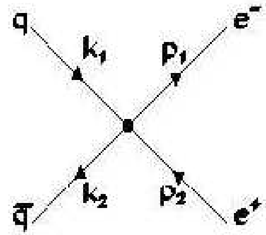


J. Rohlf, LHC IV p. 29

Super-high luminosity is essential!
(more energy would be better)

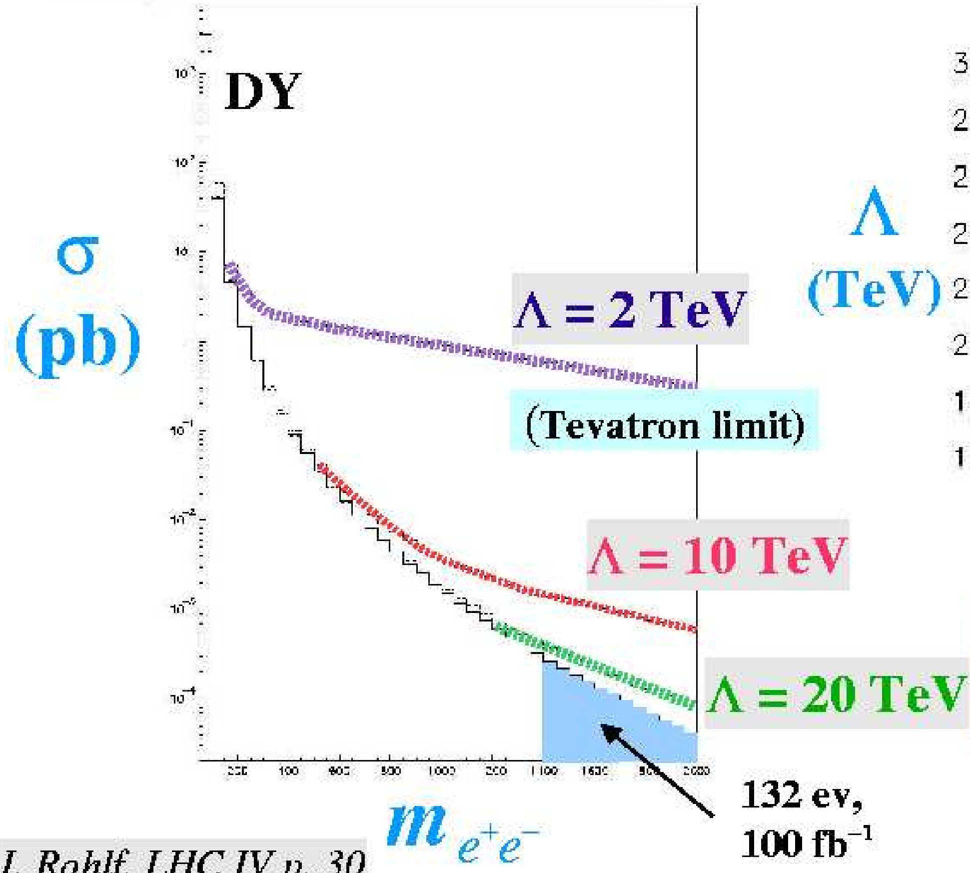
Compositeness

Contact interaction modifies Drell-Yan

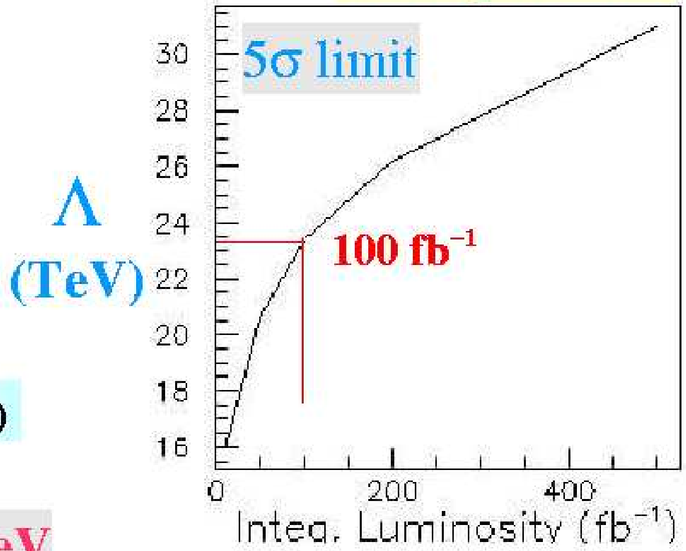


Cross section gets a term $s/(\alpha\Lambda^2)$, where $s = m^2_{e^+e^-}$

Dominates when $s >> \alpha\Lambda^2$



A. Gupta *et al.*



1000 fb^{-1} ⇒ reach to Λ = 50 TeV

Complimentary search: jet angular distribution

J. Rohlf, LHC IV p. 30

discovery

energy of probe

LHC **5 TeV**

50 years × 5000

today's limit **400 GeV**

Tevatron **UA1**

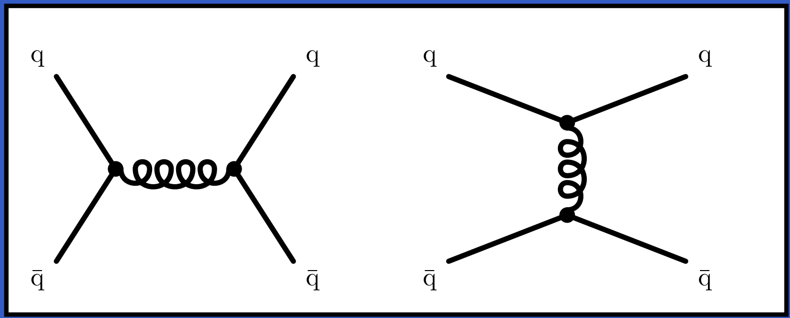
quark **1 GeV**

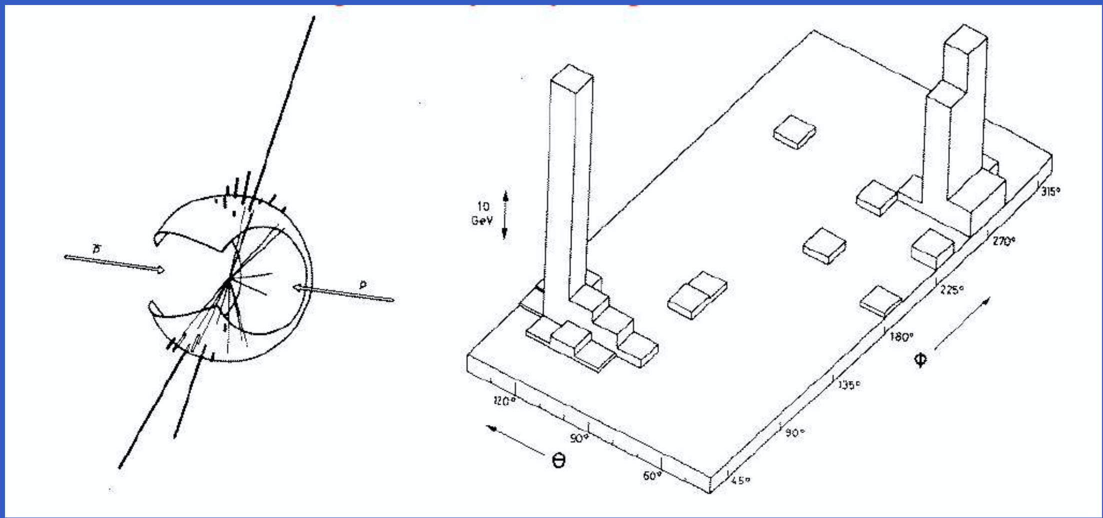
50 years × 100

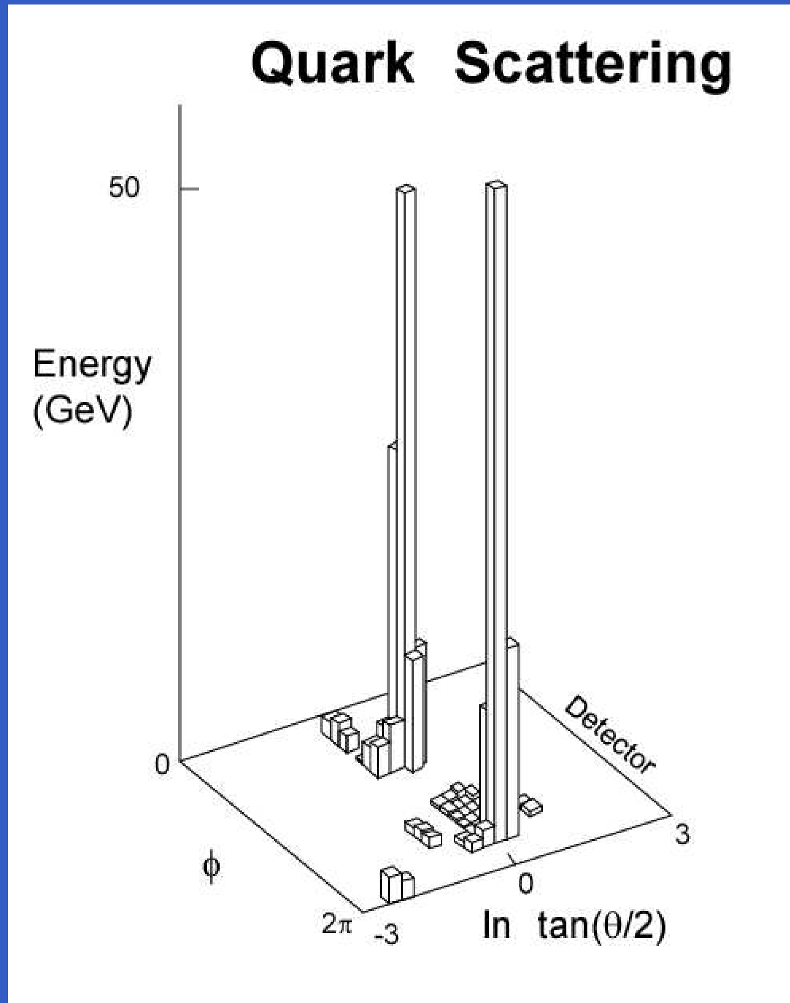
p, n **100 MeV**

nucleus **10 MeV**

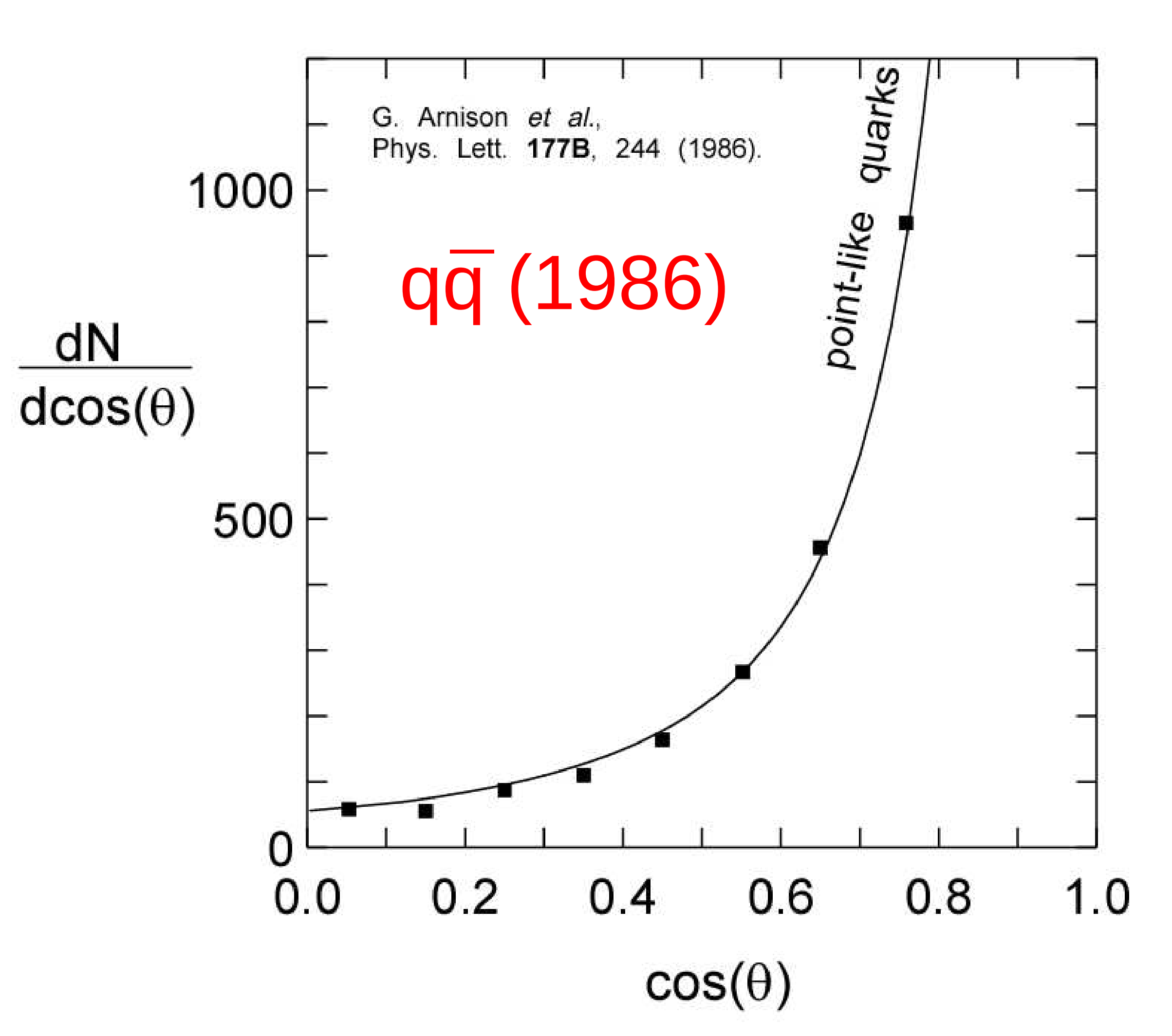
Asymptotic freedom CERN jet events 1982







Scattering quarks 1986

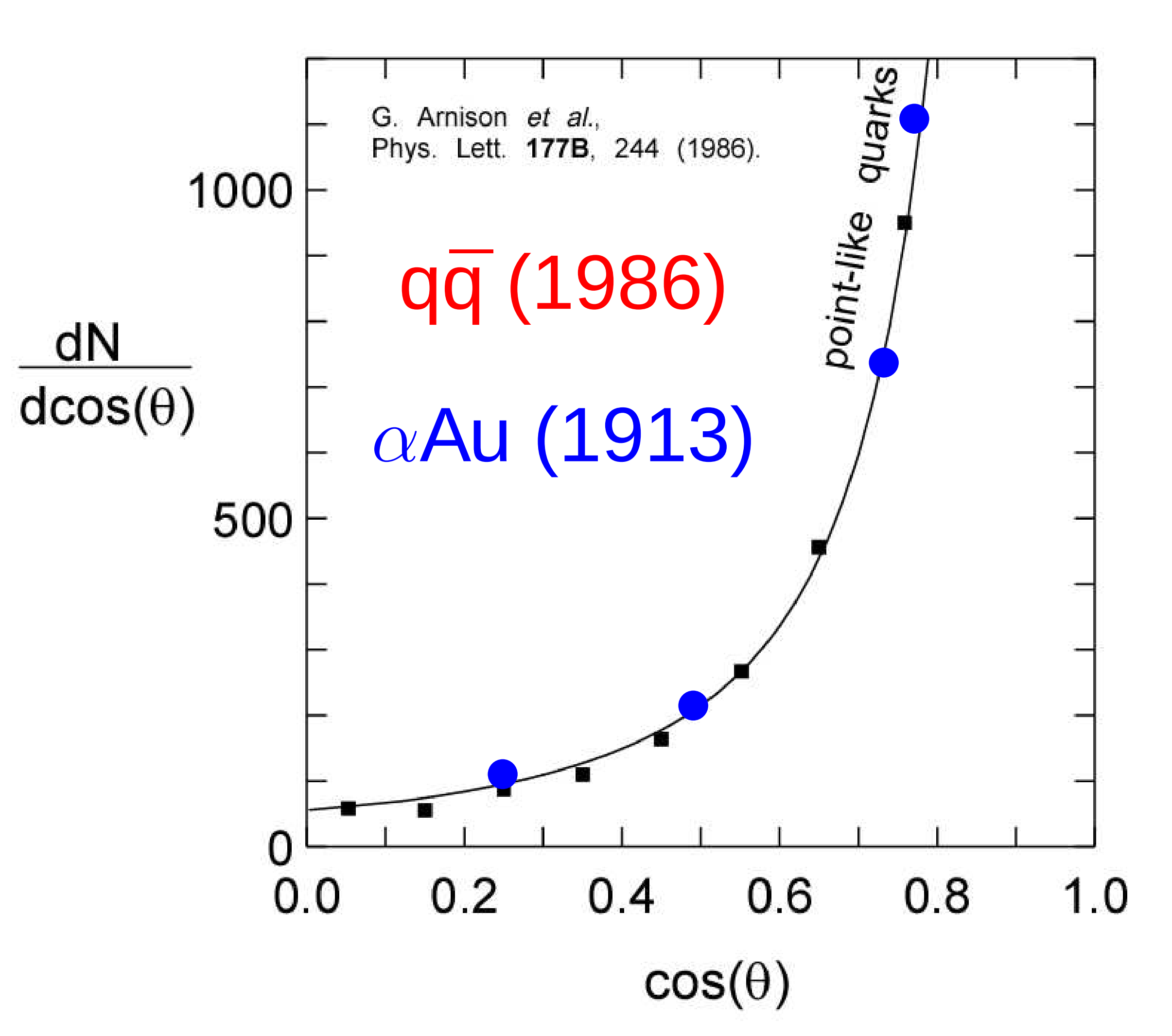


demonstrating:

- $1/r^2$ strong force
- spin 1 gluon
- pointlike quarks

$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2 \left(\frac{\hbar c}{E_{\mathrm{CM}}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

Scattering quarks 1986



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$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2 \left(\frac{\hbar c}{E_{\rm CM}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

Tracker

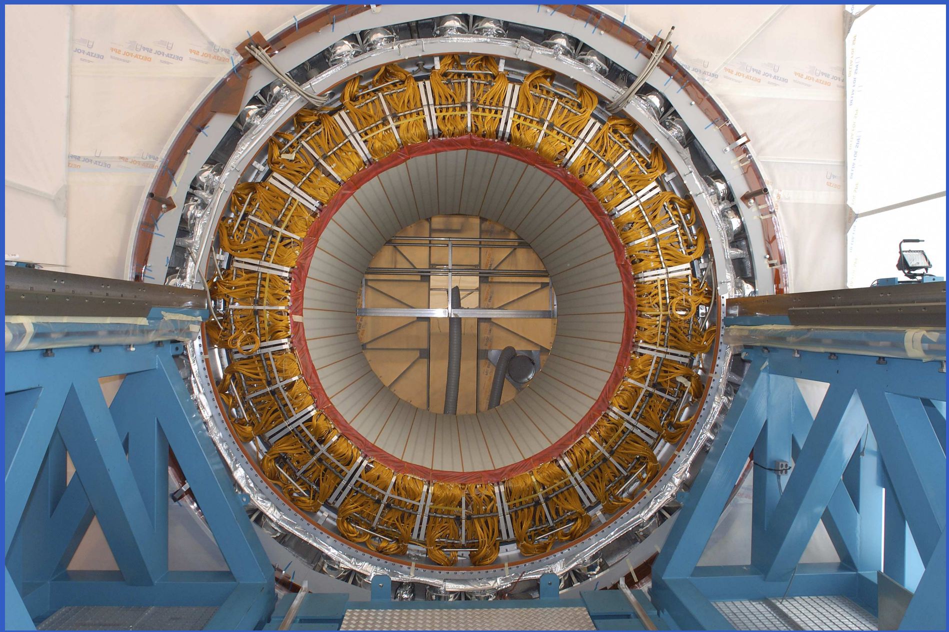
ATLAS: silicon + straws

CMS: silicon

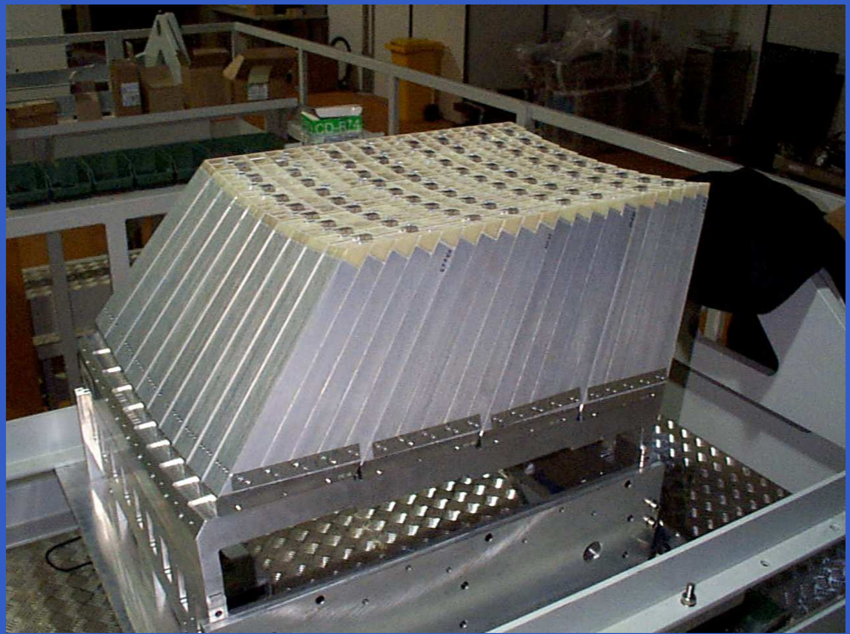
	pixels	*strips*	*trt straws*
ATLAS	80M ch, 2 m^2	6M ch, 60 m^2	420k ch.
CMS	50M ch, 1 m^2	10M ch, 220 m^2	

ECAL

ATLAS: liquid argon / Pb



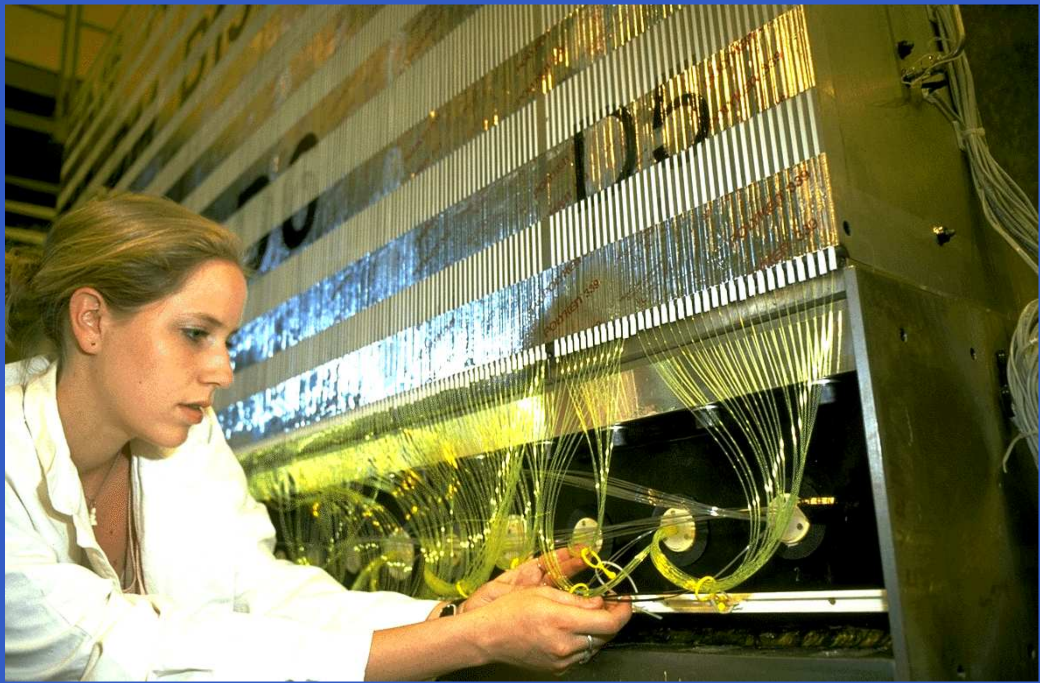
CMS: crystal ($PbWO_4$)



	res. @ 50 GeV	*material in front*	*thickness*	$\Delta\eta \times \Delta\phi$
ATLAS	1.5%	2-4 χ_0	21-36 χ_0	front 0.003 $\times$ 0.1 middle 0.025 $\times$ 0.025 back 0.05 $\times$ 0.025
CMS	0.8%	0.4-1.3 χ_0	25-27 χ_0	0.0174 $\times$ 0.0174

HCAL barrel

ATLAS: scintillator / Fe

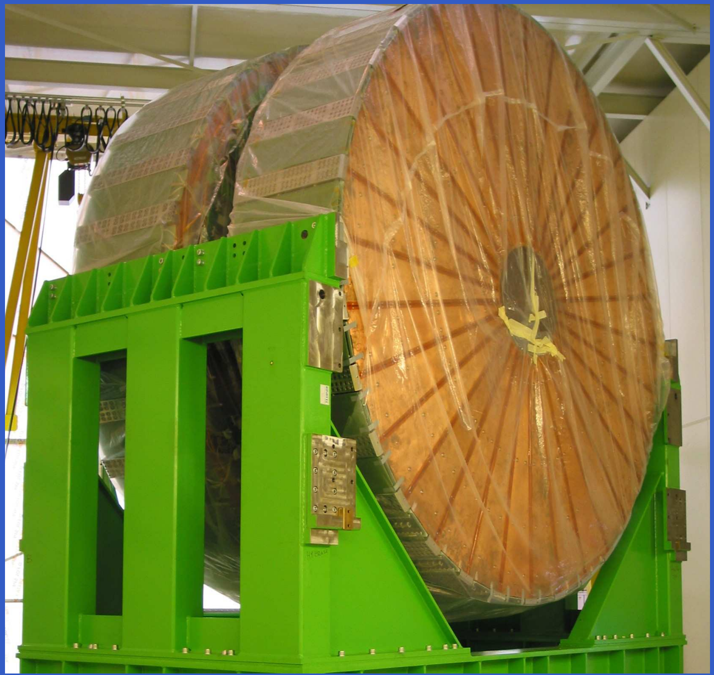


CMS: scintillator / brass

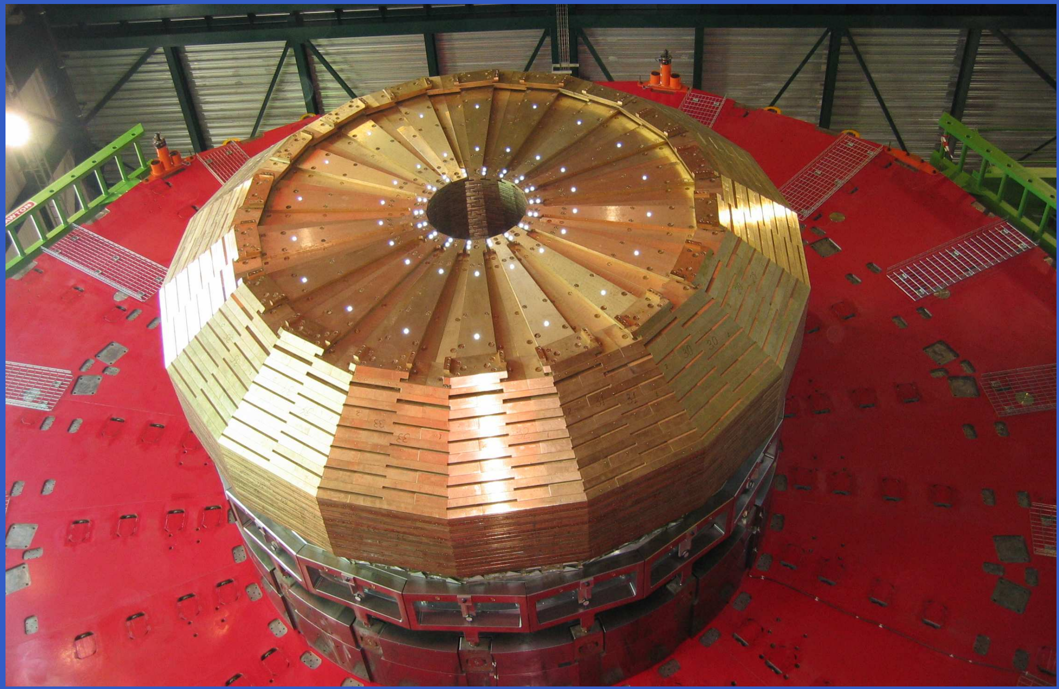
	coverage	*res. @ 100 GeV*	*thickness*	$\Delta\eta \times \Delta\phi$
ATLAS	$\lvert\eta\rvert < 1.0$	8%	8-10 λ	front 0.1 $\times$ 0.1
extended barrel	$0.8 < \lvert\eta\rvert < 1.7$			back 0.2 $\times$ 0.1
CMS	$\lvert\eta\rvert < 1.4$	10%	11-15 λ	0.087 $\times$ 0.087

HCAL end cap

ATLAS: liq. argon / Cu

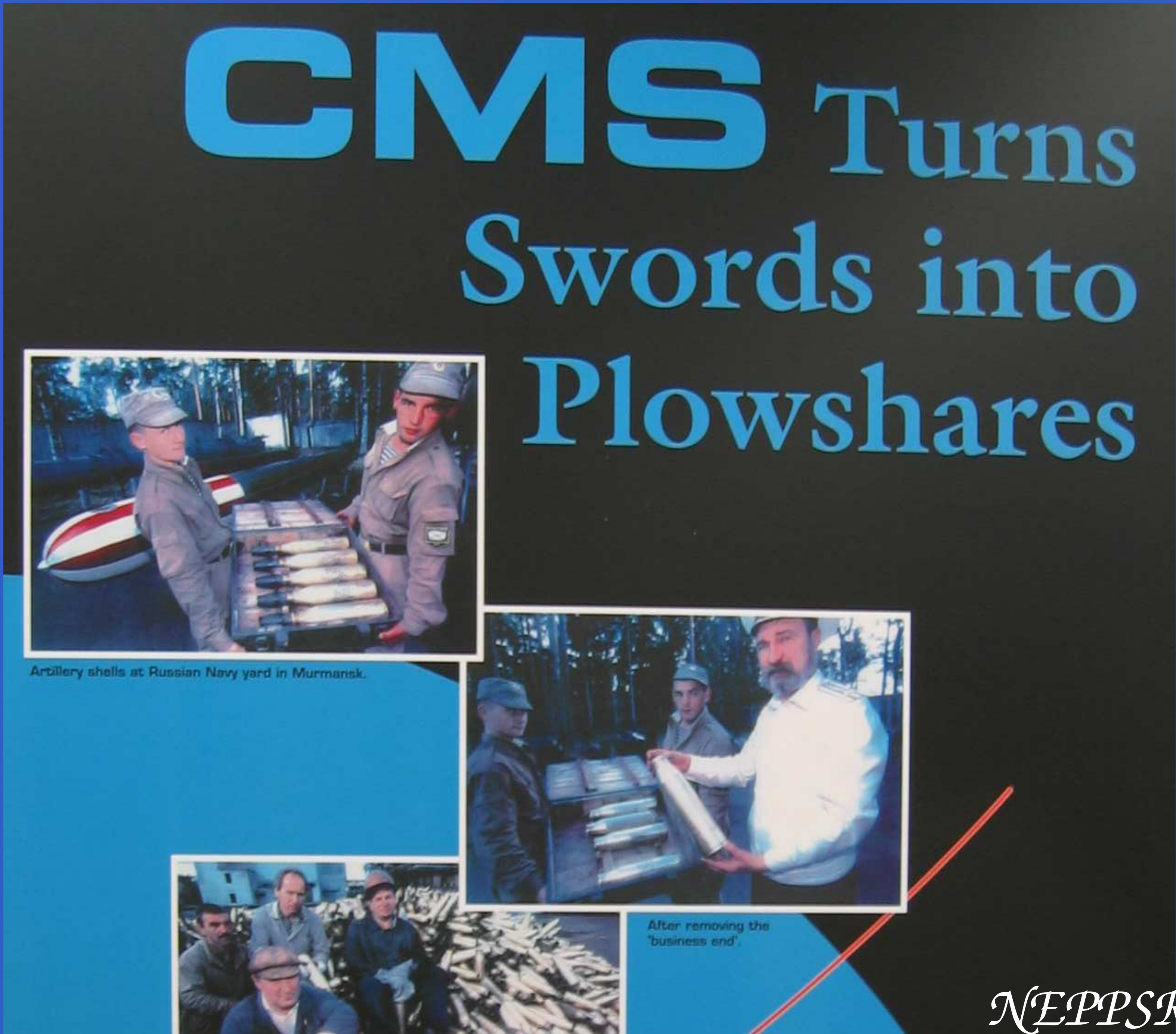


CMS: scintillator / brass



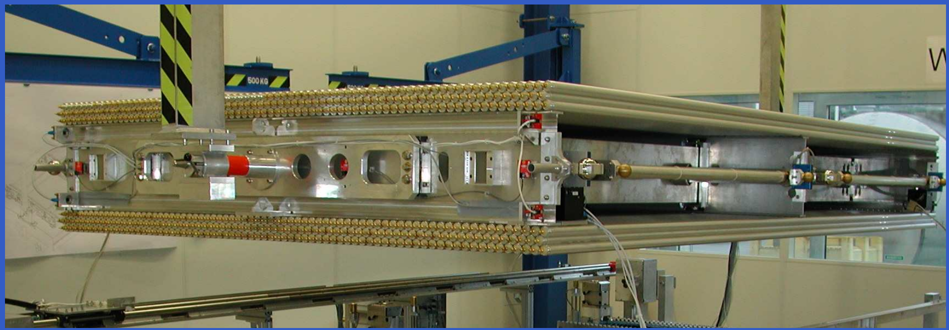
	coverage	*res. @ 100 GeV*	*thickness*	$\Delta\eta \times \Delta\phi$
ATLAS	$1.5 < \|\eta\| < 3.2$	8%	9 λ	$1.5 < \|\eta\| < 2.5$ 0.1 $\times$ 0.1 $2.5 < \|\eta\| < 3.2$ 0.2 $\times$ 0.1
CMS	$1.4 < \|\eta\| < 3.0$	10%	11 λ	$1.4 < \|\eta\| < 1.7$ 0.087 $\times$ 0.087 $1.7 < \|\eta\| < 3.0$ 0.087 $\times$ 0.17

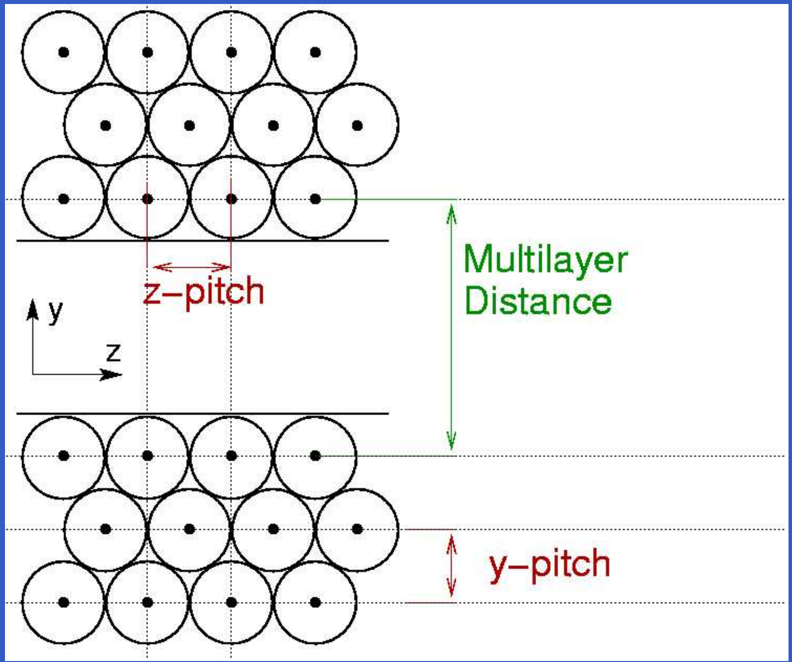
CMS endcap contribution of Russian Navy



Muon Barrel drift tubes

ATLAS

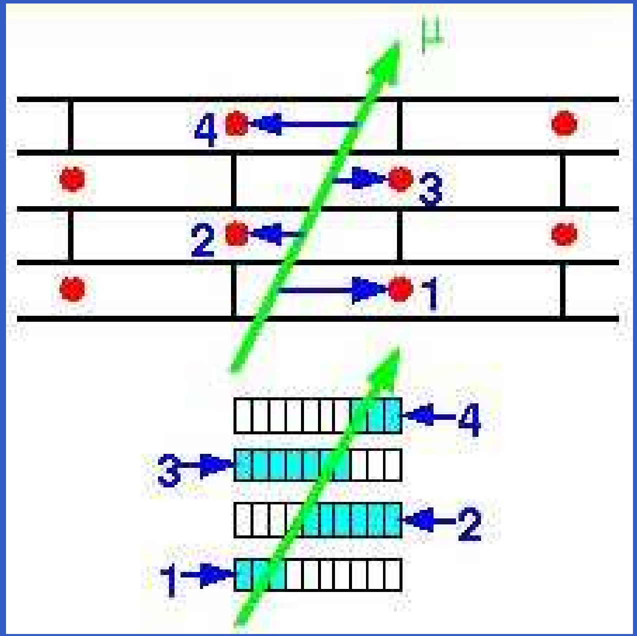




30 mm diameter

$\sigma = 100 \ \mu m$

CMS



42 mm $\times$ 13 mm

$\sigma = 300 \ \mu m$

Muon End cap cathode strip chambers

ATLAS

CMS

	coverage	*space res.*	*time res.*
ATLAS	$1 < \|\eta\| < 2.7$, 4 disks	60 μm	7 ns
CMS	$1 < \|\eta\| < 2.4$, 4 disks	75-150 μm	4.5

11th Annual Joe Cronin Memorial Bluefish Tournament

The Jimmy Fund
DANA-FARBER CANCER INSTITUTE

Experimental high-energy physics is not unlike fishing...
to be successful you gotta know where (and how!) to fish!

Feynman x

"I am more sure of the conclusions than of any single argument which suggested them to me for they have an internal consistency which surprises me and exceeds the consistency of my deductive arguments which hinted at their existence."

Richard Feynman, “Very High Energy Collisions of Hadrons,” *Phys. Rev. Lett.* **24**, 1415 (1969)

Feynman x

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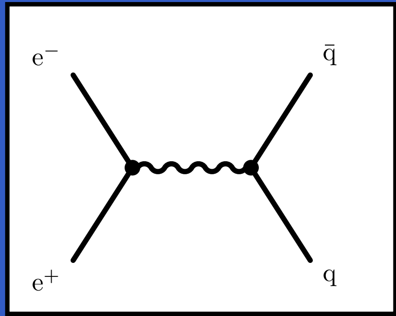
Sound confusing? Things were a mess!

Predicting R London conference (July 1974)

$$R = \frac{\sigma_{e^+e^- \to \mathrm{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}} = \sum q_i^2$$



0.36	Bethe-Salpeter bound quarks
2/3	Gell-Mann Zweig quarks
0.69	vector meson dominance I
1	composite quarks
10/9	Gell-Mann Zweig with charm
2	colored quarks
2.5-3	vector meson dominance II
2-5	vector meson dominance III
3 1/3	colored charmed quarks
4	Han-Nambu quarks
5.7	trace anomaly

6	Han-Nambu with charm
6.69 - 7.77	Broken scale invariance
8	Tati quarks
8	trace anomaly II
9	gravitational cut-off
9	broken scale invariance
16	$SU_{12} \times SU_2$
35 1/3	rm $SU_{16} \times SU_{1}6$
5000	high-Z quarks
70,383	Schwinger's quarks
∞	∞ partons

Reported by John Ellis

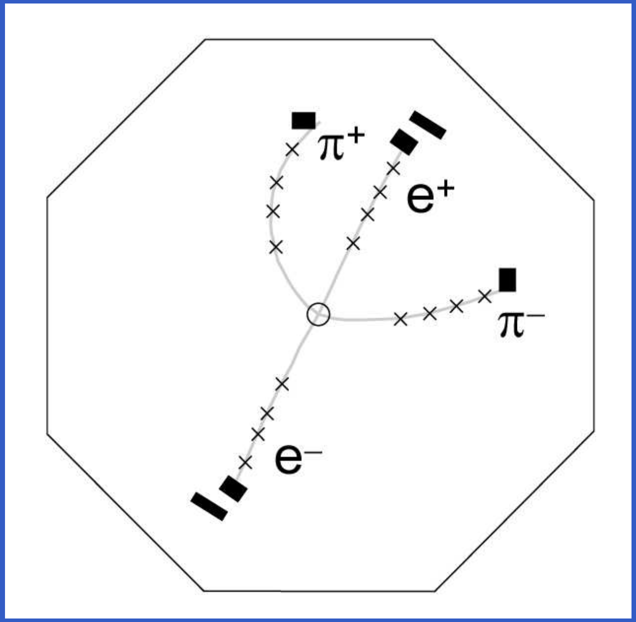
November Revolution 1974

Charmonium:
Quantum mechanics of two spin 1/2 particles.

$$\vec{\mathbf{s}} = 1/2 \oplus 1/2$$

$$\vec{\mathbf{j}} = \vec{\ell} \oplus \vec{\mathbf{s}}$$

n = radial QN.



The next step

"An even more fundamental set of questions which I find more interesting than the number of quarks... have to do with the possiblility of a unified picture of forces in nature... Weinberg and Salam have made the first models of a unified weak and electromagnetic interaction theory... The experimental information required to establish these unified pictures will almost certainly require still higher energies: several hundred GeV in the center-of-mass and again, I believe, in the e^+e^- system."

Burt Richter, Nobel Lecture (1976).

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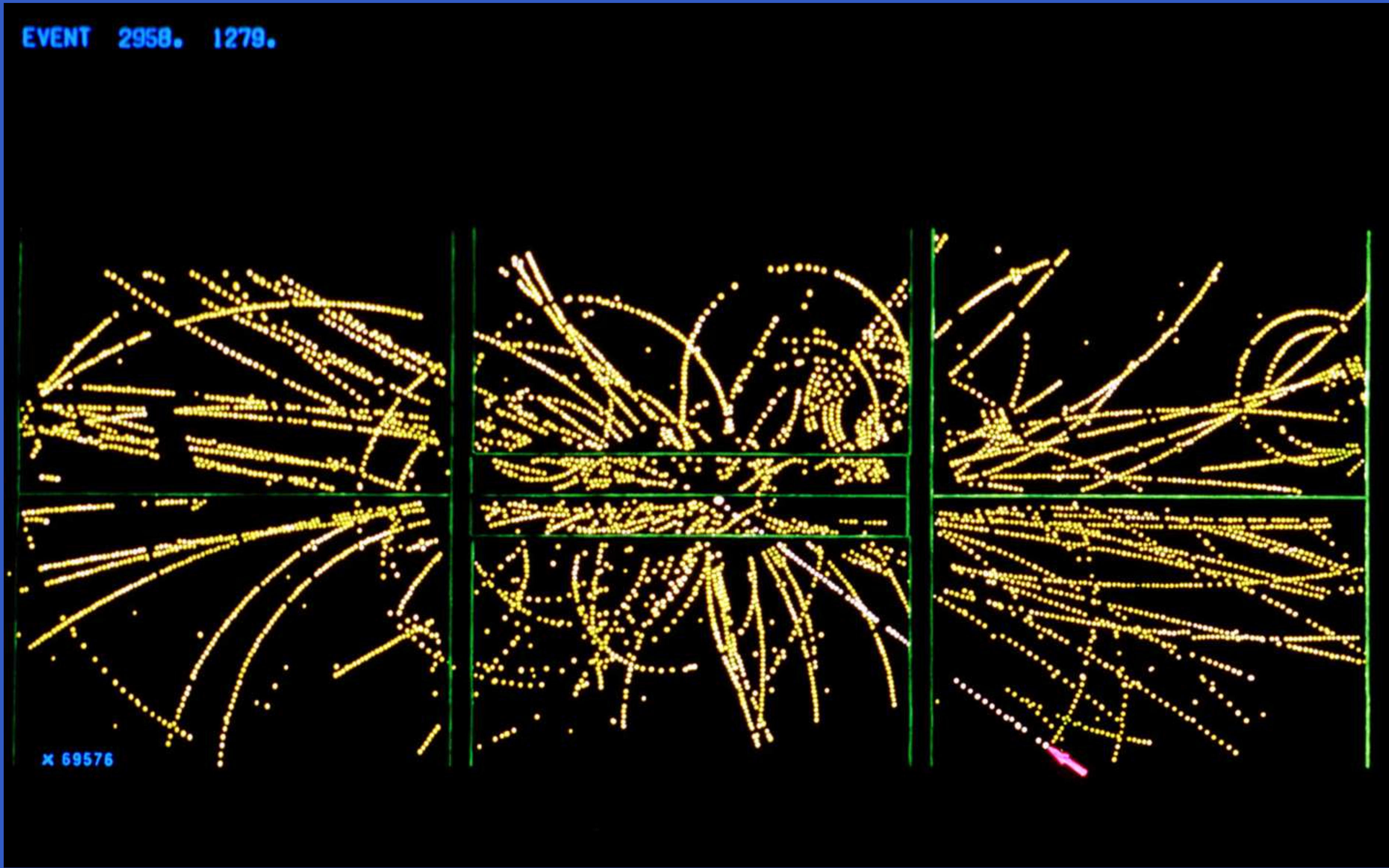
Letter from Richter to Carlo Rubbia on $\bar{p}p$:
Z^0 maybe (IF machine works), W never!

Tracking the W boson UA1



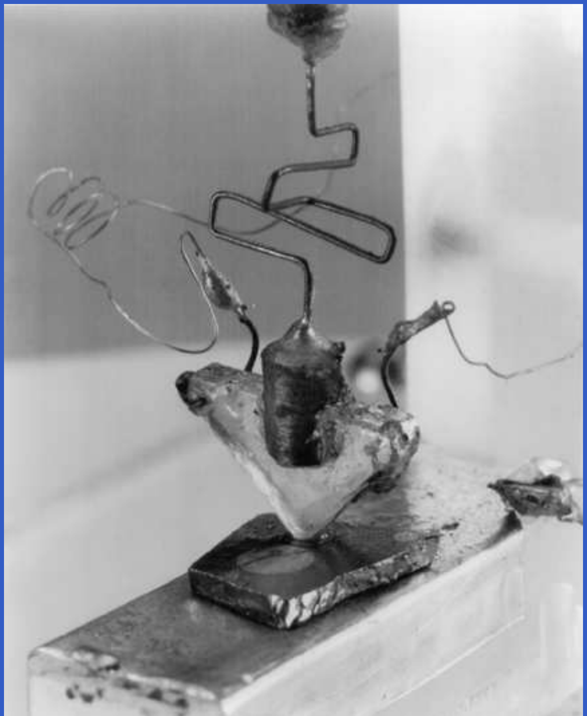
Readout 10-100 million channels

The readout is made possible by two important developments in the last 5-10 years:

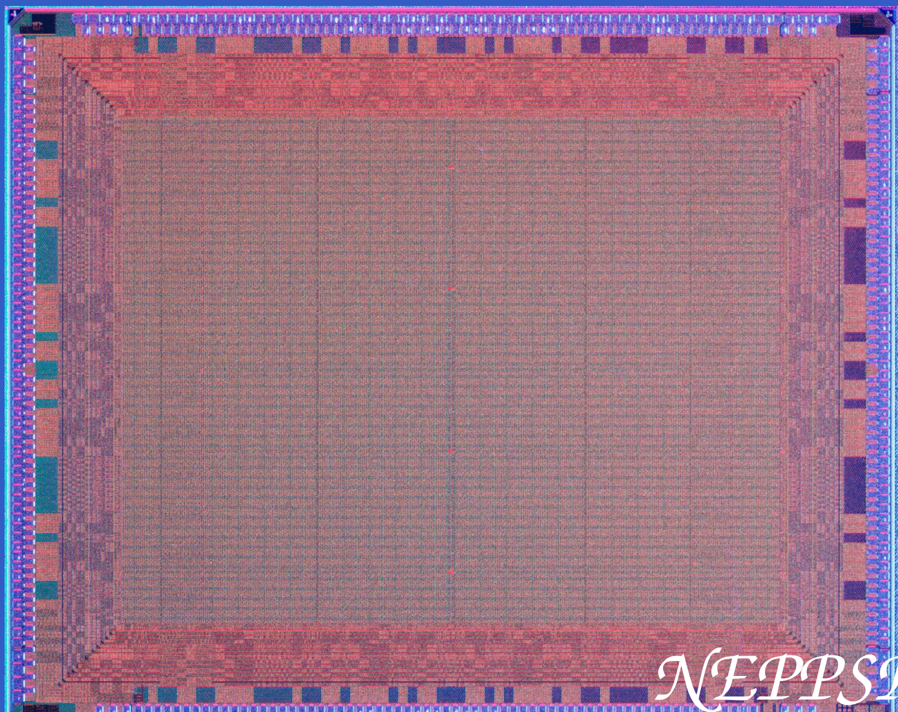
- availability of millions of logic gates in a single package at low cost (< $\$10^{-4}$ per "transistor")
- availability of radiation hard electronics

  cold war dividend

First transistor 1947



Modern FPGA 2004



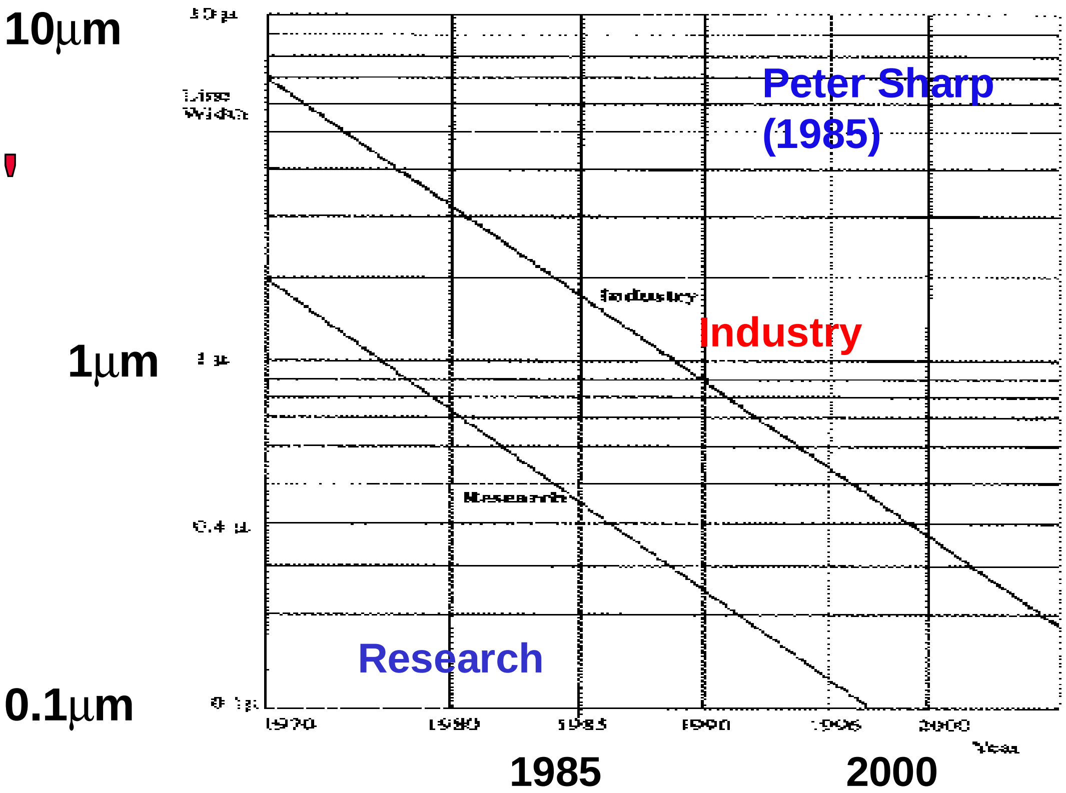
Moore's Law prediciting the trend

What has been Learnt from the last 15 Years ?

' Moores Law '

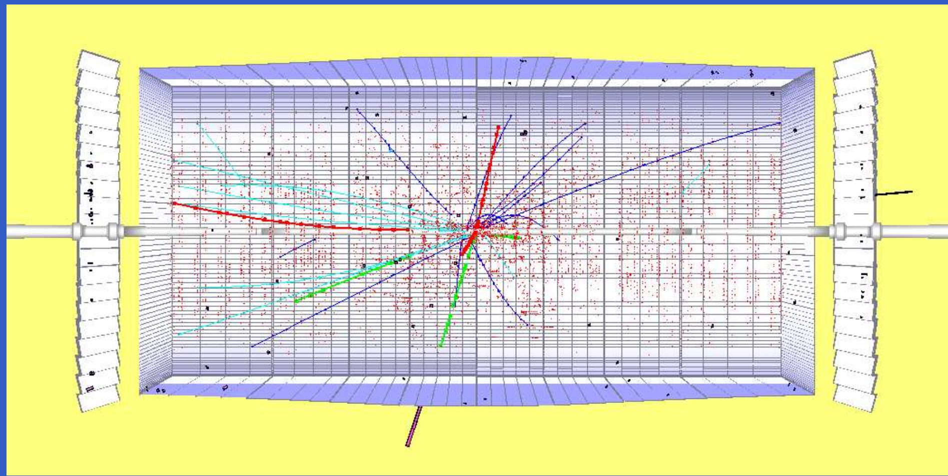
A plot made in 1985

Evolution of Line Width

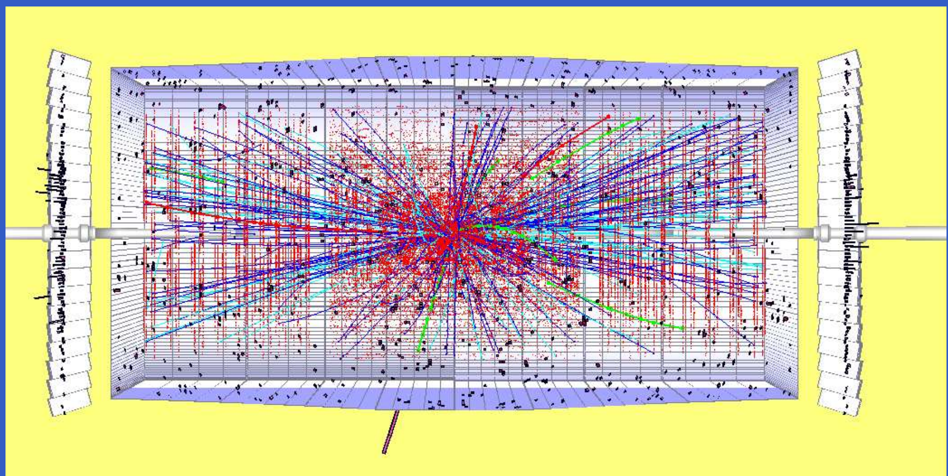


Events at the LHC!

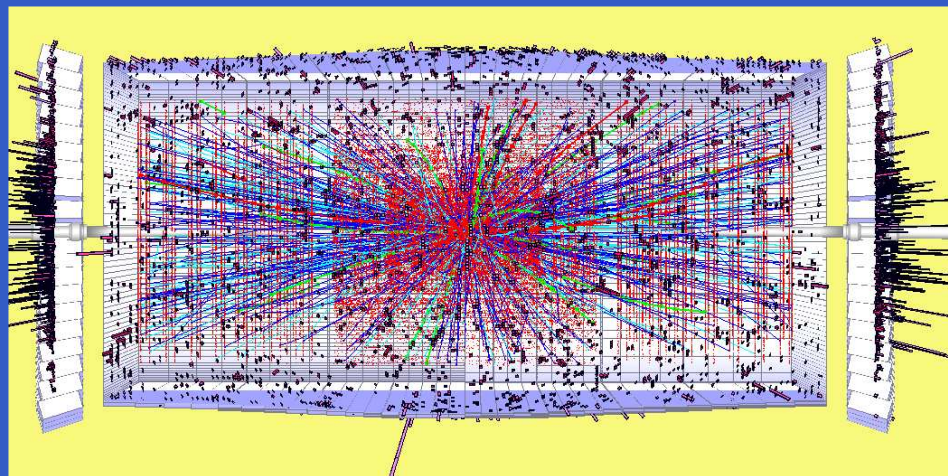
$10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

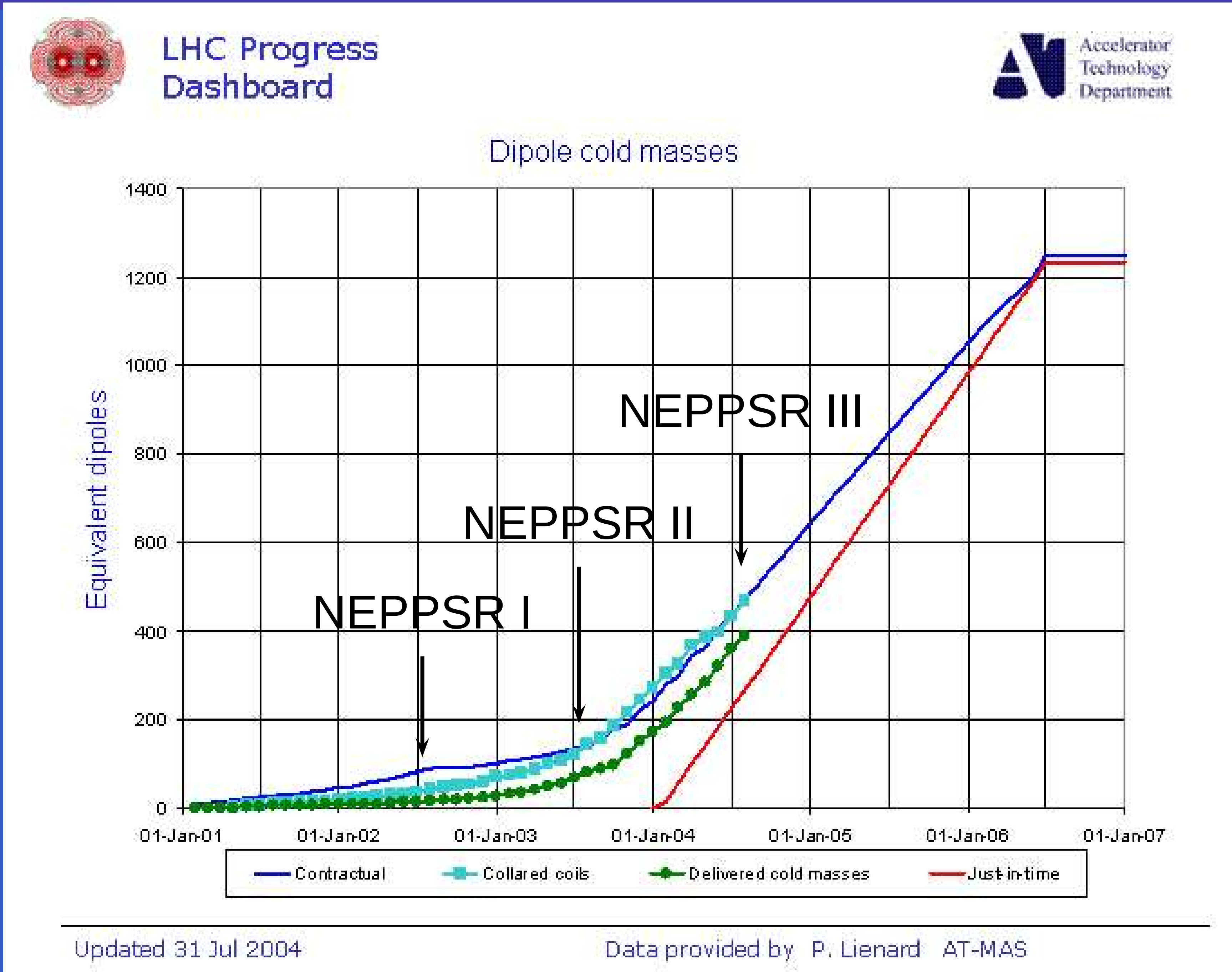


$10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

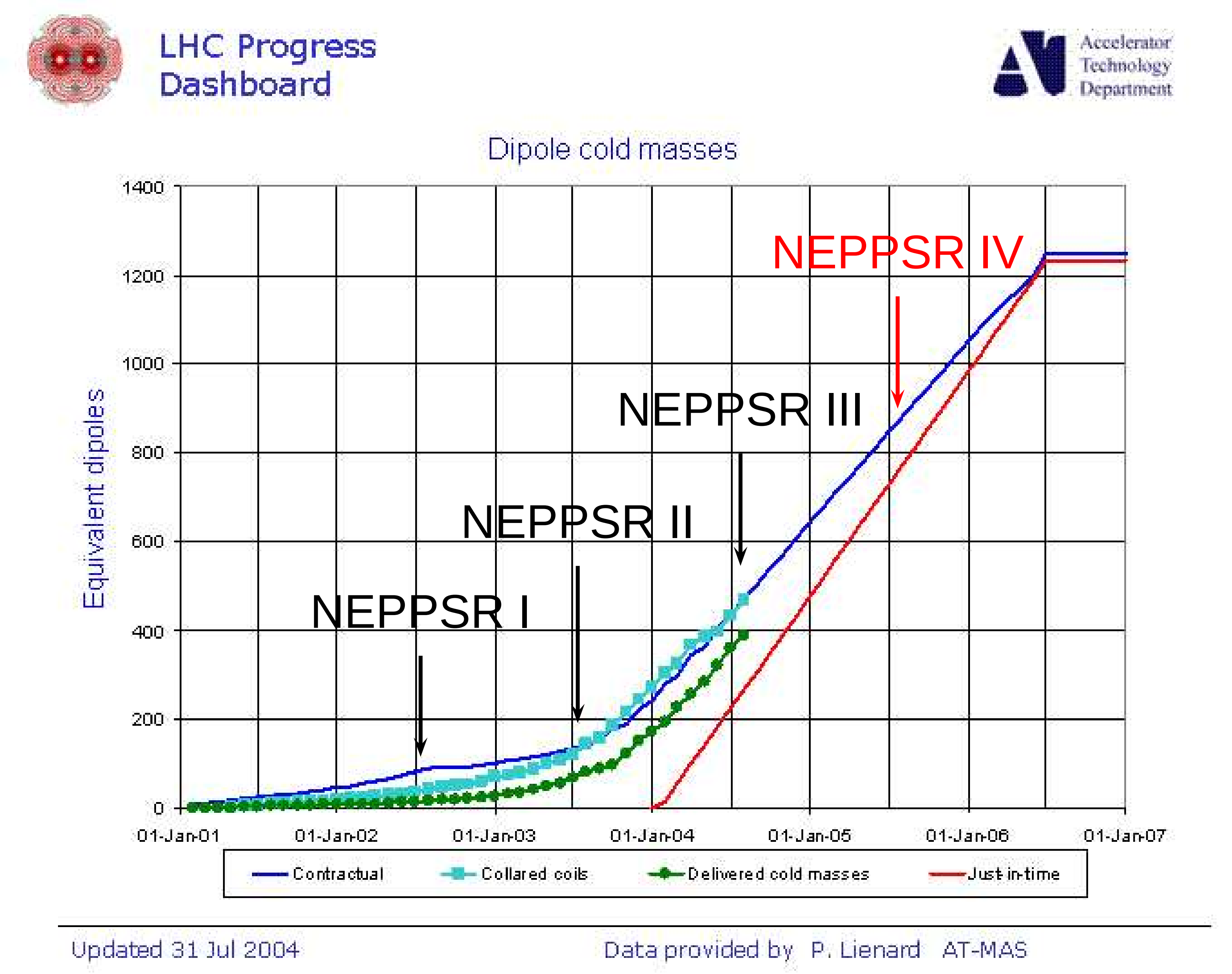


LHC 26 km of superconducting magnets

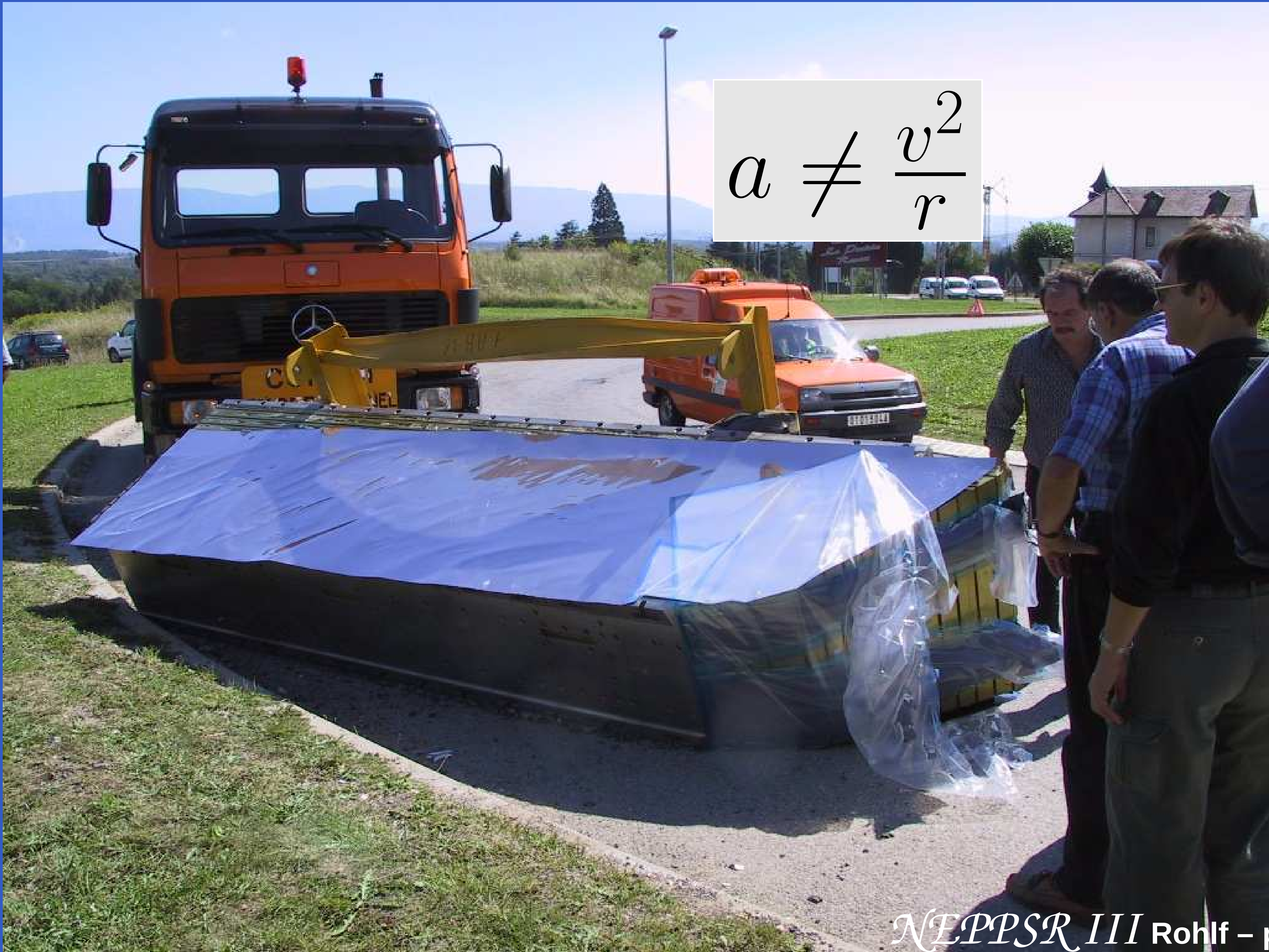
LHC Dashboard dipole cold masses



LHC Dashboard dipole cold masses



Physics will not go as planned...



$$a \neq \frac{v^2}{r}$$

Outlook

- LHC physics is almost here (!)
- Higgs is the planned discovery, but the excitement is the UNKNOWN
- How could anyone not want to participate?