The Intrinsic Charm of the Proton

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Physics 290E Seminar

April 19, 2016

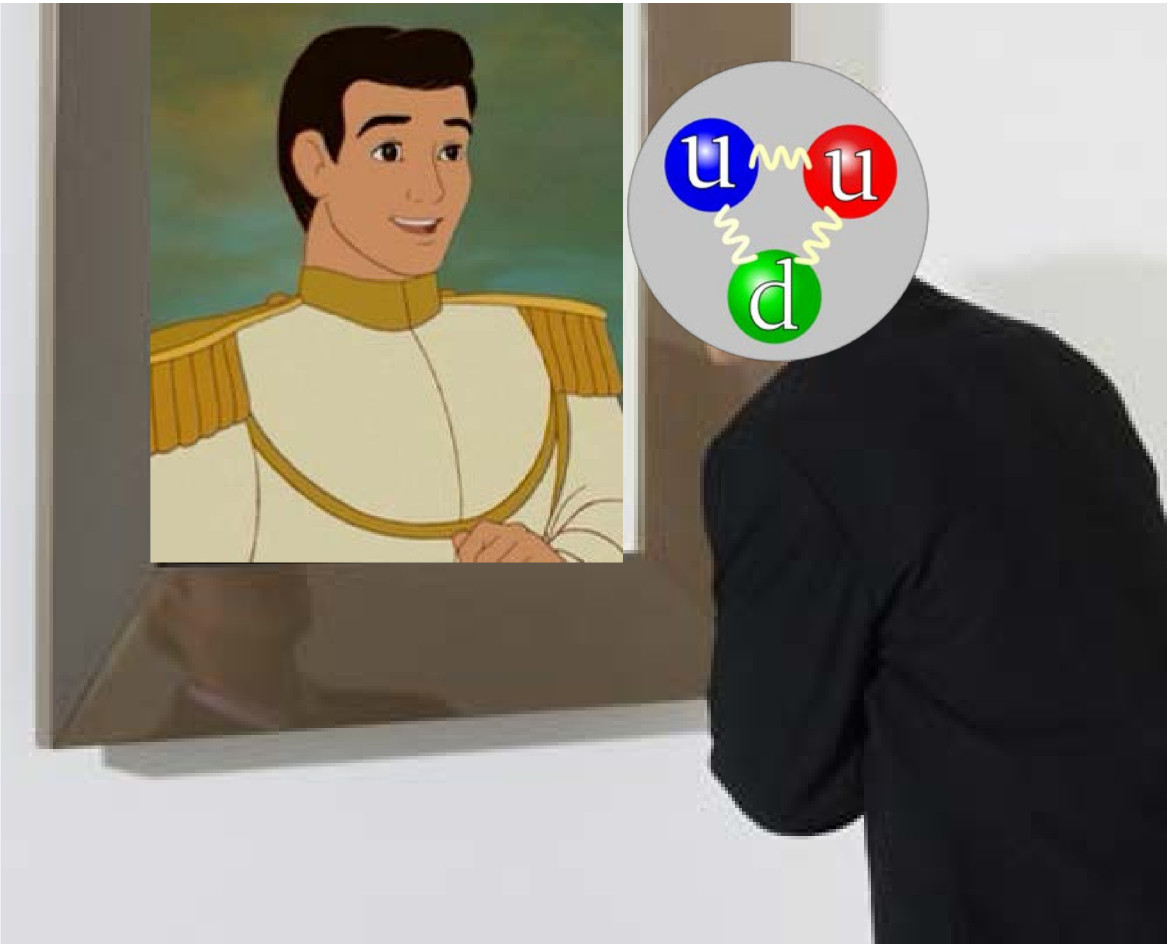
What is intrinsic charm?

- First efforts at recognizing intrinsic charm were made by Brodsky, Hoyer, Peterson, and Sakai in 1980 [1]
- They noticed some oddities in recent experiments:

  CERN Intersecting Storage Rings

  CERN NA3 Experiment

  QCD Calculations



Above:
Proton looks for intrinsic charm in the mirror

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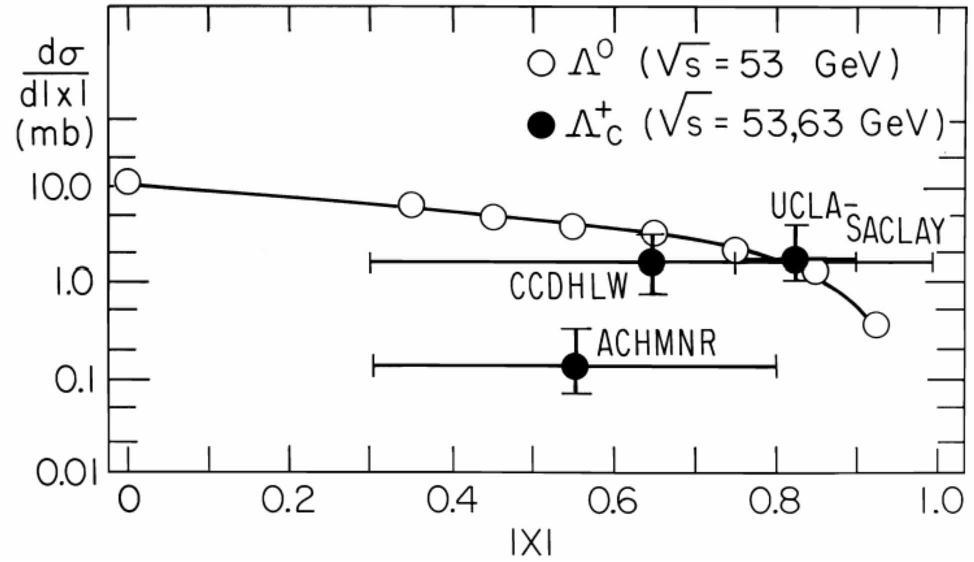
  - CERN ISR measured production of Λ_c^+ (ucd) and D^+ $(c\bar{d})$ at $\sqrt{s} = 53\ GeV$ and 63 GeV, and the results were consistent with a diffractive production mechanism (at right) [2]
  - Diffractive production (DP): a particle beam is decomposed into virtual dissociations of the particle, each one interacting separately (i.e partial wave expansion from a quantum mechanical perspective)
  - Characteristics of DP include: narrow distribution in transverse momentum, same quantum numbers between final and initial particle, and large rapidity gap in the final state (a region of rapidity where particle production is suppressed)
  - But this is unusual; the quarks for Λ_c^+ and especially D^+ are not found in the valence quarks of the proton.

  CERN NA3 Experiment

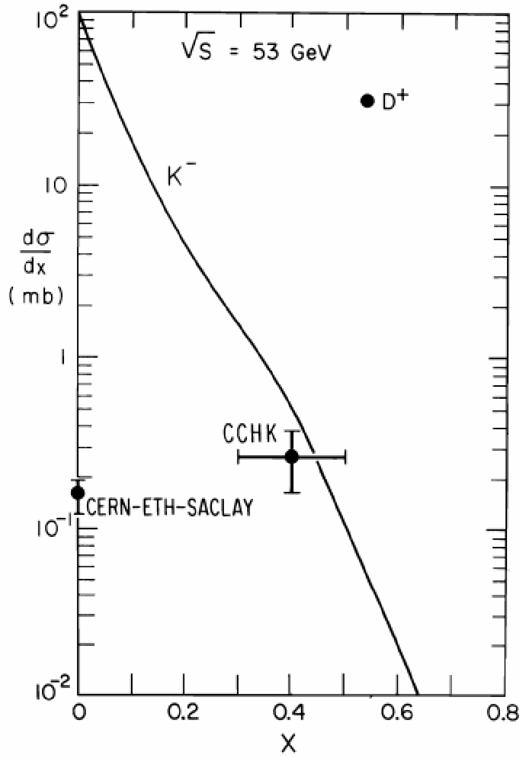
  QCD Calculations



Above and right:

Production cross-sections of Λ_c^+ and D^+ in several experiments at CERN ISR [2]

Note: Define $x = x_F = \frac{p_A^3}{p_{A,max}^3}$ for $p + p \rightarrow A + X$, where p_A^3 is the longitudinal momentum of particle A in pp frame, and $p_{A,max}^3$ is the maximum possible momentum of A given the masses and $\sqrt{s}$ of the collision



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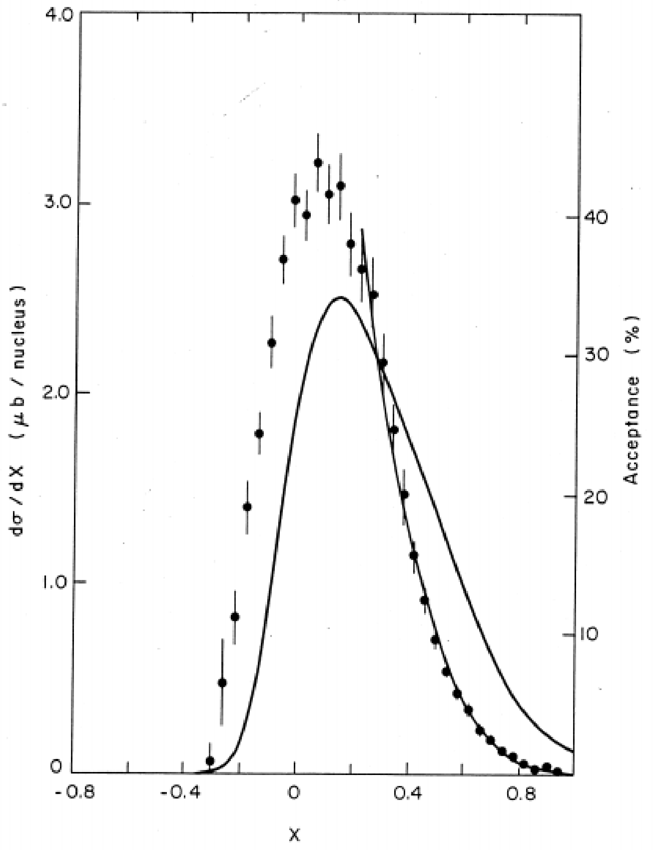
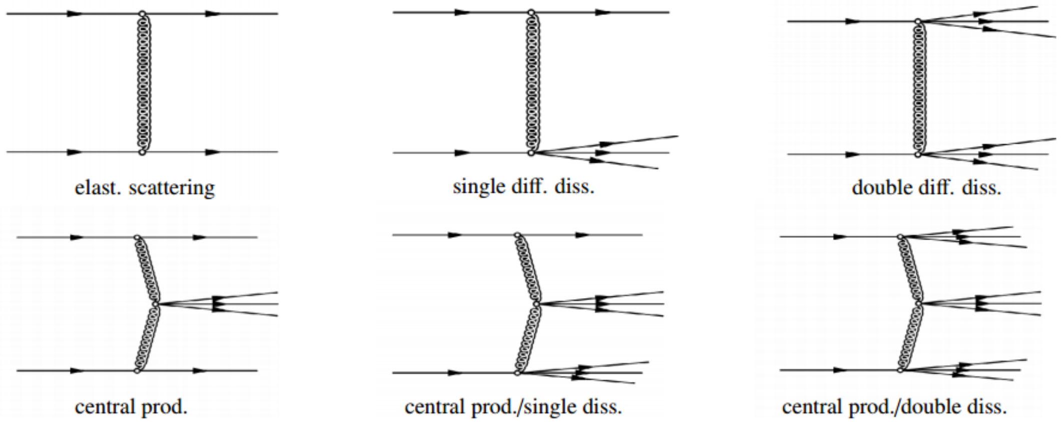
- Production spectrum of J/ψ is consistent with a central production mechanism; see right [3]
- Central production (CP): hadrons produced in quark-antiquark pairs from gluon(s)
- Characteristics: The distribution peaks at low x_F and falls off rapidly at high x_F
- Also shown at right: Topologies of central production and diffractive production of hadrons [4]

QCD Calculations

At right:
Acceptance (solid) and differential cross-section (dots) for J/ψ production by pion beam on proton target
At bottom:
Topologies of production methods





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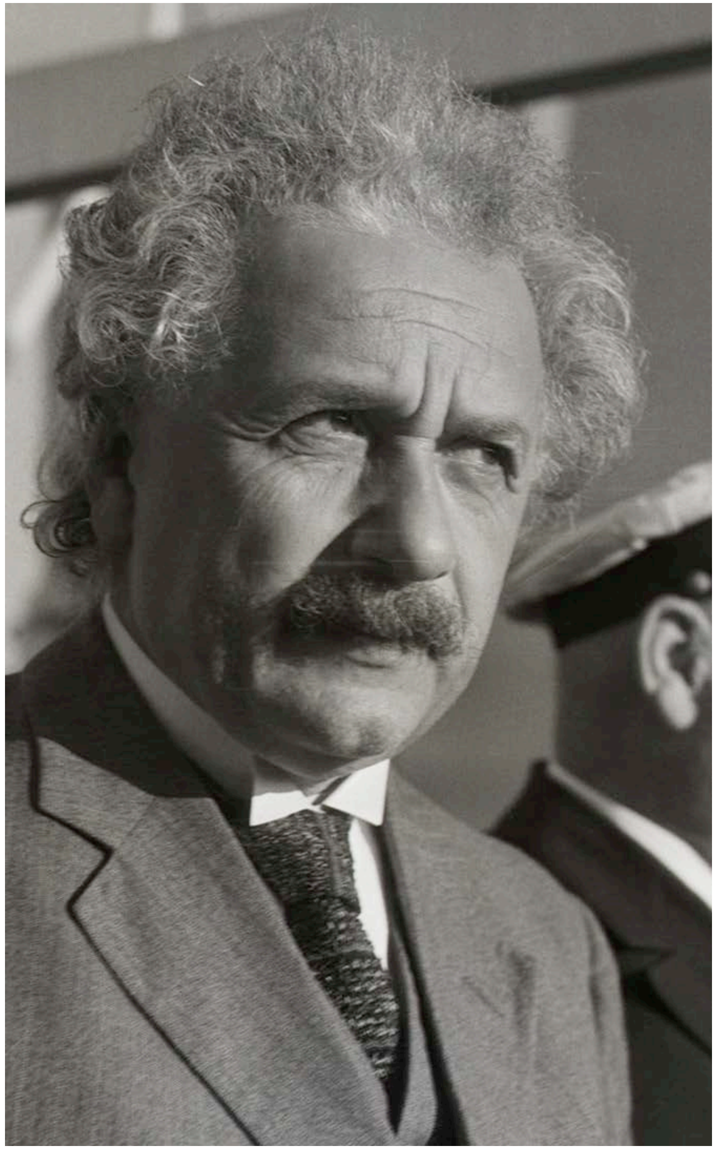
  QCD Calculations

  - Calculations had been done using perturbative QCD to find the expected hadronic production of heavy quark flavors—these give charm cross-sections of $10 - 50\ \mu b$, in comparison to measured $100 - 500\ \mu b$.
  - These calculations can be enhanced via bound-state effects, but always predict suppression at high x_F, i.e. central production.
  - Soft (low-energy) mechanisms give larger x_F spread, but in the context of nonperturbative fragmentation models, the quark-antiquark creation probability is proportional to $e^{-\pi\alpha m_Q^2}$, so the $c\bar{c}$ production is suppressed by 10^{10} with respect to $u\bar{u}$.
  - These mechanisms cannot predict why D^+ is produced so abundantly in the forward direction.



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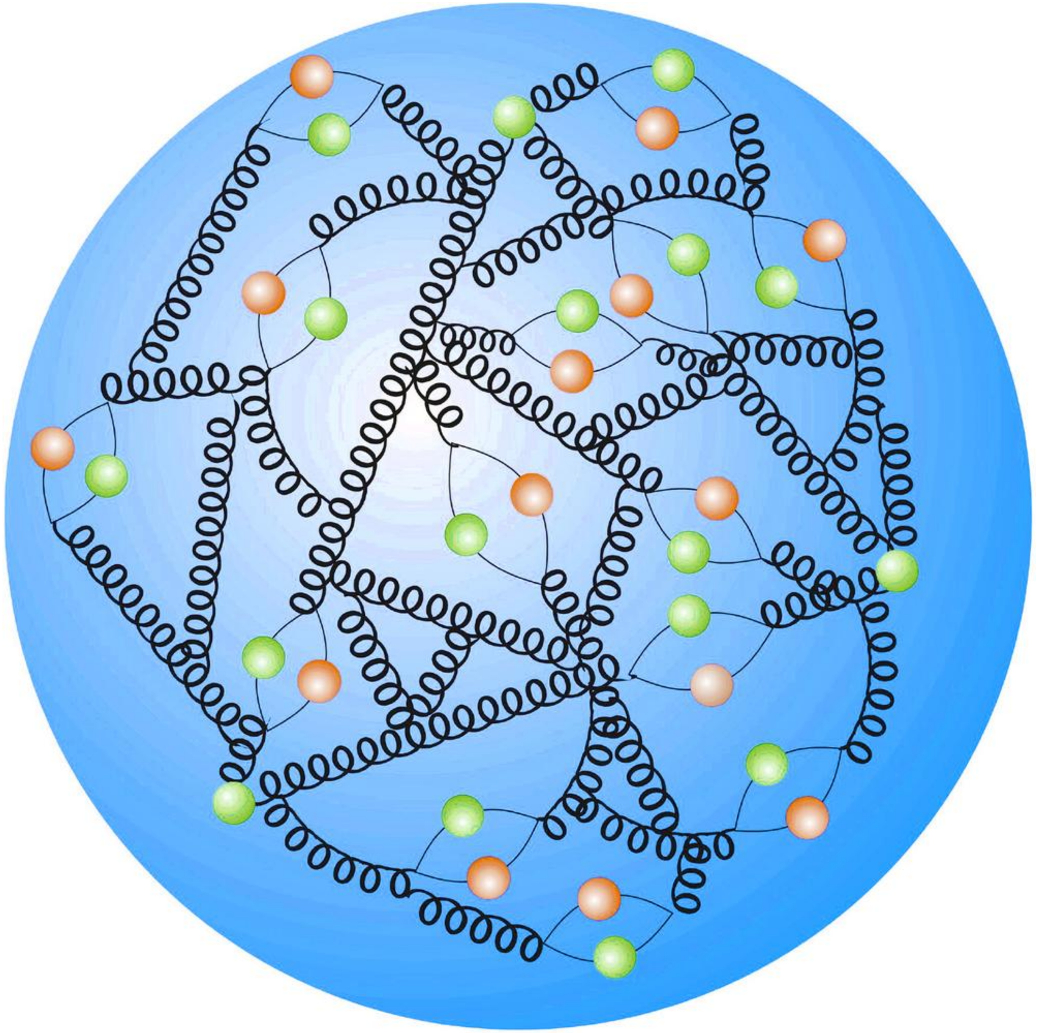
  QCD Calculations
- Proposed solution by BHPS: The proton has *intrinsic charm*, i.e. a long-lived charm component. This state has lifetime much longer than the interaction time of the probe.
- Quick aside on physics: In QM, we can take a generic wavefunction and decompose it into components of fixed particle number; called a *Fock space decomposition*.
- BHPS proposal is that the proton wavefunction contains a **non-negligible $uud c\bar{c}$ Fock component.** Further studies have considered variations on this, like a $\bar{D}^0(u\bar{c})\ \bar{\Lambda}_c^+(udc)$ two-body state.
- This is *independent* of the parton distributions of the proton, which certainly contain charm and anticharm components.



Characteristics of intrinsic charm

- Using standard perturbation theory, it is easy to find the momentum distribution of the quarks in the $uudc\bar{c}$ intrinsic component:

$$P(x_1 \ldots x_5) = N_5 \delta\left(1 - \sum_{j=1}^{5} x_j\right)\left(m_p^2 - \sum_{j=1}^{5} \frac{m_j^2}{x_j}\right)^{-2}$$

- Integrate over $x_1 \ldots x_4$ to get the intrinsic charm distribution:

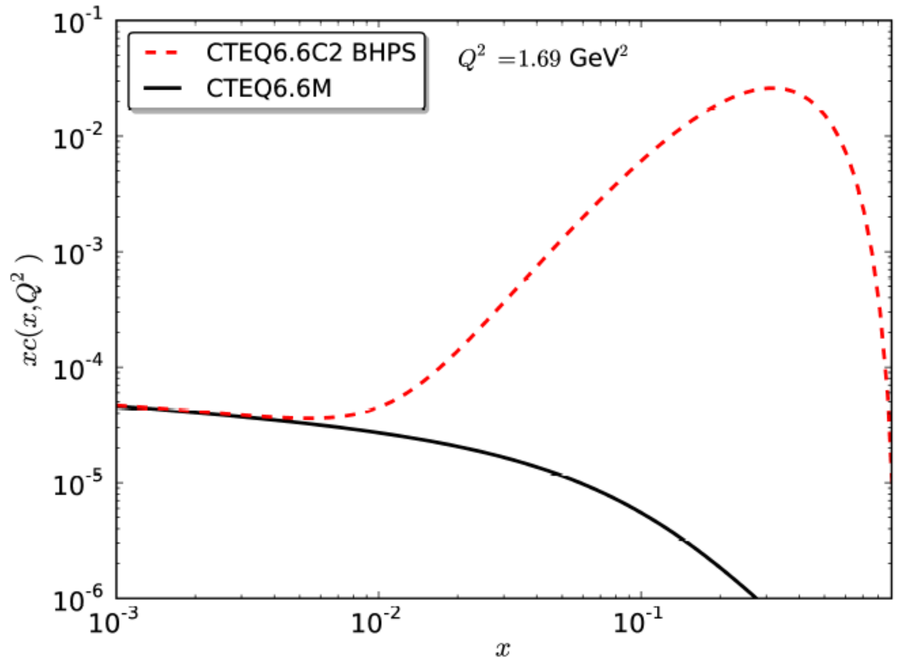
$$c_{int}(x, \mu_0^2) = c_0 w x^2 [(1-x)(1+10x+x^2) + 6x(1+x)\ln(x)]$$

  where μ_0 is the starting energy scale, c_0 is a normalization constant, and w is the probability to find the state $|\, uudc\bar{c} >$ in the proton (roughly $w = |\psi|^2$)

- The total charm density in a proton is the sum of extrinsic and intrinsic components:

$$xc(x, \mu_0^2) = xc_{ext}(x, \mu_0^2) + xc_{int}(x, \mu_0^2)$$

- Then, the total density at any energy scale $xc(x, \mu^2)$ is calculated using the standard DGLAP parton evolution equations from QCD (not sure if these have been discussed yet in 290E)



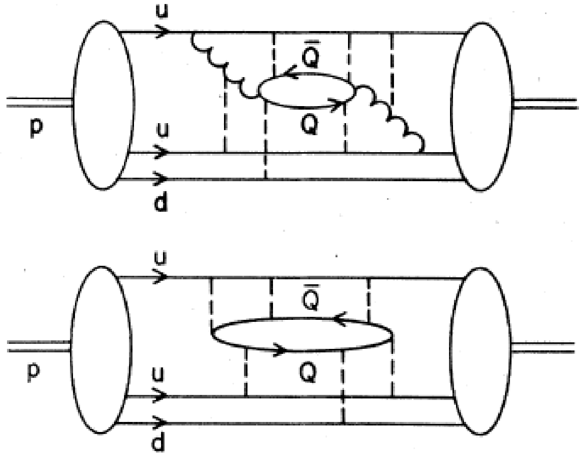
Above:
Density functions from the CTEQ database. The solid black line represents only the extrinsic (parton) distribution. The red dashed line represents the total distribution function, including the intrinsic component. Calculated using $Q^2 = m_c^2$ and $w = 0.035$. [5]

Characteristics of intrinsic charm

- The existence of intrinsic heavy quarks was hypothesized by BHPS to be from gluon-exchange or vacuum polarization graphs (see below).
- Under this hypothesis, all colored particles are confined in an effective QCD potential. Using the MIT "bag model", the probability of finding a $uudc\bar{c}$ state is about 1-2%.
- To be consistent with HERA DIS results, we can set a bound $w_{IC} < 3.5\%$. (This bound is controversial + debated – don't take it too seriously.)
- Vacuum polarization mechanism leads to the scaling

  $n_Q \sim m_Q^{-2} \rightarrow \frac{w_{IB}}{w_{IC}} \approx 0.1.$

- Much more experimentally attractive to look for intrinsic charm, rather than intrinsic bottom.



At left:

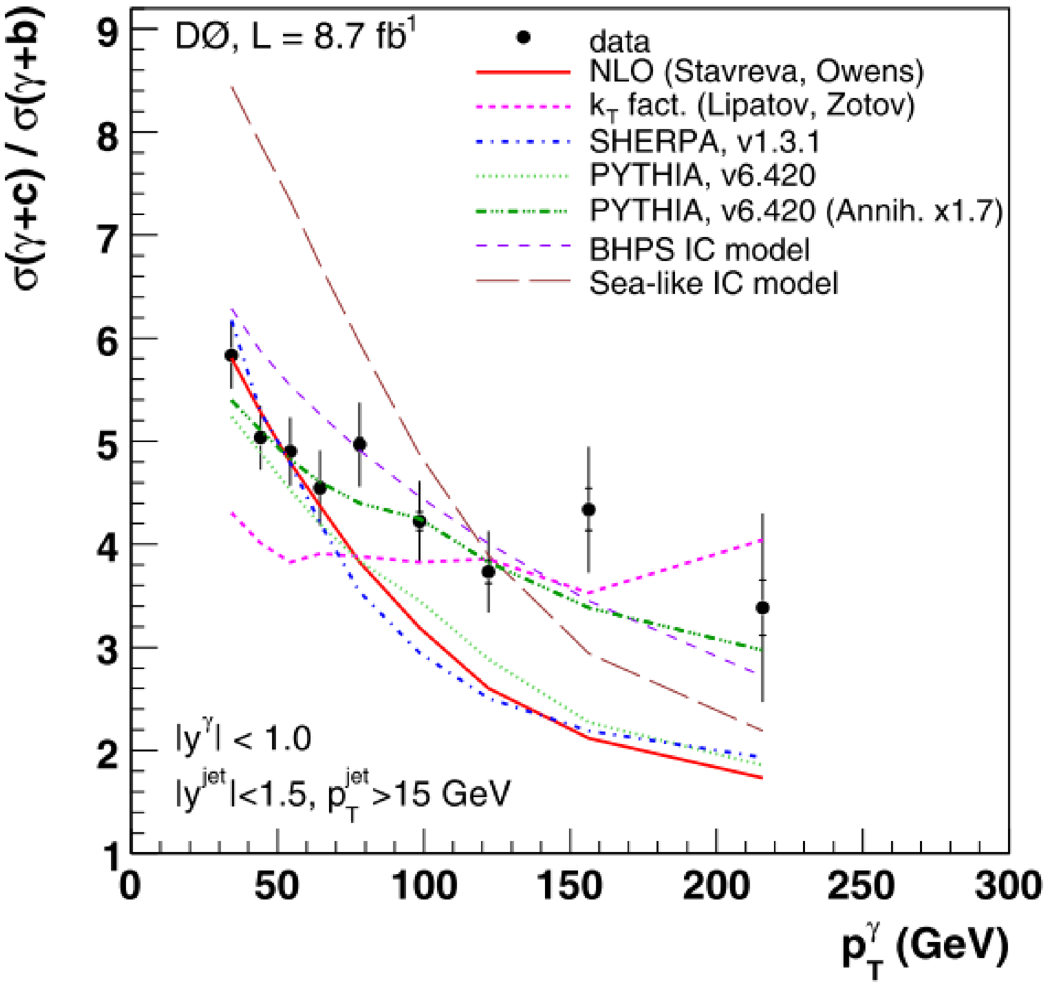
Diagrams which could give rise to intrinsic heavy quarks ($Q\bar{Q}$) in the proton. Curly lines represent transverse gluons; dashed lines represent longitudinal gluons. [6]

Above:

Current leading model for intrinsic beauty

Searching for intrinsic charm at the Tevatron

- How can we confirm or reject the existence of intrinsic heavy quark states?
- In 2013, the D0 collaboration found experimental hints of intrinsic charm at the Tevatron.
- Looking at prompt photon production associated with heavy quark (charm and bottom) jets, the data were more consistent when including IC than when neglecting it (see right)
- Ratio of $\frac{\sigma(\gamma+c)}{\sigma(\gamma+b)}$ should decrease at high p_T, but distribution flattens out at about 100 GeV
- Suggests that the LHC should probe this mechanism



Above:

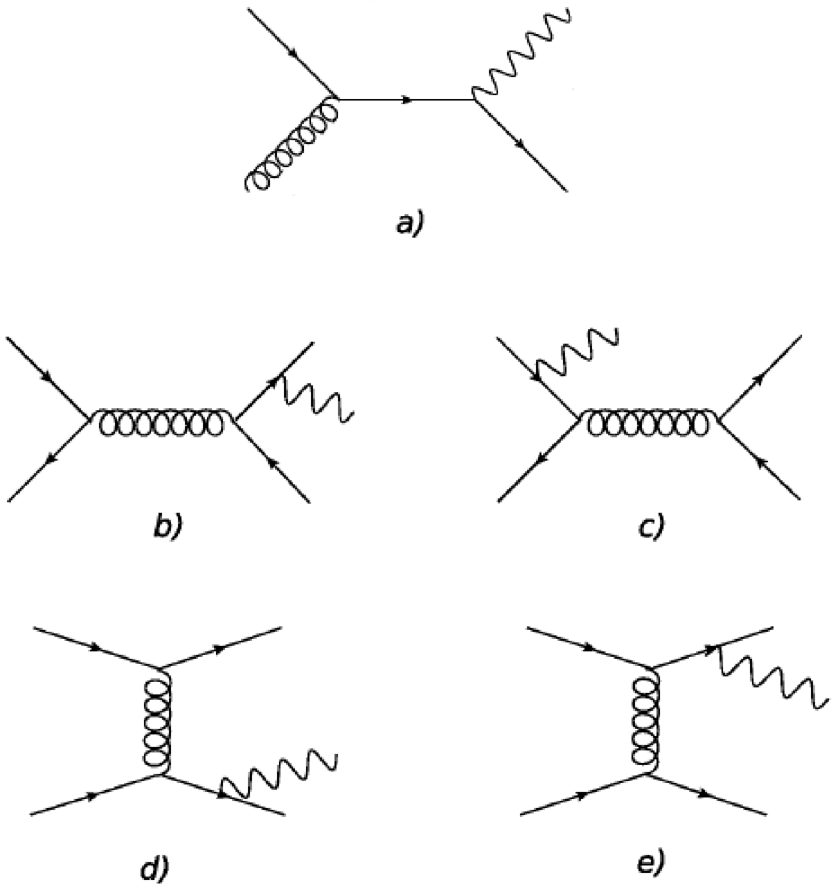
Ratio of γ + c-jet and γ + b-jet production cross sections. Theoretical predictions include k_T factorization, SHERPA, PYTHIA, and BHPS intrinsic charm. [7]

Searching for intrinsic charm at the LHC

- Intrinsic charm can be probed at the LHC via photon or Z boson production, accompanied by heavy jets. A study of this was done by Lipatov, Lykasov, Stepanenko, and Bednyakov [8].
- Relevant Feynman diagrams at right
- Production cross-sections calculated using the MCFM Monte Carlo generator, next-to-leading-order perturbative QCD, and the k_T factorization method
- We demand that the lifetime of the intrinsic charm state is at least 5 times the interaction time. This ratio is proportional to p_T^2, so we constrain $p_T^2 > 10^4\ GeV^2$
- Furthermore, we use constraints based on the setup of ATLAS and CMS: (Note: Q below refers to heavy quark jet)

$$1.5 < |\eta| < 2.4 \qquad p_T > 50\ GeV$$

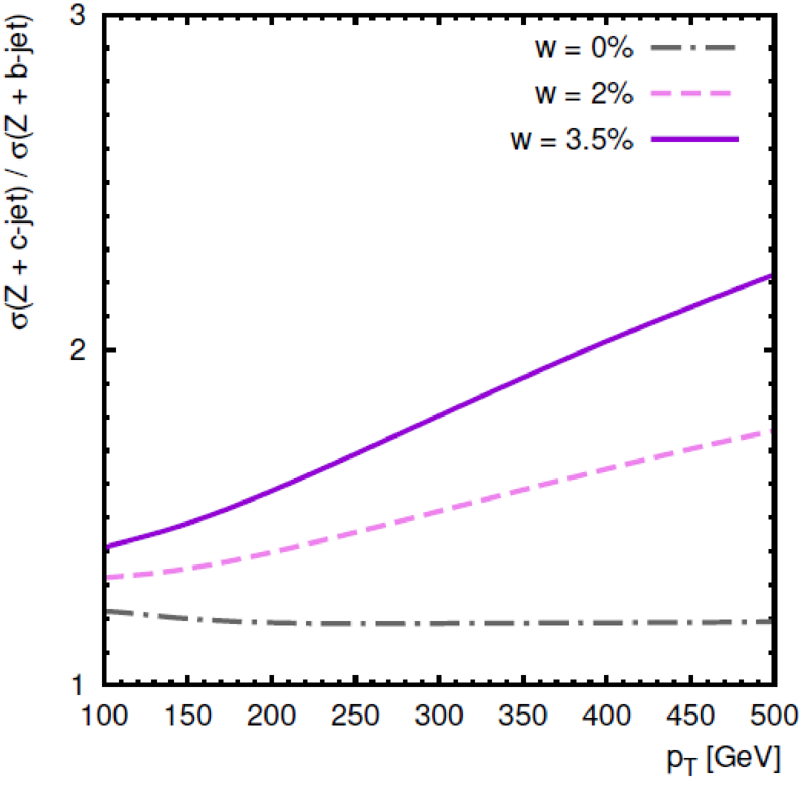
$$|\eta(Q)| < 2.4 \qquad p_T(Q) > 25\ GeV$$

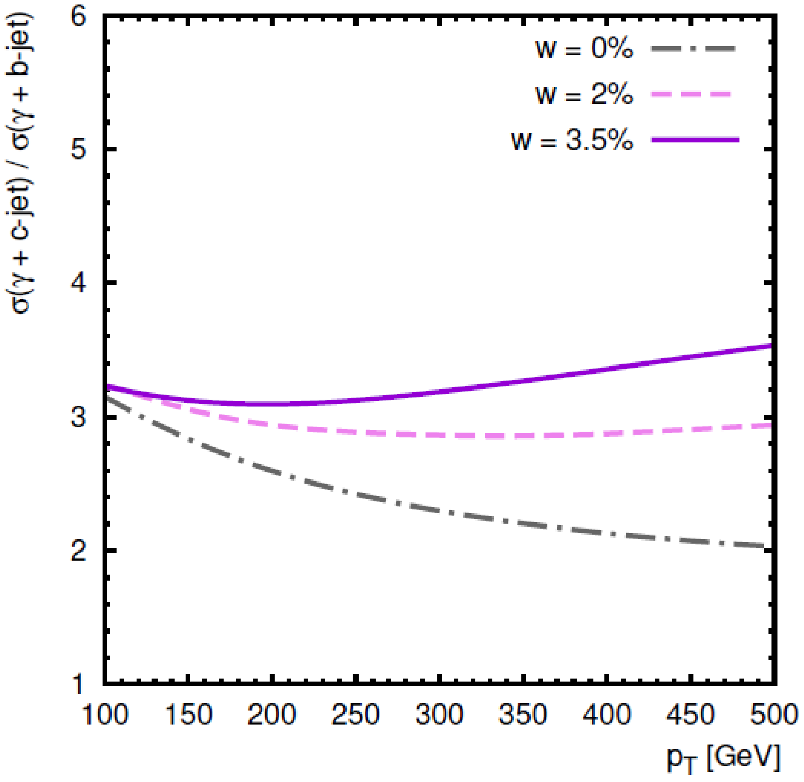


Above:
Diagrams which are used in calculating QCD/QED cross-sections. Note that a wavy line can be a photon or a Z. [8]

Searching for intrinsic charm at the LHC

- Results from the above-described calculations (all results at $\sqrt{s} = 13\ TeV$)





Above:

Calculated ratios of γ + c-jet and γ + b-jet production cross sections, as a function of photon transverse momentum, for different IC probabilities. [8]

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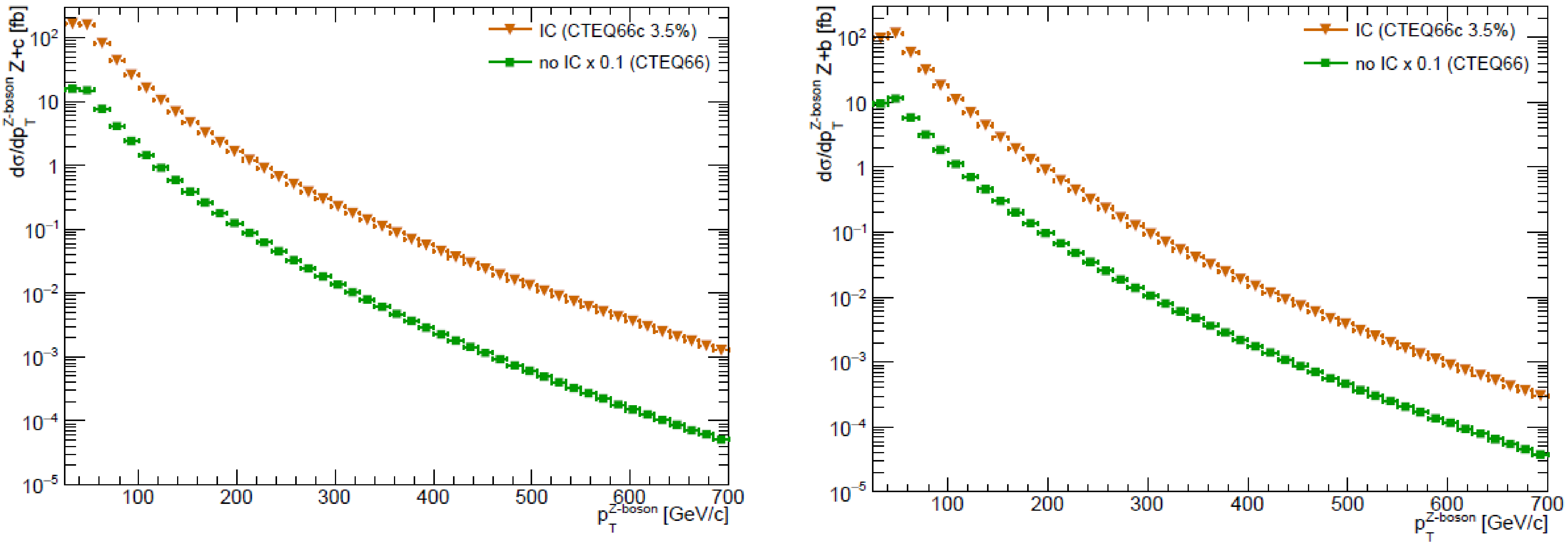

Above:

Calculated cross-sections of Z+c and Z+b as a function of Z boson transverse momentum. Considered w/ and w/o IC. [8]

Searching for intrinsic charm at the LHC

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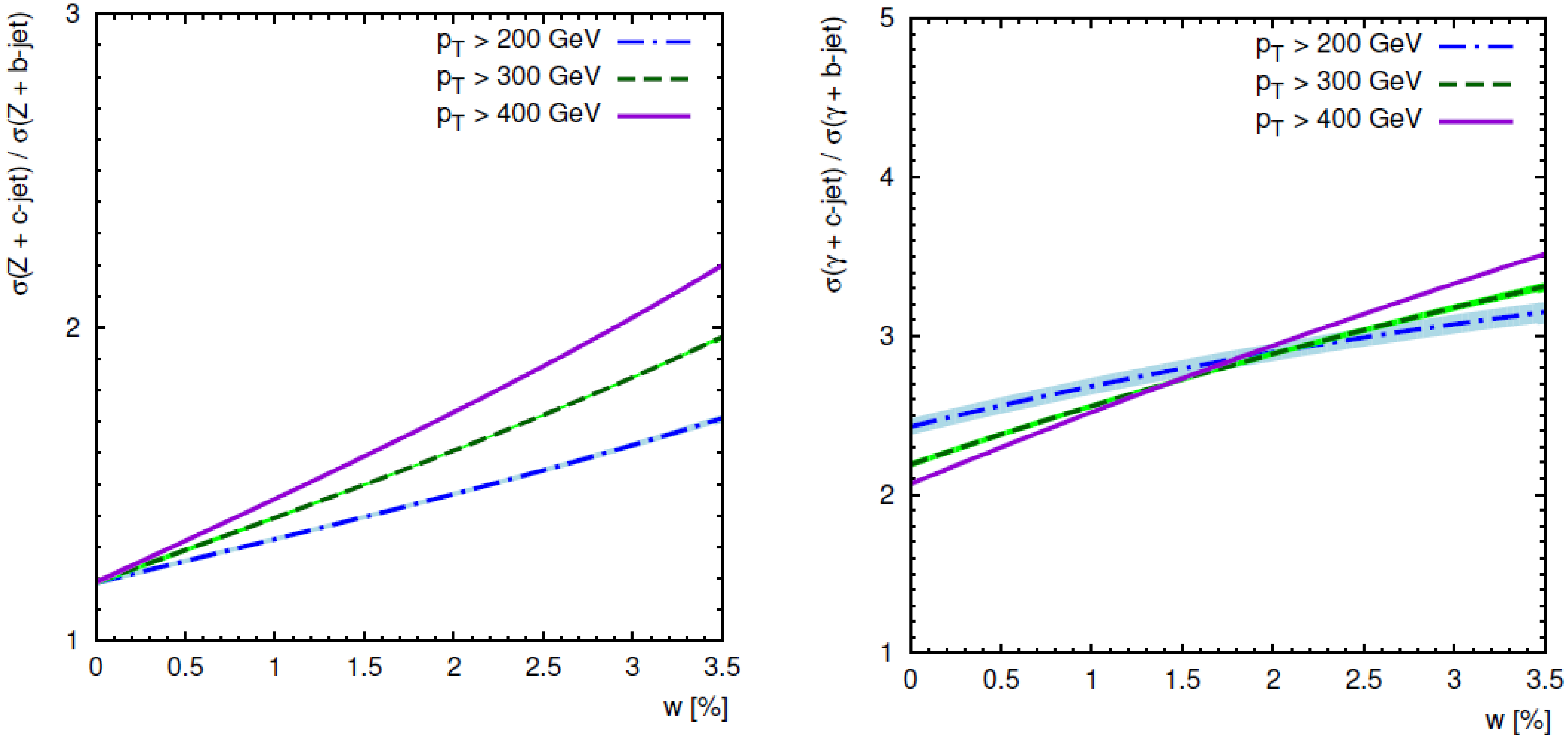
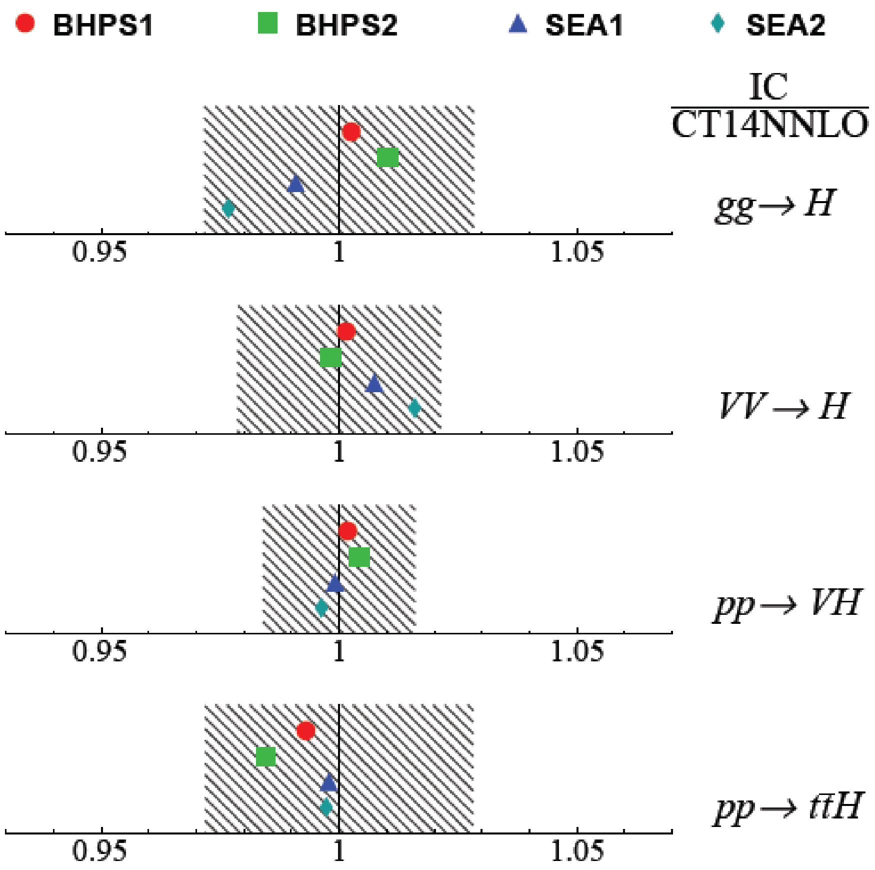


Above:

Integrated cross-section ratios as functions of IC probability; note that the integrals are done with a threshold momentum. The bands correspond to varying the renormalization scale over a factor of 4. [8]

Searching for intrinsic charm at the LHC

- Why is this all relevant? (Apart from gaining an understanding of proton structure)
- Presence of IC/IB would affect other measured cross-sections, either due to enhanced $c/\bar{c}$-driven hadron production or due to conservation of momentum in PDFs
- E.g. changes in the gluon PDF could affect Higgs boson production, which would affect Higgs-mediated dark matter sensitivities
- Non-LHC consequences, as well: e.g. cosmic ray interactions in the atmosphere produce c-hadrons, and their decay products are a background to astrophysical neutrino measurements
- At right: Impact of IC on major Higgs production mechanisms, assuming SM Higgs and ATLAS/CMS acceptance.
  - Note that these IC models include both valence-like IC and sea-like IC.
  - We haven't discussed sea-like IC, but a sea-like IC contribution goes like $IC \sim [\bar{u}(x,\mu_0^2) + \bar{d}(x,\mu_0^2)]$ with $\mu_0^2 < m_c^2$.
- LHCb projection: can constrain the effect of valence-like IC on Higgs production to be <0.5% (1% for sea-like)



Above:
Impact of IC models on Higgs production, with the hashed boxes representing PDF uncertainties. [9]

Conclusions

- The proton could have a non-negligible $uudc\bar{c}$ Fock component, at the level of a few percent. Similarly, it have an intrinsic bottom component, but at a much lower fraction.

- The Tevatron showed hints of IC in the proton, and the LHC has the ability to make even more precise measurements to confirm this hypothesis.

- The measurement of IC could have deep effects on other measurements, particularly in collider physics and in neutrino detection.

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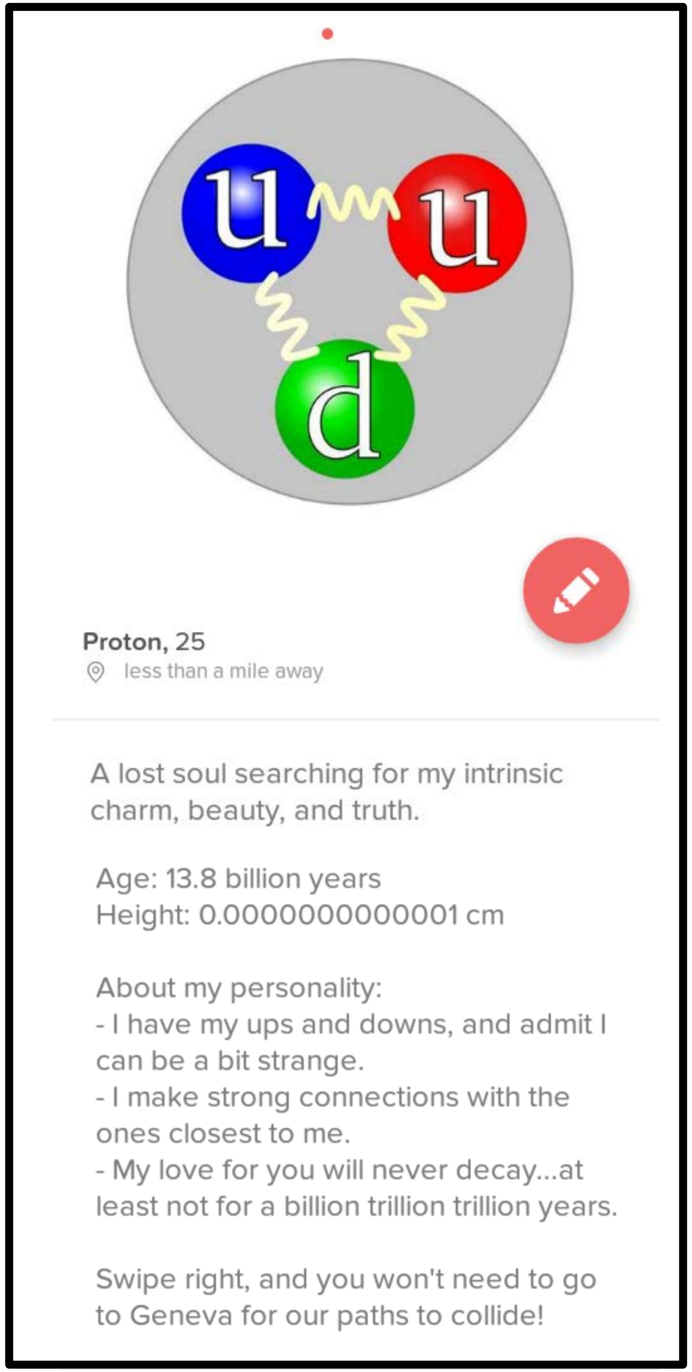
- The measurement of IC could have deep effects on other measurements, particularly in collider physics and in neutrino detection.
- But wait…there's more! I am proposing a novel new method to search for the proton's intrinsic charm and beauty.

Searching for intrinsic charm on tinder

- I have created a Tinder account for the proton to measure its level of intrinsic charm and beauty
- Conducted a rigorous experiment by right-swiping (“liking”) at least 200 men and women within a 100-mile range of Berkeley
- Results:
  - 48 matches (46 humans, 2 robots)
  - 7 direct messages (5 humans, 2 robots)
- Conclusion: proton contains $46/198 \approx 23\%$ intrinsic beauty, and $5/198 \approx 2.5\%$ intrinsic charm, which is consistent with the DIS HERA results.



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