PHYS 2356: Jour 7

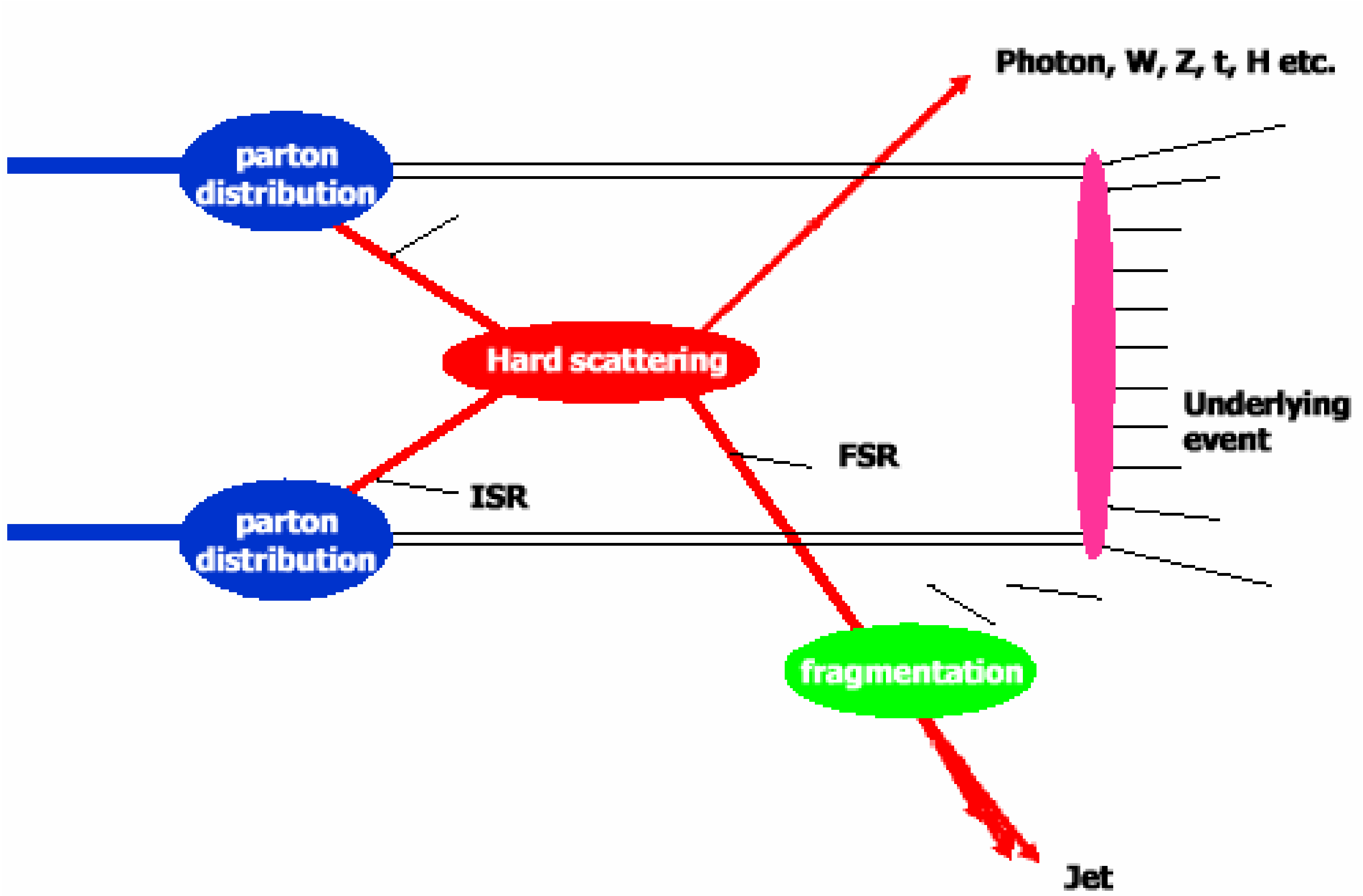
Physique des particules élémentaires - aspects expérimentaux

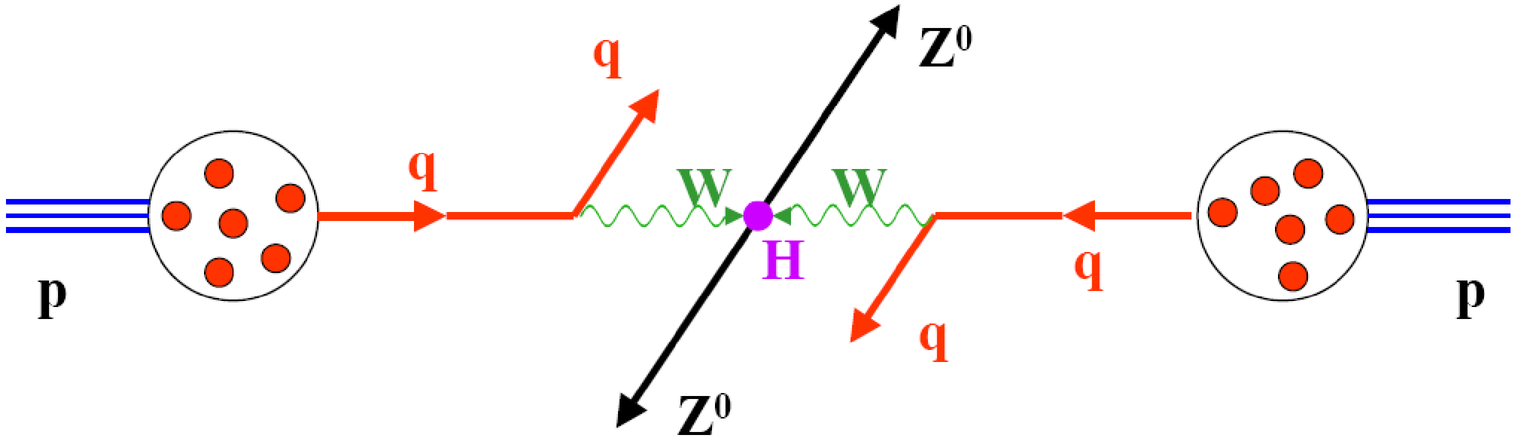
Suive/complémente le PHYS 2263 (d)

La référence de base: D.H. Perkins *Introduction to High Energy Physics*, 4th edition +
PDG, *Review of Particle Physics*, les chapitres selectionnés à http://pdg.lbl.gov

+ les références supplémentaires:
Aitchison&Hey, Halzen&Martin, Ferbel(ed), Kleinknecht

Plan du cours


Photon, W, Z, t, H etc.
parton distribution
Hard scattering
ISR
FSR
parton distribution
Underlying event
fragmentation
Jet



M_H ~ 1000 GeV

$E_W \geq$ 500 GeV

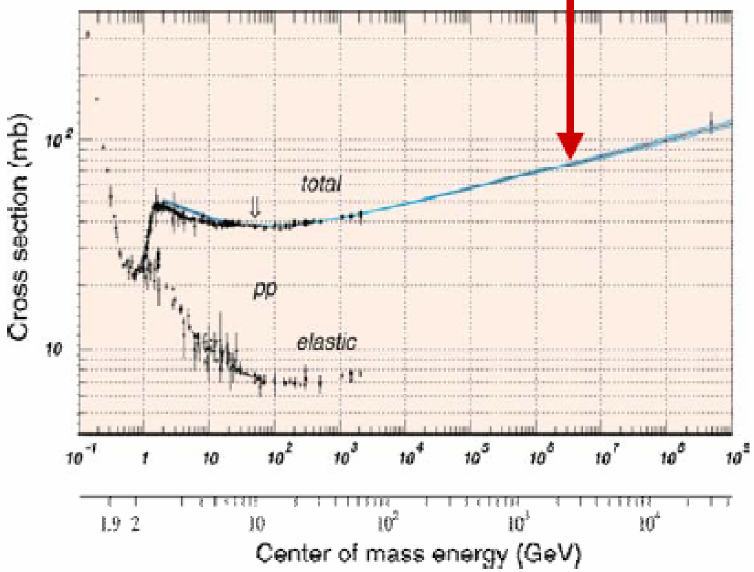
$E_q \geq$ 1000 GeV (1 TeV)

$E_p \geq$ 6000 GeV (6 TeV)

→ Proton Proton Collider with $E_p \geq$ 7 TeV

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} cm^{-2}s^{-1}=10^{7}mb^{-1}Hz
    - σ(pp) = 70 mb
    - Interaction Rate, R = 7×10^{8} Hz
  - Events/beam crossing:
    - Δt = 25 ns = 2.5×10^{-8} s
    - Interactions/crossing=17.5
  - Not all p bunches are full
    - Approximately 4 out of 5 (only) are full
    - Interactions/"active" crossing = 17.5 x 3564/2835 = 23

σ(pp)$\approx$70 mb



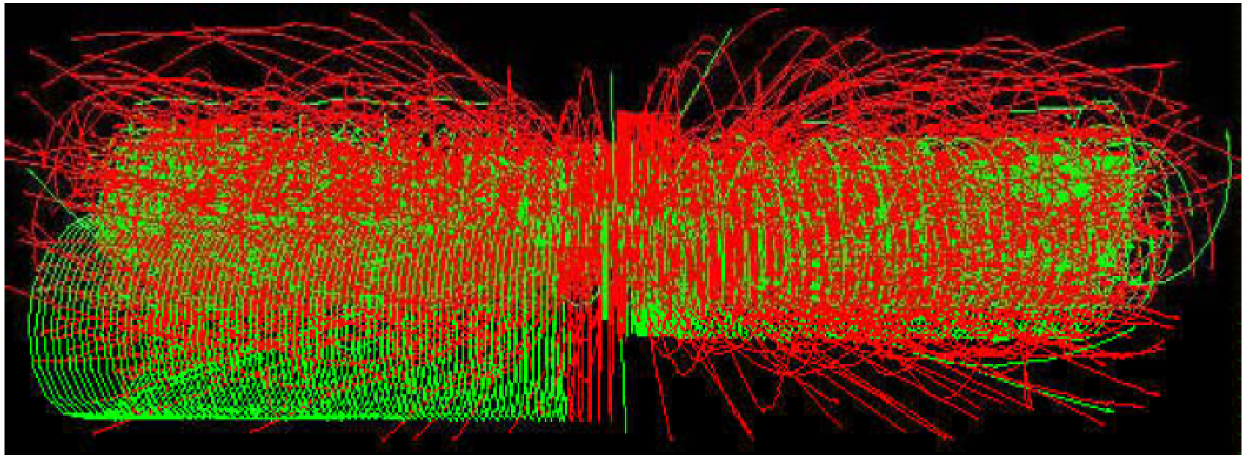
Operating conditions (summary):
1) A "good" event containing a Higgs decay +
2) $\approx$ 20 extra "bad" (minimum bias) interactions

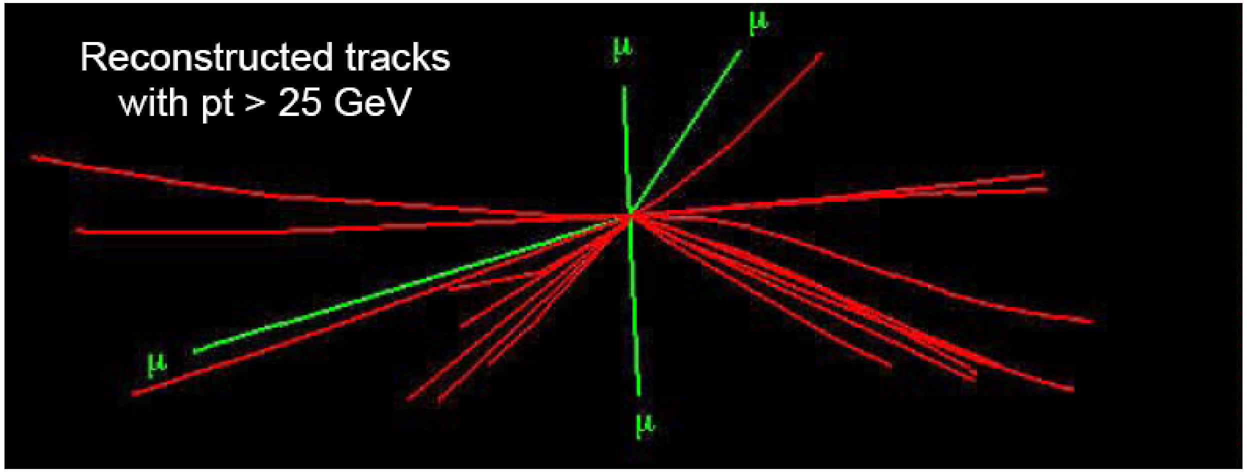
- 20 min bias events overlap
- H→ZZ

Z →μμ

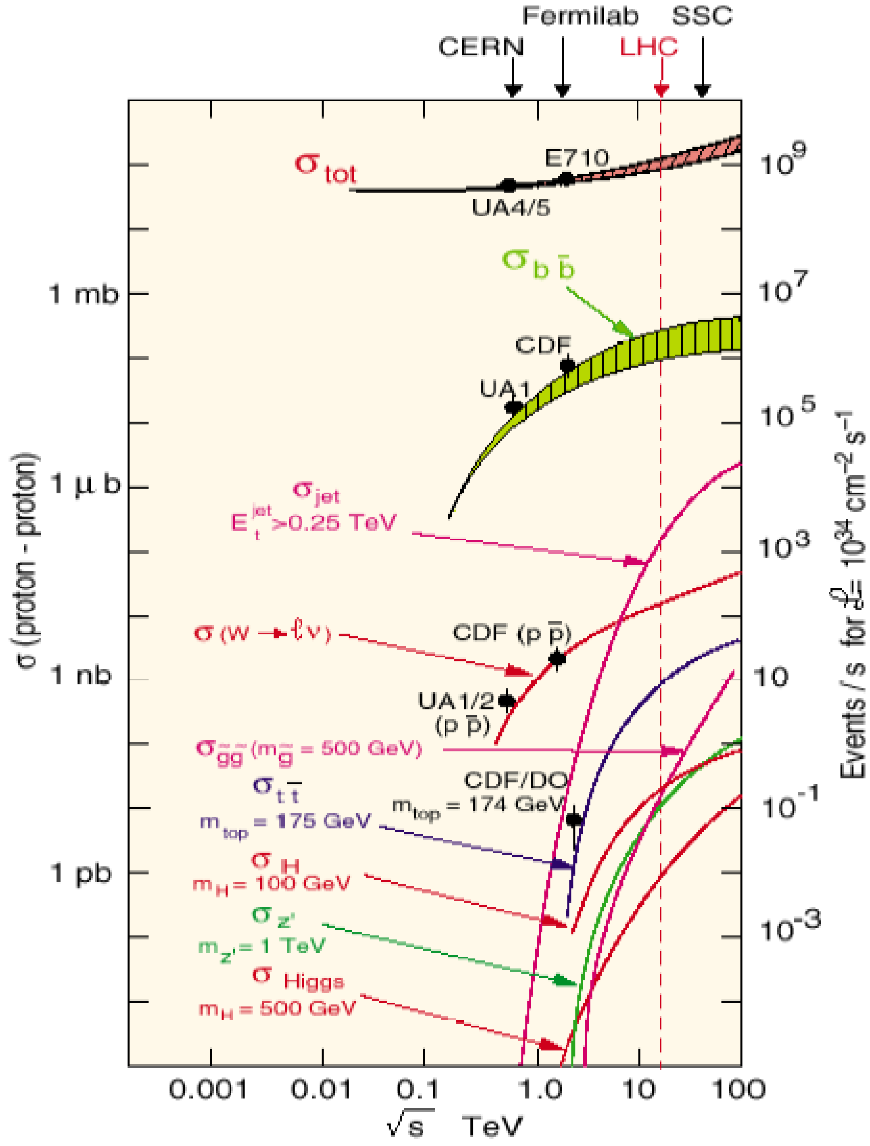
H→ 4 muons: the cleanest ("golden") signature

And this (not the H though…) repeats every 25 ns…





- Cross sections for various physics processes vary over many orders of magnitude
  - Inelastic: 10^9 Hz
  - $W \to \ell \nu$: 10^2 Hz
  - $t\bar{t}$ production: 10 Hz
  - Higgs (100 GeV/c^2): 0.1 Hz
  - Higgs (600 GeV/c^2): 10^{-2} Hz
- Selection needed: 1:10^{10-11}
  - Before branching fractions...



Caractérisation globale d'une collision hadronique, les variables cinématiques utilisées

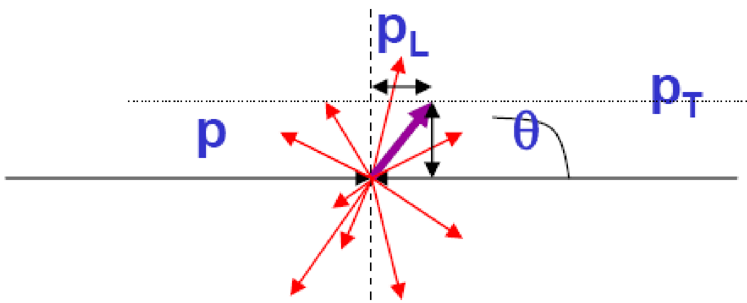
$$p_T = p_\perp = \sqrt{p_x^2 + p_y^2} = p \sin\theta$$ **Moment transversal**

Section efficace invariant

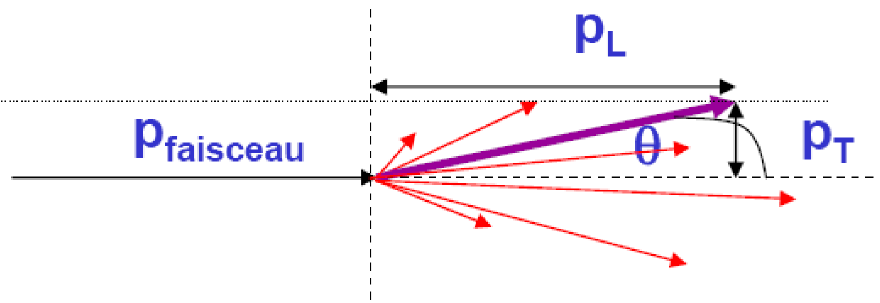
$$E\frac{d^3\sigma}{dp^3} = E\frac{d^3\sigma}{dp_x dp_y dp_z} = \frac{1}{2\pi}\frac{d^2\sigma}{p_T dp_T d\left(p_L/E\right)} \sim \underbrace{F\left(p_T\right)F'\left(p_L\right)}_{\text{(Feynman scaling)}}$$

$$F\left(p_T\right) \sim e^{-bp_T} \; ; \; < p_T >_{\text{particules sécondaires}} \approx 0.3 - 0.5 \; GeV/c \; \approx \frac{\hbar}{R}$$

$$E_T = \sum_{i=\text{part.sécondaires}} E_i \sin\theta_i$$ **Energie transversal**



Système de centre de masse



Système de laboratoire

Caractérisation globale d'une collision hadronique, les variables cinématiques utilisées

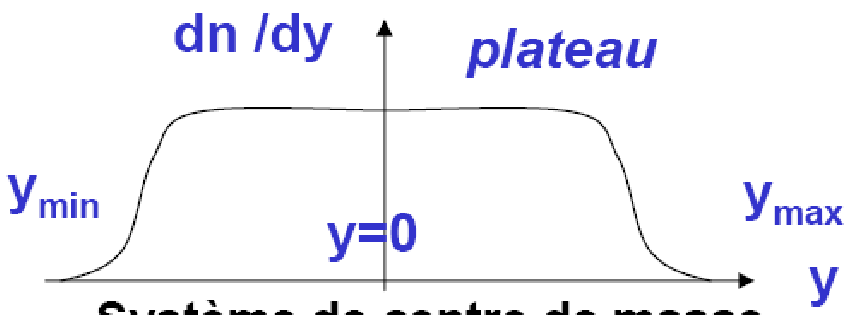
$$x_F = p_L / p_L^{\max} = p_L / \left(\sqrt{s}/2\right) \quad \text{(Feynman "}x\text{")}$$

Rapidité *y*, « invariante » de Lorentz

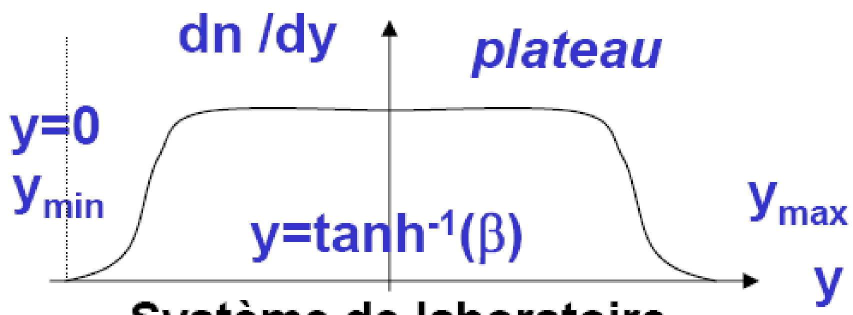
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) \overset{\beta\to 1,\, m\to 0}{\approx} \eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

η, pseudo-rapidité

$$y \to y + \tanh^{-1}(\beta) \qquad y_{\max} = \frac{1}{2}\ln\left(\frac{s}{m^2+p_T^2}\right)$$



Système de centre de masse



Système de laboratoire

38.5.2. ***Inclusive reactions***: Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y \ , \quad (38.35)$$

where m_T is the transverse mass

$$m_T^2 = m^2 + p_x^2 + p_y^2 \ , \quad (38.36)$$

and the rapidity y is defined by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

$$= \ln \left(\frac{E + p_z}{m_T} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right) \ . \quad (38.37)$$

Under a boost in the z-direction to a frame with velocity β, $y \to y - \tanh^{-1} \beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E \frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi \, dy \, p_T \, dp_T} \Longrightarrow \frac{d^2\sigma}{\pi \, dy \, d(p_T^2)} \ . \quad (38.38)$$

For $p \gg m$, the rapidity [Eq. (38.37)] may be expanded to obtain

$$y = \frac{1}{2} \ln \frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots}$$

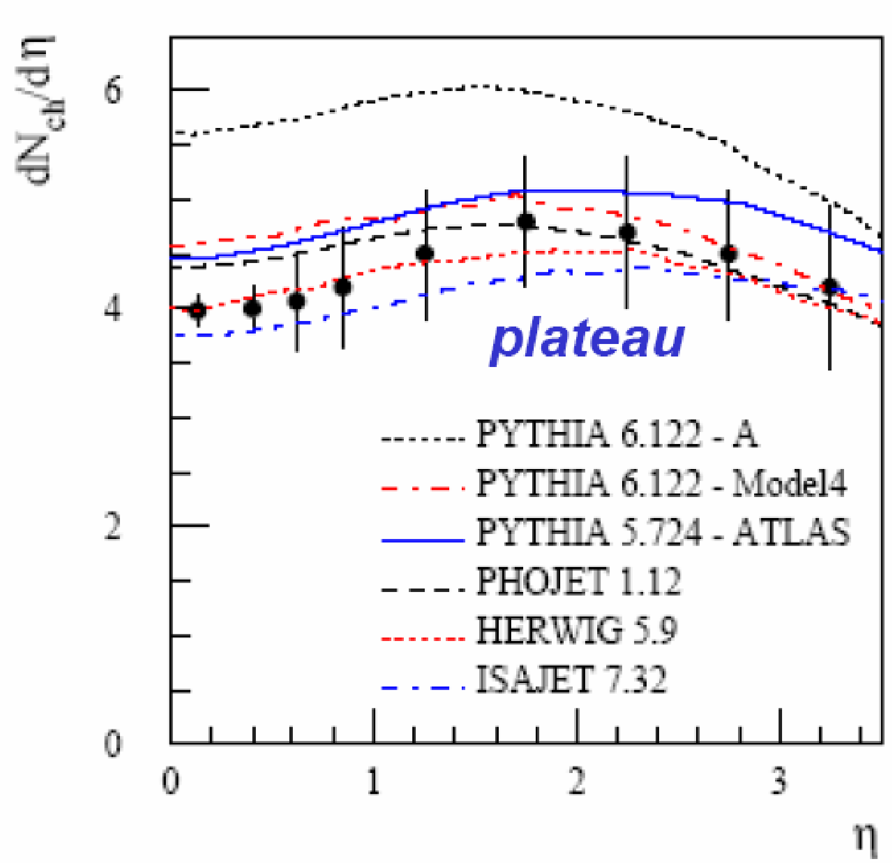
$$\approx -\ln \tan(\theta/2) \equiv \eta \quad (38.42)$$

where $\cos \theta = p_z/p$. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $p \gg m$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

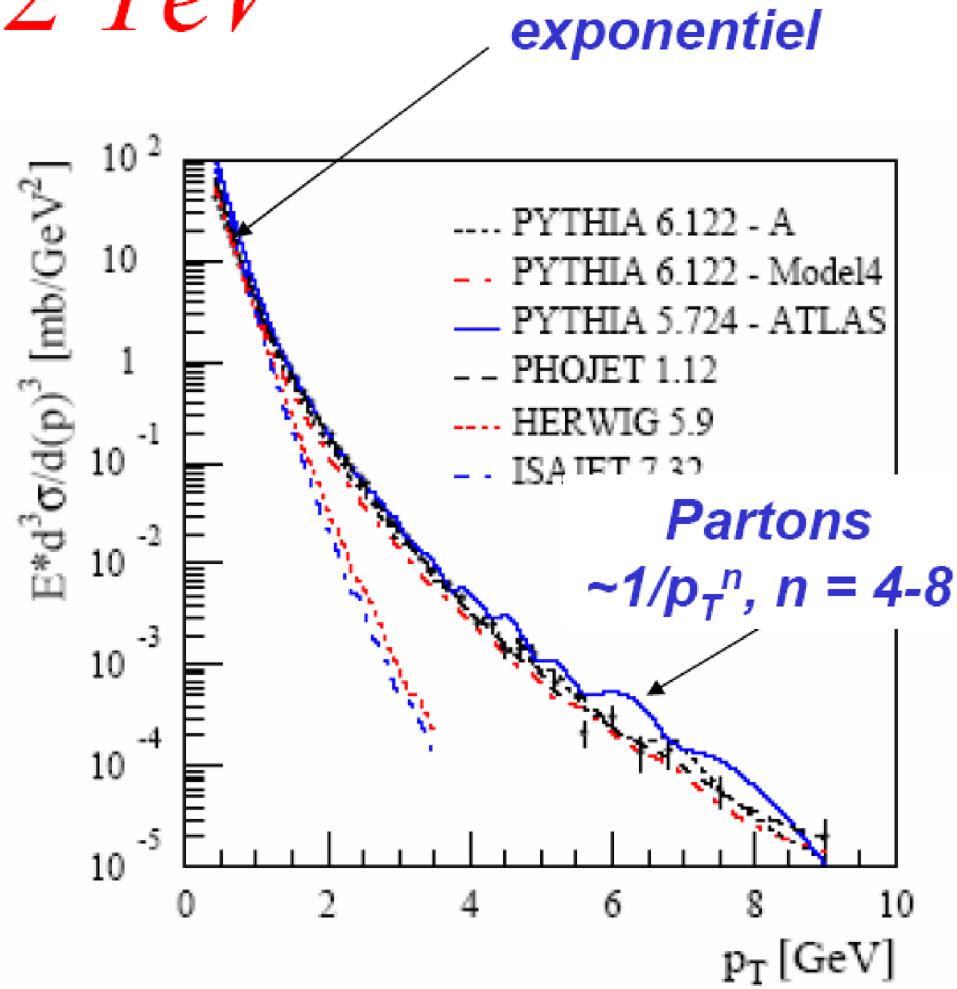
$$\sinh \eta = \cot \theta \ , \quad \cosh \eta = 1/\sin \theta \ , \quad \tanh \eta = \cos \theta \ . \quad (38.43)$$

Particules chargées au Tevatron

$$p\bar{p},\ \sqrt{s} = 2\ TeV$$



Pseudo rapidité, y_{max}= 7.6



Moment transversale

Pseudorapidity Distributions in $\overline{p}p$ Interactions

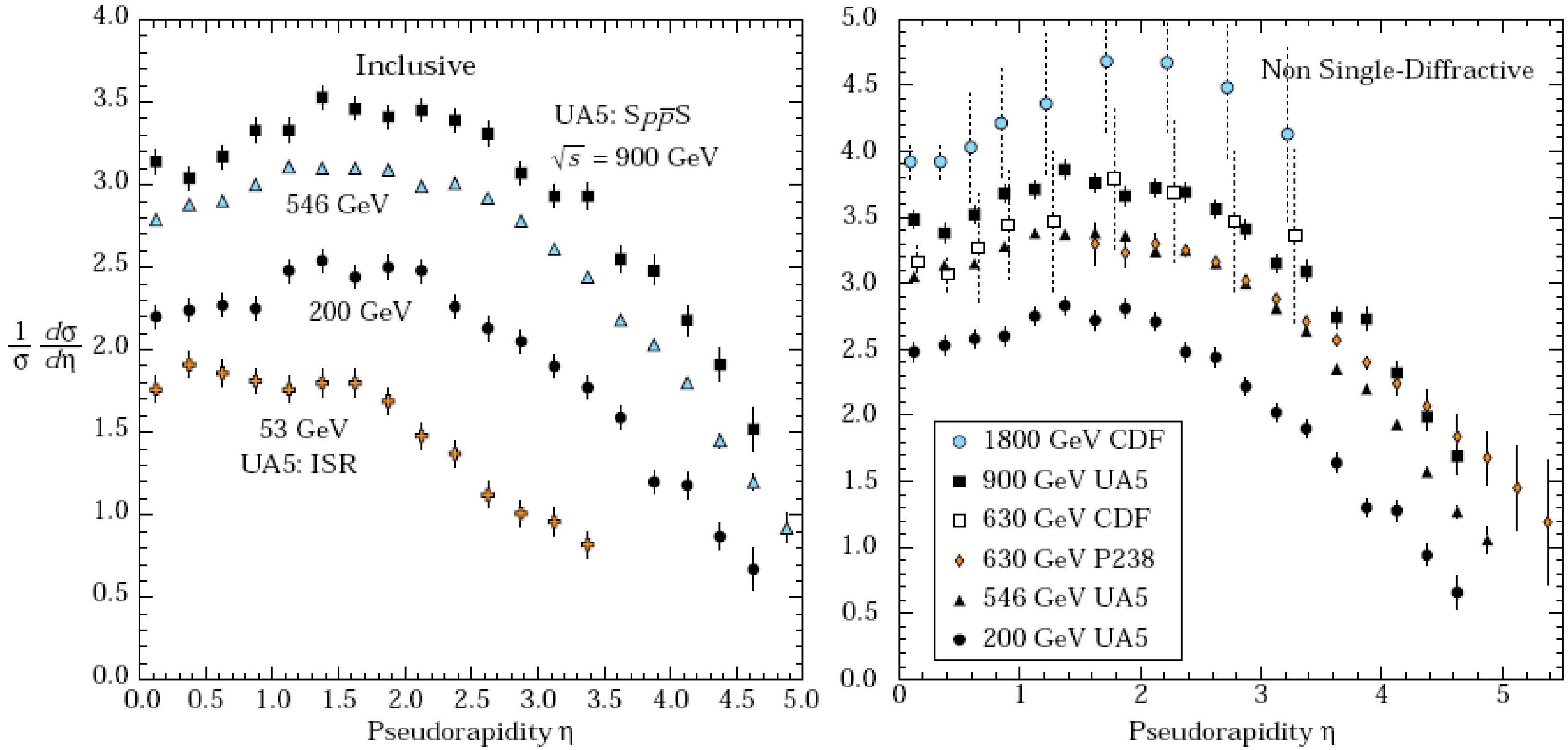
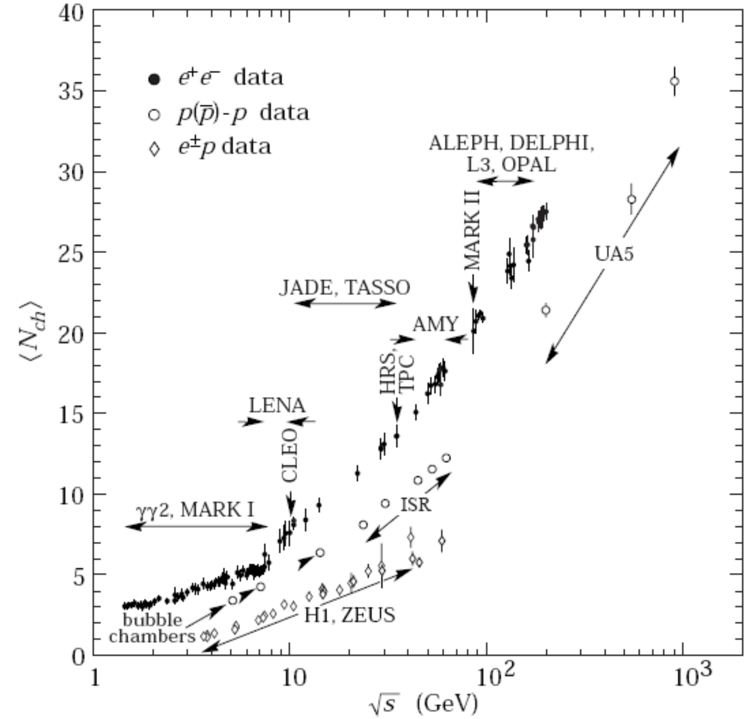
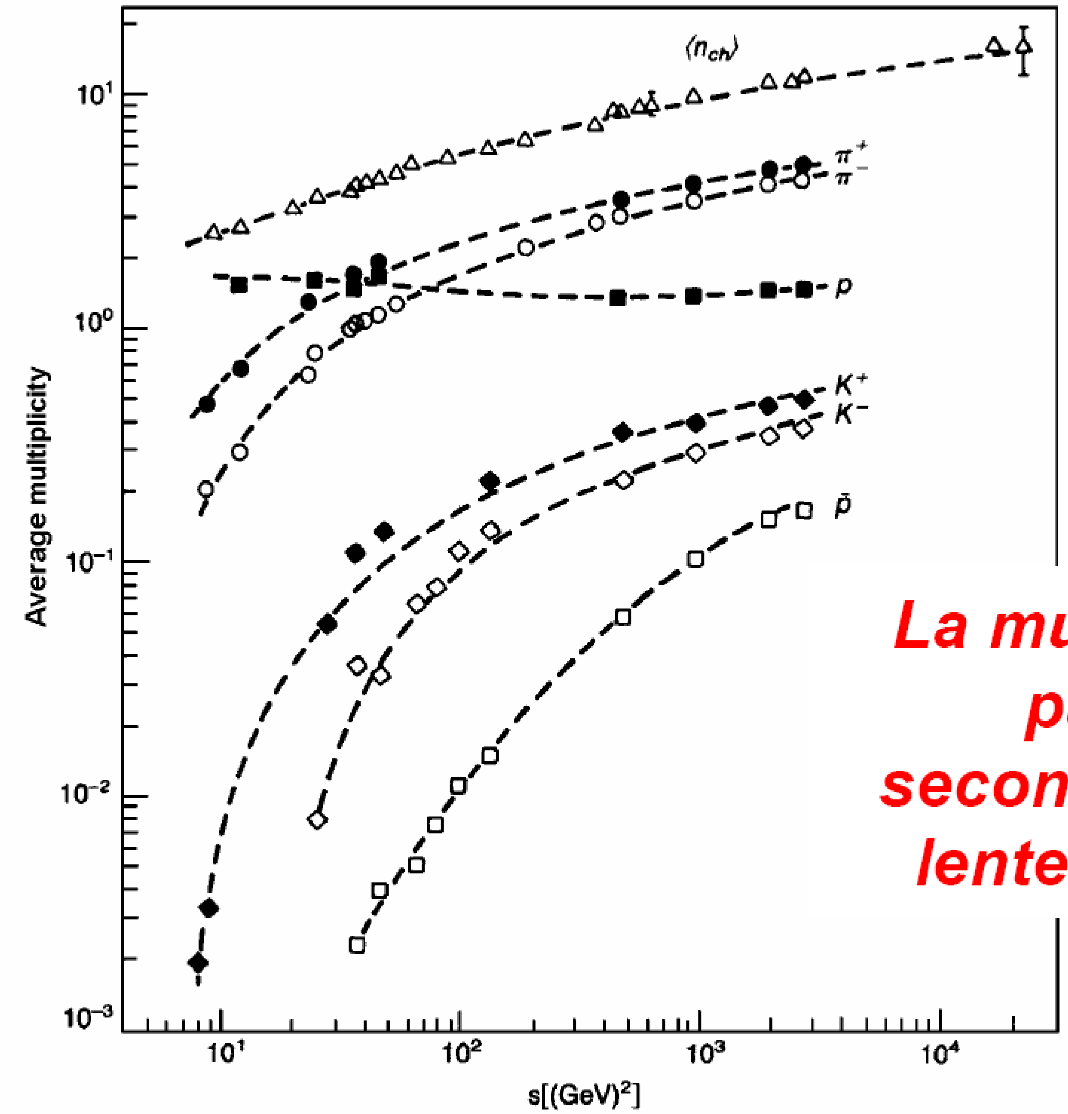


Figure 40.4: Charged particle pseudorapidity distributions in $p\overline{p}$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 1800 GeV. UA5 data from the $Sp\overline{p}S$ are taken from G.J. Alner *et al.*, Z. Phys. **C33**, 1 (1986), and from the ISR from K. Alpgøard *et al.*, Phys. Lett. **112B**, 193 (1982). The UA5 data are shown for both the full inelastic cross-section and with singly diffractive events excluded. Additional non single-diffractive measurements are available from CDF at the Tevatron, F. Abe *et al.*, Phys. Rev. **D41**, 2330 (1990) and Experiment P238 at the $Sp\overline{p}S$, R. Harr *et al.*, Phys. Lett. **B401**, 176 (1997). (Courtesy of D.R. Ward, Cambridge Univ., 1999.)

Average e^+e^-, pp, and $\overline{p}p$ Multiplicity





La multiplicité des particules secondaires monte lentement avec s

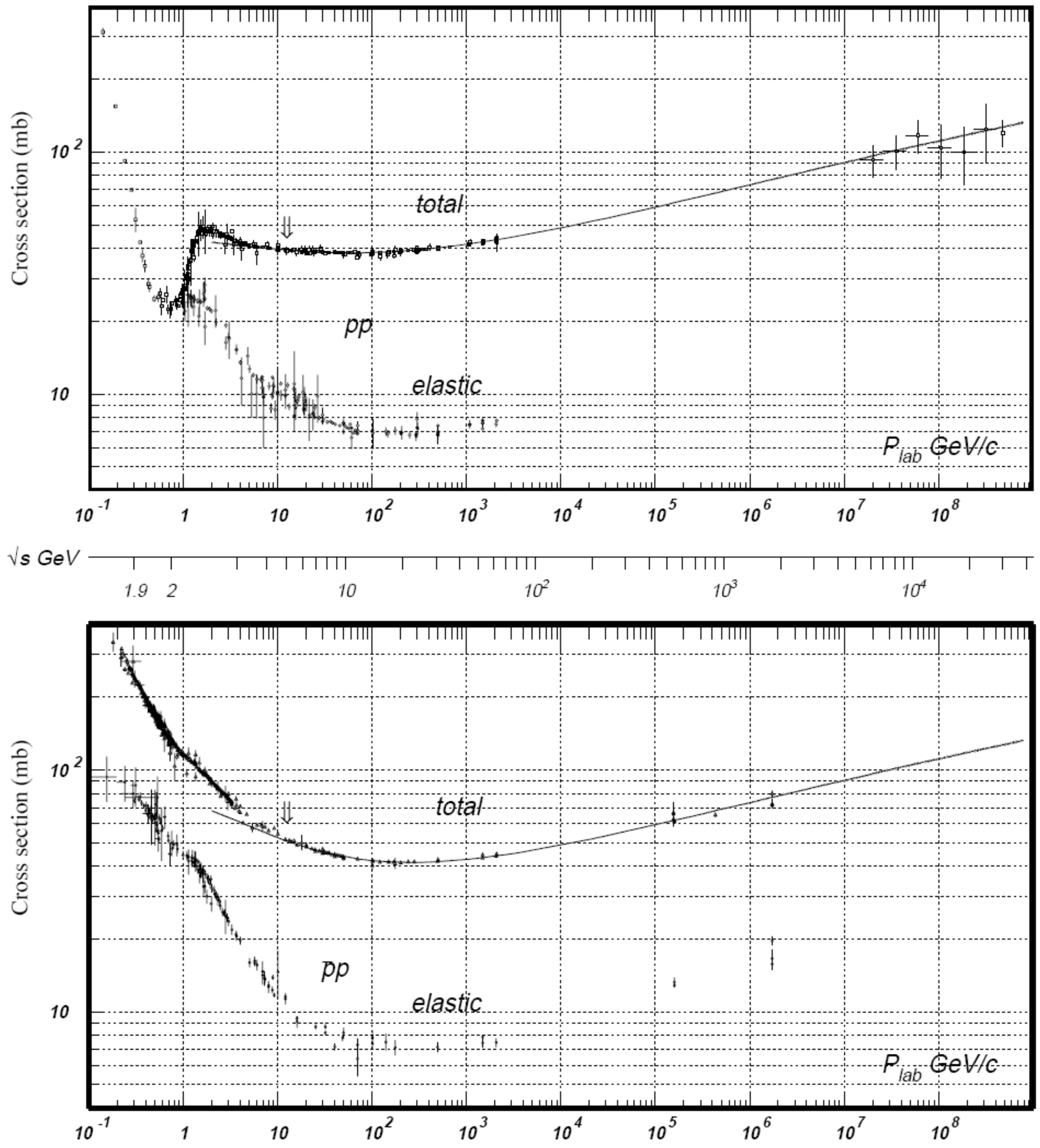
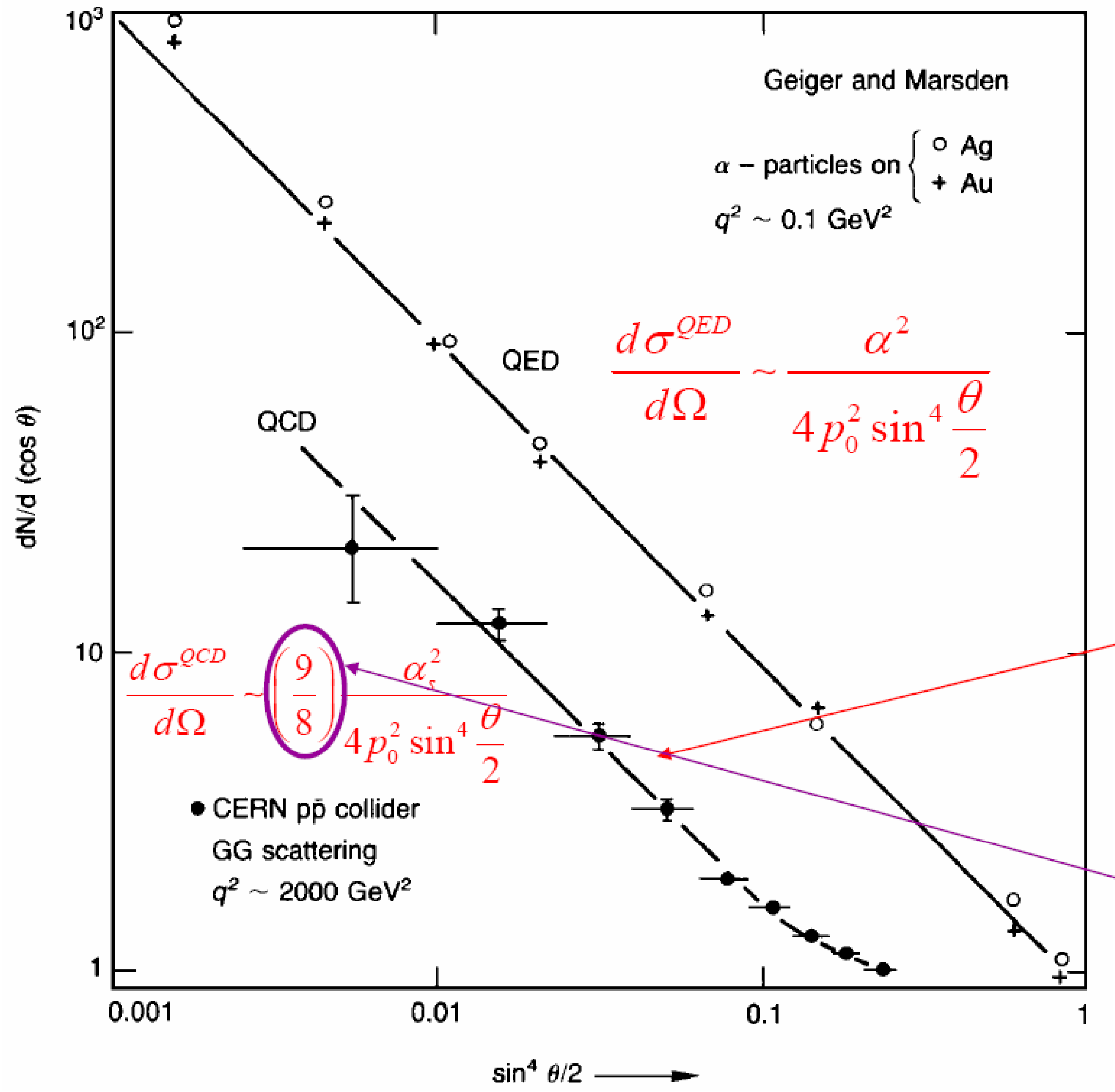


Figure 40.11: Total and elastic cross sections for pp and $\bar{p}p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html`. (Courtesy of the COMPAS



$$\frac{d\sigma^{QED}}{d\Omega} \sim \frac{\alpha^2}{4p_0^2 \sin^4\frac{\theta}{2}}$$

$$\frac{d\sigma^{QCD}}{d\Omega} \sim \left(\frac{9}{8}\right)\frac{\alpha_s^2}{4p_0^2 \sin^4\frac{\theta}{2}}$$

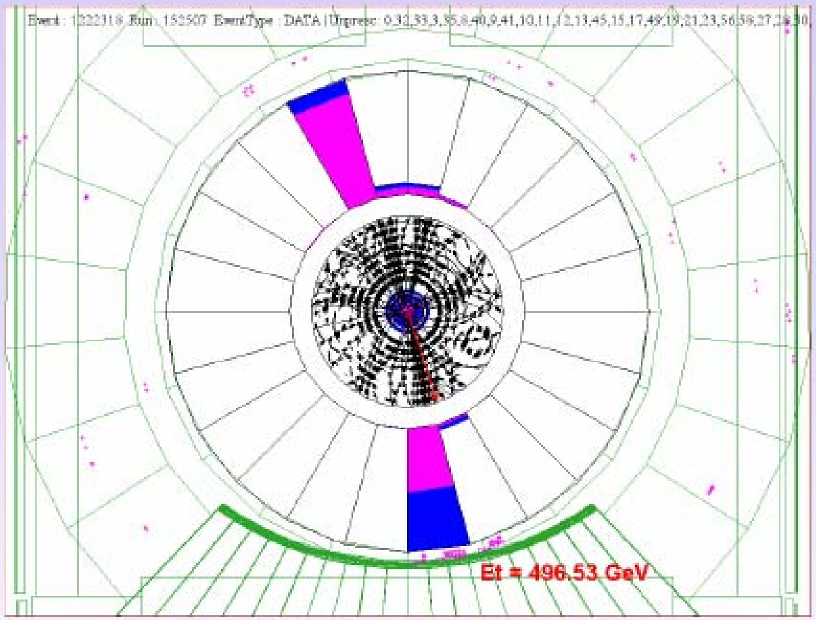
Diffusion élastique de partons et la diffusion de Rutherford

$\Rightarrow$

Les quarks sont des particules élémentaires

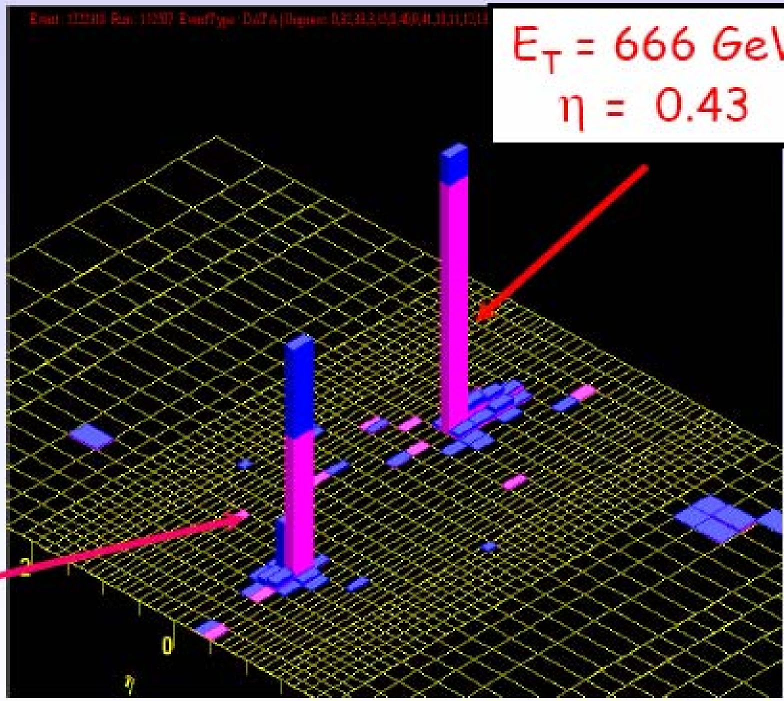
couleur

A two jet event at the Tevatron



CDF (ϕ-r view)

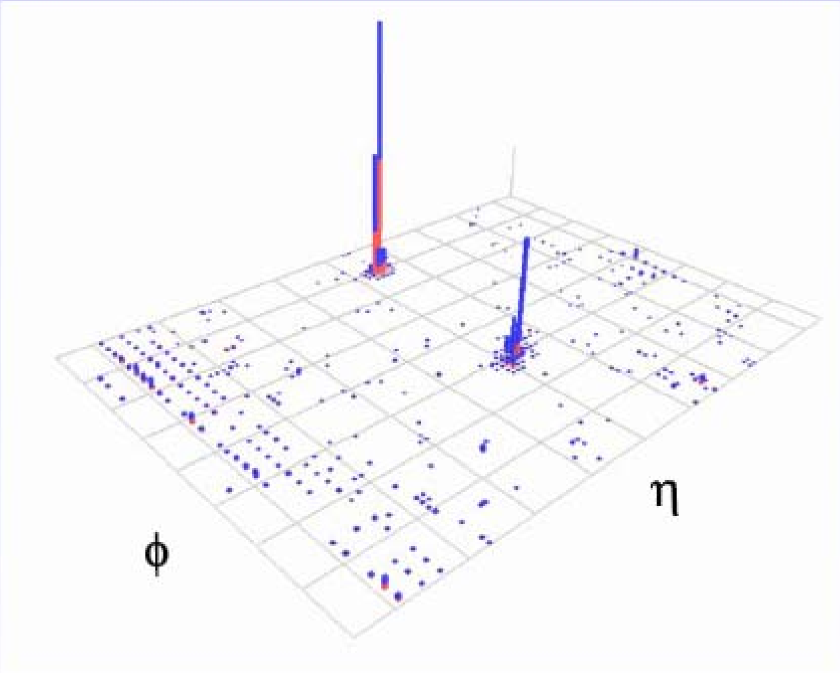
Dijet Mass = 1364 GeV/c^2

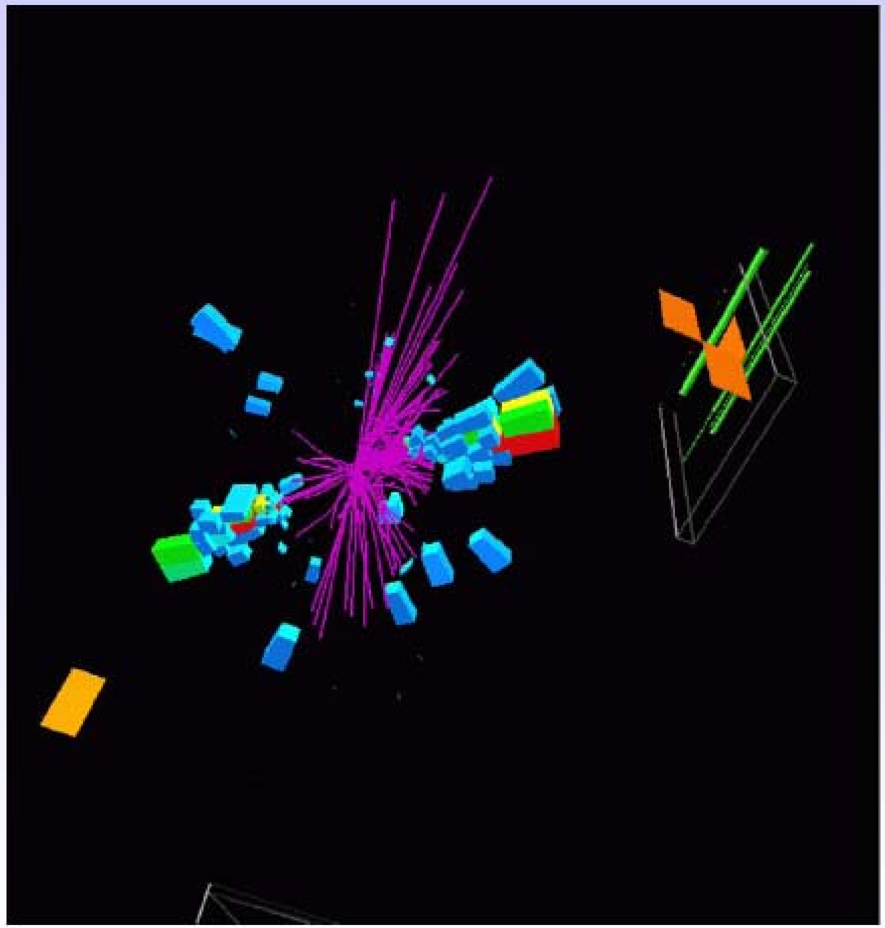


E_T = 666 GeV
η = 0.43

E_T = 633 GeV
η = -0.19

A two jet event in the DØ experiment



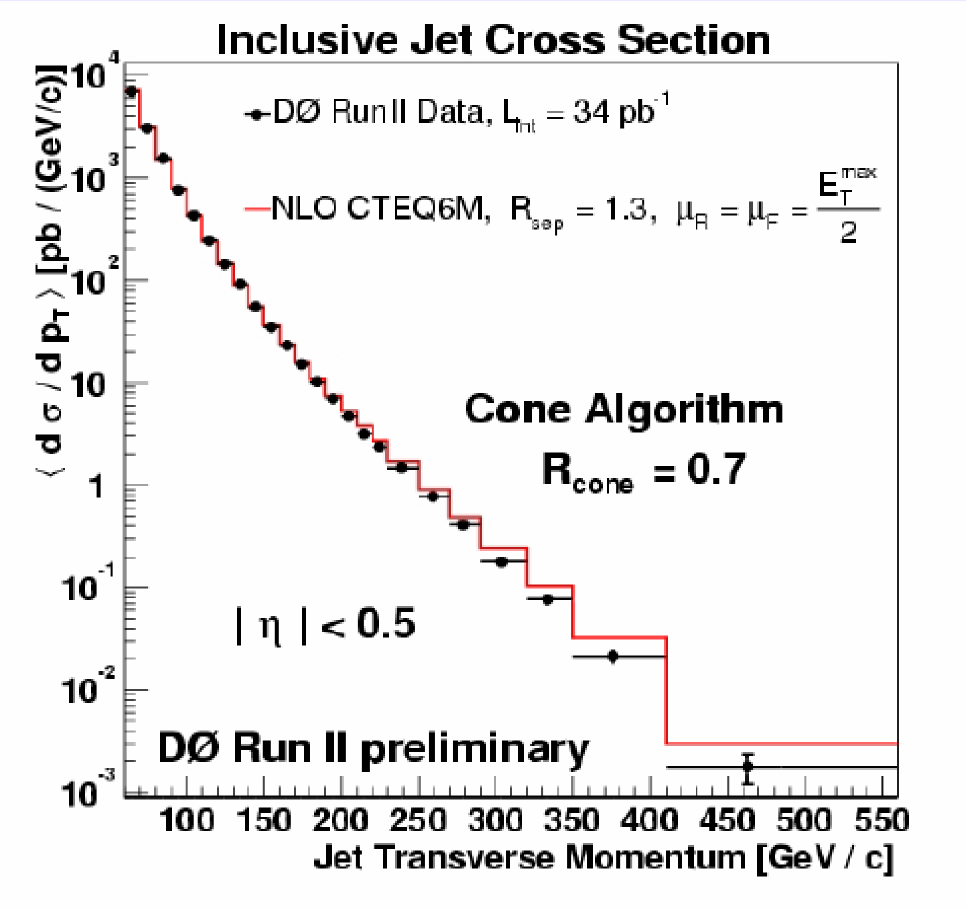


M_{jj} = 838 GeV/c^2

$p_T(1)$ = 432 GeV/c

$p_T(2)$ = 396 GeV/c

Test of QCD Jet production



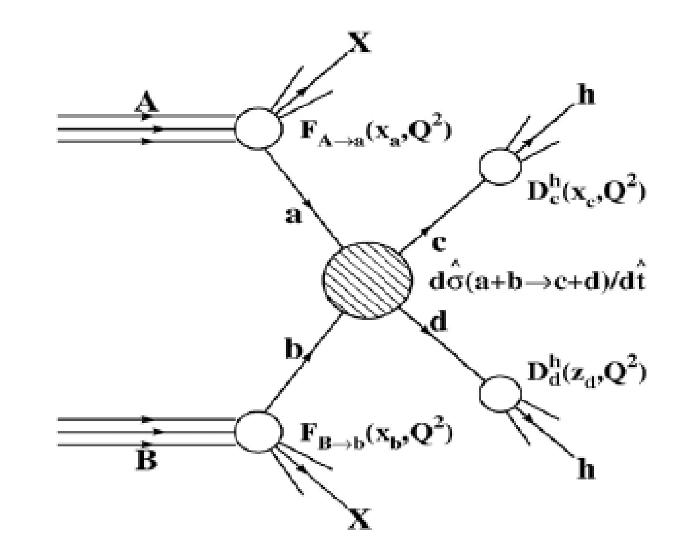
Data from the DØ experiment (Run II)

Inclusive Jet spectrum as a function of Jet-P_T

very good agreement over many orders of magnitude !

within the large theoretical and experimental uncertainties

Calculation of cross sections



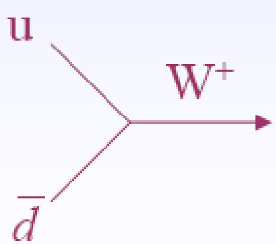
$$\sigma = \sum_{a,b} \int dx_a\, dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab}(x_a, x_b)$$

Sum over initial partonic states a,b

$\hat{\sigma}_{ab} \equiv$ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton density function

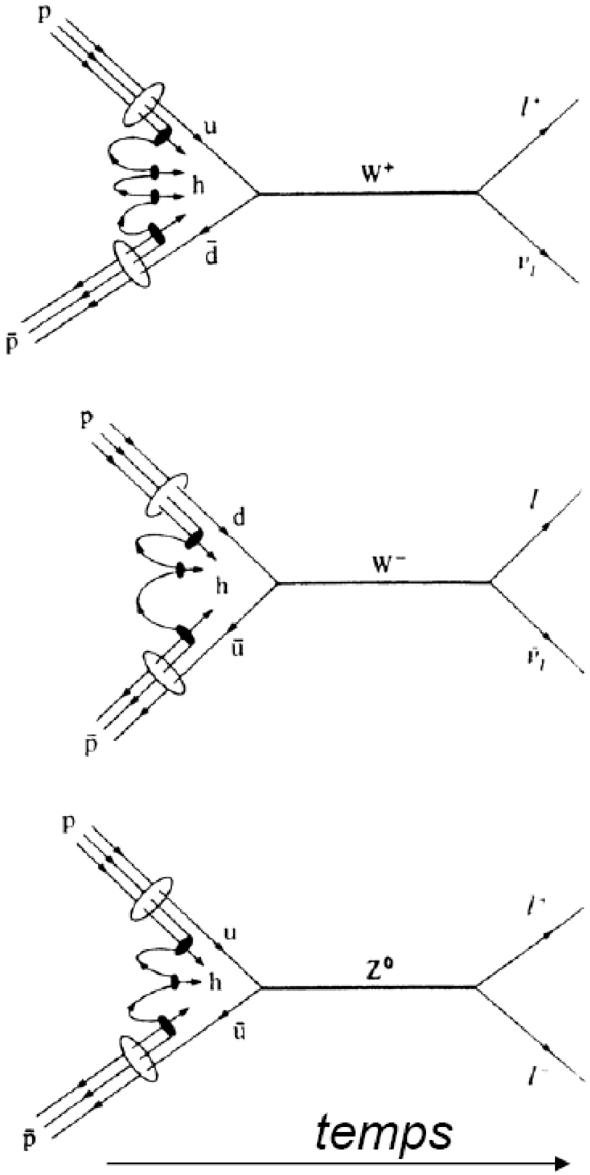
Example: W-production: (leading order diagram)

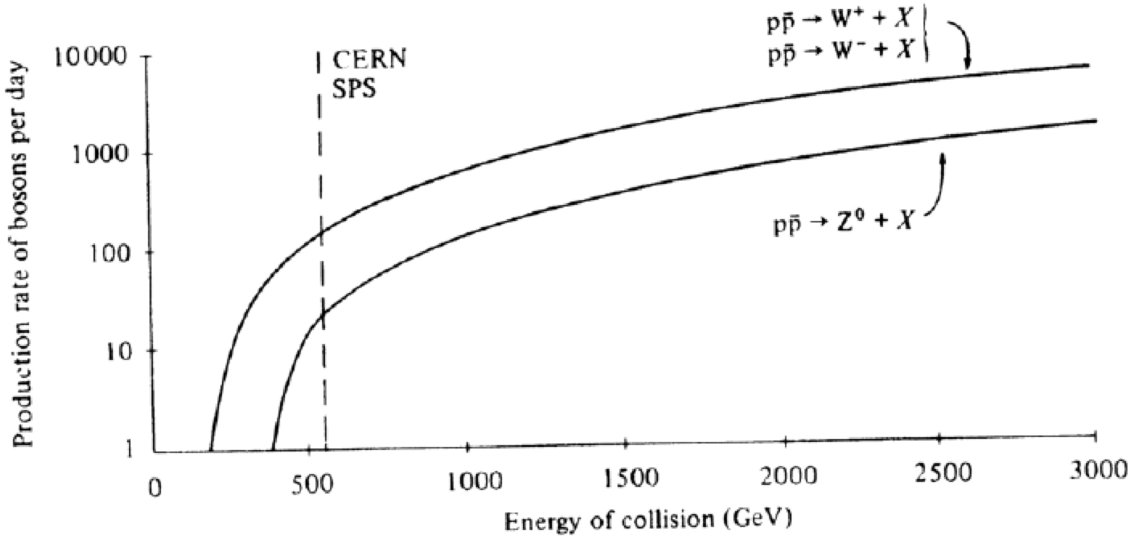


$\sigma(pp \to W) \sim 150$ nb $\sim 2 \cdot 10^{-6}\, \sigma_{tot}(pp)$

… + higher order QCD corrections (perturbation theory)

Observation des Bosons W et Z





$$u+\bar{d} \rightarrow W^{+} \rightarrow e^{+}+\nu_{e}, \text{ ou } \mu^{+}+\nu_{\mu}$$

$$\bar{u}+d \rightarrow W^{-} \rightarrow e^{-}+\bar{\nu}_{e}, \text{ ou } \mu^{-}+\bar{\nu}_{\mu}$$

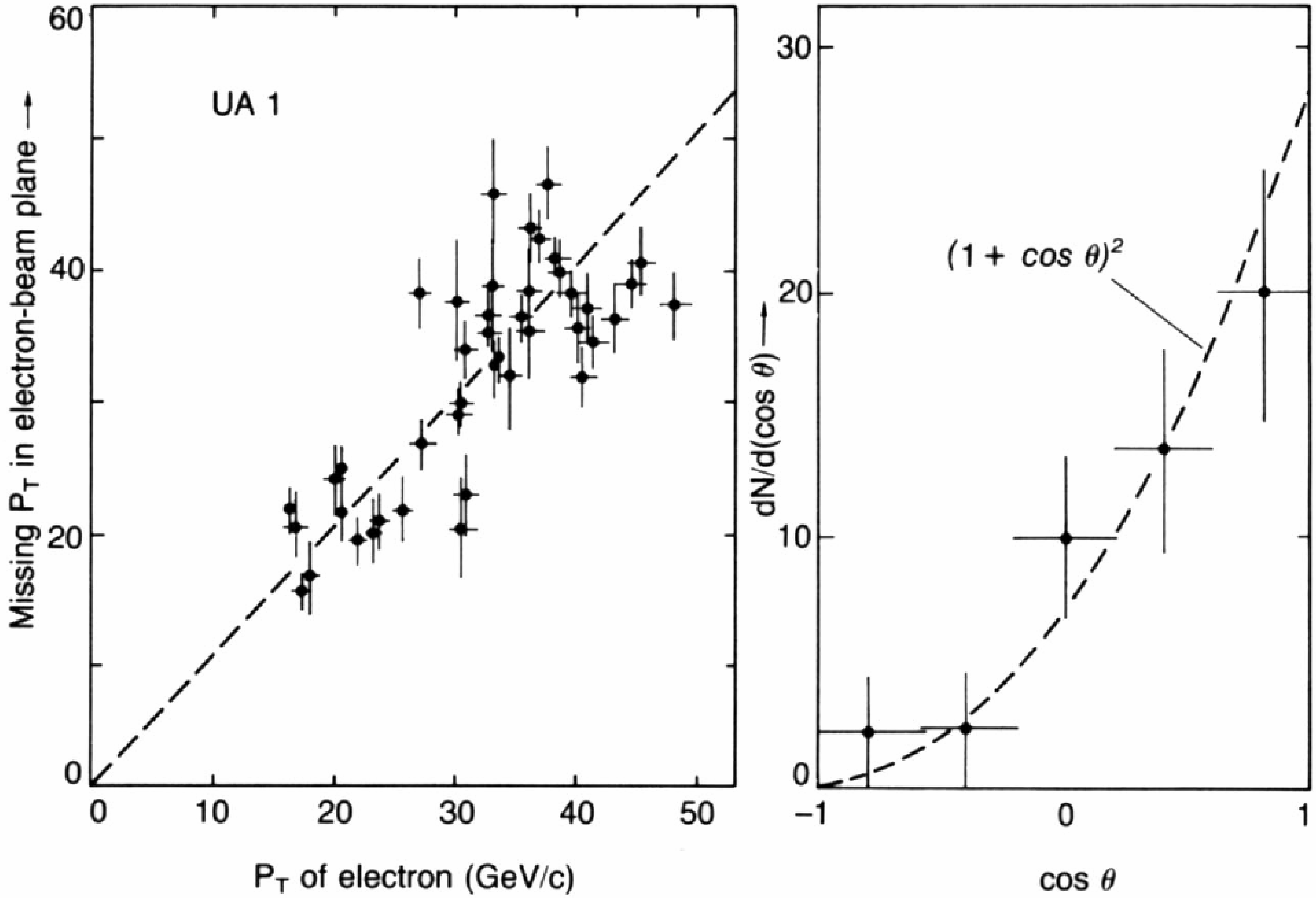
$$u+\bar{u} \rightarrow Z^{0} \rightarrow e^{+}e^{-}, \; \mu^{+}\mu^{-}$$

$$\langle x_{v}\rangle \approx 0.12, \quad \langle x_{s}\rangle \approx 0.04$$

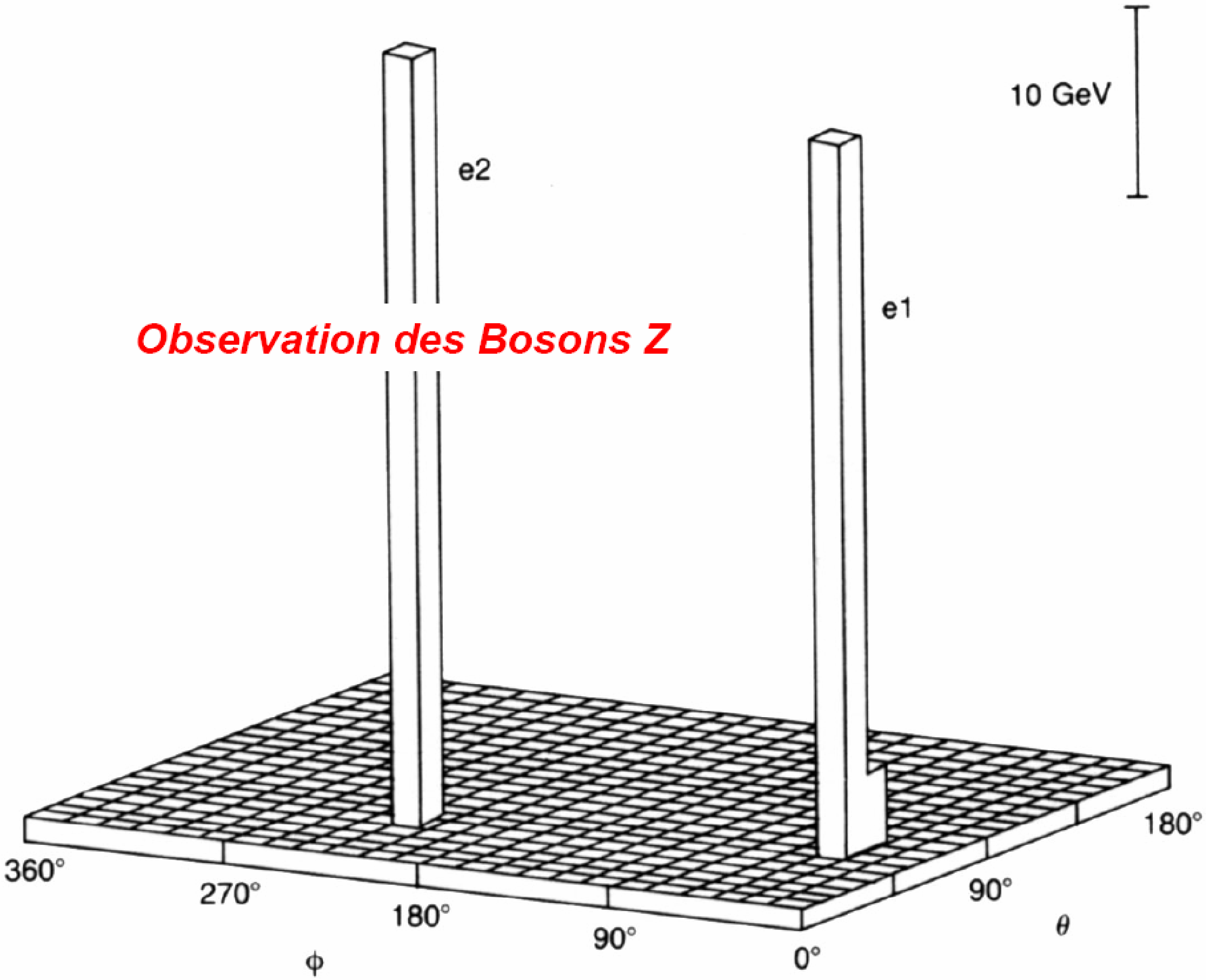
$$\sqrt{\hat{s}} \simeq \sqrt{\langle x_{v}\rangle\langle x_{s}\rangle \cdot s_{pp}} \simeq \sqrt{s_{pp}/200}$$

$$\sqrt{\hat{s}} \simeq \sqrt{\langle x_{v}\rangle\langle x_{\bar{v}}\rangle s_{p\bar{p}}} \simeq \sqrt{s_{p\bar{p}}/70}$$

Observation des Bosons W



Observation des Bosons Z



Measurement of W mass with precision

Method used at hadron colliders different from e^+e^- colliders

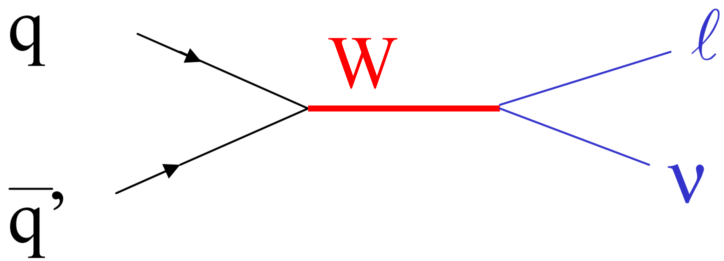
- $W \rightarrow$ jet jet : cannot be extracted from QCD jet-jet production $\Rightarrow$ cannot be used

- $W \rightarrow \tau\nu$: since $\tau \rightarrow \nu + X$, too many undetected neutrinos $\Rightarrow$ cannot be used

only $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays are used to measure m_W at hadron colliders

W production at LHC :

Ex.



$$\sigma\,(pp \rightarrow W + X) \approx 30\ \text{nb}$$

└→ eν, μν

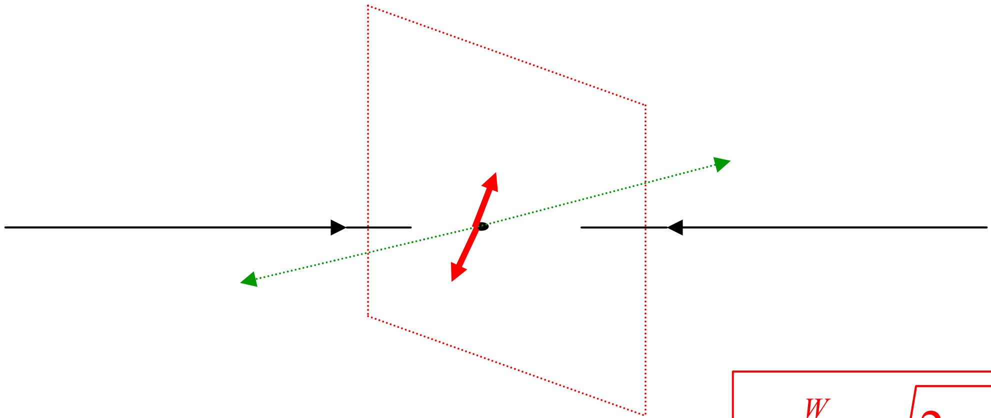
~ 300×10^6 events produced
~ 60×10^6 events selected after analysis cuts

} one year at low L, per experiment

~ 50 times larger statistics than at Tevatron
~ 6000 times larger statistics than WW at LEP

$$m_W{}^2 = (E_\ell + E_\nu)^2 - (\vec{p}_\ell + \vec{p}_\nu)^2 = 2E_\ell E_\nu (1 - \cos\theta_{\ell\nu})$$

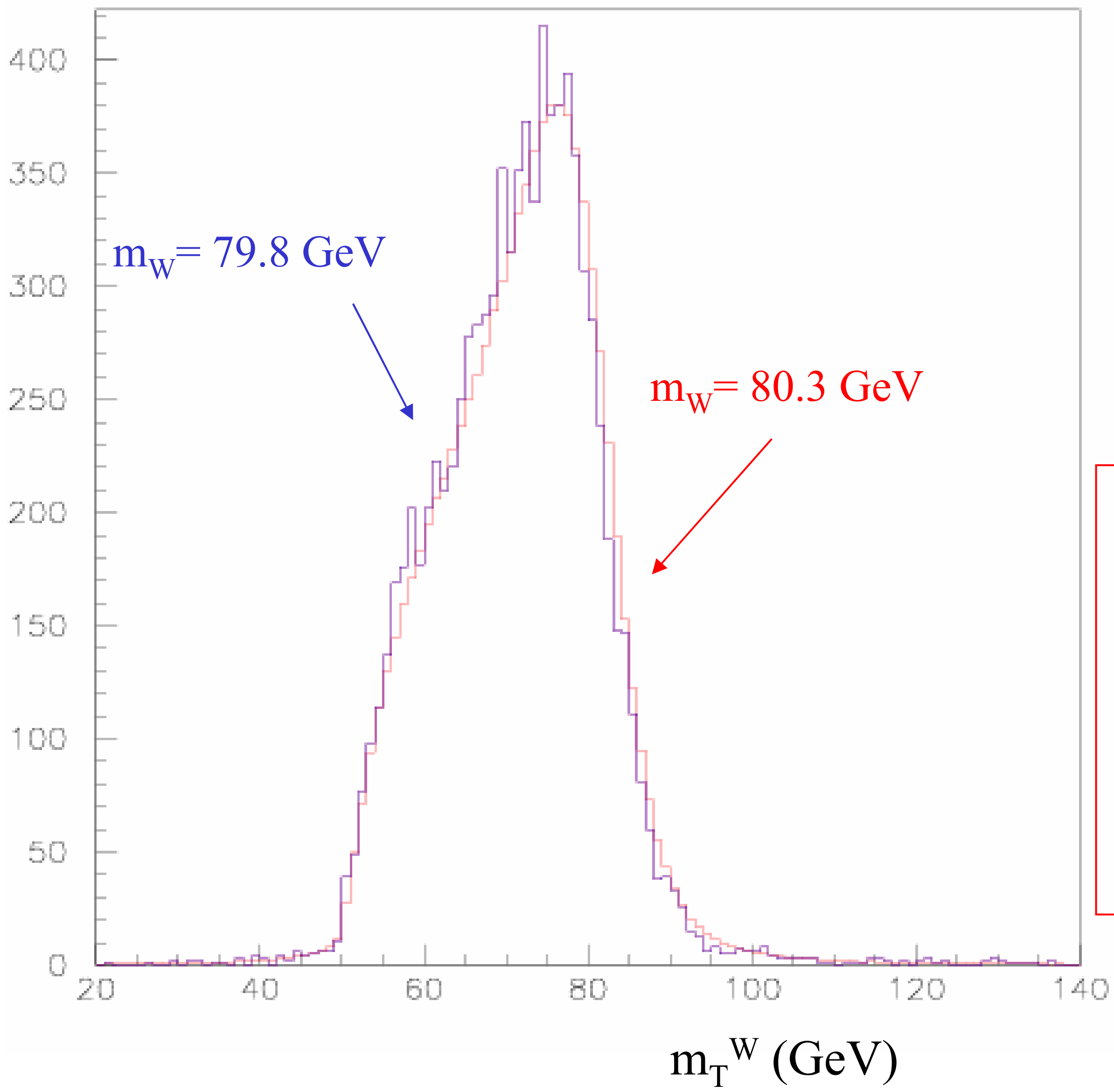
Since $\vec{p}_L{}^\nu$ not known (only $\vec{p}_T{}^\nu$ can be measured through $E_T{}^{miss}$), measure transverse mass, i.e. invariant mass of $\ell\nu$ in plane perpendicular to the beam :



$$m_T{}^W = \sqrt{2p_T{}^\ell \, p_T{}^\nu (1 - \cos\varphi_{\ell\nu})}$$

$p_T{}^\nu \equiv E_T{}^{miss}$

m_T^W distribution is sensitive to m_W



⇒ fit experimental distributions with SM prediction (Monte Carlo simulation) for different values of m_W → find m_W which best fits data

Uncertainties on m_W

Come mainly from capability of Monte Carlo prediction to reproduce real life, that is:

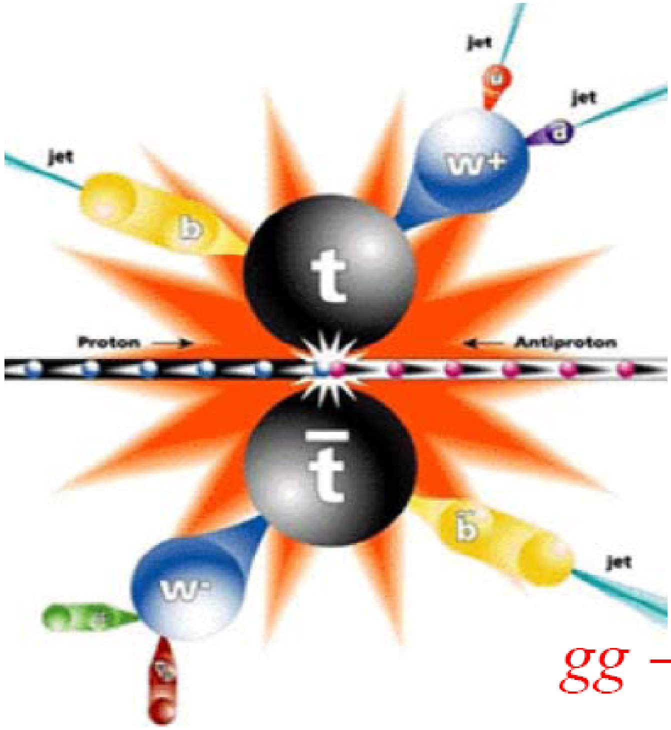
- detector performance: energy resolution, energy scale, etc.
- physics: p_T^W, θ_W, Γ_W, backgrounds, etc.

Dominant error (today at Tevatron, most likely also at LHC):
knowledge of lepton energy scale of the detector:
if measurement of lepton energy wrong by 1%,
then measured m_W wrong by 1%

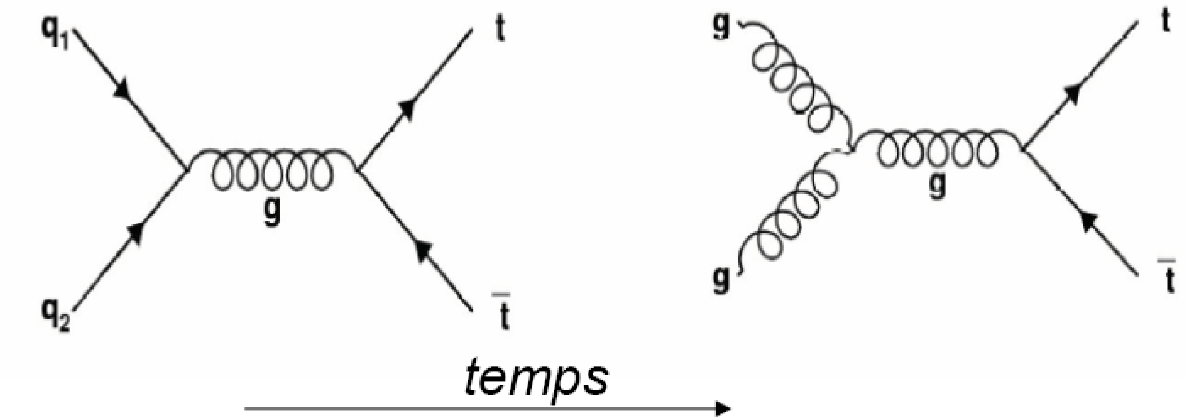
Expected precision on m_W at LHC

Source of uncertainty	Δm_W
Statistical error	<< 2 MeV
Physics uncertainties (p_T^W, θ_W, Γ_W, …)	~ 15 MeV
Detector performance (energy resolution, lepton identification, etc,)	< 10 MeV
Energy scale	15 MeV
Total (per experiment, per channel)	~ 25 MeV

Combining both channels ($e\nu$, $\mu\nu$) and both experiments (ATLAS, CMS),
$\Delta m_W \approx 15$ MeV should be achieved.
However: very difficult measurement



Observation du quark top



$$gg \to t\bar{t};\ t \to bW;\ \begin{cases} W \to l\nu;\ W \to q\bar{q}';\ q \to jet \\ b \to cl\nu;\ b \to jet \end{cases}$$

- **Dilepton channel:**

$$\sigma_{tt} = 13.2 \pm 5.9_{stat} \pm 1.5_{sys} \pm 0.8_{lum}\ \text{pb}$$

- **Lepton + jets channel:**

$$\sigma_{tt} = 5.3 \pm 1.9_{stat} \pm 0.8_{syst} \pm 0.3_{lum}\ \text{pb}$$

NLO for M_{top} = 175 GeV: $6.70^{+0.71}_{-0.88}$ pb

Measurement of m_{top}

- Top is most intriguing fermion:

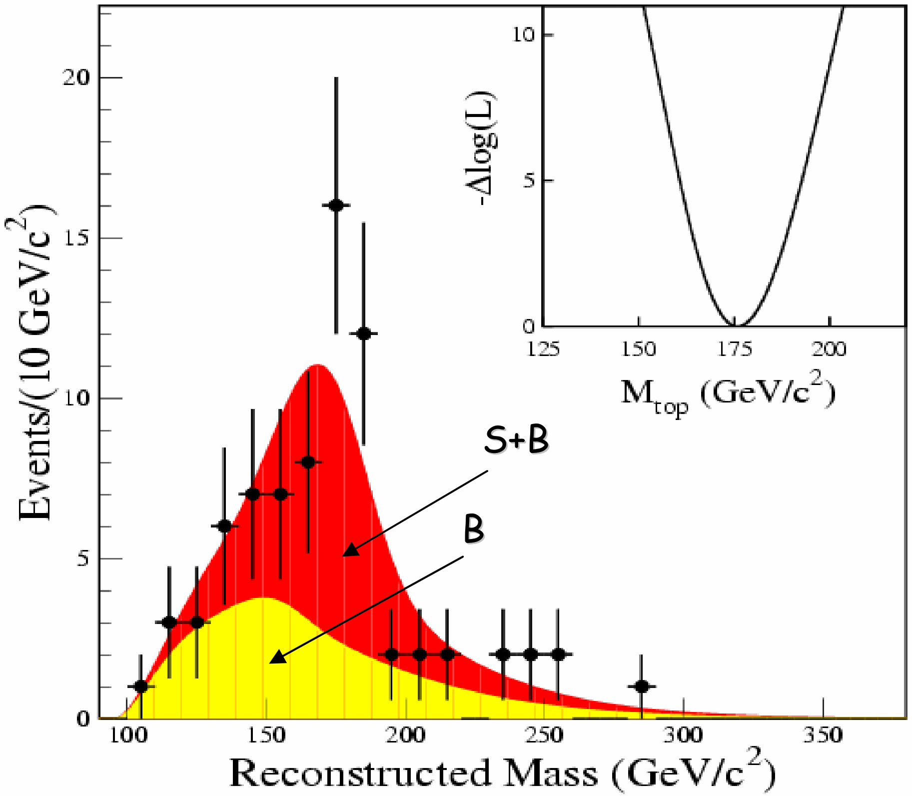
-- $m_{top} \approx 174$ GeV $\rightarrow$ clues about origin of particle masses ?

-- $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ ⟵ Δm (t-b) $\approx$ 170 GeV $\rightarrow$ radiative corrections

- Discovered in '94 at Tevatron – precise measurements of mass, couplings, etc. just started

Top mass spectrum from CDF

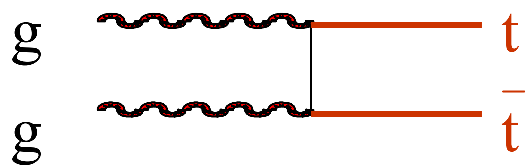
$t\bar{t} \rightarrow \bar{b}\ell\nu\, bjj$ events

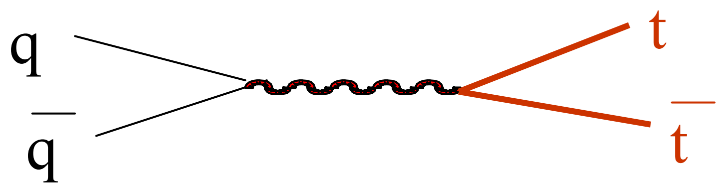


K. Piotrzkowski, PHYS 2356

Top production at LHC:

e.g.





$$\sigma\,(pp \rightarrow t\bar{t} + X) \approx 800\ \text{pb}$$

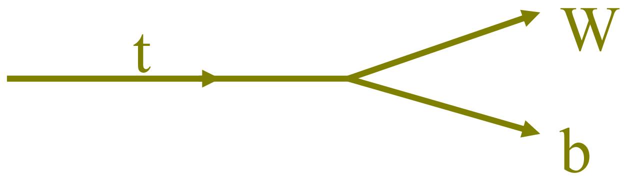
10^7 $t\bar{t}$ pairs produced in one year at low L

$\sim 10^2$ times more than at Tevatron

☺ measure m_{top}, σ_{tt}, BR, V_{tb}, single top, rare decays (e.g. $t \rightarrow Zc$), resonances, etc.

☹ $t\bar{t}$ production is the main background to new physics (SUSY, Higgs)

Top decays:



BR ≈ 100% in SM

-- hadronic channel: both $W \to jj$

⇒ 6 jet final states. BR ≈ 50 % but large QCD multijet background.

In all cases two jets are b-jets ⇒ displaced vertices in the inner detector

-- leptonic channel: both $W \to \ell\nu$

⇒ 2 jets + 2ℓ + E_T^{miss} final states. BR ≈ 10 %.
Little kinematic constraints to reconstruct mass.

-- semileptonic channel: one $W \to jj$, one $W \to \ell\nu$

⇒ 4 jets + 1ℓ + E_T^{miss} final states. BR ≈ 40 %.
If ℓ = e, μ : gold-plated channel for mass measurement at hadron colliders.

Expected precision on m_{top} at LHC

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

If / when Higgs discovered, comparison of measured m_H with indirect measurement will be essential consistency checks of EWSB

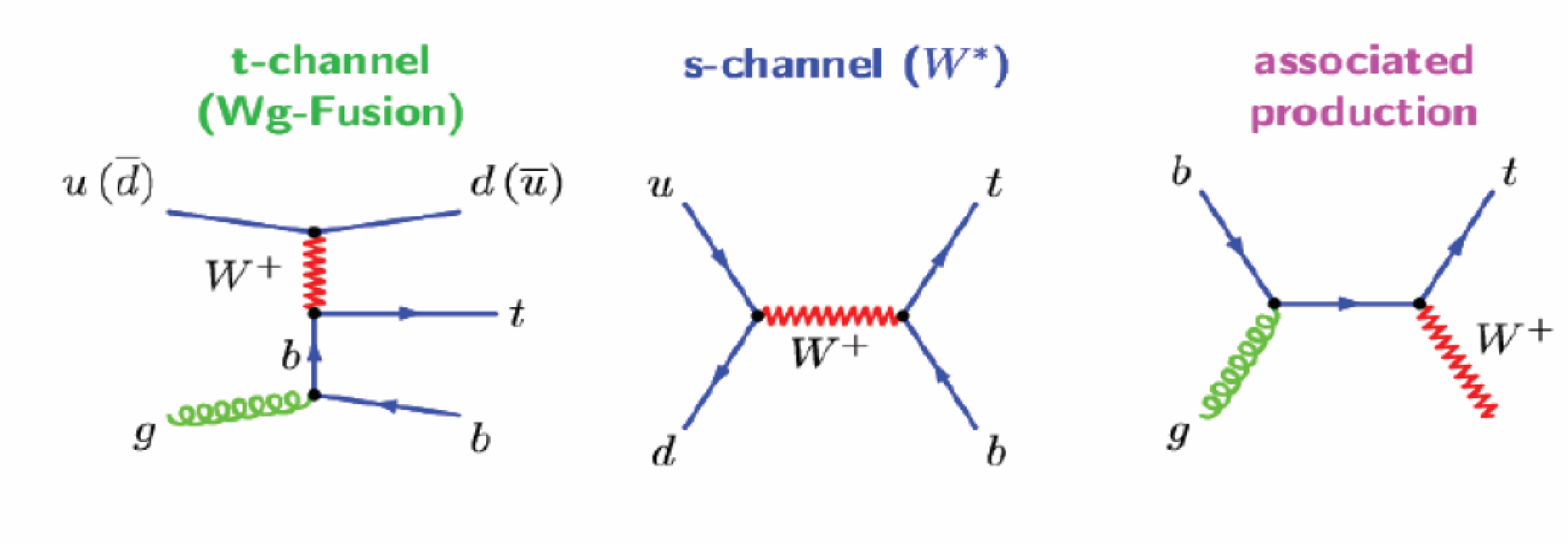
- Uncertainty dominated by the knowledge of physics and not of detector.
- By combining both experiments and all channels: $\Delta m_{top} \sim 1$ GeV at LHC

From $\Delta m_{top} \sim 1$ GeV, $\Delta m_W \sim 15$ MeV $\rightarrow$ indirect measurement $\Delta m_H/m_H \sim 25\%$ (today ~ 50%)

Single top quark production

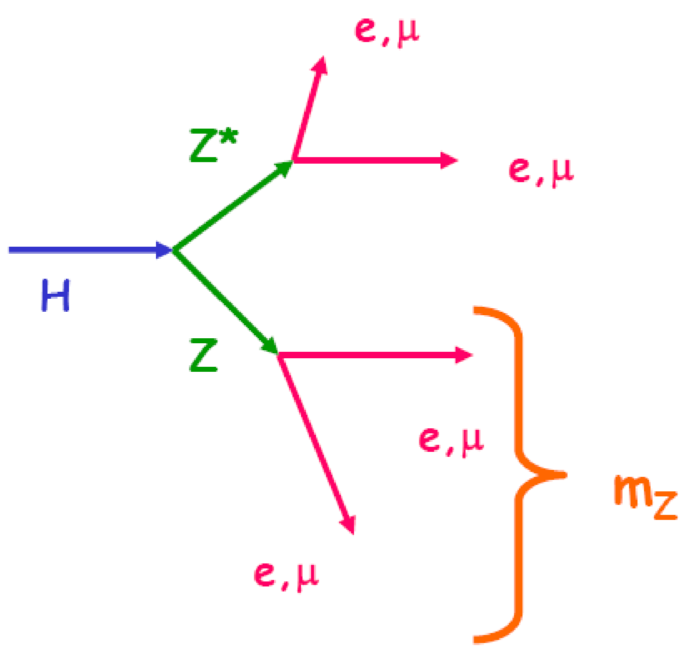
Les évennements pp peuventr être plus compliques !

Production via l'interaction faible!



Pas encore observé !!

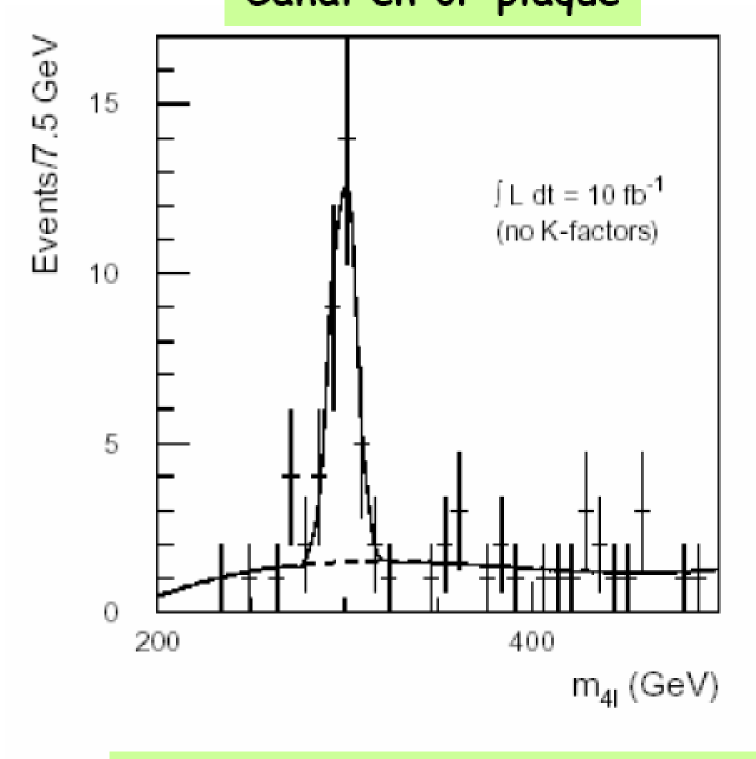
$H \to ZZ^{(*)} \to 4l$
$120 < m_H < 700$ GeV



- Sélectionner 4 leptons Haut Pt
- Exiger une paire consistante avec la masse du Z
- Masse invariante 4l :

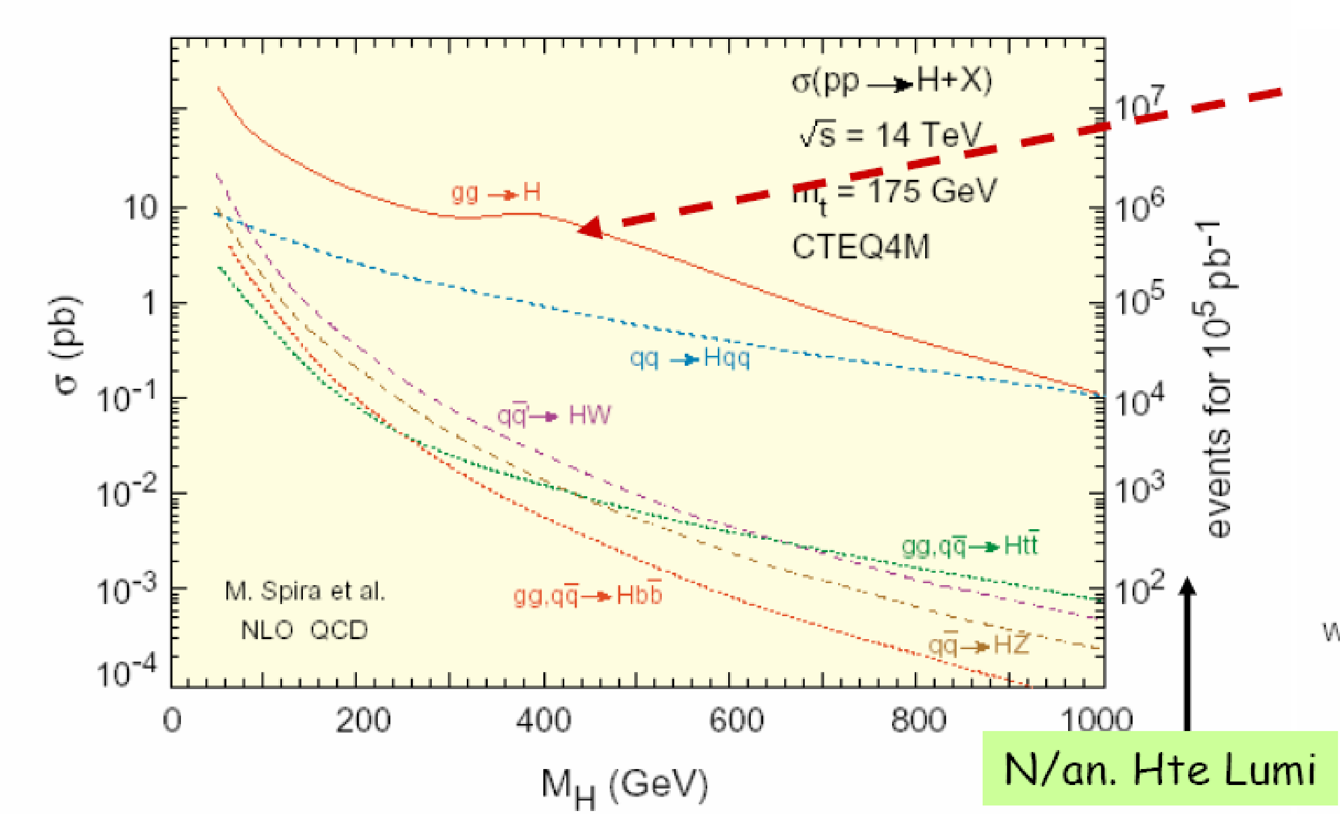
$$m^2 = \sum_i E_i^2 - (\sum_i \vec{p}_i^{\,2})$$

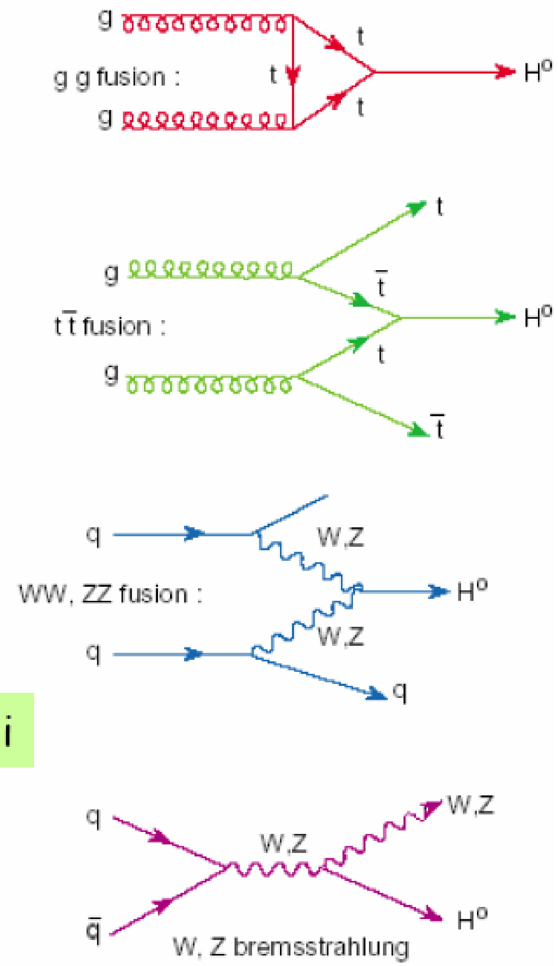
Canal en or plaqué



$H \to ZZ^{(*)} \to 4l$
pour m_H = 300 GeV, 10fb^{-1}, ATLAS

Production du Higgs au LHC





- **Section efficace de production et Luminosité ~ 10 fois plus élevée au LHC qu'au Tevatron**

  Exploitation des canaux rares

  qg->qg, gg->gg,…

Rapport d'embranchement

Basses masses

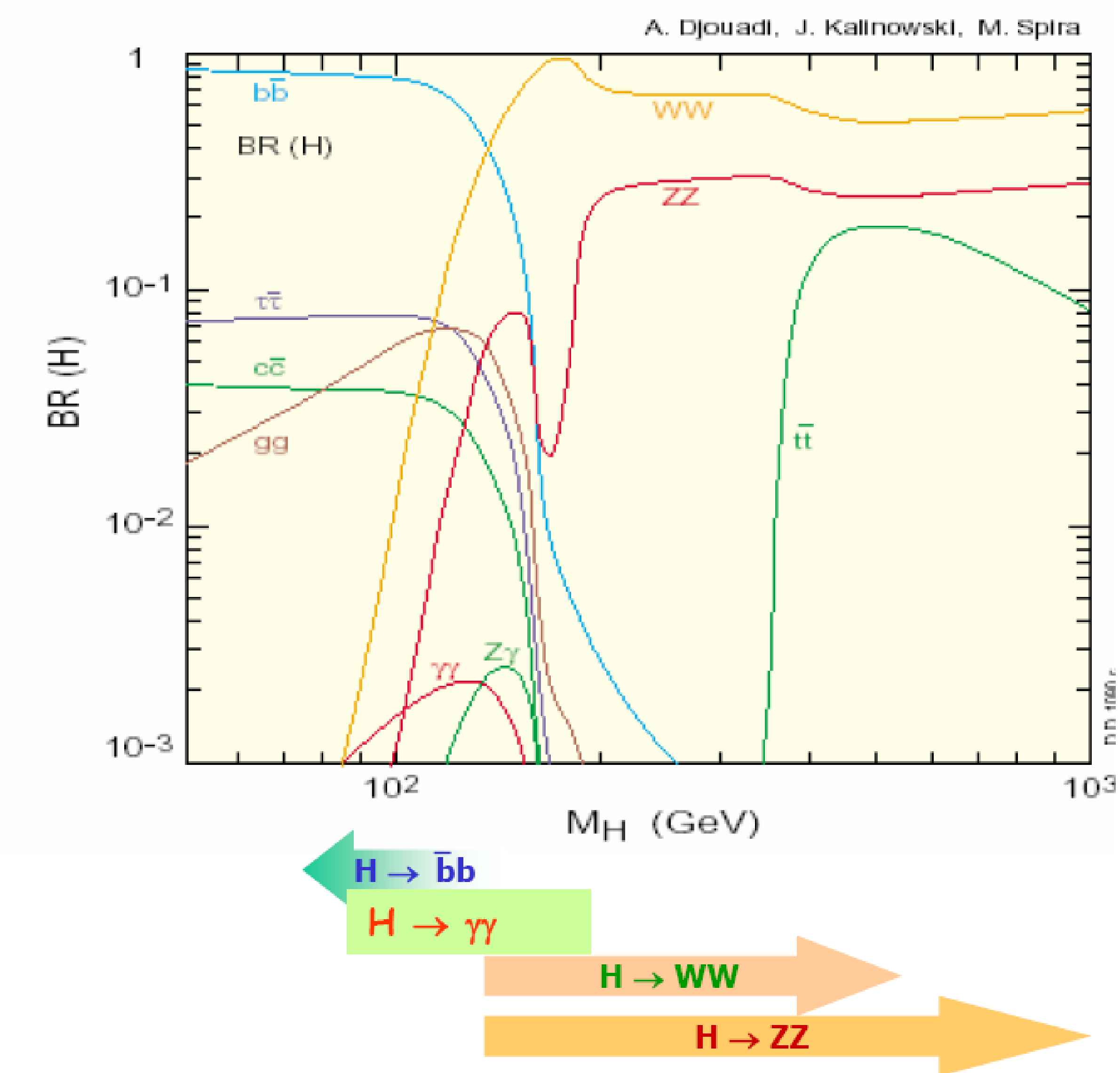
- σ(H->bb)~20 pb (120GeV)
- σ(bb)~500μb

- Mode γγ (ECAL)
- Ouverture WW, ZZ

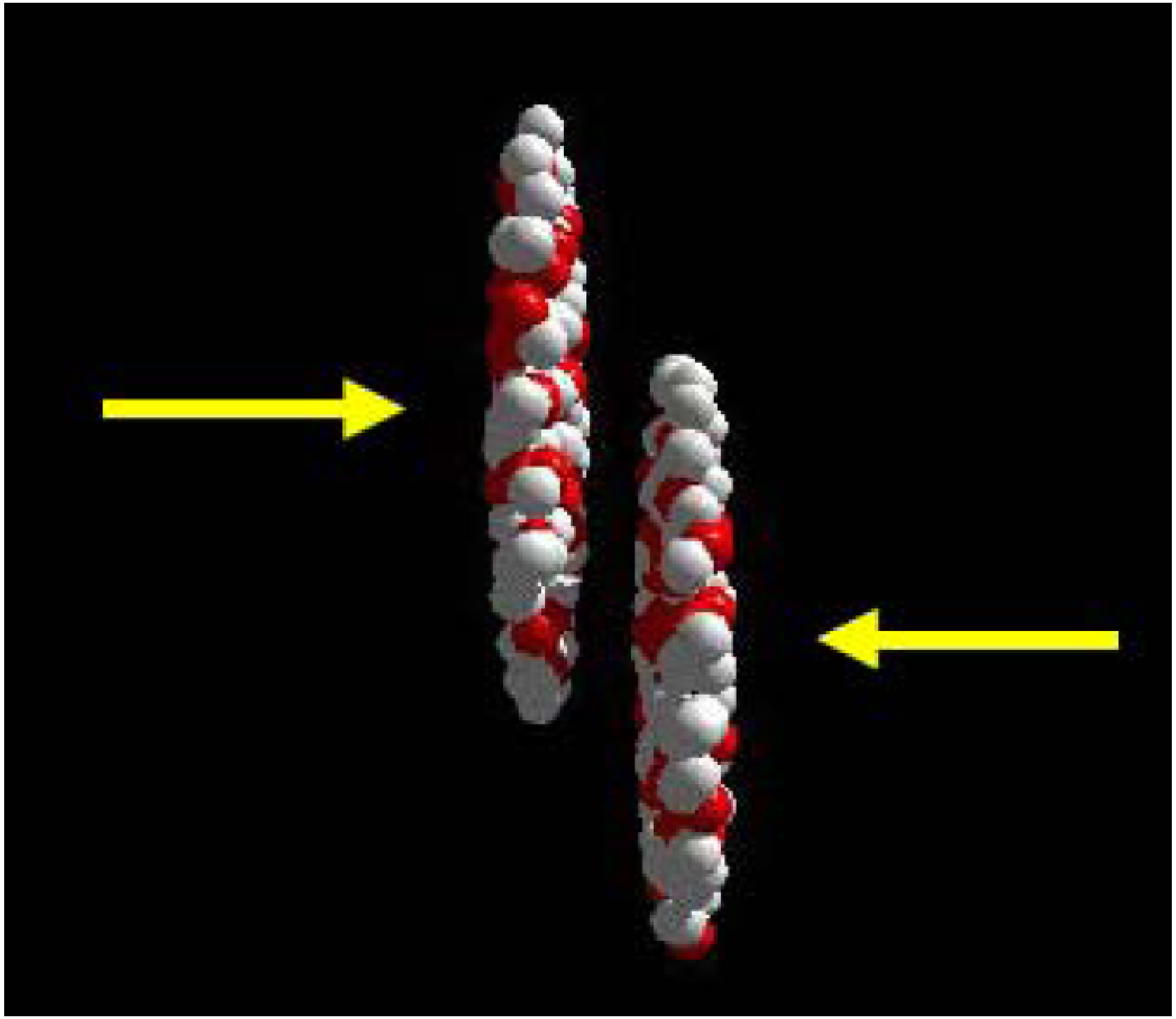
(hautes masses)

- WW, ZZ
- Modes W en jets ou l ν

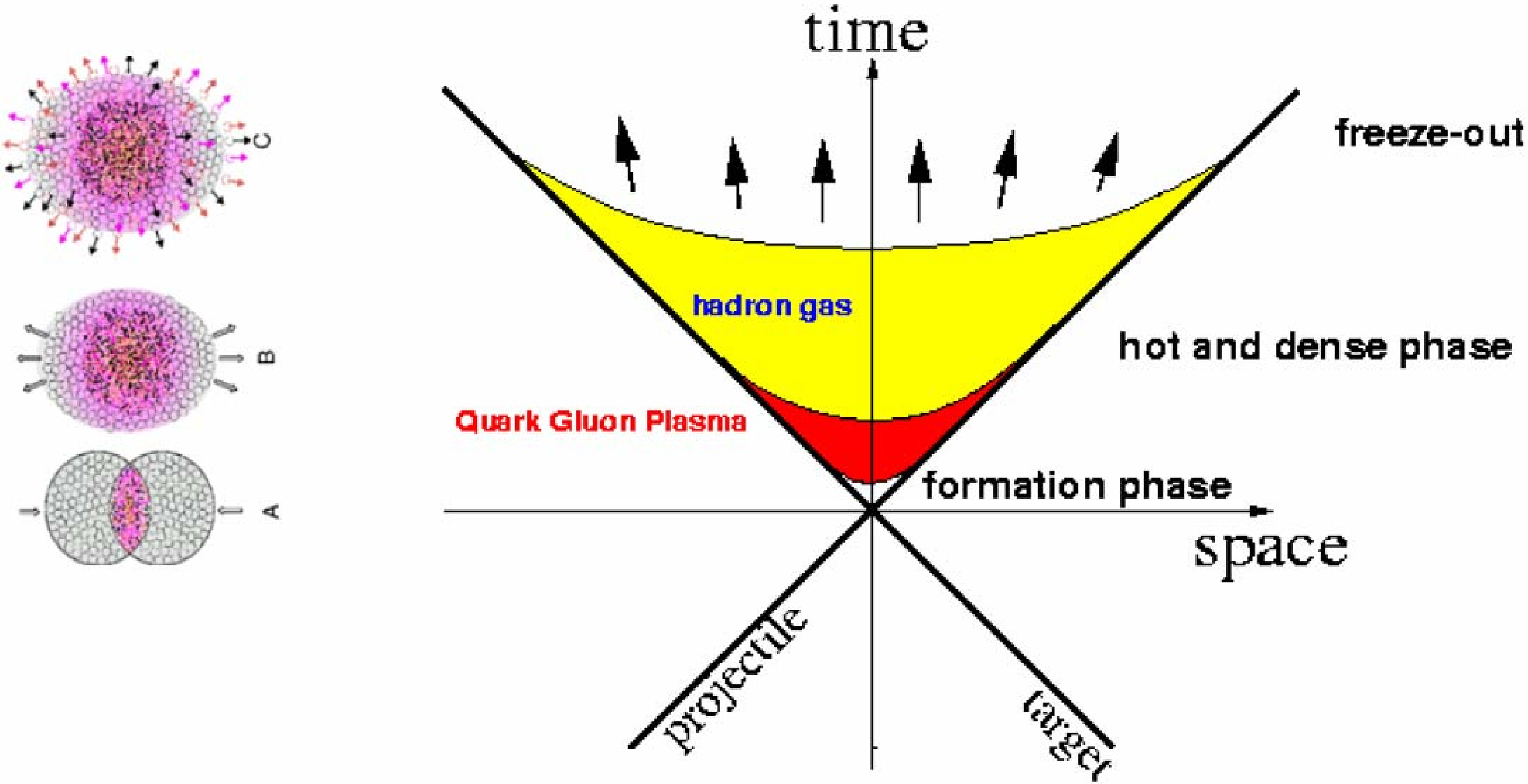
(E_T Manquante)



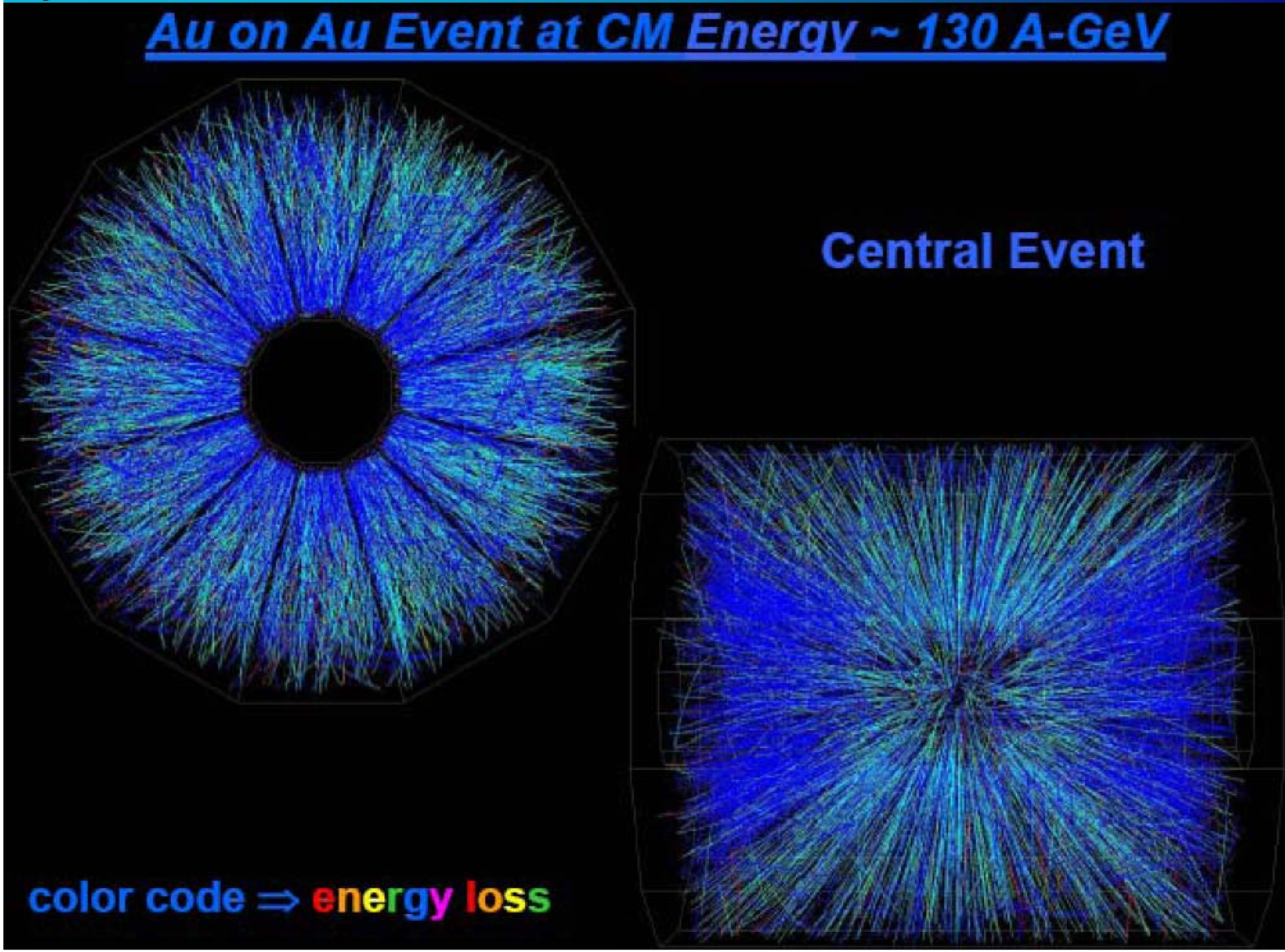
Collision de ions lourds ultra-relativiste et le plasma de quarks et gluons



Dynamique de collision



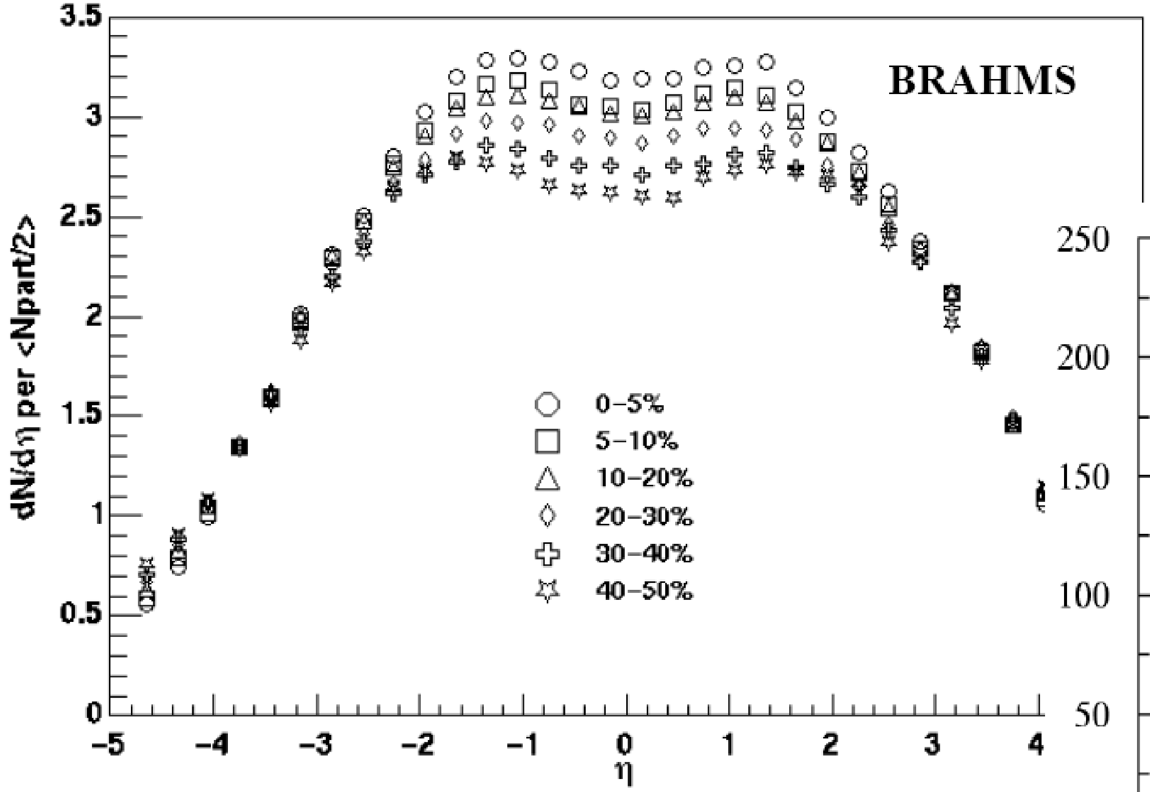
Real event at RHIC (BNL)



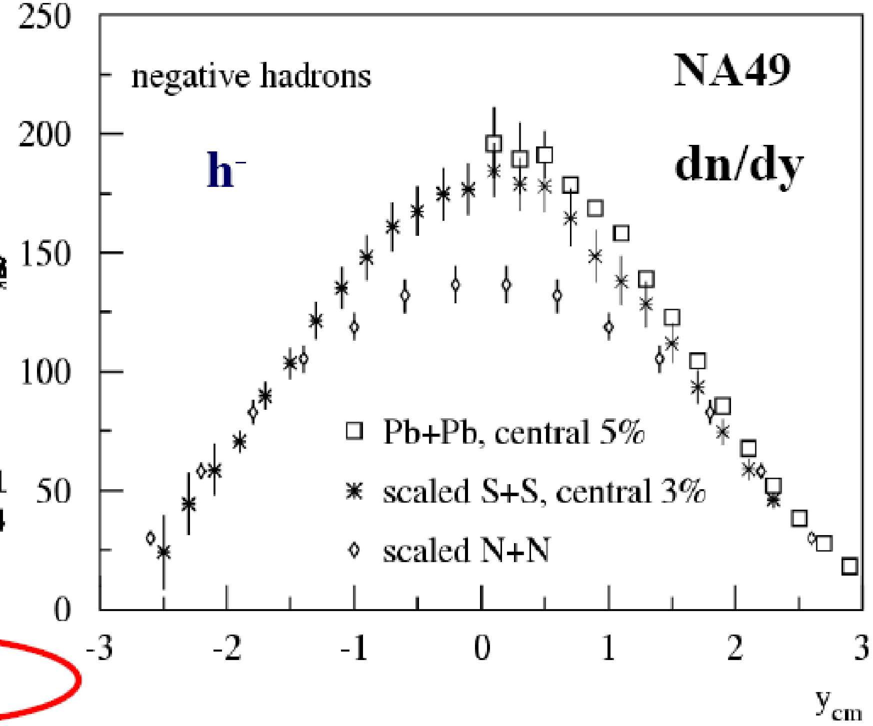
Distribution inclusive des particules

× $N_{participants}$

RHIC



SPS

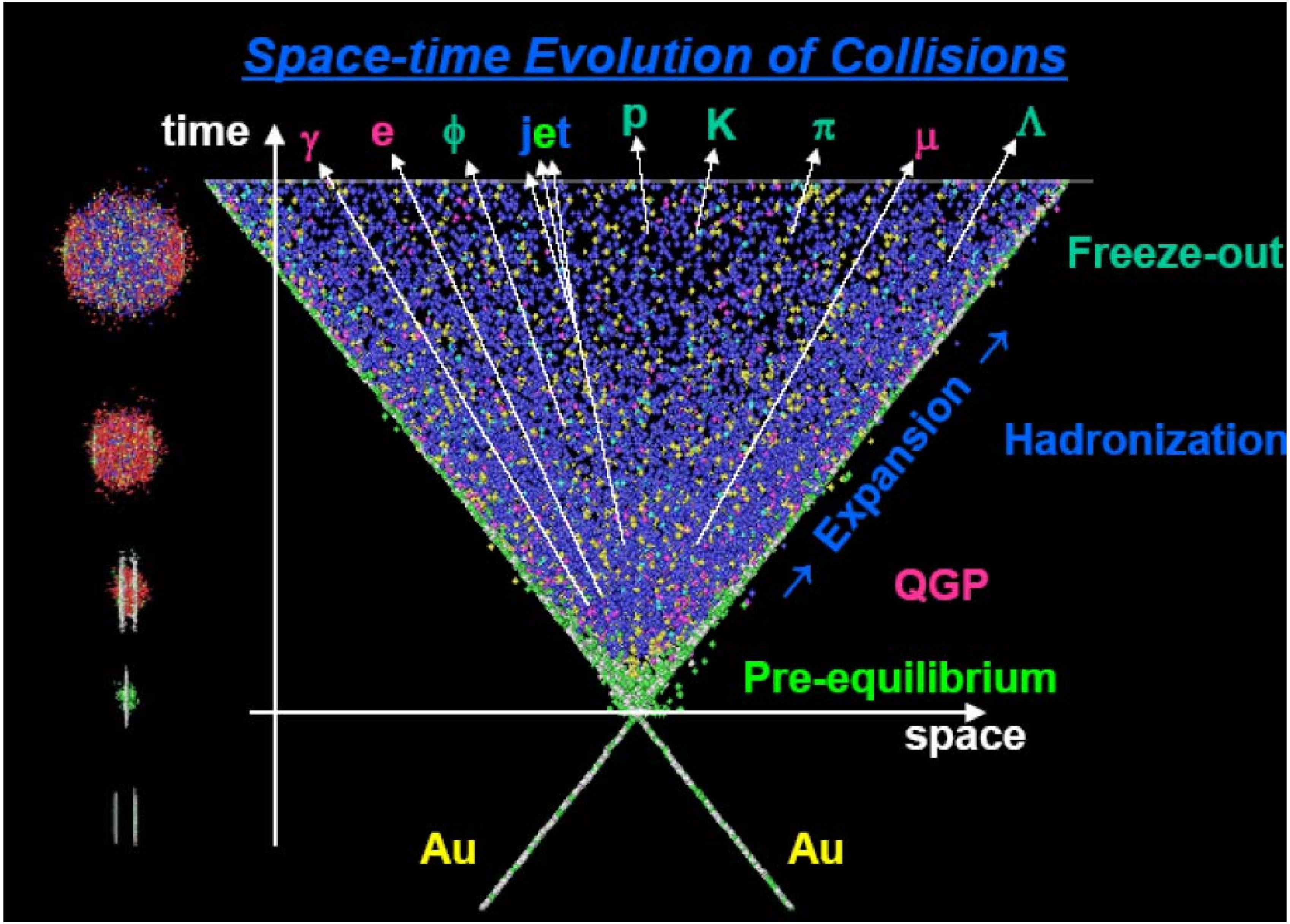


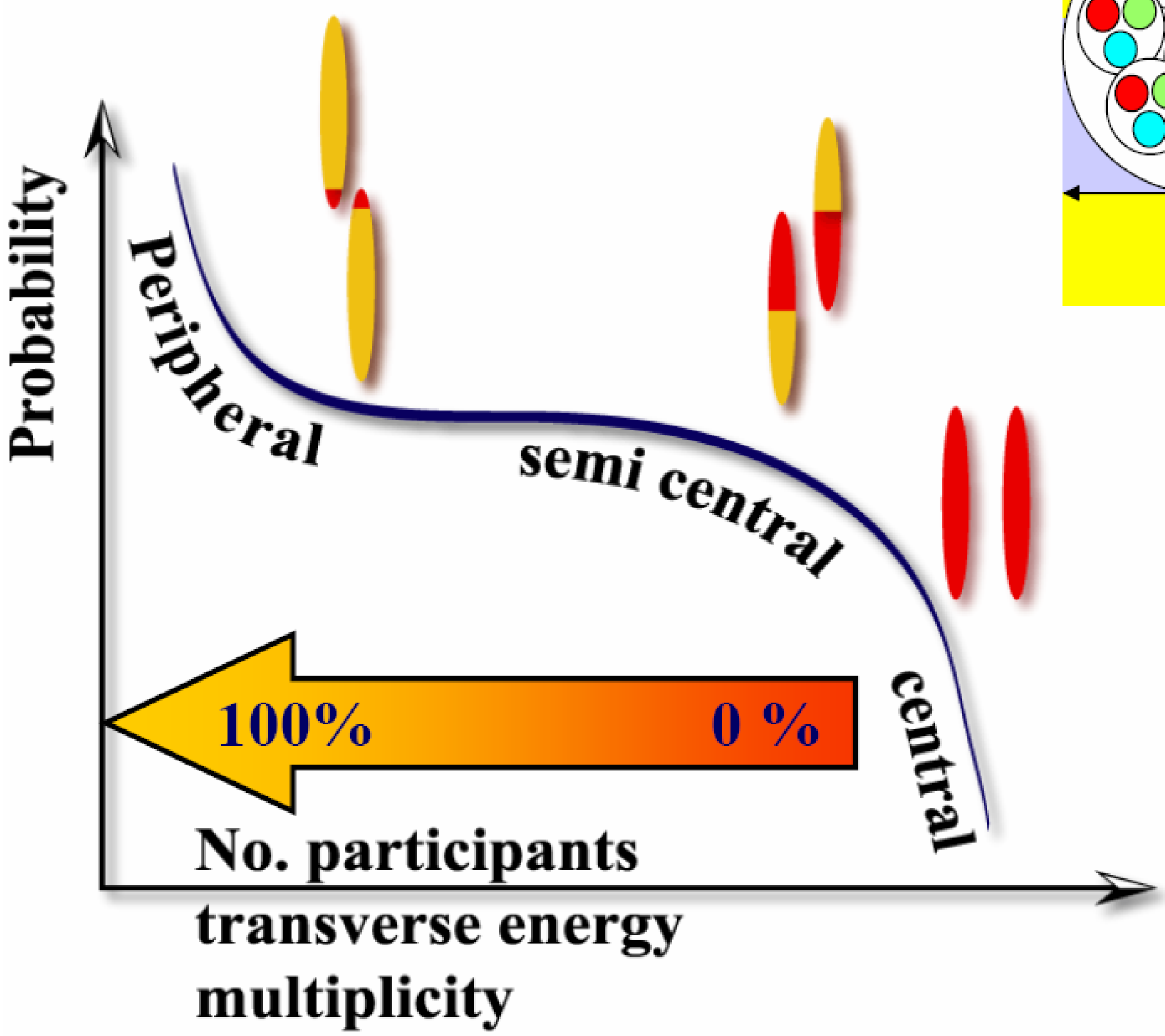
BRAHMS (0-5%): N_{ch} ($|\eta|<4.7$) = 3860 ± 300

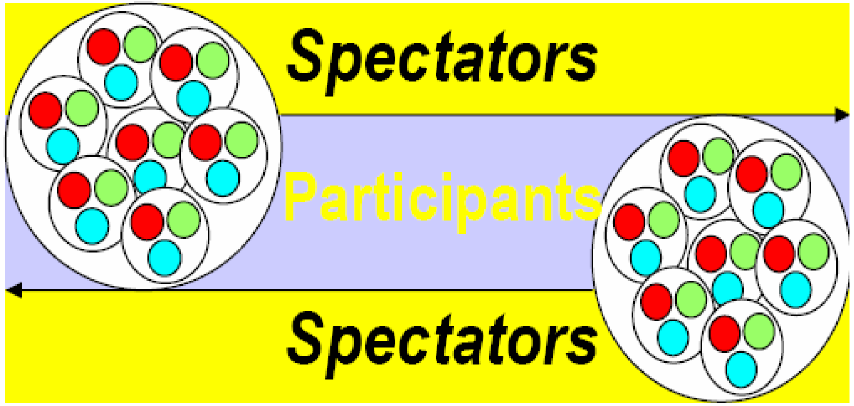
NA49 (0-5%): N_{h^-} ($|y| < 3$) = 695 ± 30

- Factor of ~ 3 more particles produced at RHIC than at SPS

- Wider η distribution


Space-time Evolution of Collisions
time
γ
e
φ
jet
p
K
π
μ
Λ
Freeze-out
Expansion
Hadronization
QGP
Pre-equilibrium
space
Au
Au





Nuclei are extended objects

- Impact parameter
- Number of participants
- Centrality

(% from total inelastic cross-section)

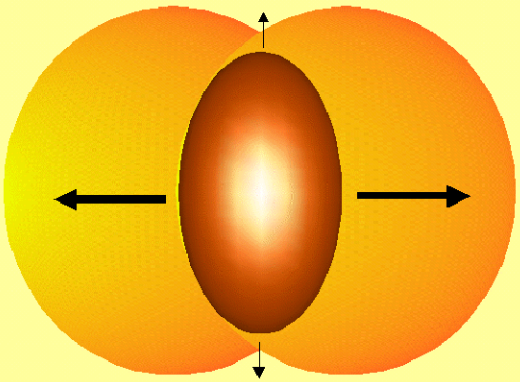
Transverse "radii" of the system at freeze-out

Initial state

Elliptic shape

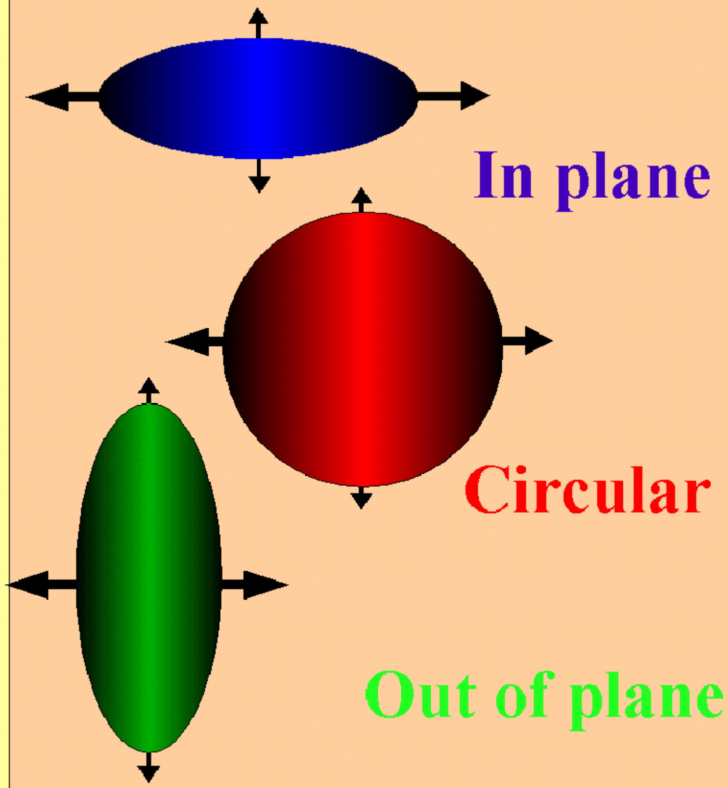
⇒ Pressure push in plane

⇒ In plane flow

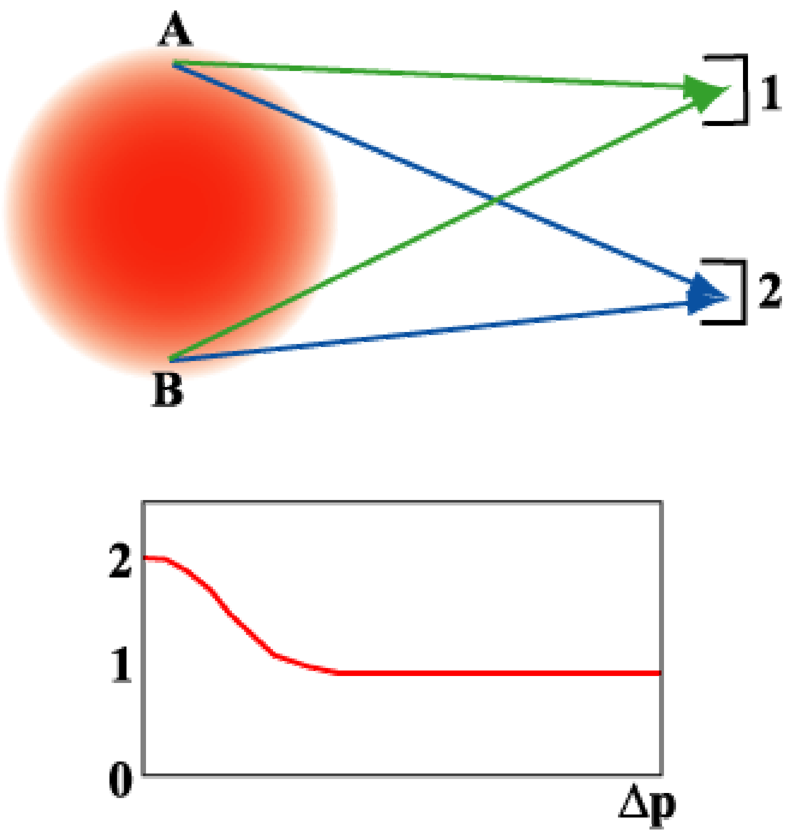


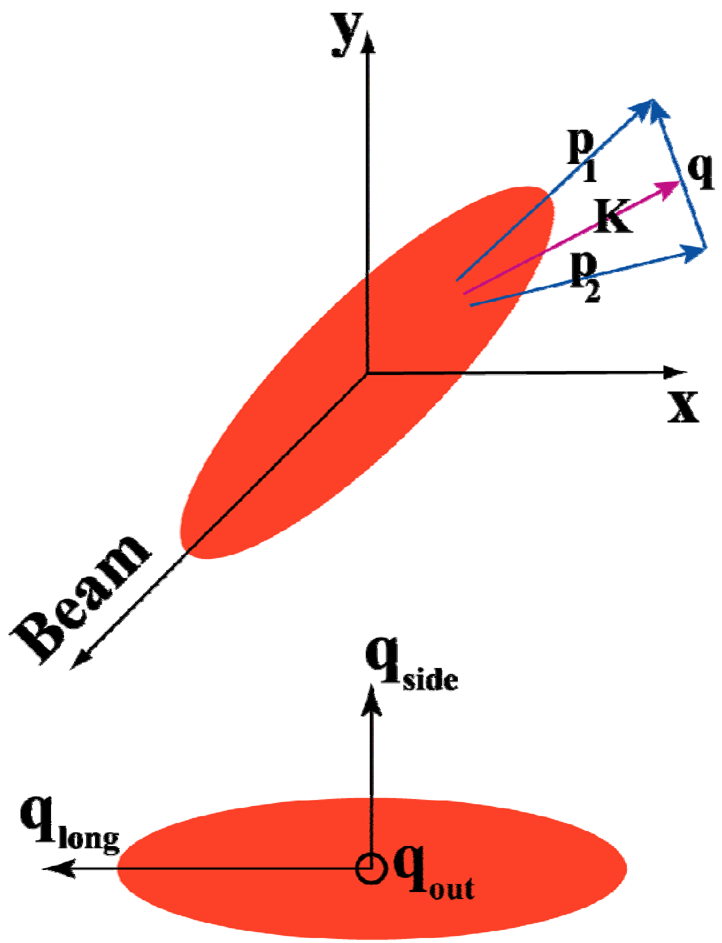
Final state

What space-time configuration?

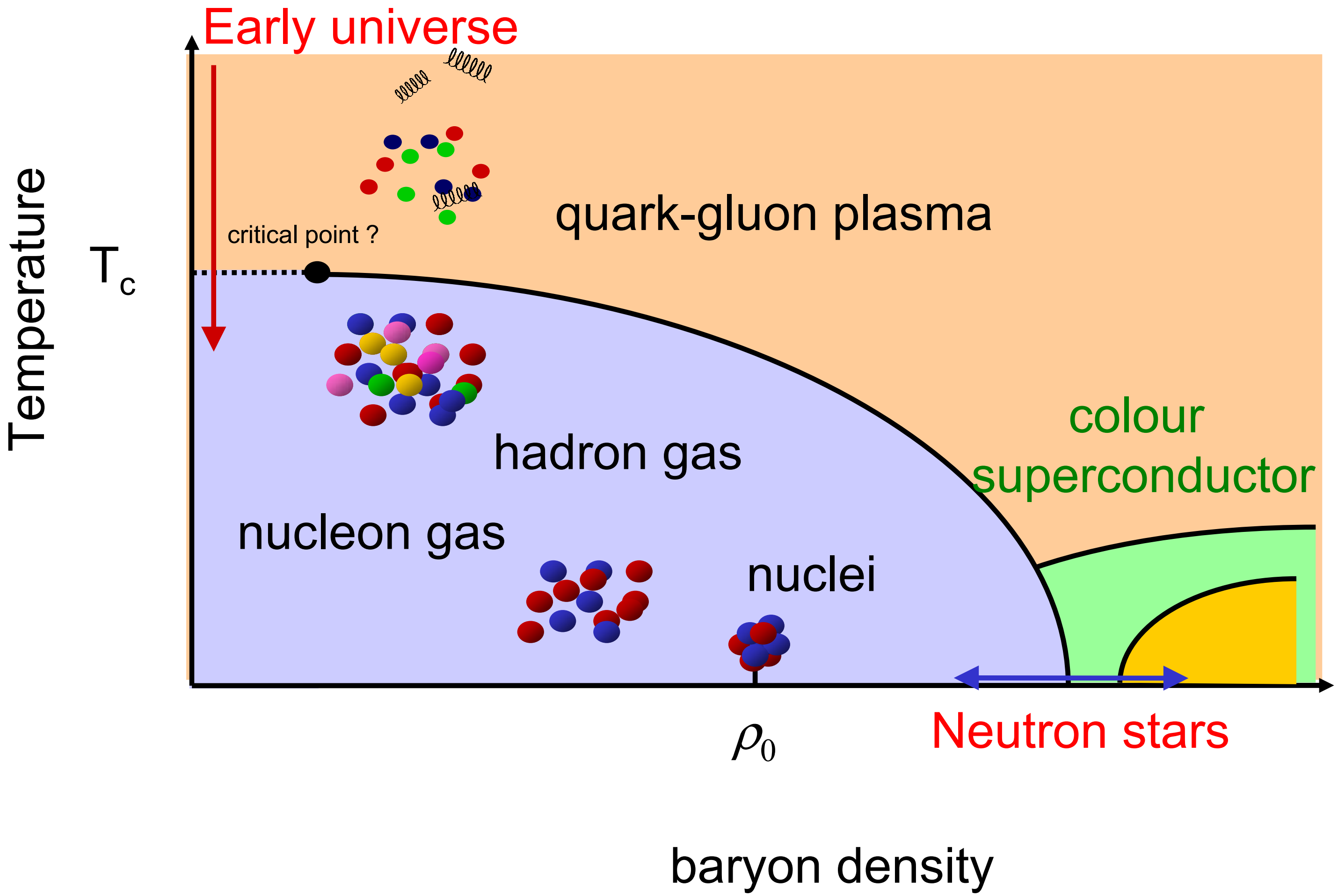


HBT; coordinate system



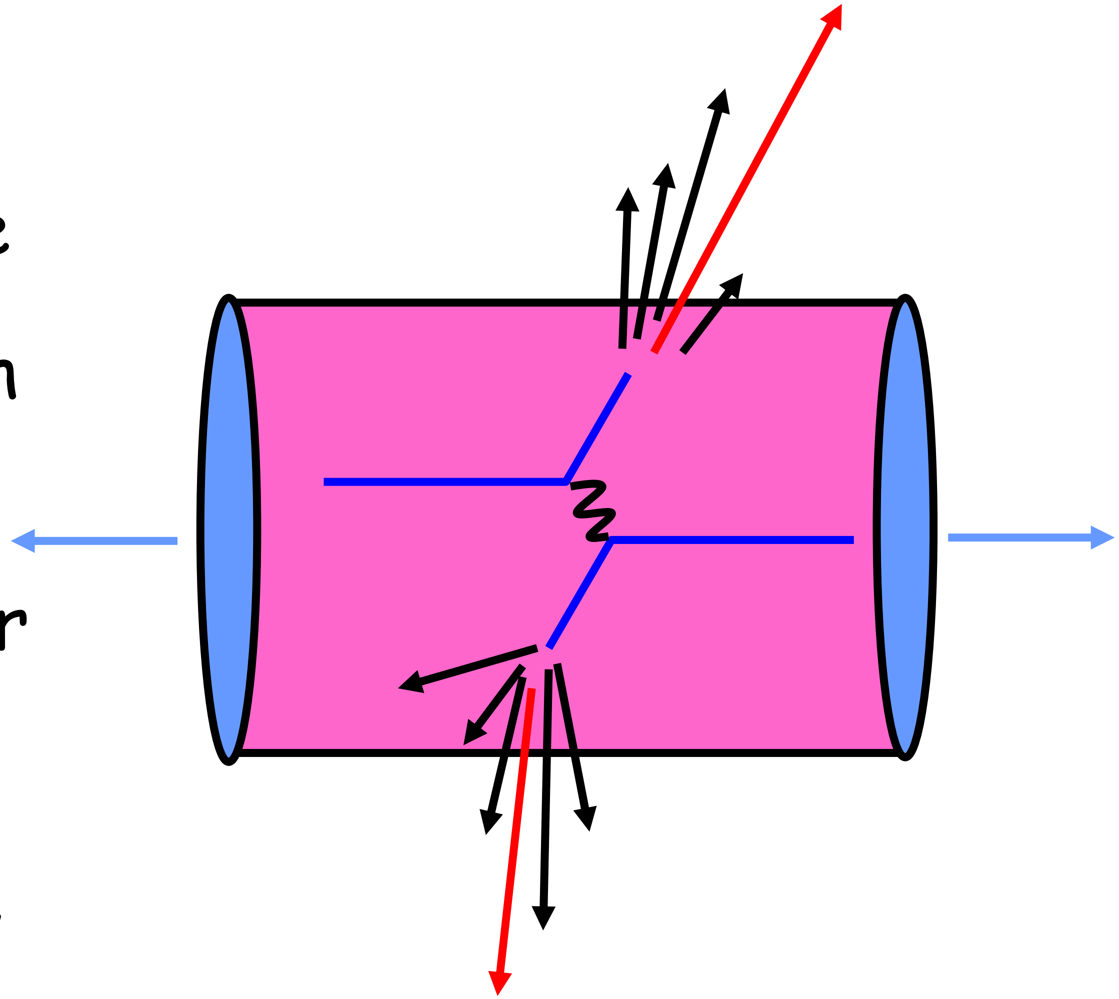


The Phase Structure of QCD



Jet quenching prediction

- Before high-p_t partons hadronize and form jets they interact with the **medium**



- $\rightarrow$ decreases their momentum
- $\rightarrow$ fewer high-p_t particles
- $\rightarrow$ "jet quenching"