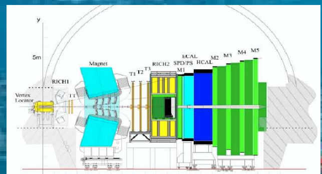
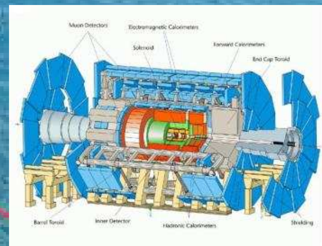
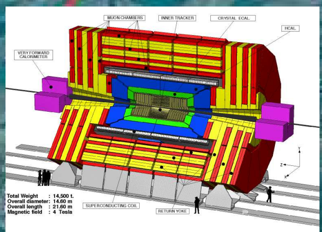
Physics with Jets at the LHC





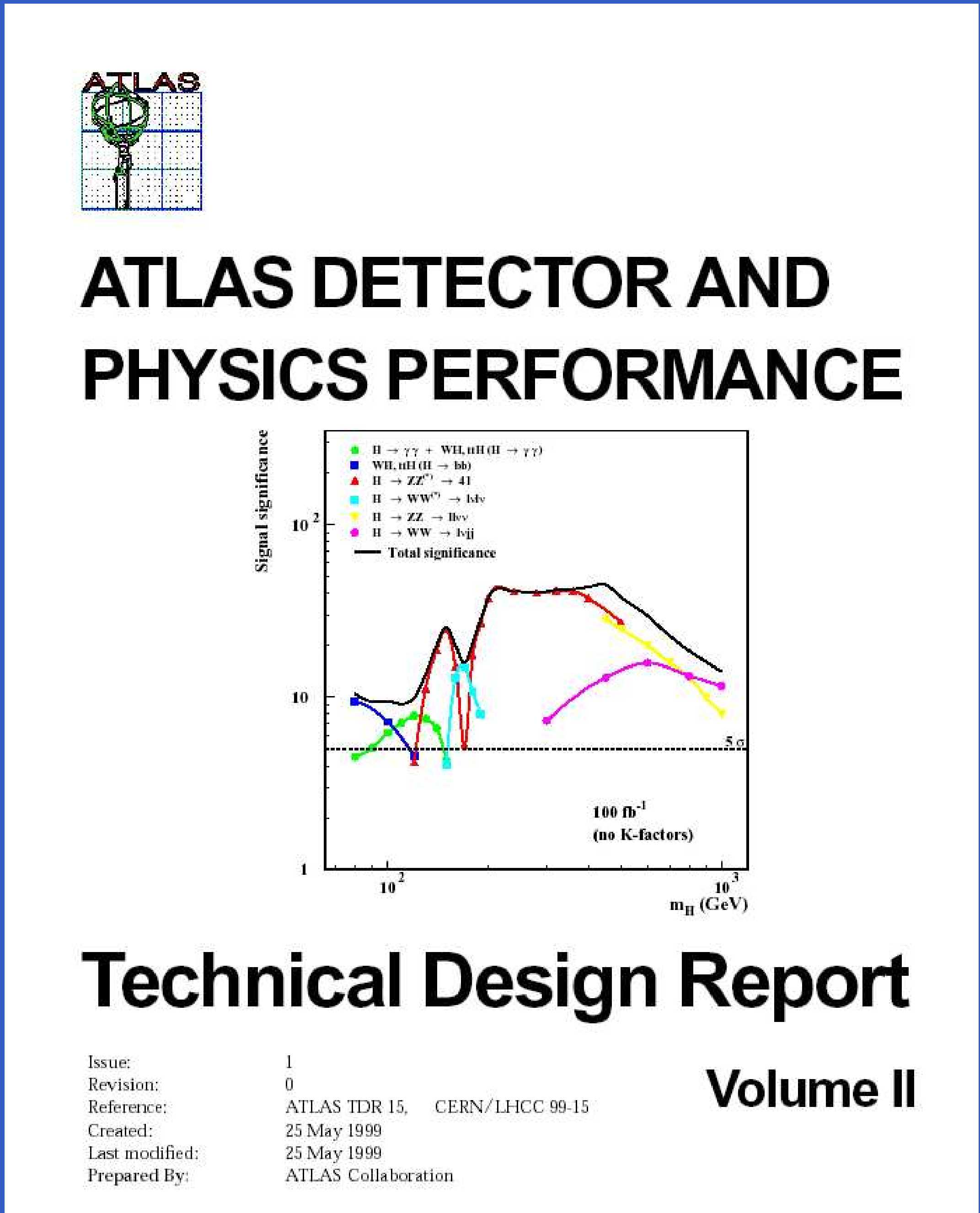
Jim Rohlf
Boston University

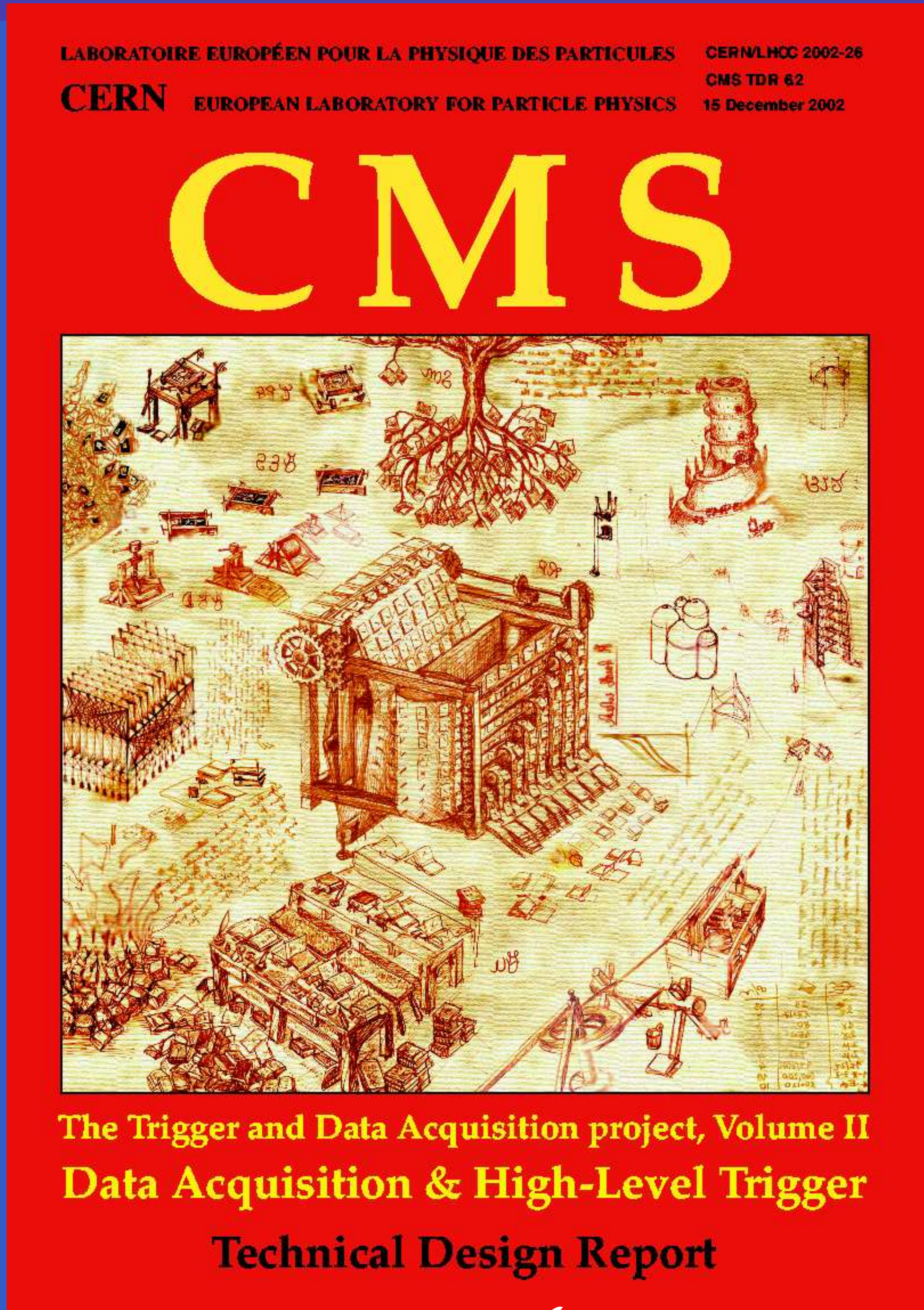


Outline

- Introduction
- Detectors and expected performance
- Event Rates and Triggering
- Calibration
- Missing transverse energy
- SUSY
- Higgs (taus and b tagging)
- Z'
- Compositeness
- Heavy Ion Collisions
- Summary and Outlook

Documents


ATLAS
ATLAS DETECTOR AND PHYSICS PERFORMANCE
Signal significance
H → γγ + WH, ttH (H → γγ)
WH, ttH (H → bb)
H → ZZ(*) → 4l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
5 σ
100 fb-1
(no K-factors)
mH (GeV)
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

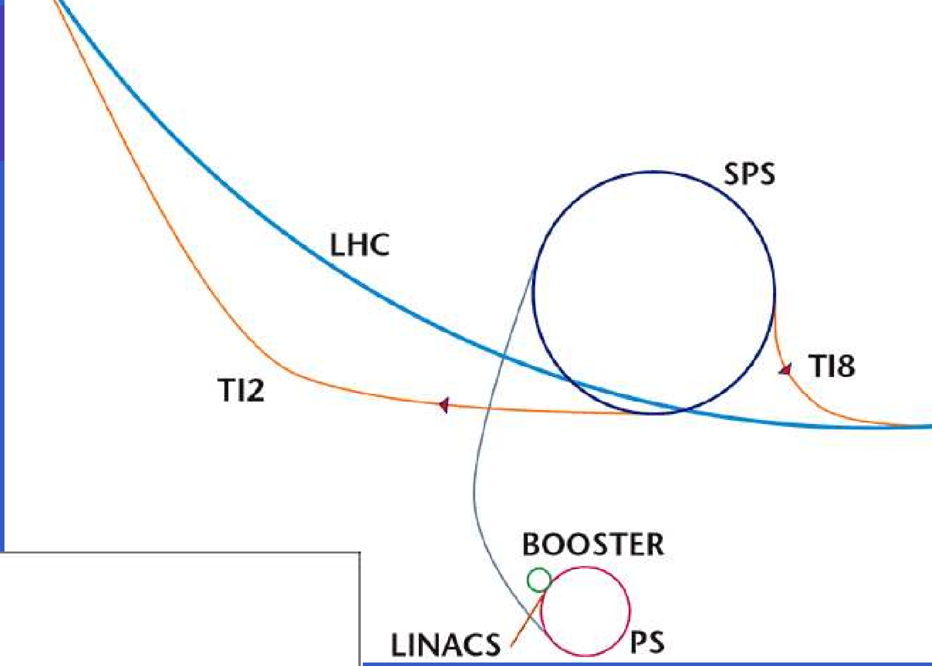
LHC Protons

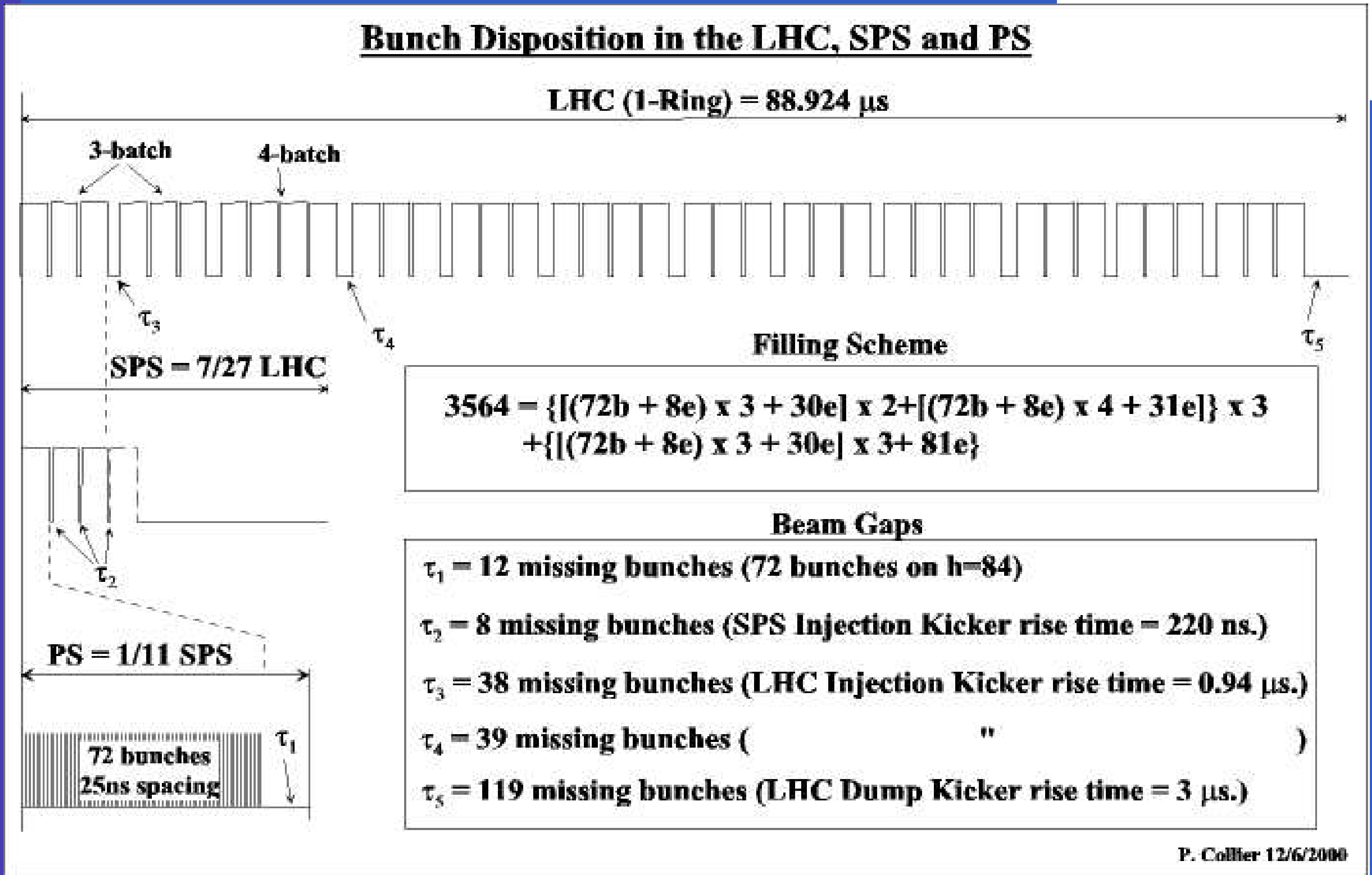
The gaps are important for synchronization!

LHC/PS = 42.4

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

= 2808 bunches



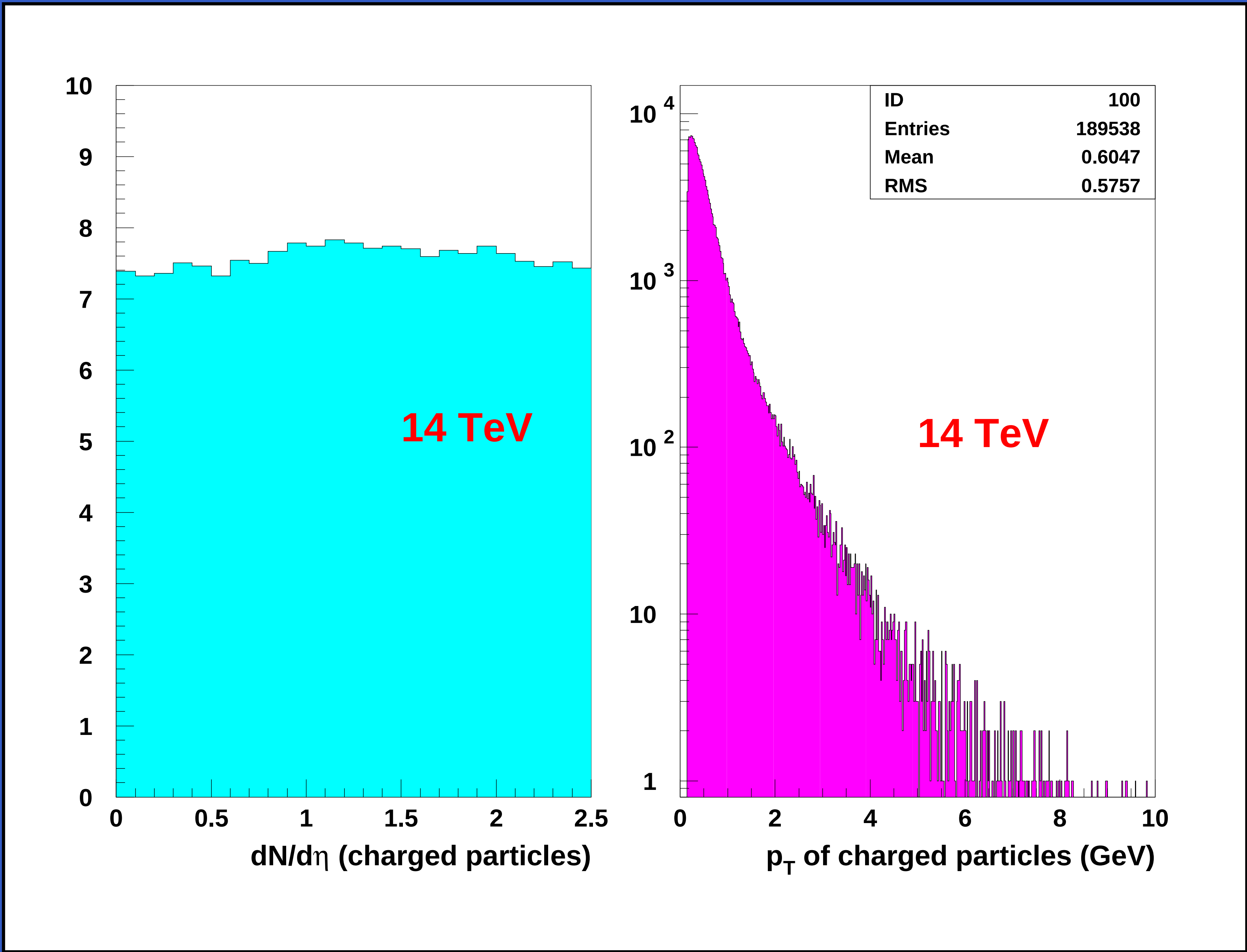


$$\Delta t = \frac{88924 \text{ ns}}{3564 \text{ ns}}$$

$$= 24.95 \text{ ns}$$

"Abort gap" $= 3\ \mu s$ used for fast reset

Charged particles



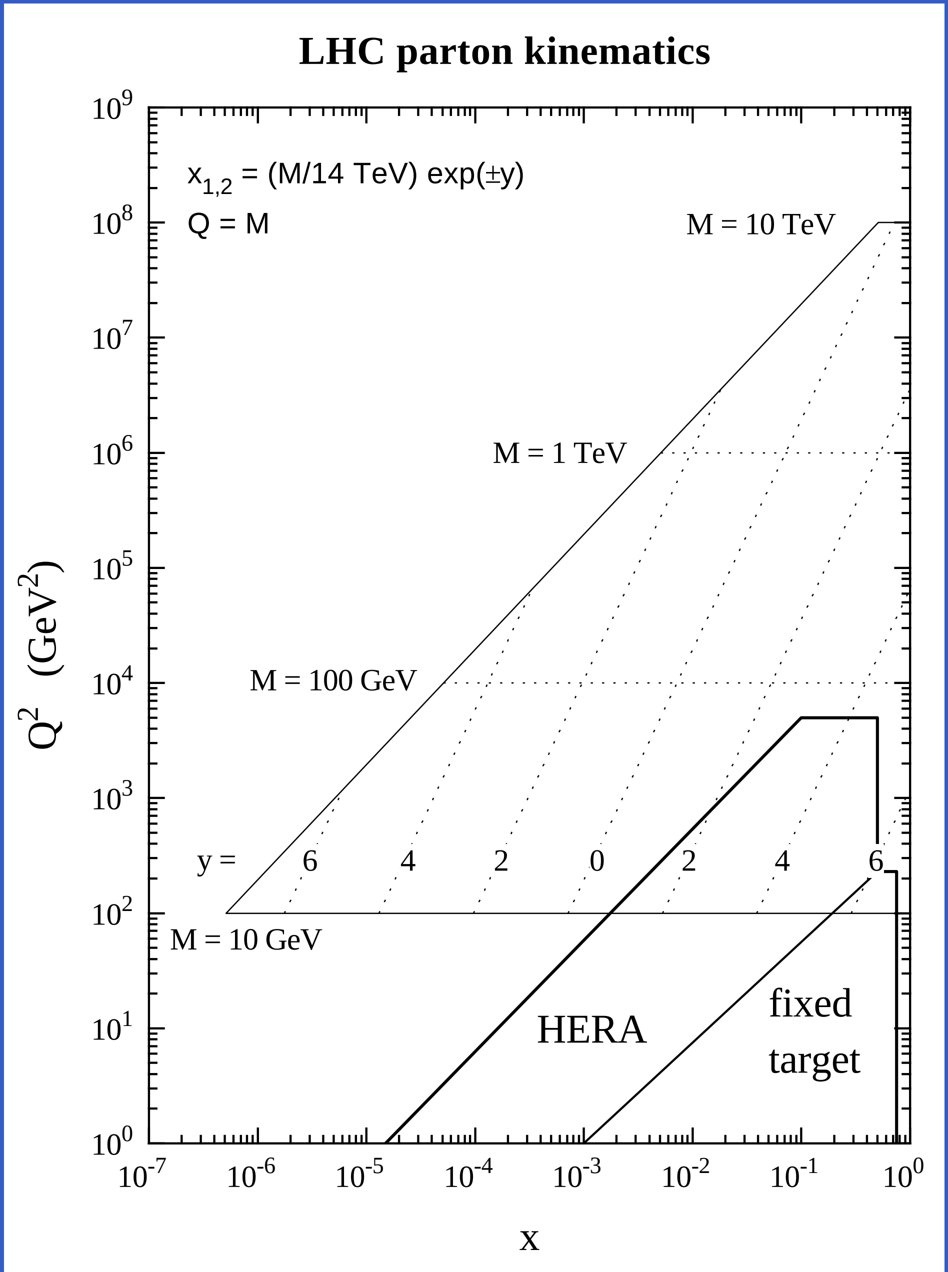
SLHC LHC parameters

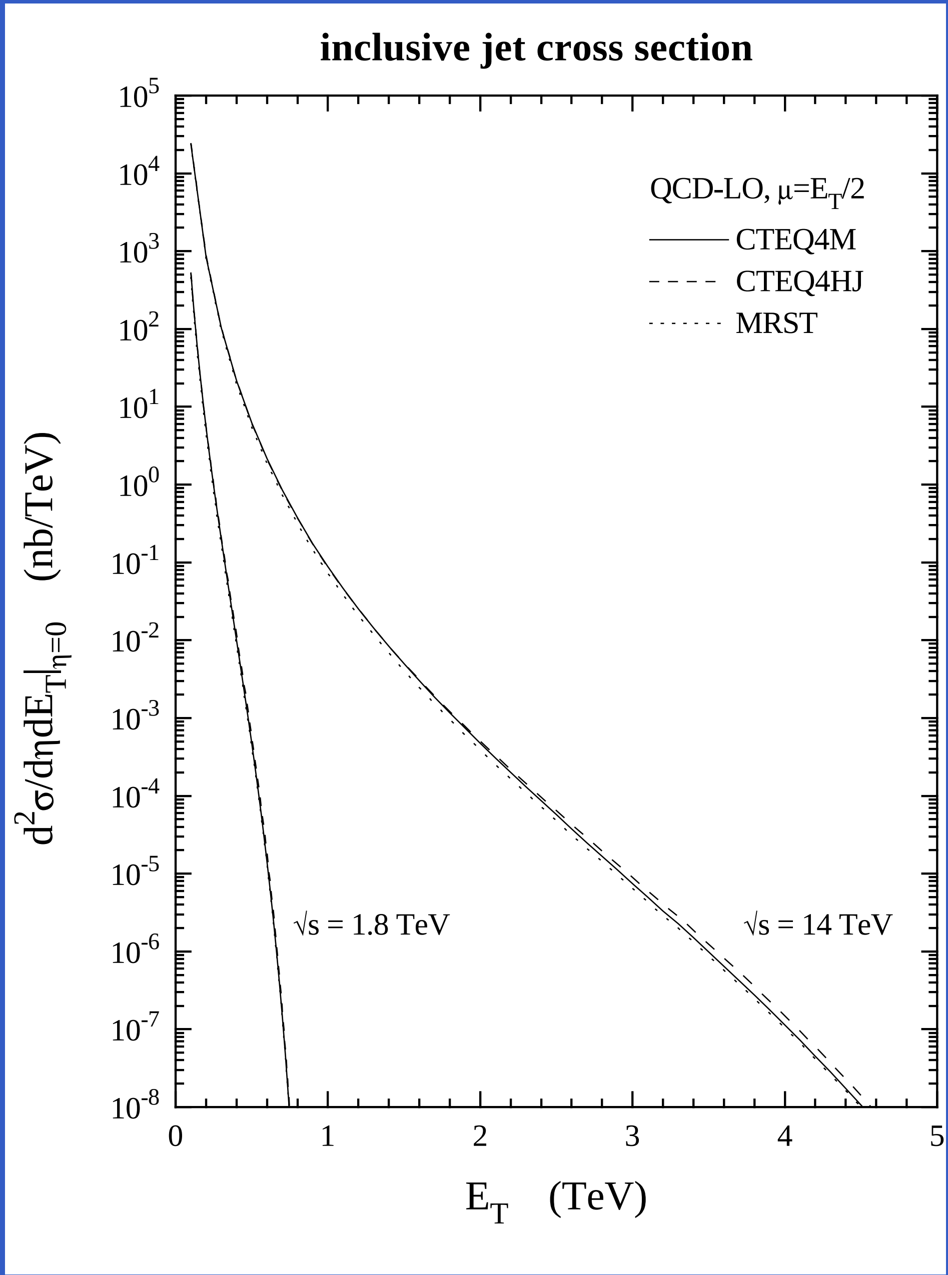
pp c.m. energy	14 TeV
luminosity	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
collision rate	1 GHz
W/Z^0 *rate*	1 kHz
bunch spacing	25 ns
interactions per crossing	20
$\frac{dN_{\mathrm{ch}}}{d\eta}$ *per crossing*	$10^{5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
track flux @ 1 m	$10^{5}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$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

First physics expected at "low luminosity":

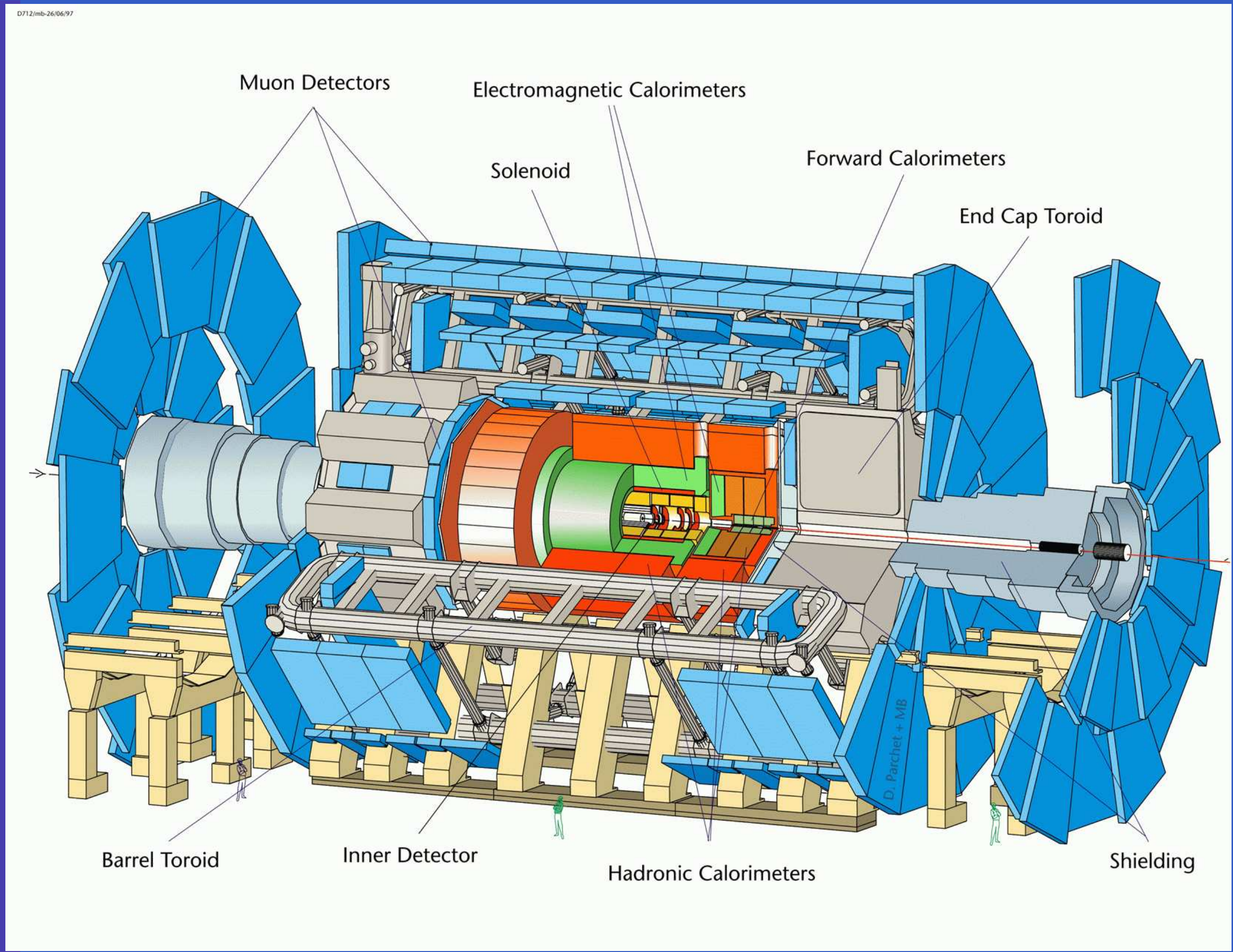
$2 \times 10^{33}\ \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Kinematics and Cross Section

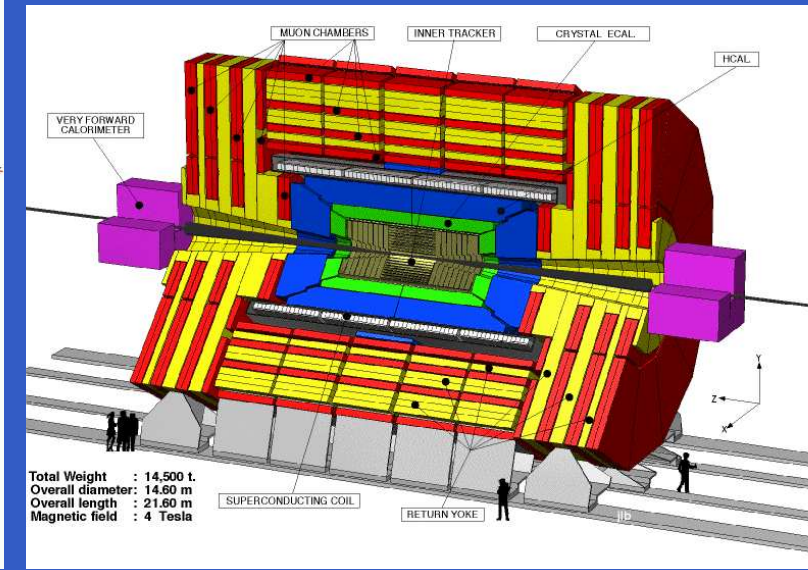




Detectors overview



- 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%)

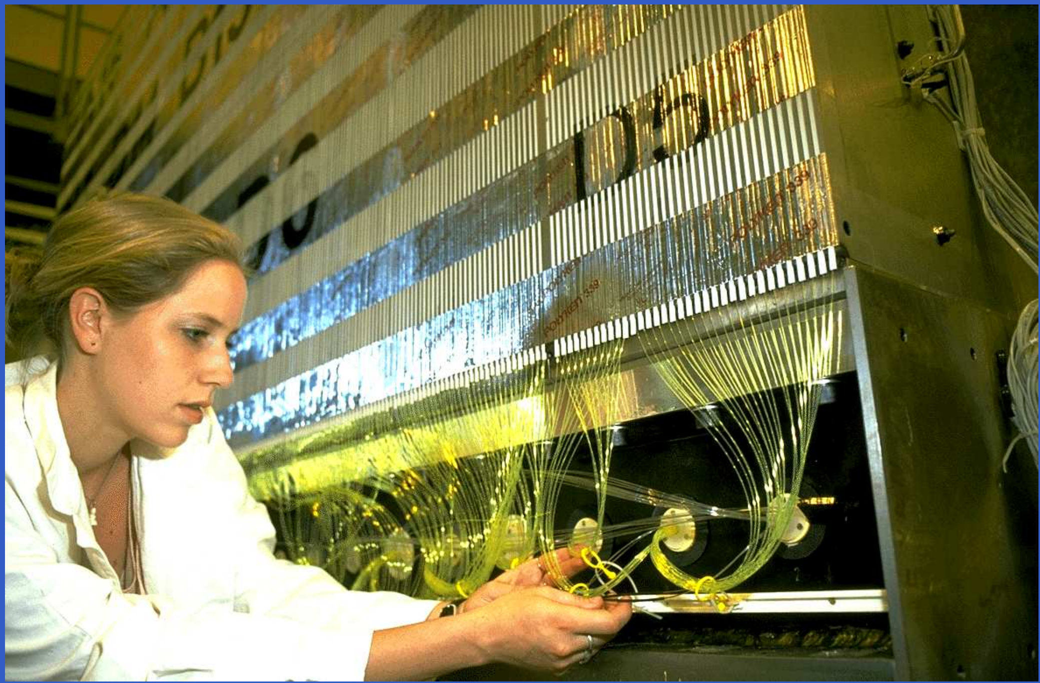
- high-resolution tracker
- high-performance ECAL

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 $(PbWO_4)$	liquid argon / Pb
	end cap	crystals $(PbWO_4)$	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

HCAL barrel

ATLAS: scintillator / Fe



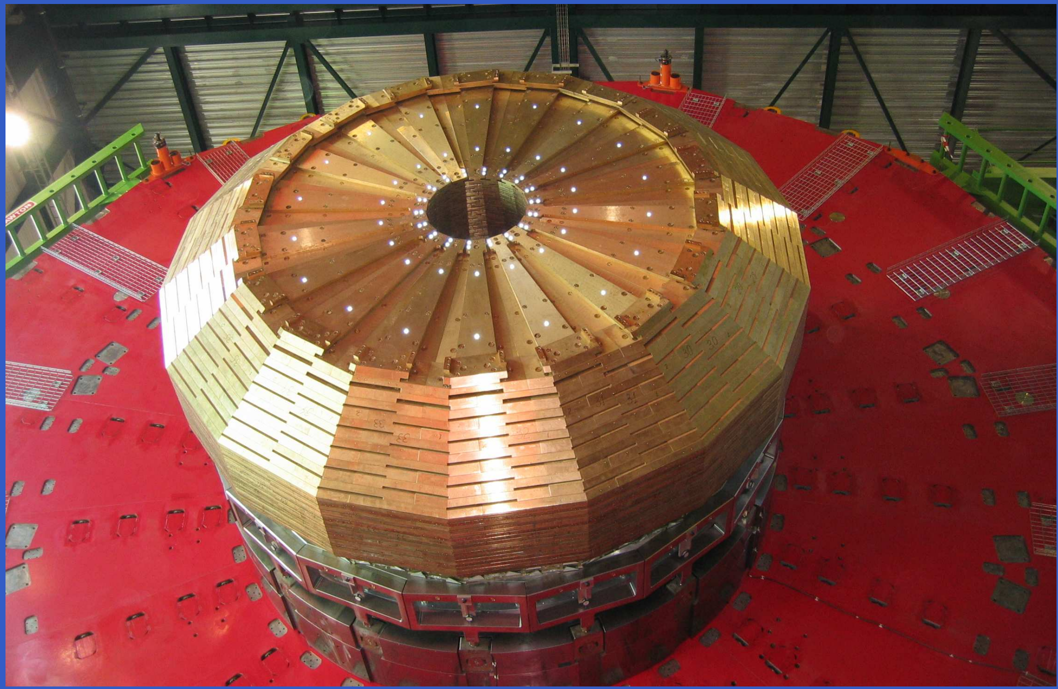
CMS: scintillator / brass

	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

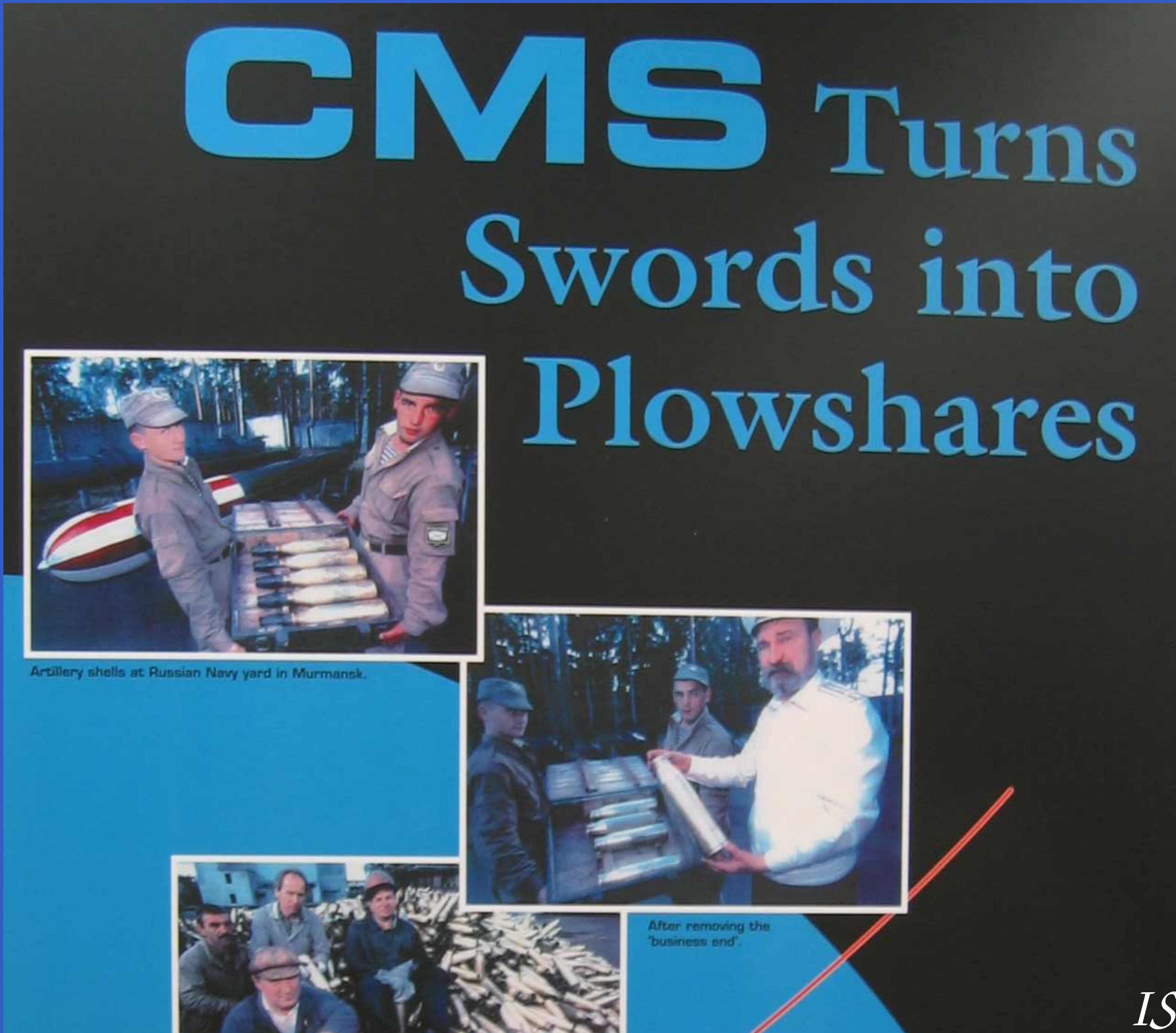
ATLAS: liq. argon / Cu

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



Forward

ATLAS: liquid argon / Cu-W

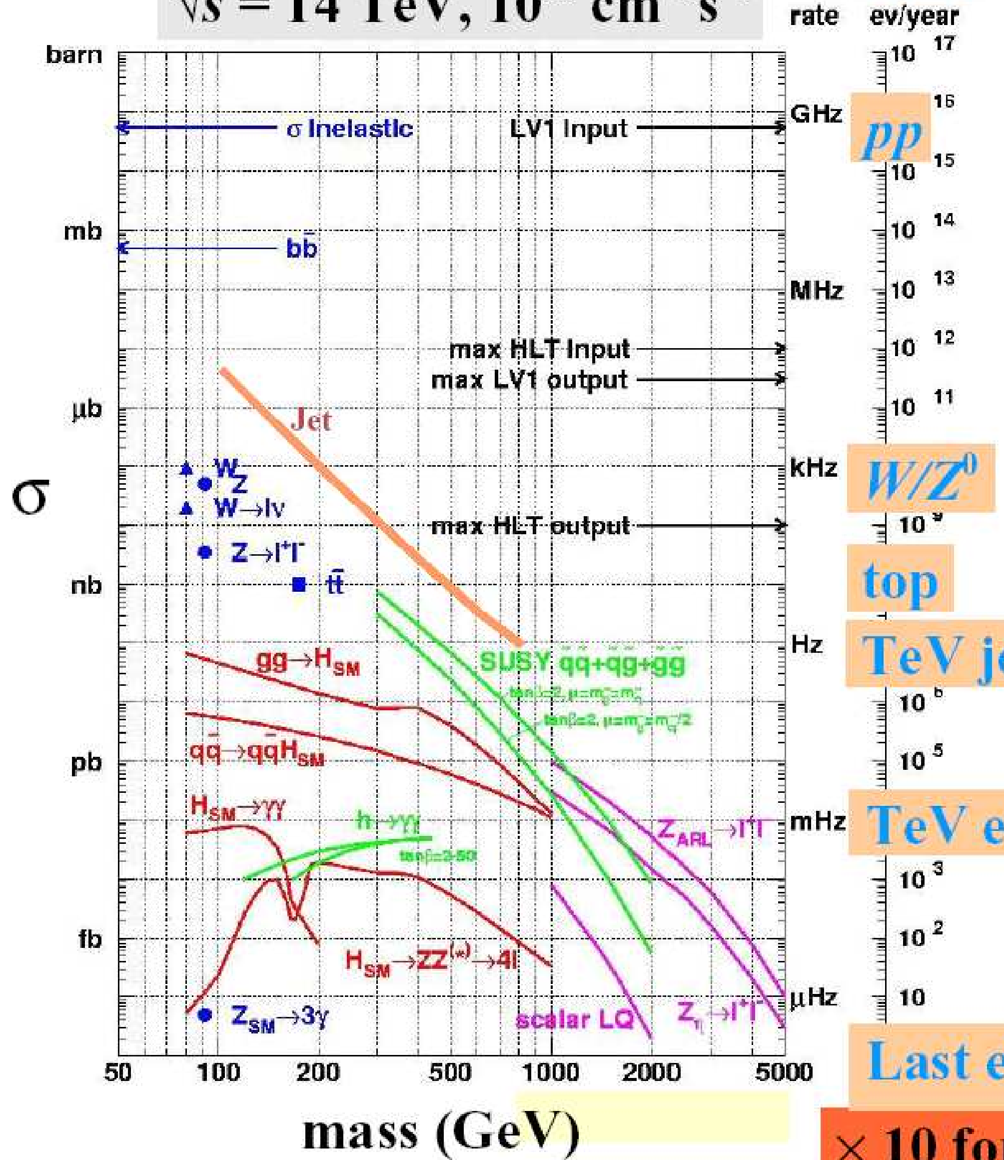
CMS: quartz / Fe

	coverage	π res. @ 300 GeV	thickness	$\Delta\eta \times \Delta\phi$
ATLAS	$3.1 < \|\eta\| < 4.9$	8%	9 λ	0.2 $\times$ 0.2
CMS	$3.0 < \|\eta\| < 5.0$	20%	10 λ	0.17 $\times$ 0.17

LHC Rates

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

high lum.



Last event: $x_F = ½$

$\times$ 10 for super-high lum.

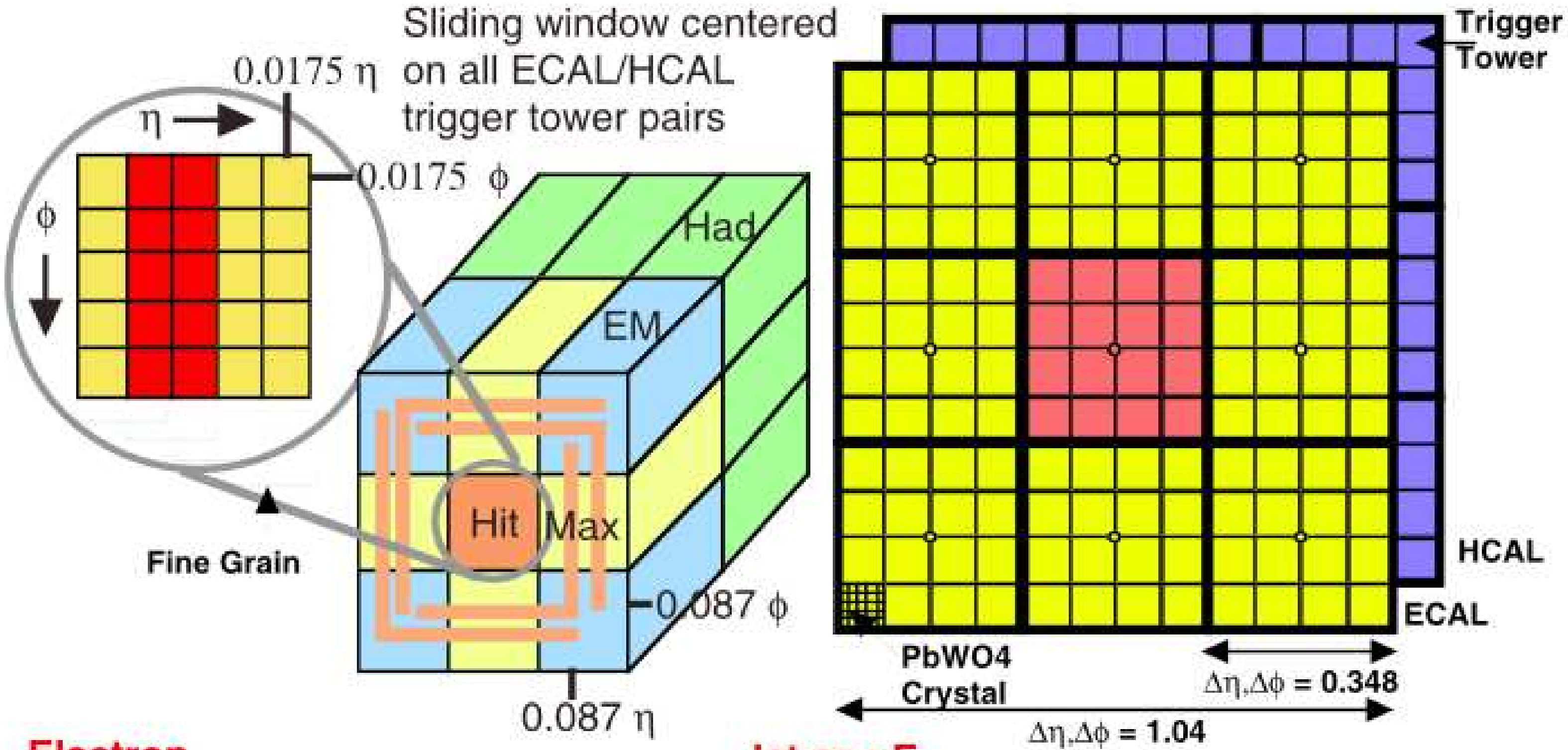
L1 trigger (high lum.)

Trigger	*Thresh.* (GeV)	*Rate* (kHz)
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

Current Algorithms



Electron

- 2-tower ΣE_T + H/E

Isolated Electron

- 2x5-crystal strips>90% energy in 5x5 (Fine Grain)
- Neighbor EM + Had Quiet

Jet or τ E_T

- 12x12 trig. tower ΣE_T sliding in 4x4 steps w/central 4x4 > rest

τ algorithm (isolated narrow energy deposits)

- Call Jet τ if all 9 4x4 region τ-vetoes off
- τ-veto: Patterns of E or H towers in 4x4

S. Dasu, University of Wisconsin   October 2003 - 3

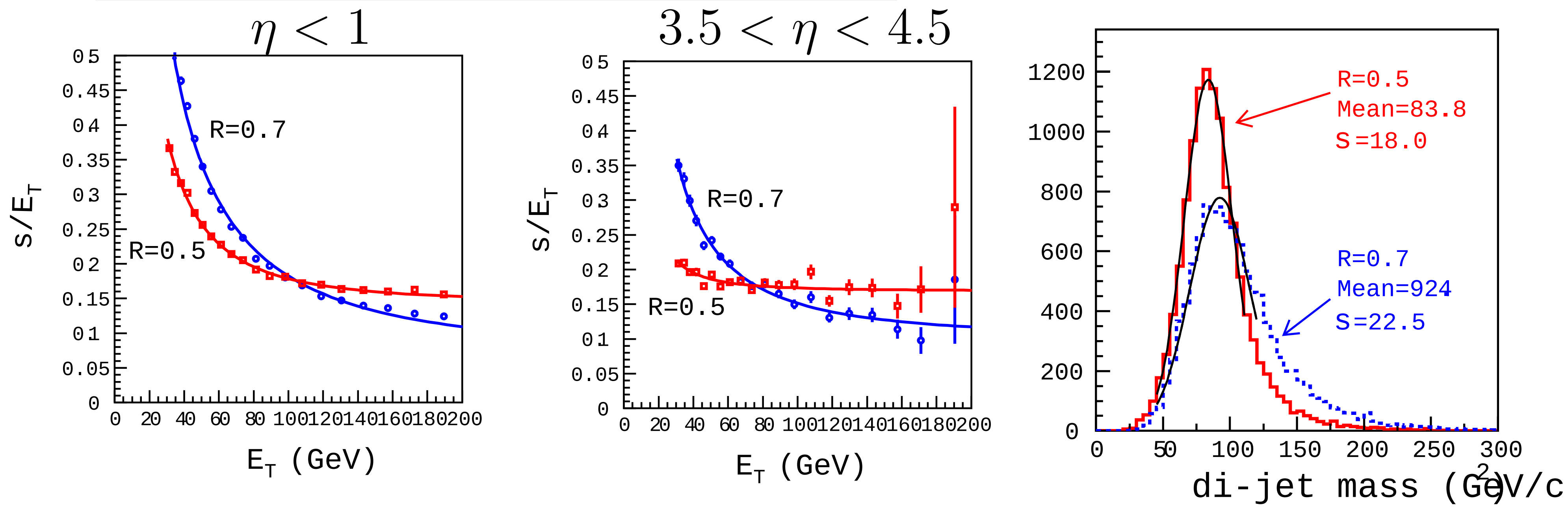
Jet Reconstruction C++ code

- cone based algorithms:
  - SimpleCone
  - IterativeCone
  - MidPointCone (CMS and CDF/DO implementation)
- cluster algorithms:
  - inclusive KtJets
  - exclusive KtJets (d_{cut})
  - exclusive KtJets (N_{jets})

HLT Jet Resolution

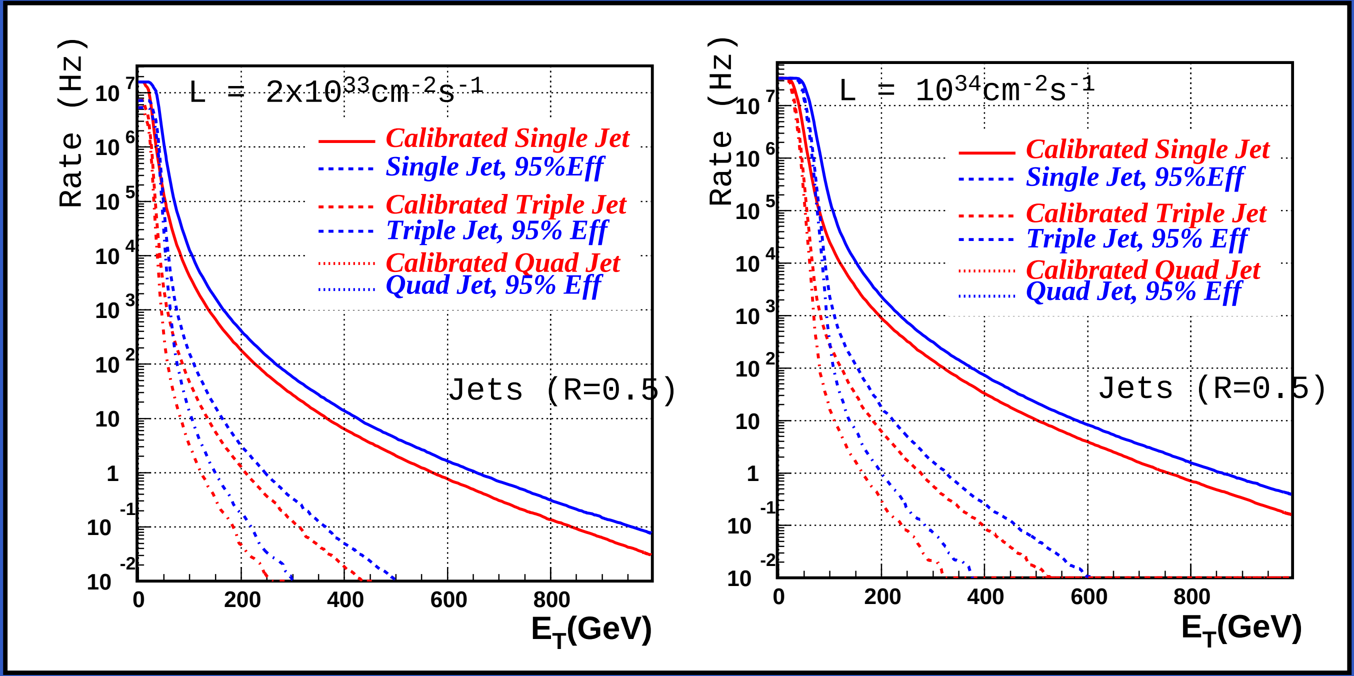
- Simple cone algorithm with 3 parameters: cone size, seed threshold, minimum jet E_T.
- Small cone contains energetic partons, but larger cone needed to include soft fragmentation which introduces noise.

Resolution *vs.* generated E_T



Jet rates

The jet rates are huge!



Low Lum.

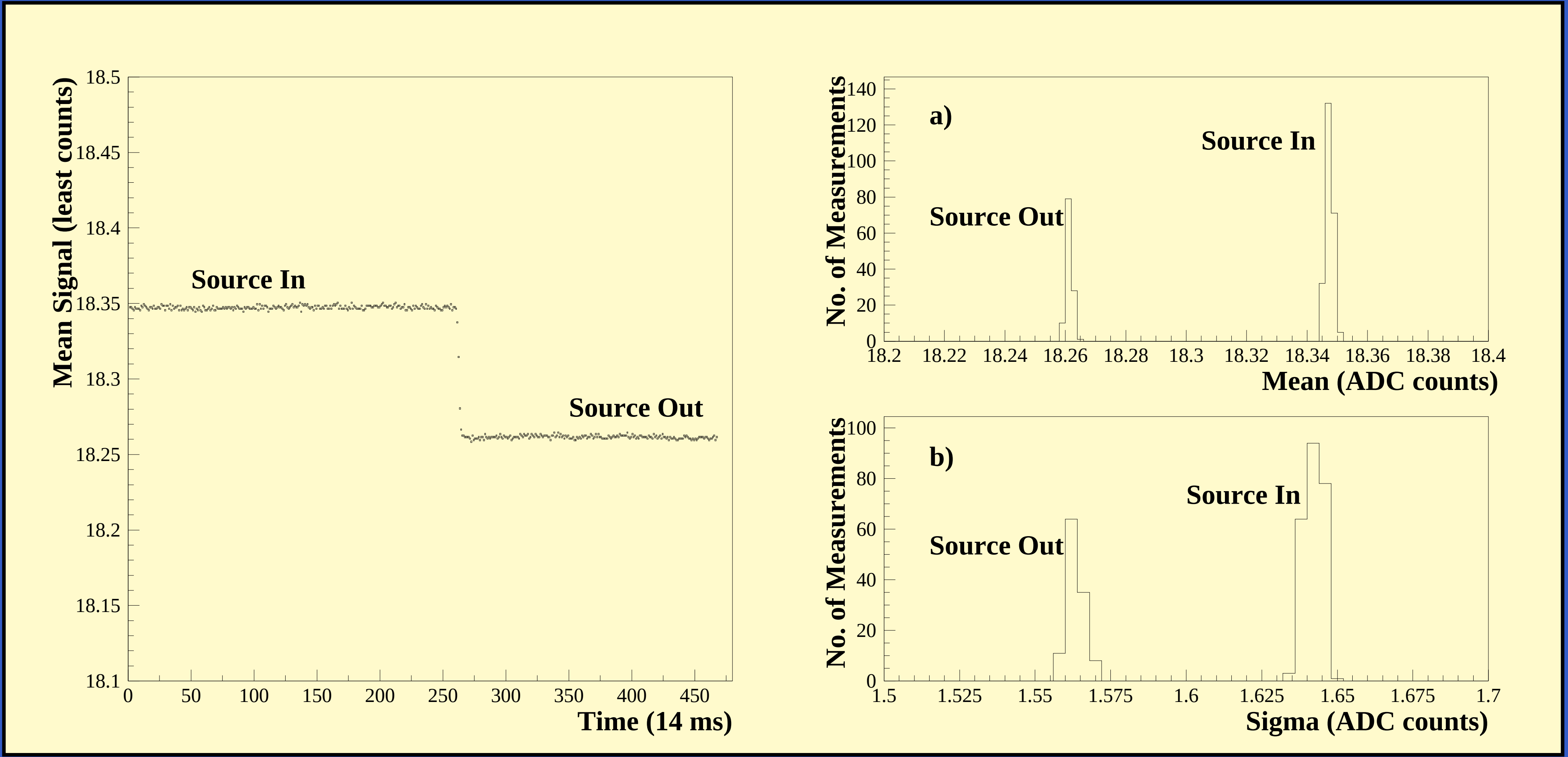
trigger	*threshold (GeV)*	*rate (Hz)*
1-jet + 3-jets + 4-jets	570, 210, 87	9
(1-jet + 3-jets + 4-jets) · $E_T^{\rm miss}$	(150, 75, 60) · 93	5
electron · jet	16 · 52	1
inclusive b jets	200	5
inclusive τ jets	93	3

Calibration overview CMS

- HCAL is a "small" system (9072 channels)...
  however, the number of active elements is "large"
  90k tiles for HB/HE/HO, 200k fibers for HF
- An absolute calibration of 2% for single particles is the goal on day 1 using radioactive sources tied to test beam measurements.
- Final calibration is likely to come from data.
  Is this not almost always the case?
  Tools: mip, ch. hadrons, γ,Z+jet, jet-jet,
  W$\longrightarrow$ jet-jet from top, ???
- Jet energy calibration and dijet mass calibration constitutes a challenge beyond that of single particle response.

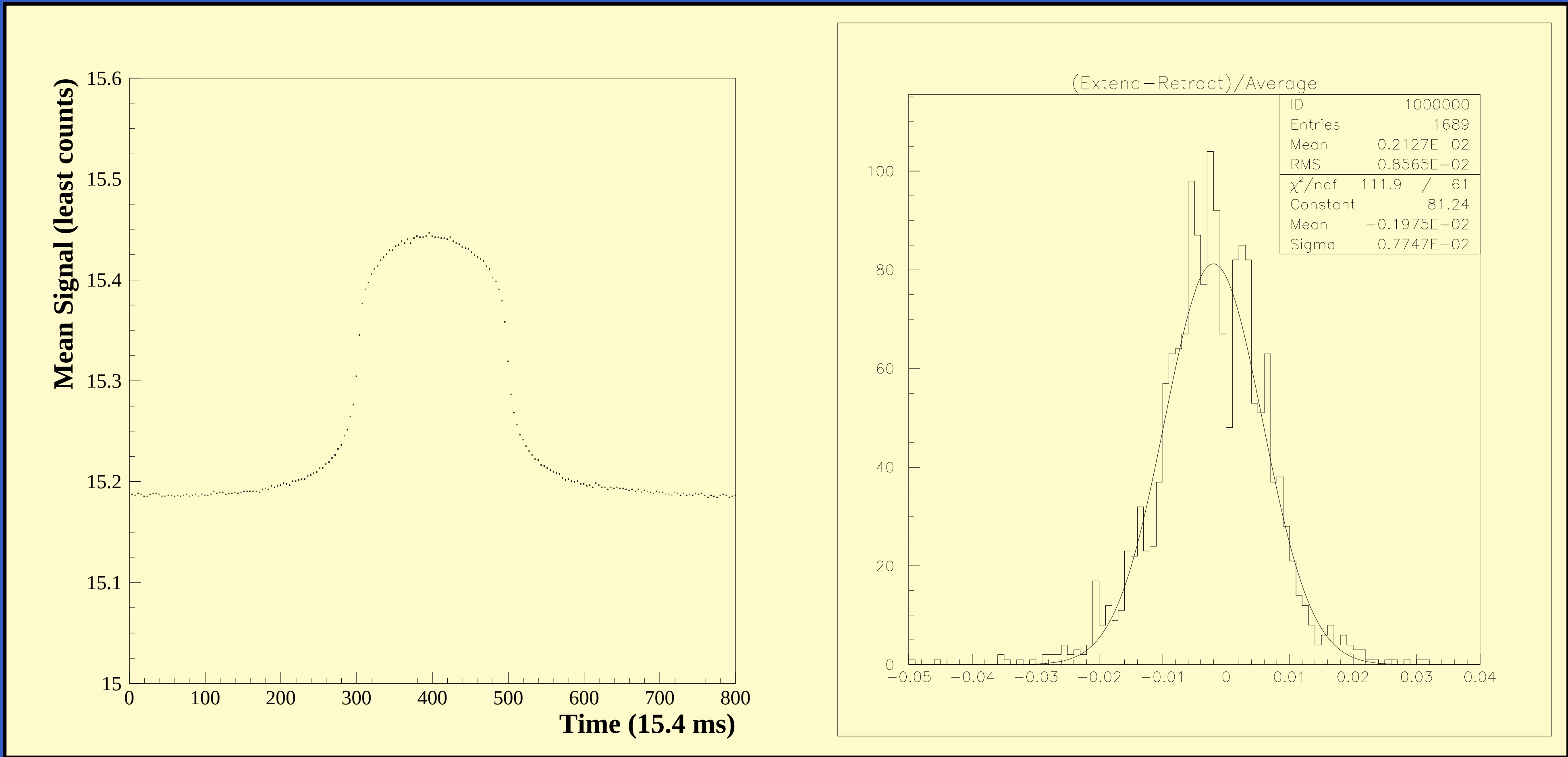
Source calibration technique

CMS HCAL is calibrated with moving radioactive sources. The technique is described in E. Hazen *et. al*, "Radioactive Source Calibration Technique for the CMS Hadron Calorimeter," Nucl. Inst. and Meth. A 511 (2003) 311.

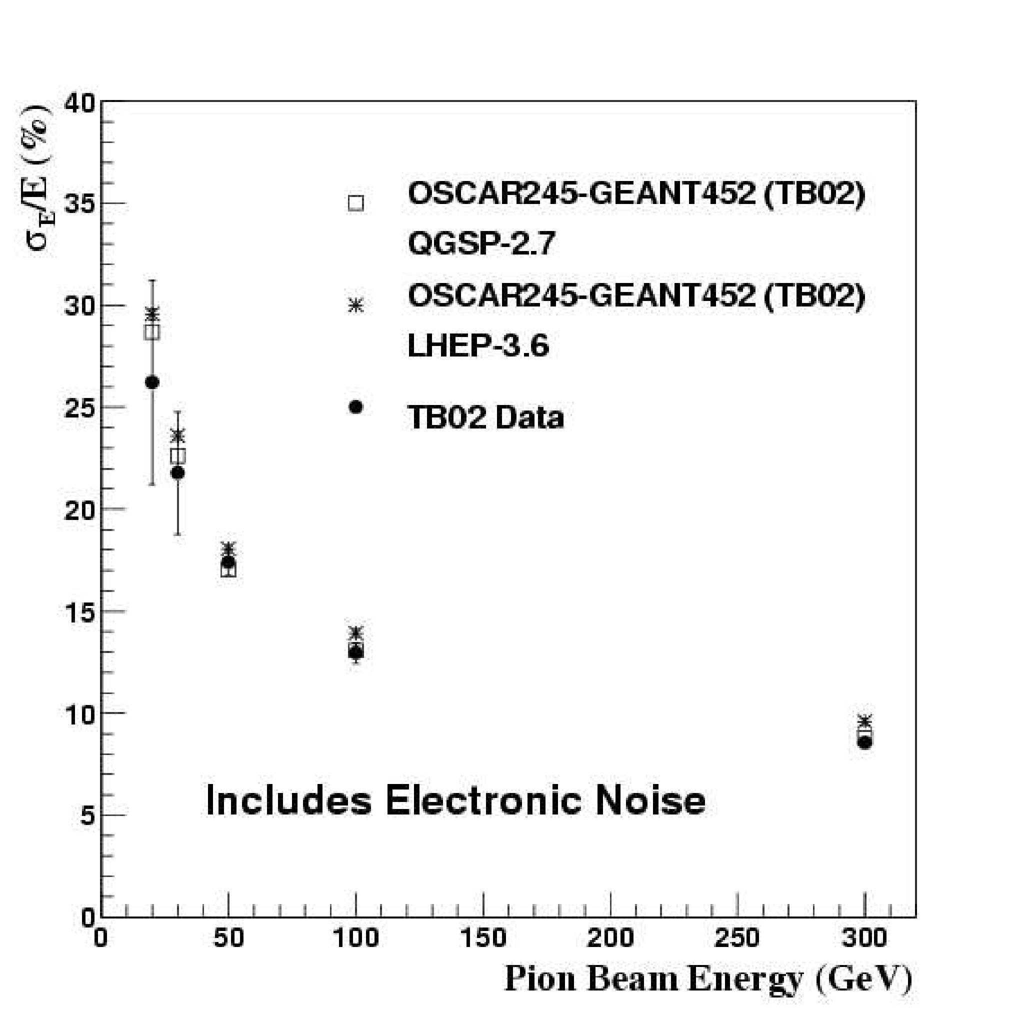


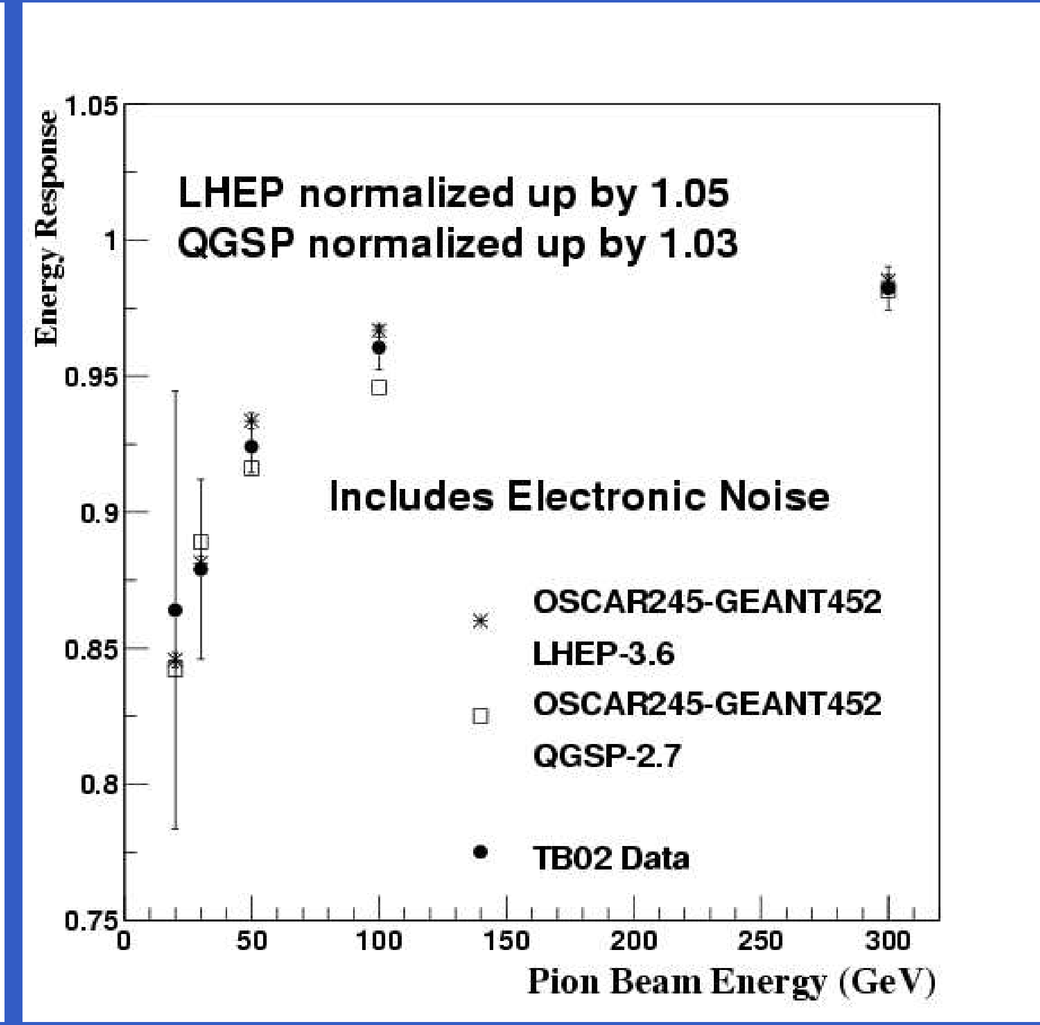
Source calibration test beam

The technique has been tested in the test beam (2002) 128 HB towers × 16 layers and repeated with HE and HF (2003 and 2004).



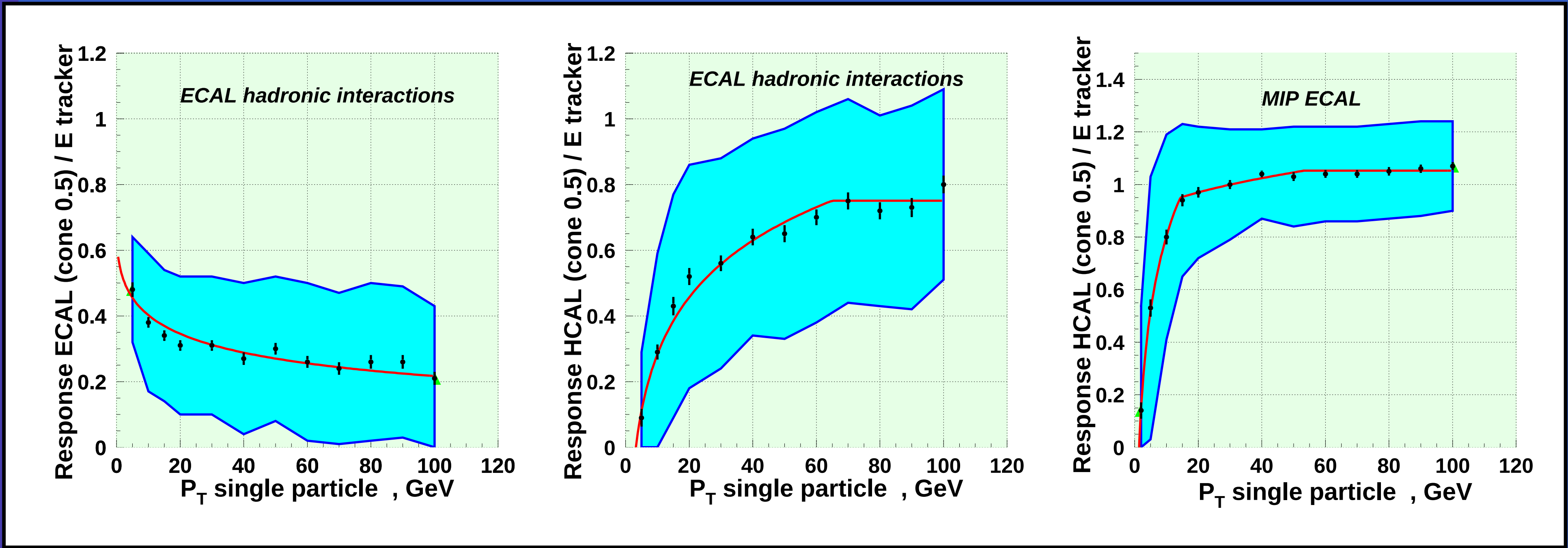
Resolution and linearity CMS





Improving jet resolution with tracks

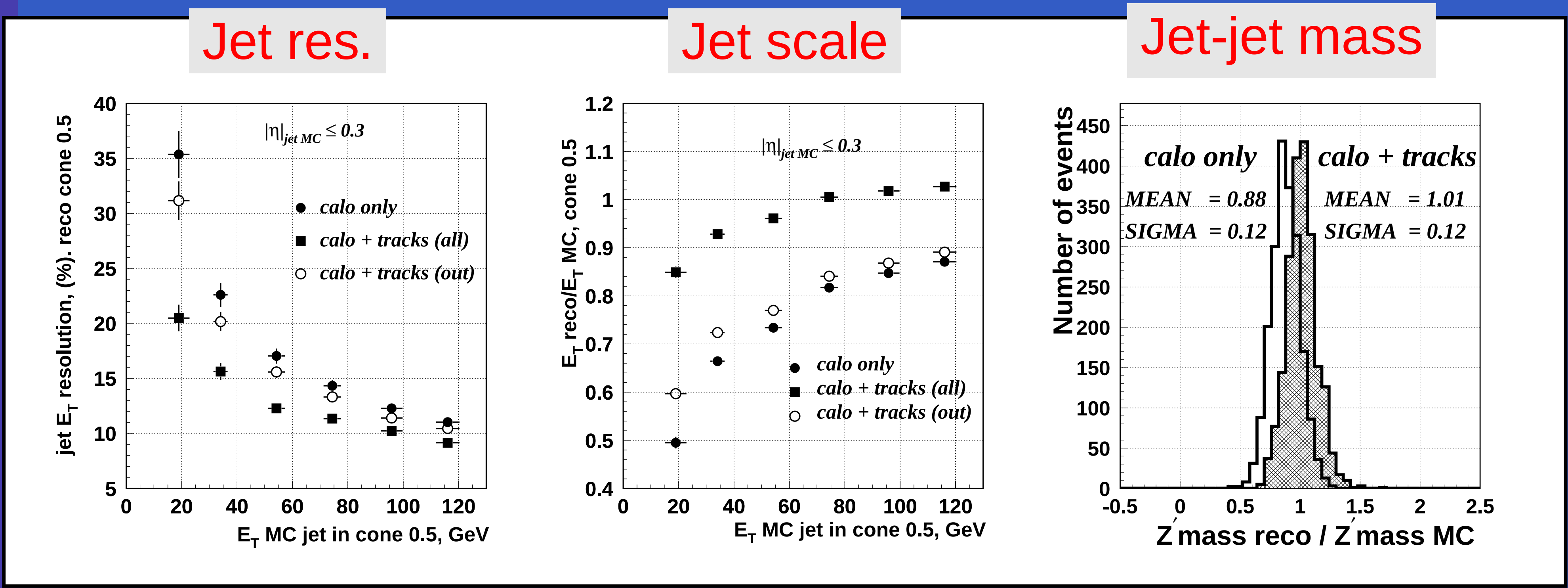
- Replace energy recorded in calorimeter with track *pc* where signals are consistent.
- Add in tracks that are swept out of jet cone by magnet.



CMS Note

Improving jet resolution with tracks cont.

- Jet resolution improved, huge corrections for central jets (about 25% for 50 GeV, $|\eta| < 0.3$), less for forward jets.
- Jet energy and jet-jet mass scale corrected.



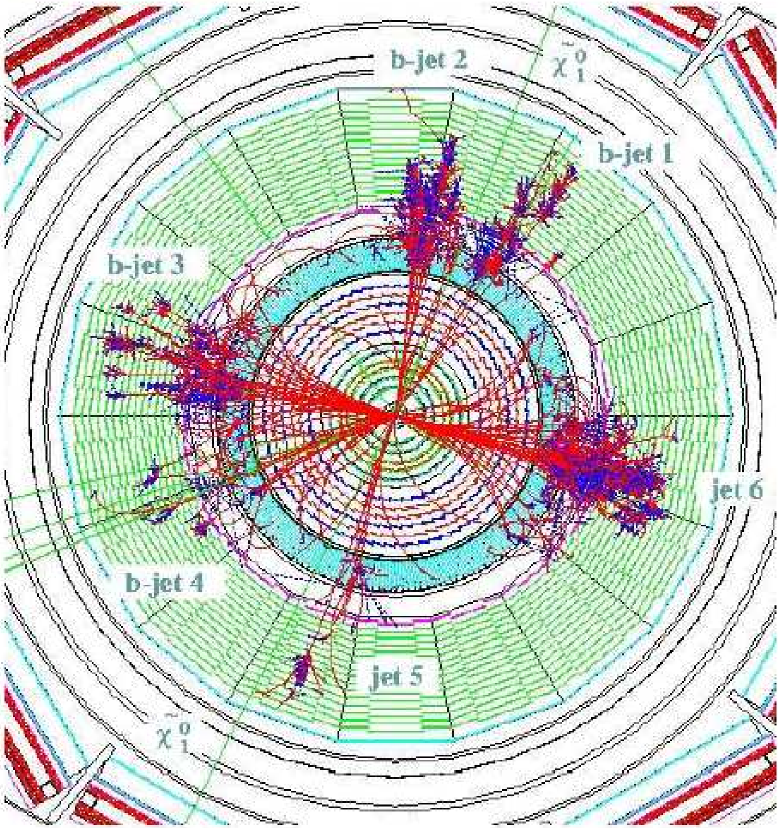
MET Resolution

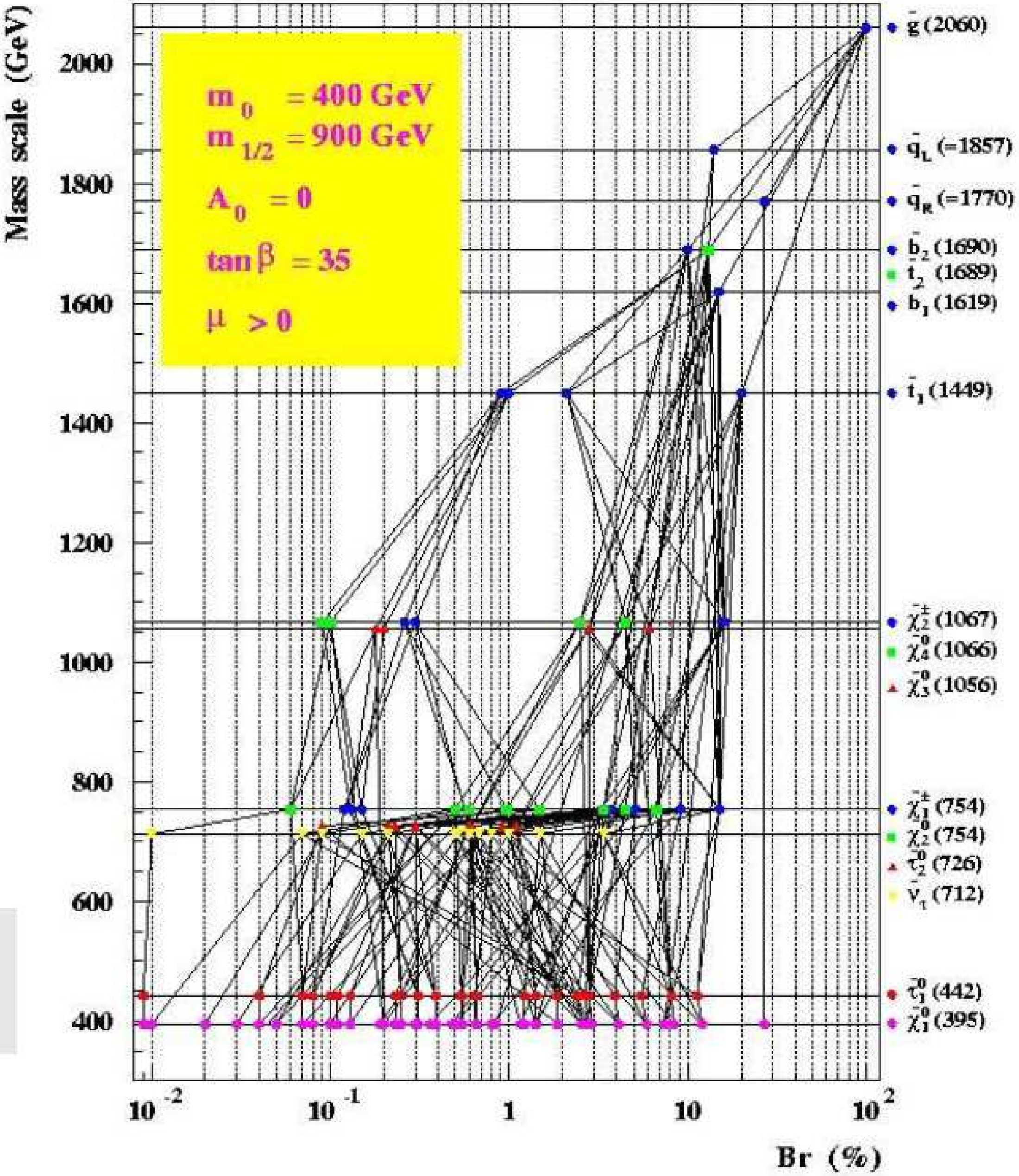
η coverage	*7-10%*
low p_{T} hadrons	*5%*
low p_{T} charged tracks	*10%*
minimum bias event	*10-15%*
pileup (low lum.)	*13-15%*
pileup (high lum.)	*20%*
electronic noise	*10-12%*
det. resolution	*15%*

"total" = 30-35% in 50 GeV MET ($t\bar{t}$ events)

SUSY: Sparticle Search

Supersymmetry

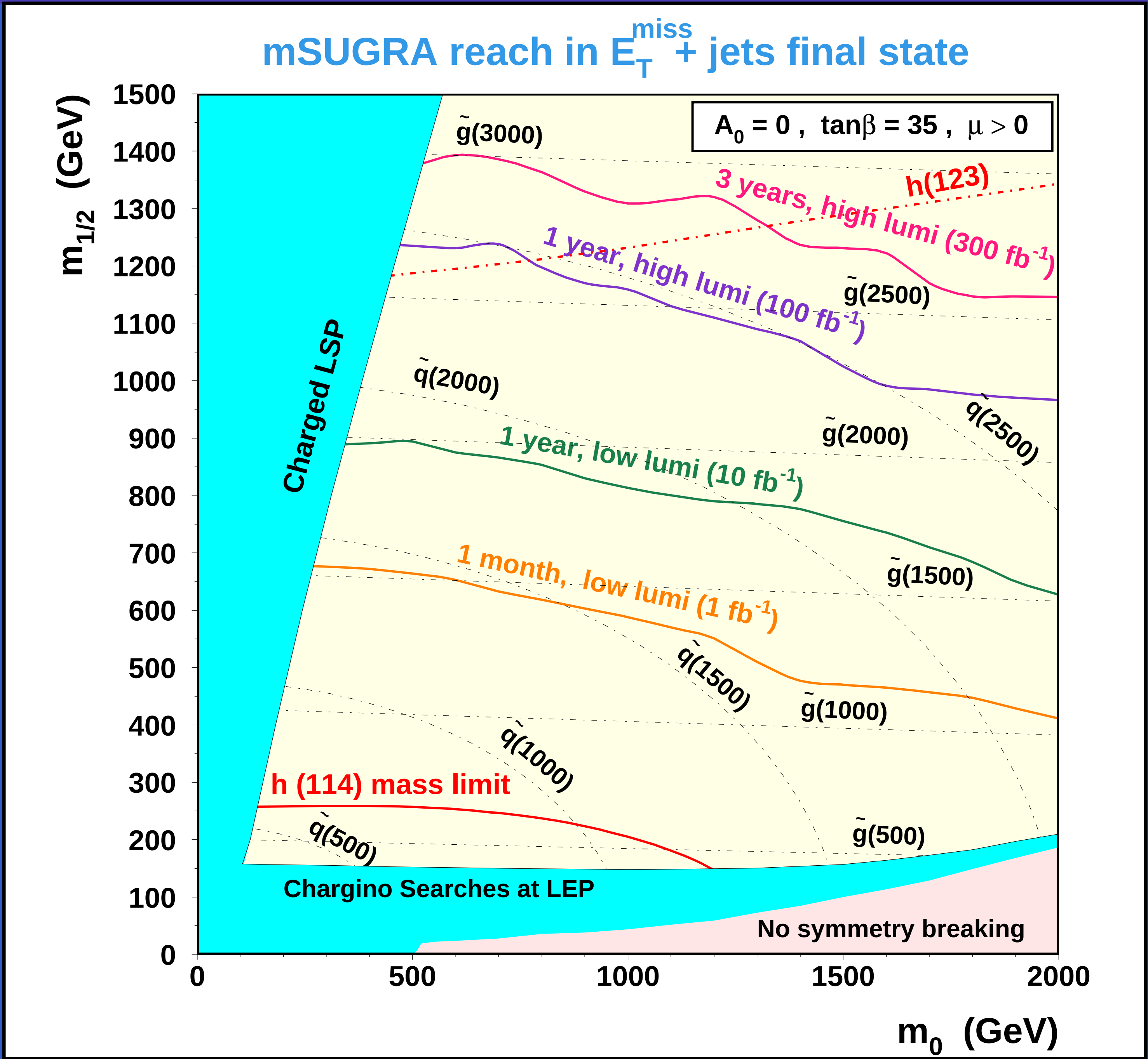




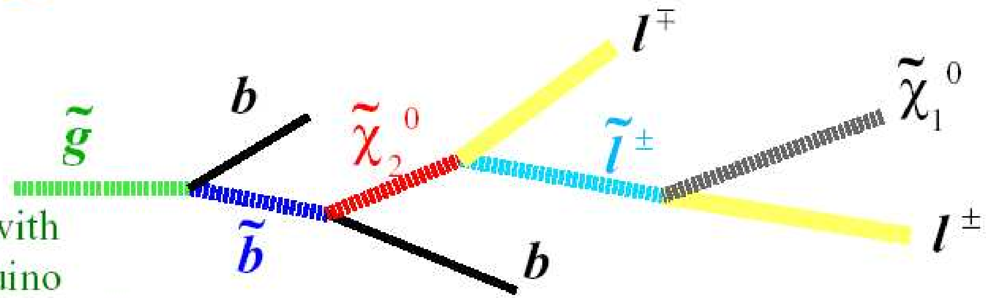
Distinctive signature of leptons, jets, missing E_T for some events

J. Rohlf, LHC IV p. 23

SUSY MET+jets



Sparticle Reconstruction



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

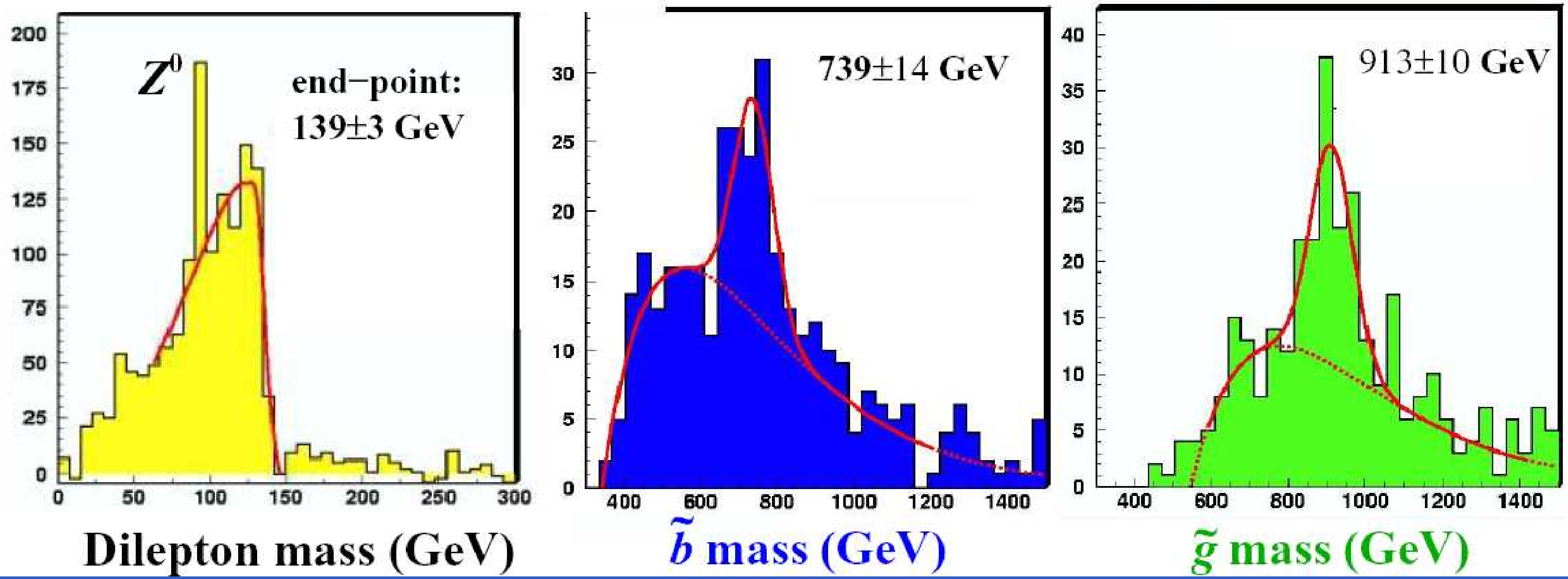
SM backgrounds:

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

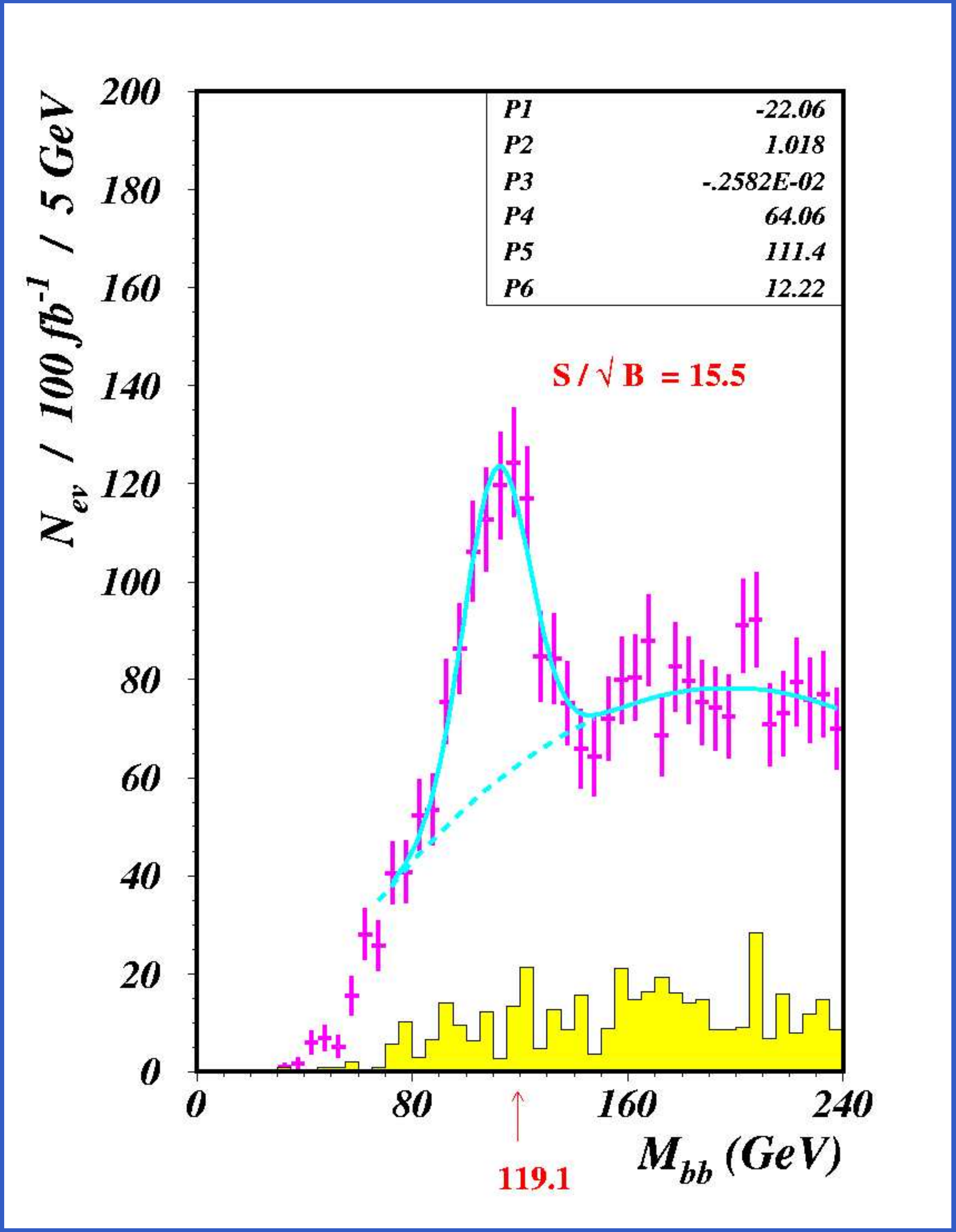
Example: $m_{1/2}$ = 375 GeV, m_0 = 120 GeV, tanβ = 20

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

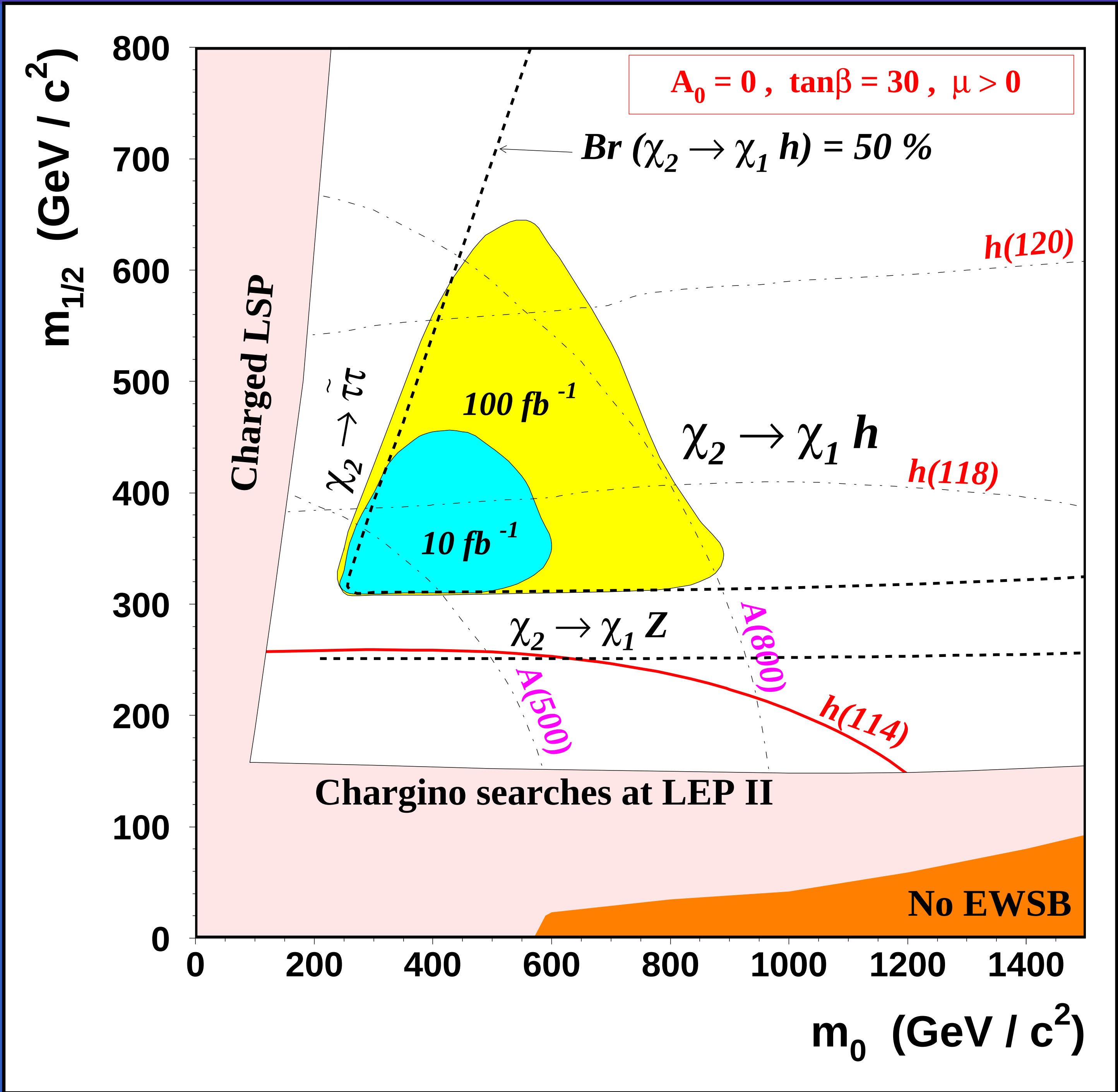
A. Tricomi *et al.*



MSUGRA Cascade $\chi_2 \rightarrow \chi_1 h \rightarrow \chi_1 b\bar{b}$



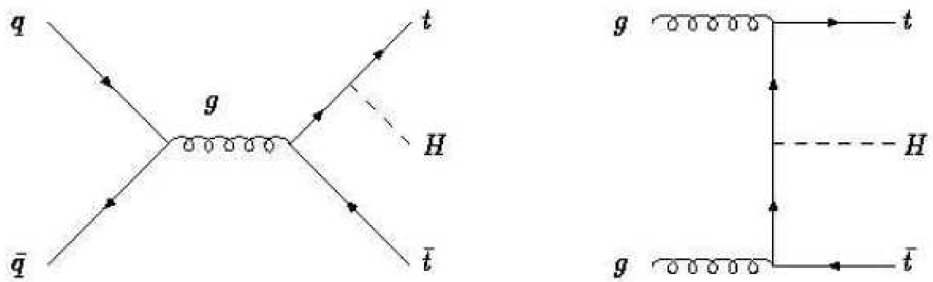
SUSY Reach $\chi_2 \to \chi_1 h \to \chi_1 b\bar{b}$



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

final state:

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



event selection:

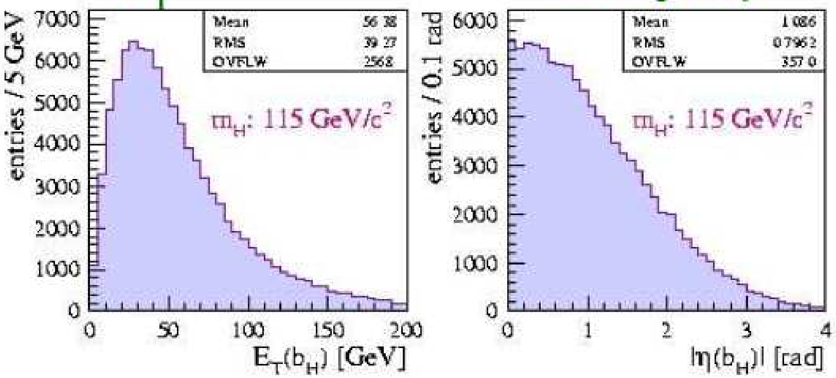
lepton, 4 *b*-tag jets, 2 non-*b* jets, *W* mass, *t* mass (2)

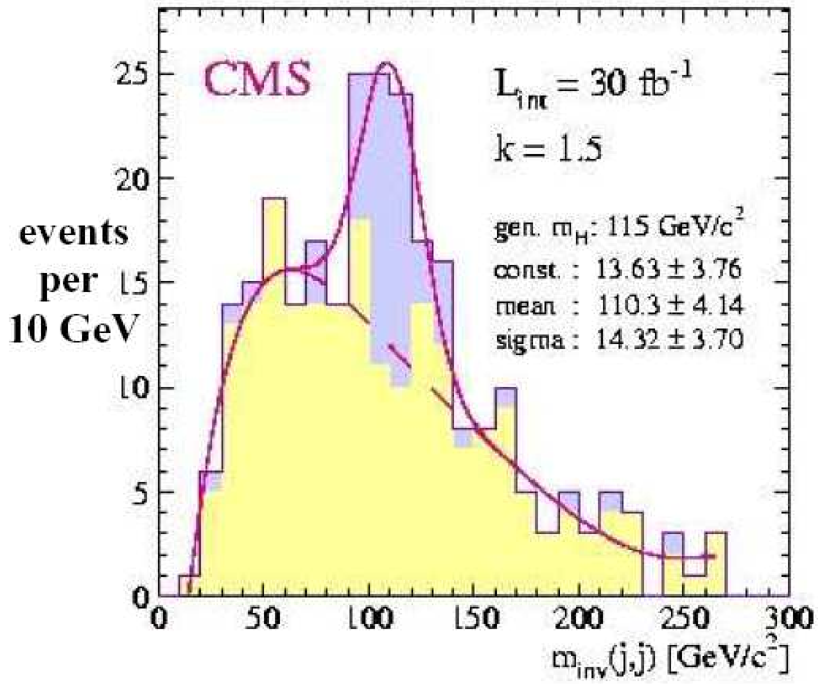
main backgrounds:

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

V. Drollinger *et al.*

b E_T **_b_ Rapidity**



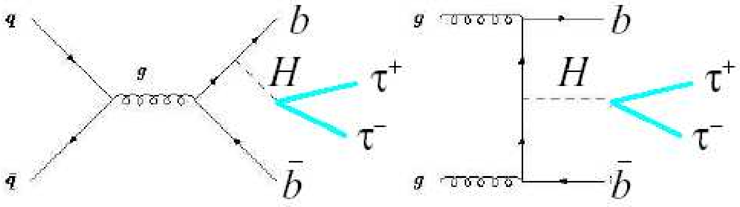


efficiency:

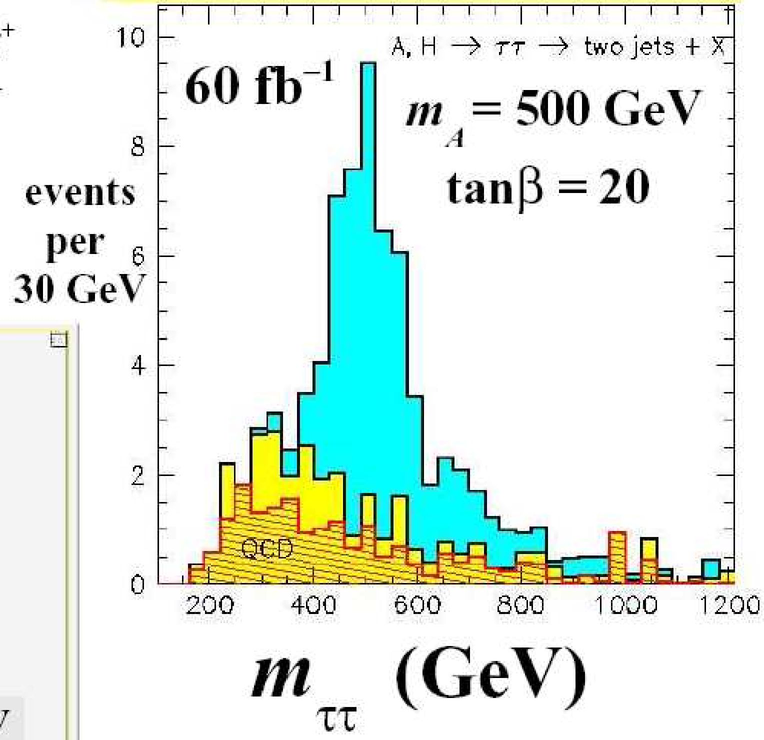
$t\bar{t}H$ (115 GeV)	1.3%
$t\bar{t}b\bar{b}$	0.4%
$t\bar{t}Z$	0.2%

J. Rohlf, LHC IV p. 9

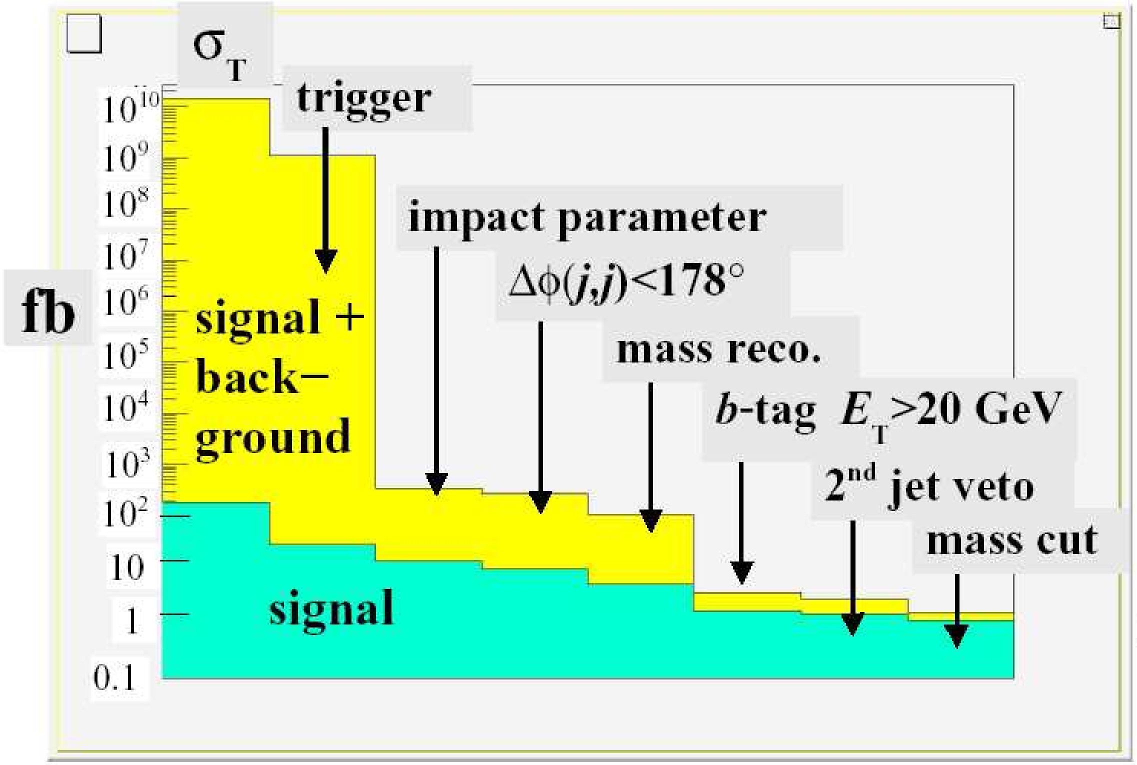
MSSM: $b\bar{b}H^0/A \to b\bar{b}\tau^+\tau^- \to b\bar{b}jj$



R. Kinnunen, A. Nikitenko



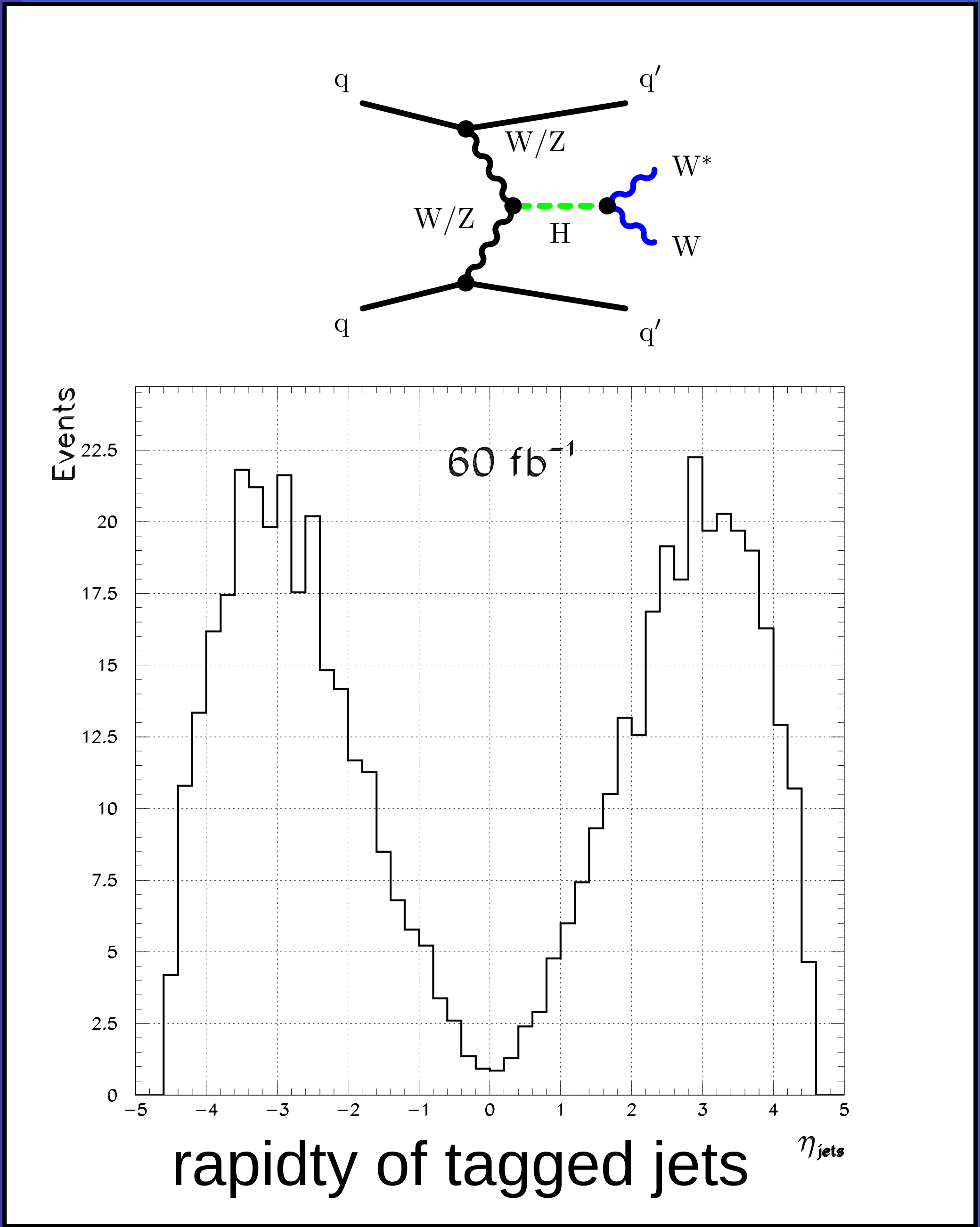
Background dominated by QCD

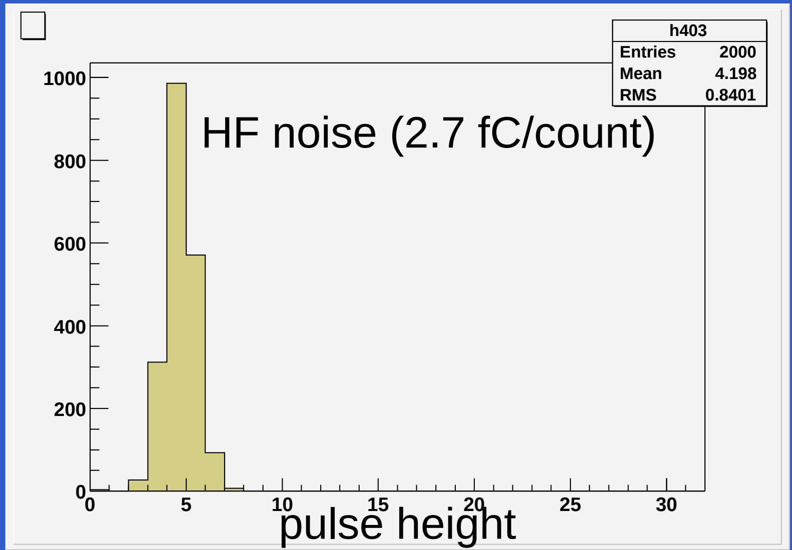


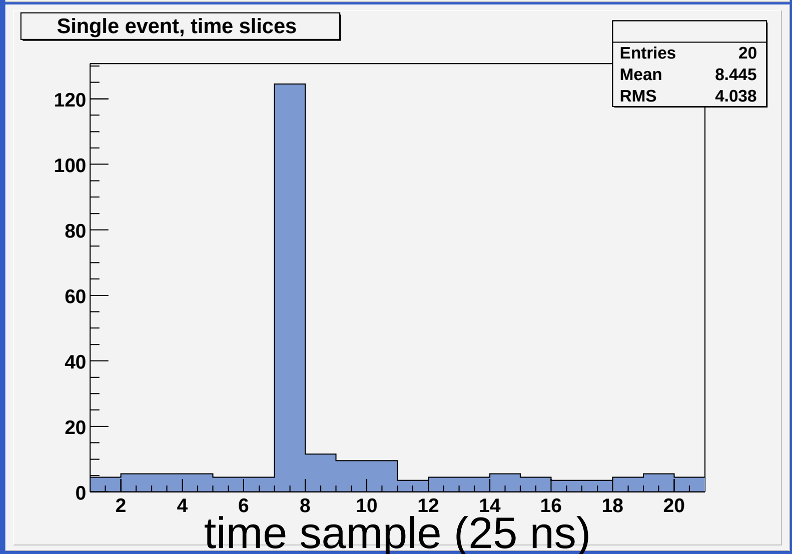
20% background from *W*, *Z*, top after cuts

J. Rohlf, LHC IV p. 15

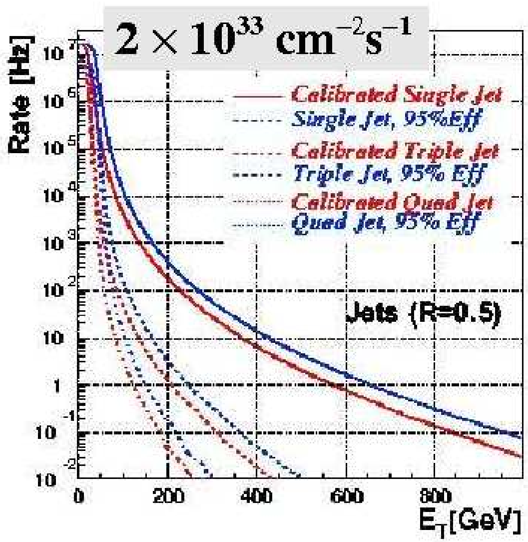
Vector boson fusion Forward cal. important!







$Z' \longrightarrow$ jet jet

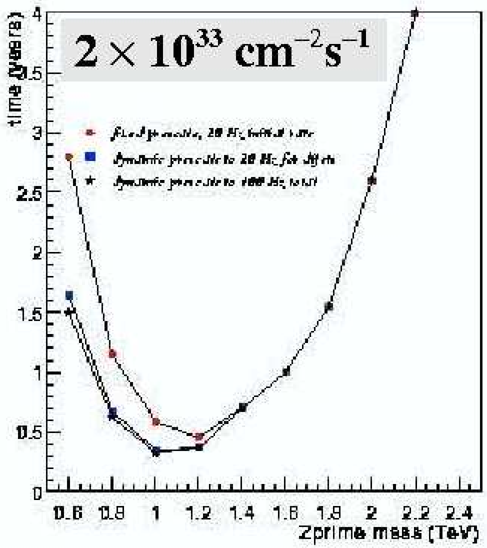


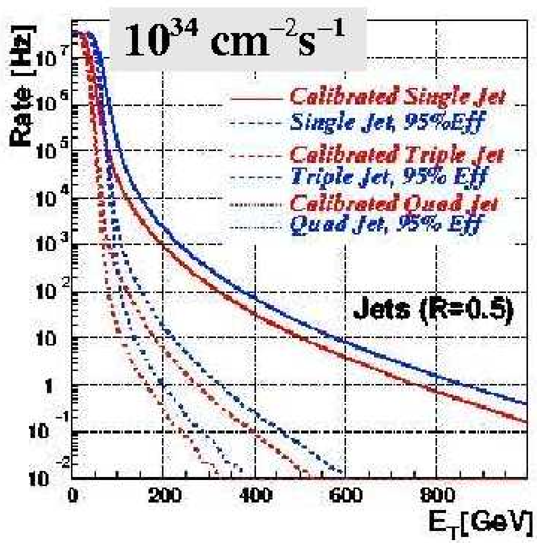
HLT will routinely discard 0.5-TeV jets!

95% efficient at E_T = 650 GeV

(prescale jets)

DAQ limited **Rate limited**

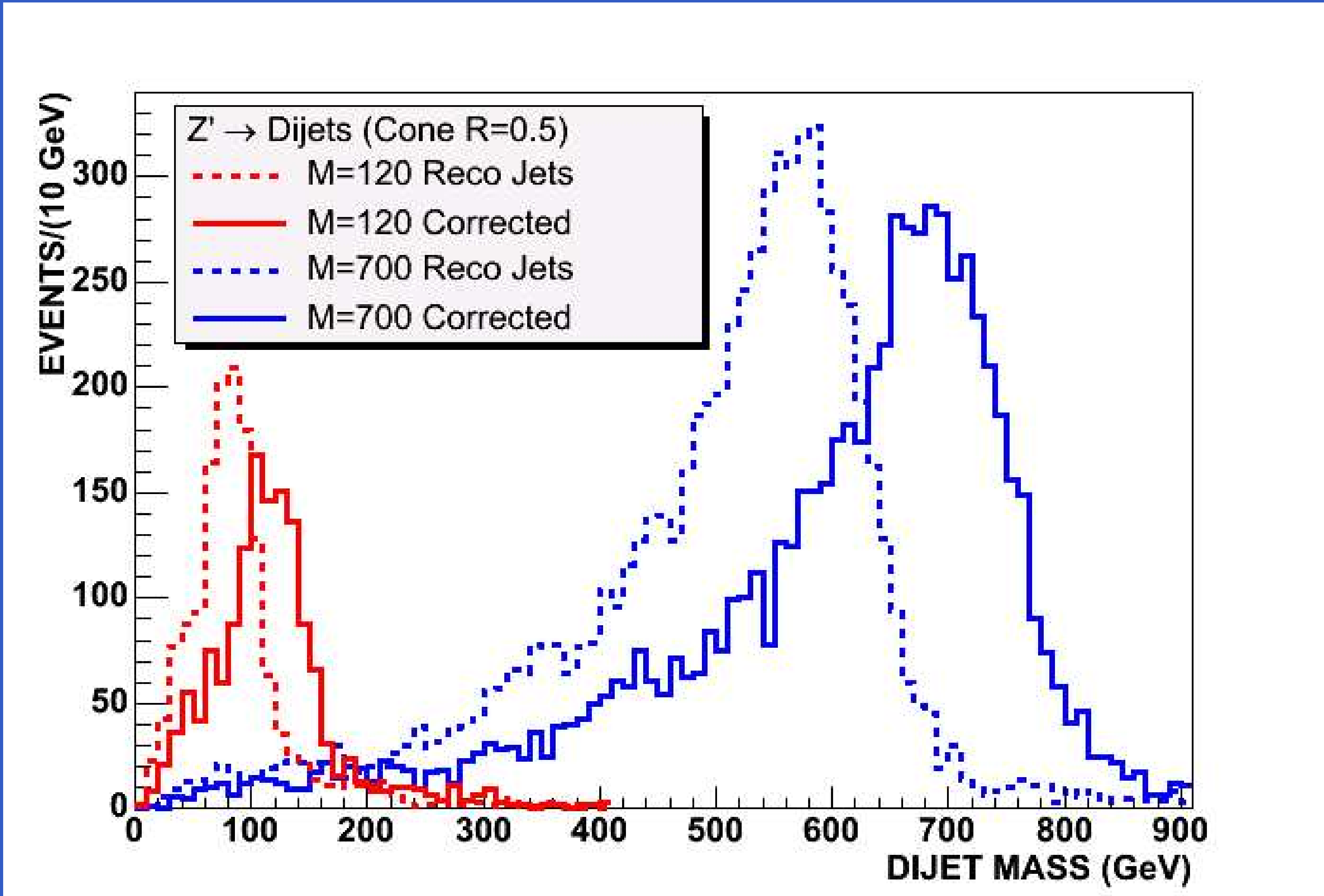




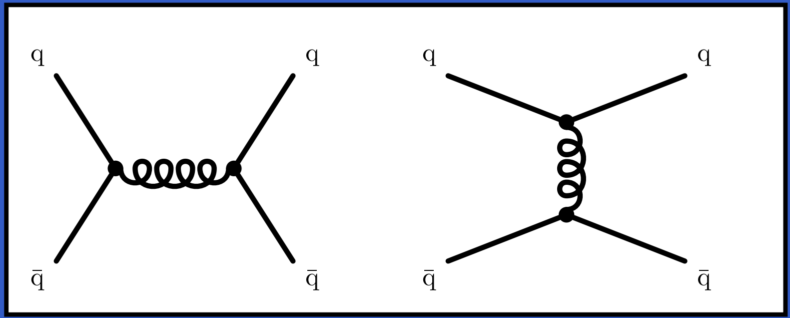
Problem is harder at design luminosity!

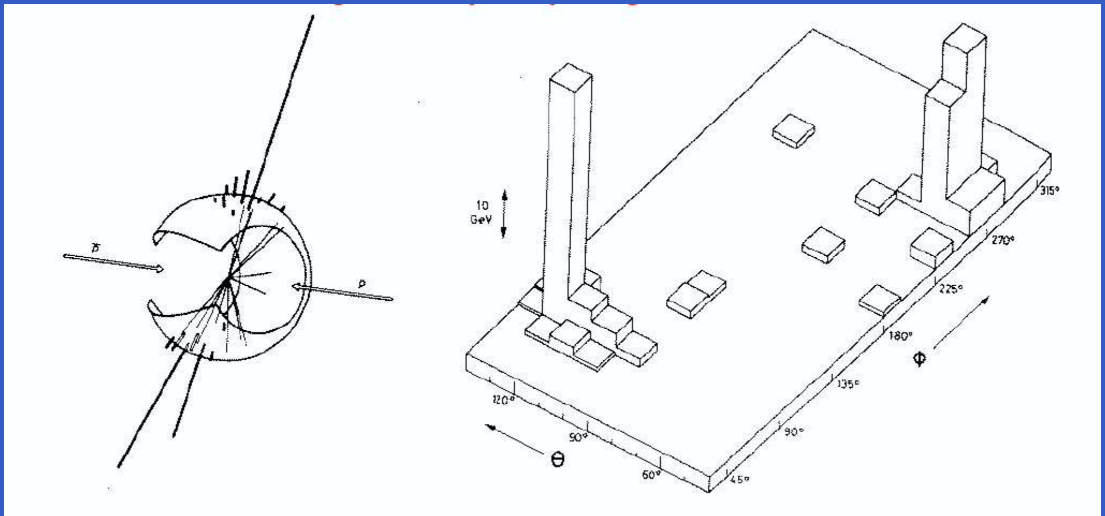
95% efficient at E_T = 860 GeV

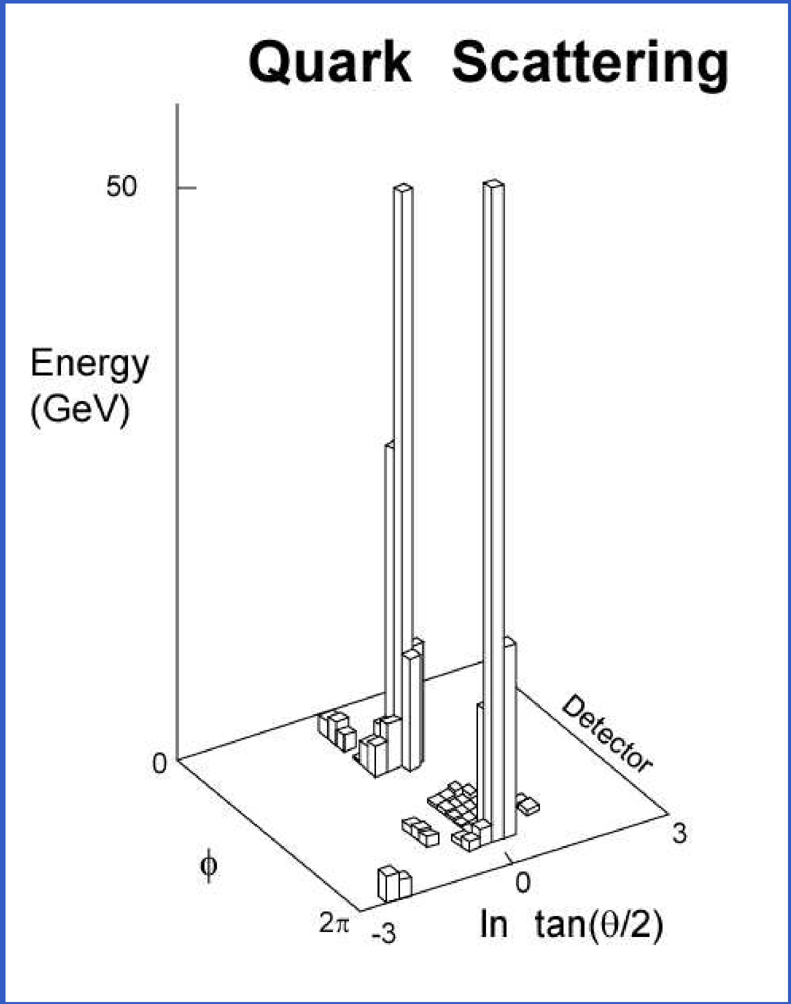
JetMET Dijet mass DC04 (R. Harris)



Asymptotic freedom CERN jet events 1982

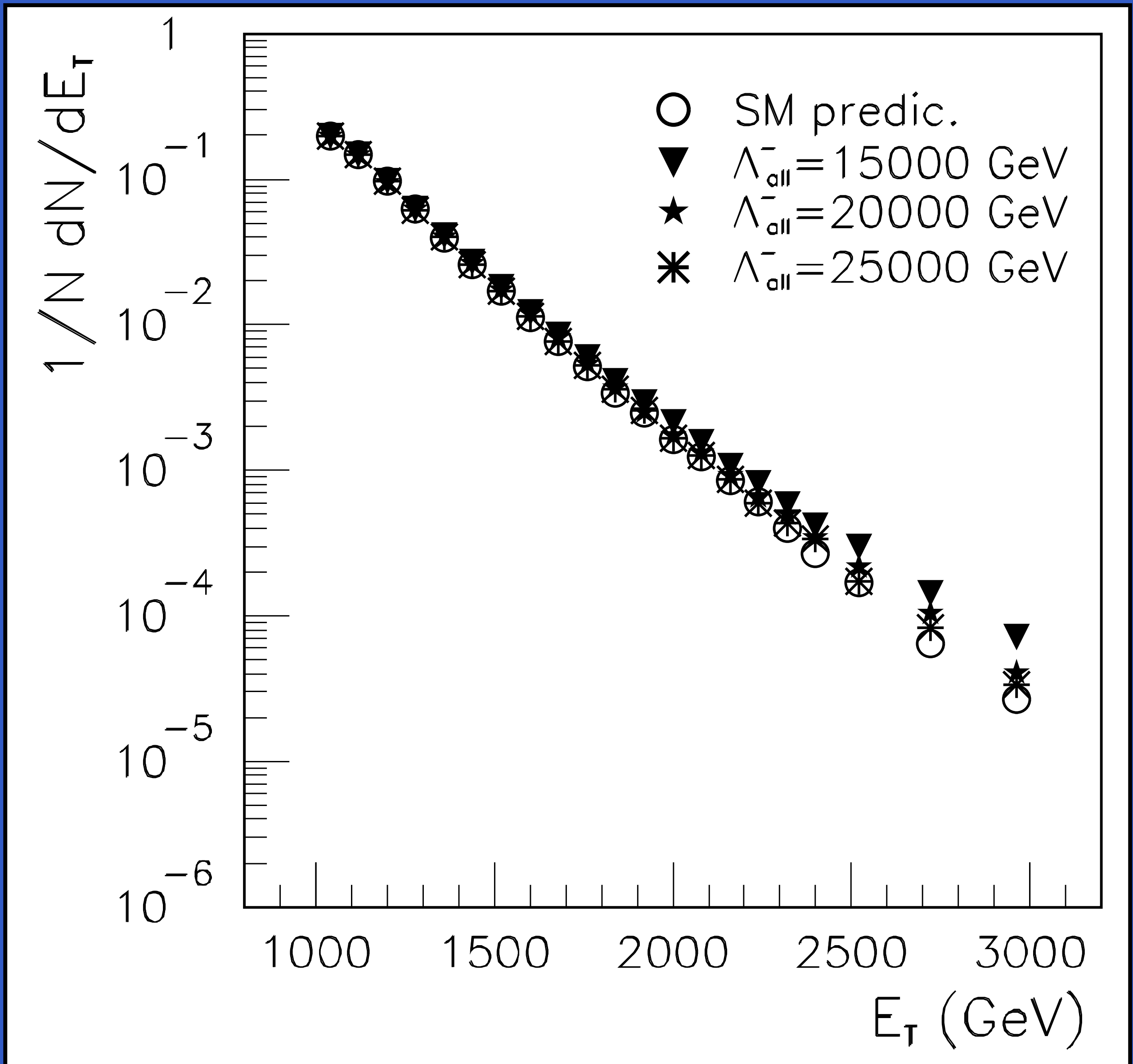


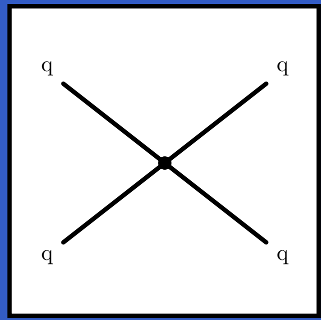




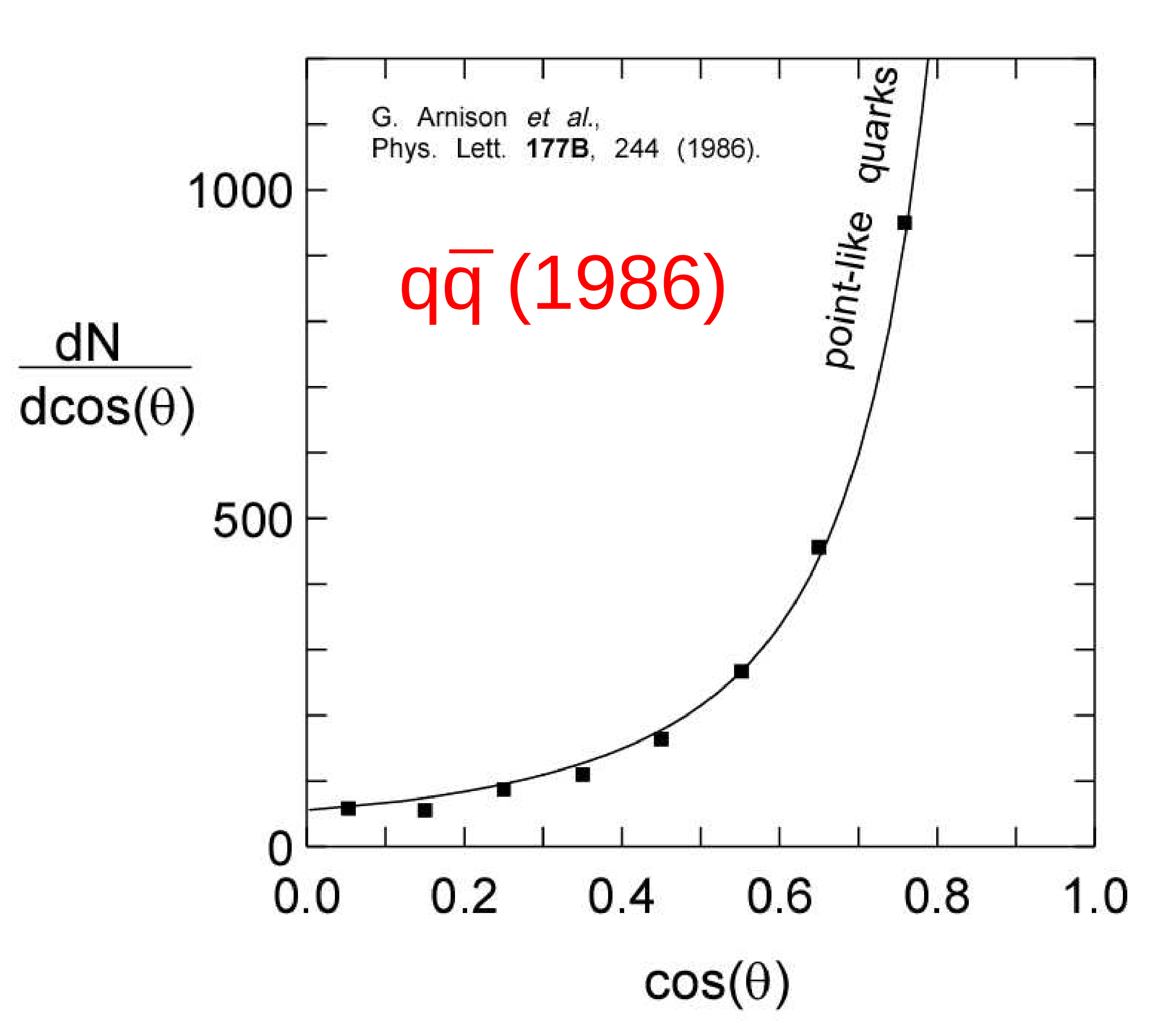
Compositeness

cross section gets a term $\frac{\hat{s}}{\alpha\Lambda^2}$





Scattering quarks 1986



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

demonstrating:

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

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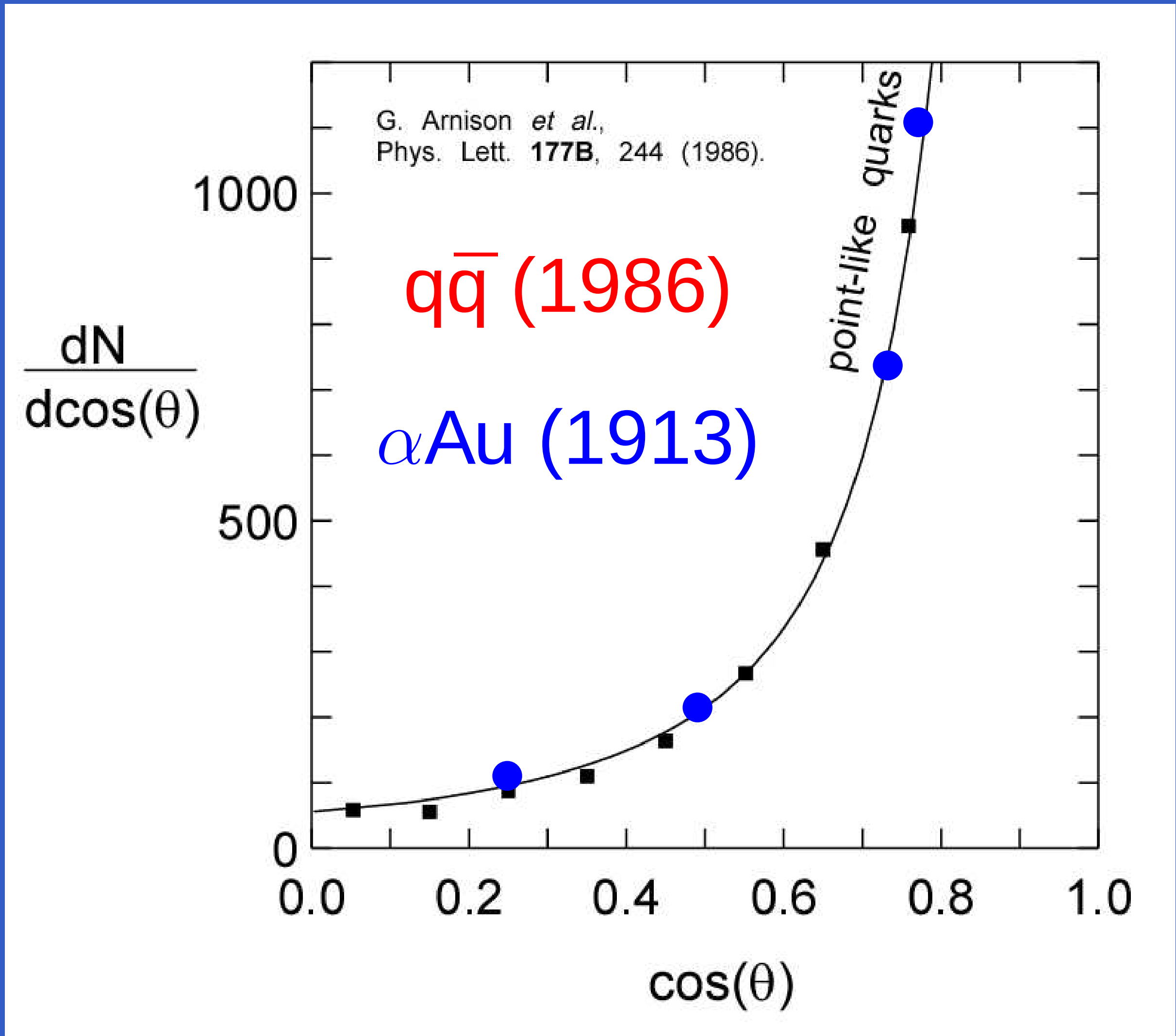

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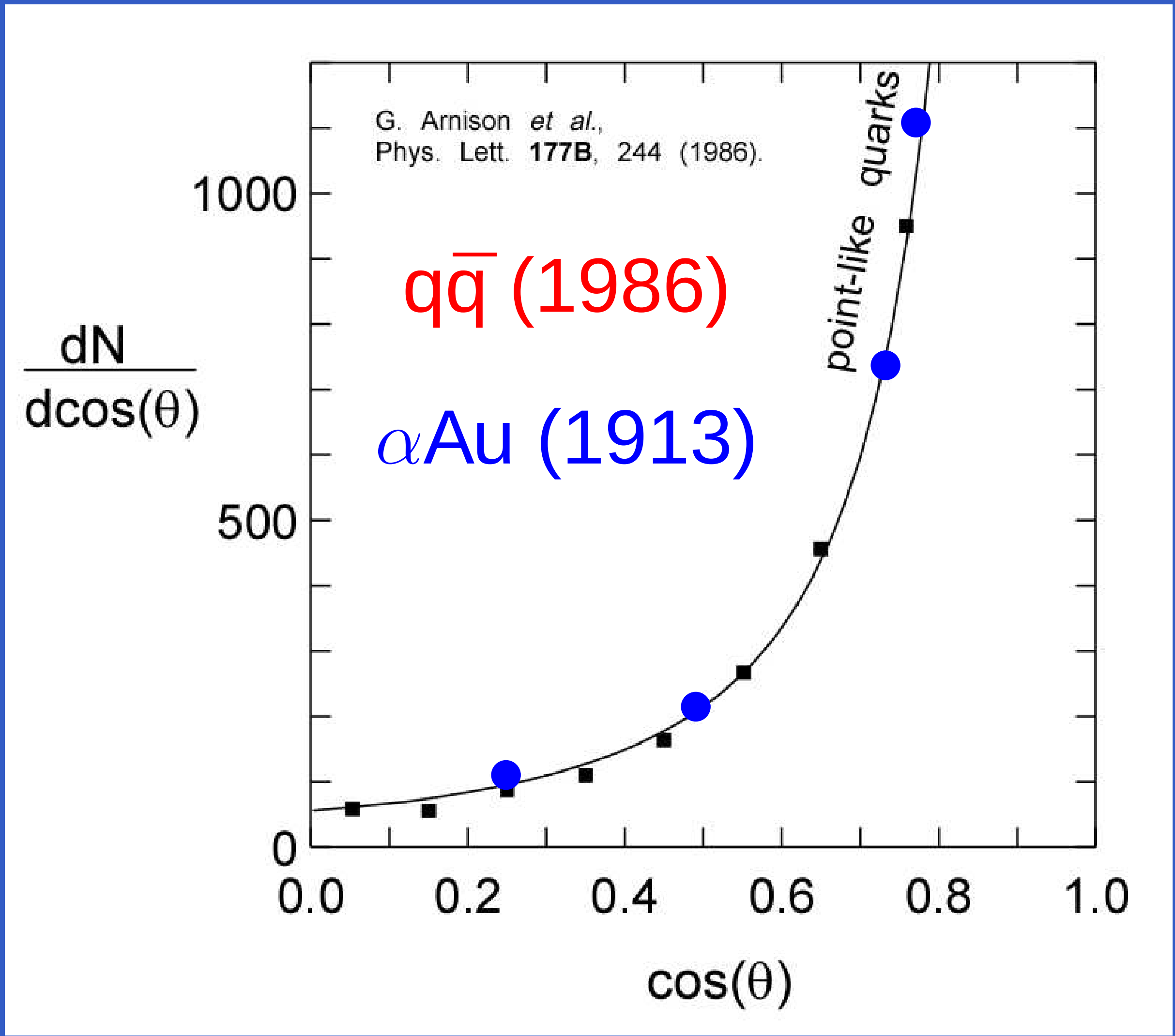
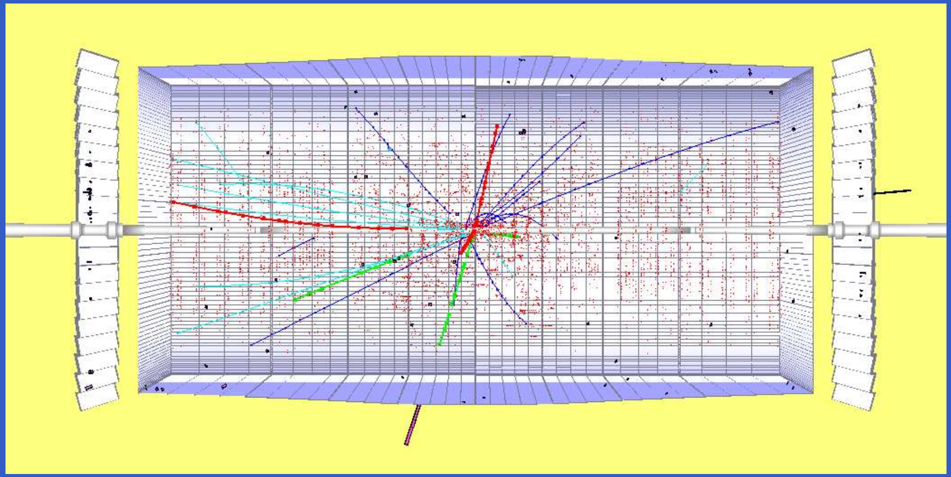
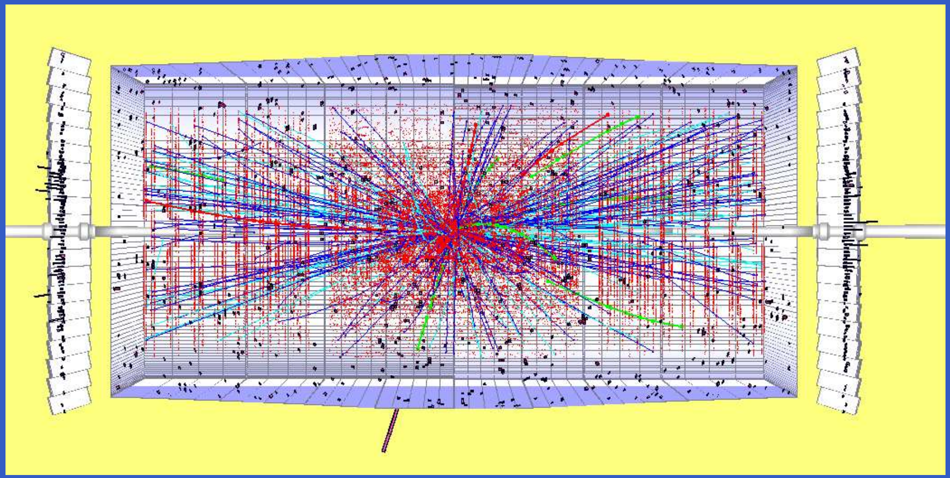


Pileup is important!

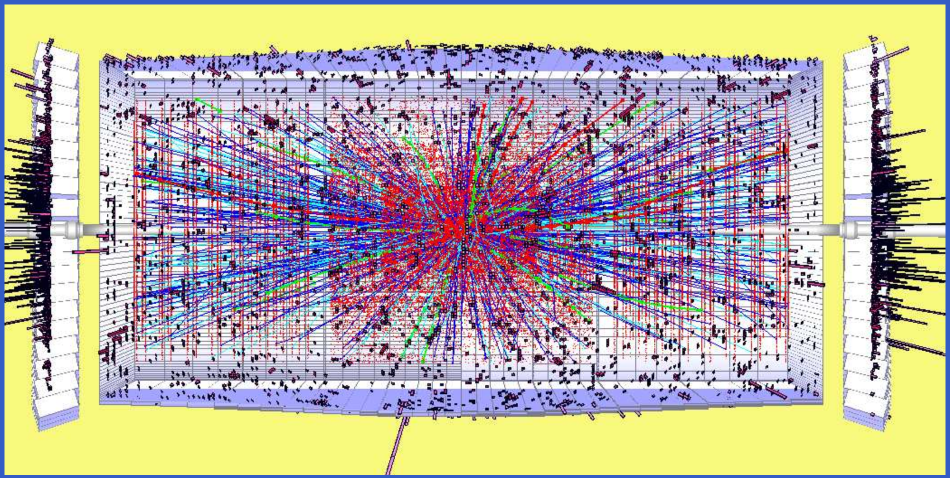
$10^{33}\ \text{cm}^{-2}\text{s}^{-1}$



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

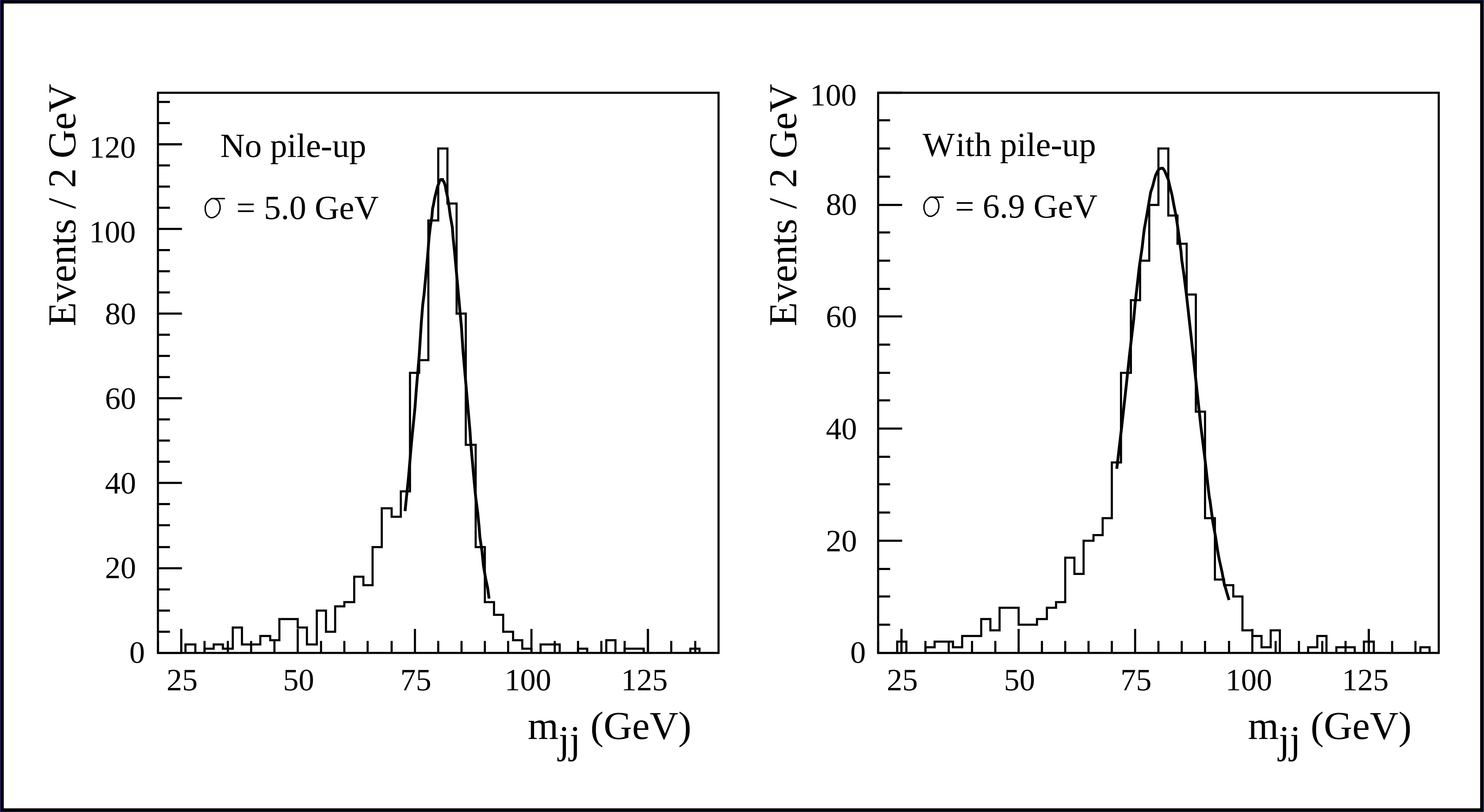


$10^{35}\ \text{cm}^{-2}\text{s}^{-1}$

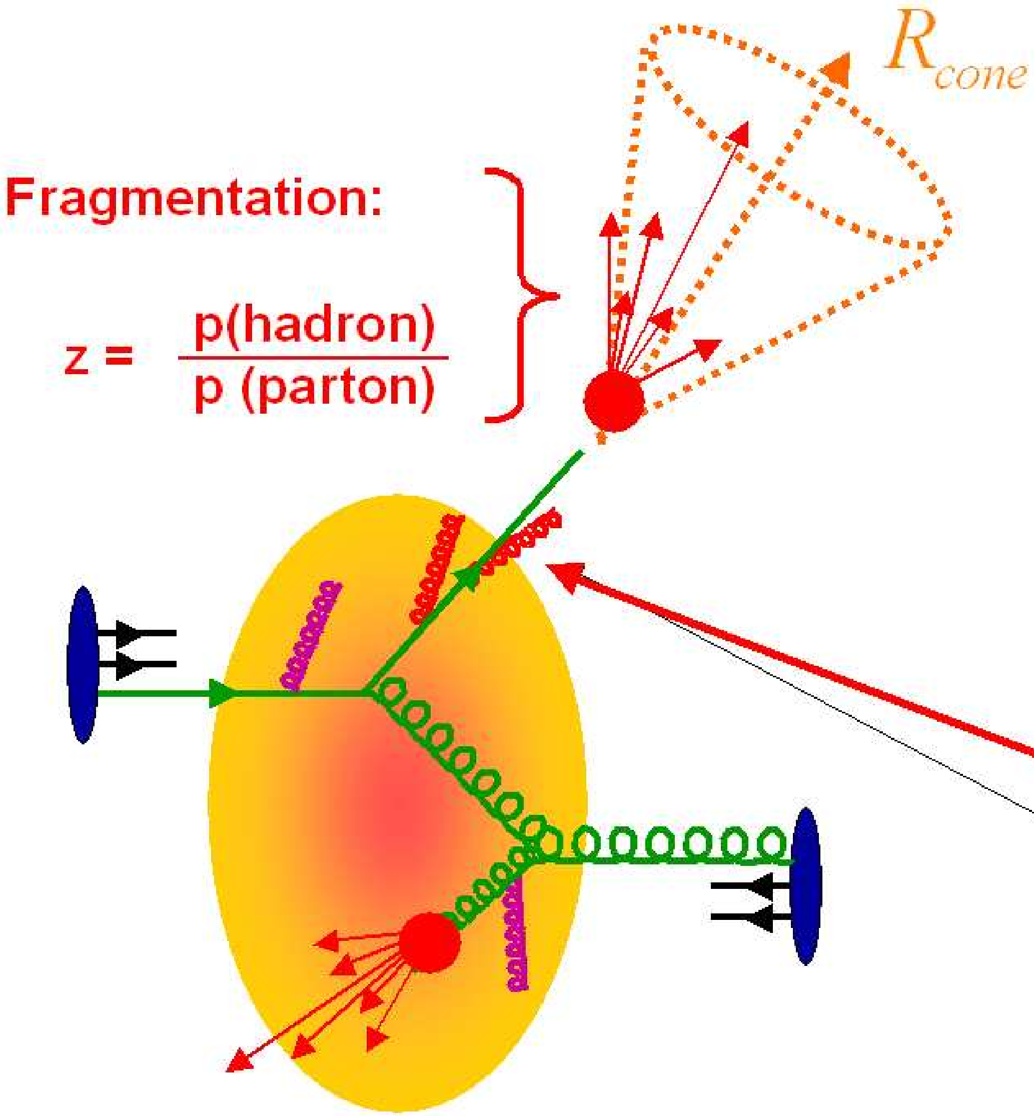


Effect of pilepup

Atlas: W→jj from top



Jets in Heavy Ion collisions



Hard probes $\Rightarrow$ early times

Calculable: pQCD

Abundant at RHIC, LHC

<u>k_T"radiative corrections"</u>

pre- and post-scattering

di-jet: $\Delta\phi \neq \pi$

<u>In QCD Medium</u>

Additional k_T

Significant energy loss?

$\Rightarrow$high p_T suppression

Sensitive to color properties of medium

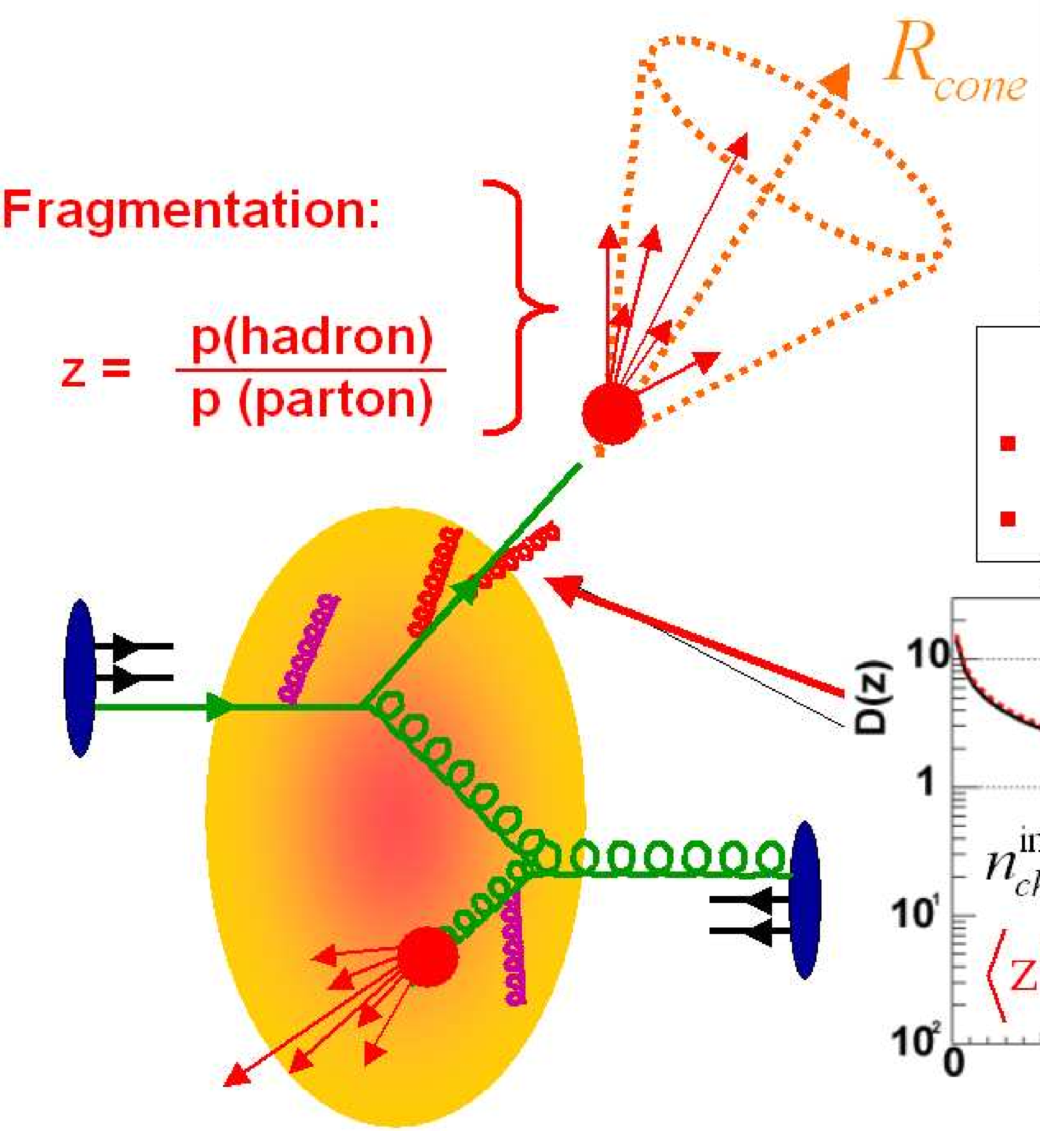
J. Harris, Vienna, July 2004

Jets in Heavy Ion collisions

Hard probes ⇒ early times

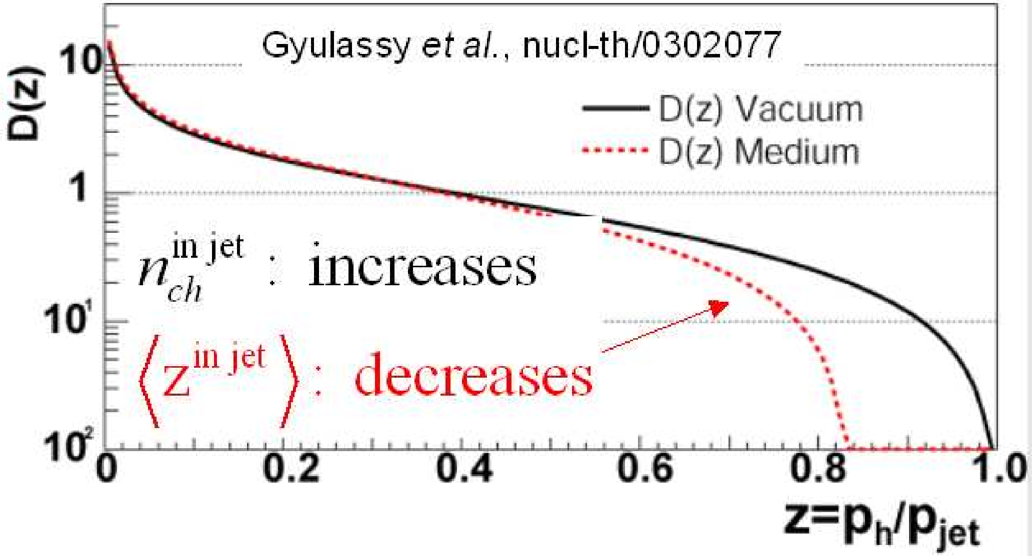
Calculable: pQCD

Abundant at RHIC, LHC



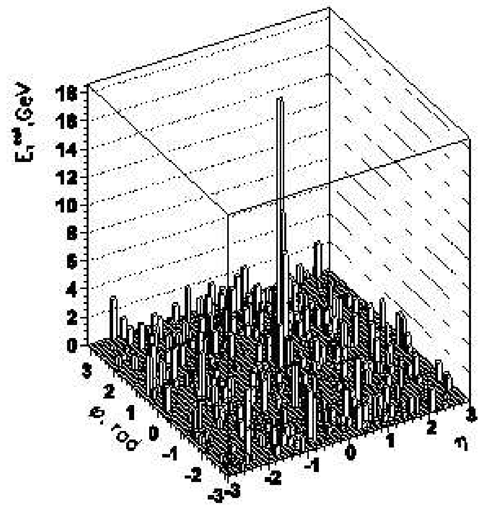
Induced Gluon Radiation

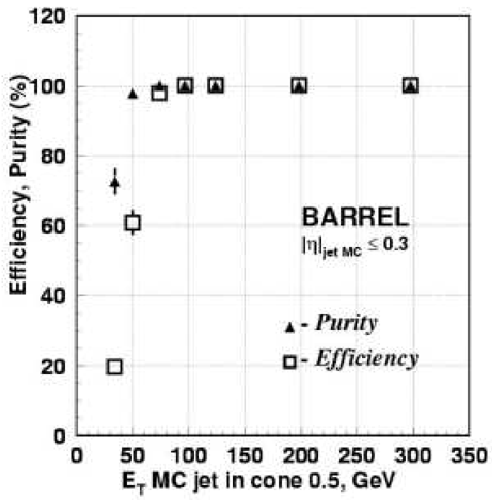
- ~collinear ⇒gluons in cone
- "Softened" fragmentation

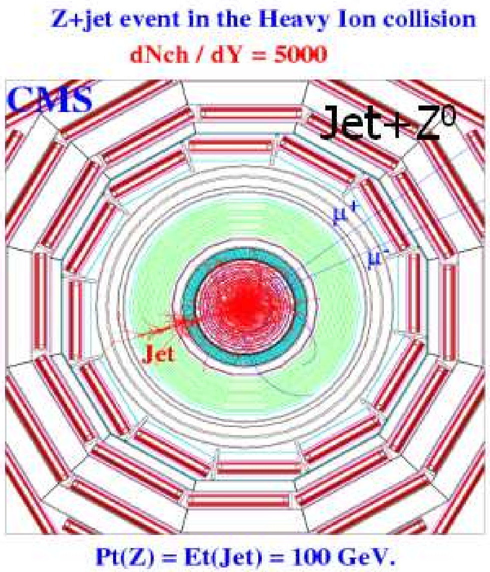


J. Harris, Vienna, July 2004

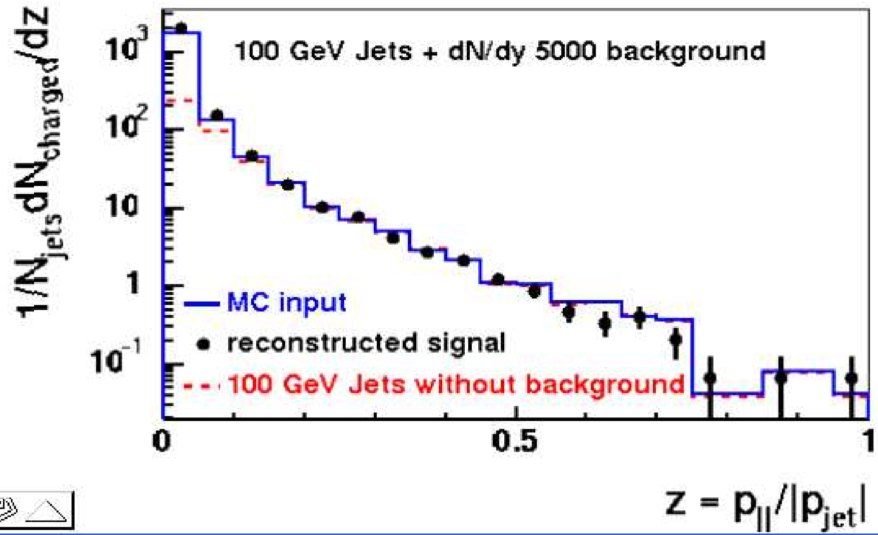
Jet identification and jet structure



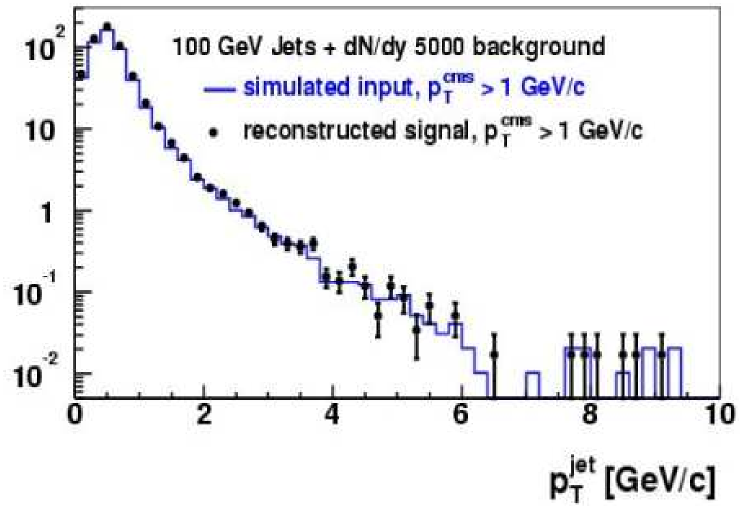




Longitudinal momentum fraction z along the thrust axis of a jet:



p_T relative to thrust axis:



VIII ISMD Kaysersberg, France, 1977

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C. Bromberg et al., COMPARISON OF HADRON JETS PRODUCED BY PI- AND P BEAMS ON HYDROGEN AND ALUMINUM TARGETS.
Kayserberg Conf.1977:B-89 (QCD161:C49:1977)

<u>What is a jet?</u> We use an empirical definition of a jet based on our apparatus: a jet is a cluster of particles with high p_t hitting our calorimeter. There are three components to this cluster: charged, electromagnetic neutral, and hadronic neutral. We require the jet vector, the vector sum of these components, to hit a fiducial area in the center of the calorimeter. The calorimeter acceptance for jets with properties described in Section I is discussed in Ref. 6.

There are a number of problems with this jet definition. A jet associated particle can miss the calorimeter, thus changing the magnitude and direction of the jet vector. In some cases the direction will change enough to move the jet vector from outside the fiducial area into the fiducial area or vice-versa, thus changing the cross-section. Another problem is a non-jet associated particle hitting the calorimeter, thus adding to the

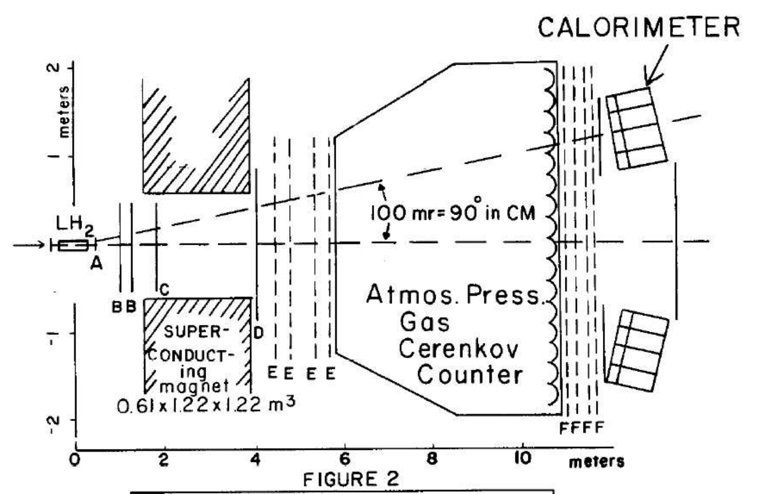
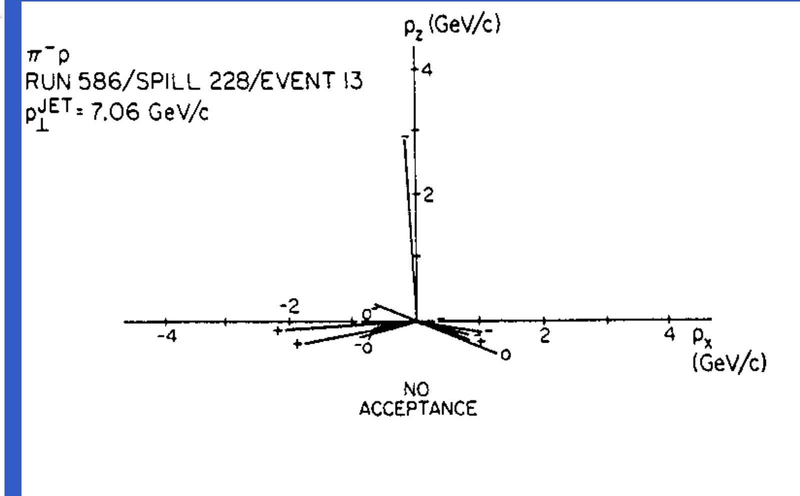
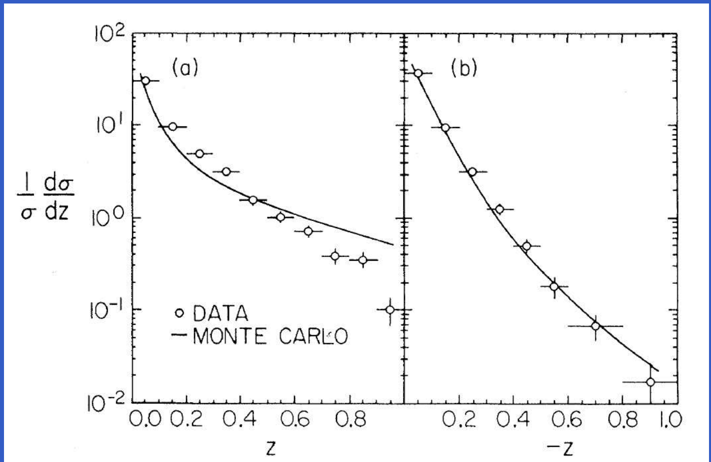


FIGURE 2

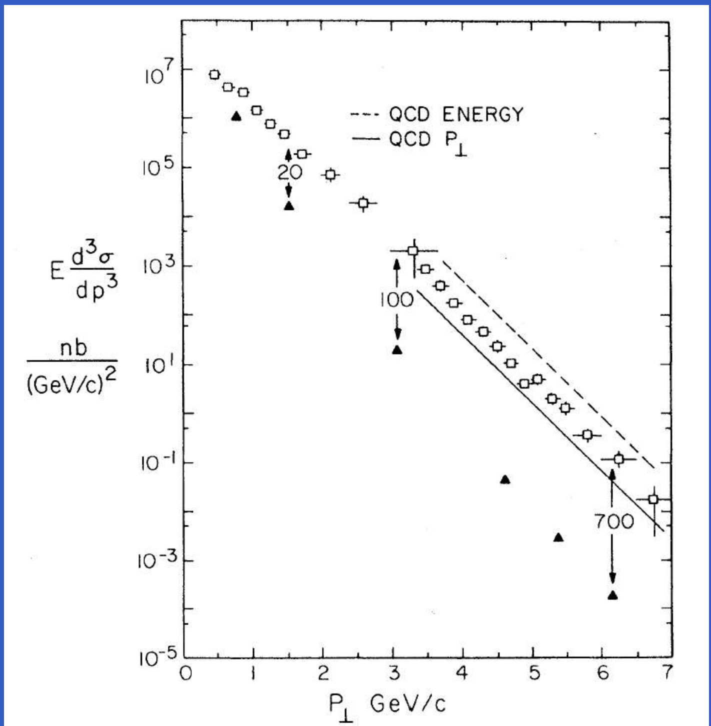


E260 First calorimeter jet trigger (1977)

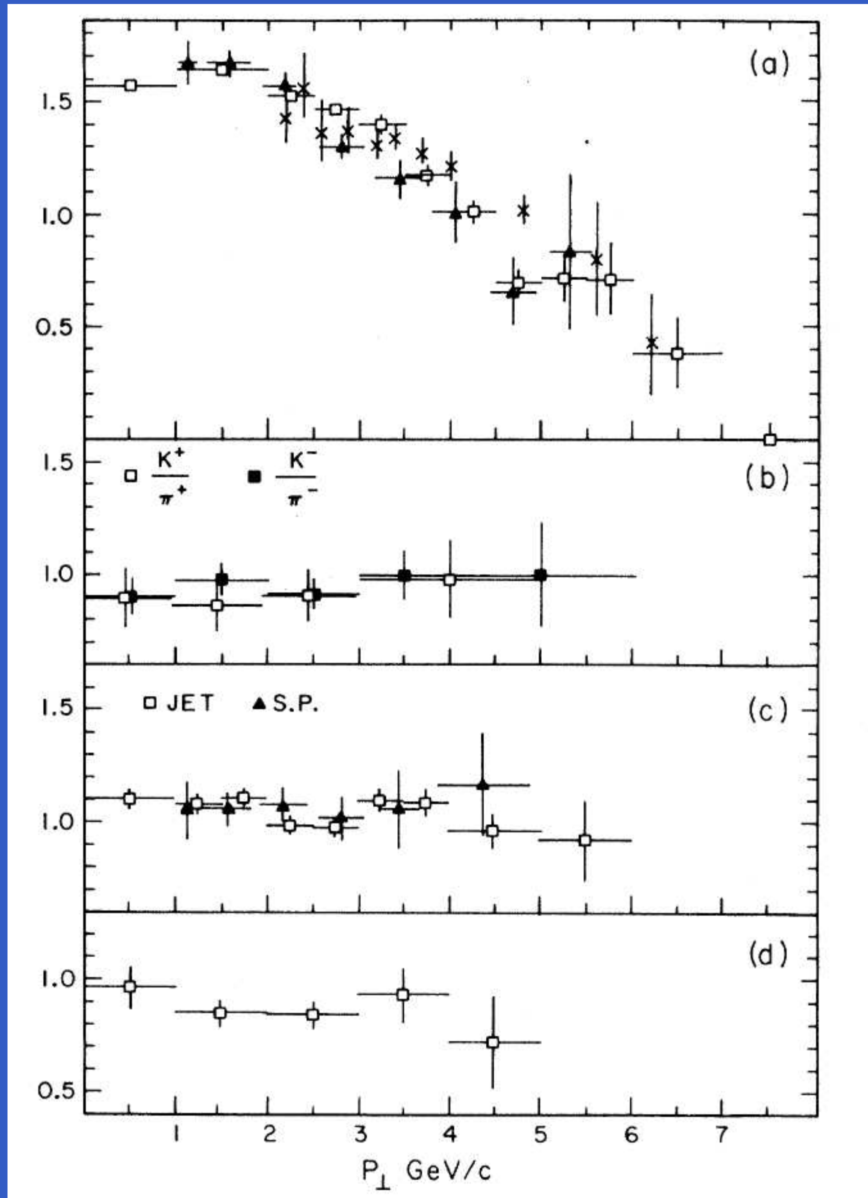
Field-Feyman fragmentation



QCD calculation (G. Fox)



$\sigma(\mathrm{pp} \to \mathrm{jet})/\sigma(\pi\mathrm{p} \to \mathrm{jet})$



XIII ISMD Volendam, 1982

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MEASUREMENT OF THE CHARM QUARK FRAGMENTATION FUNCTION. (TALK).
By J.W. Rohlf (Harvard U.),. 1982.
In *Volendam 1982, Proceedings, Multiparticle Dynamics 1982*, 589-596.

LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords
EXP CESR-CLEO

Summary

- Jets are an important part of LHC physics
  Higgs, SUSY, compositeness, and the UNKNOWN!
- Calibration and triggering will be challenging
- Relating measured jets to parton 4-vectors remains a central issue

If we are lucky, we may have an opportunity to do high-mass jet spectroscopy with high statistics... (top is both a calibration tool and a vicious background)

Predictions

Predictions

- The first physics papers from the LHC will be on jets.

    ISMD XXXVIII ?

    There will be a renewed interest in multiparticle dynamics at the TeV scale!

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- The first physics papers from the LHC will be on jets.
  ISMD XXXVIII ?
  There will be a renewed interest in multiparticle dynamics at the TeV scale!
- The results will be exciting (worth waiting for)!