The LHC machine-experiment interface (lecture 1)

Stefan Tapprogge

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Academic Training

CERN,

April 18, 2005

Experiment Machine Interface

- From Webster online (www.webster.com)
  - → Experiment
    - An operation carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law
  - → Machine
    - (1) An assemblage of parts that transmit forces, motion, and energy one to another in a predetermined manner
    - (2) An instrument designed to transmit or modify the application of power, force or motion
  - → Interface
    - (a) The place at which independent and often unrelated systems meet and act on or communicate with each other
    - (b) the means by which interaction or communication is achieved at an interface

Aims of this week's lecture series

- Various aspects of interfaces between LHC machine and five approved experiments
  - → Physics motivation and signatures
  - → Experiment design
  - → Machine and experiment operation
  - → Information interchange machine - experiments
- Talks
  - → MON: Physics topics and potential of LHC (ST)
  - → TUE: LHC experiments and requirements (ST)
  - → WED: LHC machine (R. Assmann)
  - → THU: Experimental zones (E. Tsesmelis)
  - → FRI: Machine-Experiment (D. Macina)

Contents for today

- Particle physics
  - → Where do we stand today?
- Physics motivation for the LHC
  - → Standard Model (SM) and beyond
- Snapshot on the LHC machine
- Search for (SM) Higgs boson
- Search for new physics
- B-hadron physics
- Studies of the strong interaction
- Summary

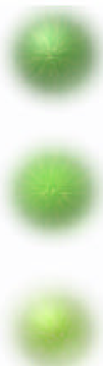
Particle physics

- Unravel nature's fundamental secrets
  - → Building blocks of matter ?
  - → Forces acting between these
- Important and significant progress over the last century (millenium)
  - → Development of the Standard Model of particle physics
    - Not complete
    - Not a final theory
    - Not fully explored

Matter and Forces

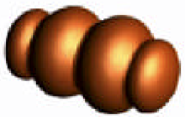
Leptons

	Electric Charge		
Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino



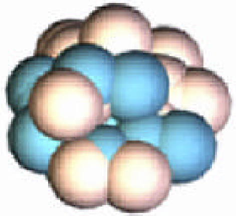
Strong

Gluons (8)



Quarks

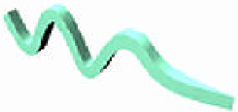
Mesons
Baryons

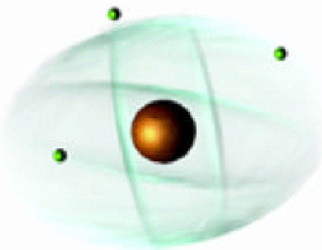


Nuclei

Electromagnetic

Photon





Atoms
Light
Chemistry
Electronics

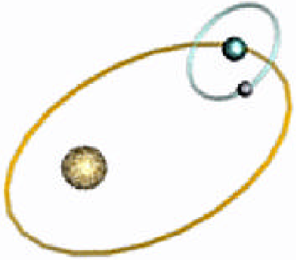
Quarks

	Electric Charge		
Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up

each quark: R, B, G 3 colors

Gravitational

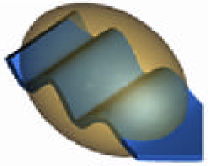
Graviton ?

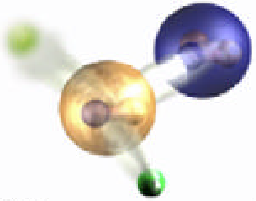


Solar system
Galaxies
Black holes

Weak

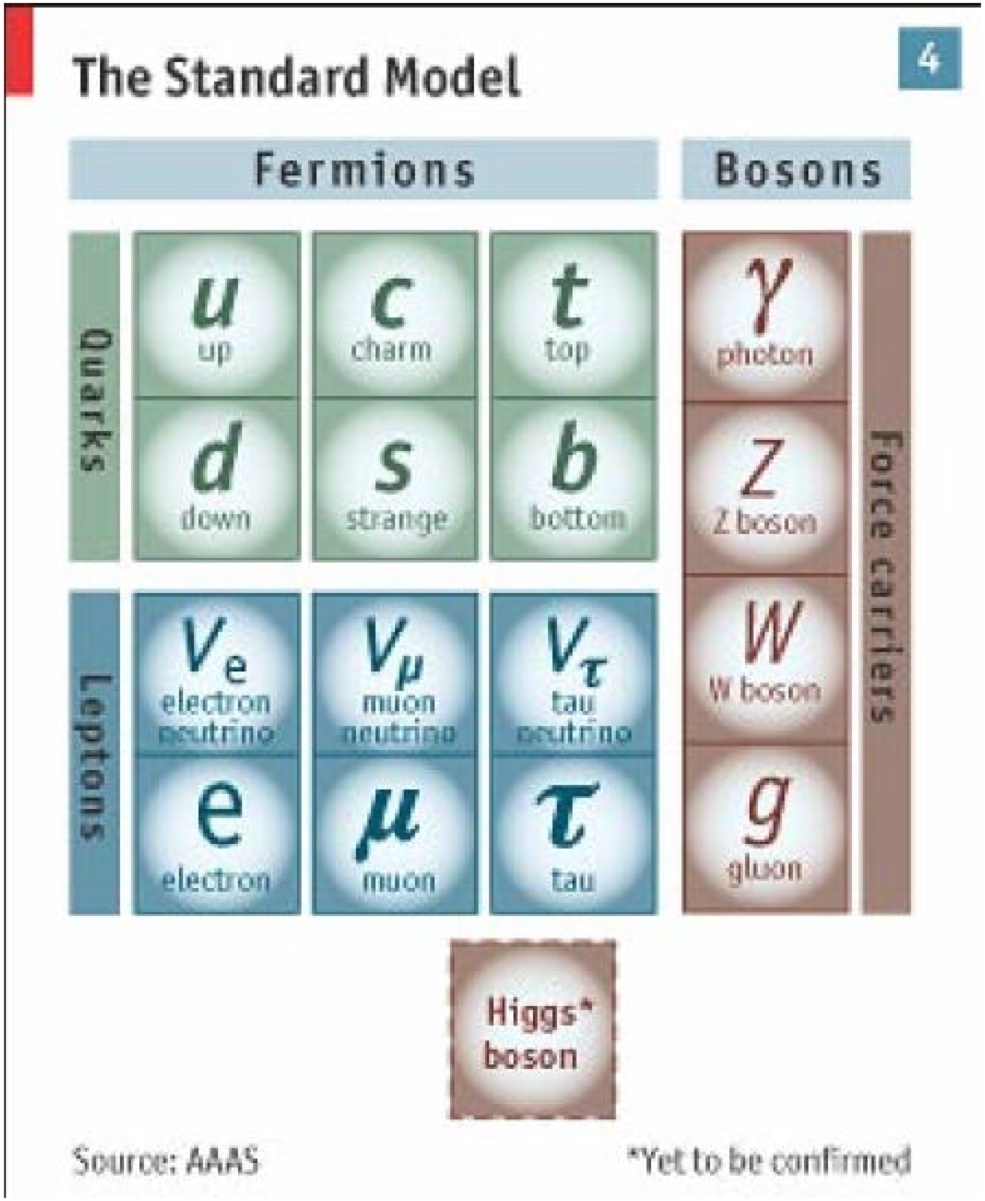
Bosons
(W,Z)





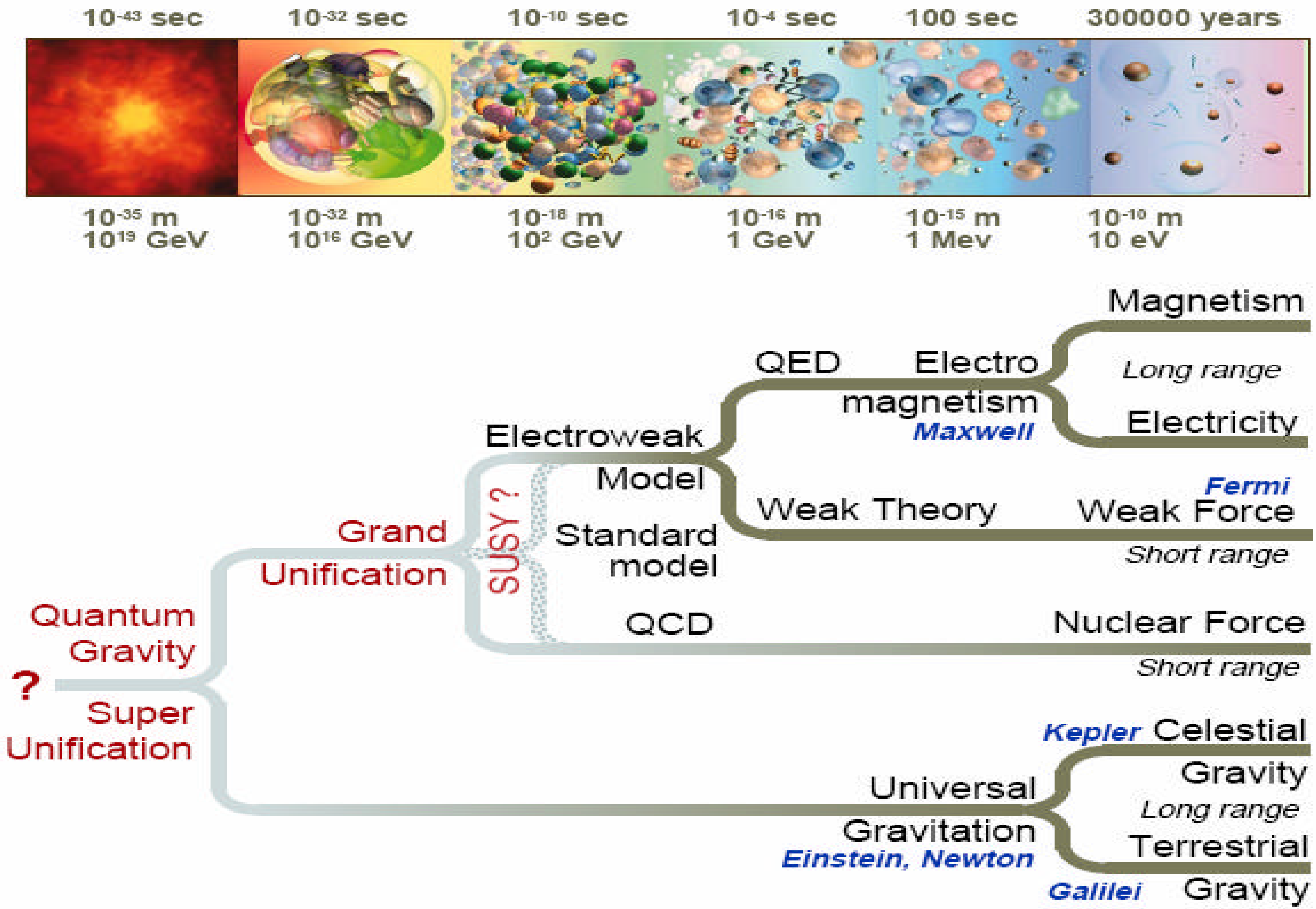
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

Standard-Model of Particle Phys.



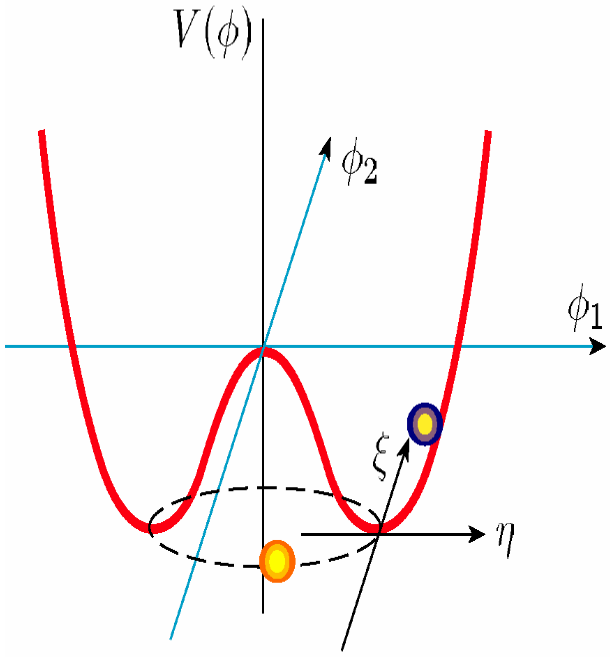
- Building blocks
  - → 3 families of fermions
    - Quarks
      - → 3 colour charges
    - Leptons
- Forces
  - → Mediated by bosons
    - Strong
    - Weak
    - Electromagnetic
- Technical terms
  - → Renormalizable quantum field theory
  - → Local gauge invariance
  - → Symmetries

Unification of Forces (?)



Missing piece in Standard Model

- Electroweak symmetry breaking
  - → Photon (carrier e.m. force) is massless
  - → W/Z Bosons (carrier weak force) are massive
    - LEP: M_Z = 91.1876 ± 0.0021 GeV (precision measurement!)
- Mechanism of electroweak symmetry breaking
  - → Higgs mechanism
  - → Add scalar field
  - → perform spontaneous symmetry breaking
    - Lagrangian has gauge symmetry
    - Ground state breaks symmetry
  - → keeps good properties of SM
    - Gauge invariance, renormalisability



Beauty of Standard Model

→ Hiding technical details using mathematical formalism

- Lagrangian Density

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}D\psi$$

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$

$$+|D_\mu h|^2 - V(h)$$

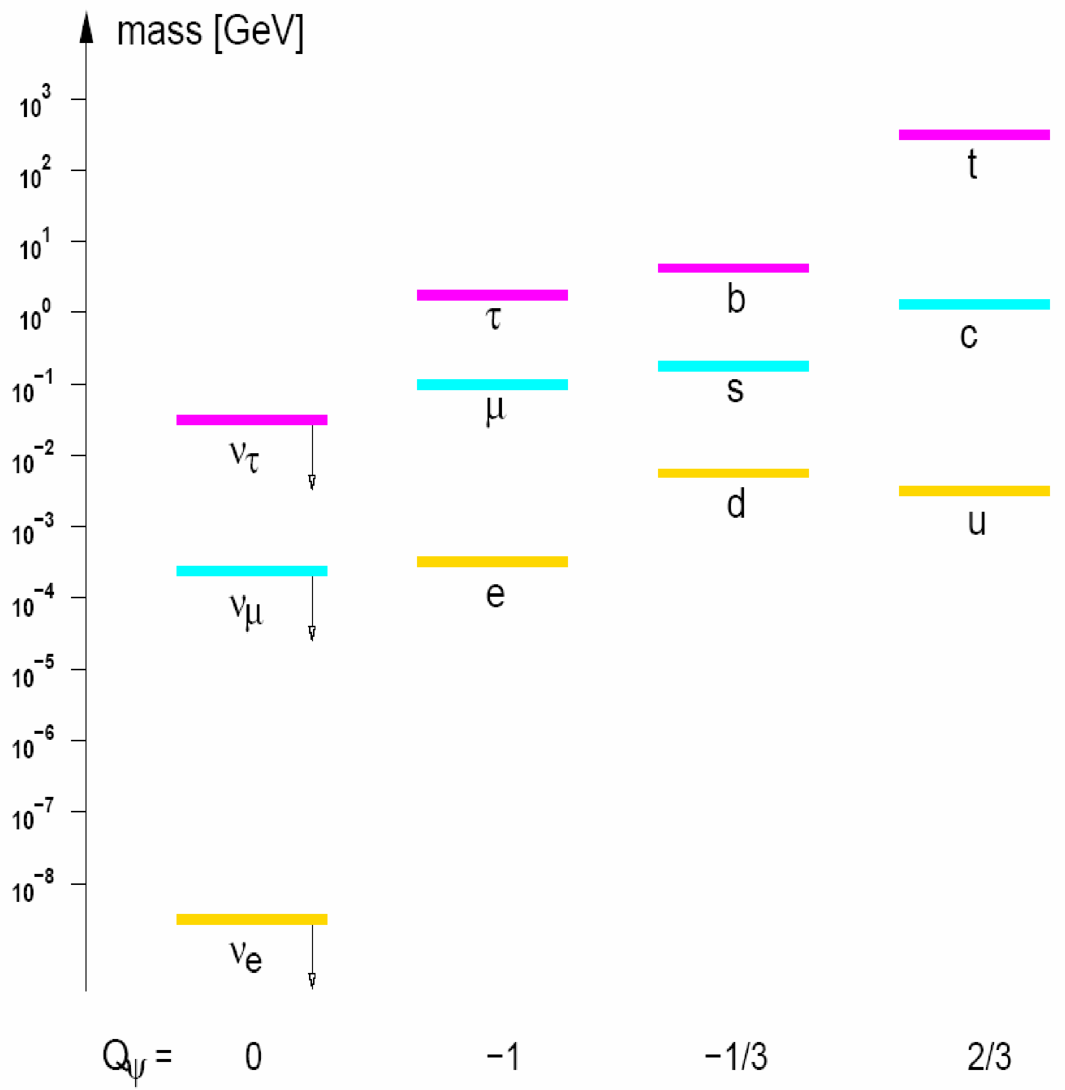
$$+\frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

- Gauge sector
- Flavour-Sector
- Electroweak Symmetry breaking
- (Neutrino-Masses)

$$D_\mu = \partial_\mu - i\,g_{\mathrm{EM}}YA_\mu - i\,g_{\mathrm{weak}}\frac{\tau^a}{2}W^a_\mu - i\,g_{\mathrm{strong}}\frac{\lambda^b}{2}G^b_\mu$$

Some open questions of SM

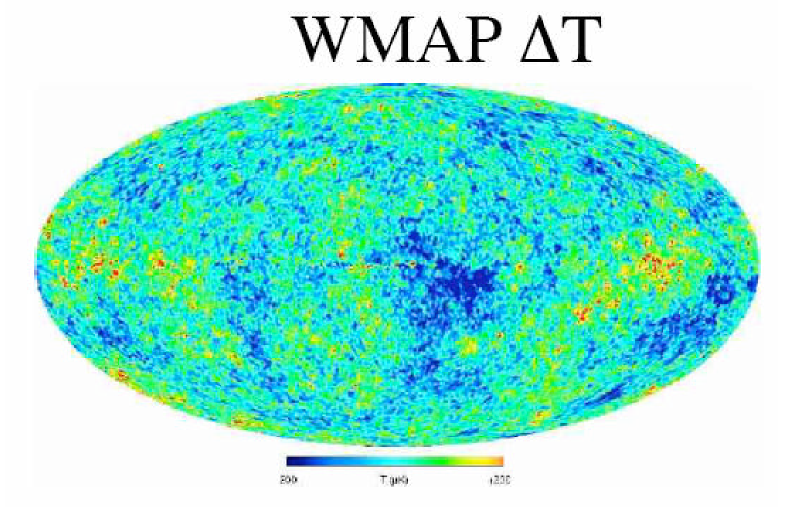
- Why 3 families of fermions?
- Why mass hierarchy?
- Unification of all forces?
- Dark matter and dark energy?
- Baryon asymmetry in Universe?
- Why quantisation of charge?
- ...

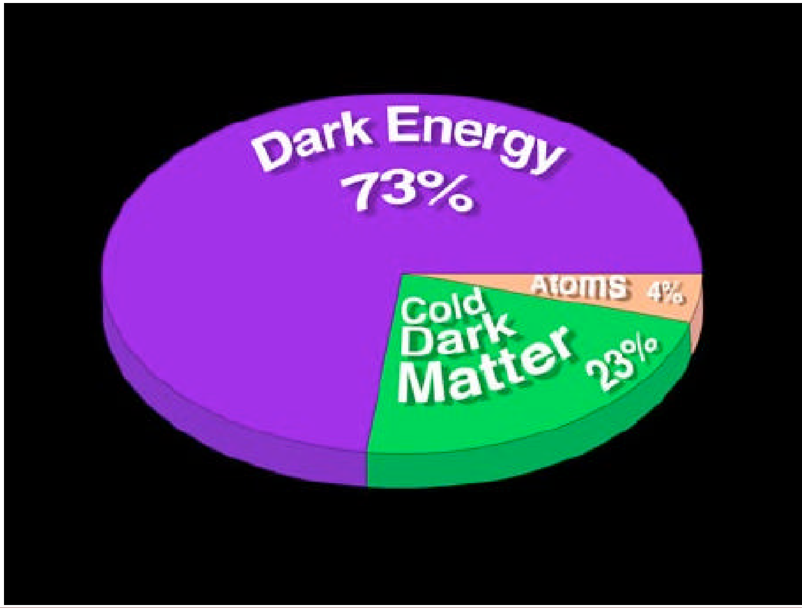


Dark Side of the Universe

→ See Acad. Train. Lecture by B. Sadoulet (June 2004)

- Fundamental problem in cosmology
  - → >99% of energy in universe is dark
  - → 96% in form of new matter/energy
- Links to particle physics
  - → Best way to study new matter and its properties
    - production under controlled conditions
  - → high energy colliders





Physics motivations for LHC

- Understand origin of electroweak symmetry breaking
  - → Find missing piece: Higgs boson (or something else)
    - Major motivation to approve and build LHC
- Discover and understand properties of new forms of matter (and forces?)
  - → Evidence (indirect) has increased over the last years
  - → Standard Model is incomplete (gravitation not included)
    - Search for a more fundamental theory (unification of forces)
- Understand more about CP violation
  - → B-hadron system
  - → Possibility to find (indirect) evidence for new physics
- Detailed studies of the strong interaction
  - → In (as yet) unexplored regions of phase space
  - → Highest densities, energies, ...

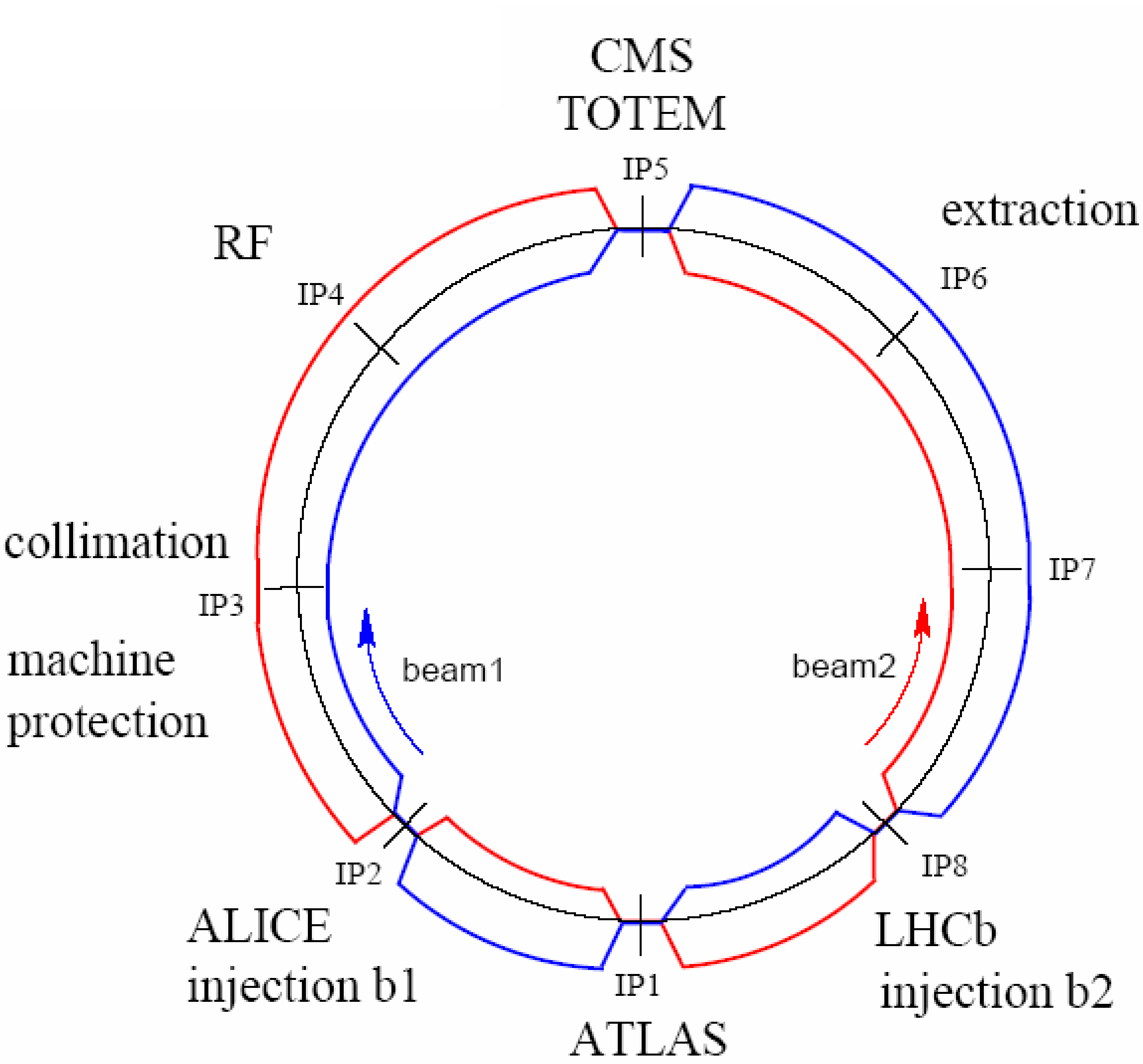
LHC machine

→ Many more details in the lecture of R. Assmann (WED)

- LHC is a multi-purpose storage ring
  - → p p: $\sqrt{s}$ = 14 TeV with L = 10^{34} cm^{-2} s^{-1}
    - $\sqrt{s}$ down to 1.8-2 TeV possible (comparison with Tevatron)
  - → A A: $\sqrt{s_{NN}}$ = 5.5 TeV for PbPb with L = 10^{27} cm^{-2} s^{-1}
    - possibly other ions, e.g. A = Sn, Kr, Ar, O
  - → p A: L ranges between $7.4 * 10^{29}$ $cm^{-2}s^{-1}$ - 10^{31} $cm^{-2}s^{-1}$

- Figure-of-merit: Integrated luminosity ? Ldt
    - remember $N_{event} = \sigma *$? Ldt
  - → Initially typically 10 fb^{-1} per year for pp collisions
  - → Nominally about 100 fb^{-1} per year for pp collisions

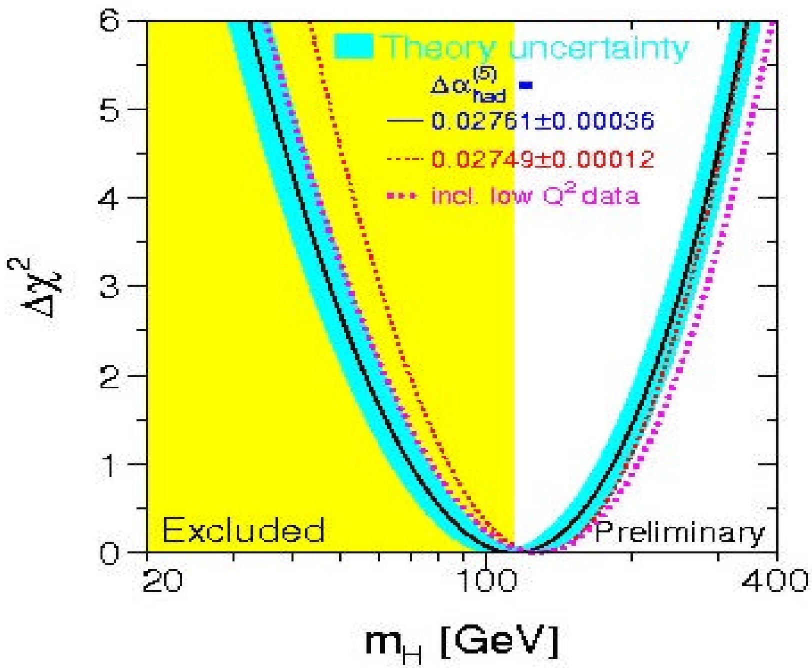
LHC layout and experiments



- 4 interaction points used by 5 approved experiments
  - → Additional letters of intent exist
    - Moedal, LHCf, ATLAS forw. det. for luminosity
- ATLAS, CMS
  - → General purpose
- LHCb
  - → Dedicated for B-physics
- ALICE
  - → Dedicated for heavy ions (+using pp, pA)
- TOTEM
  - → Strong interaction

Expectation for SM Higgs Boson

- Precision measurements of electroweak observables
  - → Very good consistency



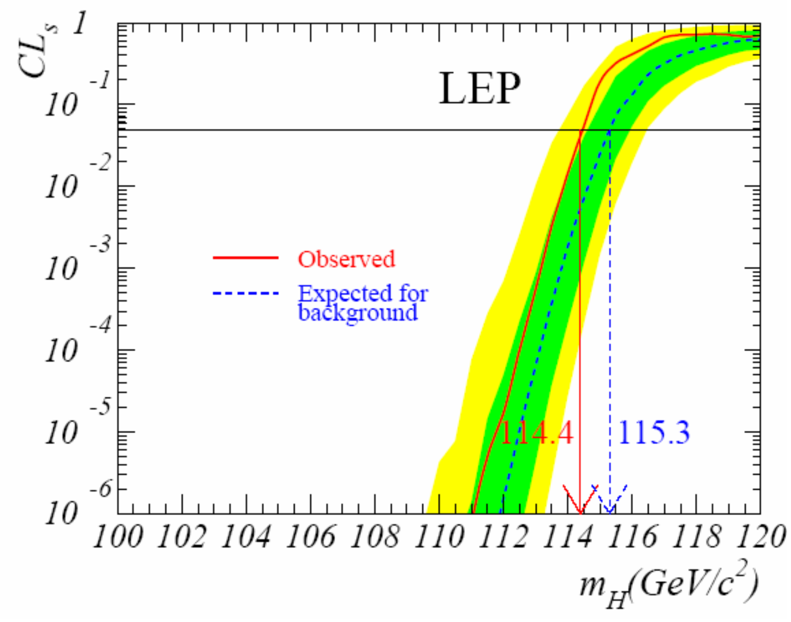
Winter 2004

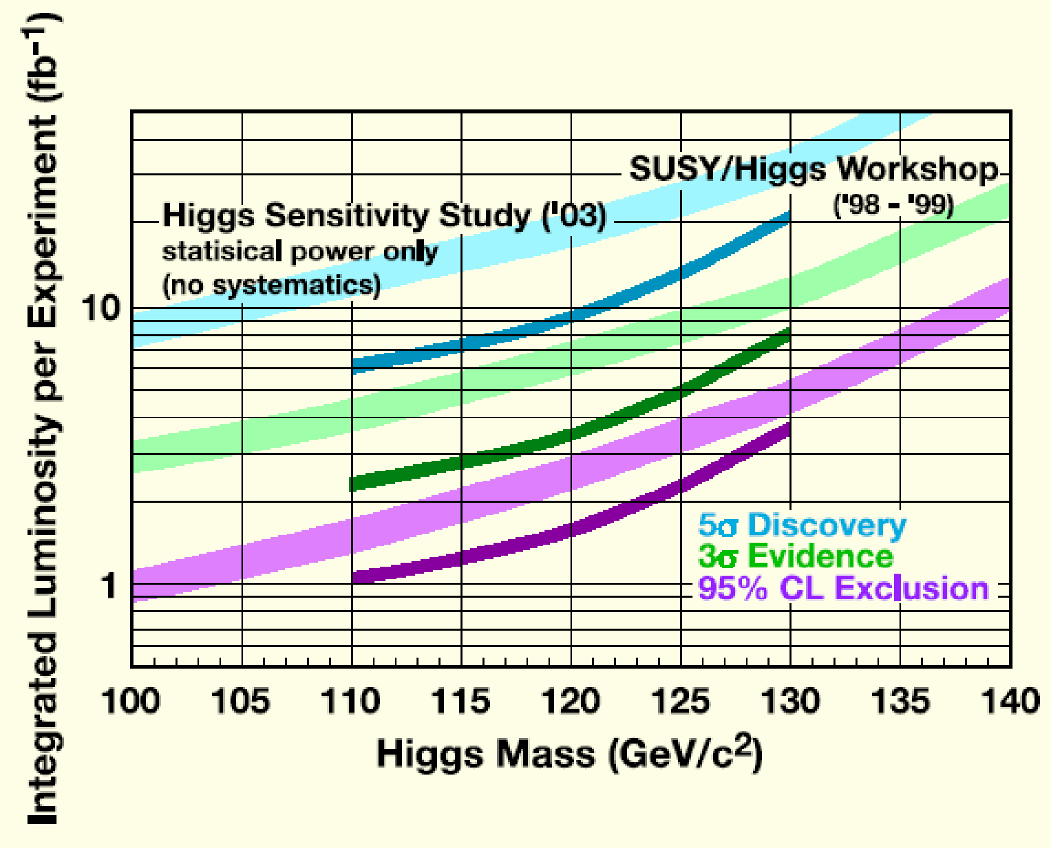
	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965	
σ^0_{had} [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21638 ± 0.00066	0.21566	
R_c	0.1720 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0742	
A_b	0.925 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.398	
Γ_W [GeV]	2.133 ± 0.069	2.094	
m_t [GeV]	178.0 ± 4.3	178.1	

- Best fit of Higgs Mass (m_{top} known)
  - → $M_{Higgs} = 114\ ^{+69}_{-45}$ GeV or $M_{Higgs} < 260$ GeV (95% C.L.)

Present searches

- Limit from LEP
  - → $M_H > 114.4$ GeV (95% C.L.)

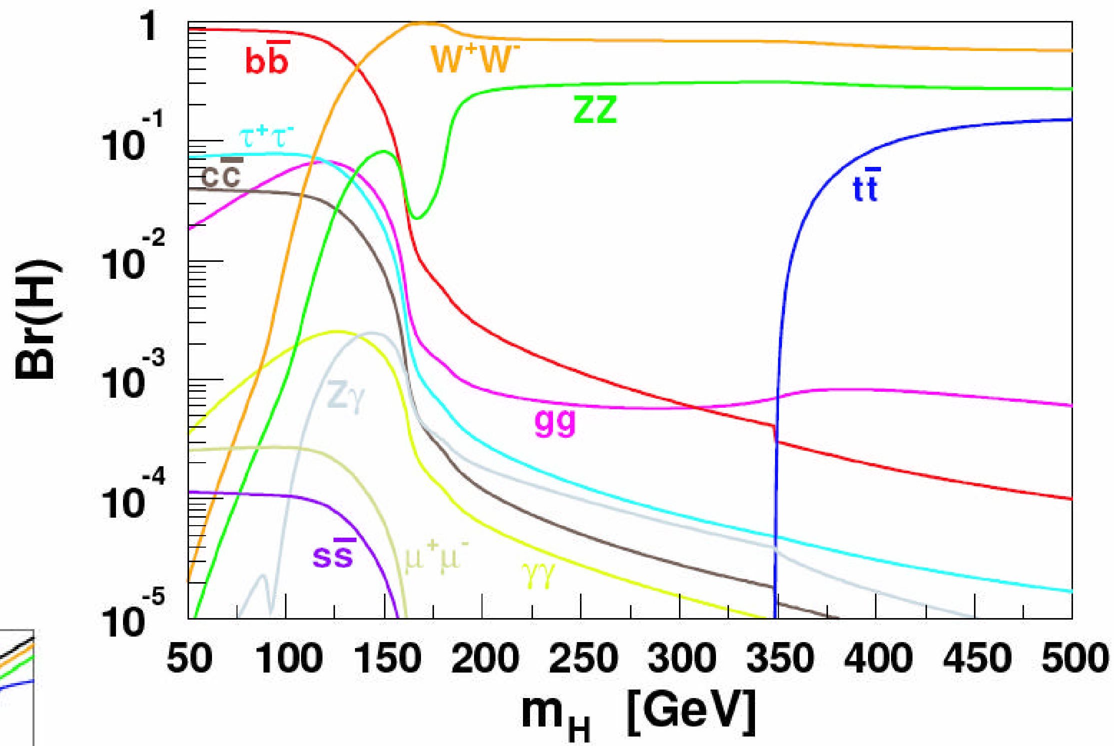


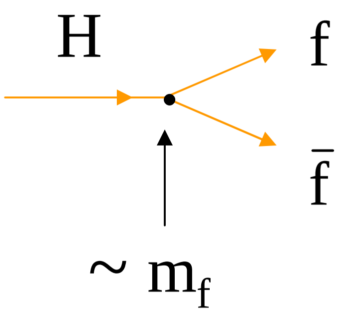


- Discovery potential at Tevatron (p anti-p)
  - $\sqrt{s} = 1.96$ TeV
  - → Integrated luminosity of 4 – 8 fb^{-1} per exp. expected by FY 2009

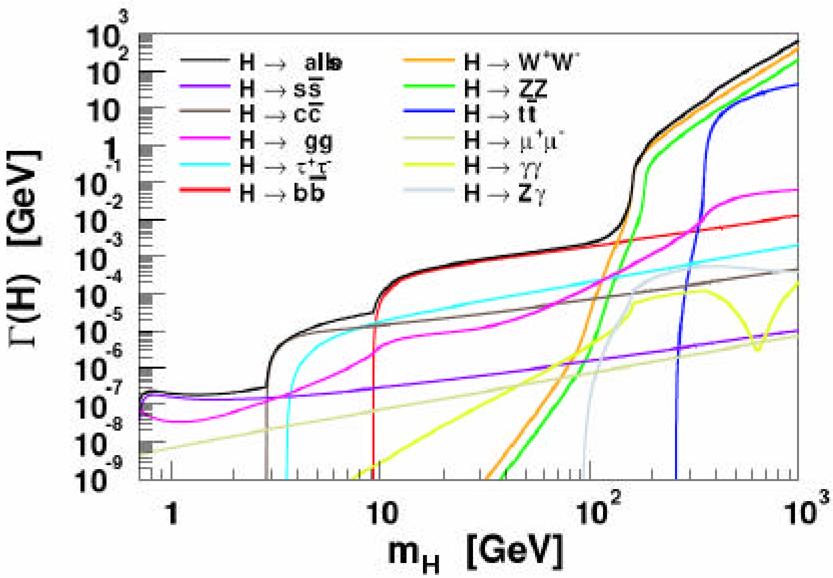
Higgs Boson properties

- Decay modes
  - → BR-dependence due to coupling proportional to mass



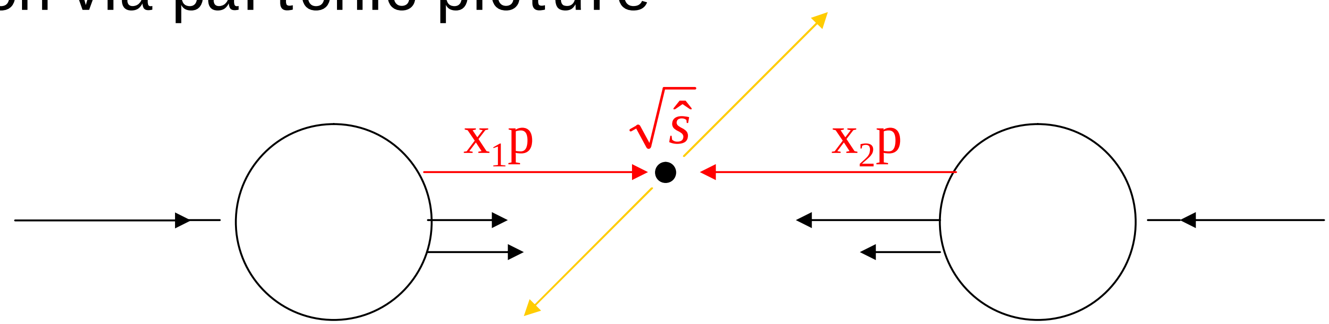


- Width

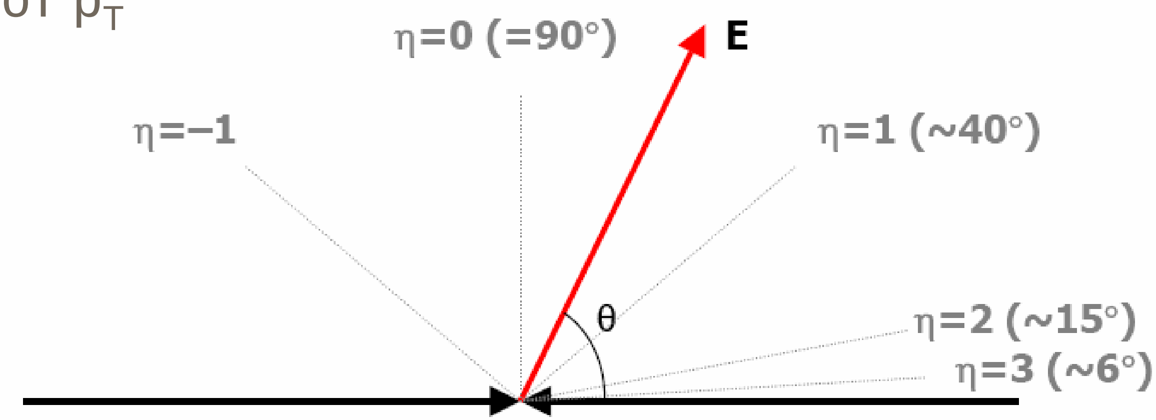


Interlude: Kinematics

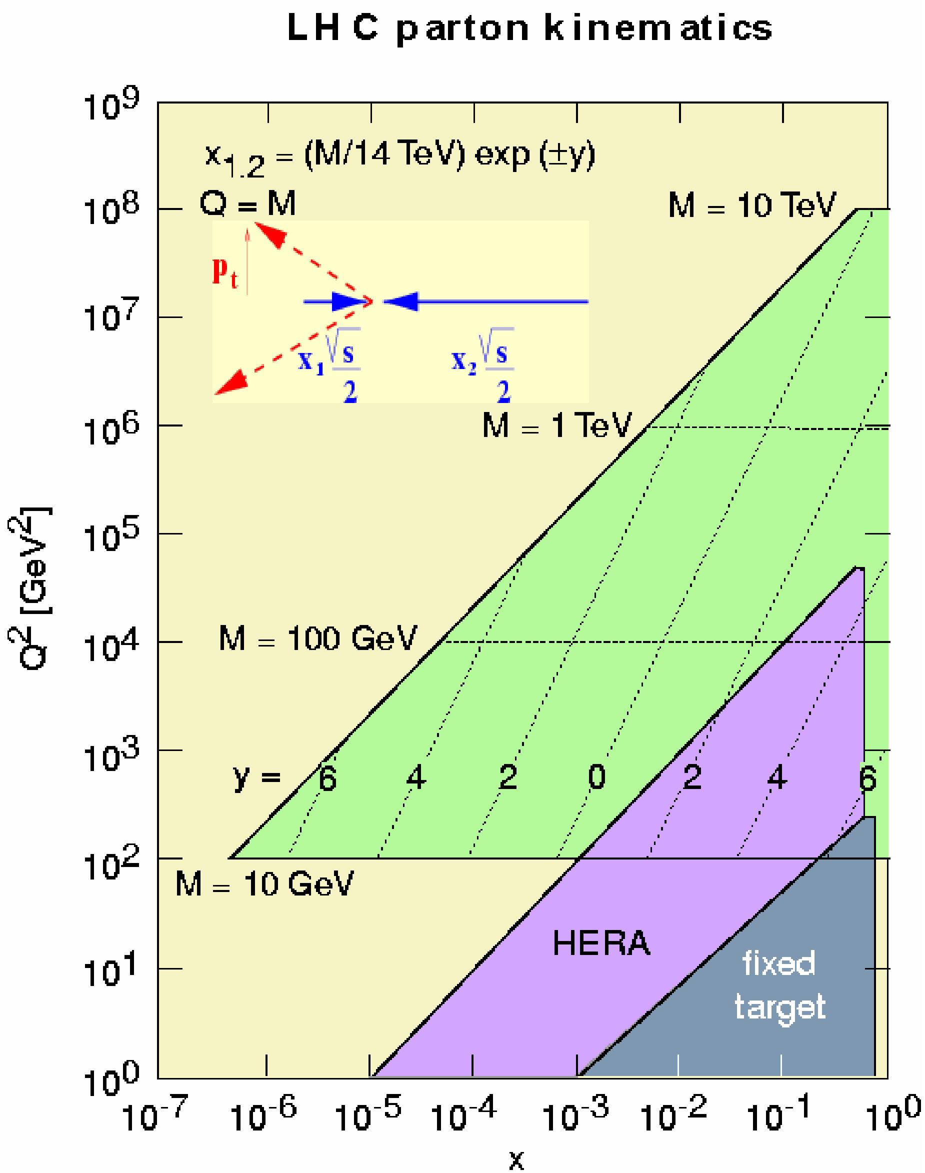
- Hadron-hadron interactions
  - → Description via partonic picture
  - → Bjorken x



- Relevant kinematic variables in hadron collisions
  - → Transverse momentum p_T
    - often E_T instead of p_T
  - → Rapidity y
  - → Pseudo-rapidity
    $\eta = -\ln\tan\theta/2$

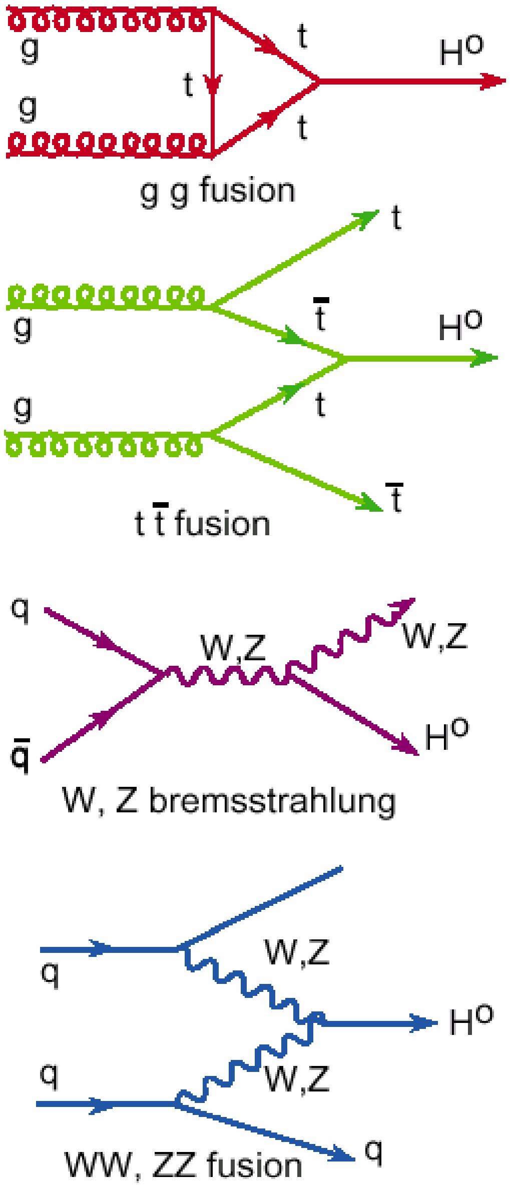


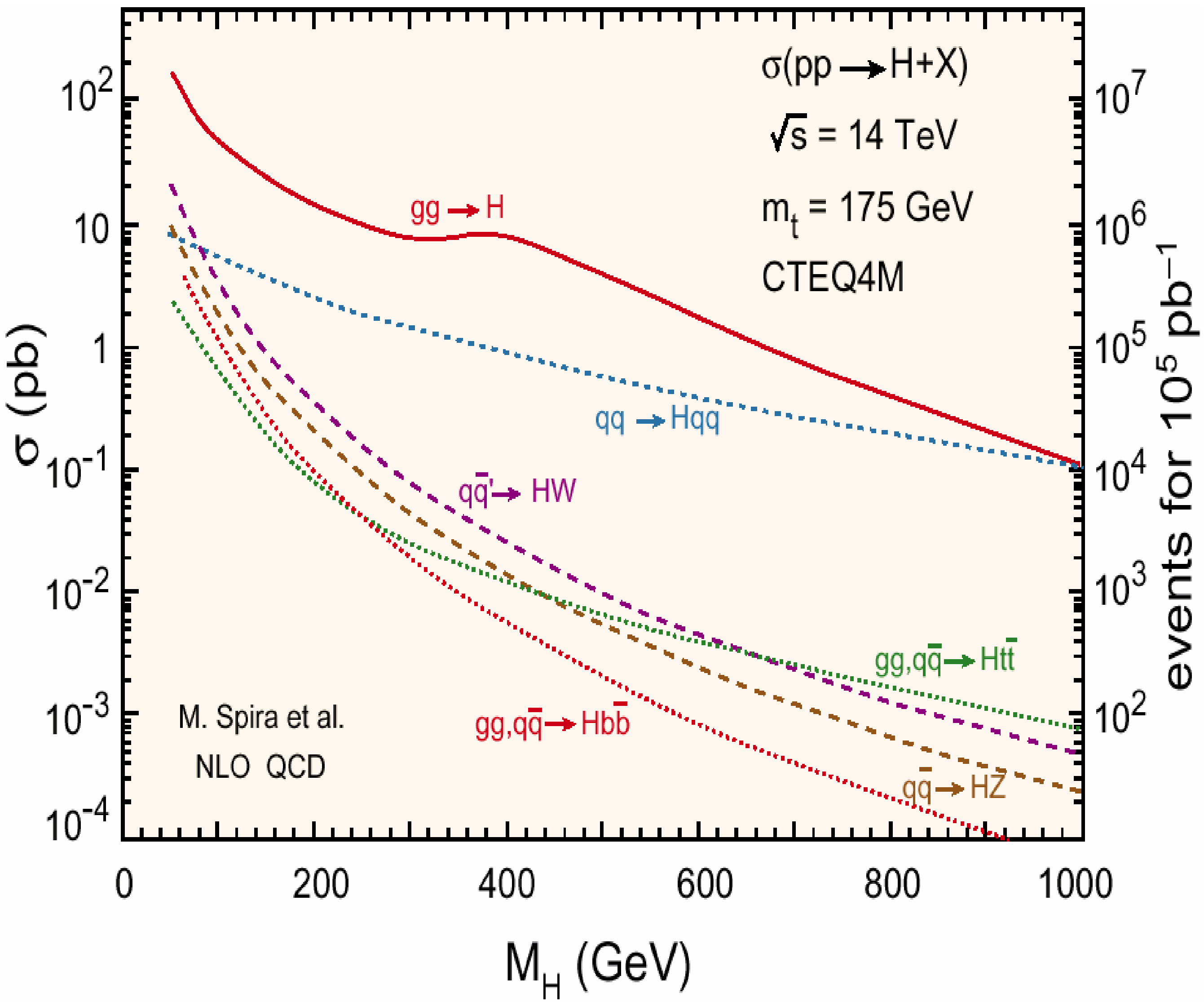
Parton kinematics at LHC



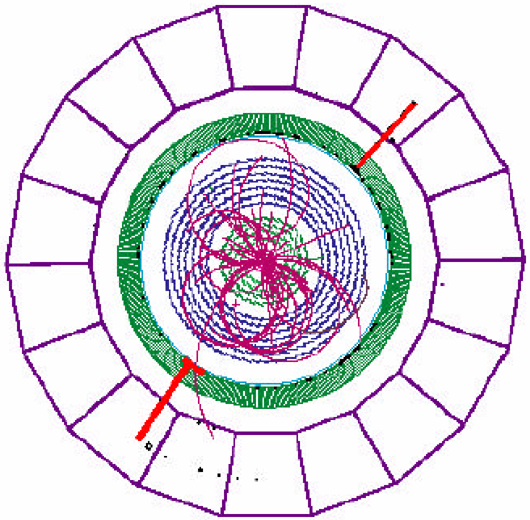
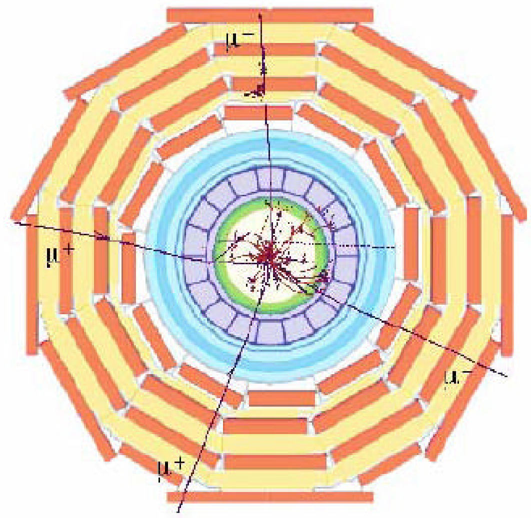
- Cross-sections can be calculated using
  - → Parton densities (pdf) of the proton
  - → Hard scattering cross-section
    - parton-parton → object
- To produce a heavy object
  - → Need partons with large momentum fraction x
  - → $M^2 = s * x_1 * x_2$

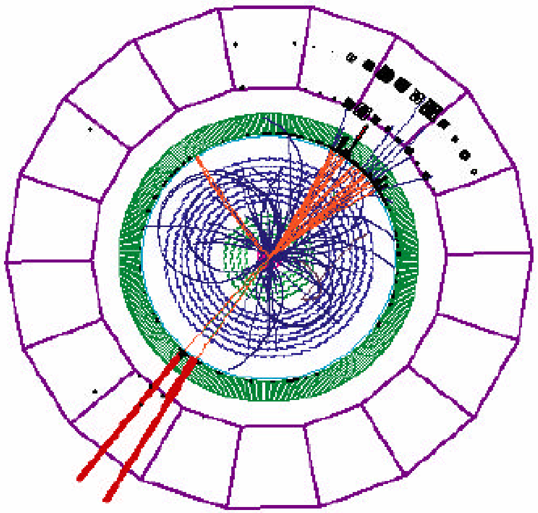
Higgs production at LHC

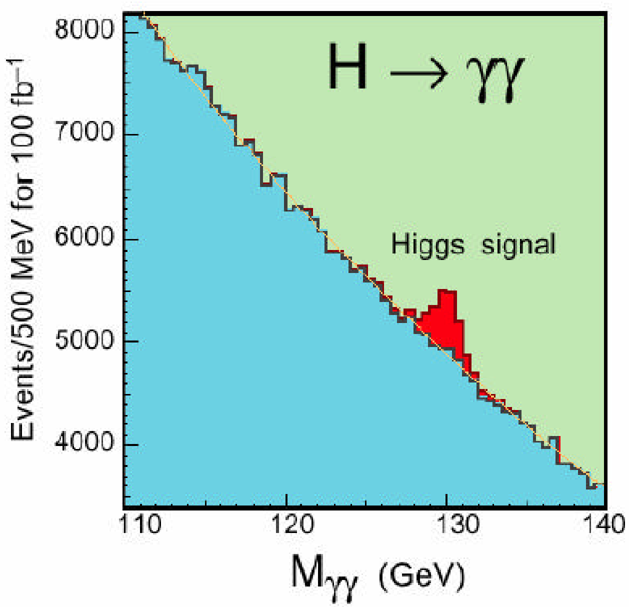


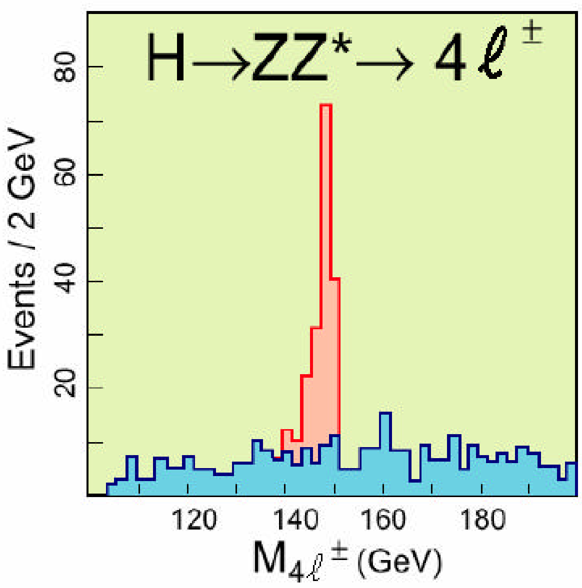


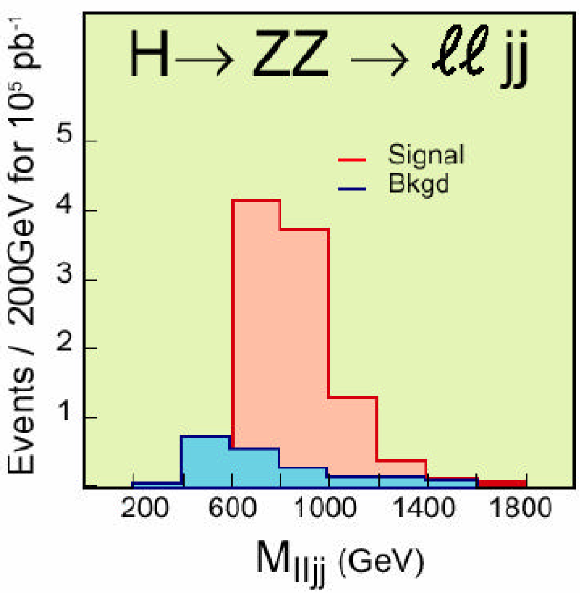
Examples for Higgs-Search at LHC



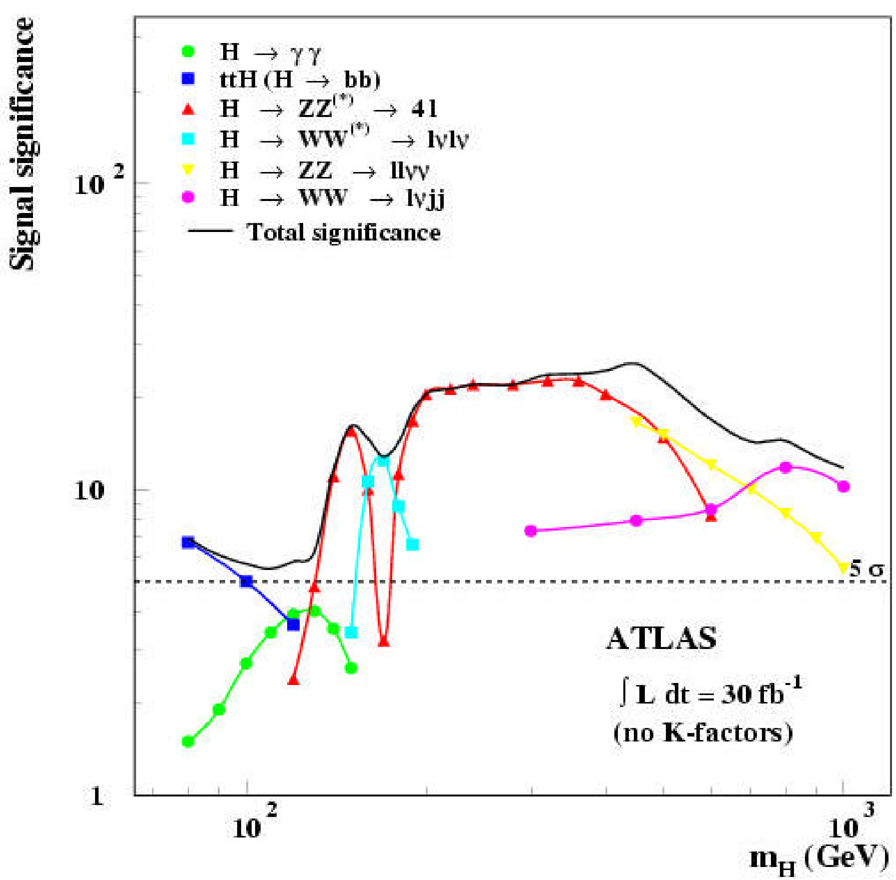


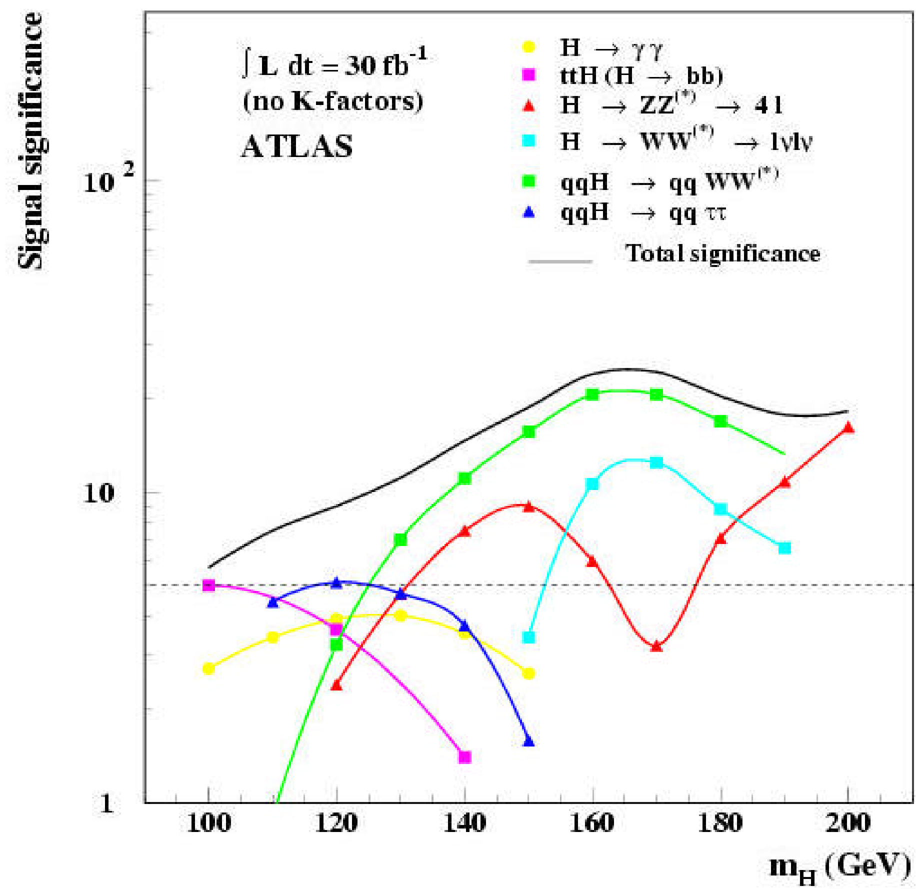




Higgs discovery potential

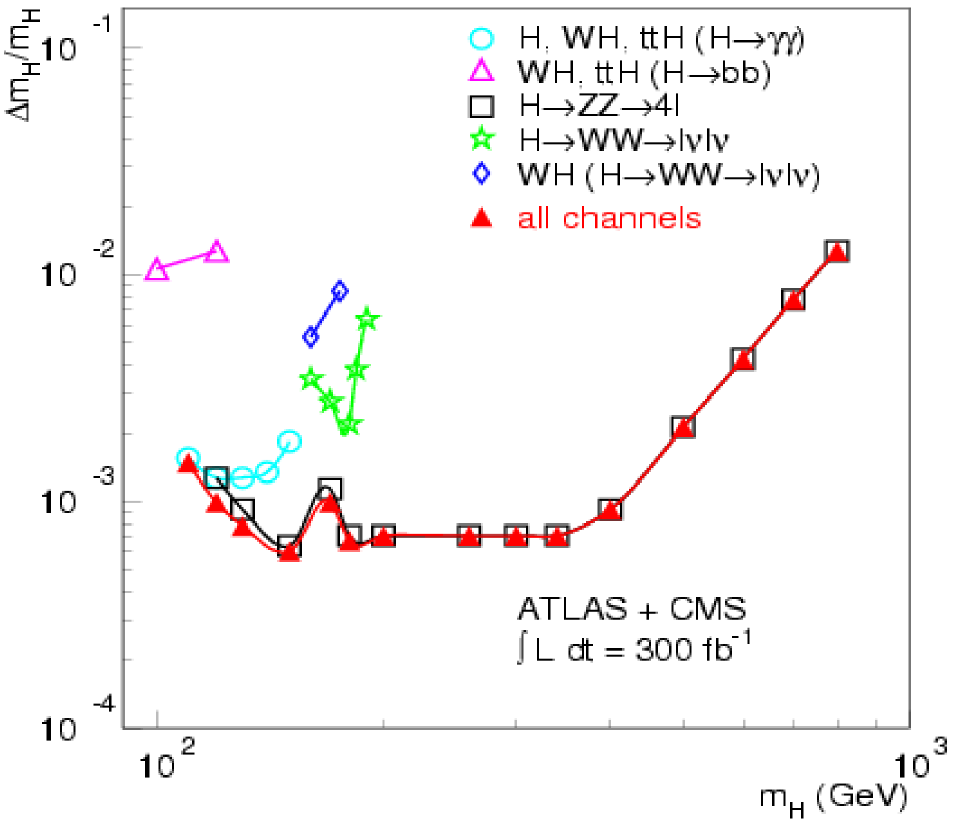
- Significance $S = N_S/\sqrt{N_B}$
  - → Discovery if: $S > 5$ (probability of statistical fluctuation $\approx 10^{-7}$)





Determination of Higgs properties

- Measurement of the mass
  - → Precise reconstruction of decay products
- Measurement of Higgs width
  - → Direct (large M_H)
  - → Indirect (small M_H)
- Determination of branching ratio
  - → Coupling to bosons and fermions



New physics processes

- Multitude of models (just to name a few ...)
  - → Compositeness
  - → Leptoquarks
  - → Supersymmetry
  - → Large extra dimensions
- Mostly: prediction of excess in high p_T signatures
- Due to its large center-of-mass energy, LHC will provide a 'quantum jump' wrt Tevatron
  - → LHC will be the first to enter the TeV scale
  - → σ_{pp} increases fast with $\sqrt{s}$ (not like e^+e^-: $\sigma \sim 1/s$)
    - due to rise of pdf's at low x
  - → Rule of thumb: increase in s by factor 2 compensated by increase of L by factor 10
    - NB: that is why SSC foresaw to have $\sqrt{s}$ = 40 TeV

Supersymmetry

- Introduce a new symmetry: fermions – bosons
  → avoids fine-tuning, unification of (3) forces, ...

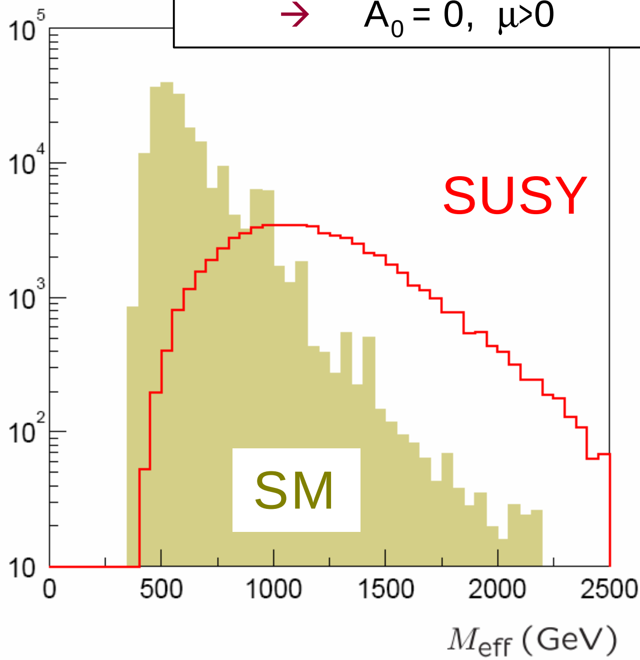
Particle		Spin	Color	Charge	R-parity
g	gluon	1	$\mathbf{8}$	0	$+1$
$\tilde{g}$	gluino	$\frac{1}{2}$	$\mathbf{8}$	0	-1
γ	photon	1	$\mathbf{1}$	0	$+1$
$\tilde{\gamma}$	photino	$\frac{1}{2}$	$\mathbf{1}$	0	-1
$W^{\pm}, Z^0$	intermediate bosons	1	$\mathbf{1}$	$\pm 1, 0$	$+1$
$\widetilde{W}^{\pm}, \widetilde{Z}^0$	electroweak gauginos	$\frac{1}{2}$	$\mathbf{1}$	$\pm 1, 0$	-1
q	quark	$\frac{1}{2}$	$\mathbf{3}$	$\frac{2}{3}, -\frac{1}{3}$	$+1$
$\tilde{q}$	squark	0	$\mathbf{3}$	$\frac{2}{3}, -\frac{1}{3}$	-1
ℓ	charged lepton	$\frac{1}{2}$	$\mathbf{1}$	-1	$+1$
$\tilde{\ell}$	charged slepton	0	$\mathbf{1}$	-1	-1
ν	neutrino	$\frac{1}{2}$	$\mathbf{1}$	0	$+1$
$\tilde{\nu}$	sneutrino	0	$\mathbf{1}$	0	-1

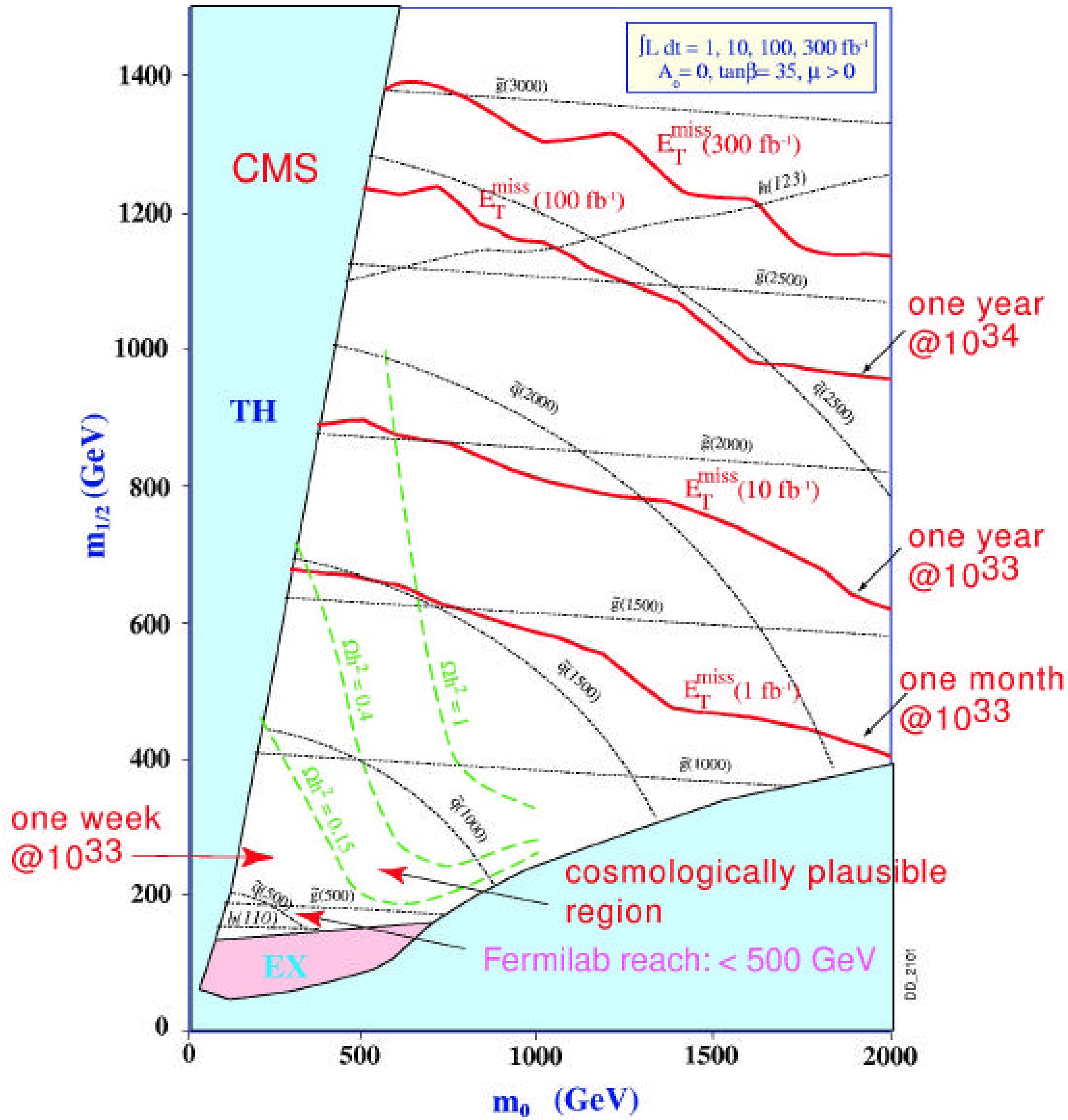
Example: Supersymmetry (SUSY)

- Mass scale M_{eff}:

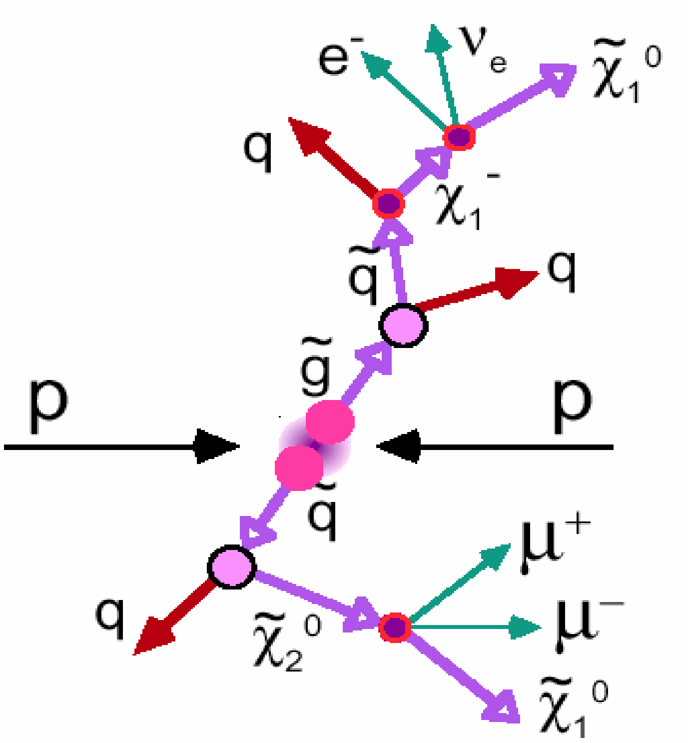
$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

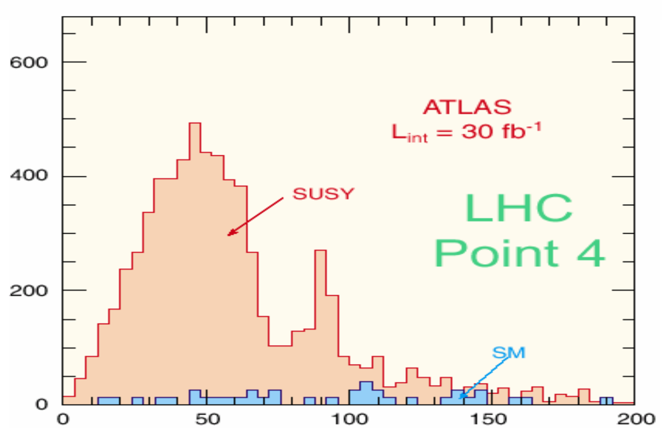
- mSUGRA example
  - → m_0 = 100 GeV
  - → $m_{1/2}$ = 300 GeV
  - → $\tan\beta$ = 10
  - → A_0 = 0, μ>0





Determining propeties of SUSY

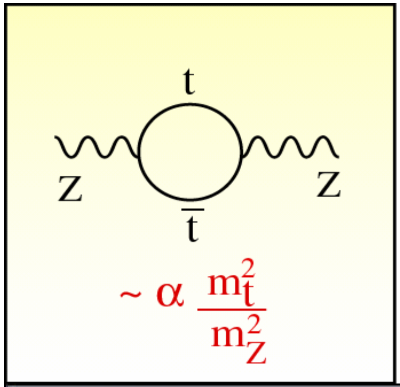


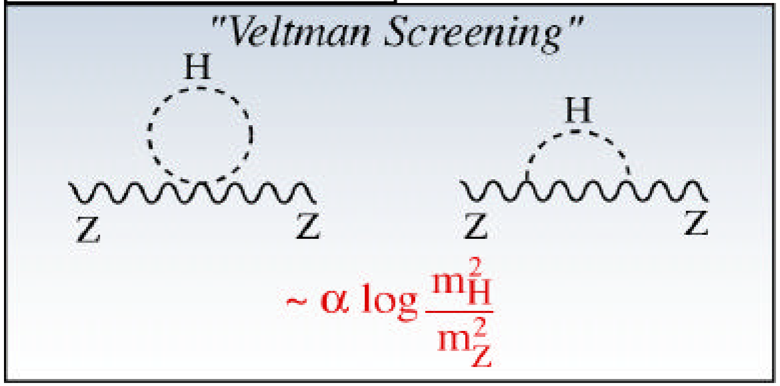


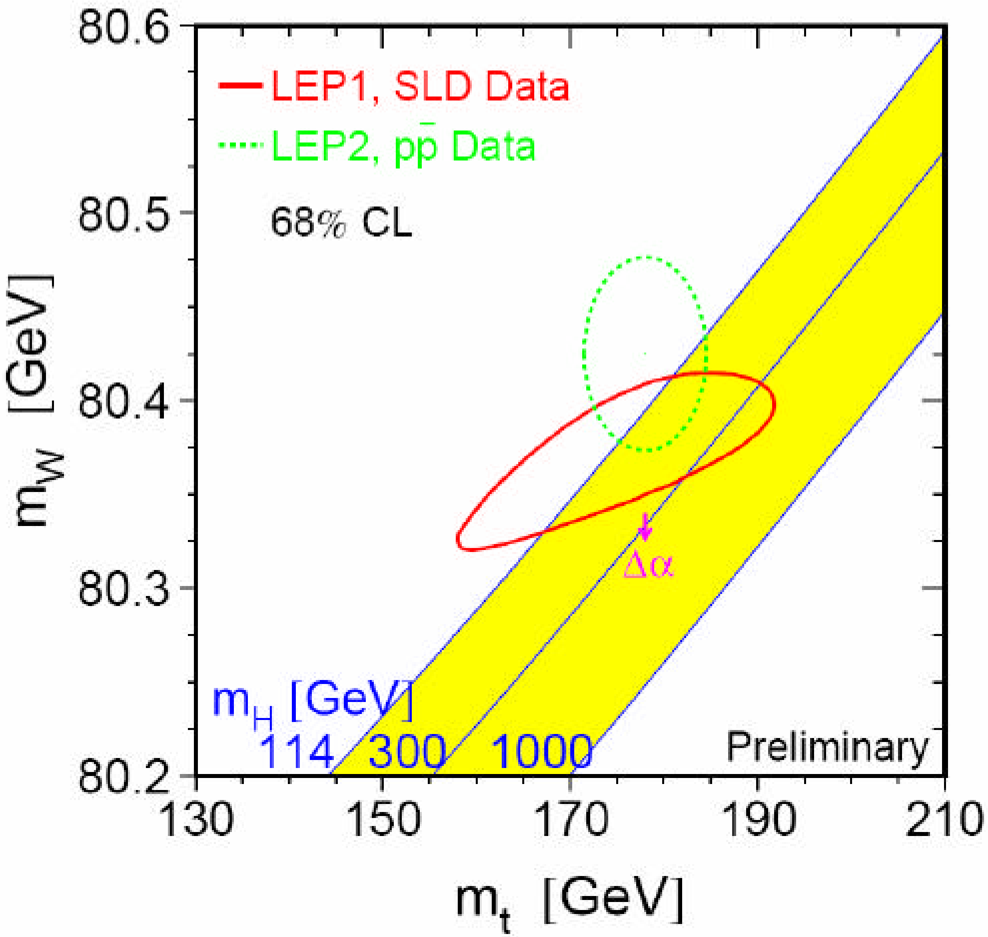
- Details depend on model parameters
  - → SUSY must be broken
- Reconstruction of decay chains
  - → Keep in mind that usually there are unobserved LSPs
    - → Lightest Supersymmetric Particles
- Example for approach
  - → Consider decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\, l^+ l^-$
    - Contribution from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\, Z$
  - → Endpoint in mass of lepton pair determines mass difference of $\tilde{\chi}_2^0$ - $\tilde{\chi}_1^0$

Example: Precision Measurements

- Motivation
  - → Indirect constraints on Higgs mass
    - And new physics



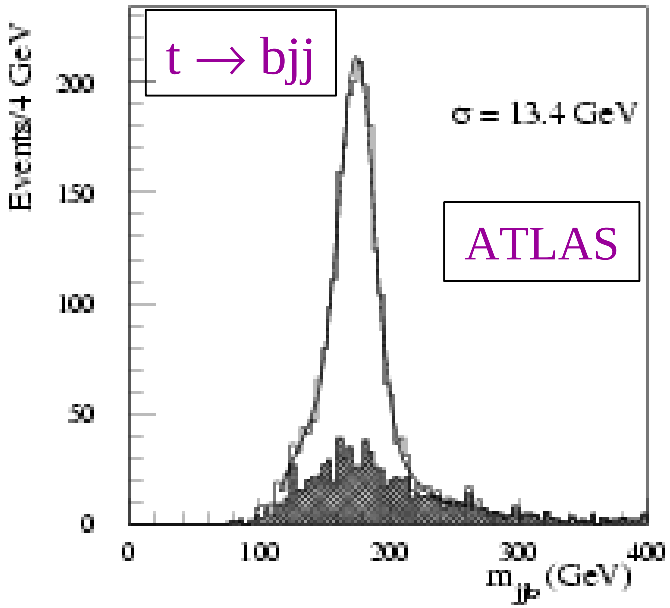




- Improve precision on mass of
  - → Top quark
  - → W boson

Example: top quark mass

- LHC will be a top factory ($6*10^6$ top-pairs at 10^{33})
  - → Production cross-section of about 600 pb

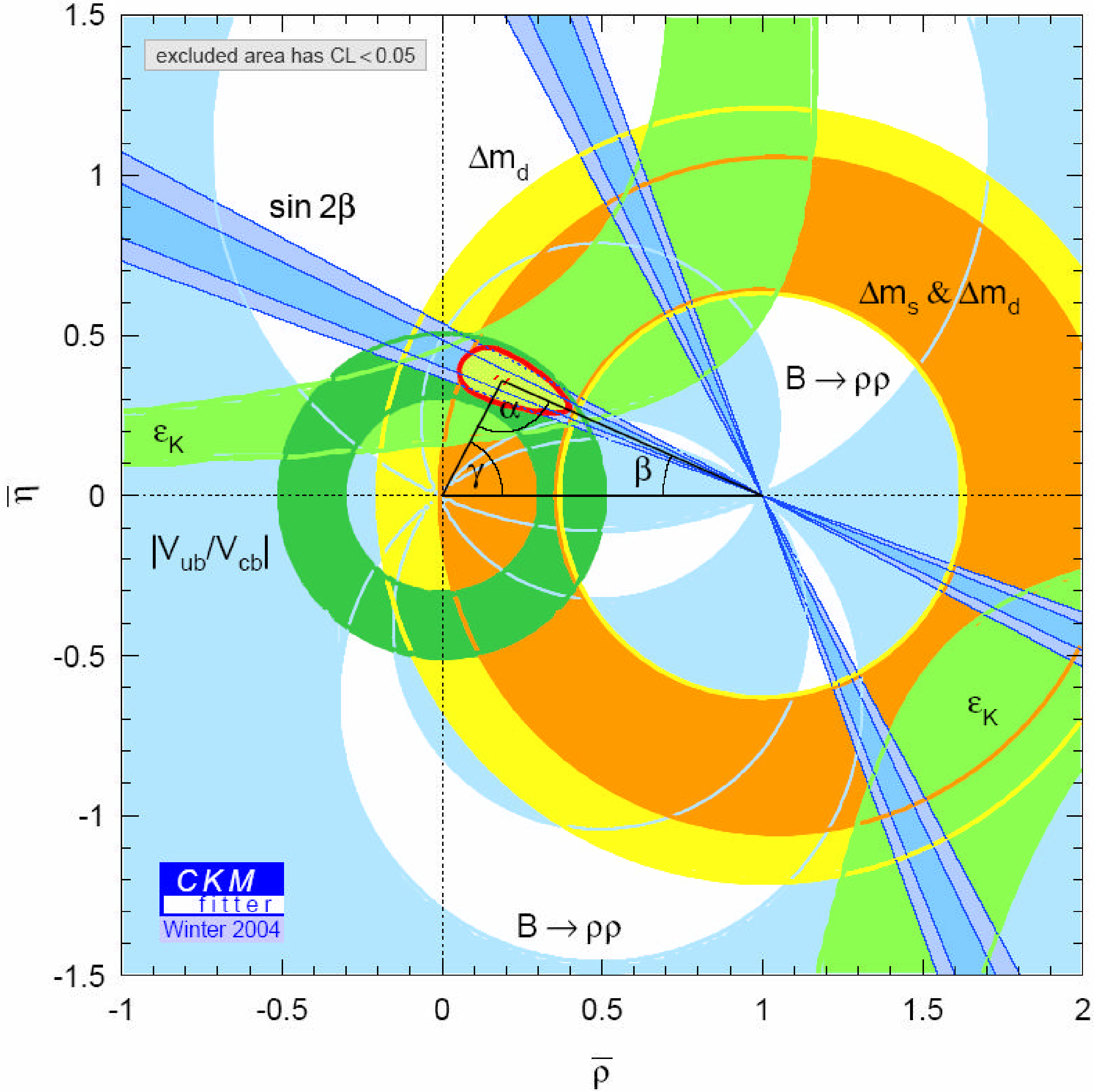


Source of uncertainty	Δm_{top}
Statistical error Physics uncertainties (background, FSR, ISR, fragmentation, etc.) Jet scale (b-jets, light-quark jets)	<< 100 MeV ~ 1.3 GeV ~ 0.8 GeV
Total (per experiment, per channel)	~ 1.5 GeV

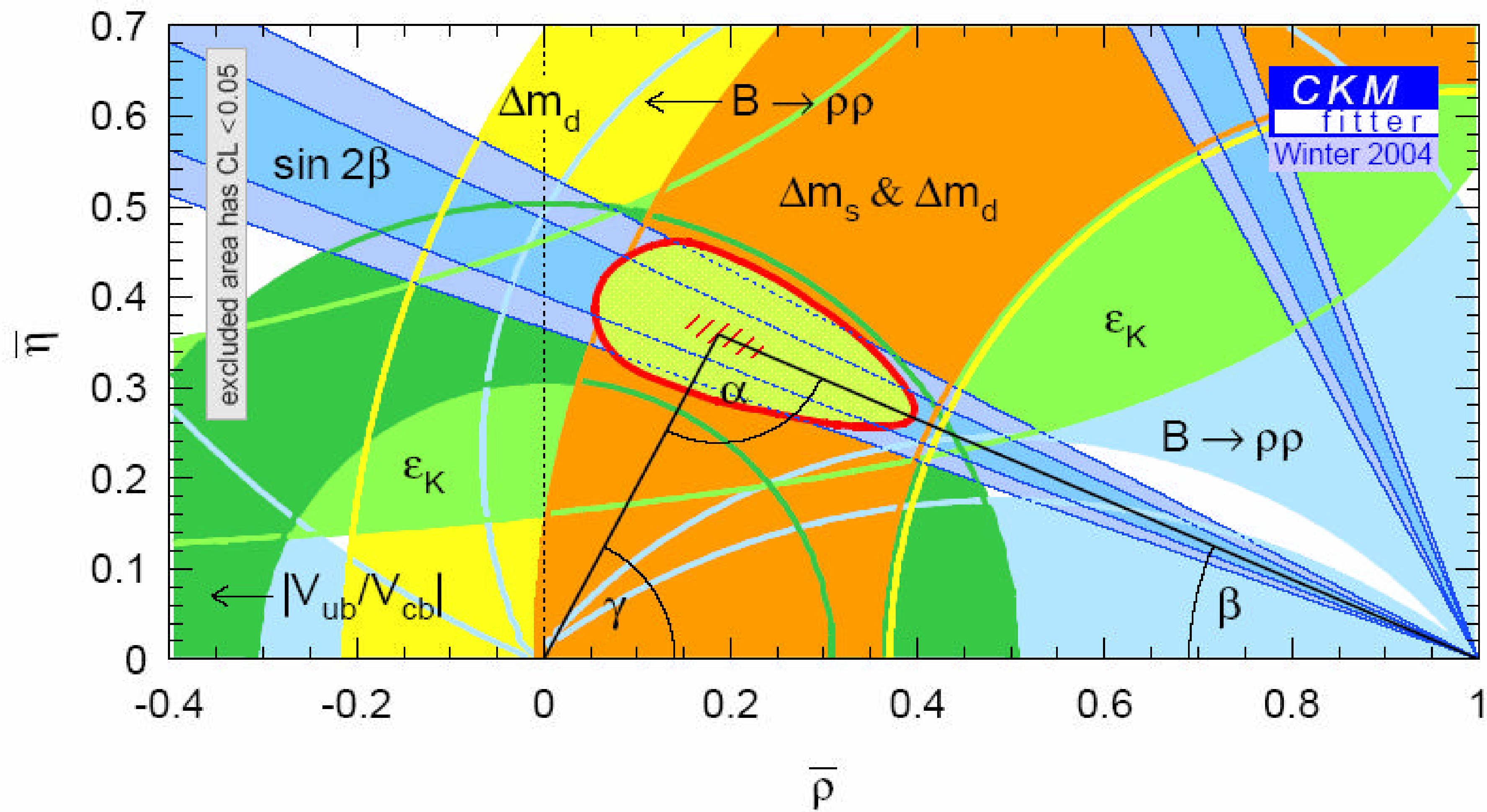
- Final state lνb jjb
  - → Lepton for trigger
  - → Hadronic decay to measure mass

CKM - Matrix

- Weak states are not mass states
  - → Quark mixing matrix (CKM)
  - → 4 parameters
  - → Three angles and …
- a single complex phase
  - → Responsible for CP violation in SM
  - → K and B system!



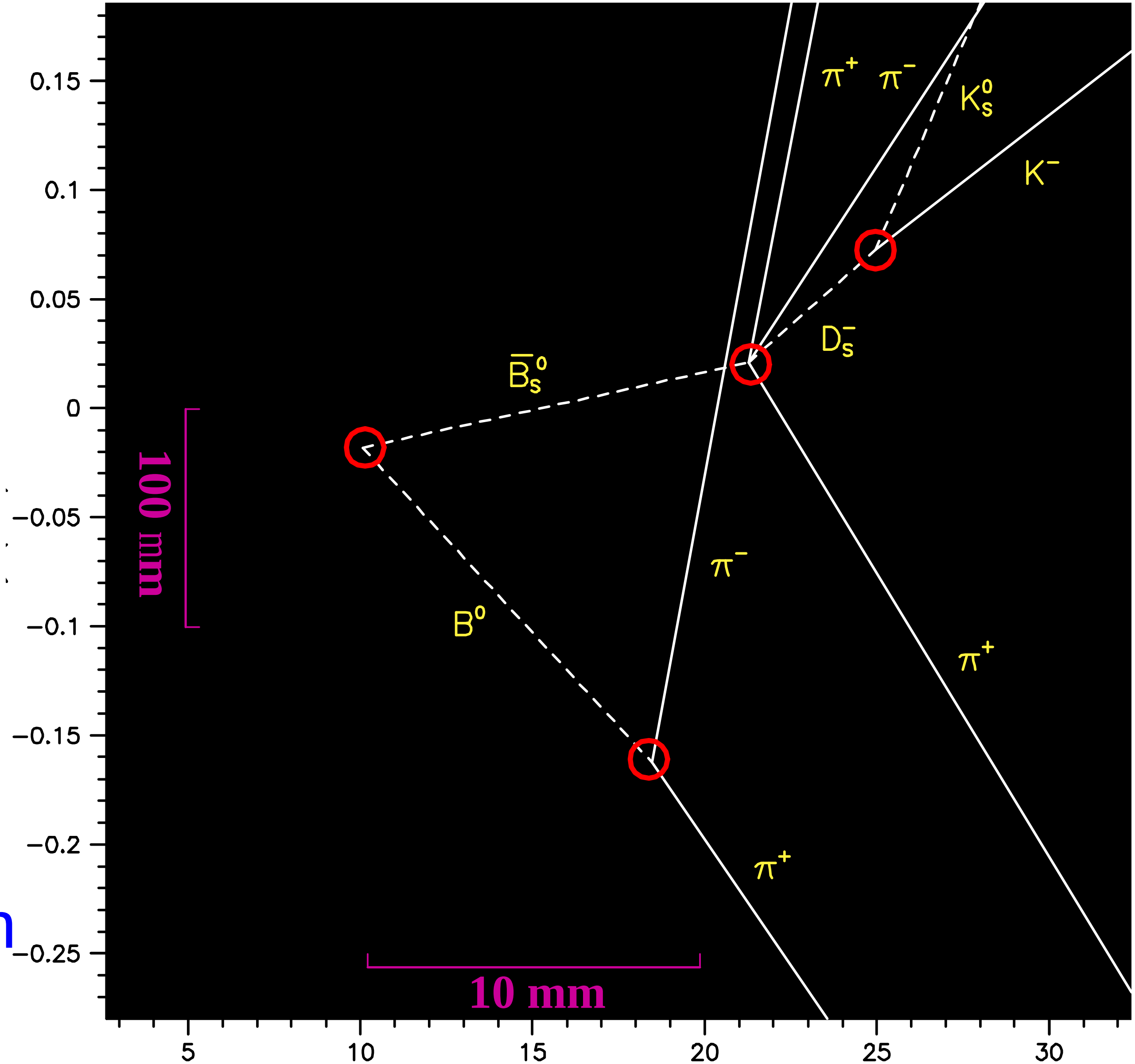
CKM Matrix: zoom-in



- Overall consistency between several observables
  - → New physics (entering via loop effects) might modify this ...

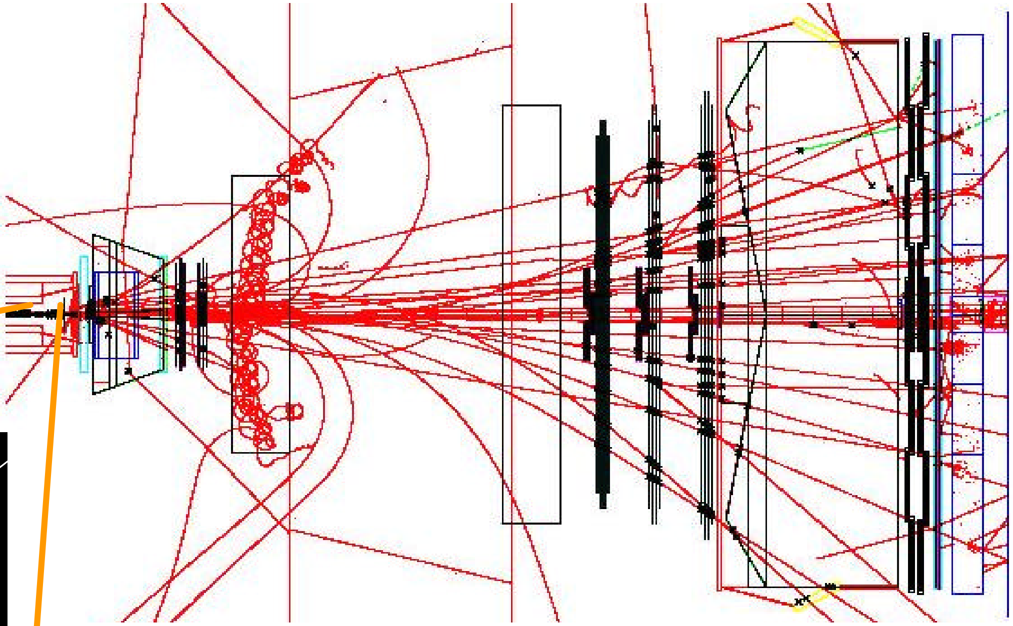
B-physics event signatures

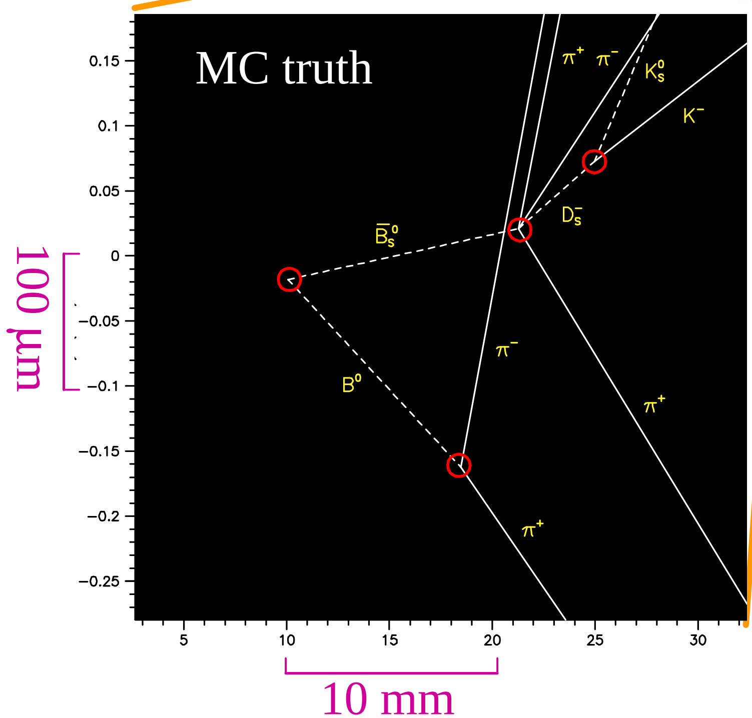
- Simulated event
  - → b and anti-b quark
  - → Decay of B-mesons
- Typical decay length of B meson at LHC
  - → ~ 10 mm
- Precise measurement of flight length
  - → lifetime



B-physics event signatures

- LHCb example
  - → Tracks seen in detector





- Need to measure precisely
  - → Low p_T tracks from decays
    - Including particle identification
  - → (secondary) vertices
    - To determine life time

Topics in B-physics

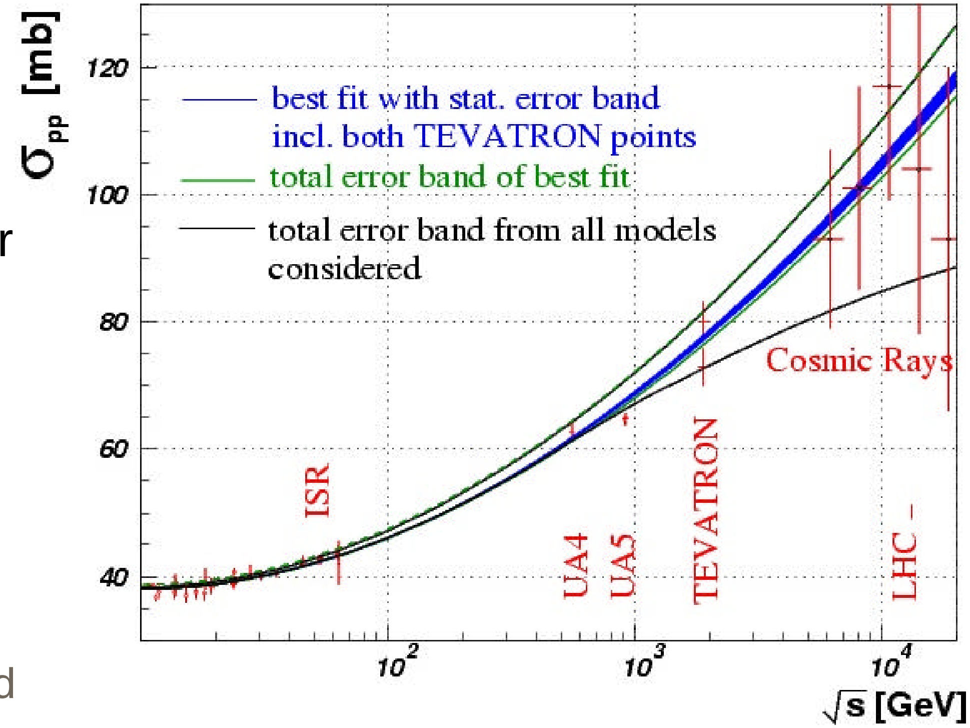
- All B-hadrons are produced at LHC
  - → B^0, B^+, B_s, B_c, b-baryons
- Observation and measurement of oscillation in B_s meson system
  - Observation and first measurement might be done at CDF/D0
  - → Flavour eigenstates are not mass eigenstates
  - → Also precise determination of phase ϕ_s and difference of widths $\Delta\Gamma_s$
- Measurement of angle γ in unitarity triangle
  - → Several processes: $B_s \rightarrow D_s K$, $B^0 \rightarrow D^0 K^{*0}$, $B \rightarrow h^+ h^-$
- Observation of rare decays
  - → Example : $B_s \rightarrow \mu^+\mu^-$ (SM: BR $(B_s \rightarrow \mu^+\mu^-) = 3.5 \times 10^{-9}$)

Strong interactions in pp

- Determination of basic properties
  - → Total cross-section
  - → Decomposition in event topologies
- Particle and energy flow
- Transition soft to hard scattering
  - → Validity of perturbative QCD
- Low-x physics
  - → QCD dynamics, proton structure, saturation, ...
- Properties of rapidity gaps
  - → Signature used in search for new physics
- Exclusive production of objects
  - → Central diffraction
    - Complementary approach for new physics
- Measurement of leading particles
  - → Relation to cosmic ray physics
    - Understanding composition of primary particle spectrum

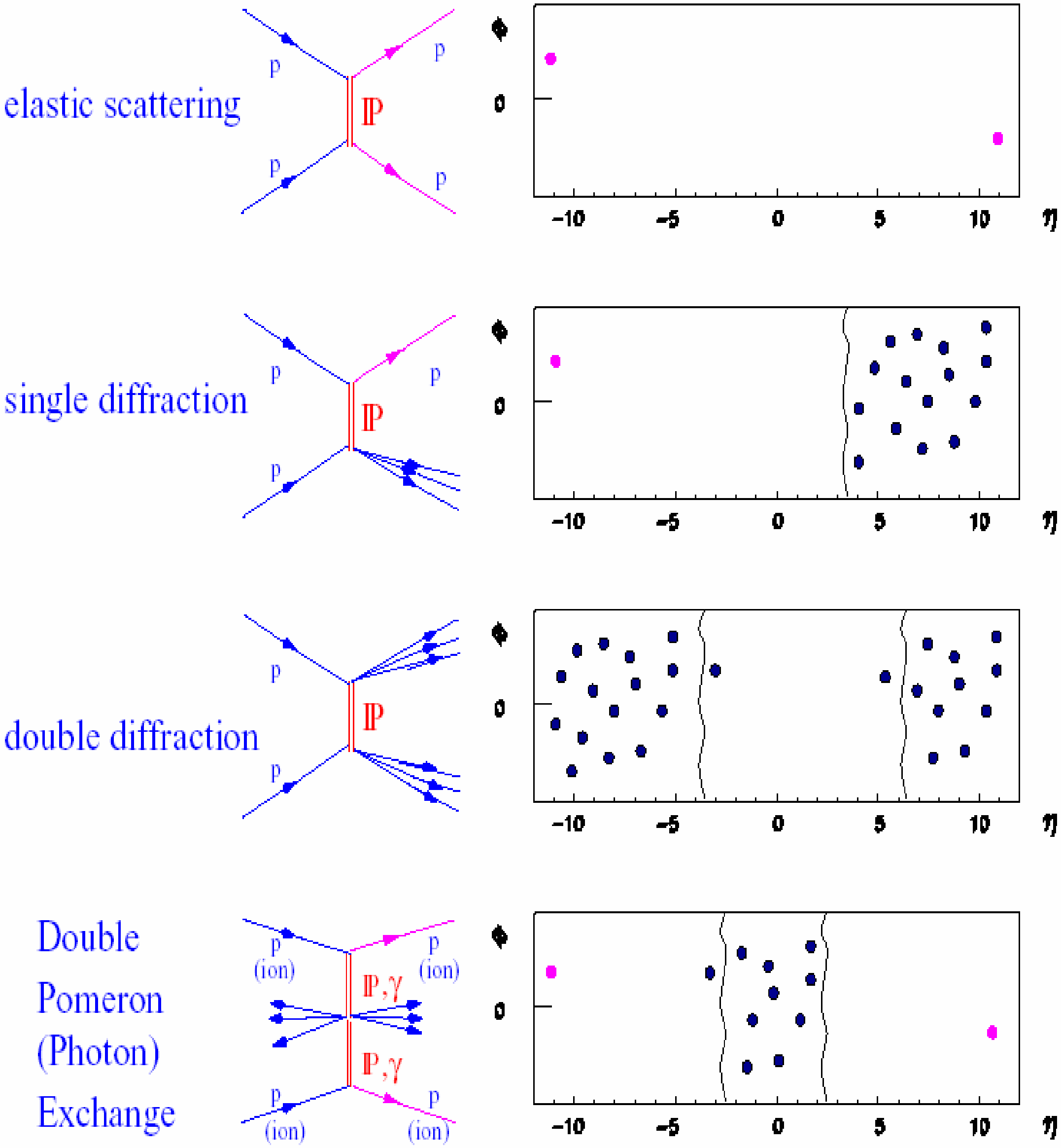
Total pp Cross-section

- Important, but difficult measurement
  - → Situation for expected total cross-section at LHC is unclear
    - Uncertainties of =10%
- Experimental approach
    - 'luminosity independent method'
  - → Measure precisely rate of elastic and inelastic events
    - Use optical theorem to 'get rid of absolute luminosity'
  - → Alternative (even more challenging)
    - Measure interference of strong and electromagnetic pp interaction



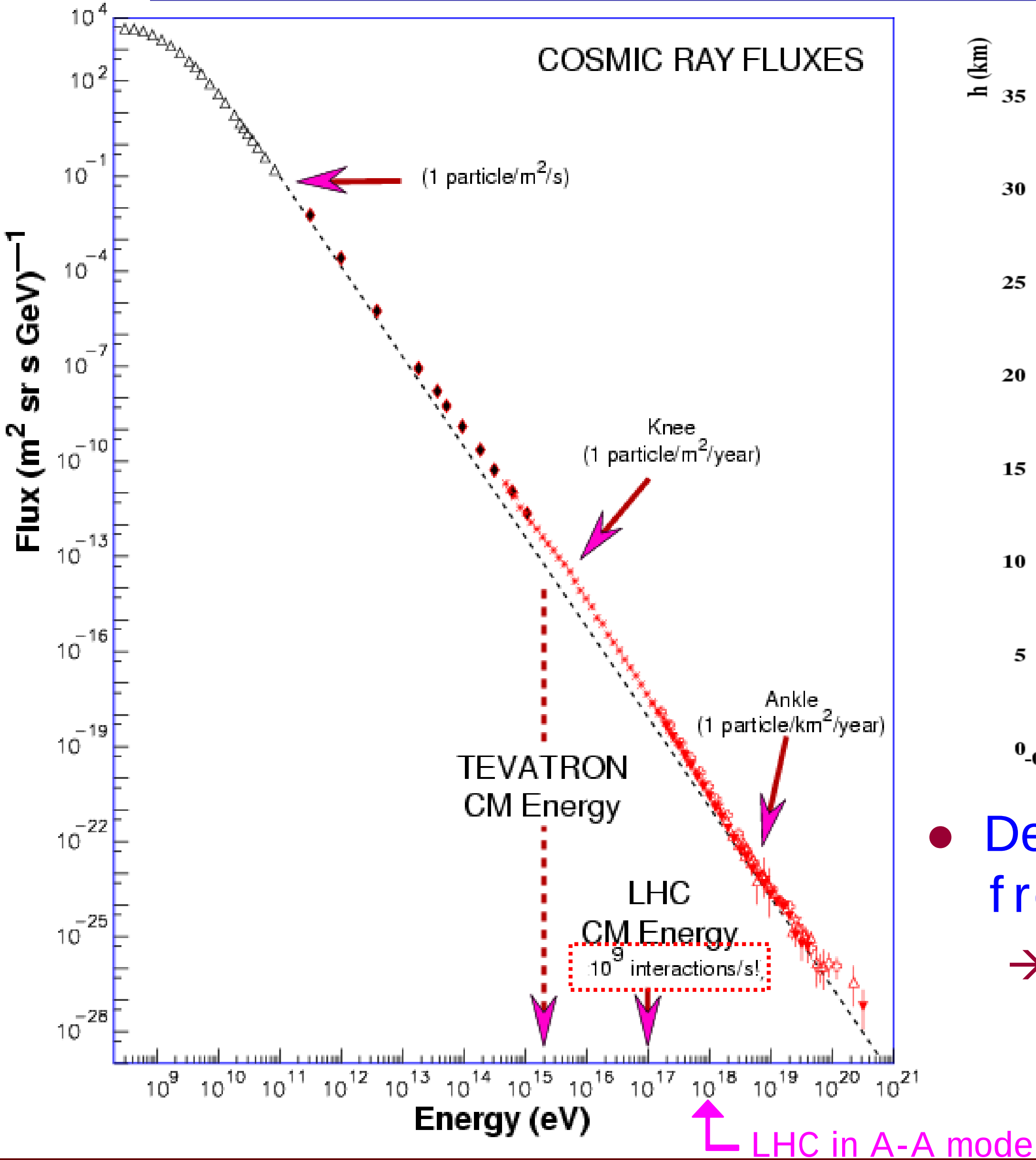
$$s_{tot} = \frac{16p}{1+r^2} \times \frac{(dN/dt)|_{t=0}}{N_{el}+N_{inel}}$$

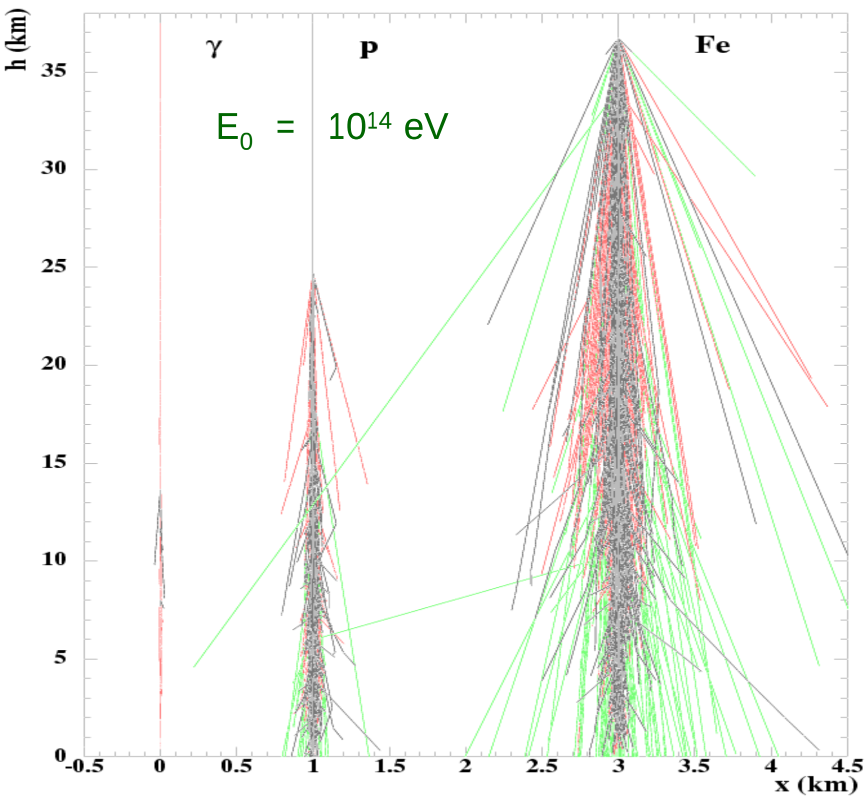
Event topologies in pp collisions



- Two signatures
  - → Leading protons
    - Carrying a very large fraction of the 7 TeV momentum
    - Want to measure the difference $\Delta p = 7\ \text{TeV} - p'$
  - → Rapidity gaps
    - Regions without particle production
- Not discussed here: pp → X

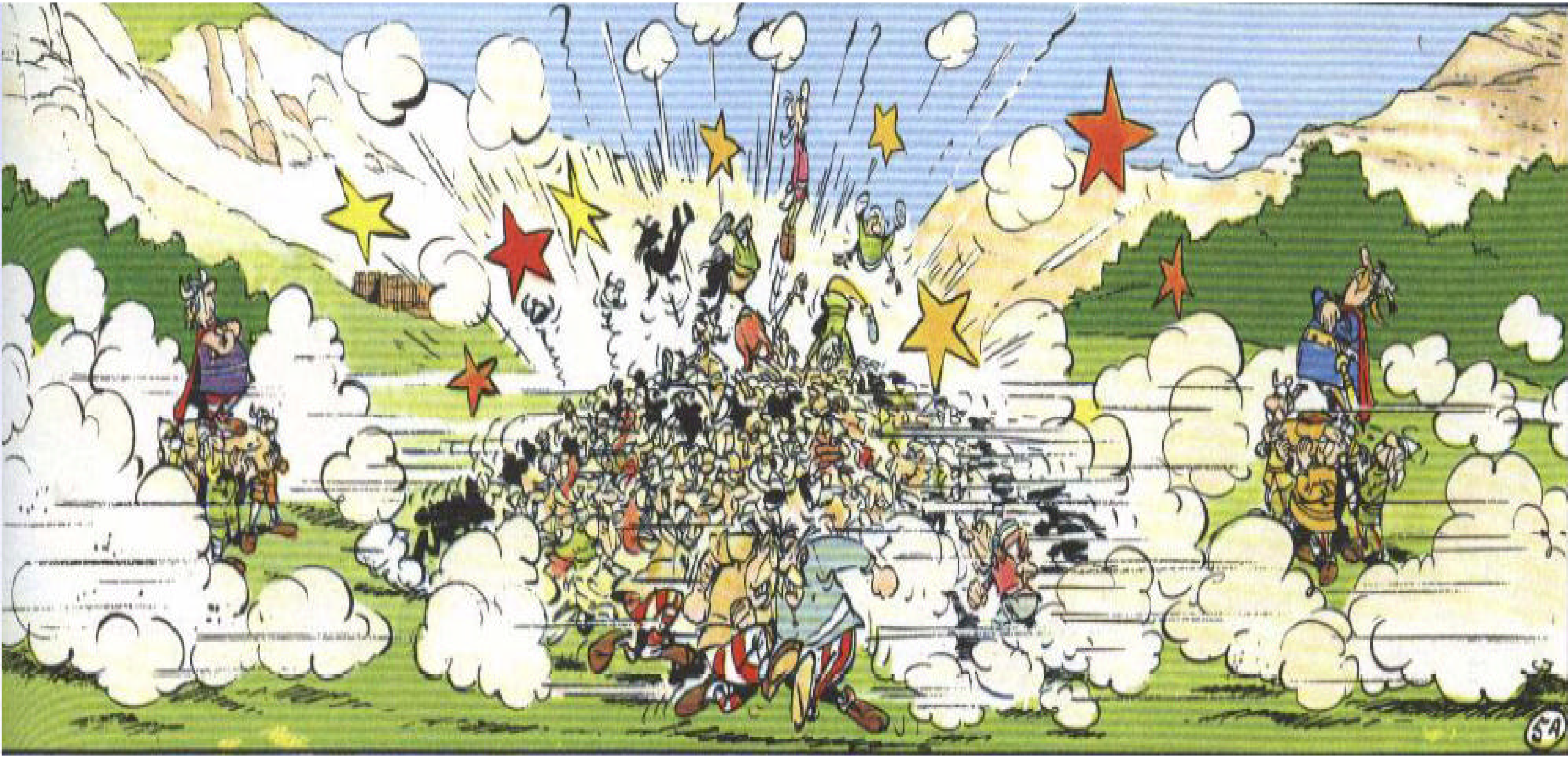
Relation to cosmic ray physics





- Deduce energy / primary particle from observed shower profile
  - → Relies on accurate hadronic simulation programs
    - Extrapolation from available accelerator energies necessary!

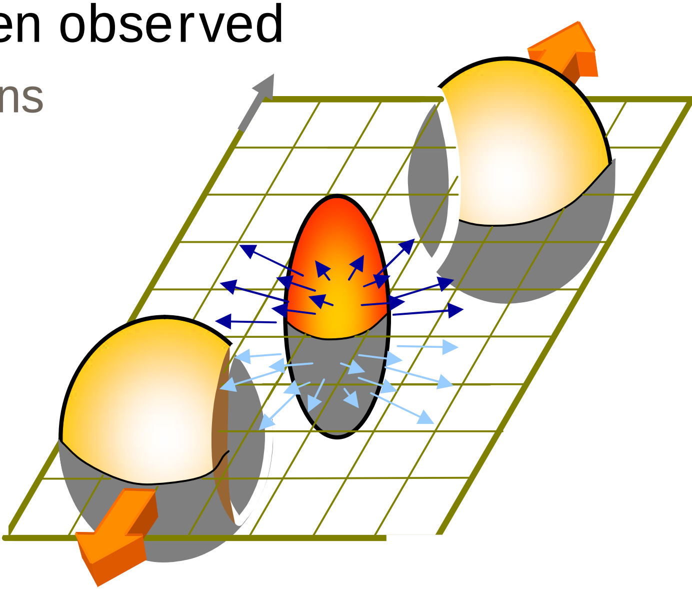
Heavy-Ion (HI) Collisions



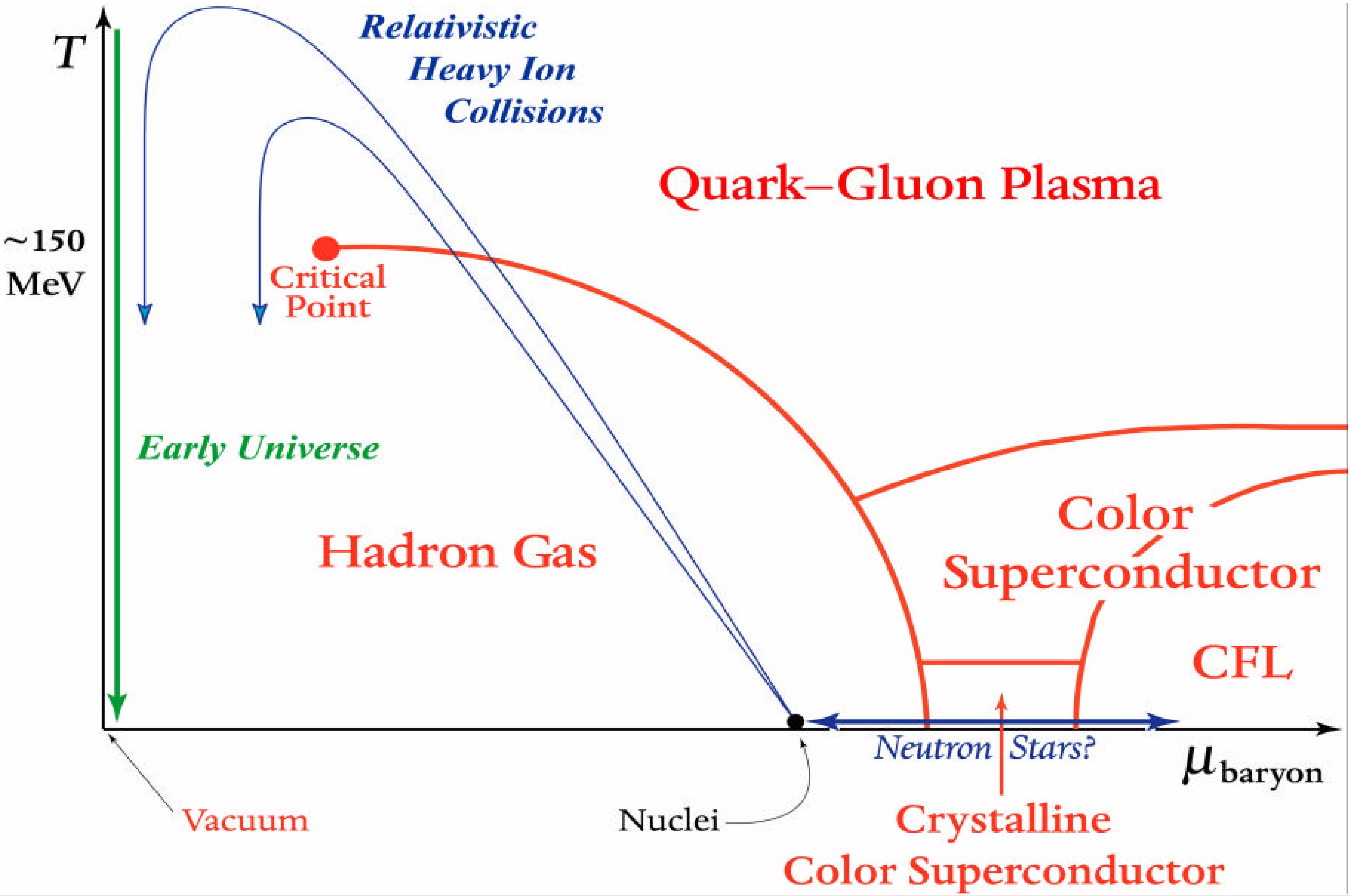
- If you thought so far that proton-proton is a 'dirty' environment, you might want to reconsider

Physics motivation for HI

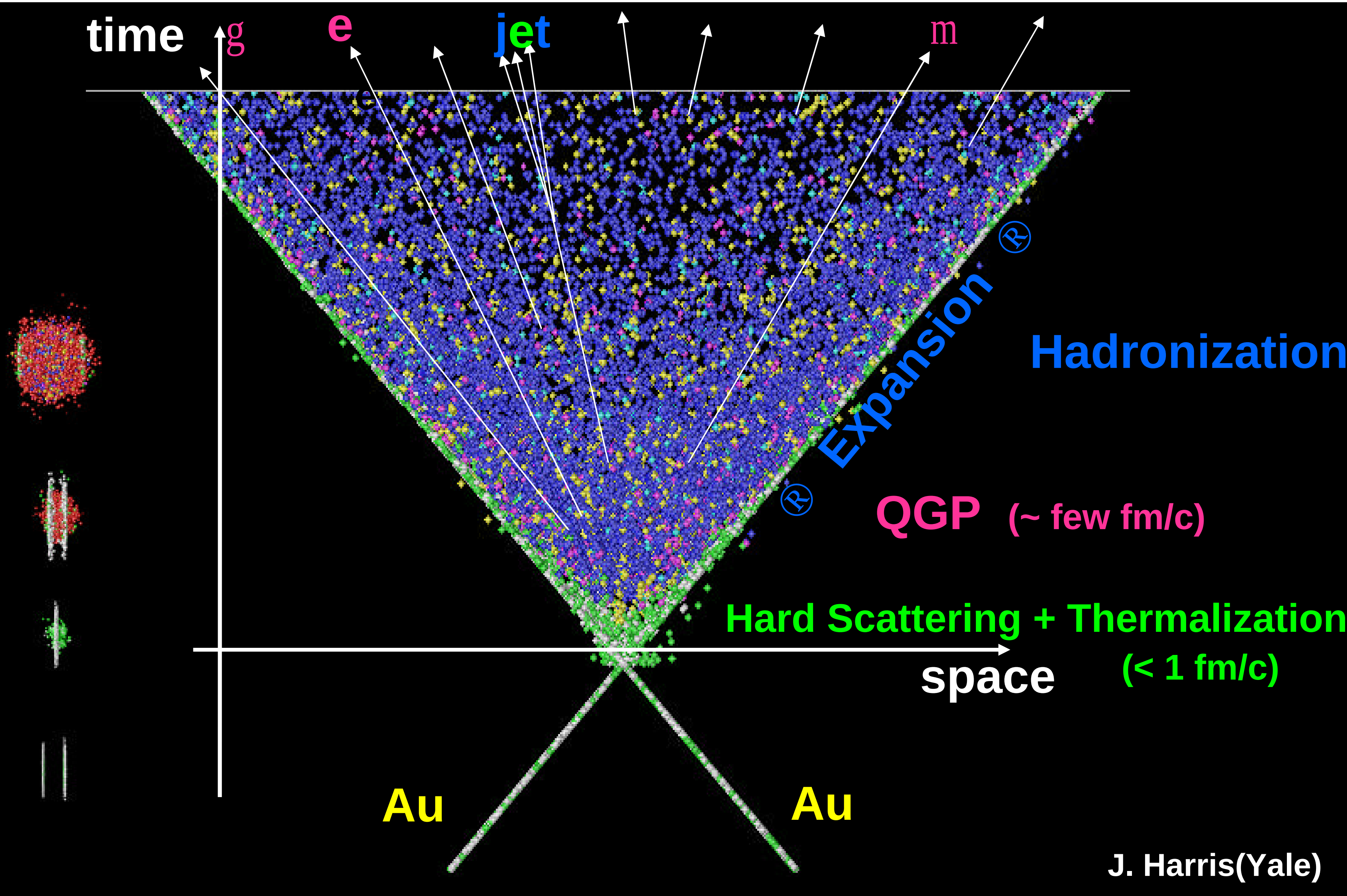
- Quark-hadron phase transition in early universe
  - → Relation to cosmology
- Properties of cores of dense stars
  - → Relation to astrophysics
- Predicted phase transition (deconfinement) in QCD at high temperate: Quark-Gluon Plasma (QGP)
  - → Lattice gauge calculation
  - → No free (coloured) quarks have ever been observed
    - Quarks are confined to the known hadrons
- Laboratory approach
  - → Collide heavy nuclei at high energies
  - → Running since a few years: RHIC at BNL
  - → Nuclei have (transverse) size
    - Impact parameter determines overlap (number of participants)



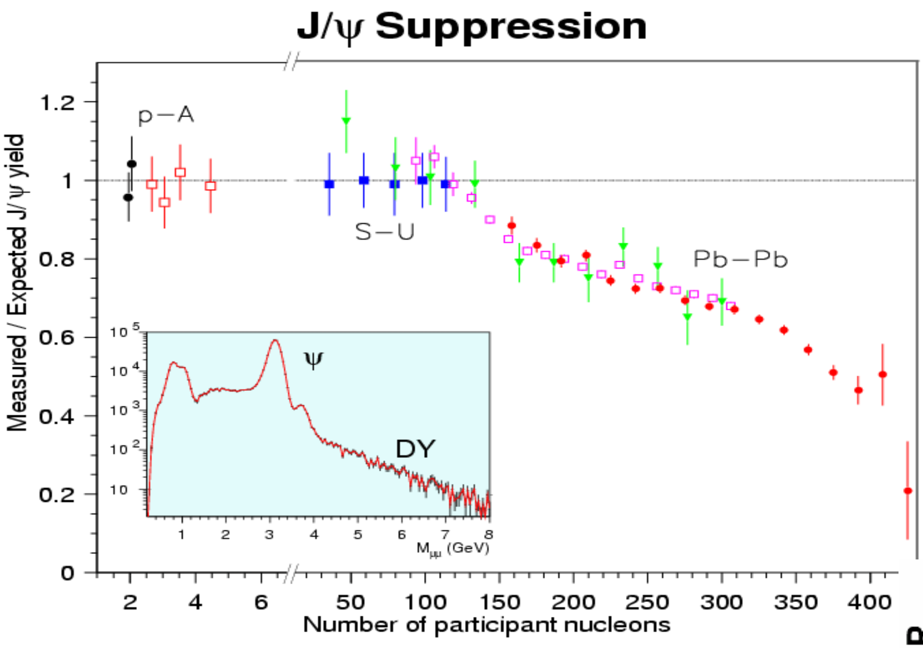
Phase diagram of nuclear matter



Space-time evolution of HI

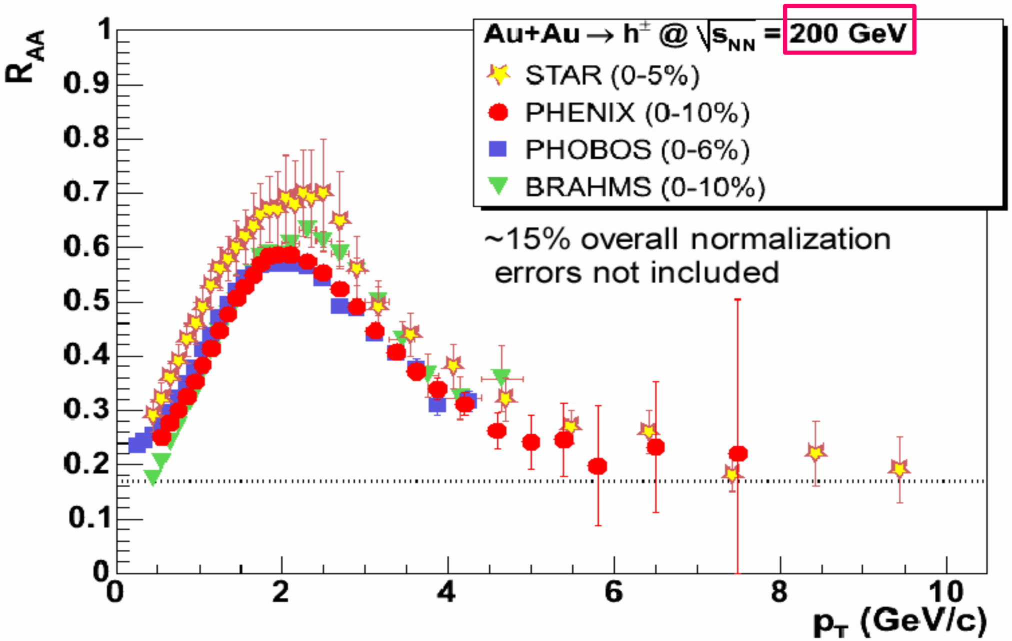


Existing measurements



- NA38/50
  - → Suppression of J/ψ meson production in Pb-Pb collisions
    - SPS fixed target

- RHIC
  - → Suppression of high p_T hadrons in central collisions
    - By factor 4-5



LHC will enter new regime

	SPS	RHIC	LHC
$v s_{NN}$ (GeV)	17	200	5500
dN_{ch}/dy	500	850	1500-8000
τ^0_{QGP} (fm/c)	1	0.2	0.1
T/T_c	1.1	1.9	3.0-4.2
ε (GeV/fm^3)	3	5	15-60
τ_{QGP} (fm/c)	=2	2-4	=10
τ_f (fm/c)	~10	20-30	30-40
V_f(fm^3)	few 10^3	few 10^4	few 10^5

Measurements in HI at LHC

- Some of the observables (low and high p_T !)
  - → Multiplicities, energy flow
    - Determine global properties
  - → Hadron spectra, dileptons and direct photons
    - Determine degrees of freedom (vs. temperature)
  - → Spectroscopy of charmonium and bottomonium
    - Study de-confinement
  - → High p_T spectra, jet quenching
    - Information on partonic energy loss (in QGP)
- Variation of energy density in AA collisions
  - → Various ion species
  - → Variation of impact parameter (centrality)
- Reference reactions to be measured precisely
  - → Use of pp collision and pA collisions

Experimental signatures overview

- ATLAS, CMS
  - → High p_T objects: e, γ, μ, τ, jet, b-jet, E_T^{miss}, ...
  - → Partially also low p_T particles from decays
- LHCb
  - → Mostly low p_T particles from decays
    - Precise measurement of secondary vertices
    - Particle identification very important
- ALICE
  - → Particle flow, multiplicities, spectra, particle identification, correlations, ...
  - → Leading neutrons, protons (centrality)
- TOTEM
  - → Leading protons
  - → Charged particles under small angles

Summary of today's lecture

- Successful development (and experimental verification) of Standard Model of particles physics
- Strong indirect evidence that new physics exists beyond SM
  - → And still need to find the missing piece (Higgs)
- LHC (and experiments): multi-purpose facility
  - → Extremely broad range in physics topics
- Several categories of experimental signatures
  - → High p_T objects
  - → Low p_T identified particles (from decays)
  - → Global properties
  - → Leading particles

Outlook for tomorrow

- How to detect and measure the various categories of signatures?
  - → Discussion of experimental conditions
  - → Description of the five experiments
- Operational aspects
  - → Commissioning of the detectors
  - → Running scenarios (physics dependent)
  - → Initial physics reach