Title: The Standard Model Experiment: Experimental QCD

Date: Jul 17, 2015 04:00 PM

URL: http://pirsa.org/15070059

Abstract:

Our Most Perfect Theory?

I encourage to take a look at this paper by Frank Wilczek: "What QCD Tells Us About Nature – and Why We Should Listen":

http://arxiv.org/pdf/hep-ph/9907340v2.pdf

Abstract: "I discuss why QCD is our most perfect physical theory. Then I visit a few of its current frontiers. Finally I draw some appropriate conclusions."

Justifications from the paper:

1. It embodies deep and beautiful principles
2. It provides algorithms to answer any physically meaningful question within its scope
3. Its scope is wide
4. It contains a wealth of phenomena
5. It has few parameters
6. … or none
7. It is true
8. It lacks flaws

Quark Colours and SU(3)

Evidence that quarks come in 3 different "colours" include

→ spin-stat. problem for baryons

→ cross section $e^- e^+ \to$ hadrons

→ Υ branching ratios

→ π^0 lifetime

→ anomaly cancelation

Could we use U(3), SO(3) as candidate gauge groups for the strong interaction?

SO(3) → no asymptotic freedom

→ existence of diquark states, no distinction between quarks and anti-quarks

QCD Intro

U(3) we get a singlet gauge boson → long-range interaction.

For the Lagrangian :

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$$

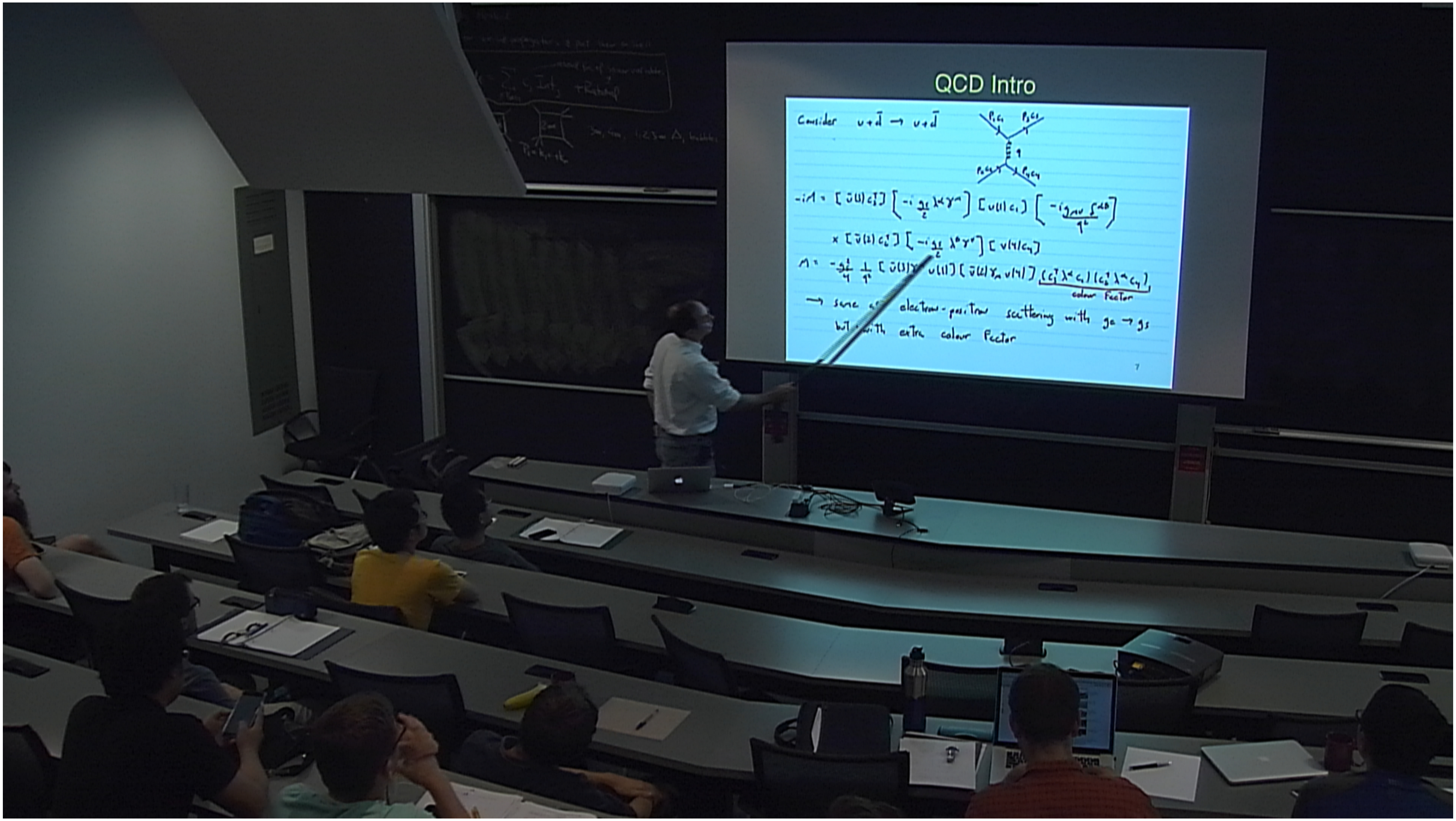
$$\psi = \begin{pmatrix} q \\ q \\ q \end{pmatrix} \qquad D_\mu = \partial_\mu + ig B_\mu$$

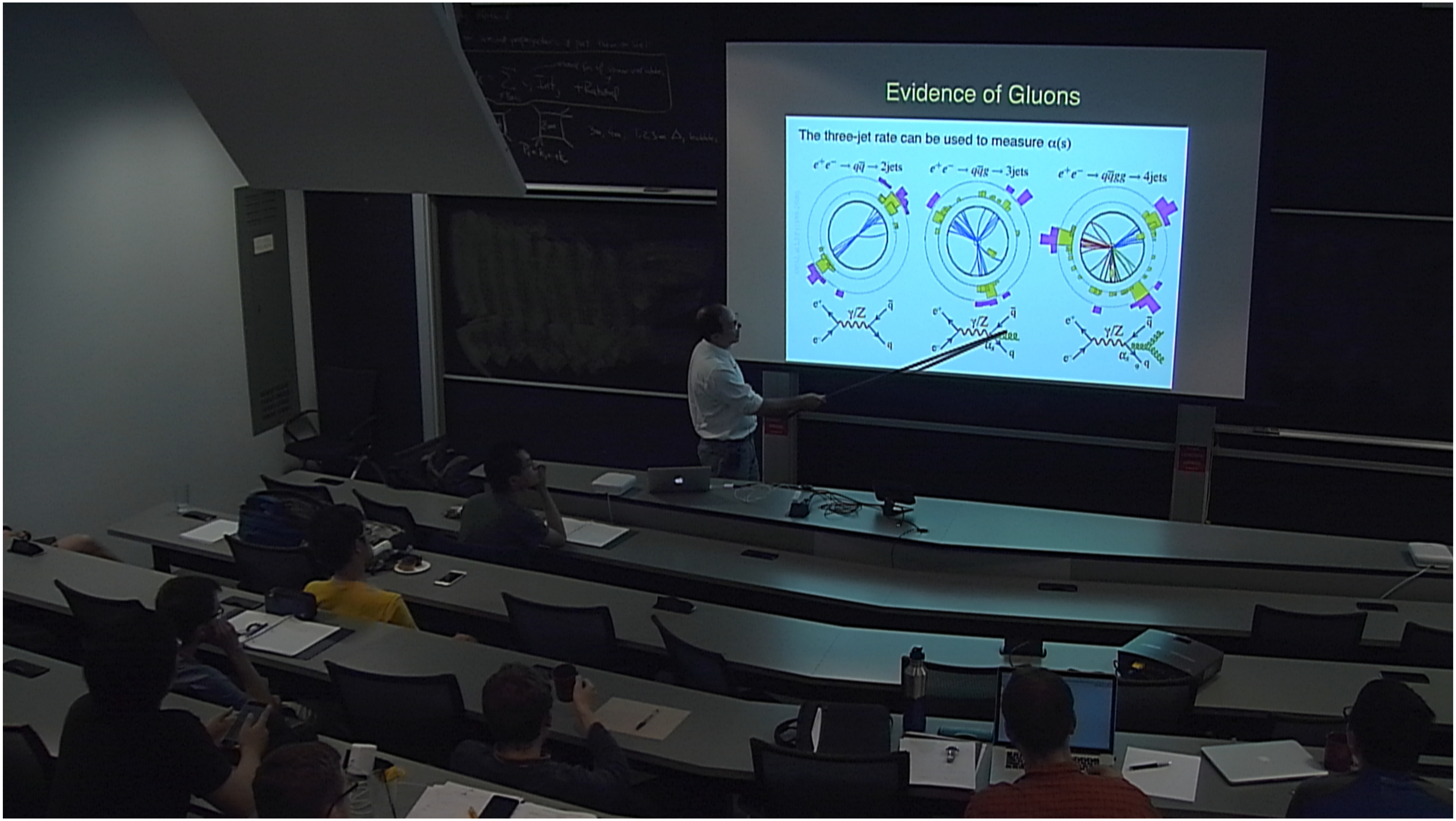
↳ 3x3 matrix : $B_\mu = \frac{1}{2}\lambda \cdot b_\mu = \frac{1}{2}\lambda^\ell b^\ell_\mu$

b_μ : 8 colour gauge fields

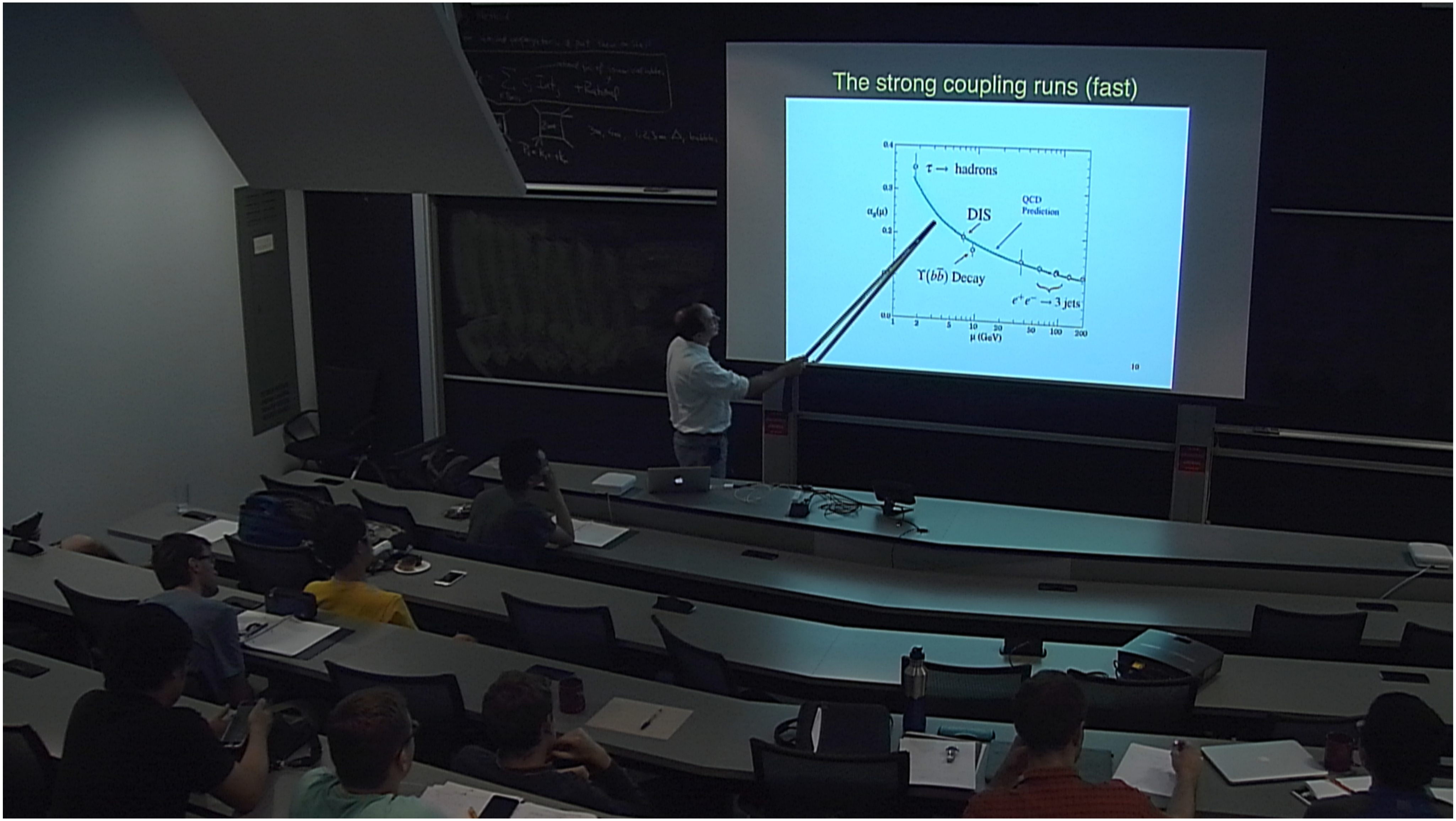
$$G_{\mu\nu} = \frac{1}{2} G_{\mu\nu} \cdot \lambda = \frac{1}{2} G^\ell_{\mu\nu} \lambda^\ell$$

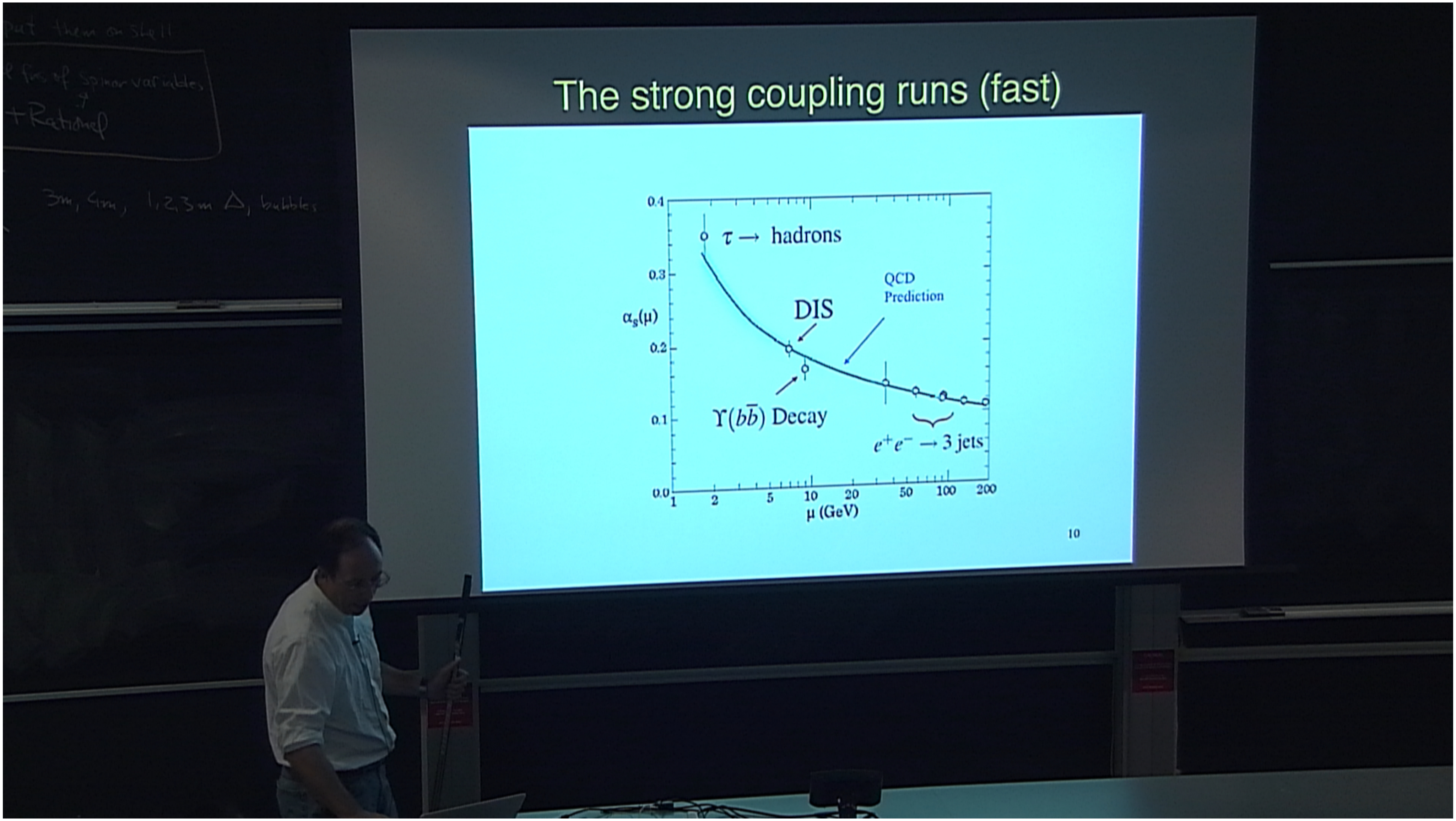
$$= (ig)^{-1}[D_\nu, D_\mu] = \partial_\nu B_\mu - \partial_\mu B_\nu + ig[B_\nu, B_\mu]$$

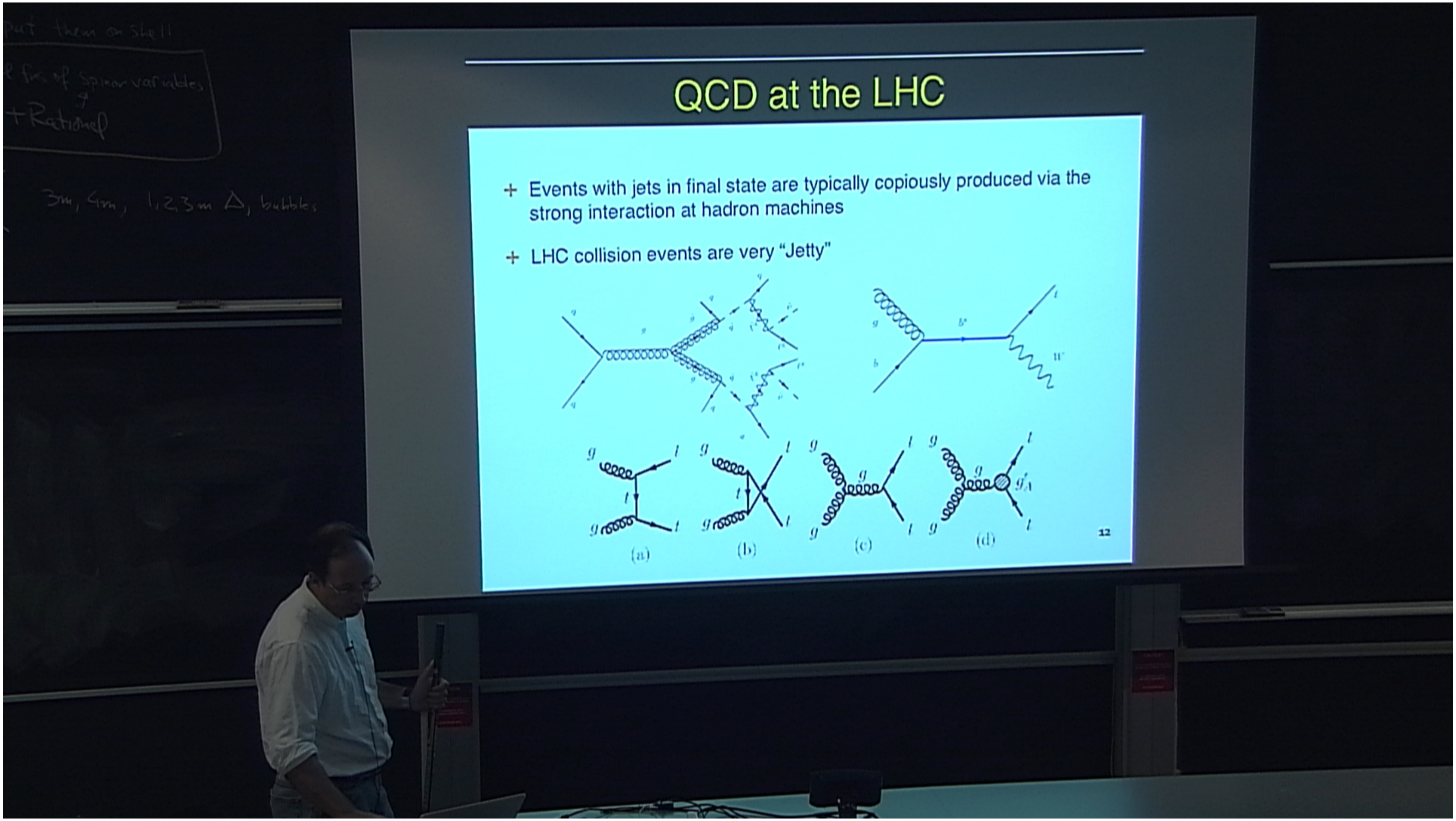

QCD Intro
Consider u + d̄ → u + d̄
colour factor
→ same as electron-positron scattering with ge → gs
but with extra colour factor

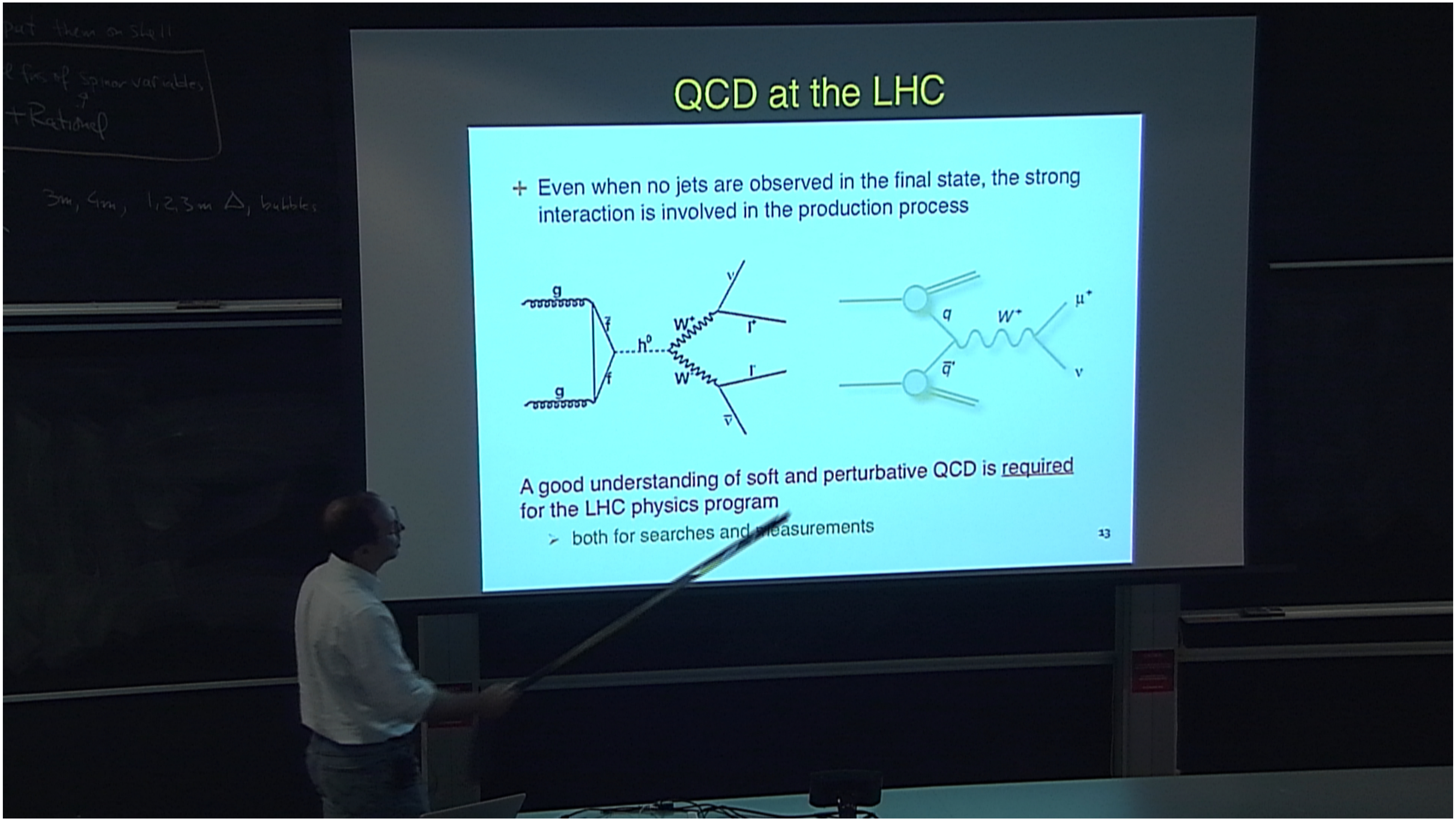


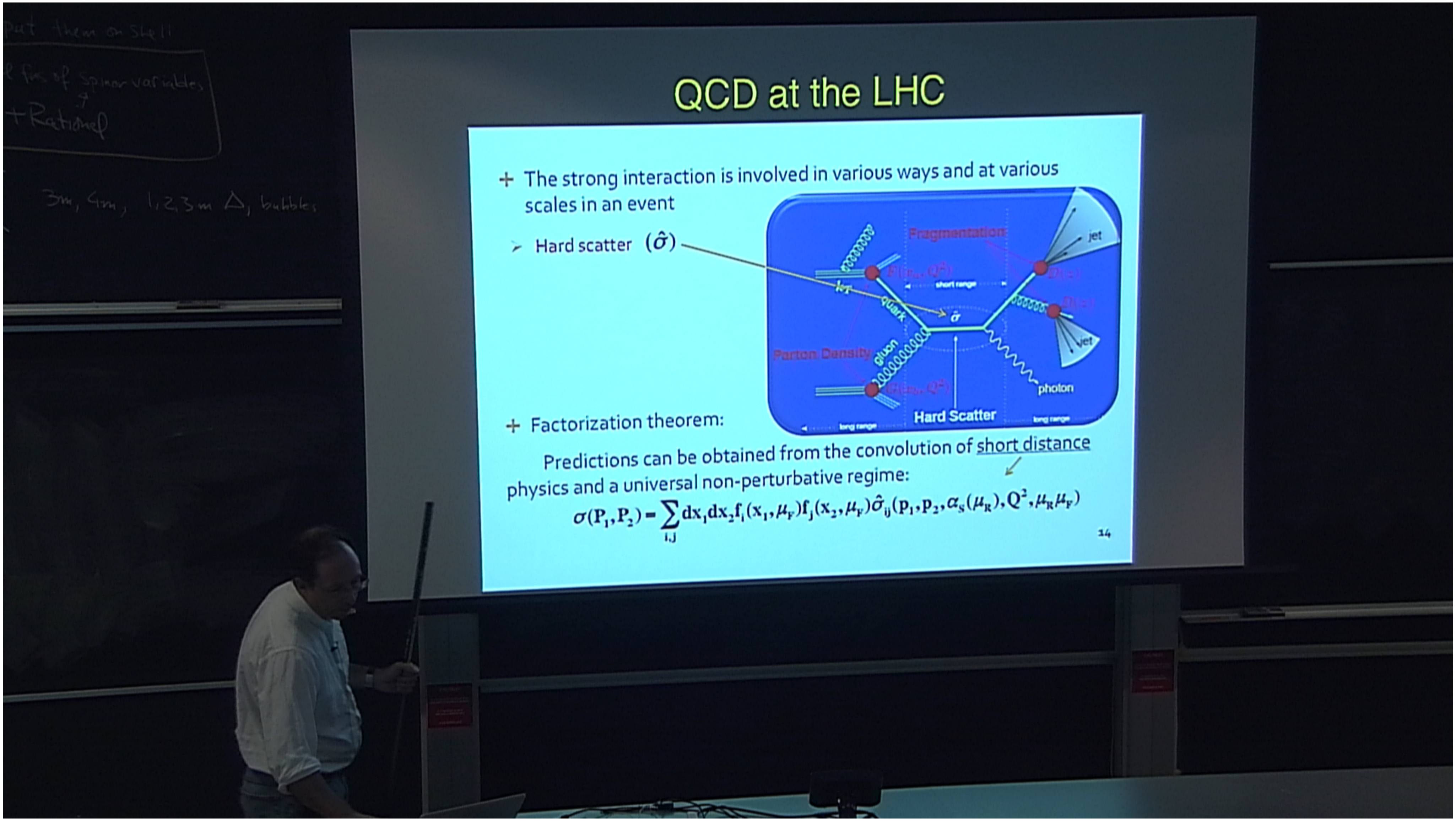
Evidence of Gluons
The three-jet rate can be used to measure α(s)
$e^+e^- \to q\bar{q} \to$ 2jets
$e^+e^- \to q\bar{q}g \to$ 3jets
$e^+e^- \to q\bar{q}gg \to$ 4jets
γ/Z

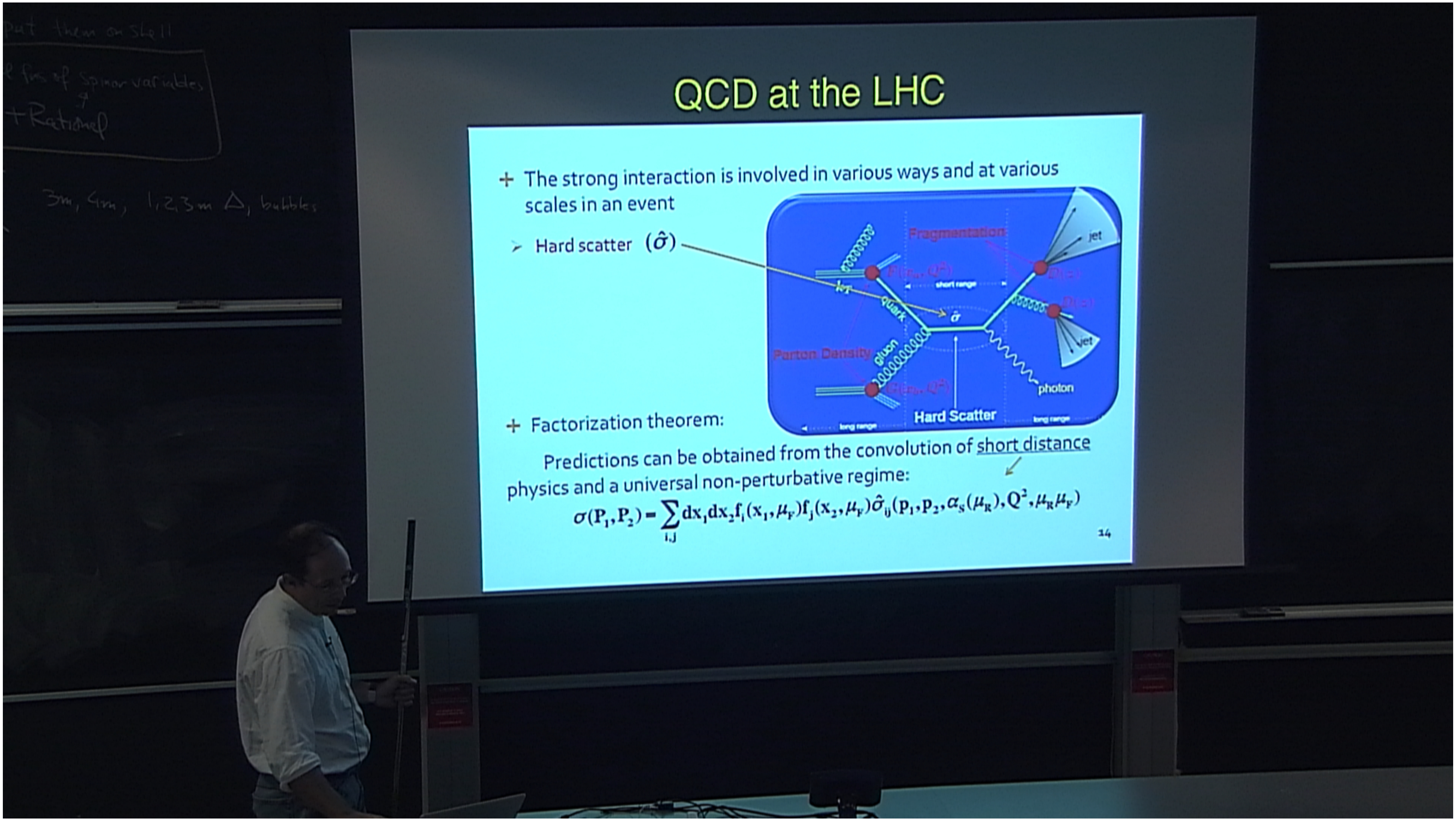

The strong coupling runs (fast)
$\tau \to$ hadrons
DIS
QCD Prediction
$\Upsilon(b\bar{b})$ Decay
$e^+e^- \to 3$ jets
$\alpha_s(\mu)$
μ (GeV)
10


The strong coupling runs (fast)
0.4
0.3
0.2
0.1
0.0
$\alpha_s(\mu)$
$\tau \to$ hadrons
QCD
Prediction
DIS
$\Upsilon(b\bar{b})$ Decay
$e^+e^- \to 3$ jets
1
2
5
10
20
50
100
200
μ (GeV)
10


QCD at the LHC
+ Events with jets in final state are typically copiously produced via the strong interaction at hadron machines
+ LHC collision events are very "Jetty"
(a)
(b)
(c)
(d)
12


QCD at the LHC
+ Even when no jets are observed in the final state, the strong interaction is involved in the production process
g
g
h0
W+
W-
l+
l-
q
q̄'
W+
μ+
ν
A good understanding of soft and perturbative QCD is required for the LHC physics program
both for searches and measurements
13
put them on shell
+Rational
3m, 4m, 1,2,3m Δ, bubbles


QCD at the LHC
The strong interaction is involved in various ways and at various scales in an event
Hard scatter $(\hat{\sigma})$
Fragmentation
jet
short range
quark
gluon
Parton Density
photon
Hard Scatter
long range
Factorization theorem:
Predictions can be obtained from the convolution of short distance physics and a universal non-perturbative regime:
$\sigma(P_1,P_2) = \sum_{i,j} dx_1 dx_2 f_i(x_1,\mu_F) f_j(x_2,\mu_F) \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R \mu_F)$
14
3m, 4m, 1,2,3m Δ, bubbles
+ Rational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Fragmentation
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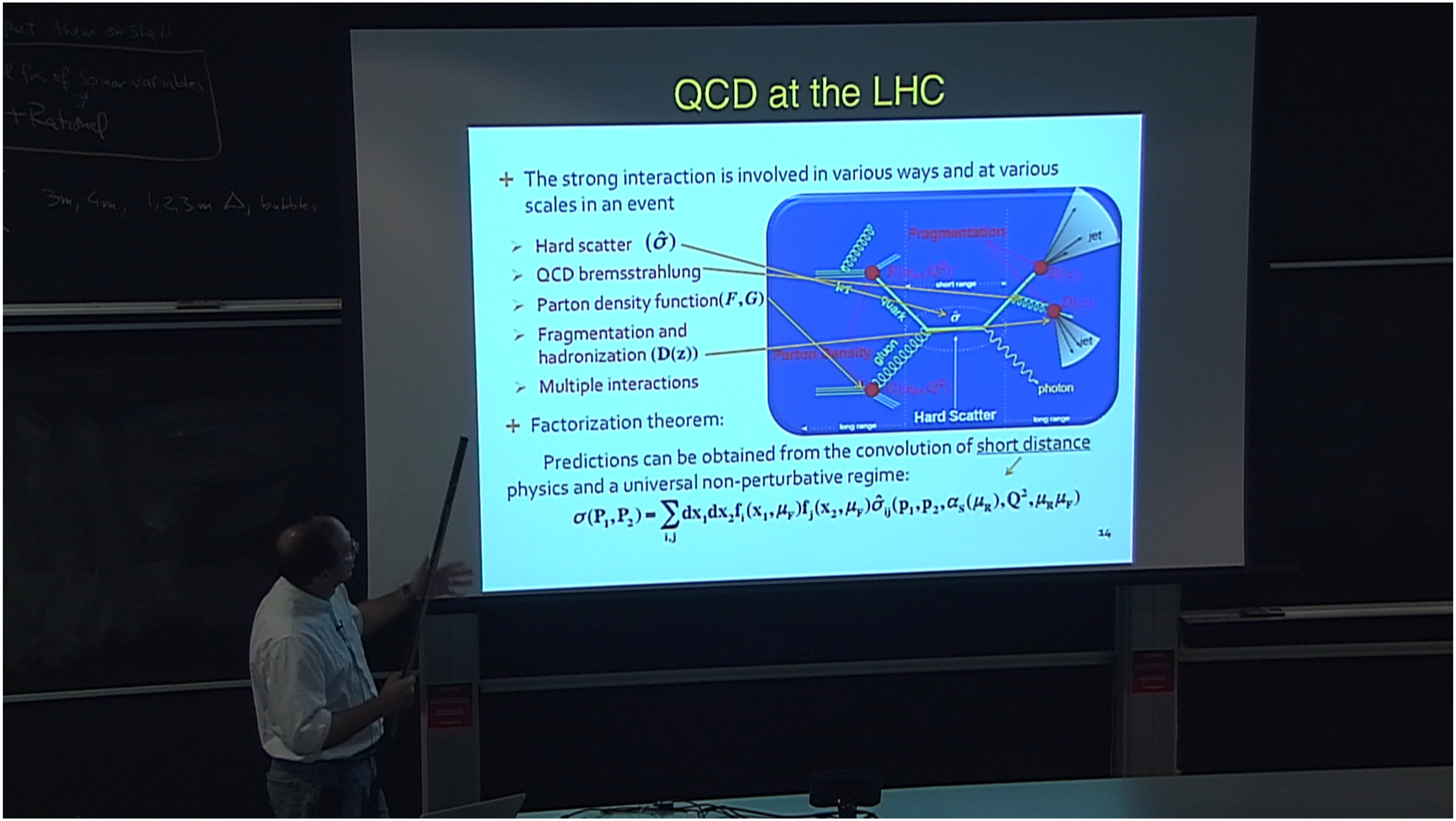
QCD at the LHC
+ The strong interaction is involved in various ways and at various scales in an event
Hard scatter $(\hat{\sigma})$
QCD bremsstrahlung
Parton density function (F, G)
Fragmentation and hadronization $(D(z))$
Multiple interactions
+ Factorization theorem:
Predictions can be obtained from the convolution of short distance physics and a universal non-perturbative regime:
$\sigma(P_1,P_2) = \sum_{i,j} dx_1 dx_2 f_i(x_1,\mu_F) f_j(x_2,\mu_F) \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R\mu_F)$
Fragmentation
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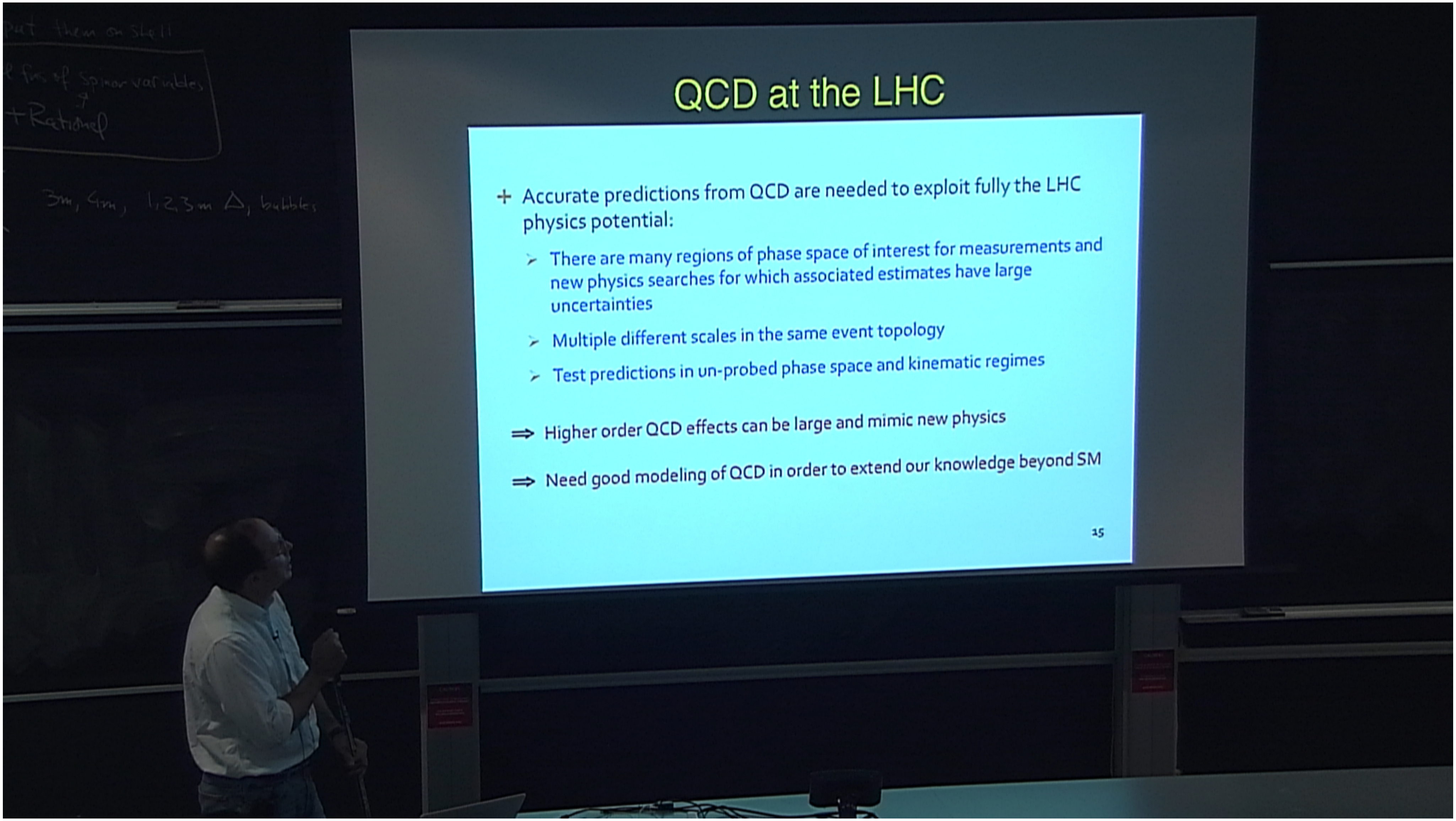
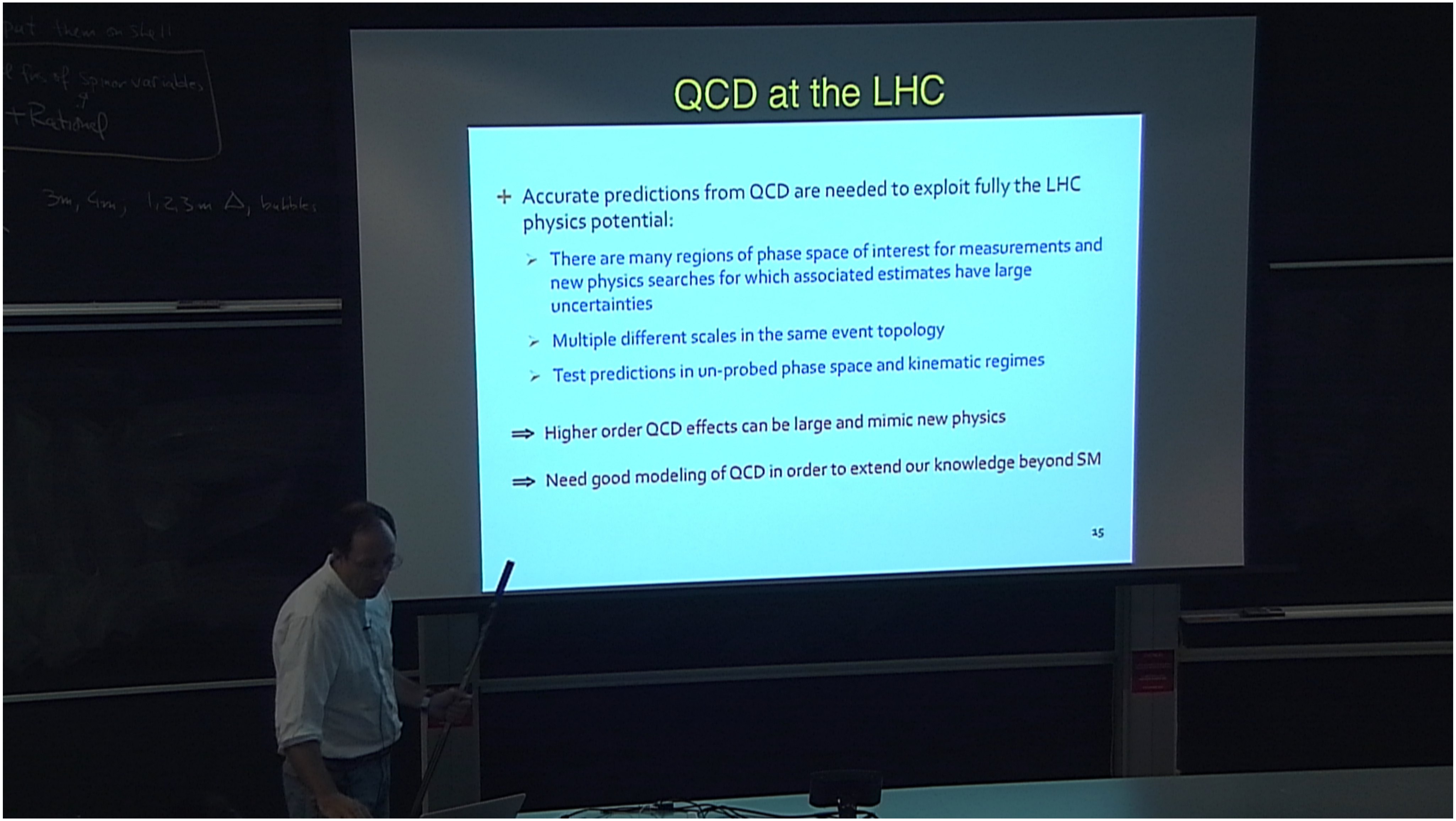
14


QCD at the LHC
+ Accurate predictions from QCD are needed to exploit fully the LHC physics potential:
➢ There are many regions of phase space of interest for measurements and new physics searches for which associated estimates have large uncertainties
➢ Multiple different scales in the same event topology
➢ Test predictions in un-probed phase space and kinematic regimes
⇒ Higher order QCD effects can be large and mimic new physics
⇒ Need good modeling of QCD in order to extend our knowledge beyond SM
15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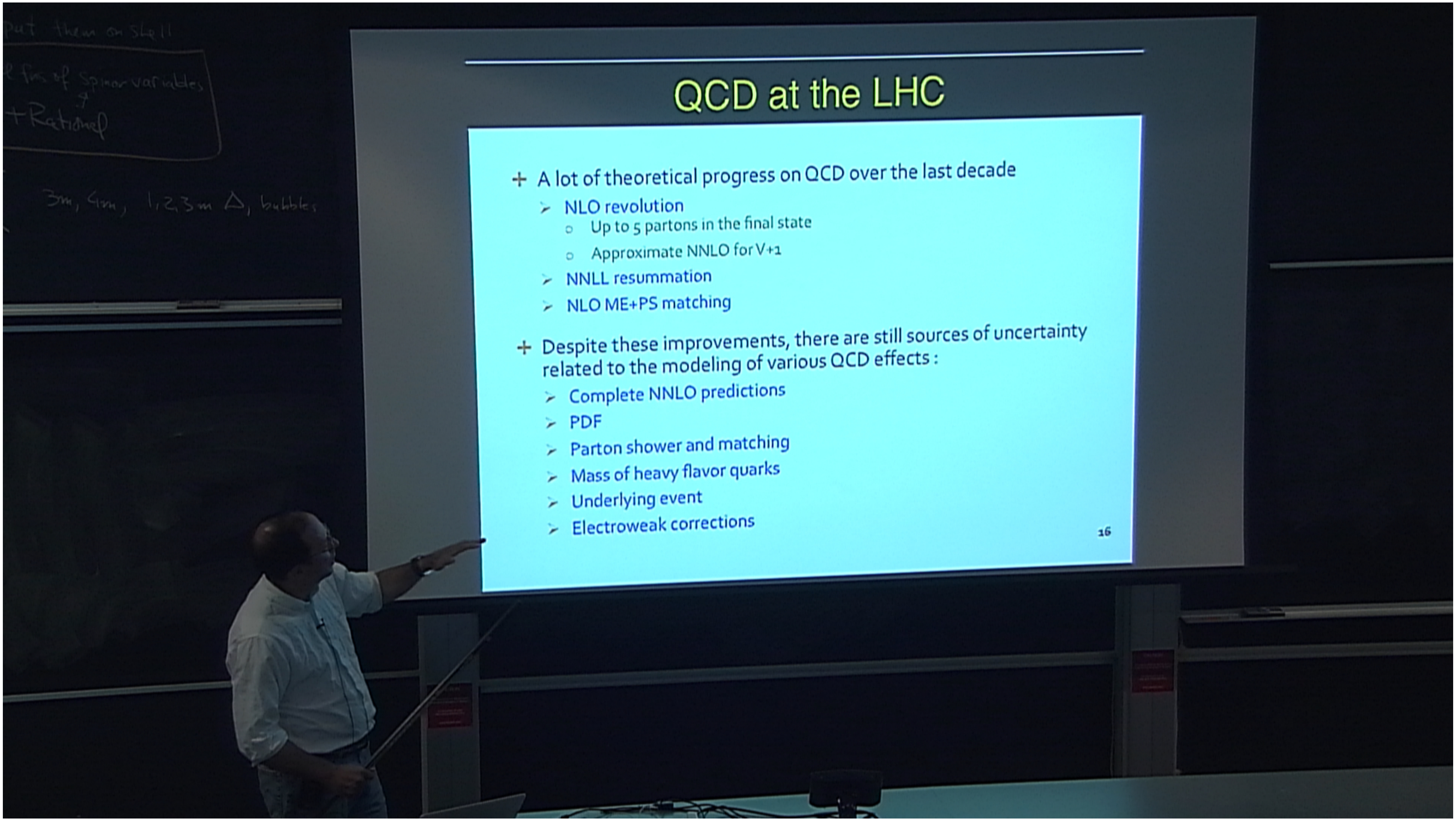
QCD at the LHC
A lot of theoretical progress on QCD over the last decade
NLO revolution
Up to 5 partons in the final state
Approximate NNLO for V+1
NNLL resummation
NLO ME+PS matching
Despite these improvements, there are still sources of uncertainty related to the modeling of various QCD effects :
Complete NNLO predictions
PDF
Parton shower and matching
Mass of heavy flavor quarks
Underlying event
Electroweak corrections
16

QCD at the LHC

- A lot of theoretical progress on QCD over the last decade
  - NLO revolution
    - Up to 5 partons in the final state
    - Approximate NNLO for V+1
  - NNLL resummation
  - NLO ME+PS matching
- Despite these improvements, there are still sources of uncertainty related to the modeling of various QCD effects :
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  - PDF
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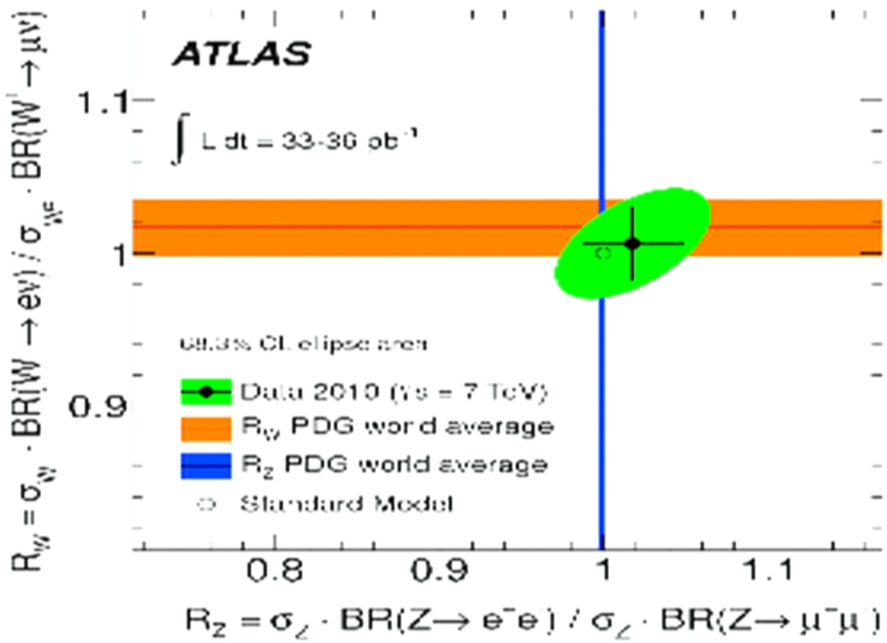
  - Electroweak corrections

W inclusive xs and PDFs

- Highly precise measurements of the ratio of W to Z cross sections allow for a test of Lepton Universality



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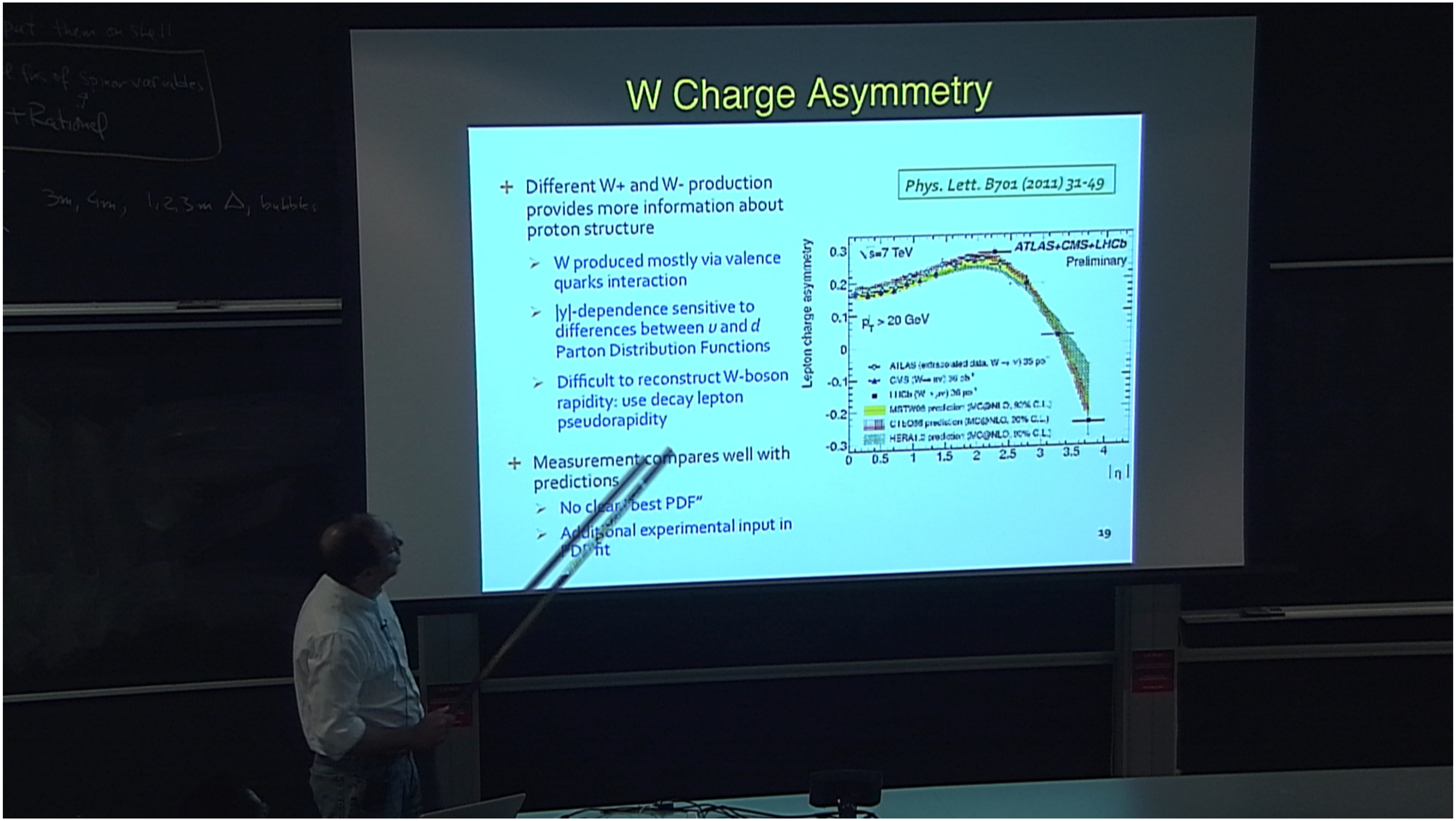
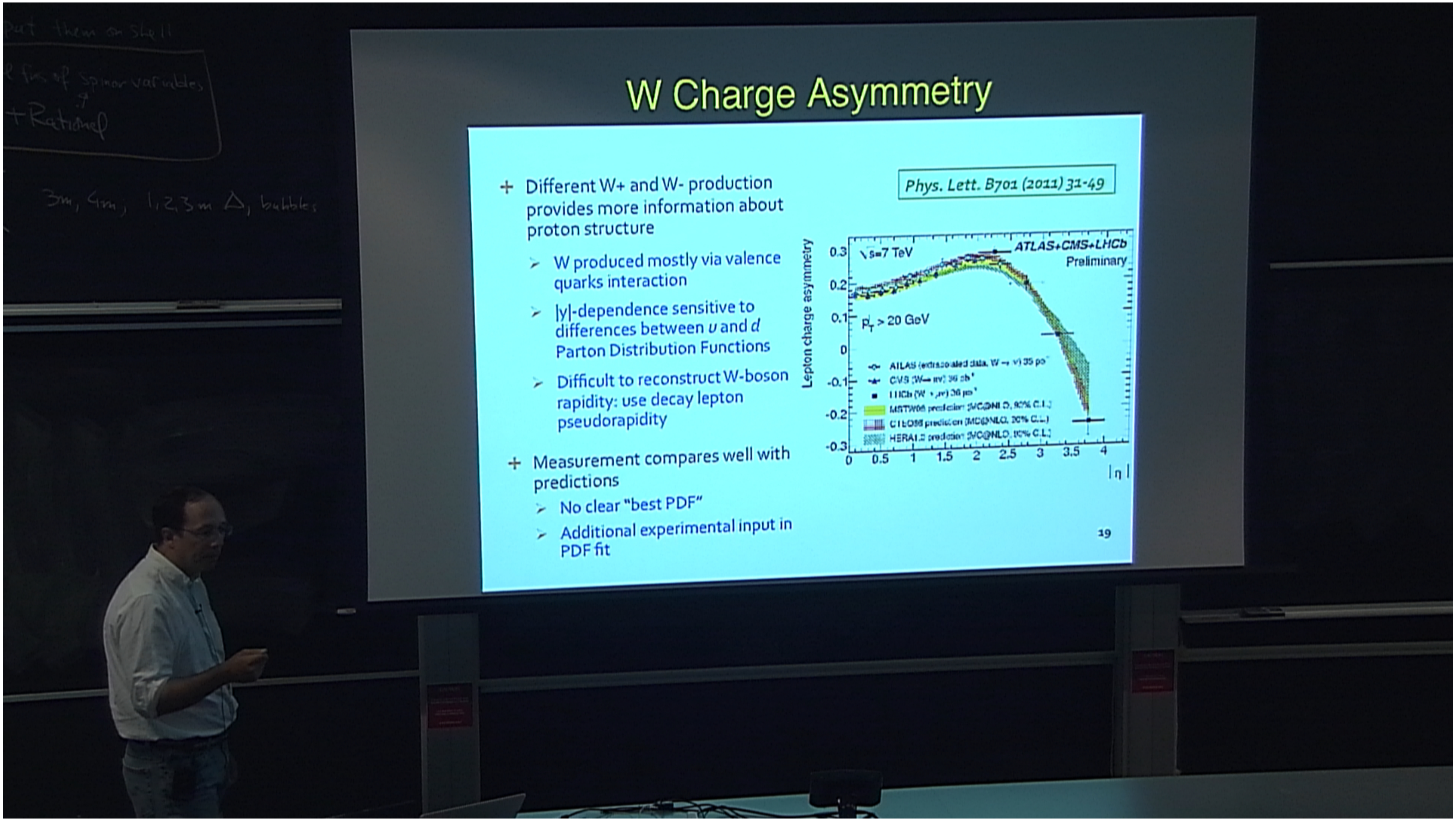

W Charge Asymmetry
Different W+ and W- production provides more information about proton structure
W produced mostly via valence quarks interaction
|y|-dependence sensitive to differences between u and d Parton Distribution Functions
Difficult to reconstruct W-boson rapidity: use decay lepton pseudorapidity
Measurement compares well with predictions
No clear "best PDF"
Additional experimental input in PDF fit
Phys. Lett. B701 (2011) 31-49
√s=7 TeV
ATLAS+CMS+LHCb
Preliminary
p_T > 20 GeV
Lepton charge asymmetry
|η|
19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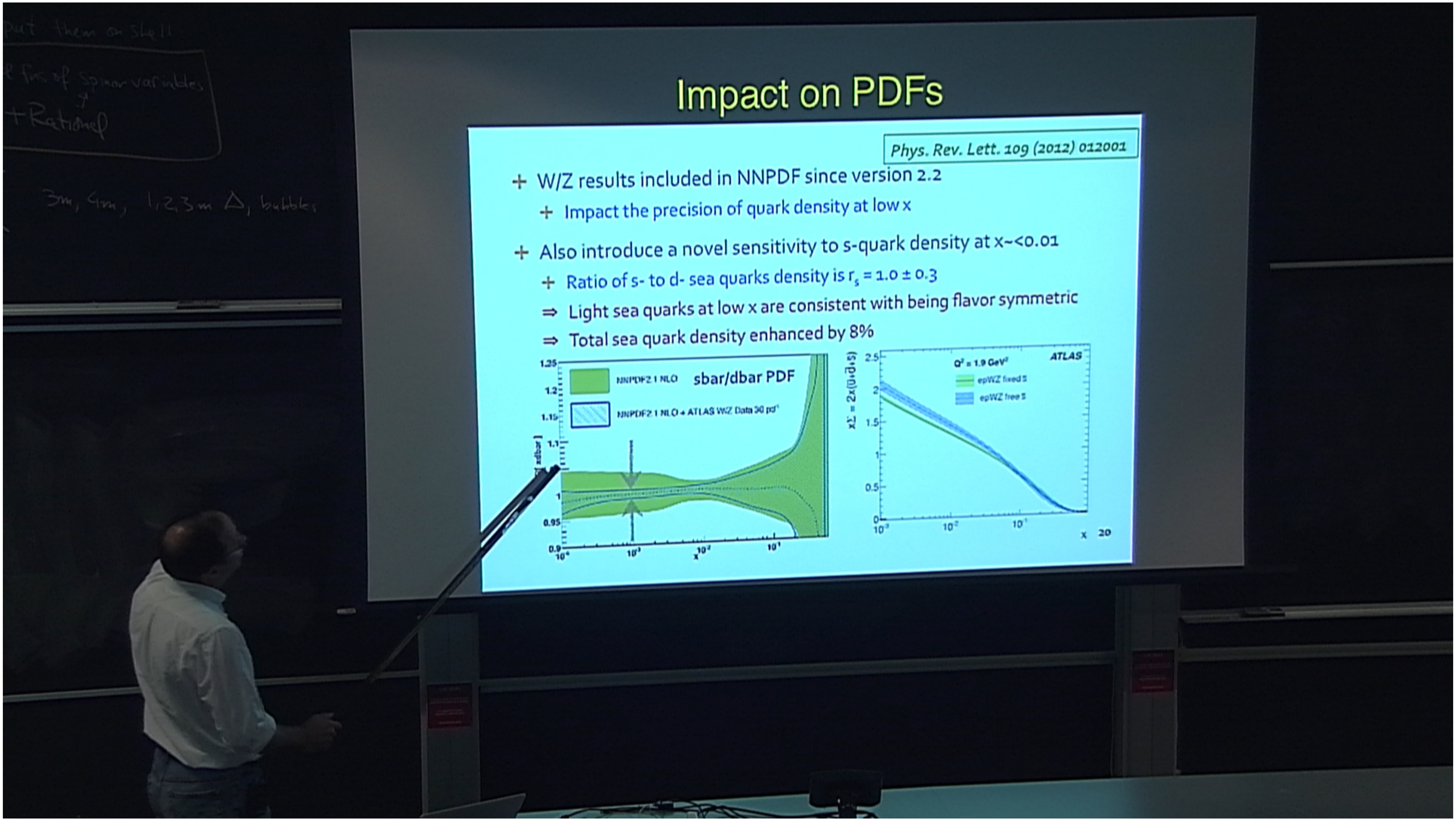
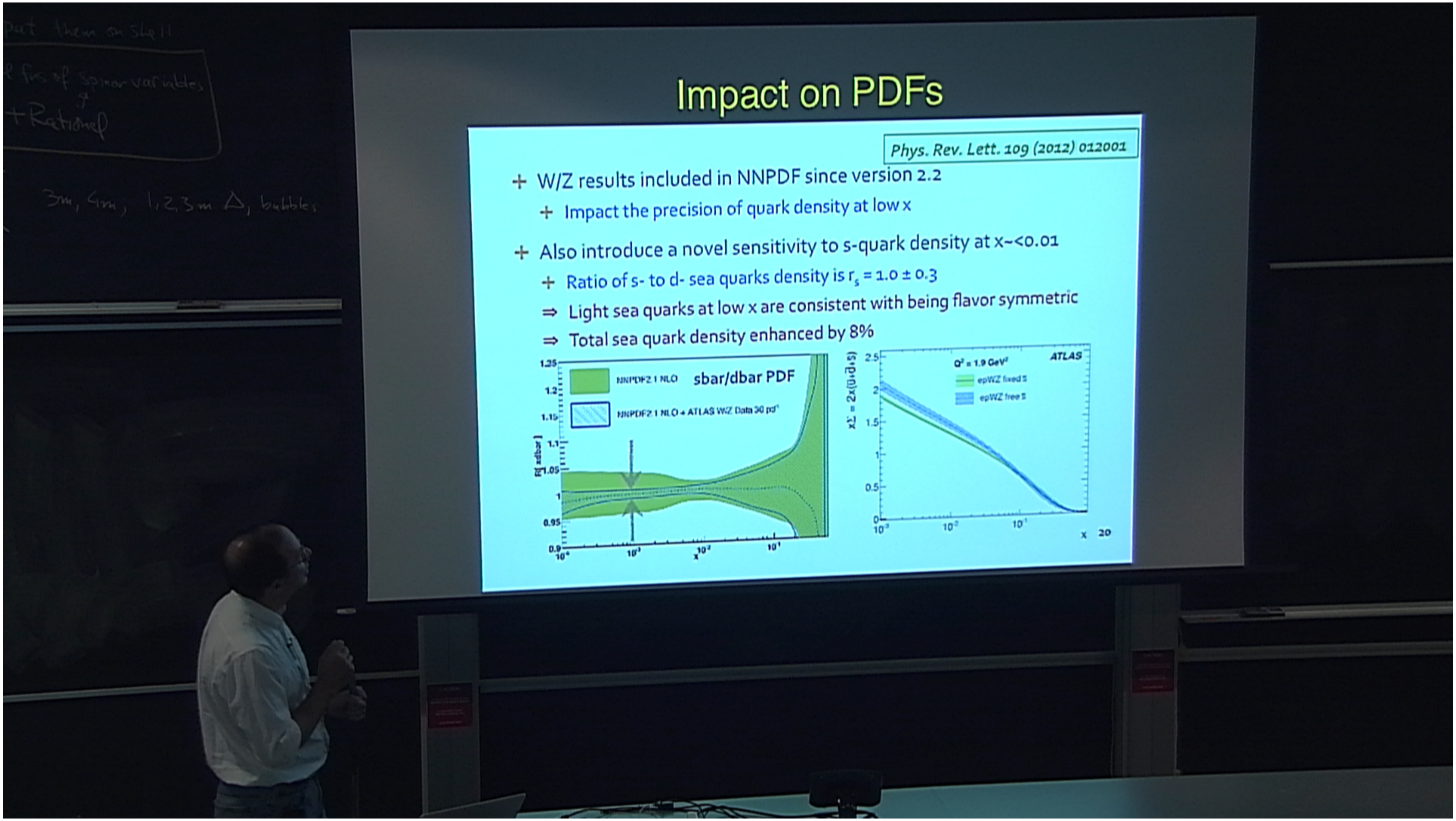


Impact on PDFs
Phys. Rev. Lett. 109 (2012) 012001
W/Z results included in NNPDF since version 2.2
Impact the precision of quark density at low x
Also introduce a novel sensitivity to s-quark density at x~<0.01
Ratio of s- to d- sea quarks density is r_s = 1.0 ± 0.3
⇒ Light sea quarks at low x are consistent with being flavor symmetric
⇒ Total sea quark density enhanced by 8%
sbar/dbar PDF
NNPDF2.1 NLO
NNPDF2.1 NLO + ATLAS WZ Data 30 pb⁻¹
ATLAS
epWZ fixed s̄
epWZ free s̄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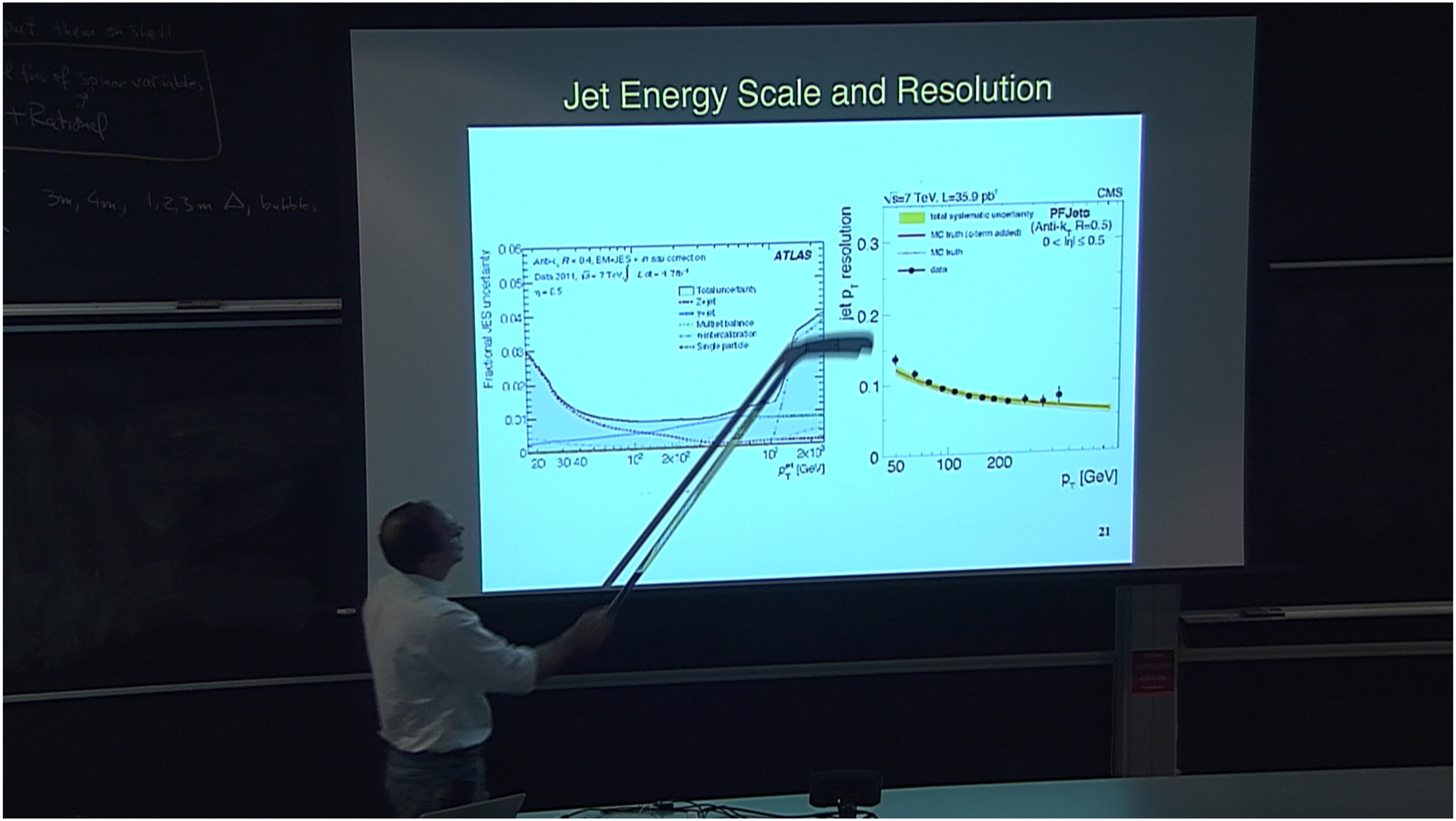
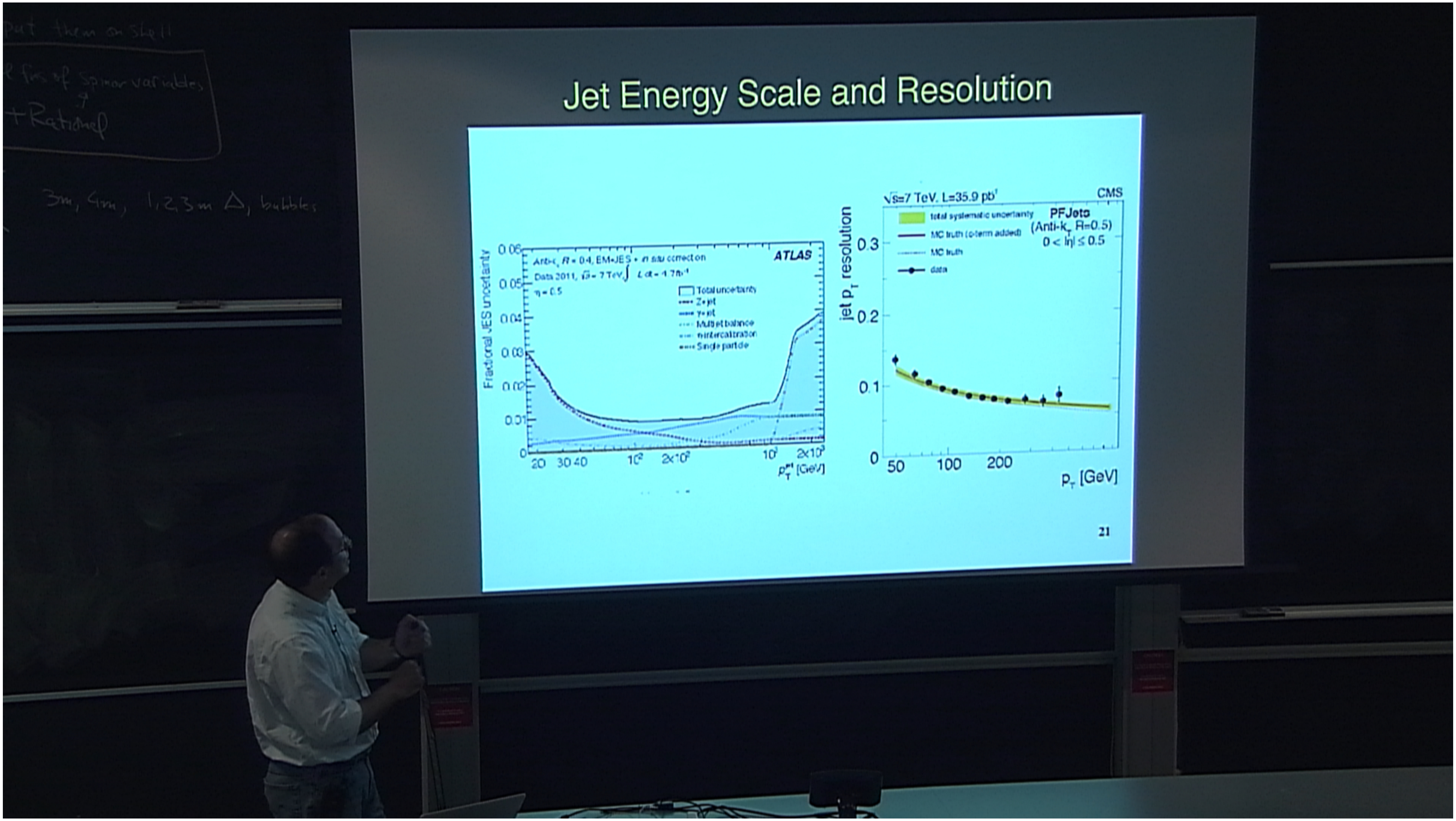
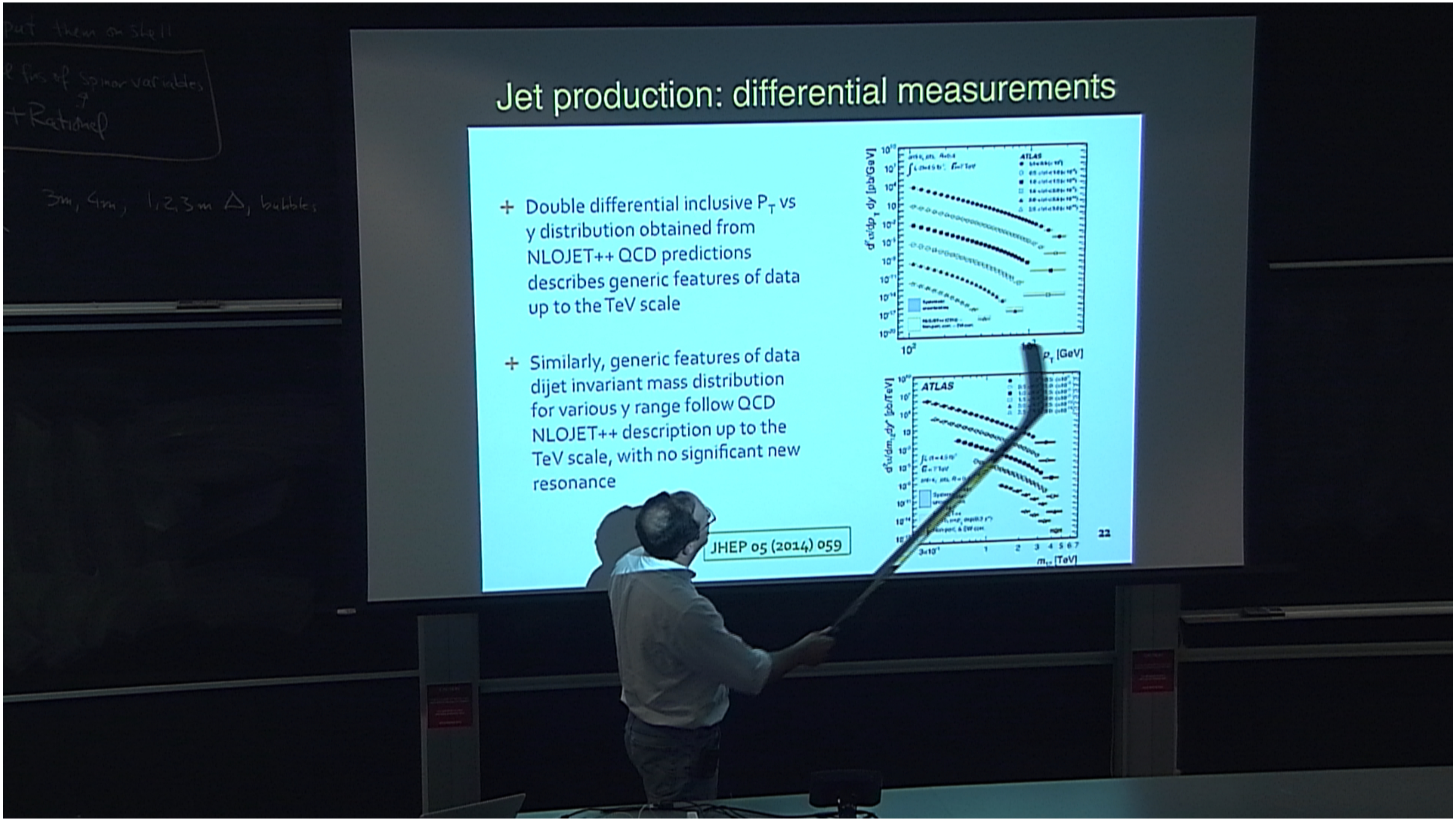
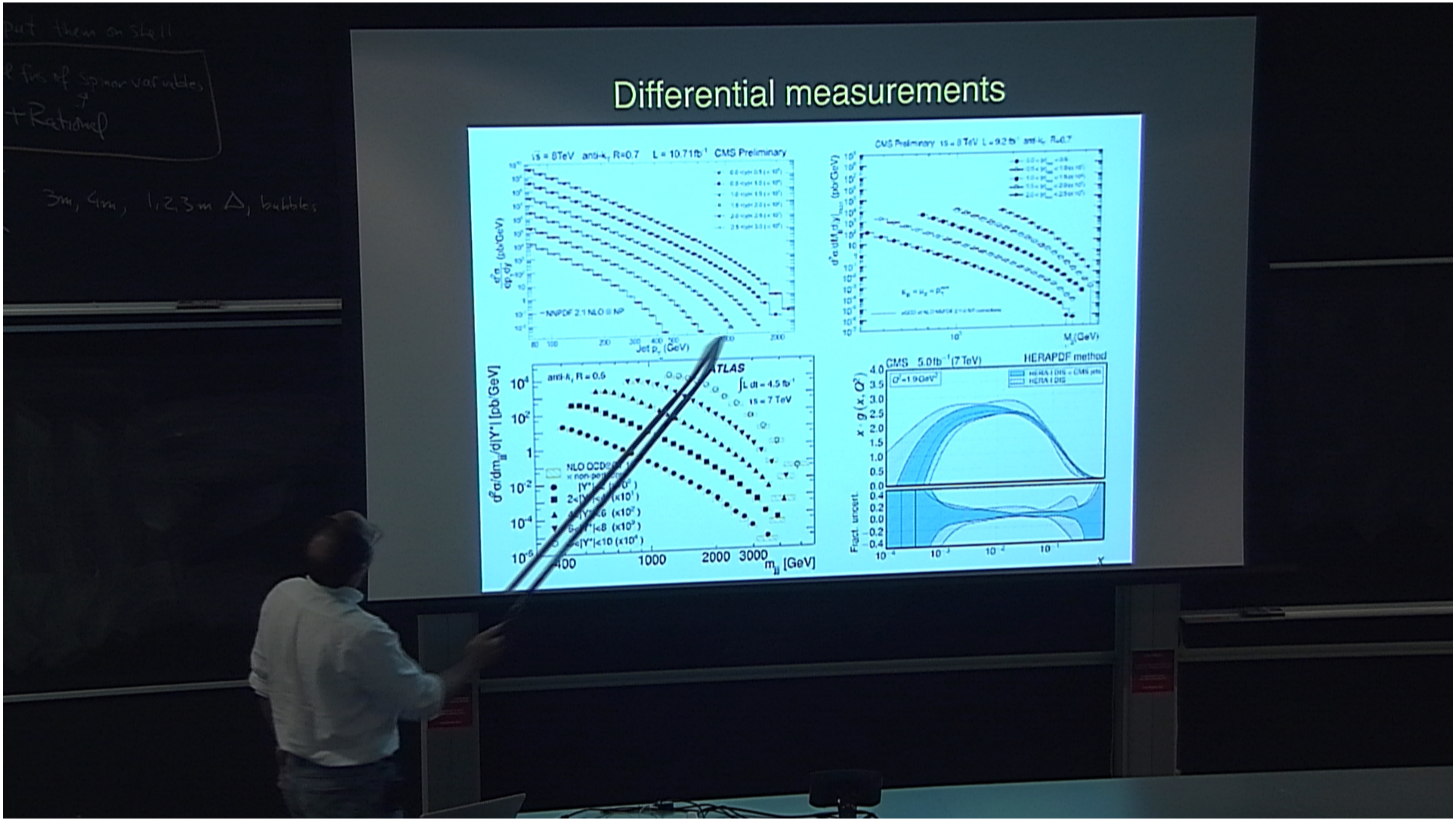
⇒ Total sea quark density enhanced by 8%
sbar/dbar PDF
NNPDF2.1 NLO
NNPDF2.1 NLO + ATLAS W/Z Data 30 pb⁻¹
ATLAS
epWZ fixed s
epWZ free s

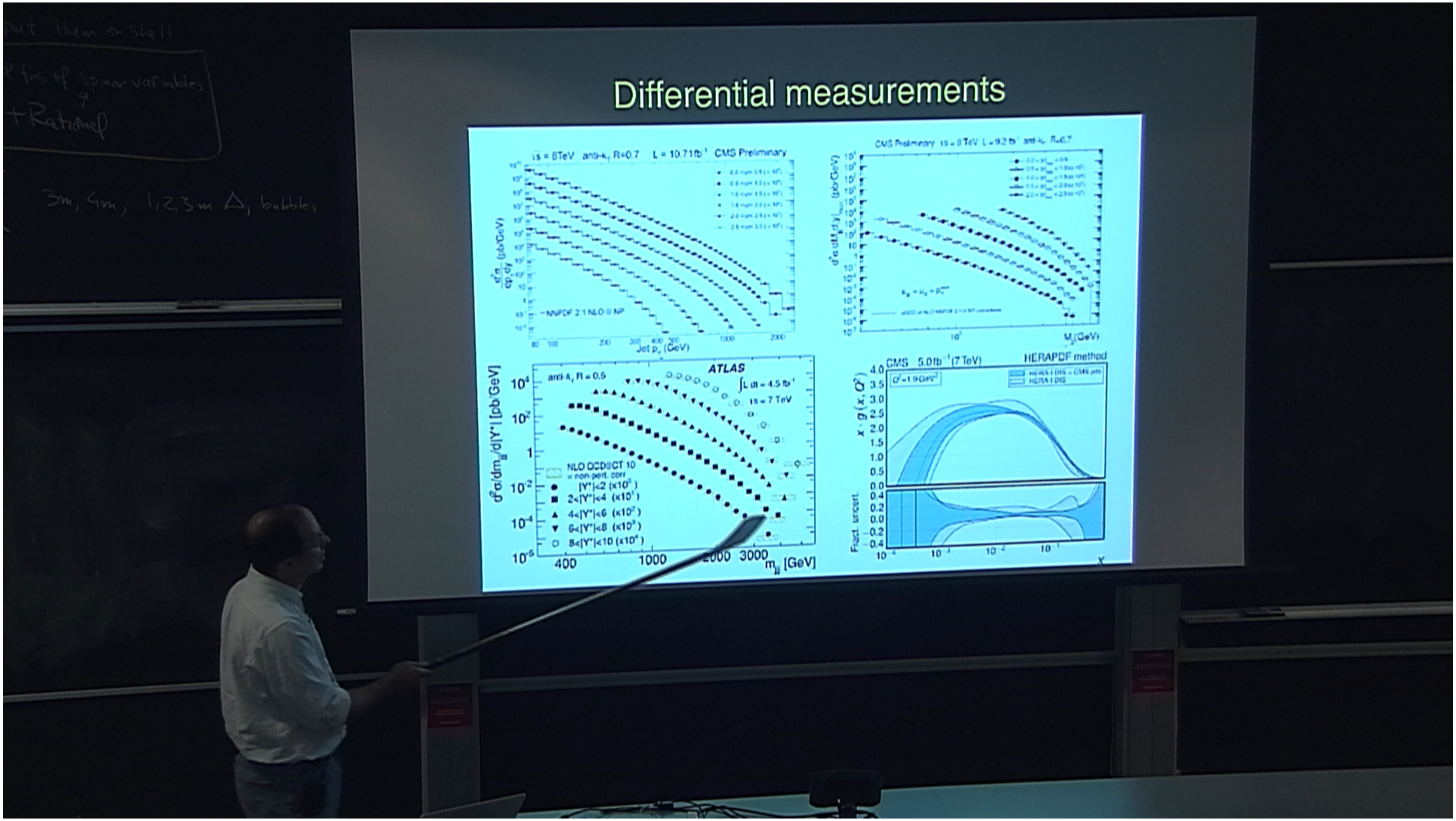

Jet Energy Scale and Resolution
ATLAS
Total uncertainty
Z+jet
γ+jet
Multijet balance
Fractional JES uncertainty
p_T^{jet} [GeV]
$\sqrt{s}$=7 TeV, L=35.9 pb^{-1}
CMS
PFJets
(Anti-k_T R=0.5)
0 < |η| ≤ 0.5
total systematic uncertainty
MC truth
data
jet p_T resolution
p_T [GeV]
21

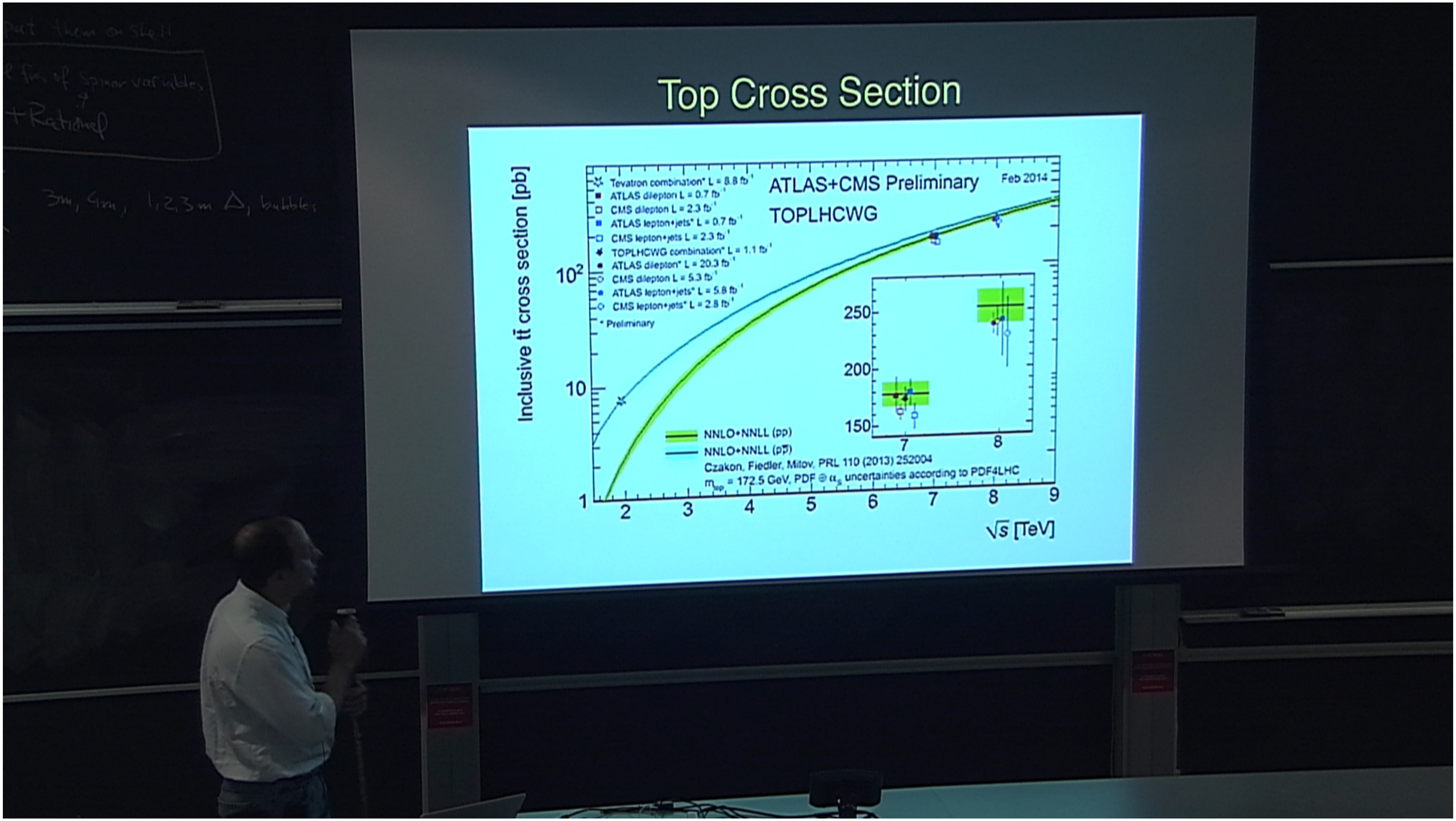

Jet Energy Scale and Resolution
ATLAS
Total uncertainty
Z+jet
γ+jet
Multijet balance
η-intercalibration
Single particle
Fractional JES uncertainty
CMS
PFJets
total systematic uncertainty
MC truth
data
jet p_T resolution
p_T [GeV]
21



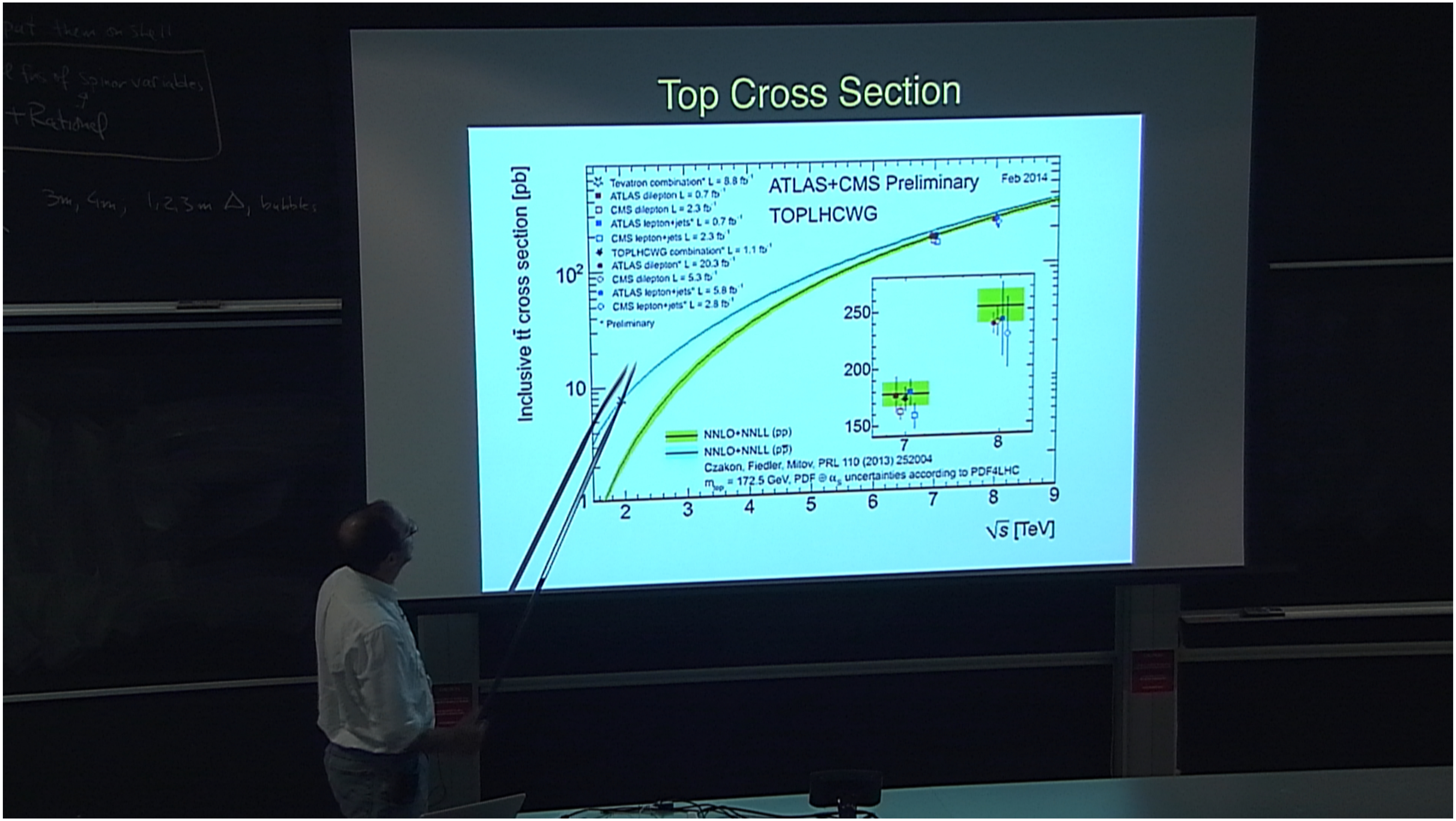
Jet production: differential measurements
+ Double differential inclusive P_T vs y distribution obtained from NLOJET++ QCD predictions describes generic features of data up to the TeV scale
+ Similarly, generic features of data dijet invariant mass distribution for various y range follow QCD NLOJET++ description up to the TeV scale, with no significant new resonance
JHEP 05 (2014) 059
ATLAS
p_T [GeV]
m_12 [TeV]
22


Differential measurements
CMS Preliminary
ATLAS
$\sqrt{s}$ = 7 TeV
Jet p_T (GeV)
m_{jj} [GeV]
CMS 5.0 fb^{-1} (7 TeV)
HERAPDF method
Fract. uncert.

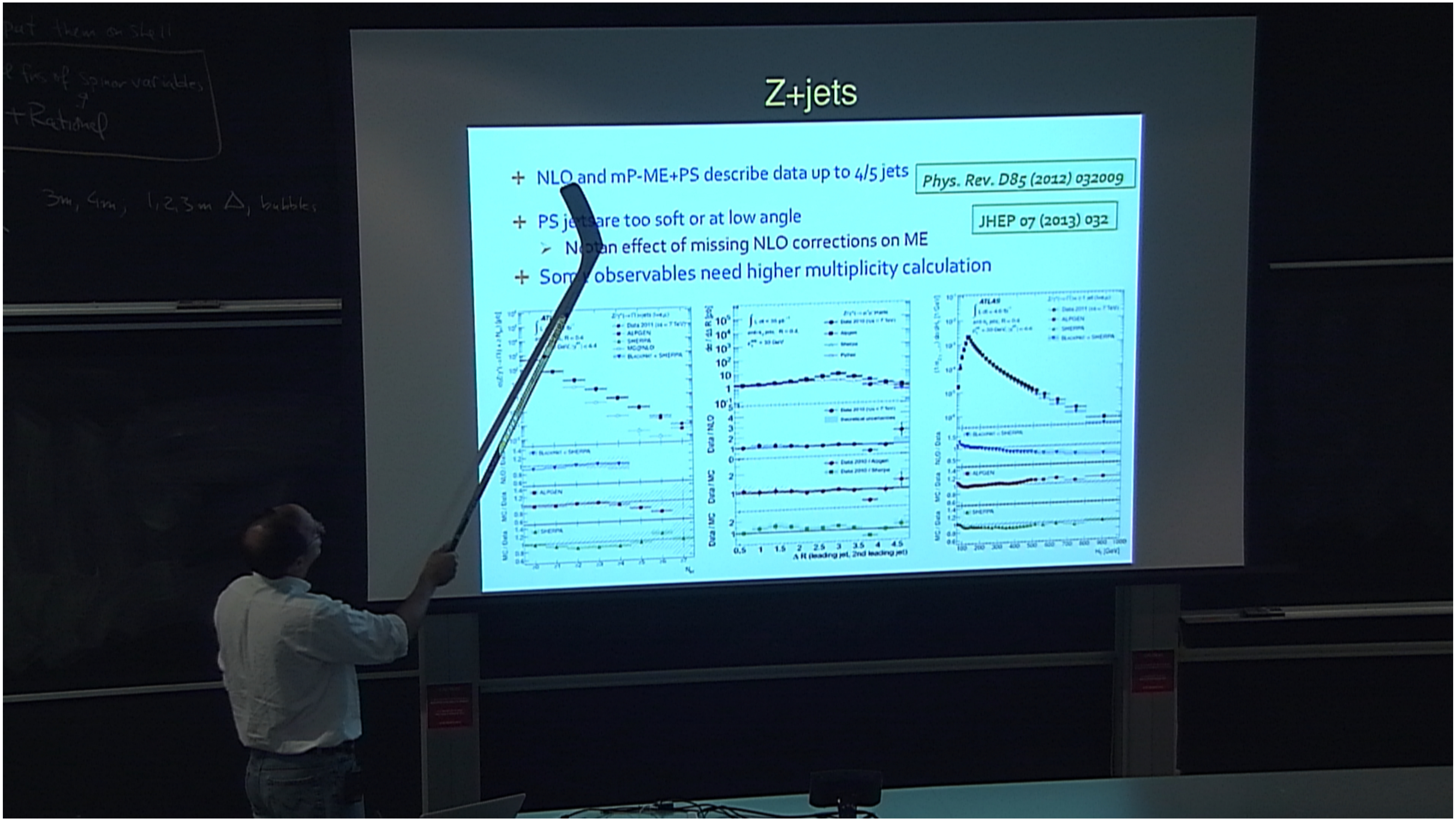

Differential measurements
CMS Preliminary
Jet p_T (GeV)
NNPDF 2.1 NLO ⊗ NP
ATLAS
anti-k_t R = 0.6
$\sqrt{s}$ = 7 TeV
NLO QCD⊗CT 10
⊗ non-pert. corr.
m_{jj} [GeV]
$d^2\sigma/dm_{jj}d|Y^*|$ [pb/GeV]
CMS 5.0 fb^{-1} (7 TeV)
HERAPDF method
$x \cdot g(x, Q^2)$
Fact. uncert.
3m, 4m, 1,2,3m △, bubbles
+Rational

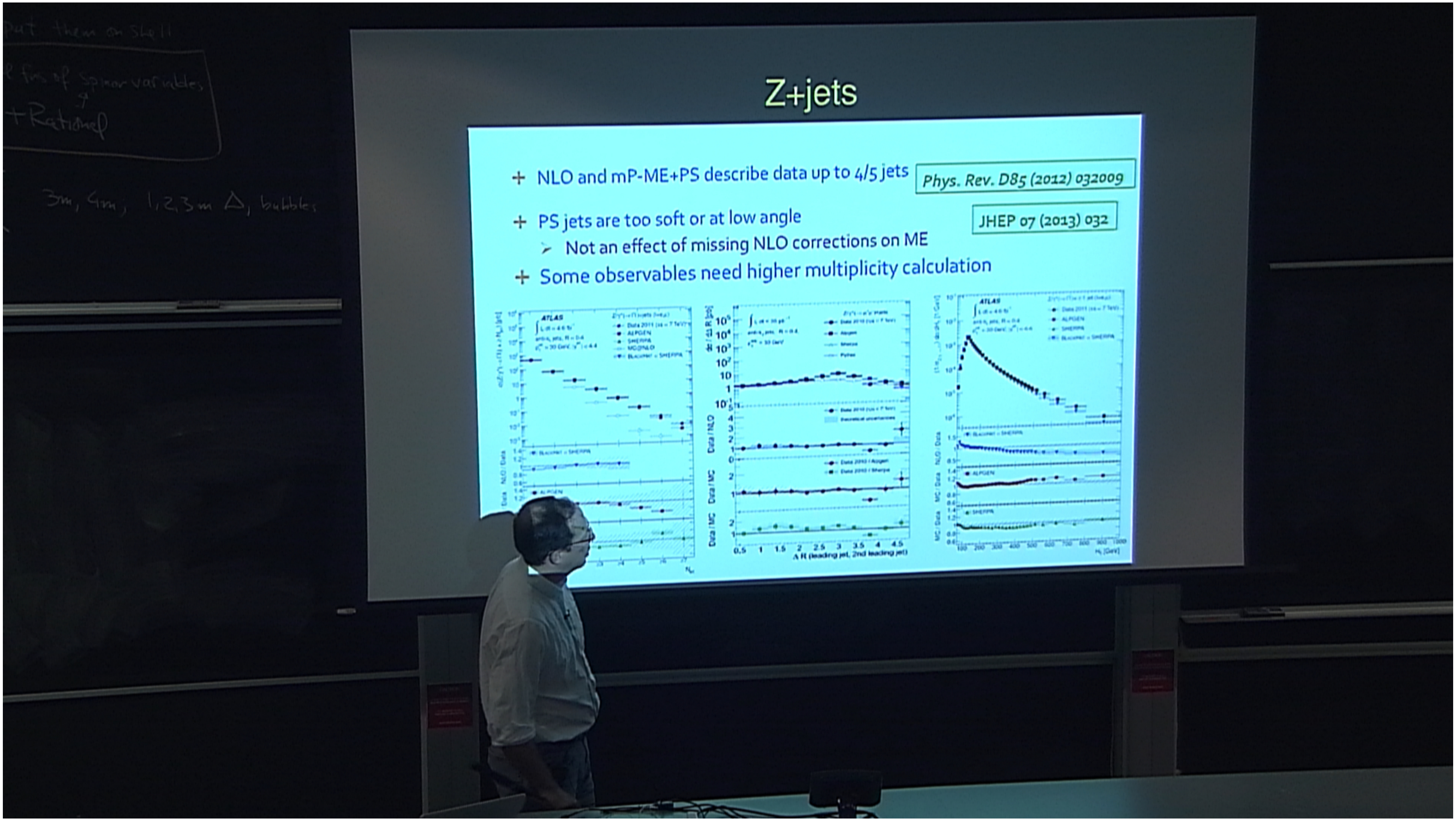


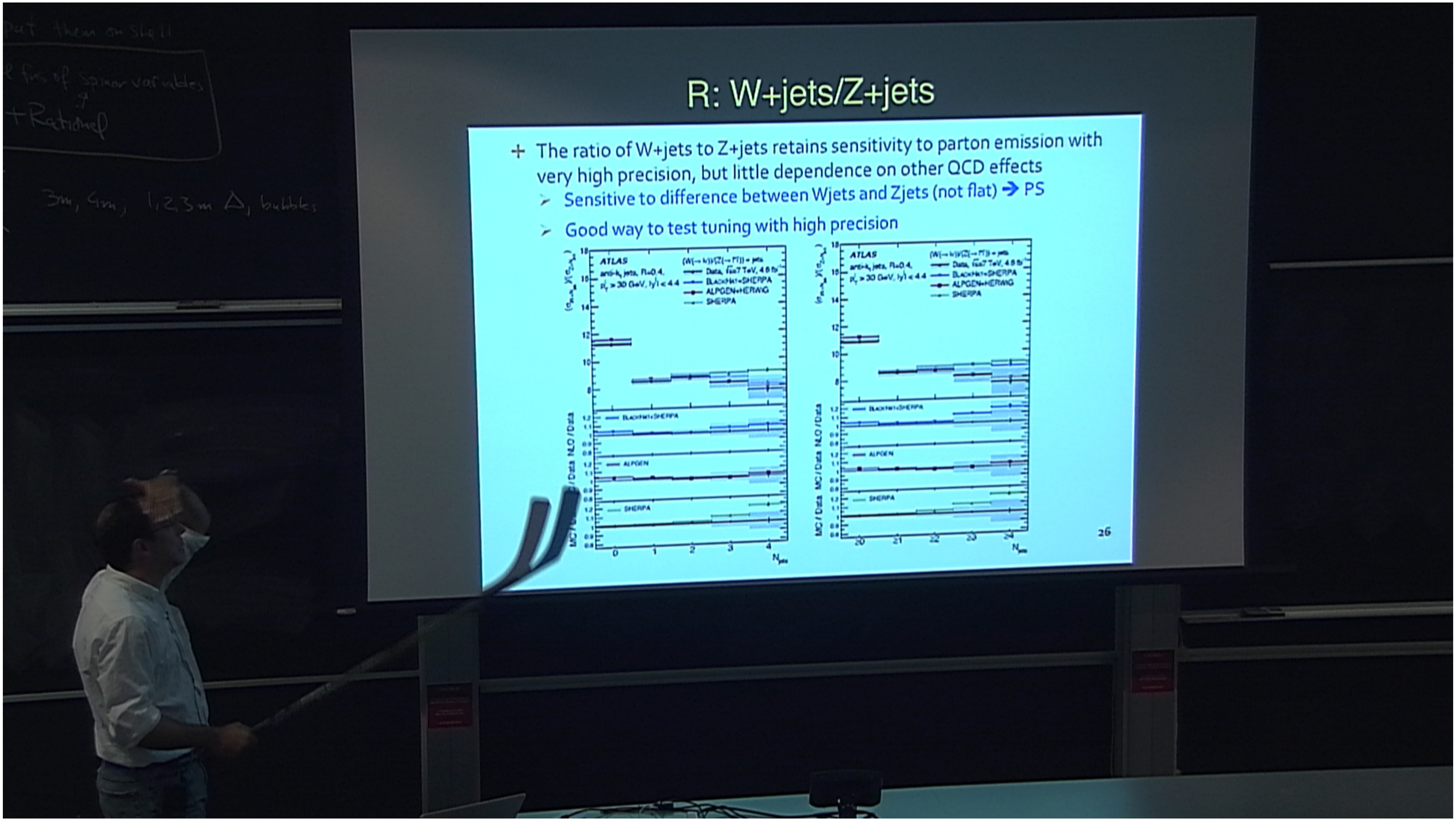
Top Cross Section
ATLAS+CMS Preliminary
TOPLHCWG
Feb 2014
Inclusive tt̄ cross section [pb]
√s [TeV]
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
* Preliminary

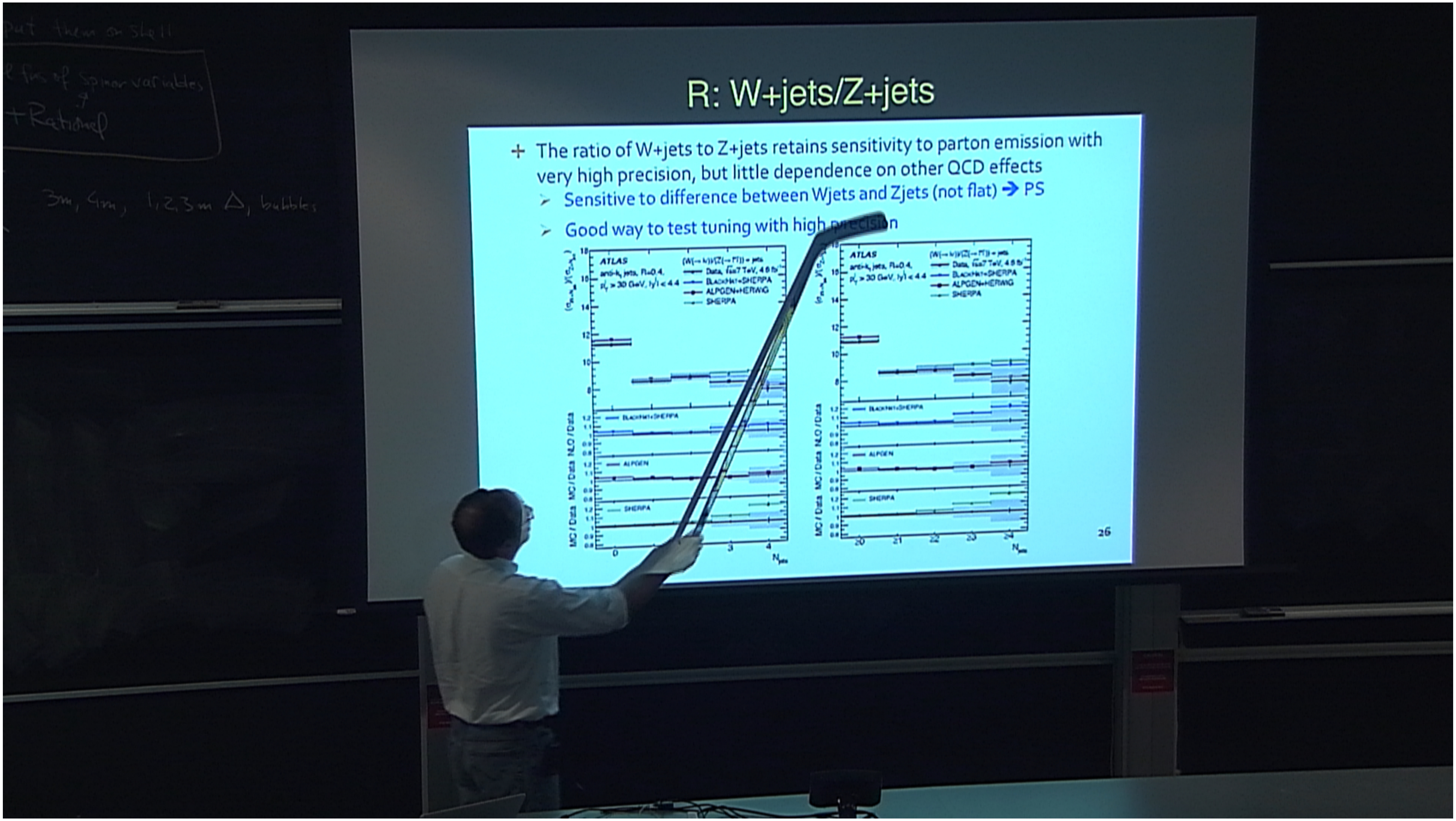


Top Cross Section
ATLAS+CMS Preliminary
TOPLHCWG
Feb 2014
Inclusive tt̄ cross section [pb]
Tevatron combination* L = 8.8 fb⁻¹
ATLAS dilepton L = 0.7 fb⁻¹
CMS dilepton L = 2.3 fb⁻¹
ATLAS lepton+jets* L = 0.7 fb⁻¹
CMS lepton+jets L = 2.3 fb⁻¹
TOPLHCWG combination* L = 1.1 fb⁻¹
ATLAS dilepton* L = 20.3 fb⁻¹
CMS dilepton L = 5.3 fb⁻¹
ATLAS lepton+jets* L = 5.8 fb⁻¹
CMS lepton+jets* L = 2.8 fb⁻¹
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_top = 172.5 GeV, PDF ⊕ α_s uncertainties according to PDF4LHC
√s [TeV]


Z+jets
NLO and mP-ME+PS describe data up to 4/5 jets
Phys. Rev. D85 (2012) 032009
JHEP 07 (2013) 032
are too soft or at low angle
an effect of missing NLO corrections on ME
observables need higher multiplicity calculation
ATLAS


Z+jets
+ NLO and mP-ME+PS describe data up to 4/5 jets
Phys. Rev. D85 (2012) 032009
+ PS jets are too soft or at low angle
JHEP 07 (2013) 032
➢ Not an effect of missing NLO corrections on ME
+ Some observables need higher multiplicity calculation
ATLAS
ALPGEN
SHERPA
Data / NLO
Data / MC
ΔR (leading jet, 2nd leading jet)


R: W+jets/Z+jets
+ The ratio of W+jets to Z+jets retains sensitivity to parton emission with very high precision, but little dependence on other QCD effects
➢ Sensitive to difference between Wjets and Zjets (not flat) → PS
➢ Good way to test tuning with high precision
ATLAS
ATLAS
26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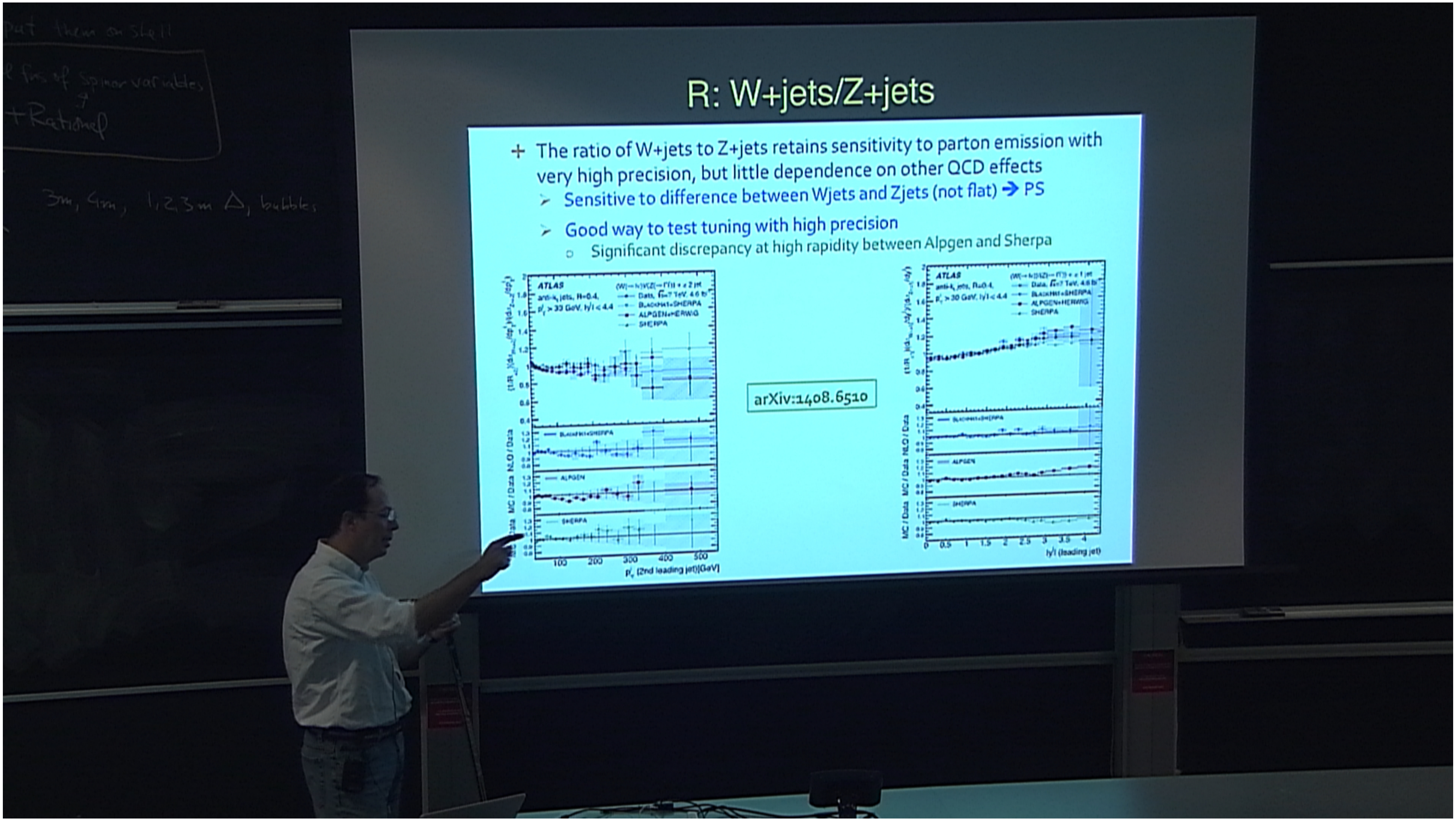
ATLAS
BLACKHAT+SHERPA
ALPGEN+HERWIG
SHERPA
MC / Data
26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The ratio of W+jets to Z+jets retains sensitivity to parton emission with very high precision, but little dependence on other QCD effects
Sensitive to difference between Wjets and Zjets (not flat) → PS
Good way to test tuning with high precision
Significant discrepancy at high rapidity between Alpgen and Sherpa
ATLAS
arXiv:1408.6510
ALPGEN
SHERPA
MC / Data NLO / Data
|y| (leading jet)
3m, 4m, 1,2,3m Δ, bubbles
+Rational

Conclusions

- QCD has been experimentally verified over a wide range of energies
- Precise QCD predictions required for various SM measurements and searches for new phenomana
  - At the LHC, higher cross section, smaller x and larger phase space for parton radiation might increase QCD uncertainties in Run-2
- An extensive set of measurements reached sufficient precision for testing state-of-the-art QCD calculations including
  - Inclusive W/Z cross section measurement used in PDF constraints
  - Differential cross section for various W/Z and W/Z+jets observable
  - Multijet and top-quark observables
  - W/Z+heavy flavor cross section measurements
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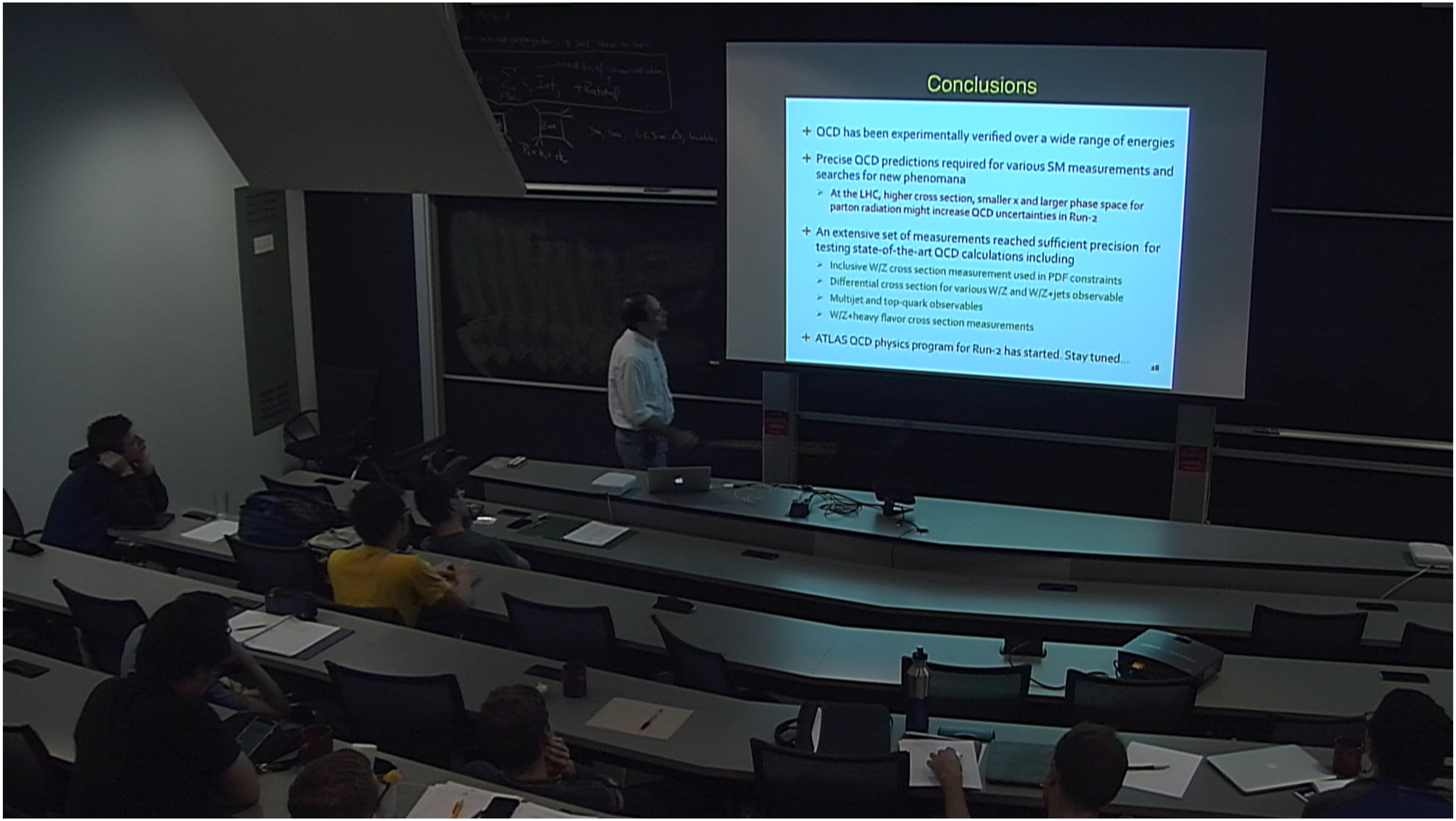
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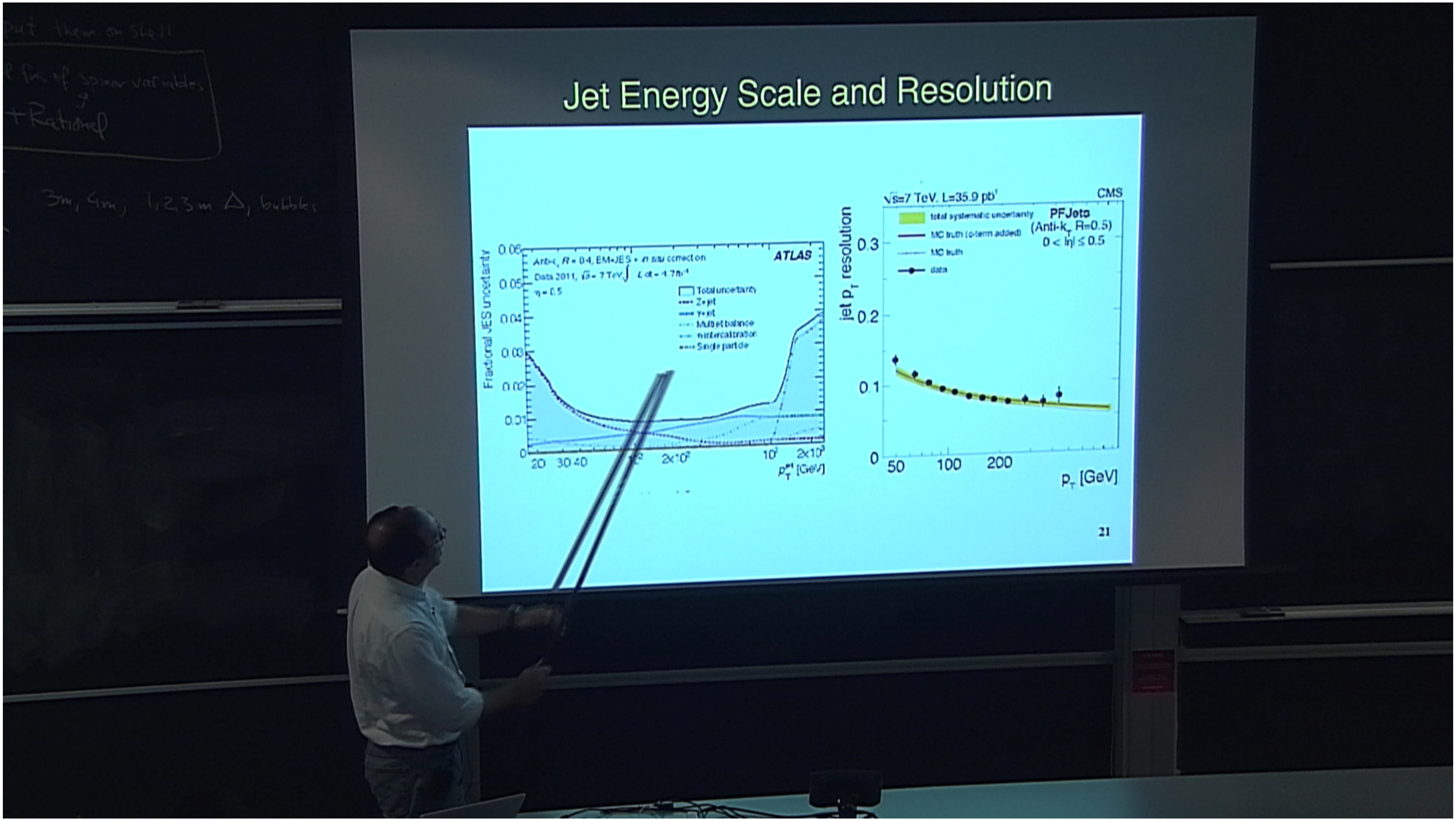
Jet Energy Scale and Resolution
ATLAS
Fractional JES uncertainty
Total uncertainty
Z+jet
γ+jet
Multijet balance
η-intercalibration
Single particle
CMS
PFJets
jet p_T resolution
total systematic uncertainty
MC truth
data
p_T [GeV]
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