Jets in heavy-ion collisions at RHIC and LHC

Carlos A. Salgado
Universidade de Santiago de Compostela

International School on Quark-Gluon Plasma and Heavy Ion Collisions: past, present, future

carlos.salgado@usc.es http://cern.ch/csalgado

- ***Jet quenching has been established at RHIC as a fundamental tool in the study of hot matter in heavy-ion collisions***
  - *Single inclusive suppression*
  - *Two- and three-particle correlations*
  - *Particle species dependence: Specially heavy-quarks*
- ***Completely new opportunities at the LHC***
  - *Larger kinematical reach*
  - *New hard probes, in particular reconstructed JETS*

[More in David D'Enterrias' lectures]

Contents

Some bibliography

[Lot of work done by now, this is just a small compilation where you can find more references]

- Vacuum, hard processes:

  Books, e.g. *QCD and Collider Physics*, Ellis, Stirling and Webber

  Lectures, e.g. A.D. Martin, arxiv:0802.0161

- Jets and energy loss in heavy ion collisions

  J. Casalderrey-Solana and C.A. Salgado, arxiv:0712.3443

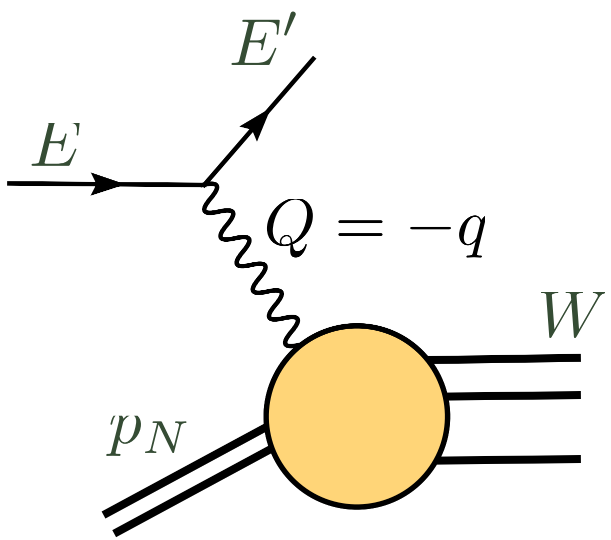
  A. Kovner and U.A. Wiedemann, hep-ph/0304151

  S. Peigne and A.V. Smilga, arxiv:0810.5702

Contents of the 1st lecture

- Gluon multiplication in vacuum
  - Deep Inelastic Scattering → DGLAP evolution
  - Jets
  - Factorization
  - Examples
- Hard probes in nuclear collisions
  - What for?

Deep inelastic scattering (DIS)



⇛ The invariant mass of the outgoing system

$$W^2 = (p_N + q)^2 = M_N^2 + 2p_N \cdot q + q^2$$

⇛ Deep ($Q^2 \gg M_N^2$) Inelastic ($W^2 \gg M_N^2$)

$$x = \frac{Q^2}{2M_N(E' - E)}$$

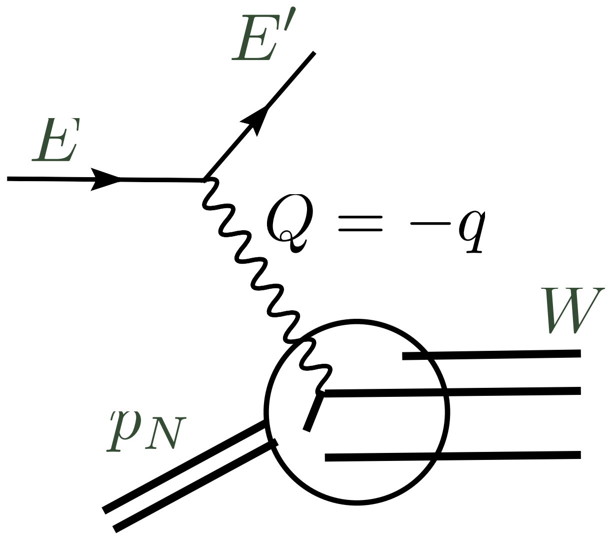
⇛ Parton model: incoherent (elastic) photon-parton scattering

↘ A proton is a cloud of free partons

$$\frac{d\sigma}{dx dQ^2} = \sum_q \int_0^1 d\xi \, f_q(\xi) \frac{d\hat{\sigma}_{eq}}{dx dQ^2}$$

⇛ $f_q(\xi)$ probability of finding a quark with fraction of momentum ξ

Deep inelastic scattering (DIS)



- The invariant mass of the outgoing system

$$W^2 = (p_N + q)^2 = M_N^2 + 2p_N \cdot q + q^2$$

- Deep ($Q^2 \gg M_N^2$) Inelastic ($W^2 \gg M_N^2$)

$$x = \frac{Q^2}{2M_N(E' - E)}$$

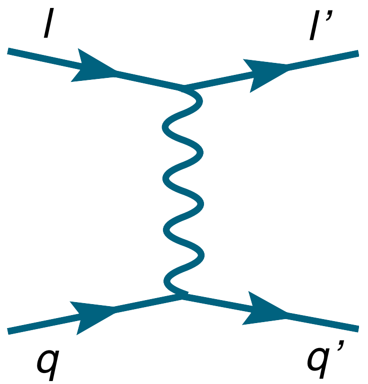
- Parton model: incoherent (elastic) photon-parton scattering
  - A proton is a cloud of free partons

$$\frac{d\sigma}{dx dQ^2} = \sum_q \int_0^1 d\xi\, f_q(\xi) \frac{d\hat{\sigma}_{eq}}{dx dQ^2}$$

- $f_q(\xi)$ probability of finding a quark with fraction of momentum ξ

Structure functions and PDFs

⇛ Taking the elastic electron-quark cross section



$$\frac{d\hat{\sigma}_{eq}}{dx dQ^2} = \frac{2\pi\alpha^2 e_q^2}{\hat{s}^2}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\delta(x-\xi)$$

⇛ Putting all together $\left(y = \frac{1}{2}(1-\cos\hat{\theta}) \simeq \frac{Q^2}{xs}\right)$

$$\frac{d\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right]\sum_q e_q^2 x f_q(x) \equiv \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right]F_2(x)$$

⇛ Bjorken scaling: structure function depends only on x

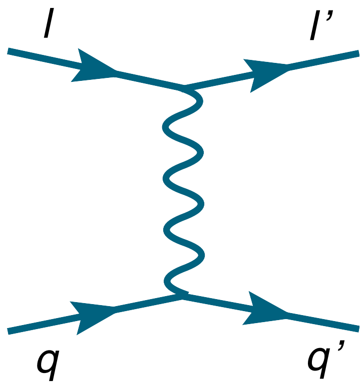
$$F_2(x) = x\left[\frac{4}{9}(u(x)+\bar{u}(x)) + \frac{1}{9}(d(x)+\bar{d}(x)) + \frac{1}{9}(s(x)+\bar{s}(x)) + \ldots\right]$$

⇛ Valence quarks:

$$u_V(x) \equiv u(x) - \bar{u}(x)$$
$$d_V(x) \equiv d(x) - \bar{d}(x)$$

Structure functions and PDFs

⇛ Taking the elastic electron-quark cross section



$$\frac{d\hat{\sigma}_{eq}}{dxdQ^2} = \frac{2\pi\alpha^2 e_q^2}{\hat{s}^2}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\delta(x-\xi)$$

⇛ Putting all together $\left(y = \frac{1}{2}(1-\cos\hat{\theta}) \simeq \frac{Q^2}{xs}\right)$

$$\frac{d\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right]\sum_q e_q^2 x f_q(x) \equiv \frac{2\pi\alpha^2}{xQ^4}\left[1+(1-y)^2\right]F_2(x)$$

⇛ Bjorken scaling: structure function depends only on x

$$F_2(x) = x\left[\frac{4}{9}(u(x)+\bar{u}(x)) + \frac{1}{9}(d(x)+\bar{d}(x)) + \frac{1}{9}(s(x)+\bar{s}(x)) + \ldots\right]$$

⇛ Valence quarks:

$$u_V(x) \equiv u(x) - \bar{u}(x)$$
$$d_V(x) \equiv d(x) - \bar{d}(x)$$

No QCD for the moment!

A "proton" in QCD...

- QCD is a quantum field theory
  - Quantum fluctuations are present...
  - A cloud of "sea" quarks and gluons together with valence quarks

A “proton” in QCD...

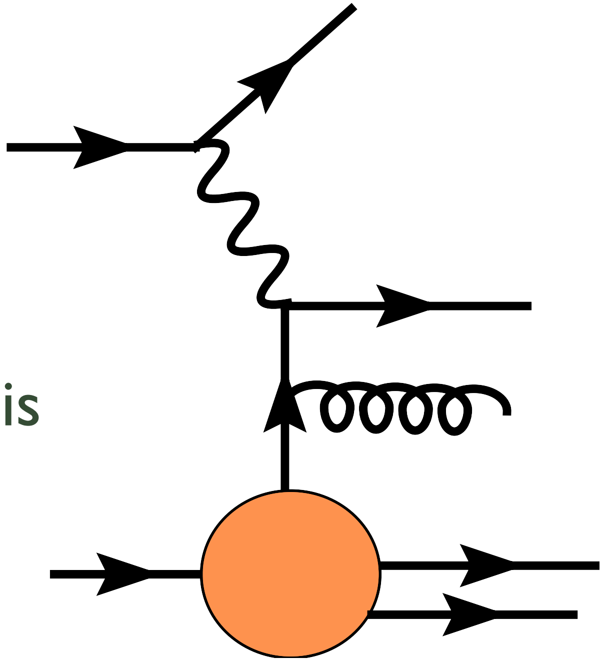
- QCD is a quantum field theory
  - Quantum fluctuations are present...
  - A cloud of “sea” quarks and gluons together with valence quarks

Including QCD-evolution

⇛ QCD corrections:

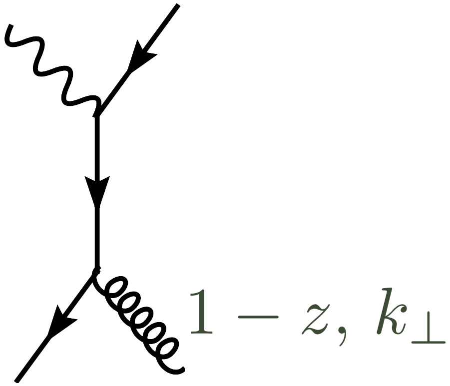
include inelastic photon-quark scattering

↘ Leading order in QCD



⇛ Or equivalently: Given an initial quark, what is the probability to split, giving a quark or gluon with fraction of momentum z

↘ Altarelli-Parisi splitting functions



$$d\mathcal{P}(z,k_\perp^2)=\frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)\ dz dk_\perp^2$$

$$P(z)=C_F\left[\frac{1+z^2}{1-z}\right]$$

Divergencies I

⇛ Including gluon radiation, the structure function is now

$$F_2(x,Q^2) = x\sum_q \int_x^1 \frac{dz}{z} f_q\left(\frac{x}{z}\right) e_q^2 \left[\delta(1-z) + \frac{\alpha_s}{2\pi}\left(P(z)\log\frac{Q^2}{\mu_0^2} + C(z)\right)\right]$$

⇛ Where an infrared regulator has been introduced $\longrightarrow \mu_0$

$$\int_{\mu_0^2}^{Q^2} \frac{dk_\perp^2}{k_\perp^2} = \log\left(\frac{Q^2}{\mu_0^2}\right)$$

Splitting is divergent

⇛ Renormalization: put divergences in parton distribution functions

$$f_q(x,\mu^2) = f_q(x) + \int_x^1 \frac{dz}{z} f_q\left(\frac{x}{z}\right) \frac{\alpha_s}{2\pi}\left(P(z)\log\frac{\mu^2}{\mu_0^2} + C_1\right)$$

⇛ So, formaly they are infinite...

Divergencies II

⇛ Renormalization: put divergences in parton distribution functions

$$F_2(x,Q^2) = x\sum_q \int_x^1 \frac{dz}{z} f_q\left(\frac{x}{z},\mu^2\right) e_q^2 \left[\delta(1-z) + \frac{\alpha_s}{2\pi}\left(P(z)\log\frac{Q^2}{\mu_2} + C_2\right)\right]$$

⇛ ... and renormalize the PDFs (F_2 does not depend on μ^2)

$$\frac{\partial F_2(x,Q^2)}{\partial \log\mu^2} = 0 \quad \Longrightarrow \quad \frac{\partial f_q(x,\mu^2)}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P(z)\, f_q\left(\frac{x}{z},\mu^2\right)$$

⇛ In this way, we can define again

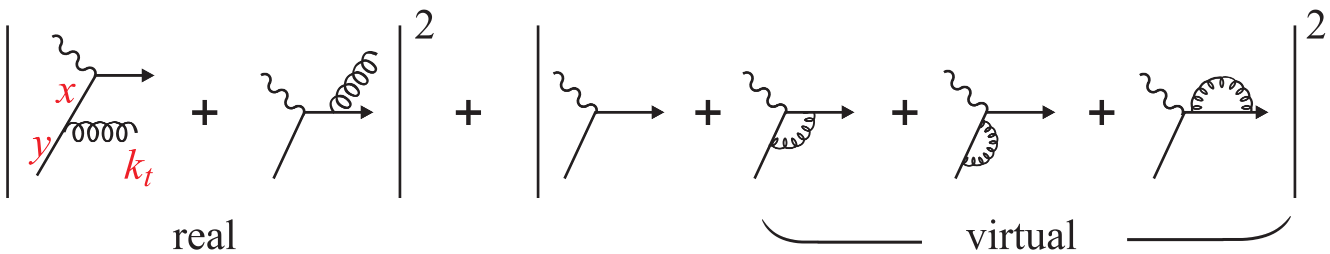
$$F_2(x.Q^2) = x\left[\frac{4}{9}(u(x,Q^2)+\bar{u}(x,Q^2)) + \frac{1}{9}(d(x,Q^2)+\bar{d}(x,Q^2)) + \frac{1}{9}(s(x,Q^2)+\bar{s}(x,Q^2)) + \ldots\right]$$

(other definitions are possible depending on the finite parts C)

A technical point

⇛ The splitting functions need to be regularized for $z \to 1$

$$P_{qq}(z) = C_F \left(\frac{1+z^2}{1-z} \right)_+$$



Sum rules

⇛ Baryon number $\int_0^1 dx \left[u_V(x,Q^2) + d_V(x,Q^2) \right] = 3$

⇛ Momentum

$$\int_0^1 dx\, x \left[g(x,Q^2) + u(x,Q^2) + \bar{u}(x,Q^2) + d(x,Q^2) + \bar{d}(x,Q^2) + \ldots \right] = 1$$

The DGLAP equations

⇛ The whole set of equations include all possible splittings and flavors

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\int_x^1 \frac{dz}{z}\sum_j P_{q_iq_j}(z)q_j\left(\frac{x}{z},Q^2\right) + P_{q_ig}(z)g\left(\frac{x}{z},Q^2\right)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\int_x^1 \frac{dz}{z}\sum_j P_{gq_j}(z)q_j\left(\frac{x}{z},Q^2\right) + P_{gg}(z)g\left(\frac{x}{z},Q^2\right)\right]$$

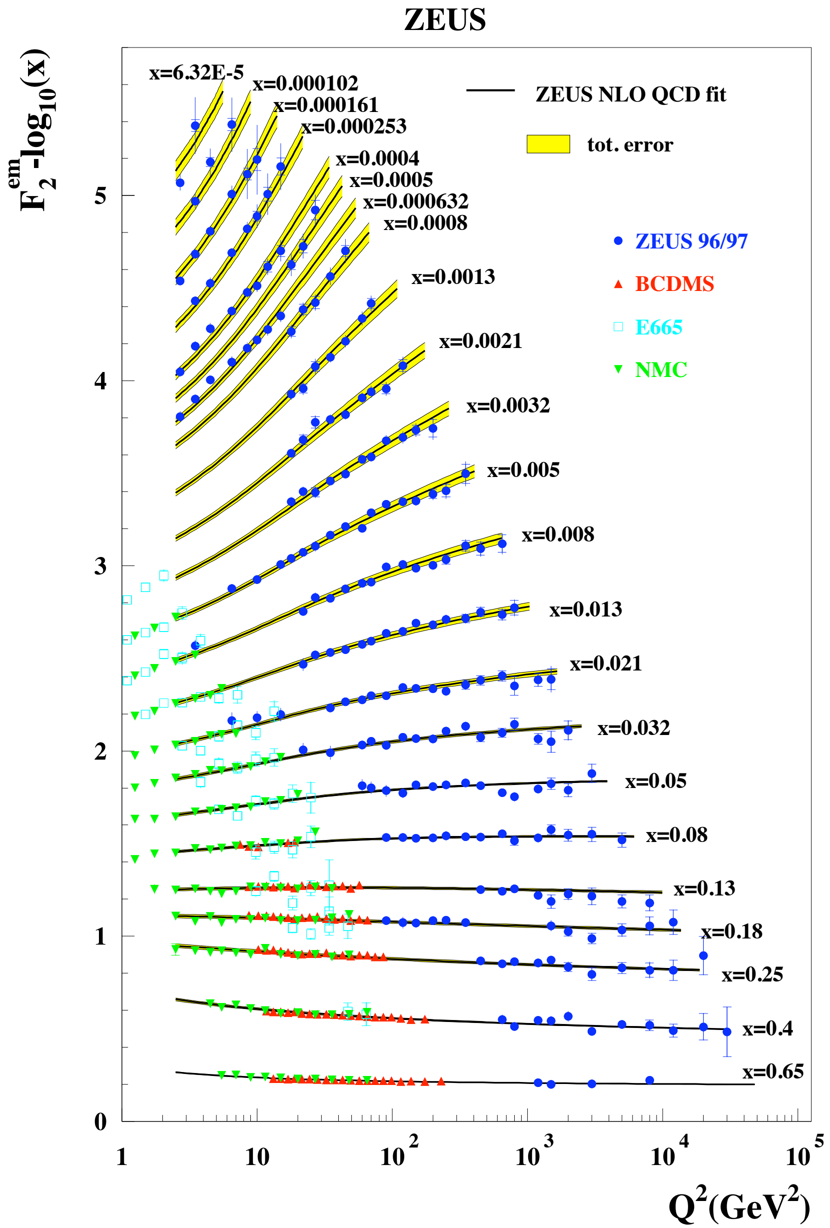
[DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi]

⇛ So, although the parton distribution functions are non-perturbative, it's evolution can be predicted by pQCD.

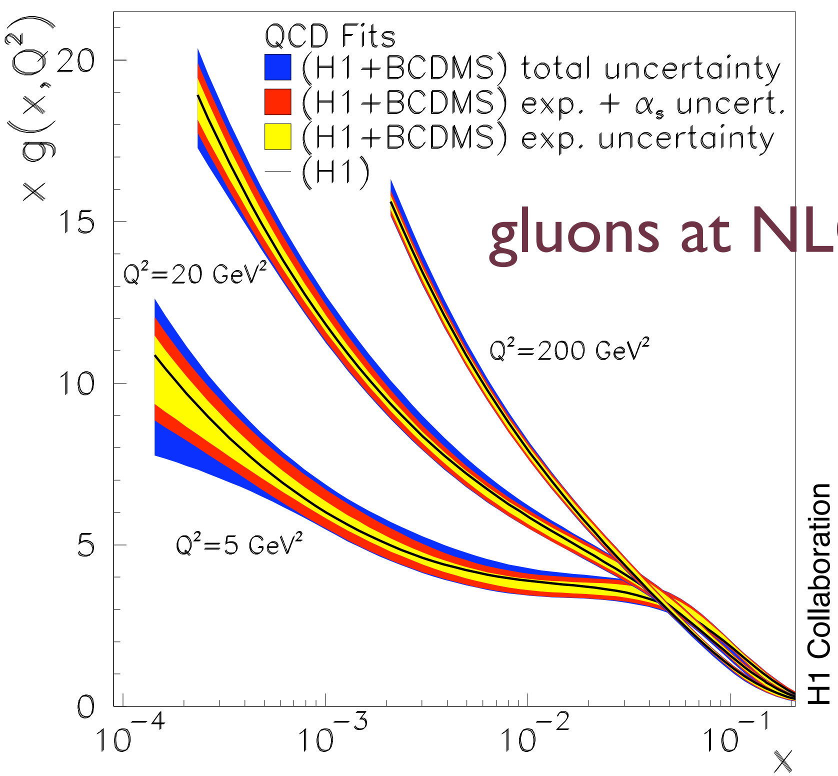
- Initial non-perturbative input taken from experiment $f_i(x,Q_0^2)$
- The proton contains also gluons: exp. half of the momentum

⇛ The description of DIS is one of the most precise tests of QCD

Description of the data



- This is obtained by global fits
  - Essential for the phenomenology
  - LHC



gluons at NLO

Probabilistic interpretation

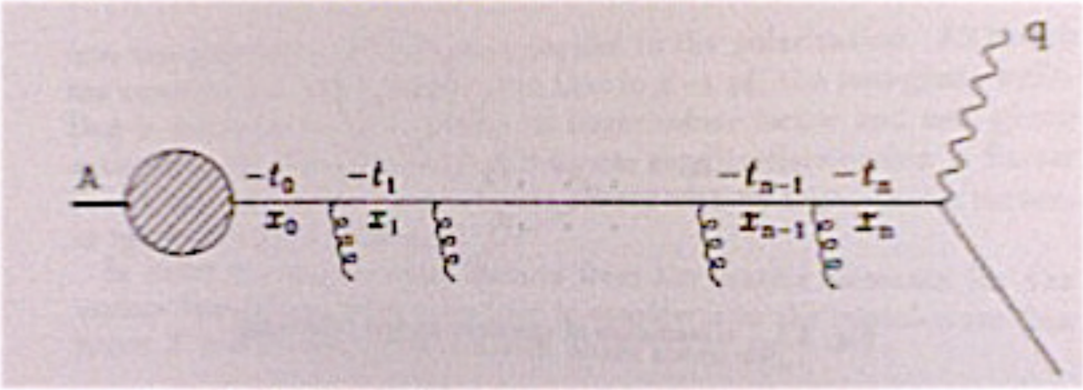
⇛ The evolution equation can be written as,

$$f_q(x,Q^2) + df_q(x,Q^2) = \int dy \int dz\, \delta(zy-x) f_q(y,Q^2) \left[\delta(z-1) + \frac{\alpha_s}{2\pi} P(z) d\log Q^2\right]$$

⇛ So that the probability of finding inside a quark another quark with fraction of momentum z of the parent parton is

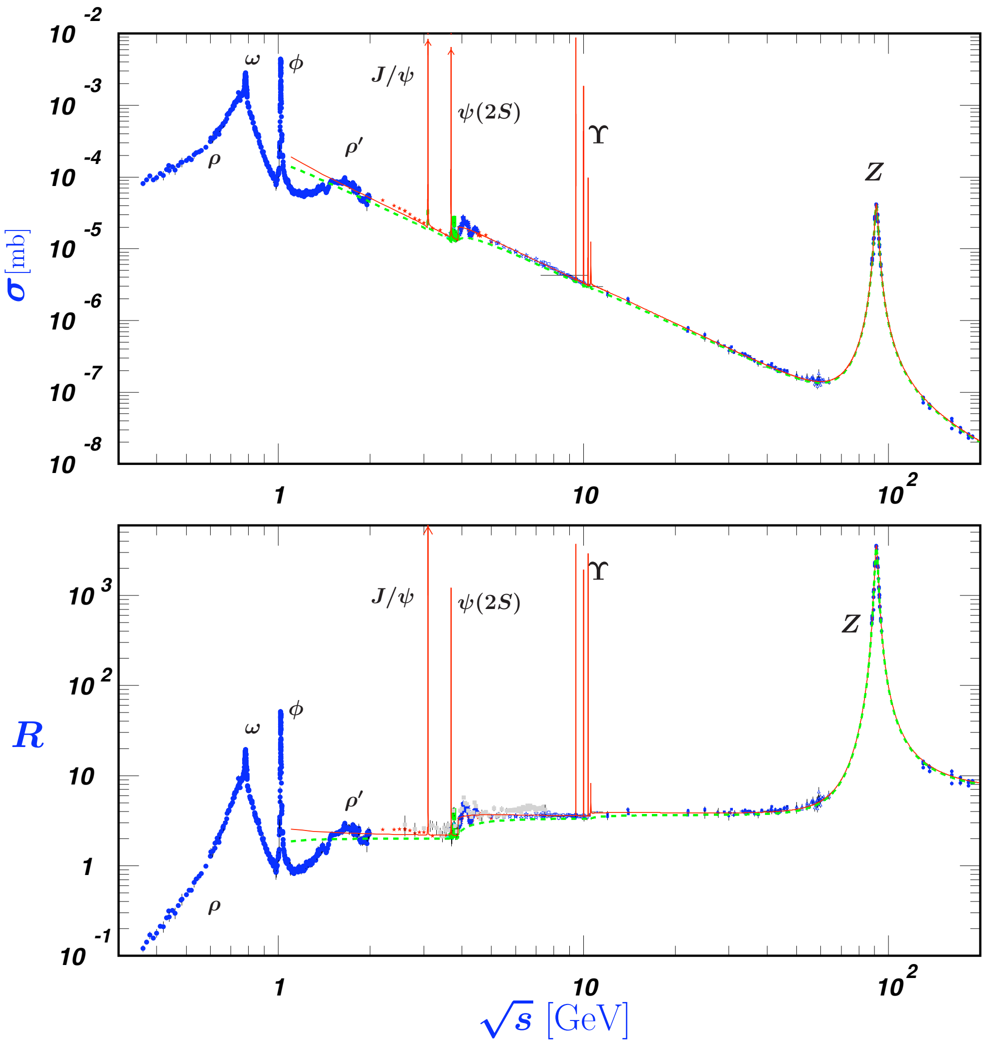
$$\mathcal{P}_{qq} + d\mathcal{P}_{qq} = \delta(z-1) + \frac{\alpha_s}{2\pi} P(z) d\log Q^2$$

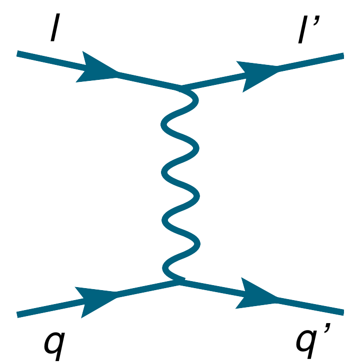
⇛ Repeating this, we resume the multiple branchings - DGLAP



$$\mathcal{O}\left(\left[\alpha_s \log Q^2\right]^n\right)$$

Gluons in e^+e^- annihilation





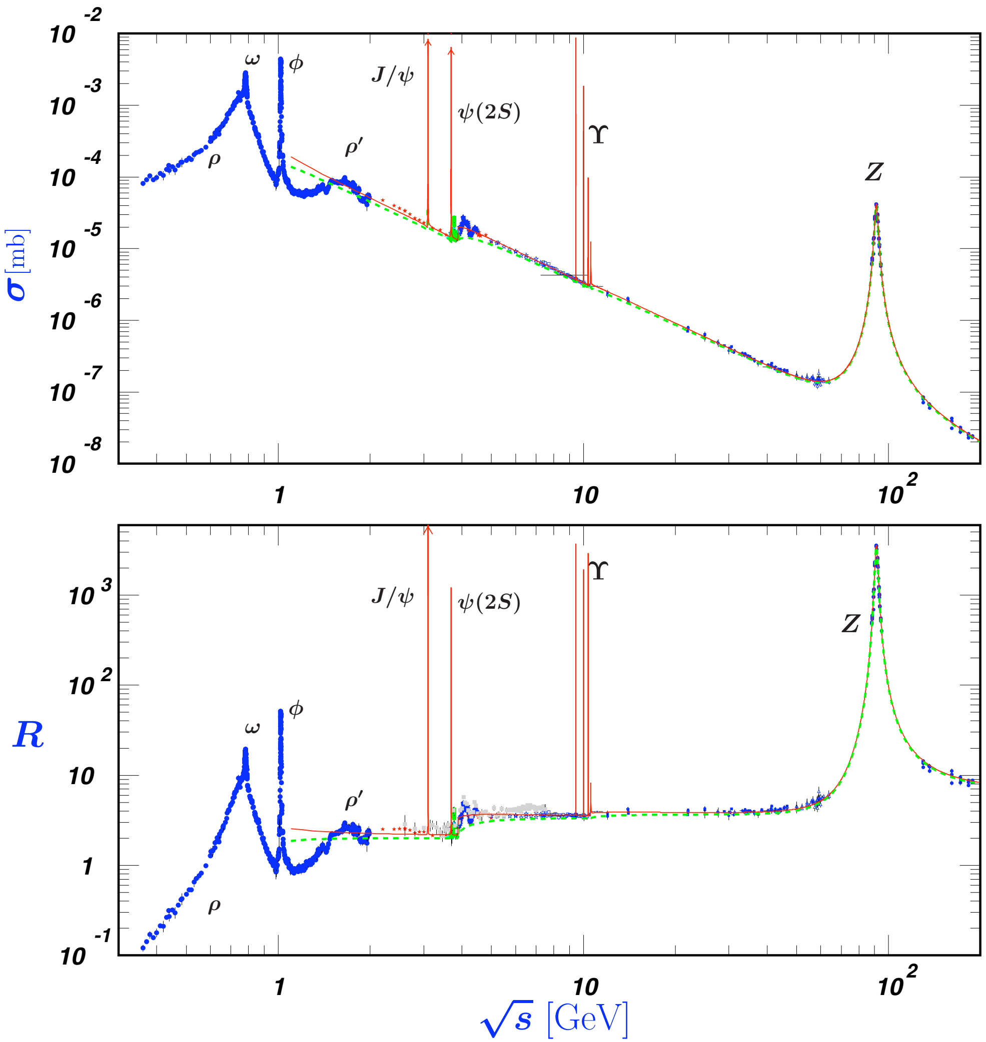
⇛ The total hadronic cross sect.

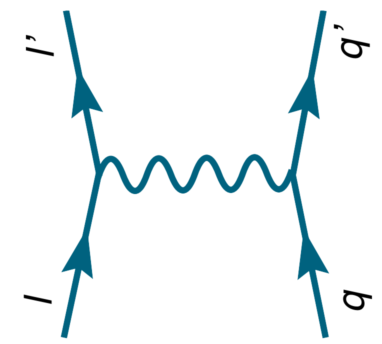
$$\sigma = \frac{4\pi\alpha^2}{3s} N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

⇛ Ratio with the muon pair prod.

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

Gluons in e^+e^- annihilation





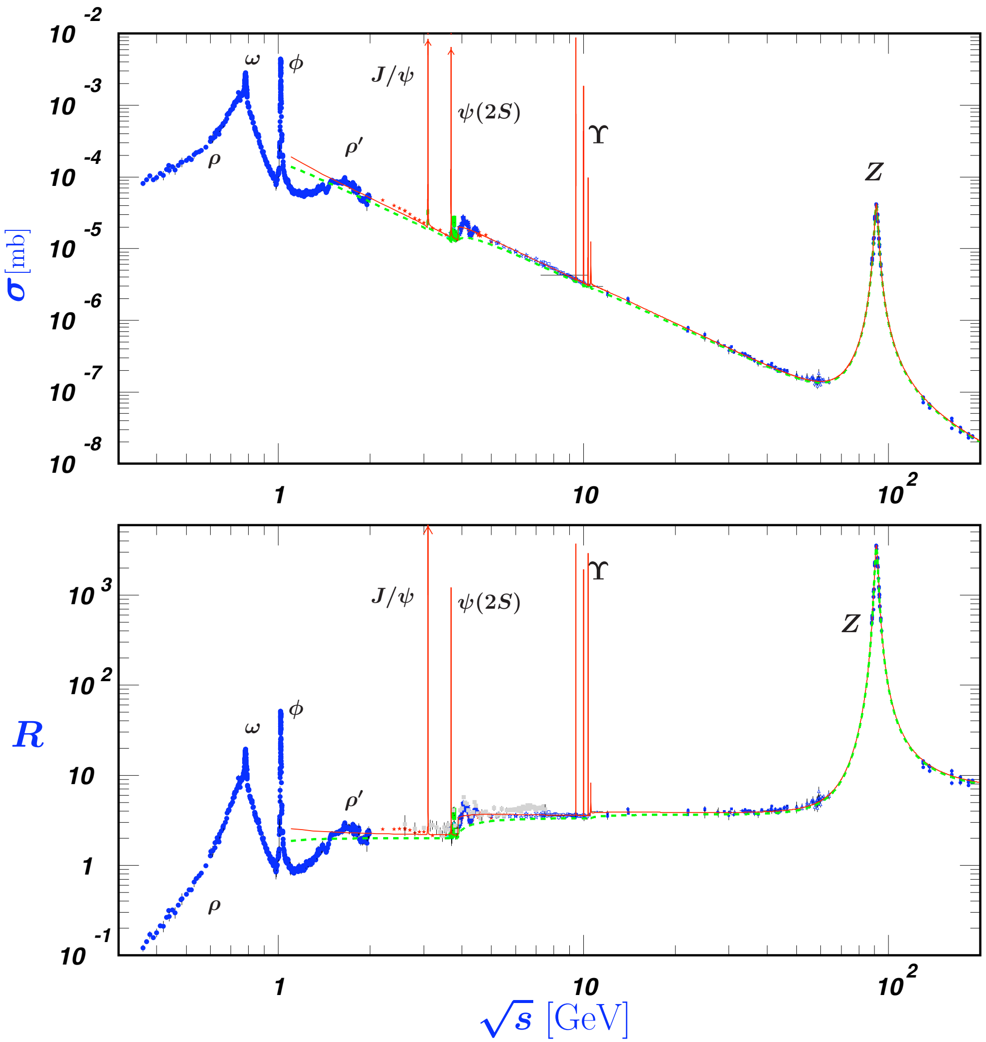
⇒ The total hadronic cross sect.

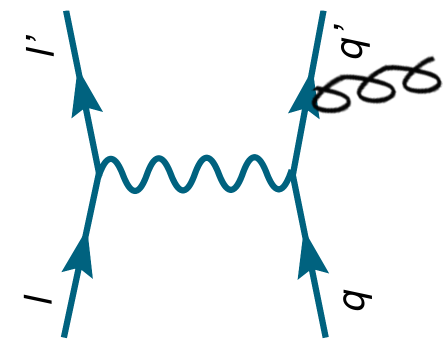
$$\sigma = \frac{4\pi\alpha^2}{3s} N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

⇒ Ratio with the muon pair prod.

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

Gluons in e^+e^- annihilation





⇛ The total hadronic cross sect.

$$\sigma = \frac{4\pi\alpha^2}{3s} N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

⇛ Ratio with the muon pair prod.

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_q e_q^2 \left[1 + \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right]$$

Jets in e^+e^- annihilation

⇛ It is interesting to study **less inclusive observables**, e.g.

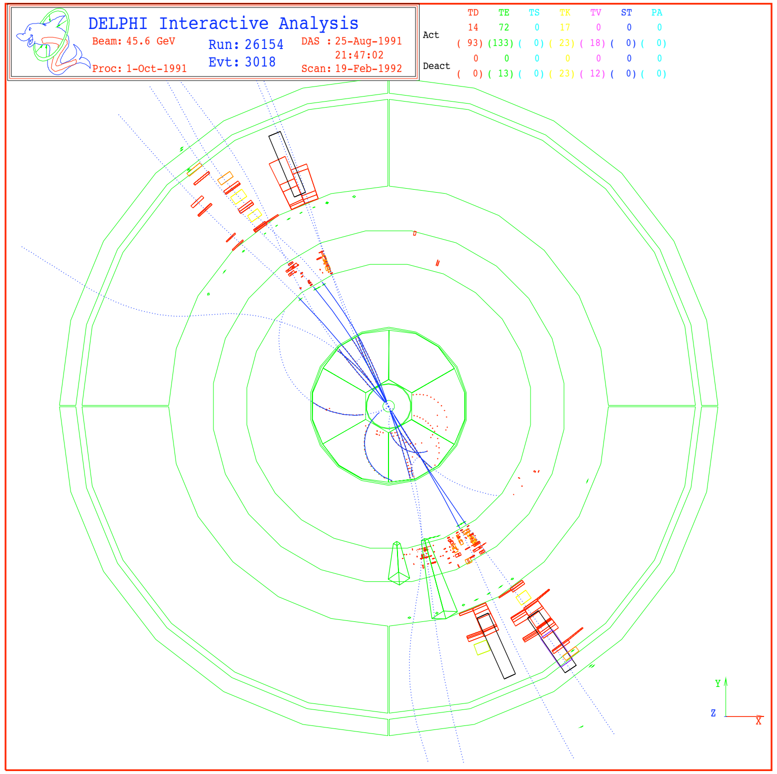
- How is the energy distributed in the final state?

Jets in e^+e^- annihilation

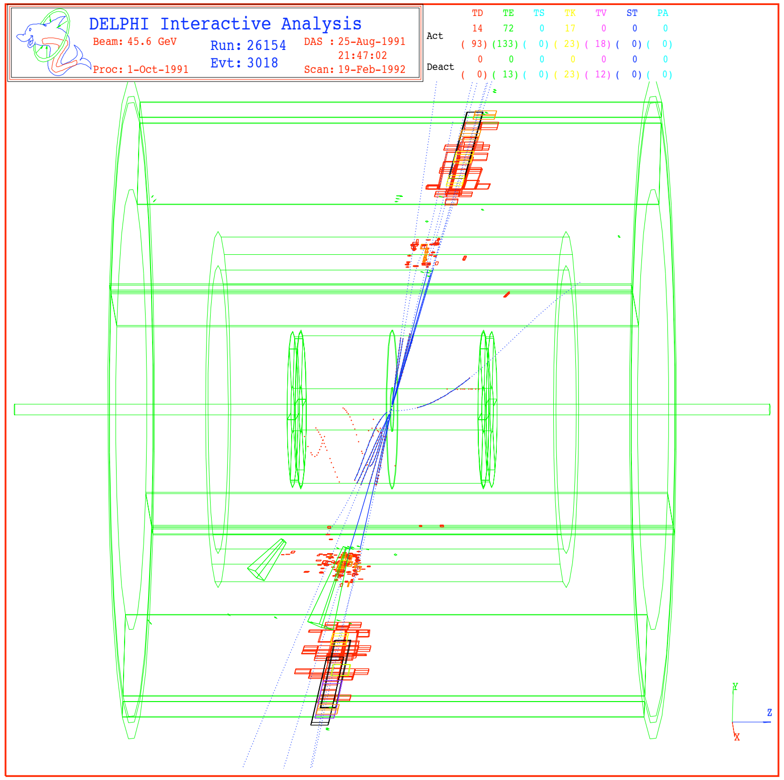
⇛ It is interesting to study **less inclusive observables**, e.g.

↘ How is the energy distributed in the final state?

A two-jet event at LEP



x-y plane



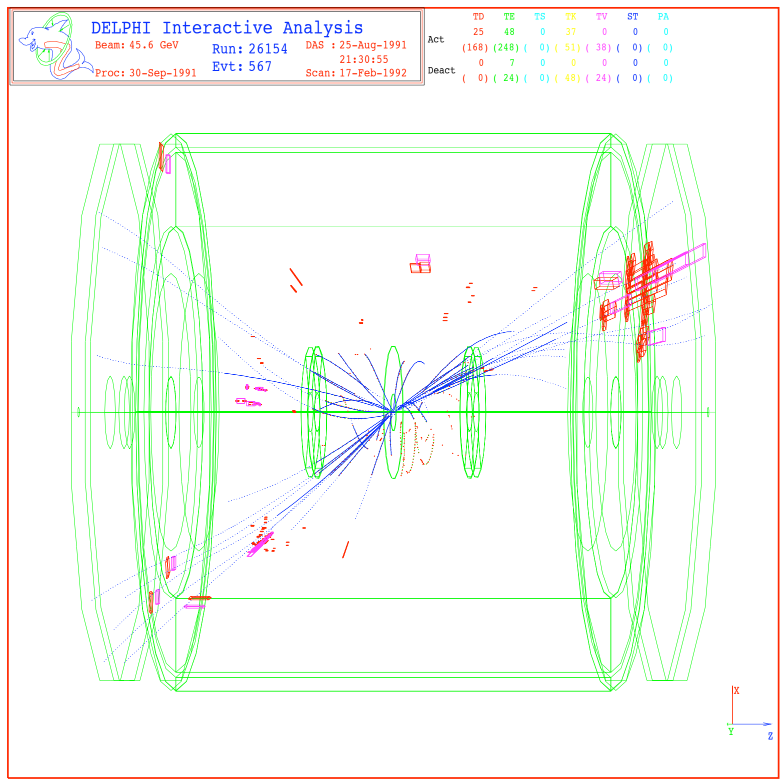
z-y plane

Jets in e^+e^- annihilation

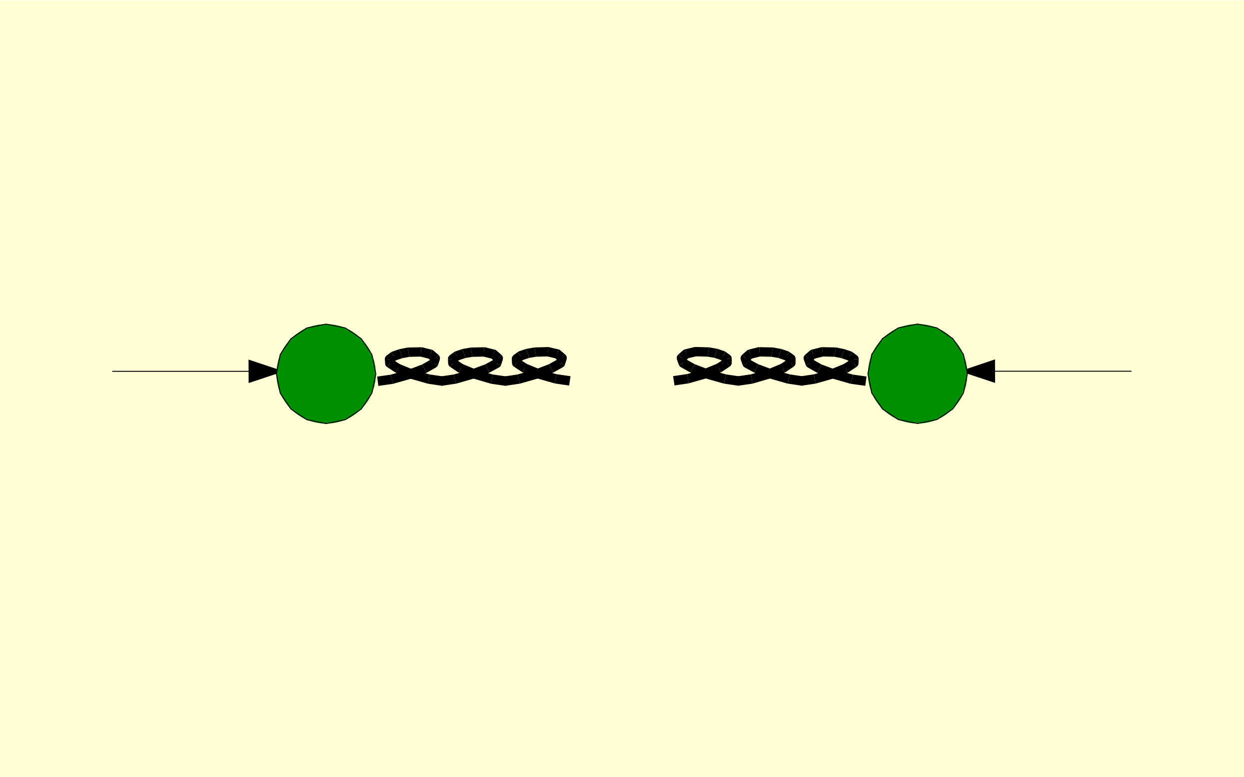
⇛ It is interesting to study **less inclusive observables**, e.g.

- How is the energy distributed in the final state?

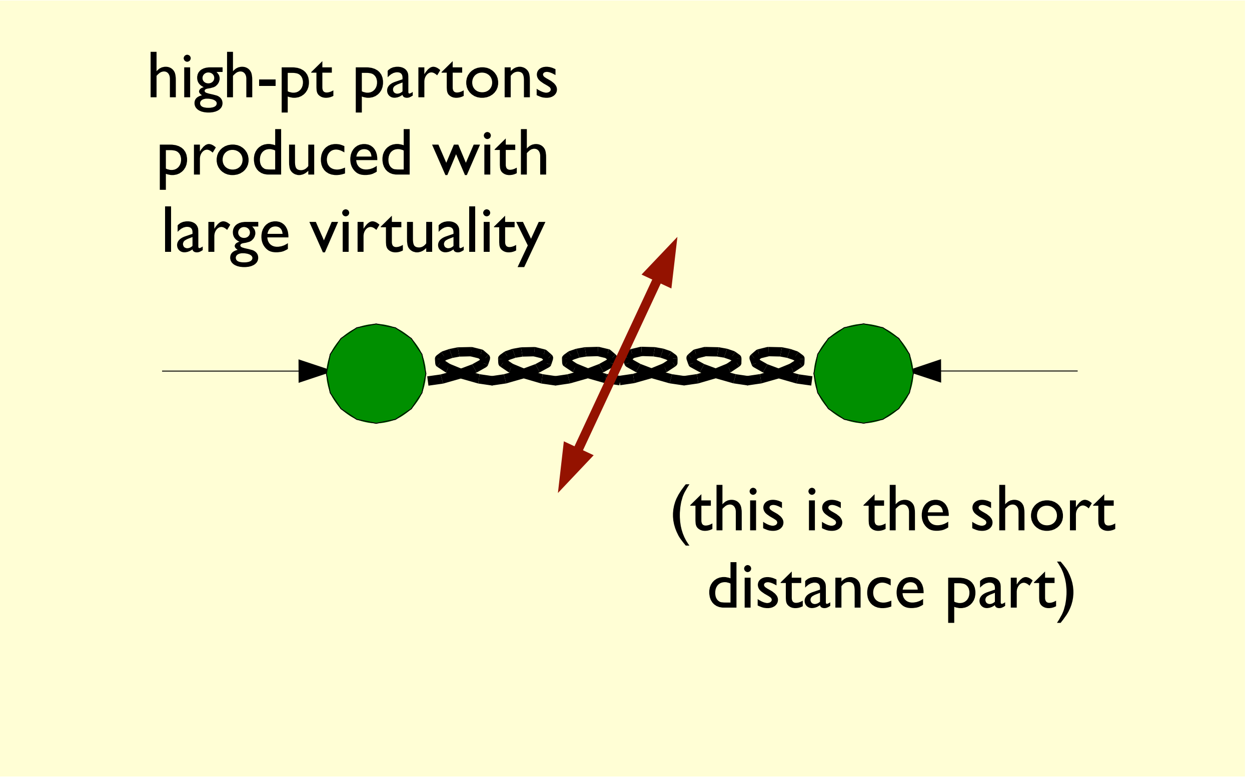
A three-jet event at LEP



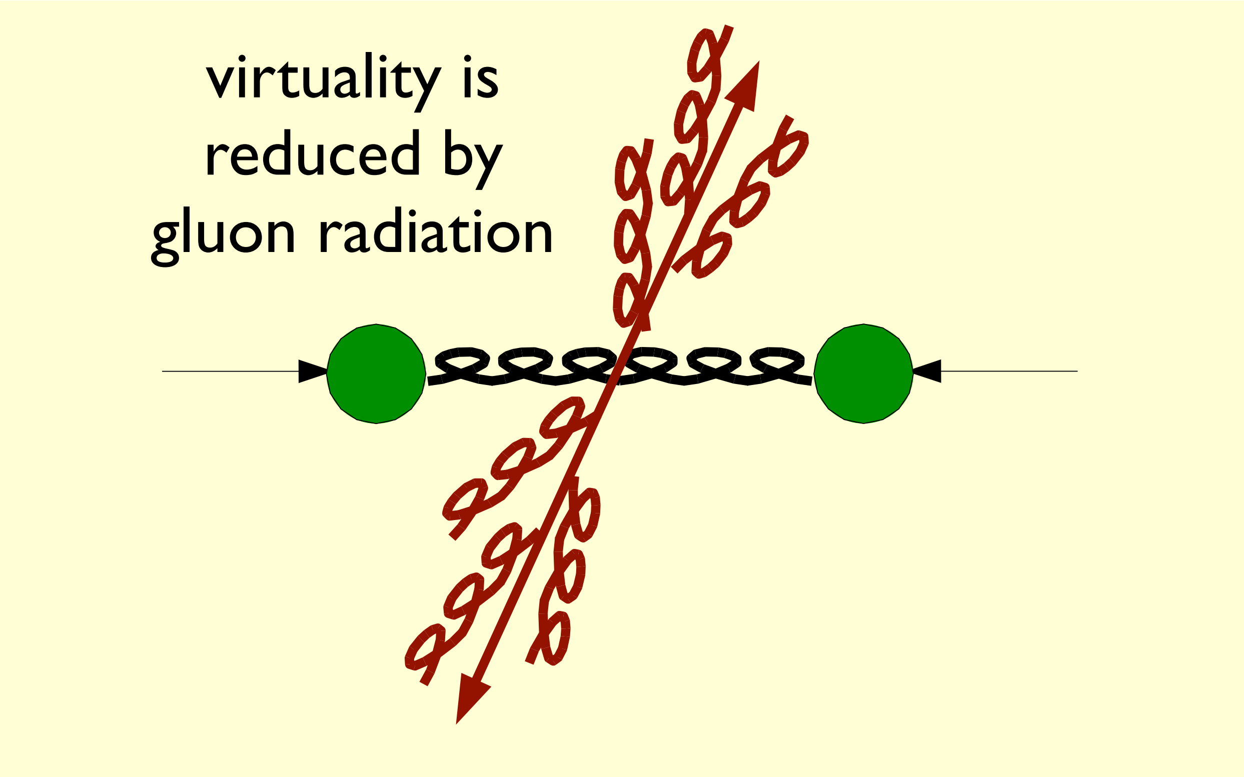
What is a jet (naively)



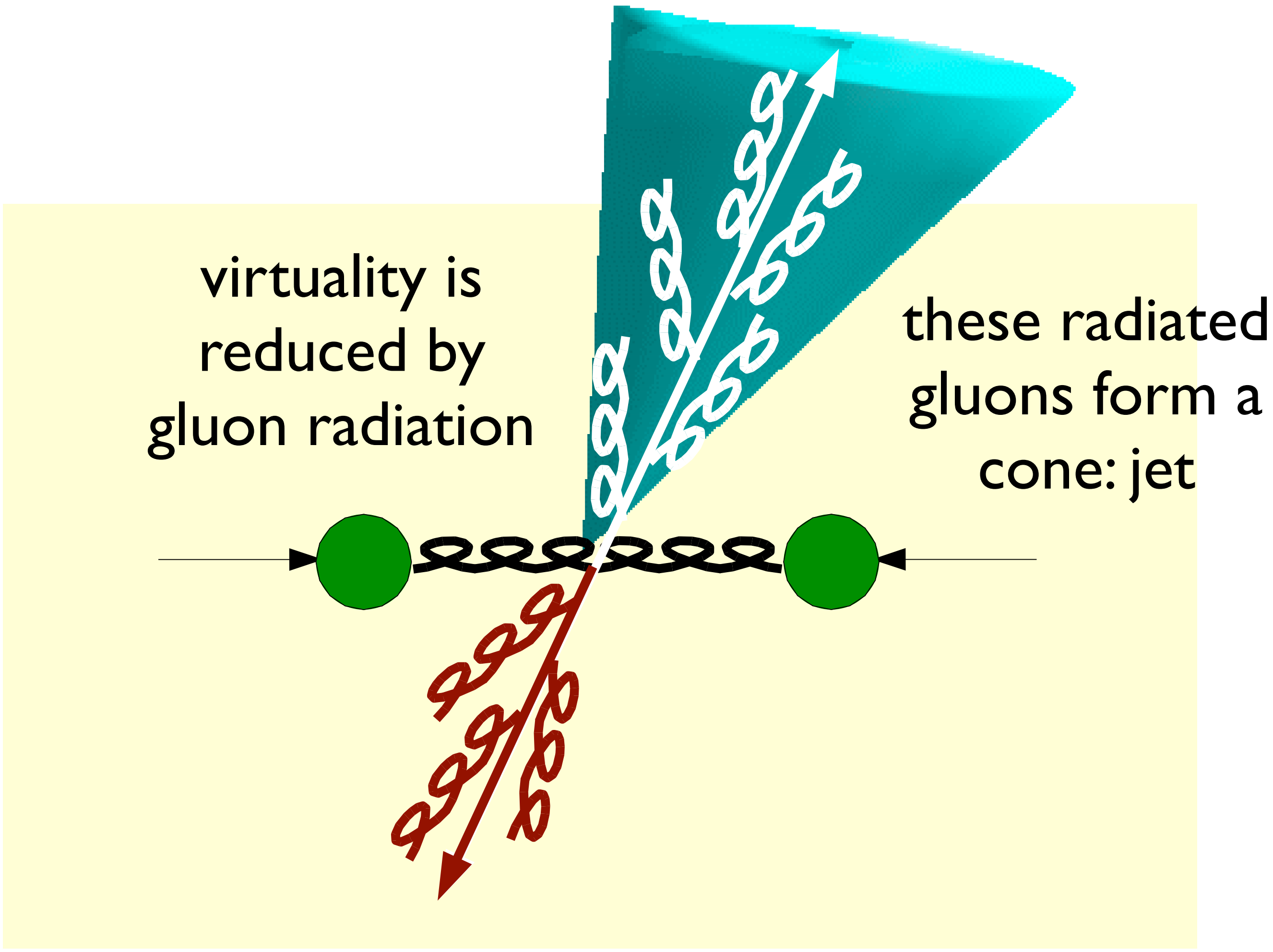
What is a jet (naively)



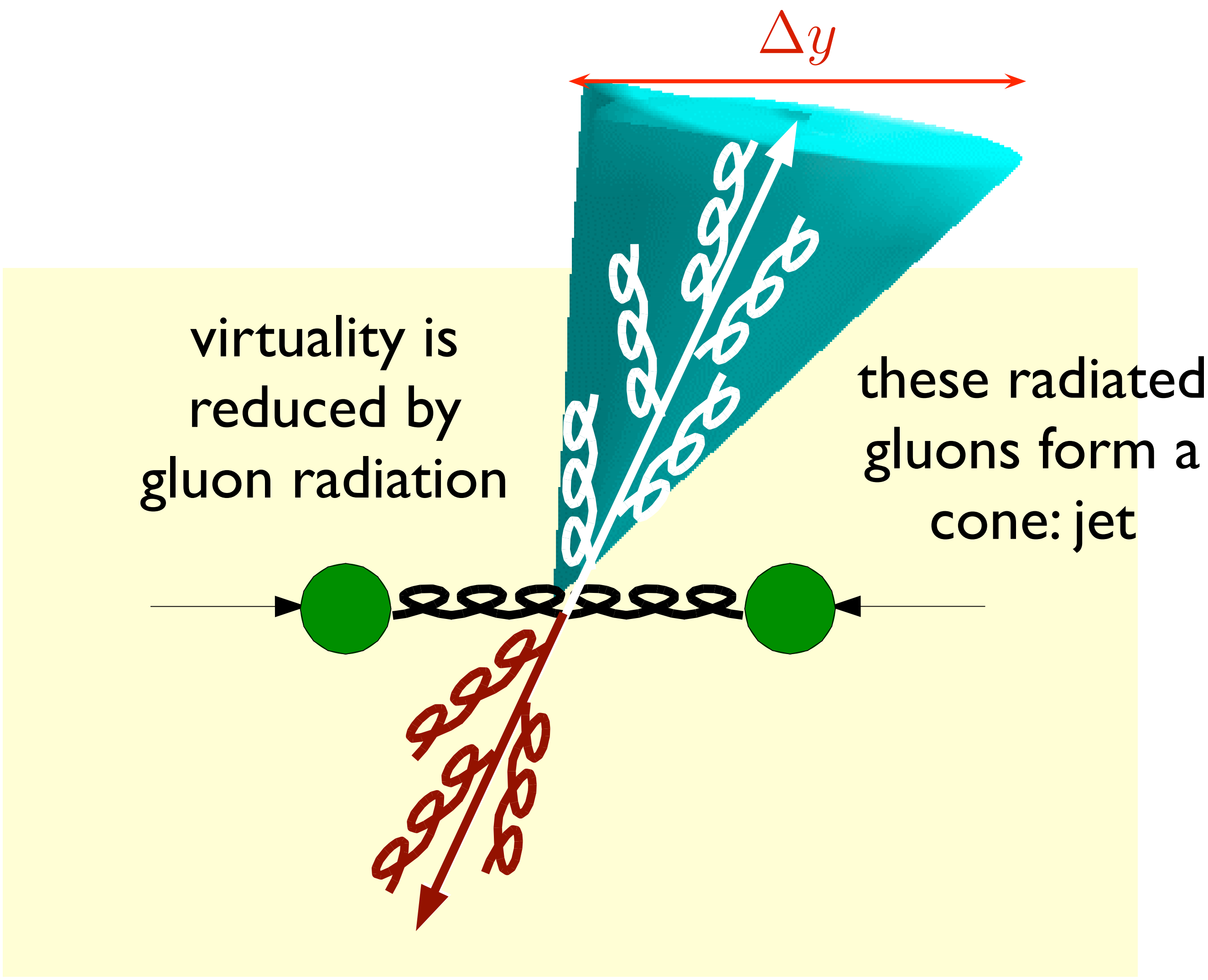
What is a jet (naively)



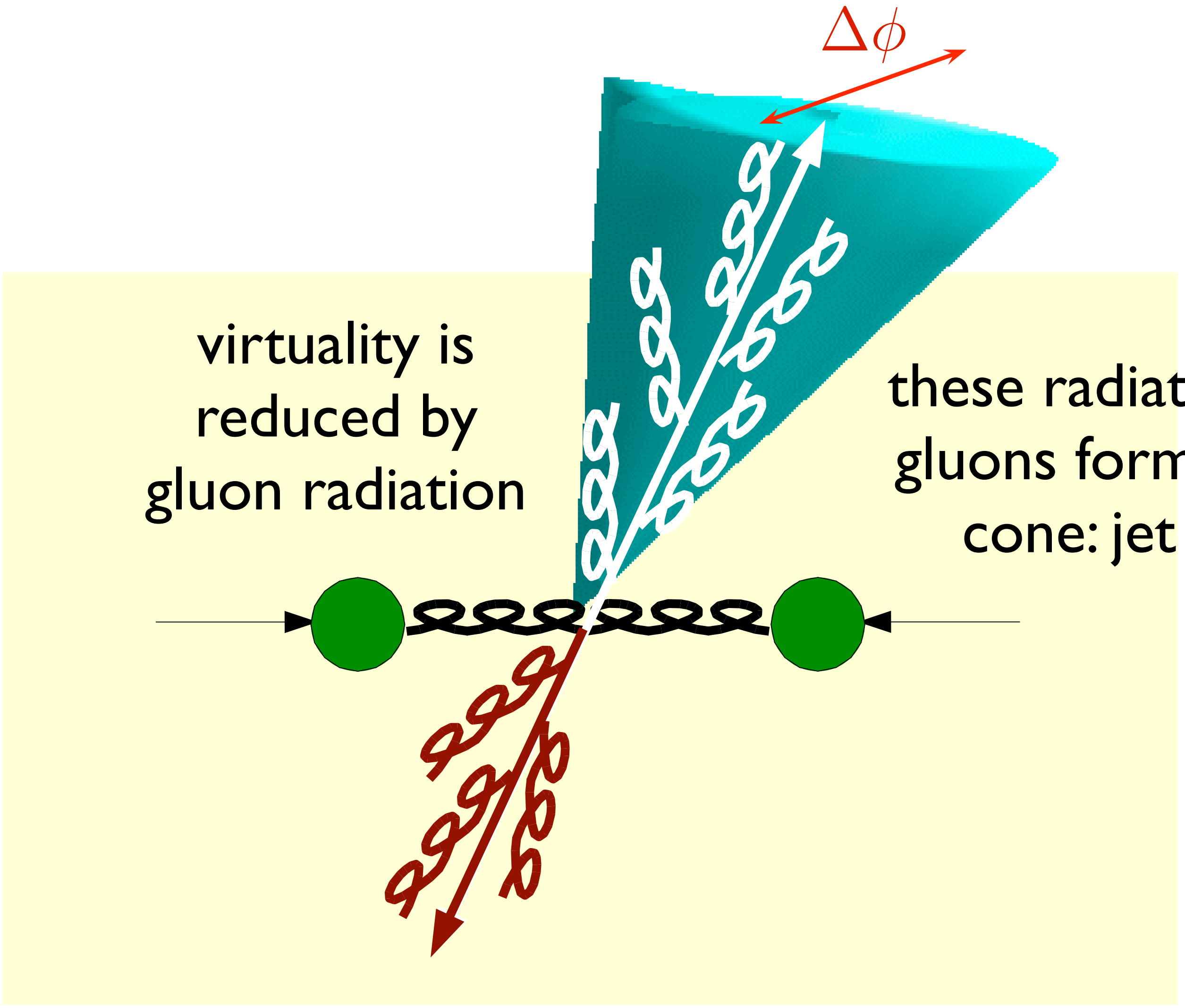
What is a jet (naively)



What is a jet (naively)



What is a jet (naively)



Jet cross sections

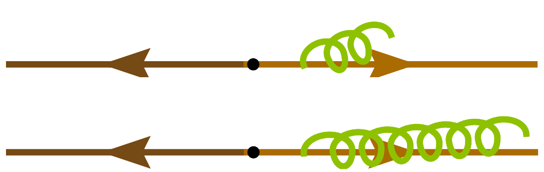
- A jet is a bunch of particles going into a given direction
- Naively, the number of emitted gluons define the number of jets in the final state
  - This is essentially true, but the gluon emission is divergent

$$\frac{1}{\sigma}\frac{d^2\sigma^{q\bar{q}g}}{dx_q dx_{\bar{q}}} = C_F \frac{\alpha_s}{2\pi}\frac{x_q^2 + x_{\bar{q}}^2}{(1-x_q)(1-x_{\bar{q}})}$$

- Where are these singularities?

$$1 - x_q = x_{\bar{q}} \frac{E_g}{\sqrt{s}} (1 - \cos\theta_{\bar{q}g})$$

  - Soft $E_g/\sqrt{s} \to 0$
  - Collinear $\cos\theta_{\bar{q}g} \to 0$

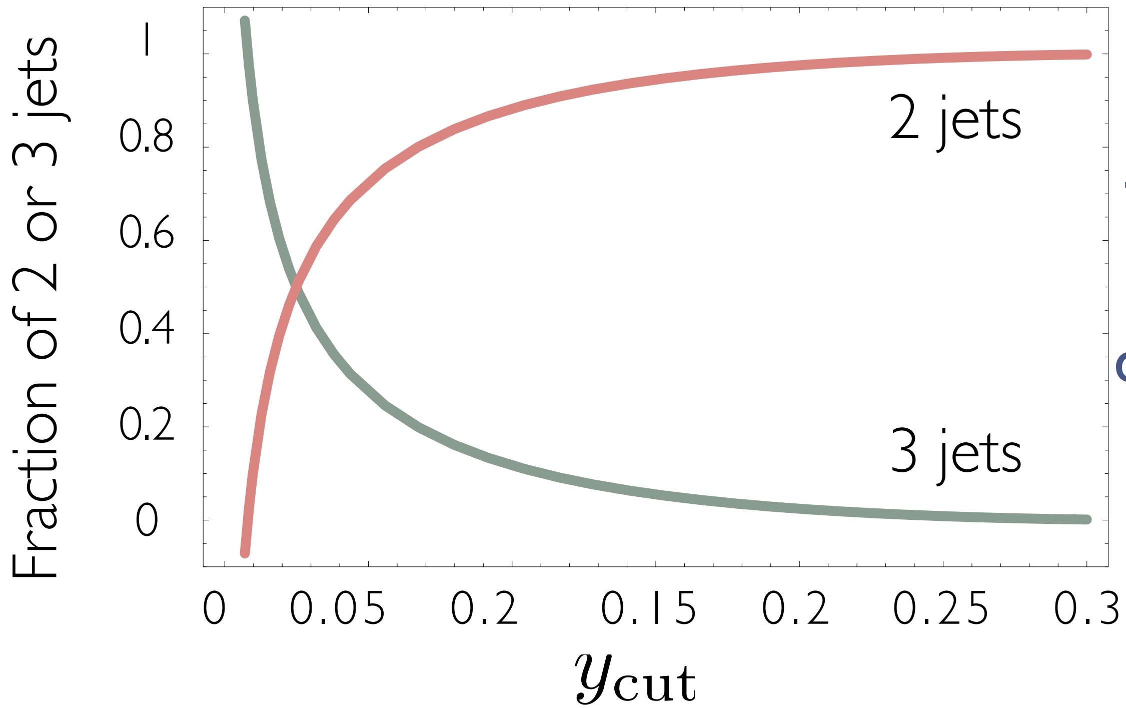


Jet definition

- Several different definitions for jets exist - jet algorithms
  - Example, define a minimum invariant mass of the parton pairs

$$\min\{(p_i+p_j)^2\} = \min\{2E_iE_j(1-\theta_{ij})\} > y_{\rm cut}\, s$$

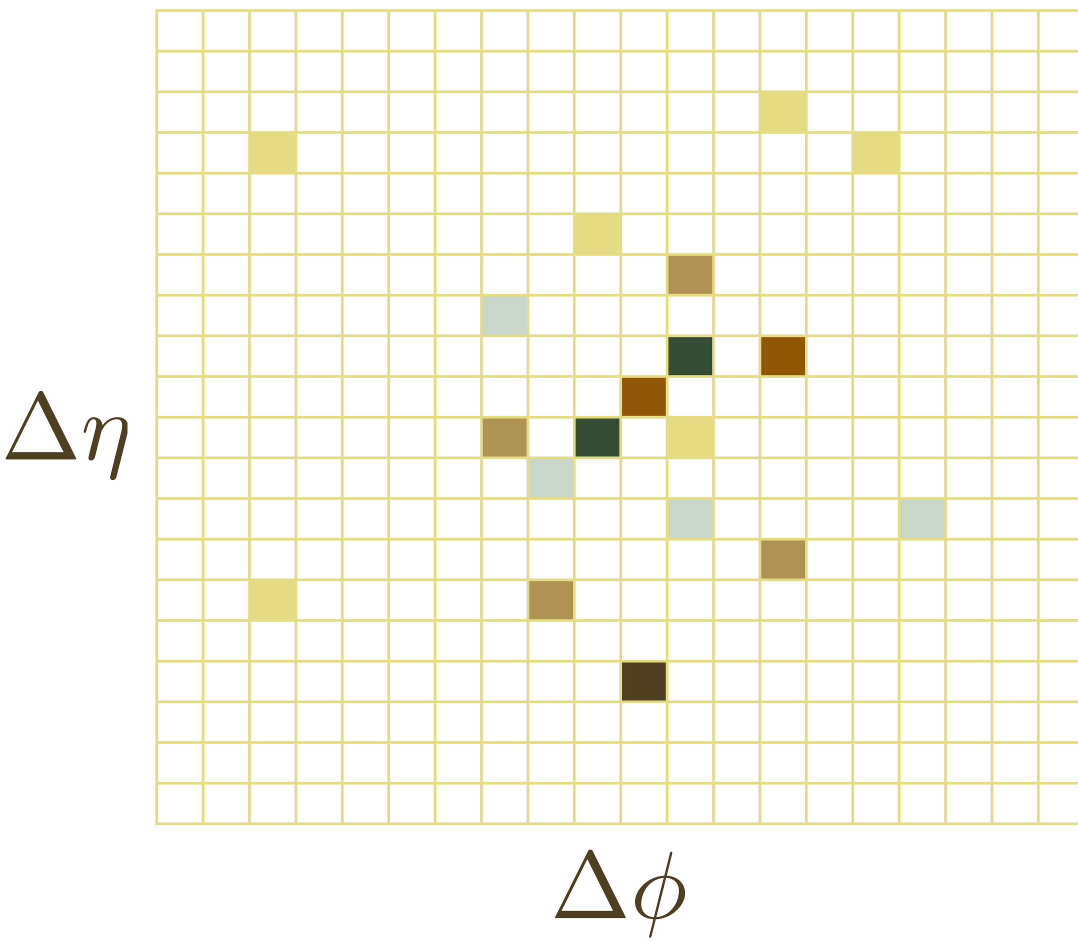
- Integrating the cross section within these limits

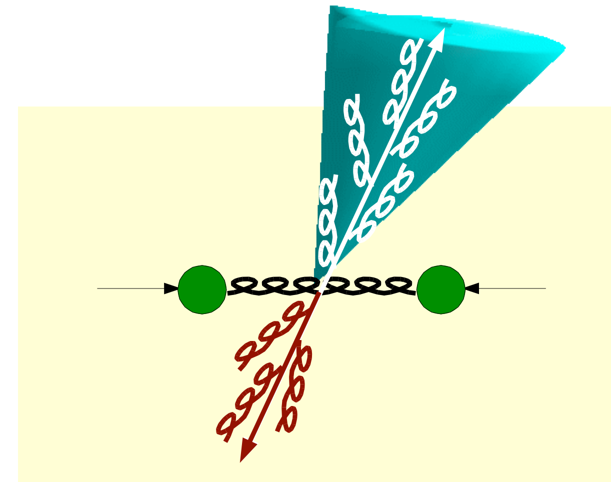


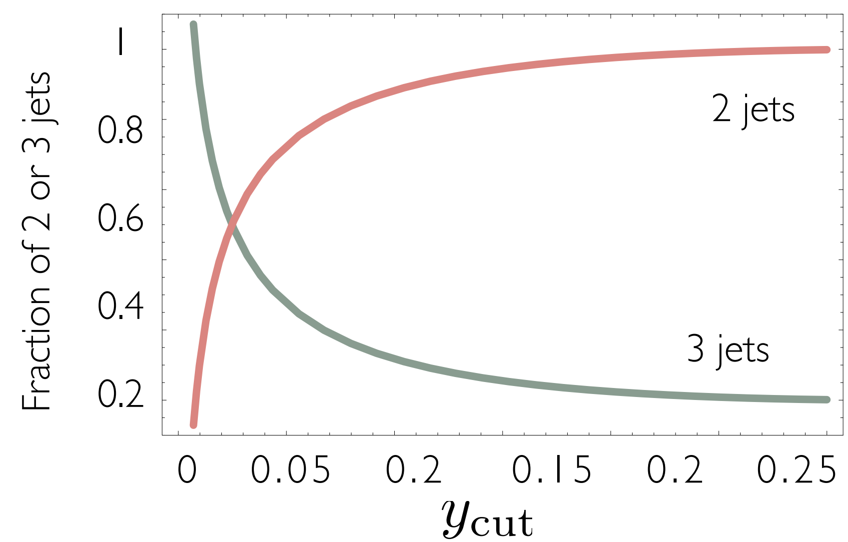
The number of "jets" depends on the definition (resolution)

Jet definition

Number of "jets" depends on the definition





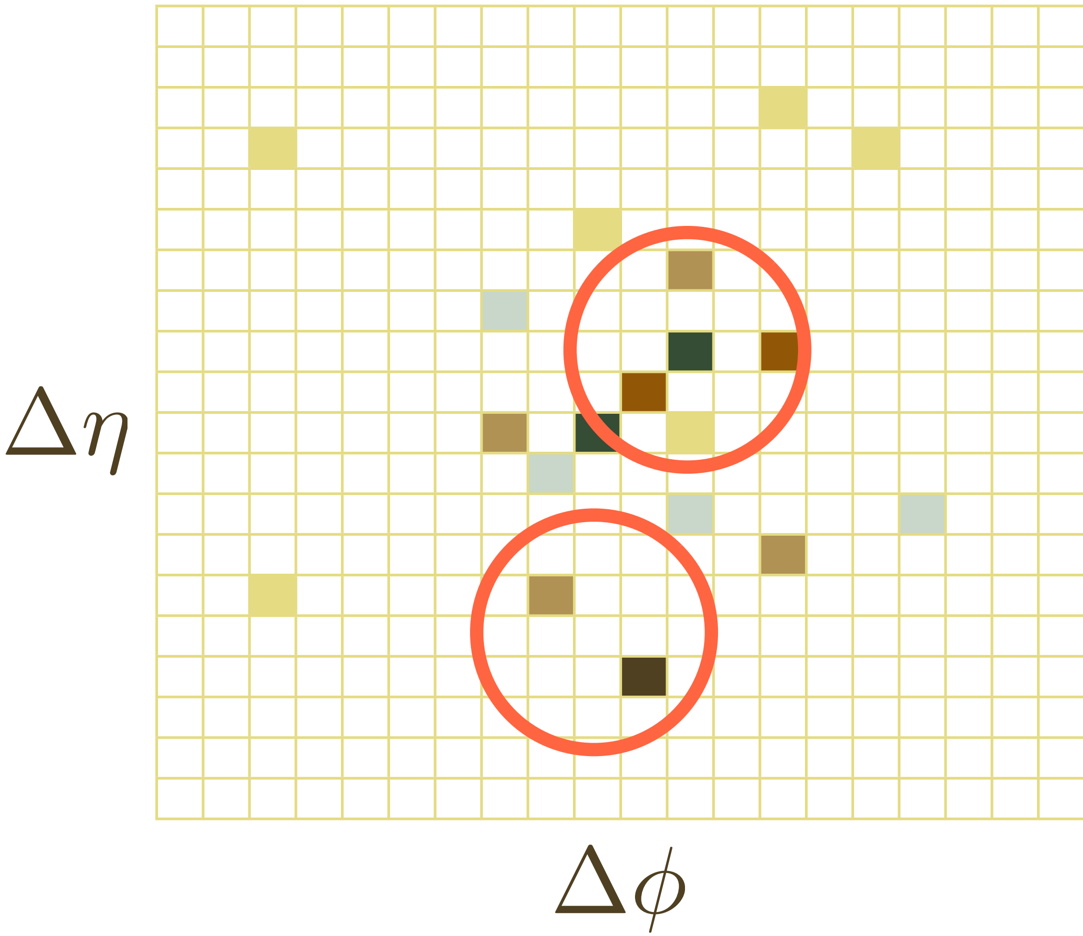


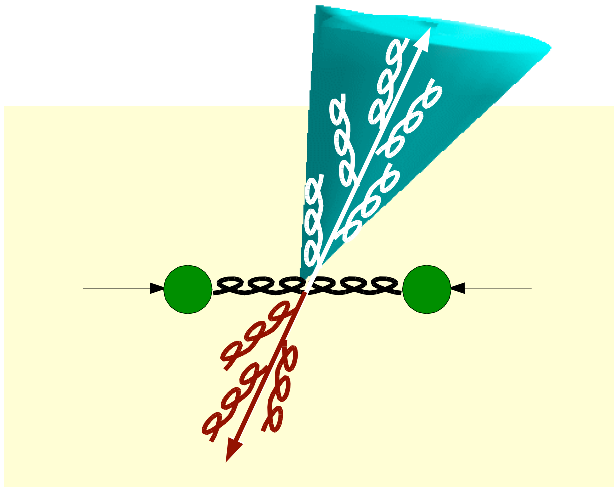
Jet definition and identification is one of the main issues at the LHC

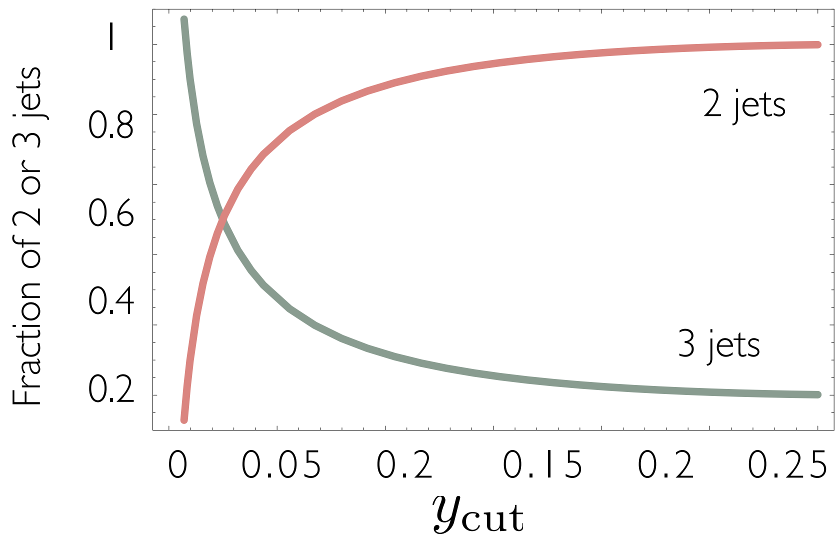
[More in David's lectures...]

Jet definition

Number of "jets" depends on the definition



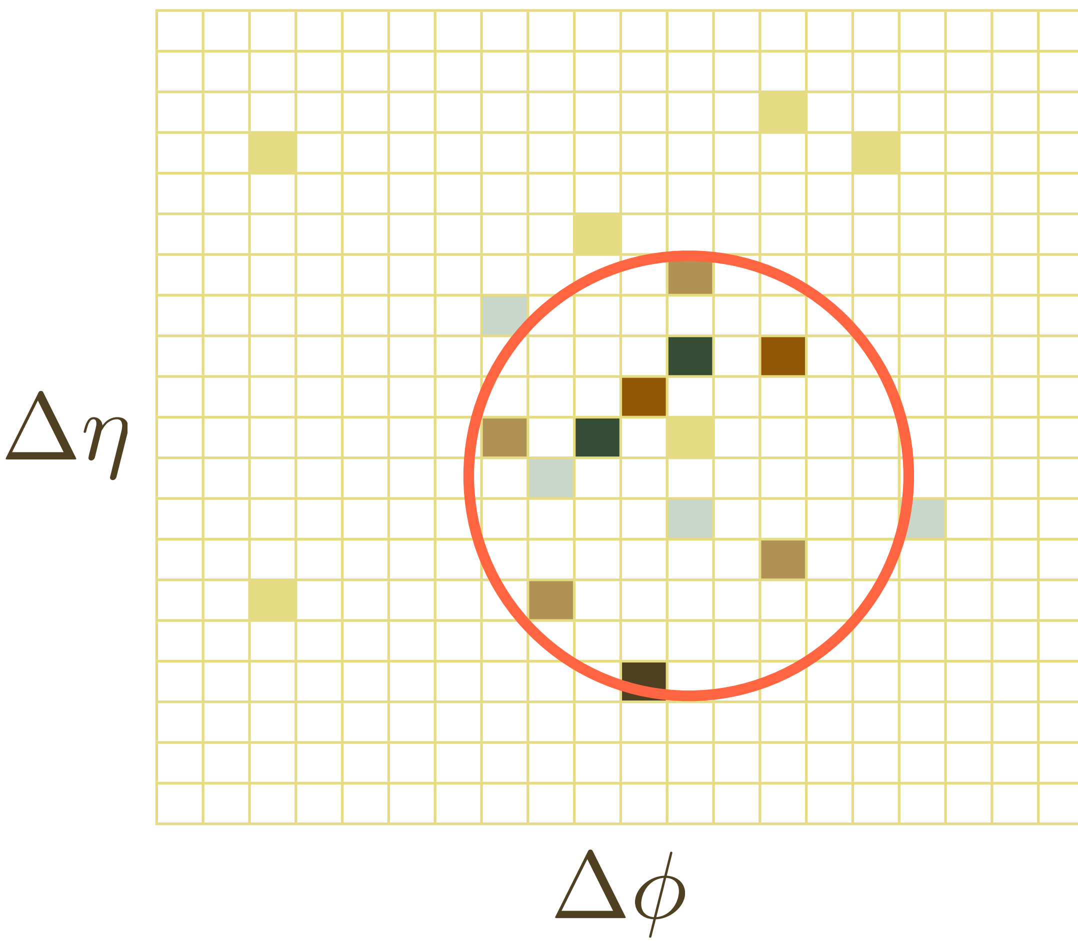


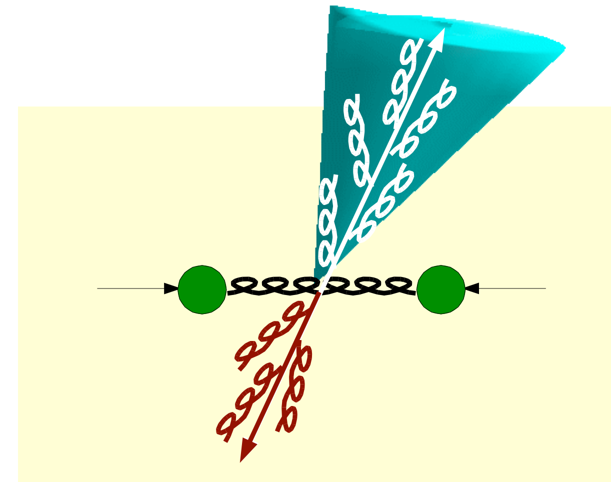


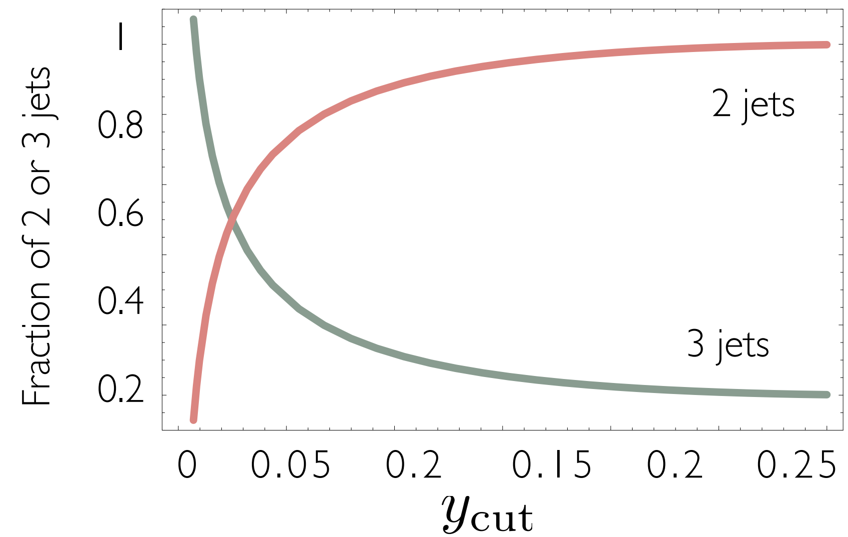
Jet definition and identification is one of the main issues at the LHC

[More in David's lectures...]

Number of “jets” depends on the definition





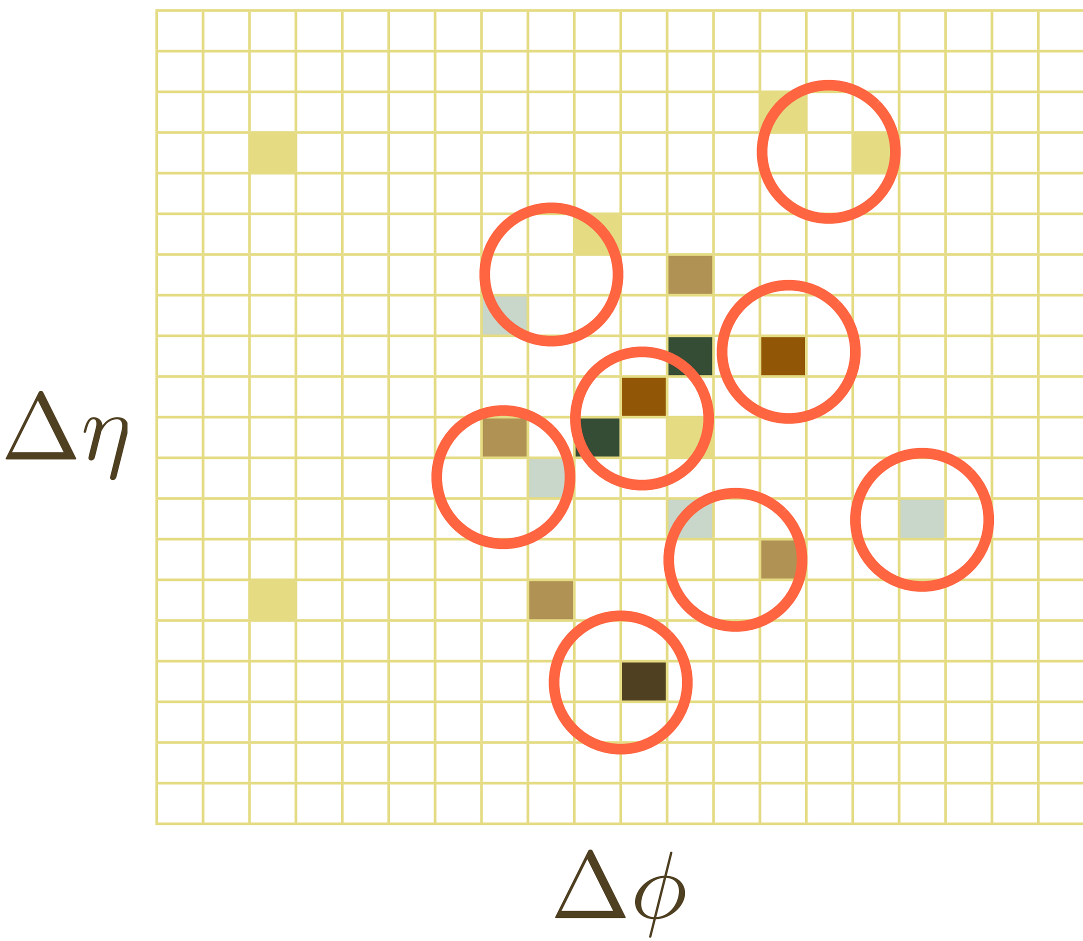


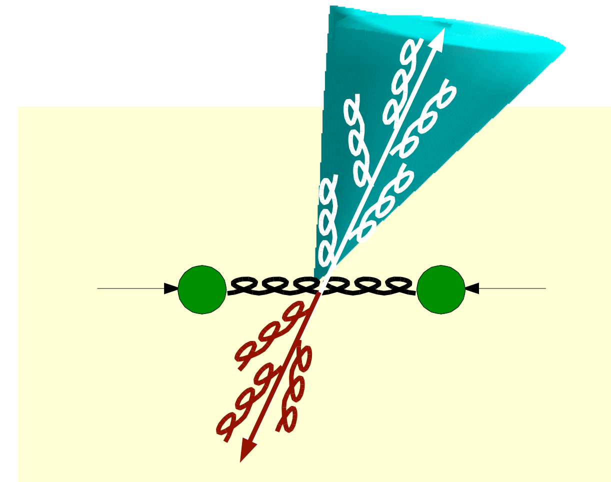
Jet definition and identification is one of the main issues at the LHC

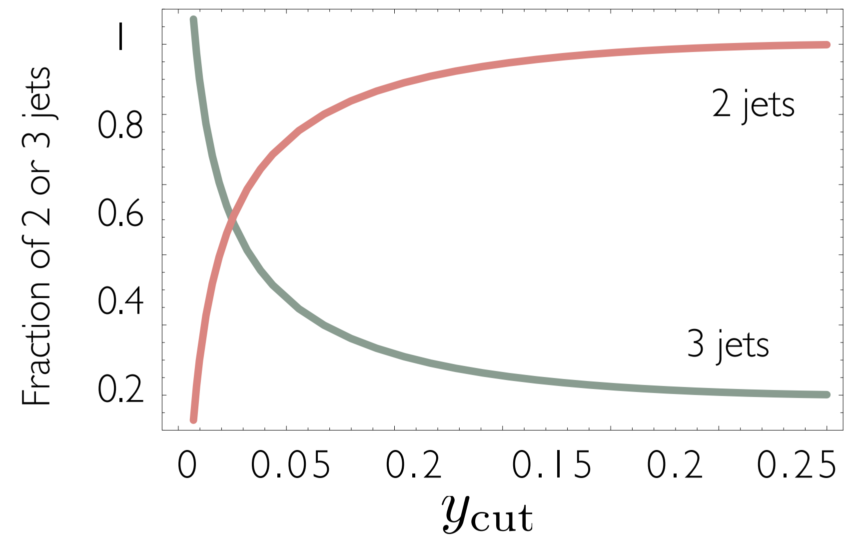
[More in David’s lectures...]

Jet definition

Number of “jets” depends on the definition







Jet definition and identification is one of the main issues at the LHC

[More in David’s lectures...]

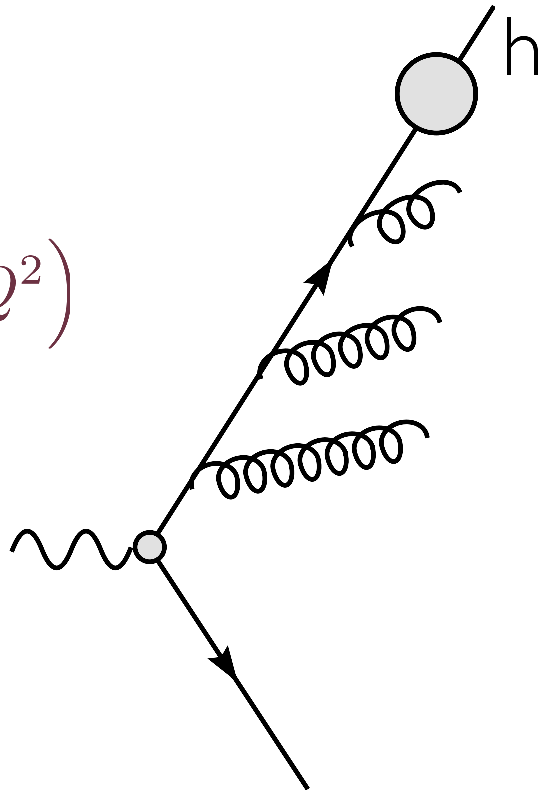
Jet evolution

⇛ The type of divergences in DIS and jets are basically the same

↘ The evolution of the jet can be described by DGLAP-like eqs.

⇛ Example: Fragmentation functions

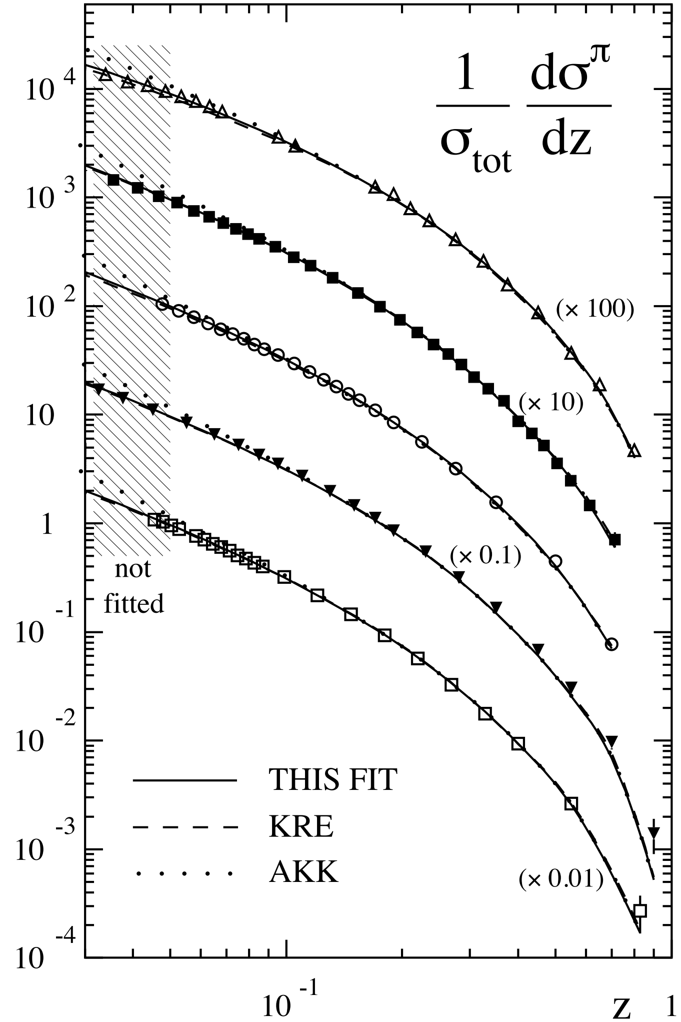
$$\frac{\partial D_i^h(x,Q^2)}{\partial \log Q^2} = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ji}(z) D_j\left(\frac{x}{z}, Q^2\right)$$



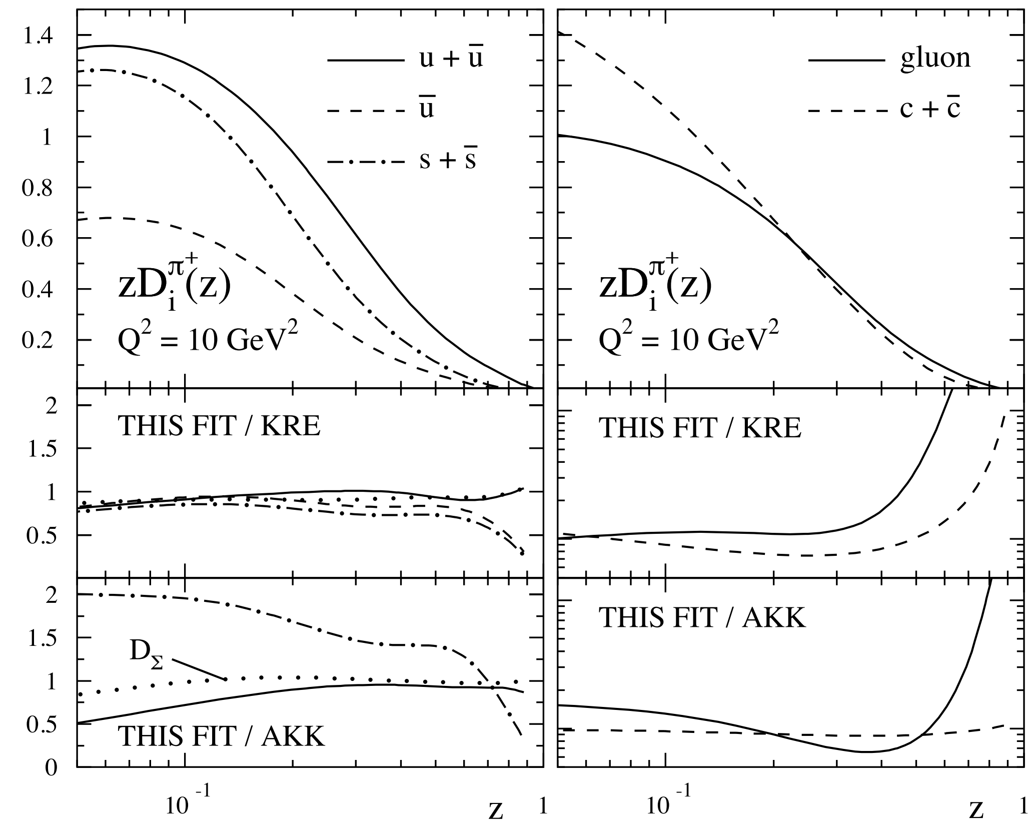
Give the probability that a parton i produced in a hard process fragments into a hadron h with a fraction of momentum x

⇛ Non-perturbative quantities (hadronization) and universal

Fragmentation functions



e^+e^-



[de Florian, Sassot, Stratmann 2007]

Factorization

- The DIS cross section has a factorization between the leptonic and hadronic parts
  - This is a special case of a more general rule
- For many observables, the cross section is the convolution of the partonic cross sections with the **universal** PDFs

$$\sigma = f(x_1,Q^2)\otimes f(x_2,Q^2)\otimes\hat{\sigma}(x_1,x_2,Q^2)\otimes D(z,Q^2)$$

- Long distance non-perturbative terms
  - Involve hadronic scales $\mathcal{O}(\Lambda_{QCD})$
  - Evolution can be computed by DGLAP equations
- Short distance perturbative elementary cross section

Factorization

- The DIS cross section has a factorization between the leptonic and hadronic parts
  - This is a special case of a more general rule
- For many observables, the cross section is the convolution of the partonic cross sections with the **universal** PDFs

$$\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes \hat{\sigma}(x_1, x_2, Q^2) \otimes D(z, Q^2)$$

- Long distance non-perturbative terms
  - Involve hadronic scales $\mathcal{O}(\Lambda_{QCD})$
  - Evolution can be computed by DGLAP equations
- Short distance perturbative elementary cross section

Factorization

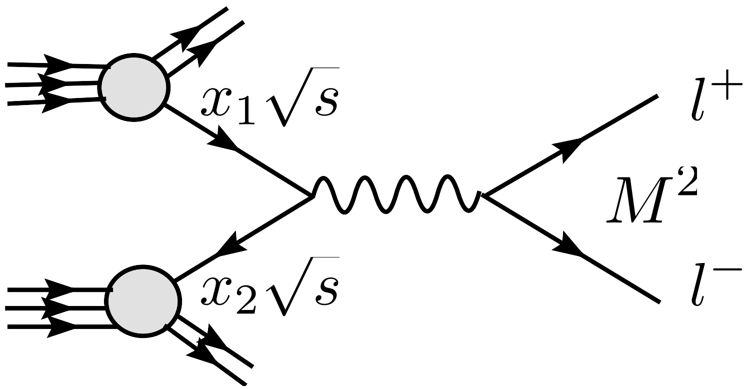
- The DIS cross section has a factorization between the leptonic and hadronic parts
  - This is a special case of a more general rule
- For many observables, the cross section is the convolution of the partonic cross sections with the **universal** PDFs

$$\sigma = f(x_1, Q^2) \otimes f(x_2, Q^2) \otimes \hat{\sigma}(x_1, x_2, Q^2) \otimes D(z, Q^2)$$

- Long distance non-perturbative terms
  - Involve hadronic scales $\mathcal{O}(\Lambda_{QCD})$
  - Evolution can be computed by DGLAP equations
- Short distance perturbative elementary cross section

Some specific examples...

Lepton-pair production (Drell-Yan)



⇛ The perturbative cross section for the partonic process

$$\sigma(q_i\bar{q}_i \to l^+l^-) = \frac{1}{N_C} e_i^2 \frac{4\pi\alpha^2}{3\hat{s}}$$

⇛ where $\hat{s} = x_1 x_2 s = M^2$

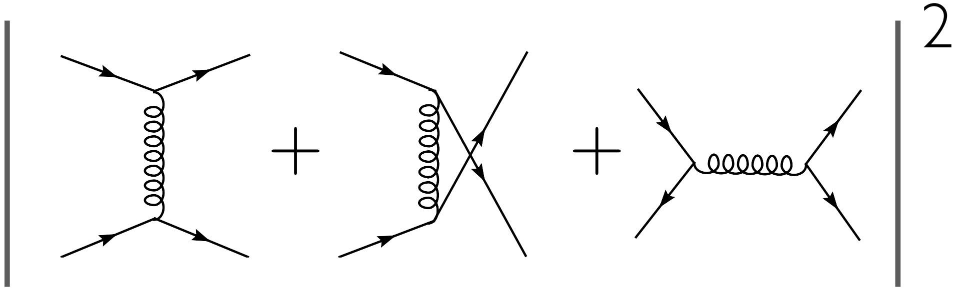
⇛ Invariant mass and rapidity of the pair determine quarks' kinematics

$$x_1 = \frac{M}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

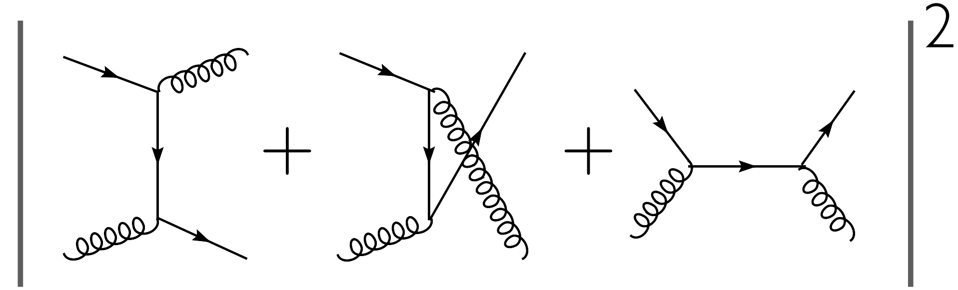
⇛ So, the factorized cross section is simply

$$\frac{d^2\sigma^{DY}}{dM^2 dy} = \frac{4\pi\alpha^2}{9M^4} \sum_i e_i^2 \left[x_1 q_i(x_1) x_2 \bar{q}(x_2) + (q \leftrightarrow \bar{q})\right]$$

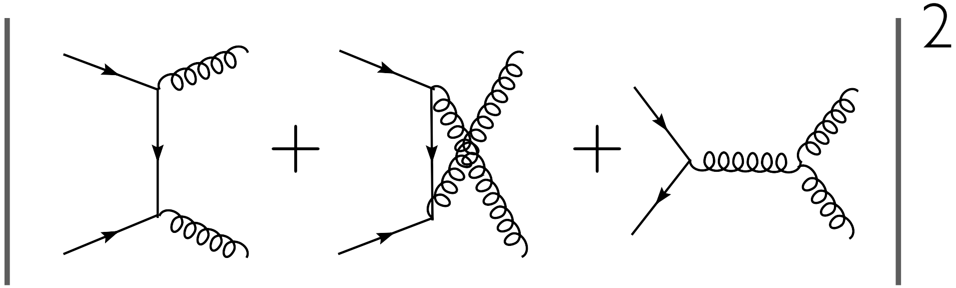
Jet production



$qq \to qq$



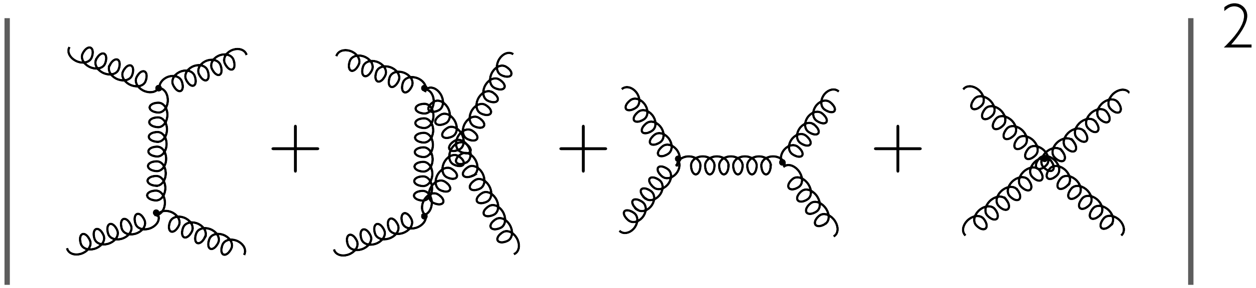
$qg \to qg$



$q\bar{q} \to gg \quad [+\, gg \to q\bar{q}]$

Lowest order perturbative processes

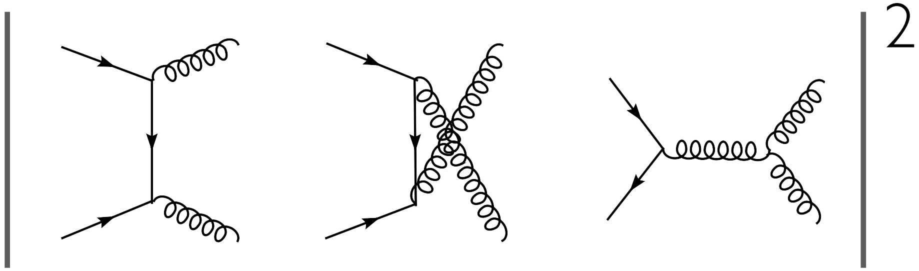
→ To be convoluted with PDFs



$gg \to gg$

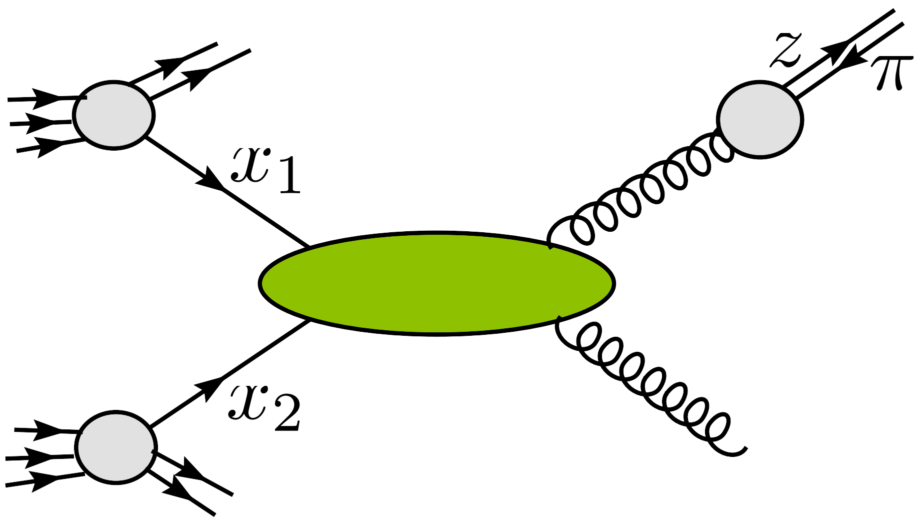
One example

⇛ $q\bar{q}$ contribution to the inclusive high-pt pion production



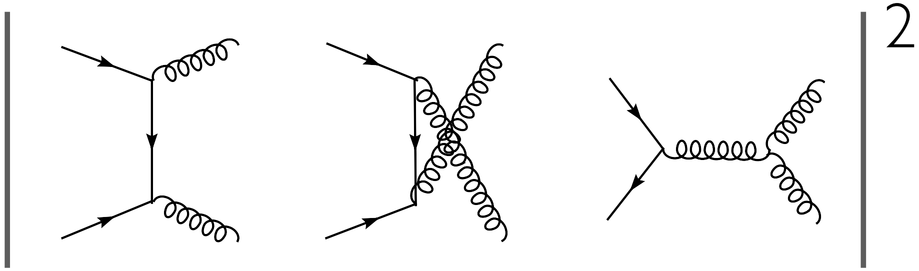
$$\frac{d\sigma}{d\hat{t}} = \frac{32\pi\alpha_s^2}{27\hat{s}}\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{9}{4}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\right]$$

$$\frac{d\sigma^{AB\to h}}{dp_T^2 dy} = \sum_i \int \frac{dx_2}{x_2}\int\frac{dz}{z}\; x_1 q_i^A(x_1,Q^2) x_2 \bar{q}_i^B(x_2,Q^2)\frac{d\sigma^{q_i\bar{q}_i\to gg}}{d\hat{t}} D_{g\to\pi}(z,Q^2)$$



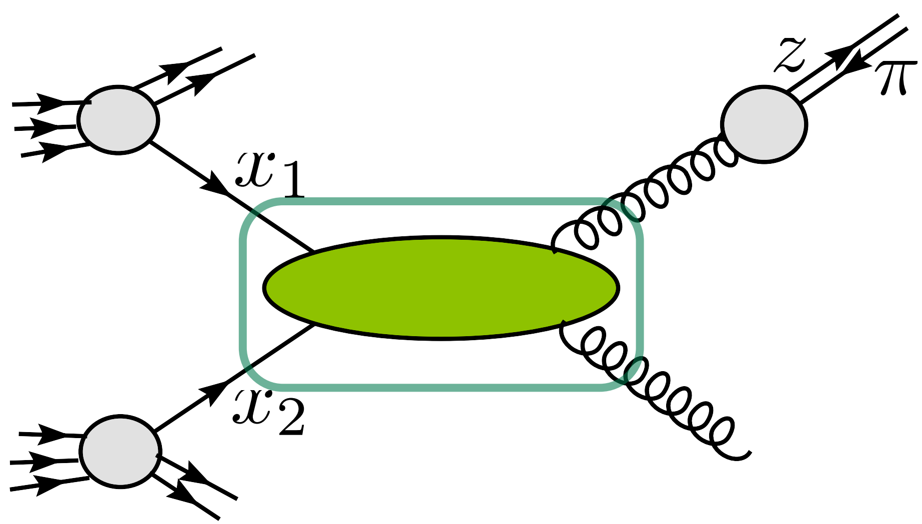
One example

⇛ $q\bar{q}$ contribution to the inclusive high-pt pion production



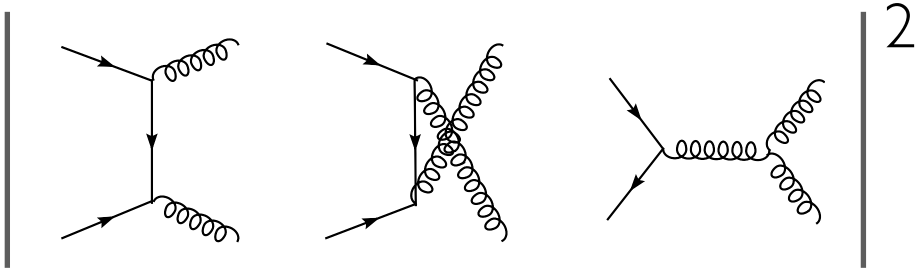
$$\frac{d\sigma}{d\hat{t}} = \frac{32\pi\alpha_s^2}{27\hat{s}}\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{9}{4}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\right]$$

$$\frac{d\sigma^{AB\to h}}{dp_T^2 dy} = \sum_i \int \frac{dx_2}{x_2}\int\frac{dz}{z}\, x_1 q_i^A(x_1,Q^2)\, x_2 \bar{q}_i^B(x_2,Q^2)\, \frac{d\sigma^{q_i\bar{q}_i\to gg}}{d\hat{t}}\, D_{g\to\pi}(z,Q^2)$$



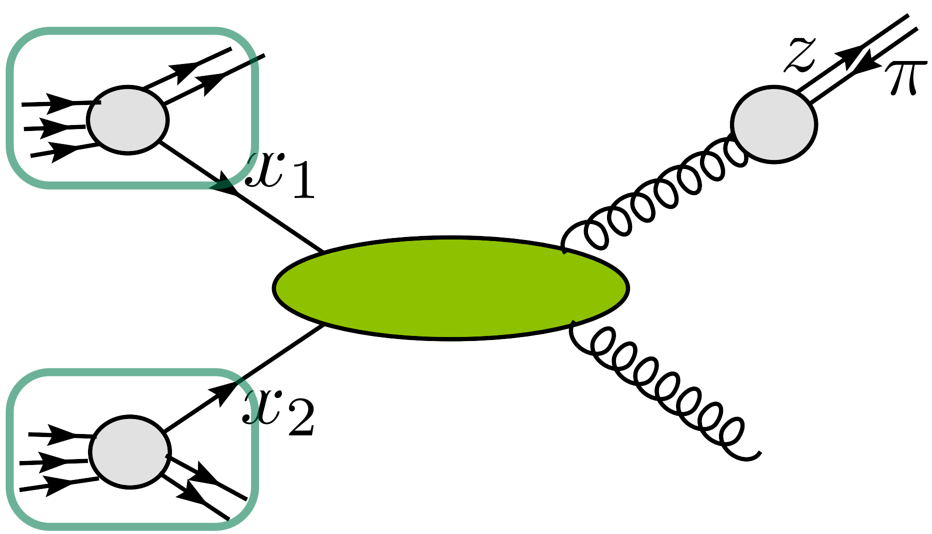
One example

⇛ $q\bar{q}$ contribution to the inclusive high-pt pion production



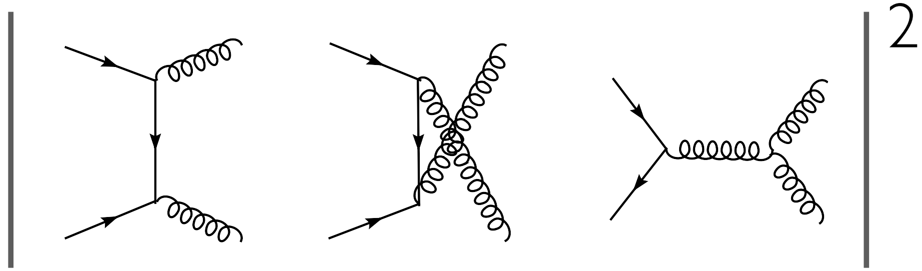
$$\frac{d\sigma}{d\hat{t}} = \frac{32\pi\alpha_s^2}{27\hat{s}}\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{9}{4}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\right]$$

$$\frac{d\sigma^{AB\to h}}{dp_T^2 dy} = \sum_i \int \frac{dx_2}{x_2} \int \frac{dz}{z}\, x_1 q_i^A(x_1,Q^2)\, x_2 \bar{q}_i^B(x_2,Q^2)\, \frac{d\sigma^{q_i\bar{q}_i\to gg}}{d\hat{t}} D_{g\to\pi}(z,Q^2)$$



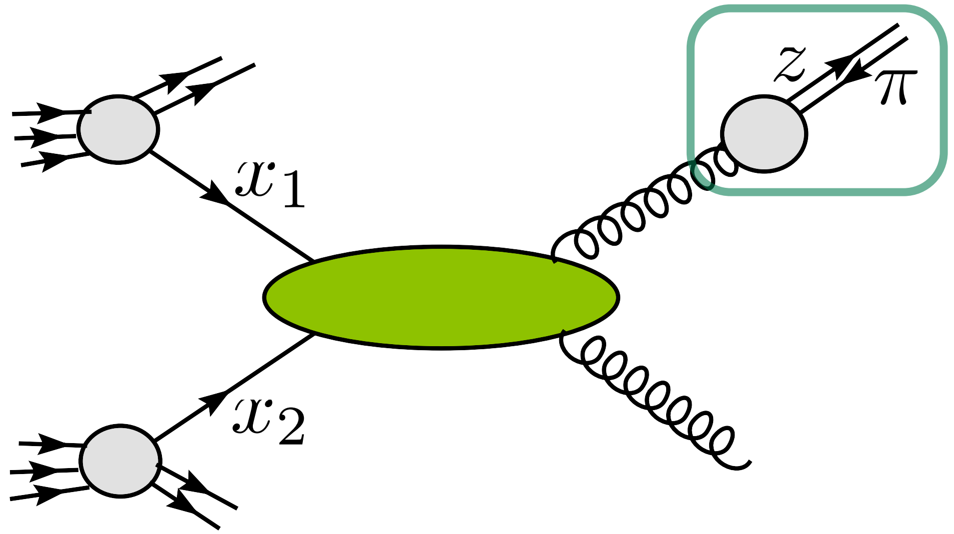
One example

⇛ $q\bar{q}$ contribution to the inclusive high-pt pion production



$$\frac{d\sigma}{d\hat{t}} = \frac{32\pi\alpha_s^2}{27\hat{s}}\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{9}{4}\left(\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)\right]$$

$$\frac{d\sigma^{AB\to h}}{dp_T^2 dy} = \sum_i \int \frac{dx_2}{x_2}\int\frac{dz}{z}\, x_1 q_i^A(x_1,Q^2) x_2 \bar{q}_i^B(x_2,Q^2) \frac{d\sigma^{q_i\bar{q}_i\to gg}}{d\hat{t}} D_{g\to\pi}(z,Q^2)$$



Everything together

- $2 \to 2$ kinematics

$$y = \frac{1}{2} \log \left[\frac{E + p_z}{E - p_z} \right]$$

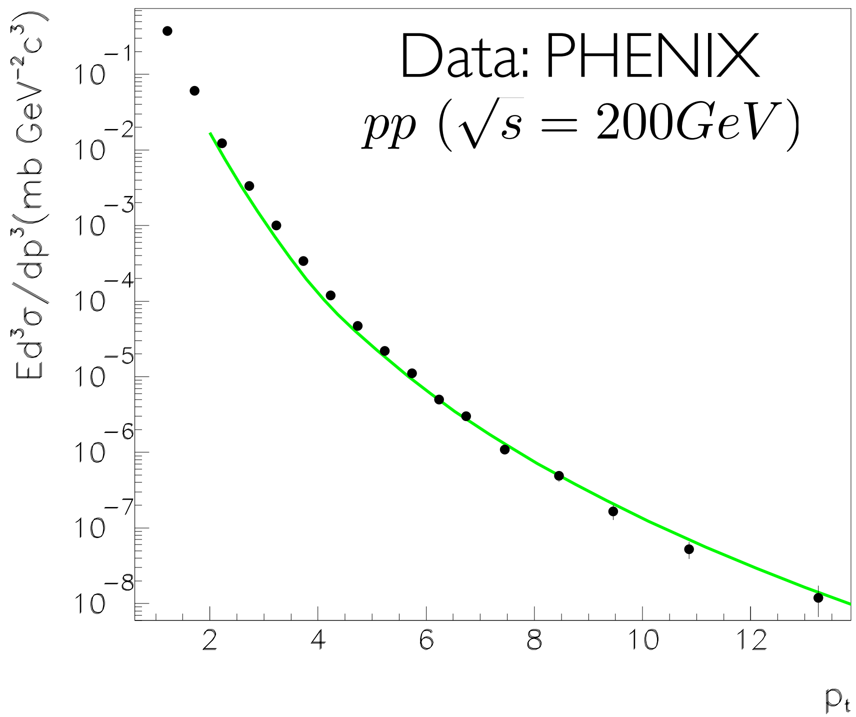
- So that the fraction of momenta

$$x_{1,2} = \frac{q_T}{\sqrt{s}} \left(\mathrm{e}^{\pm y_1} + e^{\pm y_2} \right)$$

- With the initial parton momentum

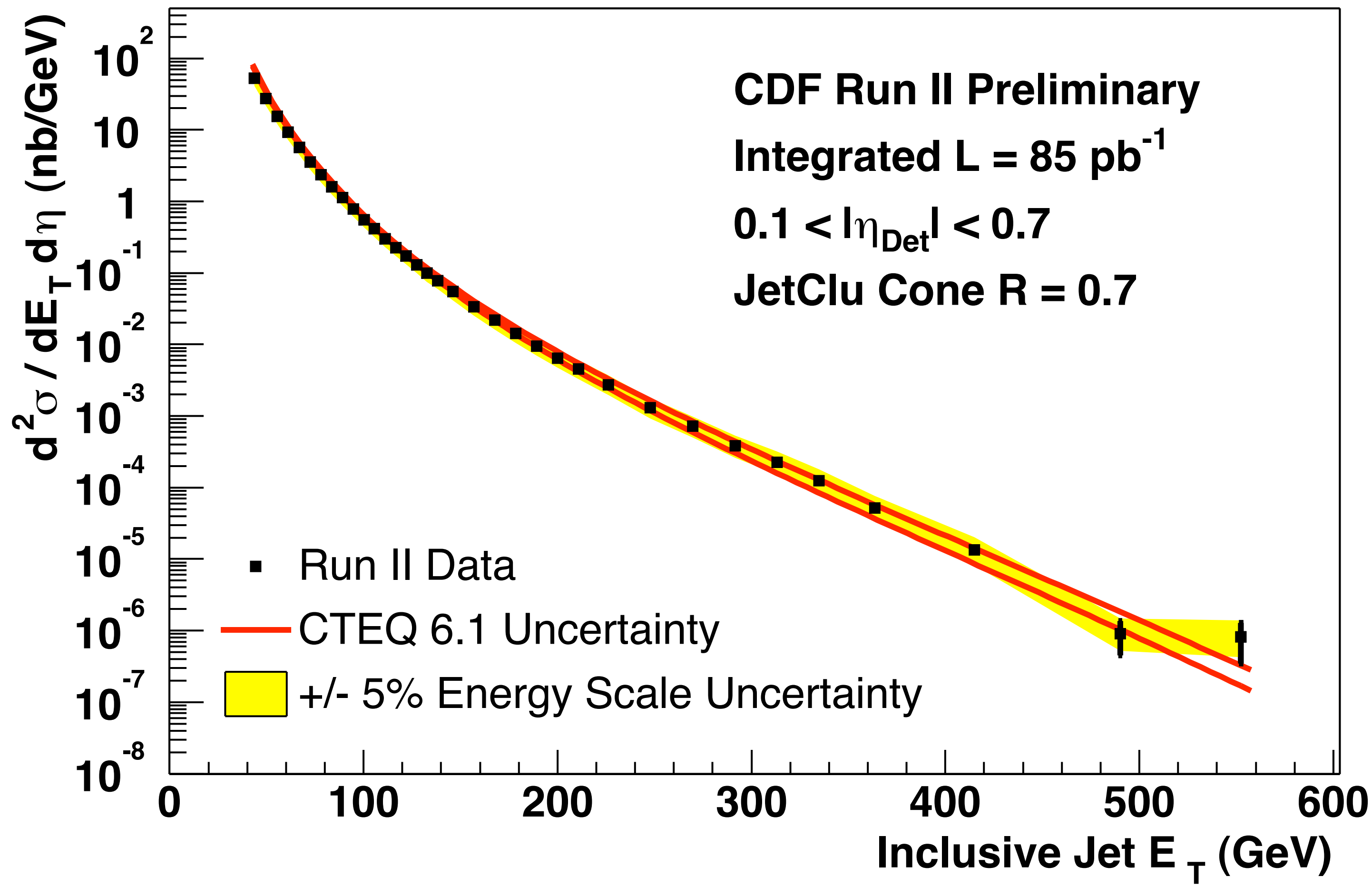
$$q_T = \frac{p_T}{z}$$

[Eskola, Honkanen 2002]



- Two integrals needed:
  - Fraction of momentum in fragmentation $z \to \langle z \rangle \simeq 0.5 \div 0.7$
  - Unobserved particle: x_2

Jets at the Tevatron



⇛ At the LHC abundant jets will be measured also in PbPb

Global fits

Global fits to proton PDFs

- How the PDFs are extracted from data?
  - Non-perturbative quantities. We cannot compute them, just evolution with DGLAP
- Strategy:
  - Fitting functions for PDFs at some initial scale $Q_0^2 \simeq 1\ \mathrm{GeV}^2$

$$xf(x,Q_0^2) = A(1-x)^\beta x^\alpha (1+\epsilon\sqrt{x}+\gamma x)$$

  - $A,\ \alpha,\ \beta,\ \gamma,\ \epsilon$ are free parameters
  - Use the sum rules to fix some parameters
  - Compute $f(x,Q^2)$ using DGLAP at a given order
  - Compute observables (DIS, jets, ...) to fit the parameters by minimizing

$$\chi^2(\{z\}) = \sum_i \left[\frac{D_i - T_i(\{z\})}{\sigma_i}\right]$$

Global fits for nuclear PDFs

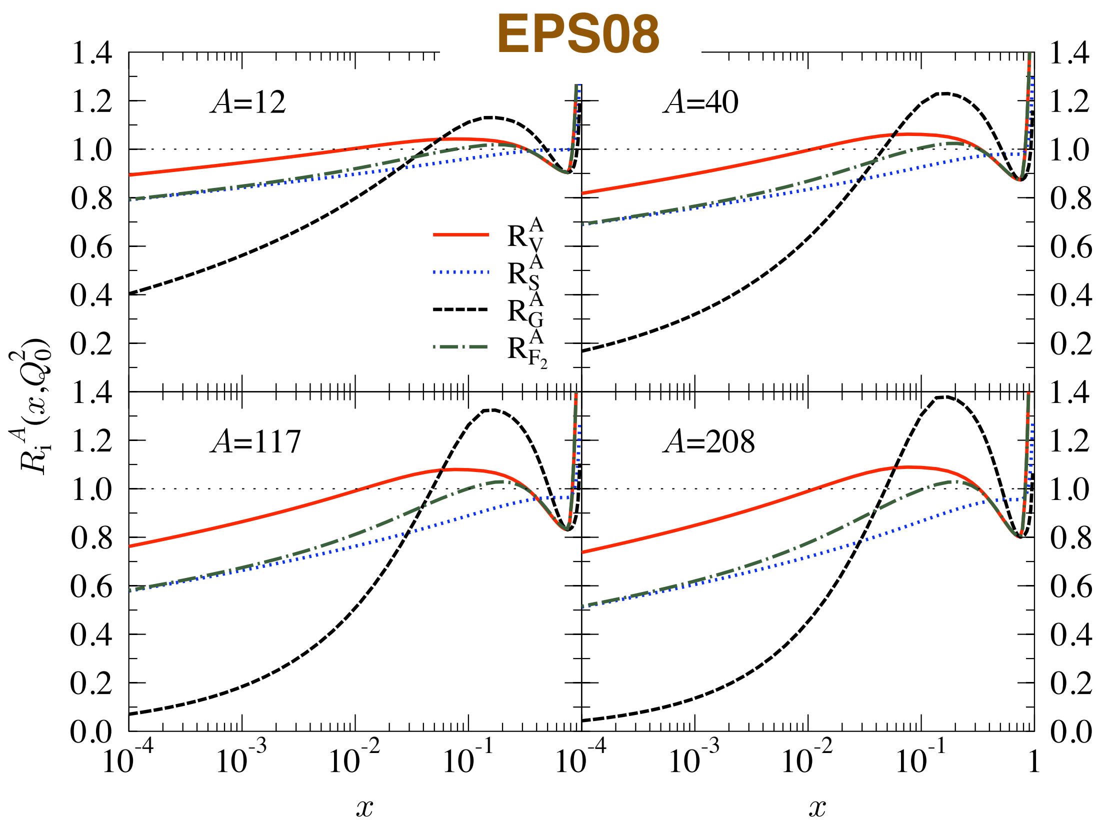
⇒ Use the same approach as for free protons

- Data is limited
- Usual solution: parametrize **ratios** of nuclear over proton PDFs

$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

[Eskola, Paukkunen, Salgado 2008]

Other nPDF sets:
EKS98, HKM, HKN,
de Florian-Sassot



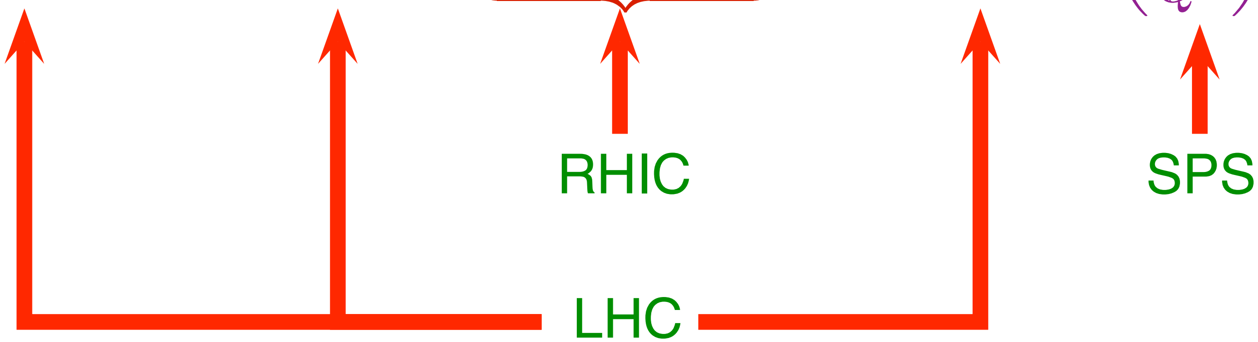
⇒ Fix the essential benchmark for other medium effects

Hard probes to study the medium properties

Hard probes in heavy-ion collisions

- ⇛ SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) $\longrightarrow$ marginal access to HP
- ⇛ RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) $\longrightarrow$ access to HP
- ⇛ LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) $\longrightarrow$ HP and QCD evolution

$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \underbrace{\sigma(x_1, x_2, Q^2)} \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$



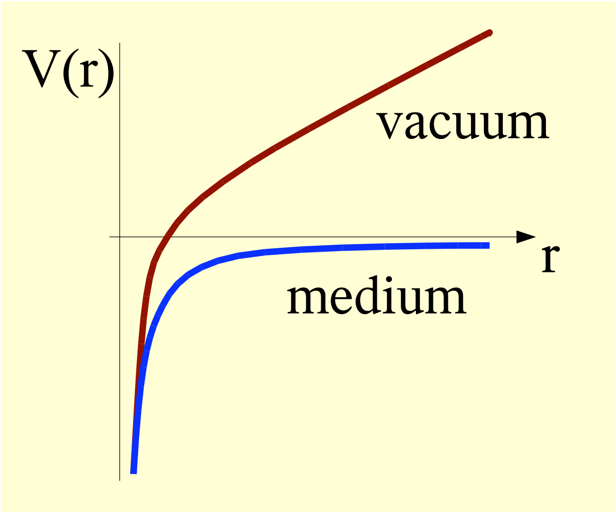
- ⇛ Partonic process happens in a very short time $t \sim 1/Q$
- ⇛ The extension of the medium modifies the long-distance terms
  - ➘ $f_A(x, Q^2); D(z, Q^2)$

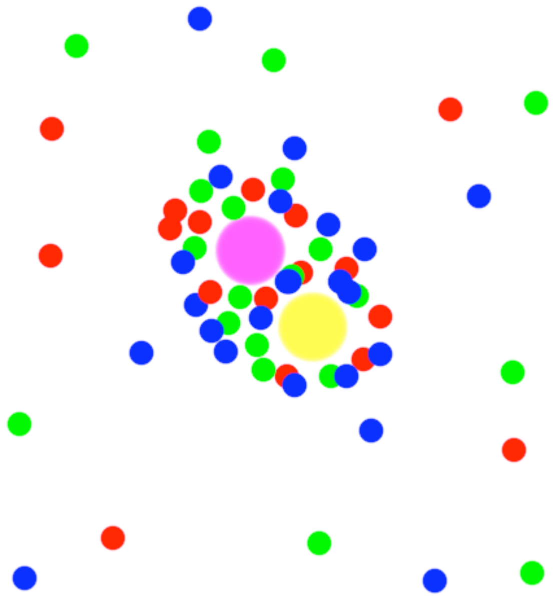
A conceptually simple example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

- The potential is screened by the medium
  - The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle \to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]





A conceptually simple example, J/Ψ suppression

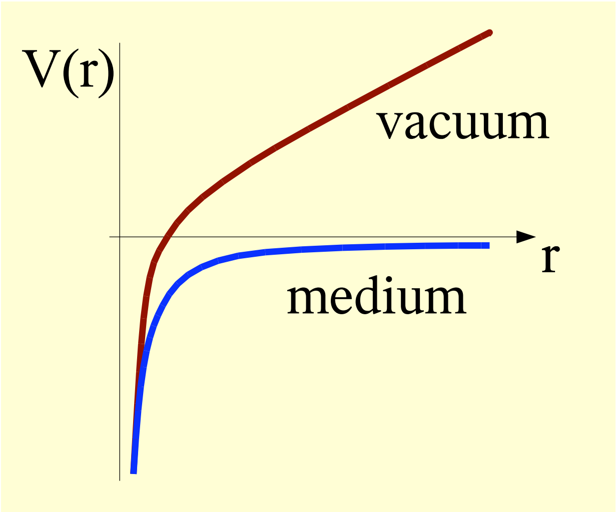
⇛ A J/Ψ is a $c\bar{c}$ bound state.

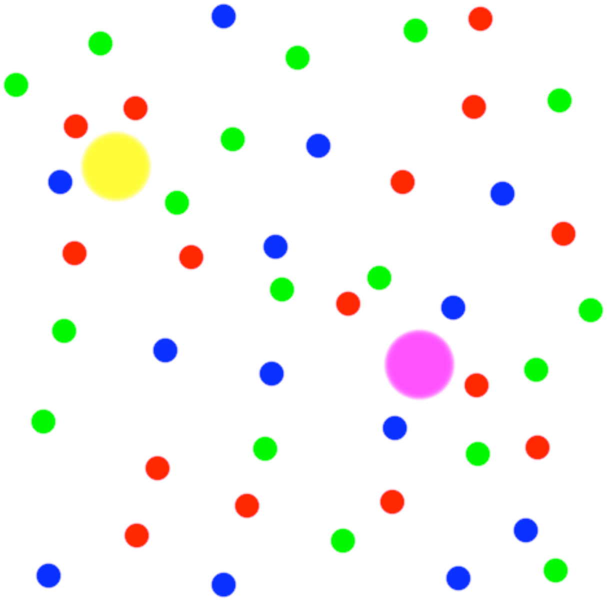
$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

⇛ The potential is screened by the medium

- The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle\to 0$

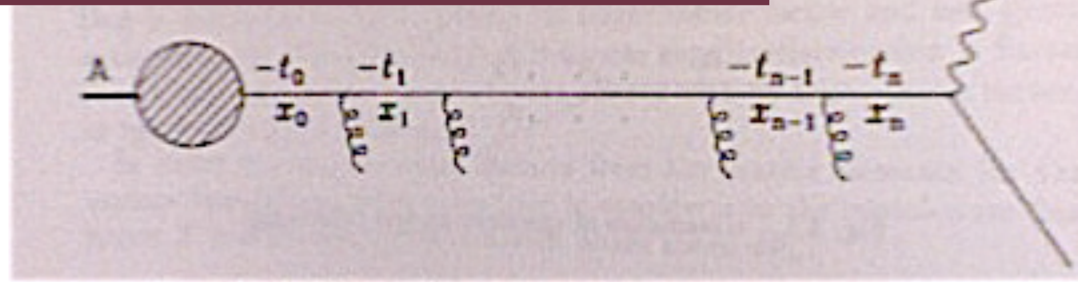
⇛ The J/Ψ production is suppressed [Matsui, Satz 1986]





DGLAP evolution in vacuum

$t = Q^2$ plays the role of time



Ordered gluon splitting given by DGLAP

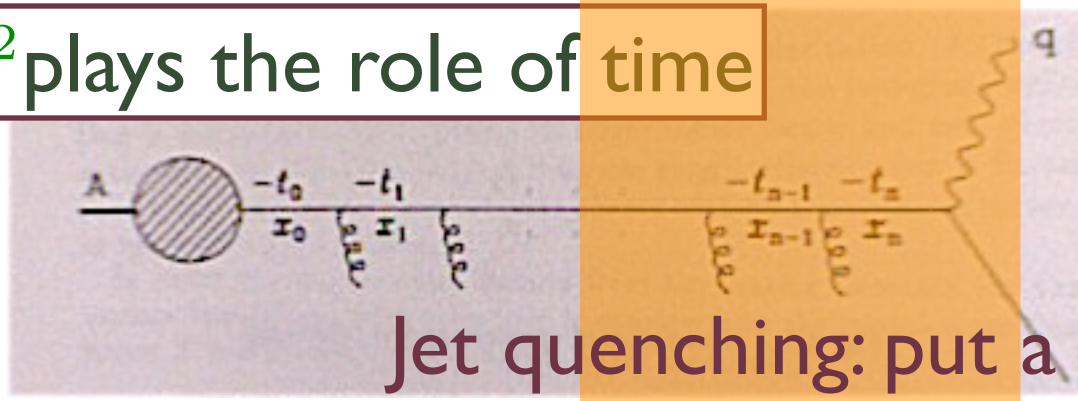
$$\frac{\partial f(x,t)}{\partial \log t} = \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z,t)$$

splitting function

f(x,t) are the PDFs or the FF

DGLAP evolution in vacuum

$t = Q^2$ plays the role of time



Jet quenching: put a medium here

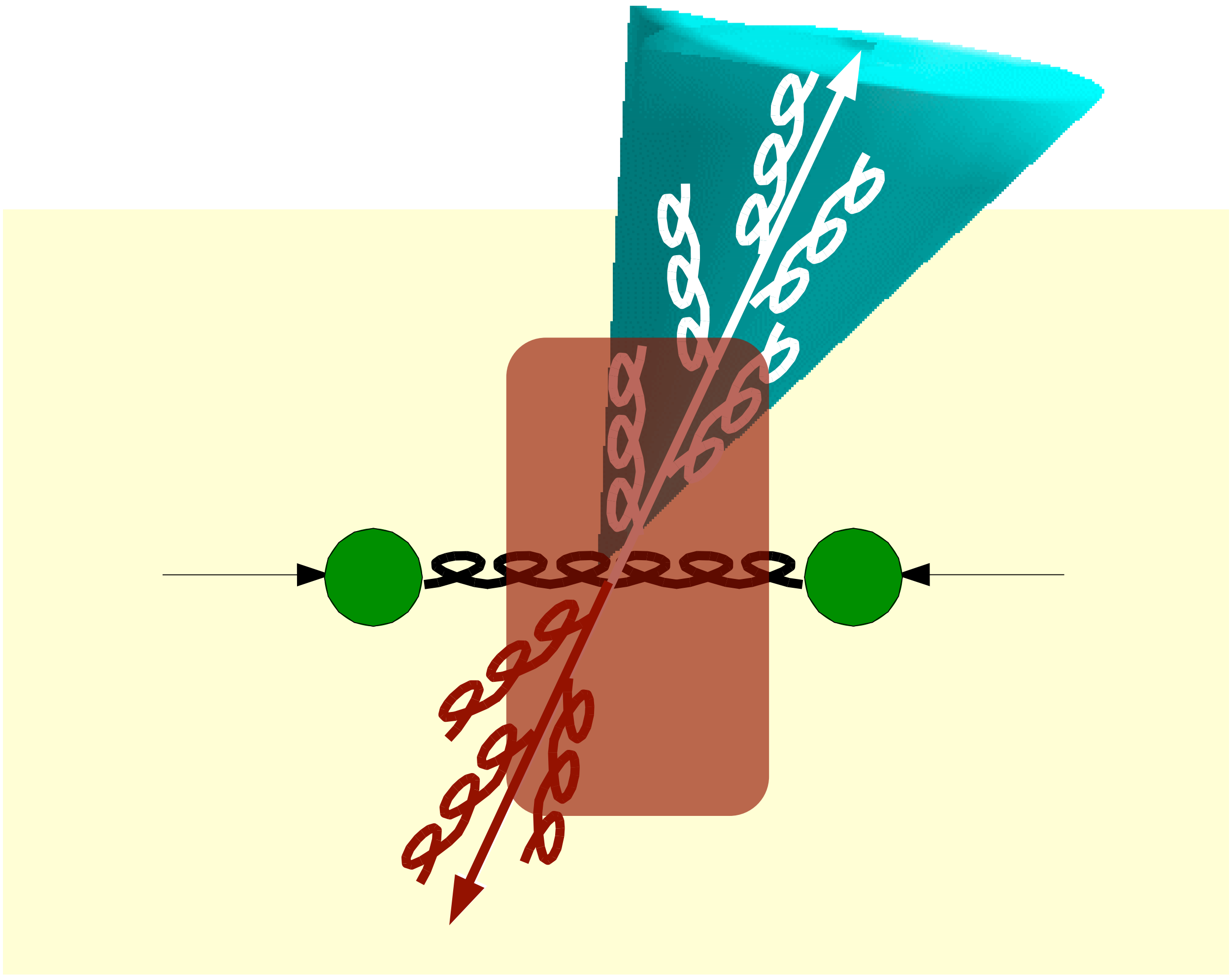
Ordered gluon splitting given by DGLAP

$$\frac{\partial f(x,t)}{\partial \log t} = \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z,t)$$

splitting function

f(x,t) are the PDFs or the FF

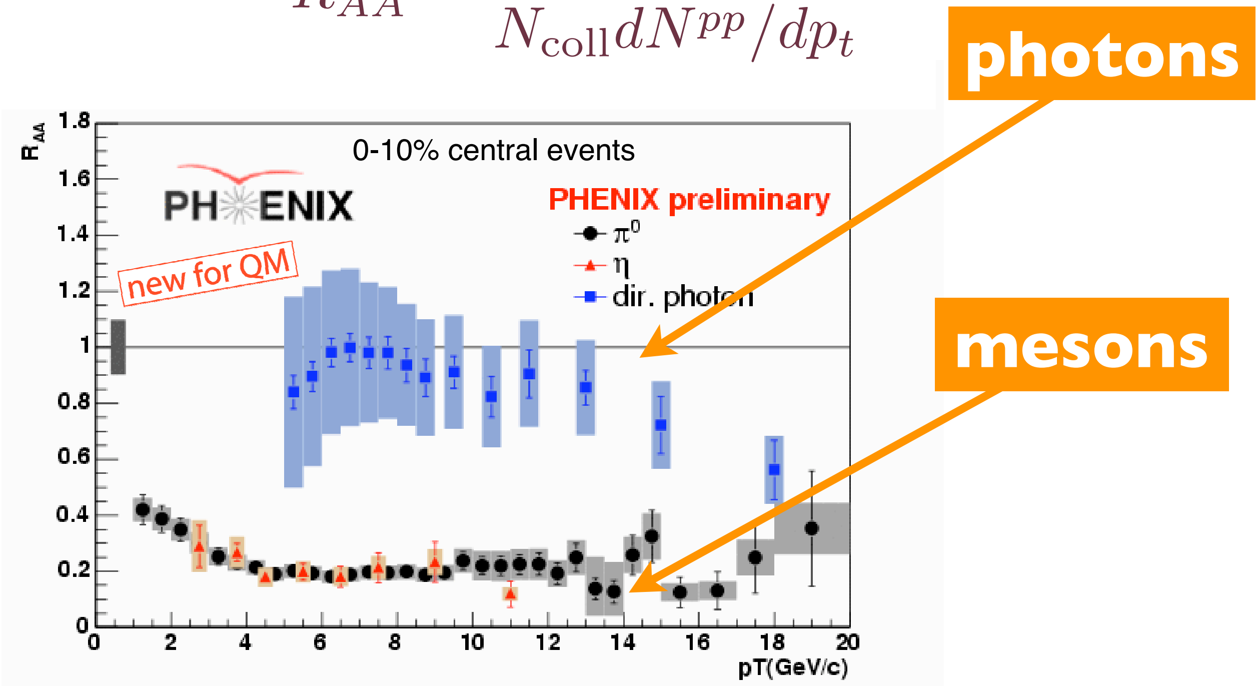
Jet quenching



What happens when this evolution takes place in the medium created in the collision??

Experimental observations

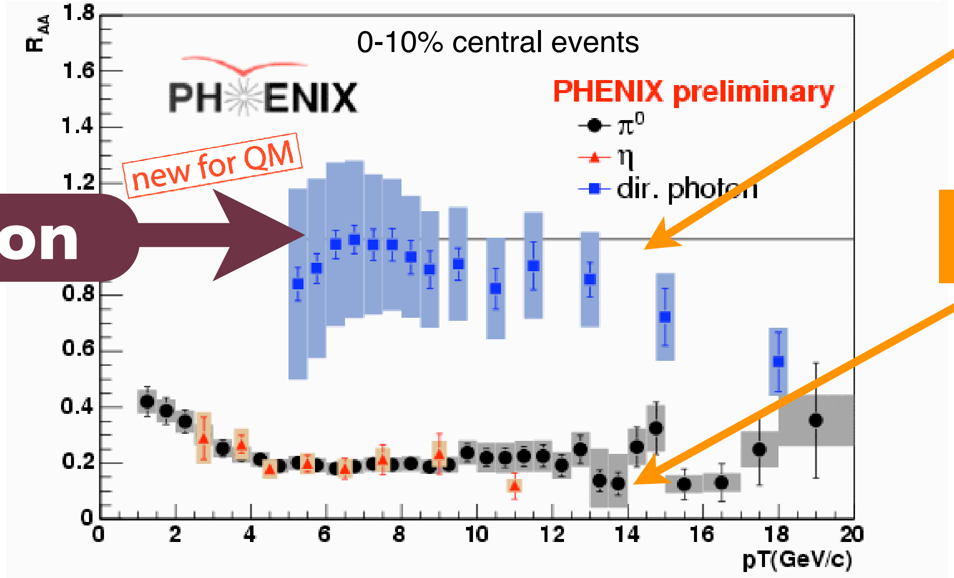
$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\rm coll} dN^{pp}/dp_t}$$



Photons don't interact with the medium quarks and gluons do

Experimental observations

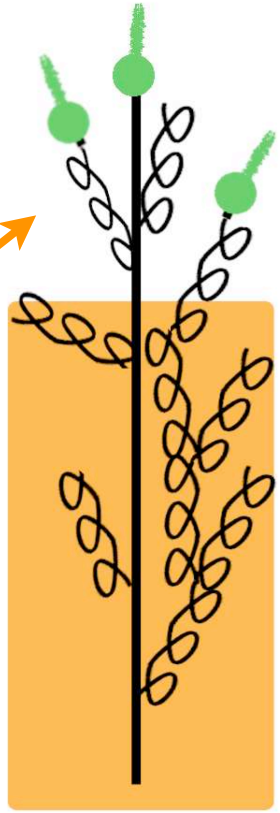
$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\text{coll}} dN^{pp}/dp_t}$$



Calibration

photons

mesons



Photons don't interact with the medium quarks and gluons do

⇒ Well calibrated and abundant probes of the medium

Hard Probes shopping list

- Probes which interact strongly with the produced matter
  - Jets and high-pT hadron production
  - Heavy quark production
  - Quarkonia production
  - ...
- Probes which do not interact strongly with the matter
  - Bosons: photons, W, Z
  - Drell-Yan
  - ...
- Combination
  - photon+jet, Z+jet ...

Hard Probes shopping list

Probe the medium

- Probes which interact strongly with the produced matter
  - Jets and high-pT hadron production
  - Heavy quark production
  - Quarkonia production
  - ...

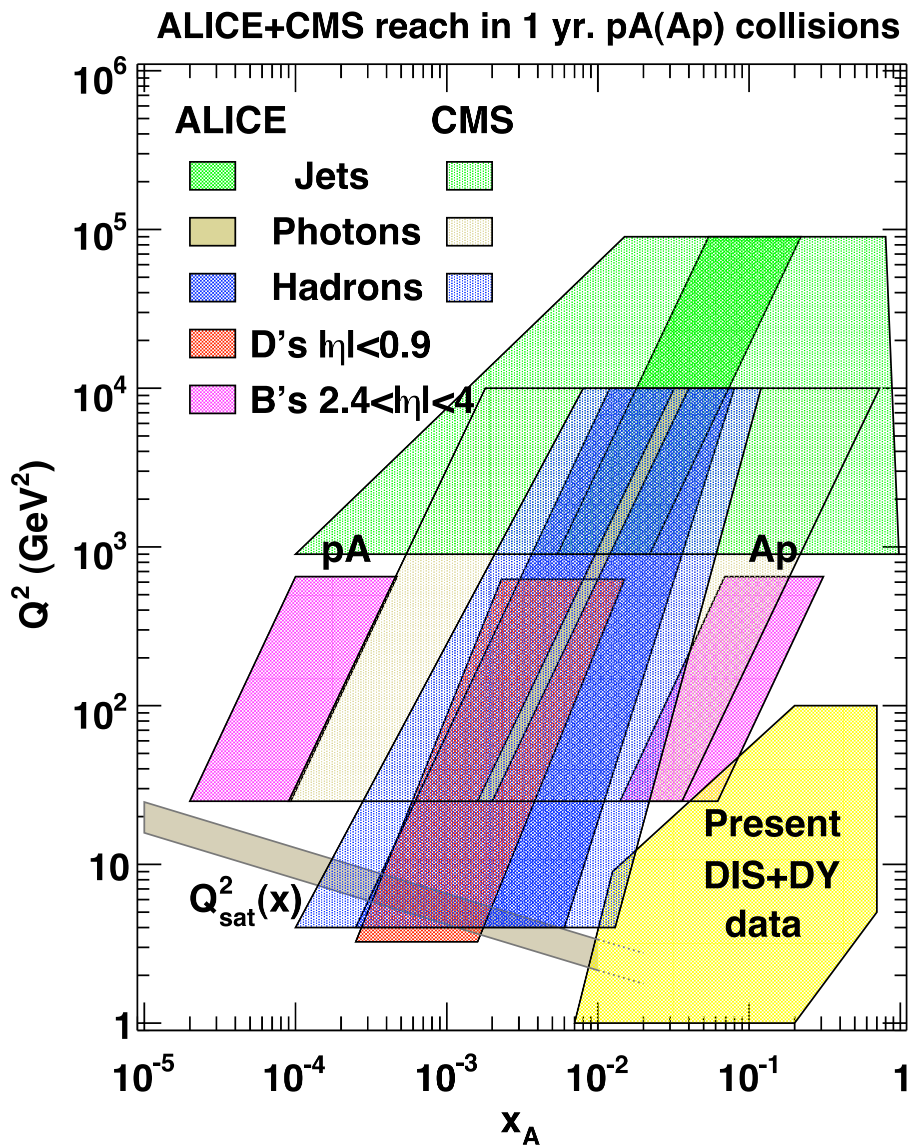
Calibration

- Probes which do not interact strongly with the matter
  - Bosons: photons, W, Z
  - Drell-Yan
  - ...

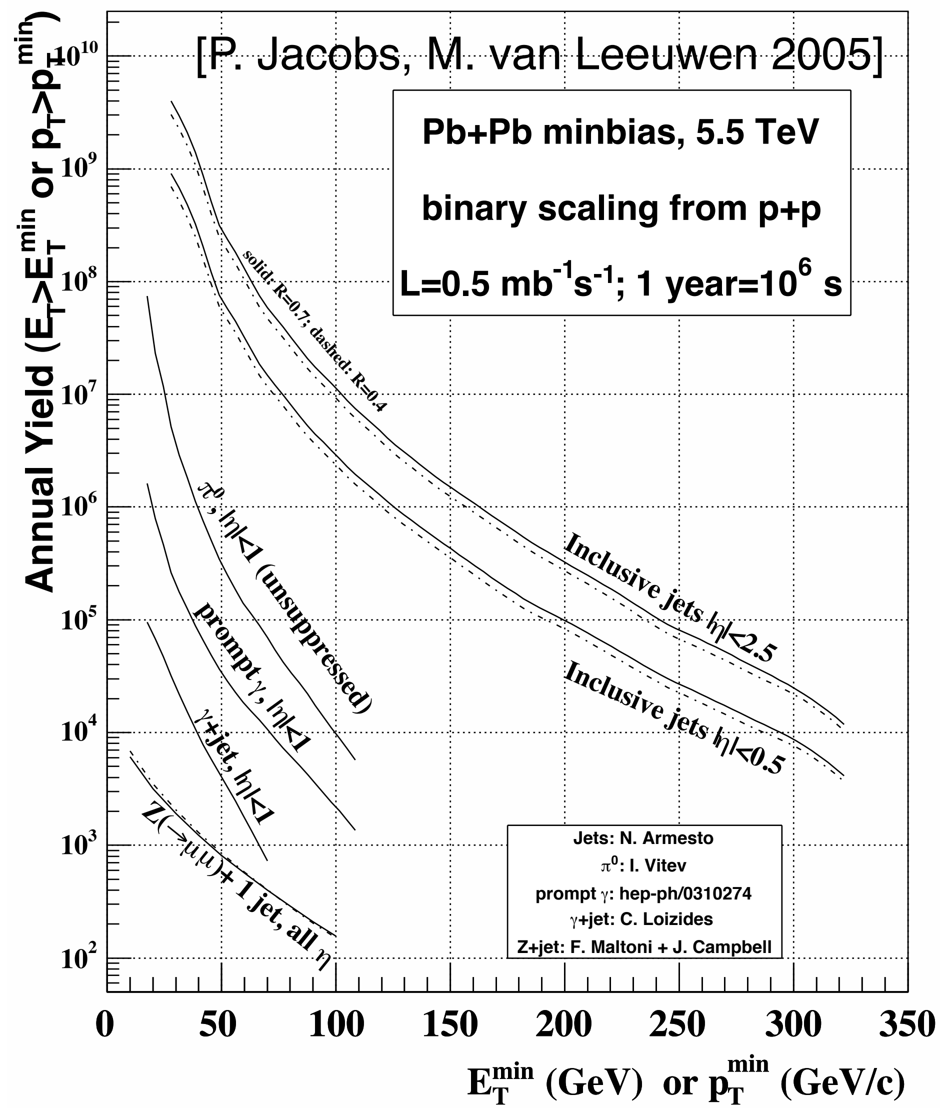
Combination

- Combination
  - photon+jet, Z+jet ...

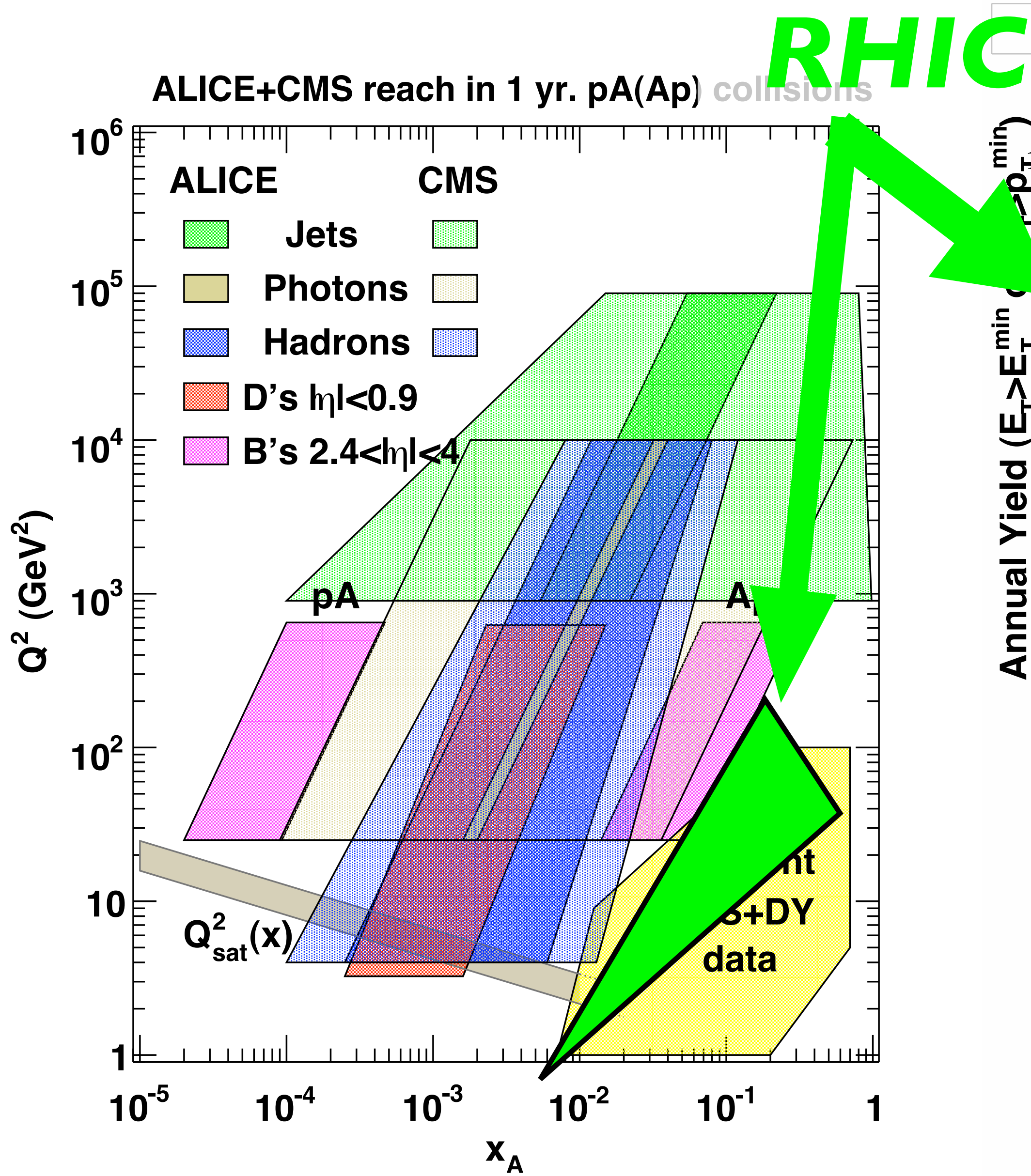
New regimes at the LHC

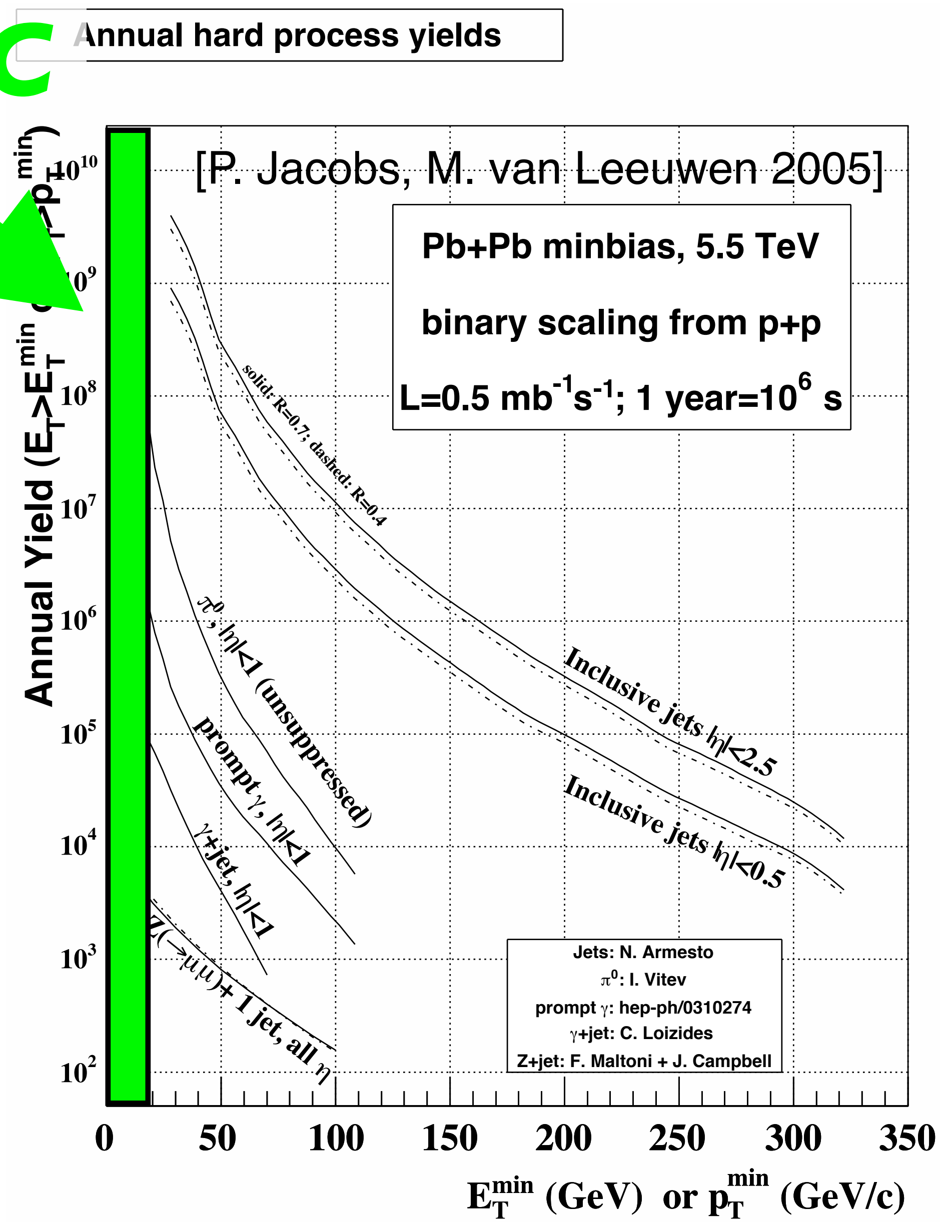


Annual hard process yields

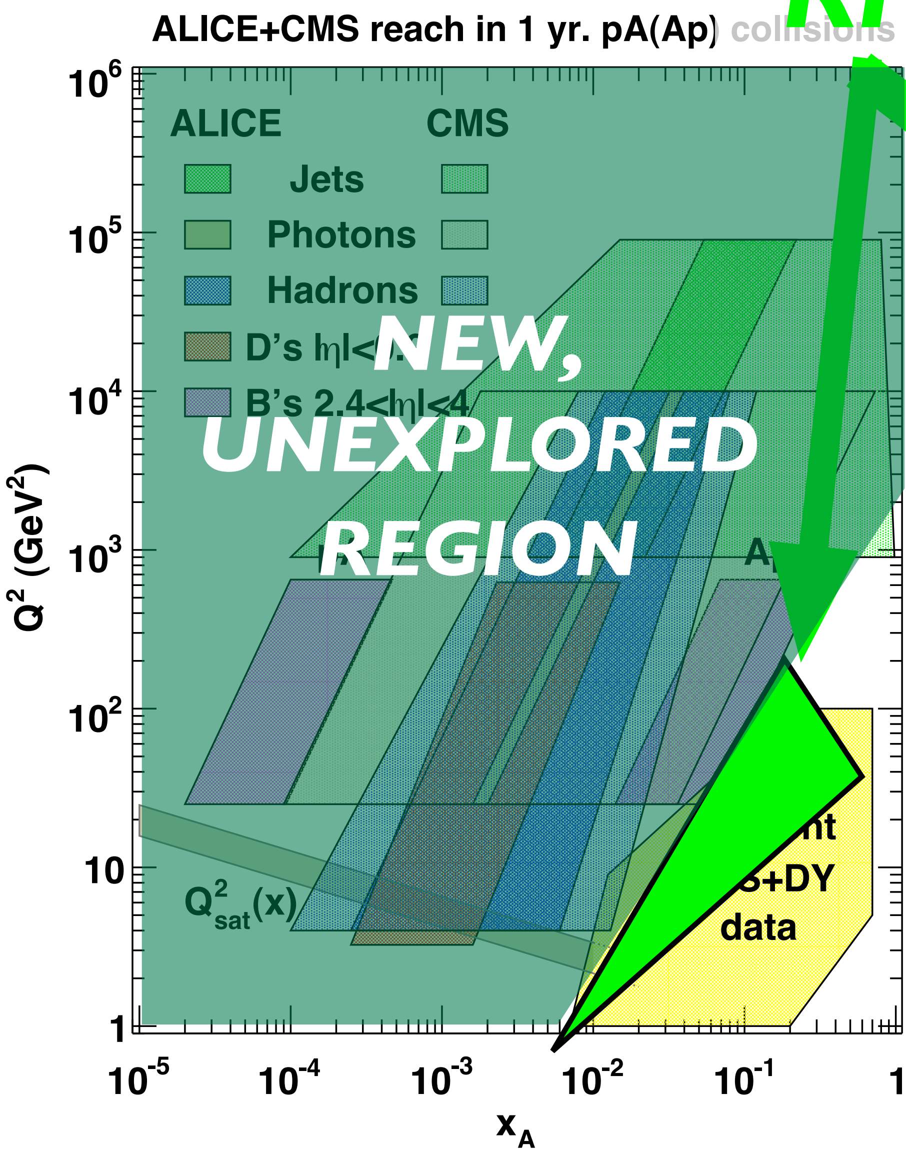


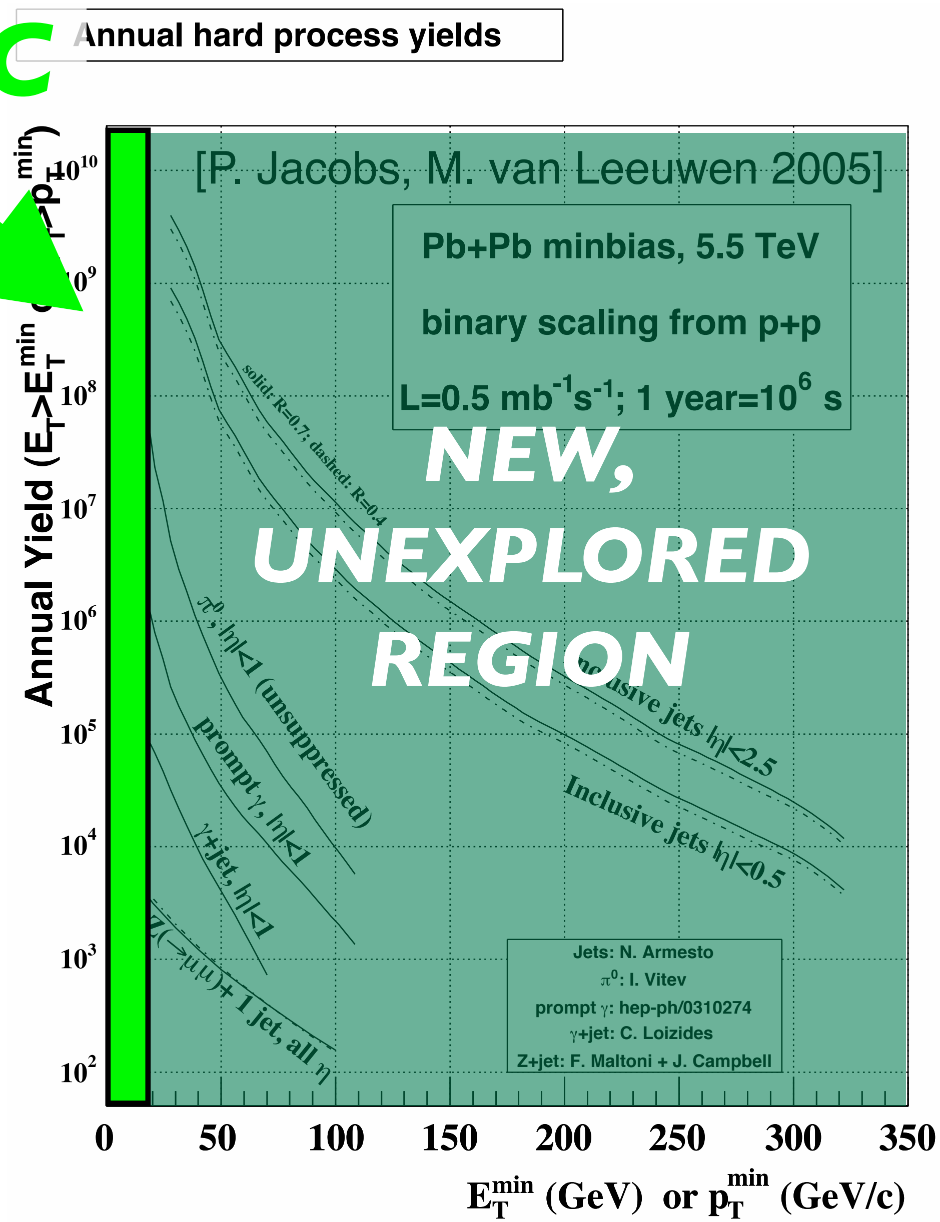
New regimes at the LHC





New regimes at the LHC





Summary

- QCD corrections to naive parton model given by parton splitting
  - Evolution of parton distribution functions PDF
  - Jet structures
- Hadronic cross sections present a factorization between long and short distance contributions
  - PDFs and FF are universal
- Hard processes are excellent probes of the medium formed in heavy ion collisions
  - Computable in pQCD
  - Framework to compute medium-effects (jet quenching)
  - New regimes at the LHC